e+p(A) physics with an electron collider at RHIC programme

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on behalf of the BNL
EIC Science Task Force
and friends

BROOKHAVEN
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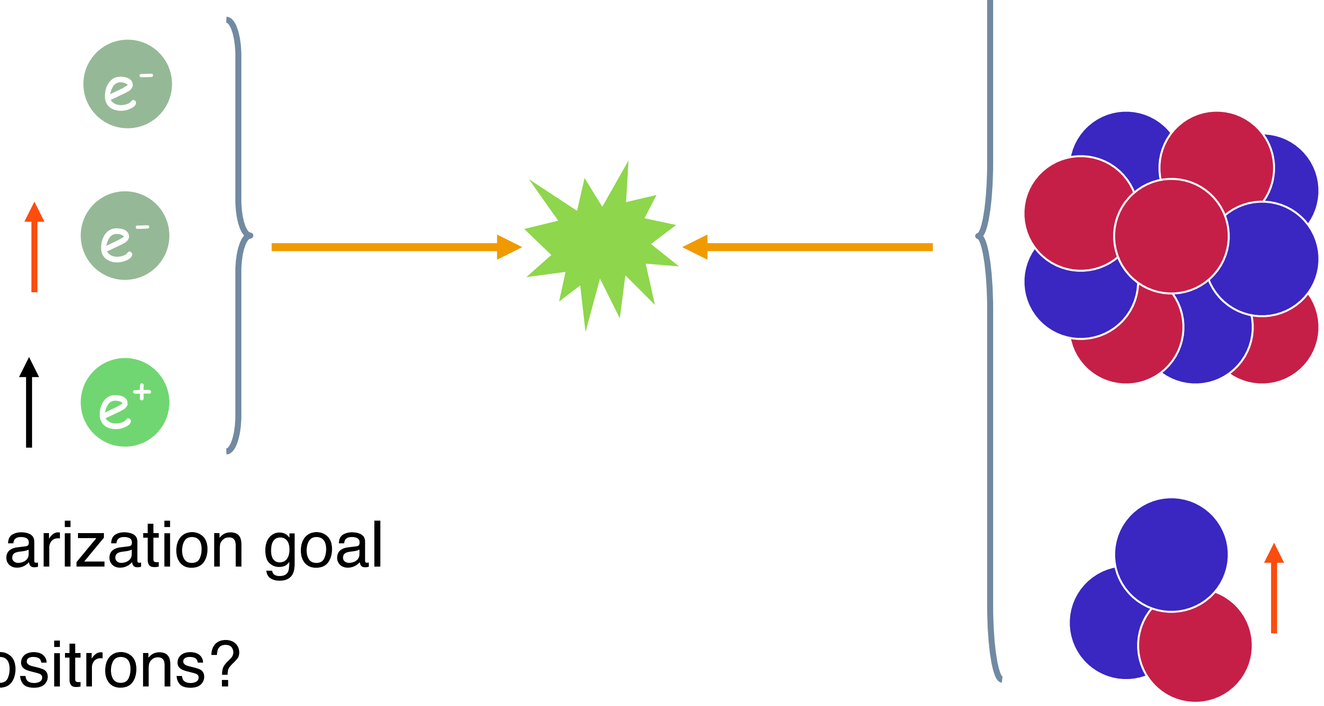
What is eRHIC?

Electron accelerator

to be built

Unpolarized and polarized leptons 5-20 (30) GeV



70% e^{-} beam polarization goal

polarized positrons?

RHIC

Existing = $2B

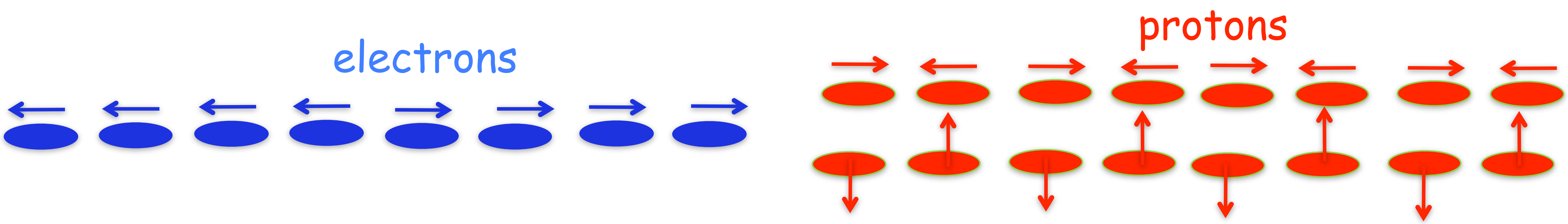
p

Polarized protons 50-250 GeV

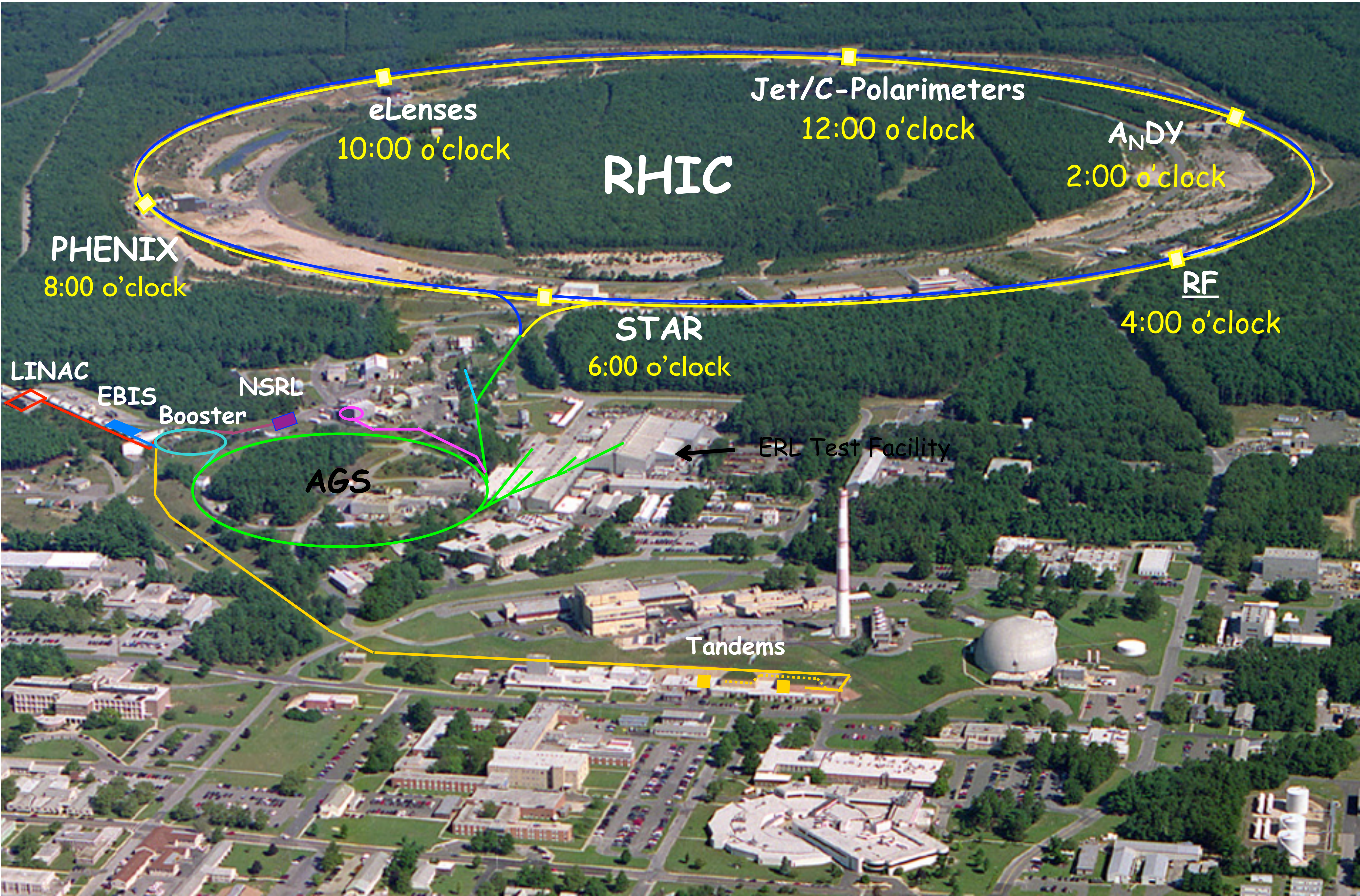
Light ions (d,Si,Cu) Heavy ions (Au,U) 50-100 GeV/u

Polarized light ions He^3 166 GeV/u

Centre-of-mass energy range: $\sqrt{s}$=30-200 GeV; L~100-1000xHera
longitudinal and transverse polarization for p/He^3 possible



From RHIC to eRHIC



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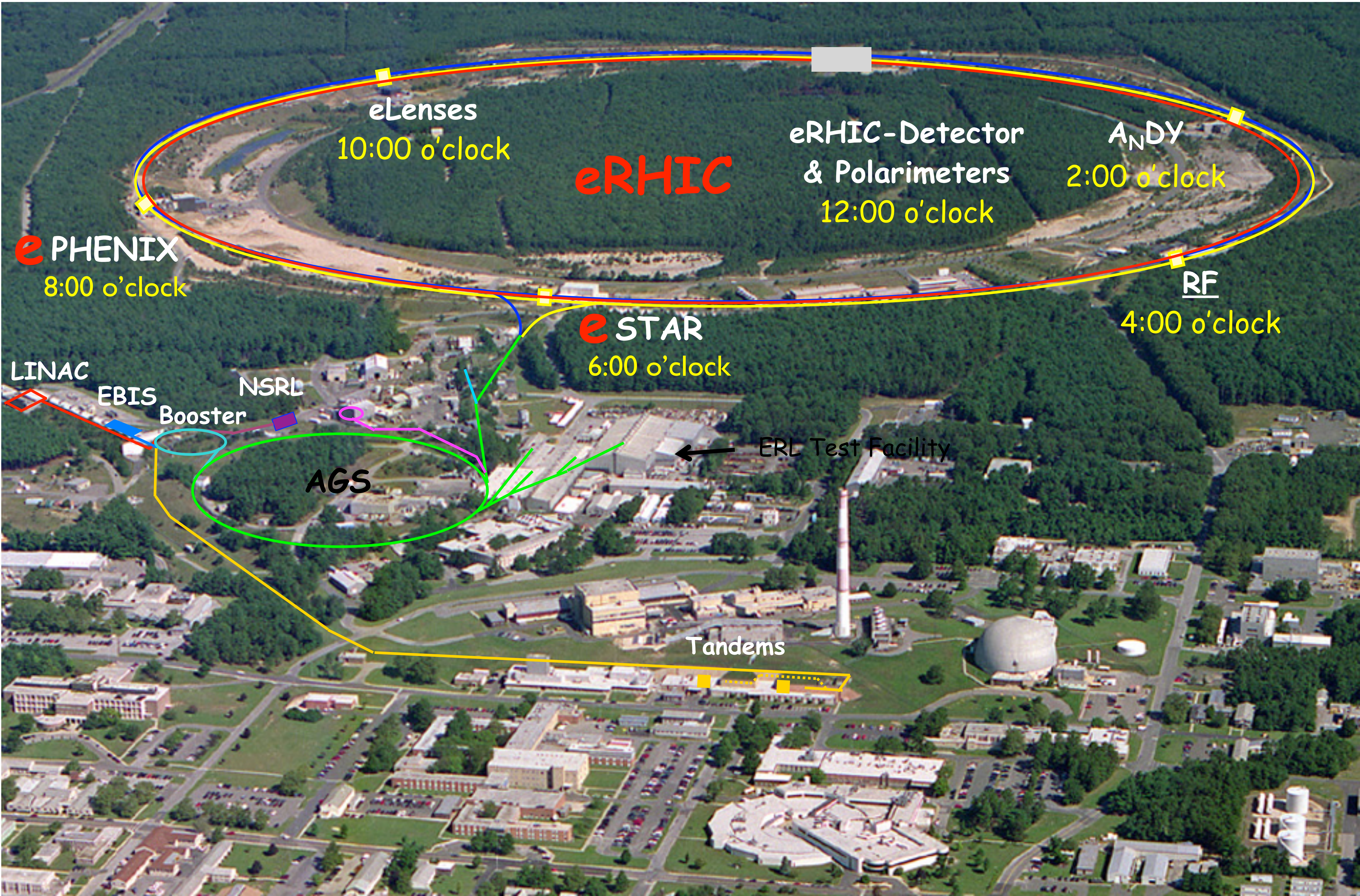
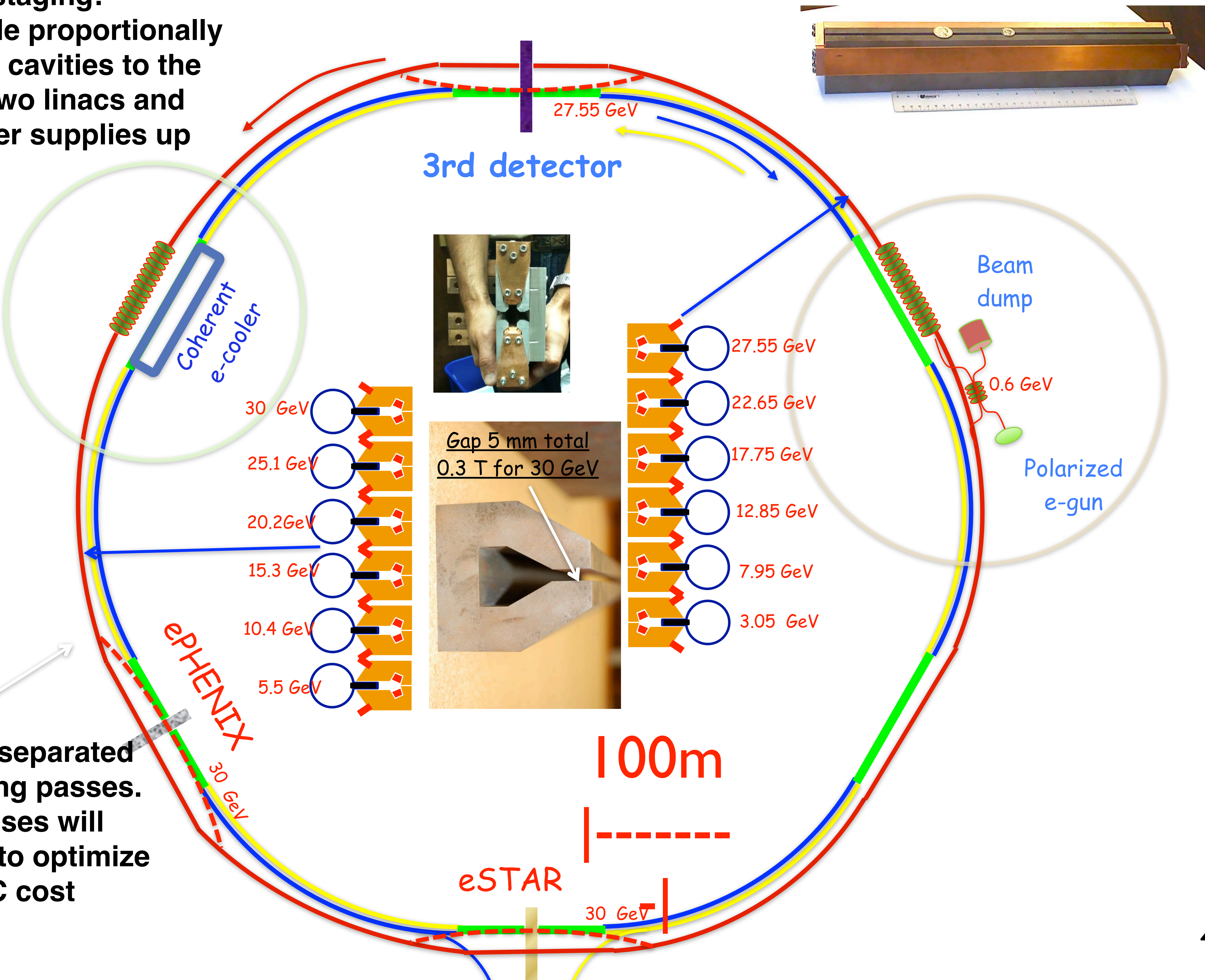


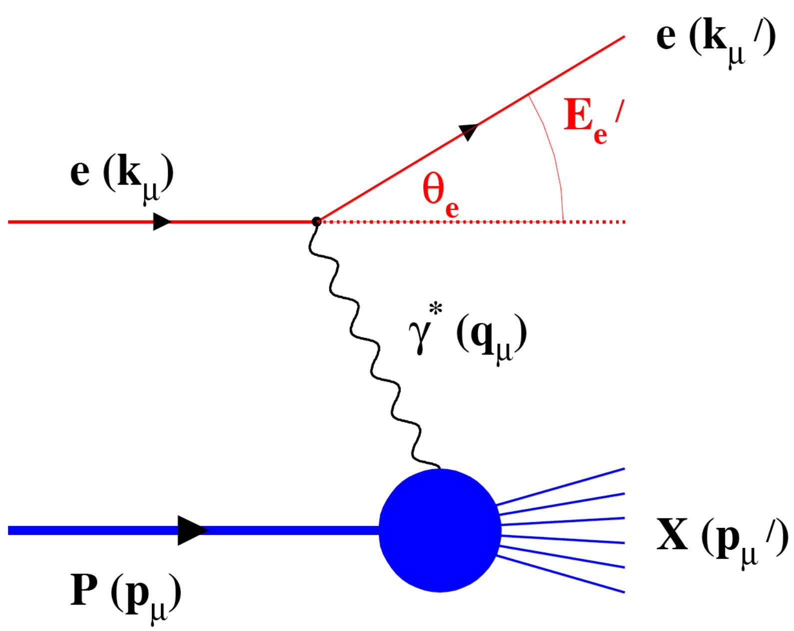
From RHIC to eRHIC

eRHIC staging:
All energies scale proportionally by adding SRF cavities to the injector and two linacs and cranking power supplies up



Vertically separated recirculating passes. # of passes will be chosen to optimize eRHIC cost

Detector requirements



Inclusive Reactions:

- Momentum/energy and angular resolution of e' critical
- Very good electron pid
- Moderate luminosity $>10^{32}$ cm^{-1} s^{-1}
- Need low x $\sim 10^{-4}$ → high $\sqrt{s}$ (Saturation and spin physics)

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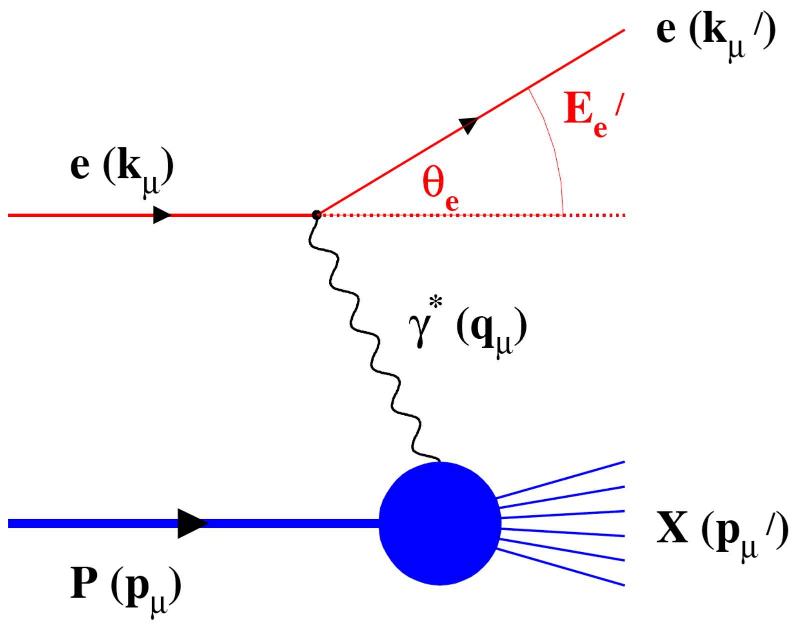

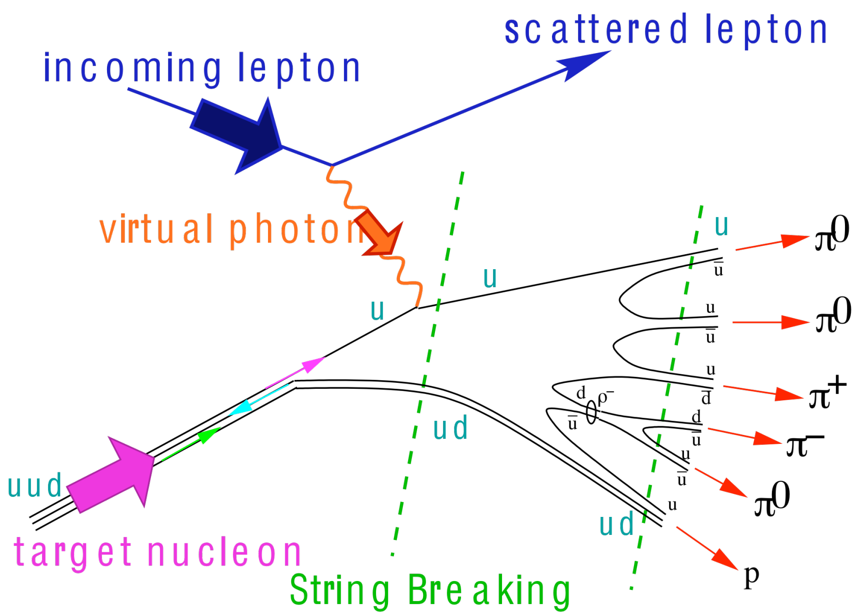

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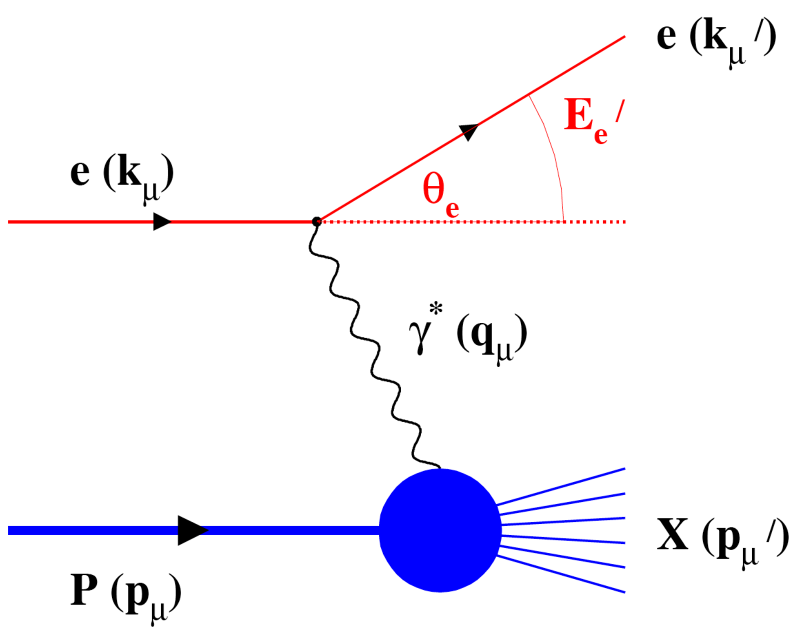
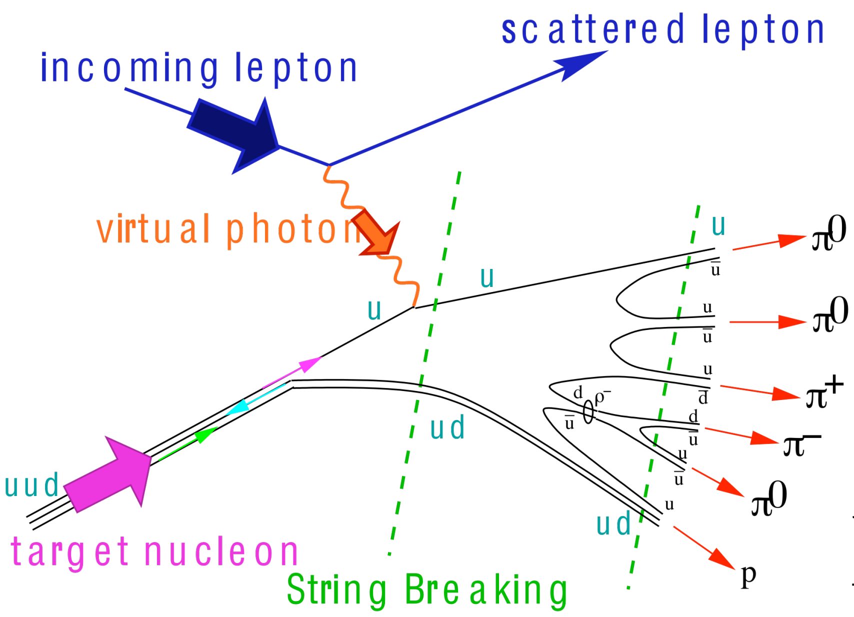
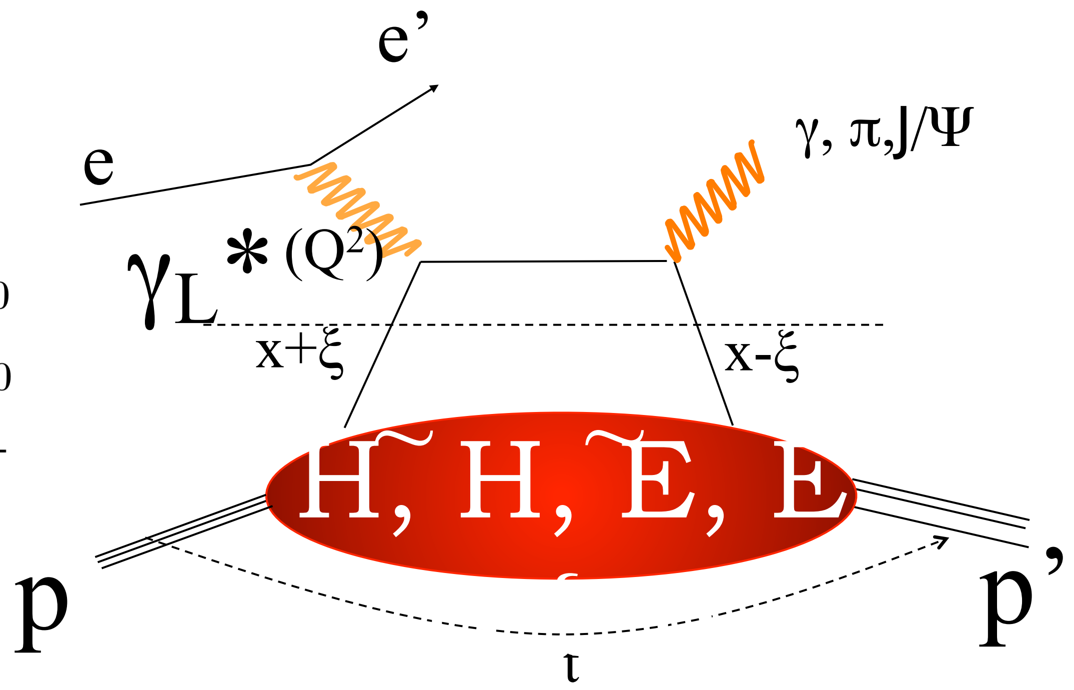
Semi-inclusive Reactions:

- Excellent particle ID: π,K,p separation over a wide range in η
- full Φ-coverage around γ^*
- Excellent vertex resolution $\rightarrow$ Charm, bottom identification
- high luminosity $>10^{33}$ cm^{-1} s^{-1} (5d binning (x,Q^2,z,p_t,Φ))
- Need low x $\sim 10^{-4}$ $\rightarrow$ high $\sqrt{s}$

Detector requirements







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Exclusive Reactions:

- Exclusivity → high rapidity coverage → rapidity gap events
- high resolution in t → Roman pots
- high luminosity >10^{33} cm^{-1} s^{-1} (4d binning (x,Q^2,t,Φ))

The pillars of the eRHIC physics programme

- Wide physics programme with demanding requirements on detector and machine performance

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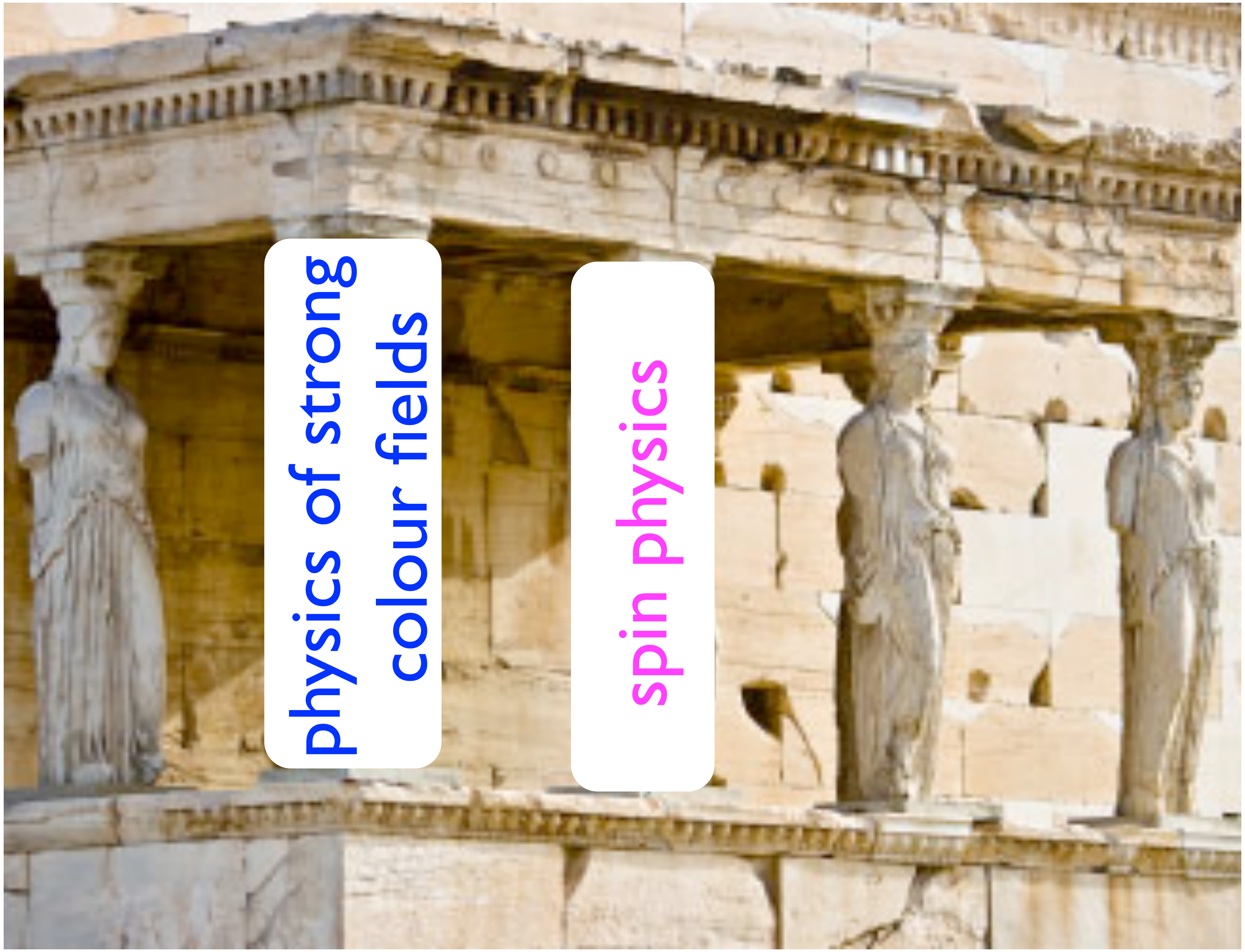
The pillars of the eRHIC physics programme



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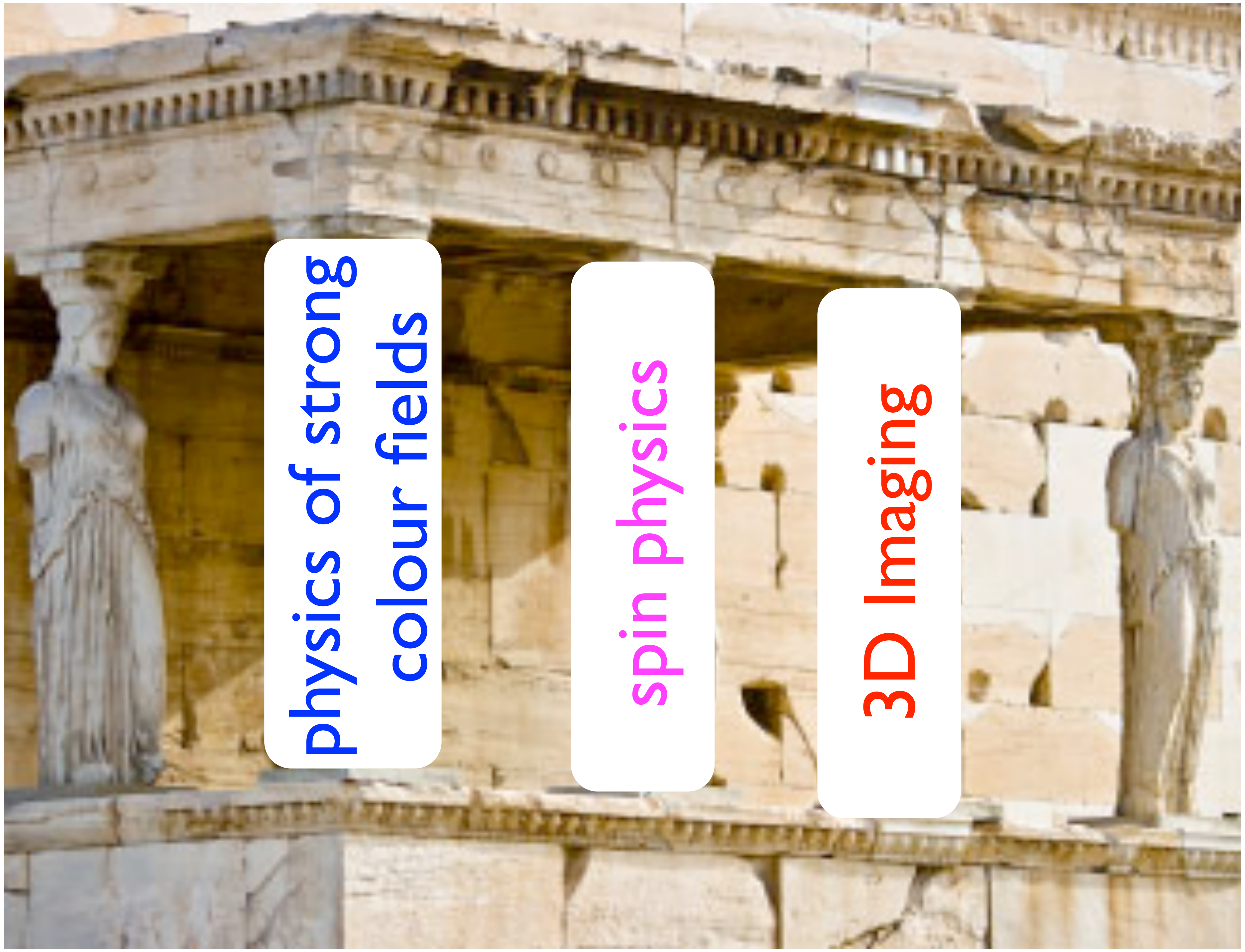

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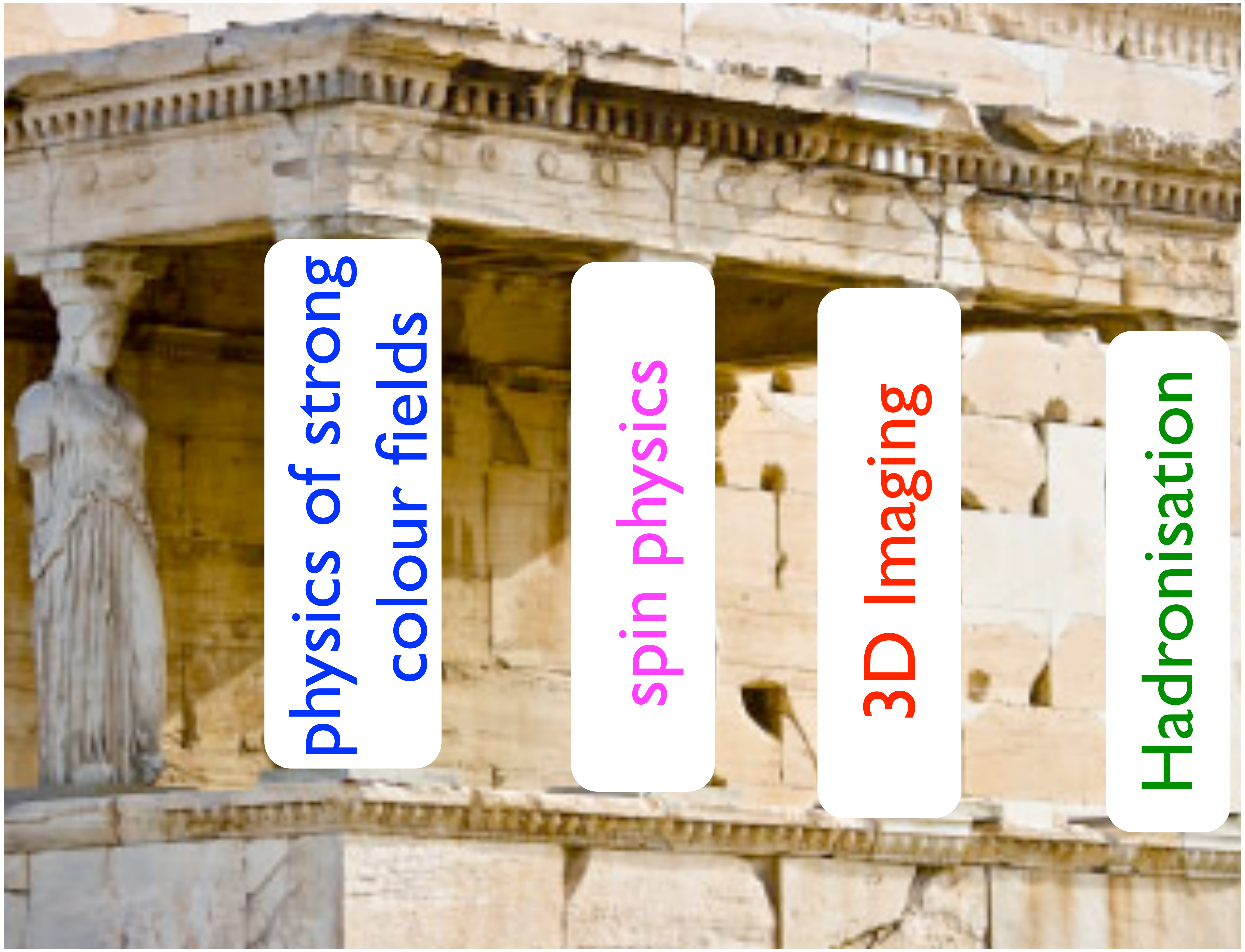

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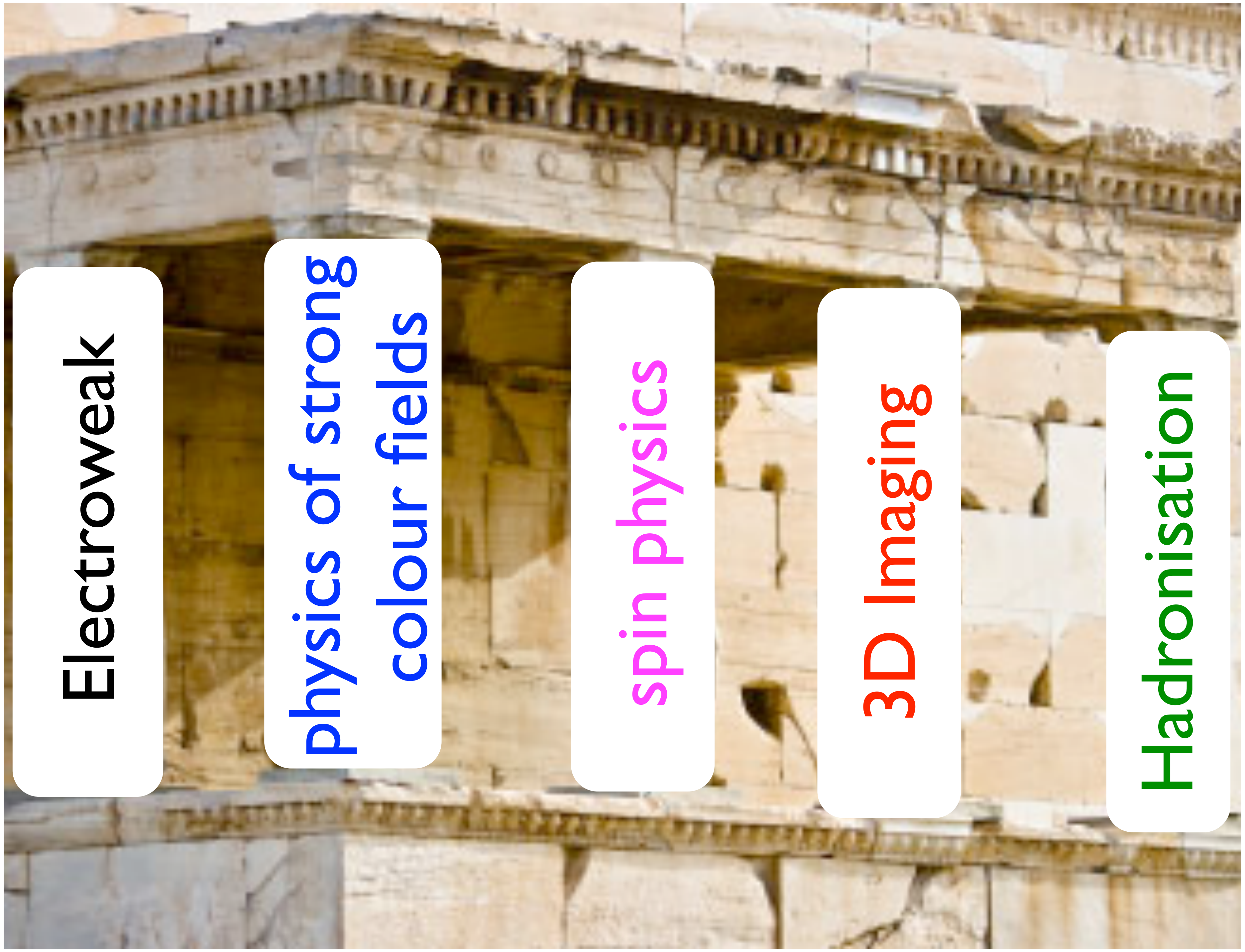

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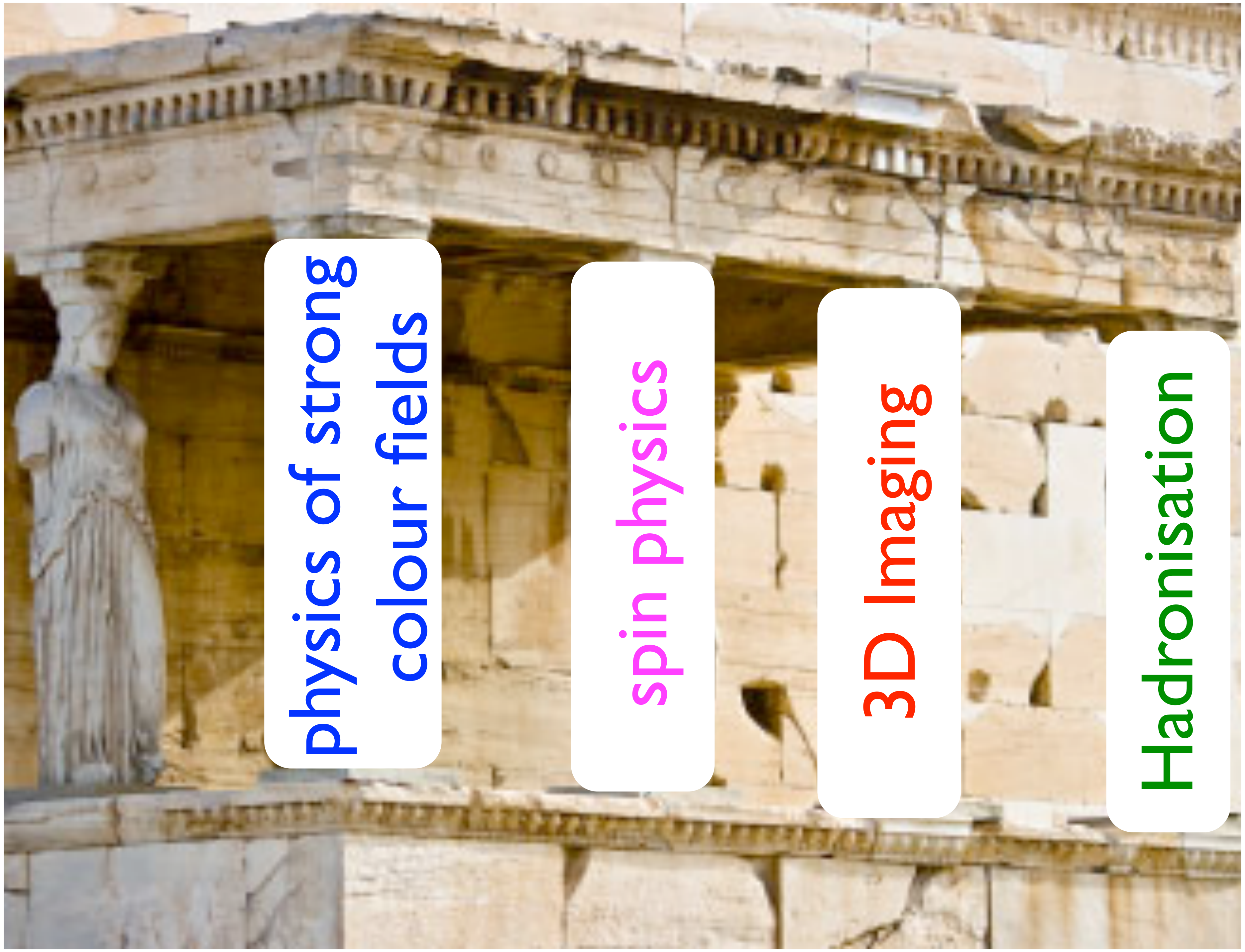

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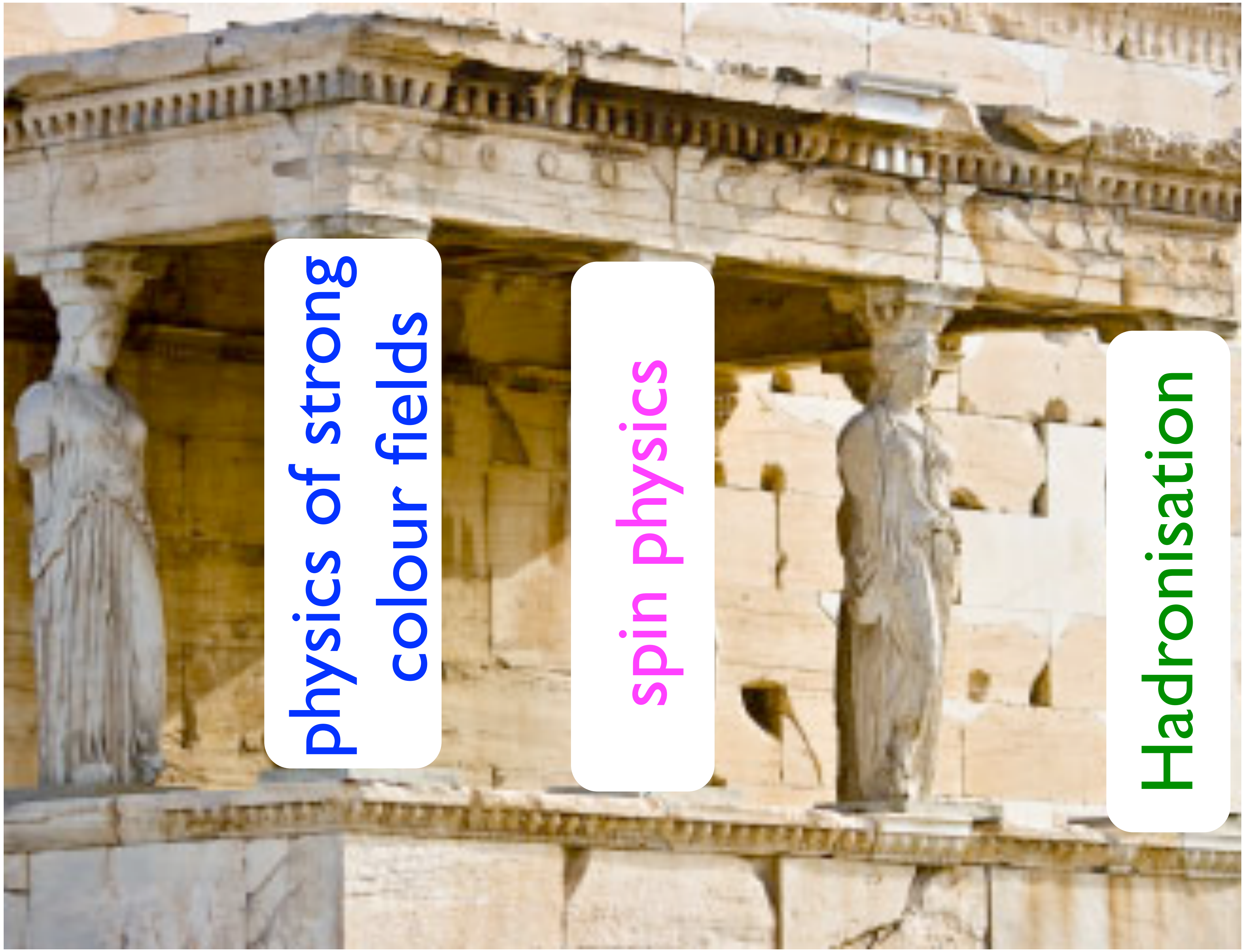
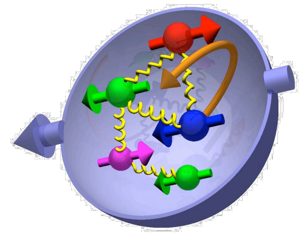


- Wide physics programme with demanding requirements on detector and machine performance

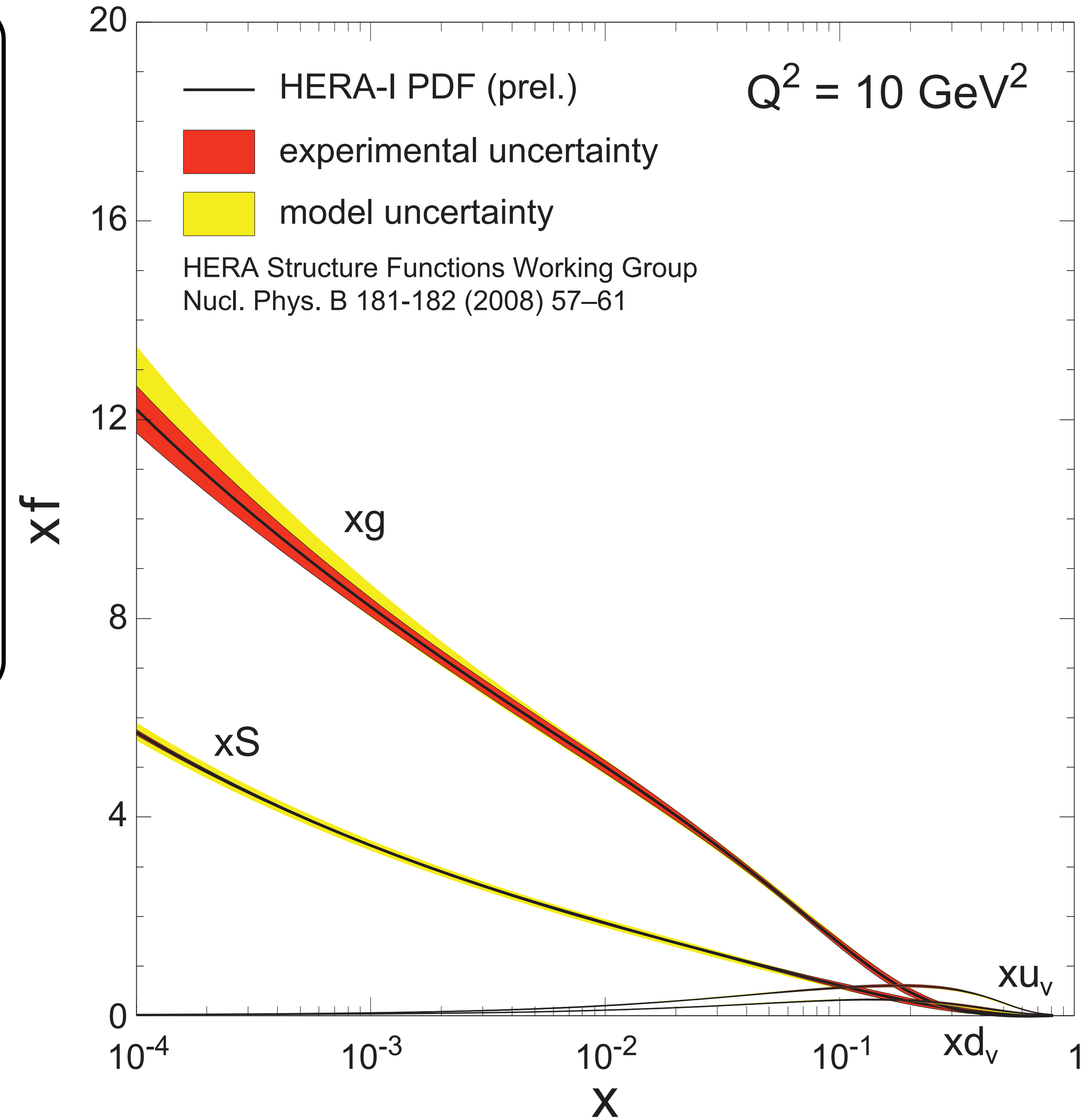
Most compelling physics questions

Spin physics



- What is the polarisation of gluons at small x where they dominate?
- What is the x-dependence and flavour decomposition of the polarised sea?

Determine quark and gluon contributions to the proton spin at last!!



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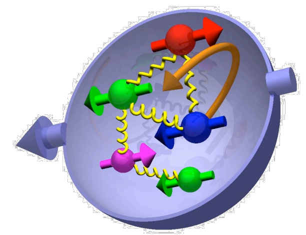

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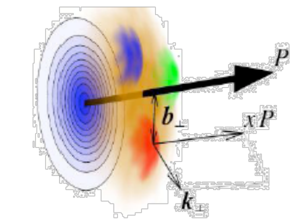
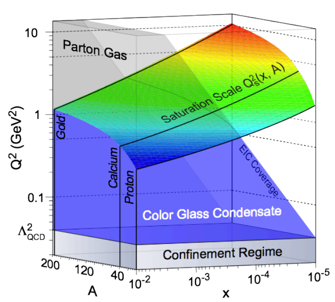
Imaging

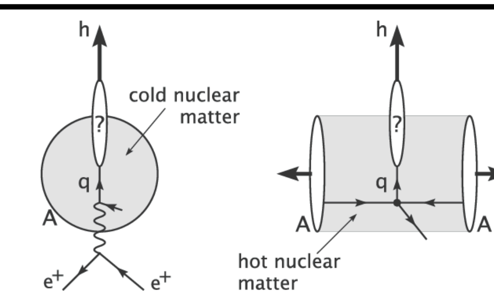


- What is the spatial distribution of quarks/ gluons in nucleons AND nuclei?
- Understand deep aspects of gauge theories revealed by k_T dependent distributions

Possible window to orbital angular momentum

Strong Colour Fields and Hadronisation





- Quantitatively probe the universality of strong colour fields in A+A, p+A and e+A
- Understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- How do hard probes in e+A interact with the medium?

Currently have no experimental knowledge of gluons in nuclei at small x!!

spin physics

10 week INT programme - Fall 2010

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Talks online

Application form

Exit report

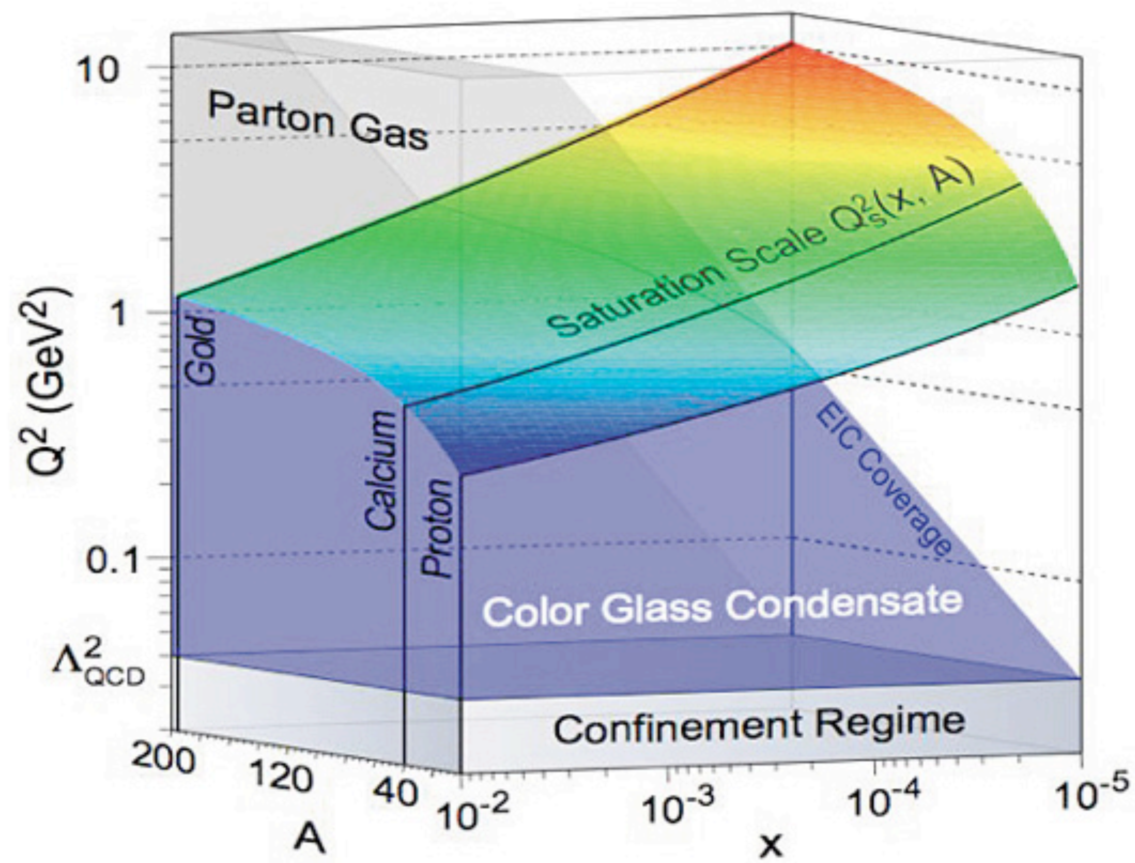
Friends of the INT

Obtain an INT preprint number

INT homepage

Gluons and the quark sea at high energies: distributions, polarization, tomography

September 13 to November 19, 2010



This INT program will address open questions about the dynamics of gluons and sea quarks in the nucleon and in nuclei. Answers to these questions are crucial for a deeper understanding of hadron and nuclear structure in QCD at high energies. Many of them are relevant for understanding QCD final states at the LHC, which often provide a background for physics beyond the standard model. The topics addressed in this program have important ramifications for understanding the matter produced in heavy-ion collisions at RHIC and the LHC.

http://www.int.washington.edu/PROGRAMS/10-3/

10 week INT programme - Fall 2010

week	dates	topics
1	13–17 Sept	**Workshop** on "Perturbative and Non-Perturbative Aspects of QCD at Collider Energies" Agenda
2	20–24 Sept	open conceptual issues: factorization and universality, spin and flavor structure, distributions and correlations Agenda
3–5	27 Sept – 15 Oct	small x, saturation, diffraction, nuclear effects; connections to p+A and A+A physics; fragmentation/hadronization in vacuum and in medium Agenda for week 3 Agenda for week 4 Agenda for week 5
6–7	18–29 Oct	parton densities (unpolarized and polarized), fragmentation functions, electroweak physics Agenda for week 6 Agenda for week 7
8–9	1–12 Nov	longitudinal and transverse nucleon structure; spin and orbital effects (GPDs, TMDs, and all that) Agenda for week 8 Agenda for week 9
10	16–19 Nov	**Workshop** on "The Science Case for an EIC" Agenda for week 10

http://www.int.washington.edu/PROGRAMS/10-3/

Golden measurements in spin

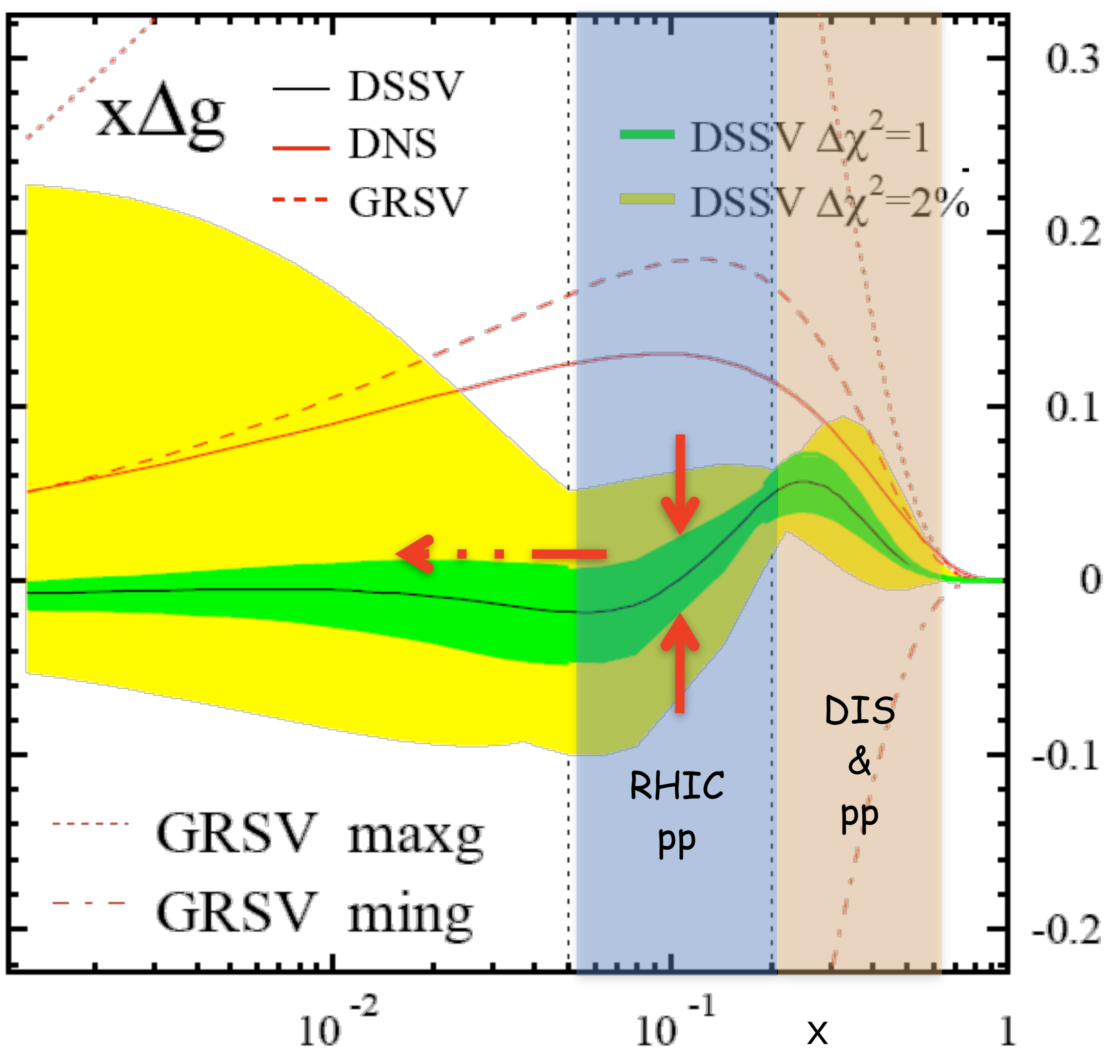
Deliverables	Observables	What we learn	Requirements
polarised gluon distribution Δg	scaling violations in inclusive DIS	gluon contribution to the proton spin	coverage down to x $\sim 10^{-4}$; $\mathcal{L}$ of about 10 fb^{-1}
polarised quark and antiquark densities	semi-incl. DIS for pions and kaons	quark contr. to proton spin; asym. like $\Delta\bar{u}$-$\Delta\bar{d}$; Δs	similar to DIS; good particle ID
novel electroweak spin structure functions	inclusive DIS at high Q^2	flavour separation at medium-x and large Q^2	$\sqrt{s} \geq 100$ GeV; $\mathcal{L} \geq 10\ fb^{-1}$; positrons; polarised ^3He beam

The quest for Δg - where do we stand?

- inclusive pions and jets remain the main probes
- jet/hadron correlations are essential to cover smaller x

current status:

DSSV global fit
de Florian, Sassot, MS, Vogelsang

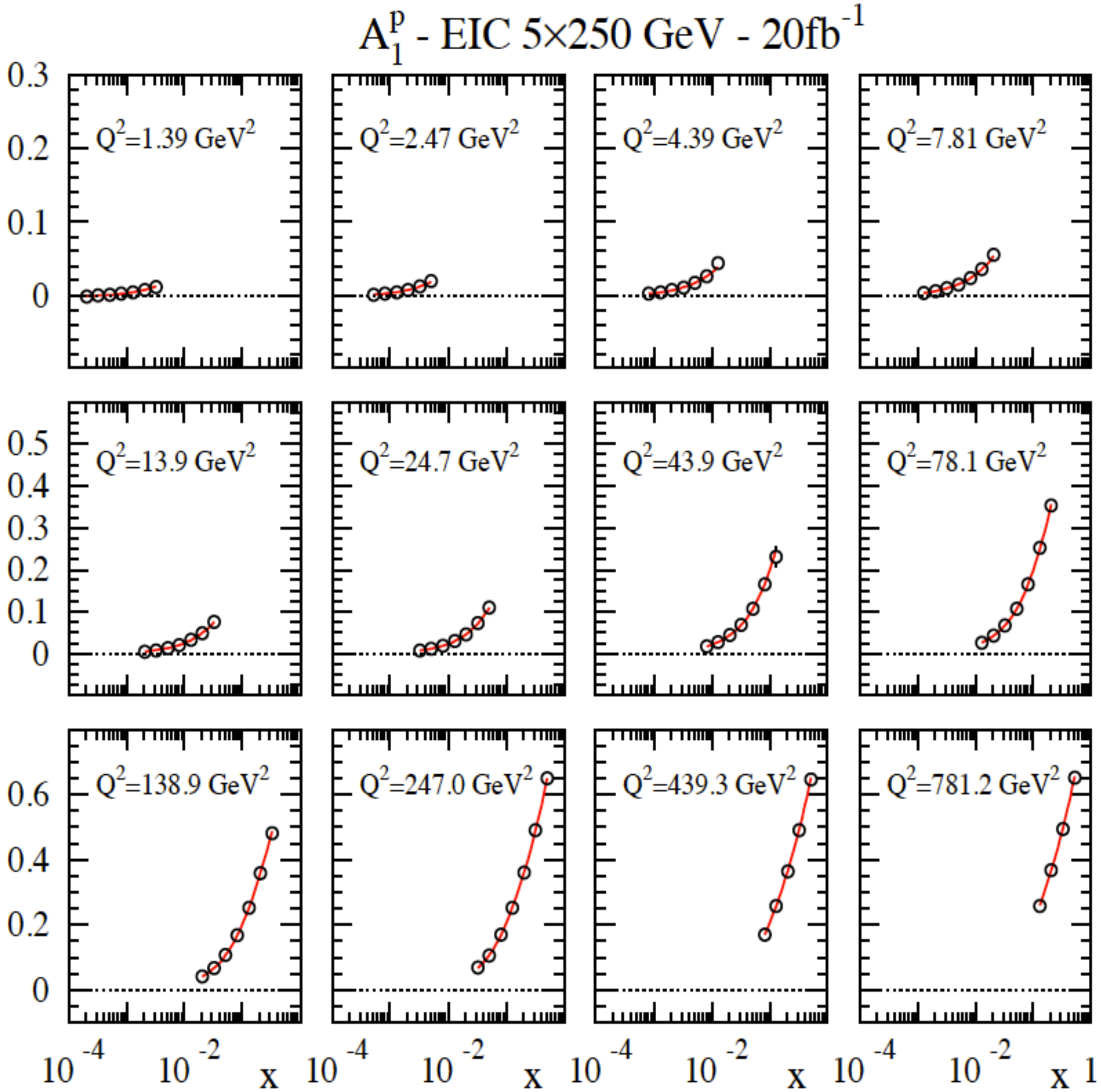


DSSV includes "only" RHIC run6 data

- low-x behaviour is unconstrained
  - ➡ significant polarisation still possible
  - ➡ no reliable error estimate for 1st moment
- By 2015 - expect to have:
  - ➡ DSSV 2.0 global analysis on new world data
  - ➡ reduced uncertainties in Δg in current x range
  - ➡ evidence of a node further scrutinised
  - ➡ extend x-range towards lower x
    - 500 GeV running and particle correlations

The quest for Δg - what can we do at eRHIC?

strategy to quantify impact: global QCD fits with realistic pseudo-data



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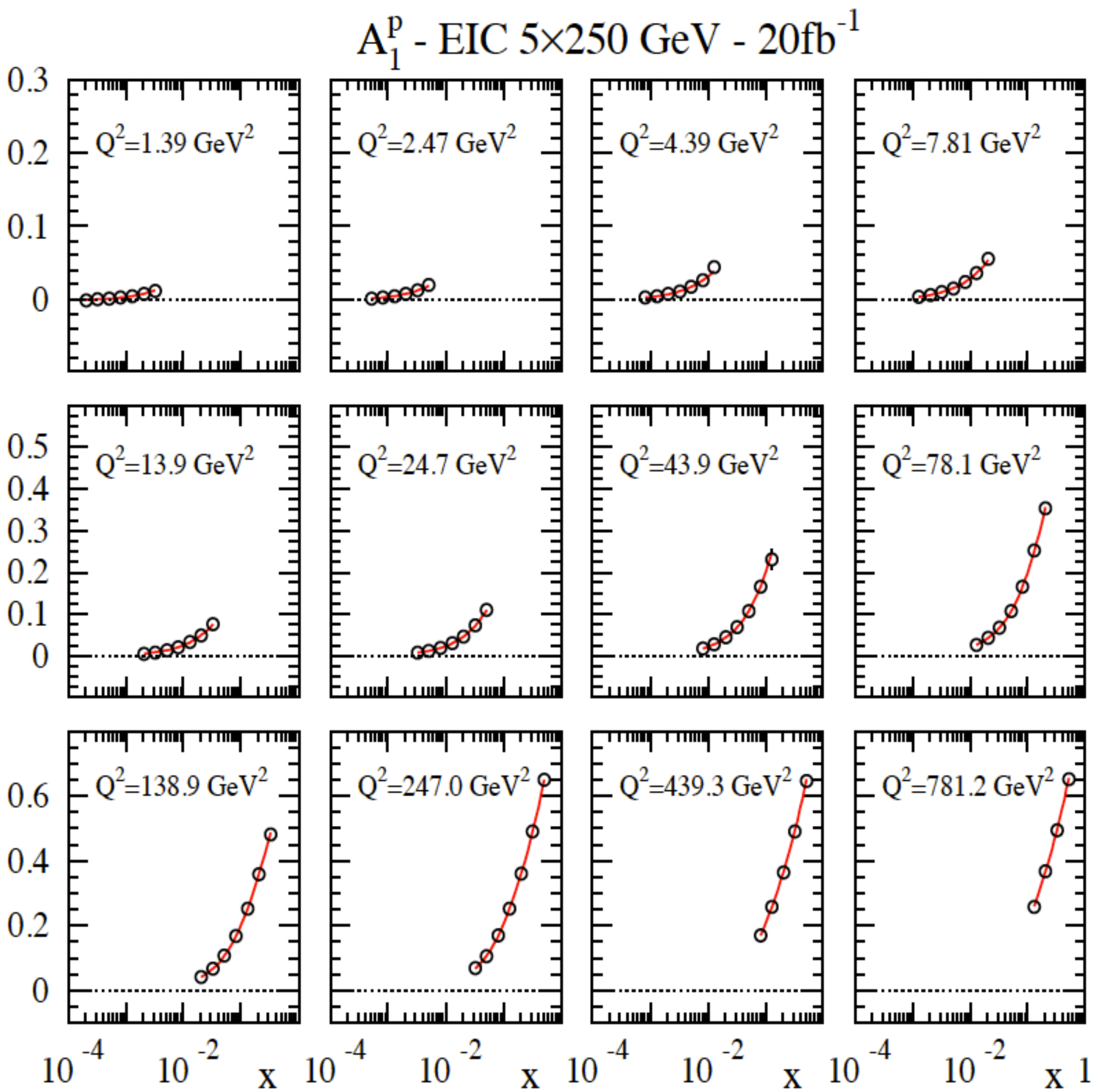

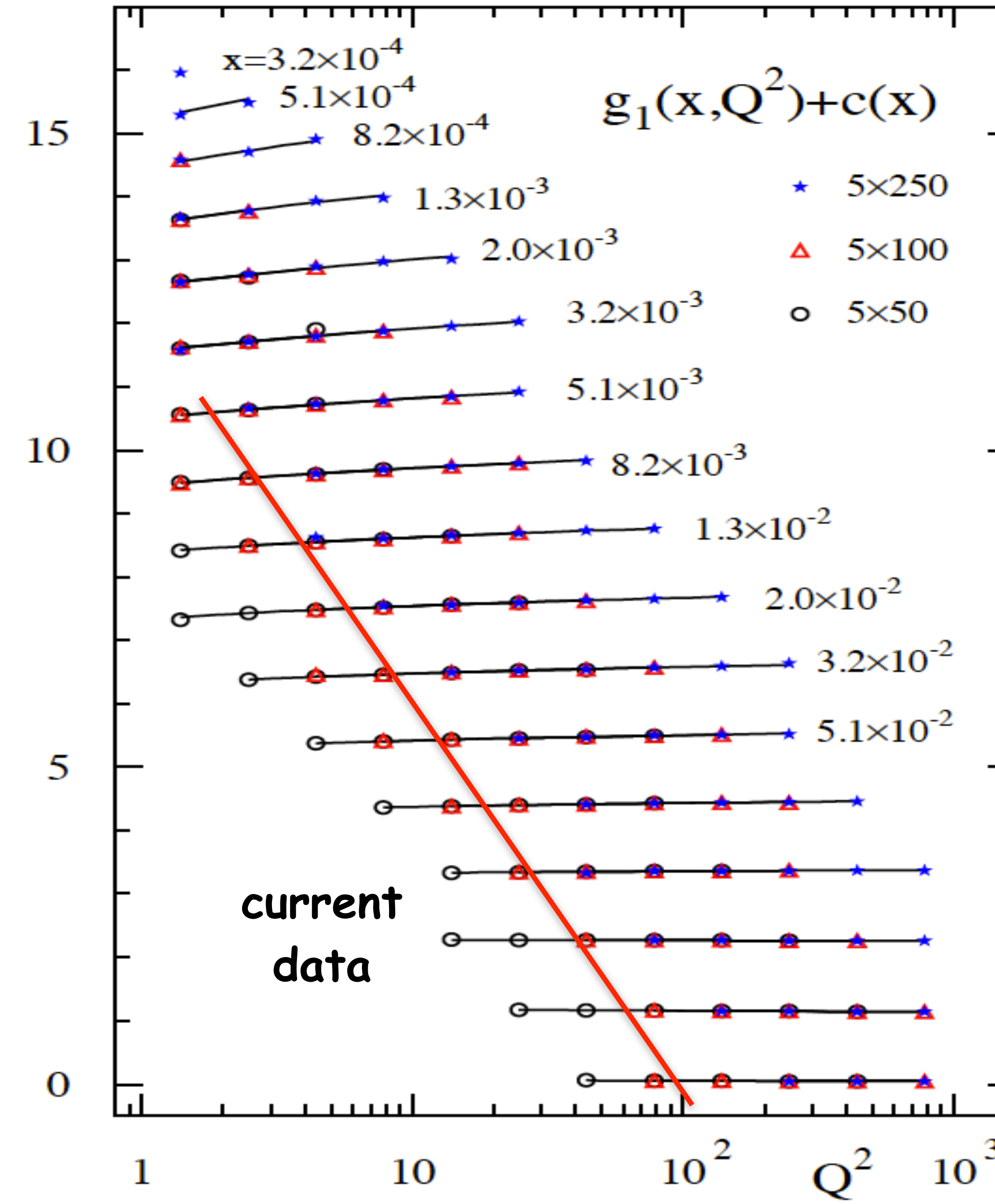

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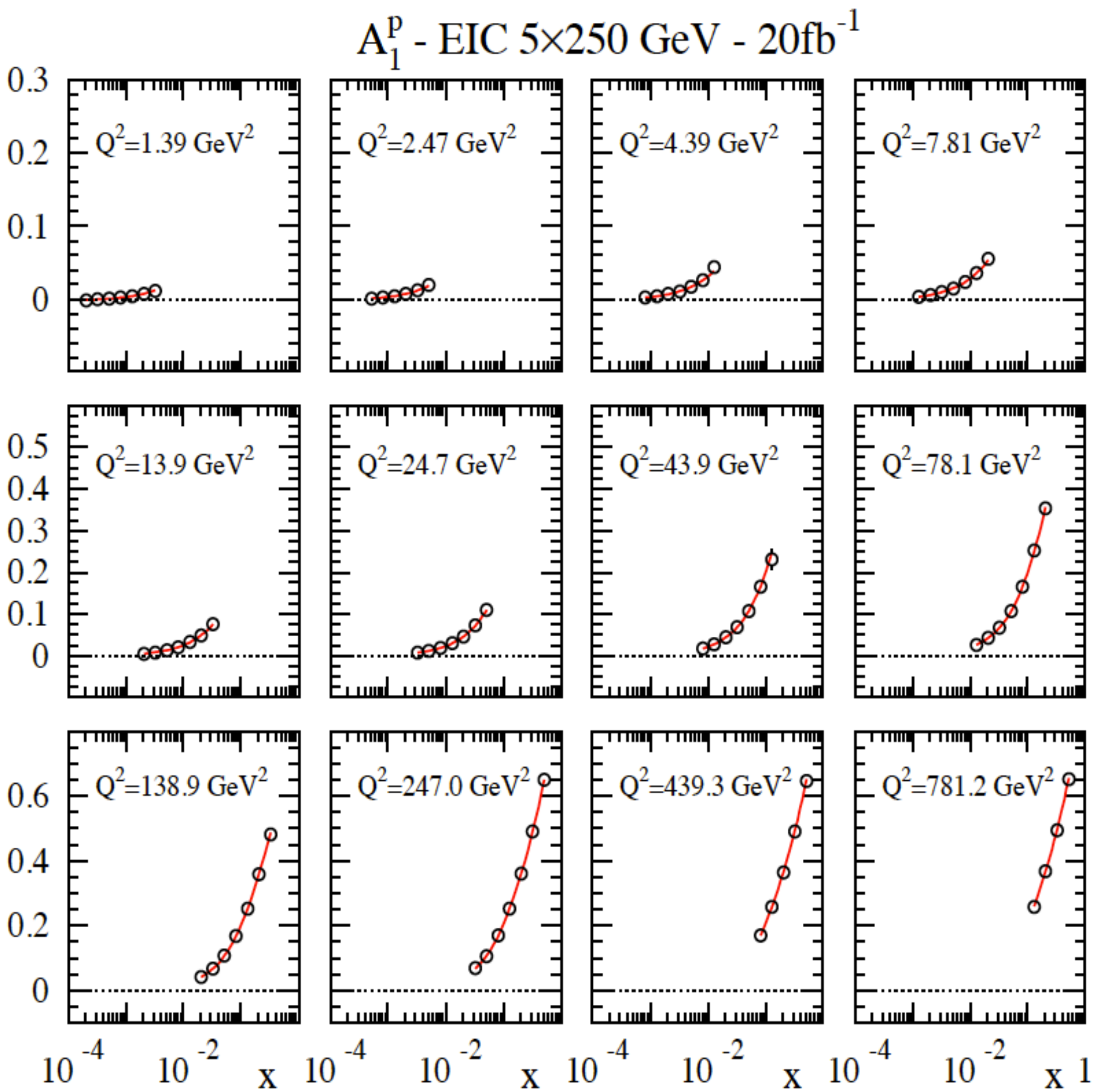
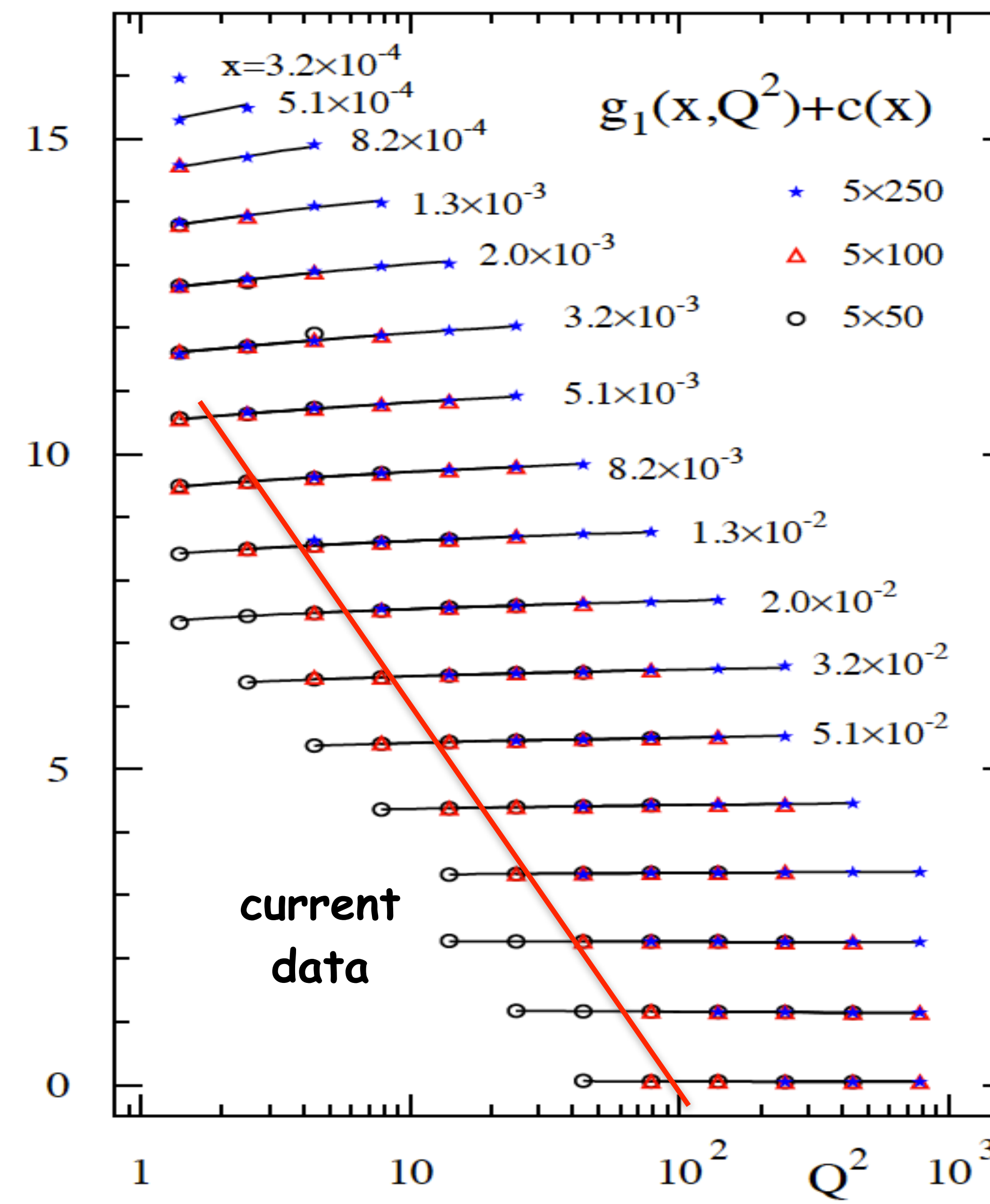




measurements limited by systematics – need to control them very well

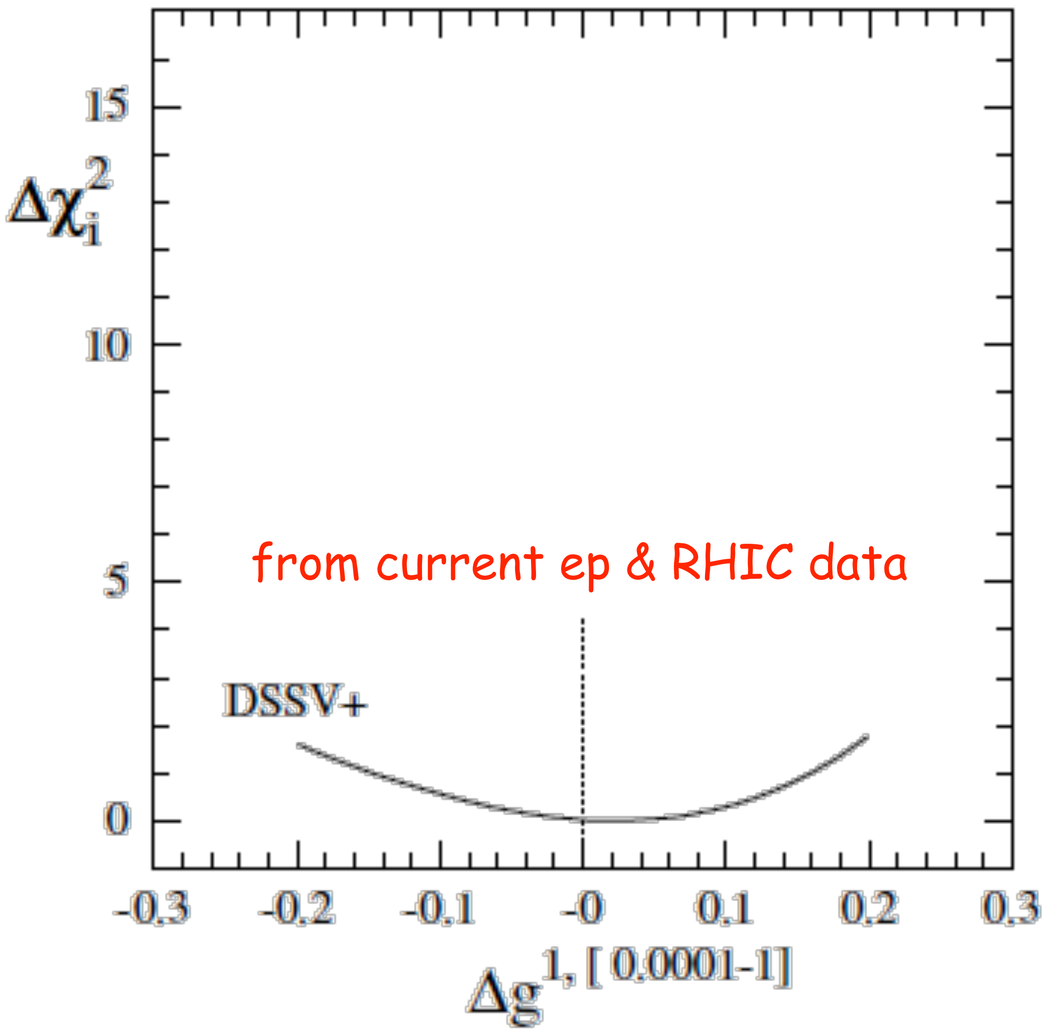
issues: bunch-by-bunch polarimetry, relative luminosity, detector performance, …

The quest for Δg - what can we do at eRHIC?

how effective are scaling violations ?

quantitative studies based on simulated data for eRHIC stage-1: 5 x (50, 100, 250, 325) GeV

χ^2 profile for $\int_{10^{-4}}^{1} \Delta g(x, Q^2)\, dx$



expect to determine $\int_0^1 dx\, \Delta g(x, Q^2)$ at about 10% level (more studies needed)

kinematic reach down to x = 10^{-4} essential to determine integral

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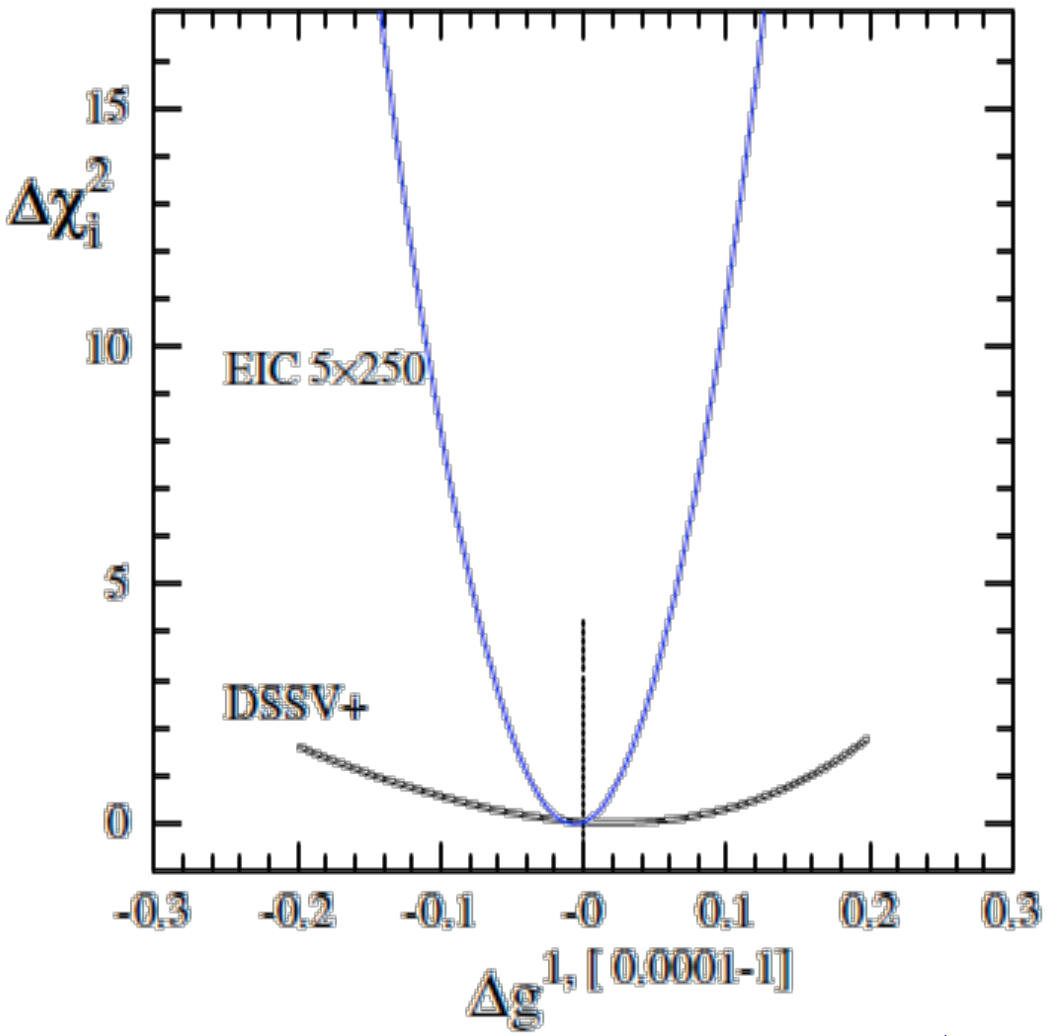

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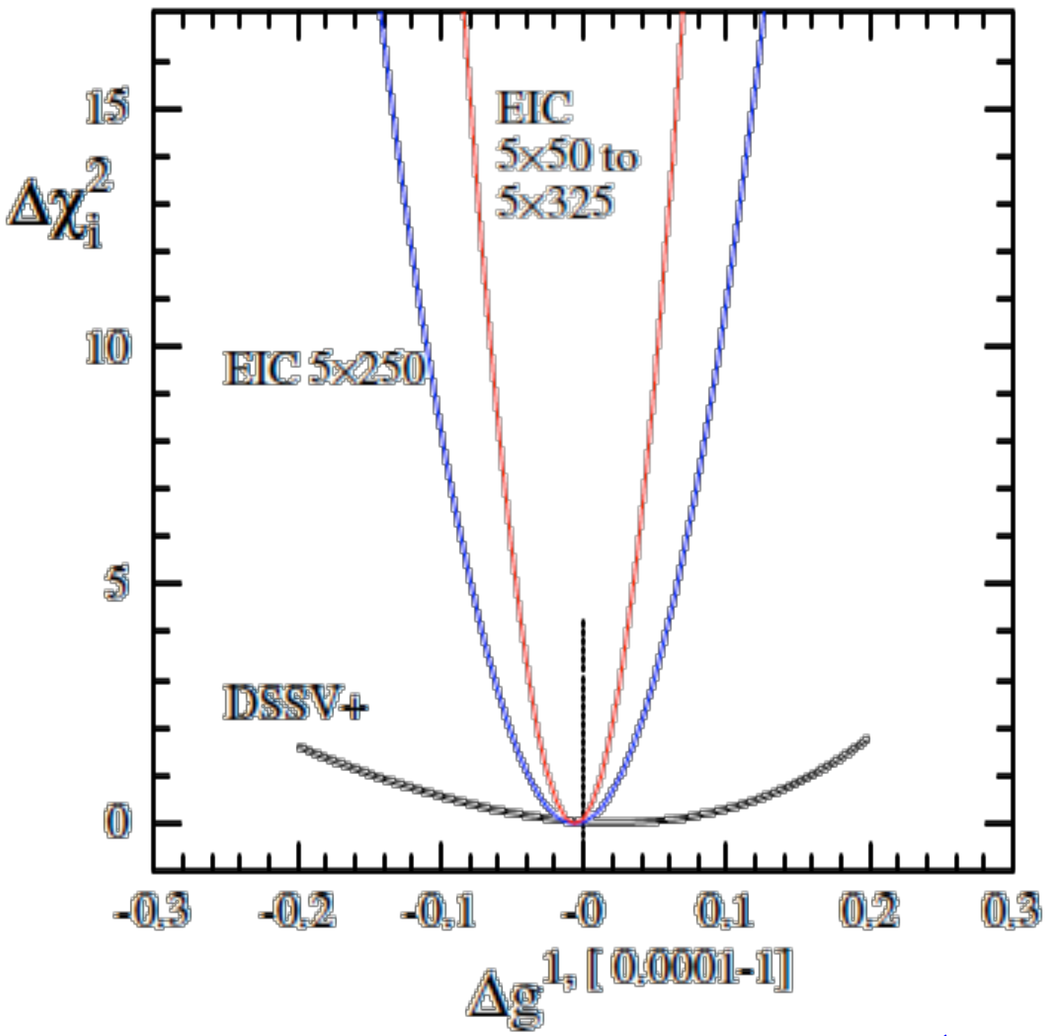

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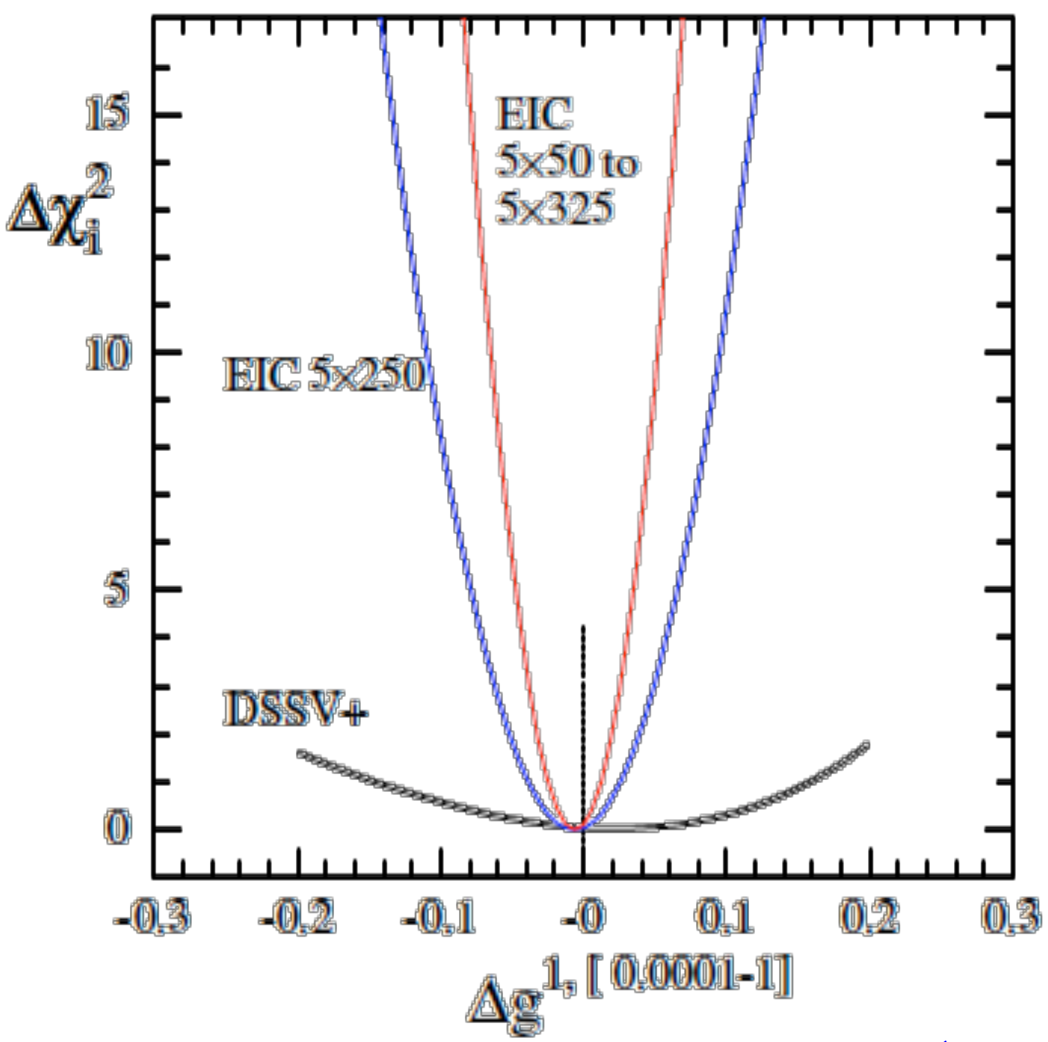
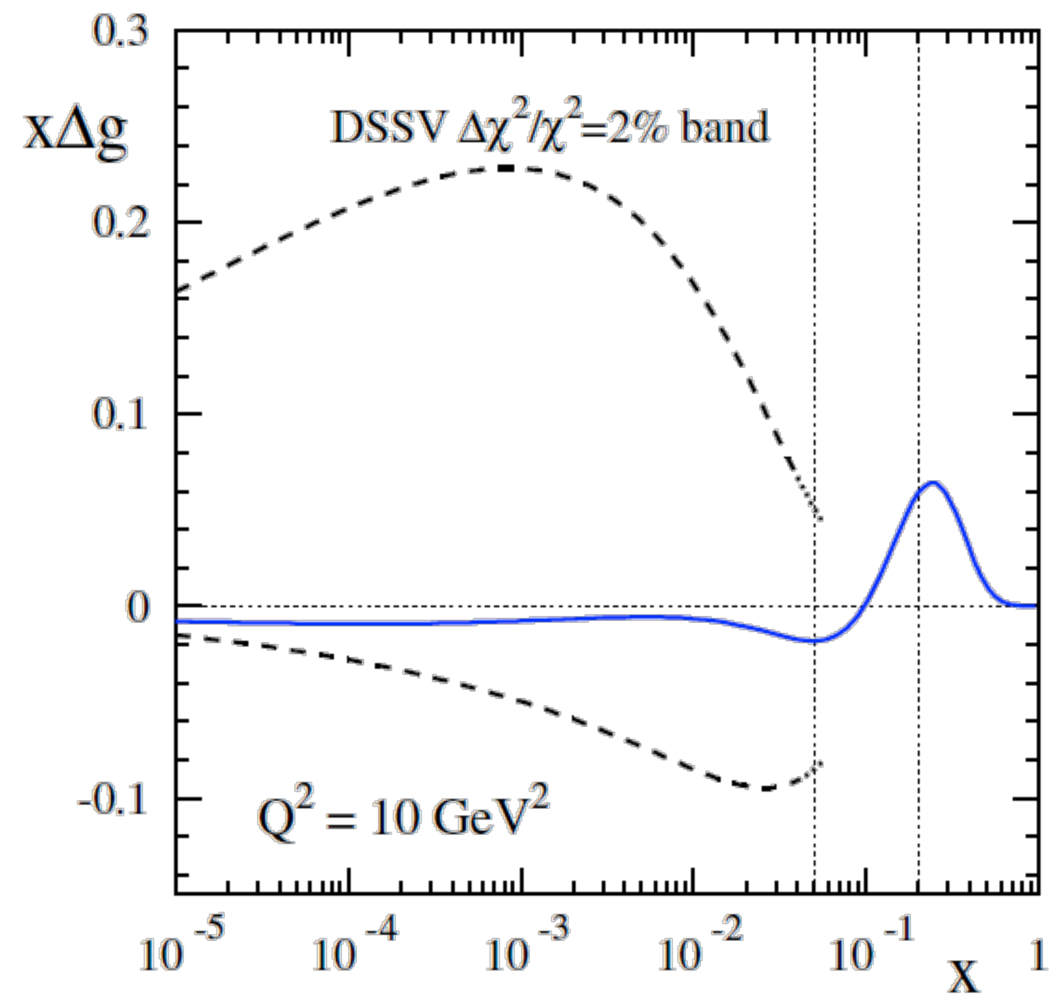
χ^2 profile for $\int_{10^{-4}}^{1} \Delta g(x, Q^2)\, dx$ uncertainties on the x-shape of $\Delta g(x, Q^2)$





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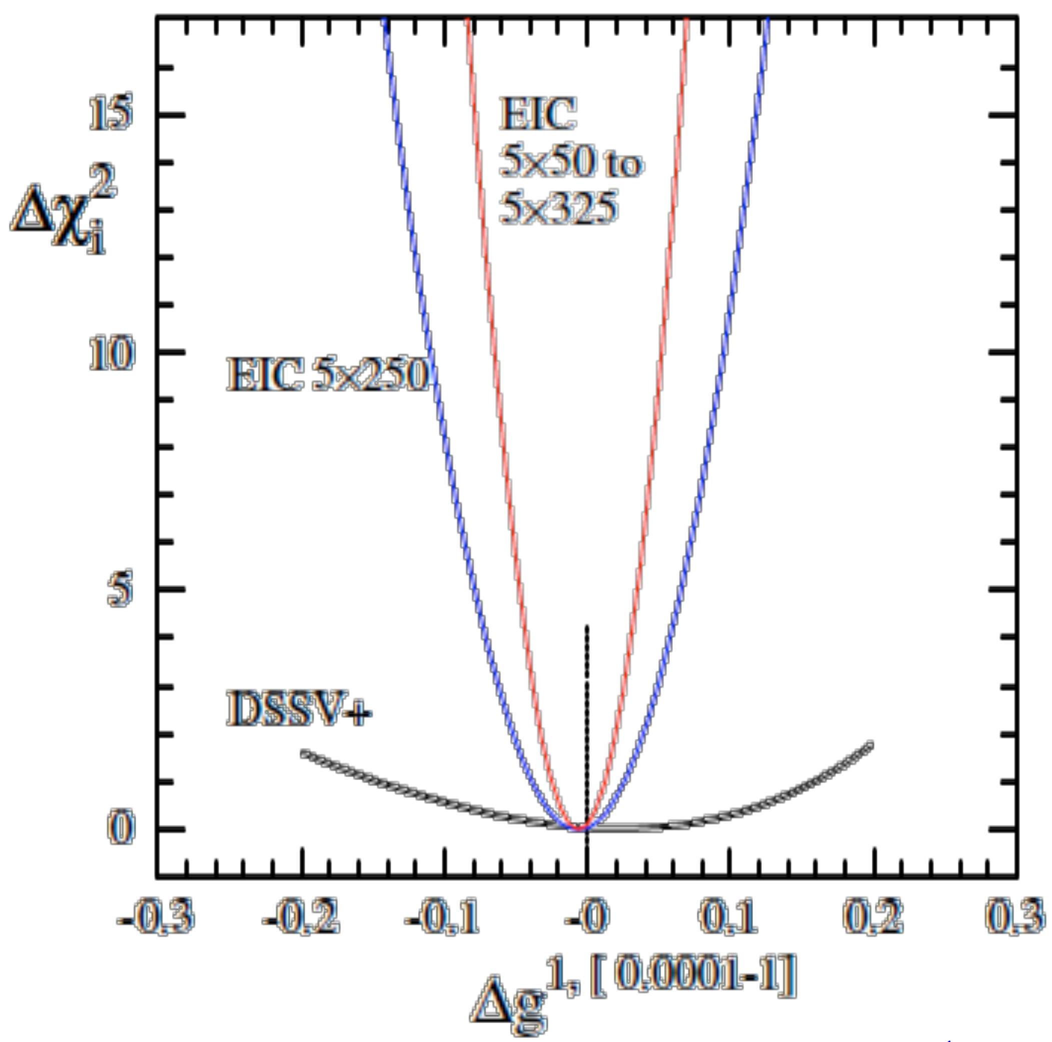

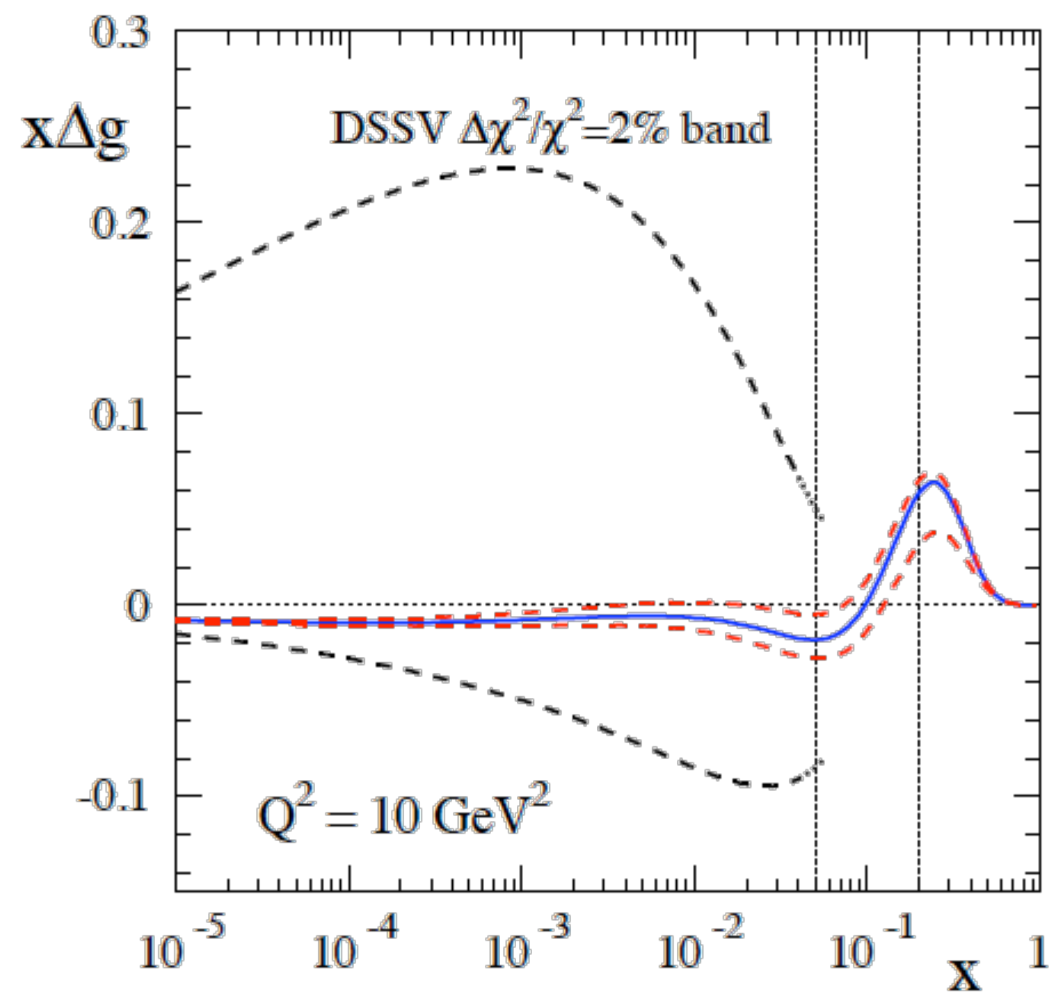

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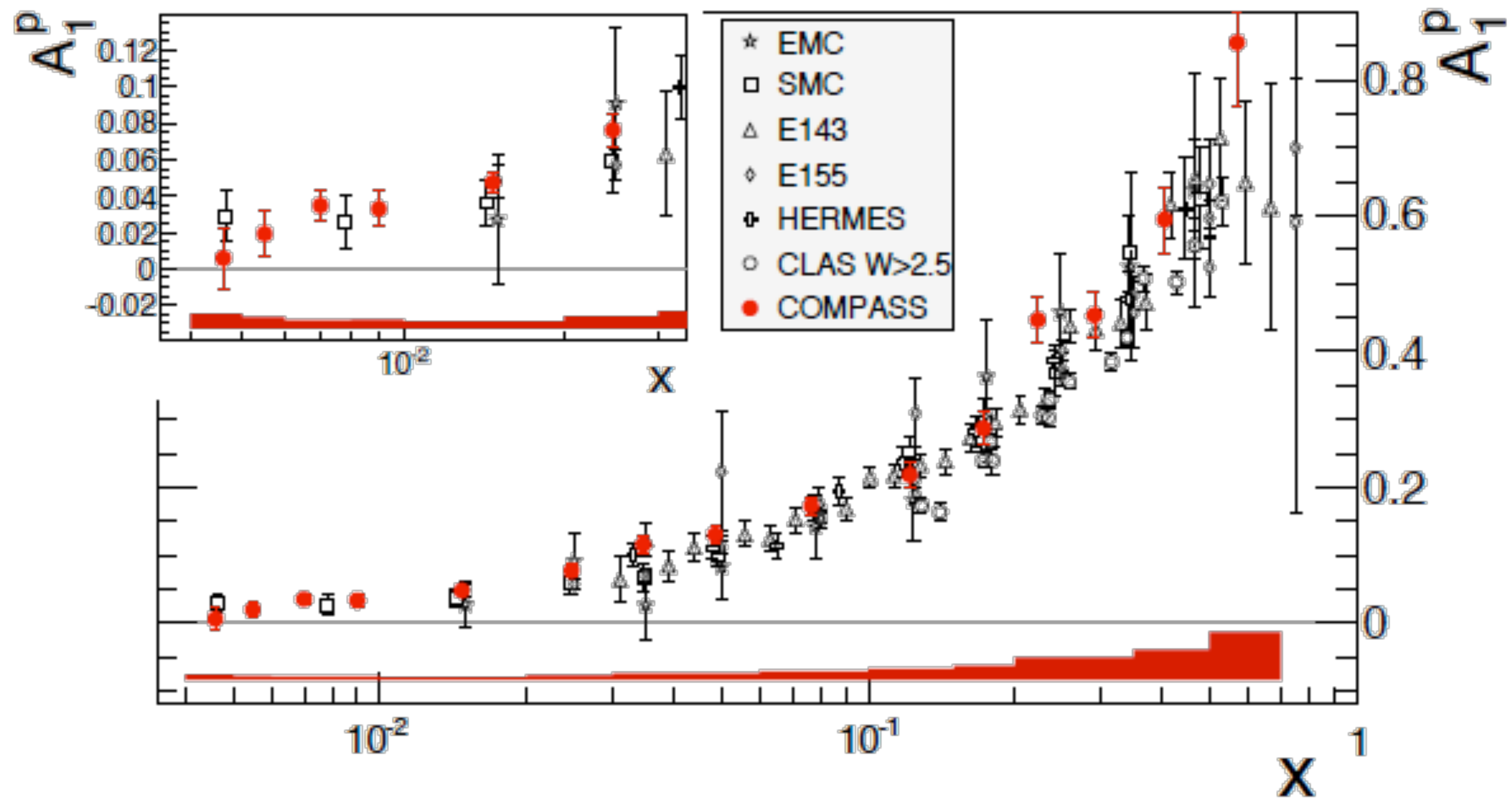
What’s new with DSSV(+)?

DSSV+ - use as a baseline for eRHIC studies



- **DIS:** A_1^p from COMPASS

  arXiv:1001.4654

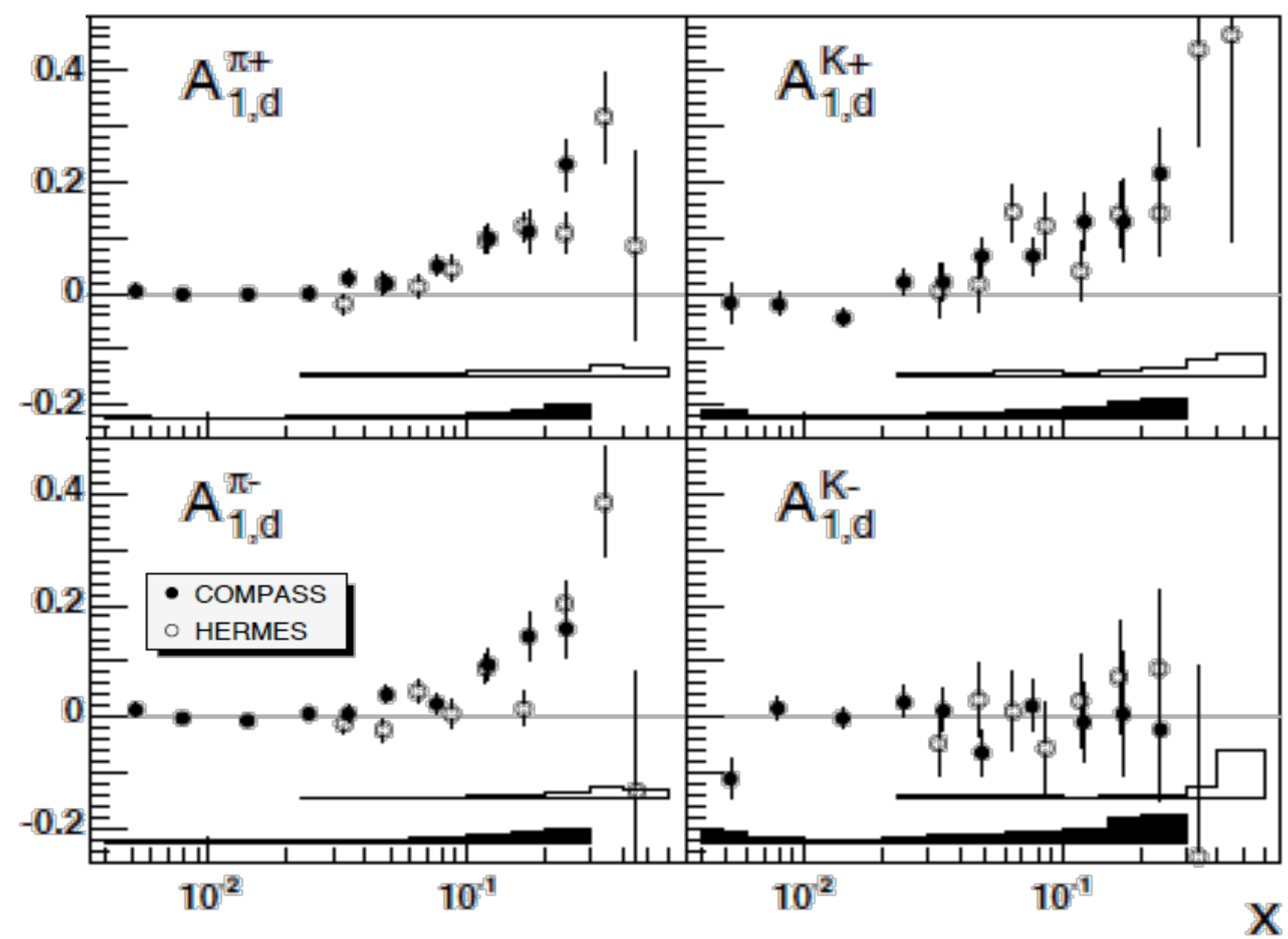
- **SIDIS:** $A_{1,d}^{\pi,K}$ from COMPASS

  arXiv:0905.2828

- **SIDIS:** $A_{1,p}^{\pi,K}$ from COMPASS

  arXiv:1007.4061

extended x coverage w.r.t. HERMES

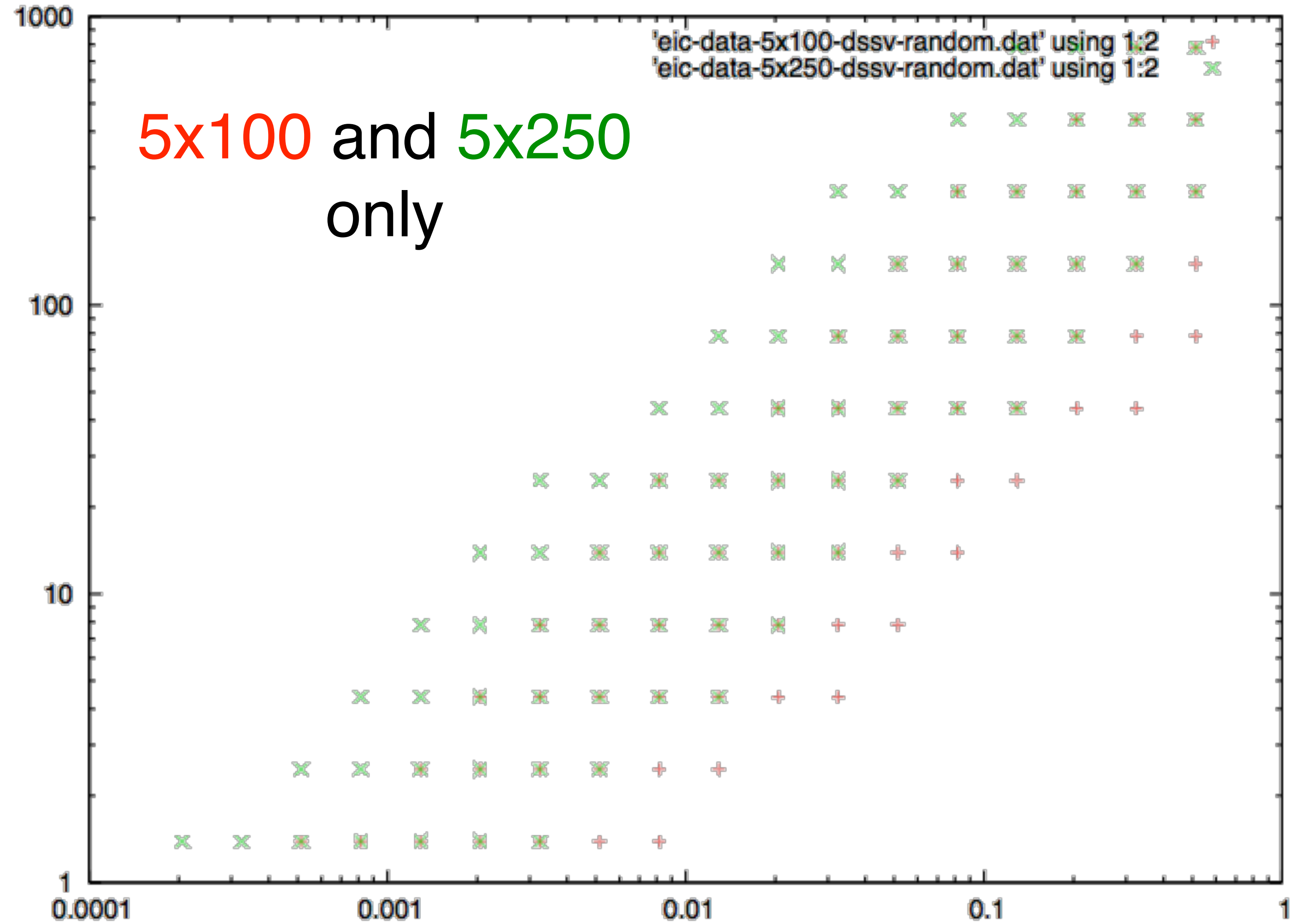


New pseudo-data

data for DIS and SIDIS ($\pi^{\pm}$, $K^{\pm}$)

10 fb^{-1} each, 70% beam pol.

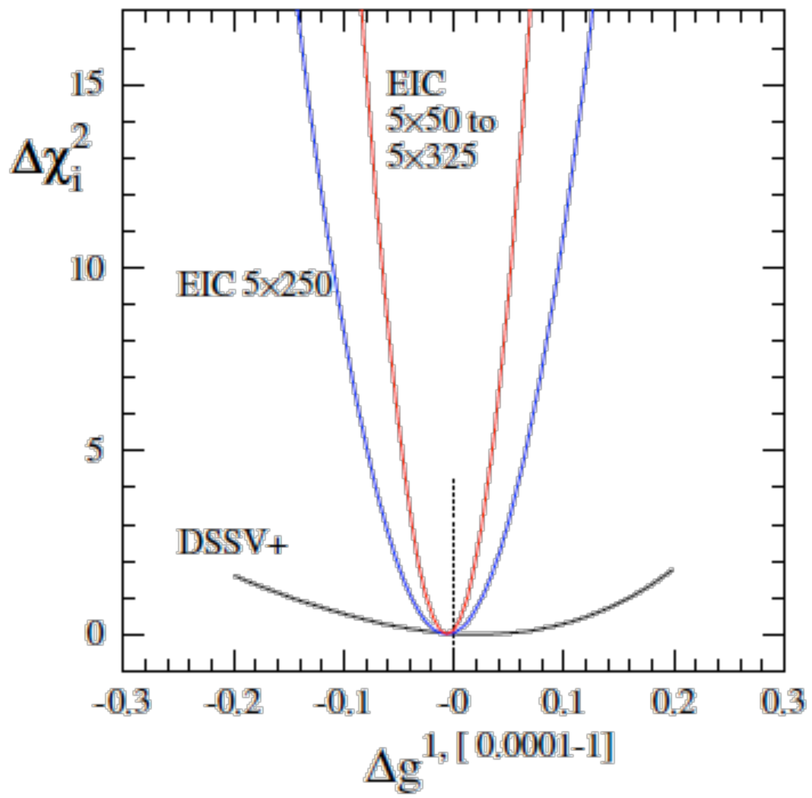
Cuts:
- $W^2 > 10\ GeV^2$
- depol. factor > 0.1
- $0.001 < y < 0.95$
- $1^o < \theta < 179^o$
- $p_e > 0.5$ GeV
- $p_{hadr} > 1$ GeV



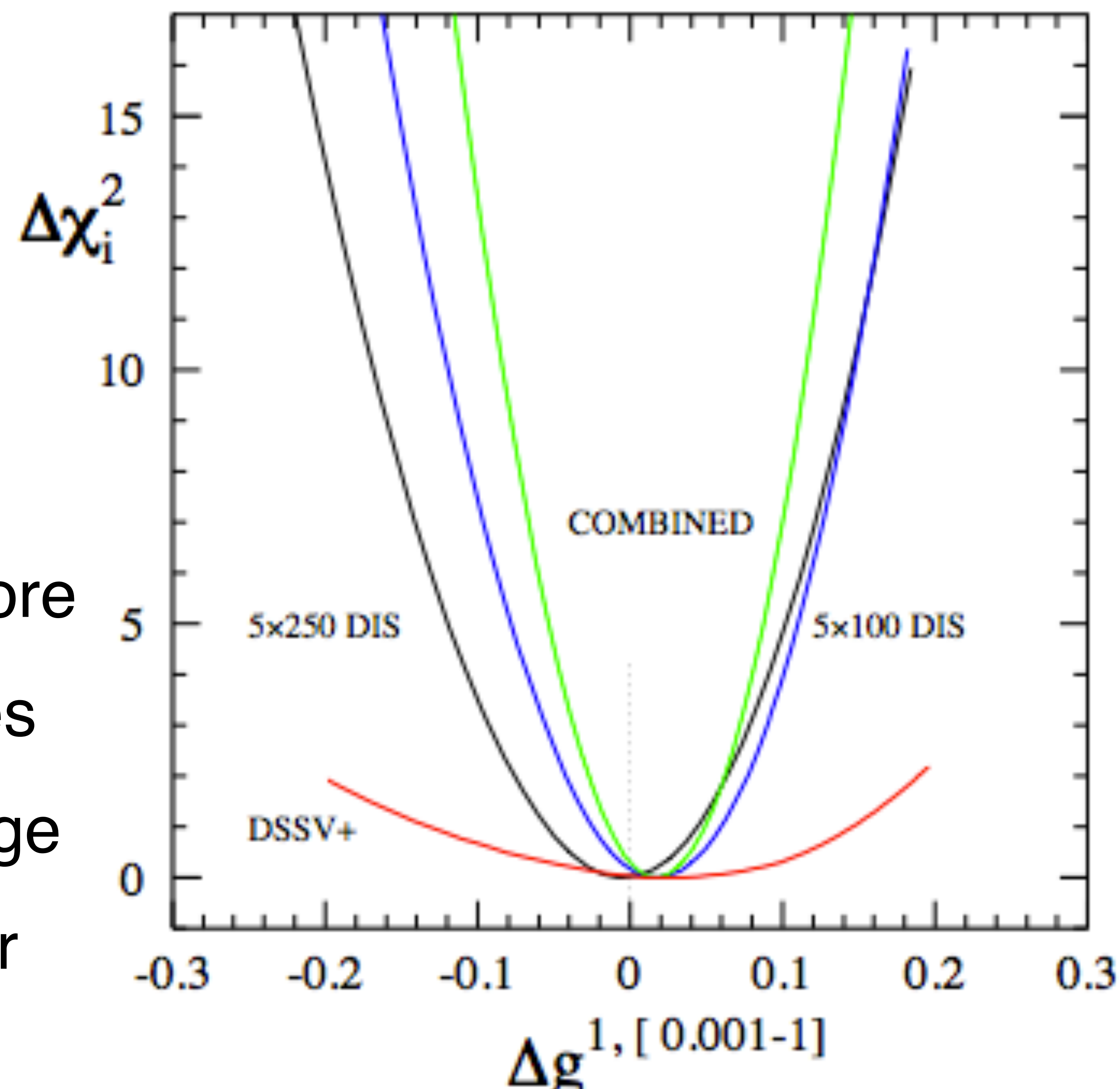
- Global analysis:
  - ➡ use relative uncertainty of each point to produce mock data (based on DSSV)
  - ➡ randomise data within 1σ
  - ➡ for SIDIS: incl. 5%(10%) uncertainty from pion (kaon) frag. functions
  - ➡ map out χ^2 profiles with Lagrange multiplier method (Hessian is work in progress)

Update on Δg

previous result

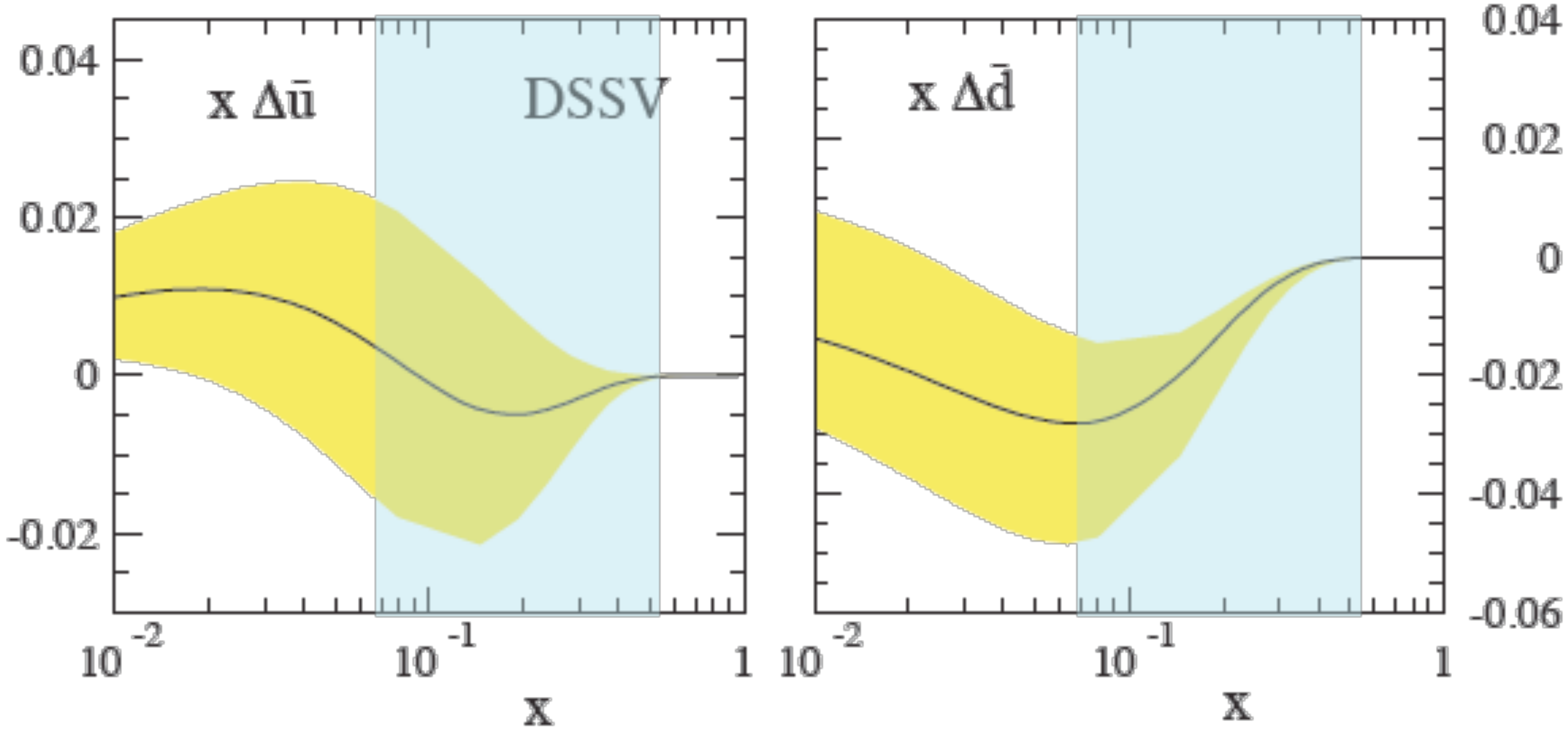


- Very similar results to before
- Slightly larger uncertainties
- need to study $10^{-4} \rightarrow 1$ range
- need to translate into error on x-shape of Δg

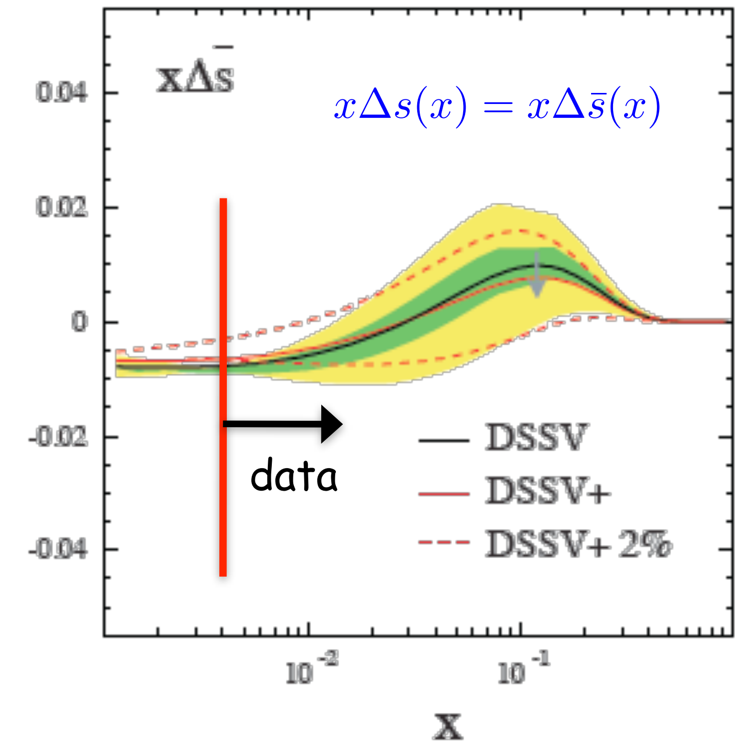


What about Δq?

current uncertainties DSSV



DSSV (incl. latest COMPASS data)



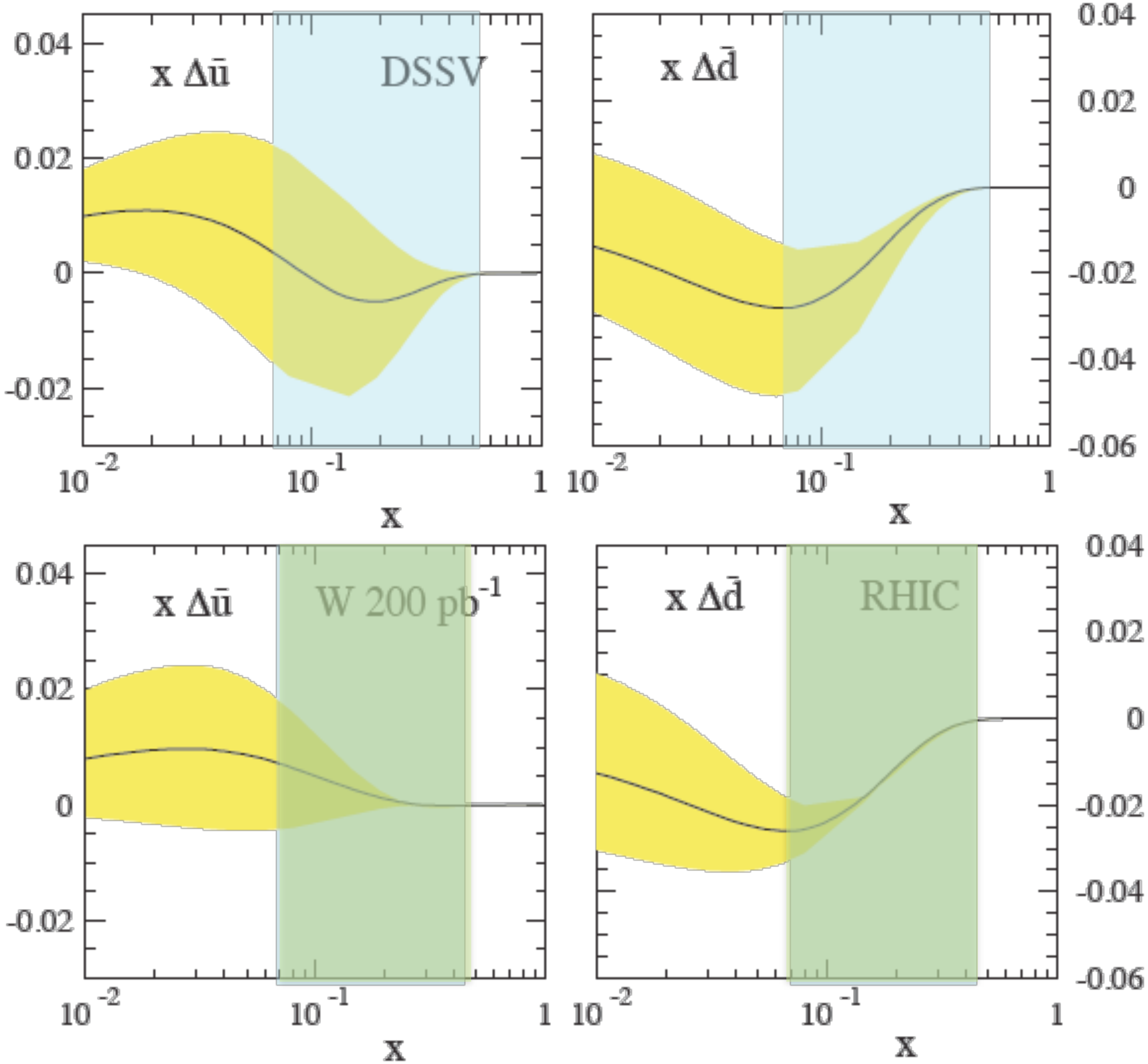
◉ **surprise:** Δs small & positive from SIDIS data

◉ but 1st moment is negative and sizable due to “constraint” from hyperon decays (F,D) (assumed SU(3) symmetry - debatable M. Savage)

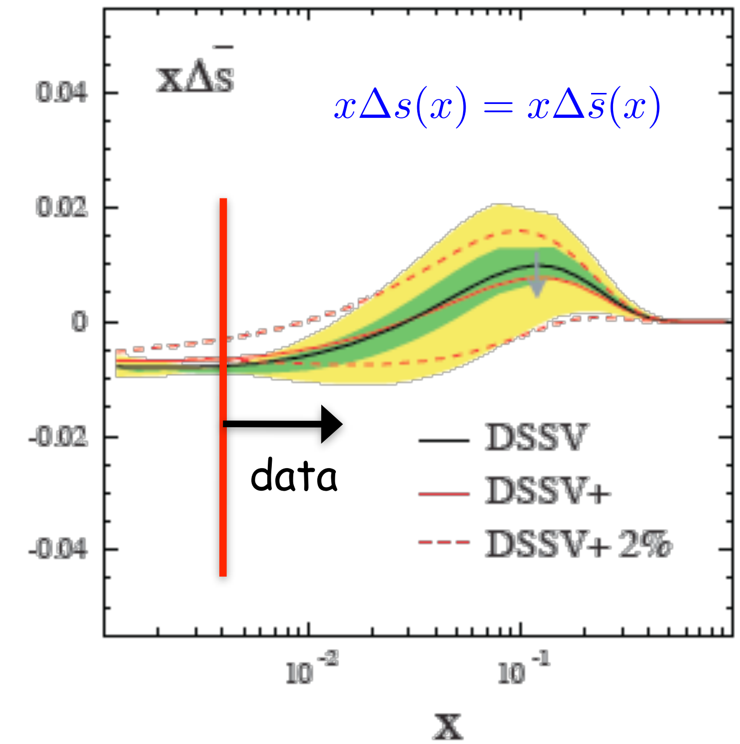
◉ drives uncertainties on ΔΣ (spin sum)

What about Δq?

current uncertainties DSSV



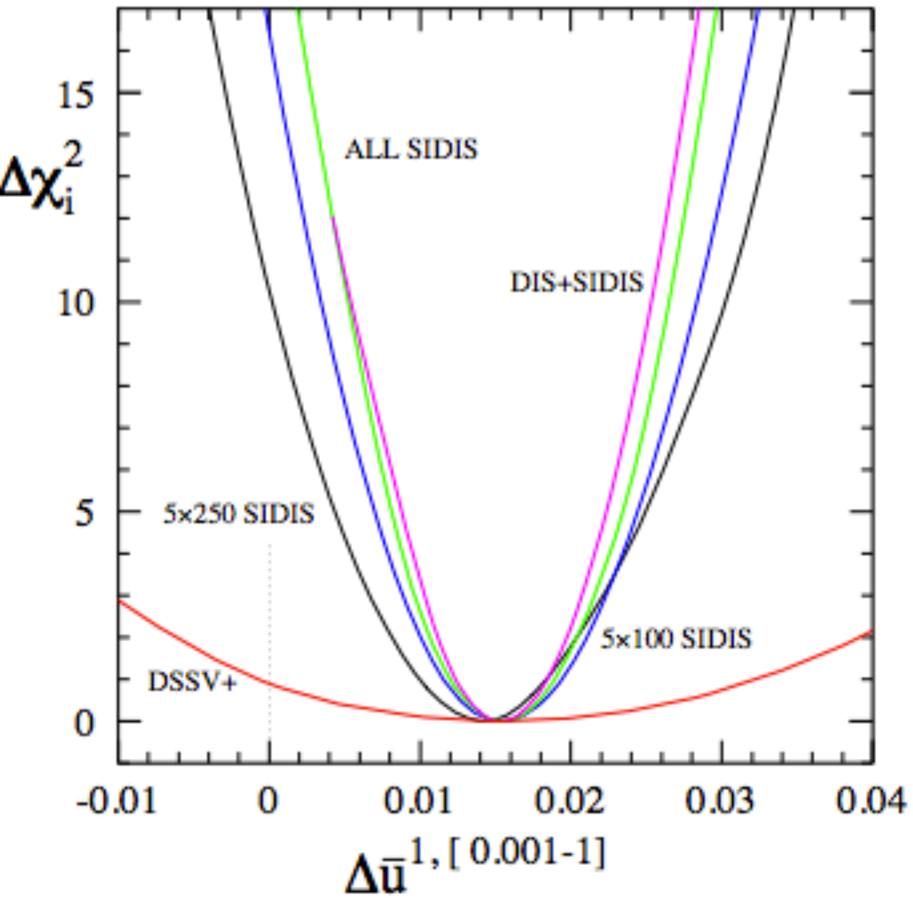
DSSV (incl. latest COMPASS data)



simulated impact of RHIC

- W boson data on global fit
- reduction of uncertainties for $0.07 < x < 0.4$ can test consistency of low Q^2 SIDIS data in that x regime

First results on the quark sea



- very encouraging results
- as expected, DIS has no impact
- need to study 0.0001-1 range
- need to translate into error on x-shape

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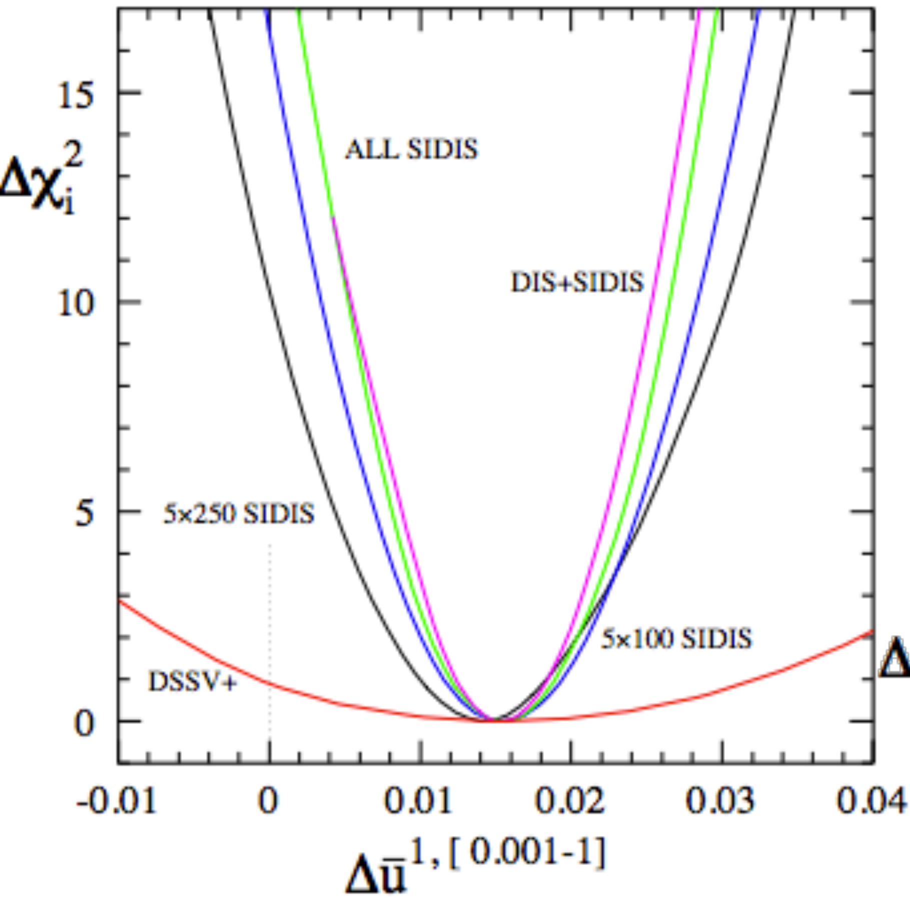

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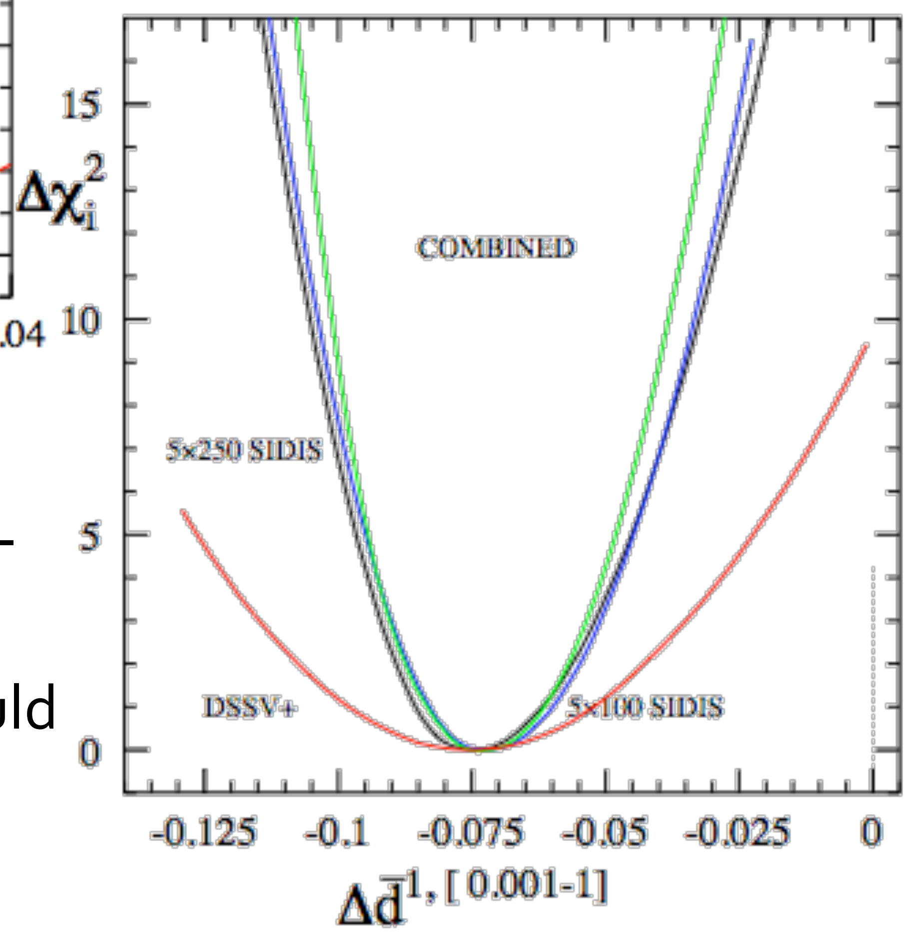

- note the change of scale on x-axis
- perhaps "neutron beam" would lead to further improvements

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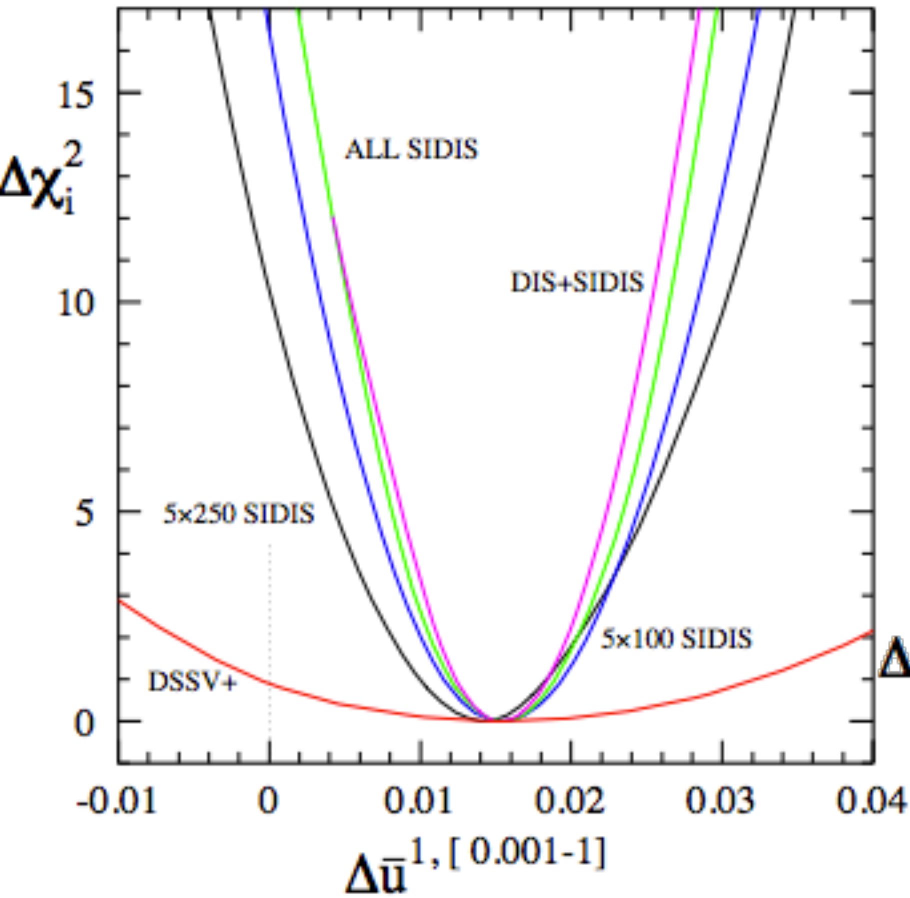

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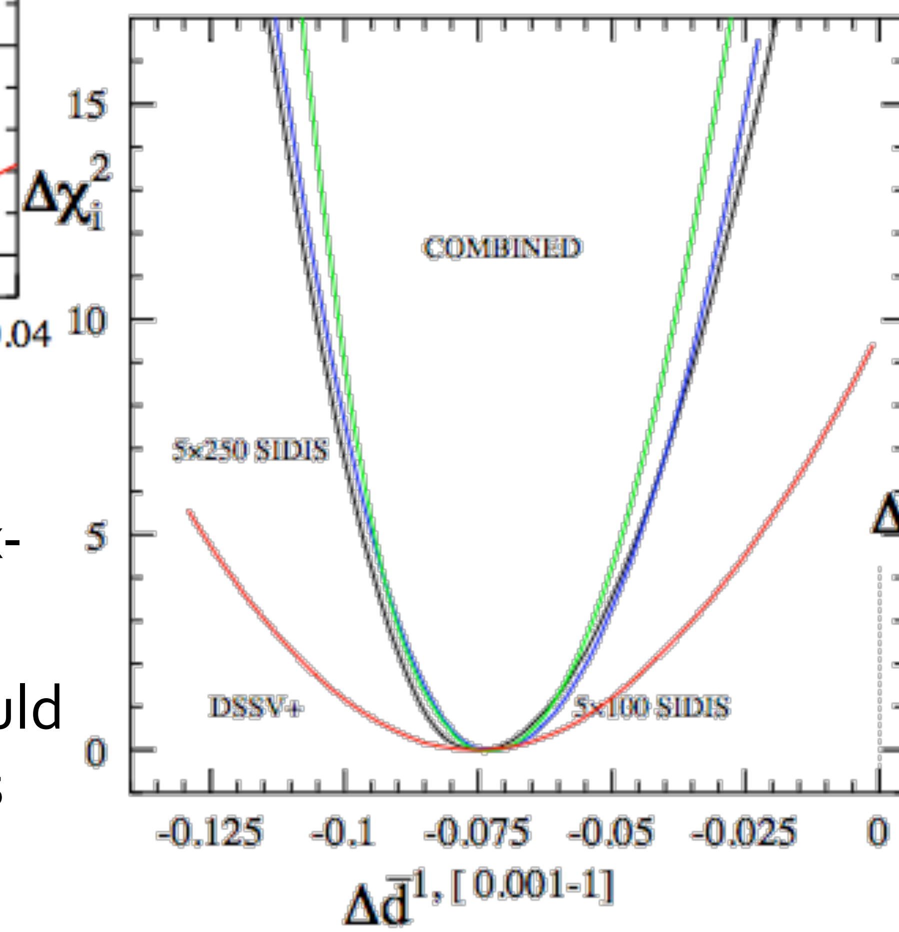

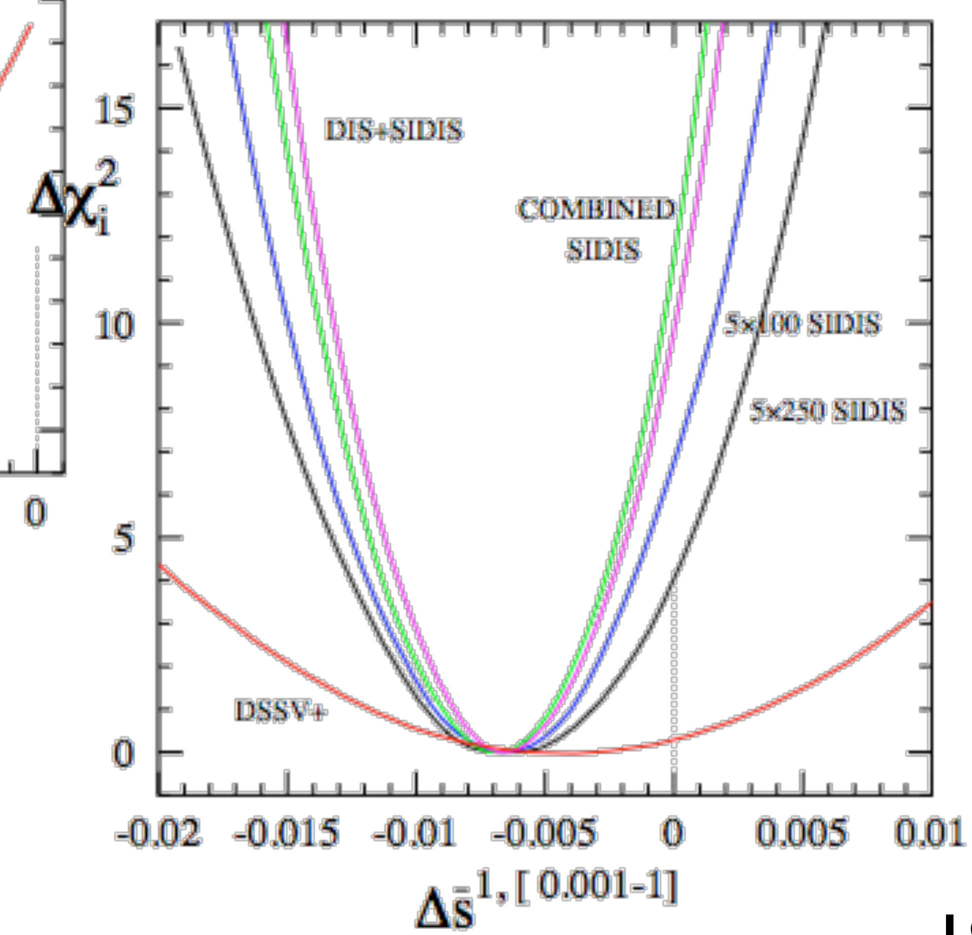

- note the change of scale on x-axis
- perhaps "neutron beam" would lead to further improvements

- should be able to test "constraint" from SU(3) symmetry (F,D values from hyperon decays)

e+A physics

10 week INT programme - Fall 2010

week	dates	topics
1	13–17 Sept	**Workshop** on "Perturbative and Non-Perturbative Aspects of QCD at Collider Energies" Agenda
2	20–24 Sept	open conceptual issues: factorization and universality, spin and flavor structure, distributions and correlations Agenda
3–5	27 Sept – 15 Oct	small x, saturation, diffraction, nuclear effects; connections to p+A and A+A physics; fragmentation/hadronization in vacuum and in medium Agenda for week 3 Agenda for week 4 Agenda for week 5
6–7	18–29 Oct	parton densities (unpolarized and polarized), fragmentation functions, electroweak physics Agenda for week 6 Agenda for week 7
8–9	1–12 Nov	longitudinal and transverse nucleon structure; spin and orbital effects (GPDs, TMDs, and all that) Agenda for week 8 Agenda for week 9
10	16–19 Nov	**Workshop** on "The Science Case for an EIC" Agenda for week 10

http://www.int.washington.edu/PROGRAMS/10-3/

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Golden Measurements

Deliverables	Observables	What we learn	Stage-1	Stage-II
integrated gluon distributions	$F_{2,L}$	nuclear wave function; saturation, Q_s	gluons at $10^{-3} < x < 1$	saturation regime
k_T dependent gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution / universality	onset of saturation	measure Q_s
transport coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mechanisms	light flavours and charm; jets	rare probes and bottom; large-x gluons

Silver Measurements

Deliverables	Observables	What we learn	Stage-I	Stage-II
integrated gluon distributions	$F^c_{2,L}$, $F^D_{2,L}$	nuclear wave function; saturation, Q_s	difficult measurement / interpretation	saturation regime
flavour separated nuclear PDFs	charged current and γZ structure functions	EMC effect origin	full flavour separation for $10^{-2} < x < 1$	measure Q_s
k_T dependent gluons	SIDIS at small x	non-linear QCD evolution / universality	onset of saturation	rare probes and bottom; large-x gluons
b-dependent gluons; gluon correlations	DVCS; diffractive vector mesons	interplay between small-x evolution and confinement	moderate x with light, heavy nuclei	smaller x, saturation

Integrated gluon distributions from inclusive structure functions

Integrated gluon distributions from inclusive structure functions

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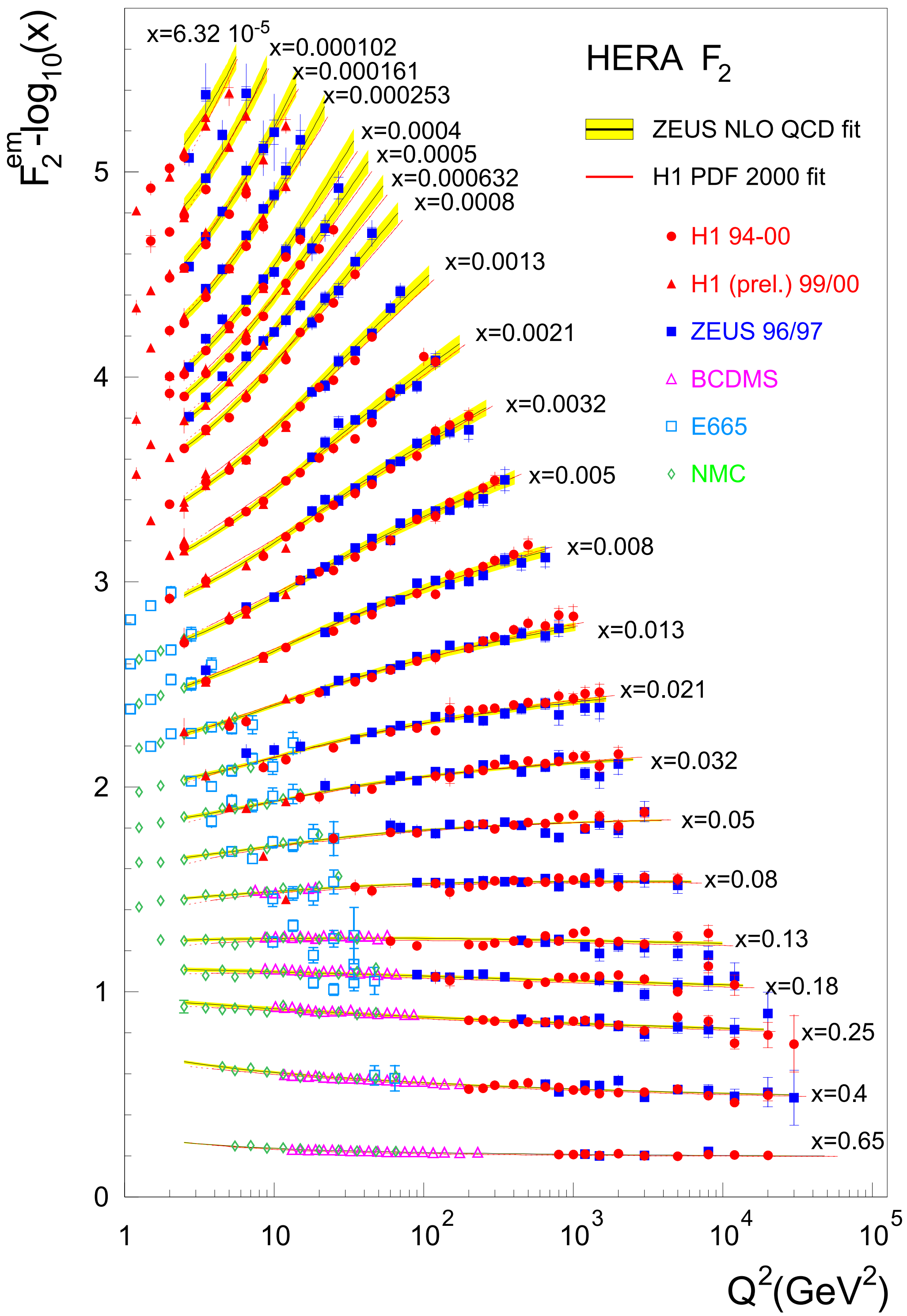
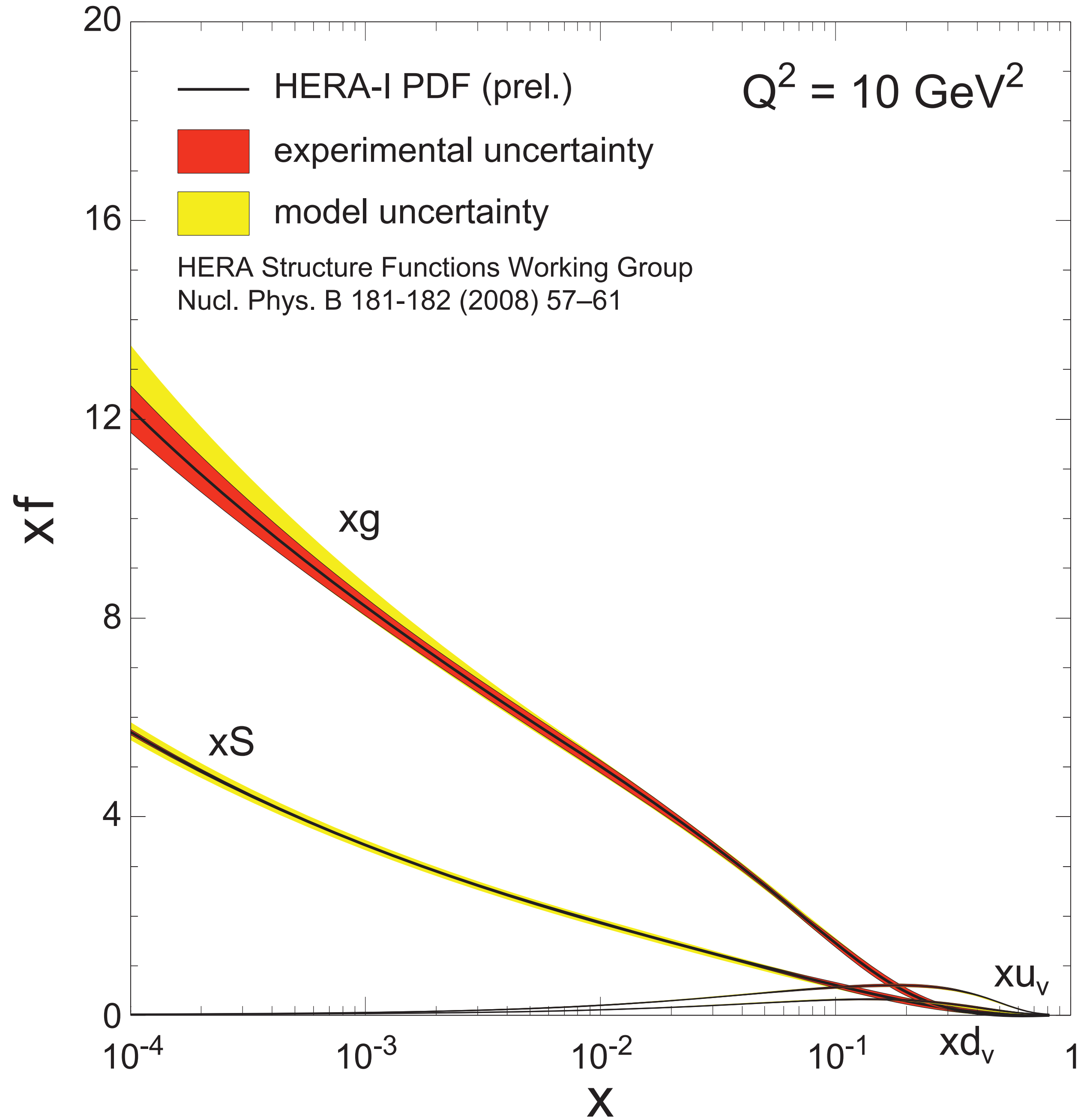
charm diffractive

Measuring the glue via Structure Functions

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+}F_L^A(x,Q^2)$$



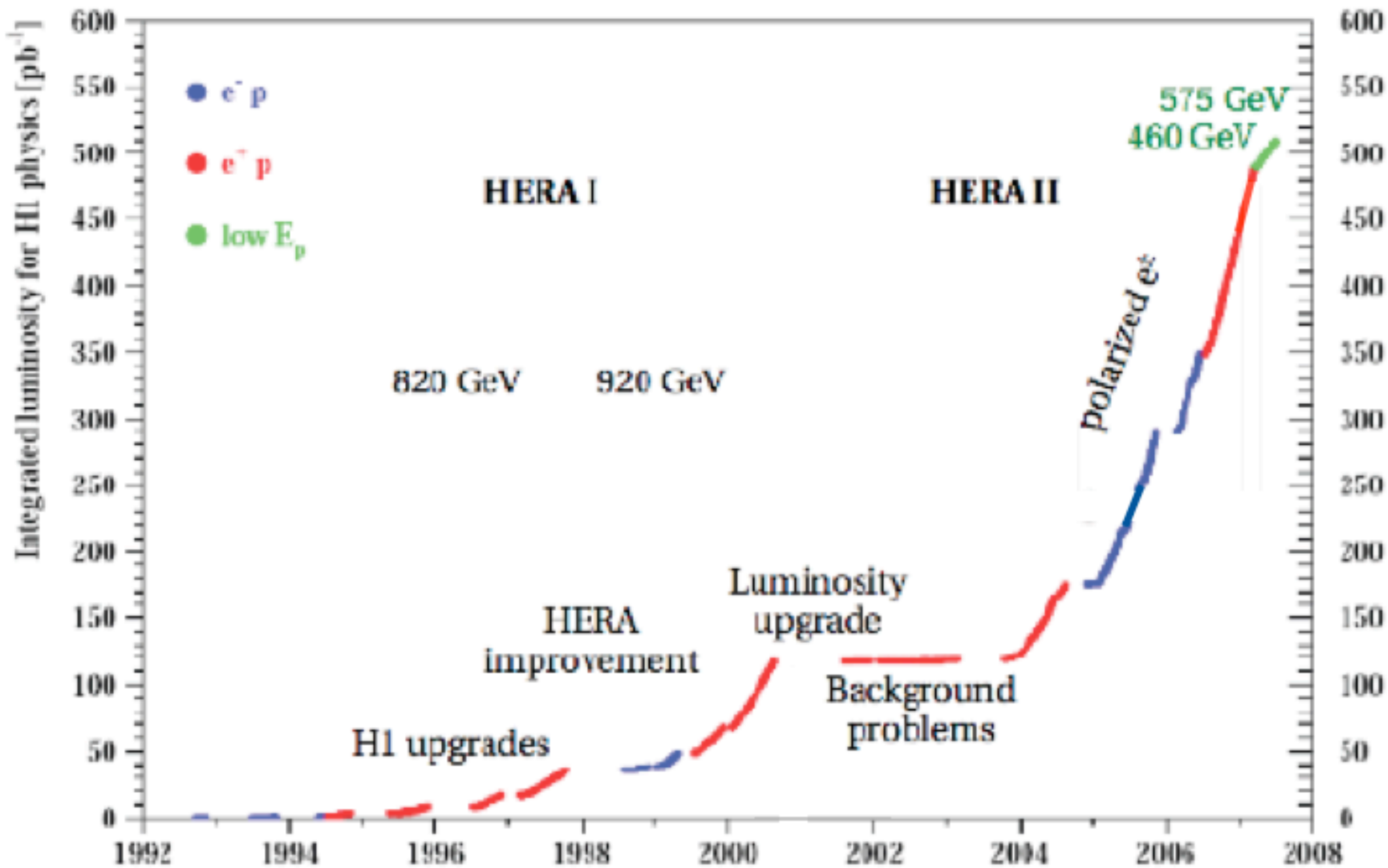
Scaling violation: *$dF_2/d\ln Q^2$* and linear DGLAP Evolution $\Rightarrow$ *$G(x,Q^2)$*



Measuring the gluons: extracting F_L

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+} F_L^A(x,Q^2)$$

- $F_L \sim \alpha_s\, xG(x,Q^2)$
  - ➡ $y = Q^2/xs$
  - ➡ require an energy scan to extract F_L
- 3 different proton energies run at HERA
  - ➡ 2 low-statistics runs
  - ➡ bad for F_L extraction



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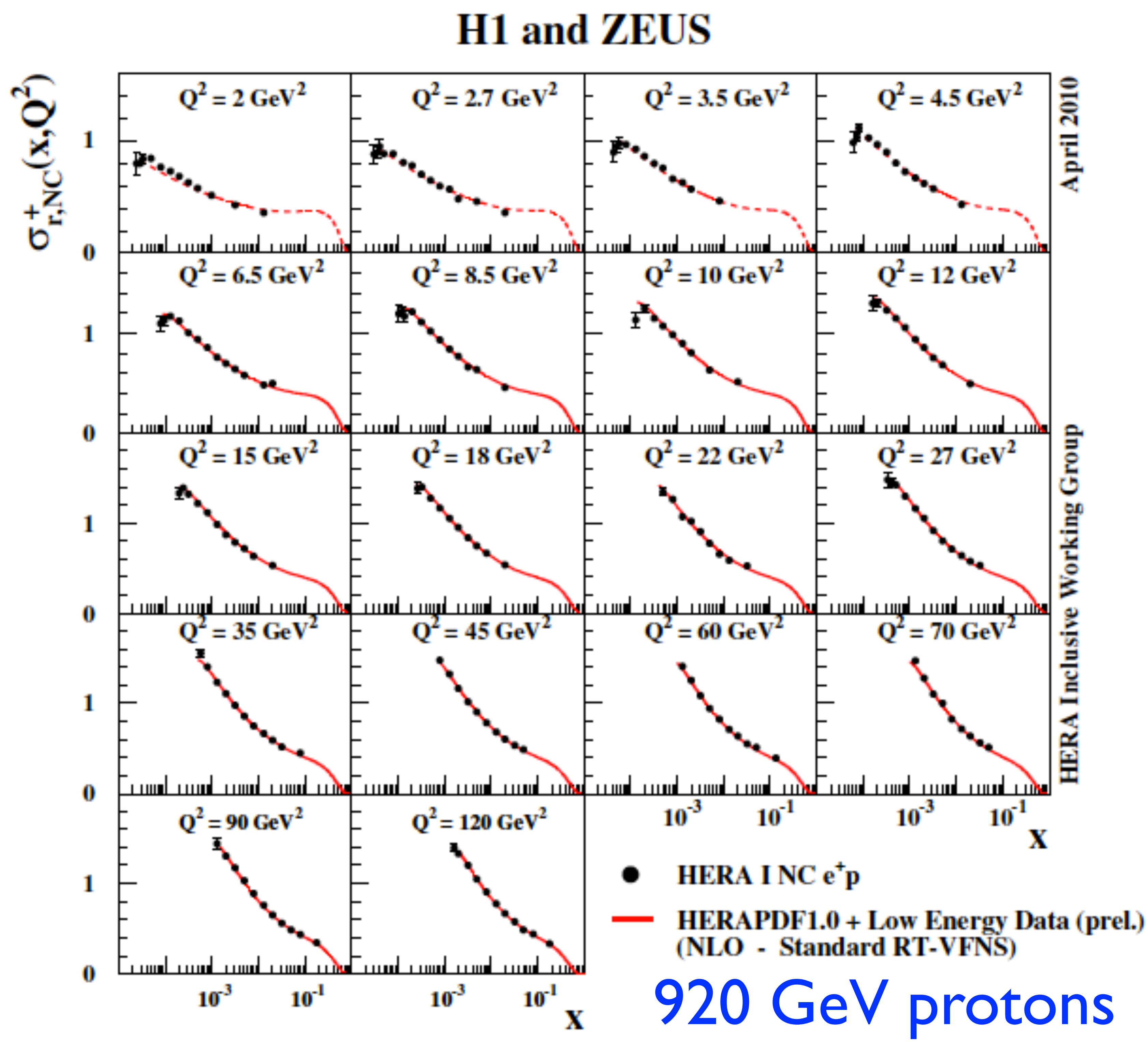

920 GeV protons

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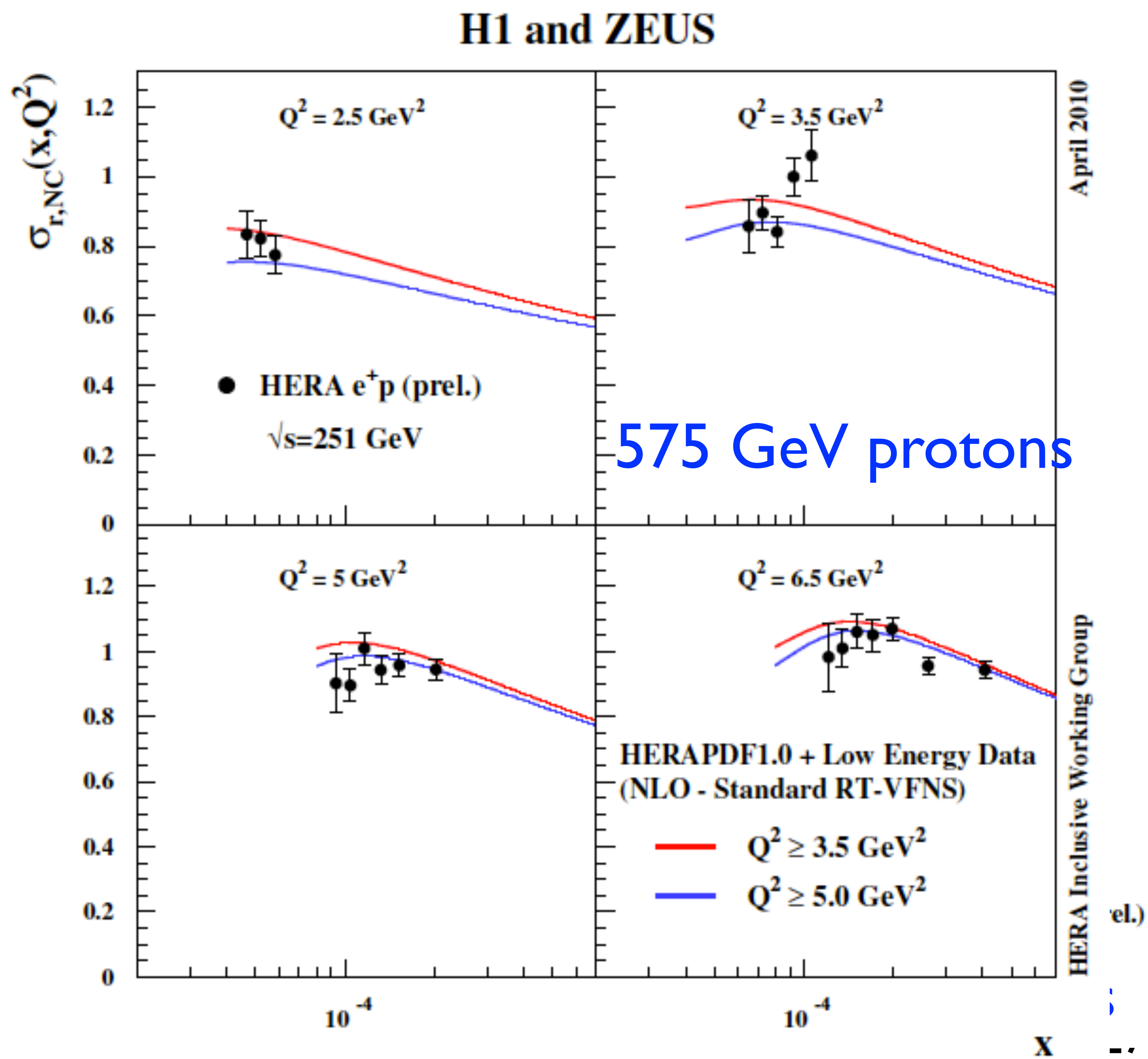

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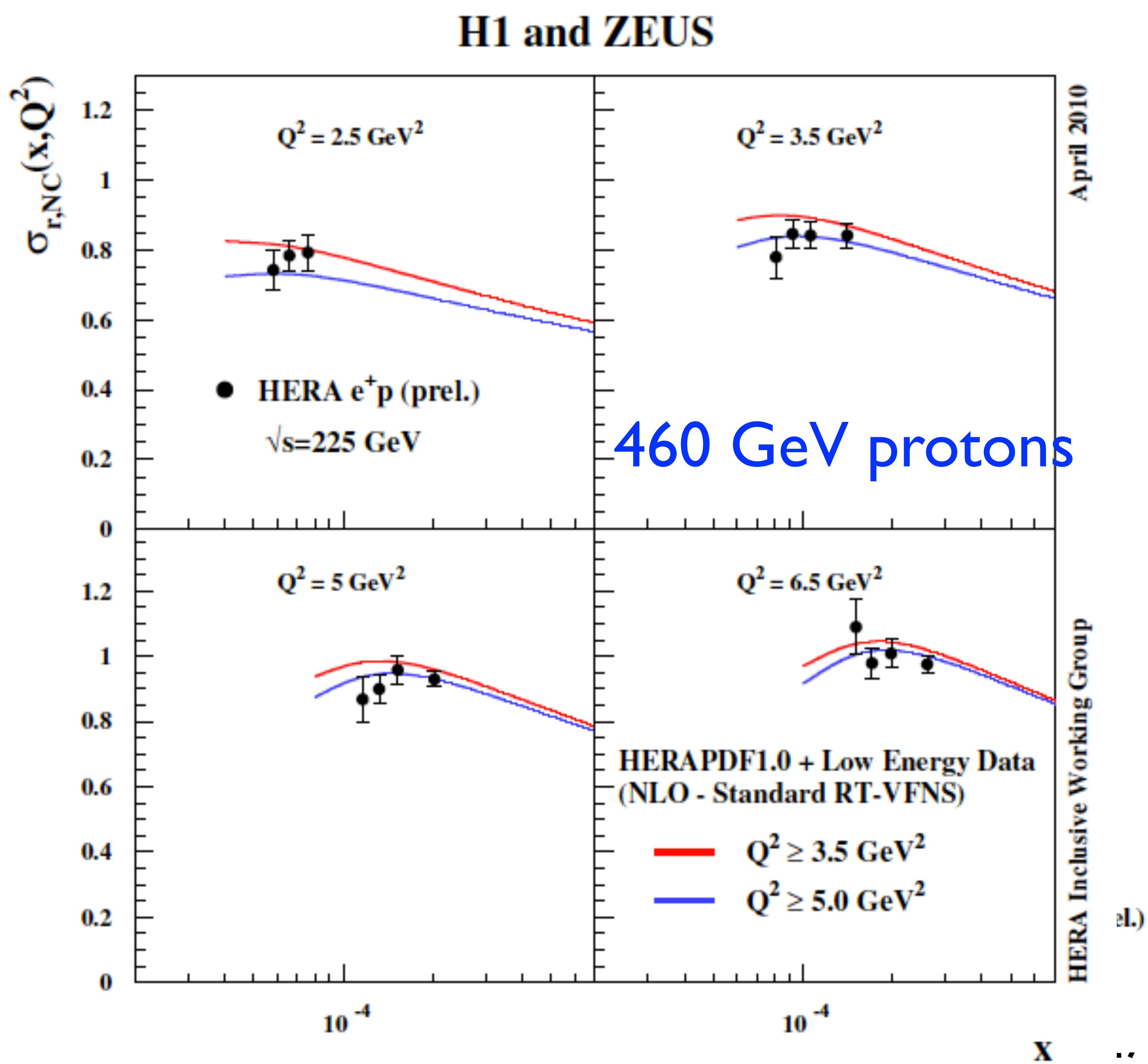

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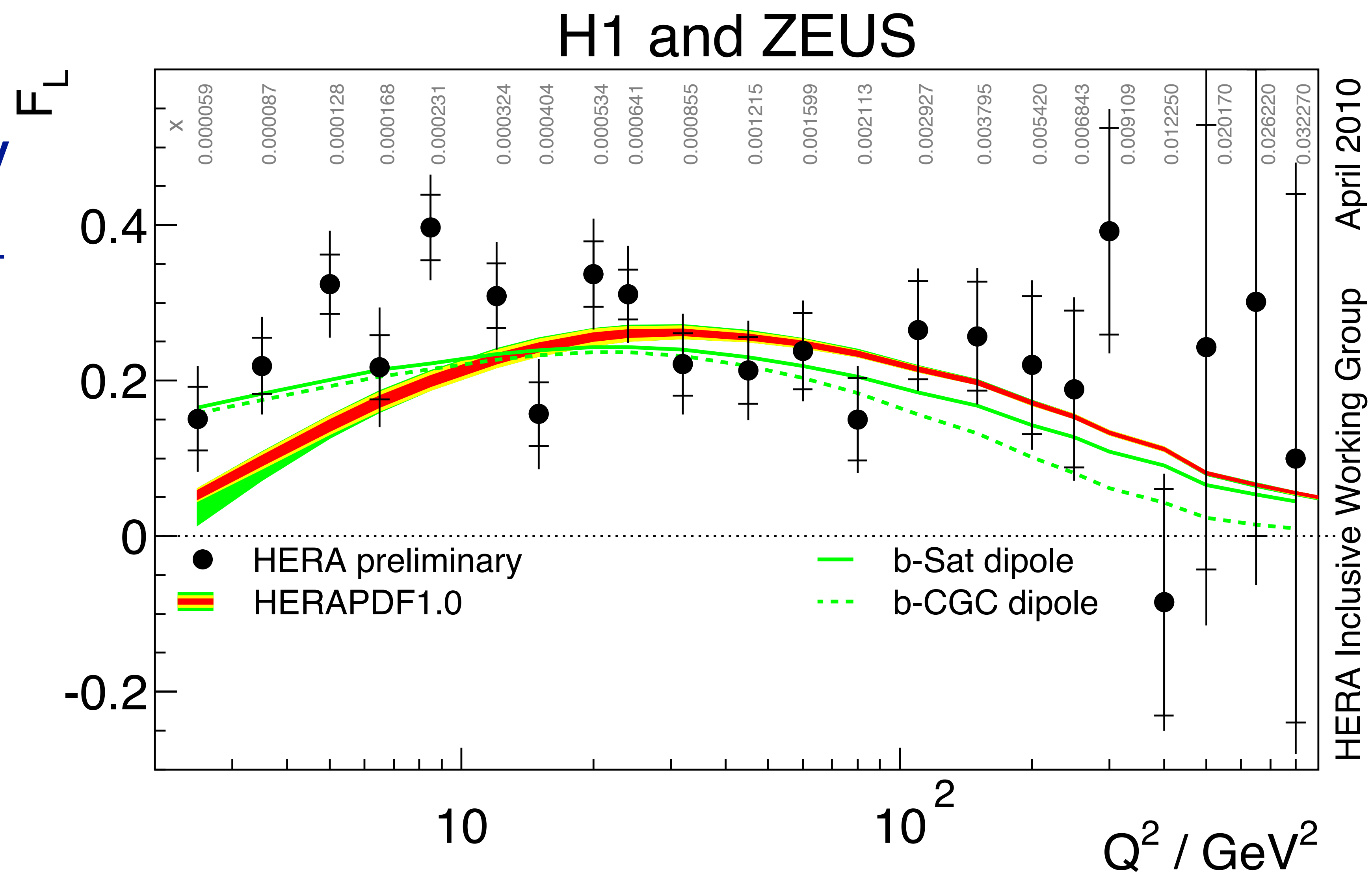
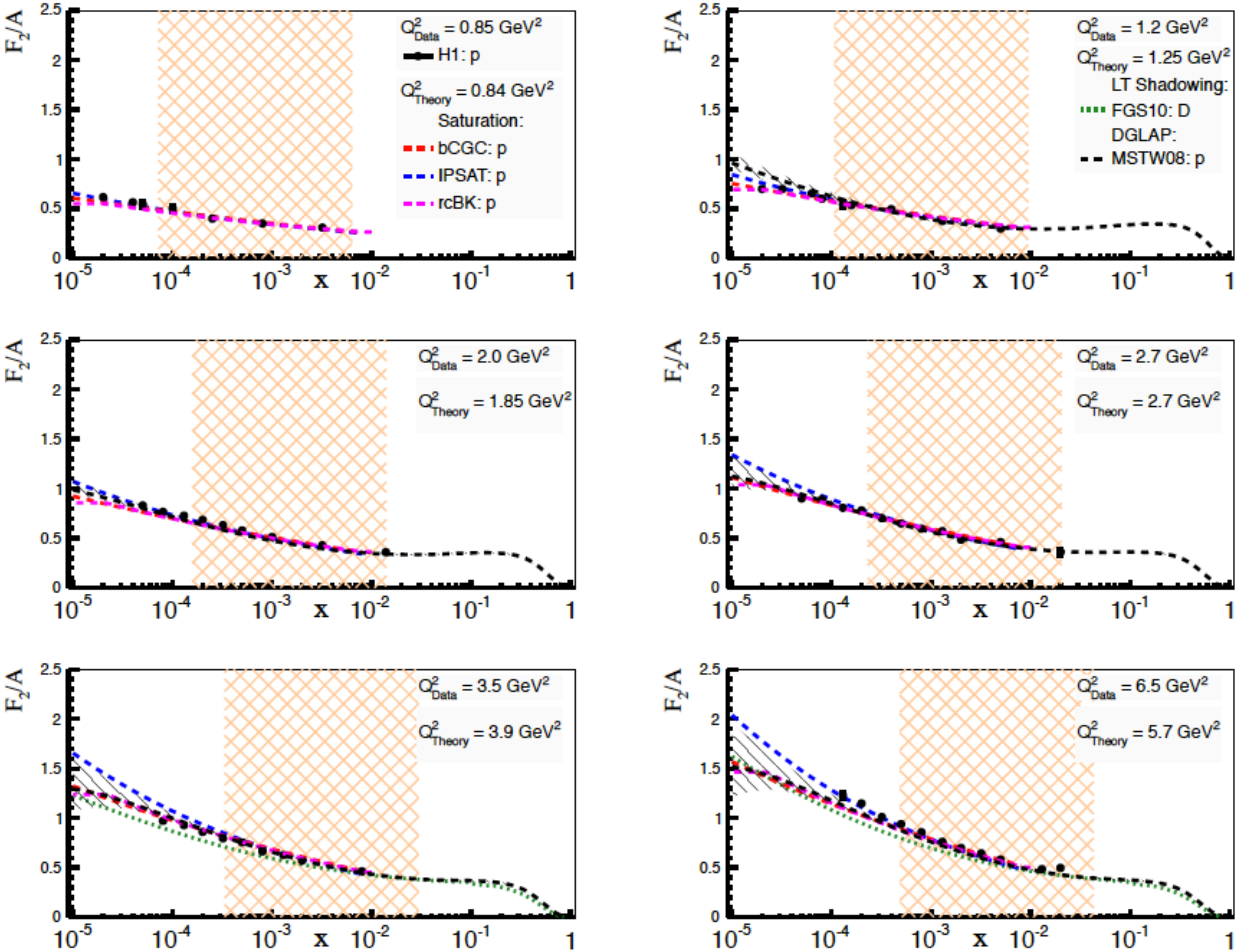


Are F_2/F_L good differentiators of models?

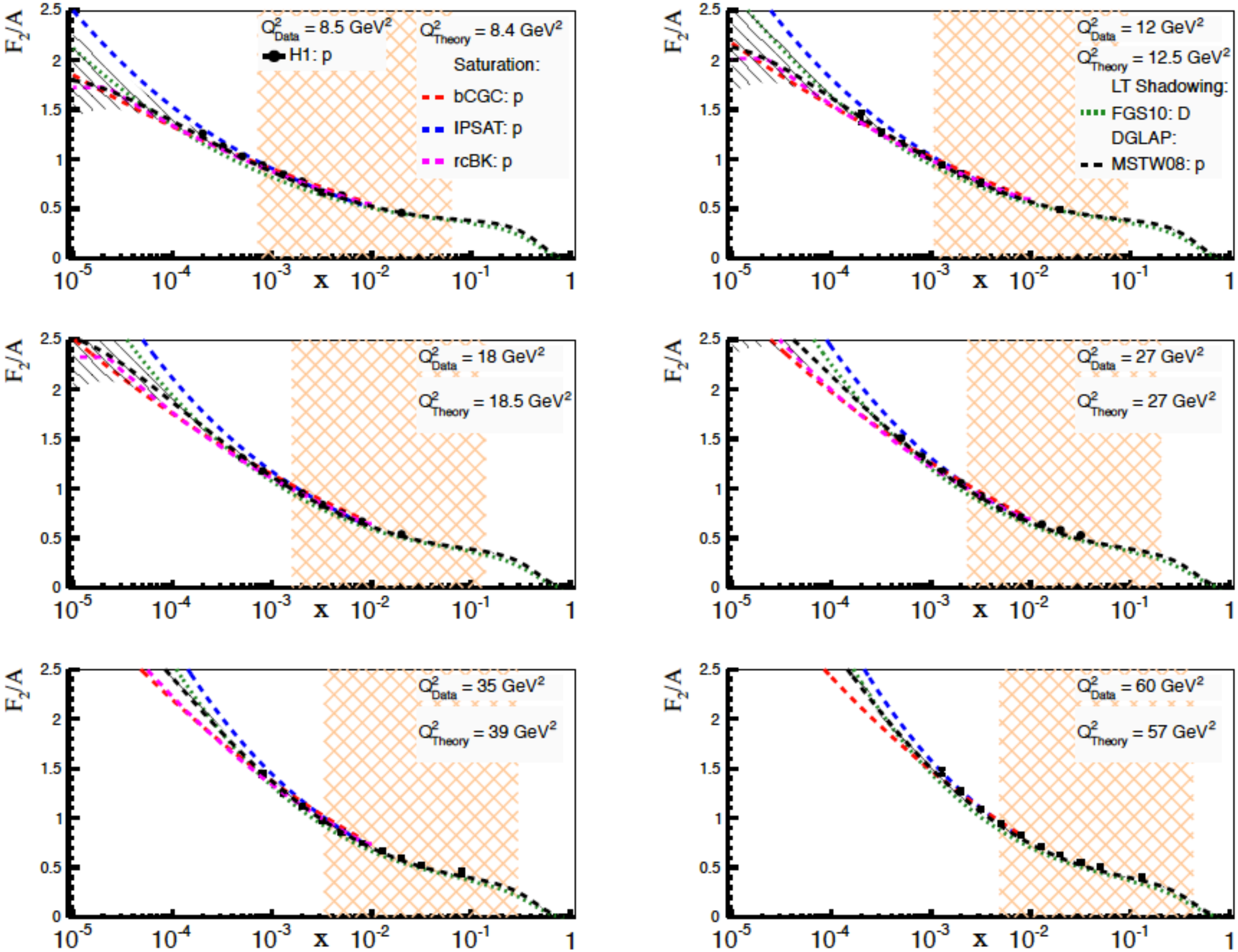
- In order to see if measuring F_2/F_L at an EIC is "worthwhile", we need to see if a measurement could differentiate between models
- Models:
  - MSTW08: code downloadable from HEPFORGE. Code to extract F_2/F_L obtained privately from Graeme Watt
    - Global fit, using total cross-section from HERA
    - DGLAP evolution
  - IPSat: data kindly provided by T. Lappi
    - Fit to ZEUS'96 data - χ^2/d.o.f. ~ 1.2
  - bCGC: data kindly provided by T. Lappi
    - Fit to Zeus'96 data - χ^2/d.o.f. ~ 1.2
  - rcBK: AAQMS data kindly provided by J. Albacete
    - Evolution along x with BK equation
    - Fit to H1+ZEUS combined 2006 data
  - Leading-Twist Shadowing: FGS10 data kindly provided by V. Guzey
    - Evolved with DGLAP
- Data:
  - F_2: H1&Zeus combined data from: http://www-h1.desy.de/psfiles/papers/desy09-158.pdf
  - F_L: H1 data from: http://www-h1.desy.de/psfiles/papers/desy10-228.pdf

$F_2(p)$ - low Q^2

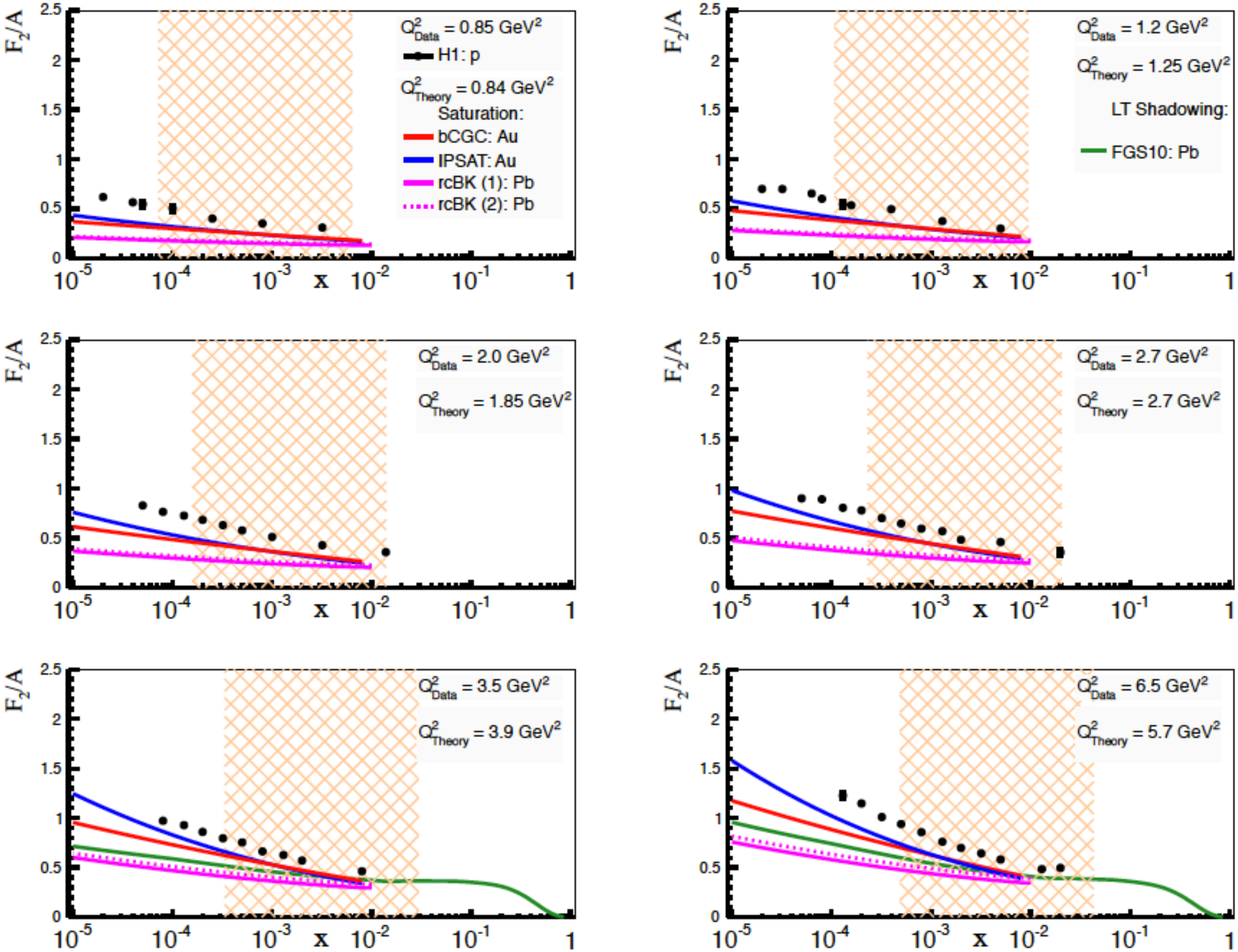


F_2/A
x
Q^2_{Data} = 0.85 GeV^2
H1: p
Q^2_{Theory} = 0.84 GeV^2
Saturation:
bCGC: p
IPSAT: p
rcBK: p
Q^2_{Data} = 1.2 GeV^2
Q^2_{Theory} = 1.25 GeV^2
LT Shadowing:
FGS10: D
DGLAP:
MSTW08: p
Q^2_{Data} = 2.0 GeV^2
Q^2_{Theory} = 1.85 GeV^2
Q^2_{Data} = 2.7 GeV^2
Q^2_{Theory} = 2.7 GeV^2
Q^2_{Data} = 3.5 GeV^2
Q^2_{Theory} = 3.9 GeV^2
Q^2_{Data} = 6.5 GeV^2
Q^2_{Theory} = 5.7 GeV^2

$F_2(p)$ - higher Q^2

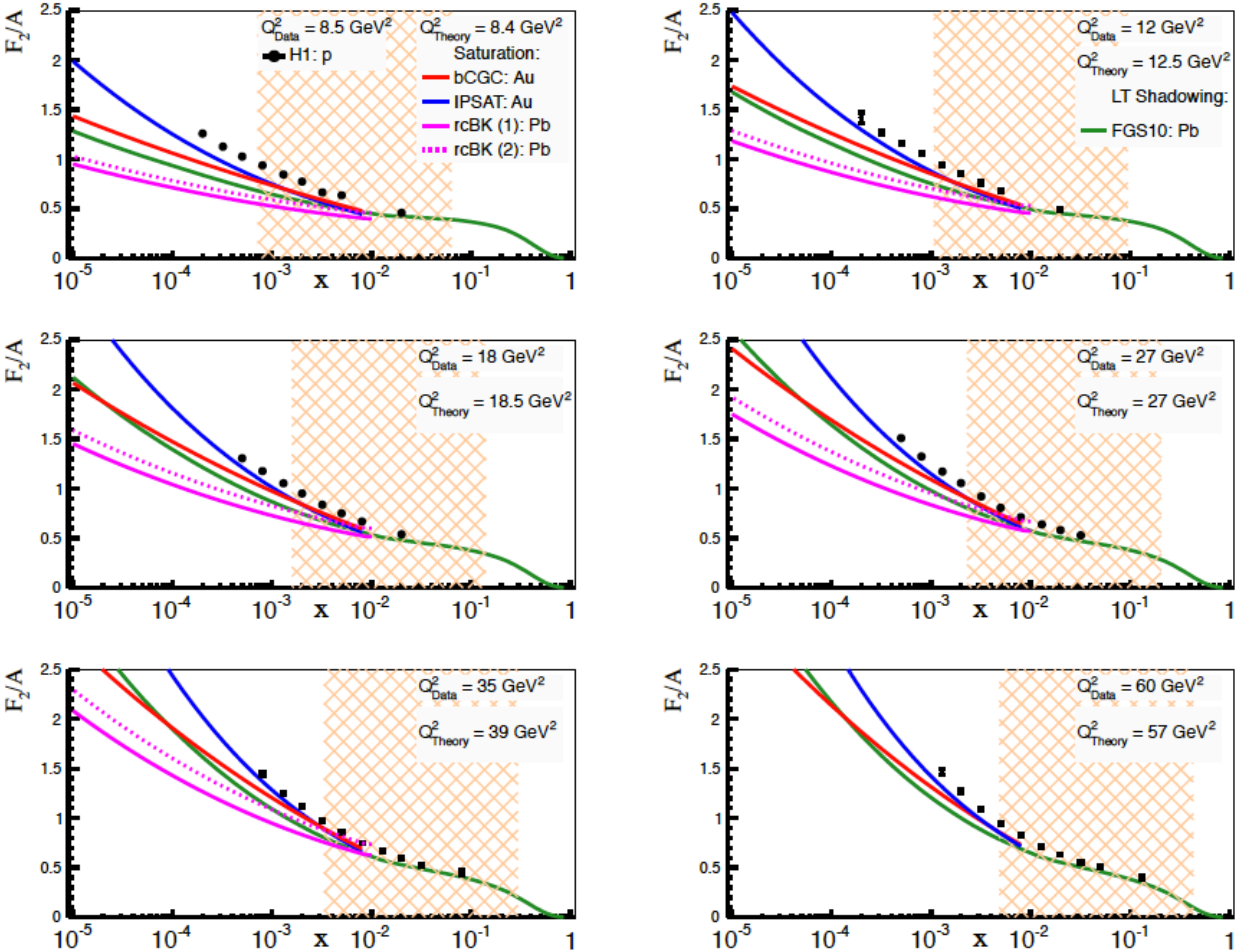


$F_2(A)/A$ - low Q^2



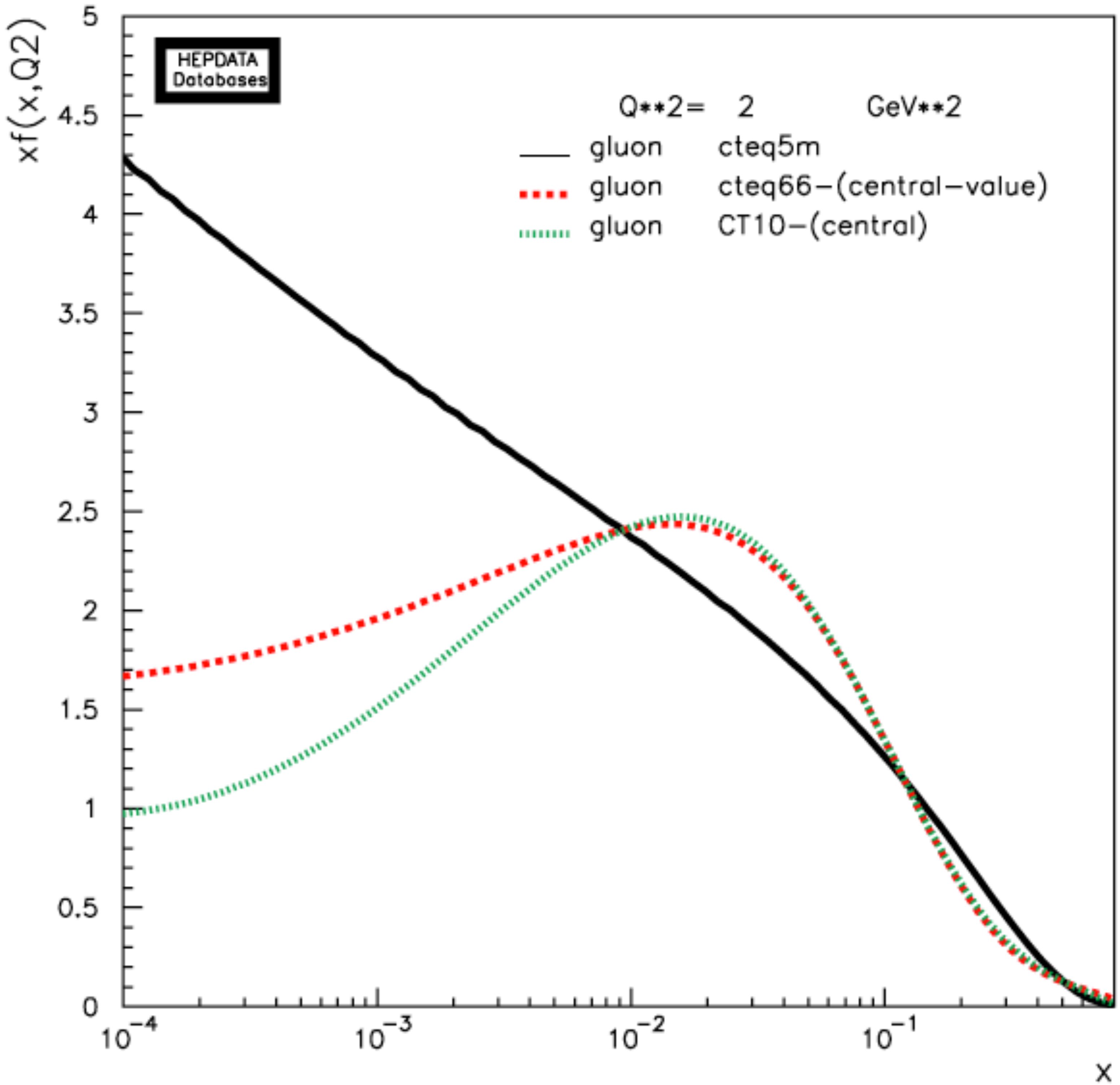
F2/A
Q²Data = 0.85 GeV²
H1: p
Q²Theory = 0.84 GeV²
Saturation:
bCGC: Au
IPSAT: Au
rcBK (1): Pb
rcBK (2): Pb
Q²Data = 1.2 GeV²
Q²Theory = 1.25 GeV²
LT Shadowing:
FGS10: Pb
Q²Data = 2.0 GeV²
Q²Theory = 1.85 GeV²
Q²Data = 2.7 GeV²
Q²Theory = 2.7 GeV²
Q²Data = 3.5 GeV²
Q²Theory = 3.9 GeV²
Q²Data = 6.5 GeV²
Q²Theory = 5.7 GeV²
x

$F_2(A)/A$ - higher Q^2

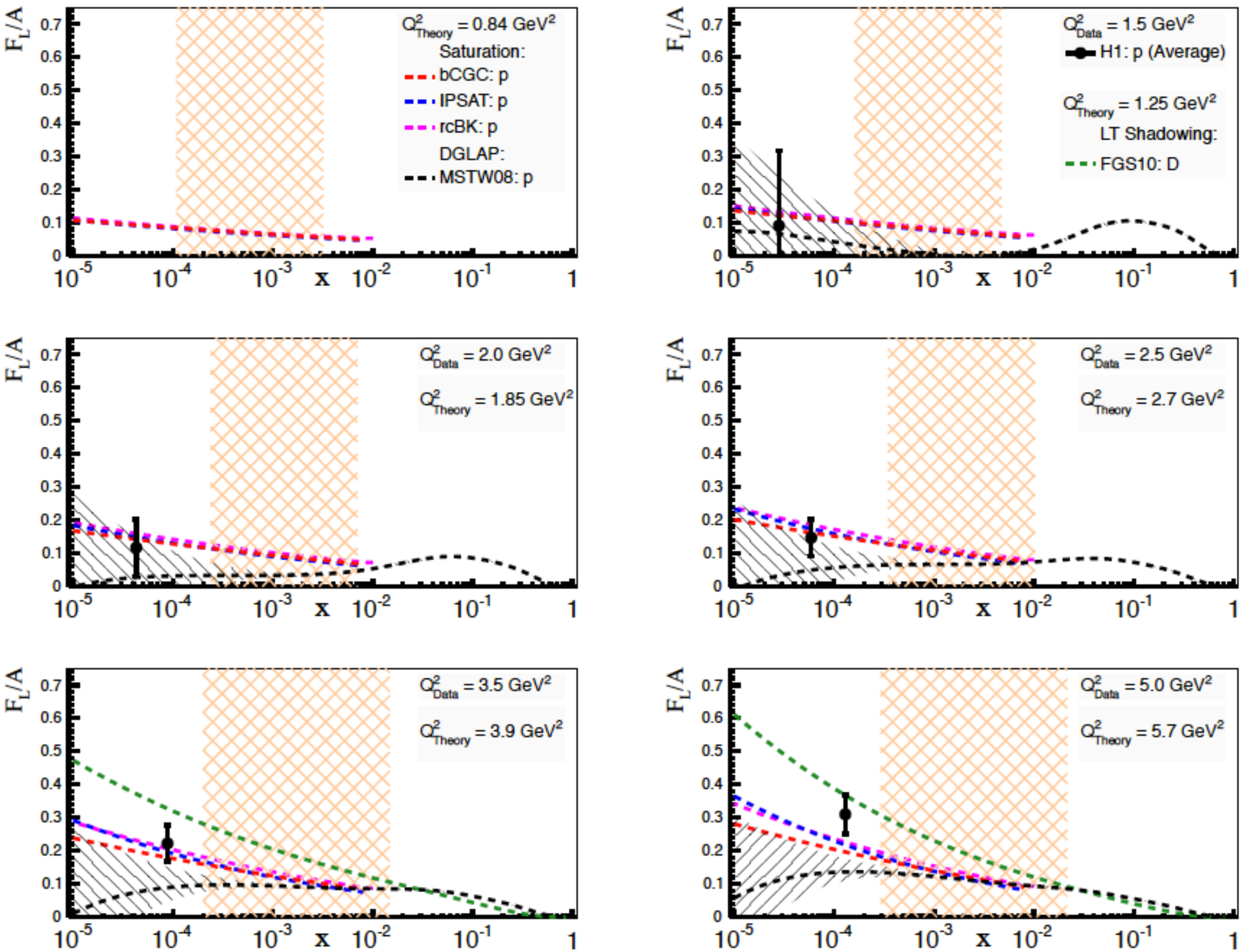


Using the correct PDF

- The current implementation of FGS10 uses CTEQ5m as its PDF
- This overestimates the gluon contribution quite drastically compared to more modern calculations
  - New curves are on their way from FGS10 with CTEQ6
  - Not ready for this meeting
  - Following F_L data therefore still uses CTEQ5m for FGS10



$F_L(p)$ - low Q^2



F_L/A
x
Q^2_{Theory} = 0.84 GeV^2
Saturation:
bCGC: p
IPSAT: p
rcBK: p
DGLAP:
MSTW08: p
Q^2_{Data} = 1.5 GeV^2
H1: p (Average)
Q^2_{Theory} = 1.25 GeV^2
LT Shadowing:
FGS10: D
Q^2_{Data} = 2.0 GeV^2
Q^2_{Theory} = 1.85 GeV^2
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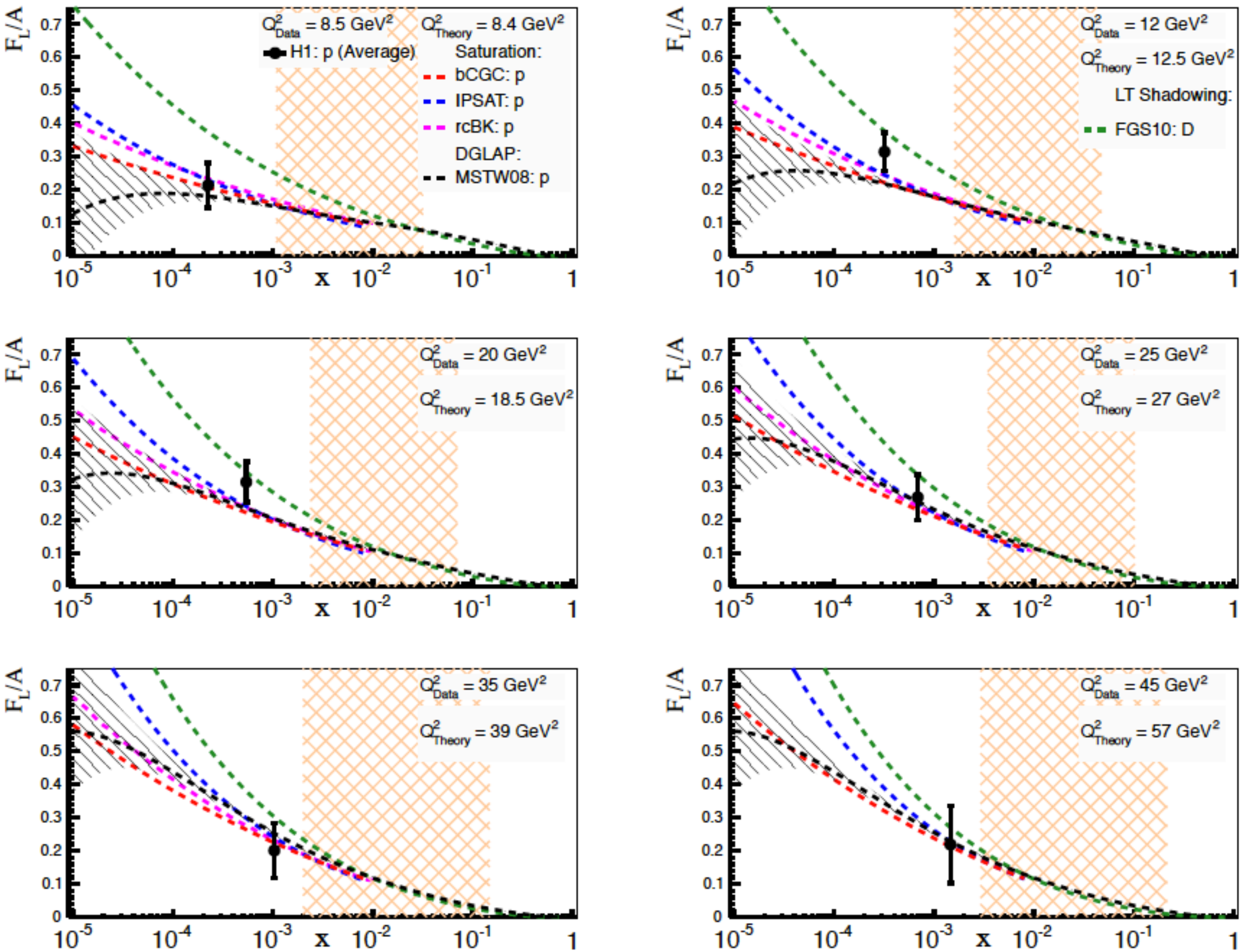
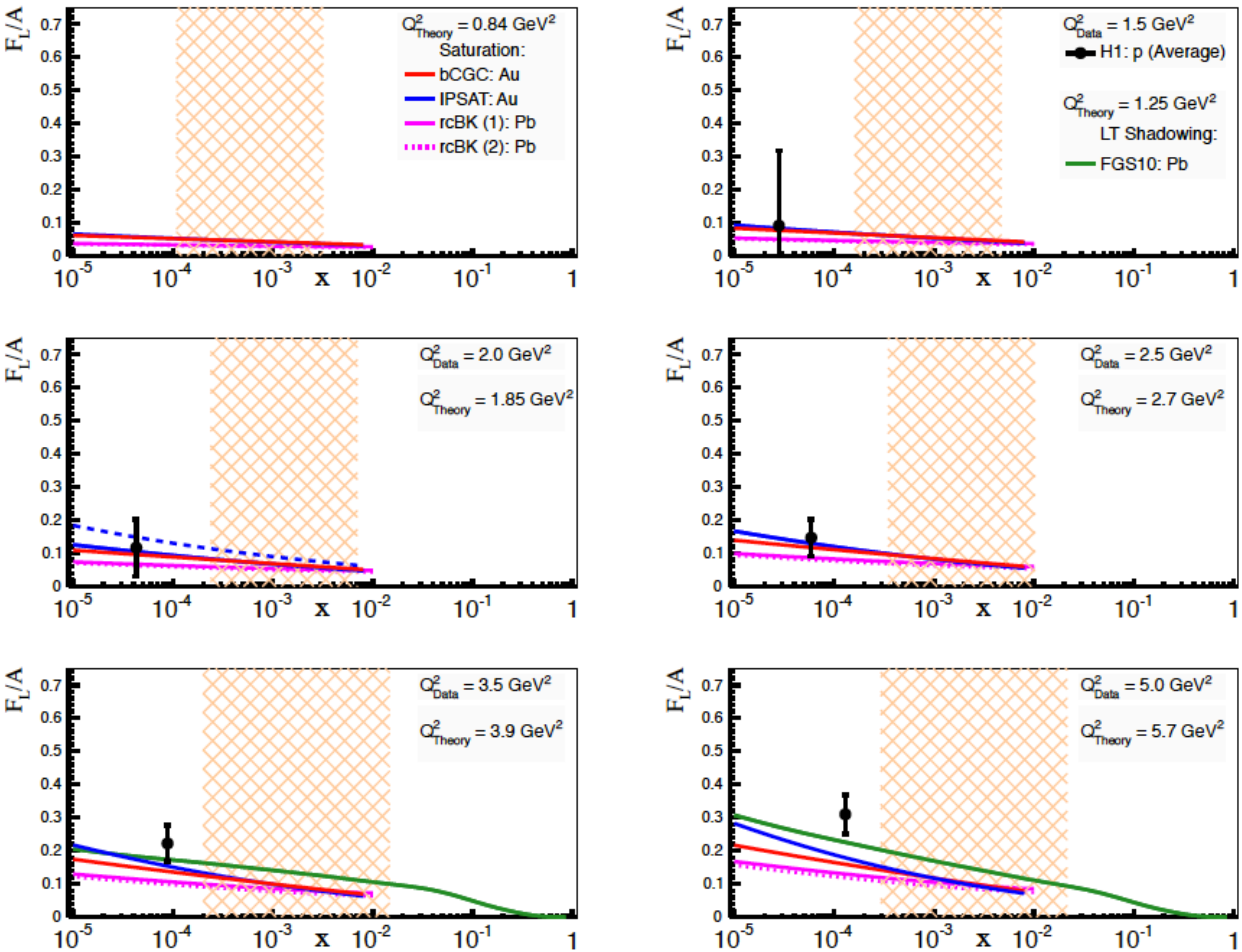
$F_L(p)$ - higher Q^2



$F_L(A)/A$ - low Q^2



Q^2_{Theory} = 0.84 GeV^2
Saturation:
bCGC: Au
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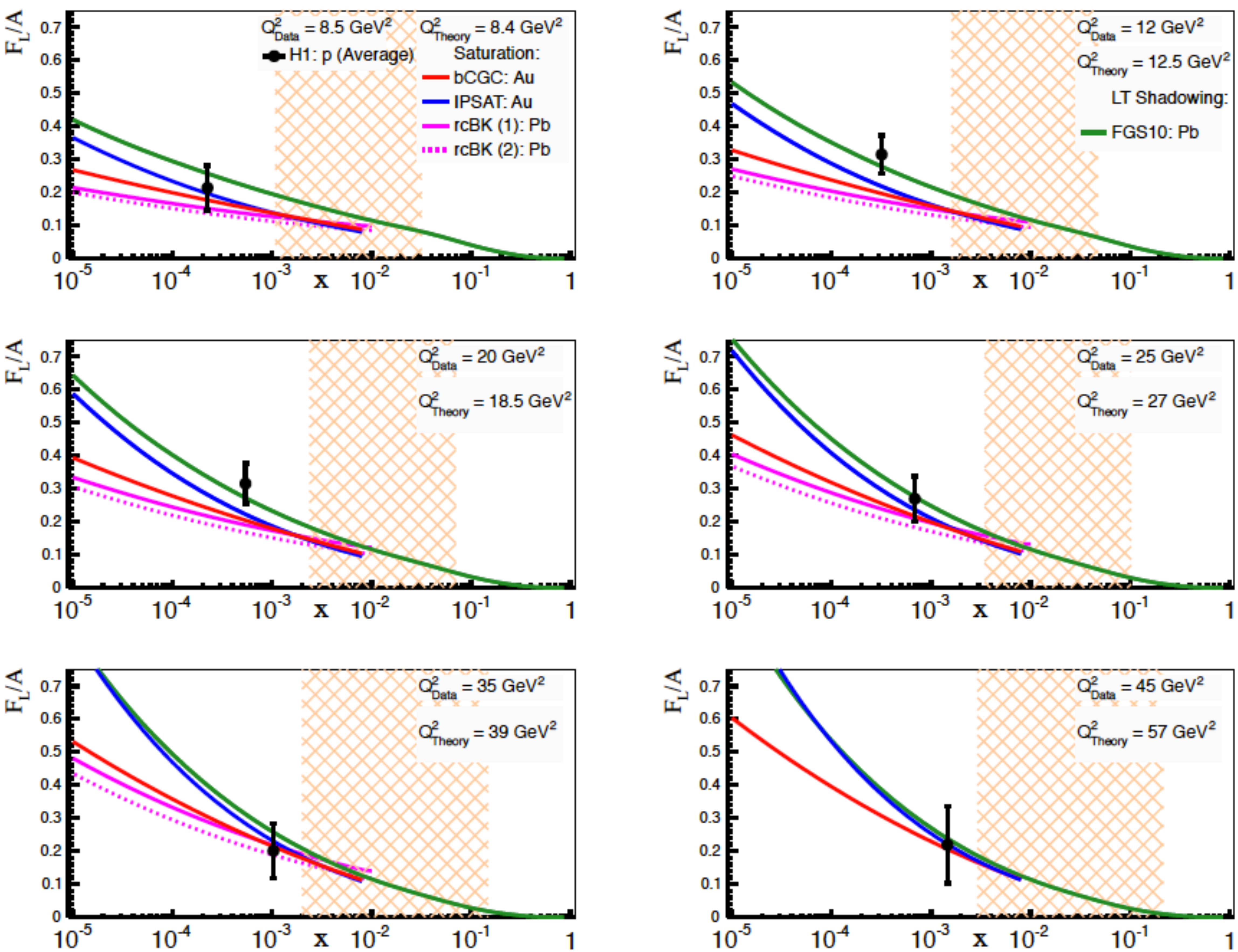
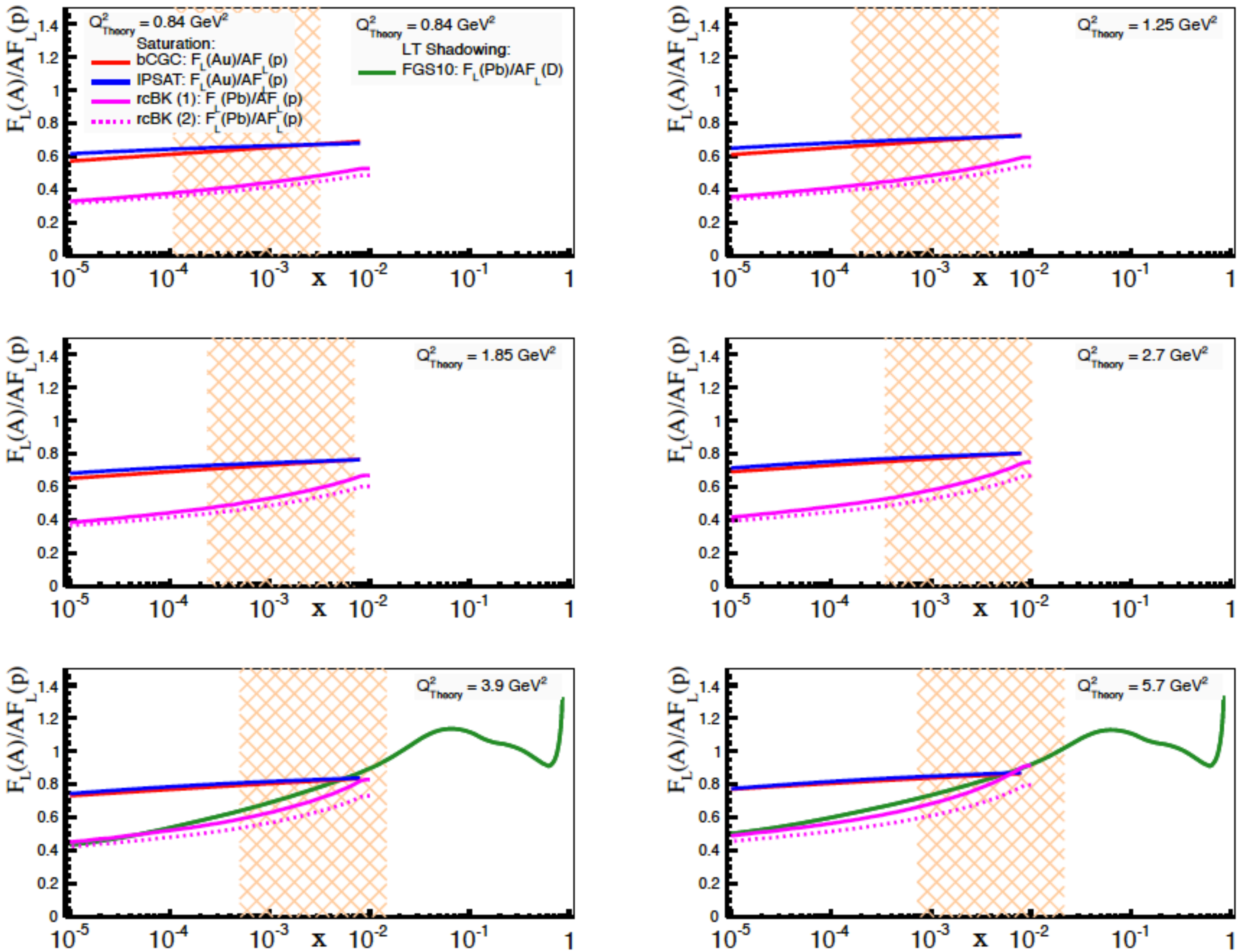
F_L/A
x

$F_L(A)/A$ - higher Q^2



F_L ratios - low Q^2



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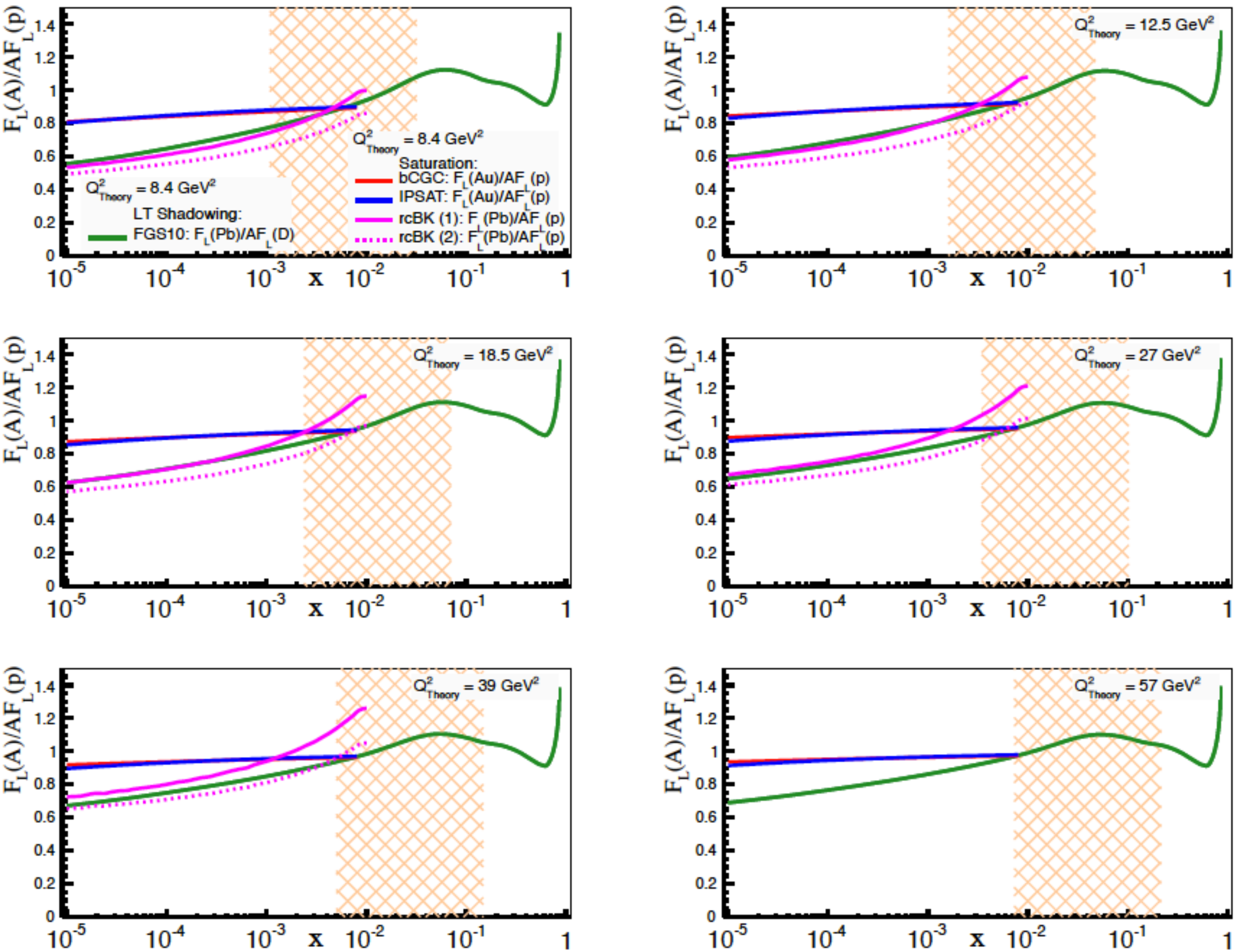
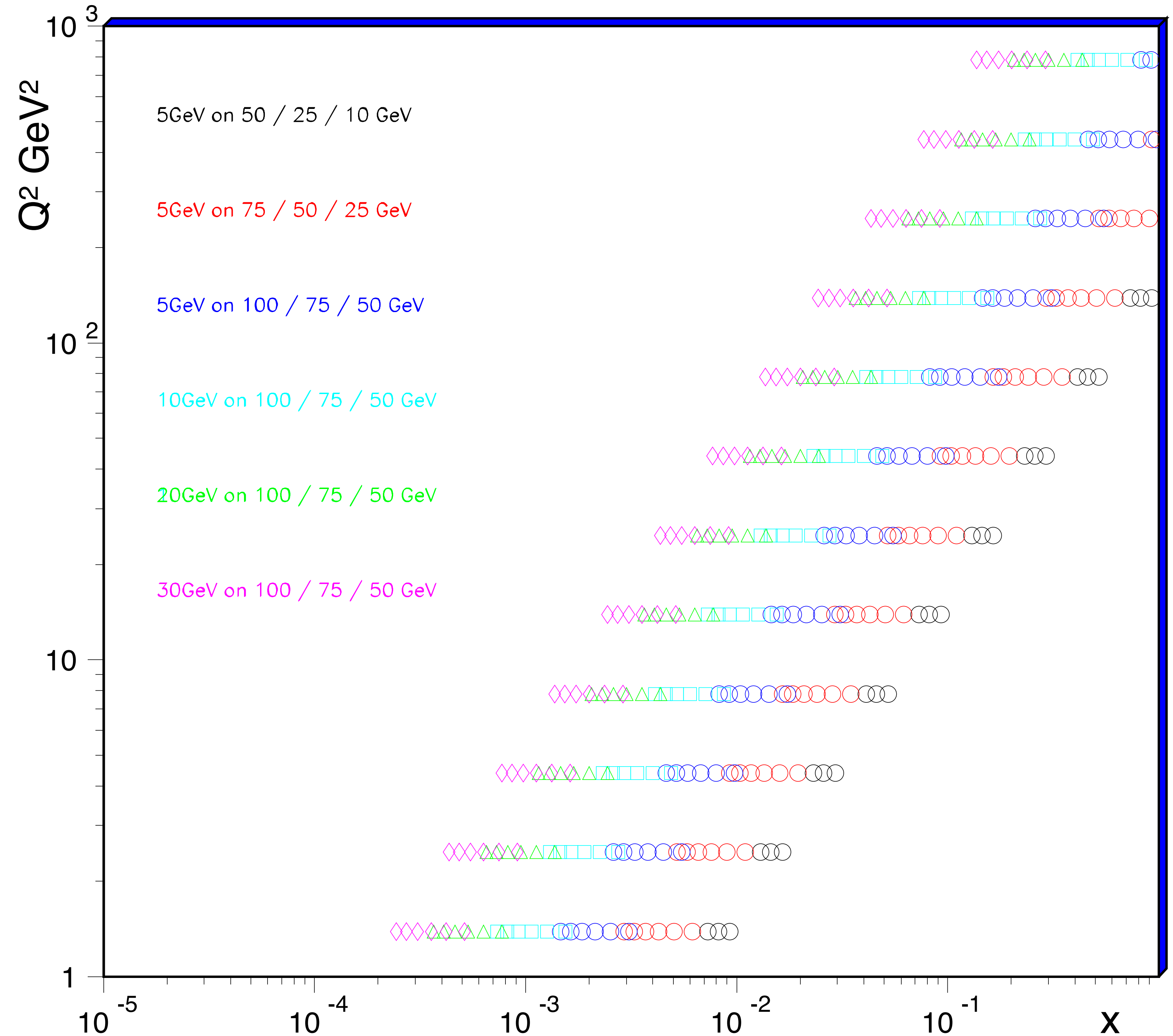


Feasibility study: $\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+}F_L^A(x,Q^2)$

- Simulated data for e+A coverage in x-Q^2 space
  - 3 energies is the minimum requirement in the F_L capability study
  - 1st stage only gets to medium x
  - Need high electron energy to get to “small” x



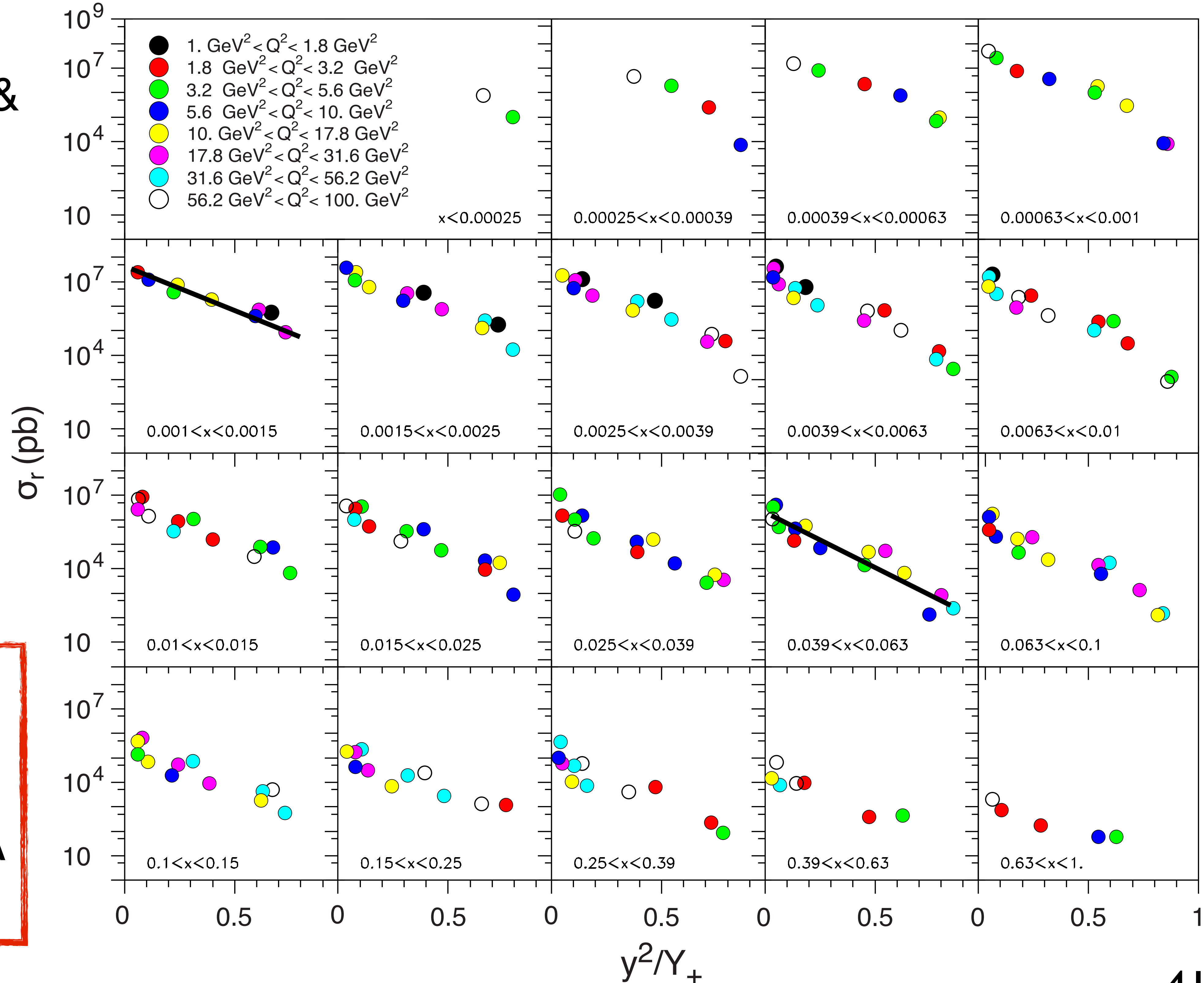
Feasibility study: $\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+}F_L^A(x,Q^2)$

Strategies:
slope of y^2/Y_+ for different s at fixed x & Q^2

e+p: 1st stage
5x50 - 5x325
running combined
4 weeks/each
(50% eff)

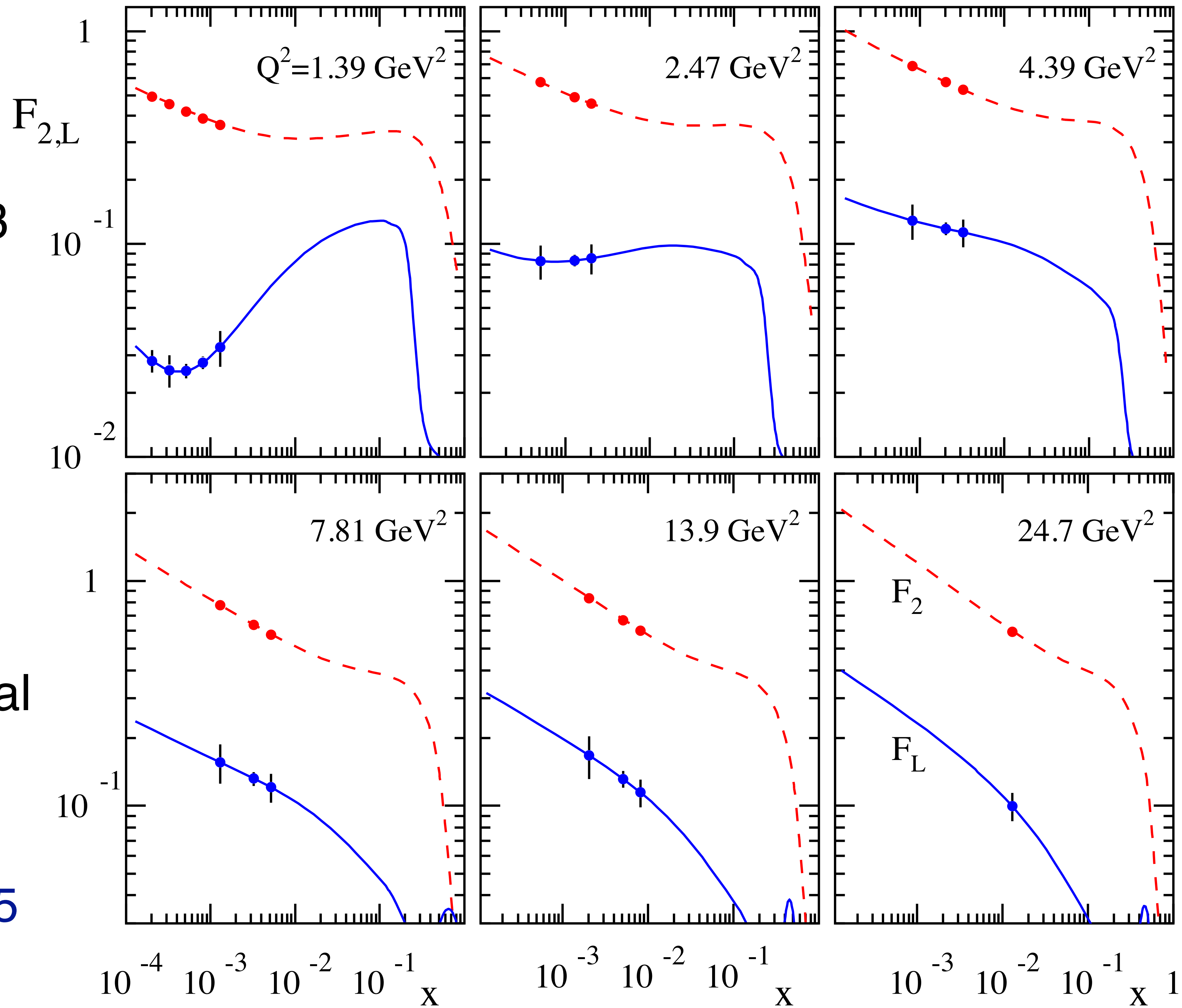
stat. error shown and negligible

To Do:
refine method & test how well we can extract F_L in e+A collisions

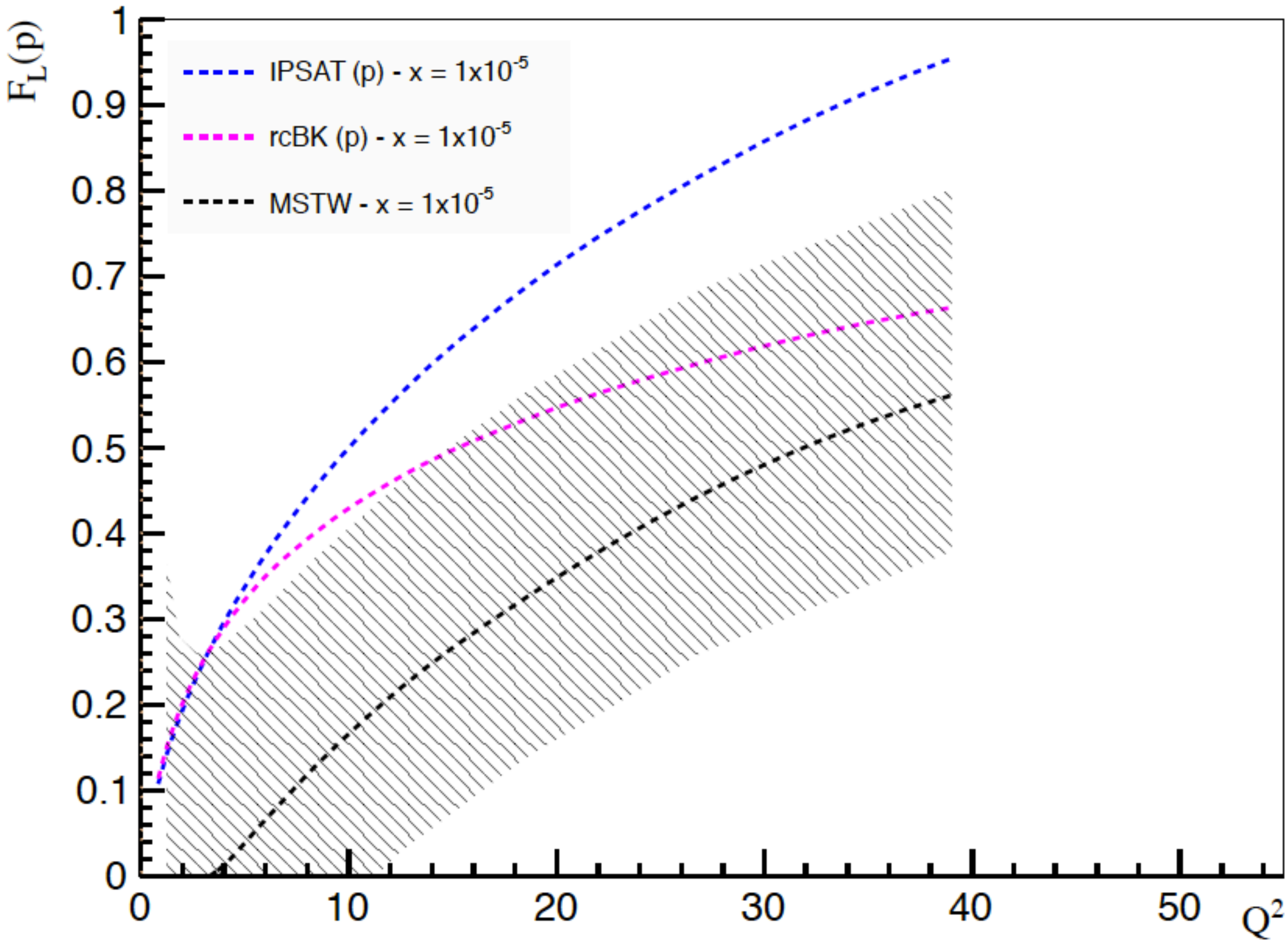


Extracting F_2 and F_L at the EIC

- $F_{2,L}$ extracted from pseudo-data generated for 1 month running at 3 eRHIC energies
  - ➡ 5+100 GeV
  - ➡ 5+250 GeV
  - ➡ 5+325 GeV
- Data, with errors, added to theoretical expectations from ABKM09 PDF set
  - ➡ valid for $Q^2 > 2.5$ GeV^2



Evolution of $F_L(p)$ with Q^2 - fixed x



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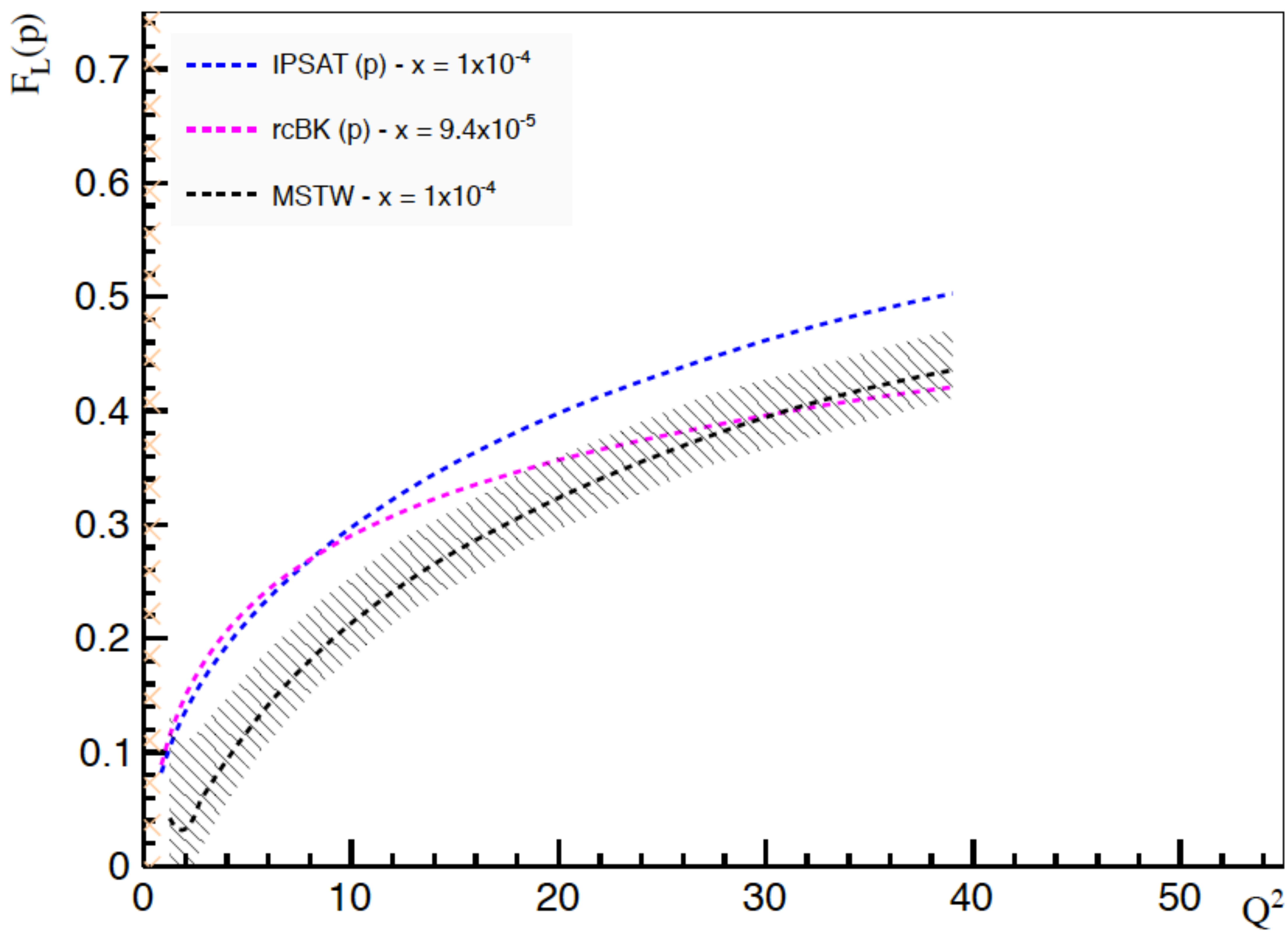

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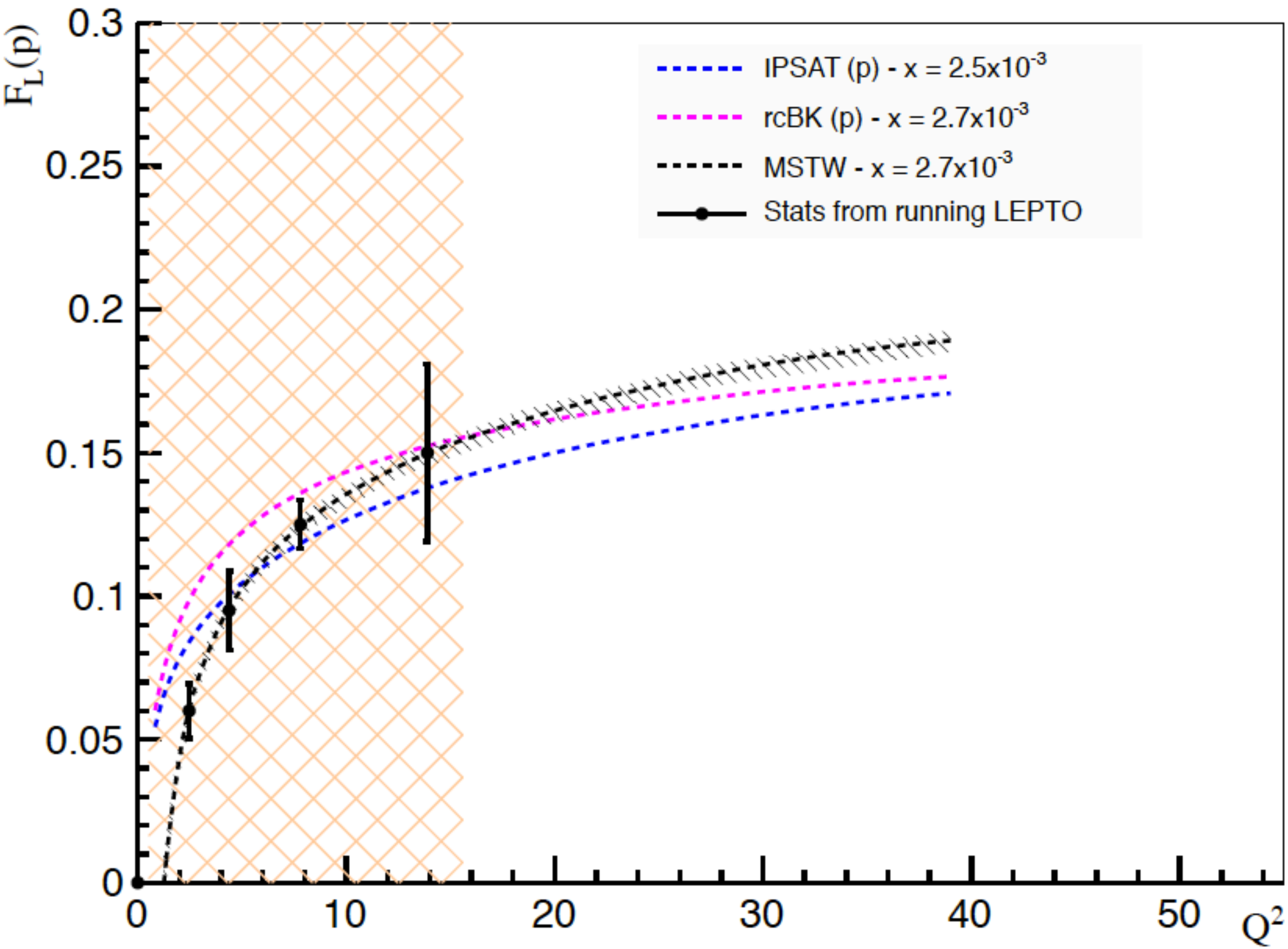

Charm and diffractive structure functions, $F^D_{2,L}$, $F^c_{2,L}$

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- $F^c_{2,L}$ give more direct access to the gluon distribution than the inclusive F_2 structure function
  - ➡ Due to the high charm mass, they probe higher values of x
    - Less sensitive to non-linear effects

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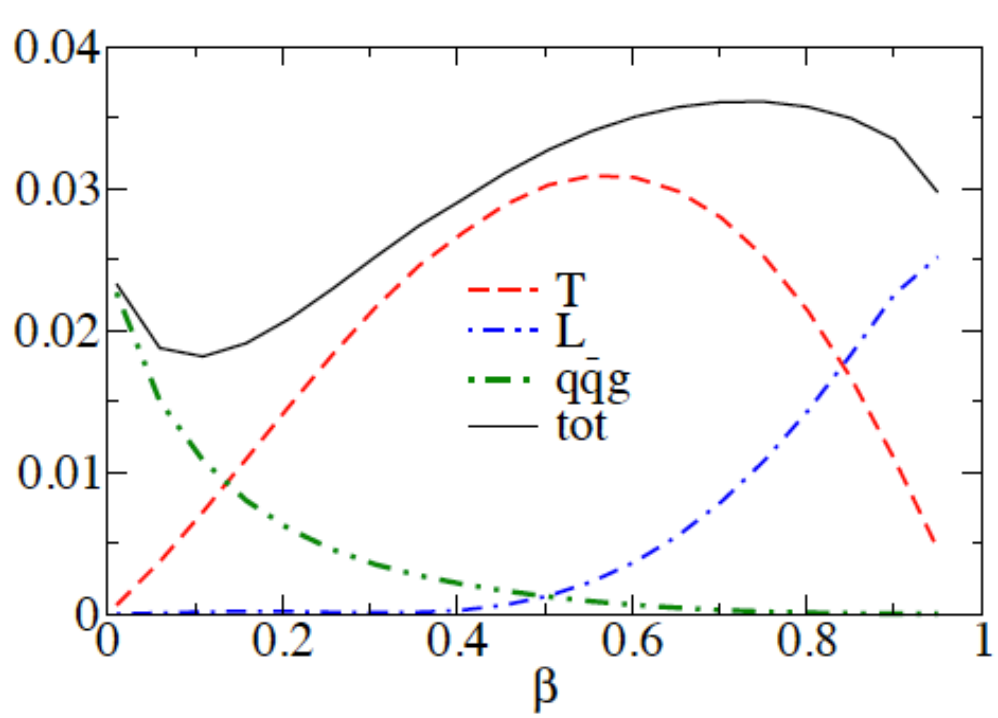
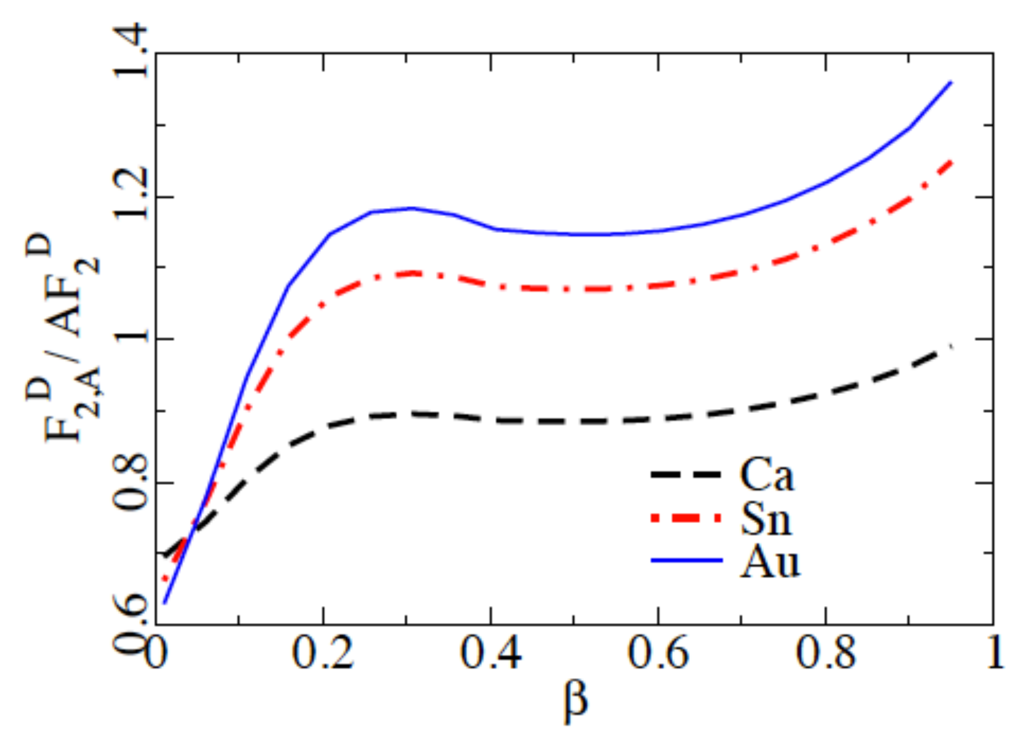
- $F^c_{2,L}$ give more direct access to the gluon distribution than the inclusive F_2 structure function
  - ➡ Due to the high charm mass, they probe higher values of x
    - ‣ Less sensitive to non-linear effects
- $F^D_{2,L}$ is also sensitive to the gluon distribution
  - ➡ Differences between linear and non-linear models appear at higher Q^2 than for F_2 (8 GeV^2 vs 2 GeV^2)
    - ‣ More experimentally challenging measurement than F_2

$$x_{\mathbb{P}} = 10^{-3}$$

$$Q^2 = 5GeV^2$$





k_T dependent gluons, gluon correlations from di-hadron correlations, SIDIS (semi-inclusive DIS)

k_T dependent gluons, gluon correlations from di-hadron correlations, SIDIS (semi-inclusive DIS)

Deliverables	Observables	What we learn	Stage-I	Stage-II
k_T dependent gluons	SIDIS at small x	non-linear QCD evolution / universality	onset of saturation	rare probes and bottom; large-x gluons

Direct link between p_T of produced hadron and that of the small-x gluon

$$e+A \rightarrow e + h + X$$

k_T dependent gluons, gluon correlations from di-hadron correlations, SIDIS (semi-inclusive DIS)

$$e + A \rightarrow e + h_1 + h_2 + X$$

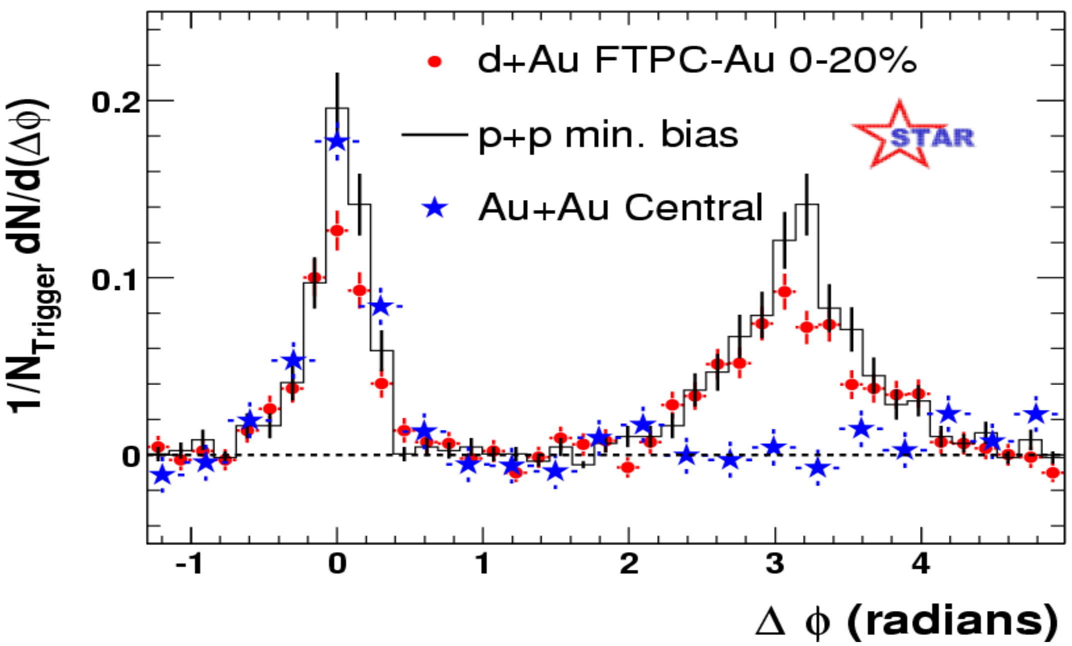
Deliverables	Observables	What we learn	Stage-I	Stage-II
k_T dependent gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution / universality	onset of saturation	measure Q_s

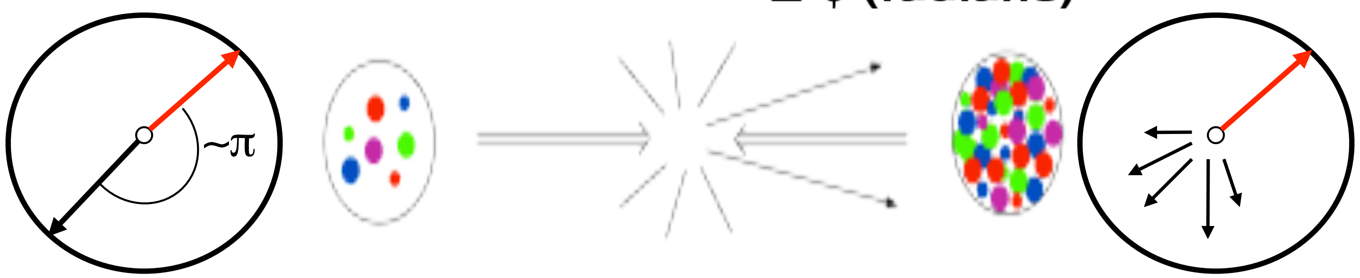
$$e + A \rightarrow e + h + X$$

k_T dependent gluons	SIDIS at small x	non-linear QCD evolution / universality	onset of saturation	rare probes and bottom; large-x gluons

di-hadron angular correlations in d+A

comparisons between d+Au → h_1 h_2 X (or p +Au → h_1 h_2 X) and p+p → h_1 h_2 X





- At y=0, suppression of away-side jet is observed in A+A collisions

- No suppression in p+p or d+A

➡ x ~ 10^{-2}

$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$

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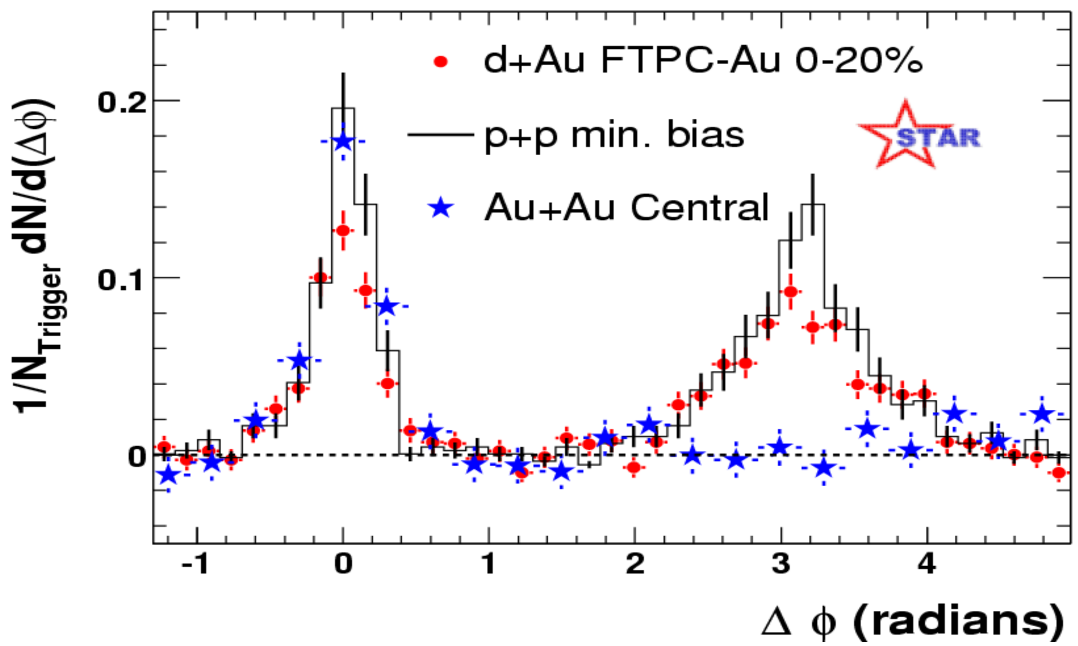

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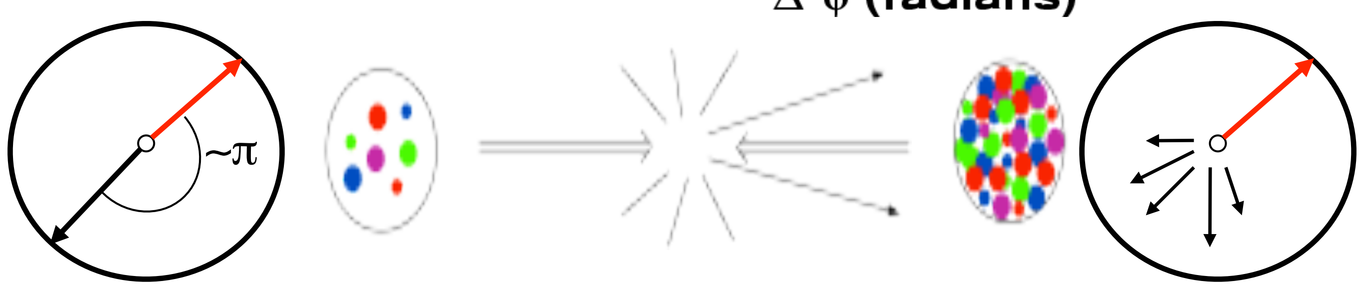
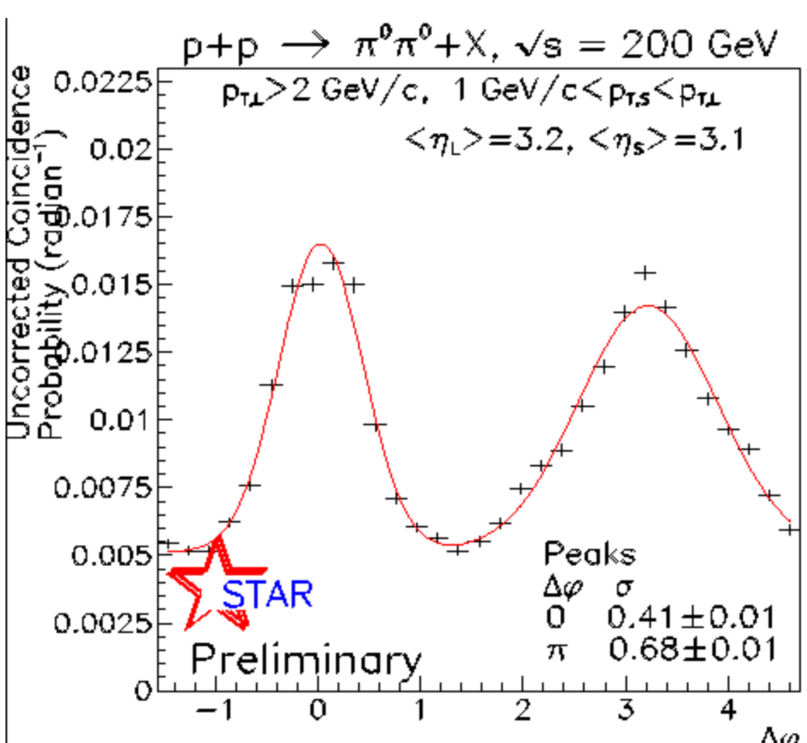
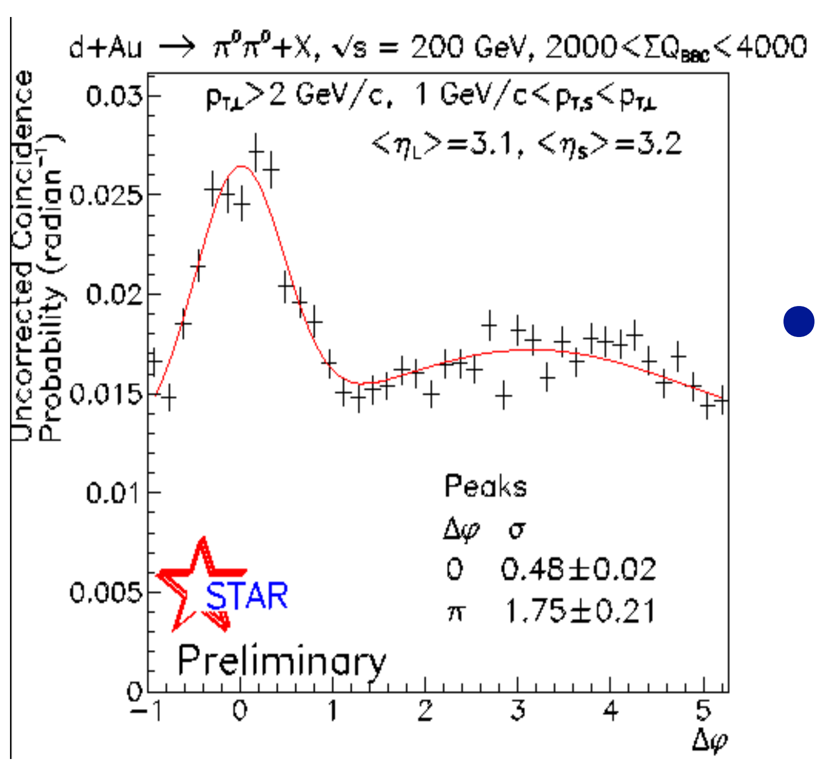






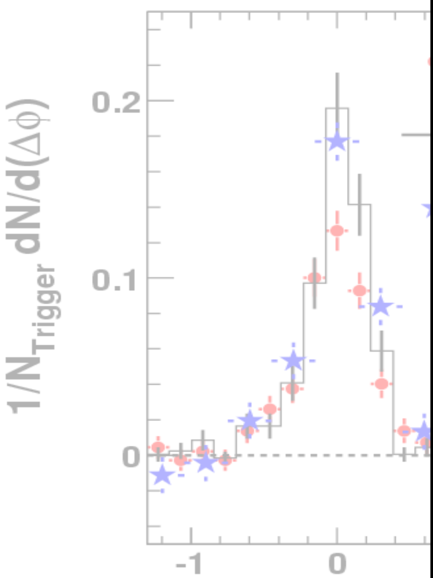
- However, at forward rapidities (y ~ 3.1), an away-side suppression is observed in d+Au
- Away-side peak also much wider in d+Au compared to p+p

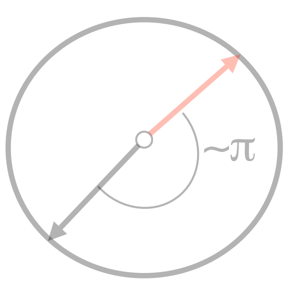
➡ x ~ 10^{-3}

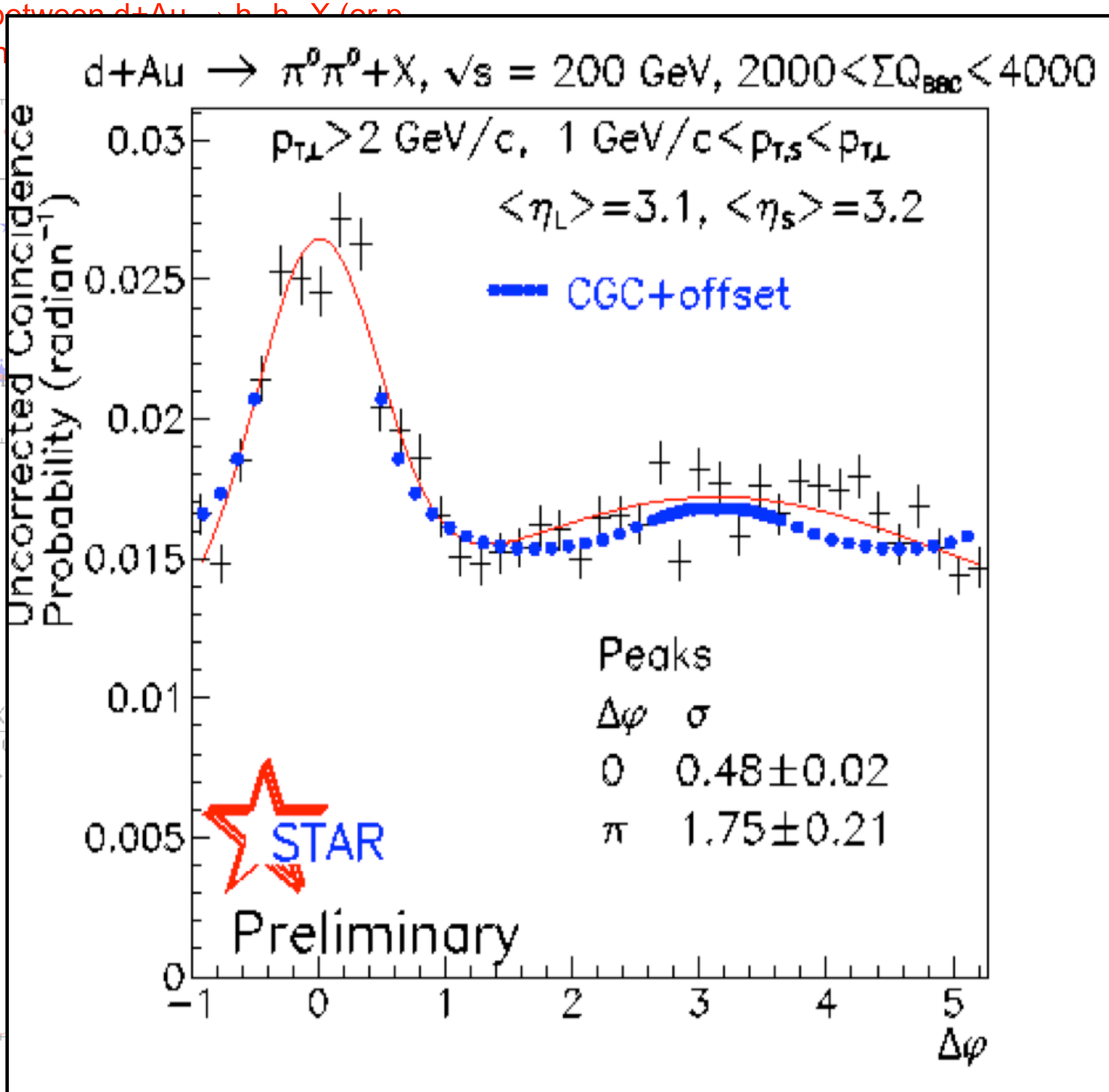
di-hadron angular correlations in d+A

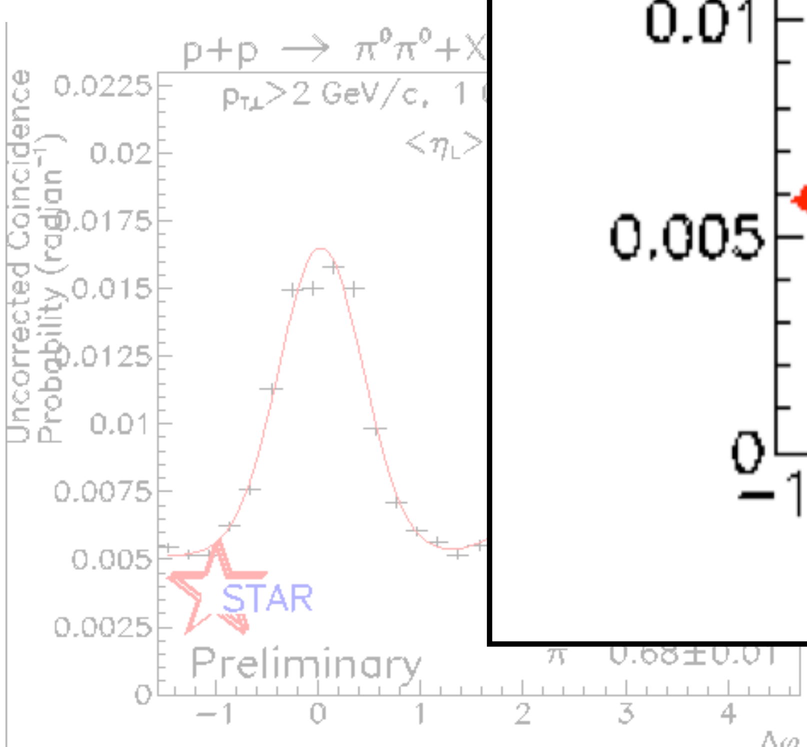
comparisons b

+Au → h_1 h









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in A+A

+p or d+A

$+ k_2\, e^{-y_2}$

$\sqrt{s}$ $<<1$

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d+Au

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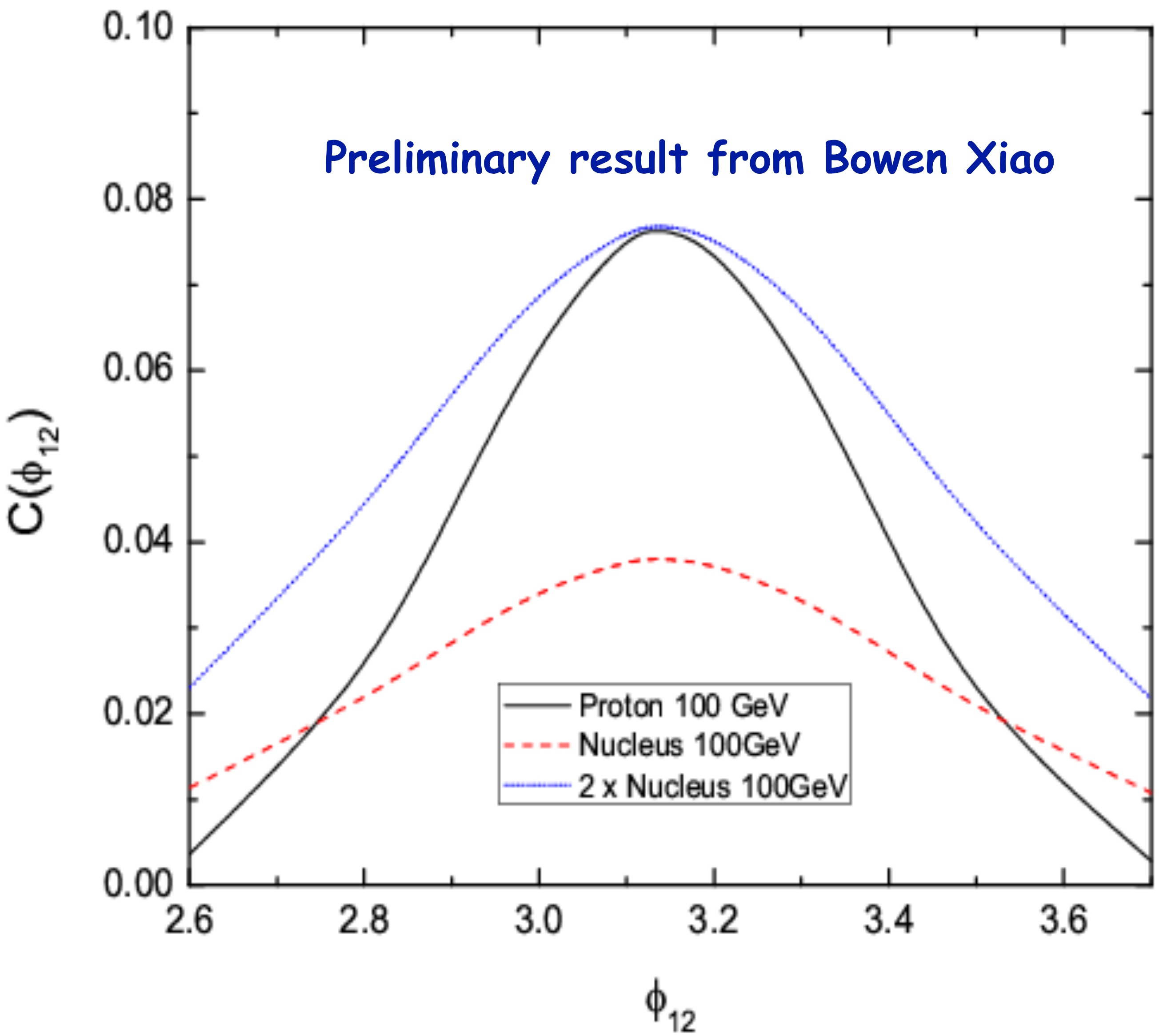
➡ $x \sim 10^{-3}$

di-hadron correlations in e+A

Never been measured - we expect to see the same effect in e+A as in d+A



$Q^2 = 4\text{GeV}^2$; $z_{h1} = z_{h2} = 0.3$

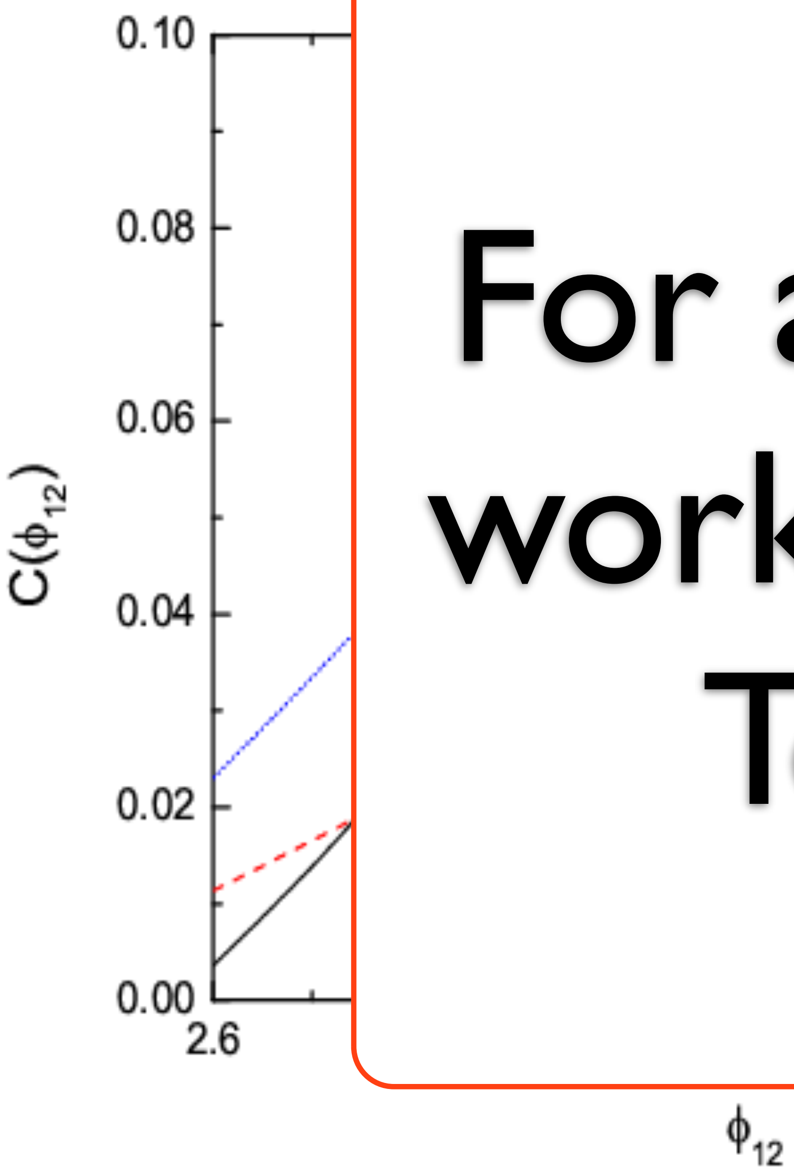
$2\text{ GeV} < p_T^T < 3\text{GeV}$

$1\text{GeV} < p_T^A < 2\text{GeV}$

- At small-x, multi-gluon distributions are as important as single-gluon distributions and they contribute to di-hadron correlations
  - ➡ The non-linear evolution of multi-gluon distributions is different from that of single-gluon distributions and it is equally important that we understand it
- The d+Au RHIC data is therefore subject to many uncertainties
  - ➡ these correlations in e+A can help to constrain them better

di-hadron correlations in e+A

Never been measured - we expect to see the same effect in e+A as in d+A



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For a discussion of this work, see talk by Tobias Toll on Thursday

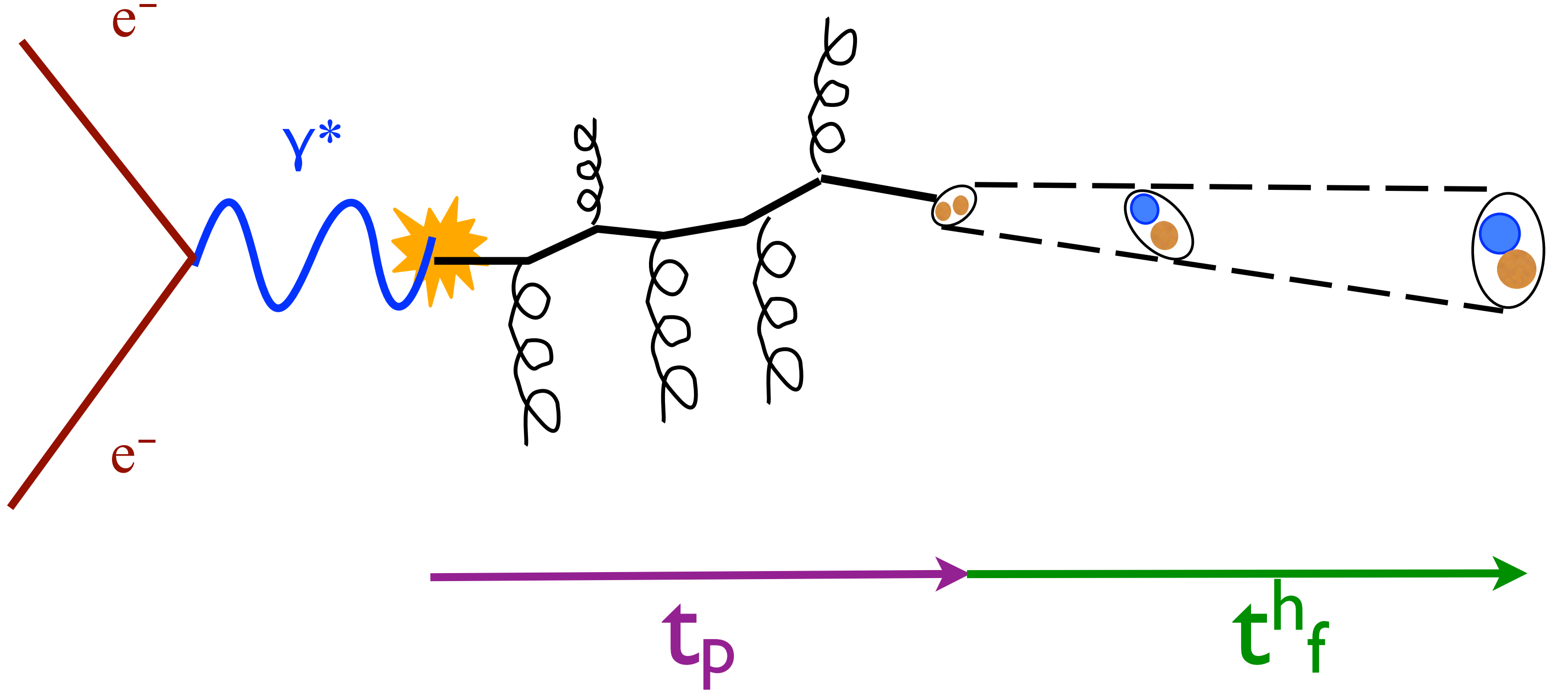
transport coefficients in cold nuclear matter from large-x semi-inclusive DIS and jets

Transport coefficients in cold nuclear matter

Deliverables	Observables	What we learn	Stage-I	Stage-II
transport coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mechanisms	light flavours and charm; jets	rare probes and bottom; large-x gluons

Jets and hadronization

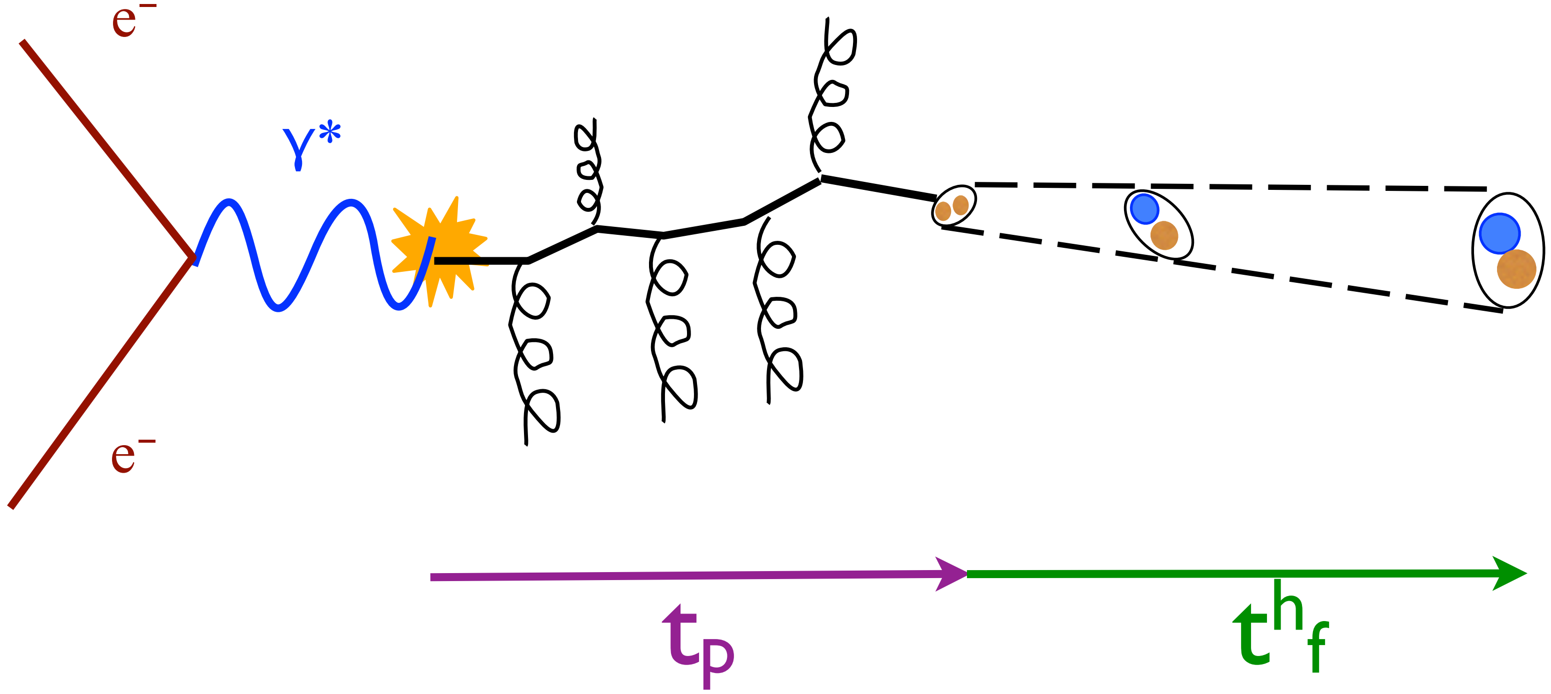
A. Accardi
R. Dupre



- t_p - production time of propagating quark
- t^h_f - hadron formation time

Jets and hadronization

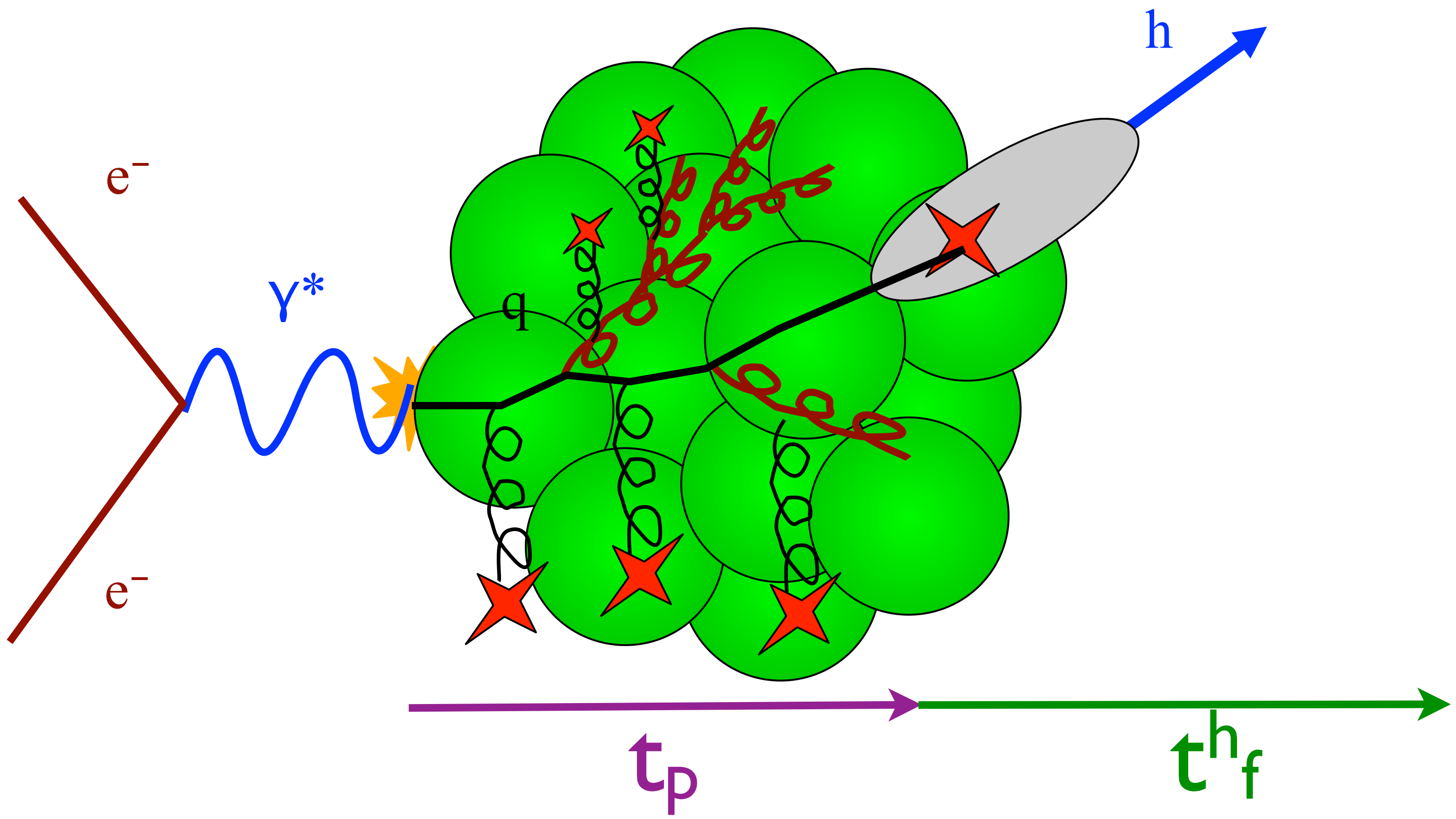
A. Accardi
R. Dupre



What happens if we add a nuclear medium?

- t_p - production time of propagating quark
- t^h_f - hadron formation time

Jets and hadronization



A. Accardi
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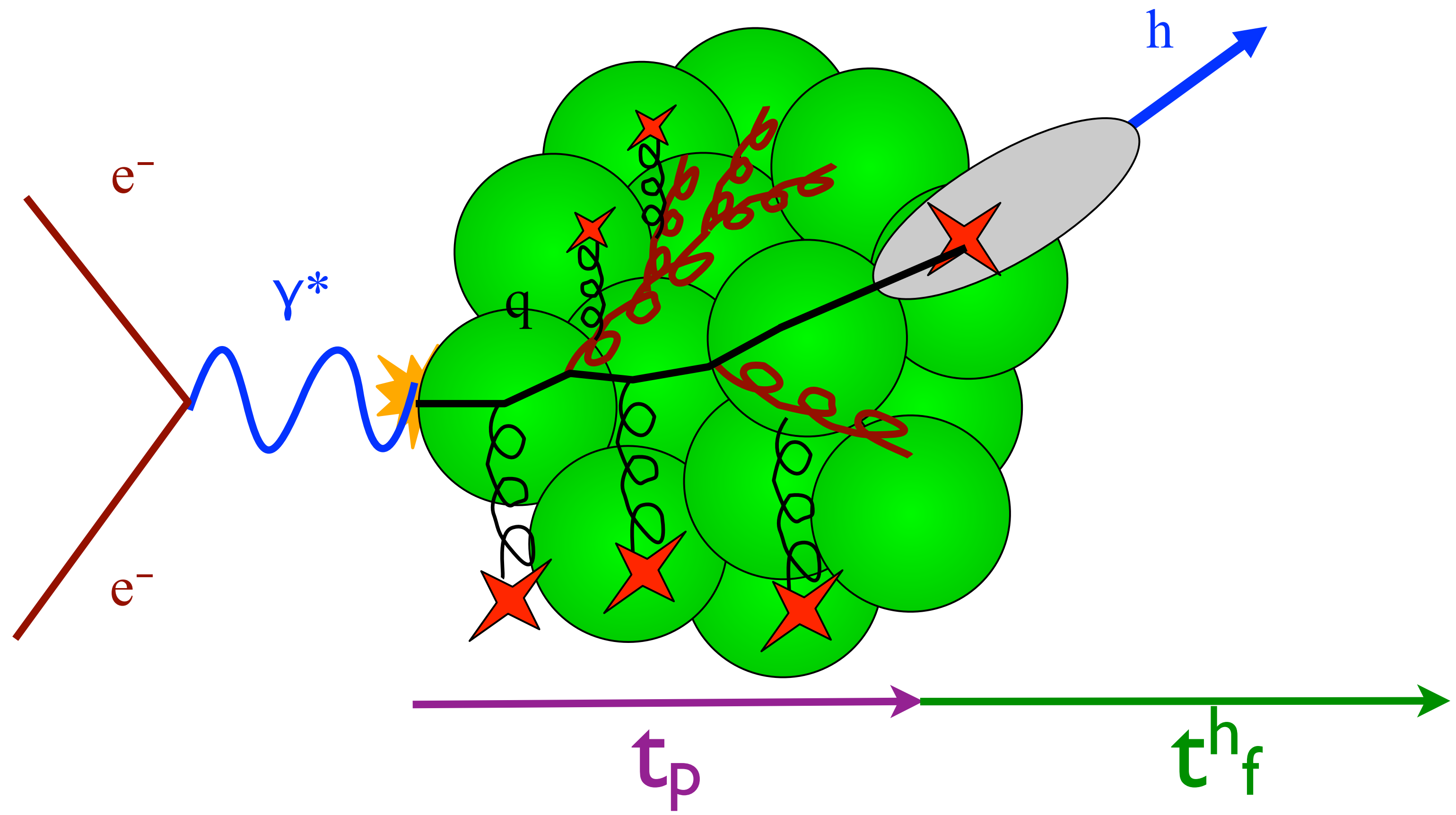

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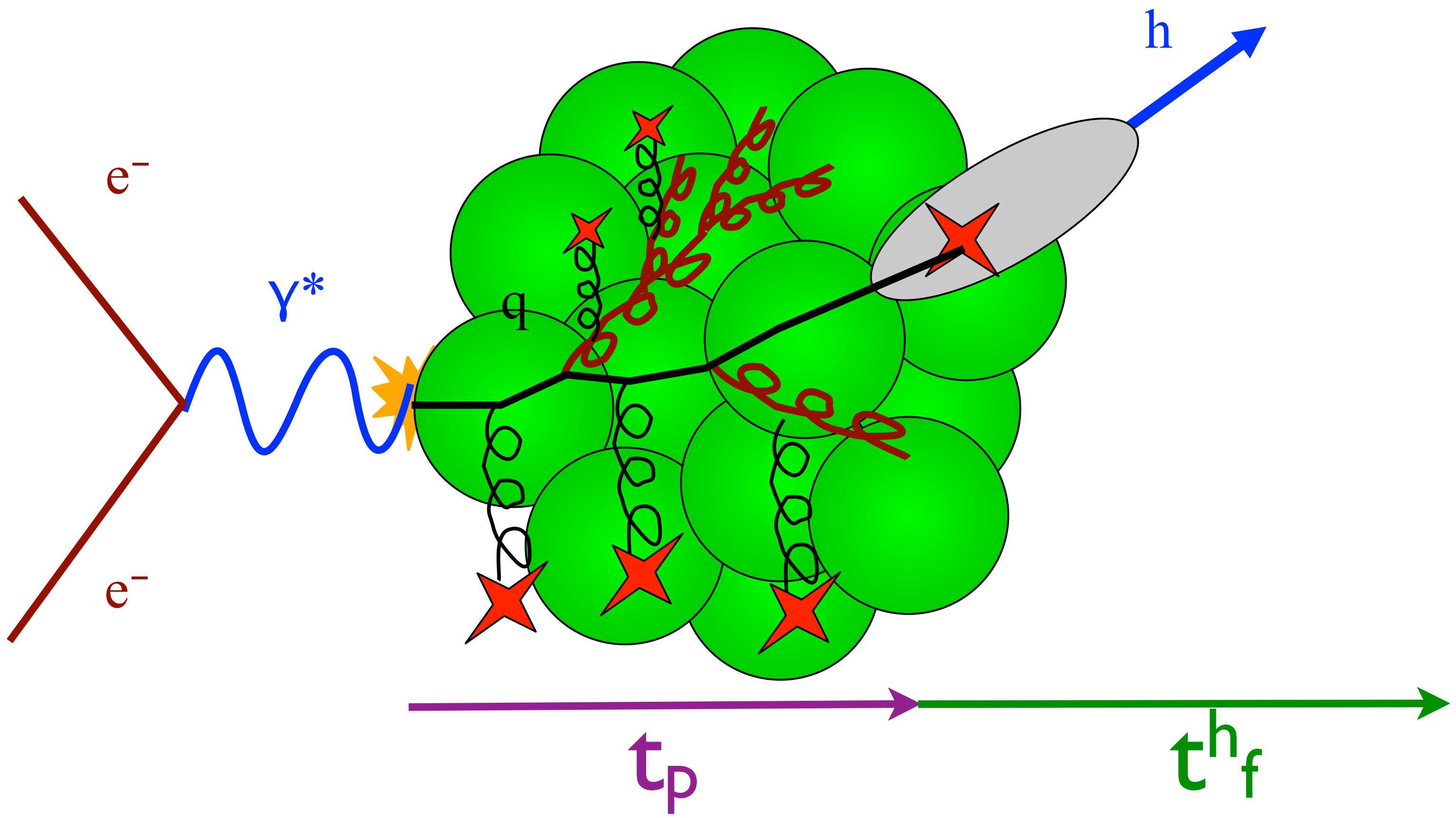
Observables:

Broadening: $\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_p$: direct link to saturation scale

Jets and hadronization



A. Accardi
R. Dupre

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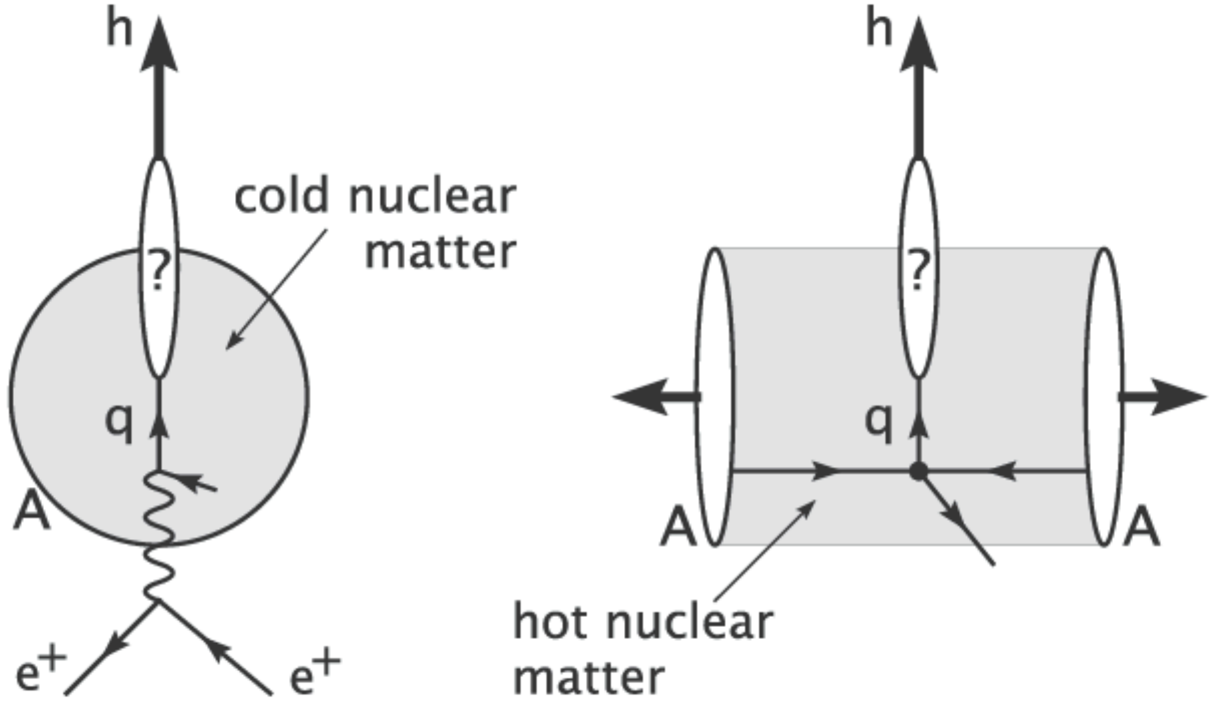
Jets and hadronization

A. Accardi
R. Dupre



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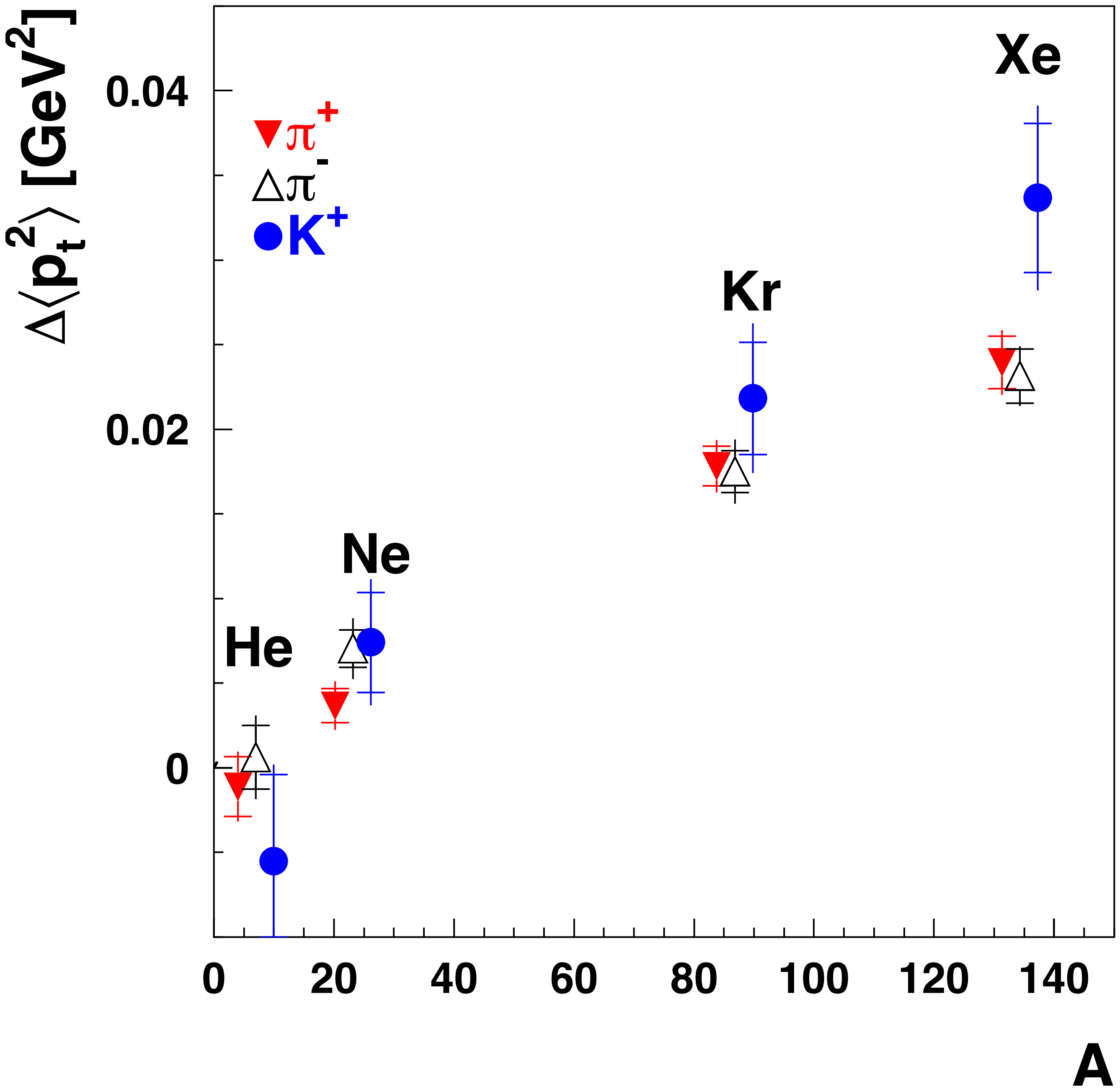
pT broadening - how can the EIC contribute?

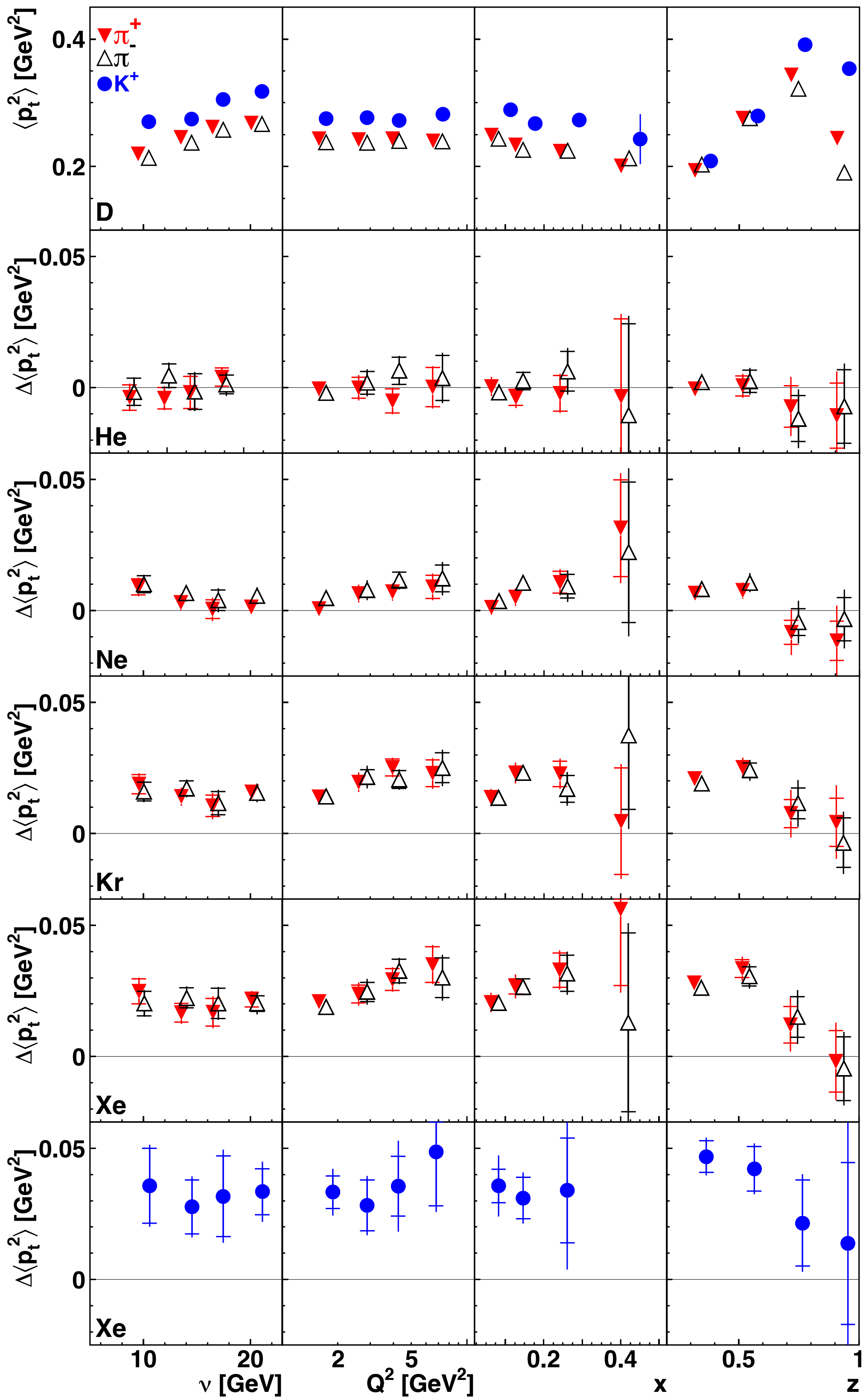
HERMES:



Increase of p_T broadening seen with increasing nuclear size - integrated over all variables

pT broadening - how can the EIC contribute?

HERMES:



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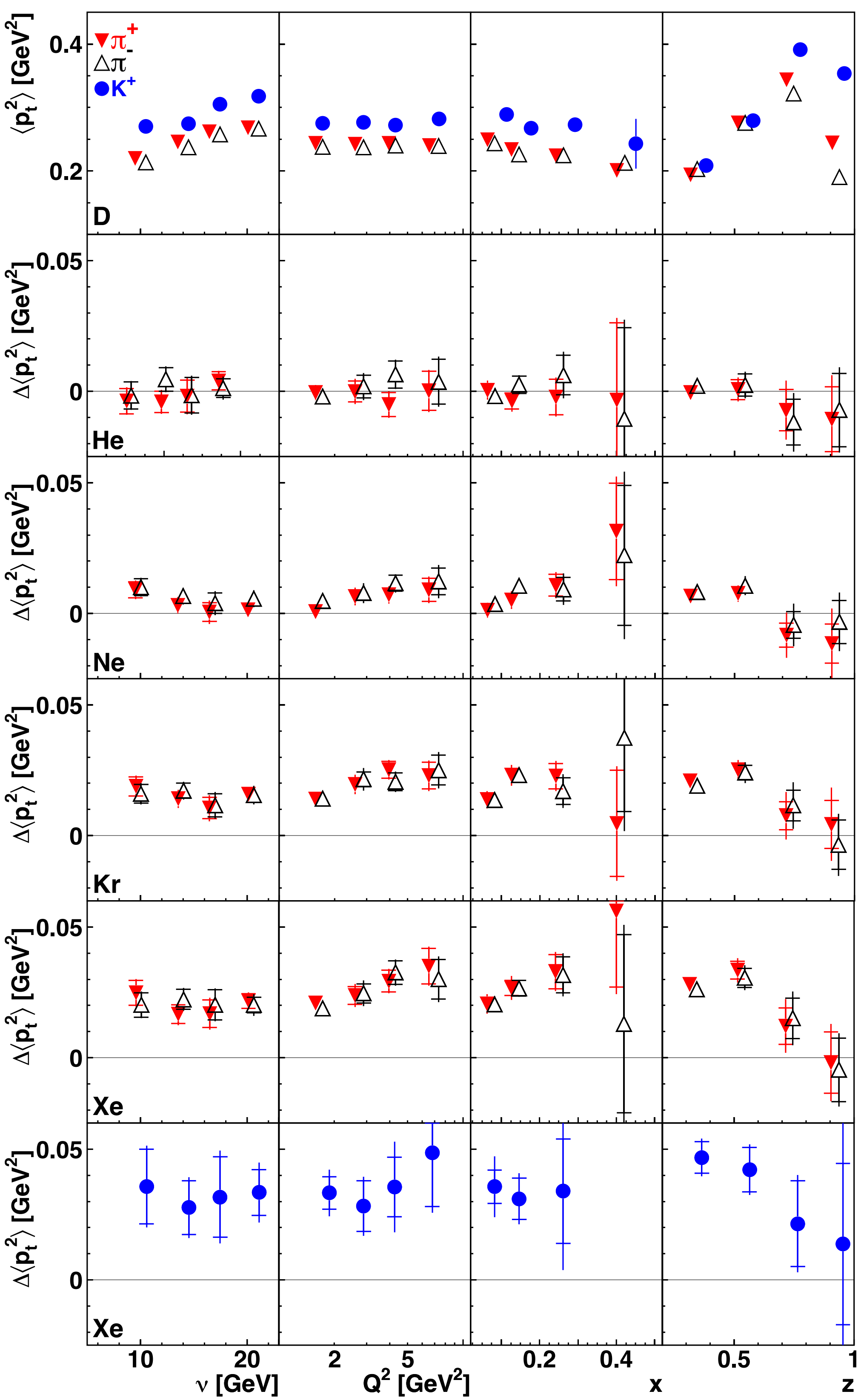
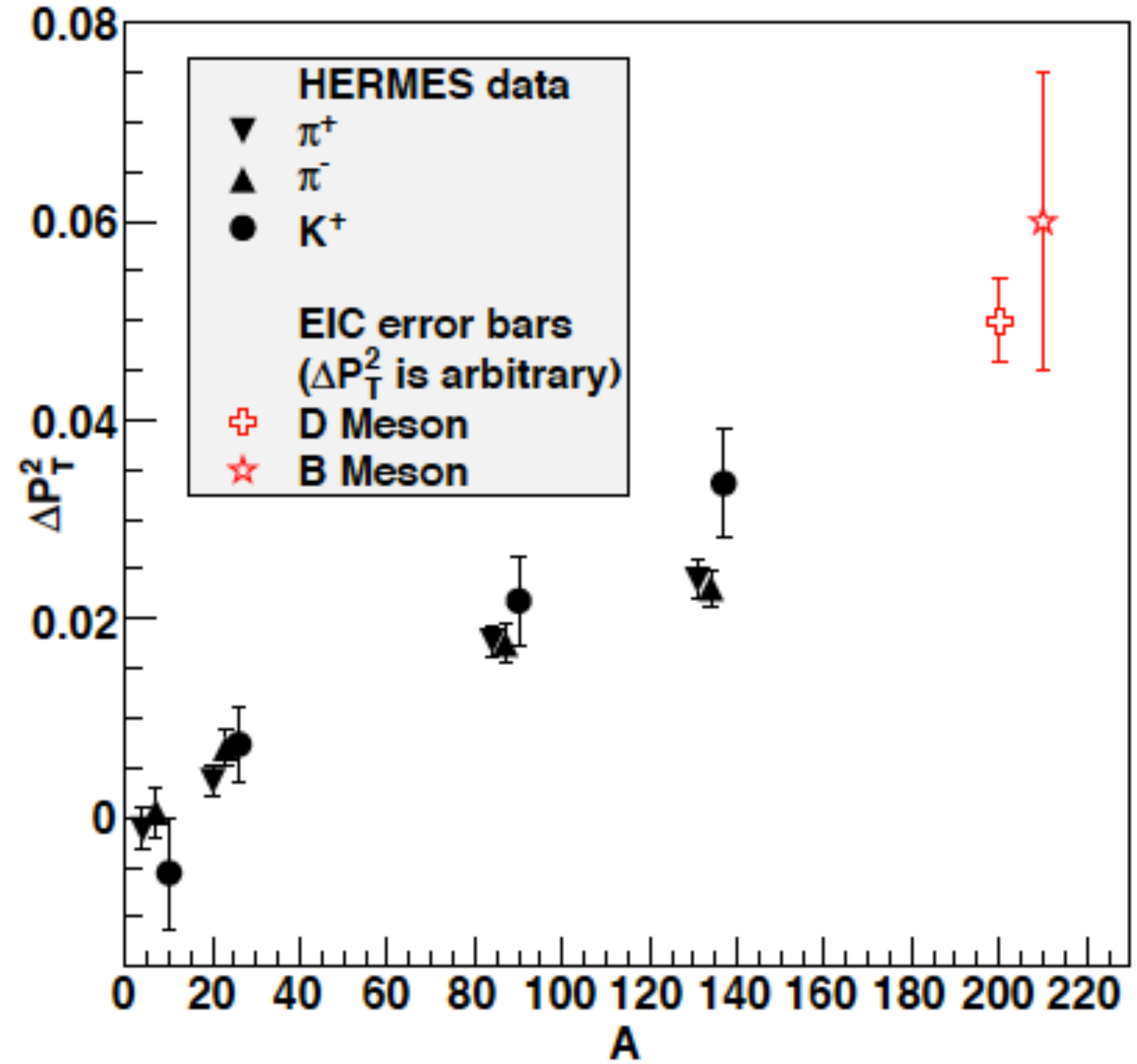


EIC:



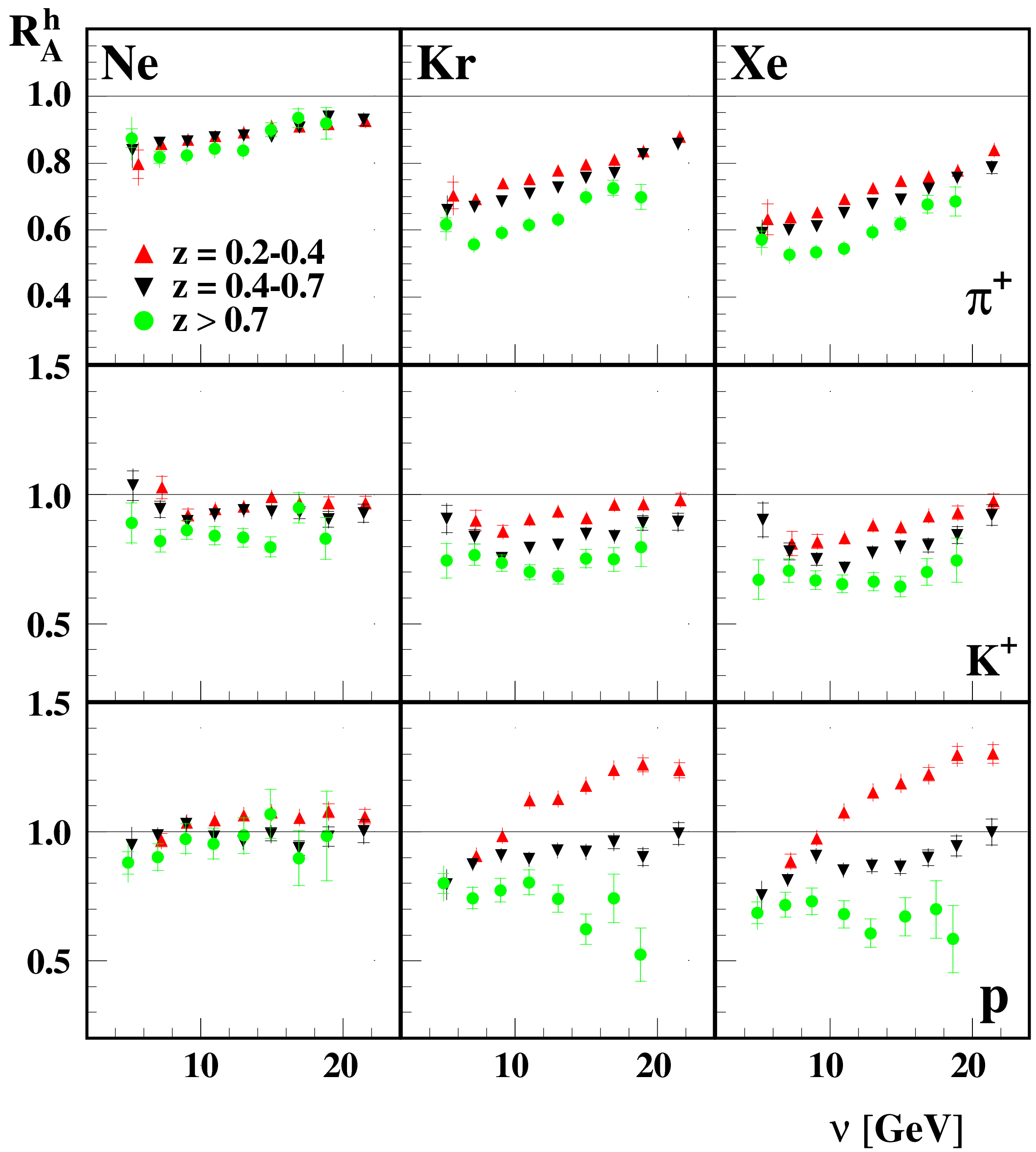
Measurements from HERMES can be repeated, with the addition of heavy quarks

Attenuation - how can the EIC contribute?

HERMES:

$E_e = 27$ GeV $\rightarrow \sqrt{s} = 7.2$ GeV

$E_h = 2\text{-}15$ GeV



ν = virtual photon energy

$Z_h = E_h/\nu$

Attenuation - how can the EIC contribute?

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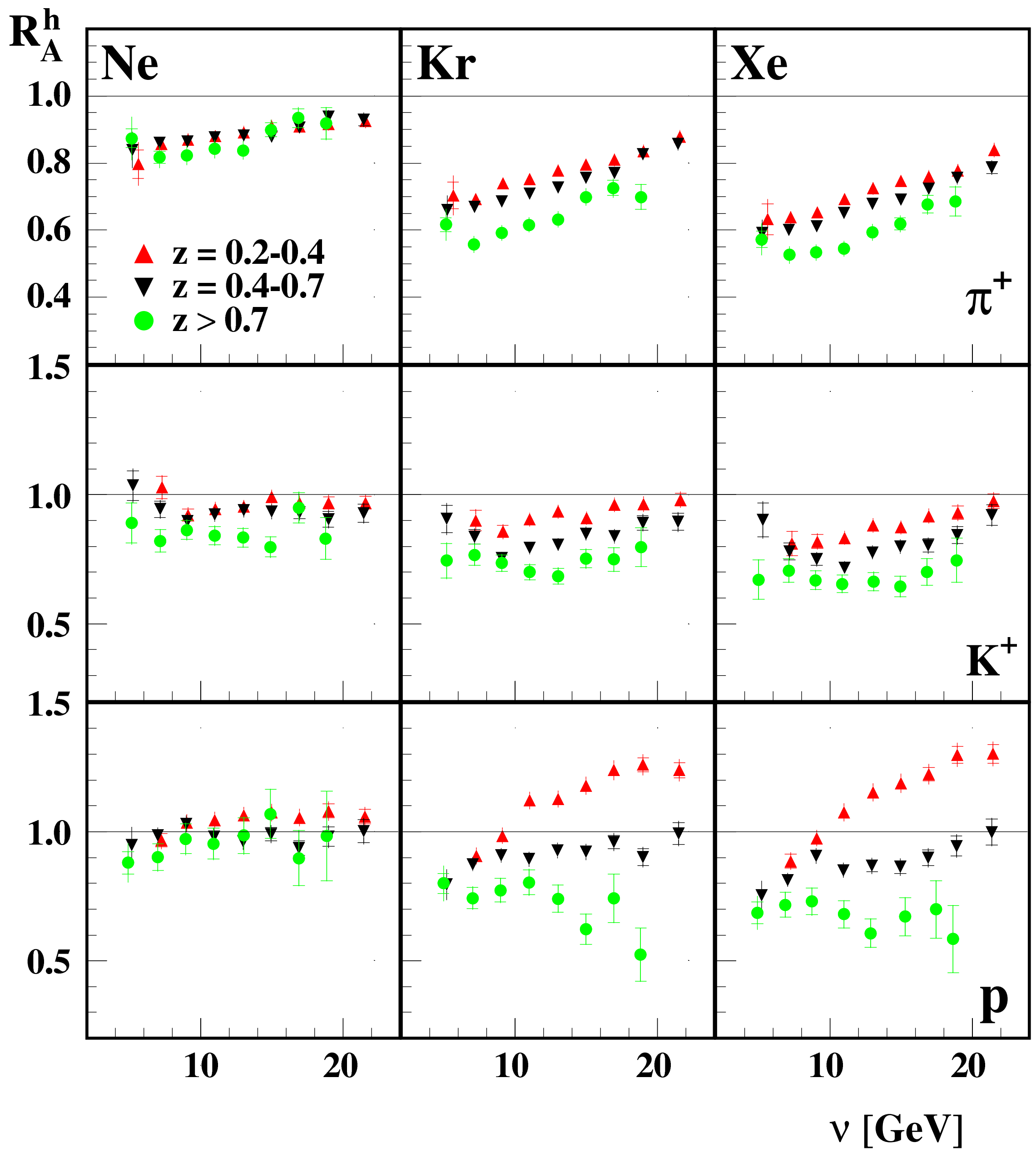
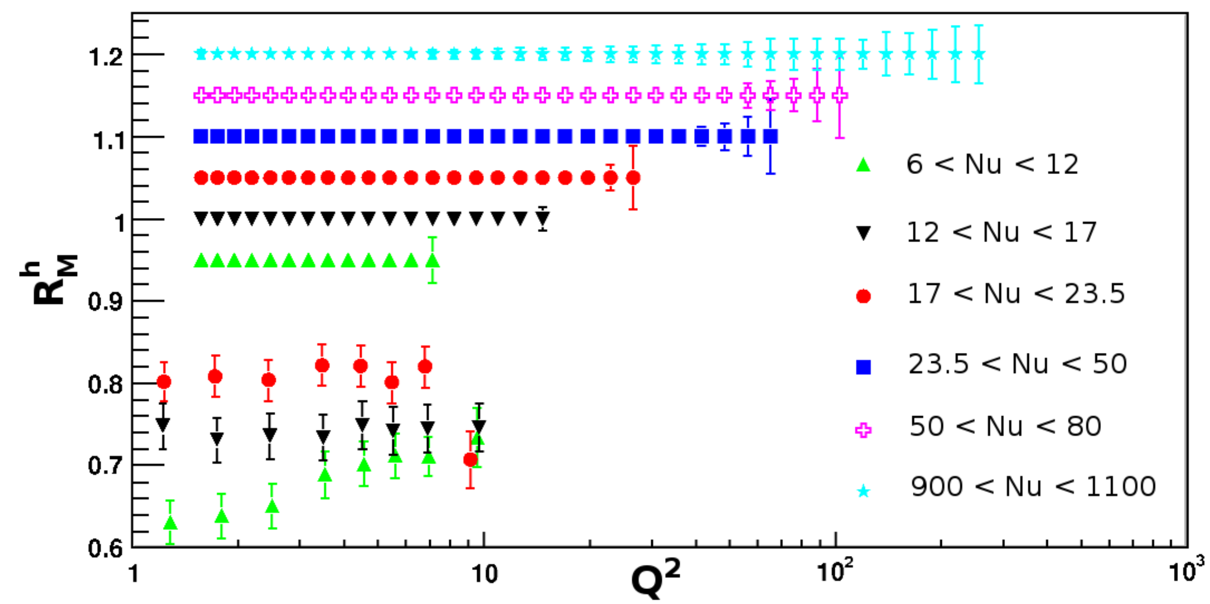
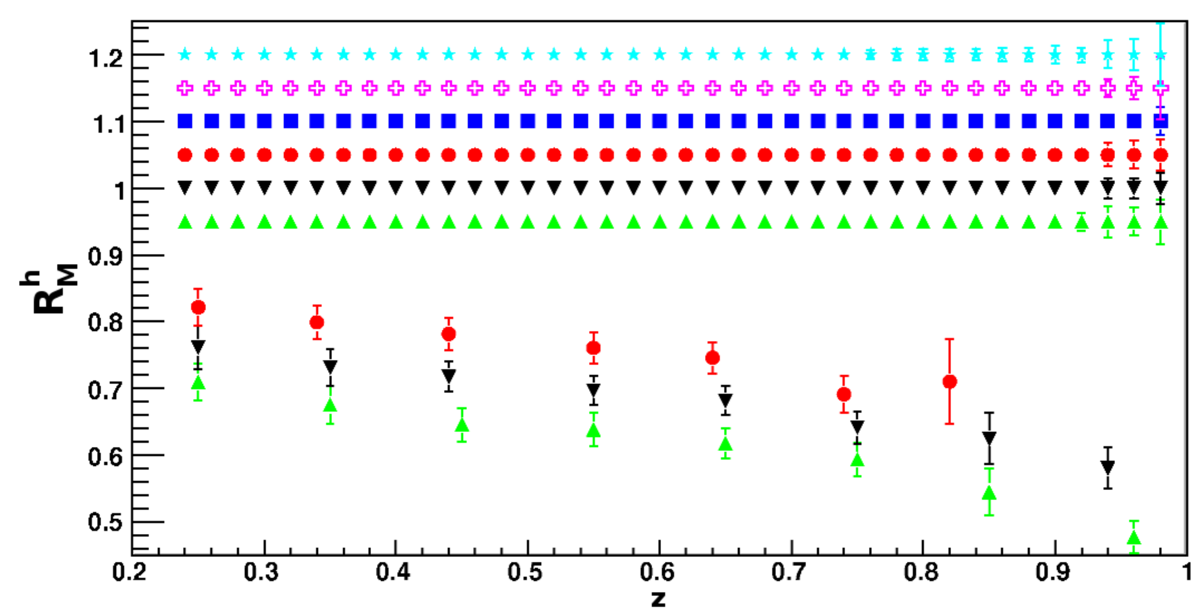


EIC:

light hadrons:





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large ν range → boost hadronization in and out of nucleus

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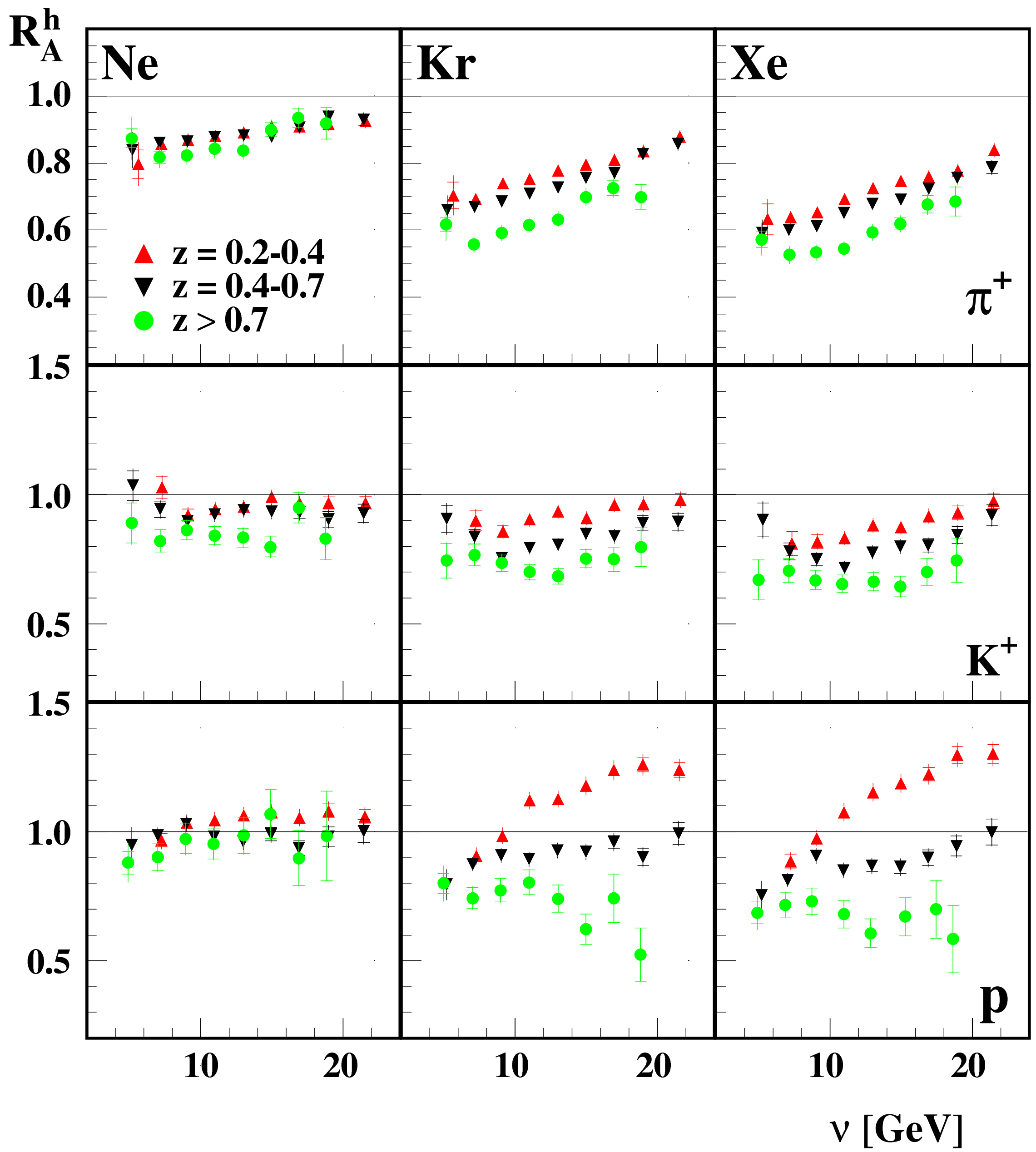
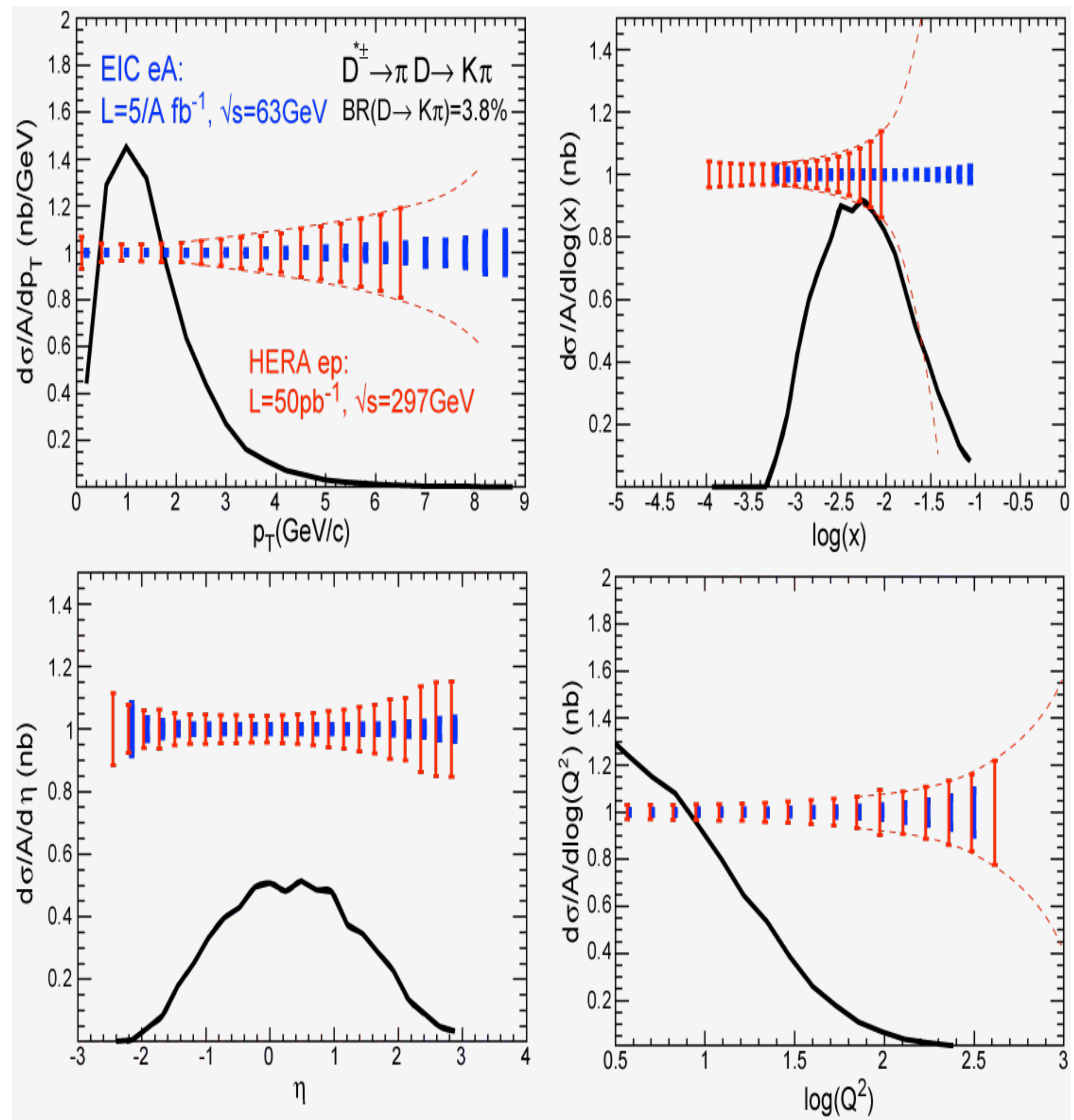


EIC:

charm hadrons:



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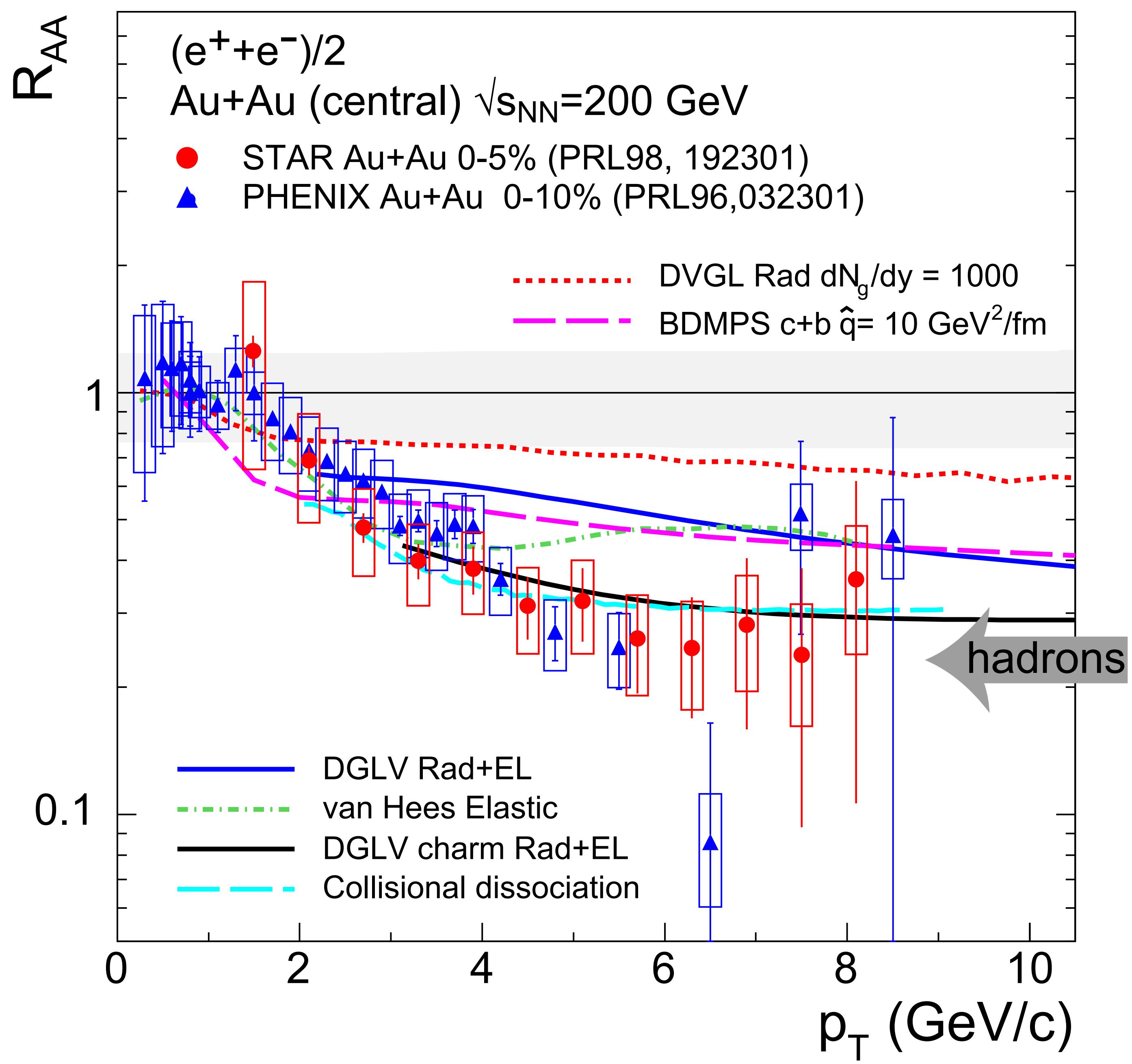
Attenuation - how can the EIC contribute?

RHIC:



EIC:

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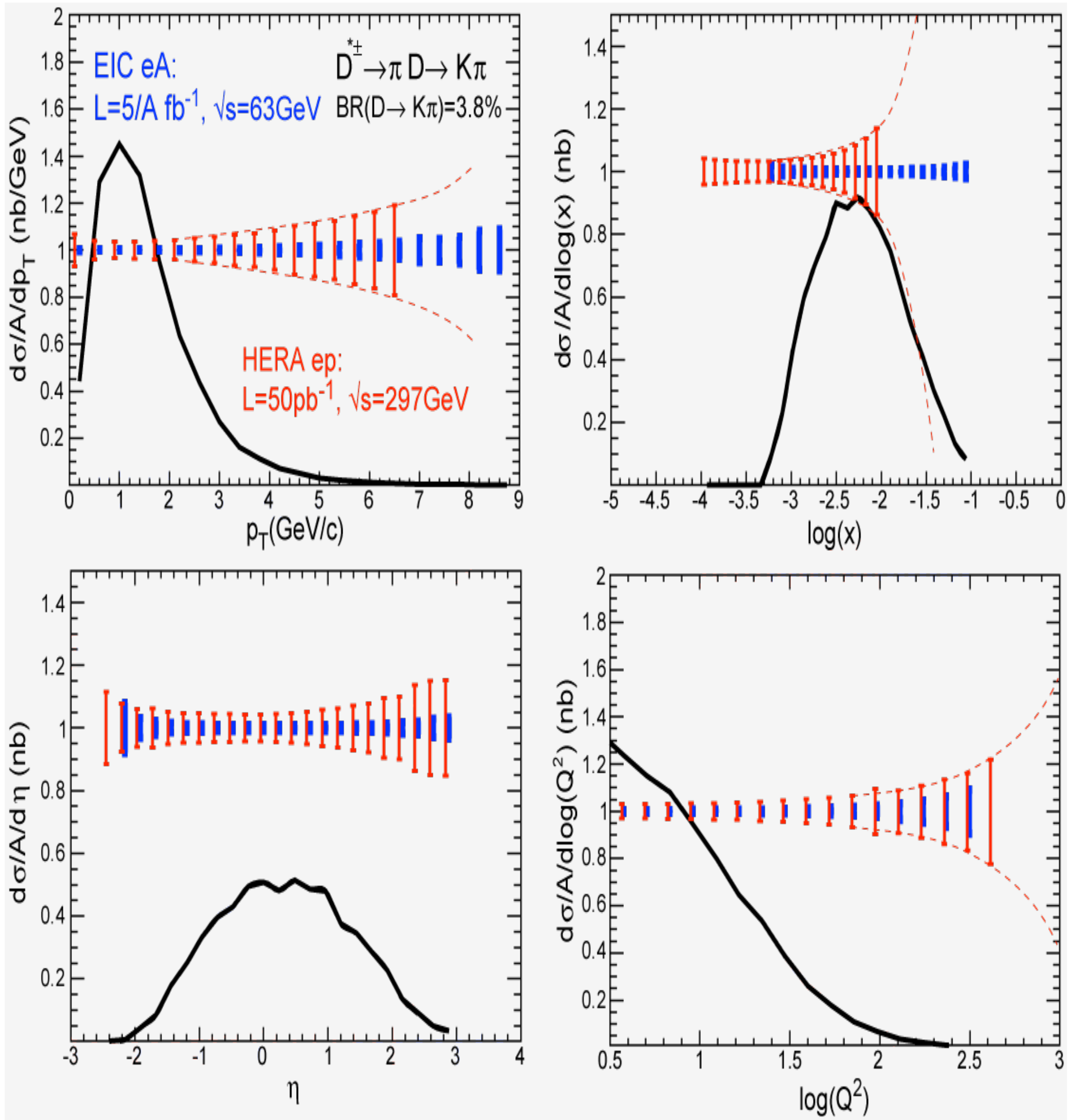

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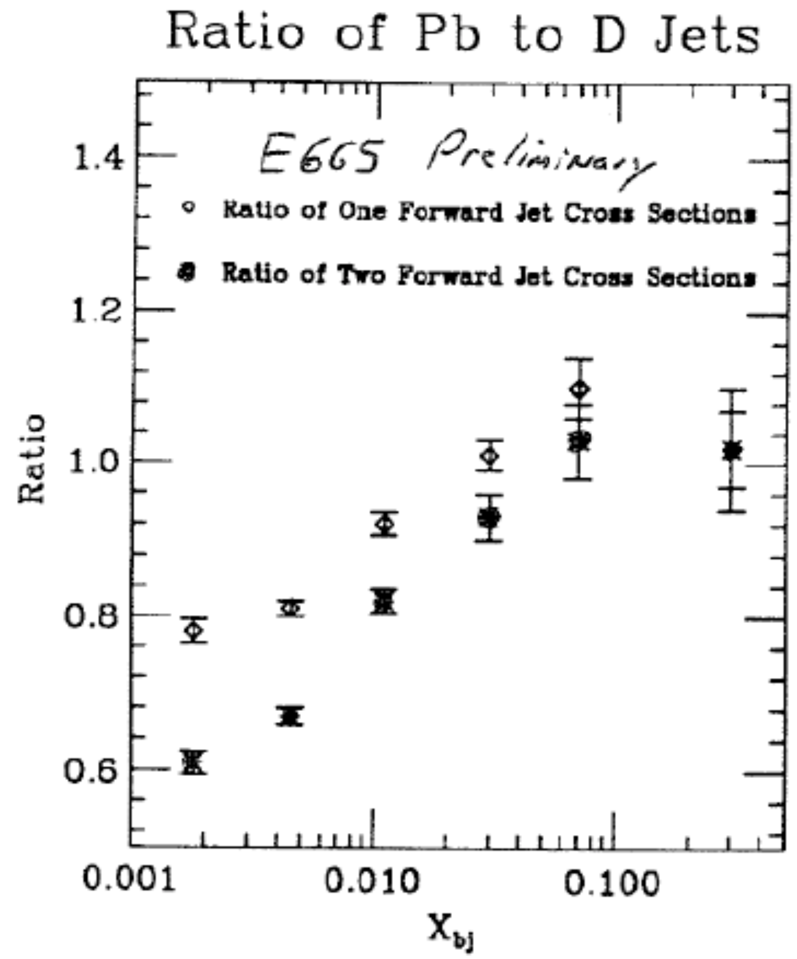
Jets at an EIC

- E665 at FNAL have measured jets in μ+A at $\sqrt{s} \sim 30$ GeV
  - Feasible to start a jet programme in phase 1
  - caveat that collider kinematics are different to fixed target



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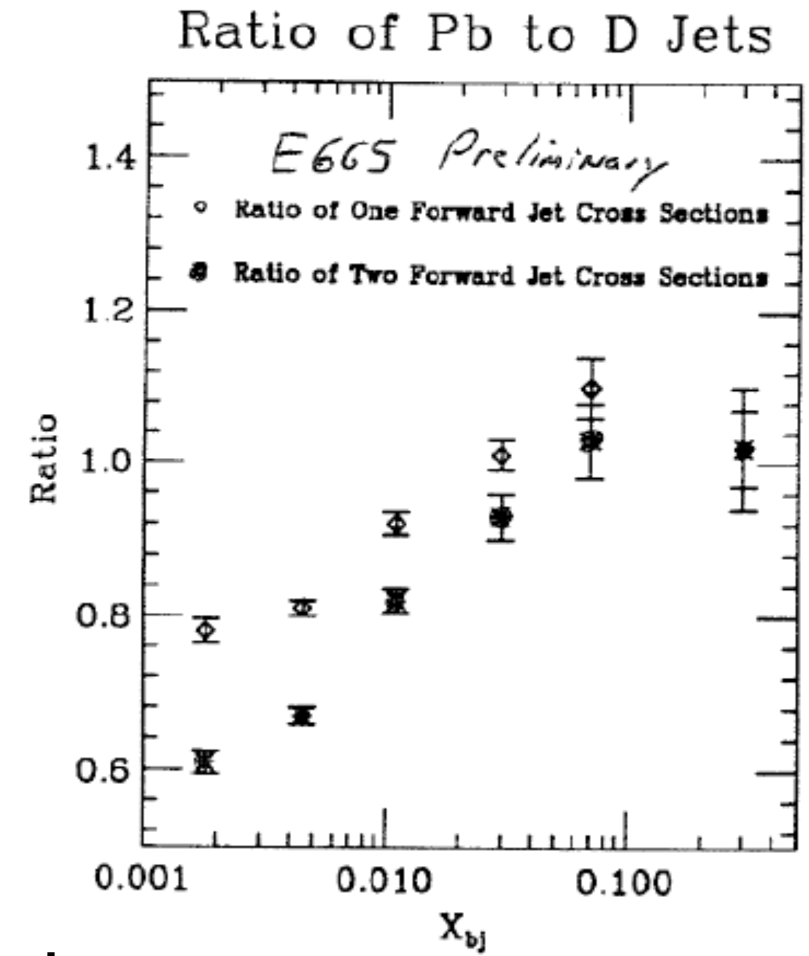
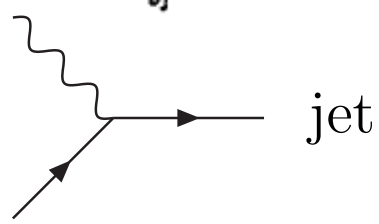


1+1 jets, dominated by q processes → allow study of parton propagation through cold nuclear matter



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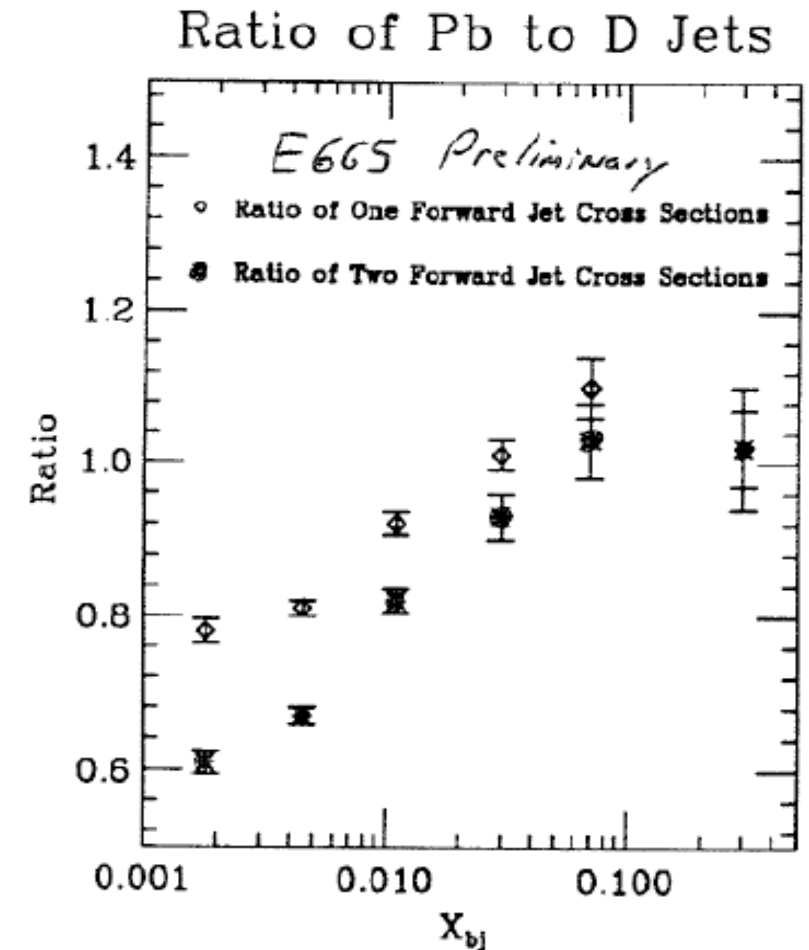

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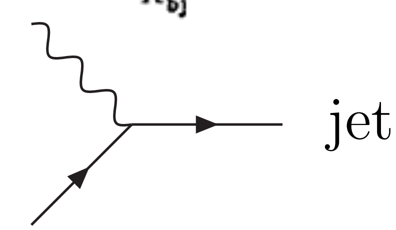
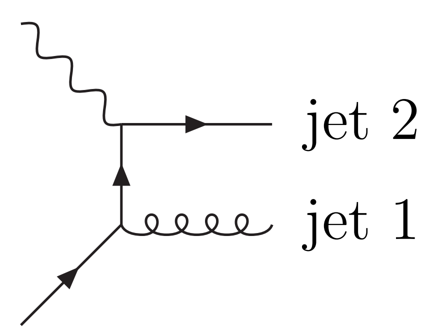
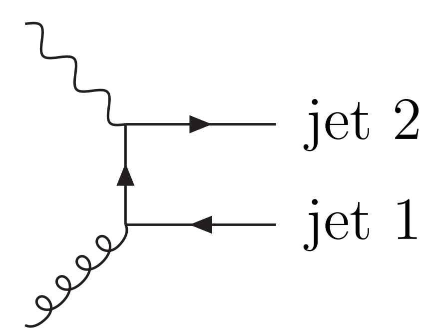


$$\frac{d^2\sigma_{2+1}}{dx dQ^2} = A_q(x, Q^2) q^A(x, Q^2) + A_g(x, Q^2) g_A(x, Q^2)$$

2+1 jets → sensitive to nuclear gluons

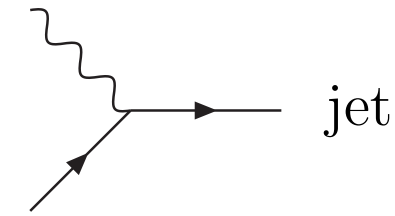




By measuring 1+1 jets, can extract information on gluons

Jets at an EIC

1+1 jets, dominated by q processes → allow study of parton propagation through cold nuclear matter



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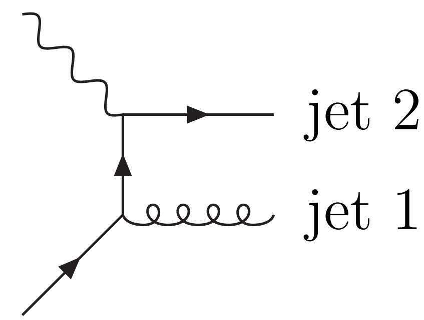

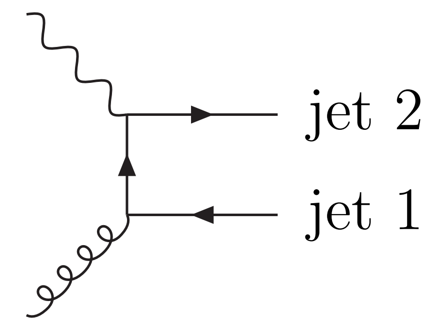

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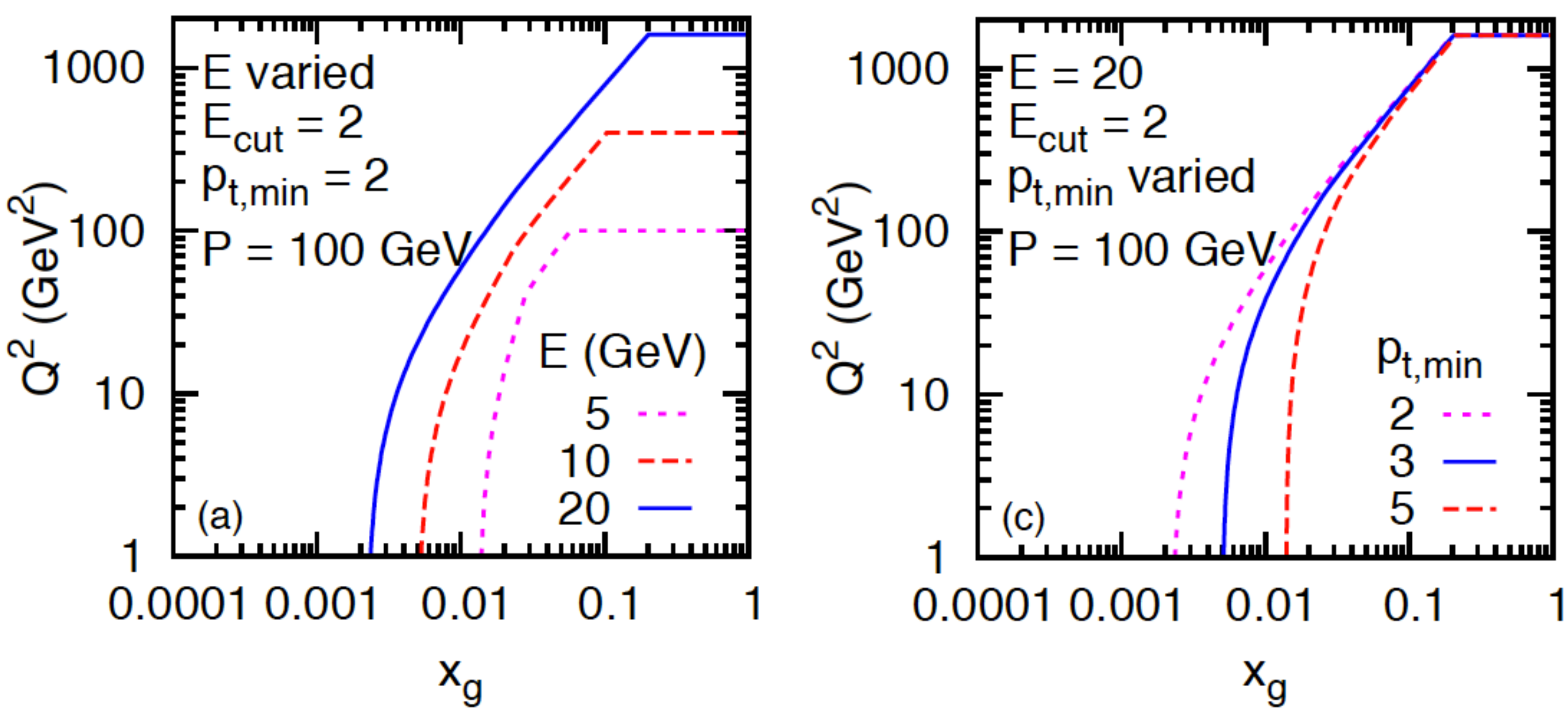


b dependent gluons, gluon correlations from DVCS and diffractive vector meson production

Silver Measurements

Deliverables	Observables	What we learn	Stage-I	Stage-II
b-dependent gluons; gluon correlations	DVCS; diffractive vector mesons	interplay between small-x evolution and confinement	moderate x with light, heavy nuclei	smaller x, saturation

See talk by Tobias Toll on Thursday afternoon

Summary and Conclusions

- The e+A physics programme at an EIC will give us an unprecedented opportunity to study gluons in nuclei
- Low-x: Measure the properties of gluons where saturation is the dominant governing phenomena
- Higher-x: Understand how fast partons interact as they traverse nuclear matter and provide new insight into hadronization
- Understanding the role of gluons in nuclei is crucial to understanding RHIC (and LHC) heavy-ion results

Good headway can be made on these measurements already with a stage-I eRHIC (E_e = 5 GeV)

- The INT programme in the Fall of 2010 allowed us to formulate the observables in terms of golden and silver measurements
  - ➡ A detailed write-up of the whole programme (encompassing both e+A and e+p) will be published shortly

with thanks

- Fellow INT workshop convenors: A. Accardi, C. Marquet
- BNL EIC science task-force: E. Aschenauer, T. Burton, R. Debbe, J. Dunlop, S. Fazio, W. Guryn, J-H. Lee, T. Toll, T. Ullrich
- Friendly theorists: M. Diehl, F. Gelis, W. Horowitz, T. Lappi, M. Stratmann, R. Venugopalan
- Summer students: W. Foreman, A. Kirleis, M. Savastio, P. Schnatz, O. Vail
- C-AD group: J. Beebe-Wang, V. Litvinenko, V. Ptitsyn, D. Trobojevic

Detector Slides

BACKUP SLIDES

SPIN BACKUP SLIDES

recall: DSSV analysis in 2008/09

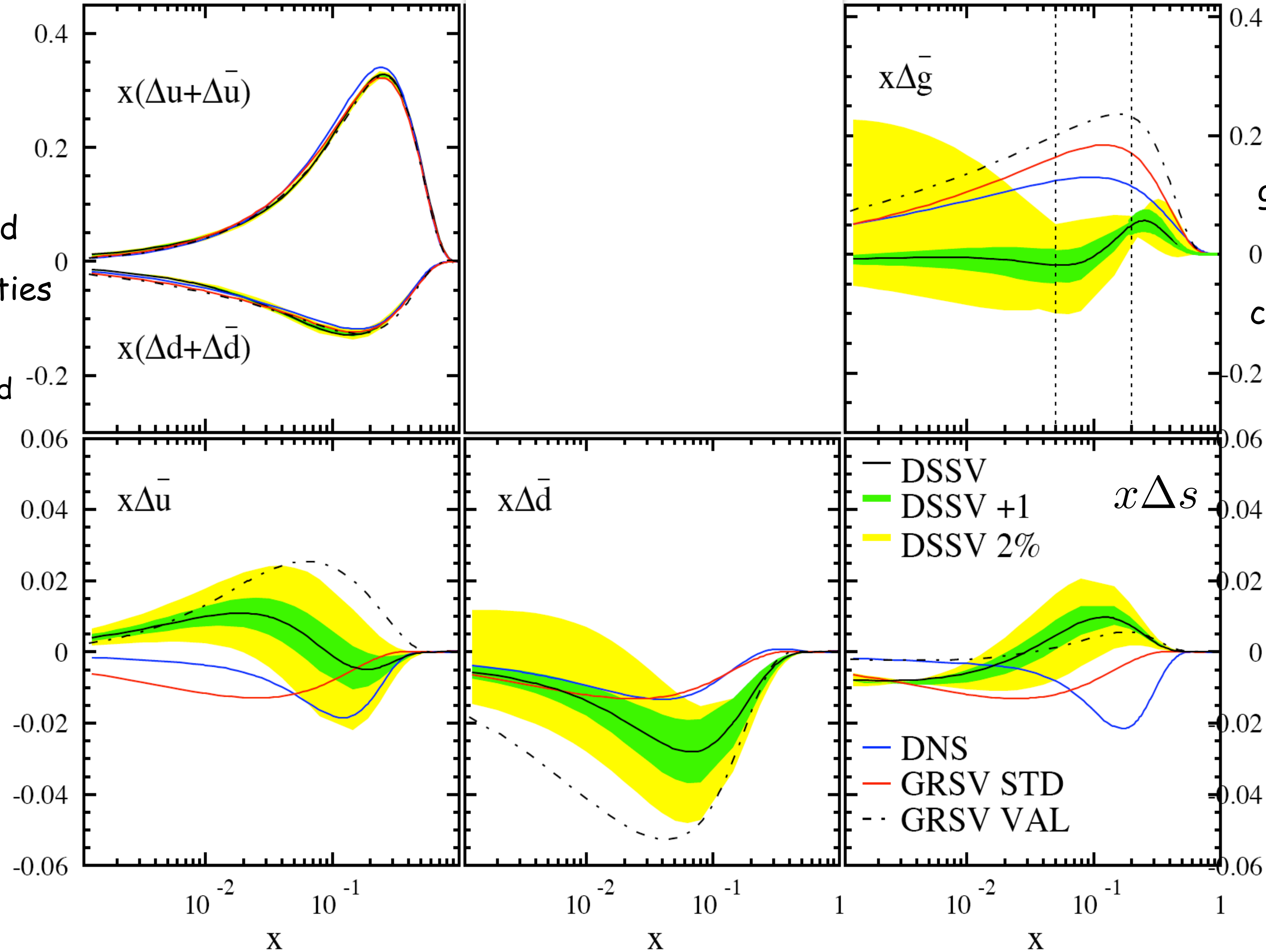
DSSV: de Florian, Sassot, MS, Vogelsang; PRL101 (2008) 072001; PRD80 (2009) 034030

well constrained

total quark densities

x -> 1 behavior

to be determined



gluon small (node?)

in x-region

constrained by data

indications for non-trivial

sea quark polarizations

$\Delta\bar{u} > 0$

$\Delta\bar{d} < 0$

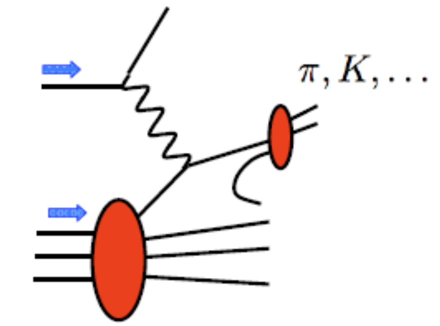
surprising strangeness polarization

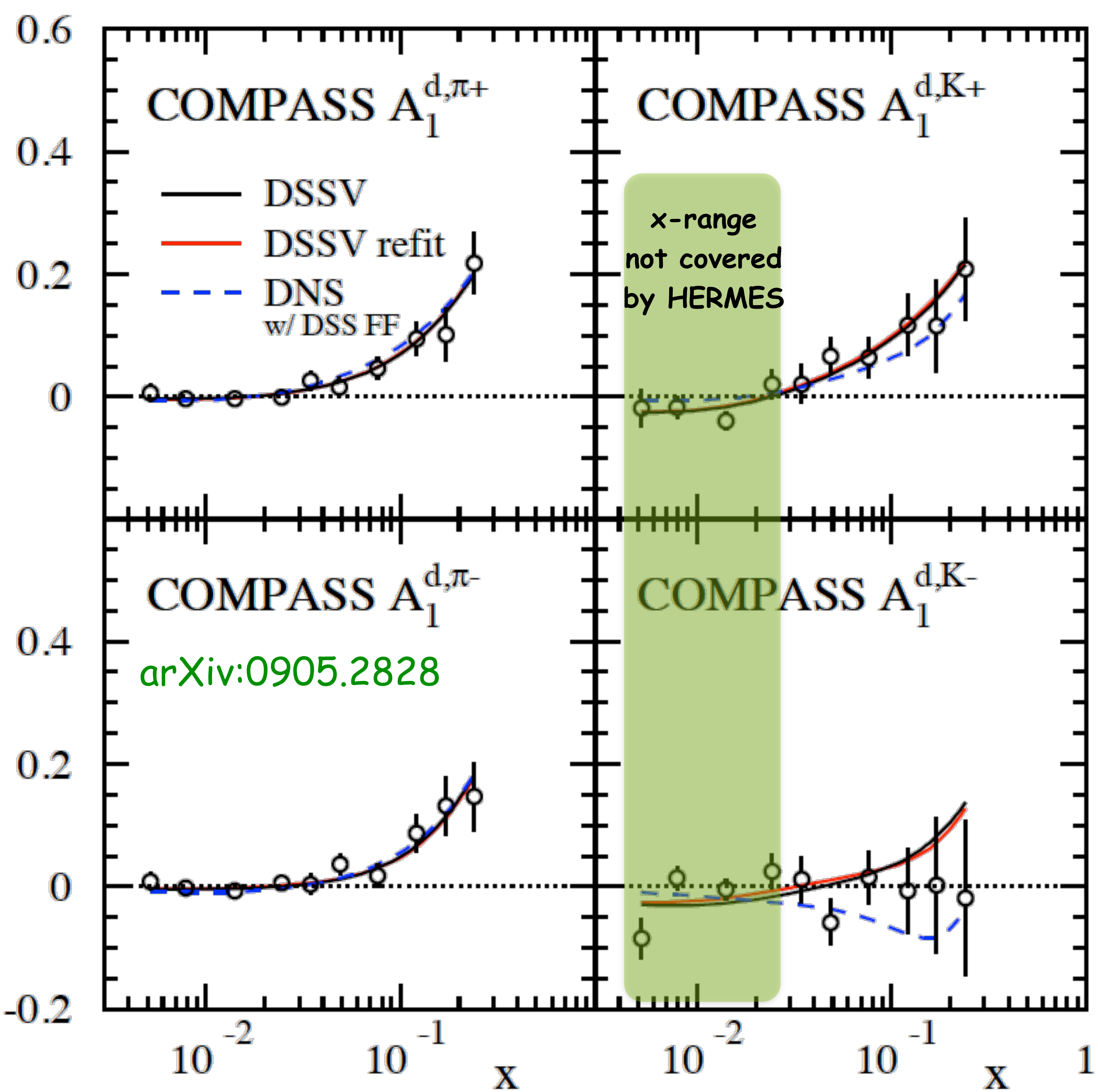
sizable SU(3) breaking?

requires reliable kaon fragmentation fcts.

lattice: Bali et al., 0811.0807; 0911.2407; 1011.2194

coping with new data: SIDIS $A_1^{d,\pi,K}$





✓ DSSV works well:

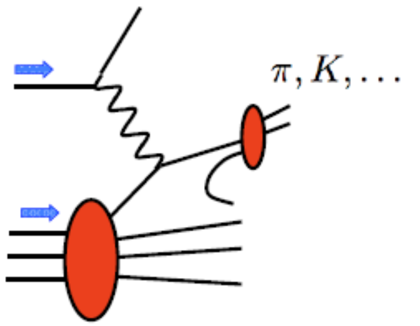
no surprises at small x

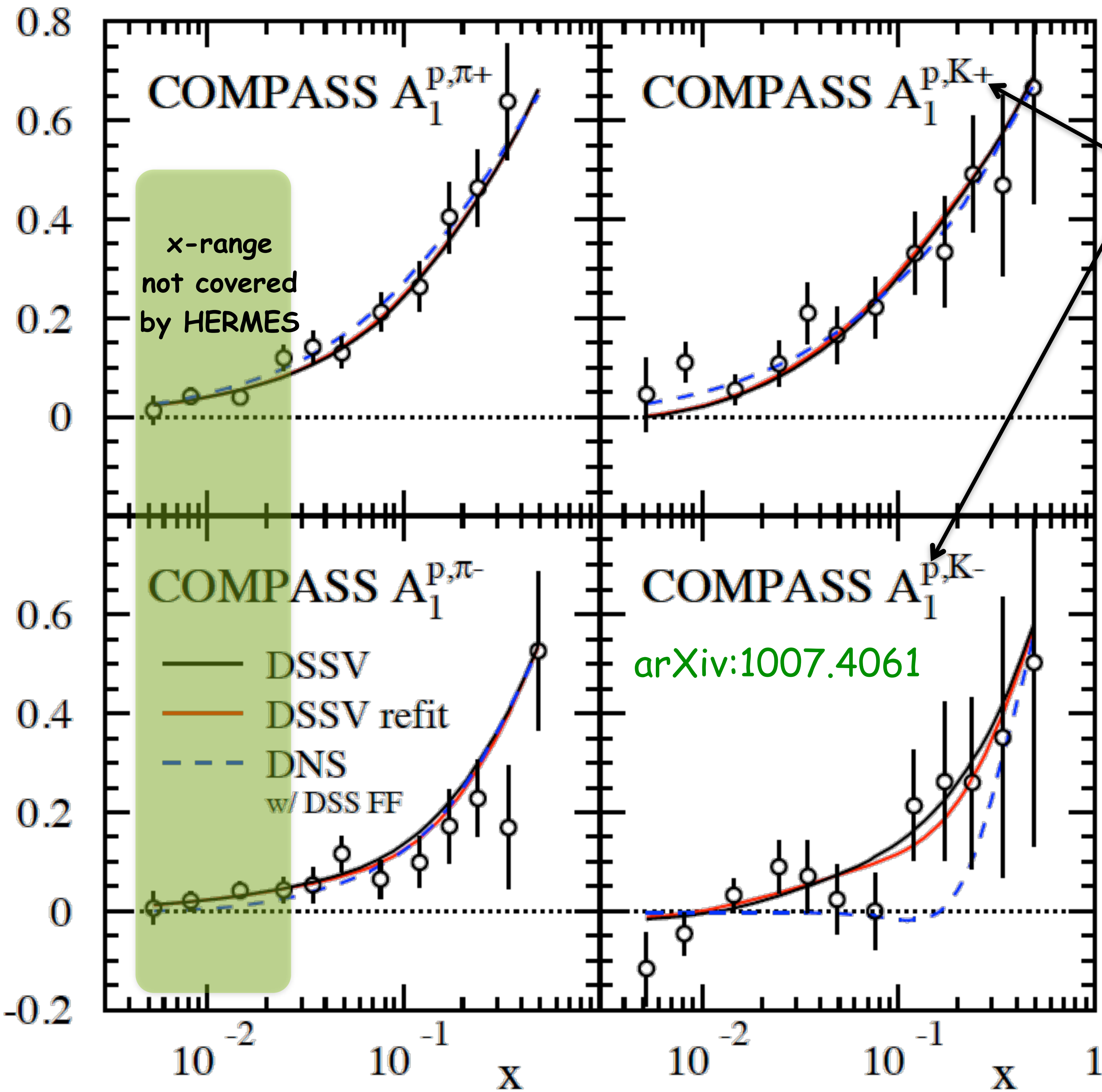
χ^2 numerology♮:

	DSSV 08 data sets	with $A_1^{d,\pi,K}$
DSSV 08	392.5	420.8
DSSV+		418.9

♮ the branch of knowledge that deals with the occult significance of numbers

coping with new data: SIDIS $A_1^{p,\pi,K}$





1st kaon data on p-target

(not available from HERMES)

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DSSV 08	392.5	456.4
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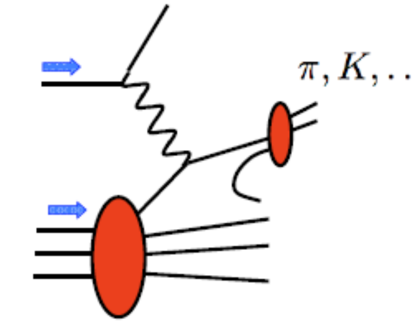

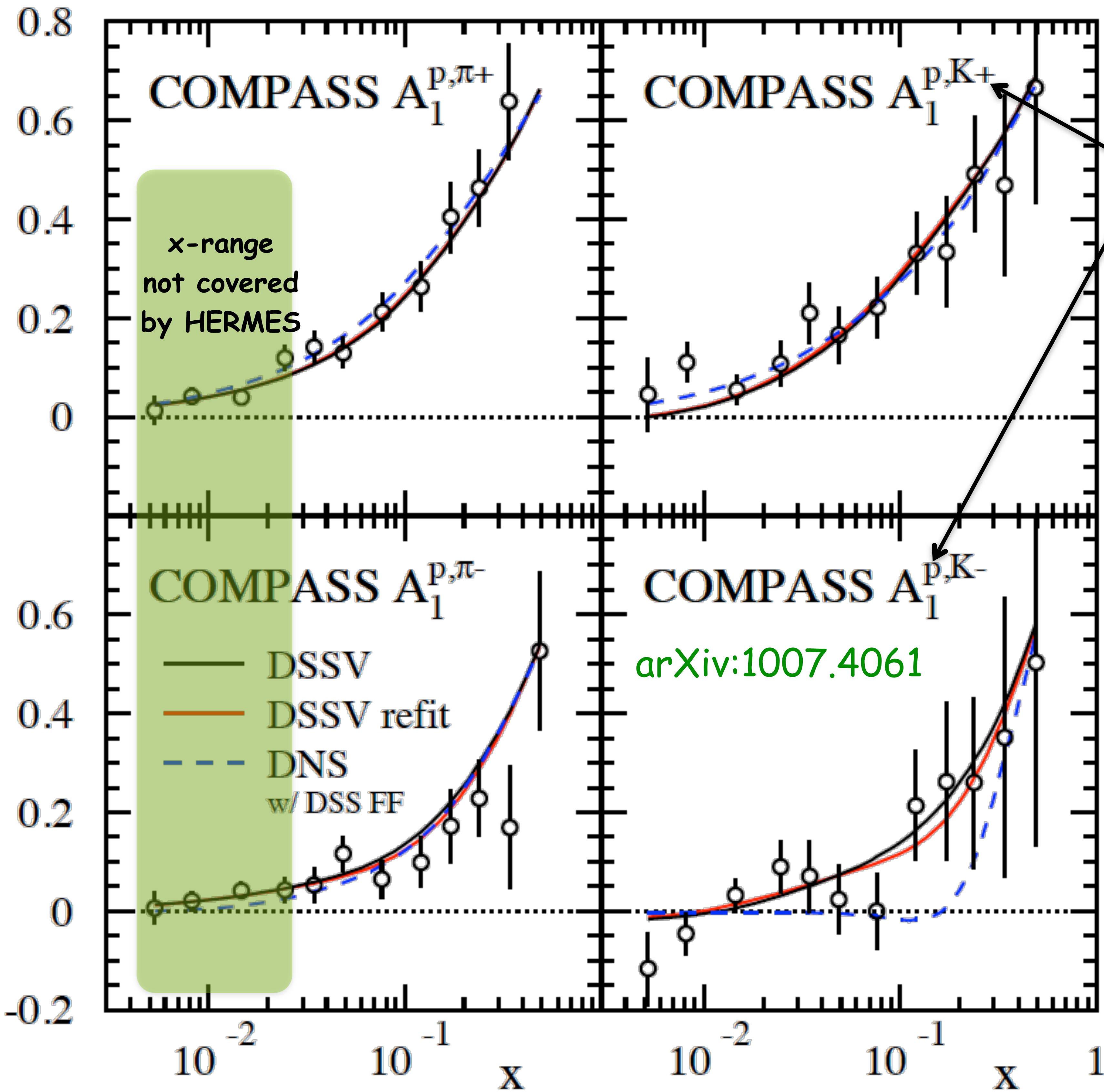

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	DSSV 08 data sets	**with** $A_1^{p\&d,\pi,K}$
DSSV 08	392.5	456.4
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✓ **no refit required**

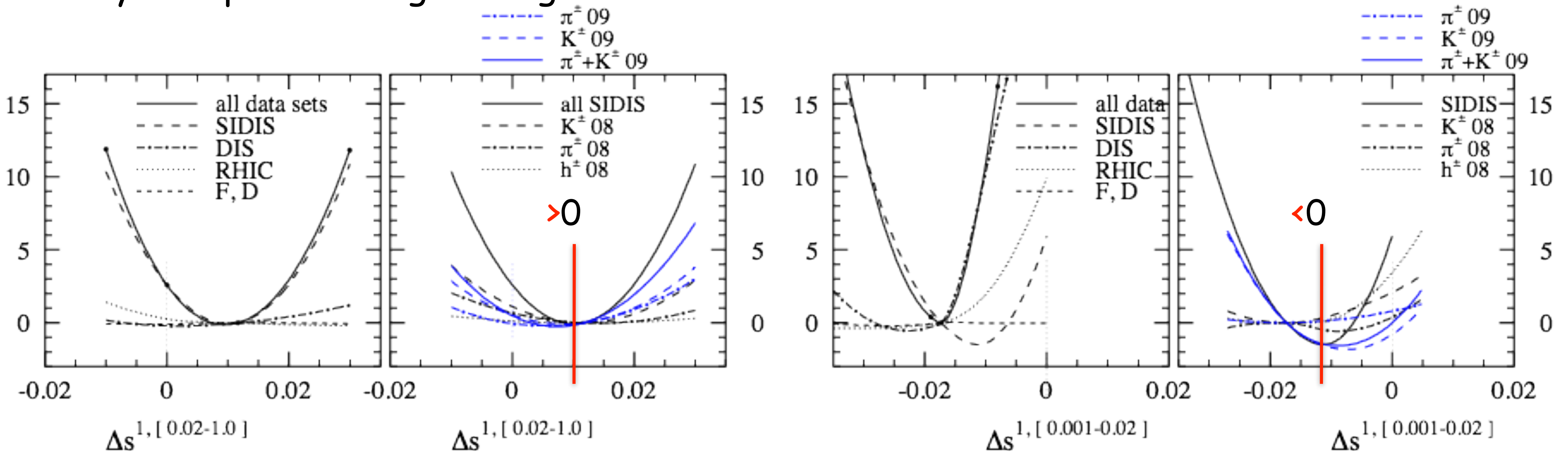
($\Delta\chi^2=1$ does not reflect faithful PDF uncertainties)

- trend for somewhat less polarization of sea quarks; $\Delta\bar{u} - \Delta\bar{d} \neq 0$ less significant

Δs revisited: impact of COMPASS data

current value for ΔΣ strongly depends on assumptions on low-x behavior of Δs

- new COMPASS data support small/positive Δs(x) at x > 0.01
- they also prefer a sign change at around x=0.01



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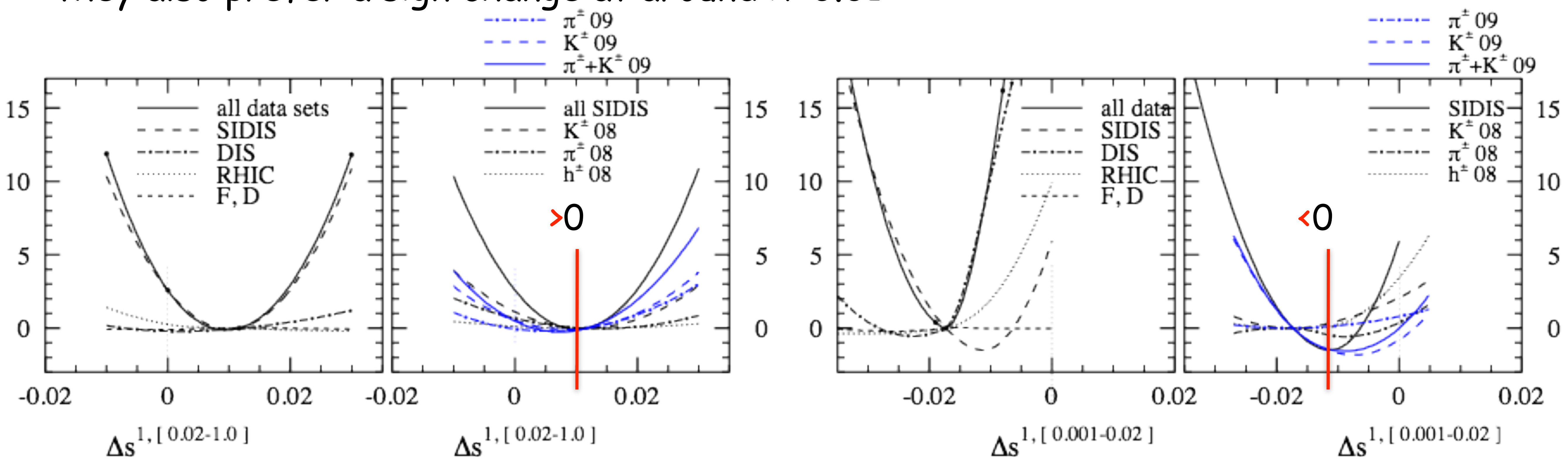
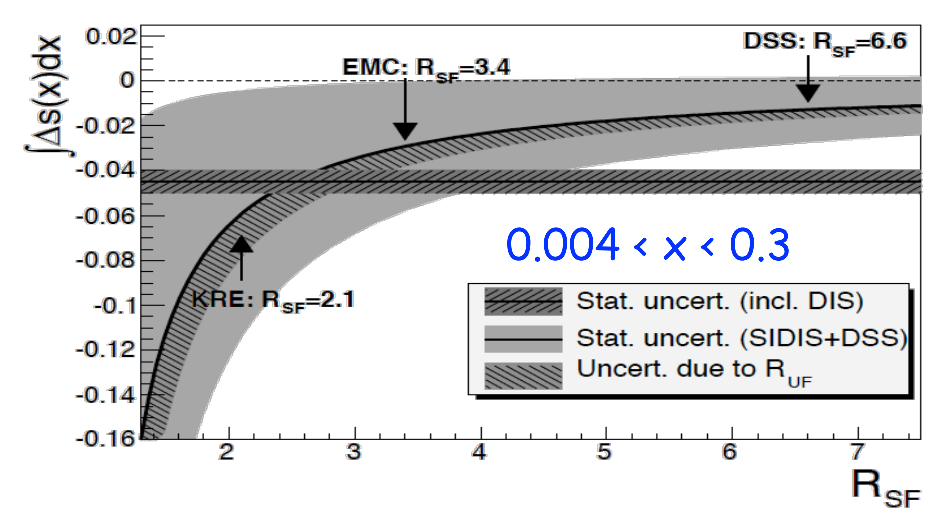


- but large negative 1st moment entirely driven by assumptions on SU(3)
- caveat: dependence on FFs

$$R_{SF} \equiv \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_{u}^{K^+}(z)dz}$$



COMPASS

Δs: can we blame it on the fragmentation fcts ?

Leader, Sidorov, Stamenov
arXiv:1103.5979

recently proposed as a "solution" to the "strange quark puzzle":

indeed, flavor decomposition strongly depends on fragmentation functions

different FFs $\longrightarrow$ different results

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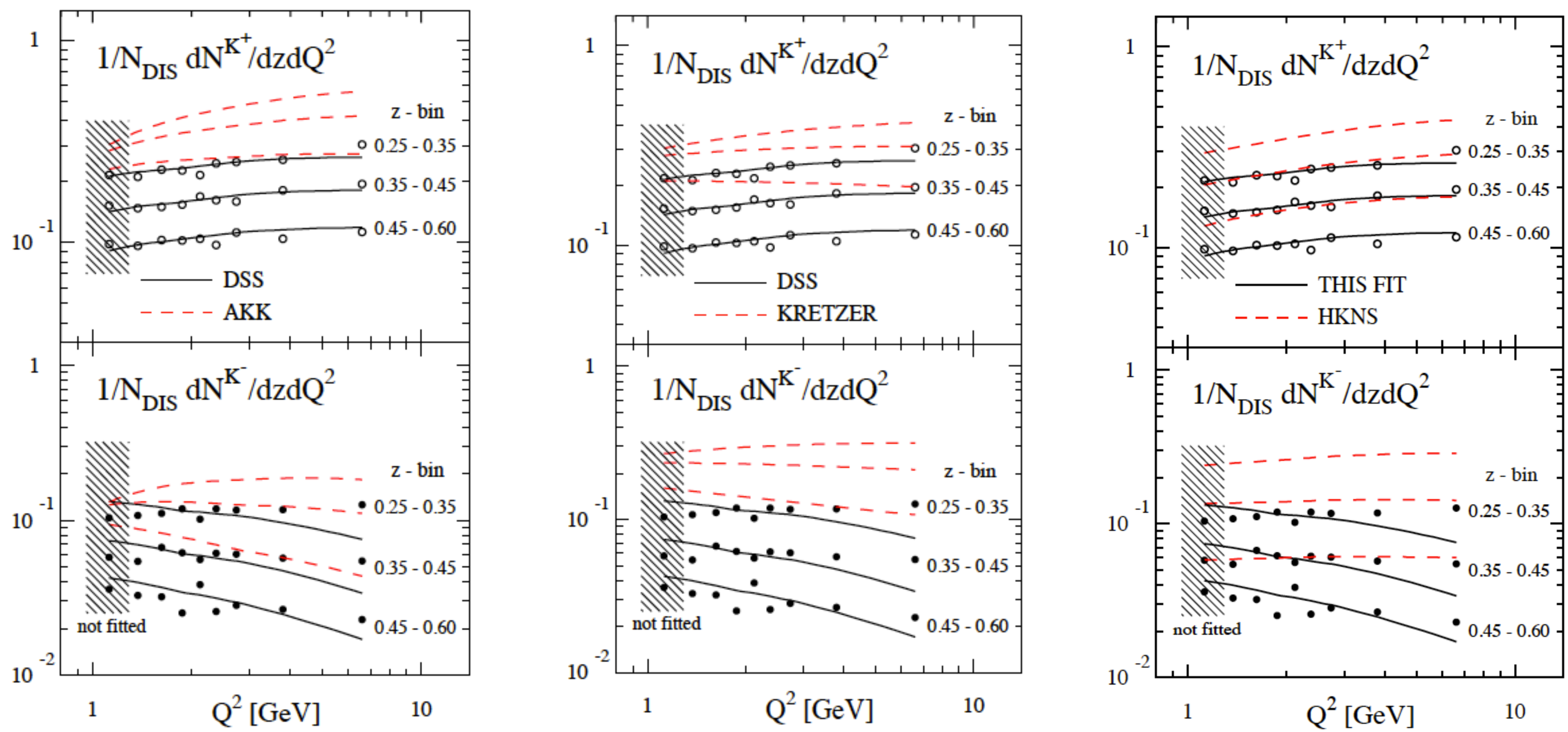
different FFs → different results   but wrong FFs → misleading results

find: only DSS FFs describe underlying unpol. cross sections in the relevant kinematics

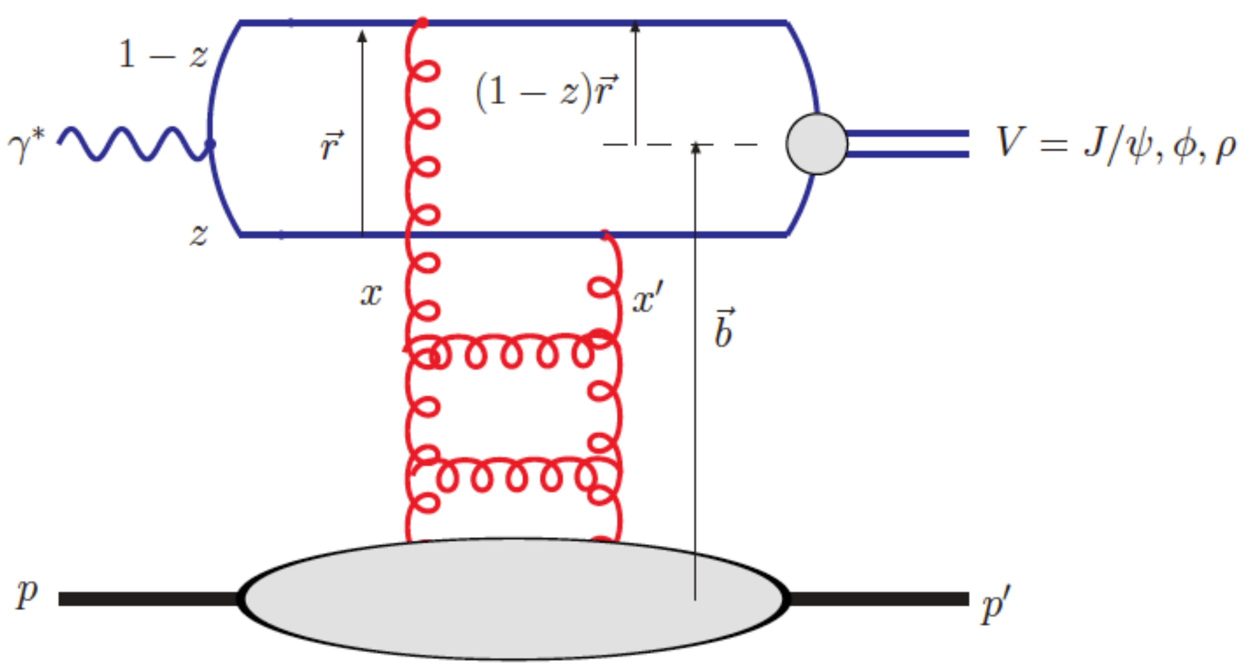
of course, this does not guarantee that we extracted the right Δs: more data are needed

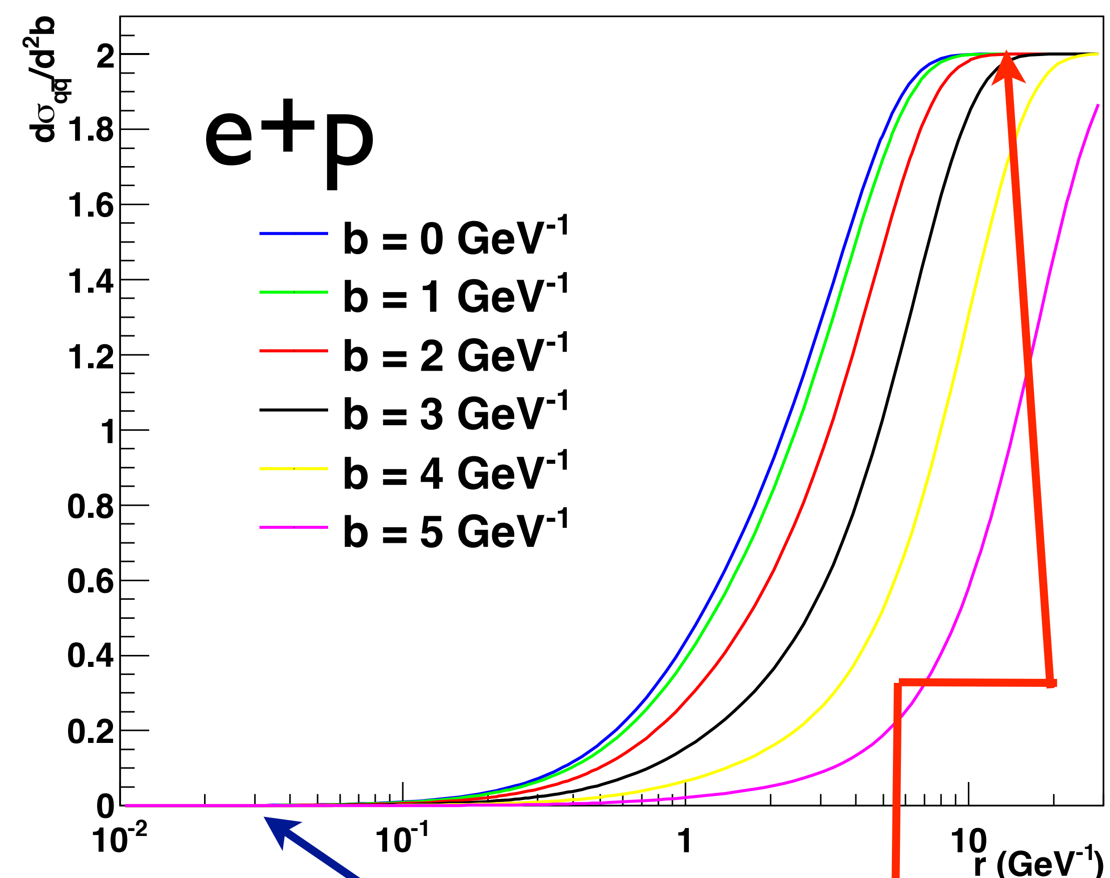


TOBIAS BACKUP SLIDES

Getting a "Feel" for Non-Linear QCD

Dipole Model: $\frac{d\sigma_{q\bar{q}}}{d^2b} = 2\mathcal{N}(x, r, b)$





$$\mathcal{N}(x, r, b) = 1 - \exp\left(-r^2 \frac{\pi^2}{2N_c} \alpha_s(\mu^2) x G(x, \mu^2) T(b)\right)$$

$\mathcal{N} =$ Dipole Scattering Amplitude

0 dilute system, linear QCD

1 saturated, non-linear regime

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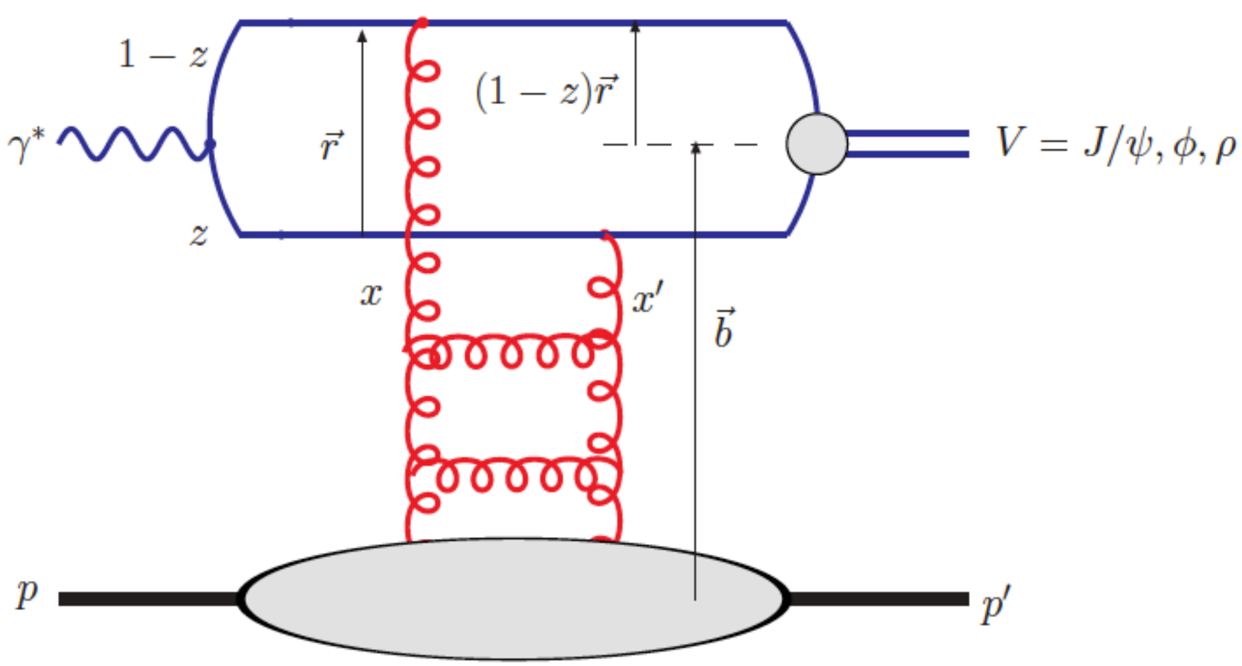

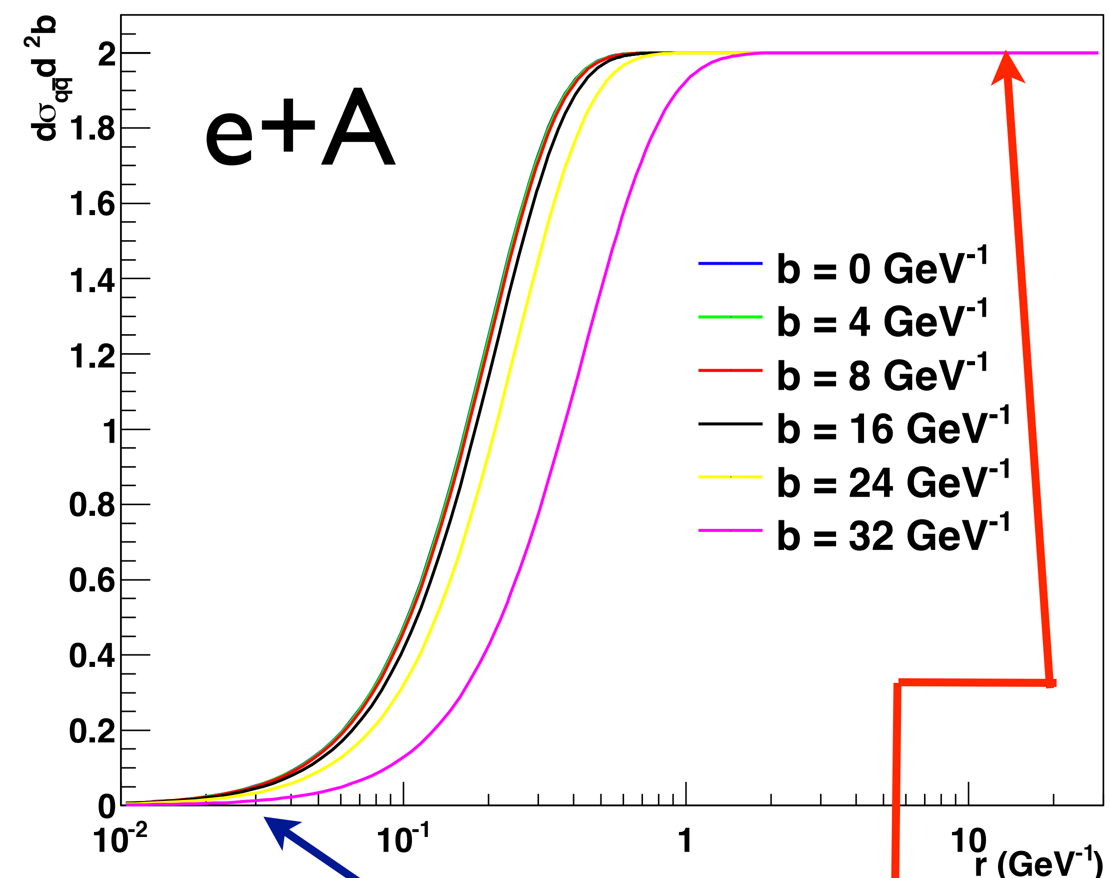

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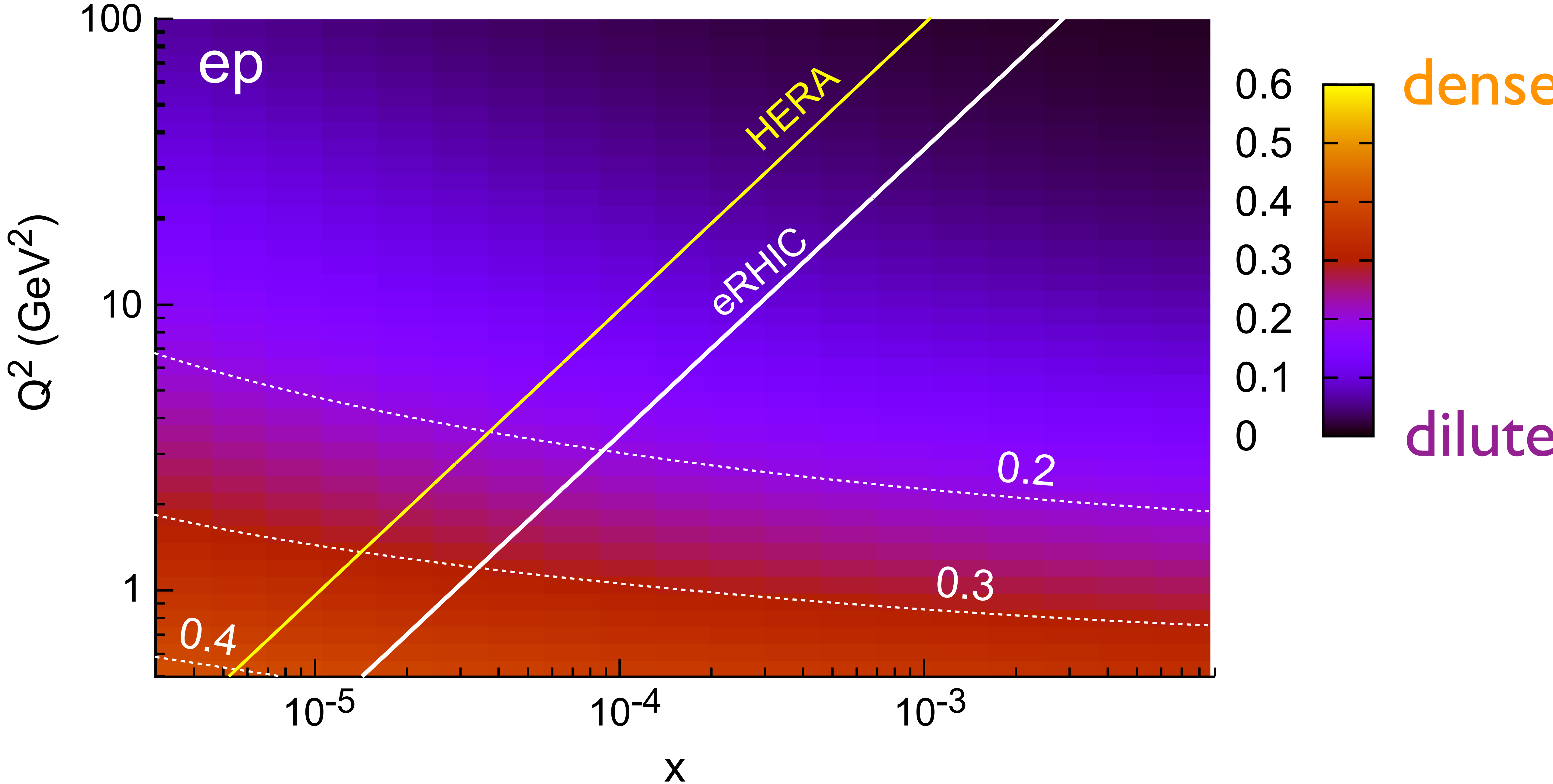
To assess typical values of $\mathcal{N}$ calculate average:

$$\langle \mathcal{N} \rangle_{2,L} = \frac{\int d^2b\, d^2r\, dz\, [\psi^*\psi]_{2,L}\, \mathcal{N}^2}{\int d^2b\, d^2r\, dz\, [\psi^*\psi]_{2,L}\, \mathcal{N}}$$

$\langle \mathcal{N} \rangle_2 \longrightarrow F_2$

$\langle \mathcal{N} \rangle_L \longrightarrow F_L$



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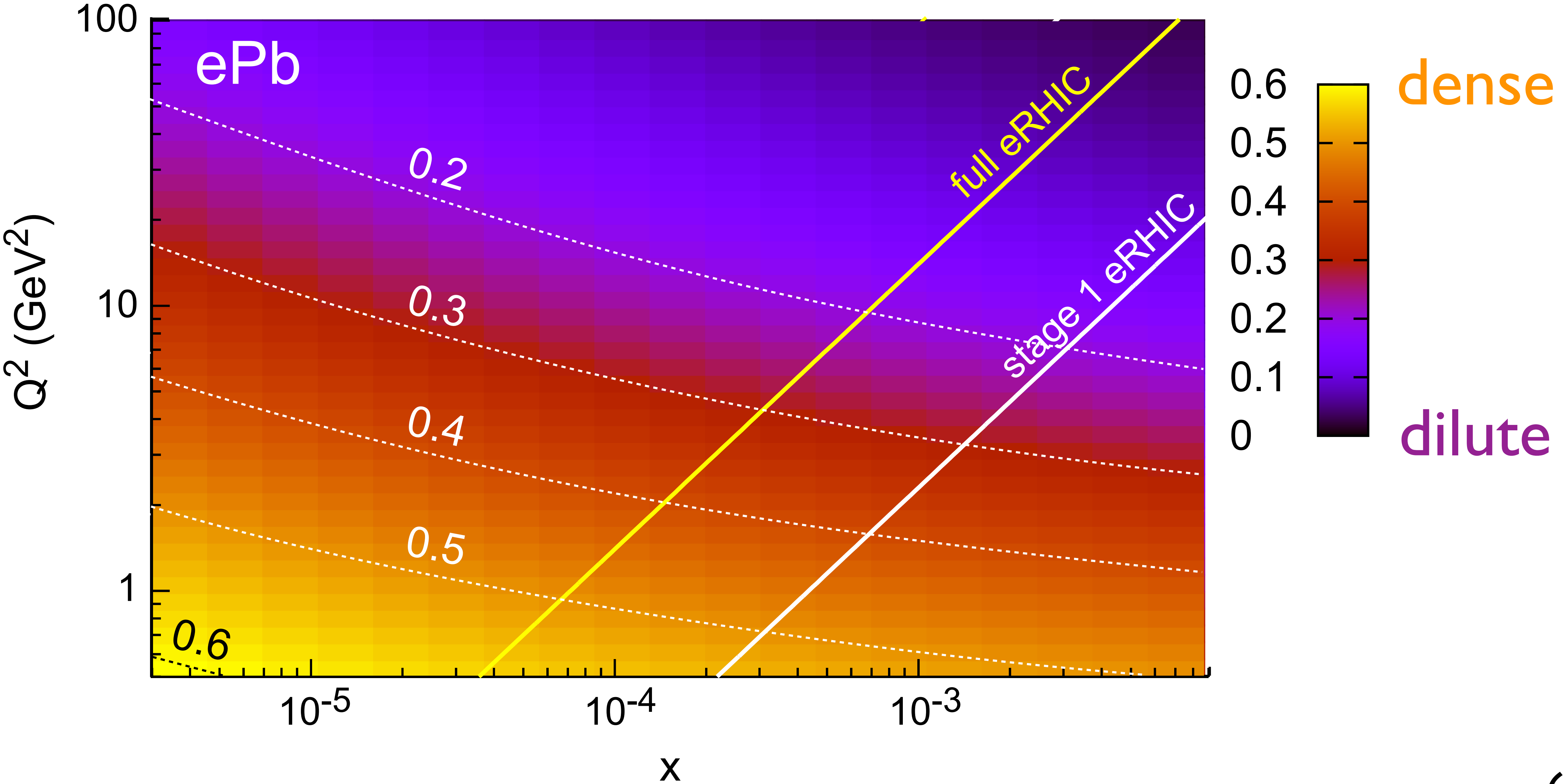

b-dependent gluons from DVCS and DVMP

- Transverse position distribution of gluons can be determined from Deeply Virtual Compton Scattering (DVCS: $e+A \rightarrow e+\gamma+A$) and Diffractive Vector Meson Production (DVMP: $e+A \rightarrow e+VM+A$)
  - Proportional to the square of the gluon distribution!!
- Coherent diffraction (intact nuclear target)
  - transverse distribution of gluon density
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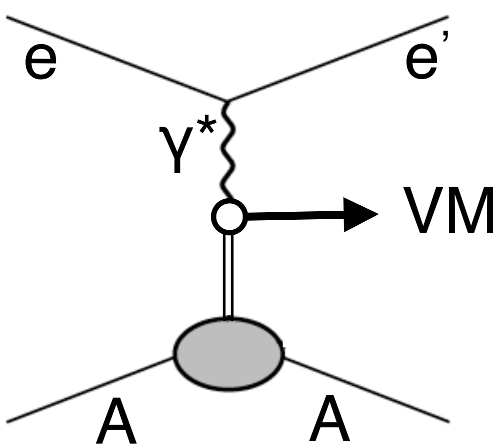
DVMP



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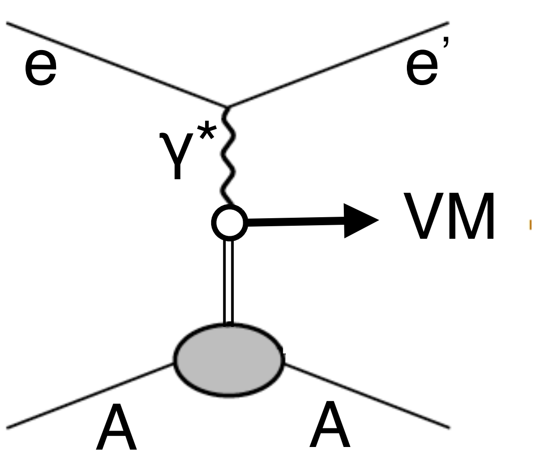
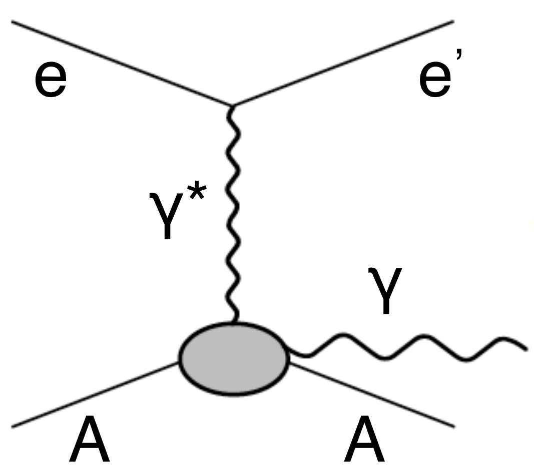


DVCS



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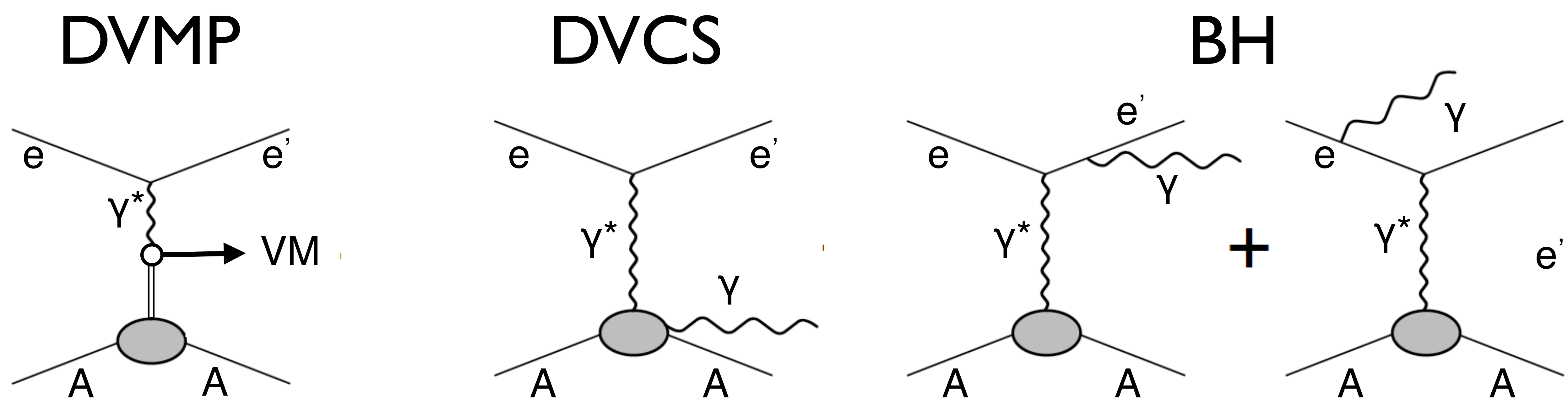


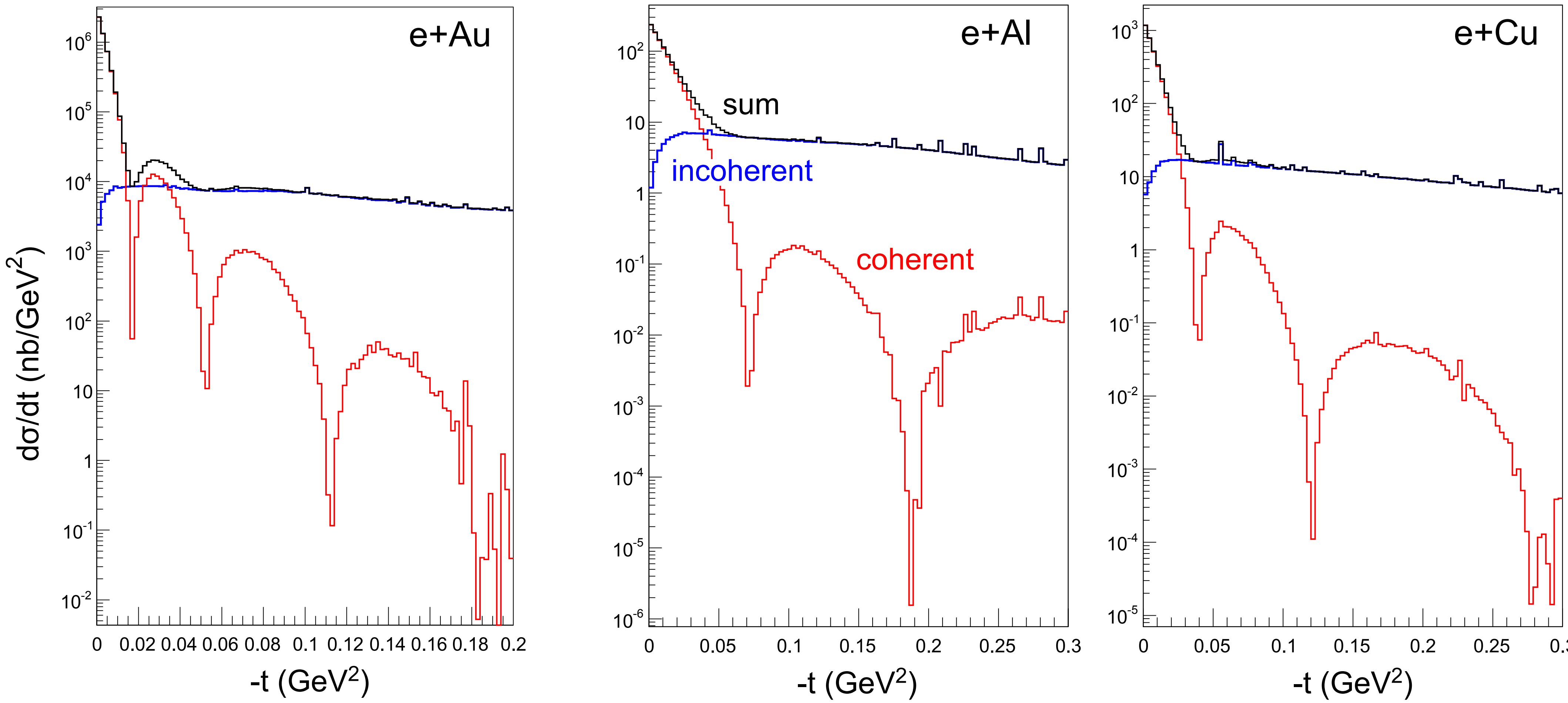
DVCS and Bethe-Heitler interference terms become difficult to distinguish experimentally

Exclusive Vector Meson Production in e+A

- Many event generators exist for e+p collisions
  - ➡ Pythia (v6), LEPTO, PEPSI, RAPGAP….
- Dearth of event generators for e+A collisions
  - ➡ DPMJET-III
- Work at BNL (T. Toll, T. Ullrich) to write an e+A generator (SARTRE)
  - ➡ Comparison of saturation vs non-saturation scenarios
  - ➡ First case study is that of exclusive diffractive J/ψ production

Exclusive Vector Meson Production in e+A

e+A → e+J/ψ+A'



- Low-t: coherent diffraction dominates - gluon density
- High-t: incoherent diffraction dominates - gluon correlations
  - ➡ For smaller nuclei, transition between coherent and incoherent is pushed out to higher |t|
  - ➡ Need good breakup detection efficiency to discriminate between the two scenarios

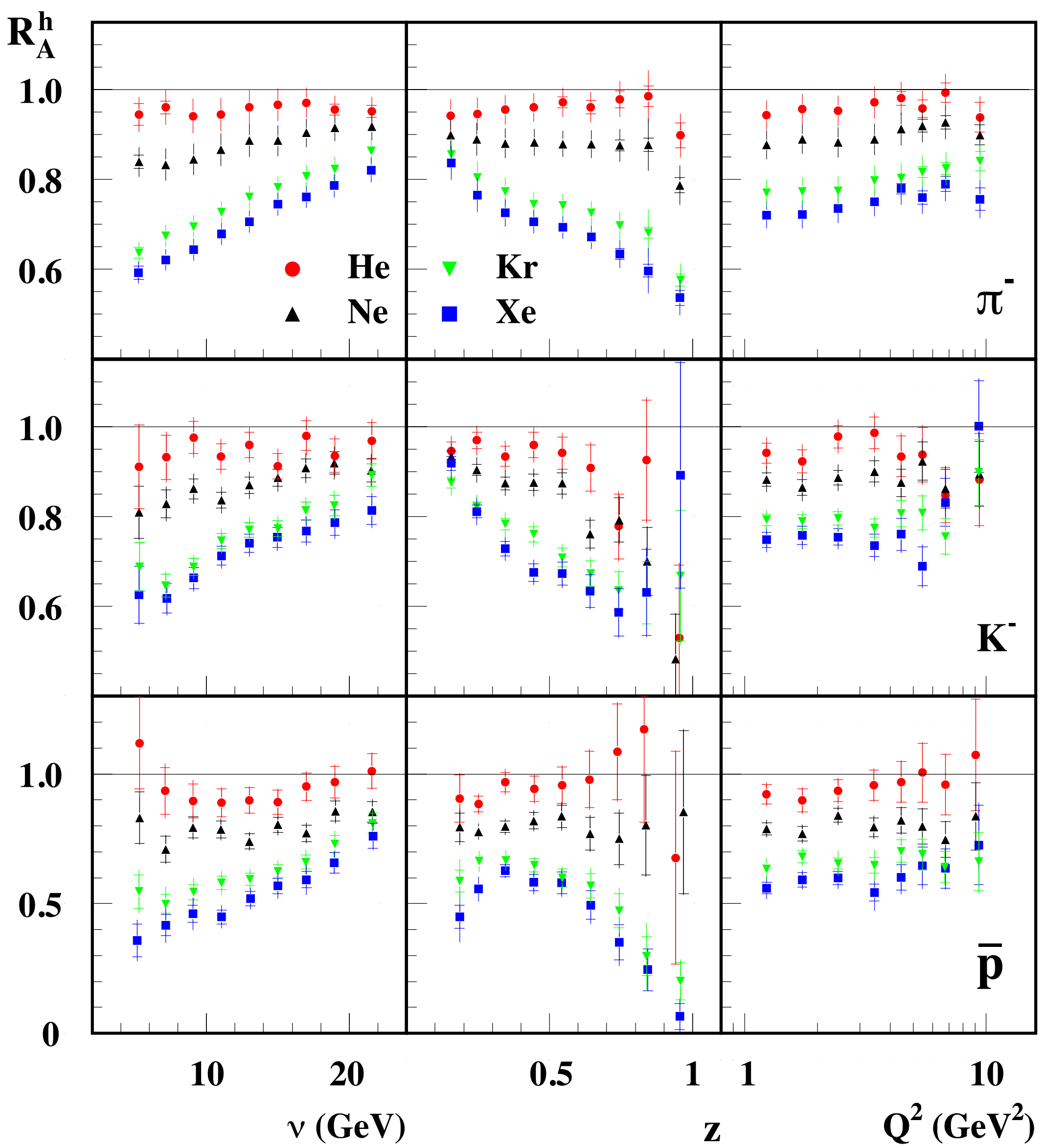
BACKUP SLIDES

How can the EIC contribute?

HERMES:

E_e = 27 GeV → $\sqrt{s}$ = 7.2 GeV

E_h = 2-15 GeV



ν = virtual photon energy

$Z_h = E_h/\nu$

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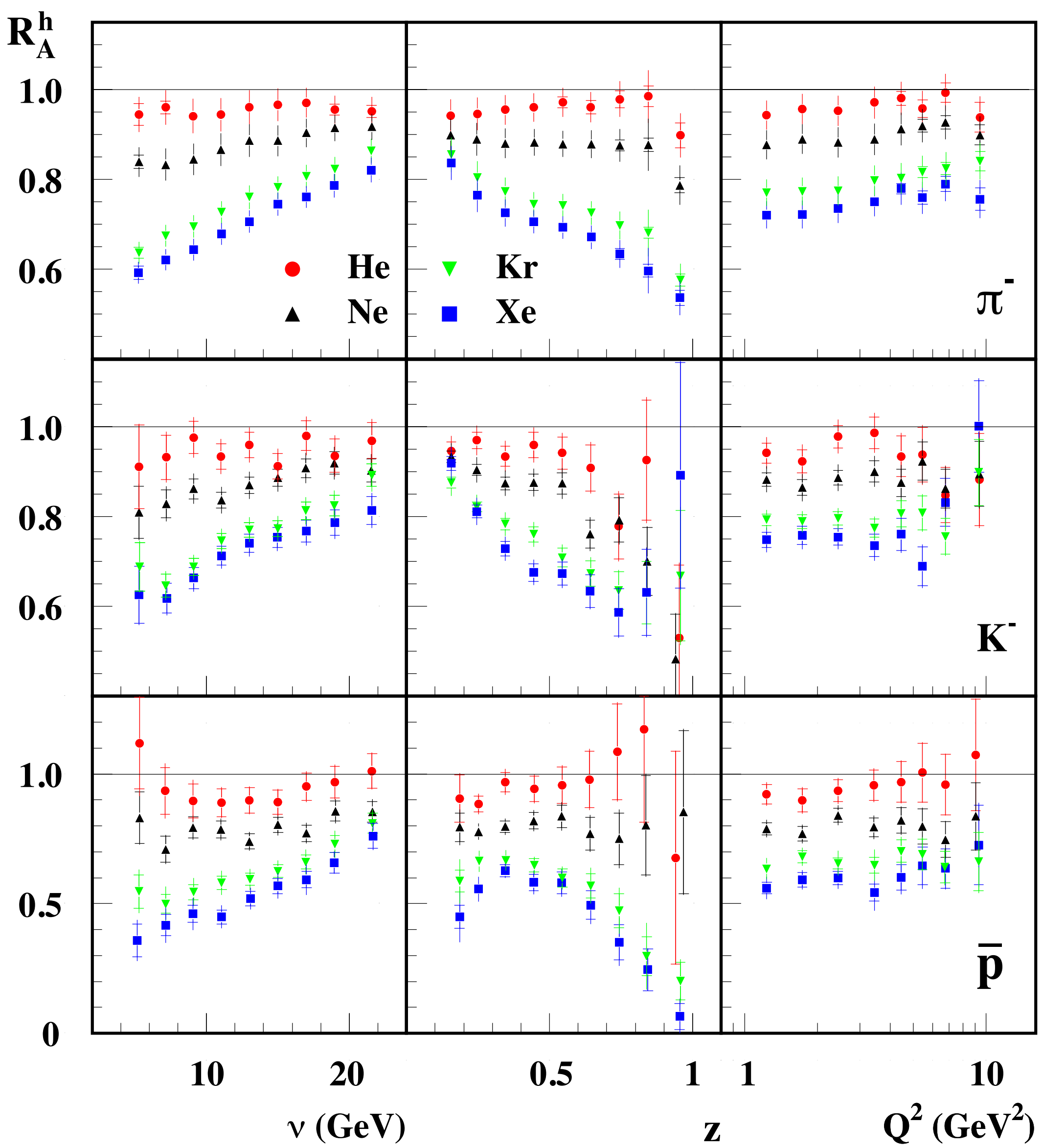

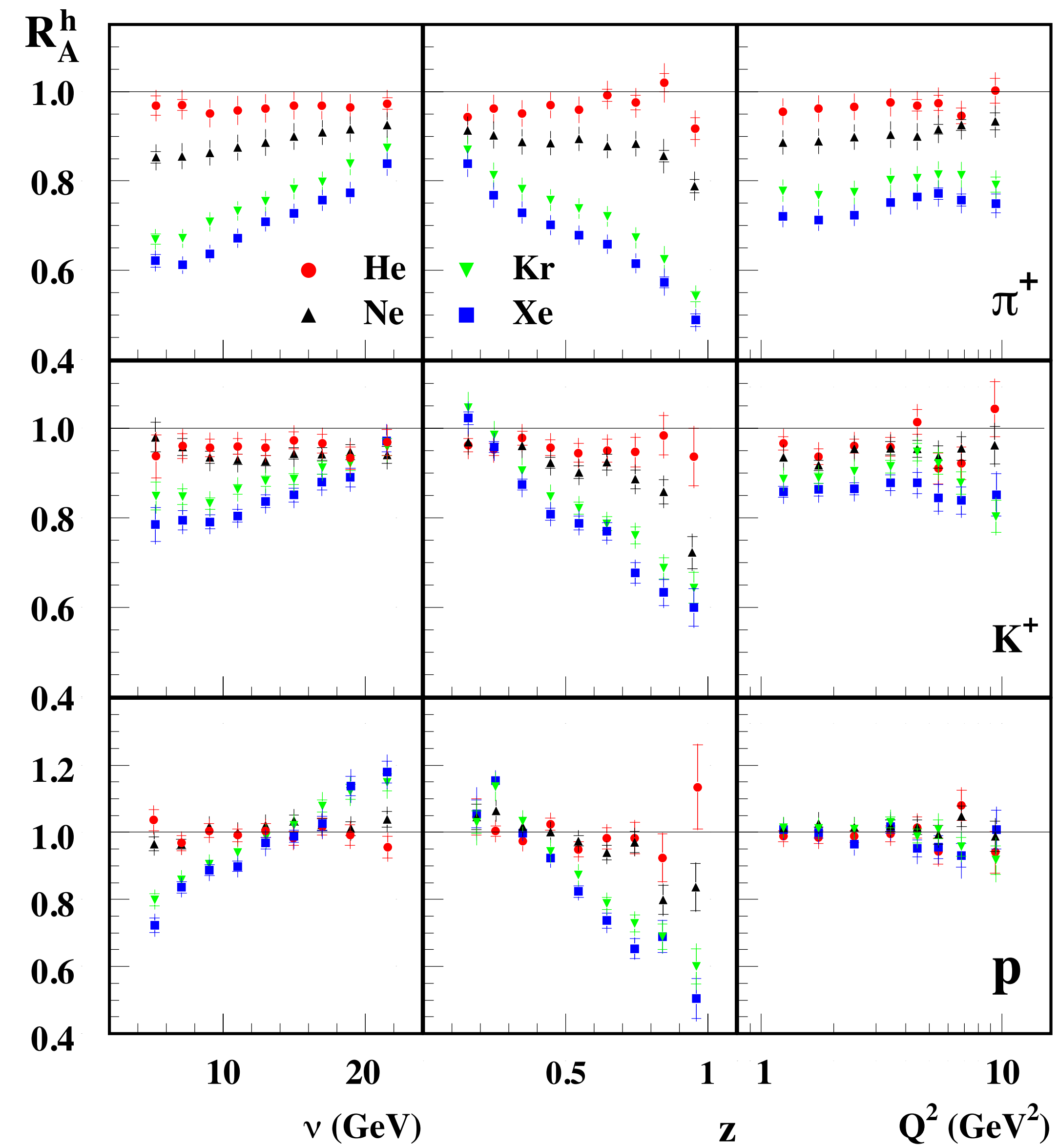

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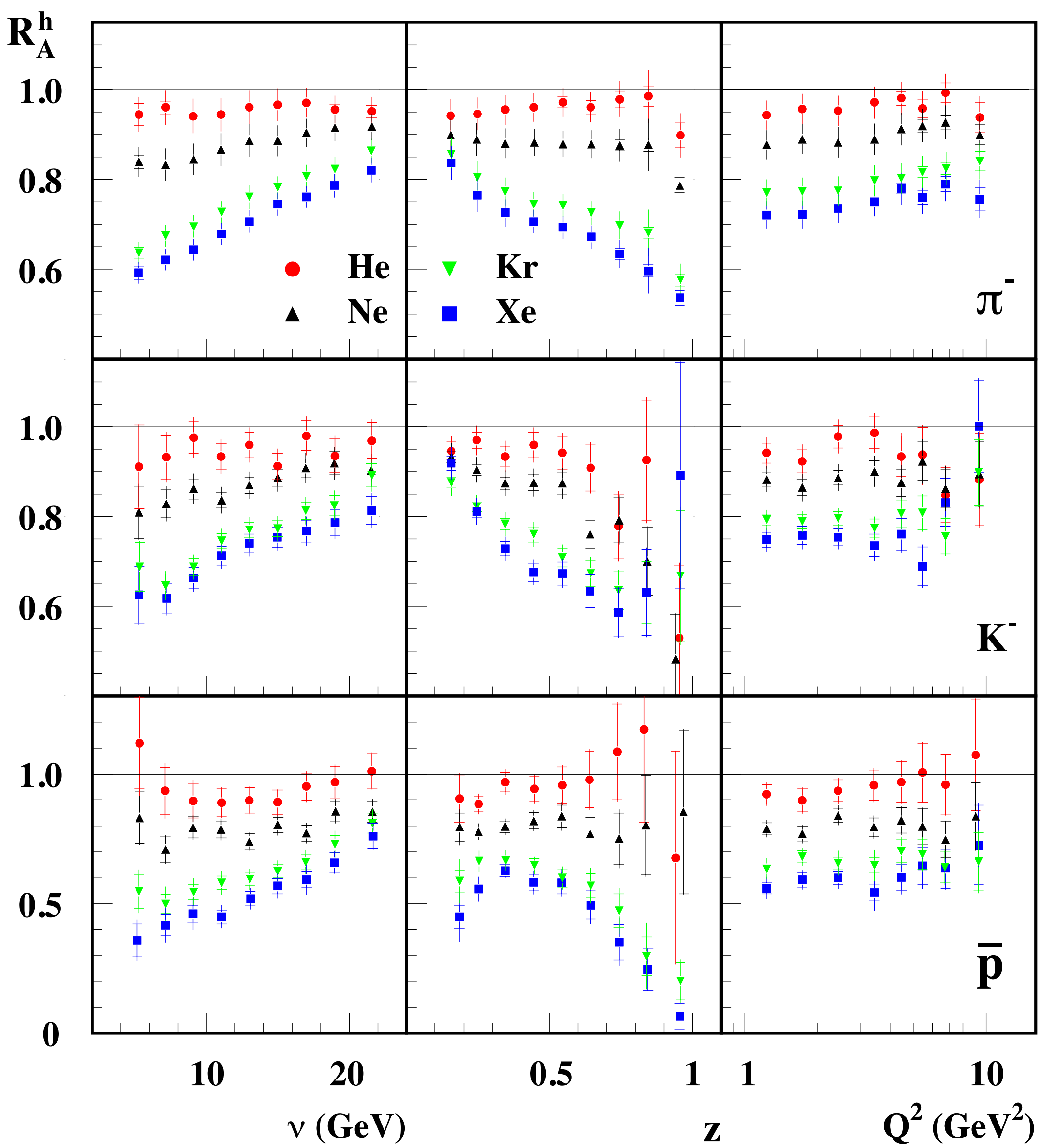
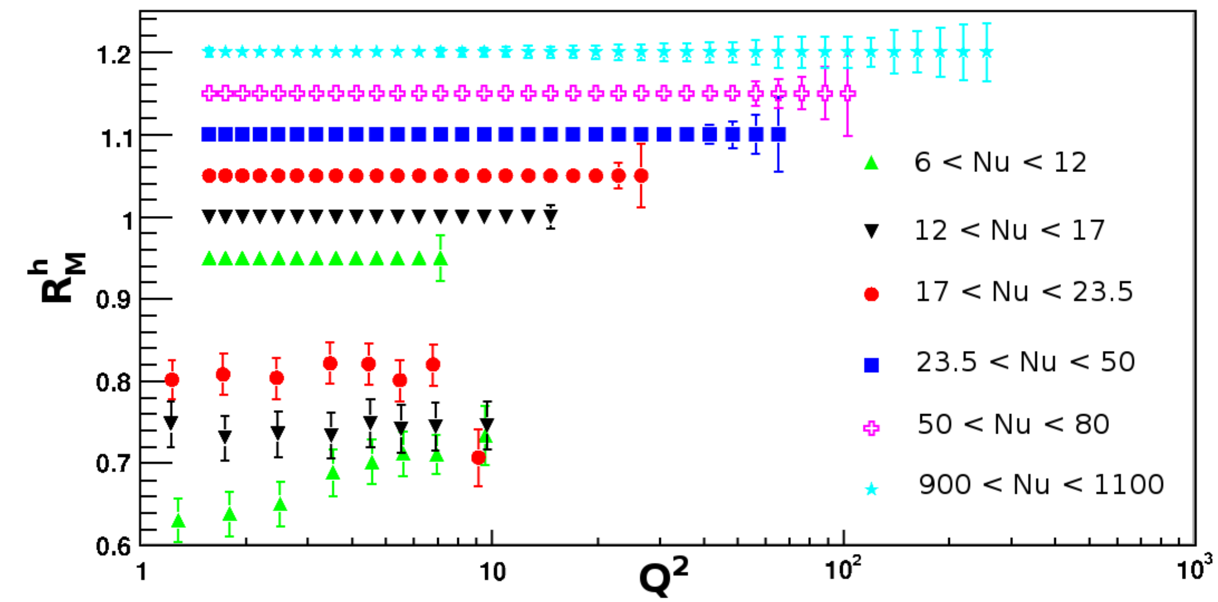
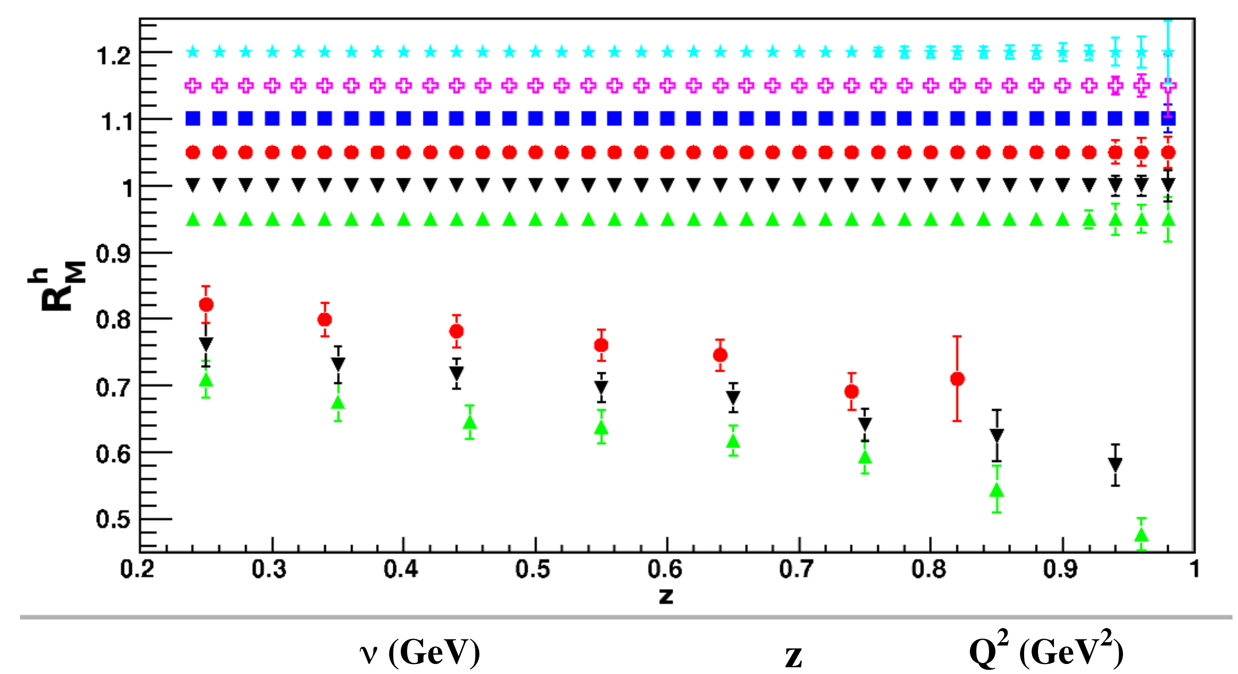


EIC:

light hadrons:





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large ν range → boost

hadronization in and out of nucleus

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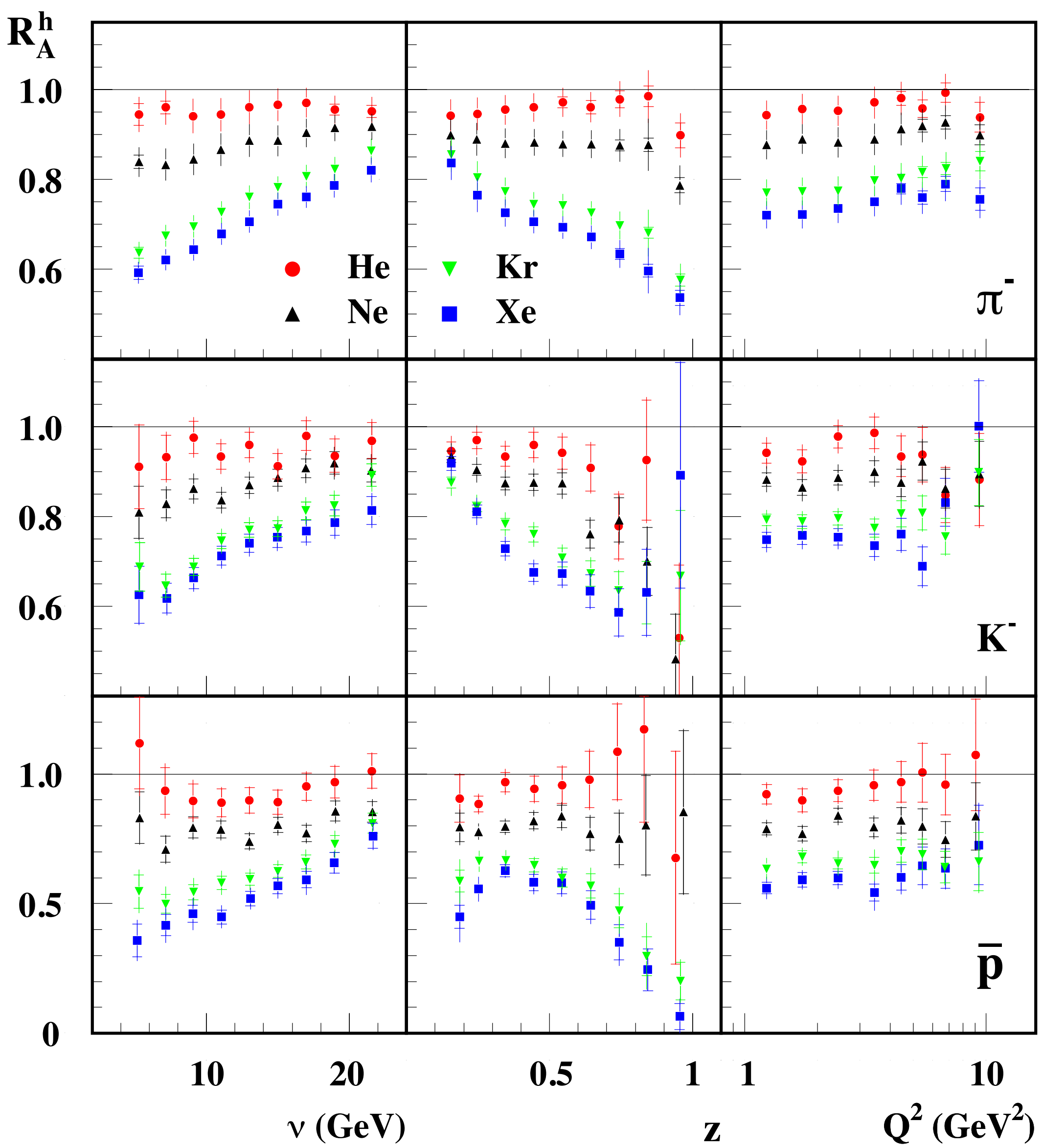
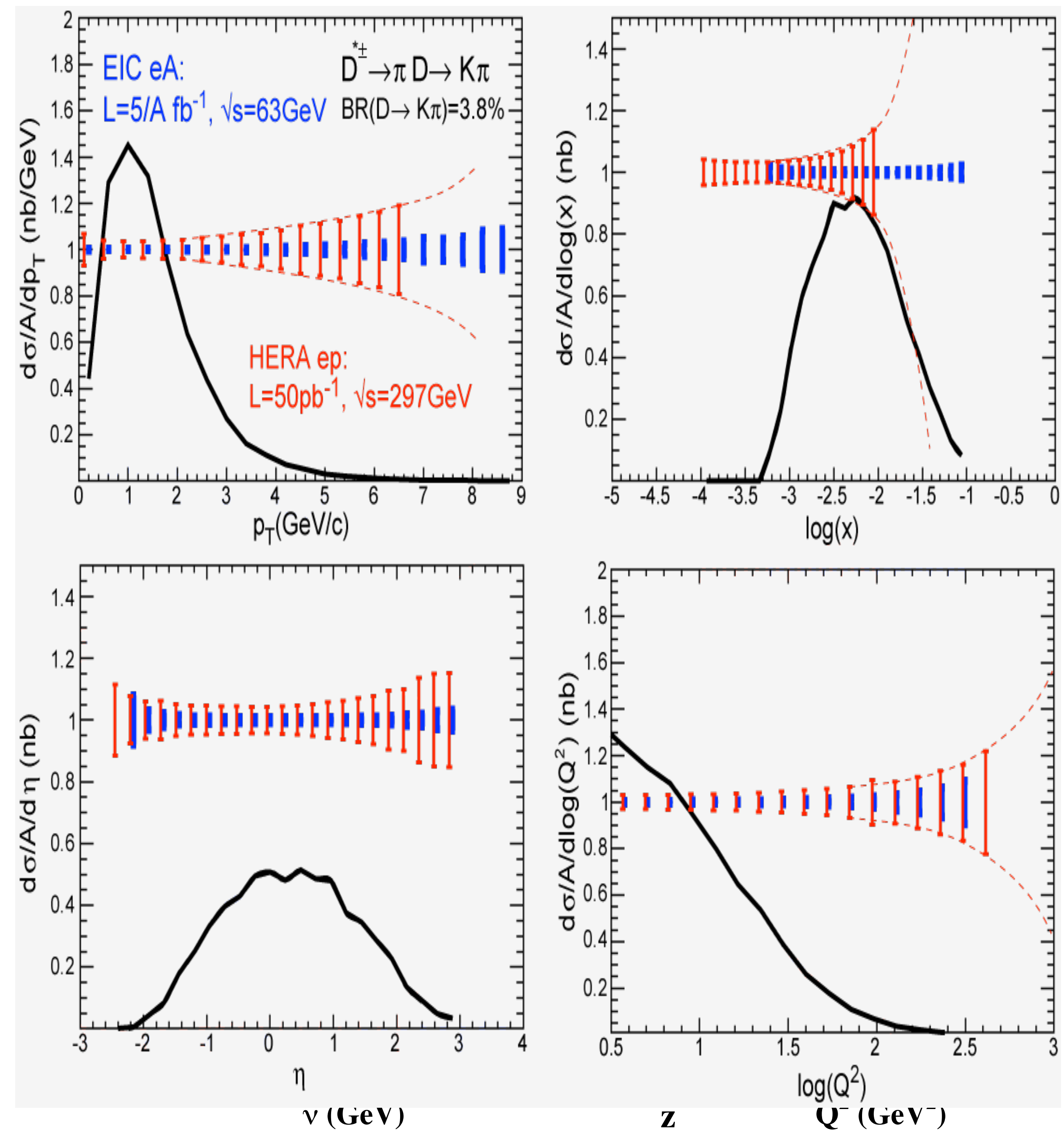


EIC:

charm hadrons:



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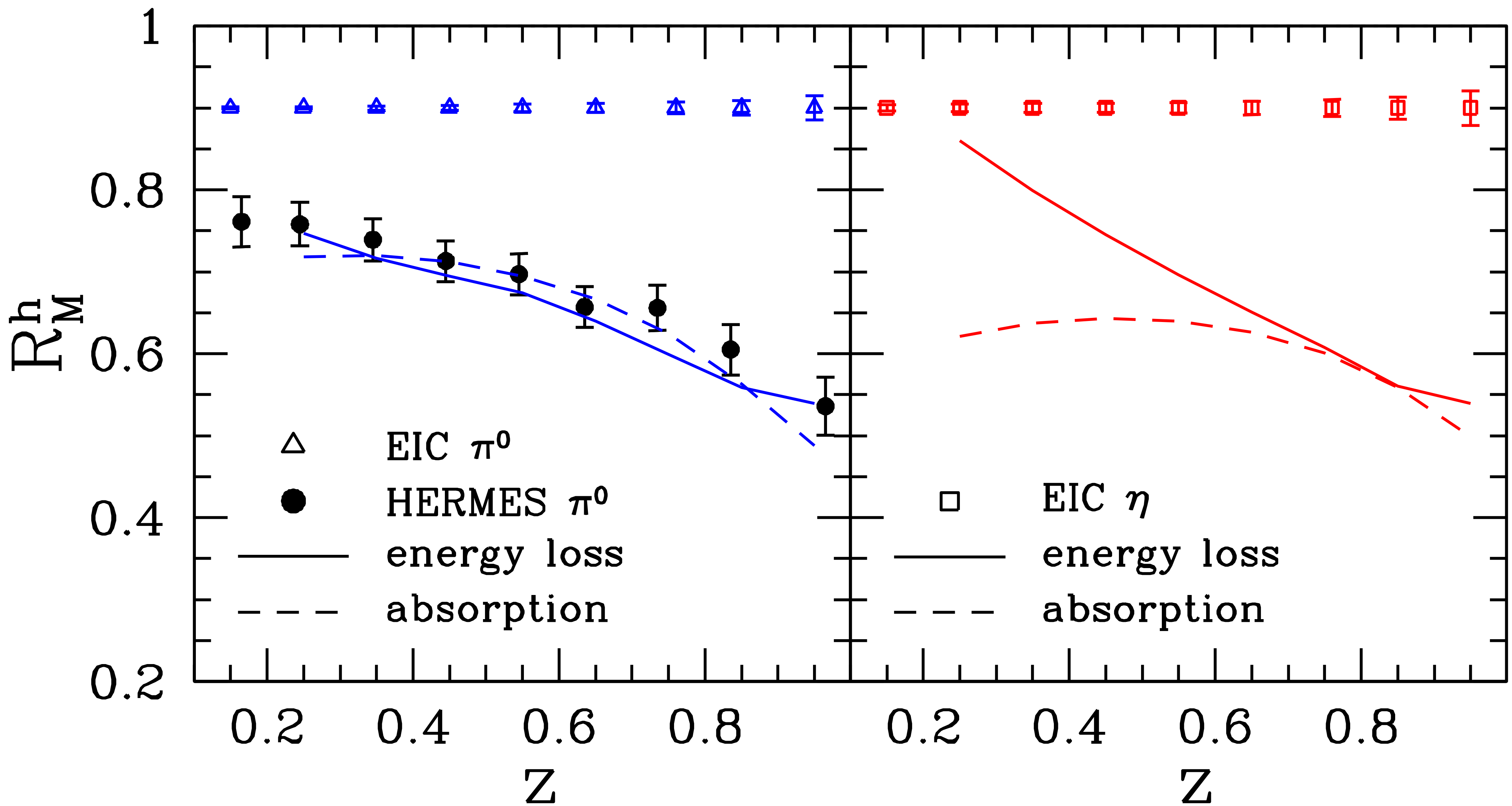

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Measuring the glue via Structure Functions

$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2^A(x,Q^2)-\frac{y^2}{2}F_L^A(x,Q^2)\right]$$

quark+anti-quark momentum distributions

gluon momentum distribution

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Reduced cross-section:

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+}F_L^A(x,Q^2)$$

where:

$$Y^+ = 1 + (1-y)^2$$

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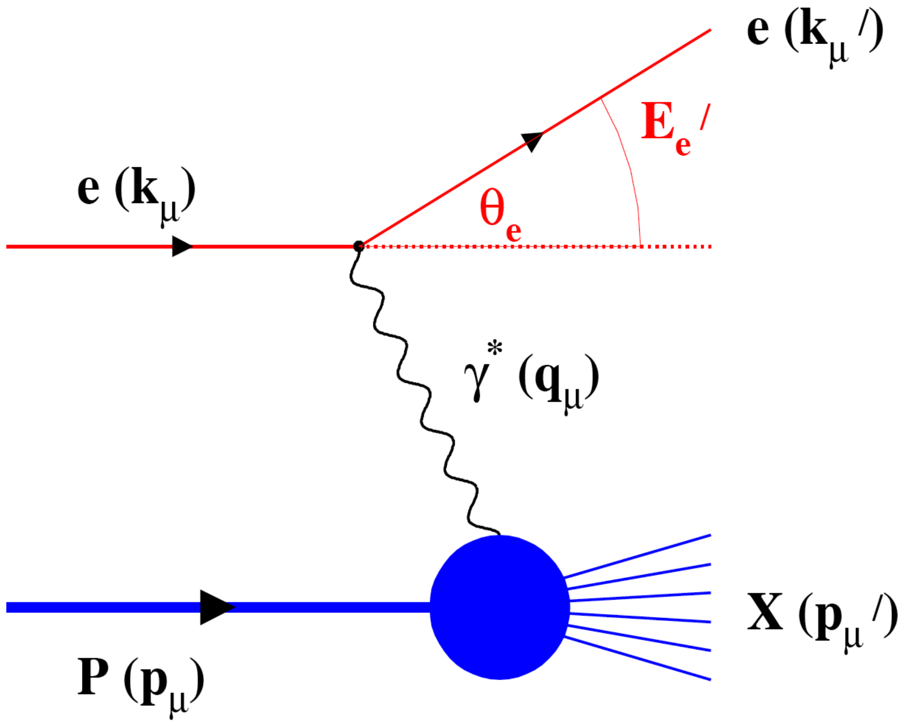
DIS Kinematics

$e(k) + p(p) \rightarrow e(k') + X(p_X)$



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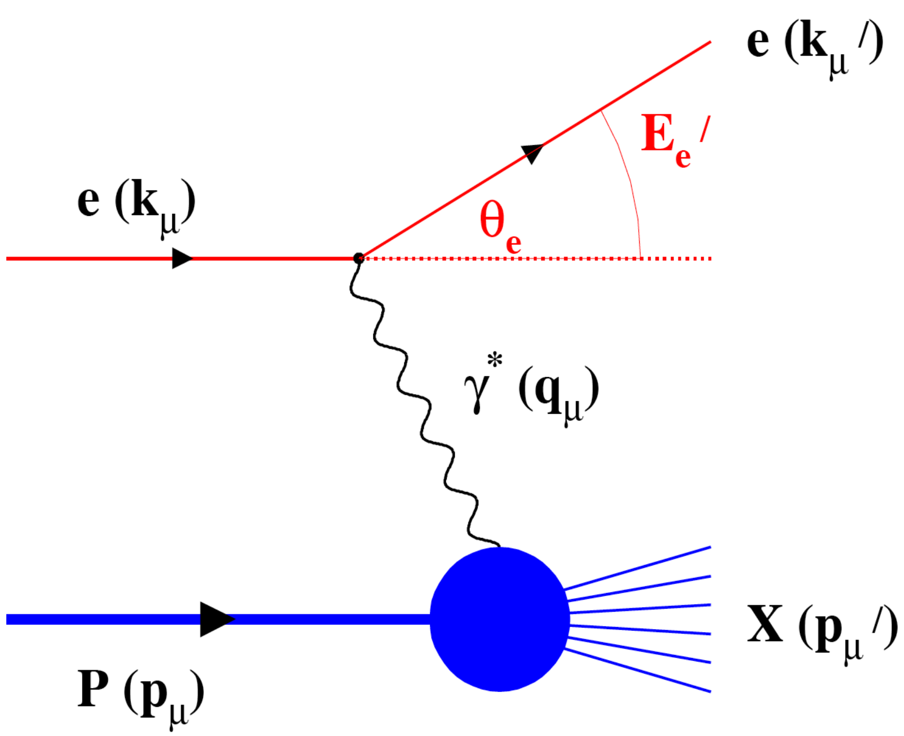

$$Q^2 = -q^2 = -(k_\mu - k_\mu^{'})^2$$

$$Q^2 = 4E_eE_e^{'}sin^2(\frac{\theta_e^{'}}{2})$$

Measure of resolution power or "Virtuality"

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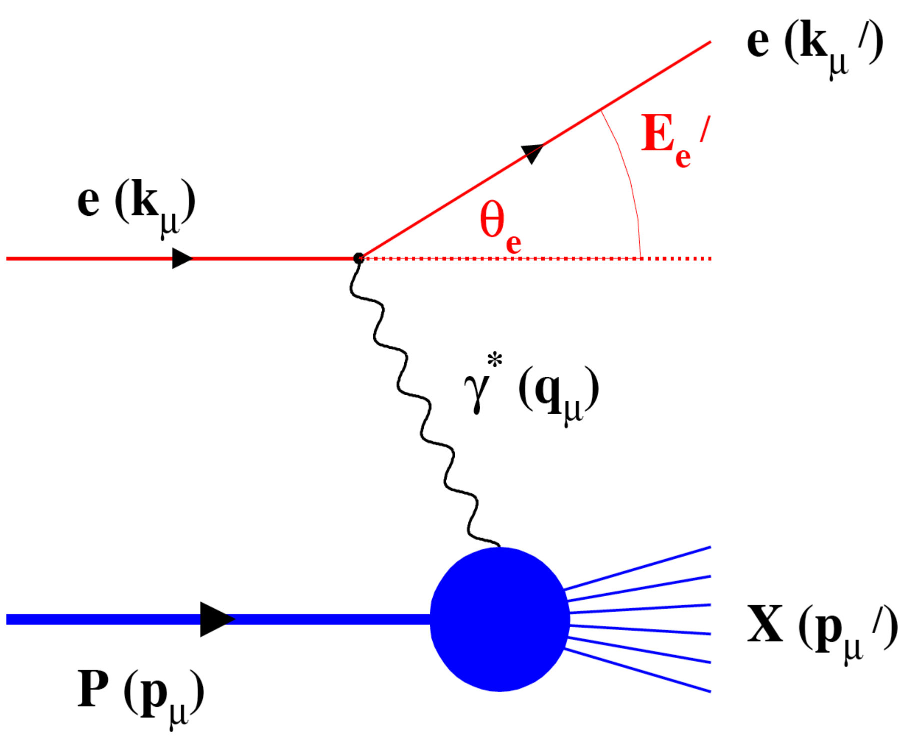

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Measure of resolution power or "Virtuality"

$$y = \frac{pq}{pk} = 1 - \frac{E_{e'}}{E_e} cos^2(\frac{\theta'_e}{2})$$

Measure of inelasticity

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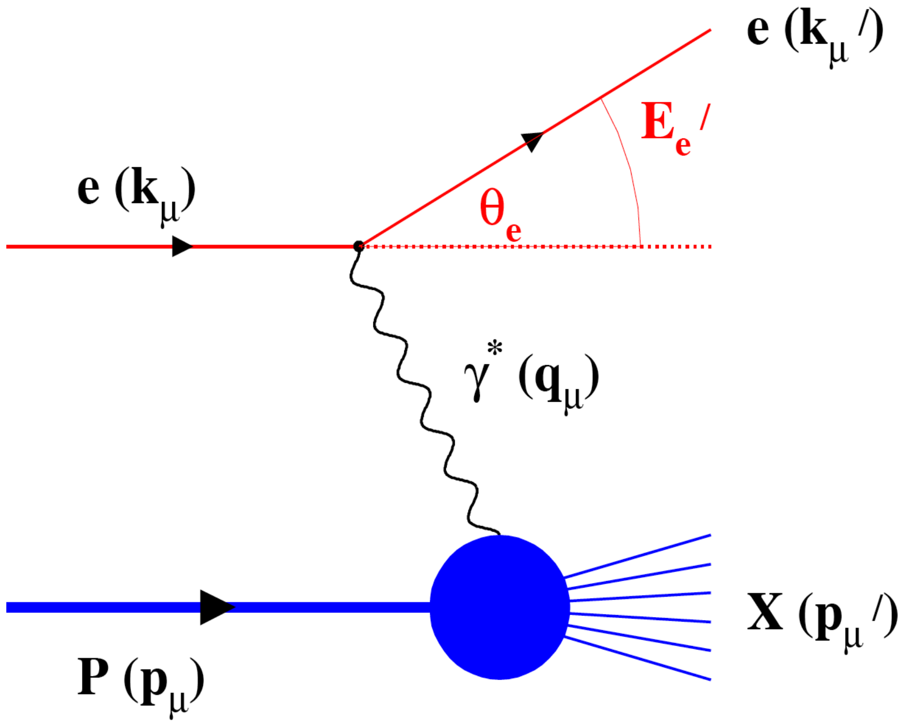

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Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

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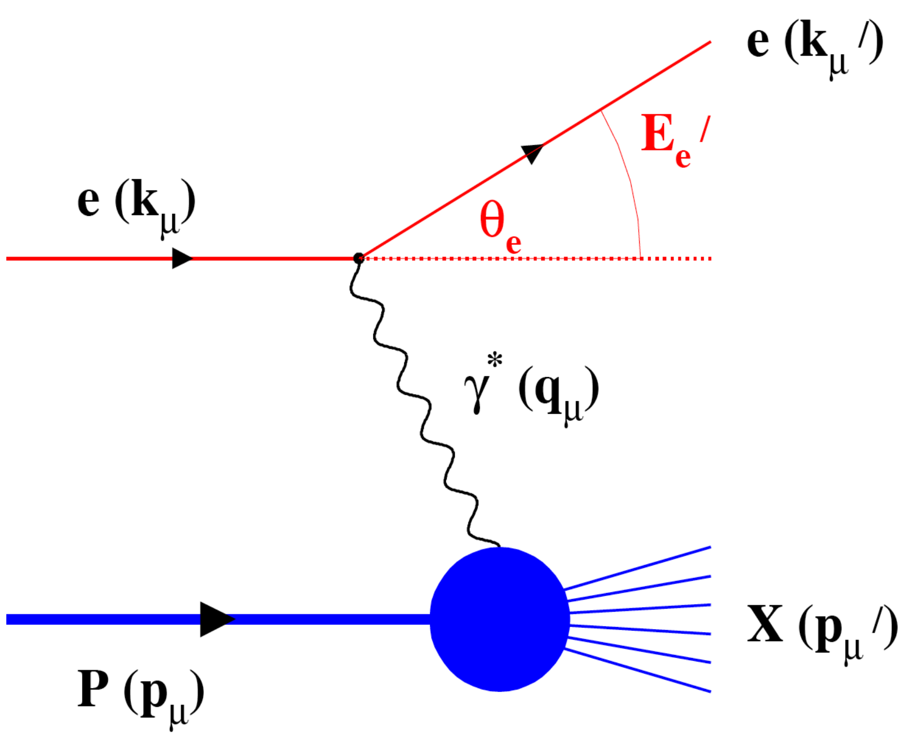

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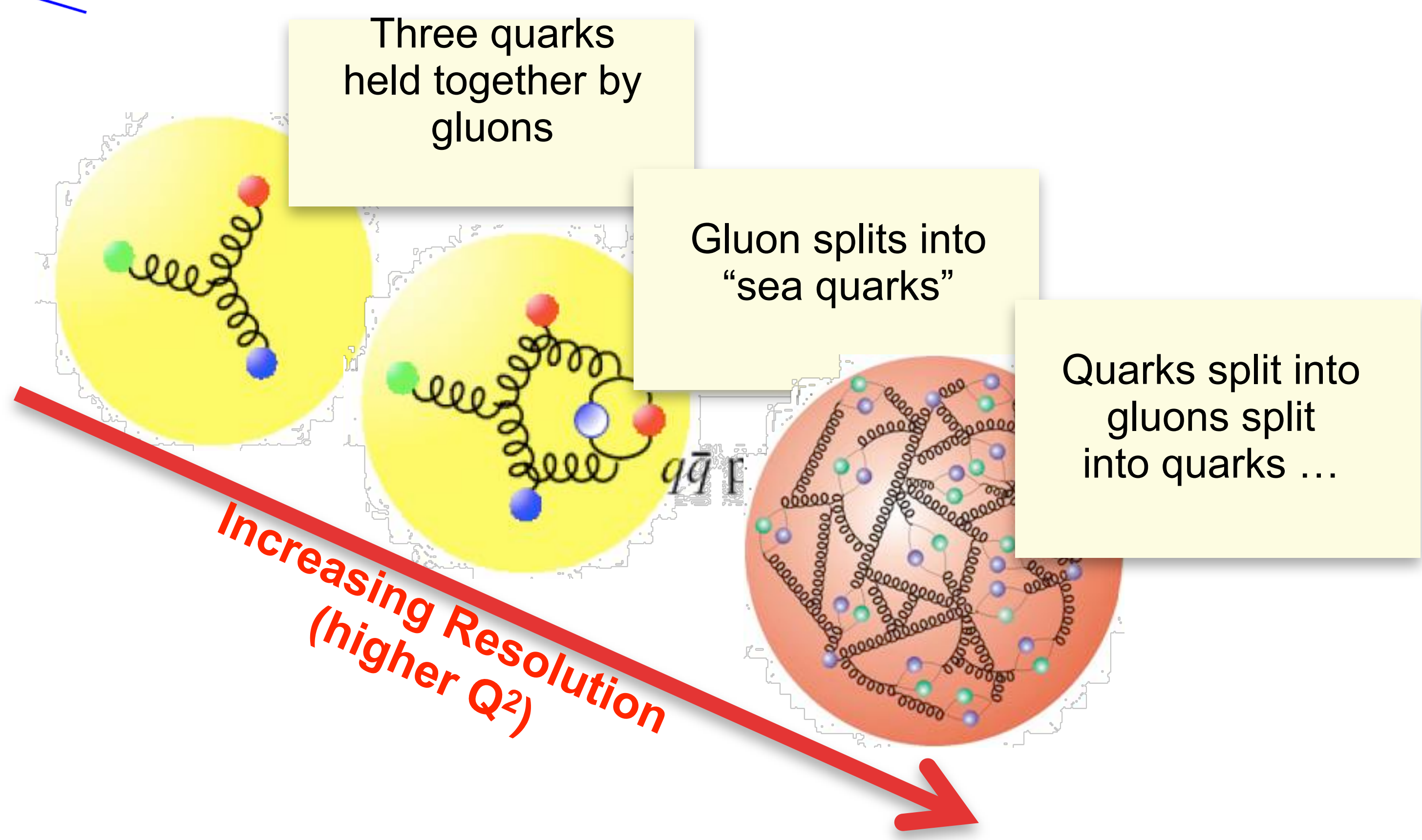
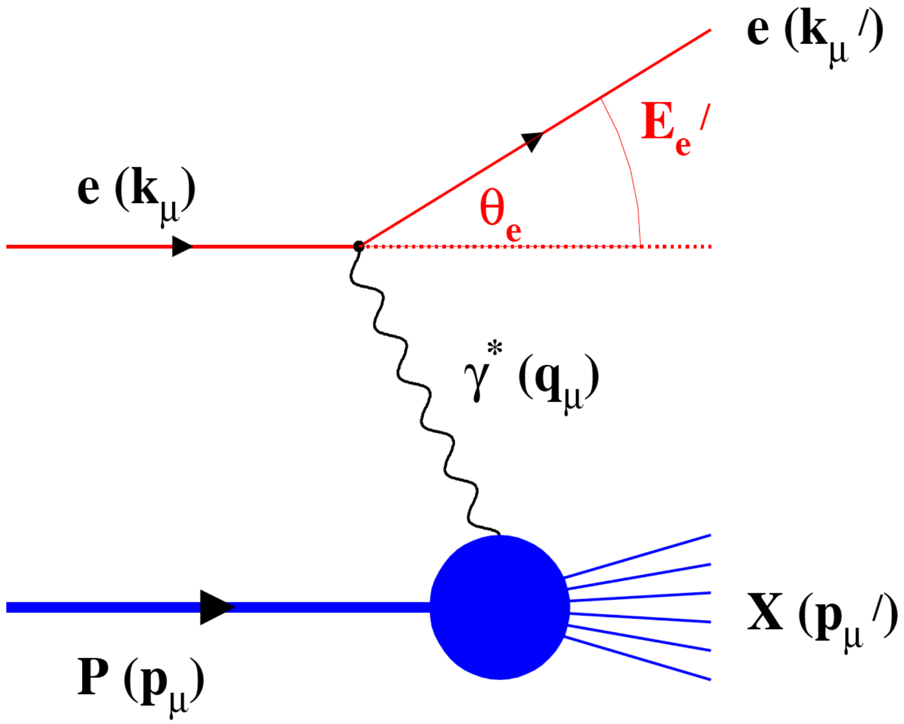


Diffractive Kinematics

$e(k) + p(p) \rightarrow e(k') + X(p_X)$



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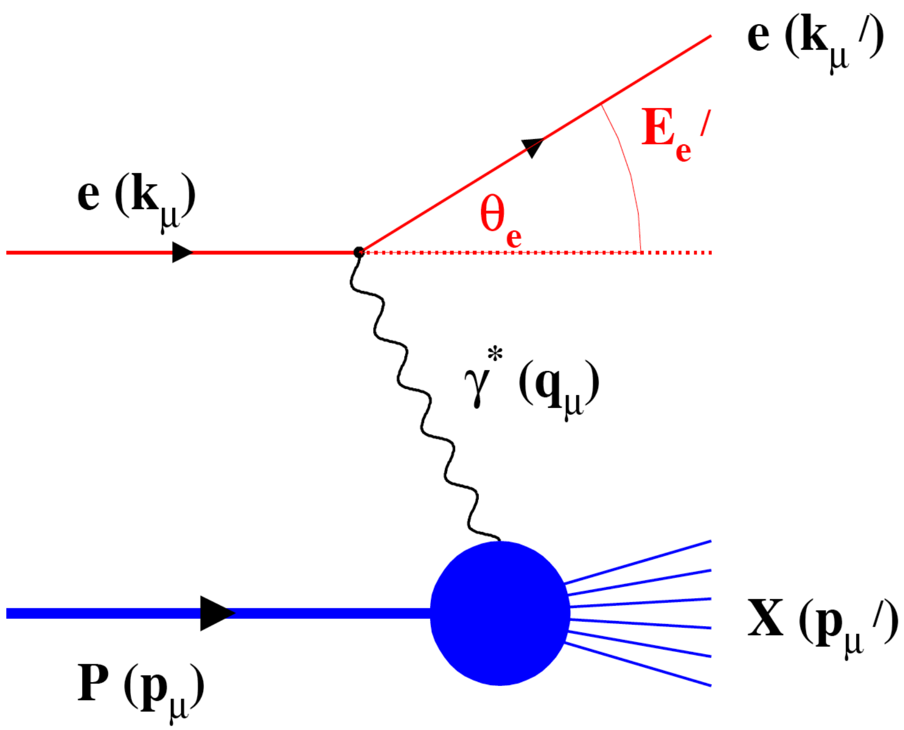

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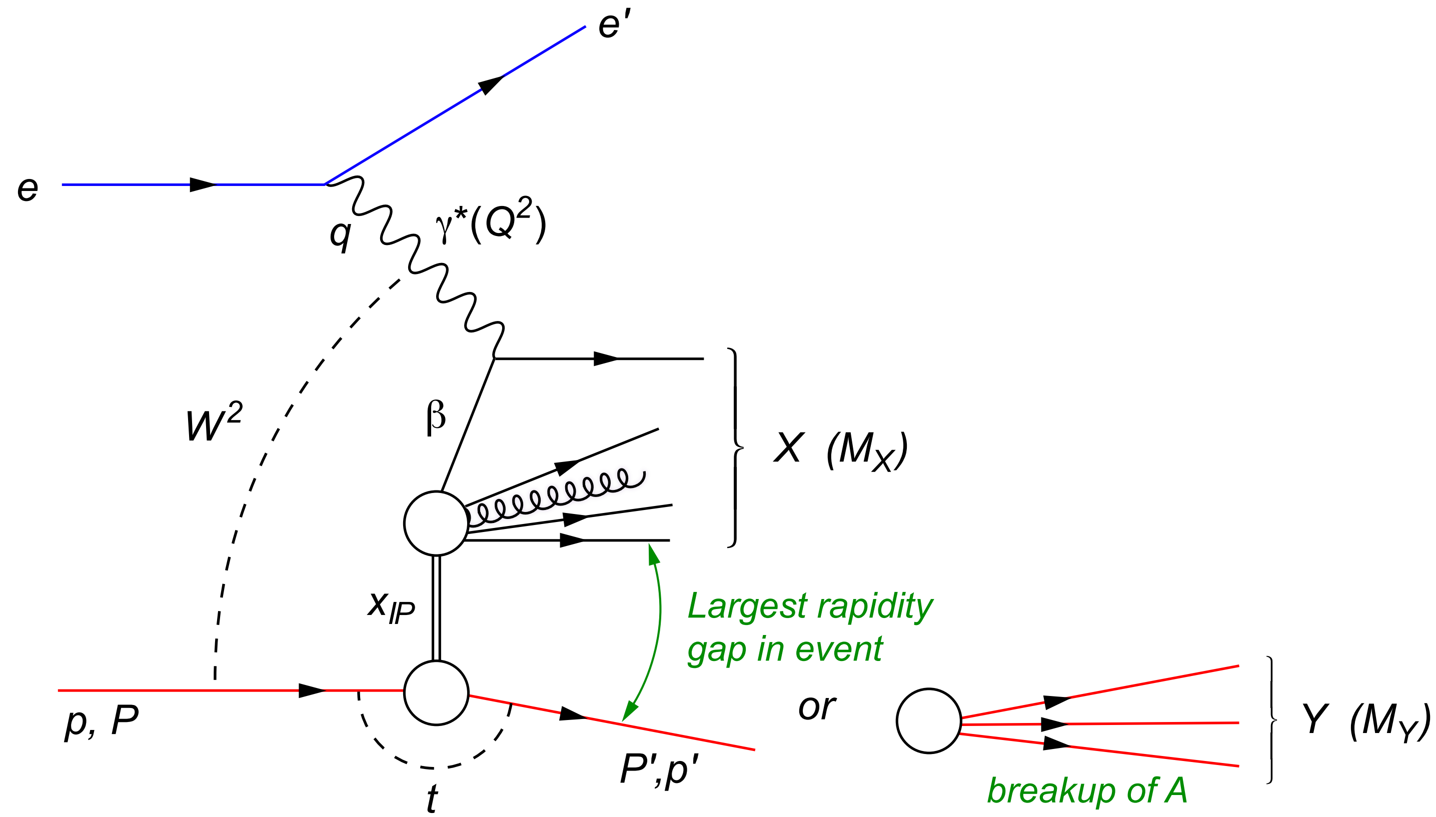

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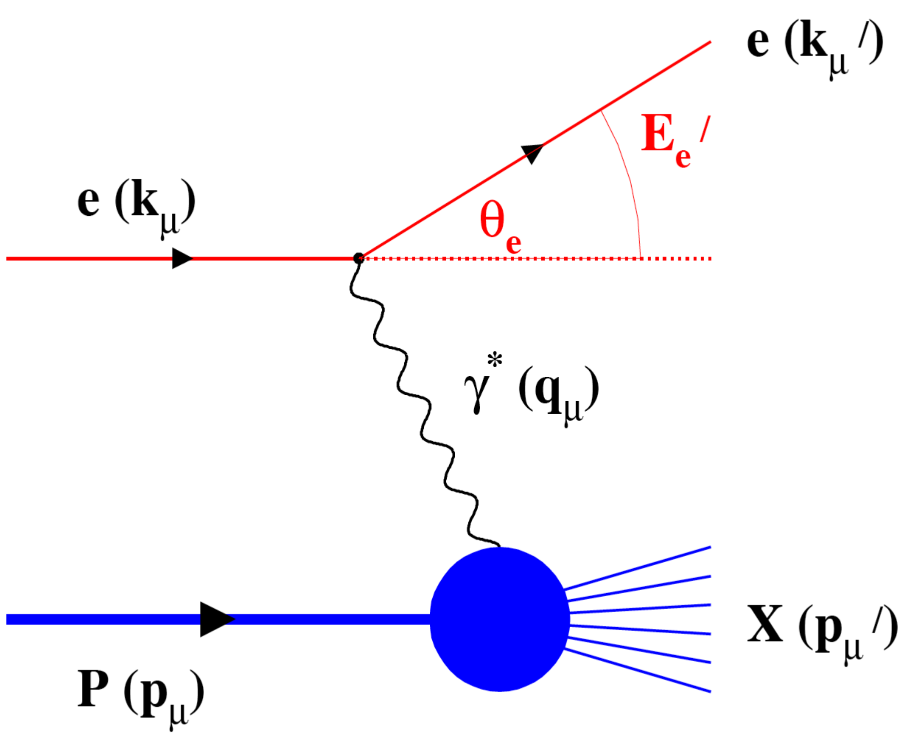

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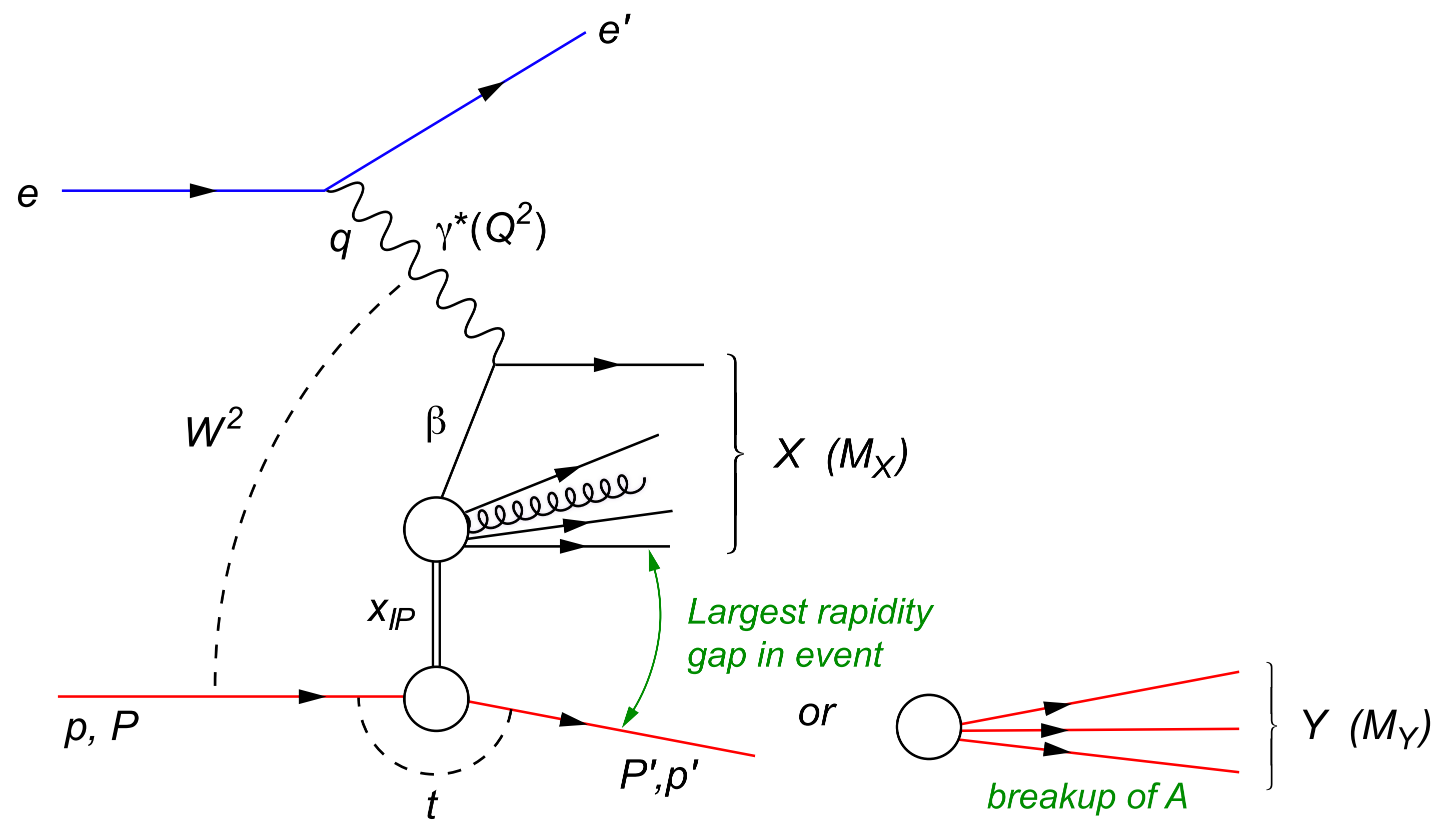

$$x_{\mathbb{P}} = \frac{q \cdot (p - p_Y)}{q \cdot p}$$

the momentum fraction of the proton carried by the pomeron

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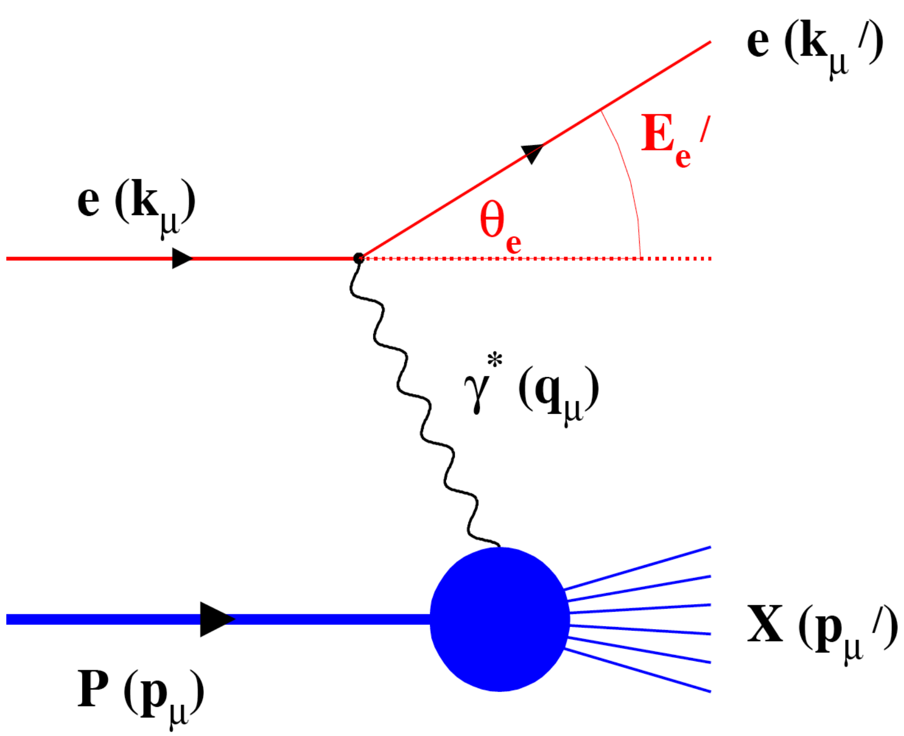

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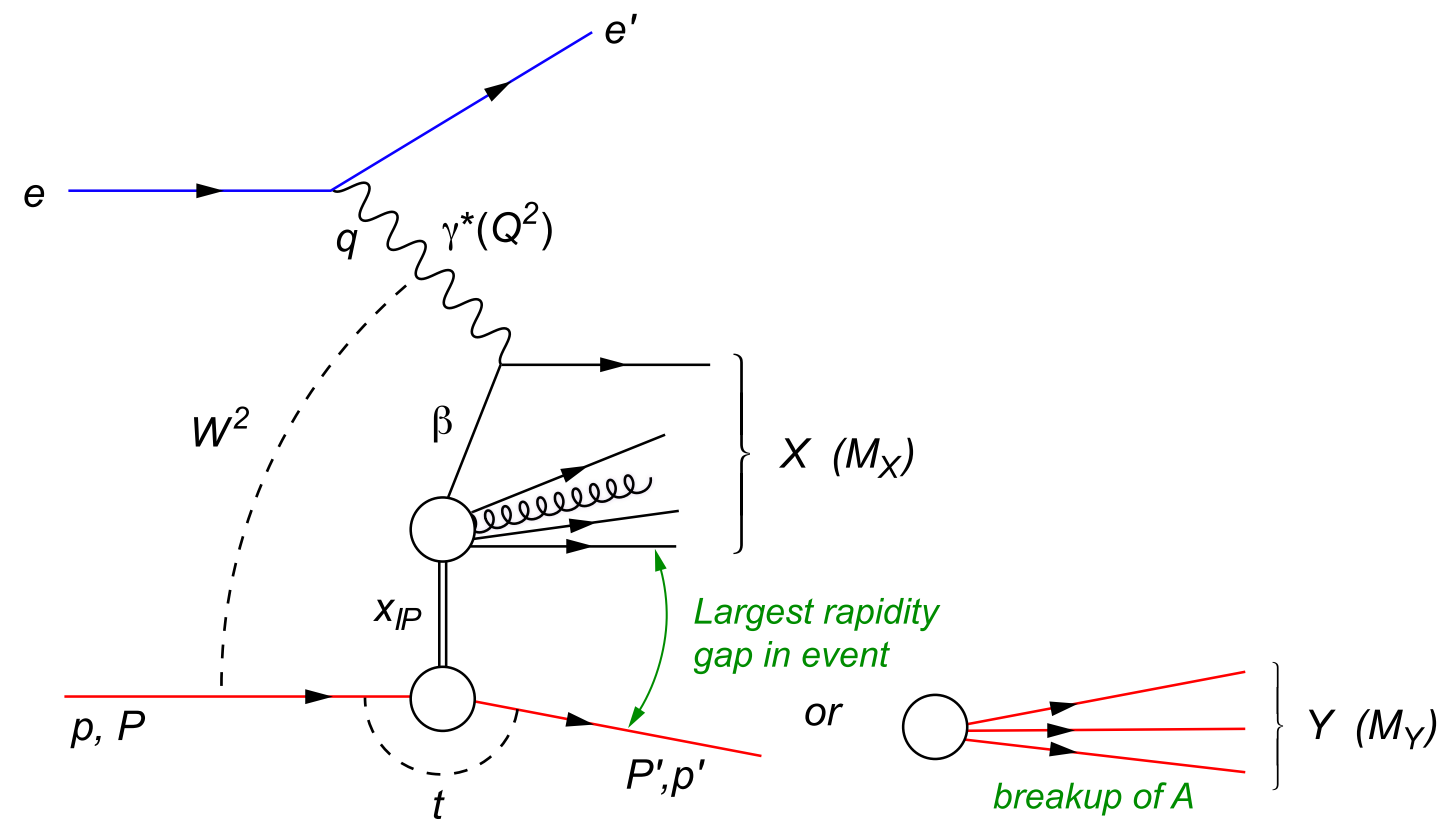

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the momentum fraction of the proton carried by the pomeron

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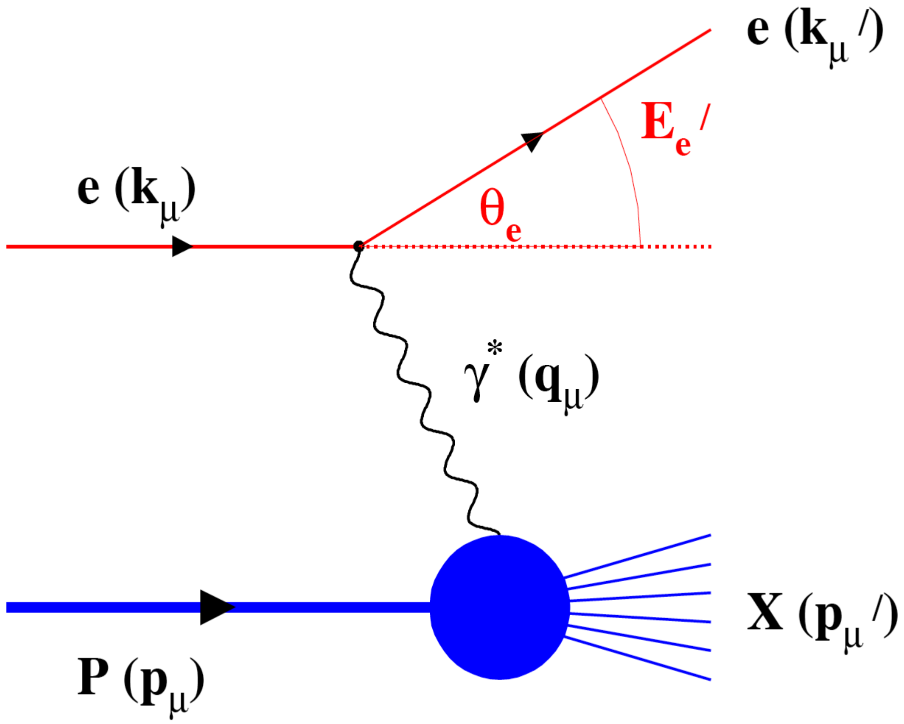
the momentum transfer at the proton vertex

Diffractive Kinematics

e(k) + p(p) → e(k') +X(pX)



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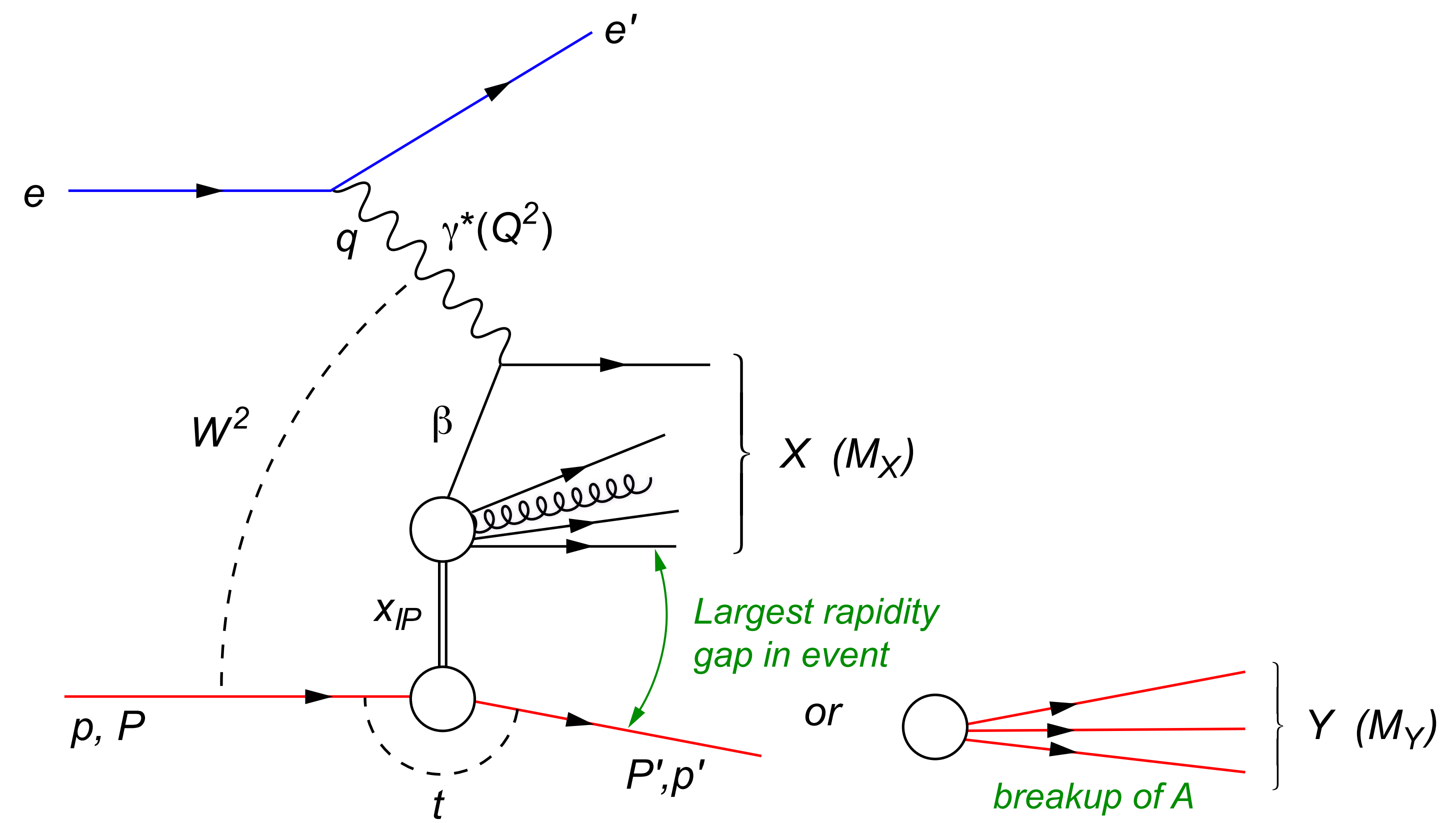

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$$\beta = \frac{-q^2}{q \cdot (p - p_Y)} = \frac{x}{x_{\mathbb{P}}}$$

the momentum fraction of the pomeron carried by the interacting quark

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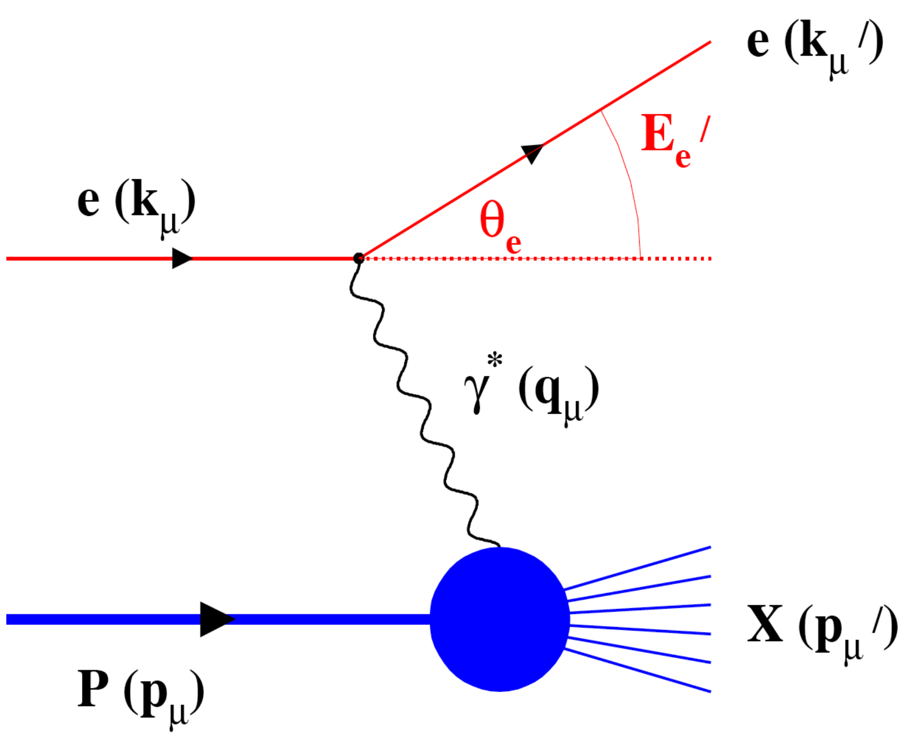

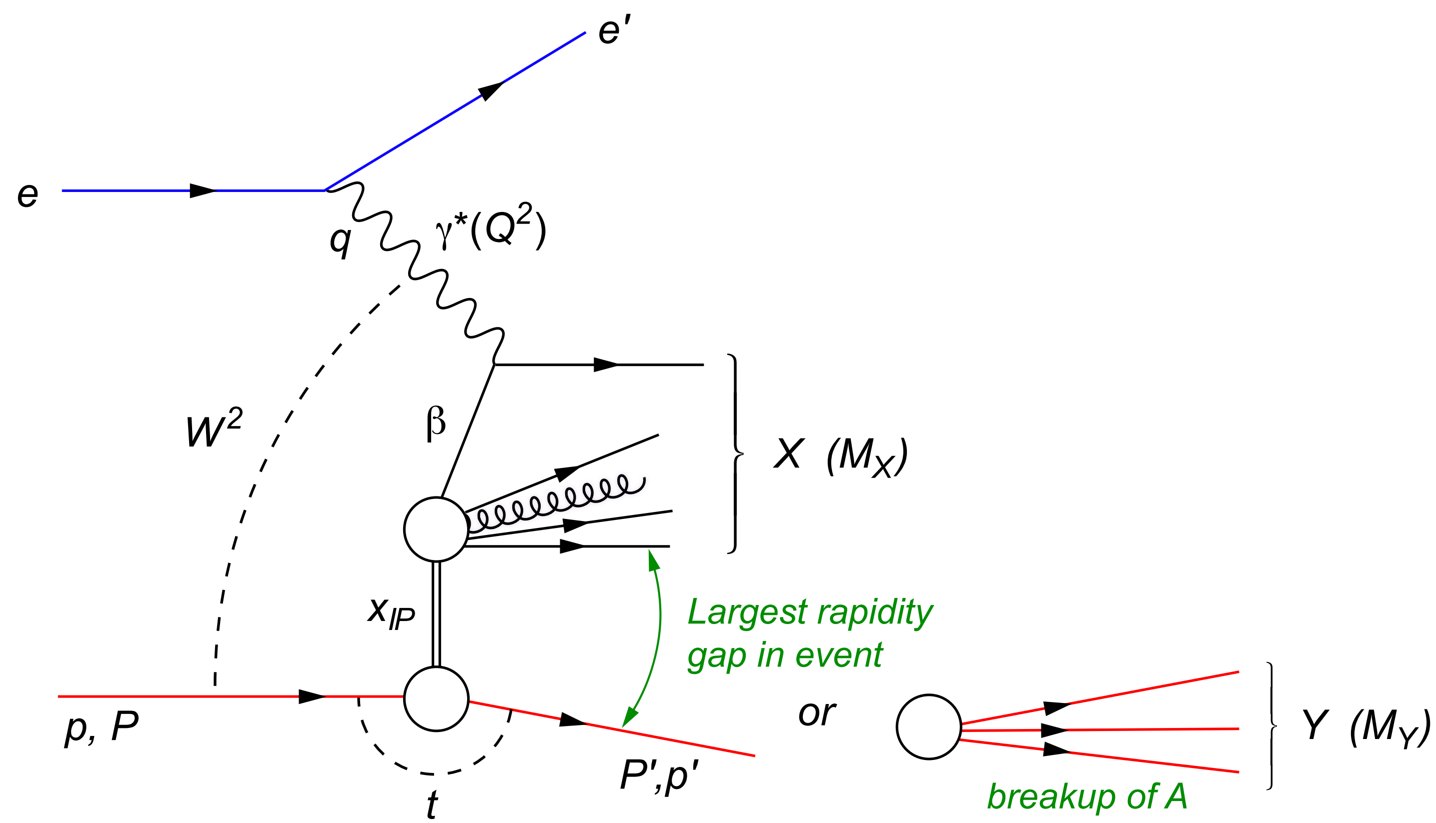

- HERA
  - ➡ 10-15% of all events were diffractive
- EIC
  - ➡ saturation models predict that 30-40% of all events will be diffractive

e+A Golden Science Matrix

Primary new science deliverables	What we hope to fundamentally learn	Basic measurements	Typical required precision	Special requirements on accelerator/ detector	What can be done in phase I	Alternatives in absence of an EIC	Gain/Loss compared with other relevant facilities	Comments
integrated nuclear gluon distribution	The nuclear wave function throughout x-Q^2 plane	F_L, F_2, F_L^c, F_2^c	What HERA reached for F2 with combined data	displaced vertex detector for charm	stage 1: large-x & large-Q^2 need full EIC, for F_L and F_2^c	p+A at LHC (not as precise though) & LHeC	First experiment with good x, Q^2 & A range	This is fundamental input for A+A collisions
k_T dependence of gluon distribution and correlations	The non-linear QCD evolution - Qs	SIDIS & di-hadron correlations with light and heavy flavours		Need low-pt particle ID	SIDIS for sure TBD: saturation signal in di-hadron p_T imbalance	1) p+A at RHIC/LHC, although e+A needed to check universality 2) LHeC	Cleaner than p+A: reduced background	
b dependence of gluon distribution and correlations	Interplay between small-x evolution and confinement	Diffractive VM production and DVCS, coherent and incoherent parts	50 MeV resolution on momentum transfer	hermetic detector with 4pi coverage low-t: need to detect nuclear break-up	Moderate x with light and heavy nuclei	LHeC	Never been measured before	Initial conditions for HI collisions – eccentricity fluctuations

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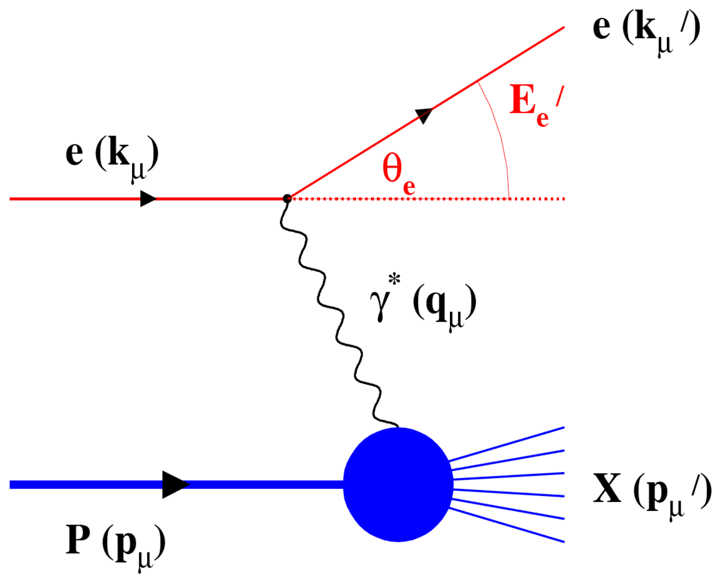
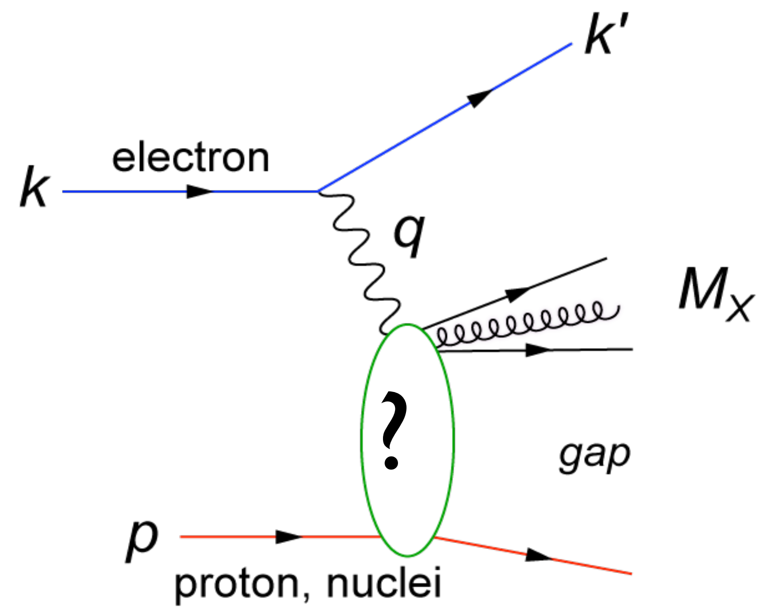
$$\frac{d\sigma}{dt}|_{t=0}(\gamma^* \to M_X A) \propto \alpha_s^2 [xG_A(x,Q^2)]^2$$





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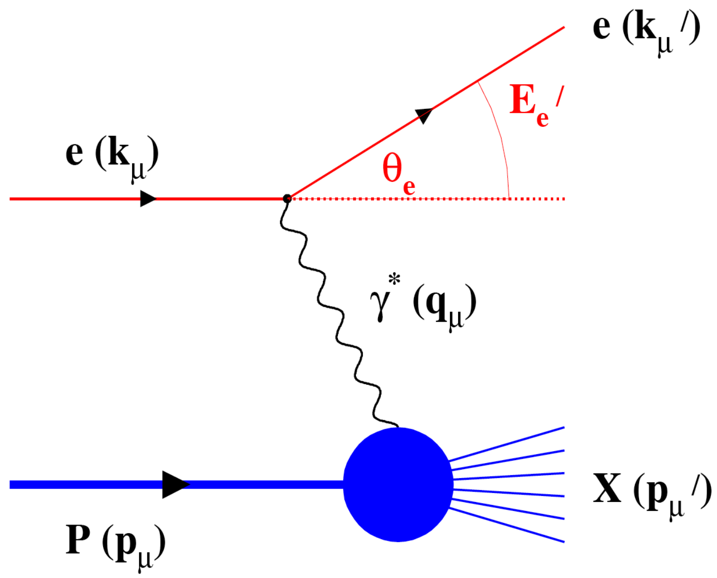

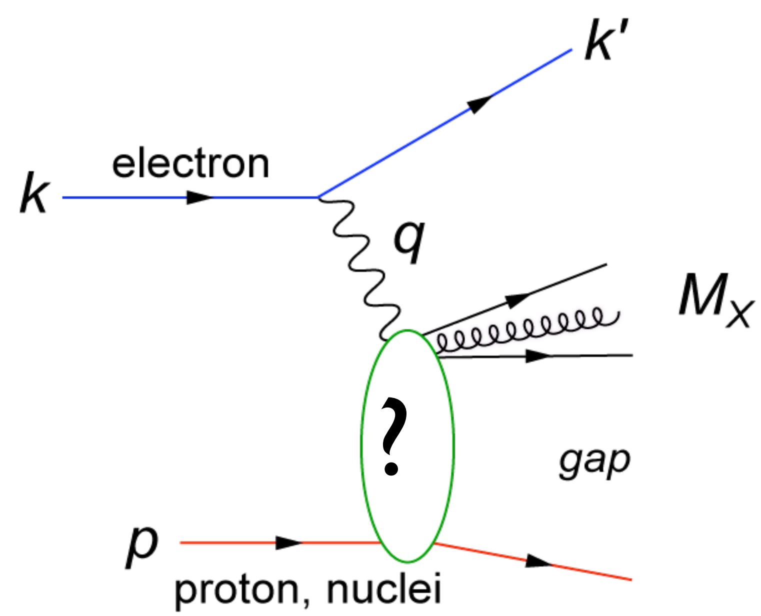

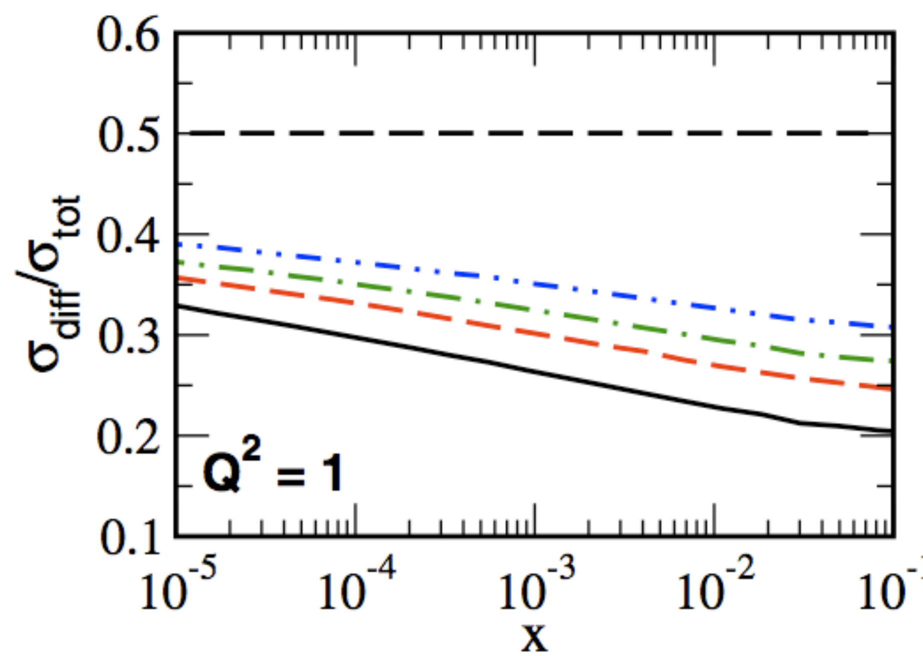

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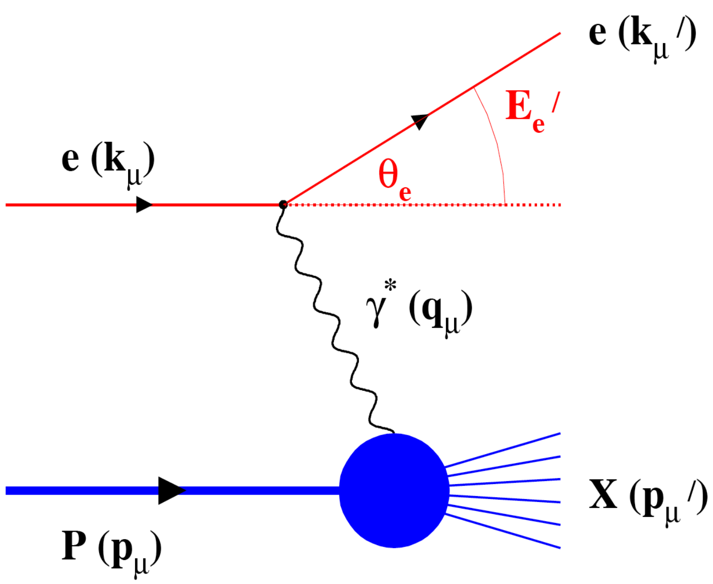

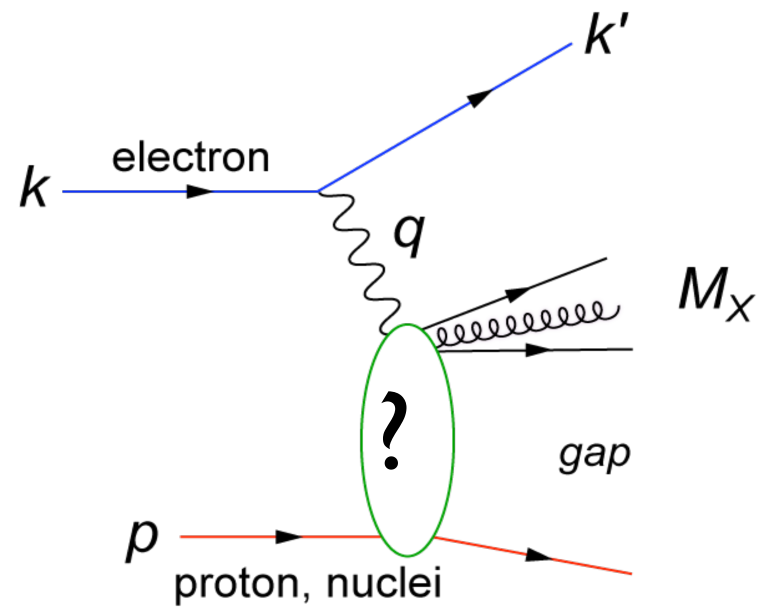

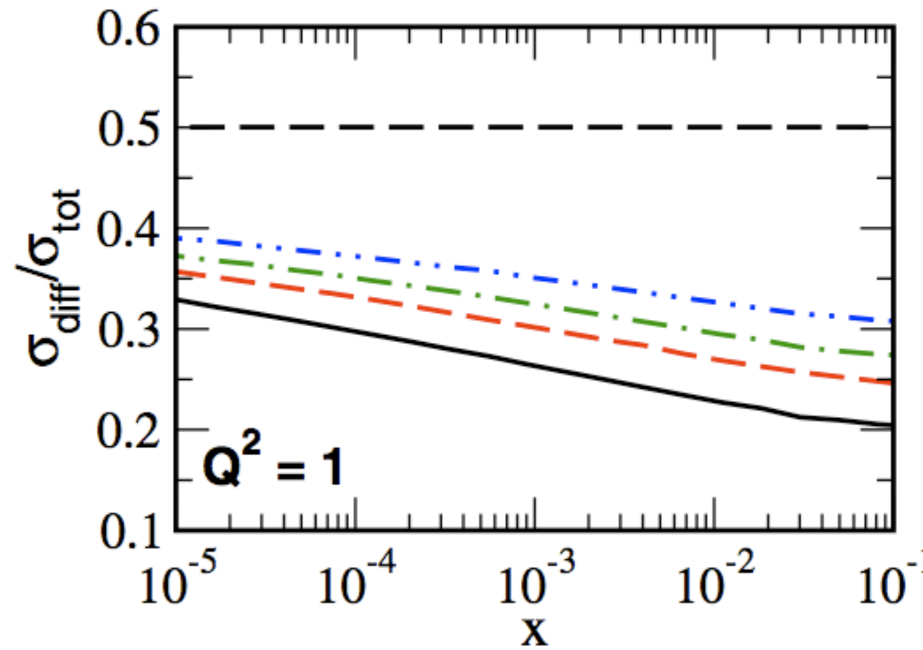

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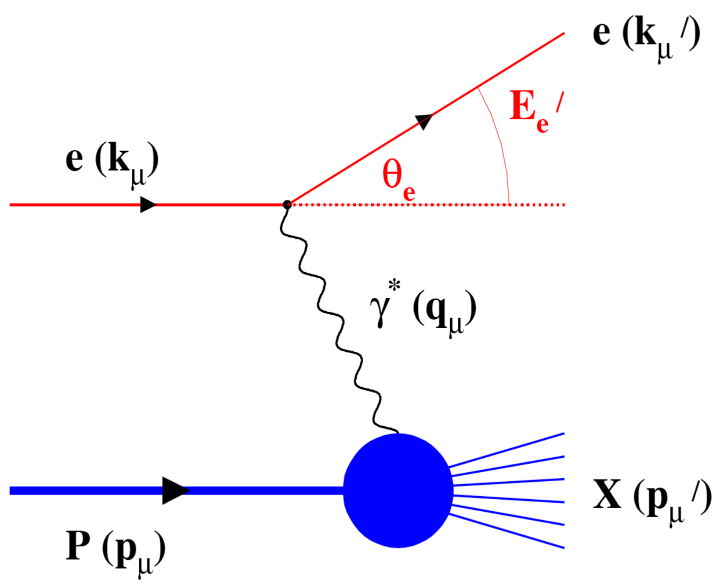

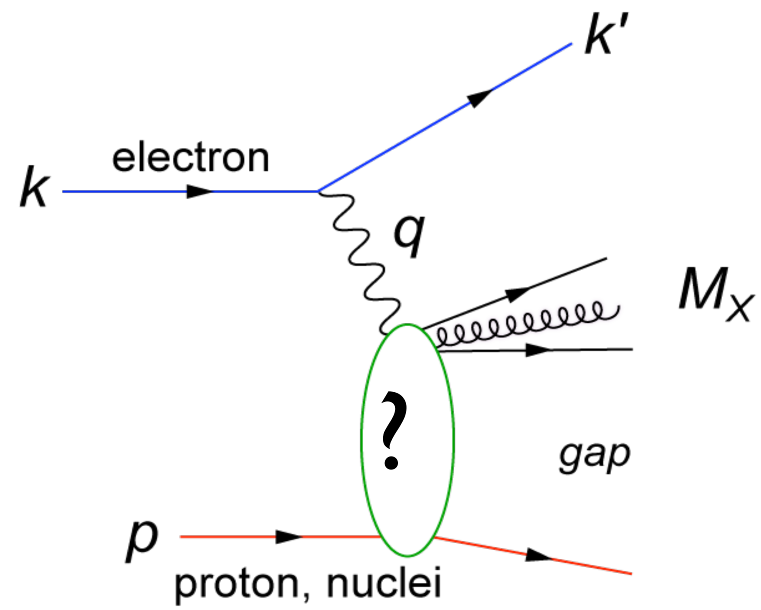

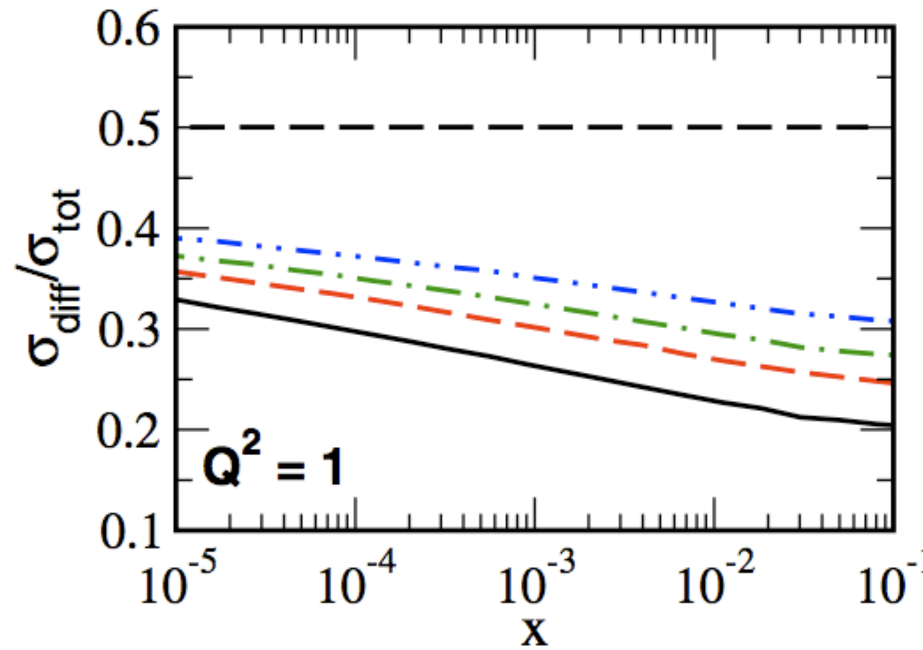

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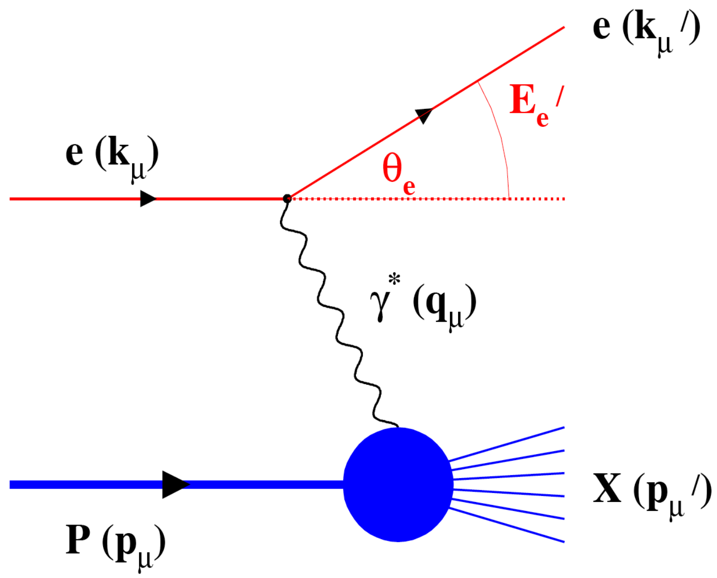

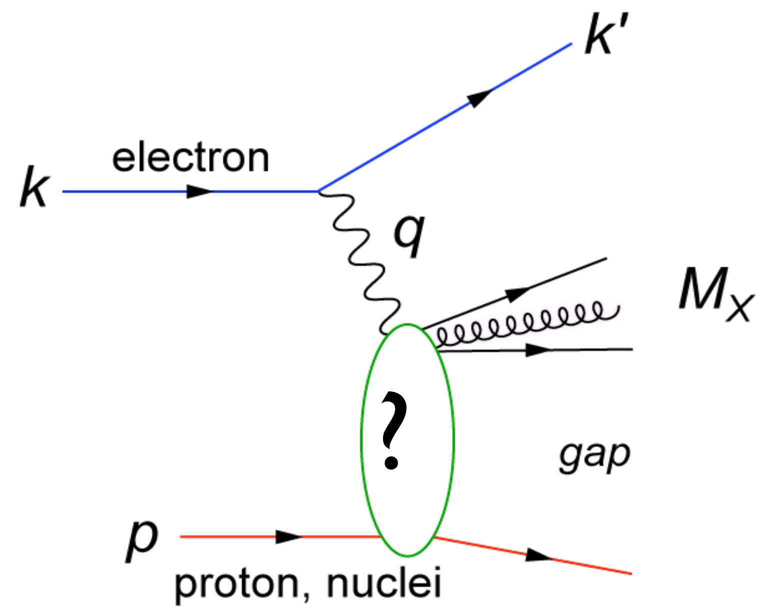

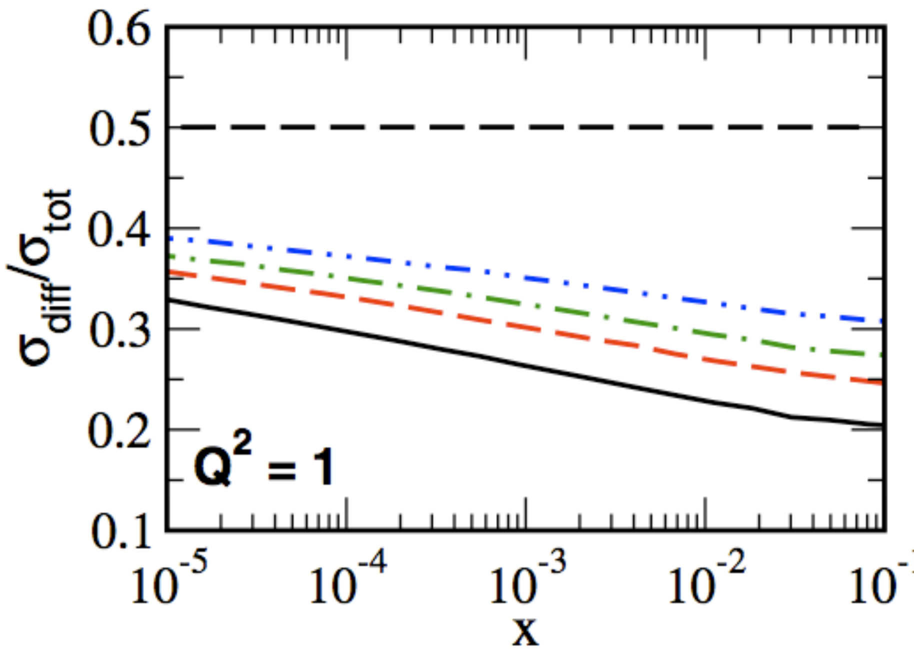

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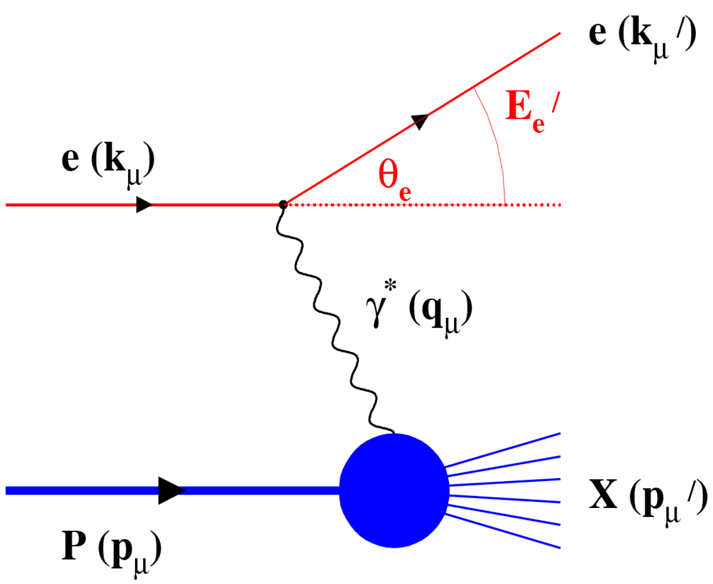

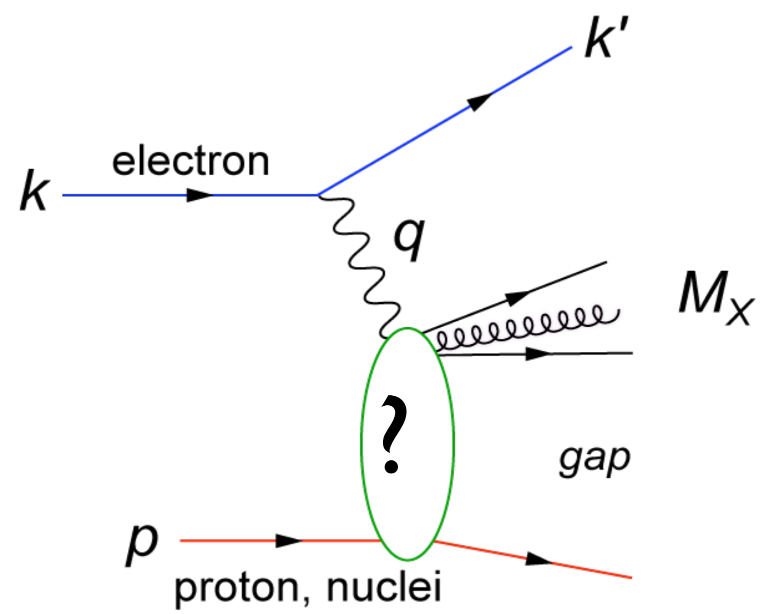

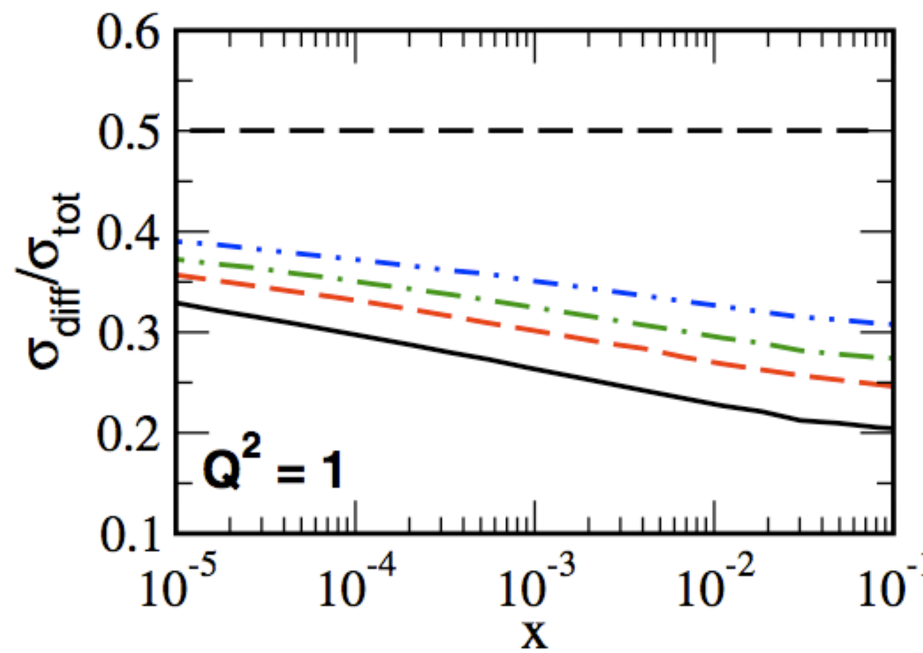

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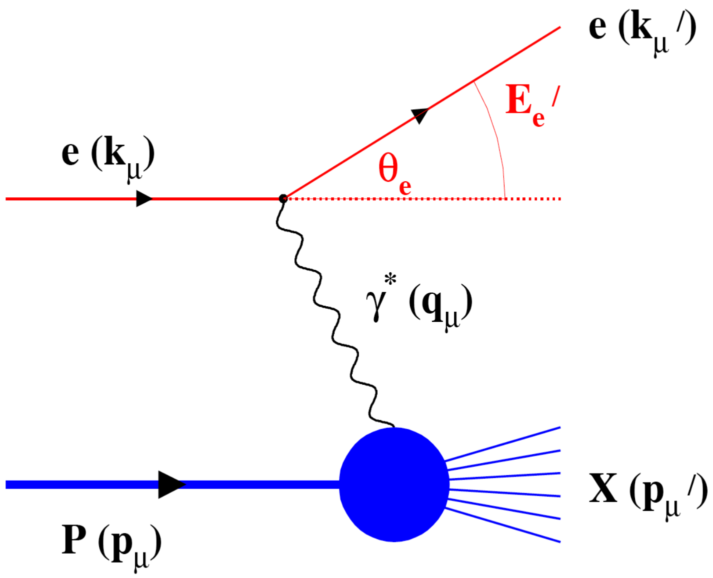

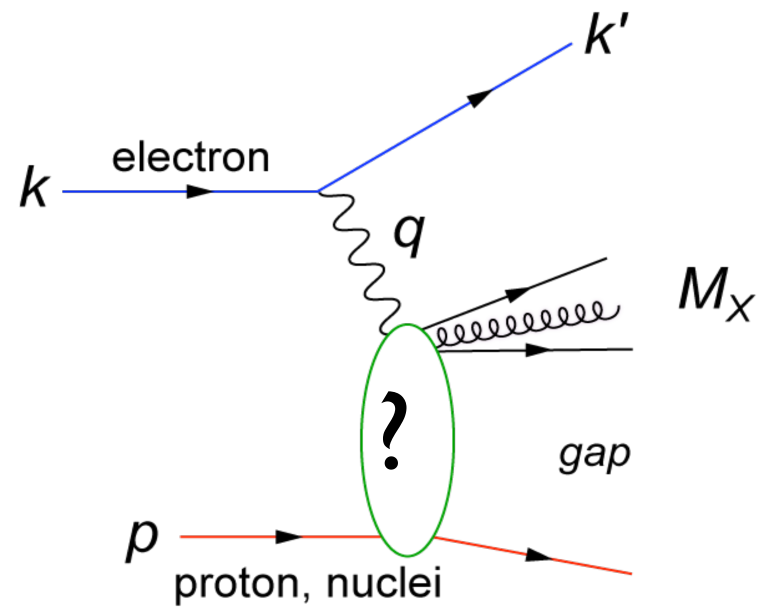

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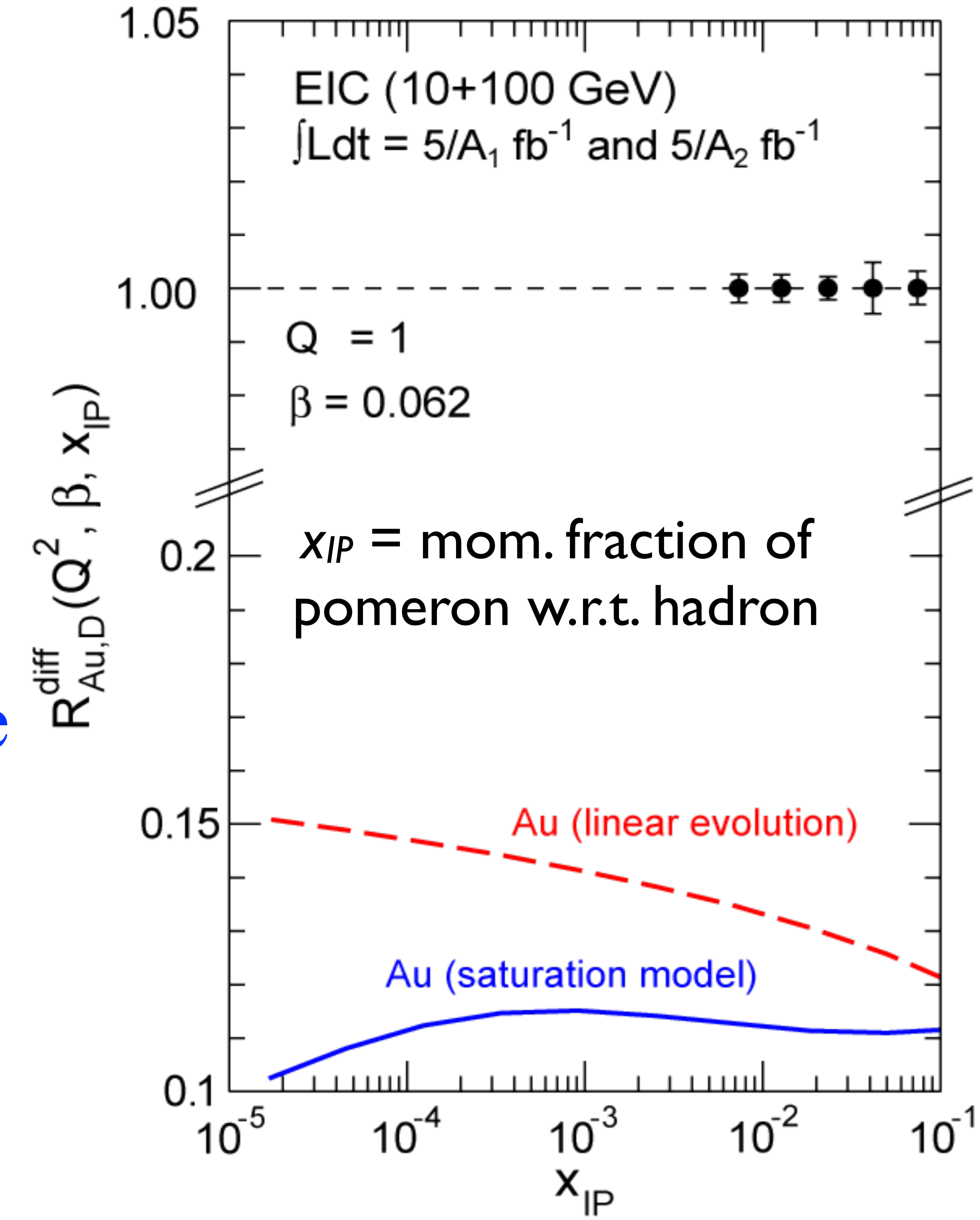

Distinguish between linear evolution and saturation models

Getting a "Feel" for Non-Linear QCD

To assess typical values of $\mathcal{N}$ calculate average:

$$\langle \mathcal{N} \rangle_{2,L} = \frac{\int d^2b\, d^2r\, dz\, [\psi^* \psi]_{2,L}\, \mathcal{N}^2}{\int d^2b\, d^2r\, dz\, [\psi^* \psi]_{2,L}\, \mathcal{N}}$$

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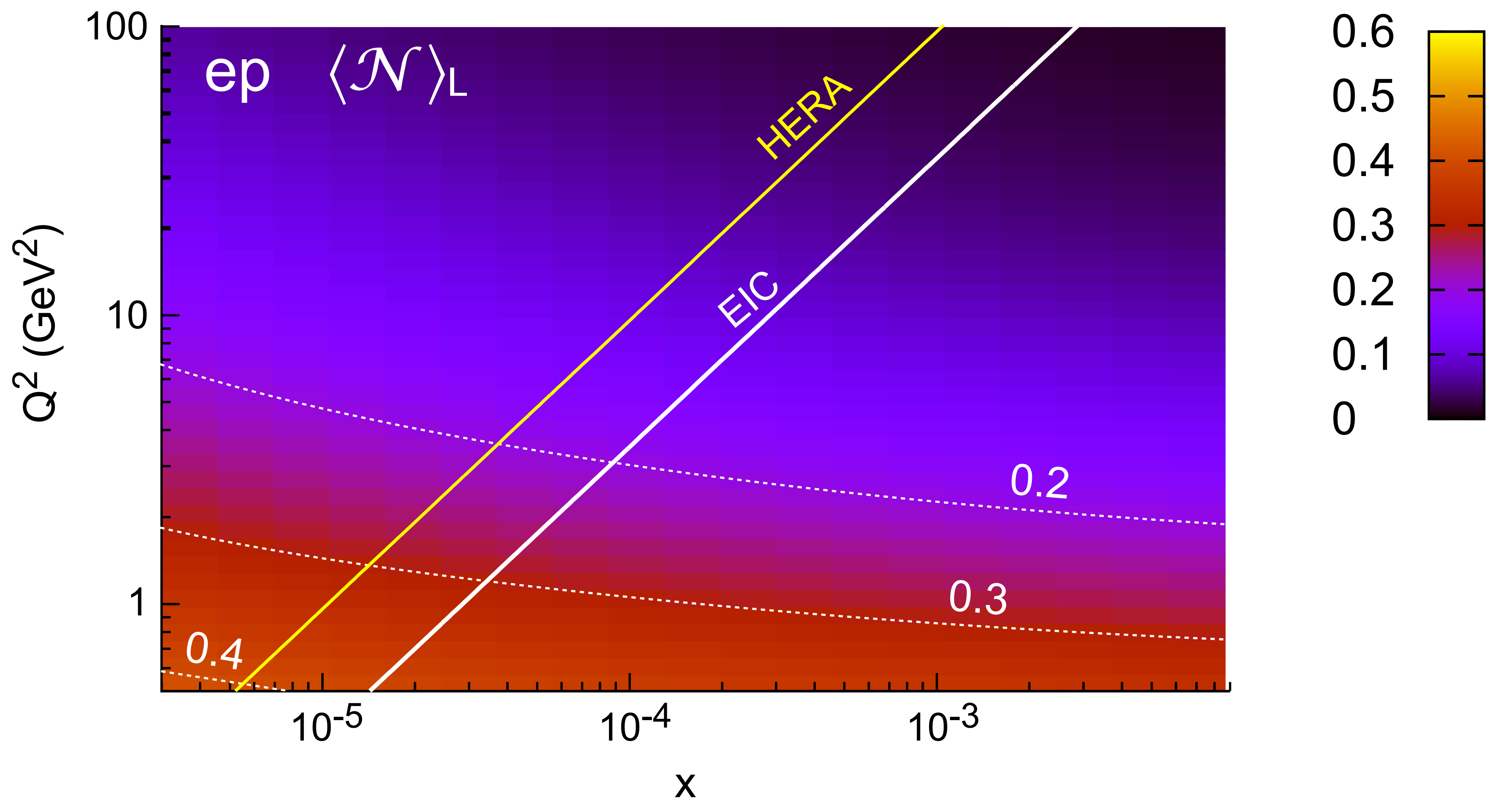

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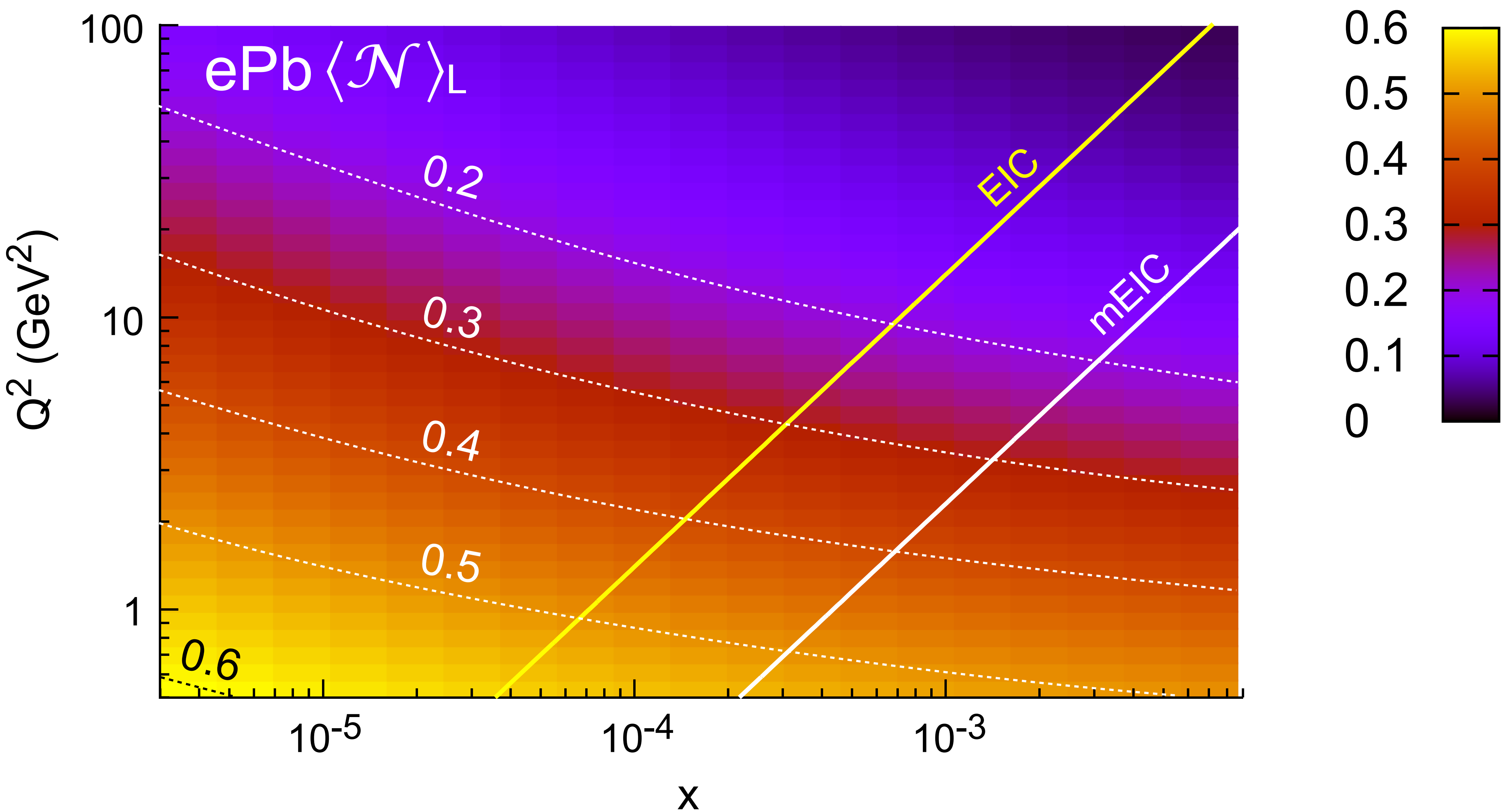

Measuring the gluons: extracting F_L

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y^+} F_L^A(x, Q^2)$$

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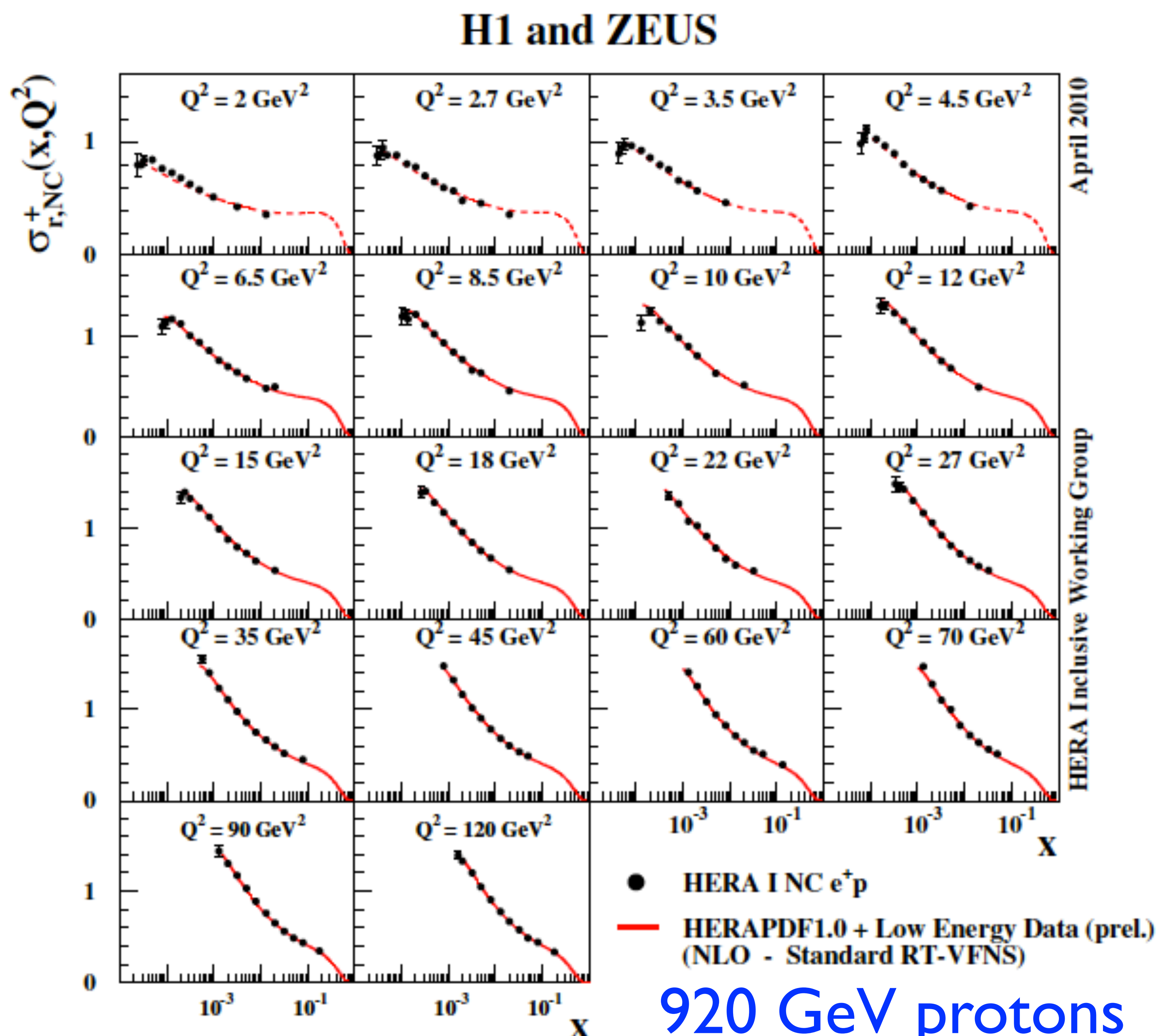

920 GeV protons

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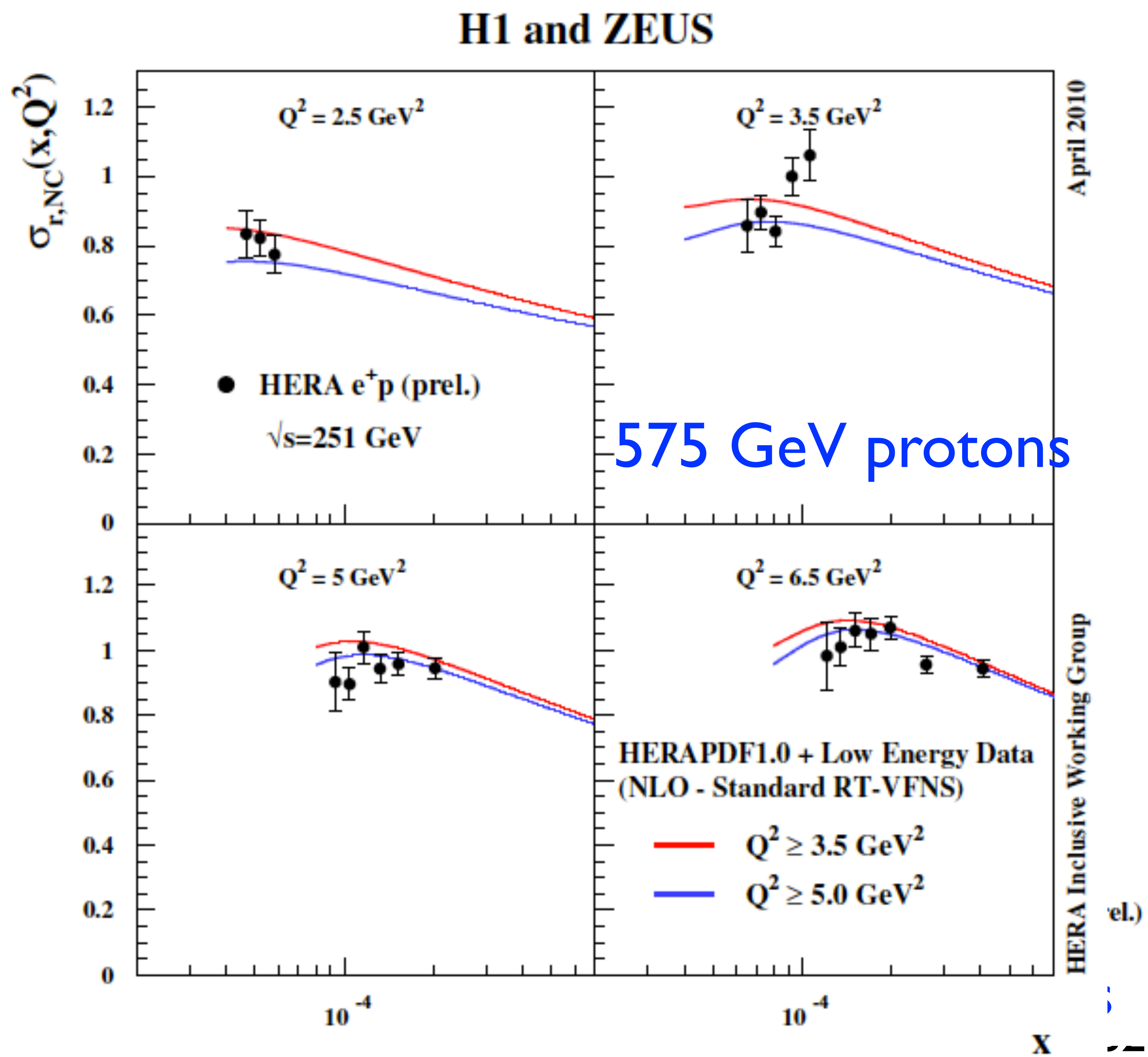

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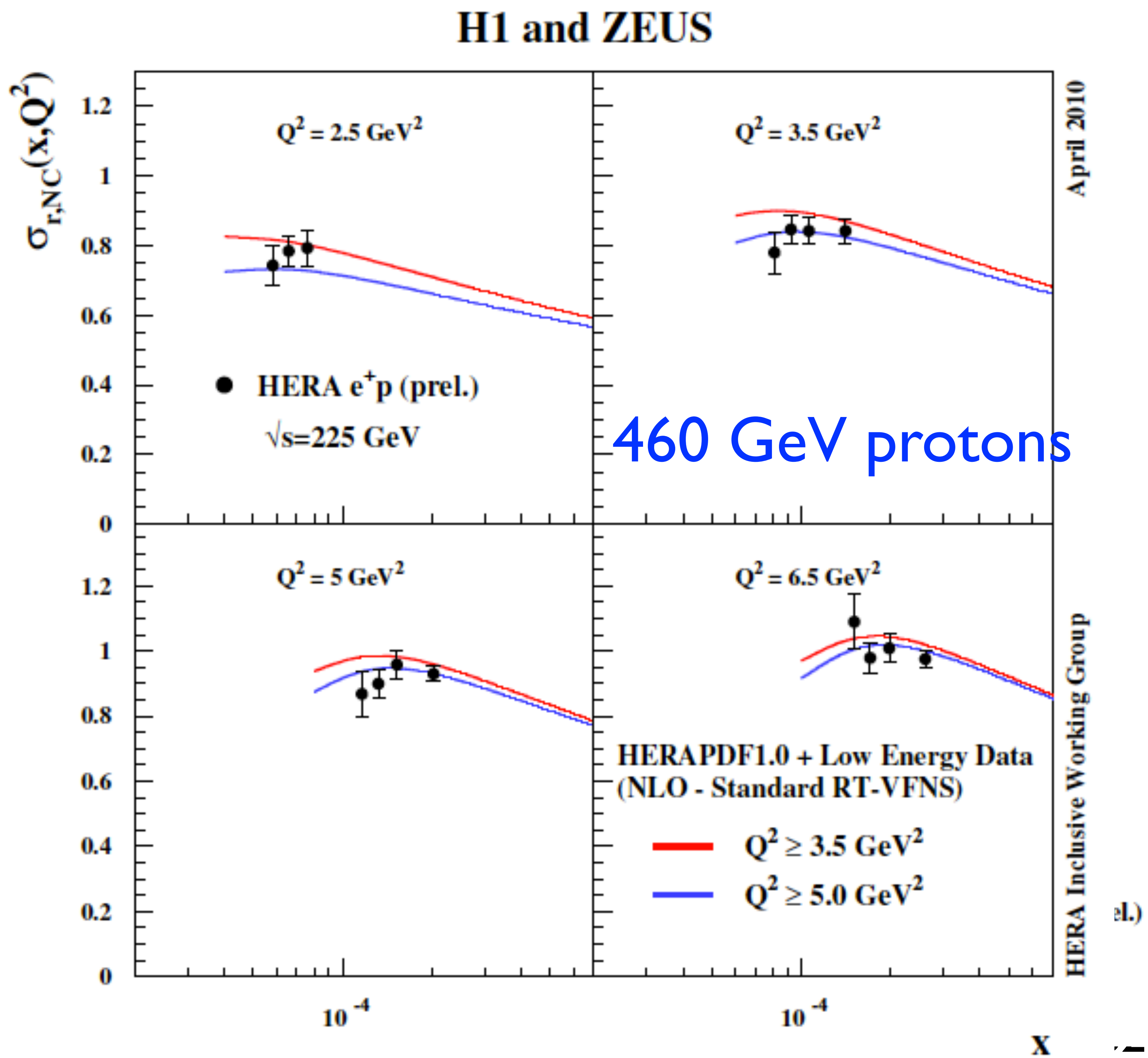

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  - ➡ 2 low-statistics runs
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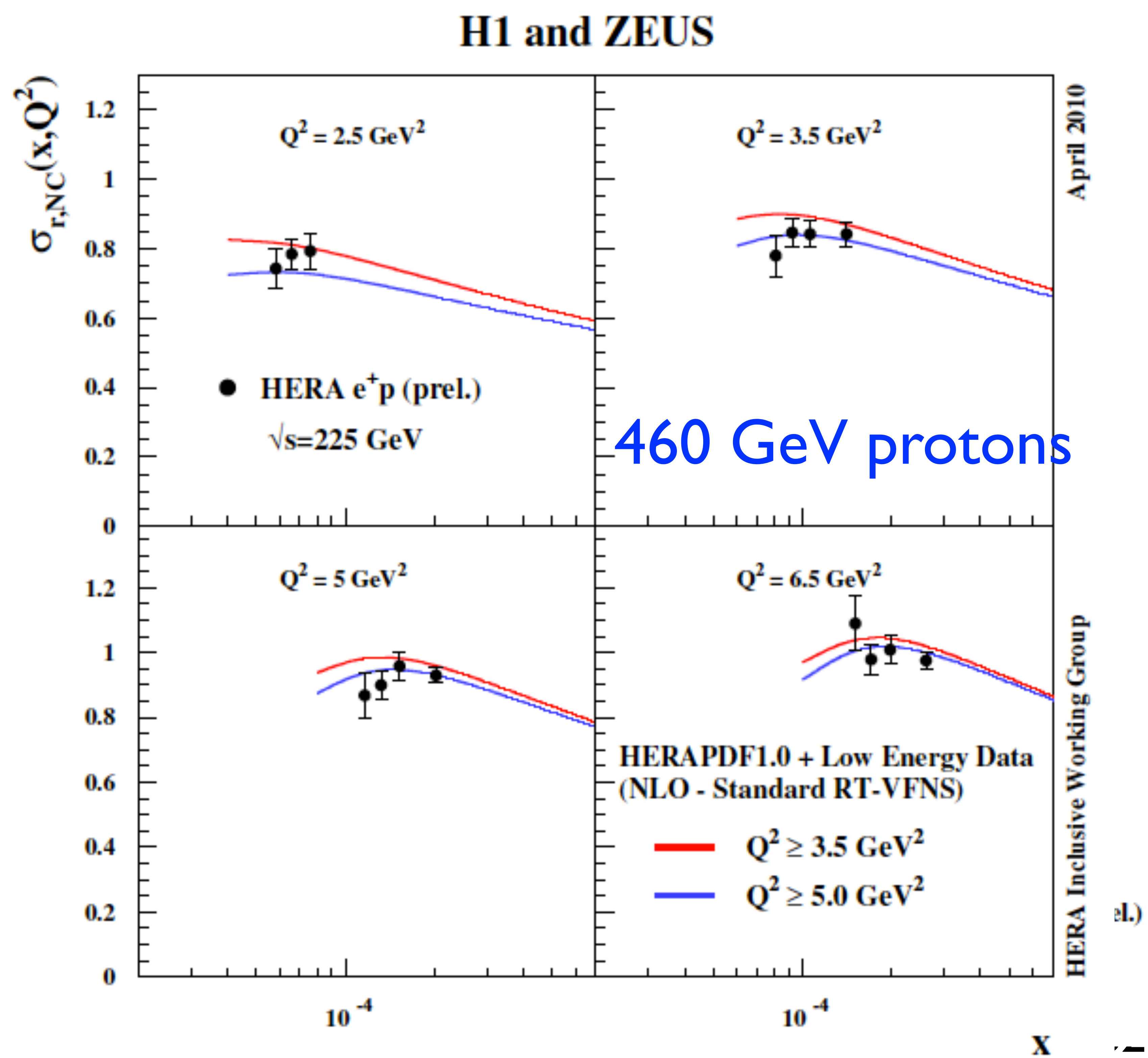

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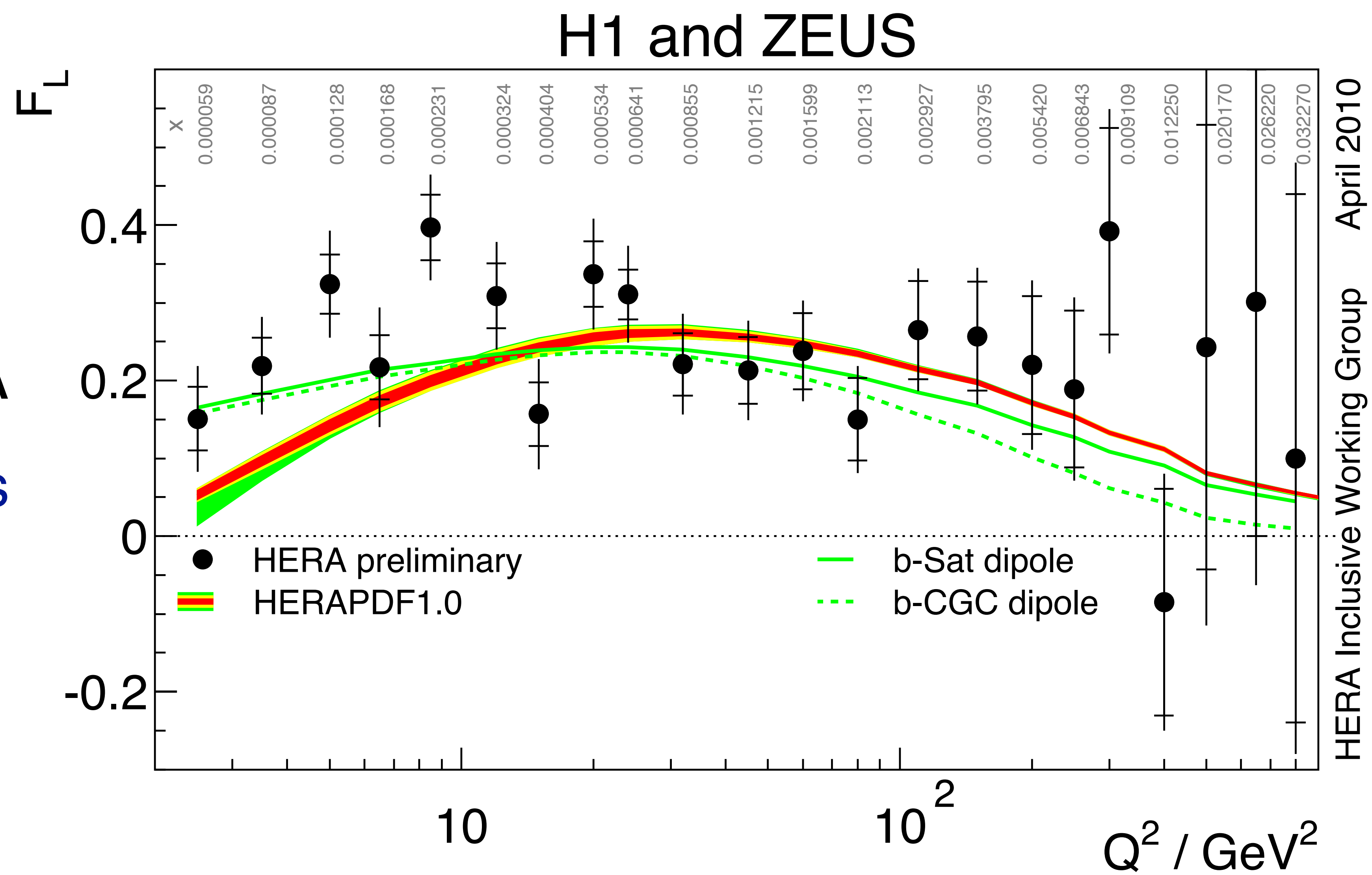
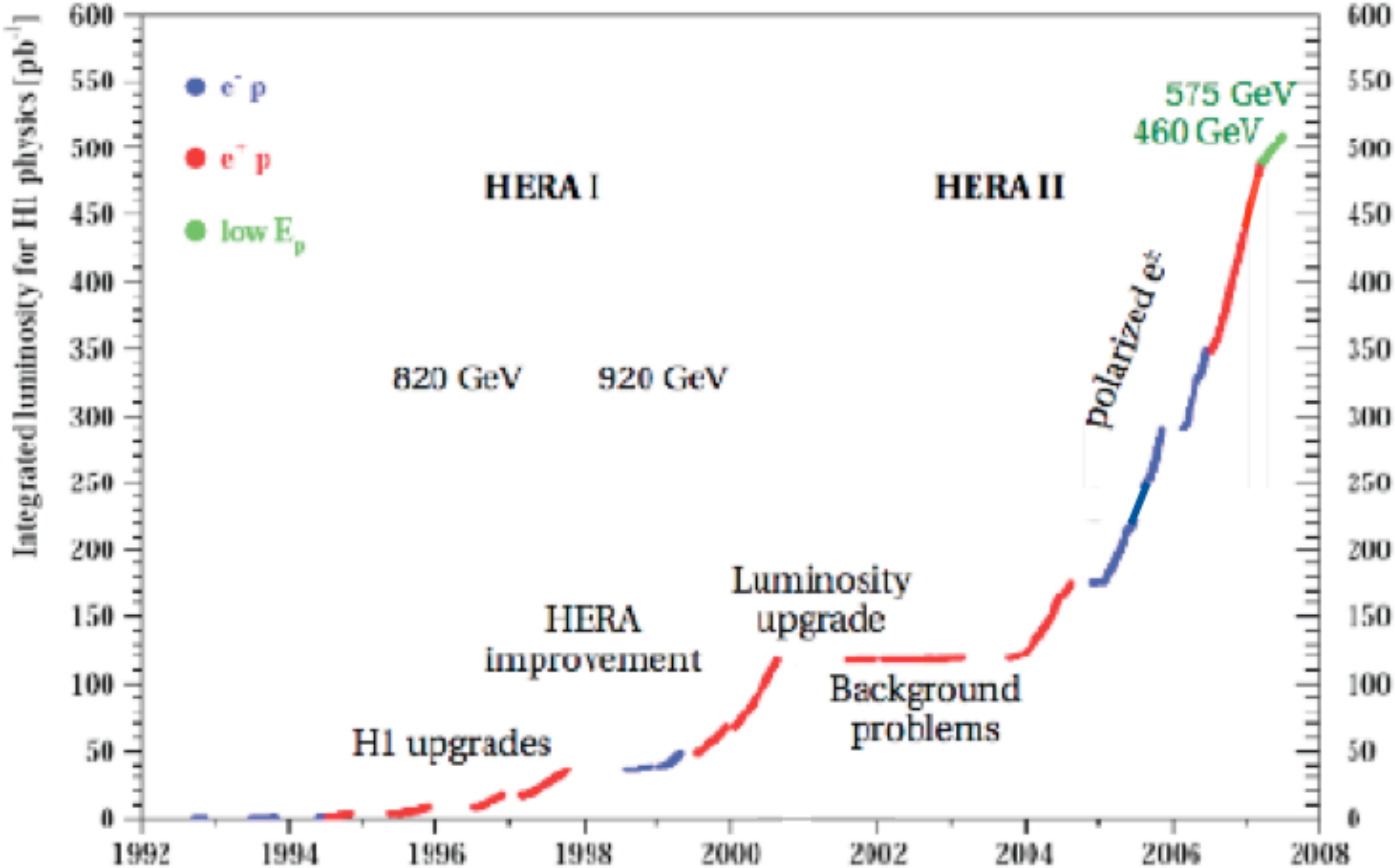
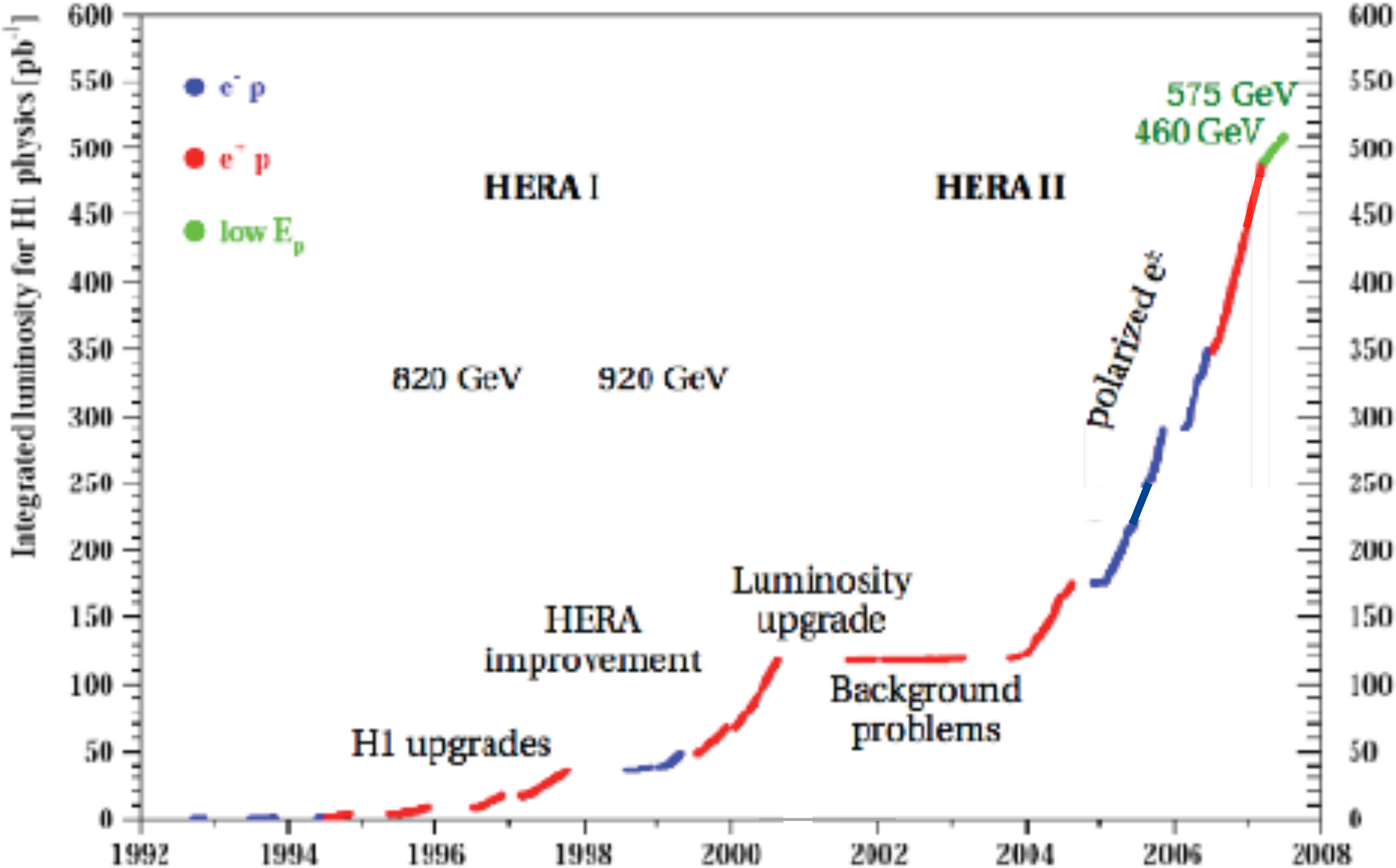
- Note that non-linear fits describe the data better at the lowest x





Integrated luminosity for H1 physics [pb^{-1}]
e^-p
e^+p
low E_p
HERA I
HERA II
820 GeV
920 GeV
575 GeV
460 GeV
Polarized $e^\pm$
H1 upgrades
HERA improvement
Luminosity upgrade
Background problems



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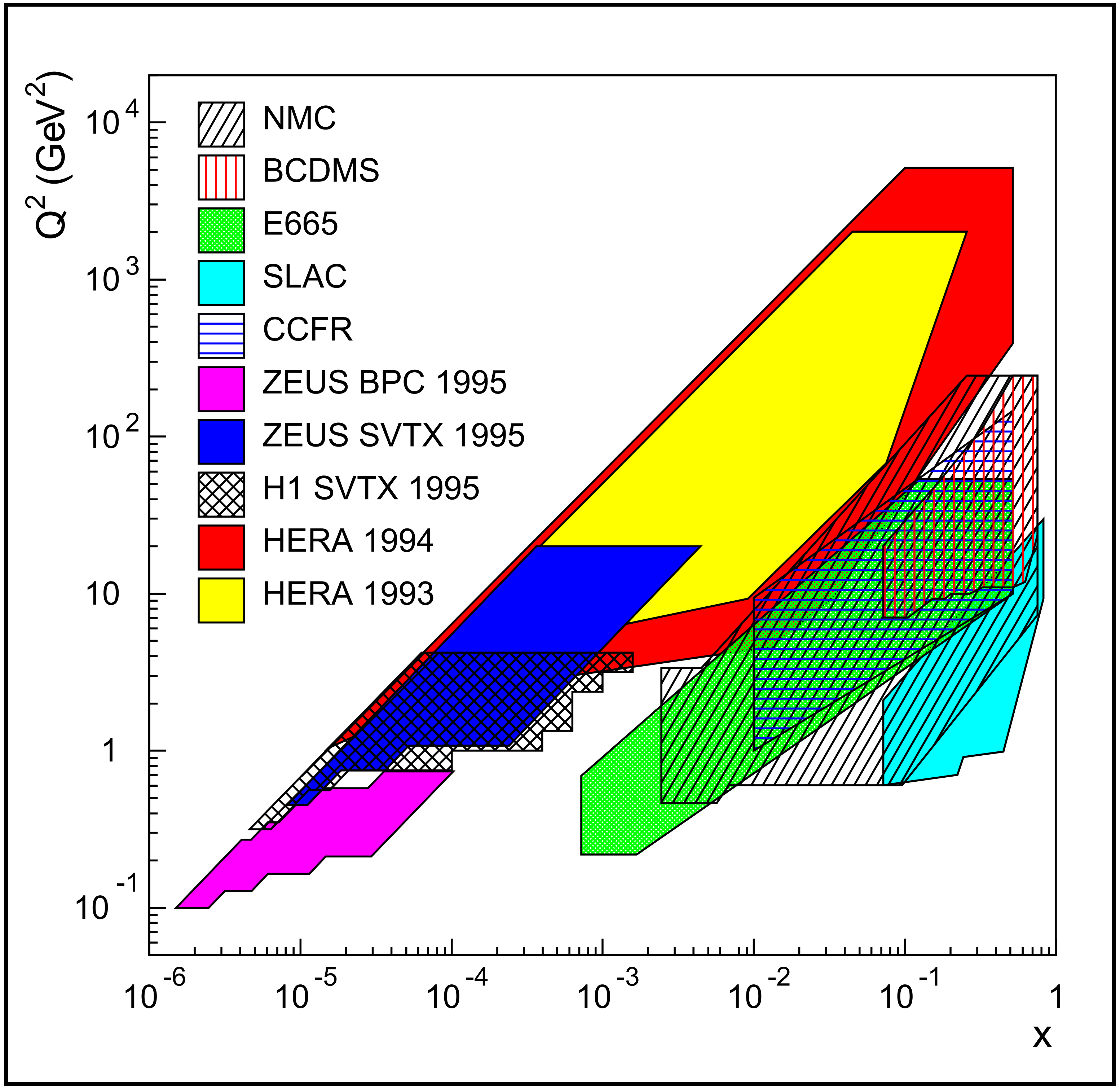
INTRO SLIDES

Requirements for an Electron-Ion Collider



Well mapped in *e+p*

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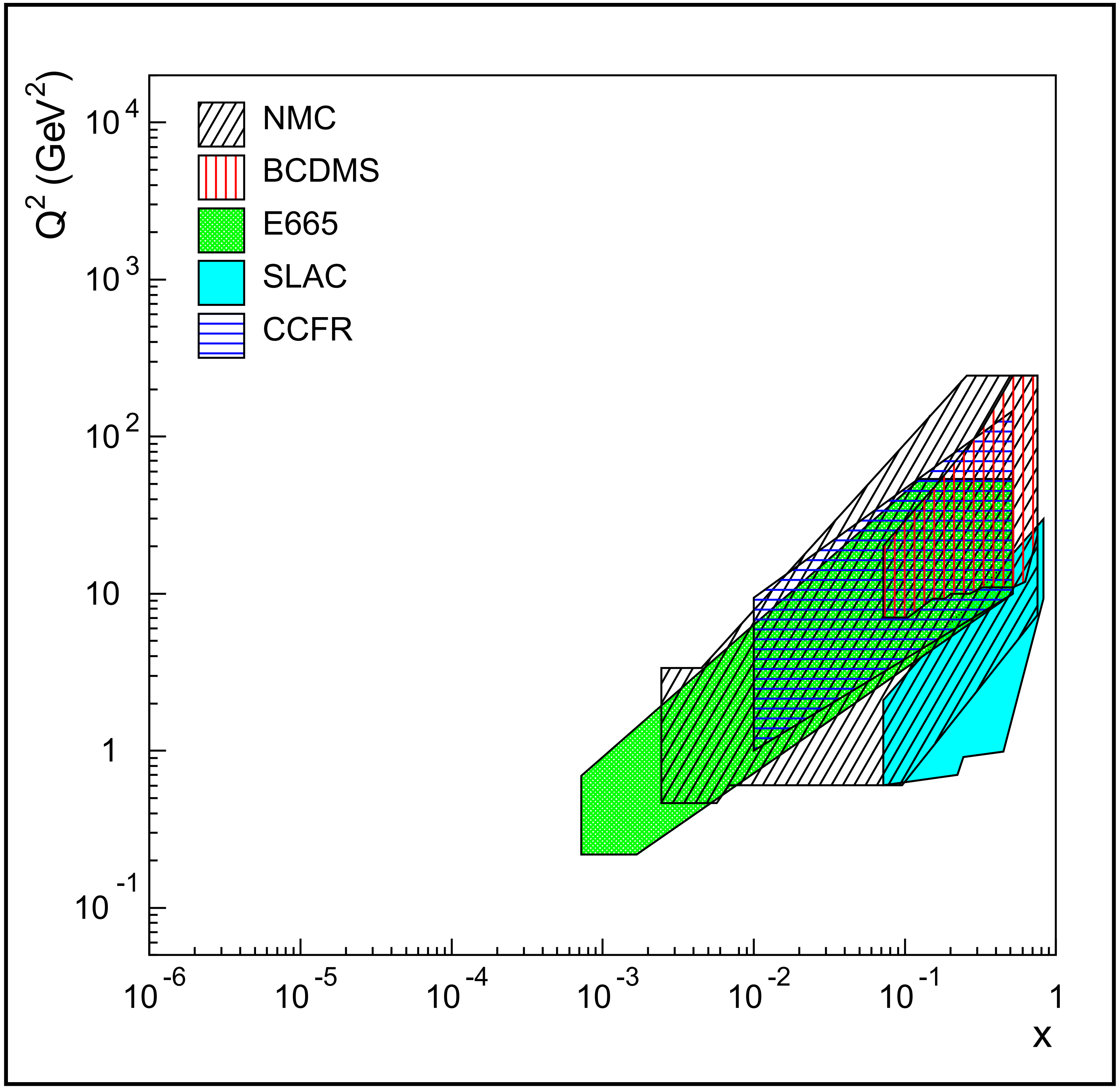

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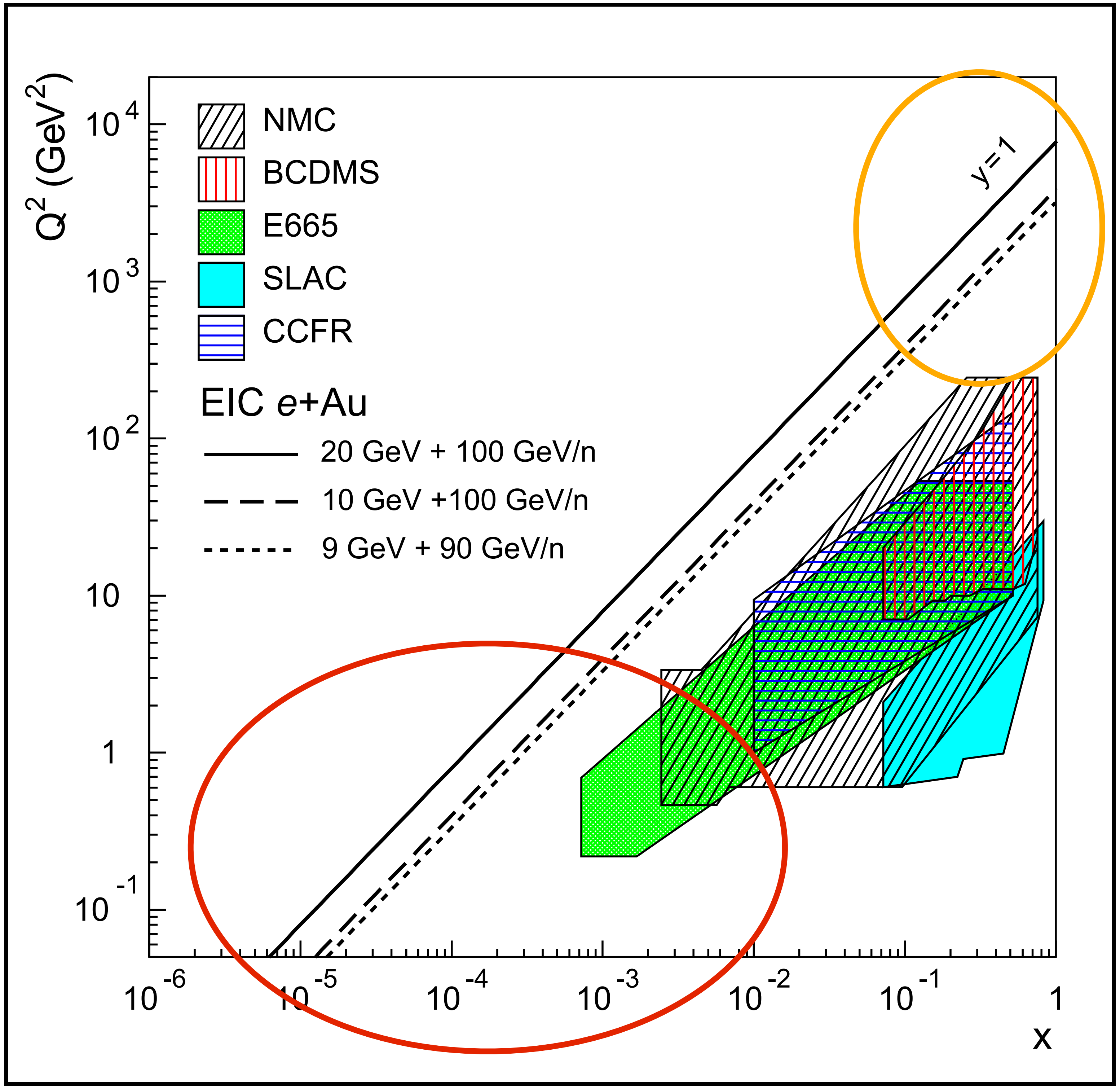

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Electron Ion Collider:

- $\mathcal{L}$(EIC) > 100 × $\mathcal{L}$(HERA)
- Electrons
  - E_e = 3 - 30 GeV
  - polarized
- Hadron Beams
  - E_A = 130 GeV
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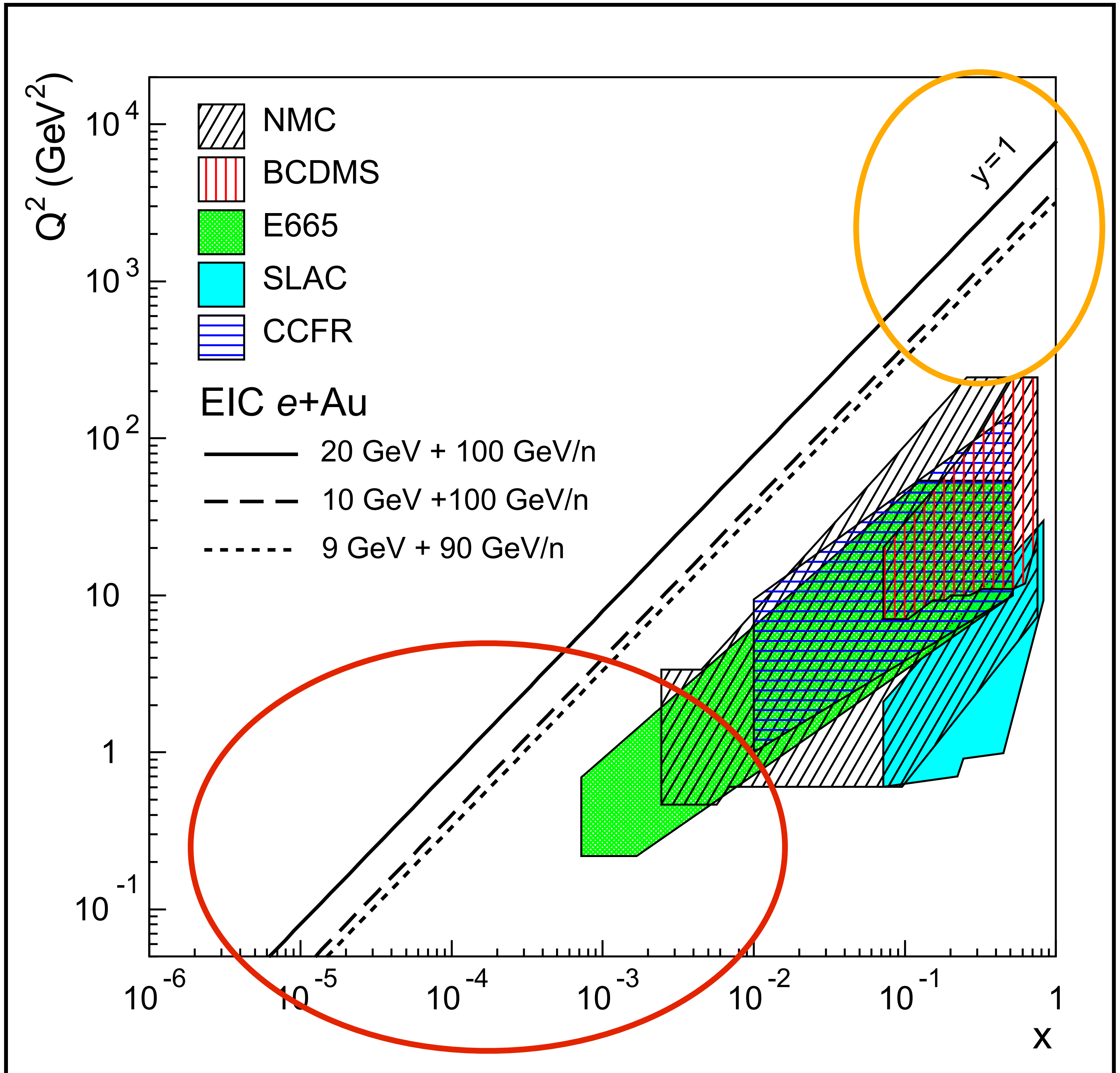

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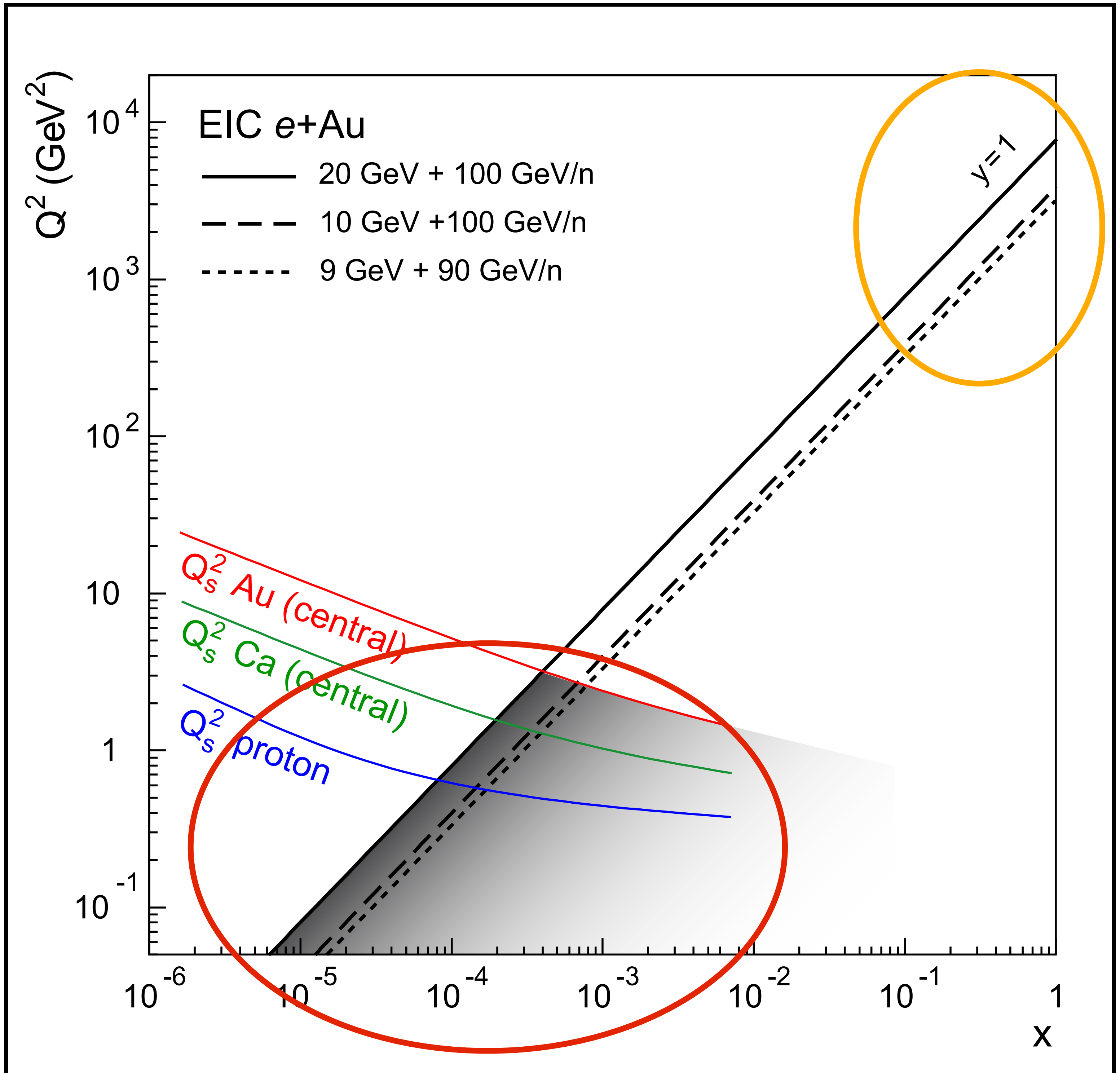

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- **Gluons:**
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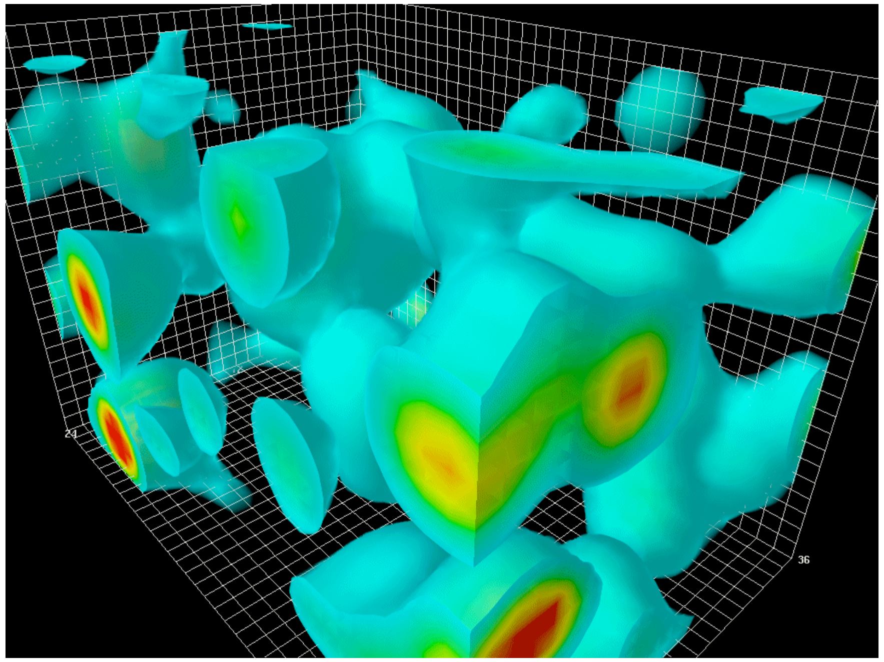
  - ➡ Determine essential features of QCD
    - ‣ Asymptotic freedom from gluon loops
  - ➡ Dominate structure of QCD vacuum



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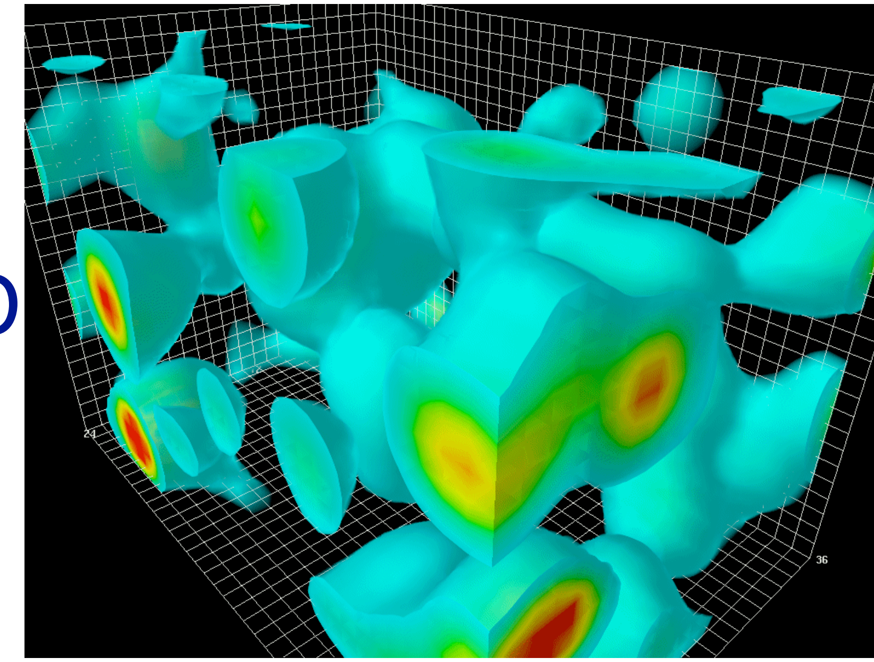
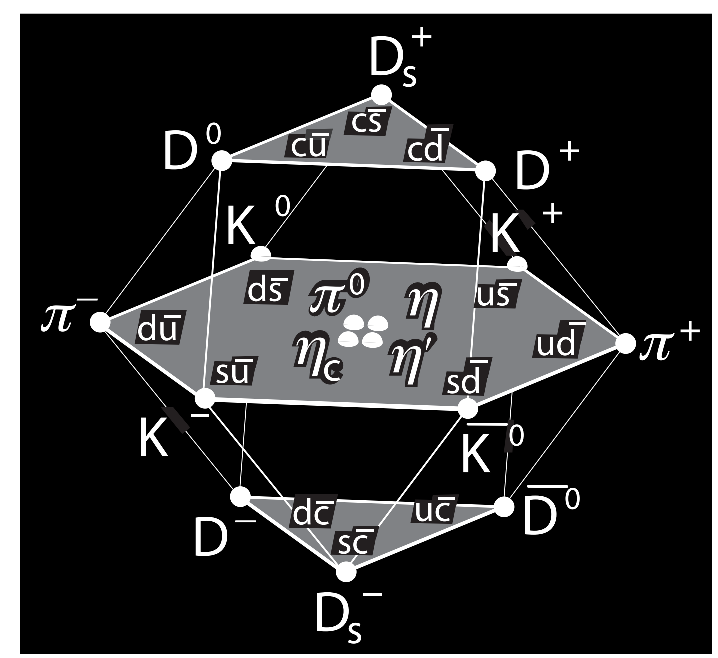


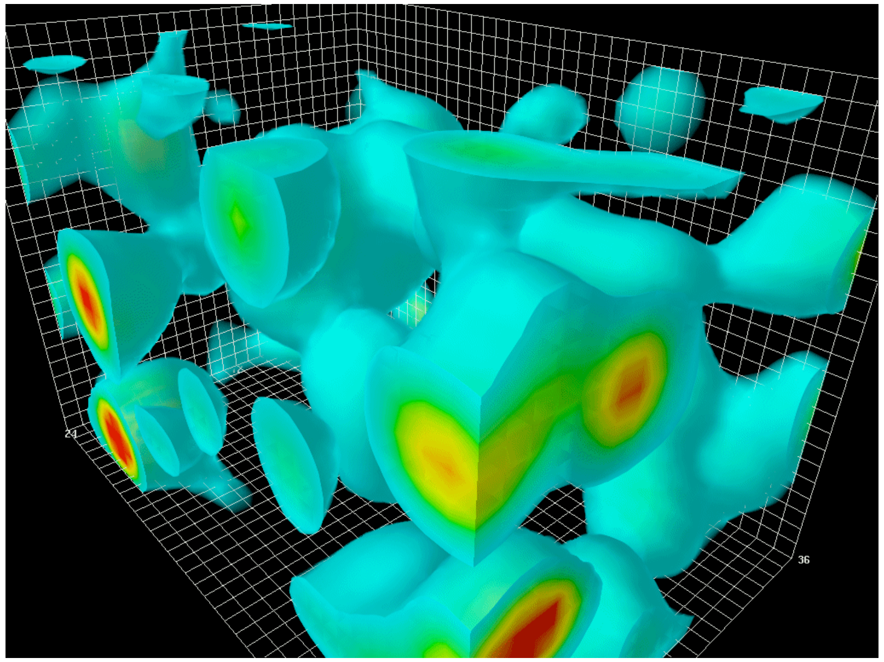
Action (~energy) density fluctuations of gluon-fields in QCD vacuum (2.4 ×2.4× 3.6 fm) (Derek Leinweber)

- **Hard to “see” glue in the low-energy world**
  - ➡ Gluon degrees of freedom “missing” in hadronic spectrum
    - ‣ Constituent Quark Picture?
  - ➡ From DIS:
    - Drive the structure of baryonic matter already at medium-x
  - ★ Crucial players at RHIC and LHC



What do we know about gluons?

- **Gluons:**
  - Mediators of the strong interaction
  - Determine essential features of QCD
    - Asymptotic freedom from gluon loops
  - Dominate structure of QCD vacuum



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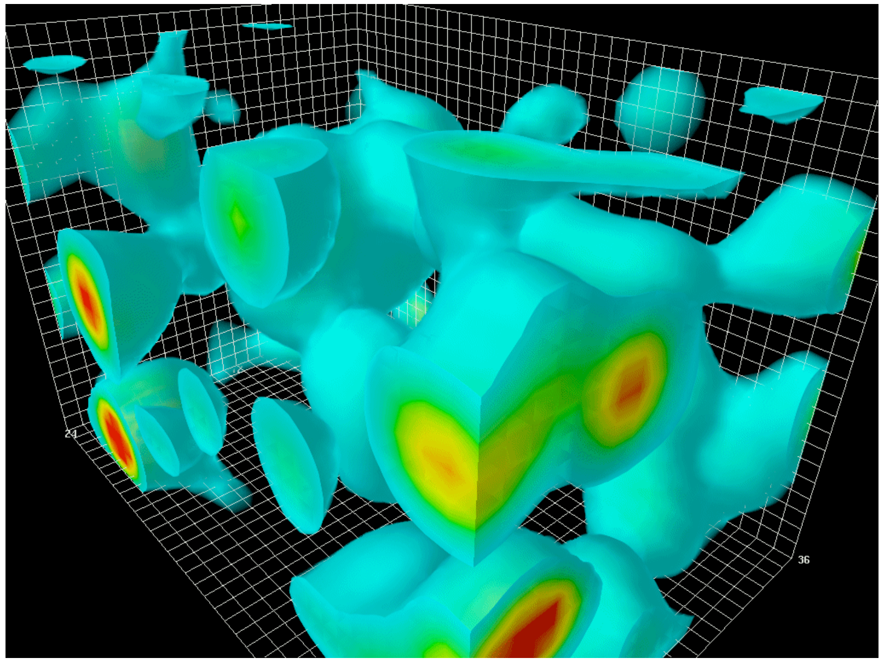

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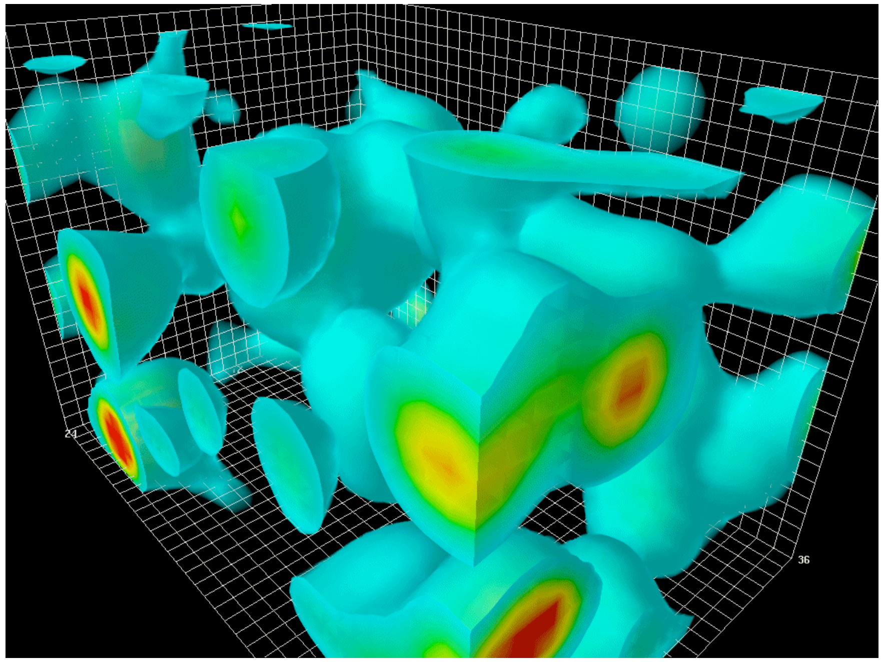

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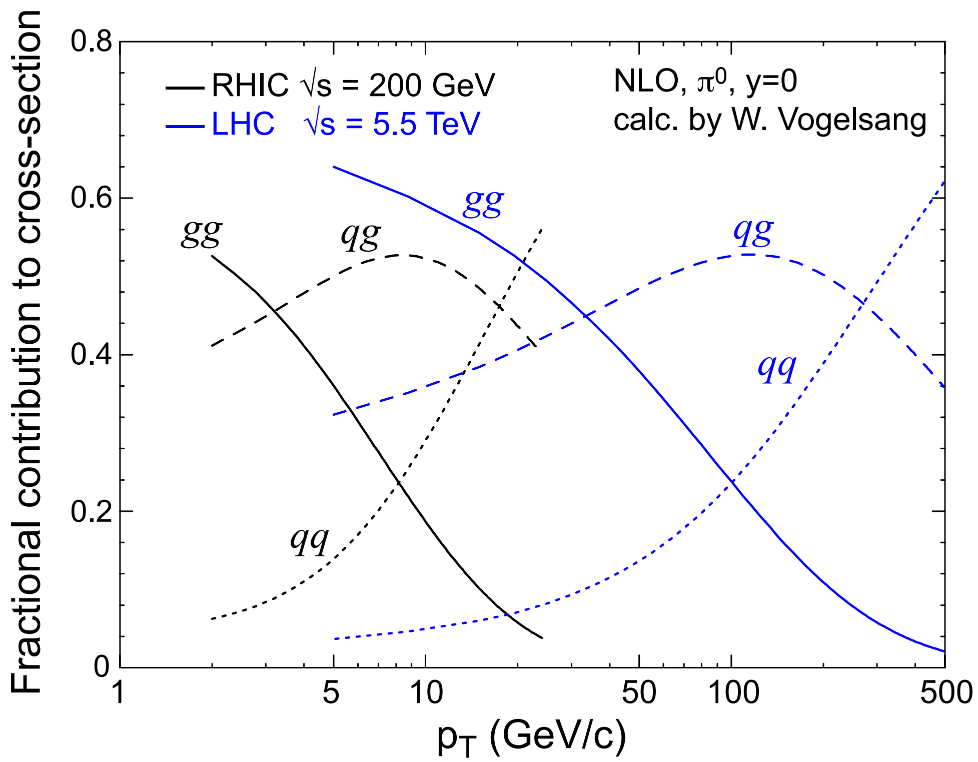
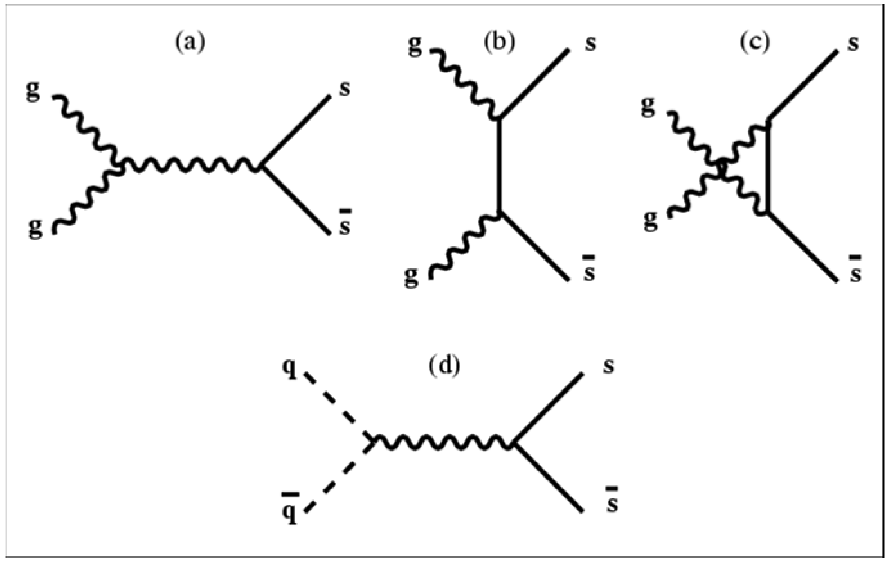
How do we get to the answers?

The role of gluons in hadronic collisions

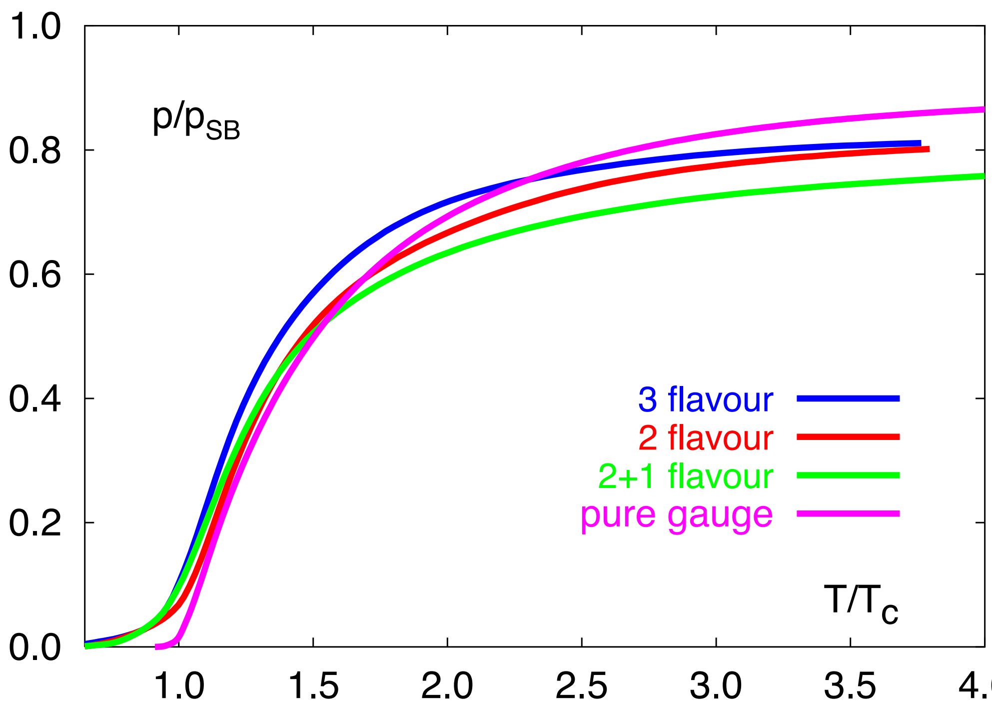
Jets (π^0 production)



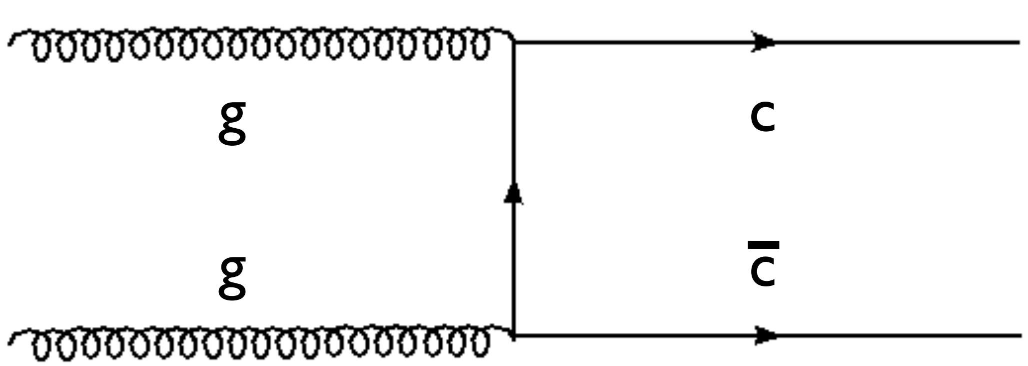
Strangeness Production



Lattice Gauge Theory

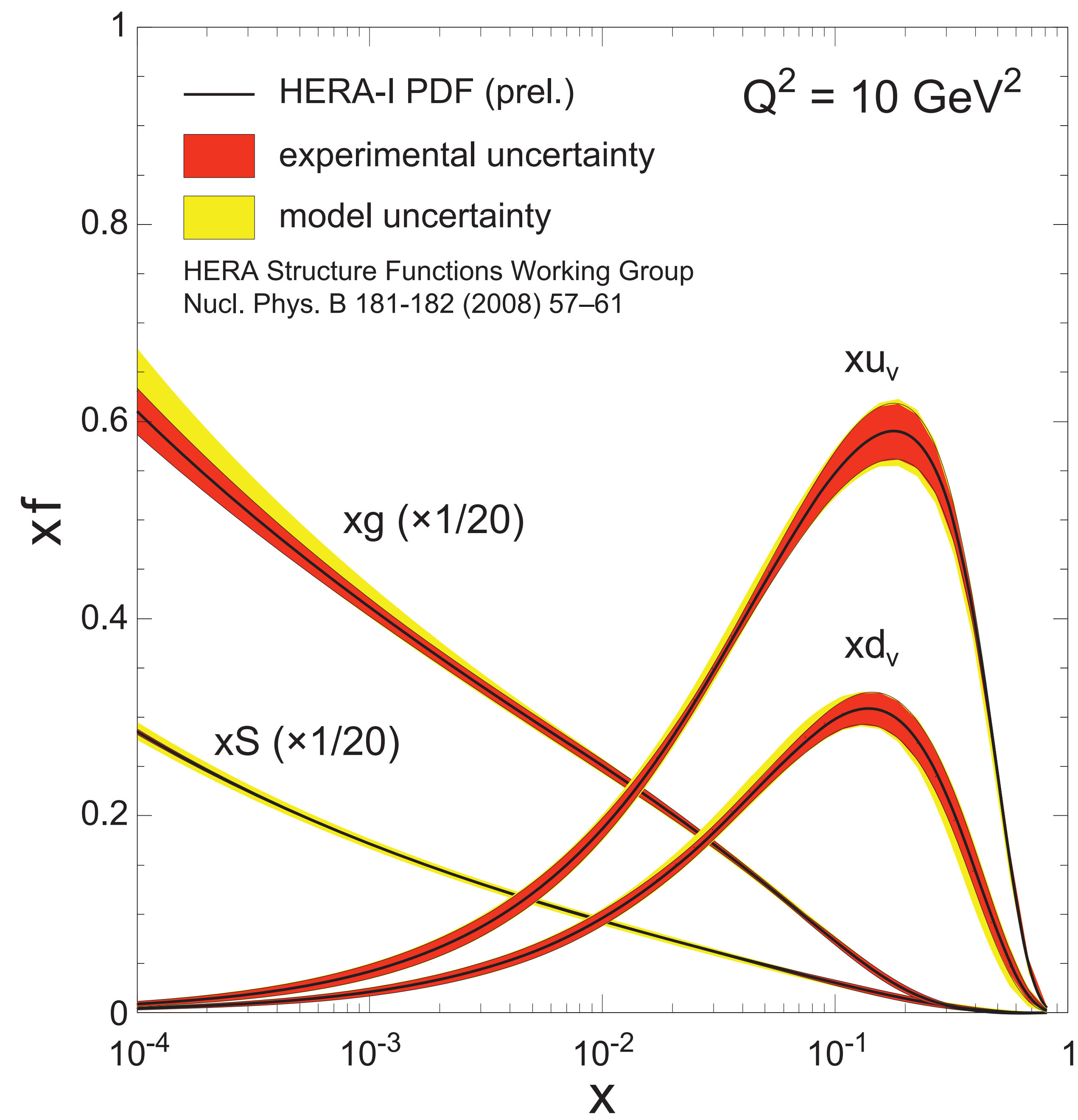


Heavy Flavour Production

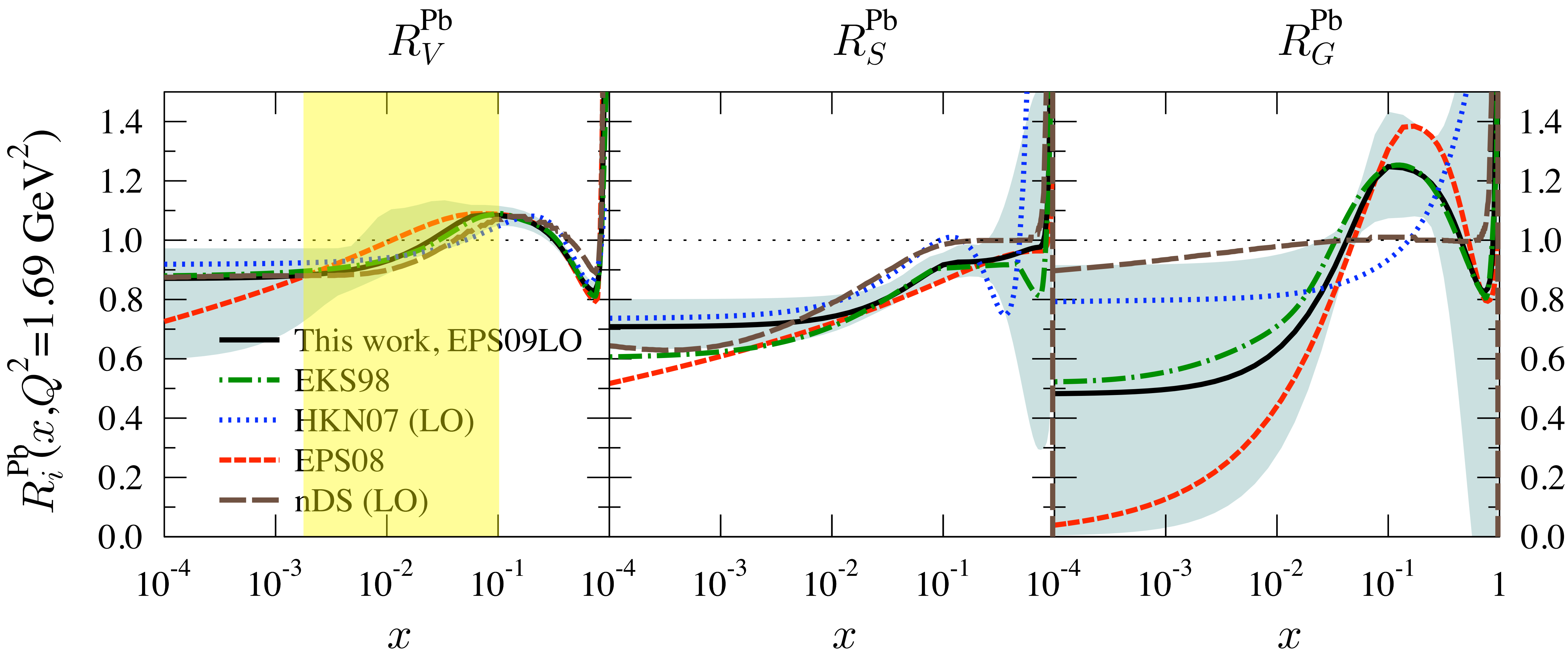


How well do we know gluon distributions in nucleons?

- HERA: e+p collisions:
  - ➡ 27.6 GeV (e^-) on
  - ➡ 920 GeV p
- Wealth of data allows a high-statistics extraction of valence quark, sea quark and gluon densities as a function of x_{Bj}
  - ➡ Gluons and sea quarks dominate over valence quarks at smaller values of x_{Bj}
- Small experimental and model uncertainties



What about gluons in nuclei?



The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

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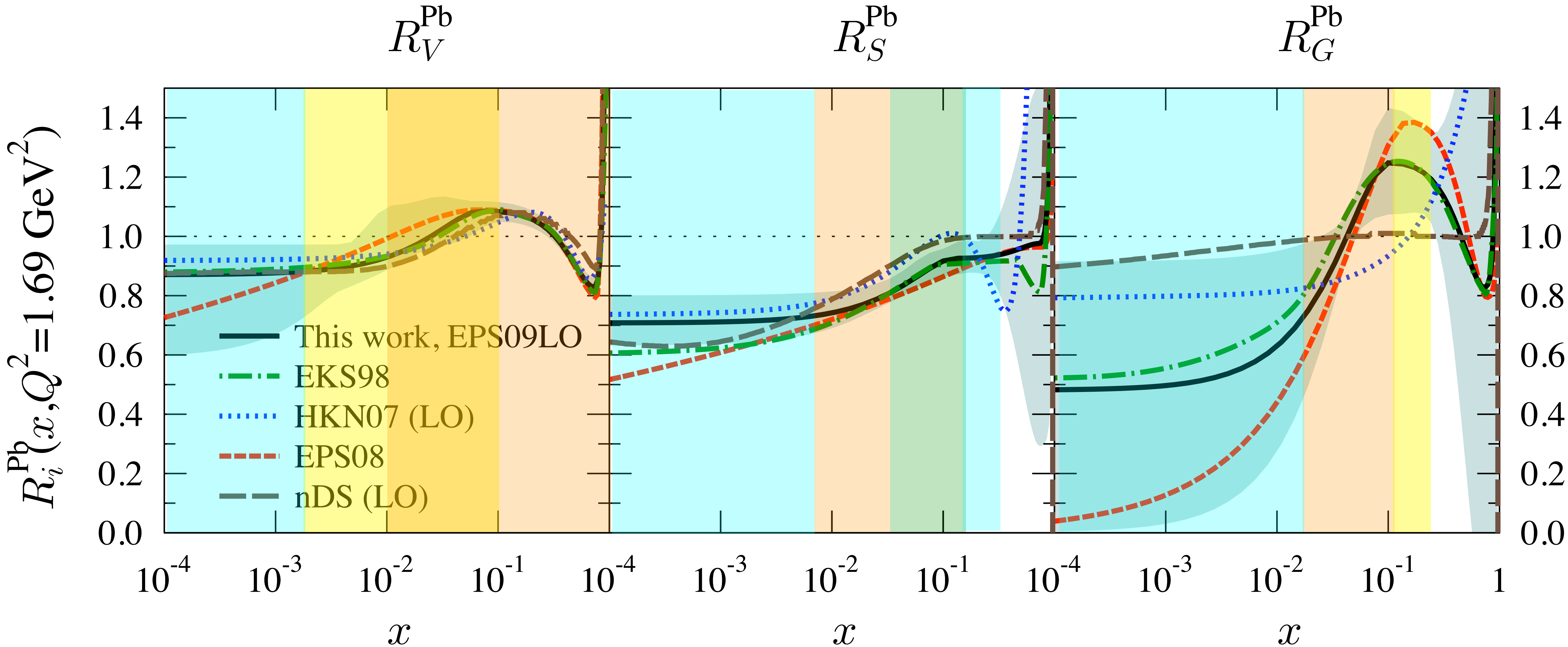

Constrained by DIS

Constrained by DY

Constrained by sum rules

Assumptions

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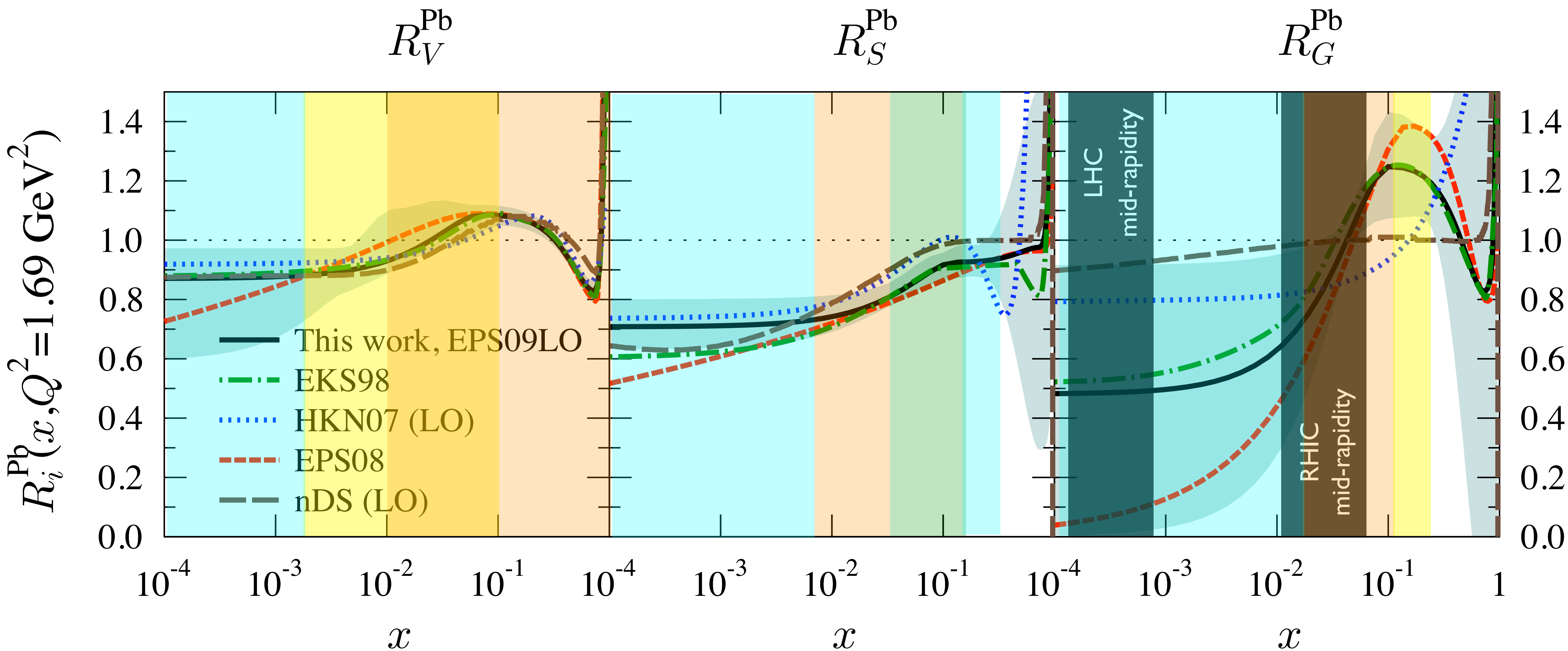

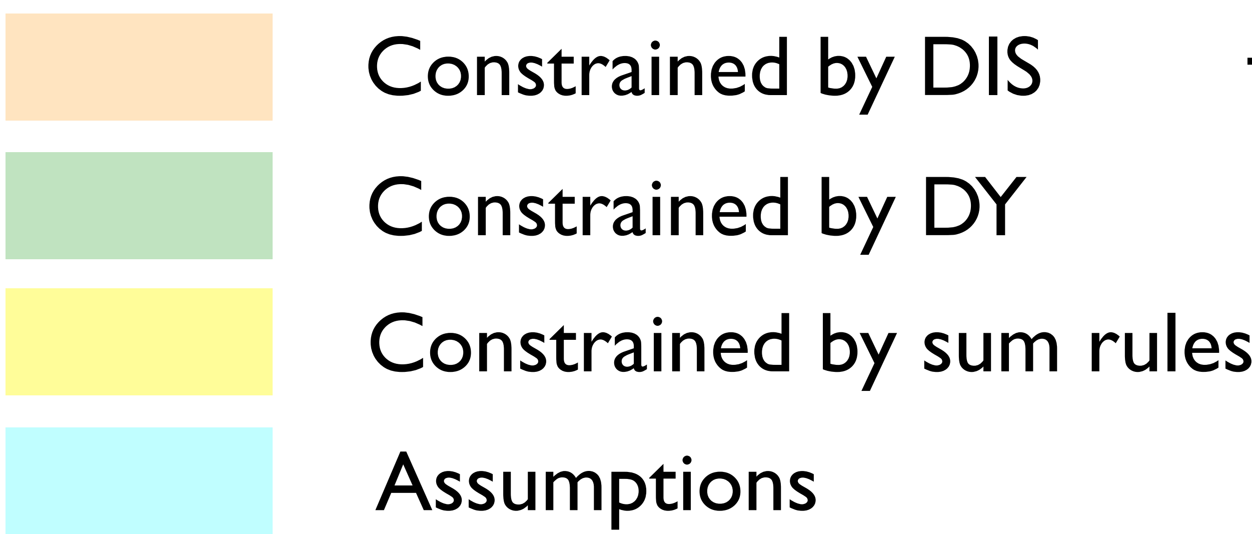

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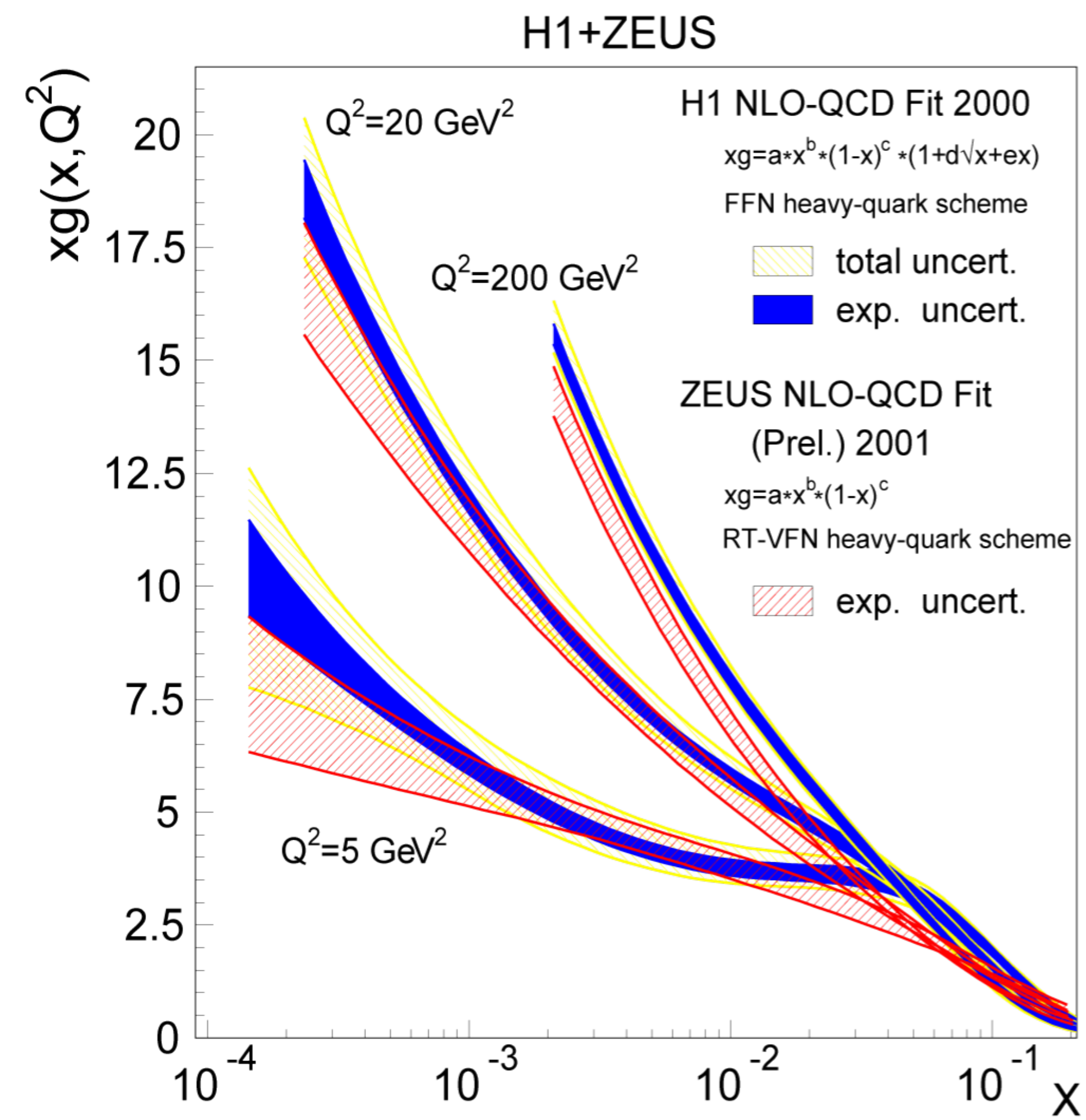
Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

The problem with our current understanding

- Using the Linear DGLAP evolution model:
  - Linear evolution has a built-in high-energy "catastrophe"
  - *xG* has rapid rise with decreasing *x* (and increasing Q^2) $\Rightarrow$ violation of Froissart unitarity bound

$$\sigma_{tot} = \frac{\pi}{m_\pi^2}(\ln\ s)^2$$

    - Must have saturation to tame the growth



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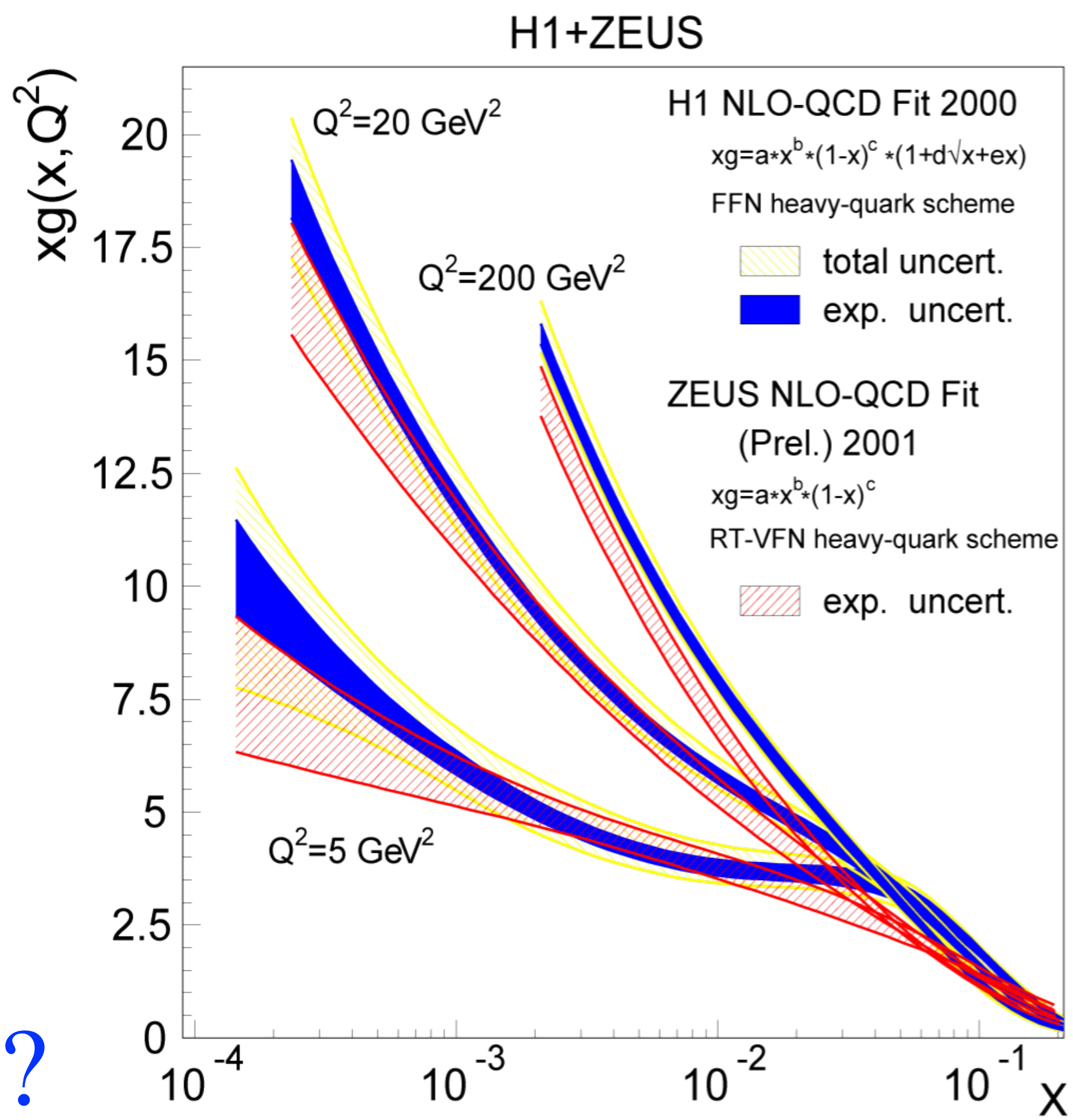
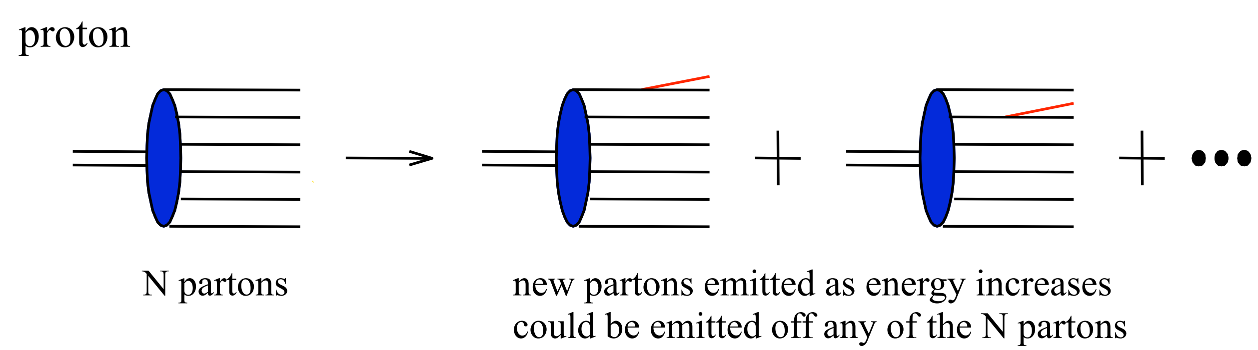
What’s the underlying dynamics?



Non-linear QCD - Saturation



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  - linear
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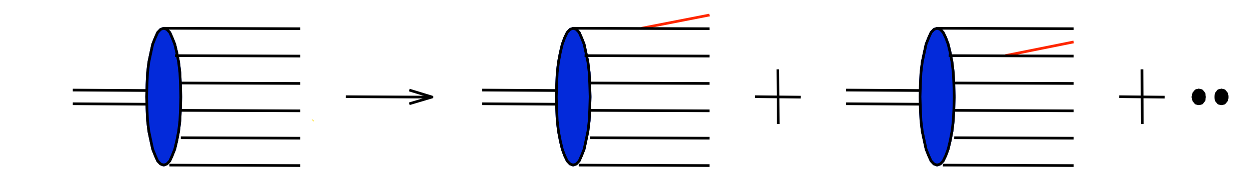
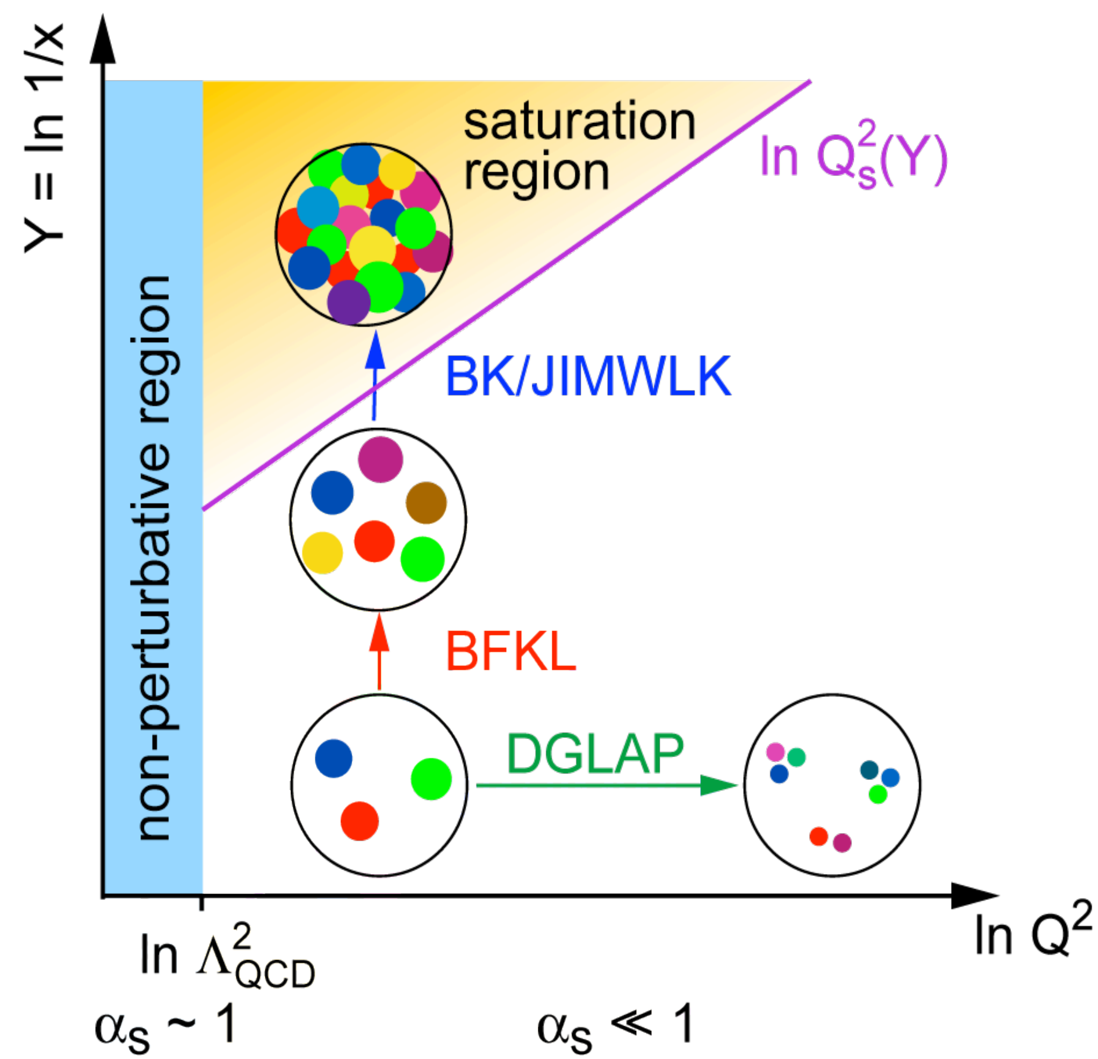
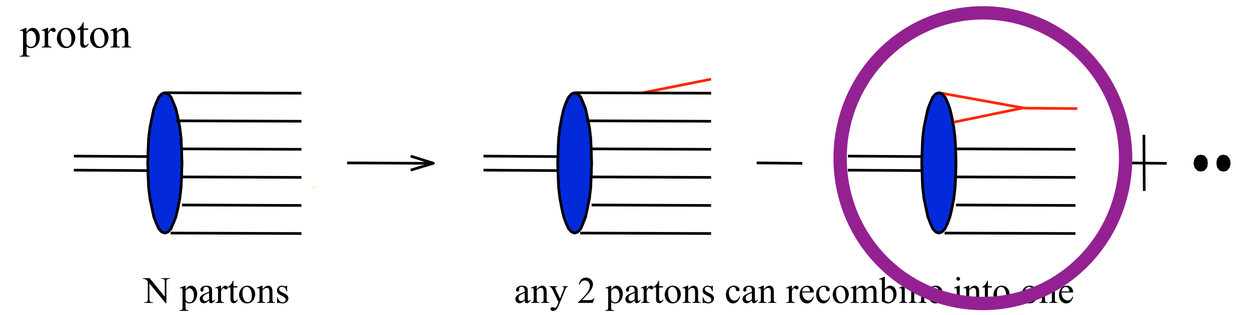
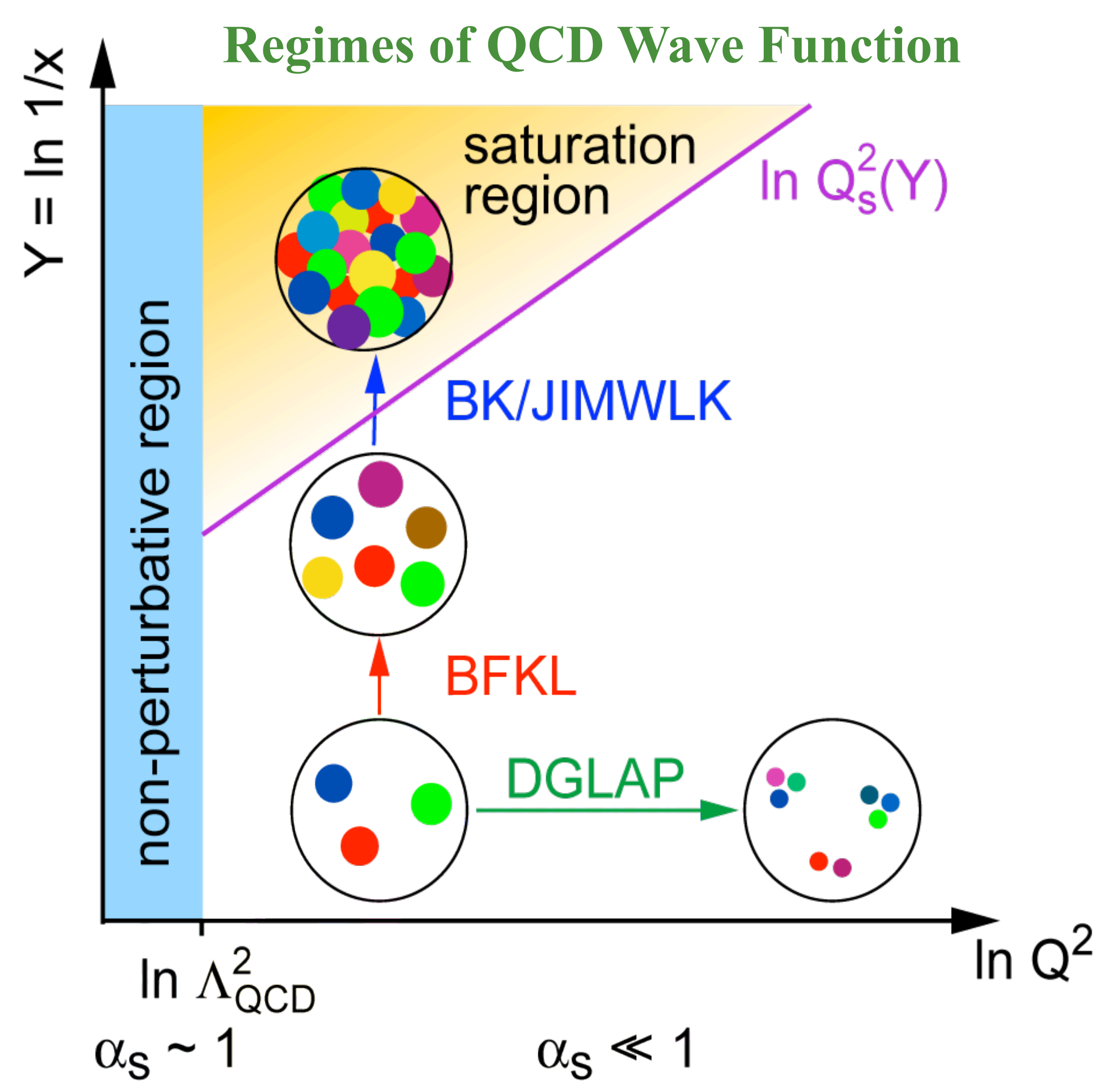




Non-linear QCD - Saturation

- BFKL: evolution in x
  - ➡ linear
    - explosion in colour field at low-x
- Non-linear BK/JIMWLK equations
  - ➡ non-linearity ⇒ saturation
    - Allows for the recombination of gluons in a dense gluonic medium
  - ➡ characterised by the saturation scale, $Q_S(x,A)$



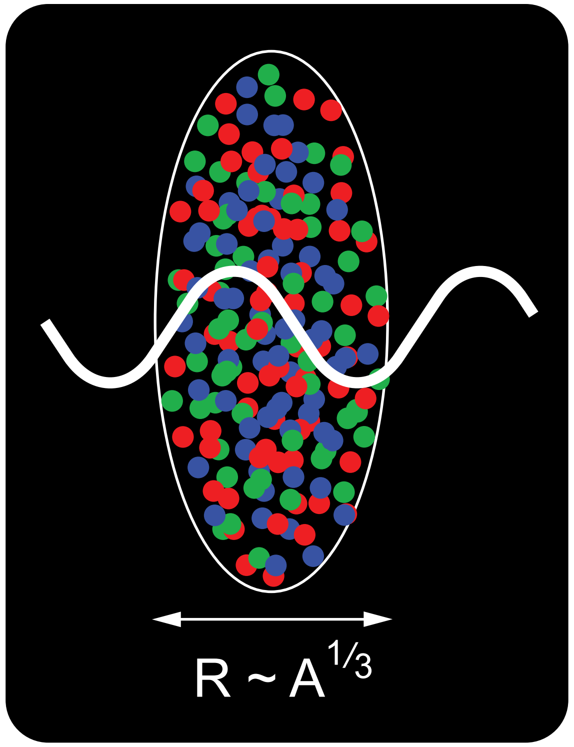


The Nuclear "Oomph Factor"

- Enhancing Saturation effects:
  - ➡ Probes interact over distances $L \sim (2m_n x)^{-1}$

    For probes where $L > 2R_A$ ($\sim A^{1/3}$) cannot distinguish between nucleons in front or back of the nucleus.

    - ▸ Probe interacts coherently with all nucleons.



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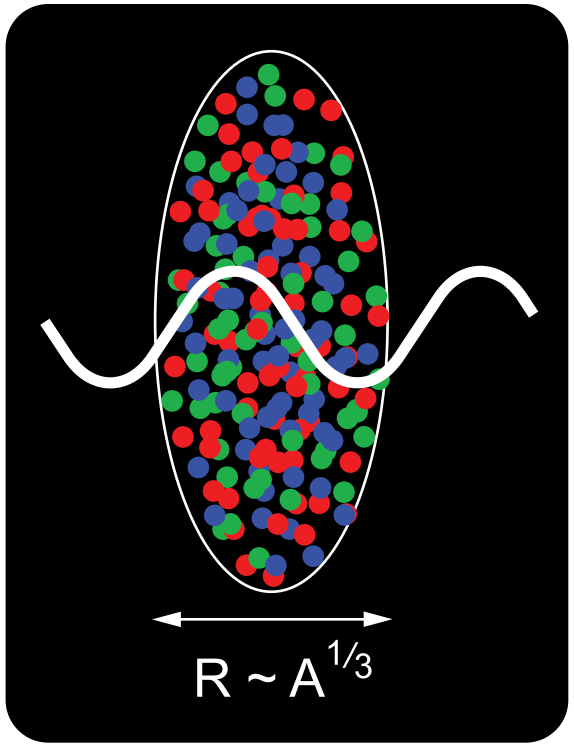


Simple geometric considerations lead to:

$$Q_s^2 \propto \frac{\alpha_s x G(x, Q_s^2)}{\pi R_A^2}$$ HERA: $$xG \propto \frac{1}{x^{1/3}}$$ A dependence: $$xG_A \propto A$$

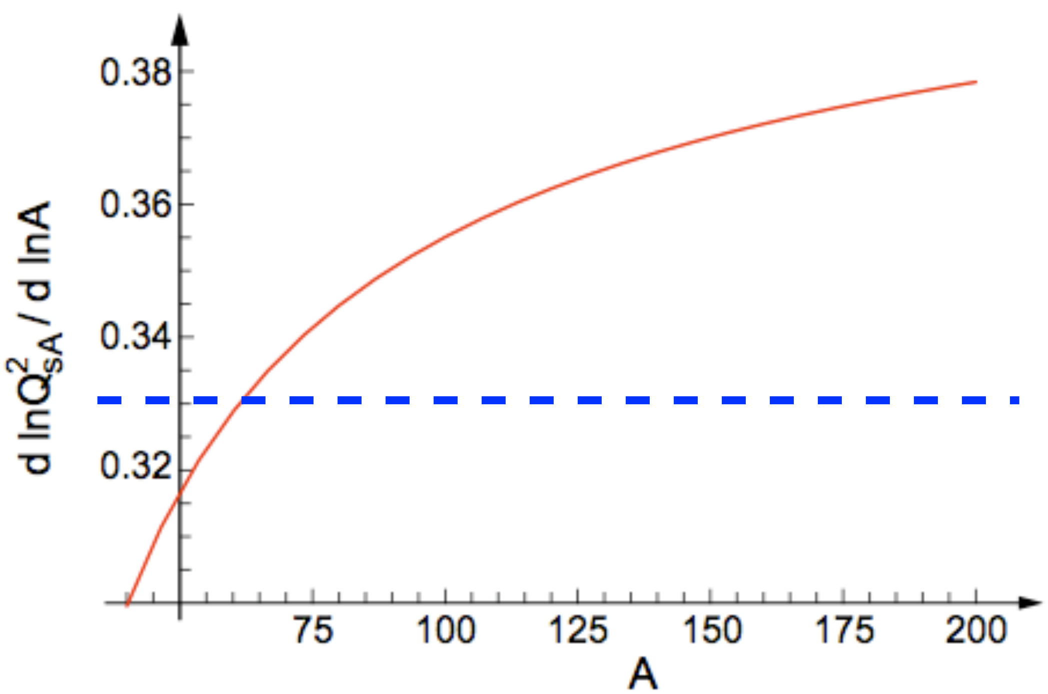
Nuclear "Oomph" Factor: $$(Q_s^A)^2 \approx c\, Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

Enhancement of Q_S with A: $\Rightarrow$ non-linear QCD regime reached at significantly lower energy in e+*A* than in *e*+*p*

The Nuclear "Oomph Factor"

More sophisticated analyses $\Rightarrow$ confirm (exceed) pocket formula for high A

e.g. Kowalski, Lappi and Venugopalan, PRL 100, 022303 (2008); Armesto et al., PRL 94:022002; Kowalski, Teaney, PRD 68:114005



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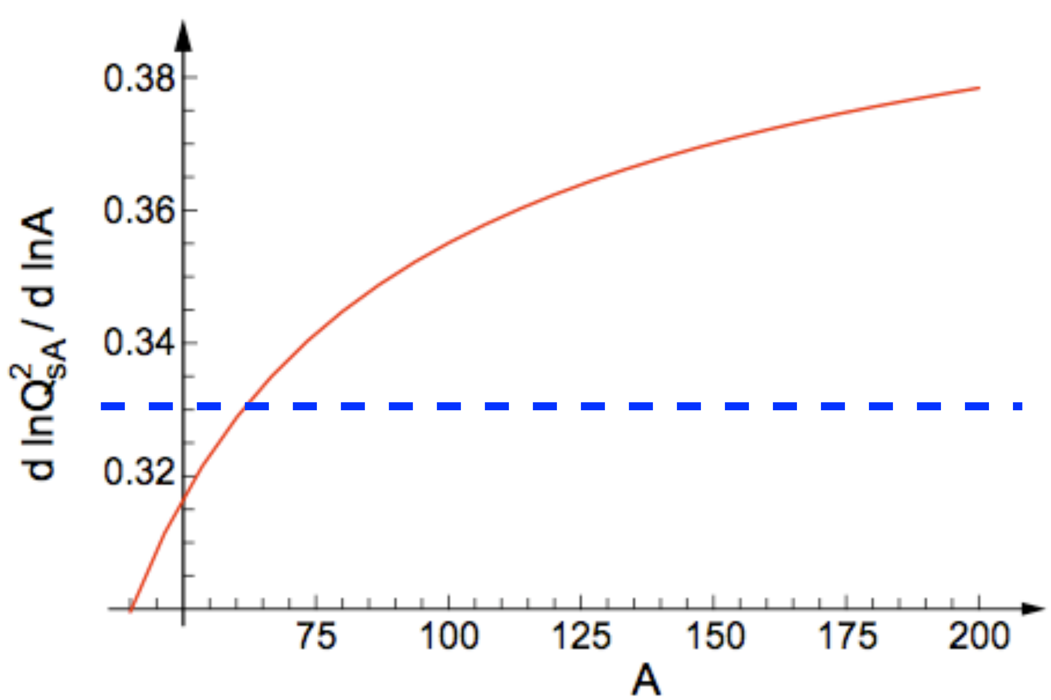

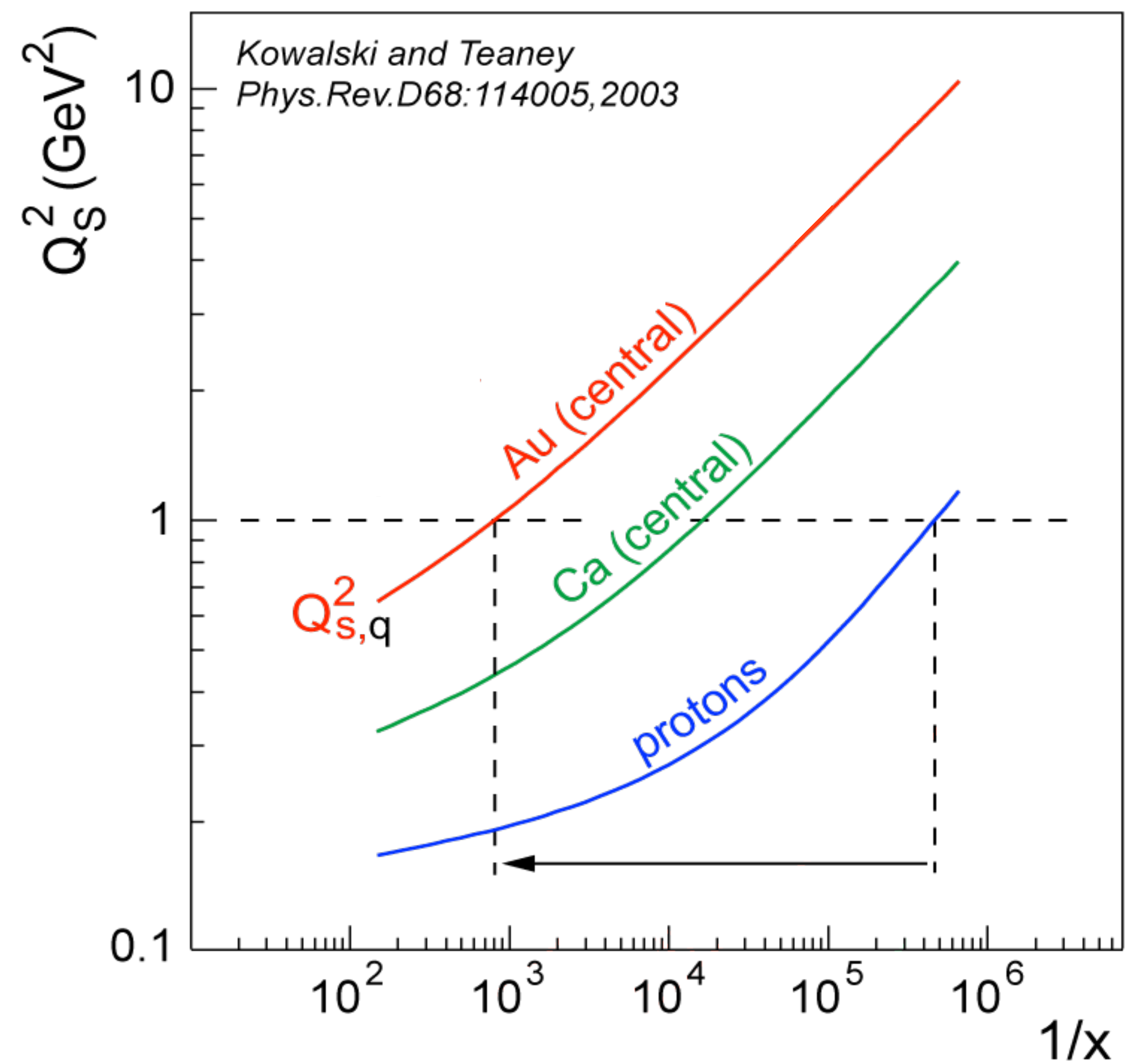

One would require an energy in e+p ~ 10-100 x e+A to get to same Q^2_S

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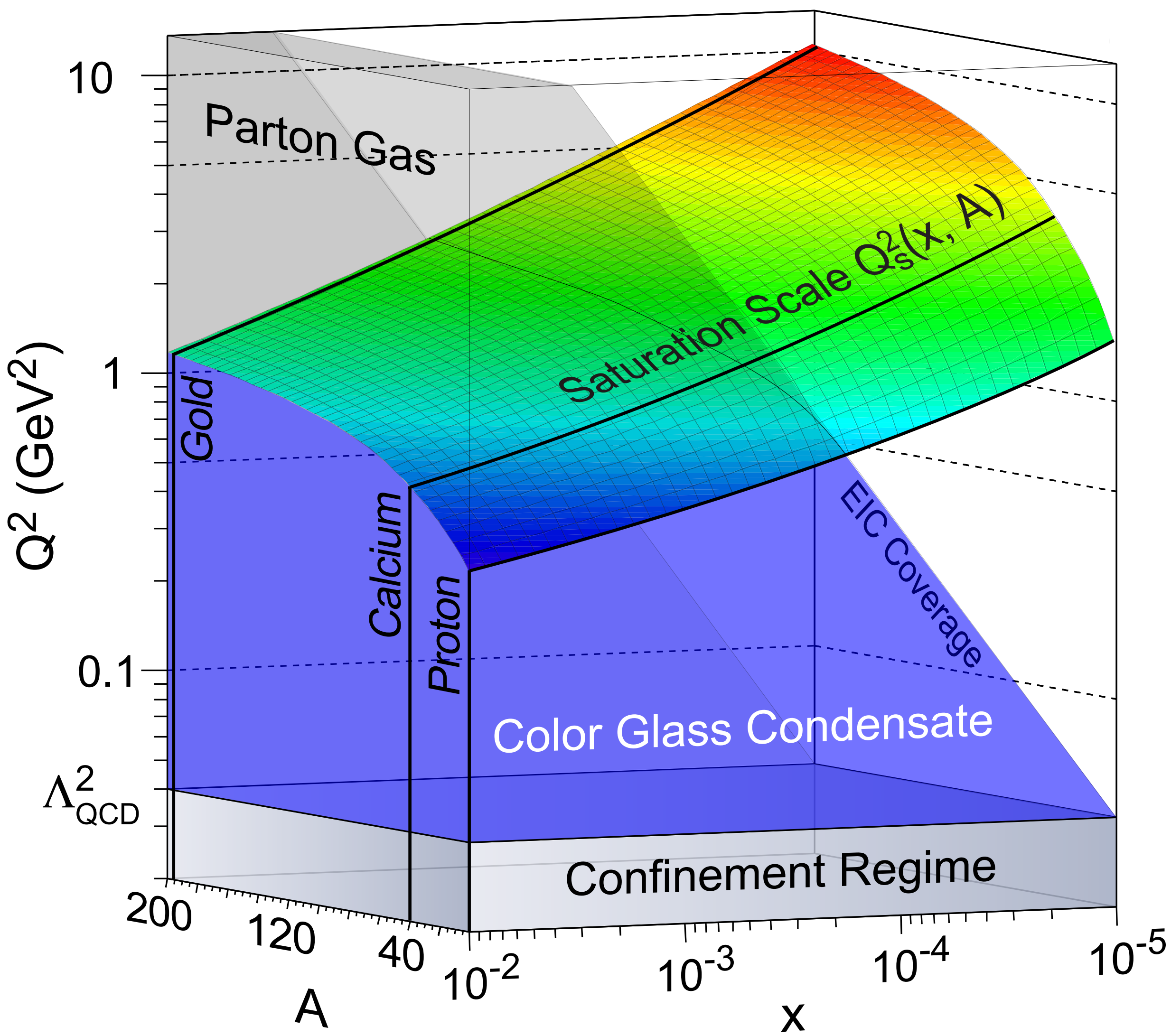

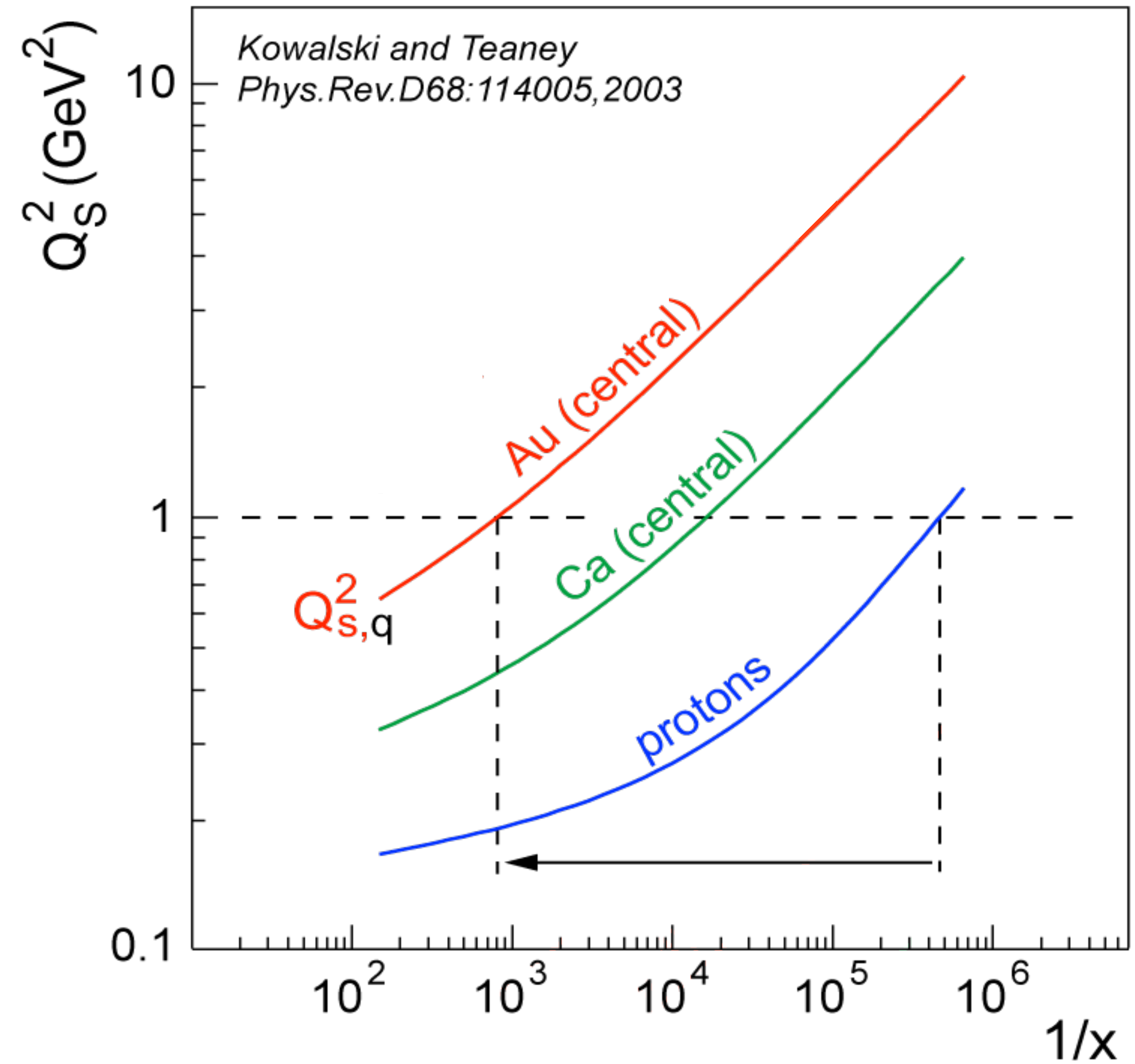

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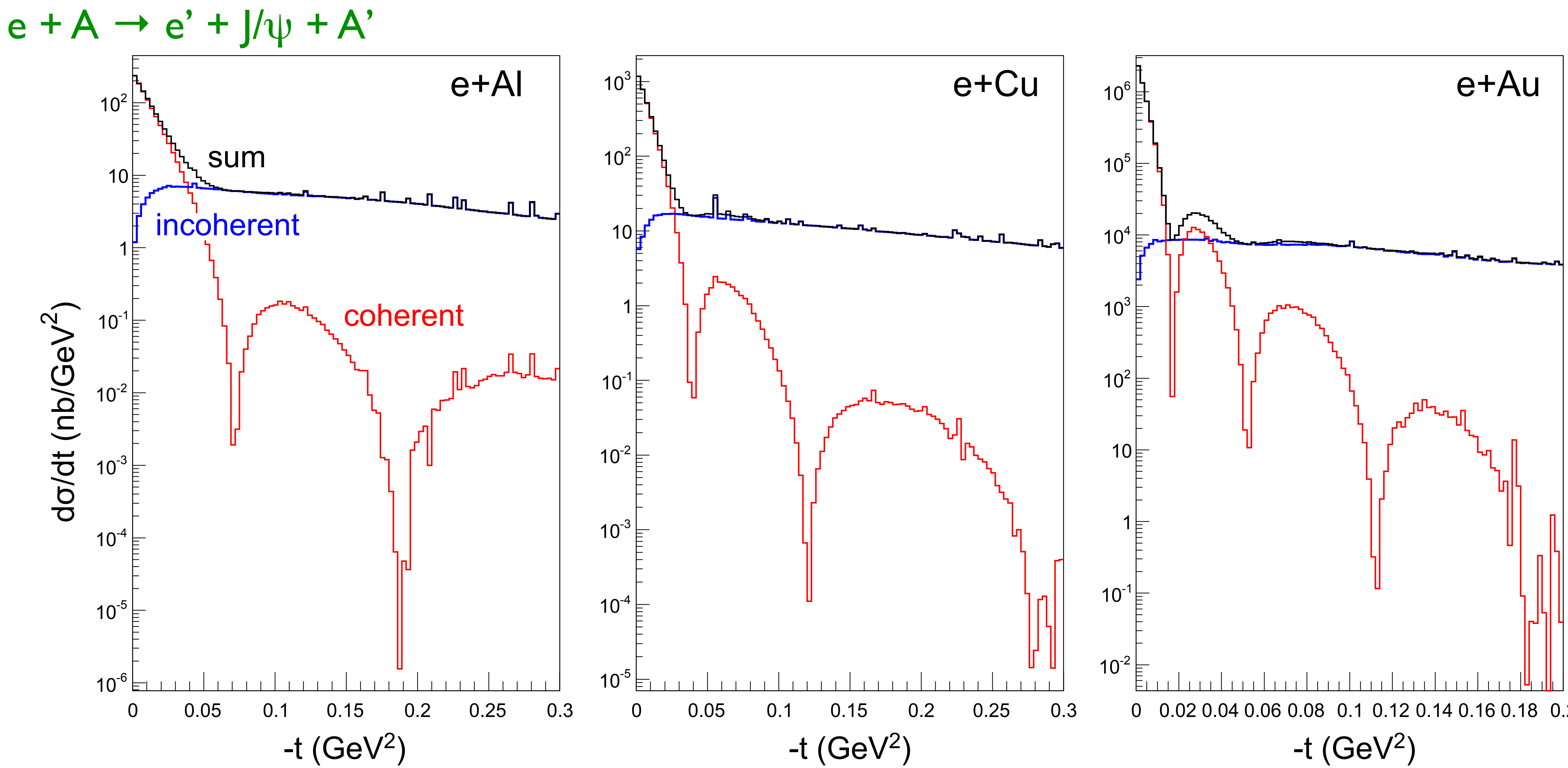
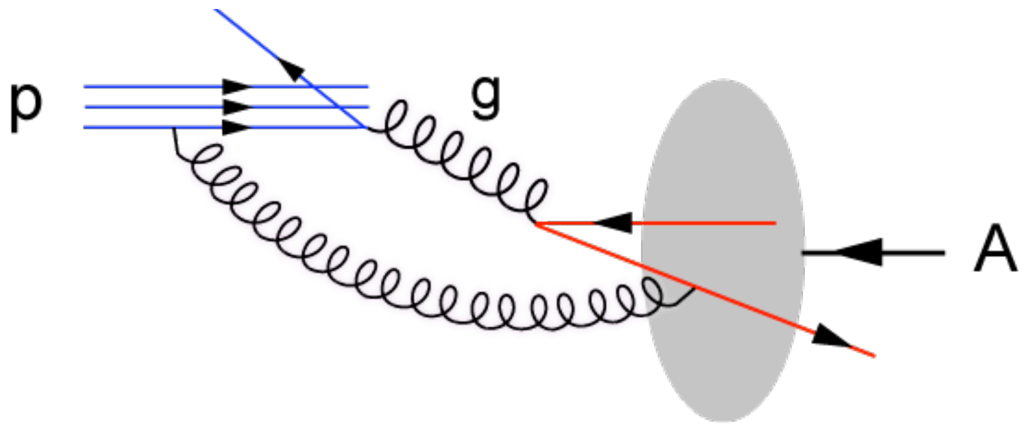
Diffraction in e+A



- Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ in e+A predicted to be ~25-40%
- Process most sensitive to $xG(x,Q^2)$
- Rich physics program on momentum & spatial gluon distribution
- Coherent vs Incoherent: requires detection of breakup with ~ $1\text{-}10^{-4}$ efficiency

Never done at a collider!

How do we measure Glue ?



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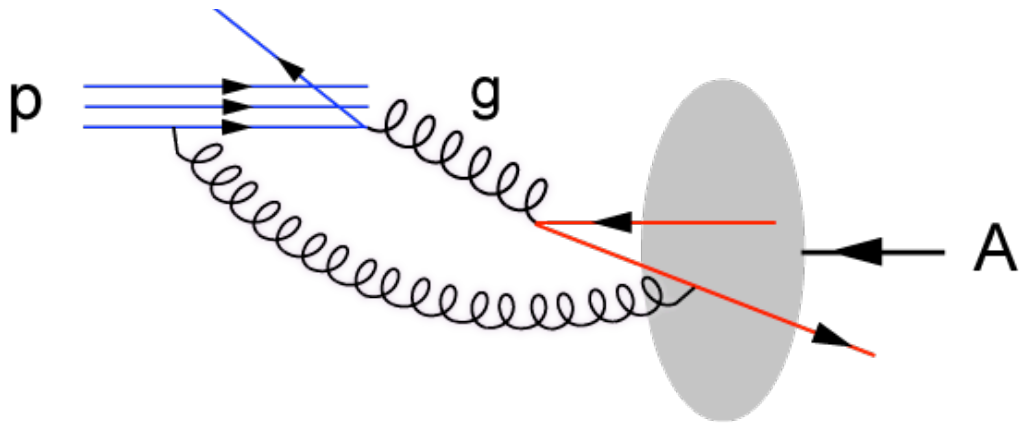

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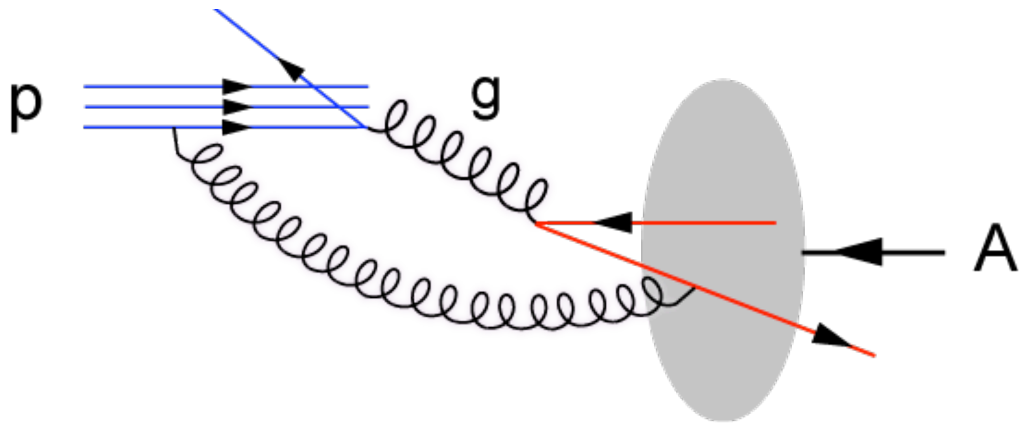

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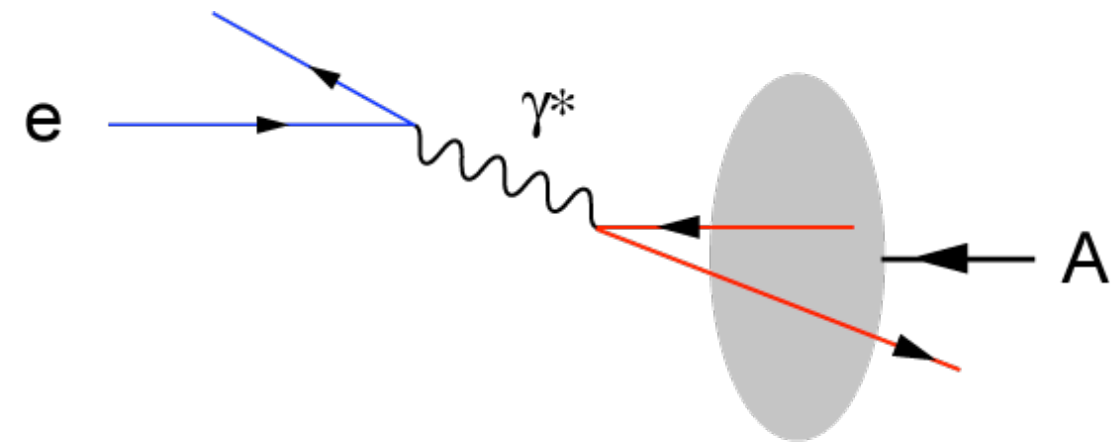

★ Explore QCD & Hadron Structure

★ Direct access to glue through photon-gluon fusion

★ High precision & access to partonic kinematics

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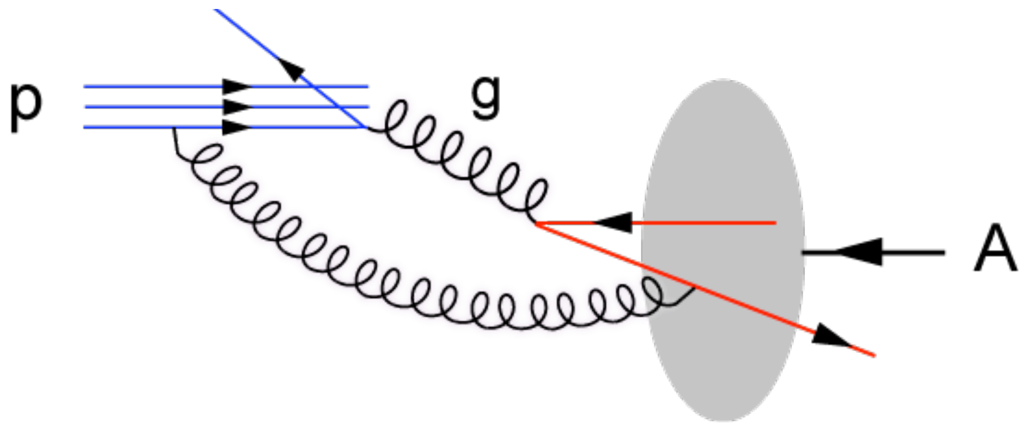
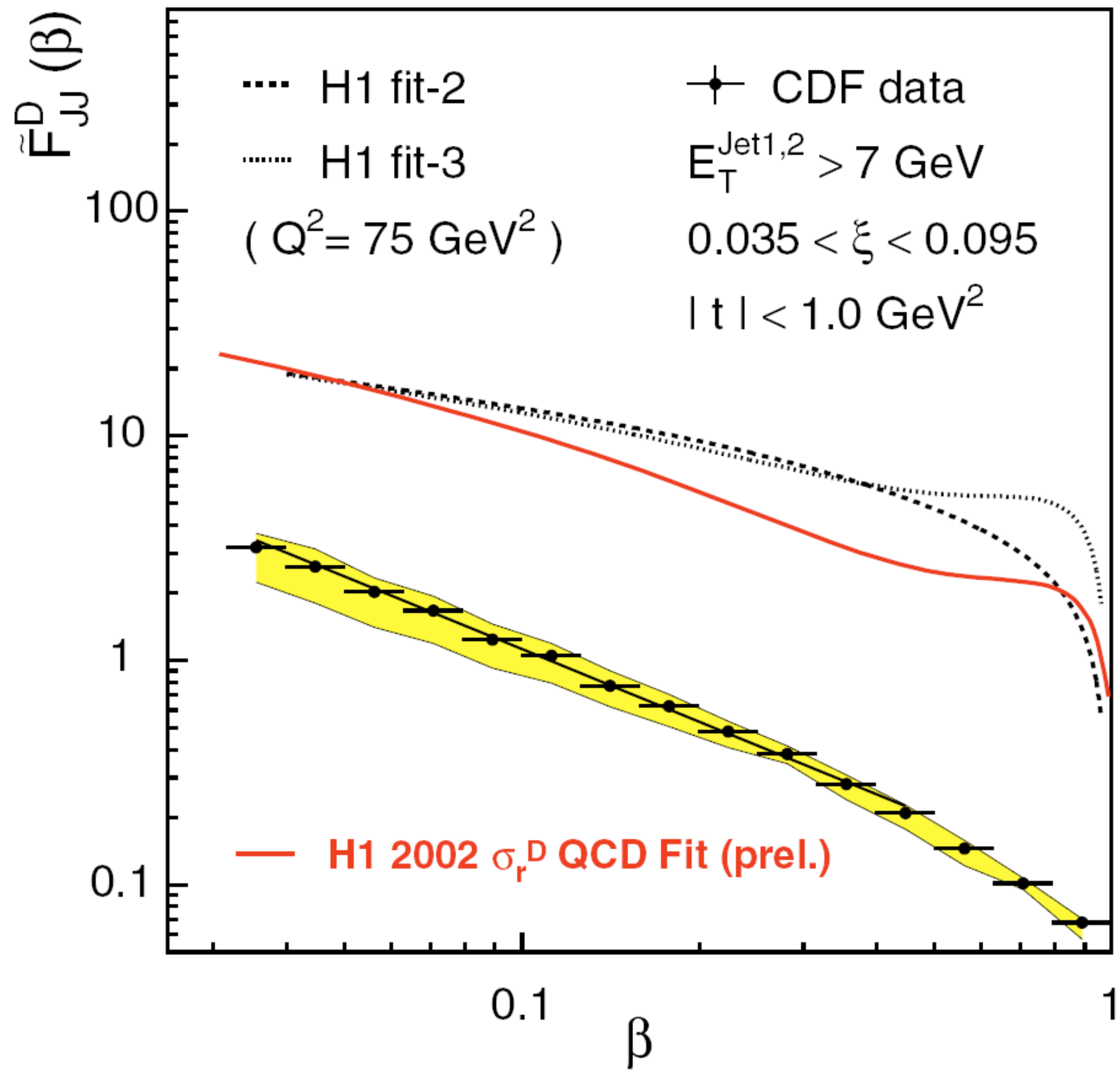


F. Schilling, hep-ex/0209001



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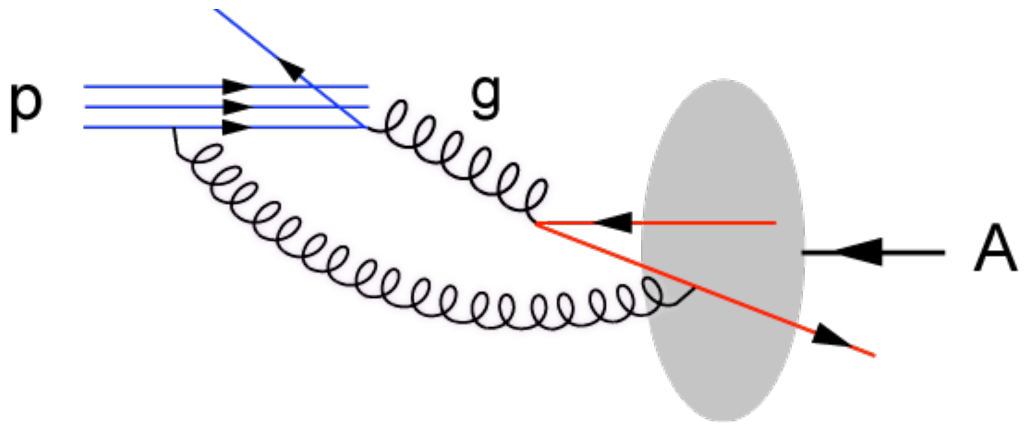

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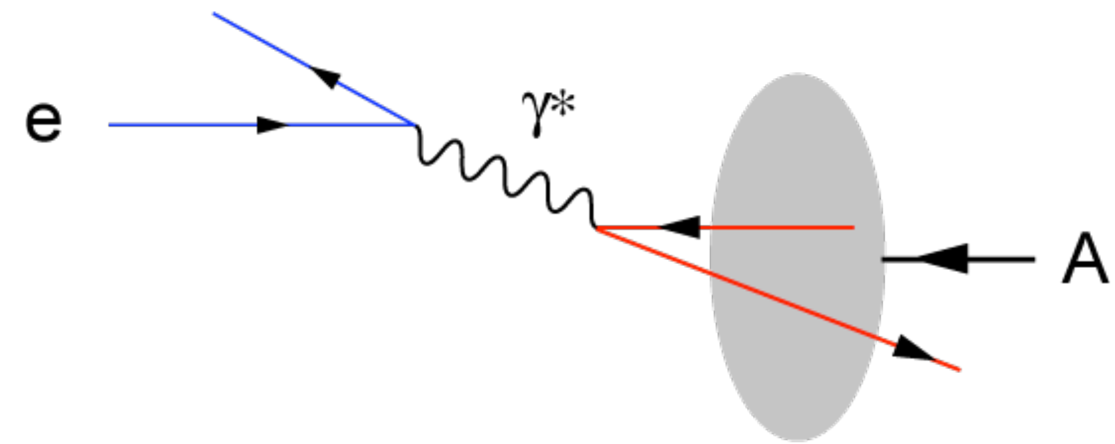

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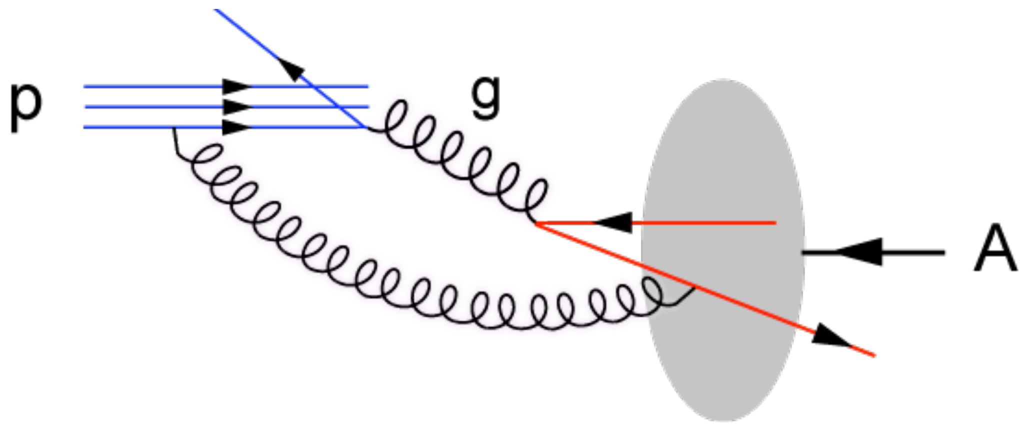

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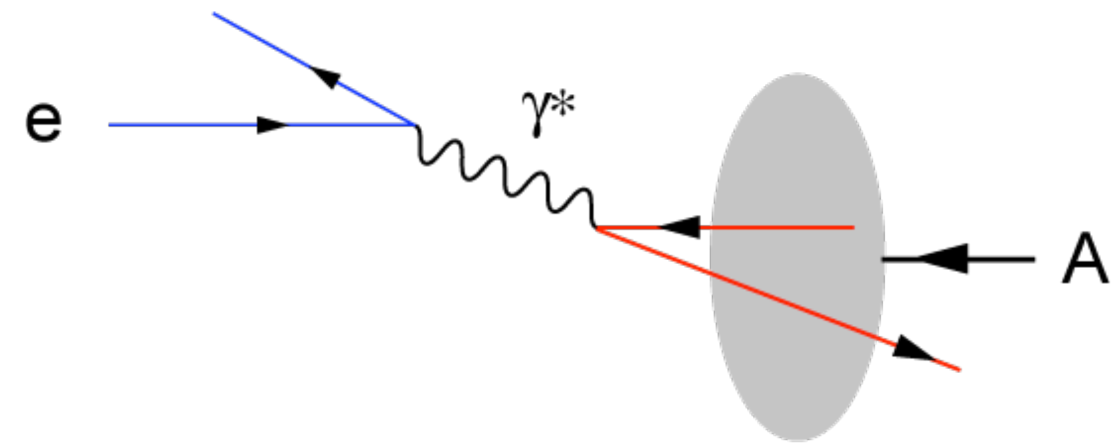

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Precision measurements $\Rightarrow$ DIS

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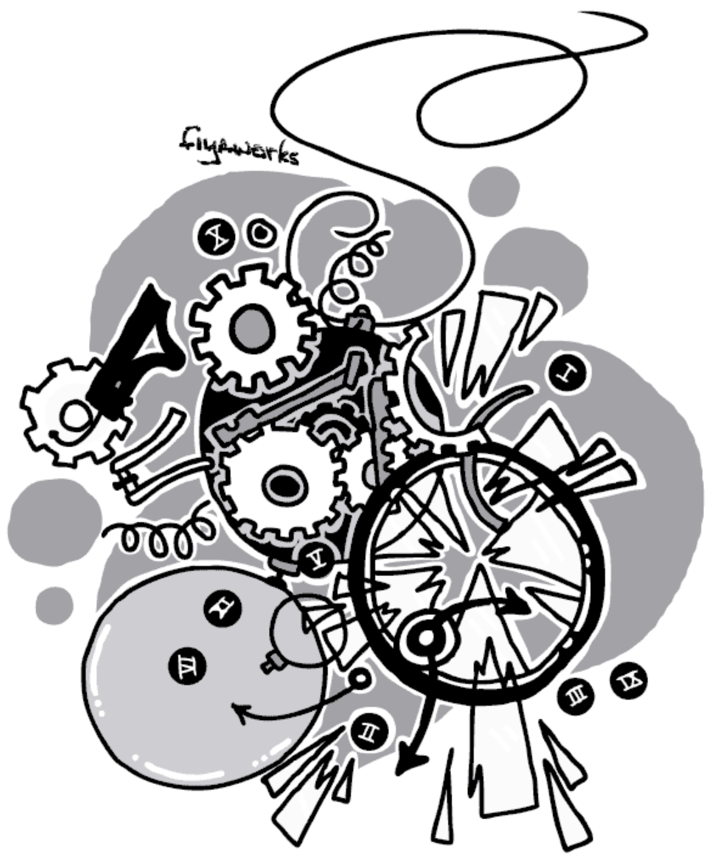
Scattering of hadrons on hadrons
is like colliding Swiss watches to find out how they are build.

R. Feynman



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- A comparison plot showing luminosities vs energy for existing and proposed e+p facilities.
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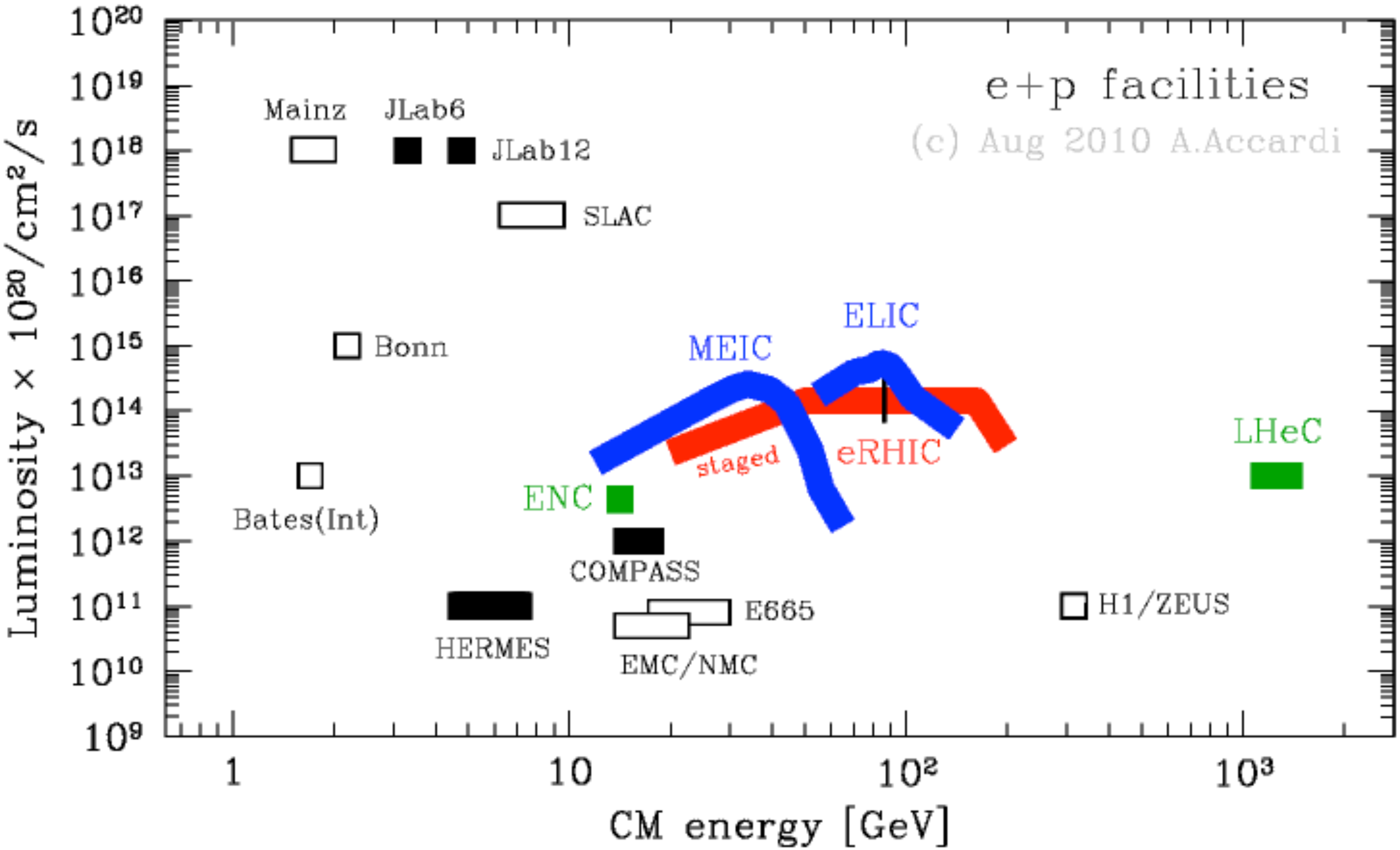

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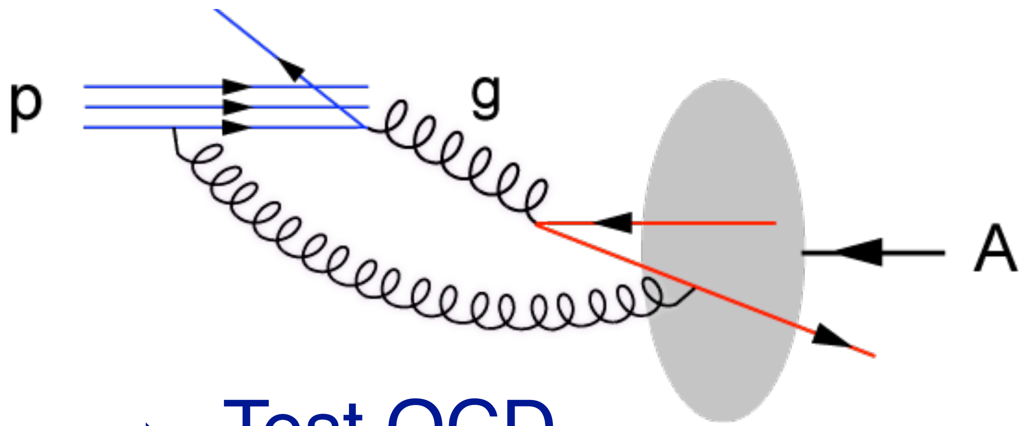

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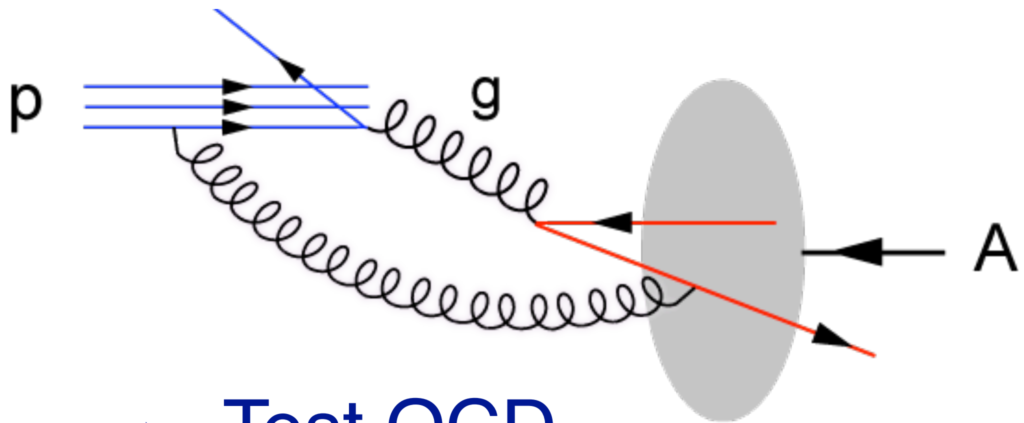

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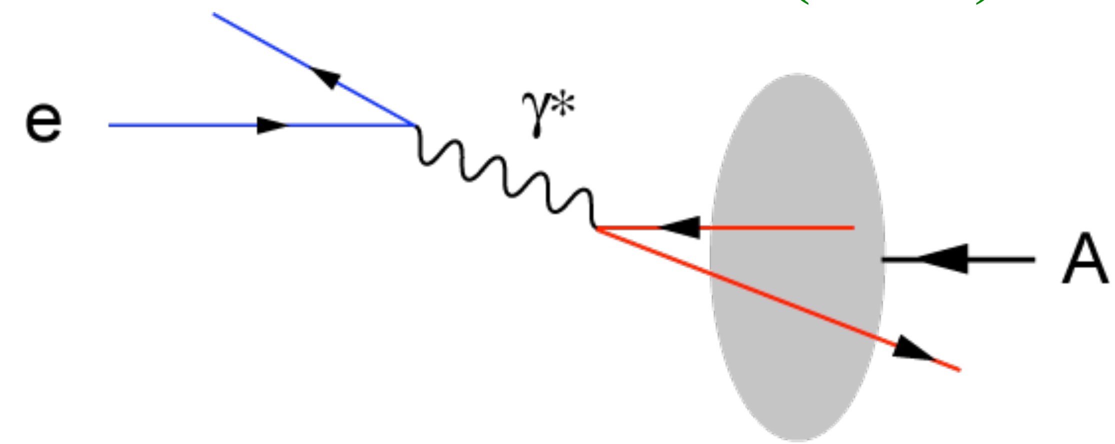

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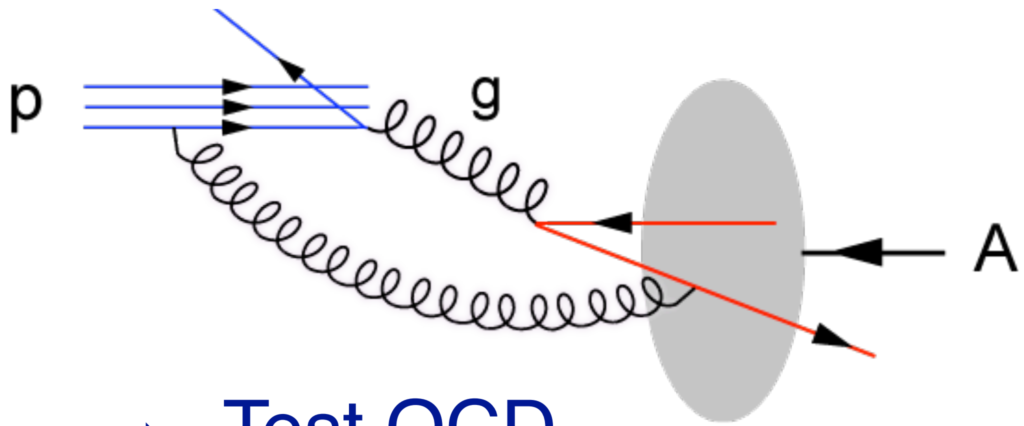

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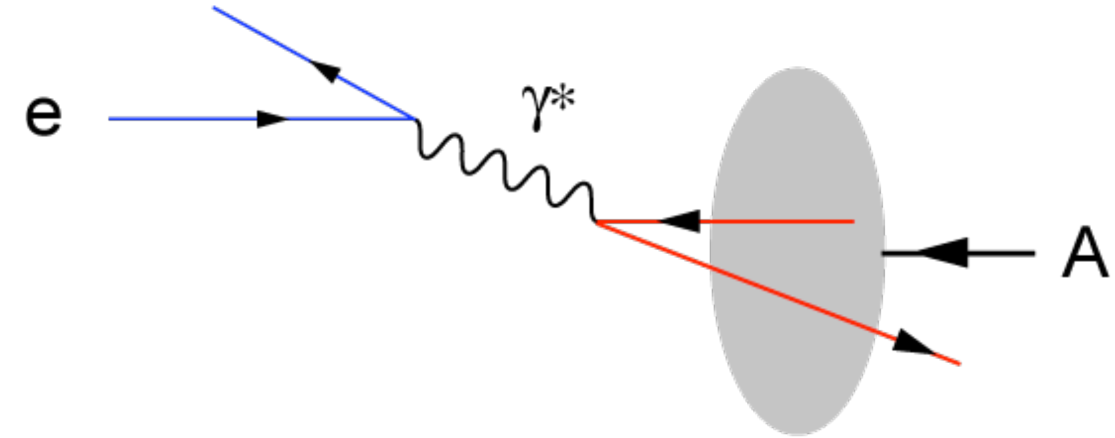

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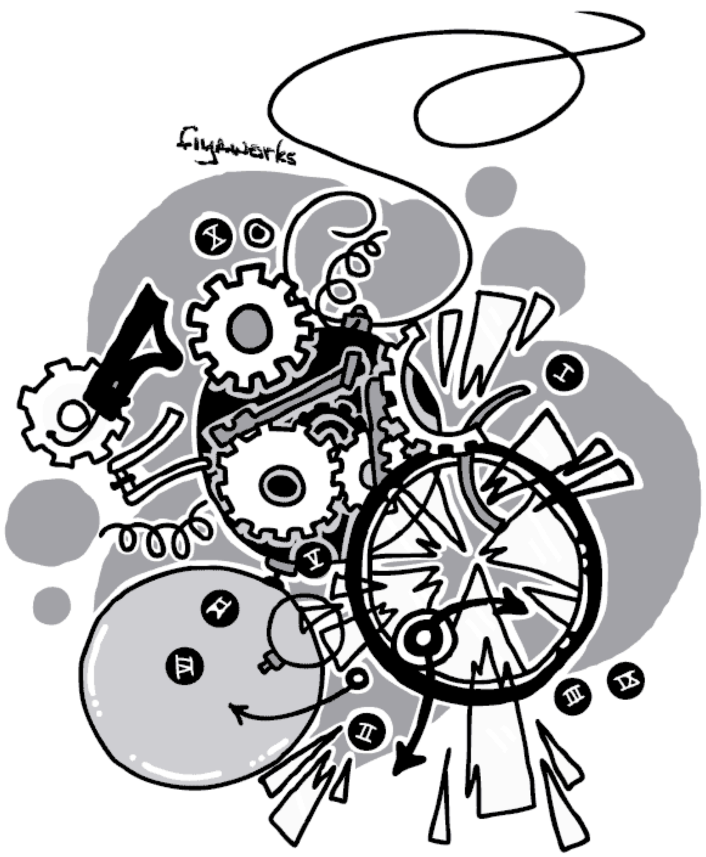


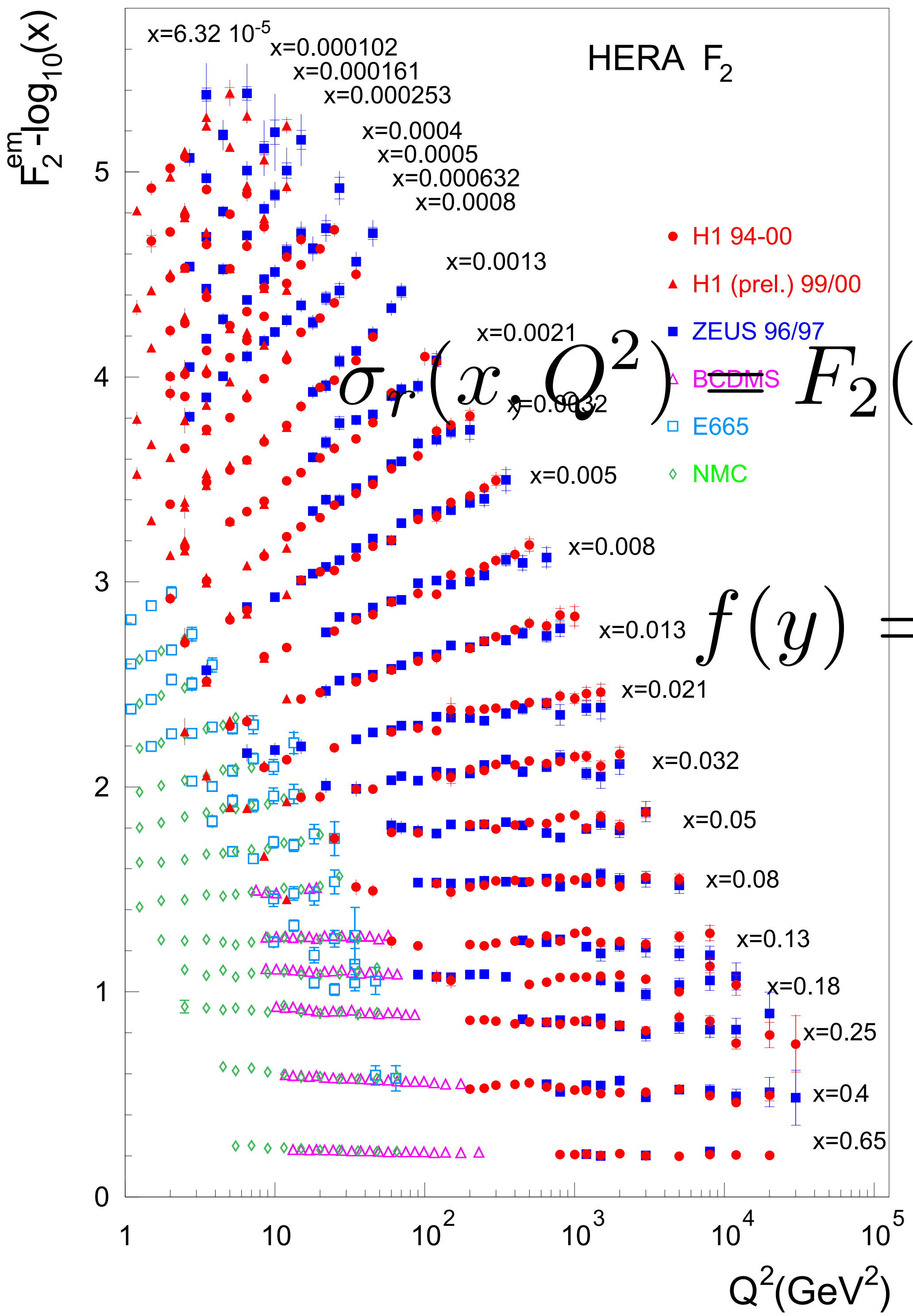
Precision measurements ⇒ DIS

Measuring the glue via Structure Functions

$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark momentum distributions

gluon momentum distribution



$$\sigma_r(x,Q^2) = F_2(x,Q^2) - f(y)F_L(x,Q^2),$$

$$f(y) = \frac{y}{1+(1-y)^2}$$

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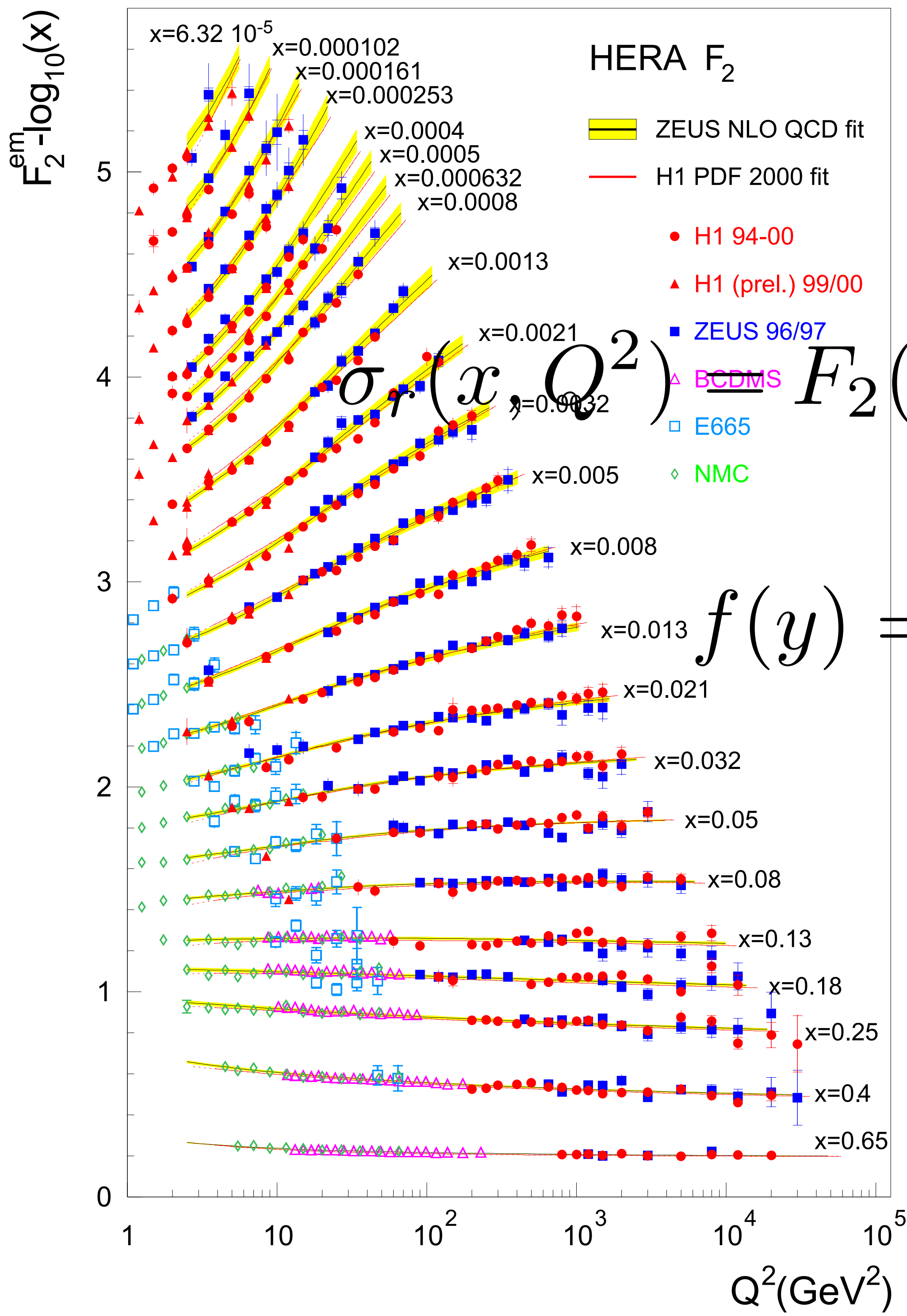
$$\frac{d^2\sigma^{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$



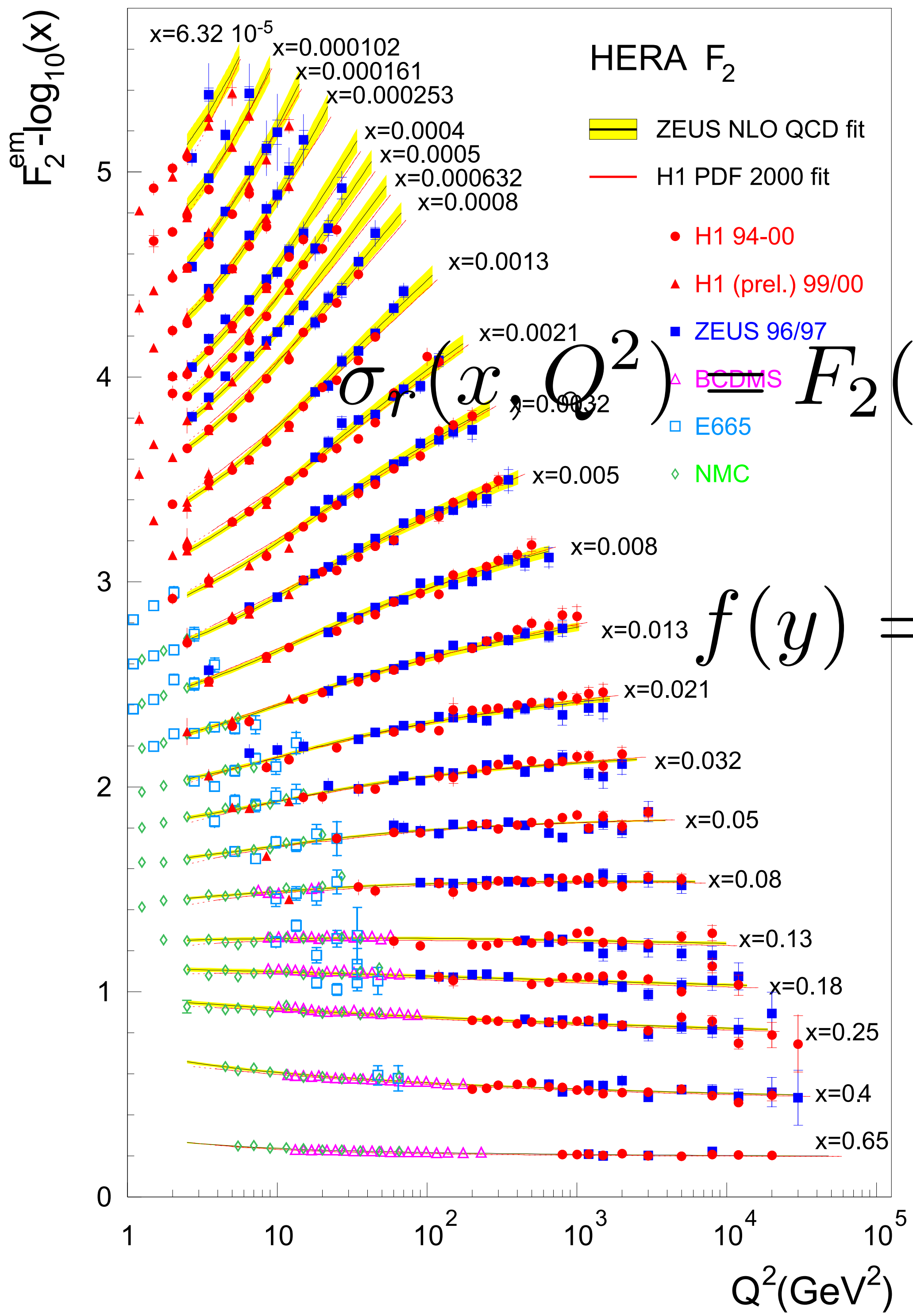
Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution $\Rightarrow G(x,Q^2)$

$$\sigma_r(x,Q^2) = F_2(x,Q^2) - f(y)F_L(x,Q^2),$$

$$f(y) = \frac{y}{1+(1-y)^2}$$

Measuring the glue via Structure Functions

$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$



Scaling violation: $dF_2/dlnQ^2$ and linear DGLAP

Evolution $\Rightarrow$ $G(x,Q^2)$

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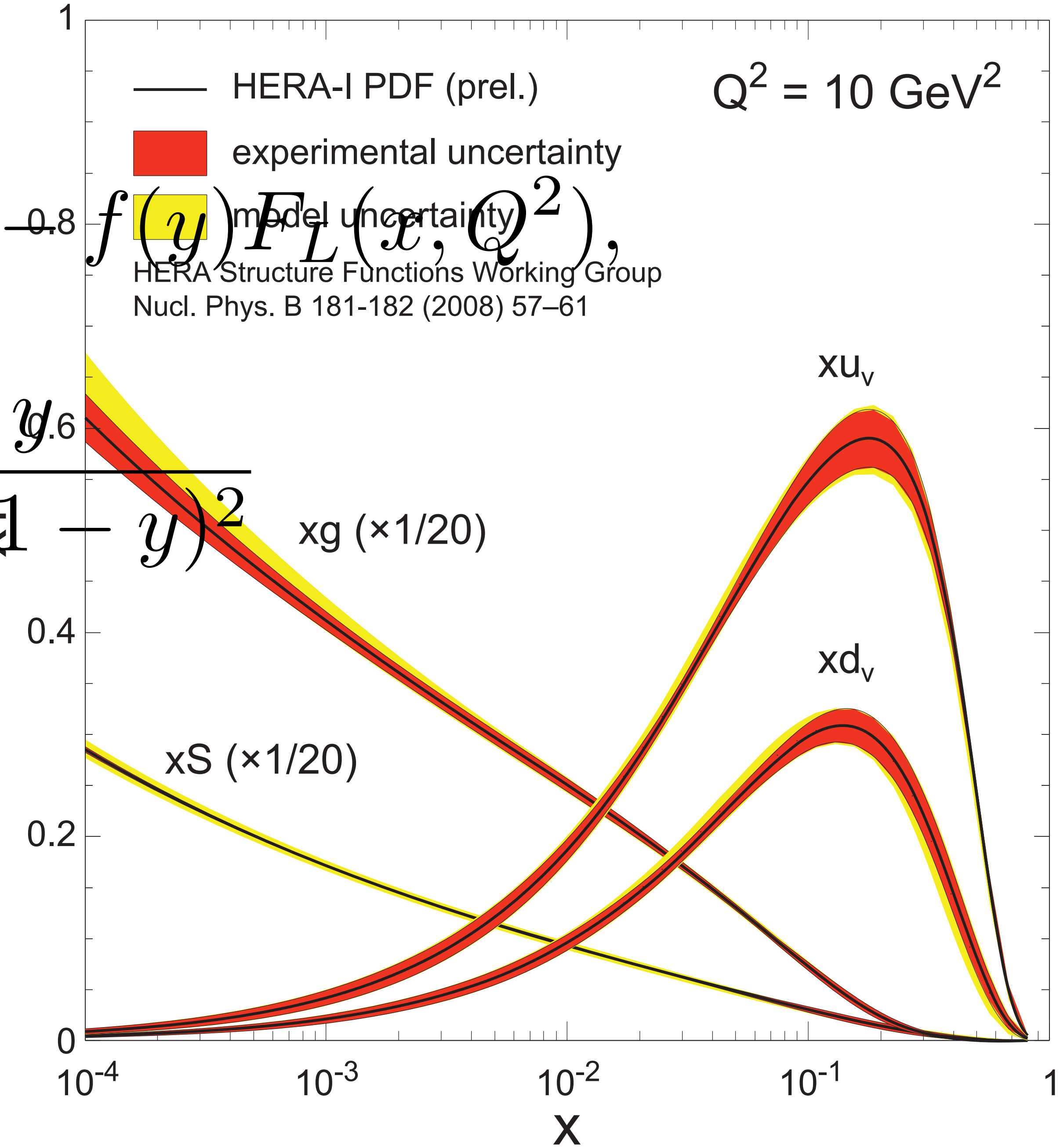

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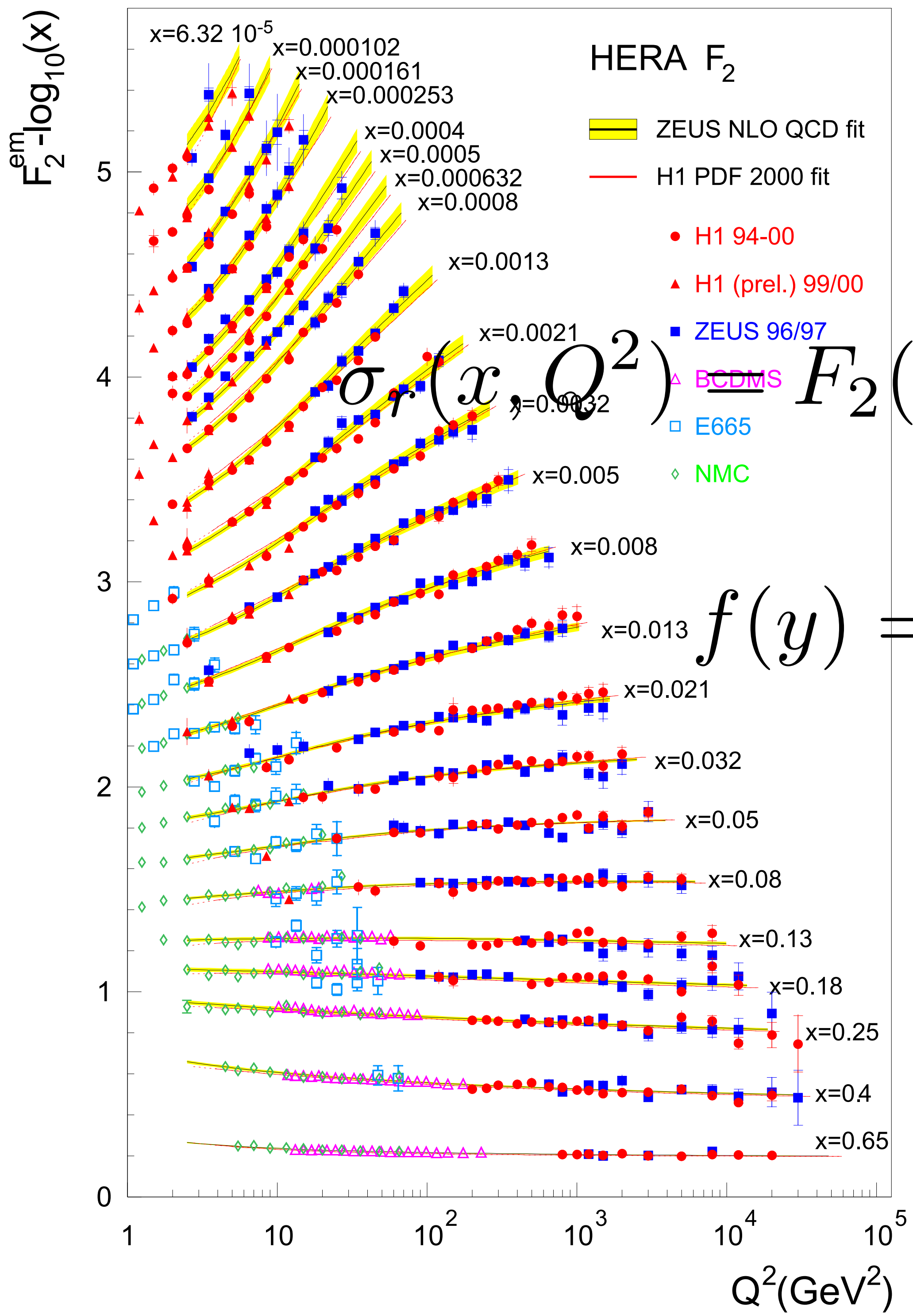

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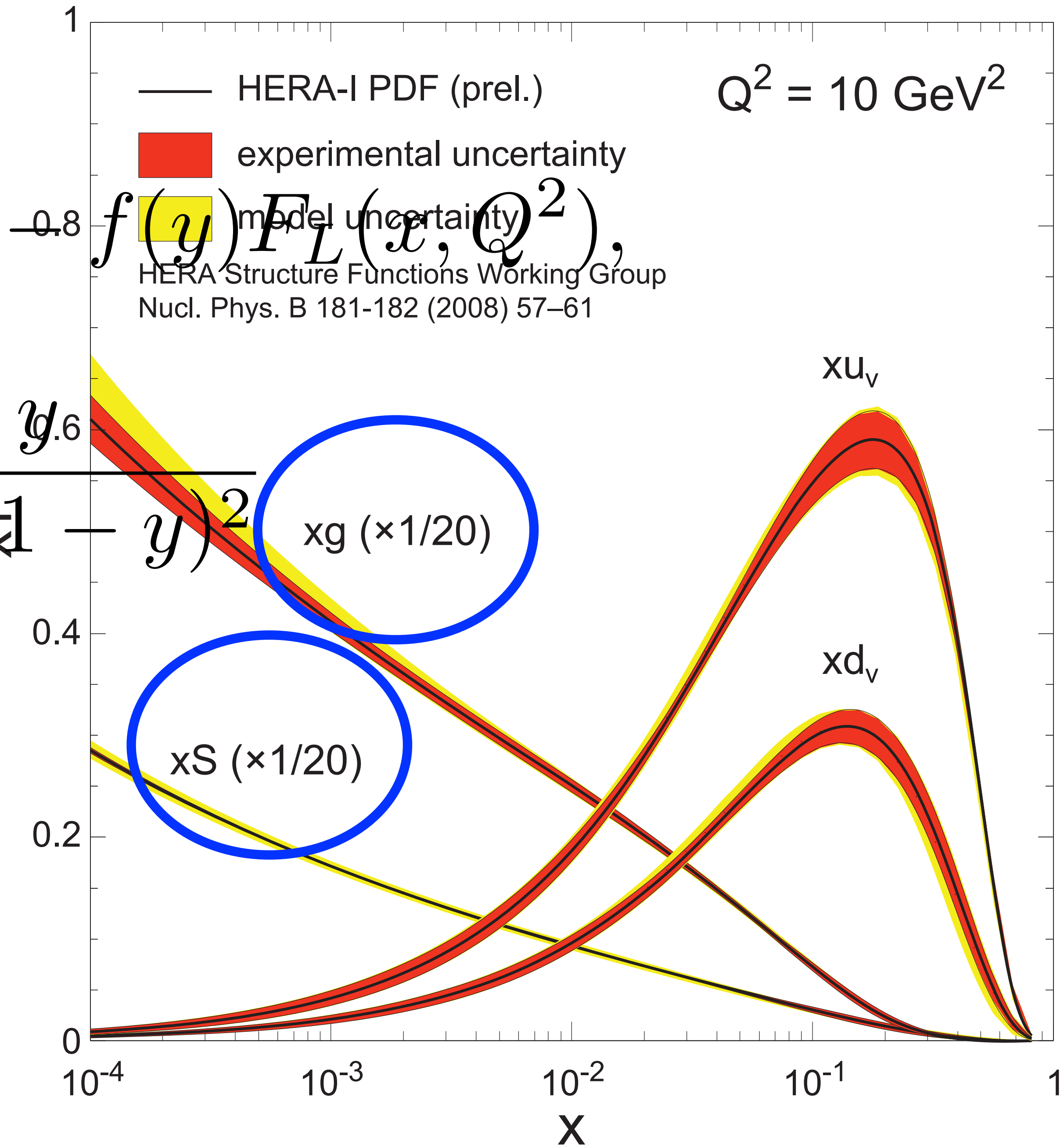

Measuring the glue via Structure Functions

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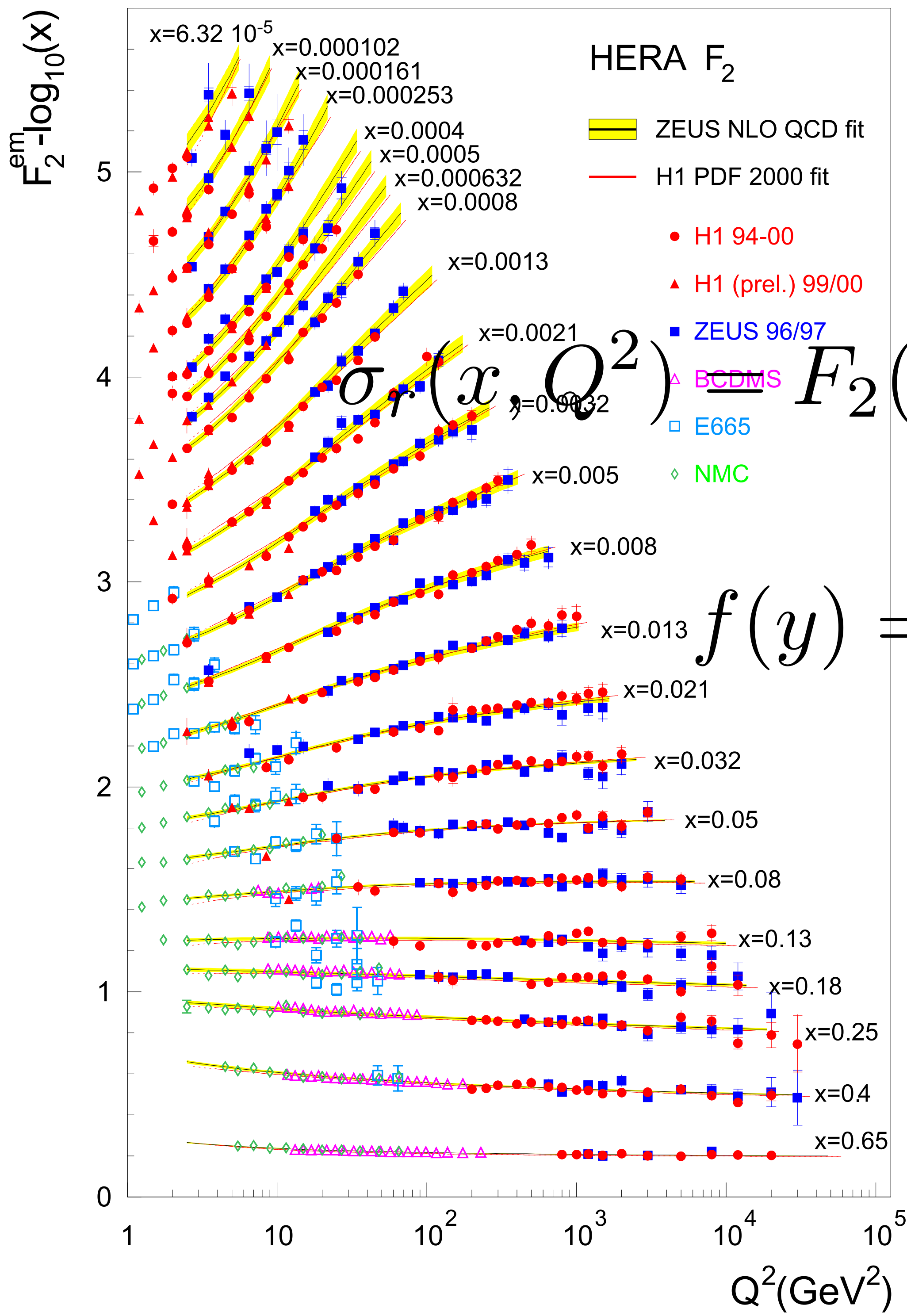

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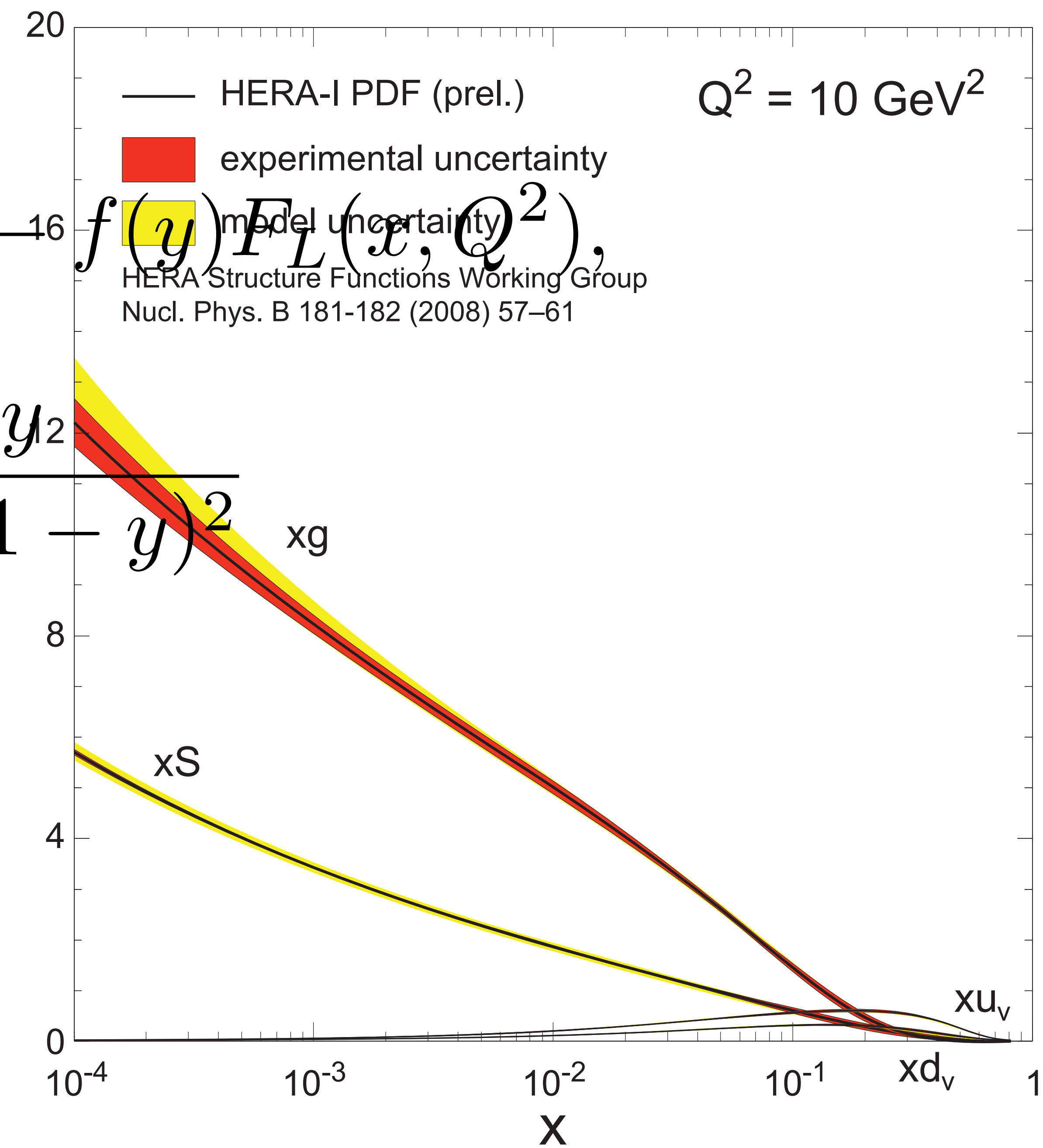
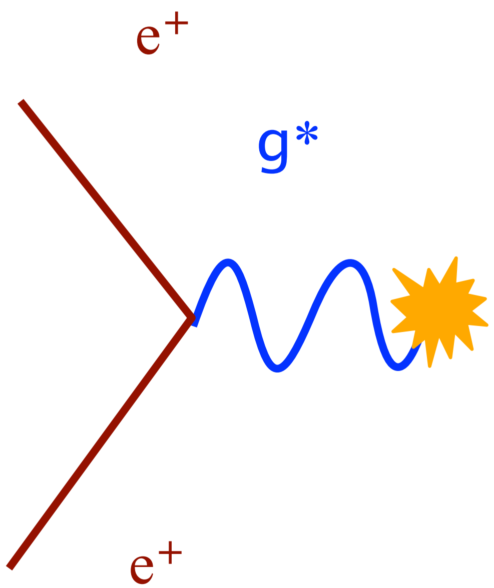
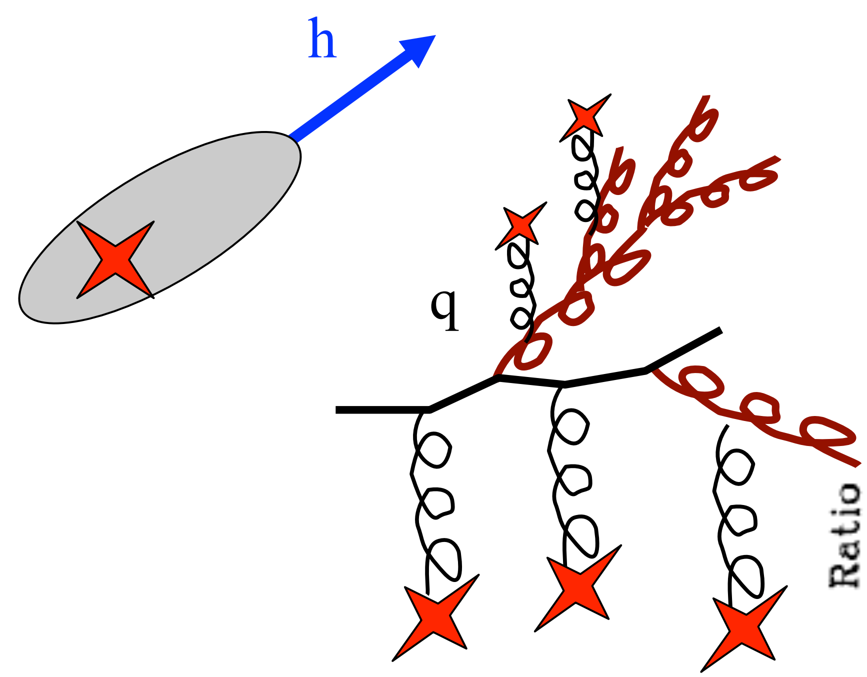
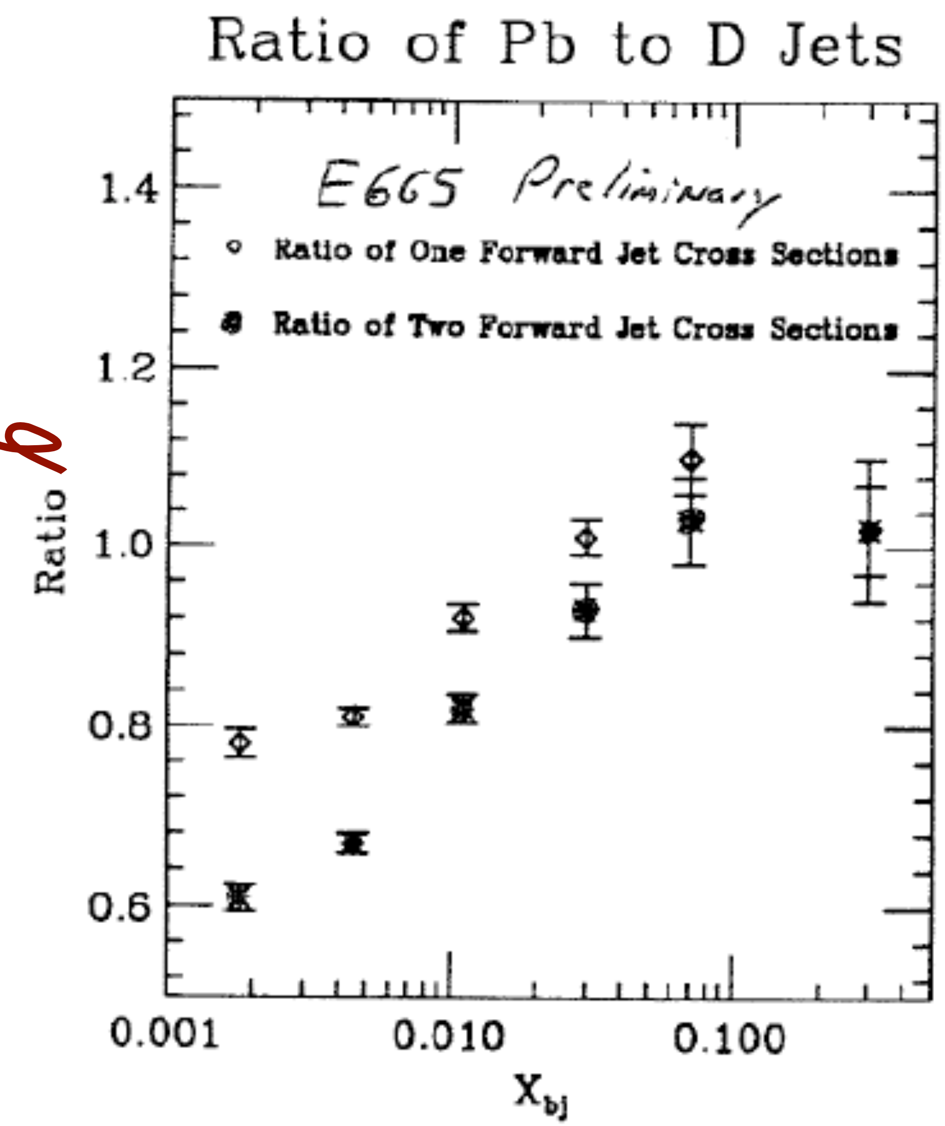


Jets and hadronization



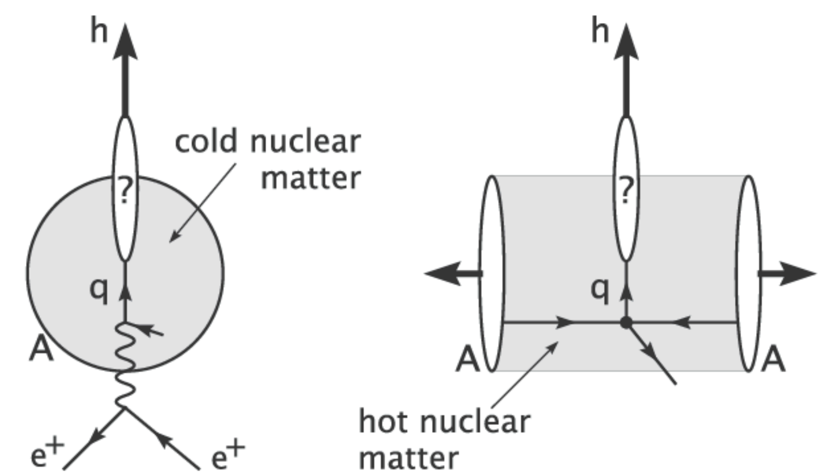




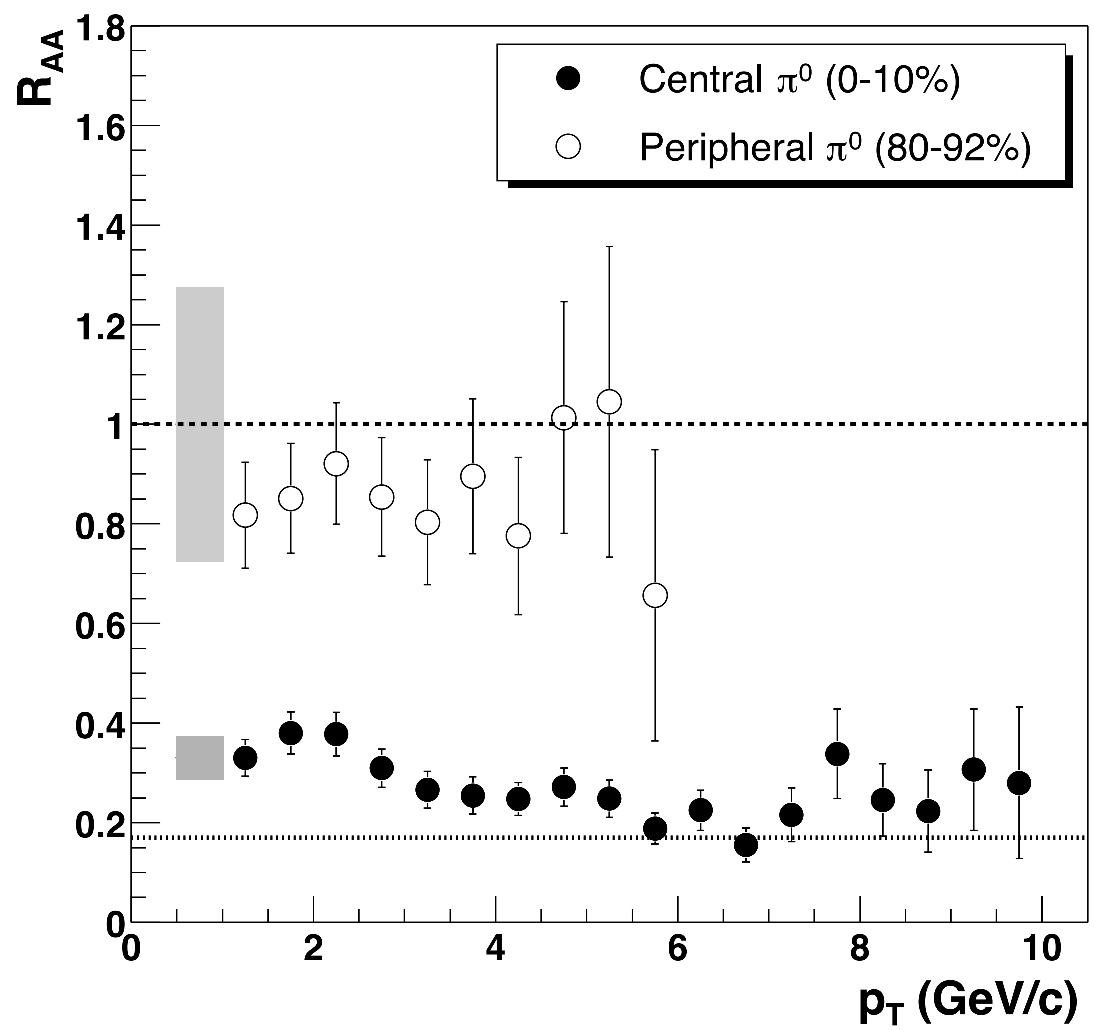
- **Use coloured probes to study soft nuclear glue**
    - ➡ a "large-x" probe of small-x gluons
- **Use nuclei to study parton propagation and fragmentation**
    - ➡ parton showers, quark-to-hadron transition
- **Ideal program for phase-1 EIC**

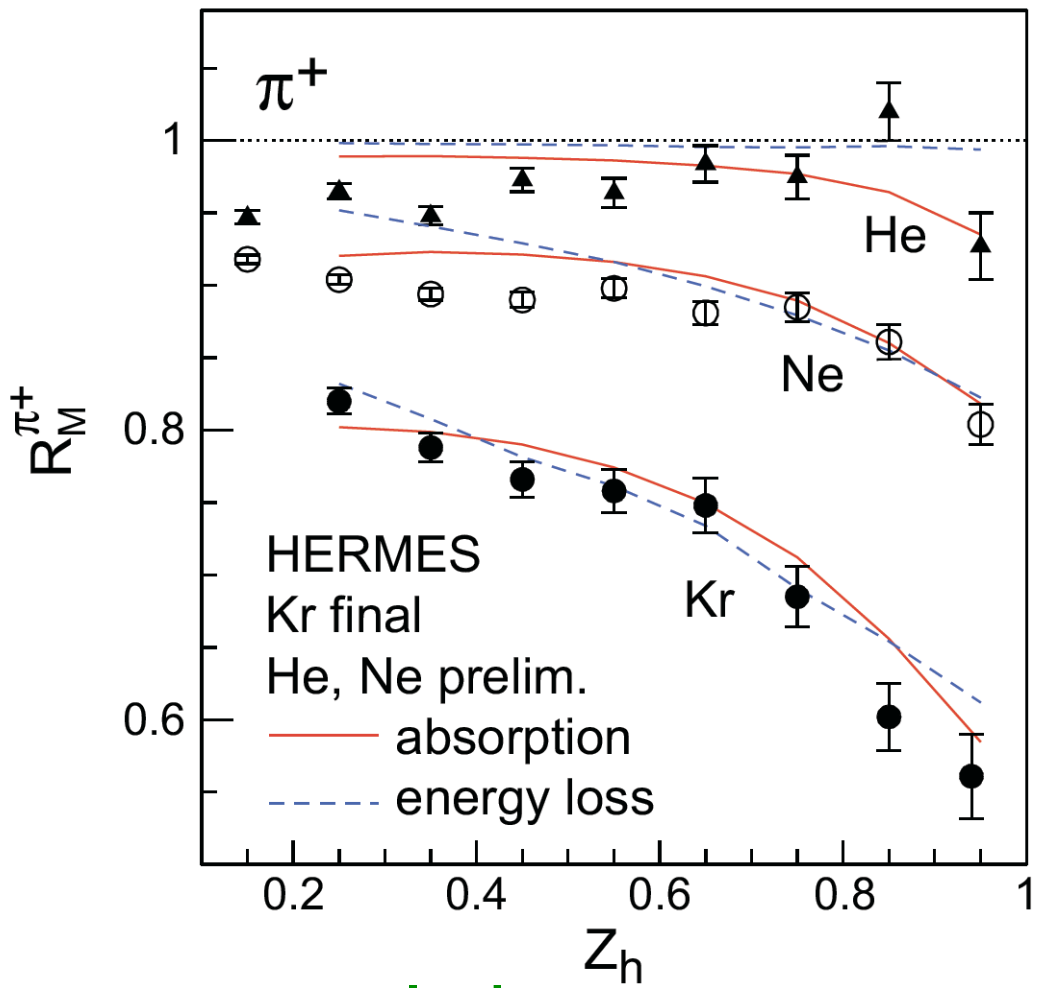
Interaction of fast probes with gluonic medium

- nDIS:
  - Clean measurement in 'cold' nuclear matter
  - Suppression of high-p_T hadrons analogous to, but weaker than at RHIC



PHENIX expt: Phys.Rev.Lett.91:072301 (2003)





ν = virtual photon energy

$Z_h = E_h/\nu$

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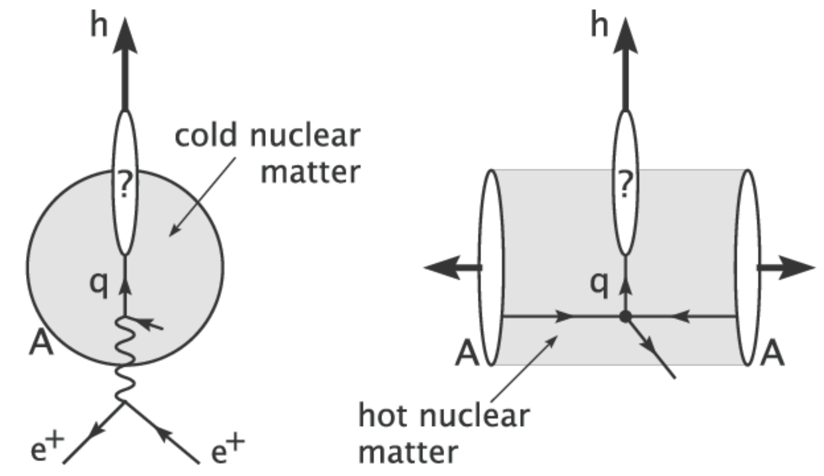
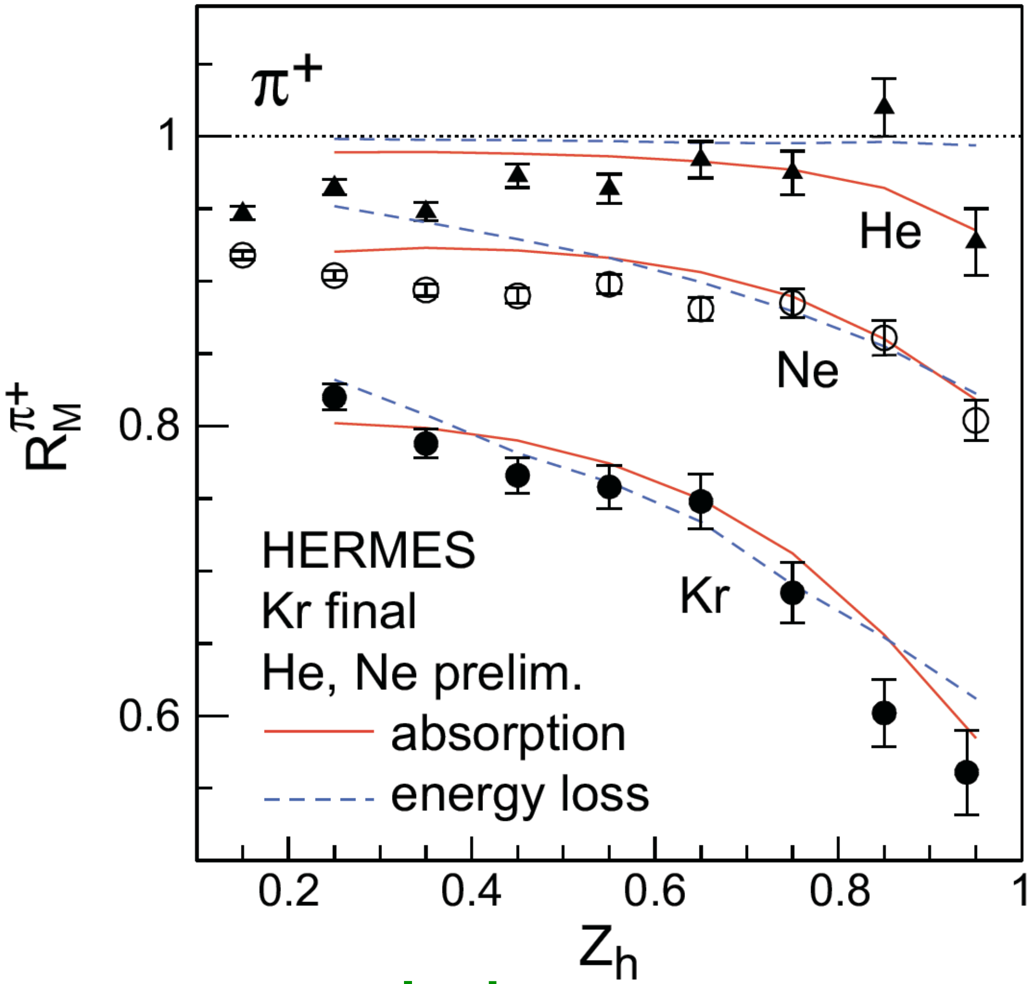


- Fundamental question:
  - When do partons get colour neutralized?

Parton energy loss vs. (pre)hadron absorption



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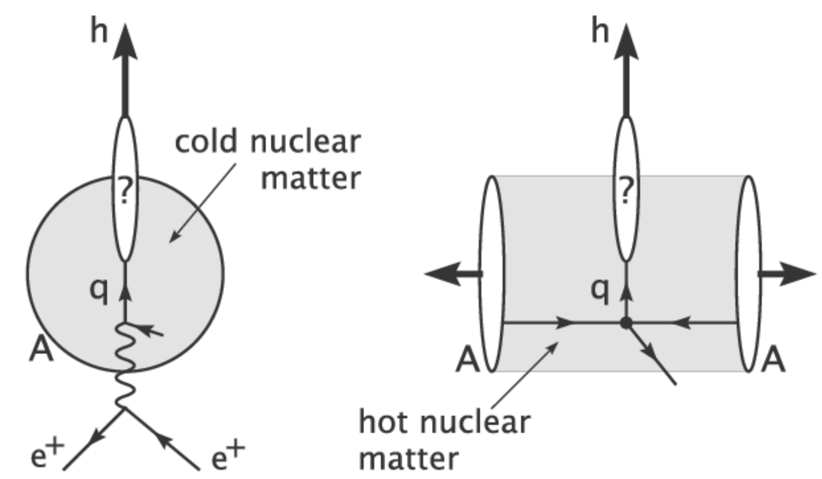

- Fundamental question:
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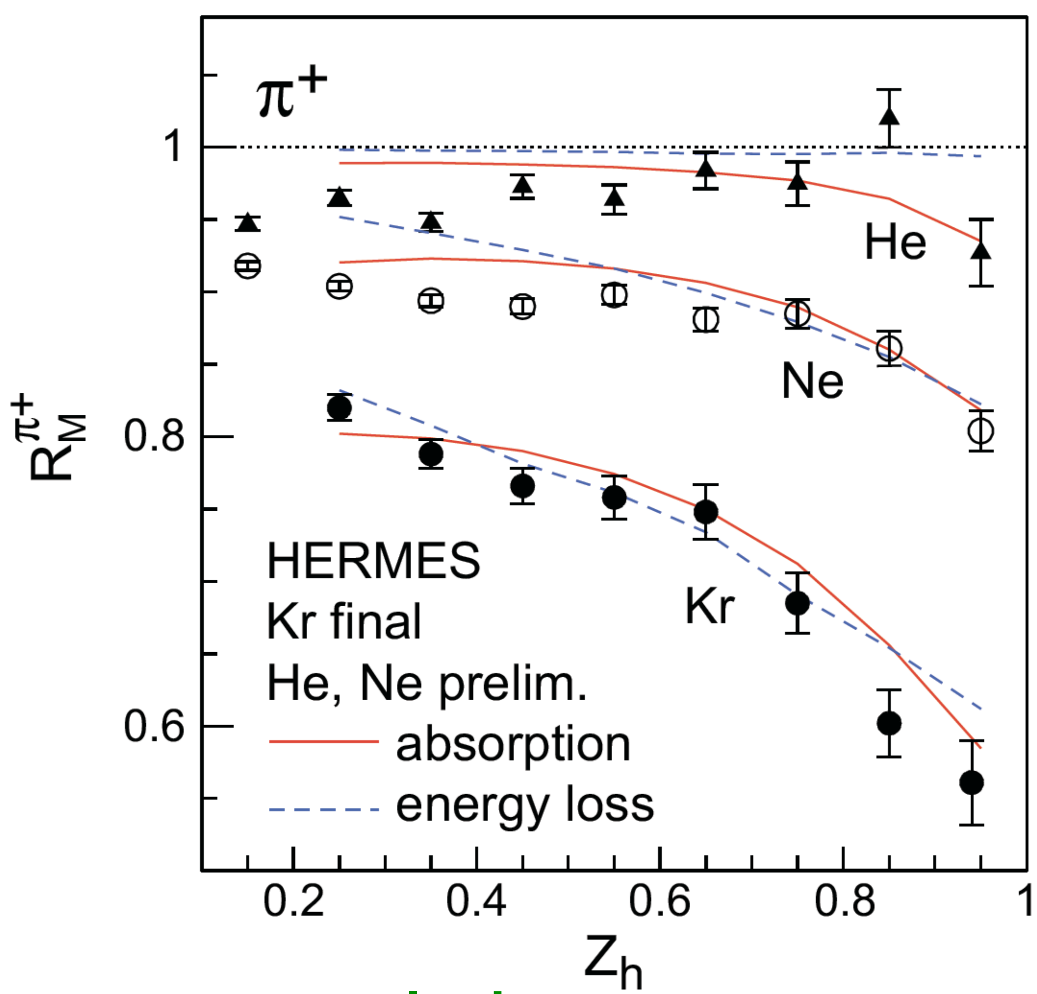
Parton energy loss vs. (pre)hadron absorption

Energy transfer in lab rest frame:
EIC: $10 < \nu < 1600$ GeV
HERMES: 2-25 GeV



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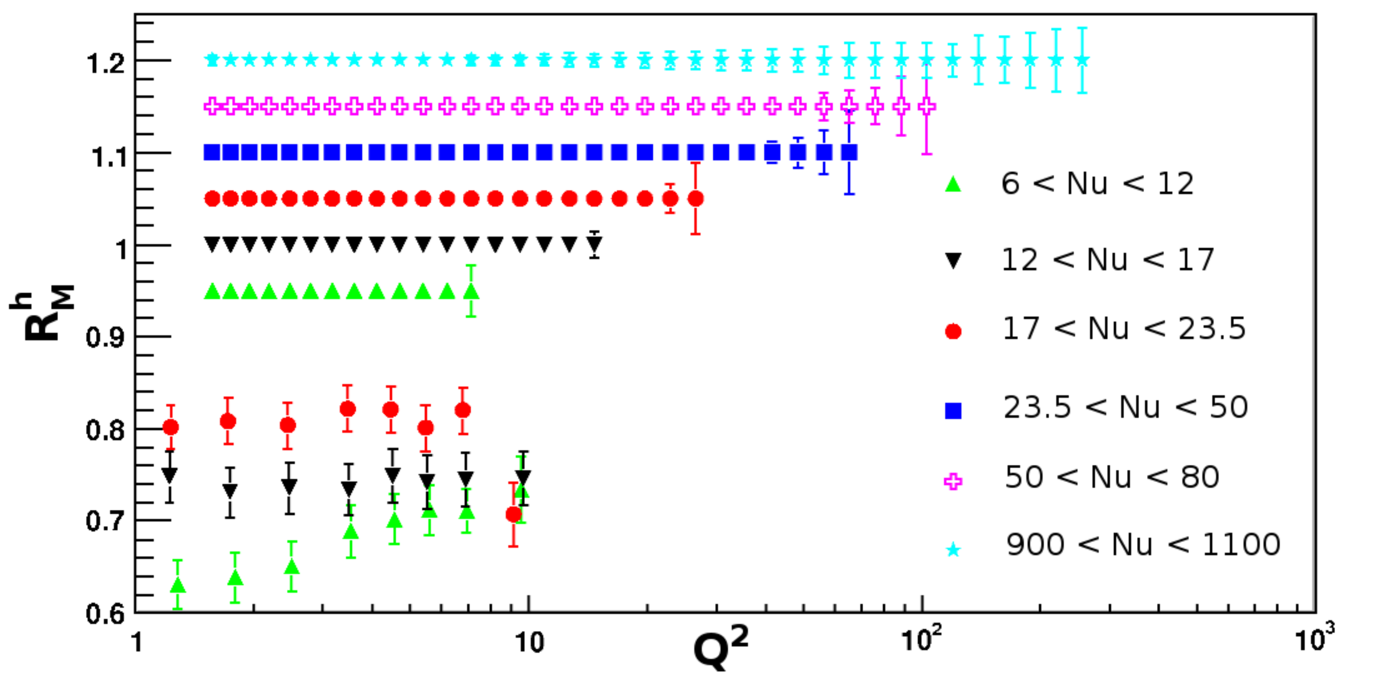

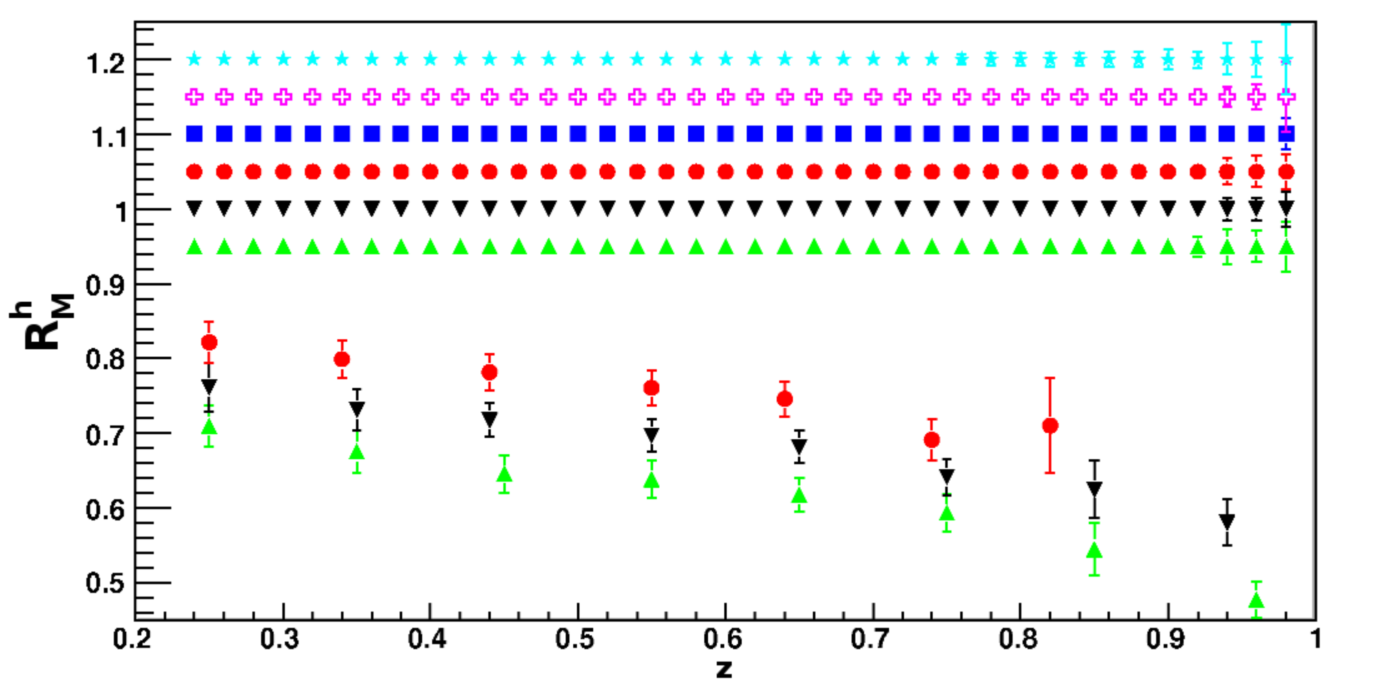

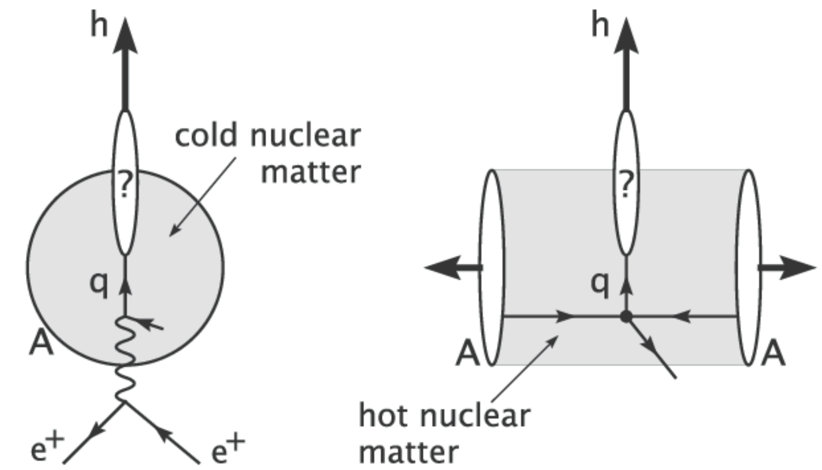

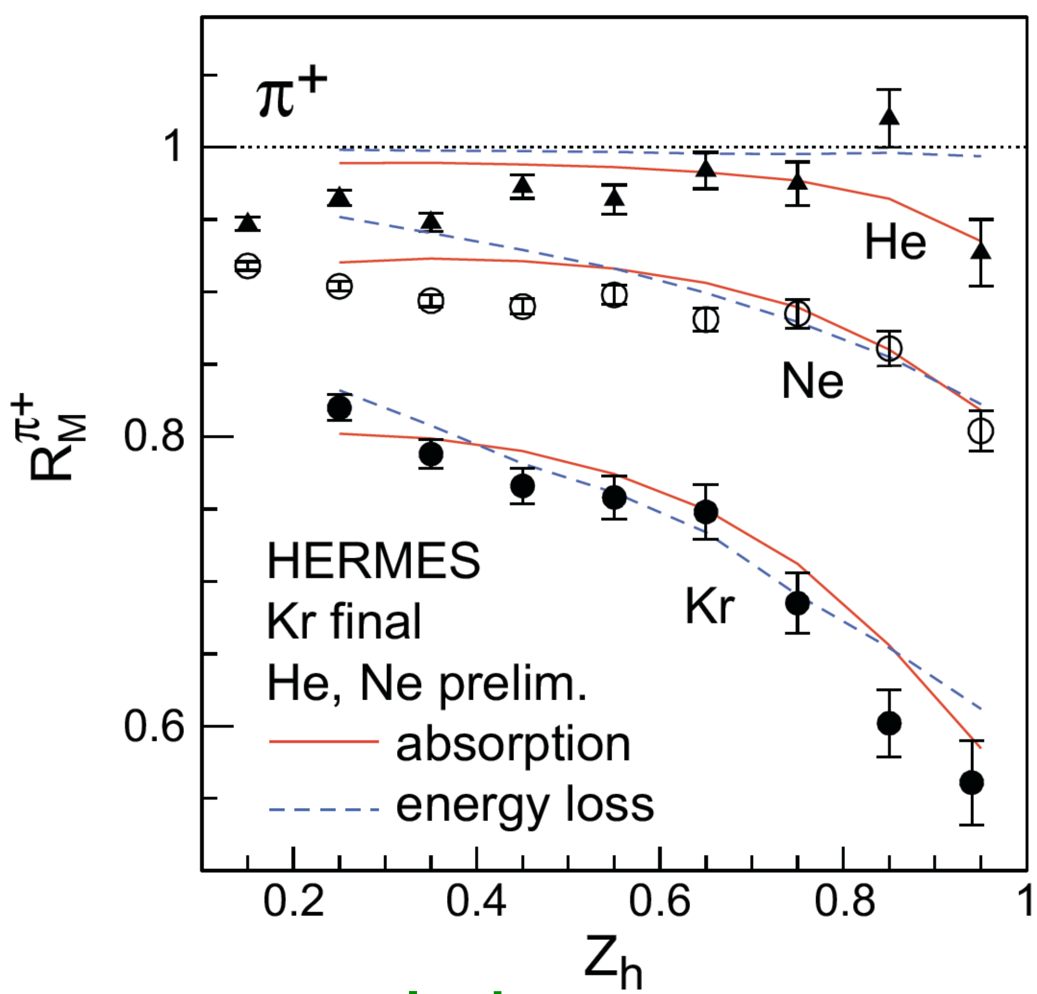

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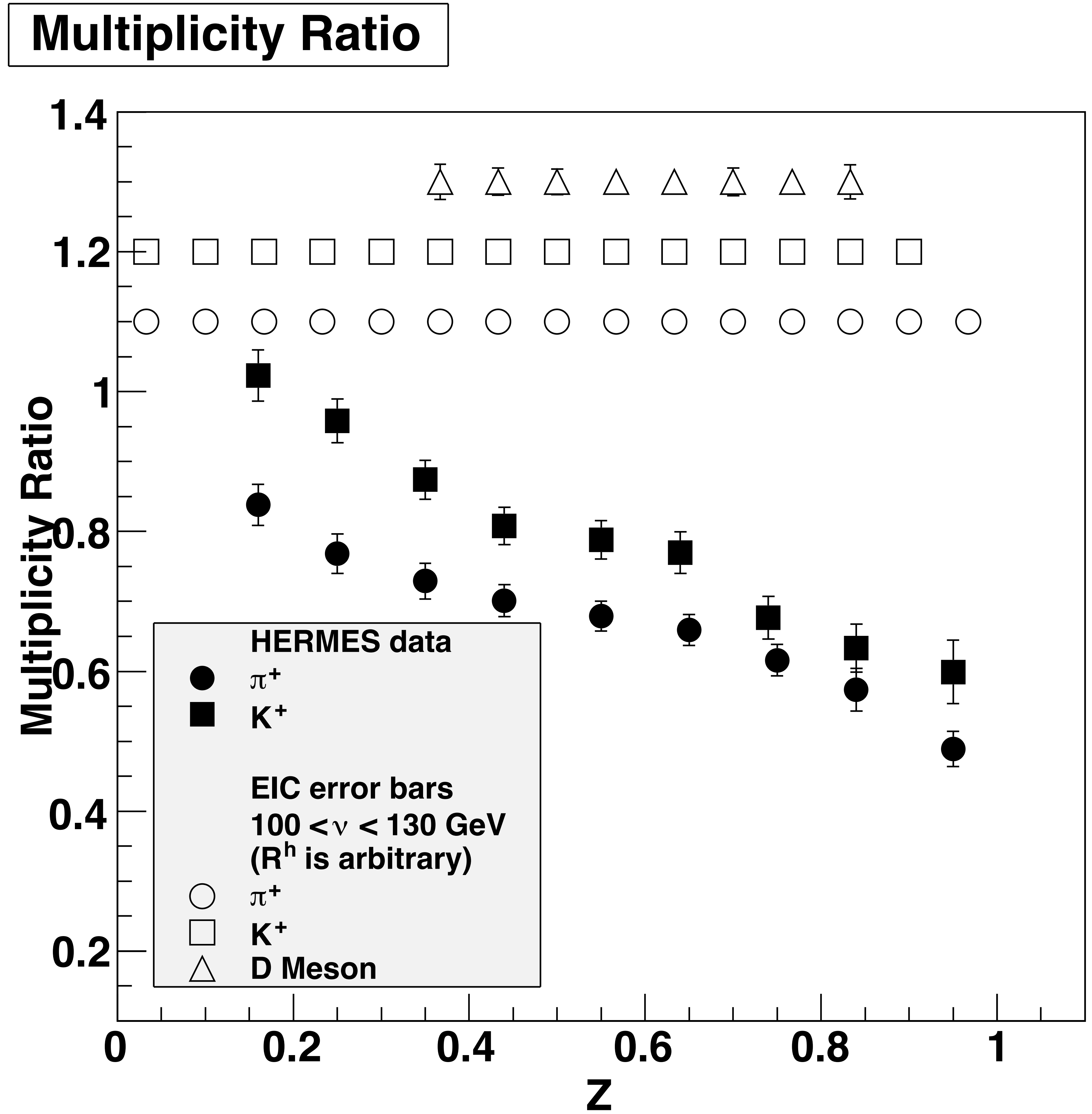

Multiplicity Ratio
1.4
1.2
1
0.8
0.6
0.4
0.2
Multiplicity Ratio
HERMES data
π+
K+
EIC error bars
100 < ν < 130 GeV
(Rh is arbitrary)
π+
K+
D Meson
0
0.2
0.4
0.6
0.8
1
Z