An Electron-Ion Collider at RHIC (eRHIC): A detailed study of the nucleus

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BNL

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Lots of work recently on the physics of e+A collisions

The EIC Science case: a report on the joint BNL/INT/JLab program

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

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arXiv:1108.1713

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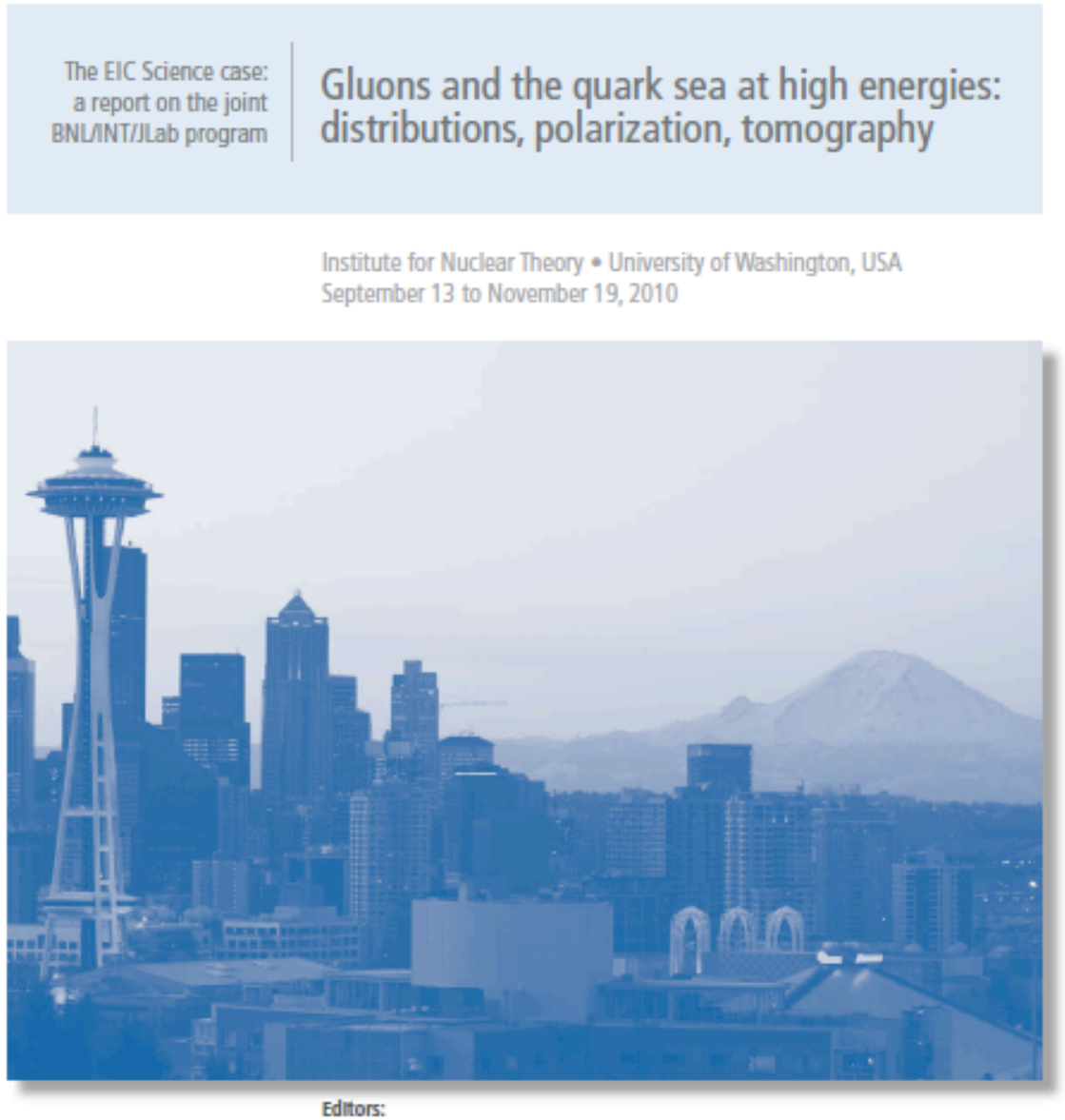

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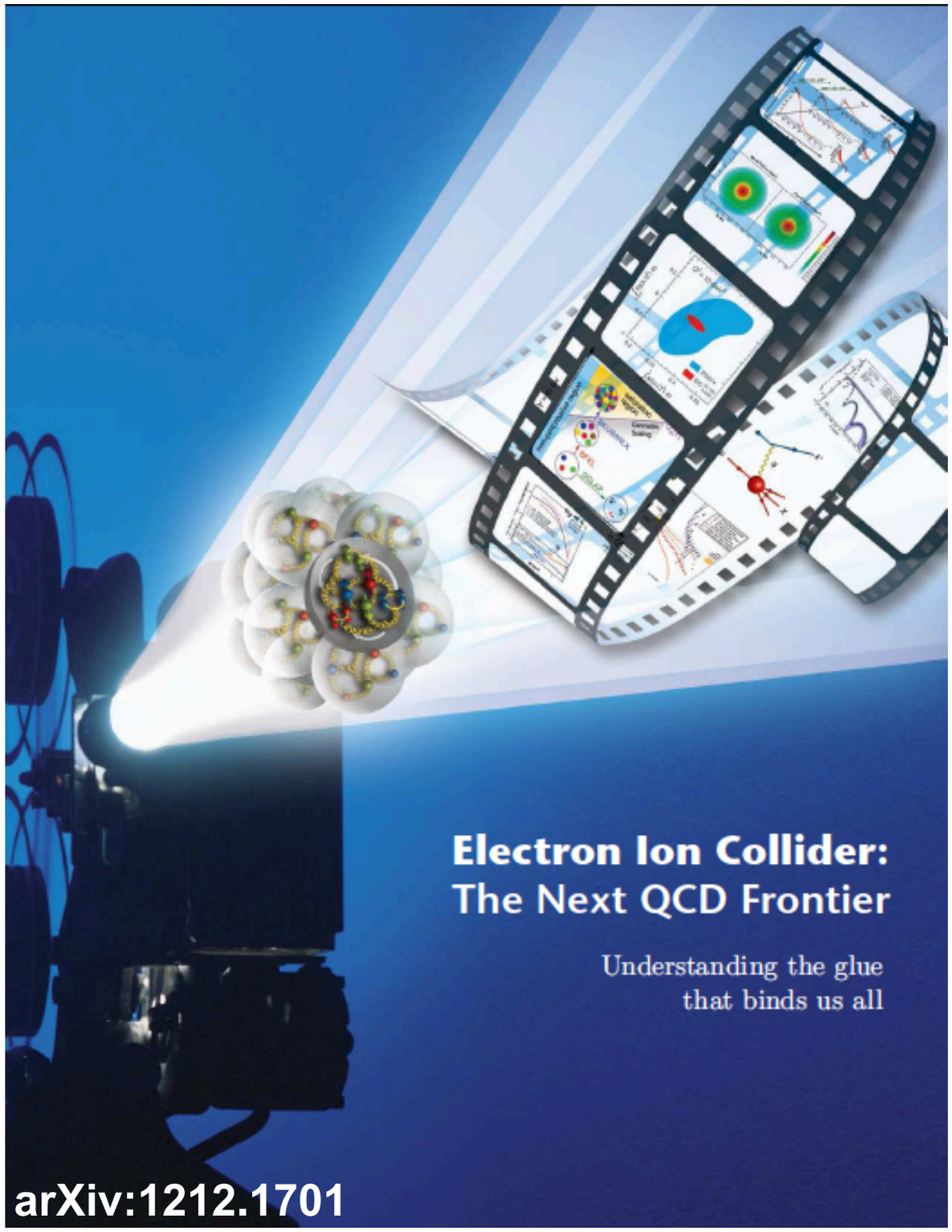
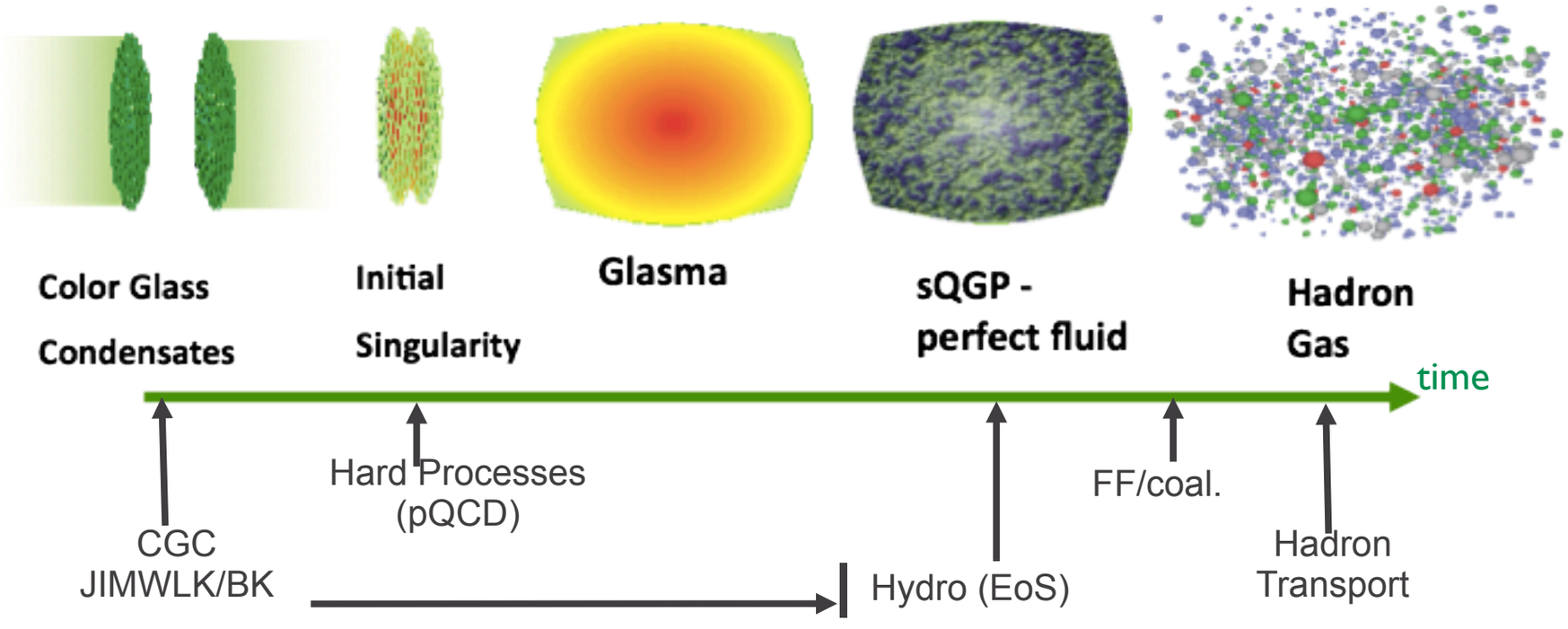
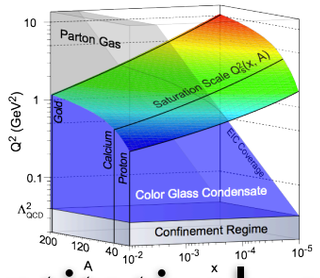


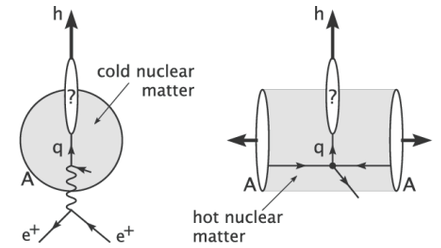
arXiv:1212.1701

Most compelling physics questions





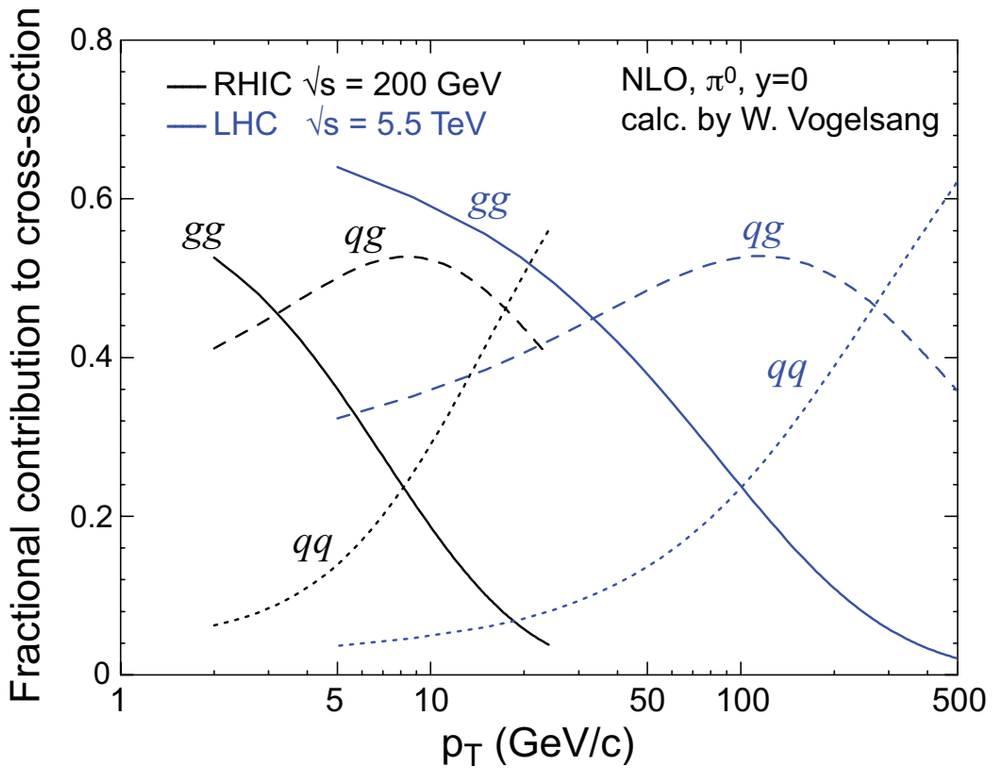
Strong Colour Fields and Hadronisation



- 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
- What is the spatial distribution of quarks and gluons in nuclei and how much does it fluctuate?
- How do hard probes in e+A interact with the medium?

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

The need to know the gluons - initial conditions



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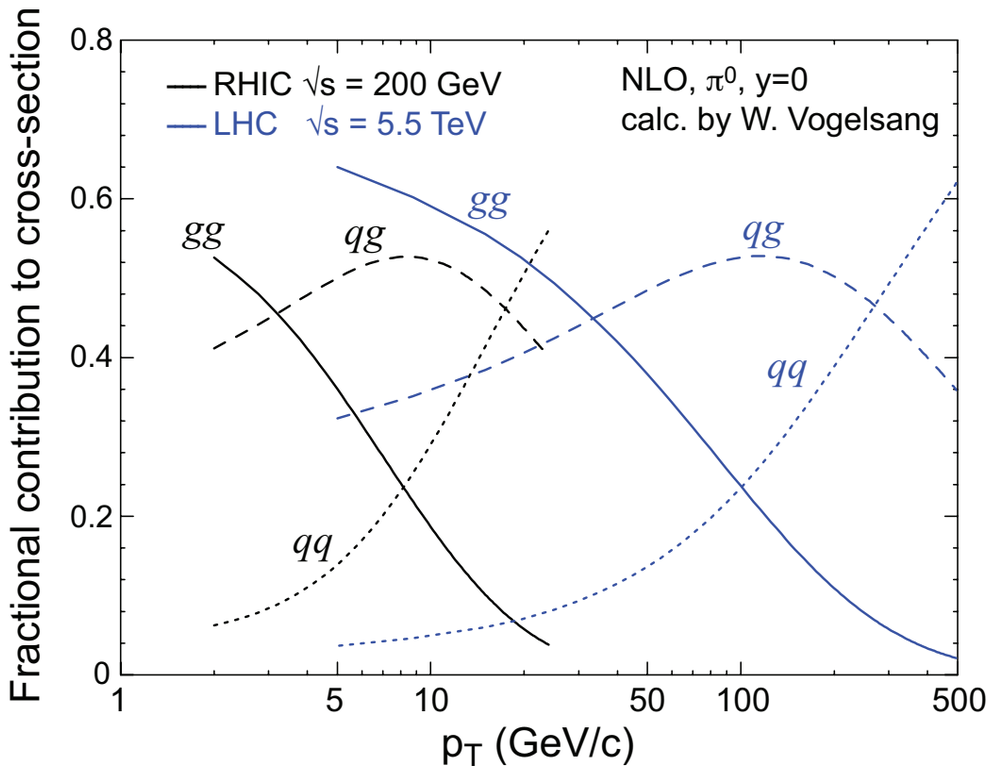

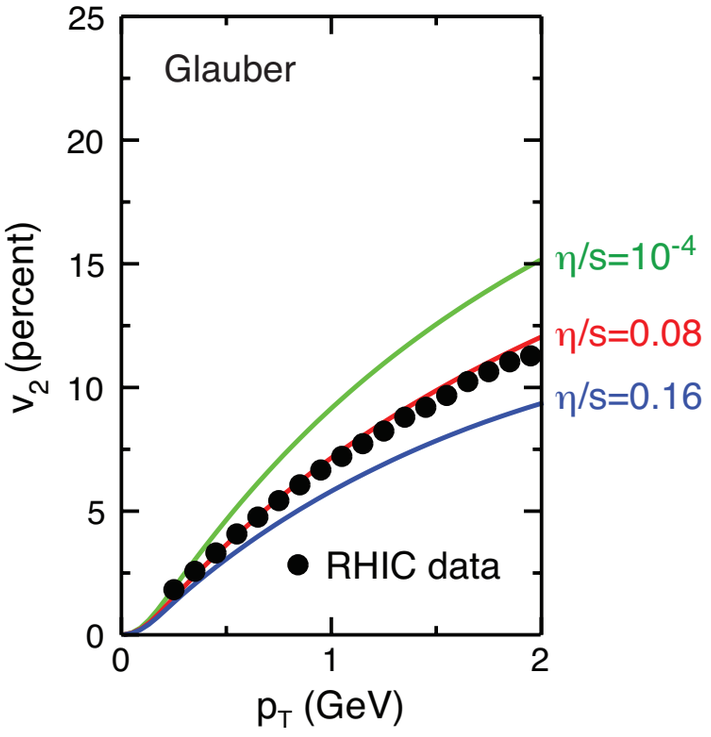

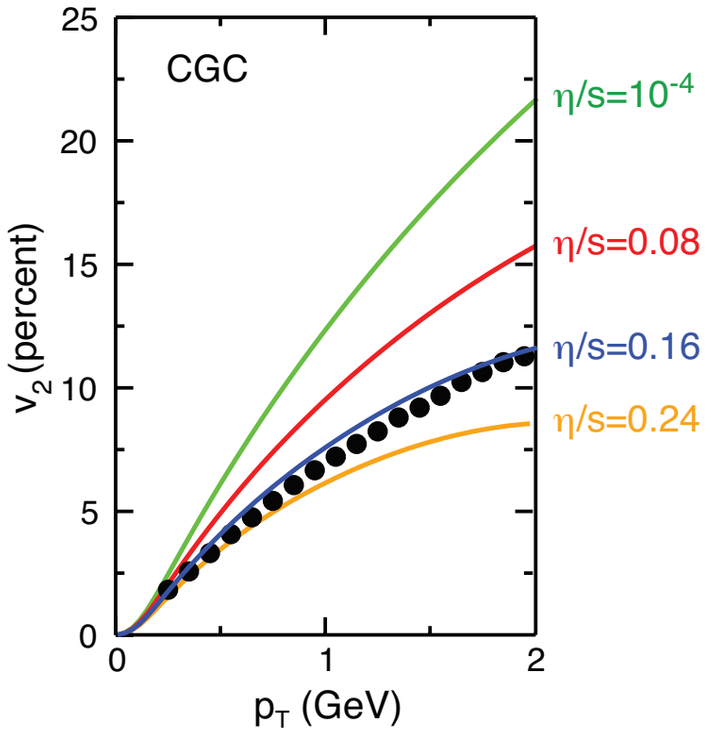

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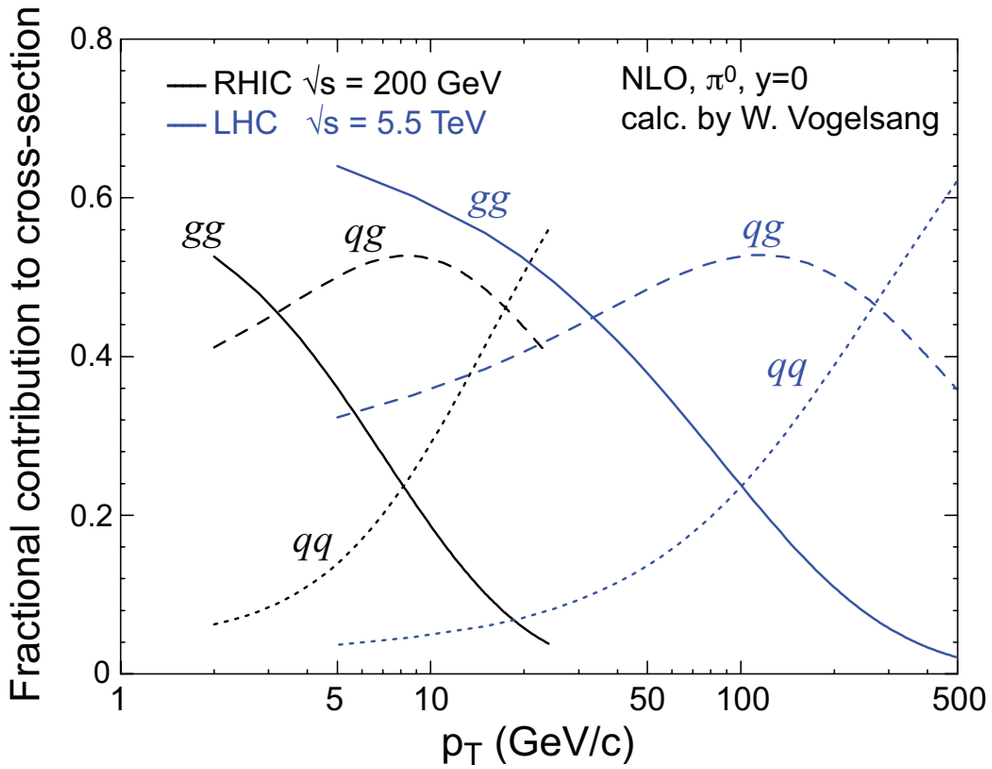

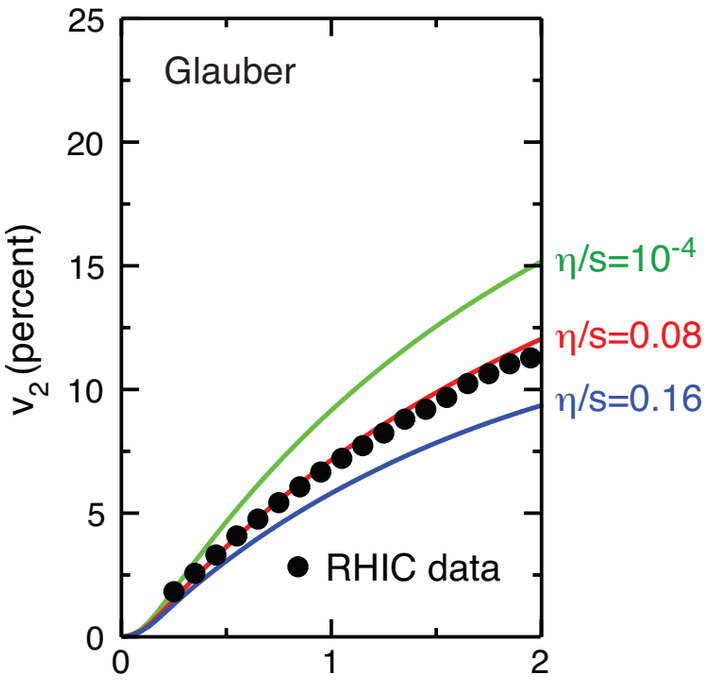

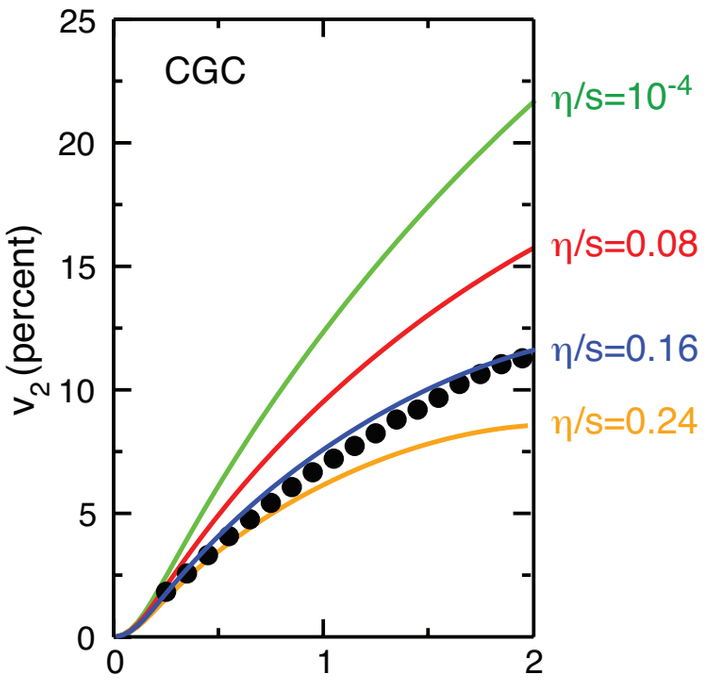

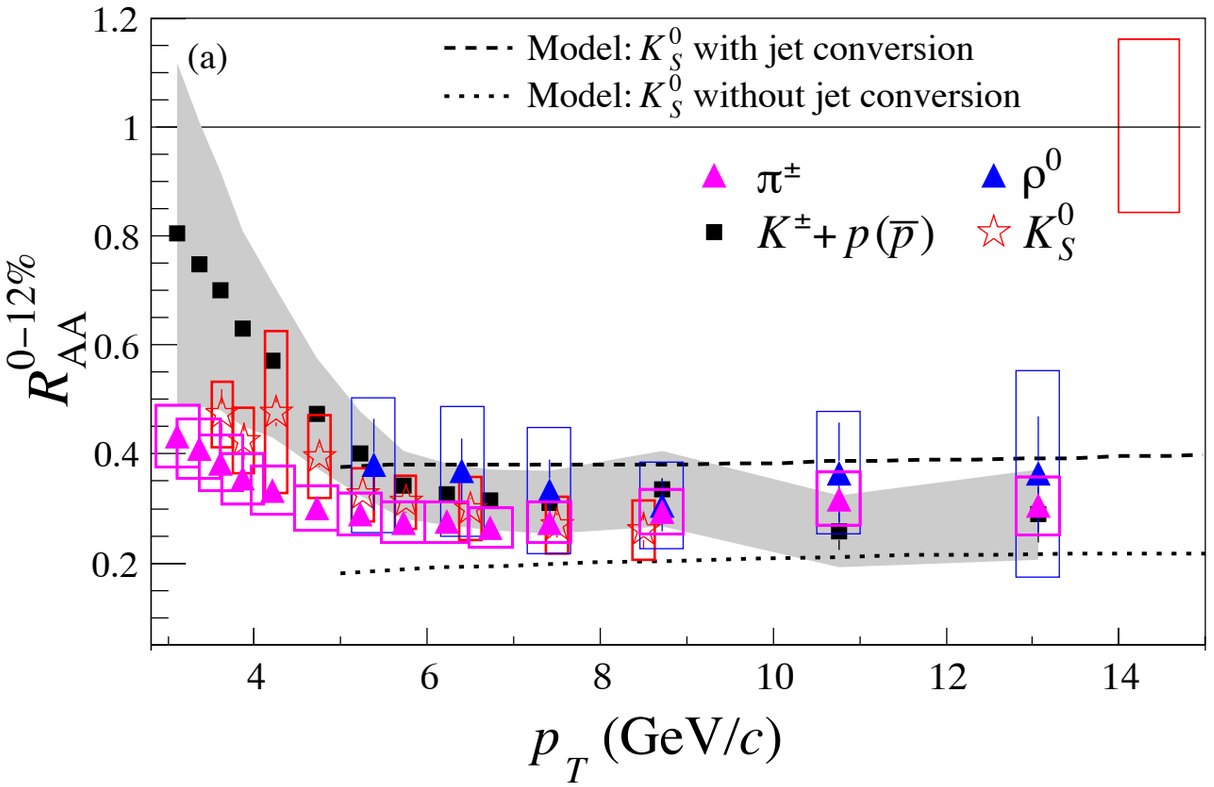

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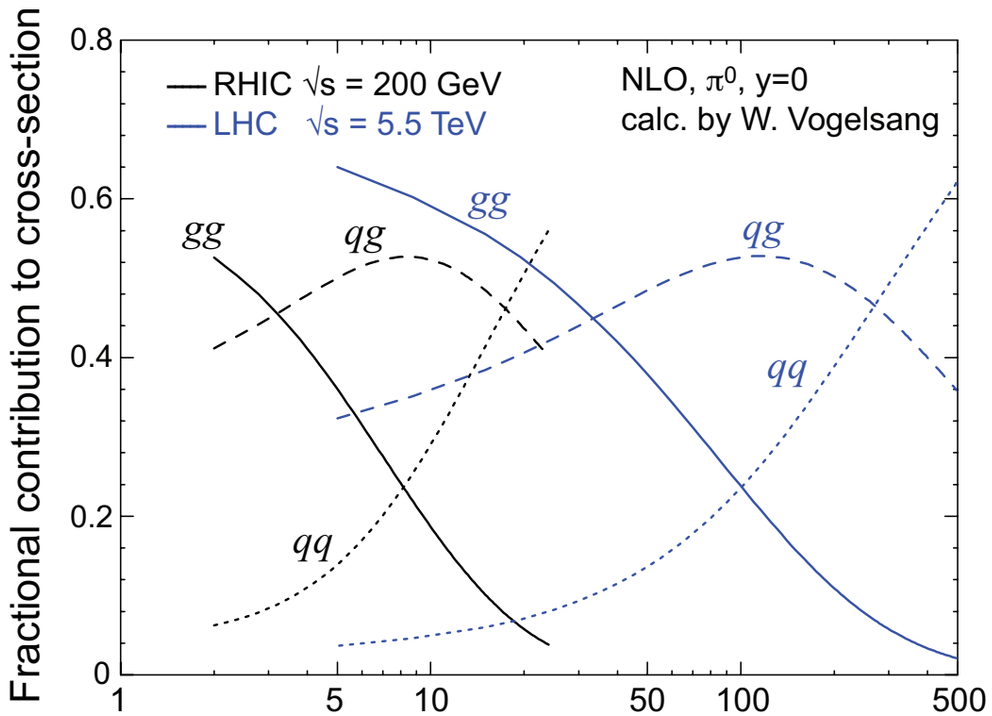
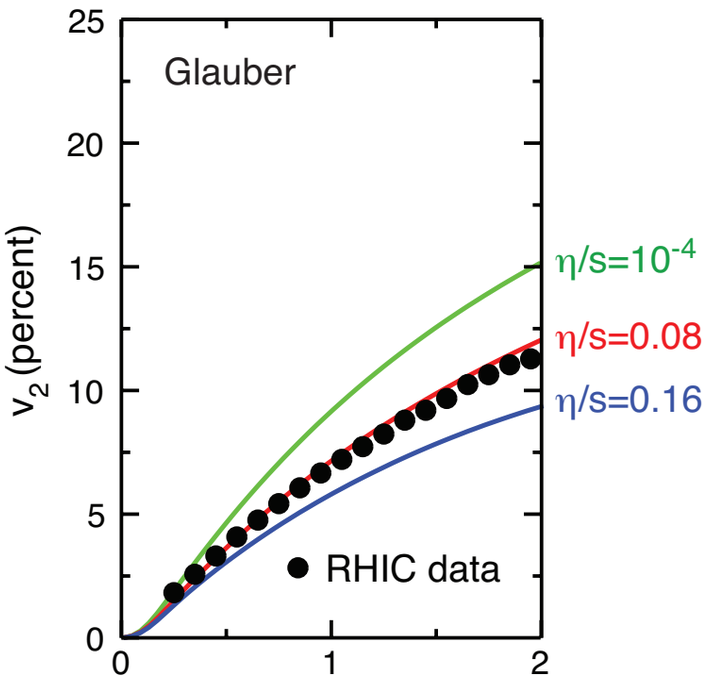
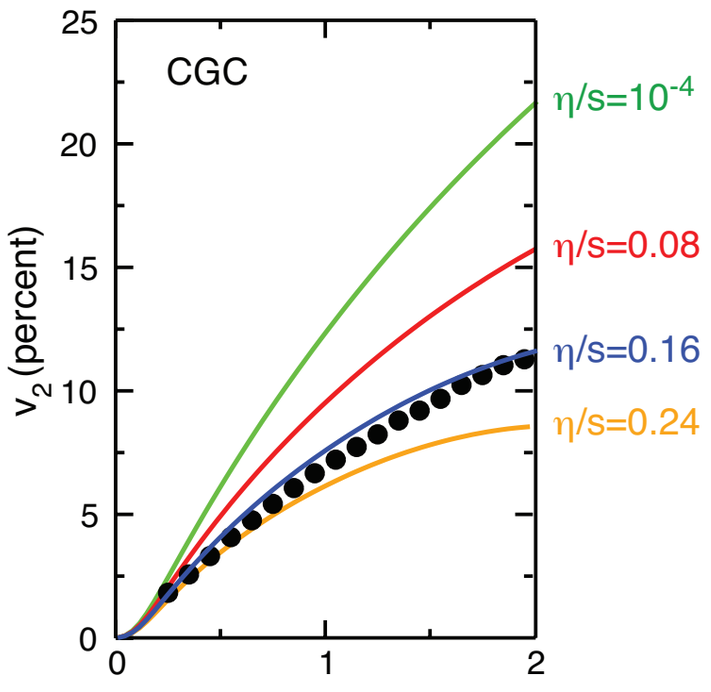
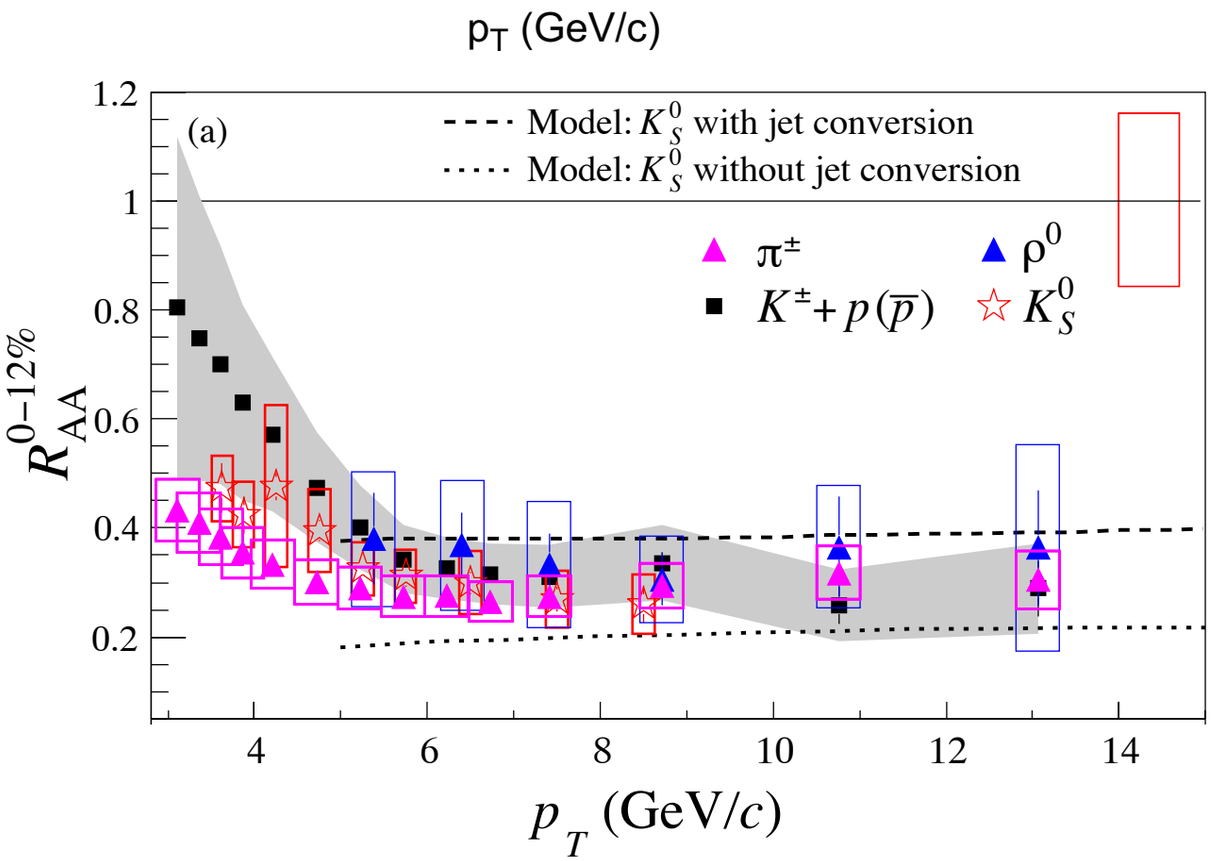
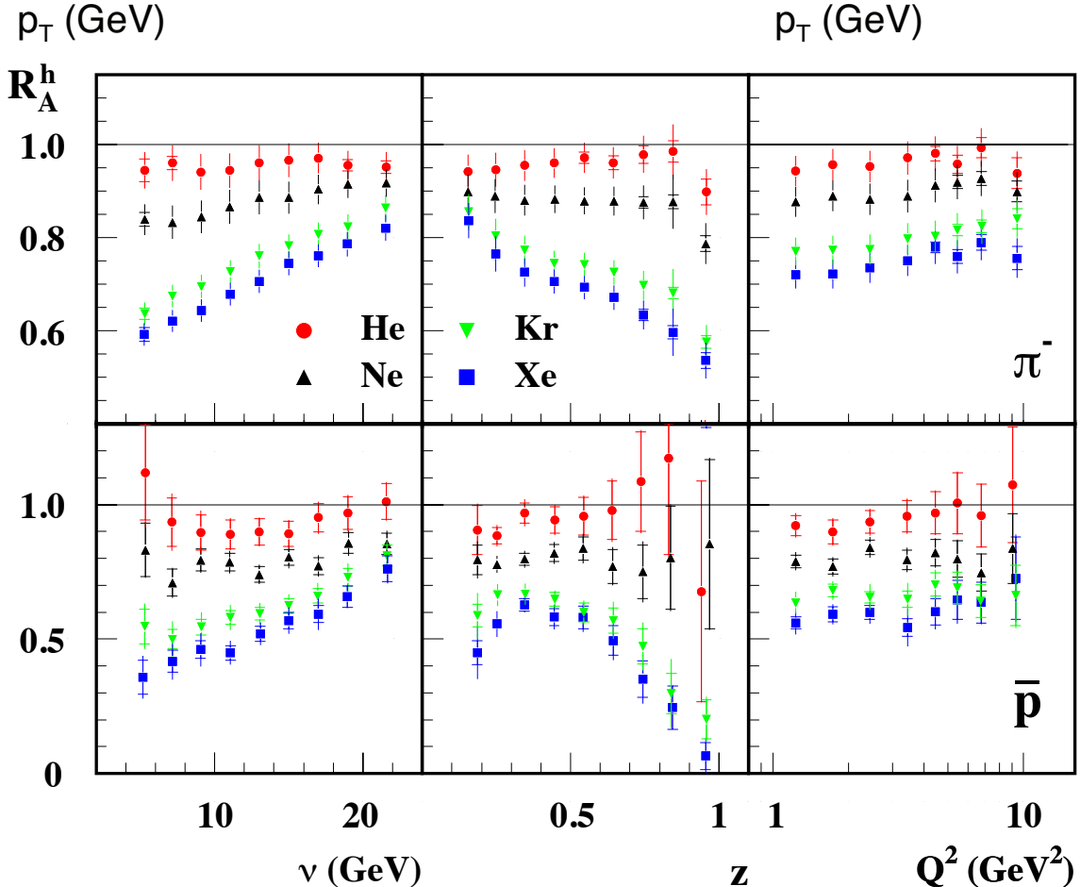




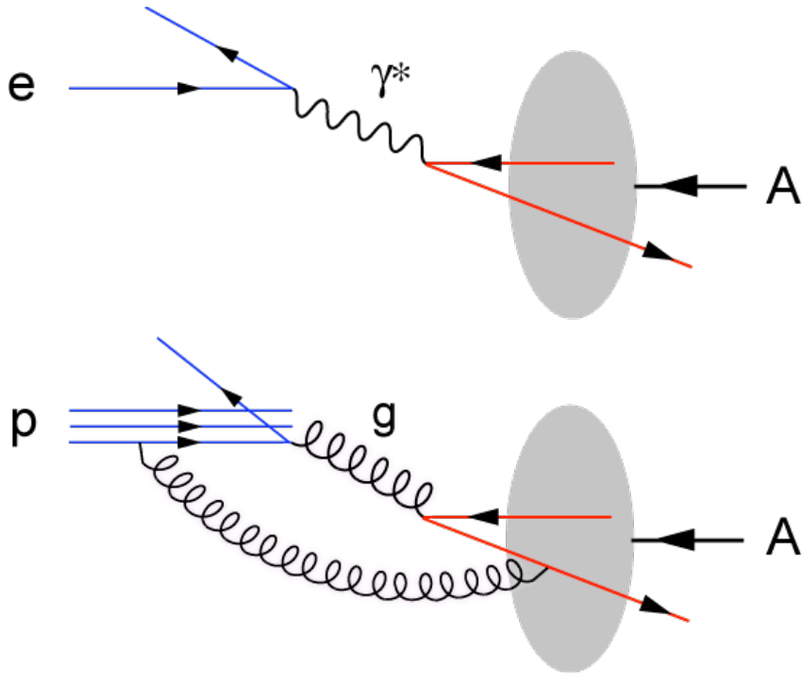






Why e+A collisions and not p+A?

- e+A and p+A provide excellent information on properties of gluons in the nuclear wave functions
- Both are complementary and offer the opportunity to perform stringent checks of factorization/universality
- Issues:
  - ➡ p+A combines initial and final state effects
  - ➡ multiple colour interactions in p+A
  - ➡ p+A lacks the direct access to x, Q^2



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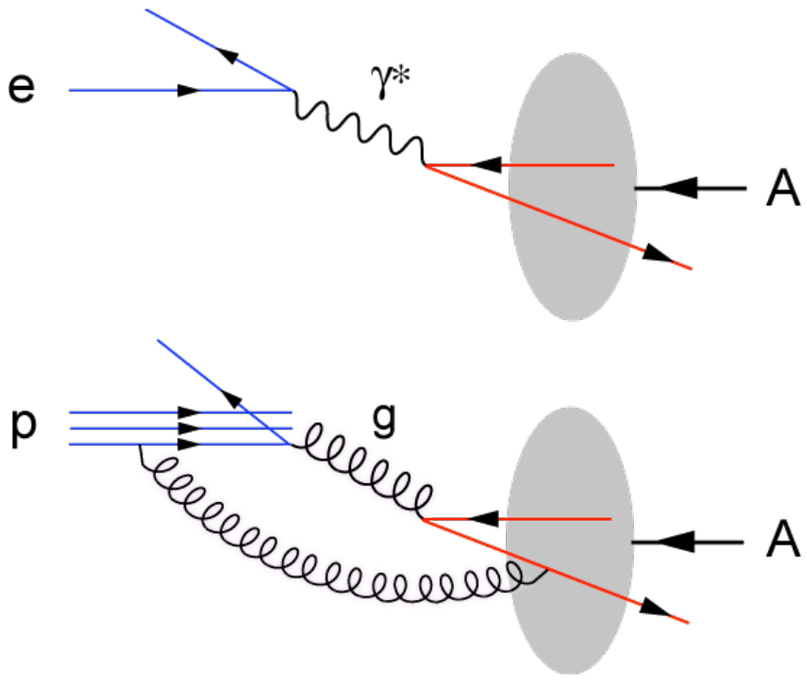

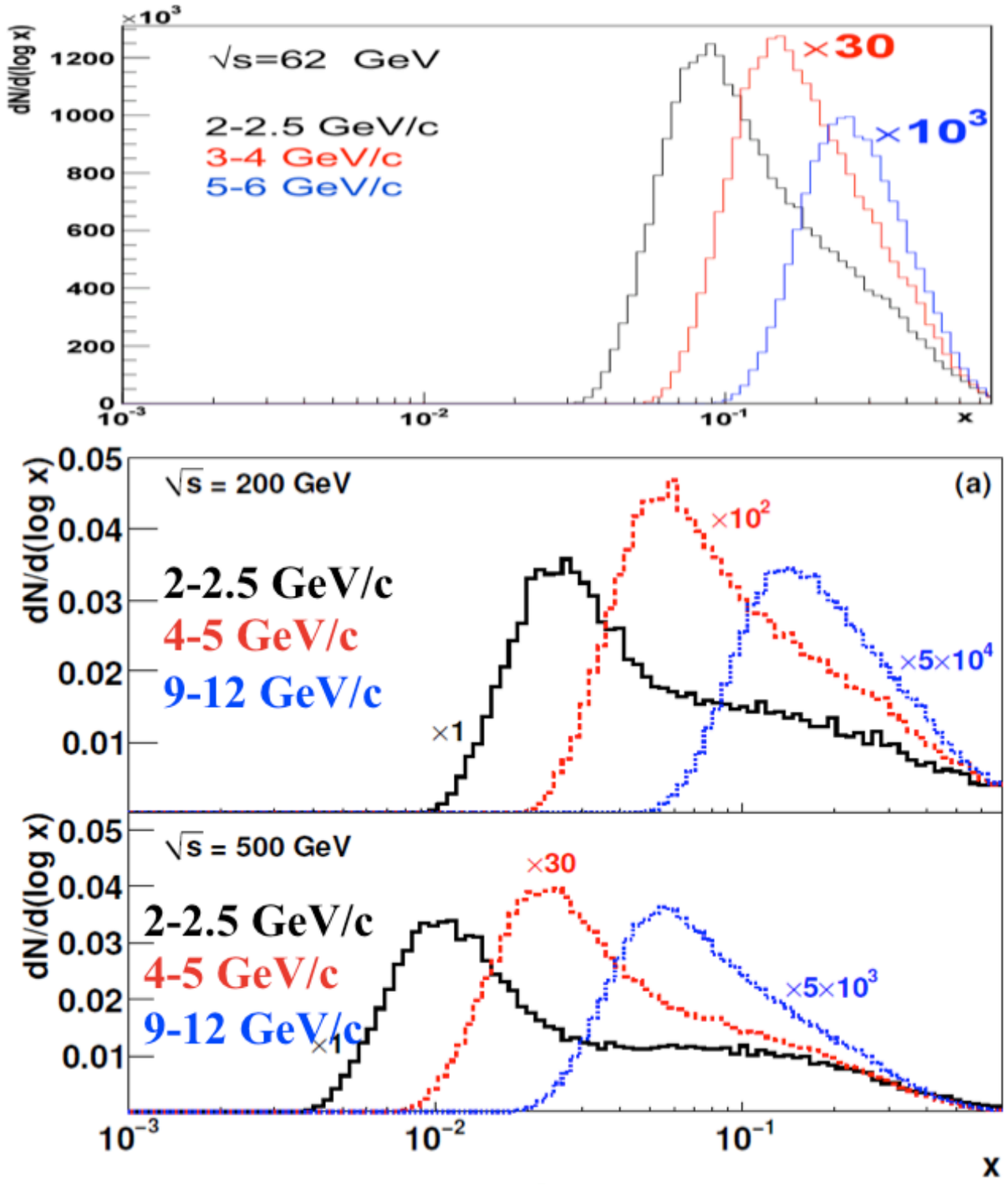

p_T - x correlation in p+p

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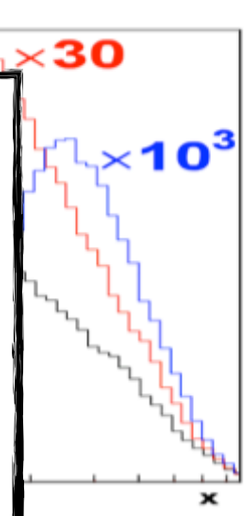
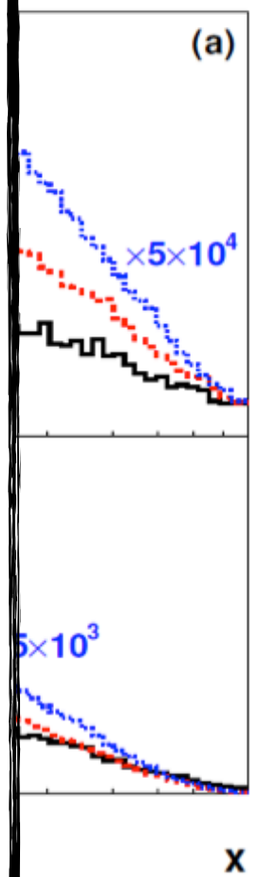
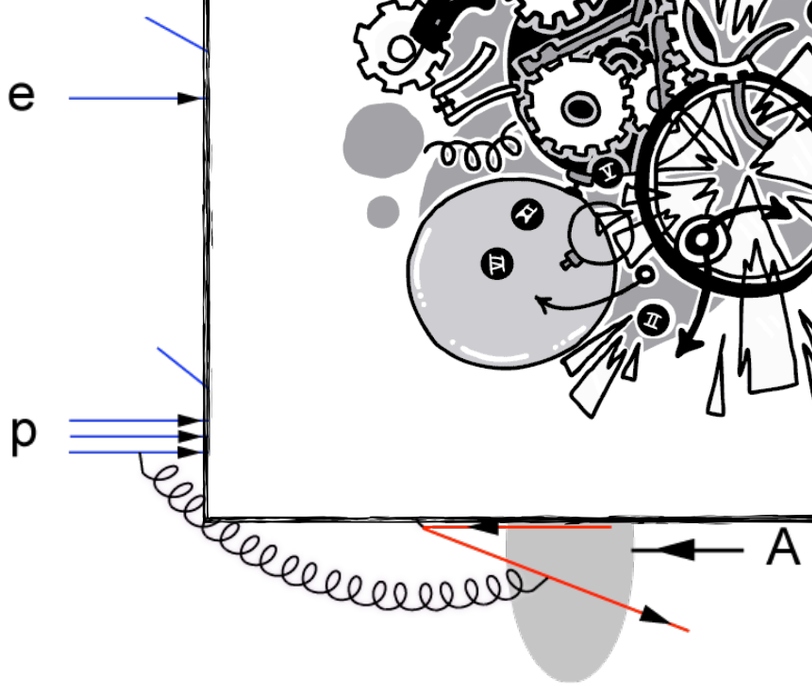
Scattering of protons on protons
is like colliding Swiss watches to find out how they are built.

R. Feynman







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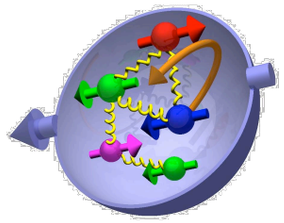
Most compelling physics questions

Spin physics

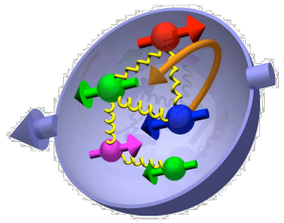


- What is the polarisation of gluons at small x where they dominate?
- What is the x-dependence and flavour decomposition of the polarised sea?

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

Constraining Δg(x) at RHIC, EIC

Spin physics



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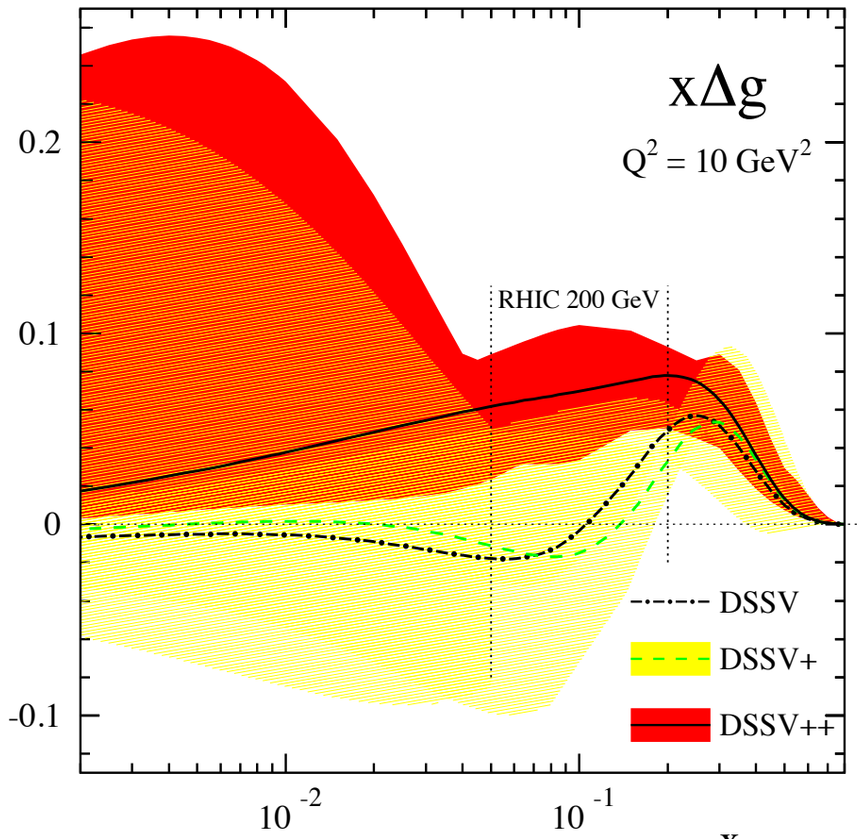

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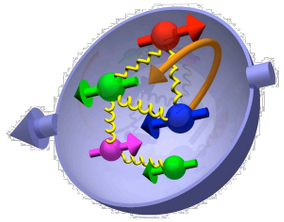

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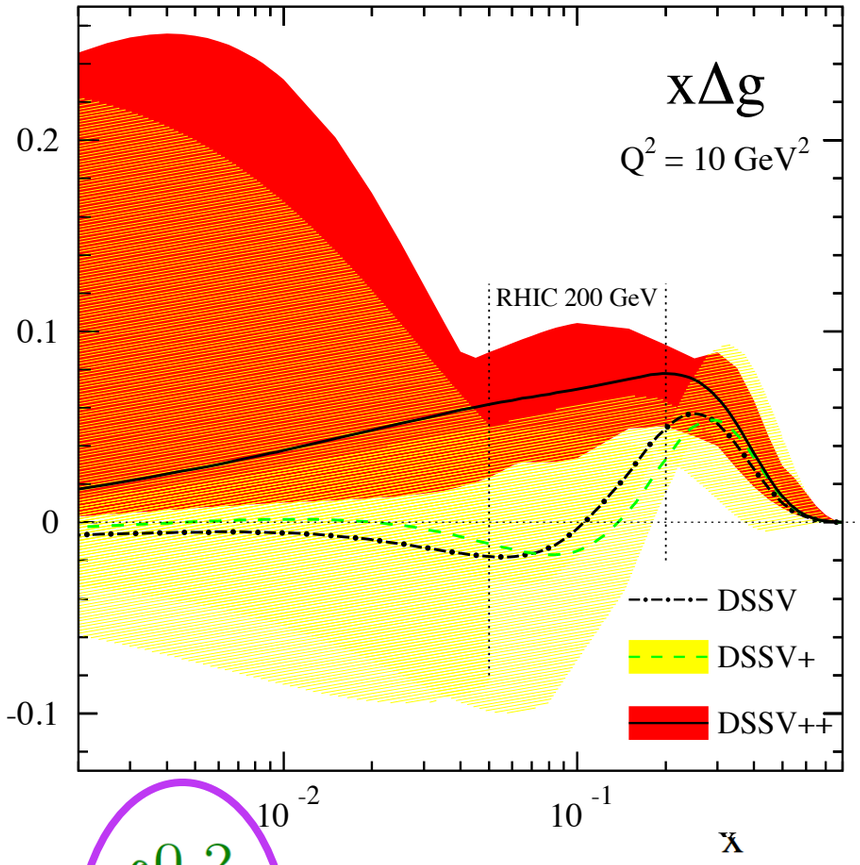

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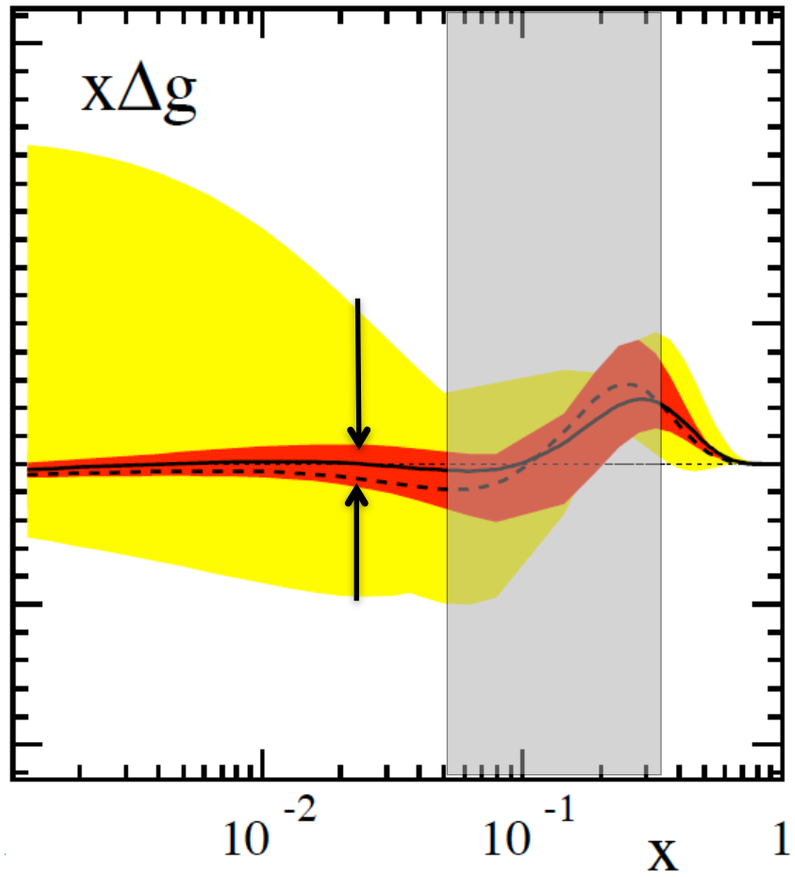
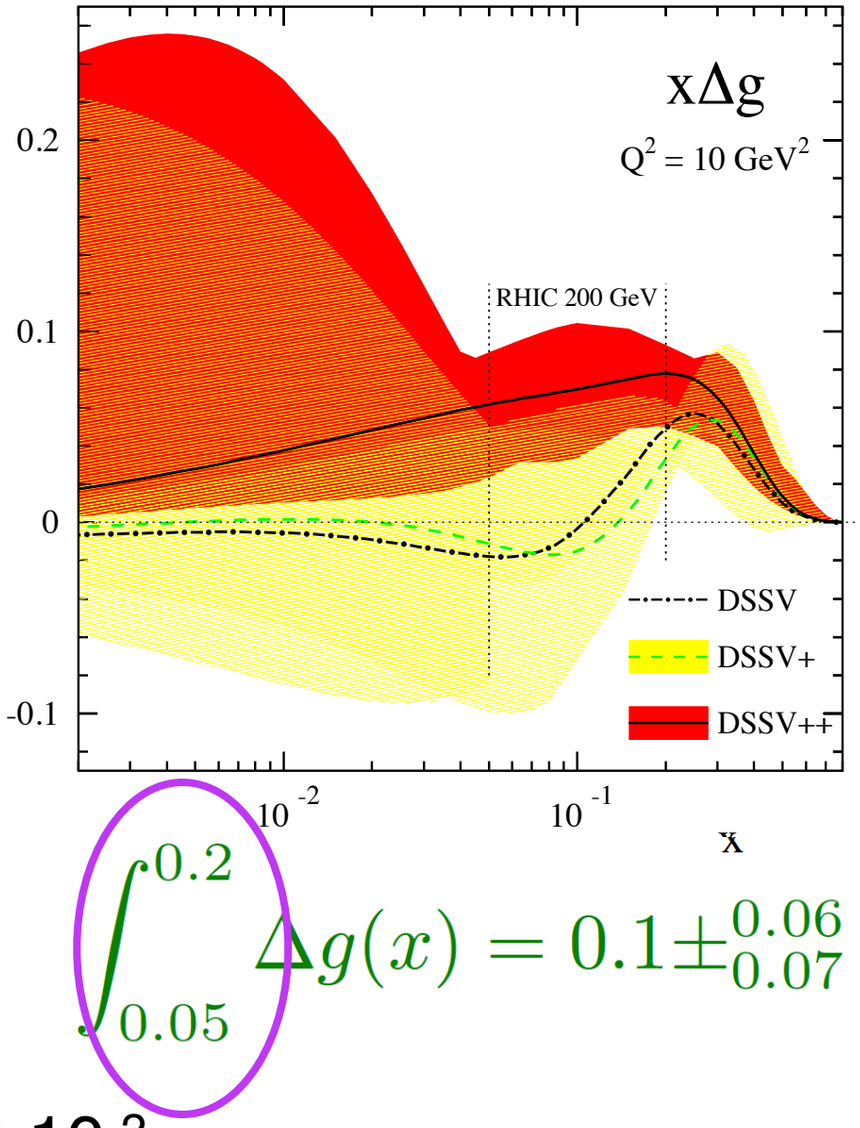


RHIC coverage

DSSV

DSSV + EIC
(5x100, 5x250)



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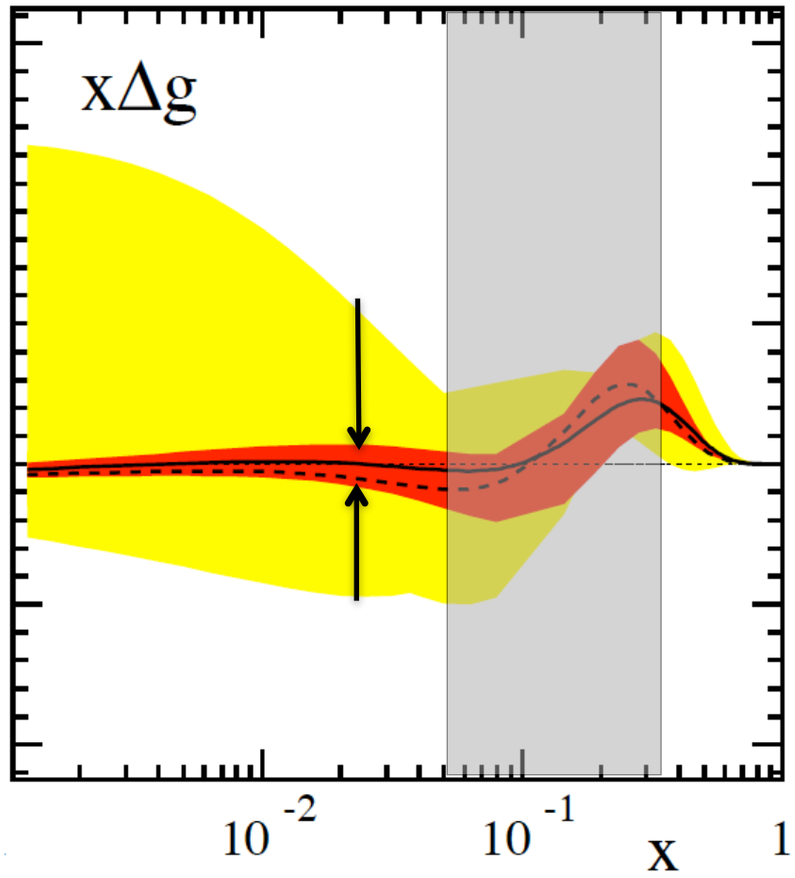

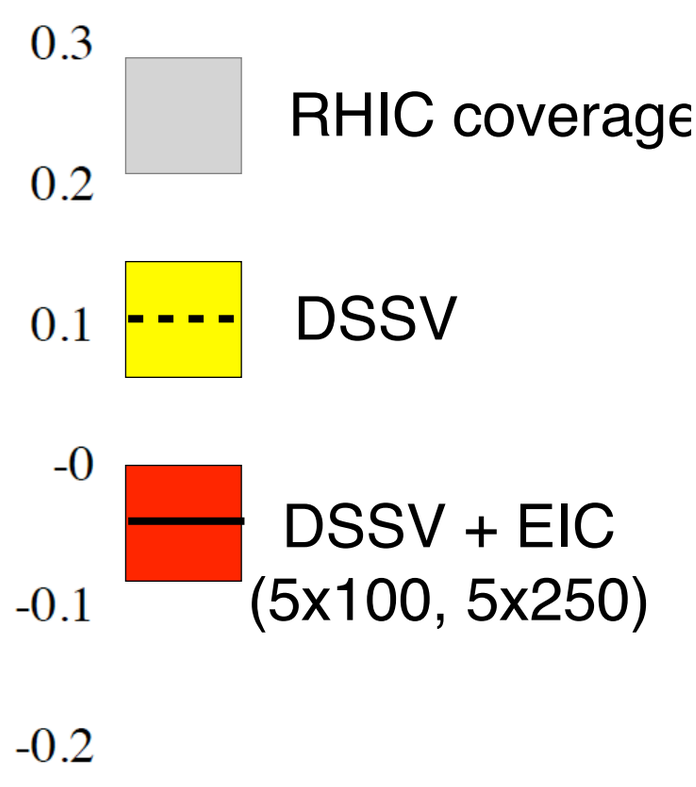

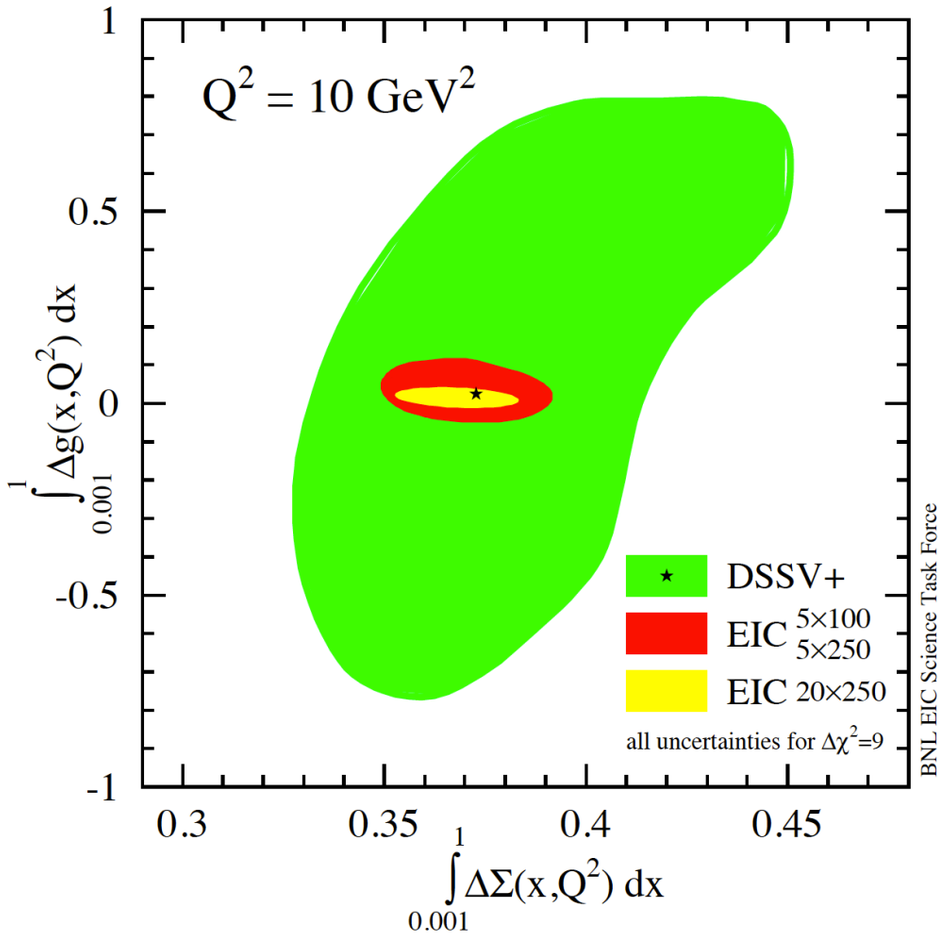

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SIDIS in e+p → flavour-separated helicity PDFs

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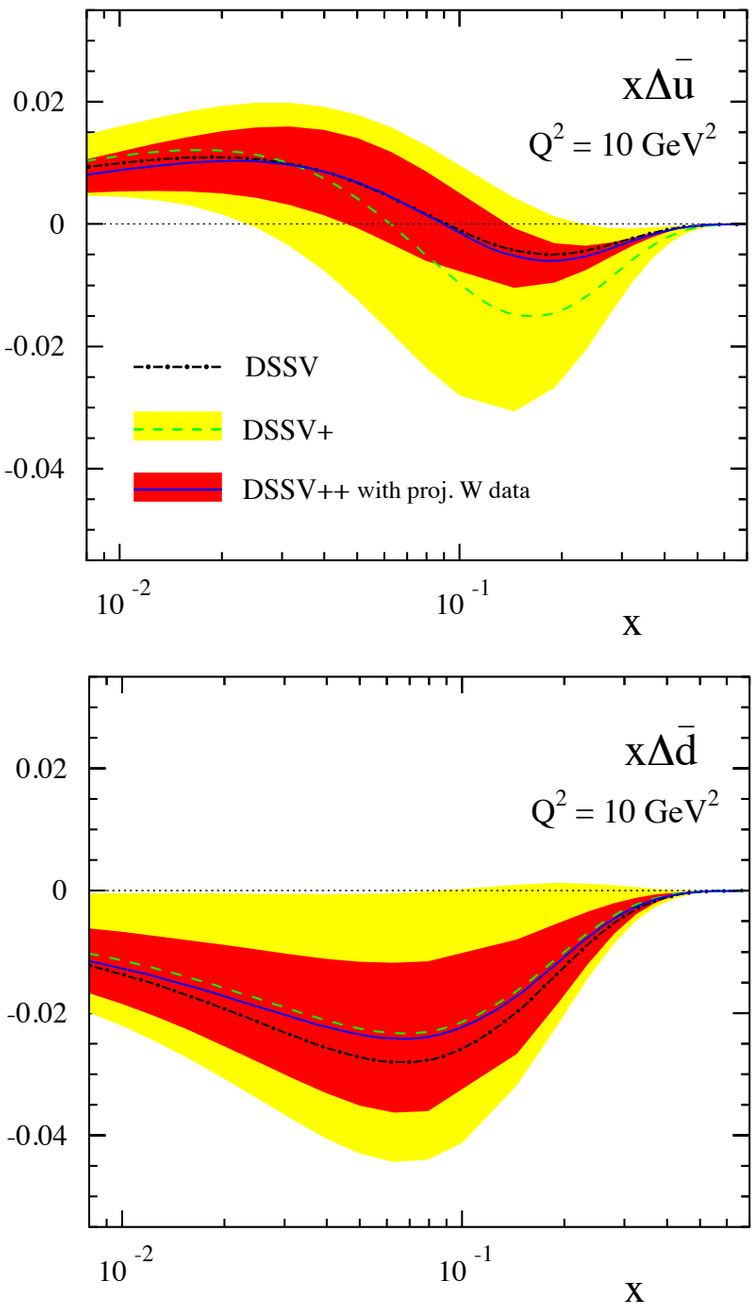

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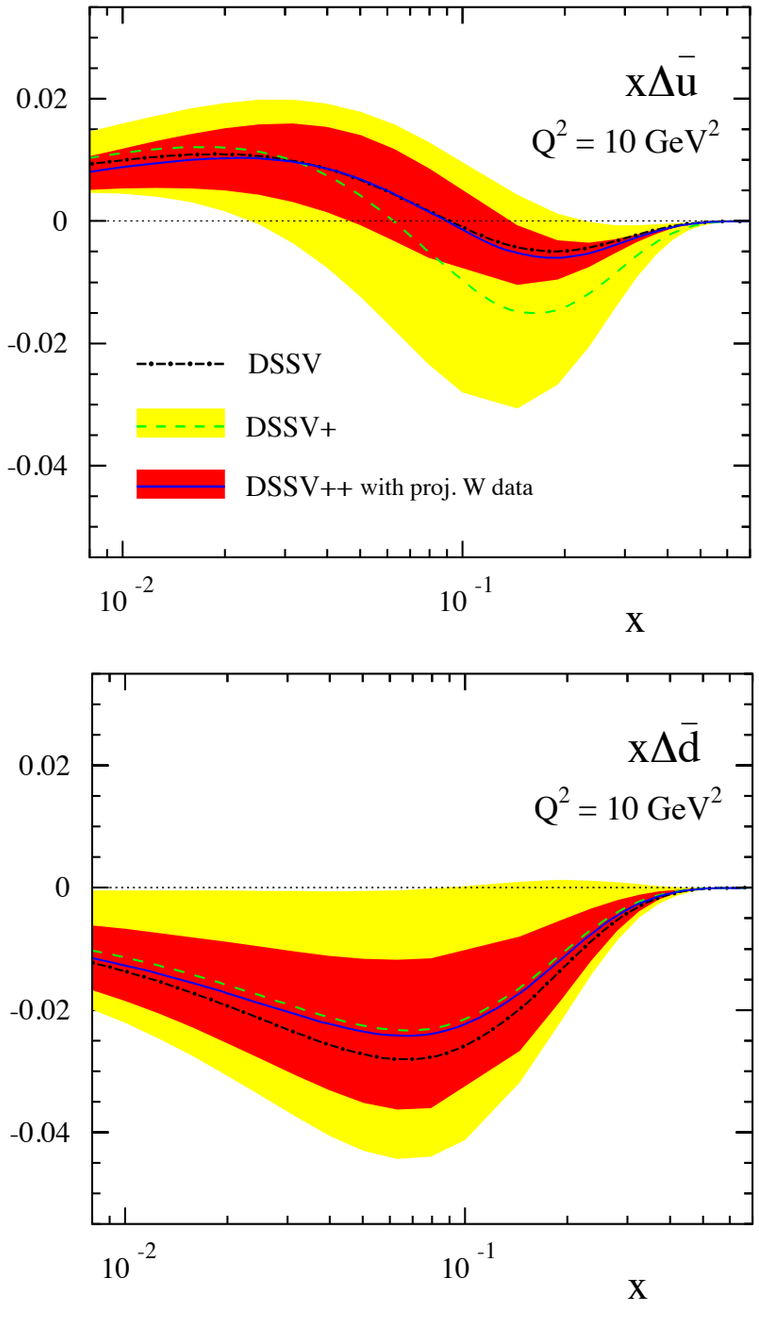
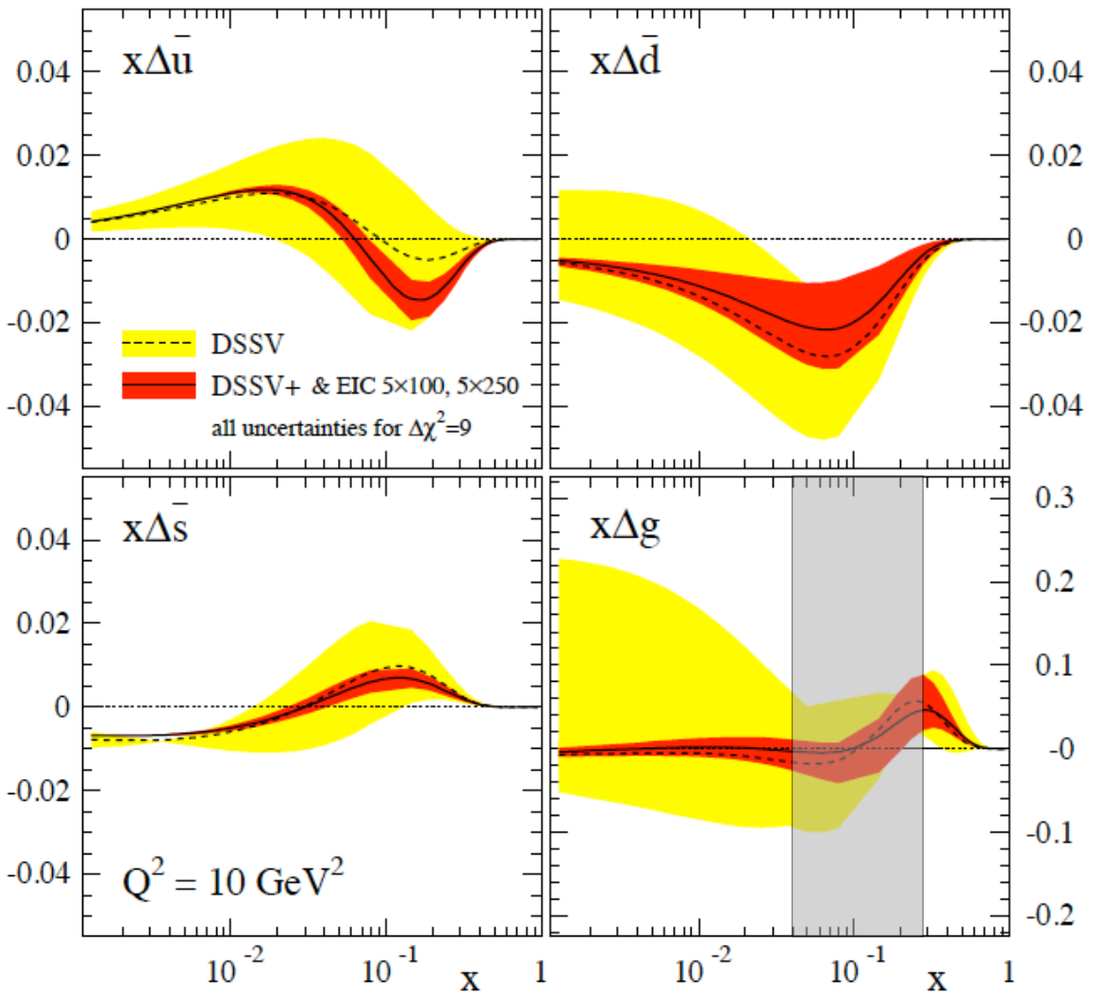


RHIC to eRHIC

smaller x; need integral from 0 to 1 for spin sum rule

Δs(s̄) cannot be accessed at existing facilities



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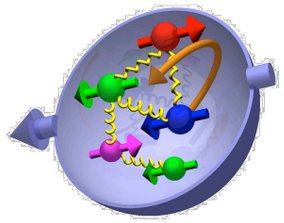

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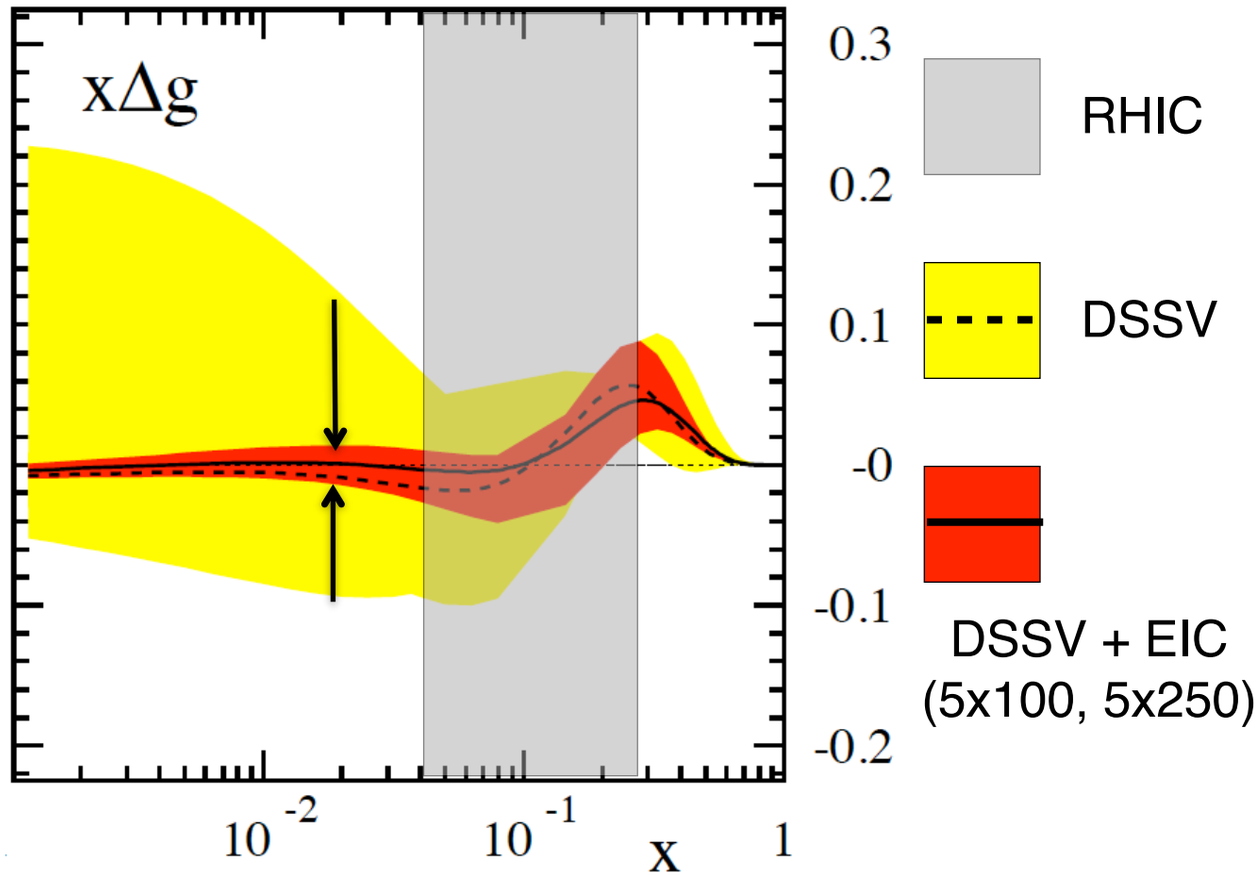
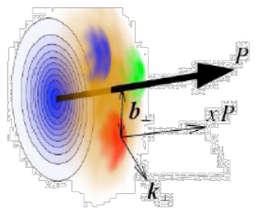
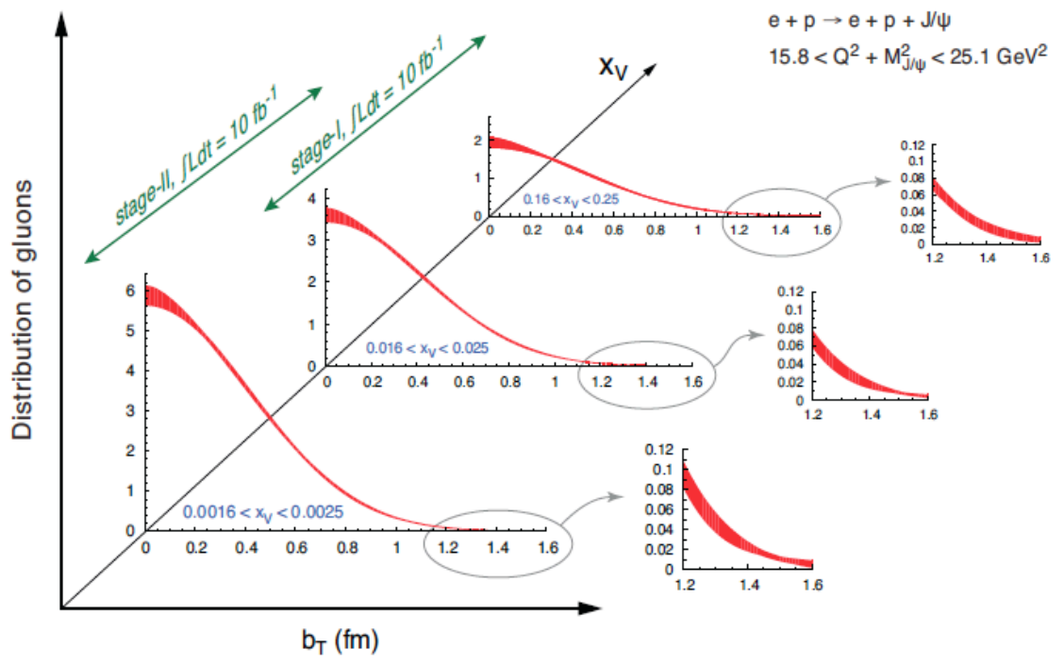


Imaging



- 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



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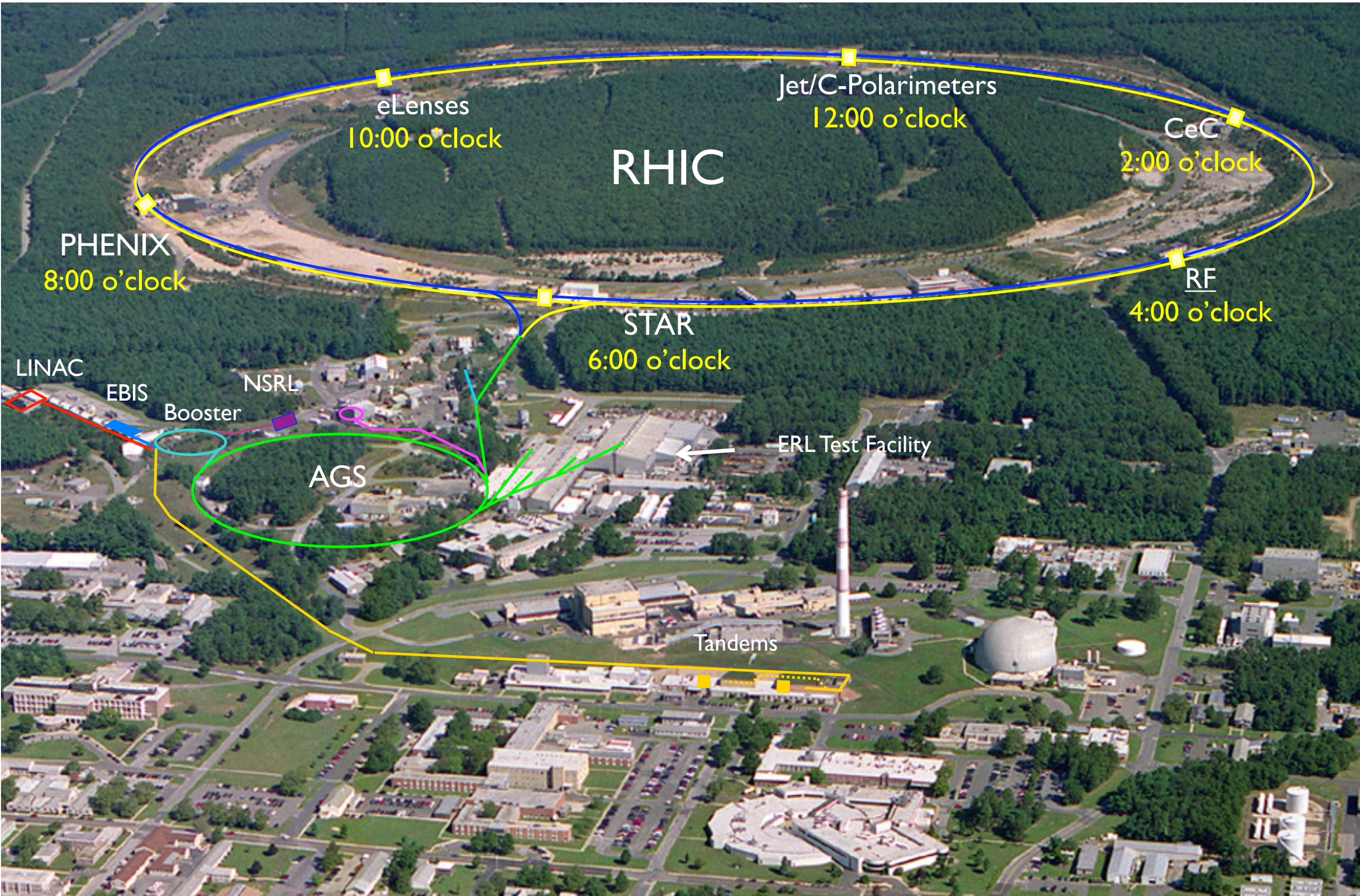

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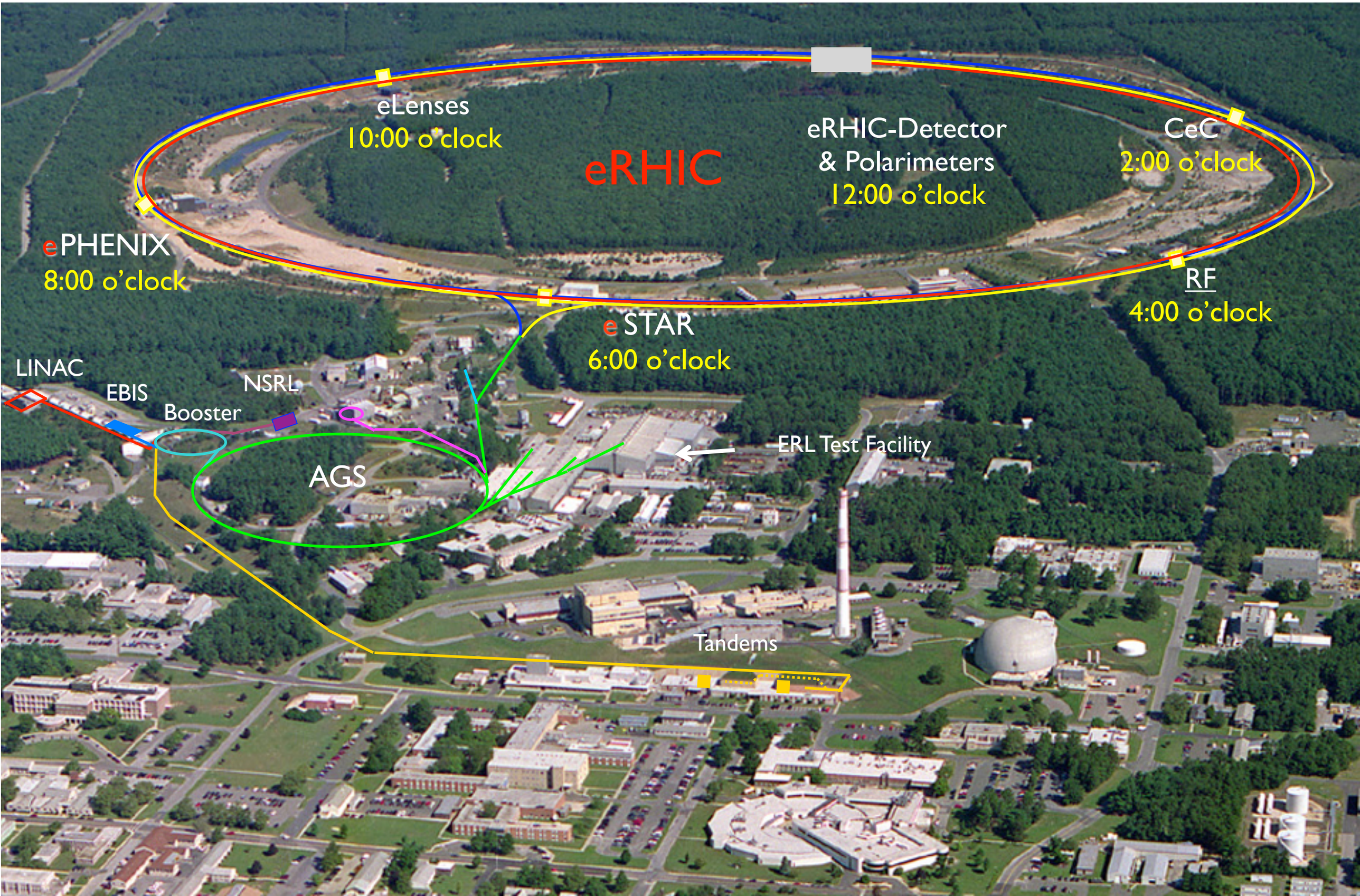
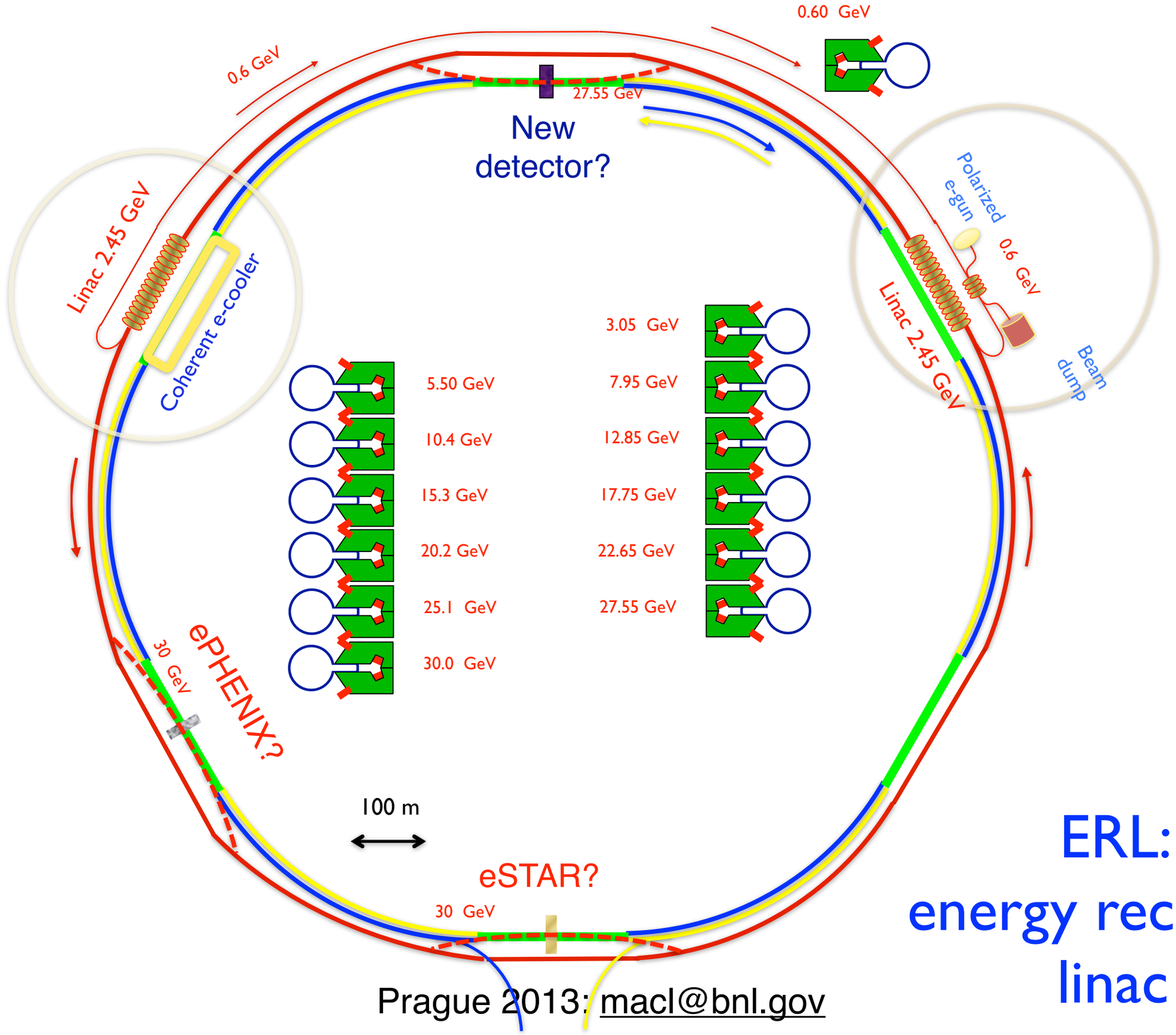


Electron beam evolution in eRHIC's ERL



ERL:
energy recovery
linac

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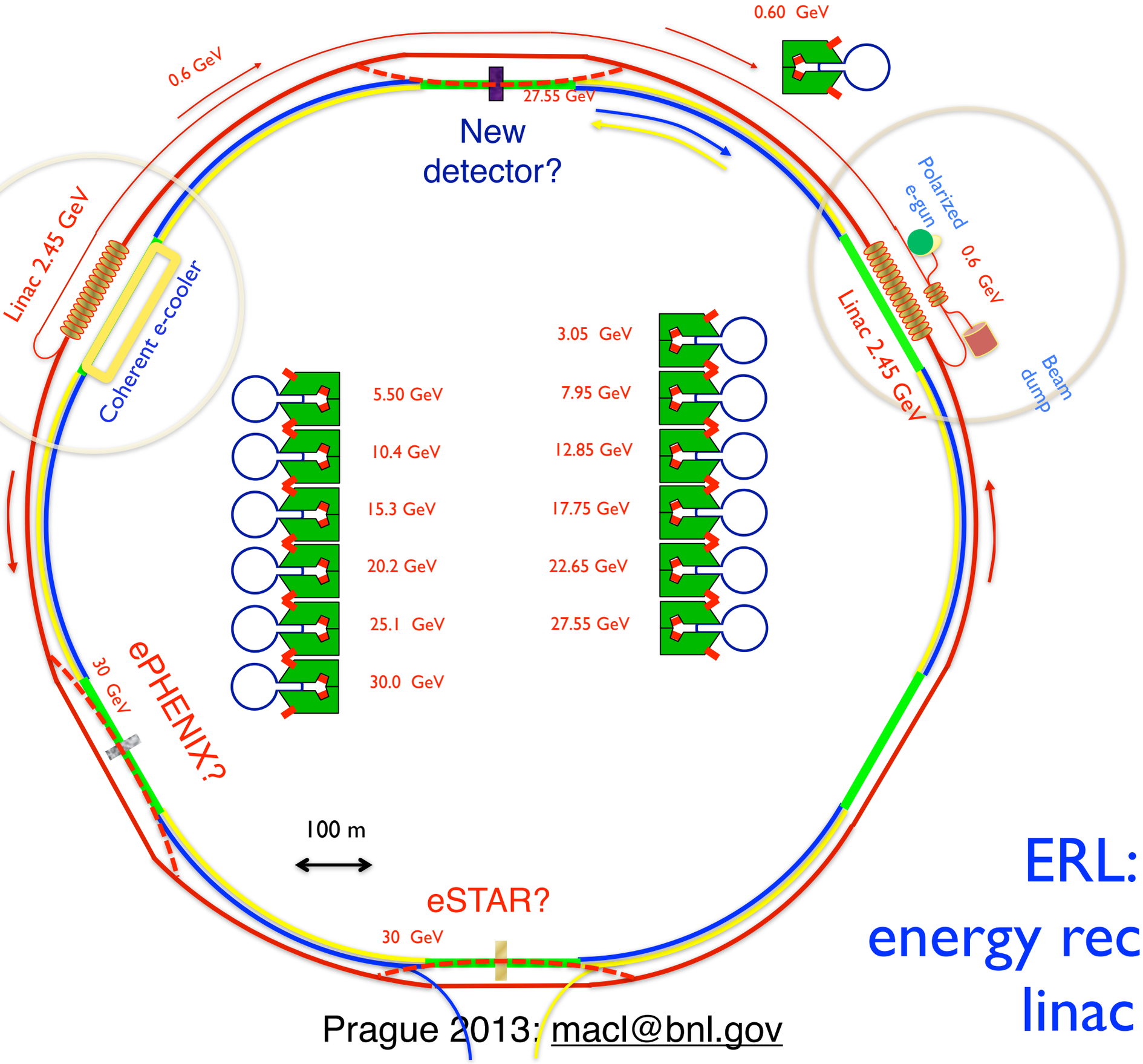

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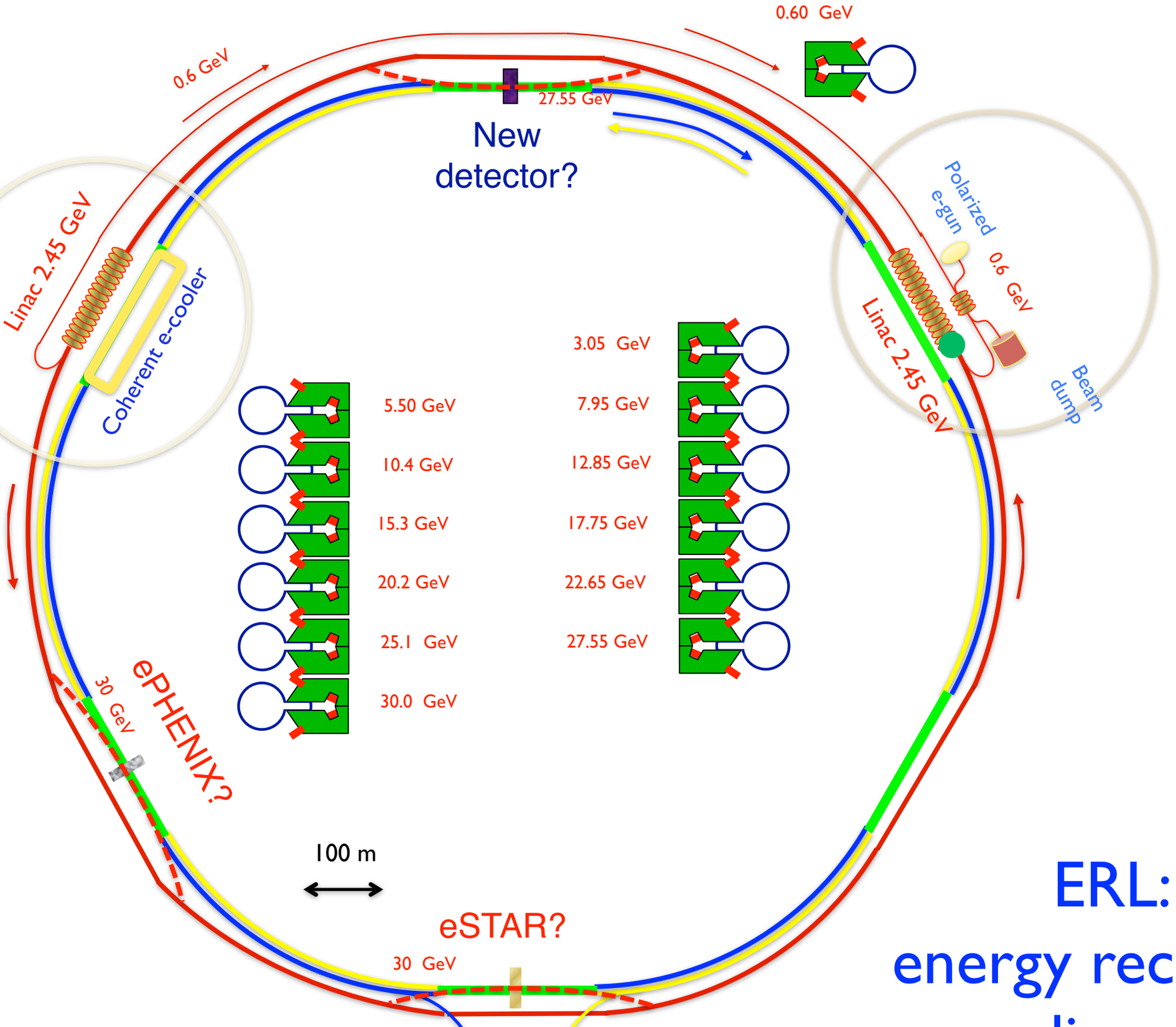

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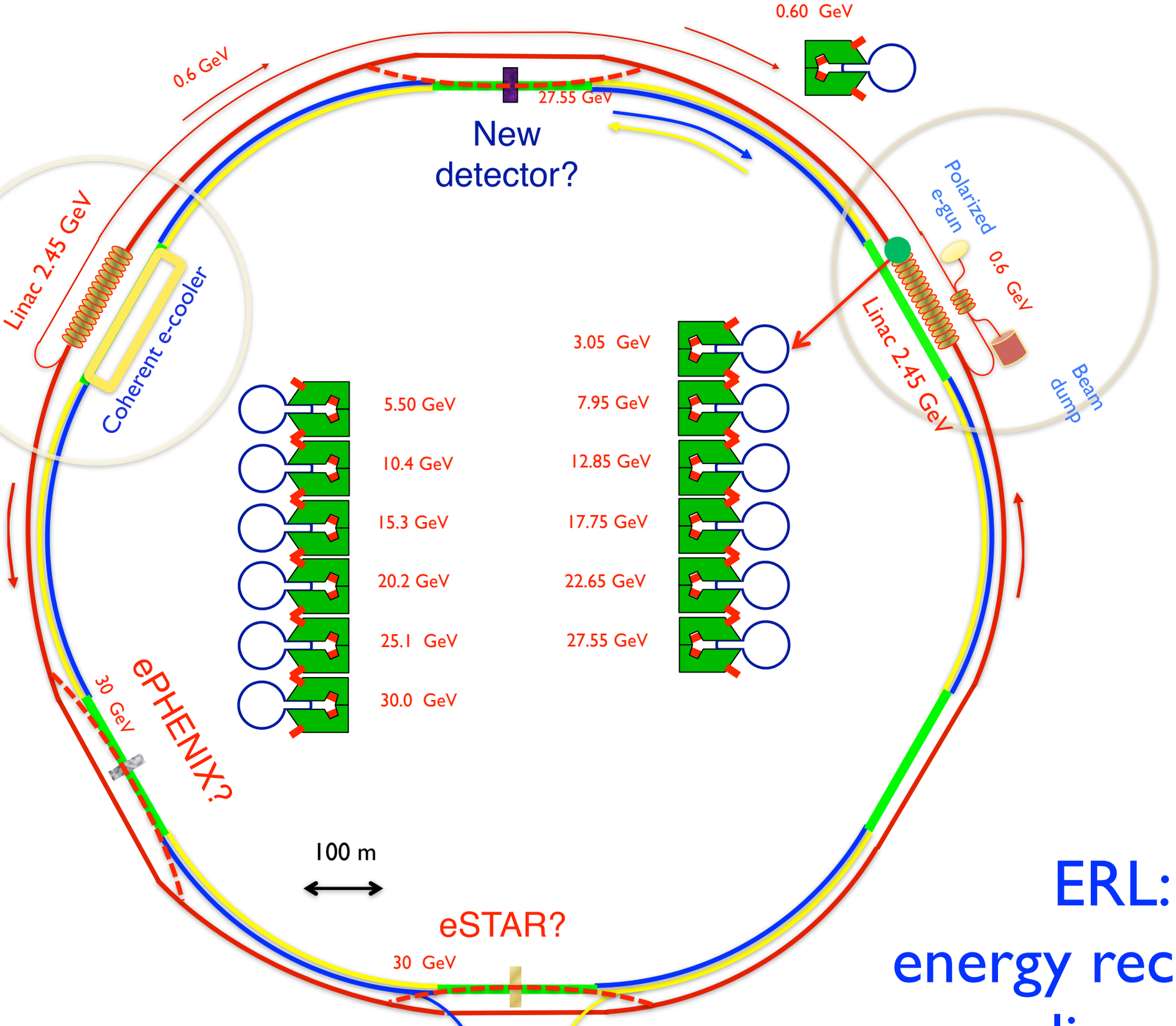

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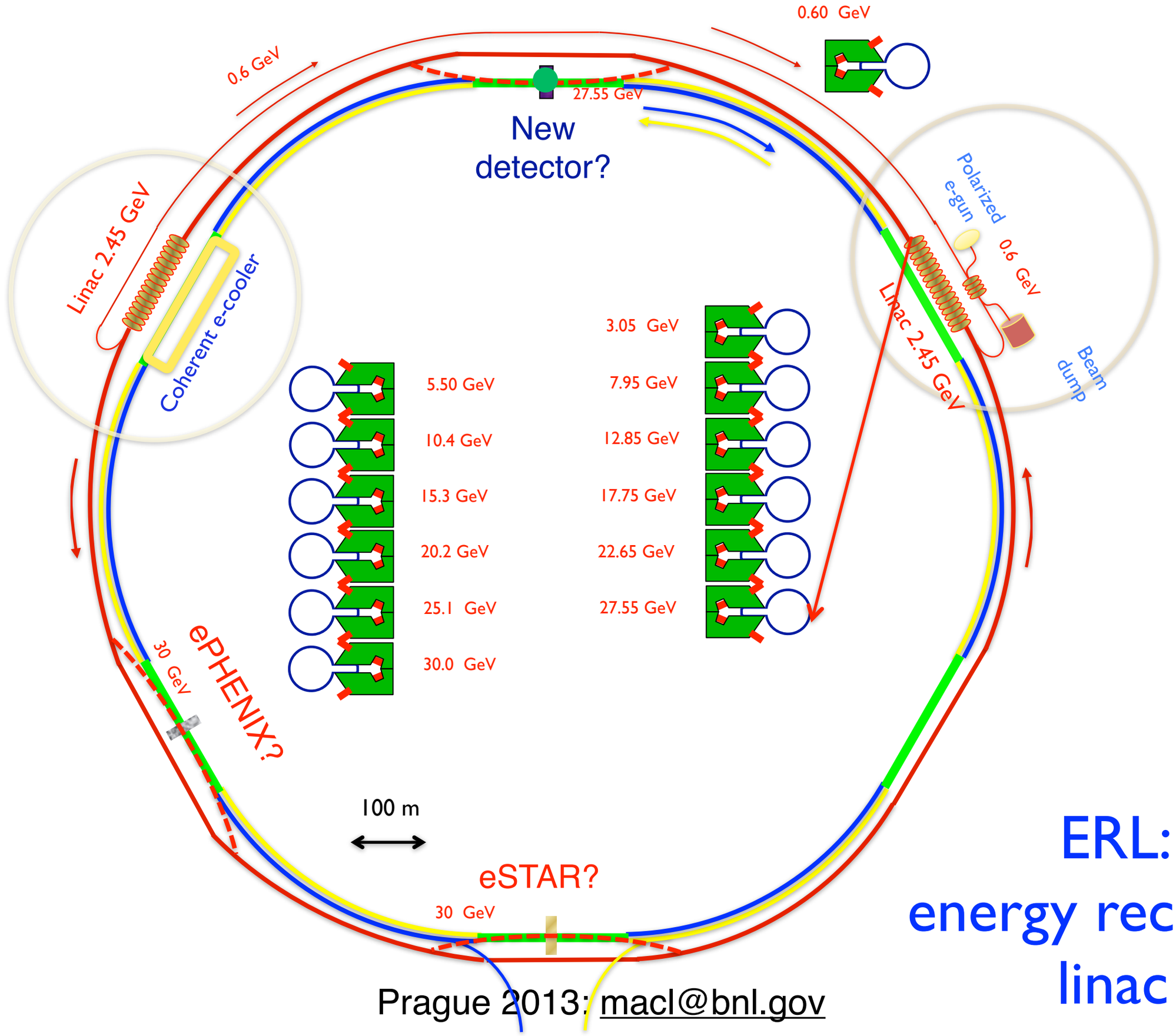

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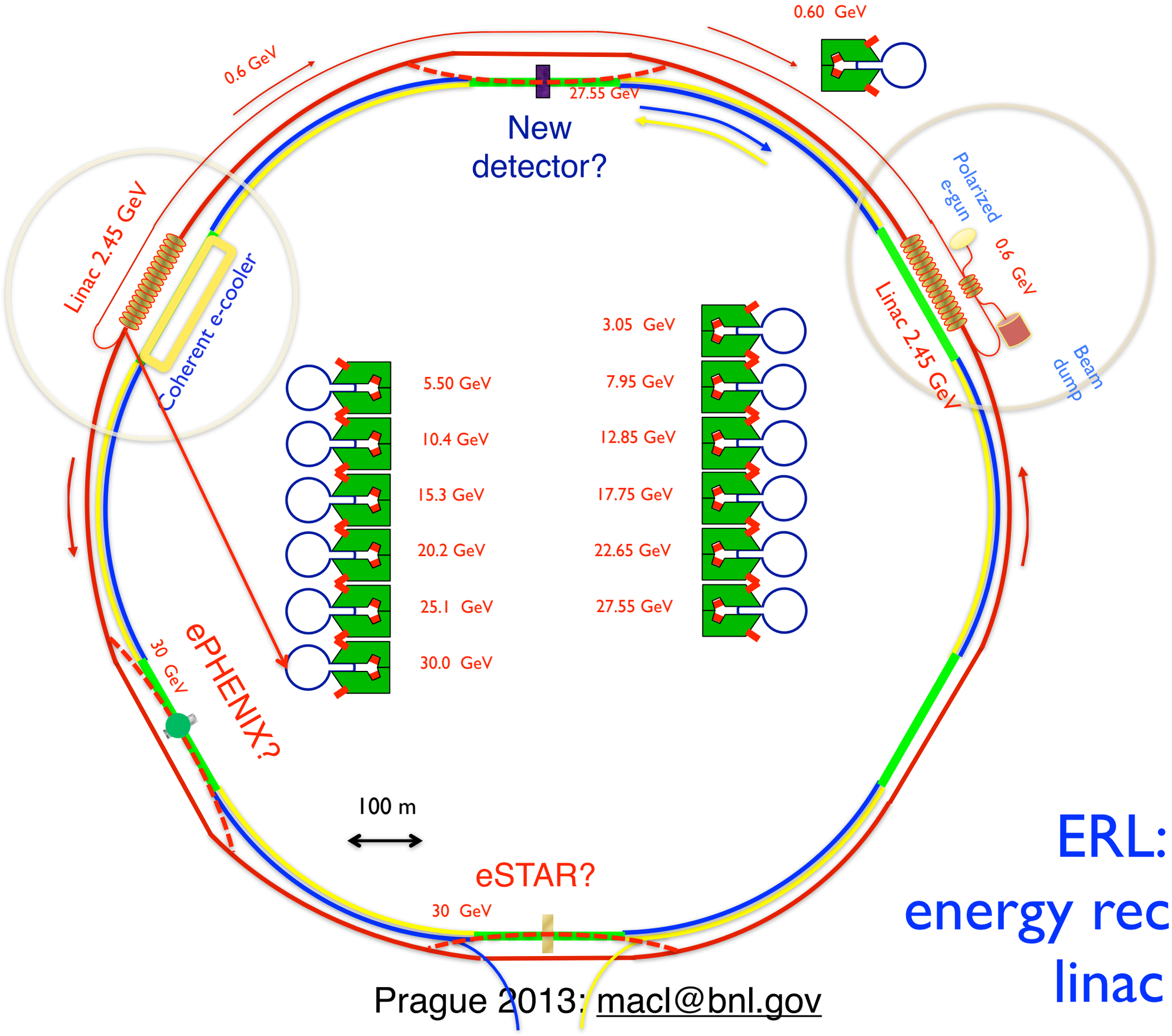
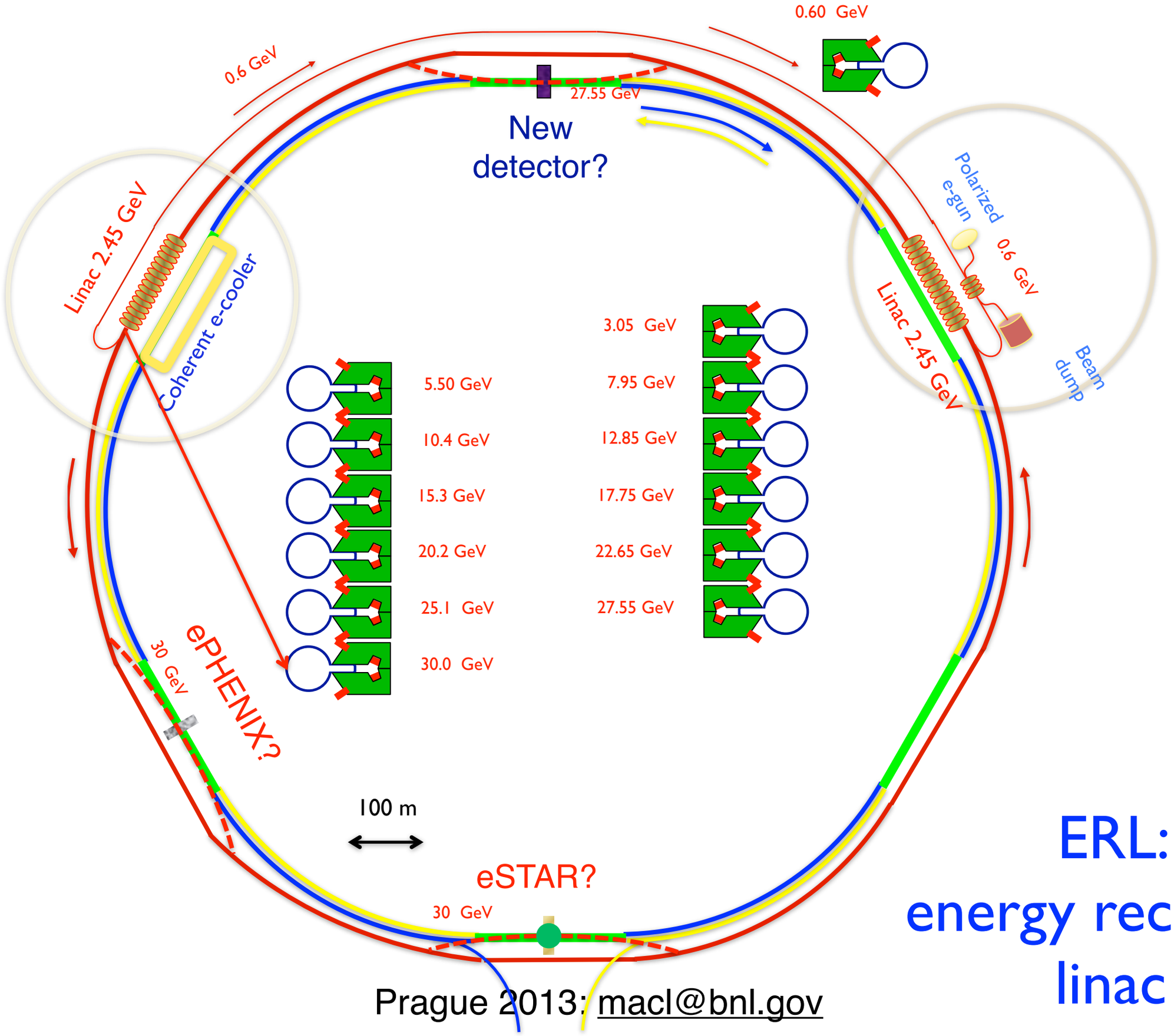


ERL:
energy recovery
linac

Electron beam evolution in eRHIC's ERL



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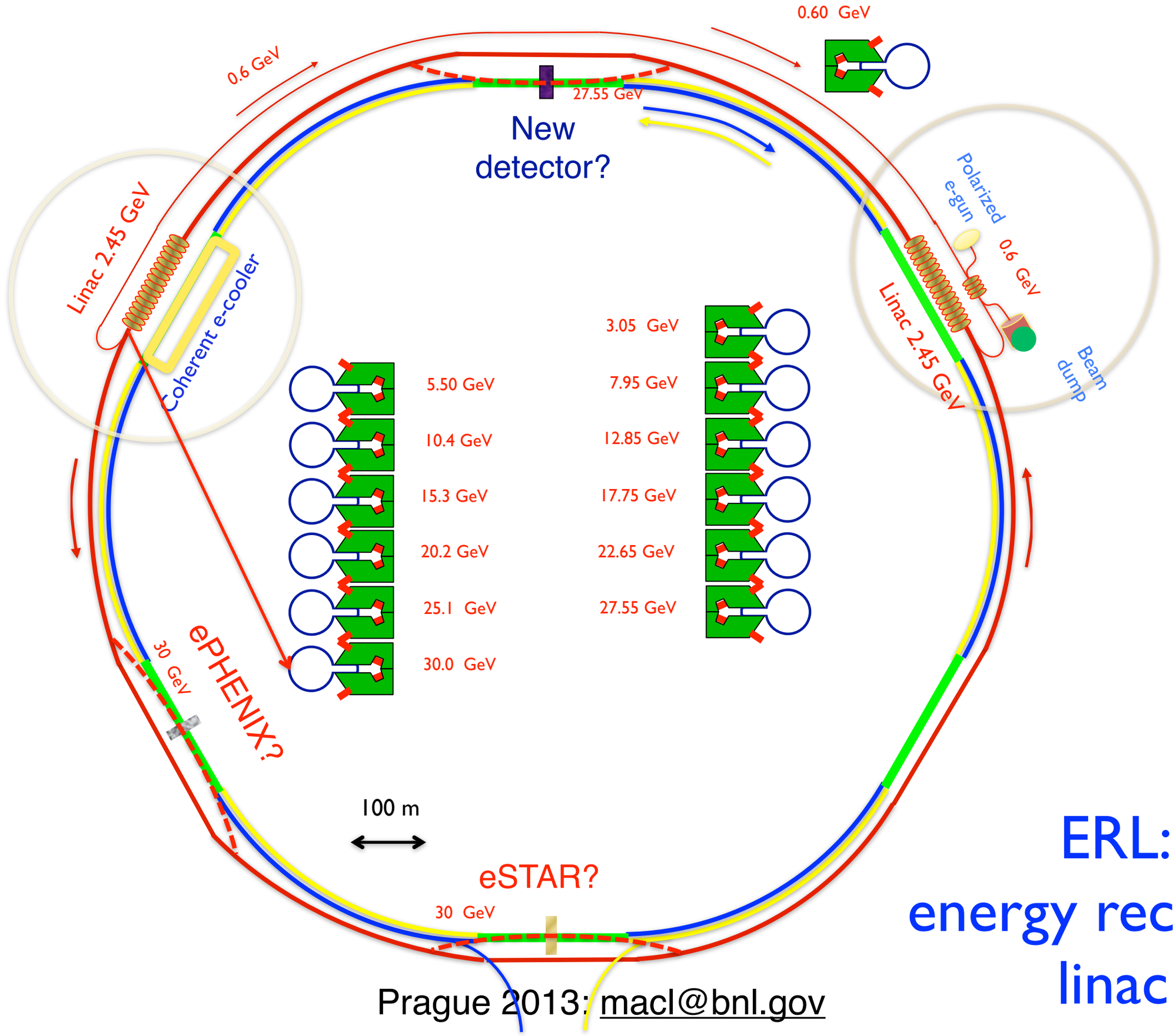
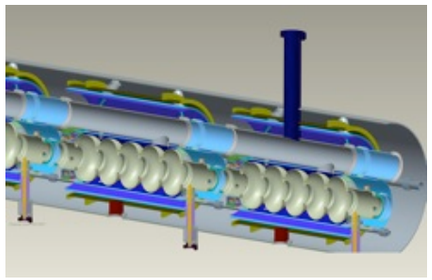
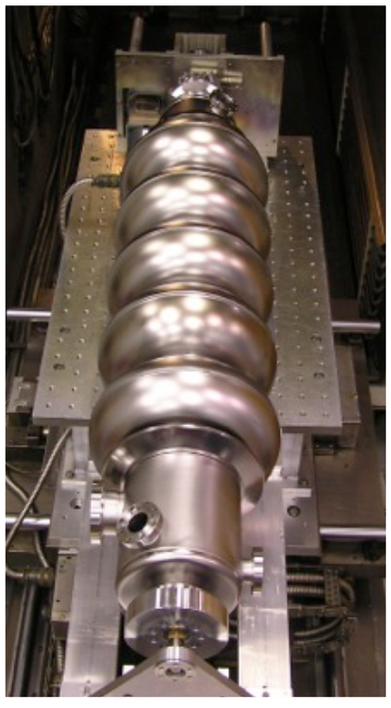


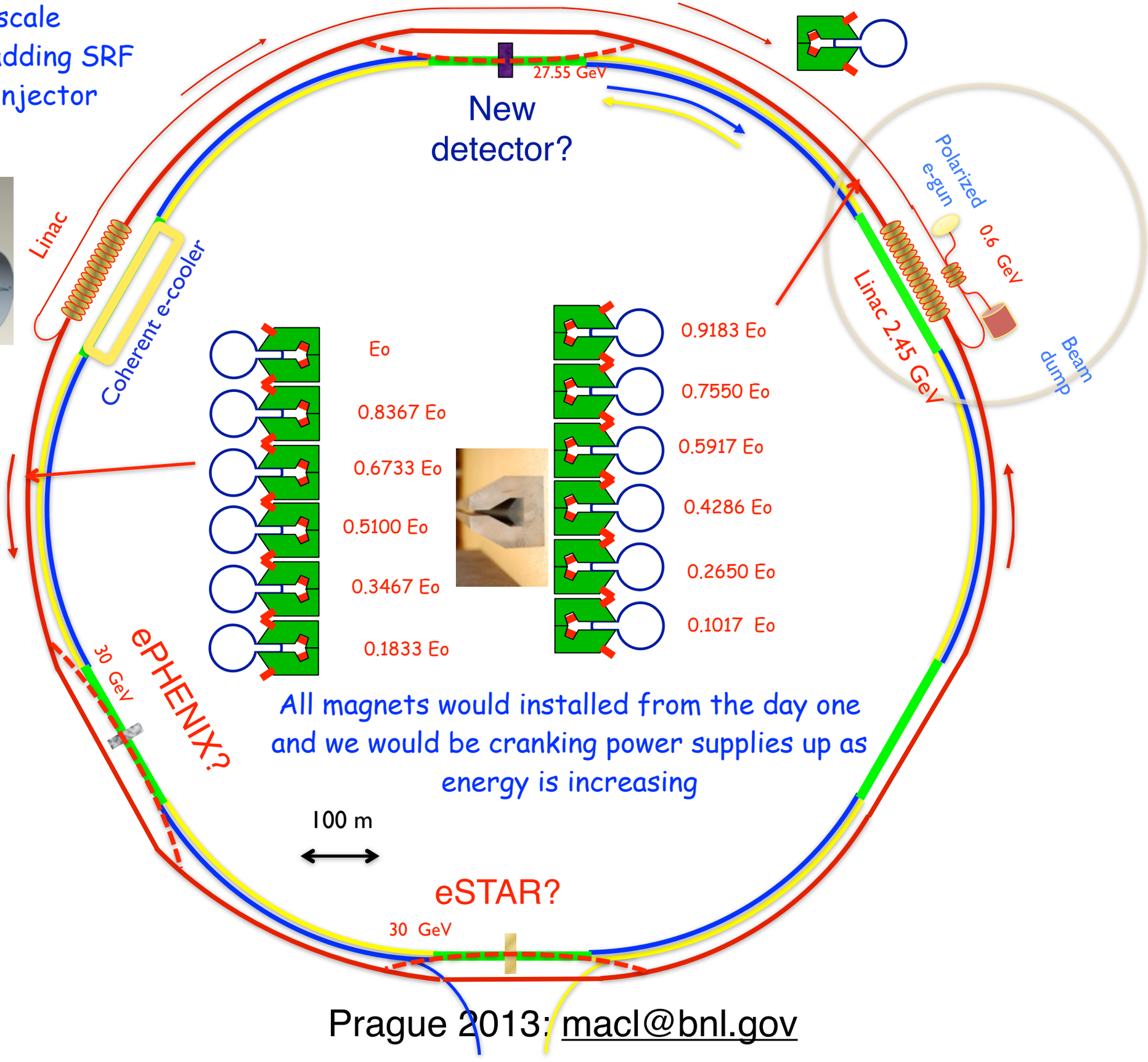
ERL:
energy recovery
linac

Staging of eRHIC: E_e: 5 to 30 GeV

All energies scale proportionally by adding SRF cavities to the injector



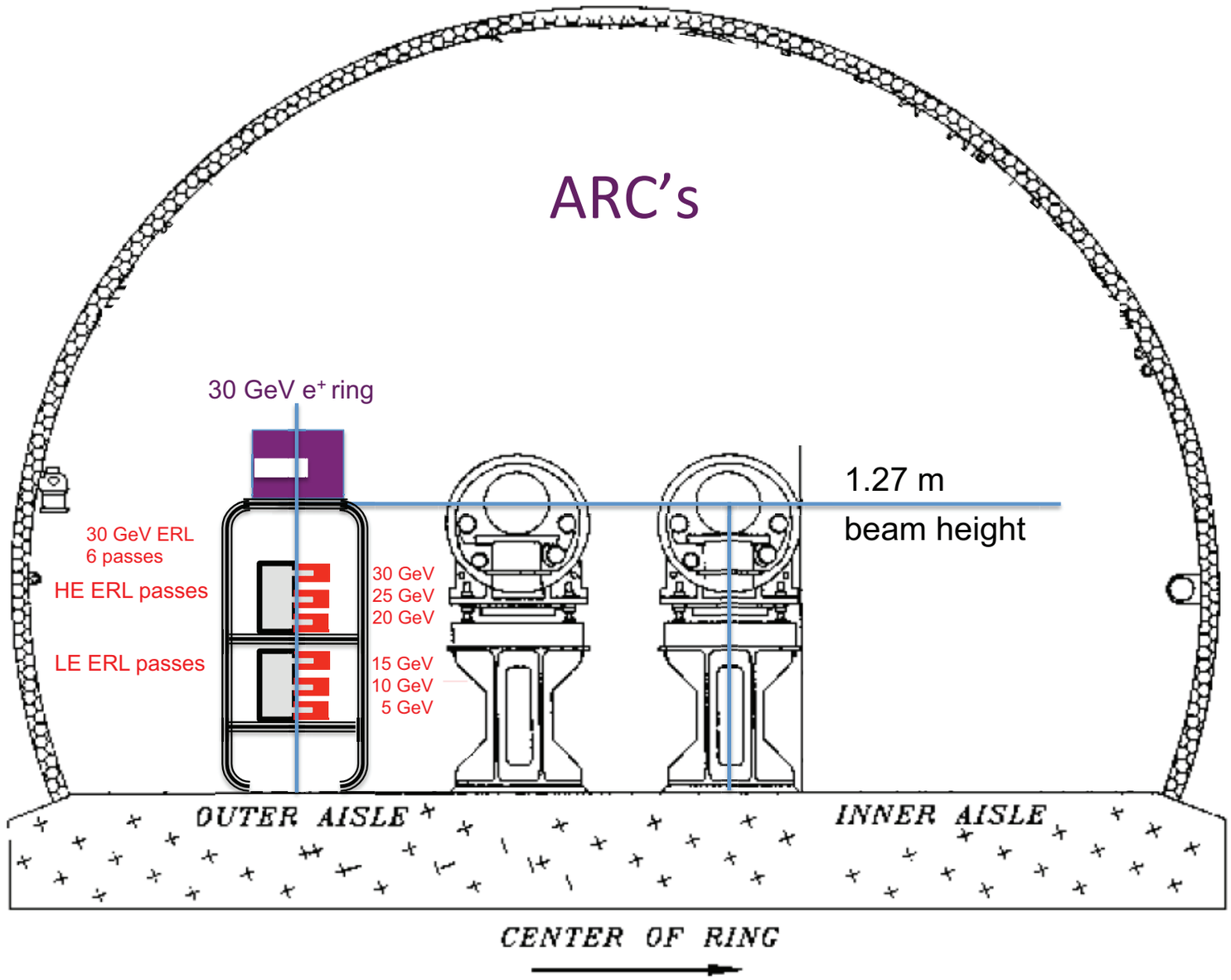




E/Eo
0.0200
0.1017
0.1833
0.2650
0.3467
0.4283
0.5100
0.5917
0.6733
0.7550
0.8367
0.9183
1.0000

The eRHIC project

- eRHIC:
  - ➡ Utilises the RHIC ion beams
  - ➡ Two 2.45 GeV Energy Recovery Linacs (ERLs) accelerate the e^- beam
    - ▸ 6 separate rings accelerate the e^- up to a maximum energy of 30 GeV
  - ➡ 2-stage approach
    - ▸ Stage 1: e^- 5-10 GeV
    - ▸ Stage 2: e^- 20-30 GeV
  - ➡ Space for new detector at IP12
    - ▸ Possibilities for collisions in current STAR and PHENIX IPs

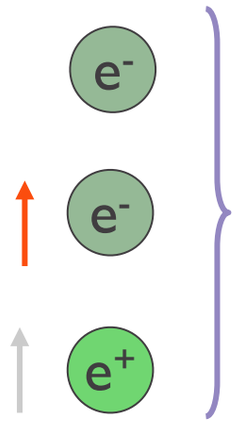


What is eRHIC?

Electron accelerator

(to be built)

Unpolarized and polarized leptons
5-20 (30) GeV



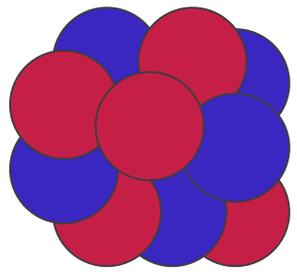
70% e^- beam polarization goal

polarized positrons?

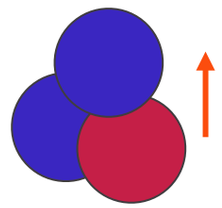
RHIC

Existing = $2B

Polarized protons
50-250 GeV

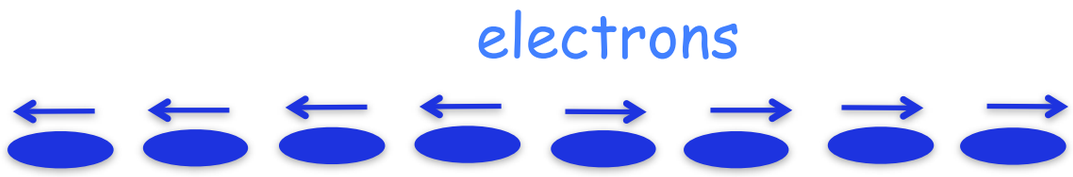


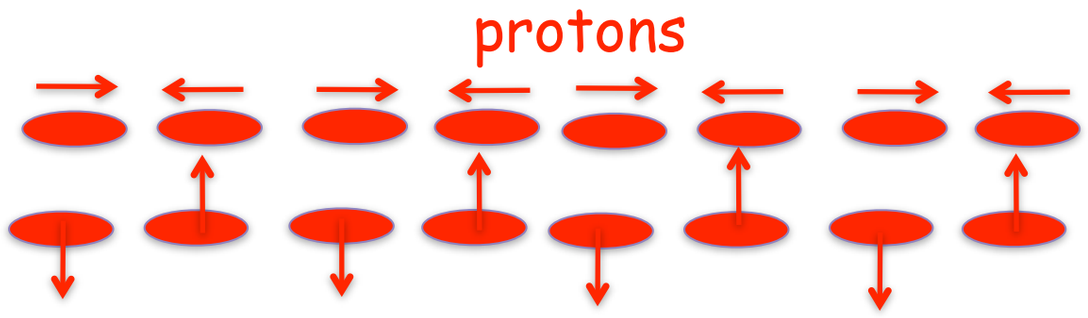
Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 GeV/u



Polarized light ions He^3
166 GeV/u

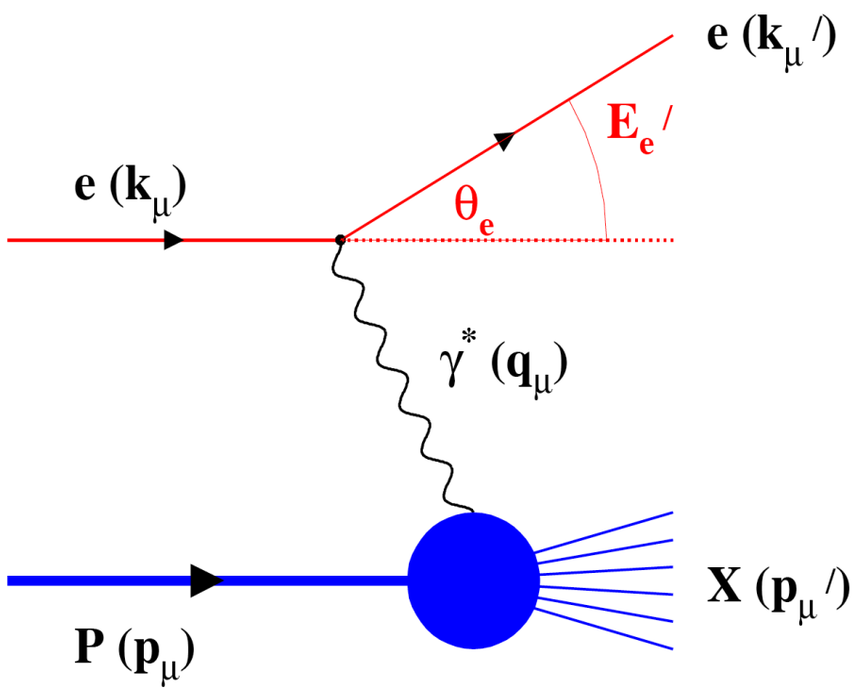
Center mass energy range: $\sqrt{s}$=30-200 GeV; L~100-1000xHera
longitudinal and transverse polarization for p/He^3 possible





DIS Kinematics

e(k) + p(p) → e(k') +X(px)



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 4E_e E'_e sin^2(\frac{\theta'_e}{2})$$

Measure of resolution power or "Virtuality"

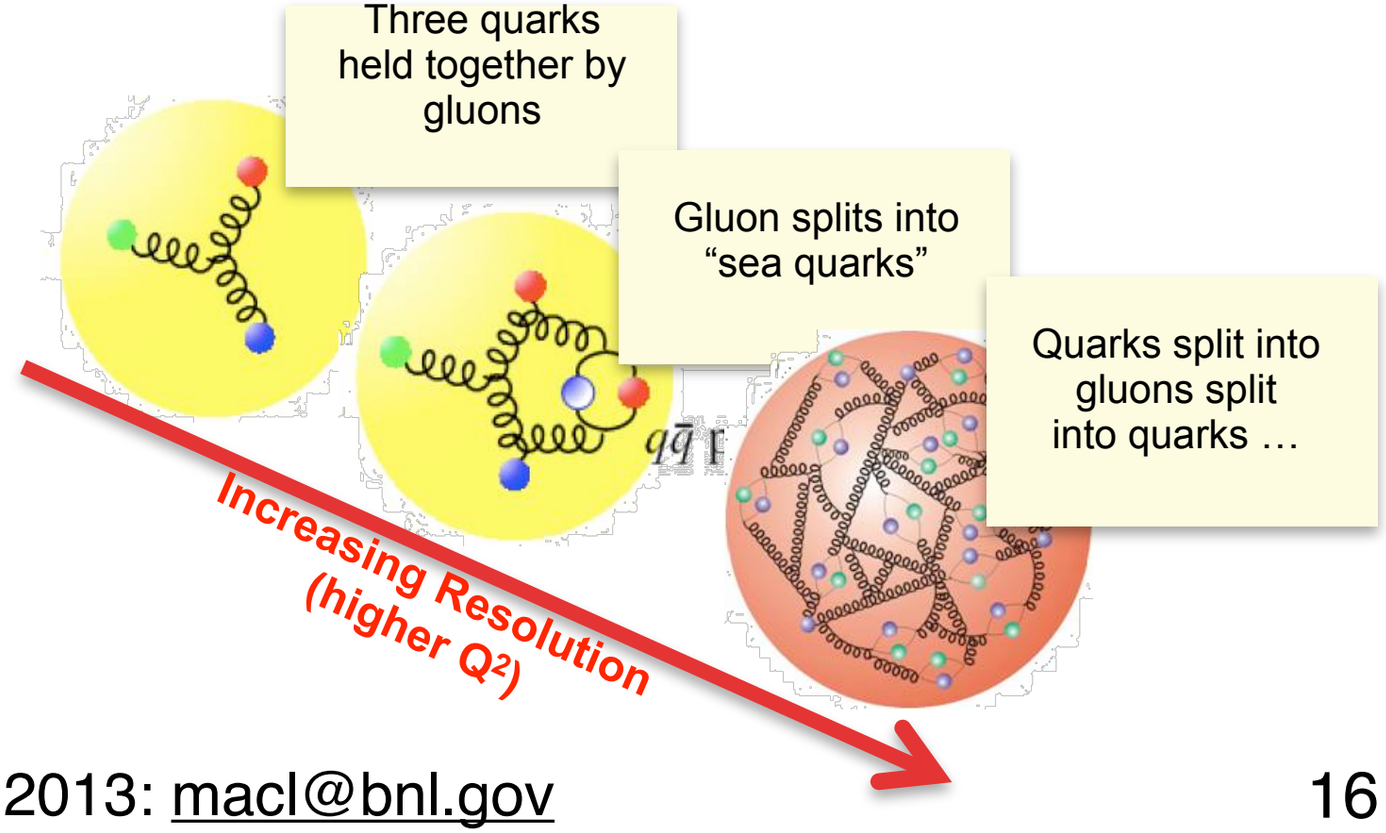
$$y = \frac{pq}{pk} = 1 - \frac{E_{e'}}{E_e} cos^2(\frac{\theta'_e}{2})$$

Measure of inelasticity

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

Measure of momentum fraction of struck quark

Important to note that in order to have different y for the same x and Q^2, need to change the beam energies

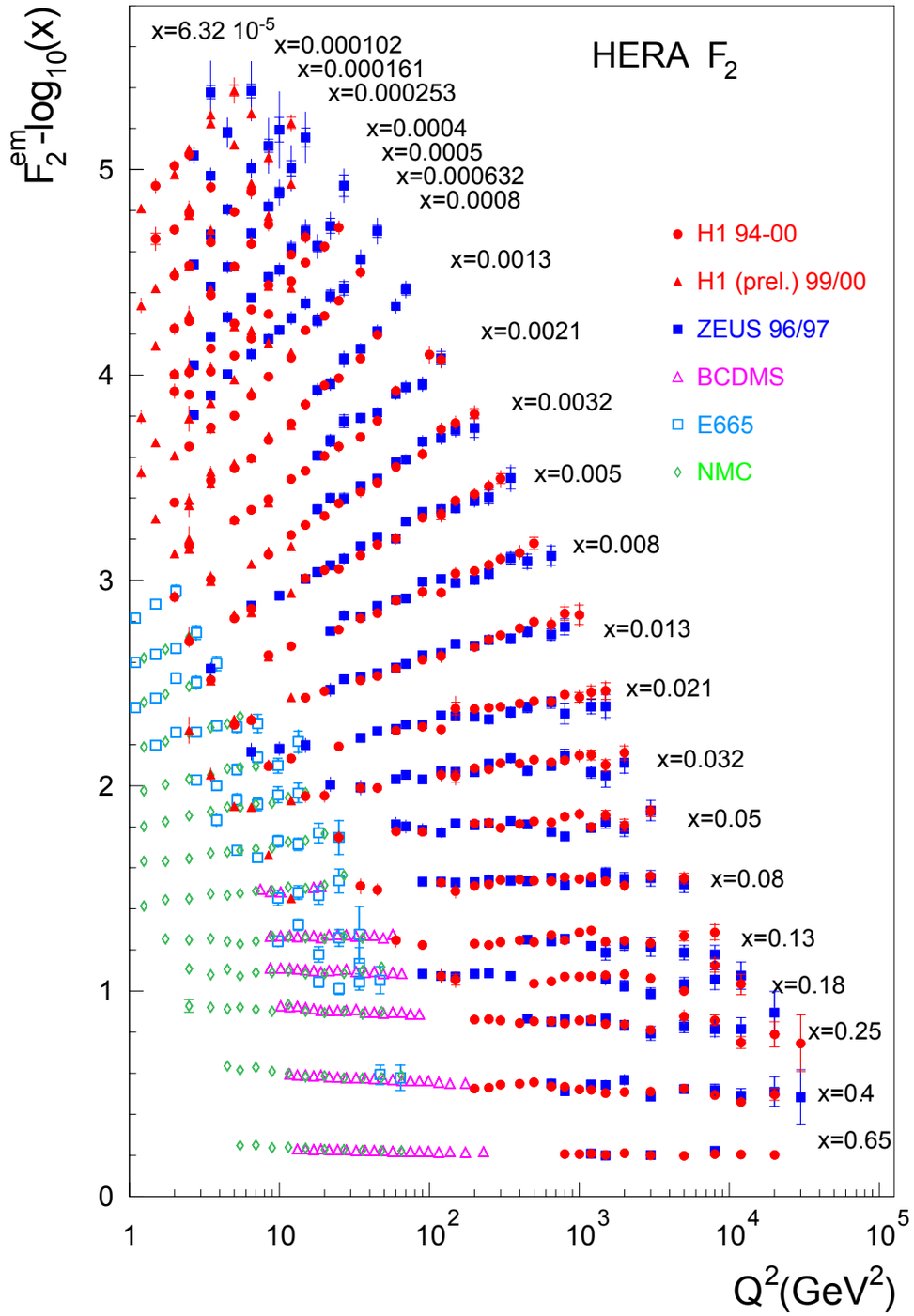


What did we learn from e+p collisions at HERA?

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

quark+anti-quark momentum distributions

gluon momentum distribution



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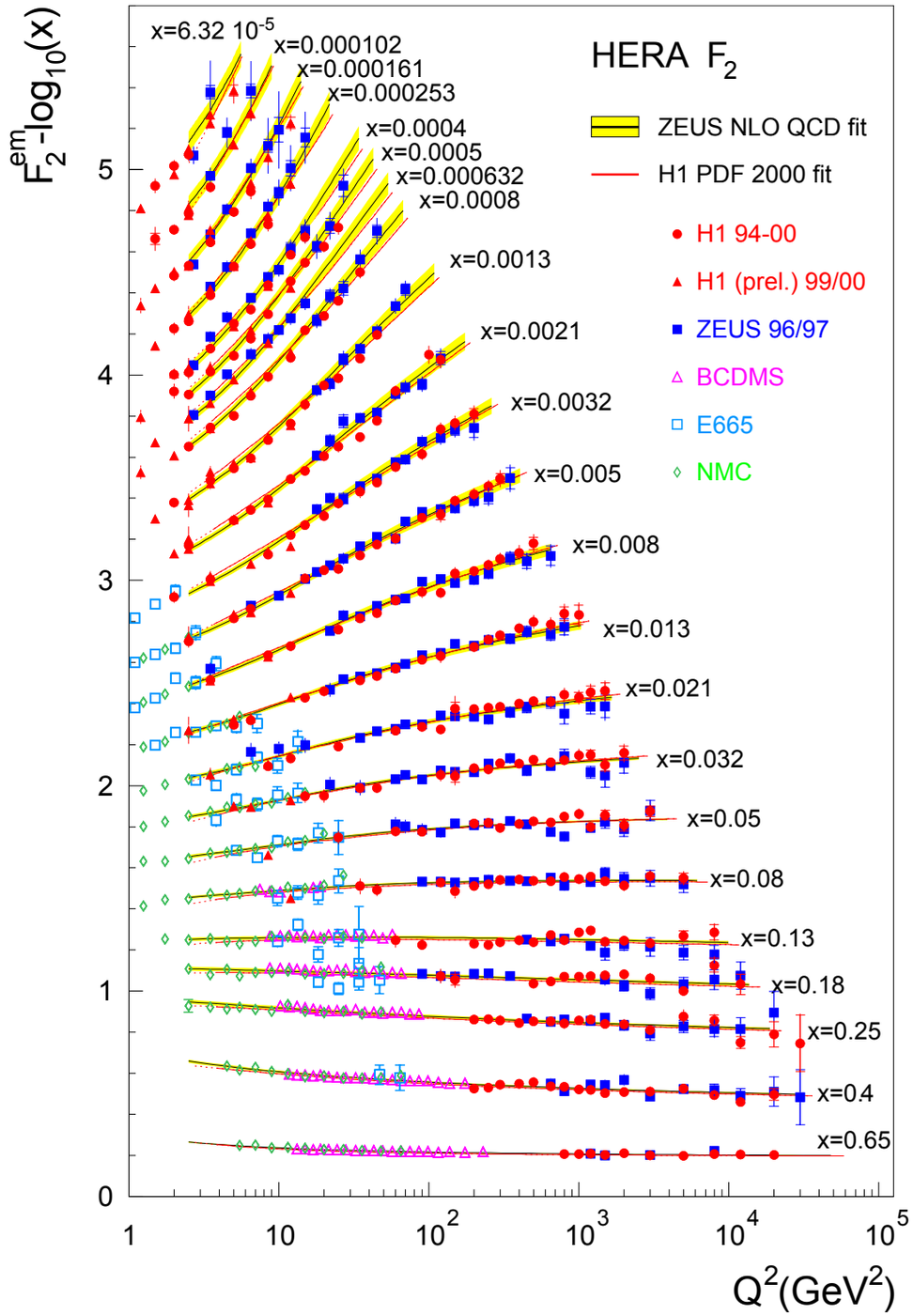

Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution $\Rightarrow G(x,Q^2)$

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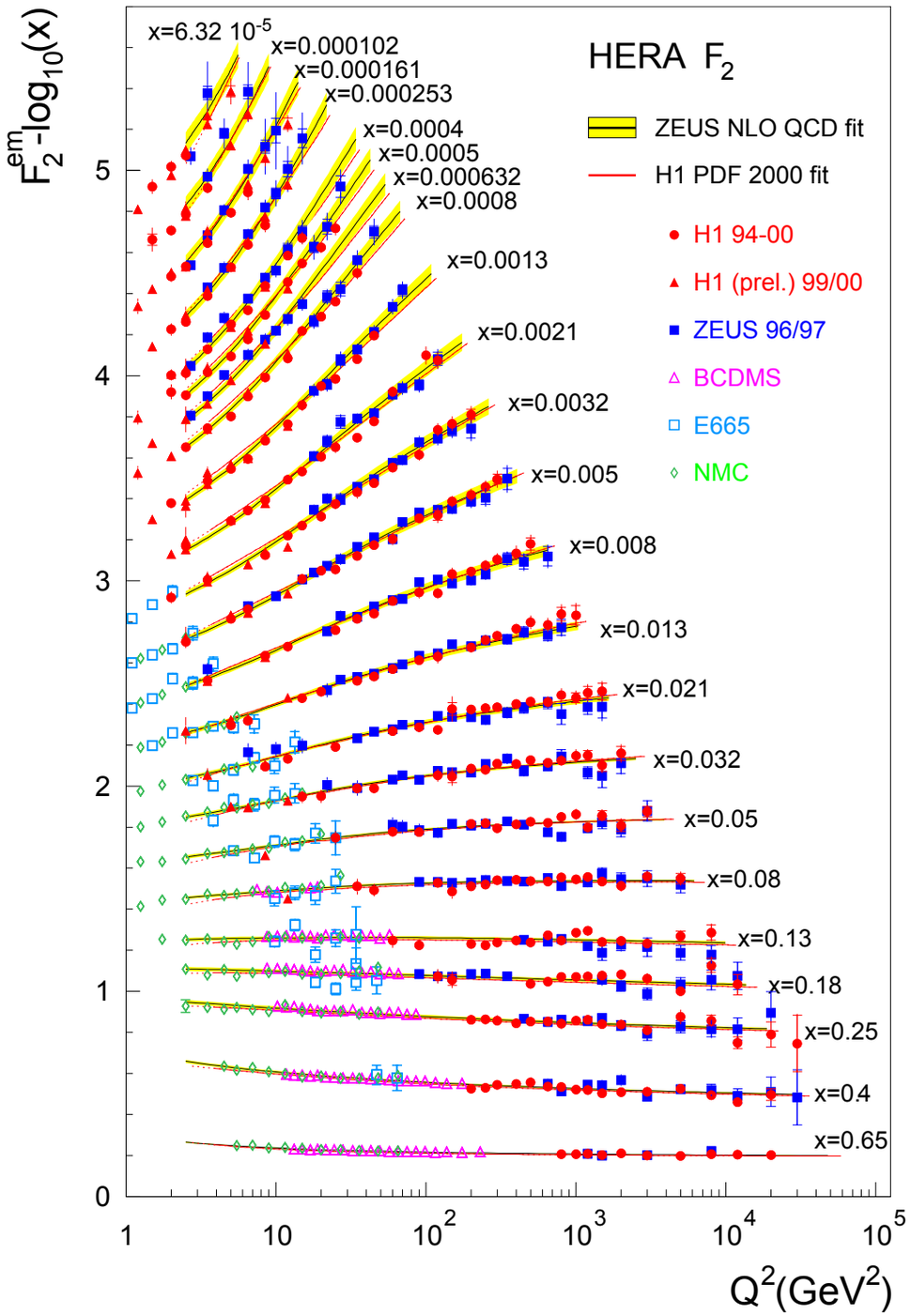

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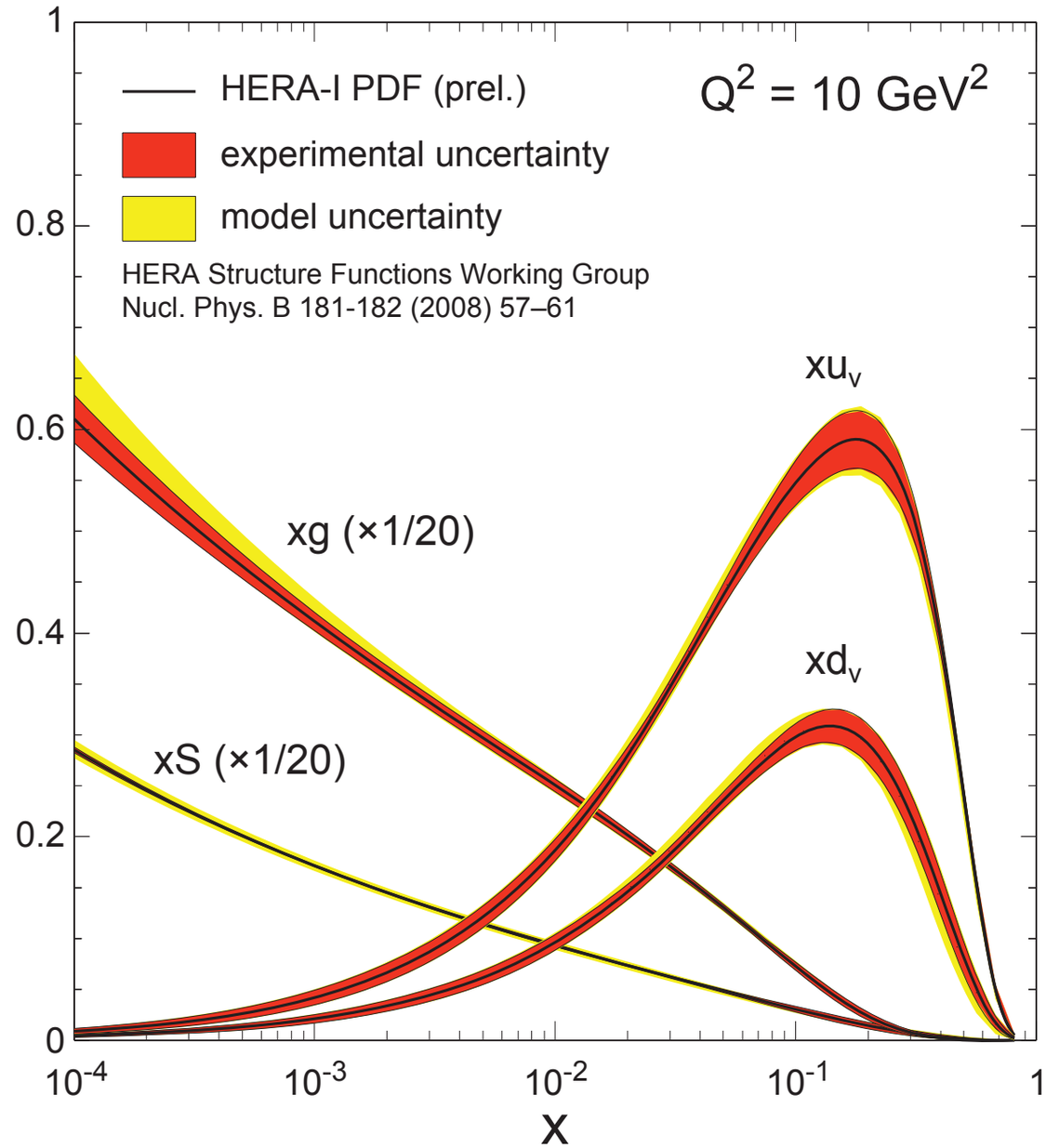

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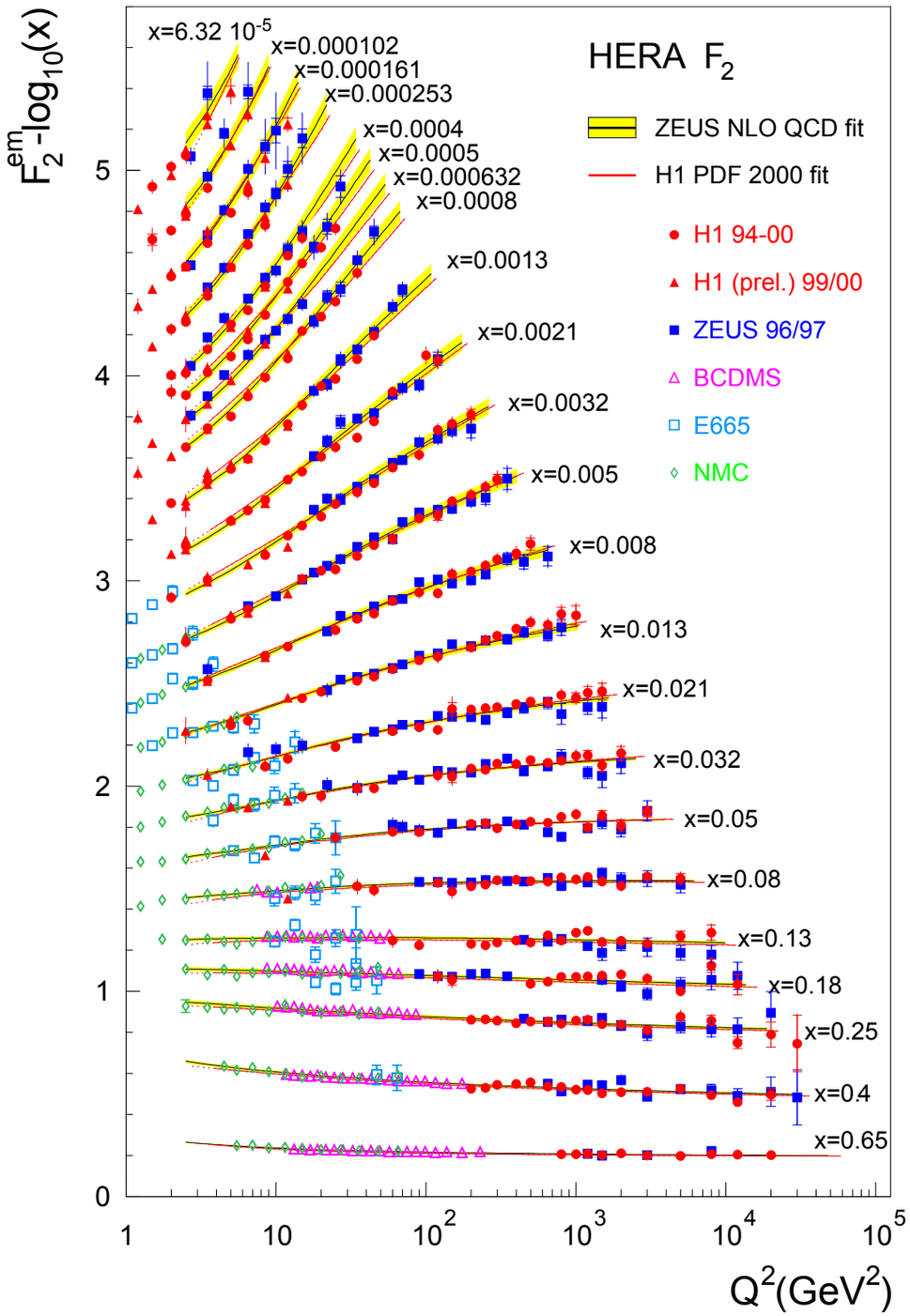

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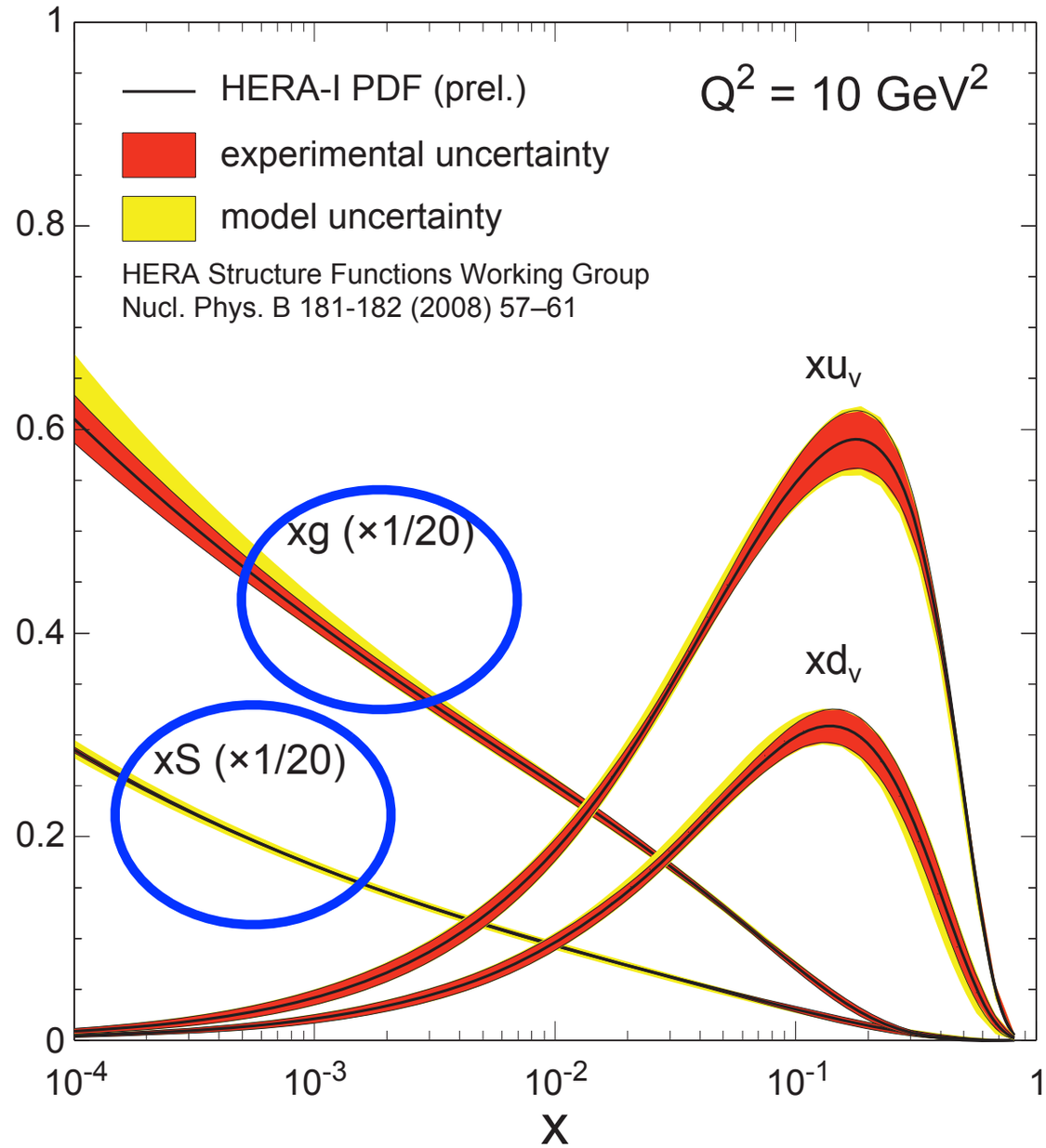

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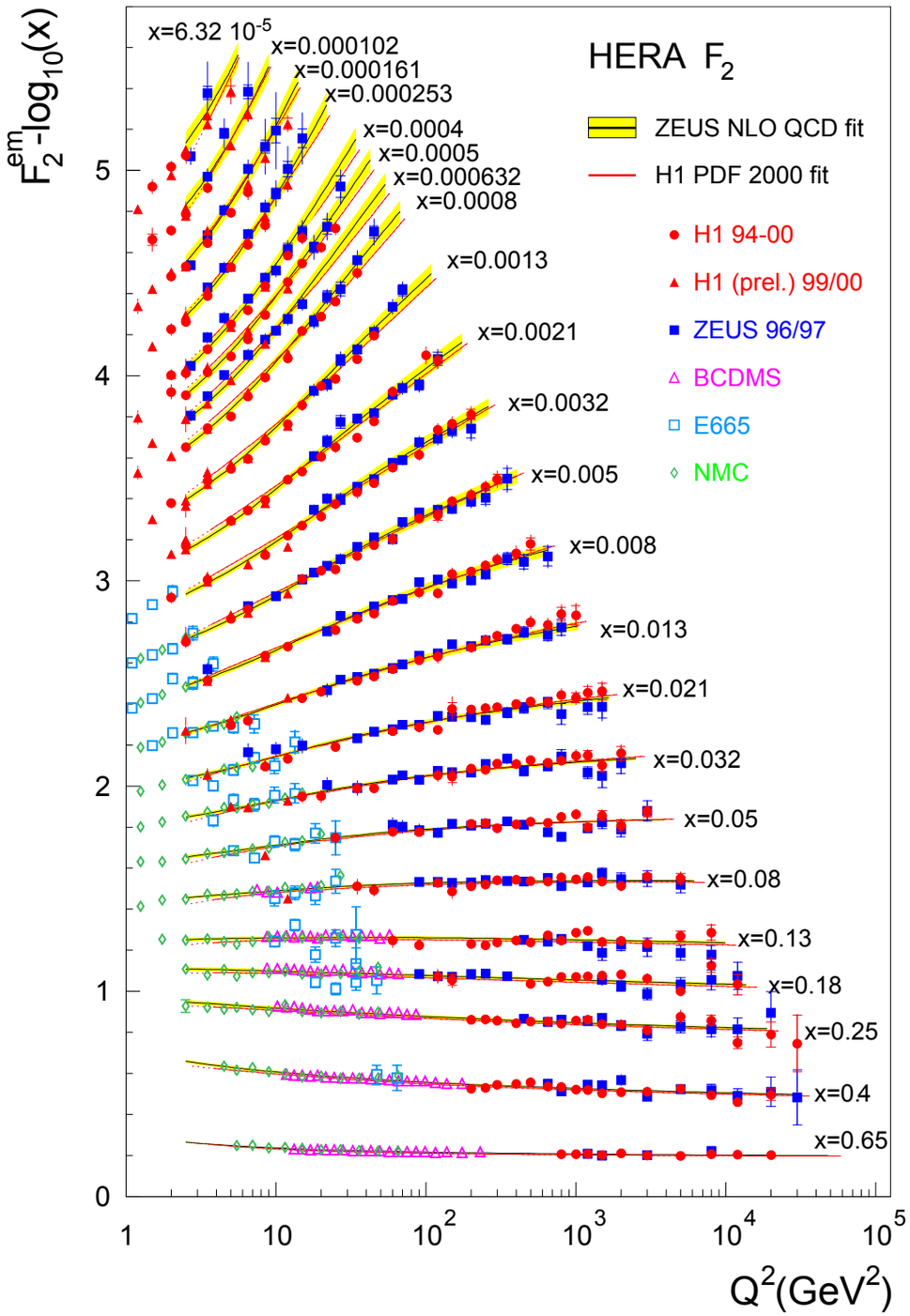

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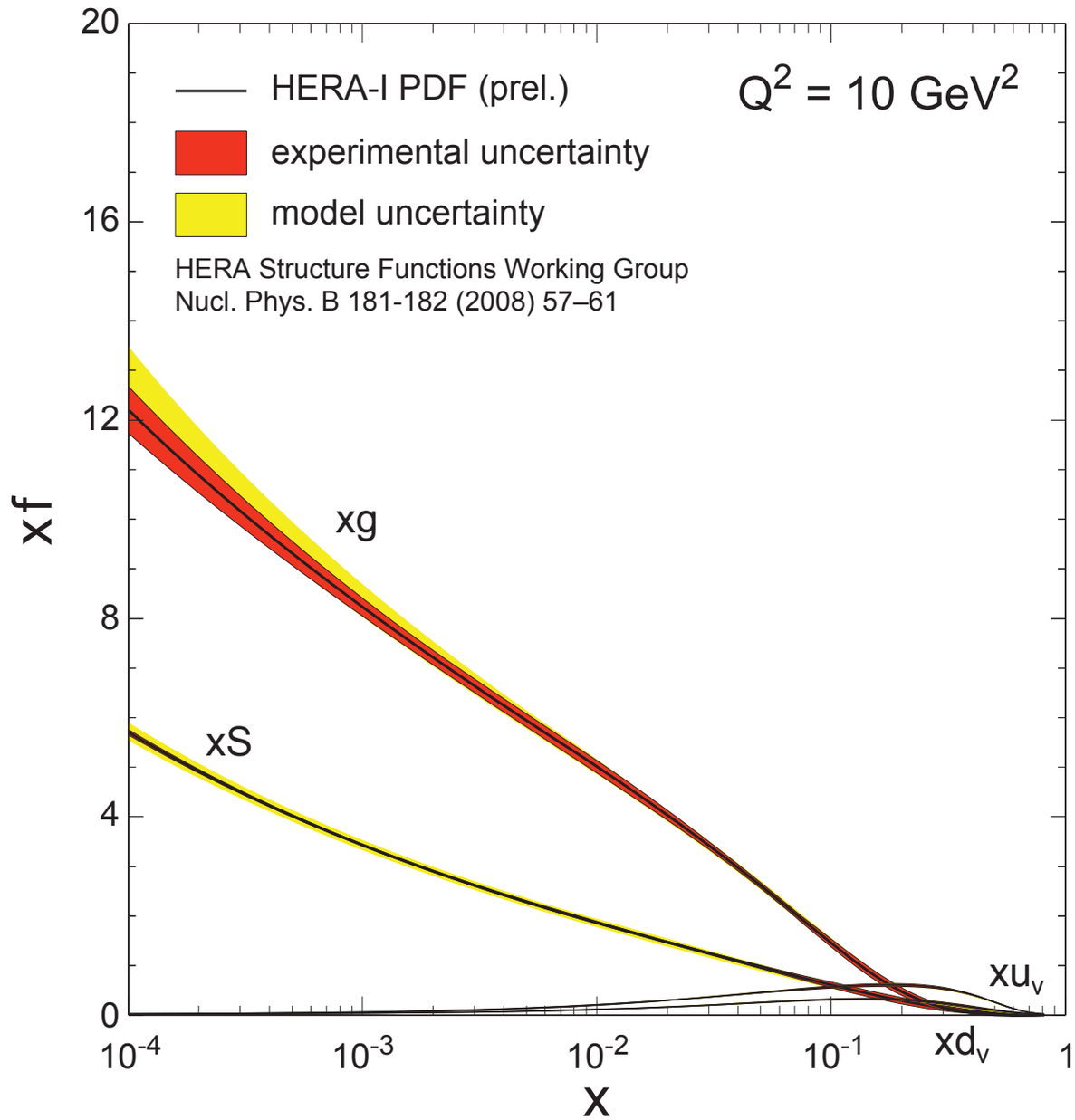
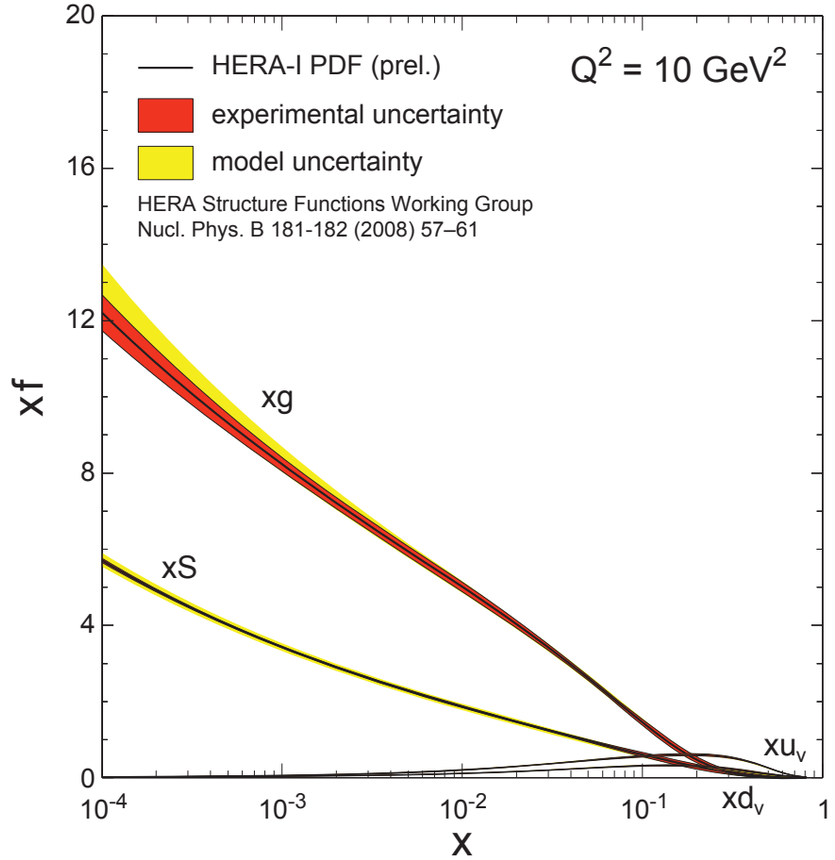
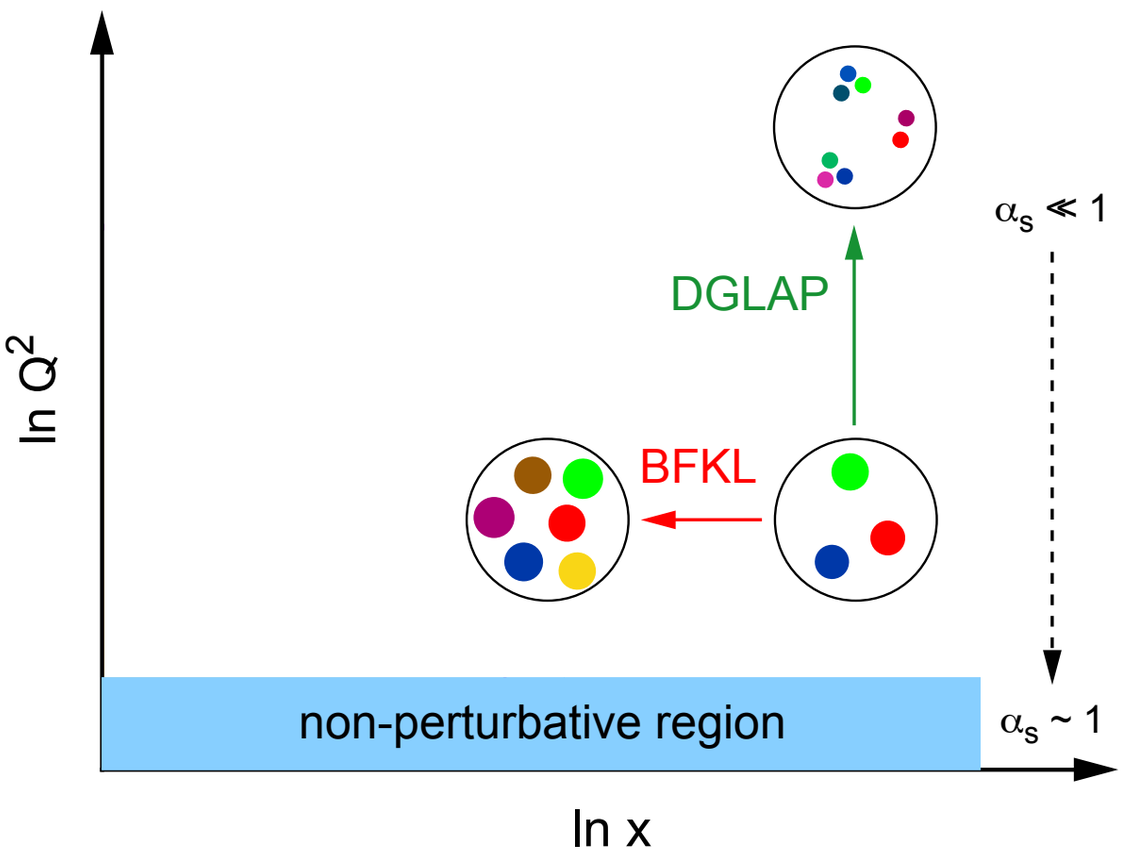
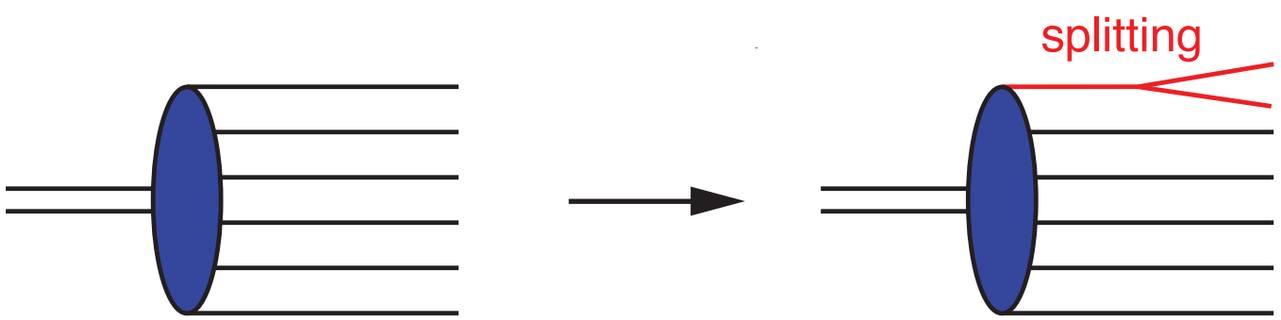


The structure of matter at small-x





- Gluons dominate the PDFs at small- to intermediate-x ($x < 0.1$)
  - ➡ Rapid rise in gluons described naturally by linear pQCD evolution equations



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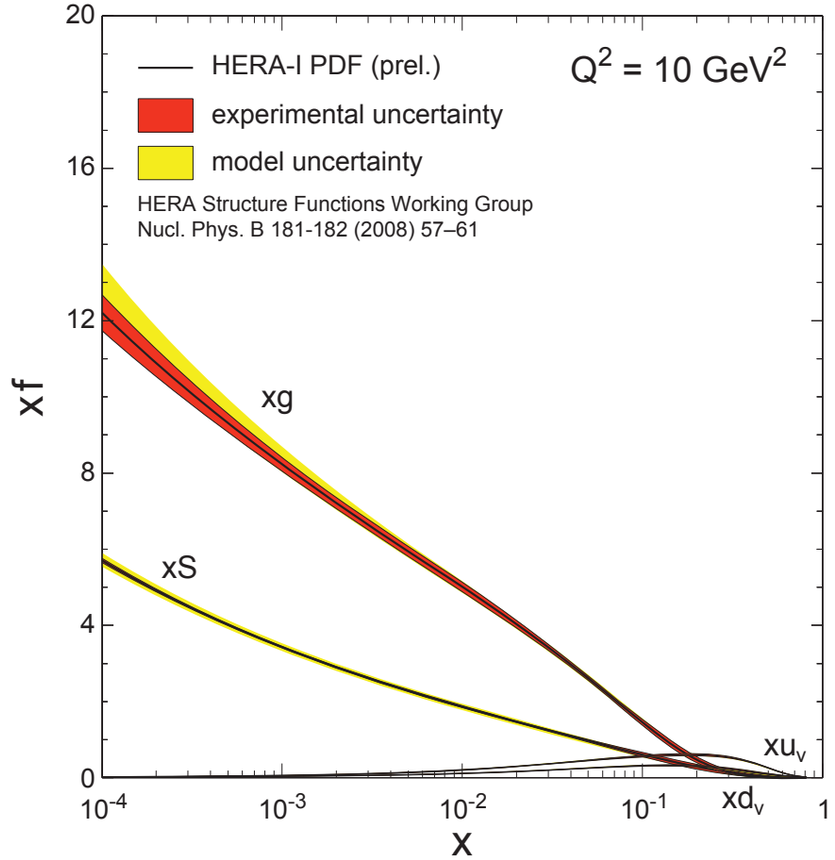
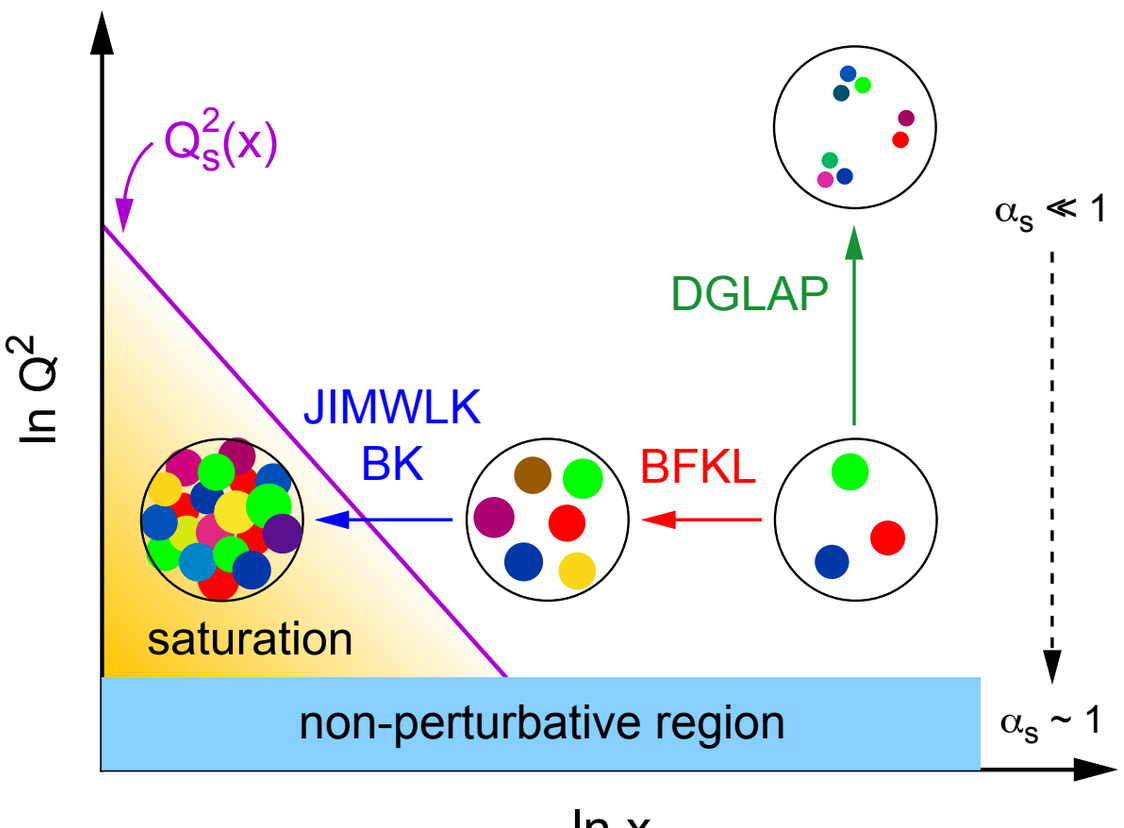
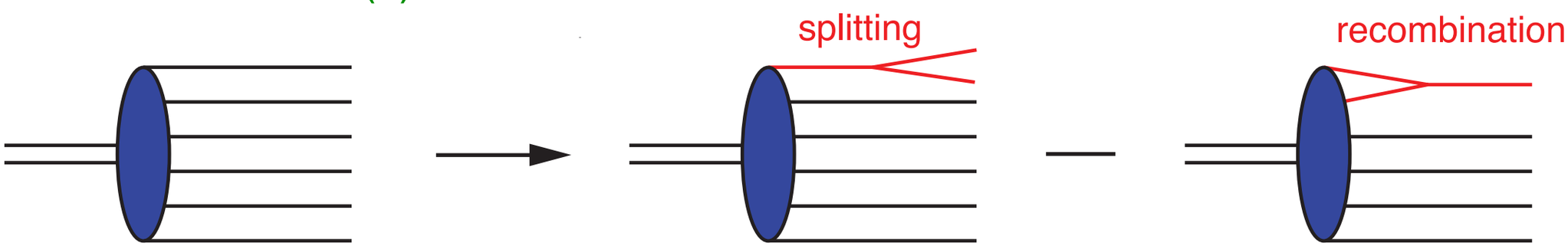




- Gluons dominate the PDFs at small- to intermediate-x ($x < 0.1$)
  - ➡ Rapid rise in gluons described naturally by linear pQCD evolution equations
  - ➡ This rise cannot increase forever - limits on the cross-section
    - ▸ non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterised by the saturation scale $Q^2_S(x)$



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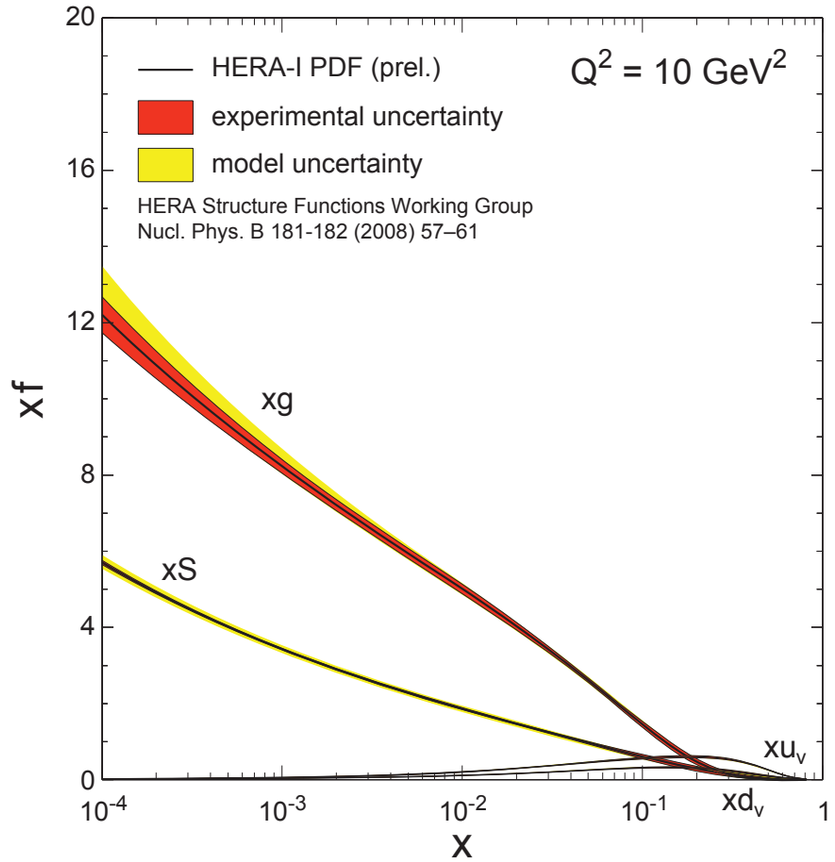

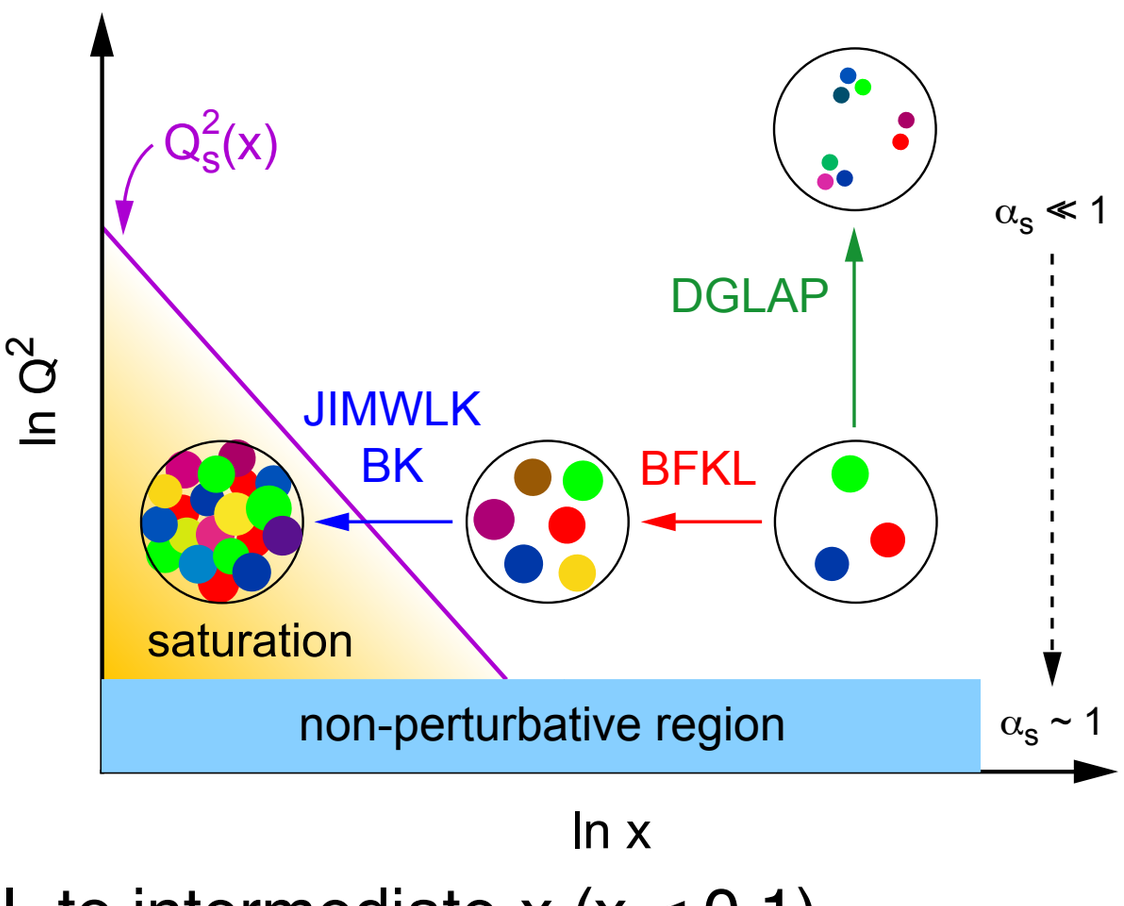

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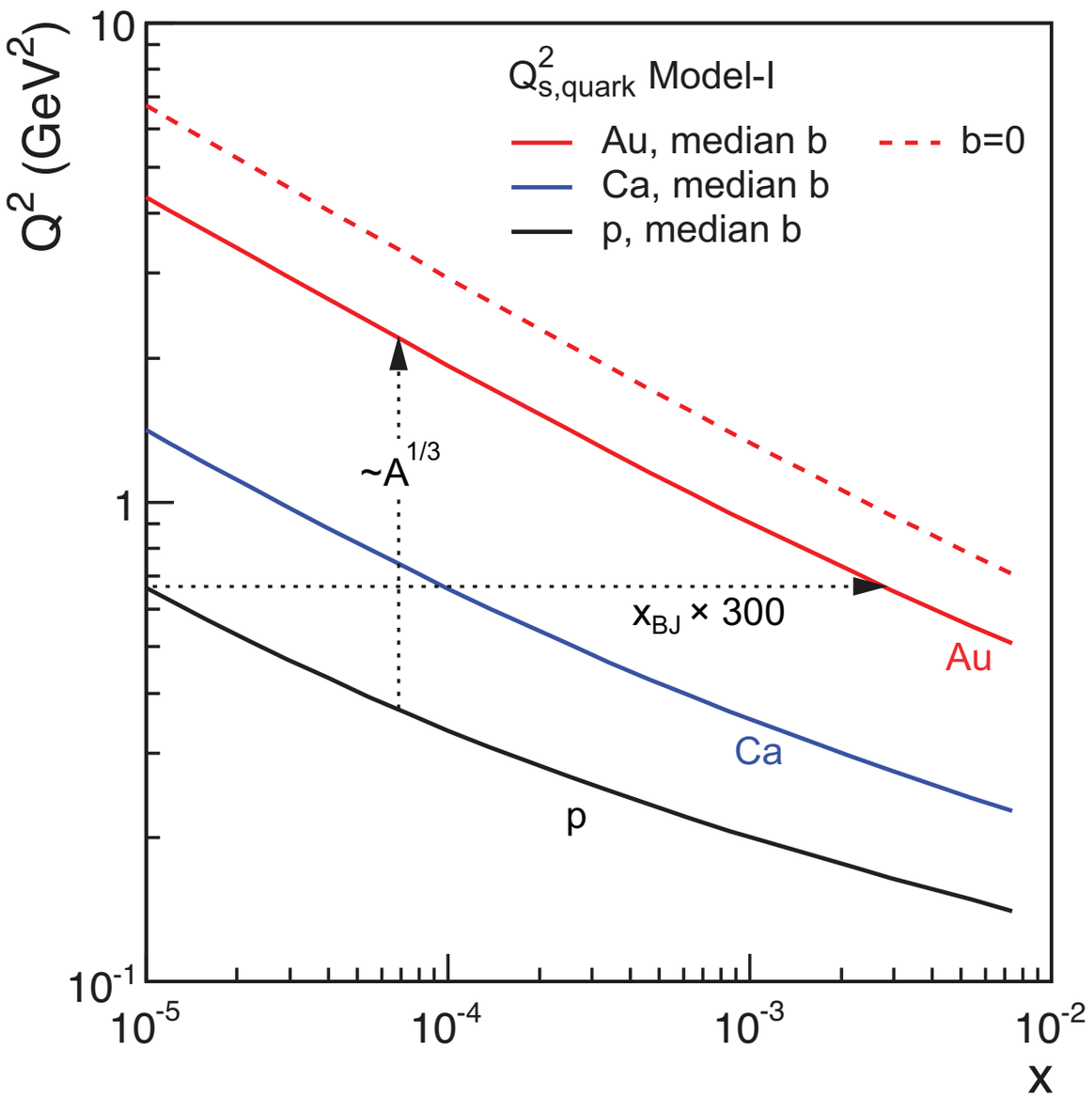
    - ▸ non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterised by the saturation

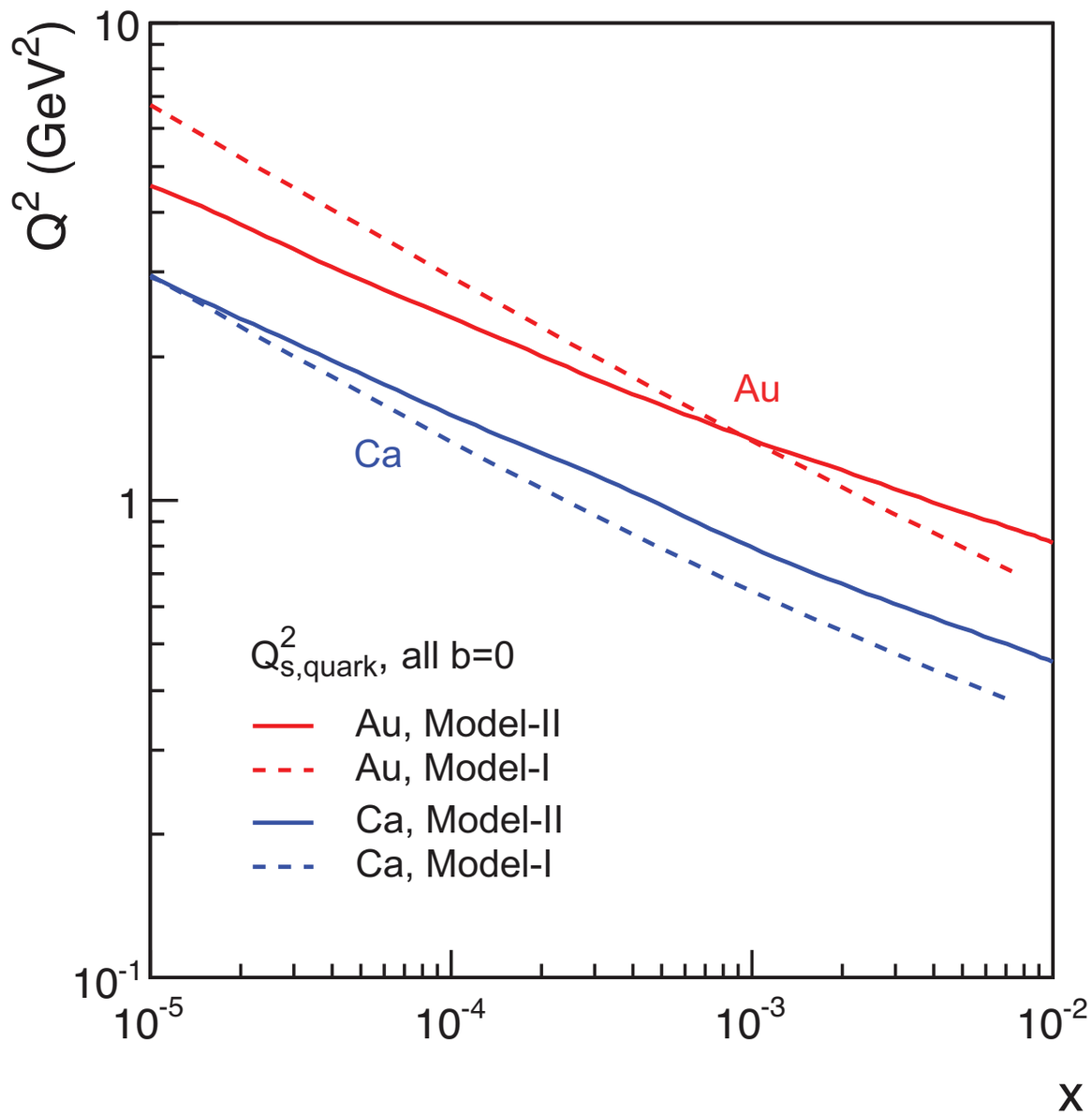
however - saturation in the gluon density is not observed in the gluon distribution at HERA -> too small an x

How can this be observed at eRHIC?

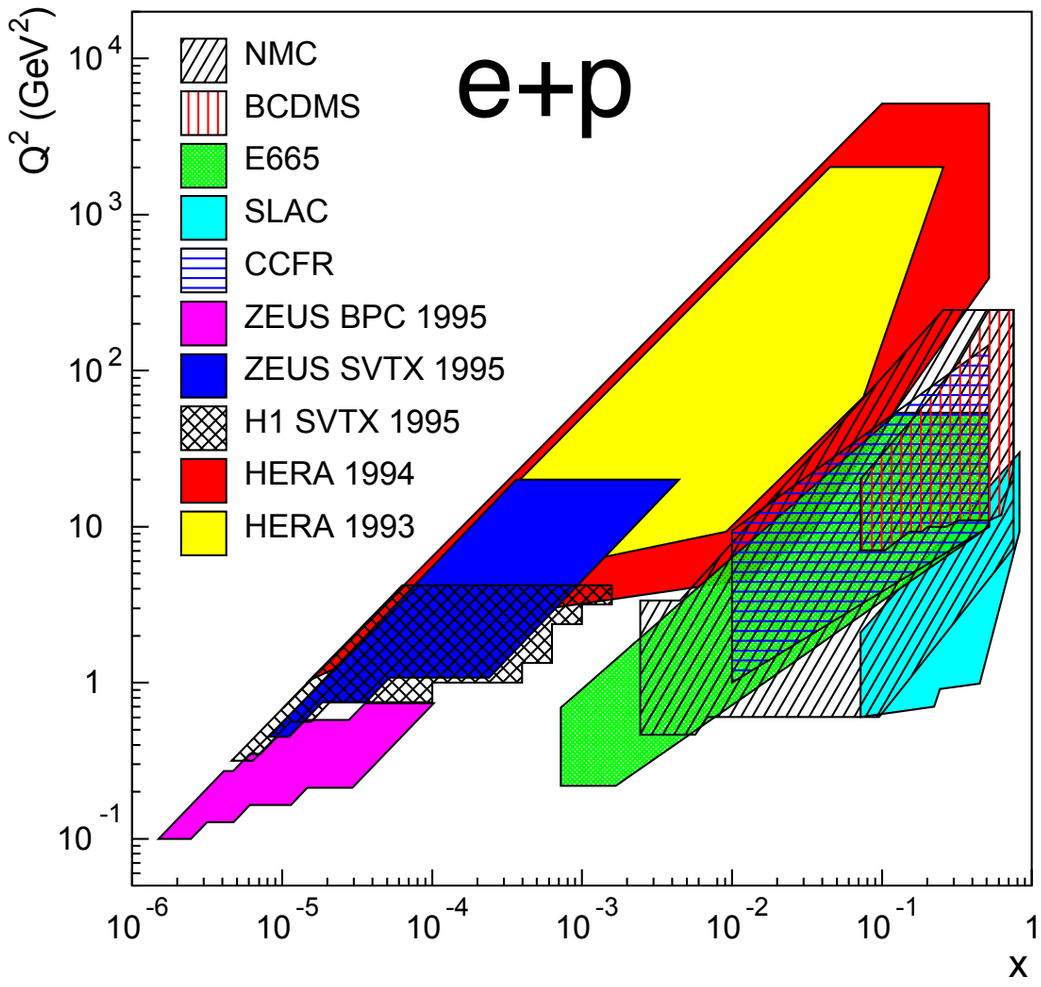
Nuclear “oomph” effect

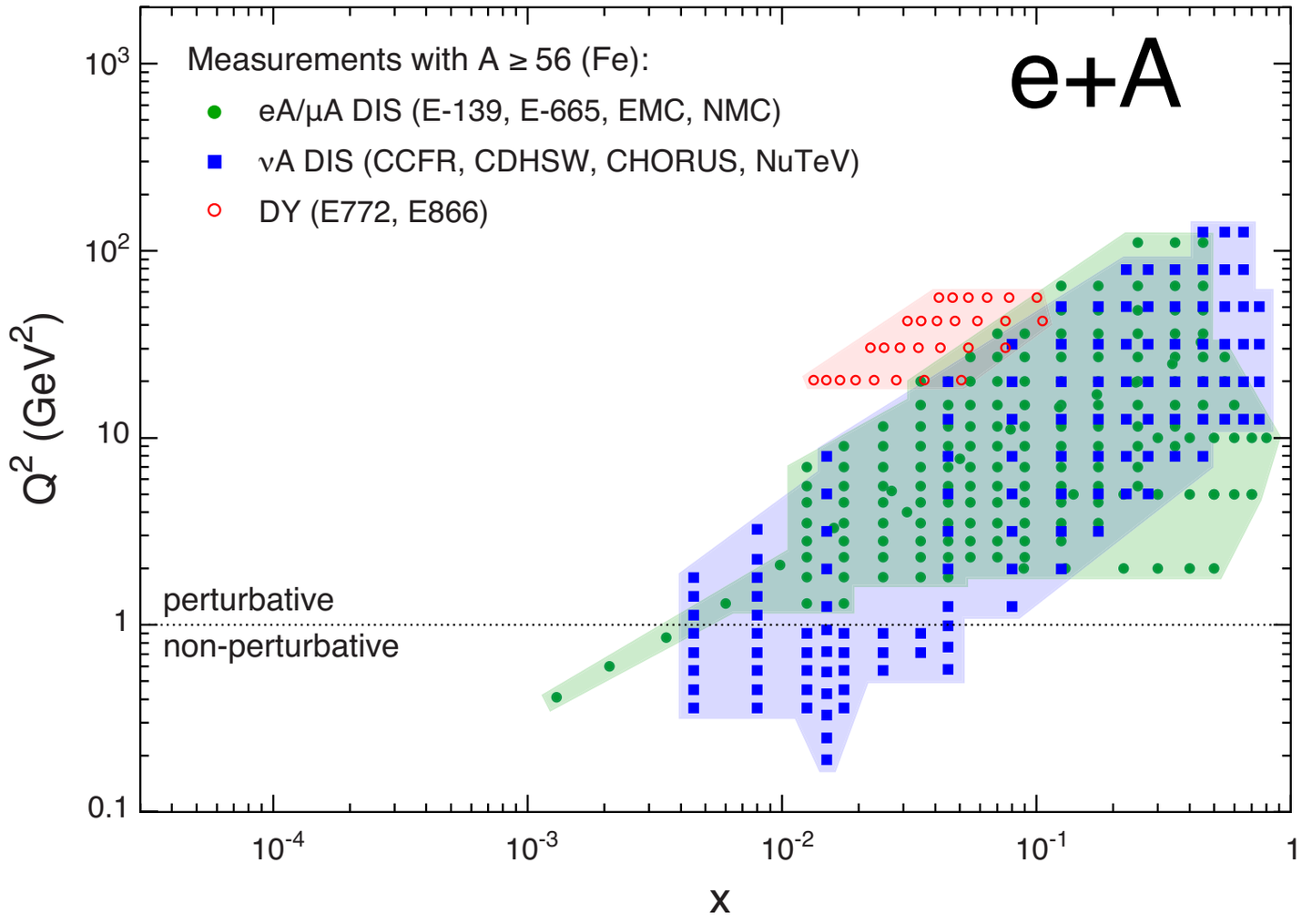
Pocket formula: $Q_s^2(x) \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda} \sim \left(\frac{A}{x}\right)^{1/3}$





What do we know about the structure of nuclei?





- e+p data covers large part of phase space
  - ➡ low x and large Q^2
- e+A data only a small fraction of this (e+A was a fixed target programme at HERA)
  - ➡ high-medium x and low Q^2

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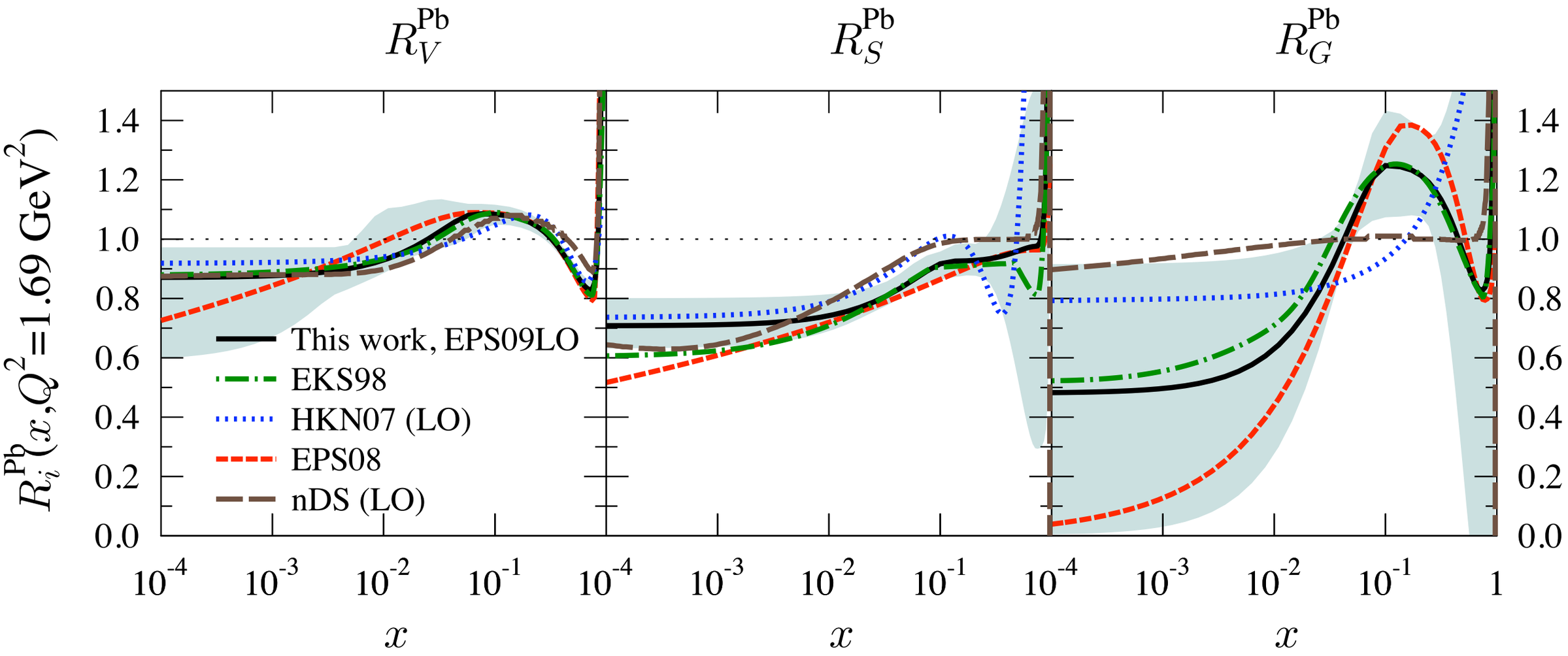

The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

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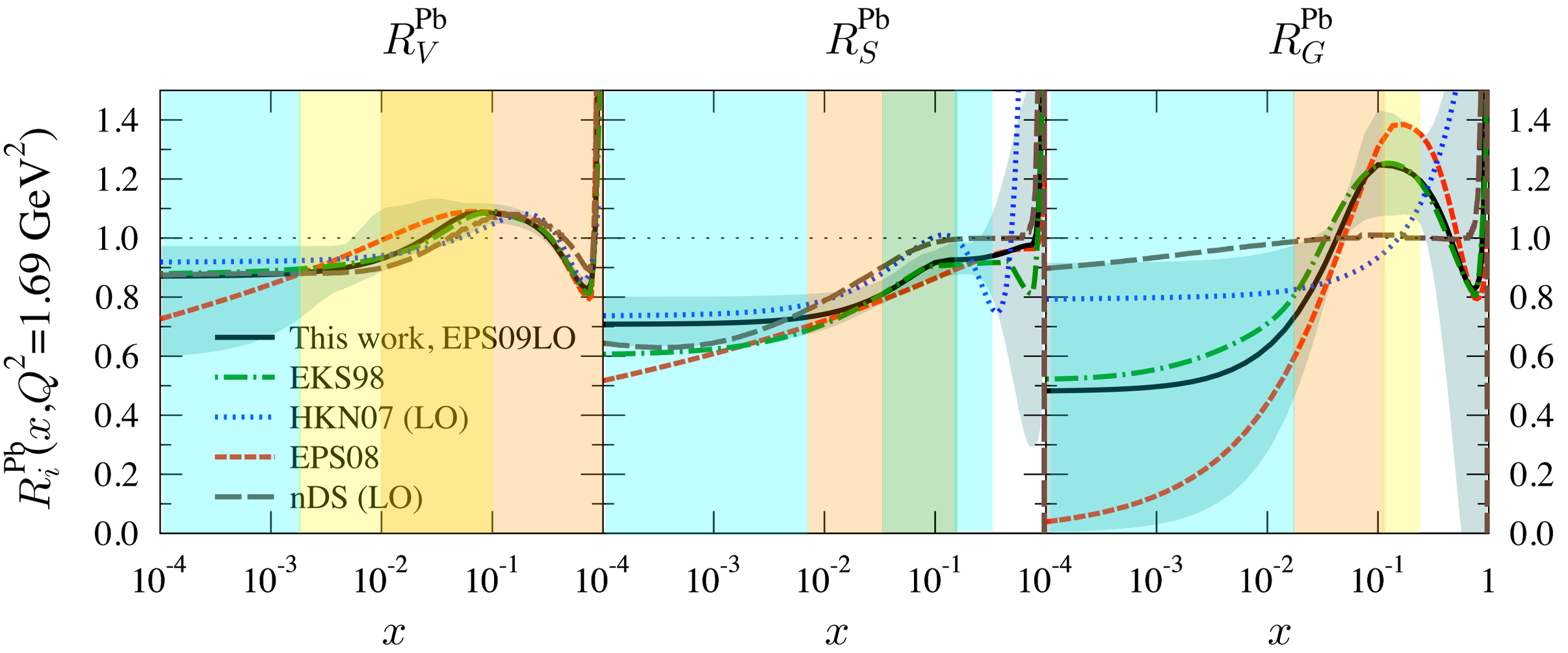

Constrained by DIS

Constrained by DY

Constrained by sum rules

Assumptions

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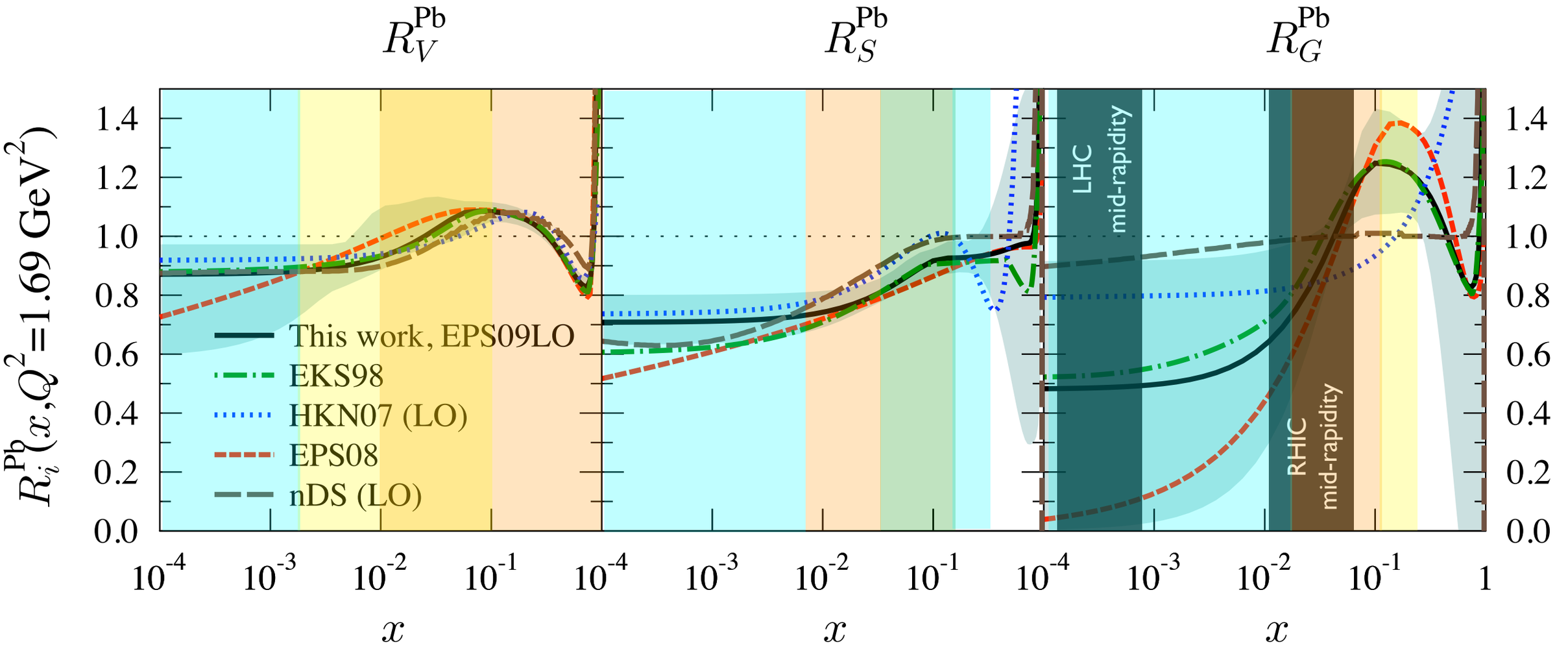
What do we know about the structure of nuclei?



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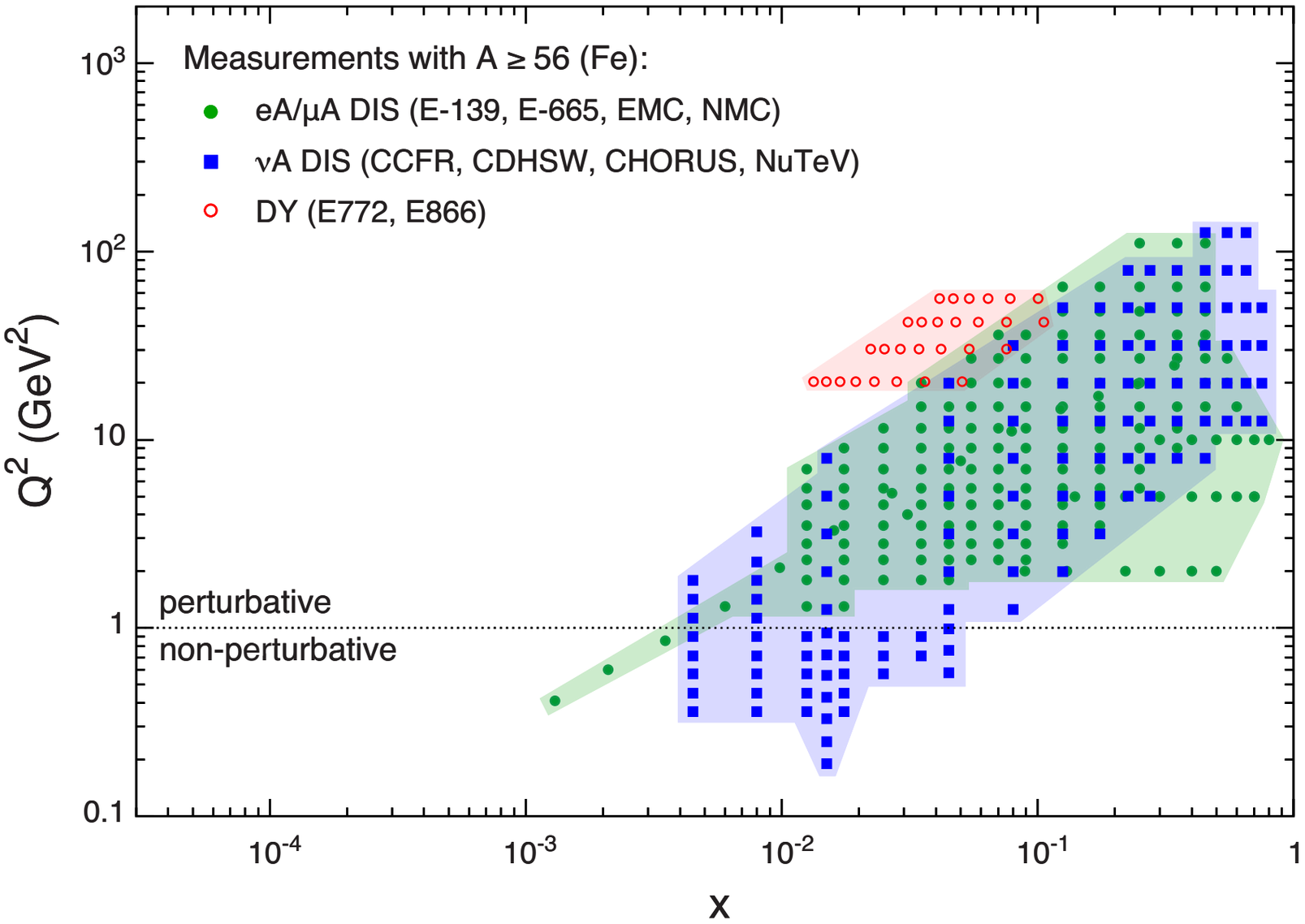
Large discrepancies exist in the gluon distributions from models for mid-rapidity LHC and forward RHIC rapidities !!

Phase-space coverage of e+A collisions for an EIC

- Existing data:
  - ➡ Low energy (fixed target)
  - ➡ Low statistics
  - ➡ Mainly light A
- EIC coverage:
  - ➡ Both “low energy” and “high energy” options extend the reach in x-Q^2 beyond current data
  - ➡ A coverage extended up to U
  - ➡ Saturation scale at moderate Q^2 can be investigated at the lowest x



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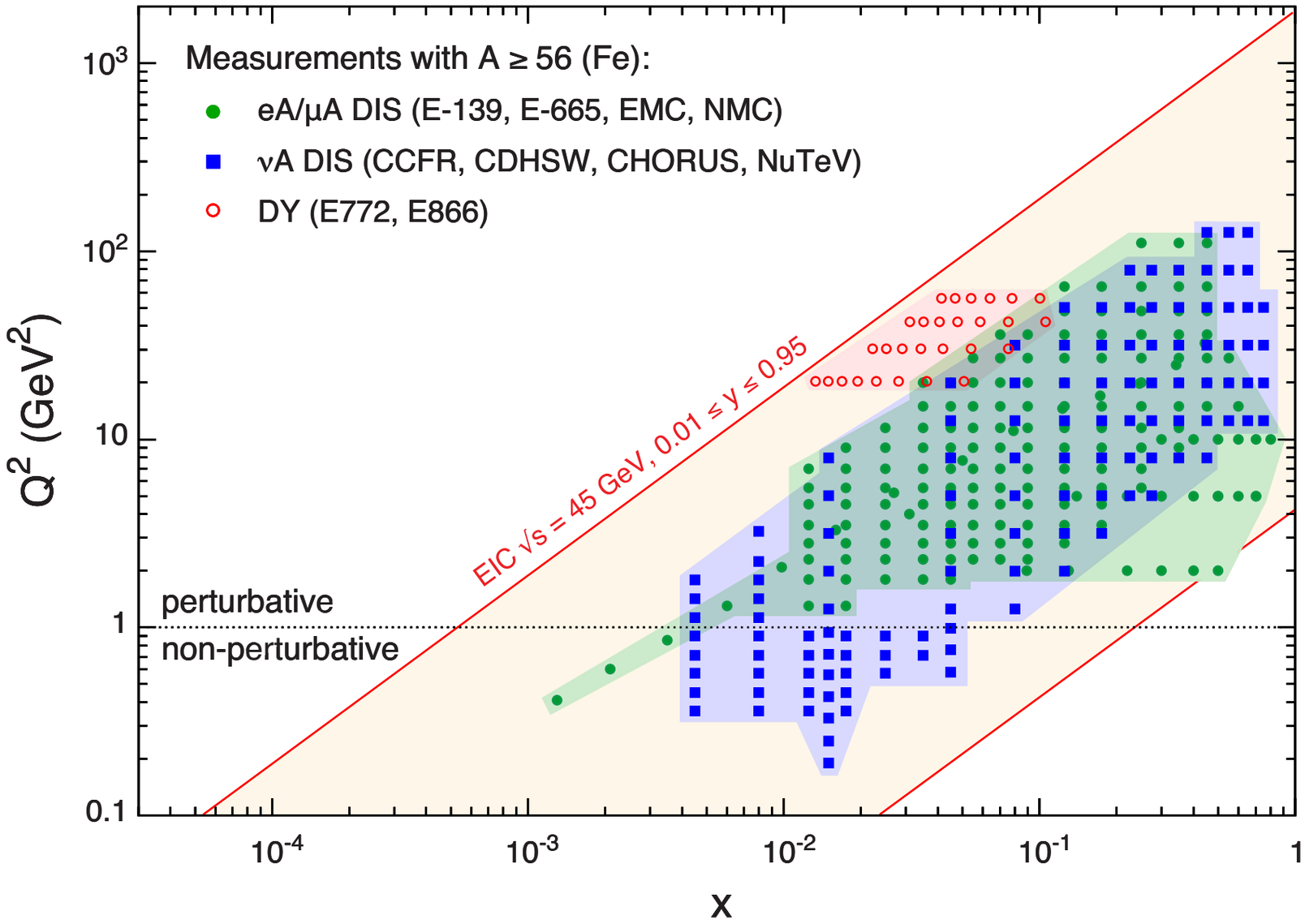

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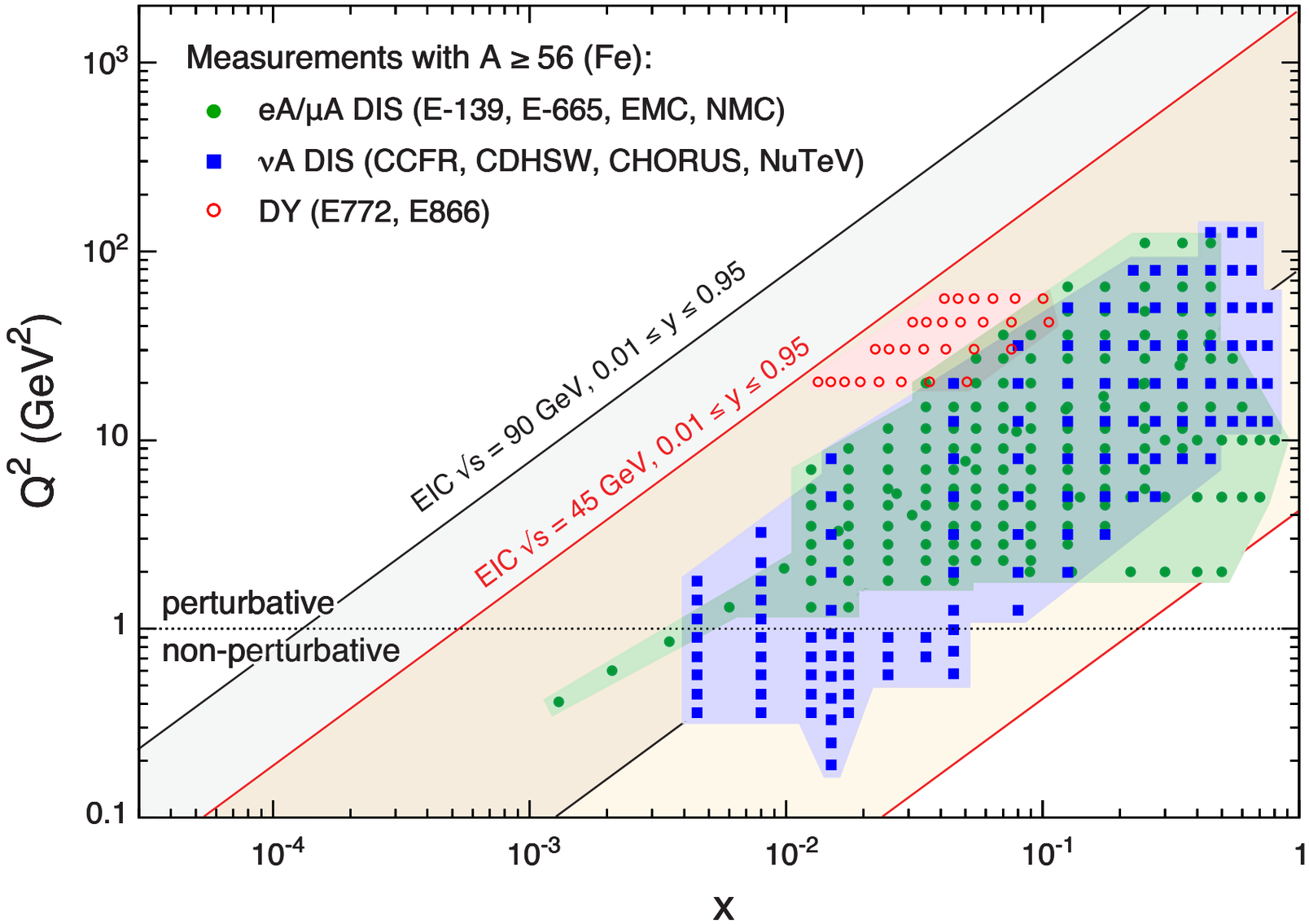

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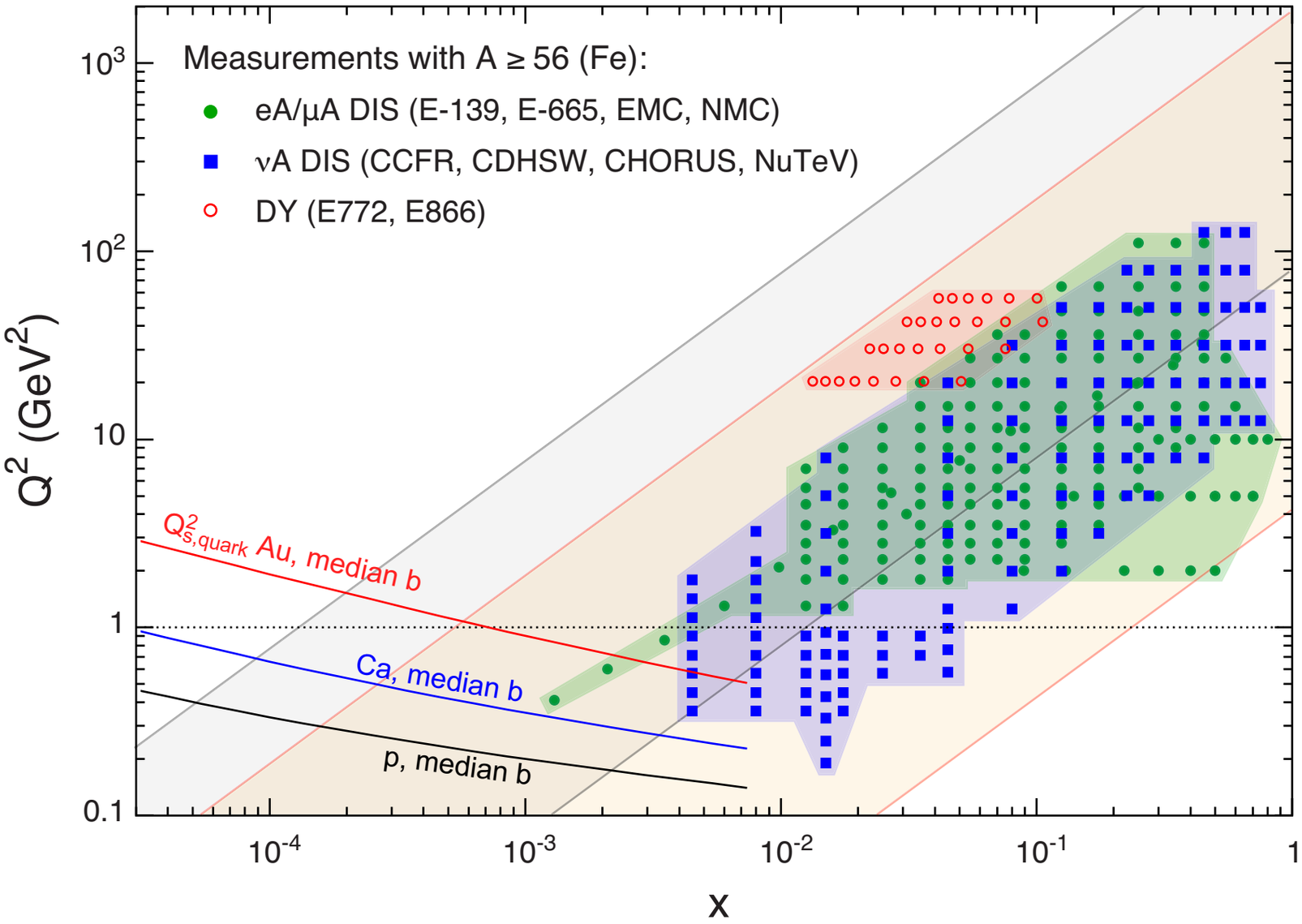


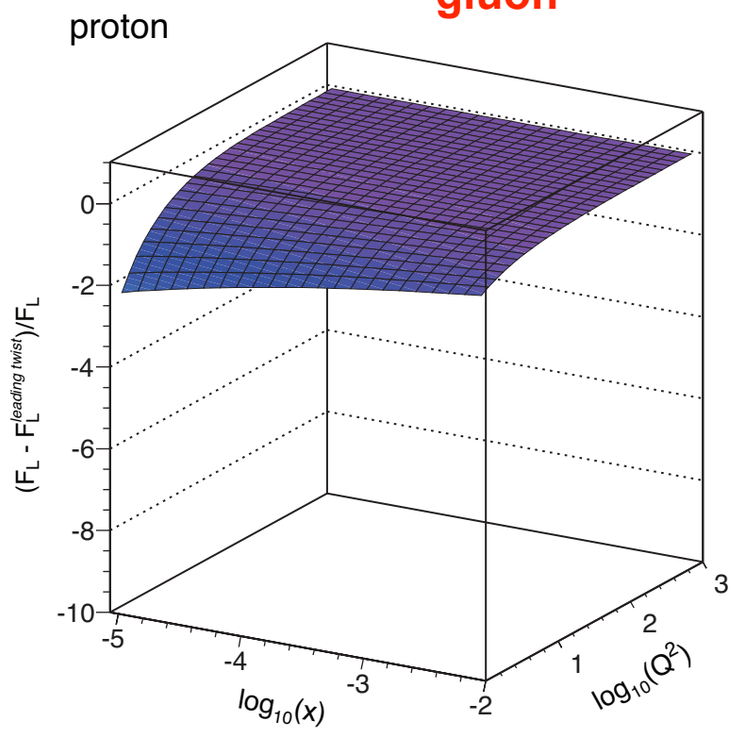
Saturation effects in the proton and nucleus

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

quark+anti-quark

gluon

Measure of non-linear effects in the F_L structure function



Dipole model (J. Bartels *et al.*)

- Plotting this distribution coming out of saturation inspired GBW model

➡ p: small effect only starting to come in at small-x and small Q^2

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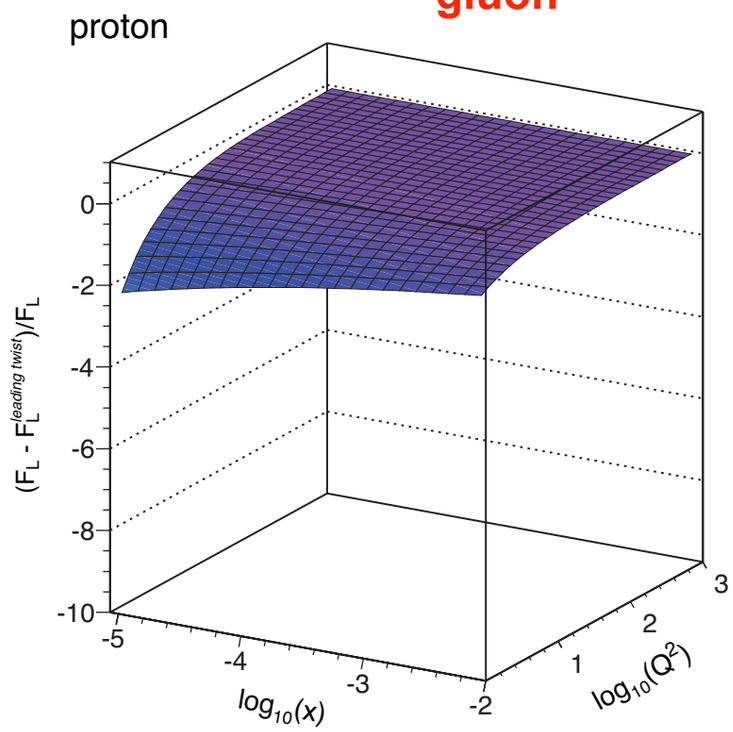

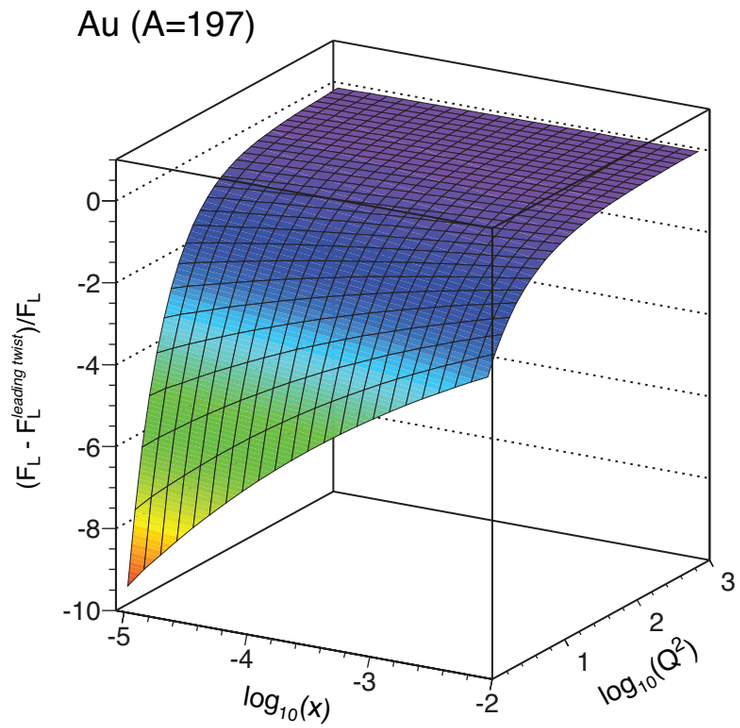

- Plotting this distribution coming out of saturation inspired GBW model
  - ➡ p: small effect only starting to come in at small-x and small Q^2
  - ➡ Au: much larger effects are visible
    - nuclear “oomph” effects well manifested in the F_L structure function

Saturation effects in the proton and nucleus

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

quark+anti-quark

gluon

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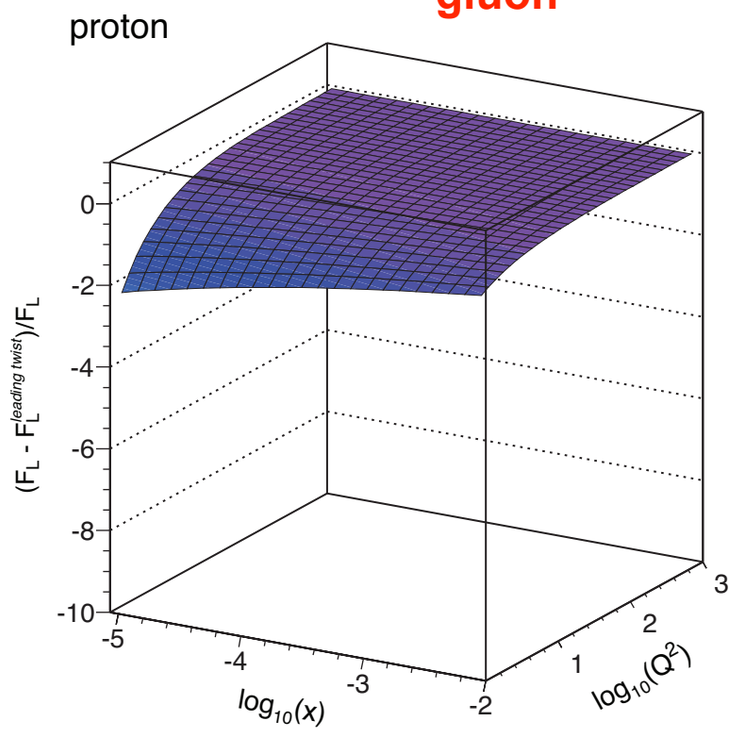

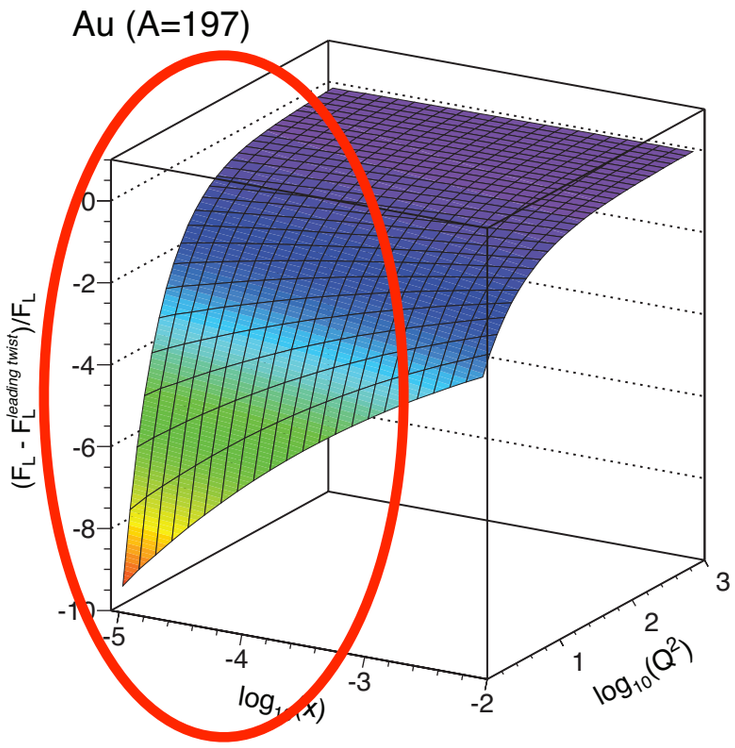

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Measuring the gluons: extracting F_L

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

- $F_L \sim \alpha_s\, xG(x,Q^2)$
  - ➡ $y = Q^2/xs$
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- 3 different proton energies run at HERA
  - ➡ 2 low-statistics runs
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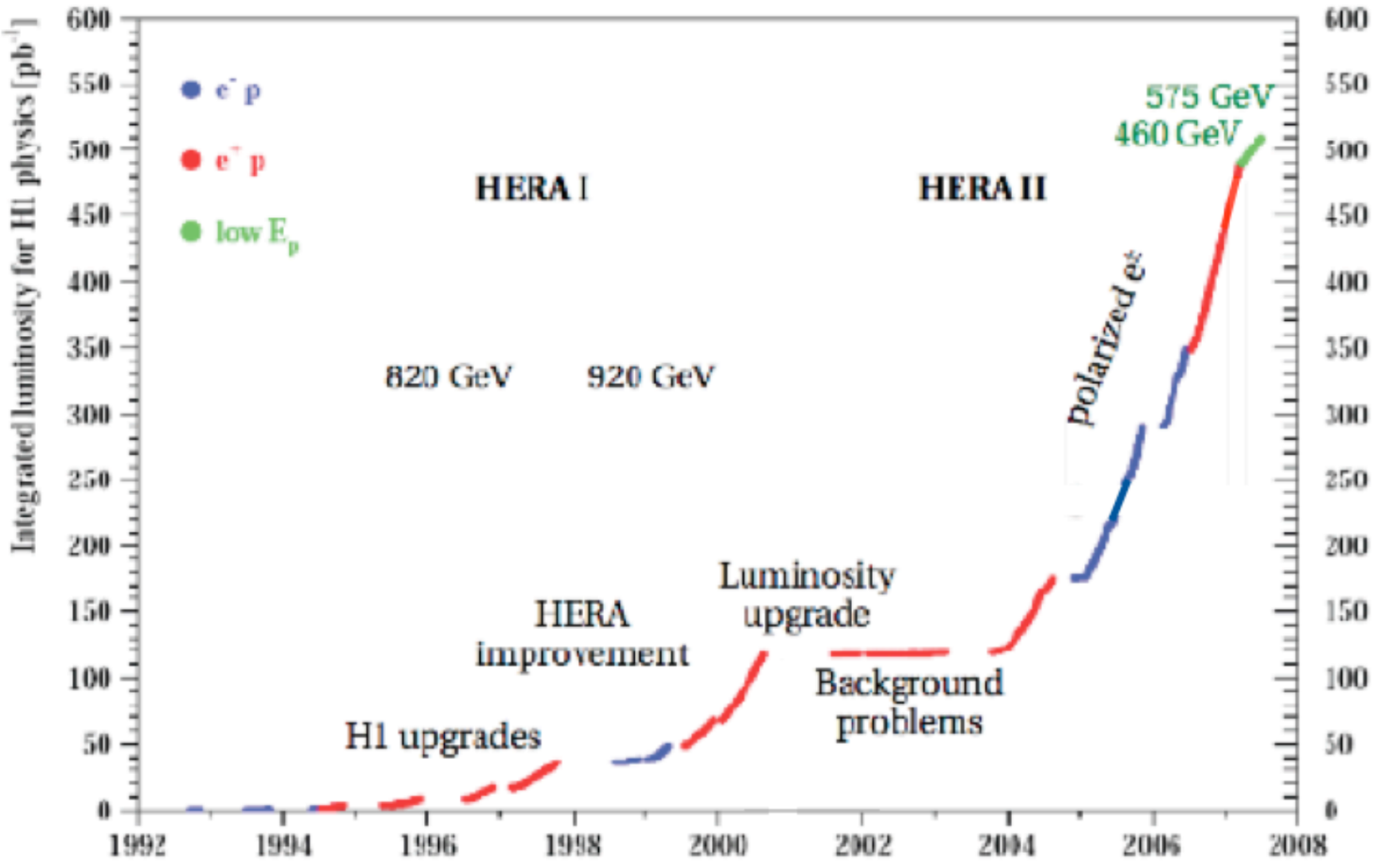

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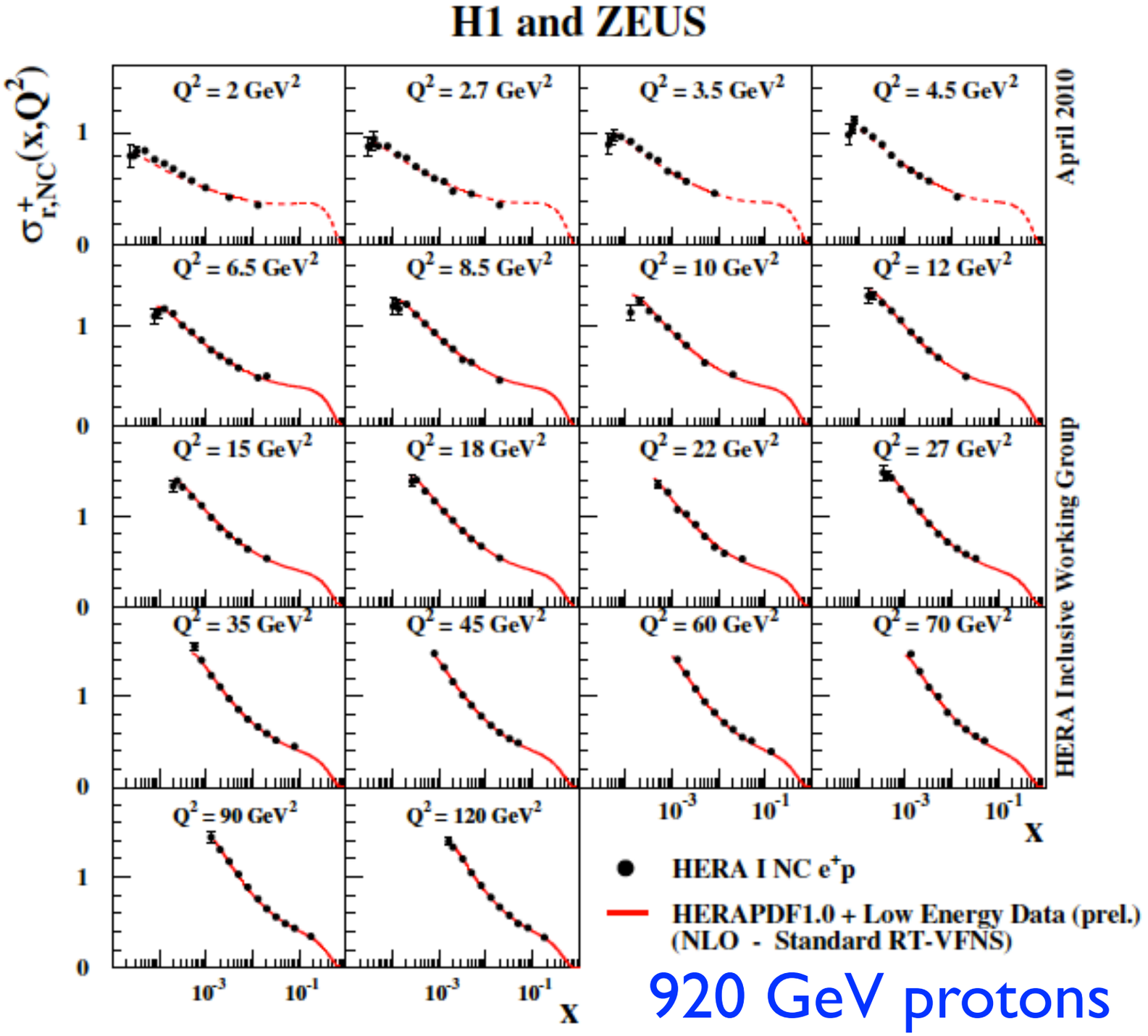

920 GeV protons

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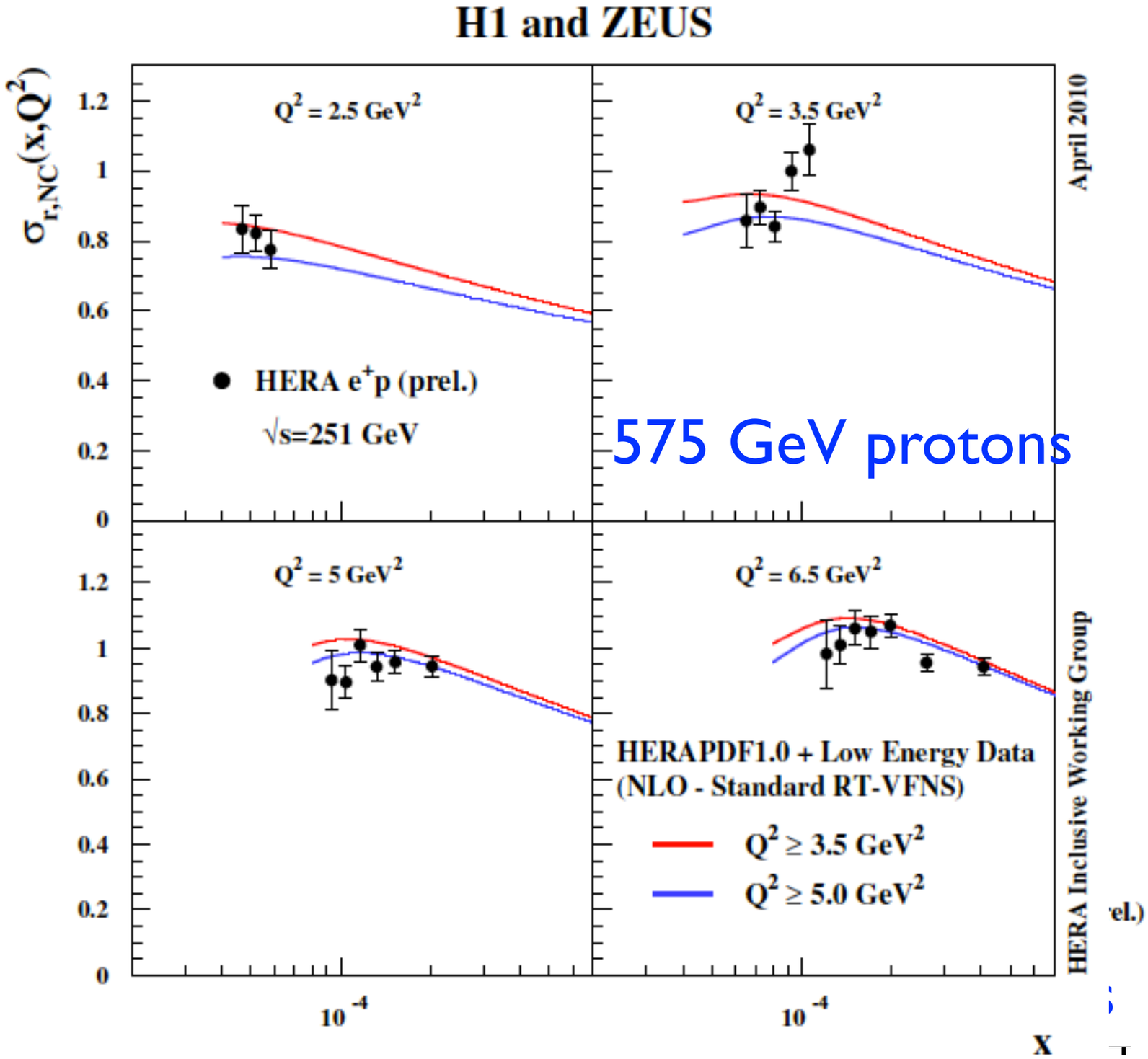

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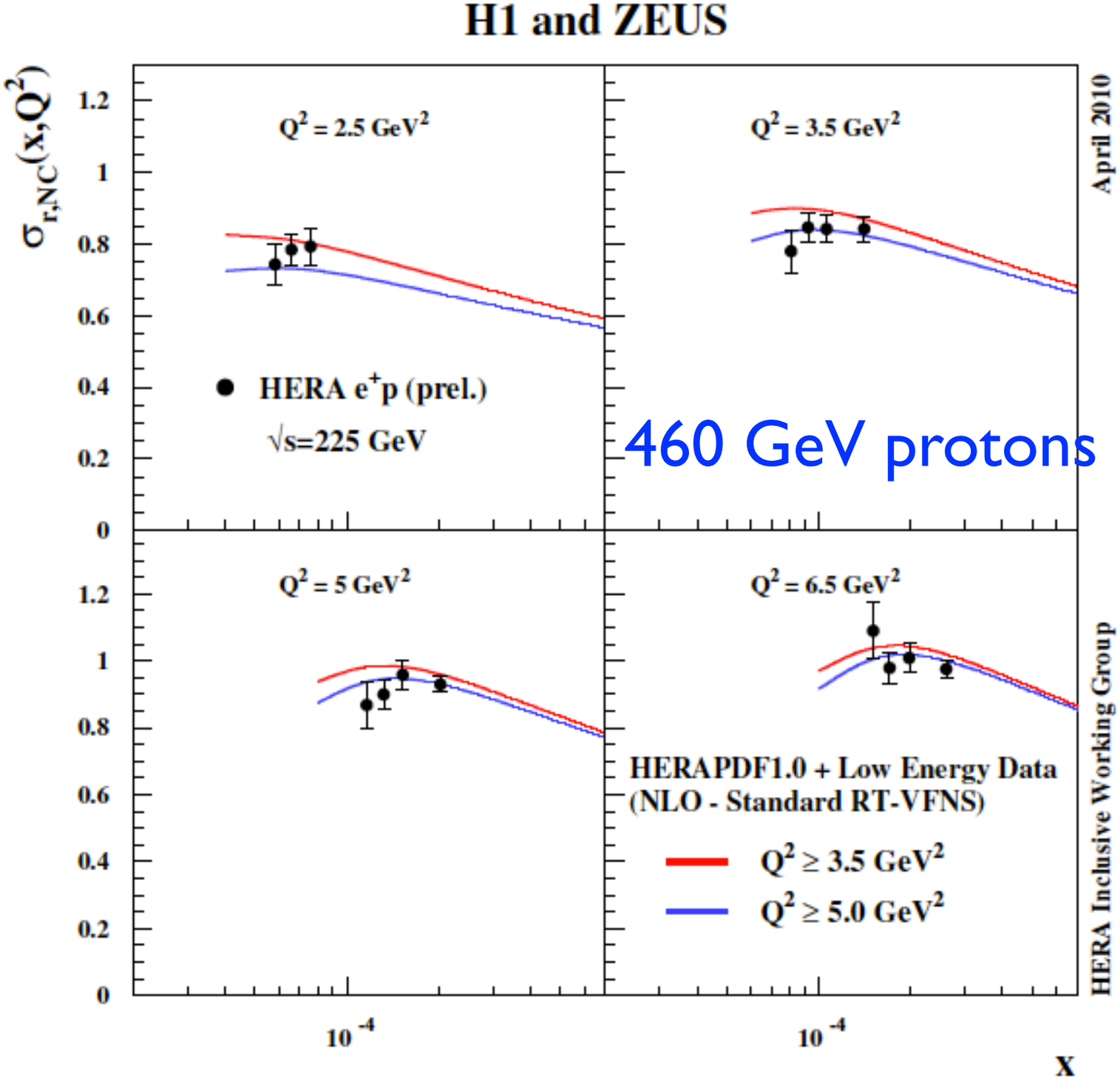

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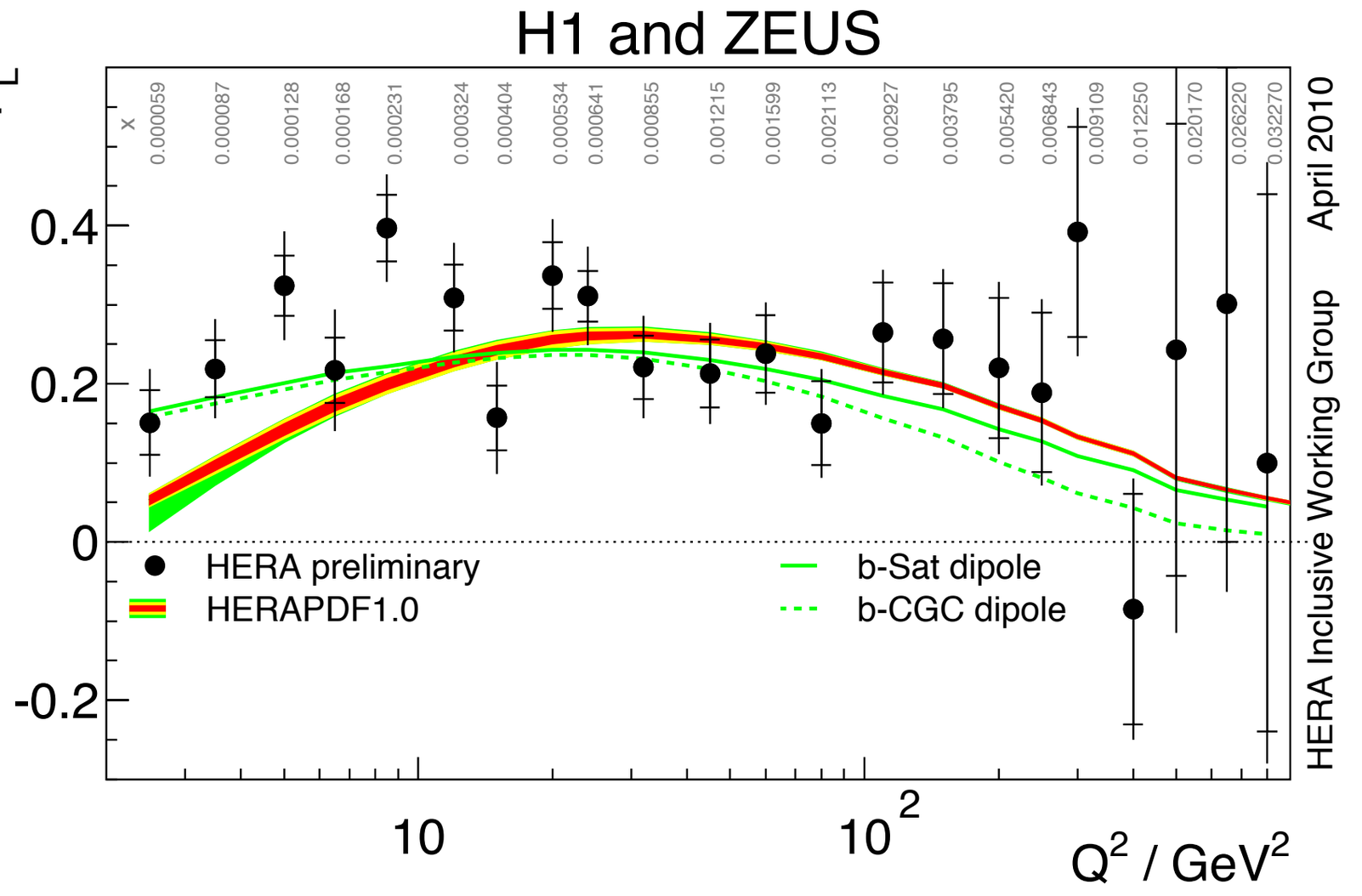

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Strategies:

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

e+Au:

20x50 - A∫Ldt = 2 fb^{-1}
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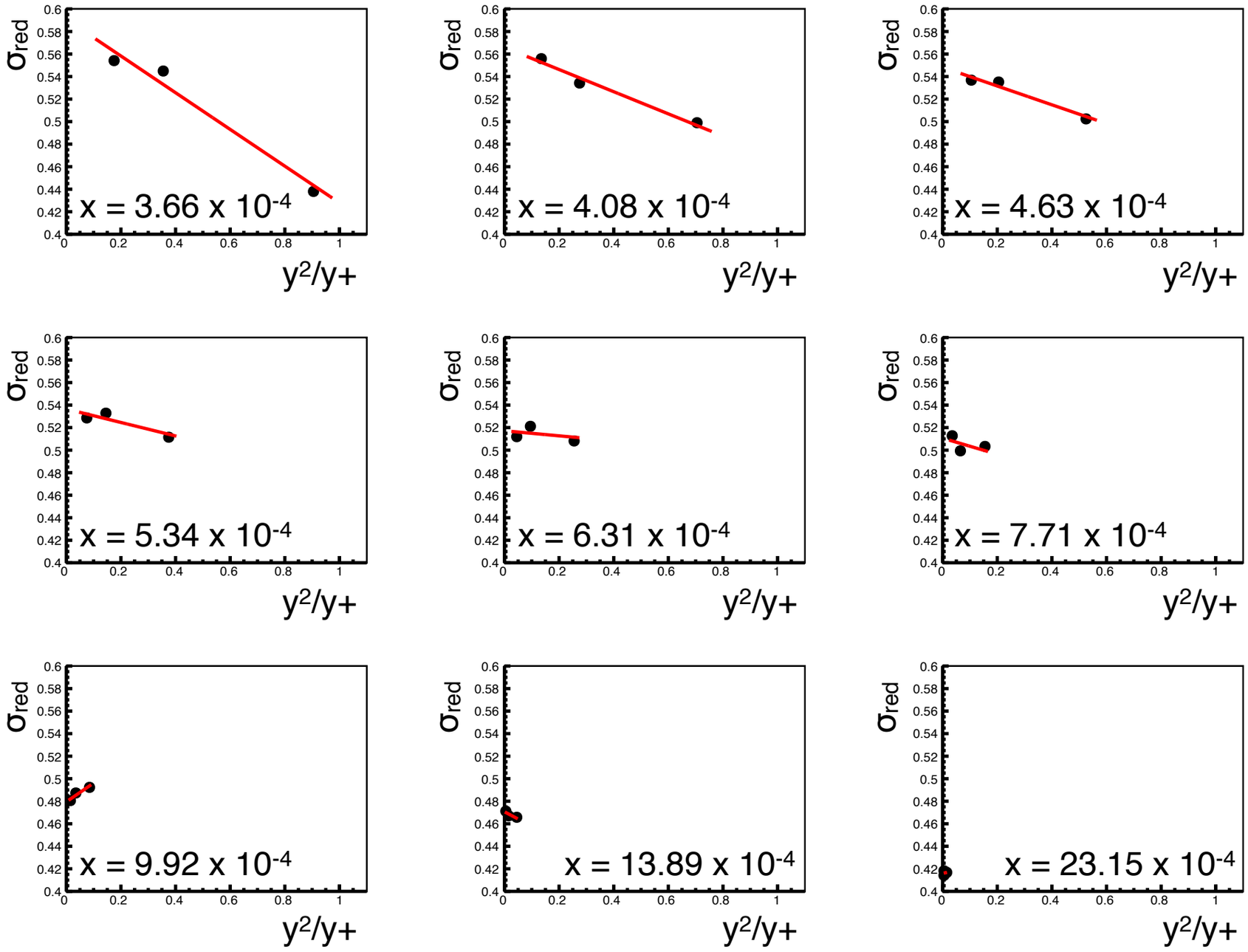
20x100 - A∫Ldt = 4 fb^{-1}
running combined
~6 months total running (50% eff)

statistical errors are swamped by the 3% systematic errors

Will be dominated by systematics, but would need a full detector simulation in order to estimate them

Q^2 = 1.389 GeV^2



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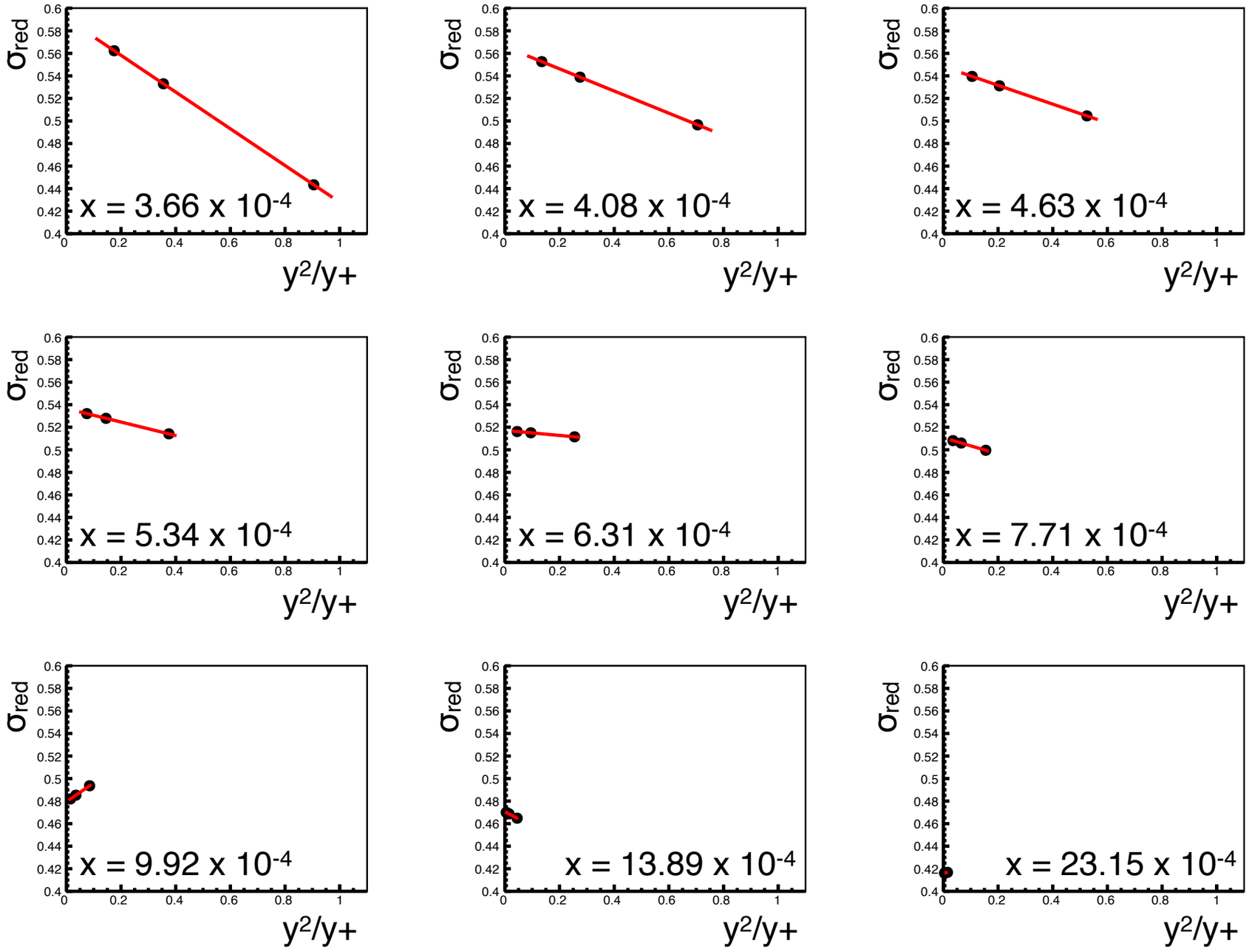

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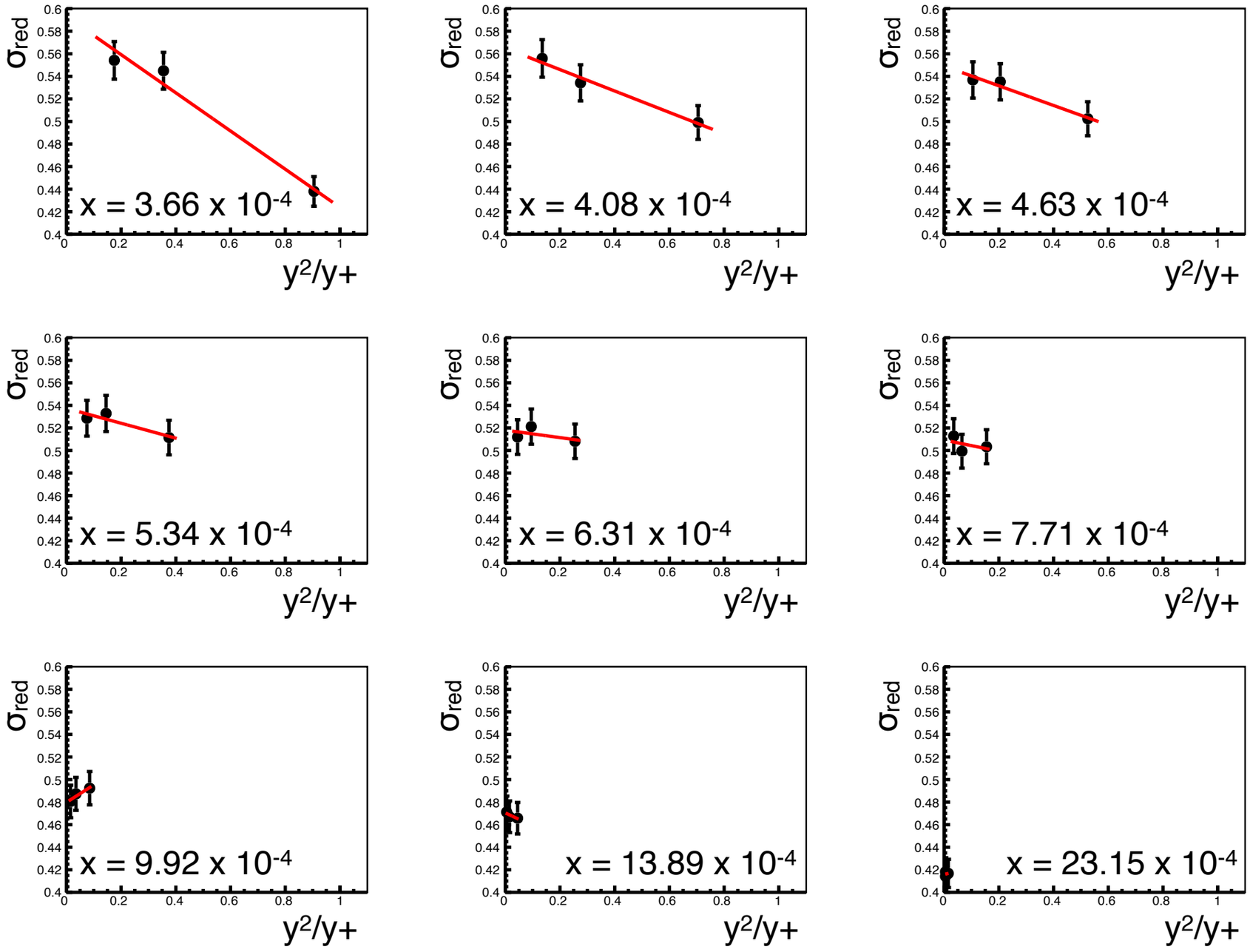

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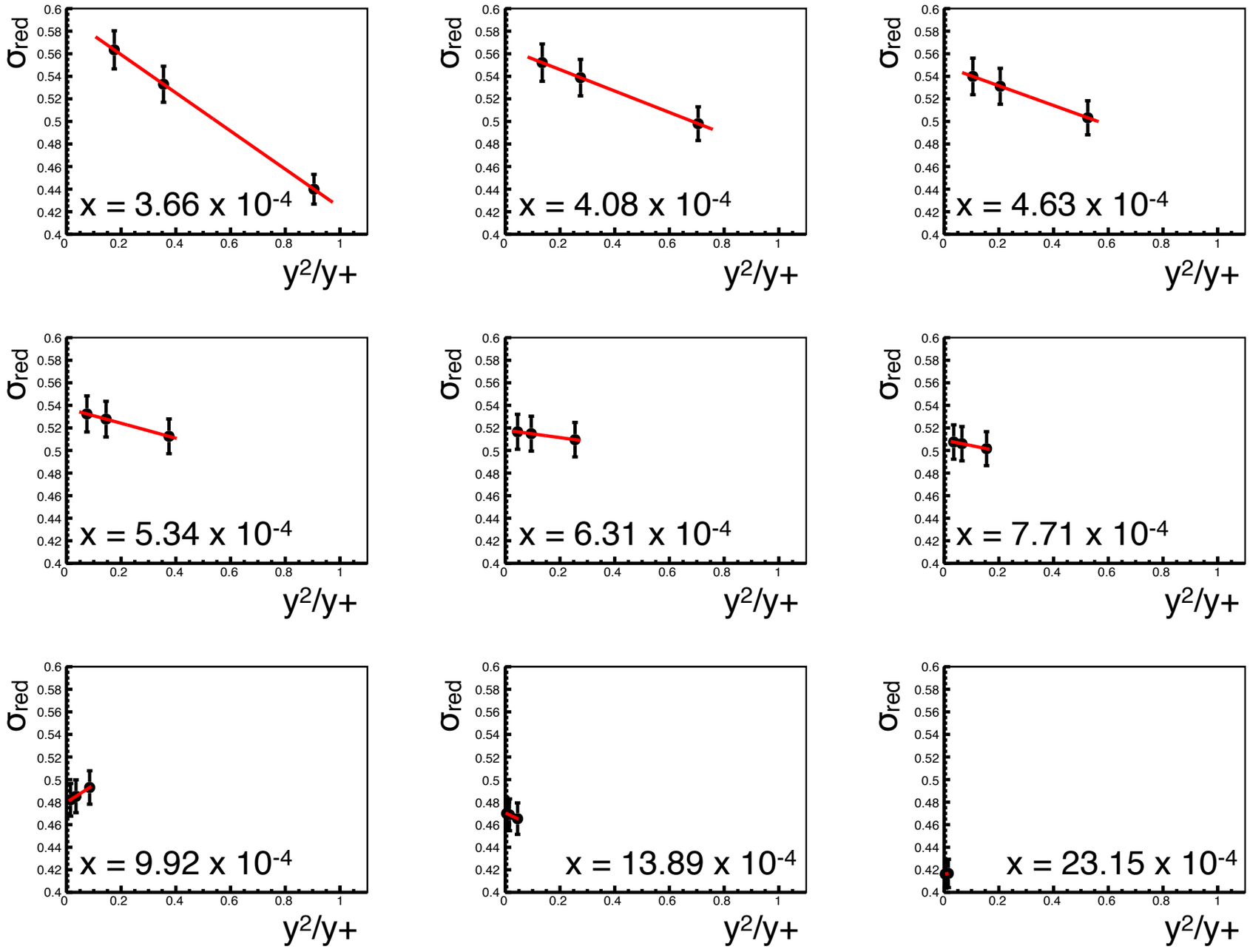

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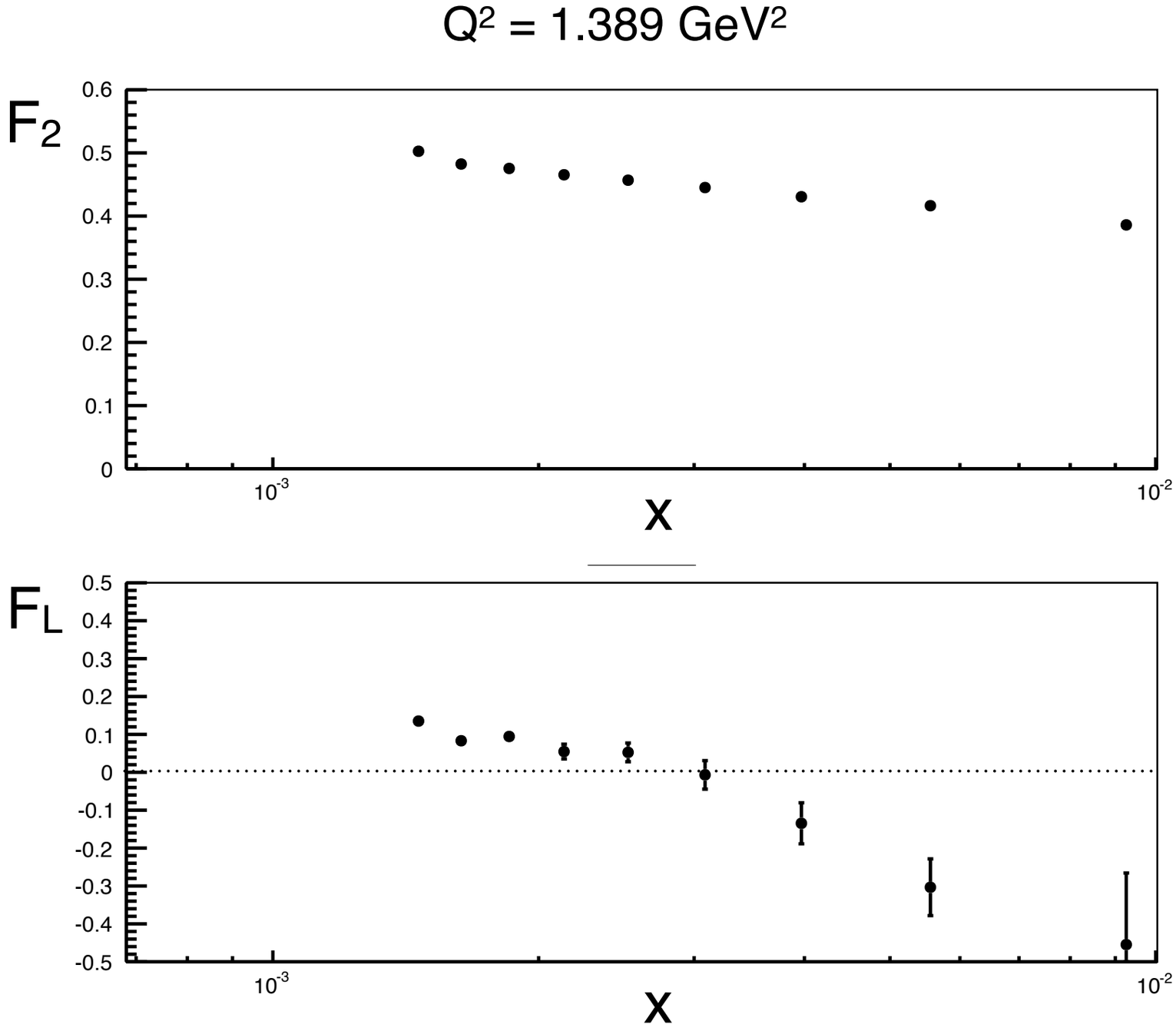

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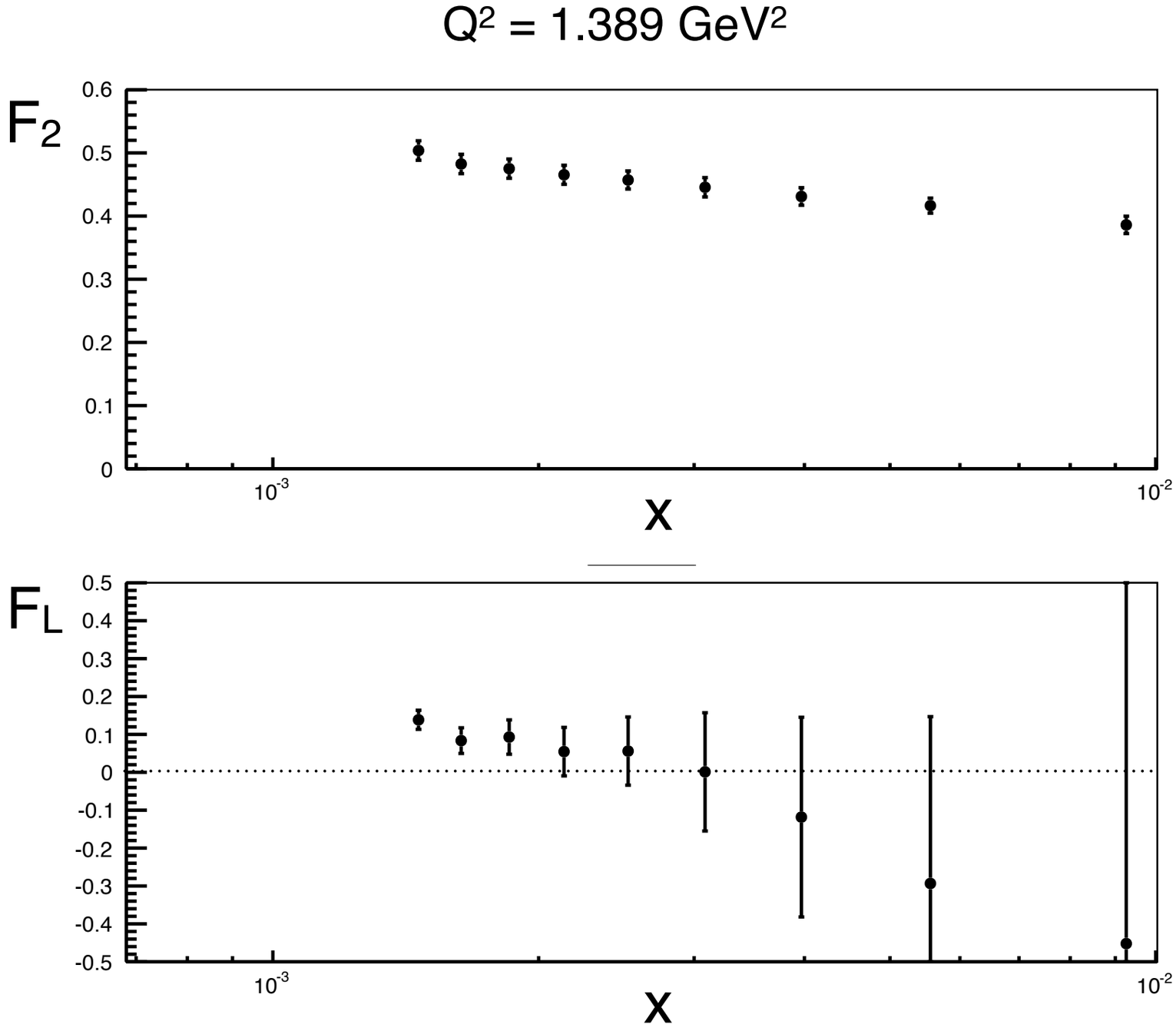

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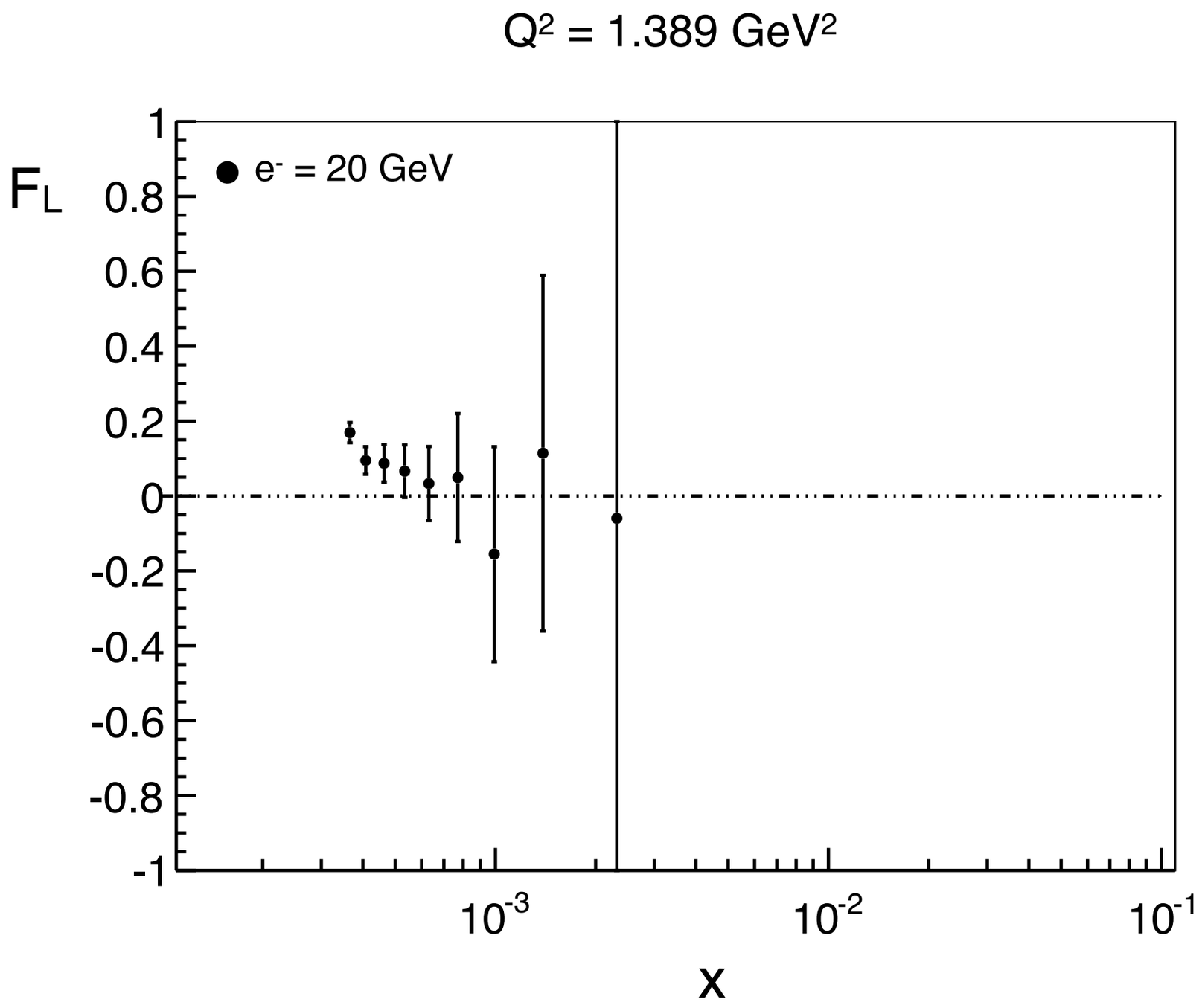

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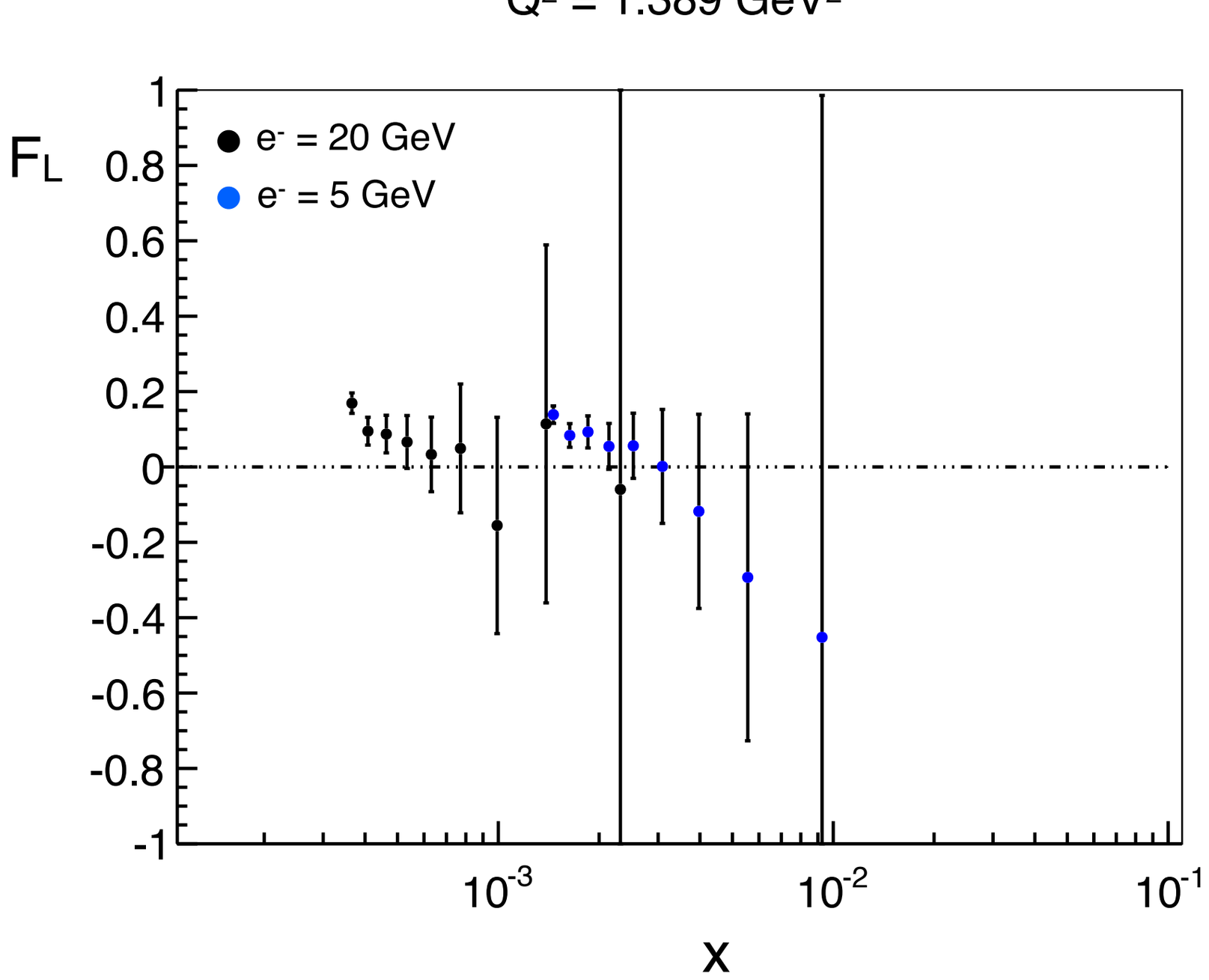

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e+Au: 1st stage

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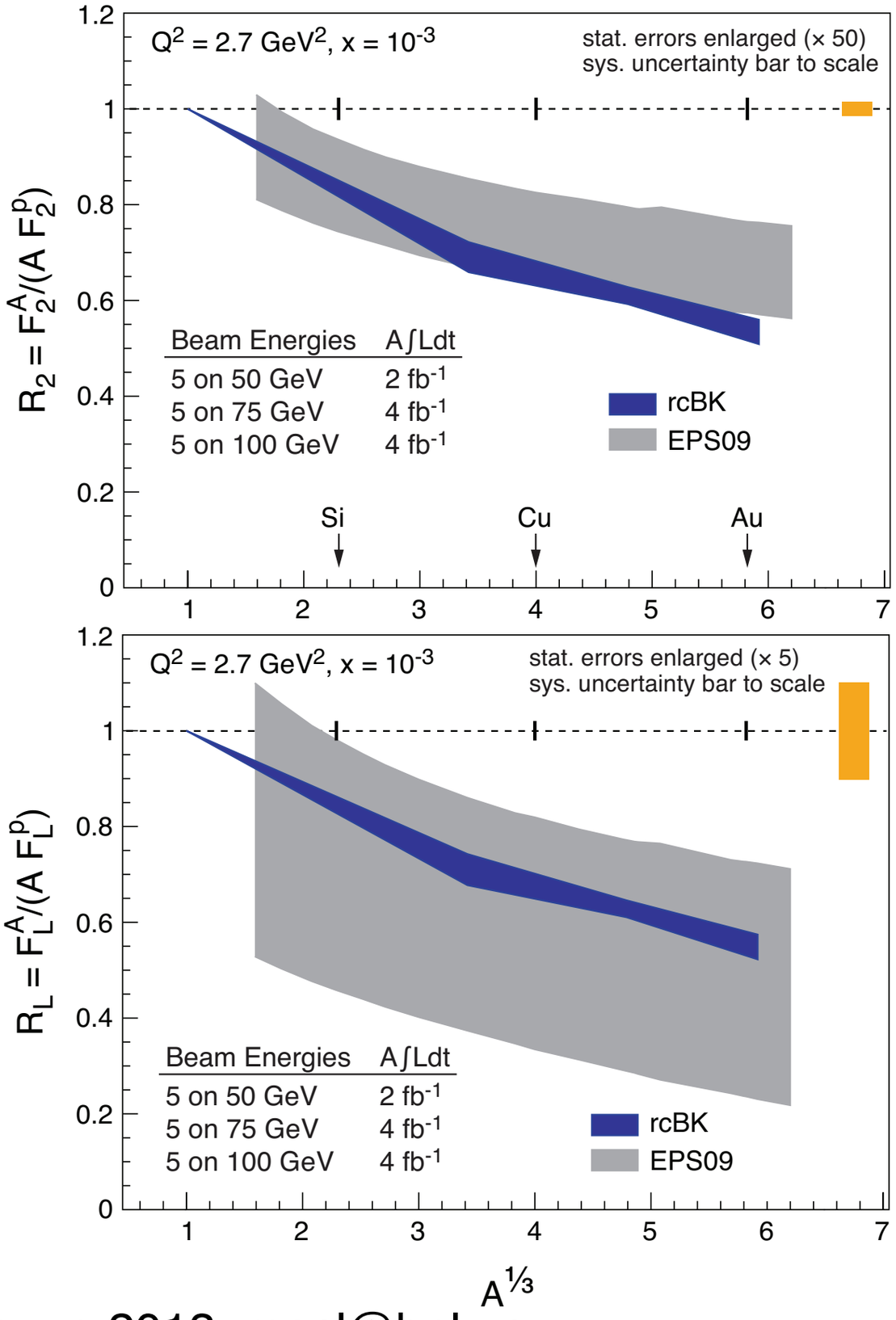
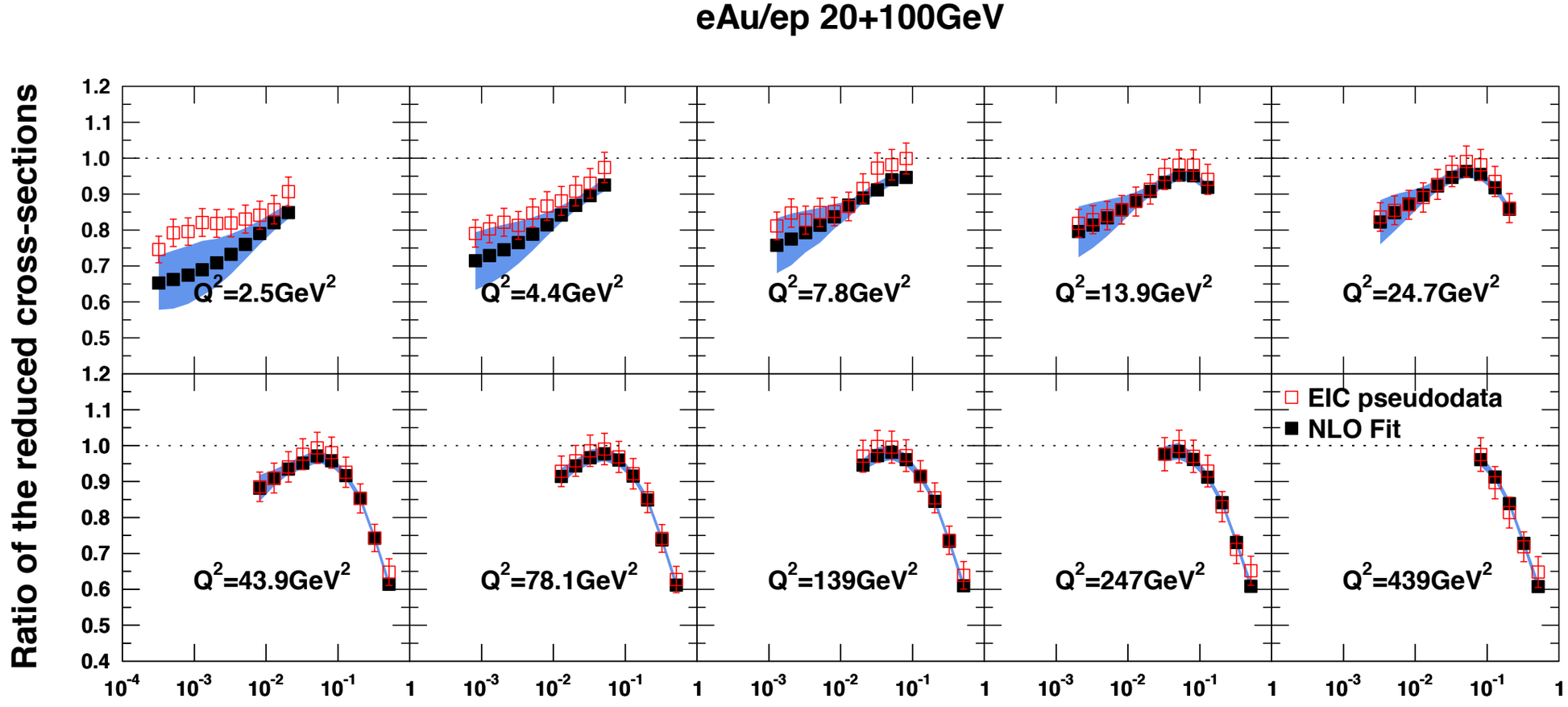


Work in progress… (H. Paukkunen)

- Take the generated Pseudo-data and include it in a global fit

➡ Only 20x100 and 5x100 included in these plots

- ▸ More data will constrain this further



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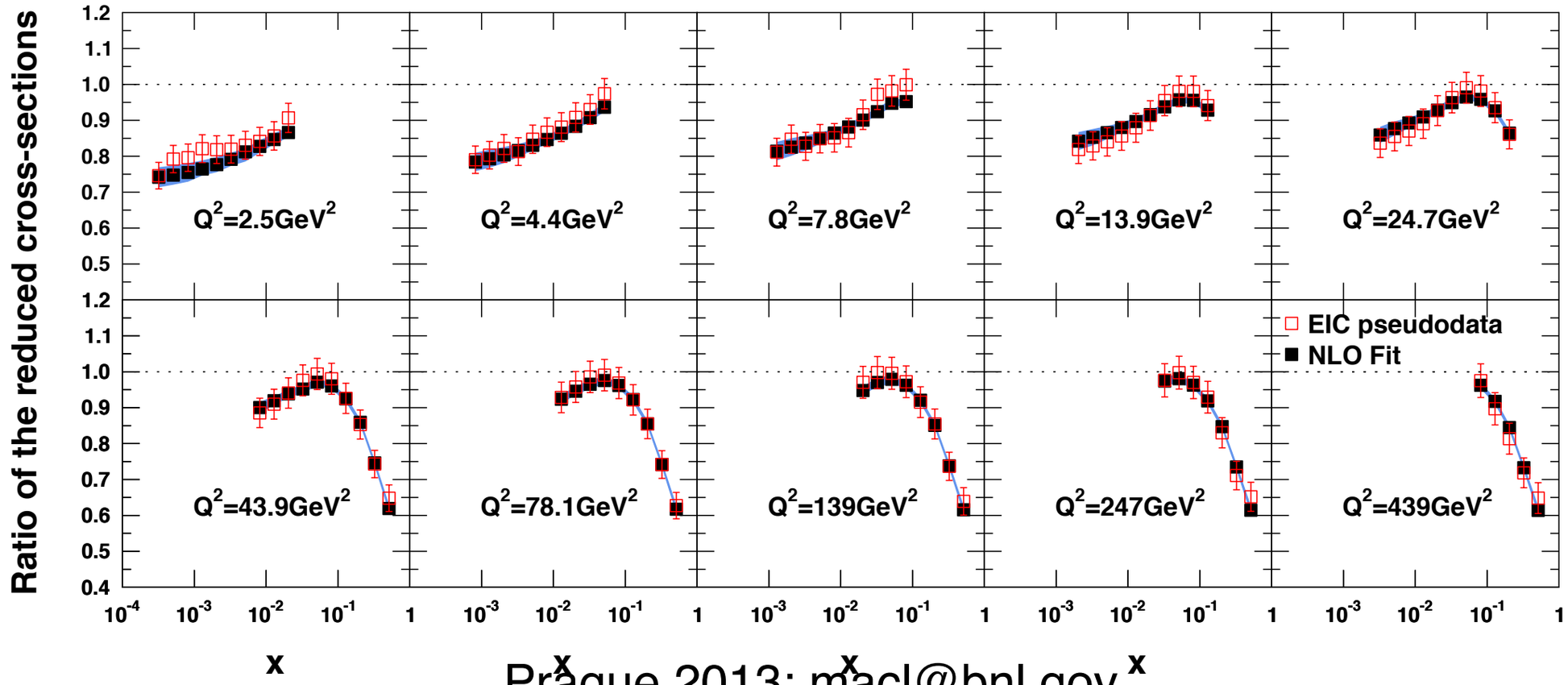

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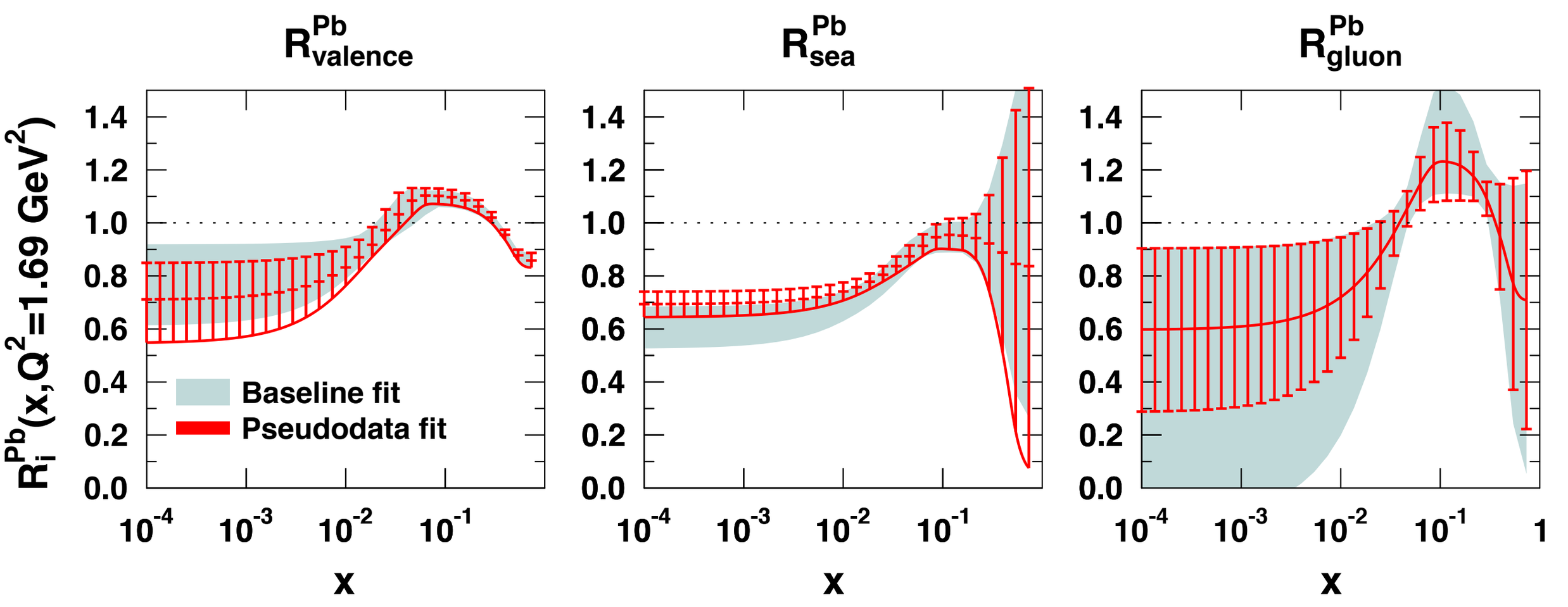

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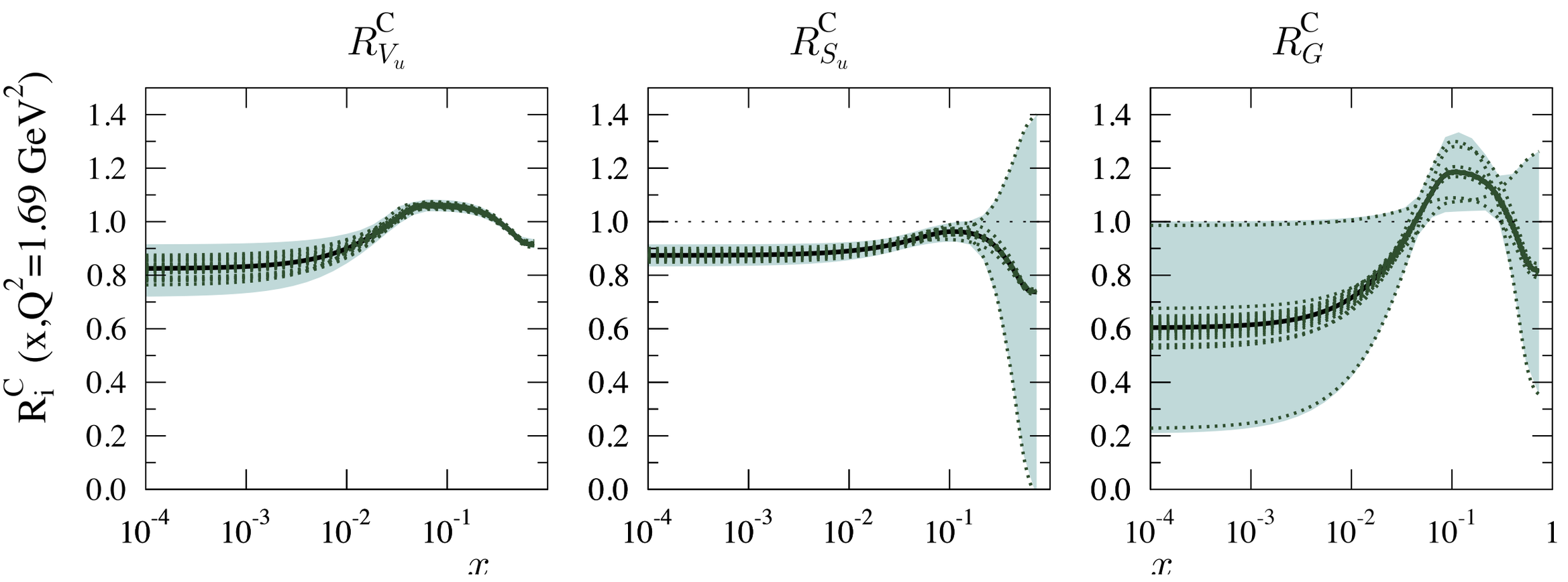
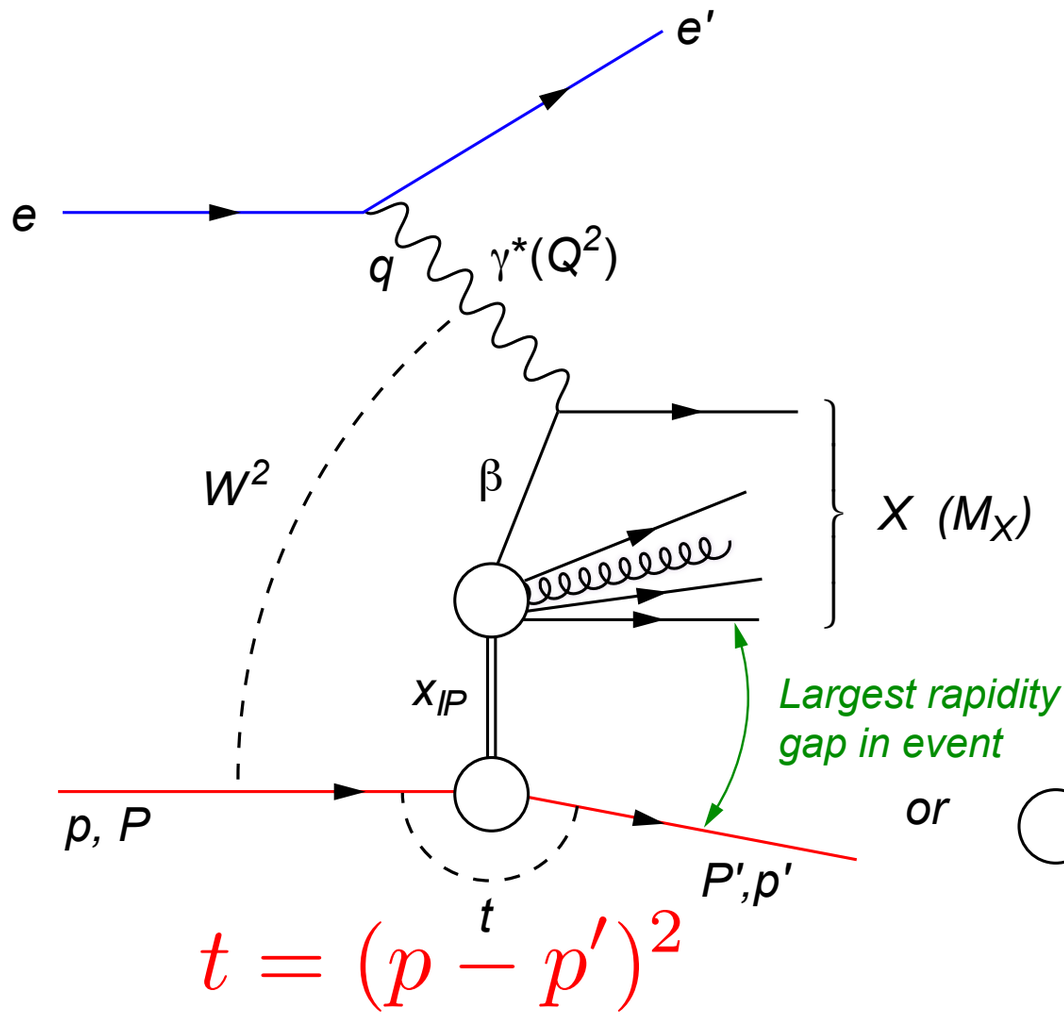


Exclusive processes in e+A - diffraction



- β is the momentum fraction of the struck parton w.r.t. the Pomeron
- $x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

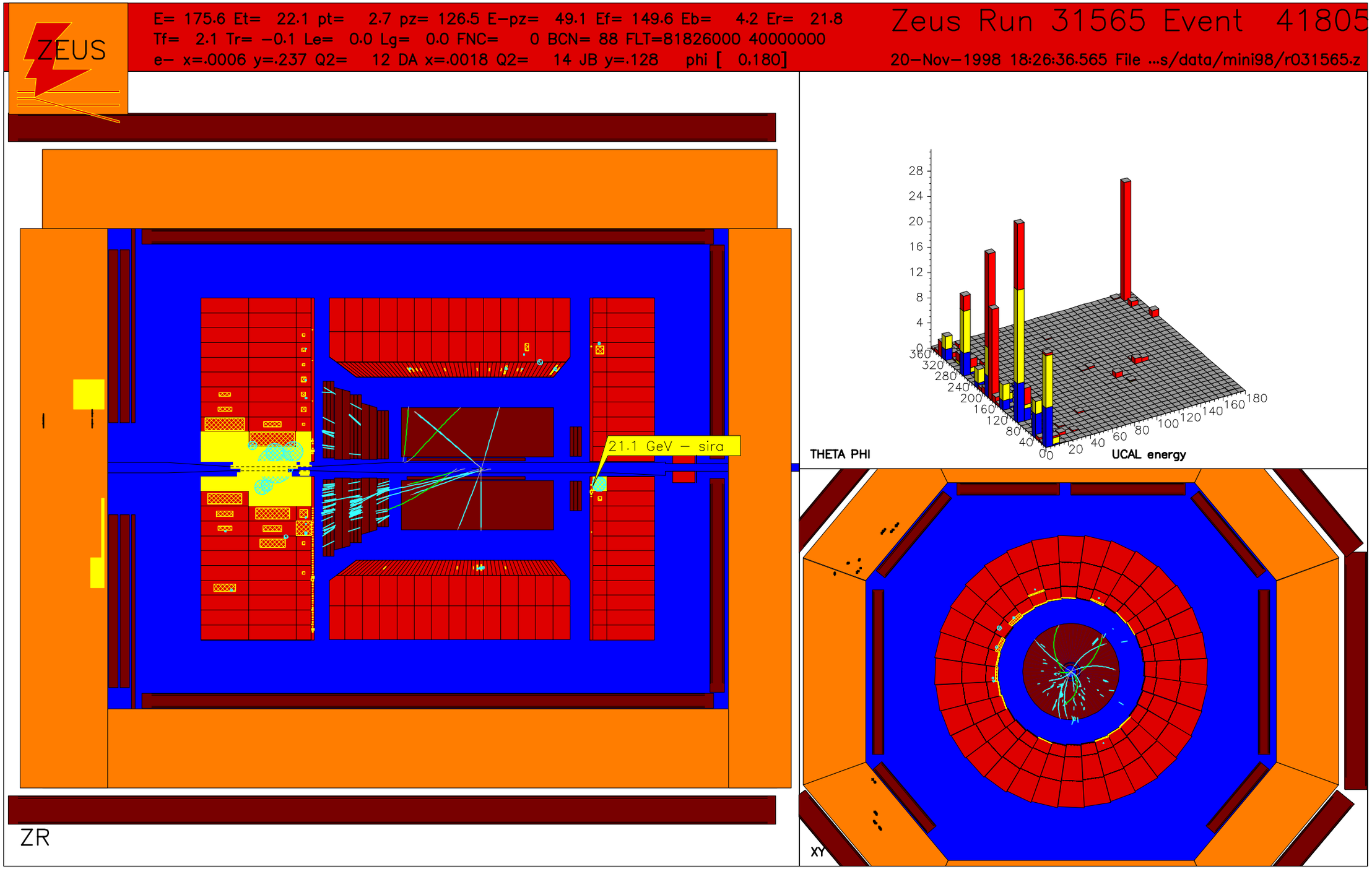
$$\beta = \frac{x}{x_{I\!P}} = \frac{Q^2}{Q^2 + M_X^2 - t}$$

- Diffraction in e+p:
  - ➡ HERA: 15% of all events are diffractive

- Diffraction in e+A:
  - ➡ Predictions: $\sigma_{diff}/\sigma_{tot}$ in e+A ~25-40%
  - ➡ Coherent diffraction (nuclei intact)
  - ➡ Incoherent diffraction: breakup into nucleons (nucleons intact)

Visualising Diffractive events

A DIS event (experimental view)



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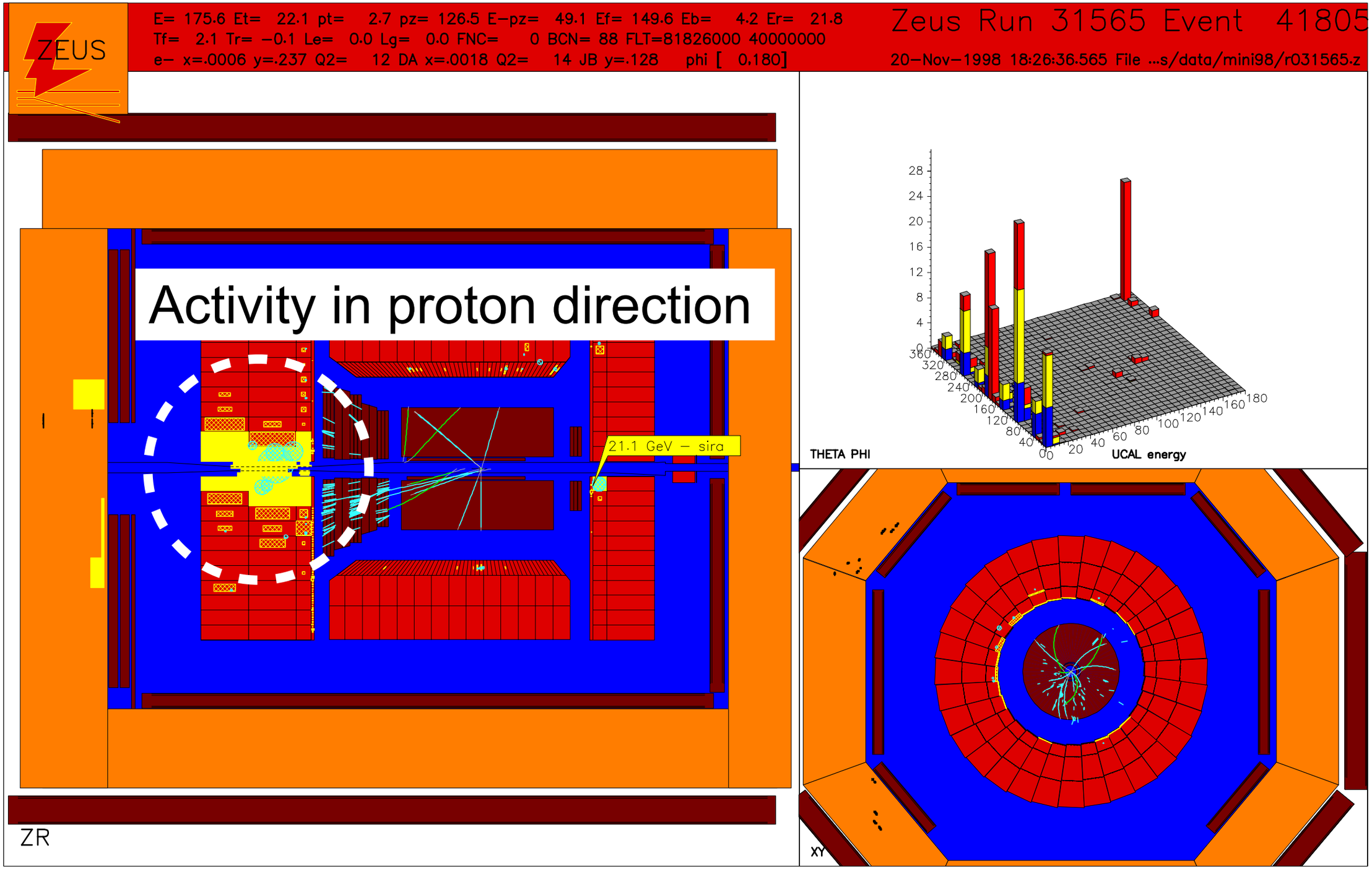

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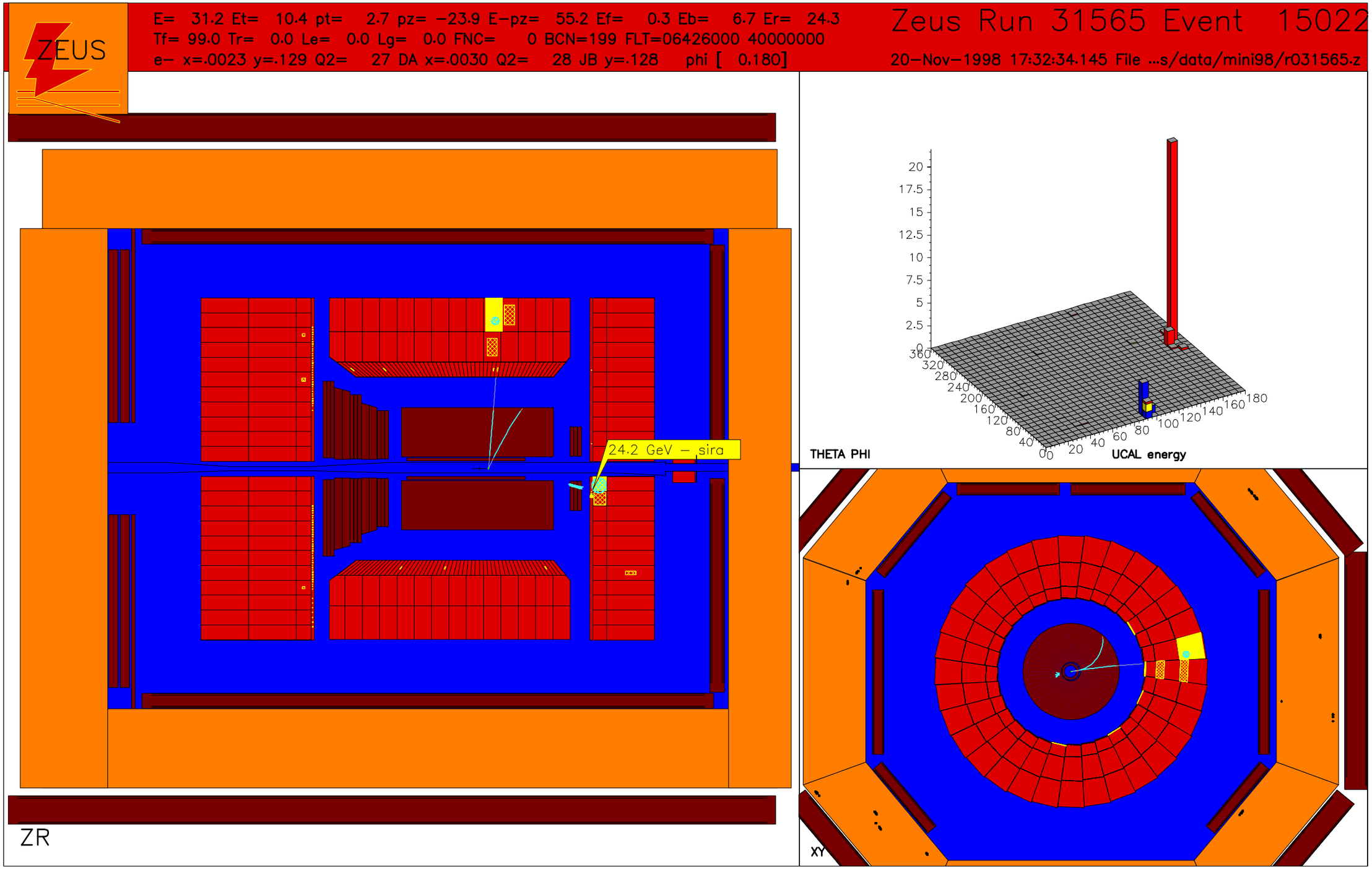

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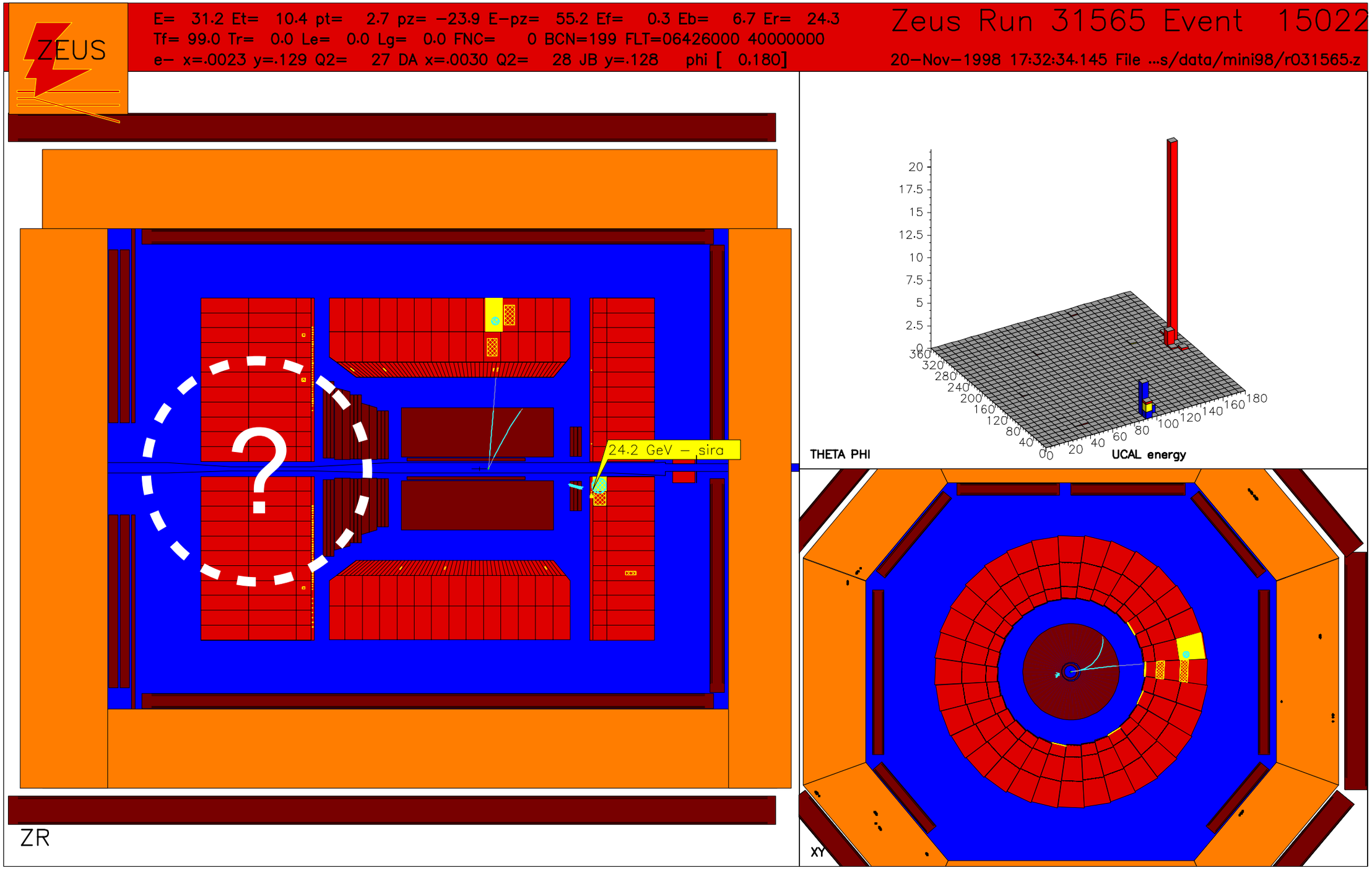
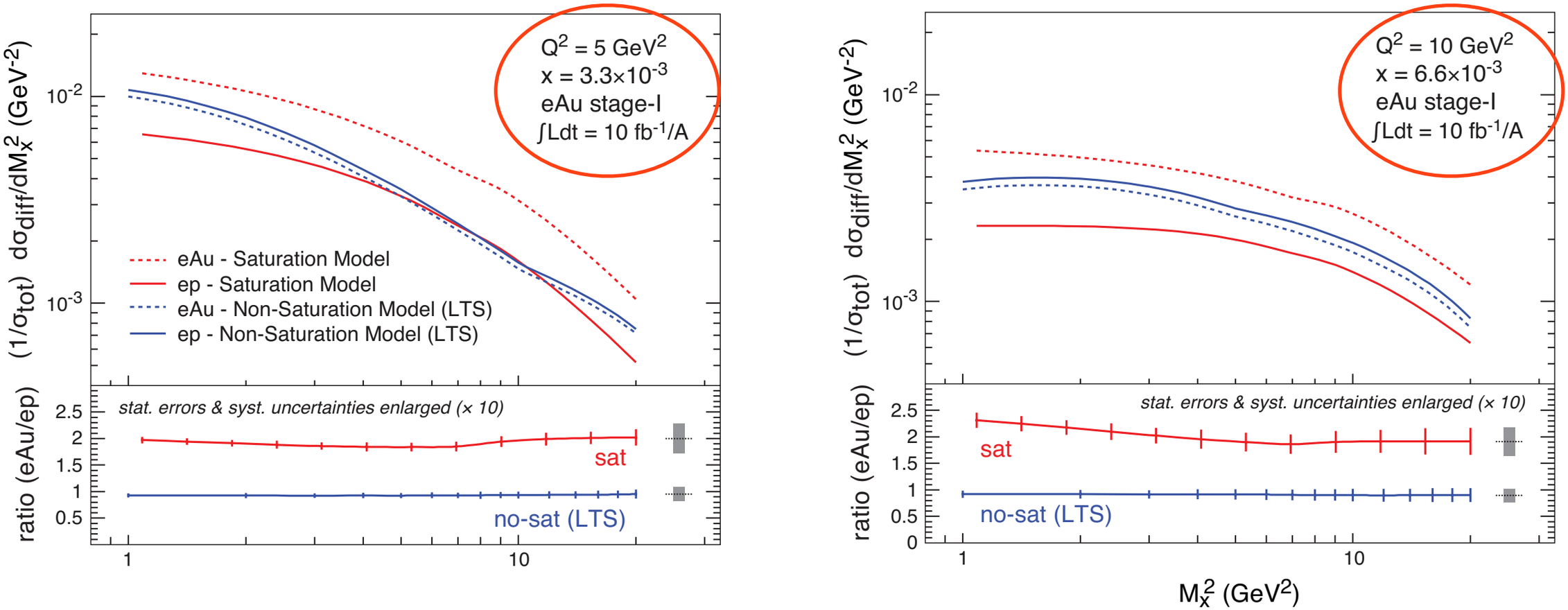
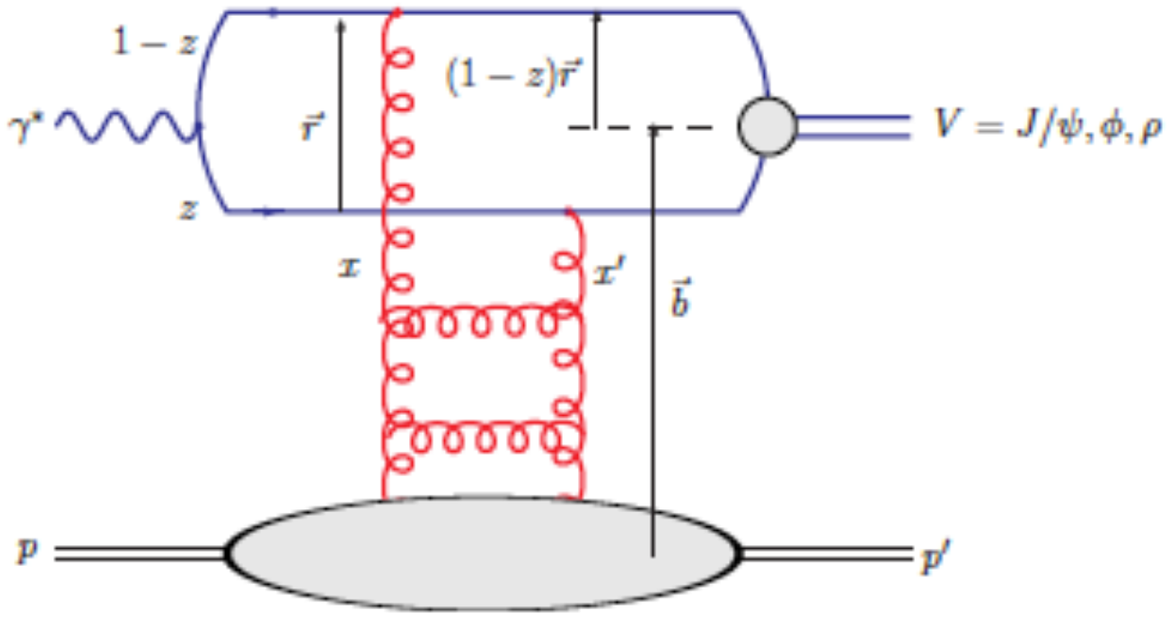


Day 1: Diffractive Cross-sections

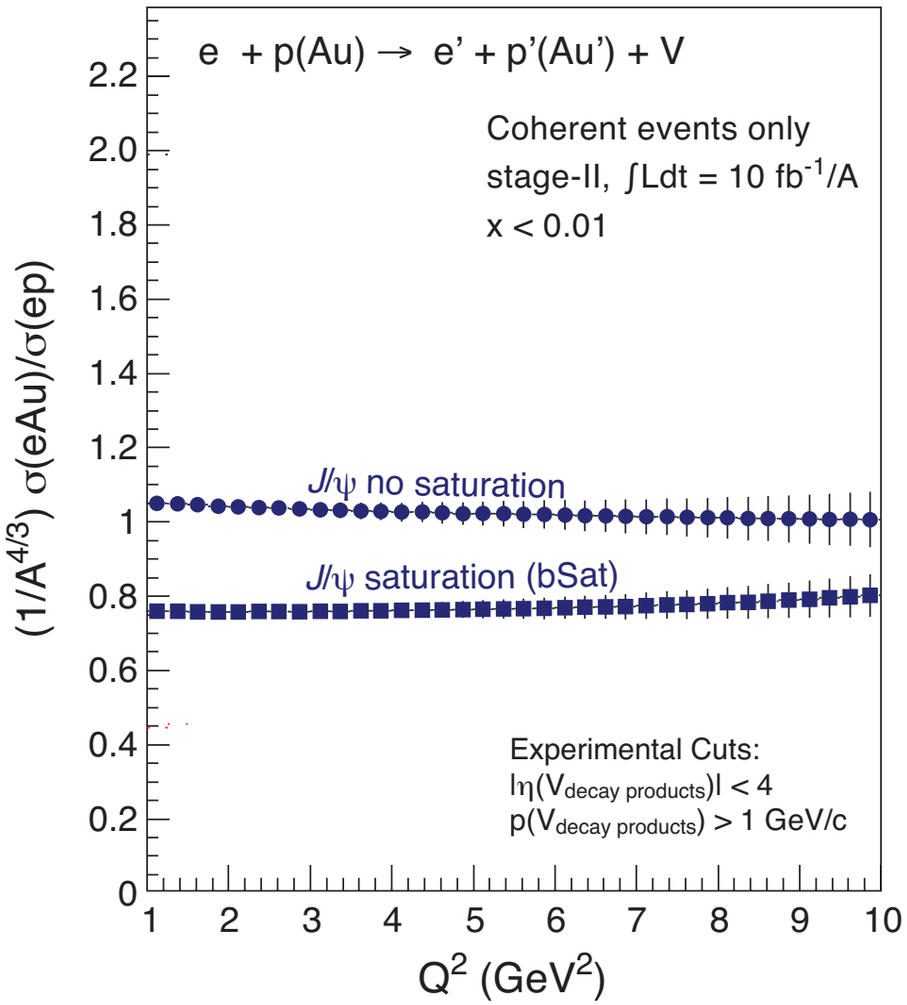


- Ratio of diffractive-to-total cross-section drastically different between saturation (Marquet) and non-saturation (Frankfurt, Guzey, Strikman) models
- Expected experimental error bars (simulated for 10 fb^{-1} of data for a low-energy eRHIC) can distinguish between the two scenarios

Exclusive vector meson production



$$d\sigma \propto g(x)^2$$



- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡ colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation

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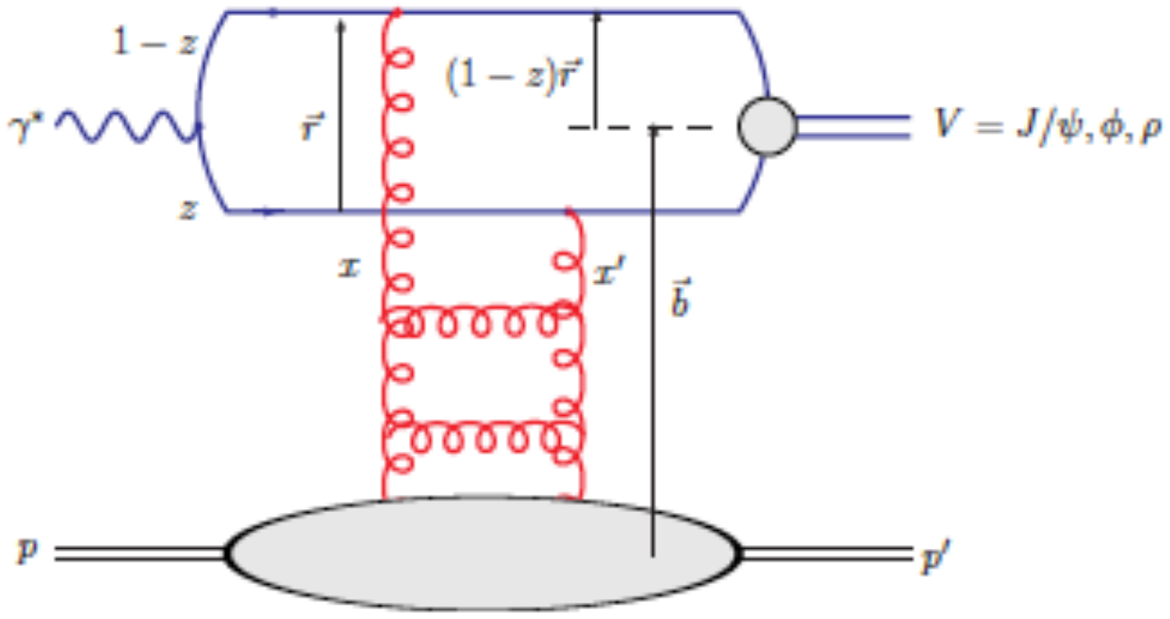

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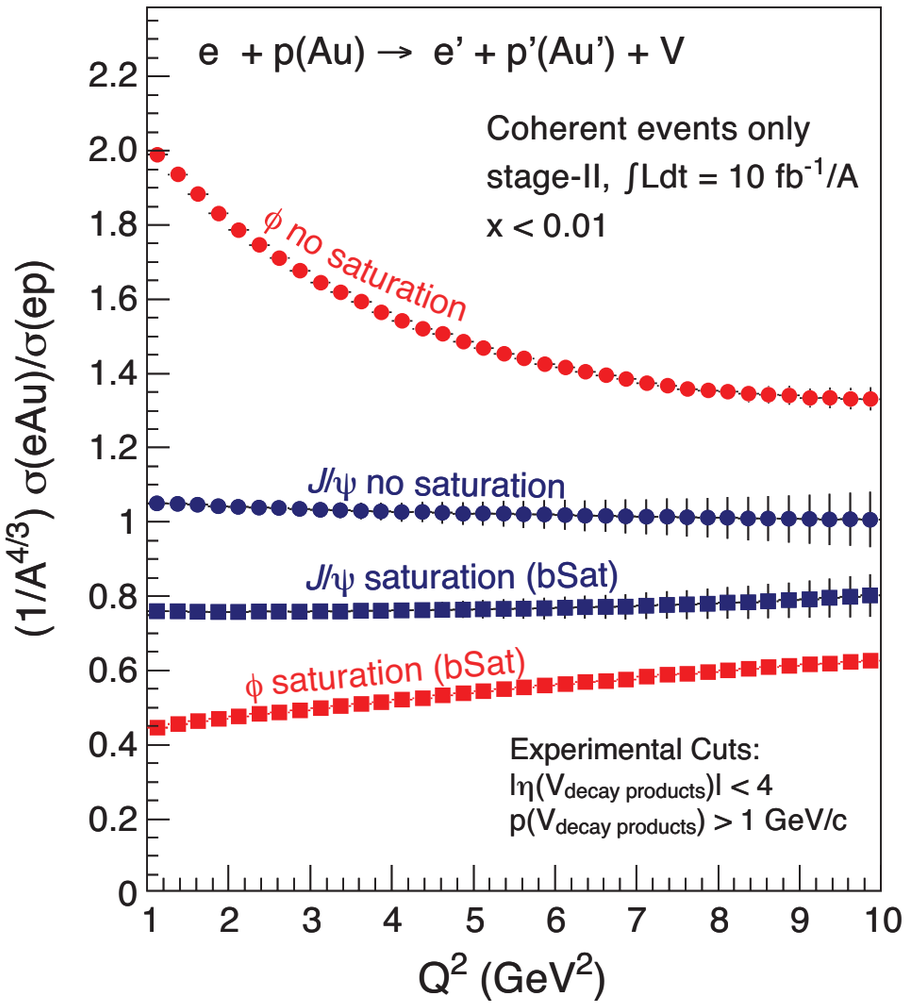
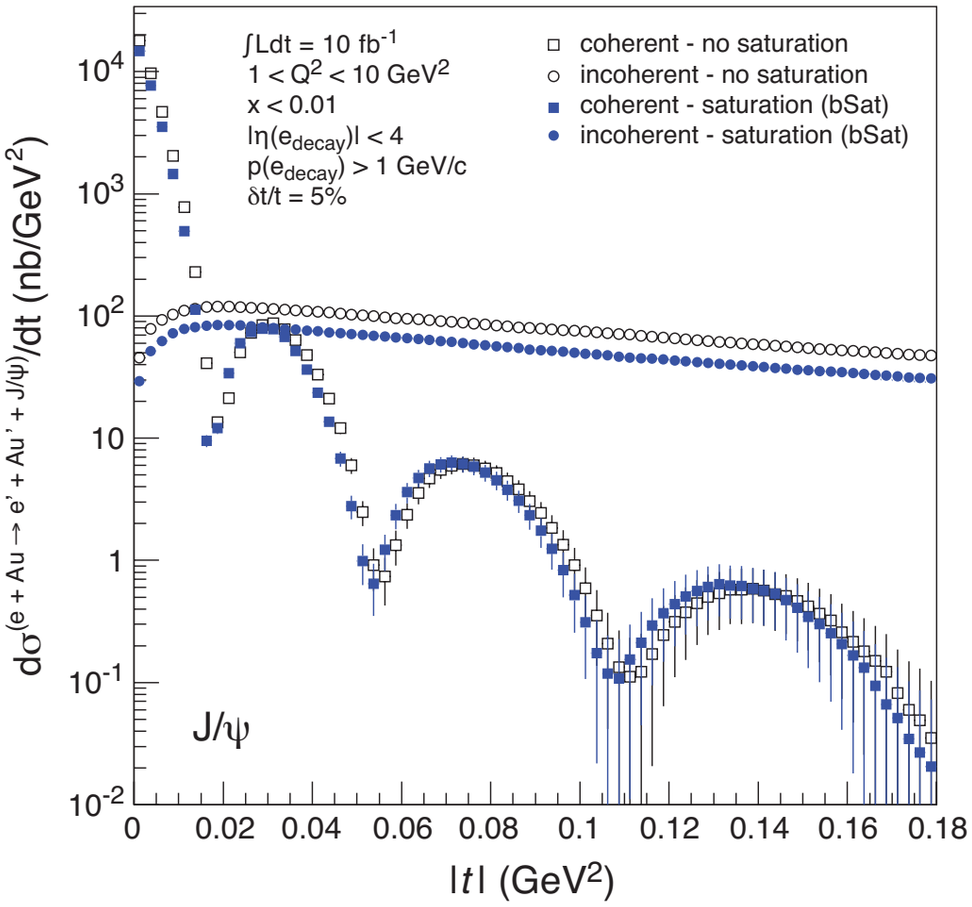
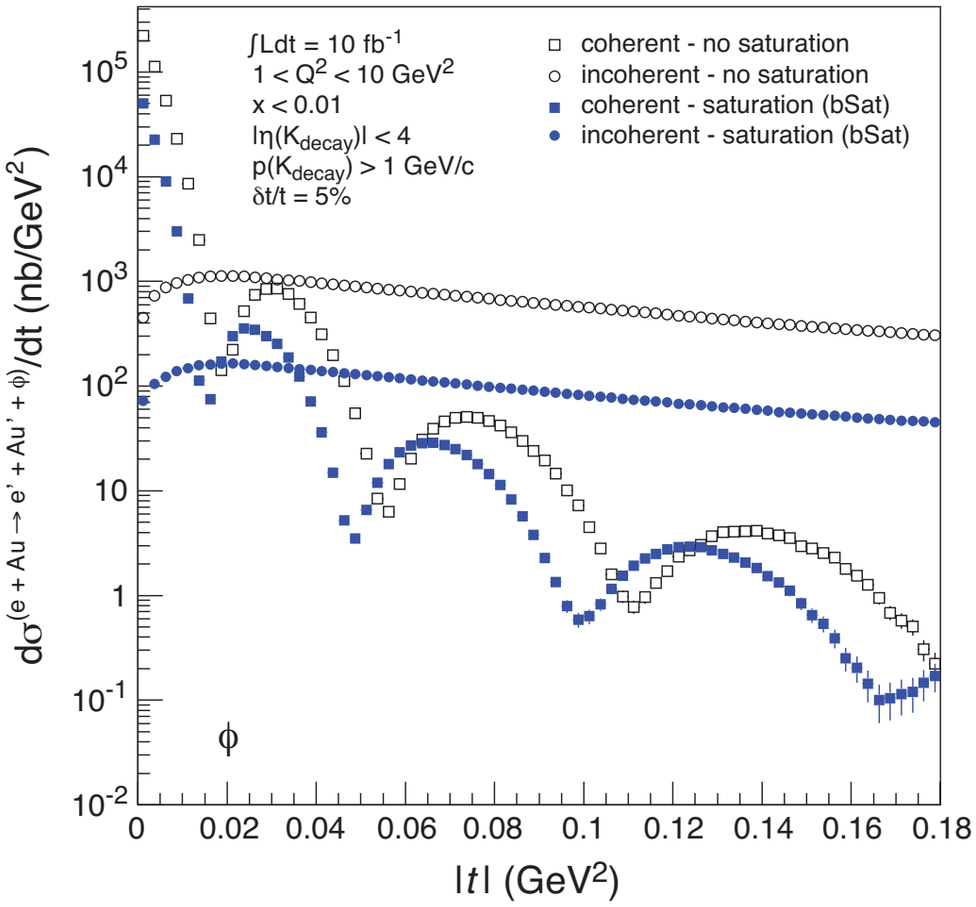


- Exclusive vector meson production is most sensitive to the gluon distribution
  - ➡ colour-neutral exchange of gluons
- J/ψ shows some difference between saturation and no-saturation
- ϕ shows a much larger difference
  - ➡ wave function for ϕ is larger and hence more sensitive to saturation effects

Exclusive Vector Meson Production in e+A





- Low-t: coherent diffraction dominates - gluon density
- High-t: incoherent diffraction dominates - gluon correlations

➡ Need good breakup detection efficiency to discriminate between the two scenarios

- unlike protons, forward spectrometer won't work for heavy ions
  - measure emitted neutrons in a ZDC
- rapidity gap with absence of break-up fragments sufficient to identify coherent events

Finding the source…

- Take the dσ/dt distribution and perform a Fourier Transform to extract the b-distribution of the gluons

$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta\, \Delta\, J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

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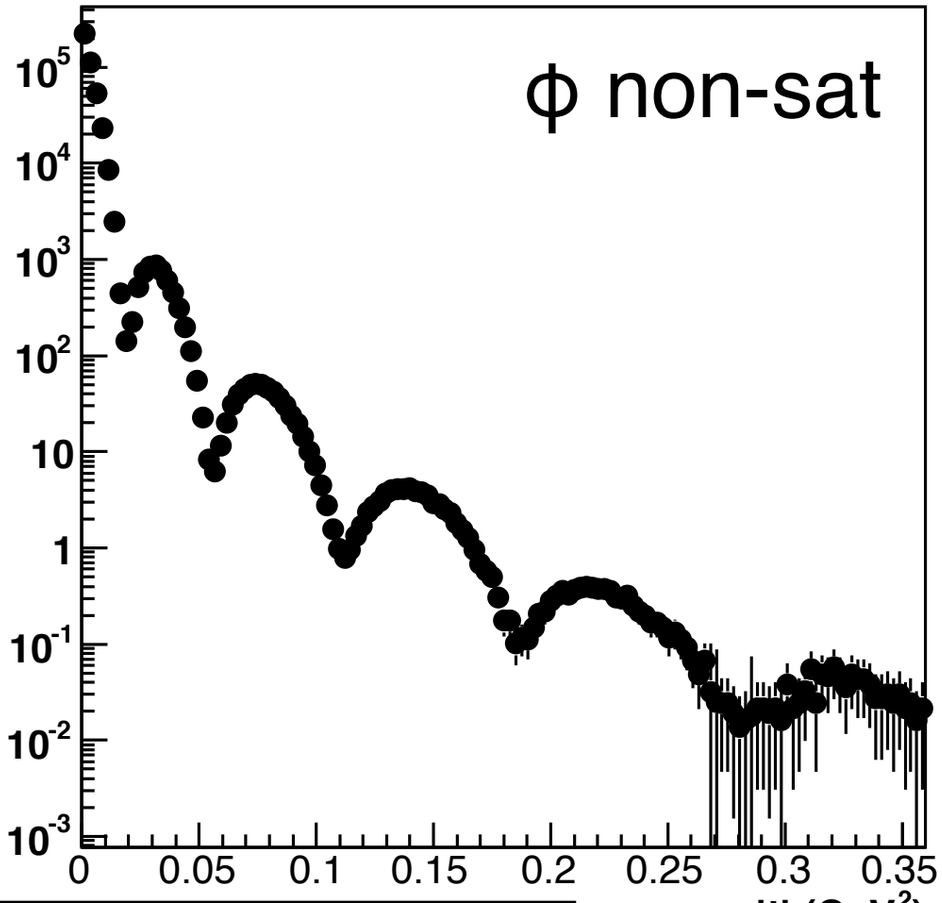

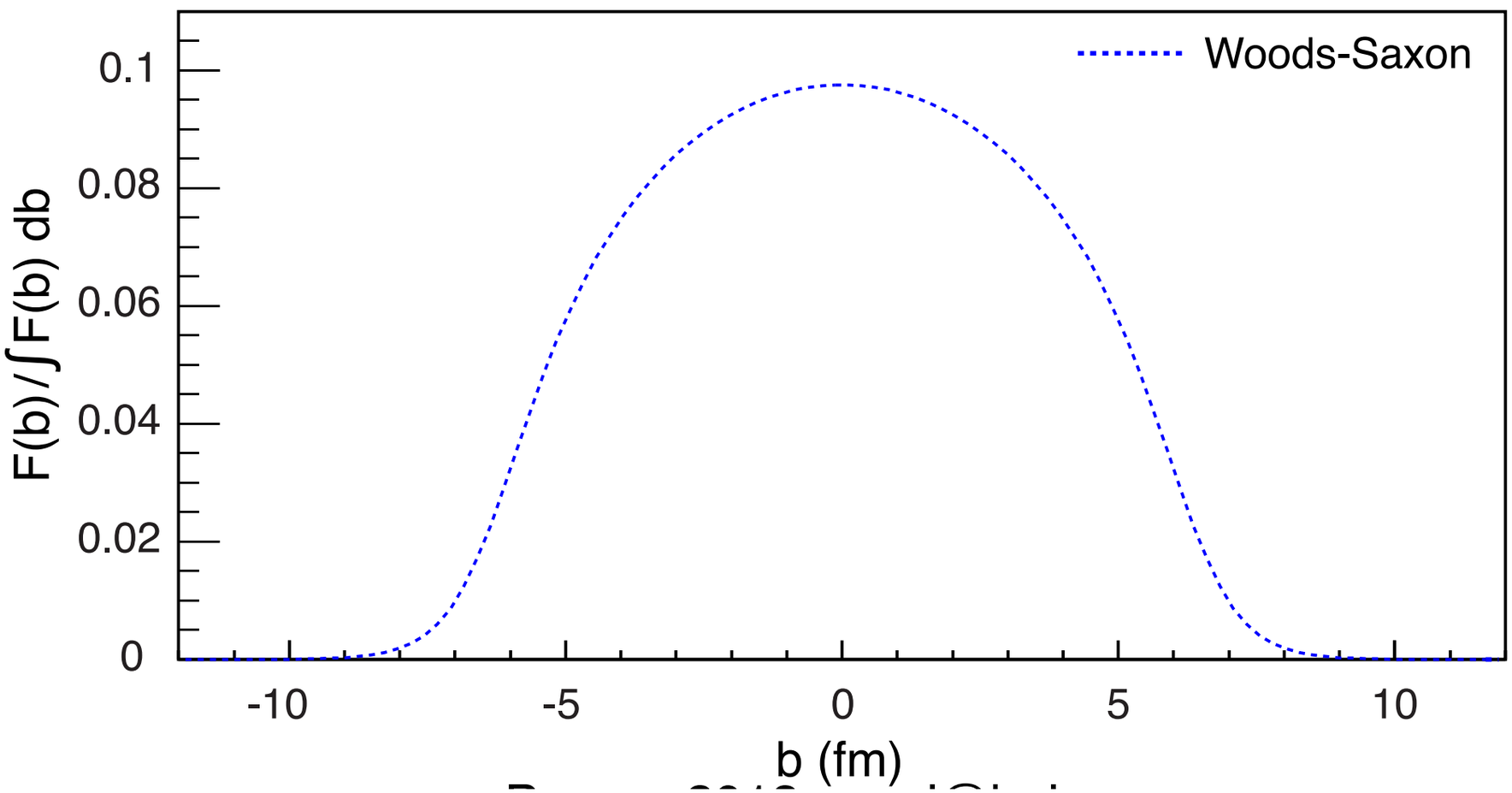

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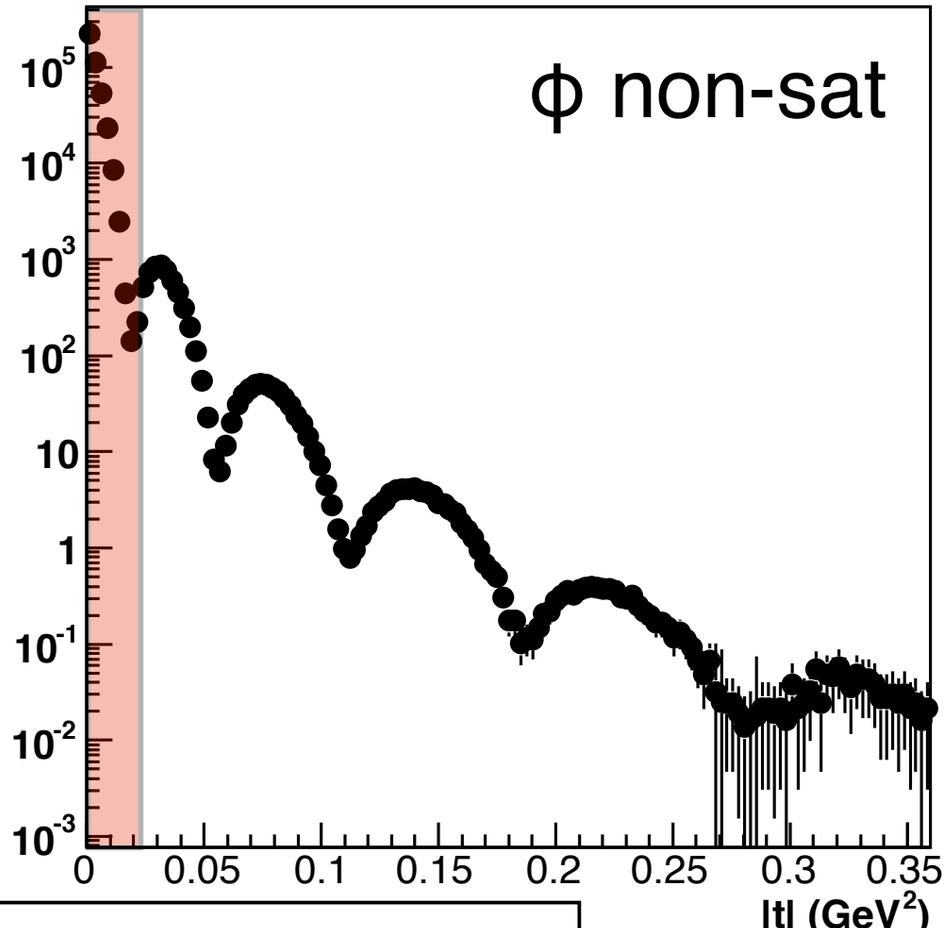

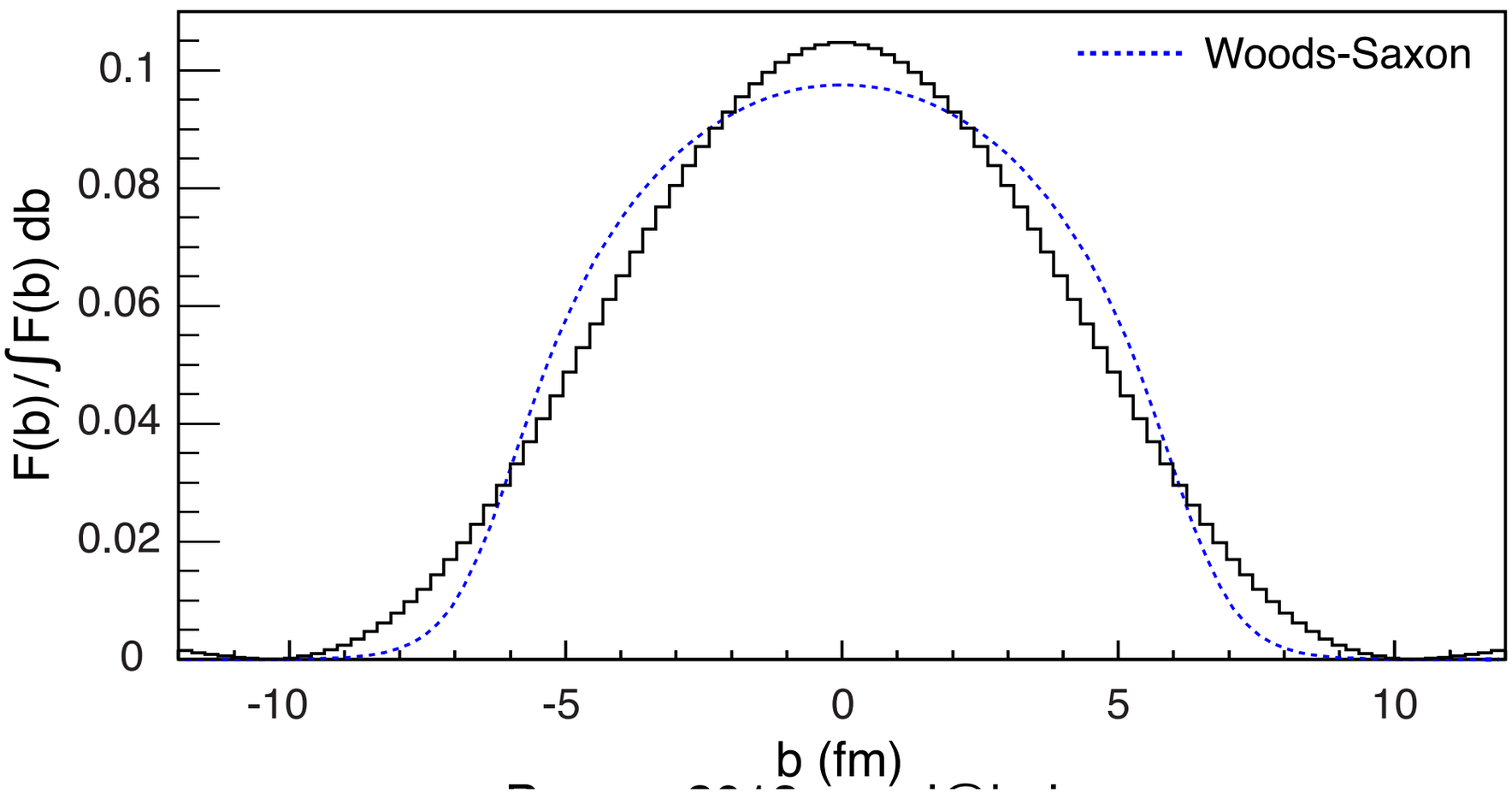

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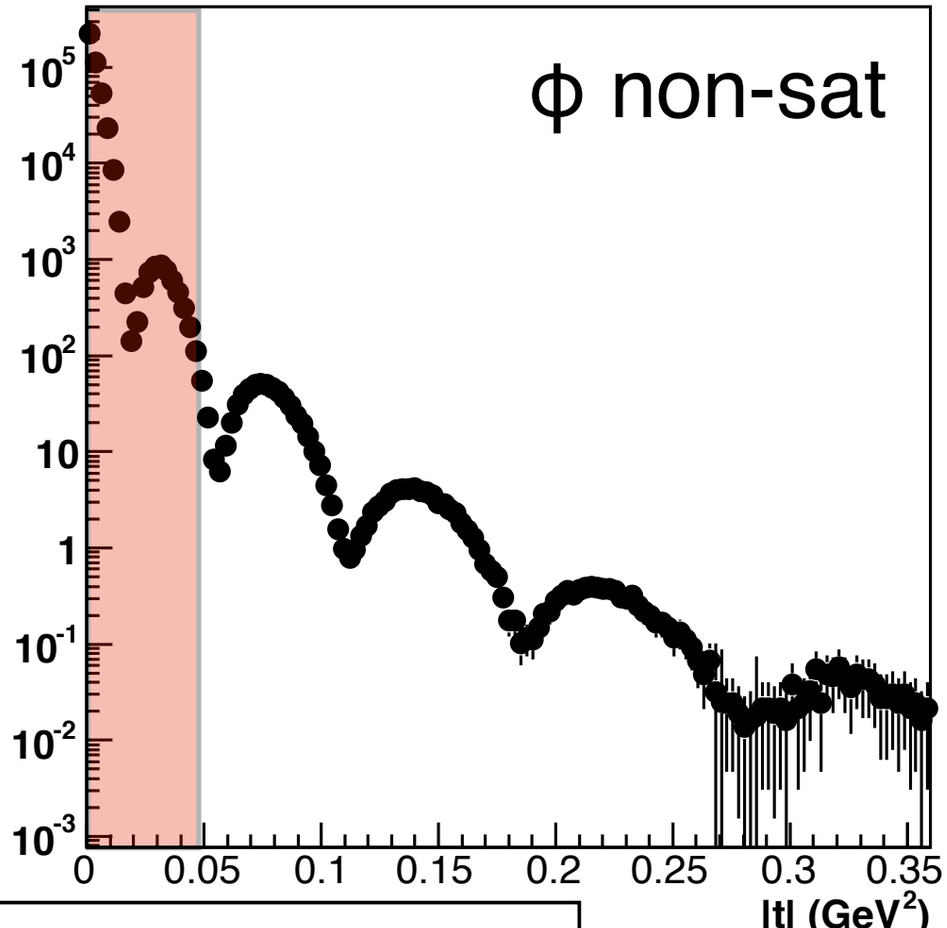

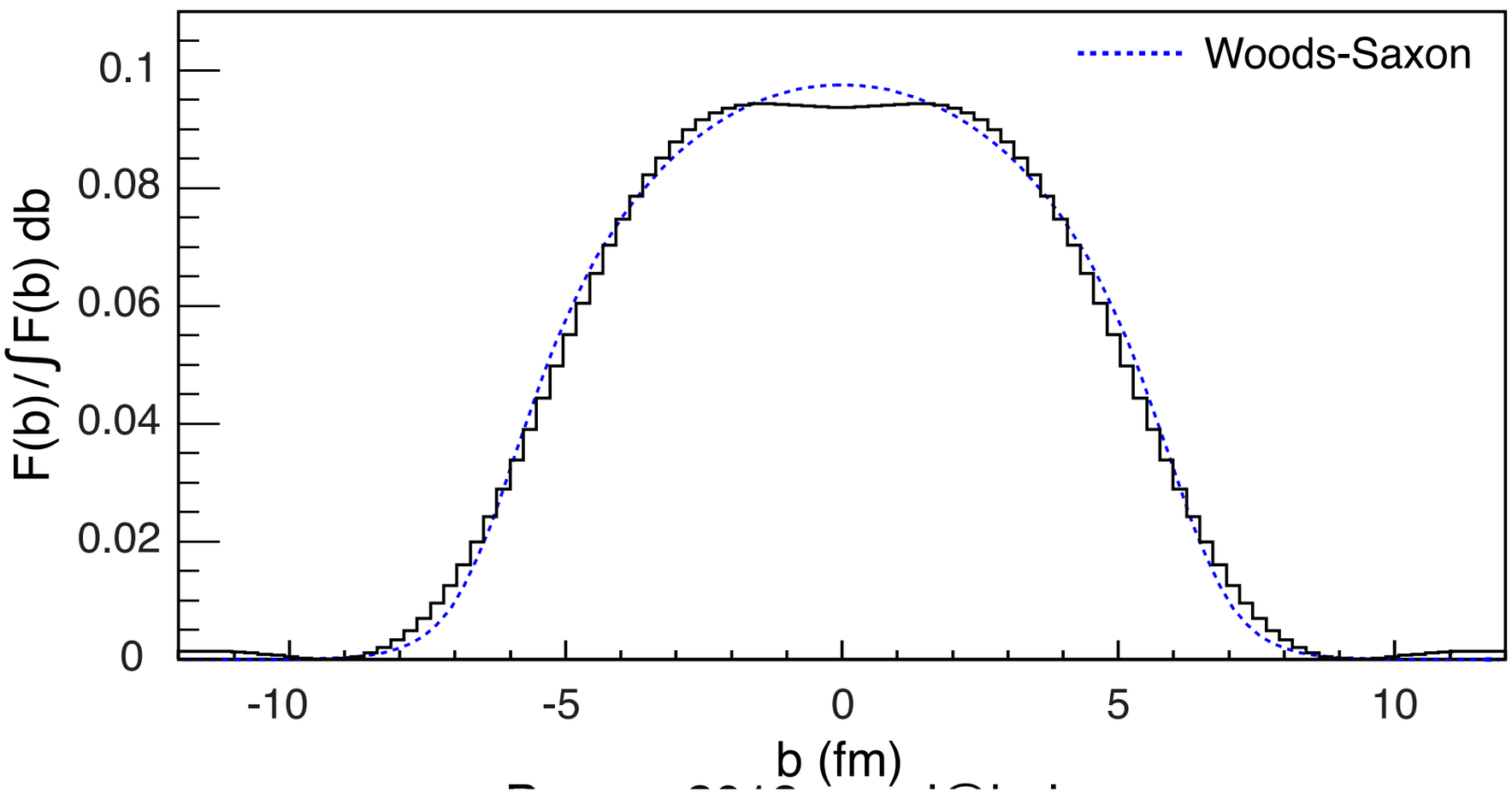

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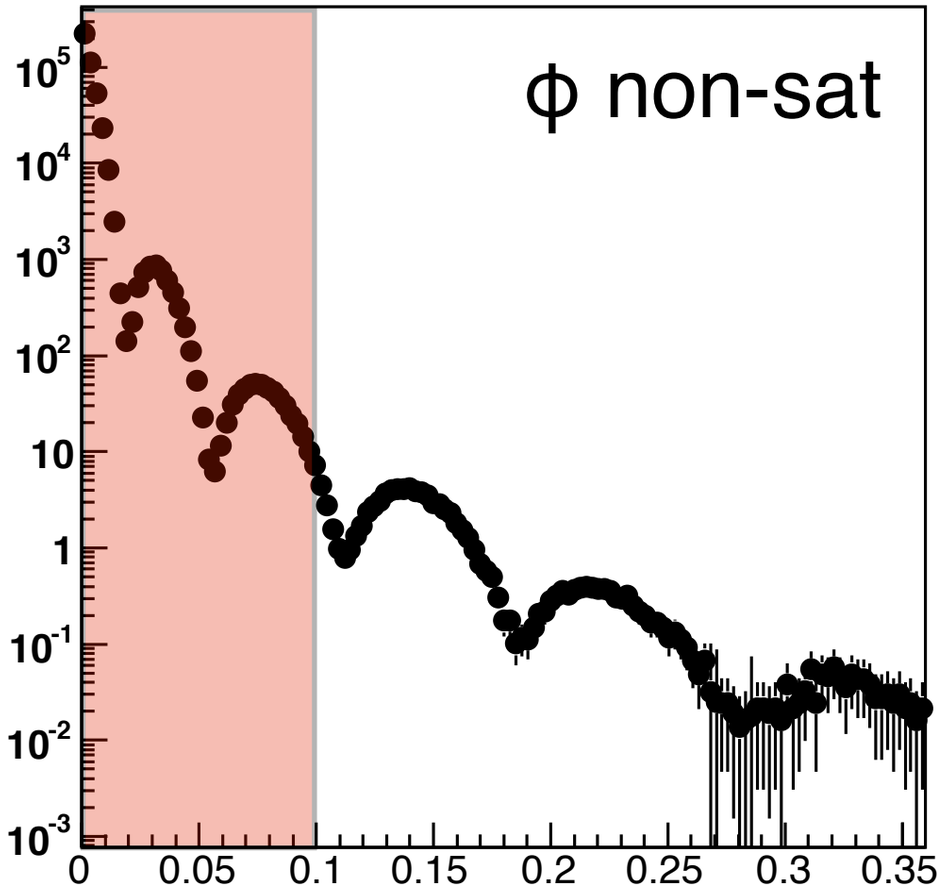

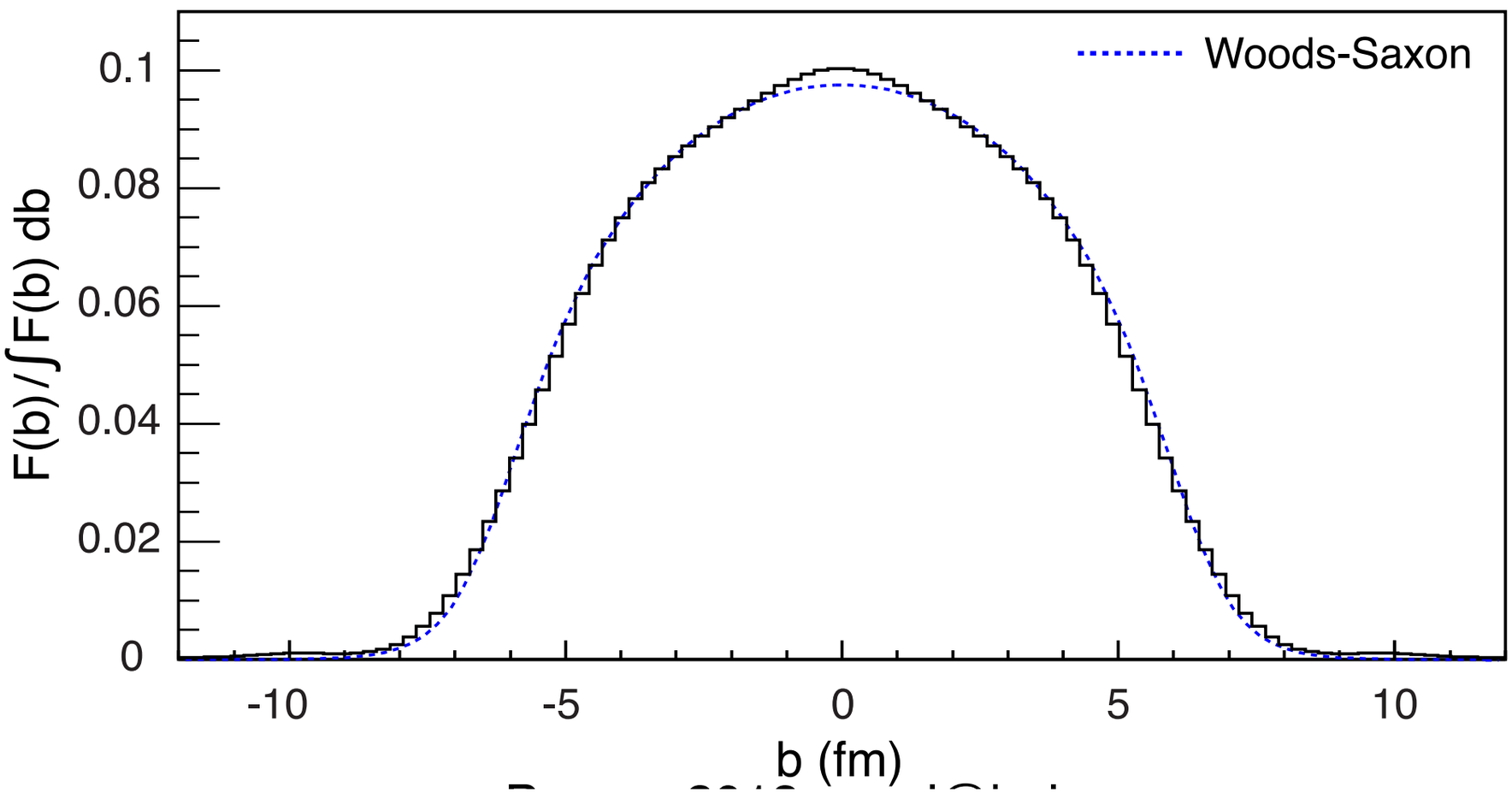

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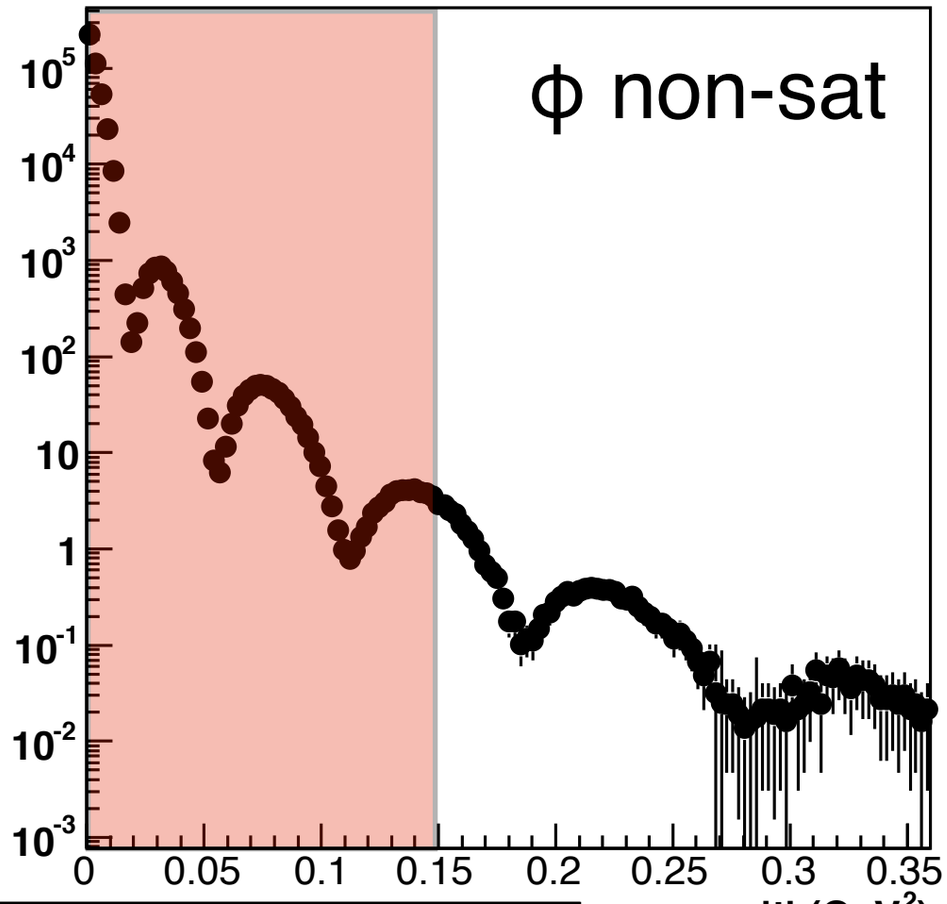

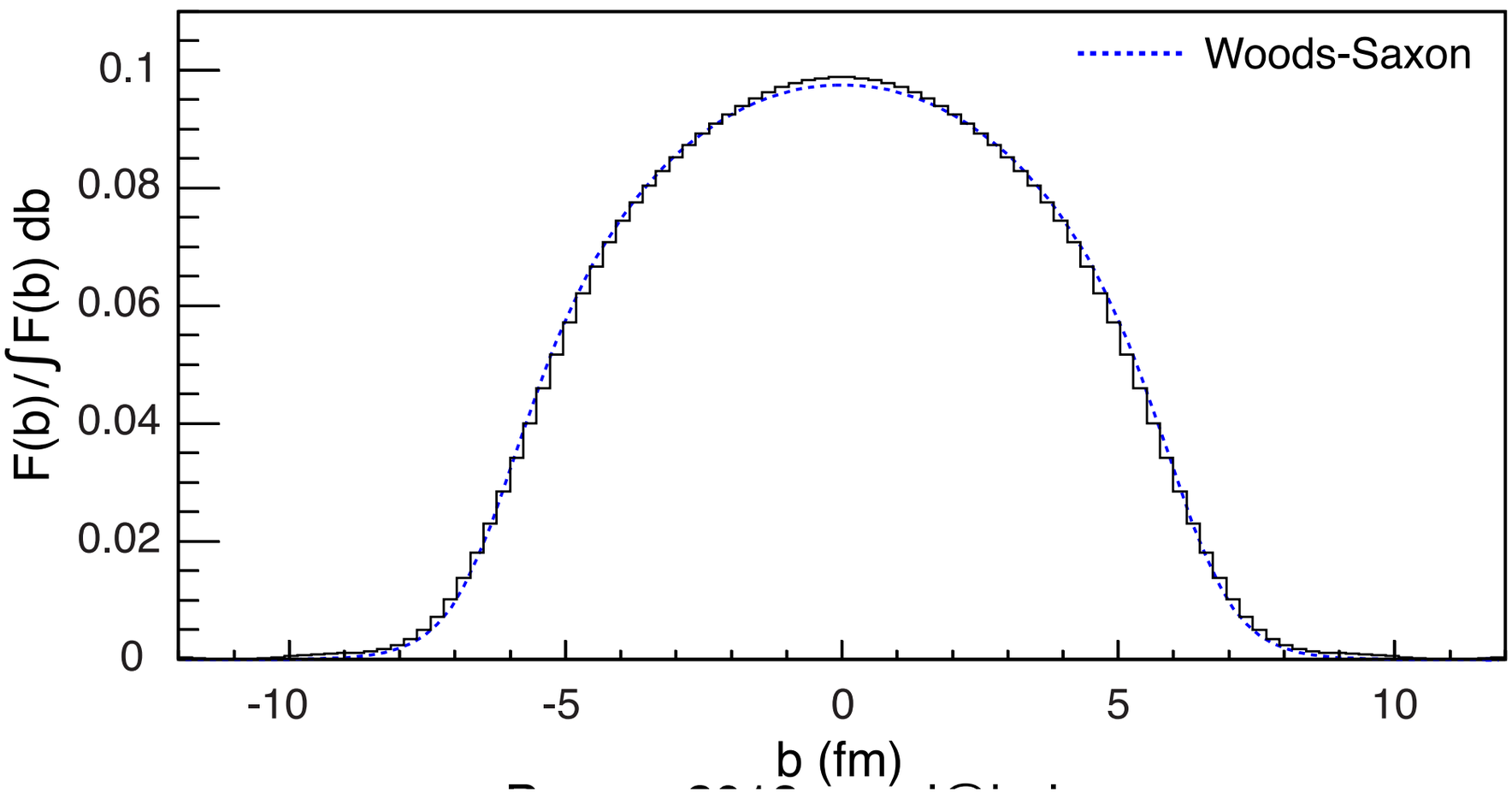

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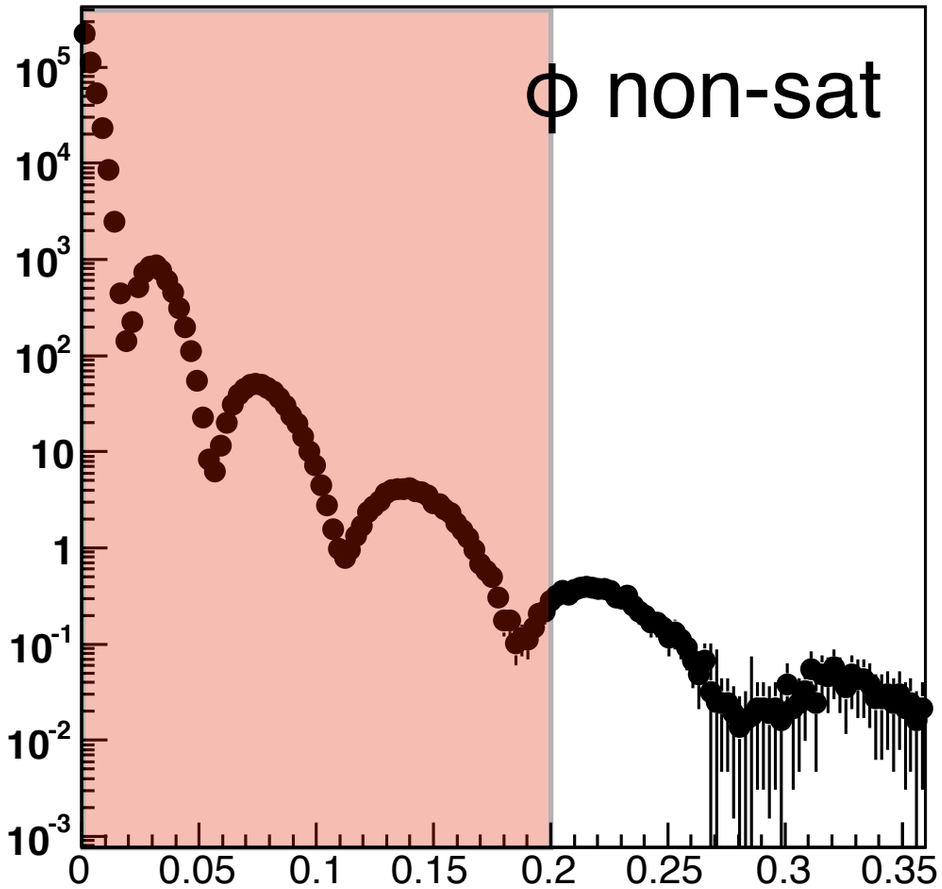

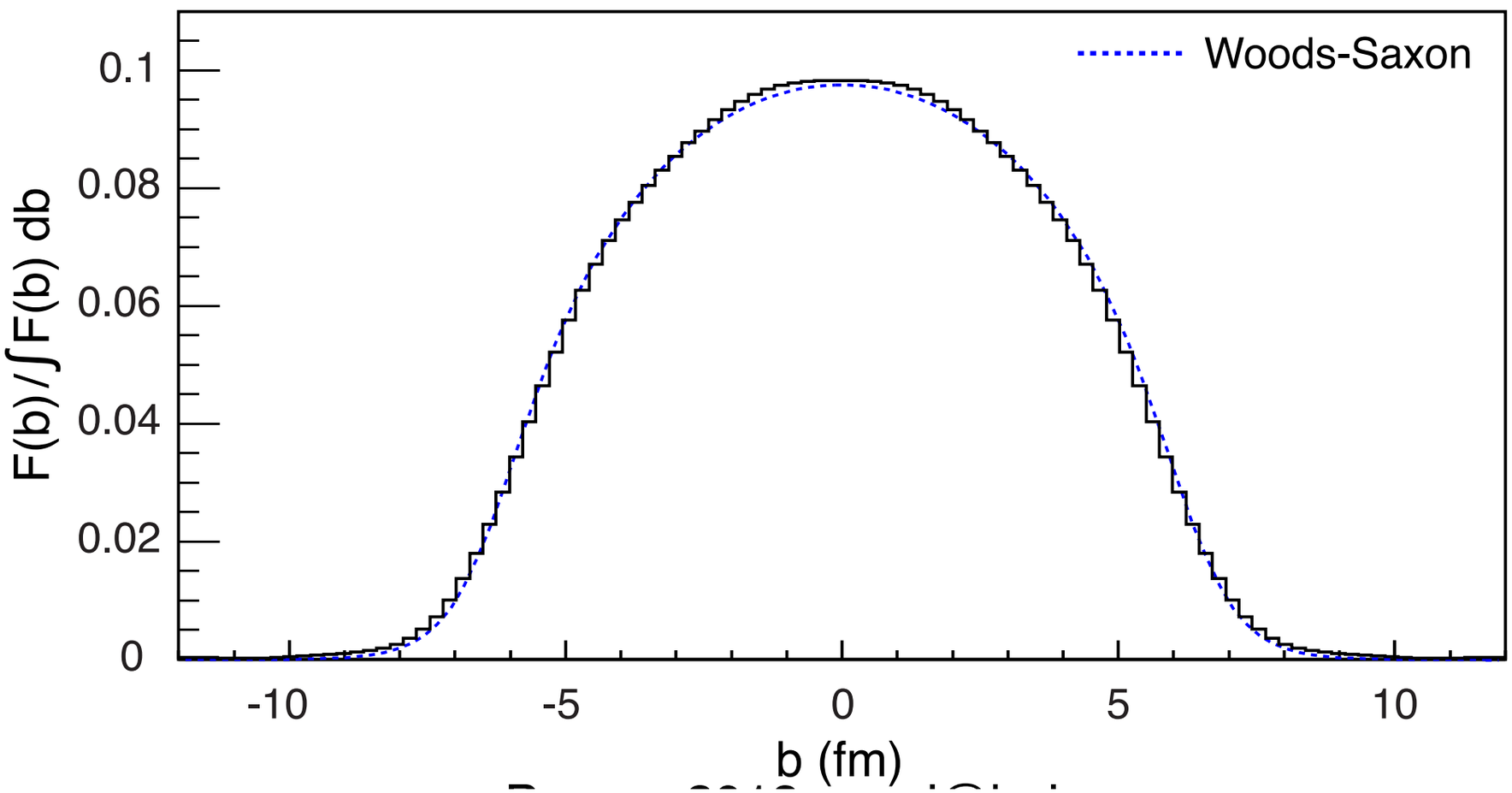

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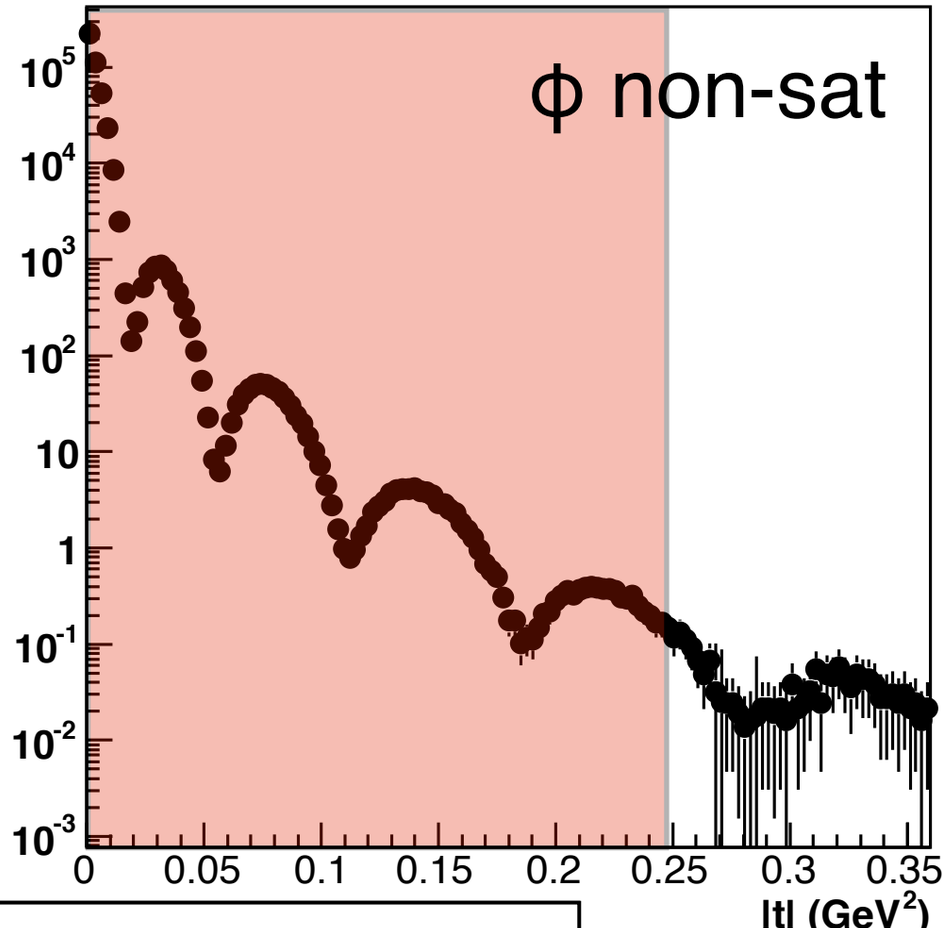

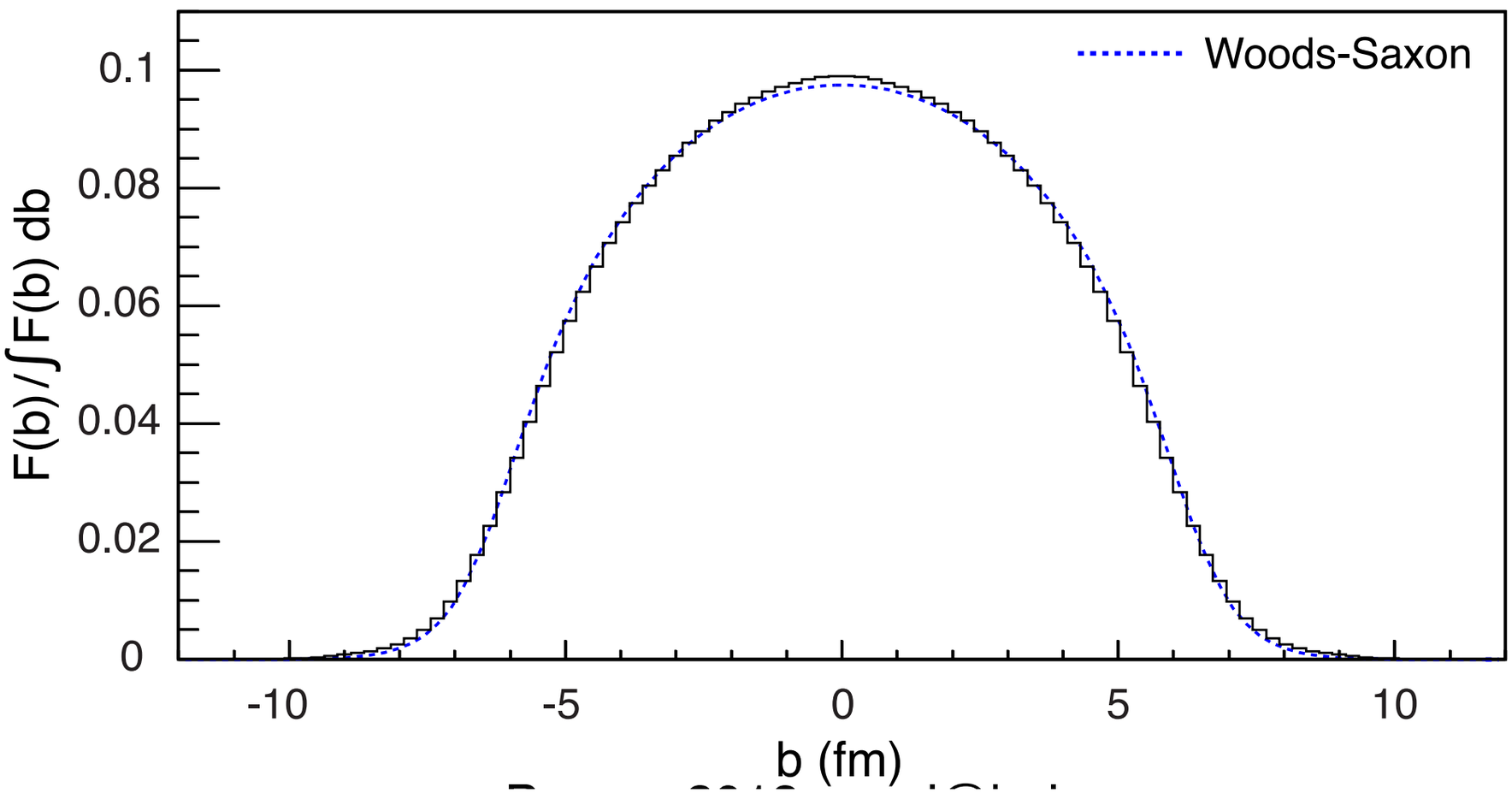

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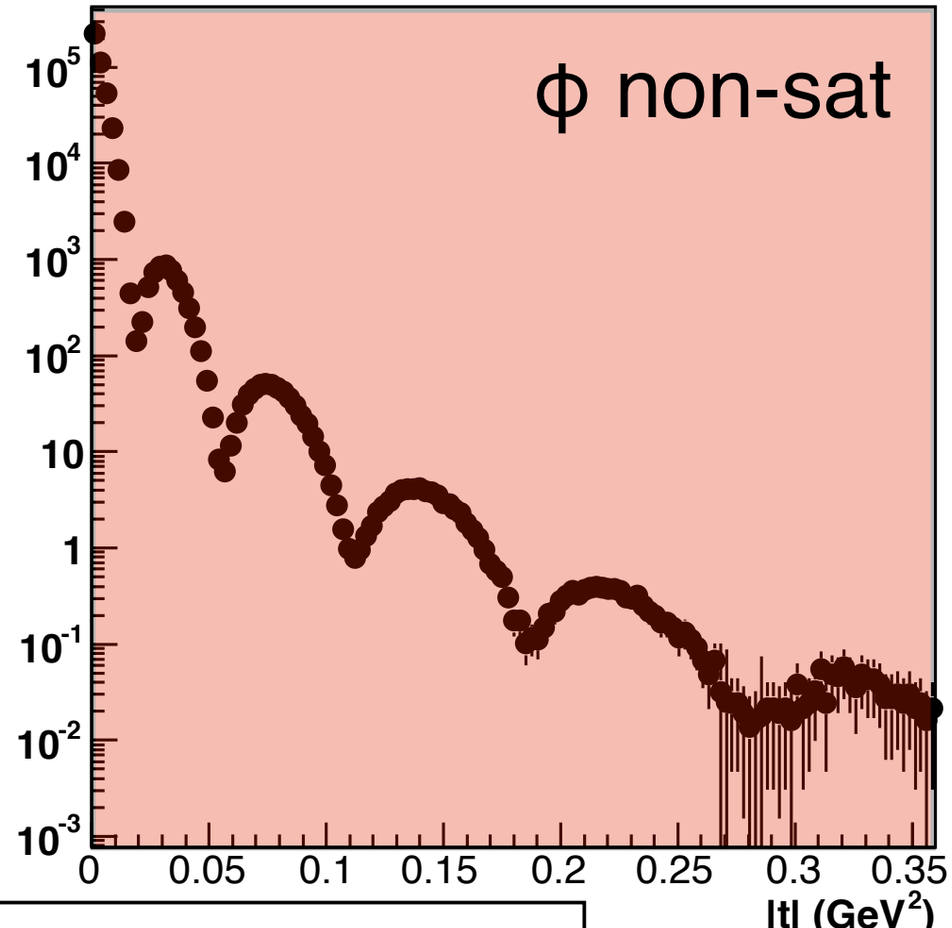
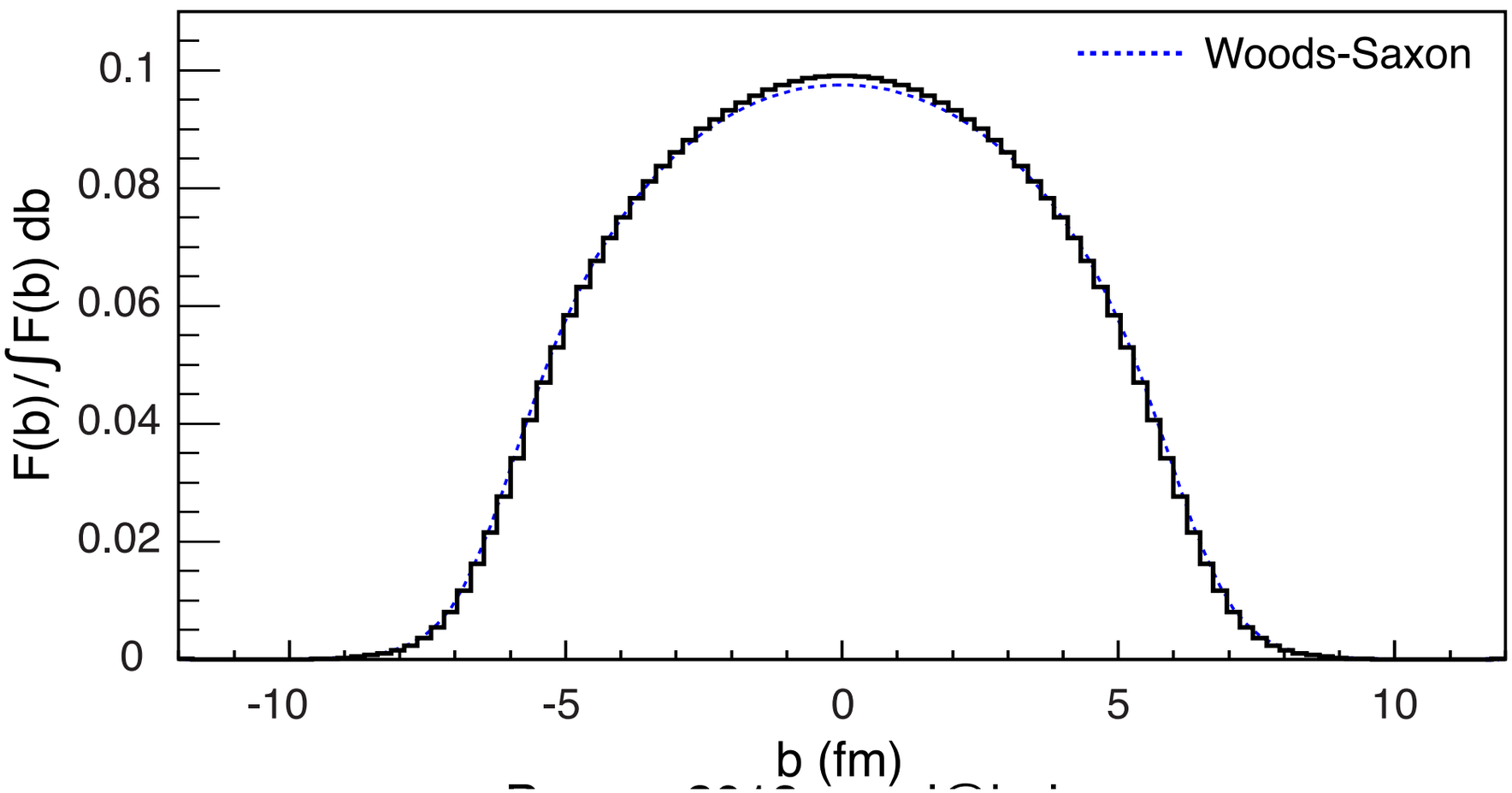
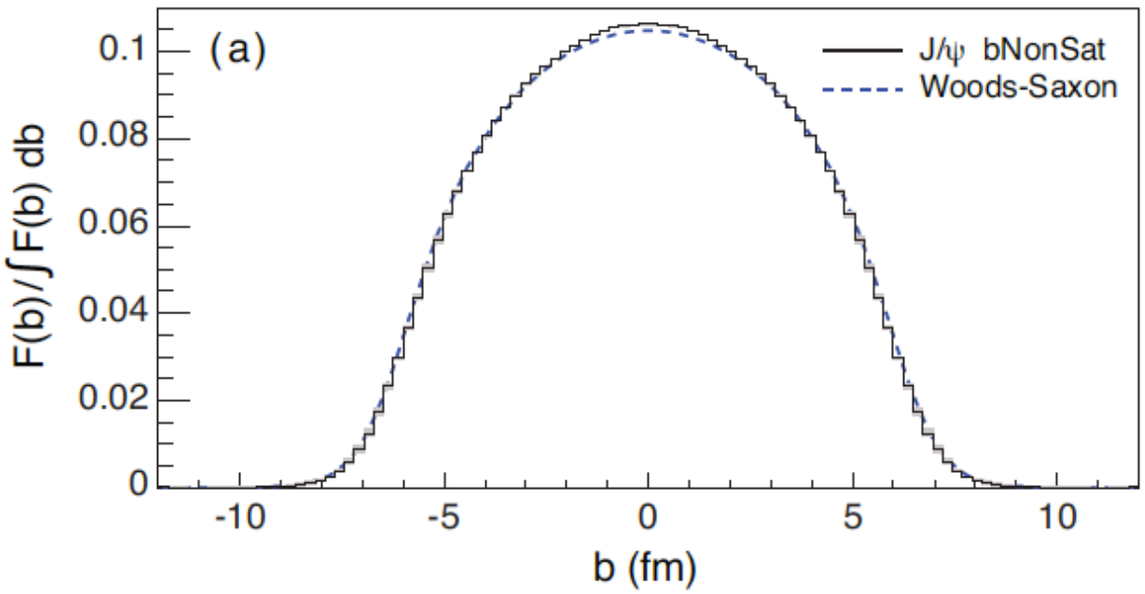
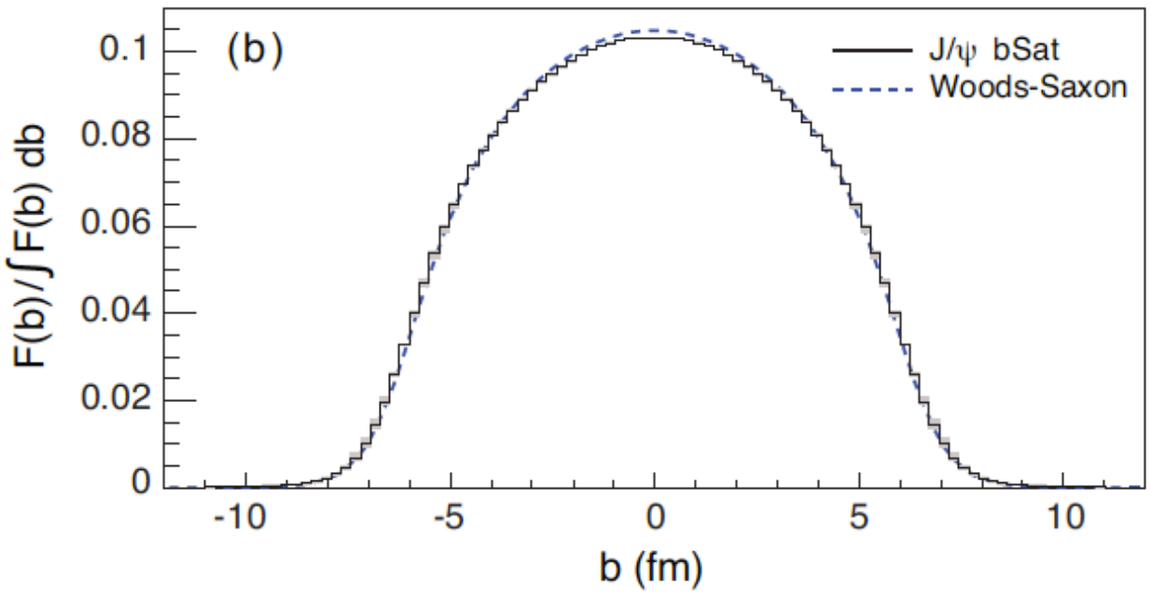


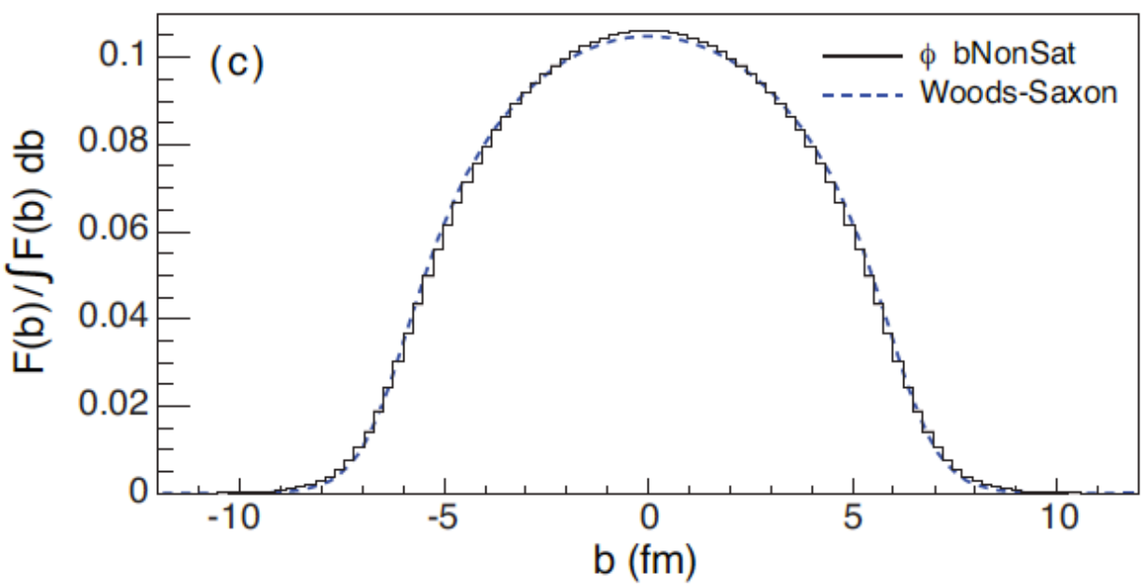


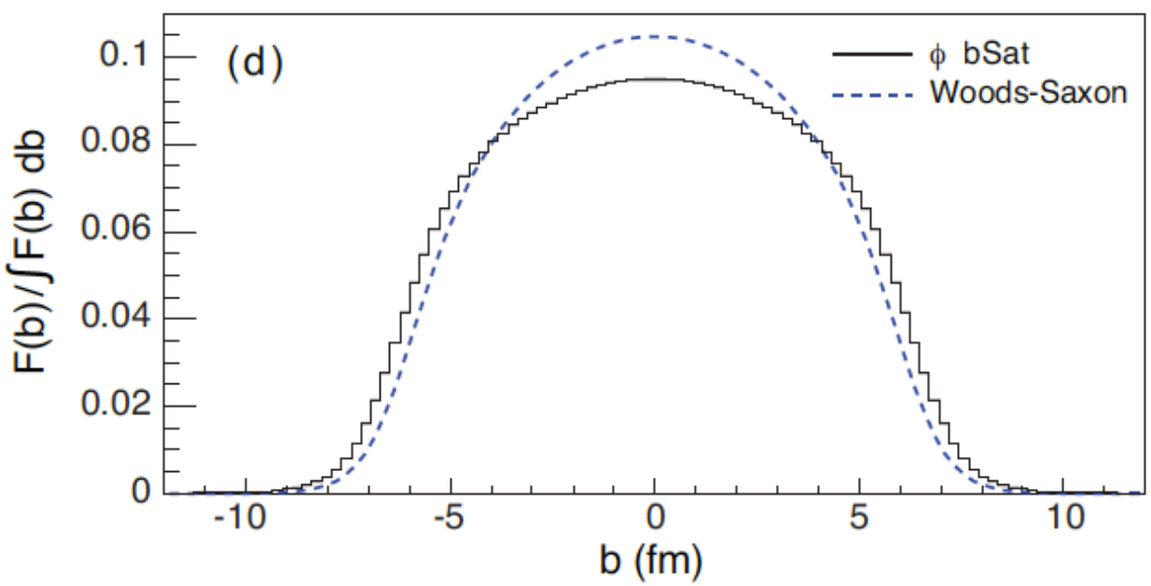
Finding the source…

- J/ψ shows little difference for both saturated and non-saturated modes.
- ϕ shows a significant difference



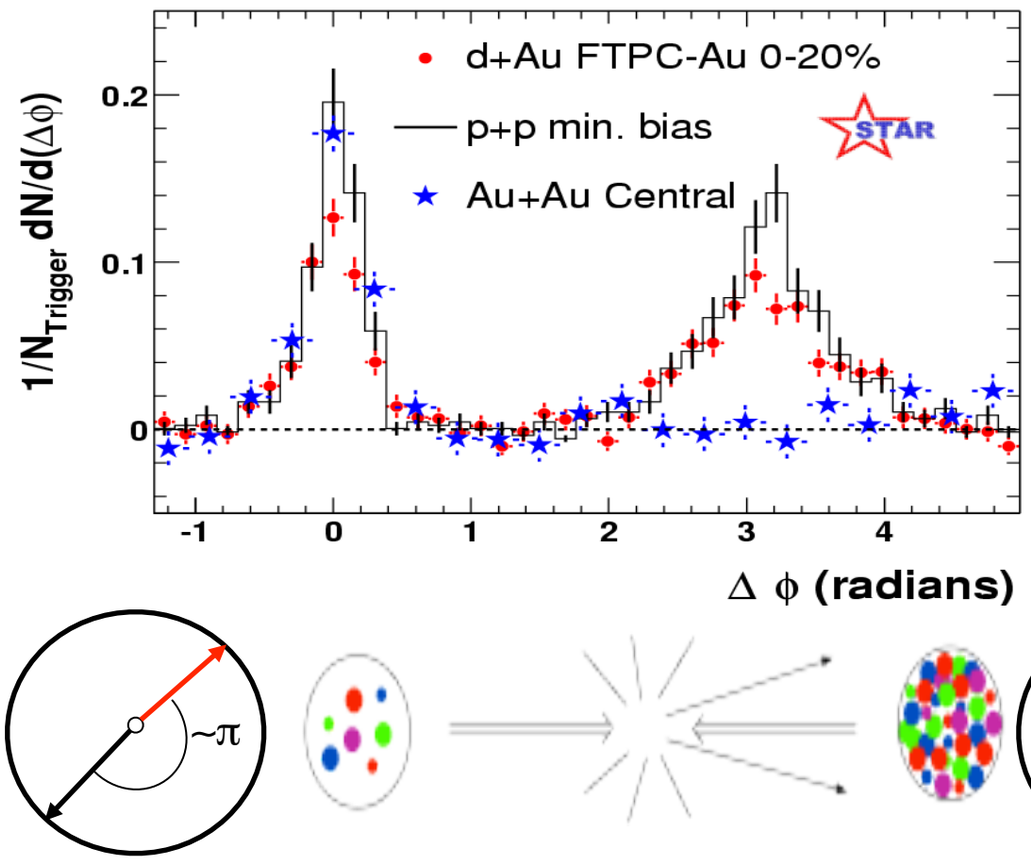






di-hadron correlations in d+A

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

➡ $x \sim 10^{-2}$

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

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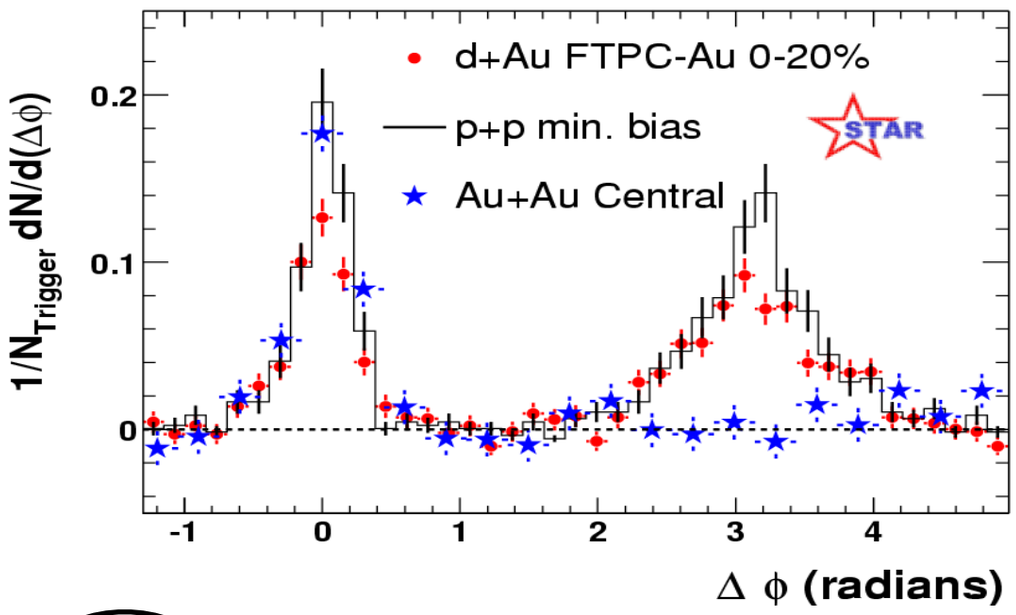

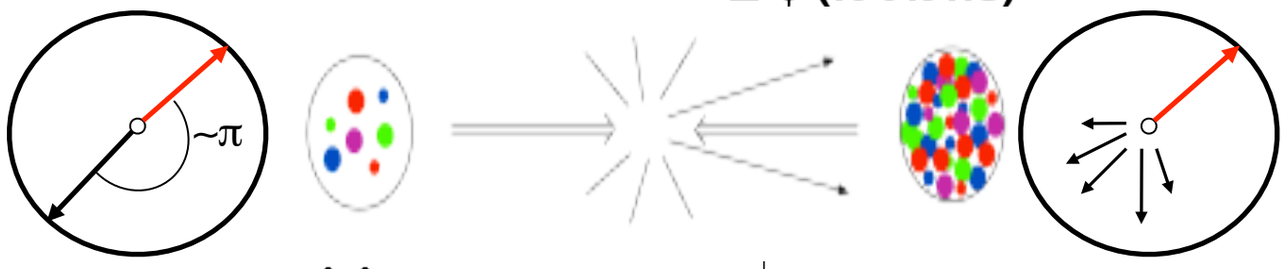

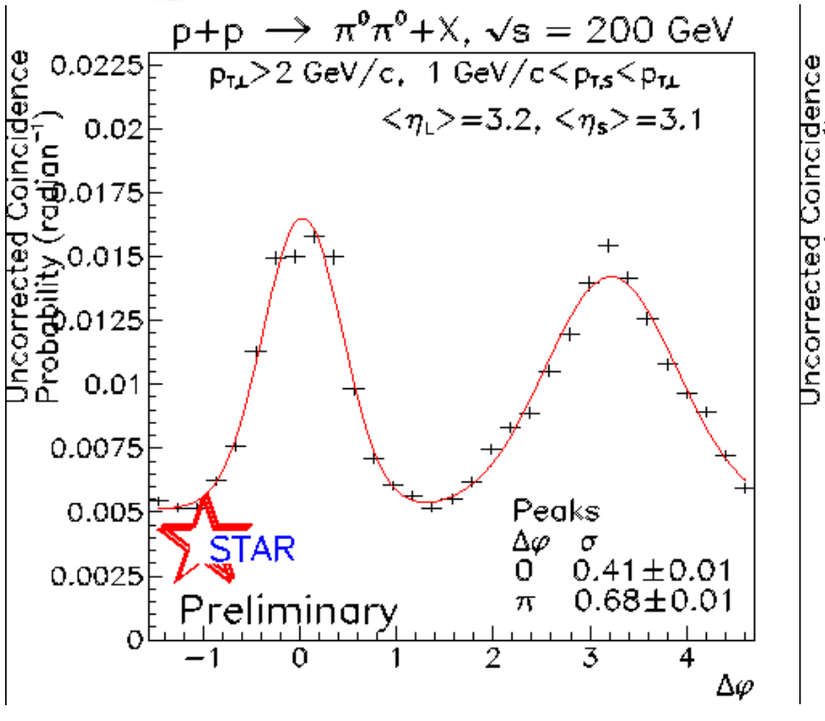

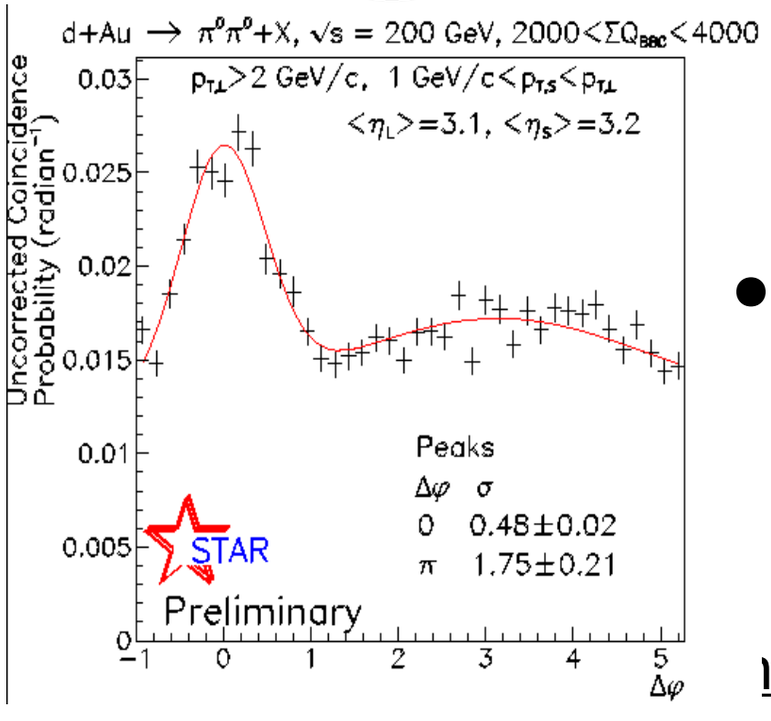

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➡ x ~ 10^{-2}

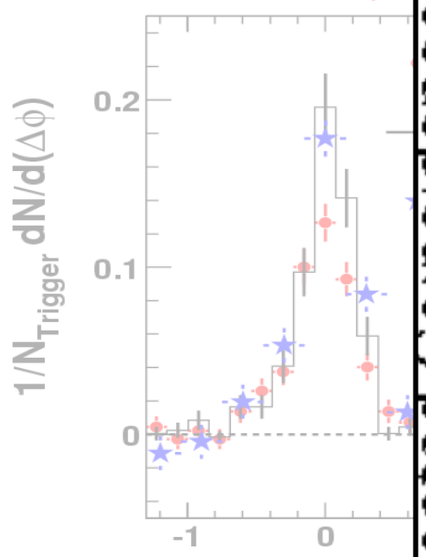
$$x_A = \frac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}} \ll 1$$

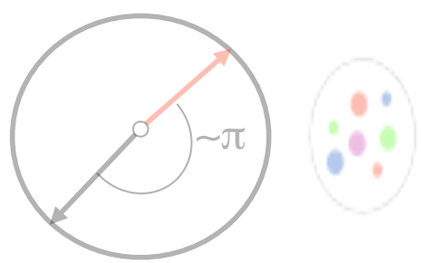
- However, at forward rapidities (y ~ 3.1), an away-side suppression is observed in d+Au
- Away-side peak also much wider in d+Au compared to p+p

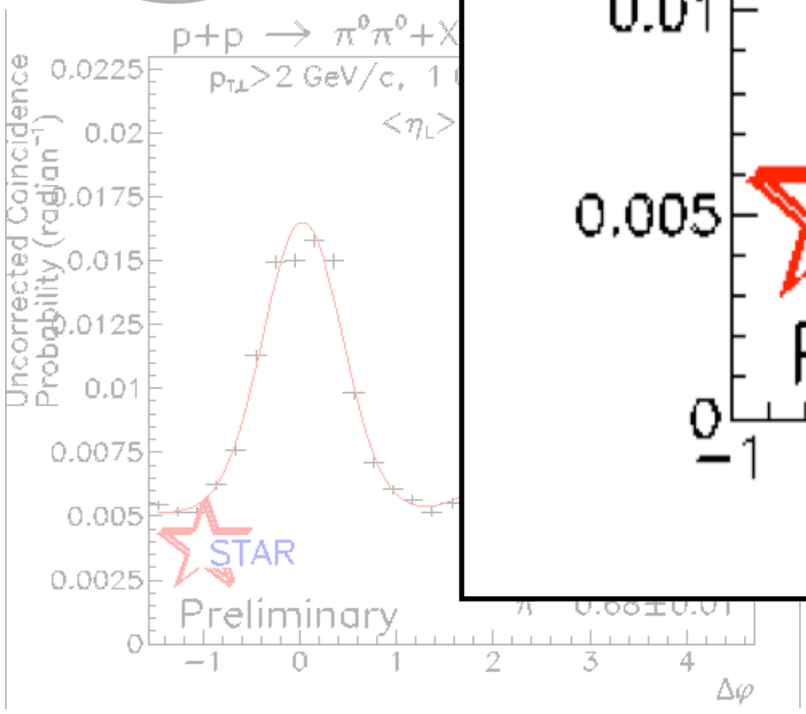
➡ x ~ 10^{-3}

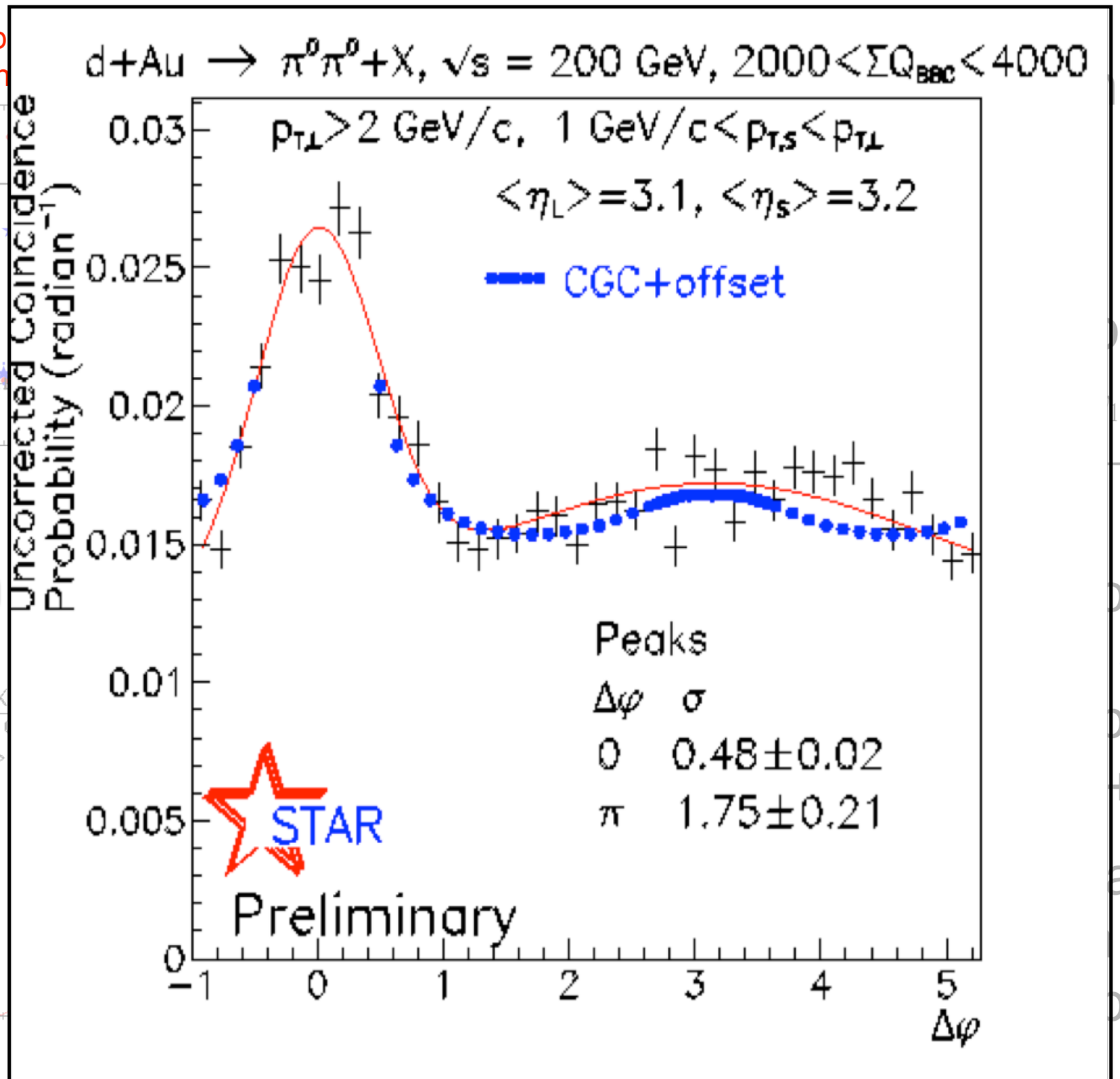
di-hadron correlations in d+A

comparisons b
+Au → h_1 h









of away-
in A+A

+p or d+A

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orward
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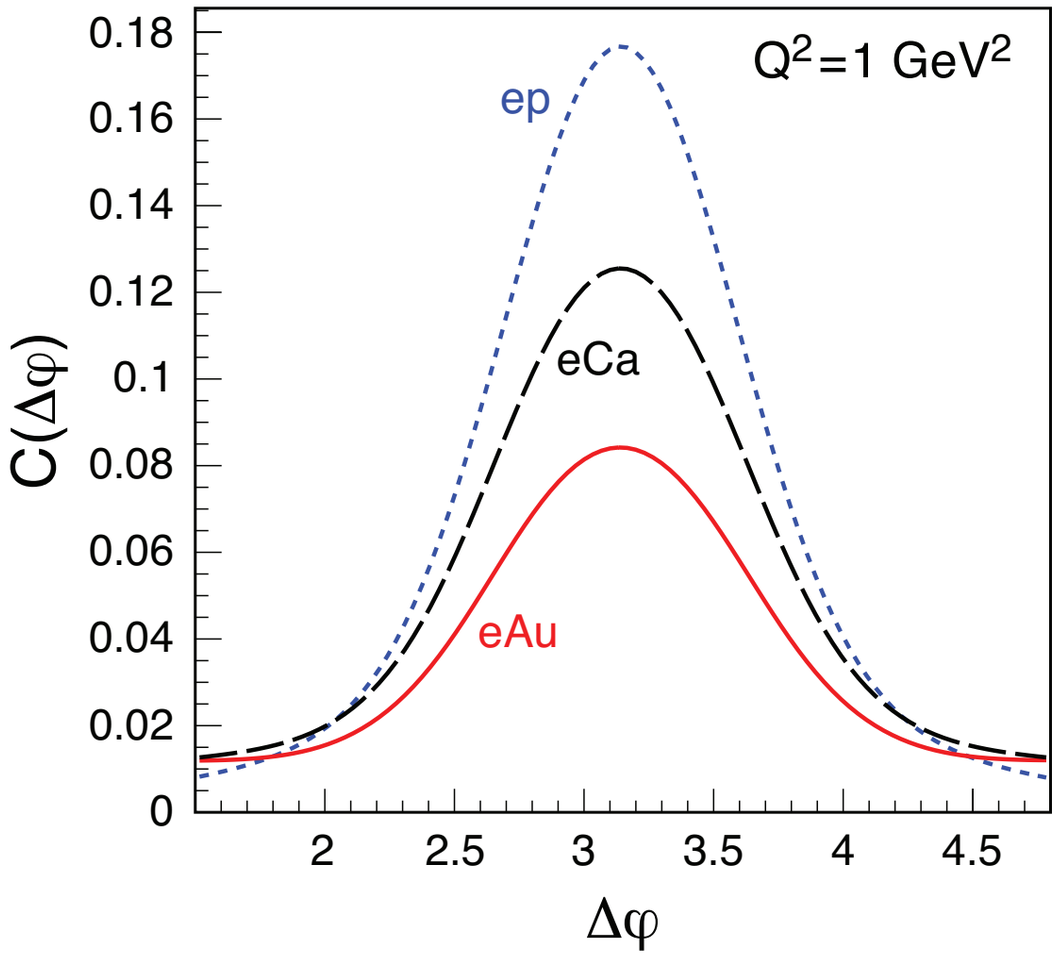
di-hadron correlations in e+A

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



Dominguez, Xiao and Yuan (2012)

- 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

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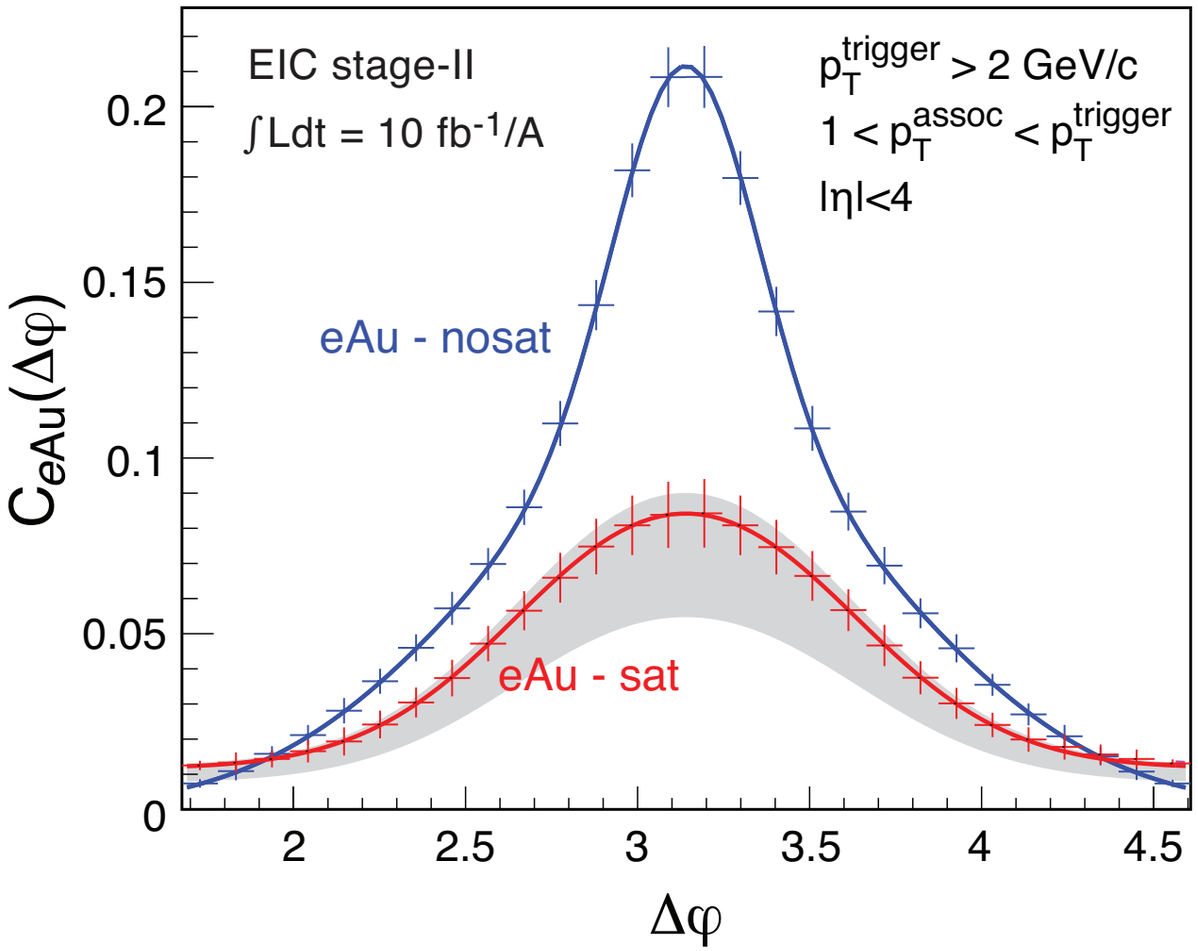

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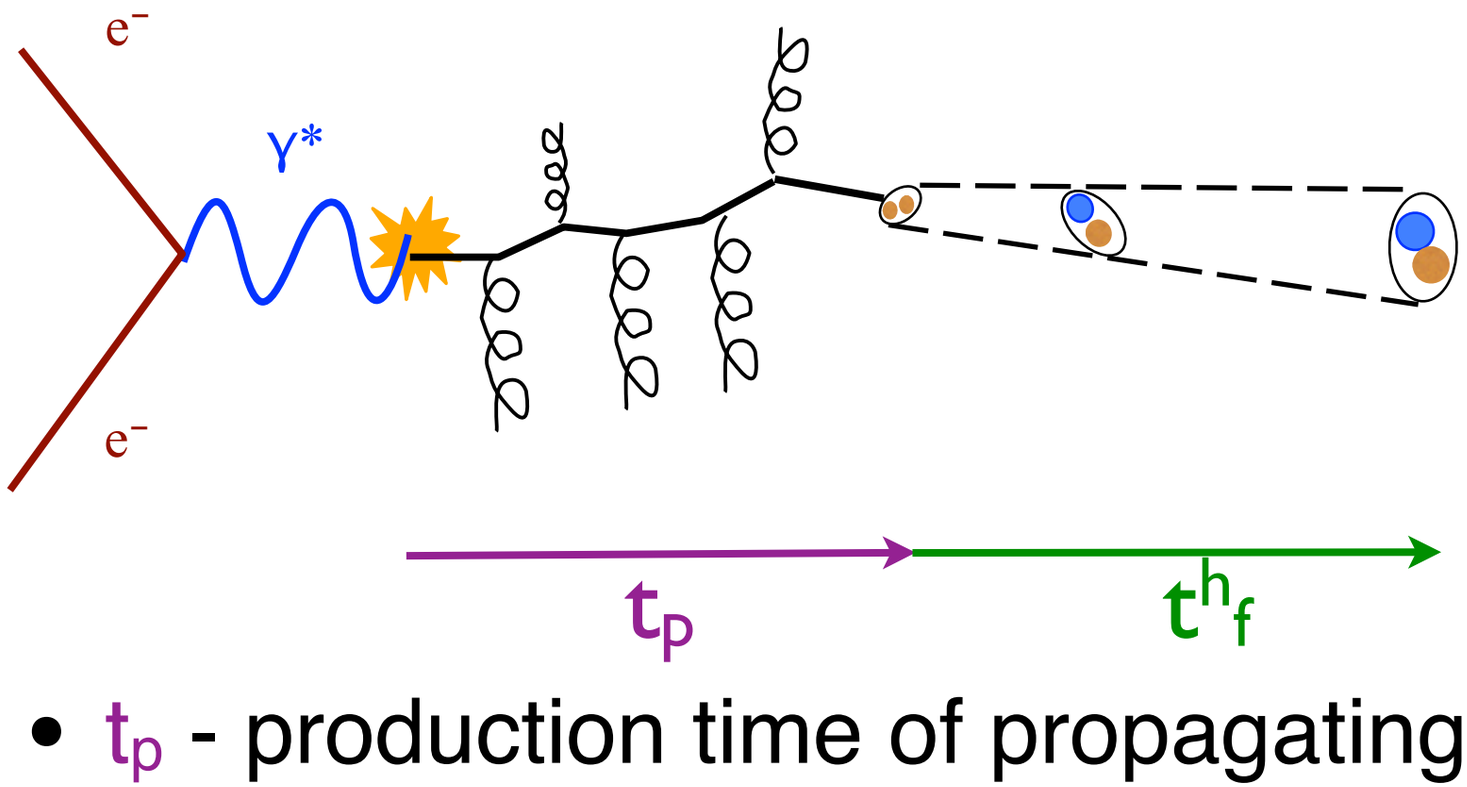
Jets and hadronization



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

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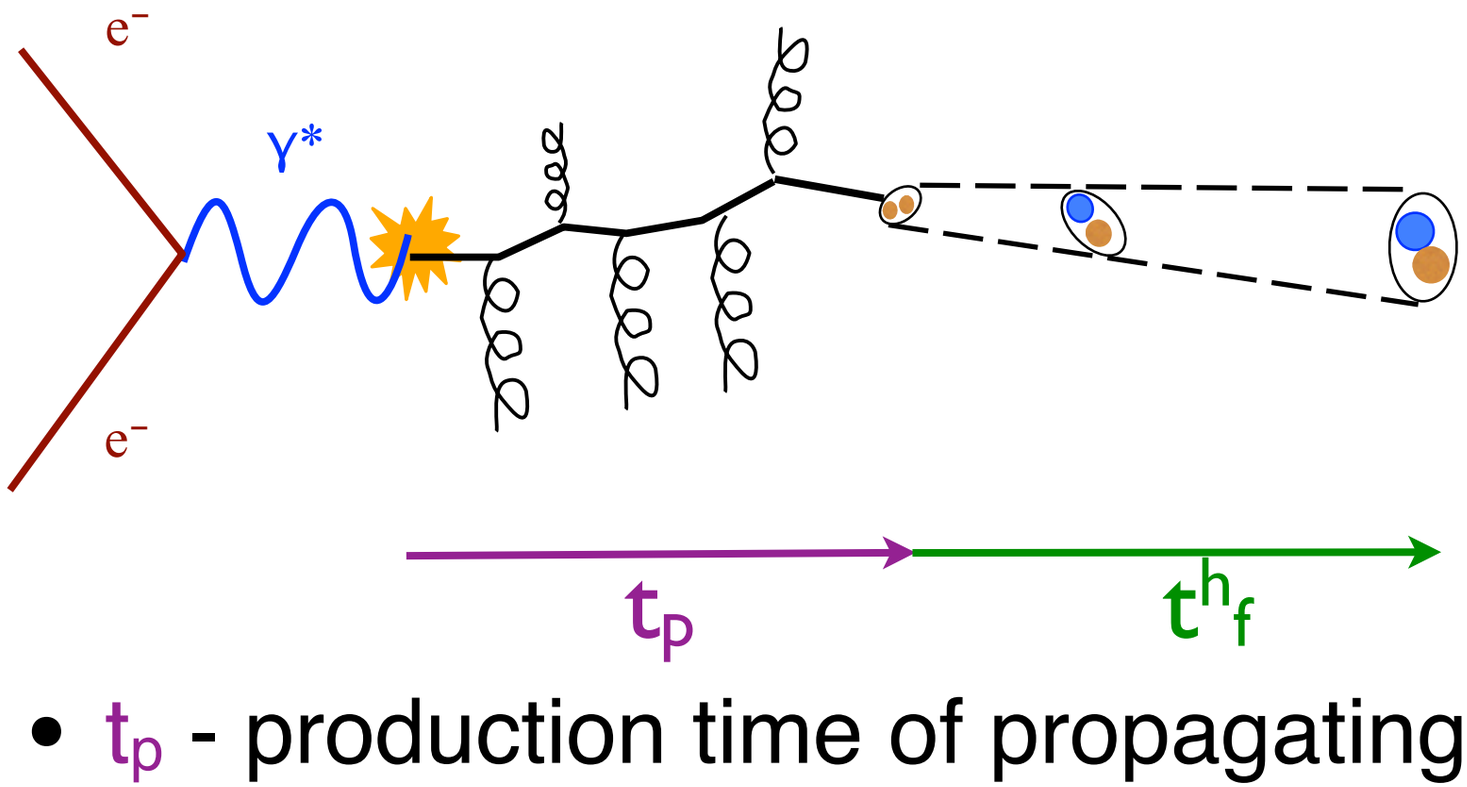

What happens if we add a nuclear medium?

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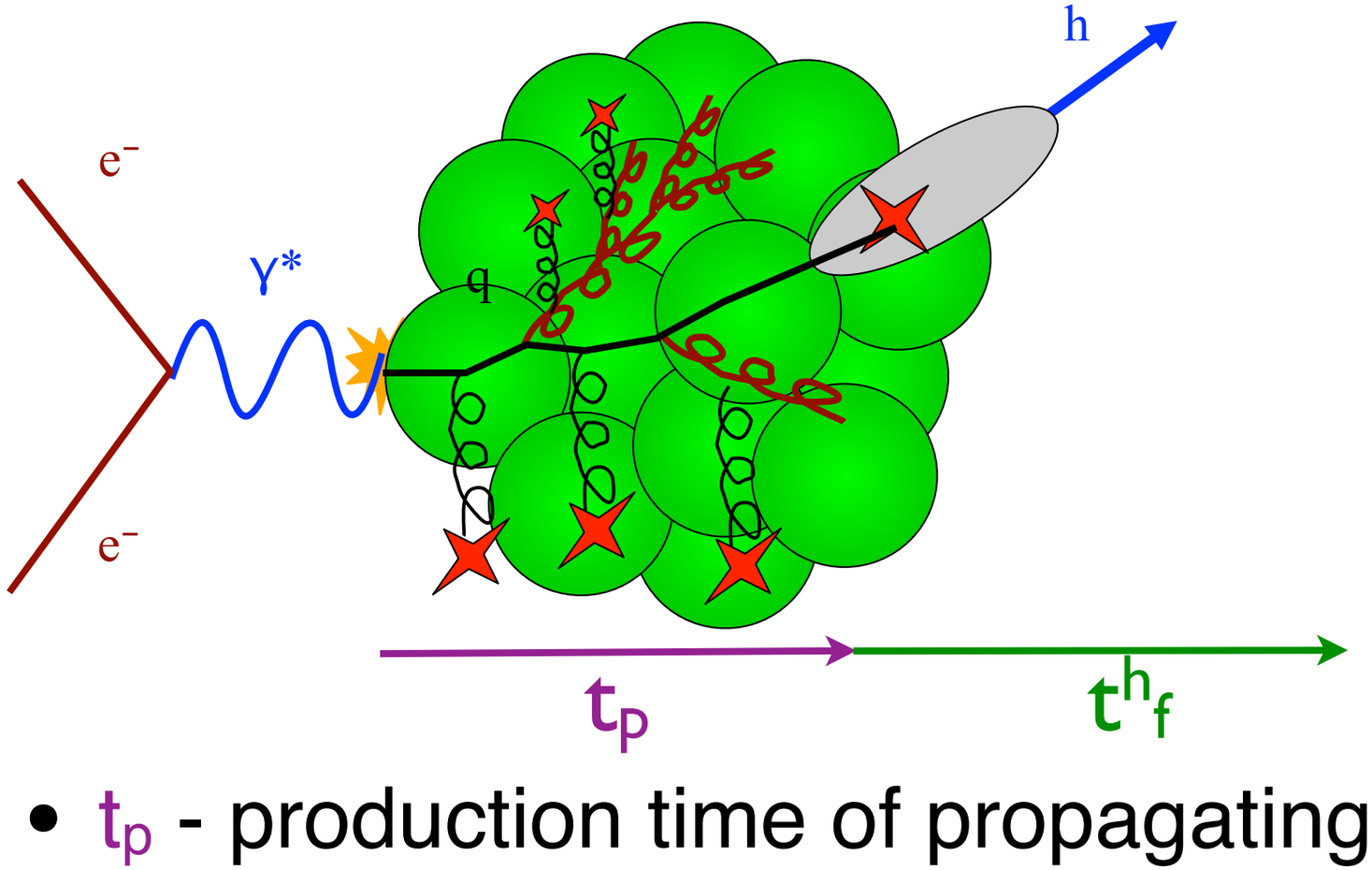

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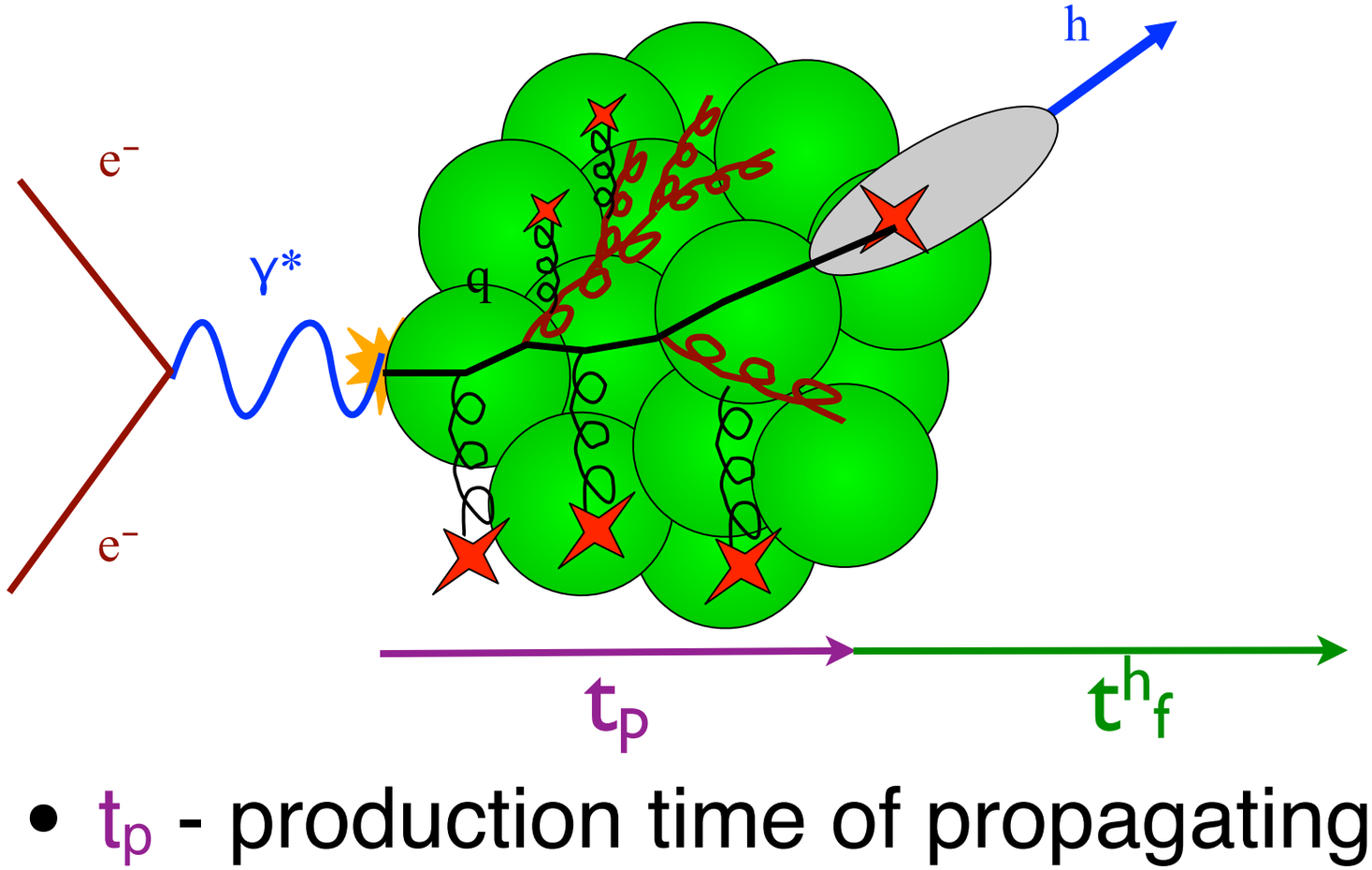

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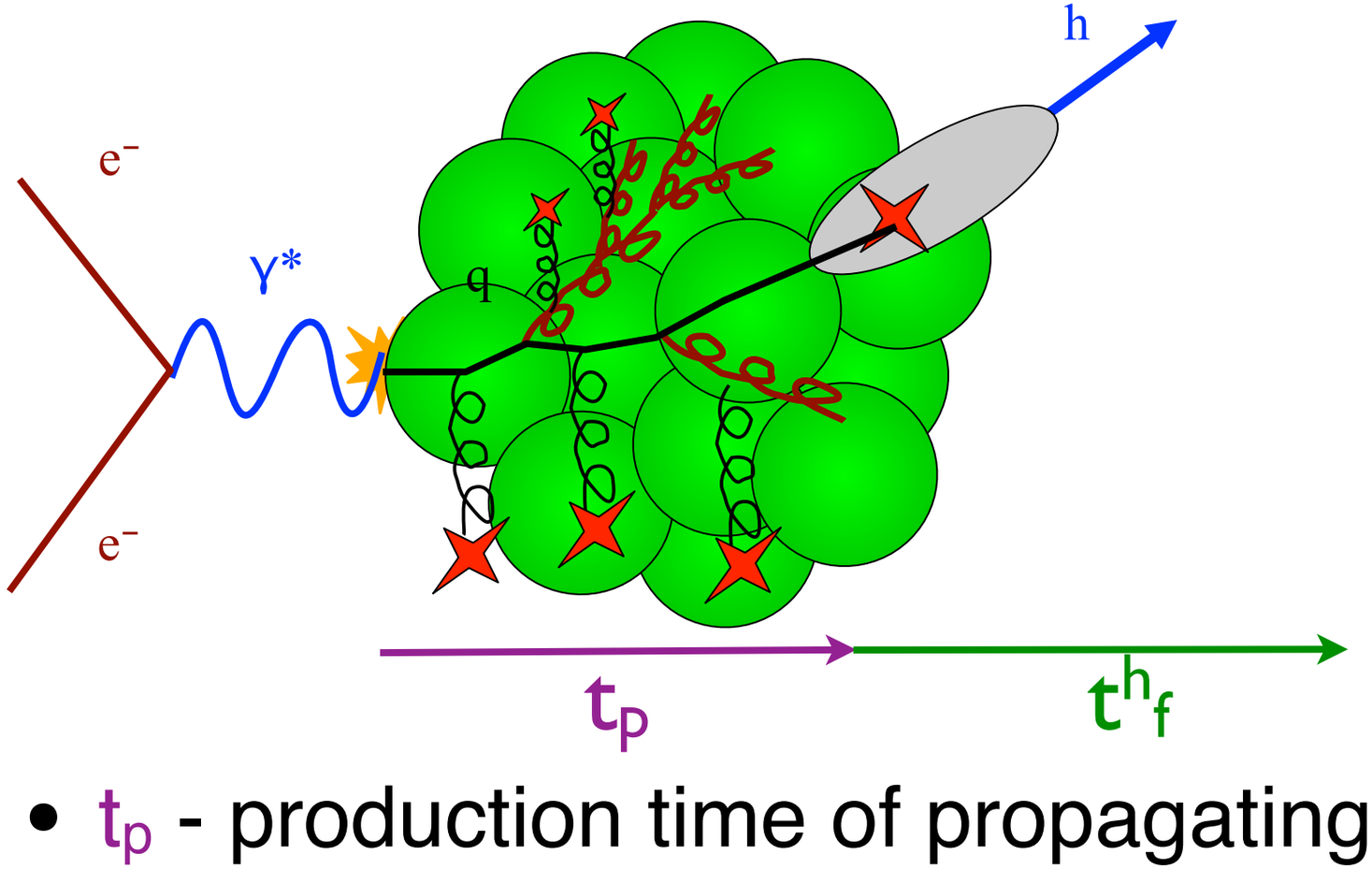

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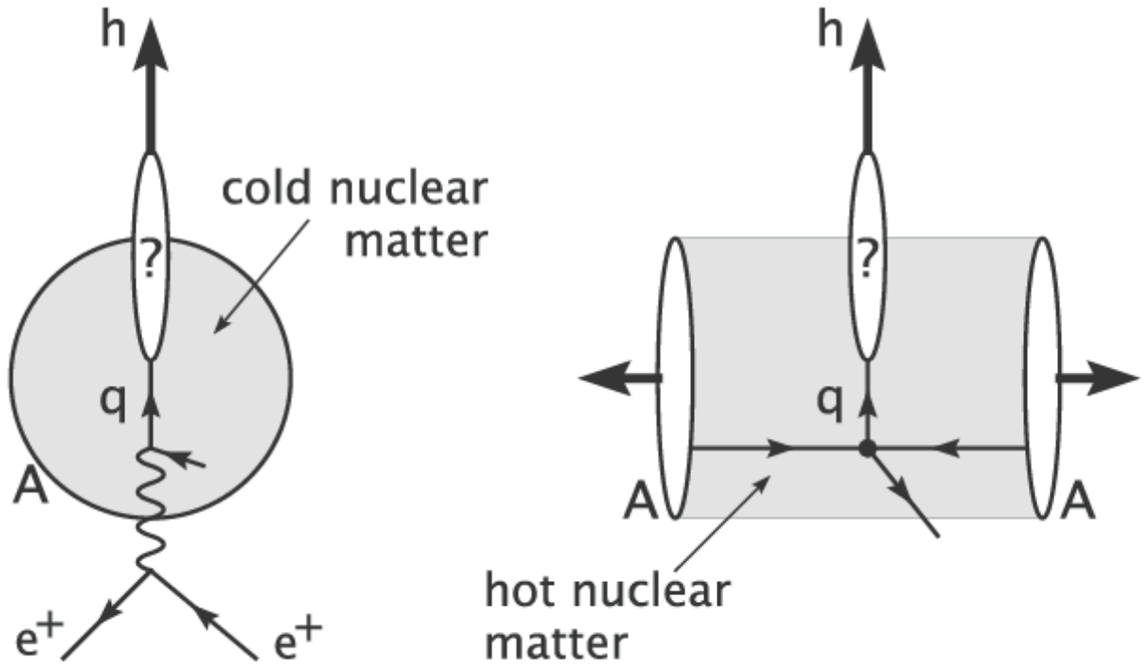

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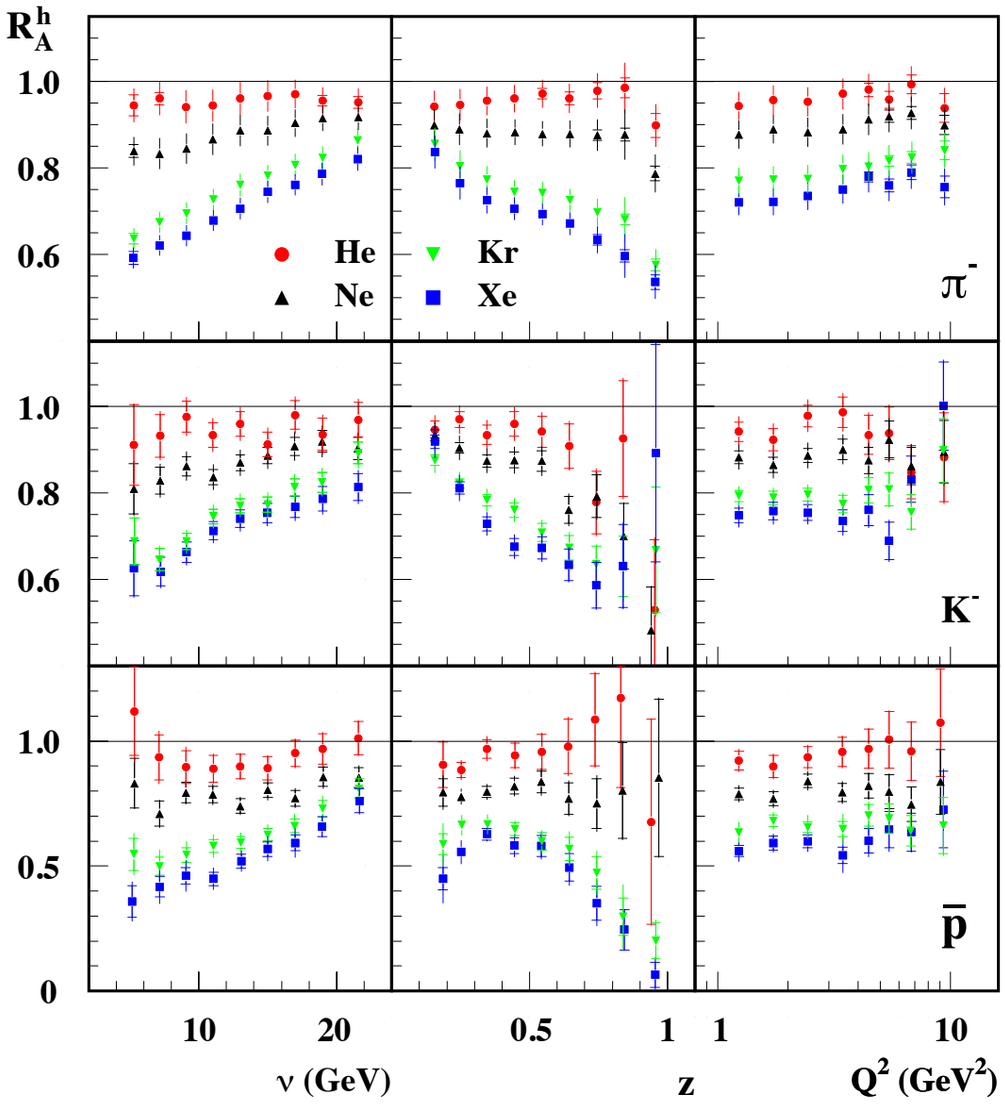
How can the EIC contribute?

HERMES:

E_e = 27 GeV → $\sqrt{s}$ = 7.2 GeV

E_h = 2-15 GeV



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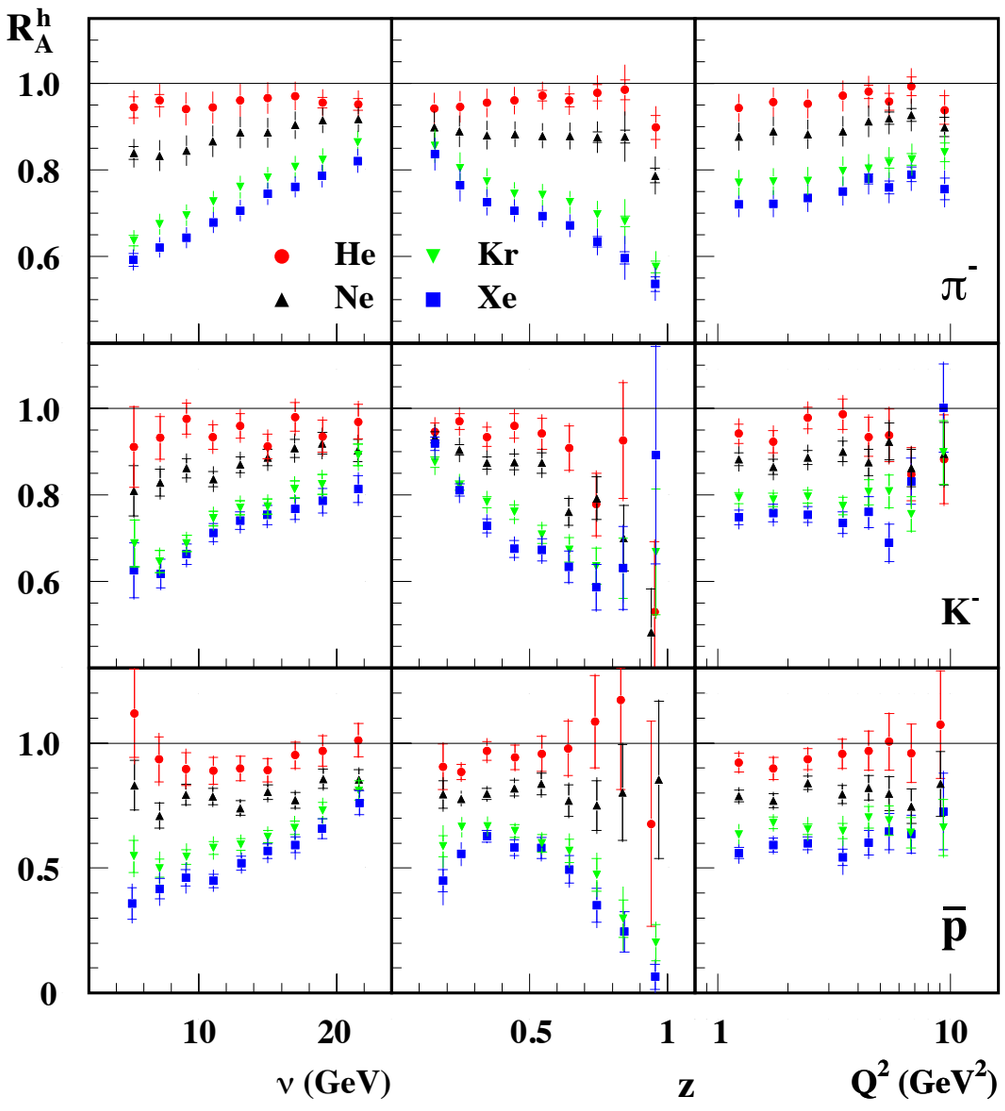

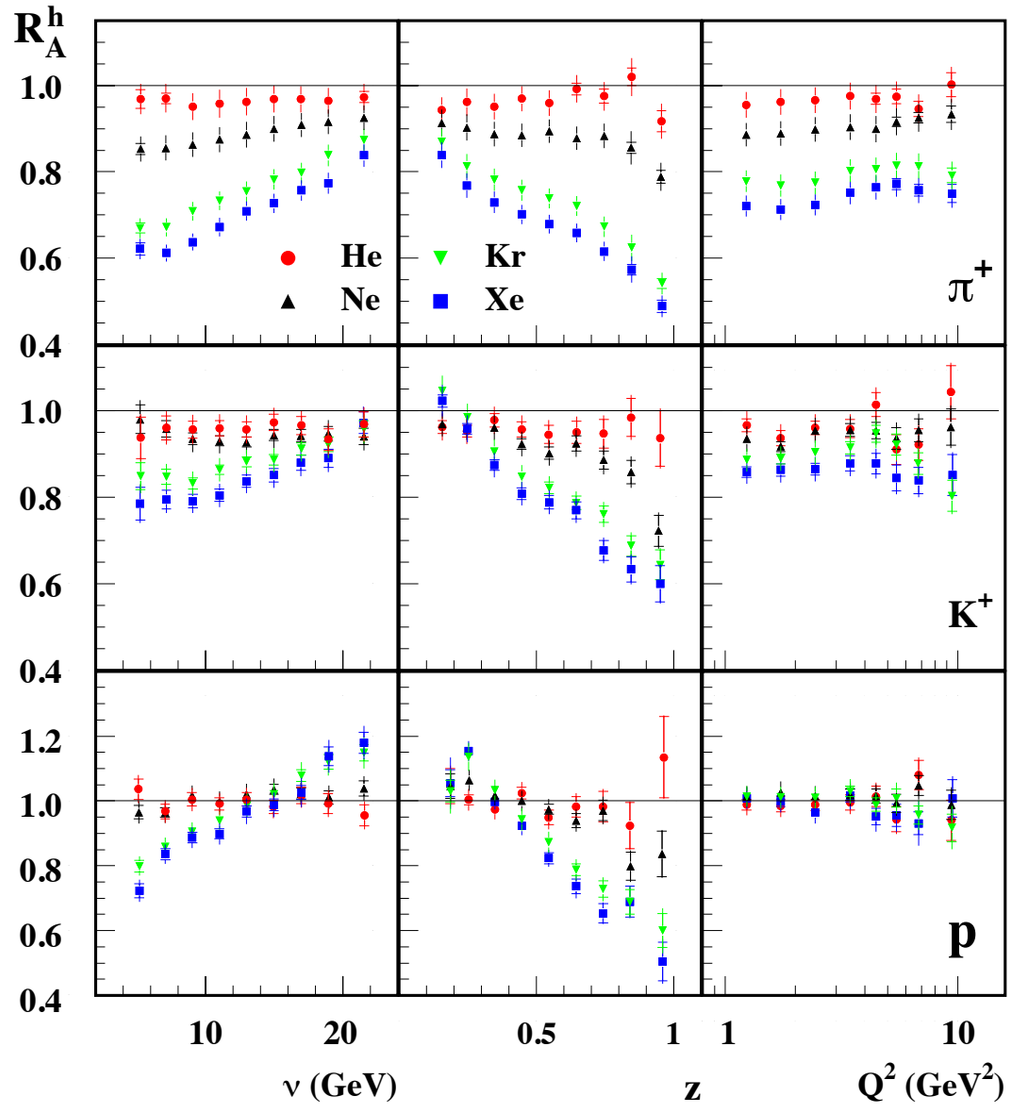

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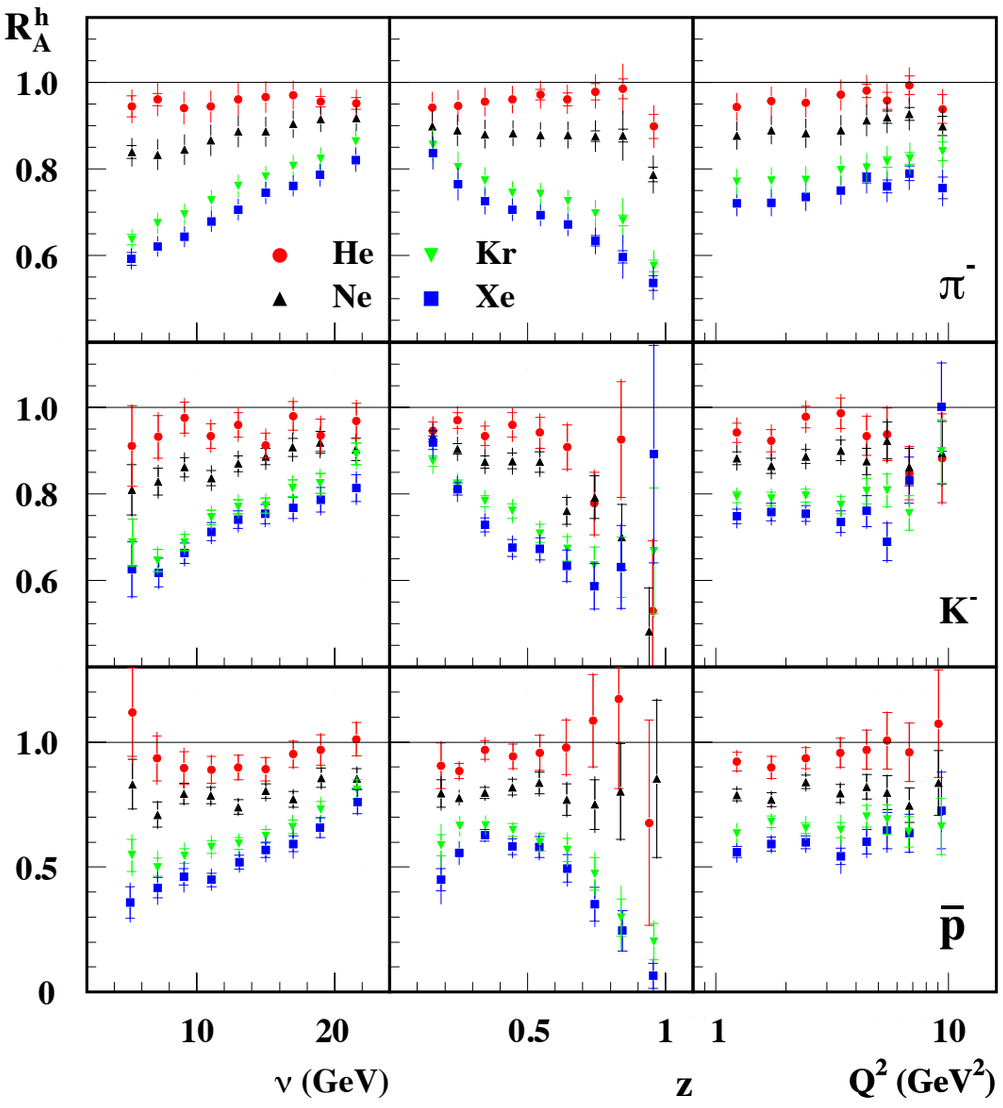
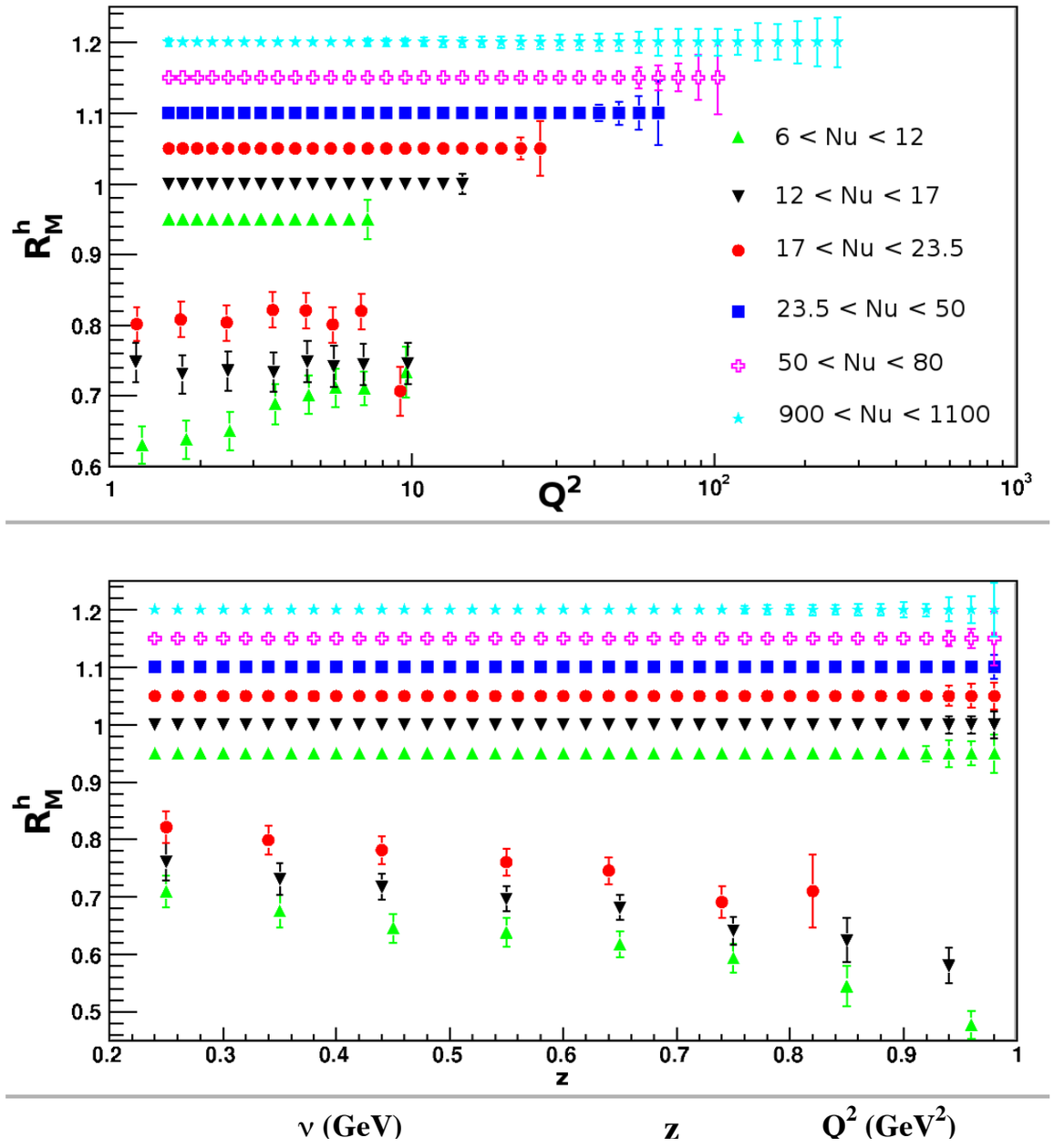


EIC:

light hadrons:



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Prague 2013: hadronization in and out of nucleus

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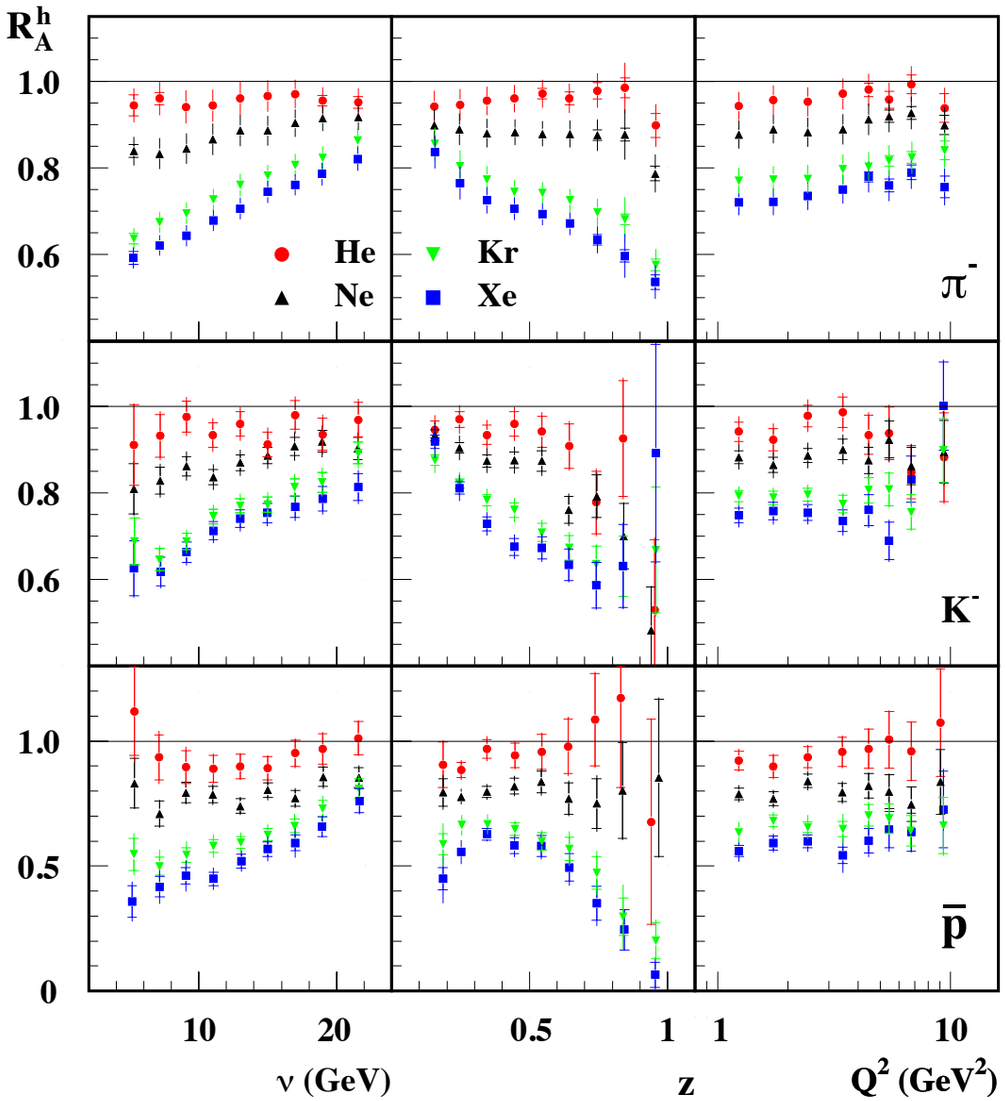
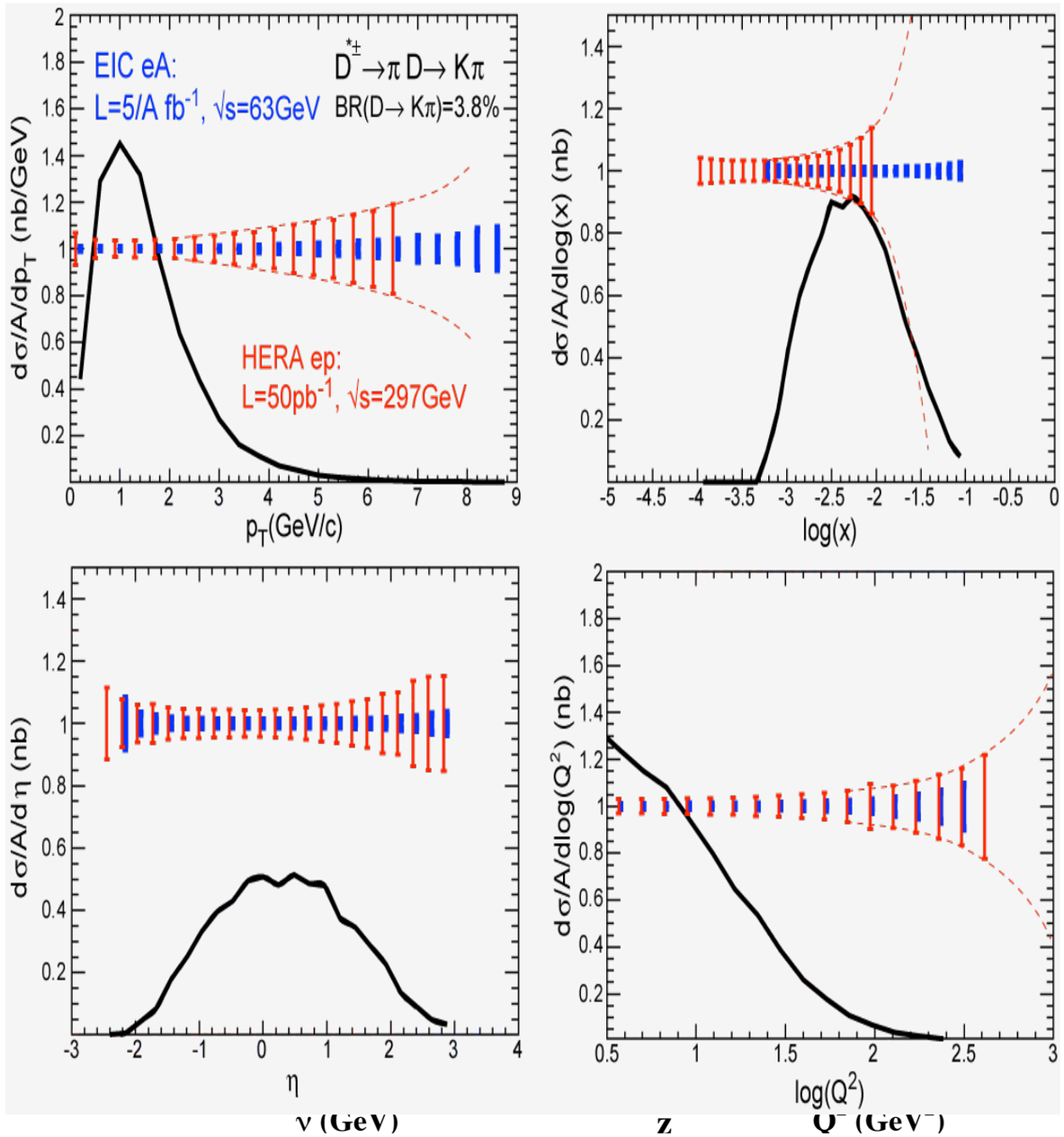


EIC:

charm hadrons:



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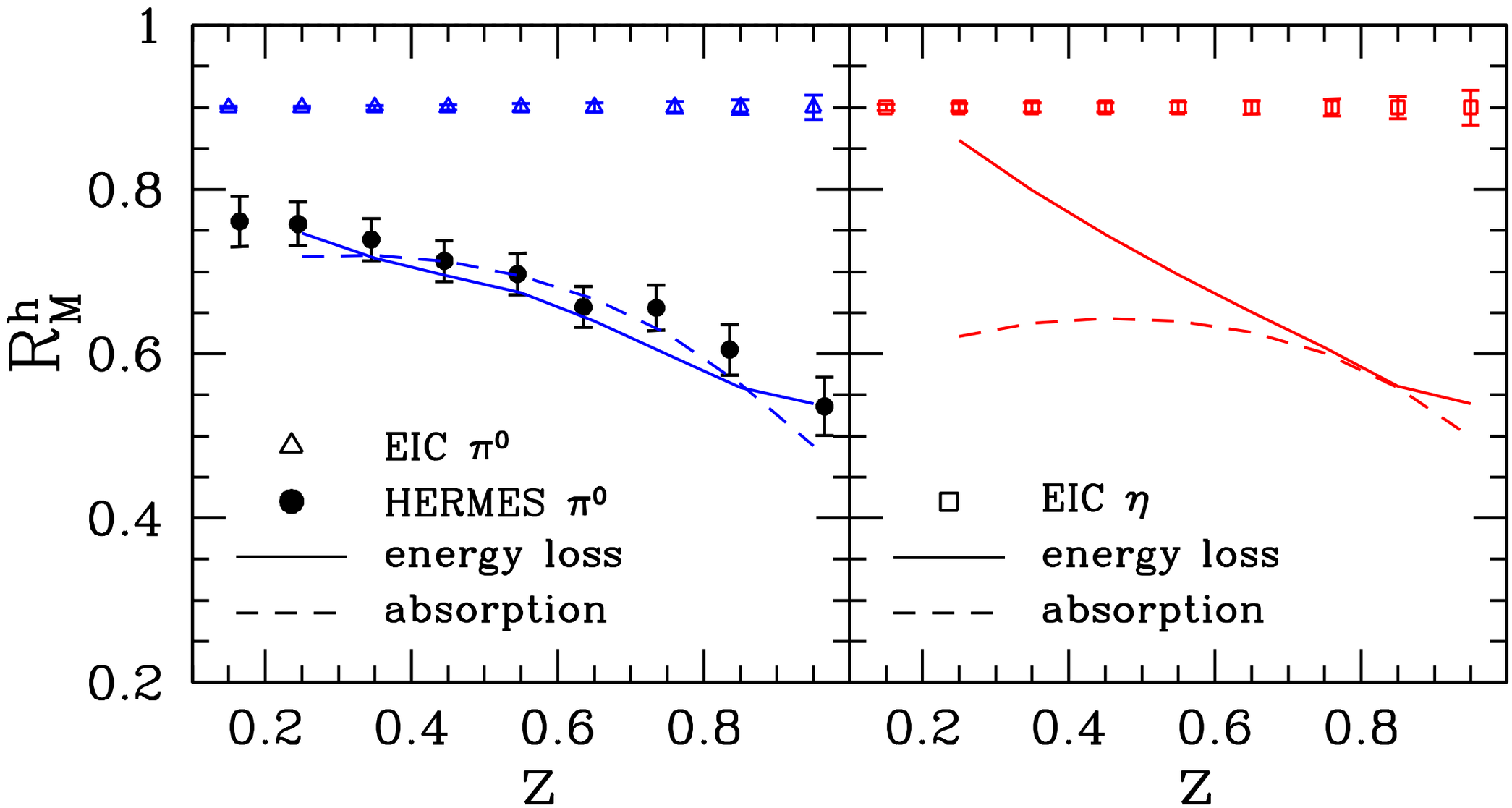
E_h = 2-15 GeV

EIC:



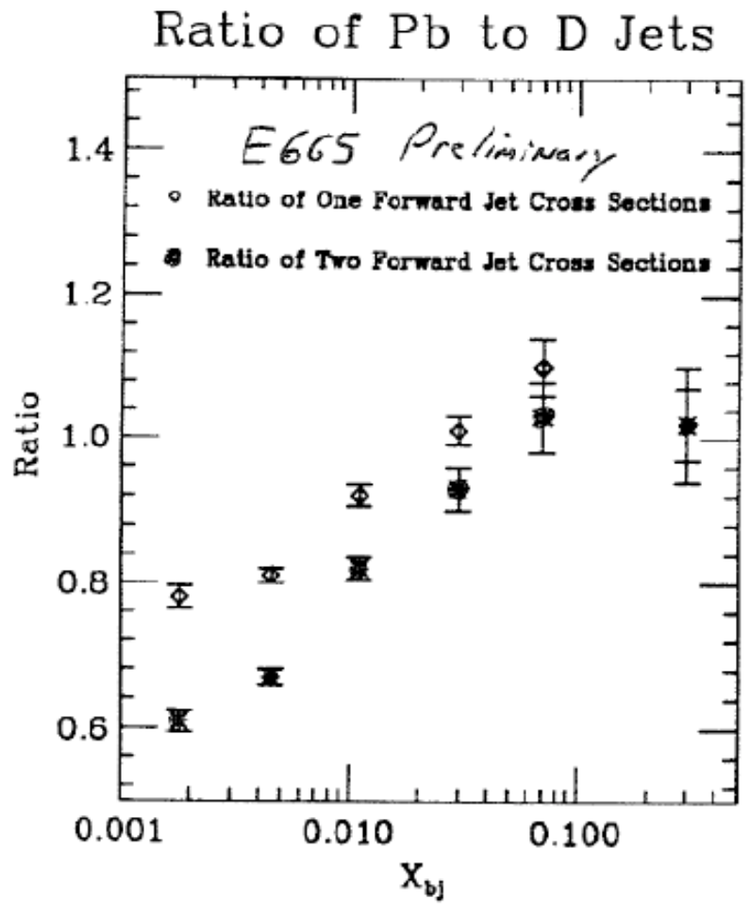
ν = virtual photon energy

$Z_h = E_h/\nu$

large ν range → boost hadronization in and out of nucleus

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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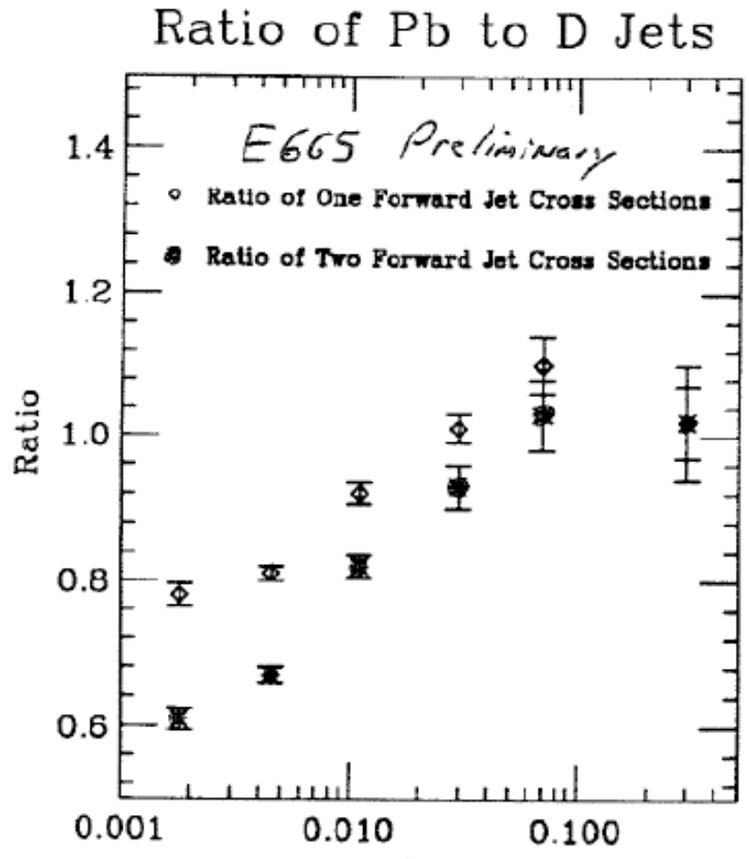
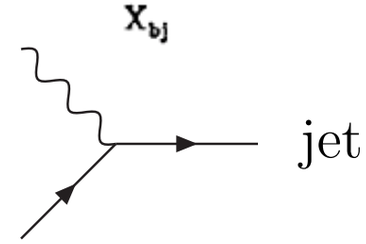


1+1 jets, dominated by q processes → allow study of parton propagation through cold nuclear matter



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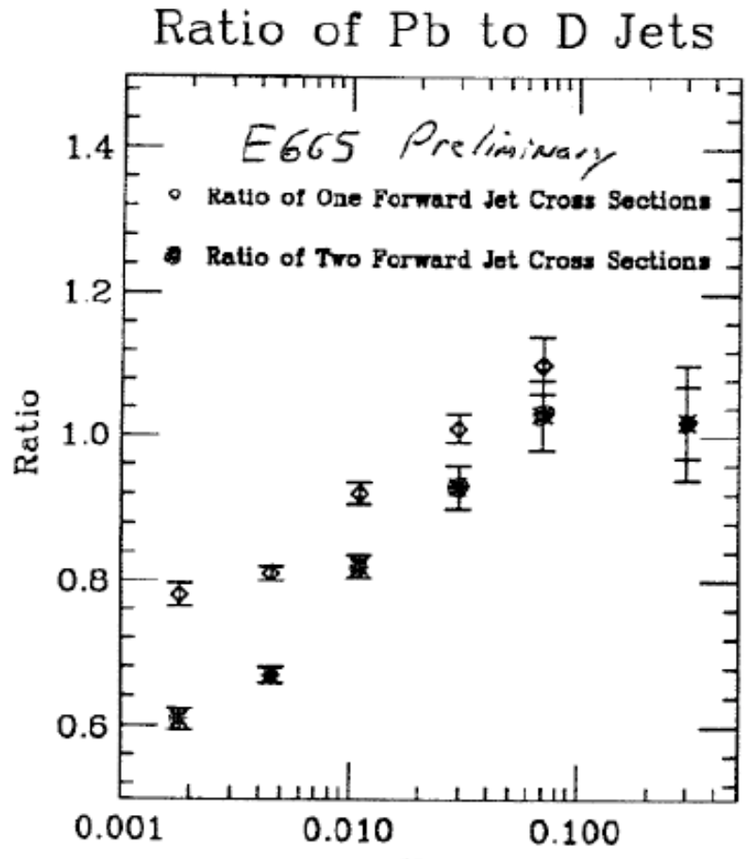

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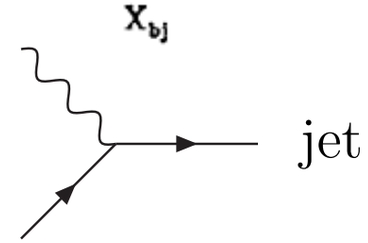
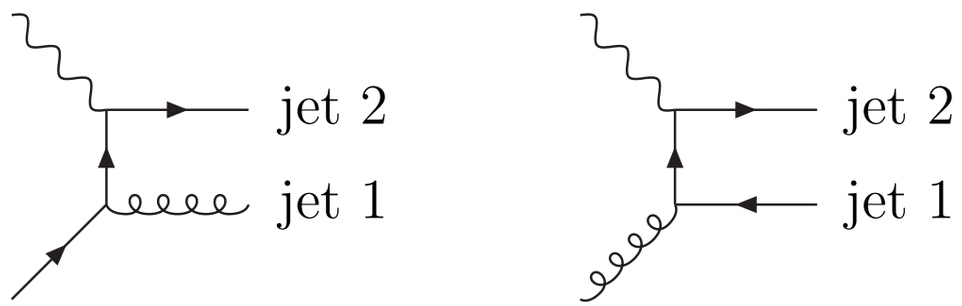


$$\frac{d^2\sigma_{2+1}}{dxdQ^2} = A_q(x,Q^2)q^A(x,Q^2) + A_g(x,Q^2)g_A(x,Q^2)$$

2+1 jets→ sensitive to nuclear gluons



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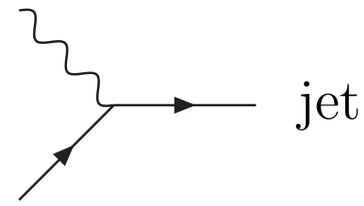

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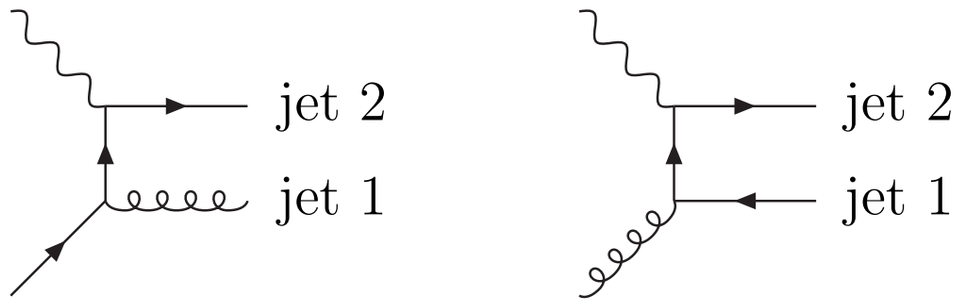

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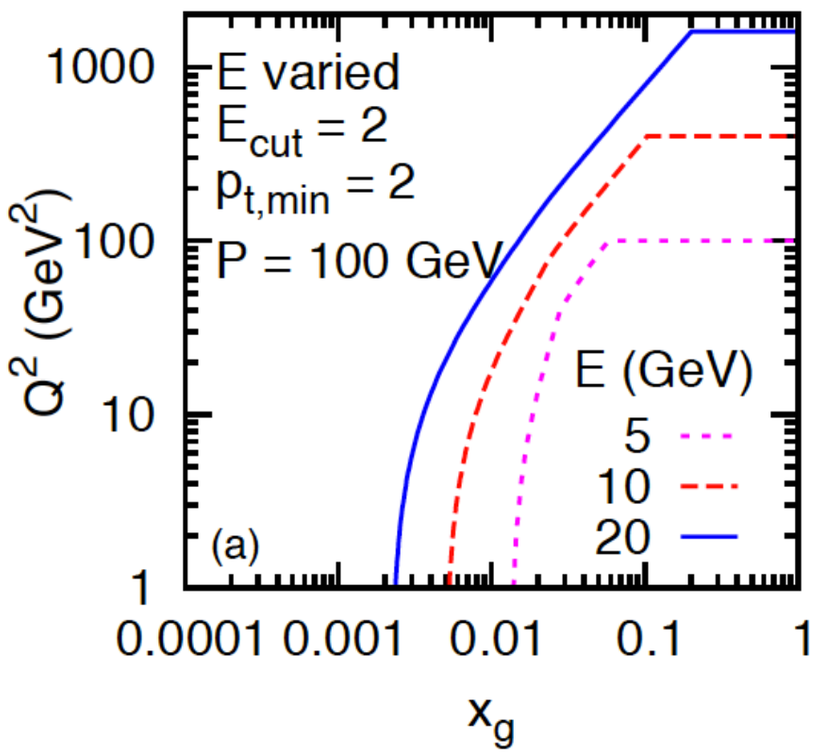
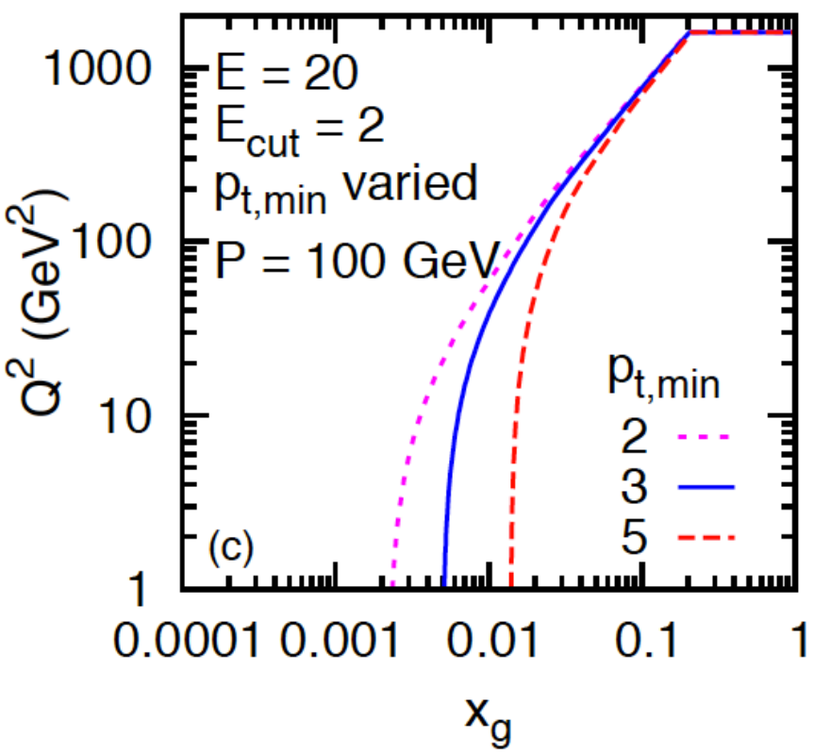
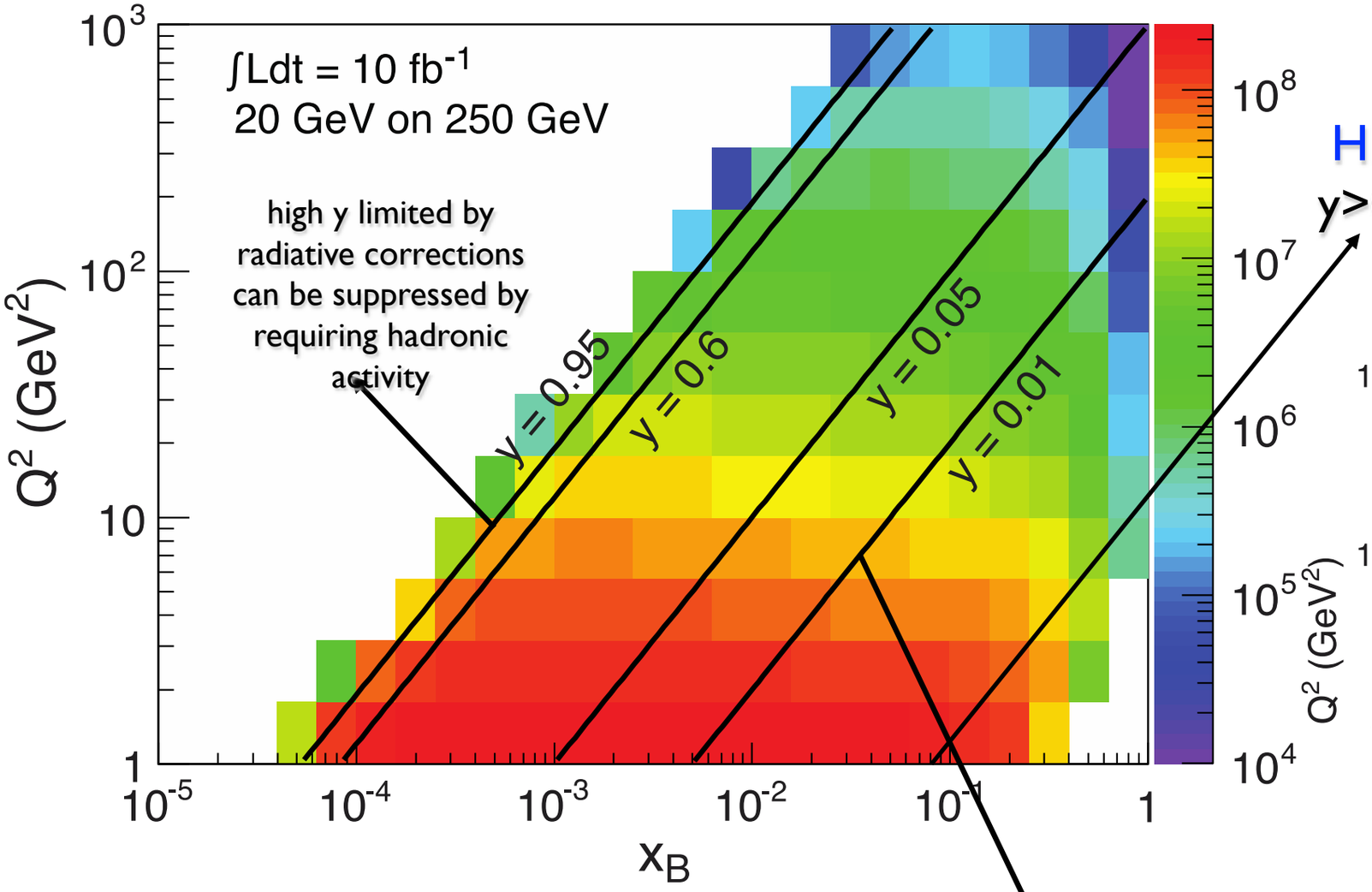


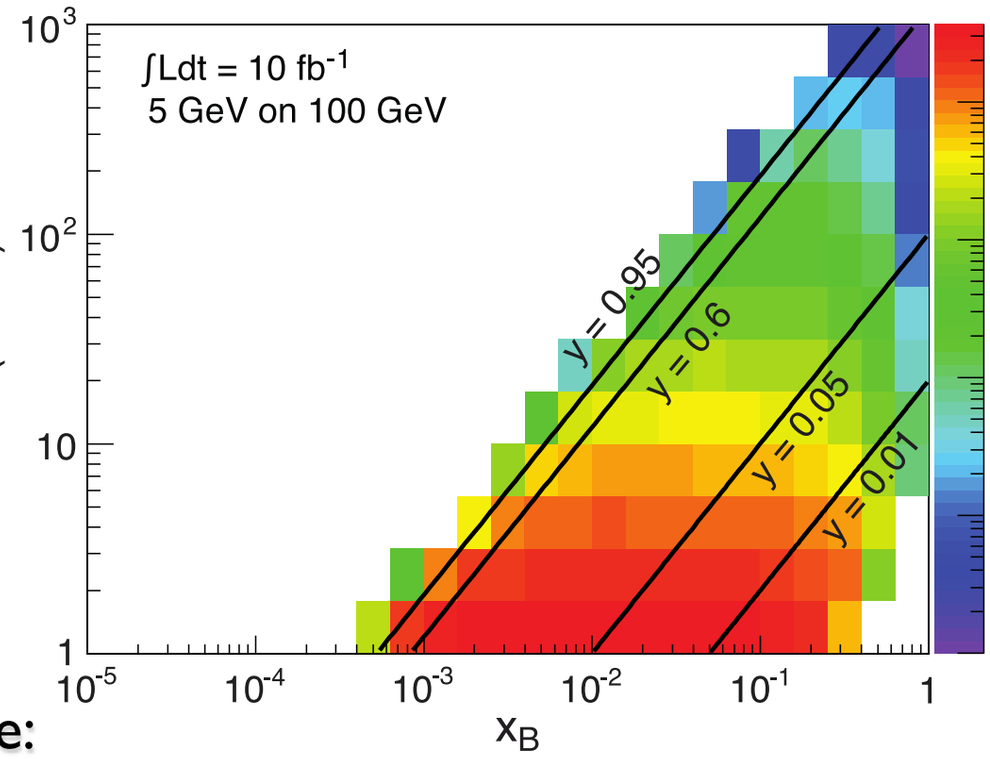


Detector Coverage: DIS Kinematics

Possible limitations in kinematic coverage:

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



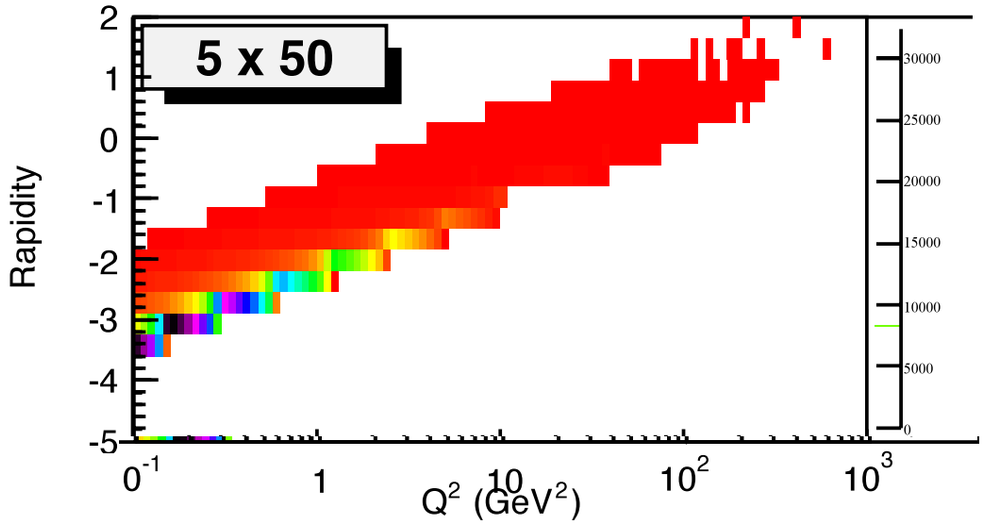


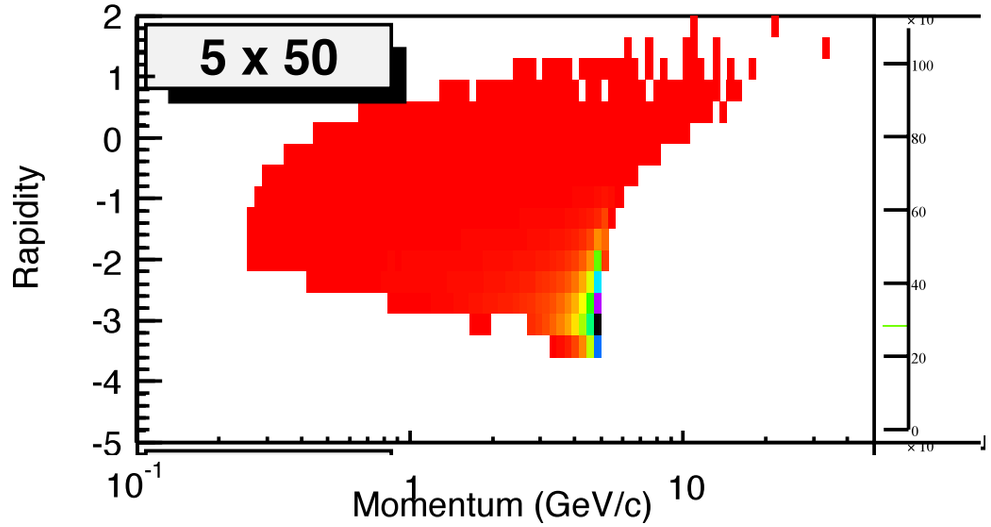
- Even for colliders:
- Strong x-Q^2 correlation
  - high x → high Q^2
  - low x → low Q^2

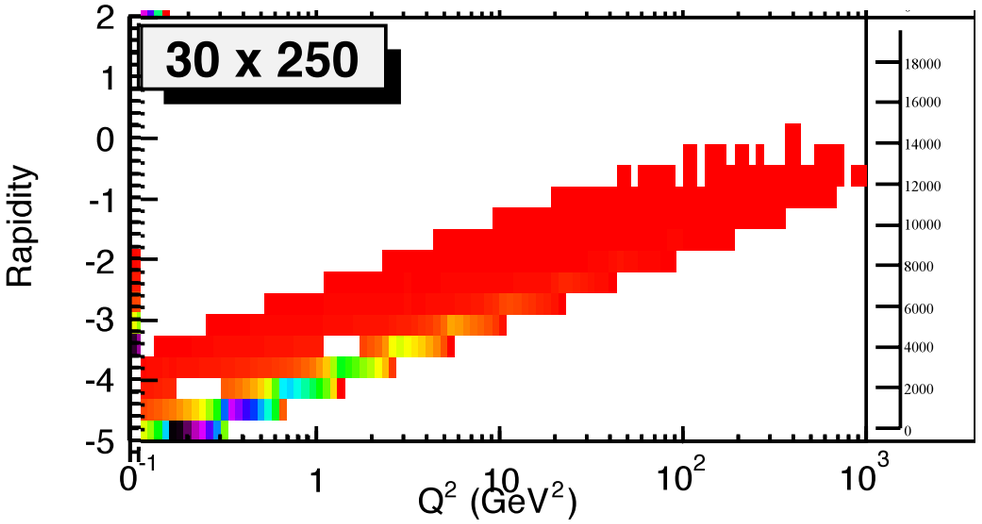
low y-coverage:
limited by E'_e resolution
→ hadron method
→ or change energy

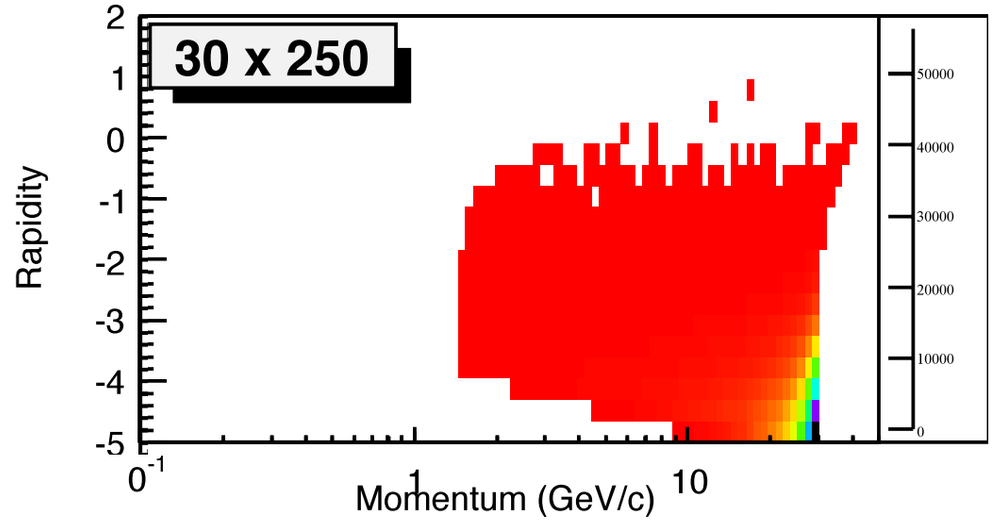
Prague 2013: macl@bnl.gov

Lepton Kinematics



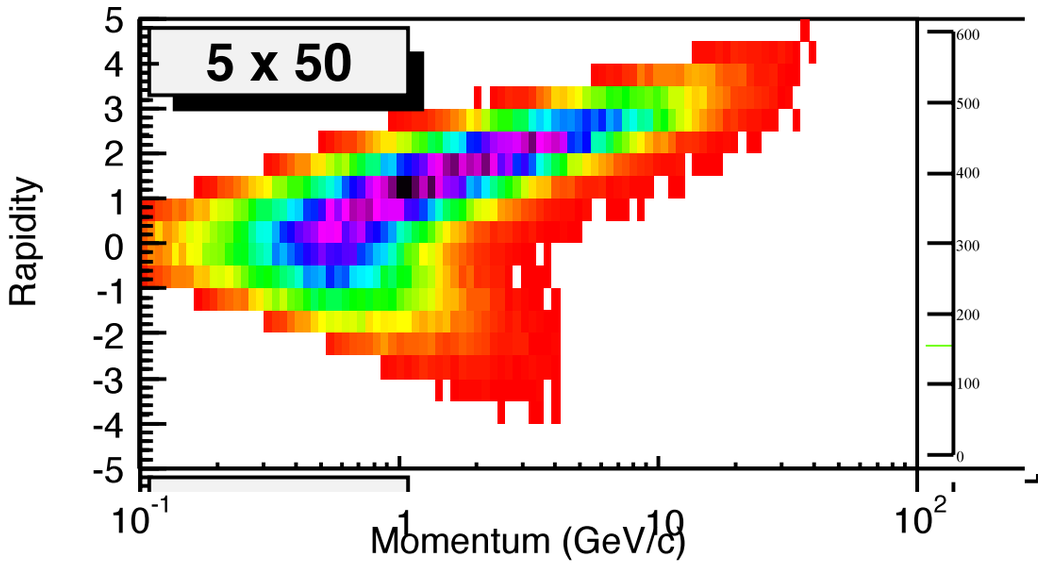


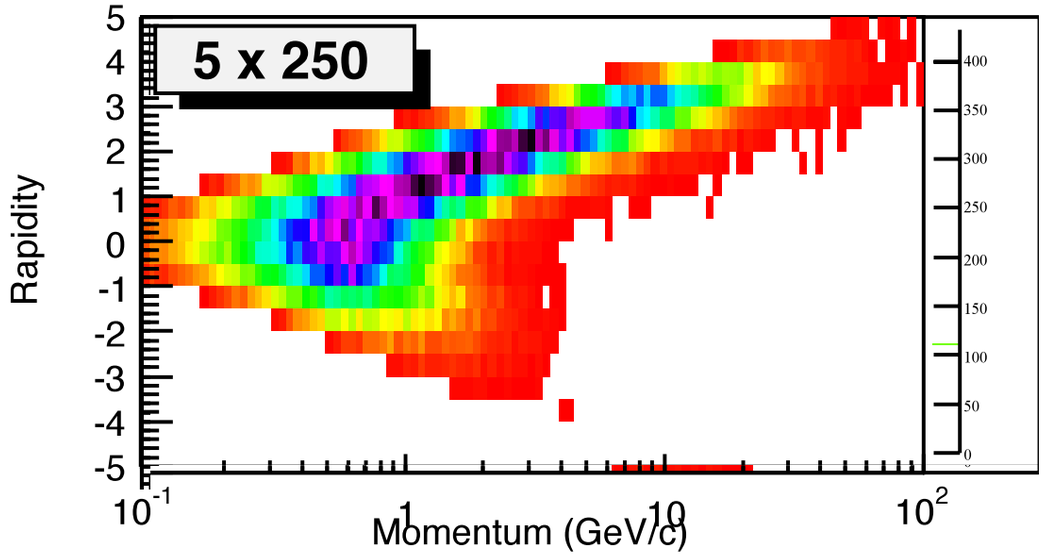




- Low-Q^2 coverage is critical for saturation physics
- Increasing beam energy ⇒ lower Q^2
  - ➡ 5 GeV: $Q^2 \sim 1$ GeV ⇒ $\eta \sim -2$
  - ➡ 10 GeV: $Q^2 \sim 1$ GeV ⇒ $\eta \sim -4$
- Strong constraints placed on the phase-space coverage of the detector

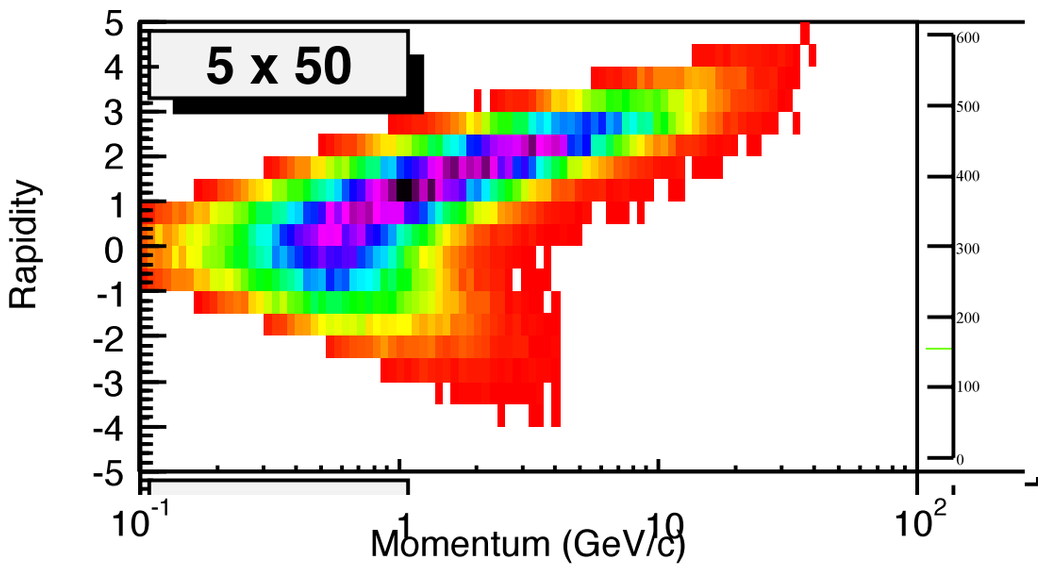
Hadron kinematics

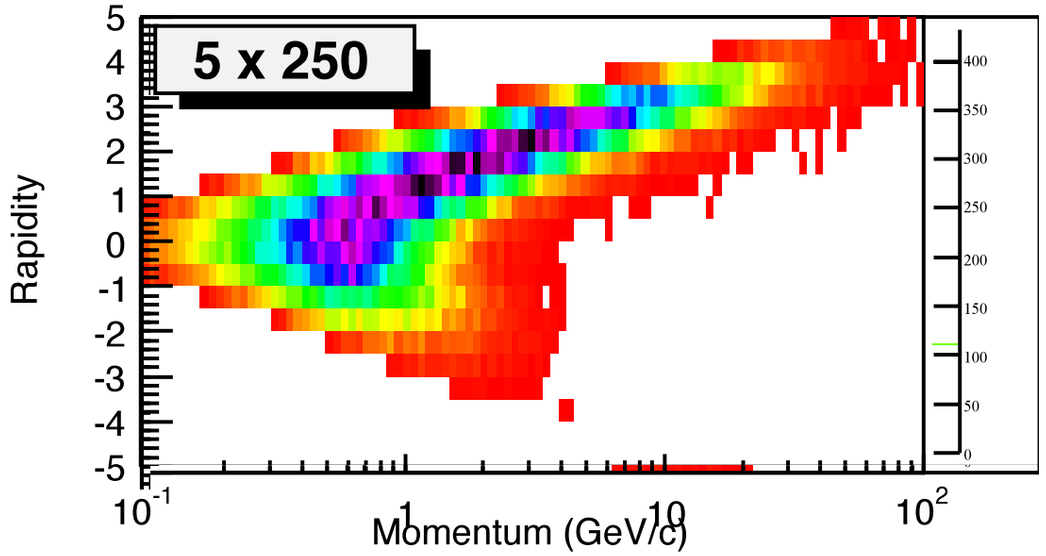


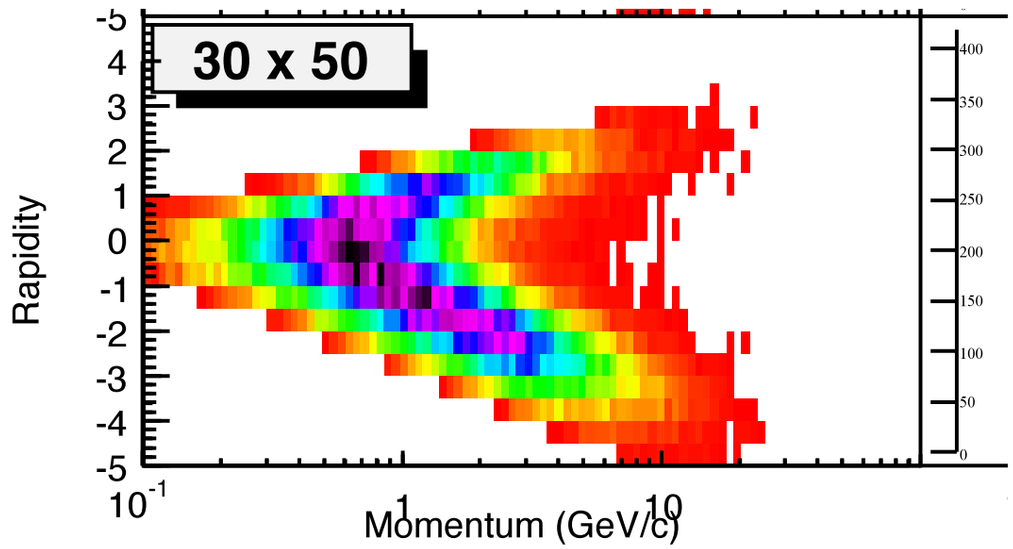


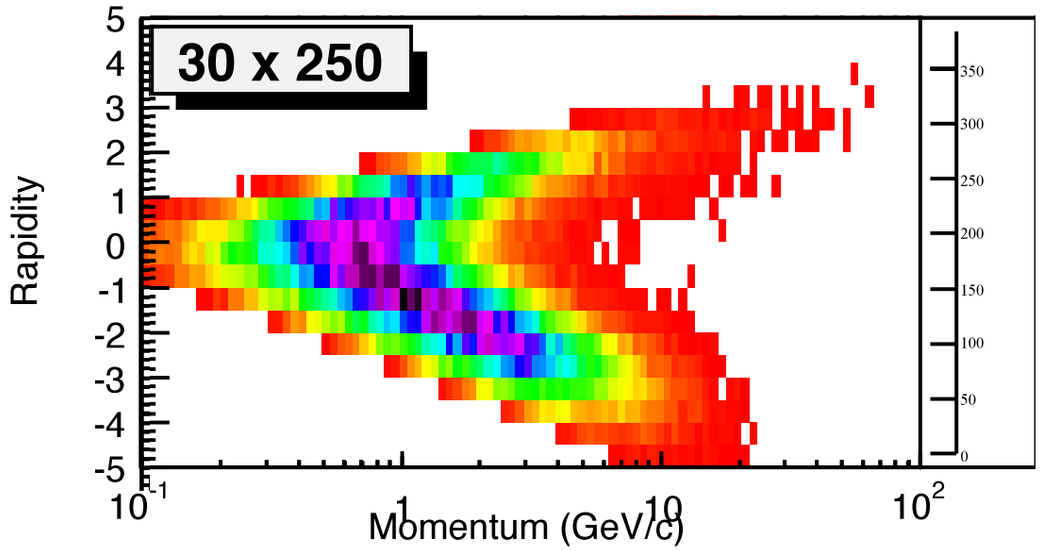
- Increasing the hadron energy
  - ➡ Increase the max hadron momentum at a fixed η

Hadron kinematics



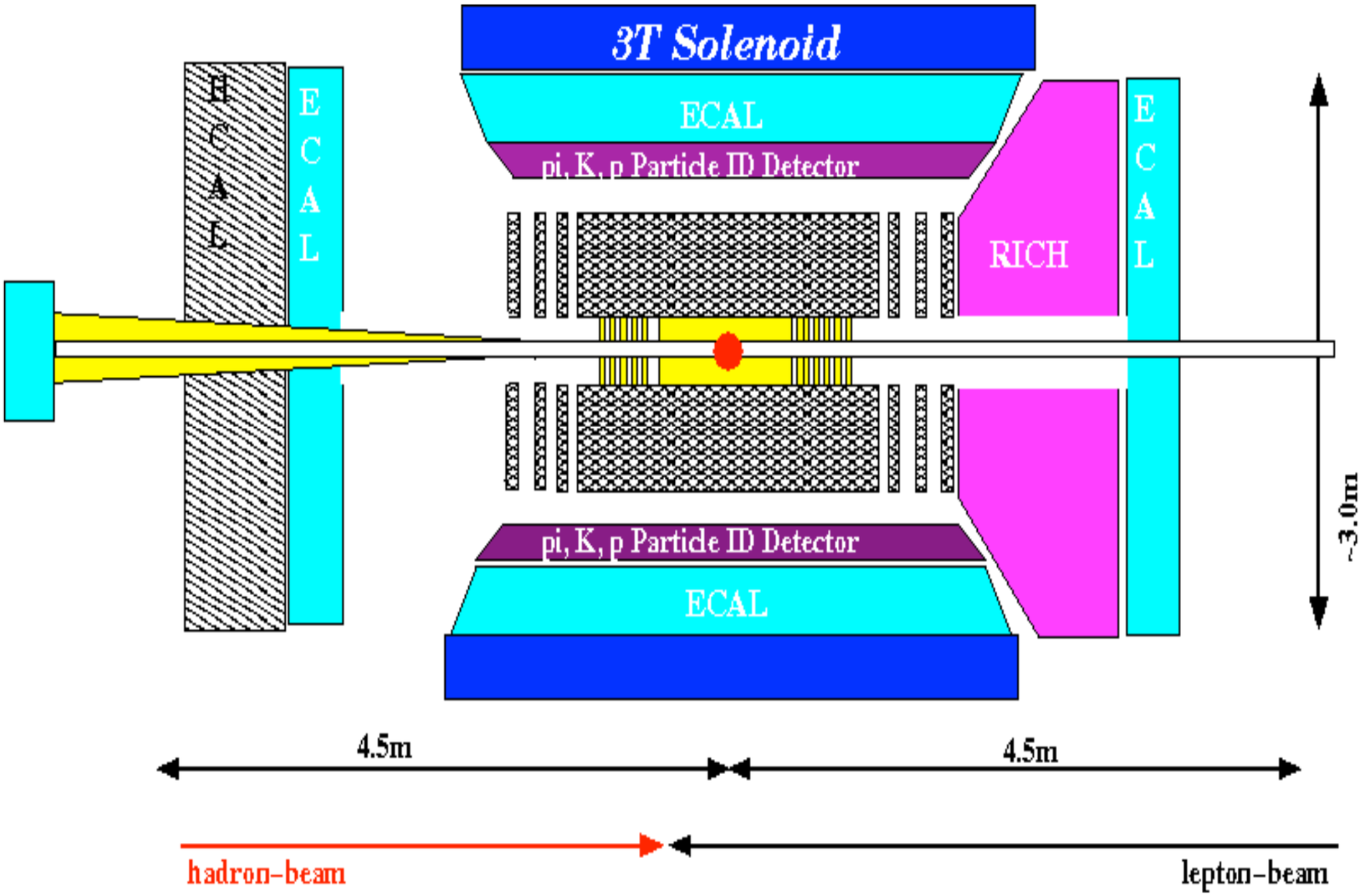






- Increasing the hadron energy
  - ➡ Increase the max hadron momentum at a fixed η
- Increasing the cms energy
  - ➡ Hadrons are boosted from forward to backward rapidities
  - ➡ No difference between π, K, p

Possible realisation of a detector



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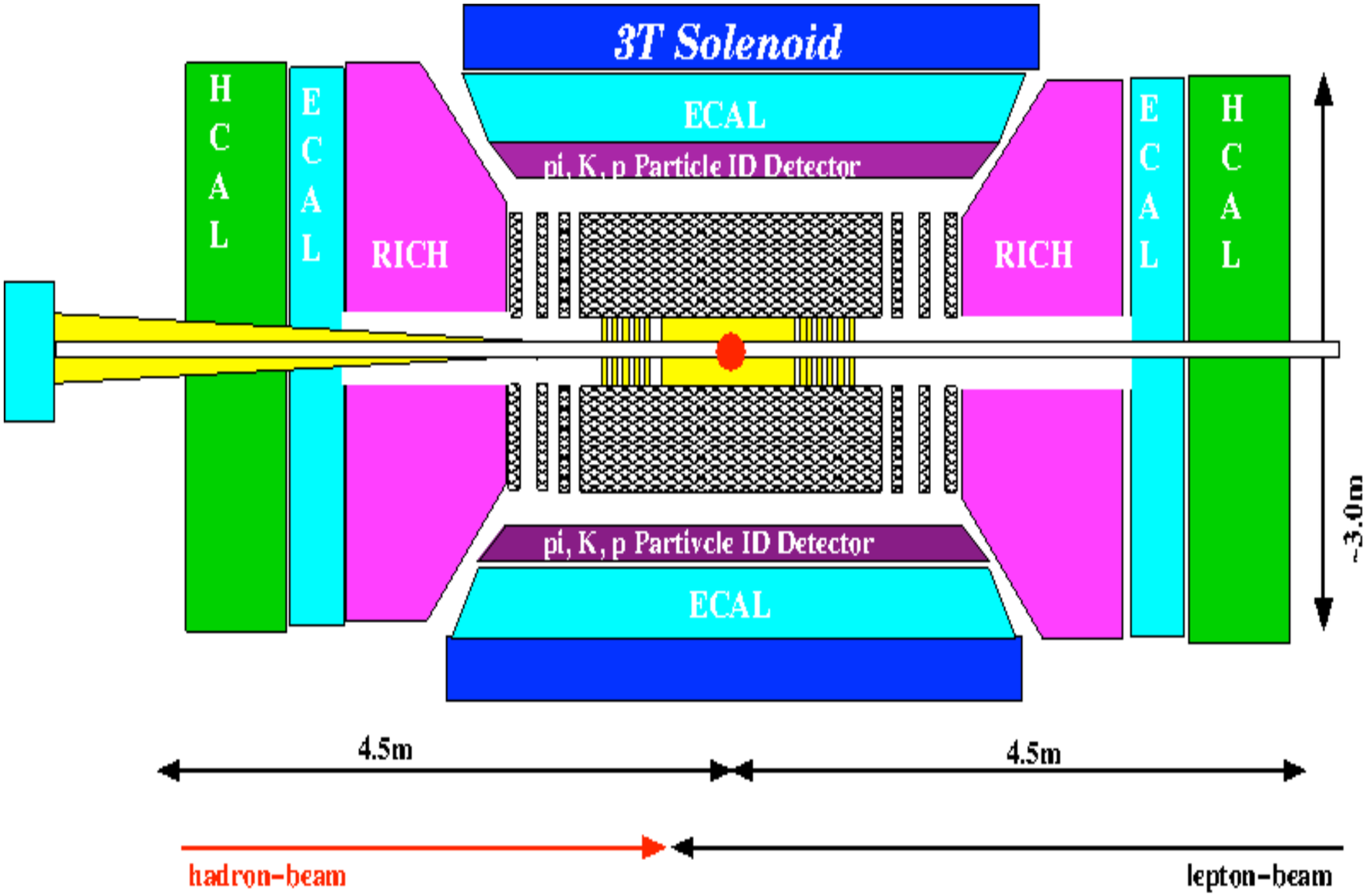
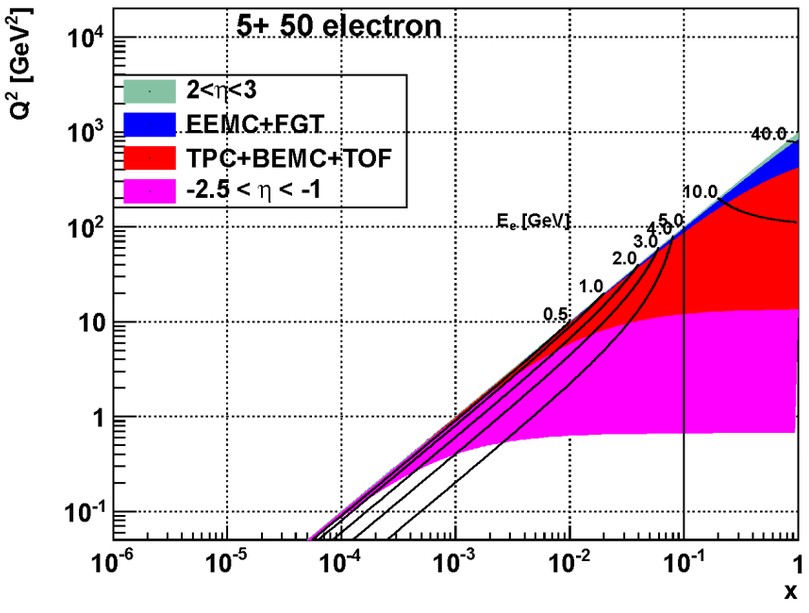


eSTAR kinematics in phase 1: 5 GeV electrons

DIS region

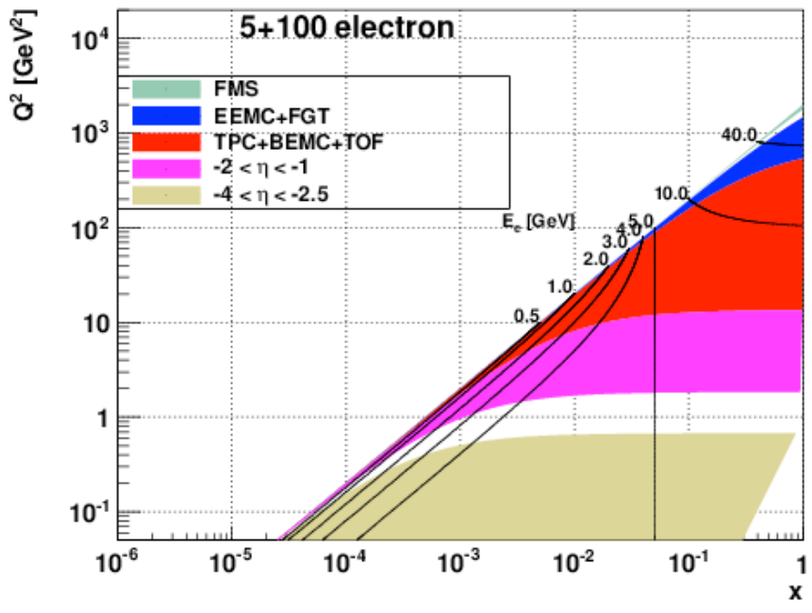
5 GeV e + 50 GeV/nucleon



TPC

Missing today

5 GeV e + 100 GeV/nucleon



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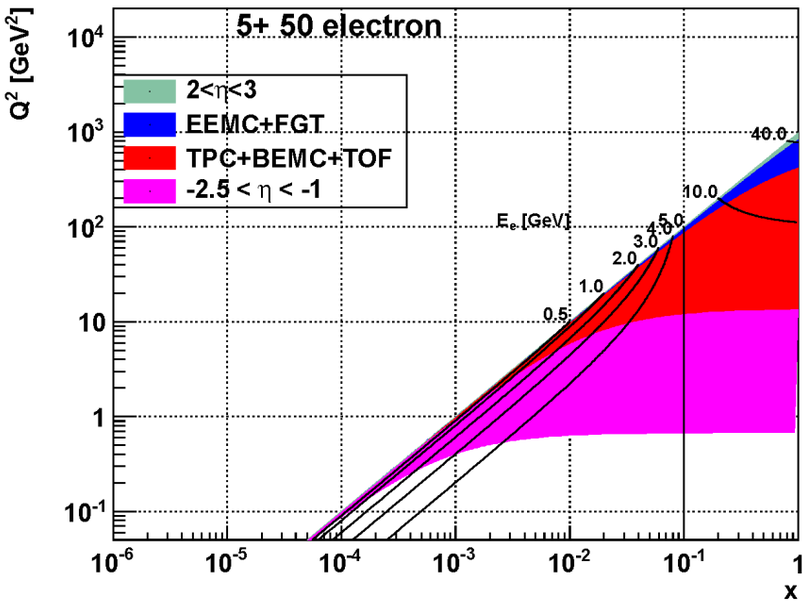

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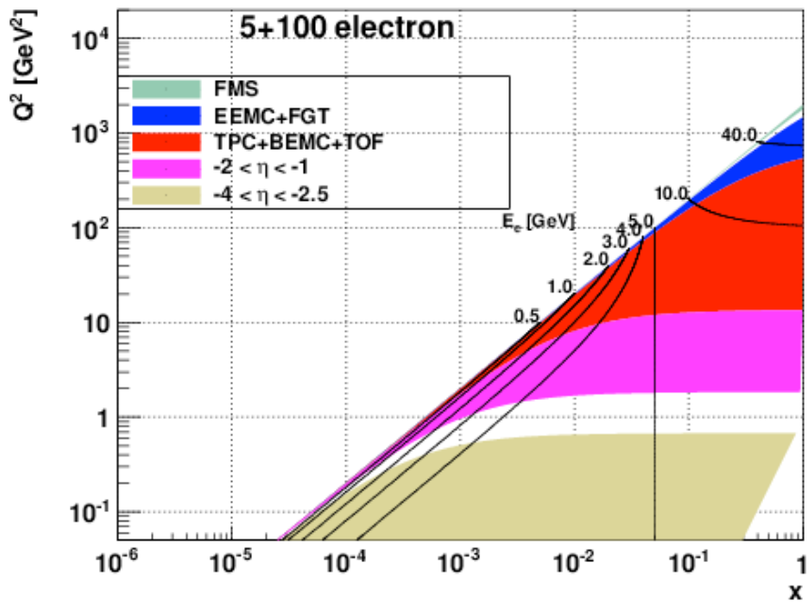

- "Forward" (-2.5 < h < -1) electron acceptance is essential in order to span the DIS regime

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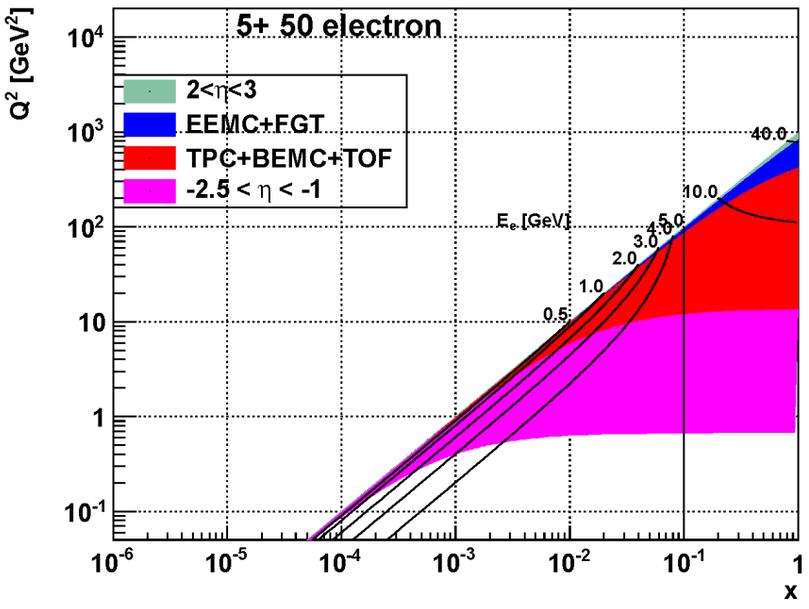

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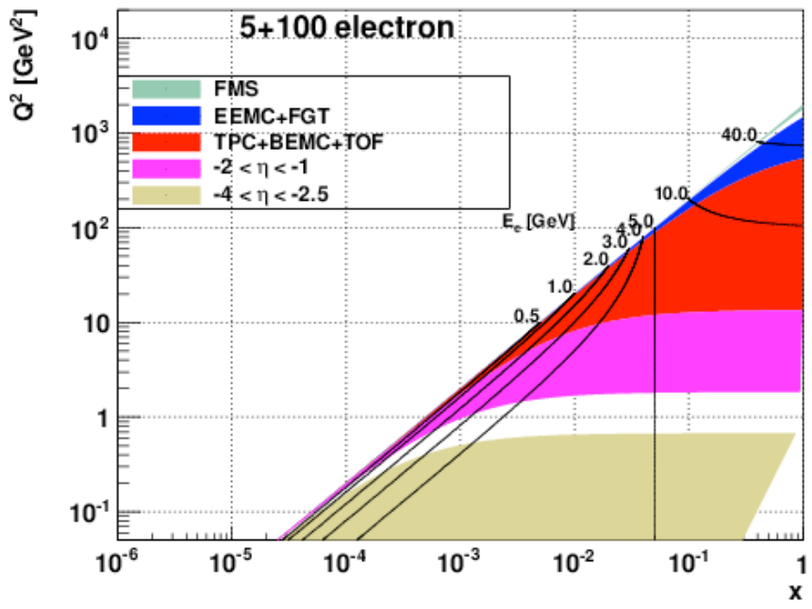

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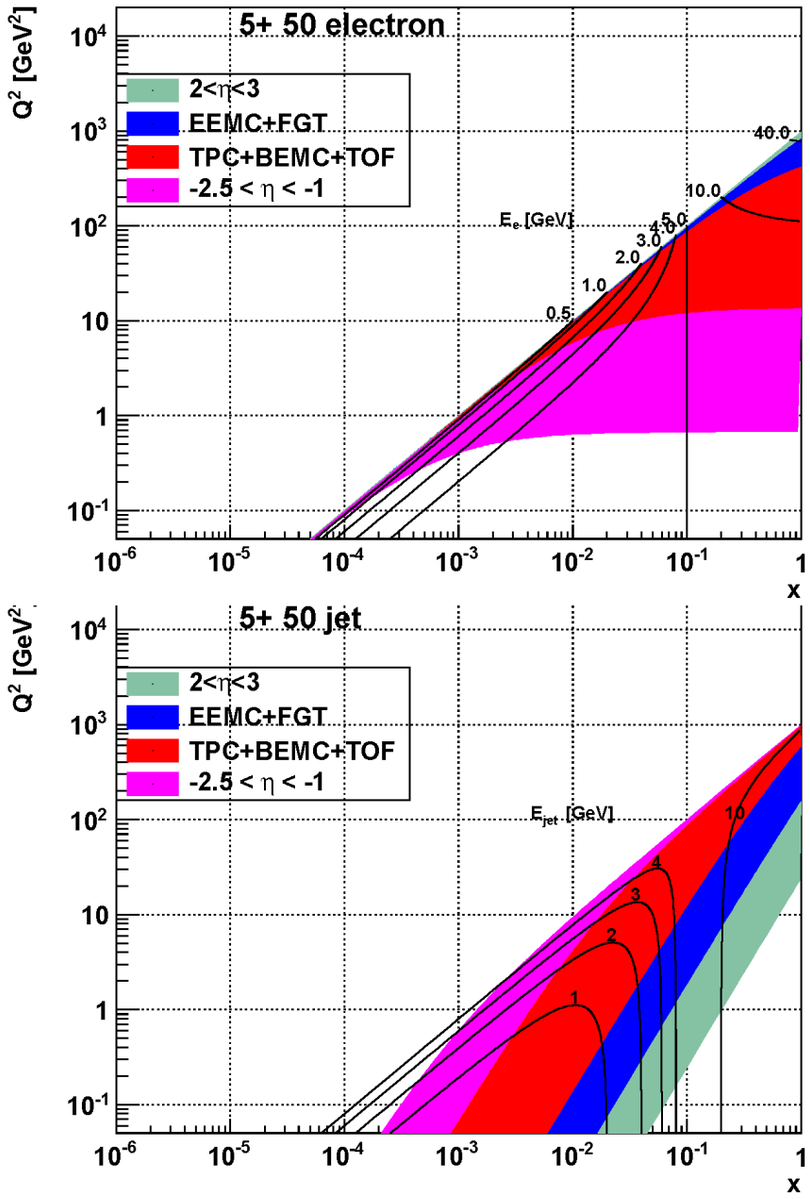
eSTAR kinematics in phase 1: 5 GeV electrons

DIS region → SIDIS region →

5 GeV e + 50 GeV/nucleon



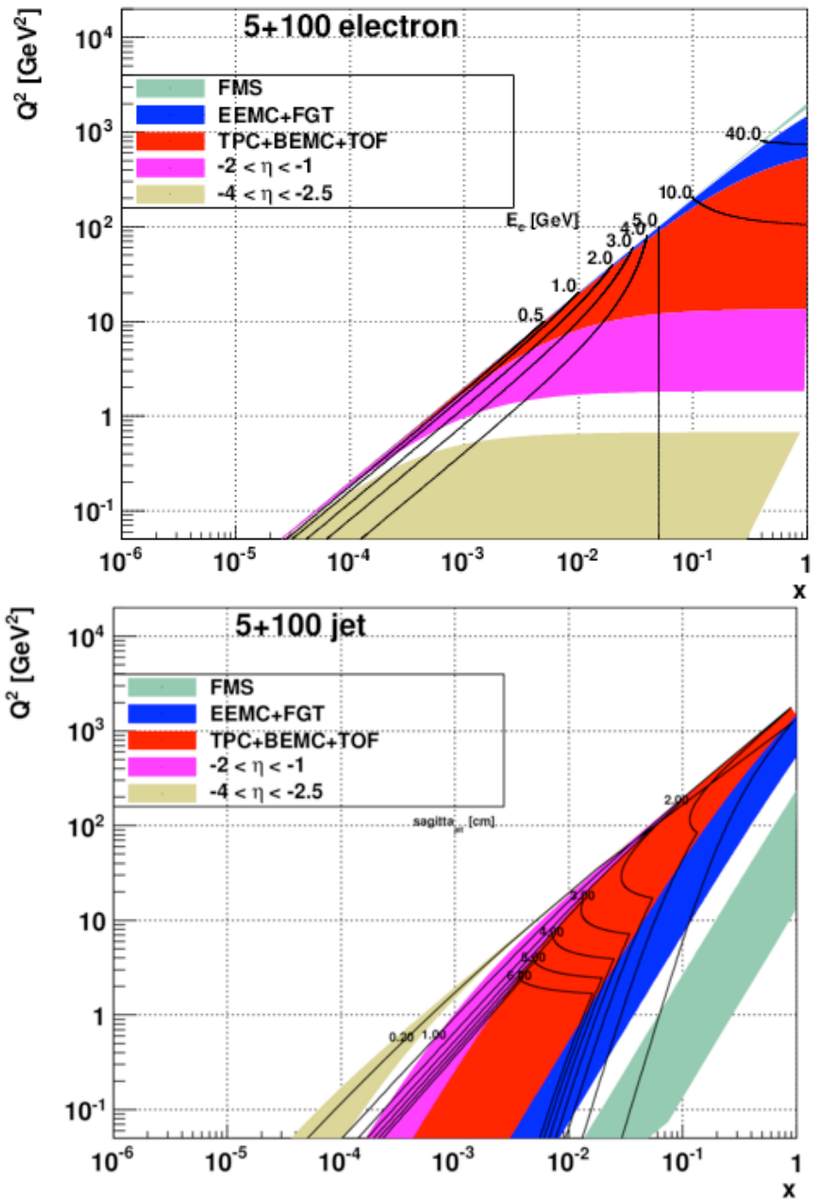
TPC

Missing today

EEMC

Missing today

5 GeV e + 100 GeV/nucleon



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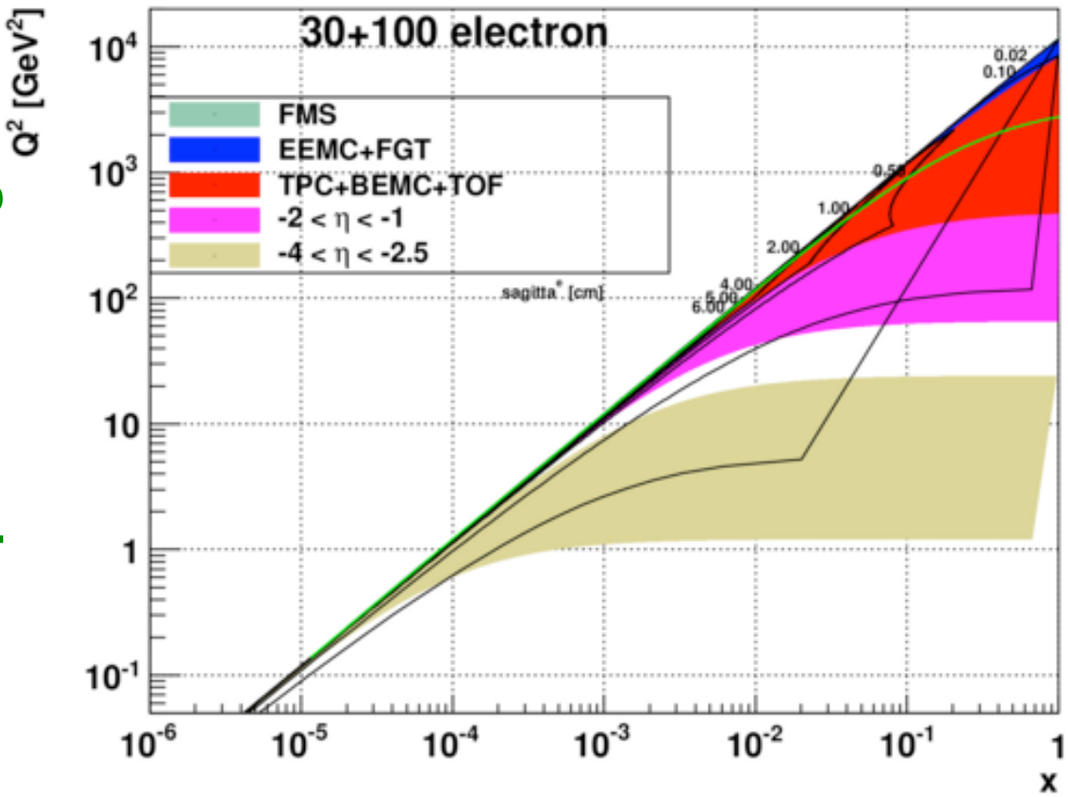
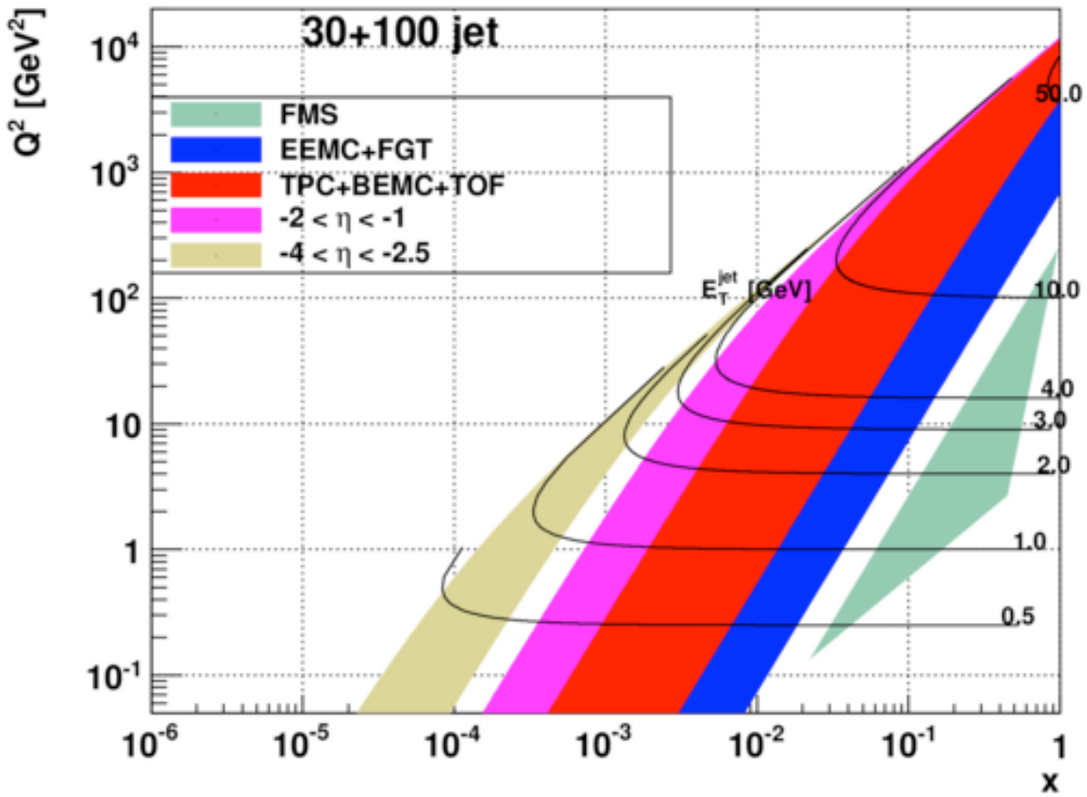
eSTAR kinematics in phase-II: 30 GeV electrons

DIS region



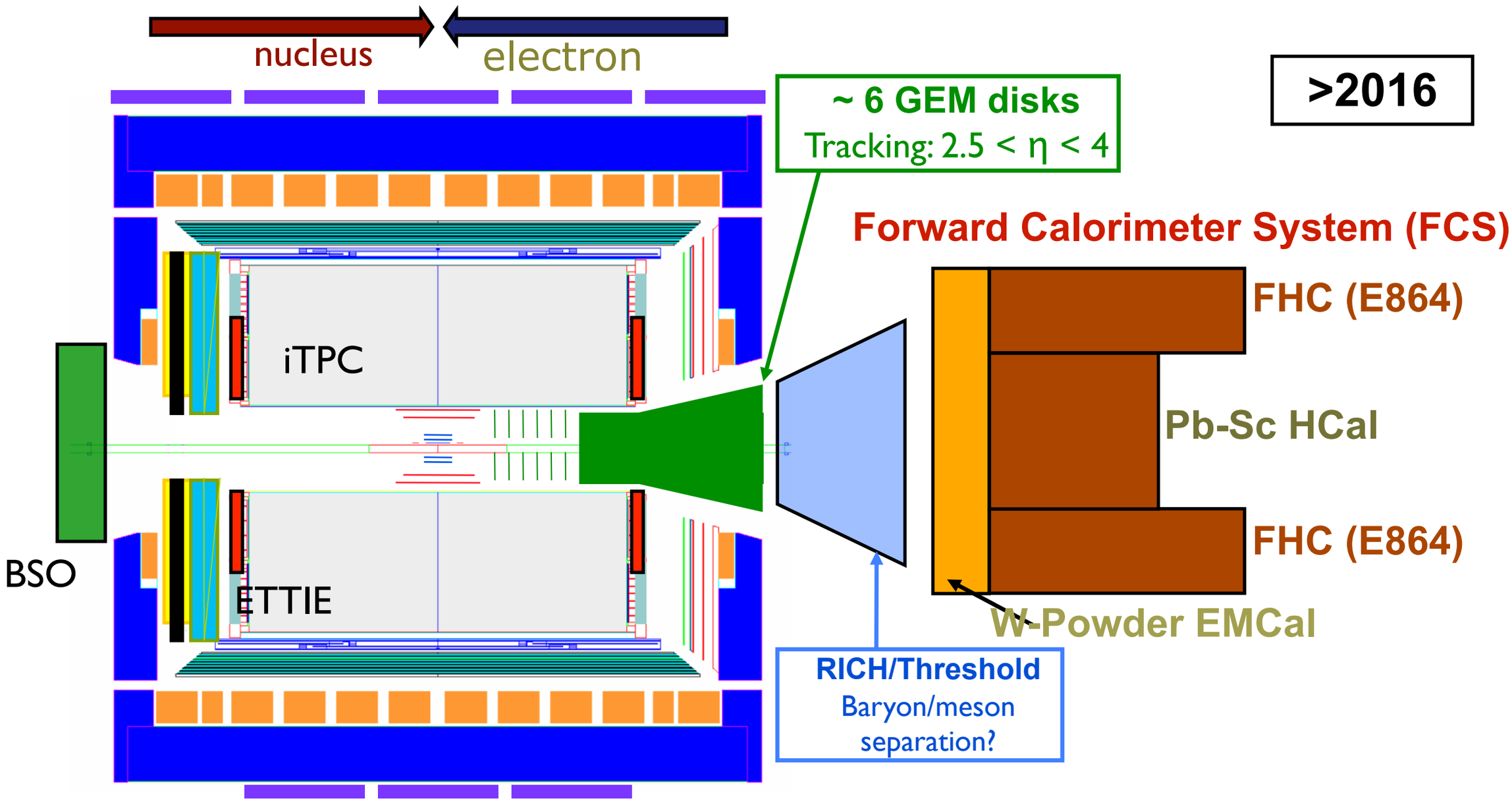
SIDIS region



- With 30 GeV electrons, need very forward coverage
- eSTAR is unsuitable for this energy regime

➡ Will need a fully comprehensive detector, which eSTAR can complement in the first phase.

STAR forward instrumentation upgrade



eSTAR specific upgrades:

ETоF: e, π, K identification,
ETRD: electron ID and hadron tracking
BSO: 5 GeV, 10 GeV electron beams
Re-instrument HFT

- **Forward instrumentation optimized for p+A and transverse spin physics**
  - **Charged-particle tracking**
  - ***e/h* and γ/π⁰ discrimination**
  - **Baryon/meson separation**

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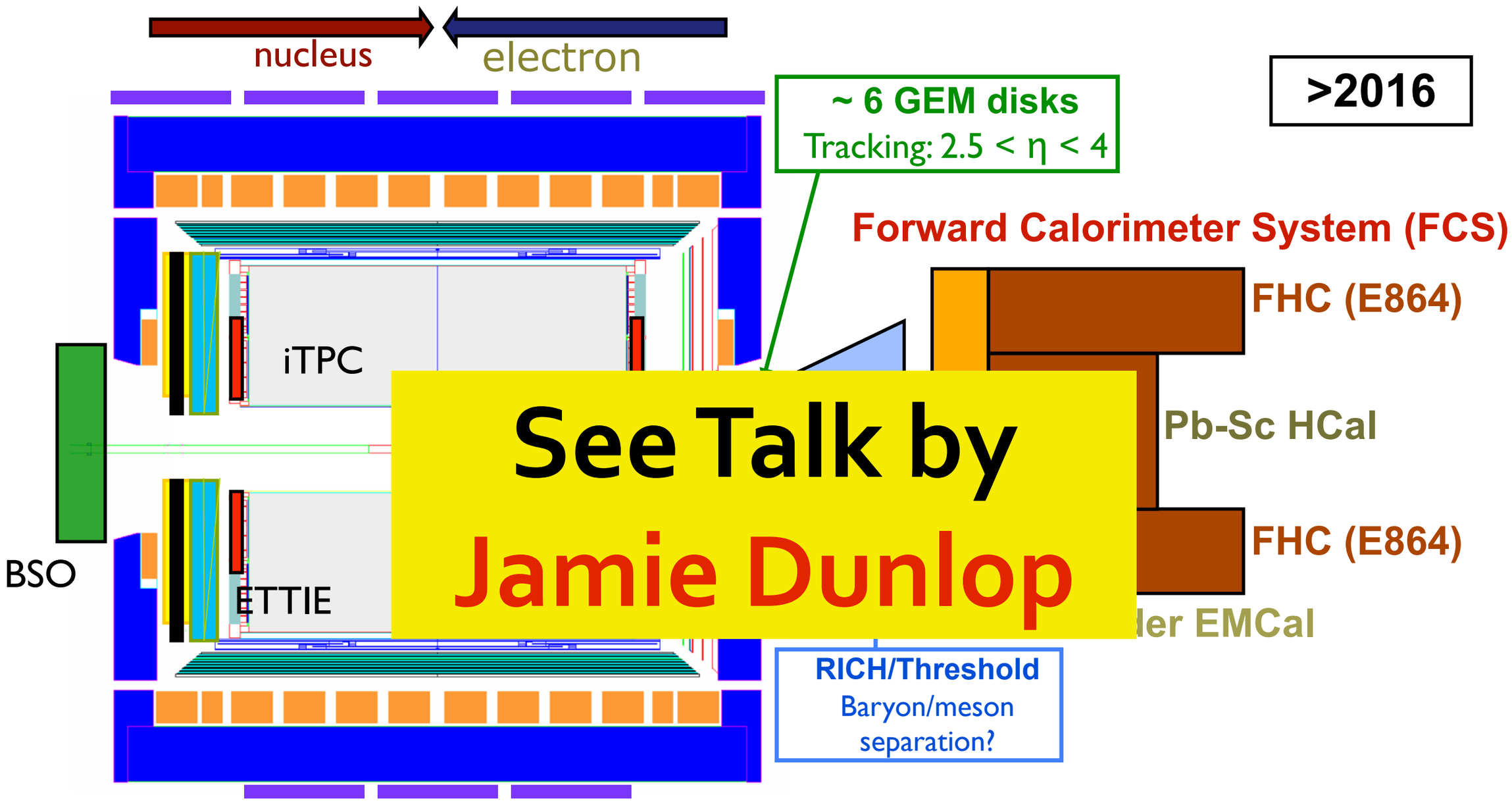

See Talk by Jamie Dunlop

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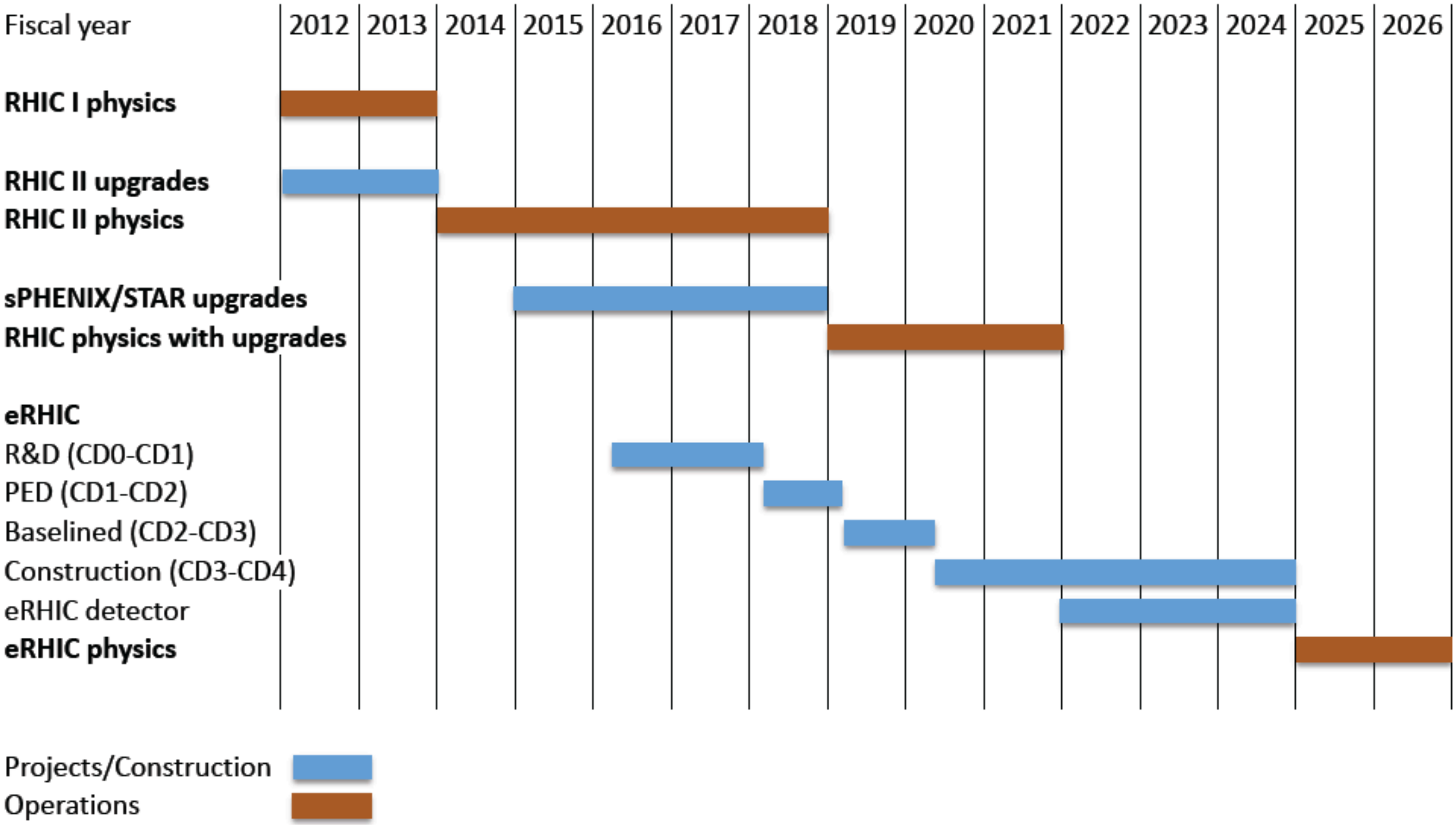
Possible Schedule To Realise eRHIC



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
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entire science programme is uniquely tied to a future high-energy electron-ion collider never been measured before & never without

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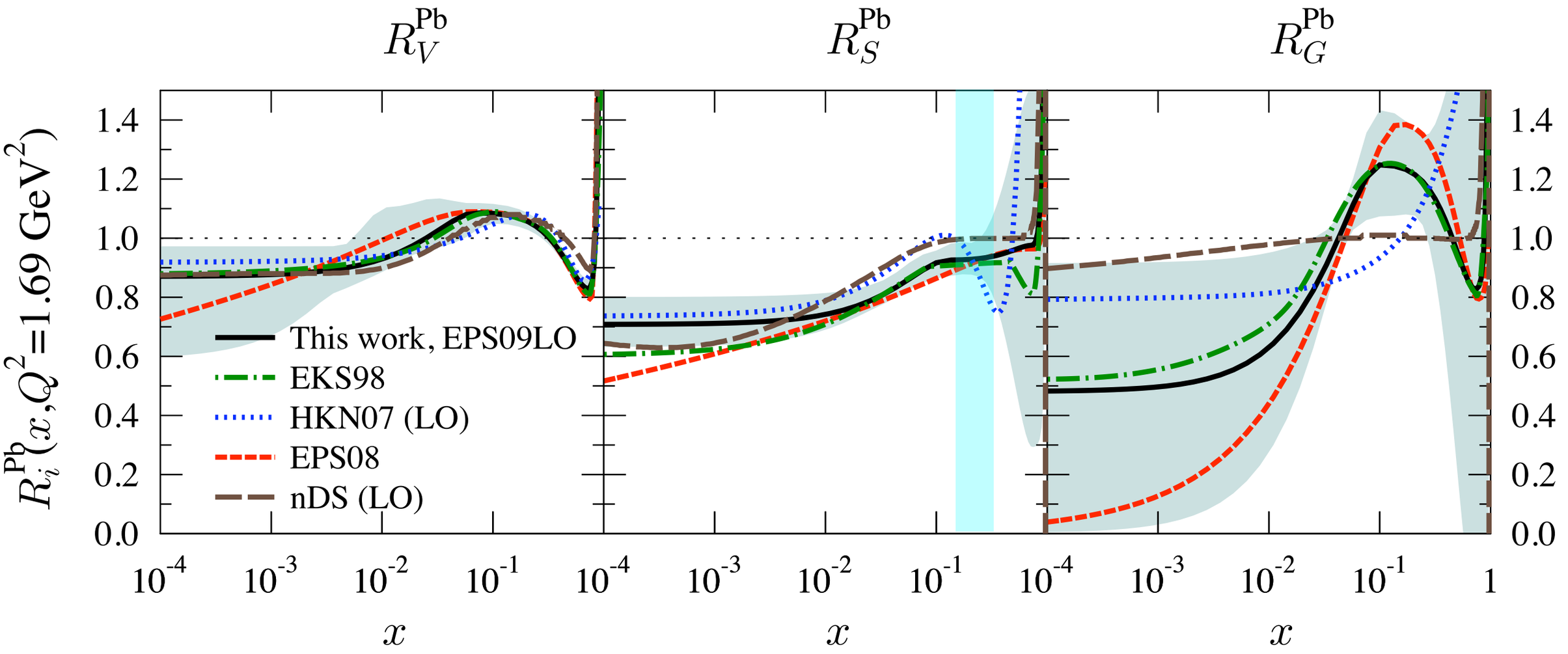
BACKUP

What do we know about the structure of nuclei?



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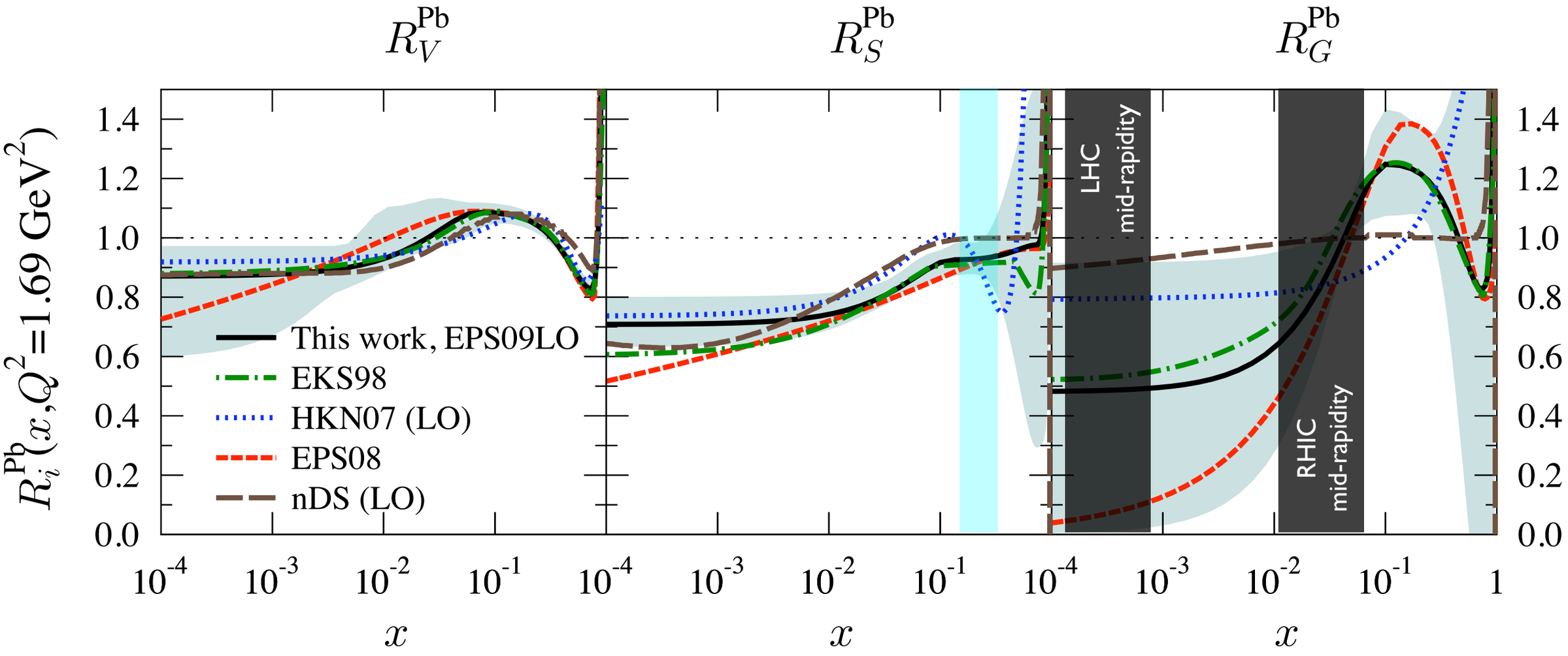


The distribution of valence and sea quarks are relatively well known in nuclei - theories agree well

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

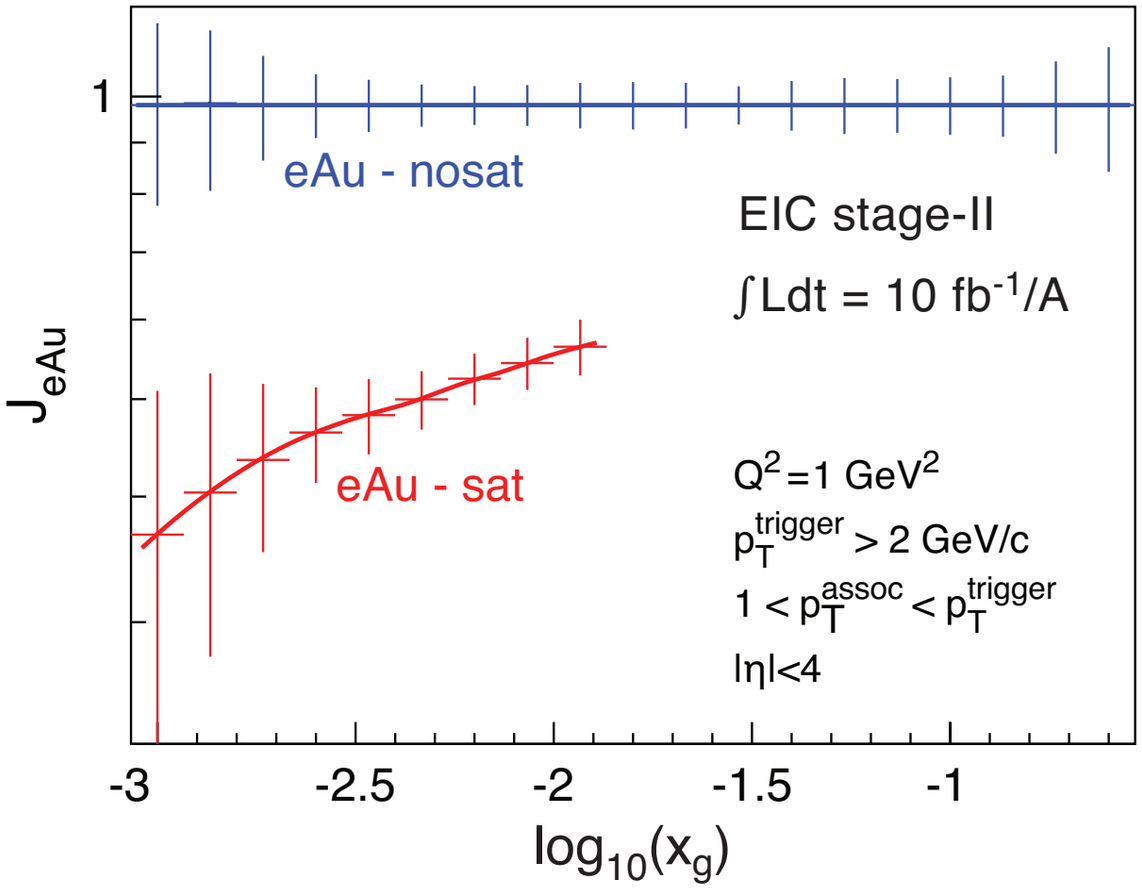
di-hadron Correlations - relative yields

- PHENIX measured J_{dAu} - relative yield of di-hadrons produced in d+Au compared to p+p collisions

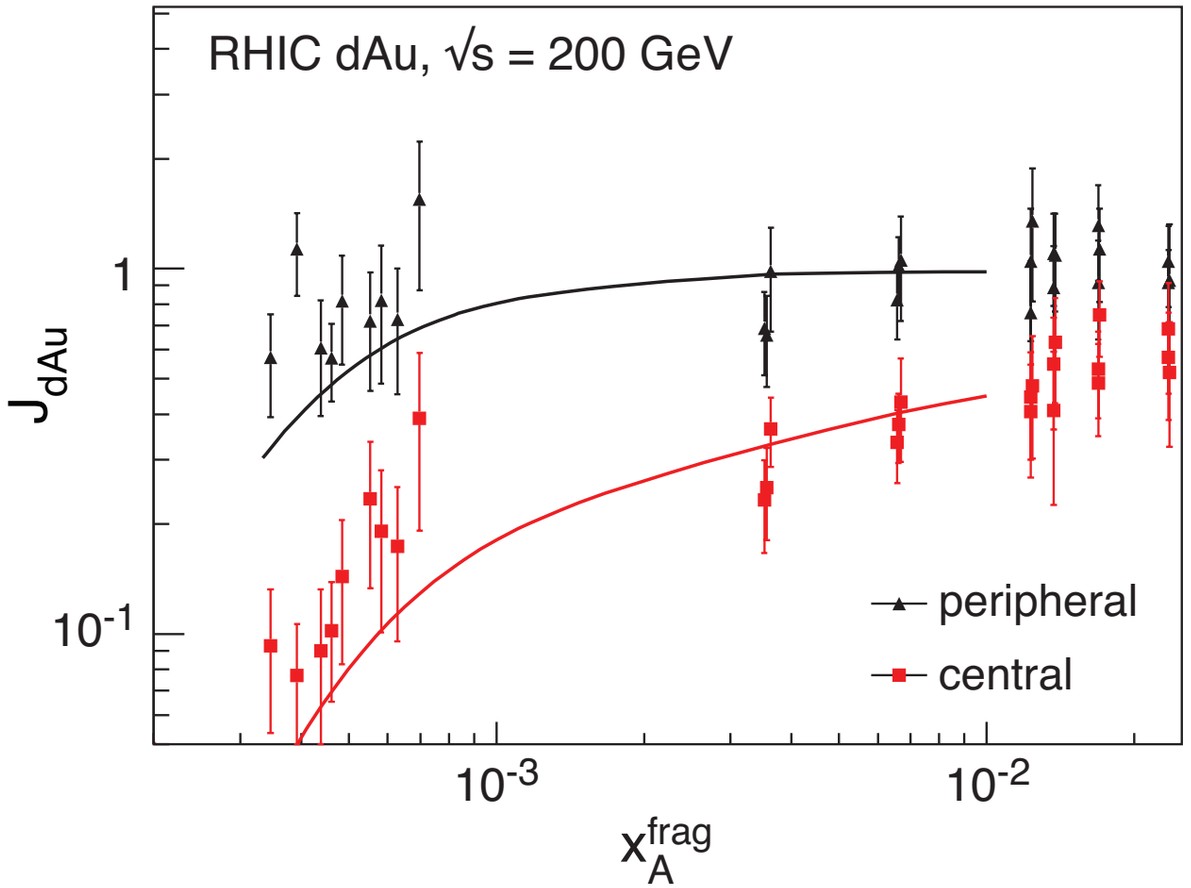
➡ Suppression in central events compared to peripheral as a function of x_A^{frag}

- Curves come from saturation model

- Can perform the same measurement in e+A collisions

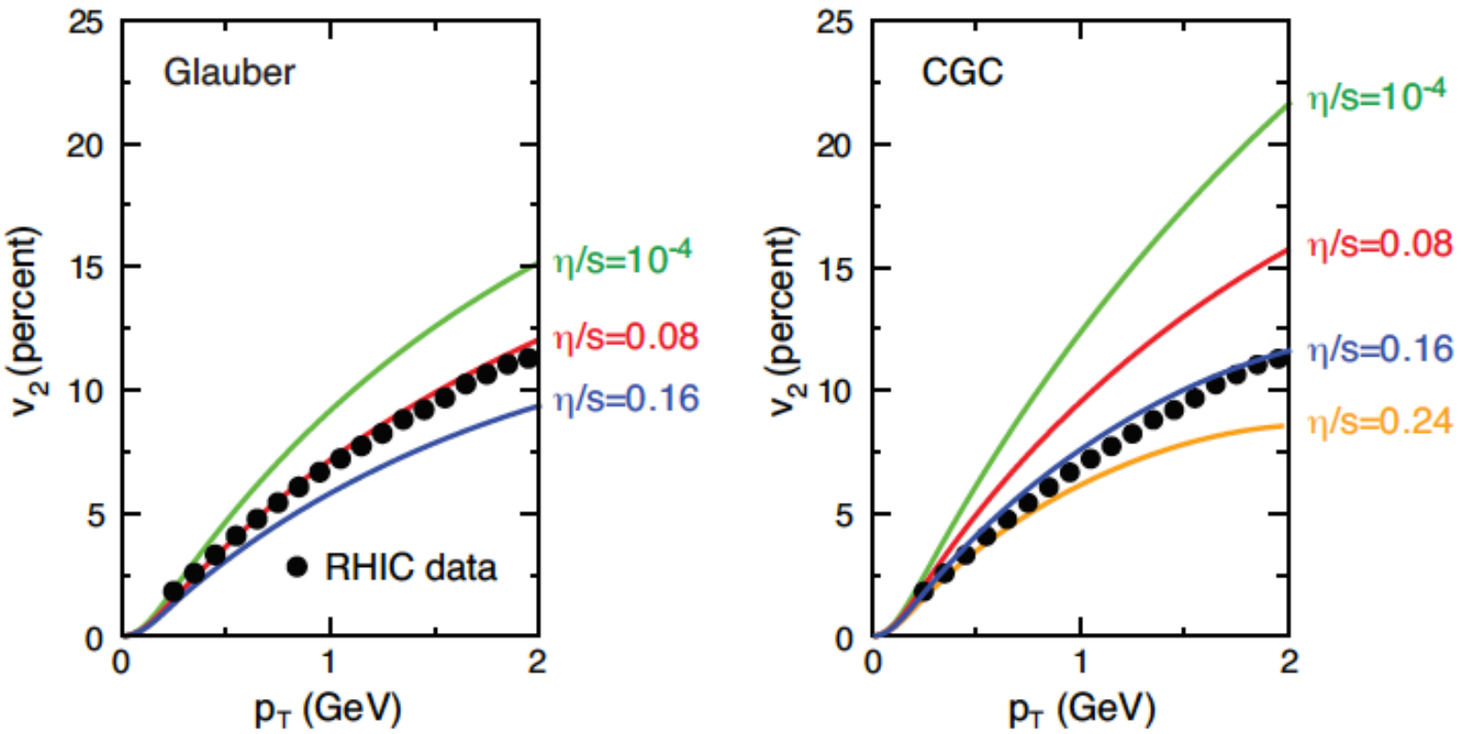


forward-forward mid-forward



A. Adare et al., Phys. Rev. Lett. 107, 172301 (2011)

Importance of the knowledge of the initial conditions



- A comparison of data and theoretical predictions using viscous hydro for $v_2^h(p_T)$ with Glauber initial conditions (left) and KLN CGC (right)
- The different assumptions in the initial conditions lead to a factor of 2 difference in the extracted η/s
- Figure adapted from: M. Luzum and P. Romatschke, Phys. Rev. C79, 039903 (2009)

Fundamental questions addressed via e+A collisions

- What is the role of strong gluon fields, parton saturation effects, and collective gluon excitations in nuclei?

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- Can we experimentally find evidence of non-linear QCD dynamics in high-energy scattering off nuclei?

  ➡ One of the main predictions of saturation is the x-dependence of DIS cross-sections and structure functions is described by non-linear evolution equations.

  - Discovery of the saturation regime would not be complete without unambiguous experimental evidence in favour of these non-linear equations

Fundamental questions addressed via e+A collisions

- What is the momentum distribution of gluons and sea quarks in nuclei?
  What is the spatial distribution of gluons and sea quarks in nuclei?

  ➡ The physics of multiple re-scatterings at larger-x, along with parton saturation (if found) would allow us to reconstruct the momentum and impact parameter distributions of gluons and sea quarks in nuclei.

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  - At small-x, the transverse momentum distribution may allow us to identify the saturation scale, Q_s.

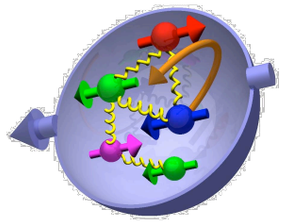
- Are there strong colour (quark and gluon density) fluctuations inside a large nucleus? How does the nucleus respond to the propagation of a colour charge through it?

  ➡ Our understanding of the spatial and momentum-space distributions of quarks and gluons would not be complete without understanding their fluctuations.

  - The typical size of colour fluctuations can be measured by sending a quark probe through the nucleus.
  - The conversion of the quark probe into a hadron my be affected by the nuclear environment, giving us a better understanding of the process.

Most compelling physics questions

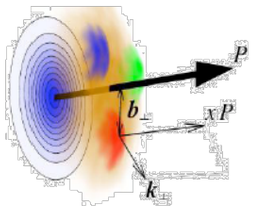
Spin physics



- 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!!

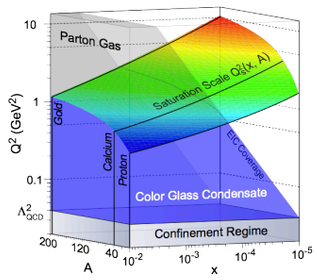
Imaging

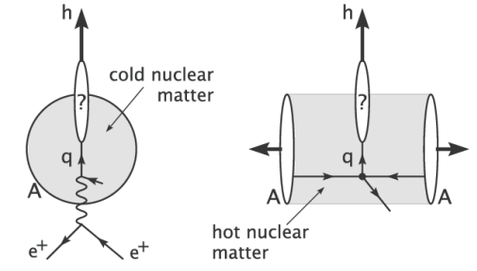


- What is the spatial distribution of quarks/ gluons in nucleons AND nuclei?
- Understand deep aspects of gauge theories revealed by k_T dependent distributions

Possible window to orbital angular momentum

Strong Colour Fields and Hadronisation

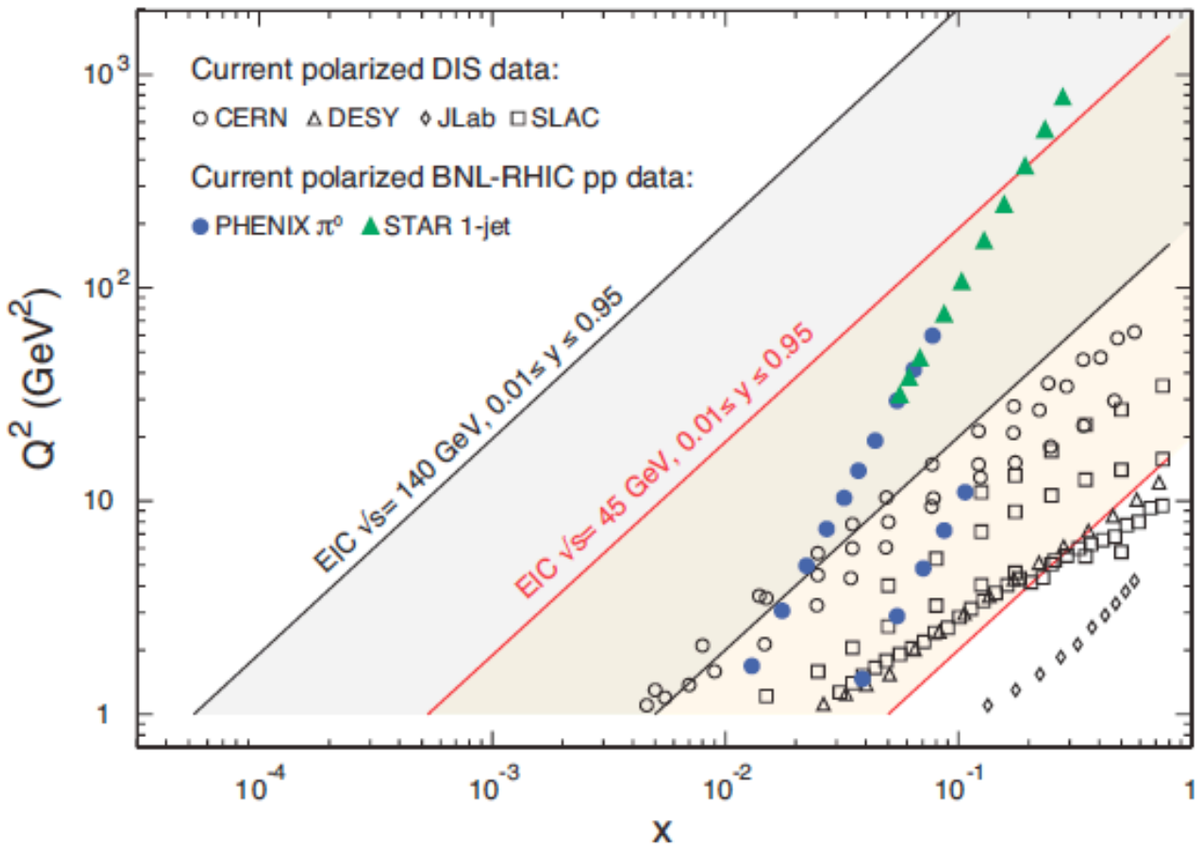


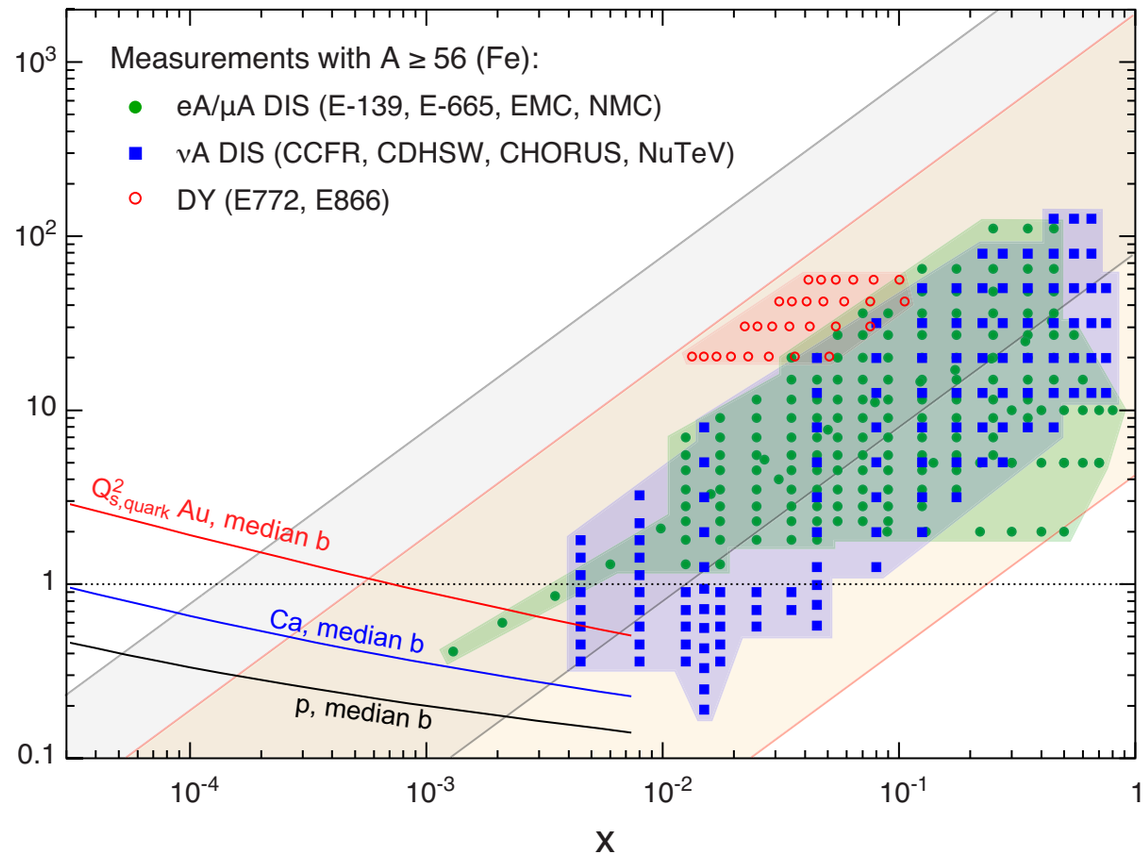


- Quantitatively probe the universality of strong colour fields in A+A, p+A and e+A
- Understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- How do hard probes in e+A interact with the medium?

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

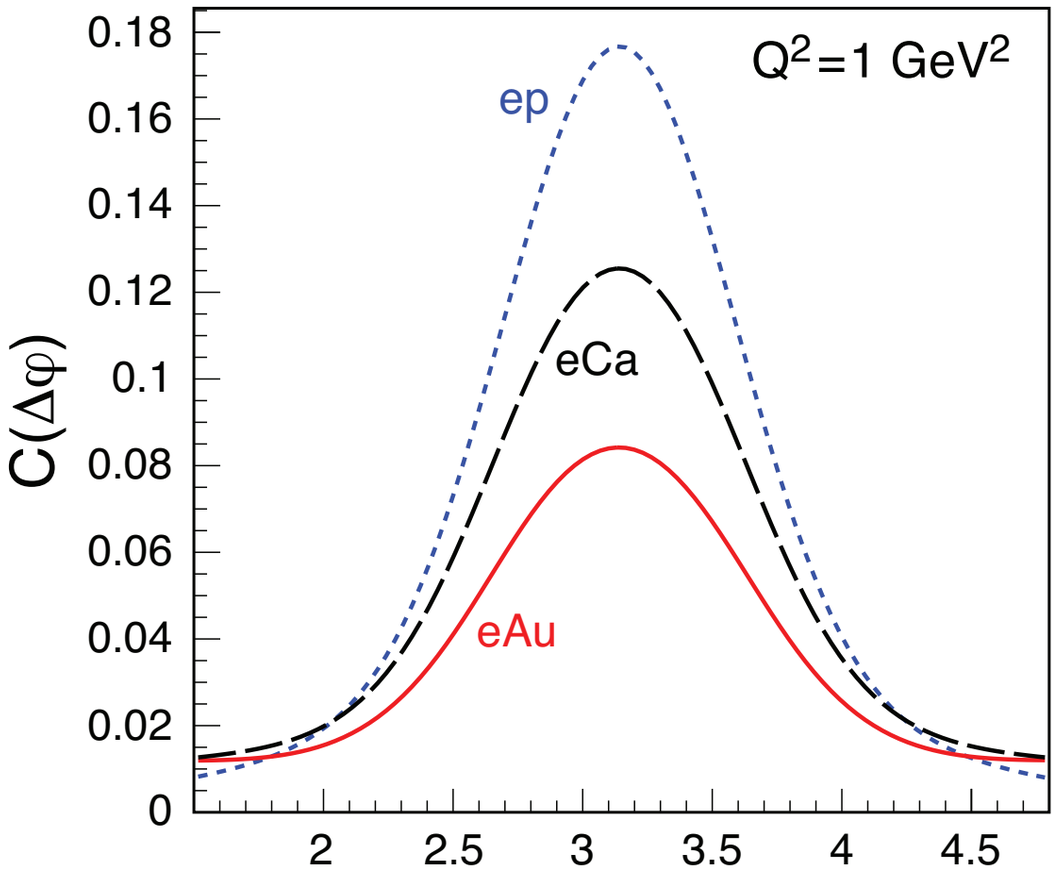
Extension of x,Q^2 coverage with an EIC





- Increase reach in x by a factor of 100 in both polarised e+p and e+A - into the range where gluons dominate
  - ➡ e+p: constrain the helicity sum rules?
  - ➡ e+A: saturation effects become visible?
- Increase in Q^2 coverage
  - ➡ study scaling violations

SIDIS in e+A → di-hadron correlations



Xiao, Yuang et al (private communication)

- Predictions from a saturation model show an ordered attenuation of the away-side with increasing nuclear mass

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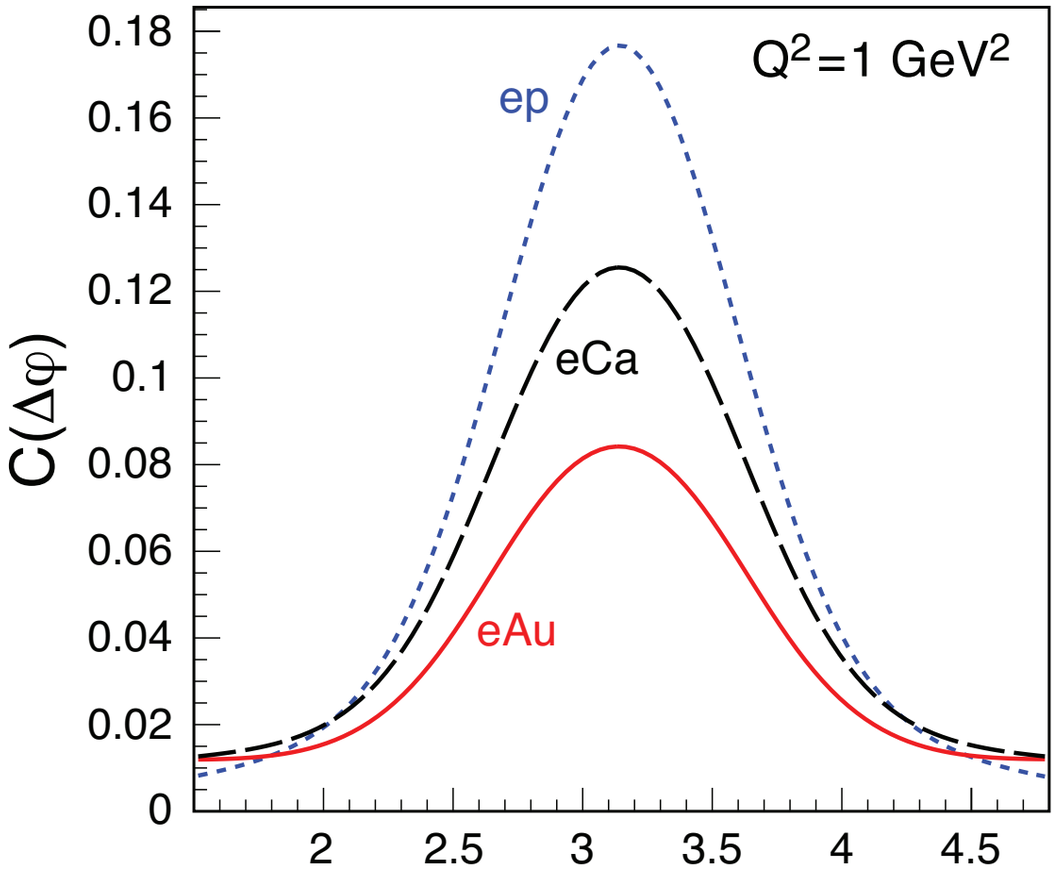

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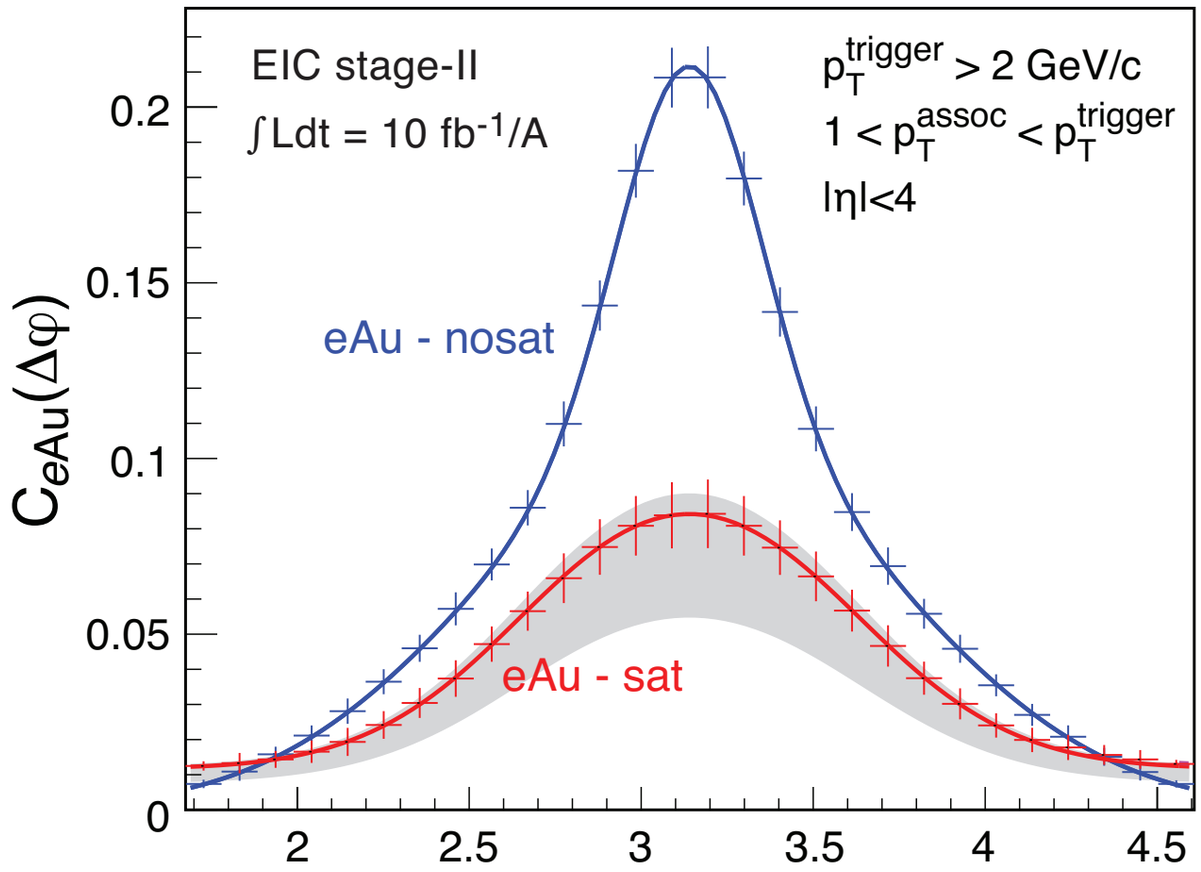


- Predictions from a saturation model show an ordered attenuation of the away-side with increasing nuclear mass
- Simulations (PYTHIA + DPMJETIII) for e+Au show that the sat/no-sat scenarios can be distinguished within errors

➡ Gives a handle on multi-gluon distributions

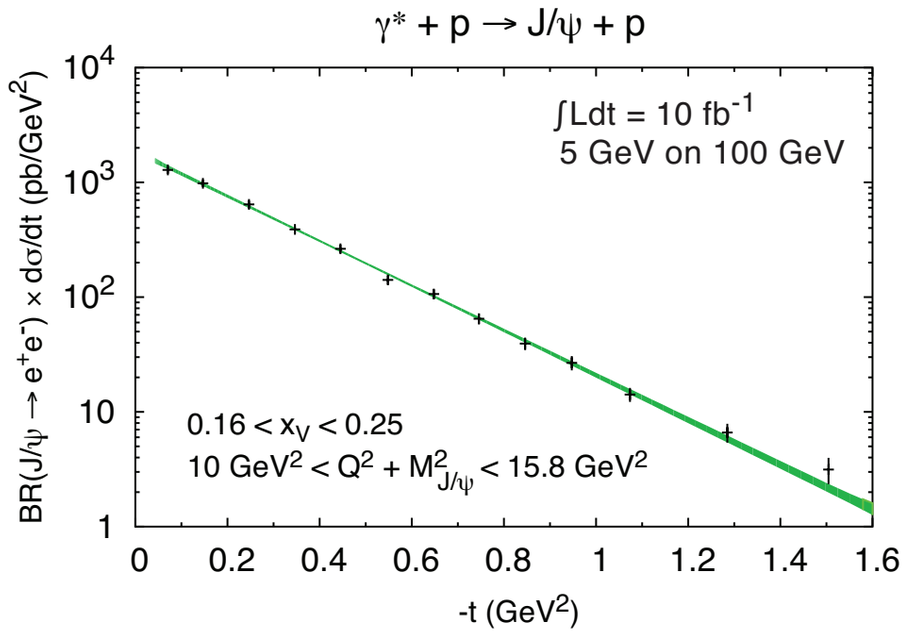
Imaging in e+p

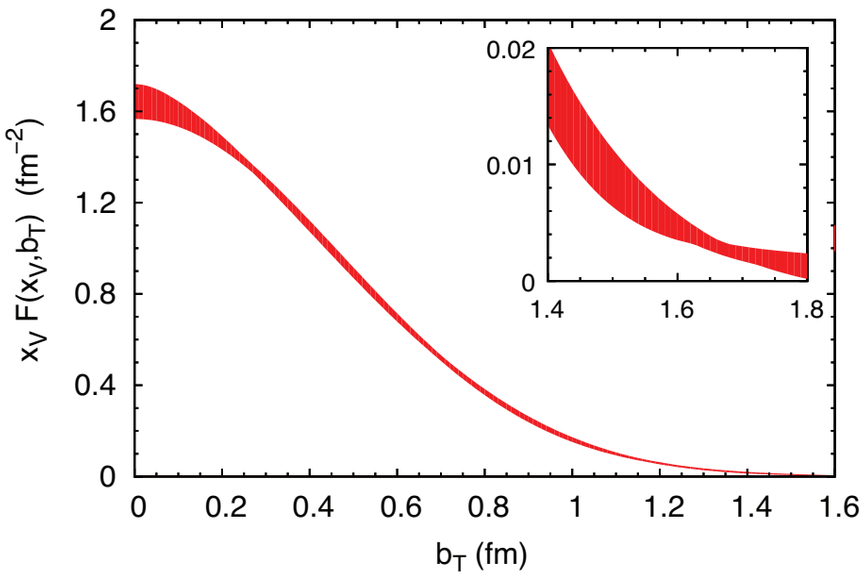
- As with e+A, exclusive measurements can be used to image momentum space (TMDs) or position space (GPDs)

- Fine binning in (x,Q^2,t) space

  ➡ Small statistical error bars in ~ 1 years running

- Fourier transform the momentum distribution to get the b-dependent gluon distribution





Imaging in e+p

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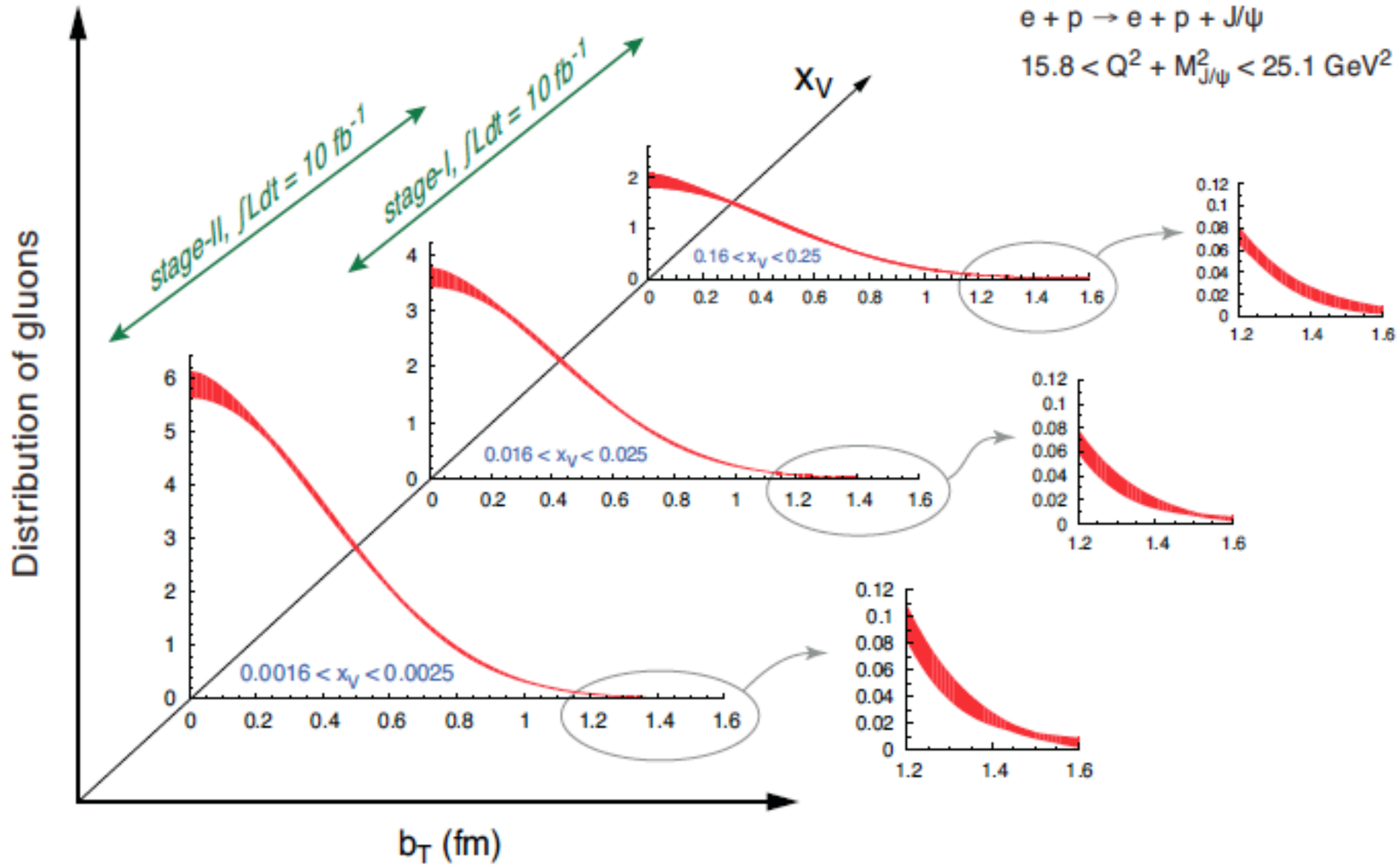
- Map out the x-dependence of the gluon distribution



Summary and Conclusions

- Both the e+A the e+p physics programmes at an EIC will give us a unique opportunity for precision studies of gluons in nuclei and nucleons
- e+A:
  - ➡ 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
- e+p:
  - ➡ Constrain $\Delta g(x)$ at small x along with the flavour-separated helicity PDFs
  - ➡ Imaging of the spatial and momentum gluon distributions in nucleons

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entire science program uniquely tied to a future high-energy electron-ion collider

never been measured before & never without

EIC White Paper

- 2010: Ten week INT programme on “Gluons and the quark sea at high energies”

  ➡ 550 page proceedings on the ArXiv: http://arxiv.org/abs/1108.1713

- 2012: White paper released to community

  ➡ ~150 page document, recently released to the community

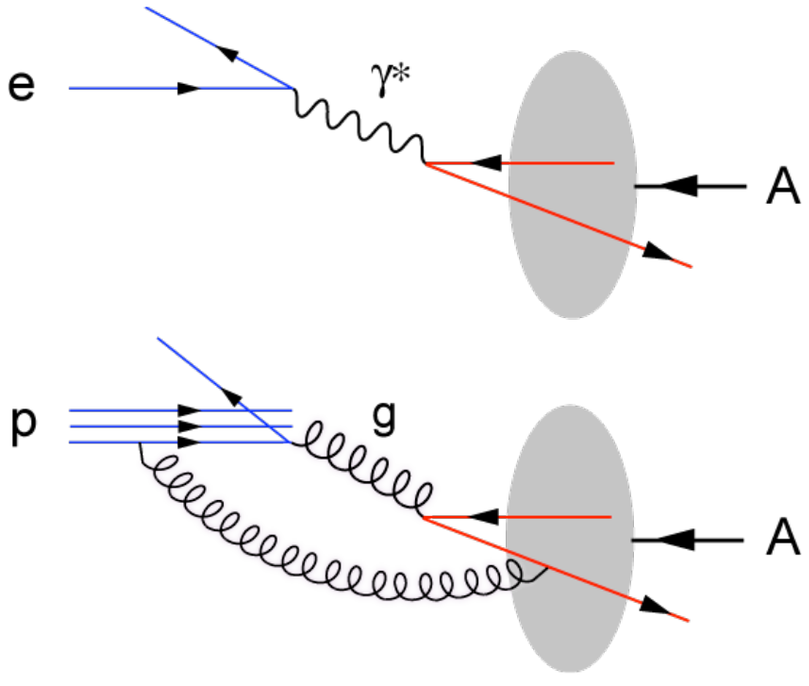
  ➡ http://www.bnl.gov/rhic/eicrev/ch/ch-files/c1-c6.pdf

    - Simulations and other tasks identified in INT programme were performed for this document and presented in this talk

- Community input and comments requested by October 31st

Why *e*+A collisions and not p+A?

- e+A and p+A provide excellent information on properties of gluons in the nuclear wave functions
- Both are complementary and offer the opportunity to perform stringent checks of factorization/universality
- Issues:
  - ➡ p+A combines initial and final state effects
  - ➡ multiple colour interactions in p+A
  - ➡ p+A lacks the direct access to x, Q^2



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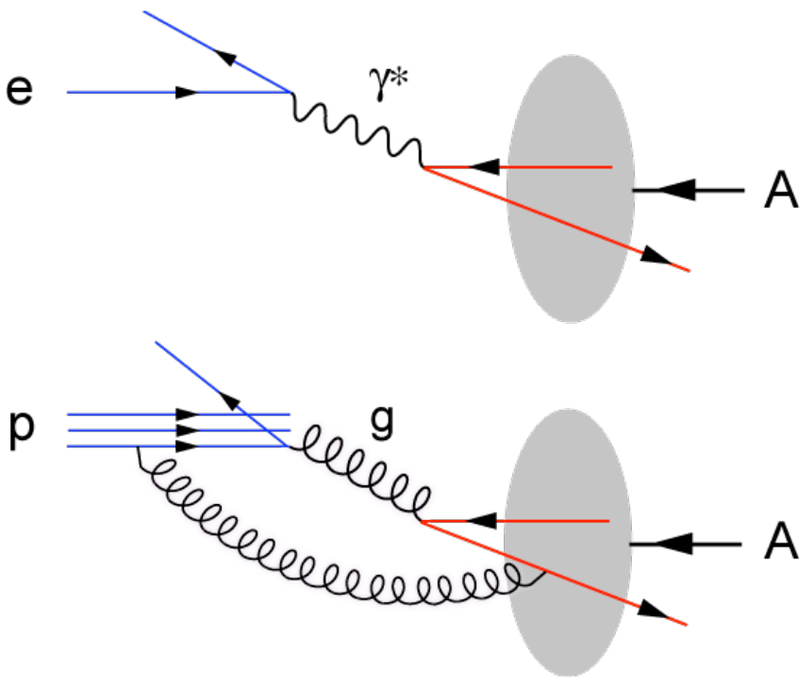
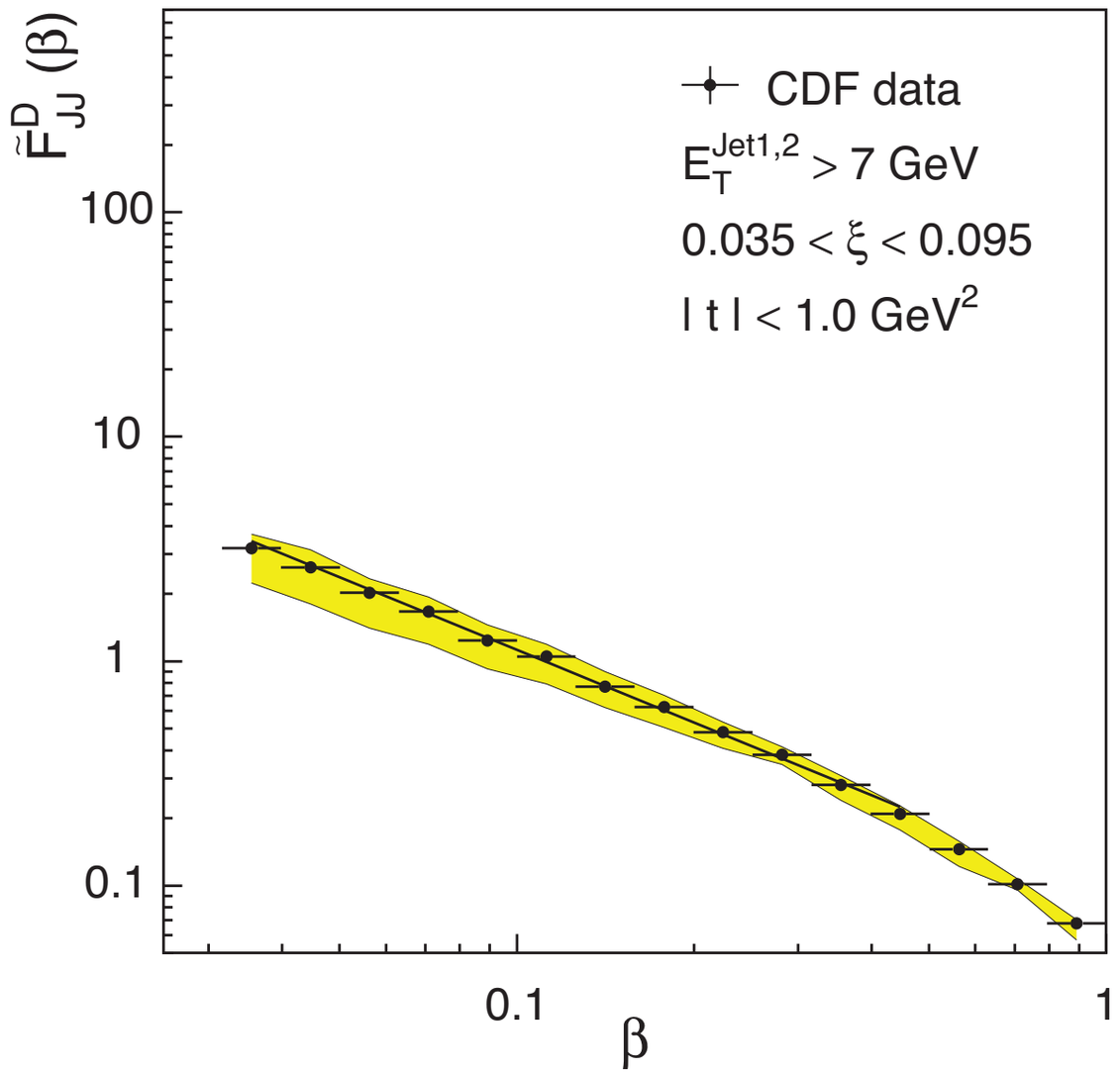


F. Schilling, hep-ex/0209001



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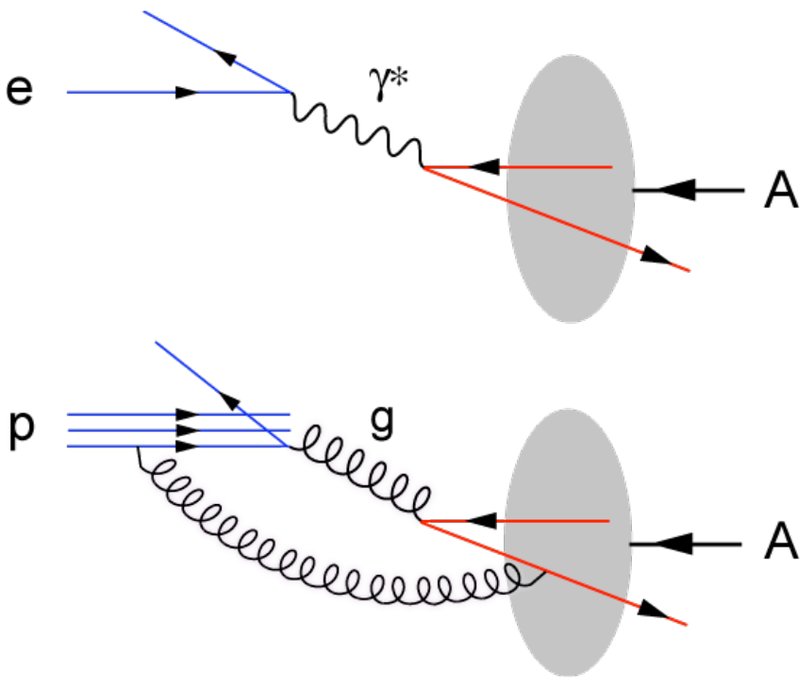

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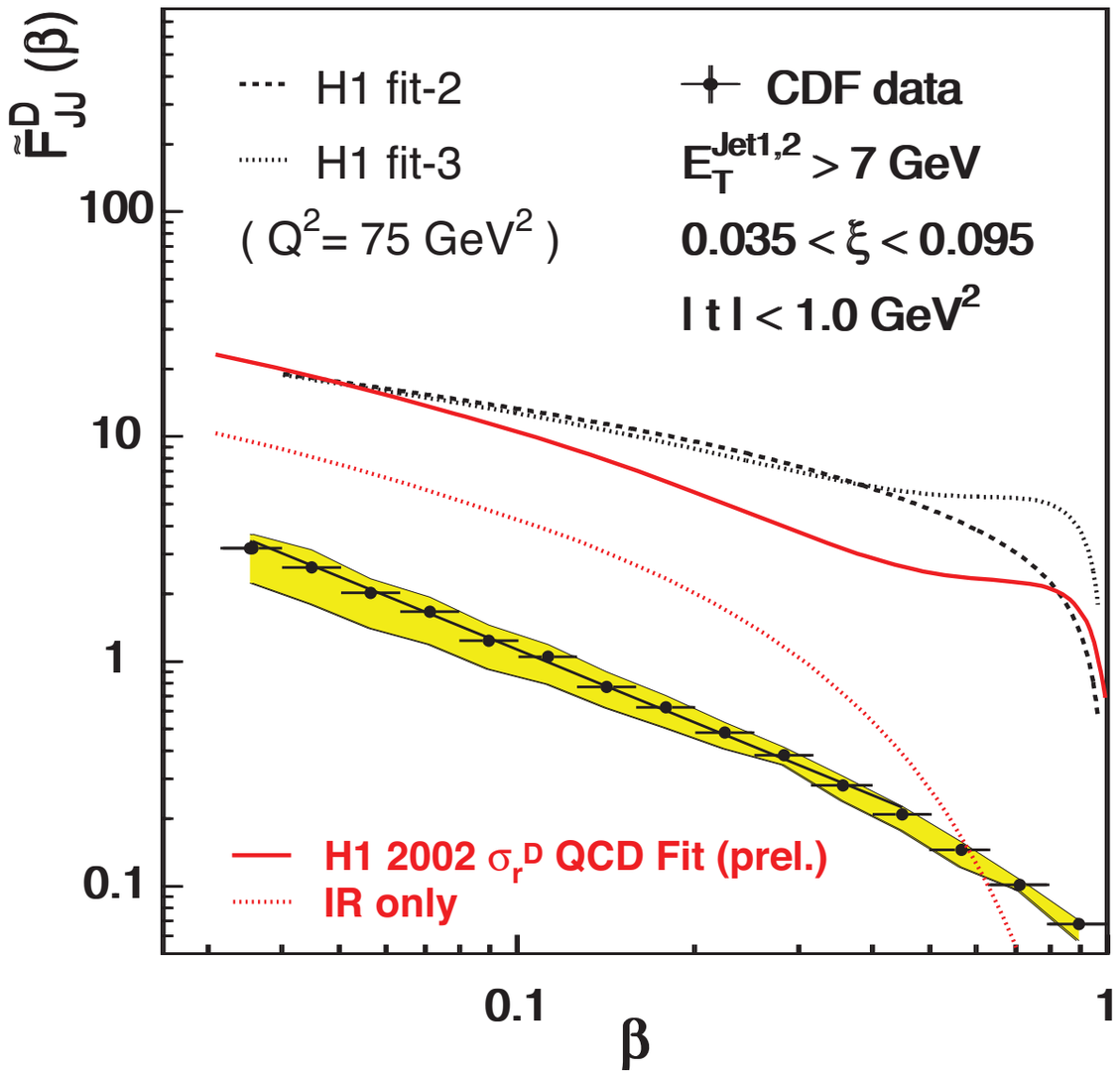

Breakdown of factorization (e+p HERA versus p+$\bar{p}$ Tevatron) observed for di-jets produced in diffractive collisions

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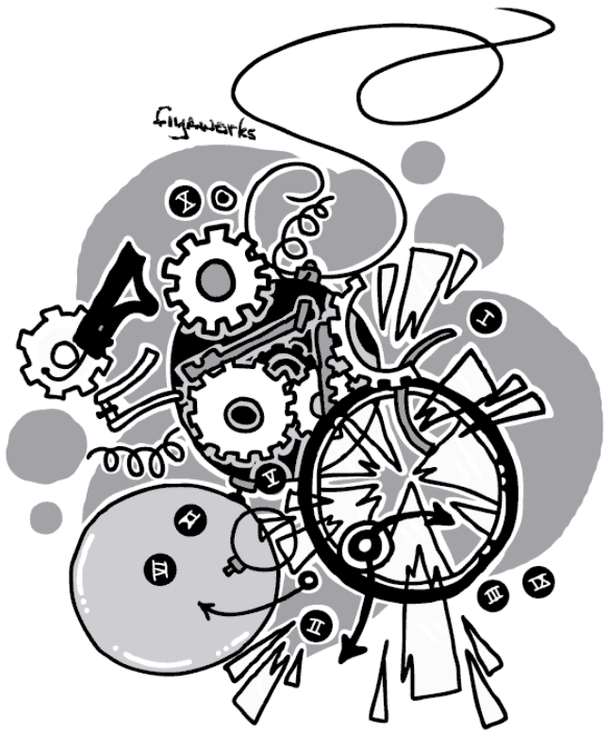
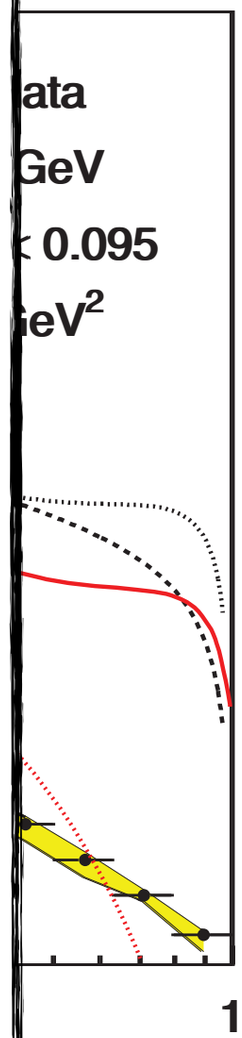
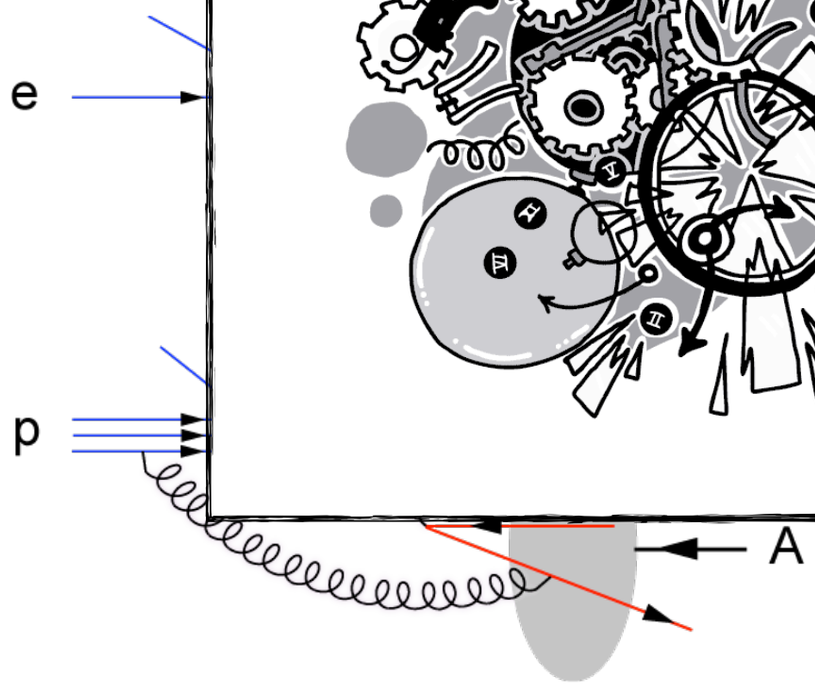
F. Schilling, hep-ex/0209001

Scattering of protons on protons
is like colliding Swiss watches to find out how they are built.



R. Feynman

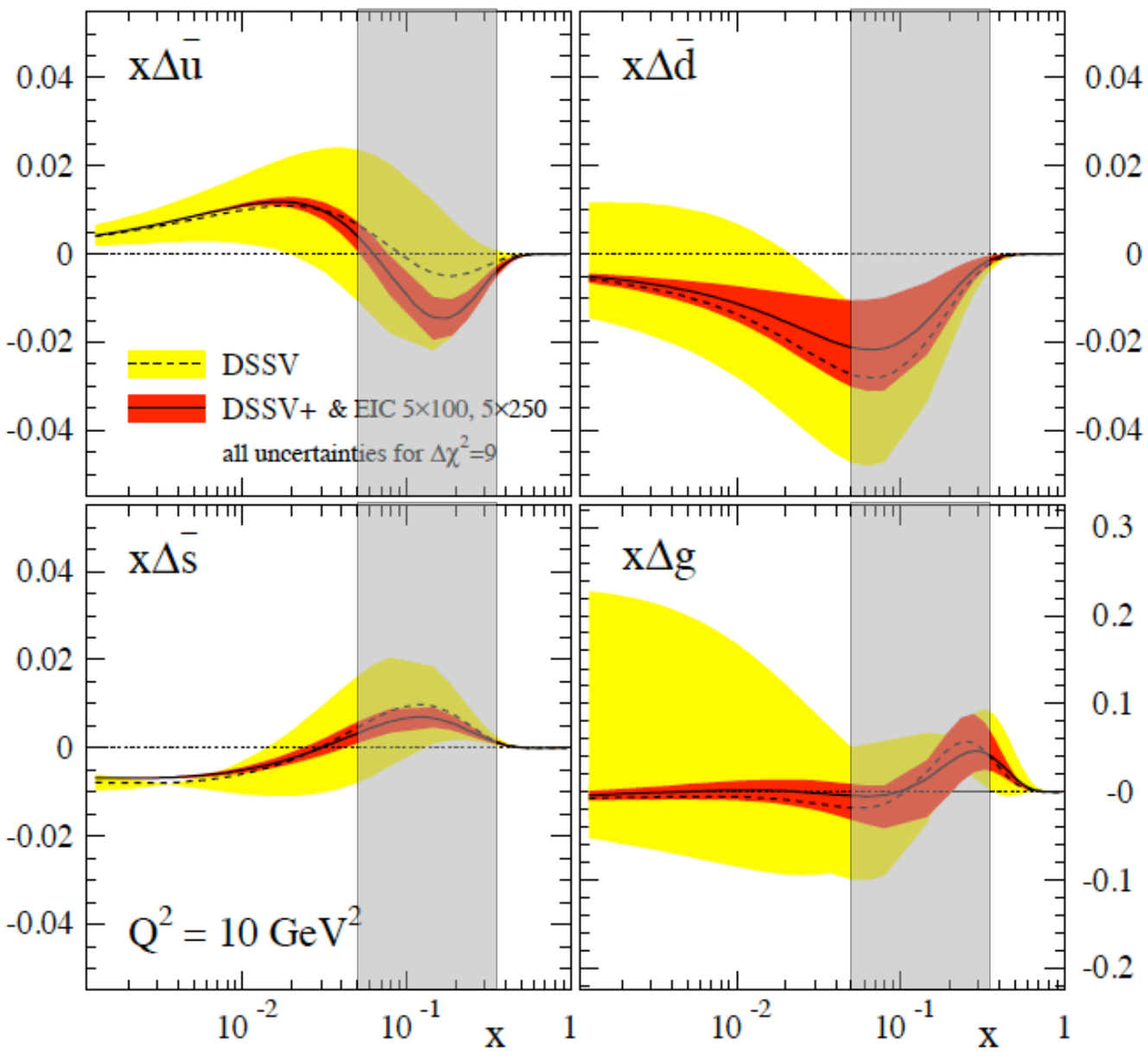




+*p* HERA
for di-jets
produced in diffractive collisions

SIDIS in e+p → flavour-separated helicity PDFs

- SIDIS measurements with identified π, k lead to much reduced uncertainties in the flavour-separated helicity PDFs as in Δg(x)



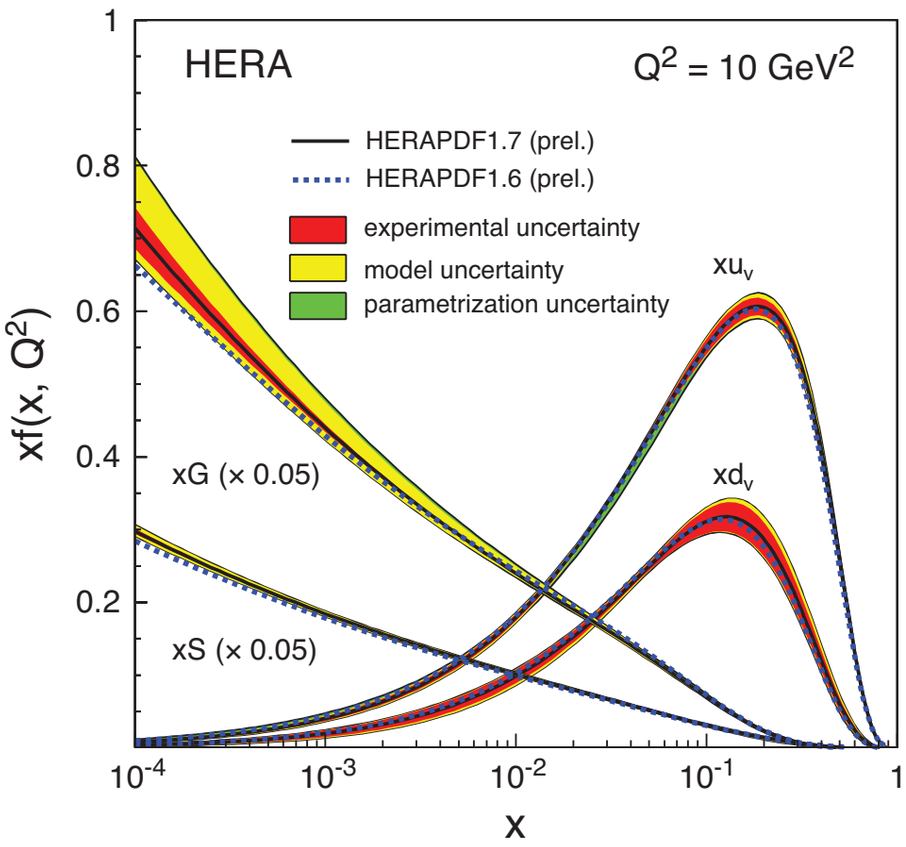
RHIC coverage

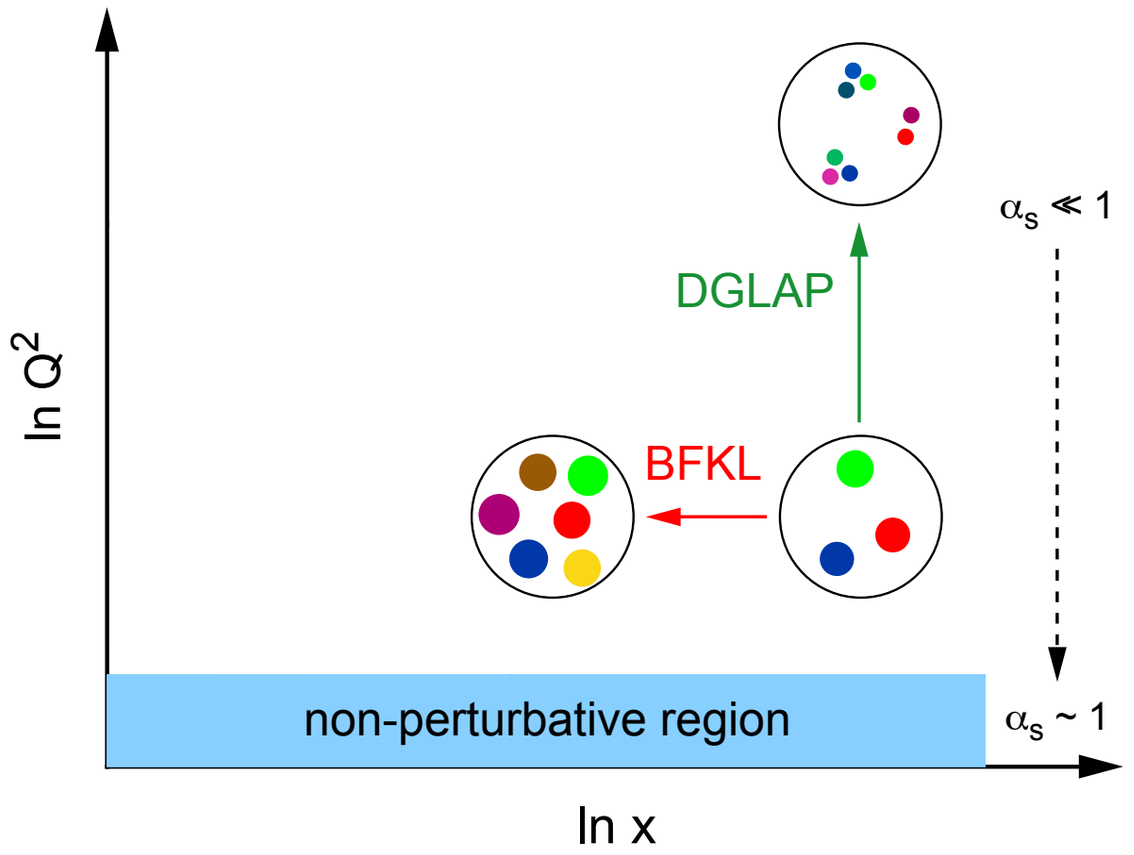
DSSV

DSSV + EIC (5x100, 5x250)

all uncertainties for $\Delta\chi^2=9$

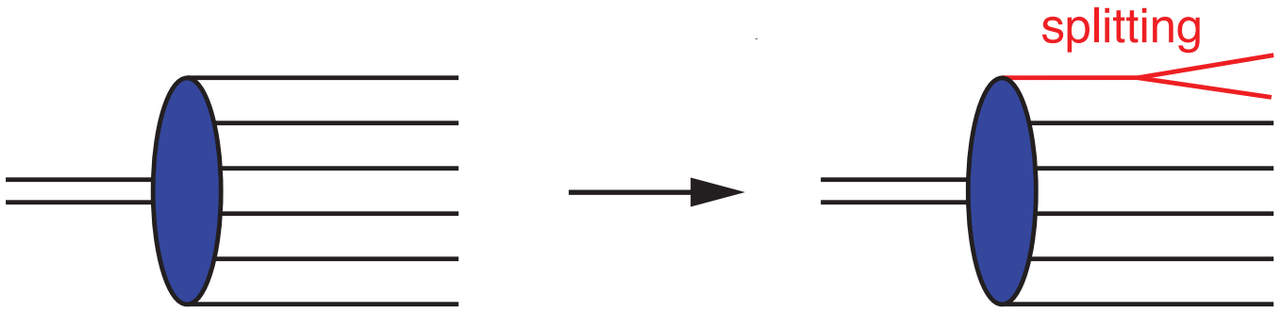
The structure of matter at small-x





- Gluons dominate the PDFs at small- to intermediate-x ($x < 0.1$)

➡ Rapid rise in gluons described naturally by linear pQCD evolution equations



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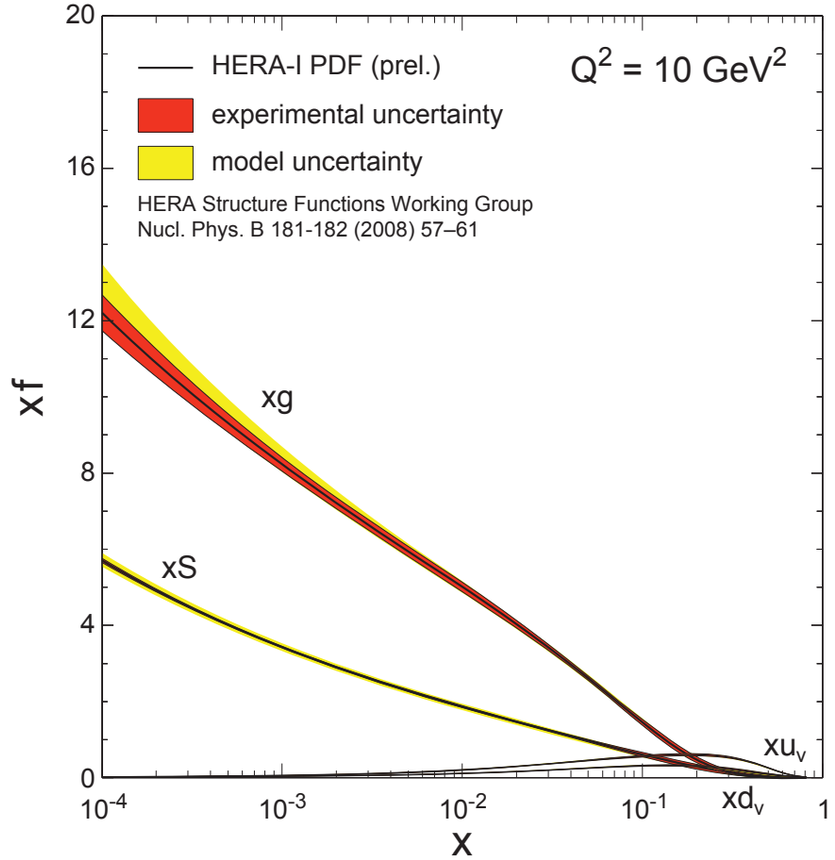

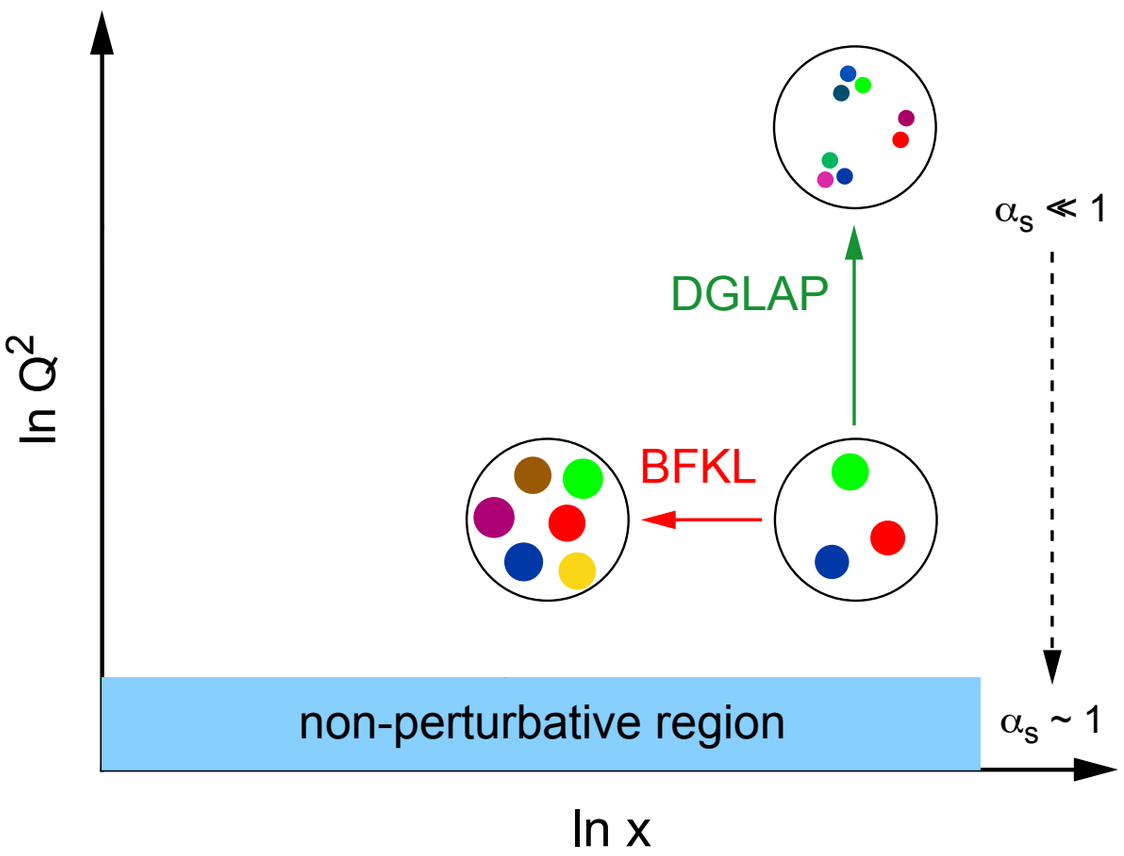

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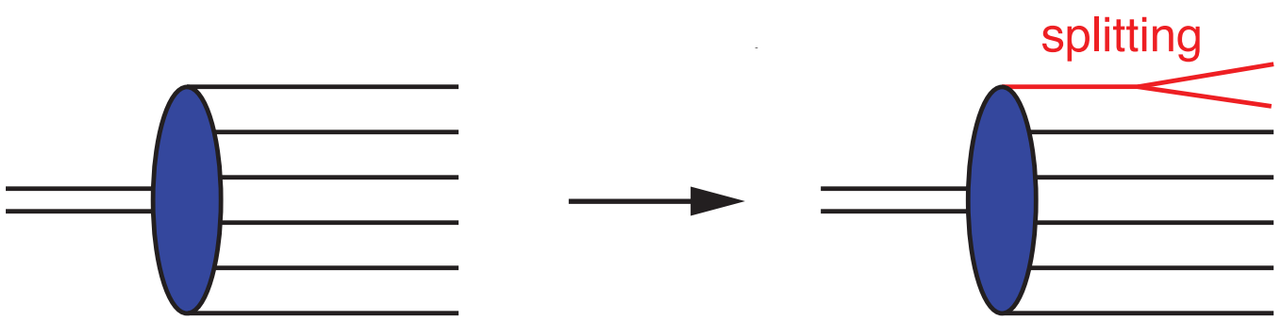

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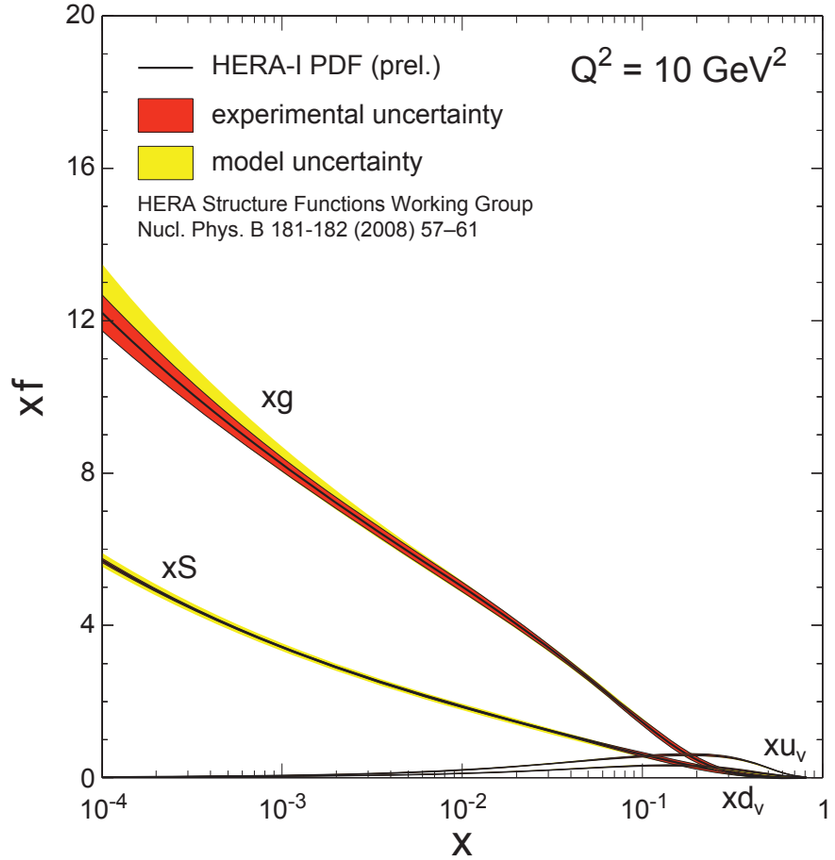
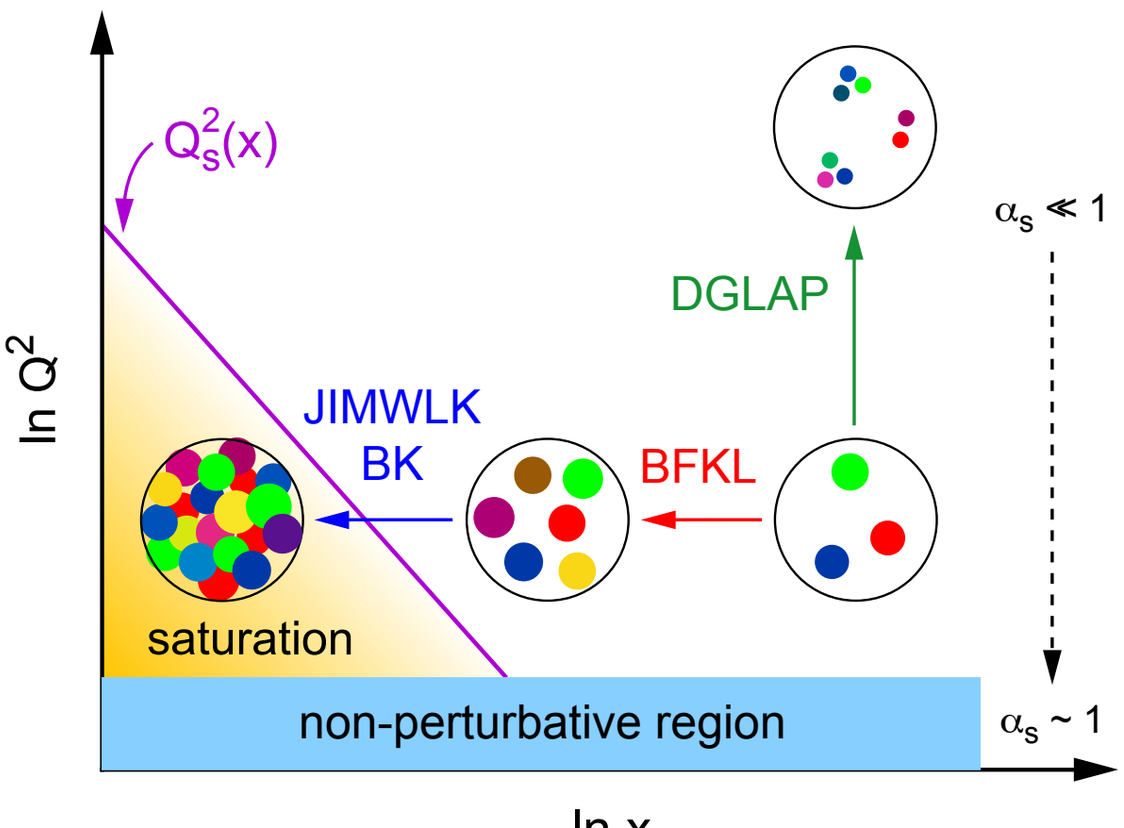
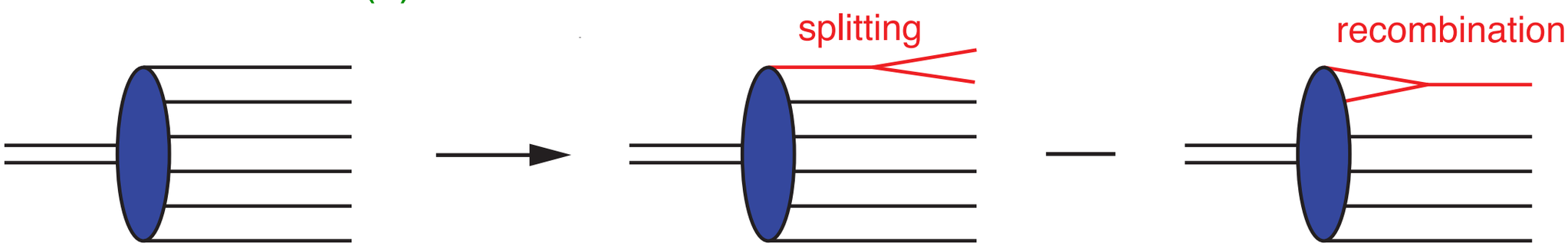
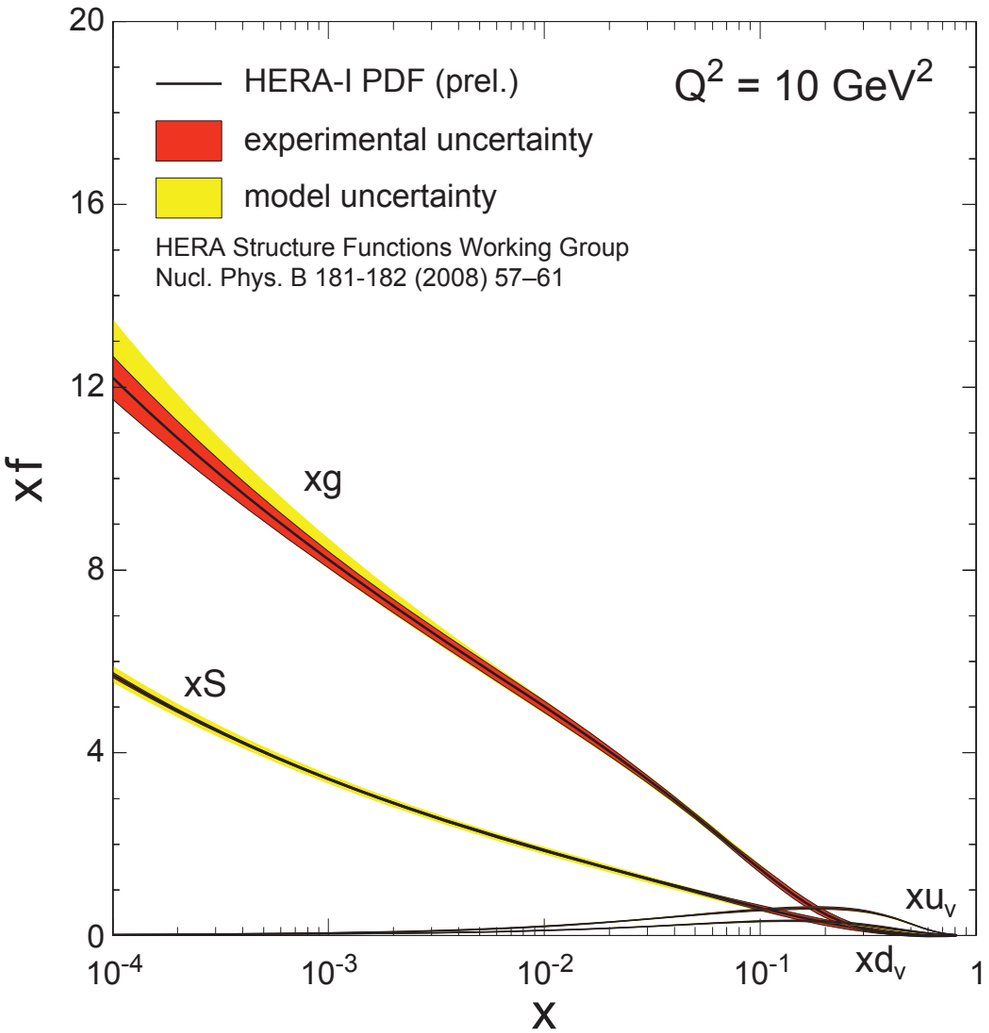




- Gluons dominate the PDFs at small- to intermediate-x ($x < 0.1$)
  - ➡ Rapid rise in gluons described naturally by linear pQCD evolution equations
  - ➡ This rise cannot increase forever - limits on the cross-section
    - ▸ non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterised by the saturation scale $Q^2_S(x)$



(Very) Brief Recap of Saturation at an EIC



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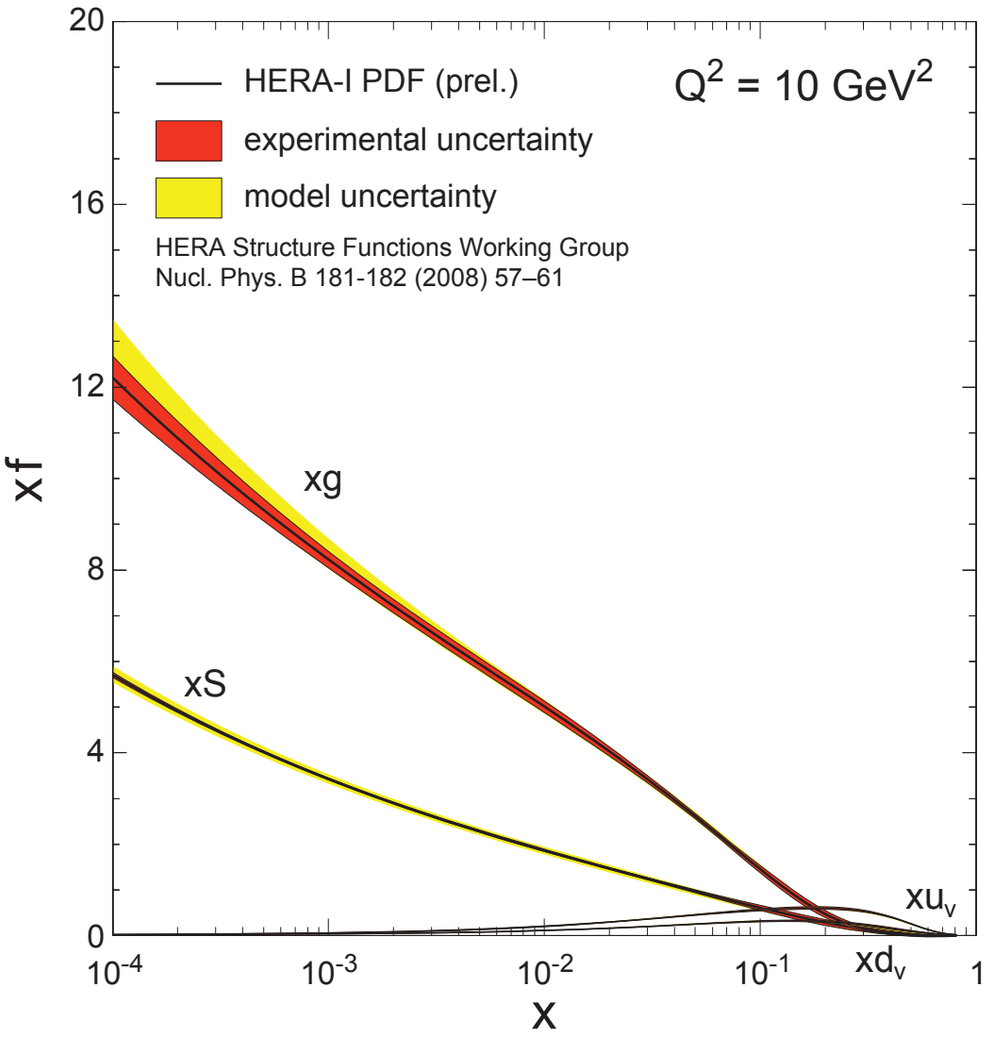

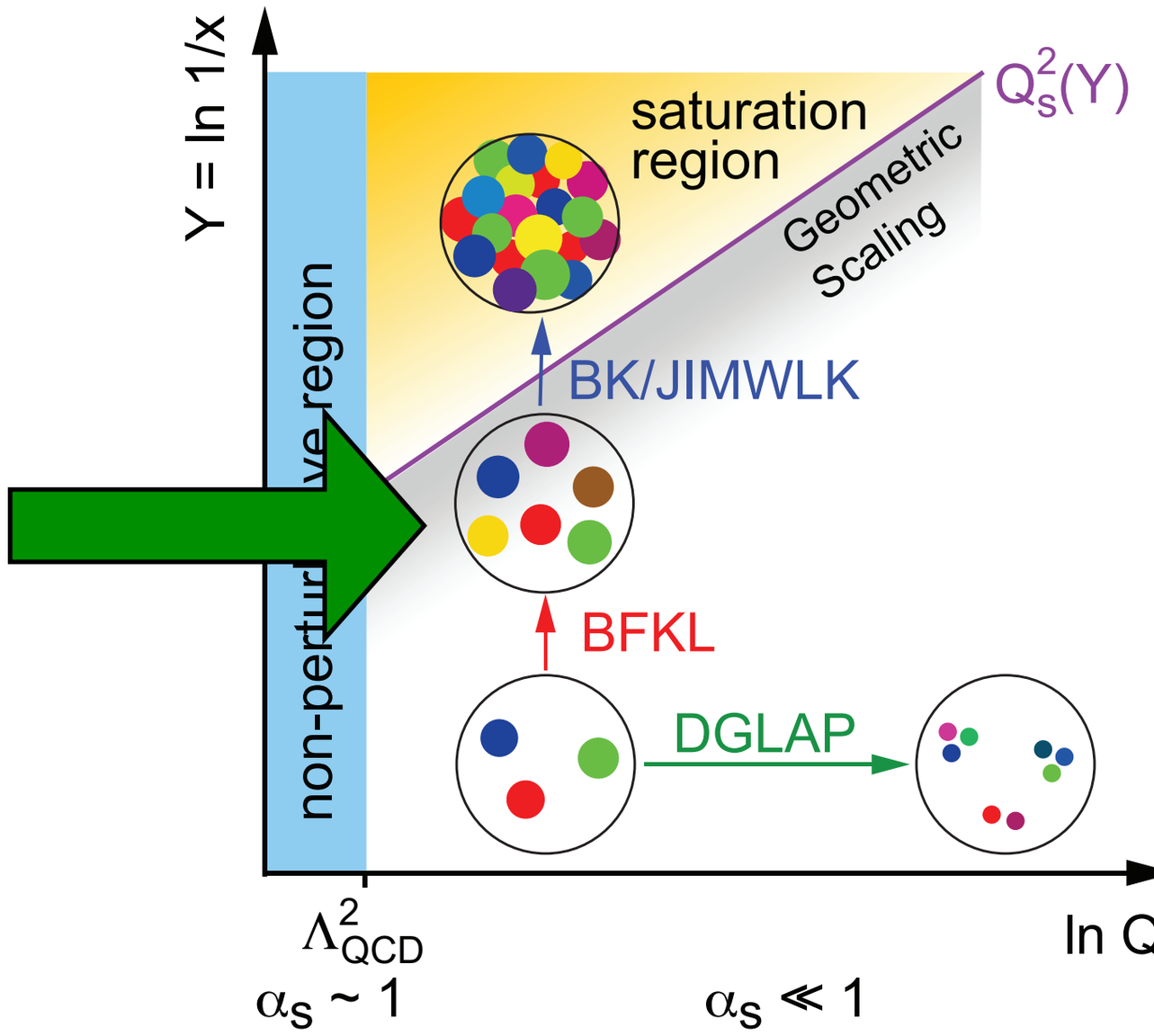

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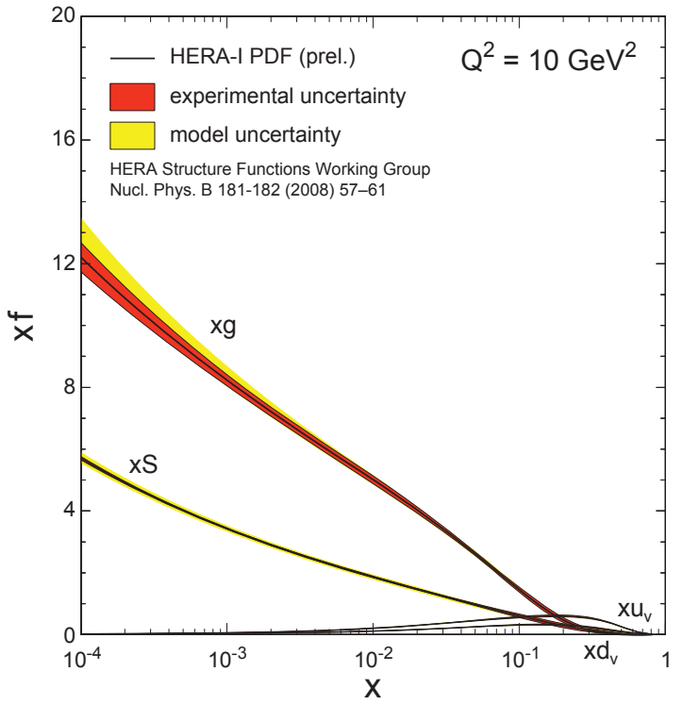
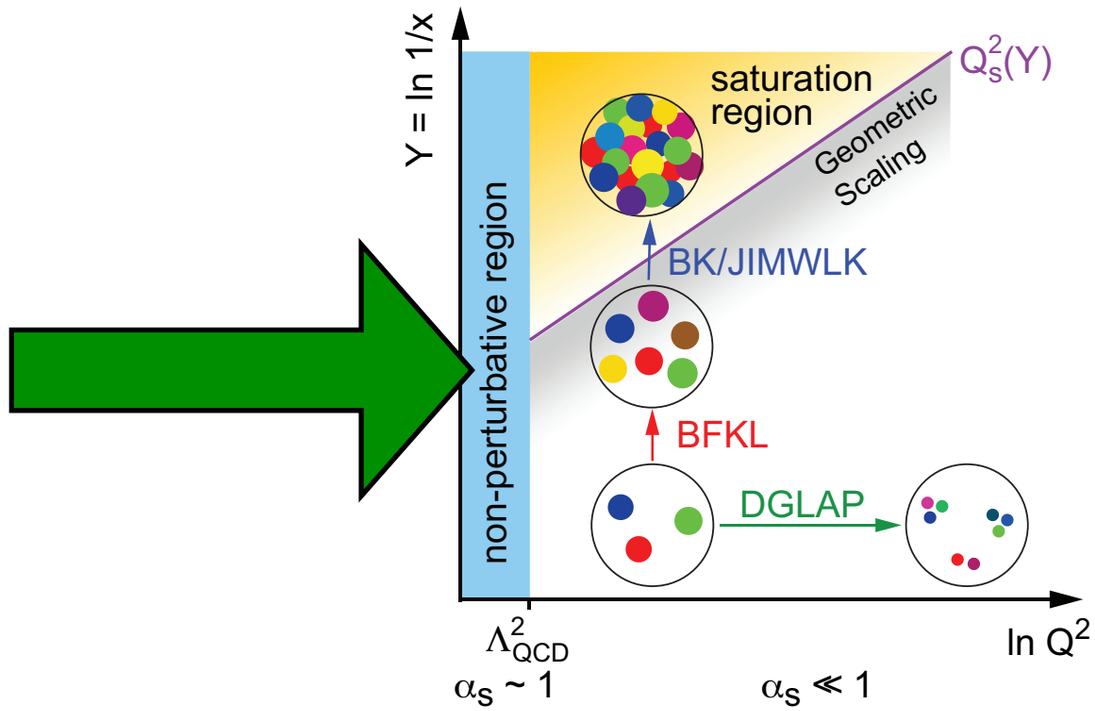
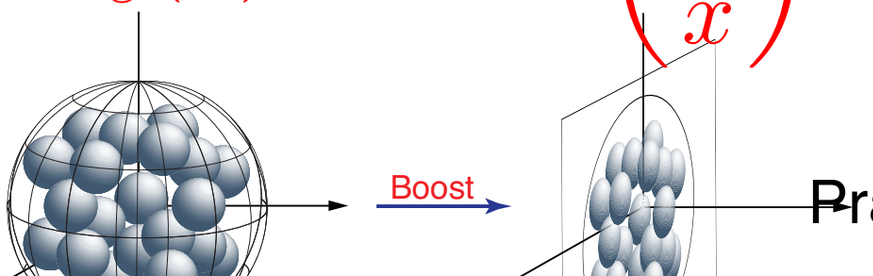




$$Q_s^2(x) \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$



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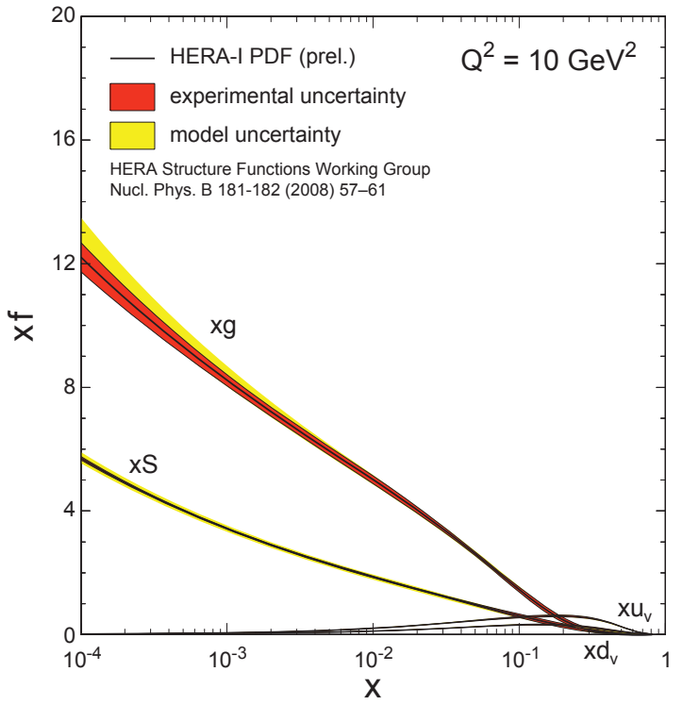

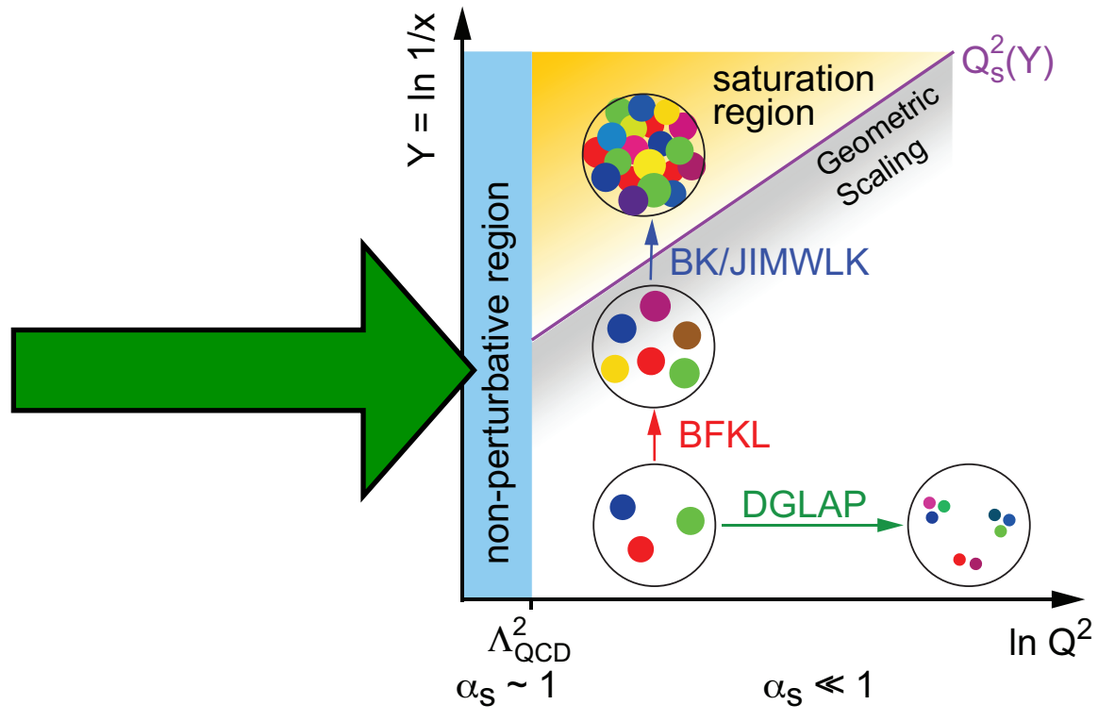

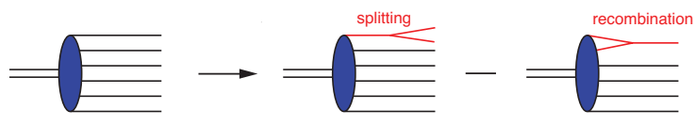

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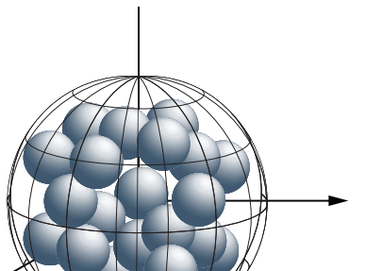

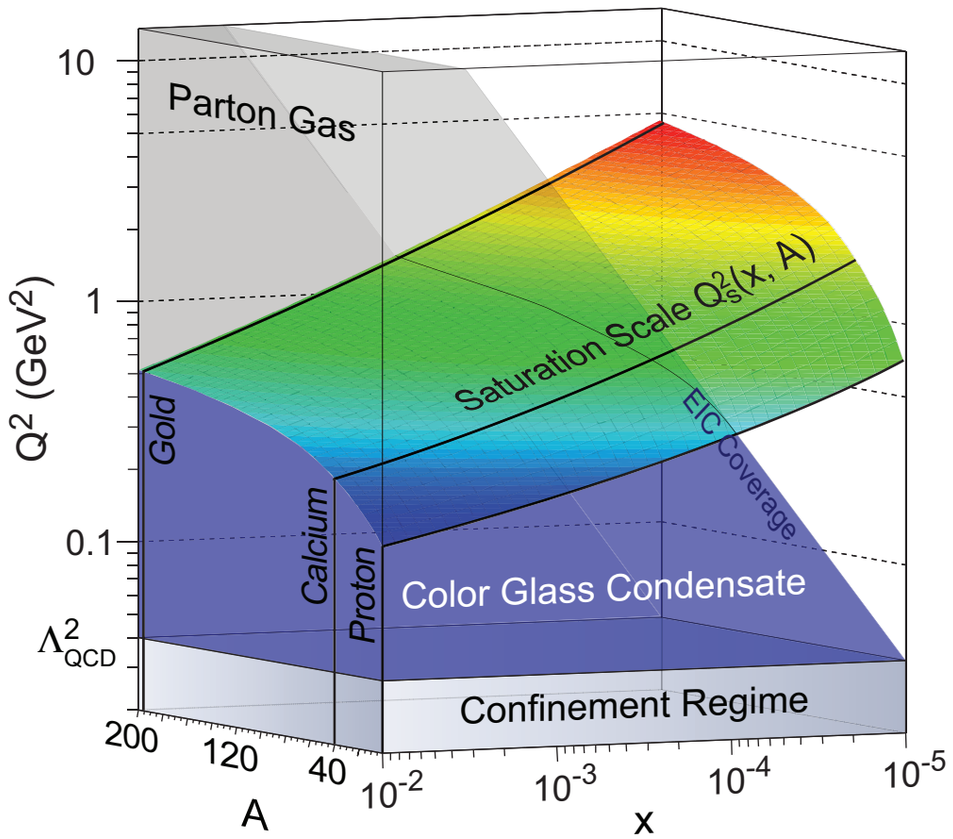

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