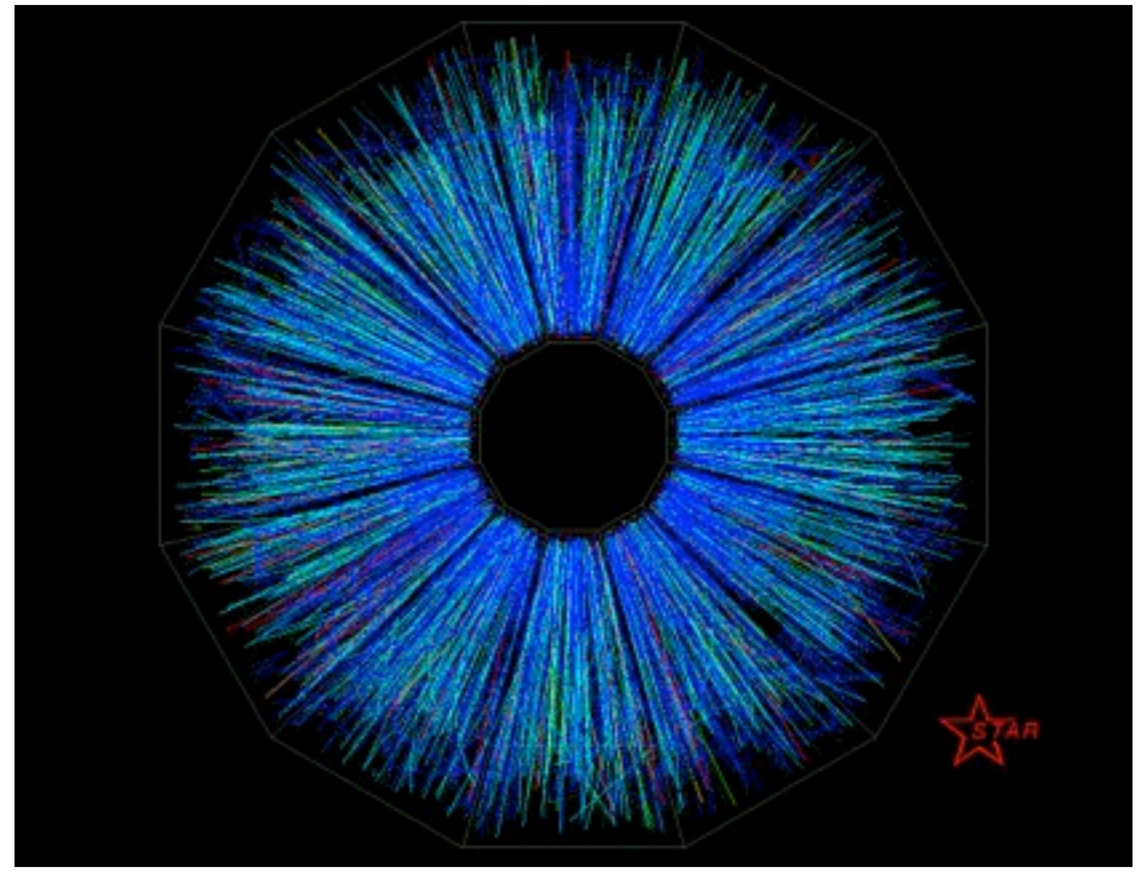
The STAR Experiment: The second decade and beyond

Matthew A. C. Lamont, BNL
for the
STAR Collaboration



1[st] Collision: June 12, 2000

Talk Outline:

1. Introduction to RHIC and STAR
2. Highlights from the first decade
3. Upgrades and near-term future of STAR
4. STAR in the eRHIC era

BROOKHAVEN
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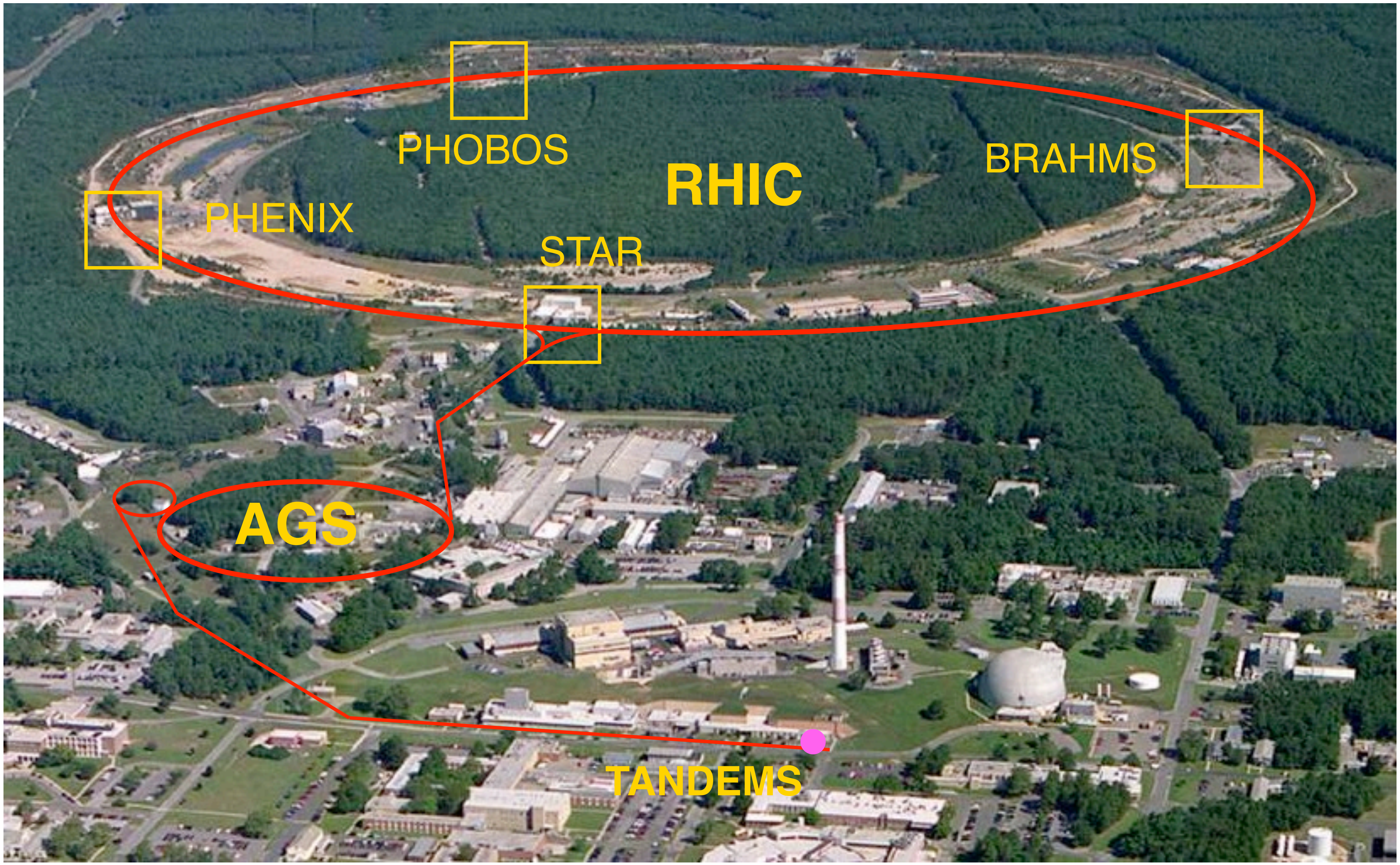
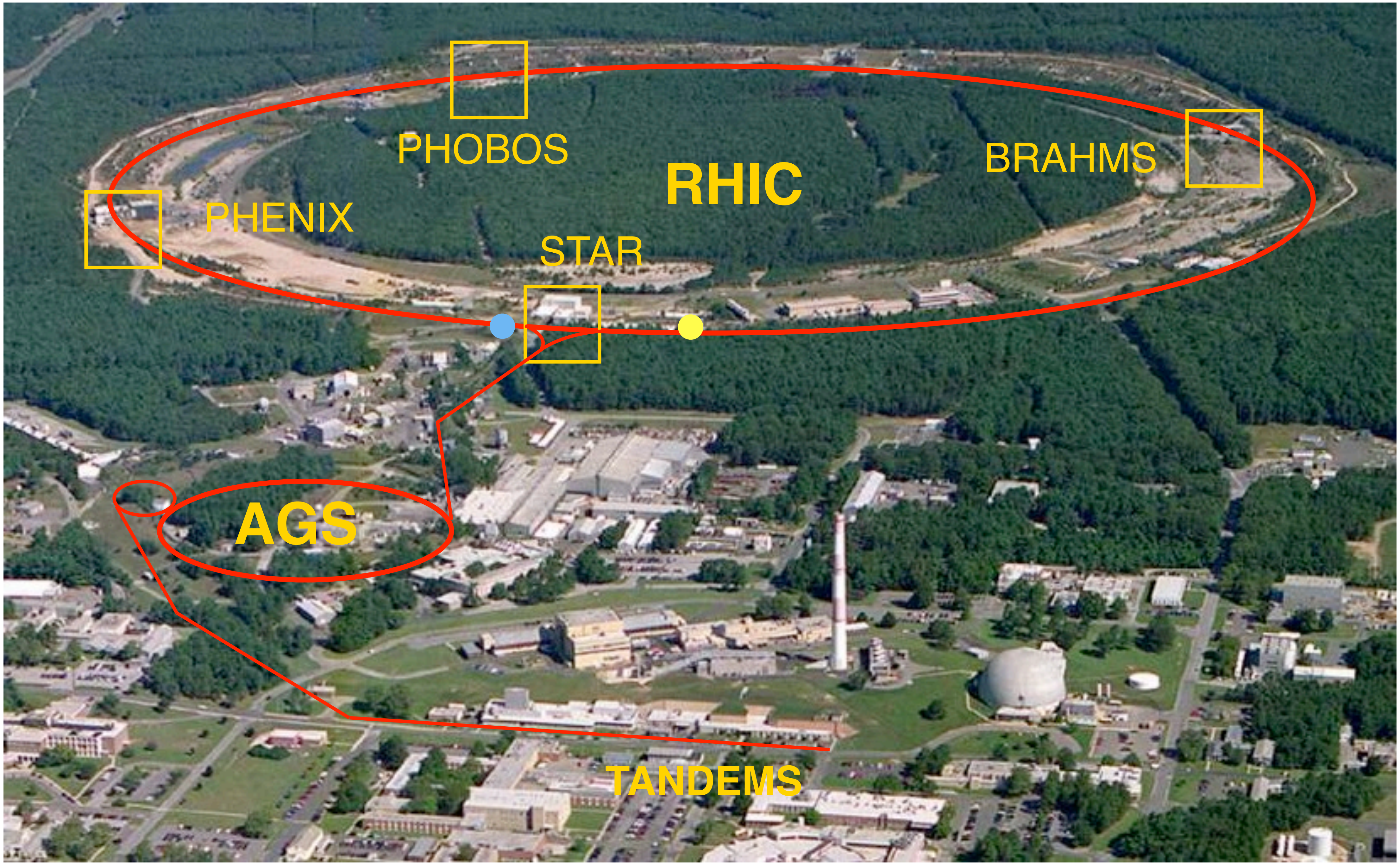
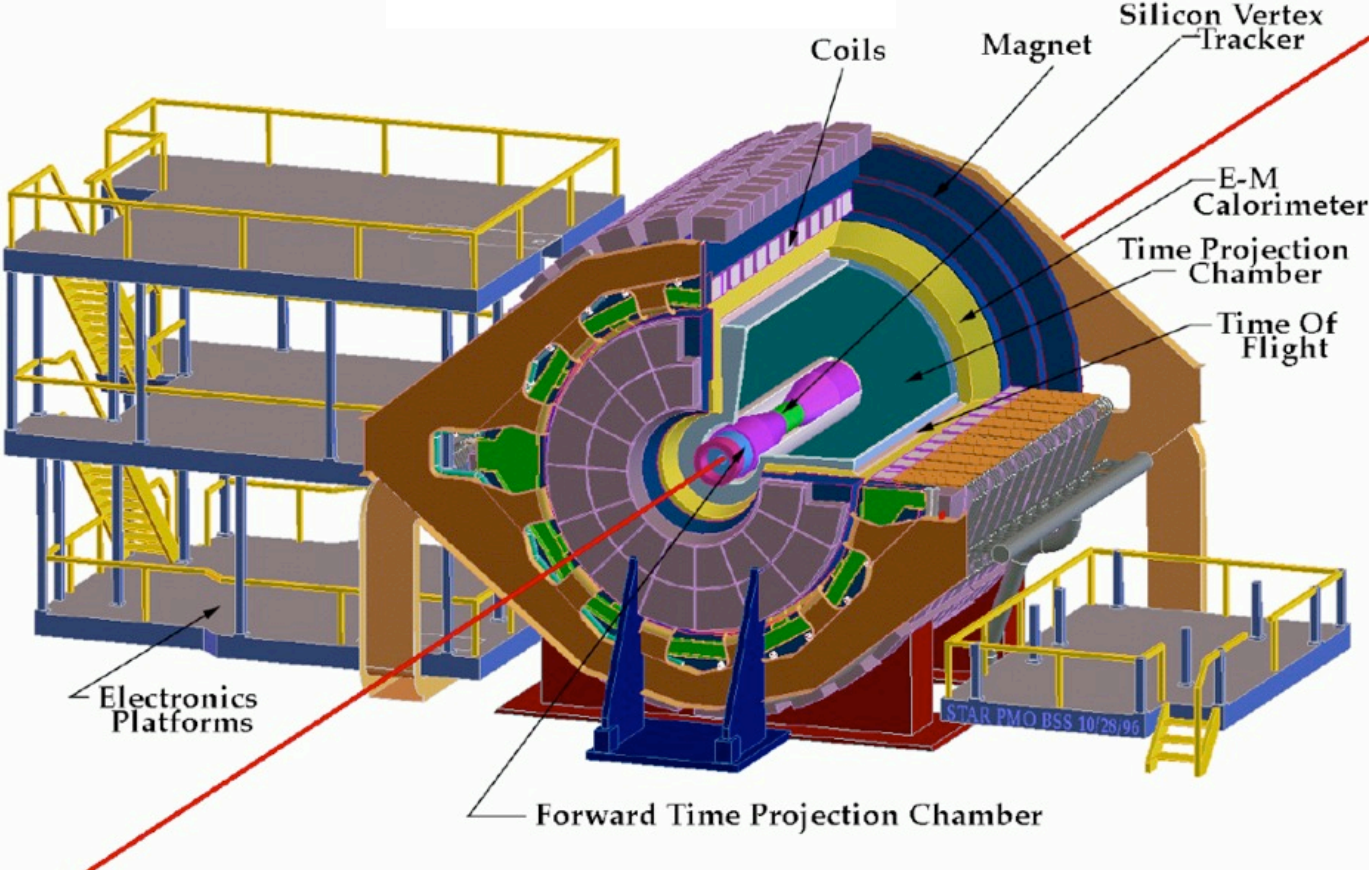
RHIC - Brookhaven Lab



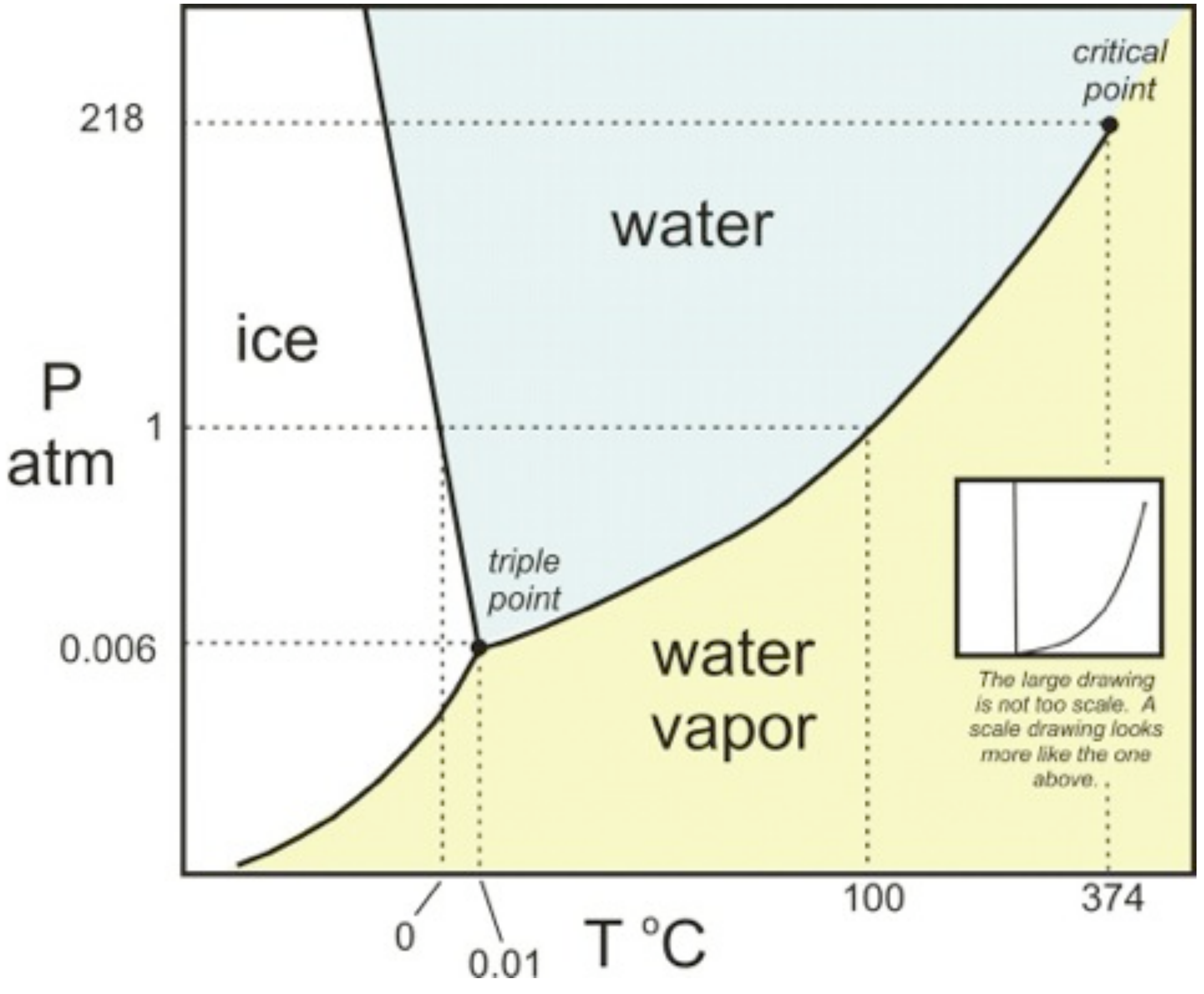
RHIC - Brookhaven Lab



The STAR Detector



The QCD phase diagram



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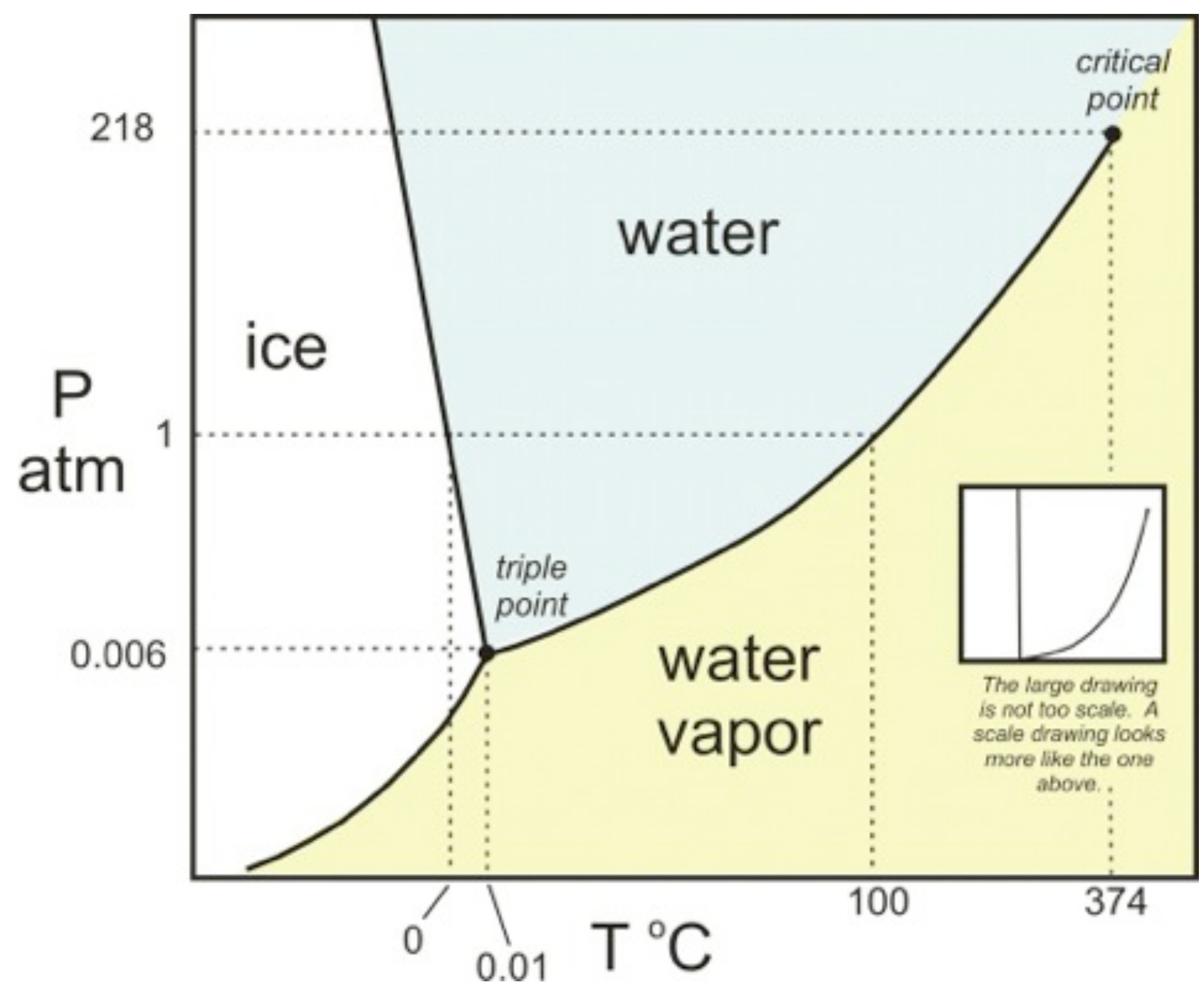
The QCD phase diagram

Just like with water, QCD has it's own phase diagram, which plots temperature vs net baryon density



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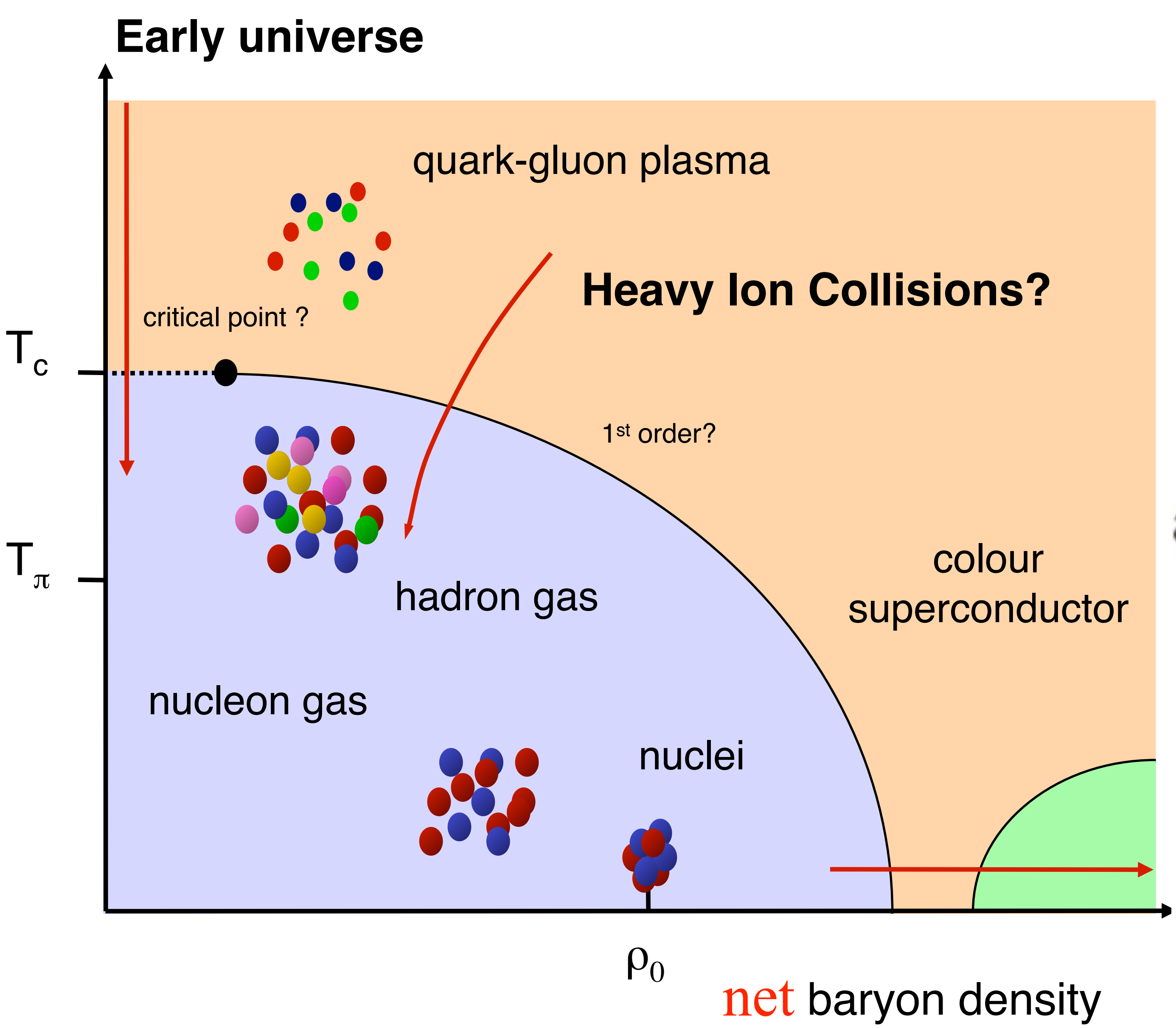

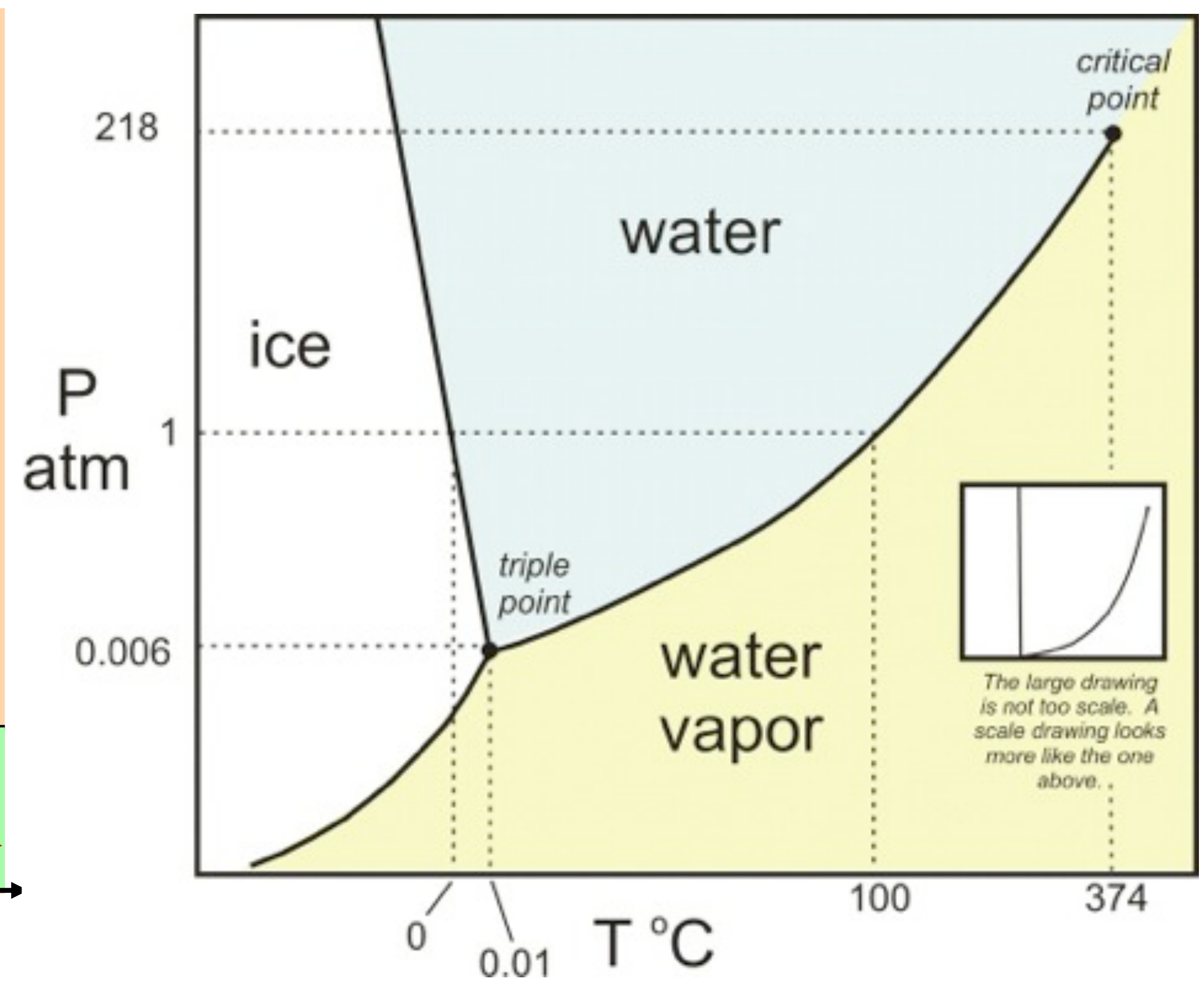

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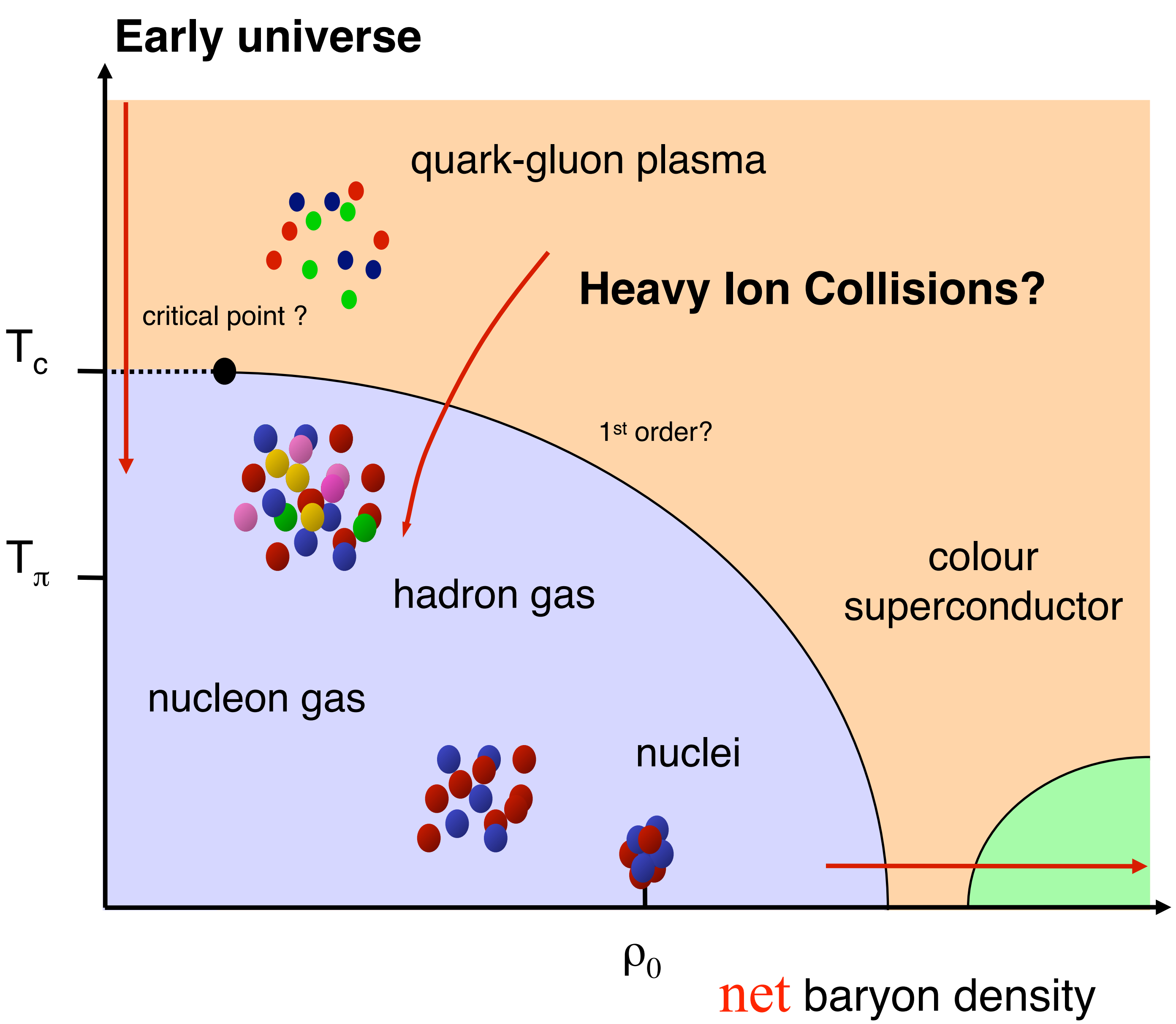

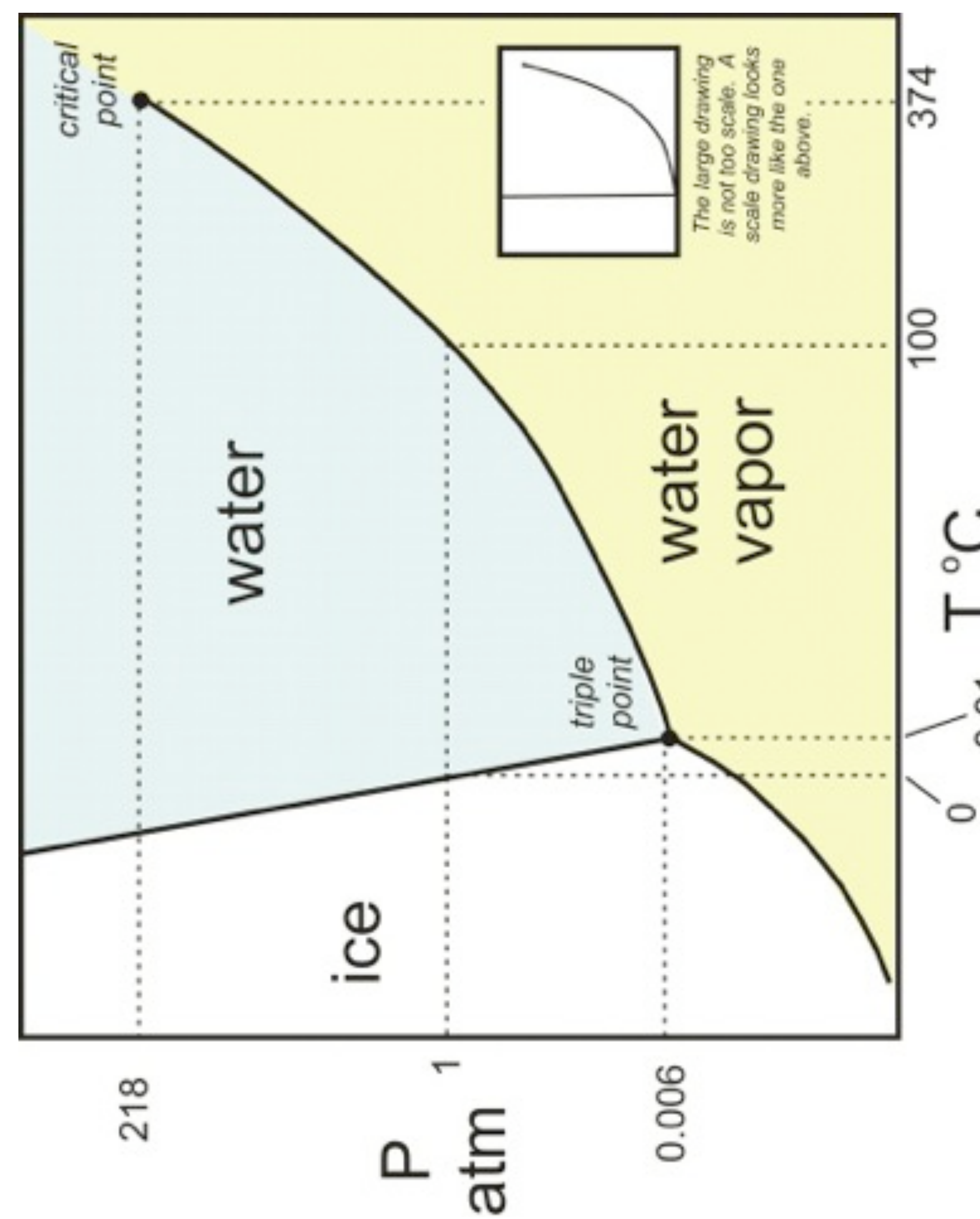

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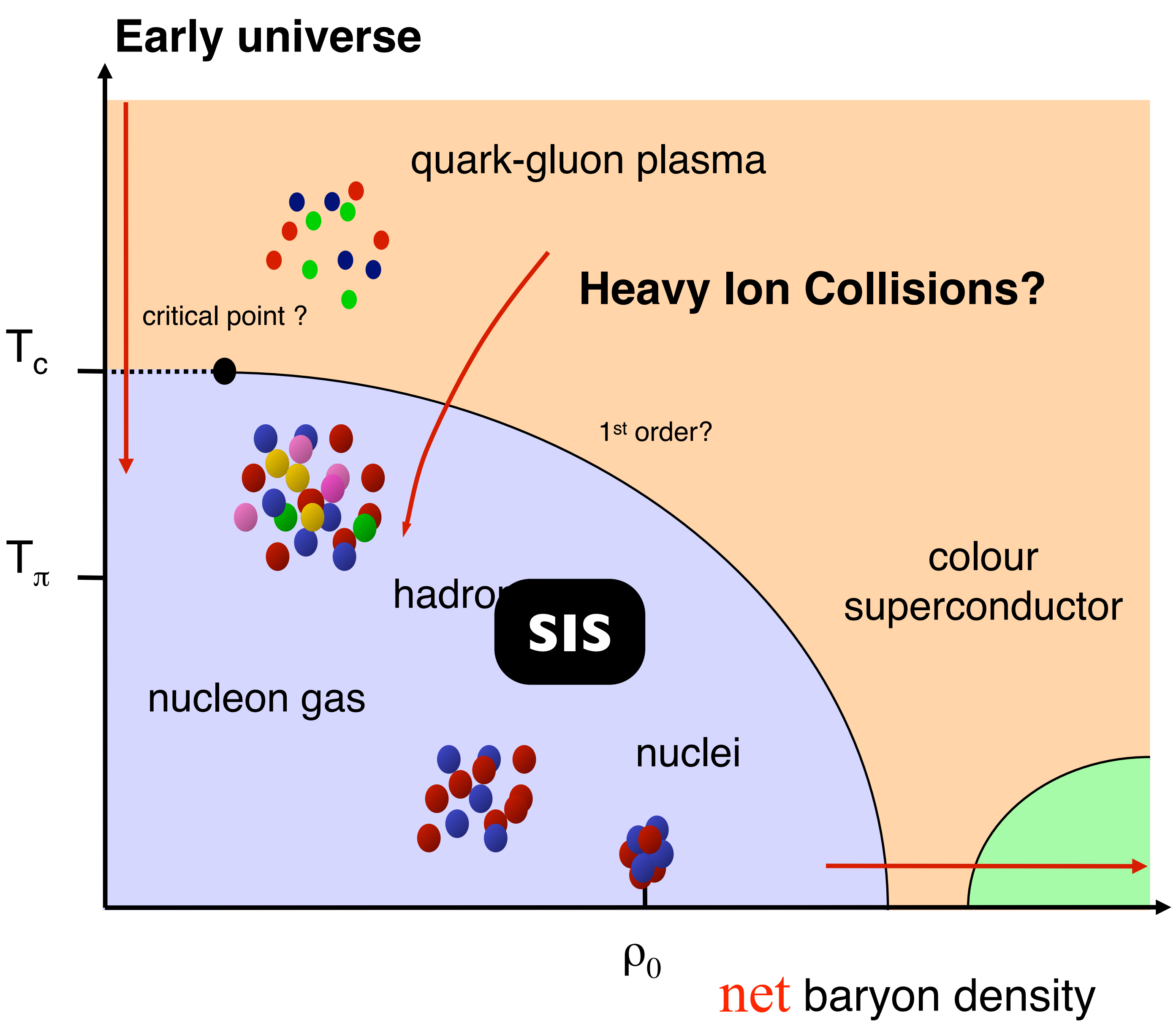

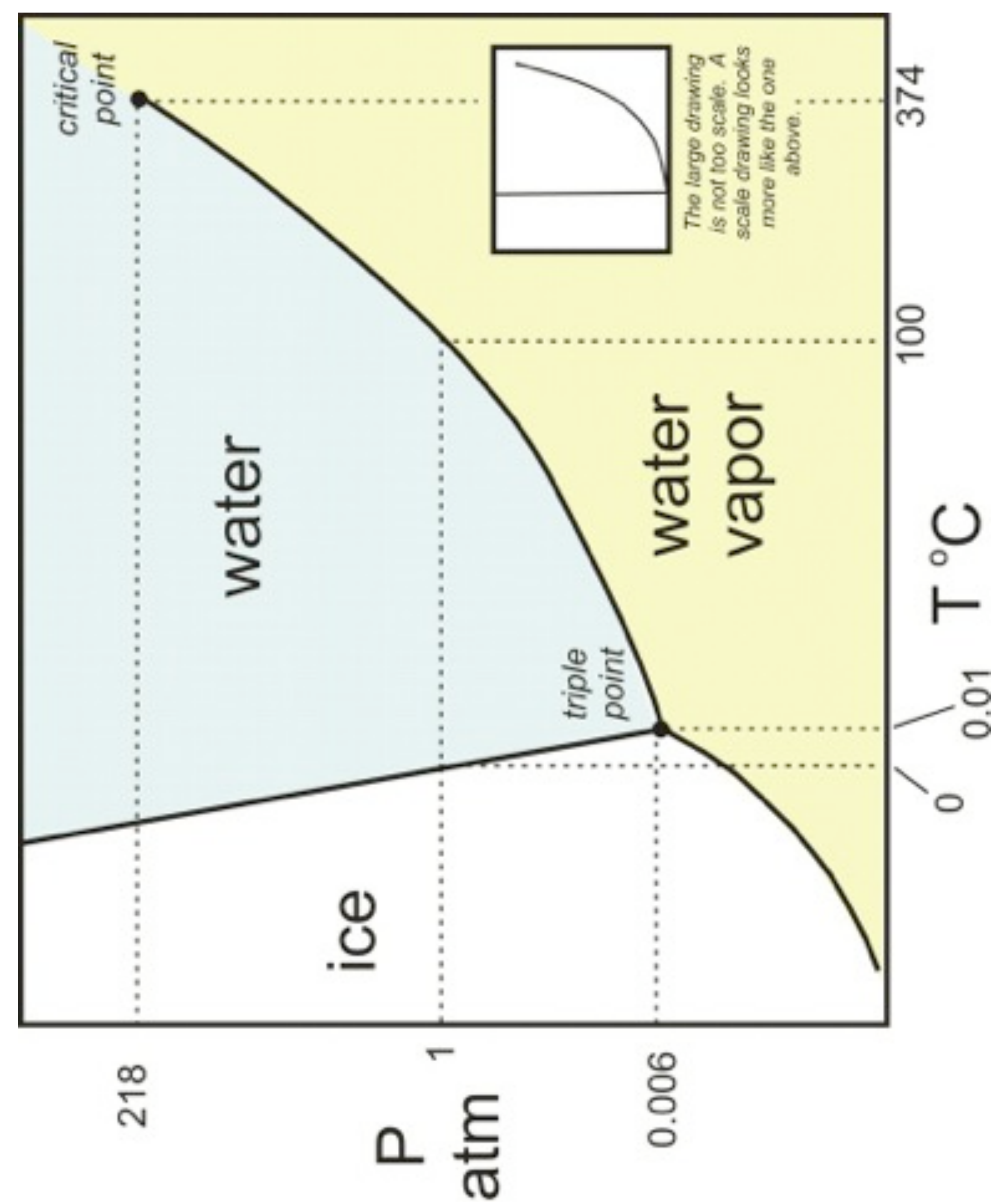

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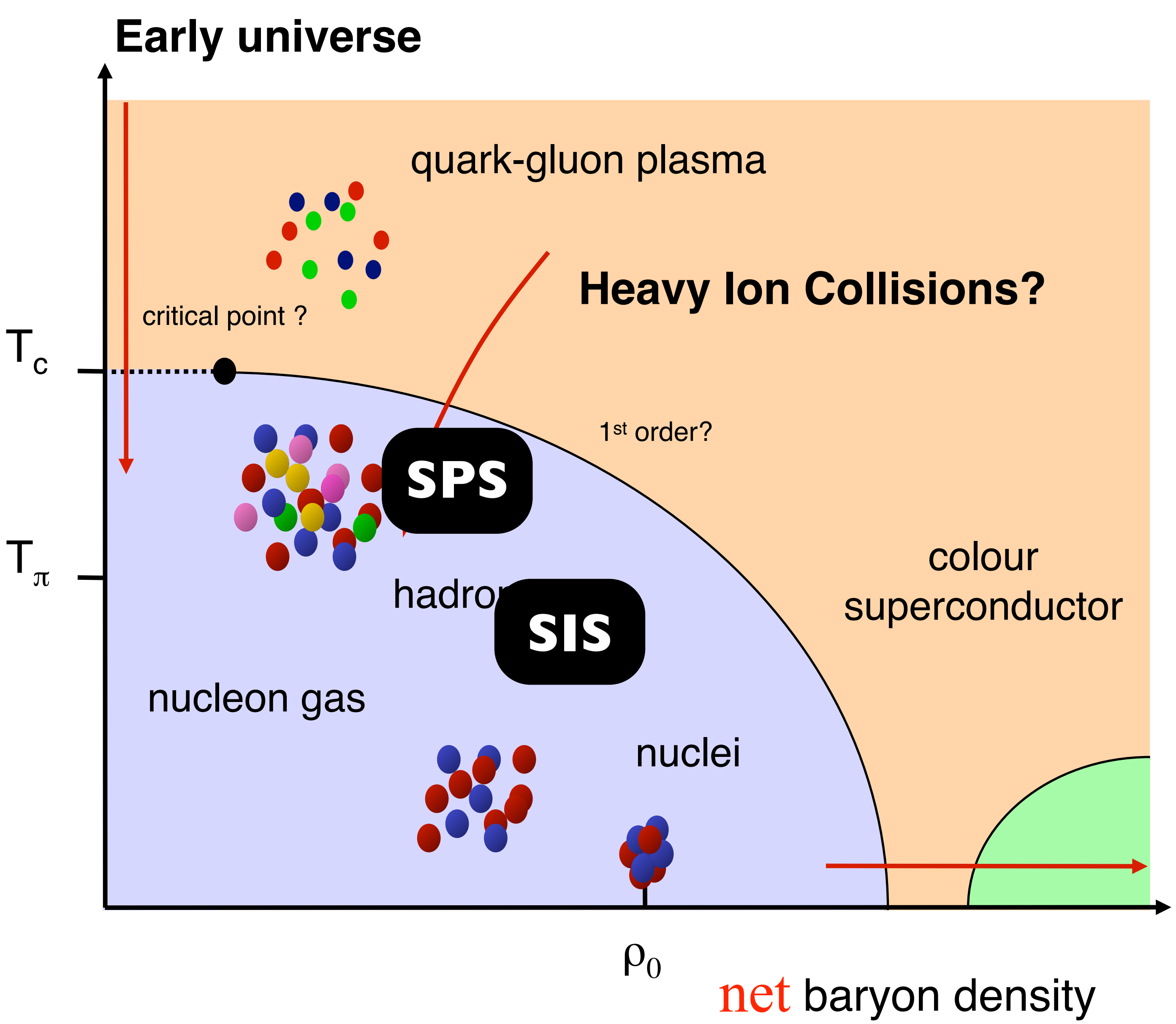

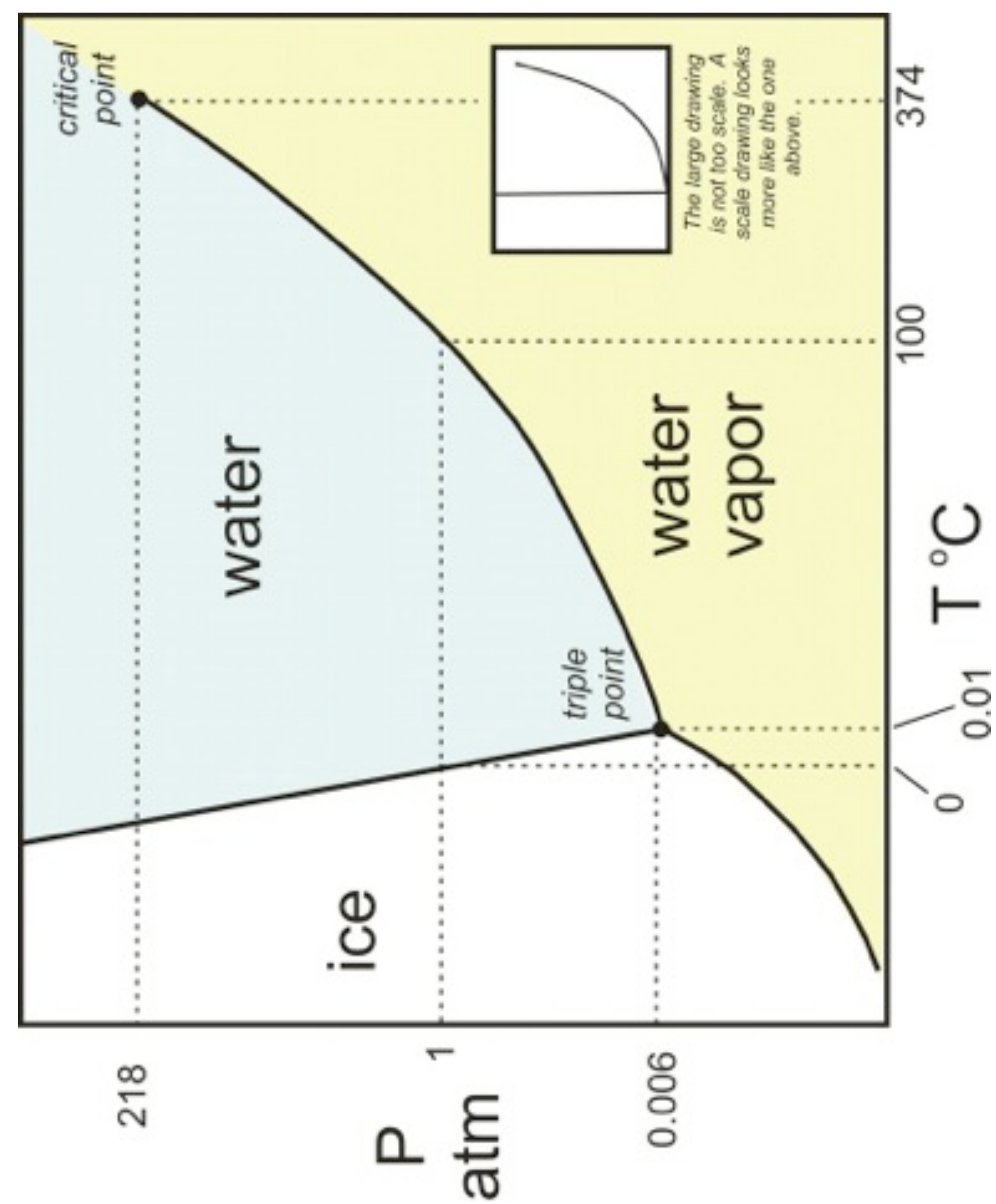

Highlights of the 1st decade of AA collisions in STAR

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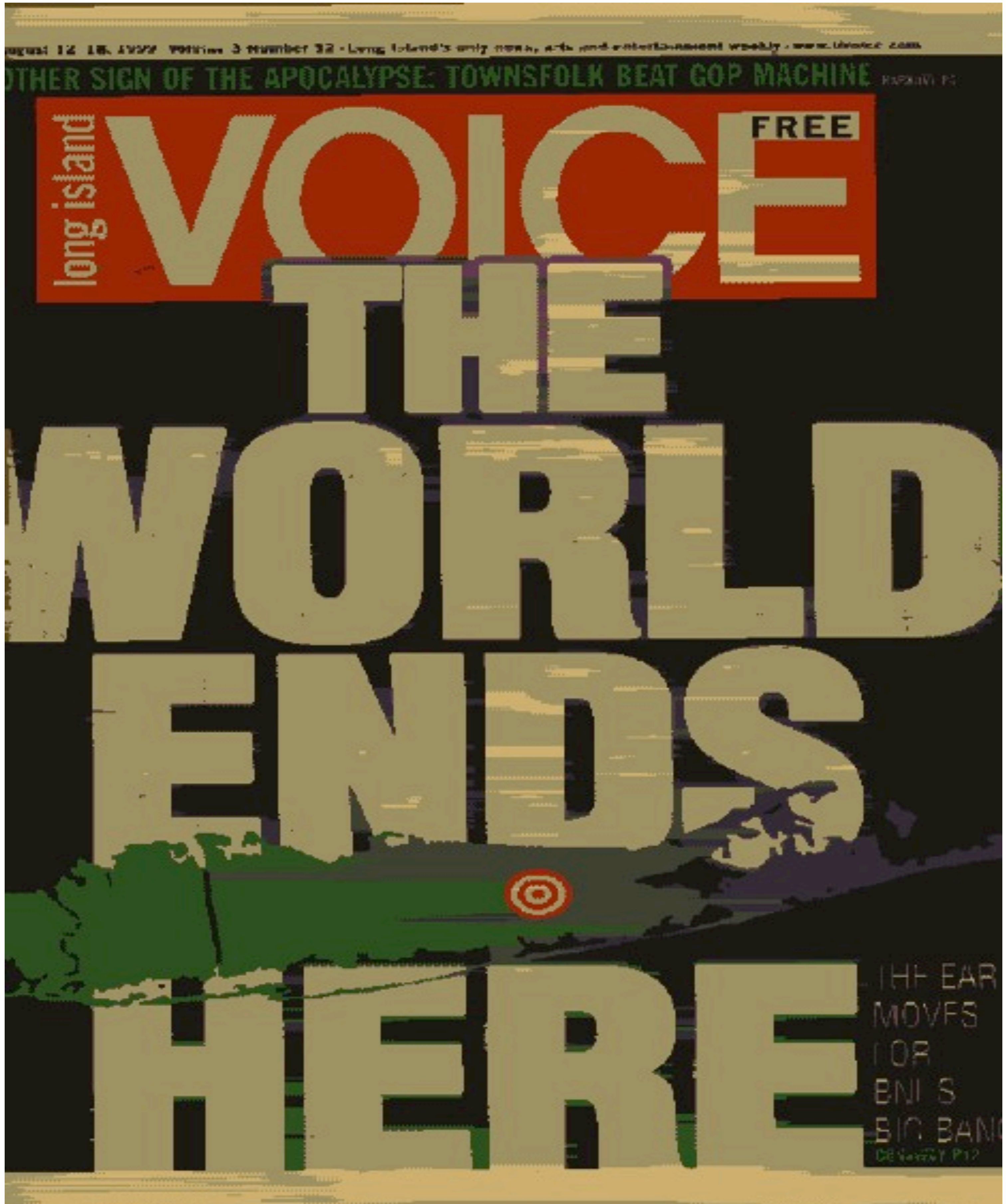

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Highlights of the 1st decade of AA collisions in STAR

- Strong Elliptic Flow
  - Collective flow of created matter
  - Constituent quark number degrees of freedom apparent in scaling laws of elliptic flow
- Particle production through recombination/coalescence dominates over fragmentation at medium p_T
- Exotic particles
  - First observations of $^{3}_{\Lambda}\overline{H}$ and $^{4}\overline{He}$
- Jet quenching
  - Energy loss of high-p_T partons traversing the hot and dense matter
- Gluon saturation at small-x?
  - Tantalising hints of saturation phenomena in d+A collisions

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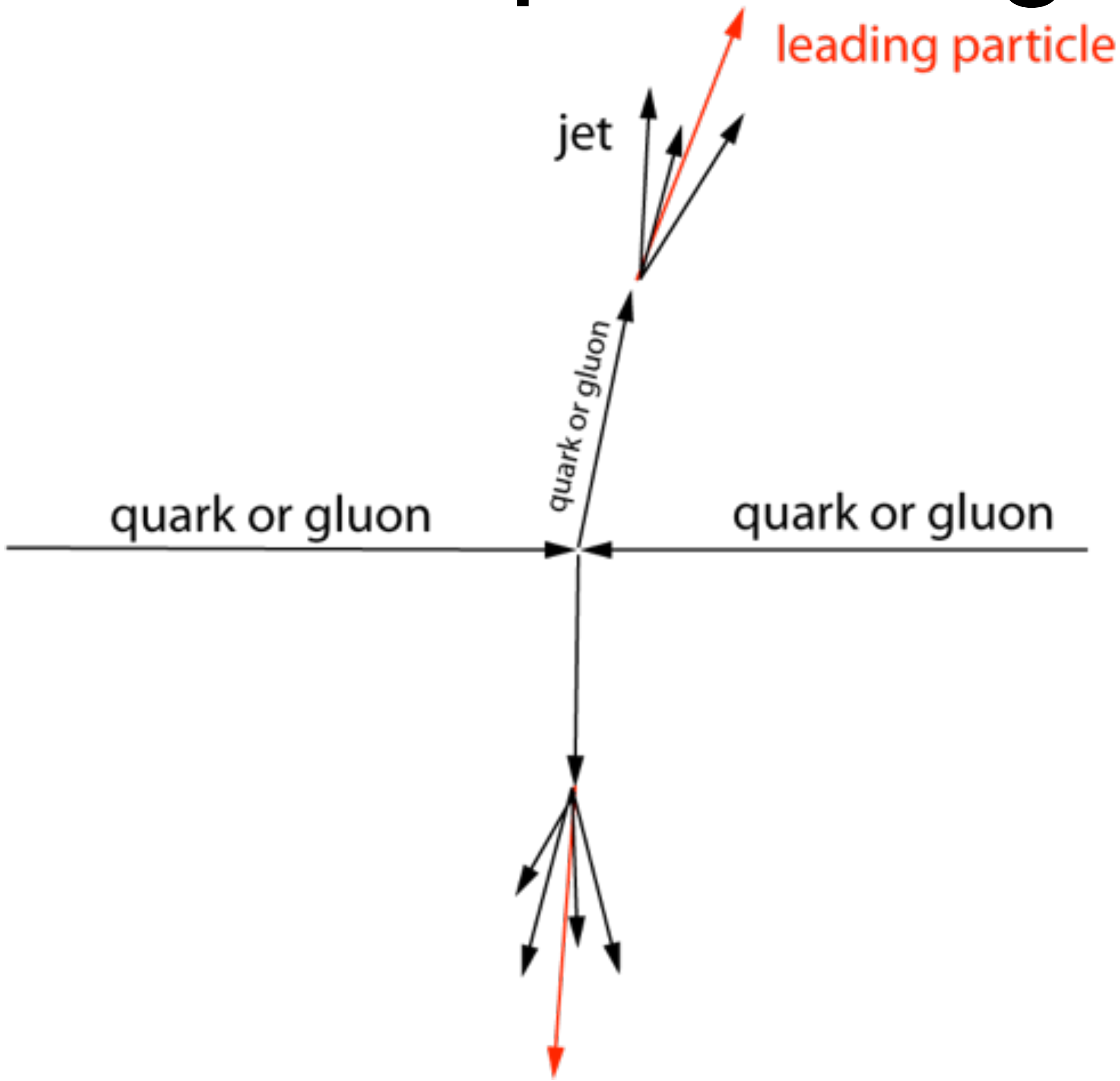
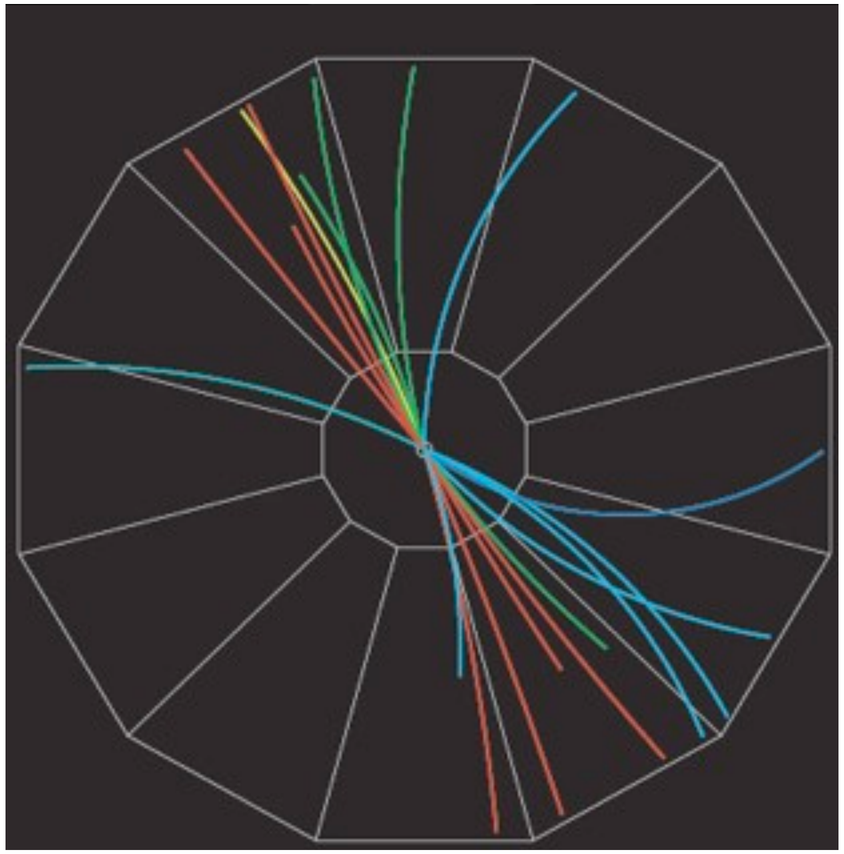
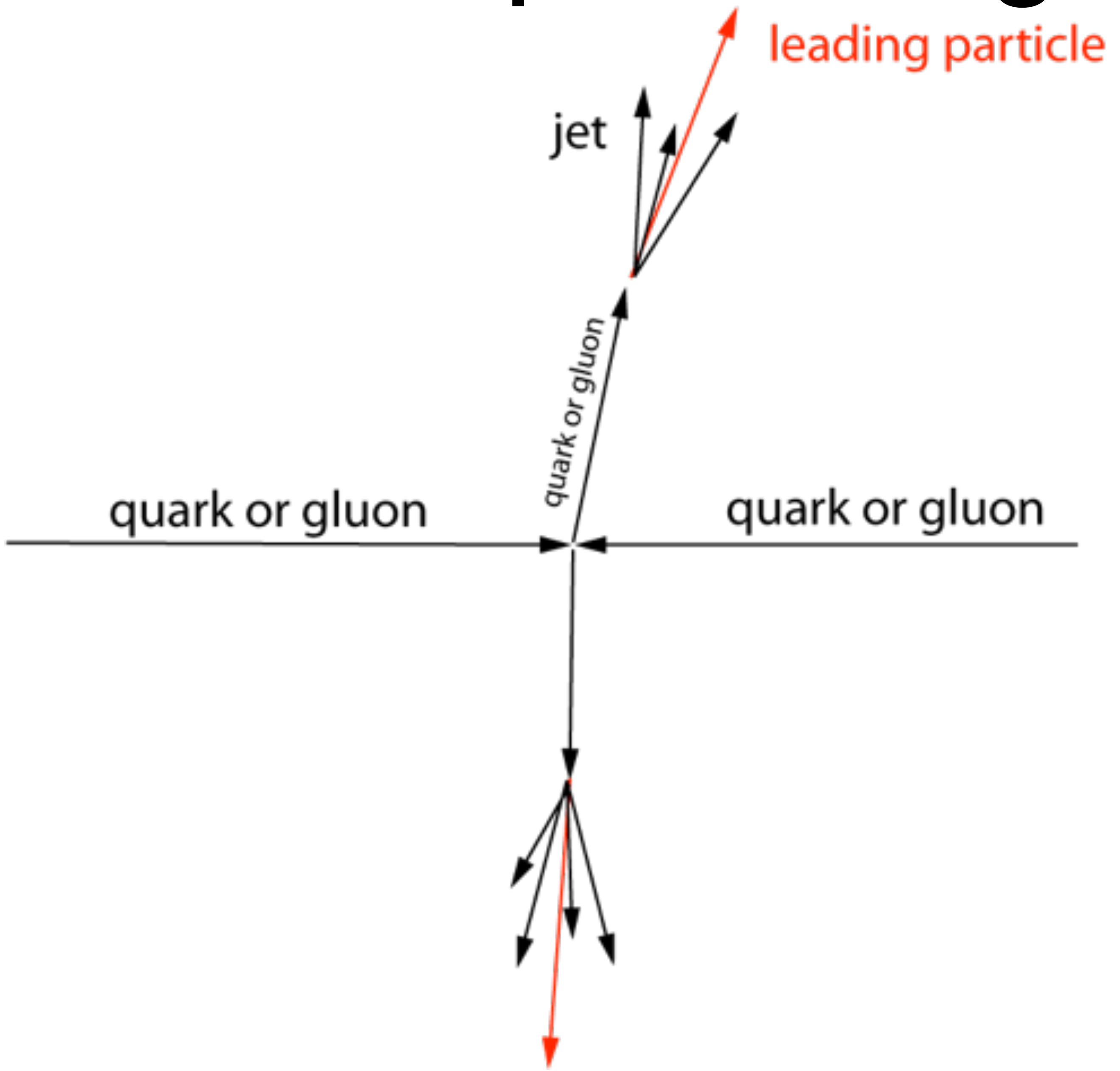
Jet quenching in A+A collisions

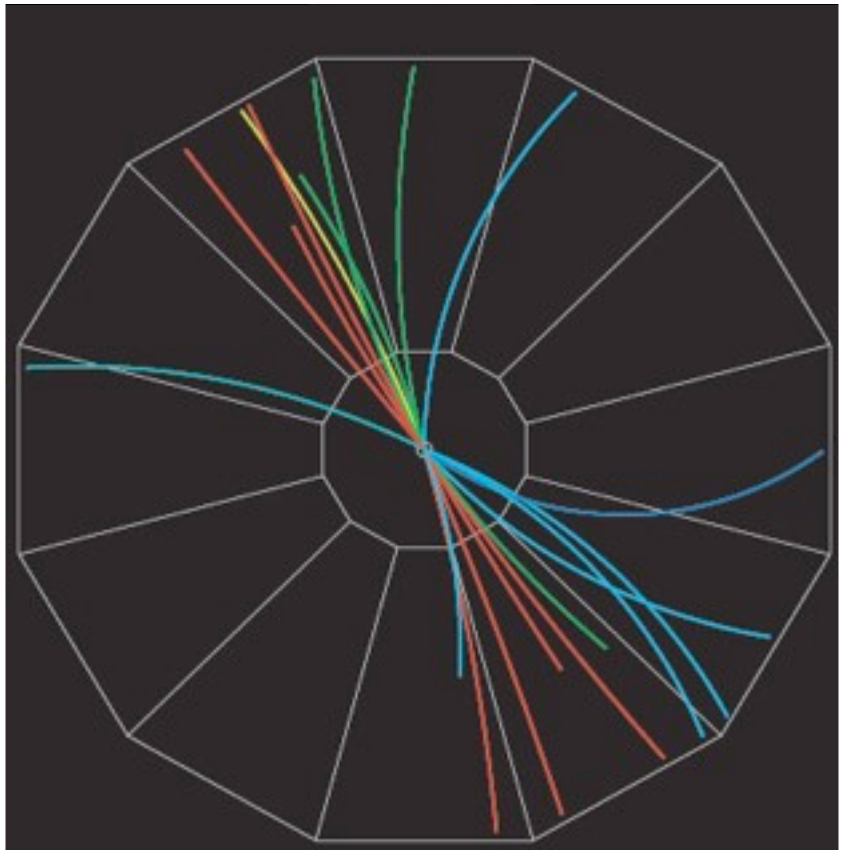




p+p Event

Jet quenching in A+A collisions

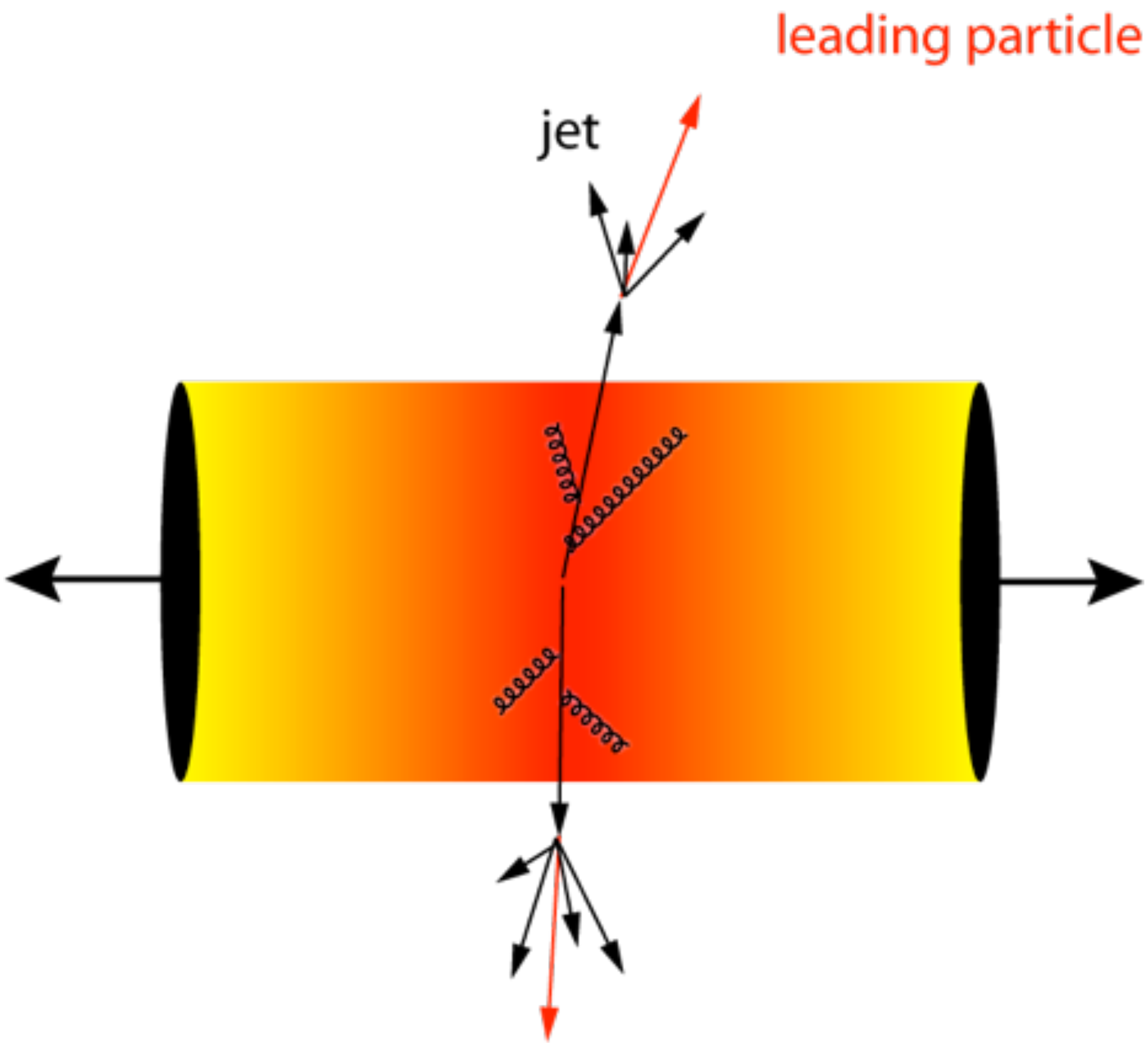


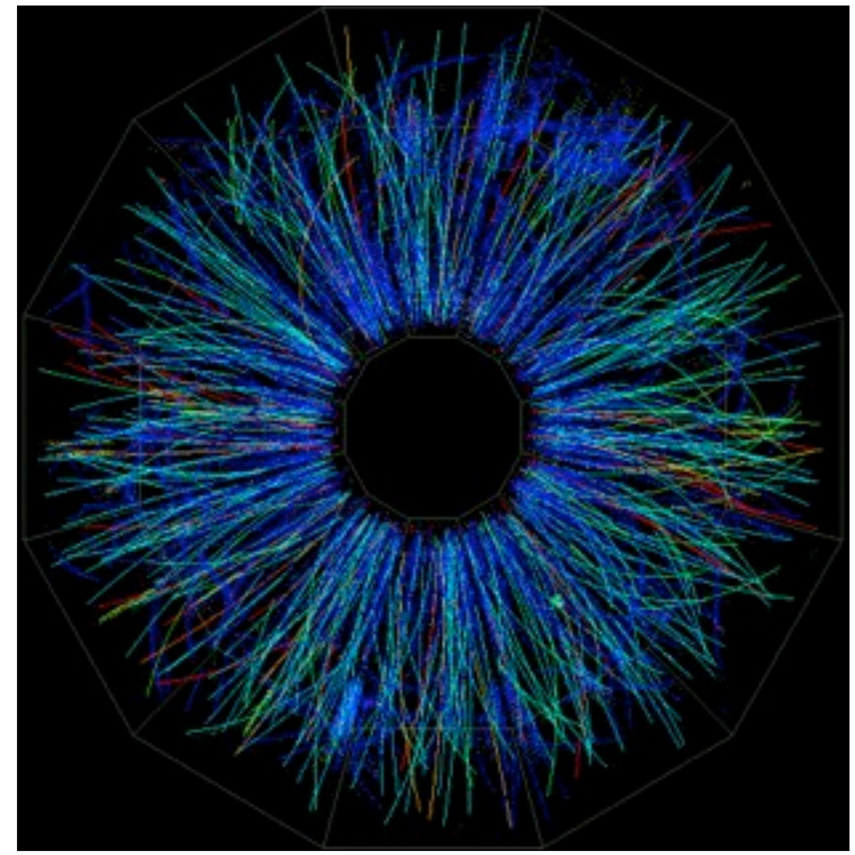


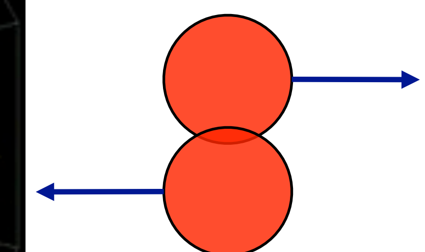
p+p Event

- Jet-finding is relatively straight-forward in low-multiplicity p+p collisions

Jet quenching in A+A collisions







Peripheral Au+Au Event

- Jet-finding is relatively straight-forward in low-multiplicity p+p collisions

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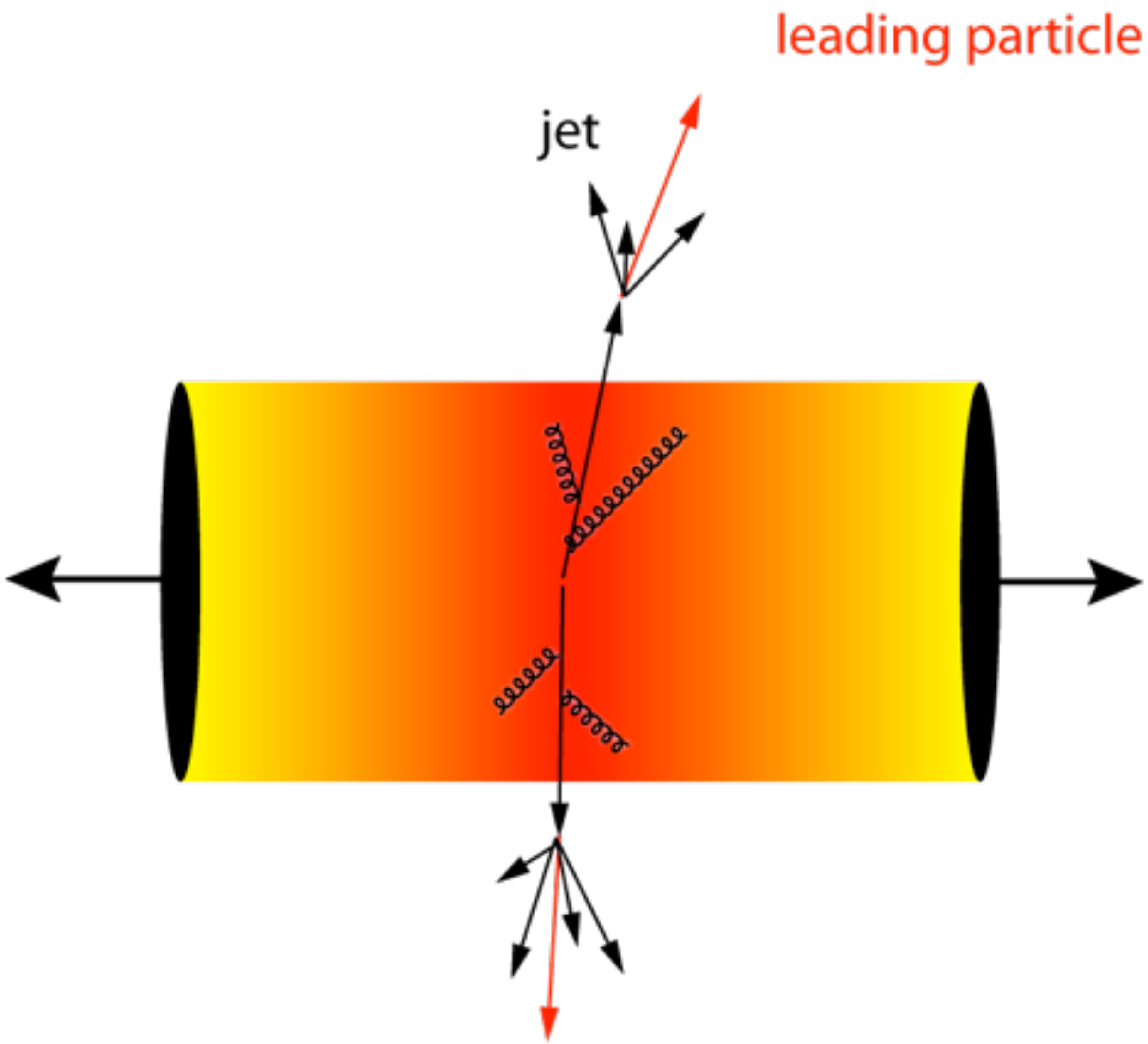
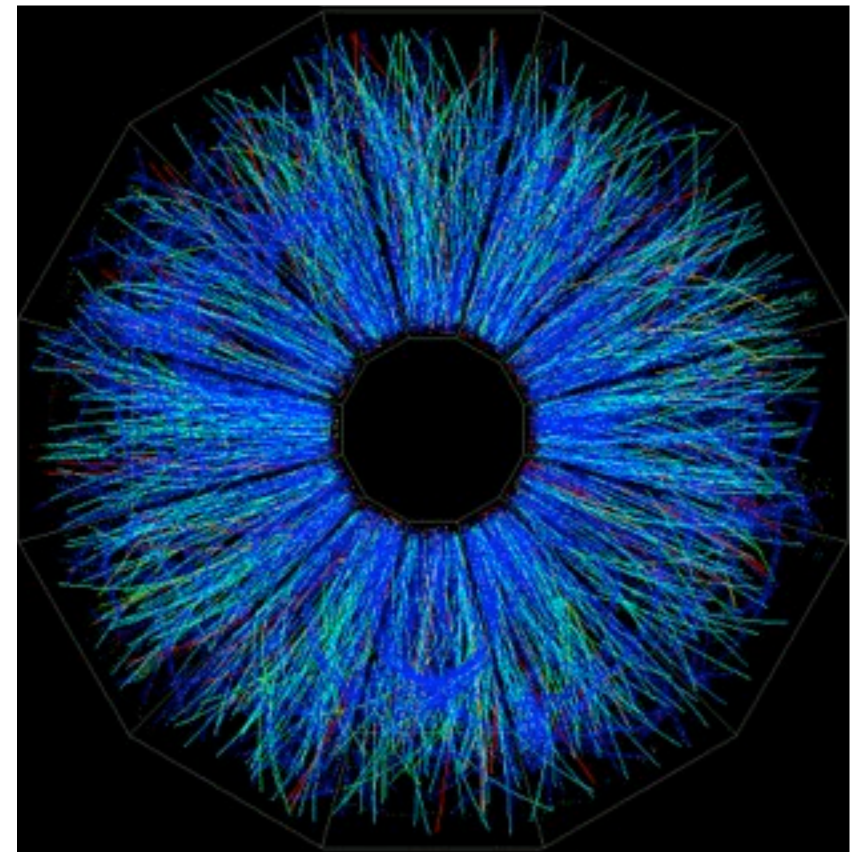
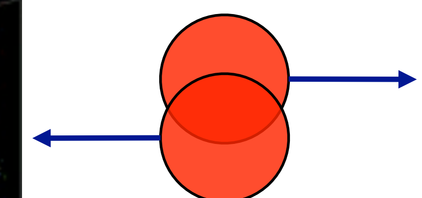
Jet quenching in A+A collisions







Mid-Central Au+Au Event

- Jet-finding is relatively straight-forward in low-multiplicity p+p collisions

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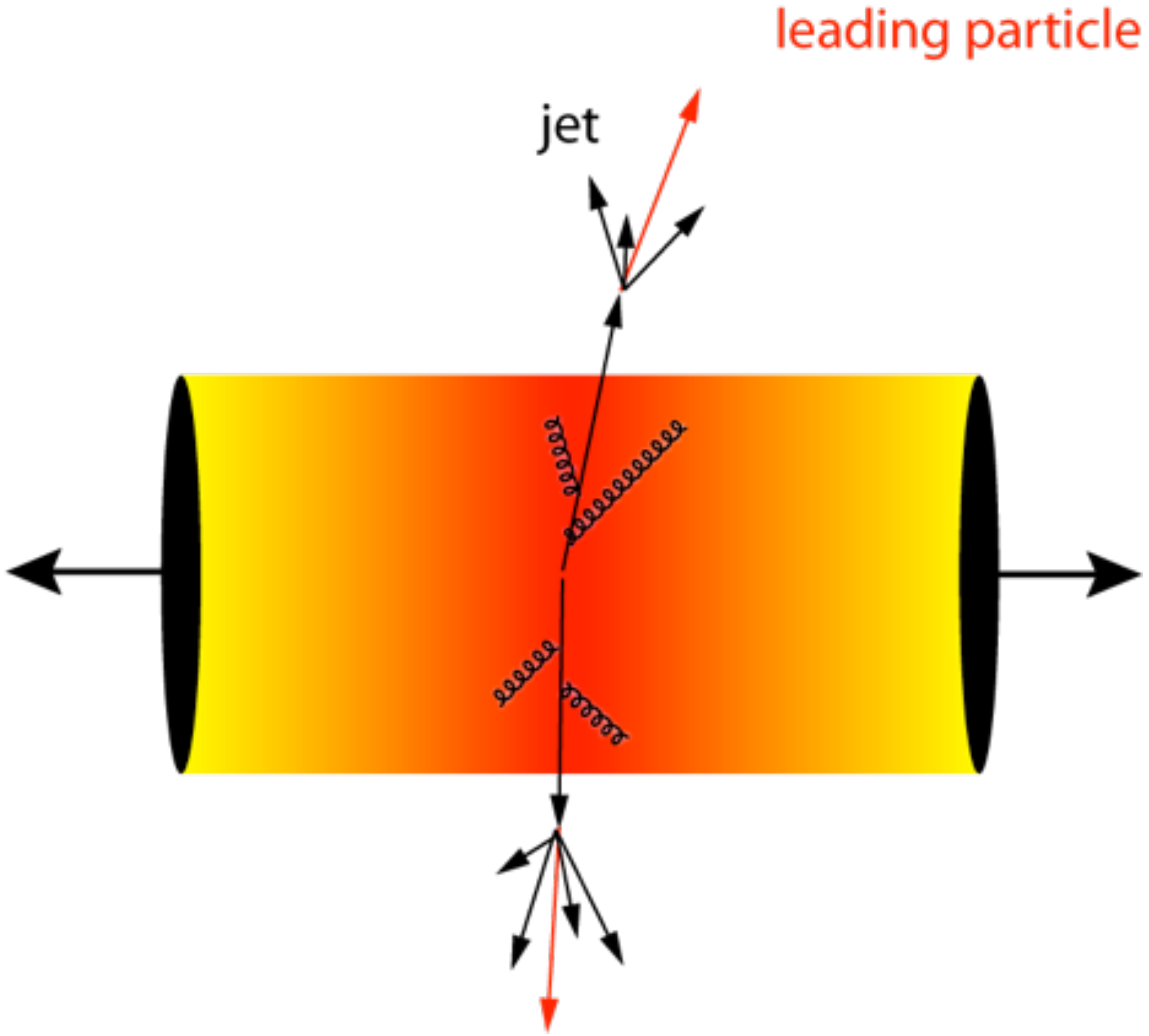
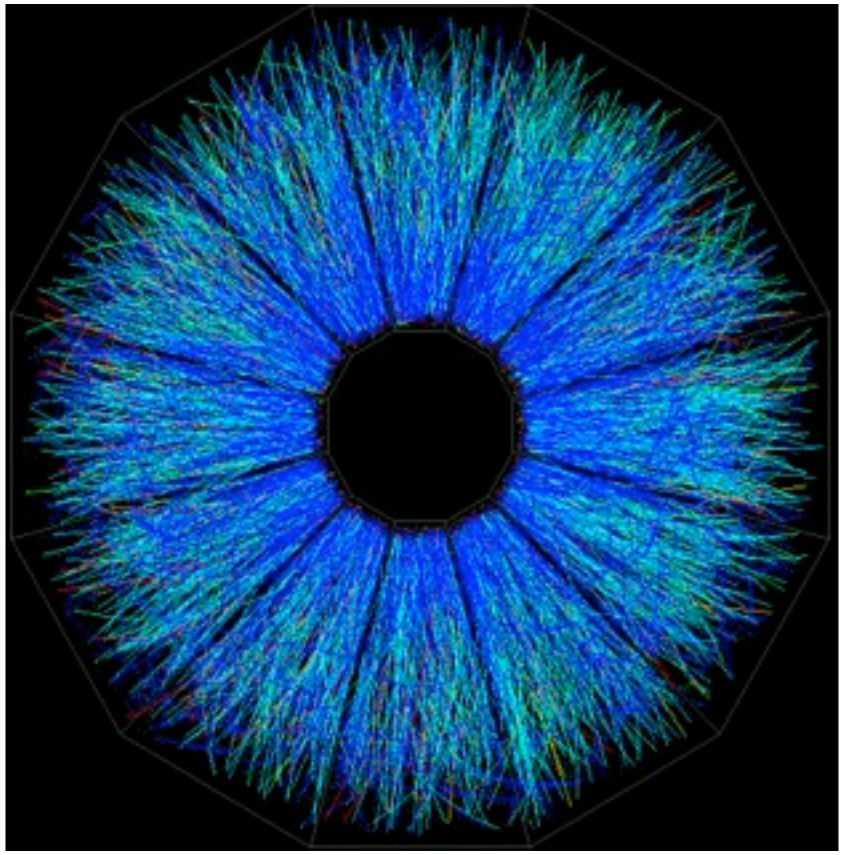
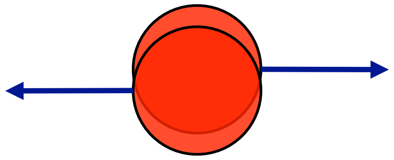
Jet quenching in A+A collisions







Central Au+Au Event

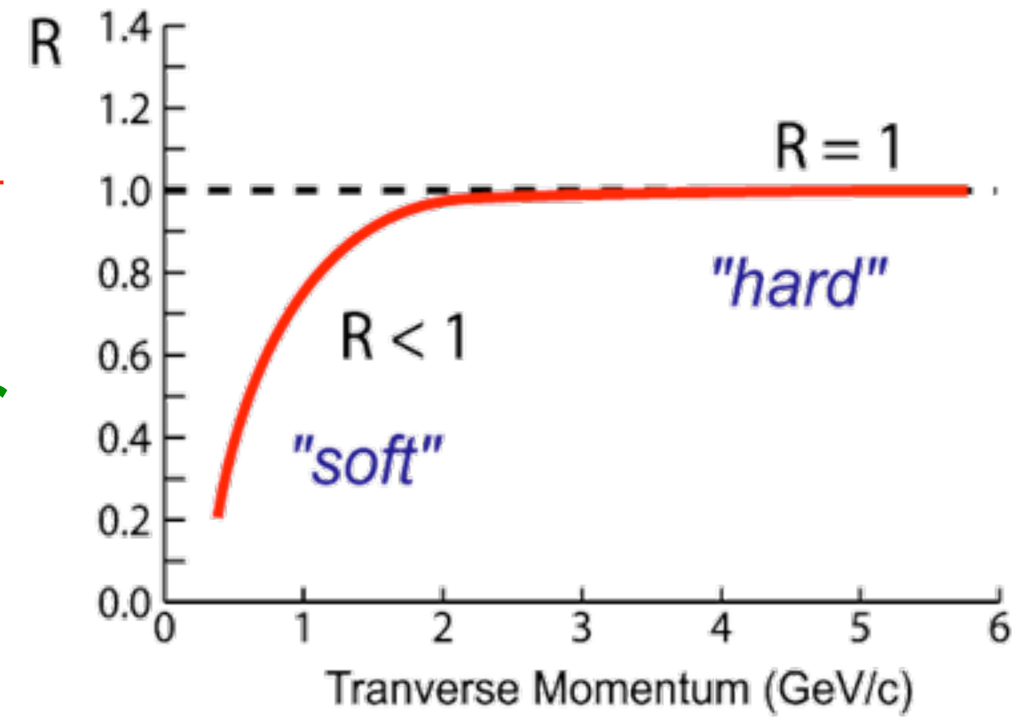
- Jet-finding is relatively straight-forward in low-multiplicity p+p collisions
- How do we do this in high-multiplicity A+A collisions?

How to measure high-p_T processes

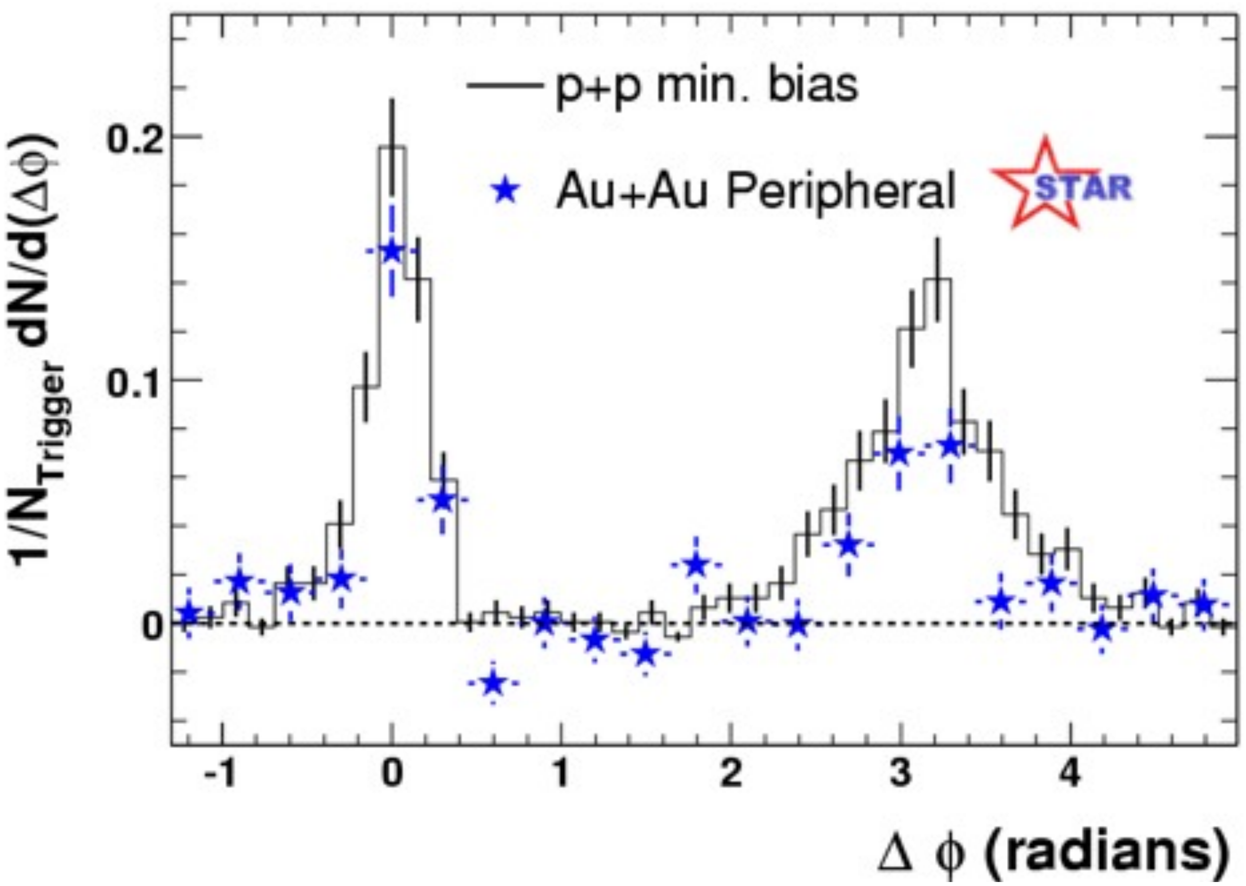
- Single particle spectra

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times <N_{coll}>}$$

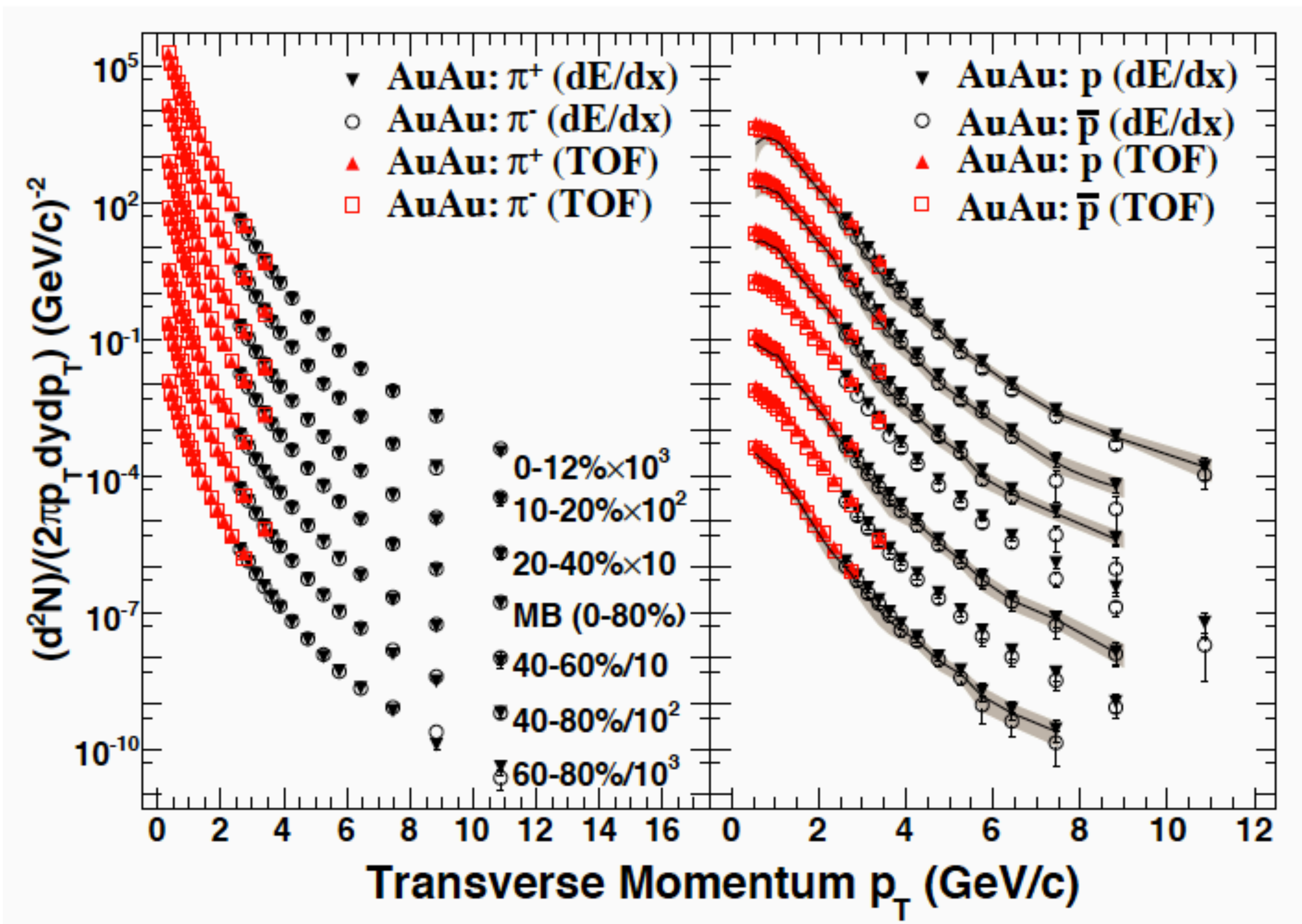
$R_{AA}(p_T)$ = Nuclear Modification Factor



- 2-particle correlations
  - Measure correlations of high-p_T hadrons in azimuth in lieu of jet-finding in high-multiplicity environments



Suppression of inclusive hadron yield at high p_T



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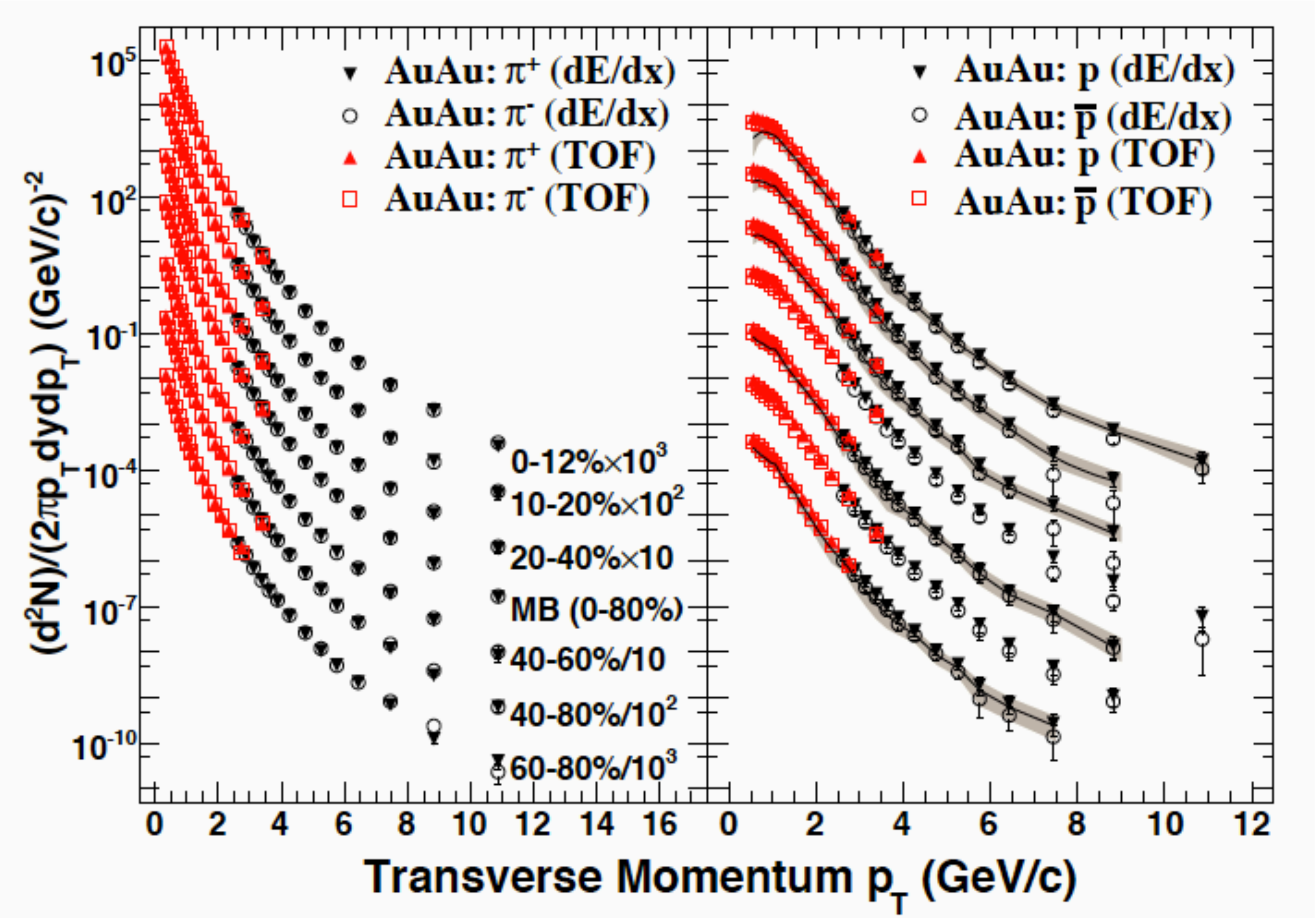
Suppression of inclusive hadron yield at high p_T

- Good quality measurements of single particle spectra as a function of collision centrality



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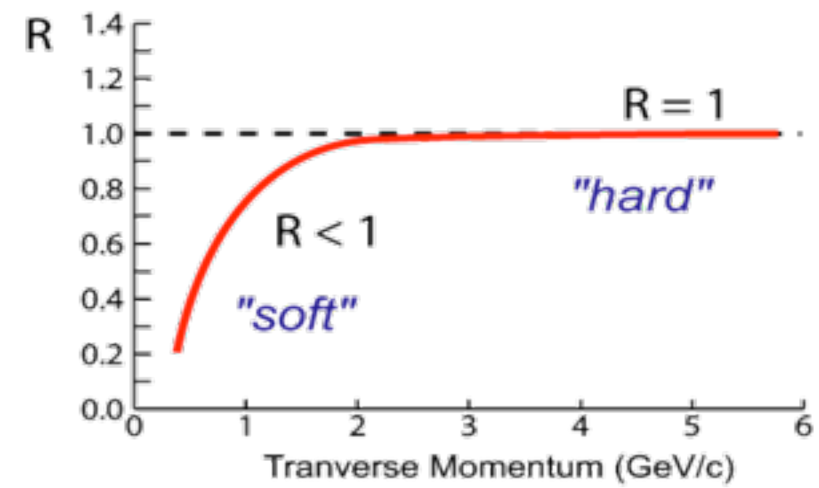

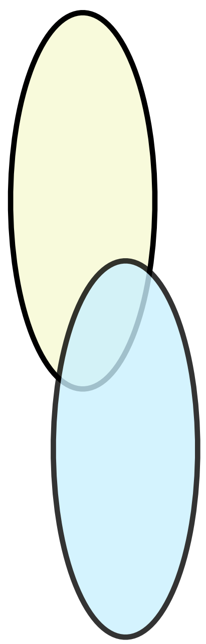

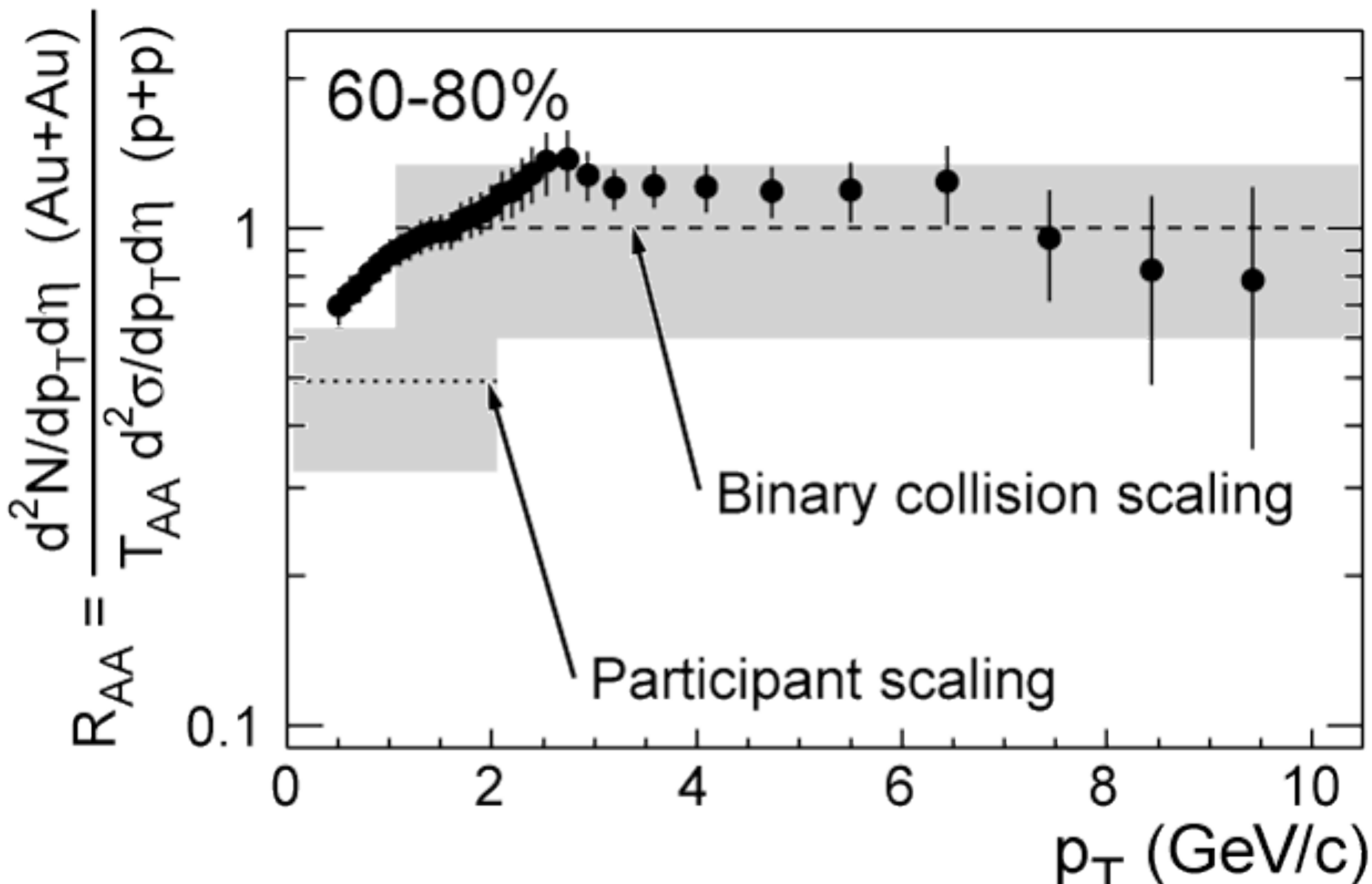

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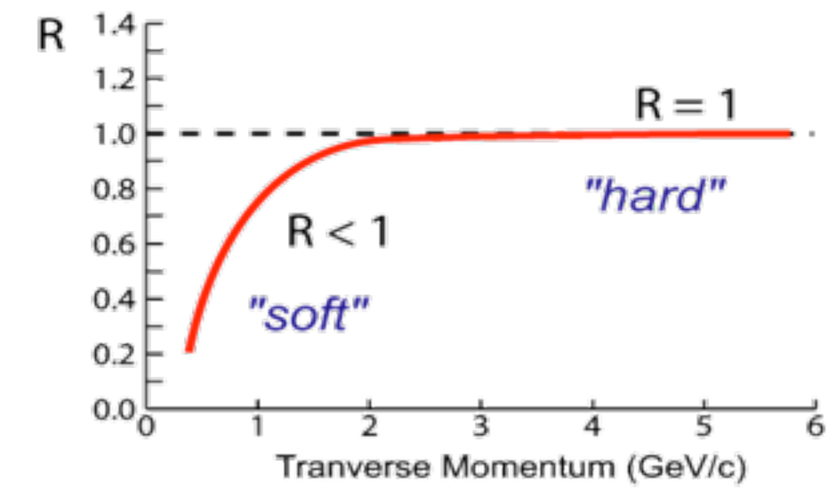
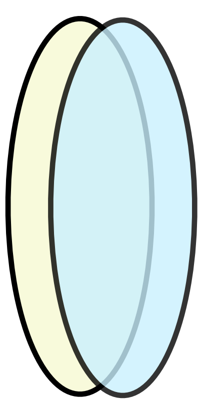
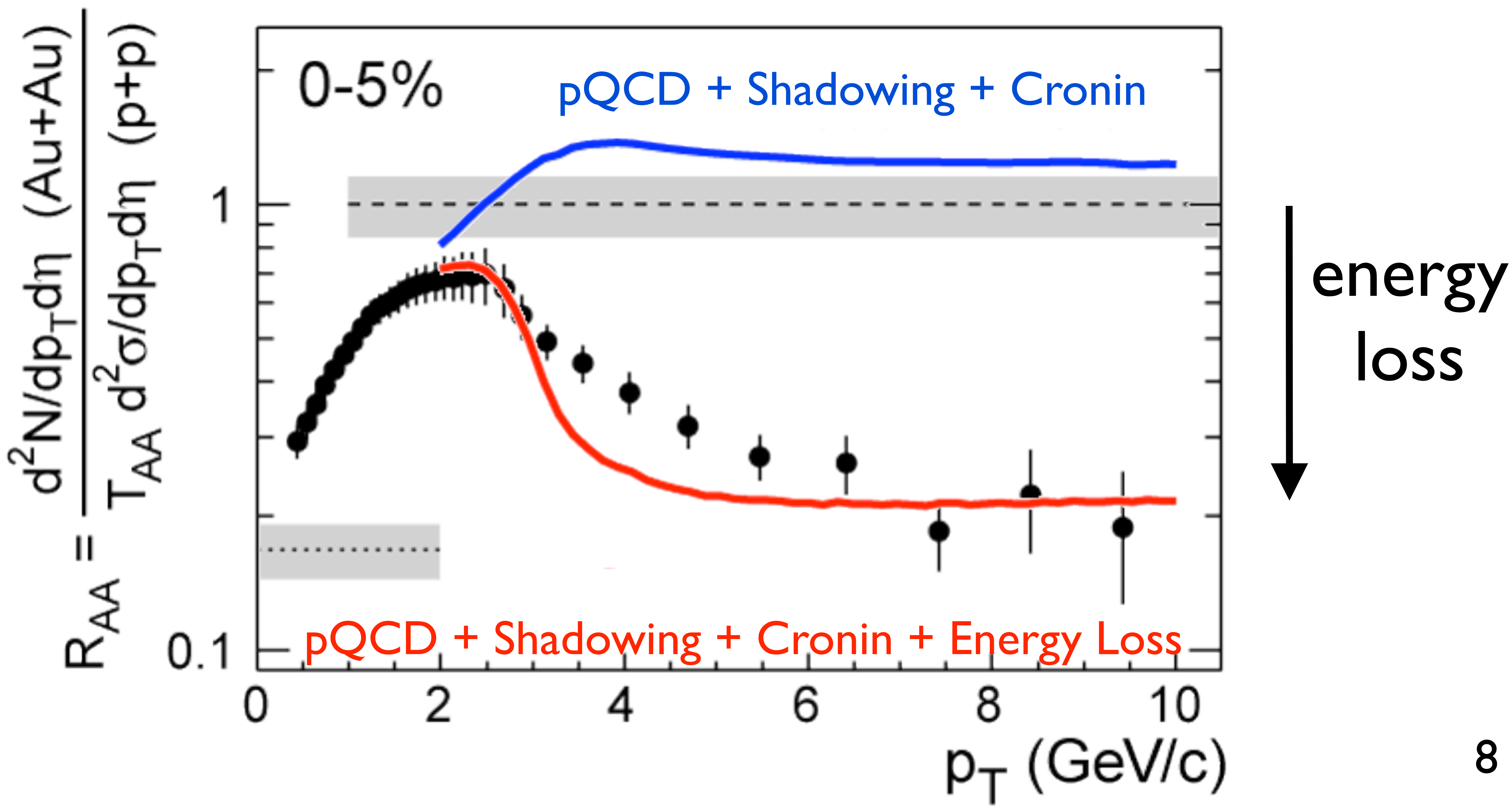
Suppression of inclusive hadron yield at high p_T

- Good quality measurements of single particle spectra as a function of collision centrality
- Increasing suppression as the A+A centrality increases
  - They appear to traverse dense opaque matter







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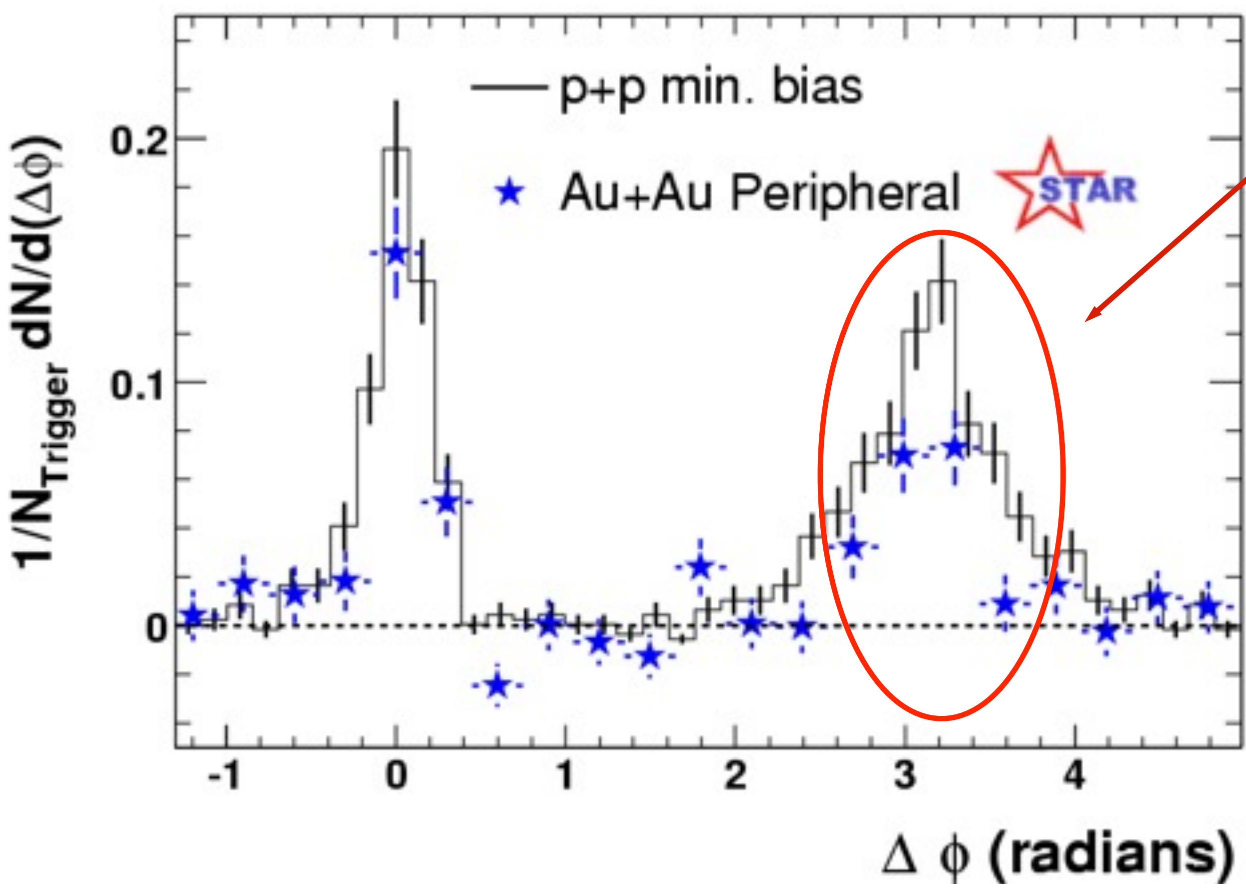
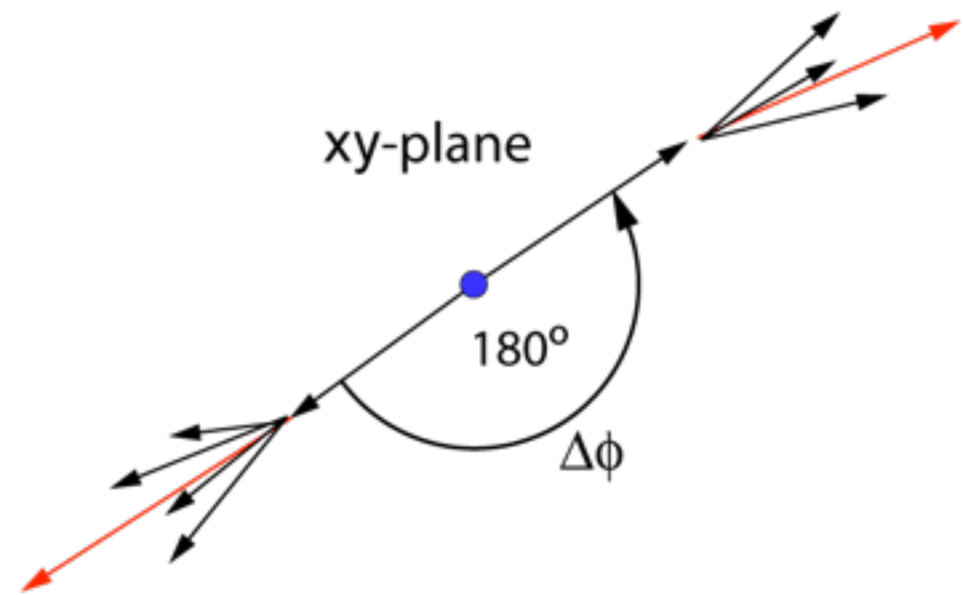
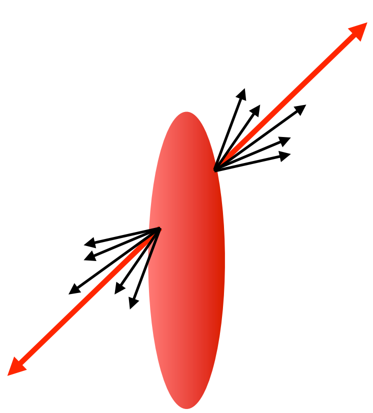
Suppression of 2-particle correlations



Back-to-back high-p_T hadrons are clearly seen in peripheral collisions.



Peripheral



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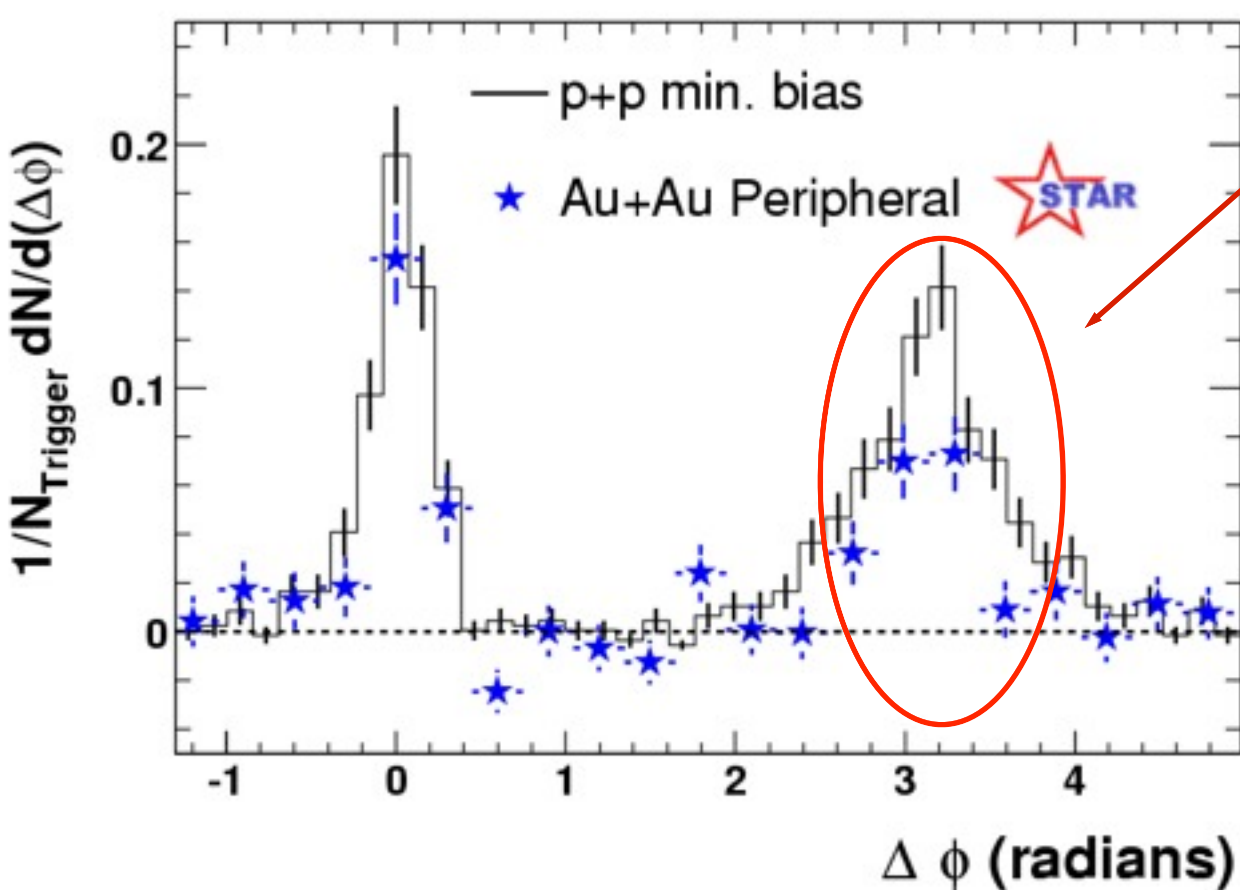
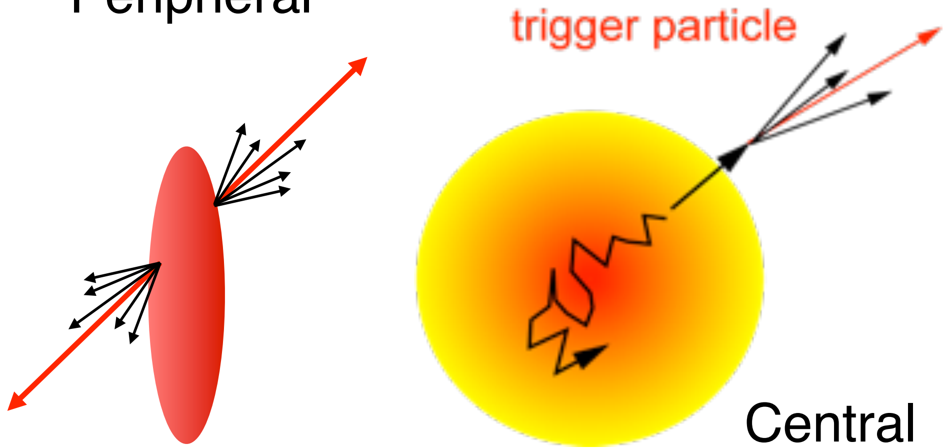
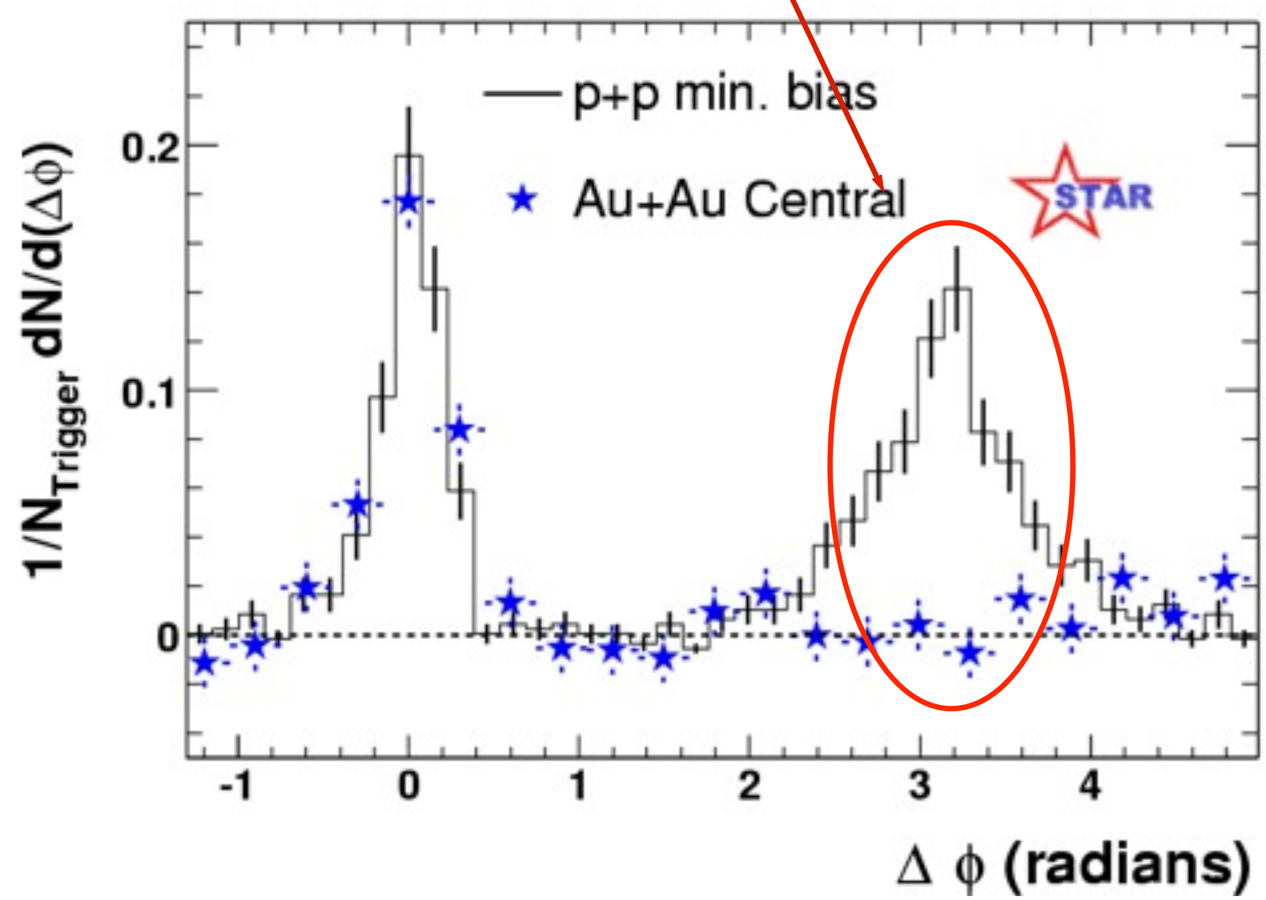


Back-to-back high-p_T hadrons are clearly seen in peripheral collisions.

Find an absence of back-to-back hadrons in central collisions





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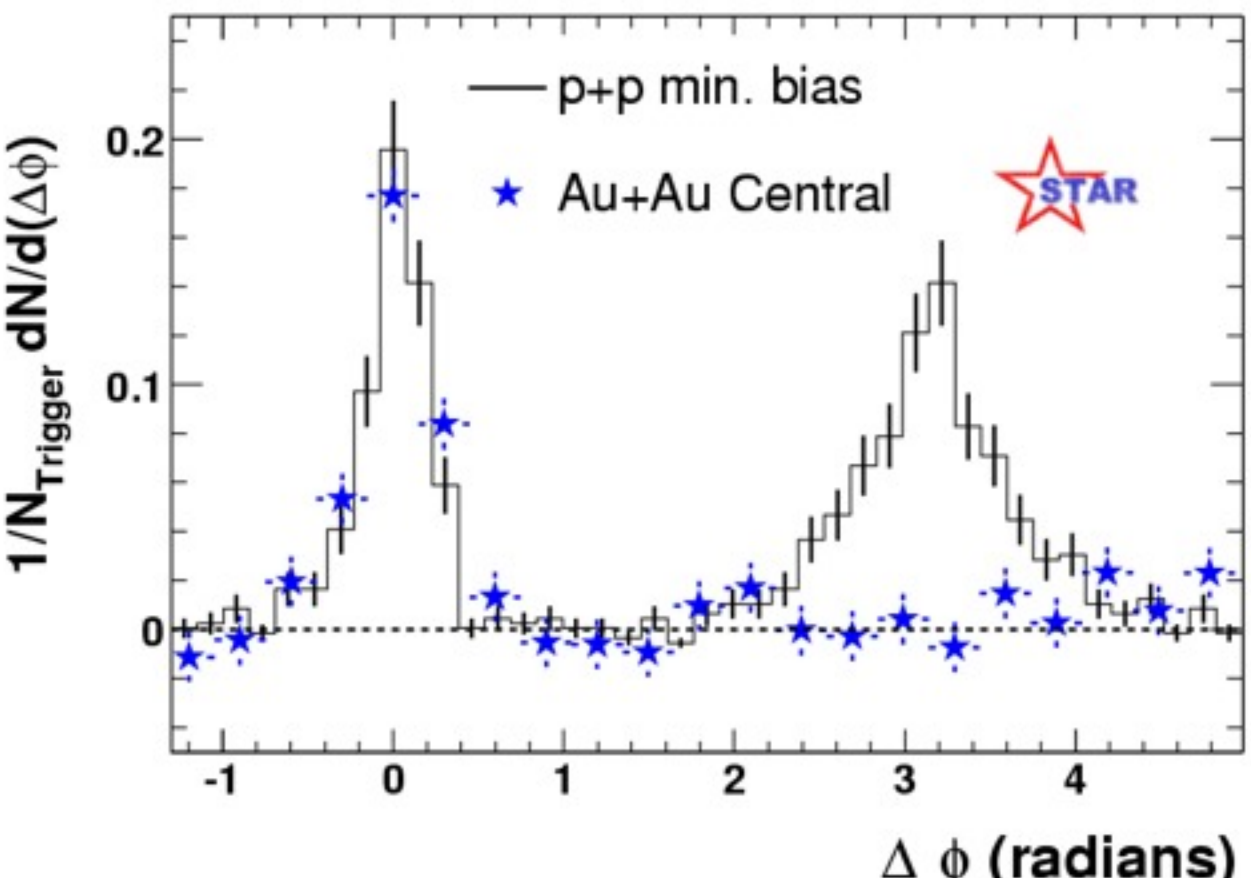
Jet suppression: final or initial state effect?



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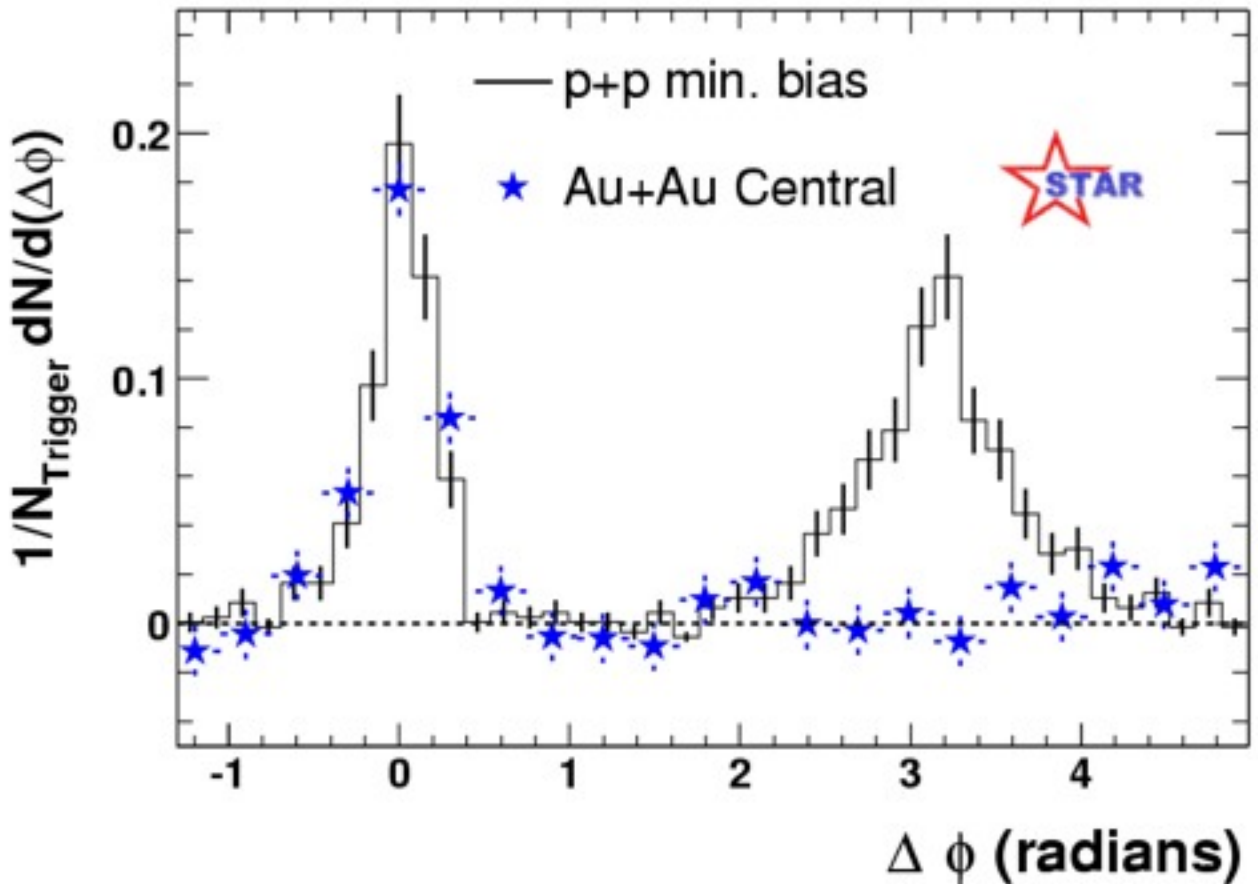
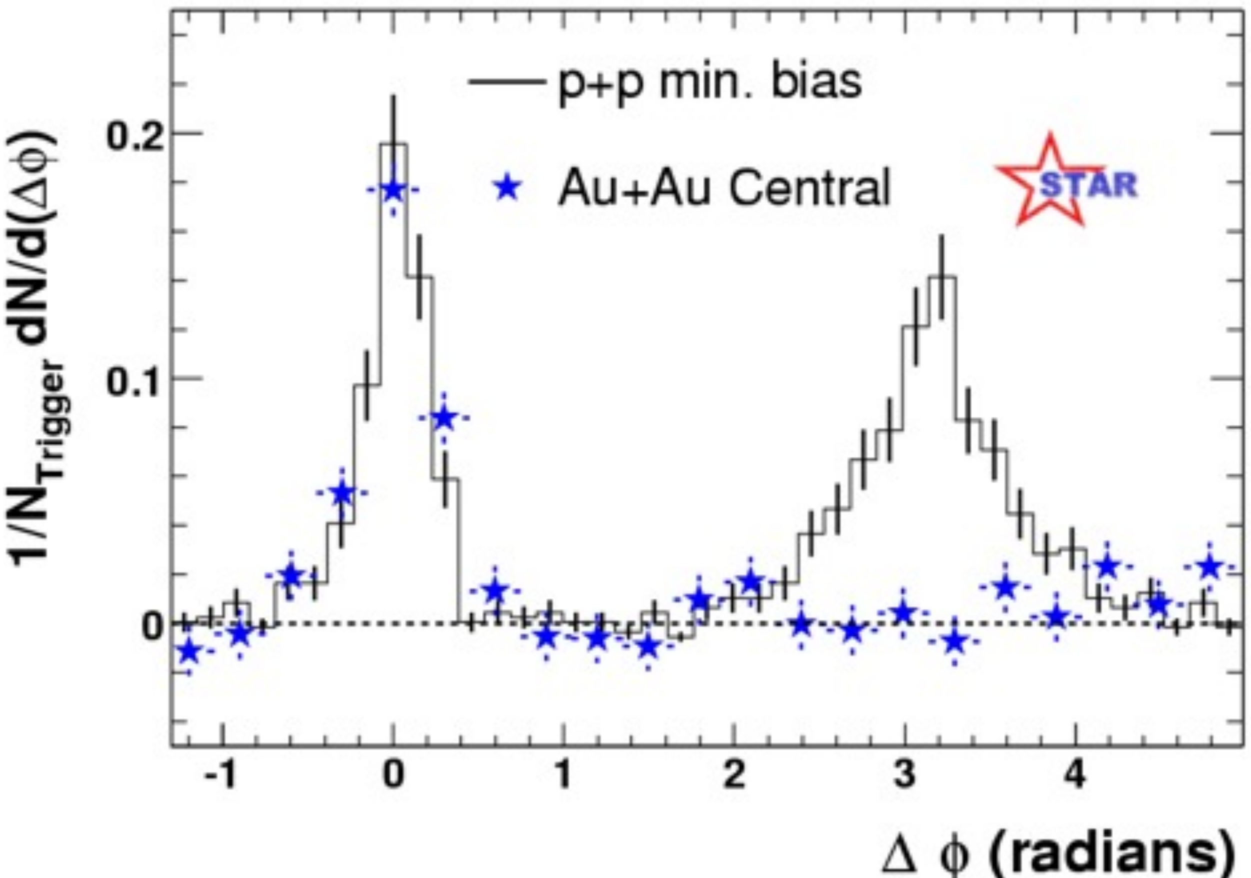
Jet suppression: final or initial state effect?

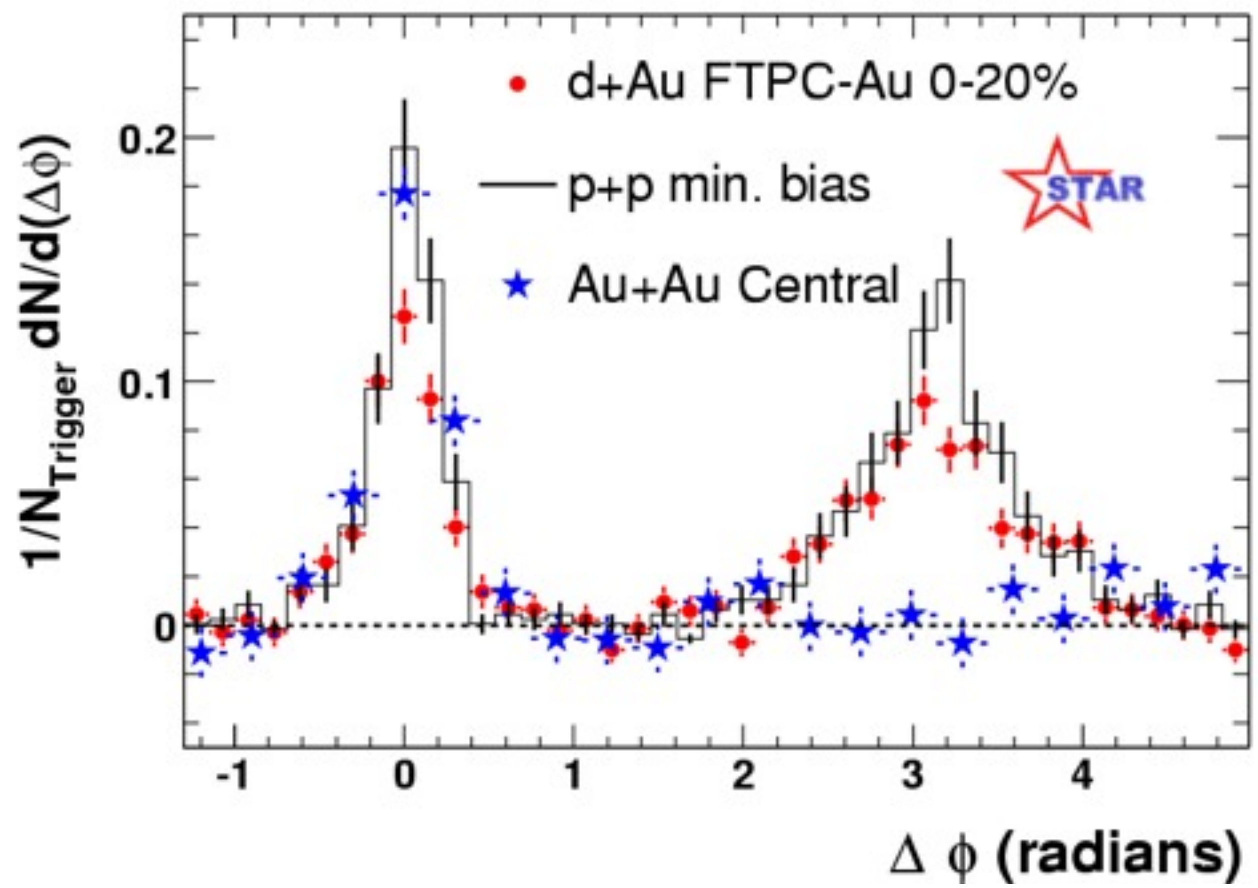
- In d+Au collisions, deconfinement is not expected
  - Measure correlations in d+Au collisions to determine if this is an initial or a final state effect



Jet suppression: final or initial state effect?

- In d+Au collisions, deconfinement is not expected
  - Measure correlations in d+Au collisions to determine if this is an initial or a final state effect
- No suppression is observed in d+Au collisions at **mid-rapidity** at RHIC
  - Jet suppression a final state effect?





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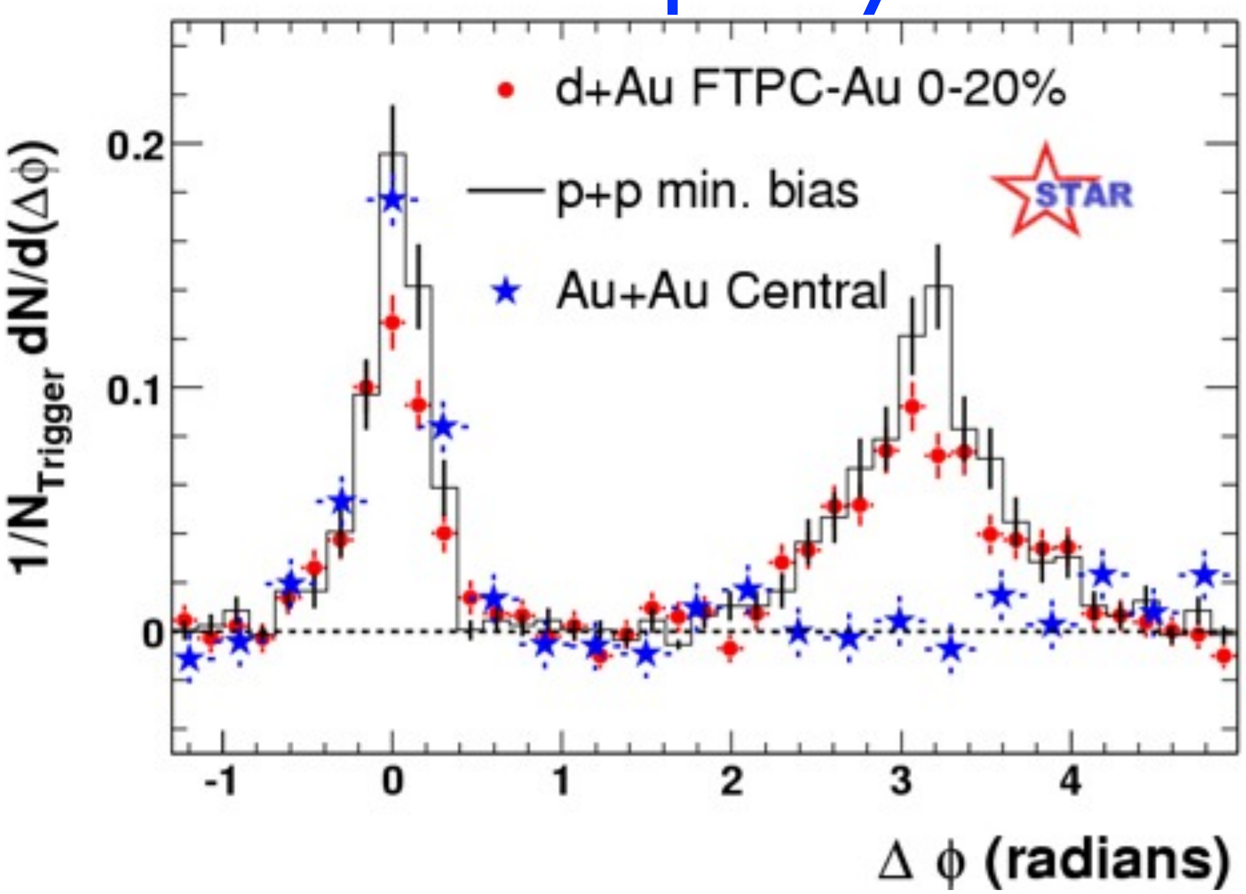
⇐ these and comparisons to models led to the "perfect fluid" hypothesis

Paradigm shift:

strongly coupled QGP = sQGP

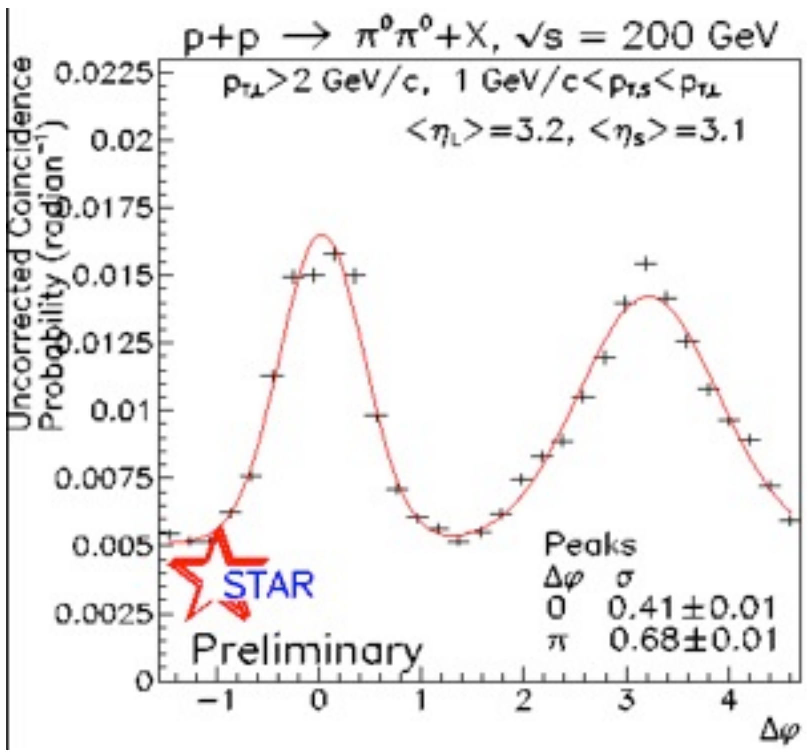
Saturation at RHIC: correlations at forward rapidities

mid-rapidity



Saturation at RHIC: correlations at forward rapidities

p+p



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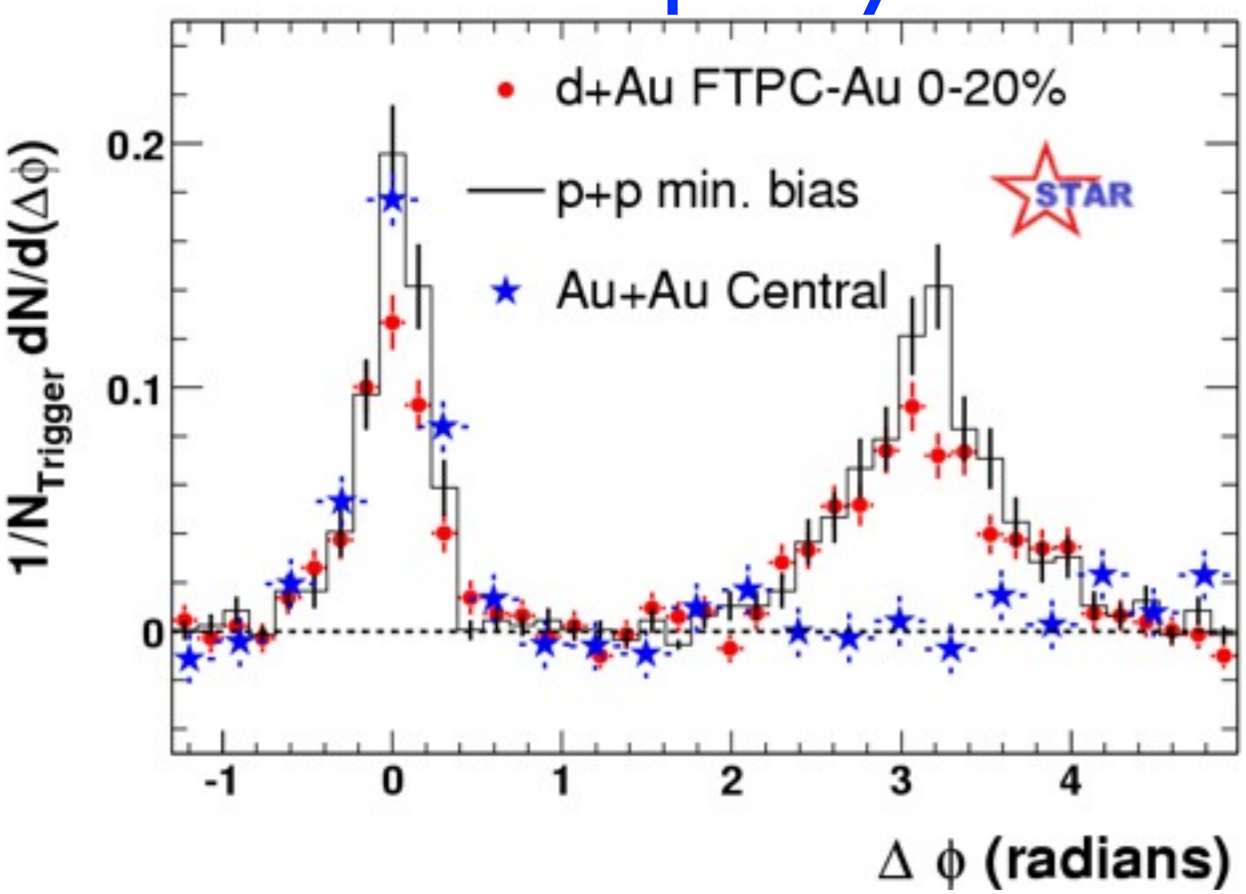

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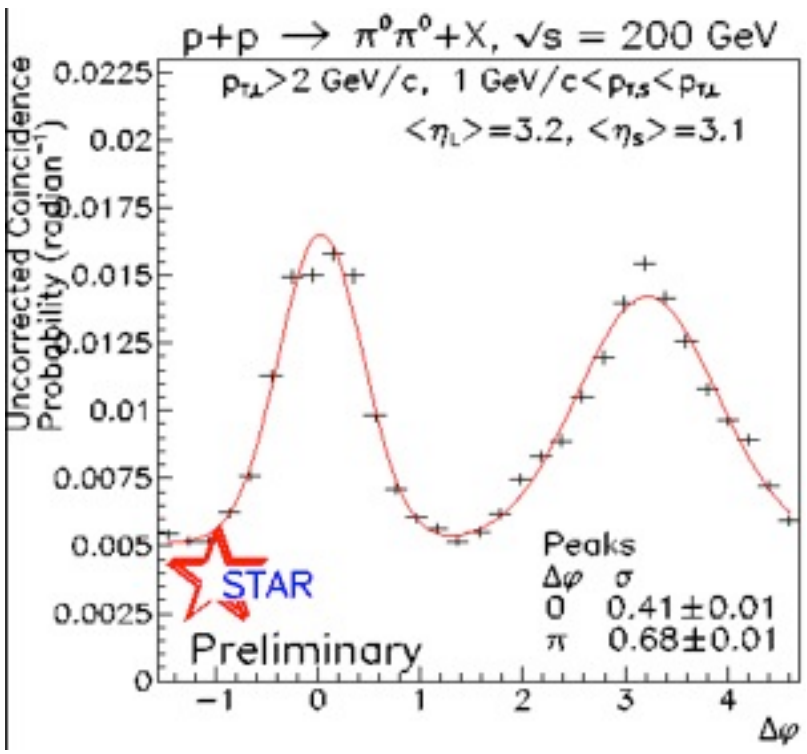
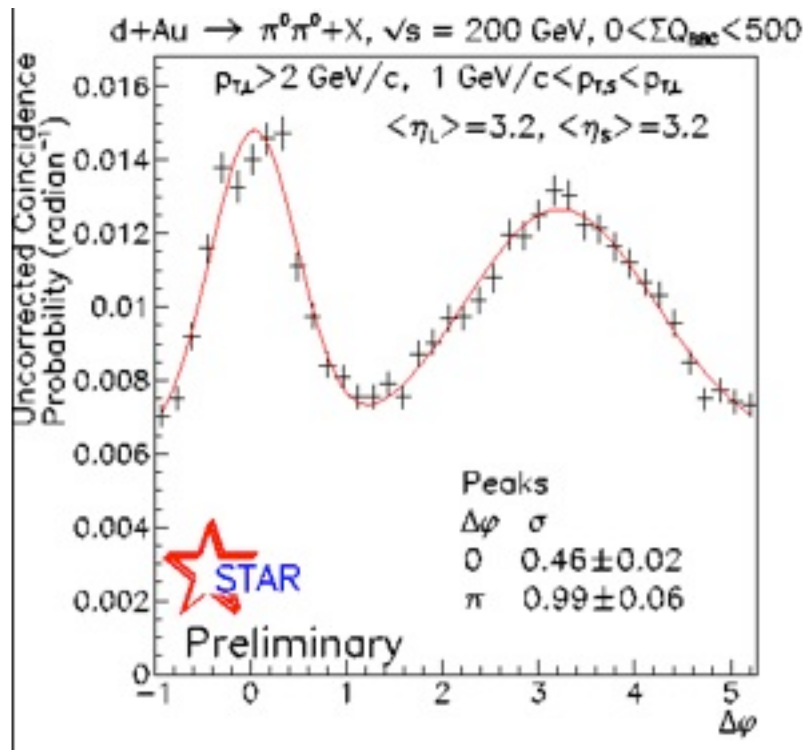
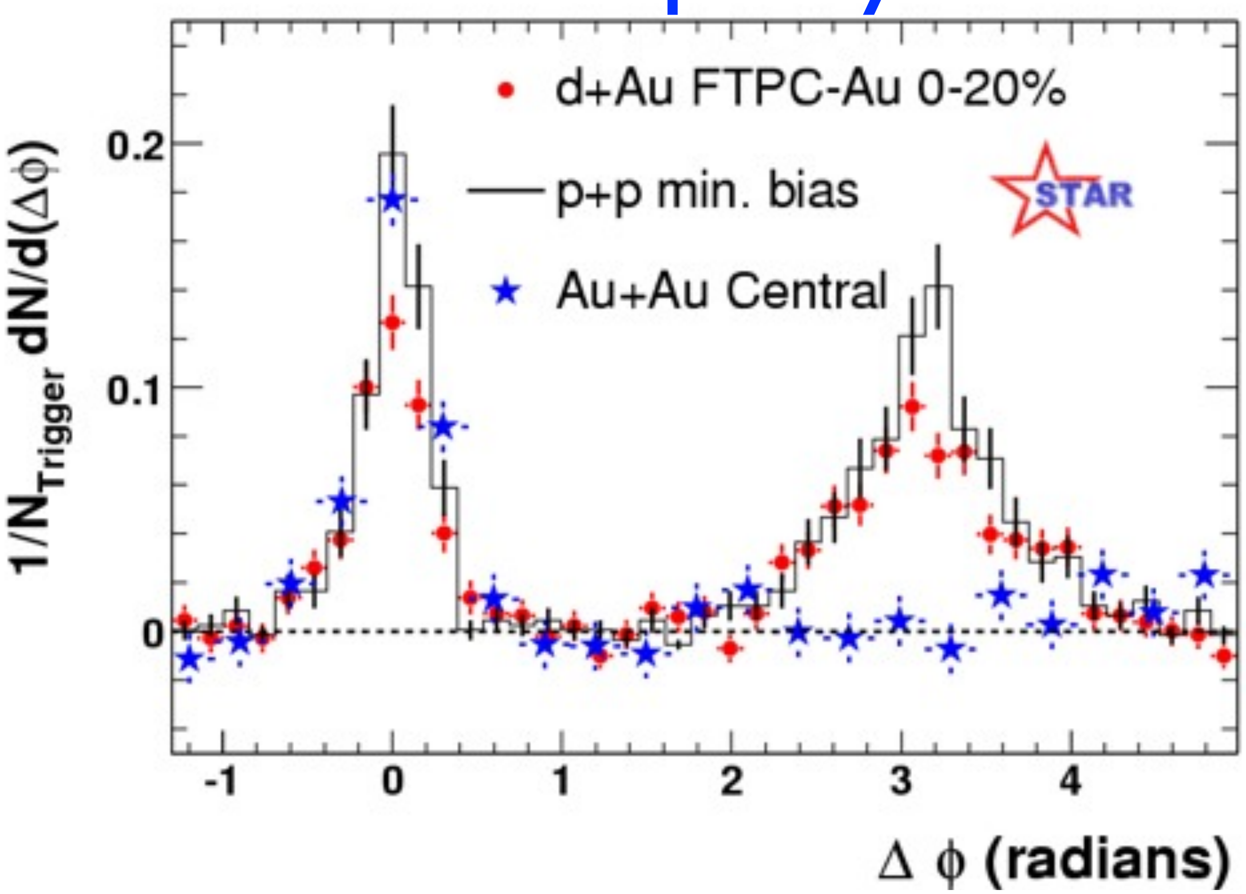


d+Au peripheral



mid-rapidity



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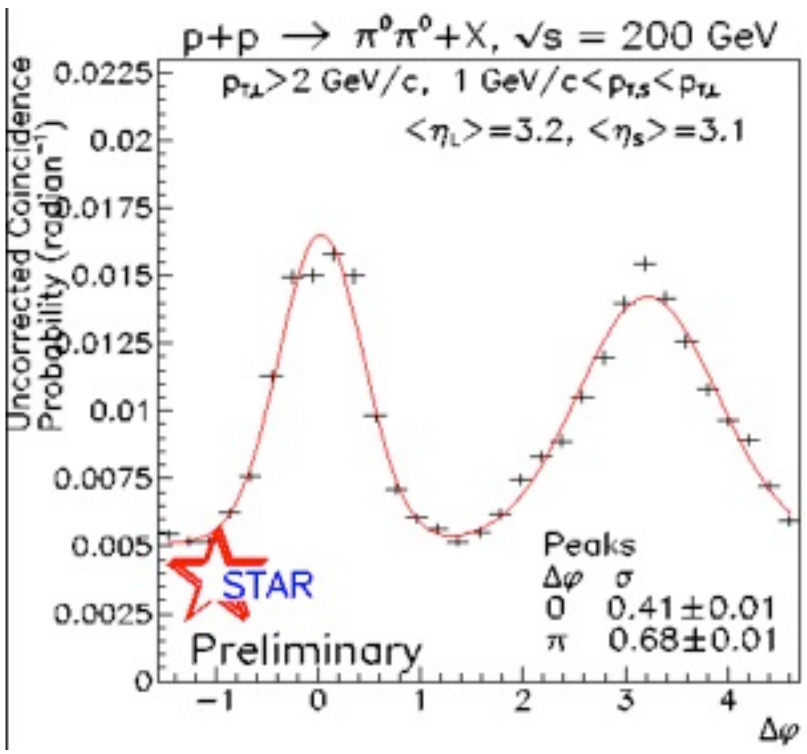
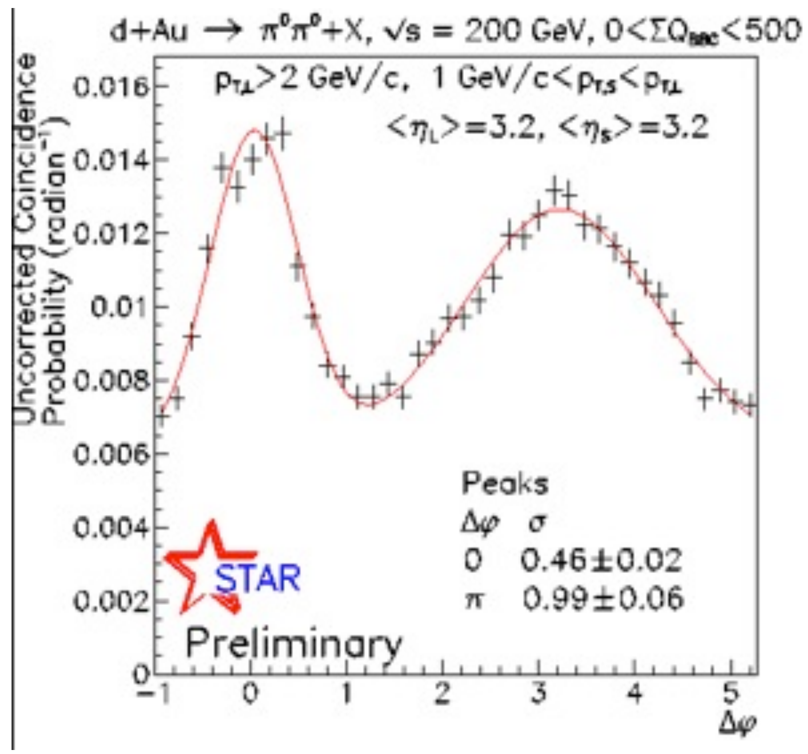
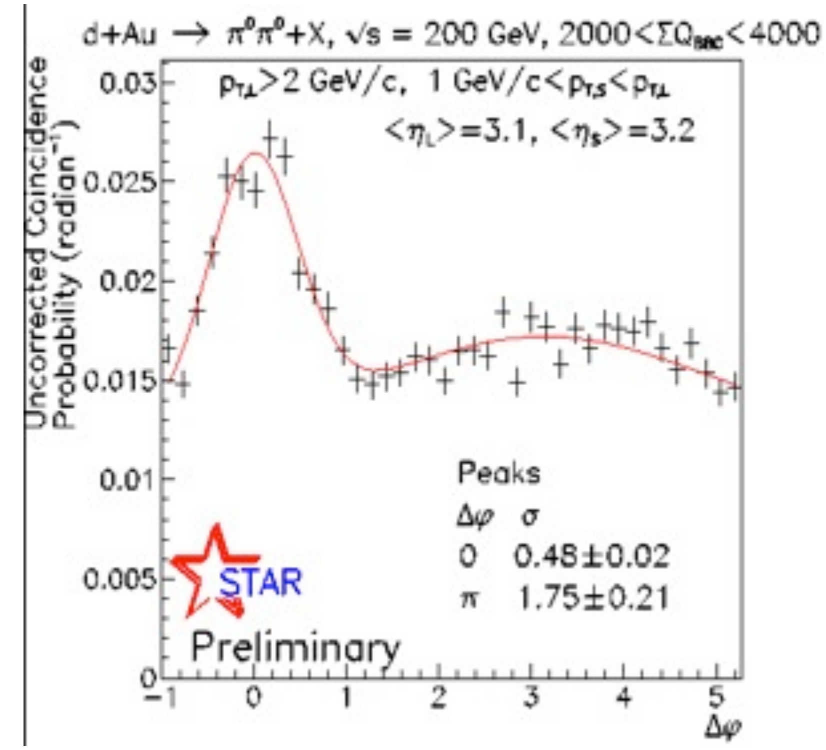


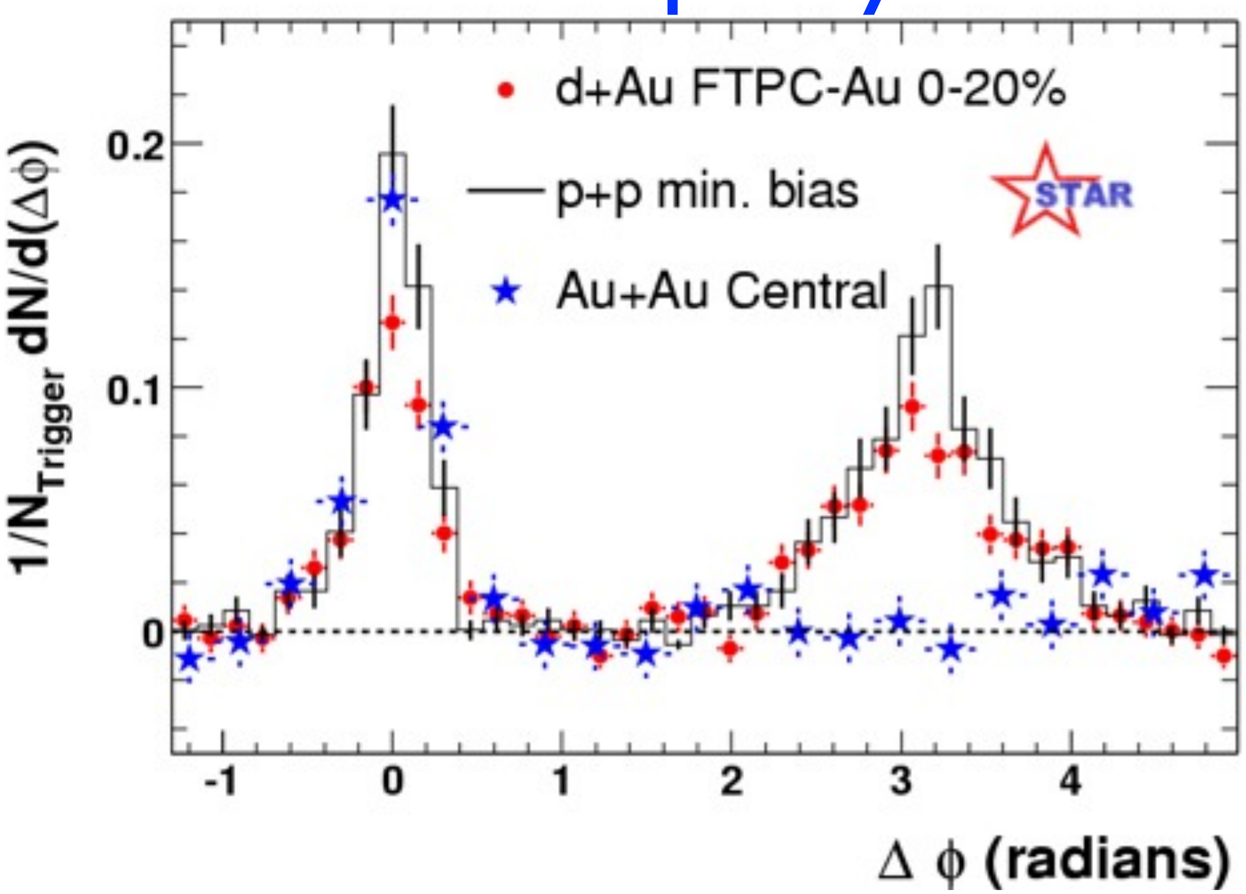
d+Au peripheral



d+Au central

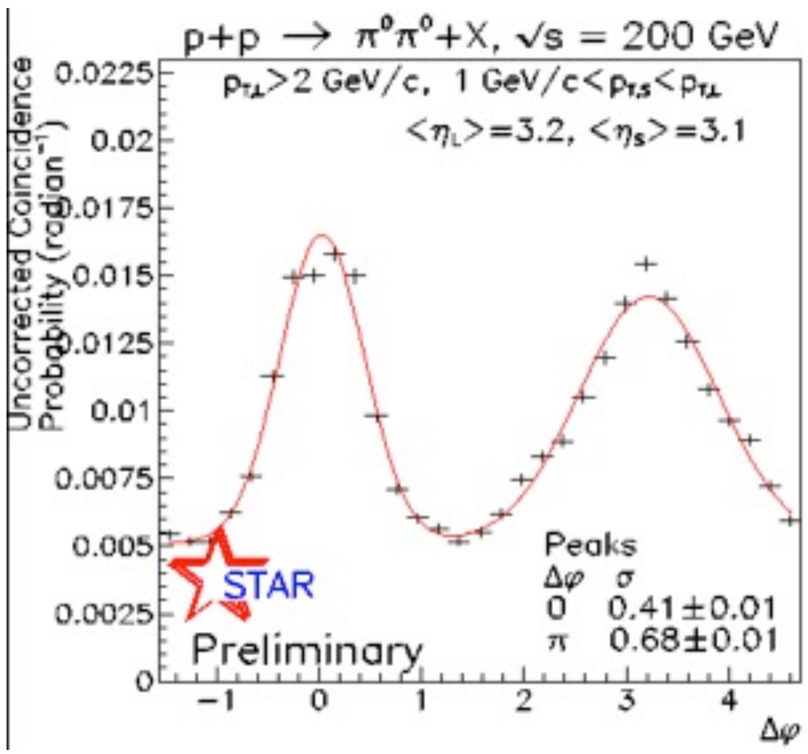


mid-rapidity

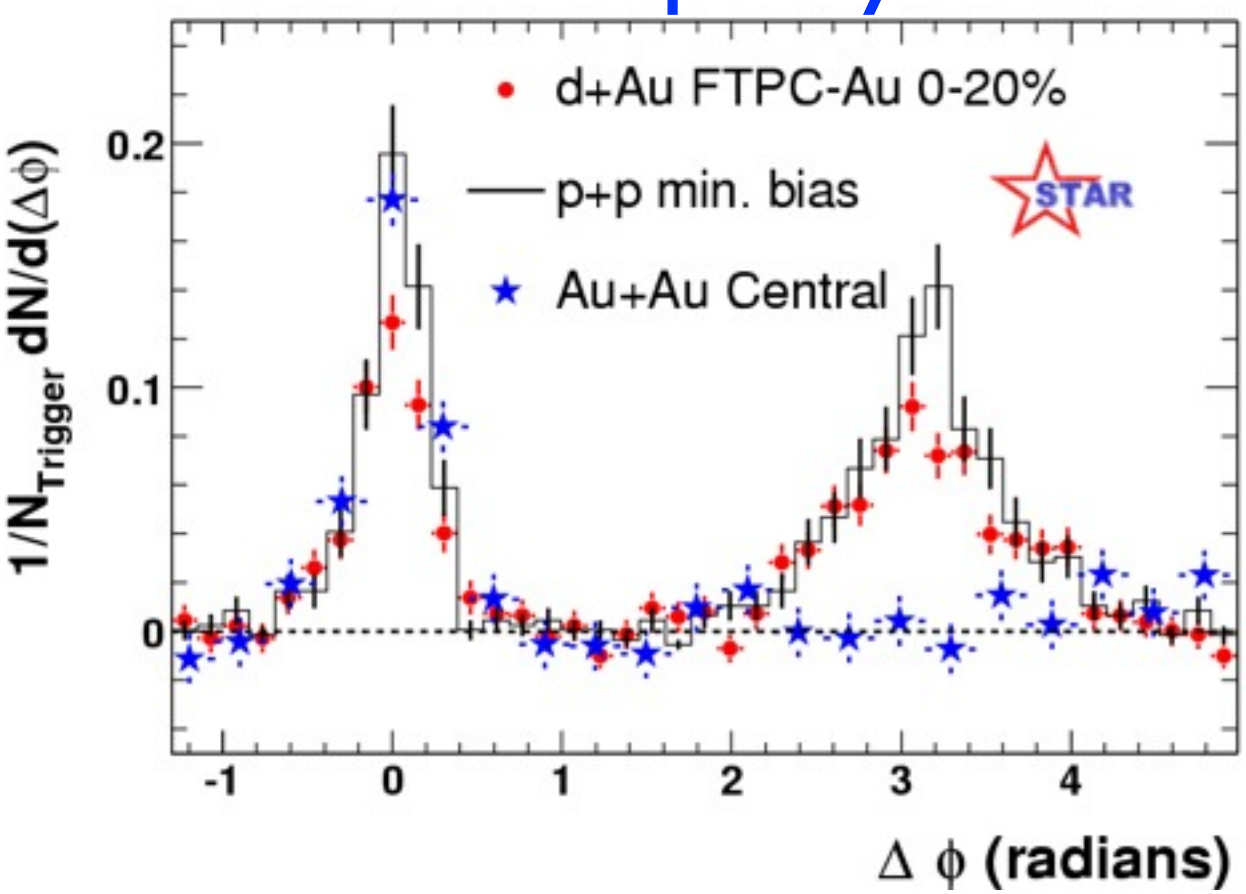


Saturation at RHIC: correlations at forward rapidities

p+p



mid-rapidity



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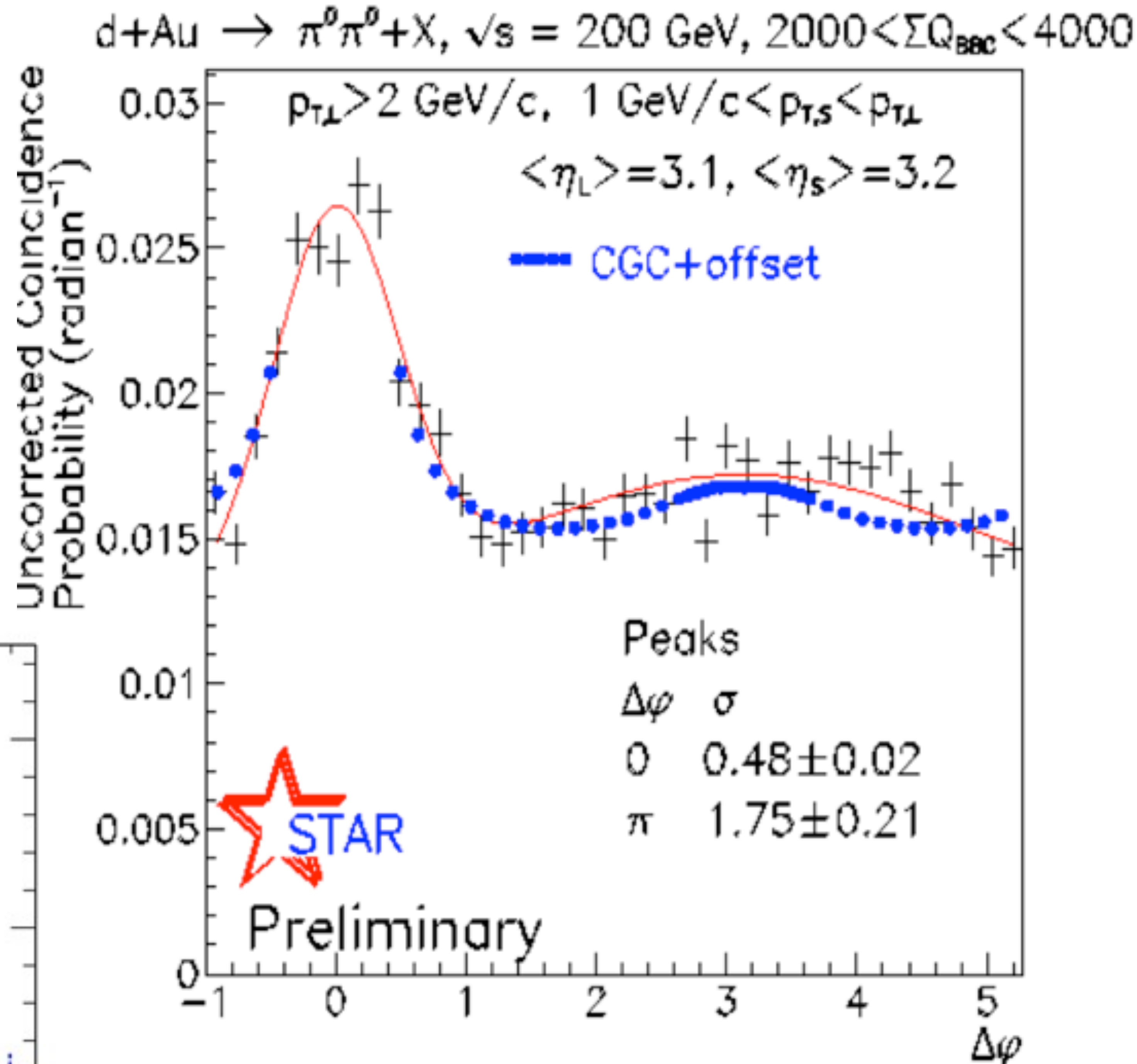
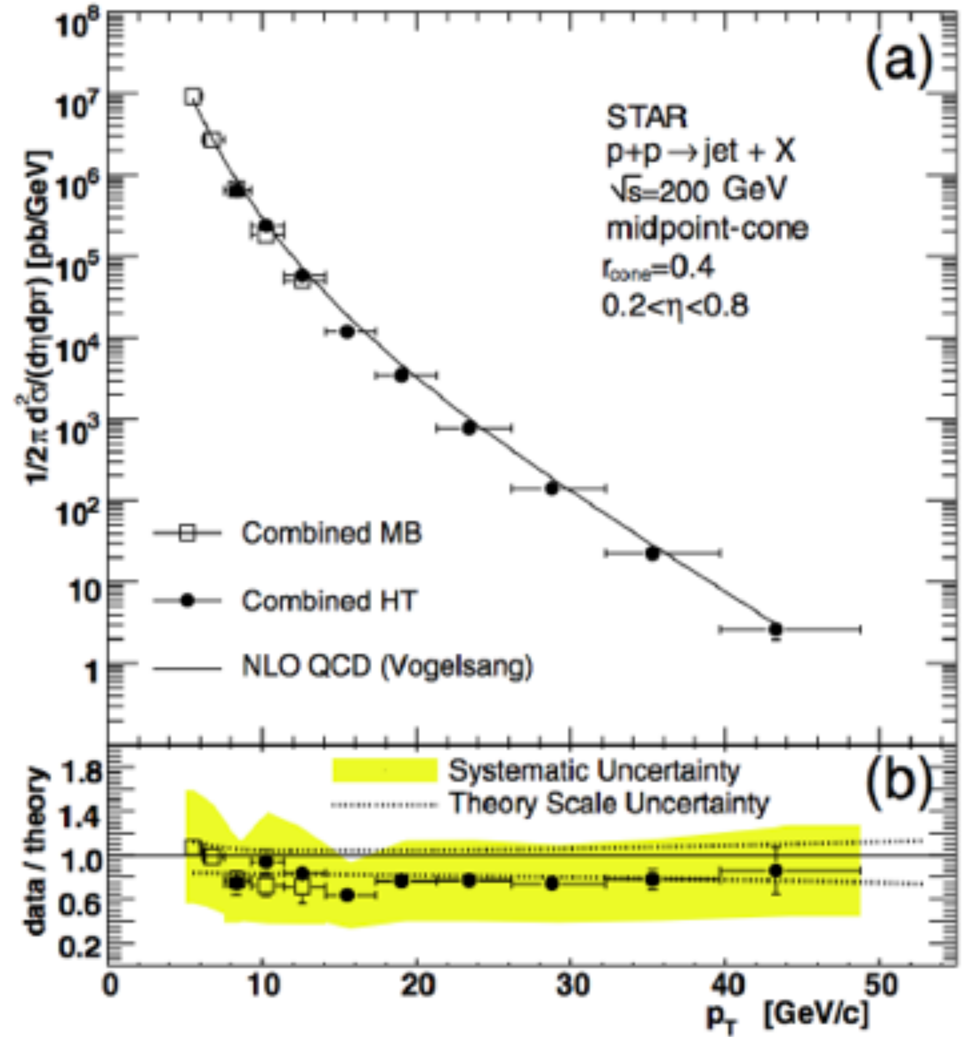
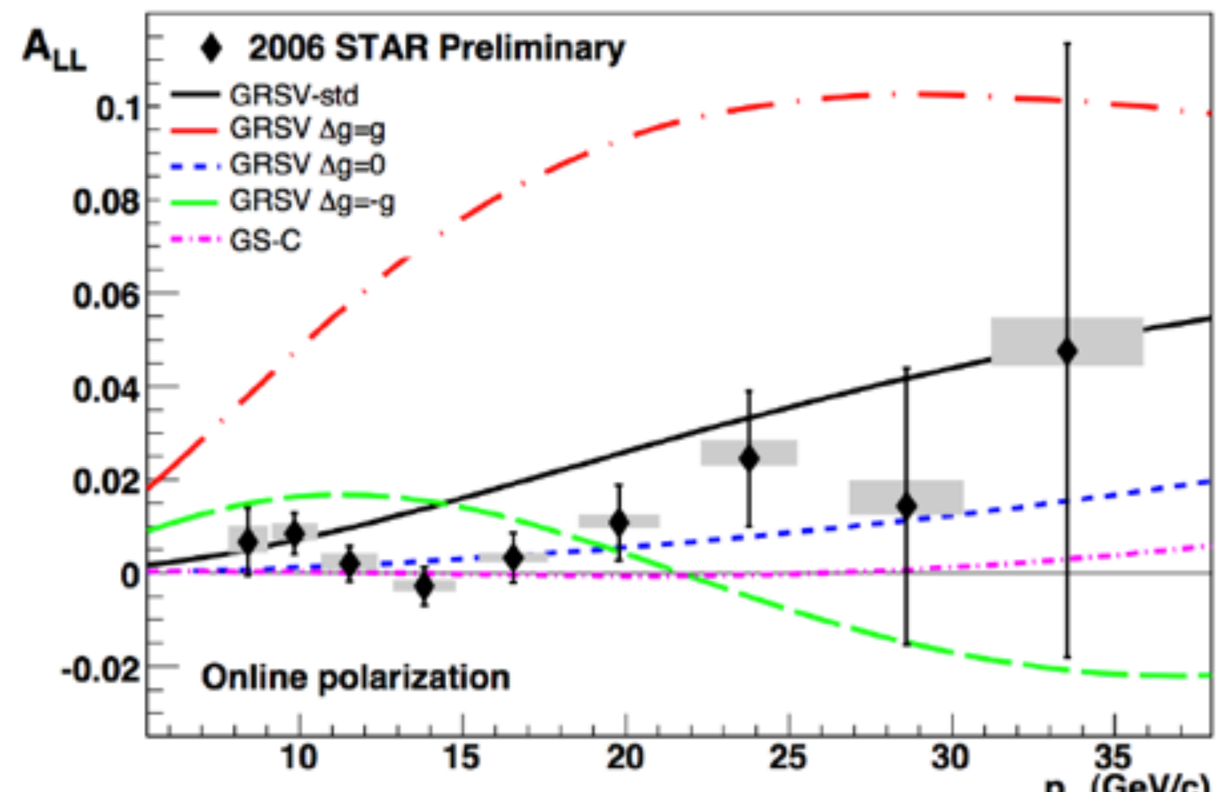


Model: Nucl.Phys.A796:41-60,2007

Spin Results

- The main aim of the RHIC polarised proton running is the measurement of Δg(x) at medium-x (0.01<x<0.3).
- Inclusive jet-yield is well reproduced by NLO pQCD calculations
  - Can use NLO pQCD to extract Δg(x) from measurements of A_{LL}
  - Measurement good enough to discriminate between some GRSV scenarios
- Lot more to do in the spin programme
  - Running at √s=500 GeV increases the x-range and available measurements





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Questions remaining to be answered

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- Despite RHIC's successful 1st decade - unanswered questions remain:
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  - What are the properties of the sQGP? How does it thermalise?
  - Are the interactions of energetic partons with QCD matter characterised by strong or weak coupling? What is the detailed mechanism of partonic energy loss?
  - Where is the QCD critical point and the first-order phase transition line?
  - Can we strengthen the current evidence for novel symmetries in QCD matter and open new avenues?
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STAR

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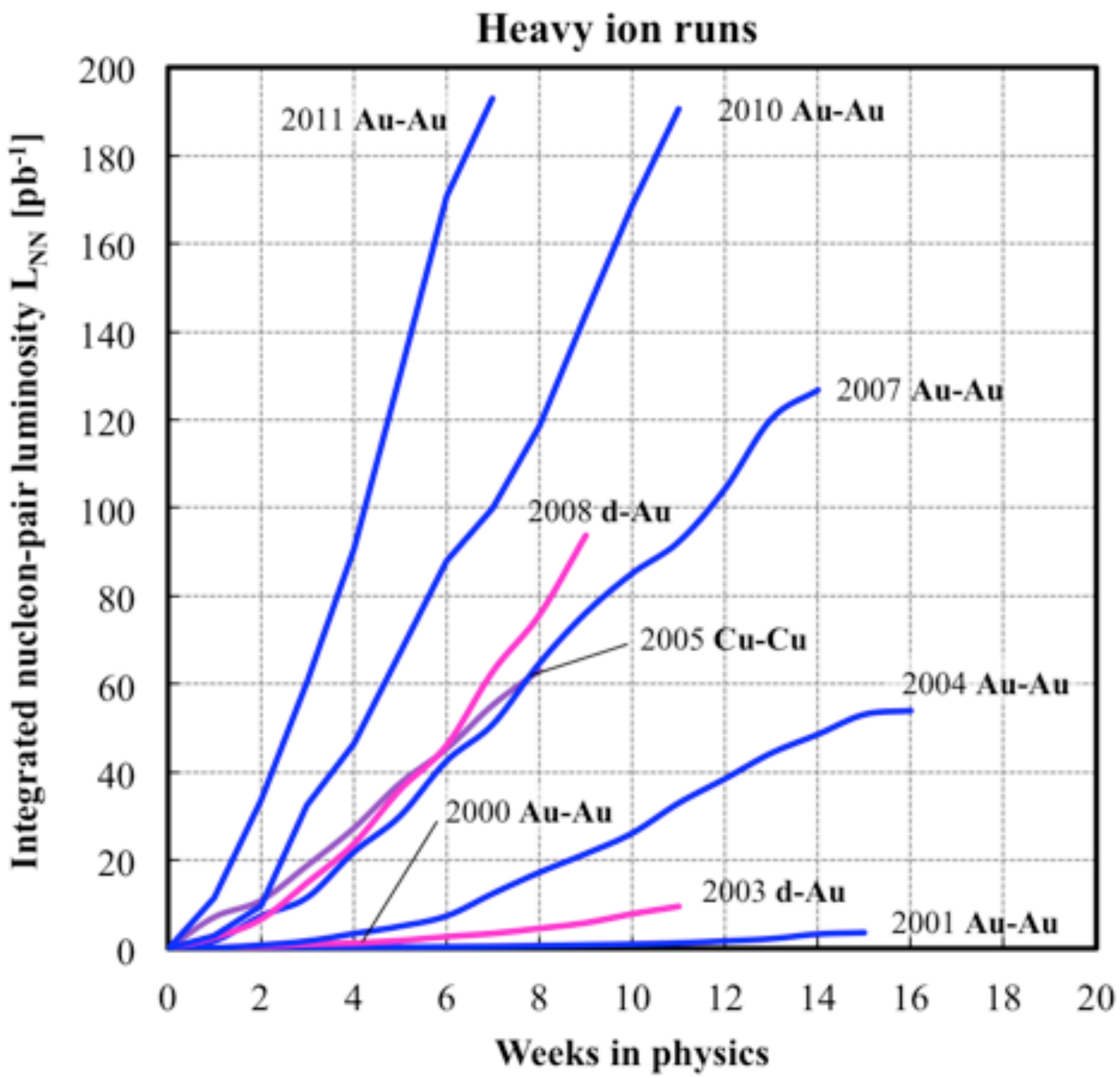
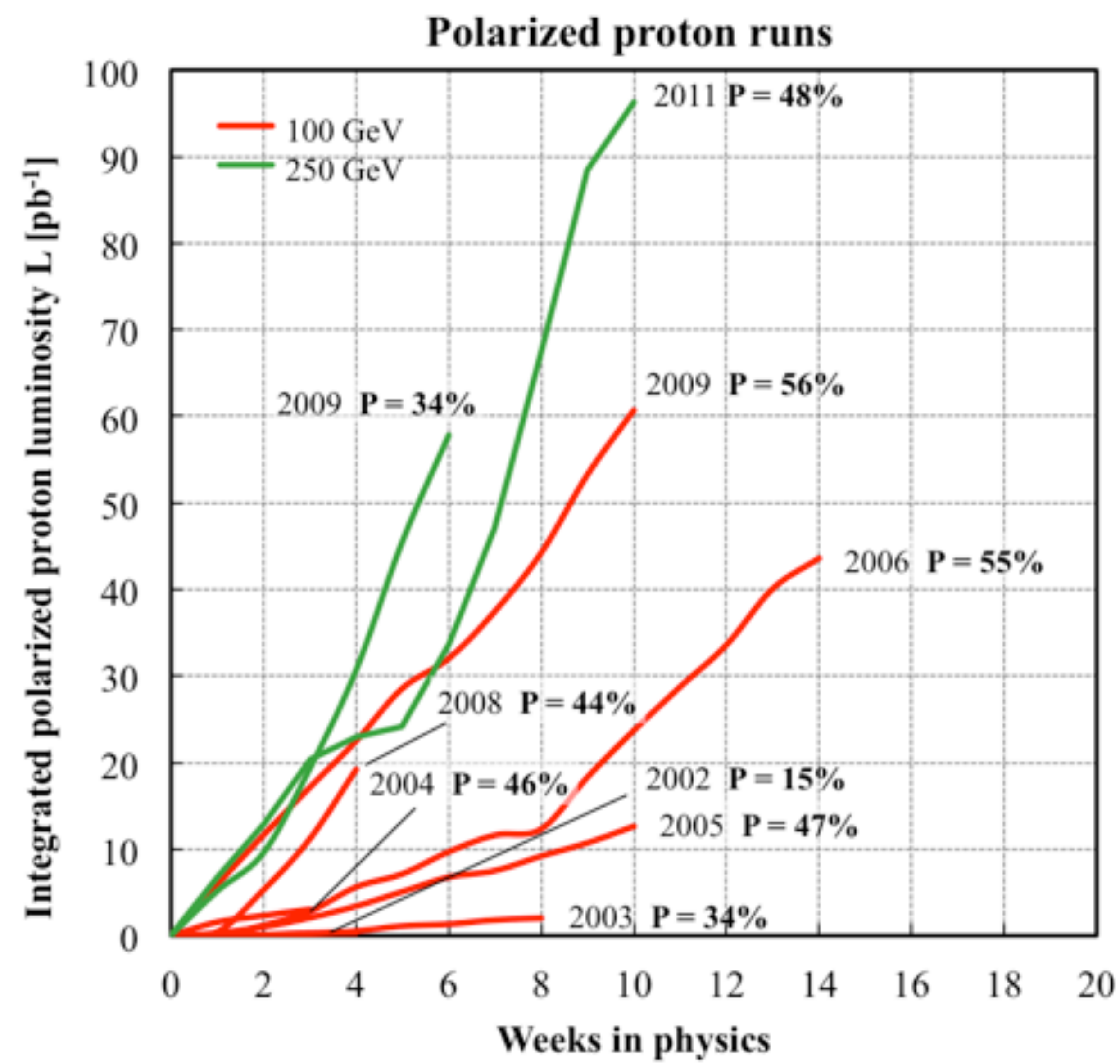
- p/d+A
  - What is the nature of the initial state in nuclear collisions?
- p+p
  - What is the partonic spin structure of the proton?
  - How do we go beyond leading-twist and collinear factorisation in pQCD?

STAR

RHIC's improvement with age….



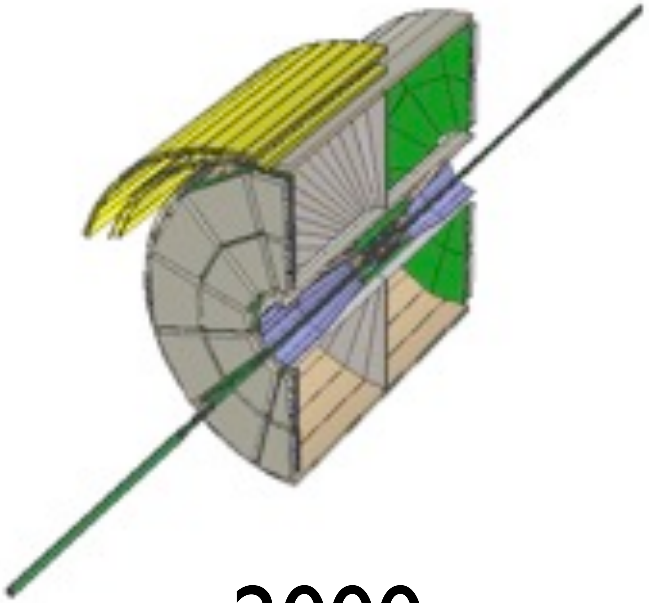


Plots courtesy of W. Fischer, C-AD

- As RHIC has improved luminosity, so STAR has improved
  - 2001: TPC DAQ ~ 8 Hz (when the stars aligned)
  - 2012: TPC DAQ ~ 1.8 kHz (test run planned for 10 kHz)

STAR

STAR through the ages



2000

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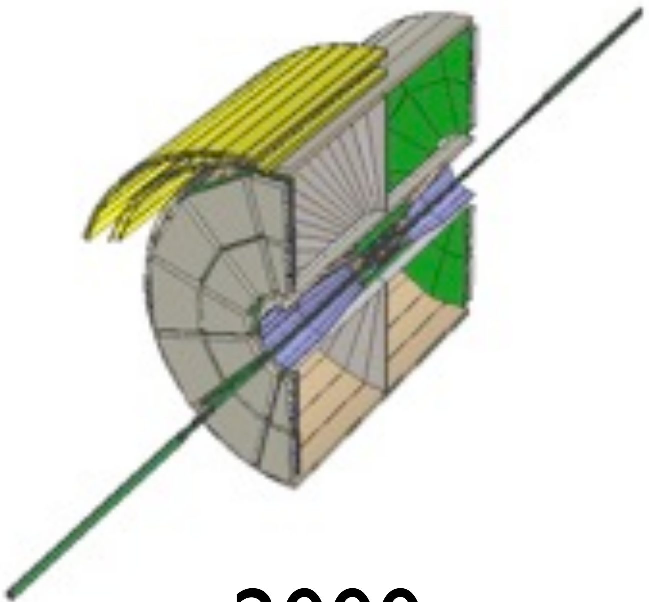

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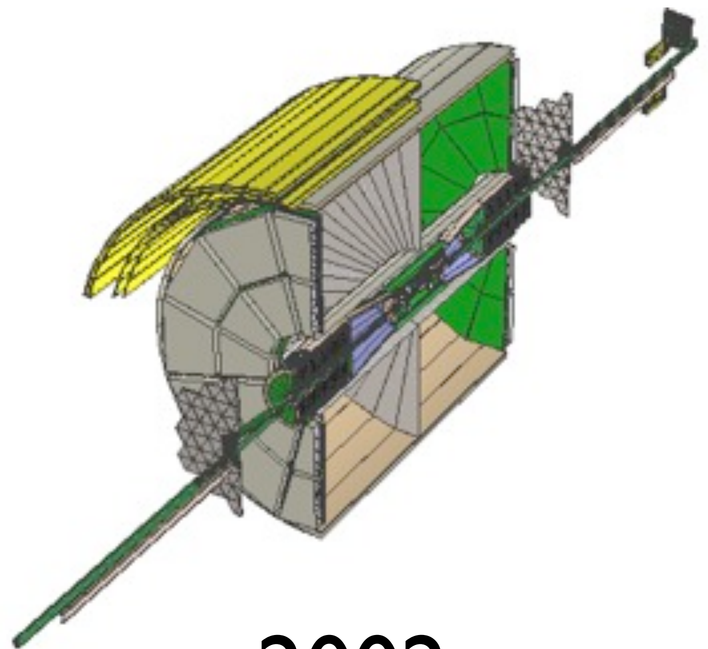

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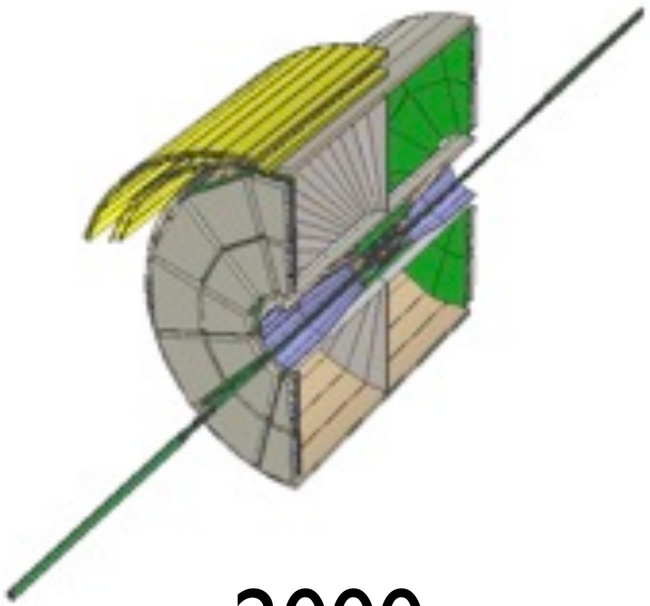

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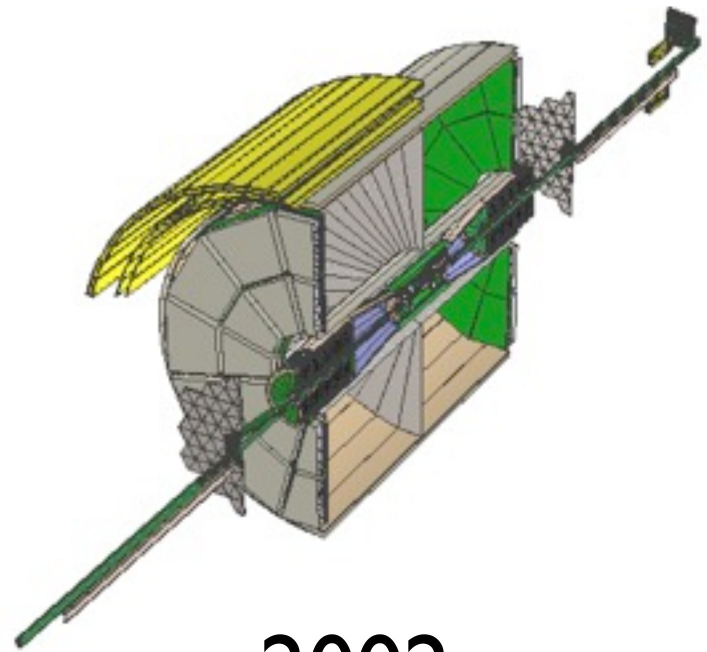

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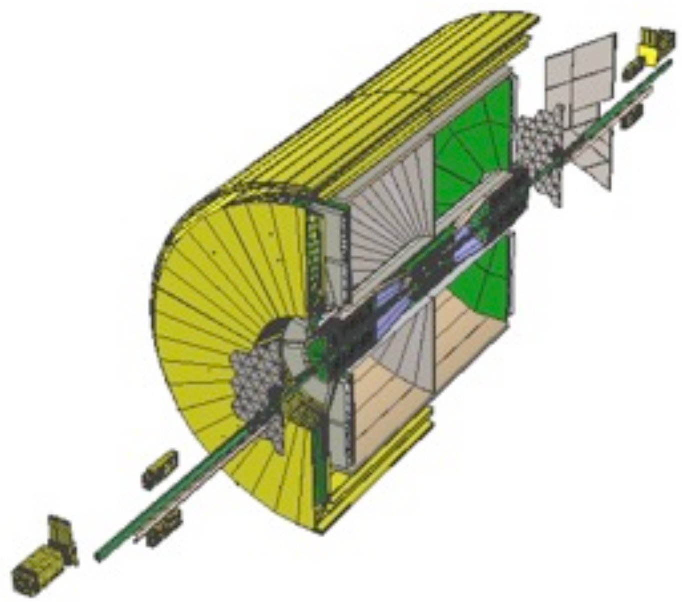

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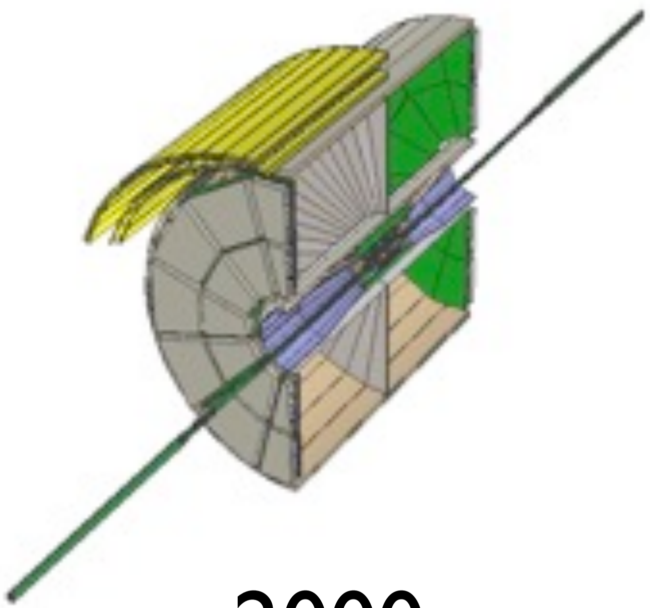
STAR through the ages



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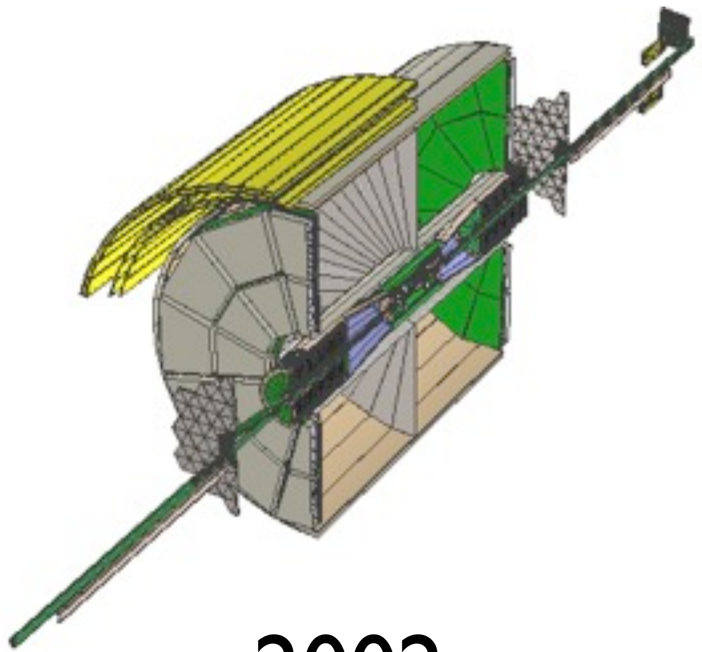

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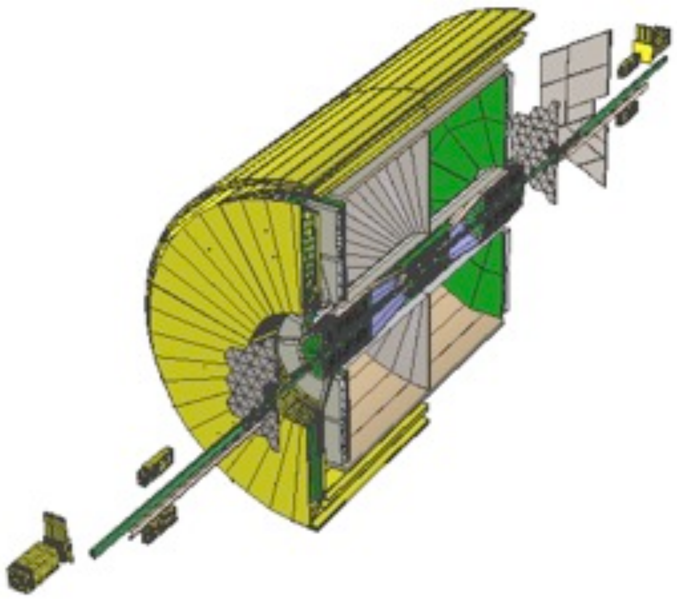

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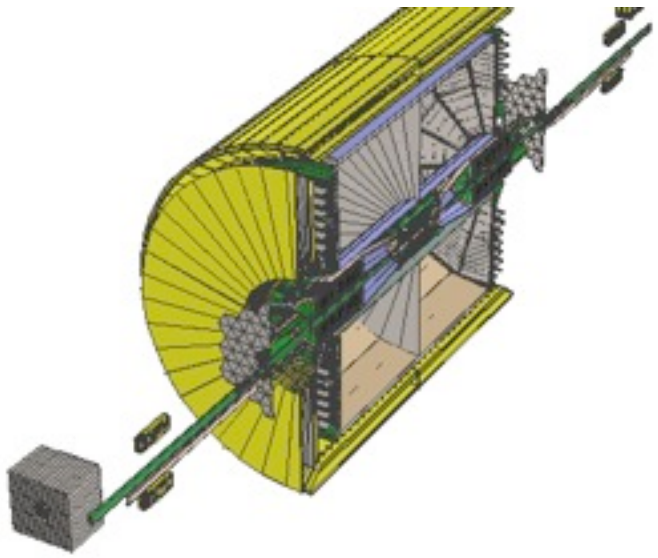

2006

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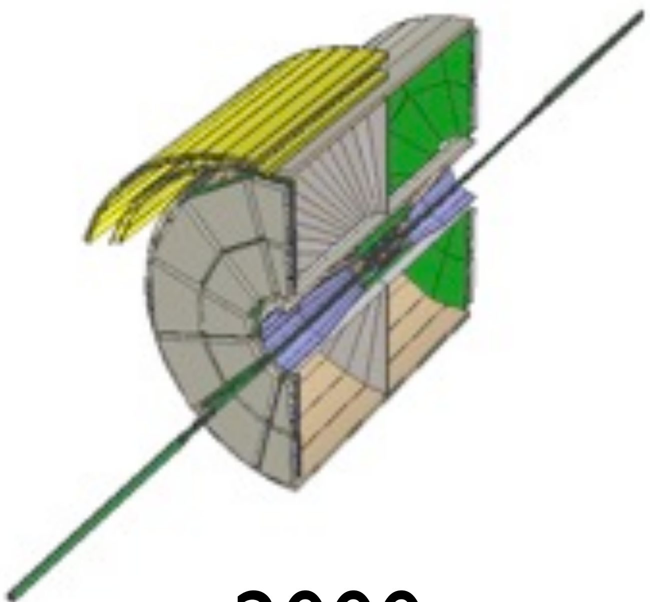

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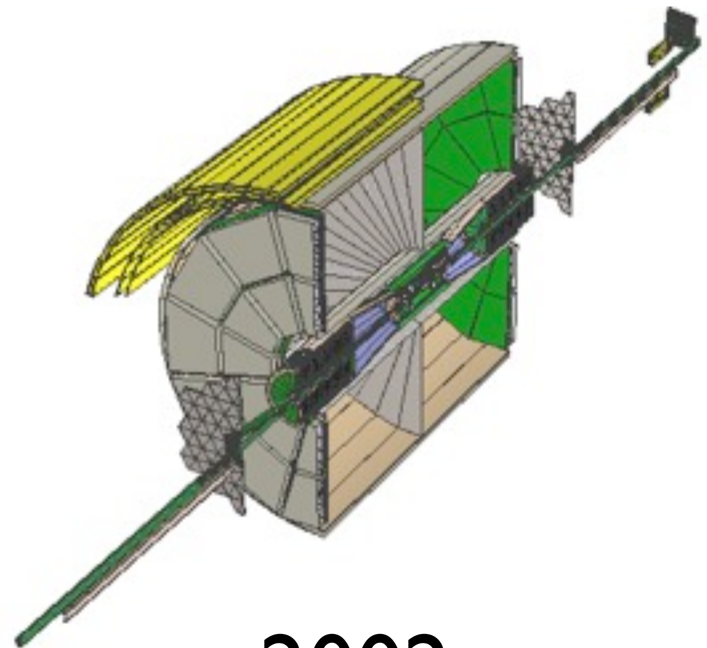

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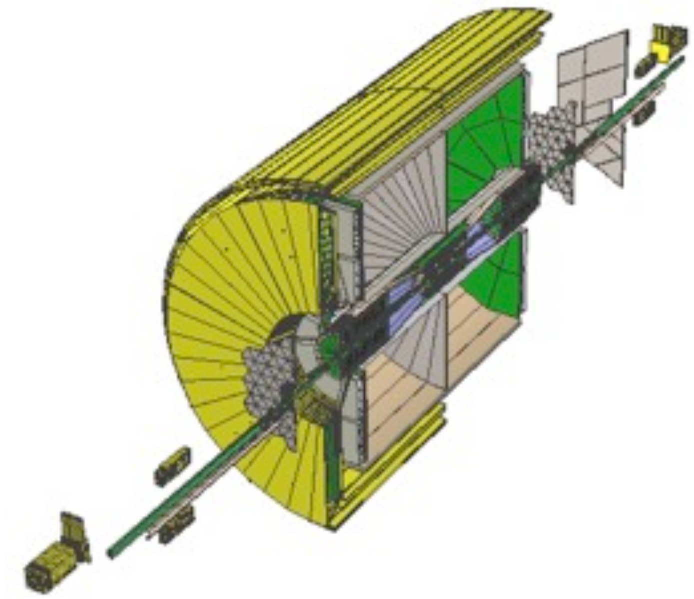

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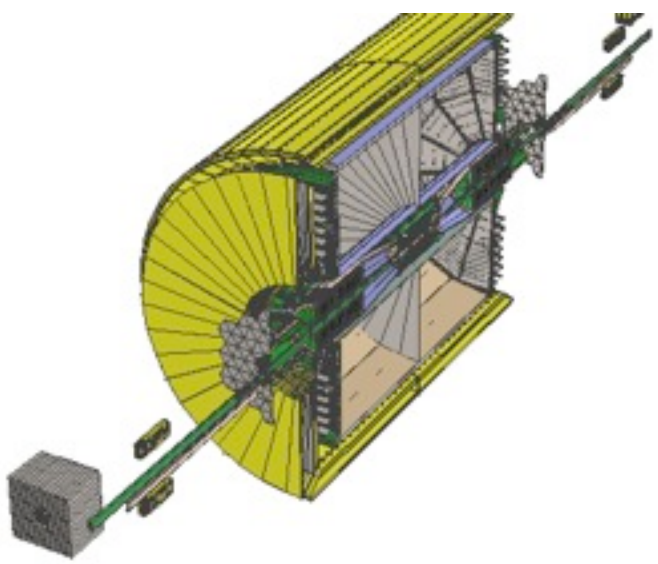
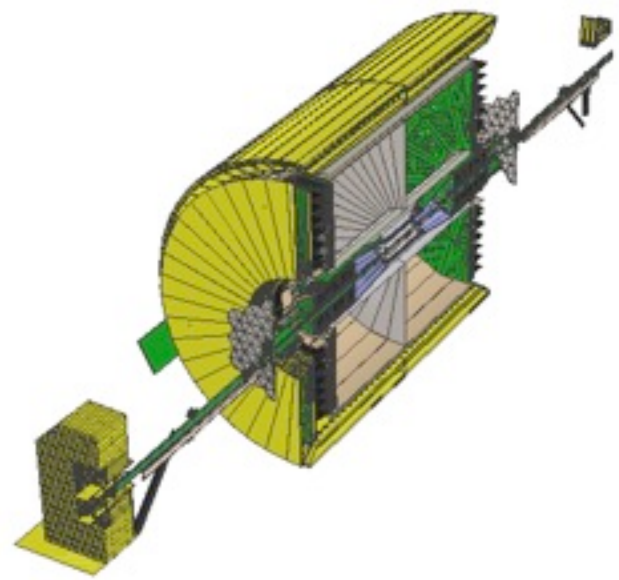
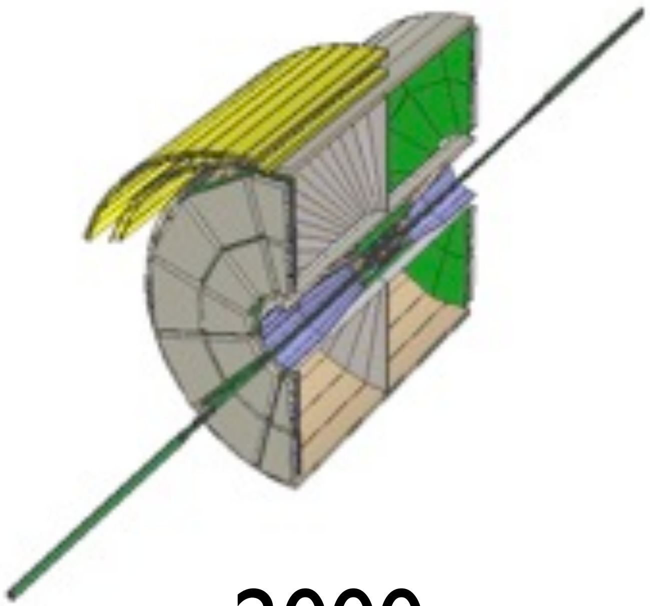


2006



2008

STAR through the ages



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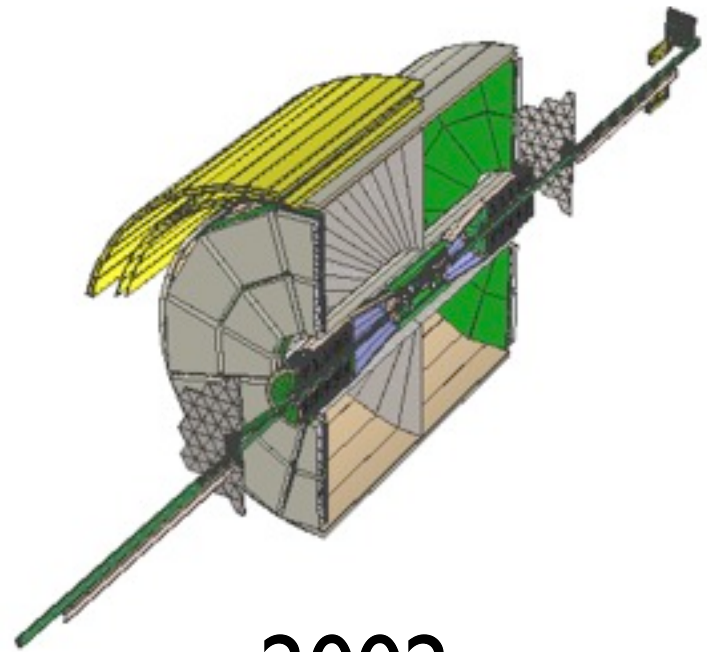

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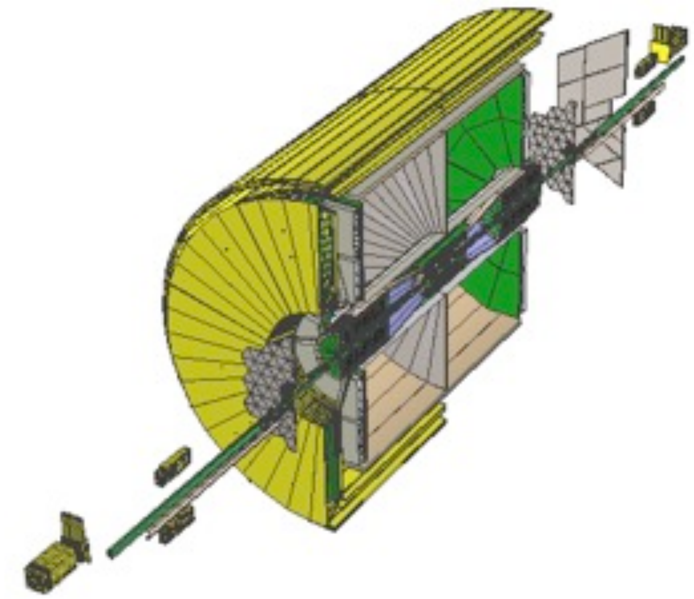

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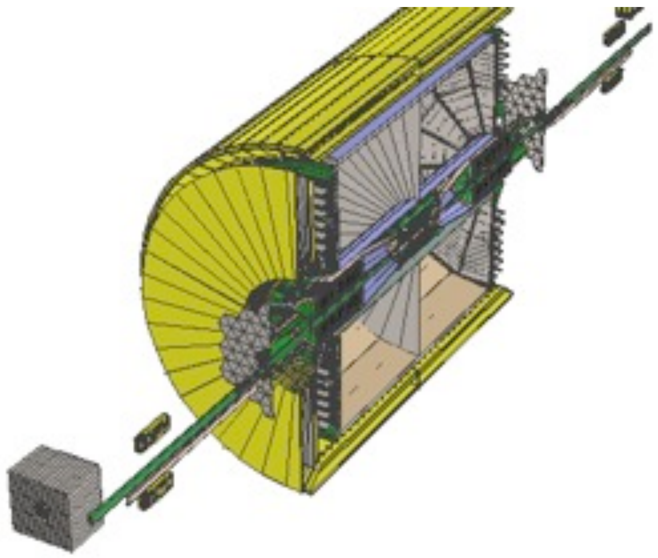

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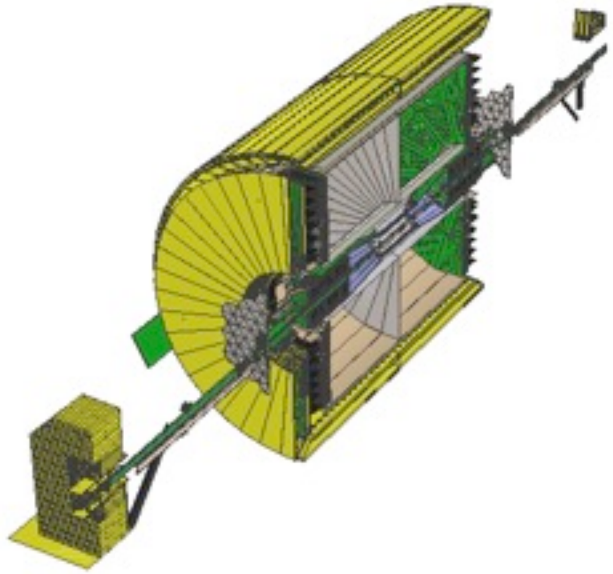
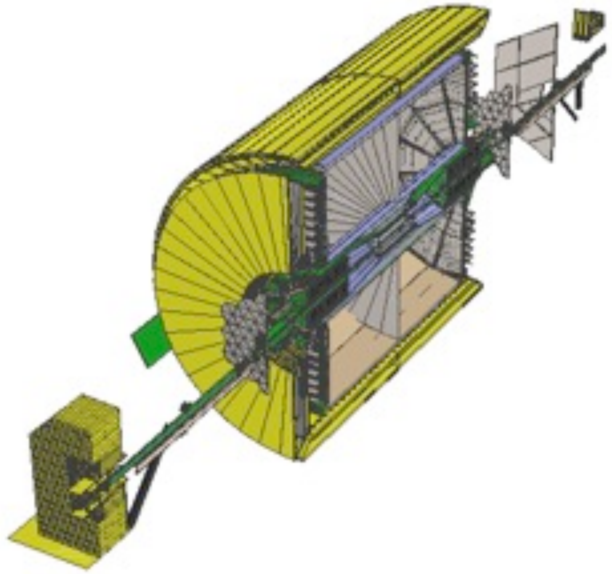


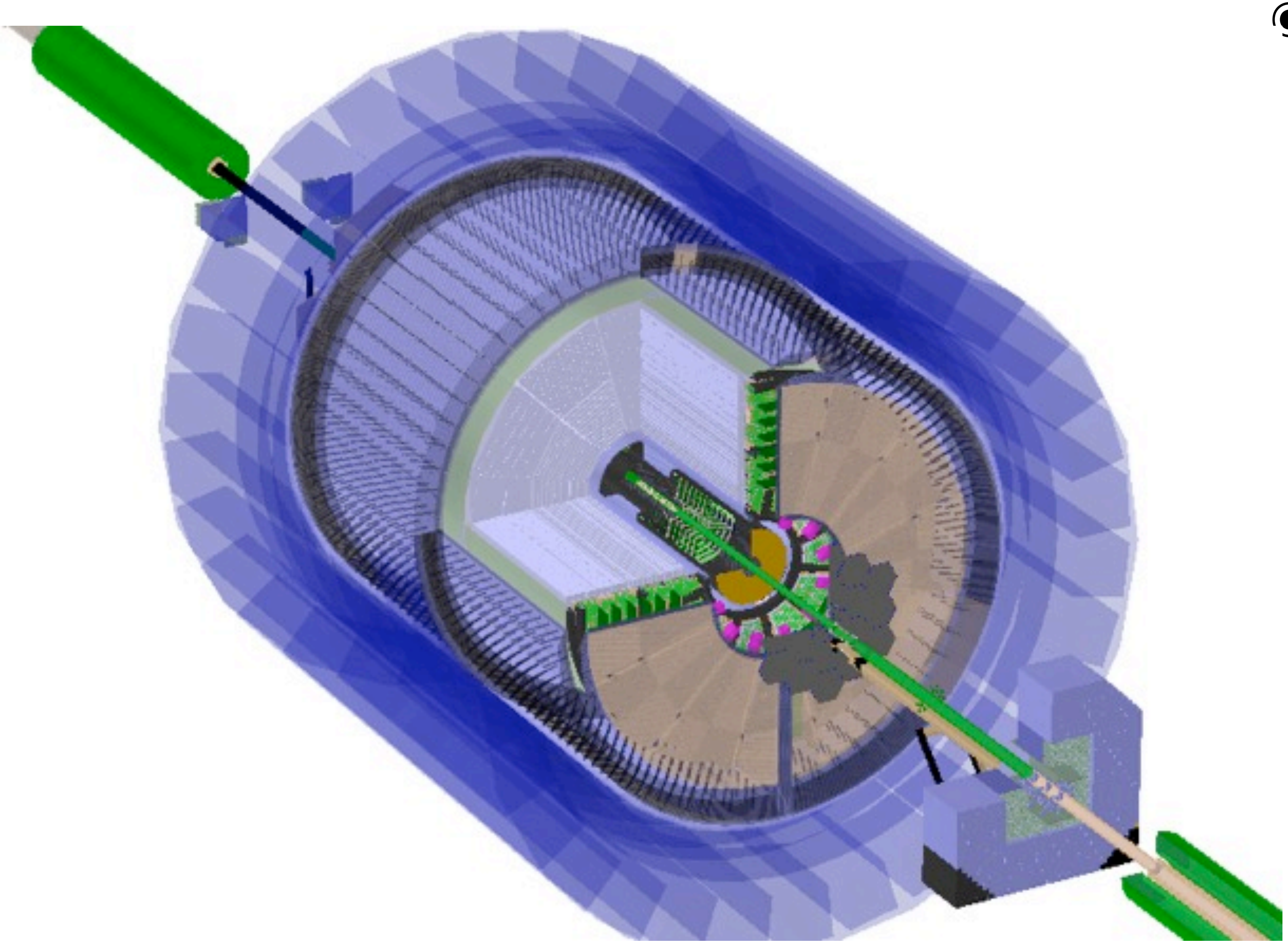
2008



2010

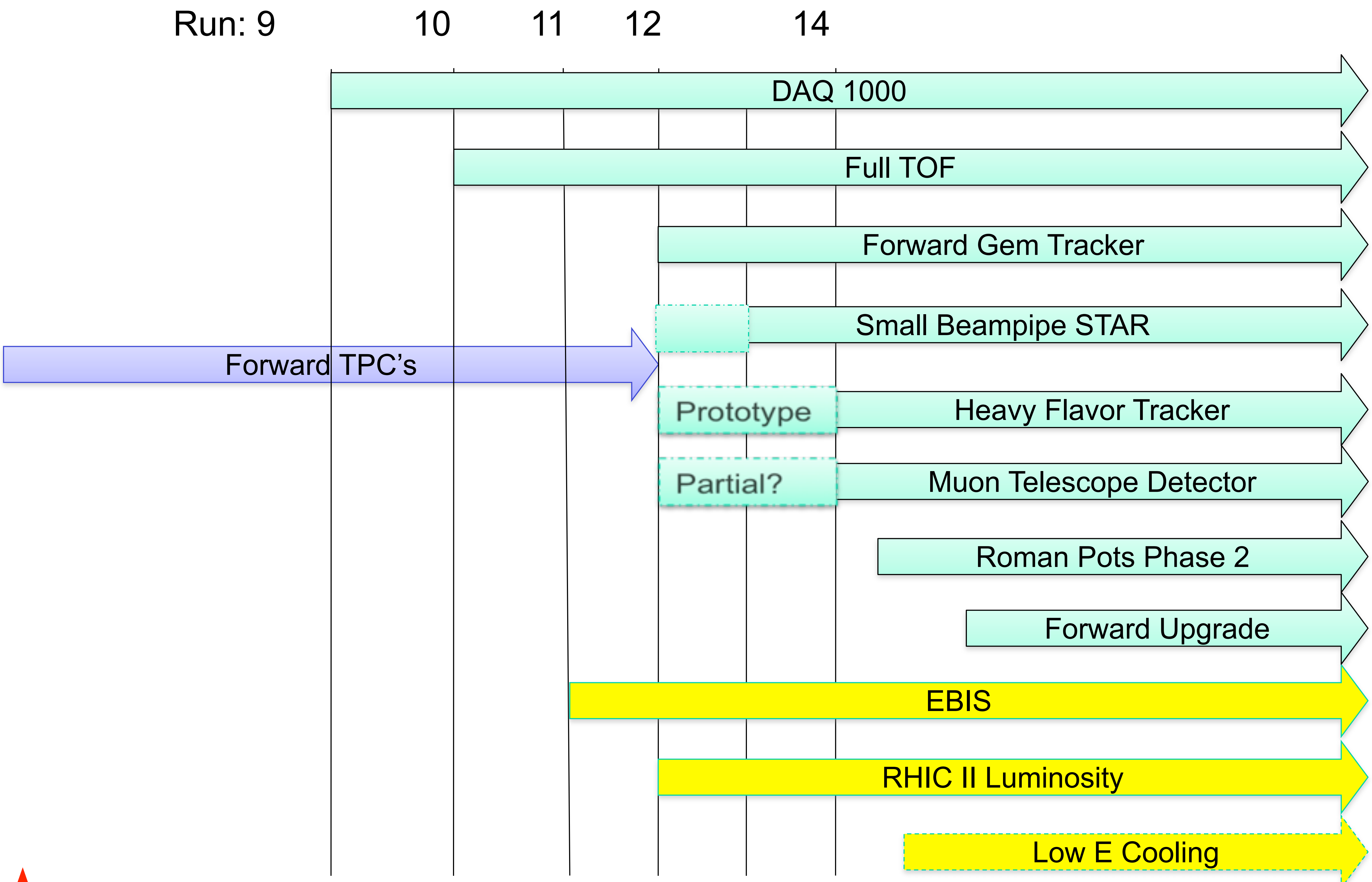
STAR

STAR in 2012



- STAR in 2012 has "evolved" from the initial concept of a decade ago
  - TPC is still the main workhorse detector
  - Many additions have been made to the original setup
  - We are not stopping here though - further upgrades are planned

Timeline of STAR detector upgrades



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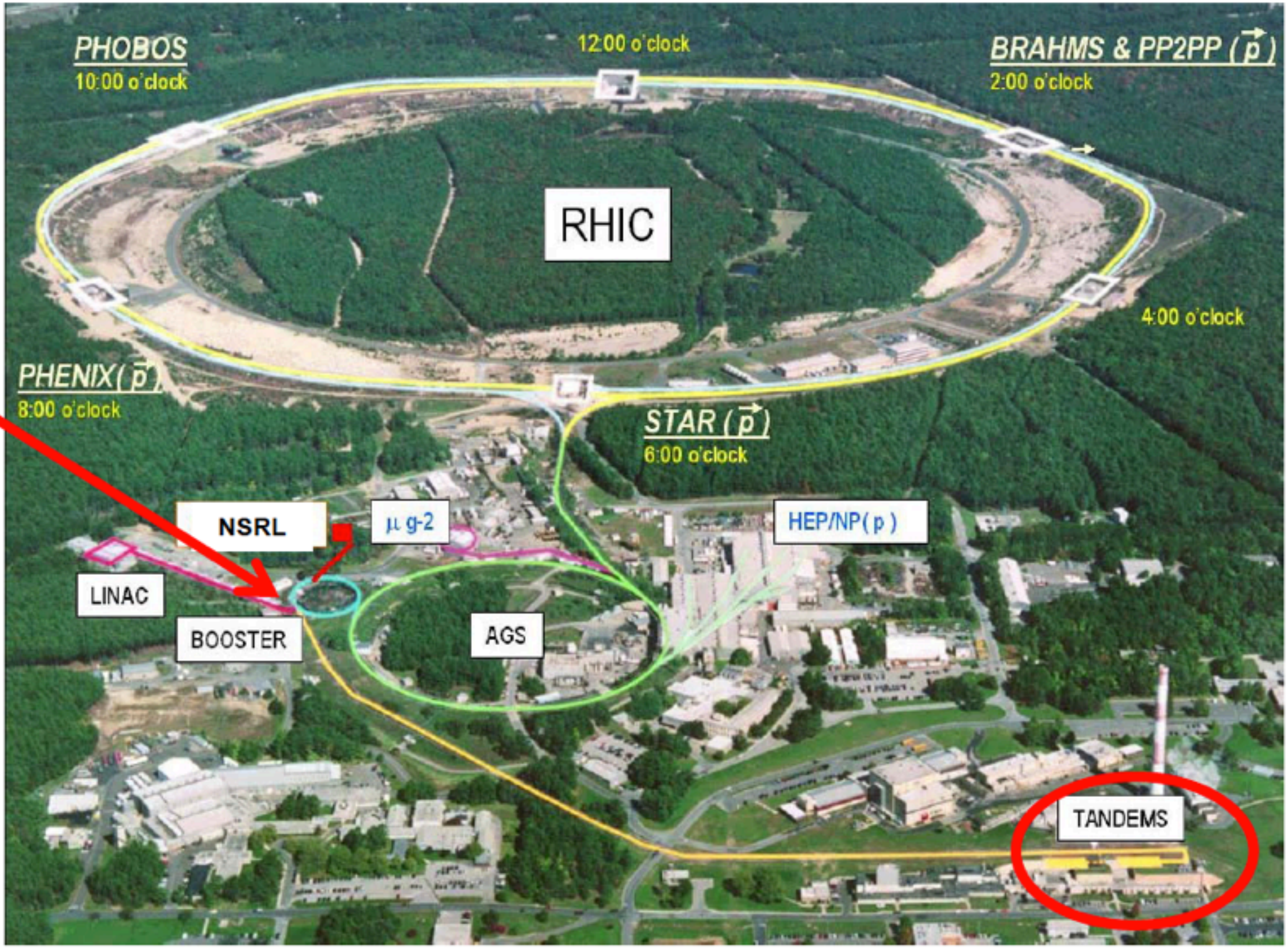
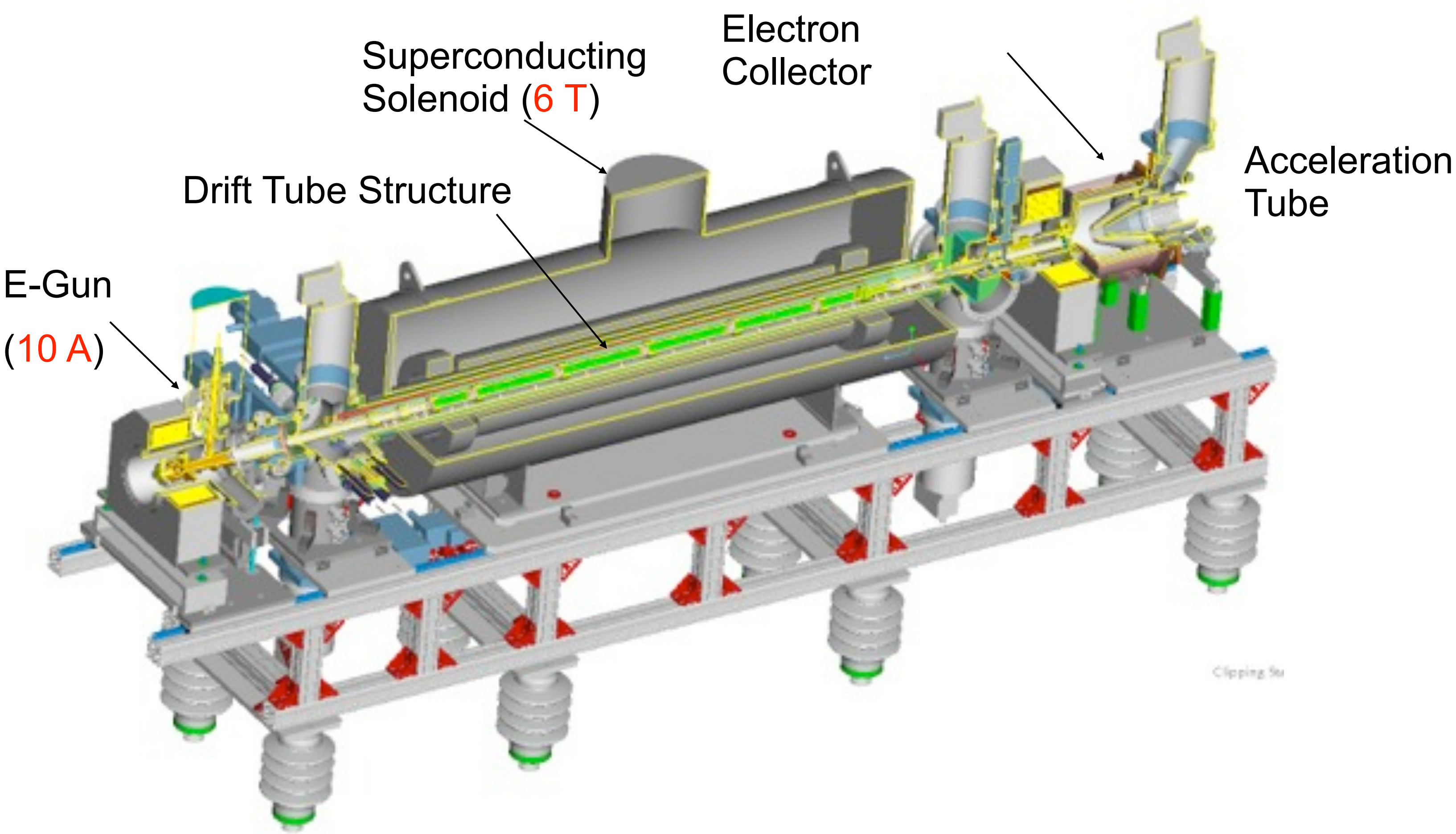
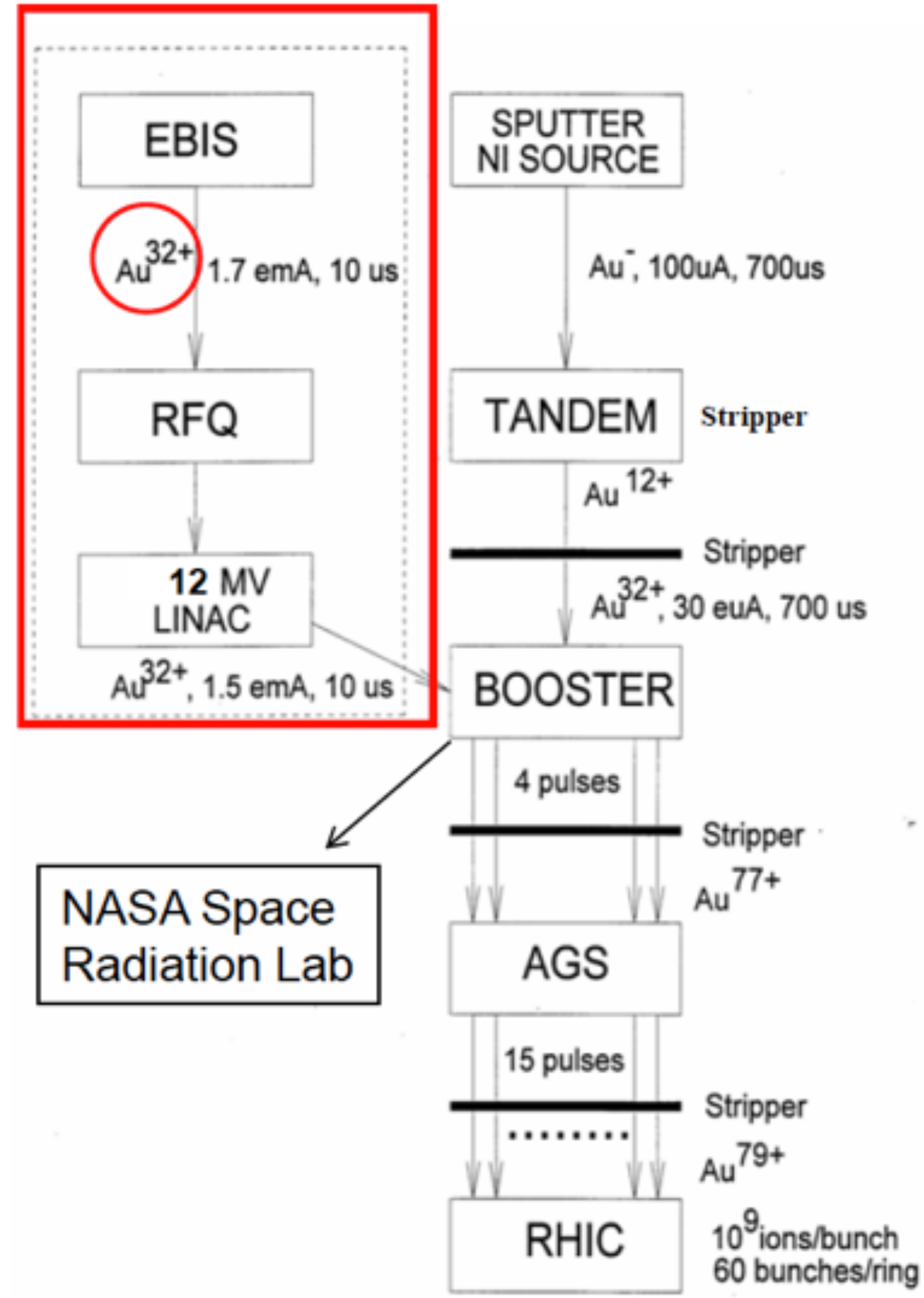
RHIC Upgrades - EBIS Source

EBIS going here



RHIC Upgrades - EBIS Source



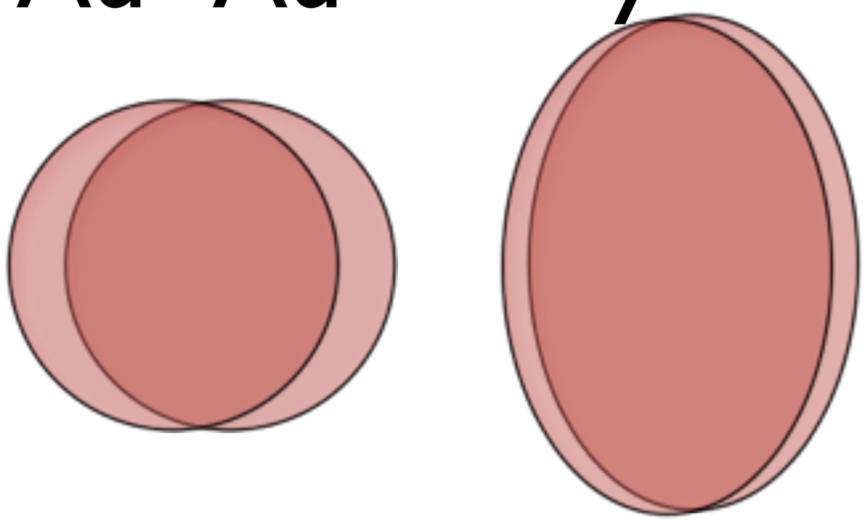


- EBIS advantages:
  - Low cost/maintenance, modern
  - Can produce any ion (e.g. ^{3}He↑, U)
  - Higher intensity
  - Fast switching between species

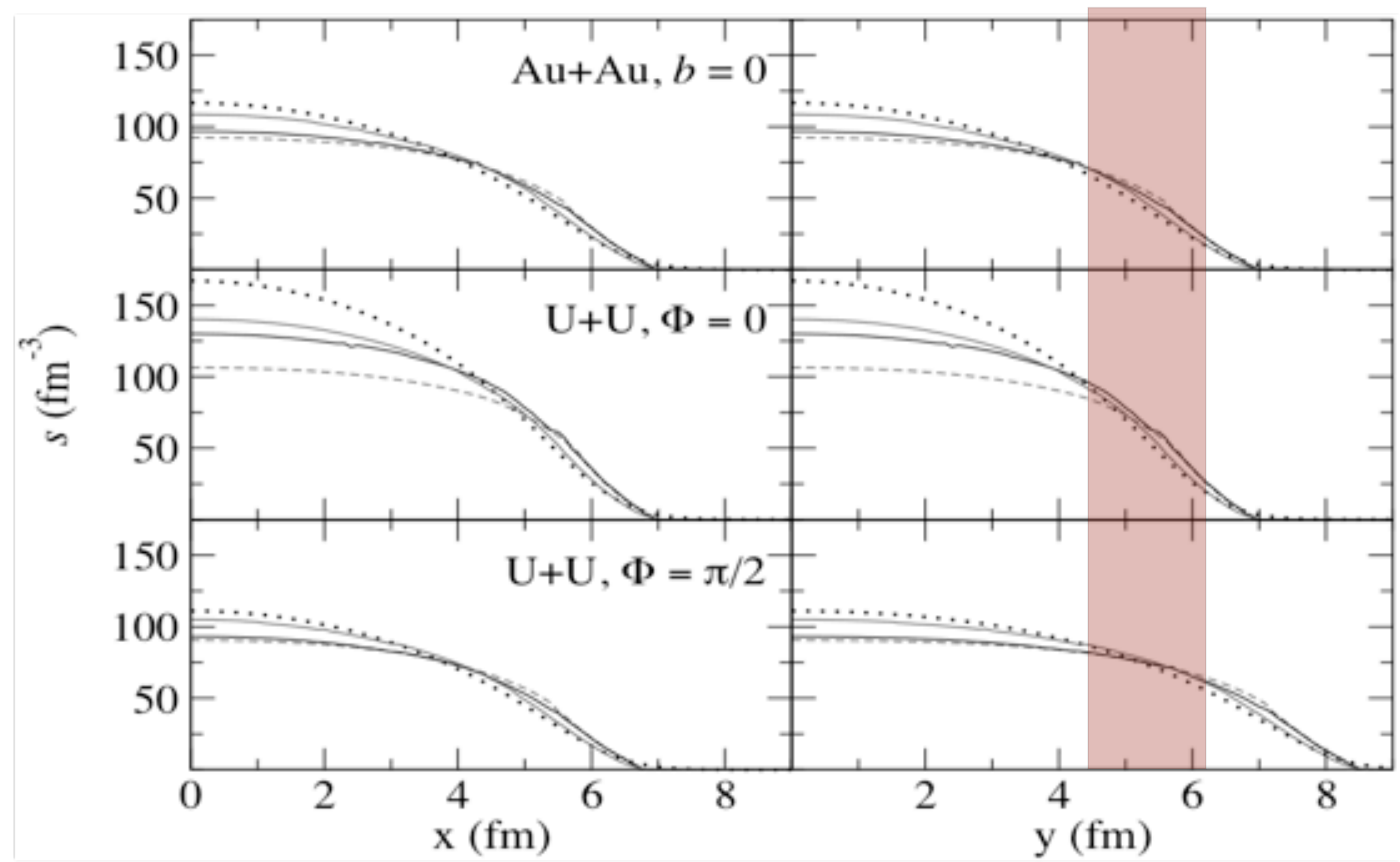
Flexibility: U+U

Au+Au

U+U
Body-Body



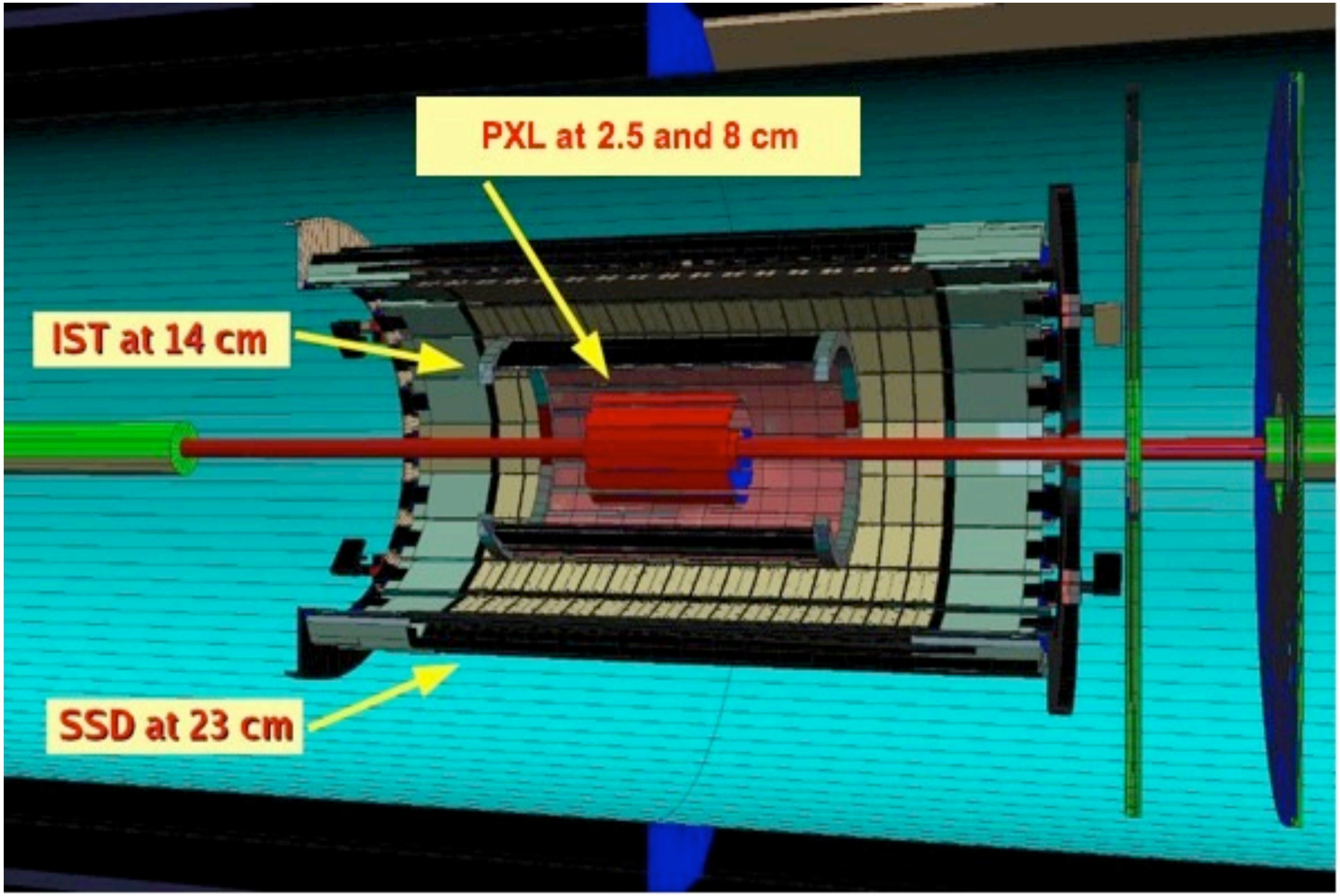
A. Kuhlman, U. Heinz, Y.V. Kovchegov, Phys. Lett. **B638**, 171(2006)



- Run 12: first feasibility studies
- Unique: pathlength dependence of quenching (50% more L)
  - Full range of measurements: γ-jet, b and c, jets, Upsilons, ...

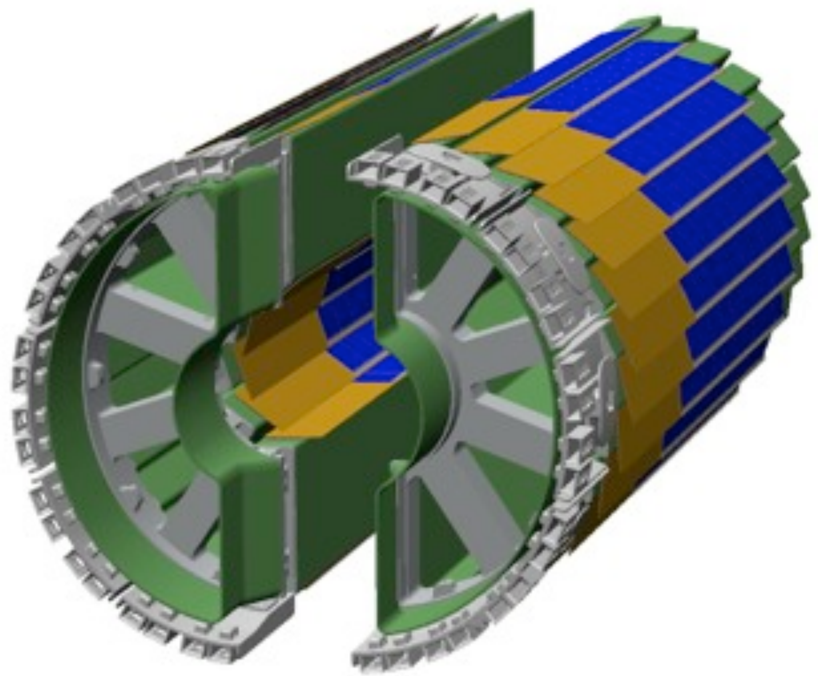
Heavy Flavour Tracker

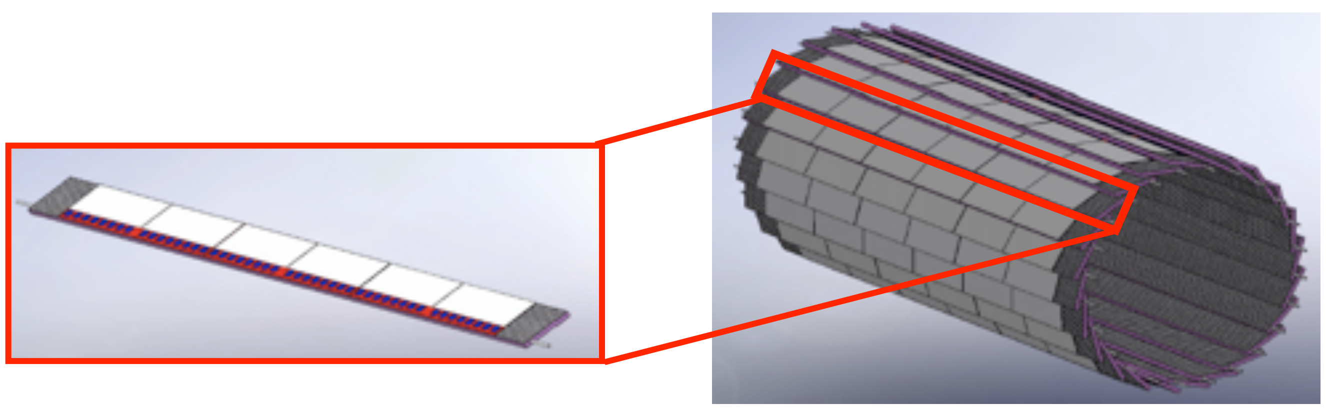
- Original mid-rapditiy Si vertex tracker at STAR not capable of identifying charm and bottom hadrons through direct reconstruction of the displaced vertex
- Heavy Flavour Tracker designed to do this. Installation begins in 2013

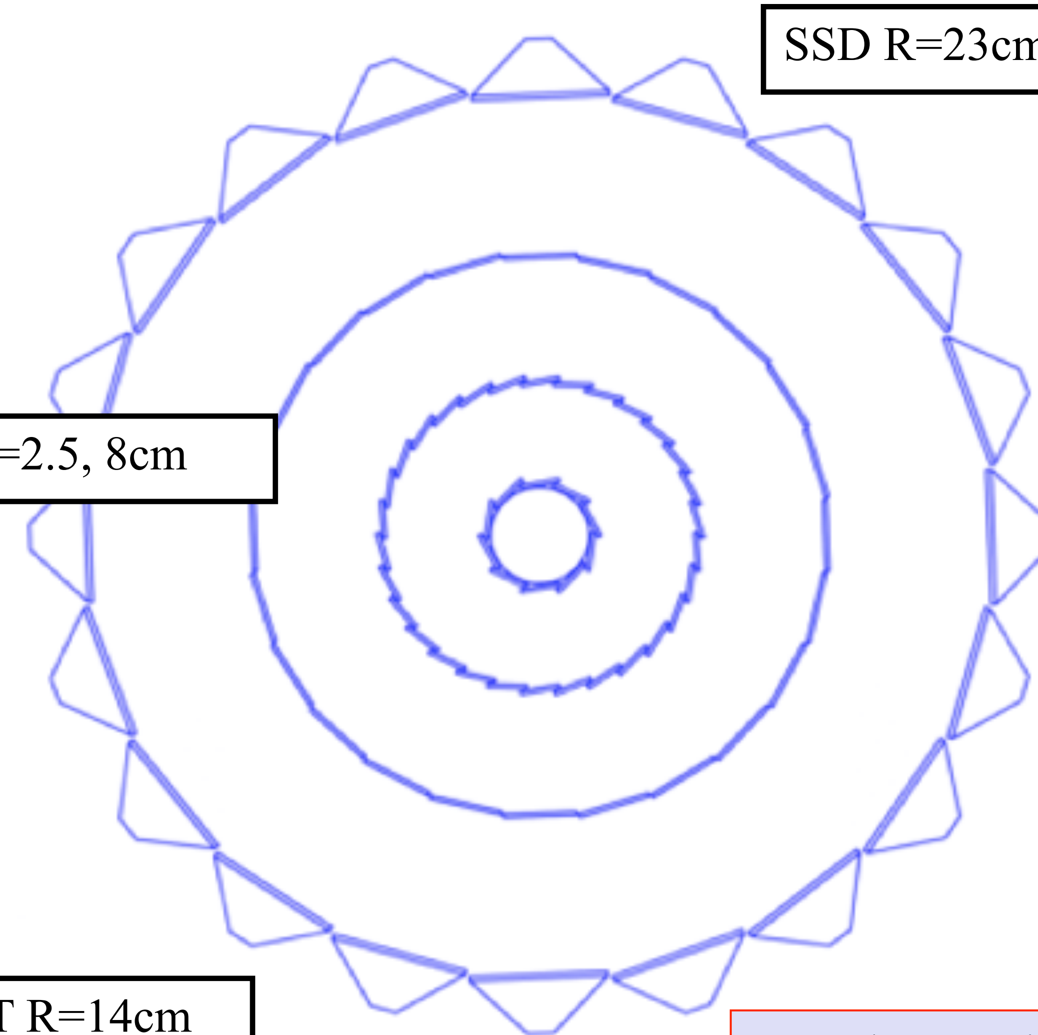


STAR

HFT Technology

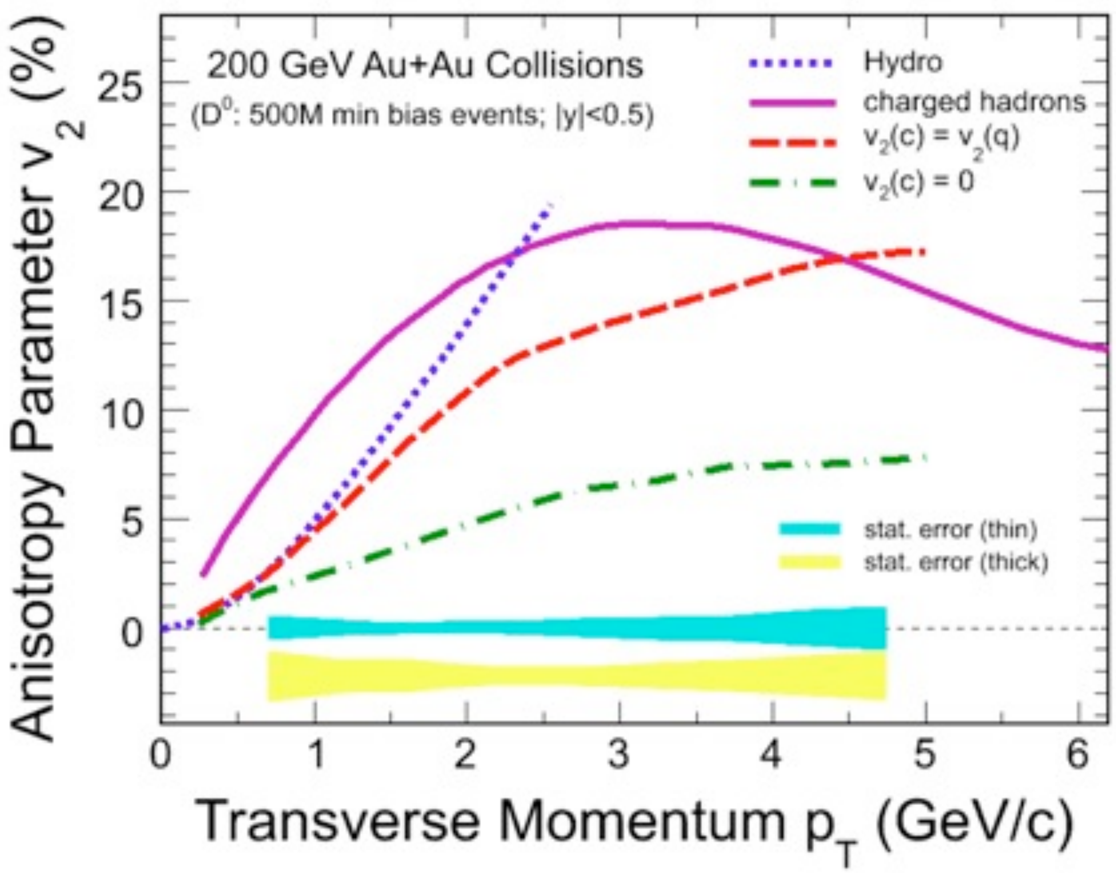


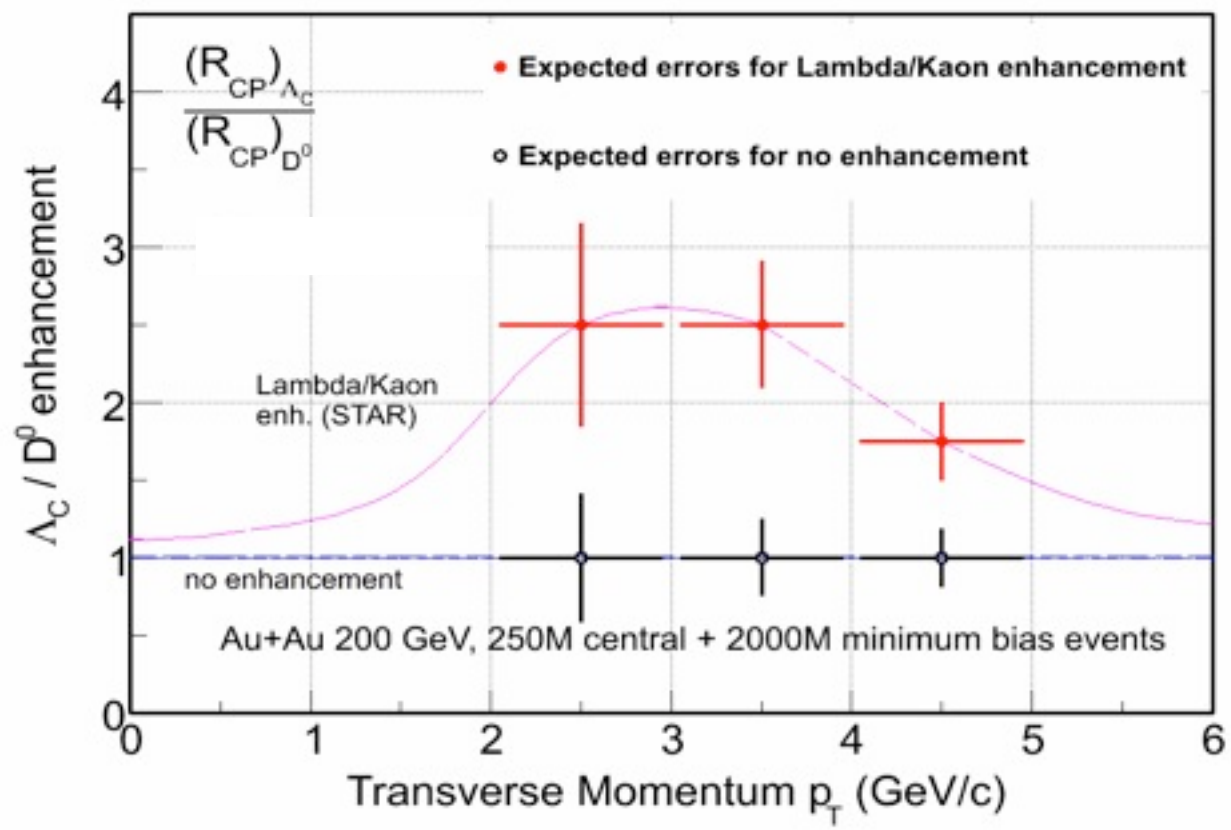




	Technology	Hit resolution R-ϕ (μm - μm)	Radiation Length
SSD	double sided strips	30 - 857	1% X_0
IST	Silicon Strip Pad sensors	170 -1700	1.2% X_0
PIXEL	Active Pixels	8.6 - 8.6	0.3% X_0

Physics of the HFT

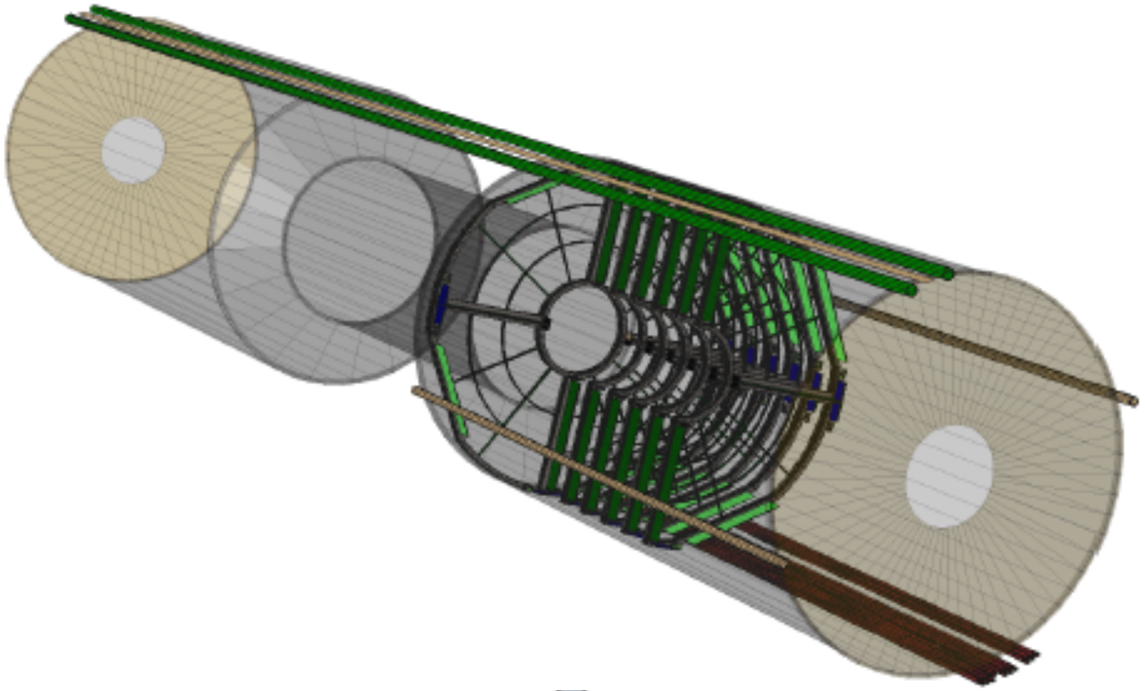




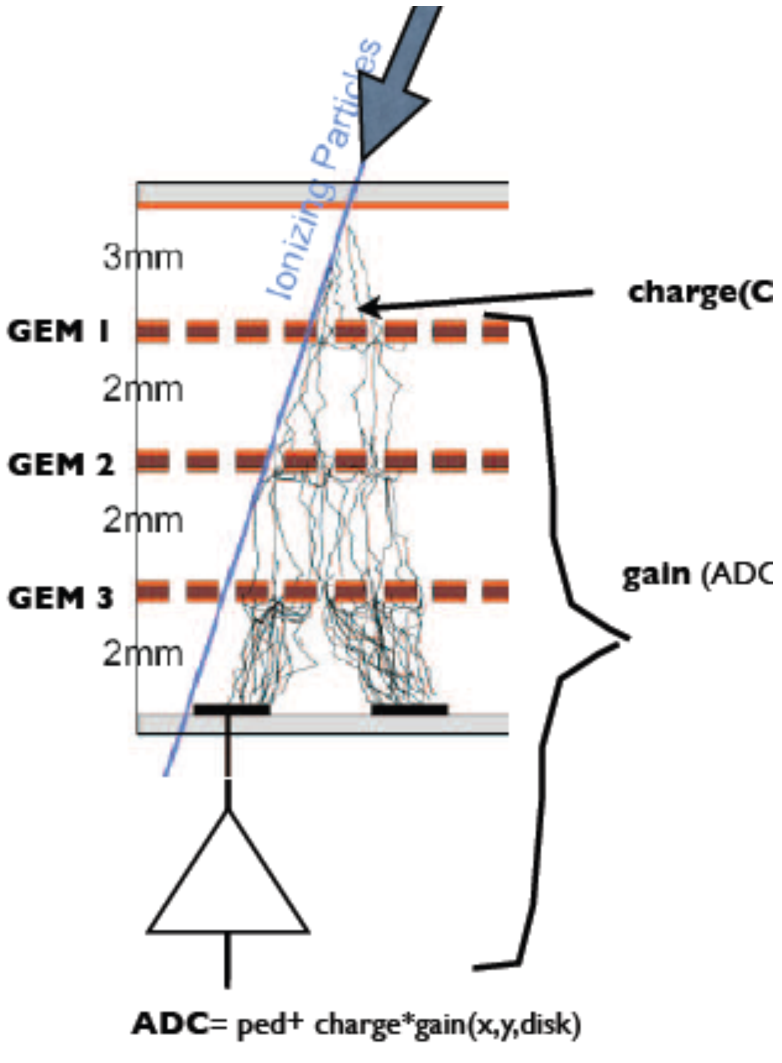
- Very thin vertexer focussed on reconstructing charm:
  - Run 14: does charm flow hydrodynamically?
  - Run 15: reference data in p+p 200 GeV
  - Run 16: baryonic composition
    - Does baryon/meson ratio at intermediate p_T behave as p/π and Λ/K?
      - If so - need to re-visit the interpretation of the non-photonic electrons due to different branching ratios than what was expected

STAR

Forward GEM Tracker



- Triple GEM Detector
- GEM foils: Hole inner r: 50micron, outer: 70micron, 140micron pitch
- Quoted resolutions in the proposal:
  - as good as 40microns in phi (120microns in R - inclined tracks) from simulations
  - Evaluate performance after this run



STAR

Physics of the FGT - Quark Helicities

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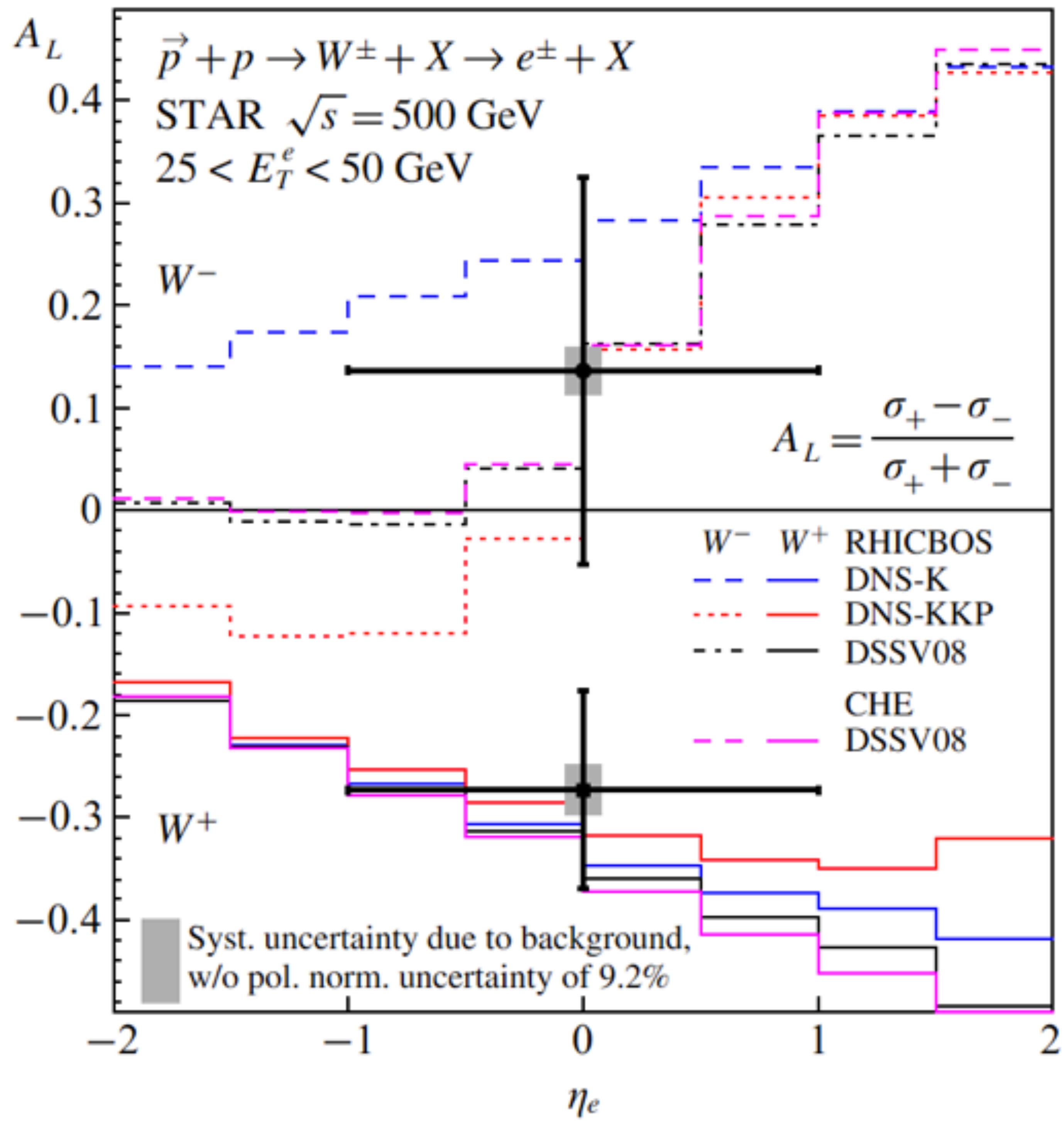
- u,d,anti-q helicity distributions obtained through A_L measurements of $W^{\pm}$
- $W^{\pm} \rightarrow e^{\pm}+X$ (11% BR) provides a clean signature with high efficiency
- Initial measurements of A_L utilised STAR's barrel and end-cap calorimeters sampled 12 pb^{-1}



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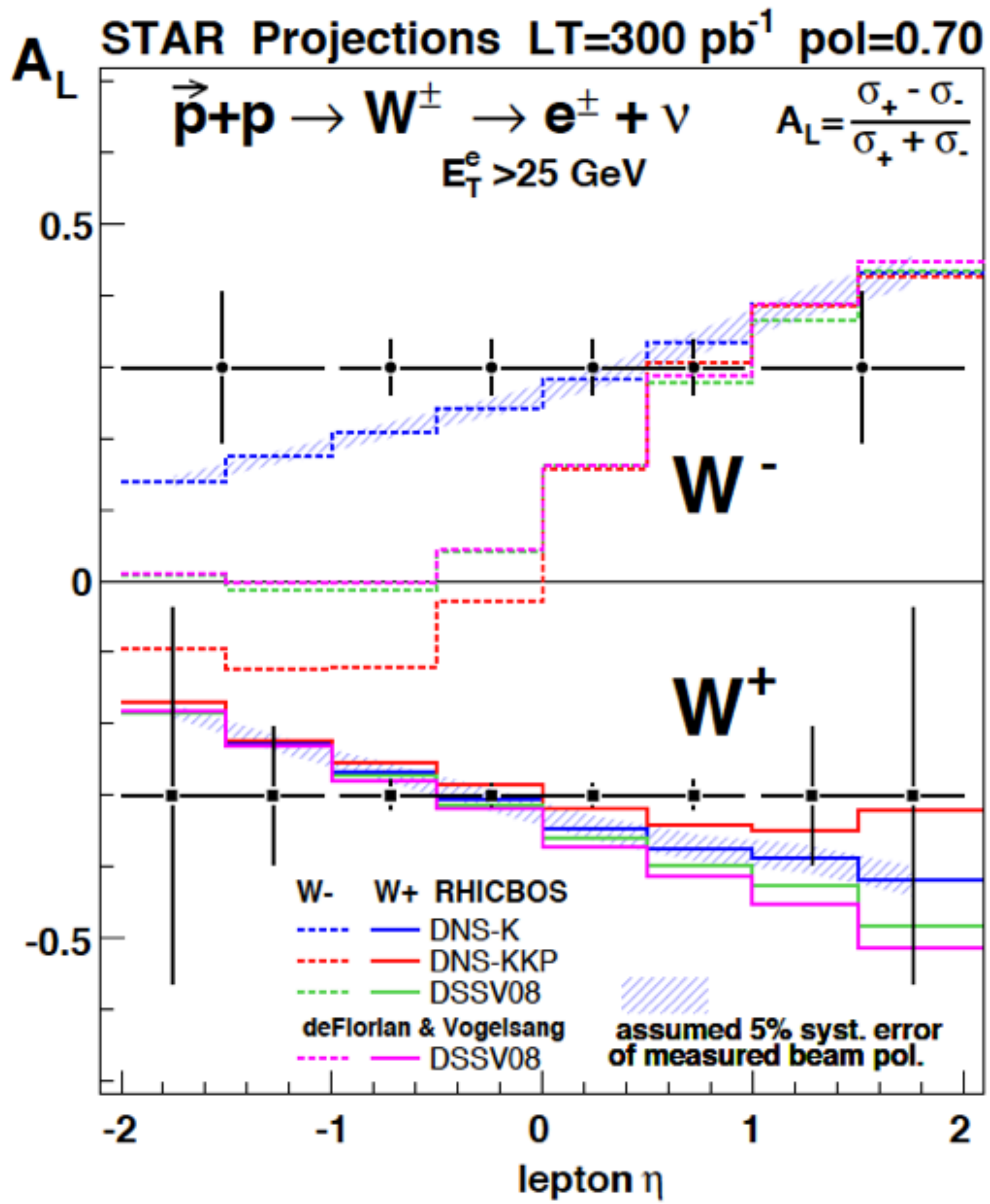
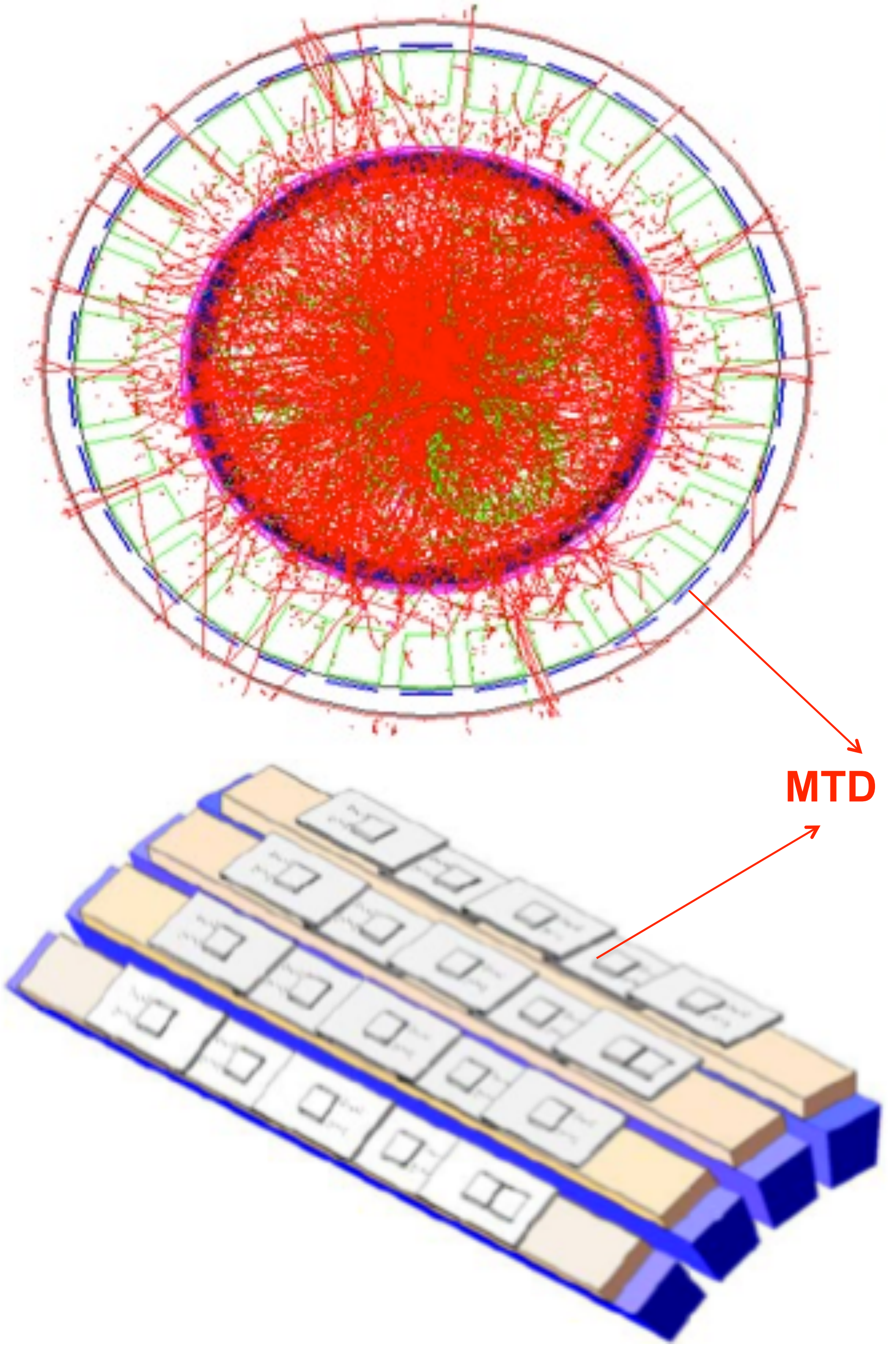
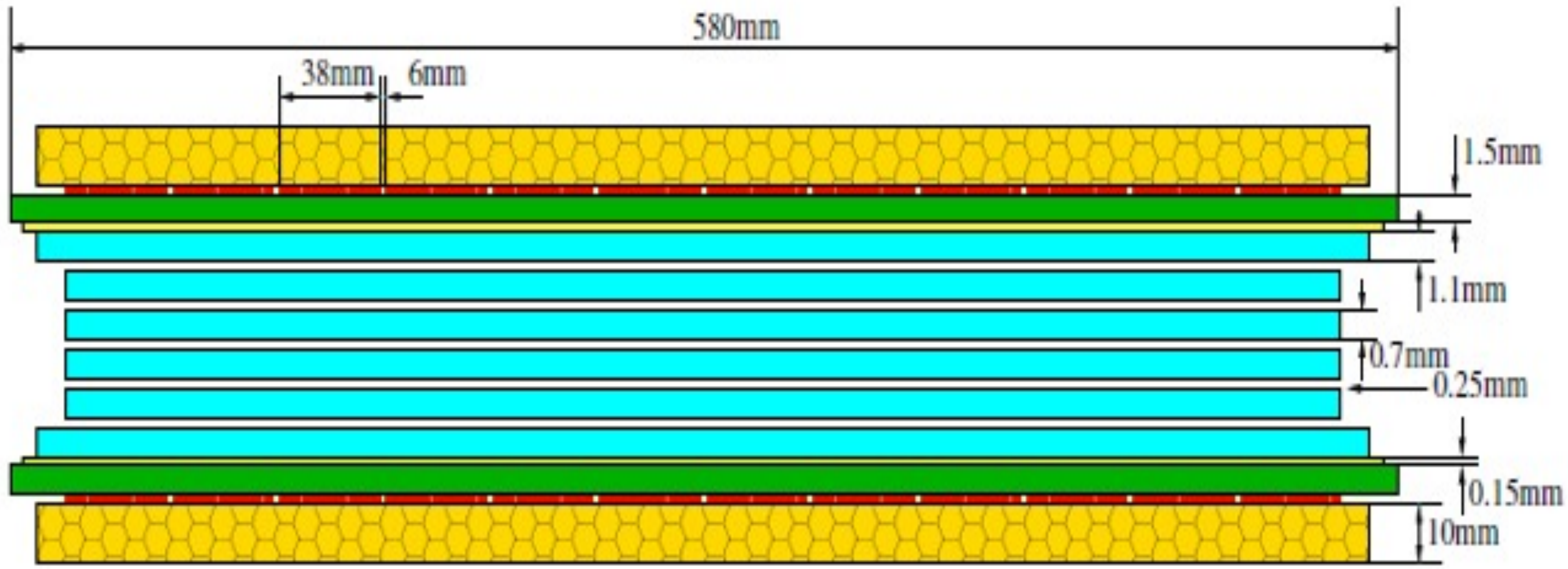
- Initial measurements of A_L utilised STAR's barrel and end-cap calorimeters sampled 12 pb^{-1}
- Upgrades to add the FGT significantly improve this measurement and allow for charge-sign discrimination
- FGT partially installed in current run (Run 12)
  - 14 out of 24 quadrants installed



STAR

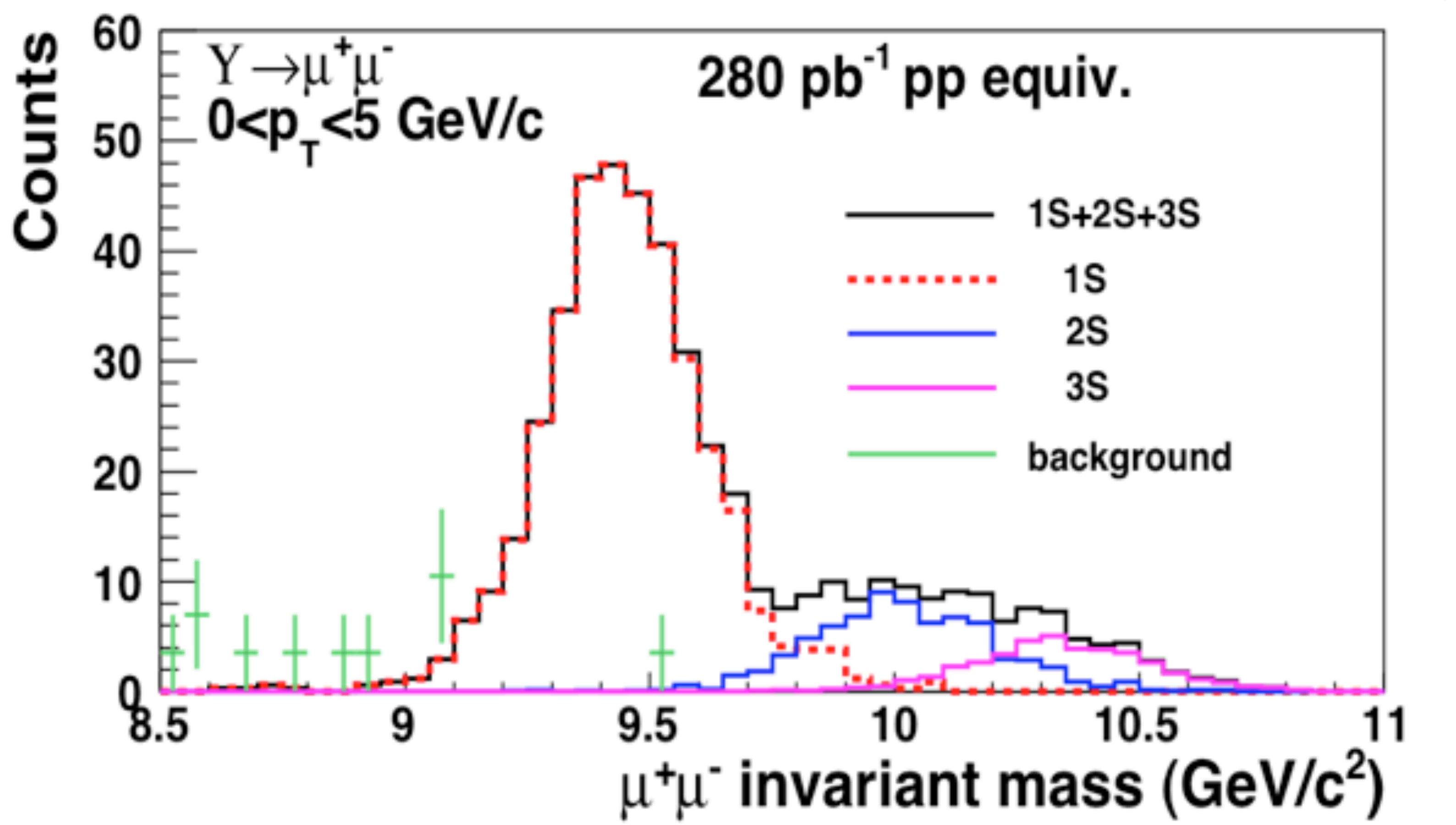
Muon Telescope Detector

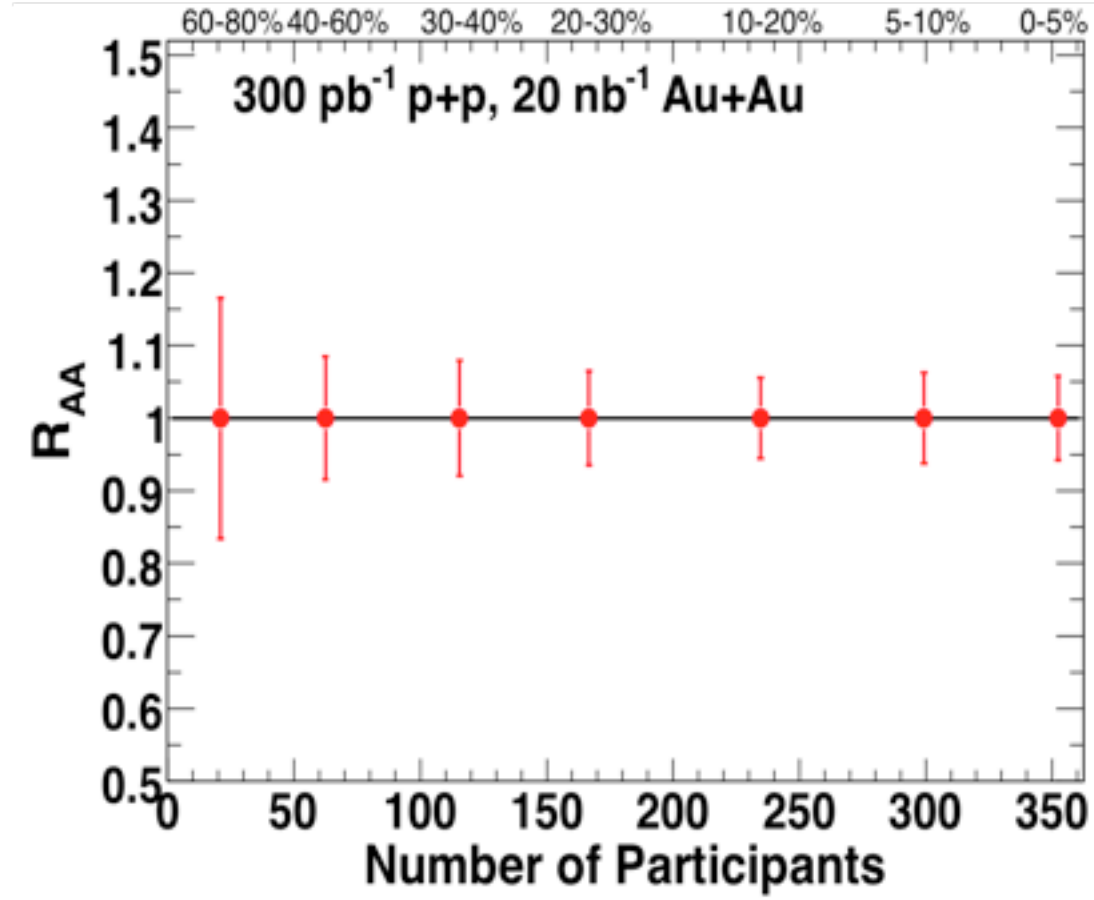




- MTD is a Multi-gap Resistive Plate Chamber gas detector
- Long MRPCs cover the whole iron bars - gaps inbetween are not covered
    - Acceptance: 45% at $|\eta|<0.5$
- 118 modules, 1416 readout strips, 2832 readout channels
- MRPC technology and electronics is the same as that used in the STAR TOF

Physics capabilities with the MTD

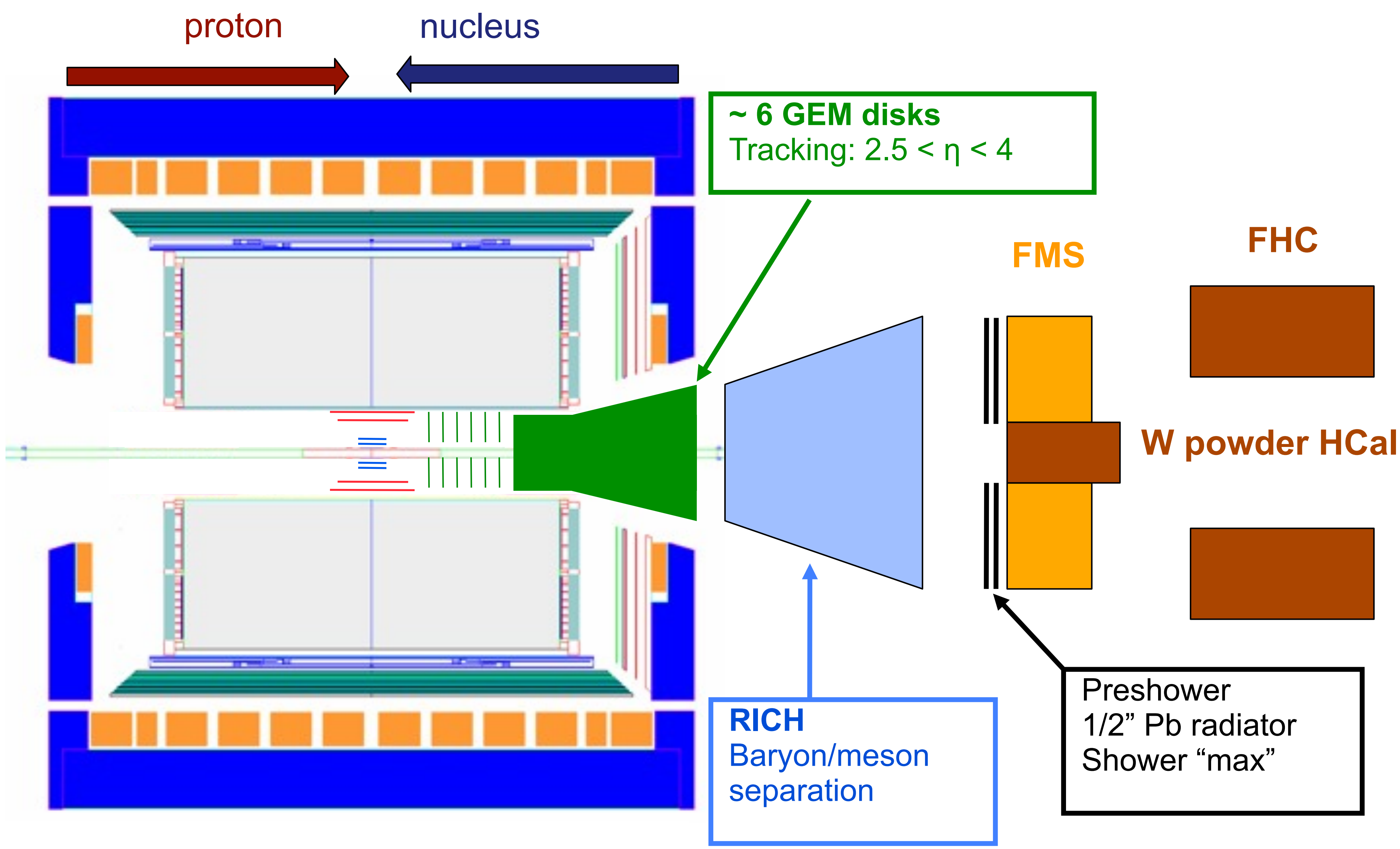




- MTD can measure muons at mid-rapidity
  - di-leptons of a different flavour
- High-precision Upsilons, J/Psi,...
  - No Bremmstrahlung tails allows effective separation of Upsilon states
    - Allows a handle on melting of lightly bound Upsilon states in hot and de-confined matter
- Possibility of further upgrade to increase the acceptance coverage

STAR

Forward instrumentation upgrade

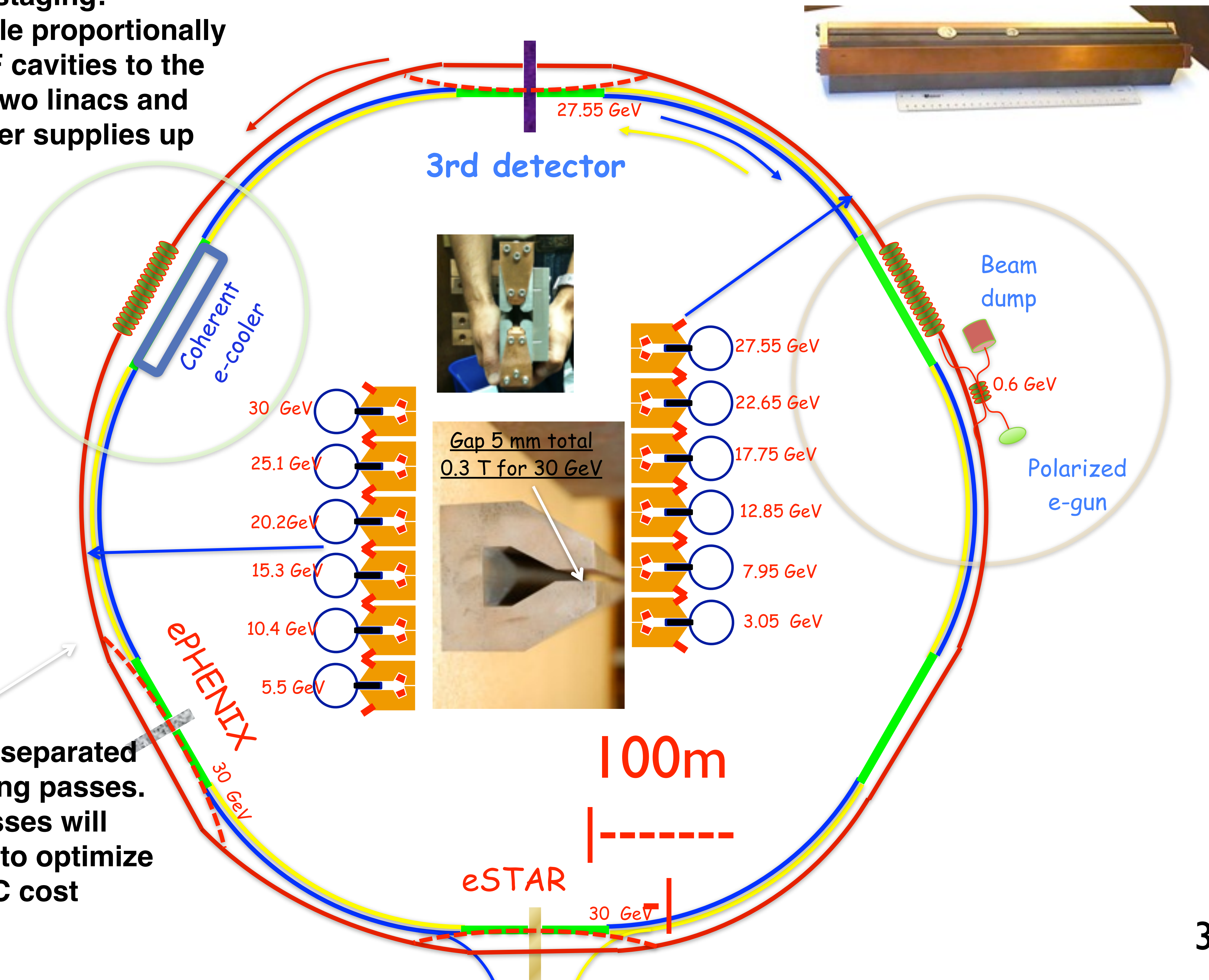


- Forward instrumentation optimised for p+A and transverse spin physics
  - charged particle tracking
  - e/h and γ/π discrimination
  - baryon/meson separation

STAR

eRHIC - the future of RHIC

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



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

STAR

eSTAR - the future of STAR?

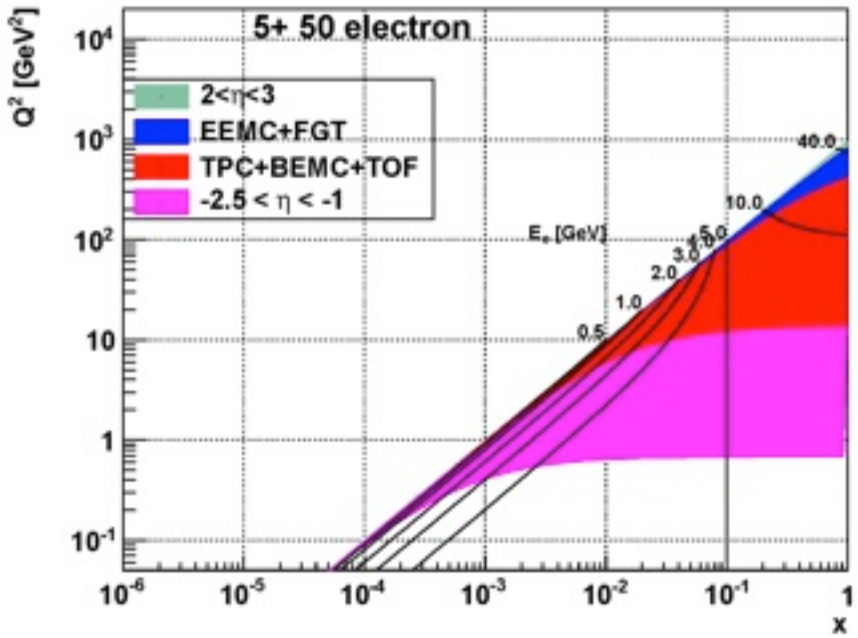
- STAR will need to be optimised/modified for its current setup for e+A collisions
  - 5 GeV electron beams currently being studied with p(A) energies from 50 GeV to 130(325) GeV
- Key measurements:
  - Inclusive scattering over the entire DIS region
    - F_L in e+A - a direct measure of nuclear gluon densities
    - F_2^A/F_2^p - parton distributions in nuclei
  - Semi-inclusive DIS over a broad (x,Q^2) range
    - Flavour-separated parton distributions in nuclei, including strangeness
    - Parton energy loss in cold nuclear matter
- What's needed?

STAR

eSTAR kinematics in phase 1: 5 GeV electrons

DIS region

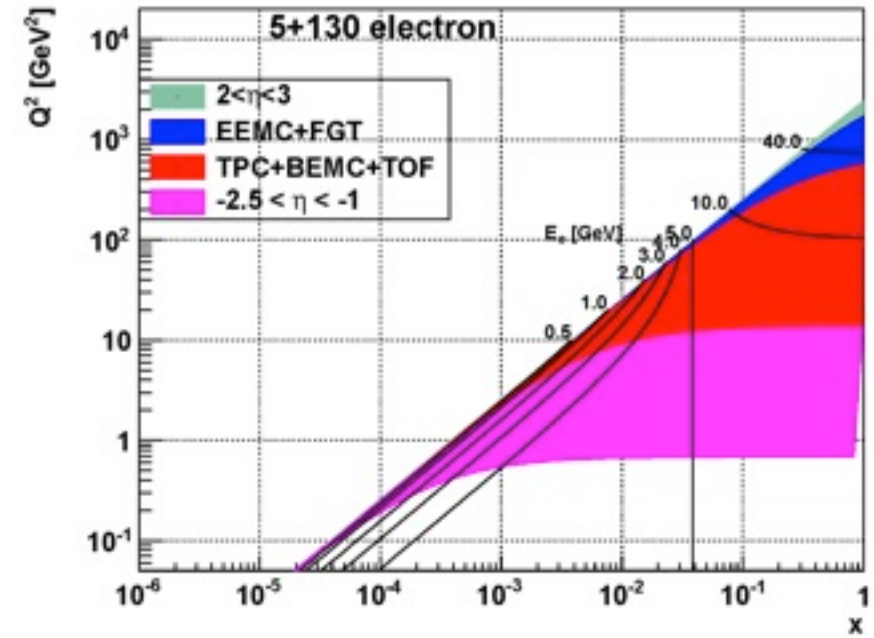
5 GeV e + 50 GeV/nucleon



TPC

Missing today

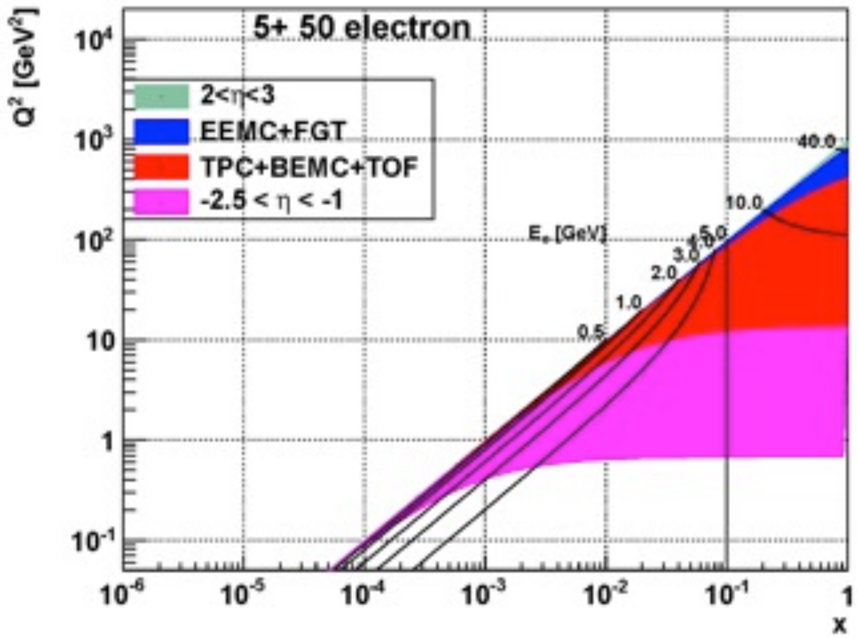
5 GeV e + 130 GeV/nucleon



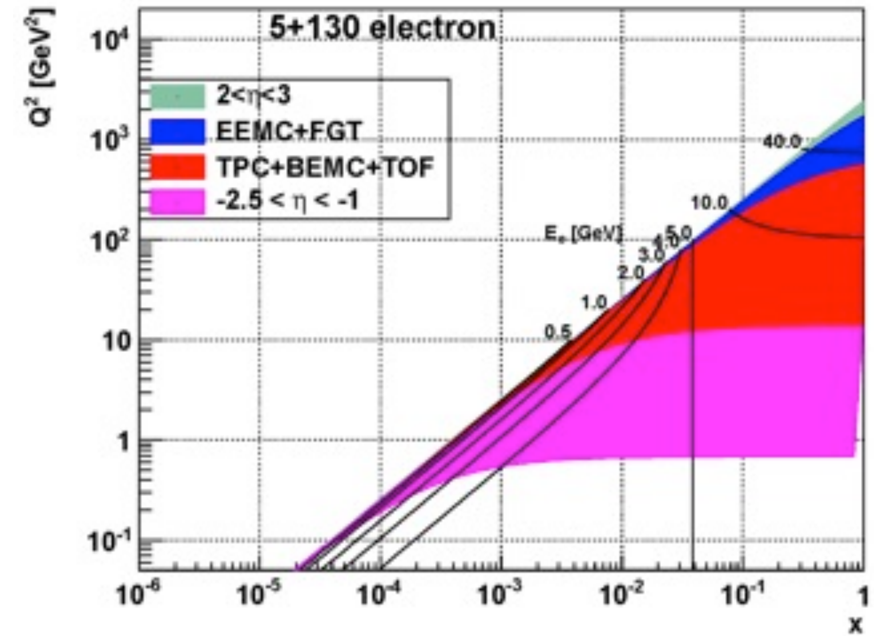
STAR

eSTAR kinematics in phase 1: 5 GeV electrons

5 GeV e + 50 GeV/nucleon



5 GeV e + 130 GeV/nucleon



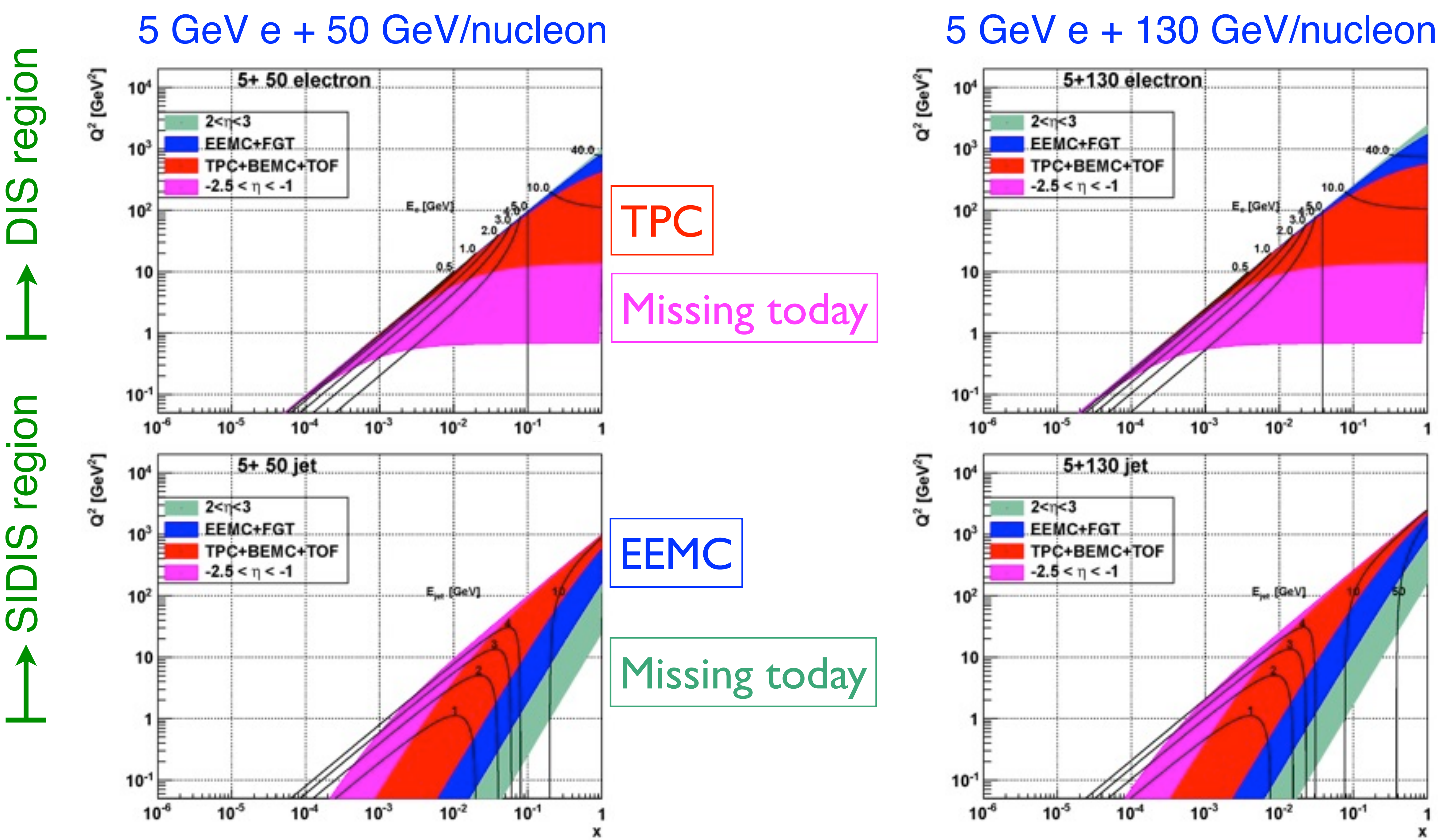
DIS region

TPC

Missing today

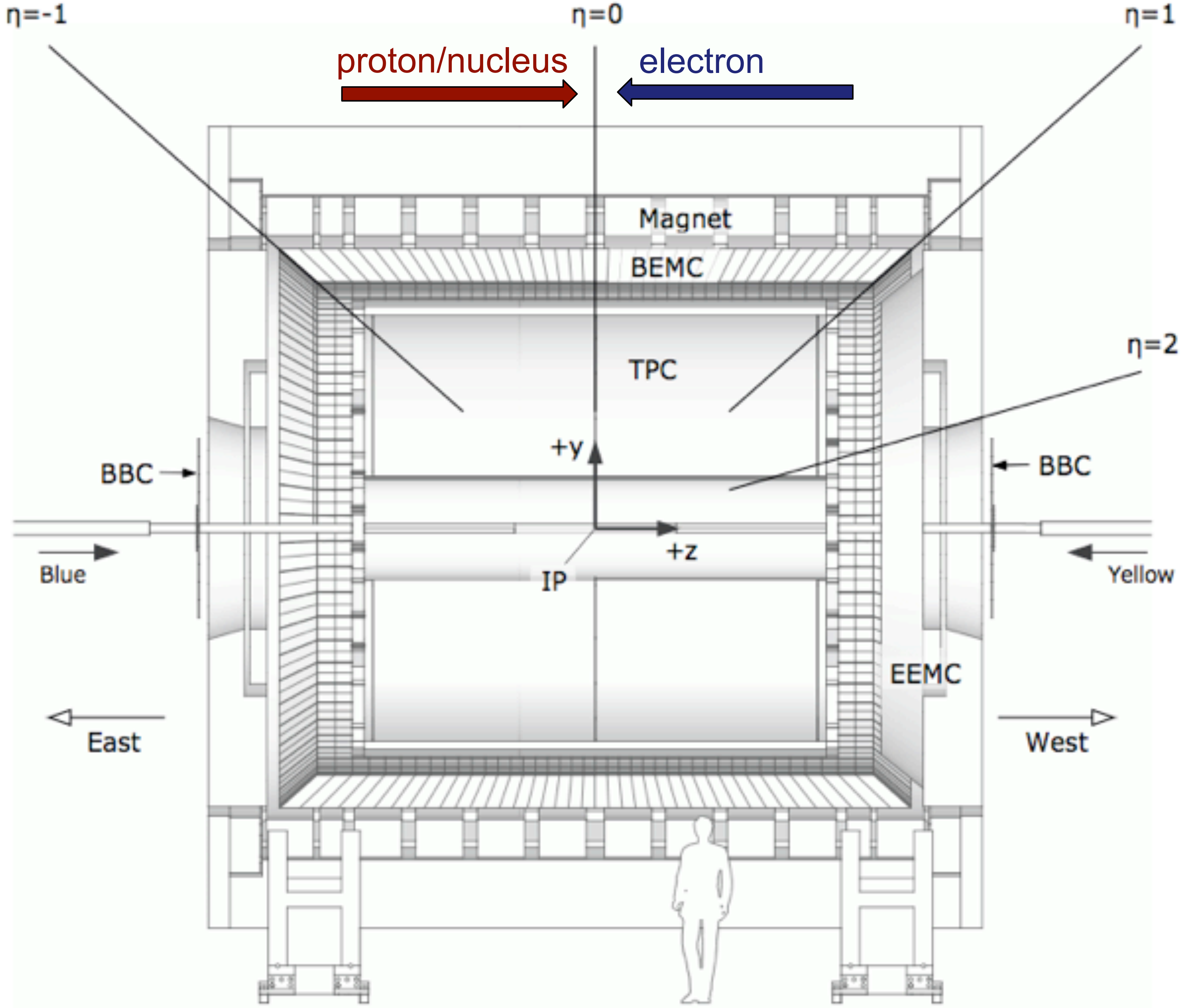
- “Forward” (-2.5 < h < -1) electron acceptance is essential in order to span the DIS regime

eSTAR kinematics in phase 1: 5 GeV electrons



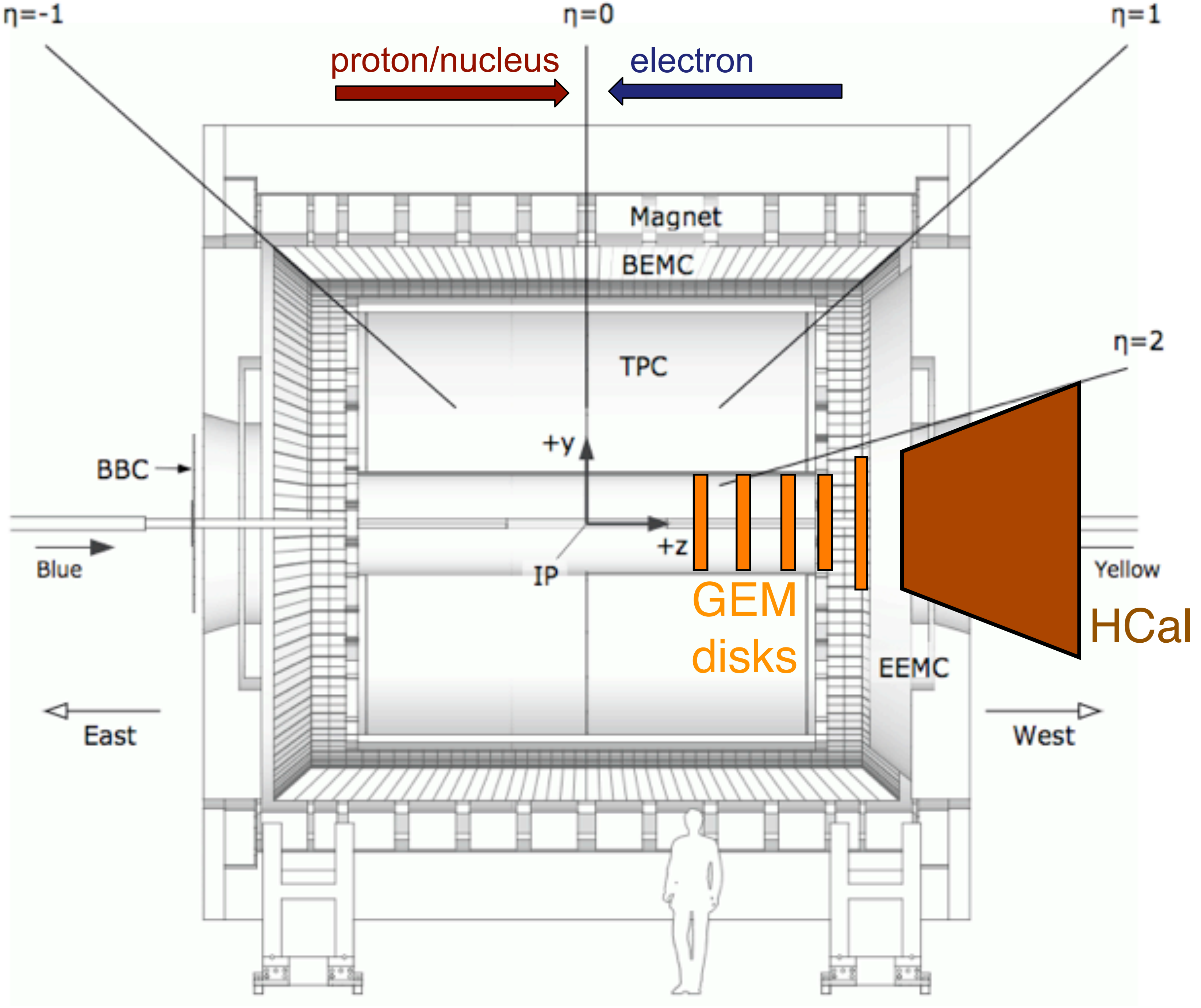
- “Forward” (-2.5 < h < -1) electron acceptance is essential in order to span the DIS regime
- Both “forward” and “backward” hadron coverage is needed for SIDIS physics

The realisation of an eSTAR detector



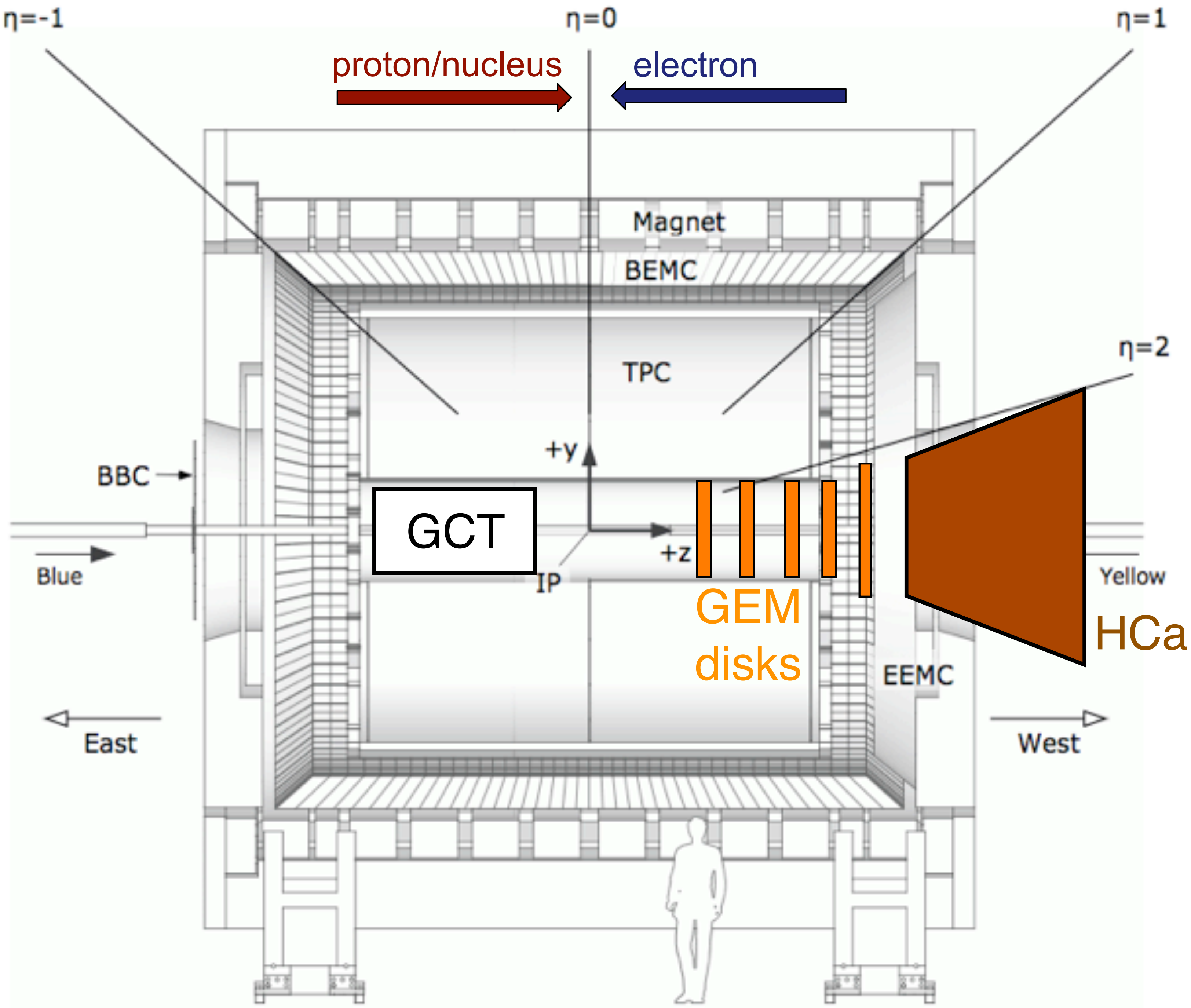
The realisation of an eSTAR detector

- HCal: W powder, spaghetti calorimeter



The realisation of an eSTAR detector

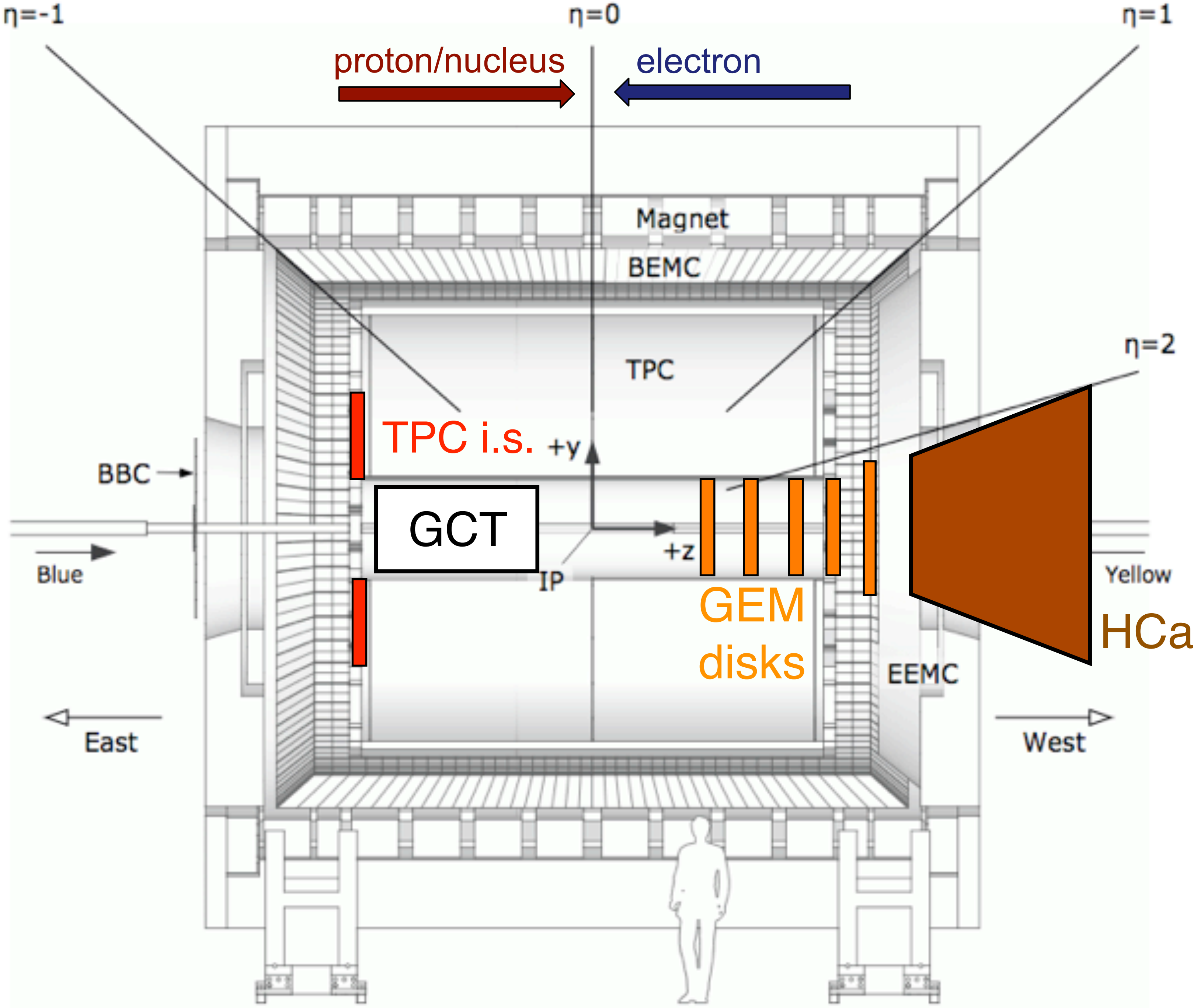
- HCal: W powder, spaghetti calorimeter
- GCT: compact tracker with enhanced electron capability
  - combine high-threshold (gas) Cherenkov with TPC-like tracking



STAR

The realisation of an eSTAR detector

- HCal: W powder, spaghetti calorimeter
- GCT: compact tracker with enhanced electron capability
  - combine high-threshold (gas) Cherenkov with TPC-like tracking
- TPC: replace inner sectors
  - make a greater density of pad rows



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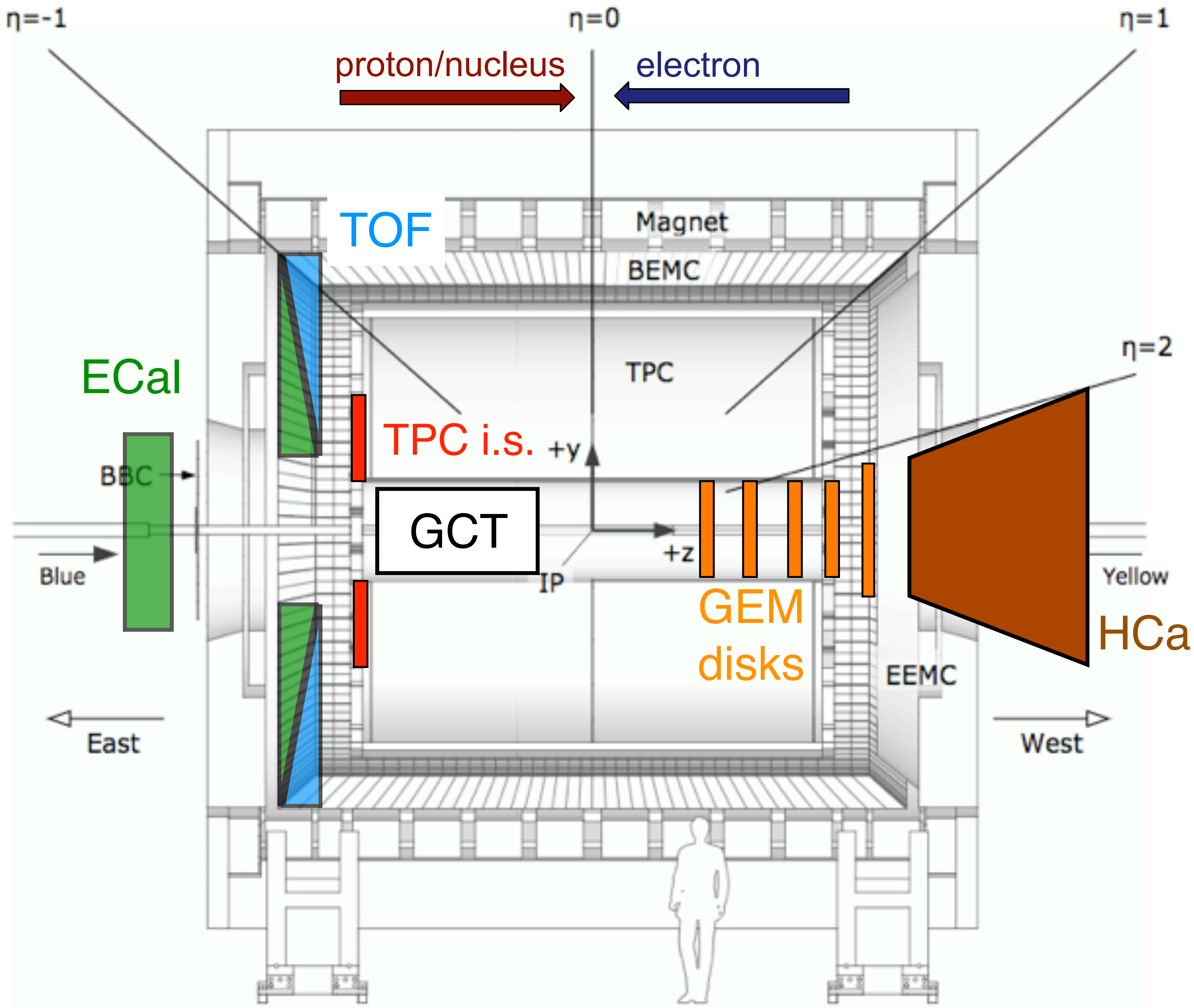
  - combine high-threshold (gas) Cherenkov with TPC-like tracking
- TPC: replace inner sectors
  - make a greater density of pad rows
- TOF: π, K i.d., t_0, electron
- ECal: electrons, photons



STAR

The realisation of an eSTAR detector

- HCal: W powder, spaghetti calorimeter
- GCT: compact tracker with enhanced electron capability
  - combine high-threshold (gas) Cherenkov with TPC-like tracking
- TPC: replace inner sectors
  - make a greater density of pad rows
- TOF: π, K i.d., t_0, electron
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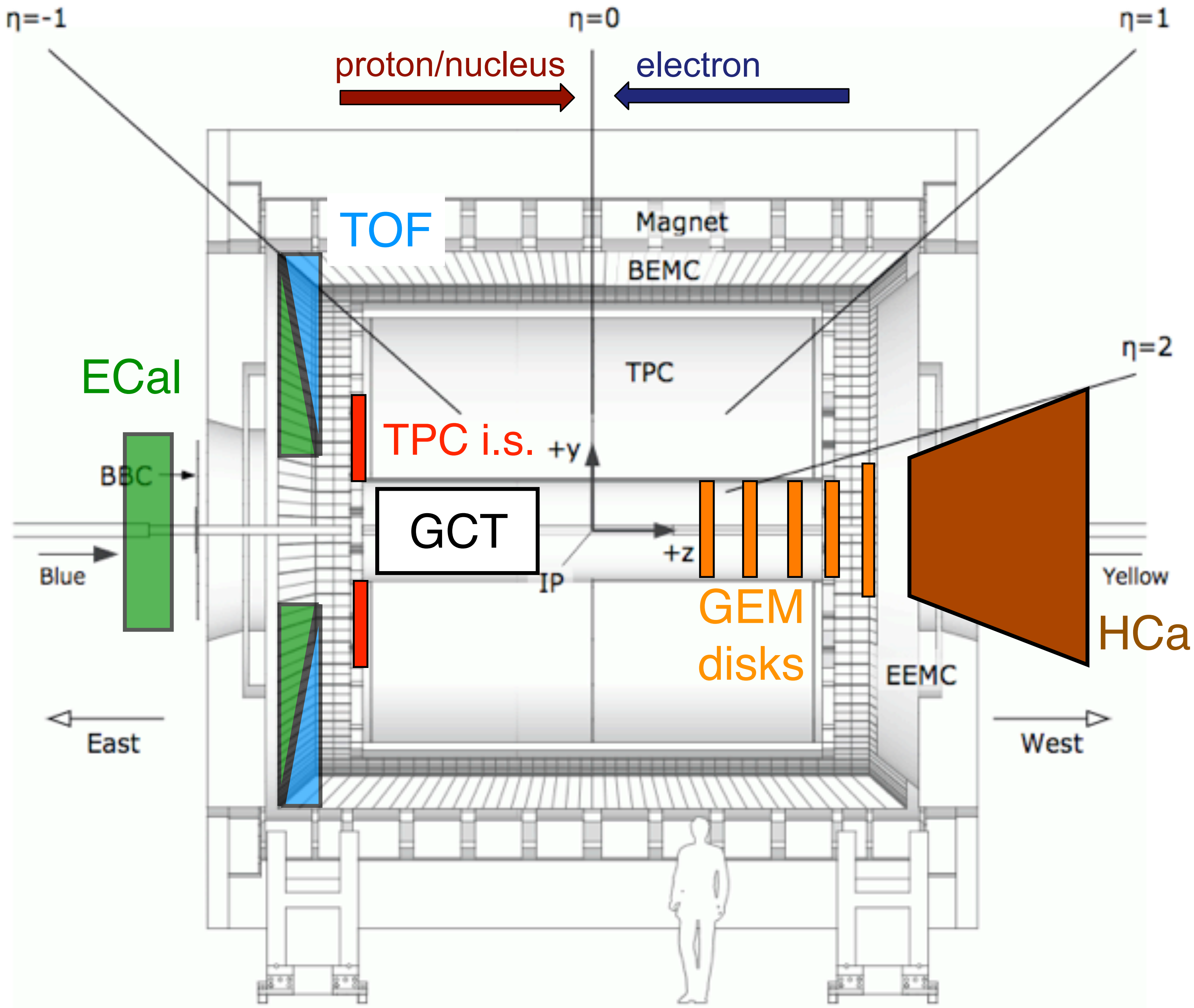
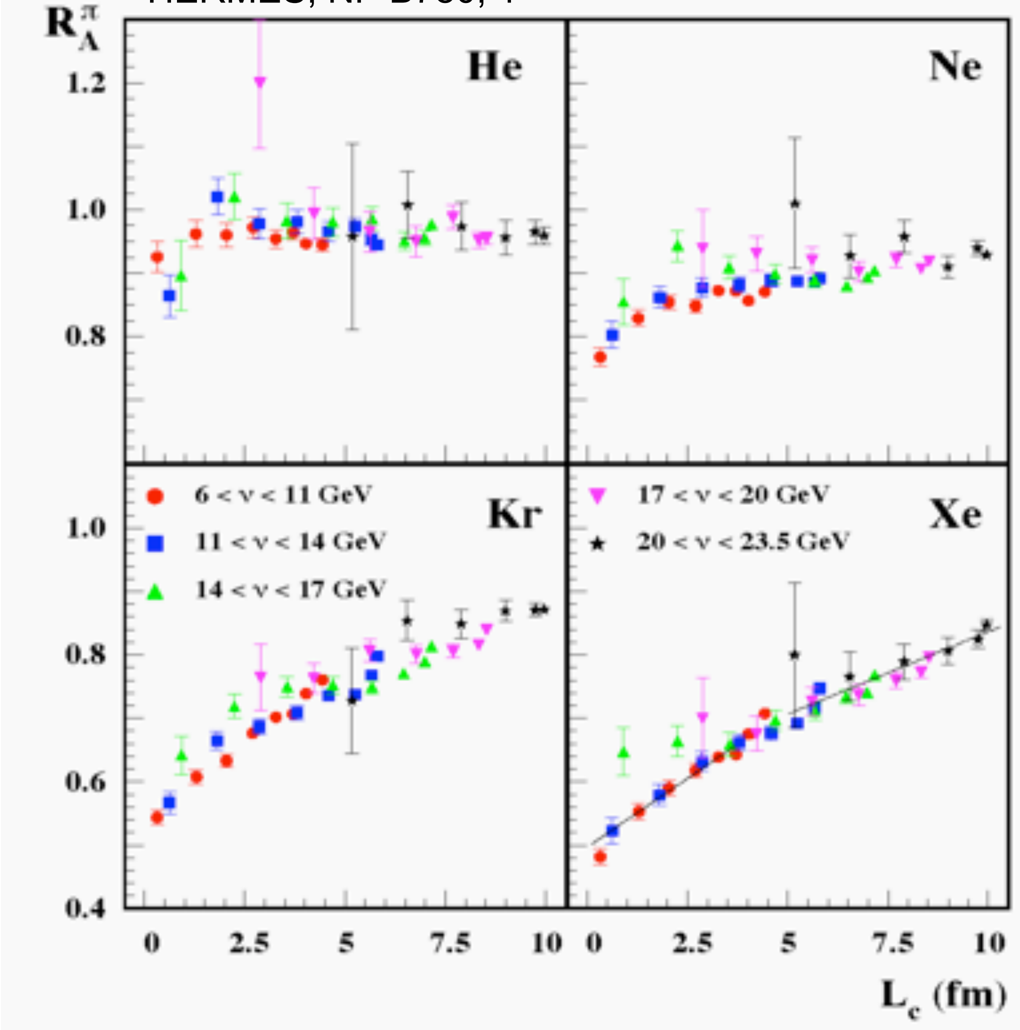
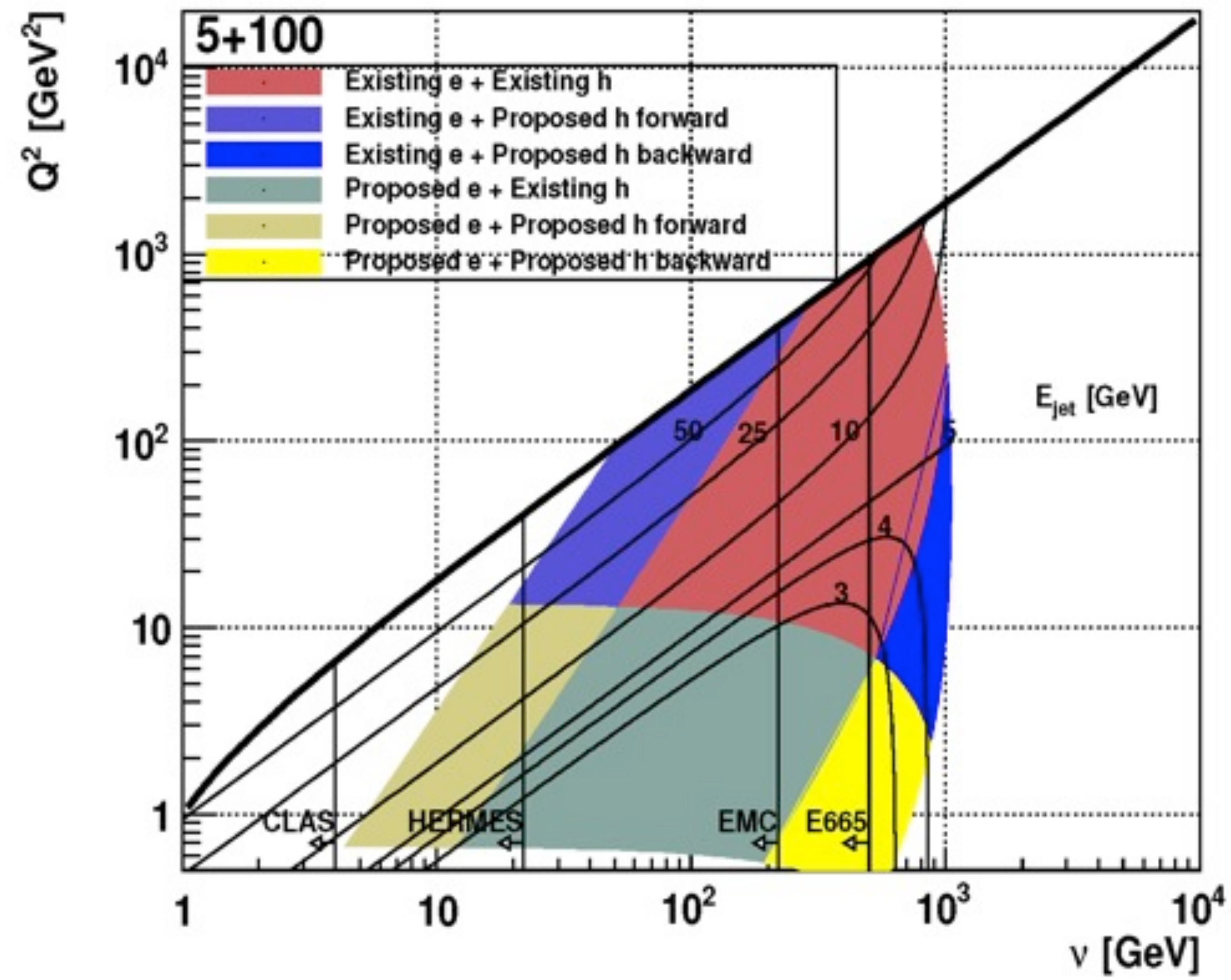


R&D ongoing thanks to BNL-directed EIC generic detector R&D funds

Example physics: parton energy loss in cold QCD matter

HERMES, NP B780, 1





- HERMES: limited range in ν
  - hadrons form partially inside the medium
- eRHIC: large range in ν (L_c up to a few 100 fm)
  - light quarks form well outside the medium
  - also ability to explore heavy-quark formation
    - probably requires stage-II eRHIC (> 5 GeV electrons) for quantitative evaluation

STAR

Summary and Conclusions

- STAR has completed it's first decade of physics with exciting and unexpected results
  - A strongly coupled plasma is formed in heavy-ion collisions, creating a perfect liquid
- STAR has a clear path of upgrades to build on the physics already learned, together with the upgrades of the machine
  - New detectors, new electronics
- In the long term (STAR's 3rd decade), a role is foreseen to for STAR → eSTAR
  - Complement but not replace the need for an all-singing, all-dancing, purpose-built detector

STAR

The future physics programme of STAR

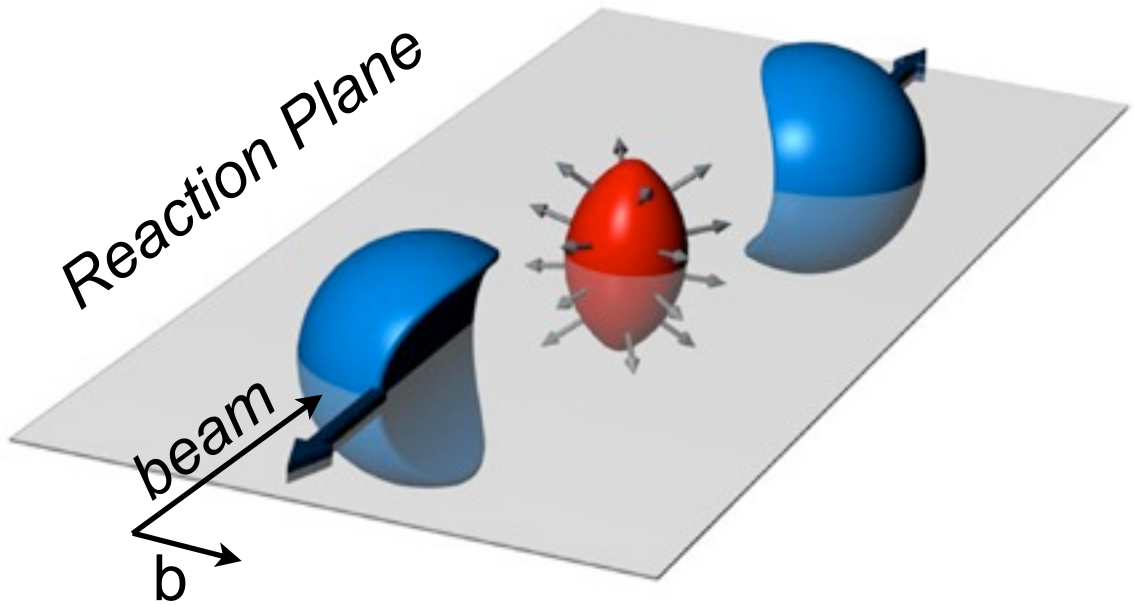
	Near term (Runs 11–13)	Mid-decade (Runs 14–16)	Long term (Runs 17–)
Colliding systems	p+p, A+A	p+p, A+A	p+p, p+A, A+A, e+p, e+A
Upgrades	FGT, FHC, RP, DAQ10K, Trigger	HFT, MTD, Trigger	Forward Instrum, eSTAR, Trigger
(1) Properties of sQGP	$\Upsilon, J/\psi \to ee$, m_{ee}, v_2	$\Upsilon, J/\psi \to \mu\mu$, Charm v_2, R_{CP}, Charm corr, Λ_c/D ratio, μ-atoms	p+A comparison
(2) Mechanism of energy loss	Jets, γ-jet, NPE	Charm, Bottom	Jets in CNM, SIDIS, c/b in CNM
(3) QCD critical point	Fluctuations, correlations, particle ratios	Focused study of critical point region	
(4) Novel symmetries	Azimuthal corr, spectral function	$e-\mu$ corr, $\mu-\mu$ corr	
(5) Exotic particles	Heavy anti-matter, glueballs		
(6) Proton spin structure	W A_L, jet and di-jet A_{LL}, intra-jet corr, $(\Lambda+\bar{\Lambda})$ D_{LL}/D_{TT}		Λ D_{LL}/D_{TT}, polarized DIS, polarized SIDIS
(7) QCD beyond collinear factorization	Forward A_N		Drell-Yan, F-F corr, polarized SIDIS
(8) Properties of initial state			Charm corr, Drell-Yan, J/ψ, F-F corr, Λ, DIS, SIDIS

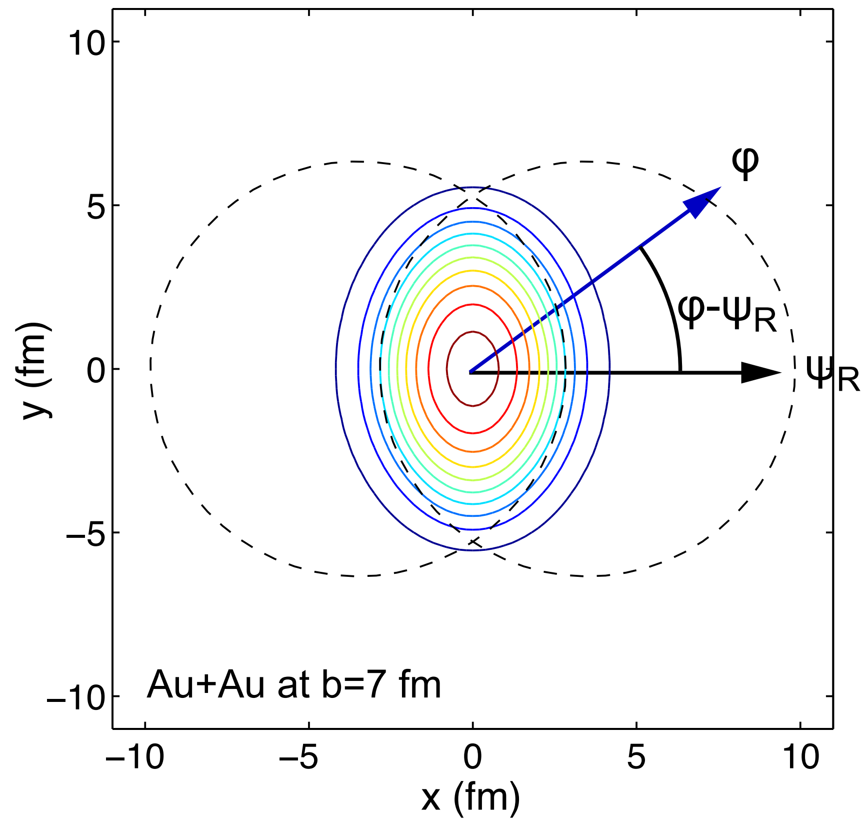
STAR

BACKUP SLIDES

v2

Strong Elliptic Flow





Initial spatial anisotropy → Interactions → Final state anisotropy in momentum space

Use a Fourier expansion to describe the angular dependence of the particle density

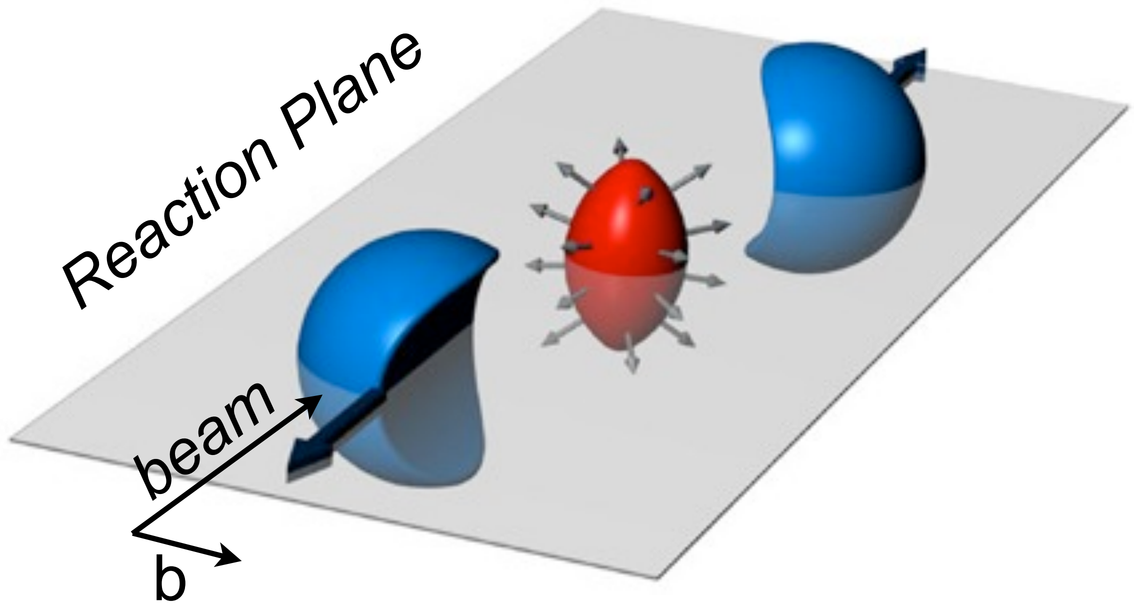
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n(\phi - \Psi_r)\right]\right)$$

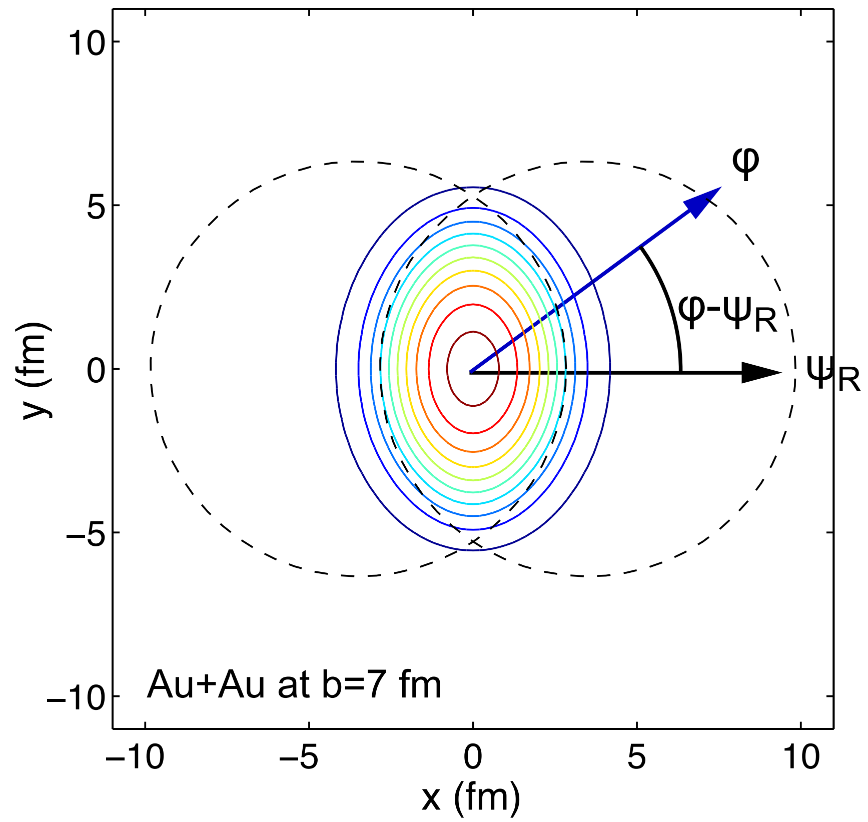
Fourier coefficient

Angle of reaction plane

STAR

Strong Elliptic Flow

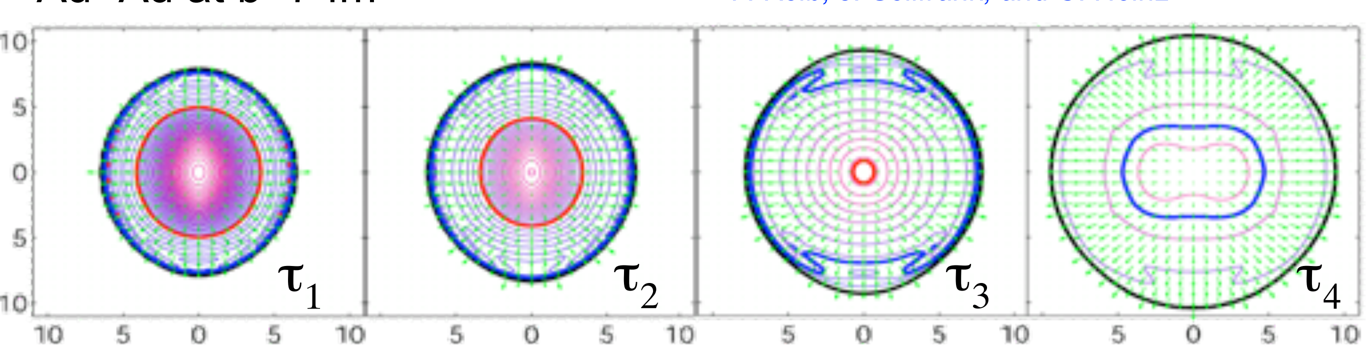




Initial spatial anisotropy → Interactions → Final state anisotropy in momentum space

Au+Au at b=7 fm

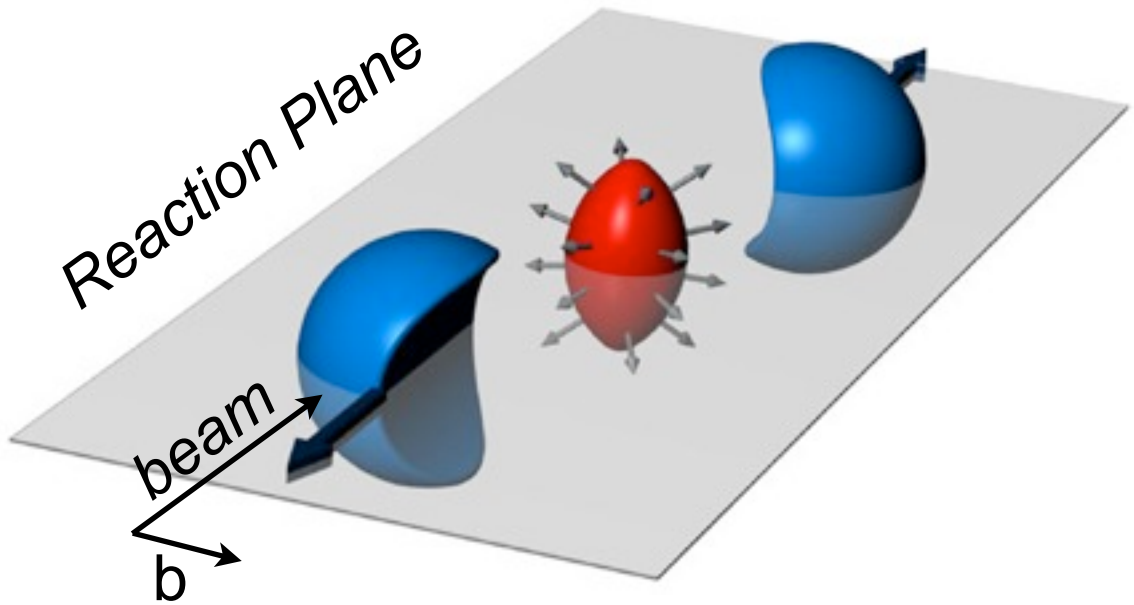
P. Kolb, J. Sollfrank, and U. Heinz

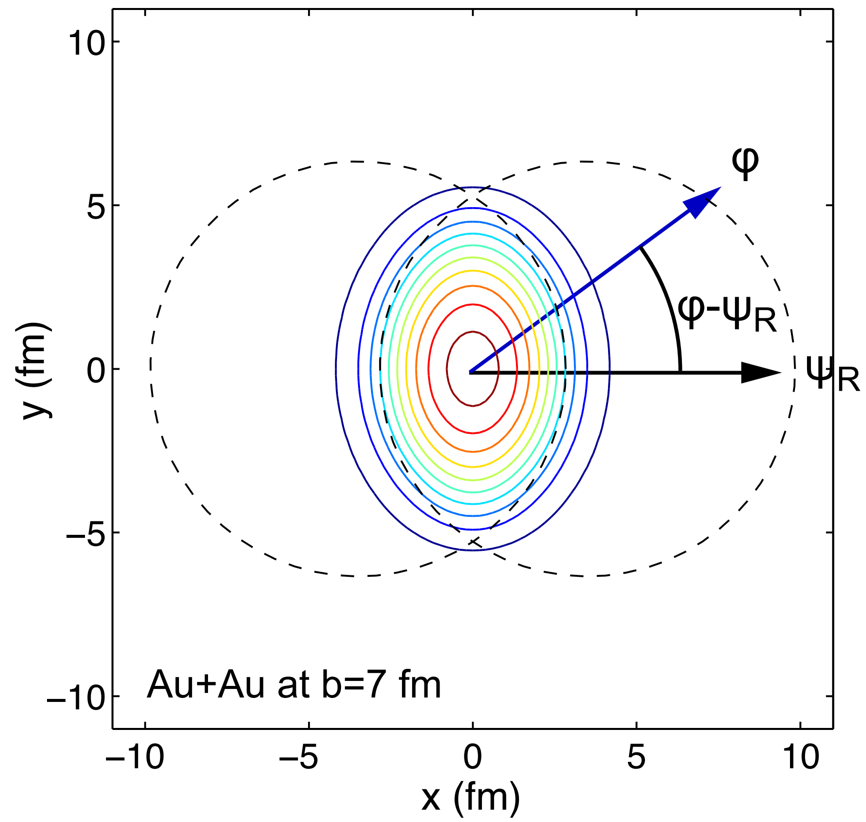


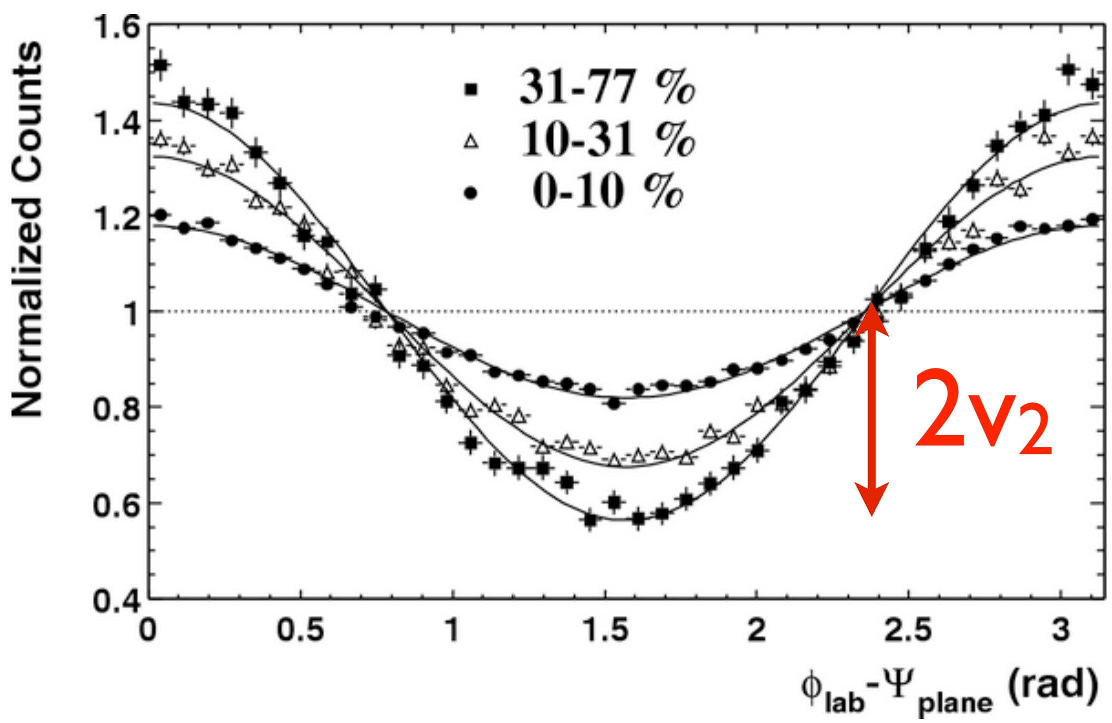
- driving spatial anisotropy vanishes
  $\Rightarrow$ self quenching
- $v_2 \rightarrow$ sensitive to **early** interactions and pressure gradients

STAR

Strong Elliptic Flow



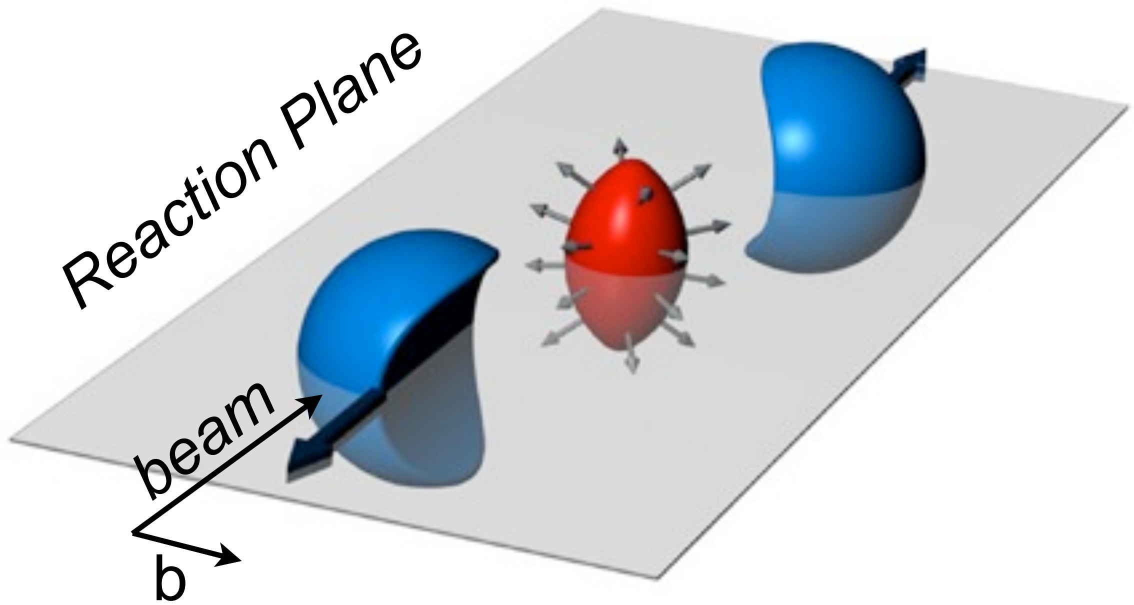


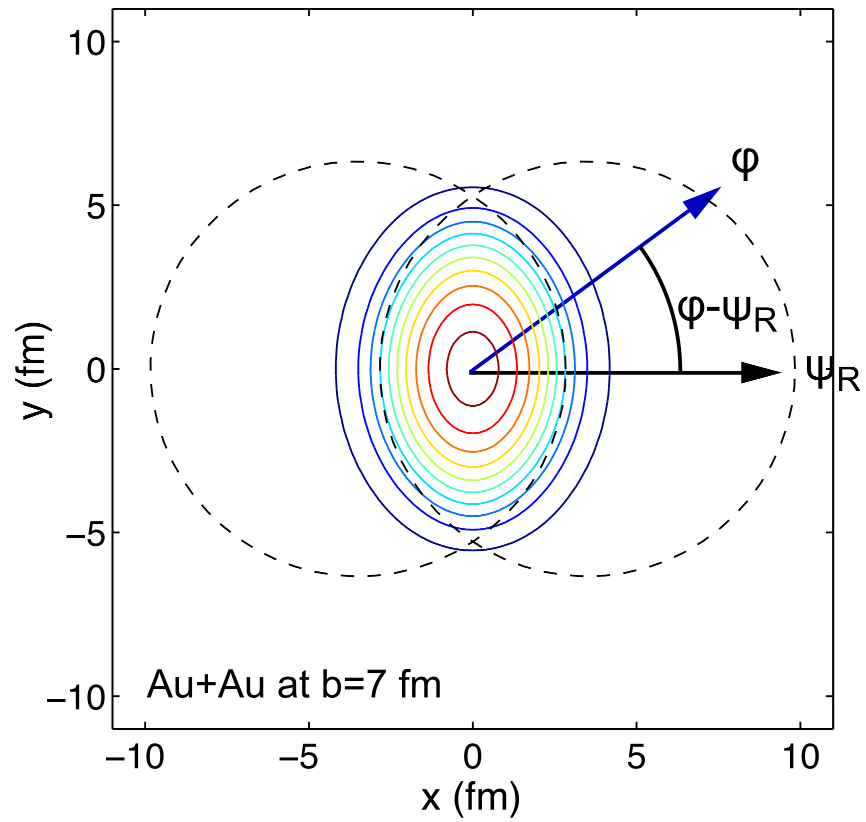


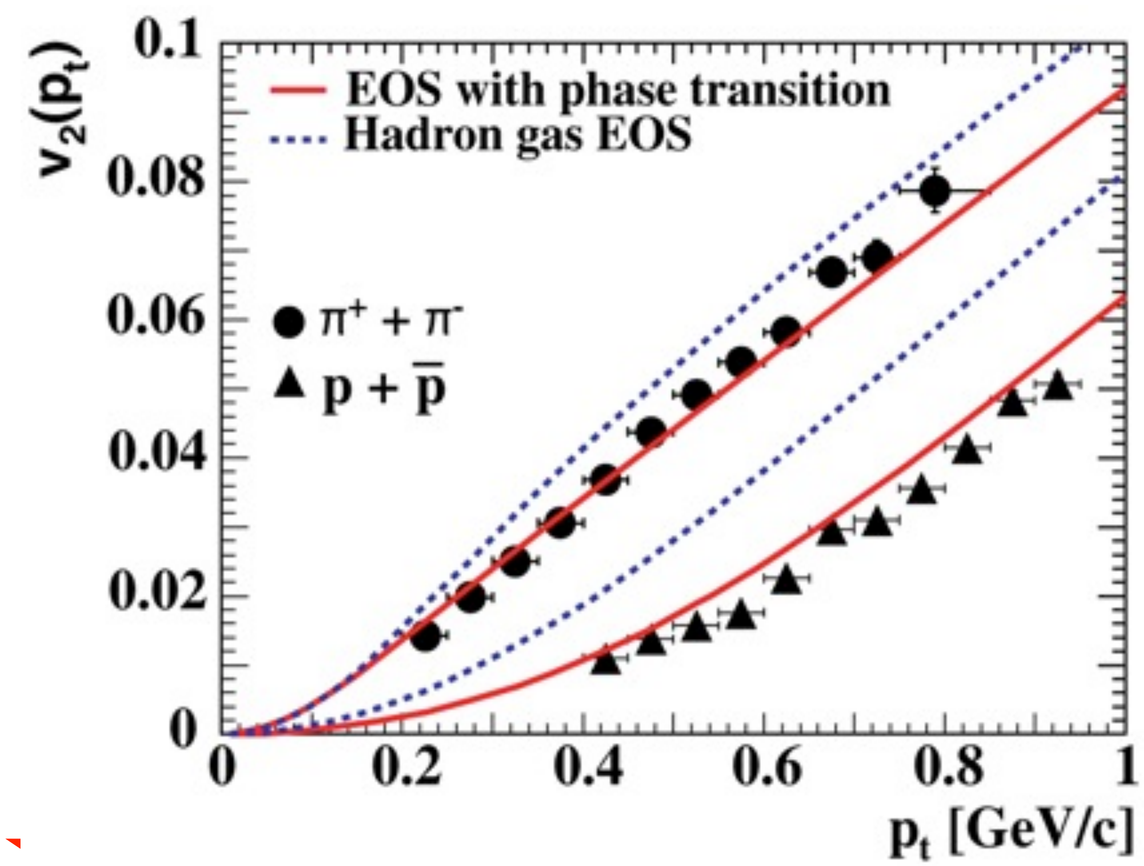
Huge asymmetry found at RHIC !!

STAR

Strong Elliptic Flow







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- Good agreement between data and ideal (zero viscosity) hydrodynamics

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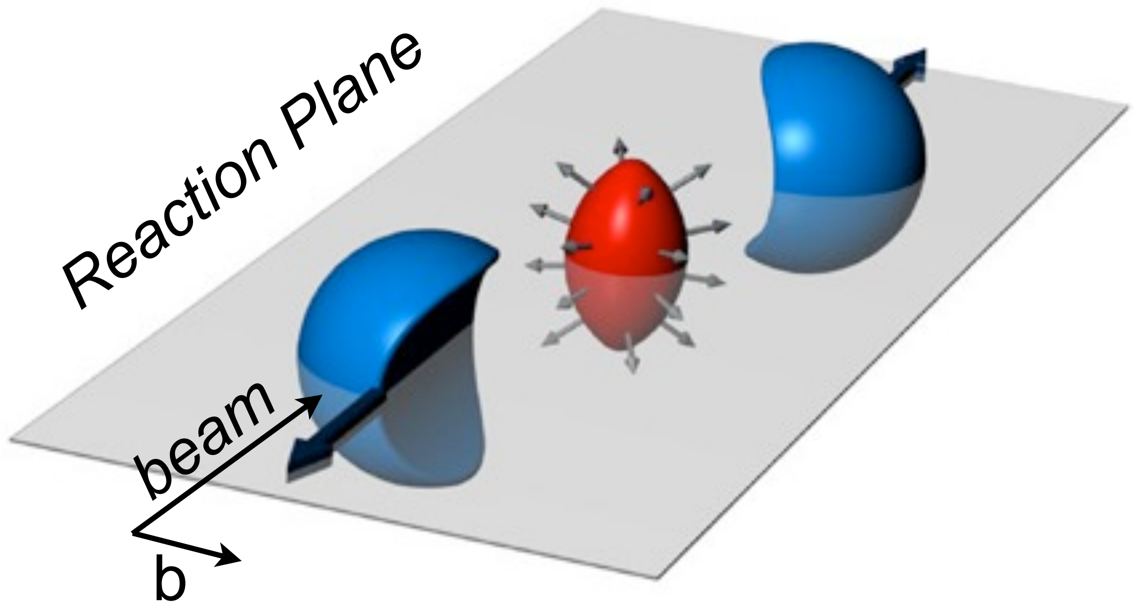

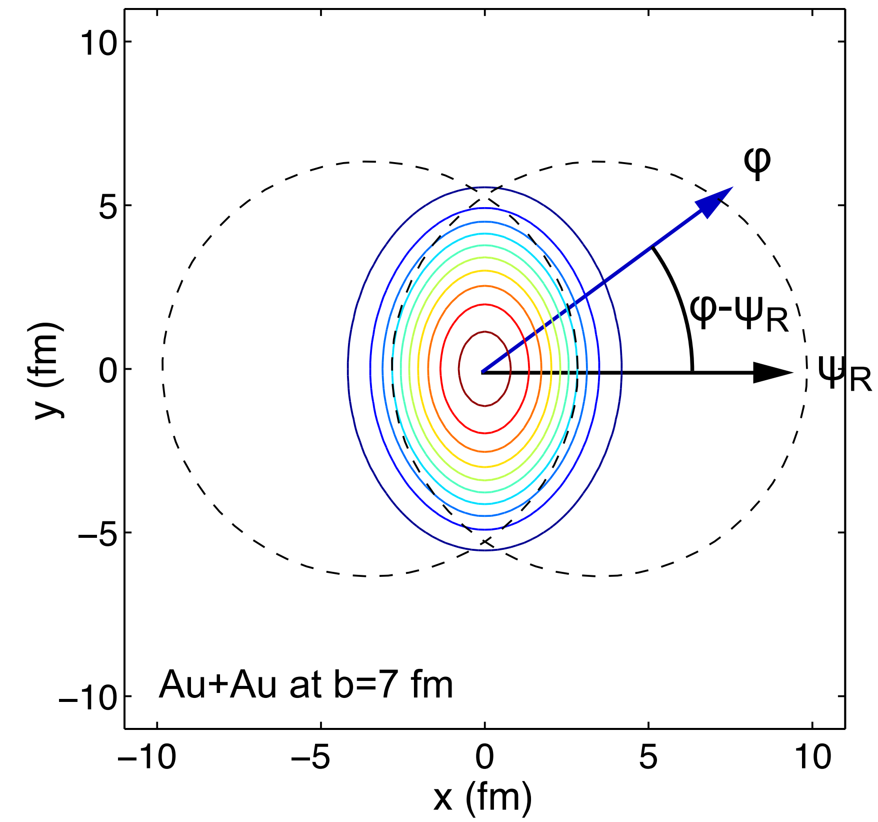

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Fourier coefficient (v_n)

Angle of reaction plane (Ψ_r)

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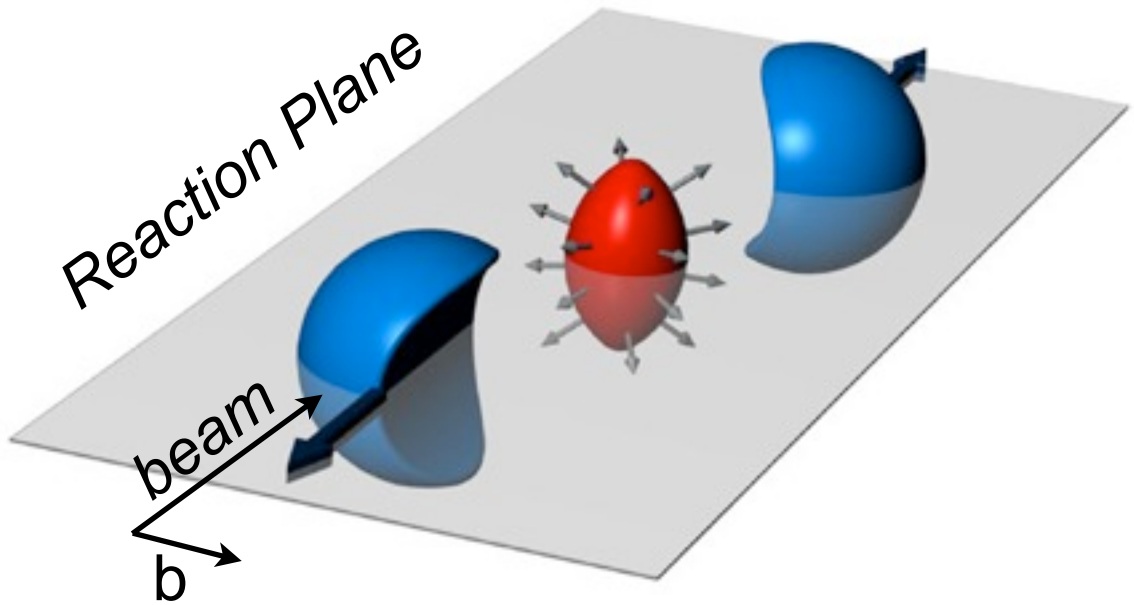

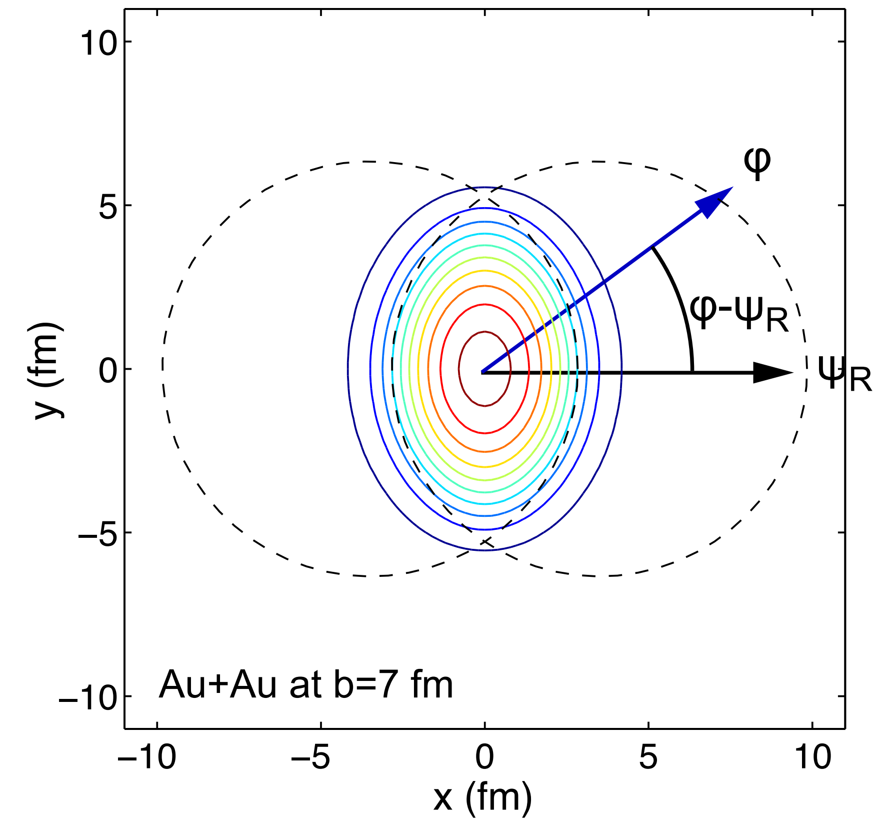

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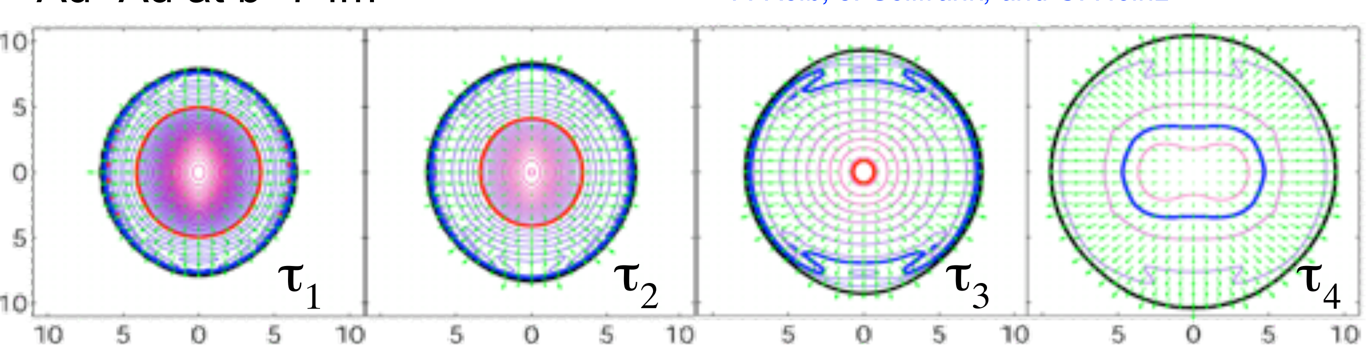

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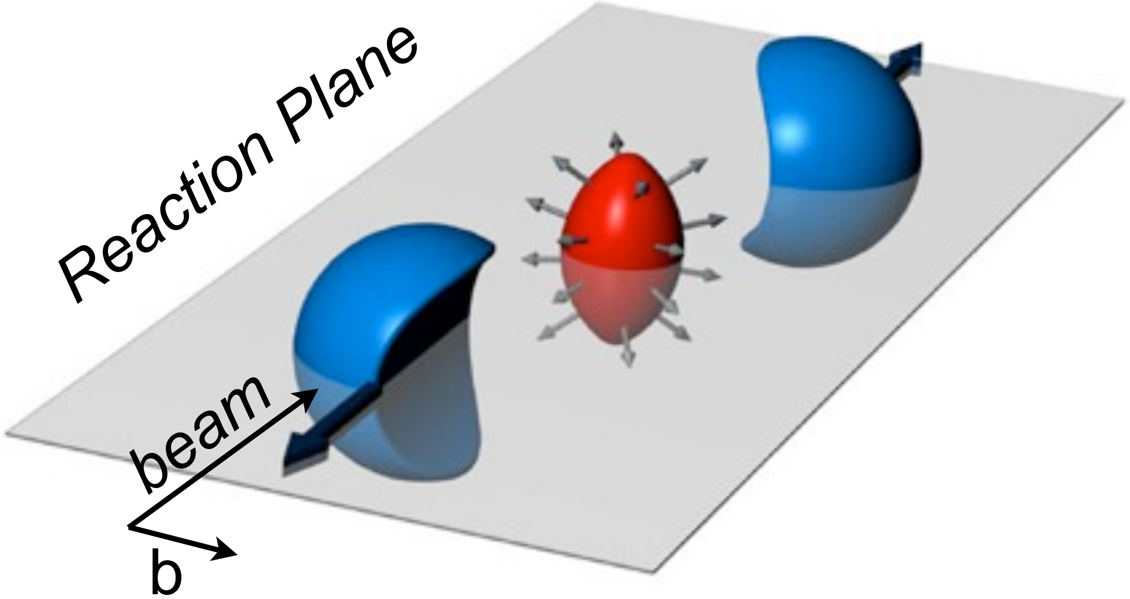
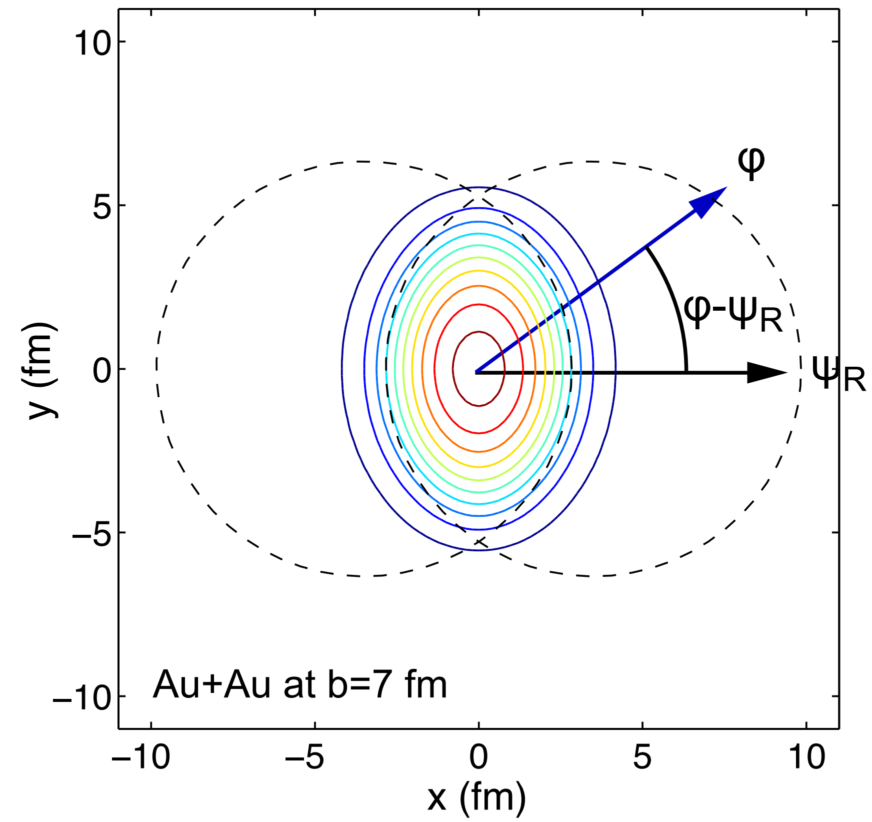
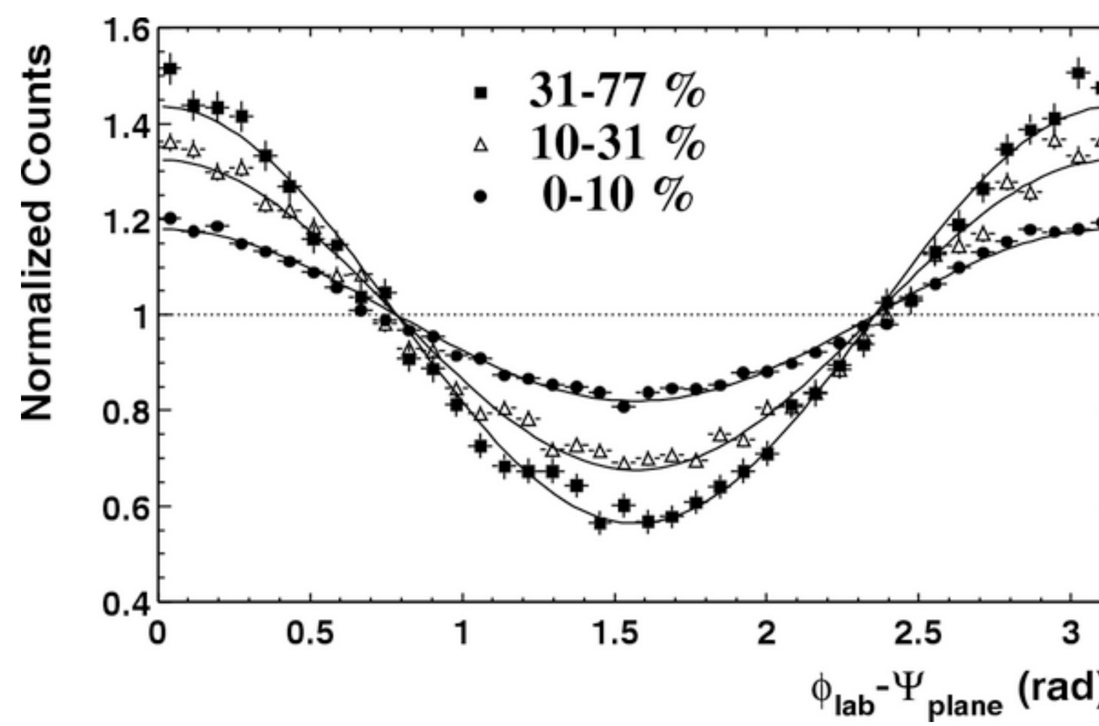




$2v_2$



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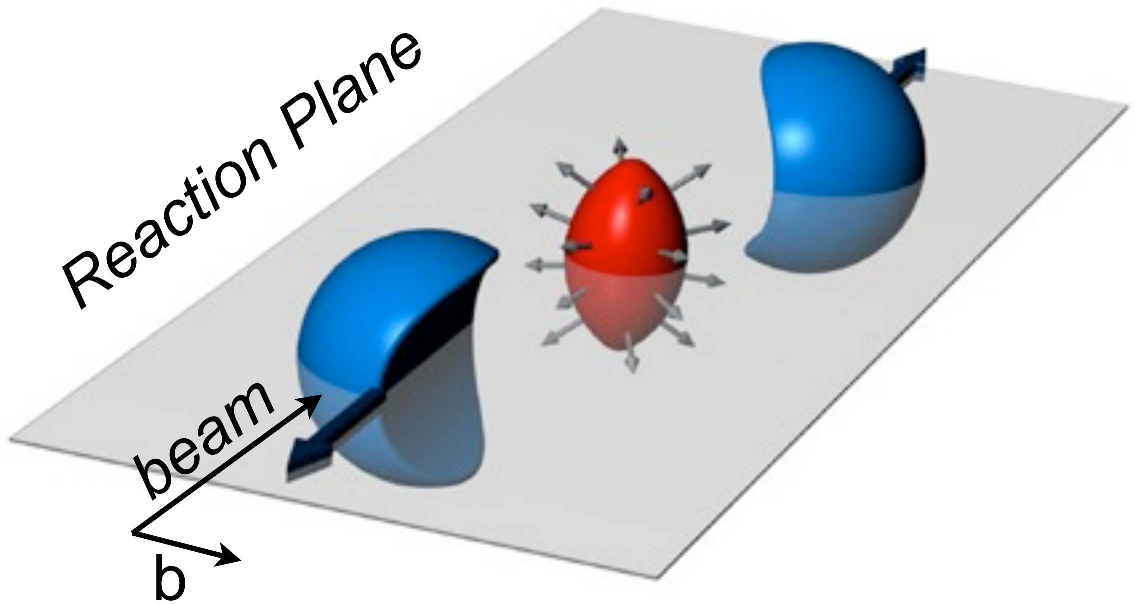
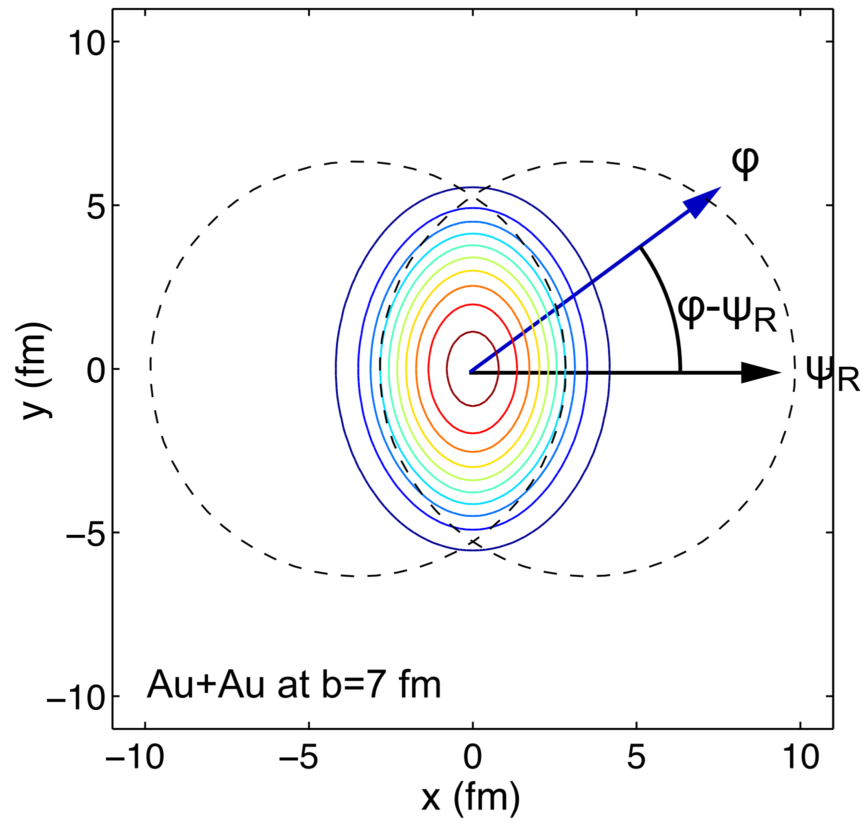
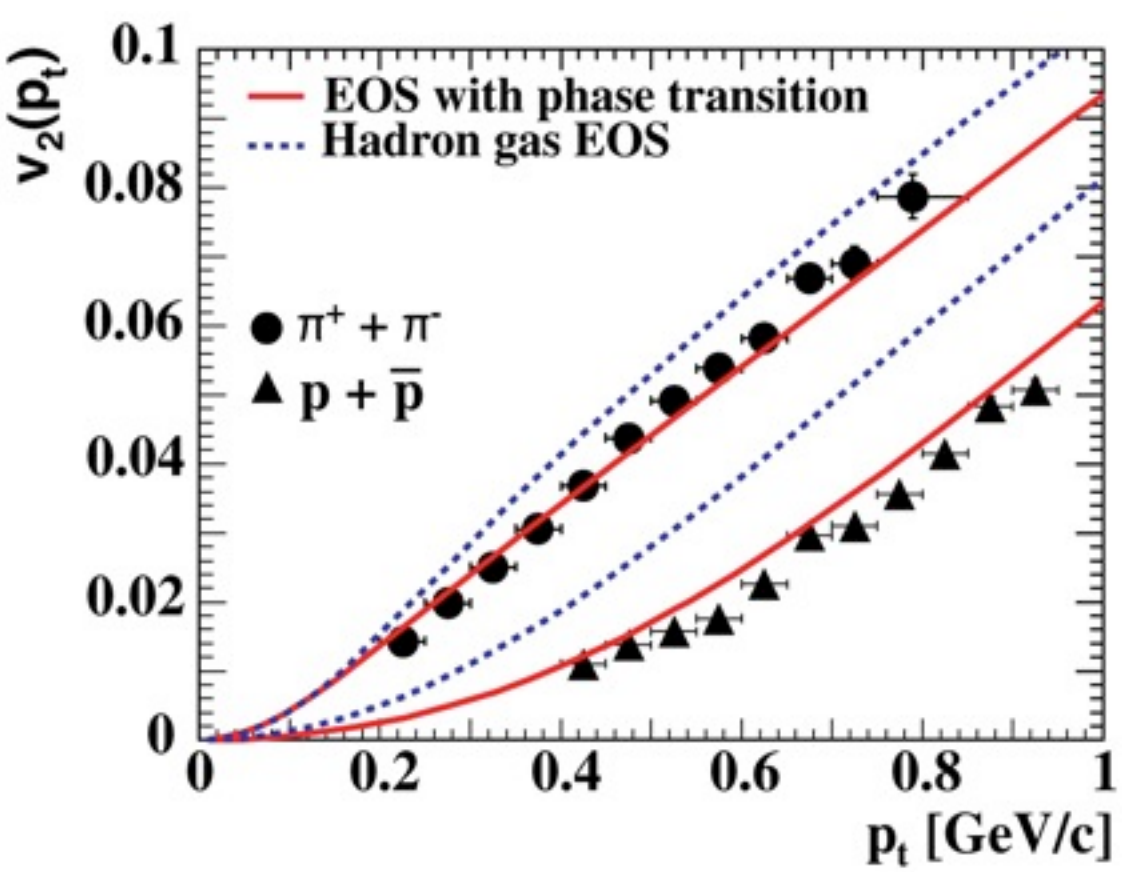
Strong Elliptic Flow







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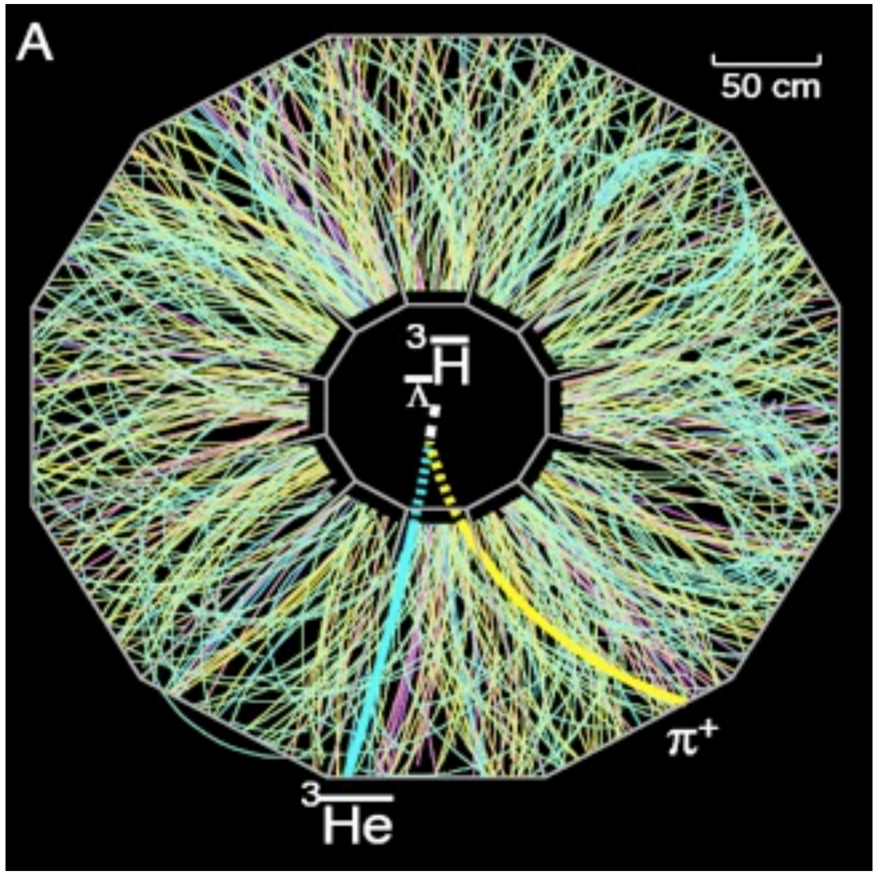
Exotic particles

Exotic particle search with STAR



***Science* 328,** 58 (2010)

- By utilising the high anti-baryon density and temperature of A+A collisions, coupled with special high-level trigger algorithms, have been able to find:
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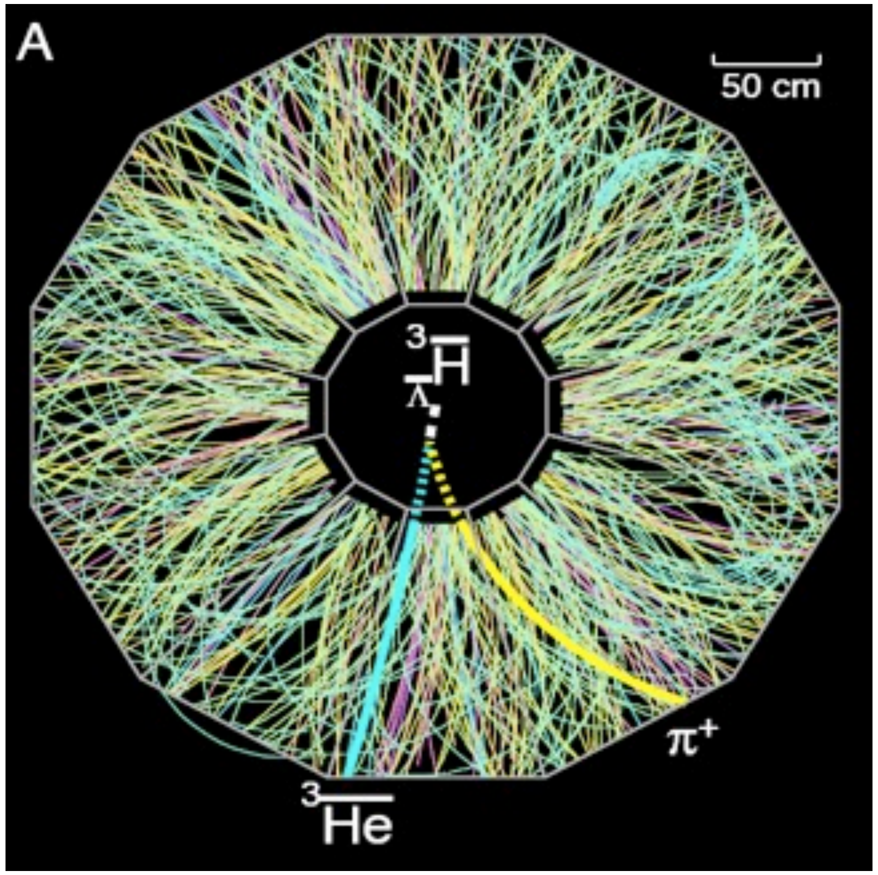

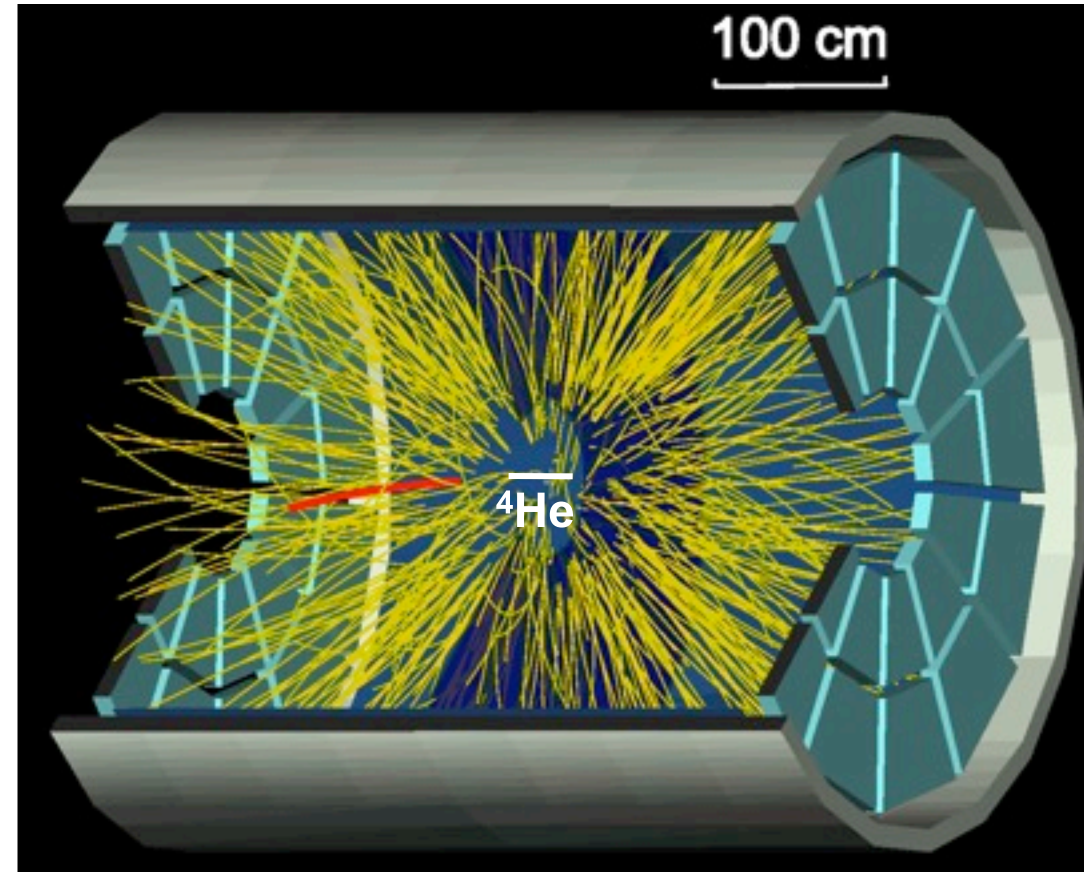

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***Nature* 473,** 353 (2011)

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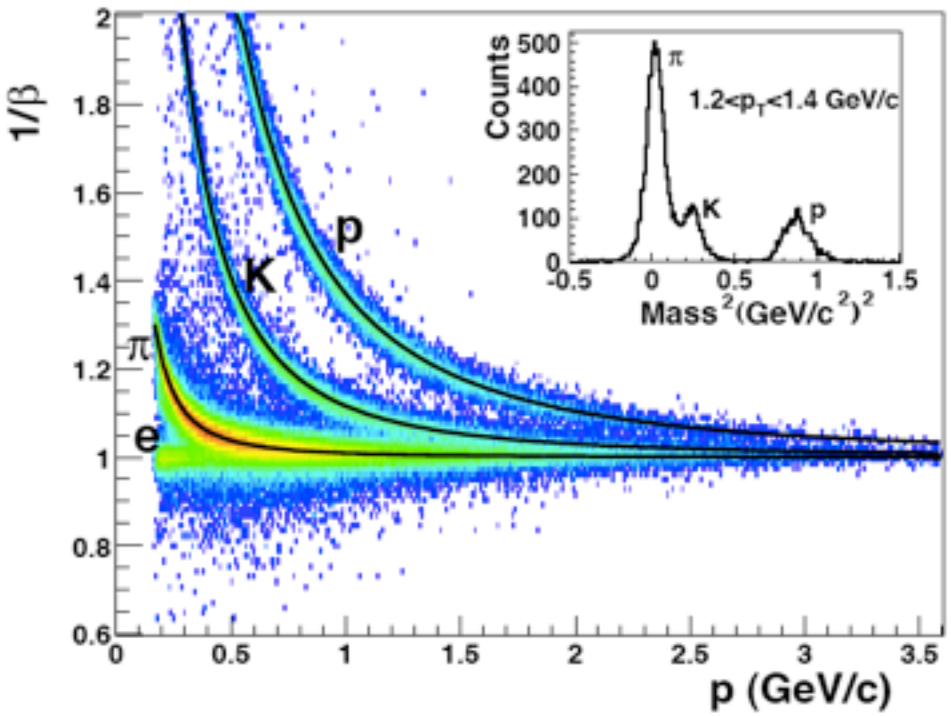
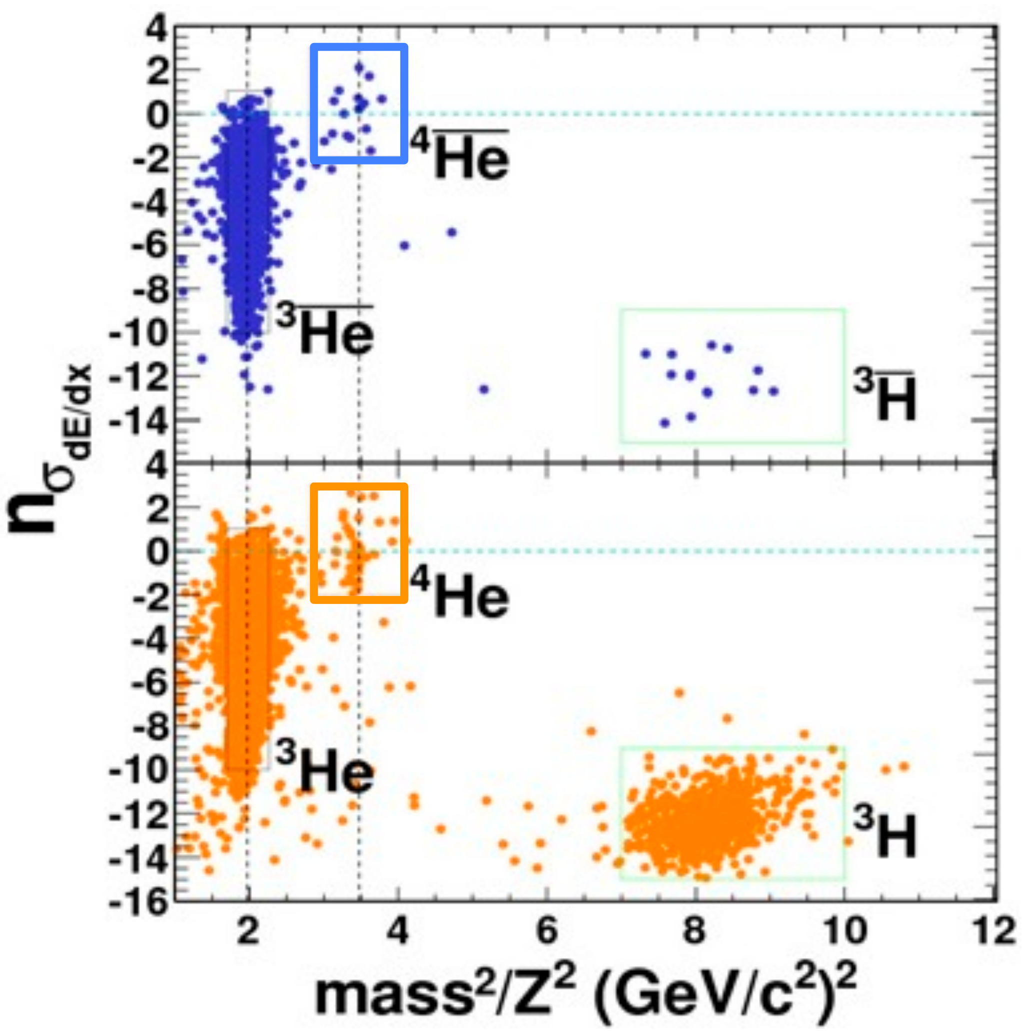
  - $^{4}\overline{He}$ - 2011

The search for exotic particles

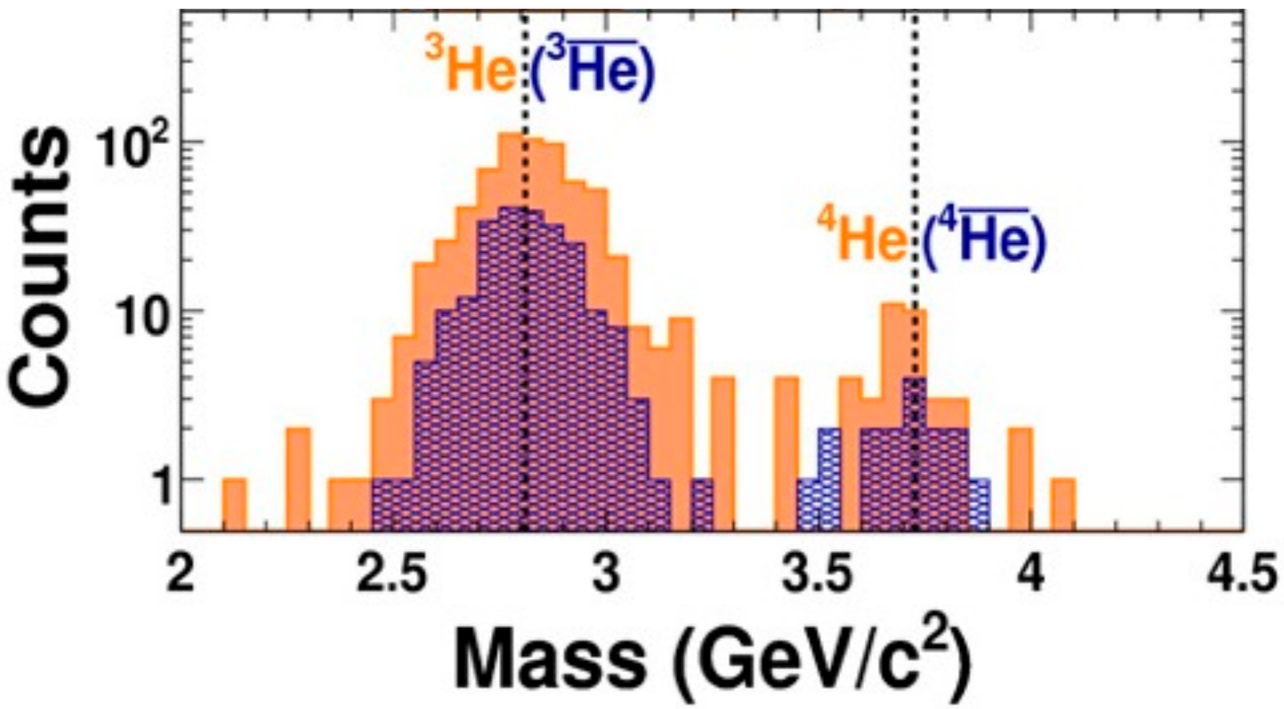


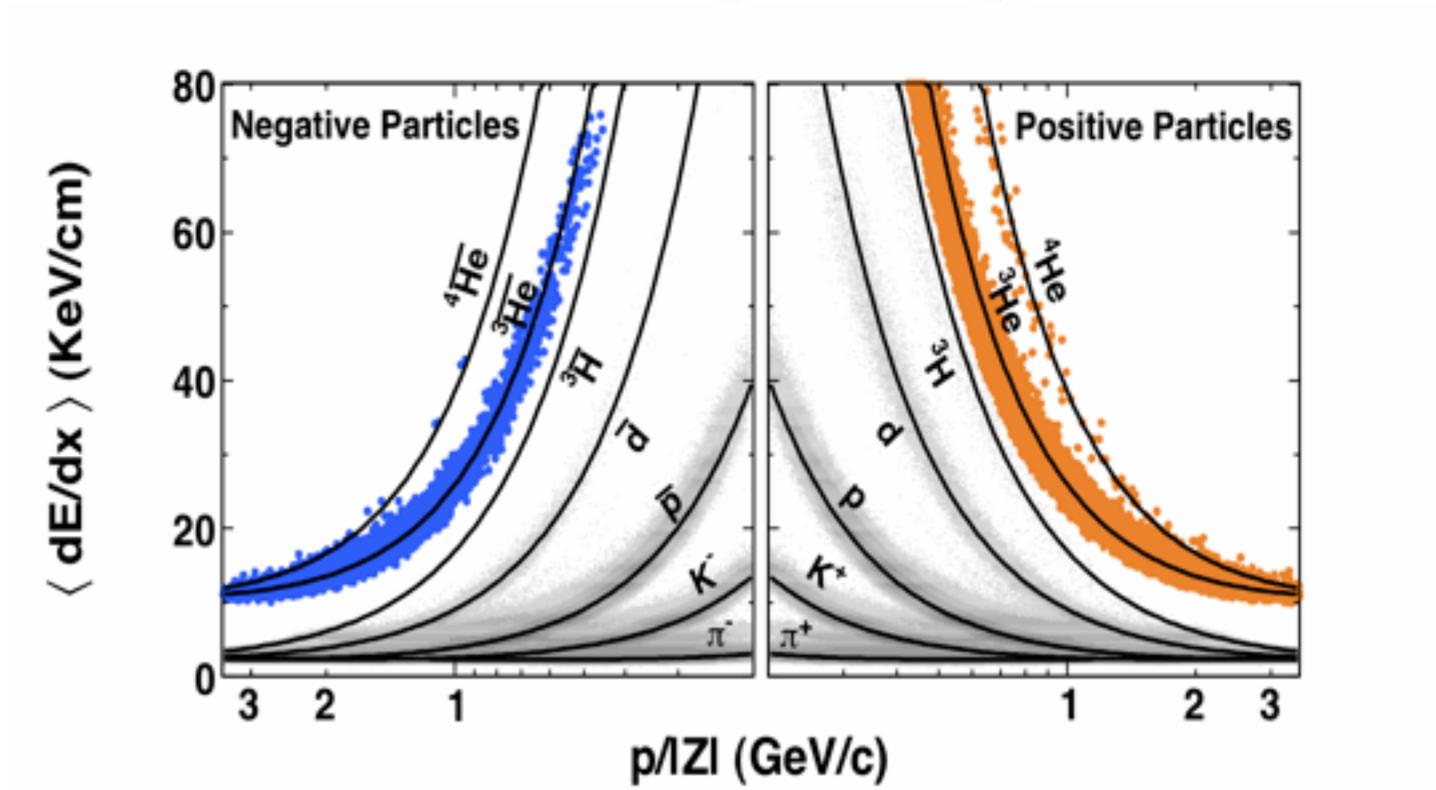


- By utilising STAR upgrades (both DAQ rate and detectors), have been able to search for exotic particles
- Combining TPC and TOF PID techniques, get clean PID out to relatively large p_T
- By measuring $n_{\sigma dE/dx}$ - the deviation from the expected energy loss of anti-^{4}He - can separate well the heavy nuclei produced
- Currently measured 18 counts of anti-^{4}He.

The search for exotic particles

nature **473,** 353 (2011)





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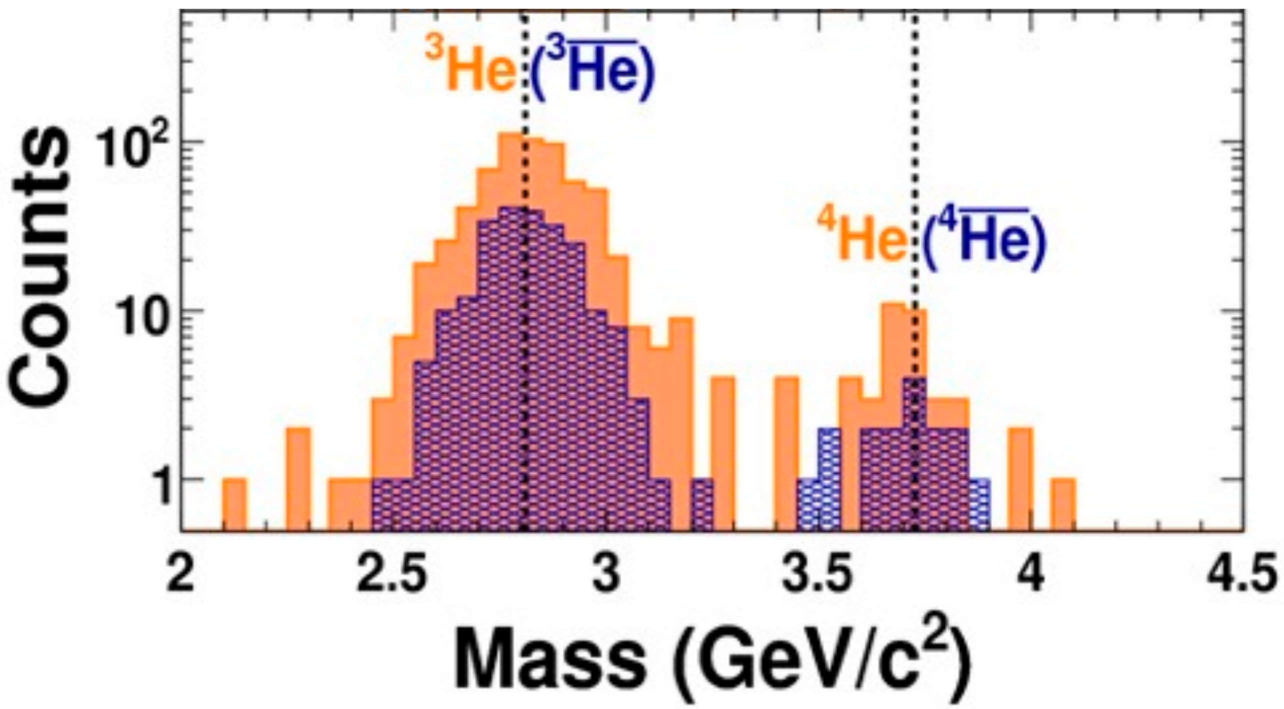

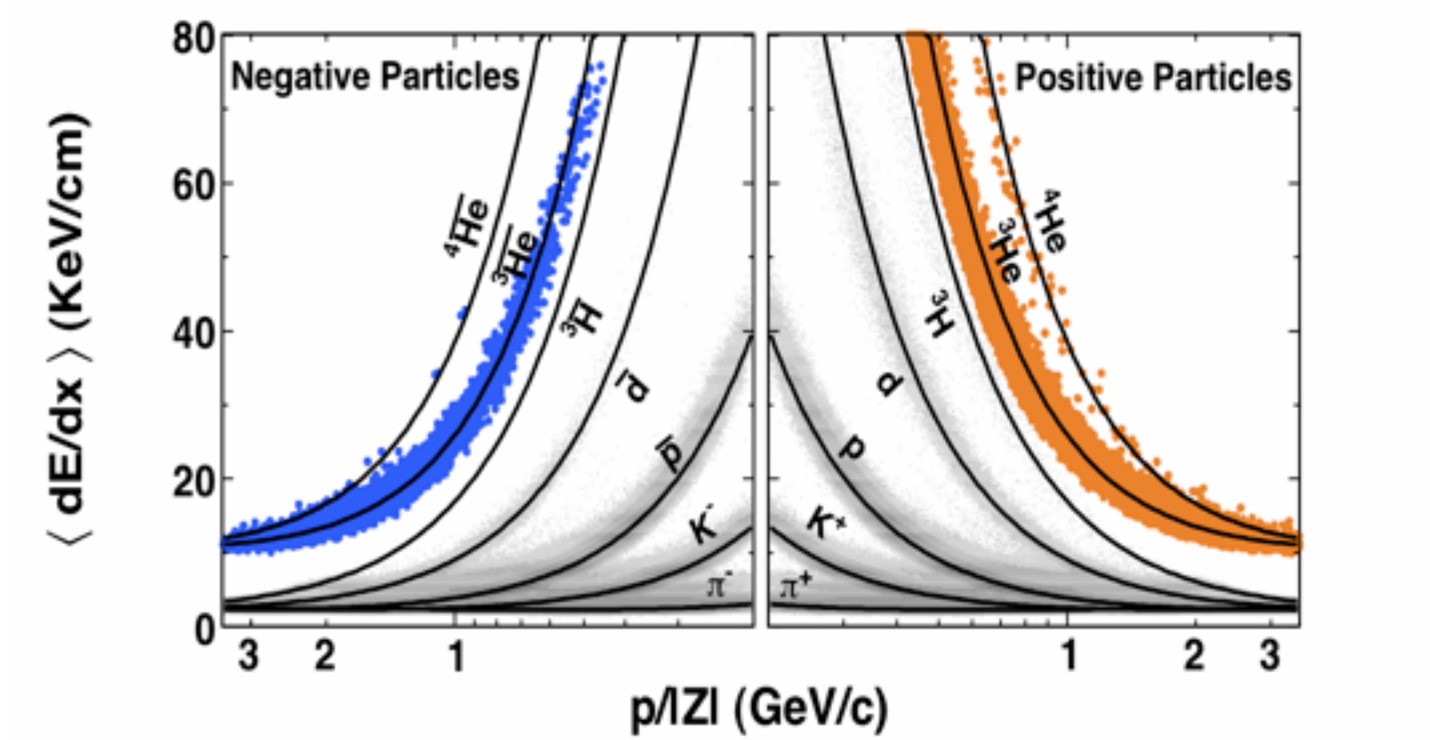

- Very clean identification after searching > 5x10^8 tracks from 10^7 Au+Au collisions!!

STAR

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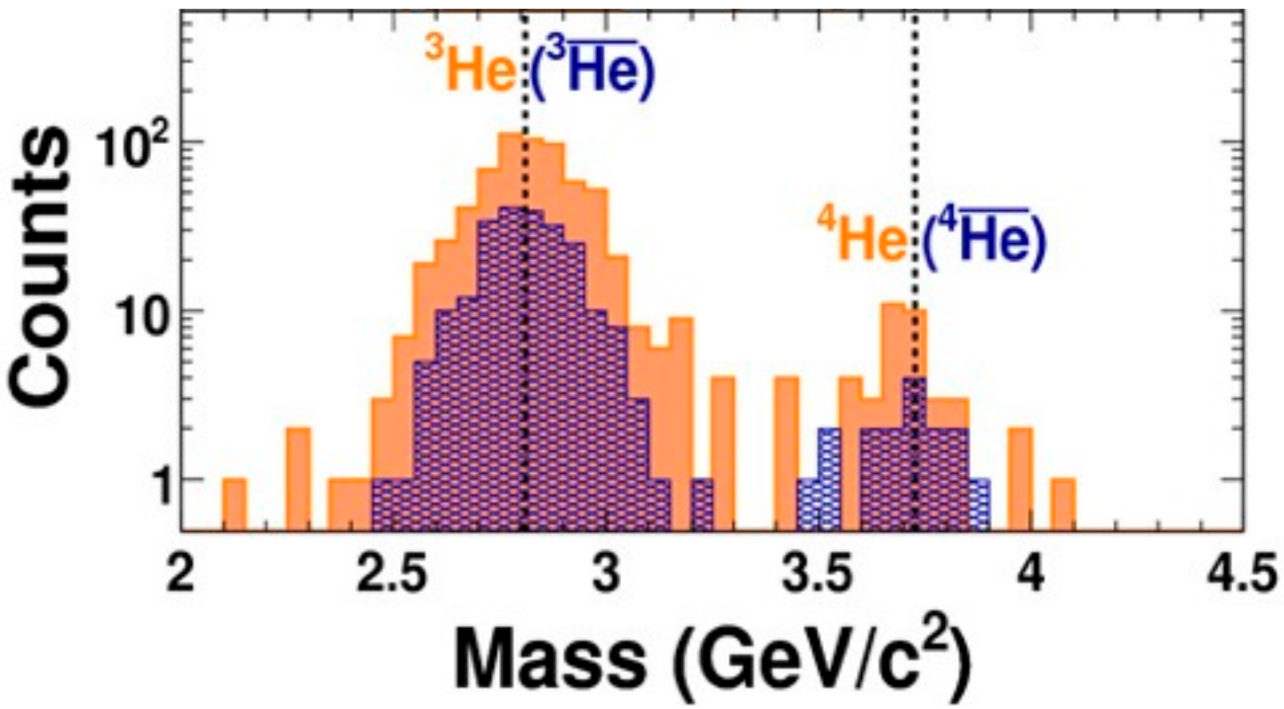
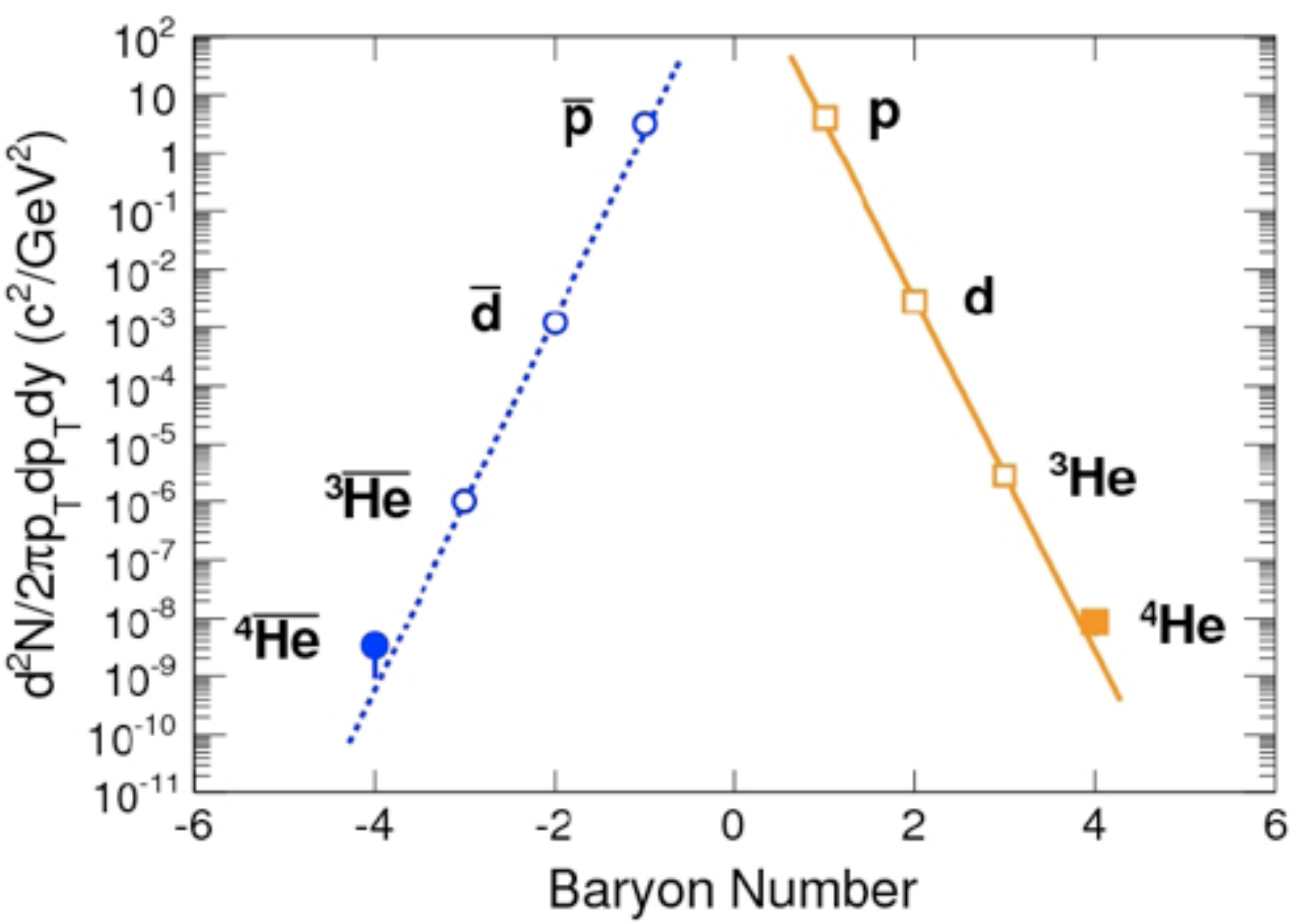
nature **473**, 353 (2011)

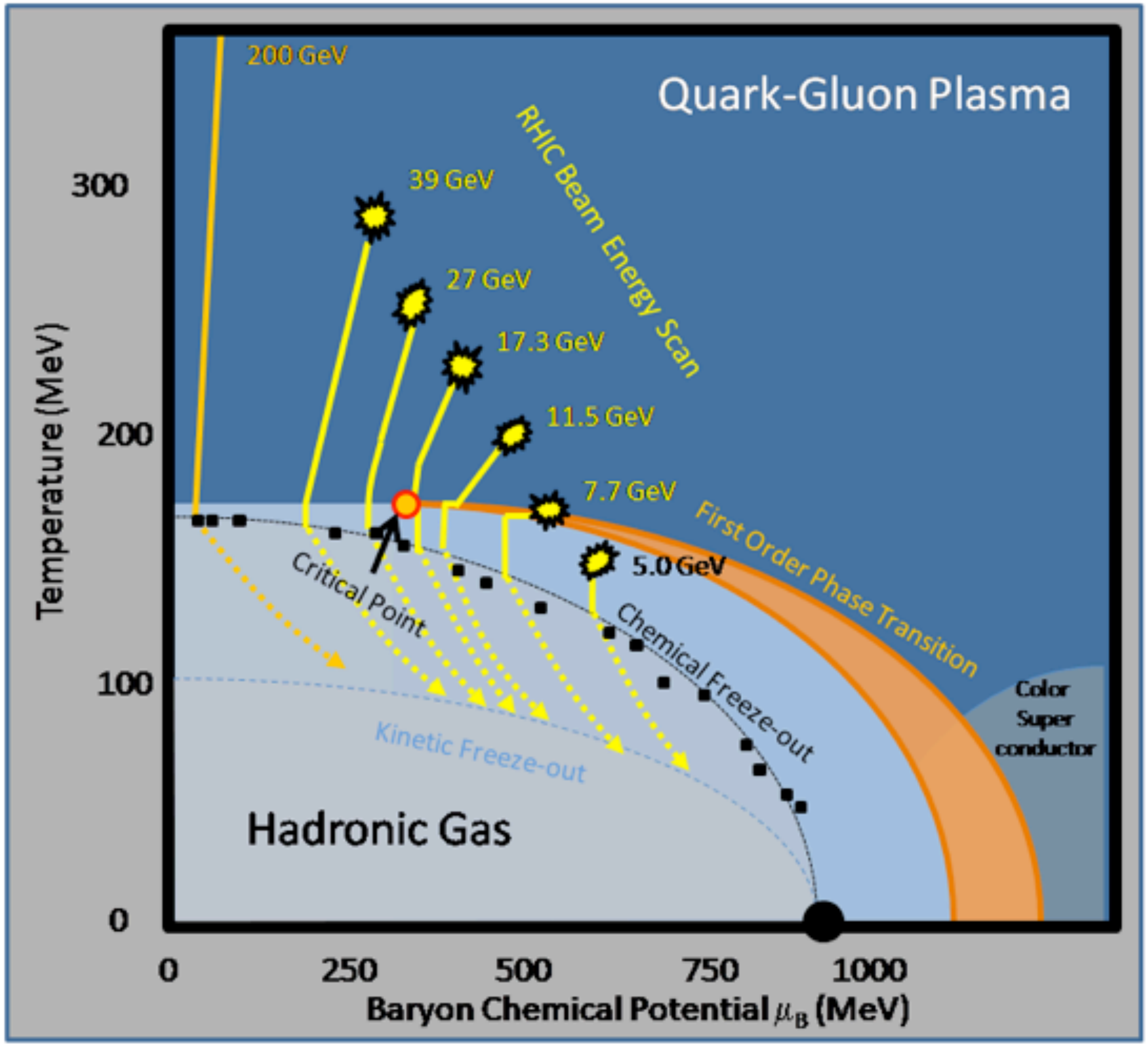




- Very clean identification after searching > 5×10^8 tracks from 10^7 Au+Au collisions!!
- Production rate reduces by a factor of 1.6×10^3 (1.1×10^3) for each additional anti-nucleon (nucleon) added to the anti-nucleus (nucleus).
  - Searching for heavier anti-nuclei becomes problematic due to required statistics
    - There are ideas and searches which can be done here (DAQ10K, H^0..)

Critical Point

Flexibility: Critical Point Search



- Phase 1: 2010, 2011
  - ~5 million events per energy and more already taken
    - Fluctuations, constituent quark scaling, HBT…
- Phase 2: 2014 and beyond
  - Luminosity improvement with electron cooling at RHIC
  - Scan to even lower energies
  - Increase event counts at energies already scanned

STAR

Flexibility: Critical Point Search

Collision Energies (GeV)	5	7.7	11.5	~~17.3~~ 19.6	27	39
Mevents taken (2010/11)		~5	~11	~17	~37	~170
Observables	Millions of Events Needed					
v_2 (up to ~1.5 GeV/c)	**0.3**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**
v_1	0.5	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Azimuthally sensitive HBT	4	**4**	**3.5**	**3.5**	**3**	**3**
PID fluctuations (K/p)	1	**1**	**1**	**1**	**1**	**1**
net-proton kurtosis	5	**5**	**5**	**5**	**5**	**5**
differential corr & fluct vs. centrality (e.g. bal. fctn)	4	**5**	**5**	**5**	**5**	**5**
n_q scaling p/K/p/L $(m_T-m_0)/n$<2GeV	8.5	**6**	**5**	**5**	**4.5**	**4.5**
f/W up to p_T/n_q=2 GeV/c		56	25	**18**	**13**	**12**
R_{CP} up to p_T ~4.5 GeV/c (at 17.3) 5.5 (at 27) & 6 GeV/c (at 39)				**15**	**33**	**24**
untriggered ridge correlations		27	13	**8**	**6**	**6**
parity violation		**5**	**5**	**5**	**5**	**5**

STAR

Perfect Liquid

How perfect is the "perfect" liquid?

Conjectured quantum limit: $\eta \geq \frac{\hbar}{4\pi}(Entropy\ Density) \equiv \frac{\hbar}{4\pi}s$

Ideal hydro $v_2 \propto$ spatial eccentricity ε: $\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$

v_2/ϵ is a sensitive probe of the system:

(S is transverse area of collision, h is ideal hydro limit of v_2/ϵ and $B \propto \eta/s$)

$$\frac{v_2}{\epsilon} = \frac{h}{1 + B/(\frac{1}{S}\frac{dN}{dy})}$$

STAR

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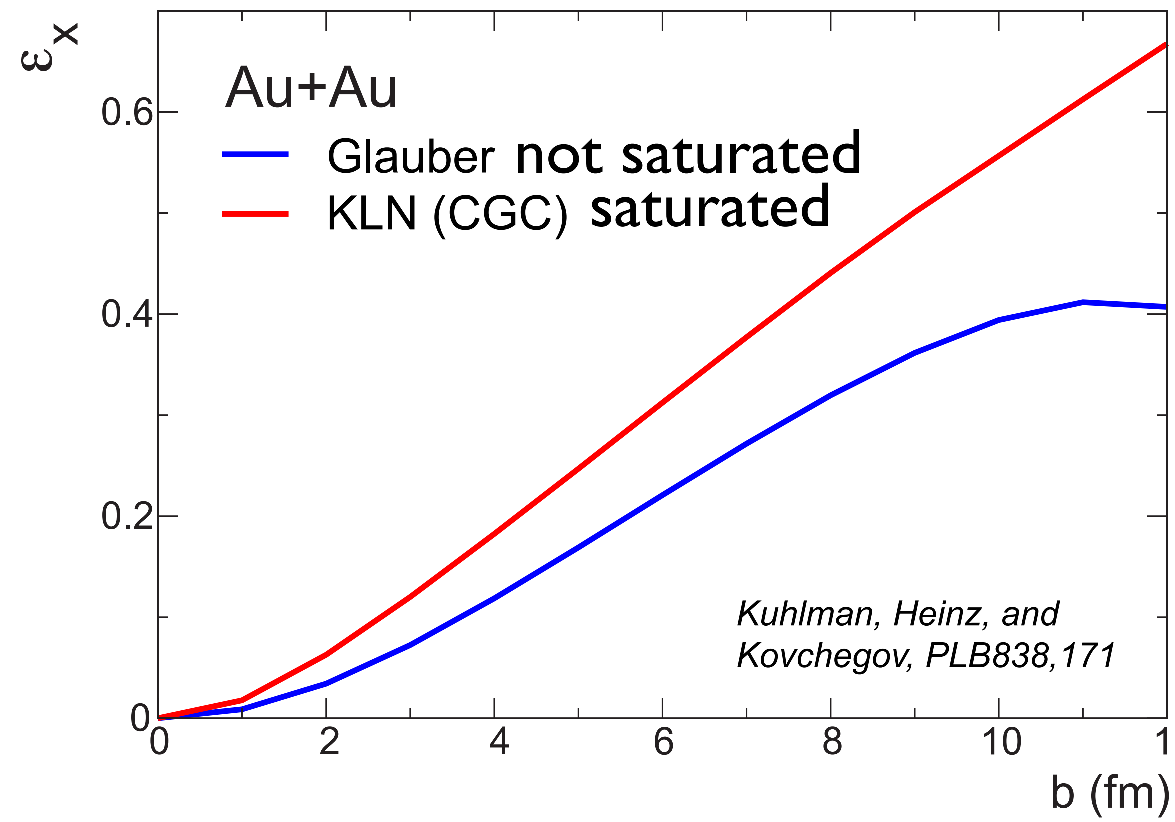

$\varepsilon_{CGC} > \varepsilon_{Glauber}$

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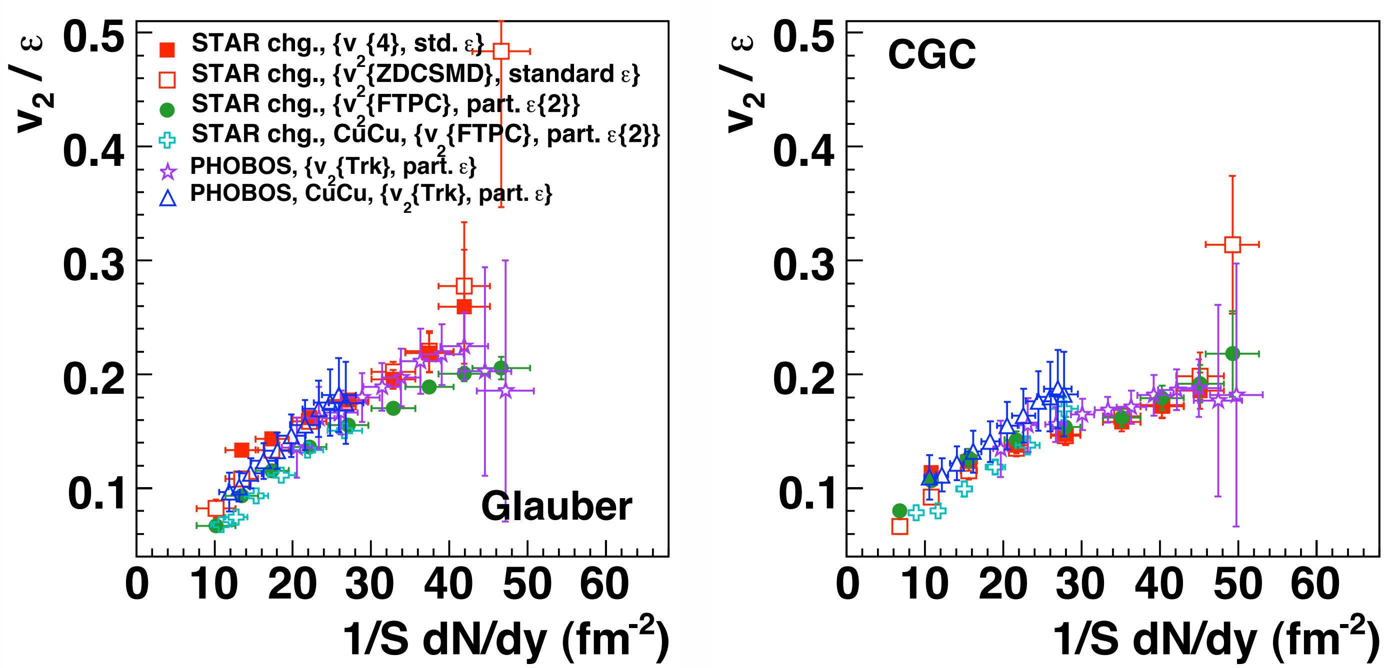

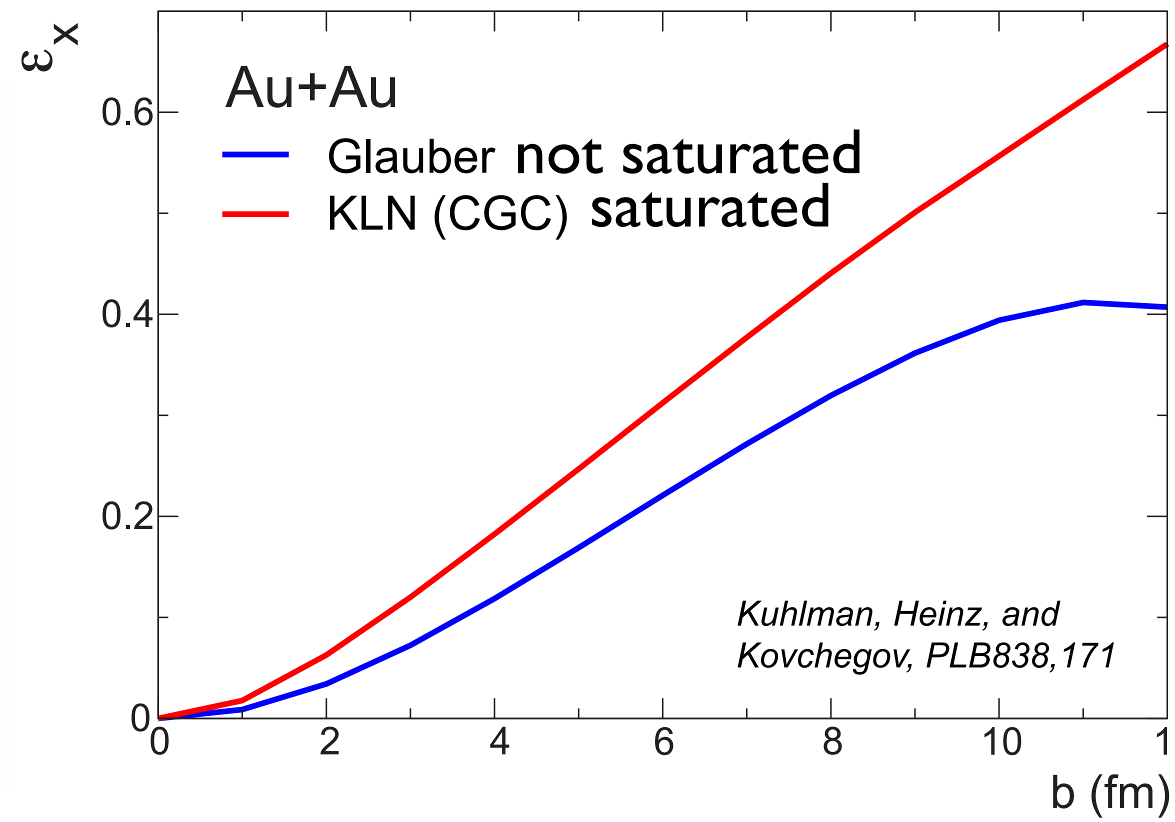

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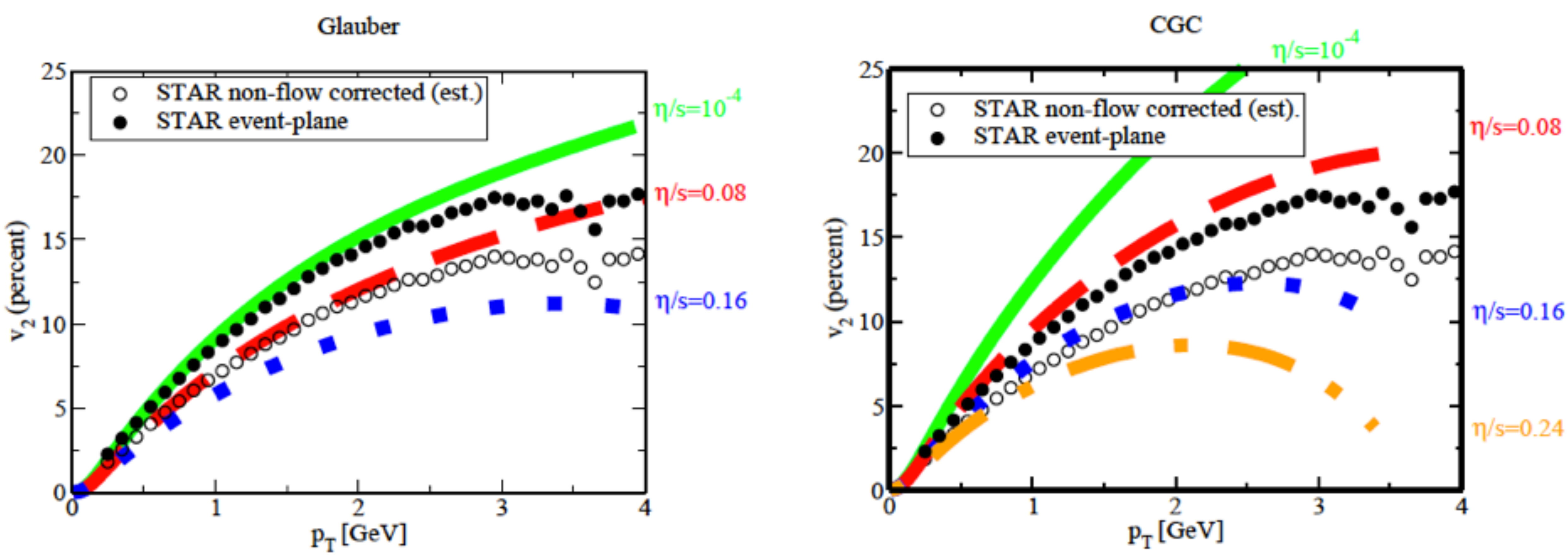

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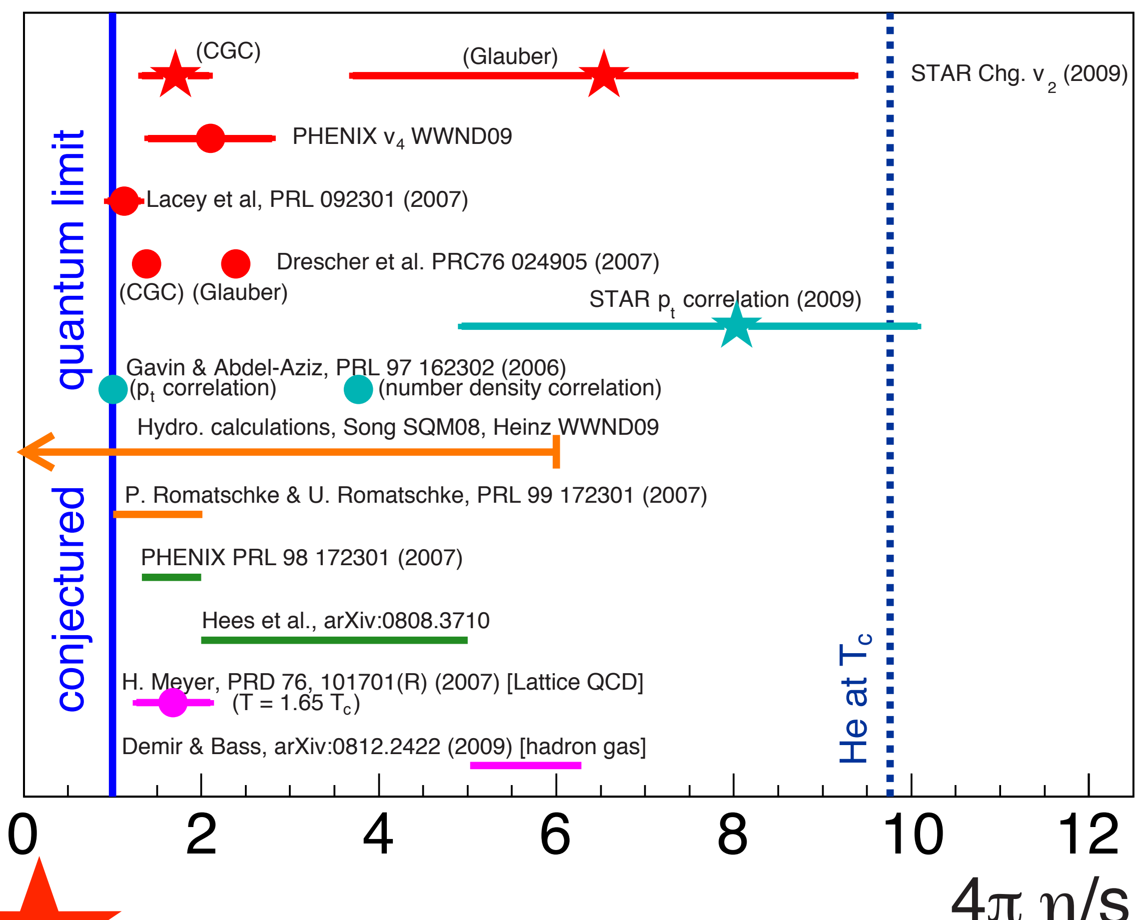
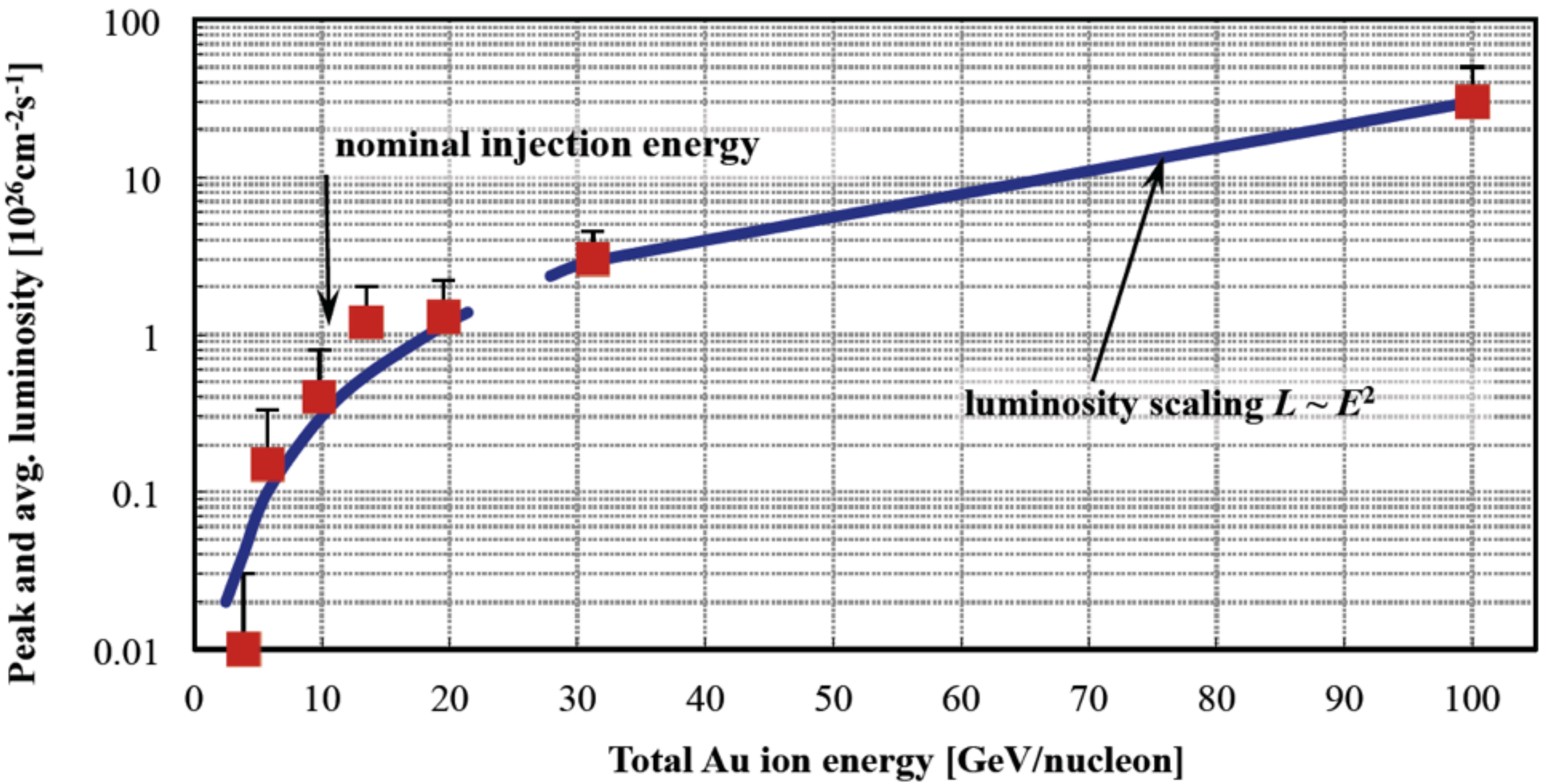


- η/s well below superfluid He for all models
- Can't yet distinguish between initial conditions - need e+A at an EIC !

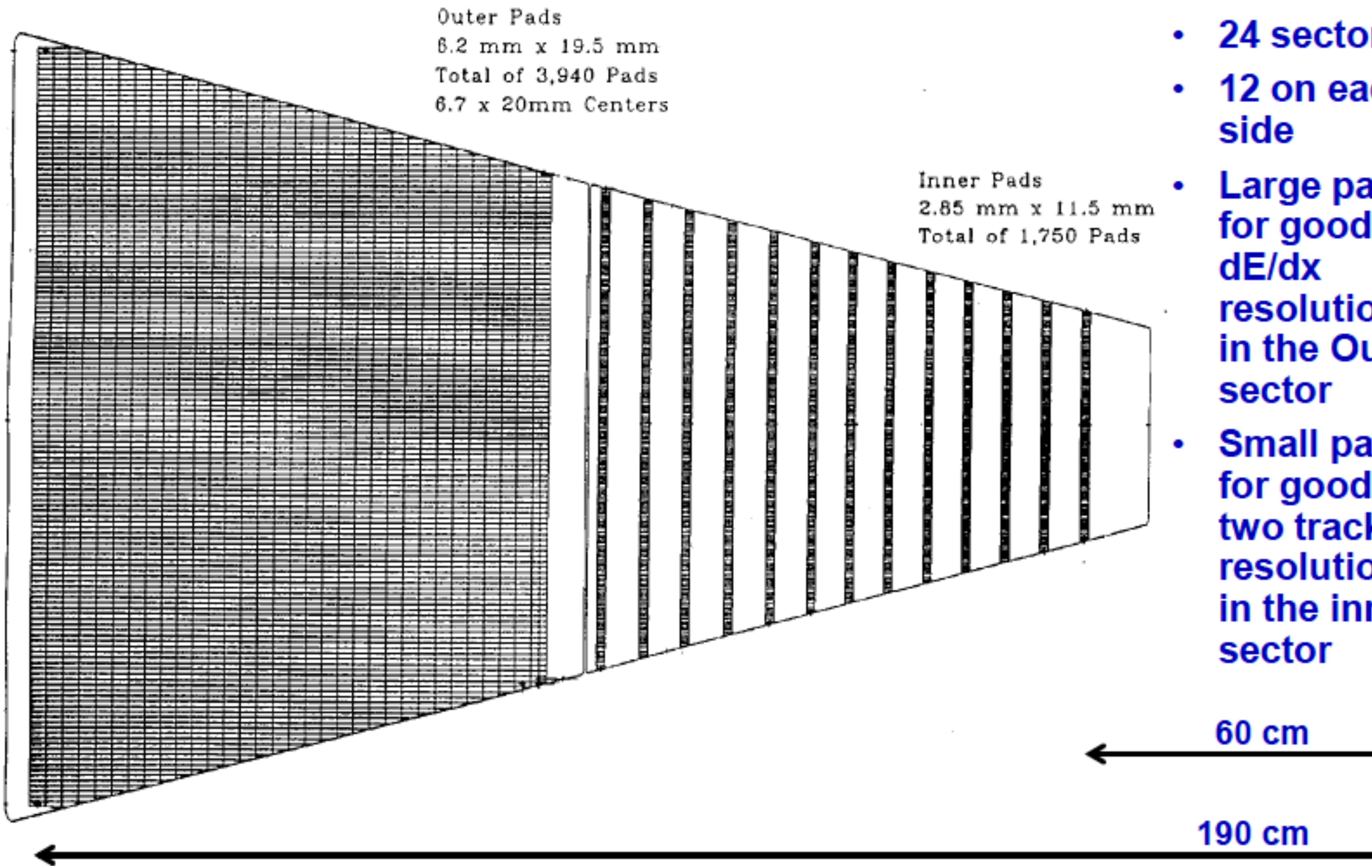
Mescellaneous

RHIC luminosity vs energy



STAR

TPC Inner Sector



- 24 sectors
- 12 on each side
- Large pads for good dE/dx resolution in the Outer sector
- Small pads for good two track resolution in the inner sector

STAR

Physics highlights from STAR

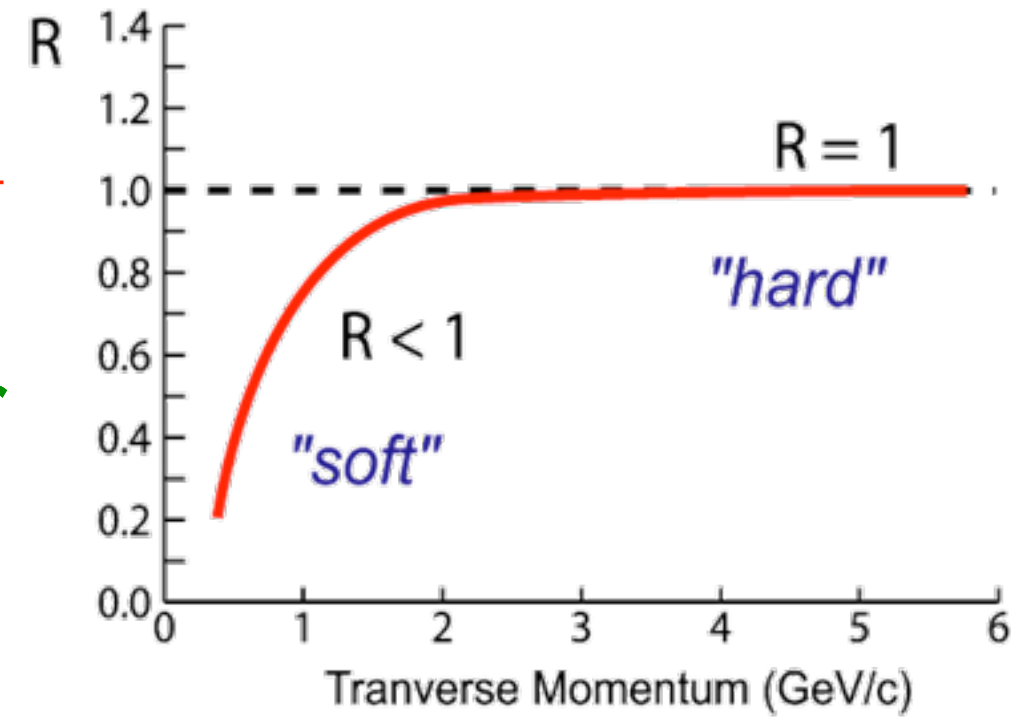
- A+A collisions
  - Jet quenching
  - Heavy-quark suppression
  - NCQ scaling
  - “Perfect” liquid
- d+A collisions
  - Gluon saturation at small-x?
- Polarised p+p collisions
  - Large transverse spin asymmetries in the pQCD regime

How to measure high-p_T processes

- Single particle spectra

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times < N_{coll} >}$$

$R_{AA}(p_T)$ = Nuclear Modification Factor



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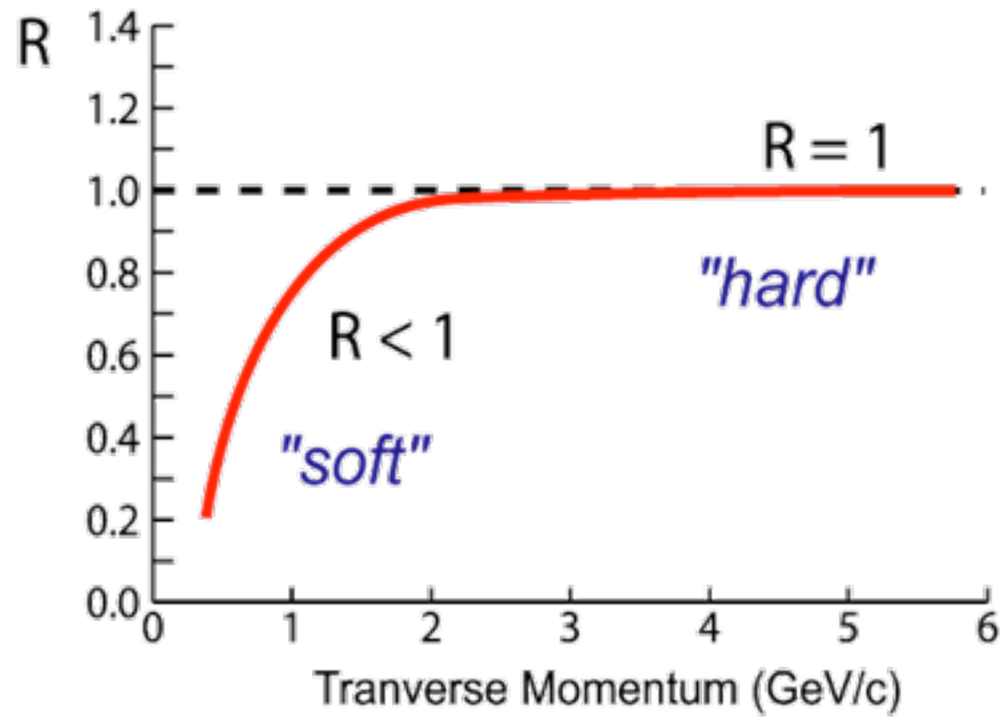
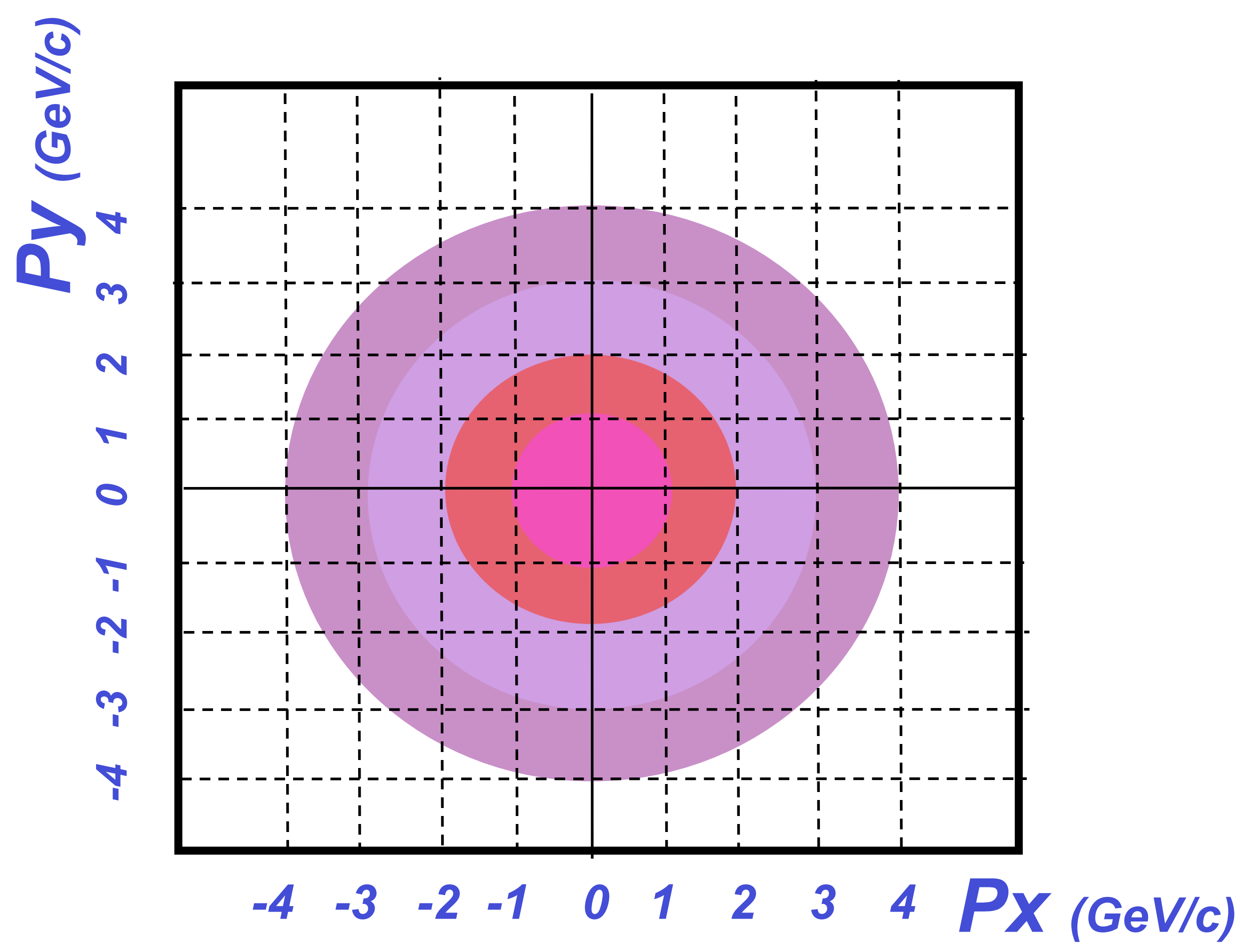


- 2-particle correlations



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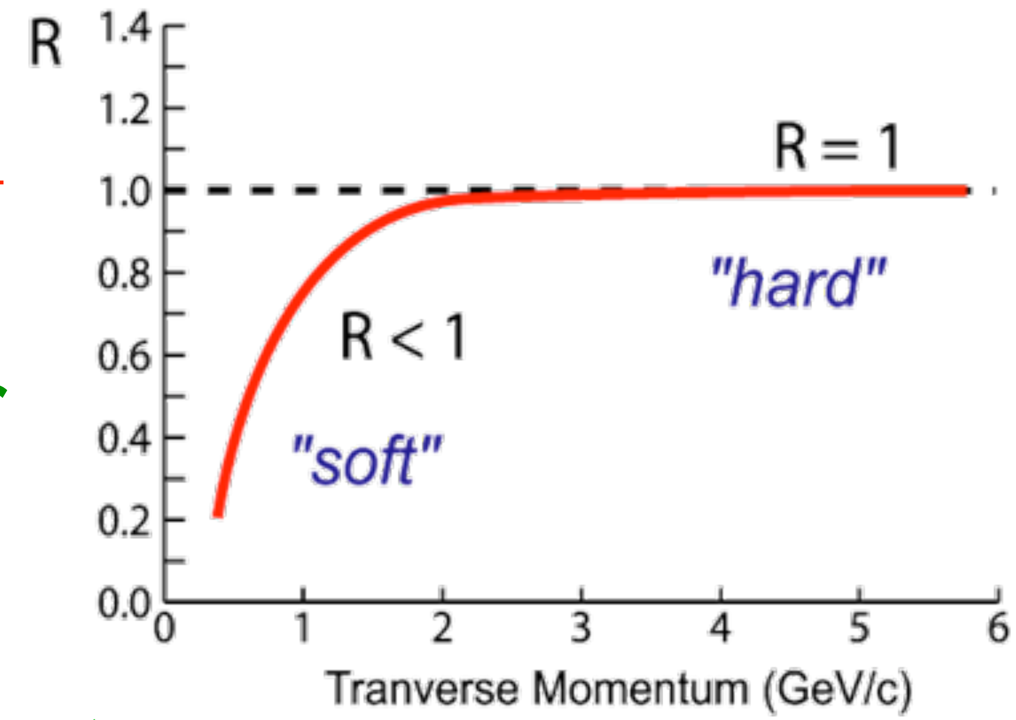

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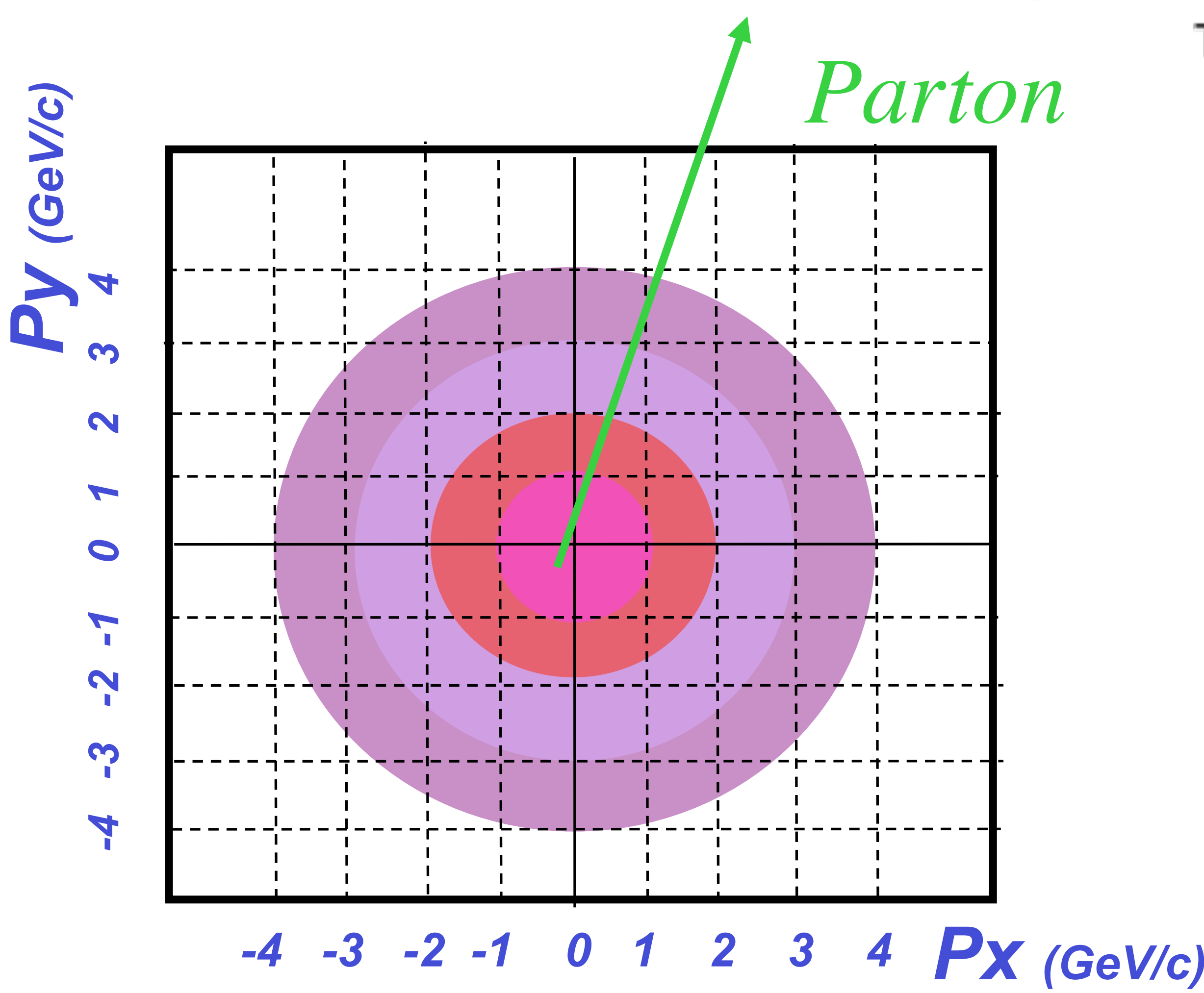

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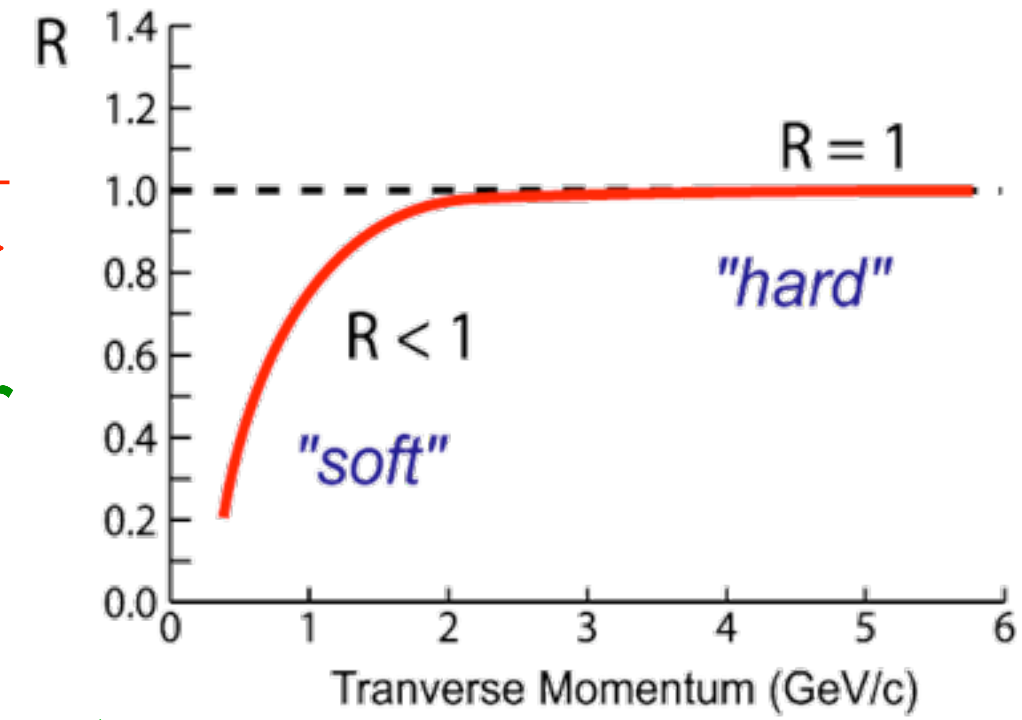

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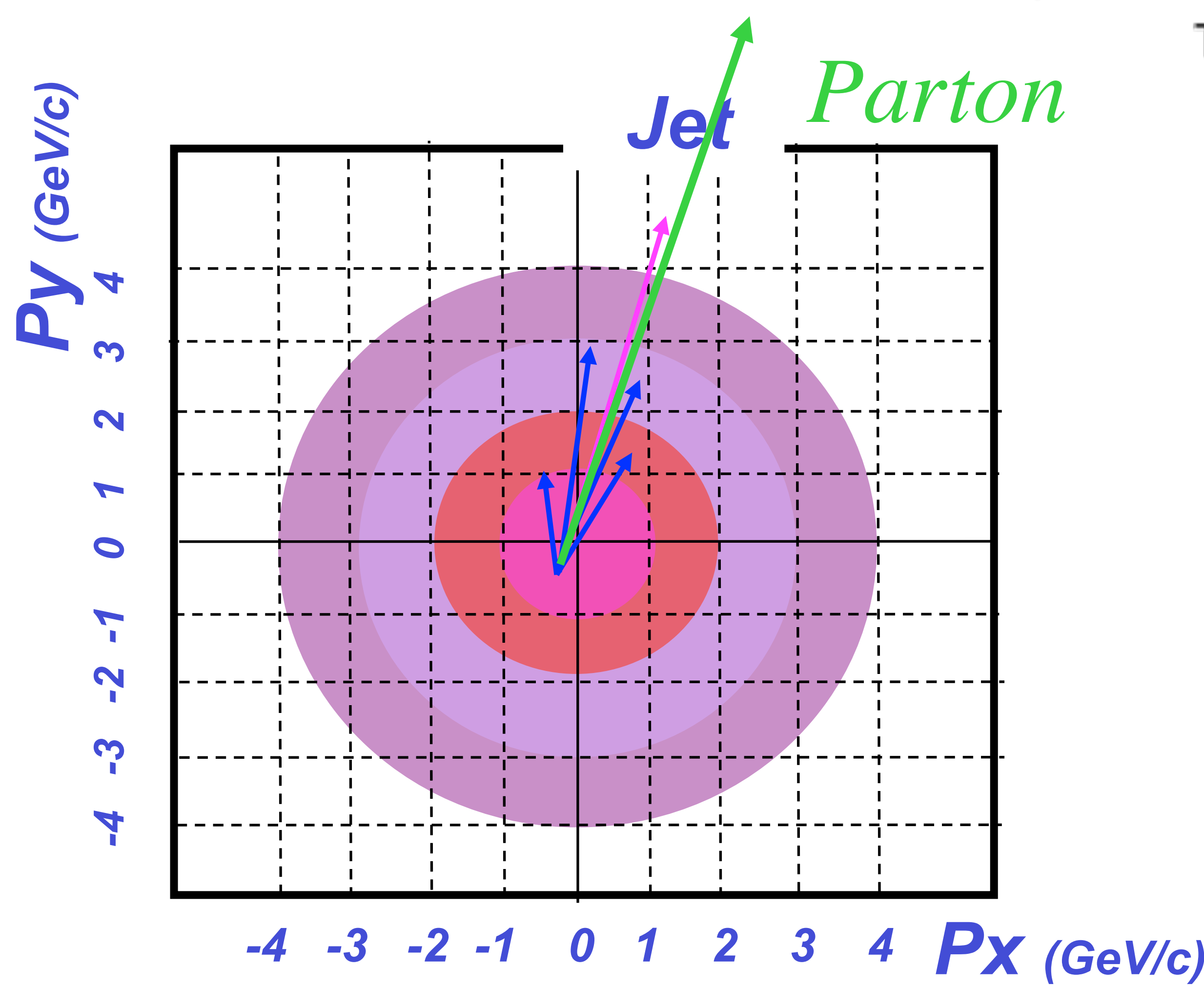

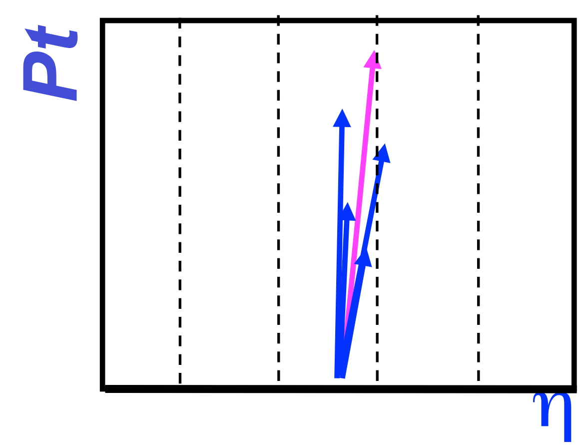

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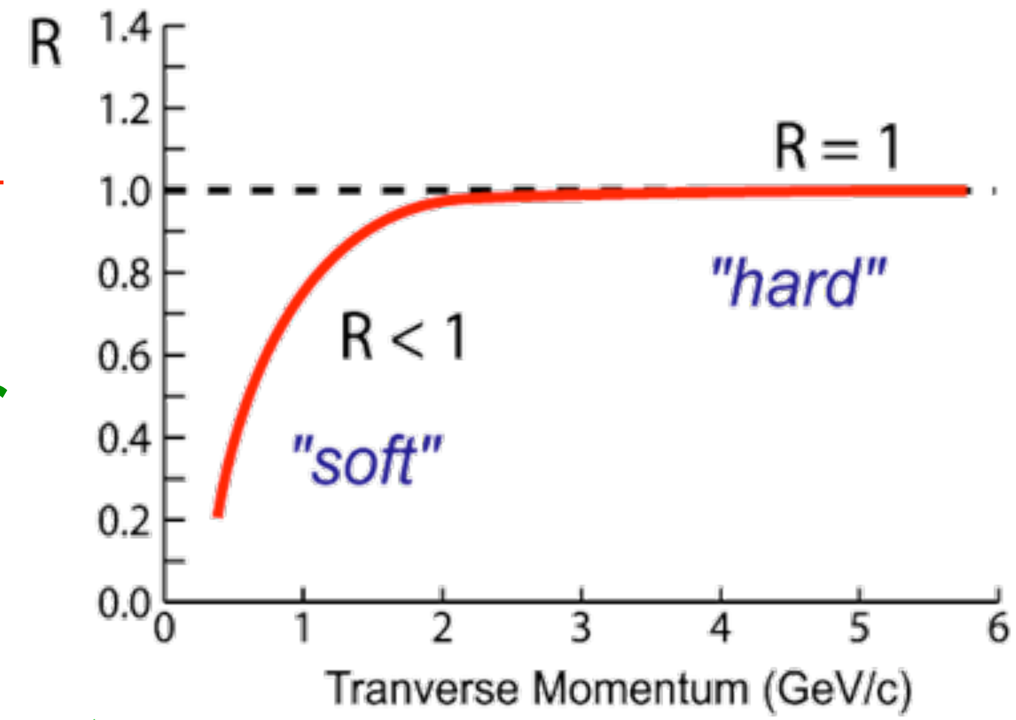

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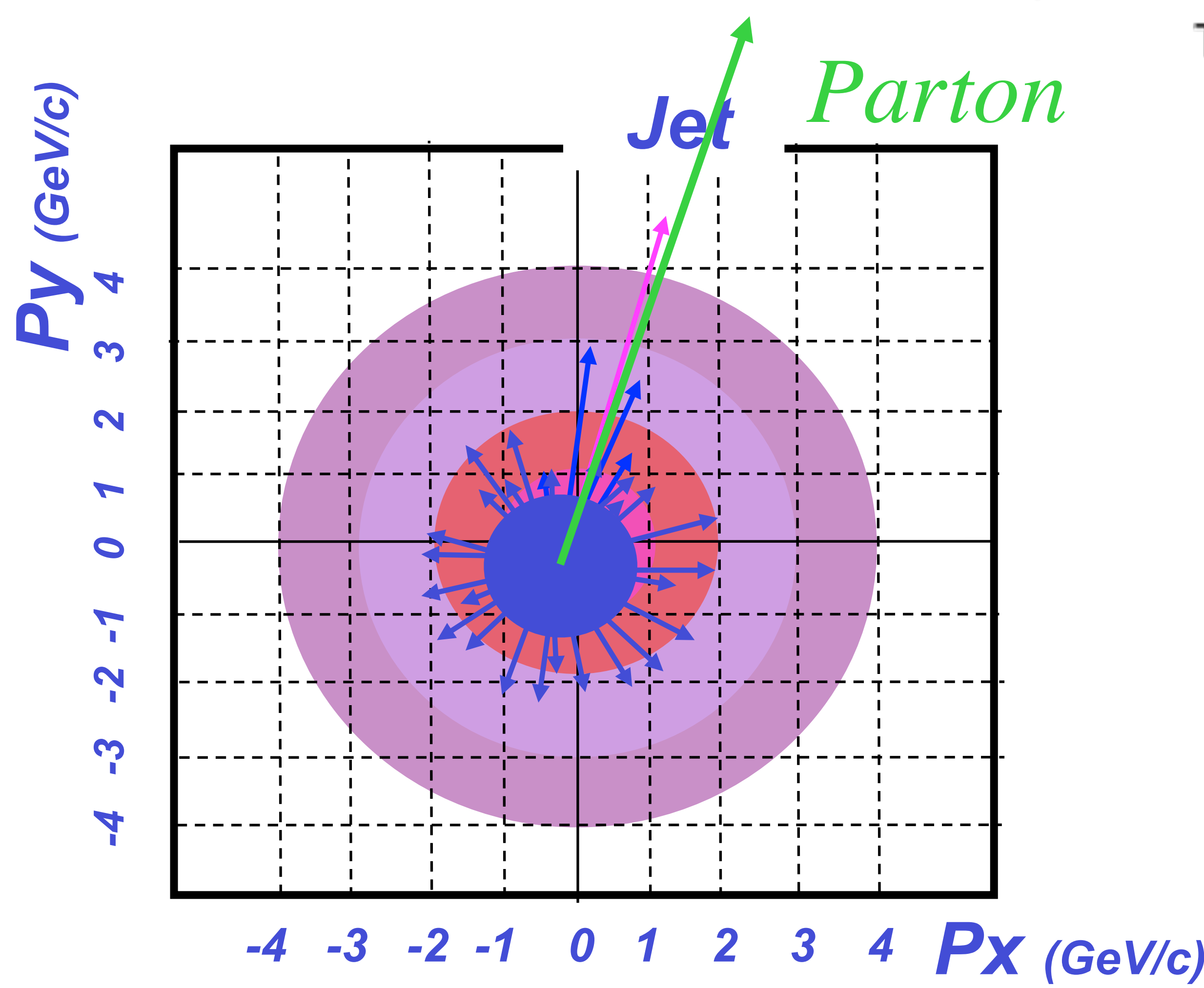

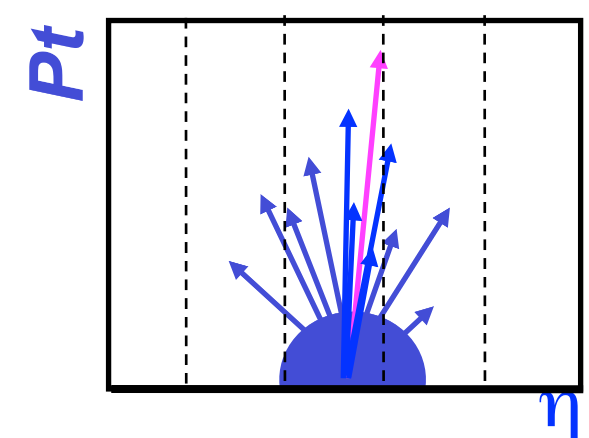

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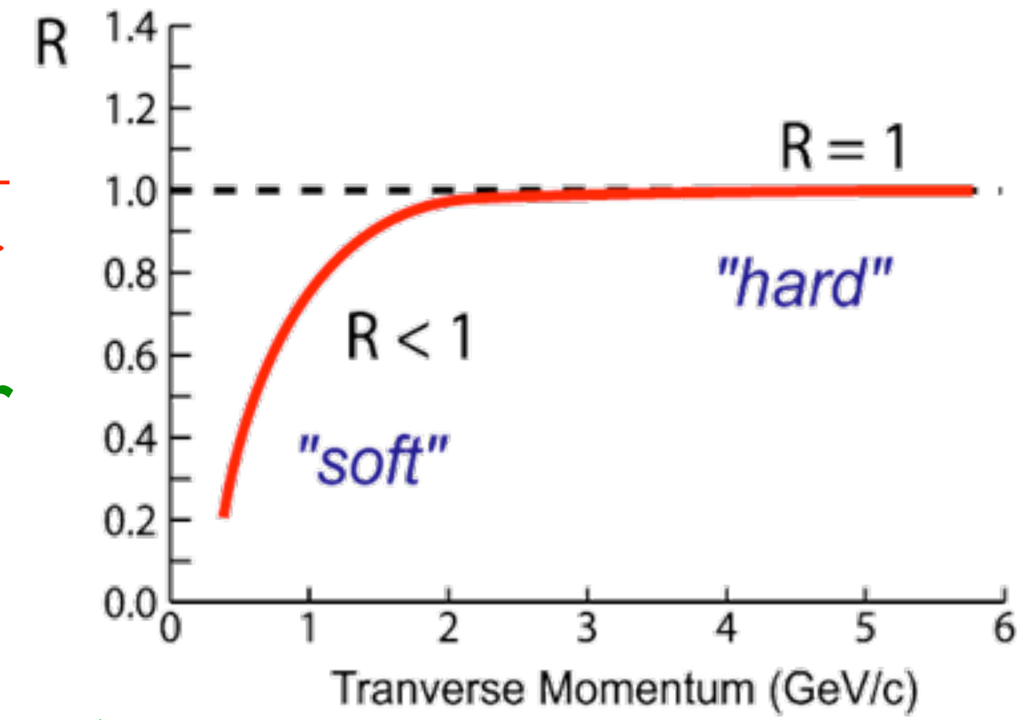

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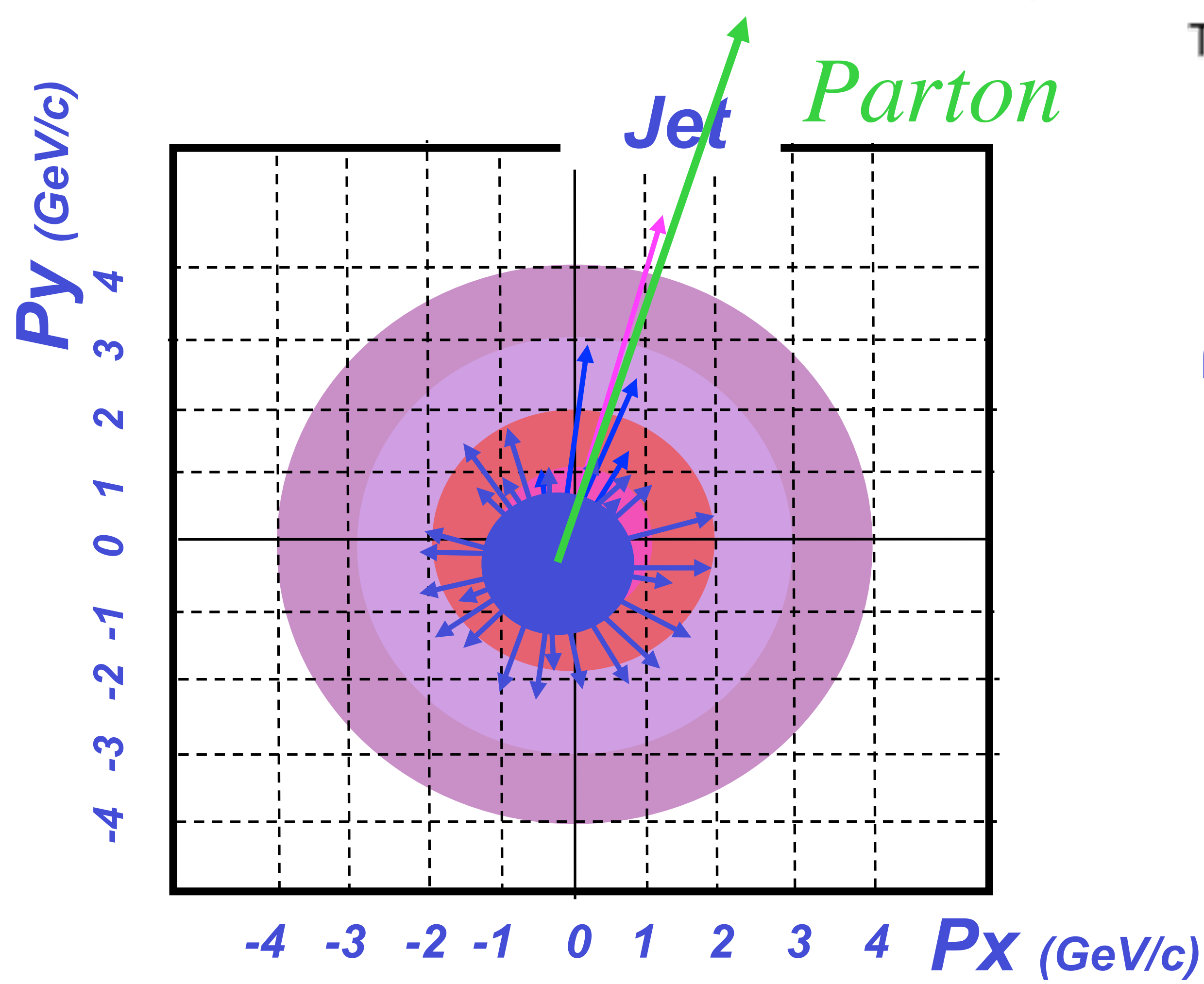

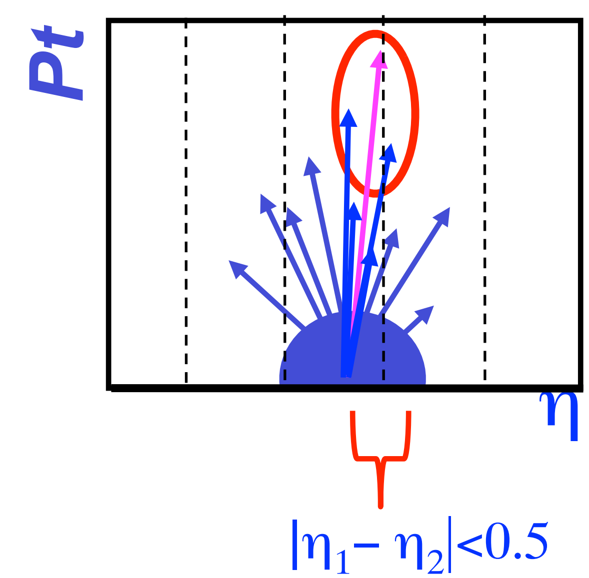

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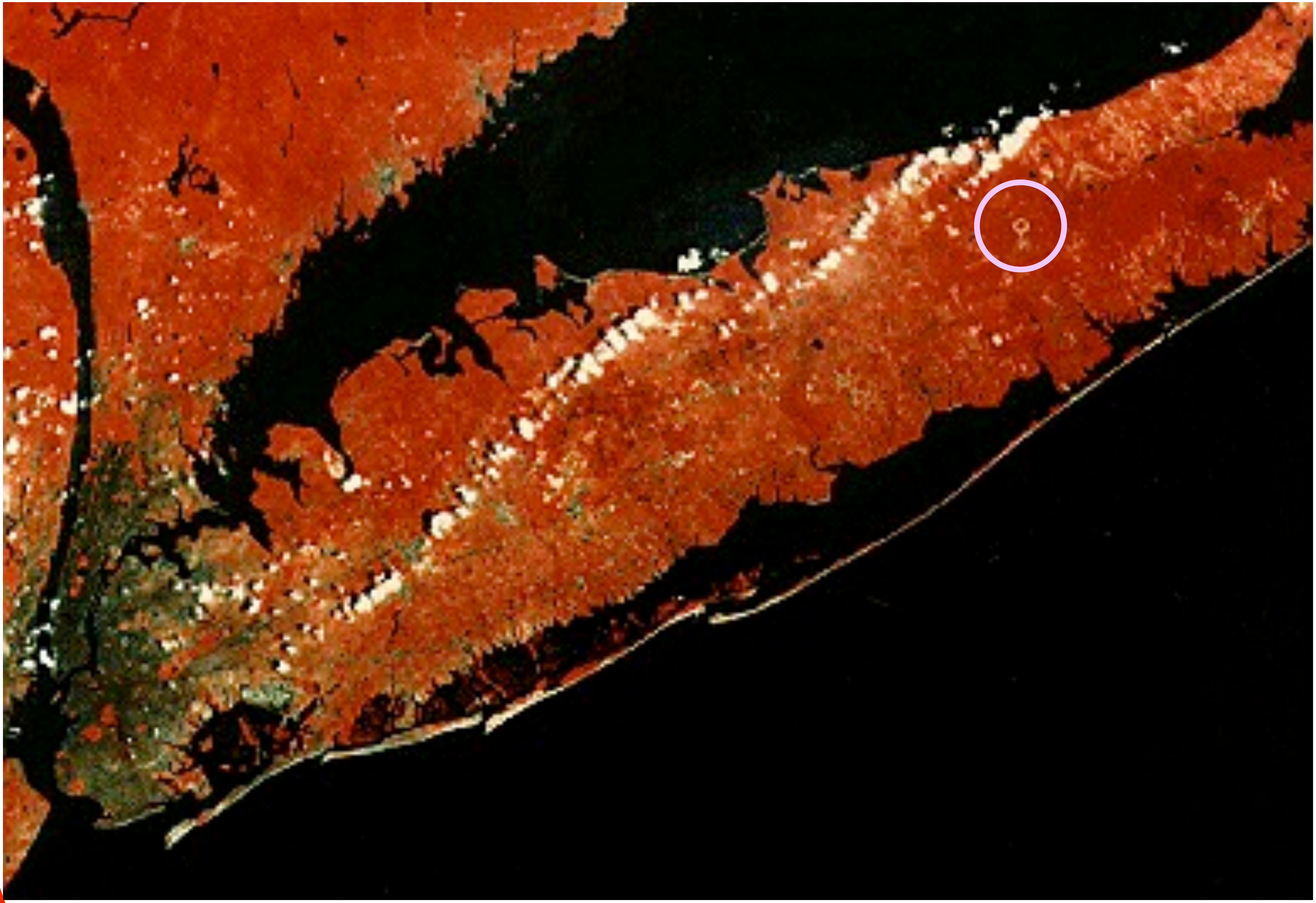
RHIC - Brookhaven Lab



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Highlights of the 1st decade of AA collisions in STAR

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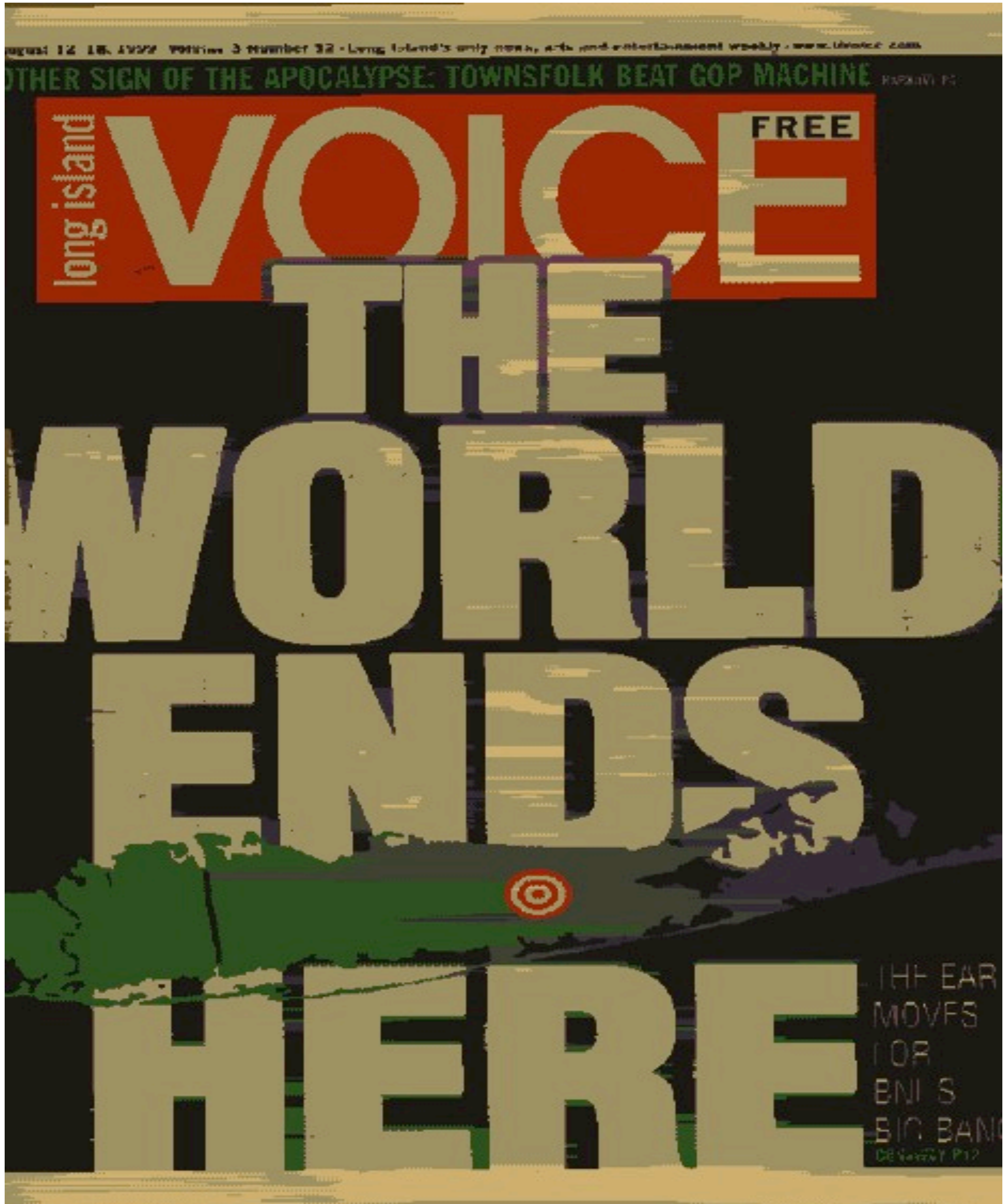

Highlights of the 1st decade of AA collisions in STAR

- Strong Elliptic Flow
  - Collective flow of created matter
  - Constituent quark number degrees of freedom apparent in scaling laws of elliptic flow
- Particle production through recombination/coalescence dominates over fragmentation at medium p_T
- Exotic particles
  - First observations of $^3_\Lambda\overline{H}$ and $^4\overline{He}$
- Jet quenching
  - Energy loss of high-p_T partons traversing the hot and dense matter
- Gluon saturation at small-x?
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⇐ these and comparisons to models led to the "perfect fluid" hypothesis

Paradigm shift:

strongly coupled QGP = sQGP

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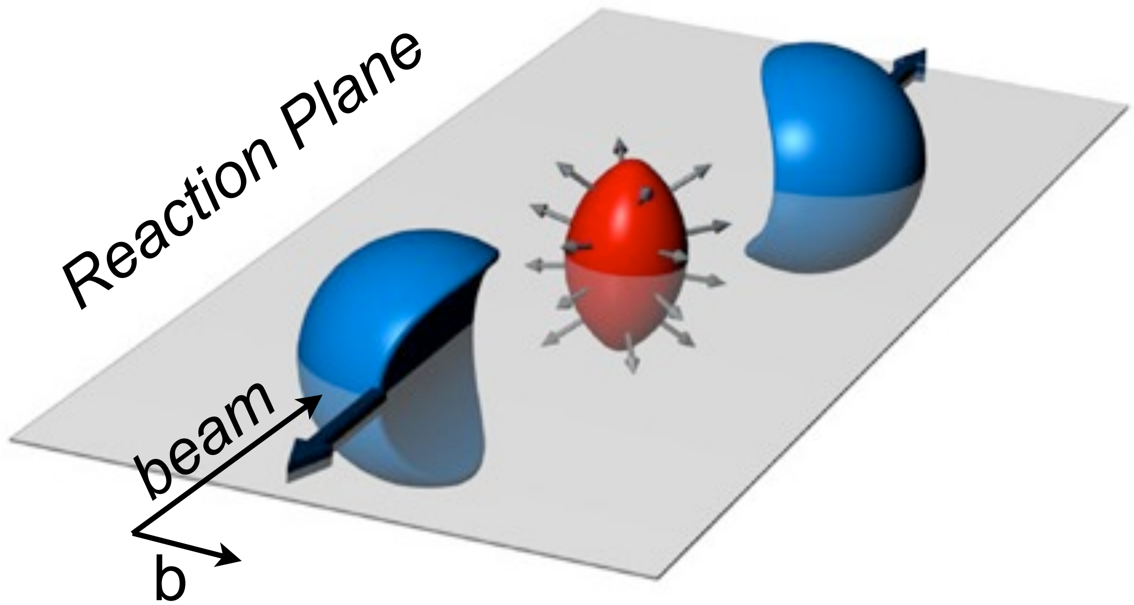
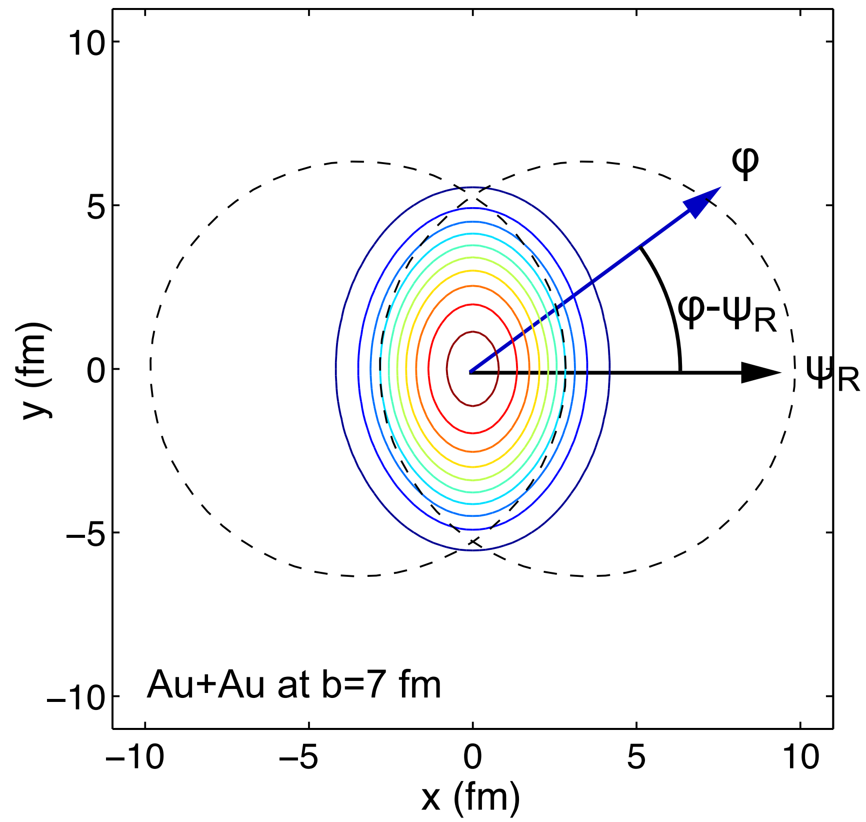
Talk Outline

- RHIC and the STAR Detector
- STAR Physics - the first decade
  - Heavy-ion physics
  - Spin physics
- STAR Physics - the second decade
  - Heavy-ion physics
    - Detector requirements
  - Spin physics
    - Detector requirements
- eSTAR
  - The physics of eSTAR and the detector requirements

Strong Elliptic Flow





Initial spatial anisotropy → Interactions → Final state anisotropy in momentum space

Use a Fourier expansion to describe the angular dependence of the particle density

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left[n\left(\phi-\Psi_r\right)\right]\right)$$

Fourier coefficient (v_n)

Angle of reaction plane (Ψ_r)

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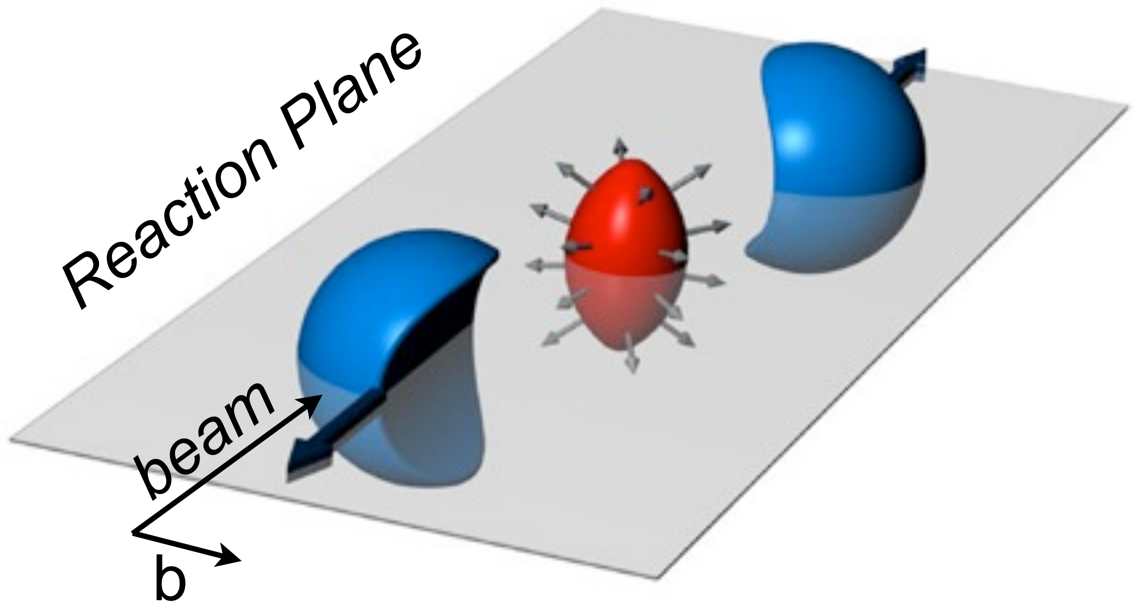
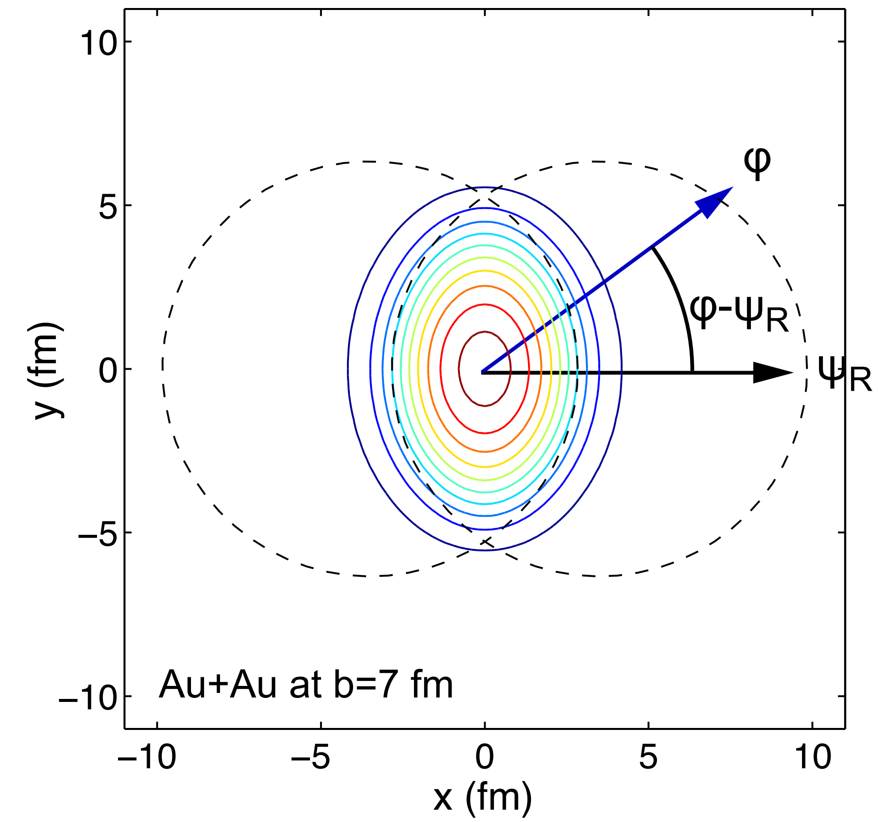
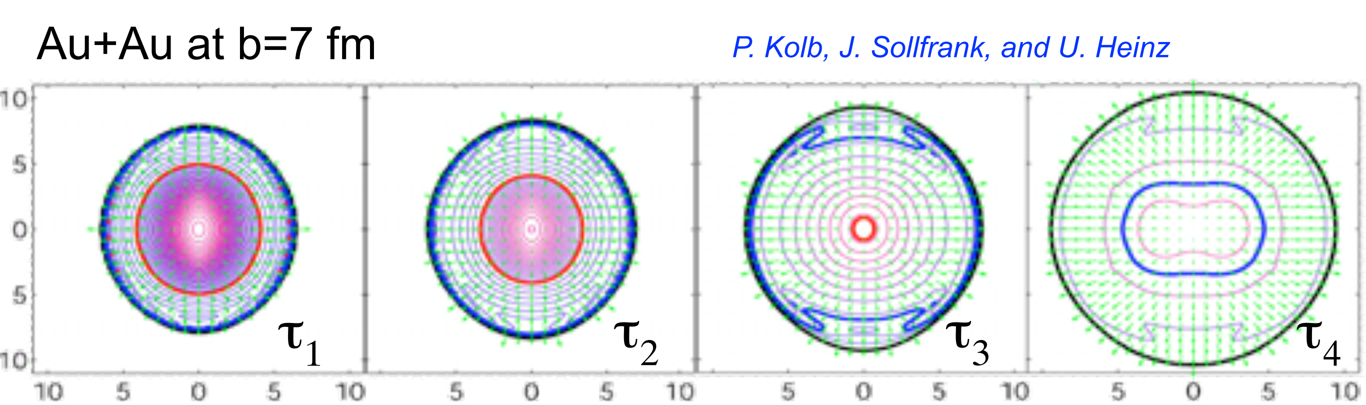
Strong Elliptic Flow



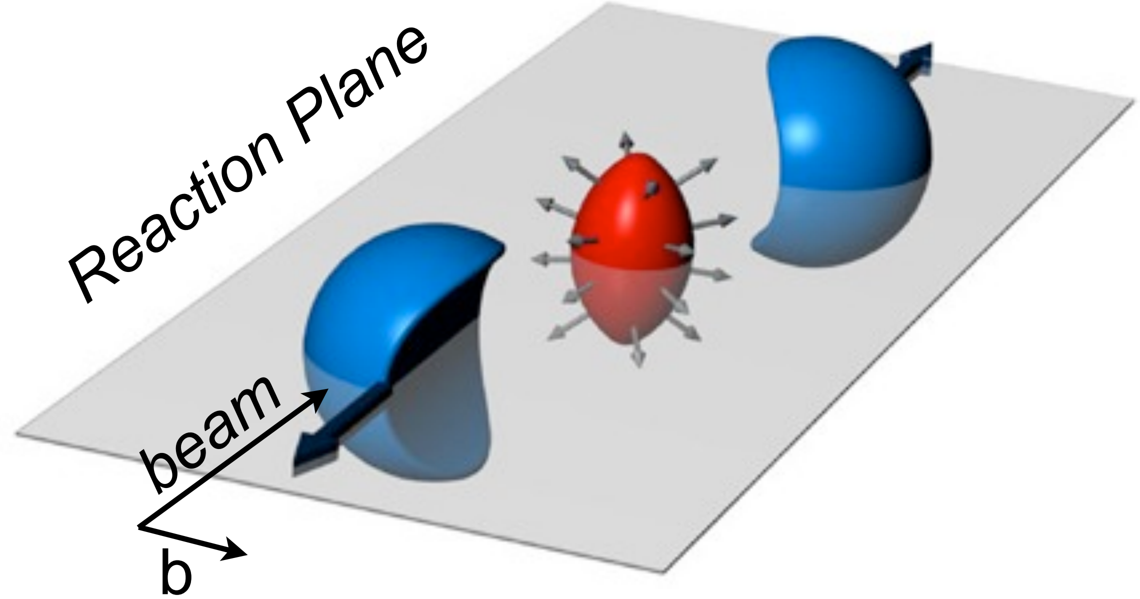


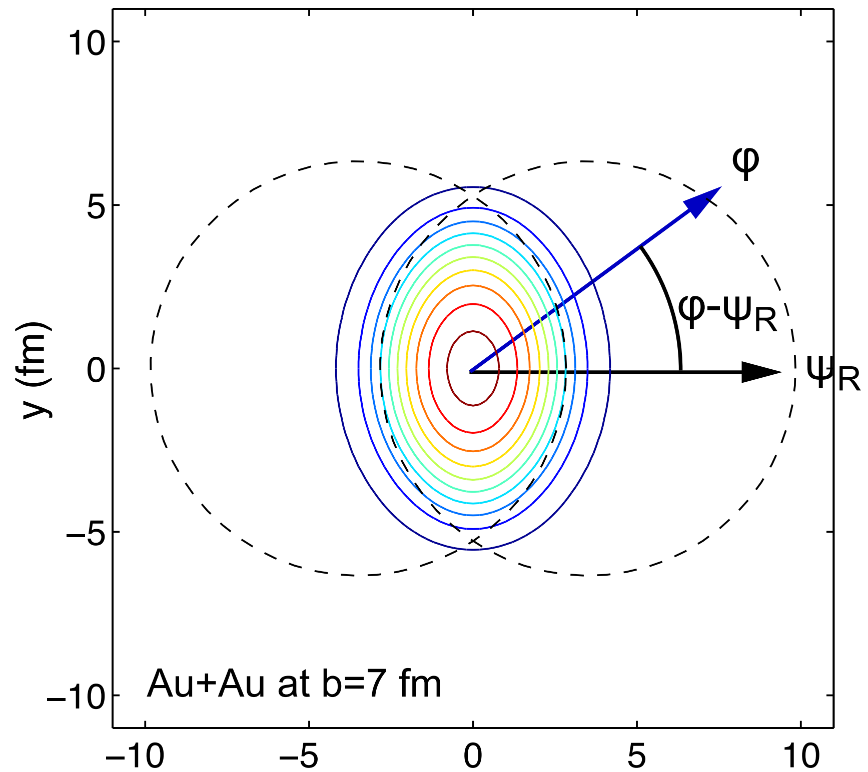
Initial spatial anisotropy → Interactions → Final state anisotropy in momentum space

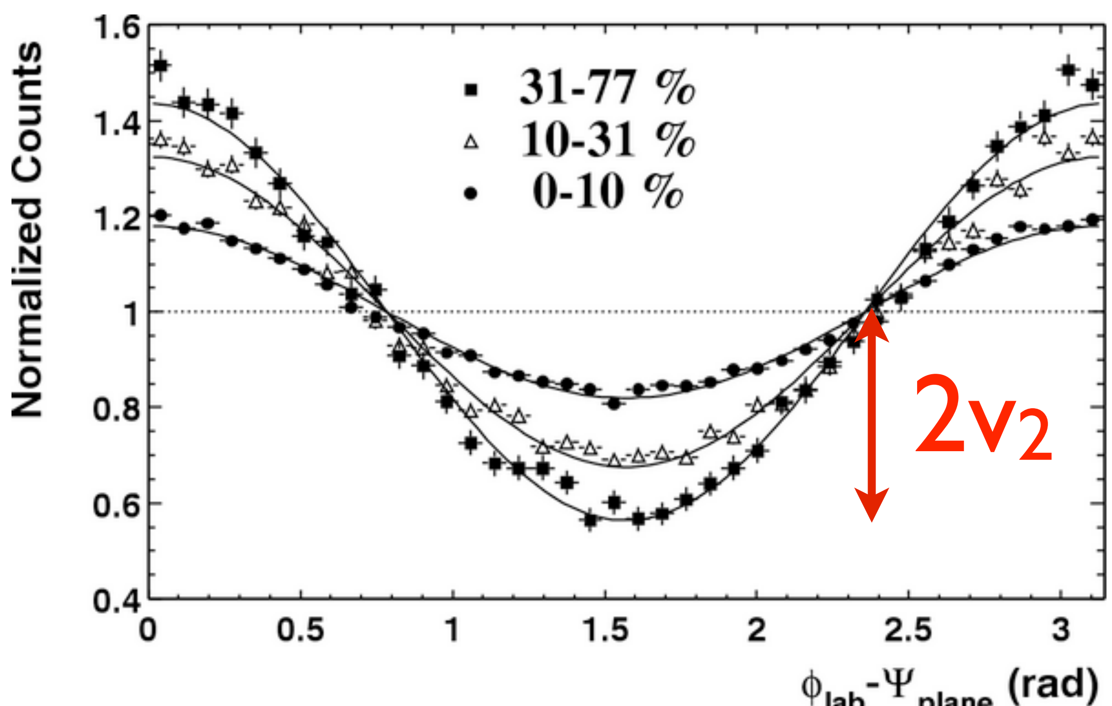


- driving spatial anisotropy vanishes $\Rightarrow$ self quenching
- $v_2 \rightarrow$ sensitive to **early** interactions and pressure gradients

Strong Elliptic Flow







Huge asymmetry found at RHIC !!

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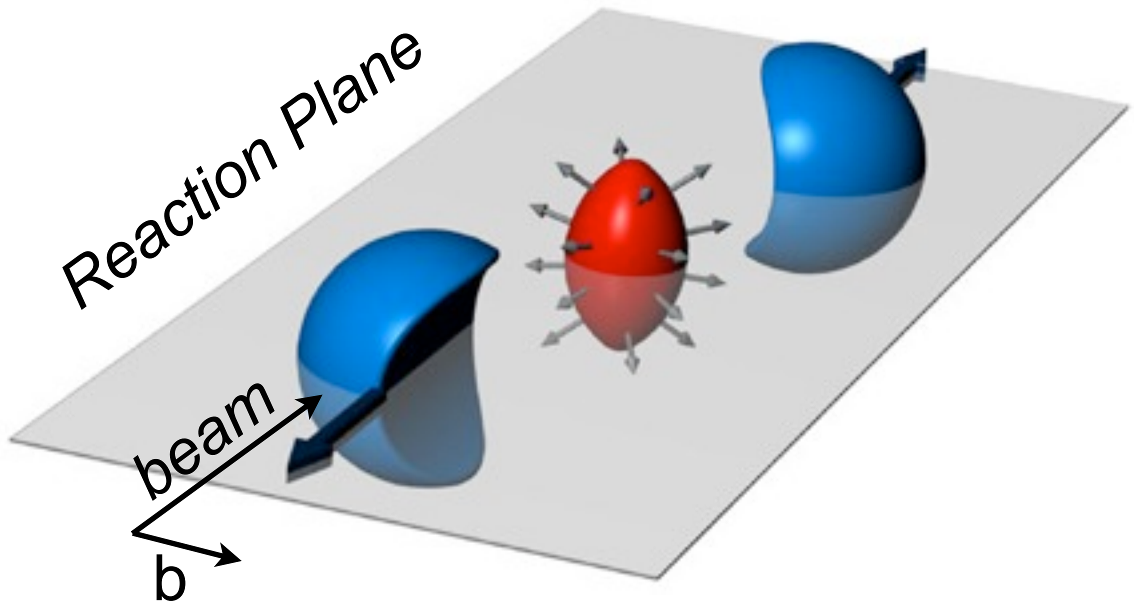
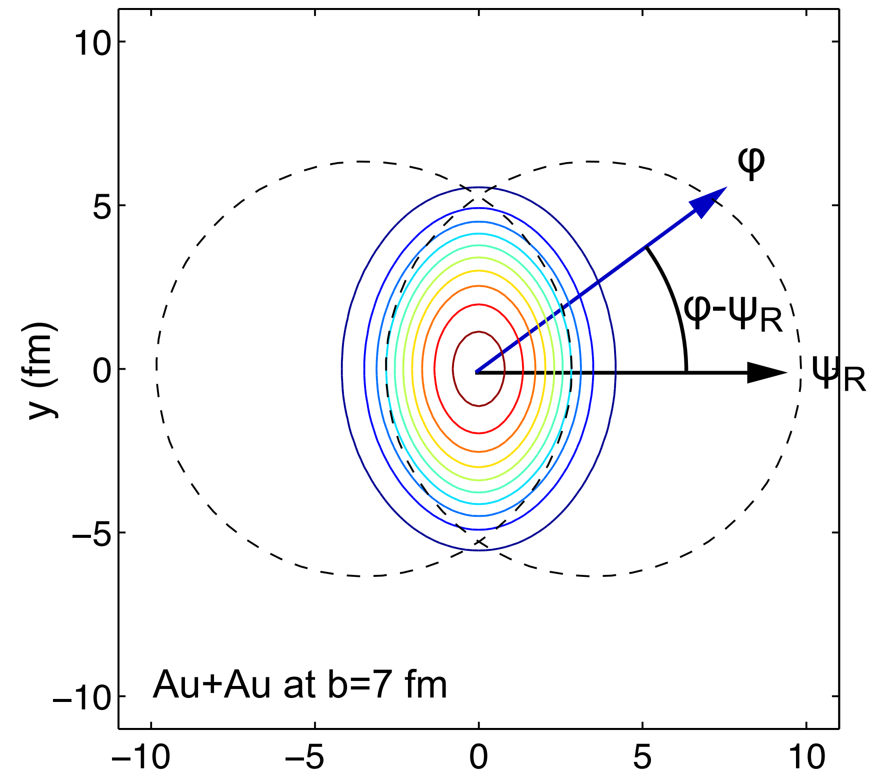
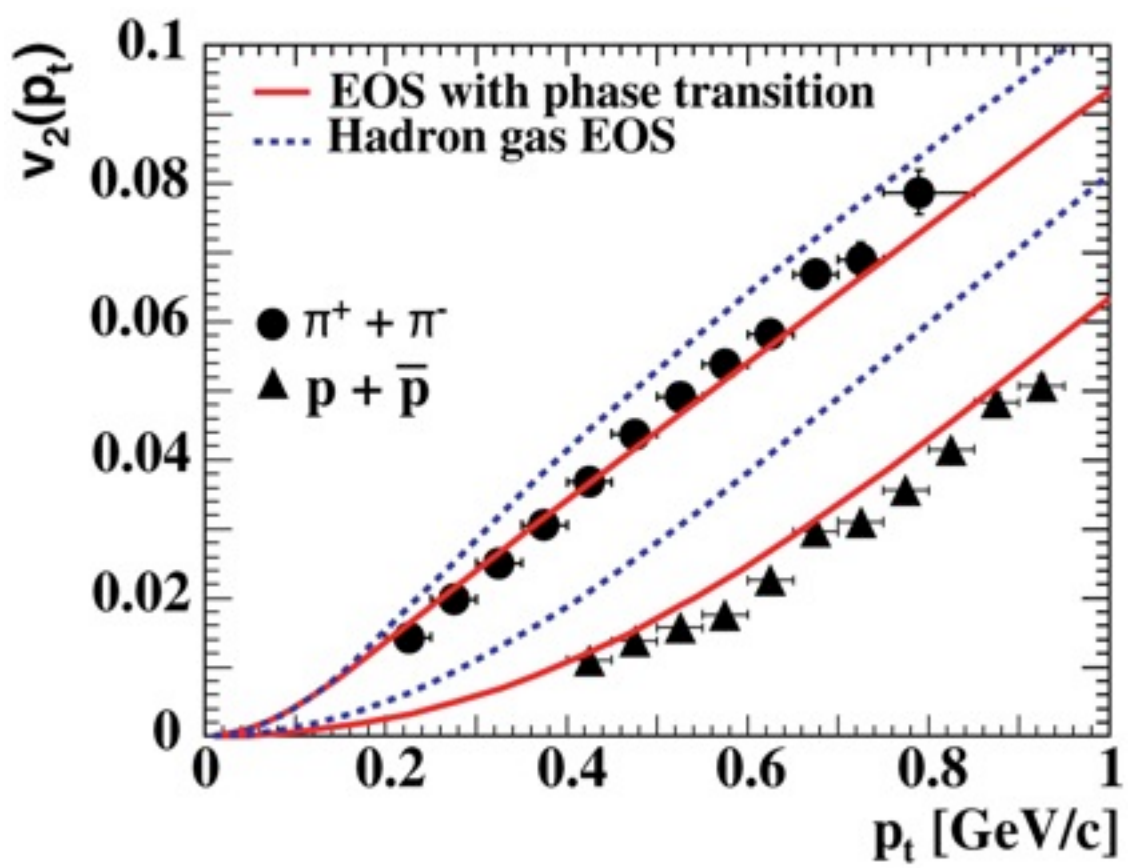
Strong Elliptic Flow







- v_2 shows particle type dependence
- Good agreement between data and ideal (zero viscosity) hydrodynamics
  - small η ⇒ strong coupling ⇒ "perfect" fluid!!

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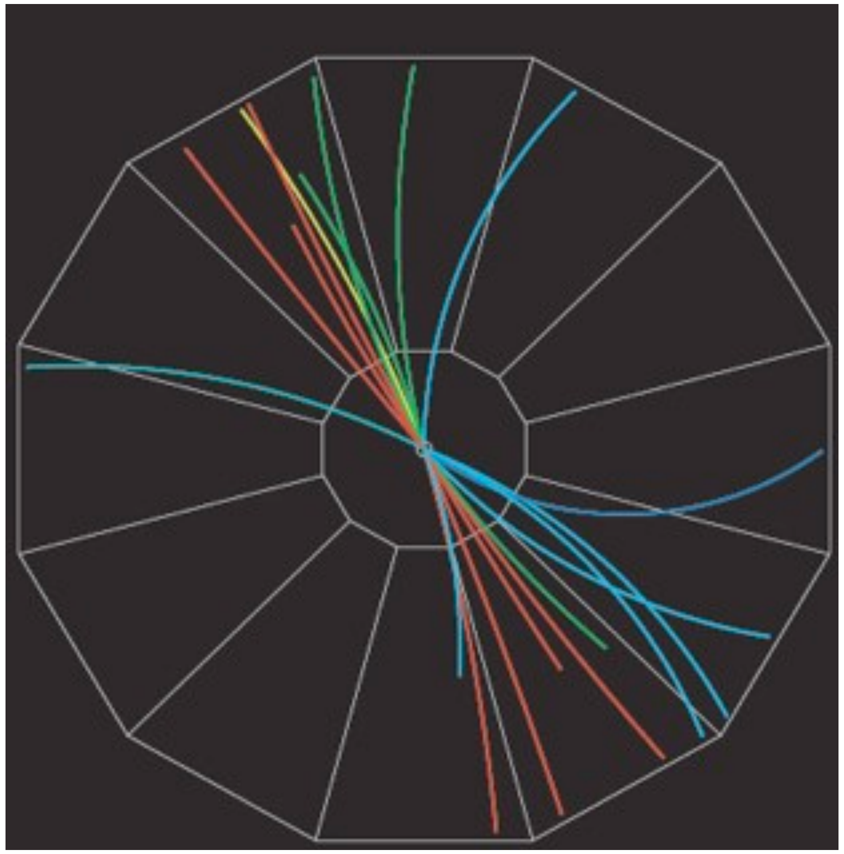
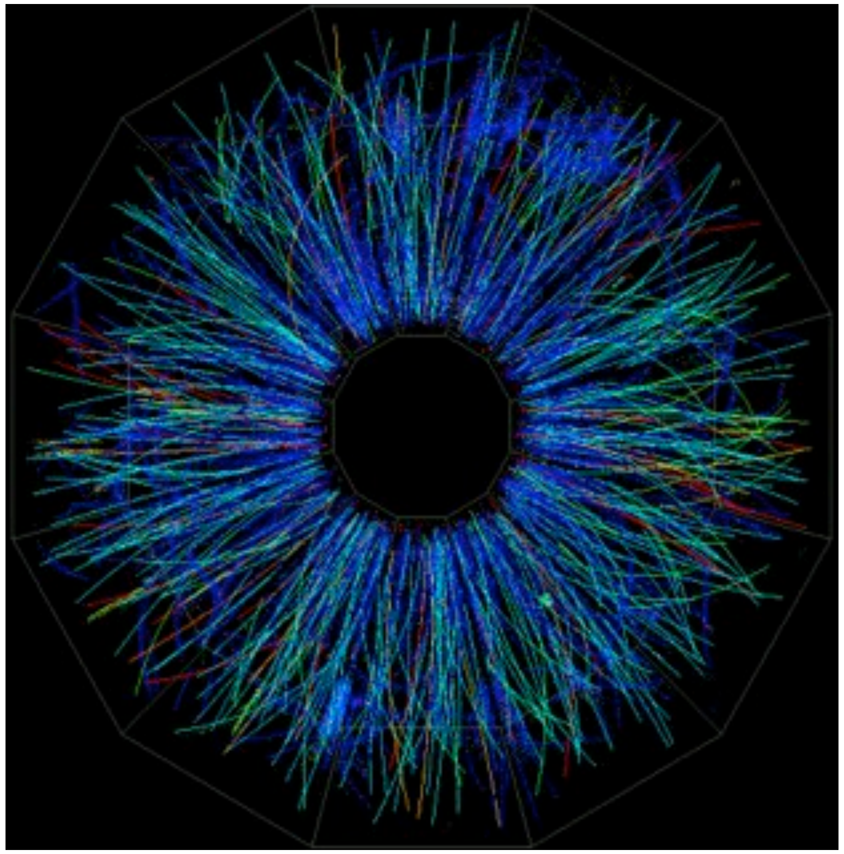
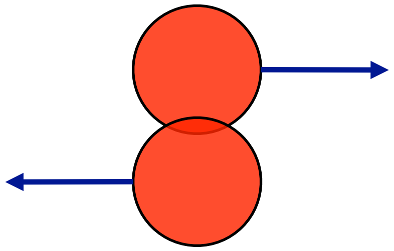
Jet quenching in A+A collisions



p+p Event





Peripheral Au+Au Event

- Jet-finding is relatively straight-forward in low-multiplicity p+p collisions

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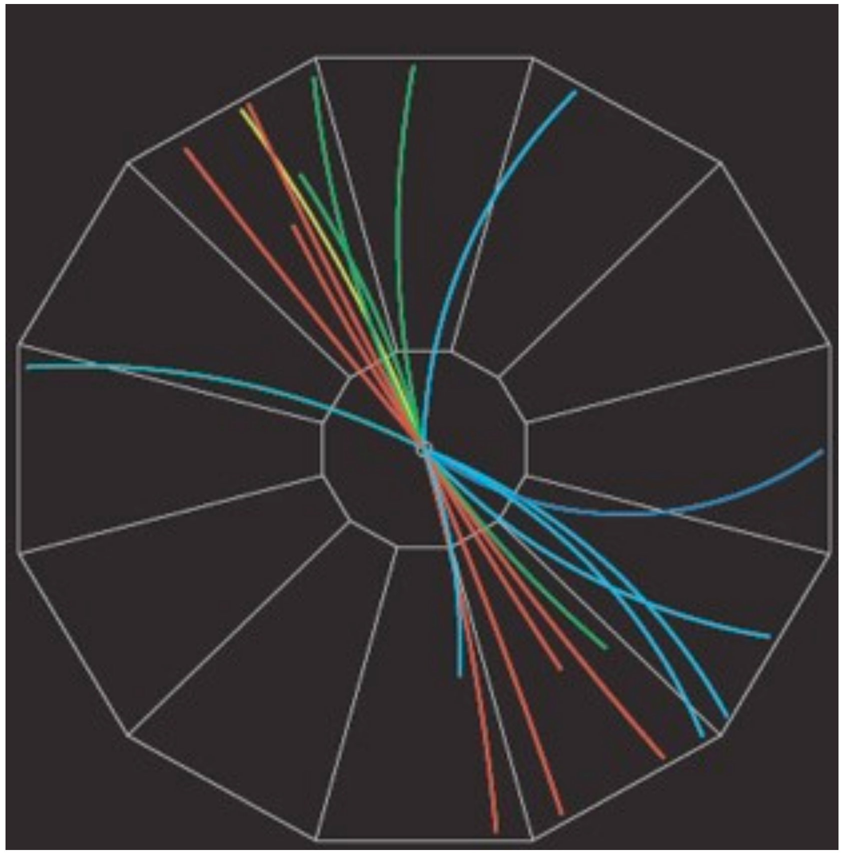
Jet quenching in A+A collisions



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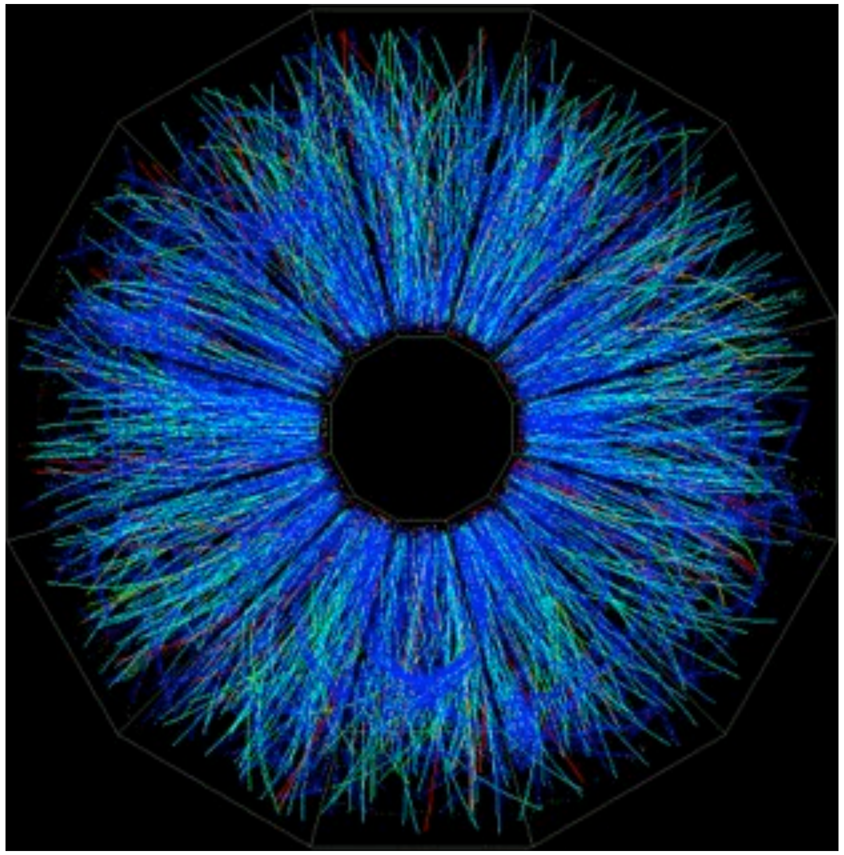
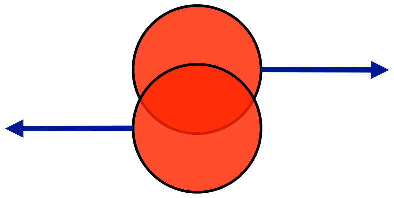


Mid-Central Au+Au Event



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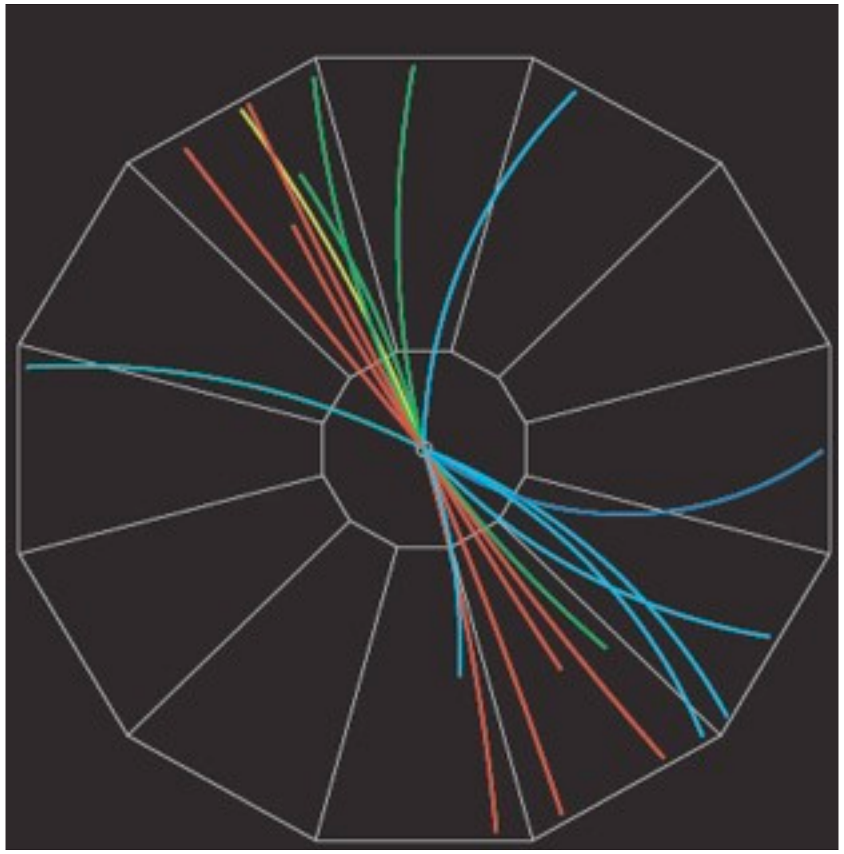
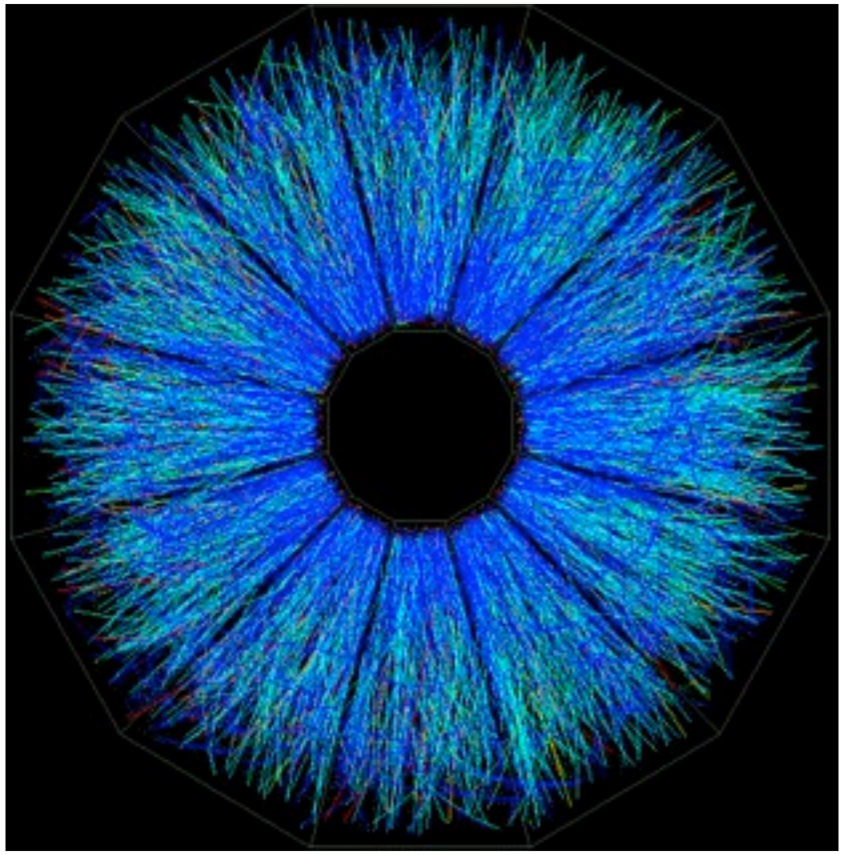
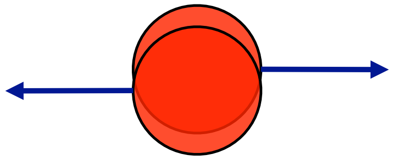
Jet quenching in A+A collisions



p+p Event



Central Au+Au Event



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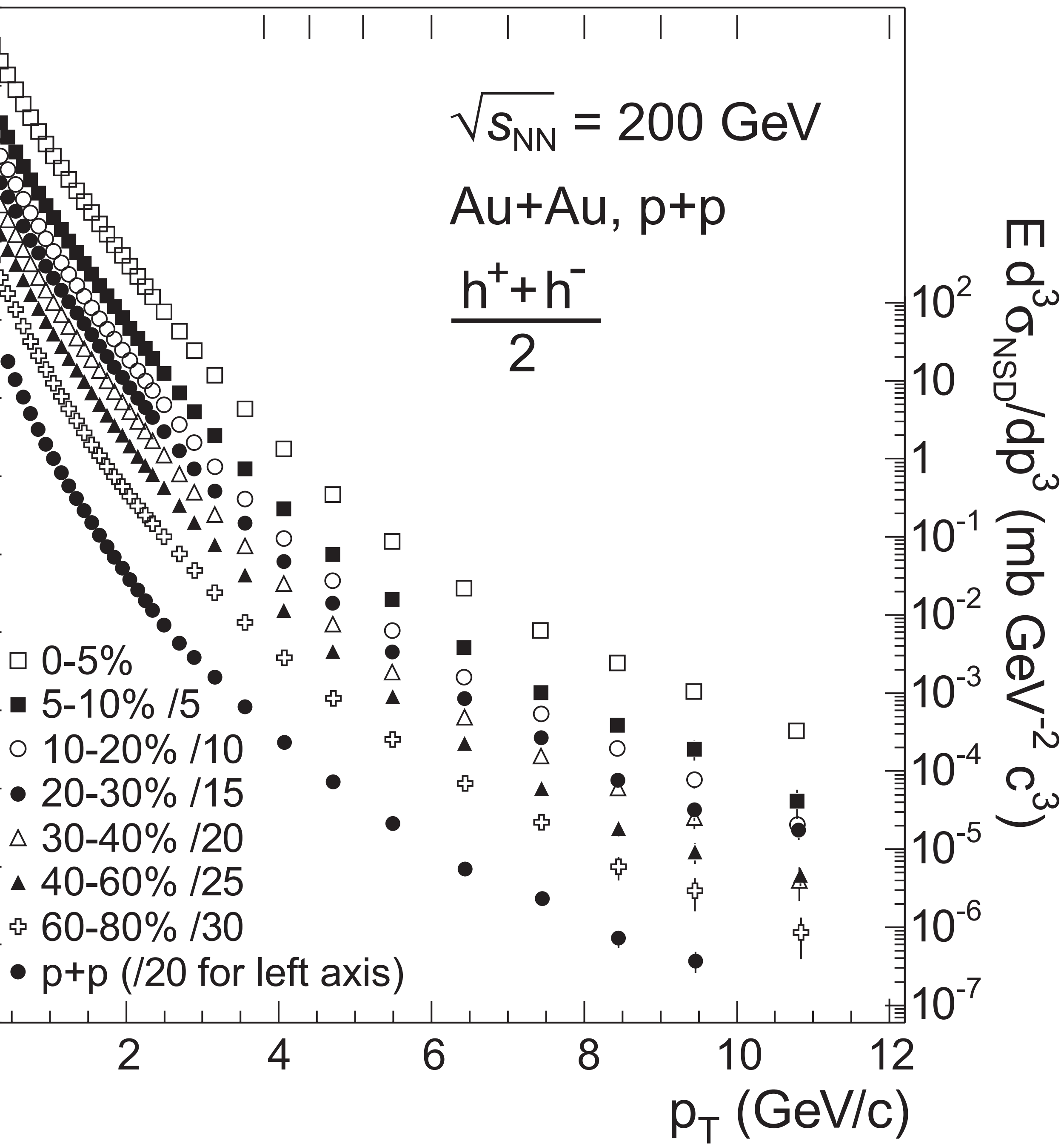
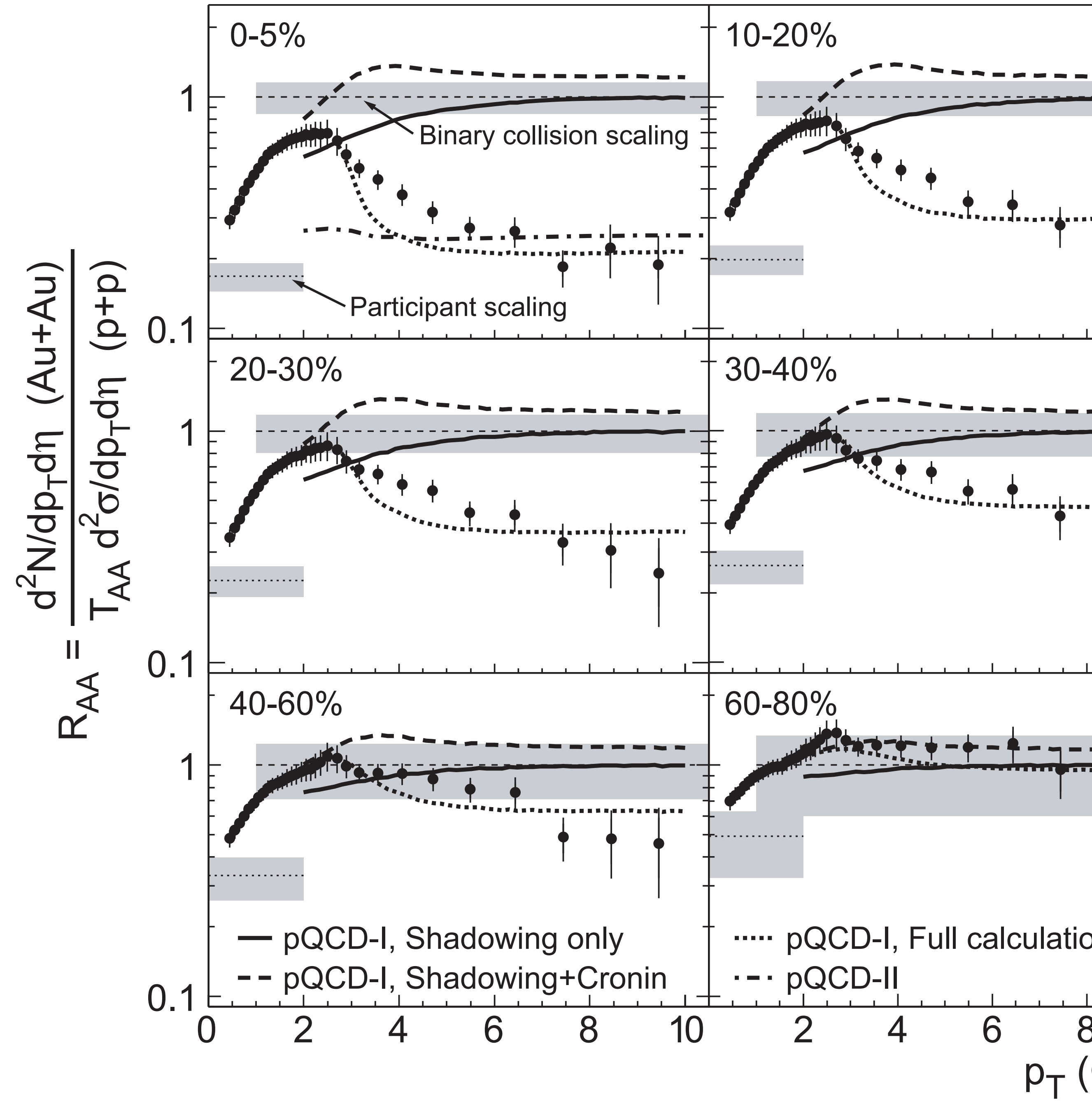
Suppression of single particle spectra





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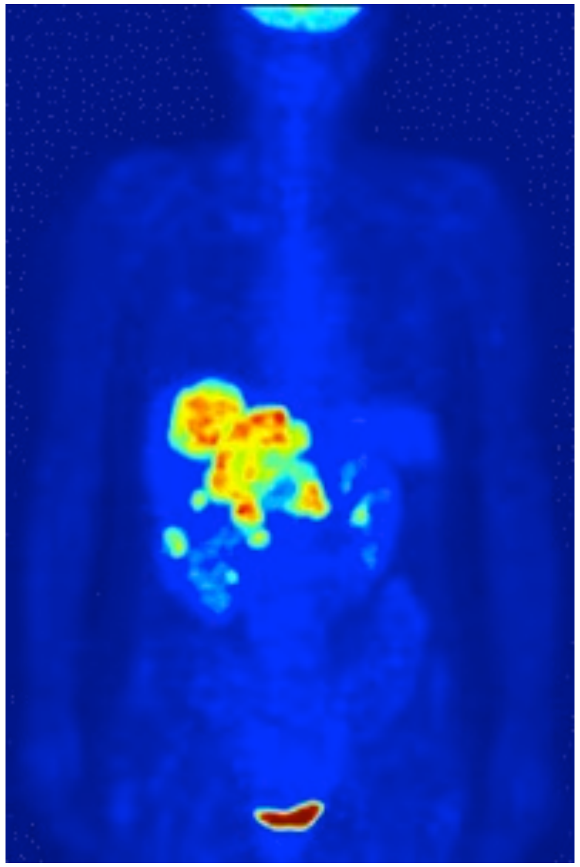
Probes of Dense Matter – Jet Tomography

Simplest way to establish the properties of a system

- Calibrated probe (electrons, X-Rays)



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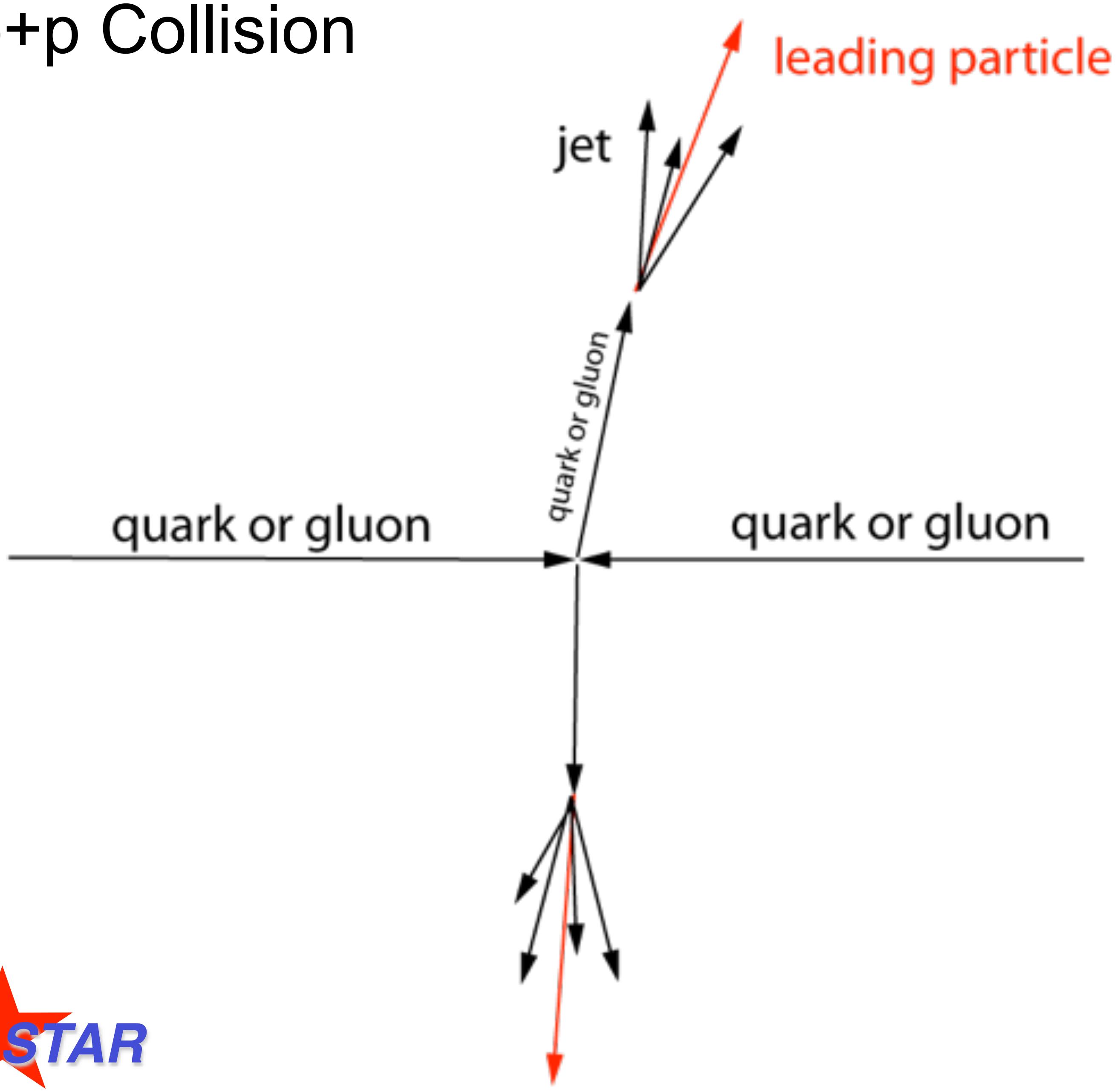
p+p Collision

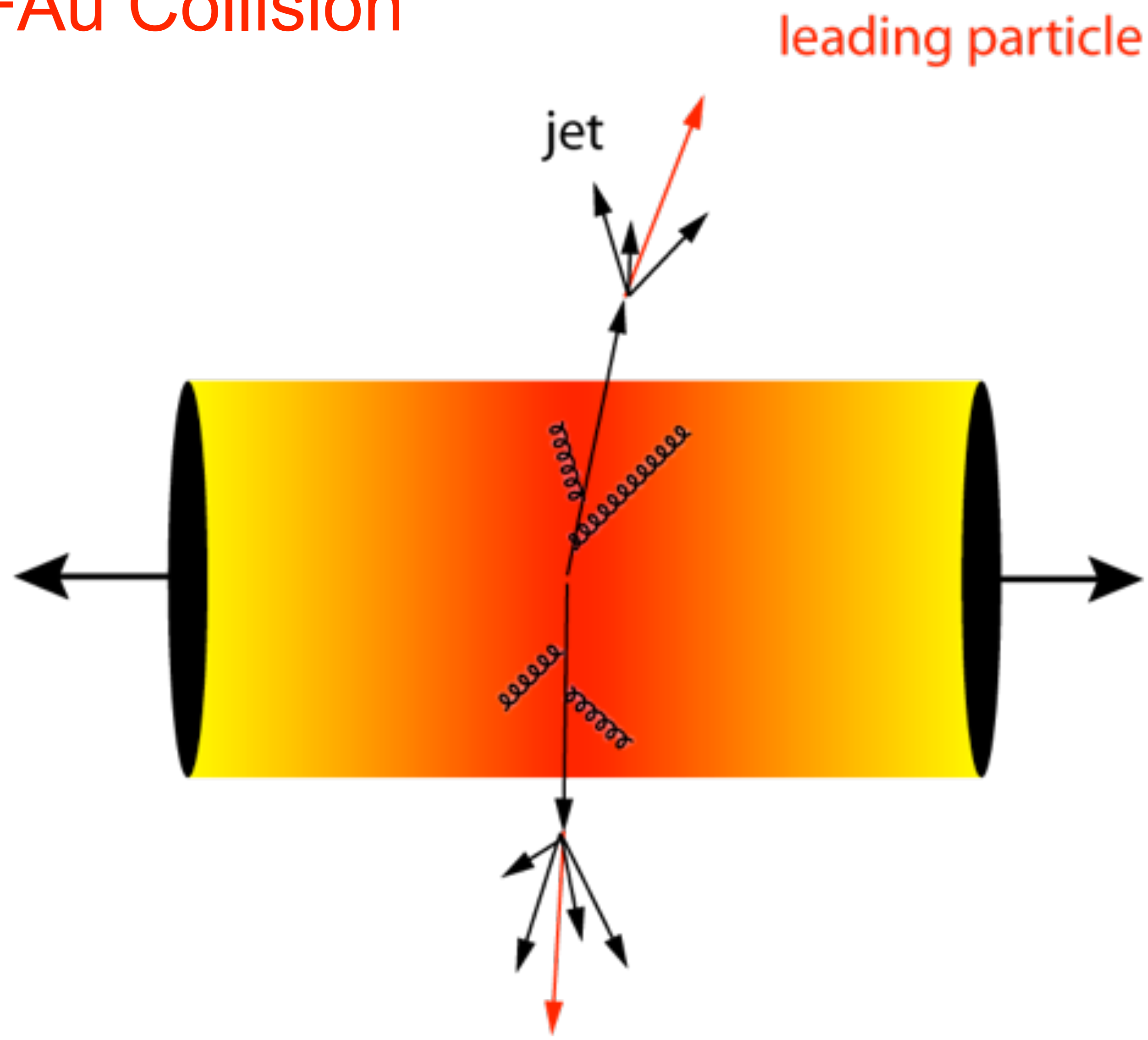


Probes of Dense Matter – Jet Tomography

Simplest way to establish the properties of a system

- Calibrated probe (electrons, X-Rays)
- Calibrated interaction (beam of known energy and direction)
- Suppression pattern tells about density profile

Au+Au Collision



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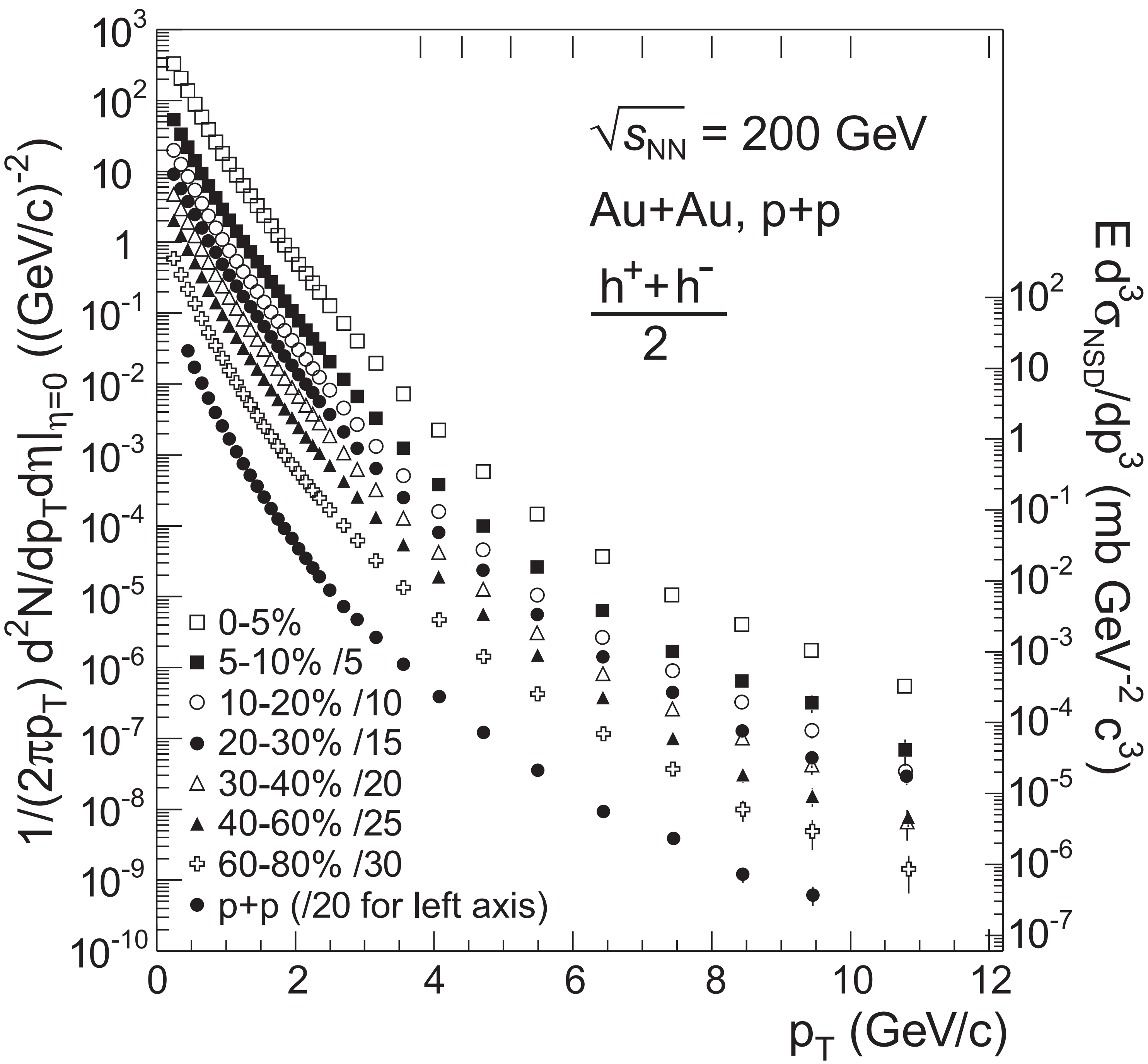
Suppression of single particle spectra

- <h^++h^-> spectra measured out to p_T = 12 GeV/c
  - Plot from 2004, can go even higher with accrued statistics
- R_{AA} ratios show a decrease in ratio with increasing centrality
  - High-p_T particles appear to be quenched by the dense medium they travel through



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