STAR Science for the Coming Decade

The ***STAR*** Decadal Plan
2012 PAC Status Report

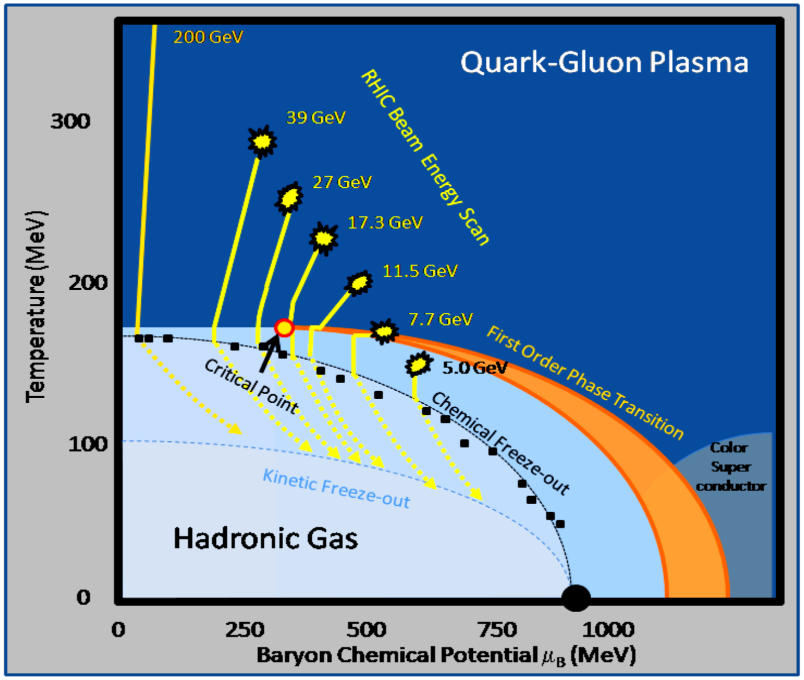
Carl Gagliardi
for the
STAR **Collaboration**

Outline

- Introduction
- Upgrades for mid-rapidity
- Upgrades for forward rapidity
- Upgrades for ***eSTAR***

RHIC: eight key unanswered questions

Hot QCD Matter



1: Properties of the sQGP

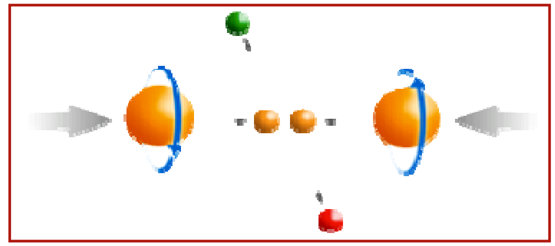
2: Mechanism of energy loss:
weak or strong coupling?

3: Is there a critical point, and if so, where?

4: Novel symmetry properties

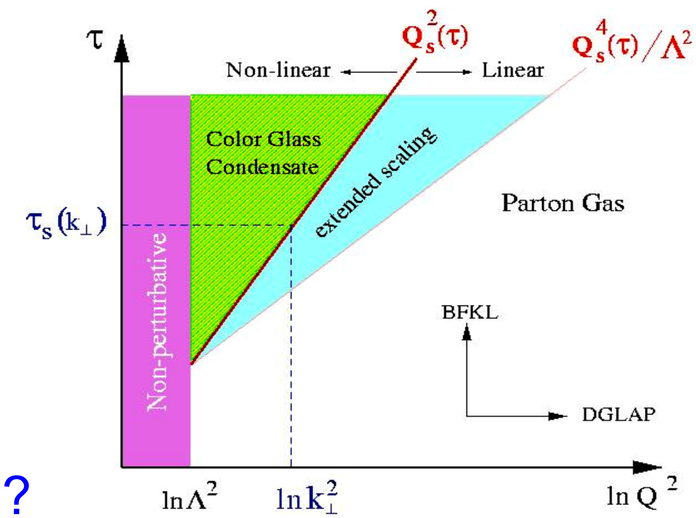
5: Exotic particles

Partonic structure



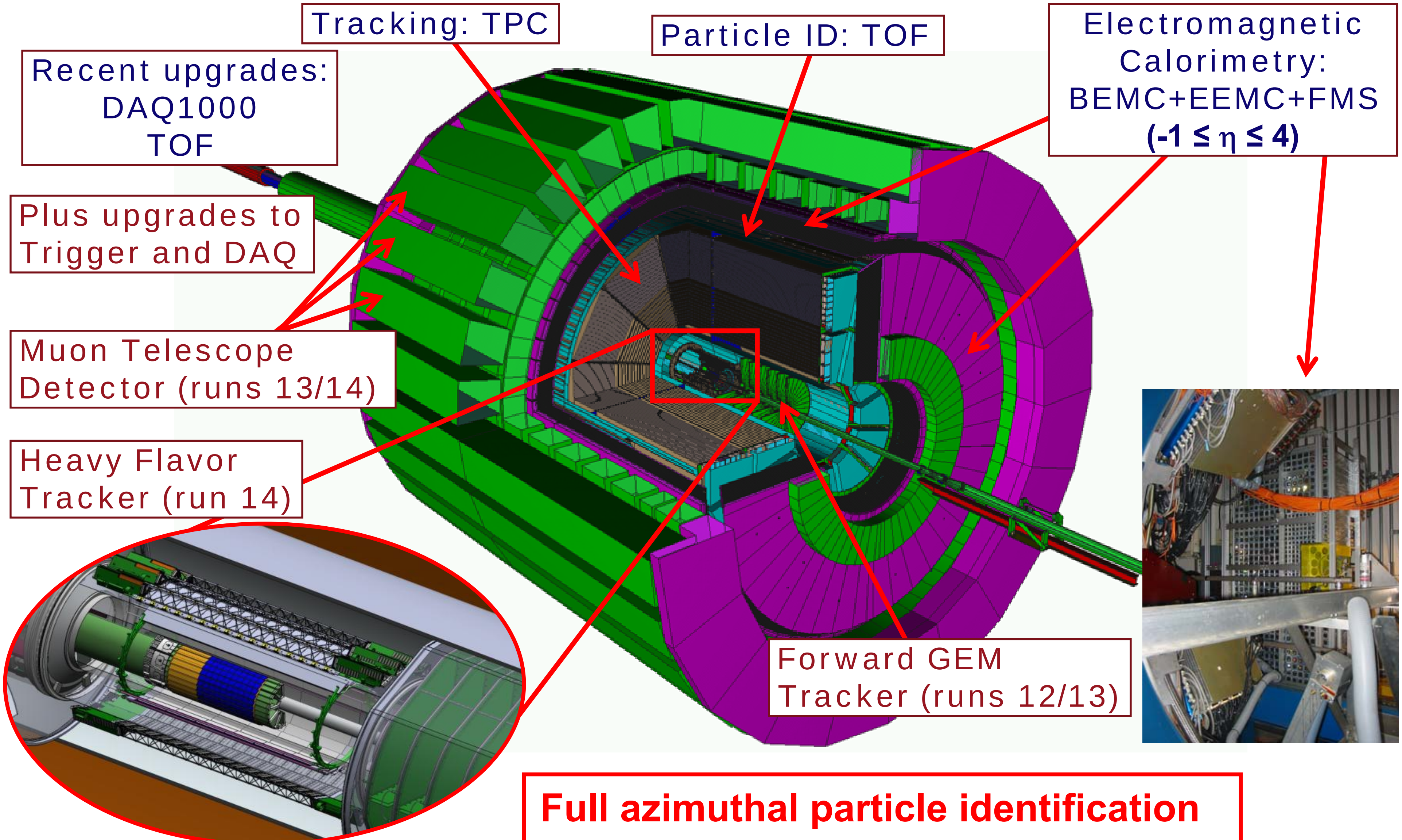
6: Spin structure of the nucleon

7: How to go beyond leading twist and collinear factorization?



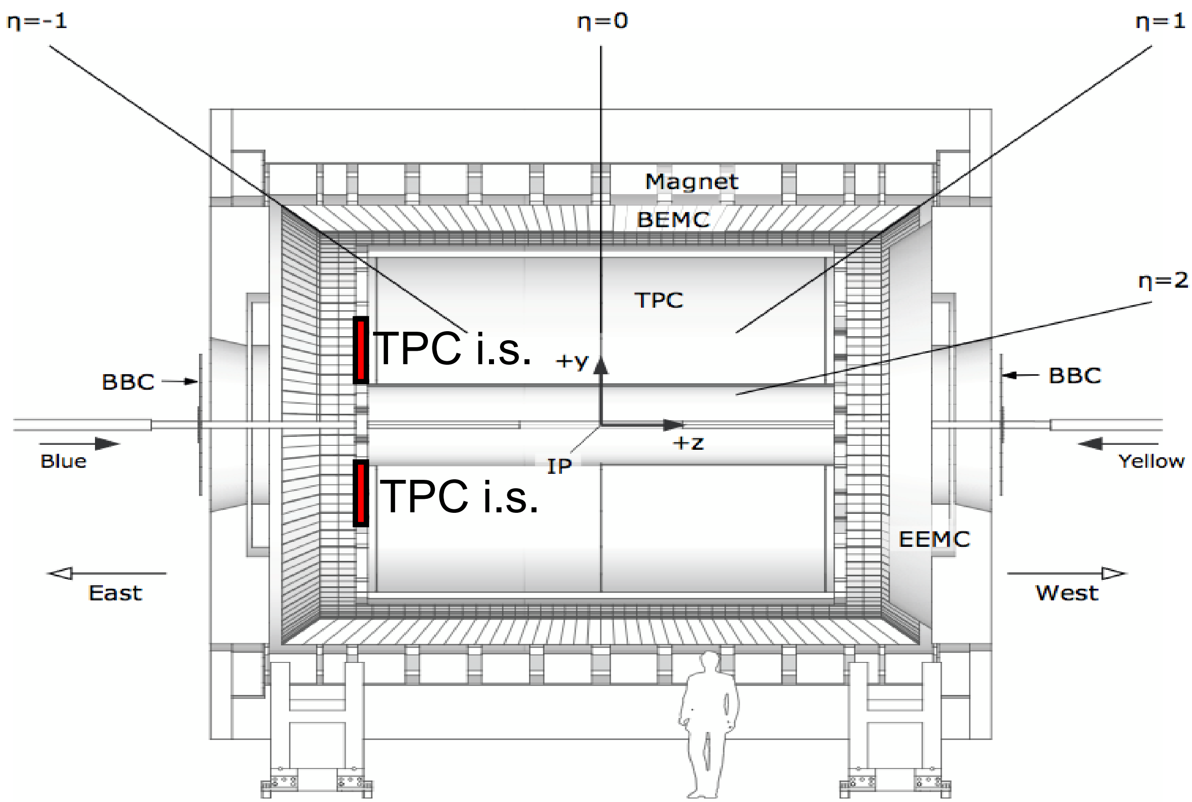
8: What are the properties of cold nuclear matter?

Mid-rapidity ***STAR***



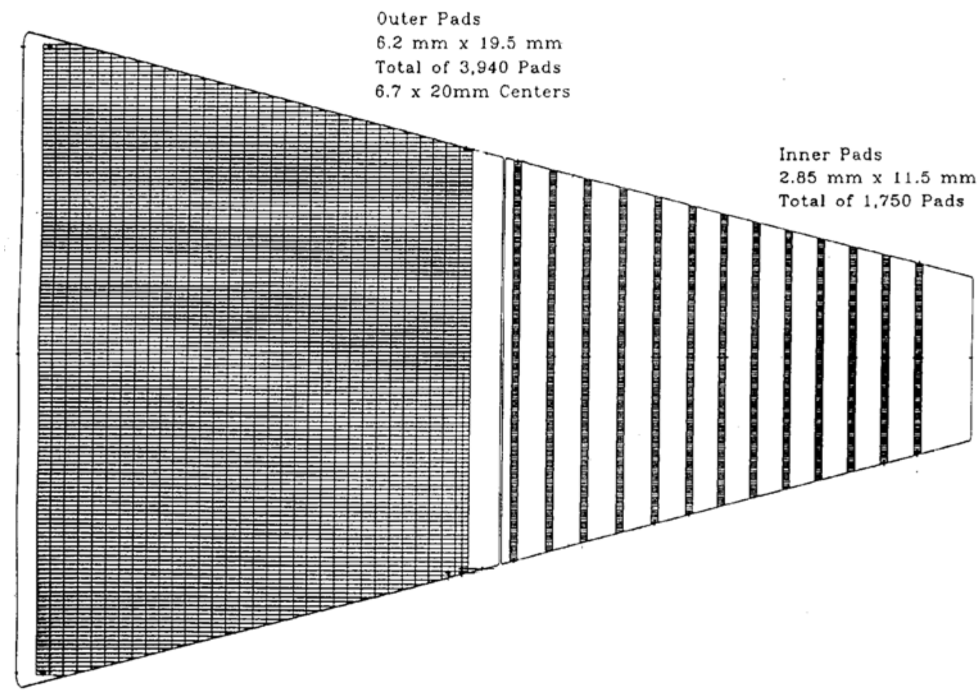
Full azimuthal particle identification over a broad range in pseudorapidity

The TPC: the heart of ***STAR***



- As of last year:
  - Verified we could rewire the inner sectors if reduced gain from accumulated charge on the wires ever makes it necessary
  - Noted that the inner sectors would play an important role for tracking during the ***eSTAR*** era

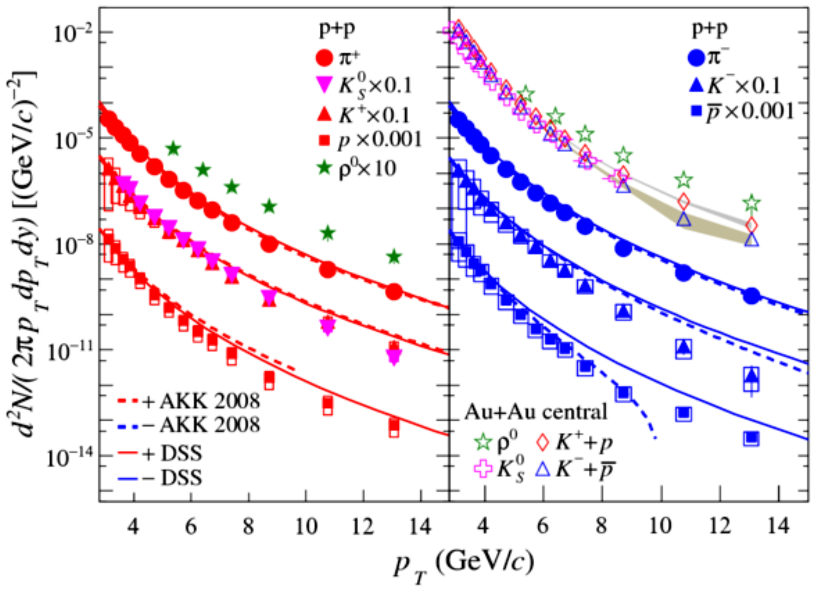
Teaching an old detector new tricks

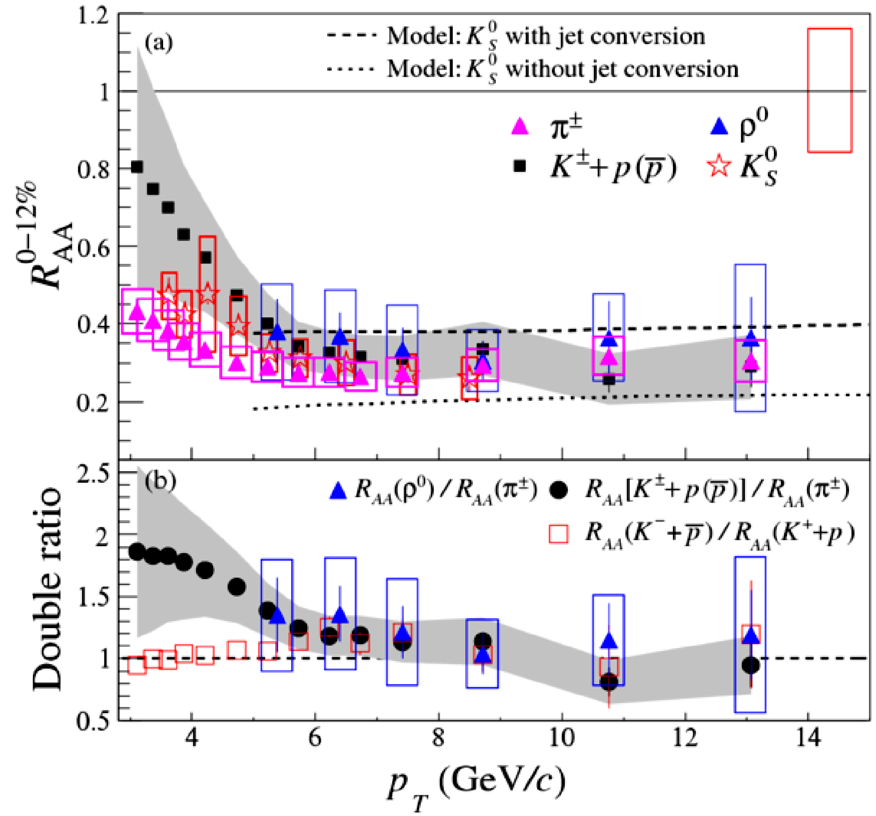


- Last year envisioned "direct" replacement of the sectors with minimal re-engineering
- Now recognize that inner sector replacement represents a major opportunity to upgrade the TPC capabilities
  - Current inner sector pads only cover ~20% of the area
  - Individual pads are smaller than necessary (3.35 x 12 mm pitch)
- Redesign the inner sector pad planes with somewhat larger pads (e.g., 4.8 x 16 mm) covering the full plane

What will we get?

STAR, PRL 108, 072302





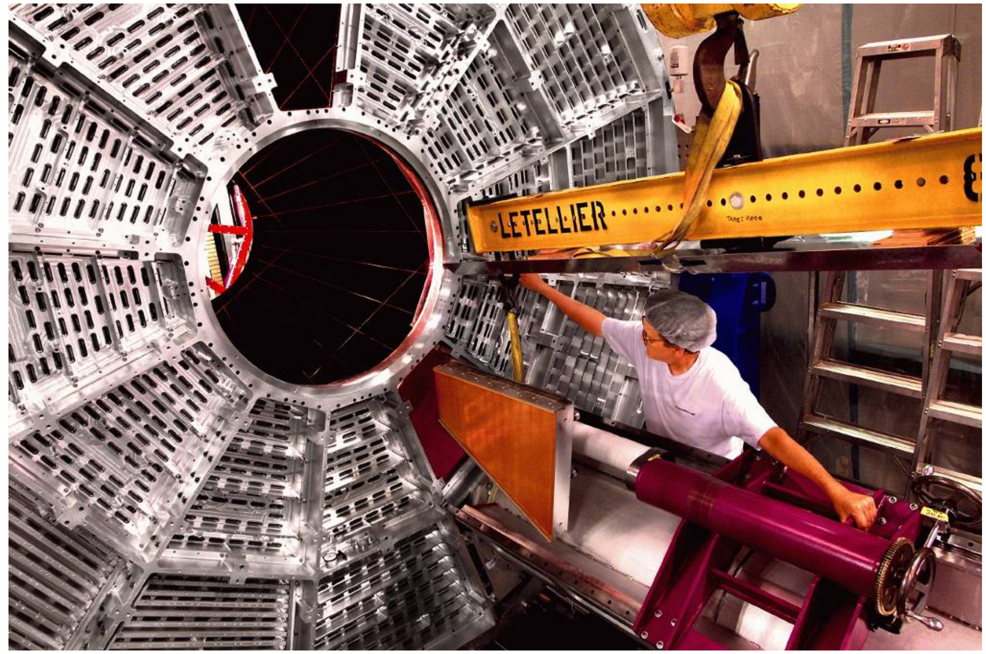
- Improved *dE/dx* resolution at mid-rapidity
  - Existing TPC *dE/dx* resolution can separate π/*K*/*p* at high-p_T in p+p collisions, but only π vs (*K*+*p*) in Au+Au
  - Doubled path length will provide better *dE/dx* resolution in Au+Au than we currently achieve in p+p, enabling π/*K*/*p* separation in Au+Au at high-p_T

Is there more?

- Extended rapidity coverage
  - Will open the window for tracking with good *dE/dx* PID from $|\eta|<1$ to $|\eta|<1.5$
    - Momentum resolution will be slightly worse at high η
  - Substantial increase in ability to study correlations in Δη vs Δφ
    - Larger Δη provides a window toward earlier times in the collision
  - Push transverse spin studies of identified di-hadrons and identified particles in jets further forward (will discuss later)

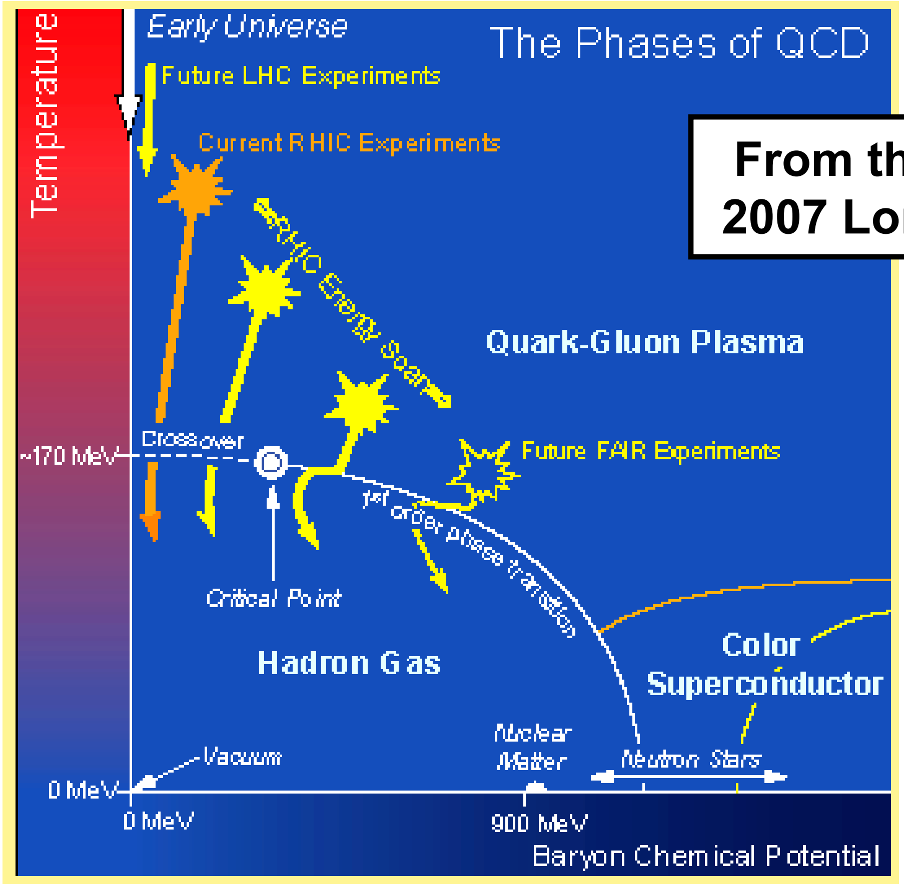
- Higher efficiency for low-p_T tracks
  - Particularly valuable for the Beam Energy Scan

What will it take?



- Current cost estimate: ~$4M
  - Half for the new pad planes and wire winding
  - Half for the new electronics
- Current time estimate: 1-2 years
- Plan to have LoI before the end of this year

Exploring the phase structure of QCD



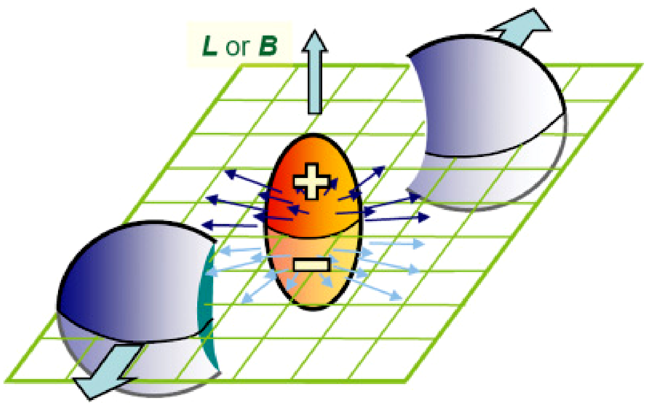
From the cover of the 2007 Long-Range Plan

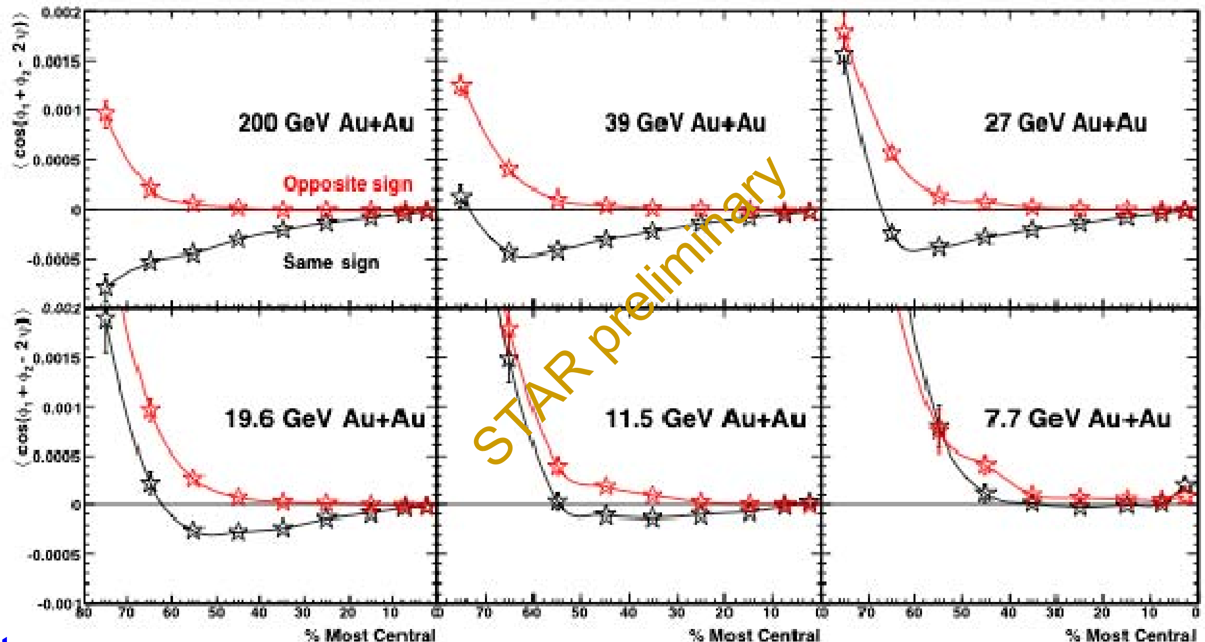
- The **QCD critical point** and the **1st order phase transition line** represent **landmarks on the QCD phase diagram**

Questions for the Beam Energy Scan

- Do we observe turn off of the new phenomena that have been observed in full-energy RHIC collisions?
  - Constituent quark number scaling of v_2
  - Jet quenching in central collisions
  - Chiral magnetic effect
- Do we observe signatures of a phase transition and/or critical point?
  - Elliptic and directed flow: indicators of the “softest point” in momentum space
  - Azimuthally-sensitive HBT: indicator of the “softest point” in coordinate space
  - Fluctuation measures

Chiral magnetic effect

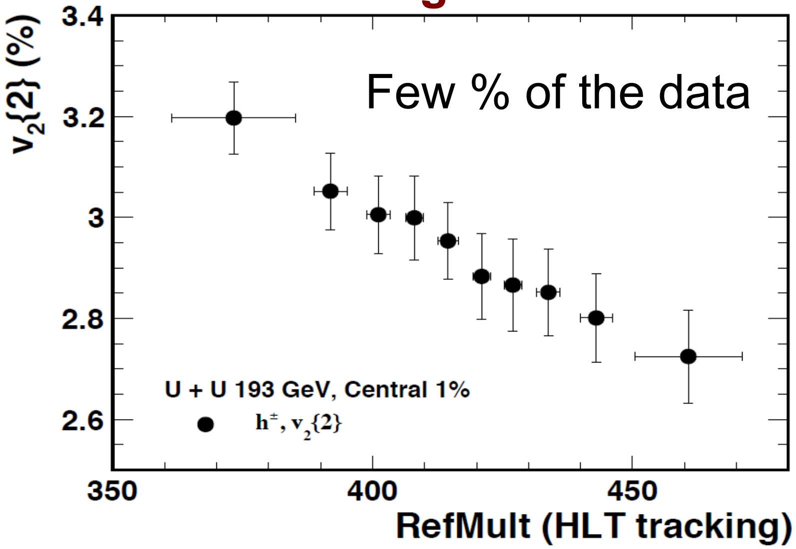




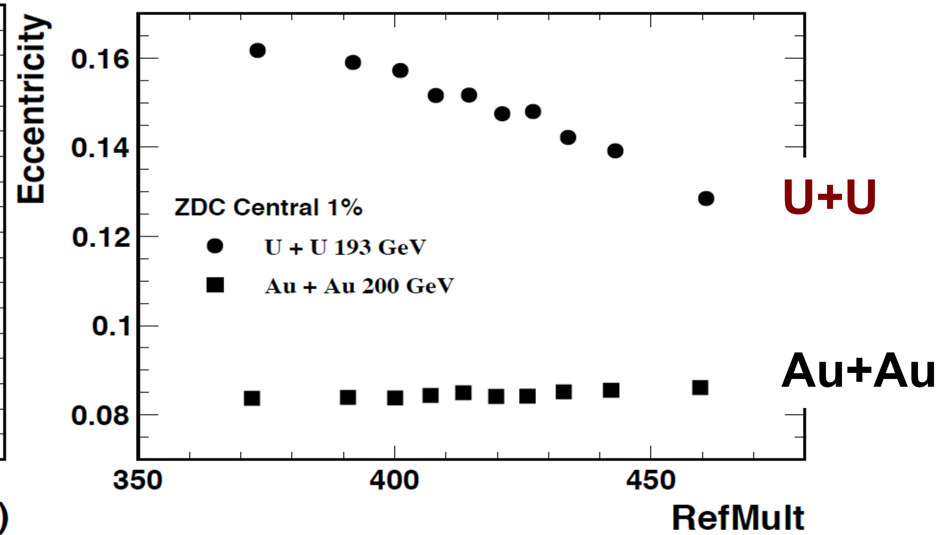
- Chiral magnetic effect:
  - Topological gluonic configurations produce asymmetry in right- vs left-handed quarks (local parity violation)
  - Charges separate along the magnetic field in non-central collisions
  - Requires **deconfined quarks** and **chiral symmetry restoration**
- If QGP is the source of the splitting, then hadronic interactions become dominant at $\sqrt{s_{NN}}$ <~ 11.5 GeV

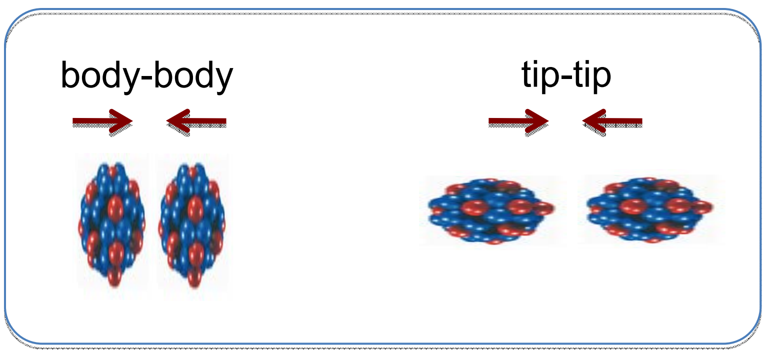
Direct experimental test: U+U

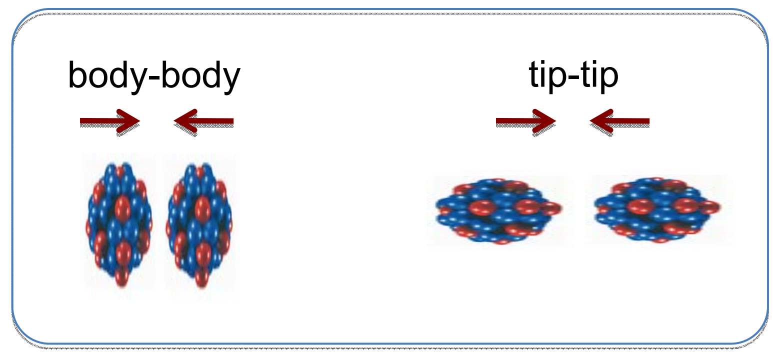
Online tracking data



Simulations

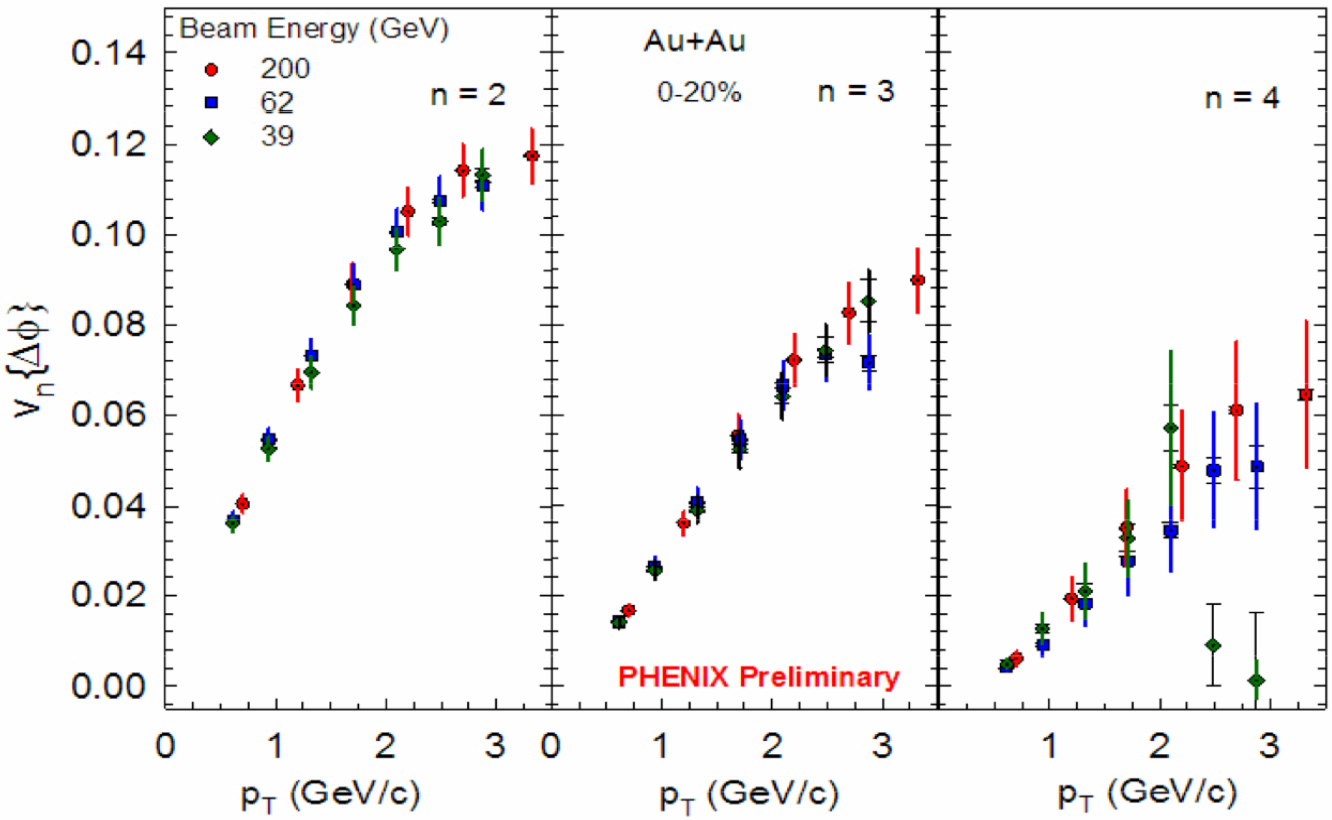






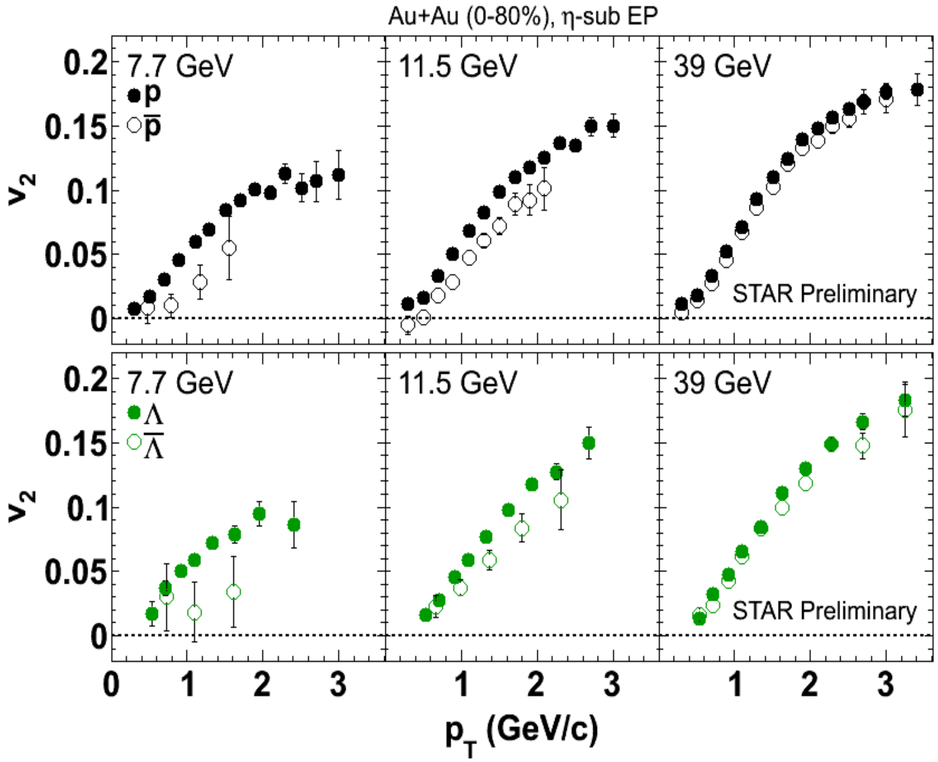
- Large v_2 in central U+U, without the magnetic field from spectators
- If chiral magnetic effect is the correct explanation for the charge separation relative to the reaction plane, the effect should disappear
  - Would **demand** further study!

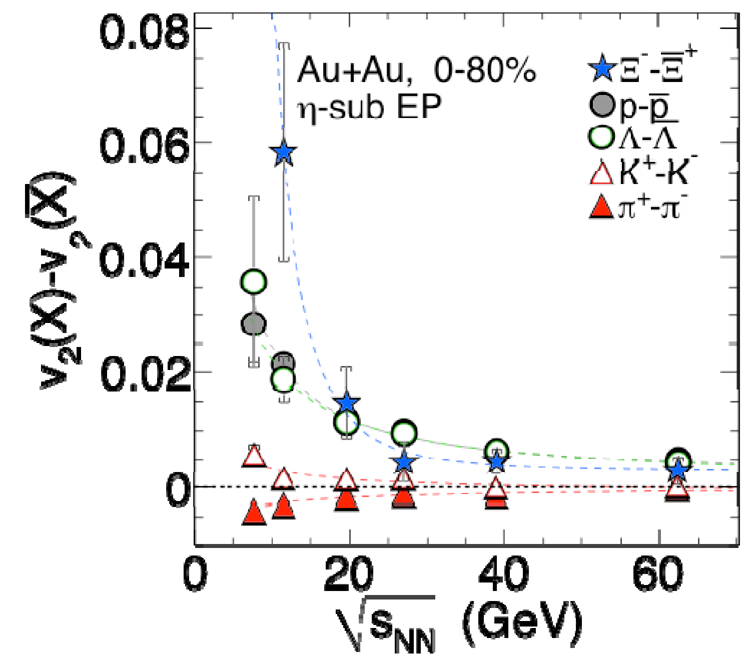
Flow and partonic collectivity



- v_2 , v_3 , and v_4 independent of energy from 39 to 200 GeV
- Also similar at LHC energies
- Partonic medium persists at least down to 39 GeV

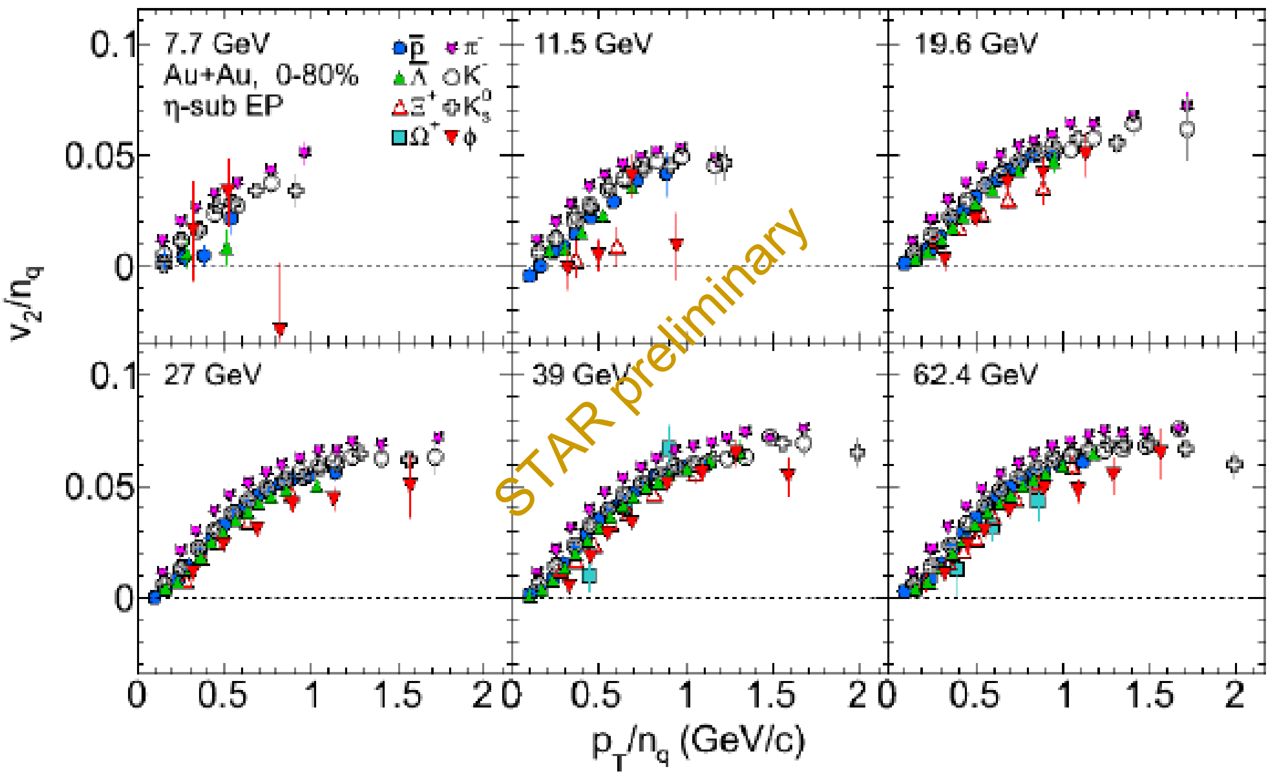
Flow at the low end of the Energy Scan





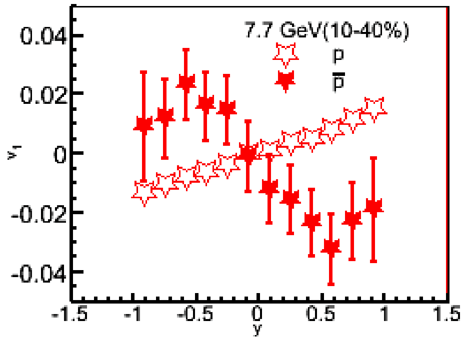
- Difference in v_2 between particles and anti-particles at lower energies
  - Difference increases with decreasing energy
  - Difference is much larger for baryons than mesons
    - Baryon transport to mid-rapidity?
- Requires significant fraction of the flow to build up during the hadronic phase

φ and Ξ v_2 at lower $\sqrt{s_{NN}}$

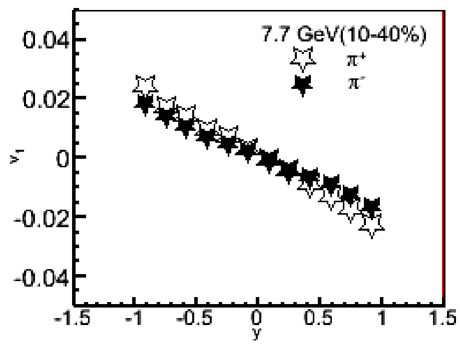


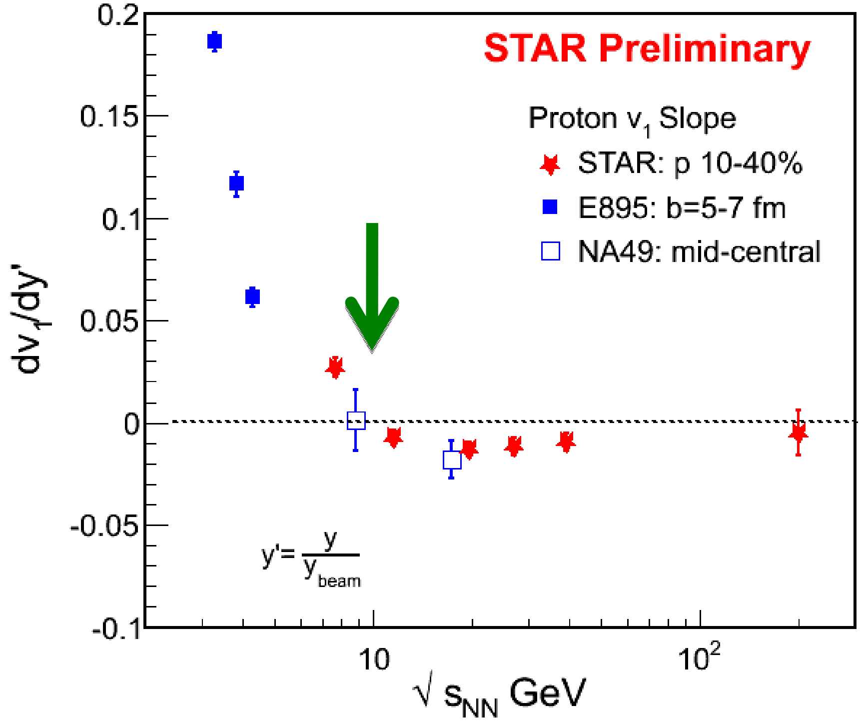
- φ and Ξ v_2 much lower than that for other hadrons at 11.5 GeV
- Have small hadronic cross sections, so decouple earlier
- Points to the hadronic phase as the origin for much of the flow at the low end of the Beam Energy Scan

Mid-y v_1 slope vs. $\sqrt{s_{NN}}$



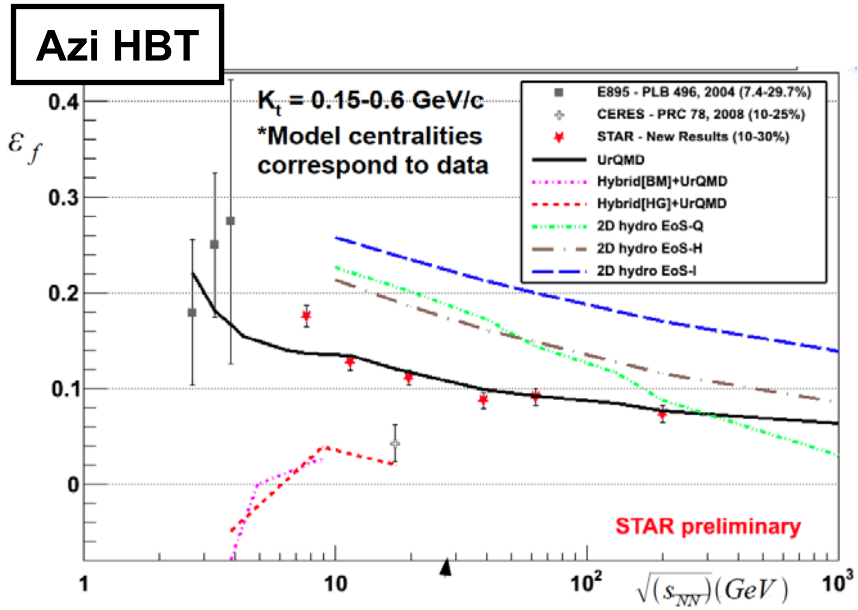
STAR preliminary

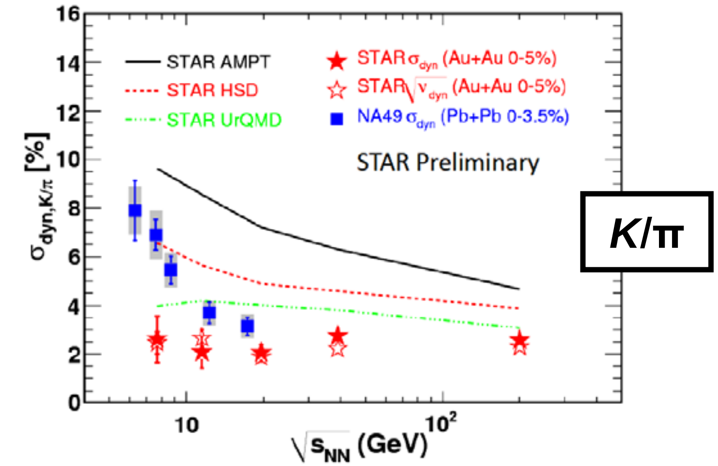


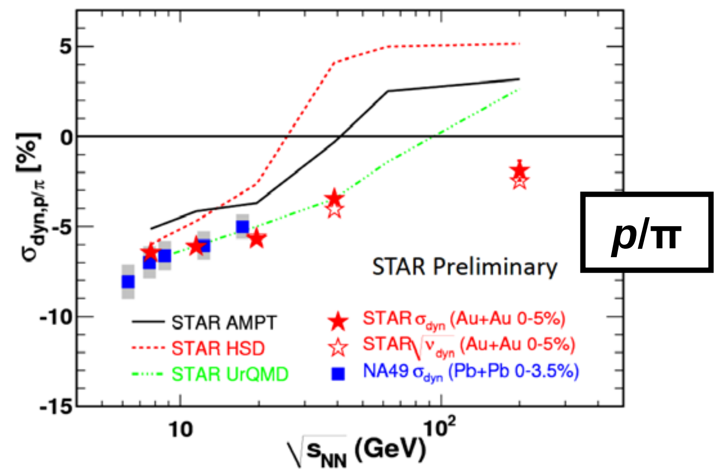


- Mid-rapidity proton v_1 is sensitive to:
  - Nuclear stopping
  - Mixture of initial and produced particles
  - Equation of state
- At low beam energy, initial nucleons are dominant
- At higher beam energies, produced particles dominate the dynamics
  - Changing EOS around $\sqrt{s_{NN}}$ ~ 10 GeV ?
- No such change is seen for other particle species

Phase transition signatures?

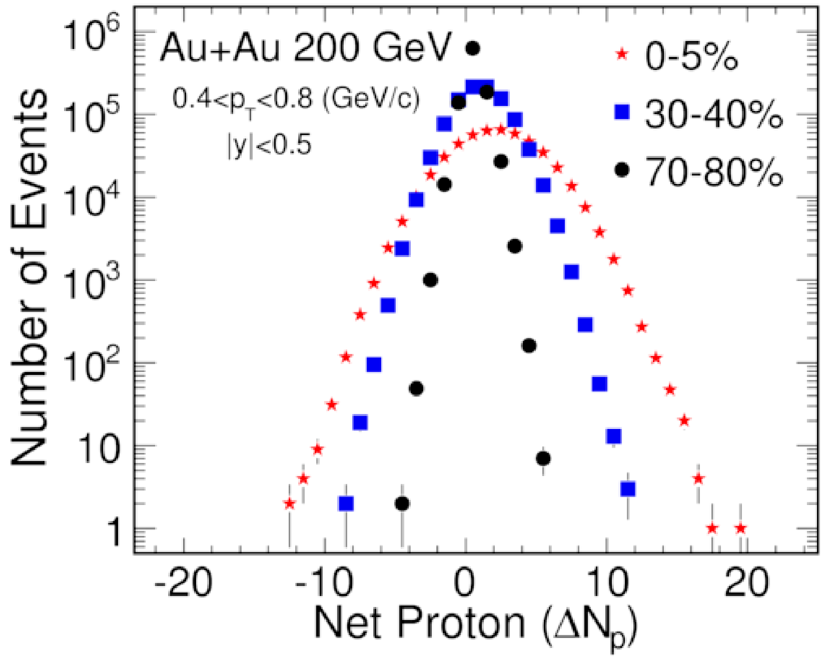






- Azimuthally sensitive HBT and event-to-event *K*/π and p/π ratios both evolve smoothly with $\sqrt{s_{NN}}$
- UrQMD describes the data trends for all three observables

Higher moments of net-proton distributions

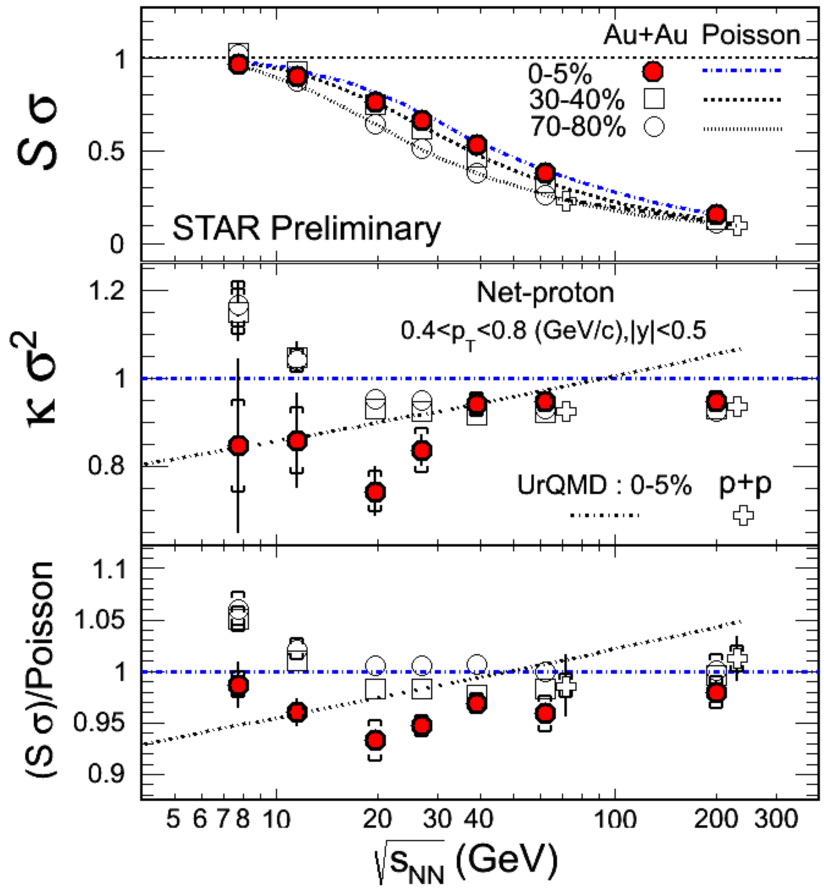


$$\chi_B^{(n)} = \left.\frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\right|_T$$

$$\chi_B^4 / \chi_B^2 = (\kappa\sigma^2)_B$$
$$\chi_B^3 / \chi_B^2 = (S\sigma)_B$$

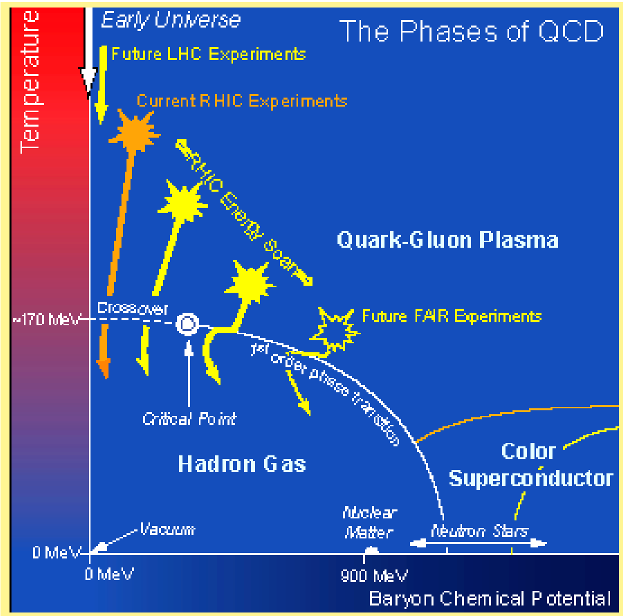
- Link between susceptibilities (e.g., from lattice QCD) and products of higher moments for conserved quantities
- Large fluctuations predicted near the critical point
  - Skewness is proportional to $\xi^{4.5}$
  - Kurtosis is proportional to ξ^7
- Measure net-proton number fluctuations as surrogate for baryon number fluctuations

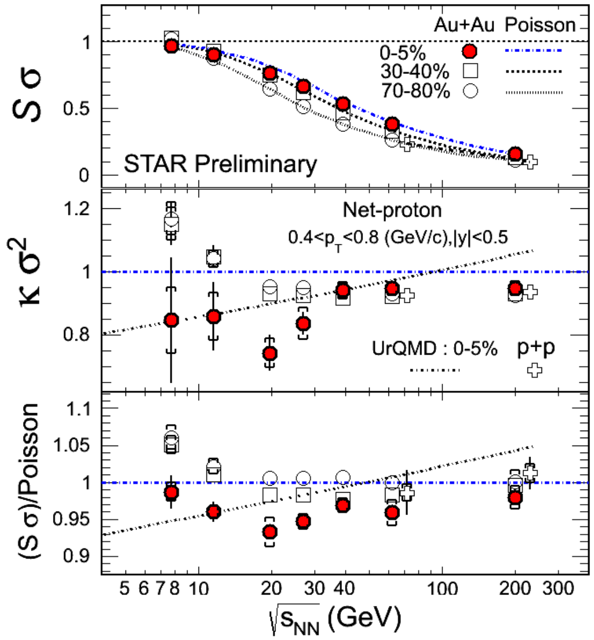
Higher moments of net-proton distributions



- Possible minimum for skewness and kurtosis in central events around $\sqrt{s_{NN}}$ ~ 20 GeV
- Not seen for 30-40% and 70-80% centralities

Phase II of the Beam Energy Scan





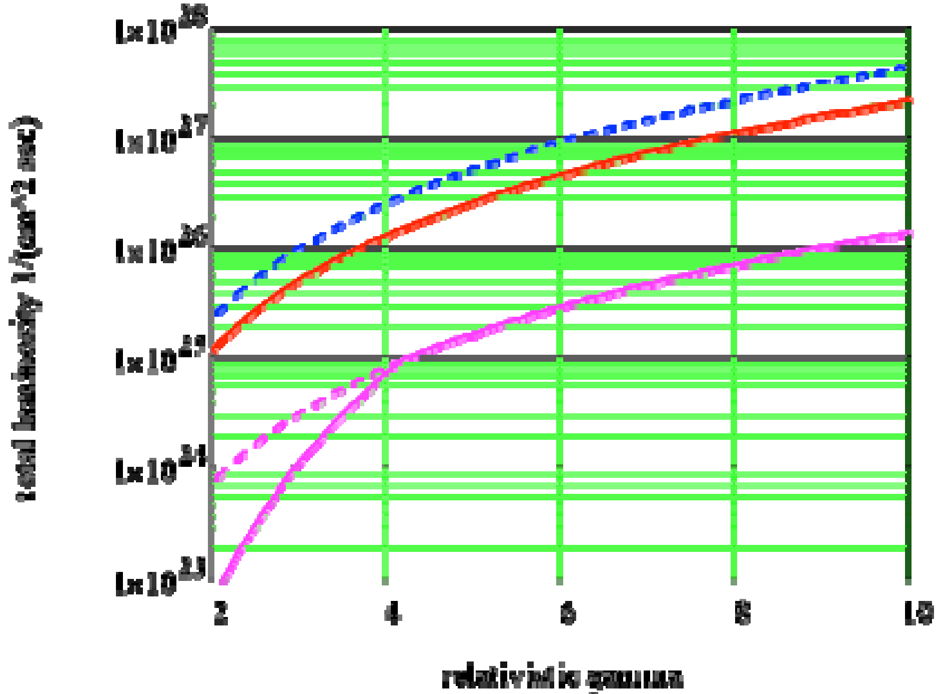
Unique opportunity for RHIC!

- Results to date **demand much higher statistics** (x10 or more) for the points below $\sqrt{s_{NN}}$ < 20 GeV, another energy point around 15 GeV, and ideally at least one point below 7.7 GeV
- Can't get there from here under the status quo with any realistic beam time scenario
- **Need electron cooling** of the low-energy Au beams in RHIC
  - Not an upgrade **to *STAR***
  - An upgrade to the accelerator **for *STAR***

e-cooling at RHIC for BES-II

Fermi Lab Pelletron

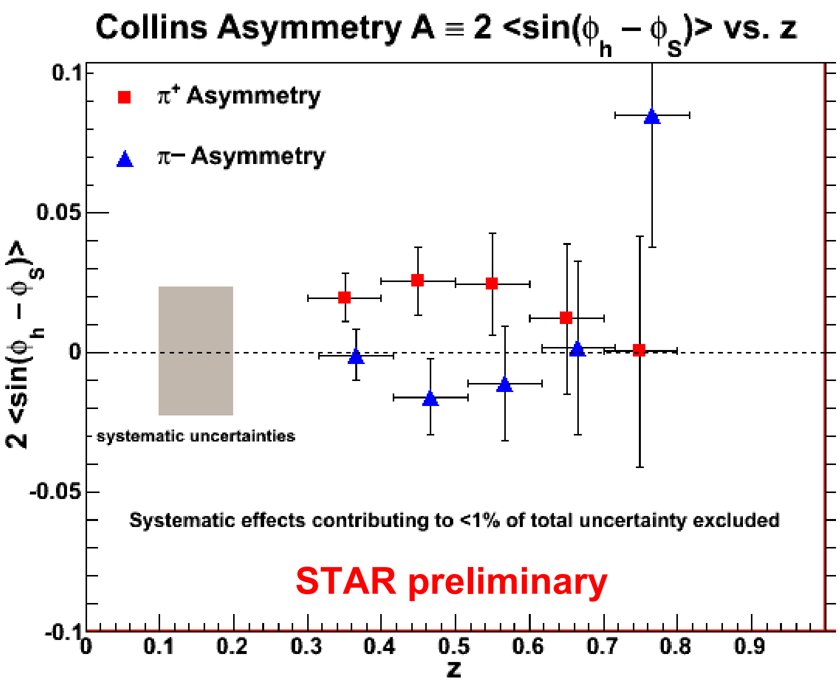
A. Fedotov, W. Fischer, private discussions, 2012.

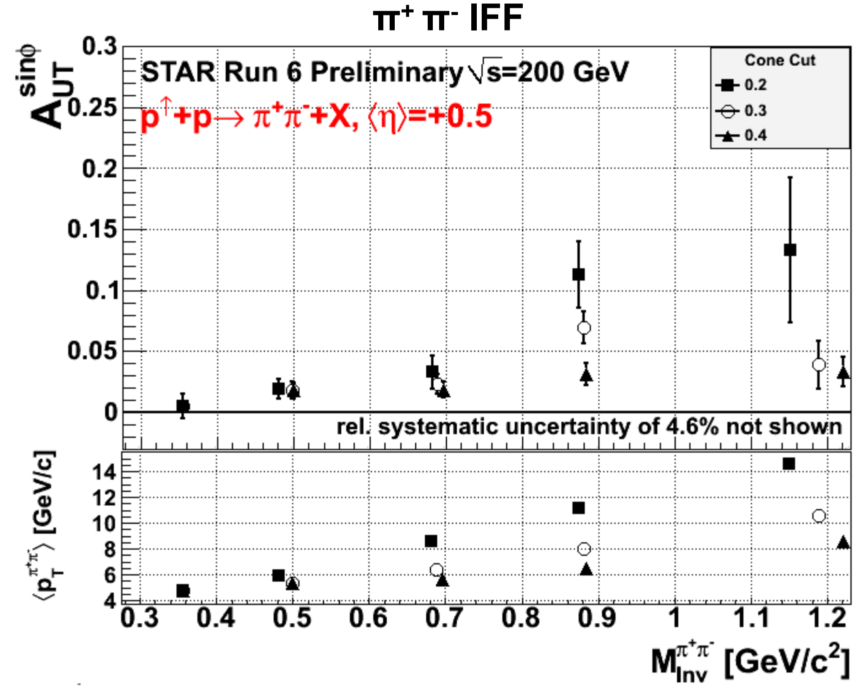


$\sqrt{s_{NN}}$ (GeV)	~ 5	~ 20
Increasing factor*	3-5	10

- C-AD estimates this will require $ 4-5M and up to 4 years
- **It's time to get started!**

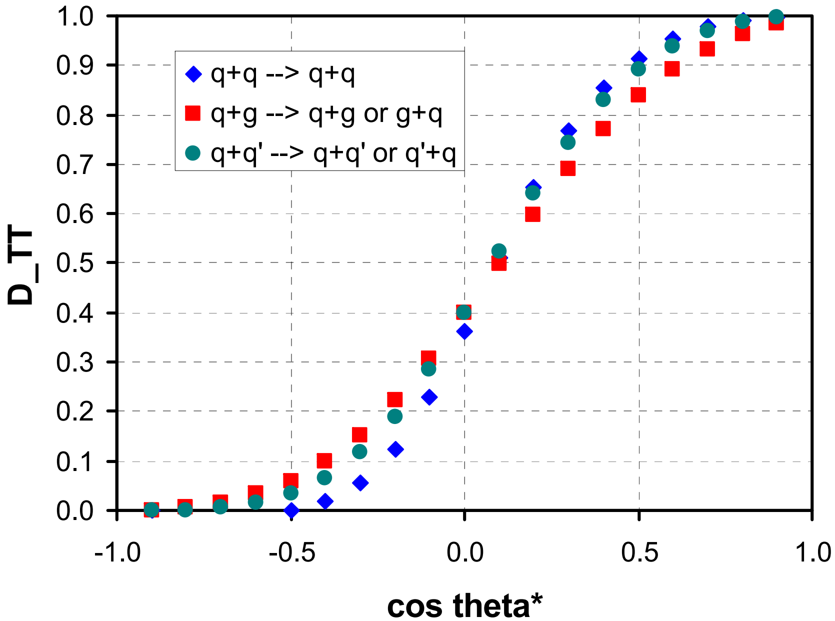
New ***STAR*** transverse spin results

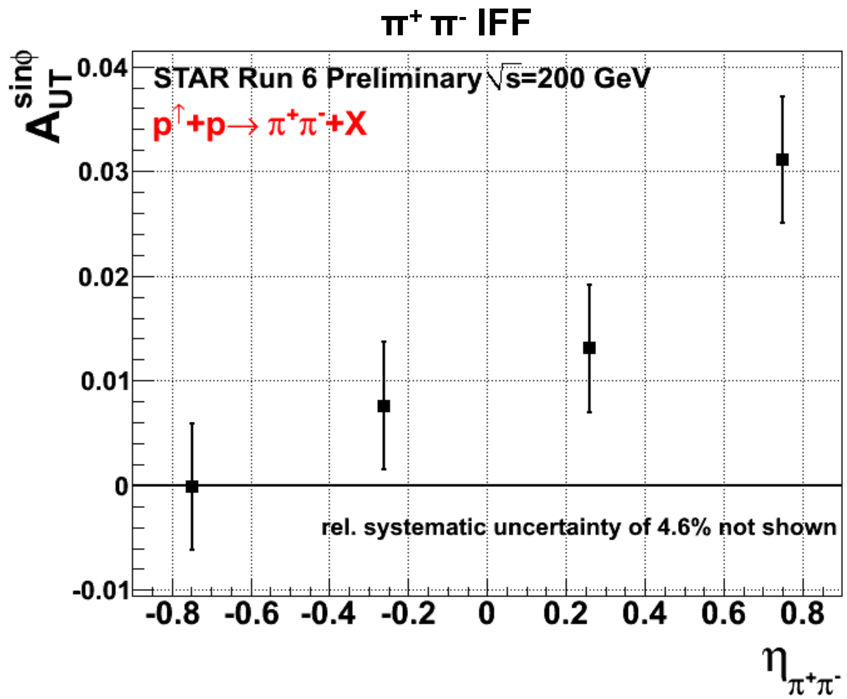




- Since last year, STAR has released new mid-rapidity measurements of:
  - Collins effect in jets
  - Interference Fragmentation Functions (IFFs)
- First clear signatures of quark transversity in p+p collisions at RHIC!

Looking forward (in time *and* rapidity)



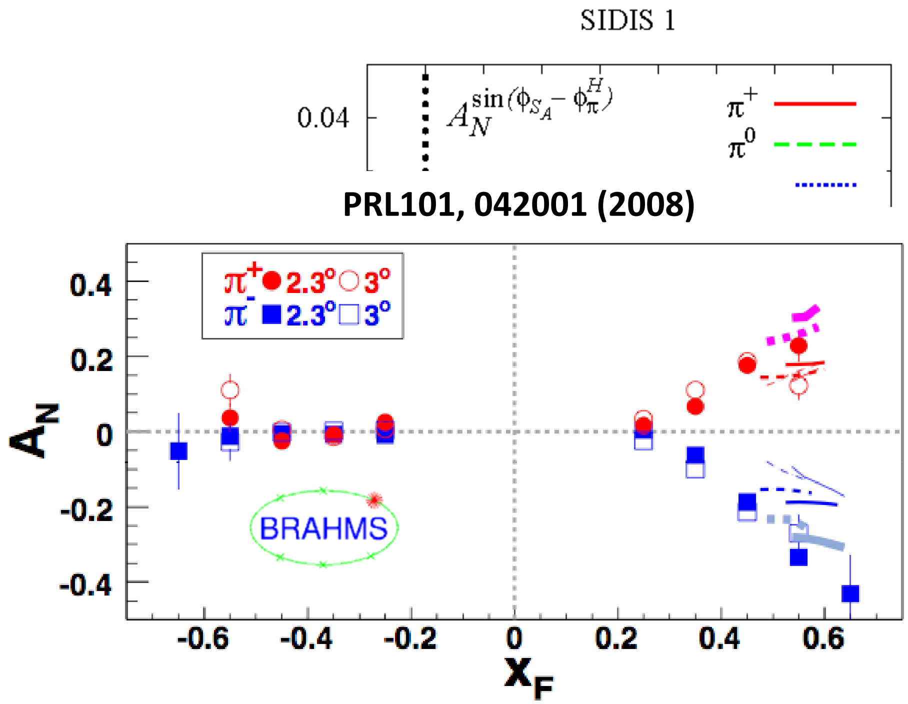


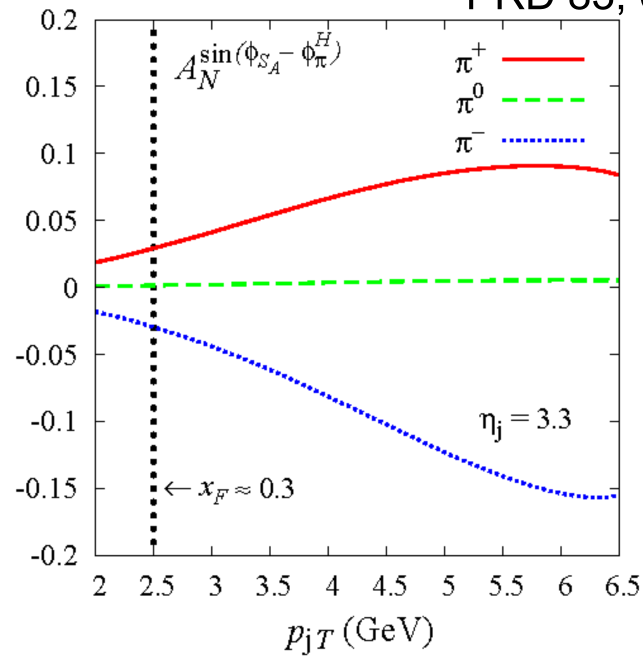
- Recorded >~10 times the figure-of-merit during the 200 GeV pp part of Run 12, with less biased triggers than we had during Run 6
- Big advantage in pushing transversity measurements more forward
  - Large increase in the polarization transfer coefficient
  - See the increasing signal very clearly in the IFF measurement
  - TPC inner sector upgrade, combined with the FGT and EEMC, will extend these studies to $\eta = 2$

Pushing transversity even further forward

Collins asymmetry in jets

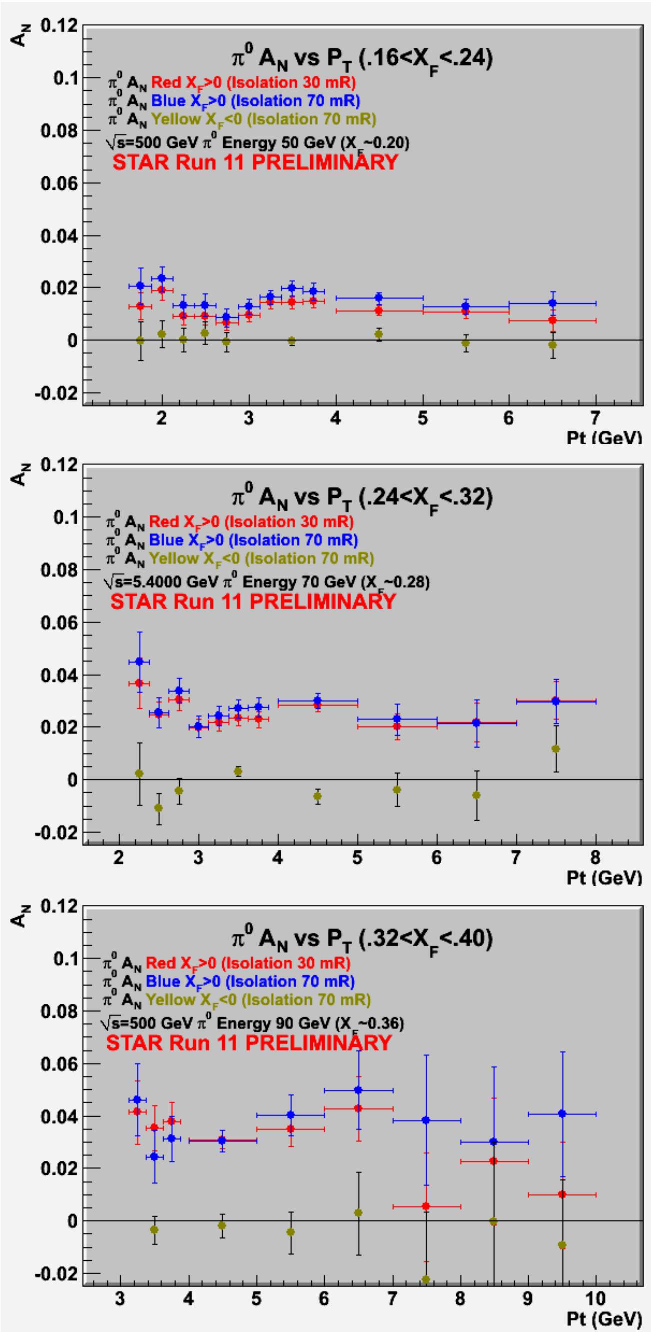
D'Alesio et al,
PRD 83, 034021





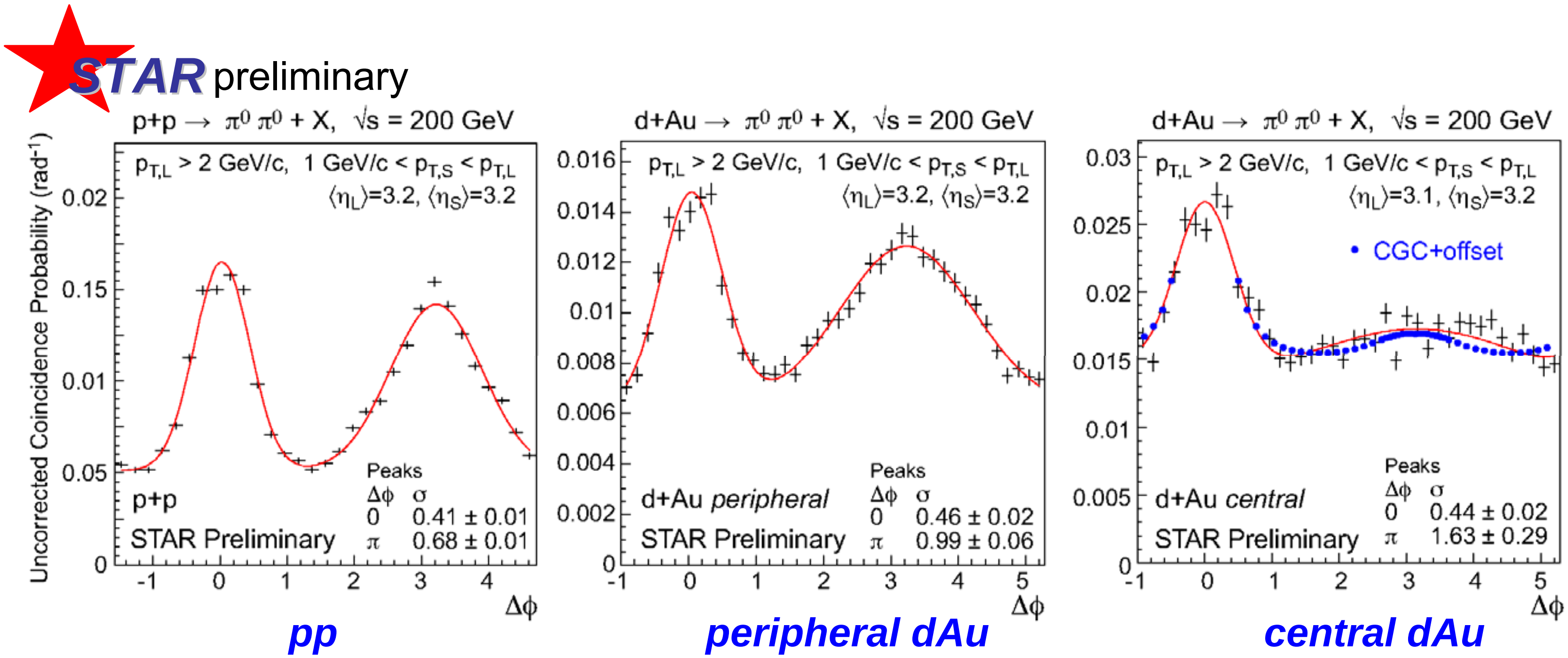
- Pushing out to the FMS rapidity will probe quark transversity at high *x*
- Need to **trigger on and measure jets** with leading **charged pions**
  - Collins effect for π^0 is expected to be very small
  - Very large, and opposite sign, A_N are observed for inclusive $\pi^\pm$

Yet another new transverse spin result from ***STAR***



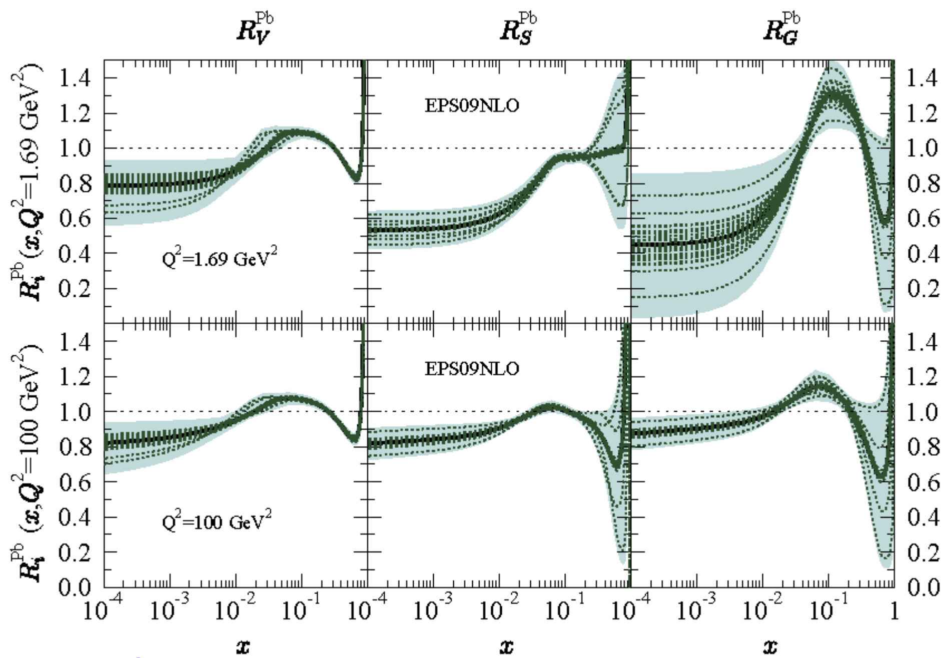
- π^0 A_N at 2.5 < η < 4 in 500 GeV polarized pp collisions
  - Measured with the FMS in Run 11
- Asymmetries extend to **very high p_T**
- For 0.16 < x_F < 0.32, **events with additional photons** in close proximity to the π^0 (>~5 GeV between 0.03 and 0.07 radians from the π^0) **contribute little to the observed asymmetry**
  - Can look for this effect in 200 GeV pp collisions with the Run 12 data
- Becoming more difficult to ascribe the observed transverse spin asymmetries for forward hadron production to the Sivers effect
- **Need much enhanced forward particle detection, including direct photons and full jets**

Cold QCD matter – the initial state at RHIC



- RHIC may provide **unique access to the onset of saturation**
- Future questions for **p+A**
  - What is the gluon density in the (x,Q^2) range relevant at RHIC?
  - What role does saturation of gluon densities play at RHIC?
  - What is Q_s at RHIC, and how does it scale with A and x?
  - What is the impact parameter dependence of the gluon density?

p+A at RHIC during the LHC era



Eskola et al, JHEP 0904:065

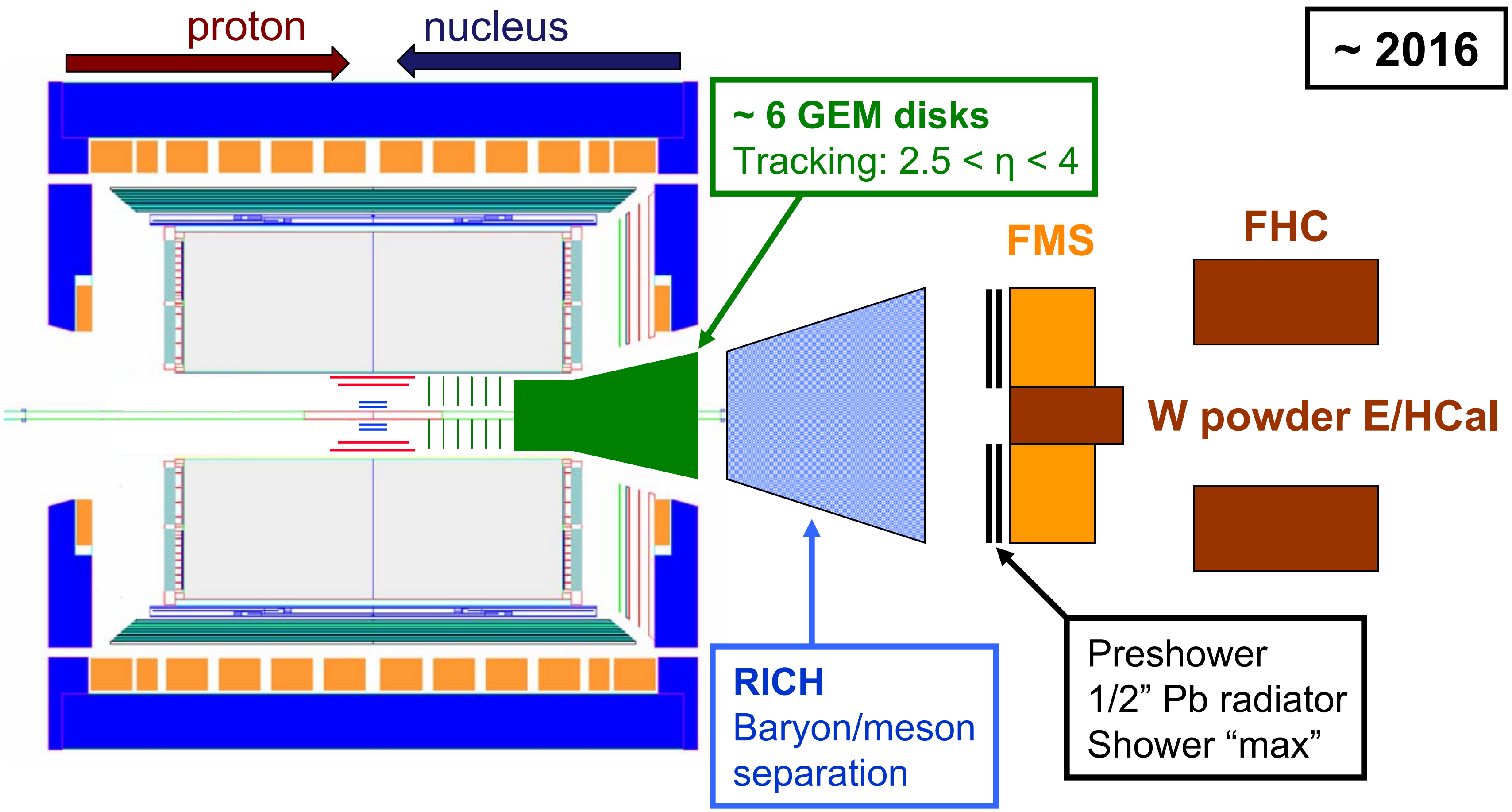
- We will learn a lot from the upcoming p+Pb run at the LHC
  - Should obtain strong constraints on the gluon density at **very low** *x*
  - Will be more difficult to explore the gluon density in the region *x* ~ 0.001 and low Q^2
- To unravel the underlying dynamical mechanism, need to:
  - Watch saturation turn on and turn off
  - Verify the A-dependence
- These tasks better accomplished at RHIC (and eRHIC)

Some planned p+A measurements

- Nuclear modifications of the gluon PDF
  - Correlated charm production
- Gluon saturation
  - Forward-forward correlations (extension of existing π^0-π^0)
    - *h*-*h* } Easier to measure
    - π^0-π^0
    - γ-*h* } Easier to interpret
    - γ-π^0
  - Drell-Yan
    - Able to reconstruct x_1, x_2, Q^2 event-by-event
    - Can be compared directly to nuclear DIS
    - True 2 → 1 provides model-independent access to $x_2 < 0.001$
  - Λ polarization
  - Baryon production at large x_F
- Scattering ***polarized* protons off nuclei**

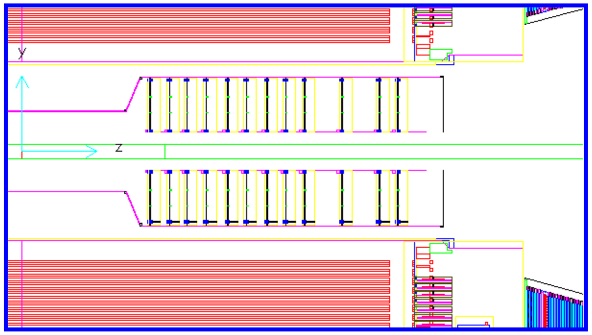
- All of these observables will also be useful to enravel the dynamics that are generating the large transverse single-spin asymmetries at forward rapidity.

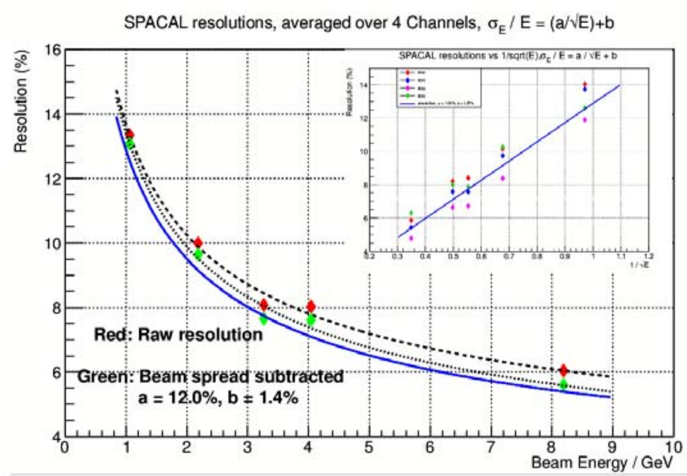
STAR forward instrumentation upgrade

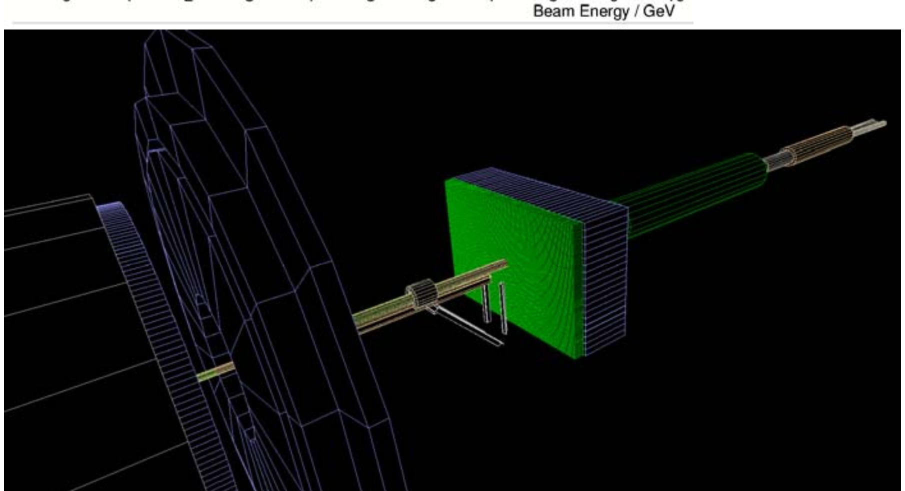


- Forward instrumentation optimized for **p+A** and **transverse spin** physics
  - Charged-particle tracking
  - *e*/*h* and γ/π^0 discrimination
  - Baryon/meson separation

Beginning simulations

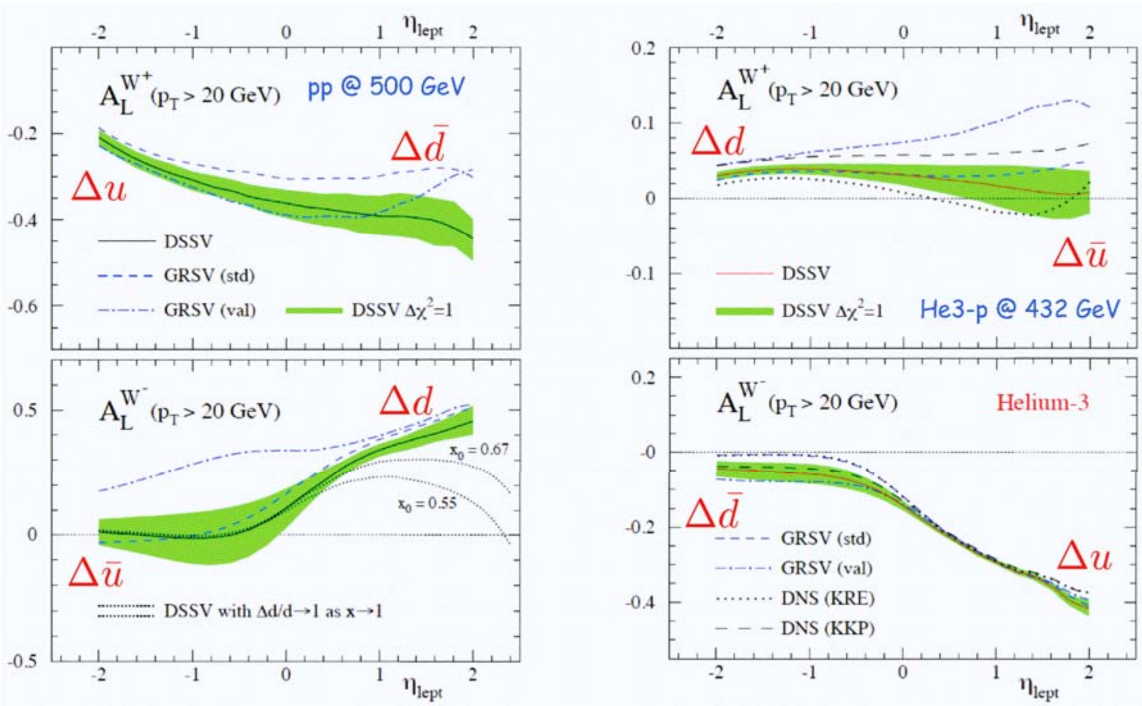


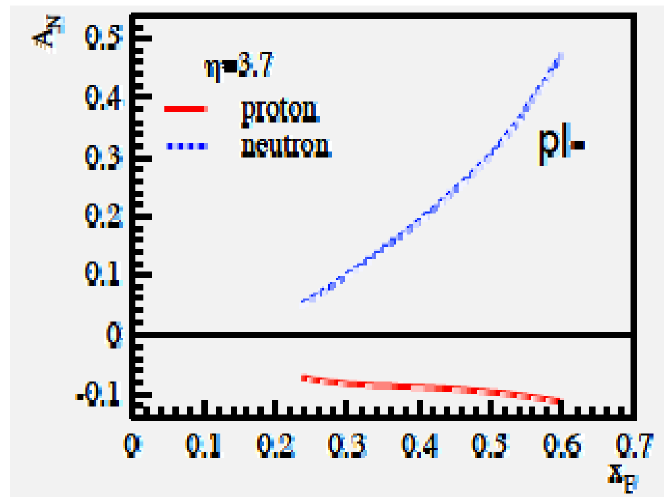




- Tracker has been dubbed the VFGT
  - In a very real sense, the existing FGT is a prototype
  - Have an initial model for the VFGT in GEANT
- Built a prototype W-powder EMcal and tested it at FNAL
  - Performed quite well!
- Switched to a W-powder EMcal, plus a “conventional” hadron calorimeter
  - Less expensive and less complex
  - Have three different models in GEANT
    - Both with and without current FMS
- Implementing the transverse spin MC generator that has been developed by the eRHIC group

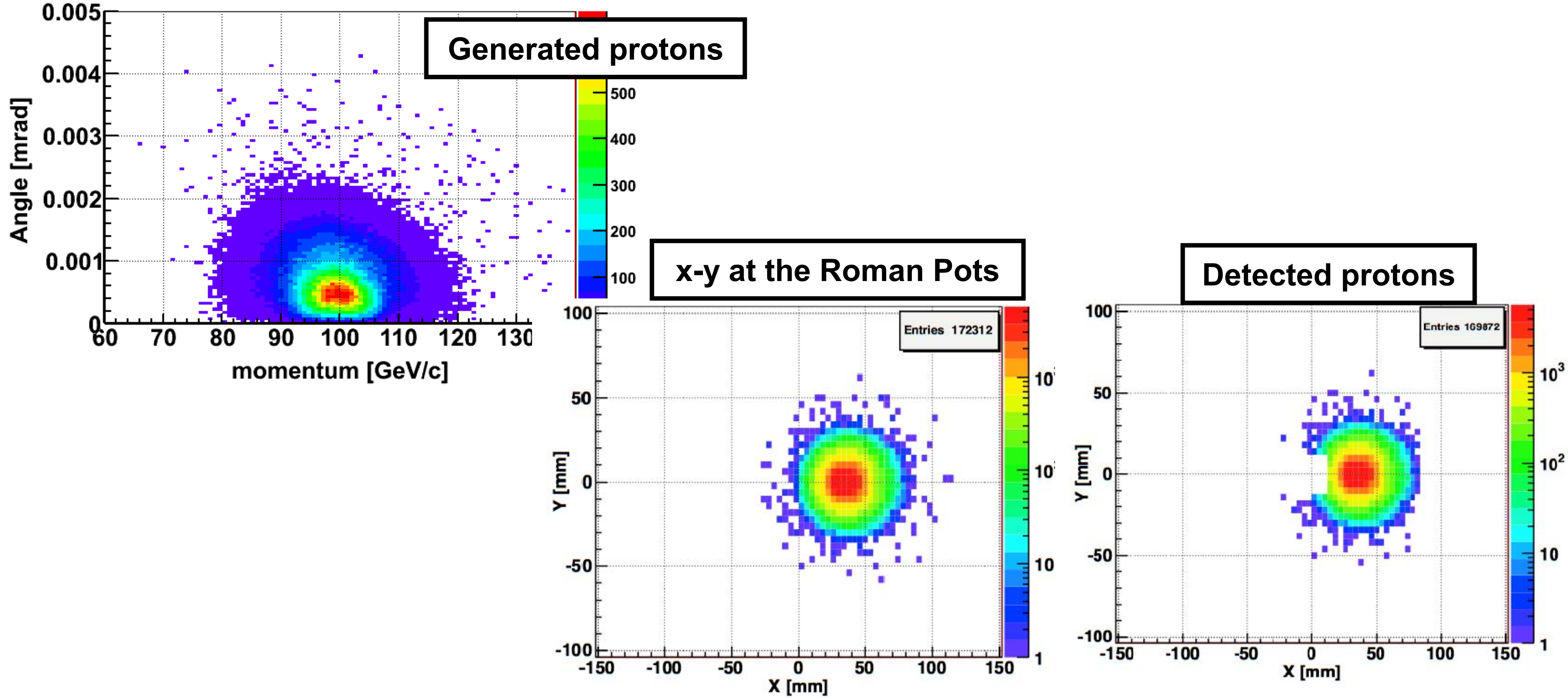
Polarized ^{3}He





- Polarized ^{3}He provides access to polarized neutron scattering
- Important for both flavor-separated helicity distributions and isolating contributions to transverse spin asymmetries
- Very important technological development on the way to eRHIC

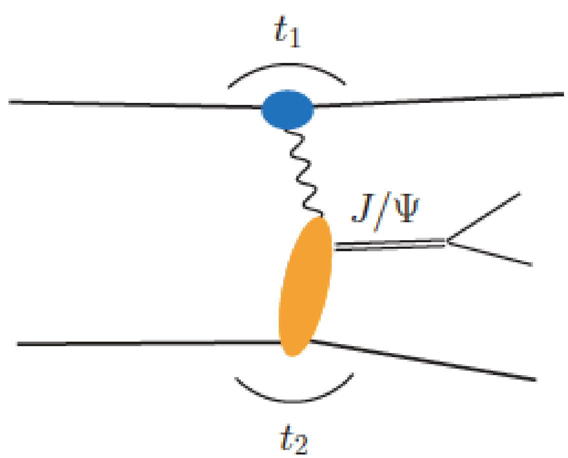
Tagging the proton spectators from ^{3}He



- Simulated the spectator protons from p+^{3}He
- Propagated them through the standard RHIC beam optics
- Roman Pots phase II upgrade **will tag ~98% of spectators**
- This will provide a **dramatic improvement in the S:B ratio** for polarized neutron measurements using a polarized ^{3}He beam

A_{UT} for exclusive J/ψ in UPCs

Detect final-state protons with Roman Pots phase II



- Get quasi-real photon from one proton
- Ensure dominance of γ from one identified proton by selecting **very** small t_1, while t_2 of "typical hadronic size" small t_1 ←→ large impact parameter b (UPC)
- Final state lepton pair ←→ timelike compton scattering
- Timelike Compton scattering: detailed access to GPDs including $E^{q;g}$ if have transv. target pol.
- Challenging to suppress all backgrounds

- Final state lepton pair not from γ* but from J/ψ
  - Done already in AuAu
  - Estimates for J/ψ (hep-ph/0310223)
- Transverse target spin asymmetry → calculable with GPDs

$$A_{UT} \sim \frac{\sqrt{t_0 - t}}{m_p} \frac{\mathrm{Im}(E^* H)}{|H|} \qquad t = \frac{M^2_{J/\psi}}{s}$$

- Information on helicity-flip distribution **E** for gluons golden measurement for eRHIC

Work by Elke Aschenauer, Jakub Wagner, Dieter Mueller, Markus Diehl

Another application of Roman Pots phase II

What if Collins and Sivers effects together don't explain the total SSA at forward rapidities? Investigate correlations between SSA and diffractive events!

Characteristics:

- Small Energy transfer is small
- Single Diffraction (SD) – Detect one proton in East Roman Pot and rapidity gap between proton and forward jet. FGT and TPC used for rapidity gap veto and VFGT used to detect forward tracking cluster.
- Double Diffraction (DD) – two jets with one central rapidity gap. Would look like SD (no FGT/VFGT on East STAR) without elastically scattered proton on east side Roman Pot.

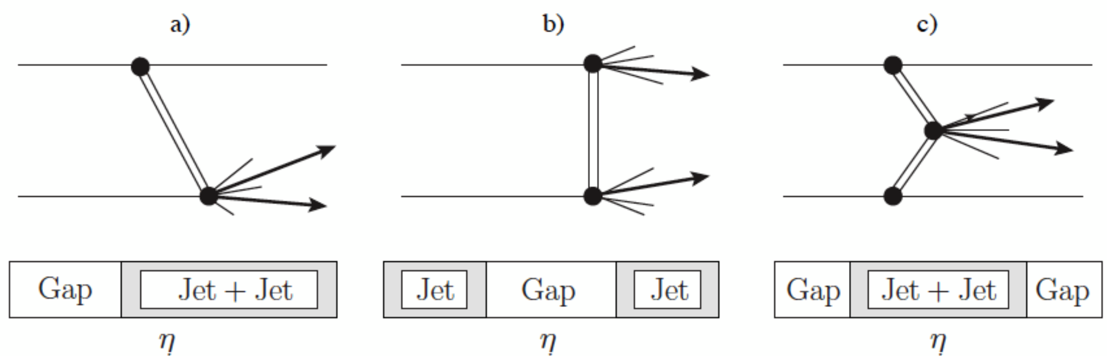


Figure 2.6: Three main colorless exchanges at hadron-hadron collider: a) single diffractive dissociation (or single diffraction), b) double diffractive dissociation c) double pomeron exchange. See text for further description.

Evolving from ***STAR*** into ***eSTAR***

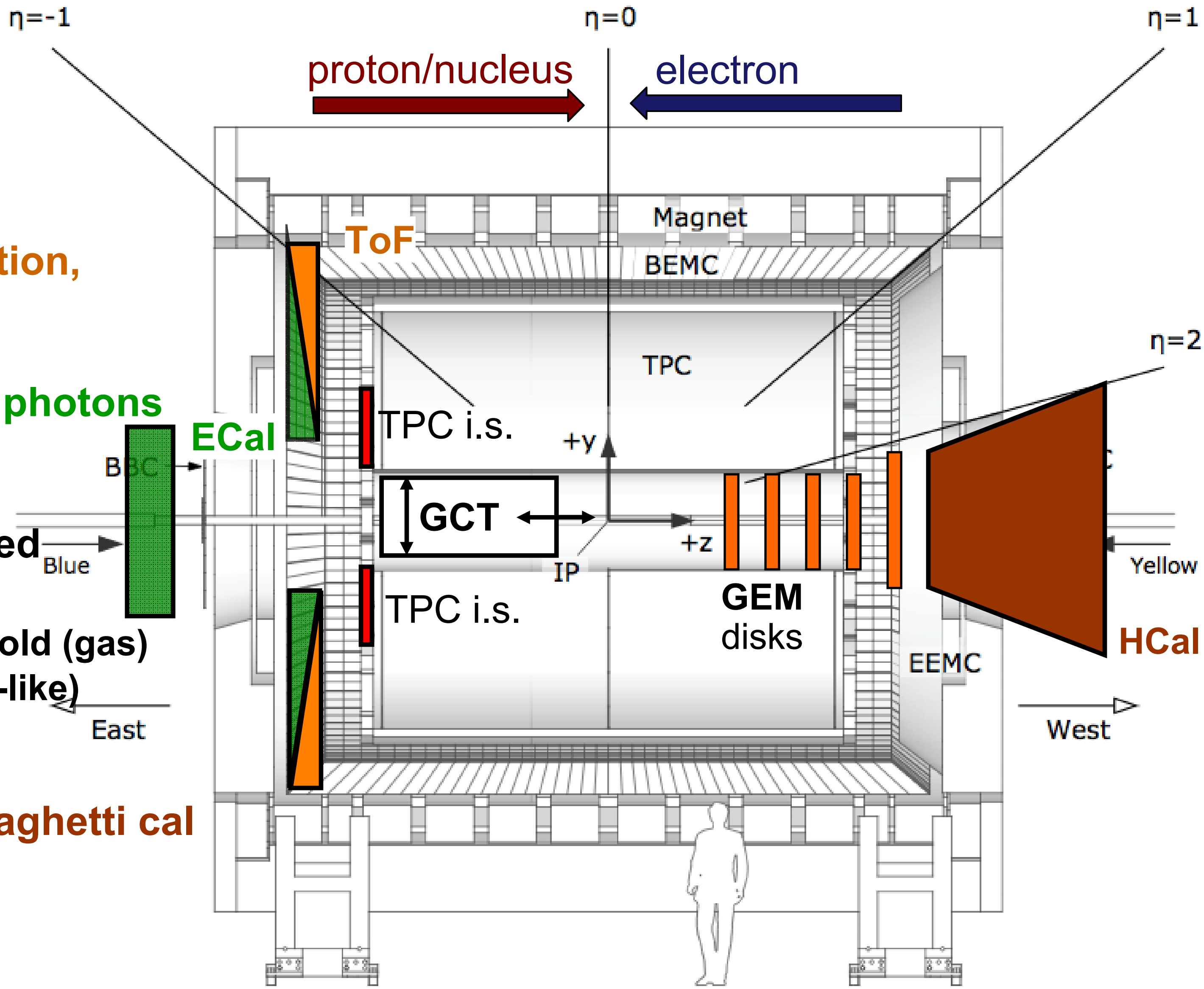
ToF: π , *K* identification, t_0, electron

ECal: electrons and photons

GCT: a compact tracker with enhanced electron capability

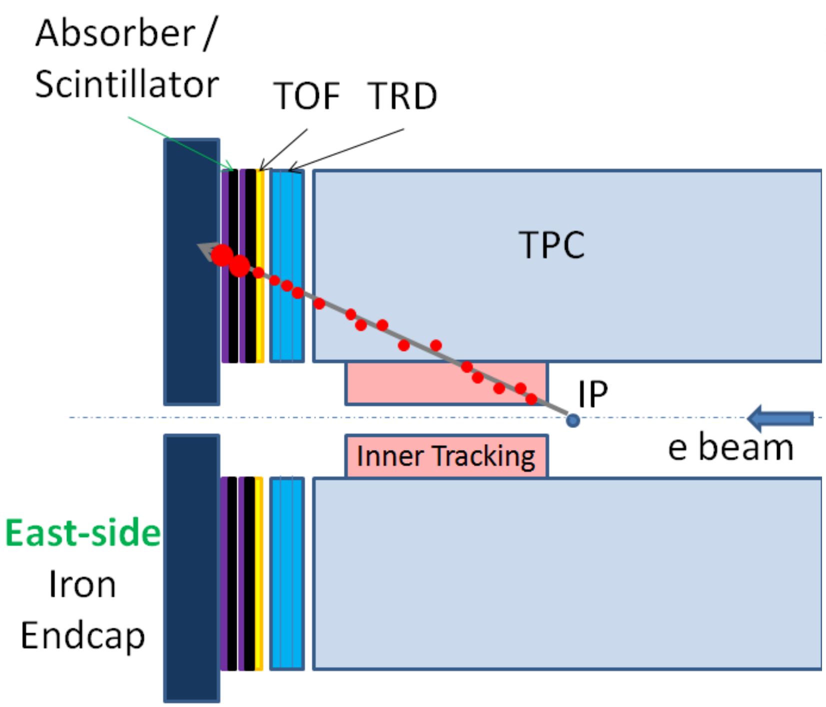
Combine high-threshold (gas) Cherenkov with TPC(-like) tracking

HCal: W powder, spaghetti cal

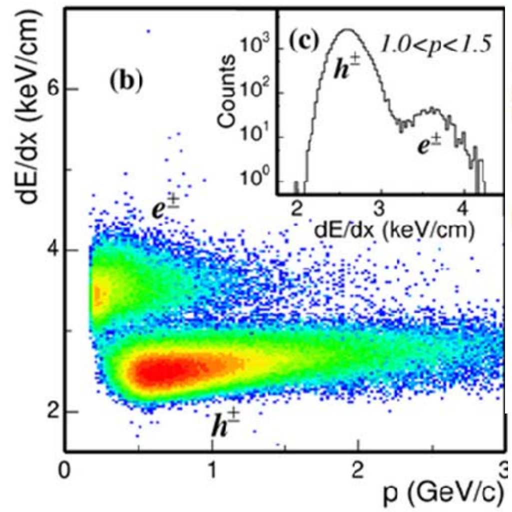


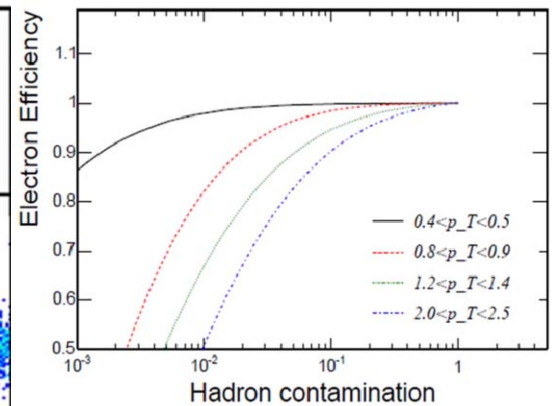
Detector philosophy & setup scheme

- Within <70cm space inside endcap
- TOF as start-time for BTOF and MTD
- TOF + dE/dx for electron ID
- TOF for hadron PID
- Extended track with precise points
- High-precision dE/dx ($Xe+CO_2$) TRD

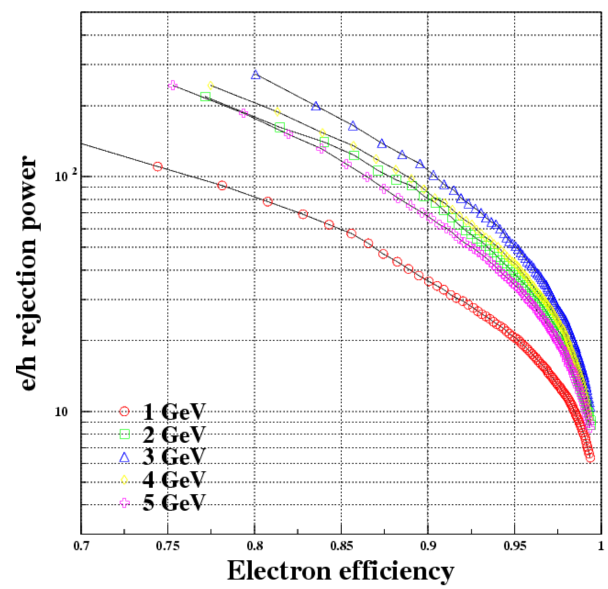


With velocity cut from TOF



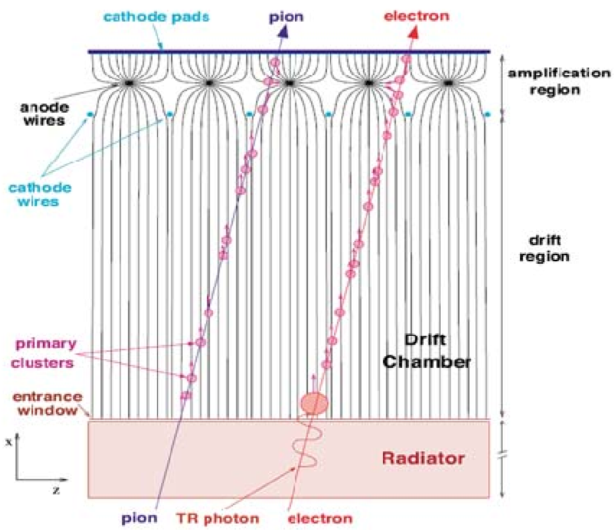


Proven at STAR mid-rapidity

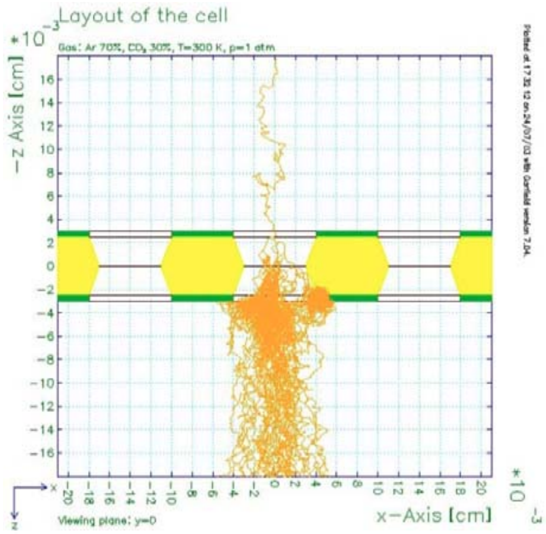


TRD e/h rejection power, based on Geant4 simulation

GEM based TRD – R&D



ALICE TRD



Readout: MWPC -> GEM

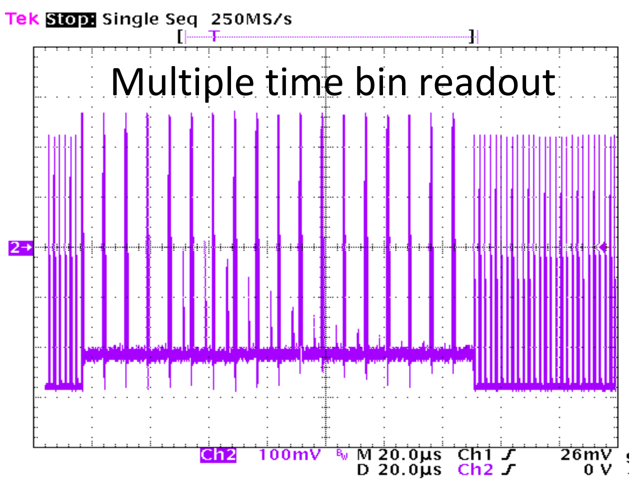
work with $Xe+CO_2$

better position resolution by GEM

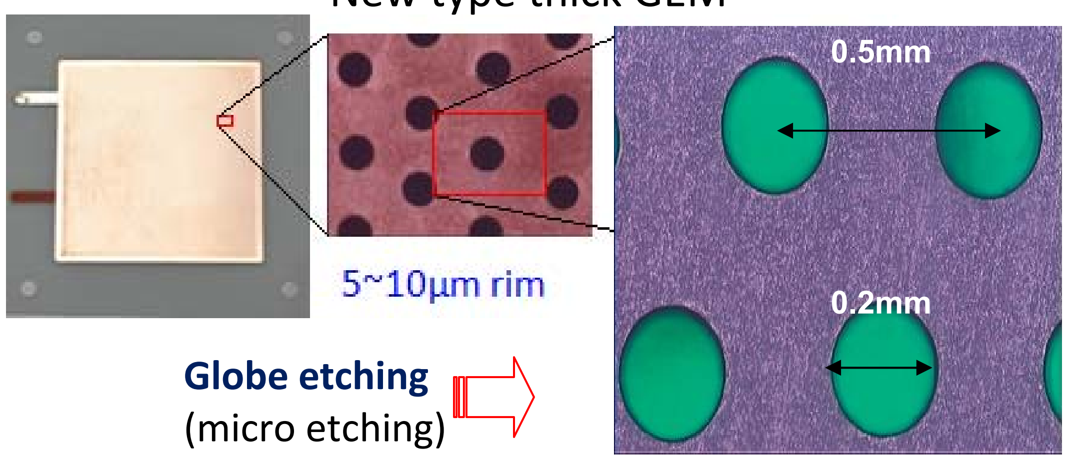
better rate capacity / space charge

Need R&D

- TRD readout structure – thin/thick GEM?
- Multiple time bin readout
- TRD gain in Xe/CO_2 and uniformity
- GEM long time stability



New type thick GEM



Globe etching
(micro etching)

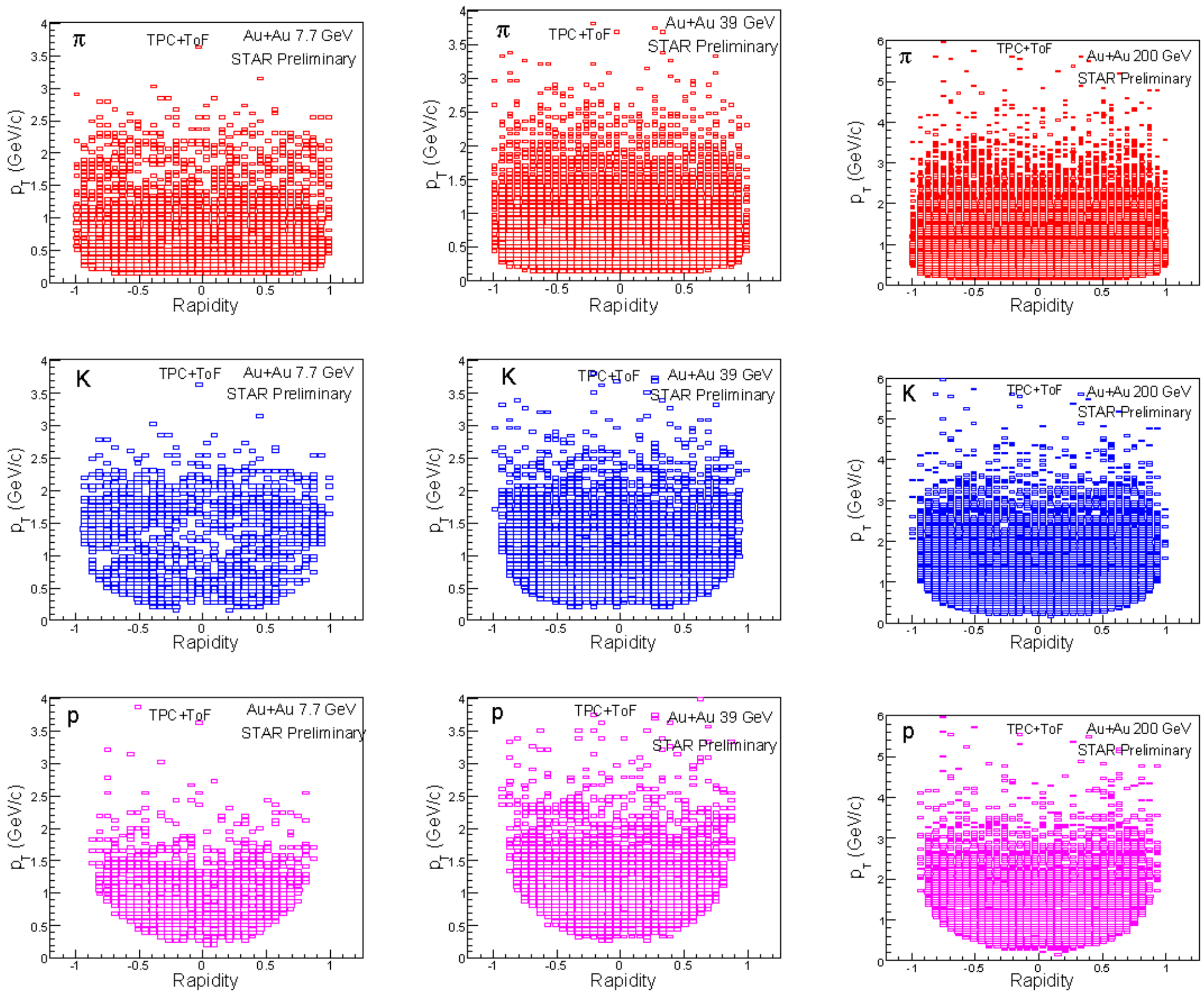
Conclusions

- The ***STAR*** Collaboration has identified **compelling physics opportunities** for the coming decade
  - Eight key questions
- The ***STAR*** Collaboration has identified the **detector upgrades** required to address these opportunities
  - TPC inner sector upgrade
  - e-cooling in RHIC
  - Forward instrumentation upgrade
  - Roman Pots phase II
  - Instrumentation for ***eSTAR*** during eRHIC phase I
  - plus the on-going projects (FGT, MTD, HFT) and improvements to the trigger and DAQ
- ***STAR*** has a vision for the future that will produce **important new results well into the eRHIC era**

Key unanswered questions

- What is the nature of QCD matter at the extremes?
  - What are the properties of the strongly-coupled system produced at RHIC, and how does it thermalize?
  - Are the interactions of energetic partons with QCD matter characterized by weak or strong coupling? What is the detailed mechanism for partonic energy loss?
  - Where is the QCD critical point and the associated first-order phase transition line?
  - Can we strengthen current evidence for novel symmetries in QCD matter and open new avenues?
  - What other exotic particles are produced at RHIC?
- What is the partonic structure of nucleons and nuclei?
  - What is the partonic spin structure of the proton?
  - How do we go beyond leading twist and collinear factorization in perturbative QCD?
  - What is the nature of the initial state in nuclear collisions?

Advantage of collider operation



- Broad and uniform acceptance **independent of collision energy**