STAR Science for the Coming Decade

The *STAR* Decadal Plan

Carl Gagliardi
for the
STAR **Collaboration**

Outline

- Introduction
- ***STAR*** through mid-decade
- ***STAR*** in the longer term
- ***eSTAR*** at eRHIC phase 1
- RHIC during the LHC era

Remarkable discoveries at RHIC

The first six years

- A+A collisions
  - Jet quenching
  - Perfect liquid
  - Number of constituent quark scaling
  - Heavy-quark suppression
- Polarized p+p collisions
  - Large transverse spin asymmetries in the pQCD regime
- d+A collisions
  - Possible indications of gluon saturation at small *x*

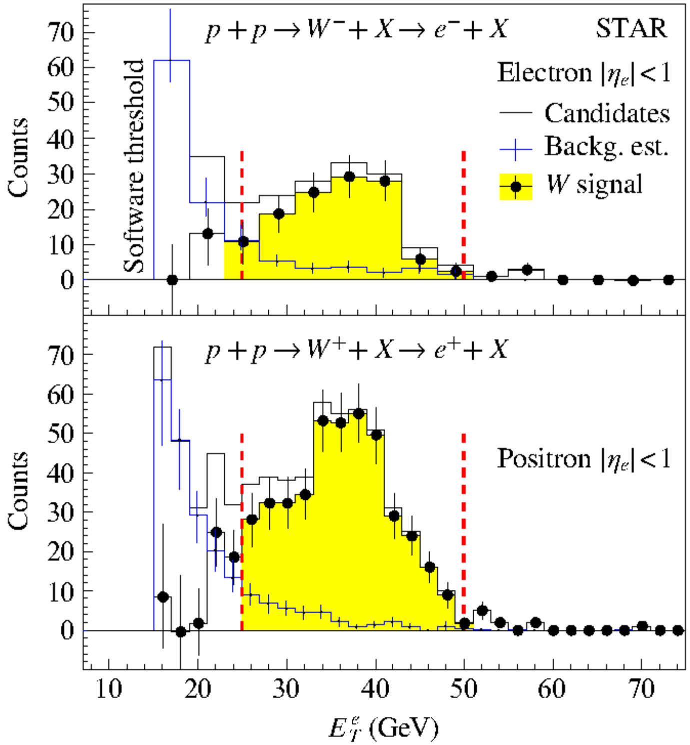
The discoveries continue

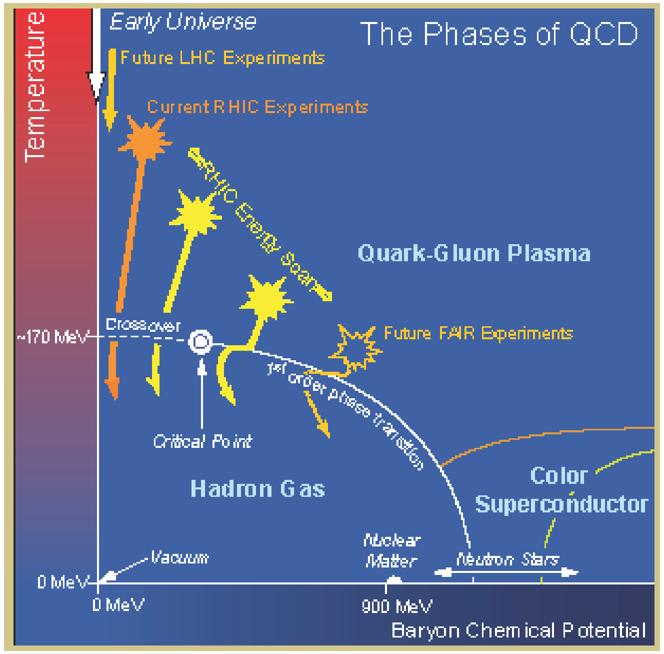
- A+A collisions
  - First ever observations of an anti-hypernucleus and anti-alpha
  - Azimuthal charged-particle correlations that may arise from local strong parity violation
  - Even b-quark production is suppressed in central Au+Au collisions

- Polarized p+p collisions
  - Most precise constraints to date on the polarization of the gluons

- d+A collisions
  - Dramatic broadening of forward π^0-π^0 correlations in central d+Au
    - Clearest indication to date that the onset of gluon saturation is accessible at RHIC

New research areas continue to open

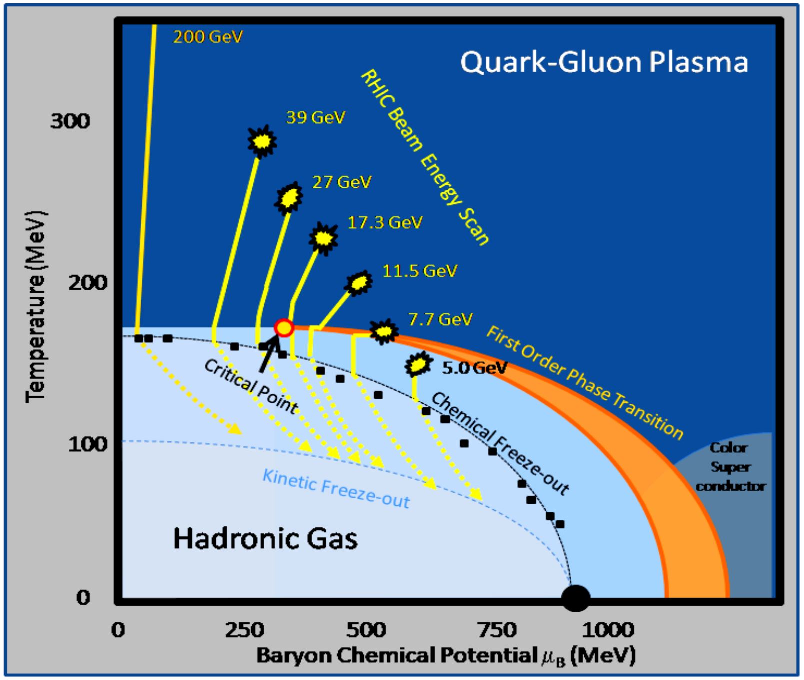




- ***STAR*** **and RHIC** continue to **perform very well** under extreme conditions
  - Charge-sign separation to p_T ~ 50 GeV
  - Au+Au collisions at 7.7 GeV

RHIC: eight key unanswered questions

Hot QCD Matter



1: Properties of the sQGP

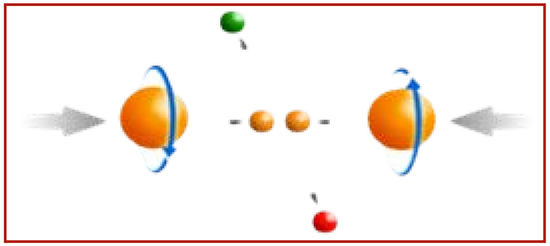
2: Mechanism of energy loss:
weak or strong coupling?

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

4: Novel symmetry properties

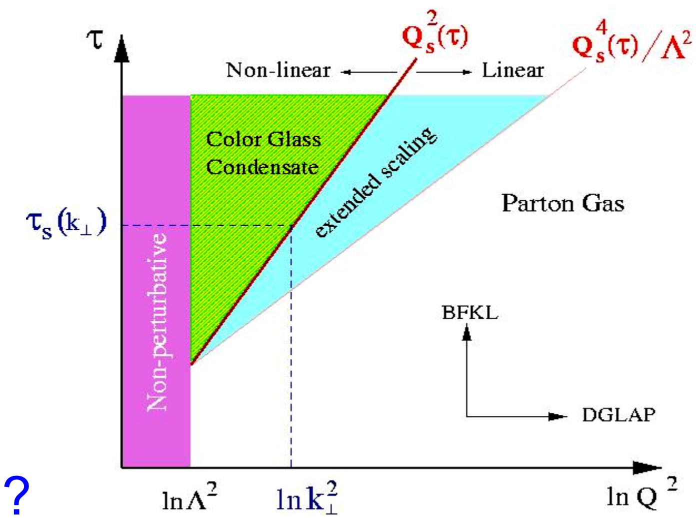
5: Exotic particles

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?

How to answer these questions

- Hot QCD matter: high luminosity RHIC II (fb^{-1} equivalent)
  - Heavy Flavor Tracker: precision charm and beauty
  - Muon Telescope Detector: e+μ and μ+μ at mid-rapidity
  - Trigger and DAQ upgrades to make full use of luminosity
- Phase structure of QCD matter: energy scan
  - Electron cooling if lowest beam energies most promising
- Near-term upgrades for p+p collisions
  - Forward GEM Tracker: flavor-separated anti-quark polarizations
  - Forward Hadron Calorimeter: strange quark polarization
  - Roman Pots phase II: search for glueballs
- Nucleon spin and cold QCD matter: high precision p+p and p+A, followed by e+p and e+A
  - Major upgrade of capabilities in forward direction
  - Devote the time to explore p+A, not d+A
  - Existing mid-rapidity detectors well suited for portions of the initial e+p and e+A program, but must extend detection capability to larger rapidities

Summary of the plan

	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	ϒ, $J/\psi \to ee$, m_{ee}, v_2	ϒ, $J/\psi \to \mu\mu$, Charm v_2, R_{CP}, 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*-μ corr, μ-μ 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}		$\bar{\Lambda}$ D_{LL}/D_{TT}, polarized DIS & SIDIS
(7) QCD beyond collinear fact	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

Measurements listed when they first become possible

Many will continue in future periods

STAR through mid-decade

	Near term (Runs 11-13)	Mid-decade (Runs 14-16)	
Colliding systems	*p*+*p*, A+A	*p*+*p*, A+A	
Upgrades	FGT, FHC, RP, DAQ10K, Trigger	HFT, MTD, Trigger	
(1) Properties of sQGP	Υ, $J/\psi \rightarrow ee$, m_{ee}, v_2	Υ, $J/\psi \rightarrow \mu\mu$, Charm v_2, R_{CP}, corr, Λ_c/D ratio, μ-atoms	
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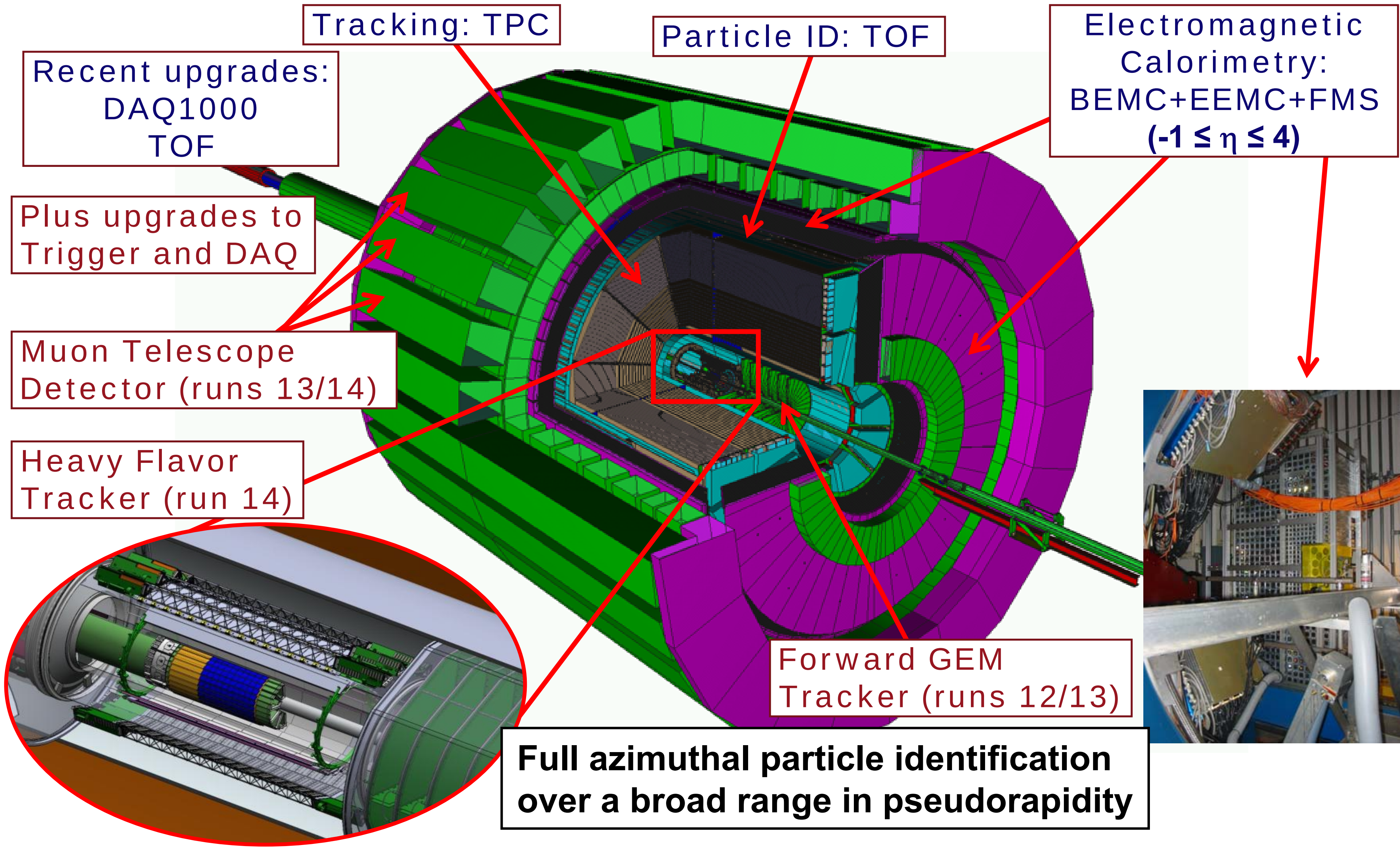
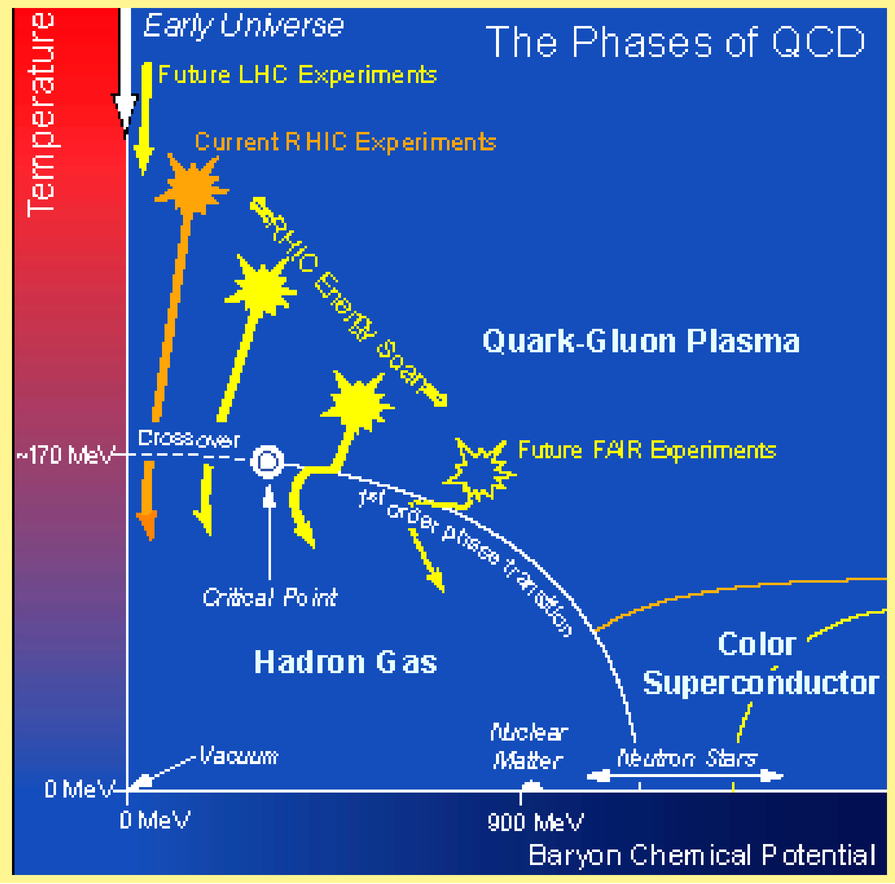
Mid-rapidity ***STAR***: now to mid-decade



Full azimuthal particle identification over a broad range in pseudorapidity

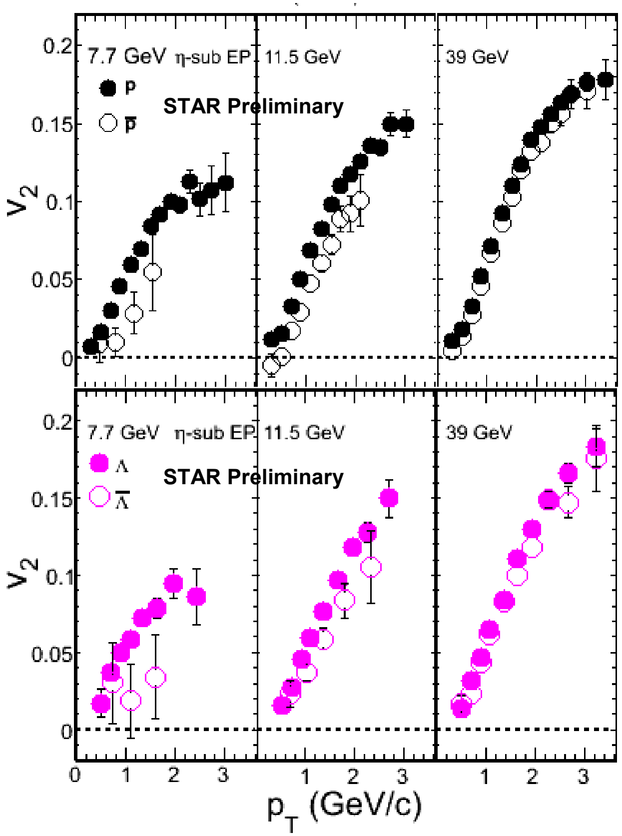
A beautiful detector gets even better!

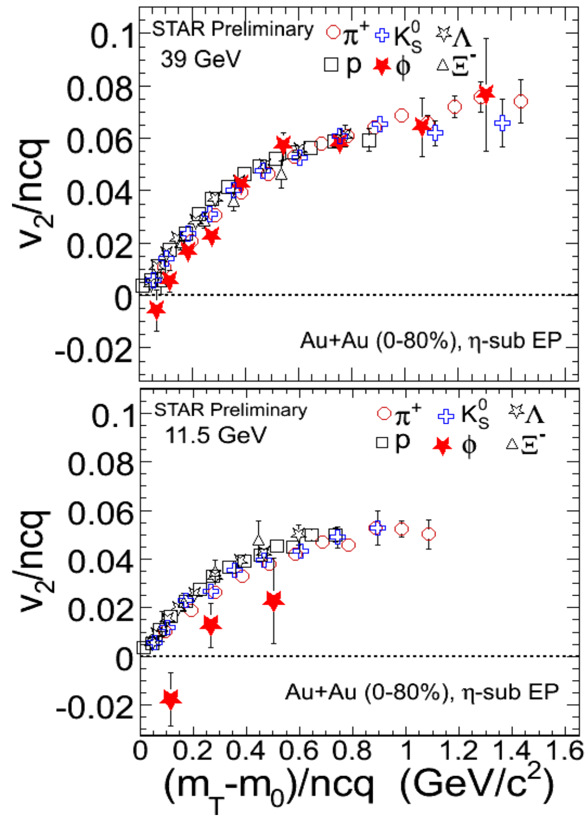
Where is the QCD critical point?

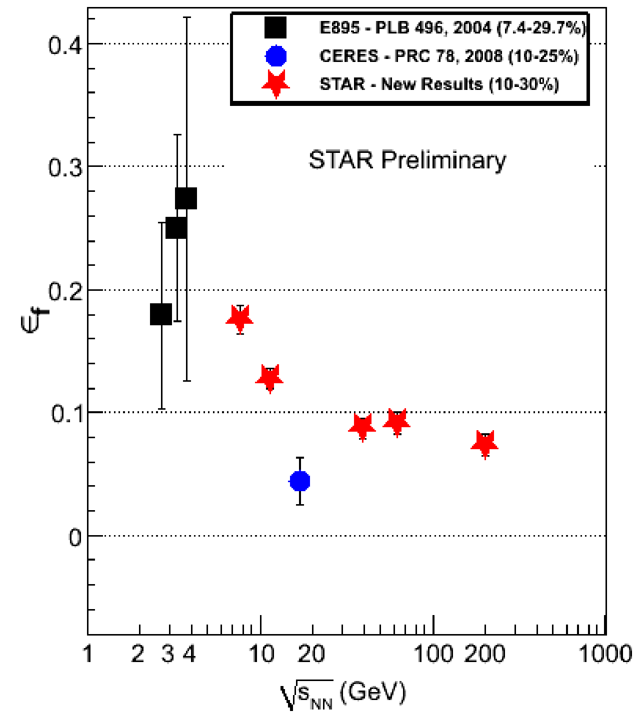


- The **QCD critical point** and the **1st order phase transition line** represent **landmarks on the QCD phase diagram**

Narrowing down the region of interest

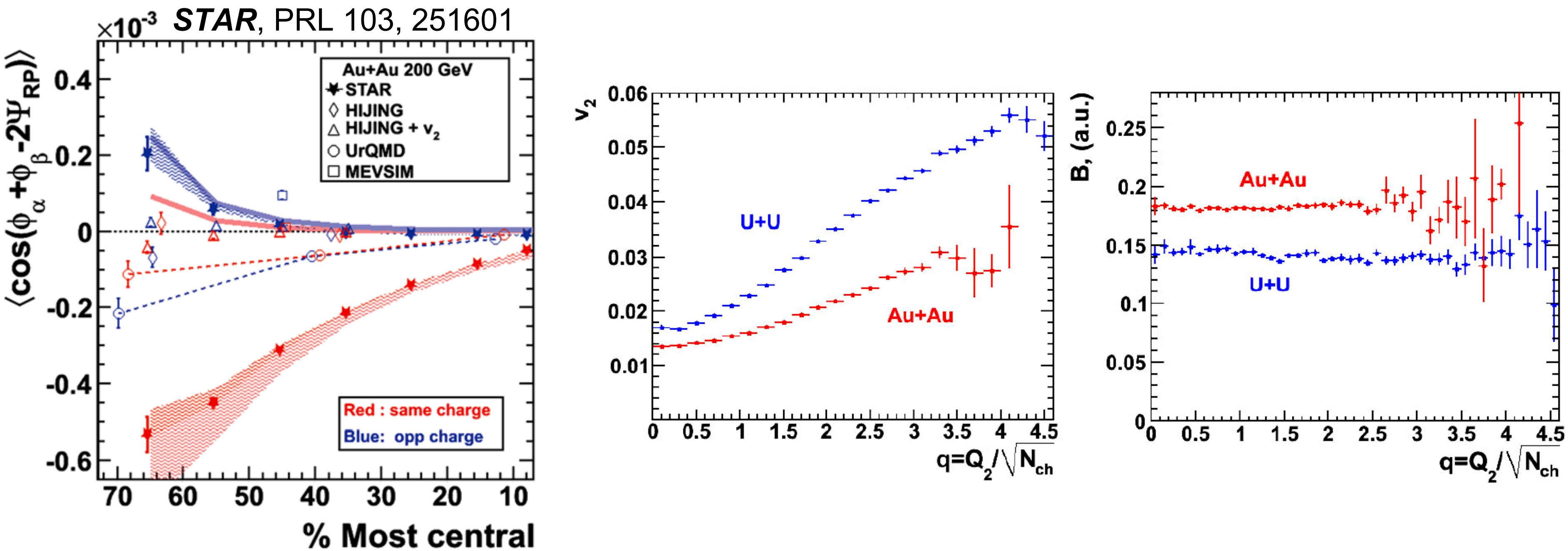






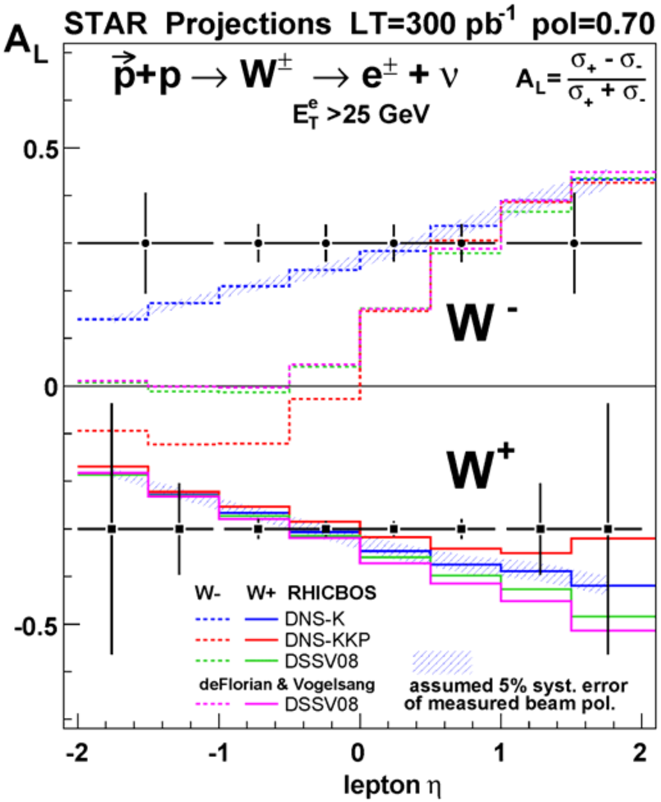
- 39, 62, and 200 GeV collisions are qualitatively similar
- Even extends to LHC energies
- But **many changes** appear **at lower energies**
- Narrowing down the region of interest during Runs 11/12
- Future: **need detailed study of the key region**
  - Finer energy steps with higher statistics

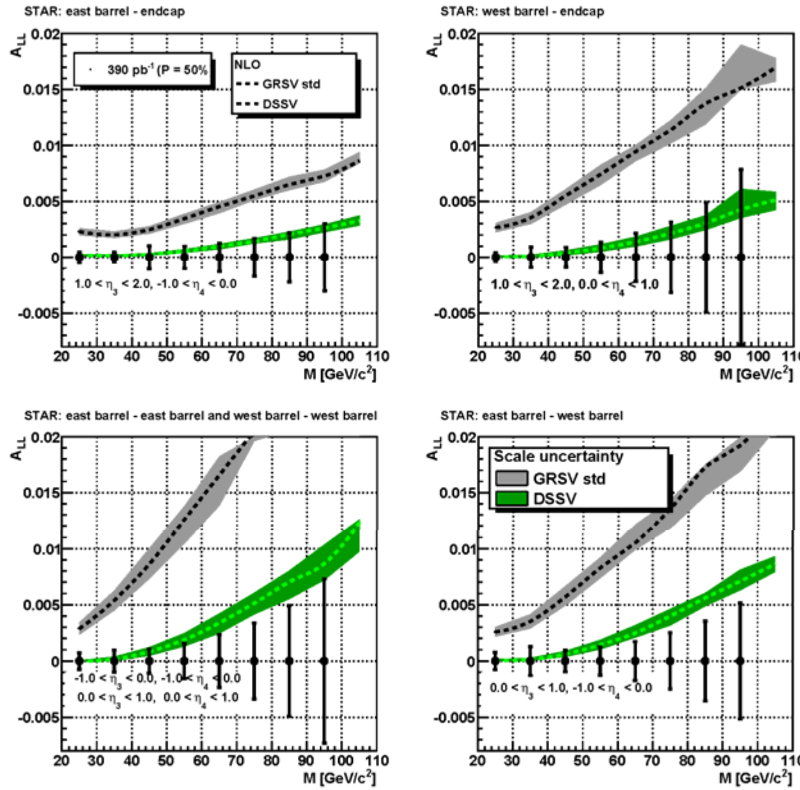
Novel symmetries: local strong parity violation



- Transitions between domains with different topological charge may induce parity violation in the dense matter
  - Similar transitions (at much higher energies) might have produced the matter-antimatter asymmetry in the early universe
- Magnetic field in A+A plays a key role: **chiral magnetic effect**
- **Crucial** to verify if parity violation is the **correct explanation**
  - Do results from Beam Energy Scan point to a turn-off?
  - **U+U collisions:** collisions with **more v_2** and **less B field** than Au+Au

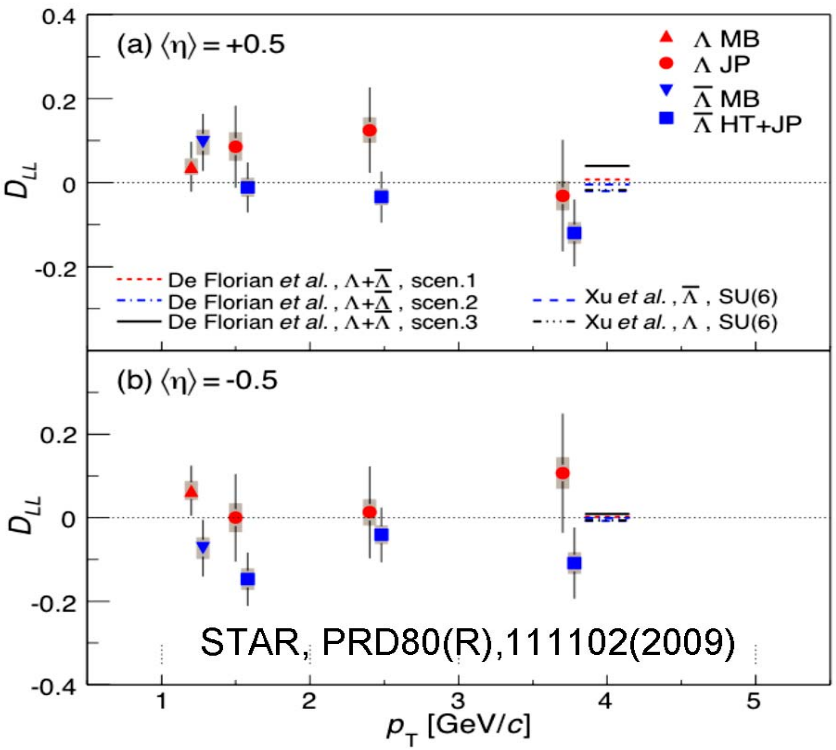
Anti-quark and gluon helicity distributions

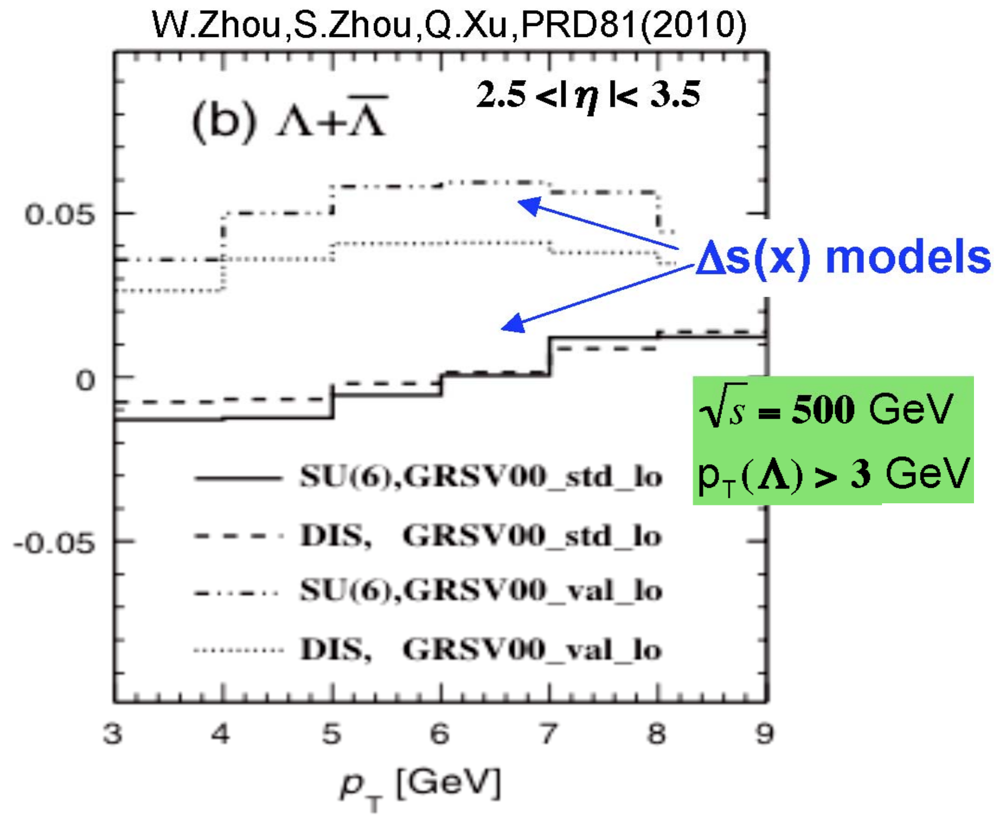




- *W* measurement will significantly reduce uncertainties on anti-quark polarizations
  - At mid-rapidity, ***STAR*** just needs the data
  - FGT essential for the forward *W*'s
- Inclusive jet and di-jet A_{LL} will extend our knowledge of gluon polarization to smaller *x*
  - Extend measurements to forward rapidities

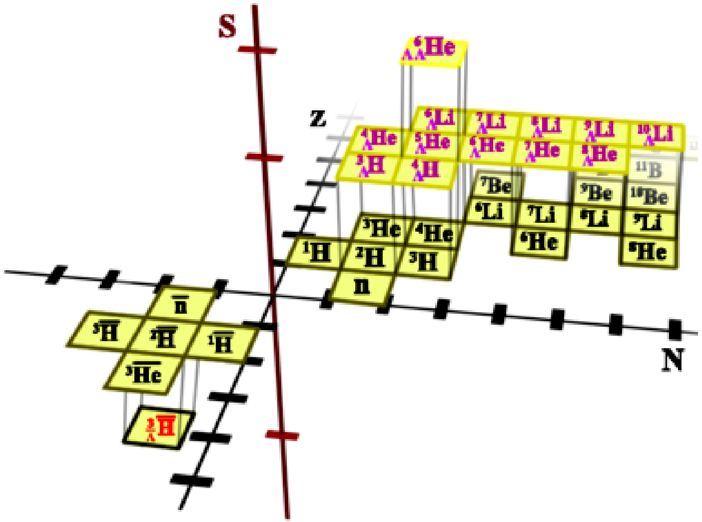
Accessing strange polarization with Λ

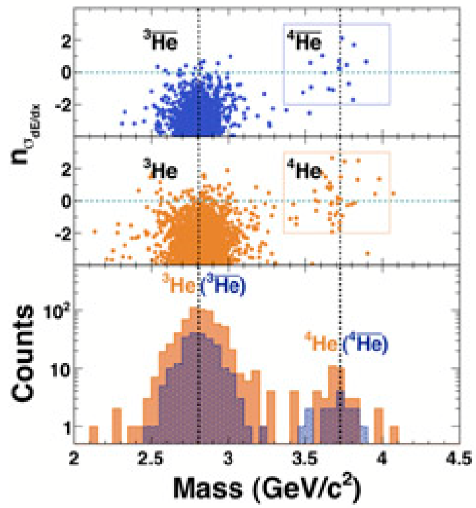


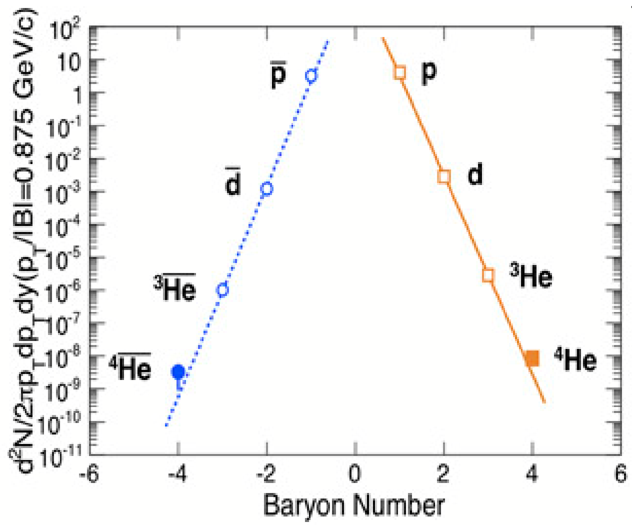


- ***STAR*** has performed initial Λ D_{LL} measurements at mid-rapidity
  - Provides access to strange quark helicity distribution
  - Most interesting with quite high p_T Λ (trigger and stat limited)
- Similar measurements at forward rapidity are **very promising**
  - Requires Forward Hadron Calorimeter

Exotic particles at RHIC

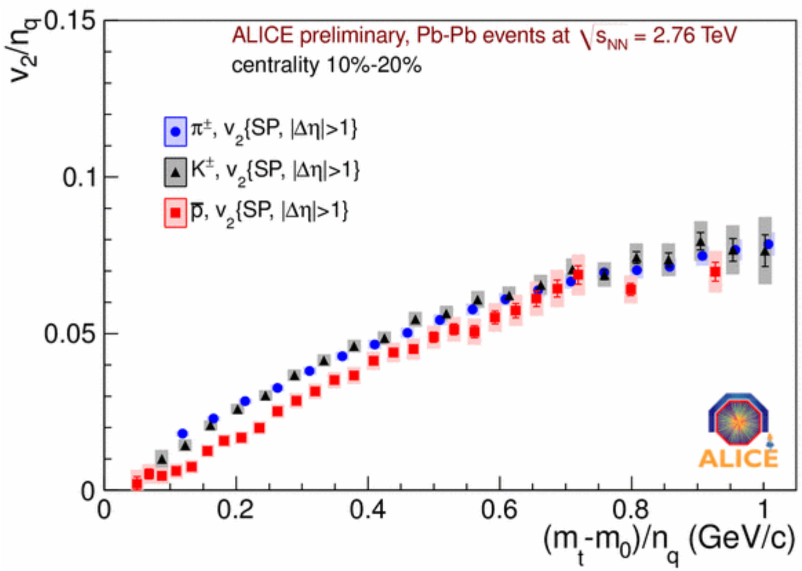


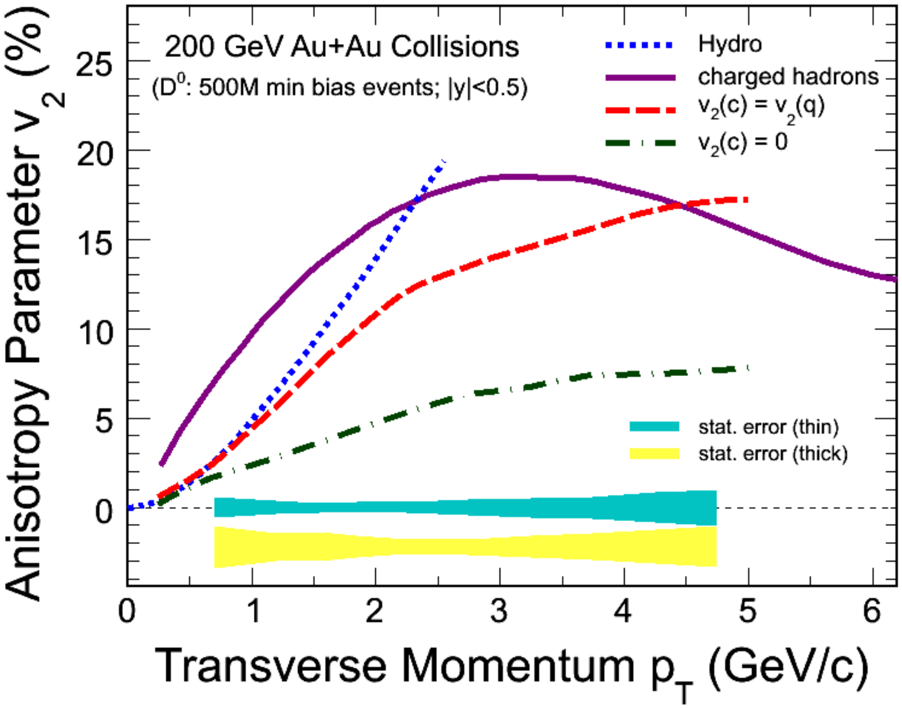




- ***STAR*** has discovered the first anti-hypernucleus and the anti-alpha
- What else is out there?
  - Heaviest anti-matter and anti-hypernuclei
  - π-μ, *K*-μ, p-μ, $\bar{p}$-μ atoms to isolate the thermal lepton distribution
  - Rare decays
  - Glueballs
  - Di-baryons
  - ….
- Various measurements depend upon DAQ 10K, MTD, HFT, and the Roman Pots phase II upgrades

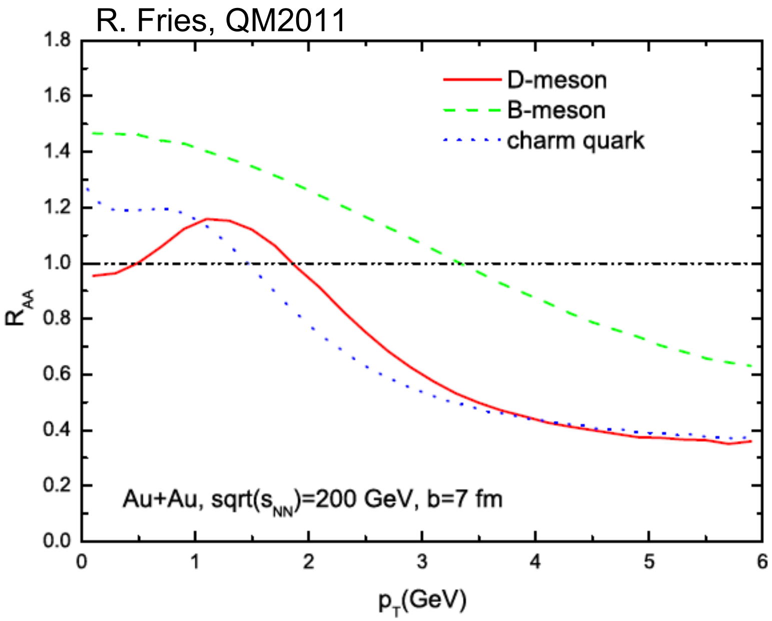
Properties of sQGP: charm flow

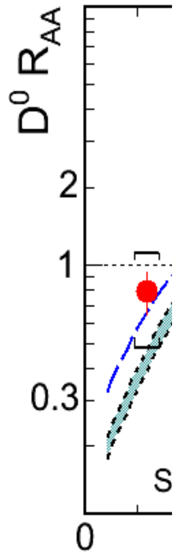


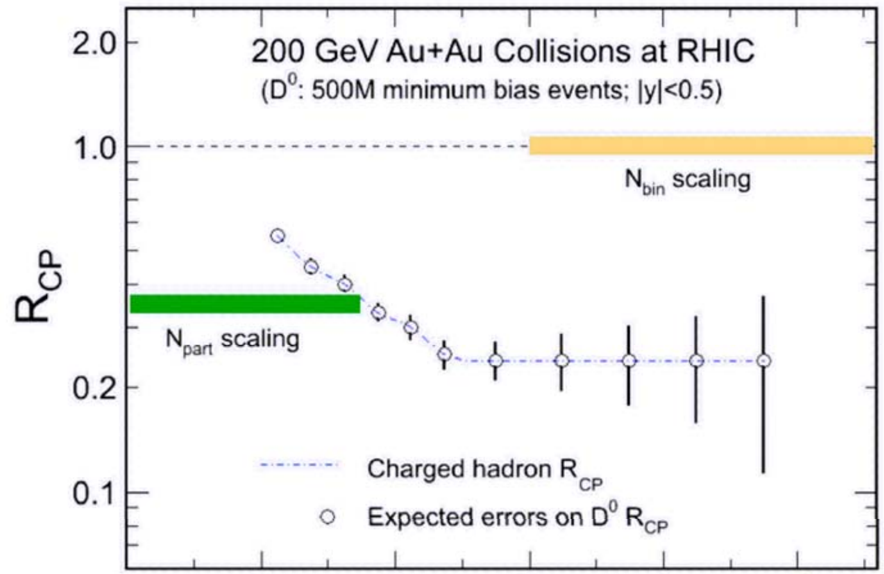


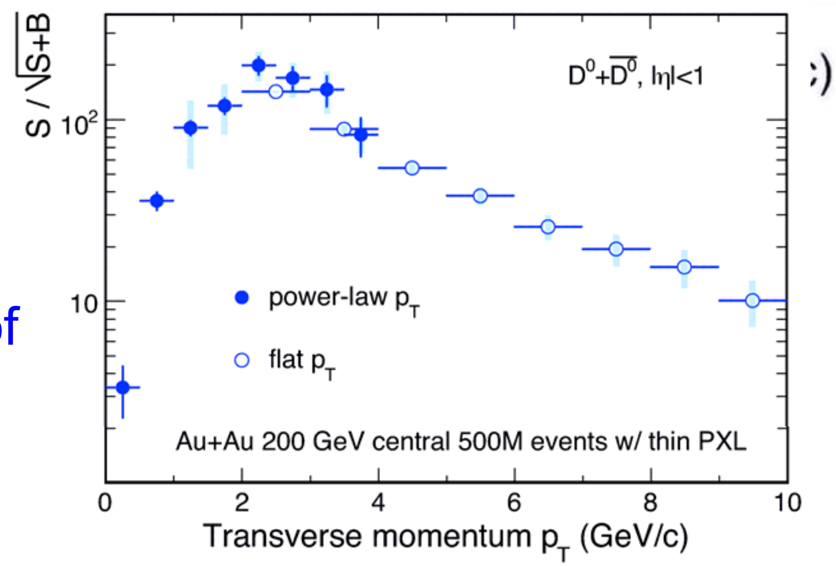
- Does charm flow **hydrodynamically**?
  - Low p_T is the hydro domain
- Heavy Flavor Tracker: unique access to **low-p_T fully reconstructed charm**

Charm diffusion: low p_T matters



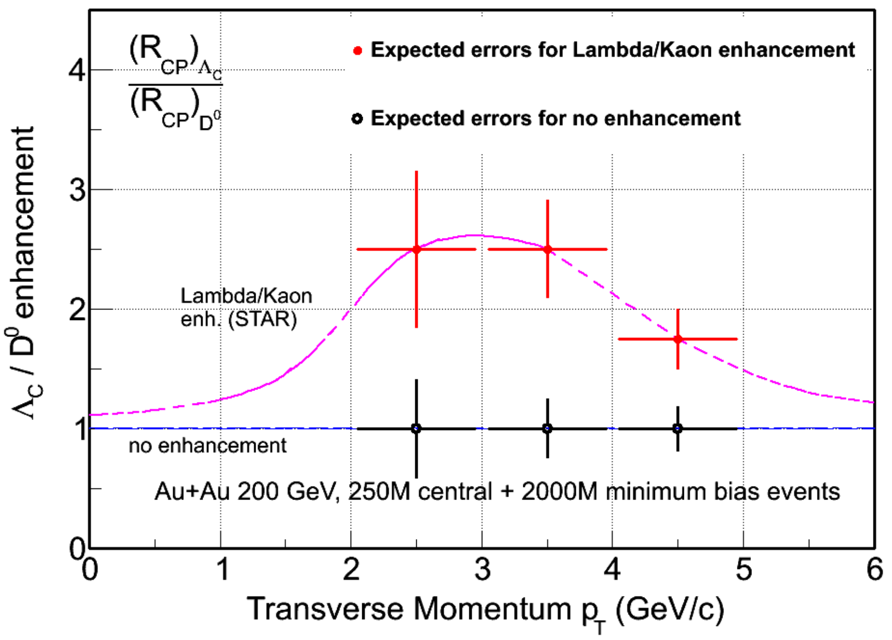


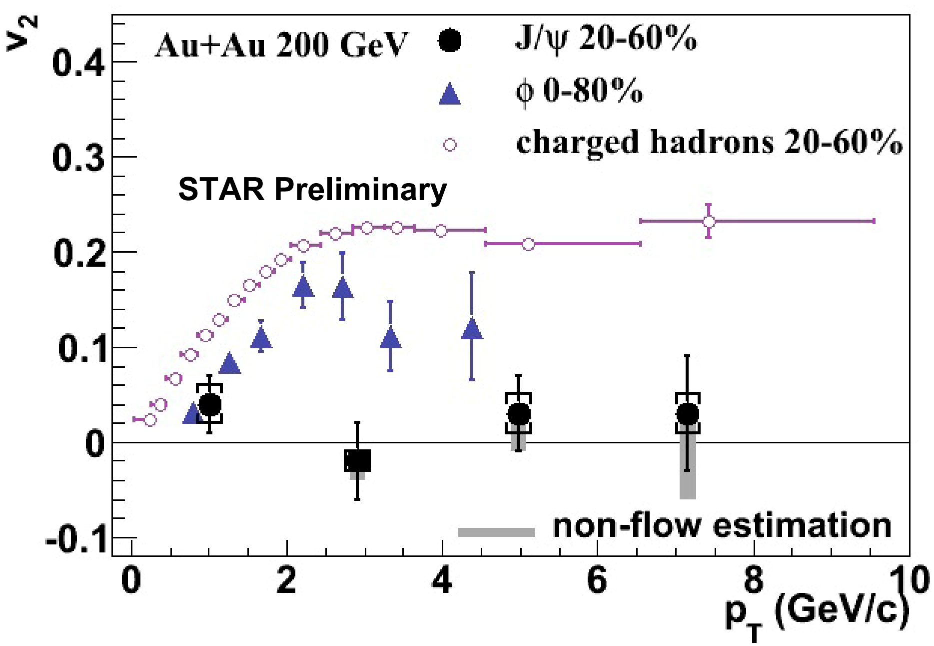




- Critical region for testing diffusion and hydrodynamic flow: p_T ~ 1 – 3 GeV/c
- ***STAR*** is just starting the exploration of this region
- ***STAR*** HFT is **optimized** for this

More to charm than just *D*'s



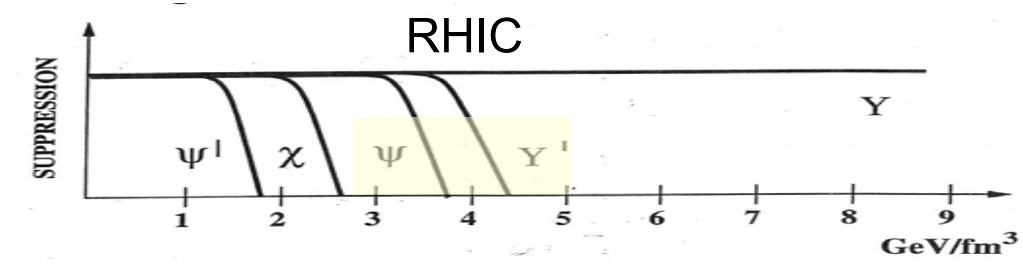


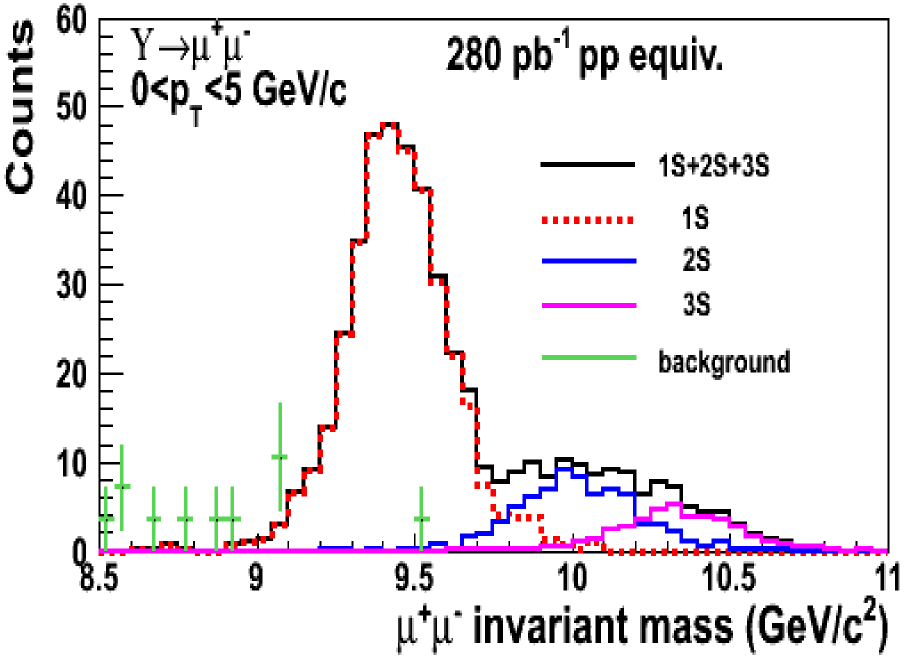
- Are charmed hadrons produced via **coalescence**?
  - Heavy Flavor Tracker: unique access to charm baryons
  - Would force a **significant reinterpretation** of non-photonic electron R_{AA}
- Muon Telescope Detector: precision measurements of *J/ψ* flow

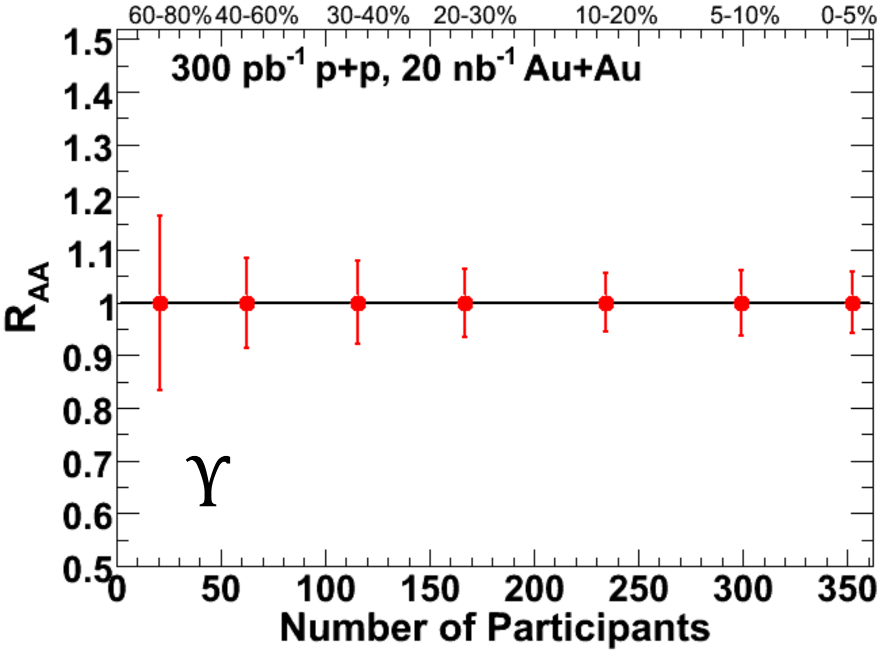
Properties of sQGP: Upsilon

What quarkonia states dissociate at RHIC energy densities?

What is the energy density?

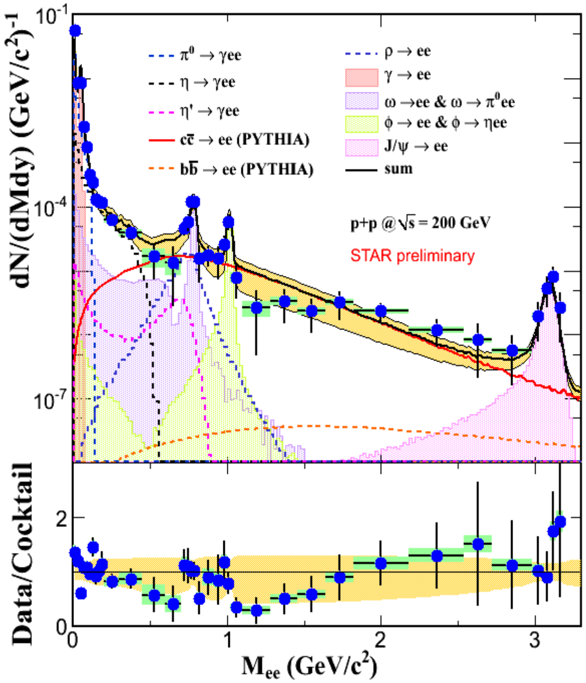


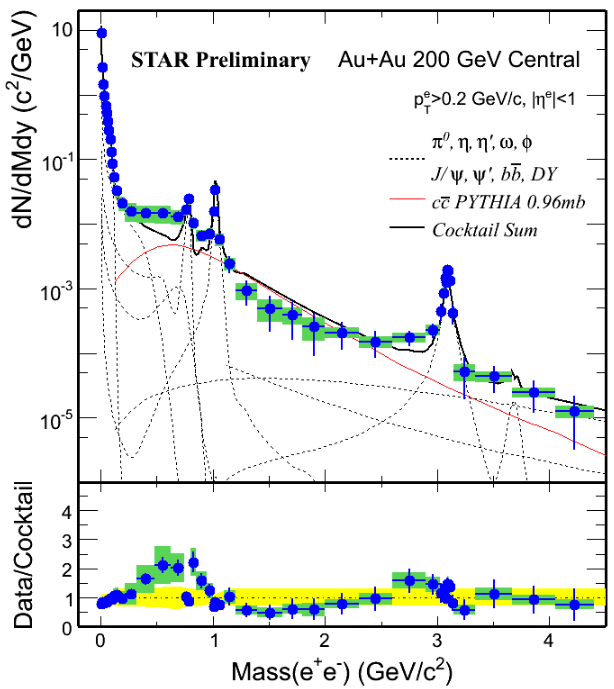


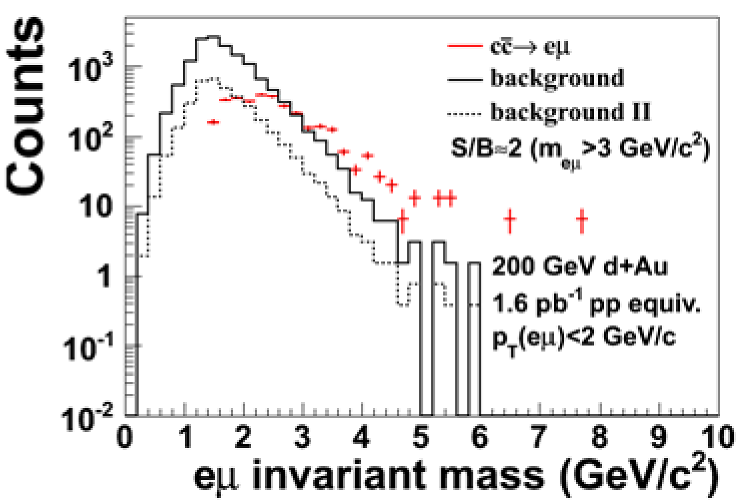


- Muon Telescope Detector: dissociation of ϒ, separated by state
  - At RHIC: small contribution from coalescence, so interpretation clean
  - No contribution of Bremsstrahlung tails, unlike electron channel

Properties of sQGP: dileptons







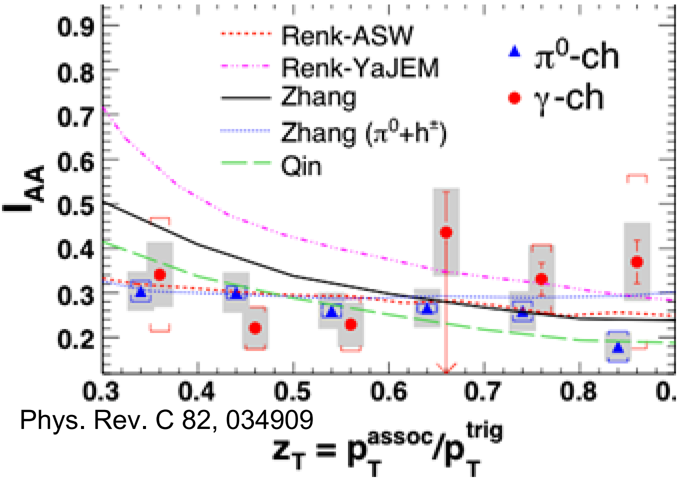
- Penetrating probe of the bulk medium
- Correlated charm dominates 1-3 GeV mass region
  - Large uncertainties in pp
  - Different in A+A?
- Address with:
  - HFT: D^0, displacement
  - MTD: e-μ correlations

Mechanism of partonic energy loss

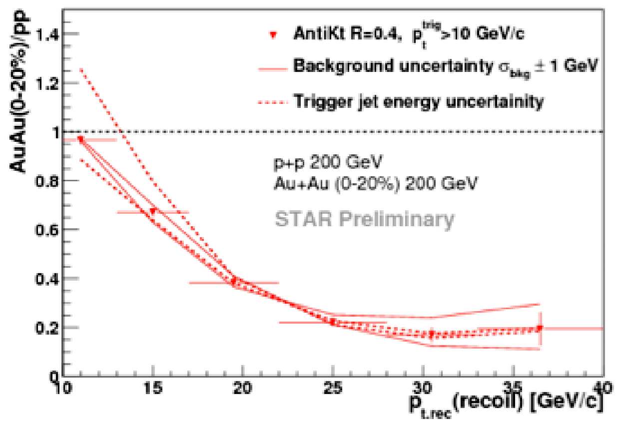
- Is the mechanism predominantly radiative or collisional?
  - Detailed, fully kinematically constrained measurements via gamma-hadron and full jet reconstruction
  - Pathlength dependence, especially with U+U
- Does the mechanism depend on the parton type?
  - Gluons: particle identification, especially baryons
  - Light quarks: gamma-hadron
  - Heavy quarks: Heavy Flavor Tracker and Muon Telescope Detector
- Does the energy loss depend on the parton energy and/or velocity?
  - High precision jet measurements up to 50 GeV
  - Vary velocity by comparing light quarks, charm, and bottom
- Example of **complementary to LHC**
  - RHIC: primarily light quarks for 30 to 50 GeV jets
  - LHC: gluons

To date: jets and γ-hadron in A+A

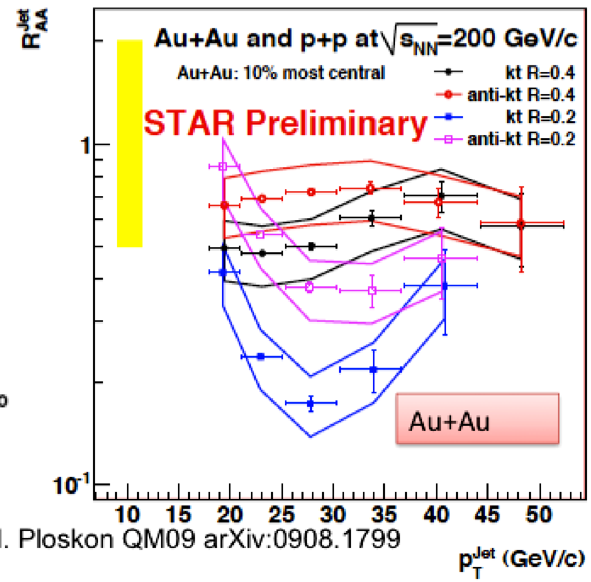
Triggered: ~0.3 nb^{-1}



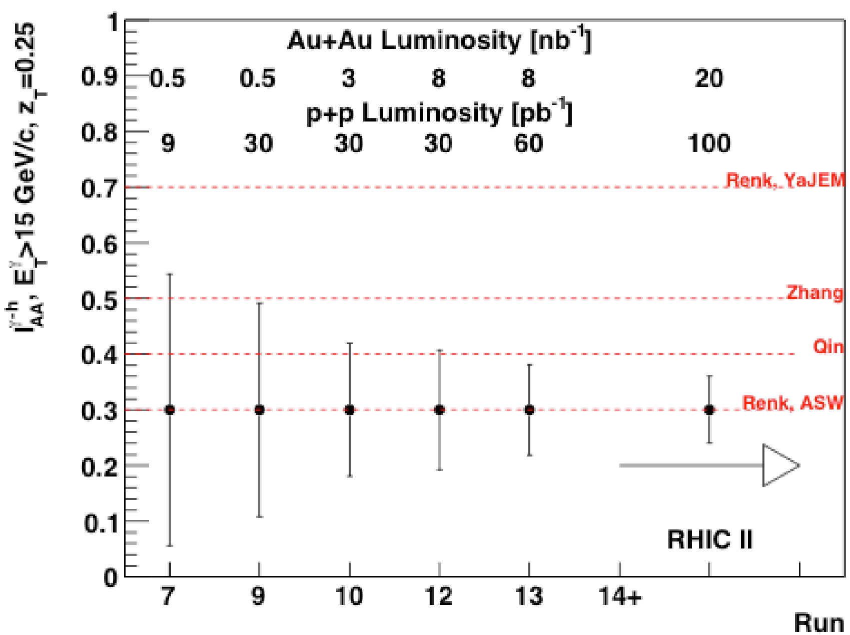
Phys. Rev. C 82, 034909



Untriggered: ~0.01 nb^{-1}

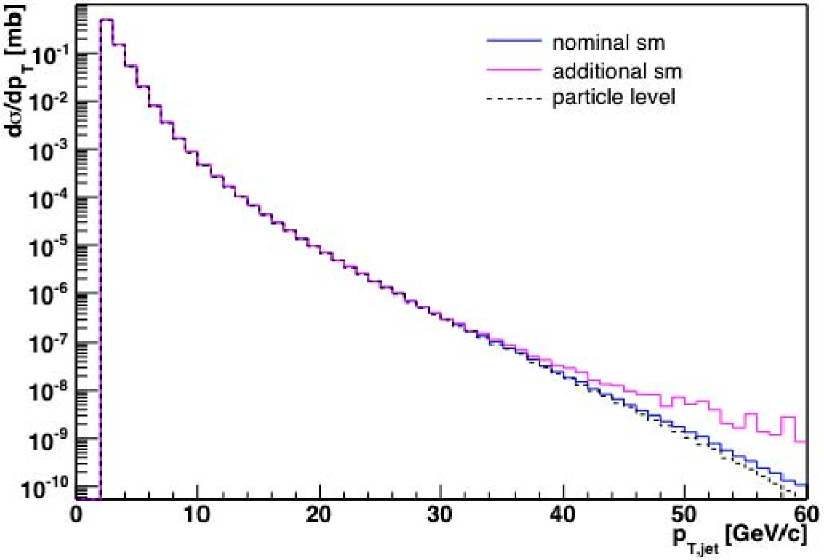


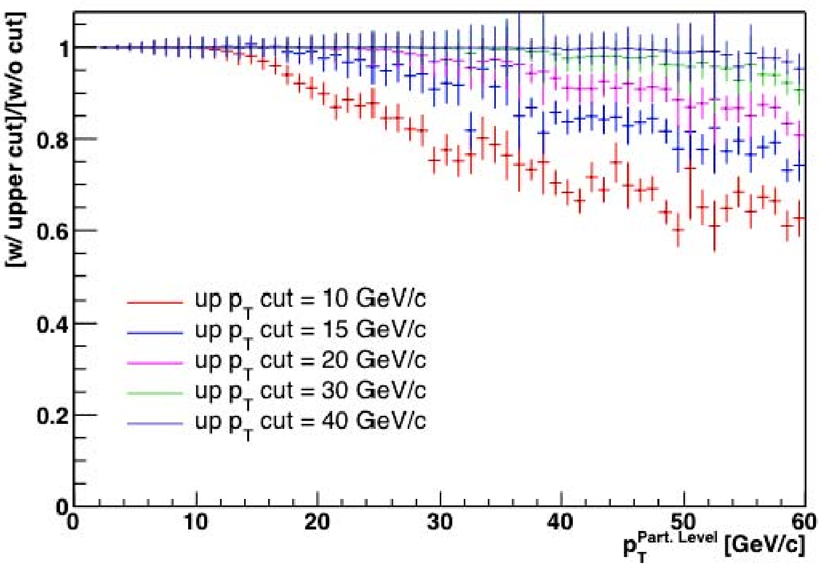
M. Ploskon QM09 arXiv:0908.1799



- Beginning results indicative, but far from final word
- **Huge increase in significance** with **trigger upgrades+luminosity**

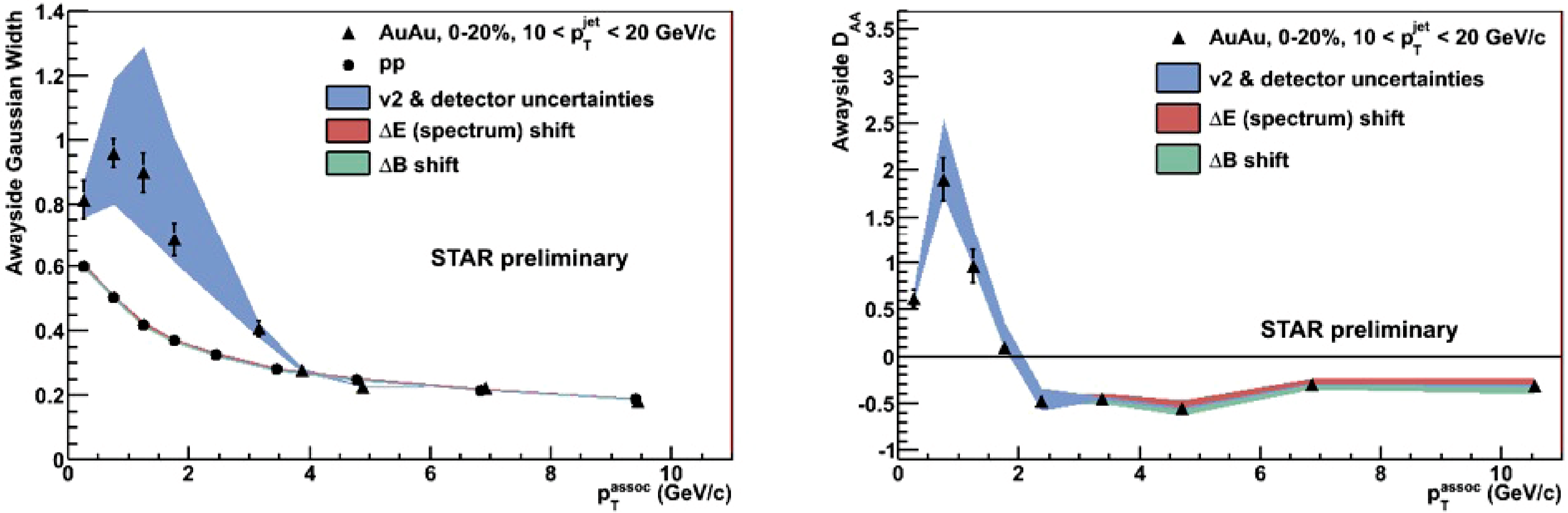
Jet capabilities in A+A: high p_T





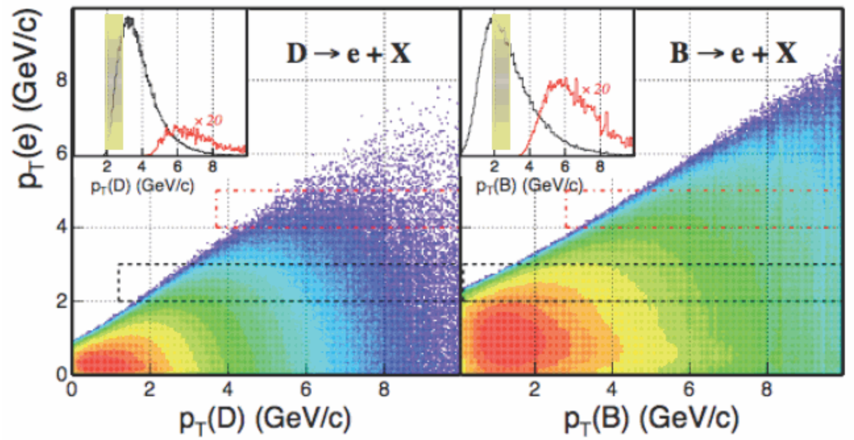
- Smearing of high momentum charged hadrons
  - Evaluated using *W* events
  - Under control to ~30 GeV/c
  - Hard cutoff in hadrons: small loss of jets that fragment hard
  - Dominant uncertainty: fluctuations in the underlying event
- Sufficient statistical reach out to ~50 GeV for precision measurements
  - Large unbiased datasets
  - Trigger upgrades to lessen bias with walking jet patches

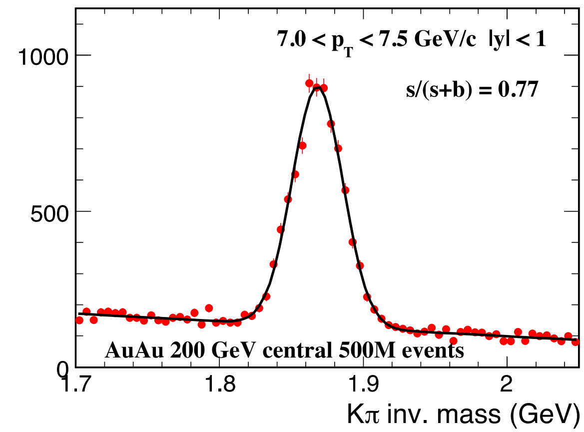
Jets in A+A: low p_T

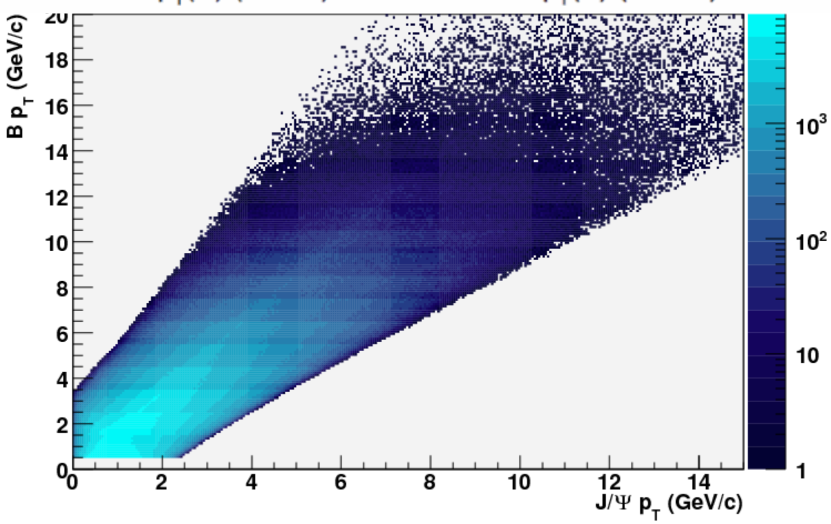


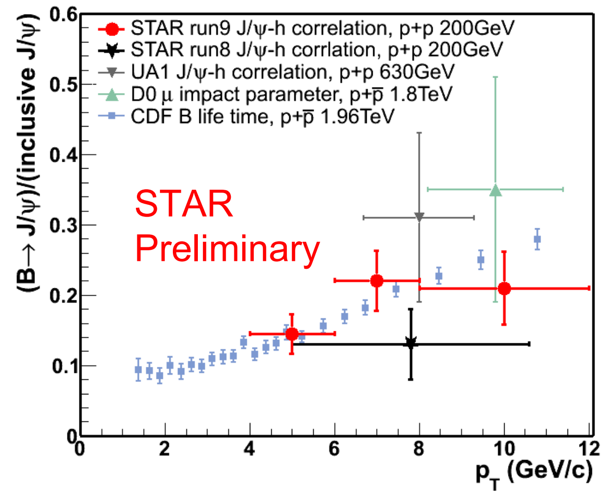
- Both CMS and ATLAS report that jet fragmentation in A+A looks like that in p+p
  - Measurements performed with significant low-p_T cut offs
- ***STAR*** sees the "lost" energy
  - Resides in low p_T hadrons
  - Spread over a broad angular region on the away side

Mass dependence via Heavy Quarks









- What is the dependence of energy loss on parton mass?
  - Key tools: heavy quarks with precise kinematic reconstruction
  - Key technology: Heavy Flavor Tracker and Muon Telescope Detector

STAR in the longer term

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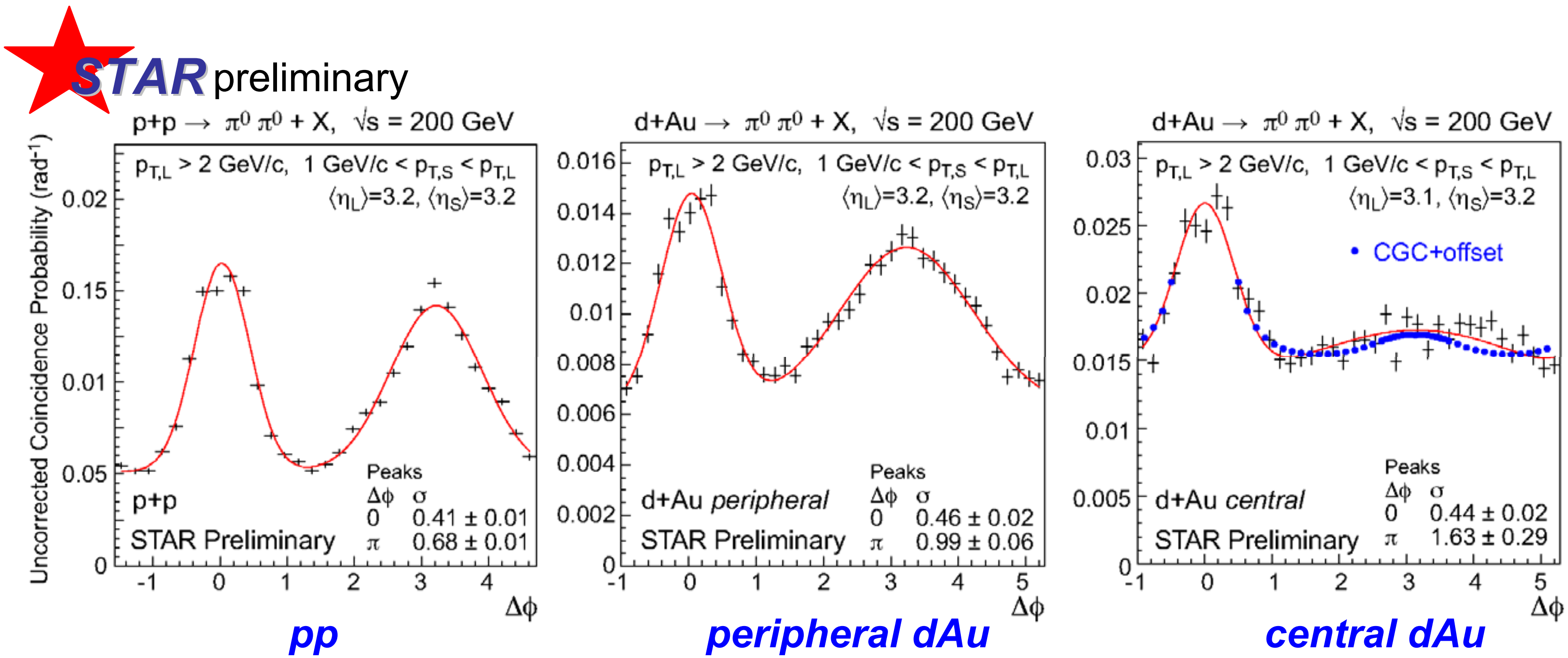
Cold QCD matter – the initial state at RHIC



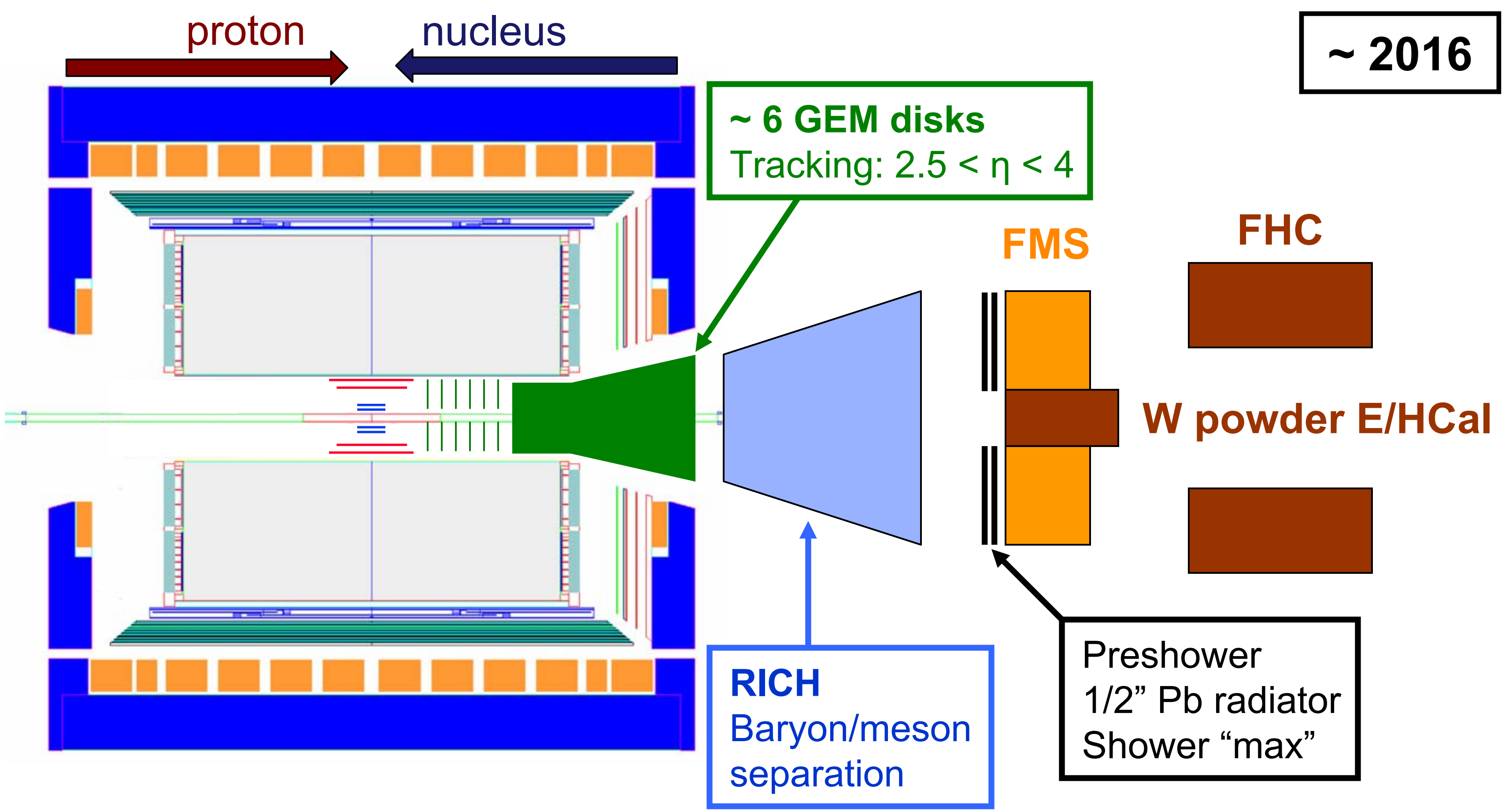
- RHIC may provide **unique access to the onset of saturation**
- Future questions for **p+A**
  - What is the gluon density in the (x,Q^2) range relevant at RHIC?
  - What role does saturation of gluon densities play at RHIC?
  - What is Q_s at RHIC, and how does it scale with A and x?
  - What is the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

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
- What more might we learn by scattering ***polarized* protons off nuclei**?

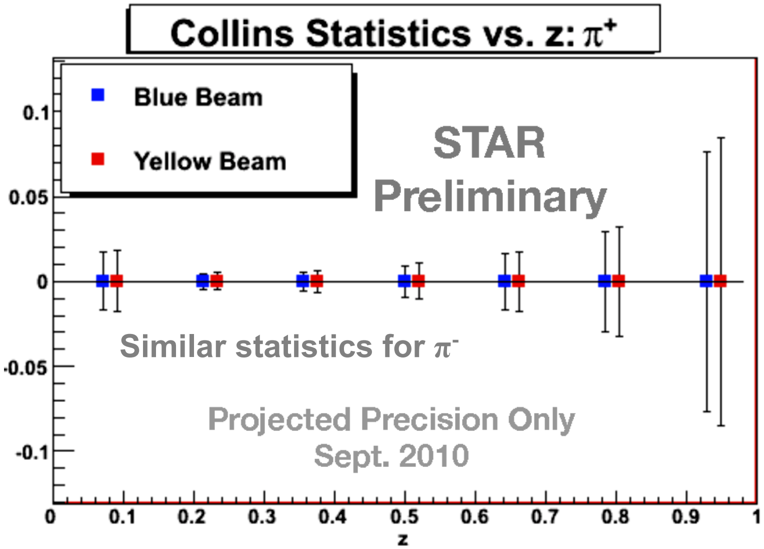
- **Forward-forward correlations, Drell-Yan, and Λs** are also very powerful tools to unravel the **dynamics of forward transverse spin asymmetries** – **Collins vs Sivers effects, TMDs or Twist-3, …**

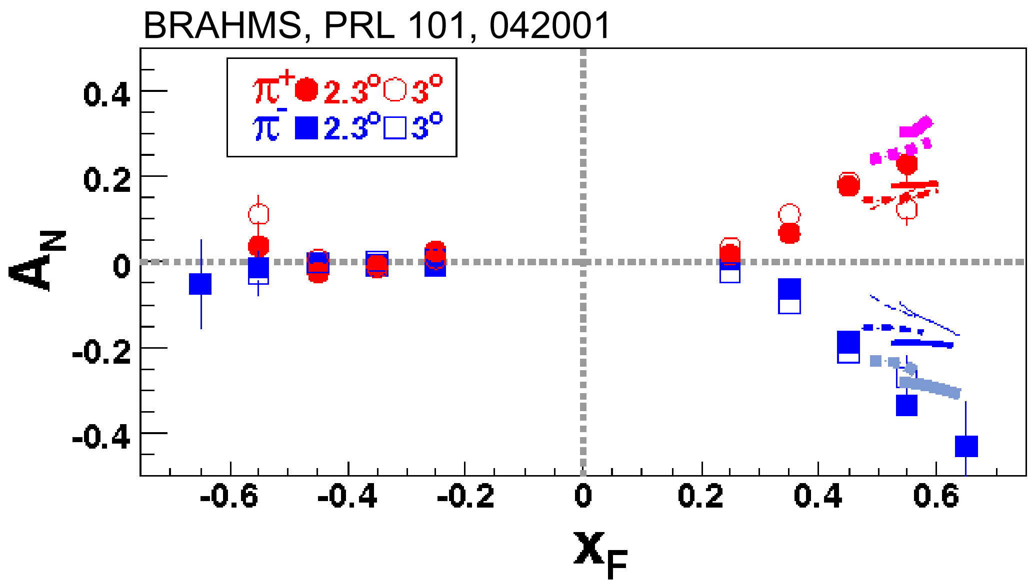
STAR forward instrumentation upgrade



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

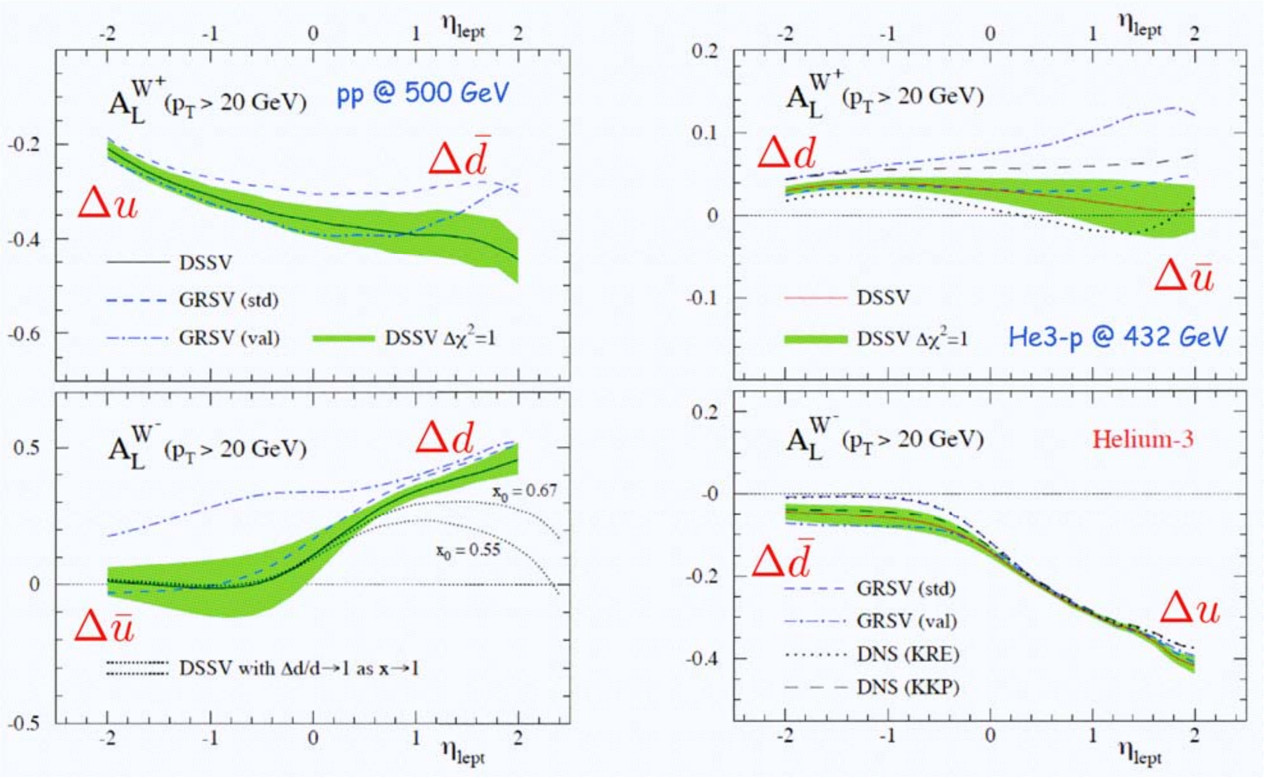
One spin example: Collins effect in jets





- STAR is measuring the Collins effect by looking at the azimuthal distribution of pions within mid-rapidity jets
- Will perform similar measurements at forward rapidity
  - Most interesting to separate positive and negative hadrons

Options with polarized ^{3}He



- Polarized ^{3}He provides access to polarized neutron scattering
- Interesting in both transverse and longitudinally polarized proton collisions
- If Roman Pots phase II can tag proton spectator(s), would lead to a dramatic increase in measurement sensitivity
- Very important technological development on the way to eRHIC

STAR → eSTAR

Optimizing ***STAR*** for e+p and e+A collisions from 5+50 to 5+325 GeV

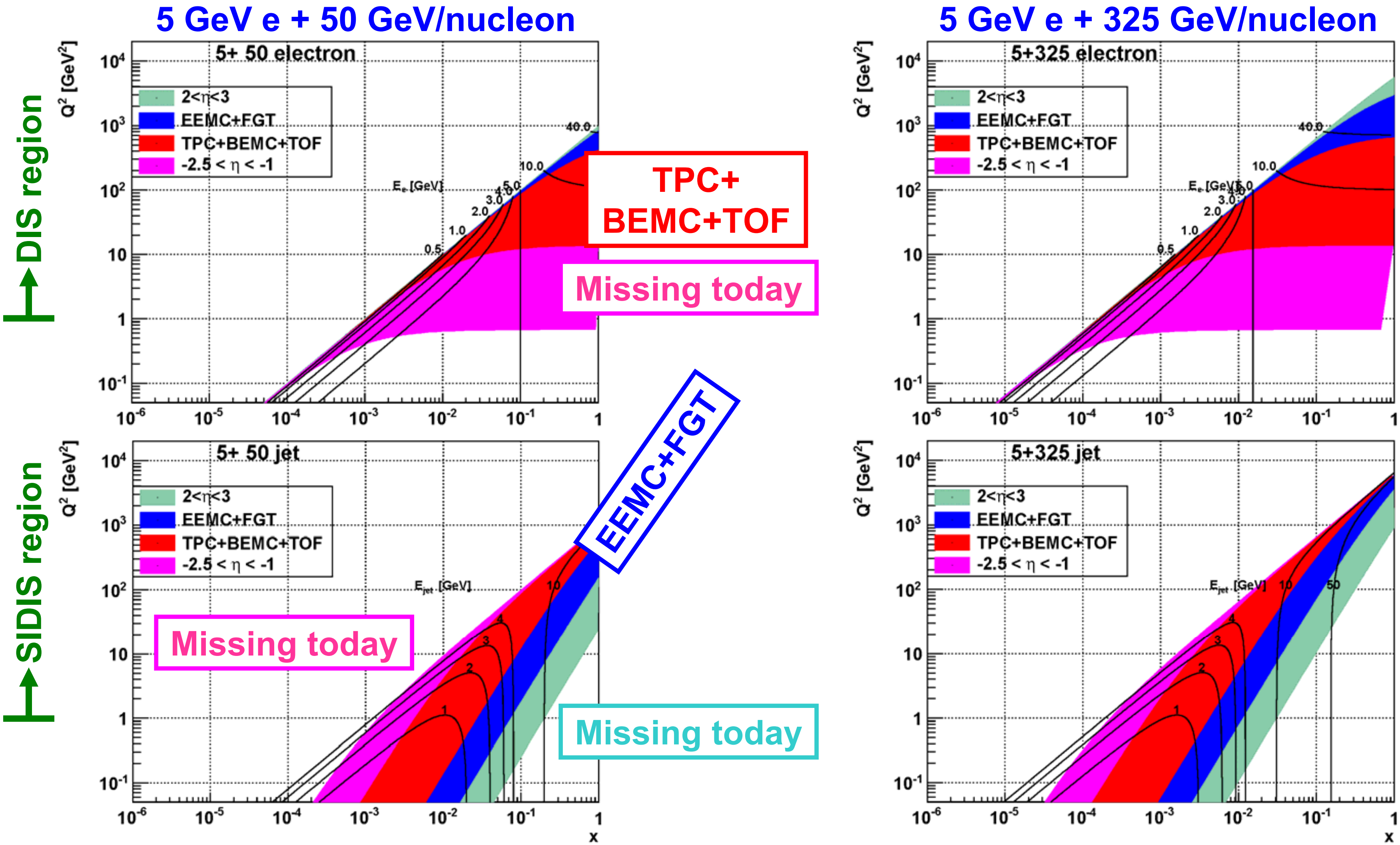
- **Inclusive scattering over the entire deep-inelastic region**
  - **Key measurements**
    - **F_L in e+p and e+A: direct measure of gluon densities in nucleons and nuclei**
    - **g_1 in e+p and e+^{3}He: nucleon spin structure**
    - **F_2^A/F_2^d: parton distributions in nuclei (including gluons via Q^2 evolution)**

- **Semi-inclusive deep-inelastic scattering over a broad (x,Q^2) domain**
  - **Key measurements**
    - **Flavor-separated helicity distributions, including strangeness**
    - **Collins, Sivers, Boer-Mulders, and other transverse spin distributions**
    - **Flavor-separated parton distributions in nuclei, including strangeness**
    - **Parton energy loss in cold nuclear matter**

- **Deeply-virtual Compton scattering**
  - **Key measurement**
    - **GPDs**

- **What's needed?**

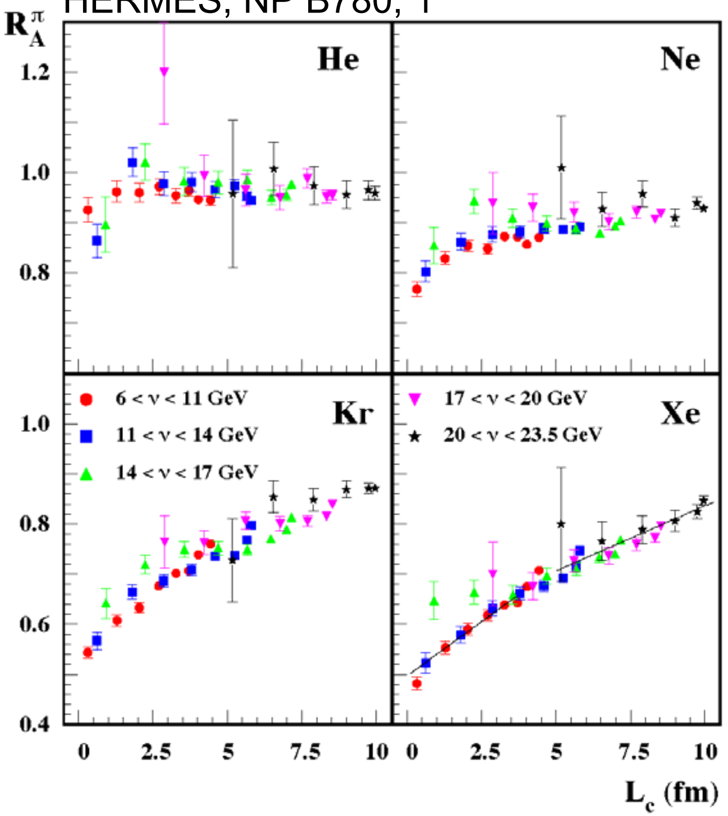
eRHIC phase 1: kinematic range

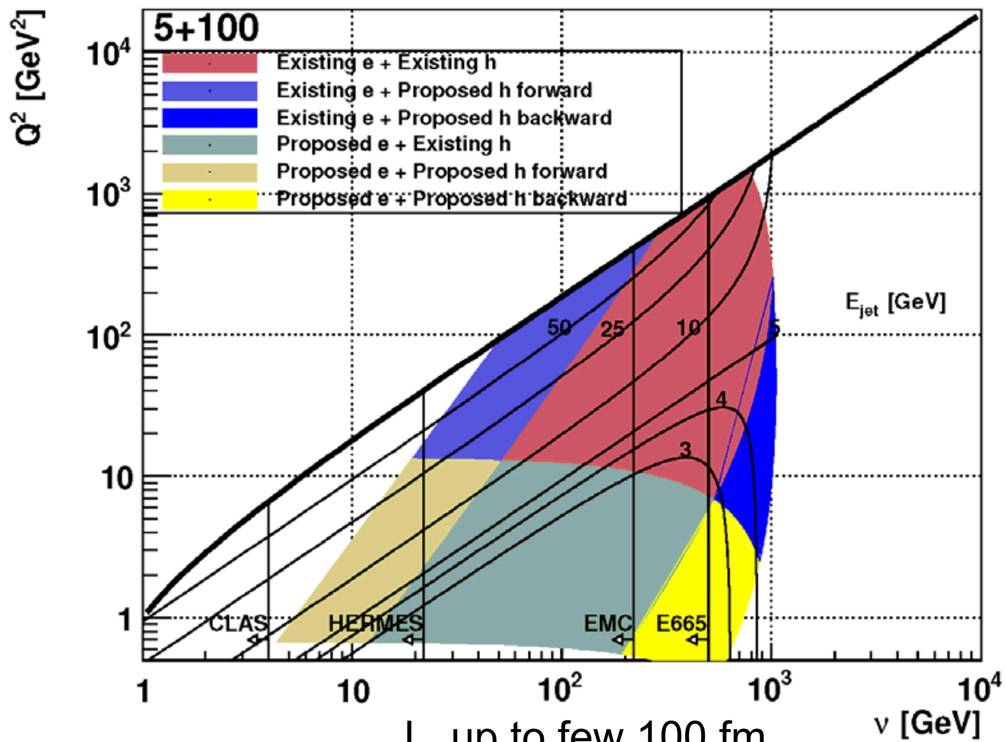


- "Forward" (-2.5 <~ η < -1) **electron acceptance essential** to span deep-inelastic (DIS) regime
- Both **backward** and **forward** **hadron coverage valuable** for semi-inclusive deep-inelastic (SIDIS) scattering

Parton energy loss in cold QCD matter

HERMES, NP B780, 1





L_c up to few 100 fm

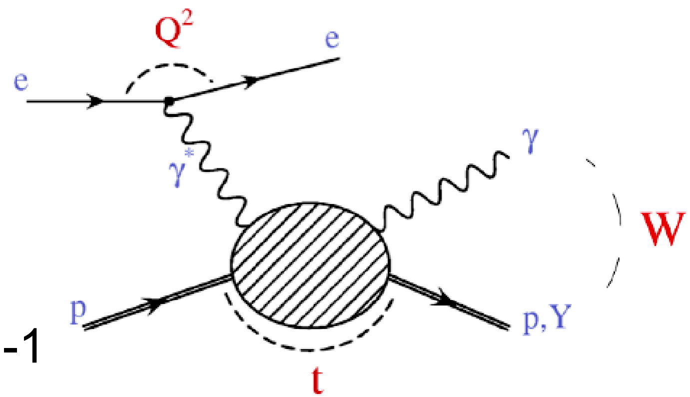
- Complementary tool to investigate partonic energy loss
- HERMES: hadrons can form partially inside the medium
  - Mixture of hadronic absorption and partonic energy loss
- eRHIC: light quark hadrons form well outside the medium
- Heavy quarks: unexplored to date. Low β → short formation time

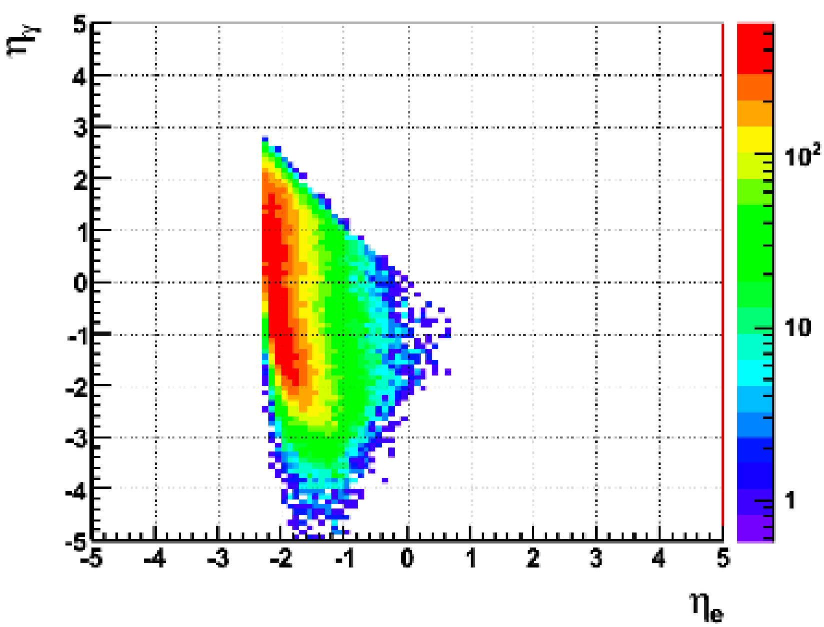
Beyond DIS: DVCS

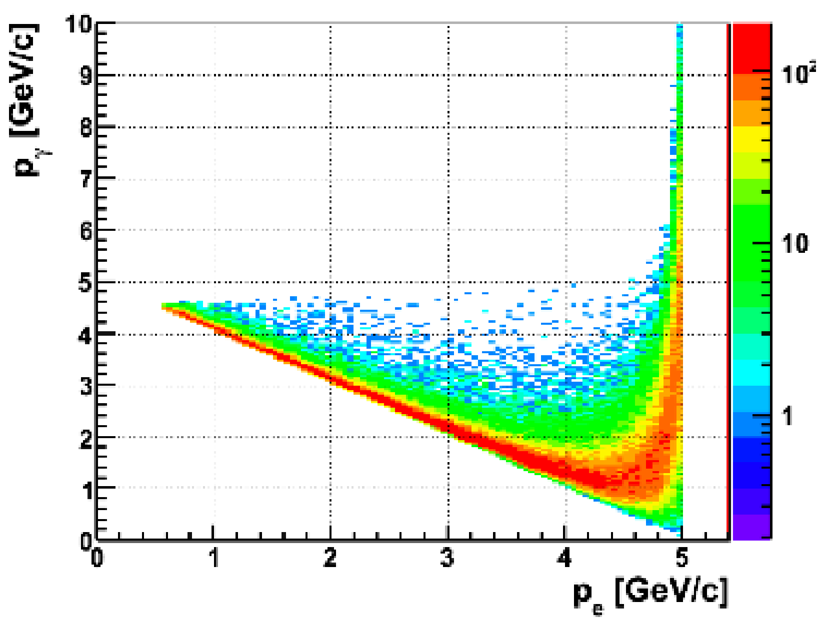
Deeply Virtual Compton Scattering

- Must measure electron, proton, and photon

- Proton requires Roman Pot, tied to I.R. design
  - Aperture needs mostly driven by proton energy
- Electron requirements similar to DIS
  - Especially important to measure over -2.4 <~ η < -1







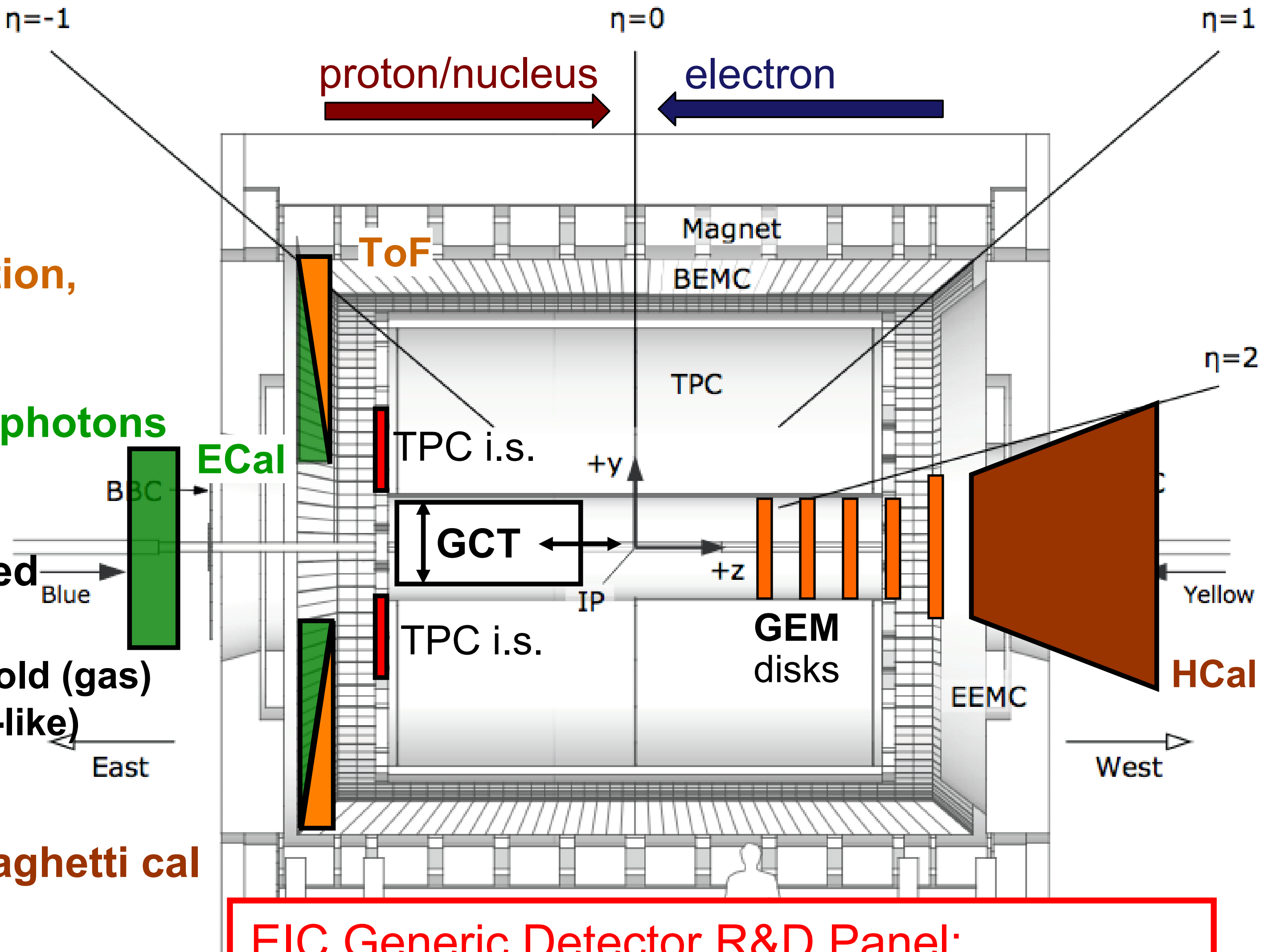
Further possibilities under investigation: diffraction in *J*/ψ, …

STAR → ***eSTAR***

Optimizing ***STAR*** for e+p and e+A collisions from 5+50 to 5+325 GeV

- **Inclusive scattering over the entire deep-inelastic region**
  - **Key measurements**
    - **F_L in e+p and e+A: direct measure of gluon densities in nucleons and nuclei**
    - **g_1 in e+p and e+^{3}He: nucleon spin structure**
    - **F_2^A/F_2^d: parton distributions in nuclei (including gluons via Q^2 evolution)**
  - **Need electron detection, ID, and triggering over -2.5 <~ η < -1**
    - **Combined mini-TPC/threshold gas Cherekov detector**
- **Semi-inclusive deep-inelastic scattering over a broad (x,Q^2) domain**
  - **Key measurements**
    - **Flavor-separated helicity distributions, including strangeness**
    - **Collins, Sivers, Boer-Mulders, and other transverse spin distributions**
    - **Flavor-separated parton distributions in nuclei, including strangeness**
    - **Parton energy loss in cold nuclear matter**
  - **Need hadron detection and identification beyond the TPC/EEMC**
    - **Extend TOF to cover -2 < η < -1**
    - **GEM disks (from forward instrumentation upgrade) plus hadronic calorimetry in the region 2 < η < 3**
- **Deeply-virtual Compton scattering**
  - **Key measurement**
    - **GPDs**
  - **Need forward proton and expanded photon detection**
    - **Roman pots (also valuable for spectator proton tagging in e+^{3}He)**
    - **EM calorimetry for -4 < η < -1**

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

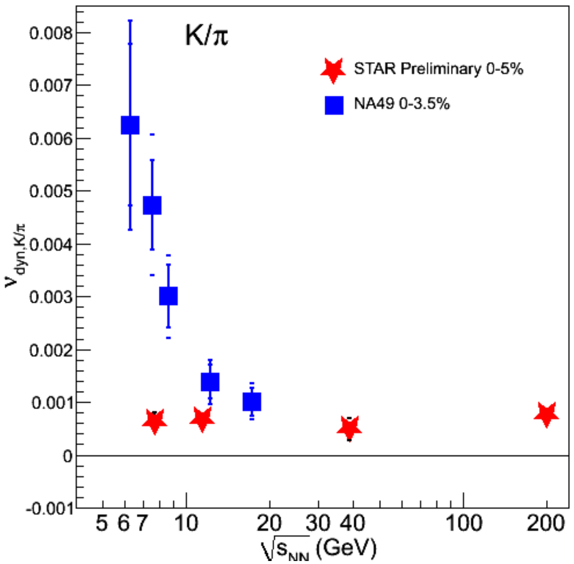
Simulations ahead:
eSTAR task force formed

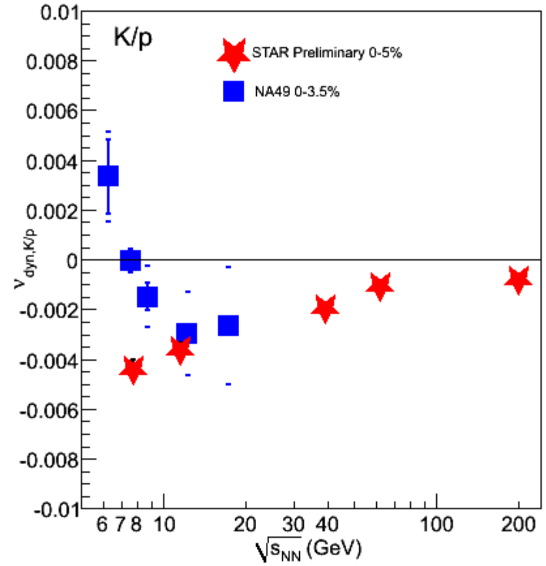
EIC Generic Detector R&D Panel:

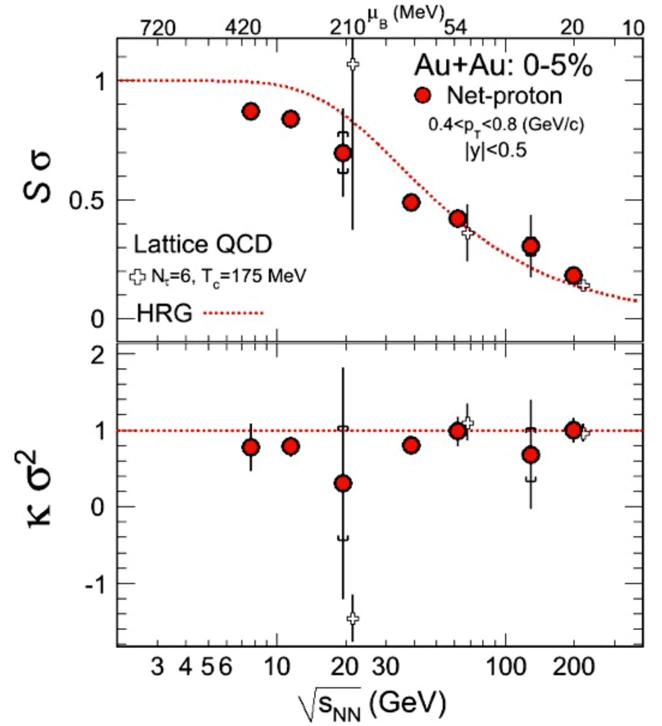
GCT: LOI toward multi-institution R&D effort

HCal: R&D proposal

RHIC in the LHC era

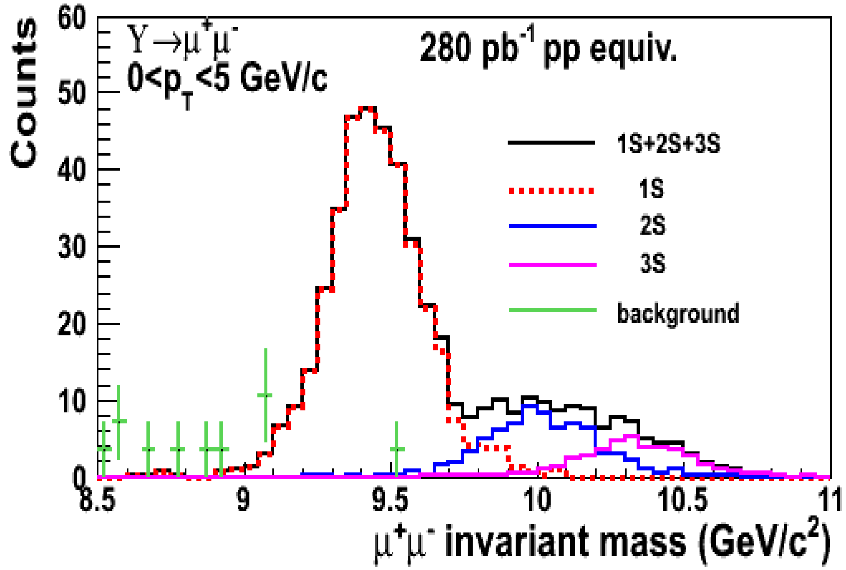






- Unique measurements at RHIC
  - Exploring the onset of saturation
    - Study the turn-on to elucidate the underlying dynamics
  - Searching for the QCD critical point and the 1st order phase transition line using collider detectors
    - Changes in the **qualitative response** of the matter appear below 39 GeV
  - **World's only** polarized hadron collider
- Unique until LHC detectors upgrade
  - Open charm in the hydrodynamic domain

RHIC in the LHC era



- Some measurements with easier interpretation at RHIC energies
  - Υ production
    - Entirely primordial at RHIC
    - Contribution from recombination at LHC ?
  - Response of the medium to a jet
- Example of complementarity
  - Light quark jets
    - Dominate above p_T ~ 30 GeV/c at RHIC
    - Only accessible via tagging at LHC

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
- The path forward:
  - Early in the decade: physics with low mass in the central region
  - Mid decade: physics of the HFT and MTD
  - Later in the decade: physics in the forward region
  - End of the decade: early phase of eRHIC
- ***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?