Cold-QCD Physics of the STAR Forward Upgrade

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for the STAR Collaboration

OUTLINE

- Open questions
- STAR Forward upgrade
- A few examples
- Summary

Open Questions in Cold QCD

The last decades in nuclear/particle physics have seen tremendous successes

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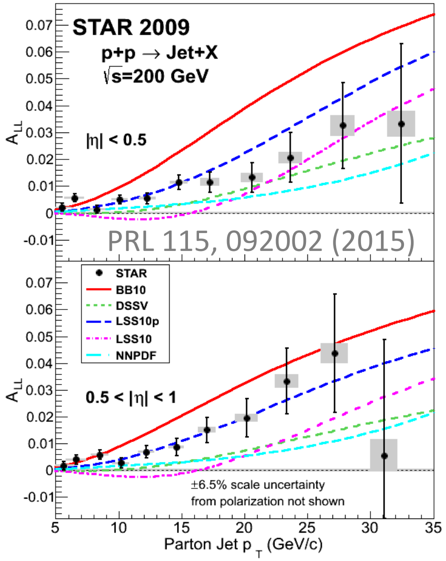
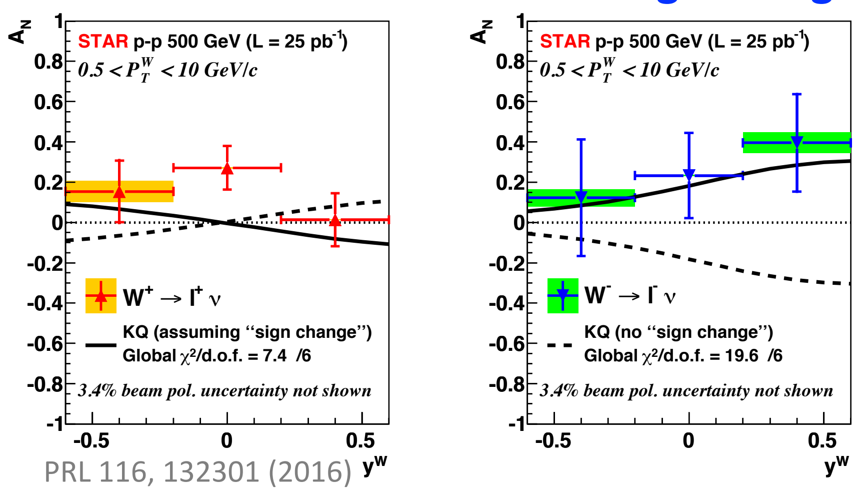
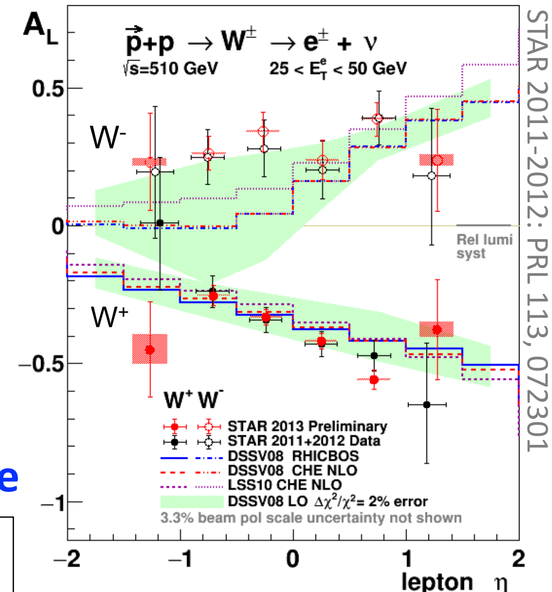


First evidence of polarized gluons

Worldwide first hint of Sivers sign change





Positive flavor asymmetry in the polarized sea

Open Questions in Cold QCD

The last decades in nuclear/particle physics have seen tremendous successes

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A few of the many fascinating questions that remain…

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from them and their interactions?
- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?
- How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions? What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

pp/pA Physics in 2020+

RHIC Cold QCD physics after BES-II at Mid- & Forward Rapidities:

The RHIC Cold QCD Plan for 2017 to 2023: A Portal to the EIC (*arXiv:1602.03922*)

→ Critical to the mission of the RHIC physics program

→ ***Fully realize*** the scientific promise of the EIC

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- *Based on existing STAR detectors, utilizing recent BES II upgrades (iTPC, eTOF, EPD)*

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- *Upgrades consist of **HCal** + **ECal** + **Tracking*** in range of $2.5 < \eta < 4.5$

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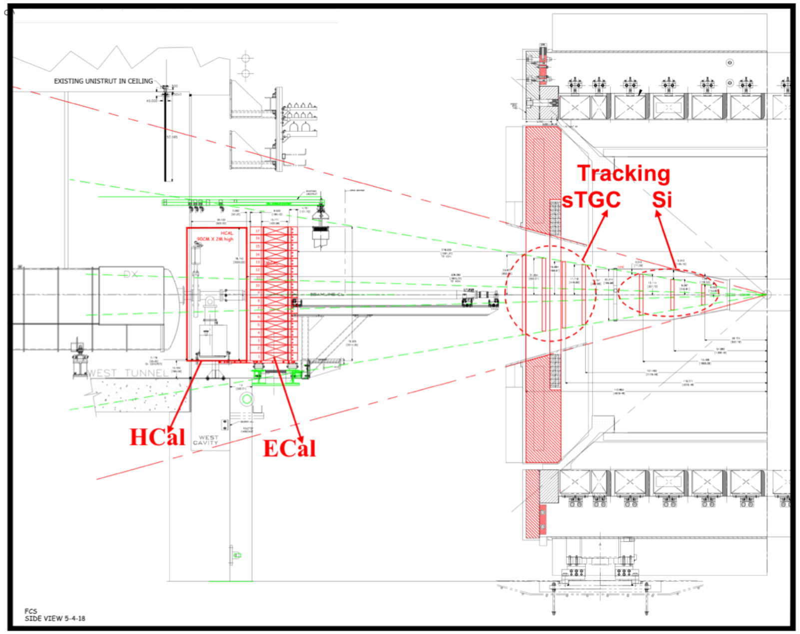

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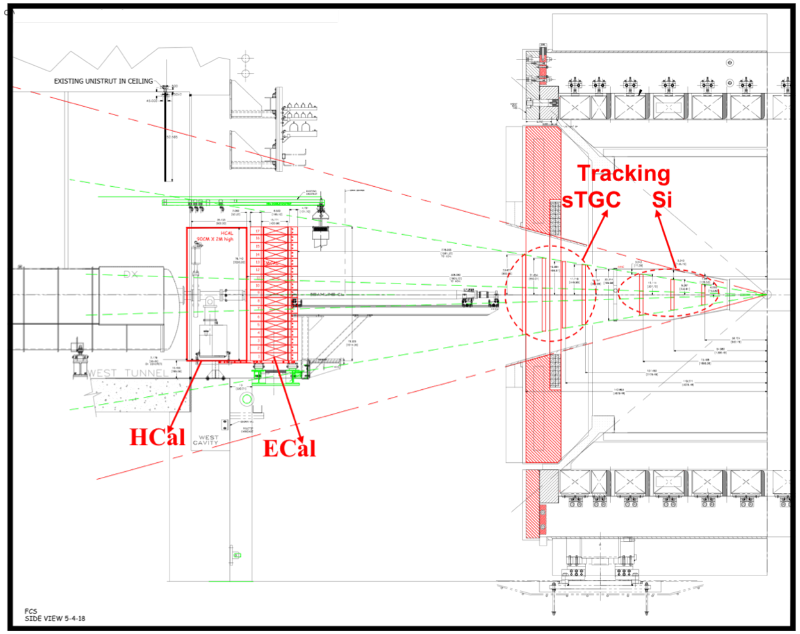
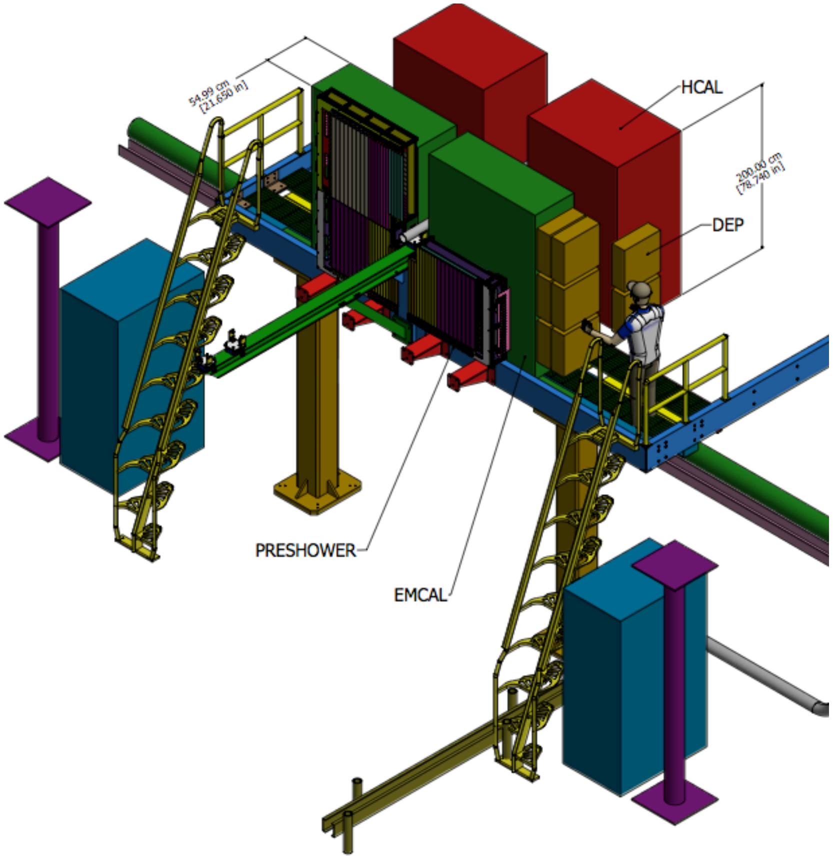


Strong endorsement by RHIC PAC:

- As the physics program that is foreseen for forward physics is substantial, ***full utilization of future polarized proton beam time must be made to realize the proposed forward physics program***.
- RHIC management is encouraged to ***find a way to enhance and include a forward physics program at RHIC***.

The STAR Forward Upgrade: Calorimetry



Performance Needs

ECal: $\sim 10\%/\sqrt{E}$ (pp/pA) and $\sim 20\%/\sqrt{E}$ (AA)

reuse PHENIX PbSC calorimeter with new readout

- **Benefit:** significant cost reduction!
- **Tradeoff:** uncompensated calorimeter system

HCal: $\sim 60\%/\sqrt{E}$ (pp/pA)

- Sandwich iron-scintillator plate sampling cal.
- Same readout for both calorimeters

Cost:

ECal: $0.57M

HCal: $1.53M

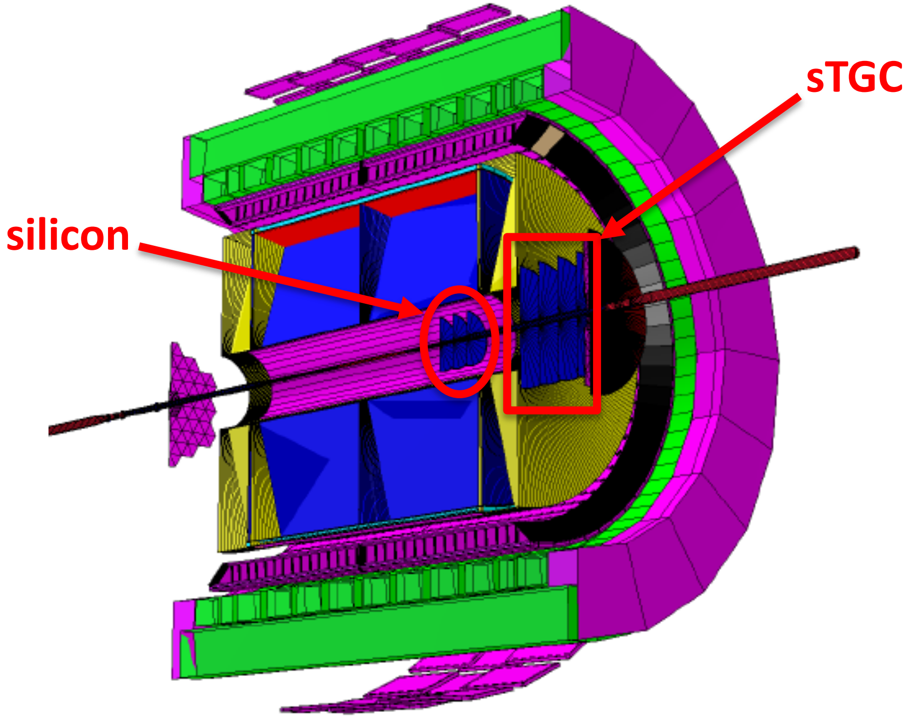
Preshower: $0.06M

Total: $2.2M*

**includes contingency and manpower*

Intensive R&D on both calorimeters as part of STAR and EIC Detector R&D, including FNAL test beam and STAR in situ tests

The STAR Forward Upgrade: Tracking



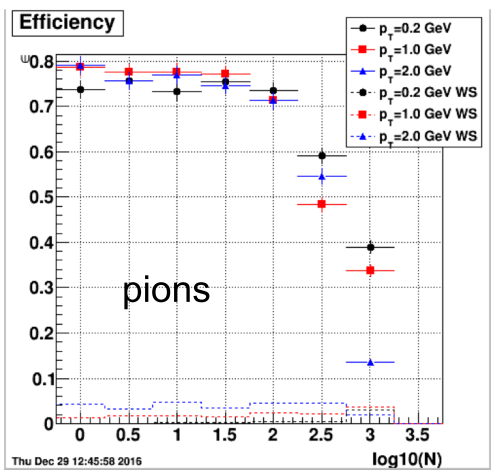
3 Si discs + 4 Small-strip Thin Gap Chambers

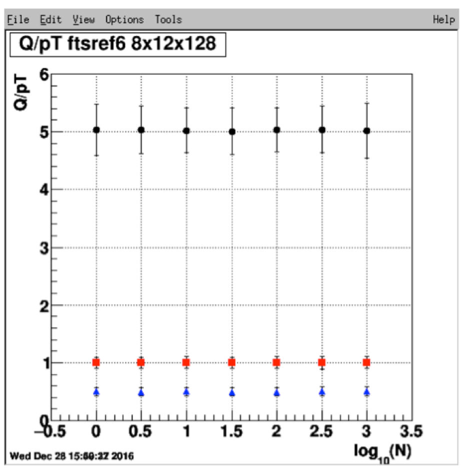
Location from interaction point:

Si: 90, 140, 187 cm

sTGC: 270, 300, 330, 360 cm

(*outside Magnet*)





Performance Needs:

Momentum resolution:

20-30% for $0.2 < p_T < 2$ GeV/c

Tracking efficiency:

80% at 100 tracks/event

Cost: $3.3 M

Forward Rapidity Physics: Transversity

Complete understanding of nucleon structure requires knowledge of

- Unpolarized PDF
- Helicity PDF
- Transversity – helicity odd → requires another chiral-odd distribution

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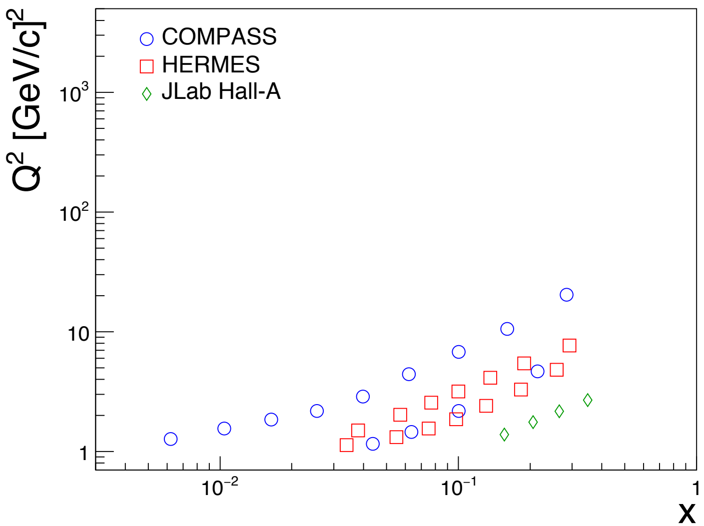

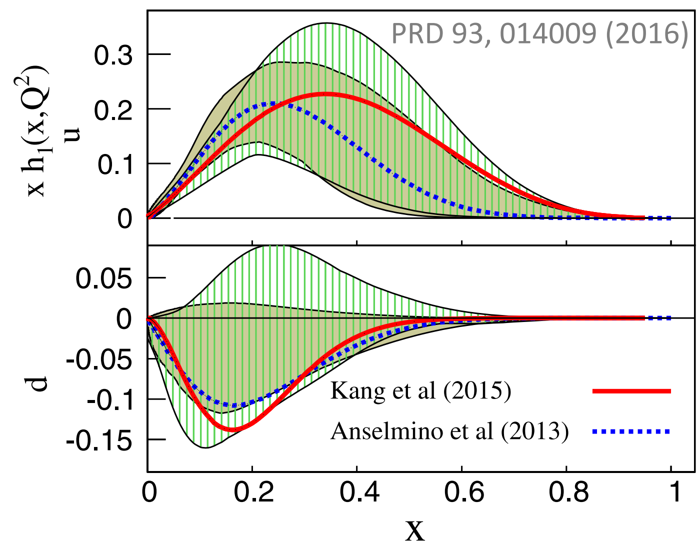

Anselmino et al: PRD 87, 094019 (2013)
Kang et al: PRD 93, 014009 (2016)
Radici et al: JHEP 05, 123 (2015)

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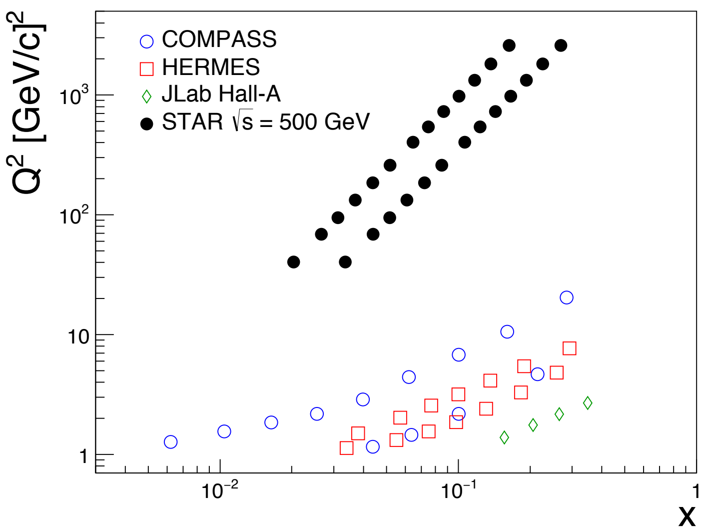

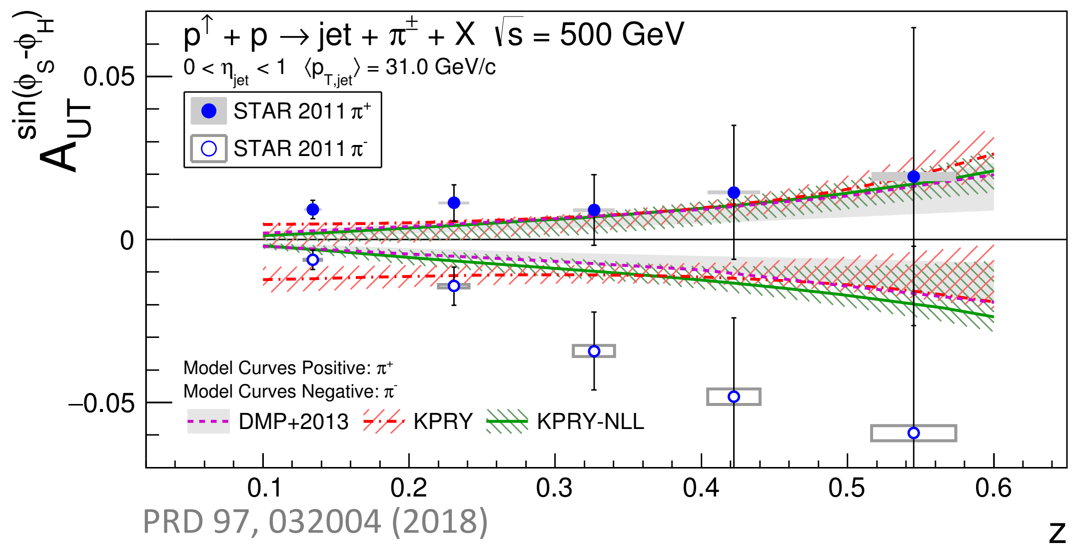

PRD 97, 032004 (2018)

Collins effect, now observed in pp and largely consistent with SIDIS+e^+e^-

- Tests of TMD factorization and universality
- Sample wider kinematic space → insight into TMD evolution

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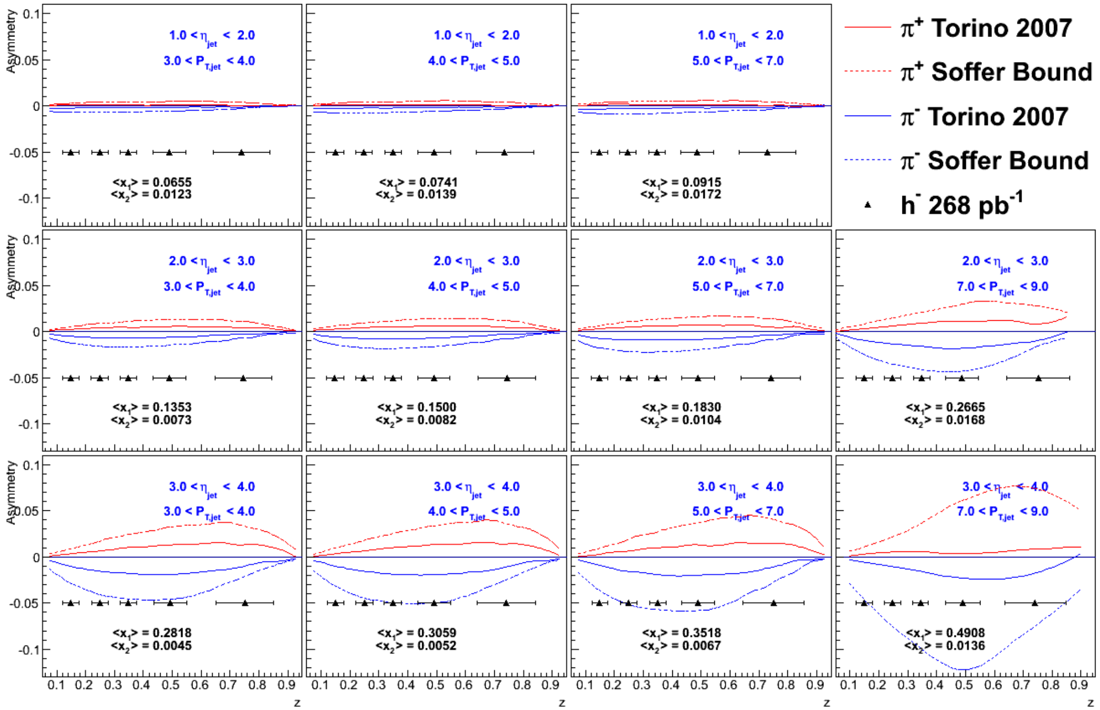
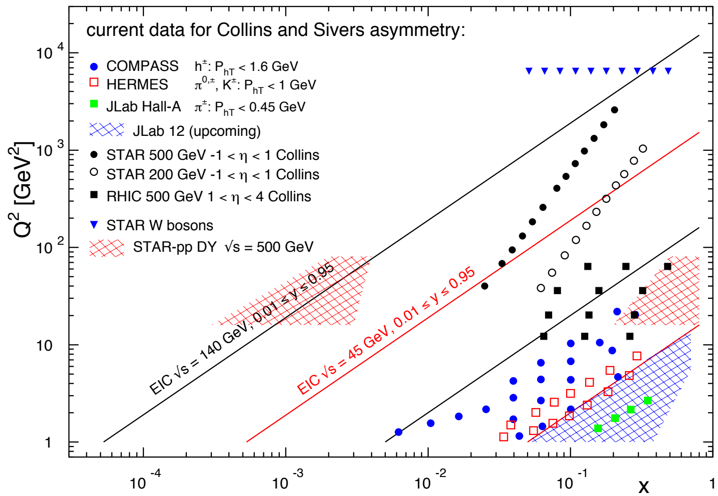
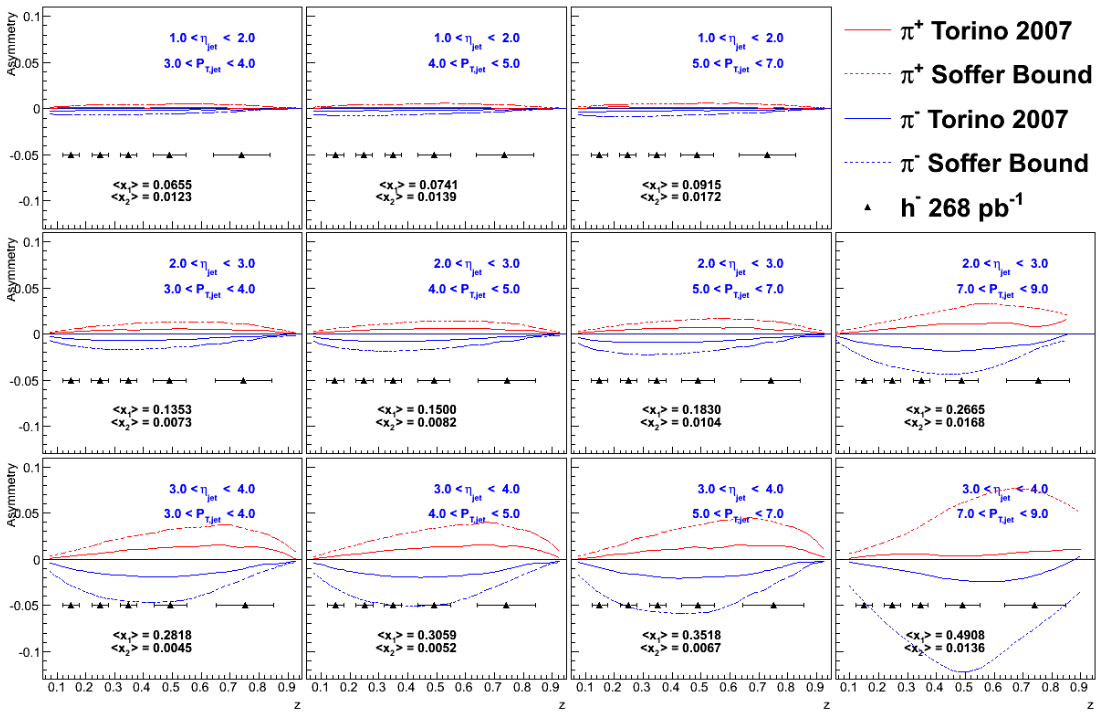
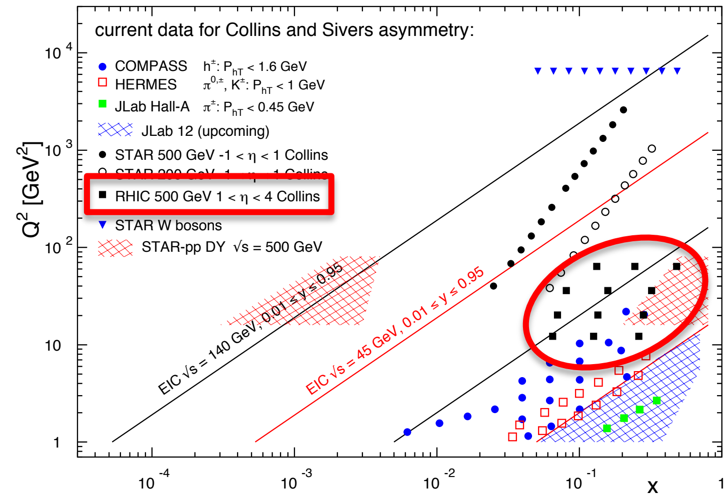




Utilize $p + p \to \mathrm{jet}(h^{\pm})$, as at midrapidity

Forward Rapidity Physics: Transversity





500 GeV

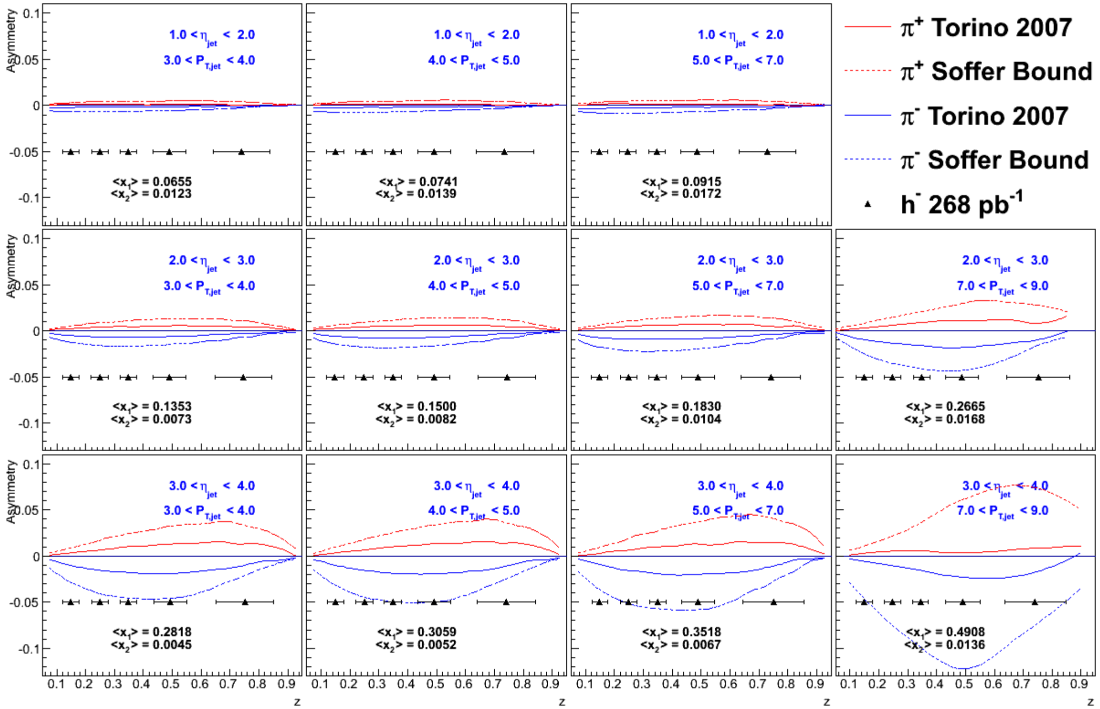
$1 < \eta < 4$

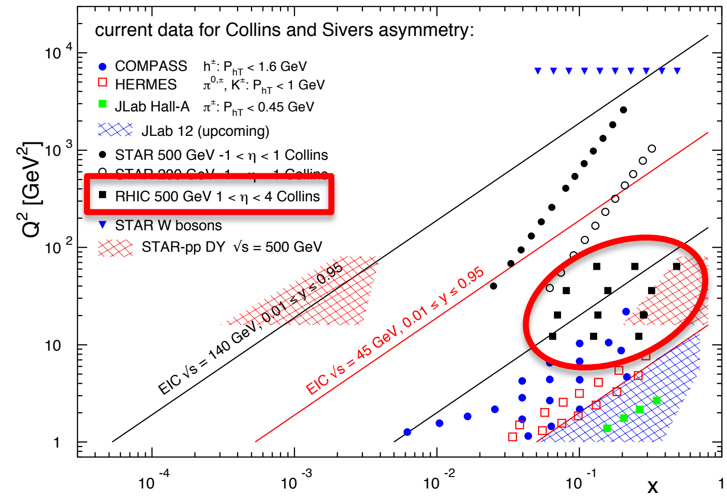
Utilize $p + p \to \text{jet}(h^{\pm})$, as at midrapidity

Pushing forward = higher x:

- $0.05 \lesssim x \lesssim 0.5$
- $10 \lesssim Q^2 \lesssim 100$ GeV²

Forward Rapidity Physics: Transversity





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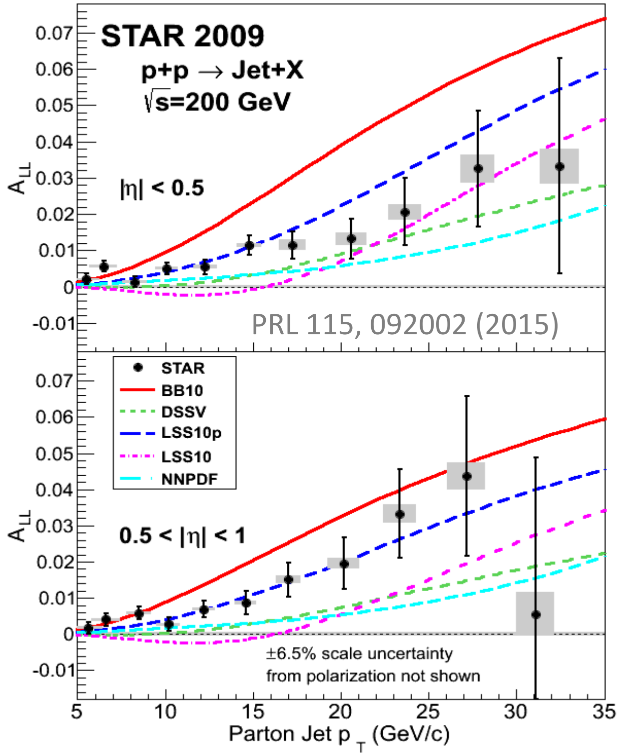
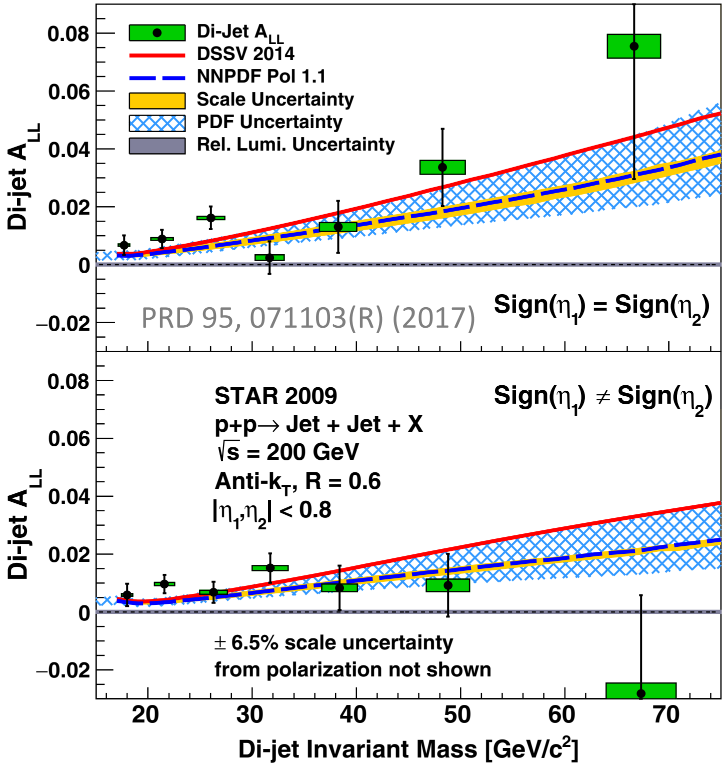
Understanding transversity enables constraints of tensor charge

$$\delta q^a = \int_0^1 [\delta q^a(x) - \delta \bar{q}^a(x)]dx$$

Forward Rapidity Physics: Gluon Helicity





RHIC data through 2009:

$$\int_{0.05}^{1} \Delta g(x)dx = 0.23 \pm 0.06 \text{ (NNPDF)}$$

$$\int_{0.05}^{1} \Delta g(x)dx = 0.20^{+0.06}_{-0.07} \text{ (DSSV)}$$

Recent data will improve uncertainties further…

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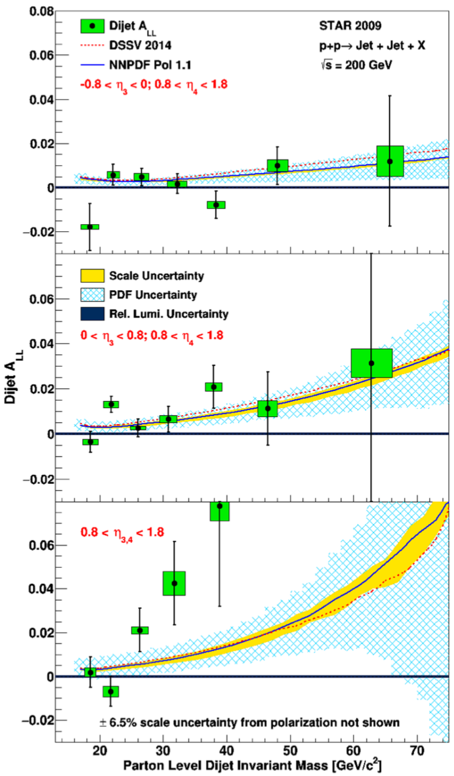
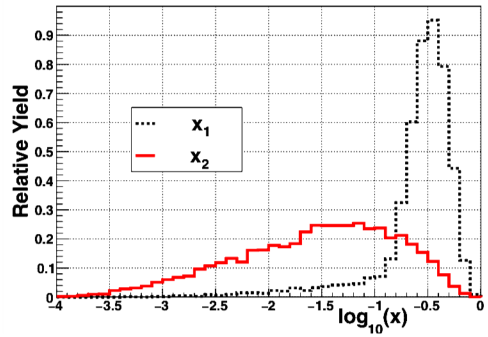
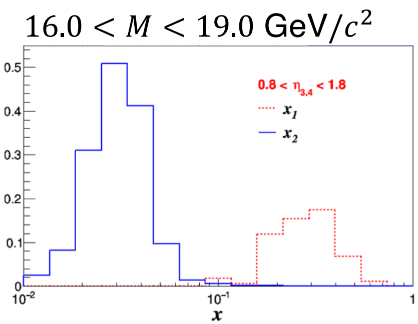
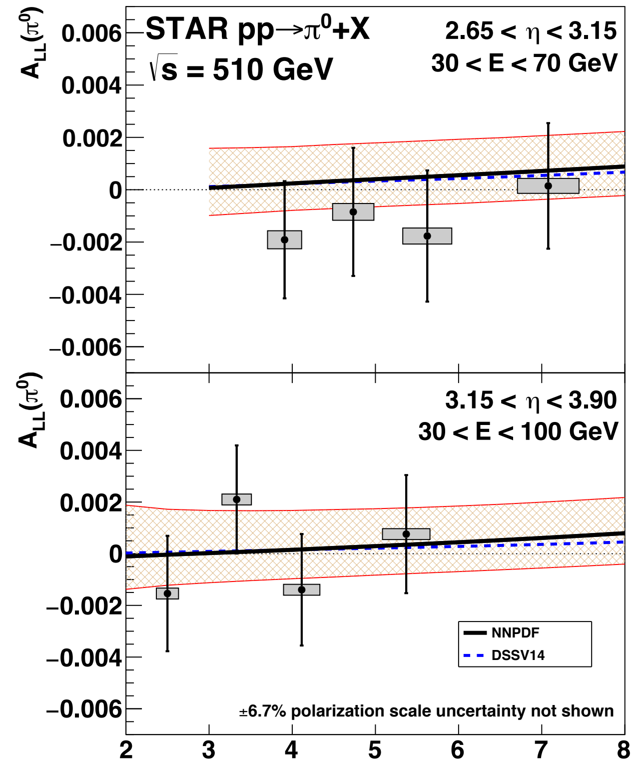


arXiv:1805.09742







arXiv:1805.09745

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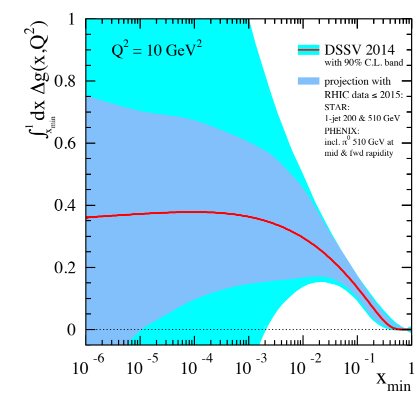
…but Δg at very low x still largely unconstrained!

For lower x: push forward!

Add'l Results:

- Mid-η (di)jets at 500 GeV
- Intermed.-η dijets at 500 GeV
- Intermed.- η π^0
- High stats 200 GeV in 2015



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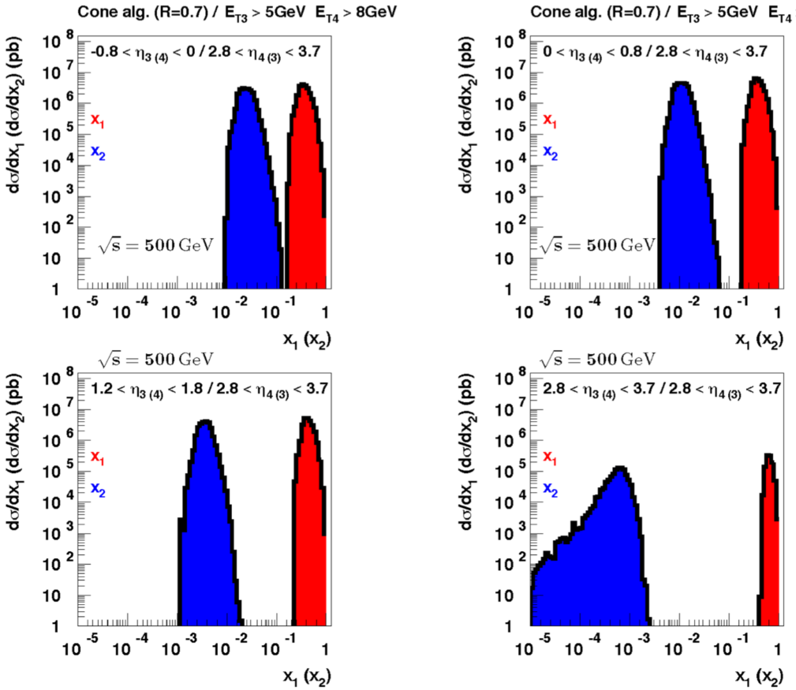
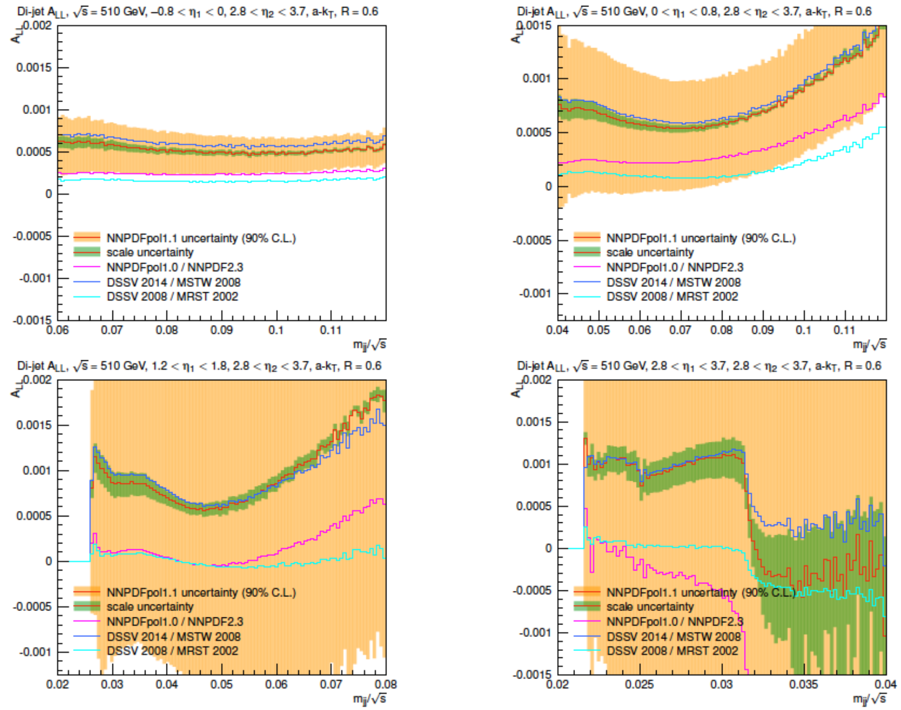




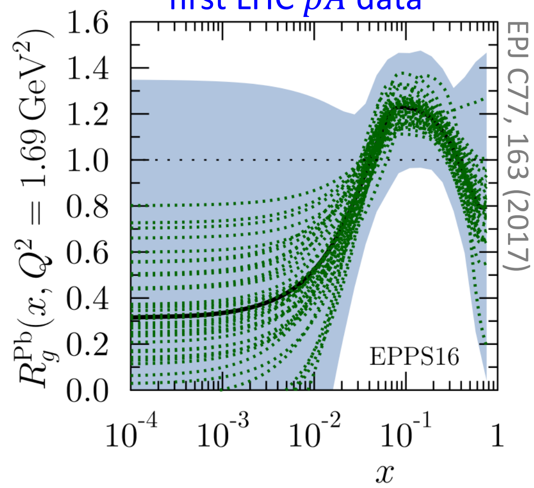
Constrain Δg at low x with forward dijets

- More sensitive to shape of $\Delta g(x)$ than inclusive probes
- Correlating forward jet with associated jet in different rapidity ranges samples a varied range of x
- Pushing both jets to $\eta > 2.8$ allows sensitivity of $x \sim 10^{-3}$

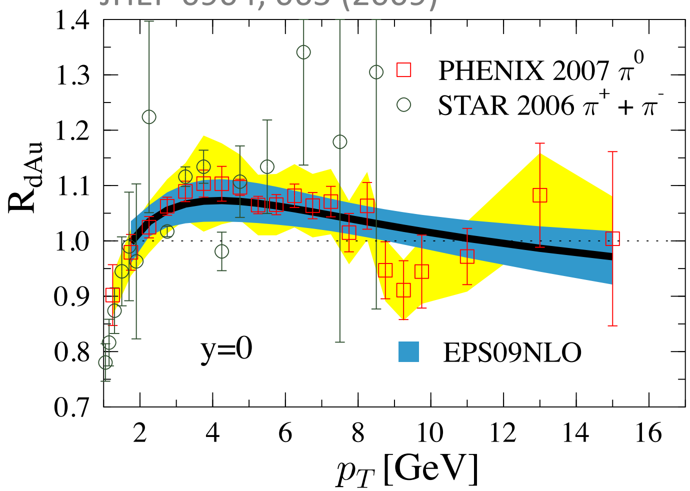
Forward Rapidity Physics: Nuclear PDFs

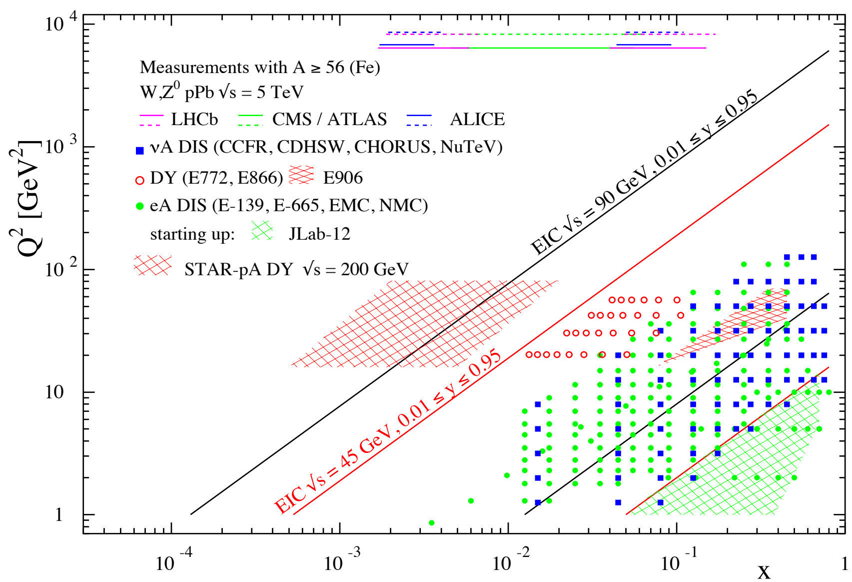
- Understanding the initial state of heavy nuclei is critical to RHIC and LHC programs
- Knowledge currently limited when compared to our knowledge of free protons
- Vital to extend understanding at low x over range of Q^2
- Furthermore, need data for different nuclei to understand A-dependence of nuclear PDFs
- Need probes with $Q^2 > Q_s^2$
- Need probes immune to final-state strong interactions

Current knowledge including first LHC pA data



JHEP 0904, 065 (2009)





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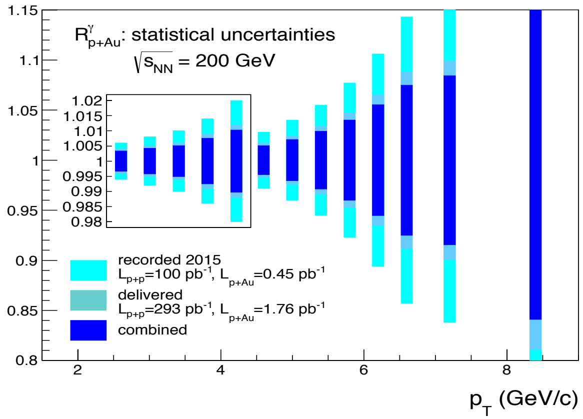
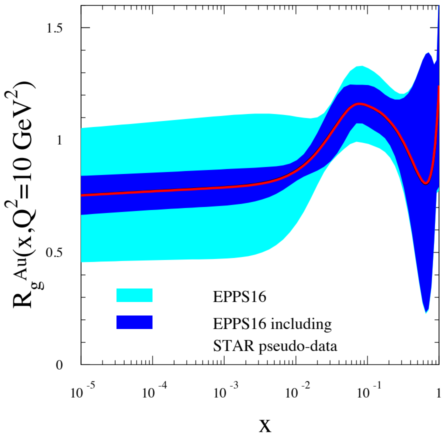
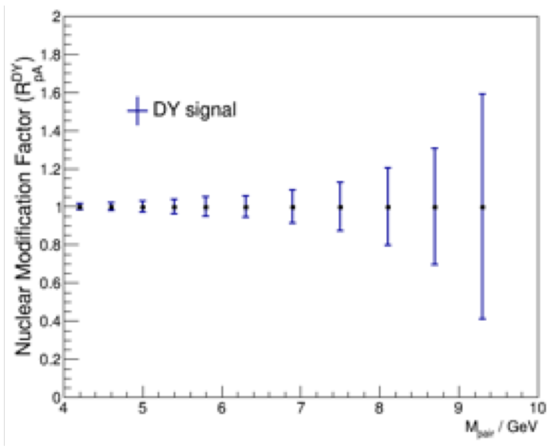
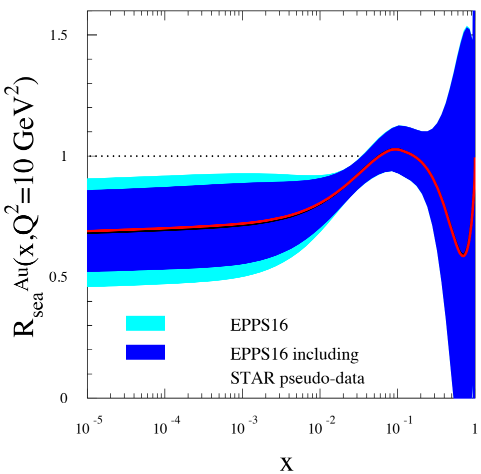




Probe **gluon** nPDF via **forward direct-γ**





Probe **sea-quark** nPDF via **forward Drell-Yan**

- Pilot measurements from 0.45 pb^{-1} pAu and 1 pb^{-1} pAl taken in 2015
- Planned 2023 runs → significant impact on global analyses
- Sensitive to $10^{-3} \lesssim x \lesssim 10^{-2}$ and $6 \lesssim Q^2 \lesssim 40\ \mathrm{GeV}^2$, where nuclear modifications should be significant
- Precision of pA data → enable stringent test of nPDF universality when combined with data from EIC

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- ***Definitive observation*** of saturation regime would significantly advance understanding of nucleon structure and high-energy nuclear interactions
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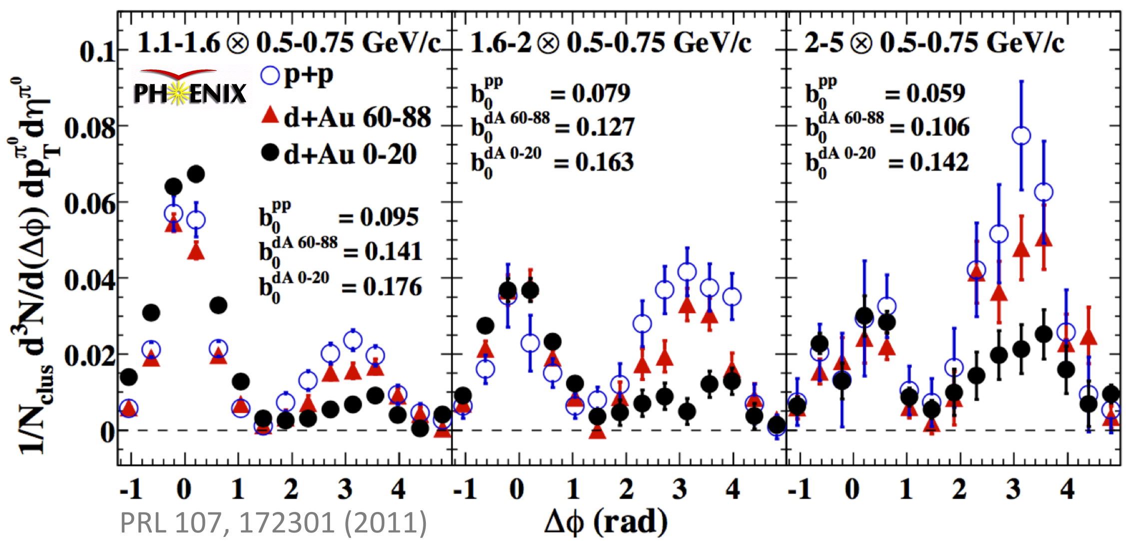

PRL 107, 172301 (2011)

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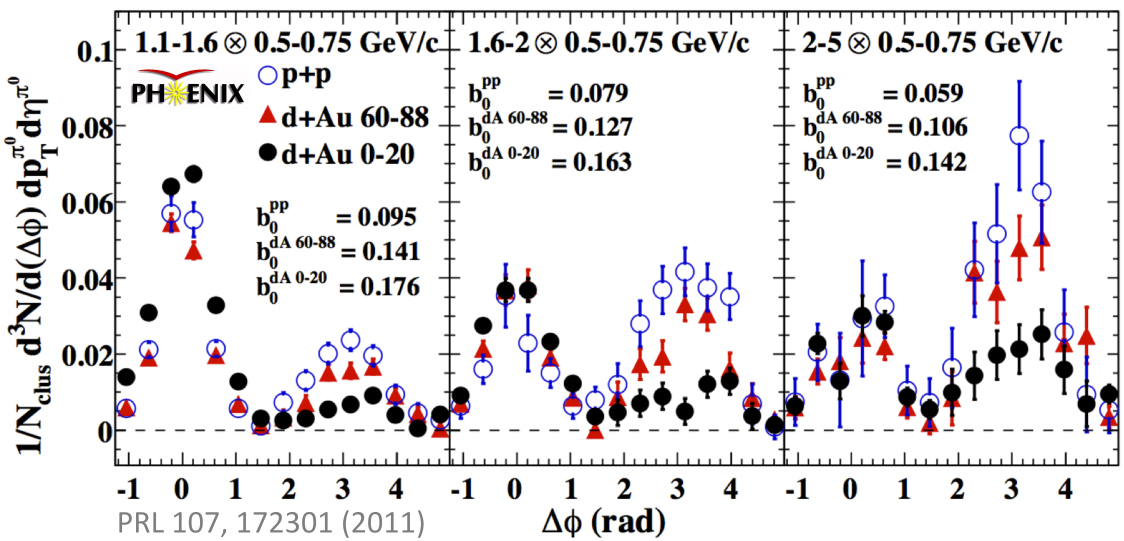
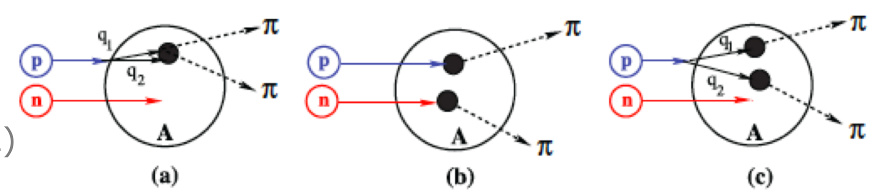
  → "double interactions" provide alternative explanation
- Theoretical complications for strongly-interacting final states



PRL 107, 172301 (2011)

double interactions:

PRD 83, 034029 (2011)



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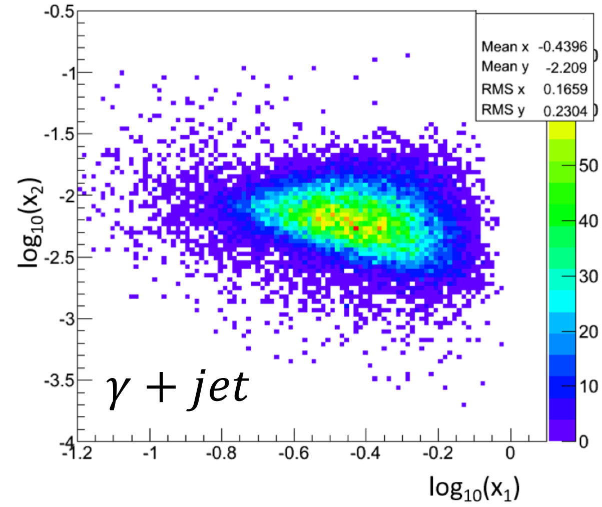
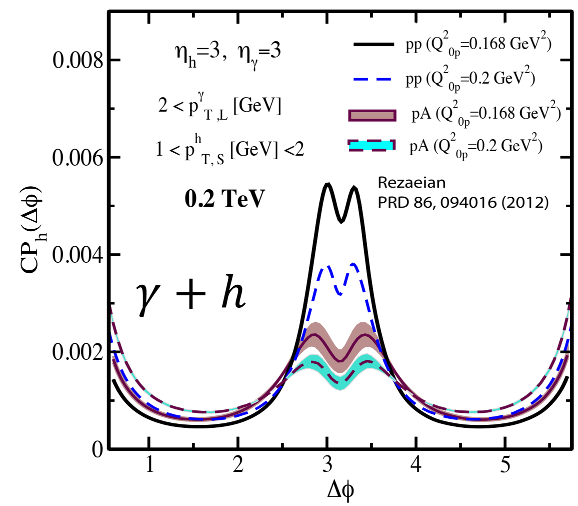
- Future increased luminosity+upgrades enables additional probes, e.g. forward $\gamma + jet$
  - Sensitive only to dipole gluon density
  - Sample $0.001 < x < 0.005$ for both γ and jet in range $1.3 < \eta < 4.0$ with $p_T > 3.2$ GeV/c
  - Complement with probes, e.g. $\gamma + h$ and di-jet





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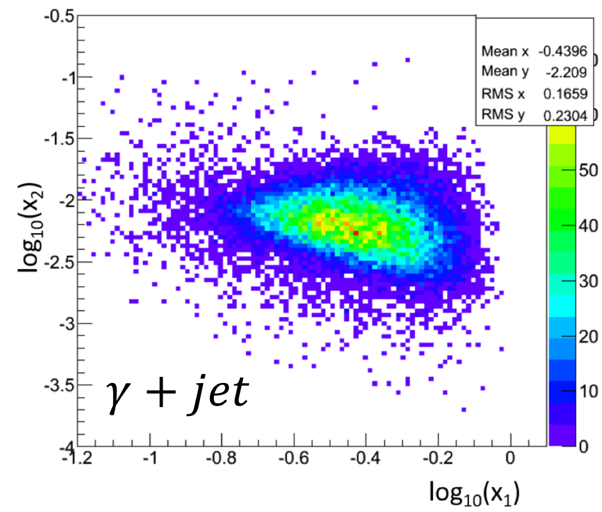
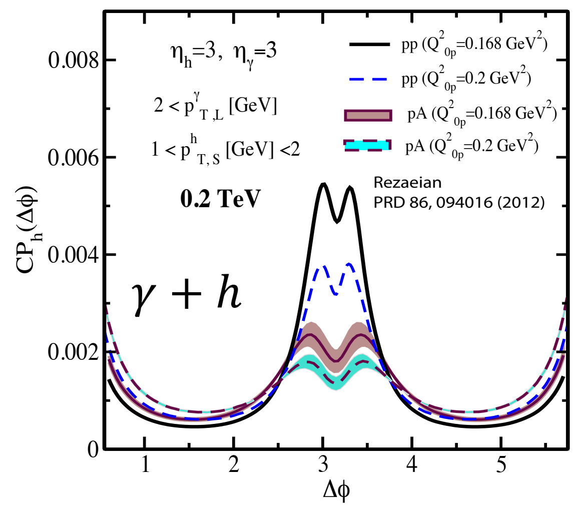
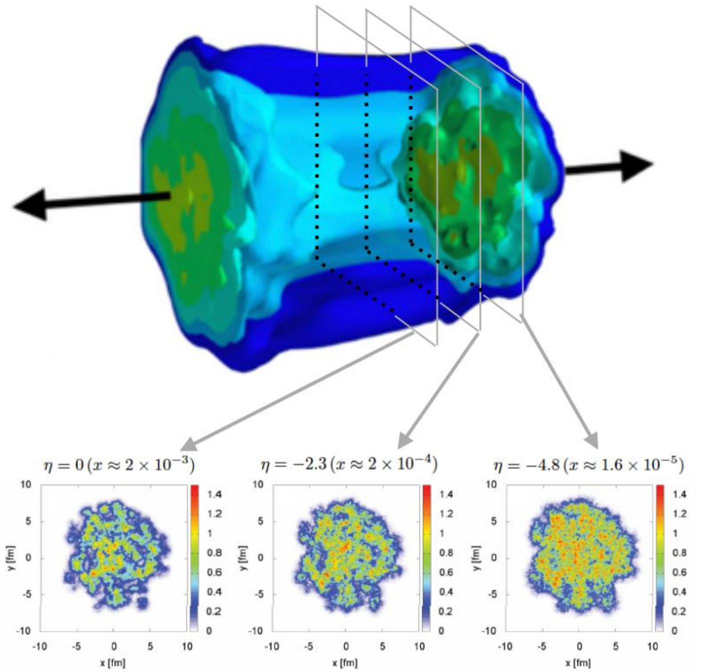
Critical test of universality when combined with EIC





Forward Rapidity Physics: Opportunities with AA

- Knowledge of ***transverse*** density fluctuations improved over recent years
- Constraints on ***longitudinal*** structure more limited
- 3D-Glasma constrained by LHC → crucial test of QCD evolution with RHIC data
- Critical to understand 3+1 dimensional viscous hydrodynamics evolution and transport of hadronic phase



PRC 94, 044907 (2016)

credit: B. Schenke

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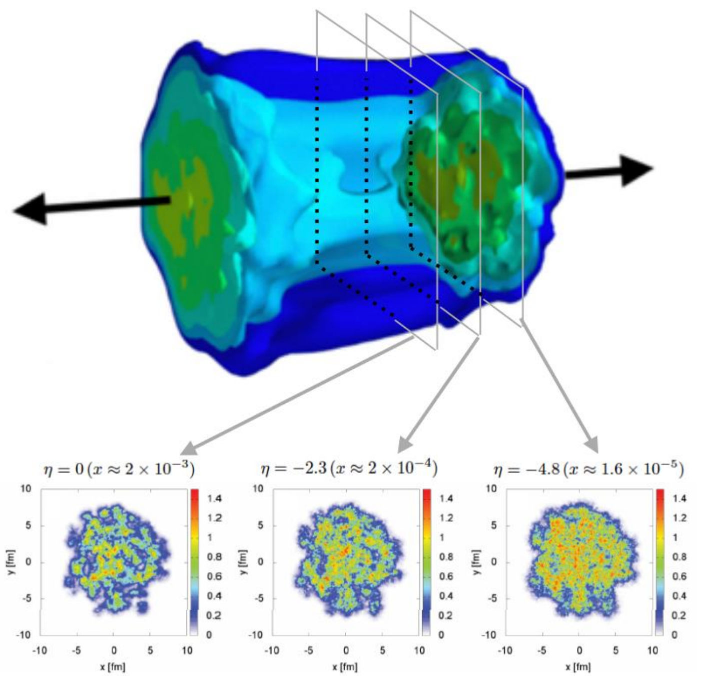
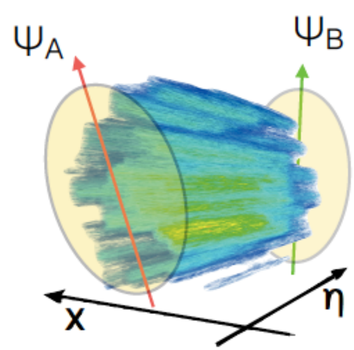
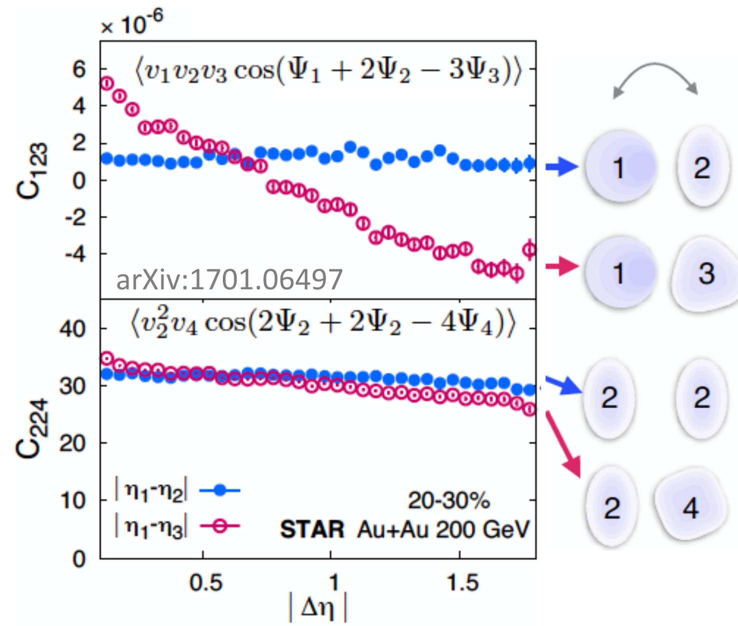
- STAR with existing detectors: Hint of longitudinal de-correlations
- Wider $\Delta\eta$ can probe in more detail



PRC 94, 044907 (2016)



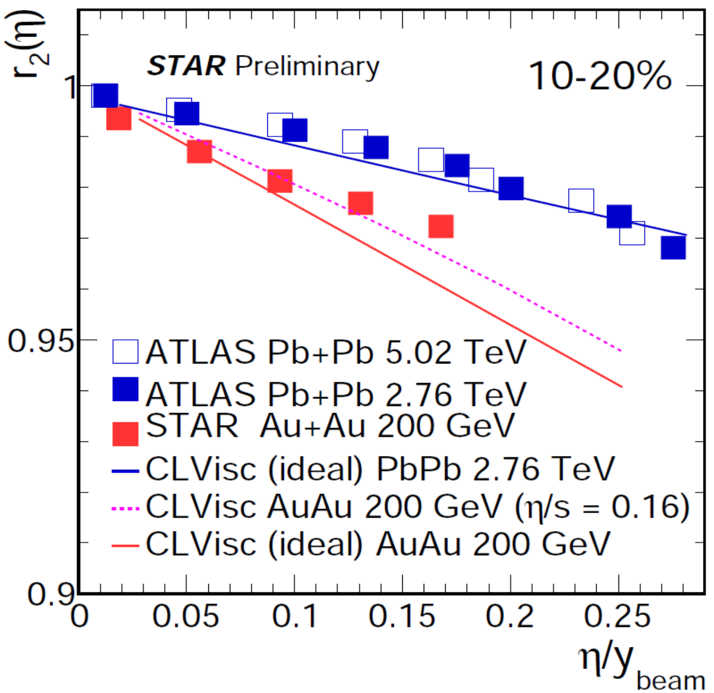
credit: B. Schenke

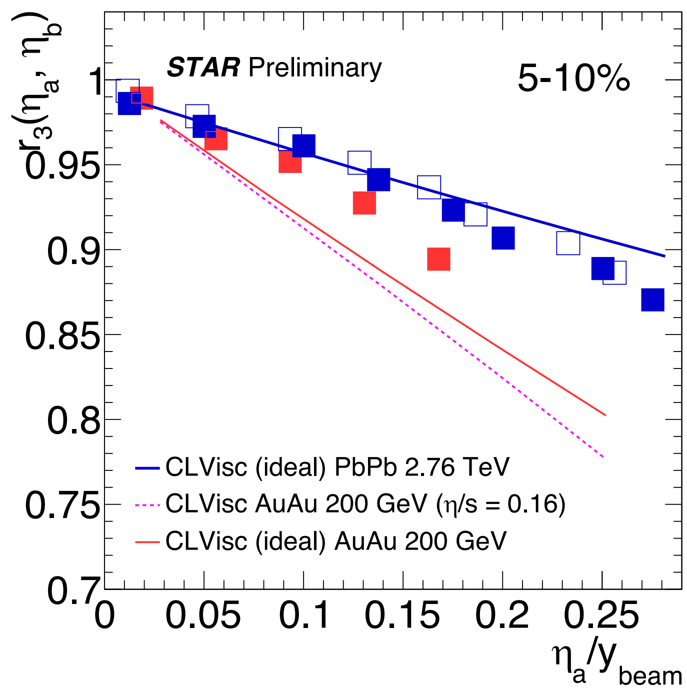


Forward Rapidity Physics: Opportunities with AA

$$r_n(\eta) = \frac{\langle V_n(-\eta) V_n^*(\eta_{ref}) \rangle}{\langle V_n(\eta) V_n^*(\eta_{ref}) \rangle} = \frac{\langle v_n(-\eta) v_n(\eta_{ref}) \cos\{n[\Psi_n(-\eta) - \Psi_n(\eta_{ref})]\} \rangle}{\langle v_n(\eta) v_n(\eta_{ref}) \cos\{n[\Psi_n(\eta) - \Psi_n(\eta_{ref})]\} \rangle}$$

- Measures relative fluctuation between $v_n(-\eta)$ and $v_n(\eta)$
- Sensitive to longitudinal flow asymmetry and event plane twist
- Decorrelation in preliminary STAR data from existing forward detector larger than seen at LHC
- Models with viscosity correction describe r_2 fairly well but discrepancies in r_3





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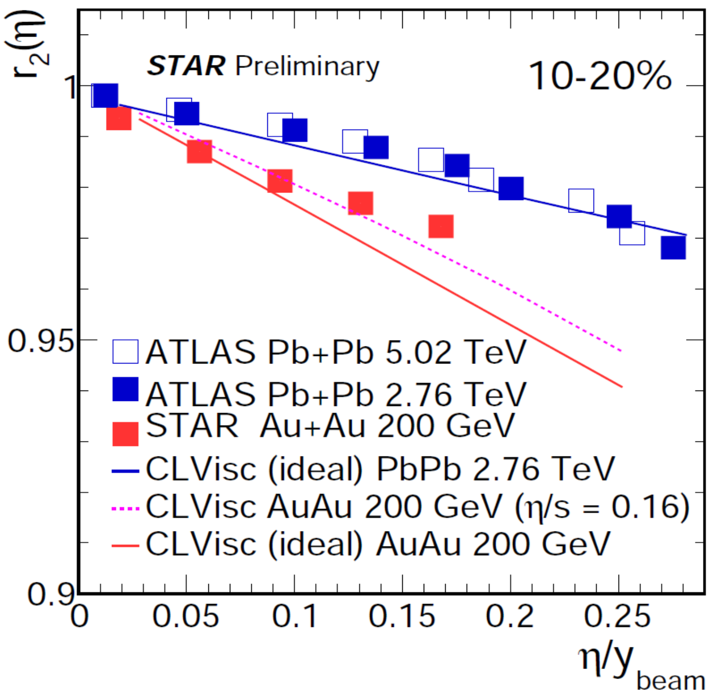


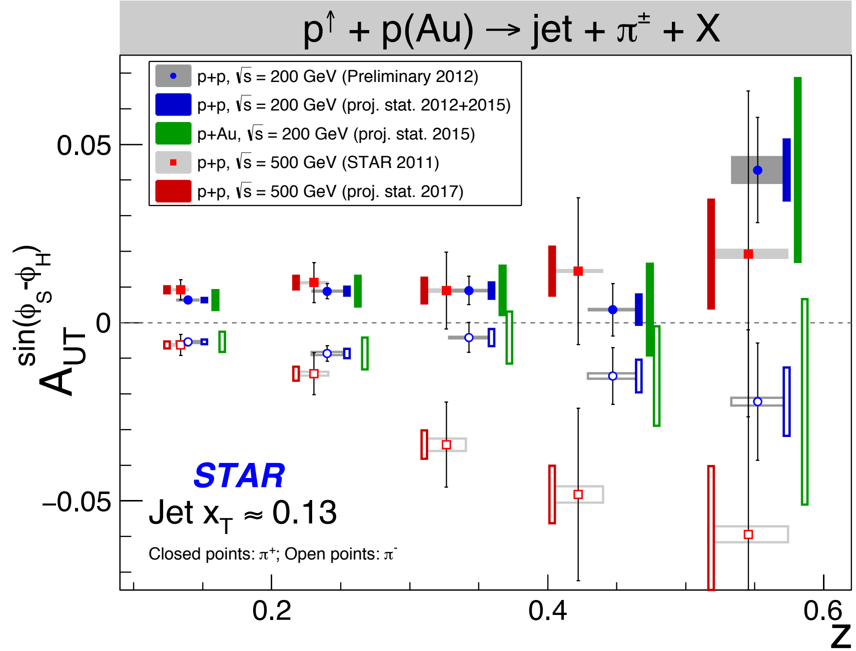
Forward Upgrade:

- Higher statistics and improved detectors
- Additional probes: decompose in Legendre polynomials, i.e. a_{mn} coefficients
- Lower $\sqrt{s}$
  - Energy-dependence of long. fluctuations
  - Constrain hadronic transport models

Opportunities at Midrapidity

Related Studies at Midrapdity

- Fragmentation functions in pp and pA, e.g. through hadrons within jets
- Nuclear modification of hadronization, e.g. through Collins effect in pA



Diffractive Physics

- Ultra-peripheral J/ψ to access spatial gluon dist.
- Dijets in UPC to access gluon Wigner function

Much, much more!
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0669

Summary

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In the words of the RHIC PAC:

- As the physics program that is foreseen for forward physics is substantial, ***full utilization of future polarized proton beam time must be made to realize the proposed forward physics program***.
- RHIC management is encouraged to ***find a way to enhance and include a forward physics program at RHIC***.