Cold QCD studies in (f)sPHENIX

5th Korea-Japan EIC collaboration meeting,
October 12, 2019,
Sejong University, Seoul

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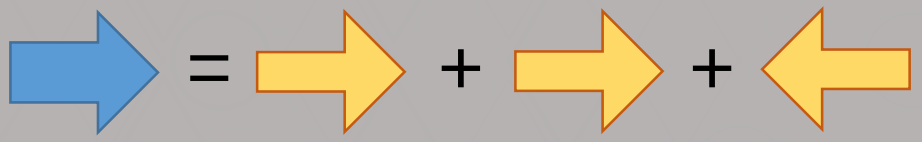
(RIKEN)

Outline

- Helicity and spin sum rule
  - Gluon polarization now
  - Near future plans
- Transverse spin
  - Transversity and tensor charge
  - Sivers/Initial state related measurements
- Realization of these plans in fsPHENIX

The Spin sum rule

Naïve Quark Model picture: 3 valence quarks make up the spin of the nucleon:



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$ Jaffe, Manohar

$$\Delta\Sigma = \int dx \left[(\Delta u(x) + \Delta\overline{u}(x)) + (\Delta d(x) + \Delta\overline{d}(x)) + (\Delta s(x) + \Delta\overline{s}(x))\right]$$

- $\Delta\Sigma$ and ΔG can be accessed in longitudinally polarized (SI)DIS and pp collisions
- Spin Crisis (1980s): Quark spins contribute only little
- Where is the rest of the spin? Gluons? Lower momentum fractions? Orbital angular momentum?

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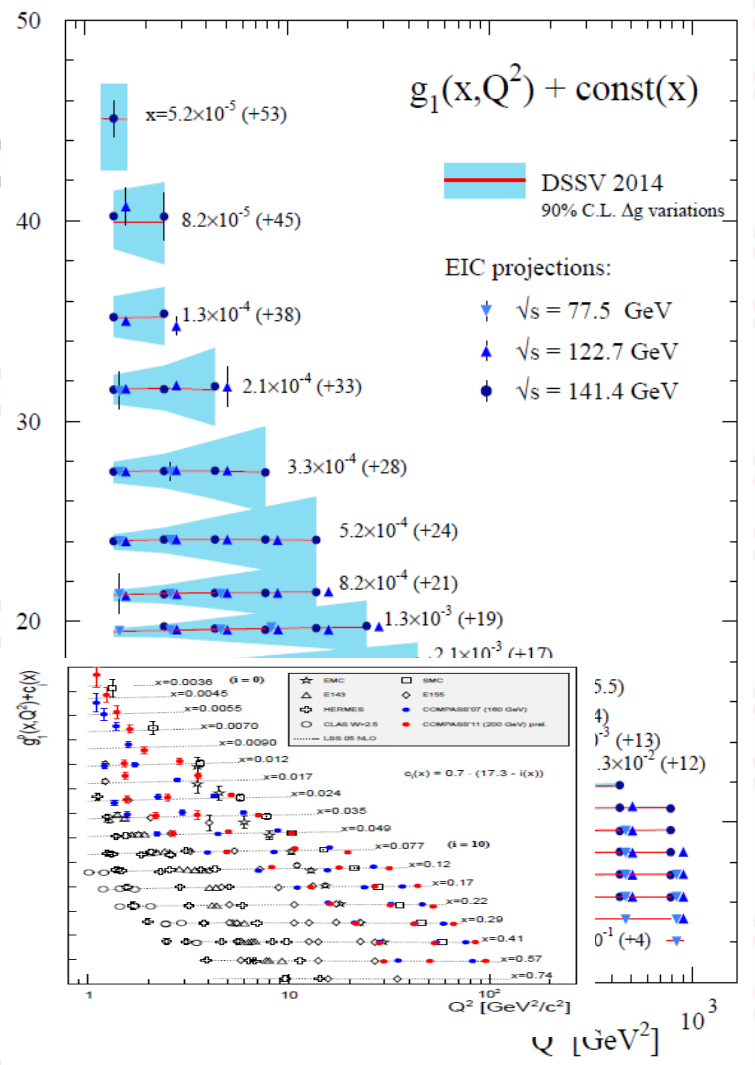
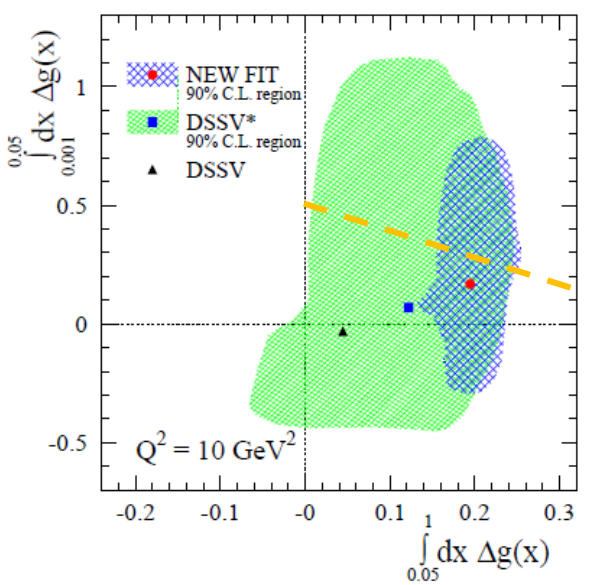
Inclusive DIS and Δg



[PRD92 (2015), 094030]

- Currently no lever arm to access gluon helicities via DIS (lepton-proton scattering)
- Dedicated high-Pt or charmed hadron analyses statistically or systematically limited
- Hadronic collisions access gluons at leading order
- Nonzero gluon polarization found from 200 GeV RHIC data
- Later at EIC: Several orders of magnitude of Q^2 at same x allows to determine gluon helicity via DGLAP evolution
- RHIC can still improve at lower and higher x!



DSSV 2014

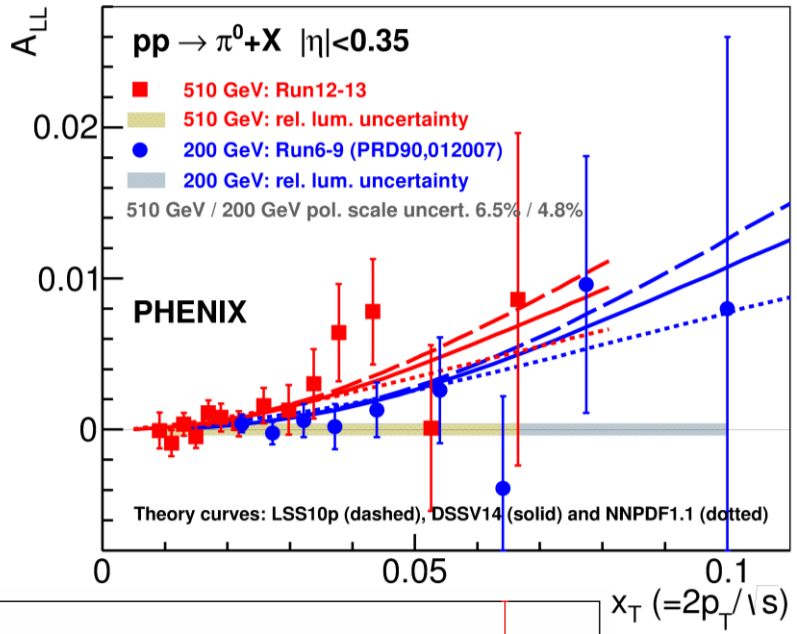
$\Delta g(x)$

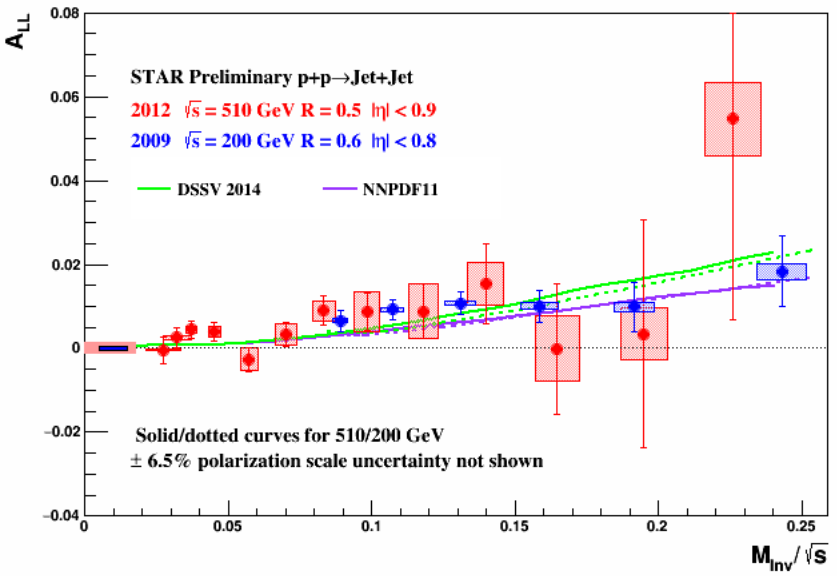
Gluon spin to lower x: higher energies

- Nonzero gluon polarization established with RHIC √s = 200 GeV data
- RHIC 510 GeV data (>2011) now confirms it in workhorse (jet, pion) measurements
- Extend access to lower x by higher energy (now~ 10^{-2})

PHENIX result:
RIKEN press release
BNL and DOE research highlights
DOE labs 2016 research highlights report

PRD 93 (2016) 011501





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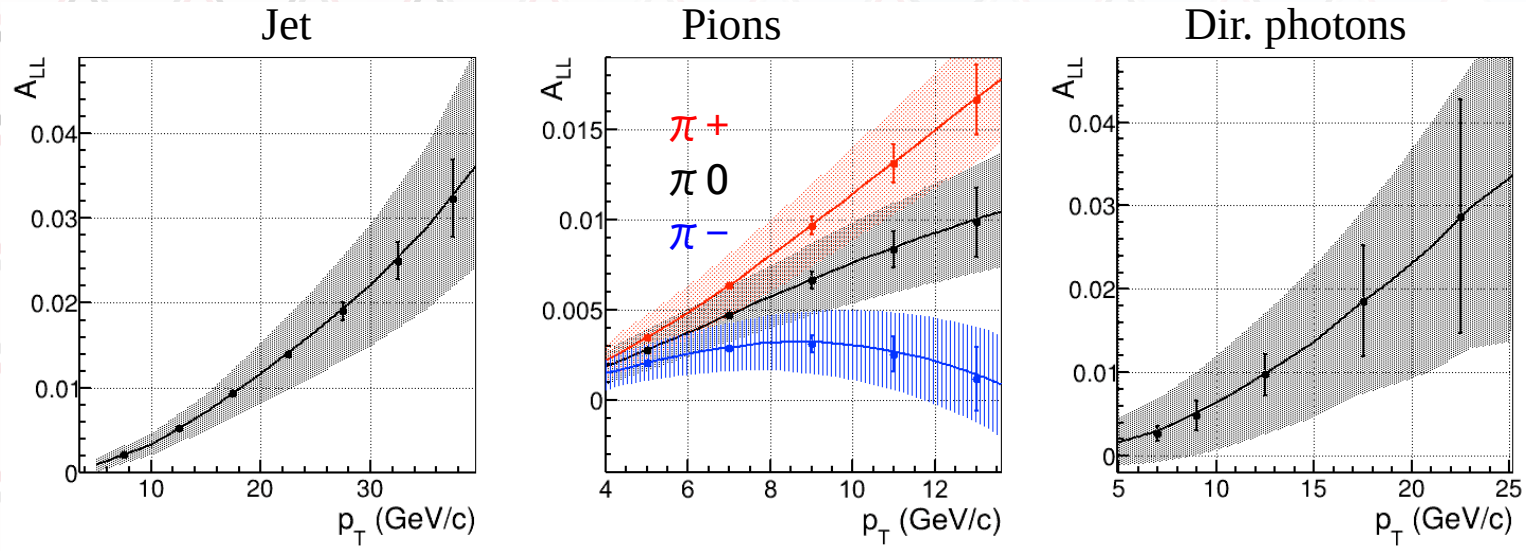
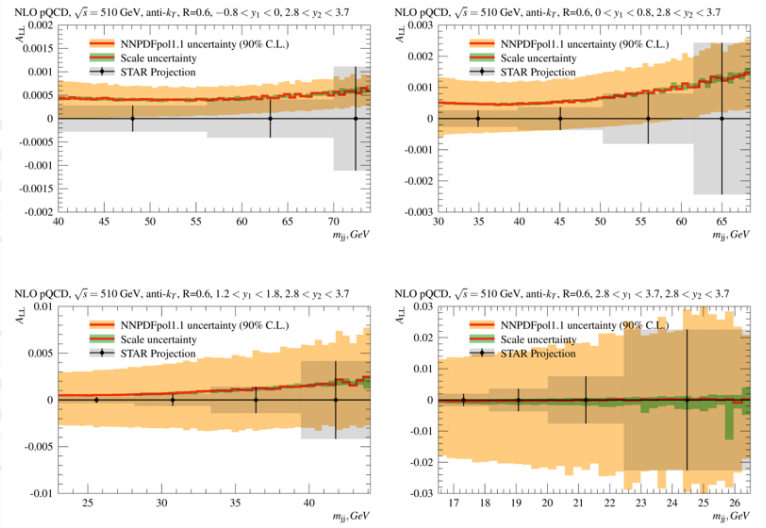
Δg at higher x: central sPHENIX

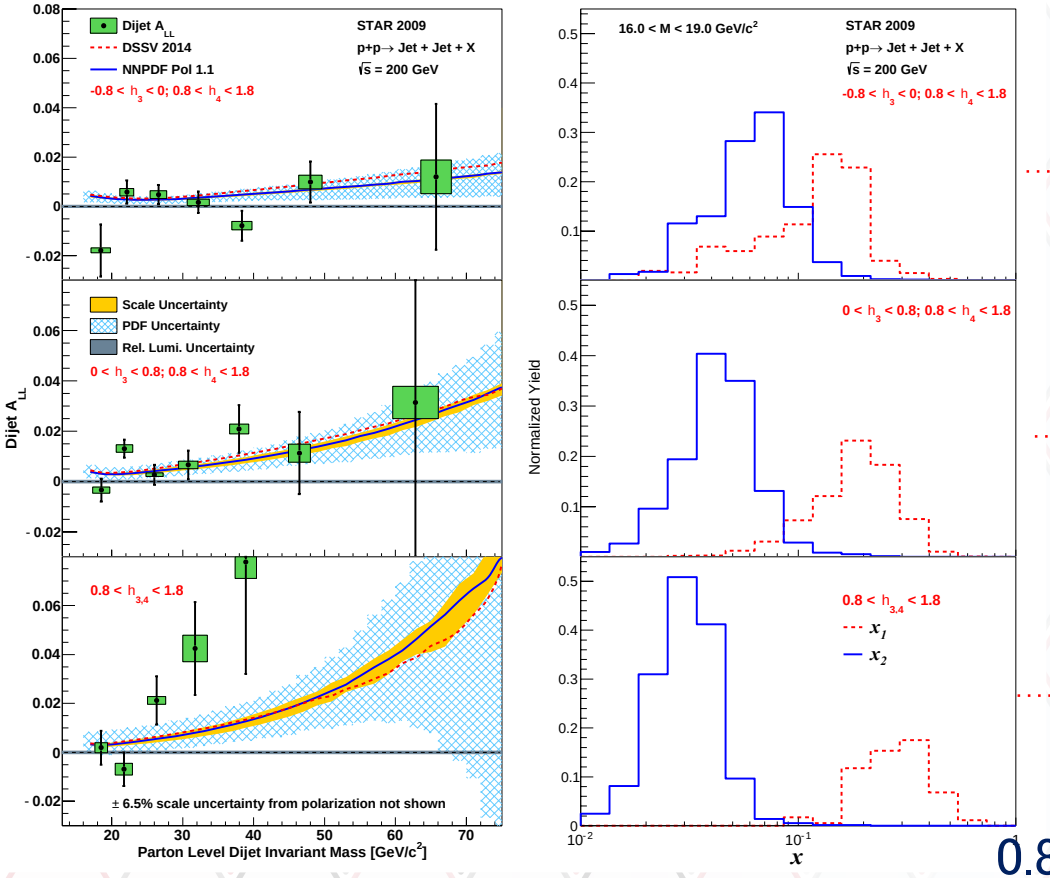
√s=200 GeV |η|<1.1
L=700 pb^{-1} P=0.6
Theory curve and band: NNPDF

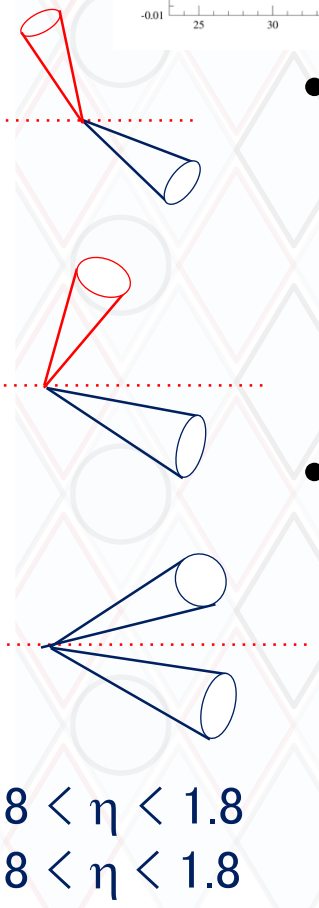


- High data taking capabilities bring era of high precision ΔG measurements:
  - Will crucially improve ΔG constraint at x>0.05
  - Δgdx-integral at x>0.05 expected to be improved by a factor >4
  - Multiple channels with different theoretical and exp. uncertainites
  - Crucial syst. cross check

Very forward di-jet A_{LL}s to probe low-x Δg







$0.8 < \eta < 1.8$
$0.8 < \eta < 1.8$

- Find di-jets in very asymmetric collisions to access lower x
- Extend exisiting measurements to rapidities of 2-4 (fsPHENIX) for values as low as 10^{-3}

All figures taken from STAR

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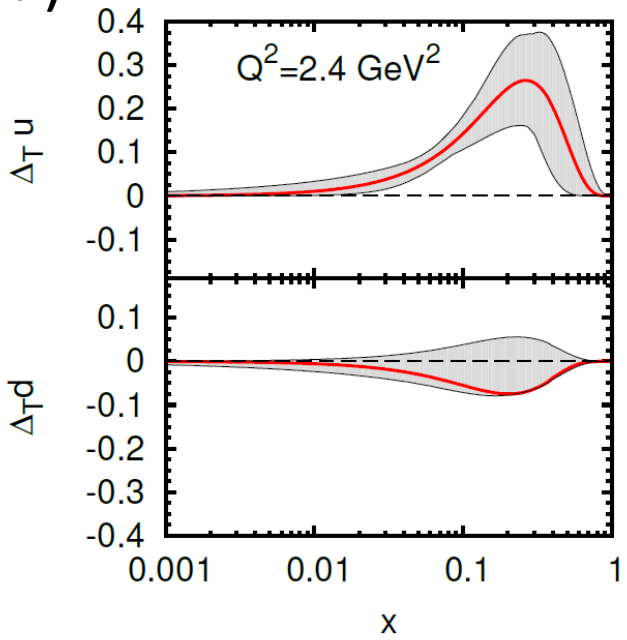
Transverse spin

Transversity

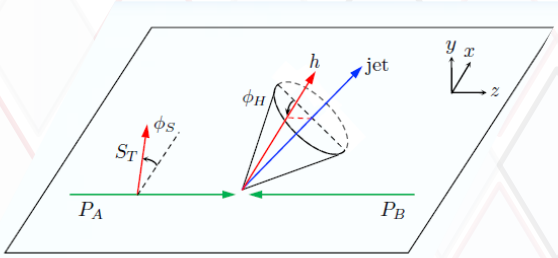
- Leading twist collinear PDF
- Chiral odd → requires chiral odd counterpart:
  - Antiquark transversity (DY)
  - Collins Fragmentation function (TMD)
  - Interference Fragmentation function
  - Polarized FF $H_1(z)$
- Nonzero Transversity discovered at HERMES, since also measured at COMPASS

- CollinsFF and IFF measured at Belle, BABAR and BesIII
- Recently also accessed at RHIC (both Collins and IFF)



PRD92 (2015), 114023

STAR Collins FFs

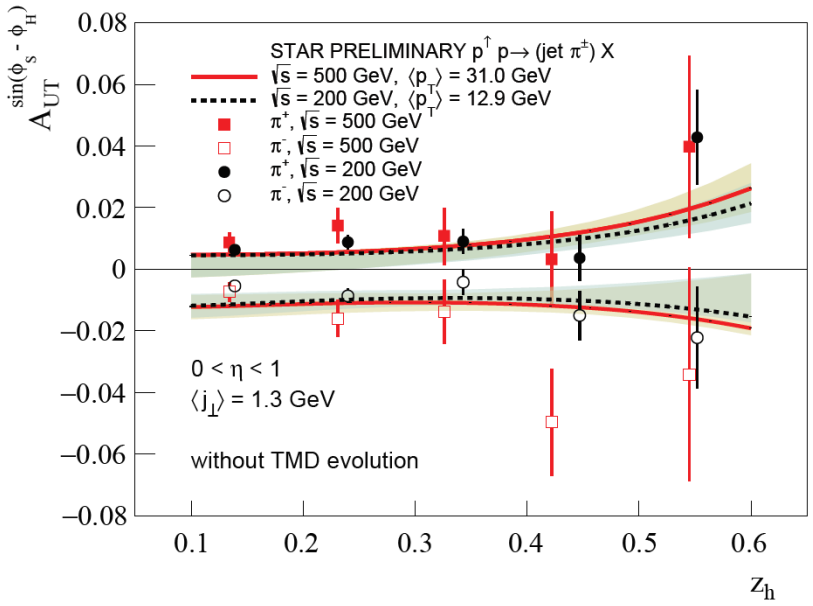


$$h_{1,q}(x,p_t) \otimes H_{1,q}^{\perp,h}(z,k_T)$$

- Nonzero Collins asymmetries (hadron in jets) at central rapidities
- Substantial theoretical progress for hadron in jet measurements
  - unpolarized: Kaufmann et al.
  - polarized Kang et al.
- STAR similar size for roughly same x and kt

  → evolution effects moderate?

Kang, Prokudin, Ringer, Yuan:
PLB774 (2017) 635-642
STAR 200: **Int.J.Mod.Phys.Conf.Ser. 40 (2016) 1660040**
500 GeV: PRD97 (2018) 032004



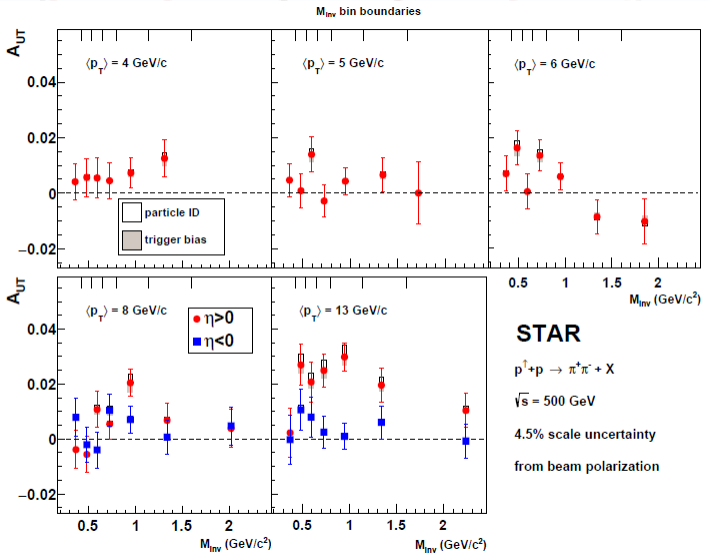
STAR IFF results

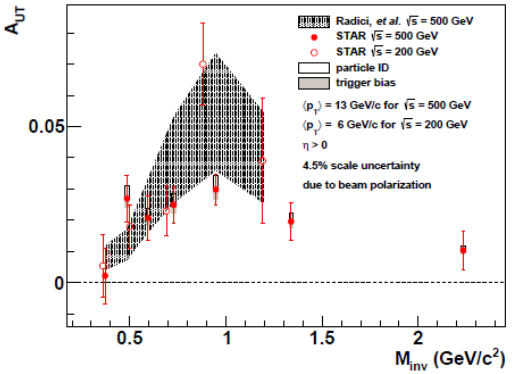
- Now both 200 and 510 GeV results finalized
- Both with substantial nonzero effects at:
  - Forward rapidities
  - Higher Pt
  - Masses around 1 GeV
- First global fit using SIDIS+Belle+STAR

  → helps improve transversity uncertainties

  →but gluon DIFFs not well known

STAR
510 GeV: PLB 780, 332 (2018)
200GeV: PRL 115 (2015) 242501



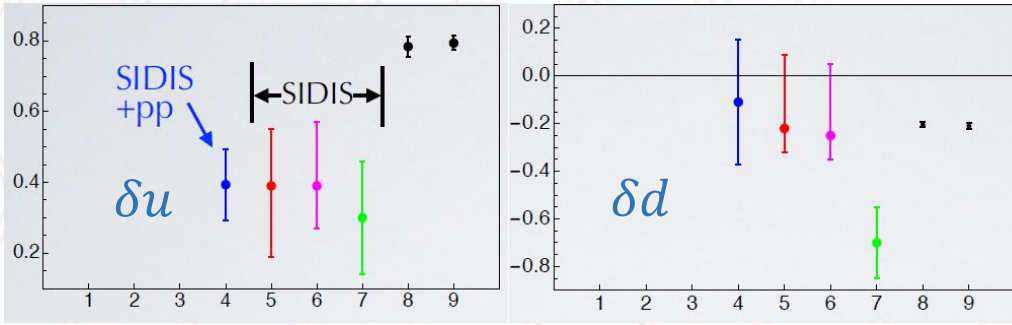


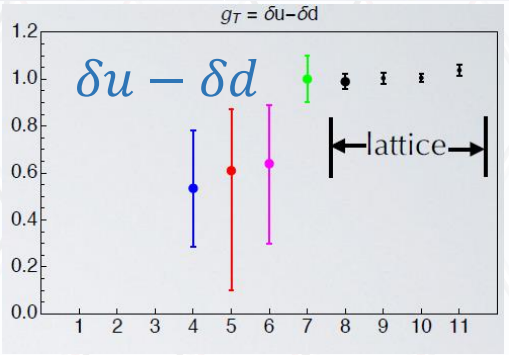
Radici and Bacchetta, PRL 120, 192001 (2018)

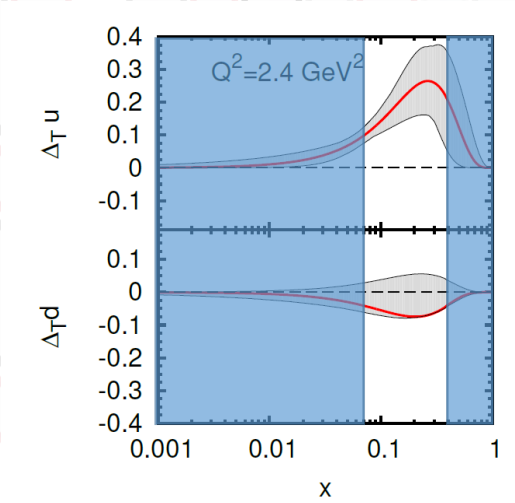
The tensor charge and BSM

- Many new interactions would require Tensor couplings
- These could be indirectly visible via measurements of the tensor charge/transversity
- Confident Lattice calculations to look for discrepancies

Radici@INT

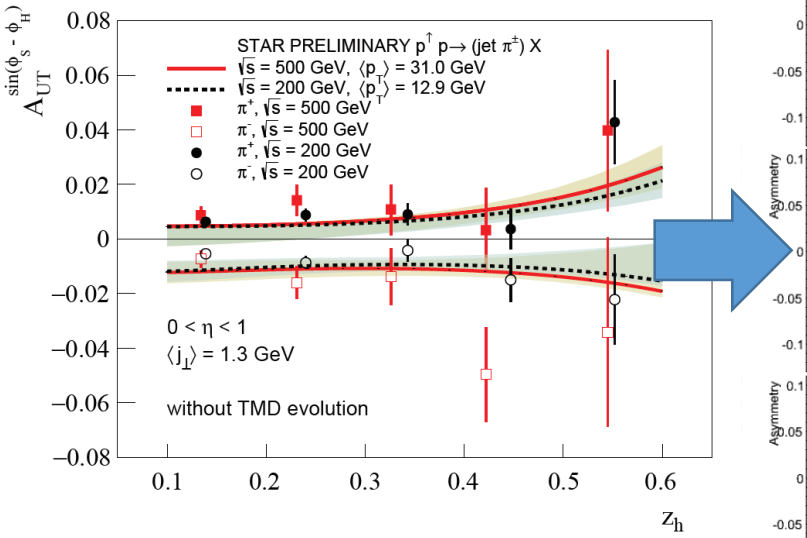


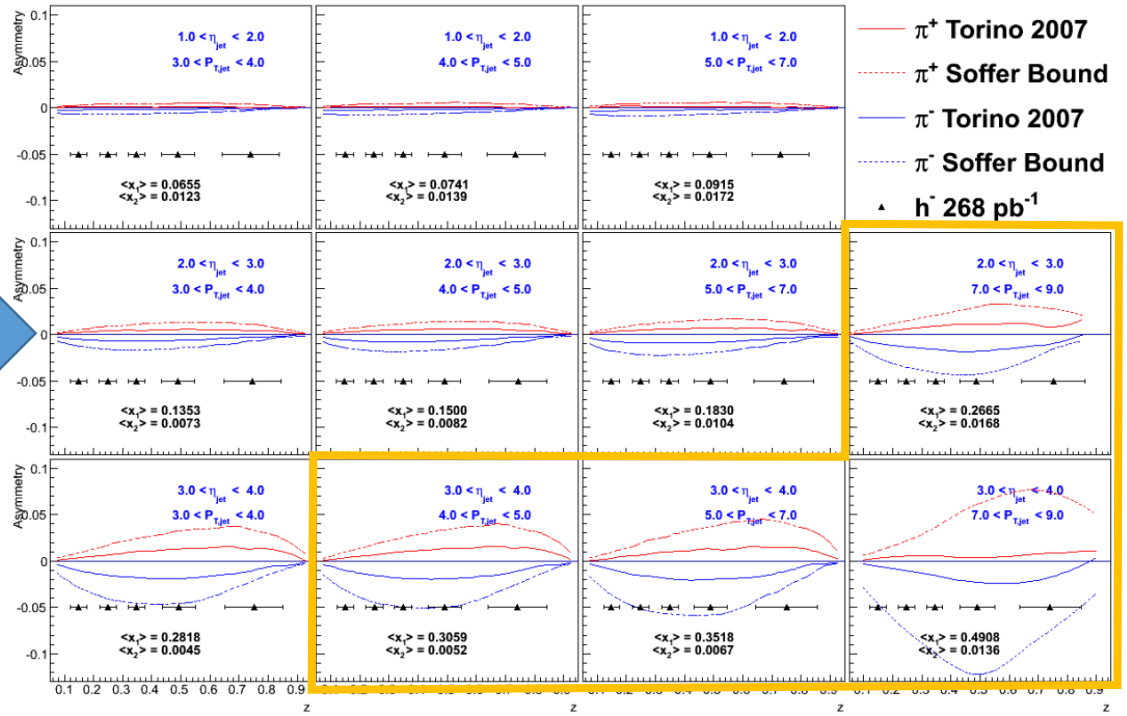




- Currently still large uncertainties due to knowledge on fragmentation functions
- High and low x data missing

Jets and Polarized Jet Structure



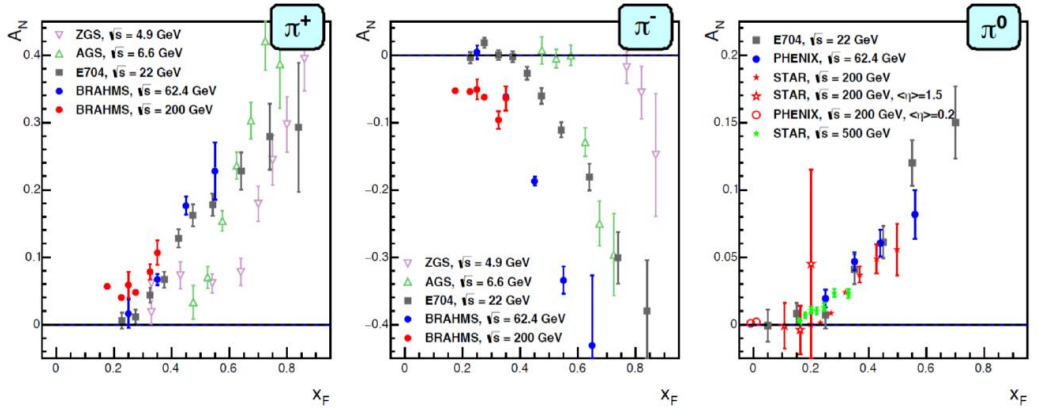


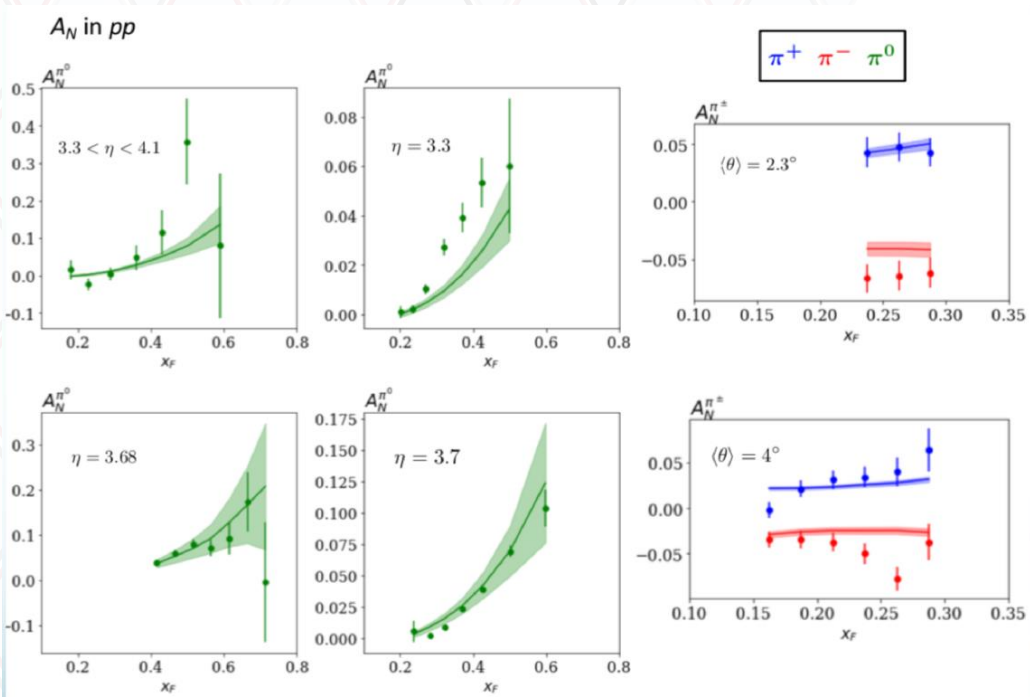
Future high luminosity measurements will allow detailed differential study of spin-dependent fragmentation

Forward measurements will cover previously unmeasured high-x region (>0.3) and at really perturbative scales

Transverse spin asymmetries in p+p(A)

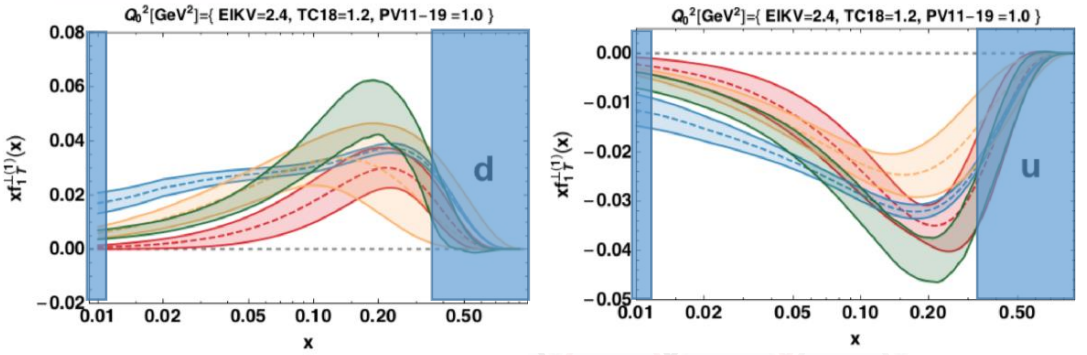
- Large single spin asymmetries in forward region at many collision energies
- Origin of ANs:
  - pQCD predictions small
  - TMDs not directly applicable
  - Higher Twist functions related to TMD moments (Sivers function, transversity x Collins FF, BM x Collins)
- Current understanding: final state contribution dominating (Transversity x Collins)
- First truly global fits of SIDIS Collins, e+e-Collins and RHIC AN data ongoing (Kang, Gamberg, et.al)
- Adds sensitivity to high-x!



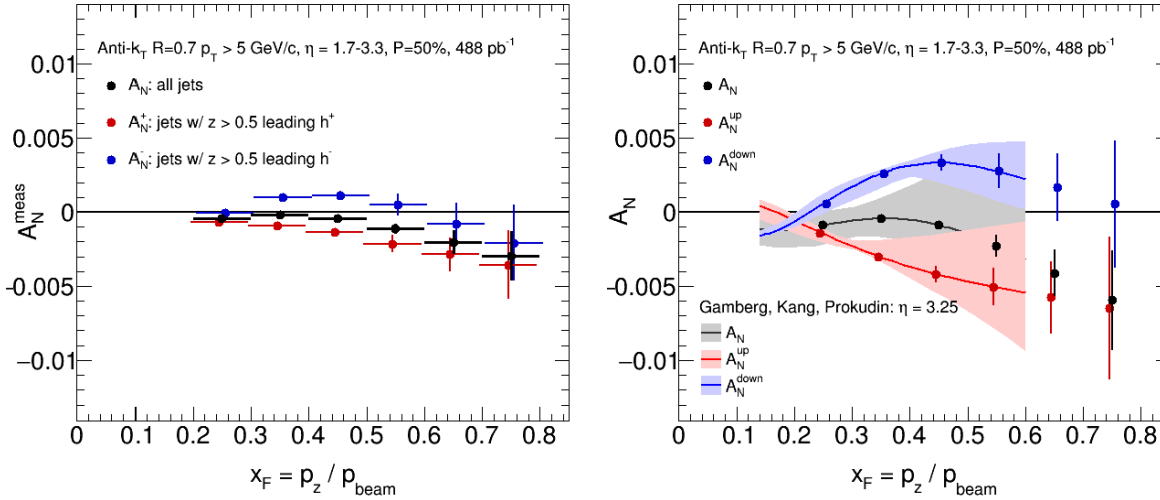


Initial state ANs

- Forward jet asymmetries mostly sensitive to initial state effects (Qiu Sterman = kt moments of Sivers function)
- Measured asymmetries small due to up and down quark Sivers cancellation
- Use high-z positive/negative hadron requirement to enhance up/down contribution



Charge-tagged measurements would allow u/d enhancement

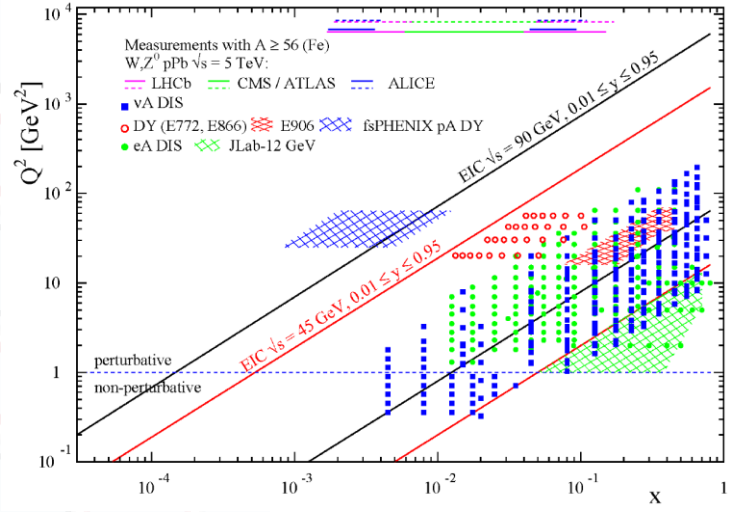


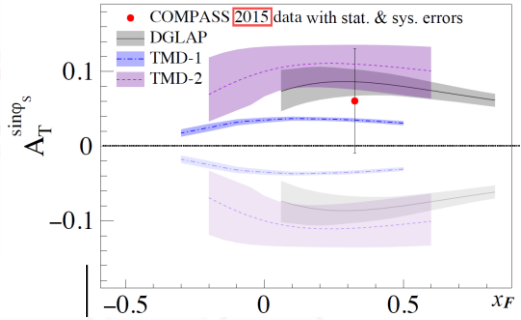
→Nonzero asymmetries expected

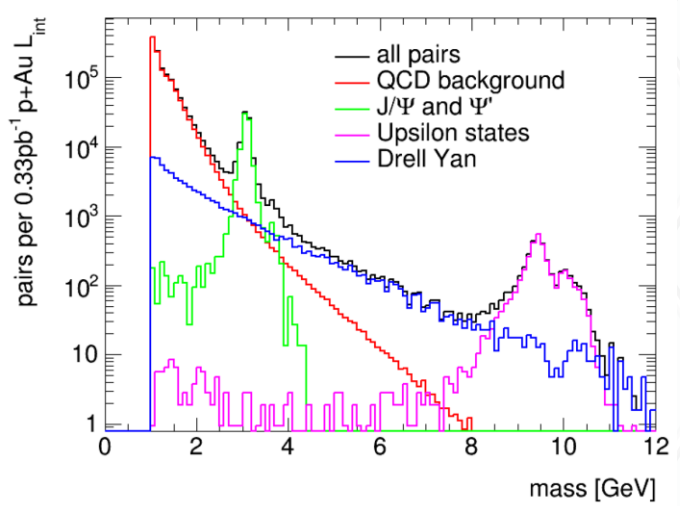
→Indirect test of the Sivers sign change

DY at forward rapidities

- Direct test of Sivers sign change in similar x as SIDIS data
- Full simulations show fsPHENIX well suited to obtain clan DY sample in pp







- Further benefit: baseline for pA measurements to cleanly measure nuclear modification factors for sea and valence quarks

Physics Goals From Cold QCD Plan

- **Key Physics Measurements**:
  - **Jets in polarized p+p (510 GeV):**
    - Kinematics limited in p+p 200 (transverse), better kinematic reach at 510 GeV
    - Jet A_N, angular distribution in jets (h^- good proxy for π^- w/o PID)
    - Di-Jet A_{LL}
  - **nFF's in p+A:**
    - Important measurement on the road to the EIC
  - **DY and Direct Photons in p+A:**
    - Measurements of saturation, A-scan required
  - **Diffraction in polarized p+p (200 GeV):**
    - A_{UT} from single-diffractive events (pol. proton breaks up).
  - **Ultraperipheral Collisions in p+Au:**
    - p-shine (unpolarized): gluon impact parameter distribution via J/Ψ
    - Au-shine (polarized): access GPD E_g via J/Ψ production (A_{UT})
      - Set the scale for a program to measure GPD E_g at the EIC

For many of these measurements RHIC offers *unique* capabilities

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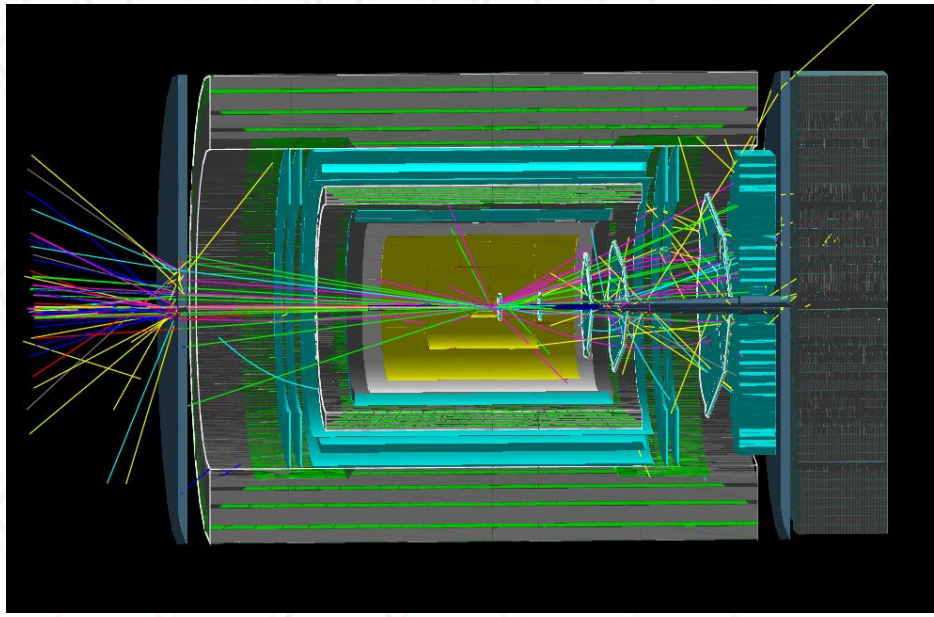
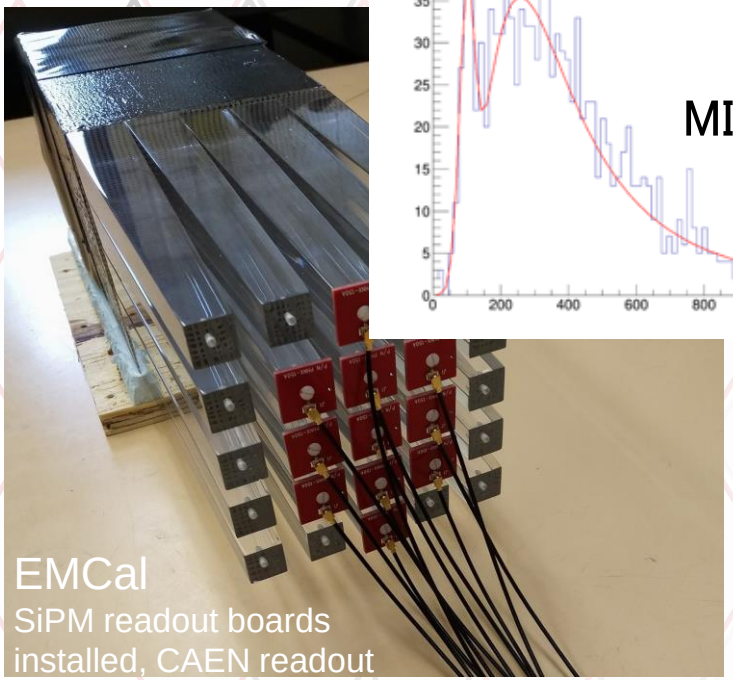
Forward fsPHENIX

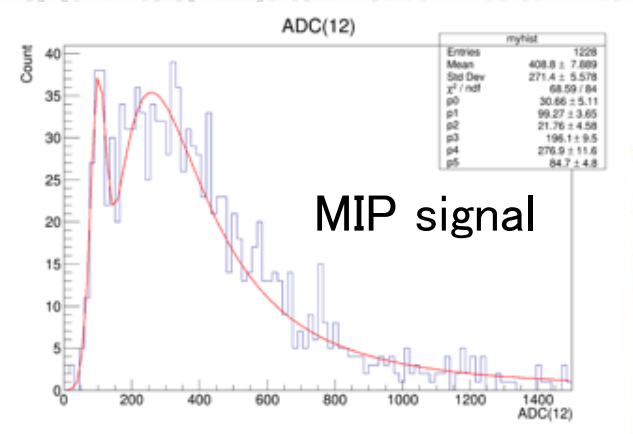
- sPHENIX detector (-1.1<η<1.1):
  - 1.4T Babar magnet
  - Central TPC + MAPS vertex tracker
  - EM+HCAL
  - CD1/3a in Fall 2018
- fsPHENIX (2<η<4):
  - Reuse PHENIX MPC, EMCal or cut up E864 Calorimeter (energy measurement of electrons and photons)
  - New HCAL (joint development for STAR/fsPHENIX/EIC led by UCLA – energy measurements for hadrons, needed for jet measurements)
  - Tracking detectors(GEMs or sTGCs: momentum measurement)
- Most detectors directly useable for eRHIC

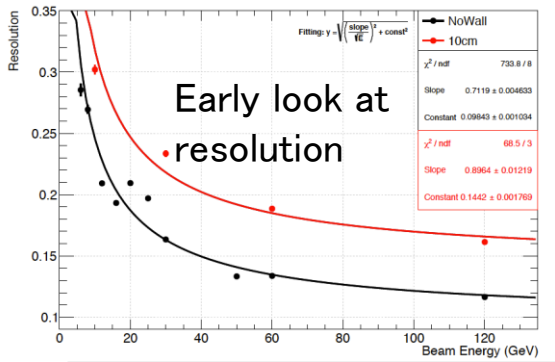


- For spin and CNM interest in Forward rapidites:
  - origin of large asymmetries,
  - high/low x reach
  - jet transverse asymmetries (flavor enhanced or Collins),
  - DY/photons in pA for nuclear /gluon PDFs
  - Hadronization in medium

Forward Arm Developments

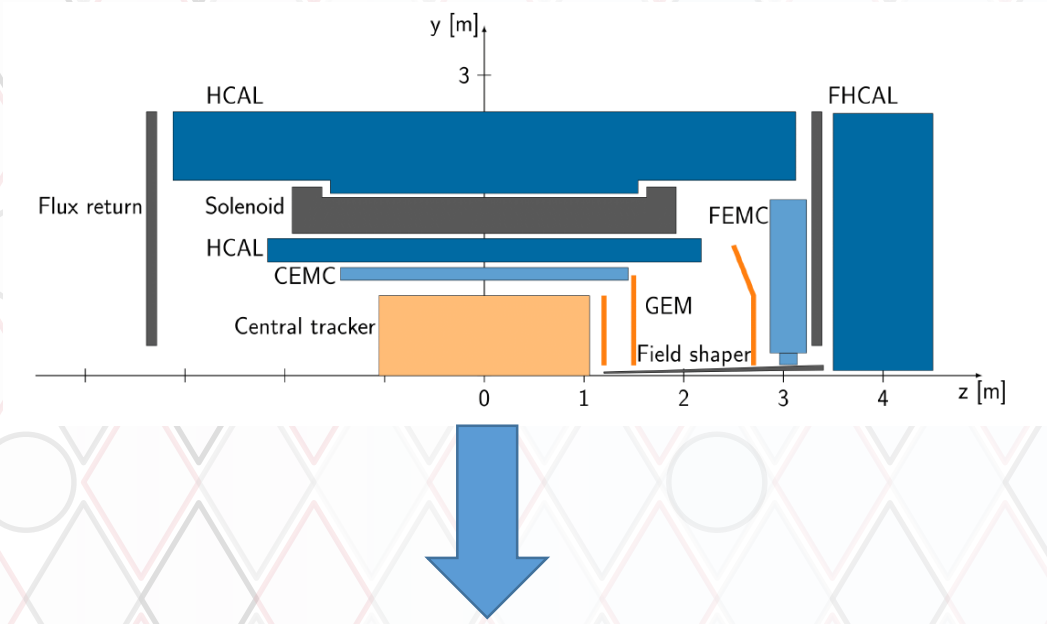




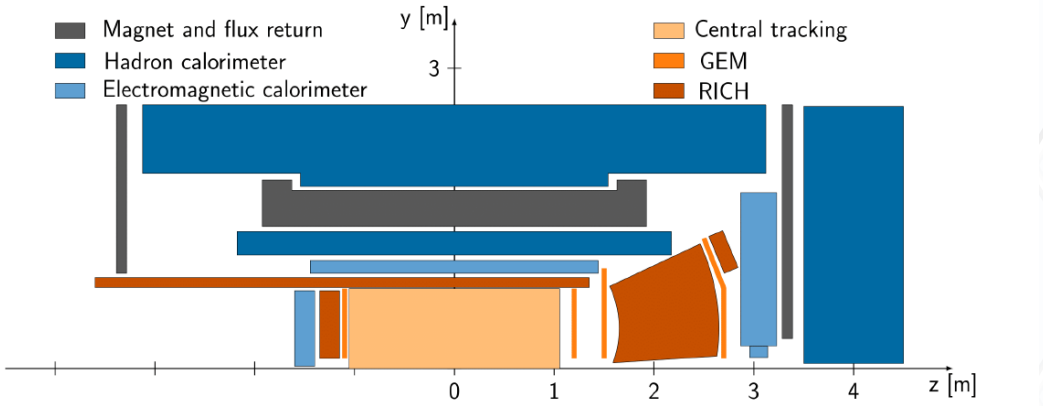


- Cut E864 module for use as a high granularity EMCal - cosmic tests ongoing at Iowa State University
- Hadronic calorimeter test beam recently finished by RIKEN

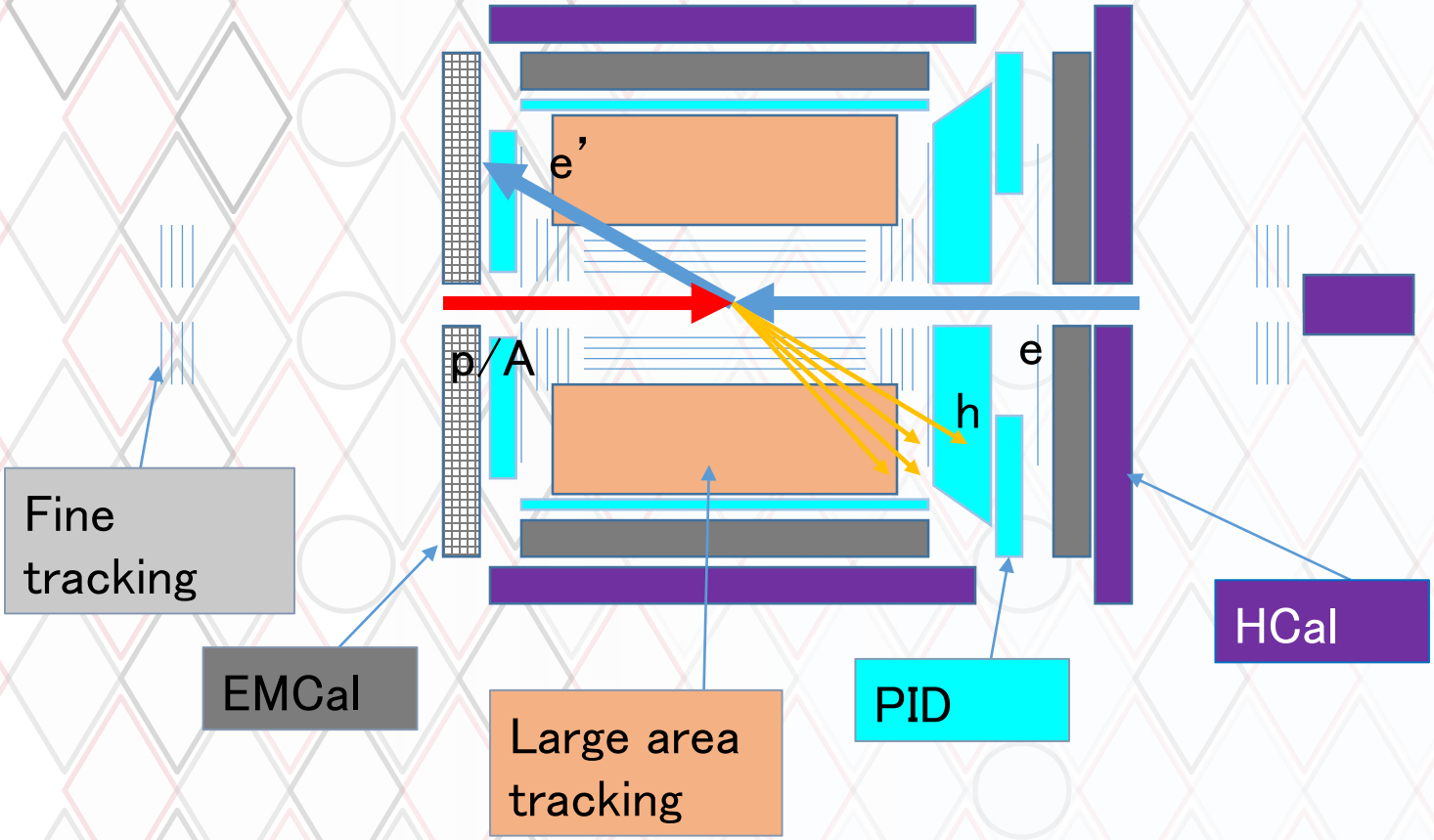
fsPHENIX detector →ePHENIX detector



PID and electron side are added



The general strawman EIC detector



Summary

- The knowledge of the nucleon as the simplest bound state of QCD (and visible matter) still needs to be improved to understand QCD
- RHIC provides substantial insights:
  - Nonzero gluon Polarization, now extracted until x>0.001
  - Asymmetric polarized light sea
  - Two new methods to access transversity
  - Interesting nuclear effects to transverse asymmetries
- Future at fsPHENIX:
  - Access higher/lower x gluons
  - Precise Transversity measurements → Tensor charge (BSM)
  - Origin of large asymmetries
  - Detector well suited as zero-day eRHIC detector!

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