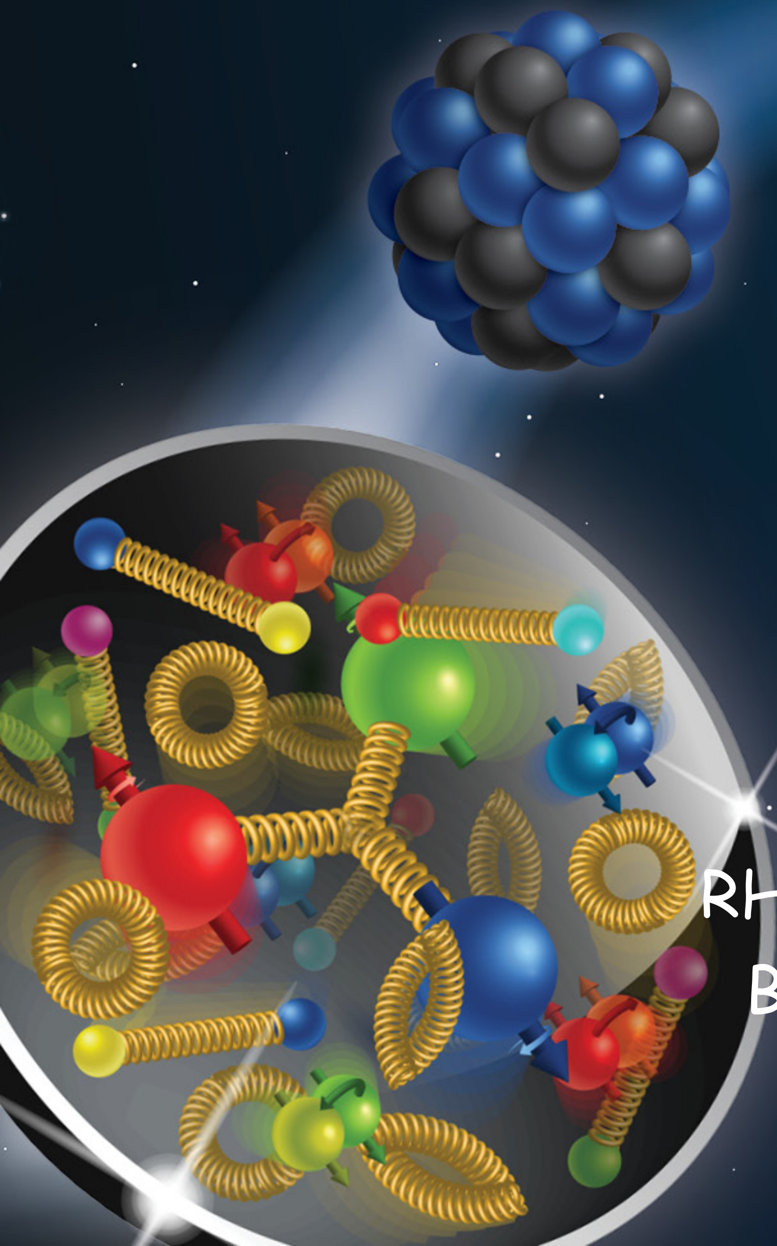
RHIC Spin Program – BNL ME Group

E.C. Aschenauer



Recent p+p and p+A results

RHIC Cold QCD Program: Status & Plans

BNL ME group efforts on EIC program

BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

Why p+p and p+A to access Cold QCD

Complementarity

QCD has two concepts which lay its foundation

factorization and universality

To tests these concepts and separate interaction dependent phenomena from intrinsic nuclear properties

different complementary probes are critical

Probes: high precision data from ep, pp, e+e-

RHIC:

unique program addressing several fundamental questions in QCD
leveraging the world wide only polarized pp collider

→ essential to

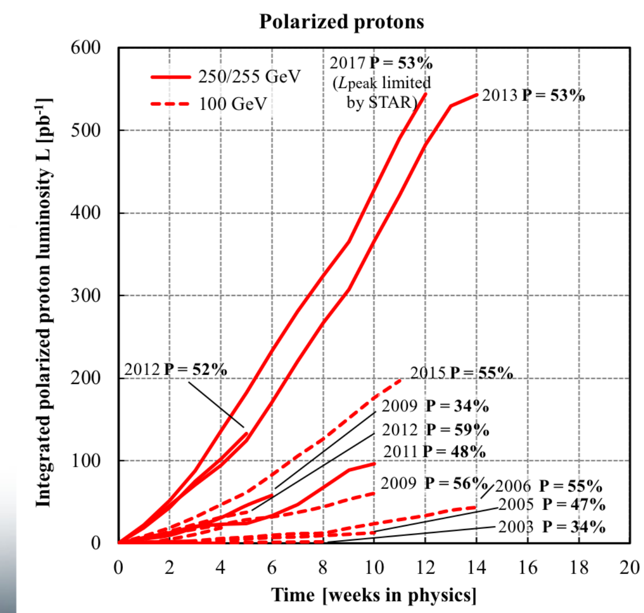
- the mission of the RHIC physics program in cold and hot QCD
- fully realize the scientific promise of the EIC
  - lay the groundwork for the EIC, both scientifically and by refining exp. requirements
  - Test EIC detector technologies under real conditions, i.e SiPMs
  - same kinematics of hadron beams as EIC

→ advantage:

- direct access to gluons through gg and gq → critical for gluon fragmentation studies

Achievements

Many, thanks to the excellent performance of RHIC

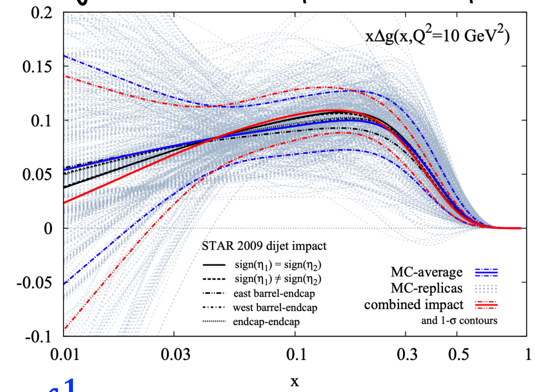


Many already presented in (s)PHENIX, STAR Talks

Achievements on Helicity Structure of Proton

Golden probes for Δg:
Double spin asymmetry A_{LL} for jets, di-jets and π^0
Remember: to increase x-range covered:
go to higher $\sqrt{s}$ (200 GeV → 500 GeV)
or
go to higher rapidity: $-1<\eta<1$ → $-1<\eta<1.8$ ($-1<\eta<4$ with fSTAR)
or both
Di-jets: constrain the shape of the $\Delta g(x,Q2)$
→ 5 papers (10, 11, 12, 13, 19) in the last 3 years

Status 2018 incl. new $\sqrt{s}$= 200 GeV di-jet data at $-1<\eta<1$ and $-1<\eta<1.8$

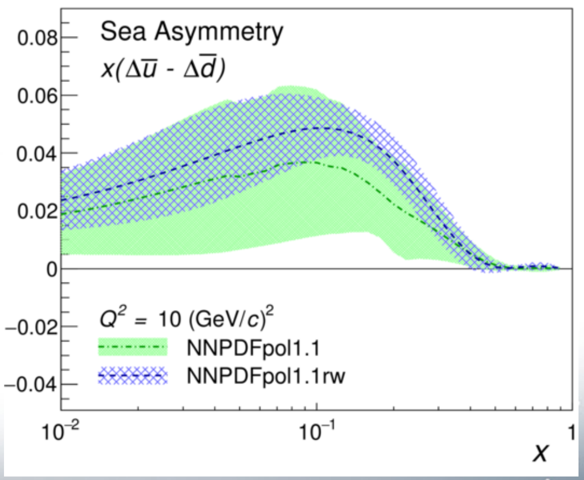


$$\int_{0.01}^{1} dx\Delta g \sim 0.126 \pm 0.023$$

@10GeV

Golden probe for light see quarks $\Delta\bar{q}, \bar{q}$: $W^{+/-}$ production
Remember:
Ws naturally separate quark flavors
→ rapidity: sea vs. valence quarks

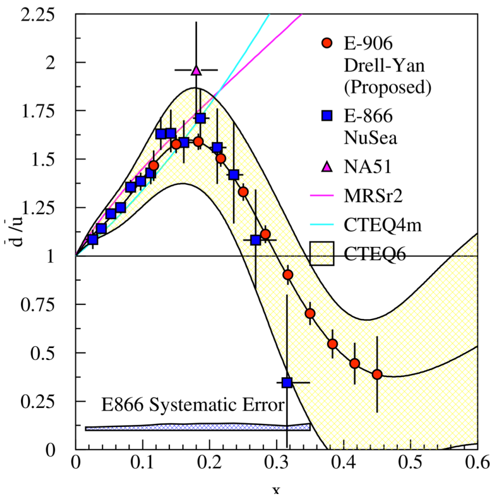
Ws are maximally parity violating
→ Ws couple only to one parton helicity
→ 2 papers (4, 14) in the last 3 years



STAR $W^{+/-}$ Results

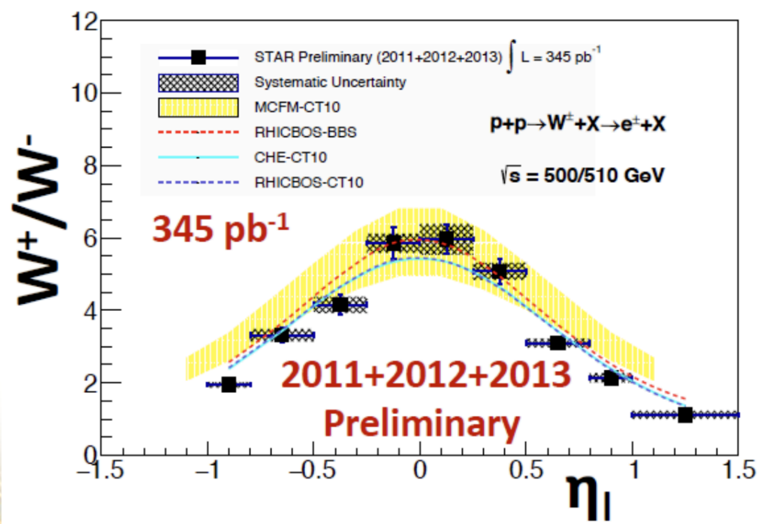
Constrain to unpolarized sea quark PDFs!

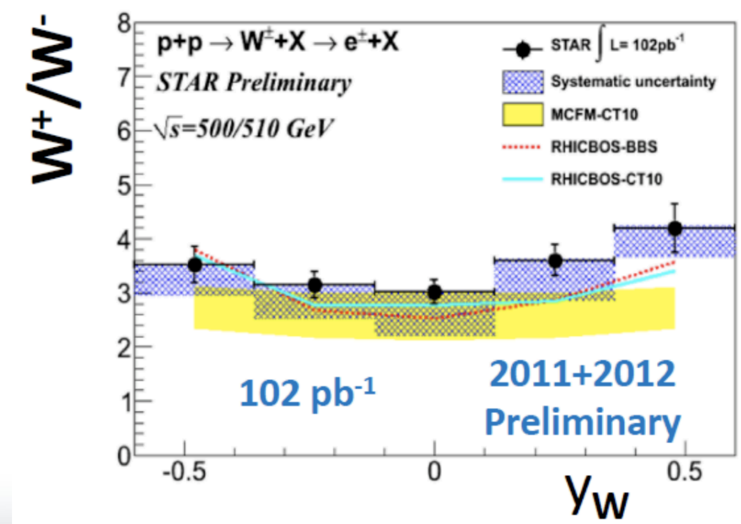
$$A(W^+/W^-) = \frac{u(x_1)\bar{d}(x_2)+\bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2)+d(x_1)\bar{u}(x_2)}$$



Why with STAR@RHIC:

- Theoretically and experimentally extremely clean
- Only experiment reconstructs full W
- Approximate kinematic range at STAR mid-rapidity
  $0.1 < x < 0.5$ for $-1 < \eta < 1$
- For collision energies of $\sqrt{s}$ = 500 GeV
  $\eta = 0$, ($x1 \approx x2$) → $x = M_W/\sqrt{s} = 0.16$
- Good complementarity to LHC ($\sqrt{s}$ = 14TeV)
  → much lower x $x = M_W/\sqrt{s} = 5.7\sim10^{-3}$ ($x1 \approx x2$)

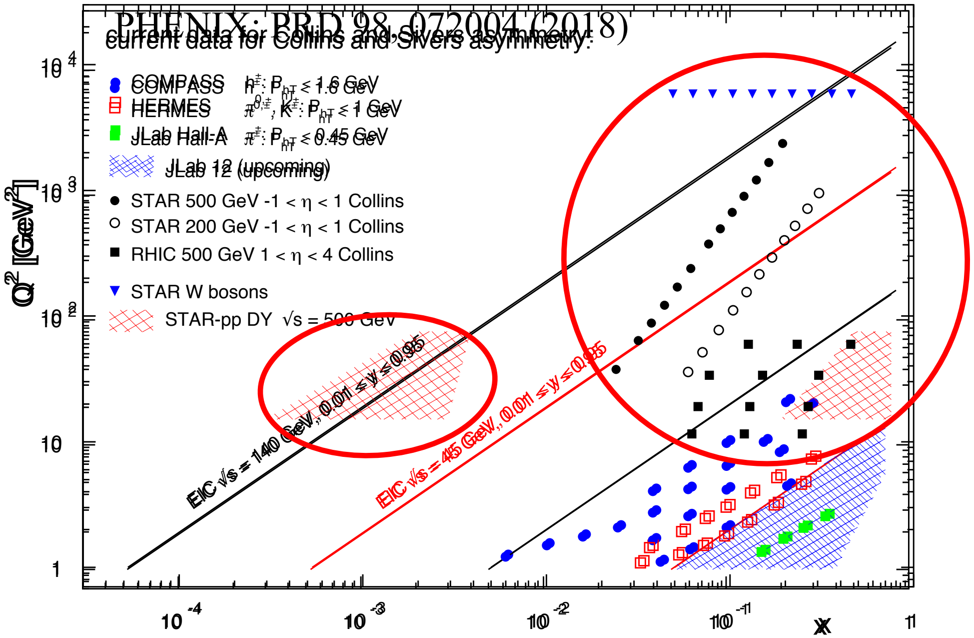




Currently prepared for publication
Run-17 will double the statistics of run-11, 12 and 13

Transverse polarized pp Physics

Transverse Momentum Dependent PDFs

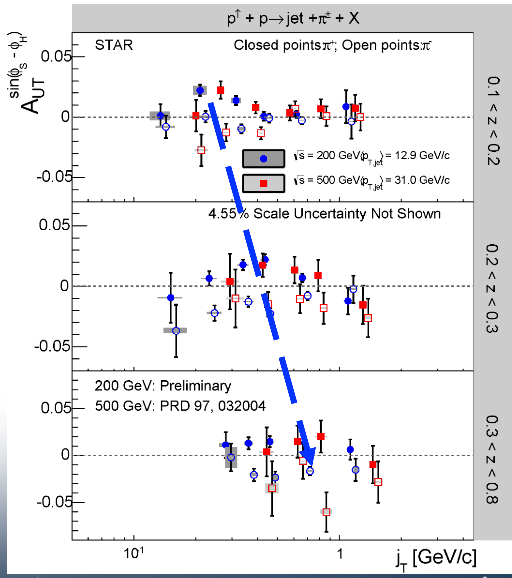


Till today TMDs came only from fixed target data → high x @ low Q^2
need to establish concept at high Q^2 and wide range in x

RHIC unique kinematics: from low to high x at high Q^2 → TMD evolution
only way to access gluon TMDs before an EIC

Recent Results:

- PRD97 (2018), 032004 first data that proof transversity x Collins significant size at low x and high Q^2
- 500 GeV and 200 GeV data show j_T as z increases
  - 200 GeV data prepared for publication



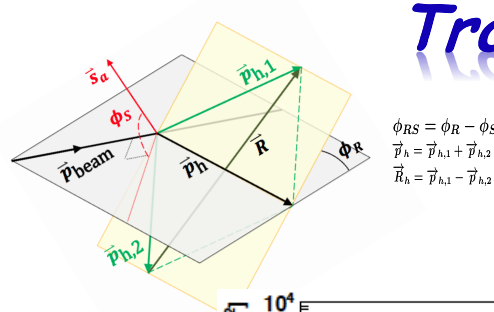
- detailed results about kT and jT devevelopment in pp & pA from PHENIX PRC99 044912 (2019) & PRD 98, 072004 (2018)

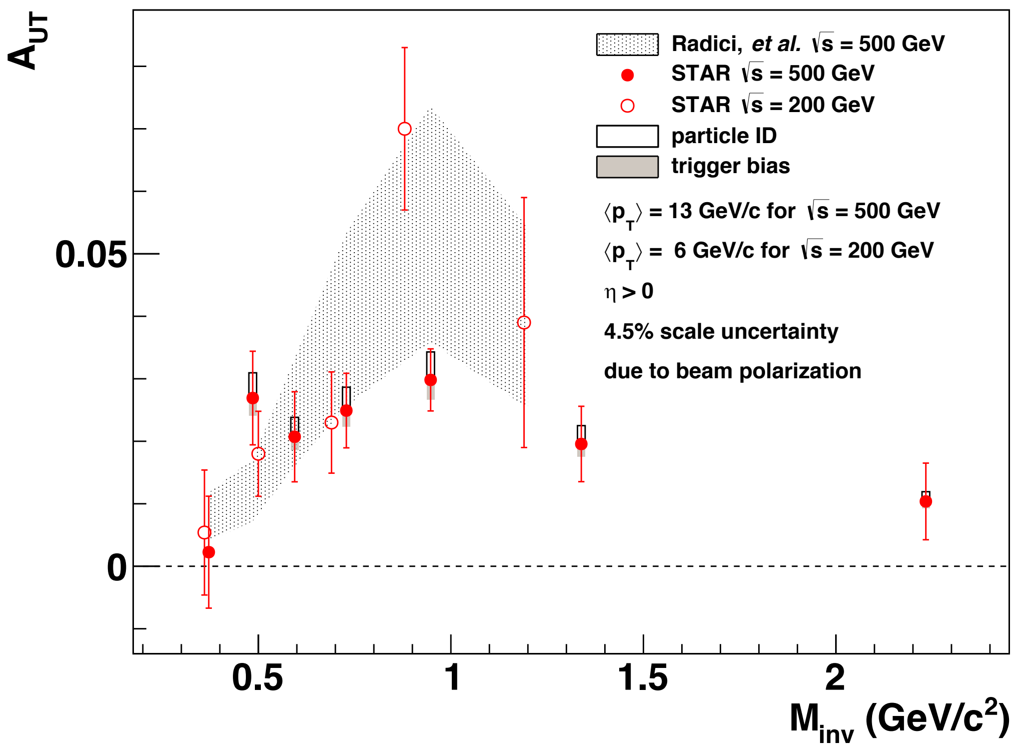
Transversity

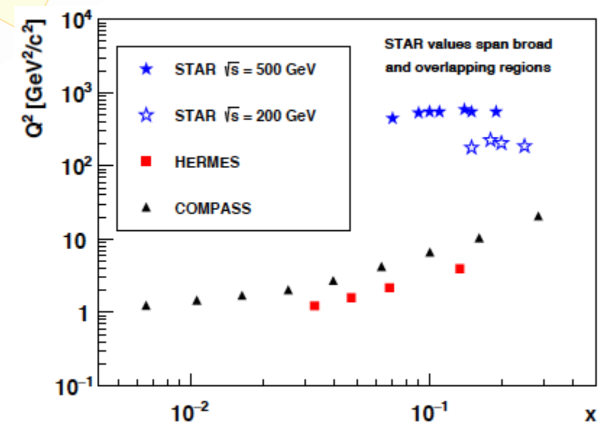
$p^{\uparrow}+p \rightarrow \pi^{+}\pi^{-}+X \rightarrow$ transversity x IFF

survives in collinear framework

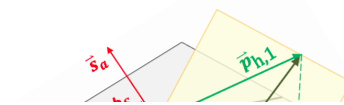
$$A_{UT}\sin(\phi_{RS}) = \frac{1}{Pol}\frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$







- Significant di-hadron asymmetries both at √s=200GeV and √s=500GeV (PLB780 (2018) 332)
- Increasing with p_T
- Access to transversity with a collinear observable
- more data at 200 GeV from 2012 and 2015 (factor 15) and 500 GeV 2017 (factor 14)



$p^{\uparrow}+p \rightarrow \pi^{+}\pi^{-}+X \rightarrow$ transversity x IFF
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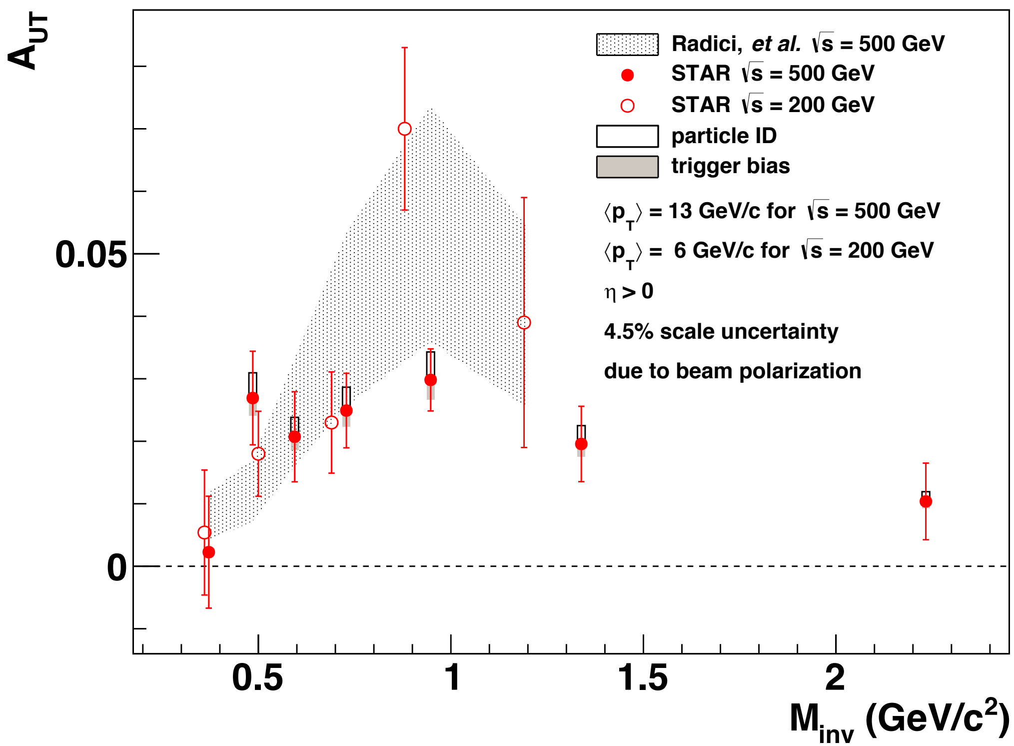

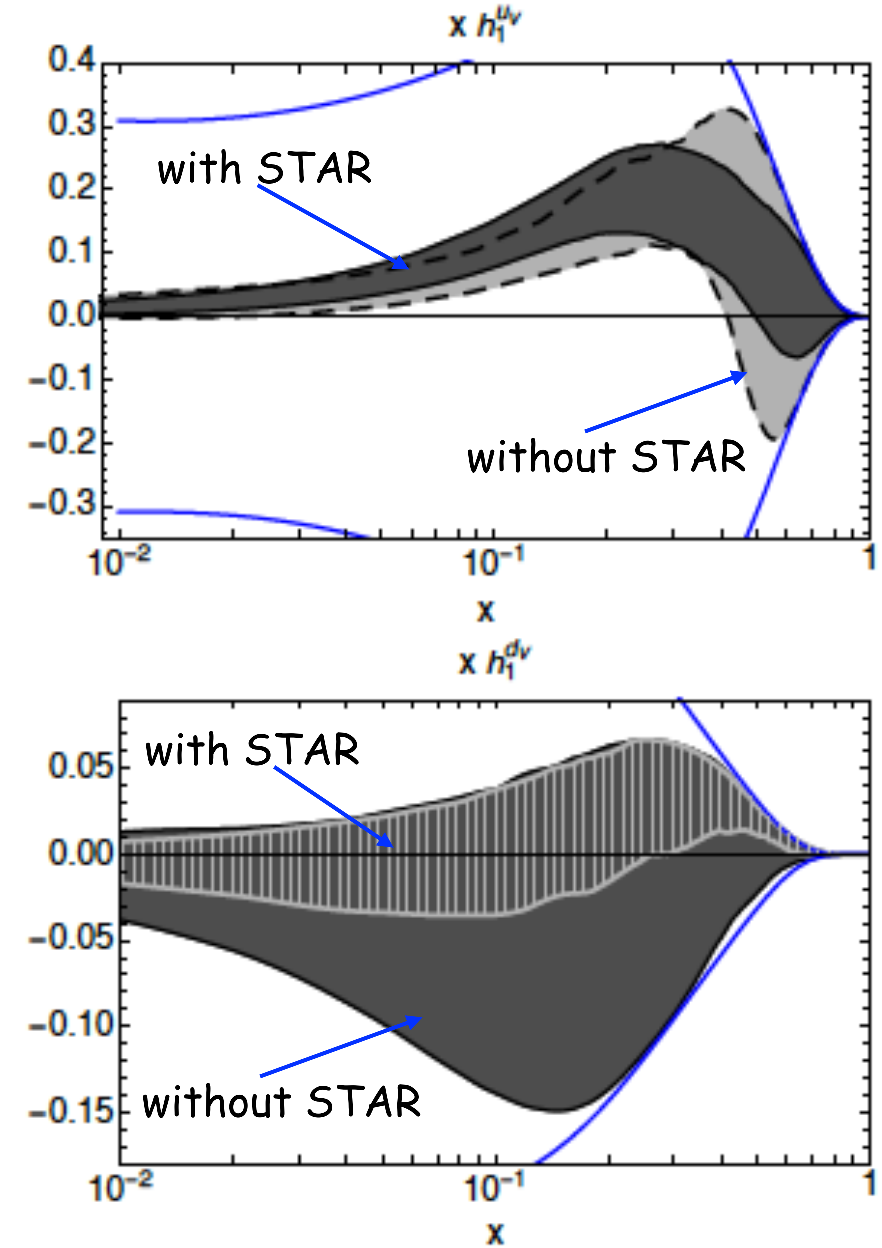

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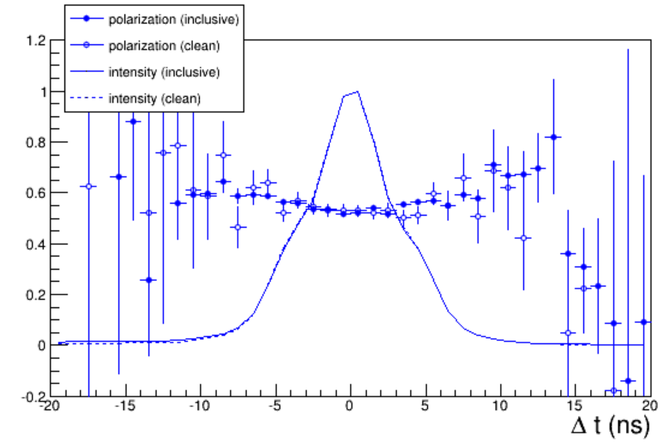
RHIC Proton Polarimetry

- Final beam polarizations for 2017 (255 GeV/c)
  - Absolute beam polarization from atomic hydrogen jet target
  - Polarization during store from fast Carbon polarimeters (polarization lifetime & profile)
- Much improved knowledge of molecular contamination in hydrogen jet

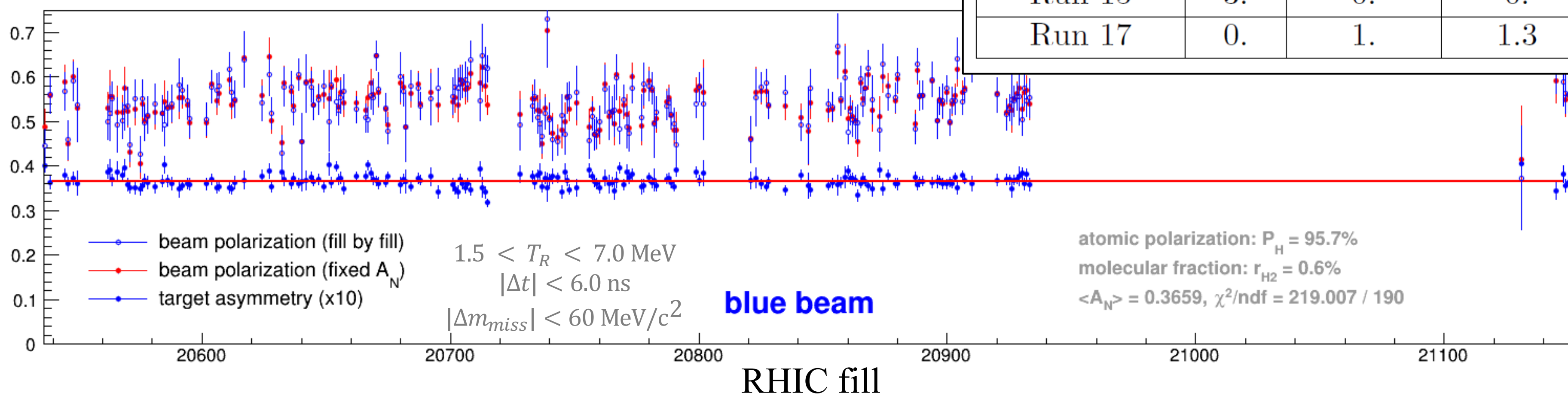
→ smallest systematic uncertainty ever 1.1% for Blue and 1.4% for Yellow beam

- First observation of longitudinal polarization profile

$$P_{Beam} = -\frac{\epsilon_{Beam}}{\epsilon_{Jet}} P_{Jet}$$

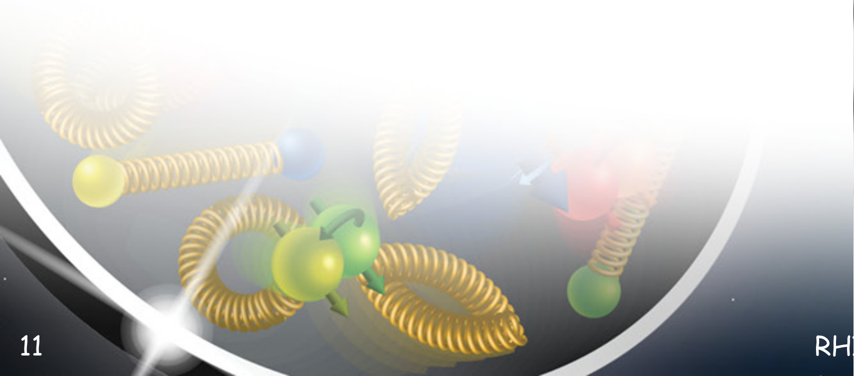


$\sigma(P)/P$ (%)	scale	Blu bkg.	Yel bkg.
Runs 9-13	3.	1.	1.
Run 15	3.	0.	0.
Run 17	0.	1.	1.3



What Will Come

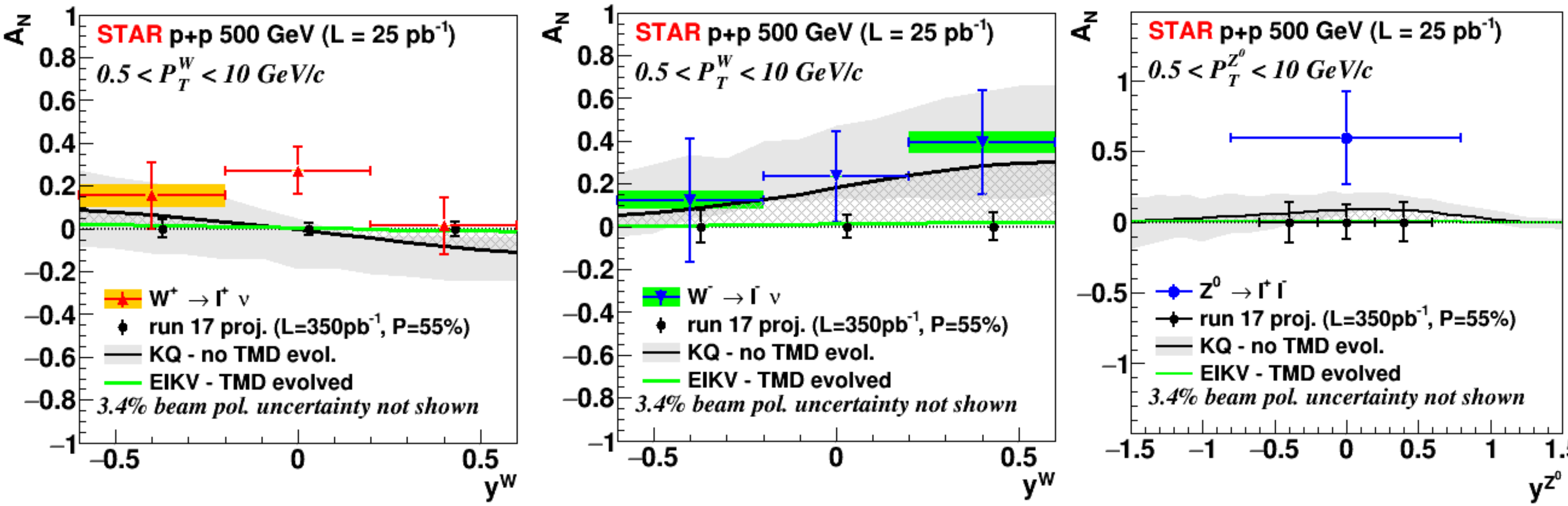
to



RUN-17: A goldmine for TMDs@STAR

Main Goal: definite measurement of Sivers sign change

$TMD_{DIS} = - TMD_{DY/W/Z0}$



Collected:

350 pb^{-1} → 14 times Run-11 for $-1 < \eta < 1.8$ → A_N $W^{+/-}$ & Z^0, Collins, ……

→ working furiously on the final calorimeter calibration of the data and ironing out some TPC space charge corrections

→ need higher precision then in previous years

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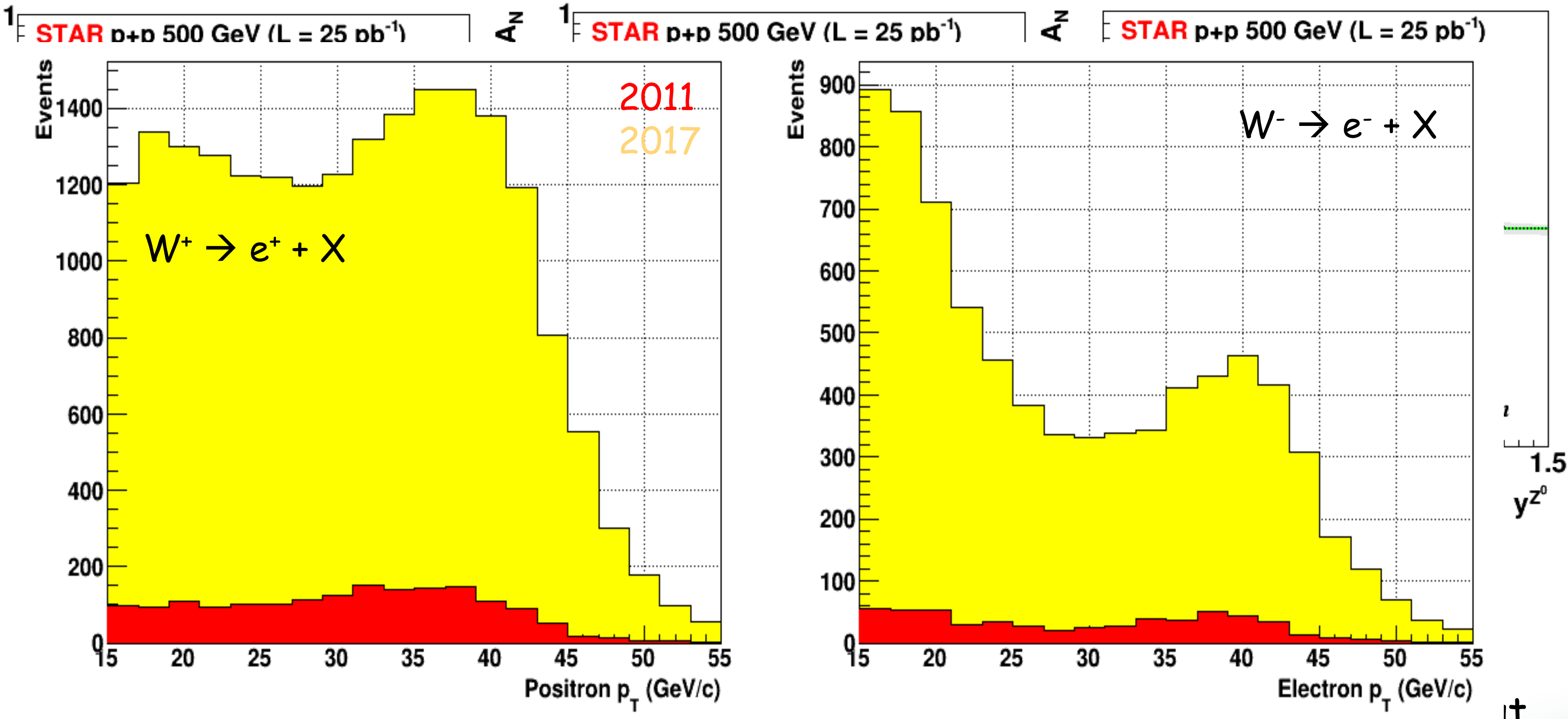


Co

35

→

some TPC space charge corrections

→ need higher precision then in previous years

There is no issues with the data

STAR Physics program after BES-II

Mid-rapidity $-1.5<\eta<1.5$ | Forward-rapidity $2.8<\eta<4.2$

p+p & p+A

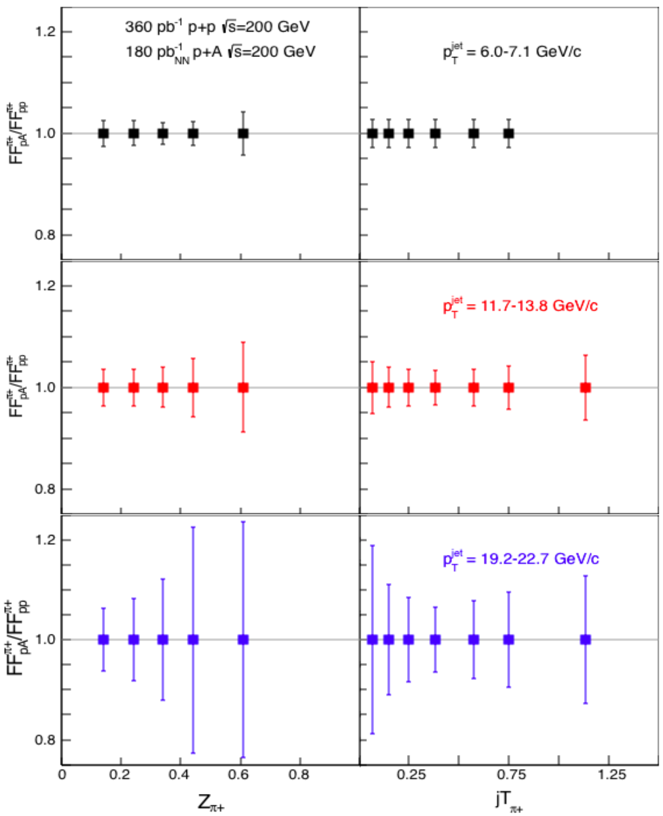
Beam:

500 GeV: p+p
200 GeV: p+p and p+A

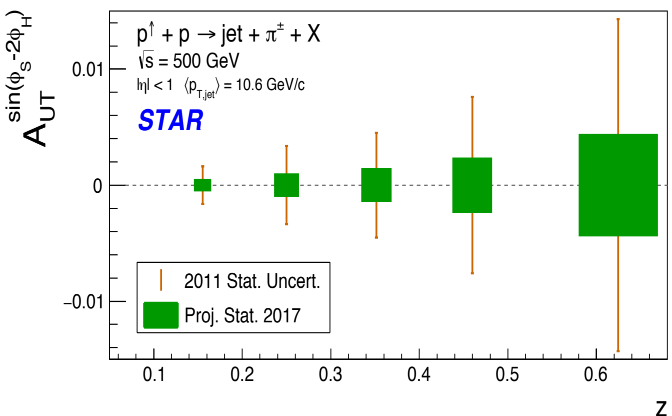
Physics Topics:

- Improve statistical precision
  - TMD measurements, i.e. Collins, Sivers, …
  - Access s & Δs through Kaons in jets
- Measurement of GPD E_g through UPC J/Ψ
- First access to Wigner functions through di-jets in UPC
- Gluon and quark vacuum fragmentation
- Gluon and quark fragmentation in nuclear medium
- Nuclear dependence of Collins FF

fragmentation functions in p+A/p+p at $|\eta|$ < 0.4



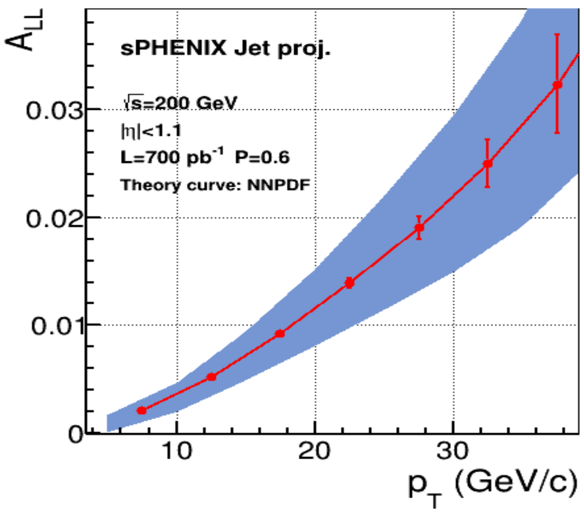
linearly polarised gluons
→ could be an explanation for the ridge seen in pp and pA



Goal: statistical precision to allow universality checks between pp and EIC

midrapidity program based on existing STAR detector utilizing iTPC, eToF and EPD upgrades

sPHENIX Midrapidity



Brings us to era of high precision ΔG measurements:

Will improve ΔG constraint at $x>0.05$

Multiple channels with different theor. and exp. uncertainites

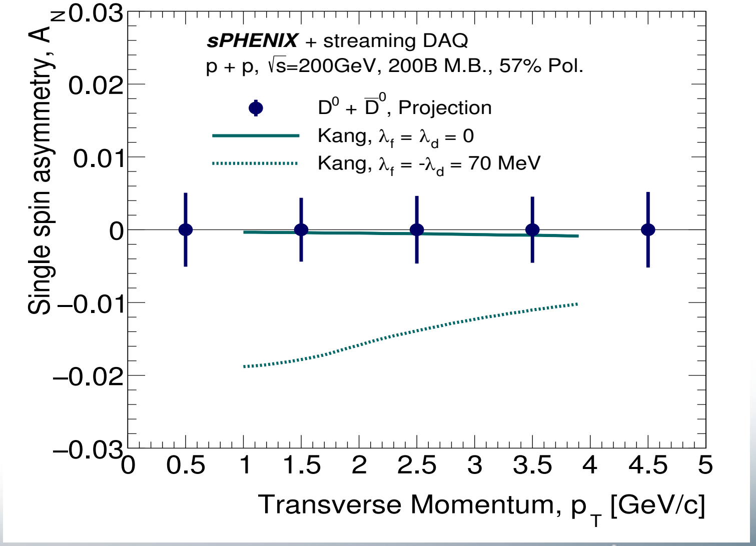
- Crucial syst. cross check

Complementary to the future EIC

- Crucial universality test in the overlapping x-range

Open HF A_N:

Sensitive to Twist-3 tri-gluon correlation fnct.



And many other high impact measurements:
Transversity, Hadronization, Nuclear PDF, etc.

STAR Physics program after BES-II

Mid-rapidity $-1.5<\eta<1.5$ | Forward-rapidity $2.8<\eta<4.2$

p+p & p+A (Mid-rapidity)

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- Improve statistical precision
  - TMD measurements, i.e. Collins, Sivers, …
  - Access s & Δs through Kaons in jets
- First access to Wigner functions through di-jets in UPC
- Gluon and quark vacuum fragmentation
- Gluon and quark fragmentation in nuclear medium
- Nuclear dependence of Collins FF

Scientific goals:

p+p:
3-dim. characterization of the proton in momentum and spatial coordinates

p+A
Nature of initial state and hadronization in nuclear collisions
Onset and A-dependence of saturation

A+A
Longitudinal medium characterization
Precision flow measurements via long range correlations

Requires new forward capabilities

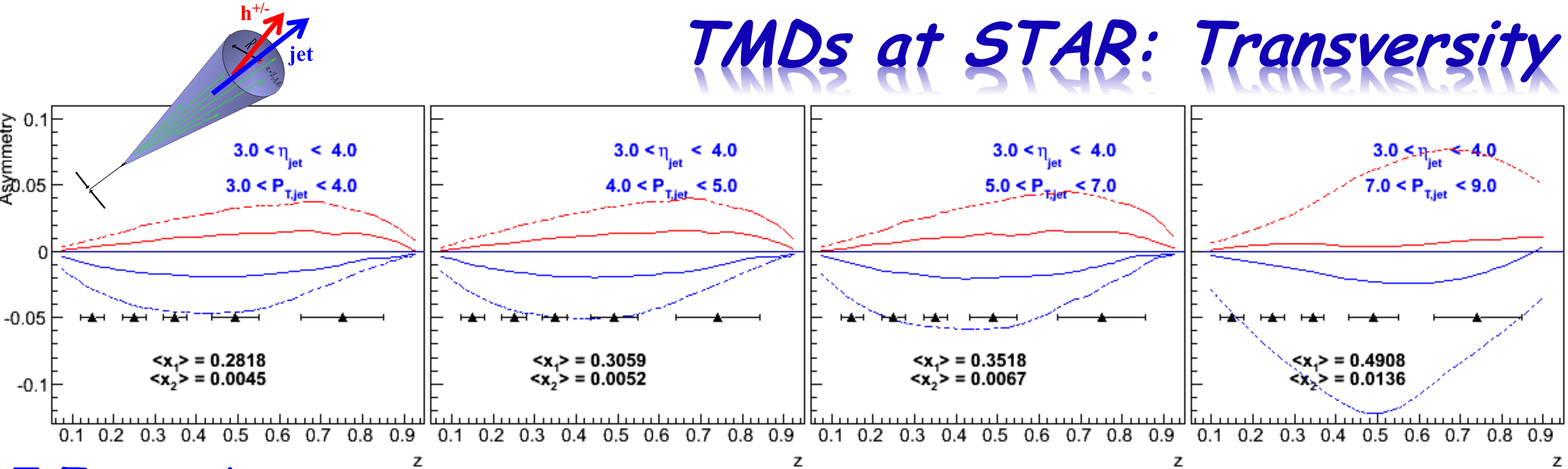
p+p & p+A (Forward-rapidity)

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
- TMD measurements at high x
  transversity → tensor charge
- Improve statistical precision for Sivers through DY
- Measurement of GPD E_g through UPC J/Ψ
- Δg(x,Q2) at low x through Di-jets
- Gluon PDFs for nuclei
  - R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-Jets

FY21/22: provides a nice opportunity to run 500 GeV polarized pp
All other data taking in parallel to sPHENIX data taking campaign

TMDs at STAR: Transversity



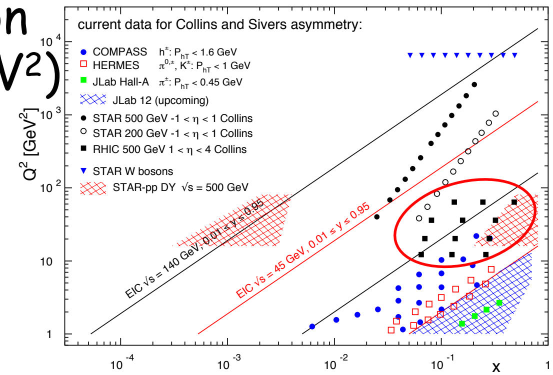
- **Transverity**

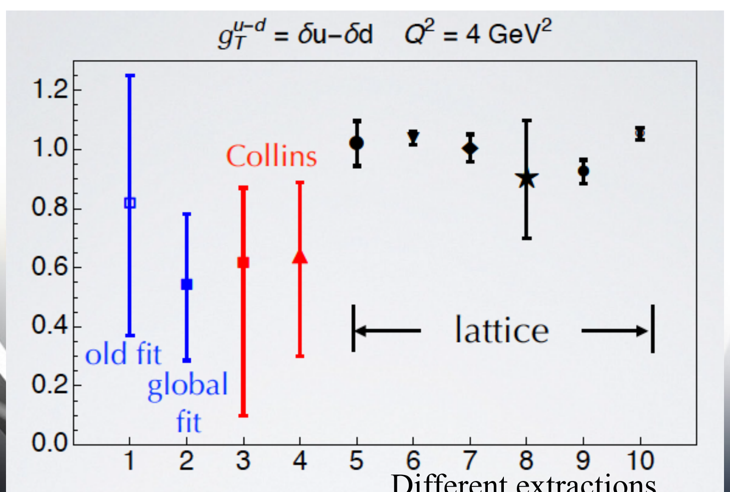
  3rd PDF critical to fully describe the Proton wave function

  → measure at high x (0.05 – 0.5) and high Q^2 (10 – 100 GeV^2)

  → Observable: hadron in jet

  → constrain tensor charge $\delta q^a = \int_0^1 \left[\delta q^a(x) - \delta \bar{q}^a(x)\right] dx$



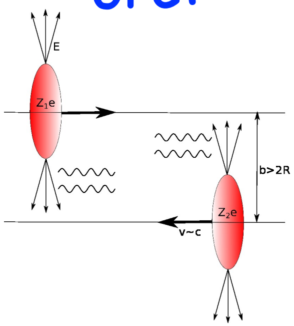


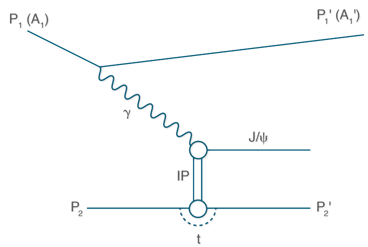
tensor charge useful for low-energy explorations of BSM

new physics ⇒ of today precision is an issue.

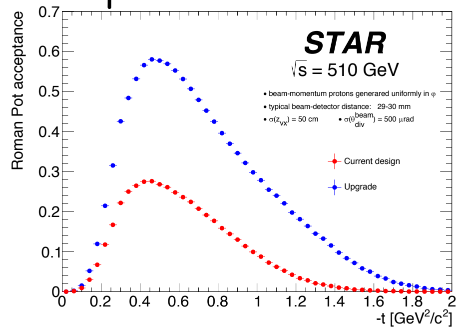
UPC: Access to GPD E_g

UPC:





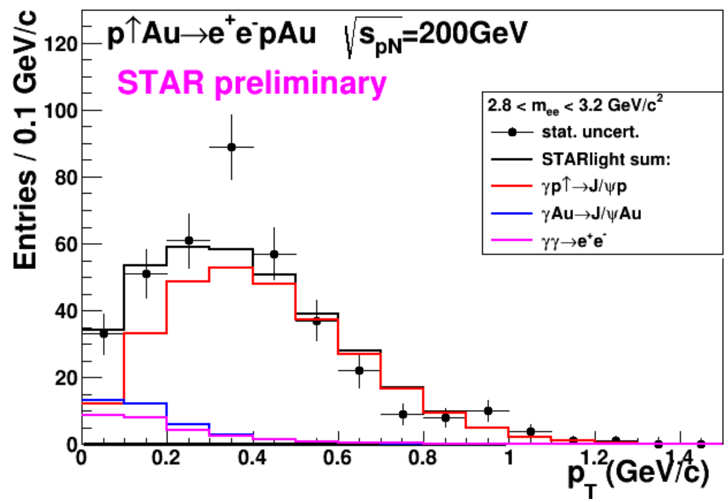
p' detected in RPs



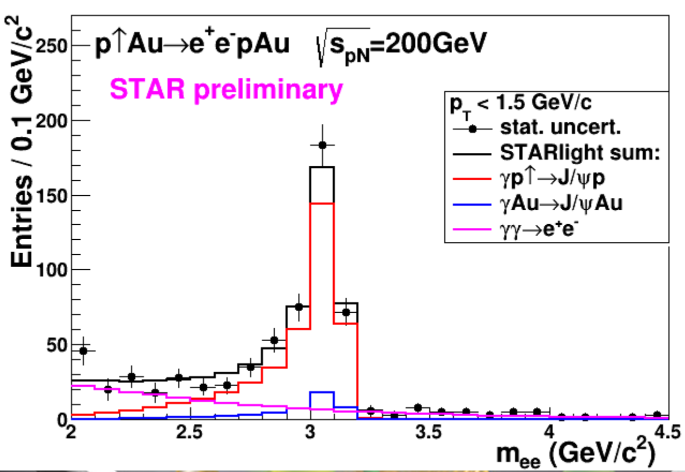
world wide only access to GPD E for gluons

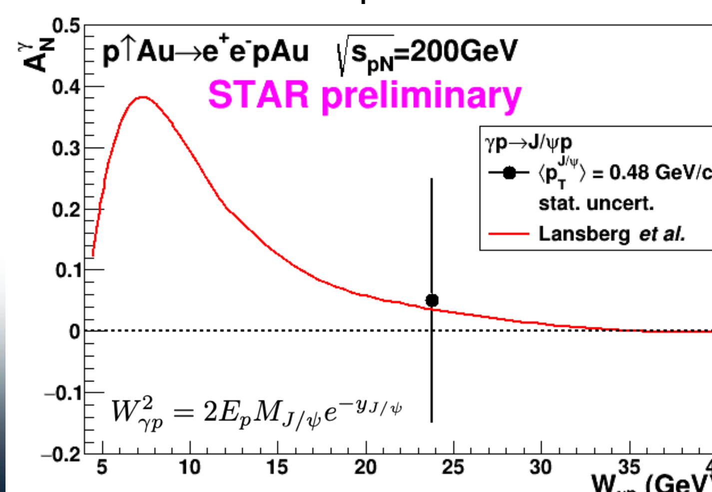
→ J/Ψ production in p↑Au /p↑p UPC

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



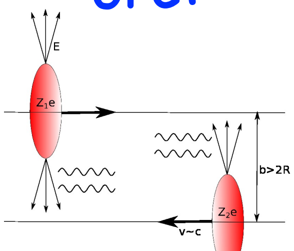
2015 polarized pA data:

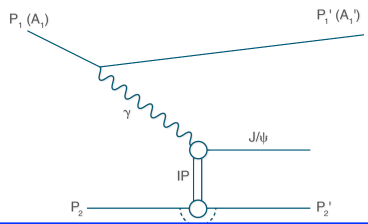




UPC: Access to GPD E_g

UPC:





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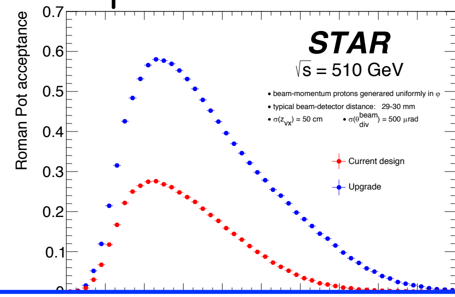
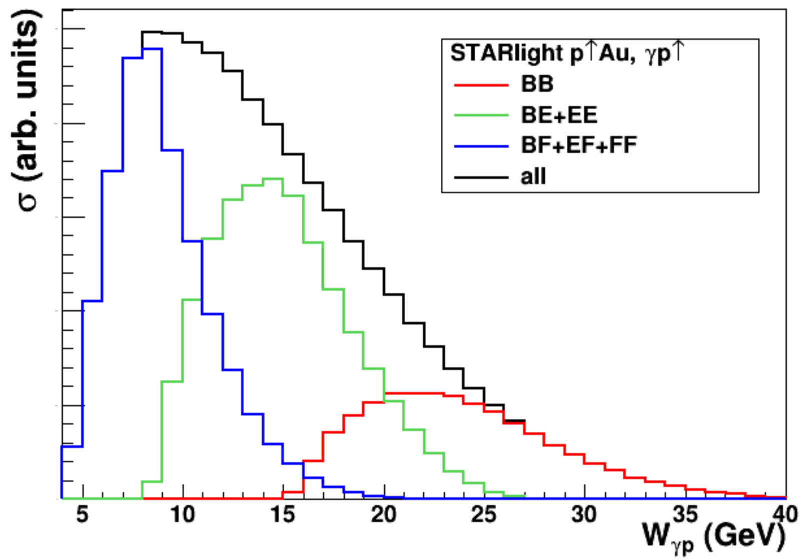


Forward rapidity gives access to the large asymmetry region

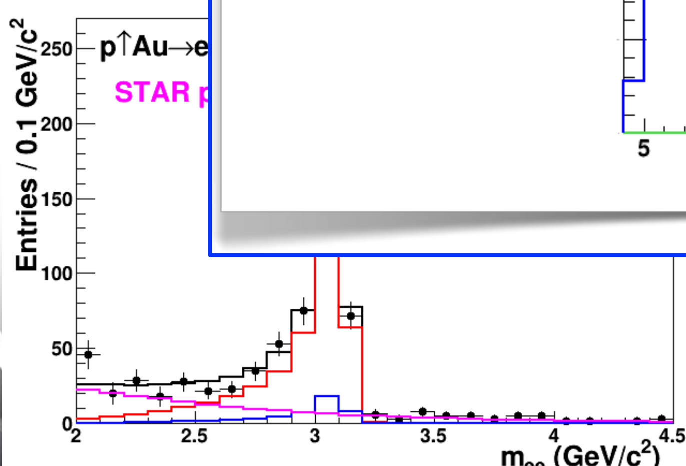


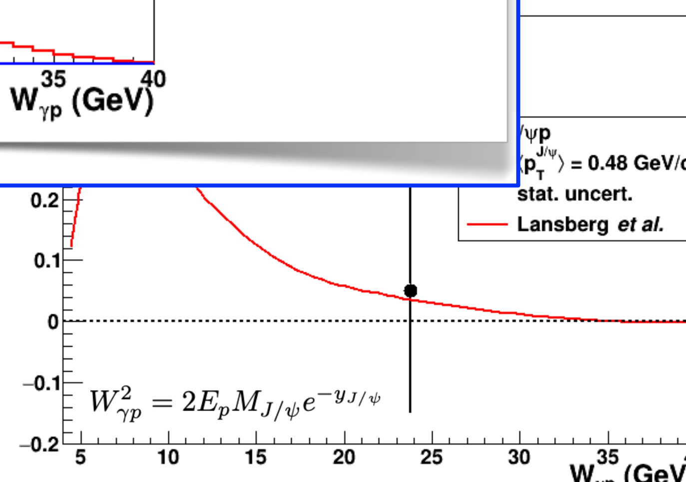
world wide

→ J/Ψ pr

$A_{UT}(\tau, t) \sim$

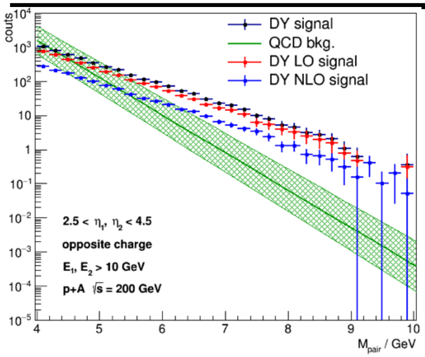
2015 p

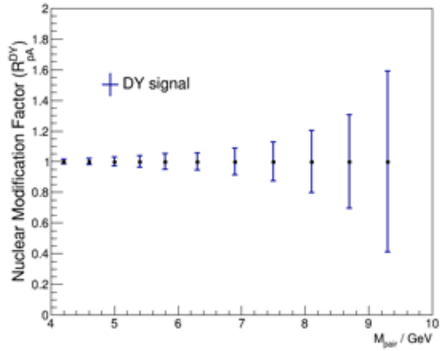




How Does The initial state IN AA Look?

pA: DY@2.5 < η < 4.5





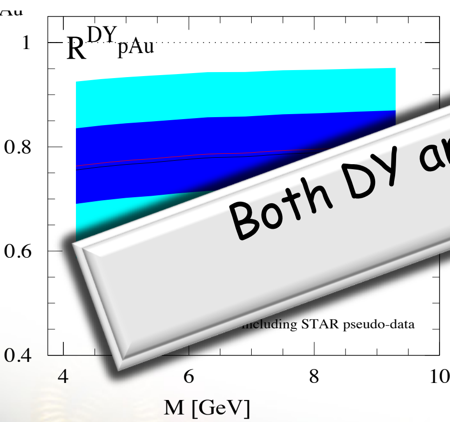
Impact on nPDFs: → sea quarks

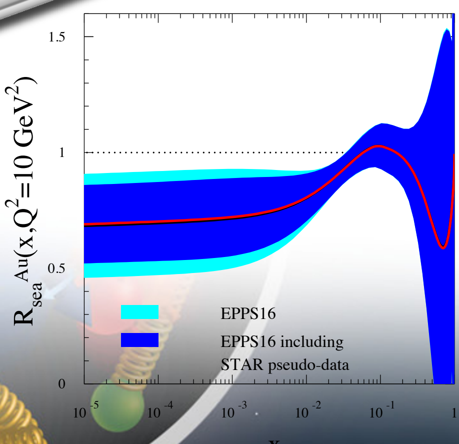
DY:

Q²:

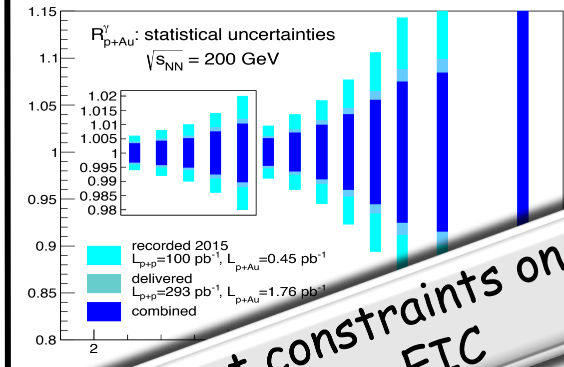
…ties:

…23 pp & pA





pA: Direct Photon@2.5 < η < 4.5

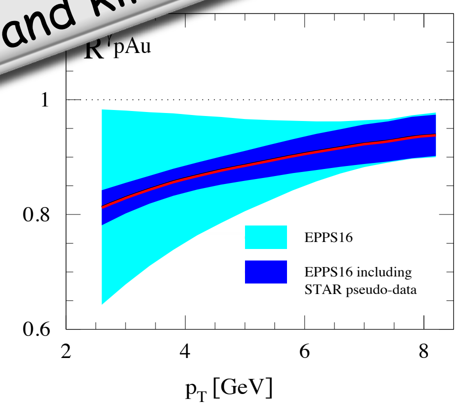


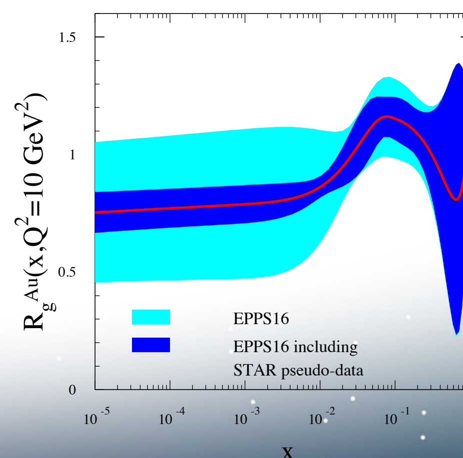
Uncertainties:
2015 + 2023 pp&pA

di… …on:

… GeV²

…DFs: → gluons





Both DY and direct photon R_{pA} give significant constraints on nPDF alternative observables and kinematics to EIC

Importance of STAR forward upgrade for EIC

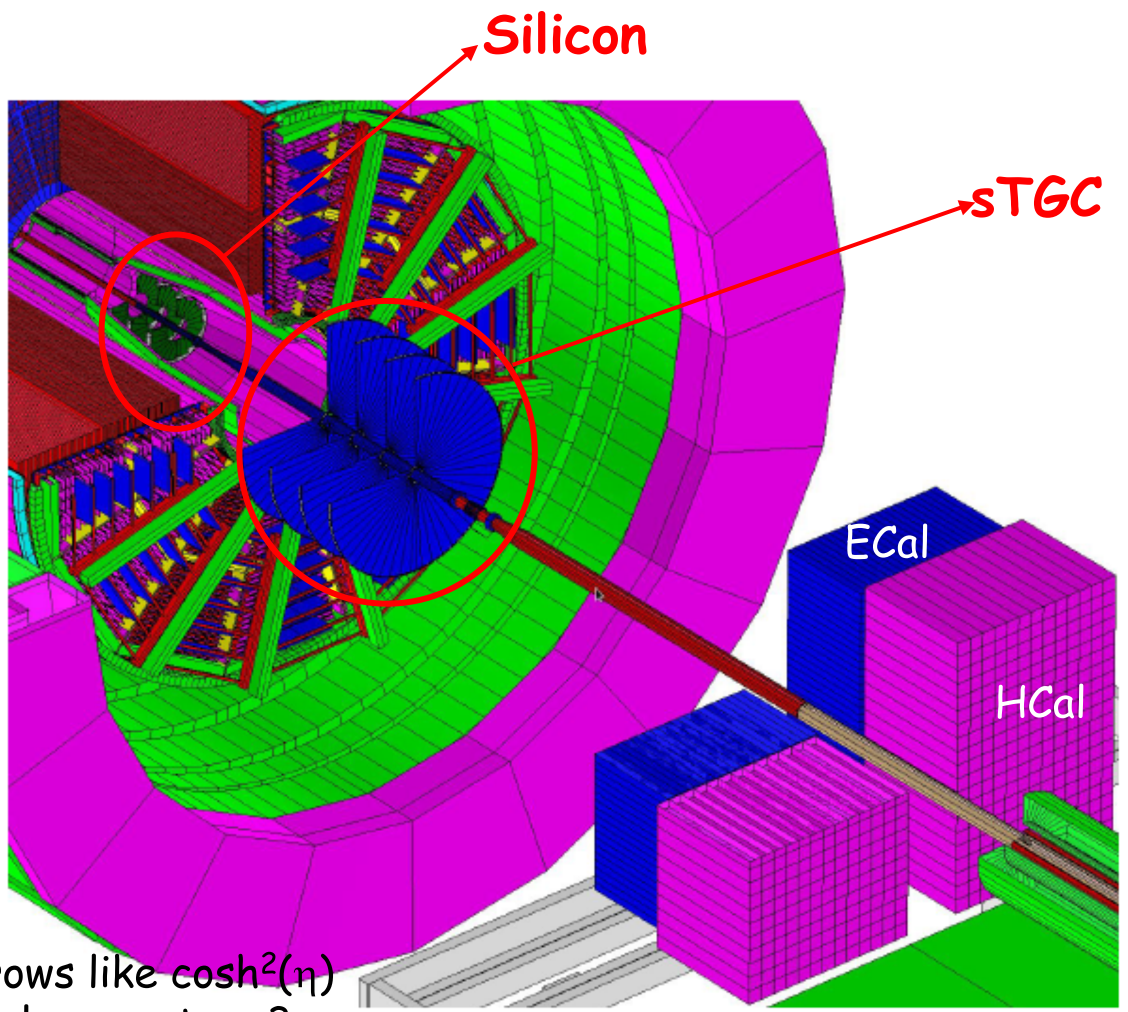
STAR forward upgrade: $2.5 < \eta < 4$

- rapidity coverage the same as EIC hadron Arm
  → high-x EIC physics

HCal +SiPM readout same as EIC-fHCAL

- same rapidity as EIC
  - background

small-strip Thin Gap Chambers (sTGC)
→ sTGC alternative technology to EIC GEM Trackers



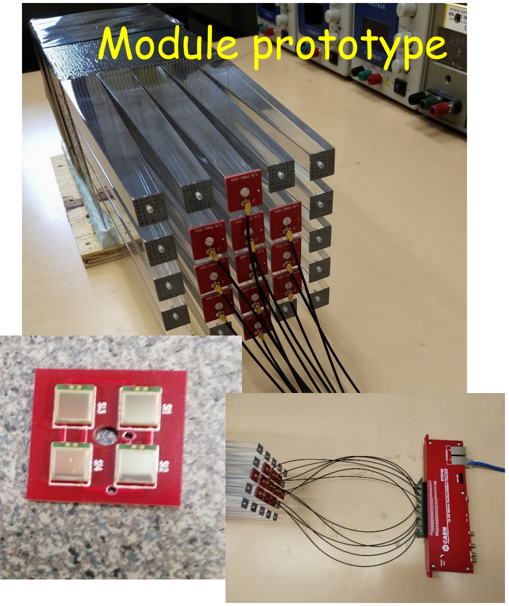
Analysis:
Learn how to reconstruct Jets close to beam rapidity

Jet solid angle ~ $R^2/\cosh^2(\eta)$.
so for fixed jet multiplicity, $dN/d\Omega$ grows like $\cosh^2(\eta)$

- 15 times larger at $\eta = 2$, 100 times larger at $\eta = 3$

→ what are the effects of underlying event ep & eA and $\sqrt{s}$

Training of young scientific generation: 15 undergrads working > 2019/06



EMCal R&D:

Use the existing E864 HCal modules for high density and high granularity EMCal

- Compensating SPACAL design: $10\times10\times117$ cm^3
- X_0=7.8mm, R_M=2cm
- 5×5 light guide array for 10×10 cm^2 modules => 2×2 cm^2
- 117 cm long => 7 cuts for 16 cm long modules (20 X_0)

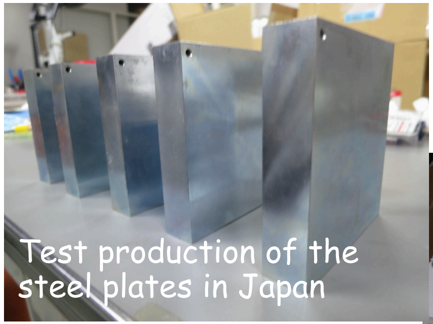
HCal R&D:

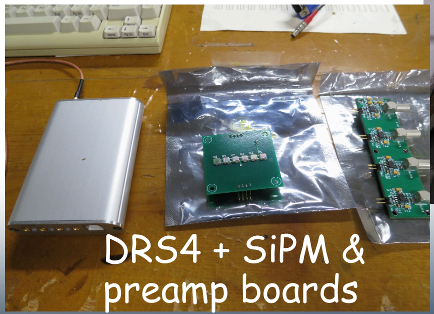
In Collaboration with STAR/UCLA

- Test beam data in Femilab, April 2019

RIKEN (Japan) R&D

- Readout development & test
- Rad. damage
- Calibration system
- Simulation






The Future
NEXT EXIT
EIC

The Medium Energy Group

Main activities: (s)PHENIX, STAR, EIC, Polarimetry

- Permanent: 6 - (s)PHENIX:1   STAR: 5   EIC: 5   Polarimetry: 3
- Postdocs:
  - 2017: 3 - STAR: 1   EIC: 2   Polarimetry: 1
  - 2018: 1 - STAR: 1   EIC: 0   Polarimetry: 1
  - 2019: 6 - STAR: 2   EIC: 4   Polarimetry: 2
- PhD Students: 2017 to 2019: 4 (STAR: 2 EIC: 2) one graduated in May 2018
- 2019: 2 female postdocs and 1 female PhD student

Extra ordinary academic merits:

Alexander Jentsch: 2019 RHIC/AGS Merit Award

E.-C. Aschenauer:

2018 Humboldt-Research Award (Humboldt-Forschungspreis)

2018 BNL Science and Technology Award

Zilong Chang: 2017 RHIC & AGS Thesis Award

Extra ordinary training:

- E.-C. Aschenauer: 2018 Project leadership institute

Other Activities:

ECA: Particle Data Group co-author for Structure Functions

2019 Contributions to BNL, RHIC, STAR, (s)PHENIX

Contributions to BNL & EIC

BNL & RHIC:

E.C. Aschenauer
- Member of the PO I&D working group (> 03/2017)
- Member of the NPP I&D Council (05/2018-08/2019)
- liaison team member for APS side visit

O. Eyser
- Member of the nuclear physics seminar committee (2014-2018)
- Member of the RHIC/AGS User group (elected) 2018-2021
- Member of the thesis award committee, RHIC/AGS 2019

EIC:

E.C. Aschenauer
- co-chair of the EIC User Working Group on Polarimetry
- Member of the eRHIC pre-CDR writing group

Contributions to STAR

STAR:

E.C. Aschenauer
- STAR upgrade coordinator 07/2017
- Member of the STAR operations management team
- Chair of the forward upgrade working group

Z. Chang:
- Convener of the STAR Jet finding focus group

O. Eyser
- Software coordinator for the FMS and detector expert for the FPS and FPOST in STAR
- co-convener of the STAR spin working group (2016-09/2019)

W. Guryn
- project leader for the Roman Pot project at STAR
- safety representative for the medium energy group

D. Kalinkin:
- Junior representatives at STAR council

A. Ogawa
- member of the STAR trigger board (chair in 2013)
- Member of the STAR operations management team
- trigger software coordinator and BBC detector expert

Contributions to (s)PHENIX

(s)PHENIX:

Alexander Bazilevsky
- PHENIX deputy spokesperson (> 01/2016)
- Co-convener of the sPHENIX Cold QCD physics working group
- Member of the writing committee for "An EIC Detector Built Around the sPHENIX Solenoid" LoI

Publications & Talks

STAR:
2017 - 2019: 9

PHENIX:
2017 – 2019: 9

EIC/eRHIC
2017 – 2019: 7

Polarimetry
2017 – 2019: 1

Other:
2017 – 2019: 6

Talks:
104 talks 89 invited
Co-organizers of 14 workshops/Conferences

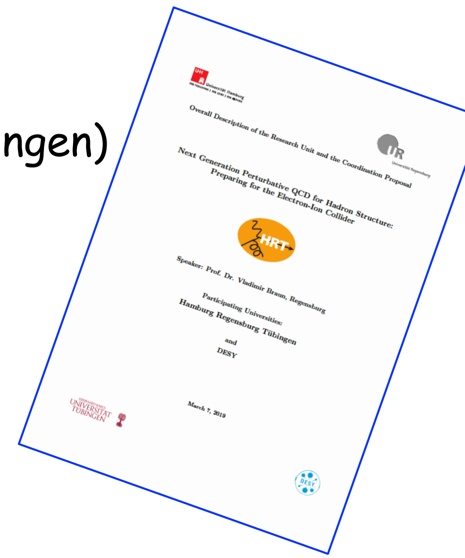
Supervising several PhD students and Postdocs from collaborating Universities

Contributions from BNL ME Group to EIC

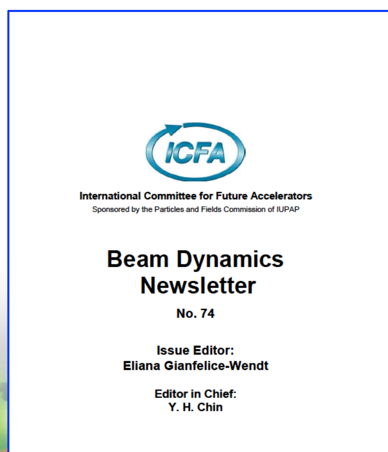
Global Contributions:

- Initiated in collaboration with M. Diefenthaler the collaboration with the experts of MCNet to develop Monte Carlo generators for EIC
  - 3 workshop with different emphasis
  - Next workshop: 20^{th}-22^{nd} of November in Vienna
  - MC-development: Beagle a MC generator for EIC

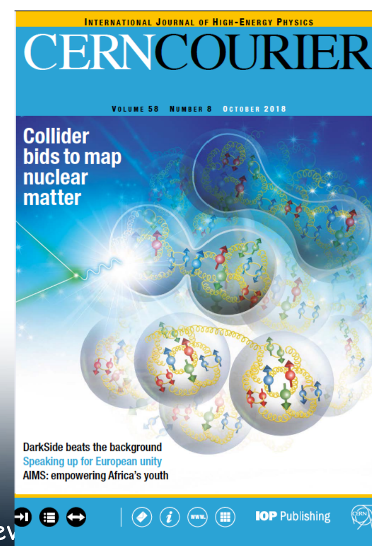
- ECA member of research group (DESY, Regensburg, Hamburg, Tuebingen)
  - Proposal to DFG:
    "Next Generation Perturbative QCD for Hadron Structure: Preparing for the Electron-Ion Collider" received highest recommendation in review
  - expect full funding (2M over 3y) starting October 2029



- "Outreach":



features EIC
Science and Designs



Contributions from BNL ME Group to EIC: SCIENCE

In total 12 papers (> 2012) addressing the science pillars of EIC

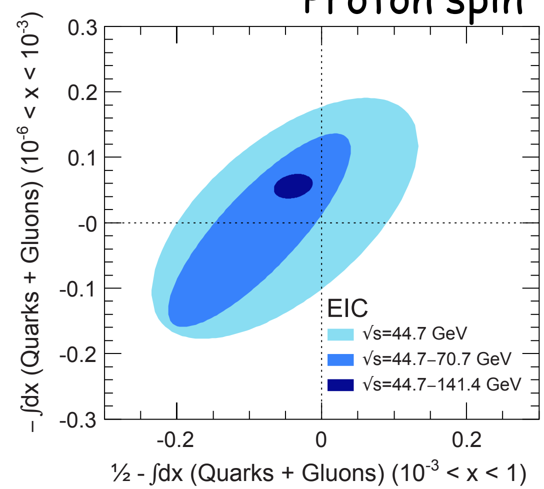
https://wiki.bnl.gov/eic/index.php/Presentations#Publications

- helicity structure of the proton
- momentum and spatial imaging of the proton
- collinear parton distribution functions of nucleons and nuclei
- Nonlinear effects in nuclei → Saturation

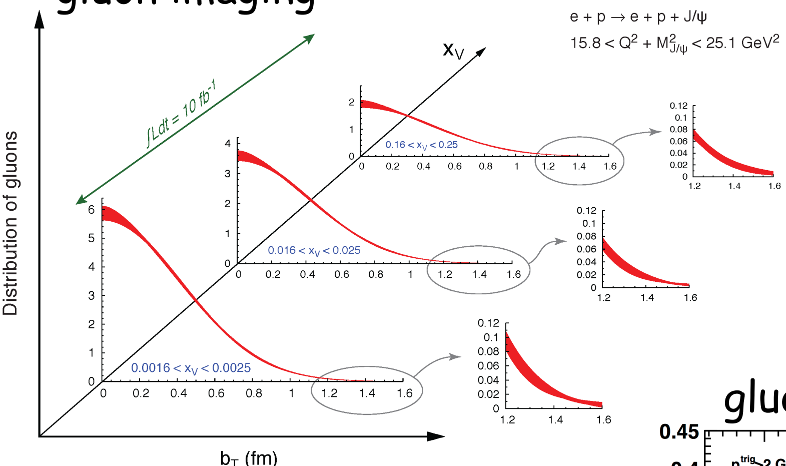
→ significant fraction of this work has been the foundation for the EIC WP

Some Highlights < 2017

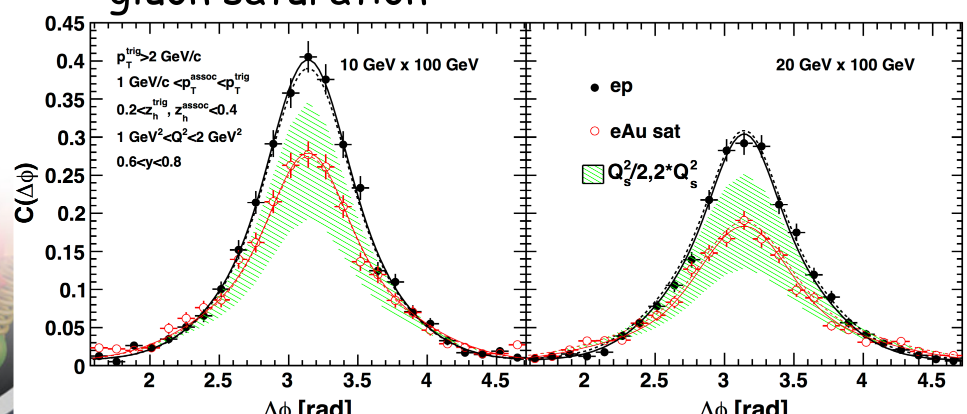
Proton spin

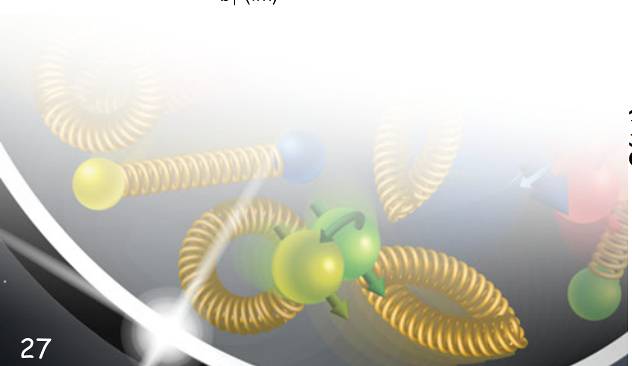


gluon imaging



gluon saturation





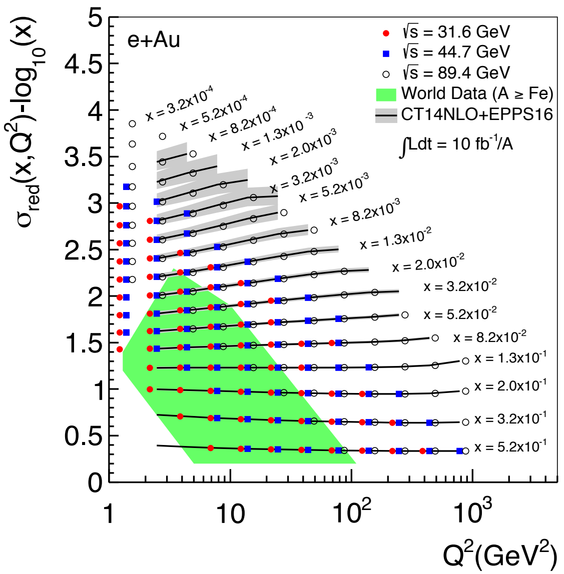
Contributions from BNL ME Group to EIC: SCIENCE

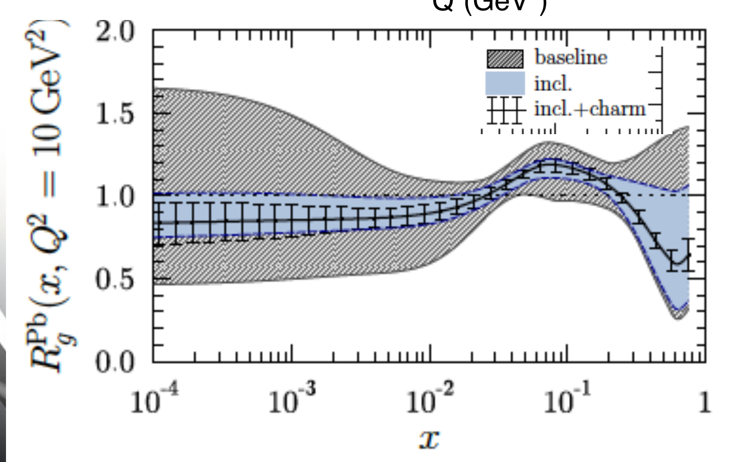
Highlights from 2017 to 2019:

Nuclear Parton distribution functions

PRD 96, (2017) 114005

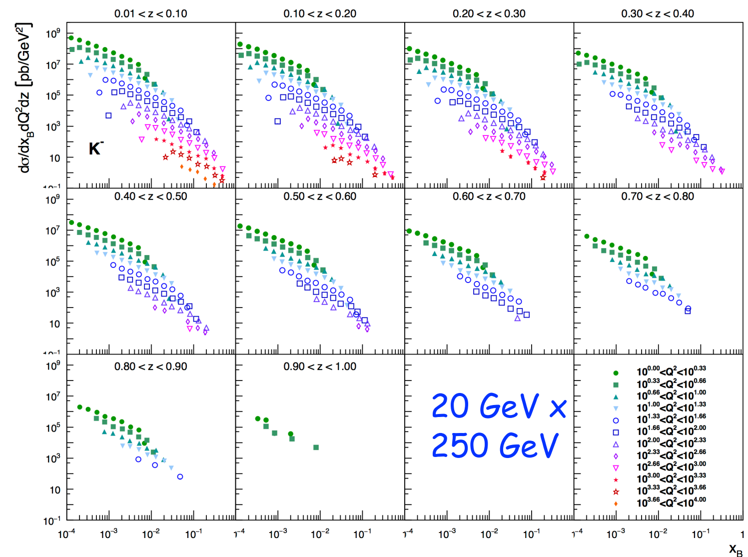
Gluon distribution ~ $d\sigma(x,Q^2)/d\ln Q^2$



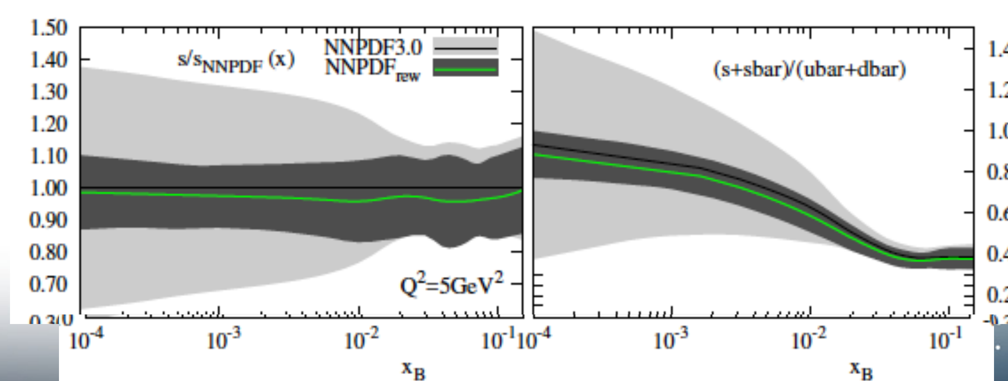


Proton Parton distribution functions

PRD99 (2019) 094004



Semi-inclusive DIS will be crucial to constrain proton PDFs and FF
→ critical input to the LHC

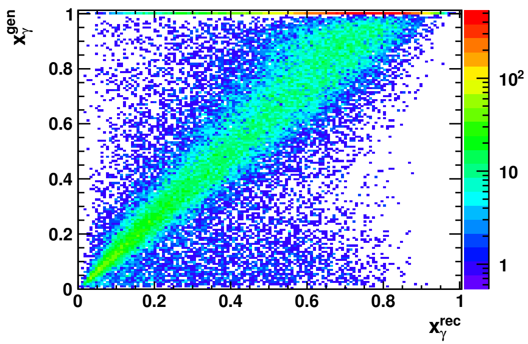


Contributions from BNL ME Group to EIC: SCIENCE

Highlights from 2017 to 2019:

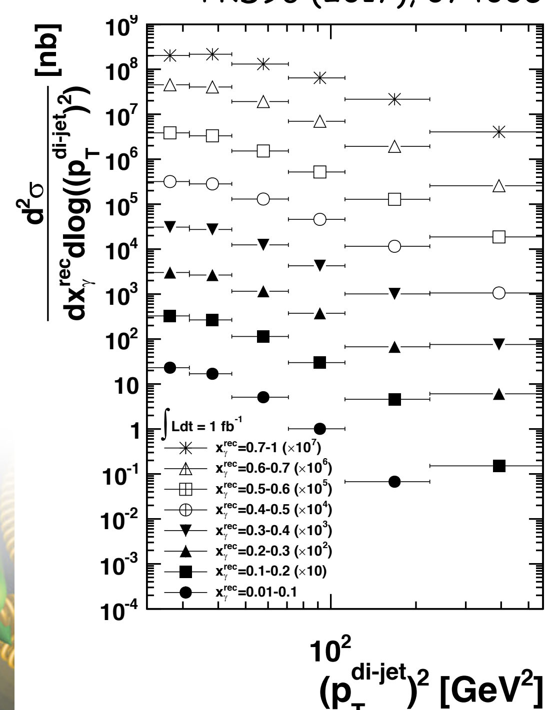
First EIC jet results

- Di-jets@EIC ideal probe to constrain (un)polarised Photon-PDFs



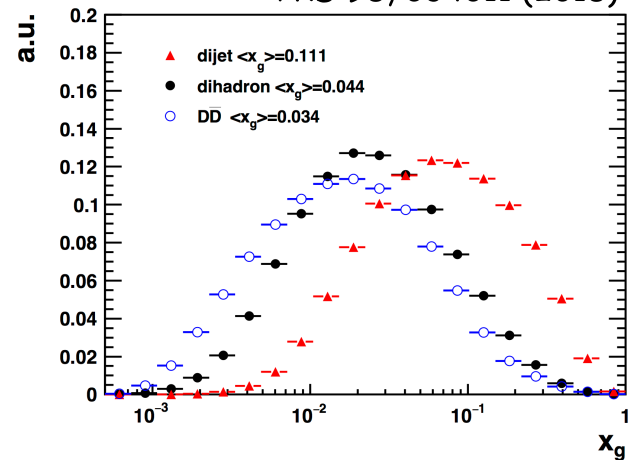
$$x_\gamma^{rec} = \frac{1}{2E_e y}(p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2})$$

PRD96 (2017), 074035



Di-jets golden probe to measure gluon TMDs
→ paper on gluon Sivers function

PRD 98, 034011 (2018)

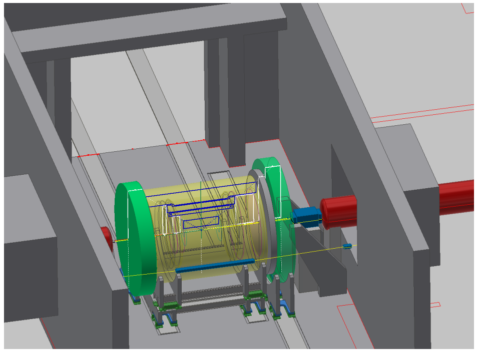


→ More jet physics papers in the pipeline

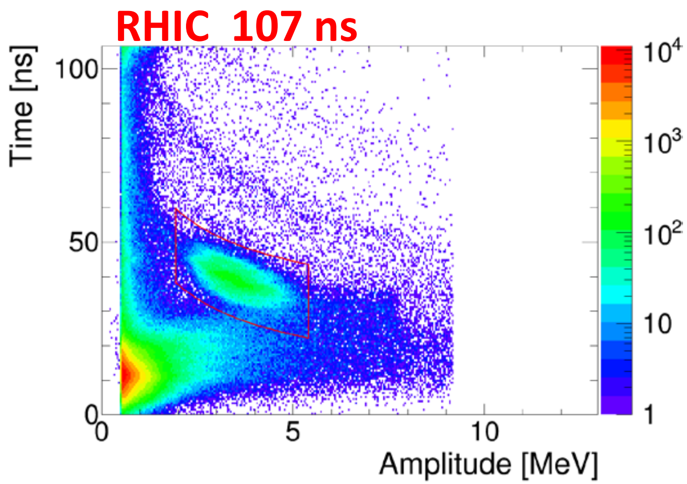
→ Paper Are "effective" neutron beams (d, He-3) needed for a flavor violation

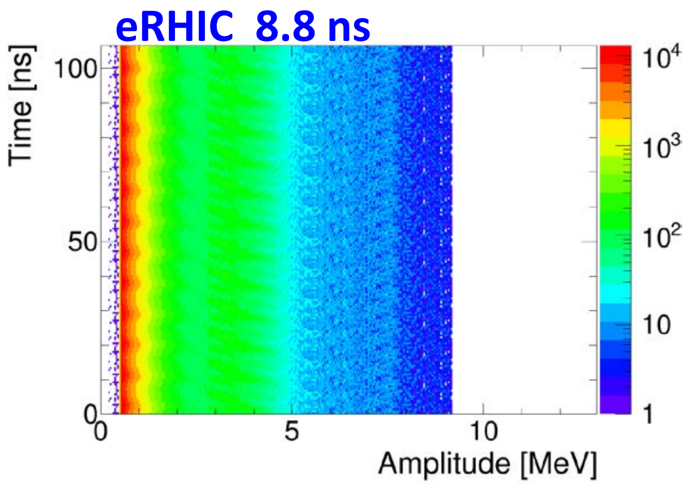
Contributions from BNL ME Group to EIC: Hardware

Contributions to accelerator IR and main/auxiliary detector design



- ❑ members of the group were engaged
  - ➢ defining the requirements for a detector fully optimized for DIS
  - ➢ study the visibility to convert sPHENIX into an Detector for EIC
  - ➢ study the integration challenges into the IR
- ❑ defined scientific requirements for polarimeters
  - ➢ ECA Co-convener of the EIC-UG polarimeter working group
  - ➢ 3 dedicated meetings organized
  - ➢ session at the upcoming PSTP - conference
- ❑ PI for the He-3 high energy polarimeter development part of a EIC Accelerator R&D proposal
- ❑ Develop a method how the RHIC hadron polarimeters can be used at EIC
  - ➢ Several challenges, i.e. need method to suppress the background of bunch **n-1** to overlap with the signal of bunch **n**
- ❑ Alternative methods for hadron polarimetry at EIC





Contributions from BNL ME Group to EIC: Hardware

Contributions to accelerator and detector/auxiliary detector design

- defined scientific requirements on IR – design
  - very close collaboration with accelerator experts (IR design, vacuum, ….)
- ECA part of the eRHIC pre-CDR writing group

- EIC R&D proposal in collaboration with BNL ATLAS group to develop on high timing (20ps) and position resolution Si Pixel Roman pots (RP)
- design and integration of Luminosity monitor, low-Q^2 Tagger, RP, ZDC, local polarimeter
  - simulate performance in GEANT and iterate with IR design team

	Hadron	Lepton
Machine element free region	+/- 4.5 m main detector beam elements < 1.5^o in main detector volume	
Beam pipe	Low mass material i.e. Beryllium	
Low Q^2 tagger		Acceptance: $Q^2 < 0.1$ GeV
Zero Degree Calorimeter	60cm x 60cm x 2m @ ~30 m	
scattered proton/neutron acc. all energies for ep	Proton: 0.2 GeV < p_t < 1.3 GeV Neutron: p_t < 1.3 GeV	
scattered proton/neutron acc. all energies for eA	Proton and Neutron: Θ < 6 mrad ($\sqrt{s}$=50 GeV) Θ < 4 mrad ($\sqrt{s}$=100 GeV)	
Integration of detectors	Local polarimeter	
Luminosity	Relative Luminosity: $R = L^{++/--}/L^{+-/-+} < 10^{-4}$	
		γ acceptance: +/- 1 mrad → $\delta L/L < 1\%$

Contributions from BNL ME Group to EIC: Hardware

Contributions to accelerator and detector/auxiliary detector design

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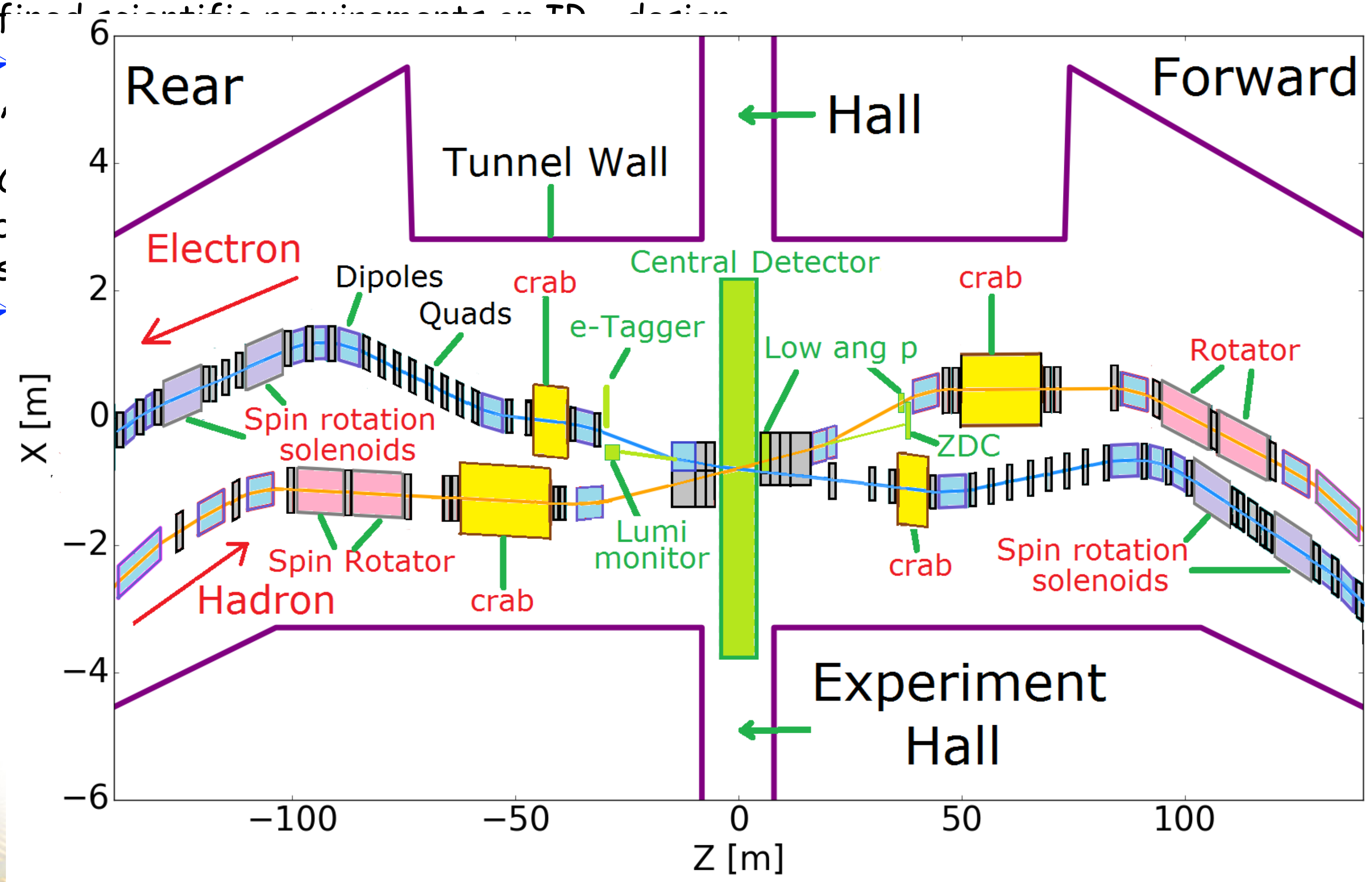


Luminosity	Relative Luminosity: $R = L^{++/--}/L^{+-/-+} < 10^{-4}$	
		γ acceptance: +/- 1 mrad → $\delta L/L < 1\%$

Summary

Recent p+p and p+A results

- many new results, which push our understanding of the nucleon and nucleus structure
  - Light sea-quarks have significant polarization $\Delta\bar{u} > \Delta\bar{d}$
  - Gluons contribute to the spin of the proton, new data will further reduce uncertainties in 0.01 < x 1
  - important constrains on TMDs and their evolution → critical for EIC

RHIC Cold QCD Program: Status & Plans

- many high impact results from Run-17 and the 2021+
  - precision will enable universality checks with EIC data
  - forward upgrade provides critical input for EIC

BNL ME group efforts on EIC program

- many contributions to (s)PHENIX, STAR, RHIC
- instrumental work to the EIC science case and its experimental realization
- strongly engaged in the training of the next generation undergrads, PhD-students and postdocs

BACK UP

Papers 2017 - 2019

Polarimetry:

1. H. Huang, J. Kewisch, C. Liu, A. Marusic, W. Meng, F. M´eot, P. Oddo, V. Ptitsyn, V. Ranjbar, T. Roser, and W. B. Schmidke, "Measurement of the Spin Tune Using the Coherent Spin Motion of Polarized Protons in a Storage Ring", Phys. Rev. Lett. 122, 204803

PHENIX:

2. Nonperturbative transverse momentum broadening in dihadron angular correlations in $\sqrt{s_{NN}}$=200 GeV GeV proton-nucleus collisions, Phys.Rev. C99 (2019), 044912.
3. Single-spin asymmetry of J/Ψ production in p+p, p+Al, and p+Au collisions with transversely polarized proton beams at $\sqrt{s_{NN}}$=200 GeV, Phys.Rev. D98 (2018), 012006.
4. Cross section and longitudinal single-spin asymmetry A_L for forward $W^{\pm}\rightarrow \mu^{\pm}\nu$ production in polarized p+p collisions at $\sqrt{s}$ =510 GeV, Phys.Rev. D98 (2018), 032007.
5. Nonperturbative transverse-momentum-dependent effects in dihadron and direct photon-hadron angular correlations in p+p collisions at $\sqrt{s}$ =200 GeV GeV, Phys.Rev. D98 (2018), 072004.
6. Nuclear Dependence of the Transverse-Single-Spin Asymmetry for Forward Neutron Production in Polarized p+A Collisions at $\sqrt{s_{NN}}$ = 200 GeV, Phys.Rev.Lett. 120 (2018) no.2, 022001.
7. Cross section and transverse single-spin asymmetry of muons from open heavy-flavor decays in polarized p+p collisions at $\sqrt{s}$ = 200 GeV, Phys.Rev. D95 (2017) no.11, 112001.
8. Angular decay coefficients of J/Ψ mesons at forward rapidity from p+p collisions at $\sqrt{s}$ = 510 GeV, Phys.Rev. D95 (2017) 092003.
9. Nonperturbative-transverse-momentum effects and evolution in dihadron and direct photon-hadron angular correlations in p+p collisions at $\sqrt{s}$=510 GeV, Phys.Rev. D 95 (2017), 072002.
10. Measurements of double-helicity asymmetries in inclusive J/ψ production in longitudinally polarized p+p collisions at $\sqrt{s}$=510 GeV, Phys.Rev. D 94 (2016), 112008.

STAR:

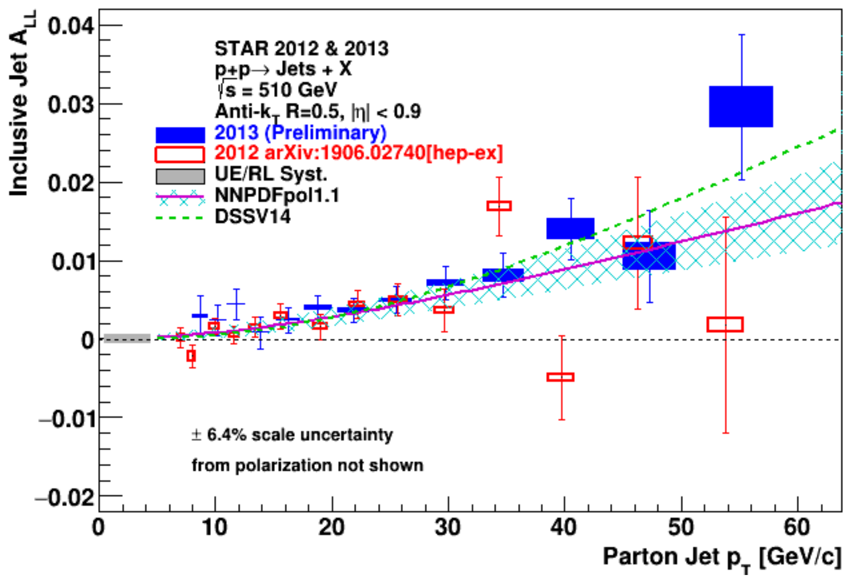
11. J. Adam (STAR Collaboration), Longitudinal double-spin asymmetry for inclusive and dijet production in pp collisions at STAR, Phys. Rev. D 100, 052005
12. J. Adam et al. (STAR Collaboration), Longitudinal double-spin asymmetries for dijet production at intermediate pseudo-rapidity in polarized pp collisions at $\sqrt{s} = 200$ GeV, Phys. Rev. D, 98:032011
13. J. Adam et al. (STAR Collaboration), Longitudinal double-spin asymmetries for π^0s in the forward direction for 510 GeV polarized pp collisions. Phys. Rev. D, 98:032013
14. J. Adam et al. (STAR Collaboration), Measurement of the longitudinal spin asymmetries for weak boson production in proton-proton collisions at $\sqrt{s} = 510$ GeV, Phys. Rev. D, 99:051102,
15. J. Adam et al. (STAR Collaboration), Transverse spin transfer to Λ and anti-Λ hyperons in polarized proton-proton collisions at $\sqrt{s} = 200$ GeV, Phys. Rev. D, 98:091103
16. J. Adam et al. (STAR Collaboration), Improved measurement of the longitudinal spin transfer to Λ and anti-Λ hyperons in polarized proton-proton collisions at $\sqrt{s} = 200$ GeV, Phys. Rev. D, 98:112009
17. Transverse spin-dependent azimuthal correlations of charged pion pairs measured in $p^{\uparrow}+p$ collisions at $\sqrt{s} = 500$ GeV, L. Adamczyk et al., Phys.Lett. B780 (2018) 332
18. Azimuthal transverse single-spin asymmetries of inclusive jets and charged pions within jets from polarized-proton collisions at $\sqrt{s} = 500$ GeV, L. Adamczyk et al., Phys.Rev. D97 (2018) no.3, 032004
19. Measurement of the cross section and longitudinal double-spin asymmetry for di-jet production in polarized pp collisions at $\sqrt{s}= 200$ GeV, L. Adamczyk et al., Phys.Rev. D95 (2017) no.7, 071103

The quest for the gluon polarization ΔG

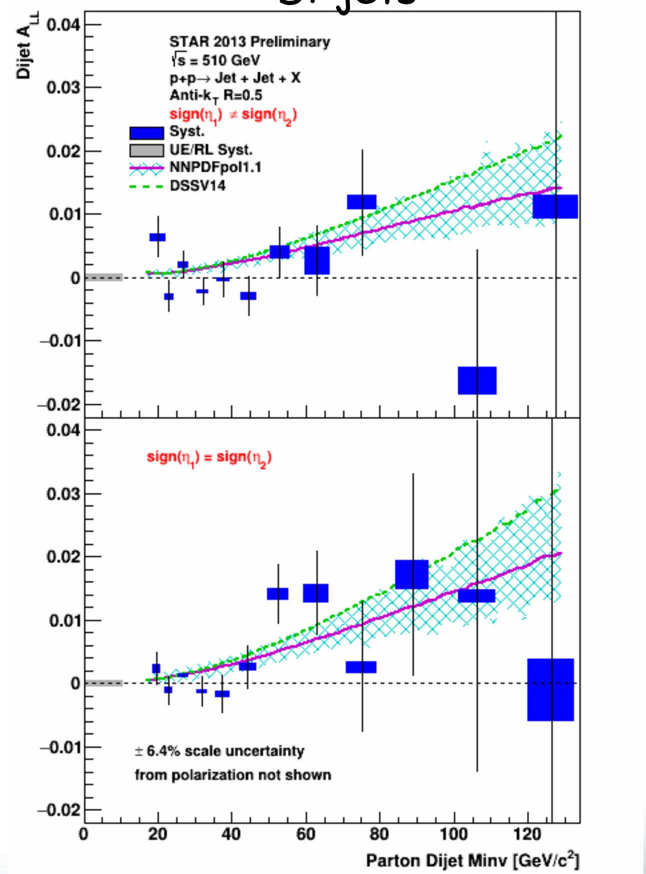
Golden probes: Double spin asymmetry A_{LL} for jets, di-jets and π^0

More incl. jets and dijets from run-12 and run-13
$\sqrt{s}$ = 500 GeV → lower x

inclusive Jets



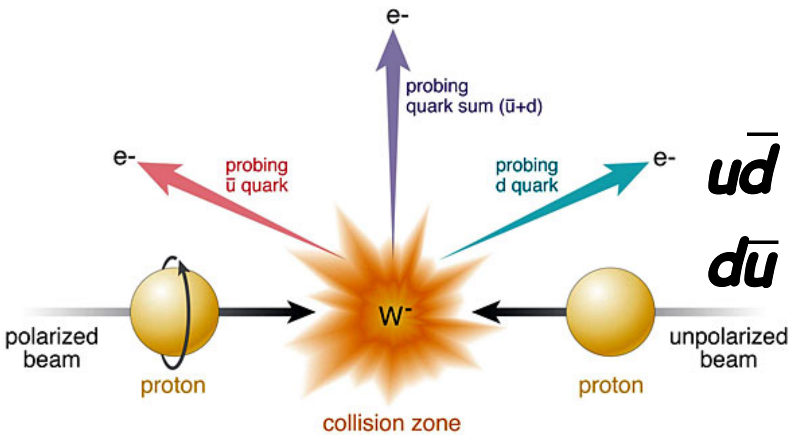
Di-jets



2012 data published:
Phys. Rev. D 100, 052005
2013 data: needs final embedding

Impact on $\int dx\Delta g$ underway and more data from run-15 at 200 GeV

W-Production



$$u\bar{d} \to W^+$$
$$d\bar{u} \to W^-$$

Ws naturally separate quark flavors
→ rapidity: sea vs. valence quarks

Ws are maximally parity violating
→ Ws couple only to one parton helicity

longitudinal polarized protons:

$$A_L^{W^+} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}} \sim \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\bar{d}(x_2)u(x_1) + \bar{d}(x_1)u(x_2)}$$

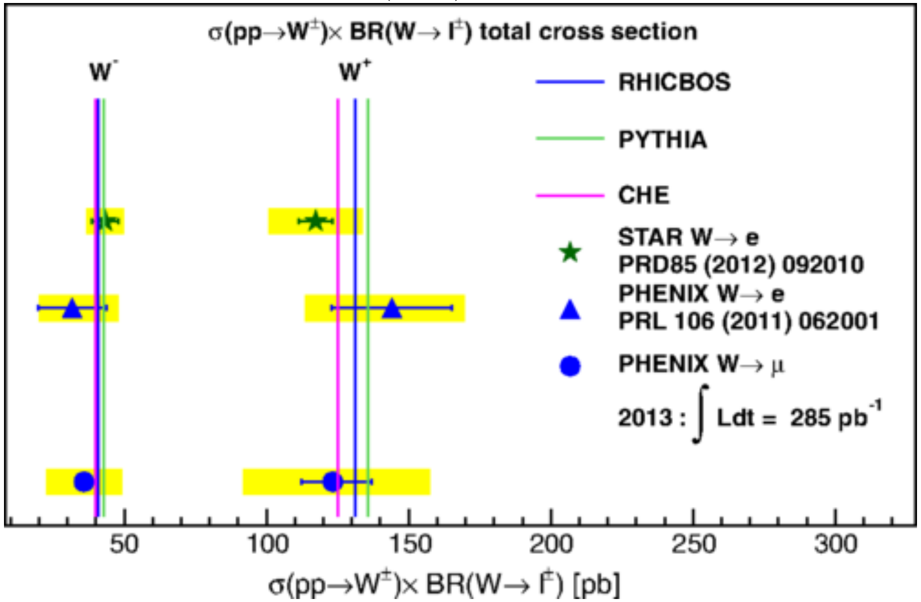
unpolarized protons:

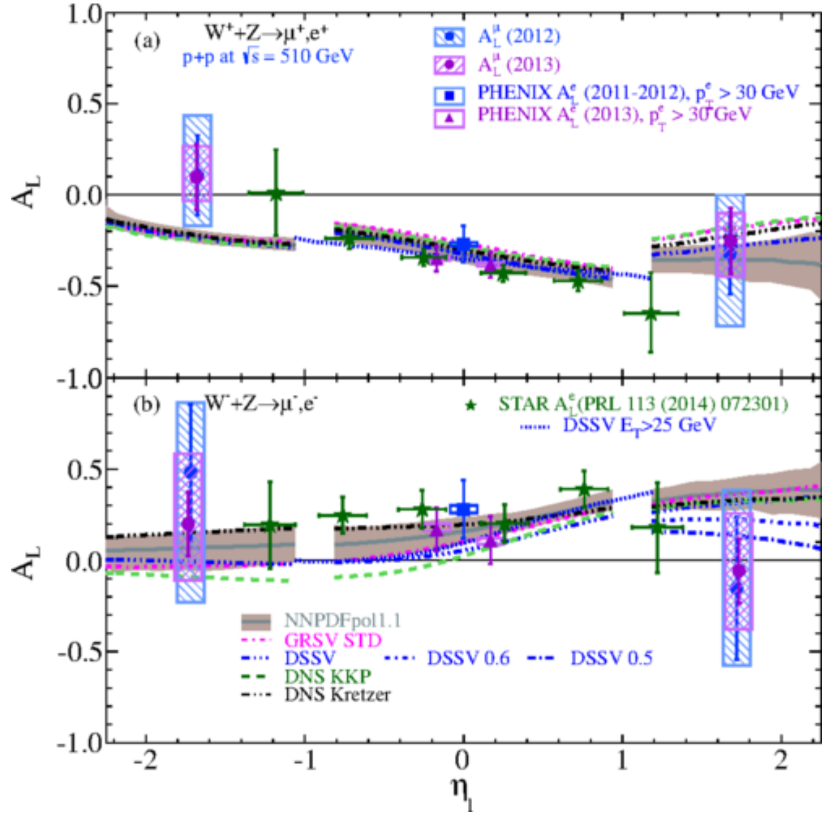
$$A\left(W^+/W^-\right) = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

Complementary to SIDIS:
very high Q^2-scale 6400 GeV^2
extremely clean theoretically
No Fragmentation function
→ stringent test on theory approach for SIDIS
UNIVERSALITY of PDFs

PHENIX: $W^{+/-}$ Results

PHYS. REV. D 98, 032007 (2018)

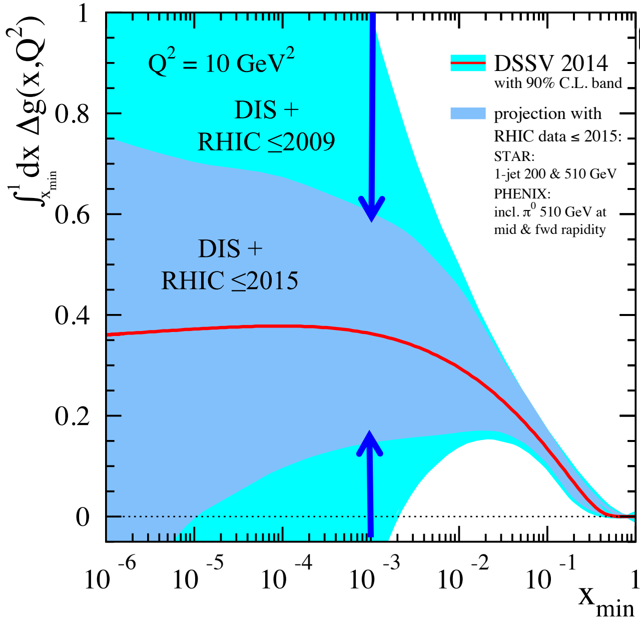




- Measured at forward and backward rapidity and averaged over arms
- 2013 W→ μ systematic error is dominated by the large uncertainty on the signal-to-background ratios.
- Good agreement with previous measurements and theoretical predictions.

- First muon channel W A_L !
- Backward μ^- are at upper limit of uncertainty bands indicating $\Delta\bar{u}$ is larger than fits without RHIC data indicate.
- Backward μ^+ show smaller than predicted asymmetries. Possibly due to under-estimated error bars in unpolarized sector.

How polarized are the Gluons?

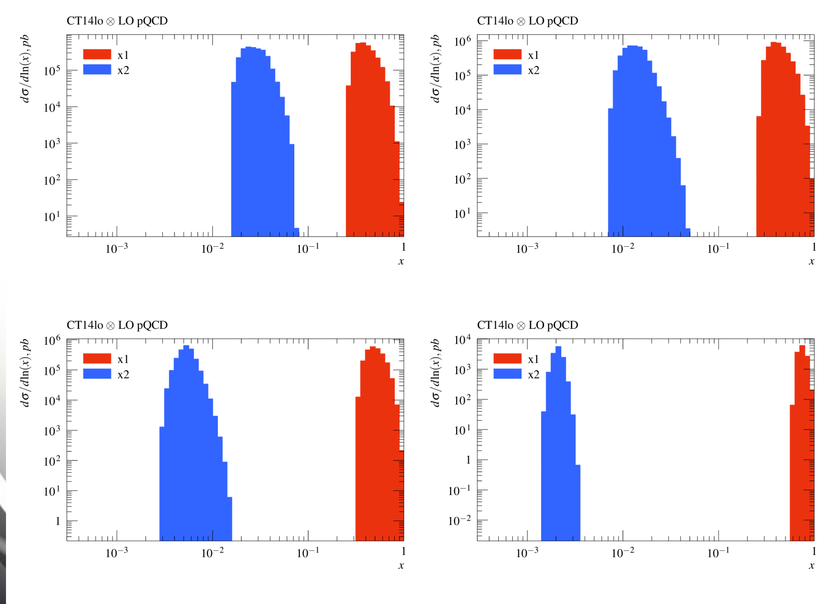


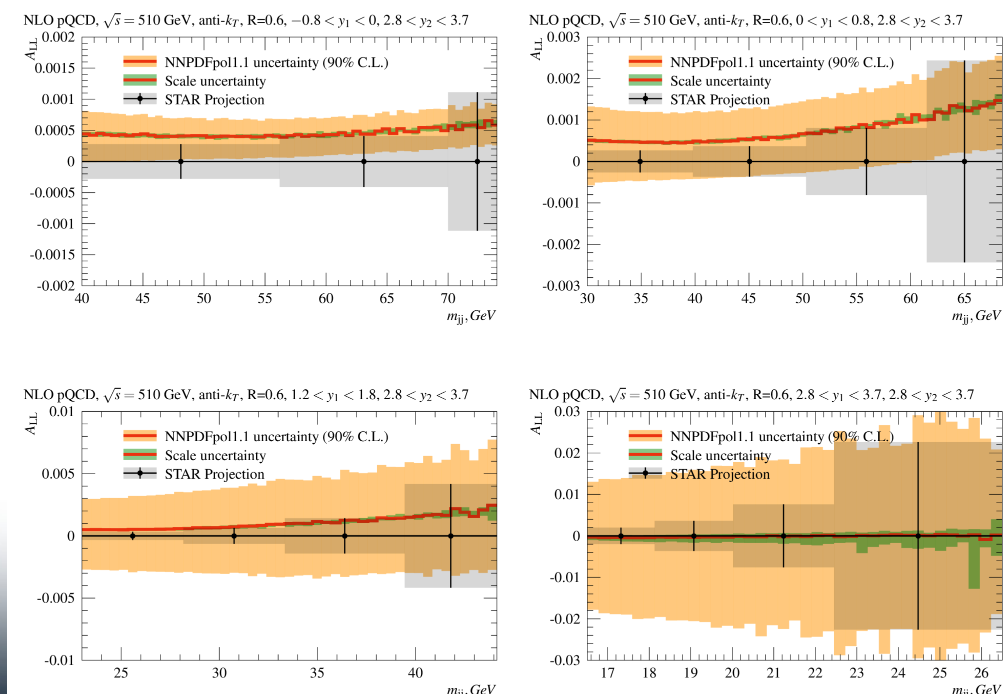
Data till 2009

$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ GeV^2$$

STAR and PHENIX data till 2015 reduce uncertainties at x ~ 10^{-3} by factor 2

only way to constrain low x further
→ go forward
Di-Jets@2.5 < η < 4.0





The objectives for TMDs

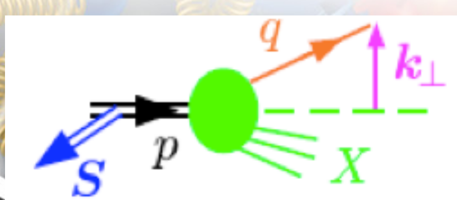
- Constrain TMDs over a wide x and Q^2 range (valence, sea-quarks & gluons)
  - → need 2 scale processes (DY, W, Z^0, Di-jet, $h^\pm$ in jet)
  - → different $\sqrt{s}$ → different p_t at the same x_t → evolution
  - → Test non-universality of TMDs ← → SIDIS
- observables as transversity can be accessed also in collinear observables (IFF)
  - → test of TMD factorization & universality
- observables purely sensitive (1-scale (π^0/γ/jet)) to the TWIST-3 formalism
  - → different $\sqrt{s}$ → evolution

Initial State

- A_N for $W^{+/-}$, Z^0, DY
  - → Sivers
- A_N for jets
  - → g-Sivers in Twist-3
- direct photons
  - → q-Sivers in Twist-3

related through

$$-\int d^2k_\perp \frac{\left|k_\perp^2\right|}{M} f_{1T}^{\perp q}(x,k_\perp^2)\Big|_{SIDIS} = T_{q,F}(x,x)$$

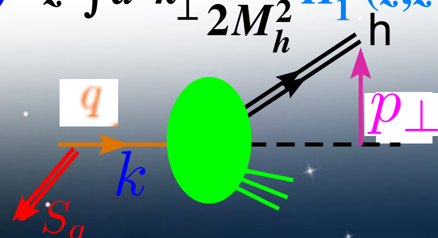


Final State

- **A_{UT} $\pi^{+/-}$-π^0 azimuthal distribution in jets**
  - → Transversity x Collins
- A_{UT} in dihadron production
  - → Transversity x Interference FF
- A_N for π+/- and π^0
  - → Novel Twist-3 FF Mechanisms

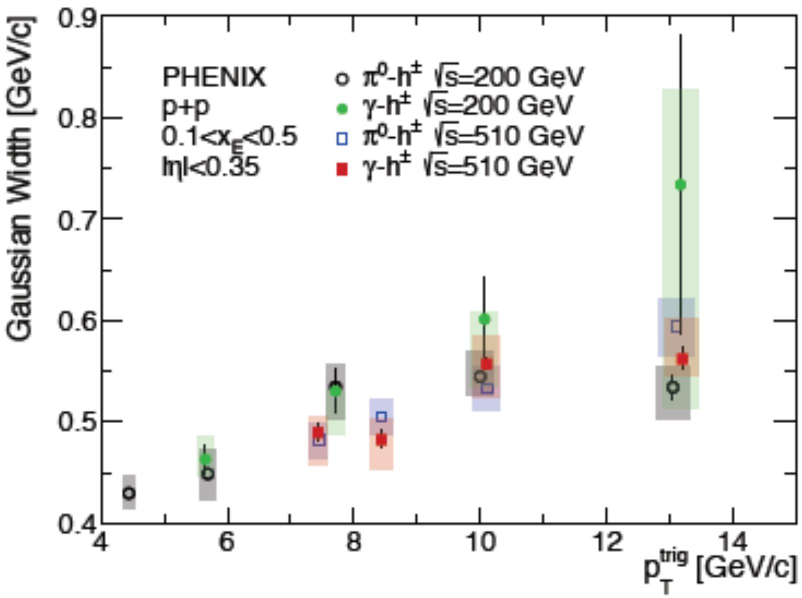
related through

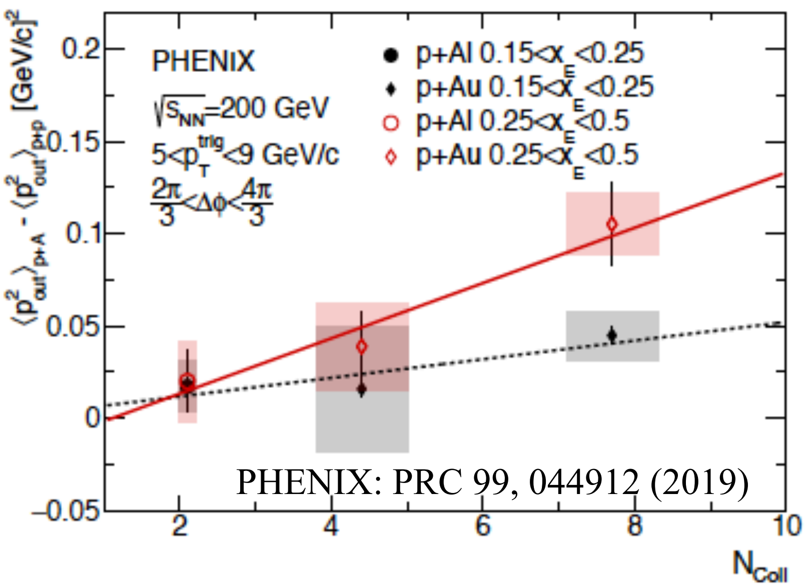
$$\hat{H}(z) = z^2 \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M_h^2} H_1^\perp(z,z^2,\vec{k}_\perp^2)$$

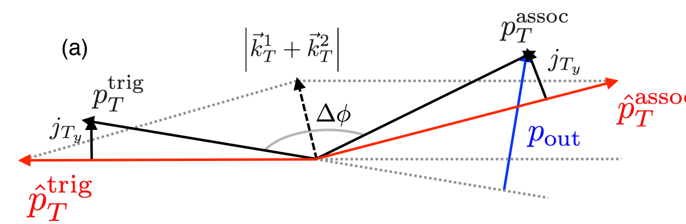


k_T and j_T evolution, p+p vs p+A

PHENIX: PRD 98, 072004 (2018)



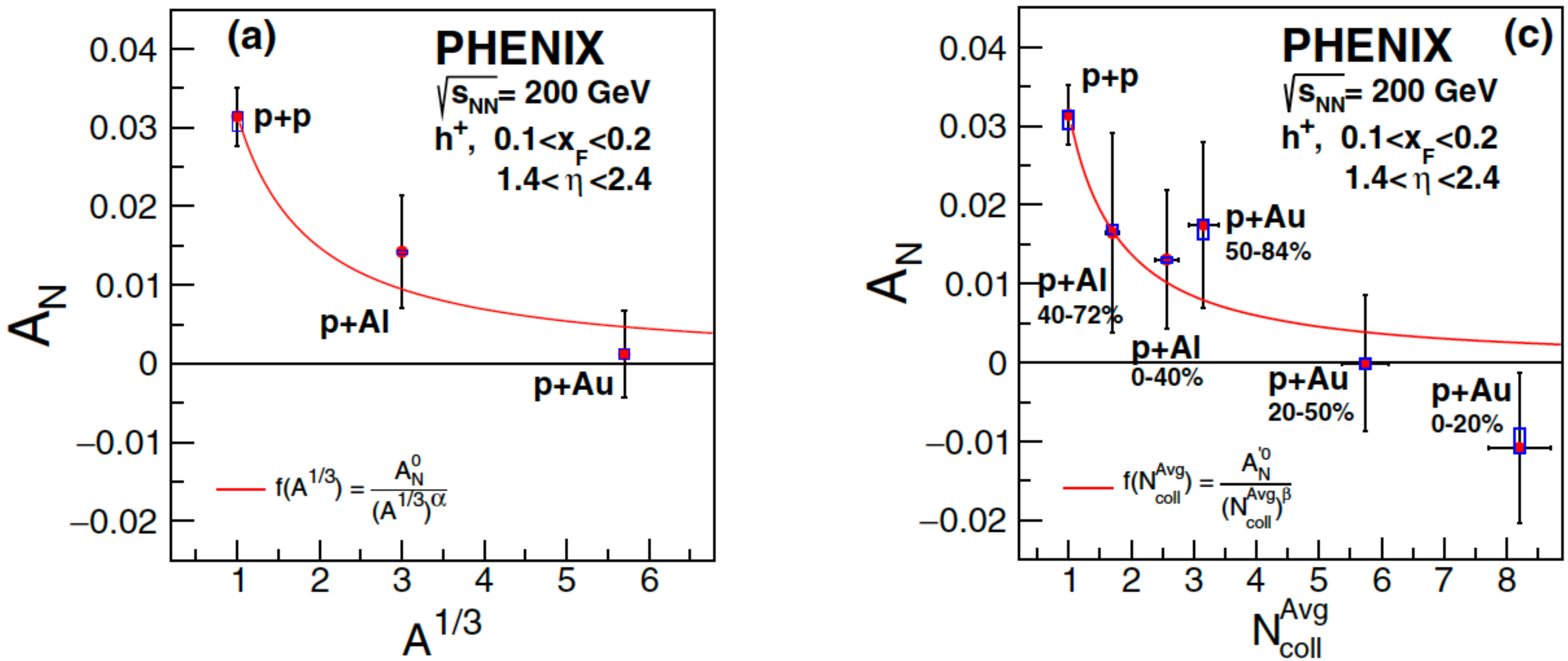




- π^0-$h^\pm$ and $\boldsymbol{\gamma}$-$h^\pm$ - correlation measurements
- Out-of-plane p_{out} is sensitive to combination of k_T and j_T
- Evolution of non-perturbative k_T and j_T with p_T^{trig} and N_{coll}
- Away side peak broadening in pA
  - No modification of near side peak
    => fragmentation not modified
  - Different mechanisms under consideration: Cronin, energy loss, additional initial k_T

$A_N(h+)$ in pA

PHENIX: arXiv: 1903.07422, accepted to PRL



A_N in p+A is suppressed compared to p+p; drops with N_{Coll} in p+A

- New insight in the origin of A_N
- Novel approach to study nuclear effects in small-system collisions