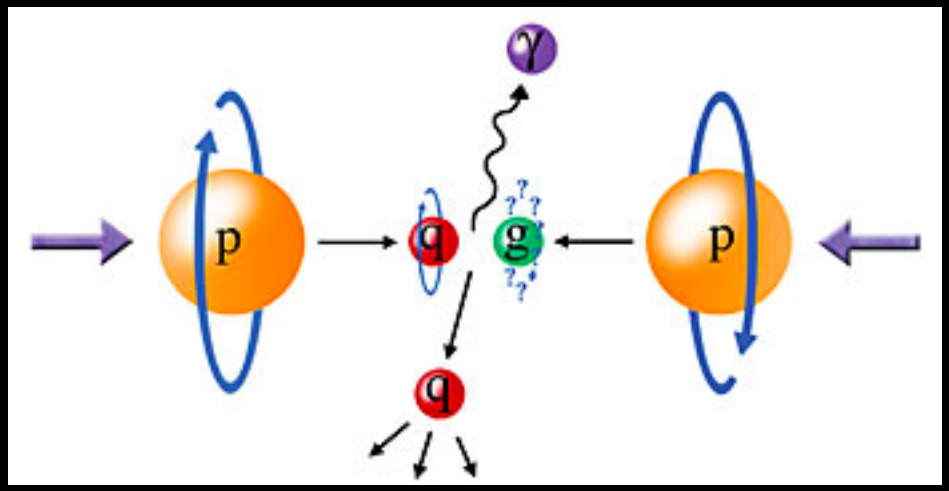
Highlights from the RHIC Spin Program

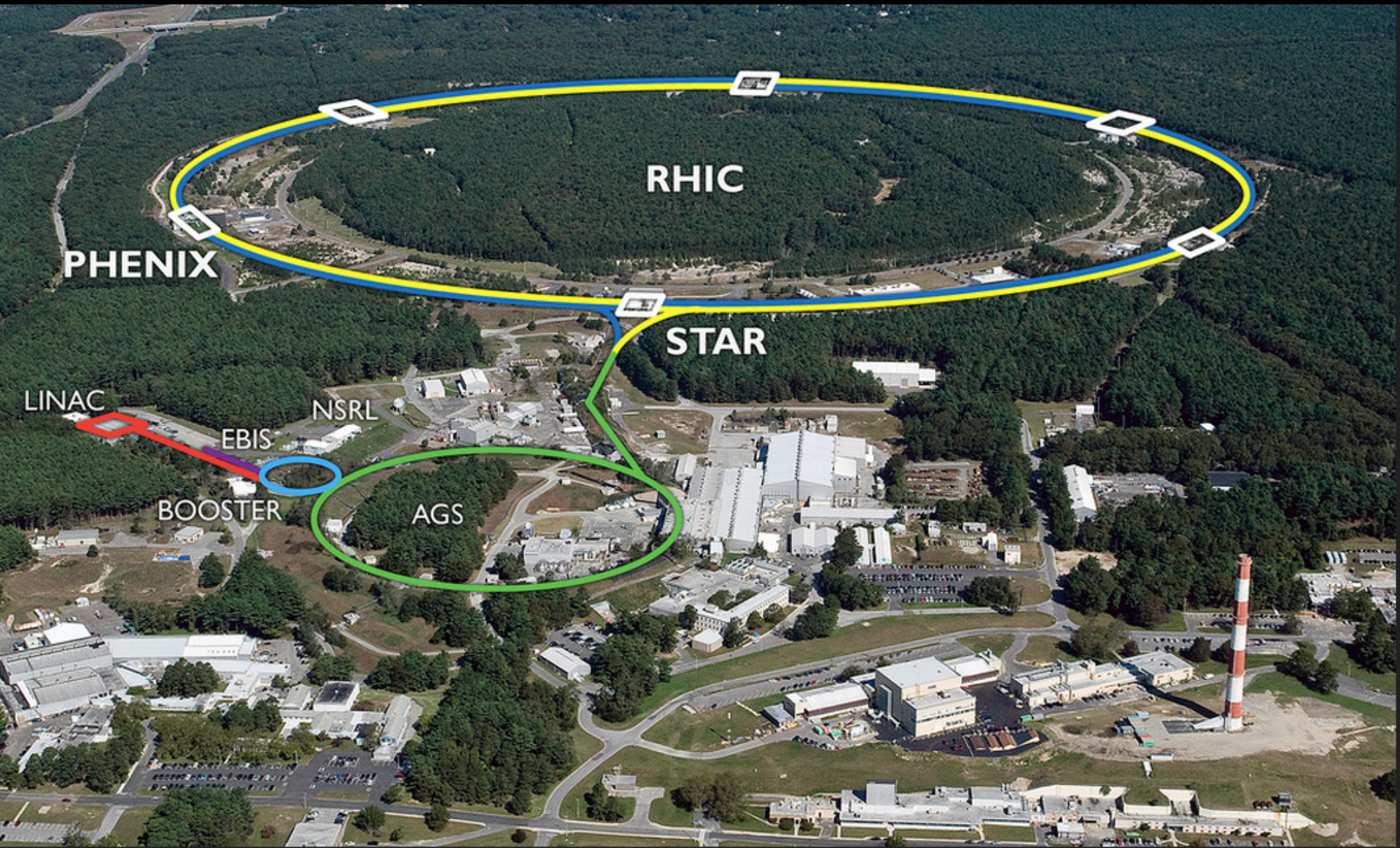


Renee Fatemi
University of Kentucky

6th Workshop of the APS Topical Group on Hadronic Physics

Relativistic Heavy Ion Collider

…worlds 1st and only $\vec{p}\vec{p}$ Collider!



Annu. Rev. Nucl. Part. Sci. 2000. 50:525–75

PROSPECTS FOR SPIN PHYSICS AT RHIC

Gerry Bunce,[1] Naohito Saito,[2] Jacques Soffer,[3] and Werner Vogelsang[4]

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[2]*RIKEN (The Institute of Physical and Chemical Research), Wako, Saitama 351-0198, Japan, and RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000; e-mail: saito@bnl.gov*

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Key Words proton spin structure, spin asymmetries, quantum chromodynamics, beyond the standard model

■ **Abstract** Colliding beams of 70% polarized protons at up to $\sqrt{s} = 500$ GeV, with high luminosity, $L = 2 \times 10^{32}\,cm^{-2}\,sec^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious production of jets, directly produced photons, and W and Z bosons. Features will include direct and precise measurements of the polarization of the gluons and of $\bar{u}$, $\bar{d}$, u, and d quarks in a polarized proton. Parity violation searches for physics beyond the standard model will be competitive with unpolarized searches at the Fermilab Tevatron. Transverse spin will explore transversity for the first time, as well as quark-gluon correlations in the proton. Spin dependence of the total cross section and in the Coulomb nuclear interference region will be measured at collider energies for the first time. These qualitatively new measurements can be expected to deepen our understanding of the structure of matter and of the strong interaction.

Highly polarized proton beam with √s up to 500 GeV

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First (ahem!) exploration of Transversity

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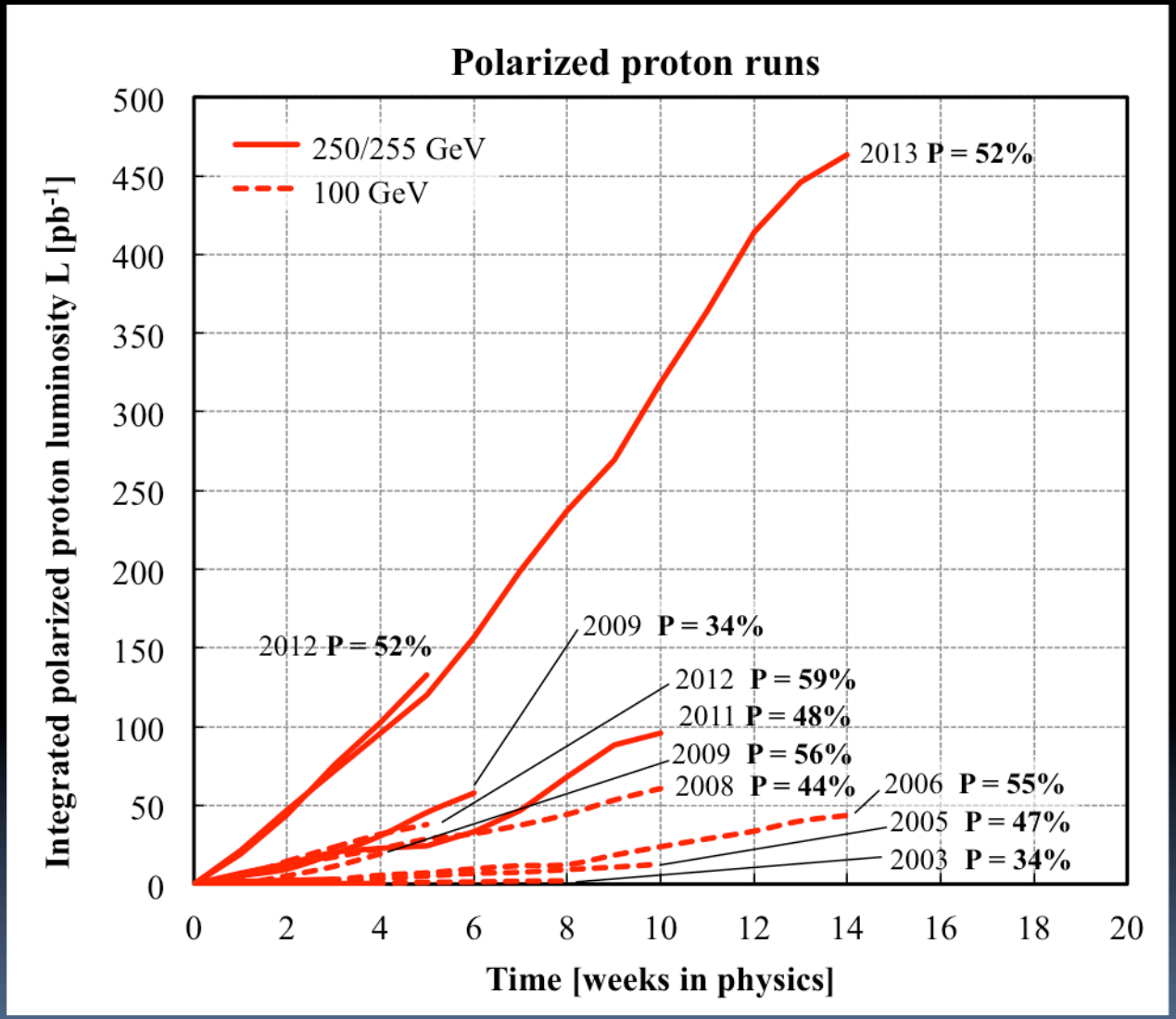
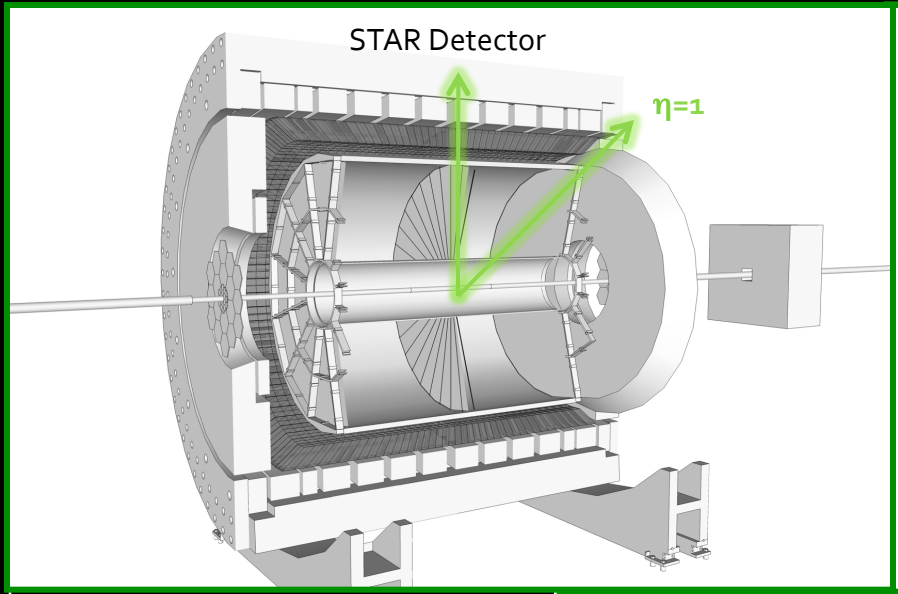
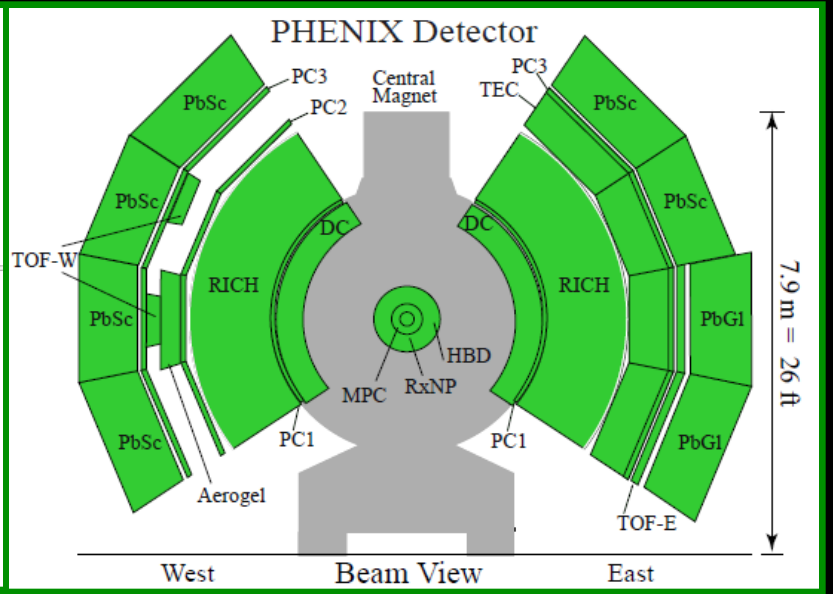
… and the physics we didn't yet know we needed to know!

Longitudinal	STAR
√s = 200 GeV	
2005	3 pb^{-1}
2006	7 pb^{-1}
2009	35 pb^{-1}
(2015)	(40 pb-1)
√s = 500 GeV	
2009	10 pb^{-1}
2011	12 pb^{-1}
2012	82 pb^{-1}
2013	300 pb^{-1}

Transverse data	STAR
√s = 200 GeV	
2006	9 pb^{-1}
2008	8 pb^{-1}
2012	22 pb^{-1}
2015	60 pb^{-1}
√s = 500 GeV	
2011	25 pb^{-1}
(2017)	(400 pb^{-1})

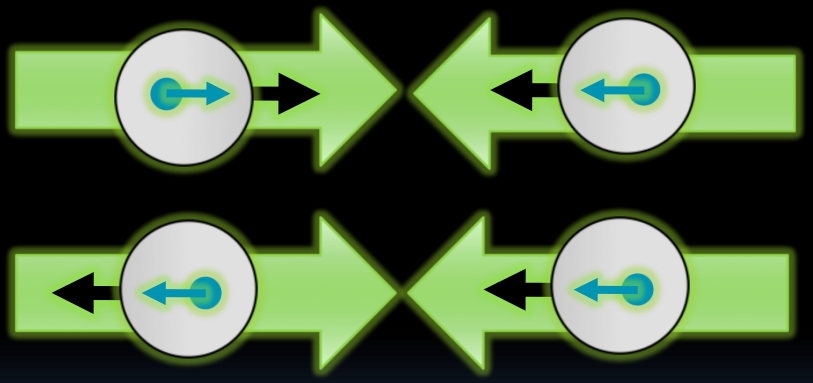




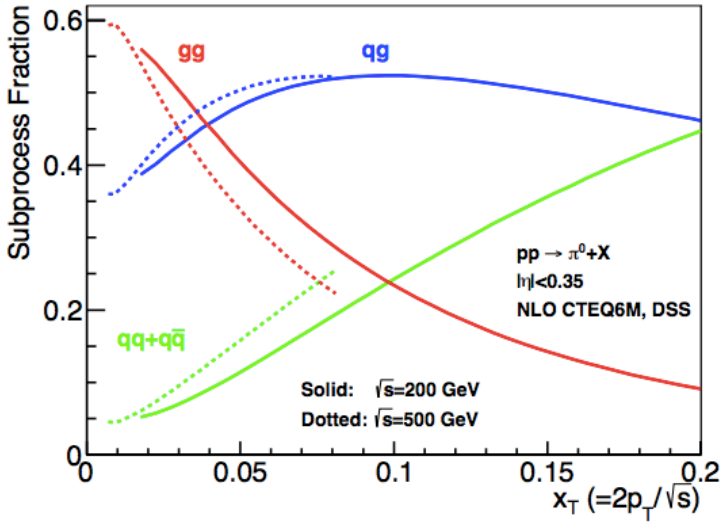


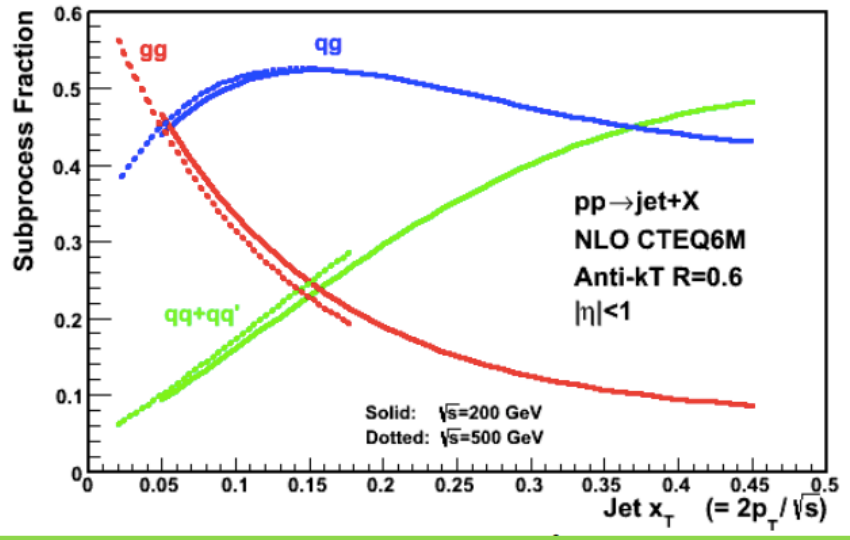
TIME PROJECTION CHAMBER	**CHARGED PARTICLE TRACKING**	DRIFT + PAD CHAMBERS
TPC + TOF	**CHARGED PARTICLE IDENTIFICATION**	RICH +TOF
EM CALORIMETER 5520 (PbSc) towers	**EM PARTICLE DETECTION HIGH PT TRIGGERING**	EM CALORIMETER 15552 (PbSc) towers 9216 (PbGl) towers
BEAM BEAM COUNTERS ZERO DEGREE COUNTERS	**RELATIVE LUMINOSITY MINIMUM BIAS TRIGGERING**	BEAM BEAM COUNTERS ZERO DEGREE COUNTERS
LARGE ACCEPTANCE (-1<η<2)	**STRENGTHS**	HIGH RESOLUTION HIGH RATE READOUT

Gluon Polarization



How to access ΔG at a pp collider?



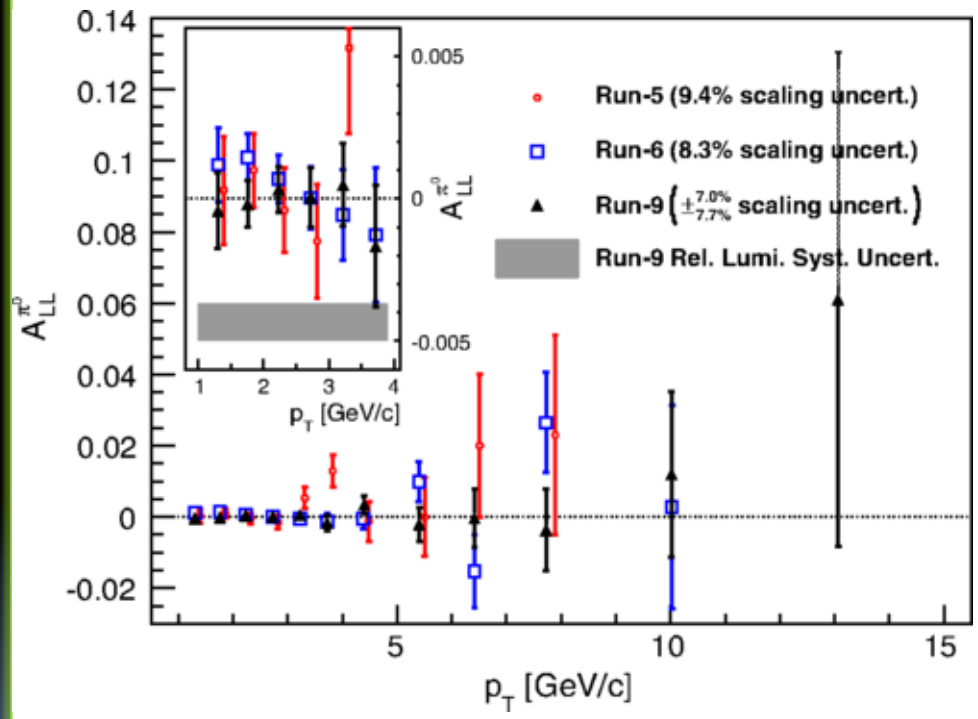


Double Spin Asymmetries of jets and pions are ideal!

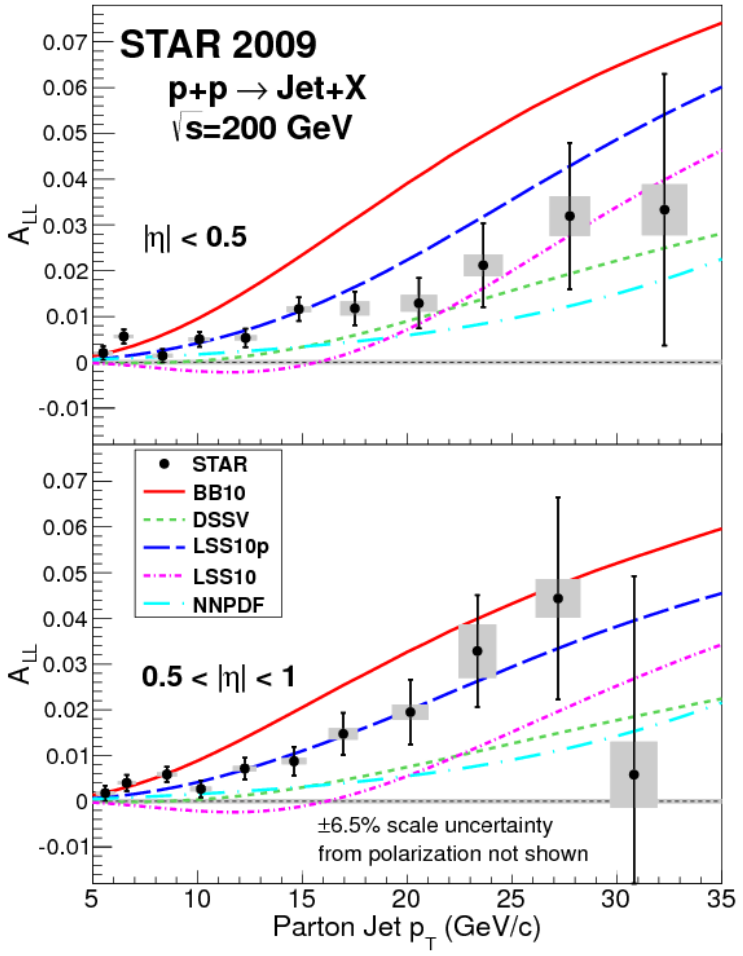
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{f_A f_B f_C} \Delta f_A \Delta f_B \times \Delta\sigma_{AB\to CX} \times D_C}{\sum_{f_A f_B f_C} f_A f_B \times \sigma_{AB\to CX} \times D_C}$$

Recent $\sqrt{s}$ = 200 GeV π^0 and jet A_{LL}

Phys.Rev.D 90, 012007 (2014)

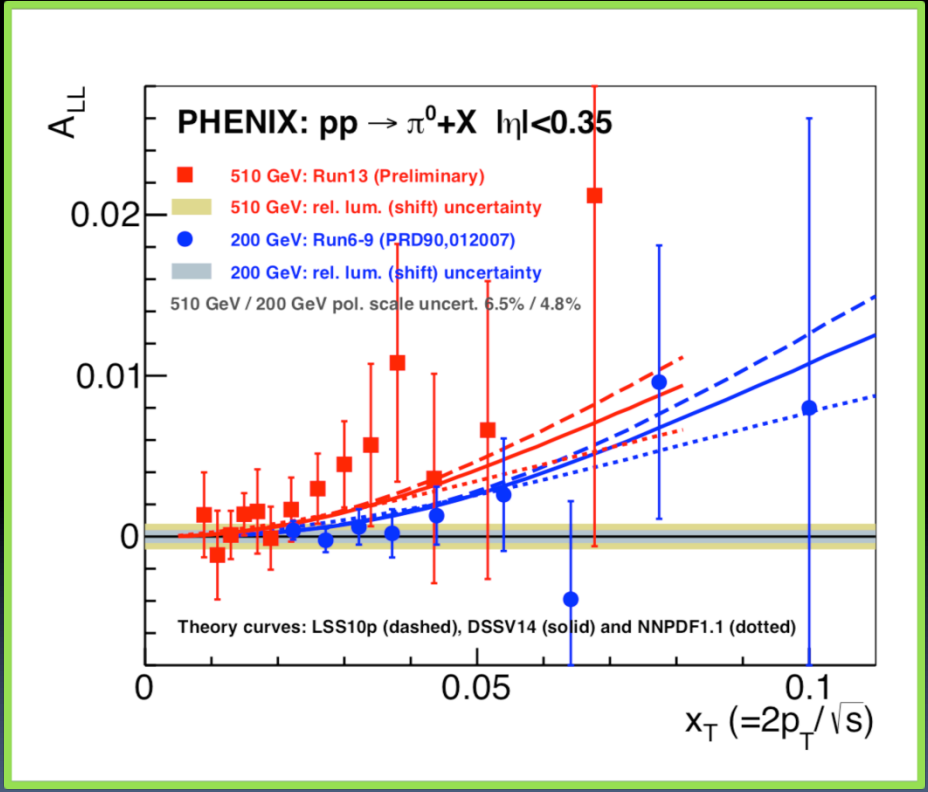


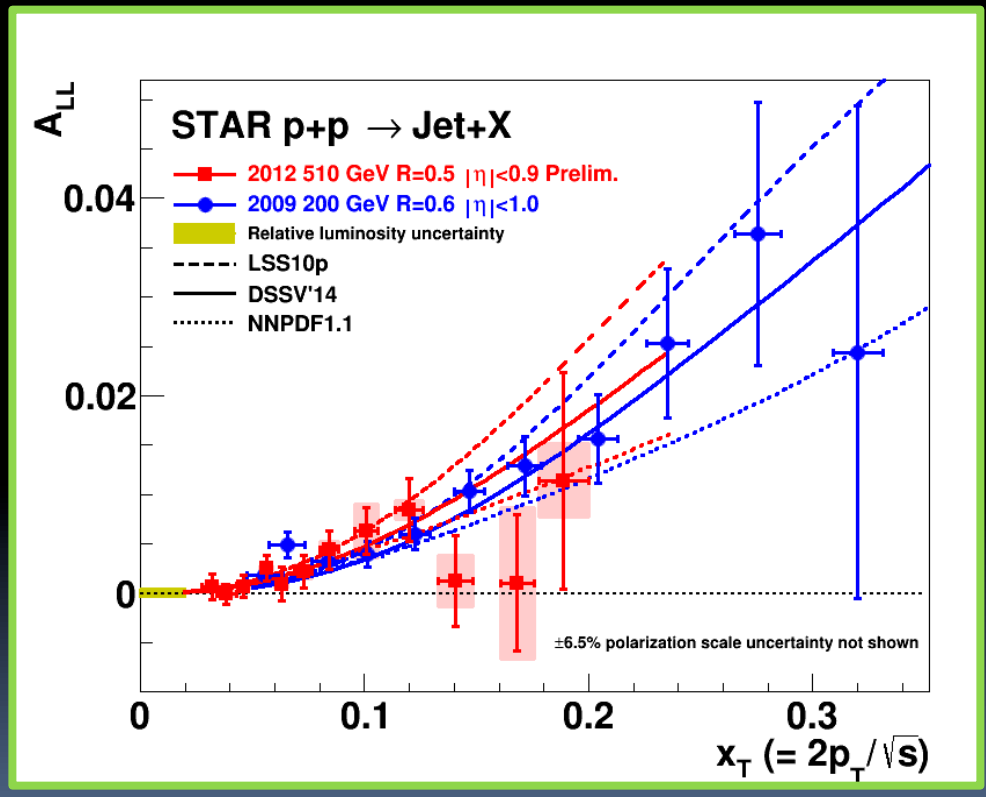
arXiv:1405.5134



First √s = 500 GeV π^0 and jet A_{LL}!

Provides first access to lower x

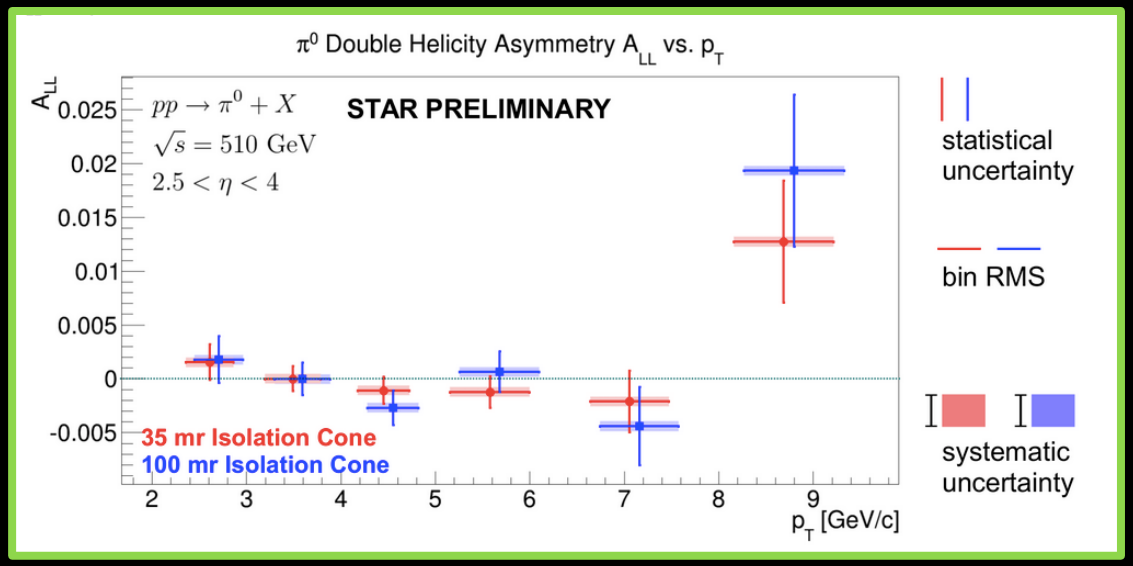


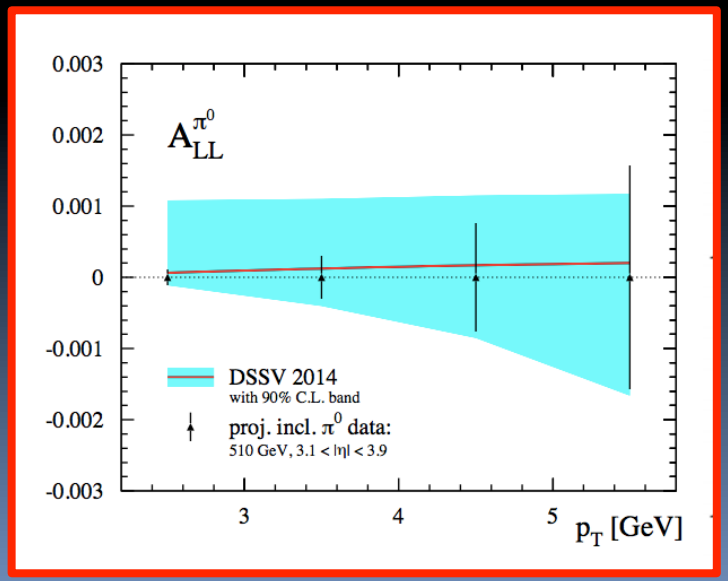


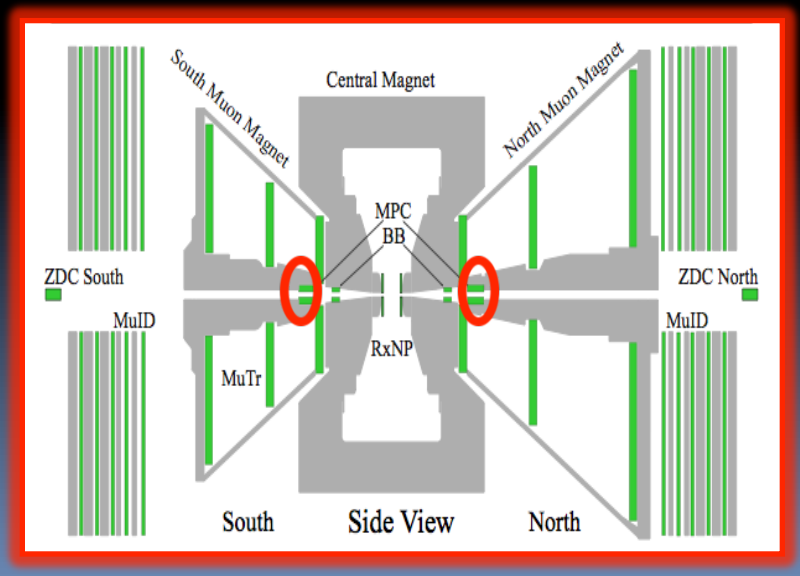
Forward A_{LL} accesses x ~ 10^{-3} region

Neutral pion A_{LL} at √ s= 500 GeV in the STAR Forward Meson Spectrometer (2.5 < η < 4)

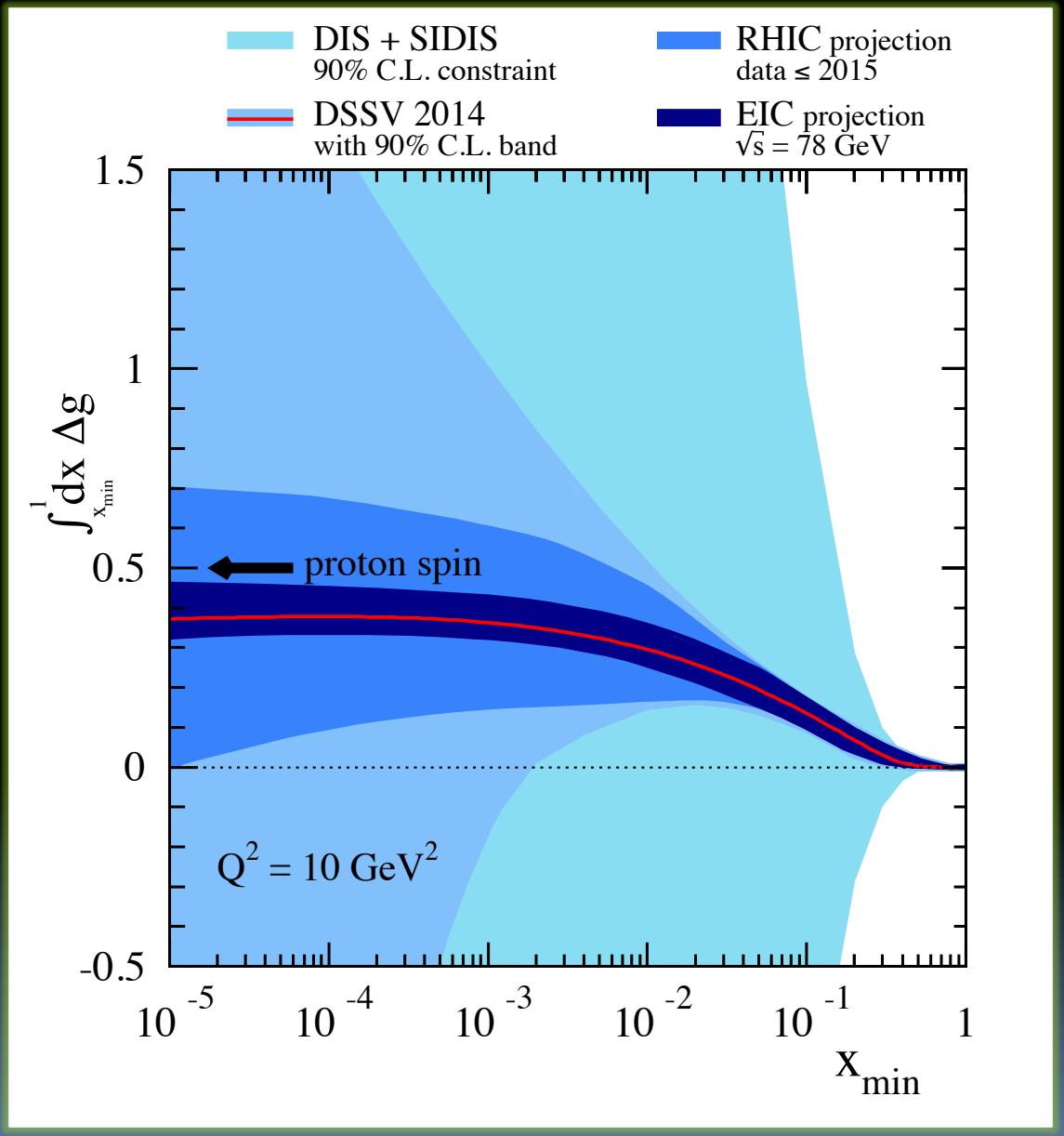
Expected inclusive π^0 A_{LL} at √ s= 500 GeV in PHENIX Forward Muon Piston Chamber (3.1 < η < 3.9)







RHIC impact on ΔG



Special thanks to DSSV for this plot!

DSSV

Phys.Rev.Lett. 113 1, 012001 (2014)

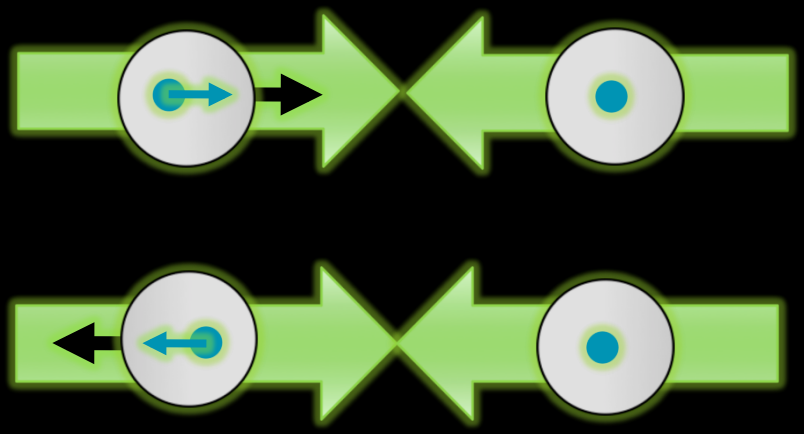
ΔG (x > 0.05)
= 0.2 (+0.06/-0.07)

NNPDF

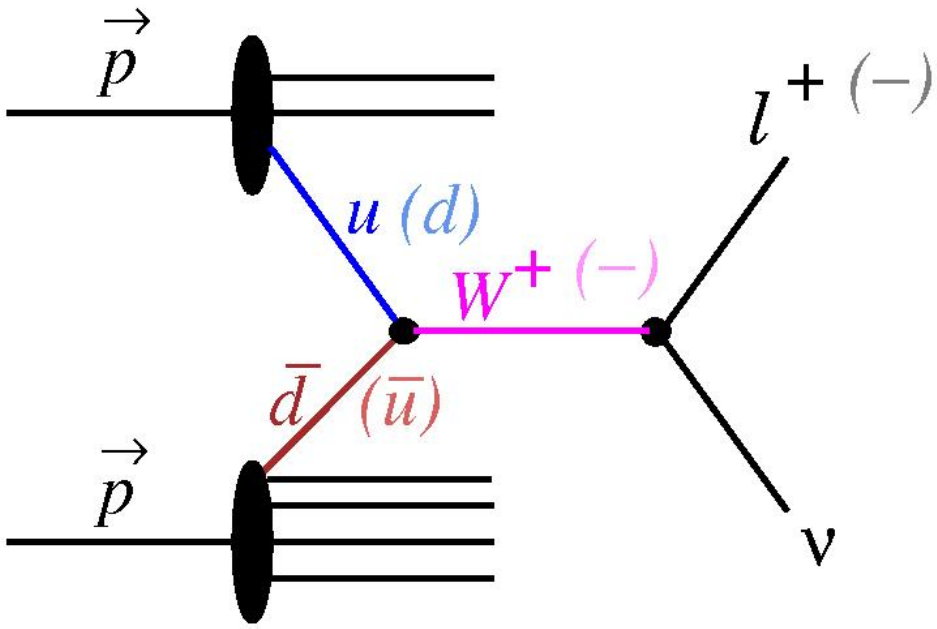
Nucl.Phys.B887, 276-308 (2014)

ΔG (0.2 > x > 0.05)
= 0.17 (+/- 0.06)

Quark Polarization



Probing the Sea Through W Production

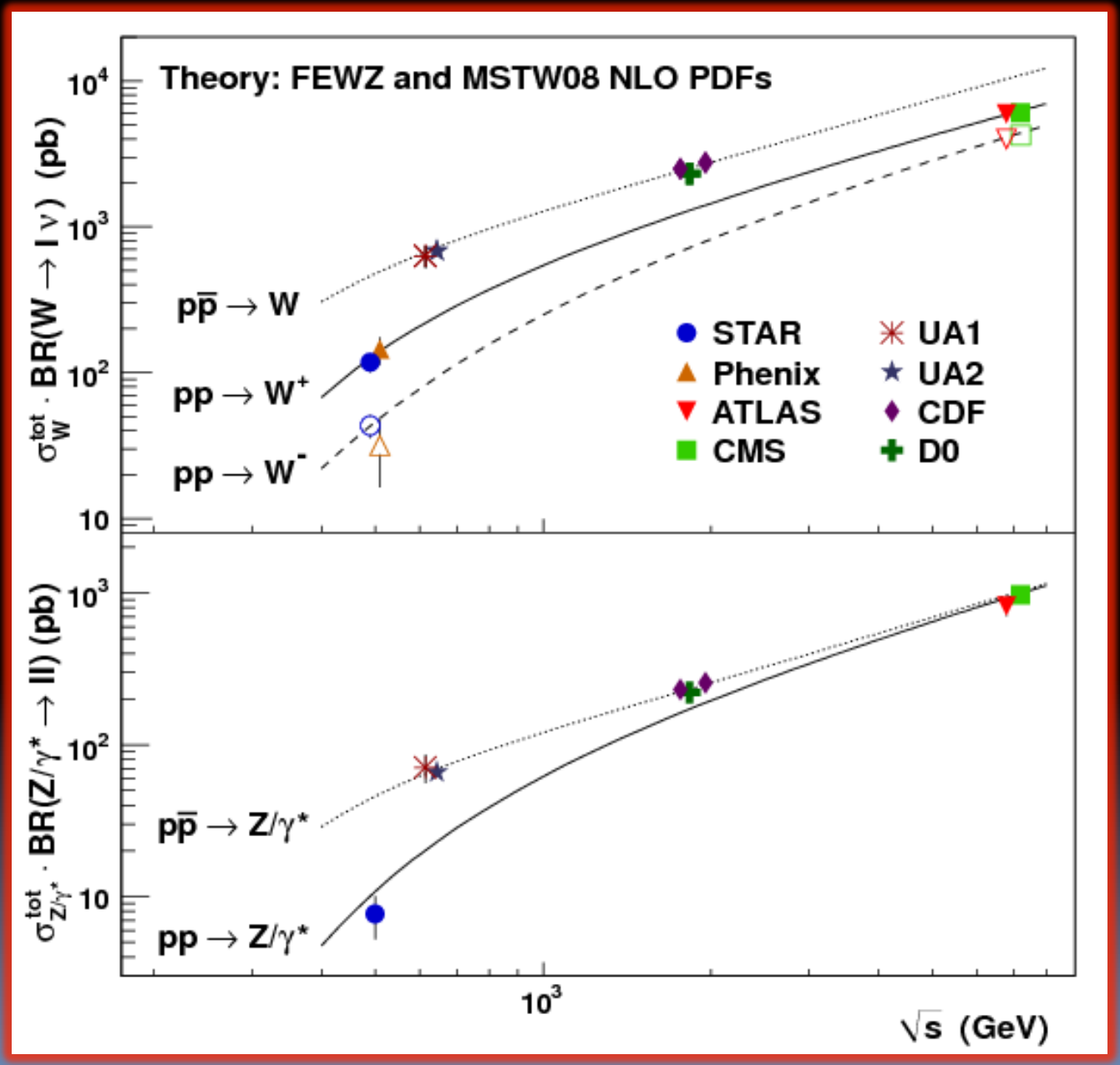


Measure parity-violating single-spin asymmetry of detected leptons:

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

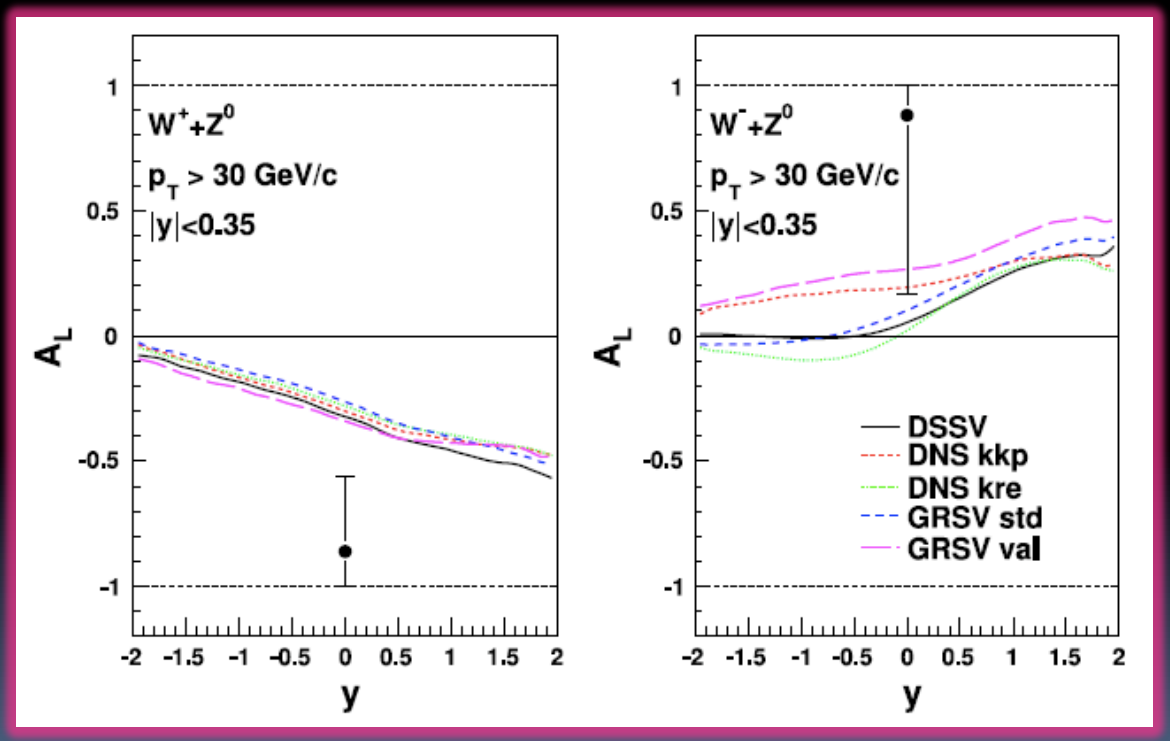
$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \qquad A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$W^{+/-}$ & Z Cross Sections

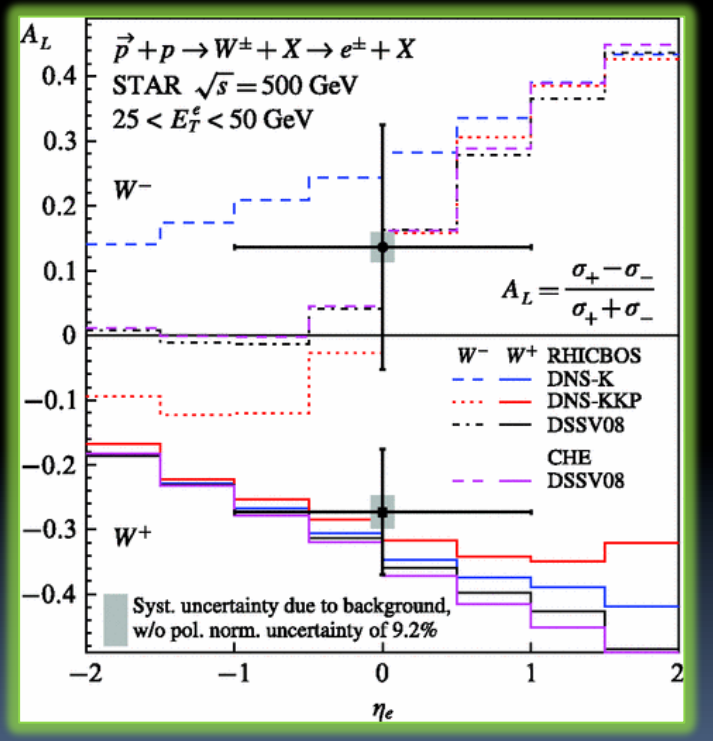


Initial STAR & PHENIX mid-rapidity W A_L

$W^{+/-} \longrightarrow e^{+/-}+\nu$

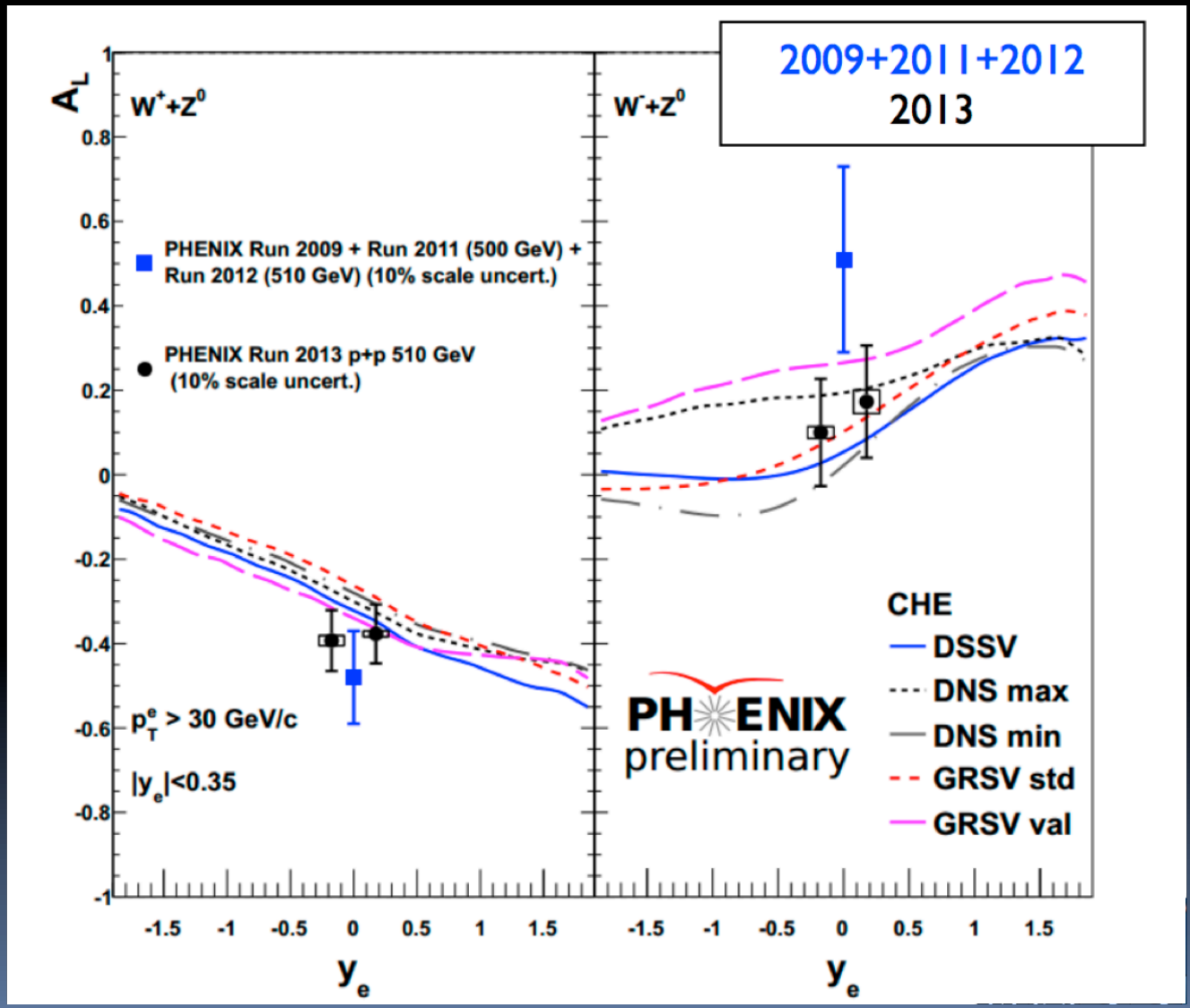


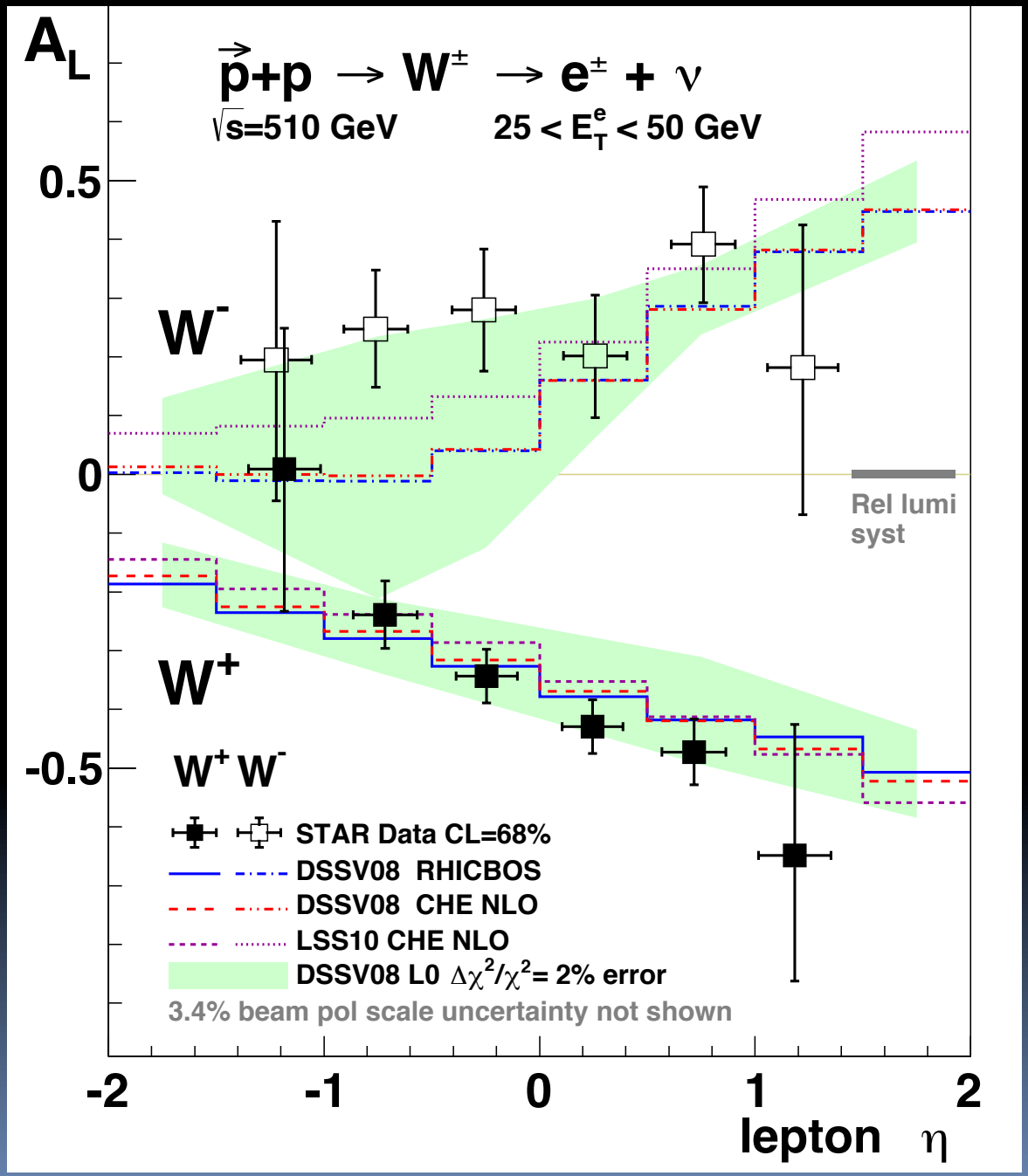
Phys.Rev.Lett 106:062001 (2011)



Phys.Rev.Lett 106:062002 (2011)

PHENIX mid-rapidity $W^{+/-} \rightarrow e^{+/-}+\nu$



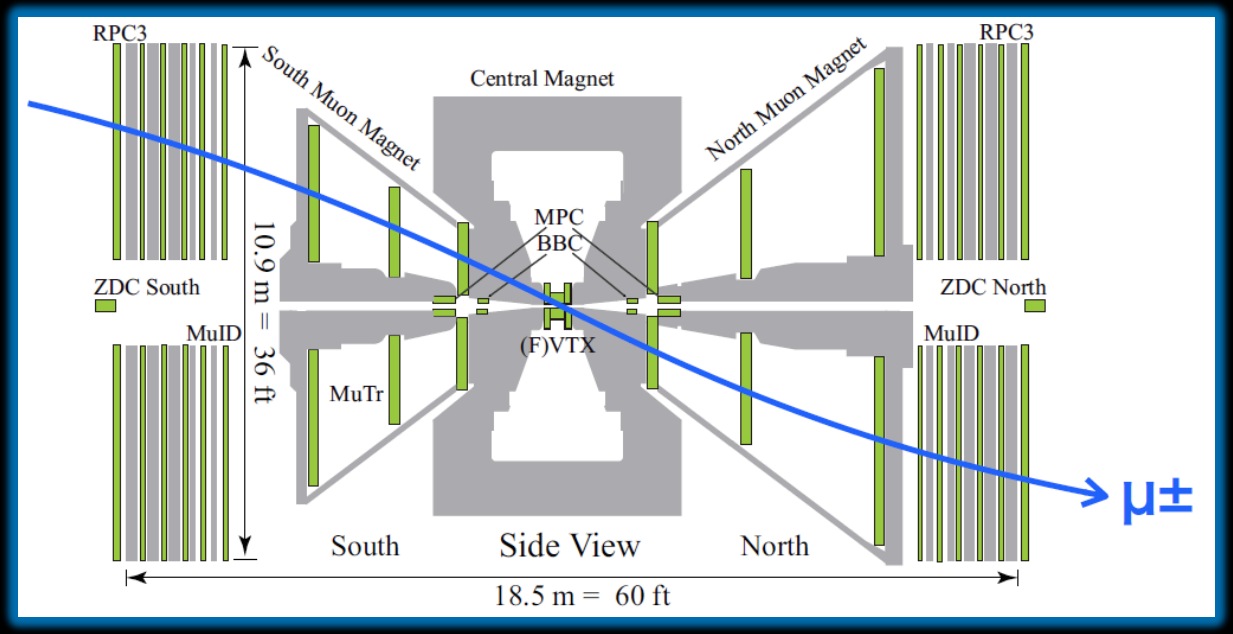


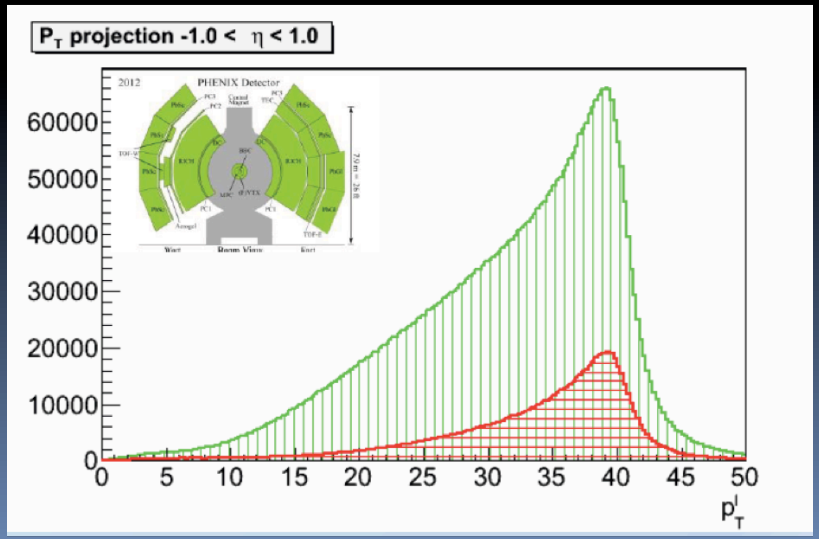
STAR mid-rapidity

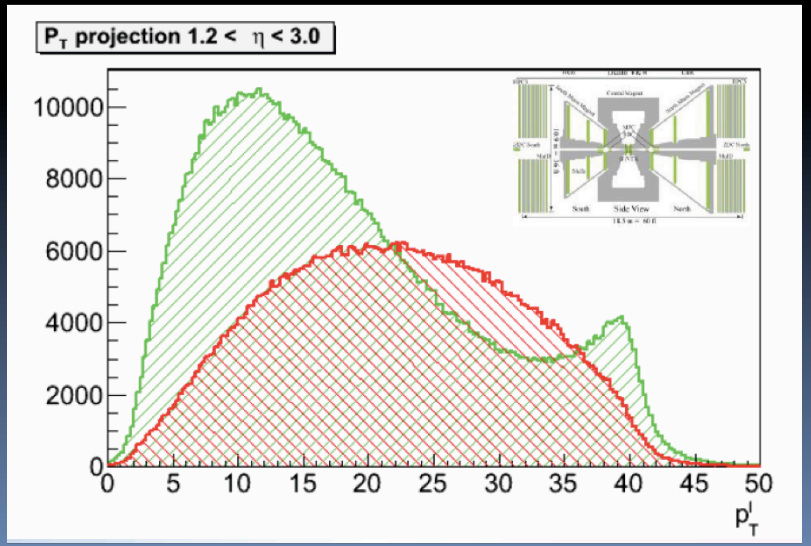
Data combined from 2011-2012. Run 2013 still being analyzed.

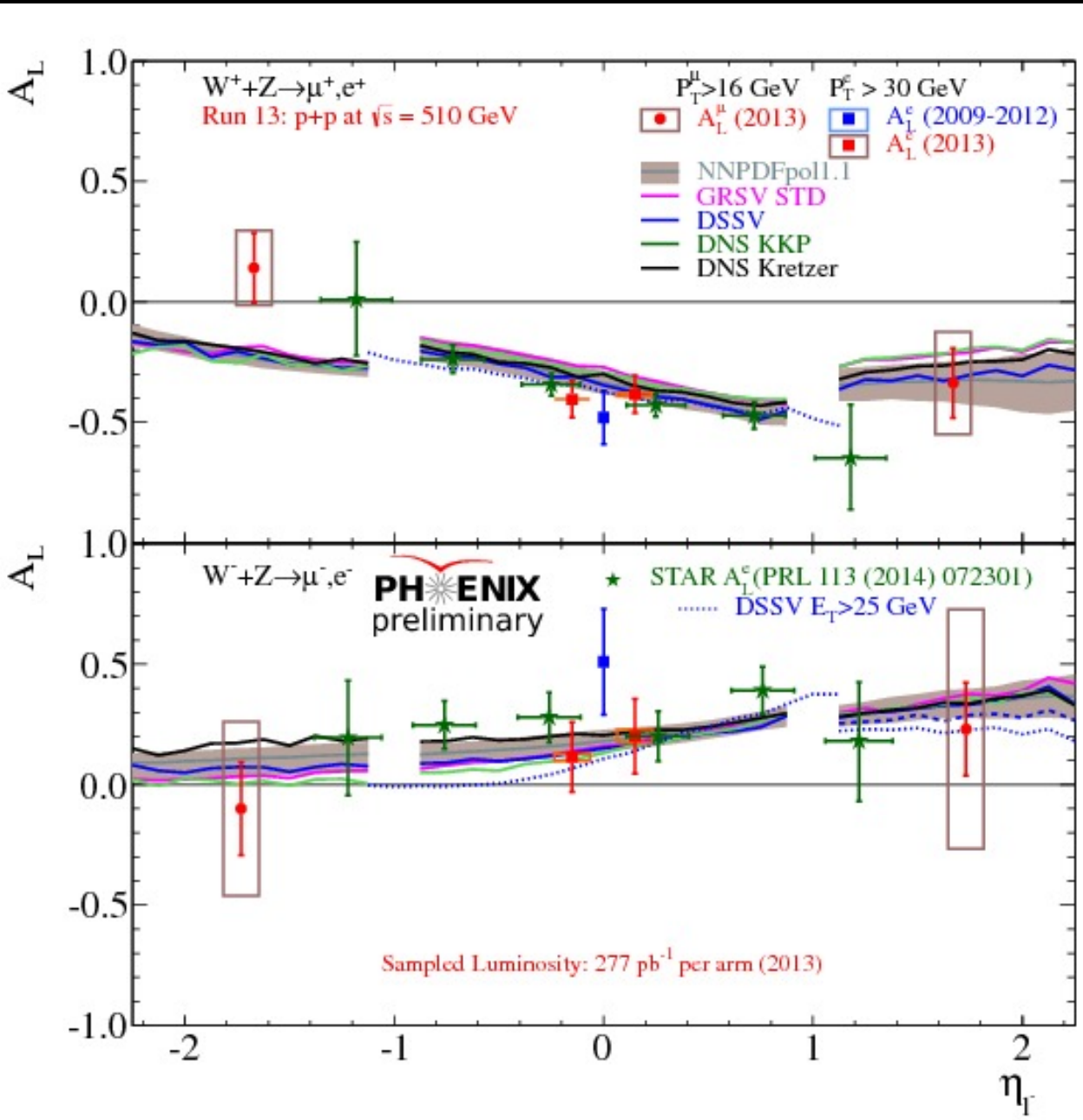
Clear evidence of broken flavor symmetry in polarized sea!

PHENIX Forward $W^{+/-} \rightarrow \mu^{+/-}+\nu$ A_L



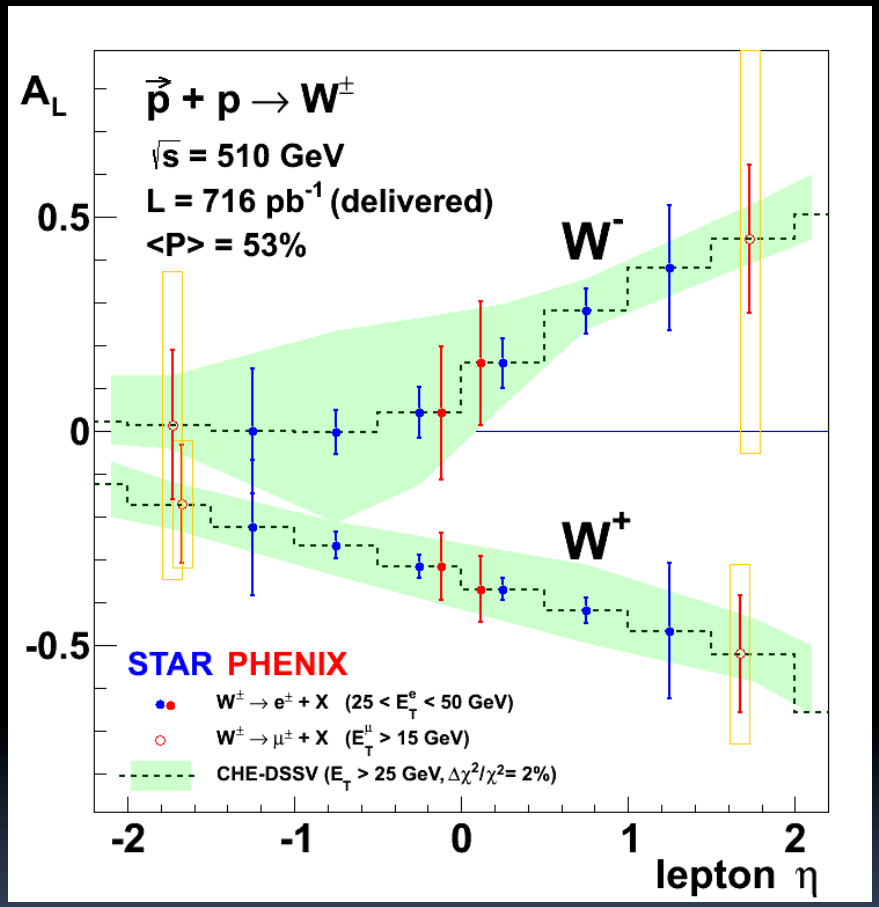


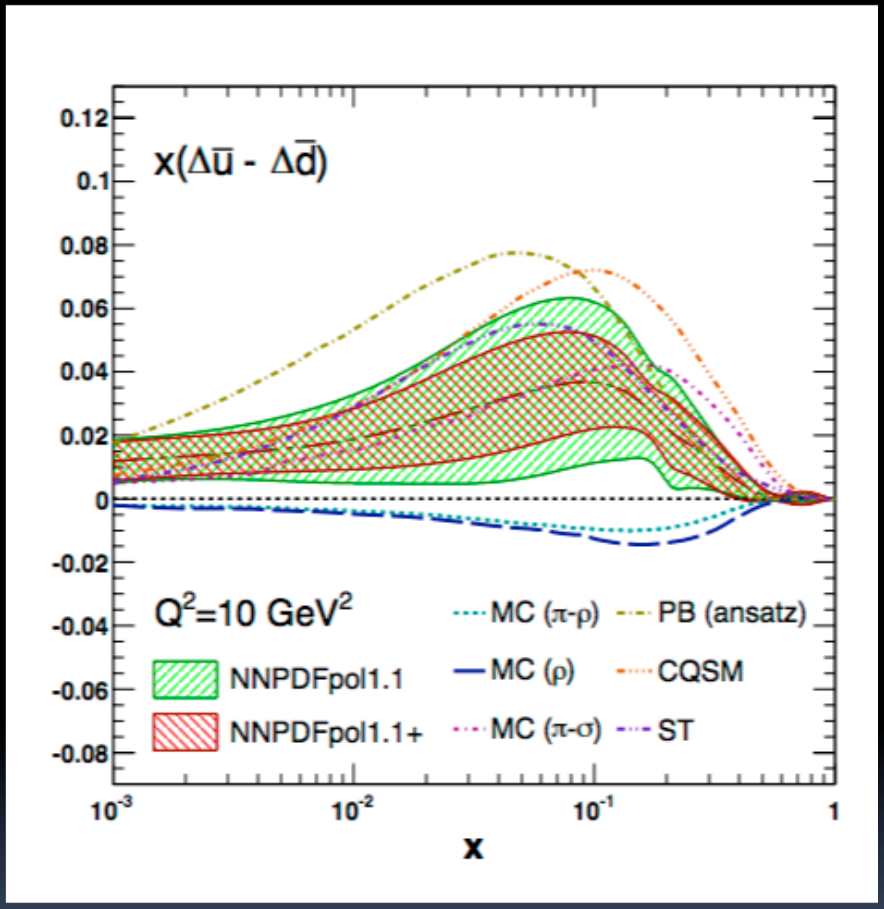




PHENIX Forward & mid-rapdity W A_L

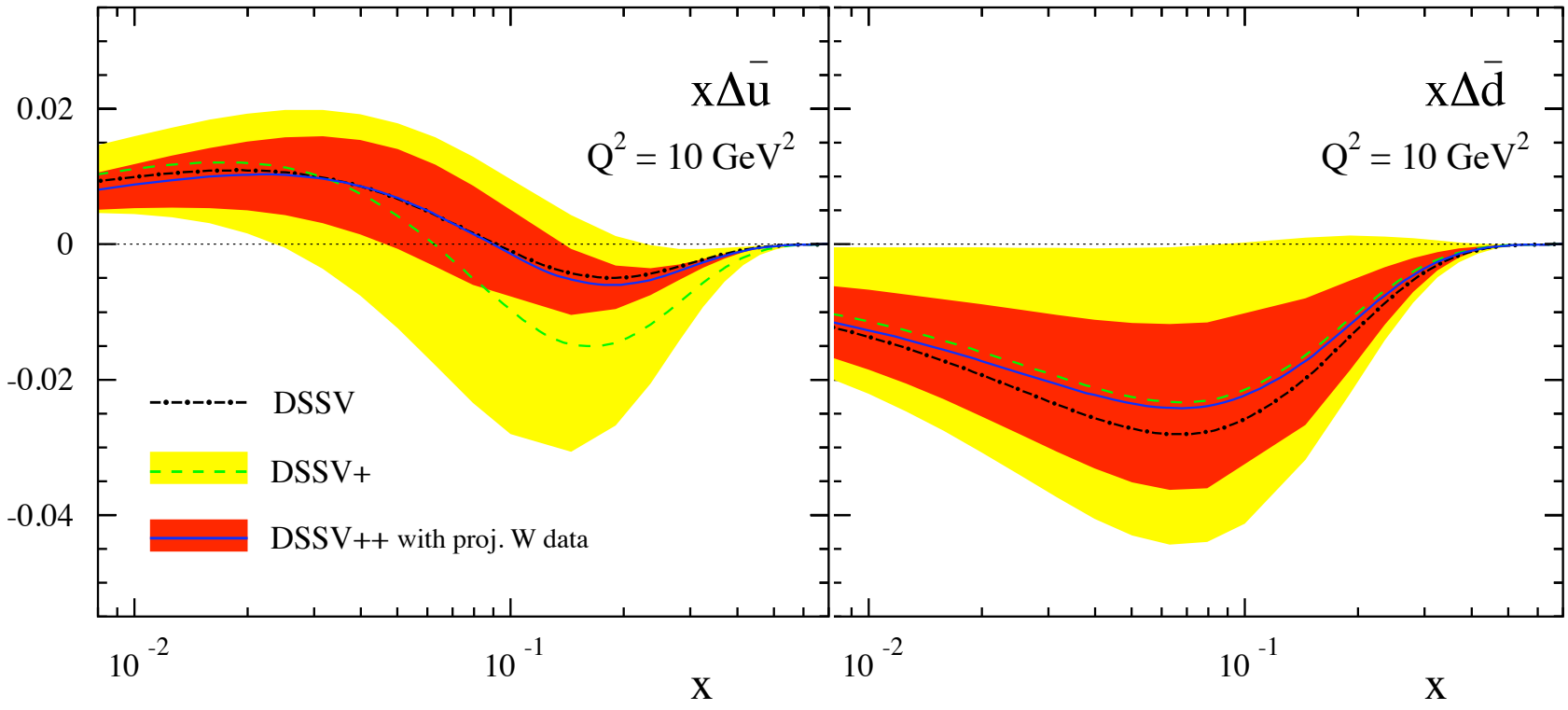
PHENIX + STAR W A_L After Run 13



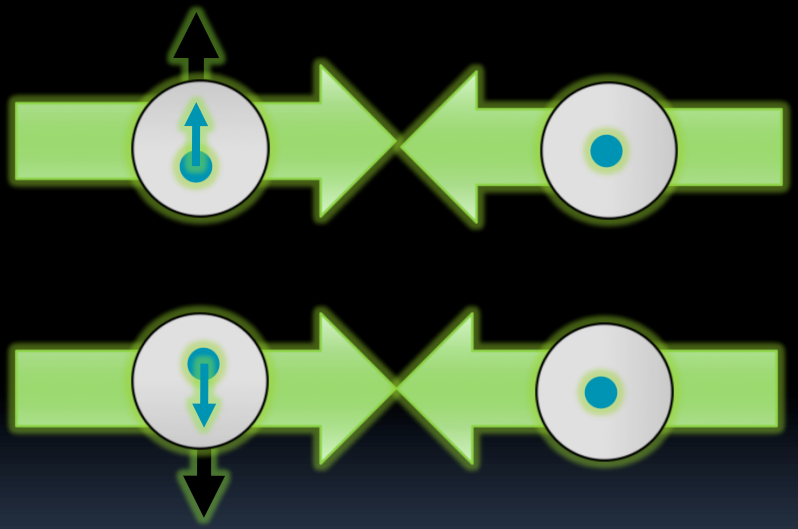


NNPDF Collaboration, Nucl. Phys. B887 276 (2014)
NNPDFpol1.1 includes STAR Runs 9-12 and PHENIX Run 9
NNPDFpol1.1 incorporates total projected statistics from RHIC

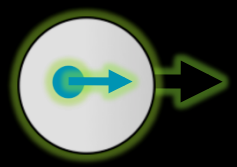
Impact on $\Delta\bar{u}$ & $\Delta\bar{d}$ PDFs?



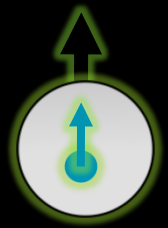
Quark Transversity

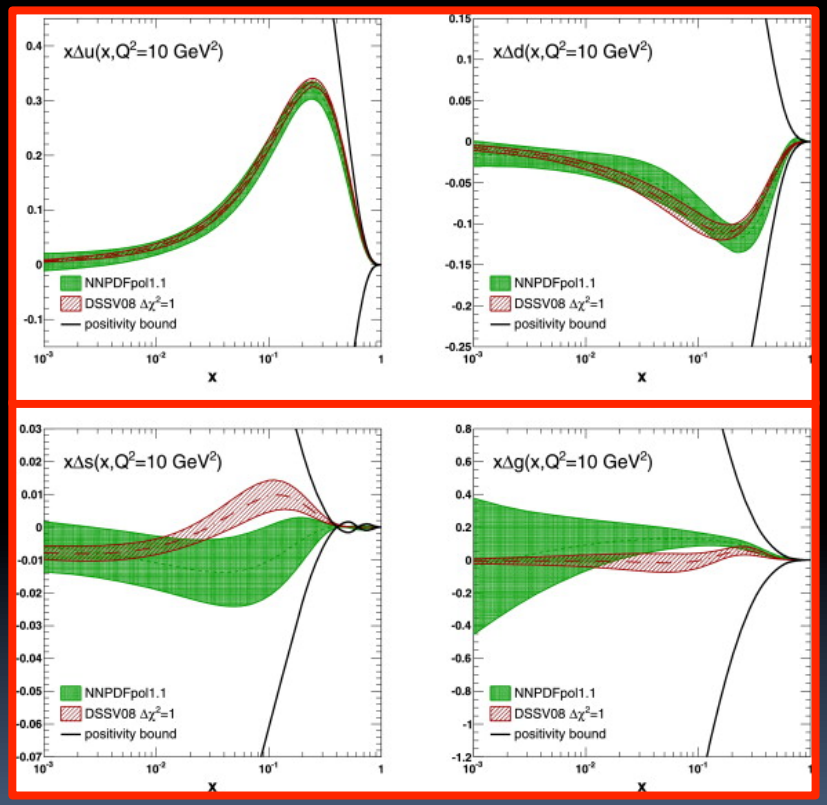


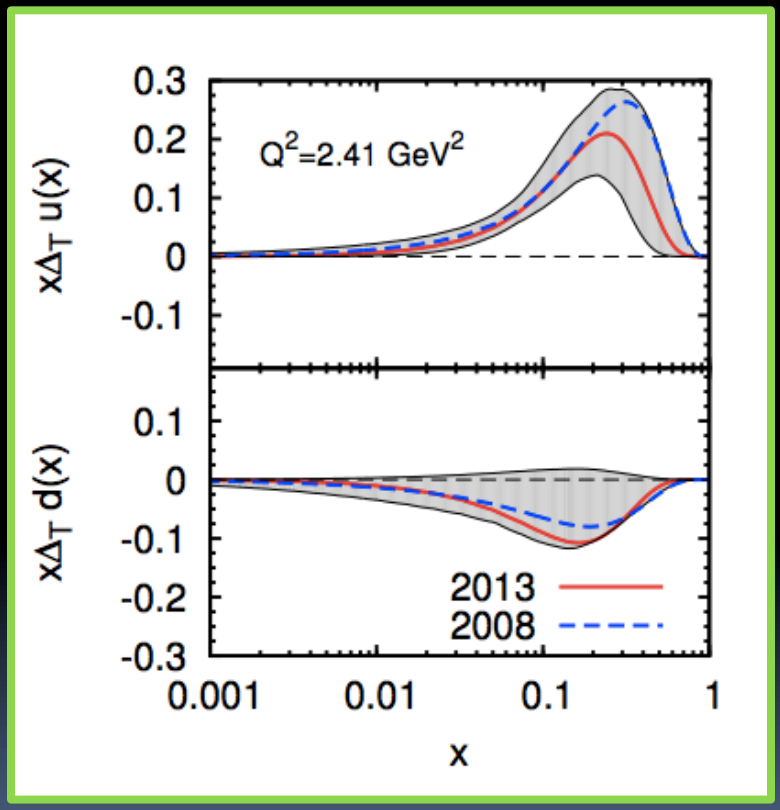
Helicity



Transversity





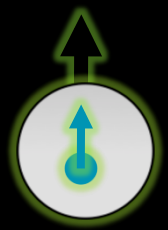


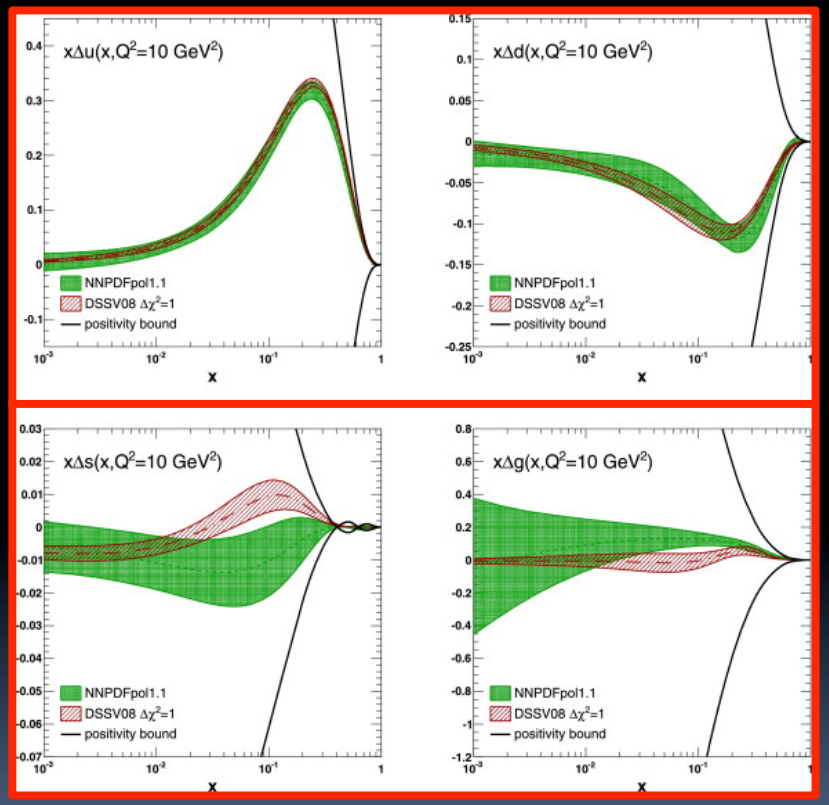
NNPDF 1.0 Nucl. Phys. B, Vol. 887, 2014, 276

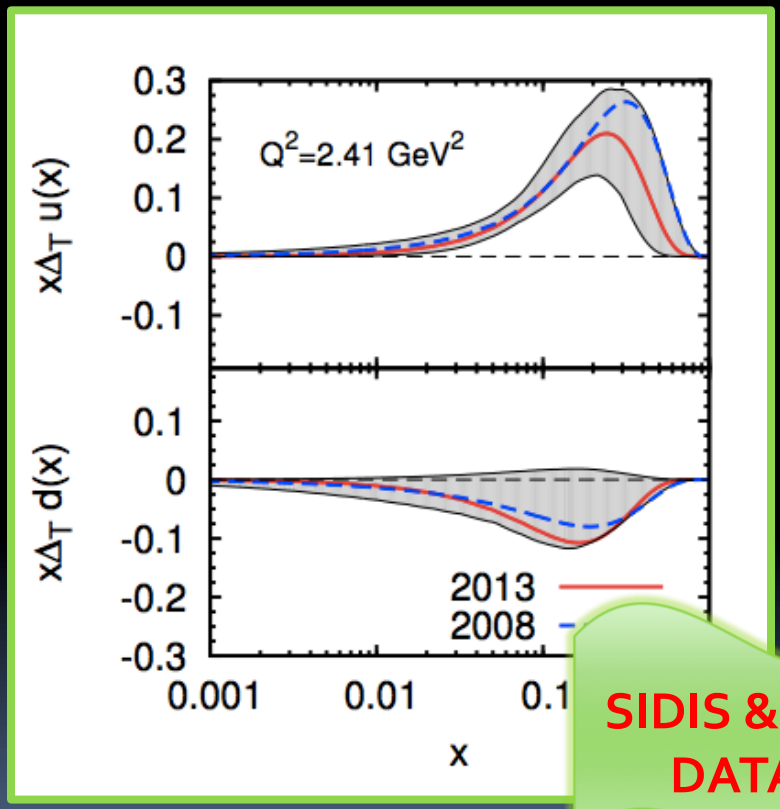
Phys.Rev. D87 (2013) 094019

Helicity

Transversity







SIDIS & e^+e^- DATA

NNPDF 1.0 Nucl. Phys. B, Vol. 887, 2014, 276

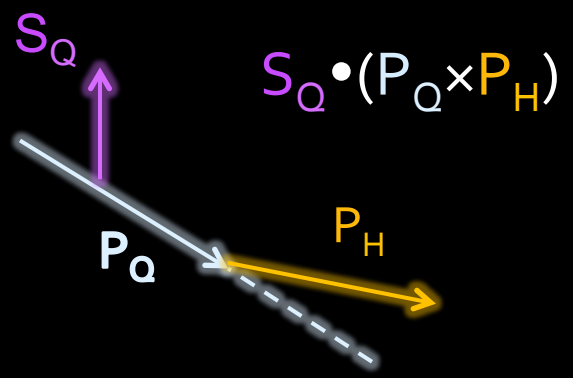
Phys.Rev. D87 (2013) 094019

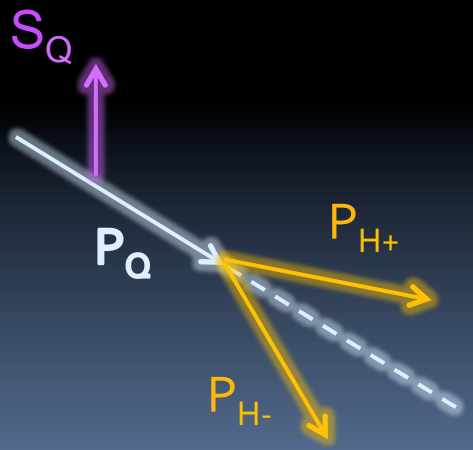
Access transversity *in pp collisions?*

….Couple a chiral odd fragmentation function with quark $\Delta_T f(x)$!

Collins Fragmentation Functions

Correlation between spin of transversely polarized quark and transverse momentum kick given to fragmentation hadron.





Interference Fragmentation Functions

Correlation between spin of transversely polarized quark and momentum cross-product of dihadron pair.

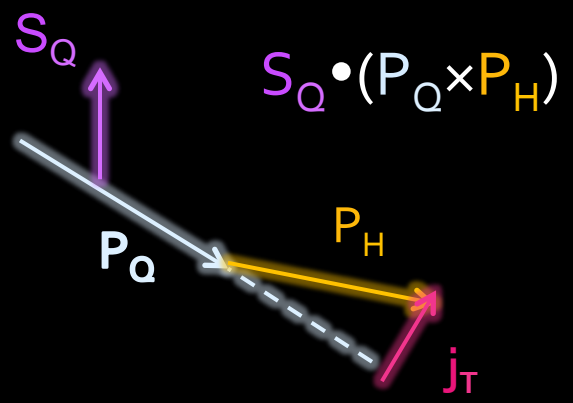
$$S_Q \bullet (P_{H-} \times P_{H+})$$

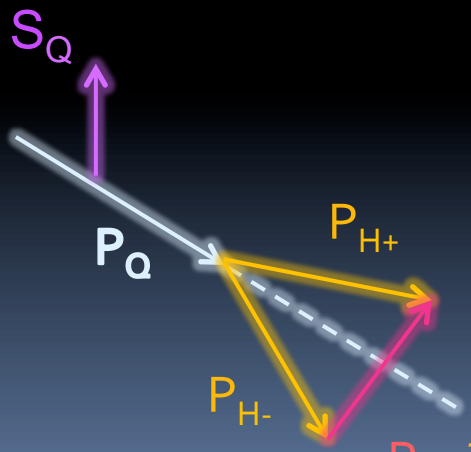
Access transversity *in pp collisions?*

….Couple a chiral odd fragmentation function with quark $\Delta_T f(x)$!

Collins Fragmentation Functions

Does not survive integration over transverse momentum of hadron j_T with respect to the jet axis. Needs Transverse Momentum Dependent framework!





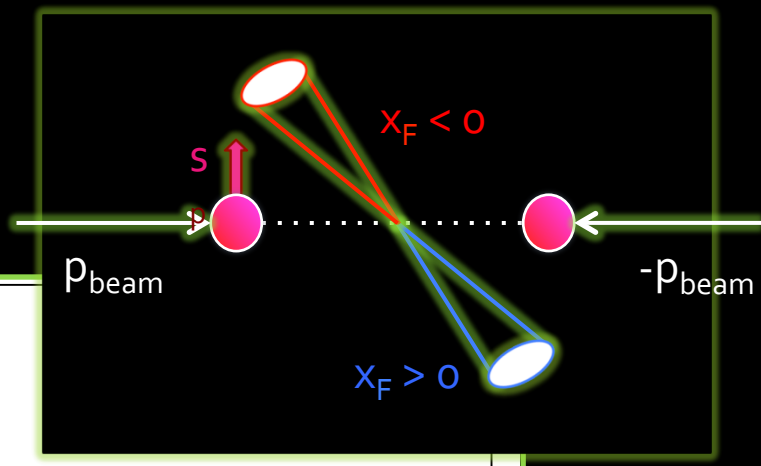
$R = \frac{1}{2}(P_{H+} - P_{H-})$

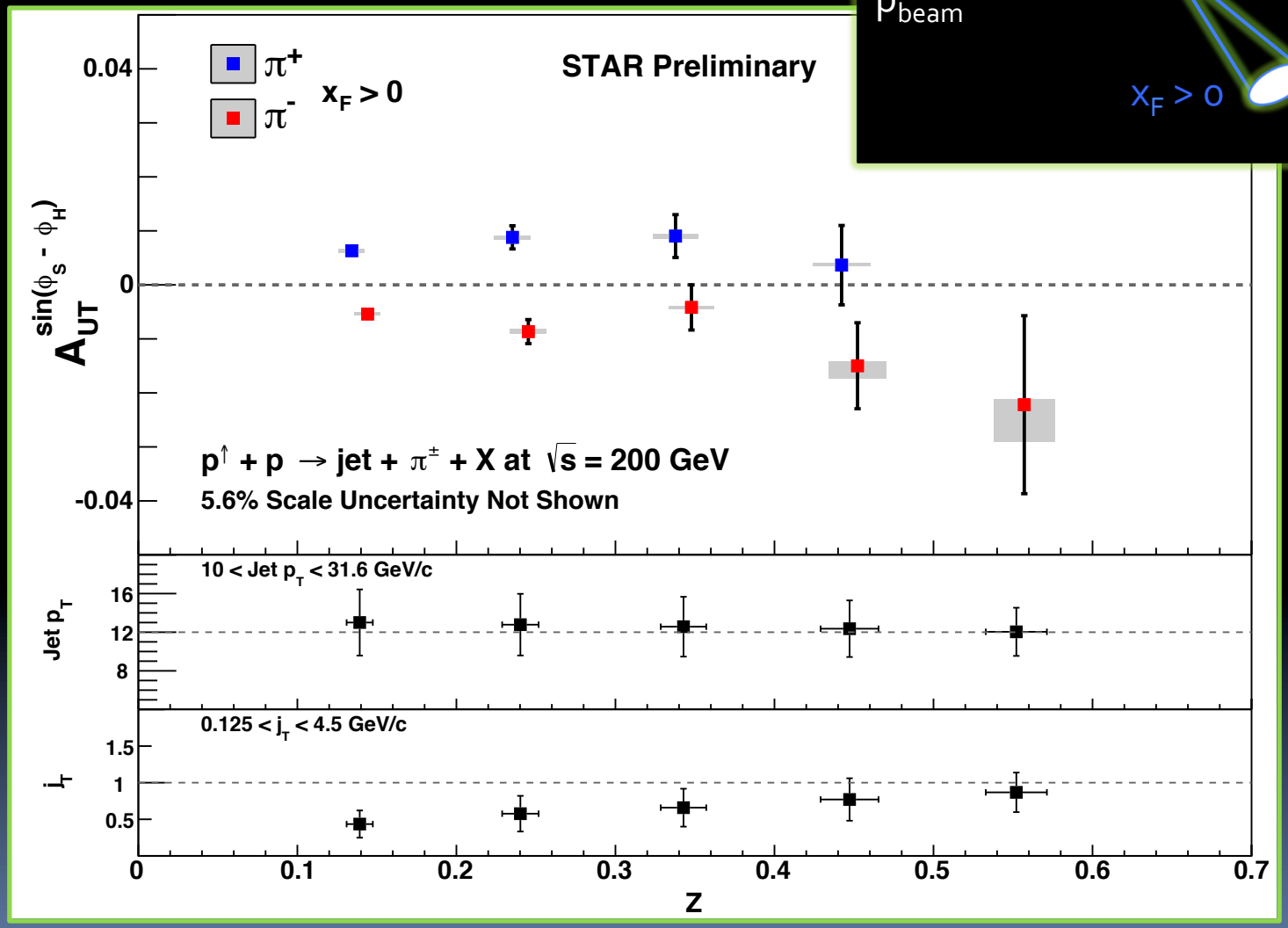
Interference Fragmentation Functions

The center of mass of the hadron pair is traveling collinear with the jet axis. IFF survives integration over j_T of hadrons and therefore works in collinear framework .

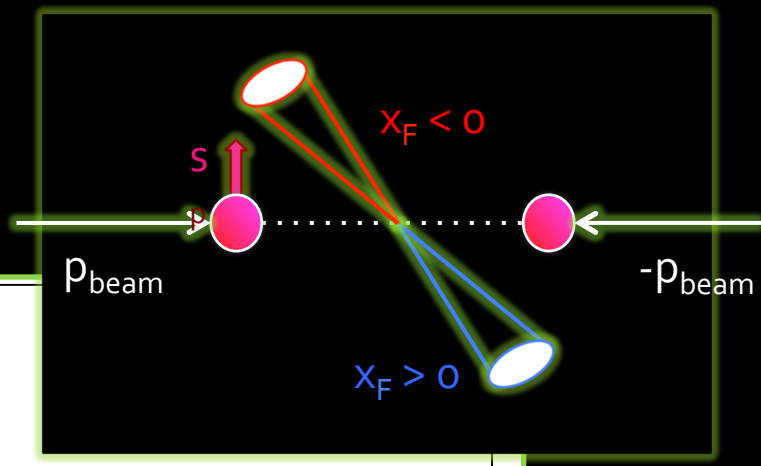
$S_Q \bullet (P_{H-} + P_{H+}) \times R$

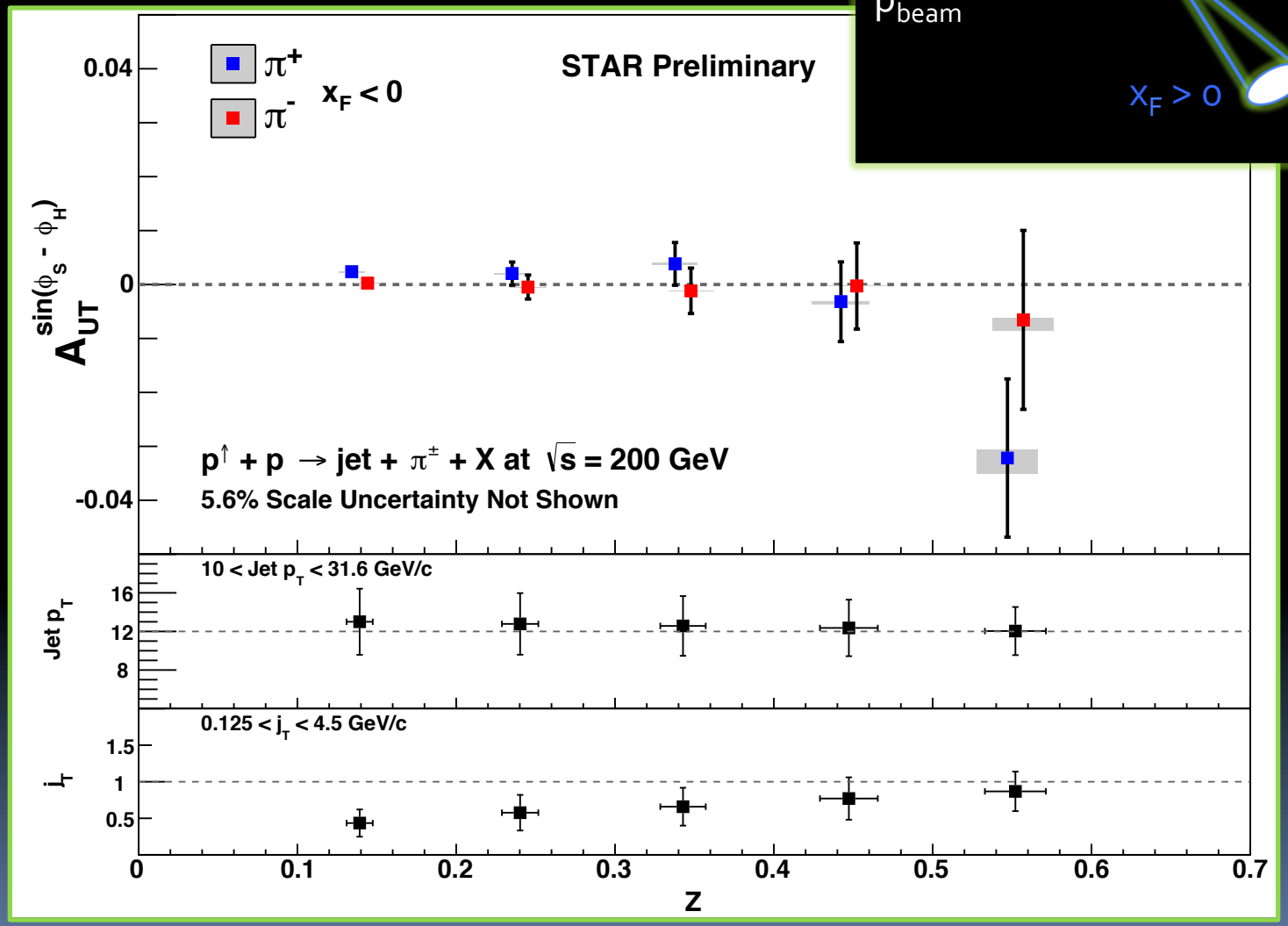
200 GeV $A_{UT}^{COLLINS}$ vs. z



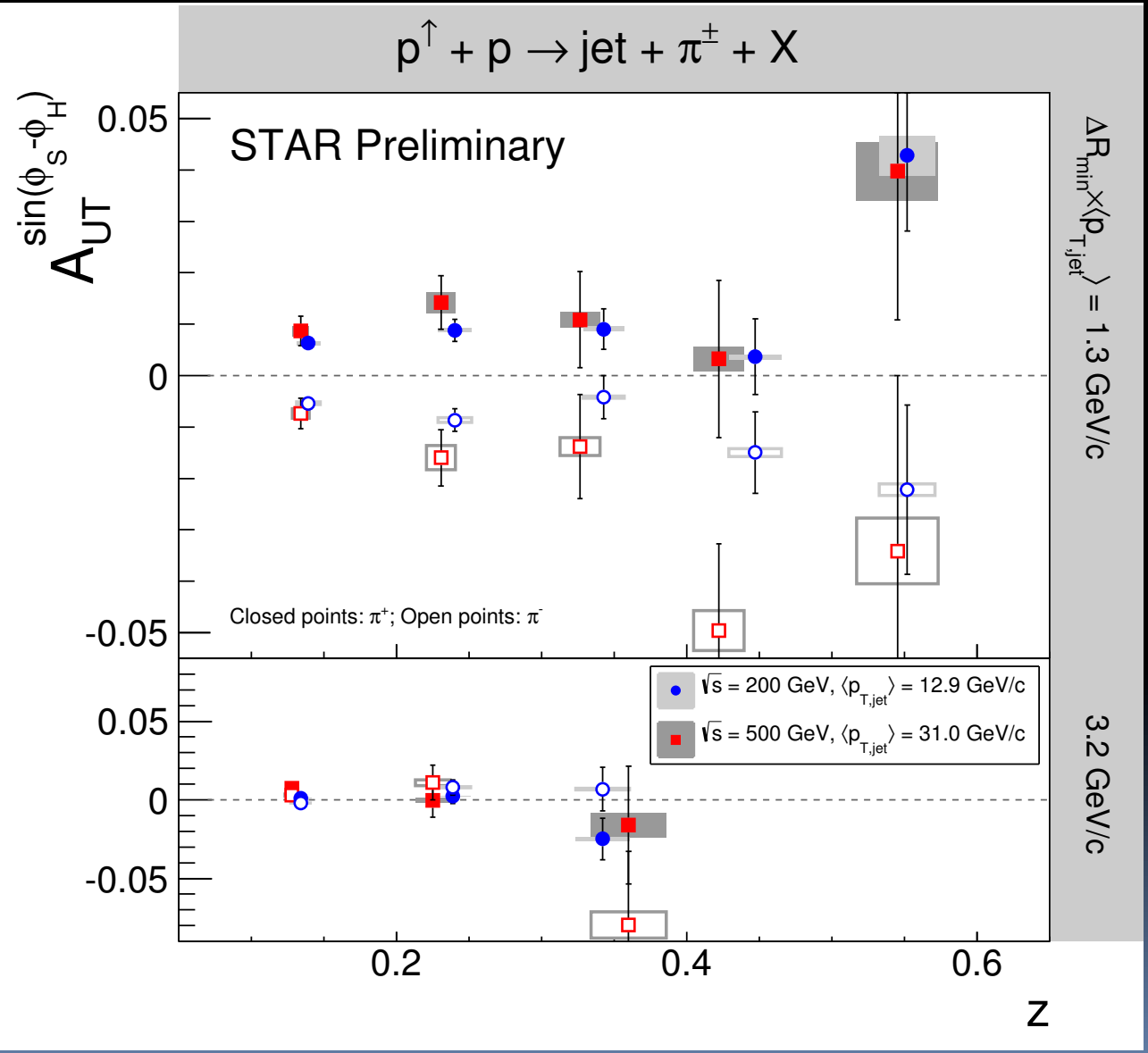


200 GeV $A_{UT}^{COLLINS}$ vs. z

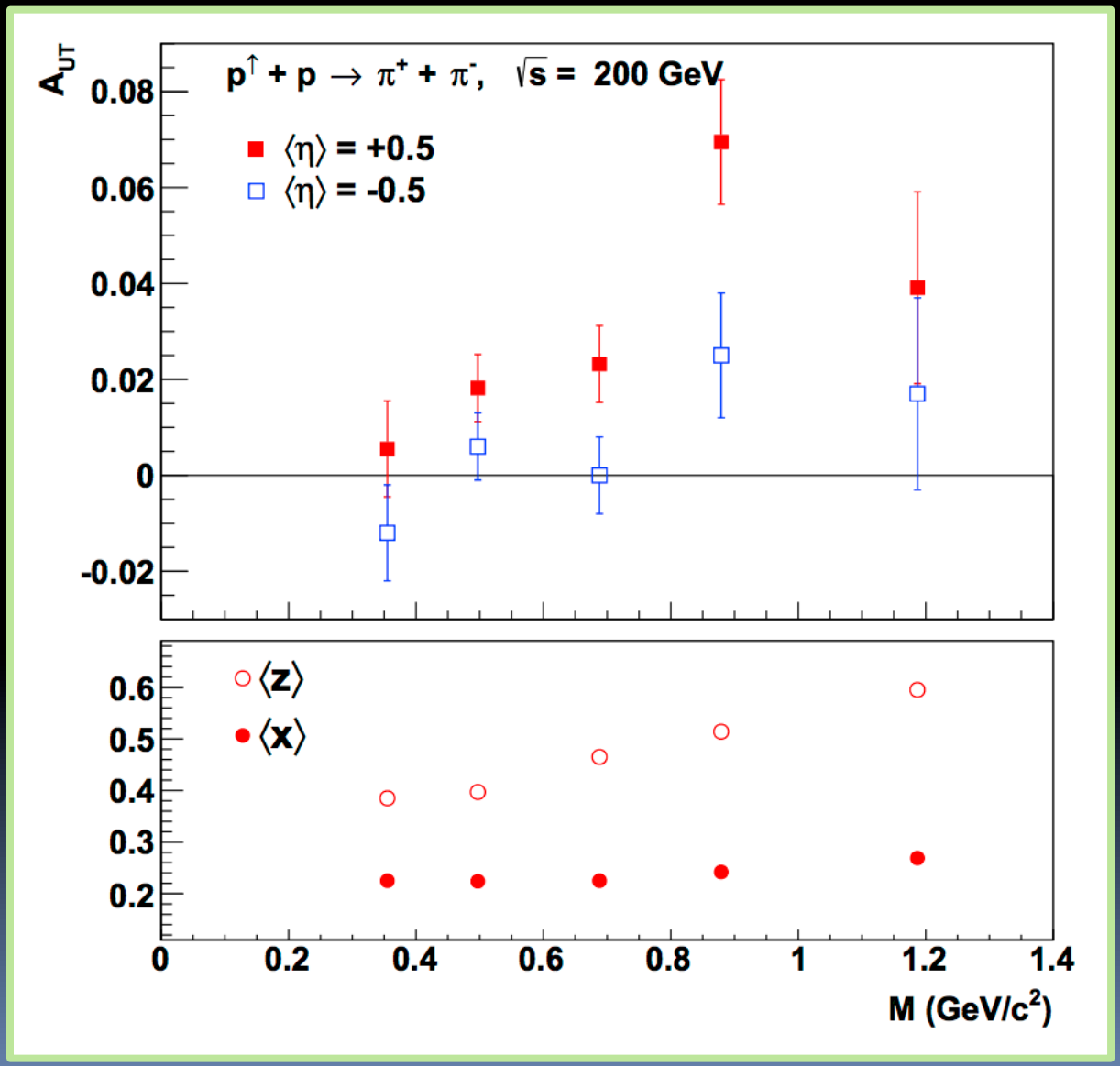




Higher Q^2 and same x? $\sqrt{s}$= 200 vs 500 GeV

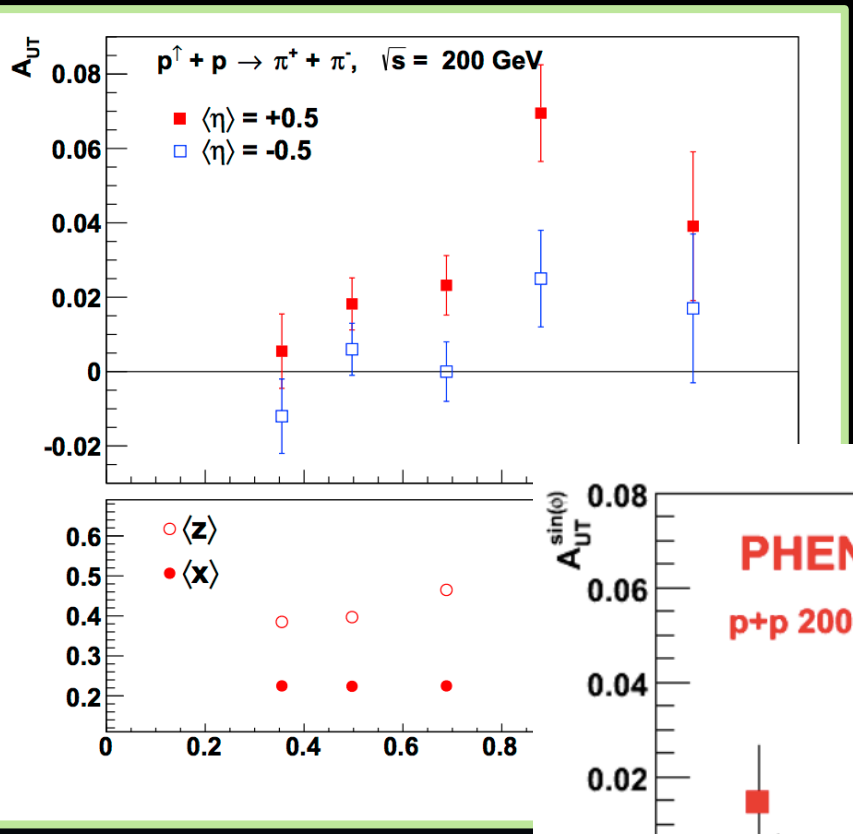


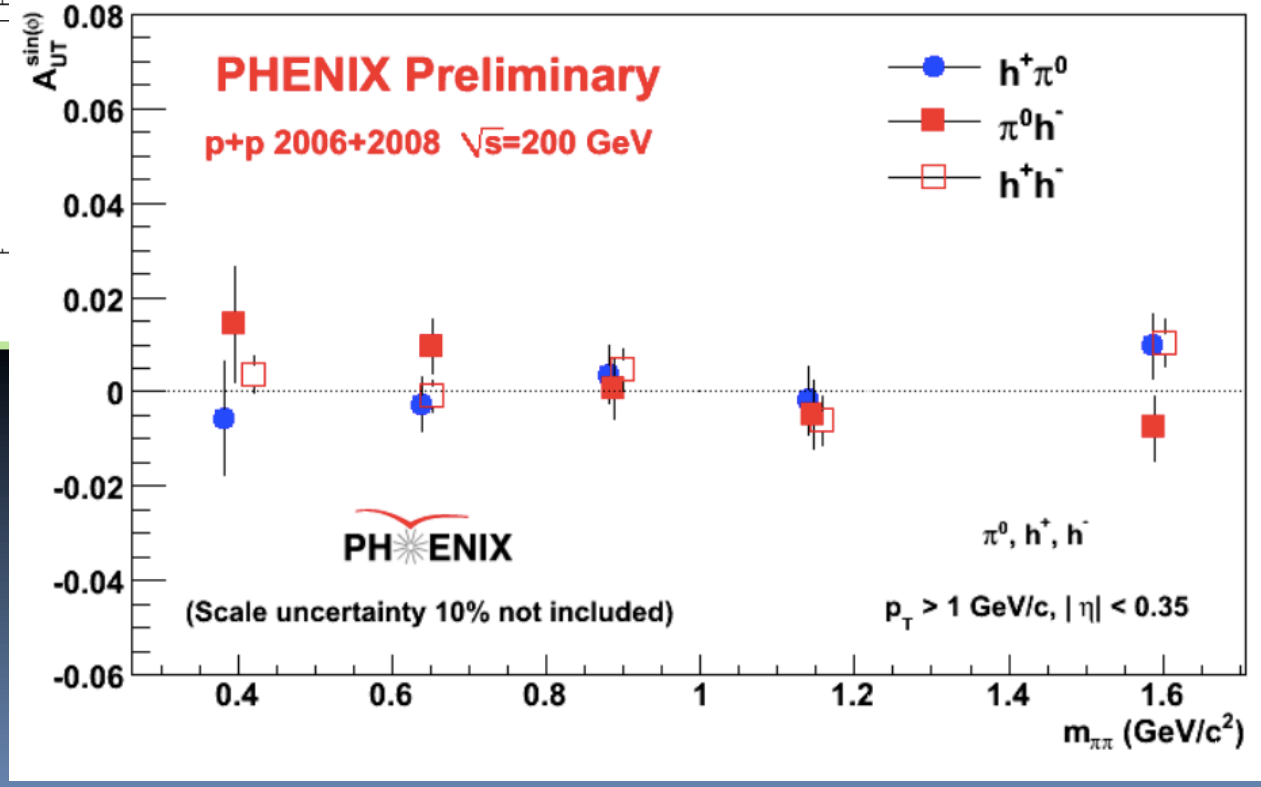
200 GeV A_{UT}^{IFF} vs. M_{inv}



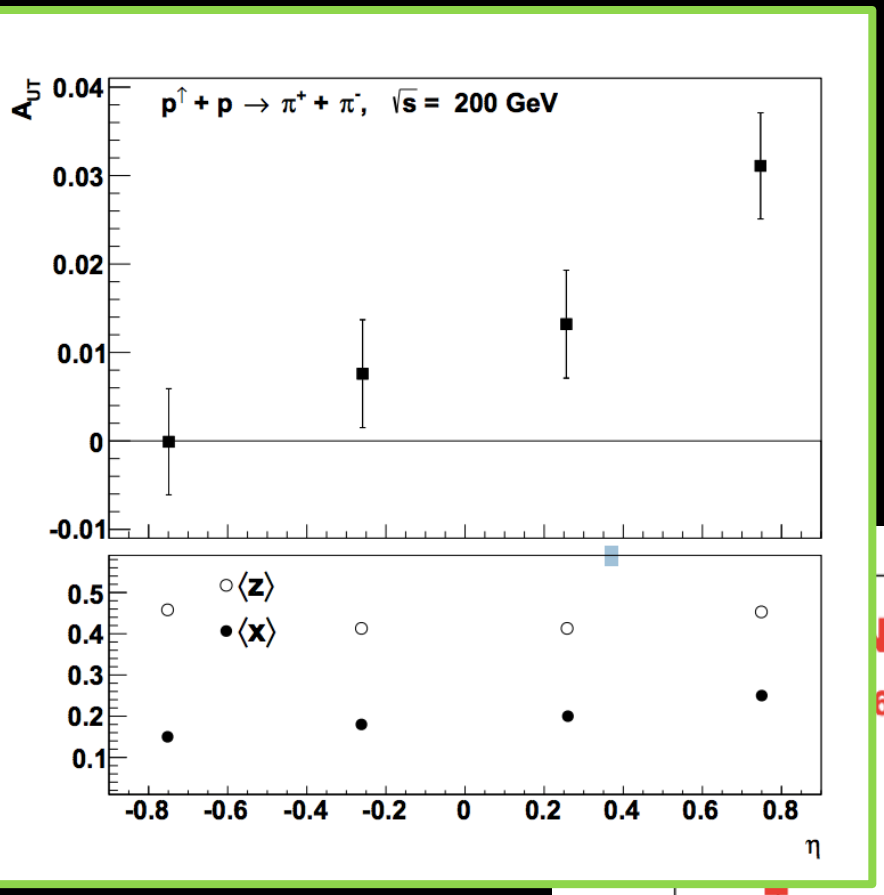
arXiv: 1504.00415

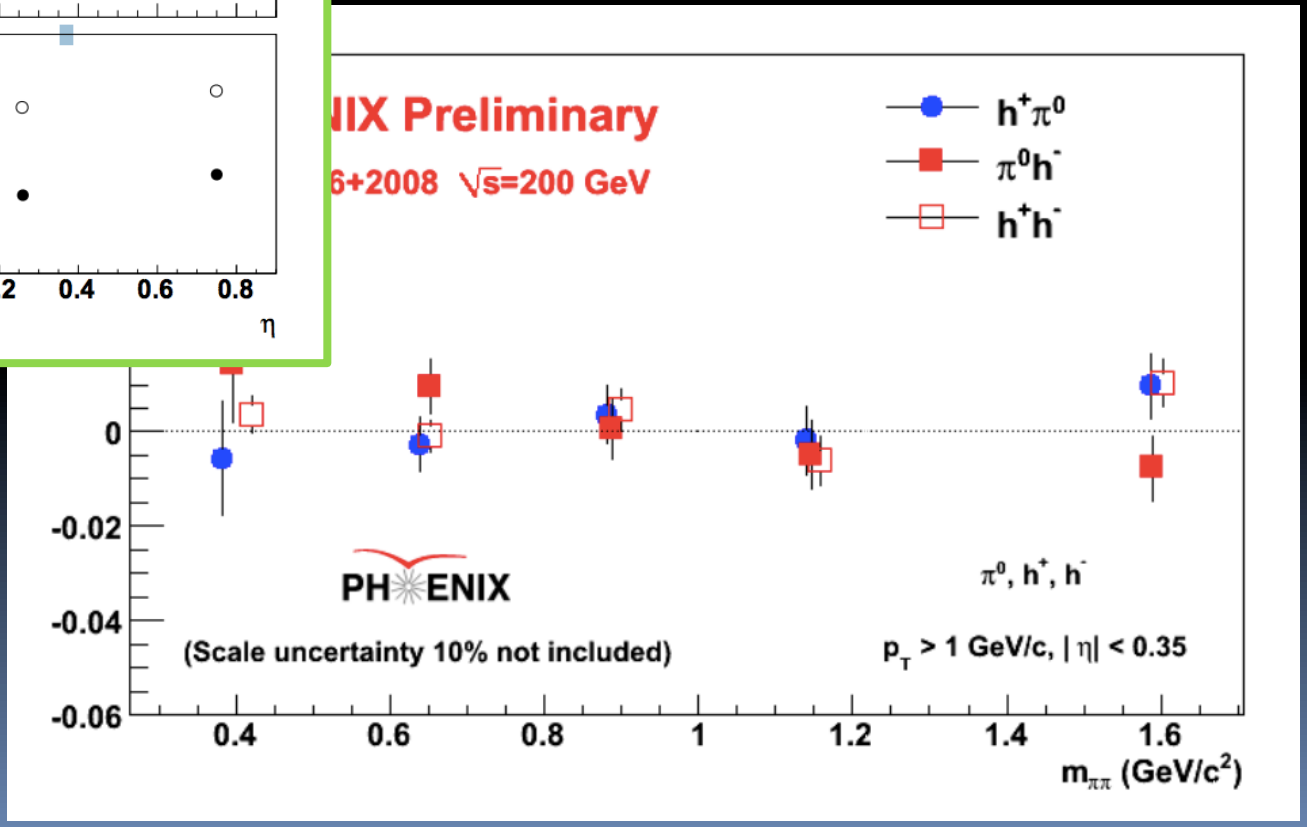
200 GeV A_{UT}^{IFF} vs. M_{inv}



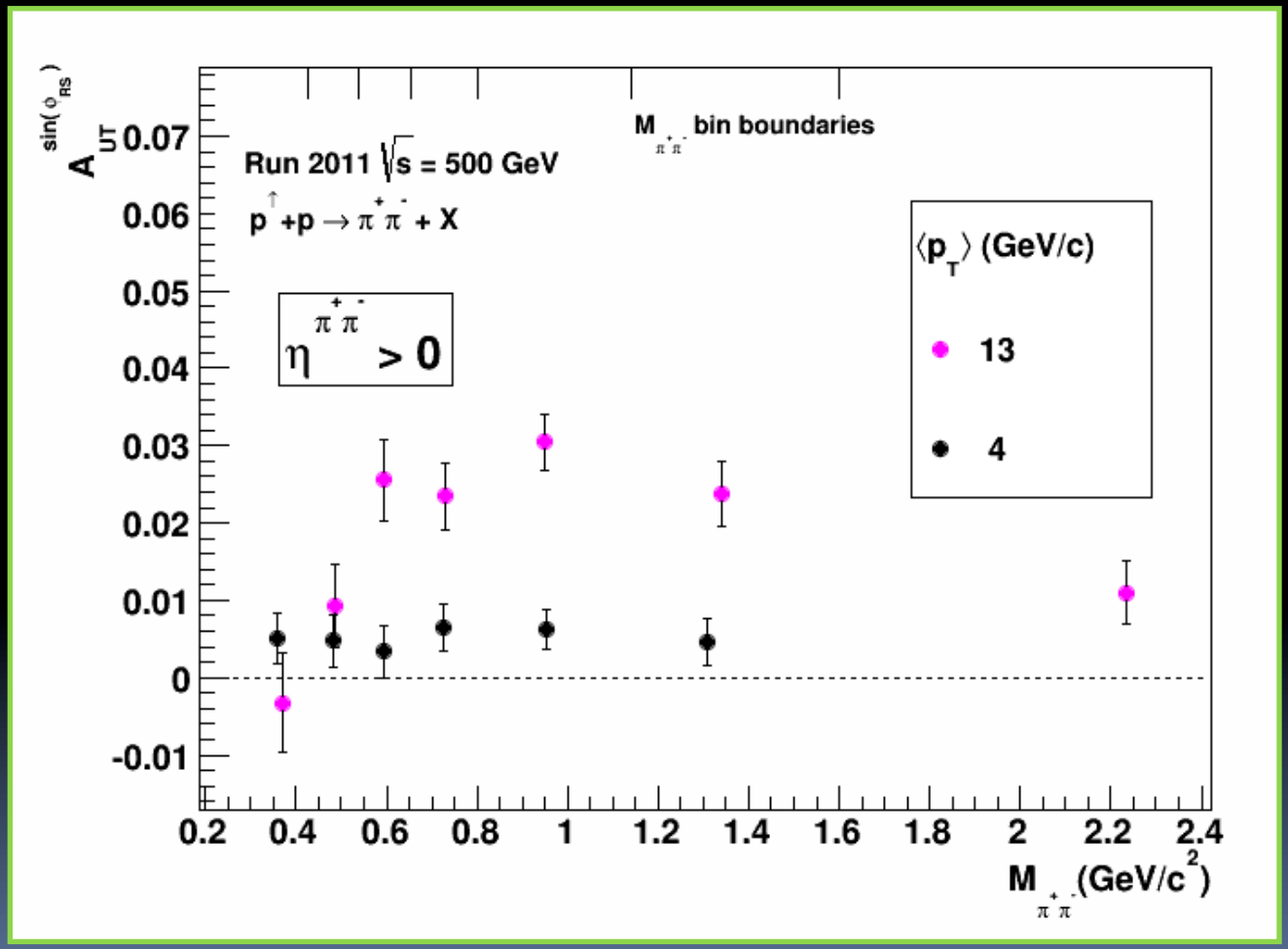


200 GeV A_{UT}^{IFF} vs. M_{inv}

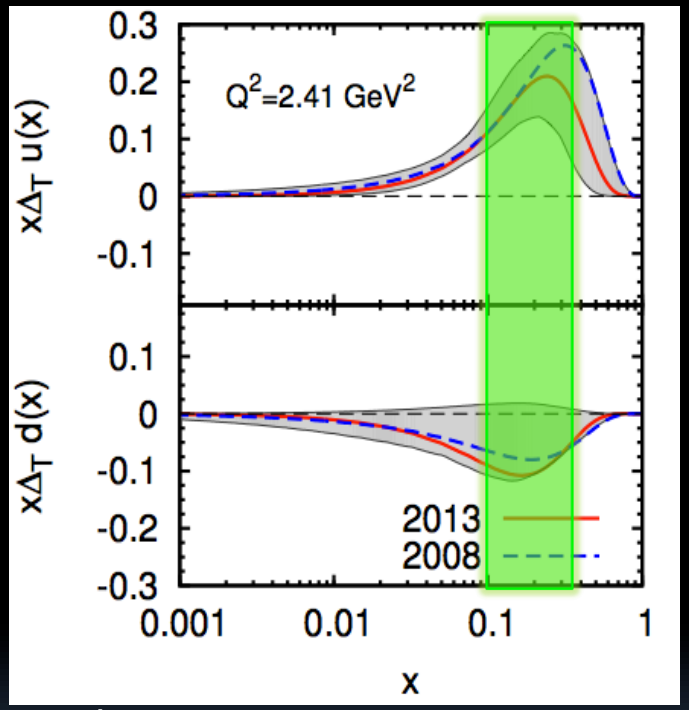




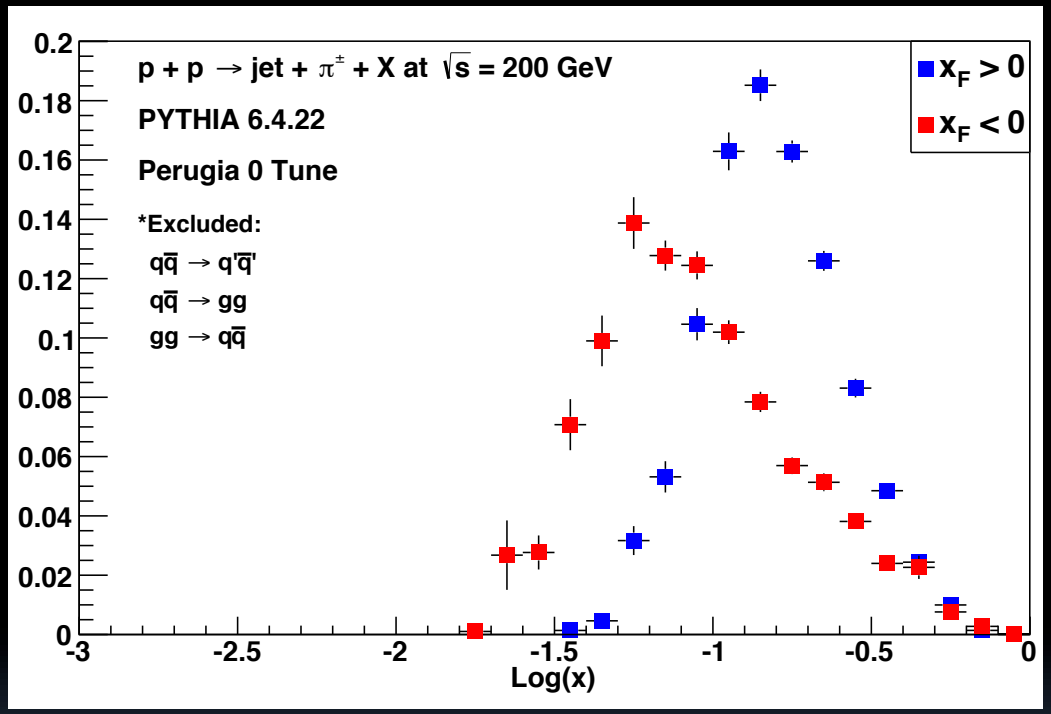
500 GeV A_{UT}^{IFF} vs. M_{inv}



RHIC data probes x > 0.1 region

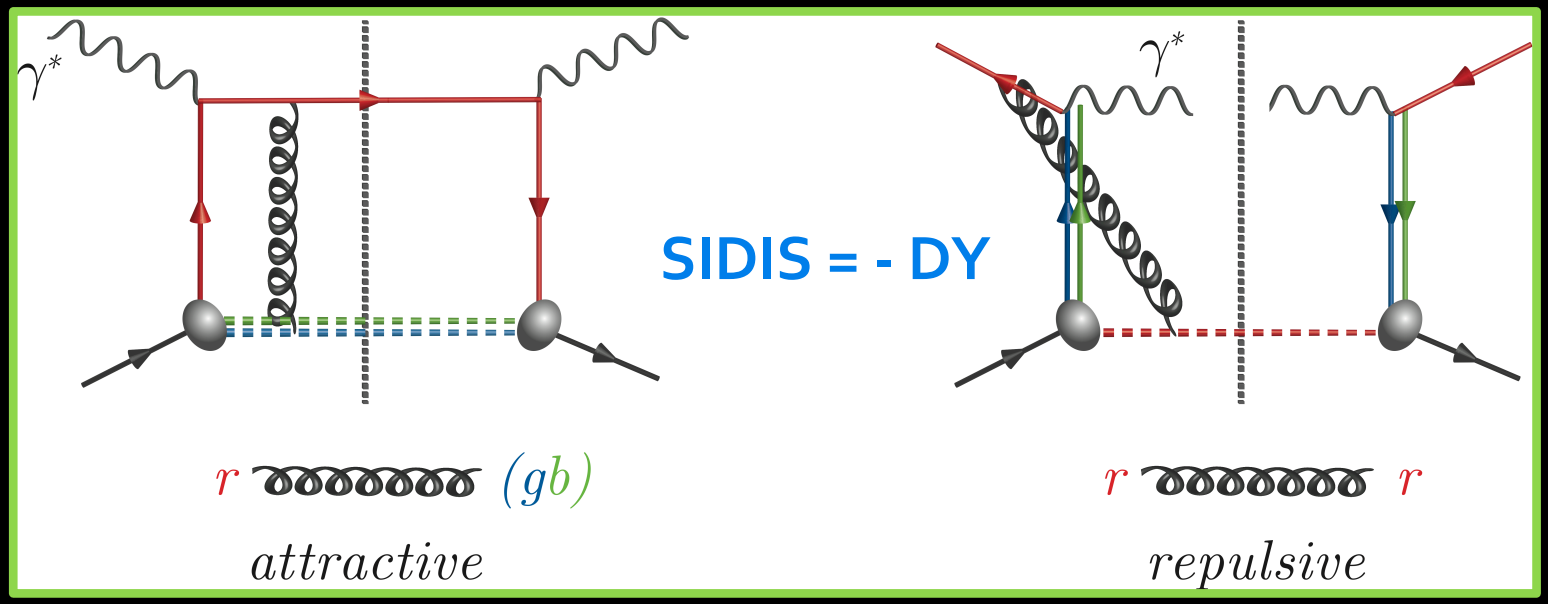


Phys. Rev. D **87** 094019 (2013)



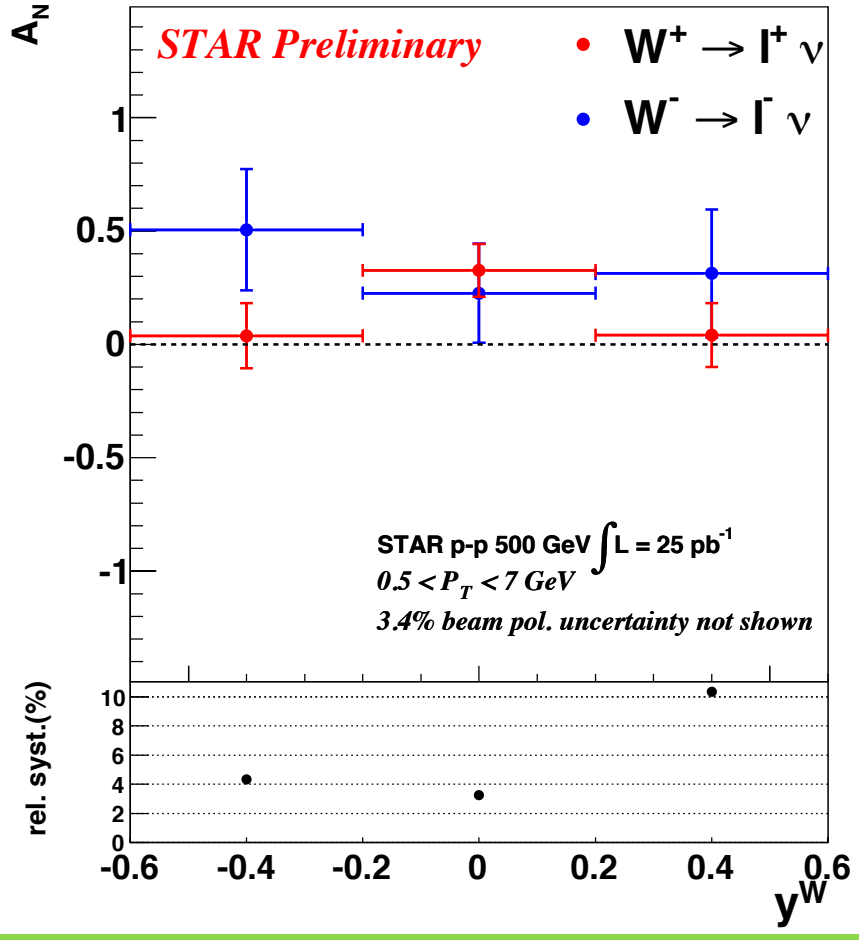
- How do Collins and Interference FF evolve with Q^2 ?
- Are the Collins and Interference FF universal?
- What are the size of factorization breaking effects for Collins in pp?

The Sivers'Sign Change



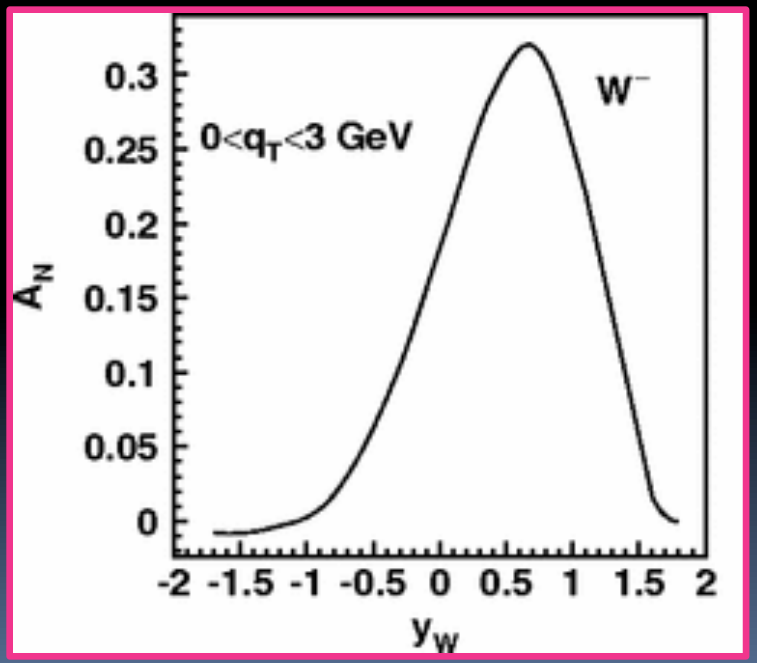
HP13 (2015): Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering

One DY observable : W^+/W^- A_N



First measurement from limited 2011 dataset.

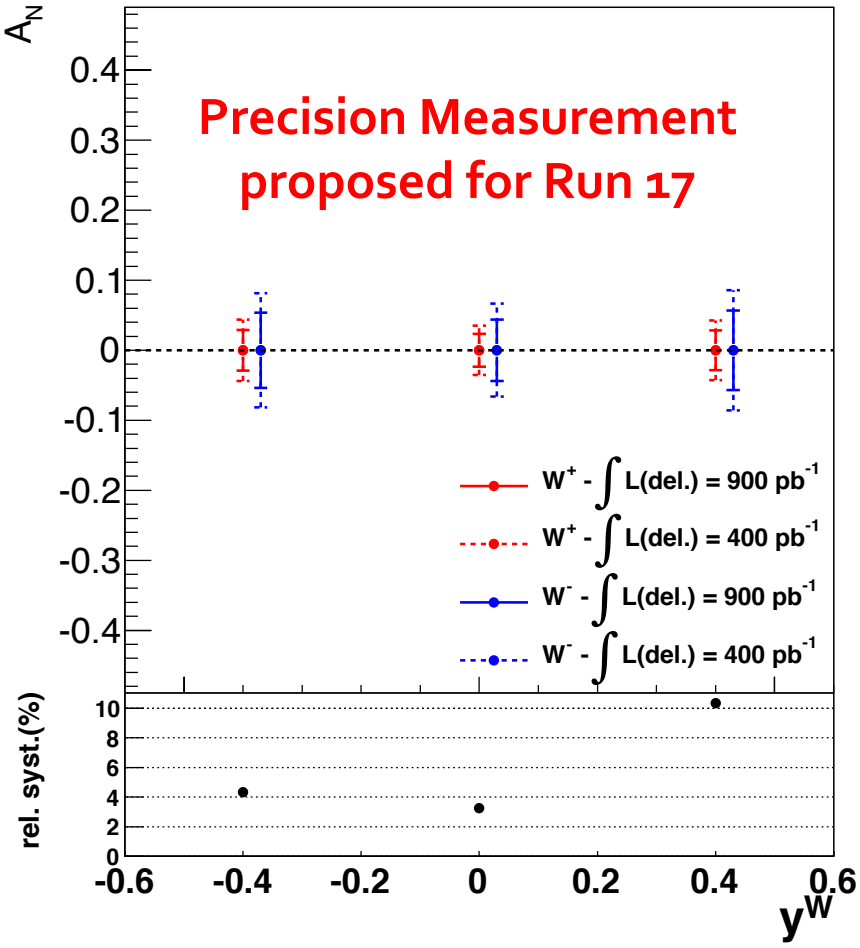
Fully reconstructed W using recoil methods.



PoS DIS2014 237 (2014)

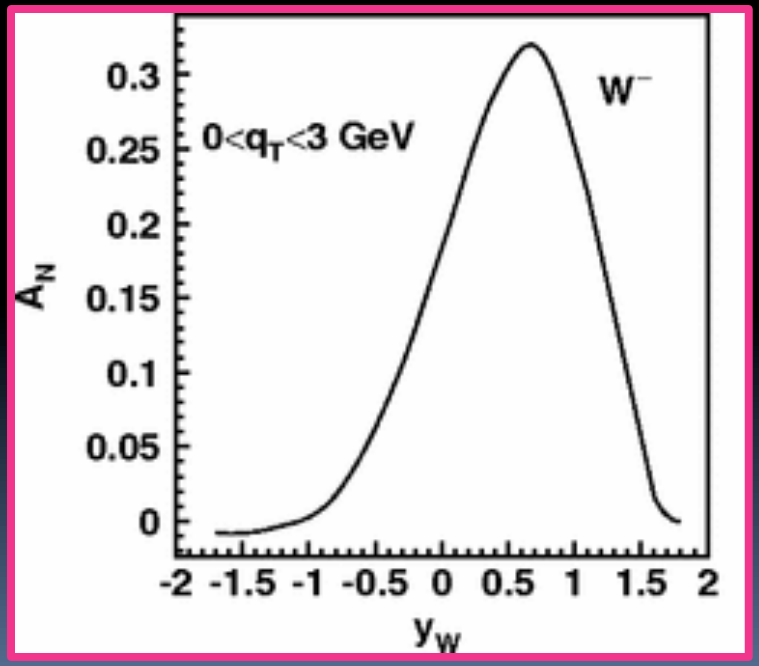
Phys.Rev.Let. 103, 172001 (2009)

One DY observable : W^+/W^- A_N



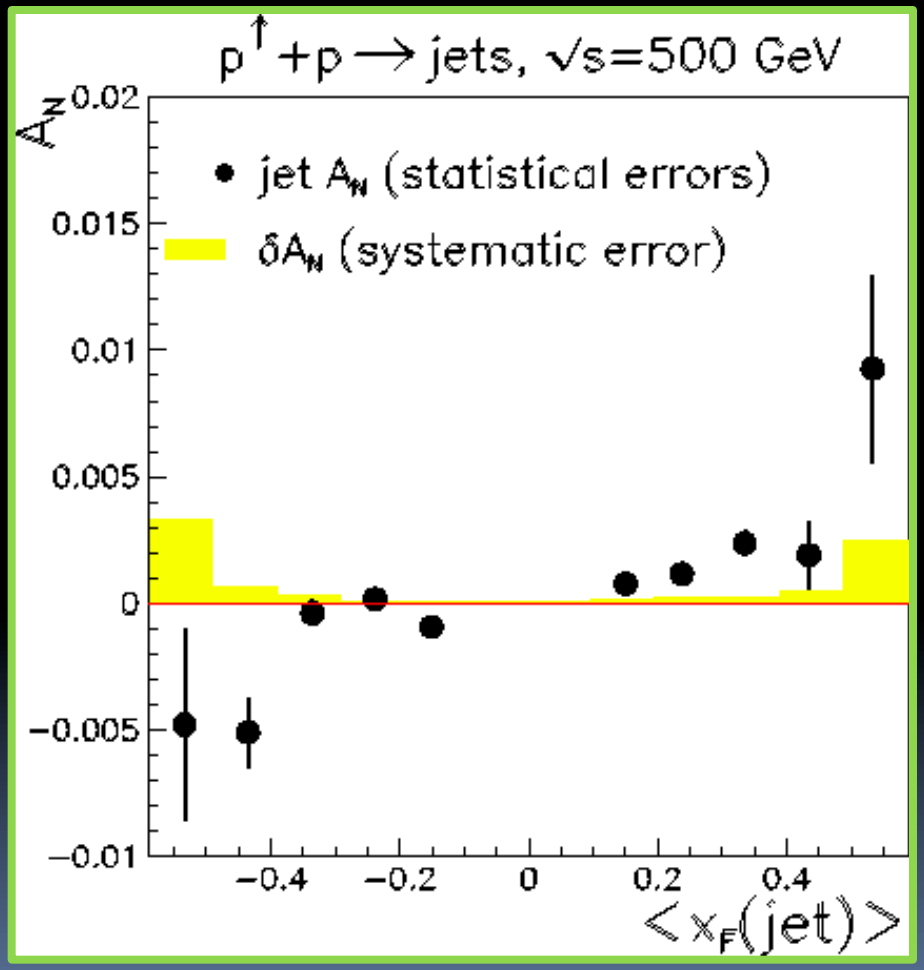
Provide critical information about TMD evolution!

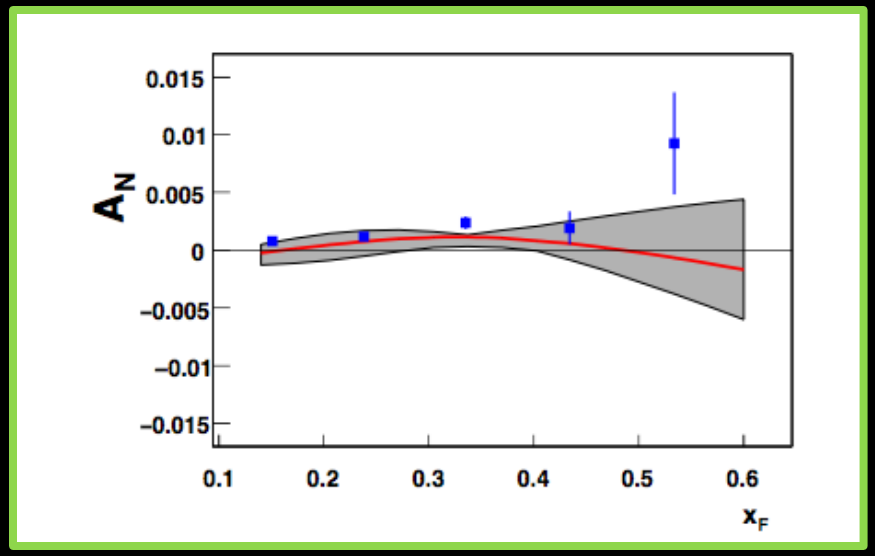
First measurement of sea-quark Sivers Functions.



Phys.Rev.Let. 103, 172001 (2009)

Another Sivers observable : Inclusive jet A_N



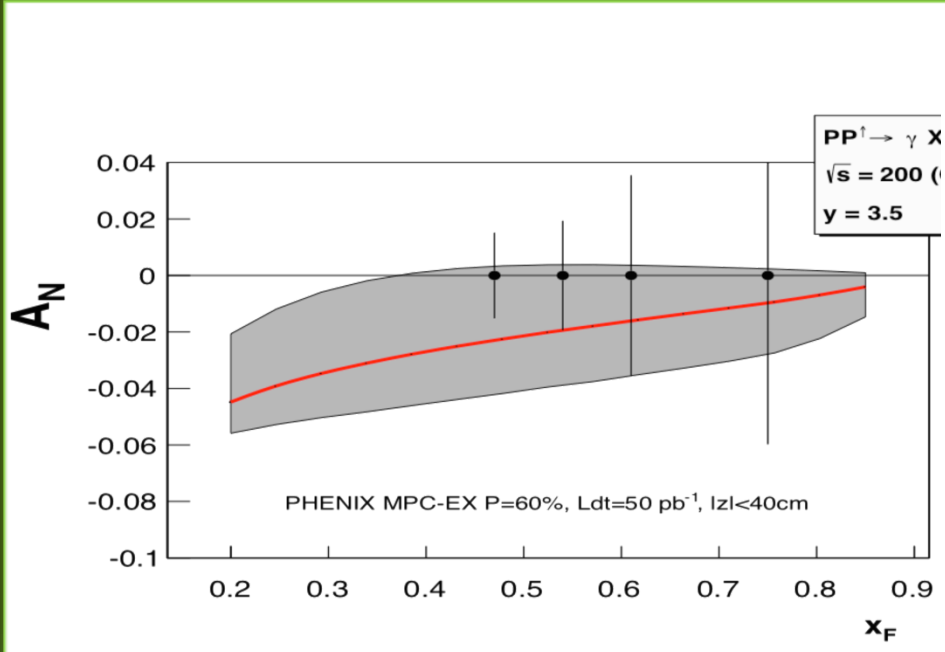


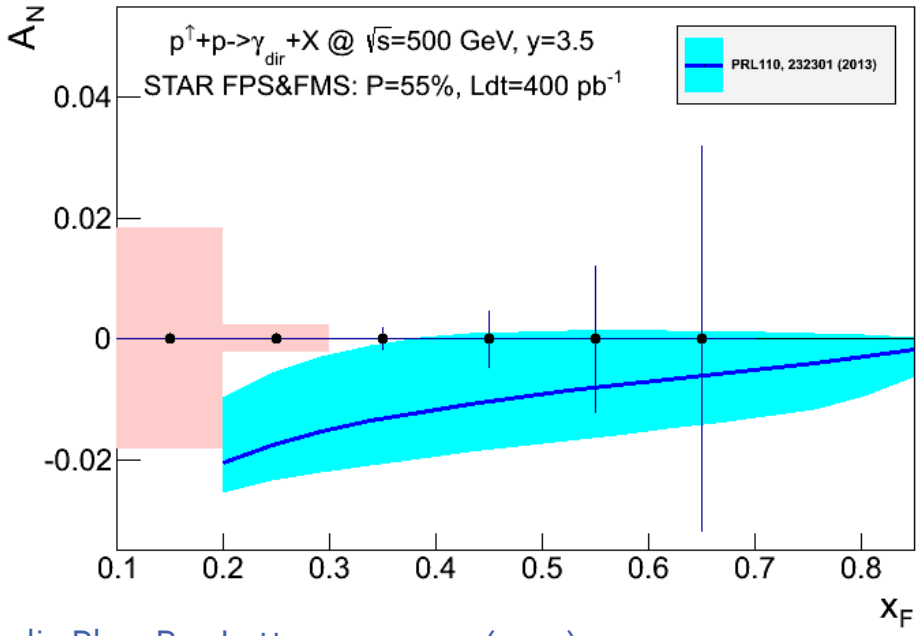
Phys.Rev.Lett. 110, 232301

A_N small due to u and d quark cancelation effects

Asymmetry is consistent with SIDIS data but too small to be conclusive.

Twist-3 "Sivers" Observable: Direct photon A_N





Theoretical curves by Gamberg, Kang, Prokudin Phys.Rev.Lett. 110, 232301 (2013)

- Twist-3 and TMD related via Efremov-Teryaev-Qui-Sterman equation
- Explores consistency between TMD and Collinear Twist-3 Formalism
- Direct photon does not suffer from u and d Sivers cancelation like inclusive jet due to charge weighting in EM interactions.

The Big Picture

(aka lunch topics…)

THE GLUON POLARIZATION IN THE PROTON ($x > 0.05$) IS COMPARABLE TO THE QUARK POLARIZATION .

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CLEAR INDICATION OF BROKEN FLAVOR SYMMETRY IN THE LIGHT POLARIZED SEA. PION CLOUD MODELS ARE DISFAVORED.

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CLEAR INDICATION OF BROKEN FLAVOR SYMMETRY IN THE LIGHT POLARIZED SEA. PION CLOUD MODELS ARE DISFAVORED.

SIGNIFICANT ASYMMETRIES, SENSITIVE TO TRANSVERSITY, MEASURED FOR THE FIRST TIME IN HADRONIC COLLISIONS.

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ESSENTIAL TESTS OF TMD FACTORIZATION, EVOLUTION AND THE EQTS RELATIONSHIP via $W^{+/-}$, INCLUSIVE JETS AND DIRECT PHOTONS ARE AT HAND.

… AND THERE IS MORE! See Anselm Vossen's talk for additional transverse spin results…

Where do we go next?

ΔG – lower X!

- RHIC Forward Upgrades to push to lower x
- Ultimately need an Electron-Ion Collider

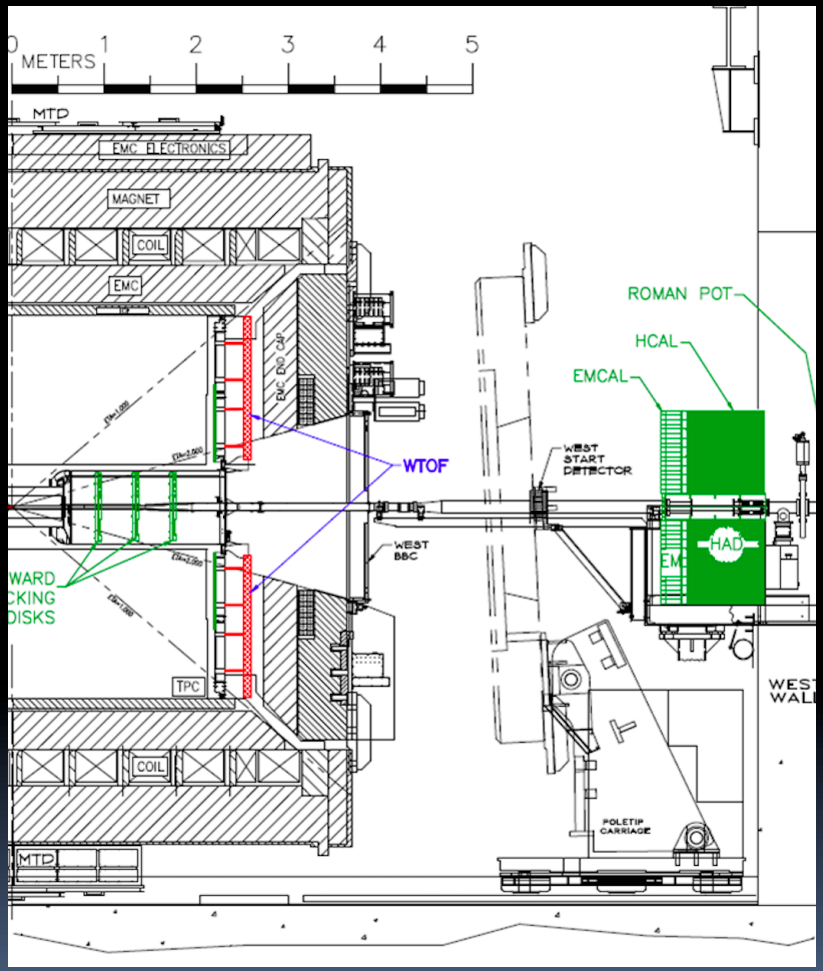
TMD and IFF Asymmetries

- RHIC Forward Upgrades will allow jet reconstruction in forward region - push to higher x

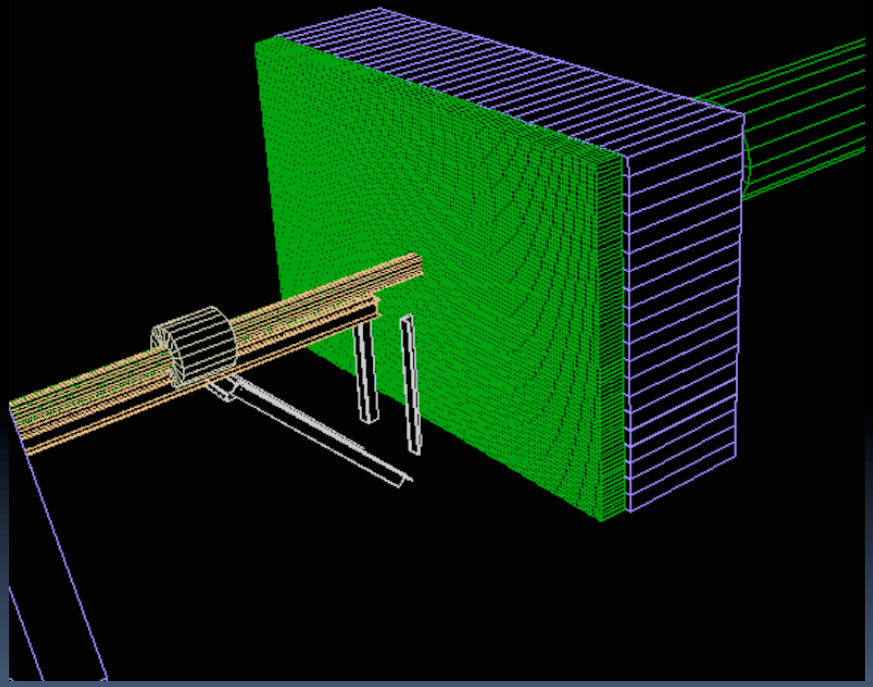
SIVERS SIGN CHANGE

- Drell-Yan in the forward direction will allow continued study of TMD evolution.

STAR Forward Upgrade (fSTAR)



Ecal: Tungsten-Powder-Scintillating-fiber
HCal: Lead and Scintillator tiles
Tracking: Silicon mini-strip detector or GEM Tracker



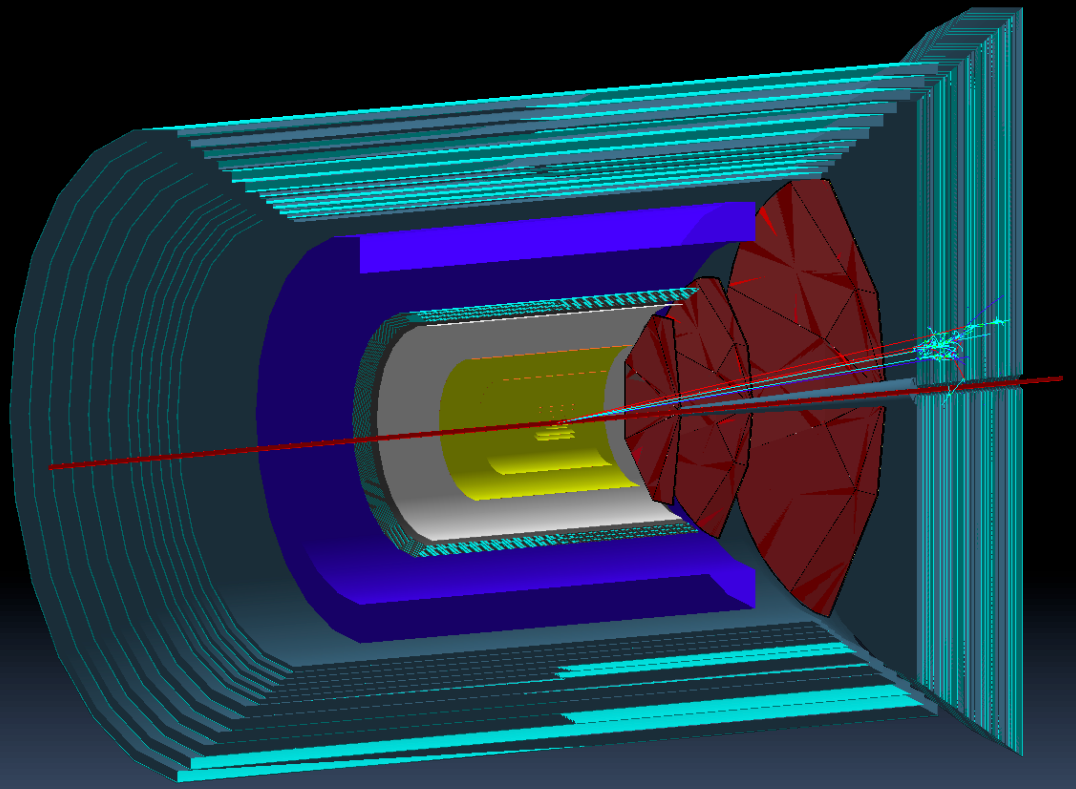
Forward jet reconstruction will extend ΔG to lower x and TMD +IFF asymmetries to higher x

PHENIX Forward Upgrade (fsPHENIX)

EIC detector GEM + H-Cal
-> Forward jet with charge sign tagging

+ reuse current silicon tracker & Muon Id detector
-> polarized Drell-Yan with muons

+central detector (sPHENIX)
-> Forward-central correlations

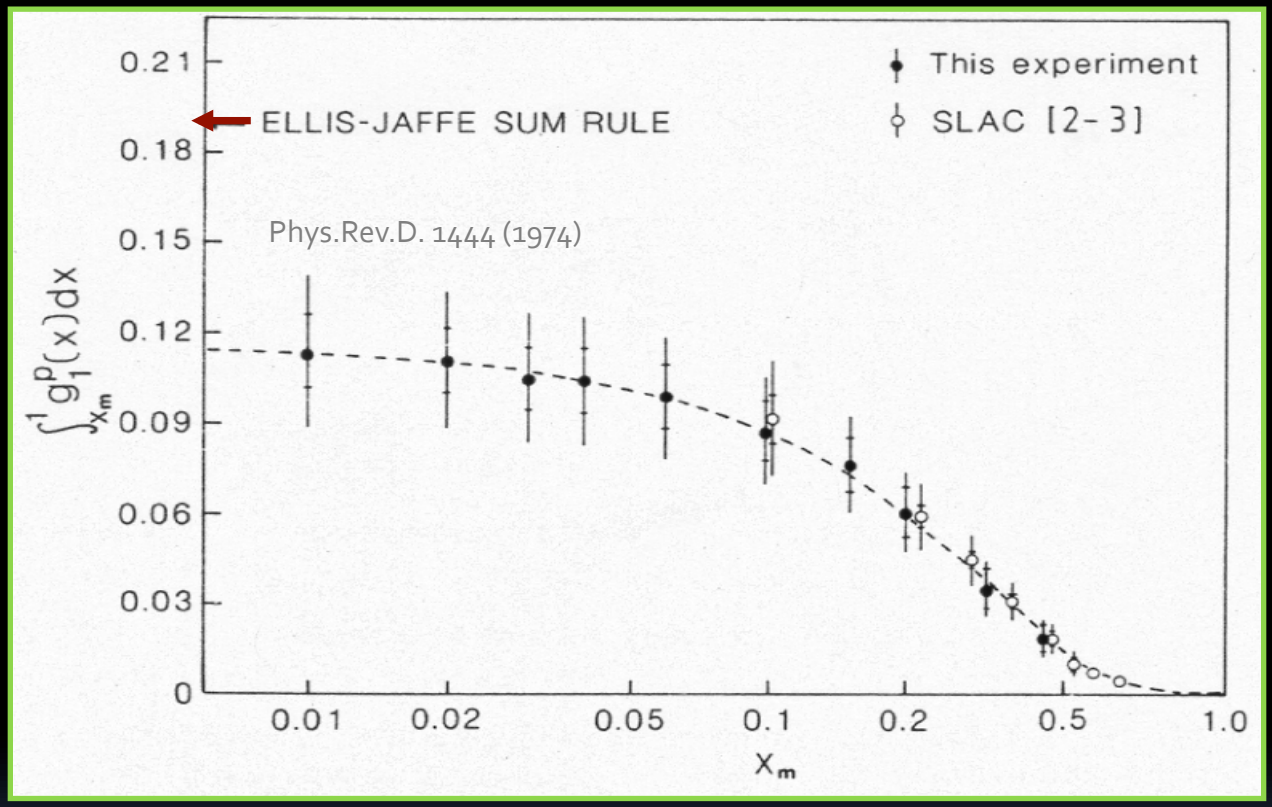


See white paper http://www.phenix.bnl.gov/plans.html

YOU WANT MORE?

Historically same trend with $\Delta\Sigma$!

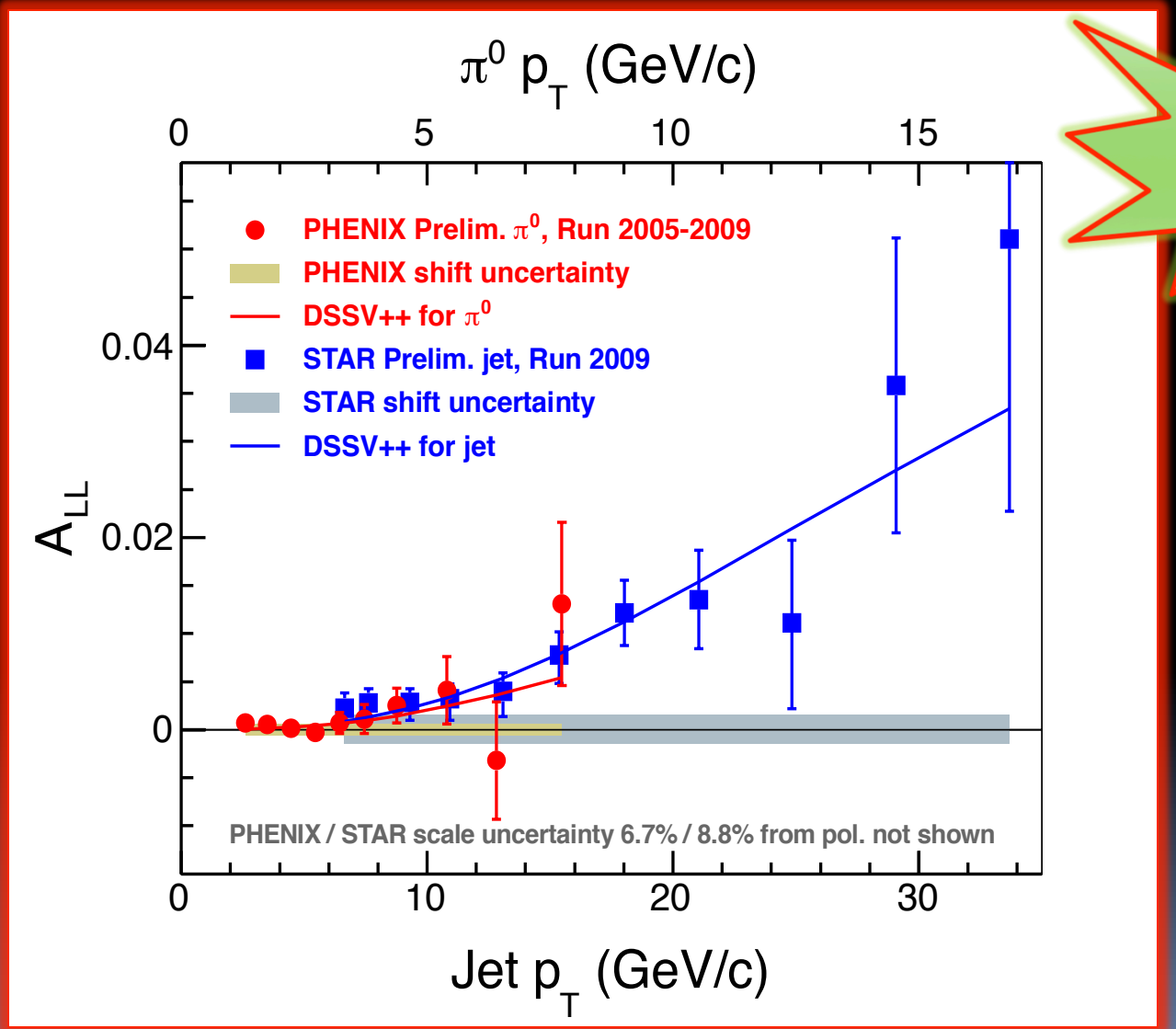
EMC Collaboration Nucl. Phys. B328, 1 (1989)



EMC 1989: $\Delta\Sigma(Q^2 = 10.7GeV) = 0.12 \pm 0.094 \pm 0.138$

DSSV 2x bigger than EMC $\Delta\Sigma$ - but still CONSISTENT!

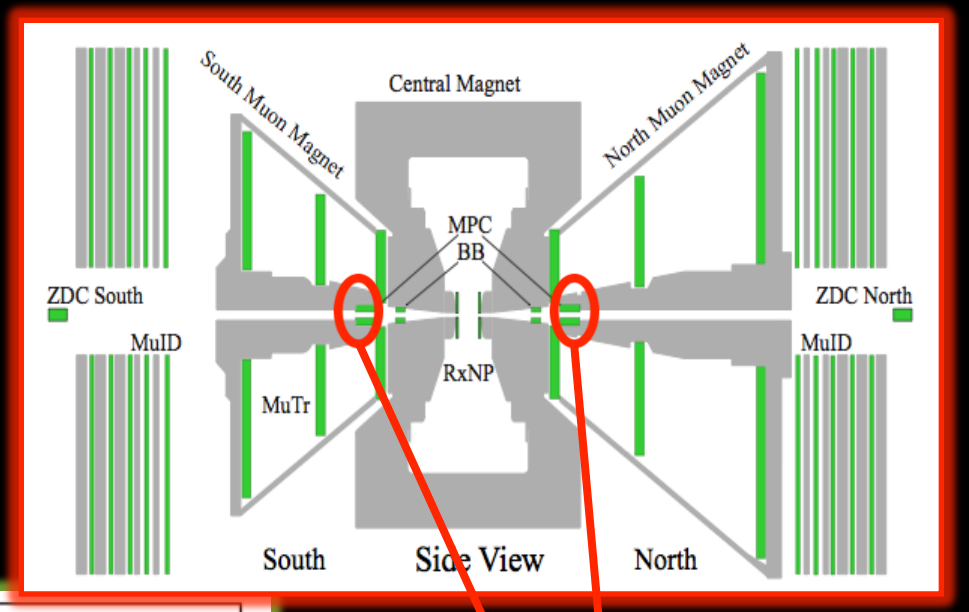
Are PHENIX and STAR data consistent?

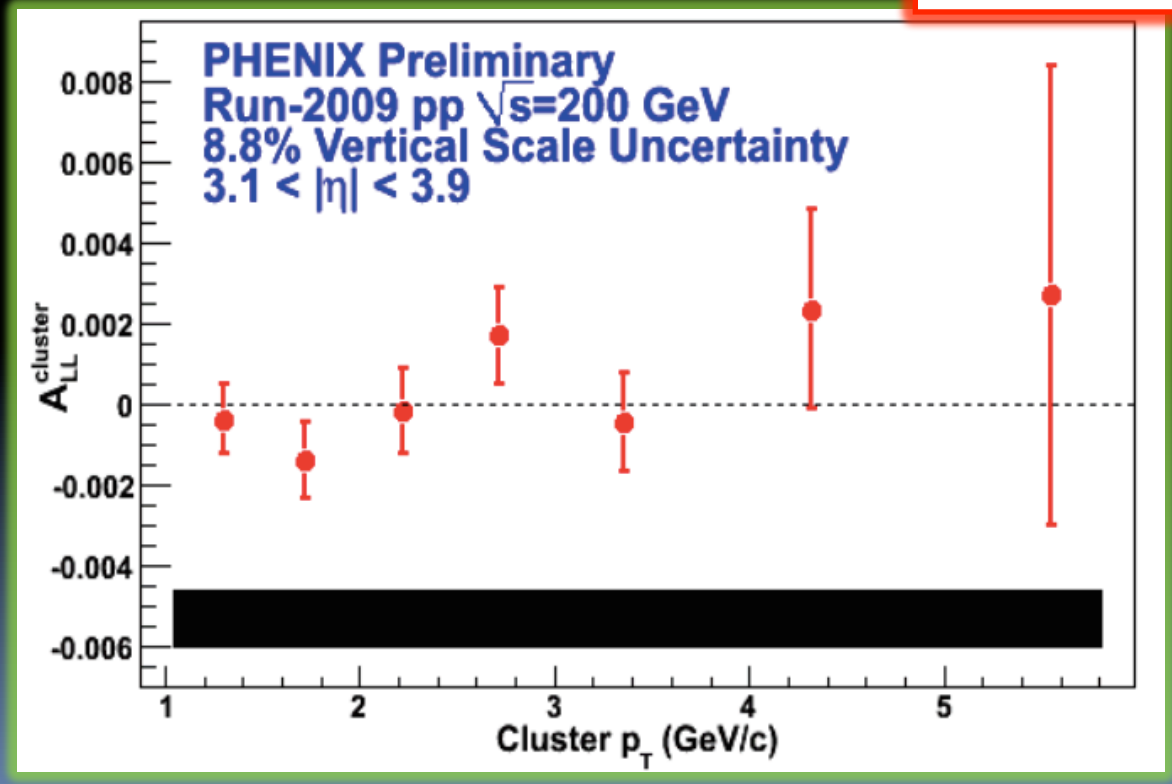


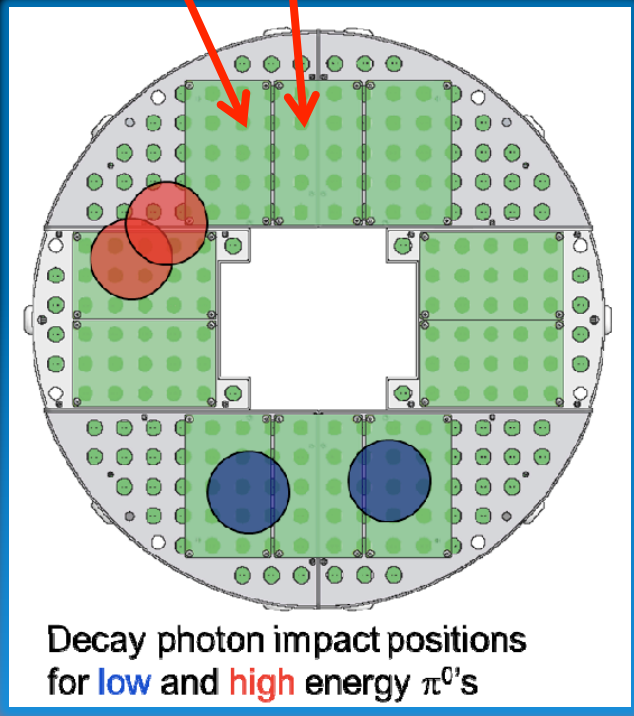
YES!

Thank you to de Florian, Sassot, Stratmann & Vogelsang for preliminary DSSV++ curves!

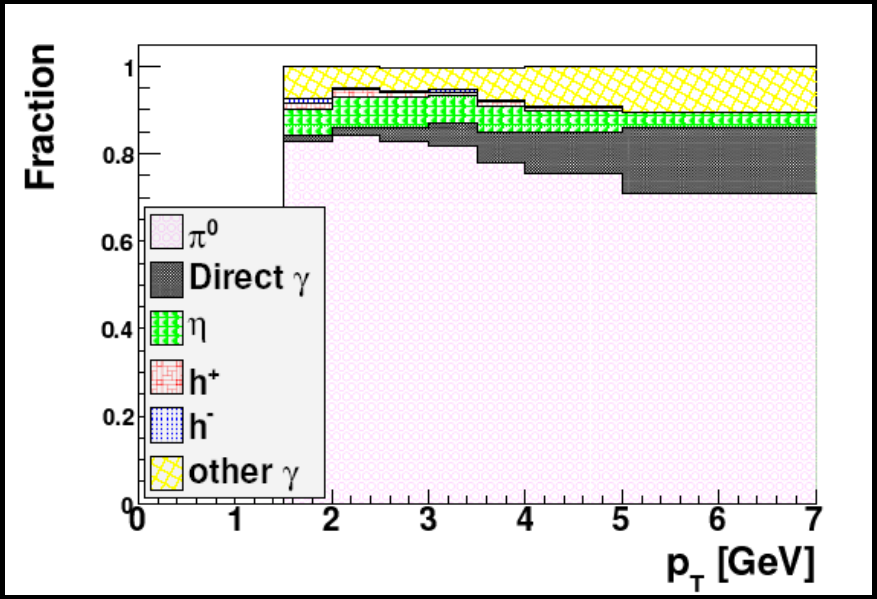
PHENIX Muon Piston Chambers access lower X region

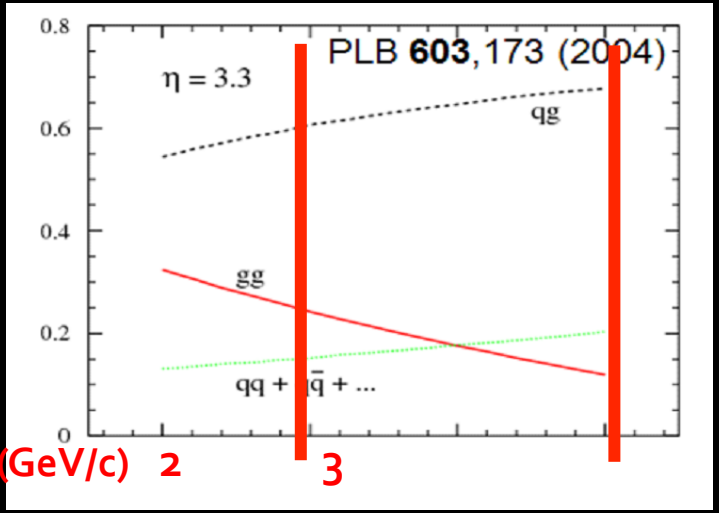






Single Cluster MPC Asymmetry

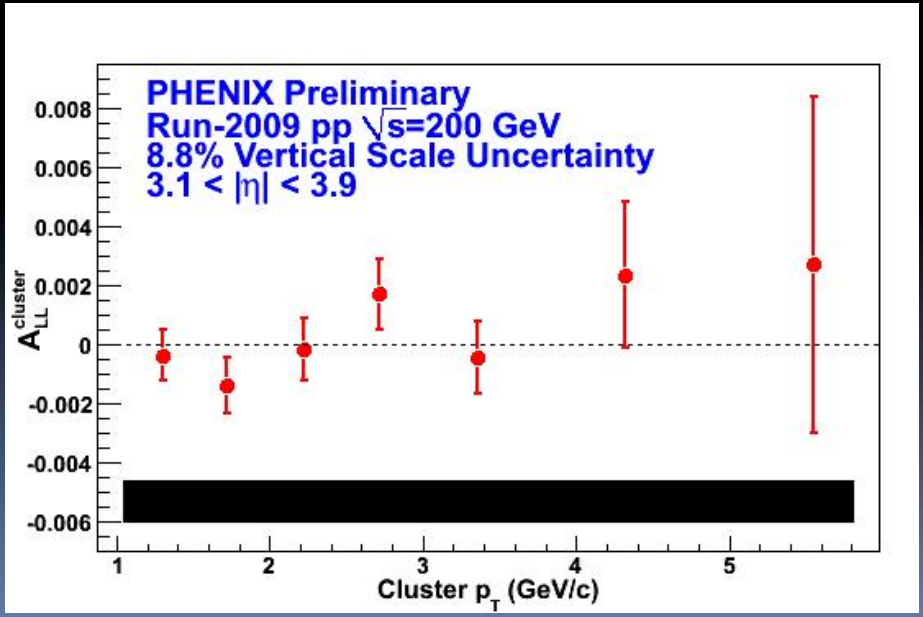




✓Cluster Decomposition: Dominated by merged π⁰'s.

✓Process decomposition skewed more heavily toward quark-gluon than mid-rapidity.

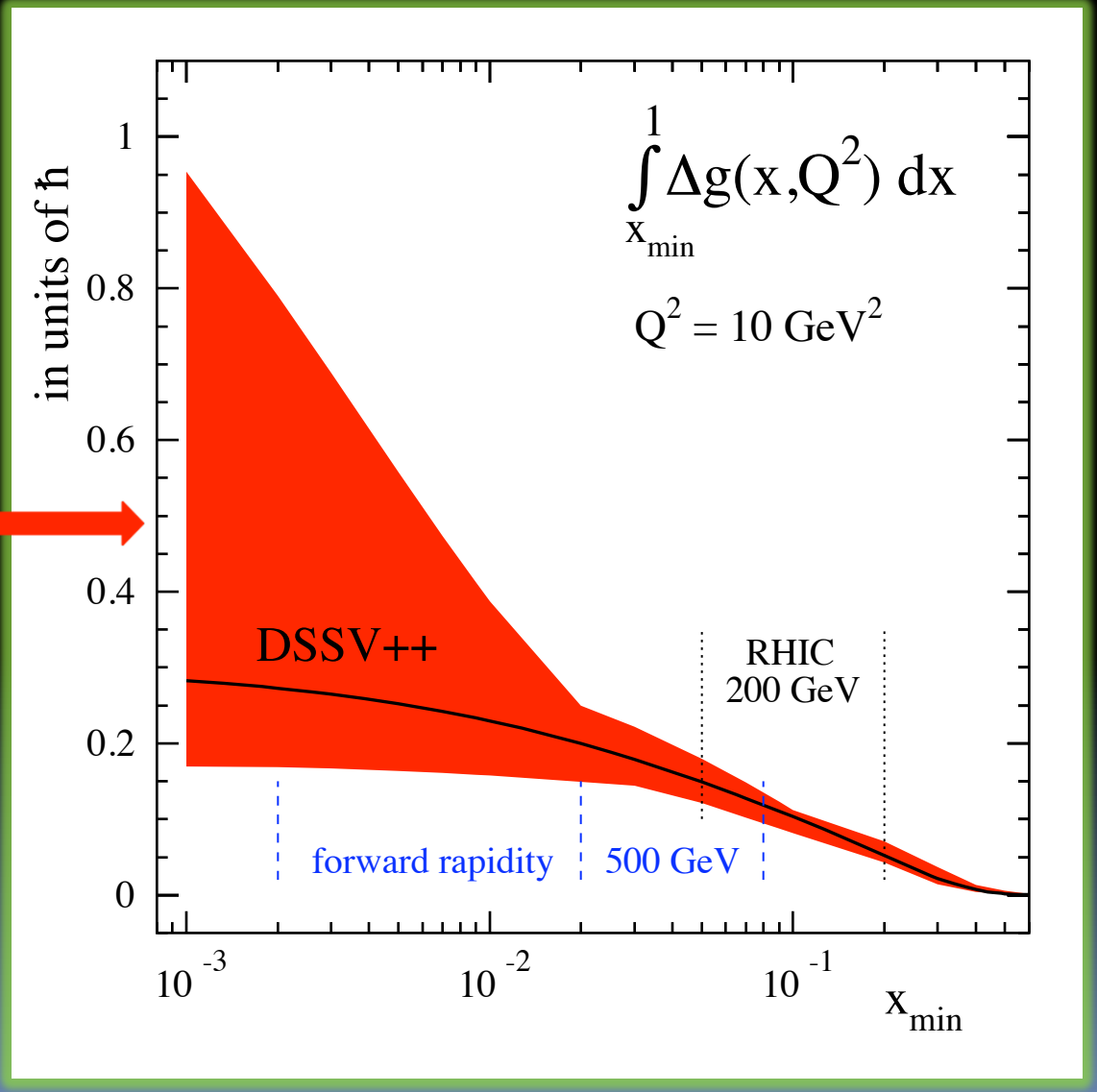
✓ Rel lumi uncertainty is significant compared to statistical.



How does this ADD UP?

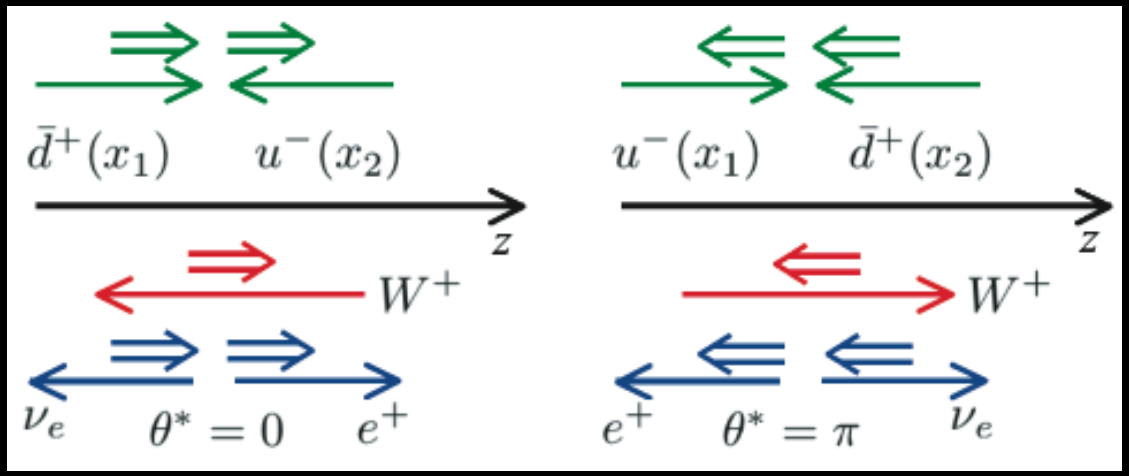
...Integration over full x range

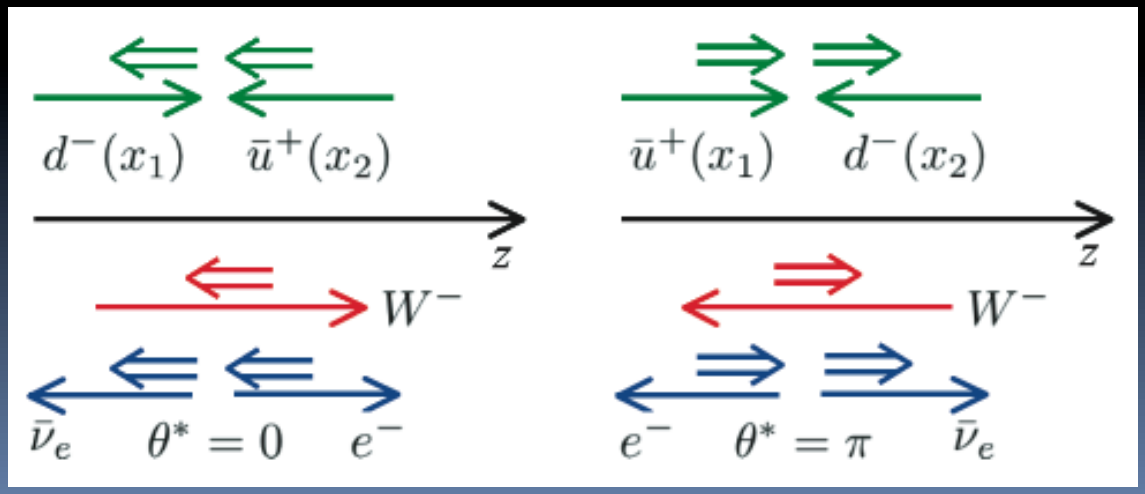
PROTON SPIN



This preliminary DSSV++ plot brought to you by de Florian, Sassot , Stratmann & Vogelsang!

Lepton Decay Kinematics

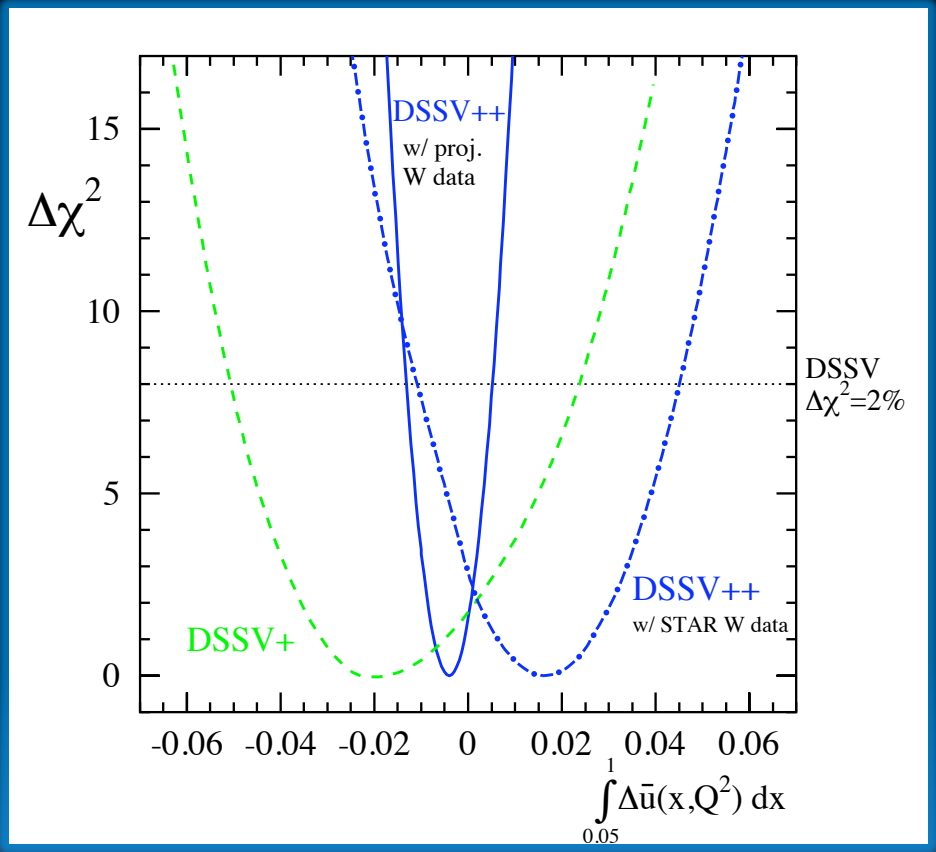


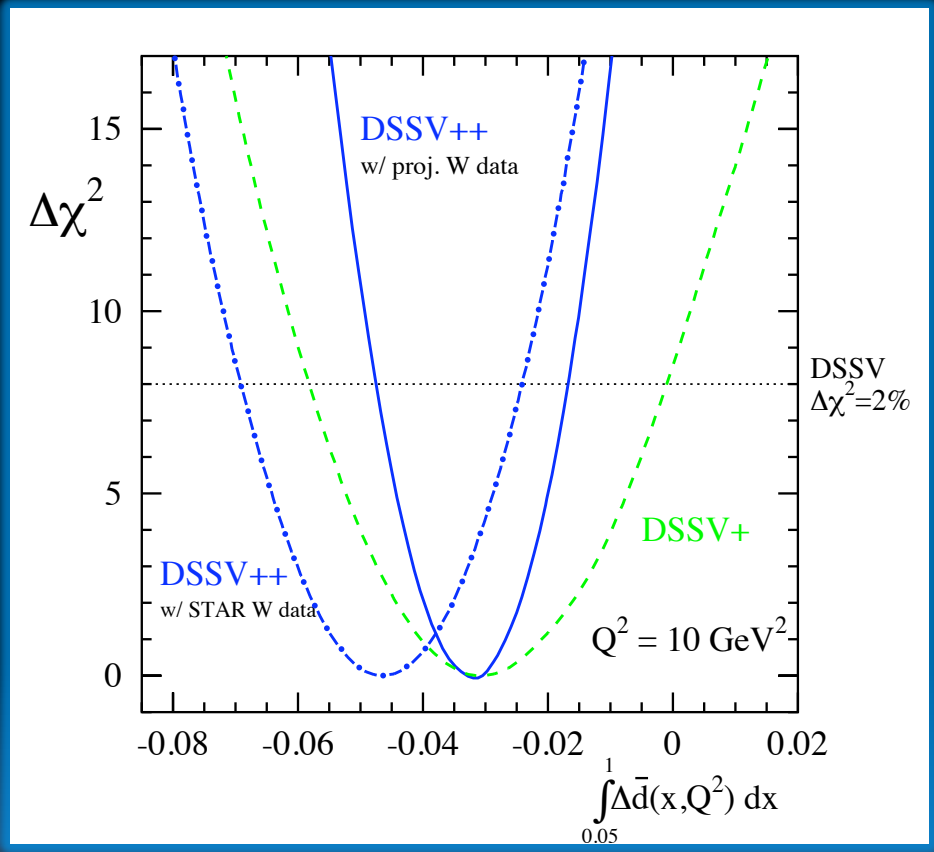


- W is Left handed
- $\bar{\nu}$ /ν R/L Handed (99.9999%)
- lepton decay direction, in the W rest frame, is set by conservation of angular momentum
- Lepton momentum aligned (anti-aligned) with W^- (W^+) momentum

Impact on $\Delta\bar{u}$ & $\Delta\bar{d}$ PDFs?

Thanks to DSSV for permission to show preliminary analysis plots!



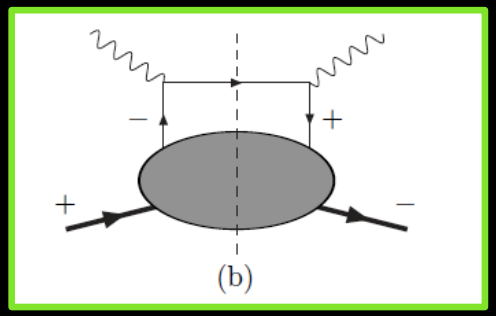


DSSV+ = DSSV & COMPASS data

DSSV++ = DSSV+ run-9 pi0 and jet & projected W data

DSSV++ = DSSV+ run-9 pi0 and jet & STAR W

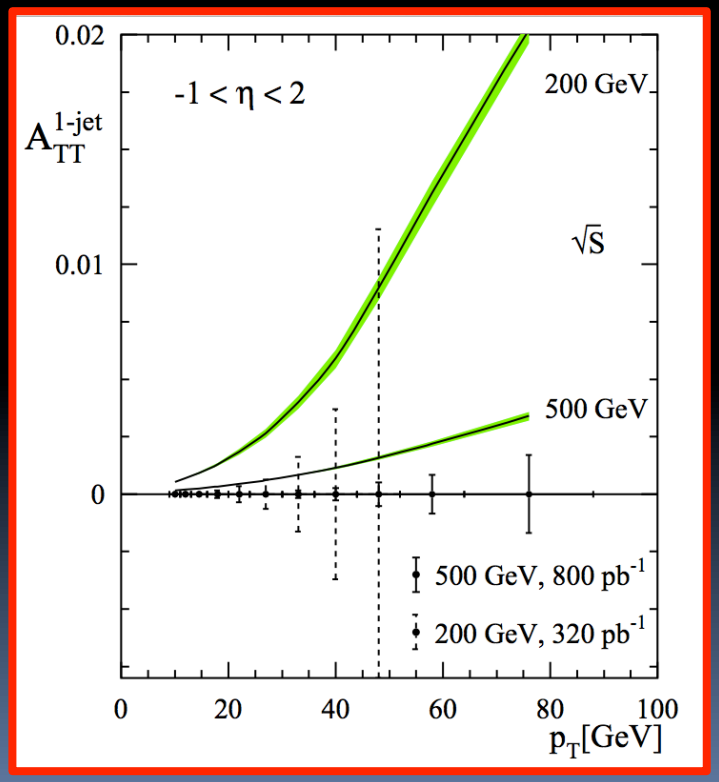
Why don't we know more ?



$\Delta_T f(x)$ is CHIRAL ODD. In a helicity basis this corresponds to a helicity flip of both the incoming nucleon and parton. $\Delta_T f(x)$ Is not probed in inclusive DIS because flipping of chirality is highly suppressed!

Must access $\Delta_T f(x)$ by coupling to a second chiral odd function.

- Ralston and Soper proposed Drell-Yan but …
  - low rates compared to other hadronic processes
  - anti-quark transversity is likely very small
- Could also look at inclusive jet A_{TT} in pp collisions, however …
  - Gluons are abundant and have ZERO Δ_T
  - $A_{TT} < A_{LL}$ due to Soffer bound



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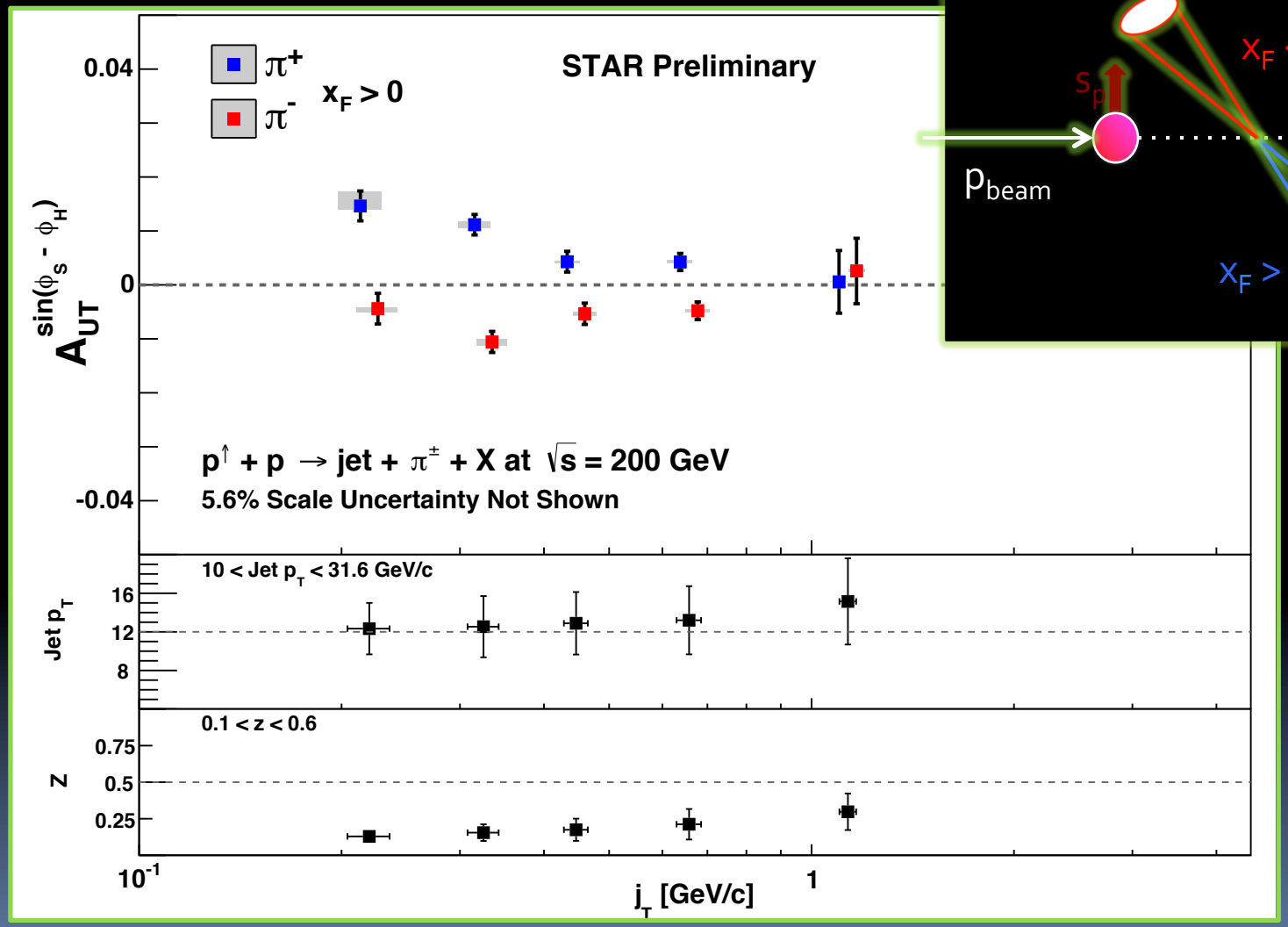
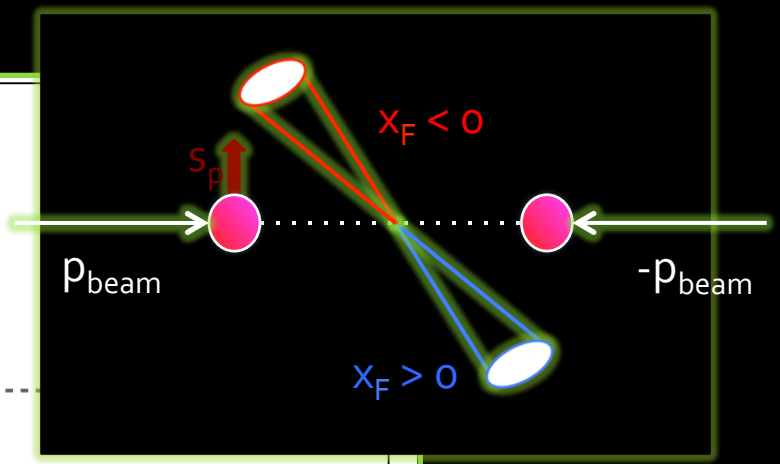
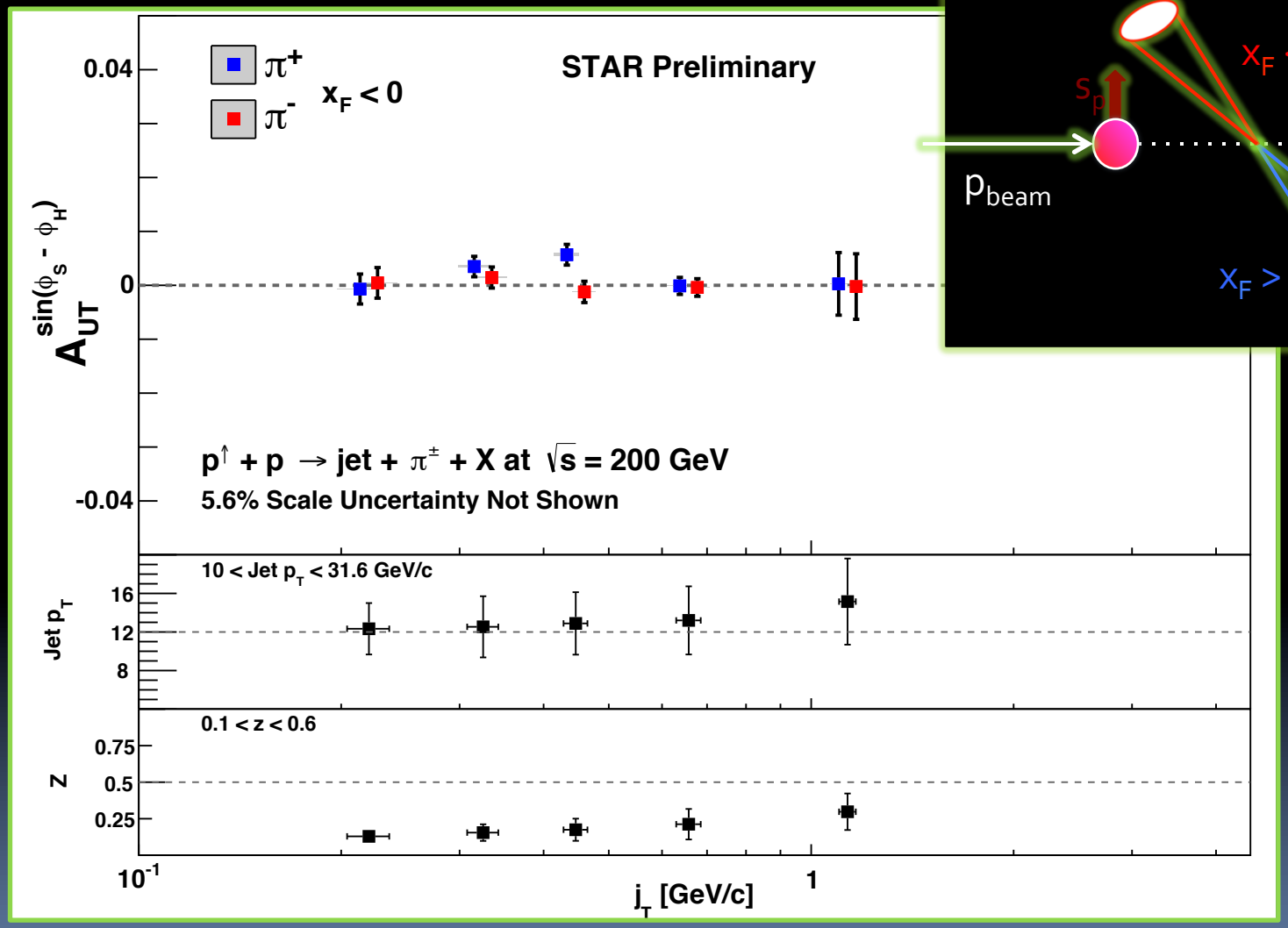
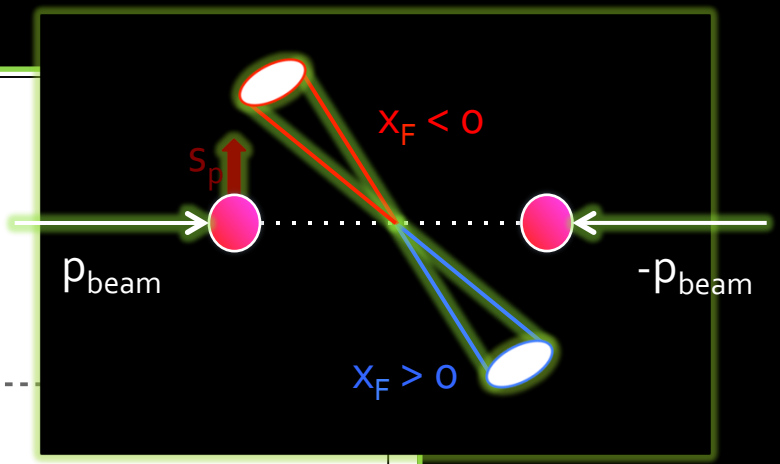
2012 $A_{UT}^{COLLINS}$ vs. j_T at 200 GeV (xF>0)



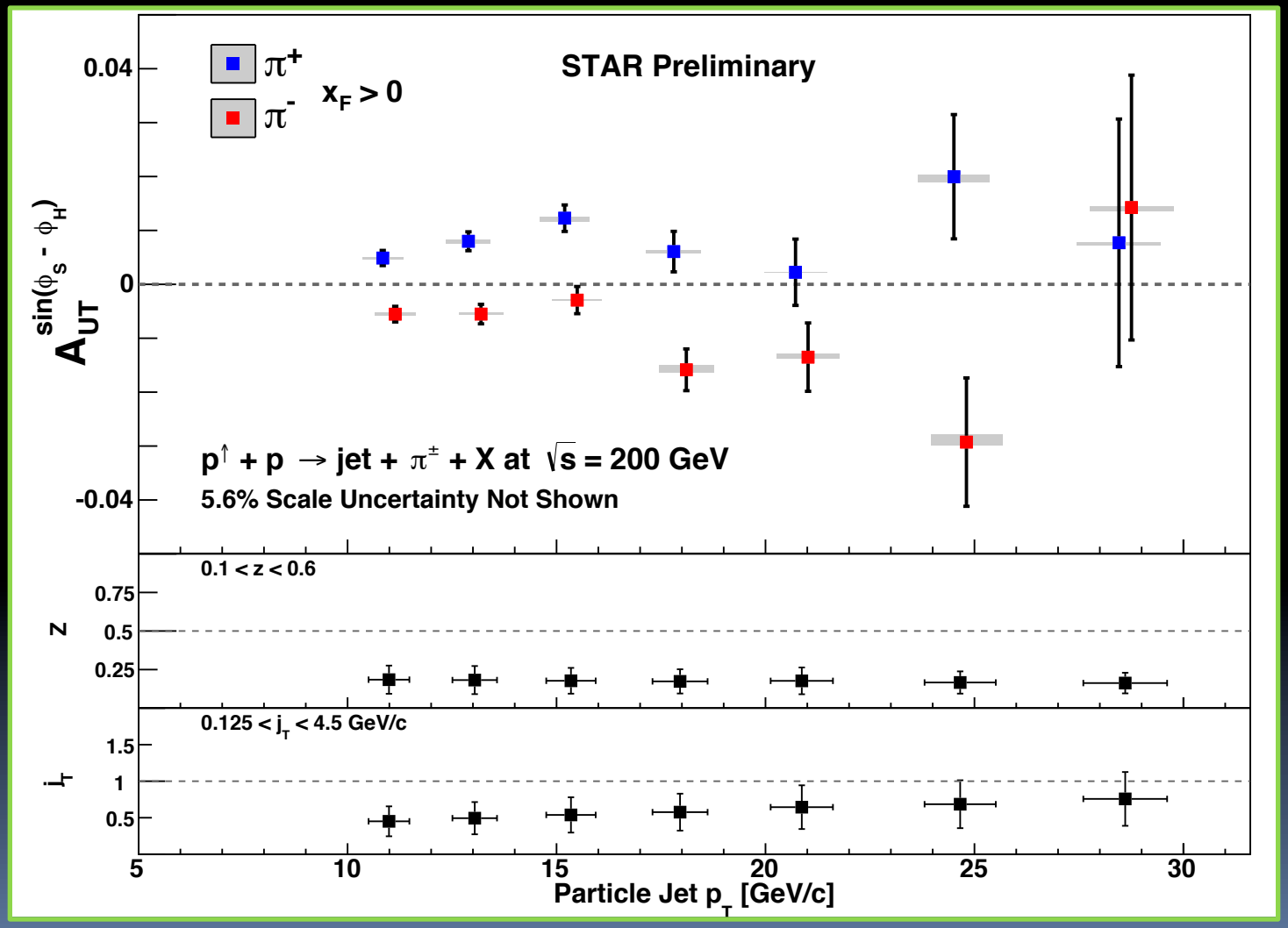


2012 $A_{UT}^{COLLINS}$ vs. j_T at 200 GeV (x_F<0)

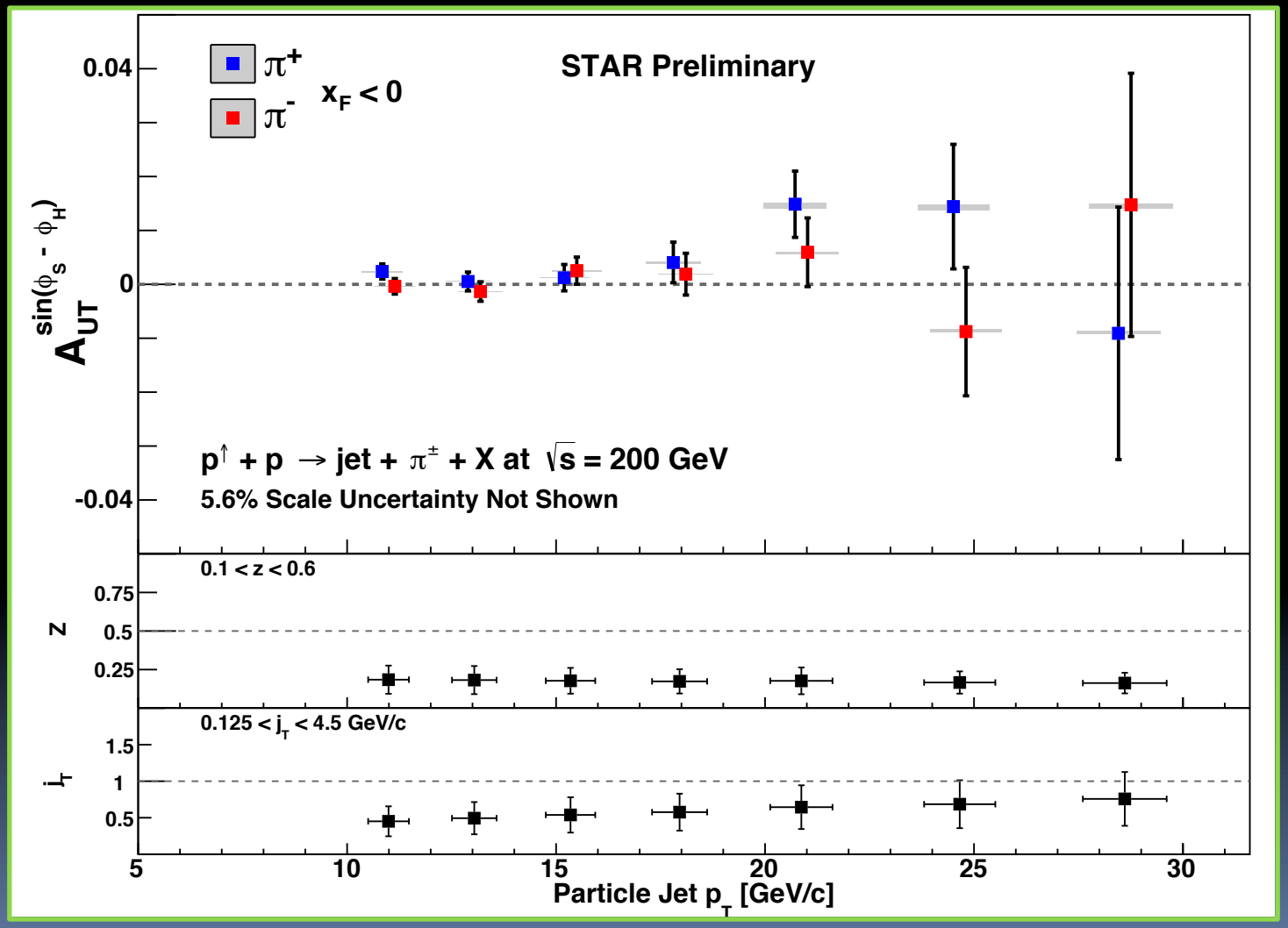




2012 200 GeV $A_{UT}^{COLLINS}$ vs. p_T ($x_F > 0$)

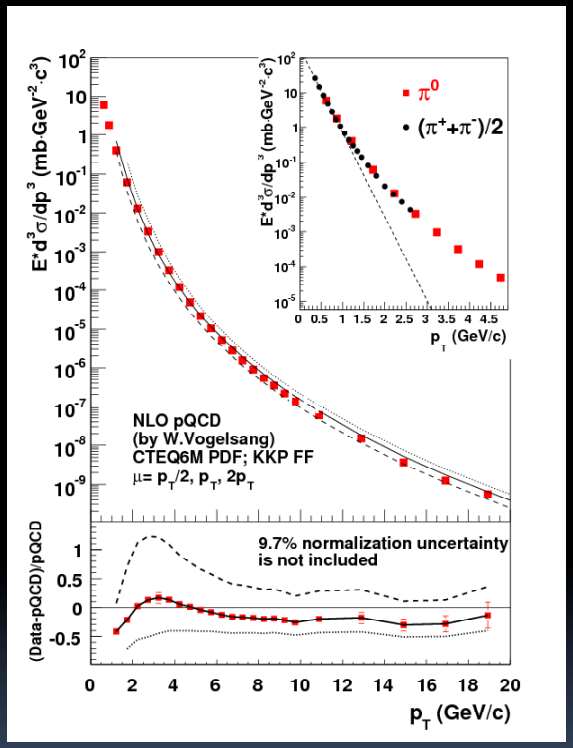


2012 200 GeV $A_{UT}^{COLLINS}$ vs. p_T ($x_F < 0$)

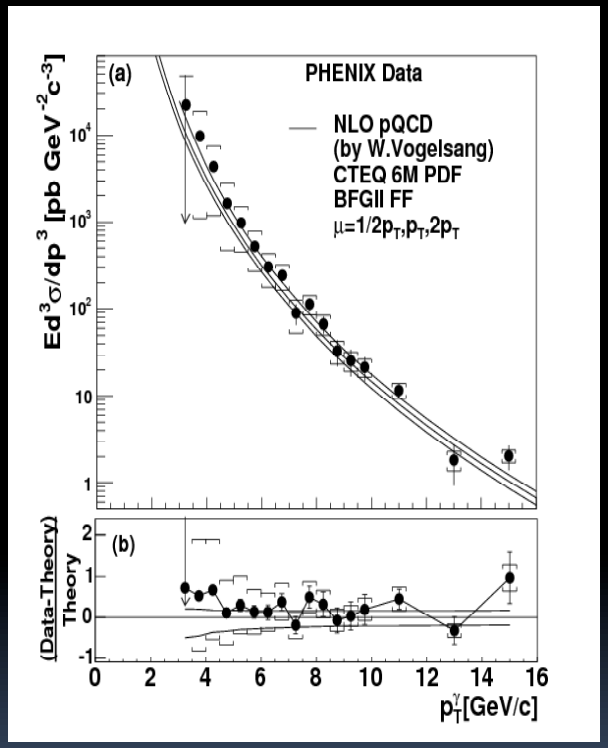


Cross sections @ √s=200 & 62 GeV

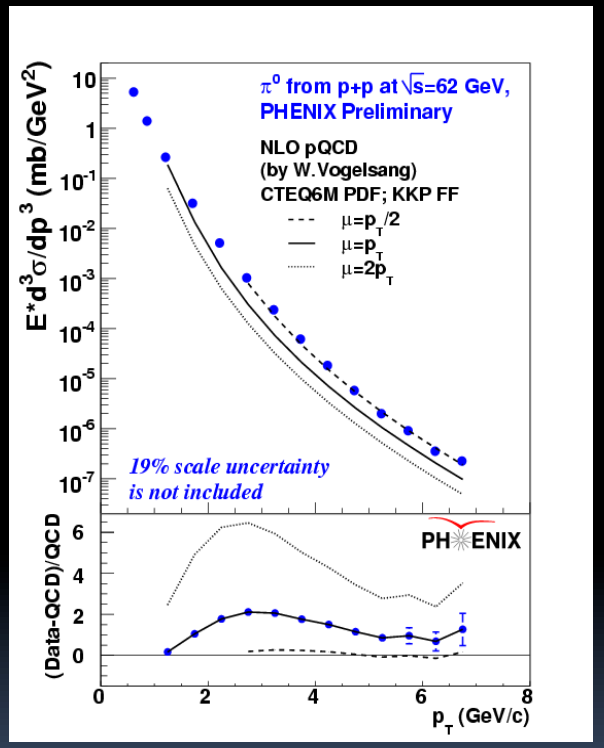
PHENIX pp→ π^0 X
PRD76, 051106



PHENIX pp→γ X
PRL 98, 012002



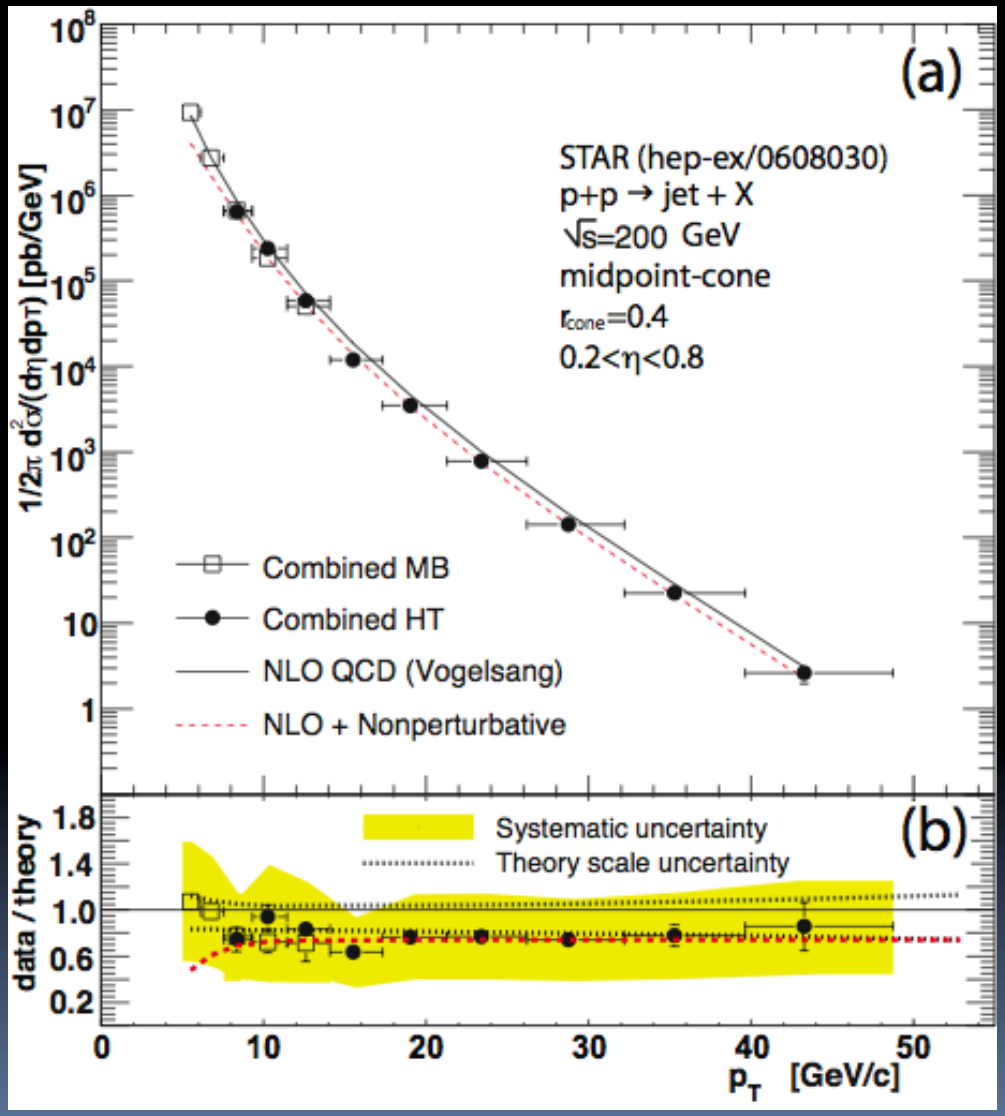
PHENIX pp→ π^0 X
62.4 GeV



Good agreement between NLO pQCD calculations and data

⇒ pQCD can be used to extract spin dependent pdf's from RHIC data.

2003/2004 Inclusive Jet Cross-Section Results

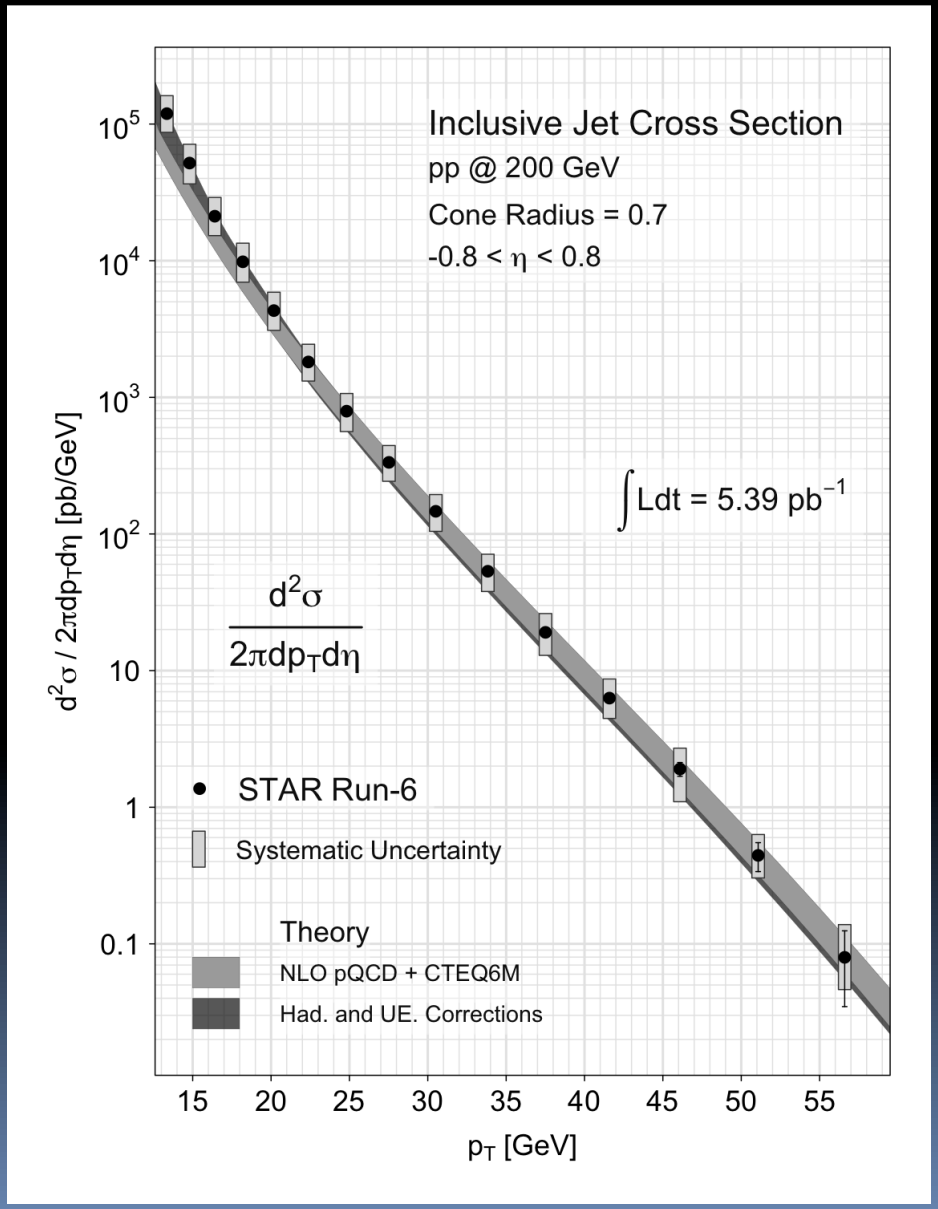


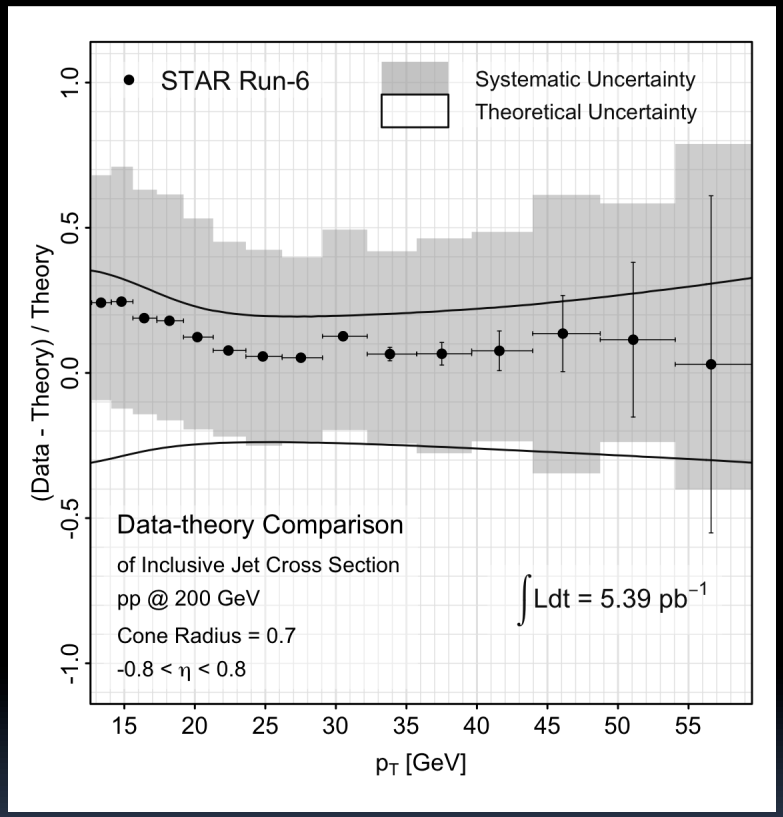
$$\frac{1}{2\pi}\frac{d^2\sigma}{d\eta dp_T} = \frac{1}{2\pi}\cdot\frac{N_{Jets}}{\Delta\eta\Delta p_T}\cdot\frac{1}{\int Ldt}\cdot\frac{1}{c(p_T)}$$

- 3 point overlap between HT and MINB show good agreement.
- 50% systematic shown in yellow band comes from uncertainty in jet energy scale. Need or gamma-jet to reduce this error.
- Application of hadronization correction removes systematic offset from NLO and data
- **Agreement -within- systematics over 7 orders of magnitude!**

2006 Inclusive Jet Cross-Section

$$\frac{1}{2\pi}\frac{d^2\sigma}{d\eta dp_T} = \frac{1}{2\pi}\cdot\frac{N_{Jets}}{\Delta\eta\Delta p_T}\cdot\frac{1}{\int Ldt}\cdot\frac{1}{c(p_T)}$$





NLO is corrected for hadronization and UE

Good agreement with theory!

B. Jager et.al, Phys.Rev.D70 034010

2006 Dijet Cross Section