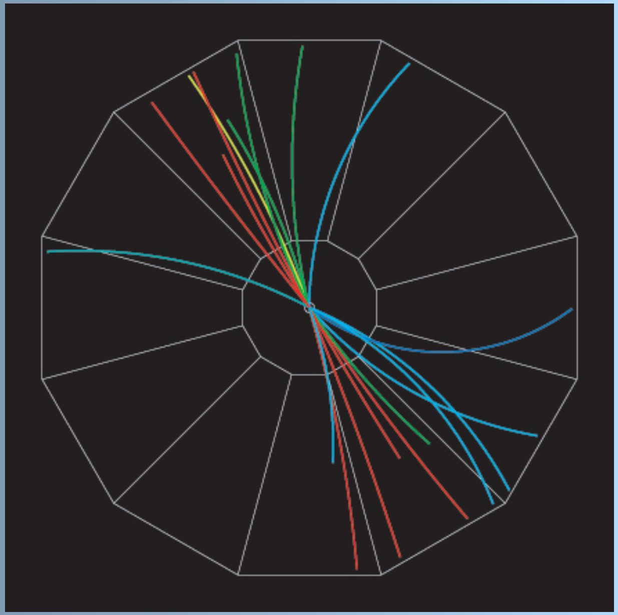
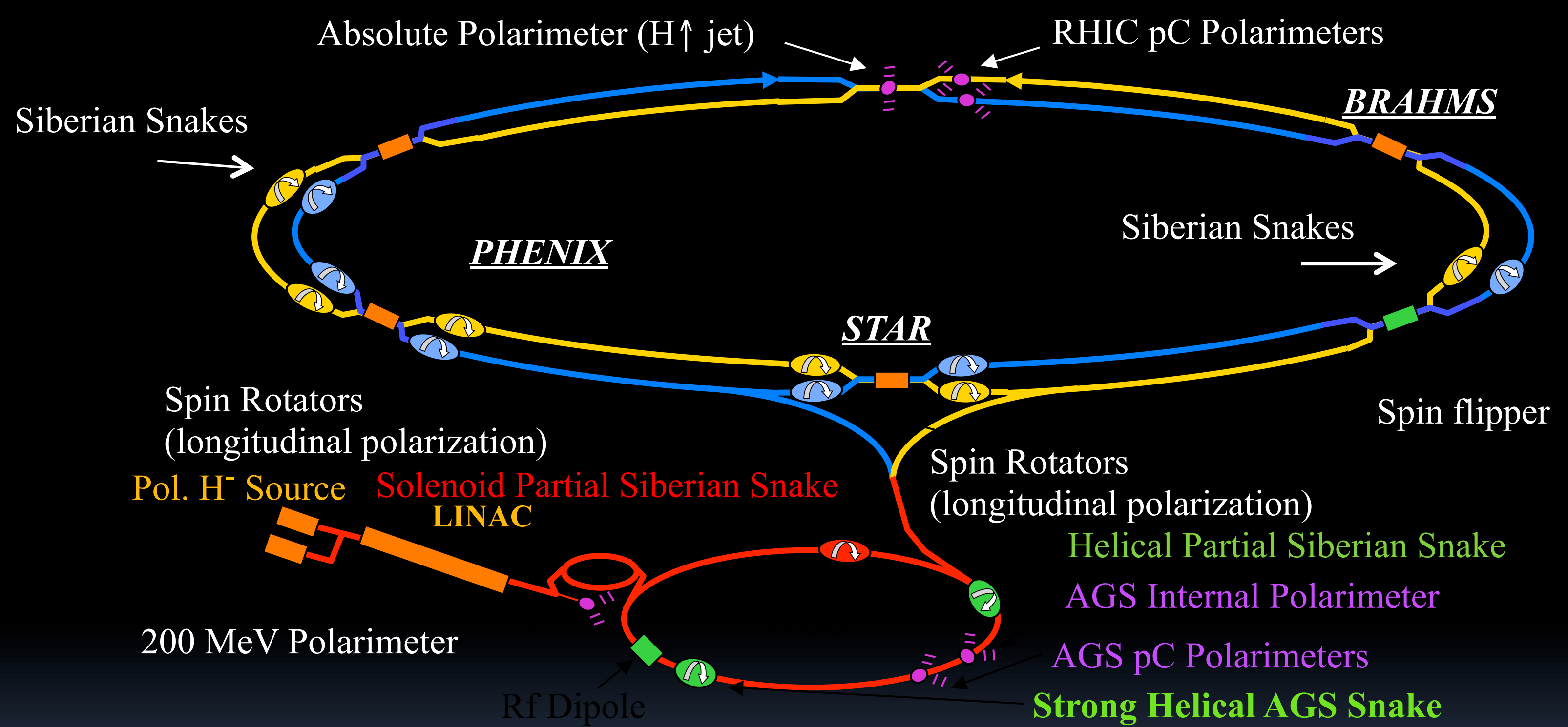
Studying Evolution with Jets at STAR



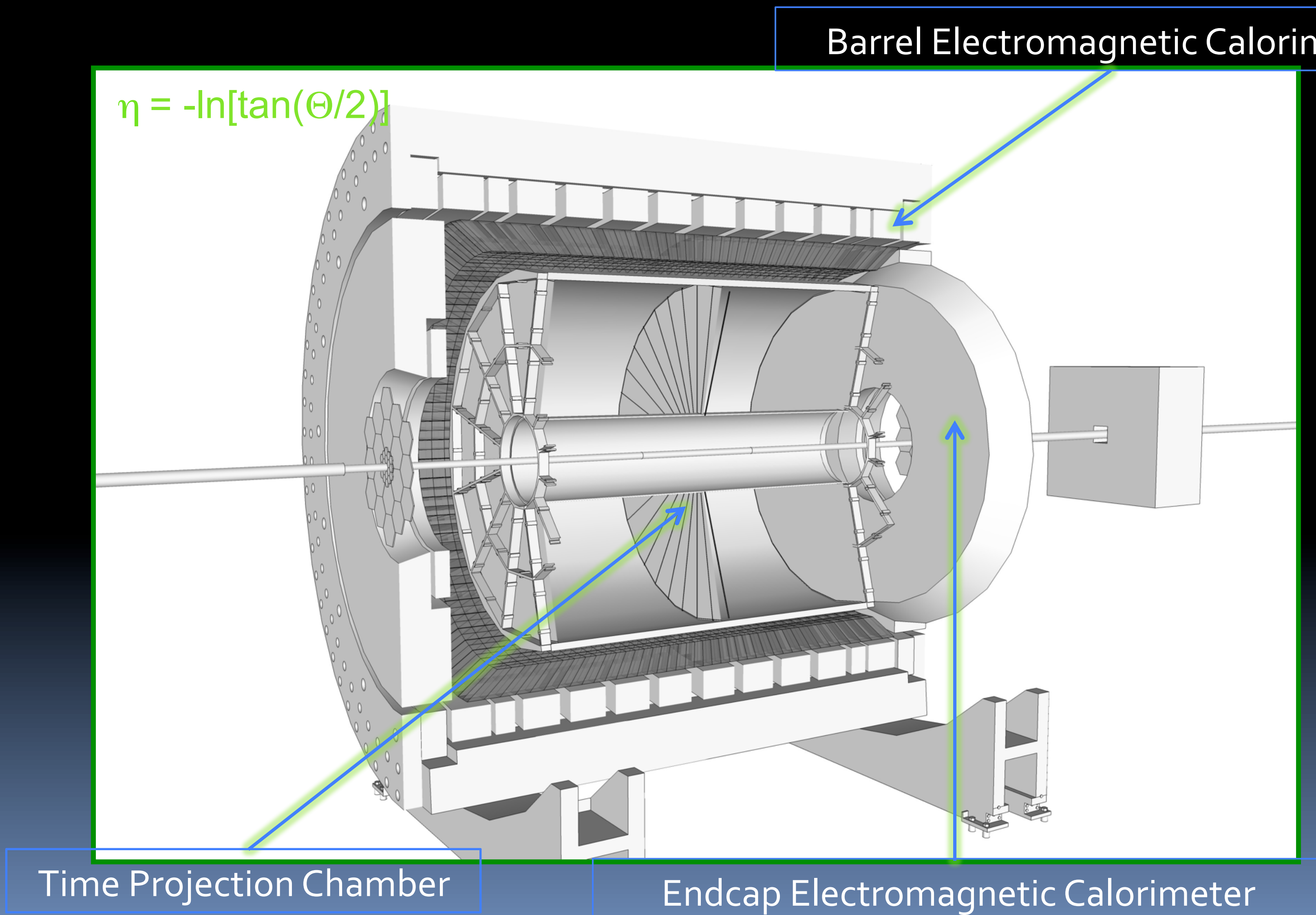
Renee Fatemi
University of Kentucky
May 28th, 2015

Relativistic Heavy Ion Collider



The Relativistic Heavy Ion Collider is the worlds first and only polarized proton colider. It can provide both longitudinal and transversely polarized proton beams.

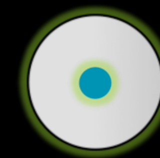
STAR's large acceptance allows for jet reconstruction and charged hadron particle identification.



Parton distribution functions in the Proton

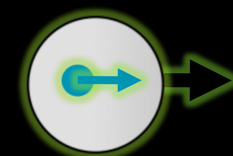
$$f(x)$$

Number density of partons with flavor f and momentum fraction x inside a nucleon



$$\Delta f(x)$$

Number density of longitudinally polarized partons inside longitudinally polarized nucleons (Helicity)

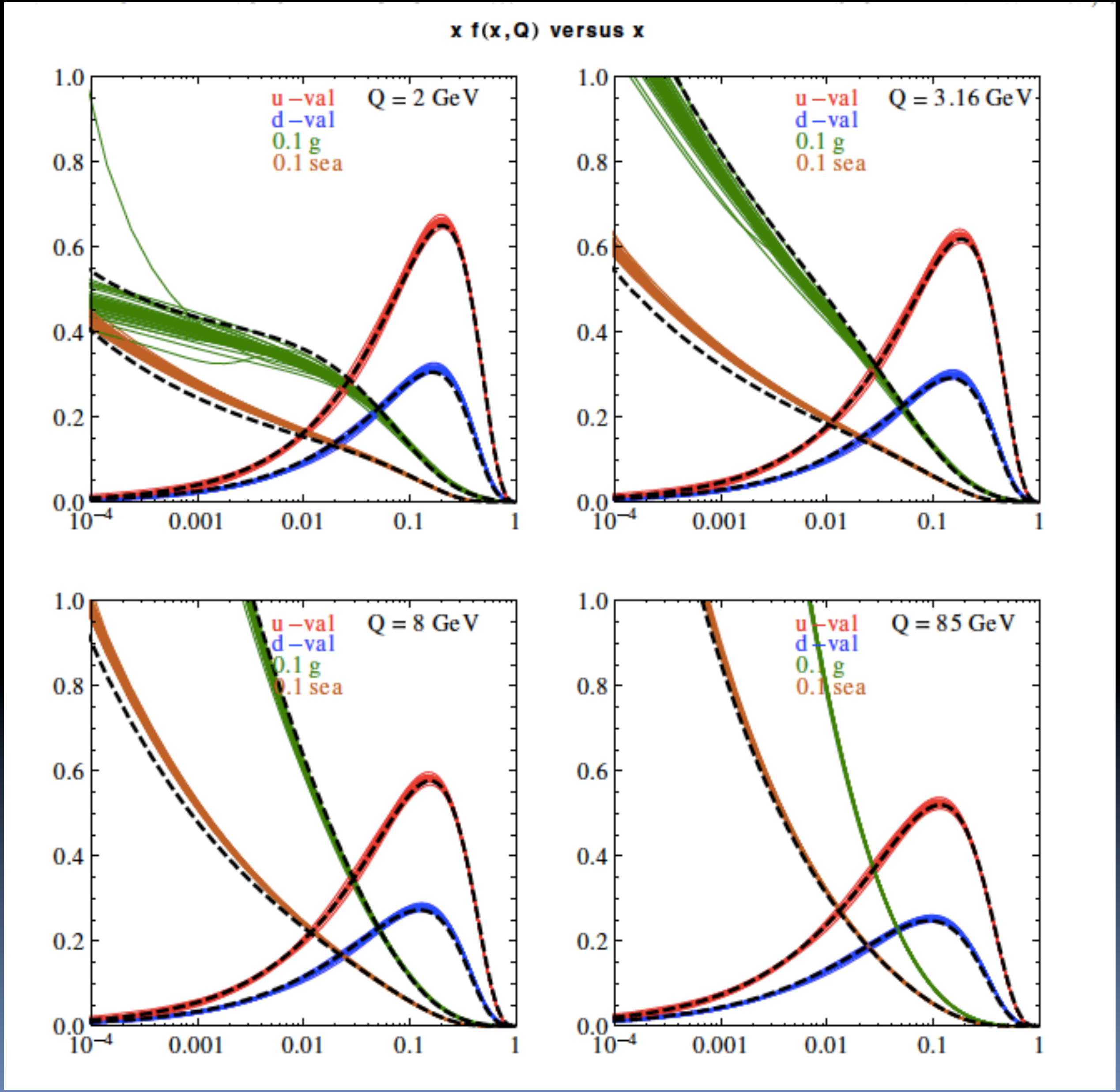


$$\Delta_T f(x)$$

Number density of transversely polarized partons inside a transversely polarized nucleon (Transversity)

Nucleon Momentum

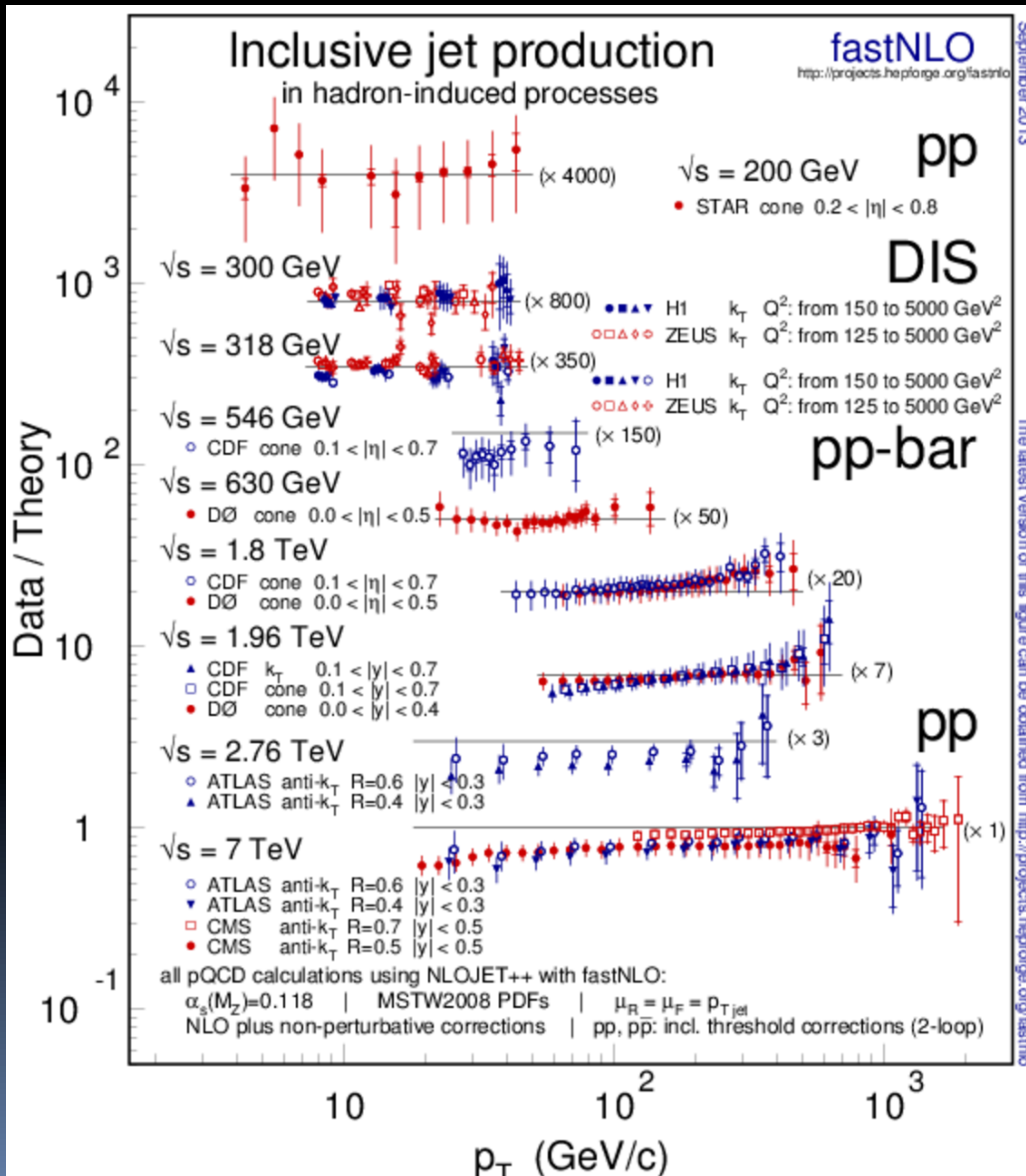
CT10 NNLO Momentum Distributions



Phys. Rev. D 89 033009 (2014)

Inclusive Jet Cross-sections

http://projects.hepforge.org/fastnlo/form/index.html



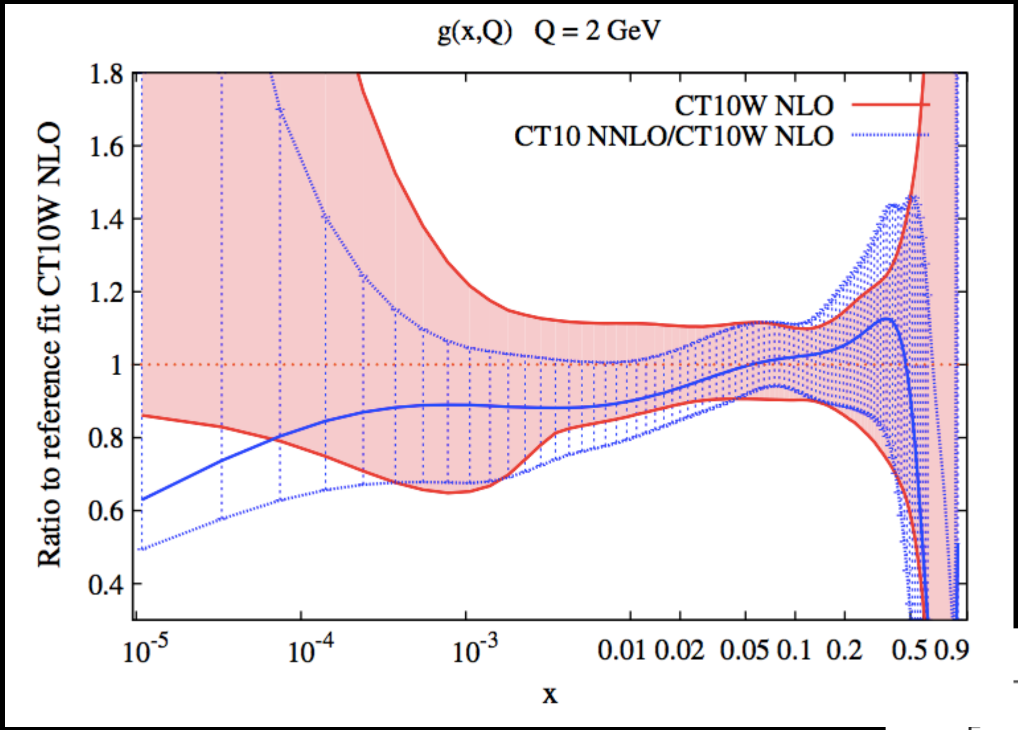
STAR inclusive jet cross-section data accesses lowest Q^2 scales to date.

Currently Tevatron Run-I inclusive jet data are excluded from CT10 NNLO.

STAR data is not included. What impact could we provide?

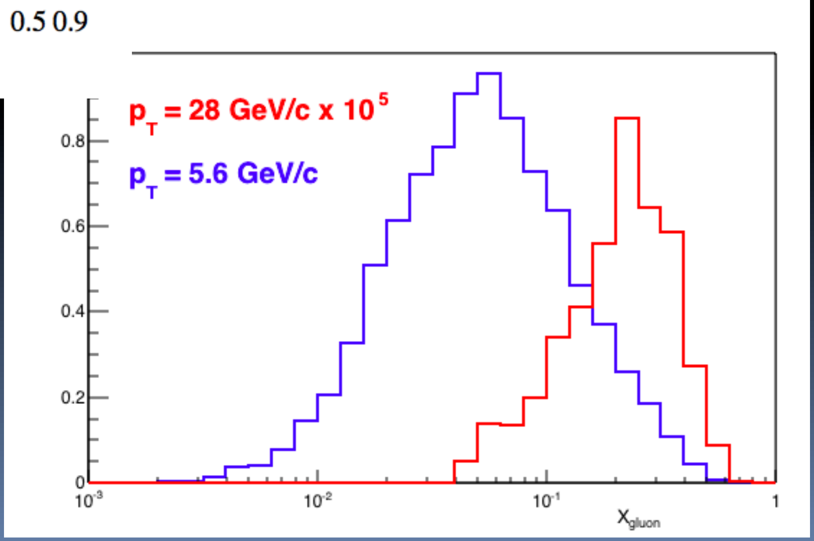
CT10 NNLO & CT10W NLO Comparison

Phys. Rev. D 89 033009 (2014)



At large x g(x,Q) is reduced in CT10 NNLO compared to CT10W due to removal of Run-I Tevatron data.

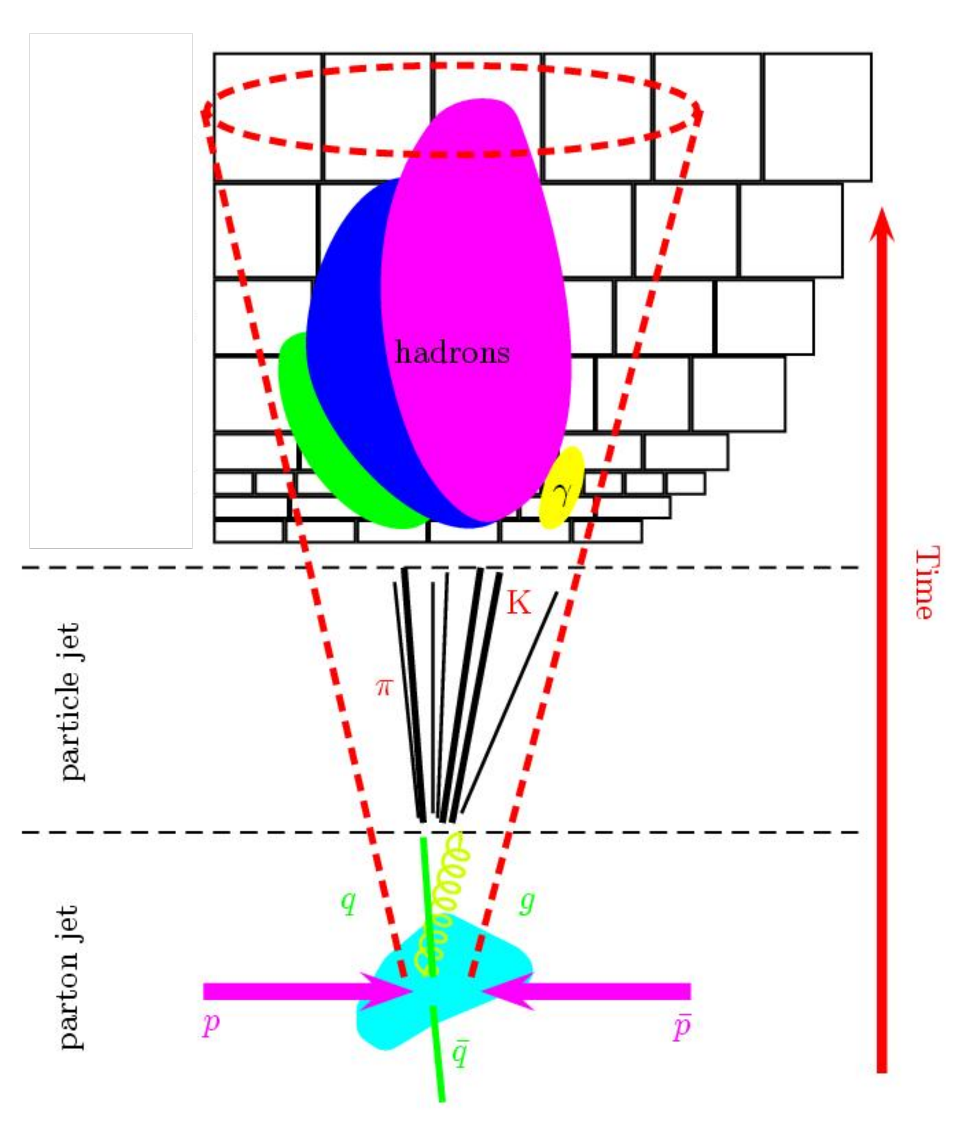
At $\sqrt{s}$ = 200 GeV high p_T jets from pp collisions at RHIC push into the high x region where PDF uncertainties start to quickly rise.



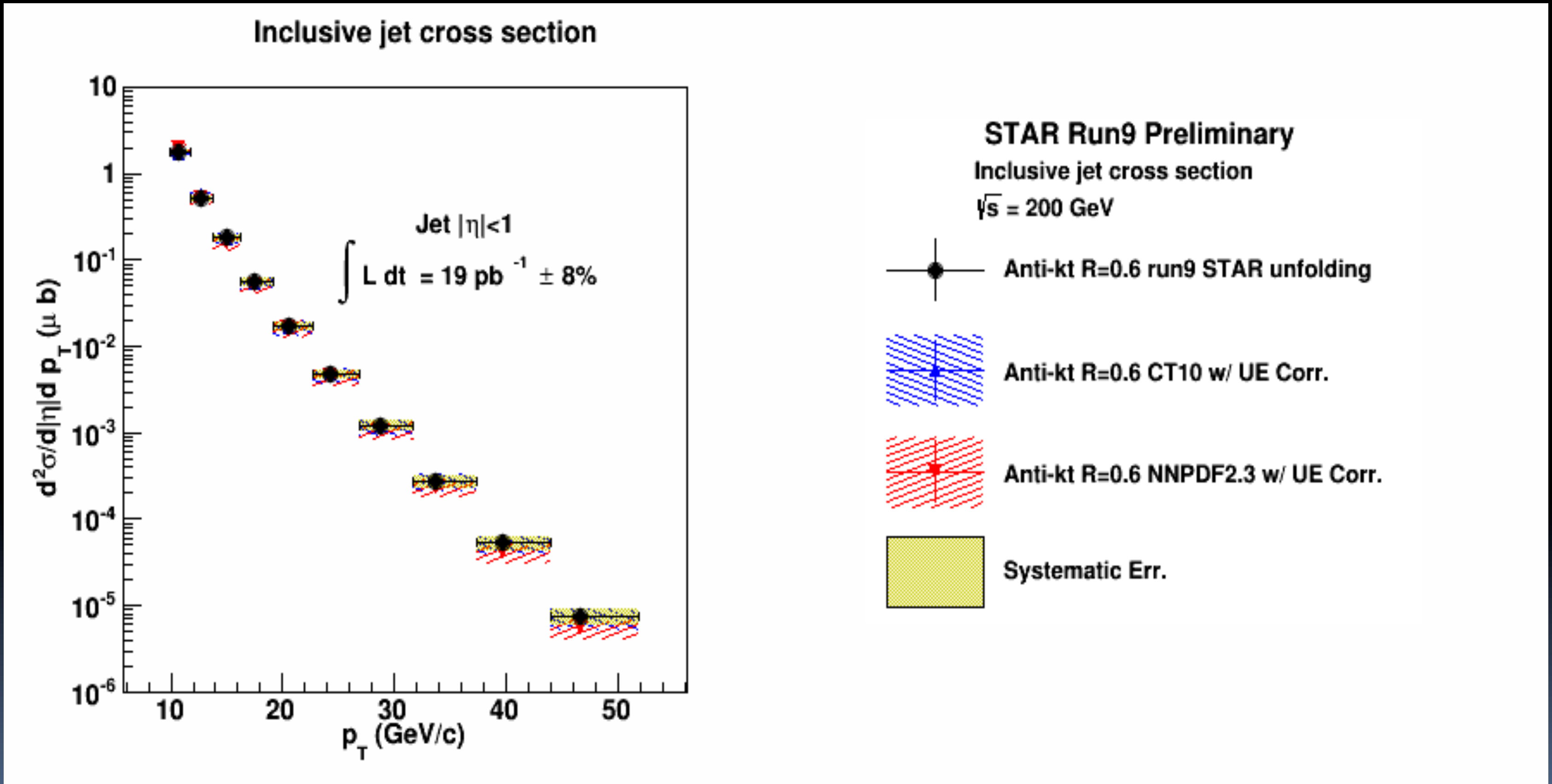
Jet Reconstruction at STAR

- Before 2009 STAR used
  Mid-point cone algorithm
  Adapted from Tevatron II – hep-ex/0005012
  - Seed E = 0.5 GeV
  - Cone Radius R = 0.7 in η-φ space
  - Split/merge fraction f = 0.5

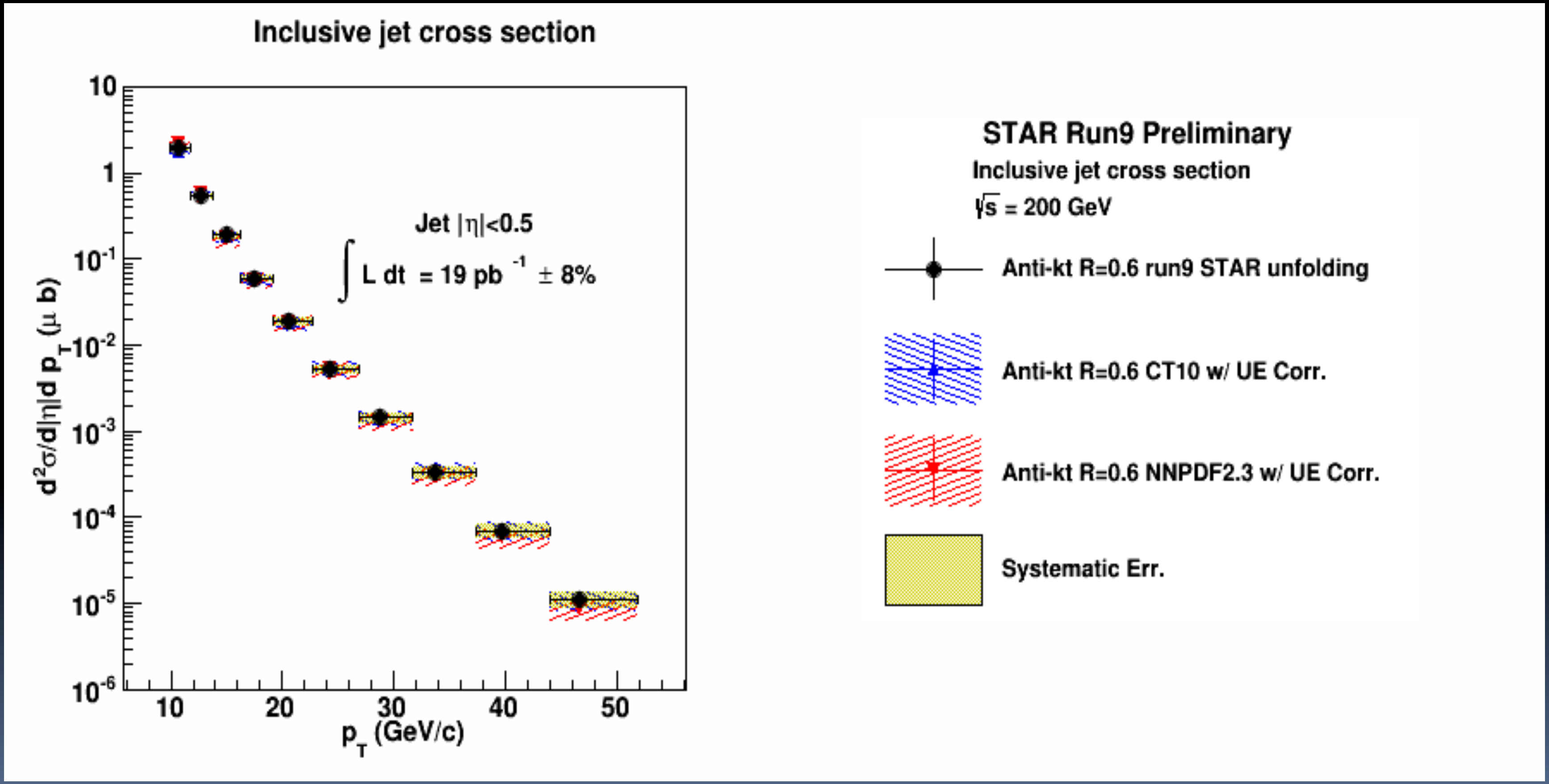
- Starting in 2009 STAR moves to
  Anti-k_T algorithm
  Cacciari, Salam, and Soyez, JHEP 0804, 063
  - Recombination radius
    R = 0.6 for 200 GeV
  - Recombination radius
    R = 0.5 for 500 GeV



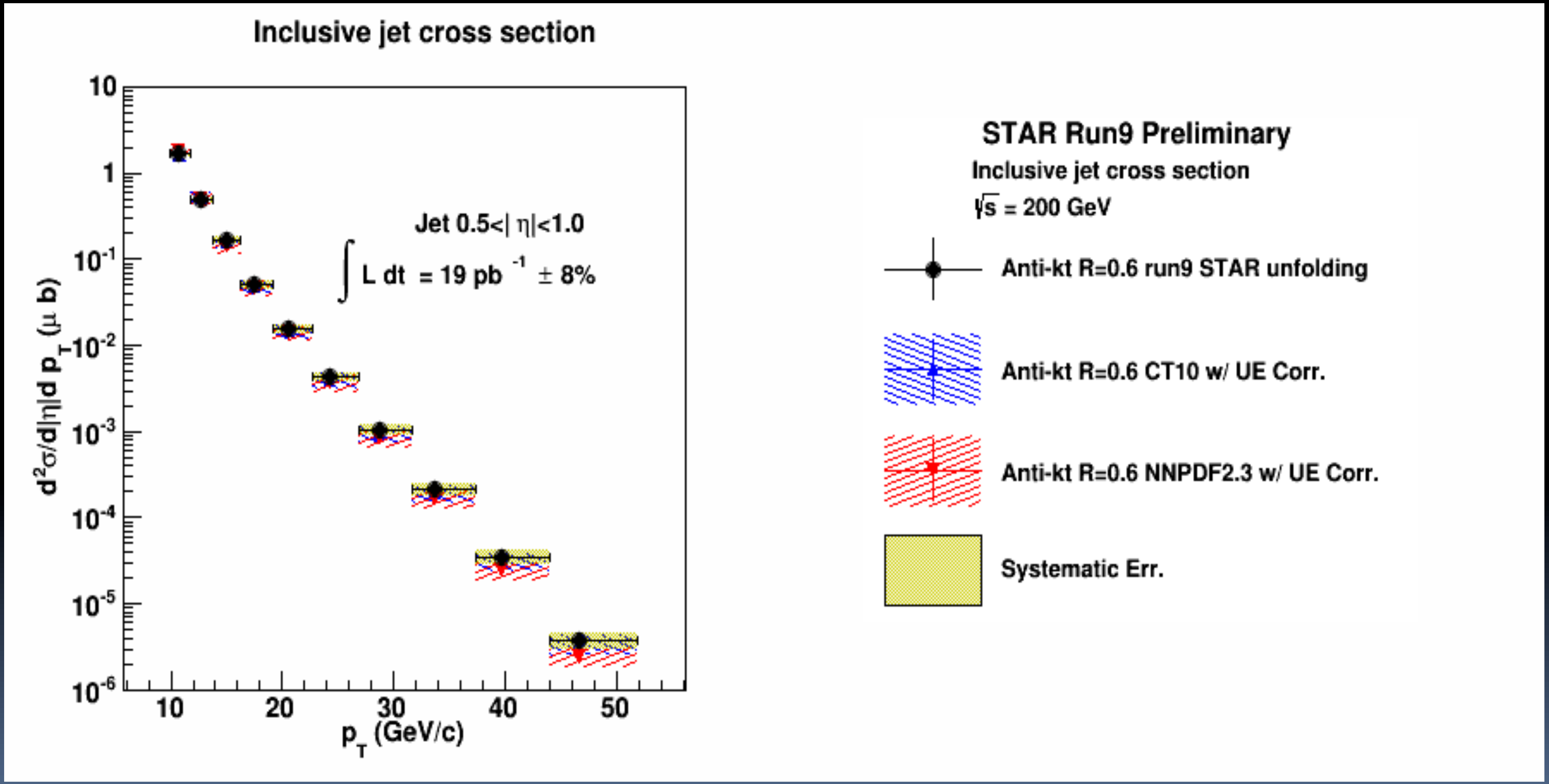
STAR 2009 inclusive jet cross section $|\eta|<1.0$



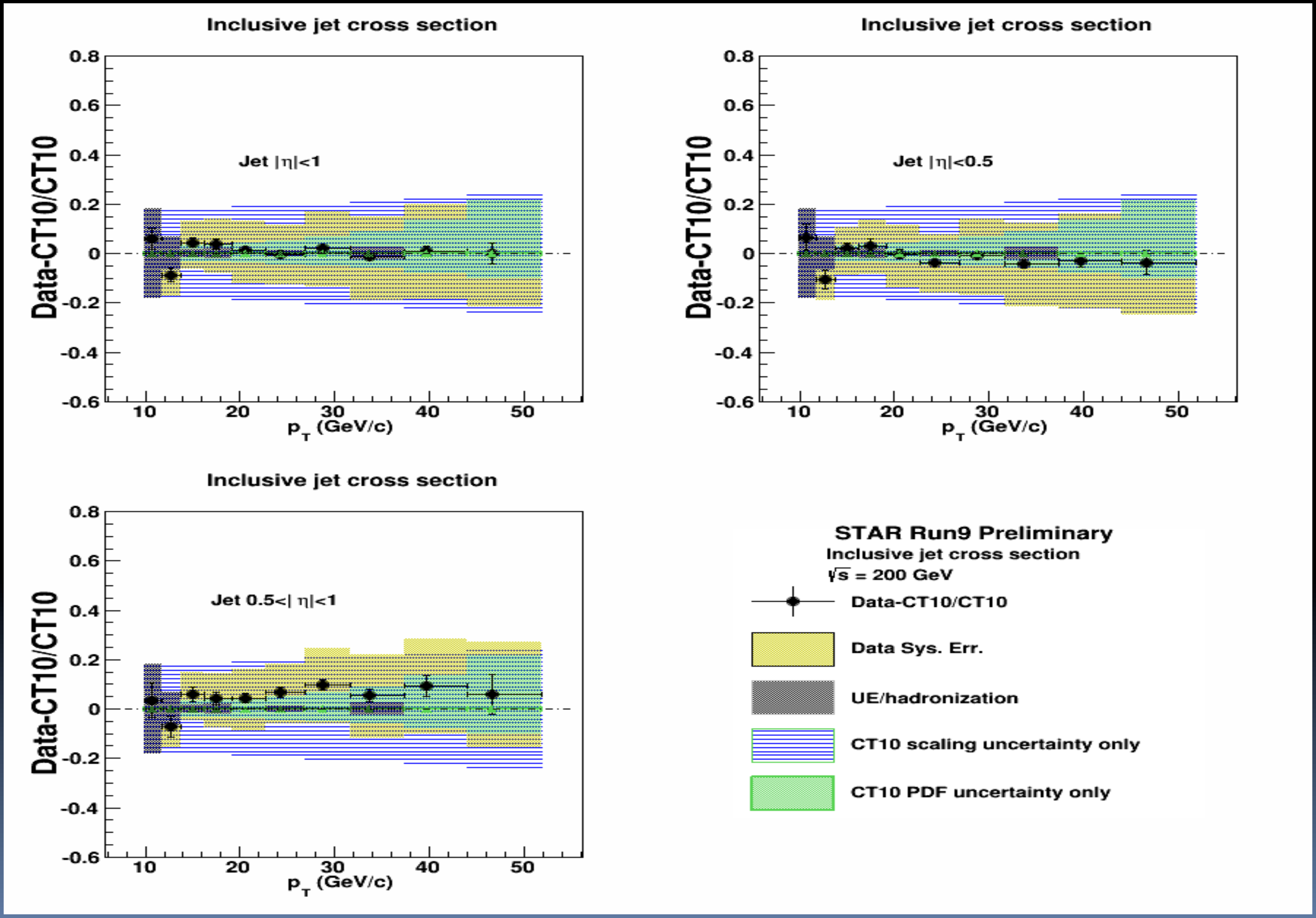
STAR 2009 inclusive jet cross section $|\eta|<0.5$



STAR 2009 inclusive jet cross section $0.5<|\eta|<1.0$

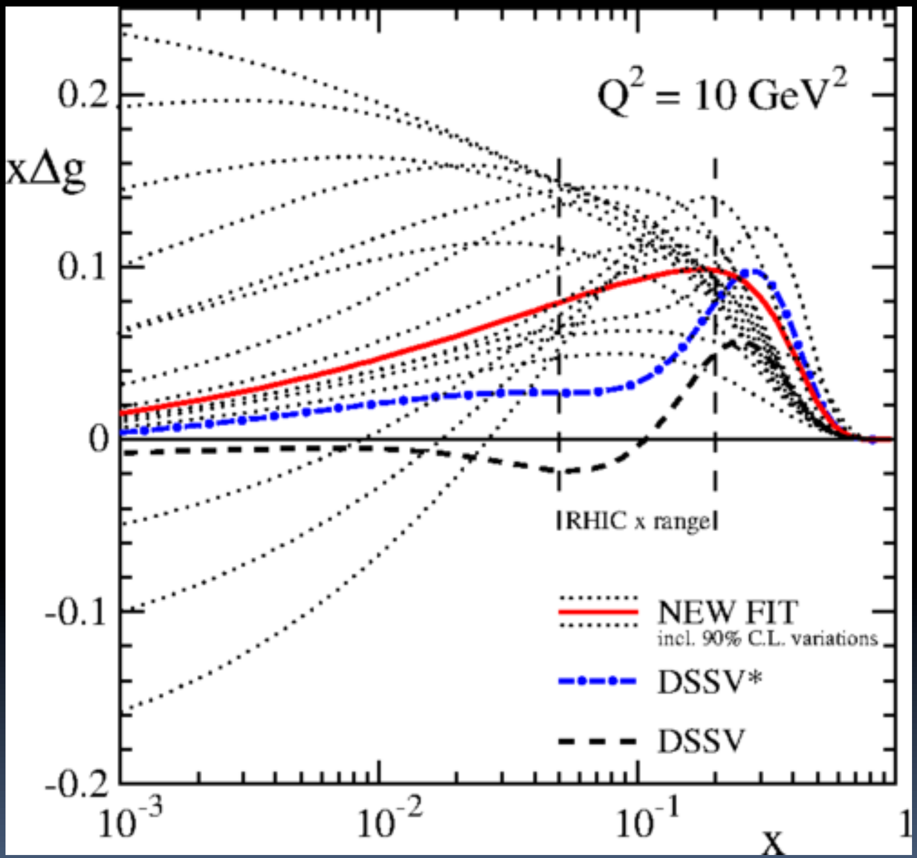


Comparisons of STAR data to C10 NLO



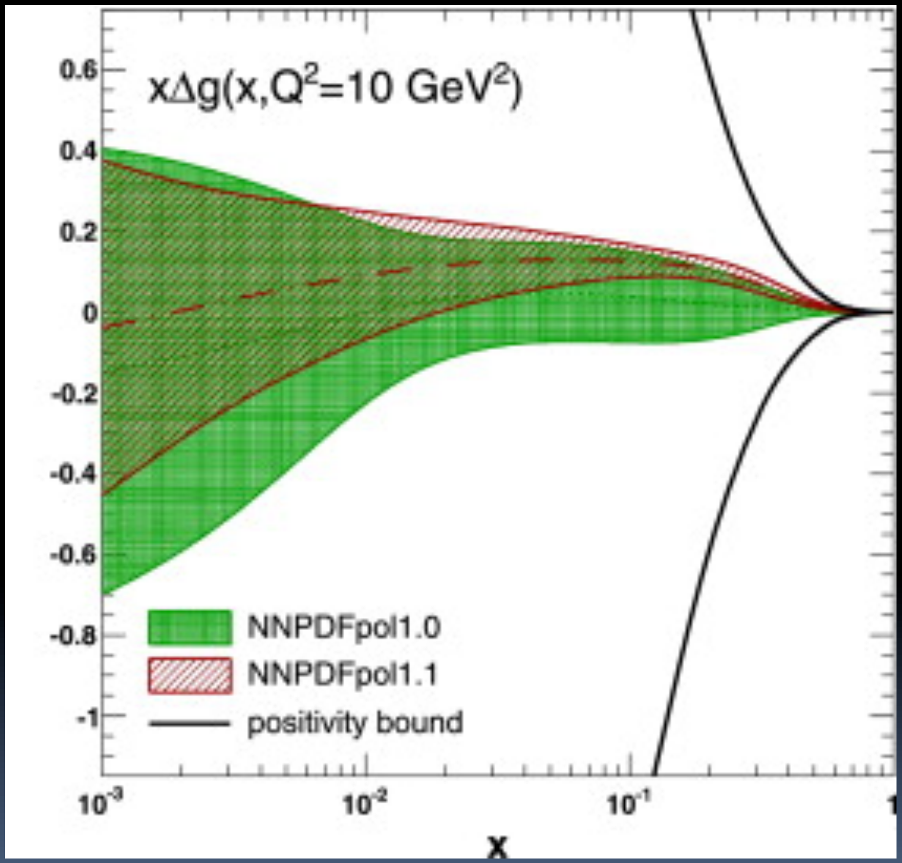
Gluon Helicity Distributions

DSSV



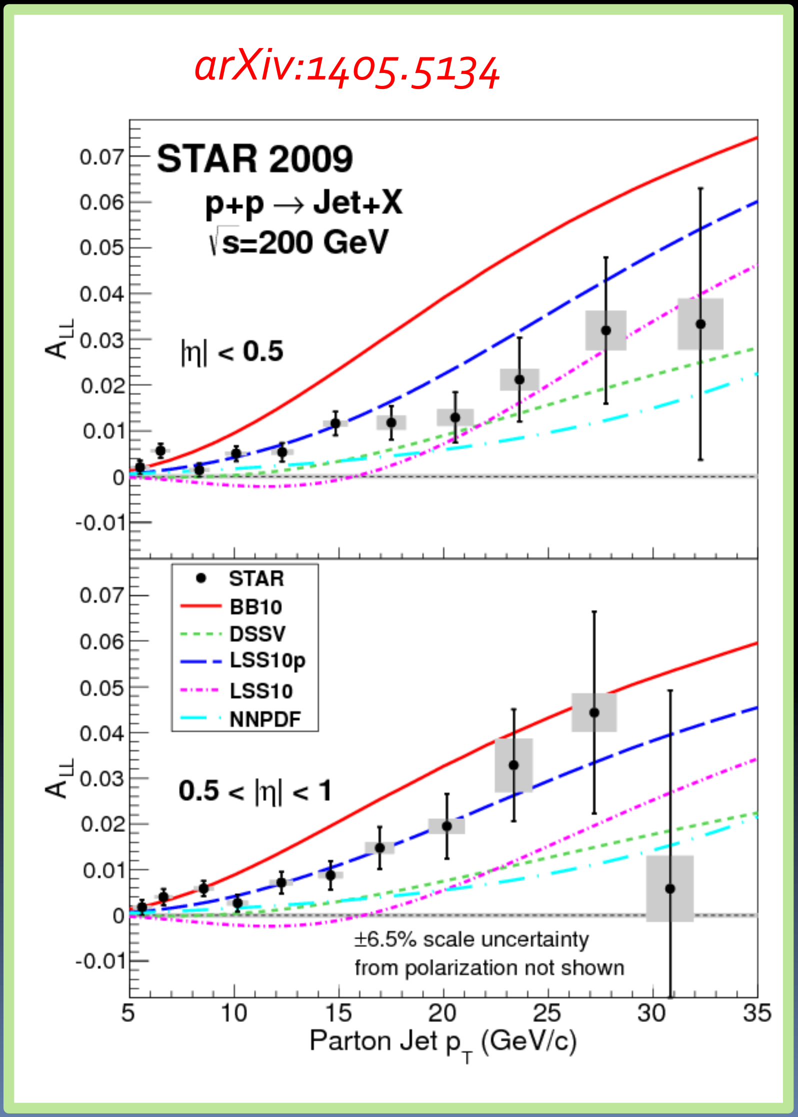
Phys. Rev. Lett. 113 (2014) 012001

NNPDF 1.1



Nucl. Phys. B, Volume 887 (2014) 276 - 308

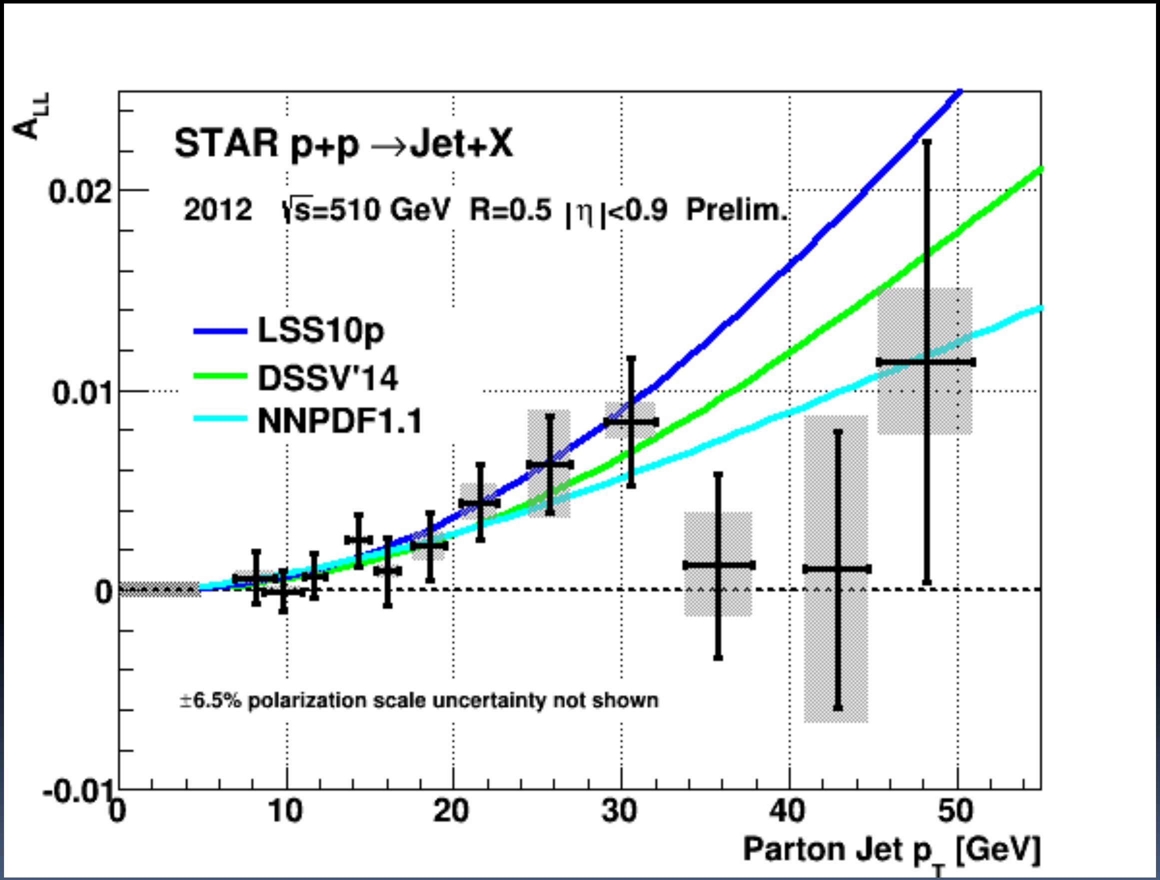
Recent √s = 200 GeV jet A_{LL}



- 2009 STAR inclusive jet A_{LL} measurements are a factor of 3 – 4 more precise than the 2006 results.
- A_{LL} falls in the middle among several recent polarized PDF fit predictions
- A_{LL} is somewhat larger than predictions from the **2008 DSSV** and NNPDF1.0 indicating a positive Δg in the accessible x region.

First √s = 500 GeV jet A_{LL}!

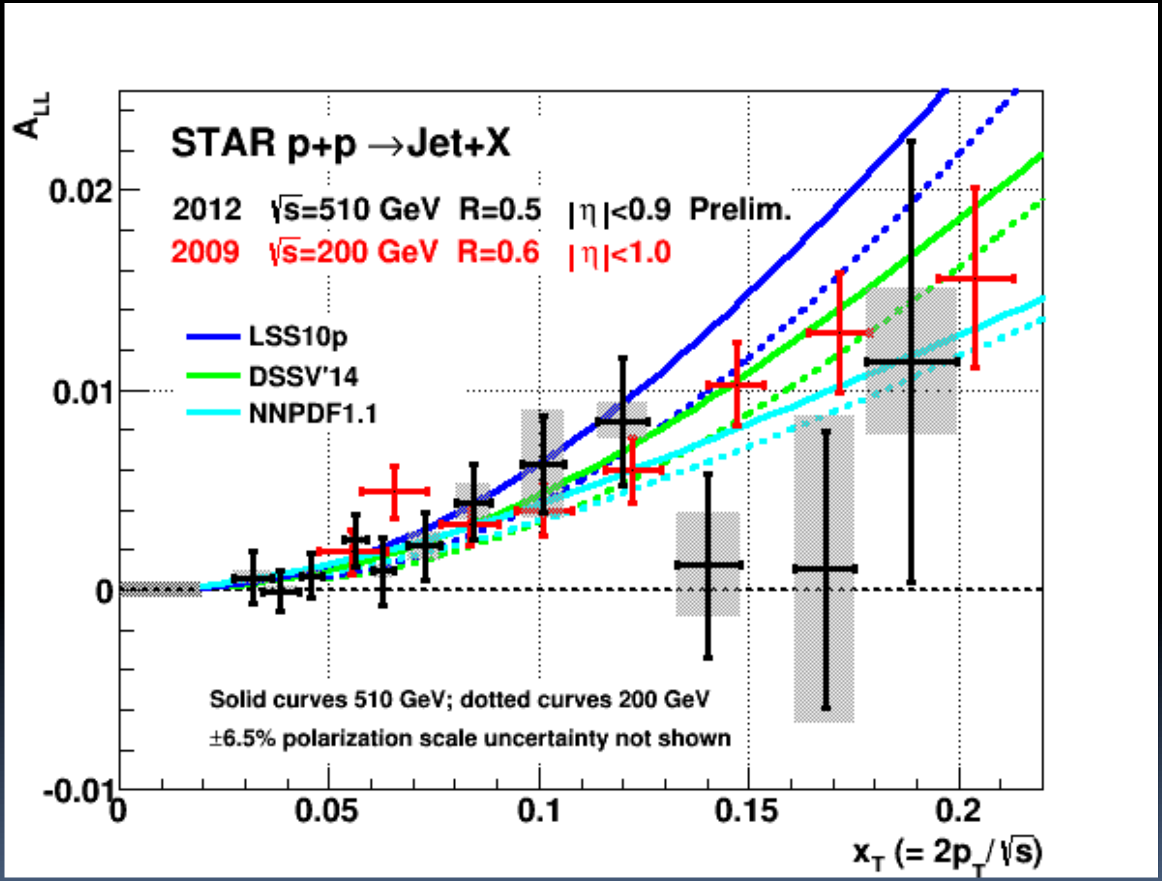
Provides first access to lower x



Results are in excellent agreement with newest DSSV and NNPDF NLO predictions!

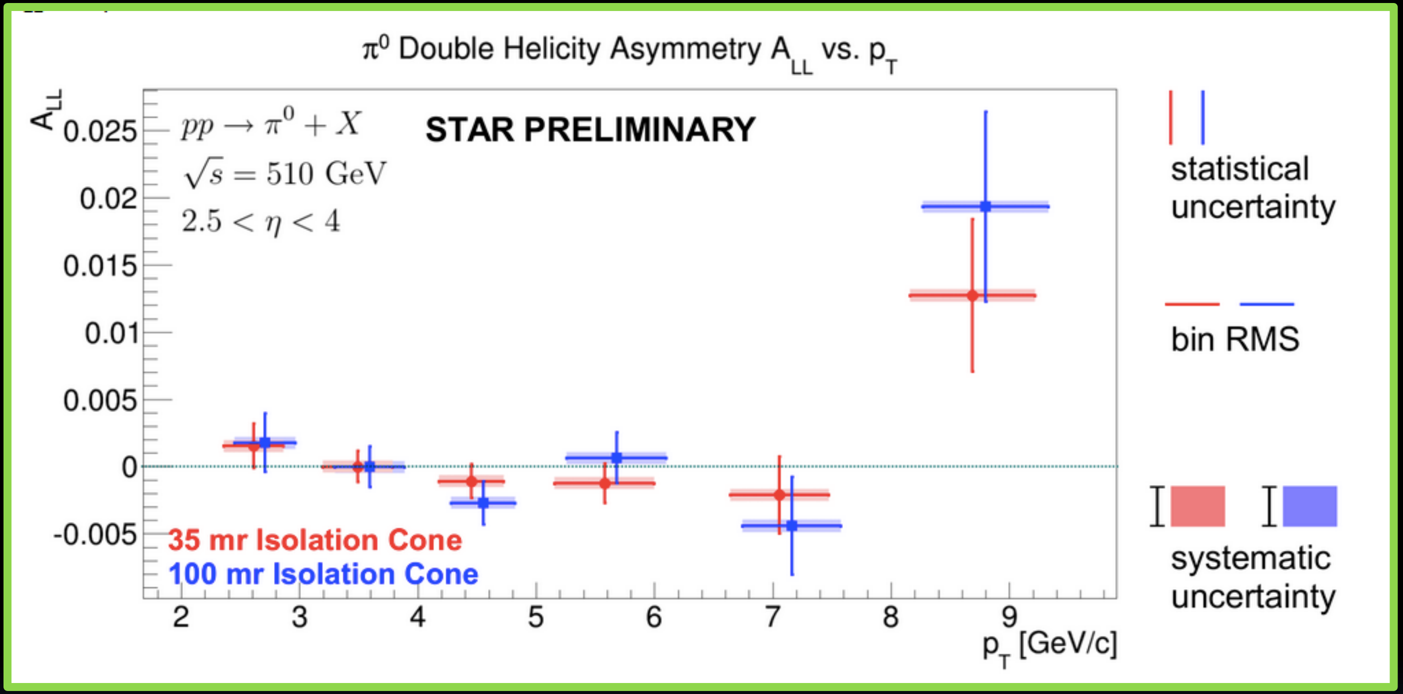
First √s = 500 GeV jet A_{LL}!

Provides first access to lower x



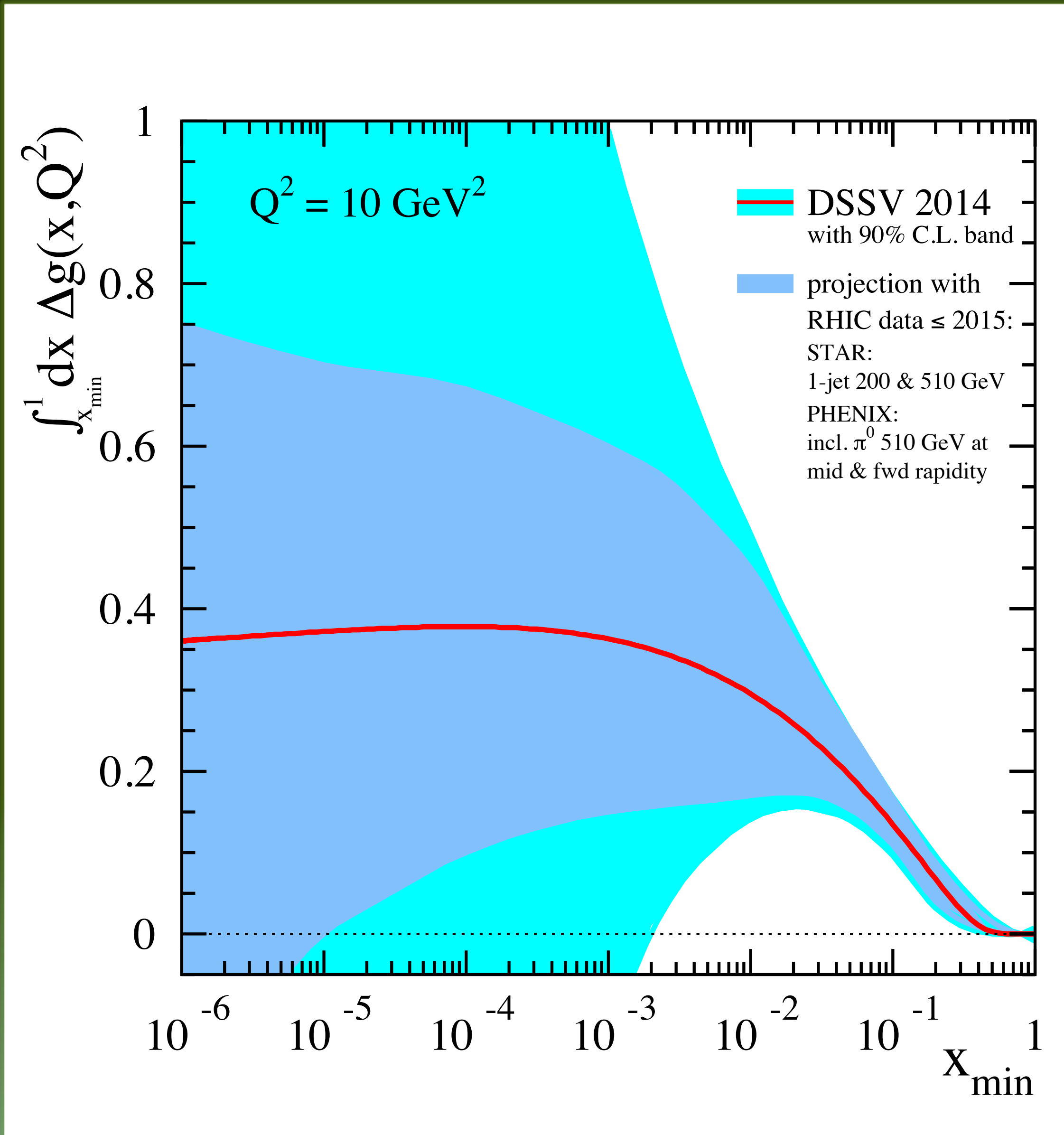
Results are in excellent agreement with newest DSSV and NNPDF NLO predictions!

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



Neutral pion A_{LL} at $\sqrt{s}$= 500 GeV in the STAR Forward Meson Spectrometer ($2.5 < \eta < 4$)

RHIC impact on ΔG



RHIC Spin Whitepaper arXiv:1501.01220

DSSV

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

ΔG (x > 0.05)
= 0.2 (+0.06/-0.07)

NNPDF

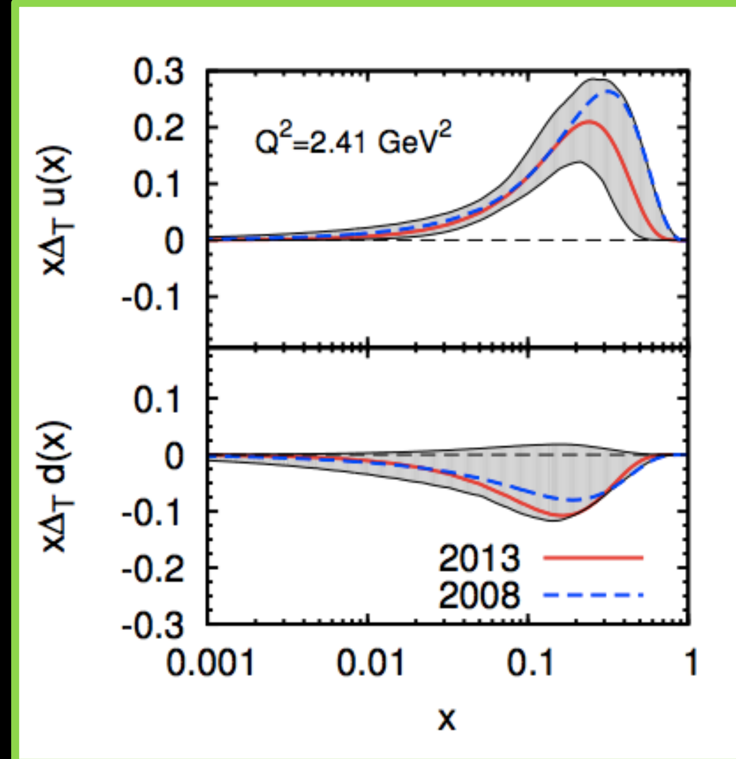
Nucl.Phys.B887, 276-308 (2014)

ΔG (0.2 > x > 0.05)
= 0.17 (+/- 0.06)

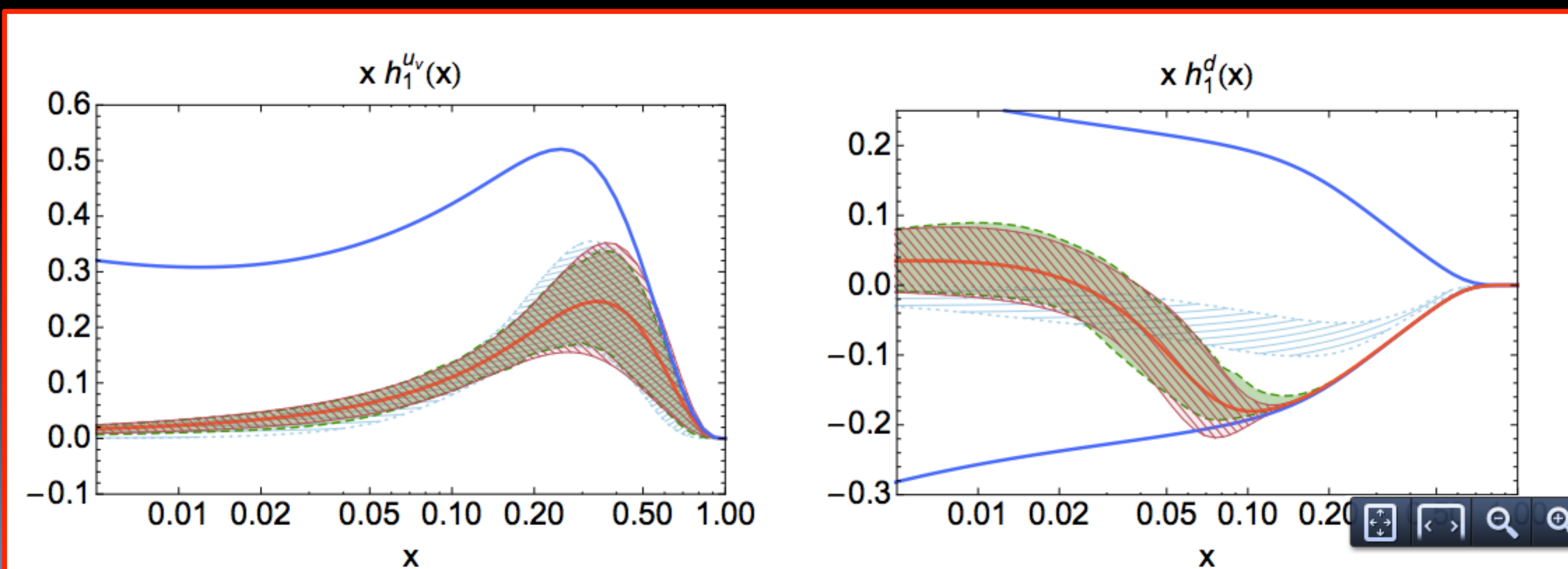
Transversity Distributions

COLLINS : Simulatneous fit of HERMES p, COMPASS p & d and Belle data →

IFF: Simulatneous fit of HERMES p, COMPASS p & d and Belle data ↓



Phys.Rev. D87 (2013) 094019



JHEP 1303 (2013)

Transversity Distributions

COLLINS : Simulatneous fit of HERMES p, COMPASS p & d and Belle data →

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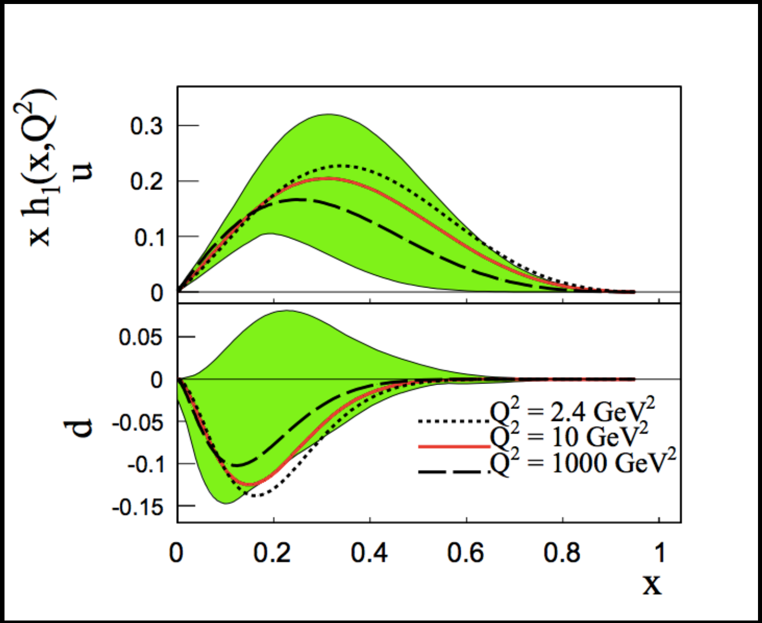
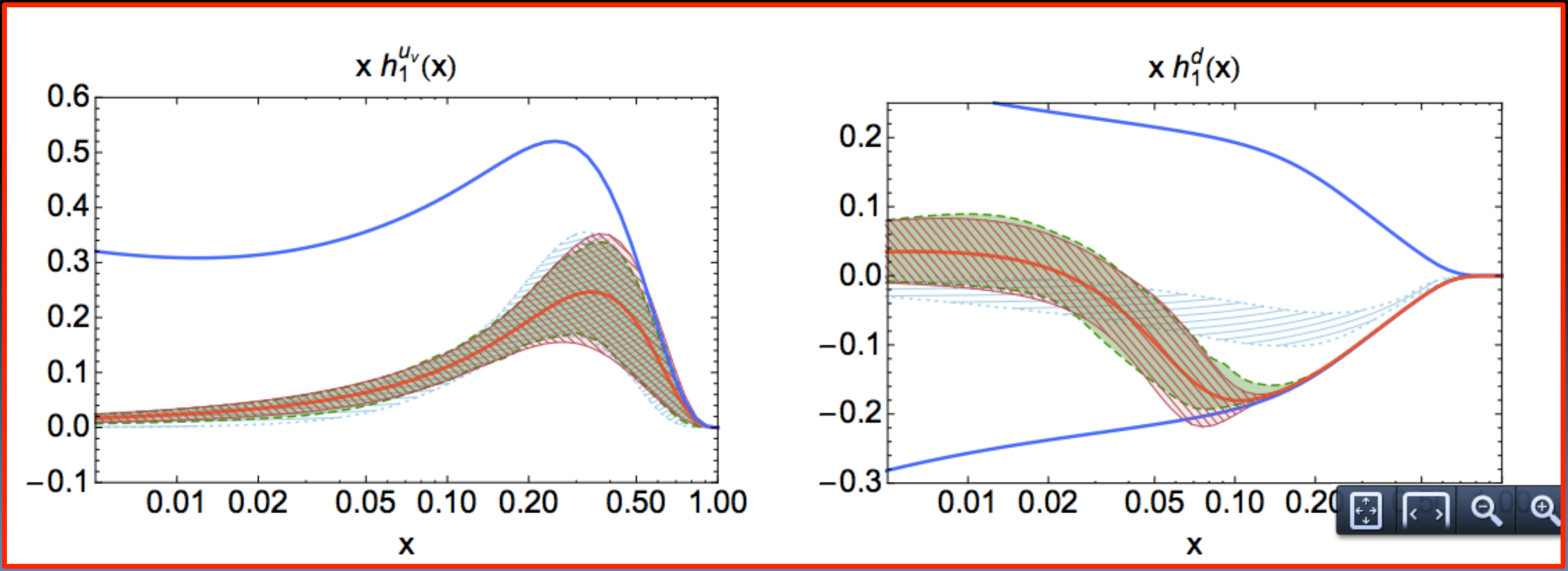


arXiv: 1505.05589

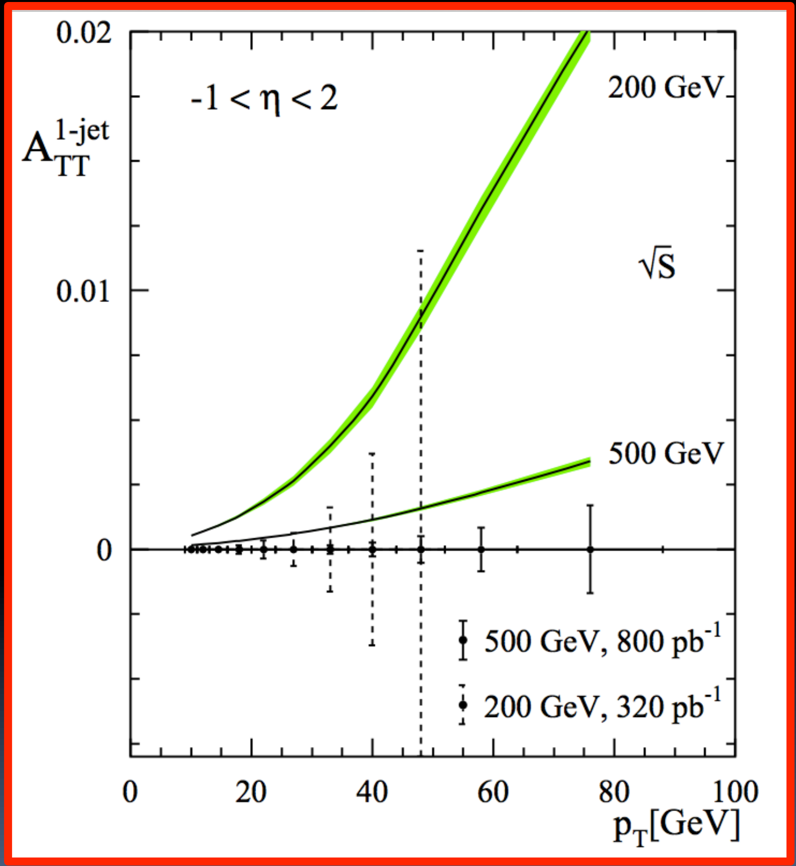
JHEP 1303 (2013)



What about pp Collisions?

Since $\Delta_T f(x)$ is CHIRAL ODD must access it by coupling to a second chiral odd function.

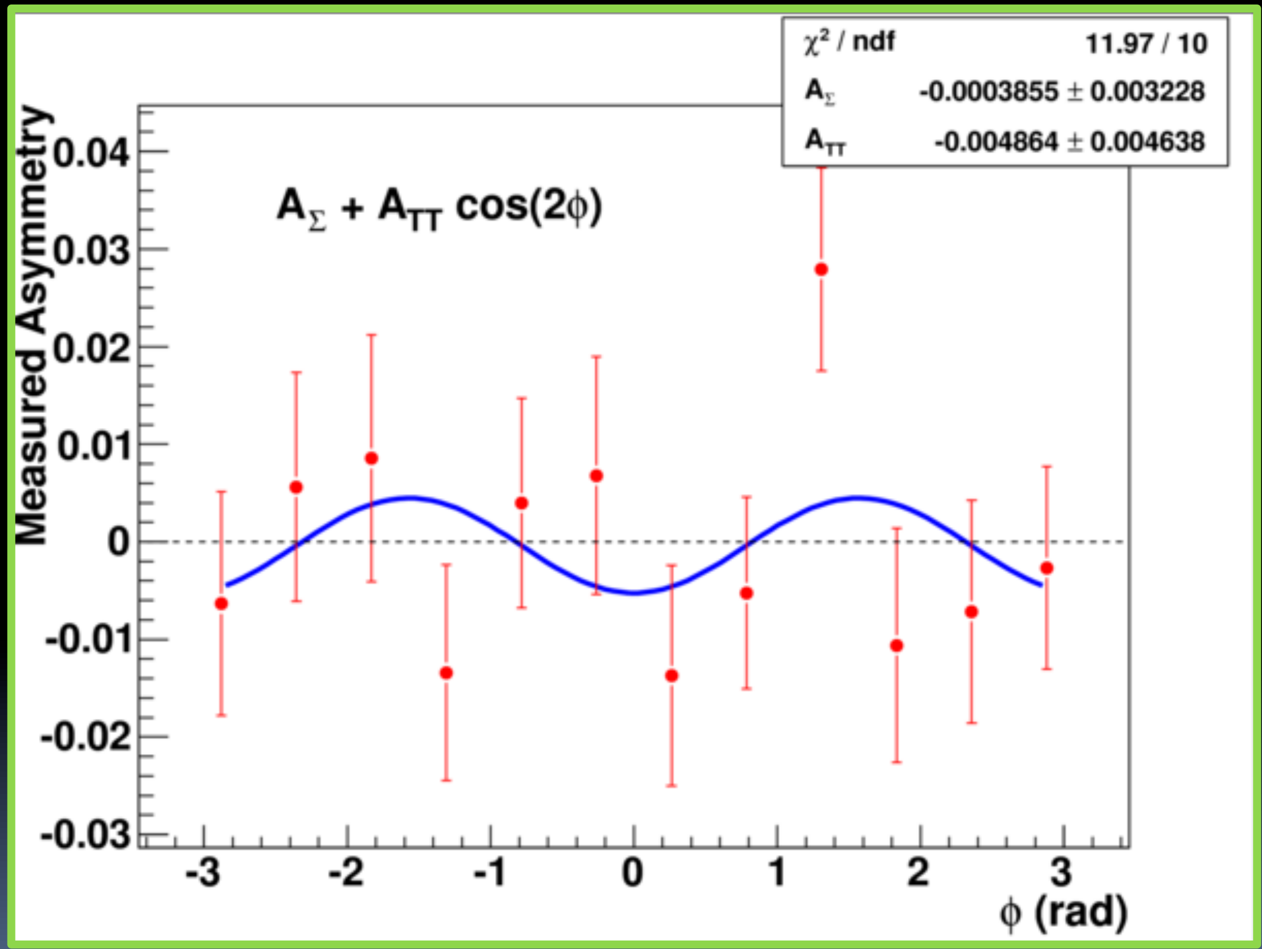
- Ralston and Soper proposed Drell-Yan but …
  - low rates compared to other hadronic processes
  - anti-quark transversity is likely very small
- Could also look at inclusive jet A_{TT} in pp collisions, however …
  - Gluons are abundant and have ZERO transversity
  - $A_{TT} < A_{LL}$ due to Soffer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



Phys.Rev. D65 (2002) 114024

STAR Inclusive Jet A_{TT}

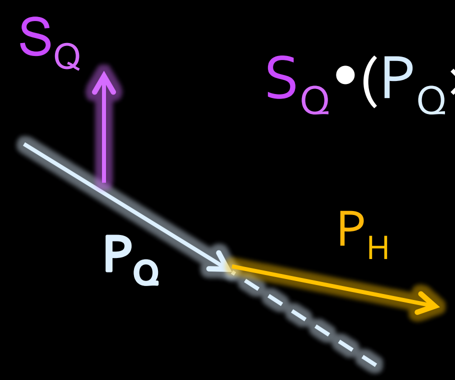
- In 2006 STAR collected 2 pb^{-1} of transversly polarized $\sqrt{s}$= 200 GeV data
- Data integrates over 7.5 < jet pT < 40 GeV
- Data Precision ~0.005
- Maximized signal for jet pT = 10 GeV is ~0.001
- Requires at LEAST x25 more data to make a significant measurement. Possibly 2015 RHIC run?



Phys.Rev. D86 (2012) 32006

Look Instead to the Final State!

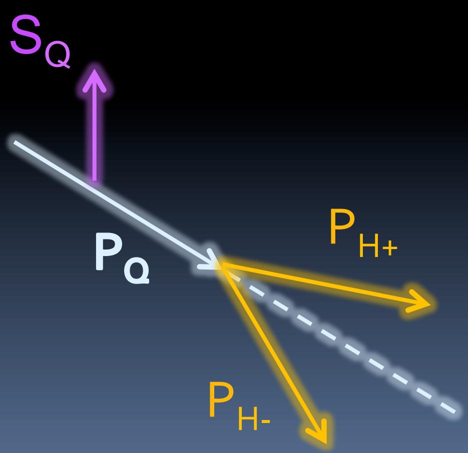
Couple a chiral odd fragmentation function with quark $\Delta_T f(x)$



$S_Q \bullet (P_Q \times P_H)$

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.

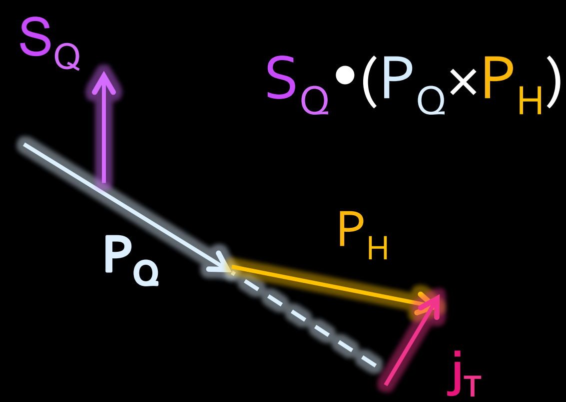
$S_Q \bullet (\mathbf{P_{H-}} \times P_{H+})$

Look Instead to the Final State!

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

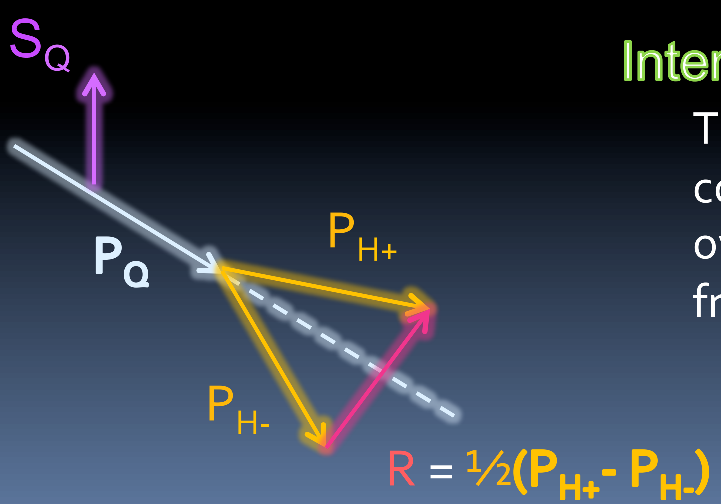
Collins Fragmentation Functions

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



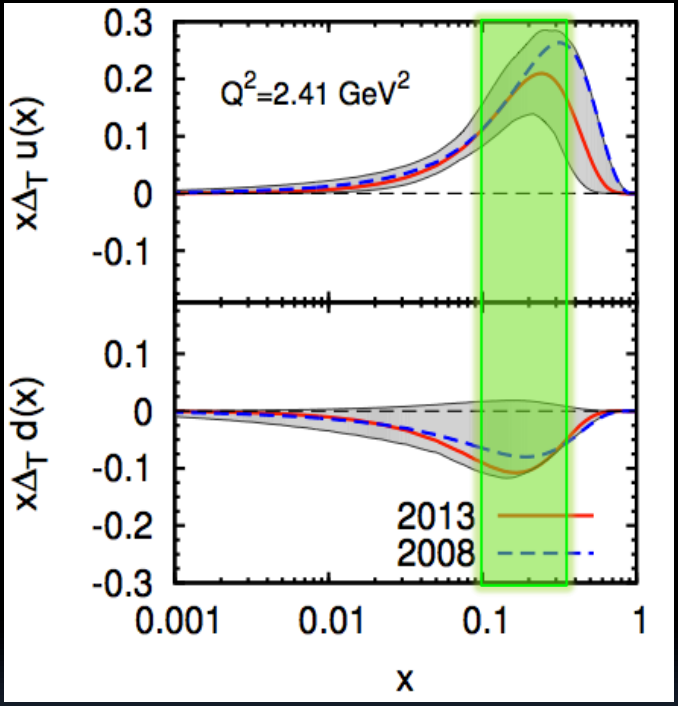
Interference Fragmentation Functions

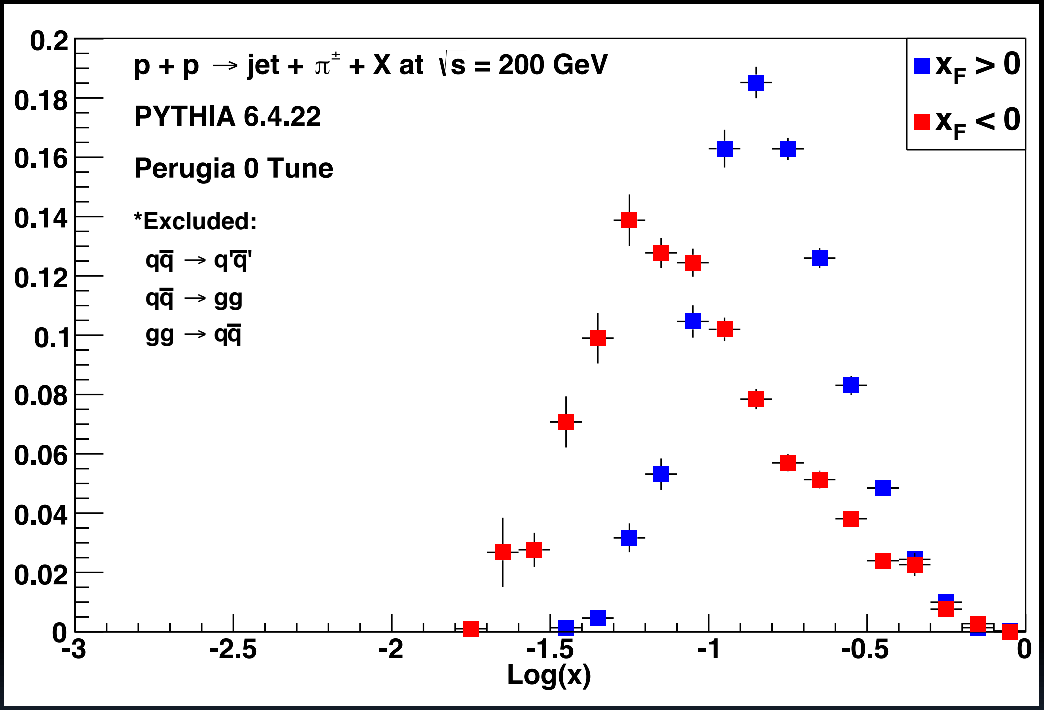
The center of mass of the hadron pair is traveling collinear with the jet axis. IFF survives integration over j_T of hadrons and therefore works in collinear framework .



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

Unique contributions from pp?

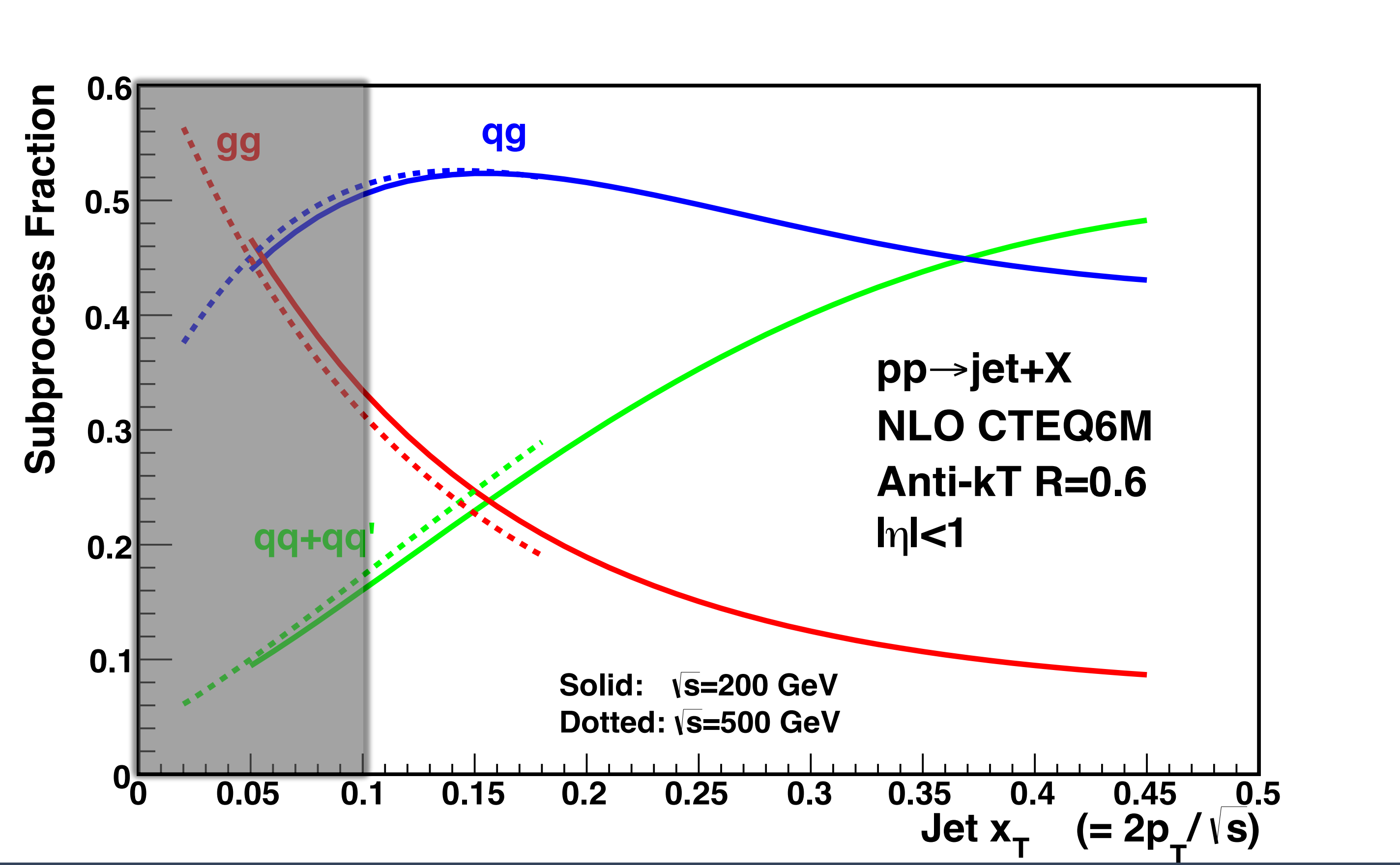




Phys. Rev. D **87** 094019 (2013)

- How do Collins and Interference FF evolve with Q² ?
- Are the Collins and Interference FF universal?
- What are the size of factorization breaking effects for Collins in pp?

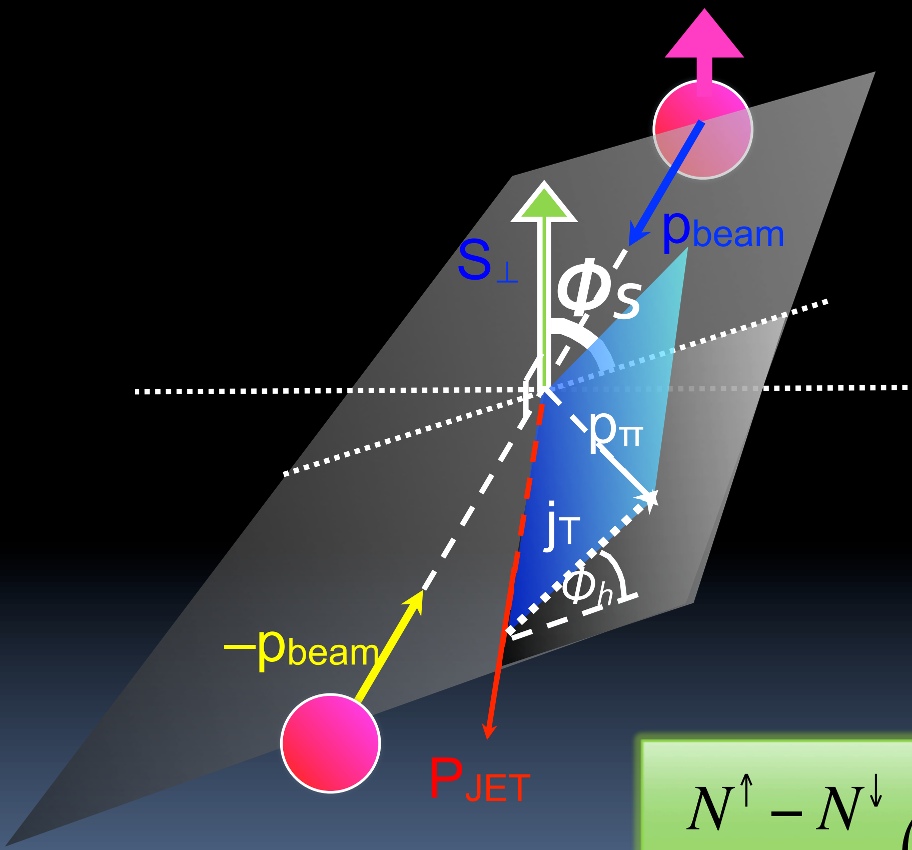
Full Disclosure



GLUONS dominate at low jet transverse momentum - need to place cut to minimize dilution to asymmetries.

SSA in pp sensitive to Transversity:

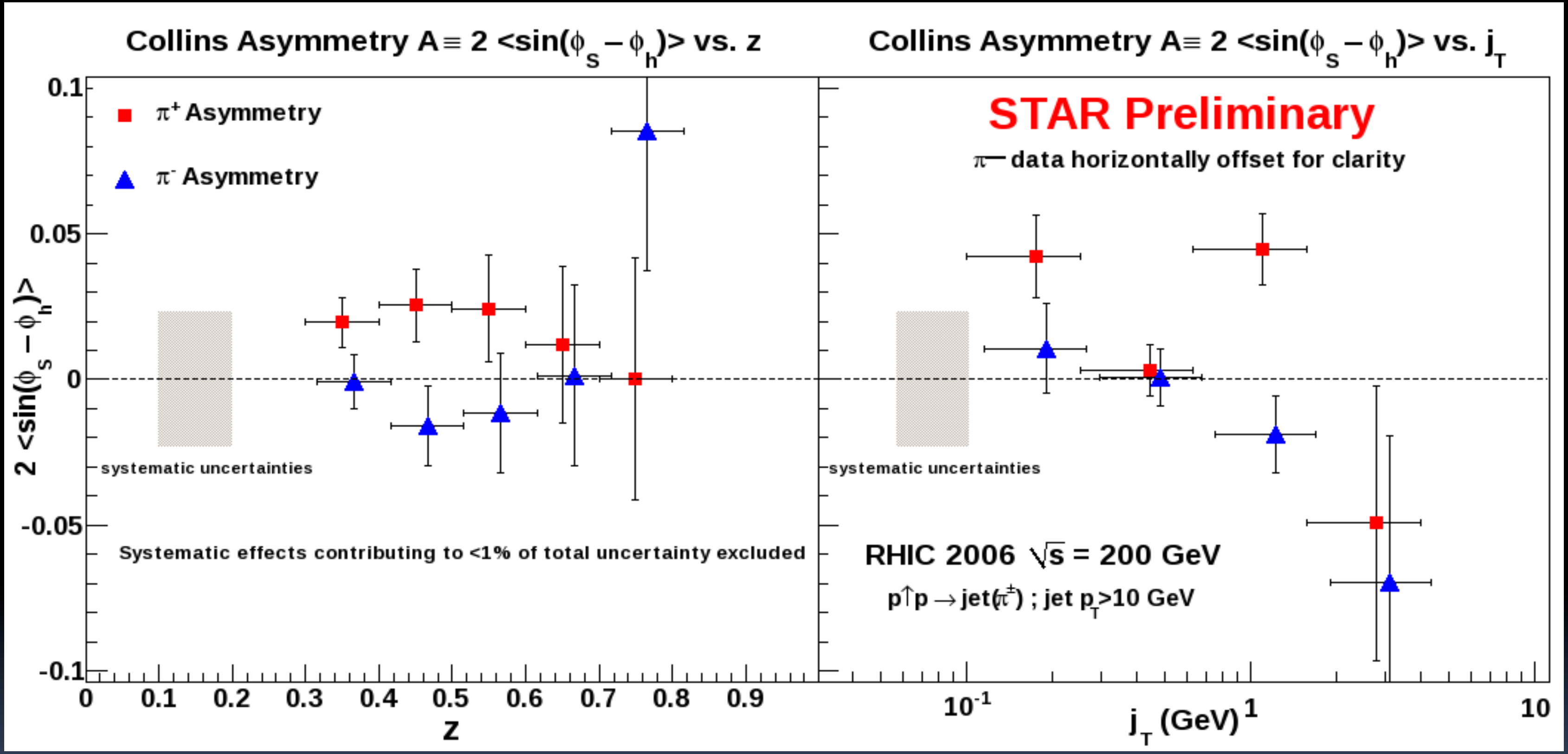
Azimuthal distributions of pions in Jets



- φ_S is defined as the angle between proton spin and reaction plane
- j_T defines particle transverse momentum in jet
- φ_H defines angle between jet particle transverse momentum and reaction plane
- $\varphi_C = \varphi_S - \varphi_H$ (Collins Angle)

$$\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}(\varphi_C) = A_{UT}^{\sin\varphi_C} \sin(\varphi_C) \propto \Delta_T q \otimes H_1^{\perp}$$

2006 $A_{UT}^{COLLINS}$ of Leading Charged Pions in Mid-Rapidity Jets at STAR in 200 GeV

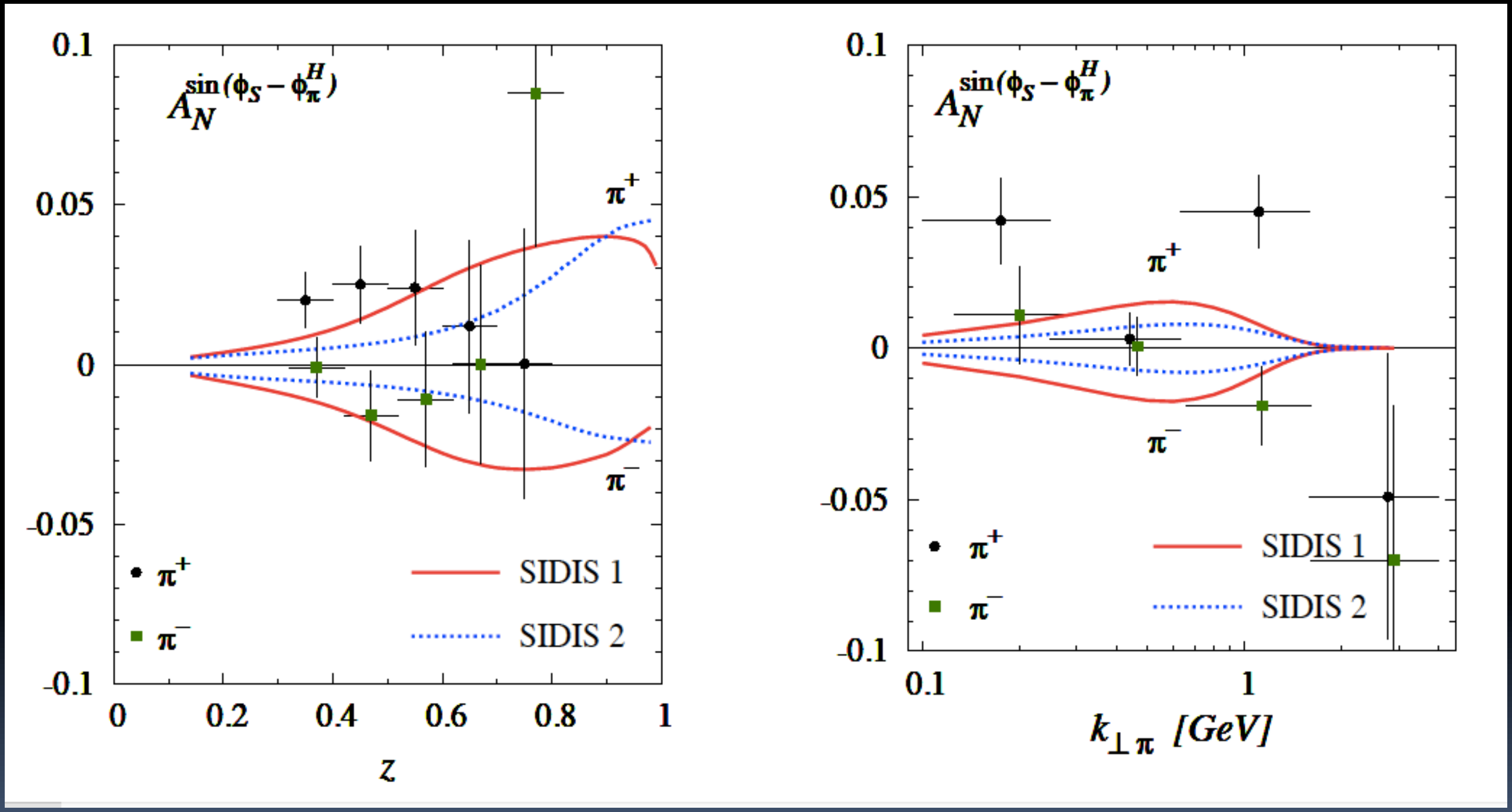


AIP Conf. Proc. 1441, 233 (2012)

Average π^+ asymmetry = 0.02082 +/- 0.0064 +/- 0.02306

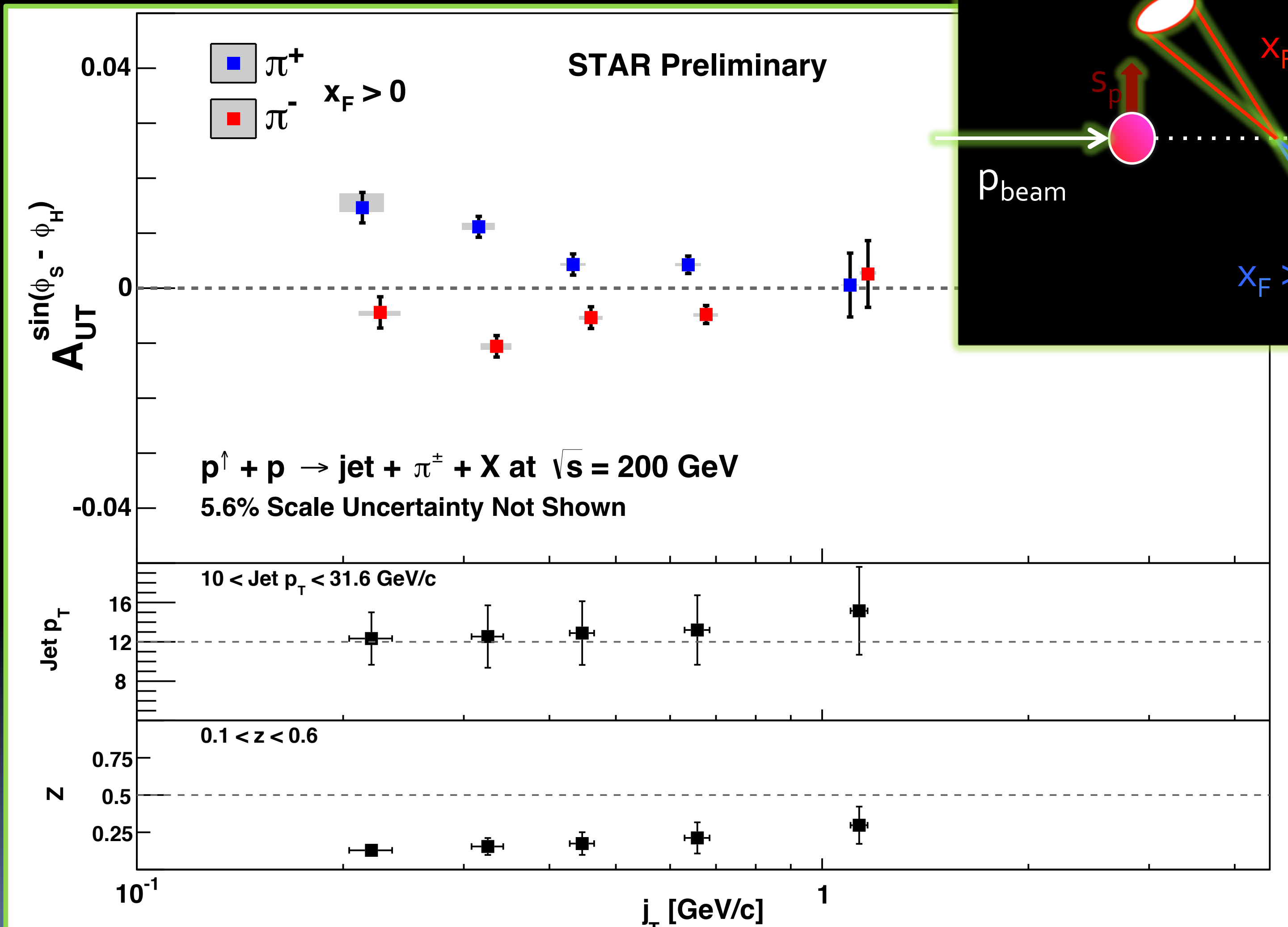
Average π^- asymmetry = -0.0040 +/- 0.0068 +/- 0.02306

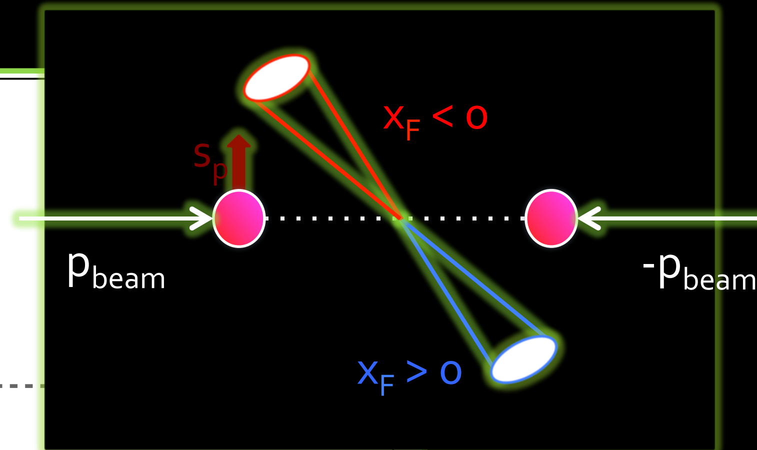
Mid-rapidity Predictions from D'Alesio, Murgia and Pisano



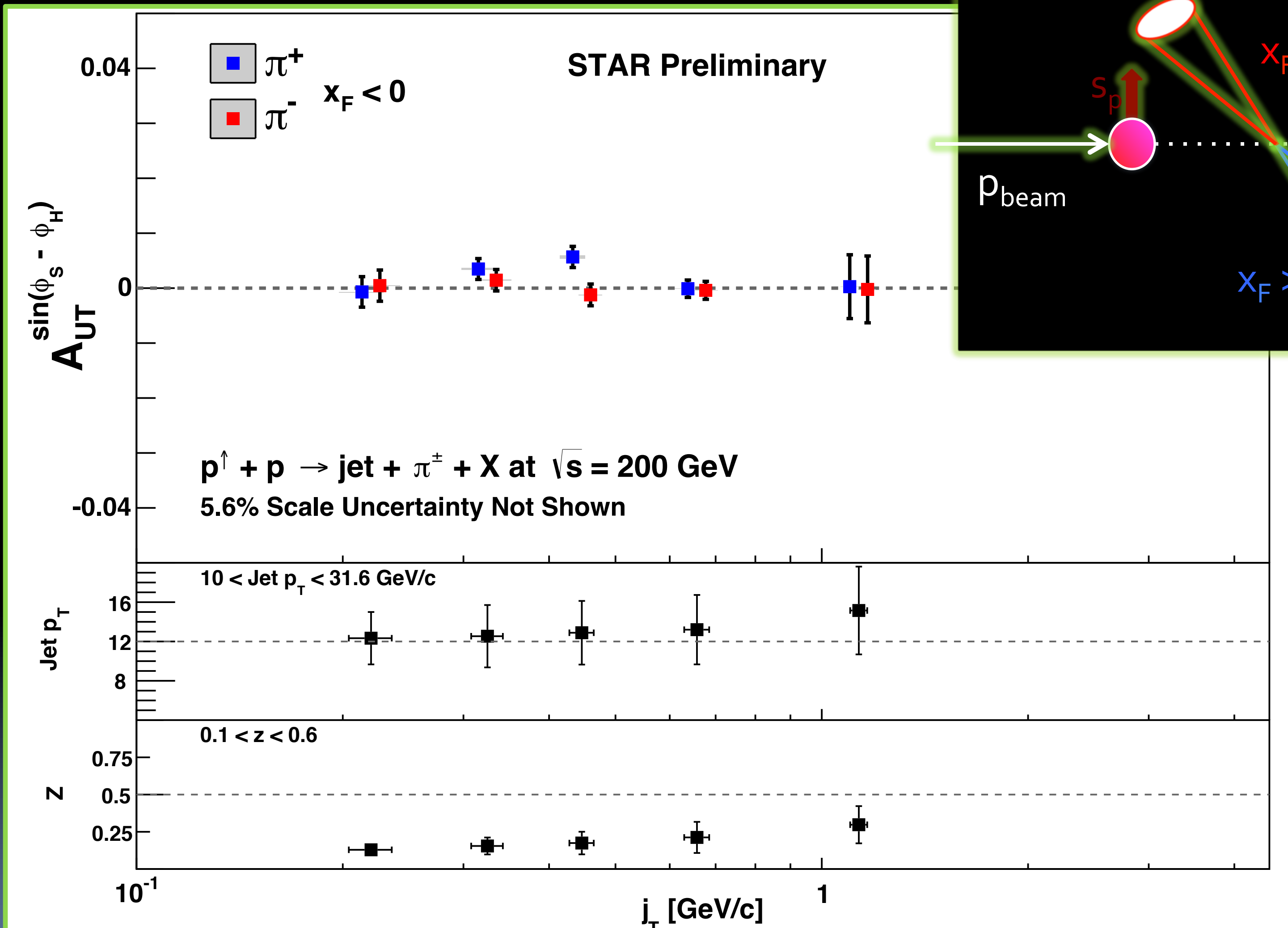
Presented at Transversity 2014 and based on work from PRD 83 034021 (2011)

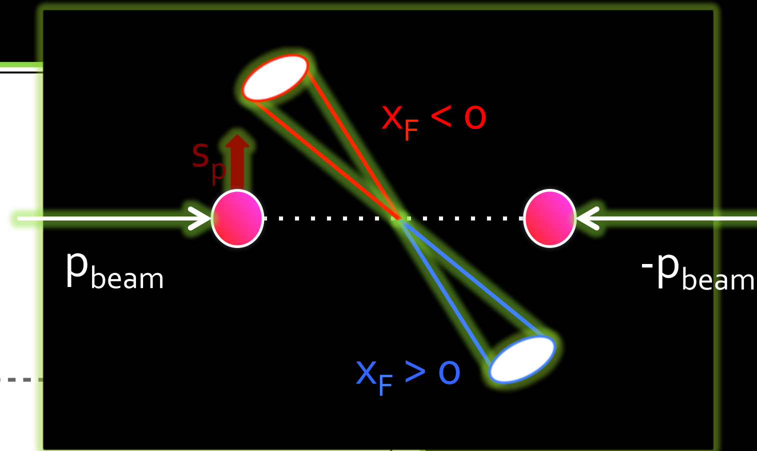
2012 $A_{UT}^{COLLINS}$ vs. j_T at 200 GeV (xF>0)



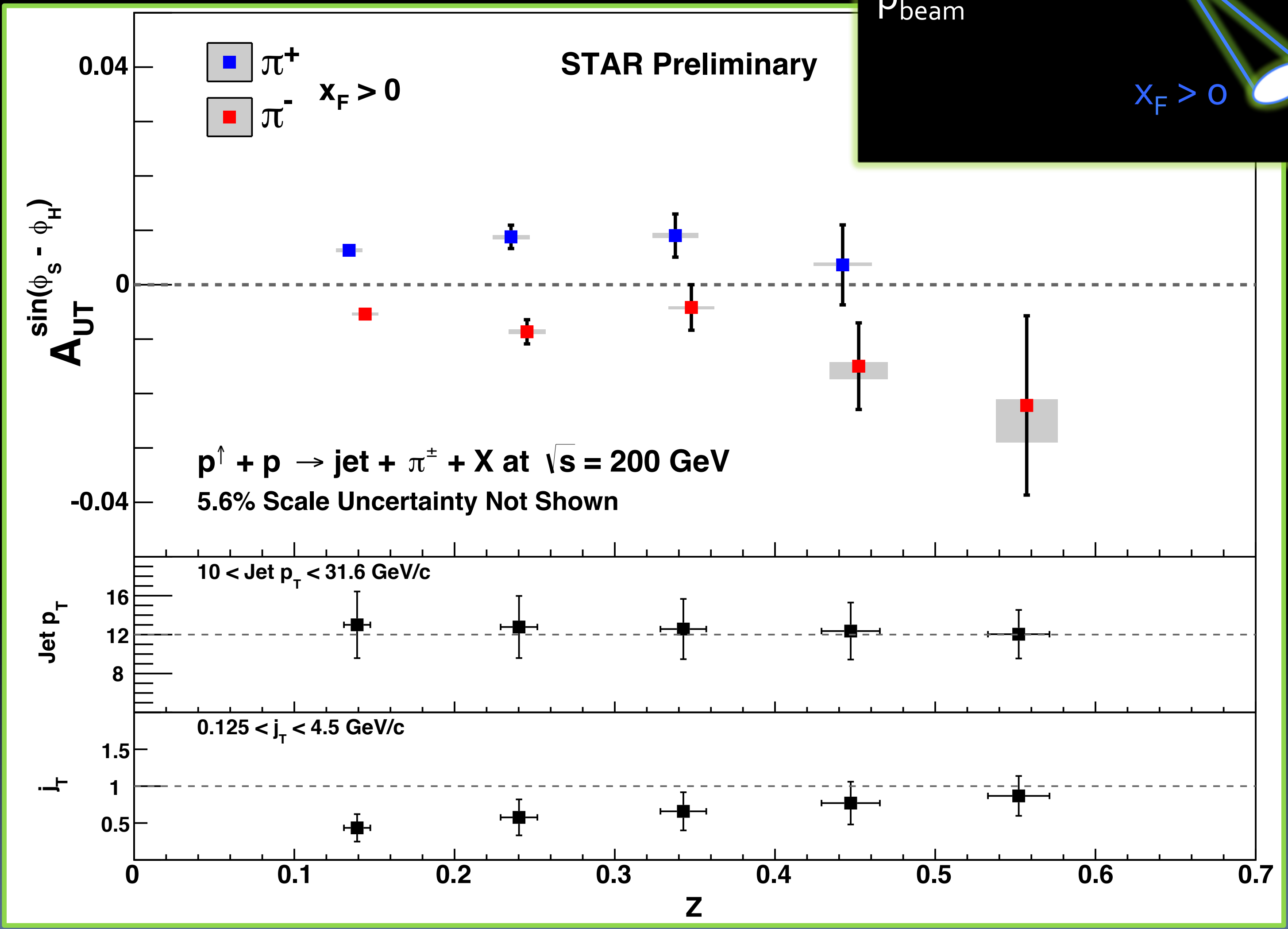


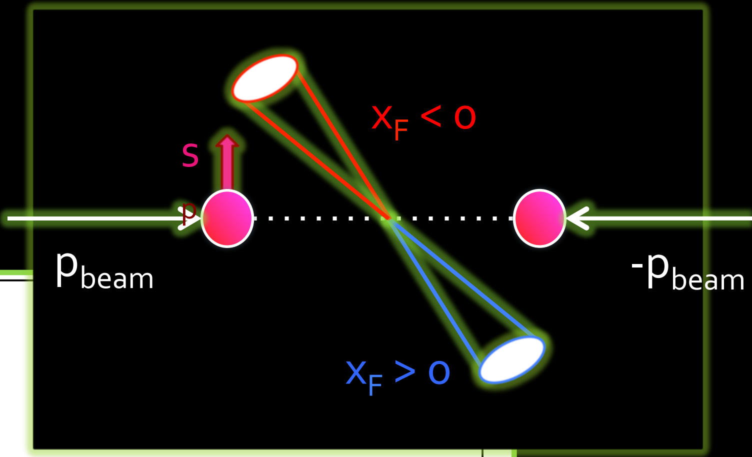
2012 $A_{UT}^{COLLINS}$ vs. j_T at 200 GeV (x_F<0)



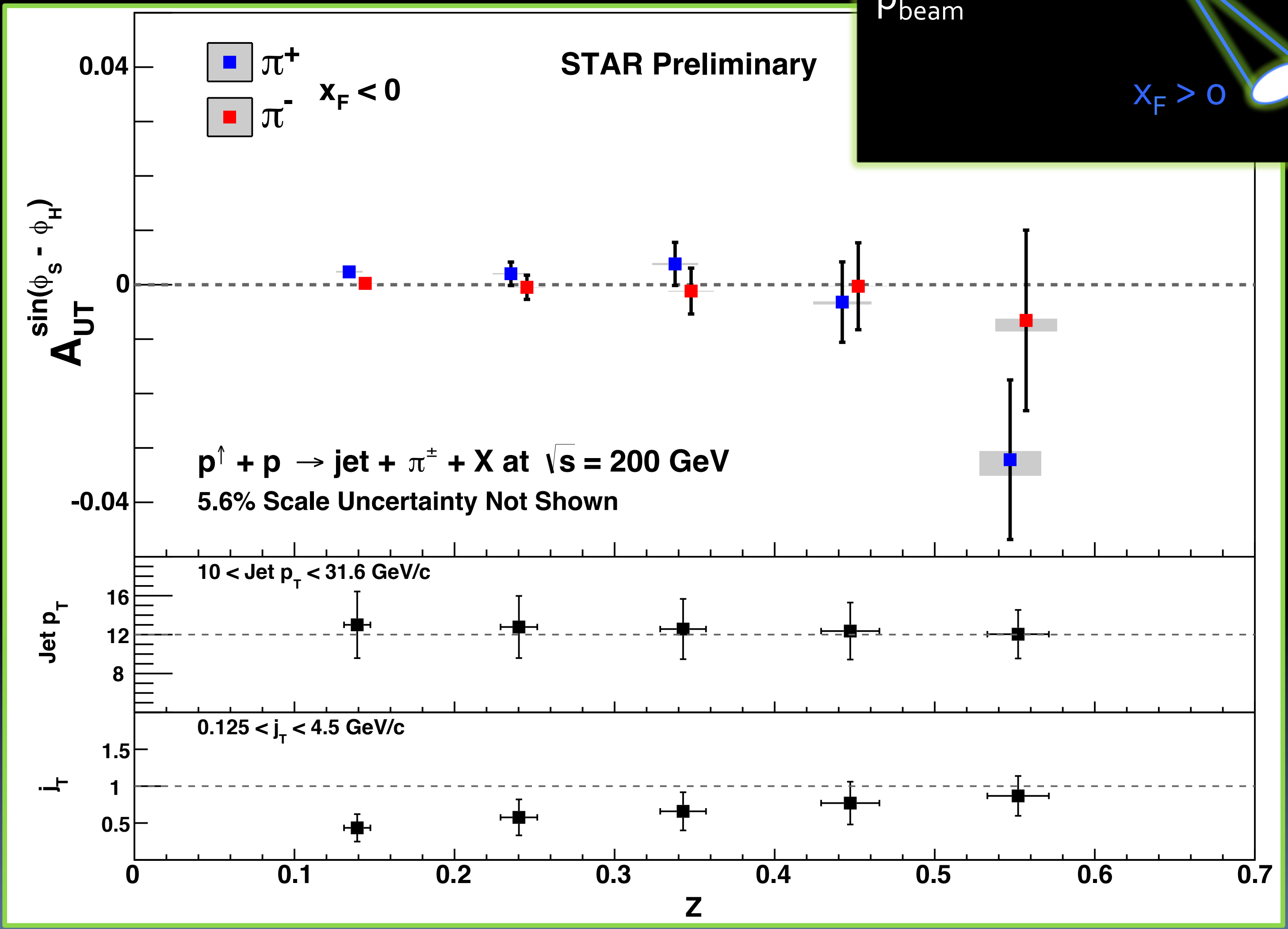


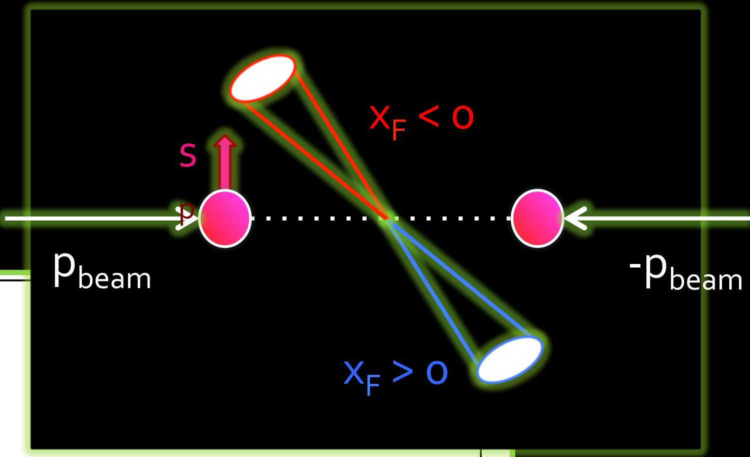
200 GeV $A_{UT}^{COLLINS}$ vs. z



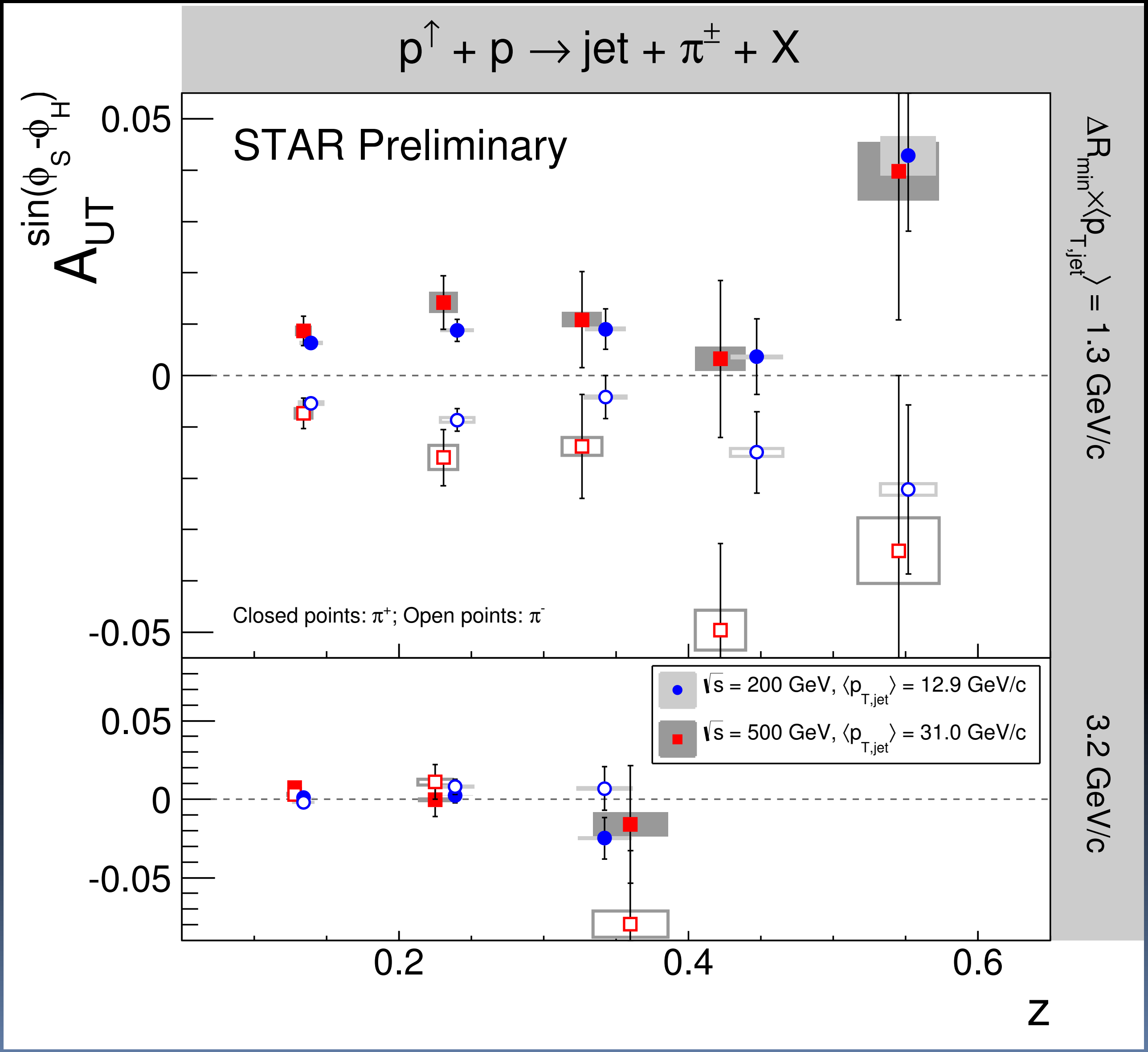


200 GeV $A_{UT}^{COLLINS}$ vs. z





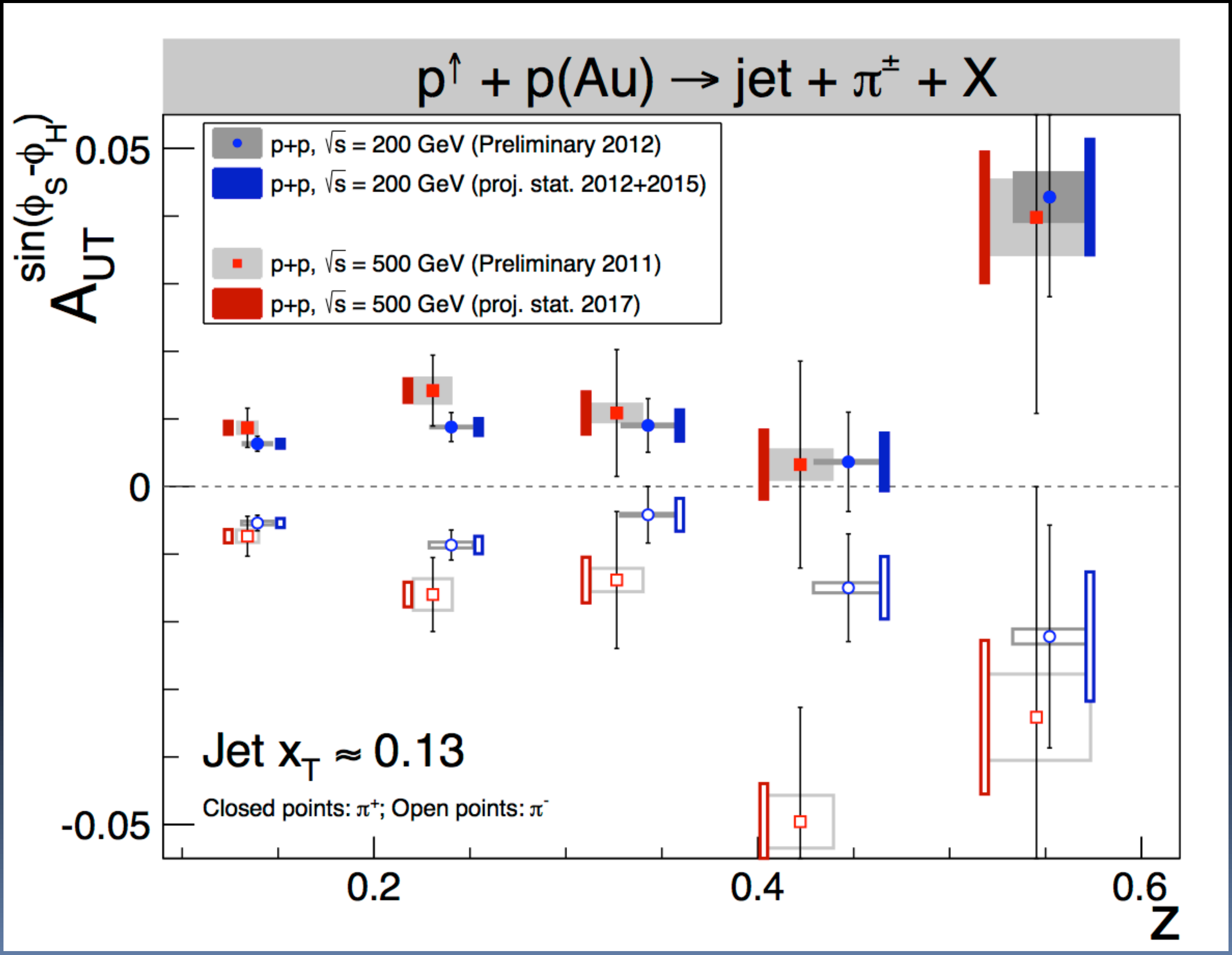
Higher Q^2 and same x_T? $\sqrt{s}$= 200 vs 500 GeV



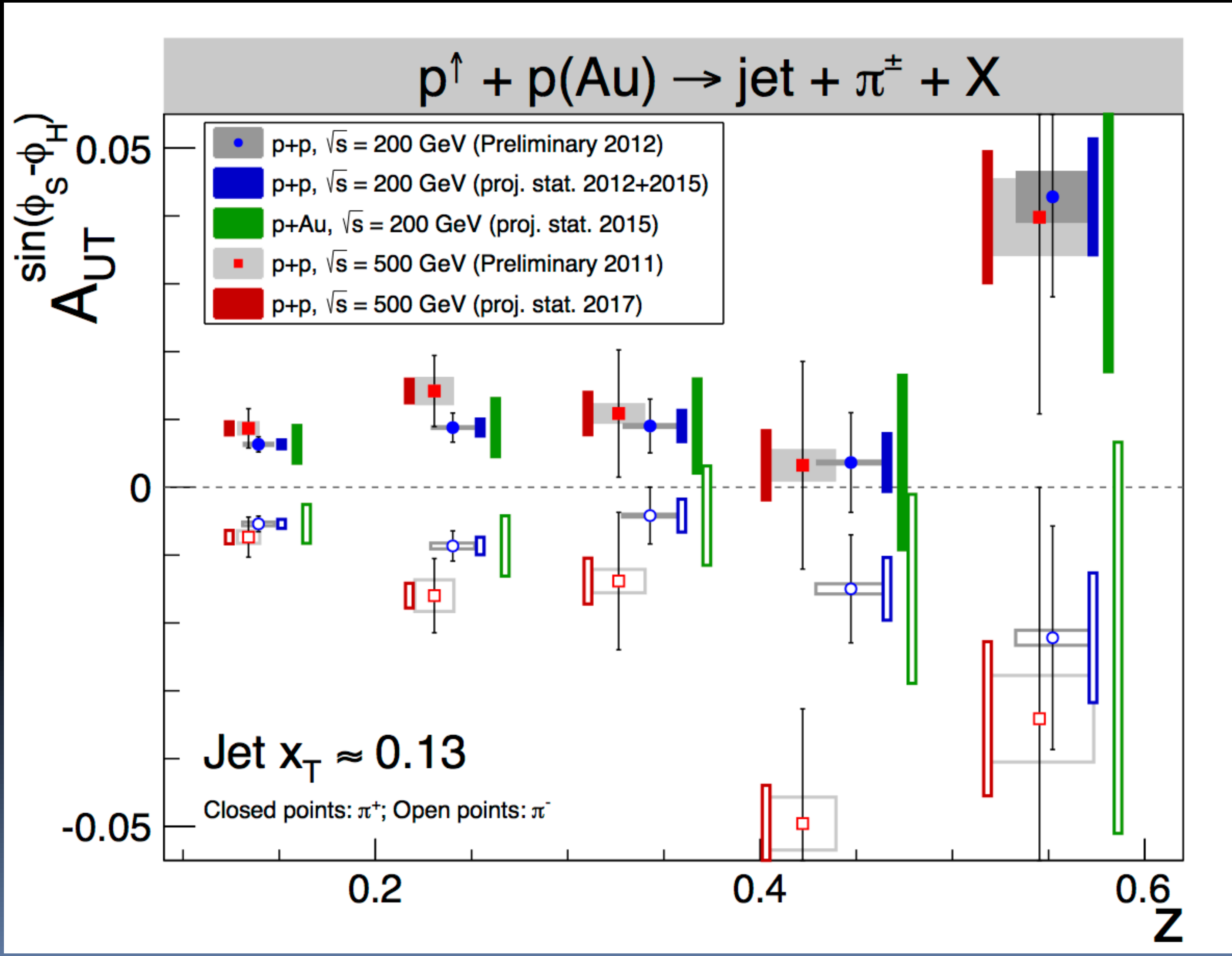
Once scaled to same x_T and average j_T the 200 and 500 GeV asymmetries are similar.

Is this evidence for small evolution effects?

Reduced uncertainties with additional data √s=200 GeV in 2015 and √s=500 GeV in 2017

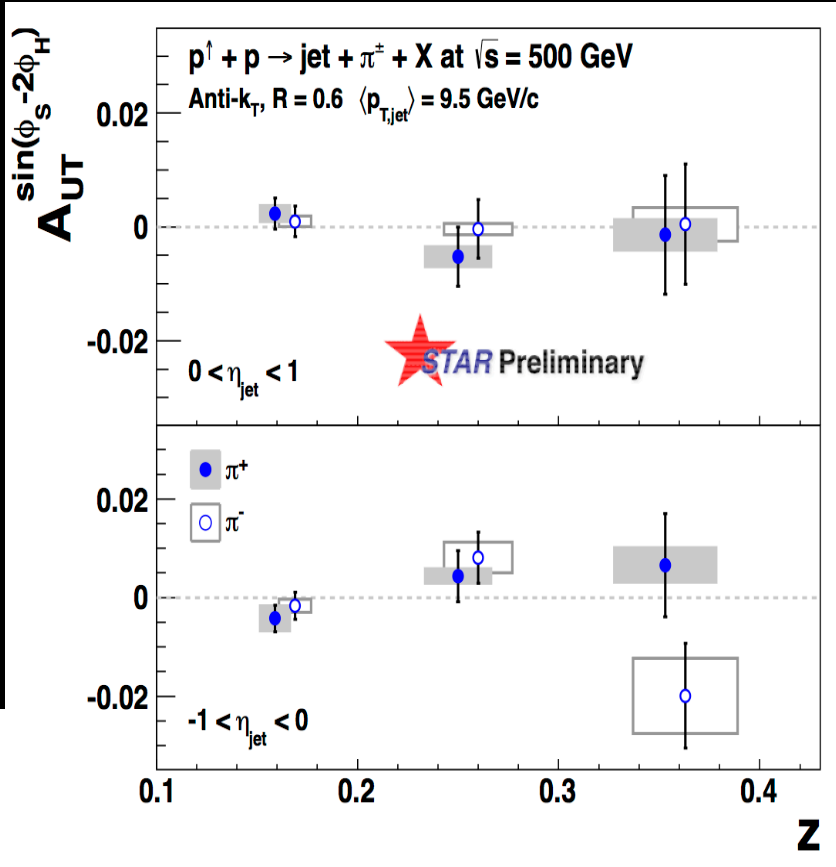


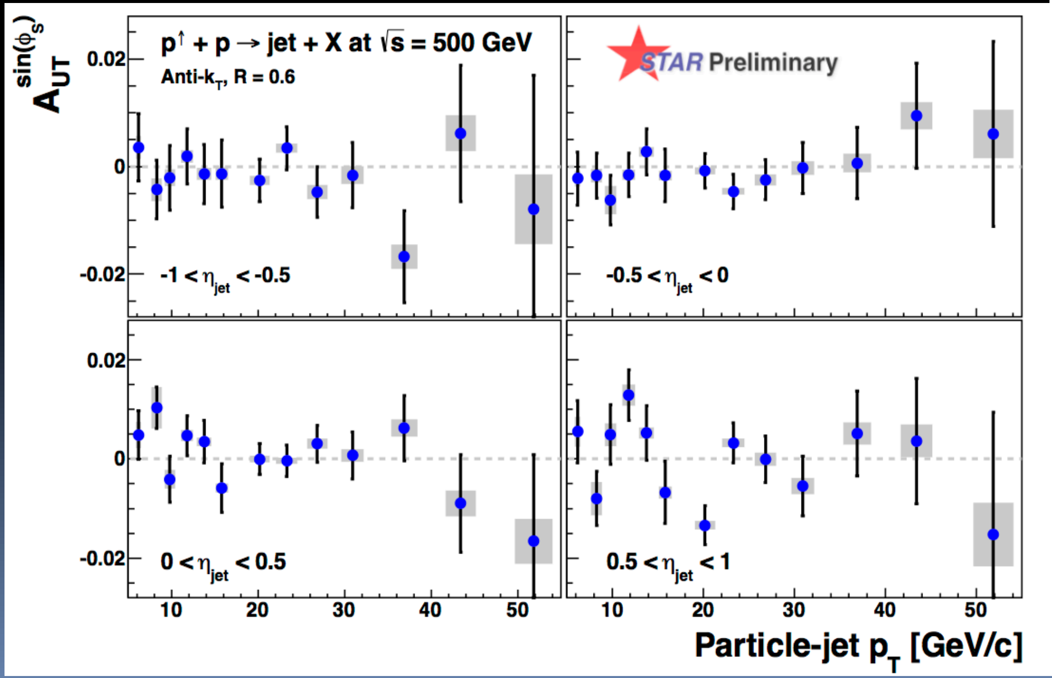
Collecting first data set of p+Au at √s=200 !



Additional moments can be and have been measured!

Linearly polarized gluons





Sensitive to Sivers

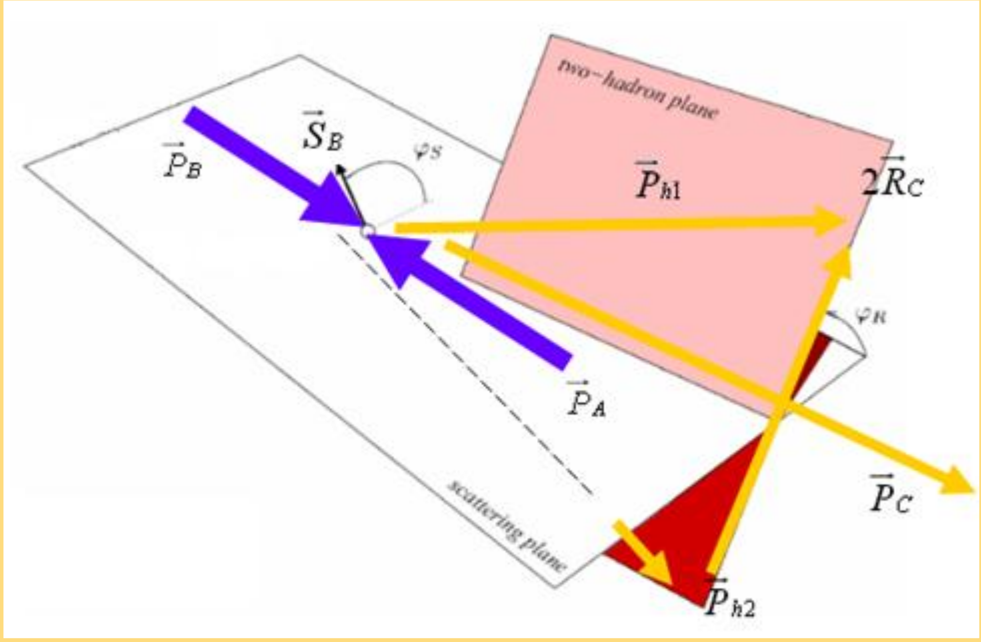
SSA in pp sensitive to Transversity:
Di-hadron pairs

$R = \frac{1}{2}\,(\mathbf{P_{H1}} - \mathbf{P_{H2}})$

φ_S: Angle between scattering plane and spin

φ_R: Angle between scattering plane and R vector

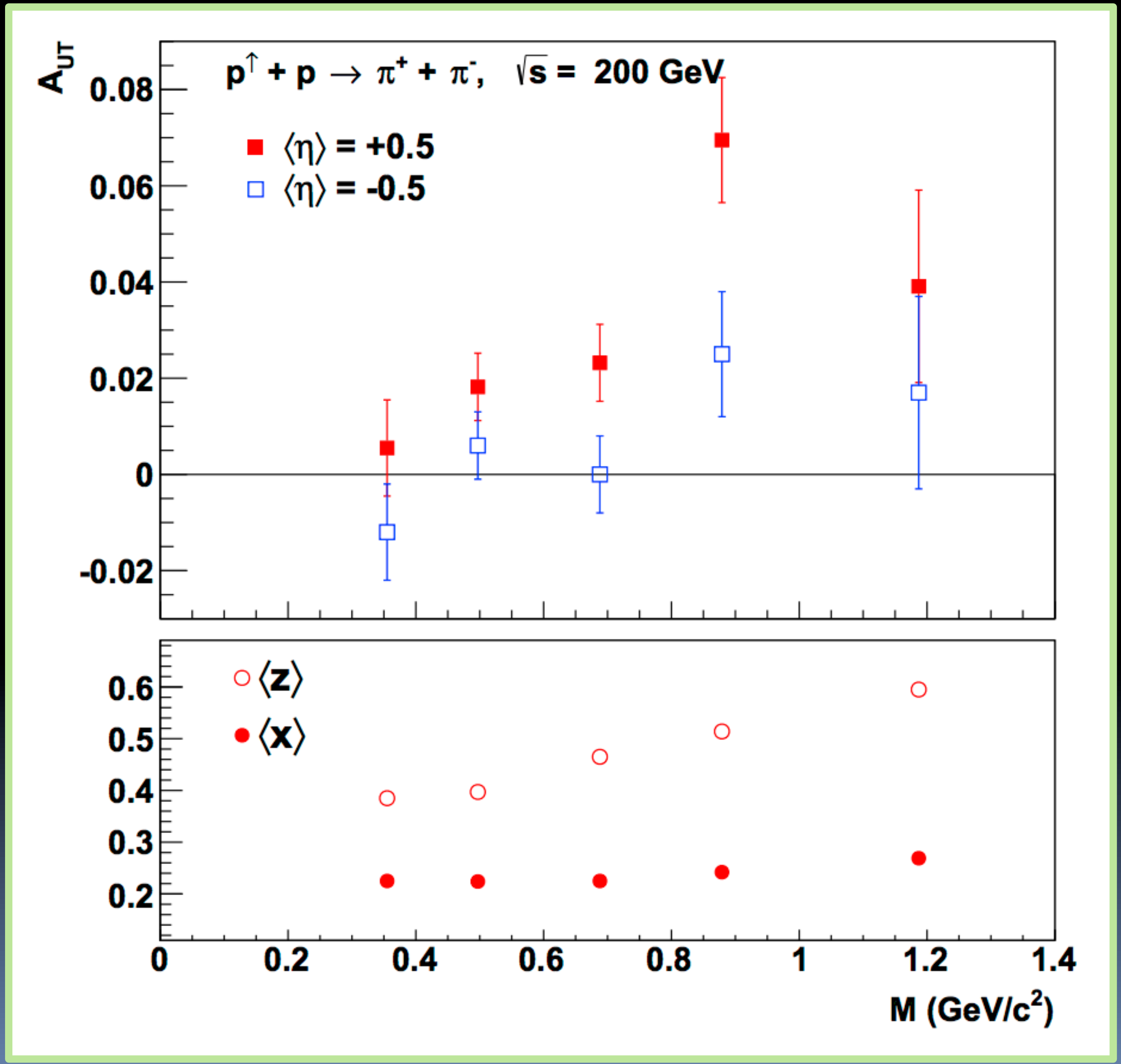
$\varphi_{SR} = \varphi_S - \varphi_R$



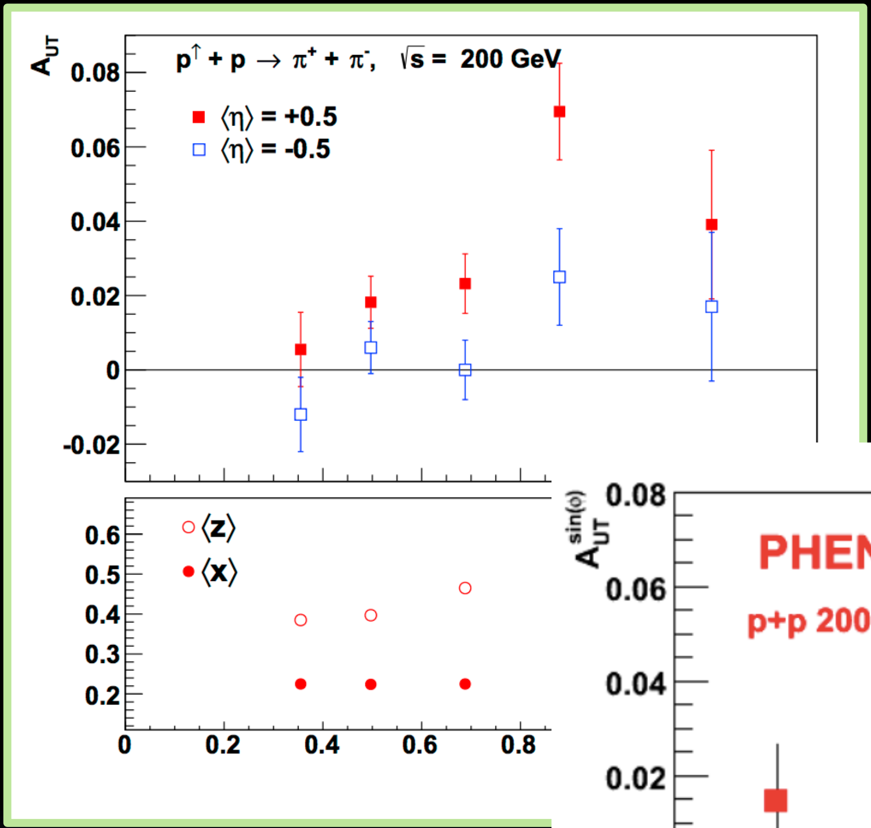
$$\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}(\varphi_{SR}) = A_{UT}^{\sin\varphi_{SR}} \sin(\varphi_{SR}) \propto \Delta_T q \otimes H_q^{\angle}$$

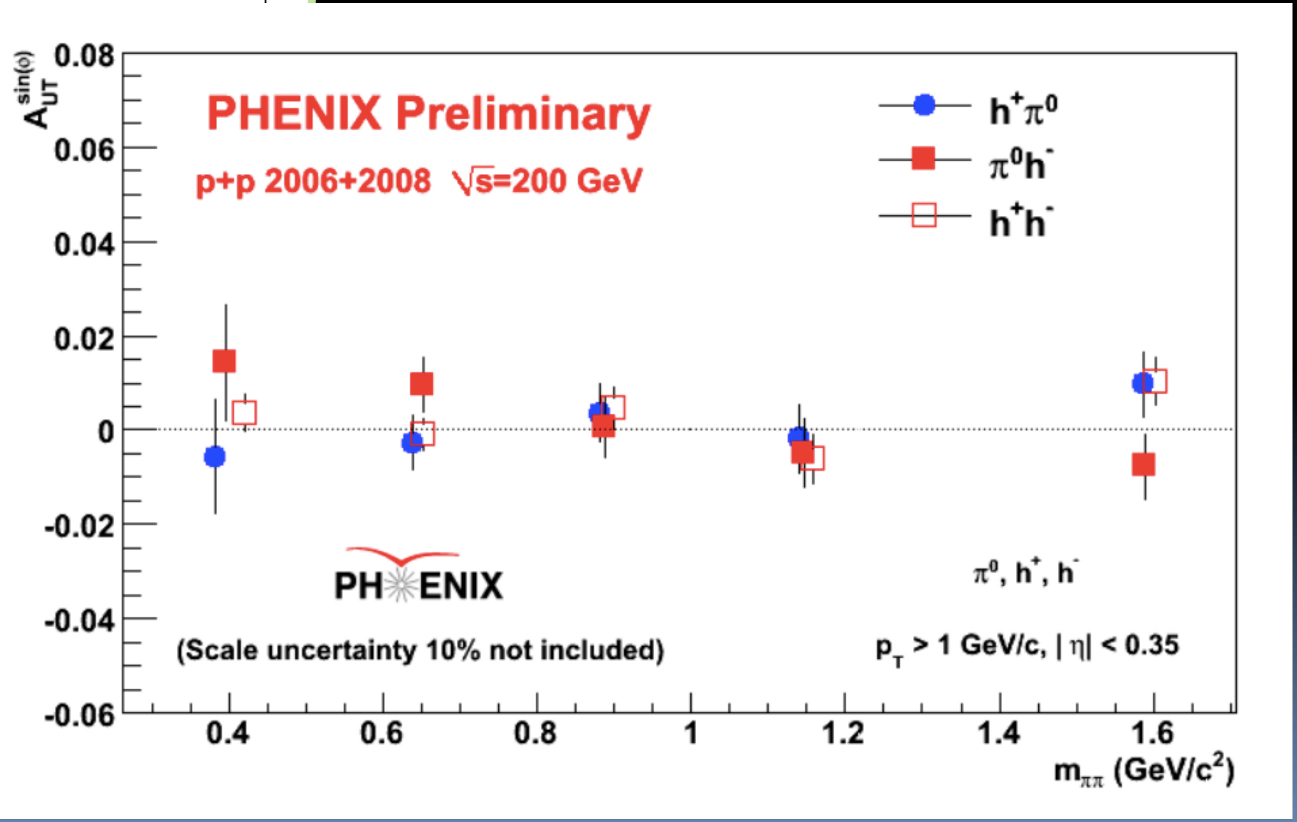
2006 A_{UT}^{IFF} vs. M_{inv} $\sqrt{s}$ = 200 GeV

arXiv: 1504.00415

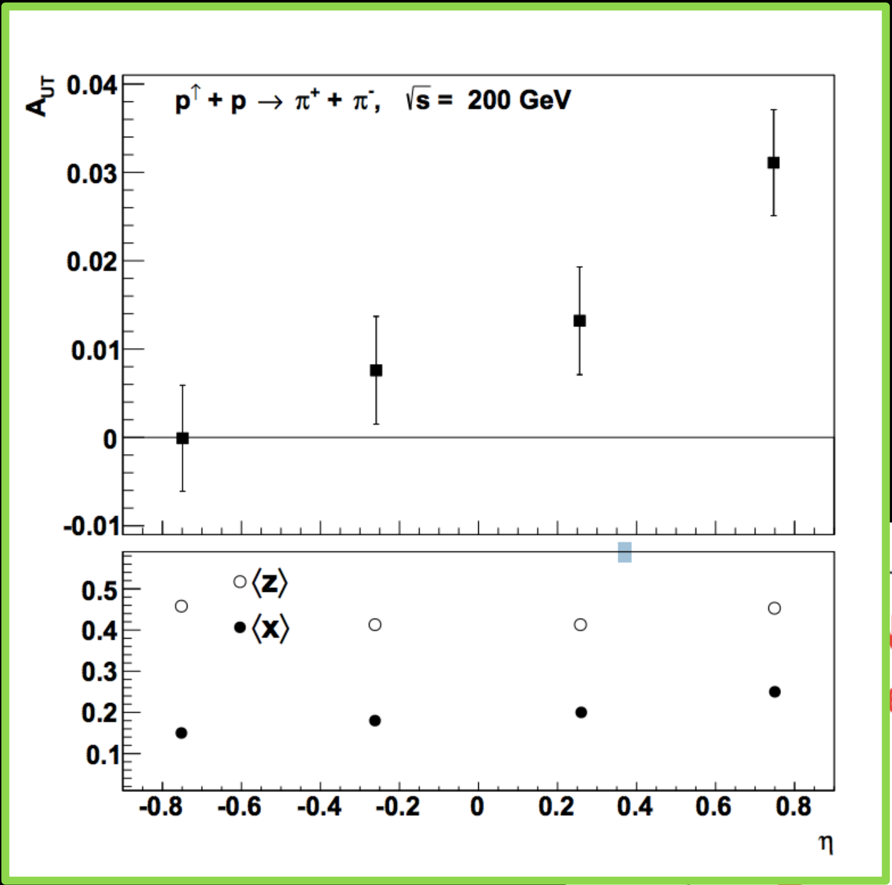


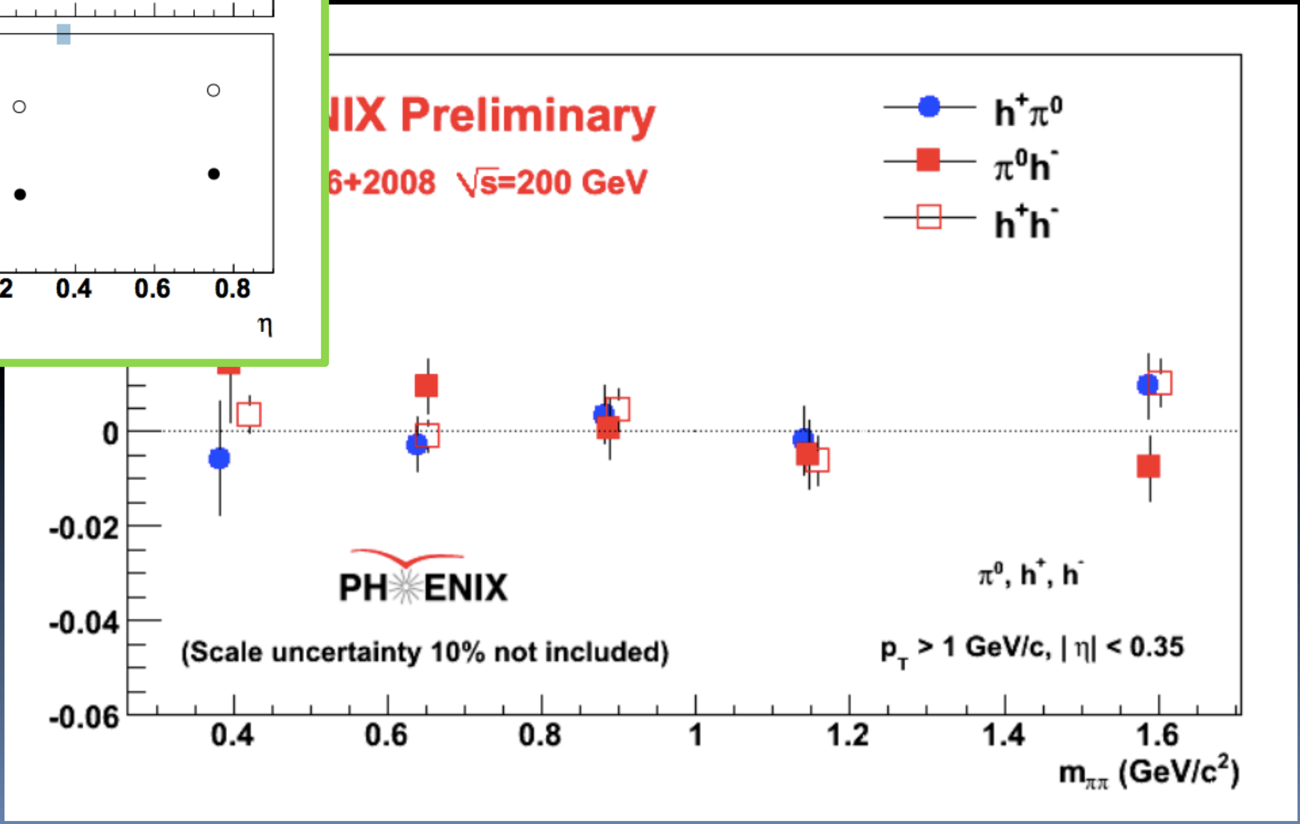
200 GeV A_{UT}^{IFF} vs. M_{inv}





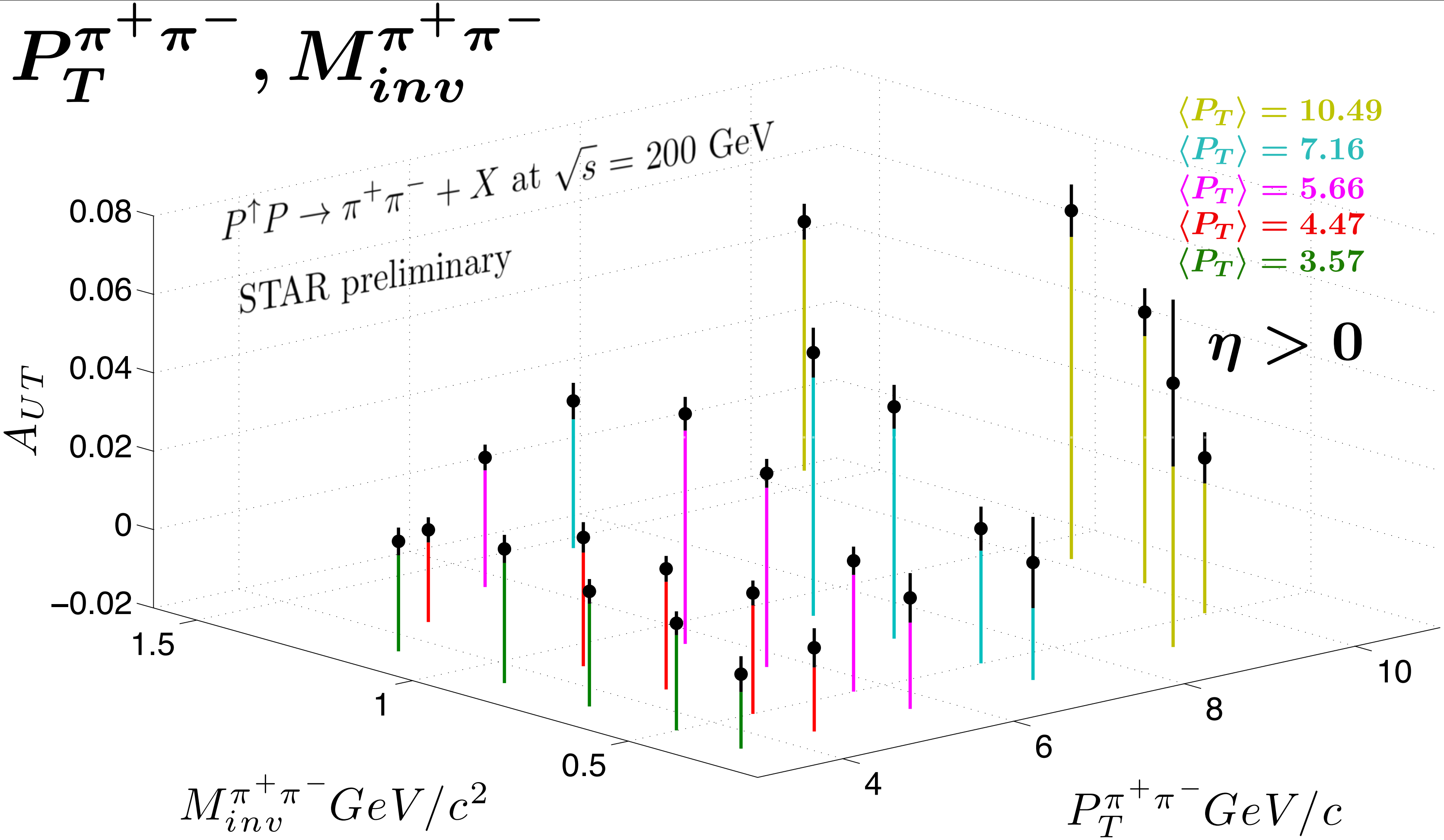
200 GeV A_{UT}^{IFF} vs. M_{inv}





2012 A_{UT}^{IFF} vs. M_{inv} $\sqrt{s}$ = 200 GeV

… x10 more data than before!



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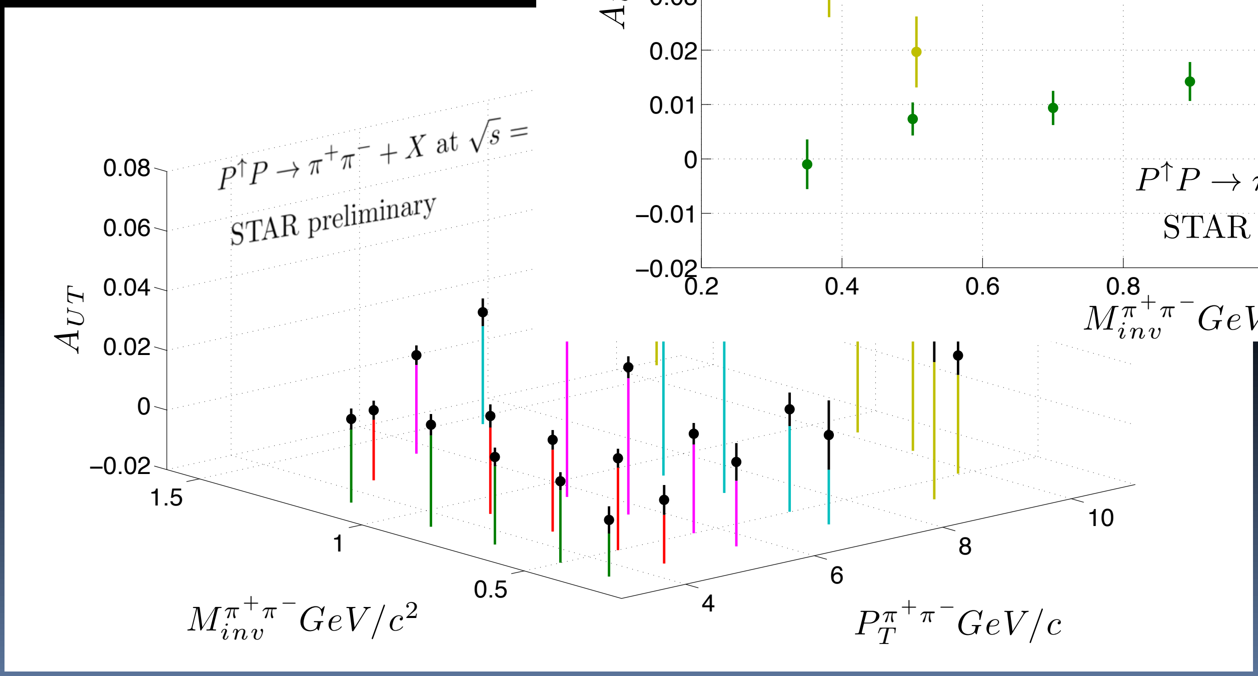

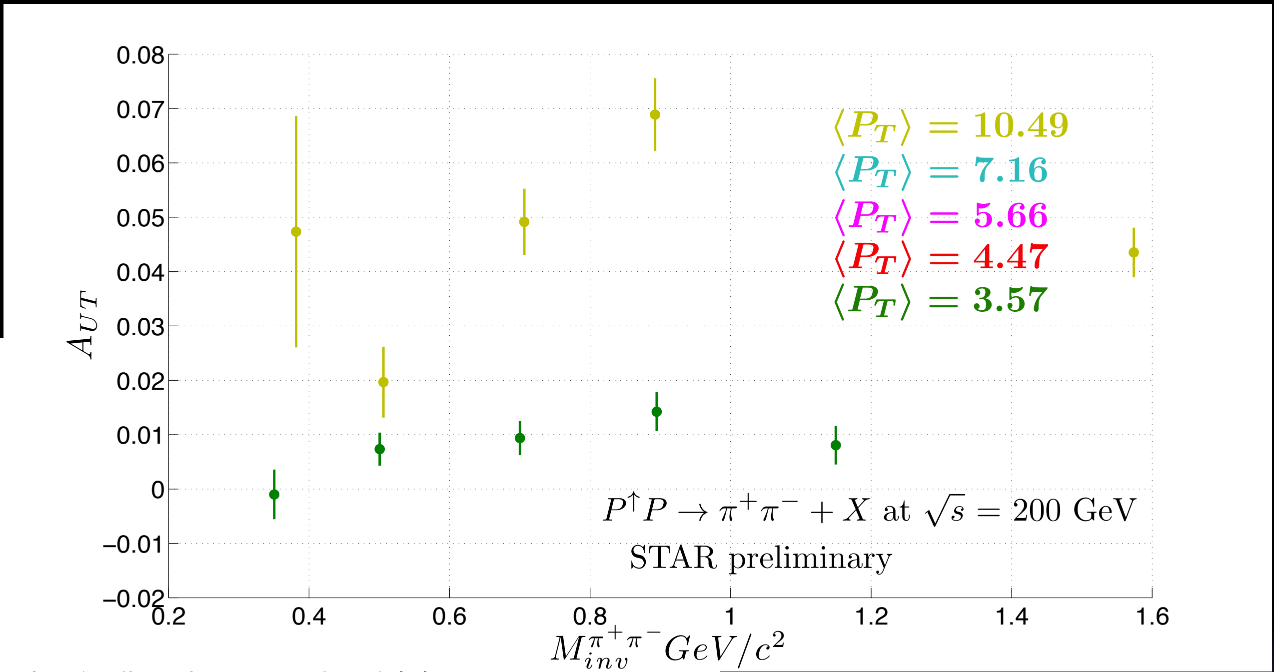

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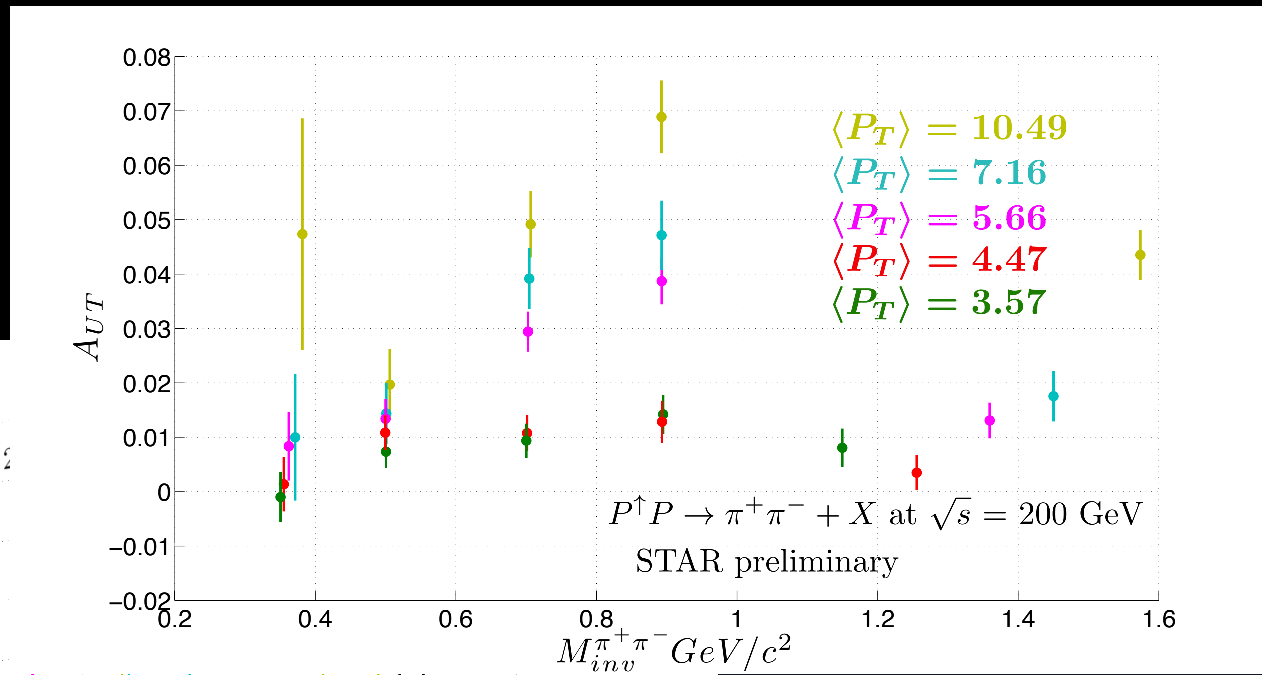
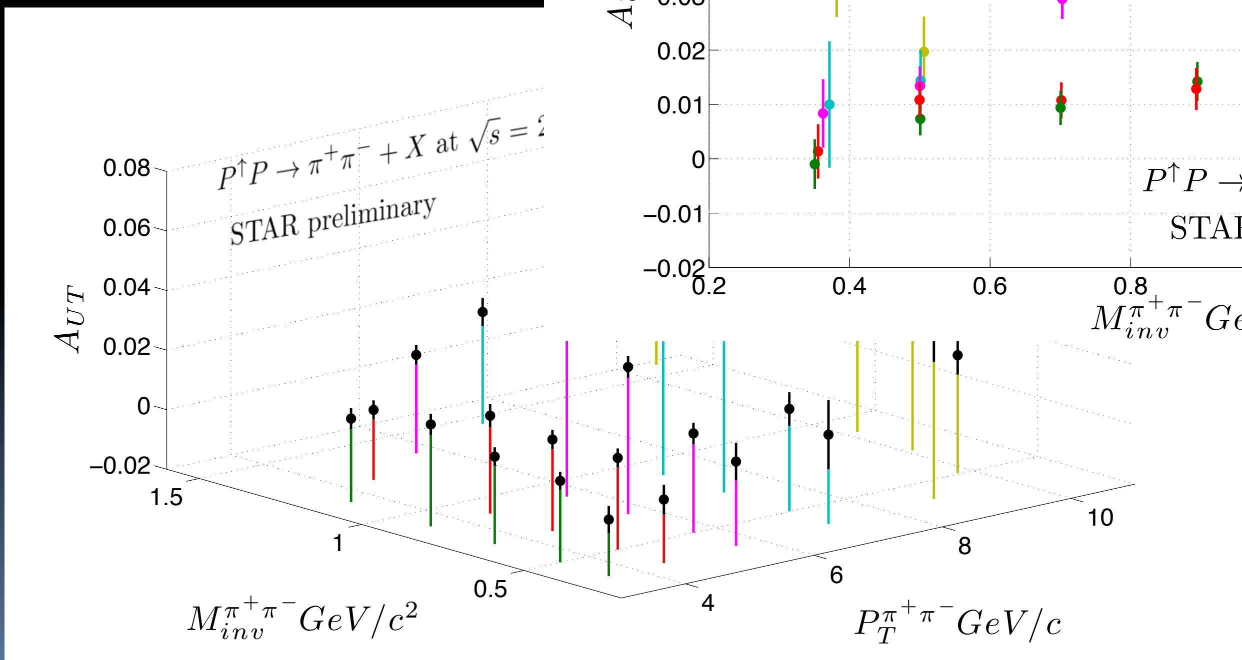
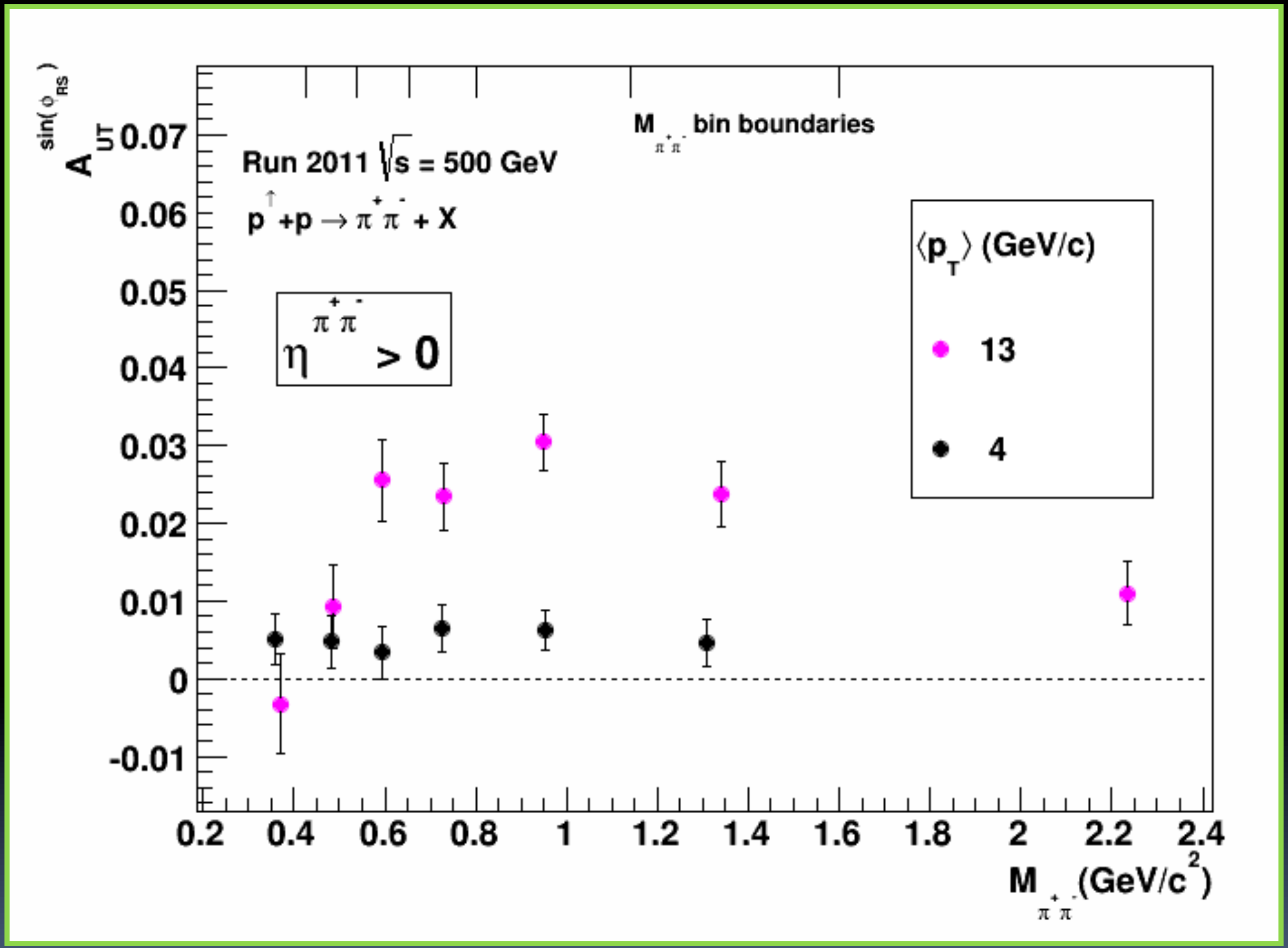




2011 π+π- IFF at √s = 500 GeV



Increasing asymmetry with increasing pT - similar to 200 GeV but overall suppression in magnitude

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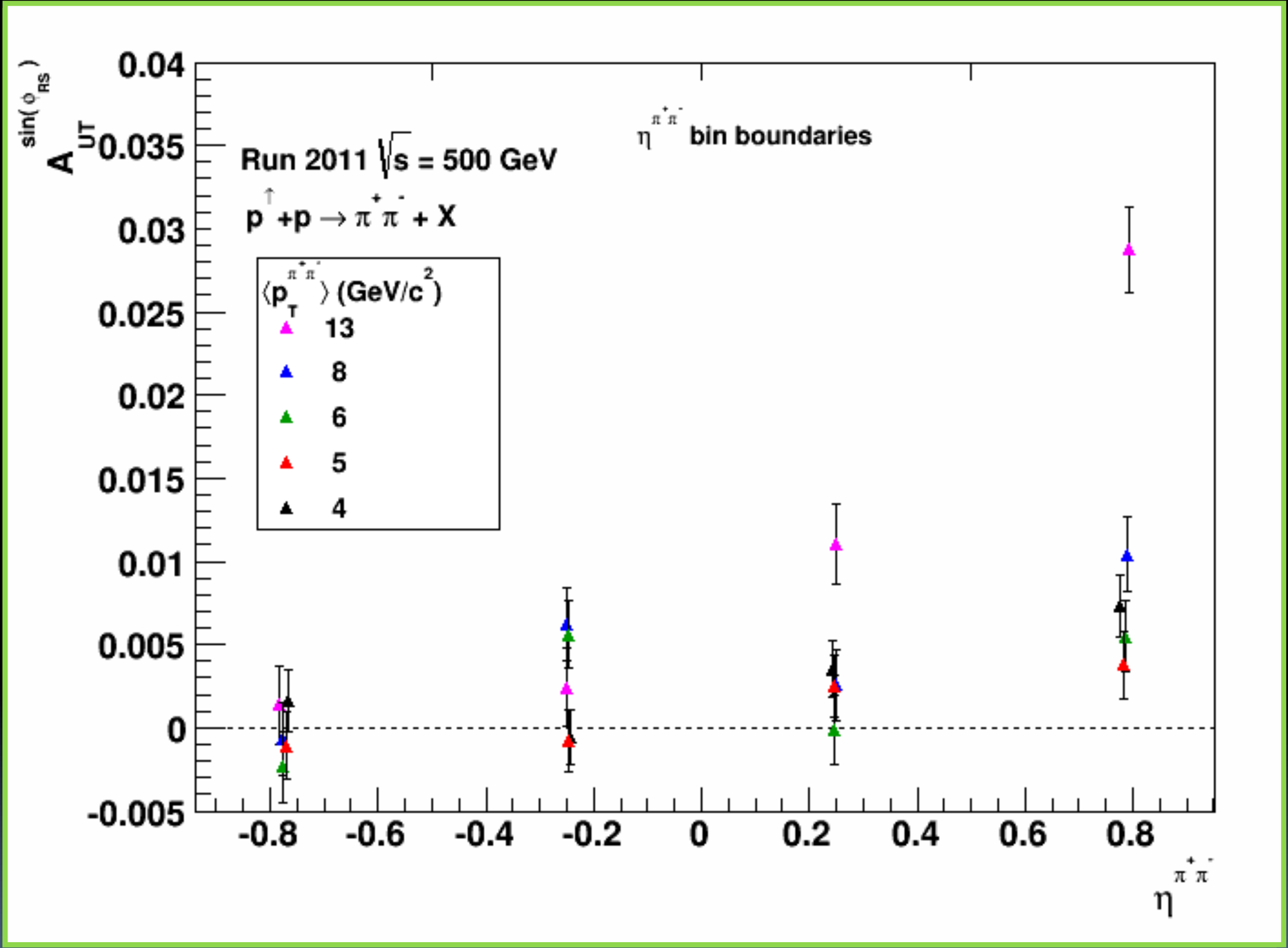

Trend is same as 200 GeV but asymmetries are smaller. Again due to higher gluon dilution and effective lower x values.

Conclusions

- INCLUSIVE JET CROSS-SECTION at $\sqrt{s}$= 200 GeV
  - Good agreement with CT10 NLO calculations
  - First STAR inclusive jet cross-section with anti-kT algorithm
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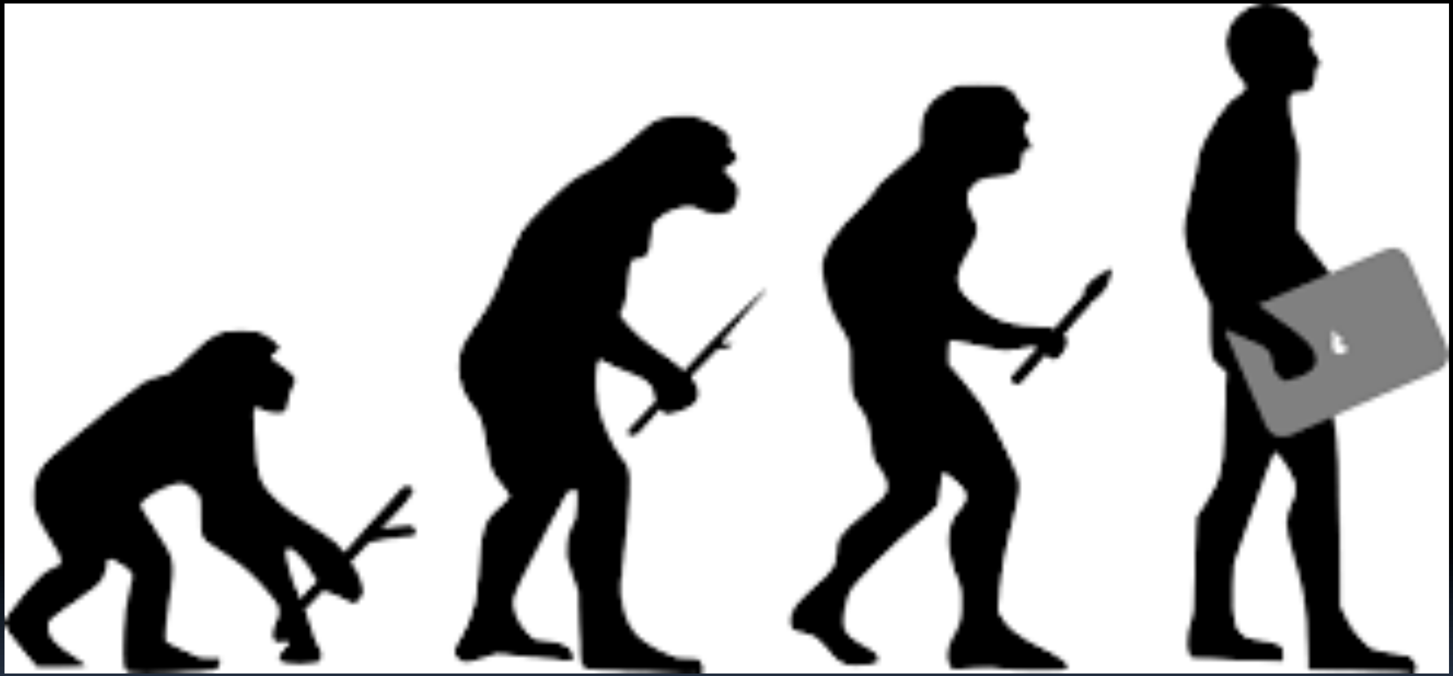
- STAR's simultaneous measurement of the IFF and Collins SSA provides a test of the TMD factorization framework and facilitates study of factorization breaking effects in pp

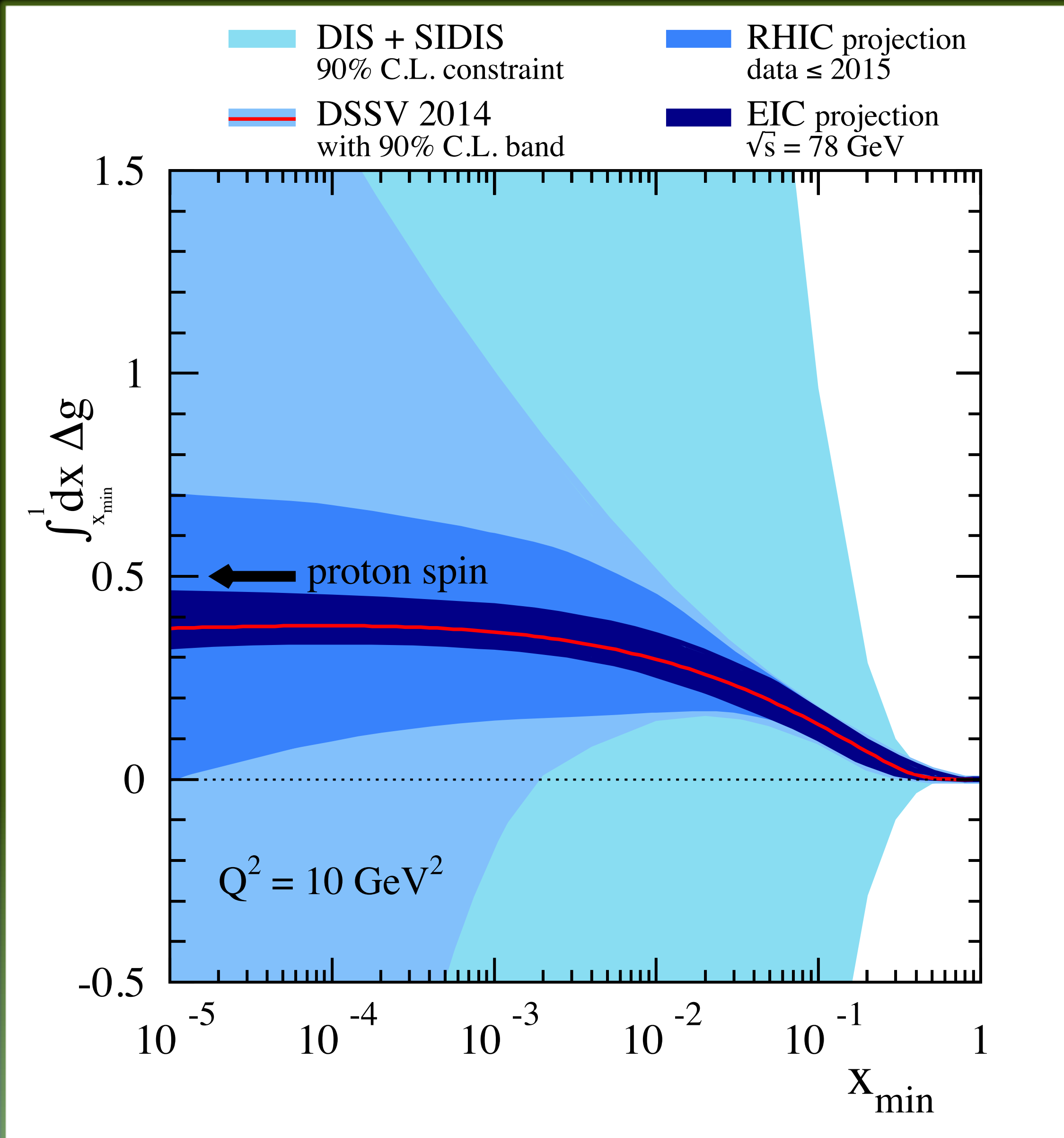
Thank you



STAR Transverse pp Running

	YEAR	$\sqrt{s}$ [GeV]	STAR	Pol [%]
	2001 (Run 1)	200	0.15 pb^{-1}	15
	2003 (Run 3)	200	0.25 pb^{-1}	30
	2005 (Run 5)	200	0.1 pb^{-1}	47
➔	2006 (Run 6)	200	8.5 pb^{-1}	57
	2006 (Run 6)	62.4	/	53
	2008 (Run8)	200	7.8 pb^{-1}	45
➔	2011 (Run11)	500	25 pb^{-1}	48
➔	2012 (Run12)	200	22 pb^{-1}	59
	2015 (Run15)	200	53 pb^{-1}	55

RHIC provides a wide range of center of mass collision energies allowing for the study of transversity and fragmentation FF evolution.



Special thanks to DSSV for this plot!

RHIC impact on ΔG

DSSV

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

$\Delta G\ (x > 0.05) = 0.2\ (+0.06/-0.07)$

NNPDF

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

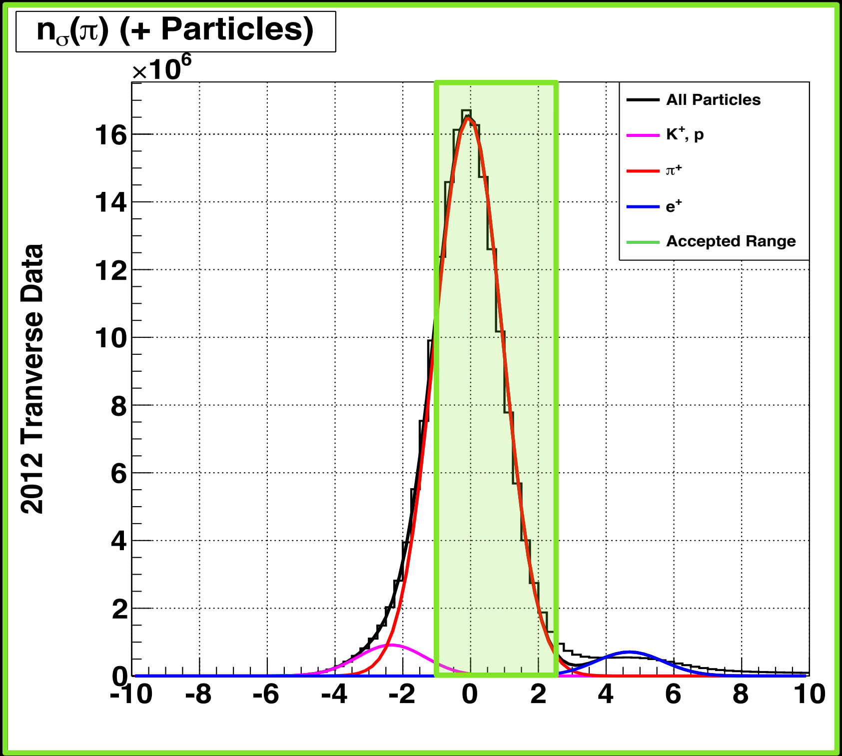
$\Delta G\ (0.2 > x > 0.05) = 0.17\ (+/- 0.06)$

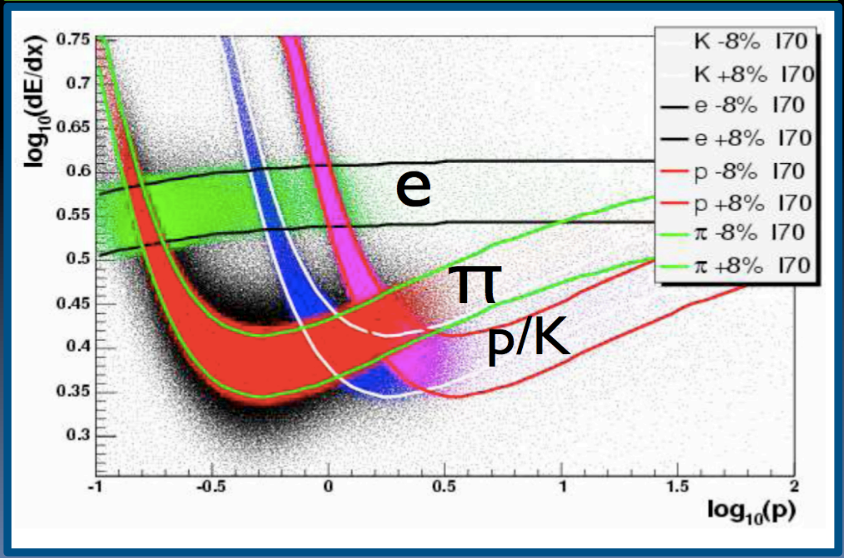
Charged pion identification

- Pions identified from TPC track dE/dx
- Use $-1 < n_\sigma(\pi) < 2.5$ cut to identify pions

$$n_\sigma(\pi) = \frac{1}{\sigma_{\exp}} \ln\left(\frac{dE/dx_{obs}}{dE/dx_{\pi,calc}}\right)$$

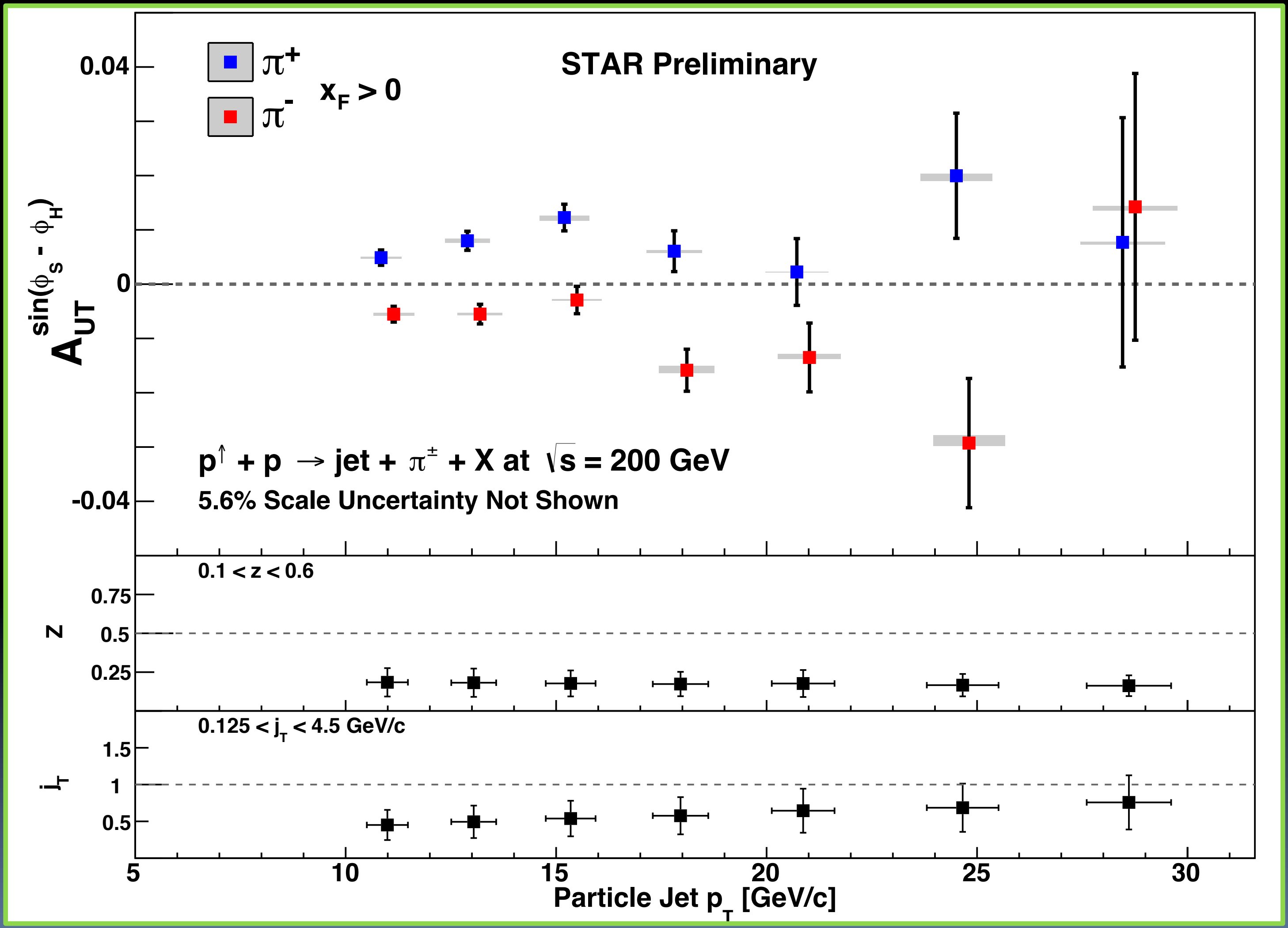
- Kaons, protons, and electrons contaminate the pion sample
- This contamination is p_T independent for Collins (3% of sytematic err) and ranges from 3 – 17% for IFF.



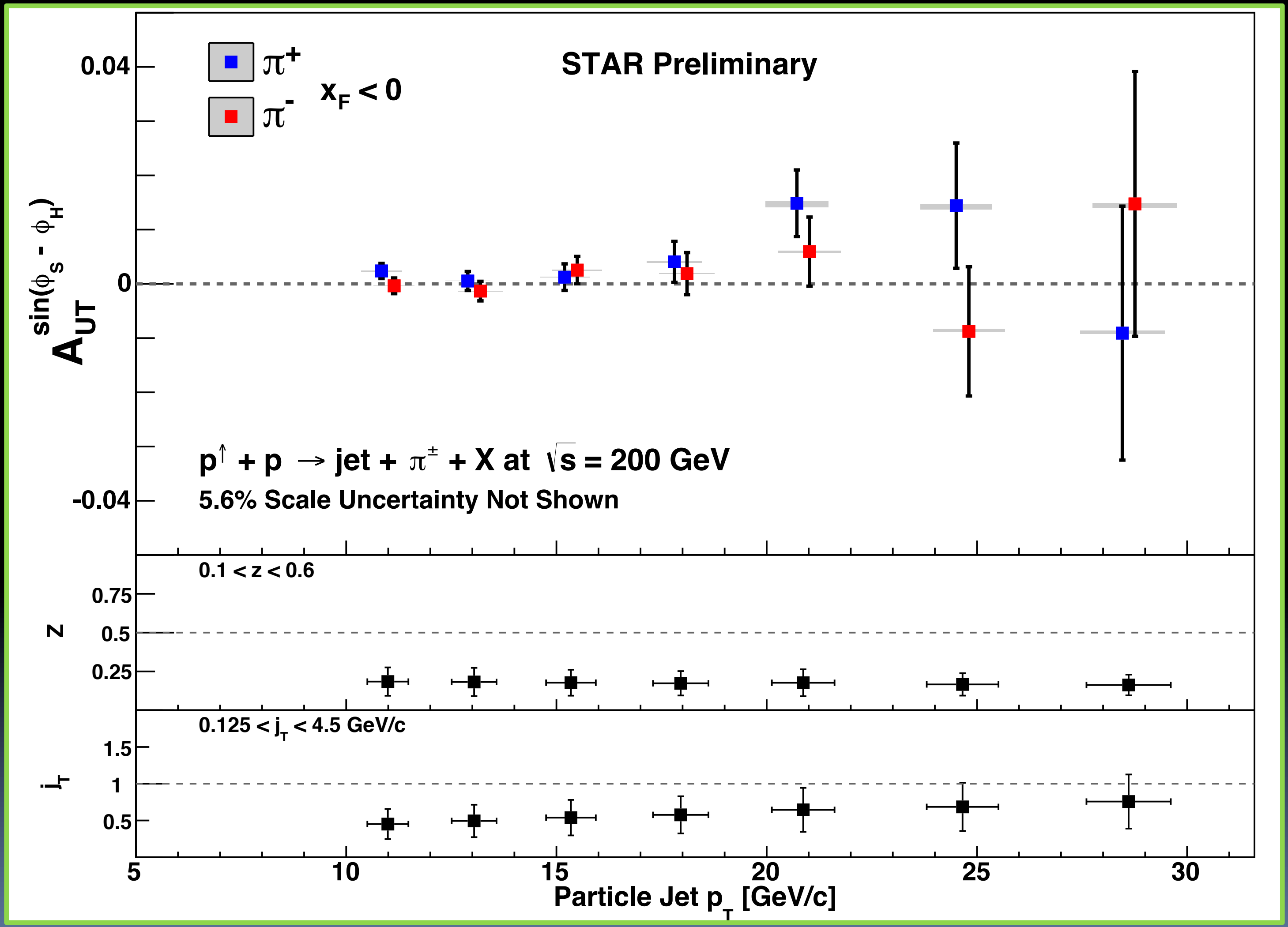


Nucl.Instrum.Meth. A558:419-429,2006

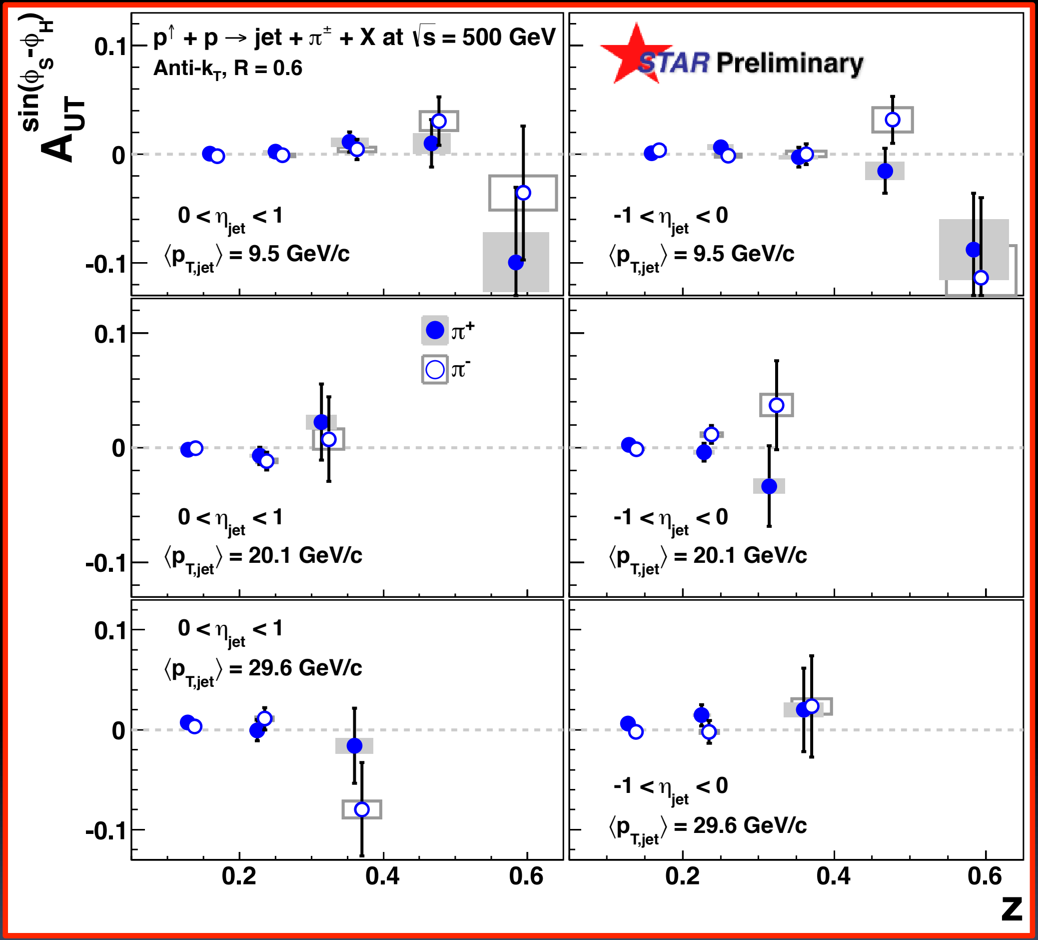
2012 200 GeV $A_{UT}^{COLLINS}$ vs. p_T ($x_F > 0$)

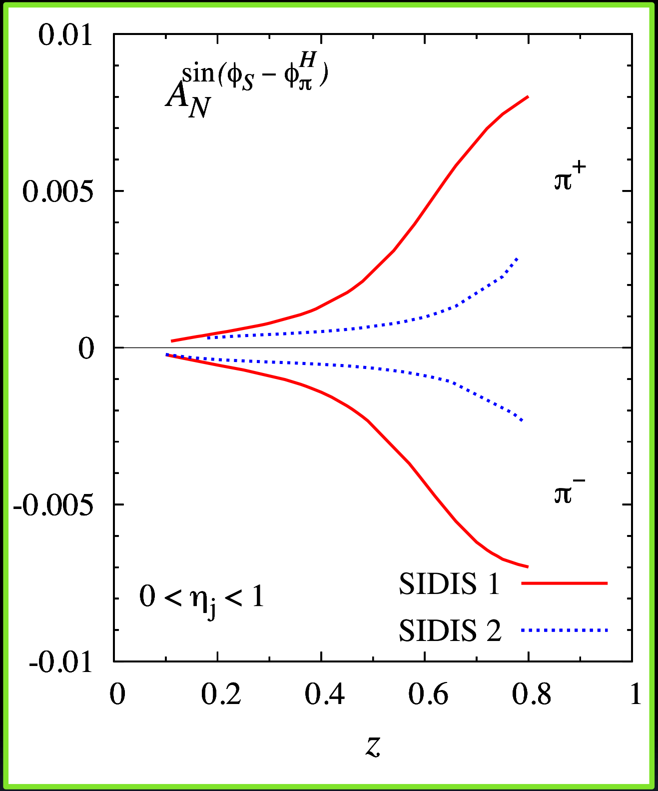


2012 200 GeV $A_{UT}^{COLLINS}$ vs. p_T (x_F < 0)



2011 $A_{UT}^{COLLINS}$ vs. Z at √s= 500 GeV





Low p_T projection for √s = 500 GeV
Based on work in PRD 83 034021 (2011)

- Asymmetries consistent with zero across the board - BUT gluon dilution larger and average x is smaller for given jet pT! Need more statistics for definitive answer!
- Projections for 500 GeV predict nothing larger than 1% at high z

Partial Wave Expansion

$$\sin\theta H_1^{\sphericalangle}(z,\cos\theta,M_{inv}^{\pi^+\pi^-2}) \approx \boxed{H_{1,ot}^{\sphericalangle}(z,M_{inv}^{\pi^+\pi^-2})}\sin\theta$$

$$+\boxed{H_{1,lt}^{\sphericalangle}(z,M_{inv}^{\pi^+\pi^-2})}\sin\theta\cos\theta$$

P/P wave interference

Interference of L=1 unpolarized pair and L=1 transversely polarized pair

S/P wave interference

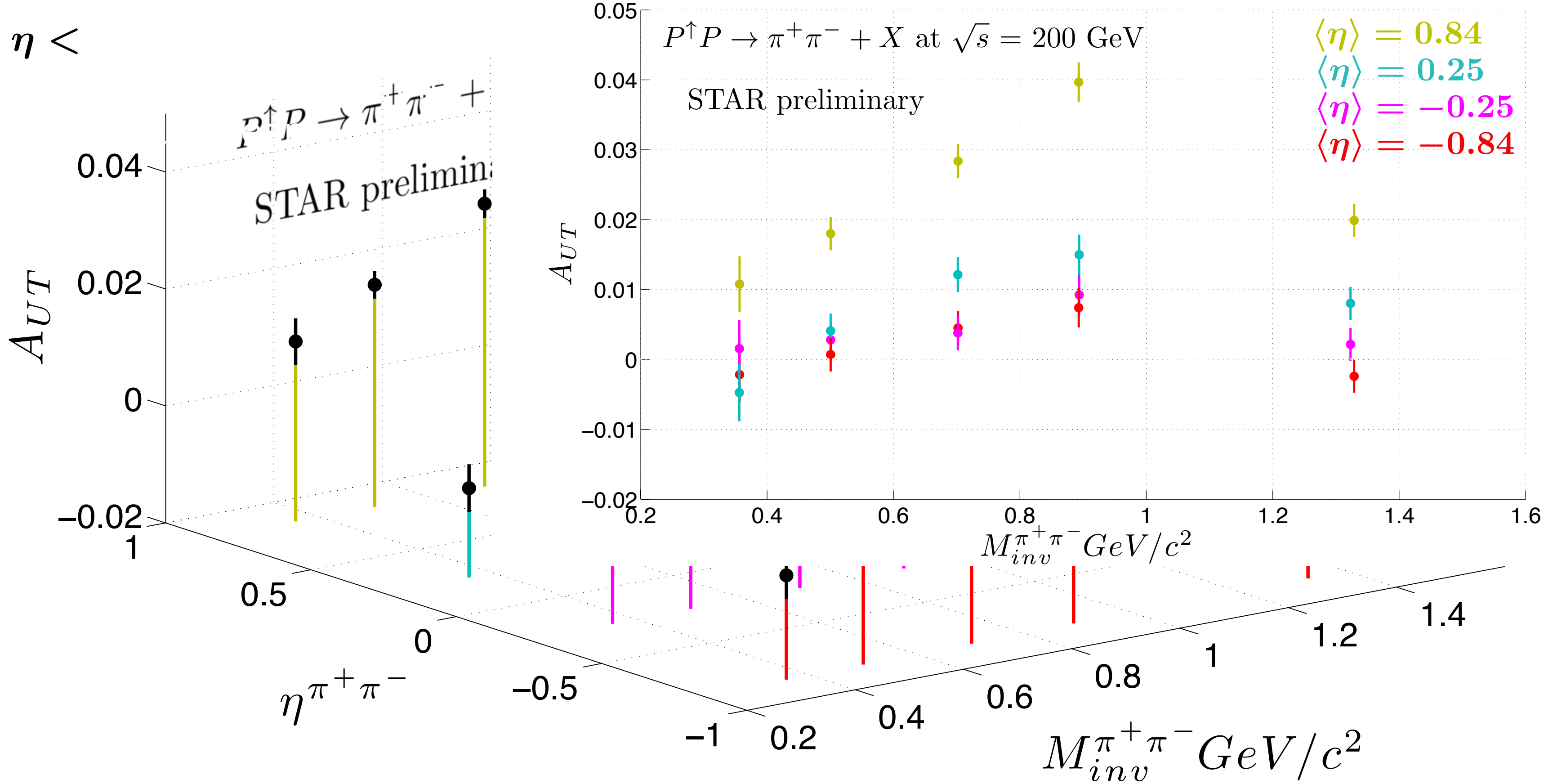
Interference of L=0 unpolarized pair and L=1 transversely polarized pair

P wave contributions come from a spin-1 resonance $\rho(770\ \mathrm{MeV})$ → expect higher asymmetry around .8 GeV

Asymmetry as function of

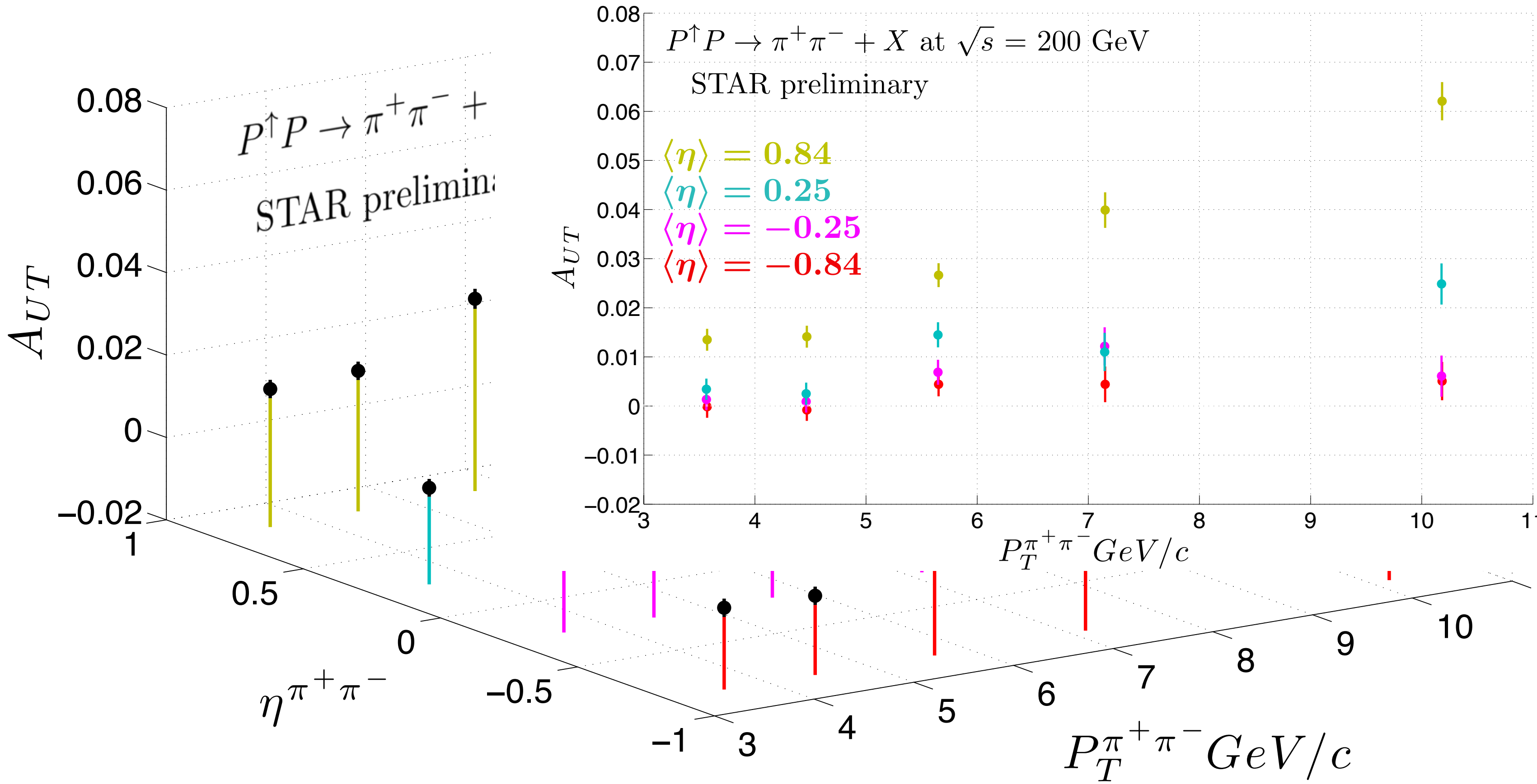
M_{inv} , η

$\eta <$

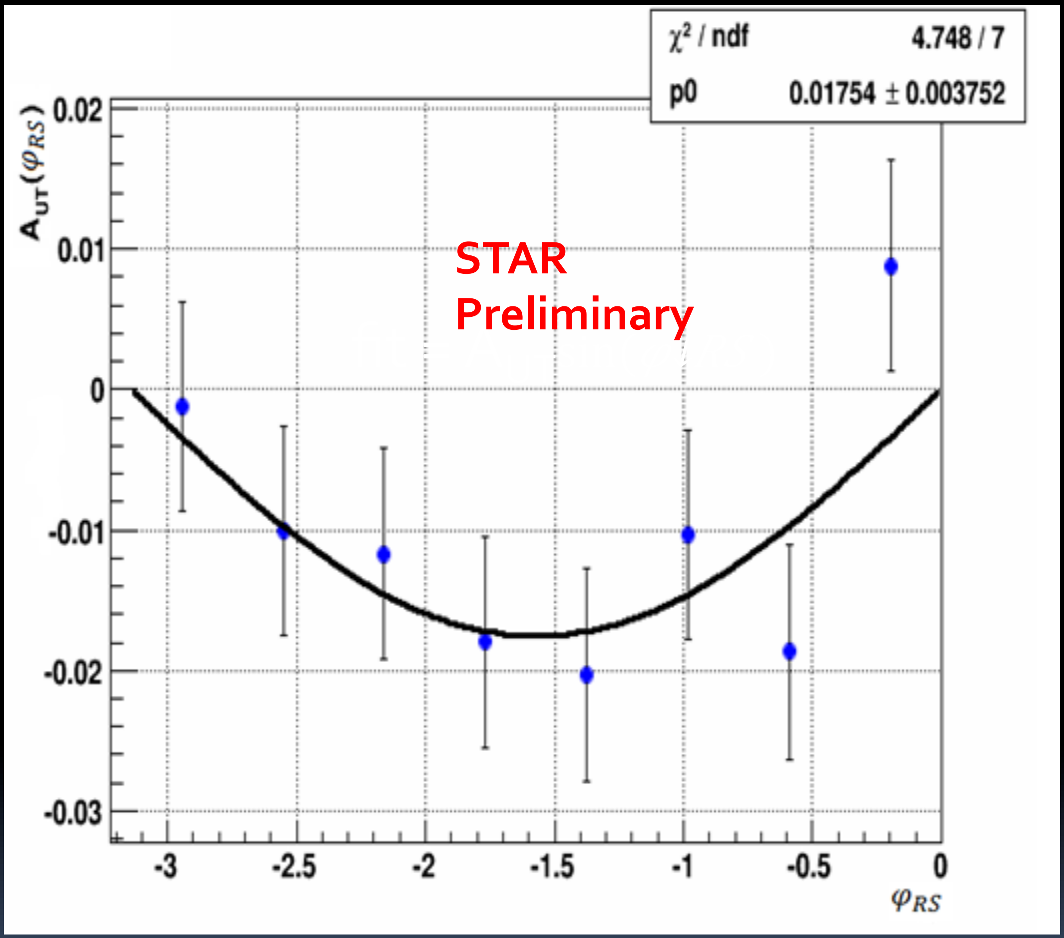


Asymmetry as function of

P_T , η



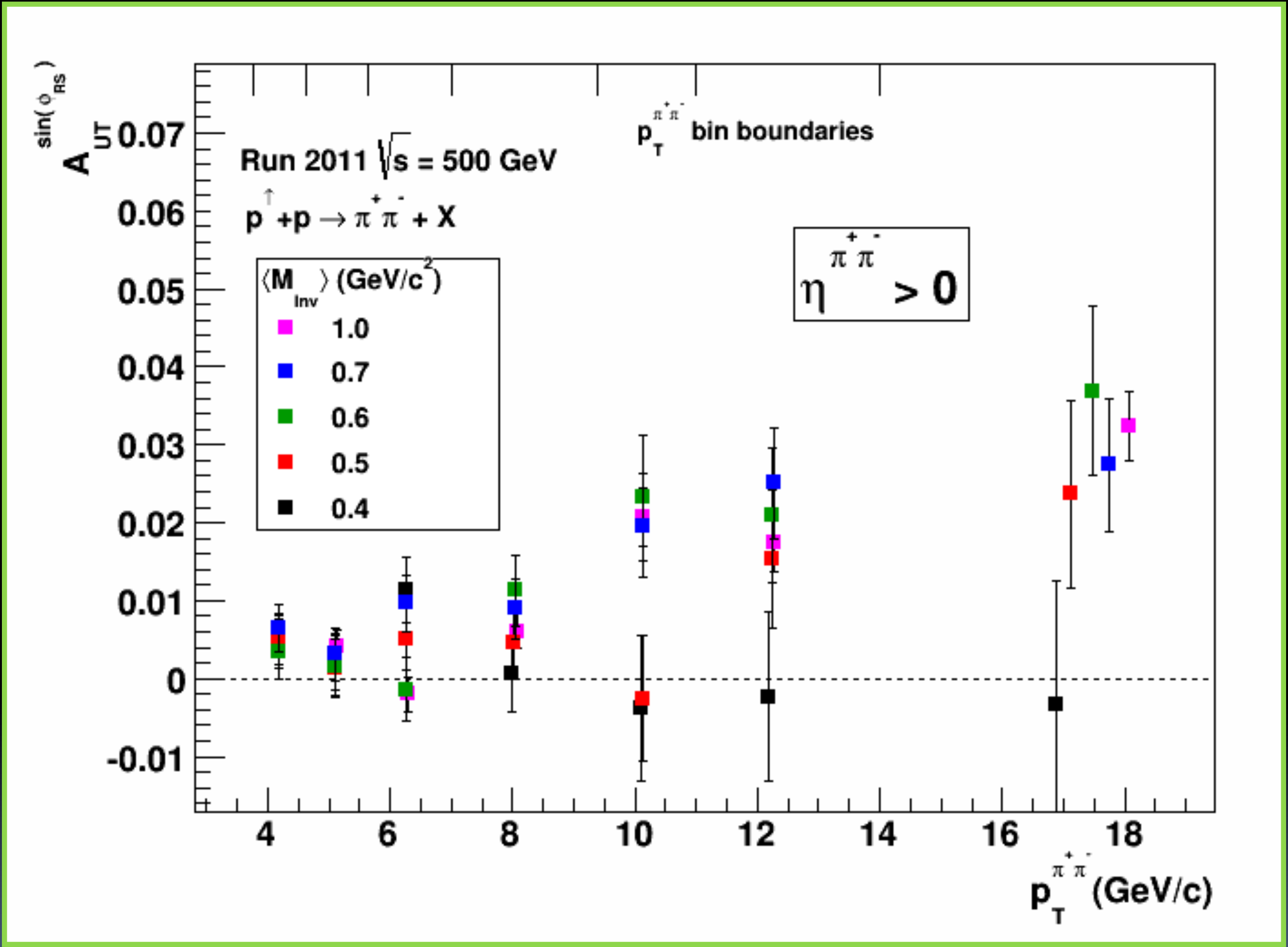
2011 500 GeV IFF Extract A_{UT}



$$A_{UT}(\varphi_{RS}) = \frac{1}{P}\frac{\sqrt{N\uparrow(\varphi_{RS})N\downarrow(\varphi_{RS}+\pi)} - \sqrt{N\downarrow(\varphi_{RS})N\uparrow(\varphi_{RS}+\pi)}}{\sqrt{N\uparrow(\varphi_{RS})N\downarrow(\varphi_{RS}+\pi)} + \sqrt{N\downarrow(\varphi_{RS})N\uparrow(\varphi_{RS}+\pi)}}$$

- Particle $p_T > 1.5$ GeV/c
- Pair $p_T > 3.75$ GeV/c
- For a given M_{Inv}, p_T bin the asymmetry is calculated for 8 ϕ_{RS} bins
- The asymmetry is the amplitude extracted from a single-parameter fit
- Example shown here is one M_{Inv}, p_T bin

2011 π+π- IFF at √s = 500 GeV



Increasing asymmetry with increasing pT - similar to 200 GeV but overall suppression in magnitude