

# Gluon polarization measurements from longitudinally polarized proton-proton collisions at STAR

Zilong Chang  
For the STAR Collaboration

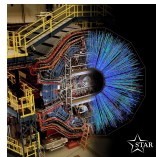
Brookhaven National Laboratory, Upton, New York 11973

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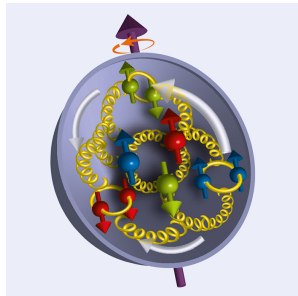
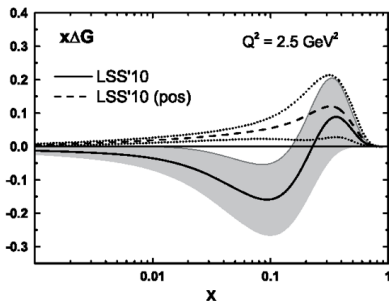


# The Proton Spin

- Proton spin sum rule:

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g}$$

- $\Delta\Sigma$ :  $\sim 0.3$  constrained by DIS and SIDIS
- $\Delta G$ : poorly constrained by DIS and SIDIS
- $L_{q,g}$ : unconstrained



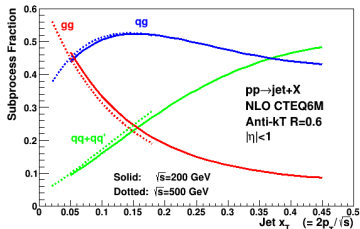
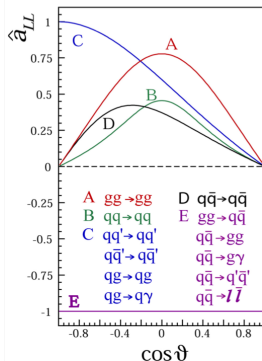
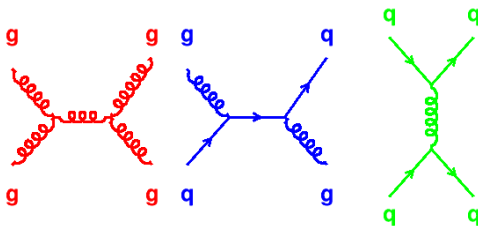
- With fit to DIS and SIDIS data,  
 $\Delta G = -0.34 \pm 0.46$ ,  
 $\Delta G = 0.32 \pm 0.19$  for pos,

Leader et al, PRD 82, 114018

# Exploring Gluon Polarization at RHIC

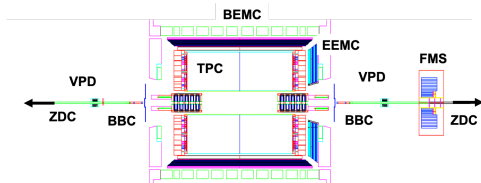
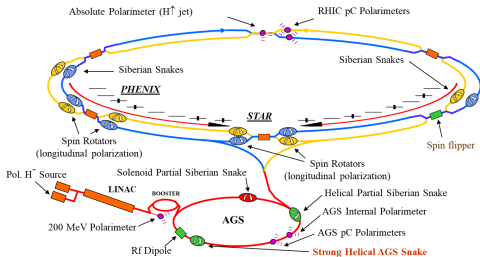
- In longitudinally polarized  $pp$  collisions, define longitudinal double-spin asymmetry  $A_{LL}$  as:

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \sim \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$



- Experimentally  $A_{LL} = \frac{1}{P_B P_Y} \frac{N_{++} - R \times N_{+-}}{N_{++} + R \times N_{+-}}$ , with beam polarizations  $P_{B(Y)}$ , and relative luminosity  $R$
- $gg$  and  $qg$  dominate jet production + large  $\hat{a}_{LL} \rightarrow$  making  $A_{LL}$  for jets sensitive to gluon polarization at both  $\sqrt{s} = 200$  and 500 GeV

# RHIC Facilities and STAR Detectors



- Polarization orientation varies from RF bunches to RF bunches (9.4 MHz).
- Spin rotators provide choice of polarization orientation (longitudinal or transverse)
- Tracking with TPC:  $|\eta| < 1.3$
- EM energy with BEMC,  $-1.0 < \eta < 1.0$ , EEMC,  $1.0 < \eta < 2.0$ , and FMS,  $2.65 < \eta < 3.9$

# Longitudinally polarized $pp$ Dataset at STAR

- Selected longitudinally polarized  $pp$  datasets at  $\sqrt{s} = 200$  and  $510$  GeV:

Year	$\sqrt{s}$ (GeV)	Recorded Luminosity ( $\text{pb}^{-1}$ )	B/Y polarization $\langle P \rangle$
2009	200	25	55
2012	510	82	50/53
2013	510	300	51/52
2015	200	52	53/57

- 2009 and 2012 data are in publication
- 2013 and 2015 data are under analysis

## Impact of STAR 200 GeV $pp$ data

# Inclusive Jet and Dijet Measurements

STAR has measured a series of inclusive jet and dijet cross-sections and longitudinal double-spin asymmetry  $A_{LL}$ s at  $\sqrt{s} = 200$  GeV

- Inclusive jets:**

$x_g$  as low as  $\sim 0.05$  at  $\sqrt{s} = 200$  GeV

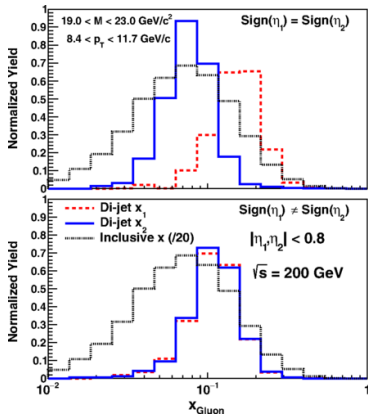
- Dijets:**

two jet correlation unfolds  $x_1$  and  $x_2$  at the leading order

$$x_1 = \frac{1}{\sqrt{s}}(p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4})$$

$$x_2 = \frac{1}{\sqrt{s}}(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4})$$

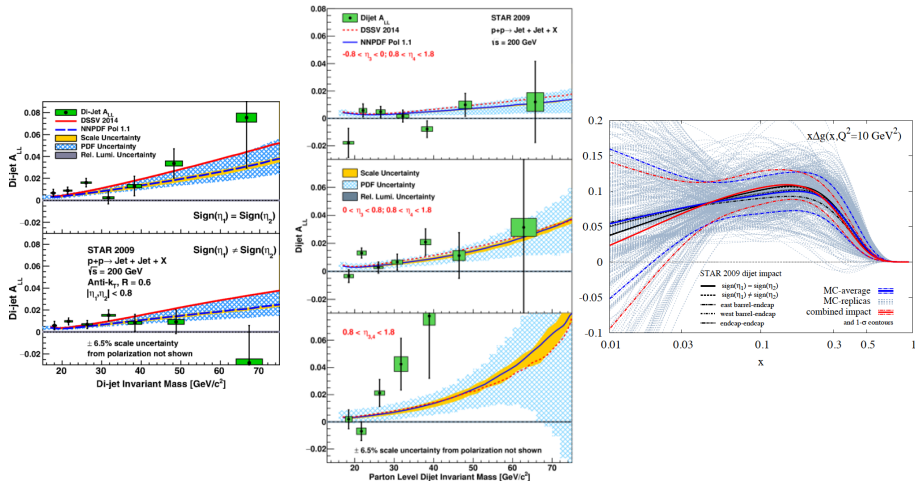
$$M = \sqrt{x_1 x_2 s}$$



- Sampled  $x_g$  distributions by inclusive and dijets at  $\sqrt{s} = 200$  GeV PRD 95, 071103(R)

# Impact of Recent STAR Results

- Recent STAR dijet  $A_{LL}$  results: both jets in  $|\eta| < 0.8$ , PRD 95, 071103(R) and at least one jet in  $0.8 < \eta < 1.8$ , PRD 98, 032011



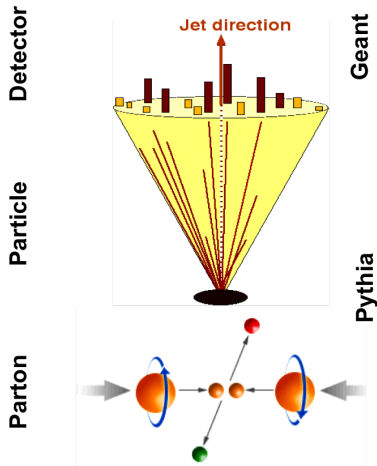
- Recent DSSV study with our STAR 200 GeV dijet results:

$$\int_{0.01}^1 \Delta g(x, Q^2 = 10 \text{ GeV}^2) = 0.296 \pm 0.108 \text{ arXiv:1902.10548 [hep-ph]}$$



Recent study of STAR 510 GeV  $pp$  data

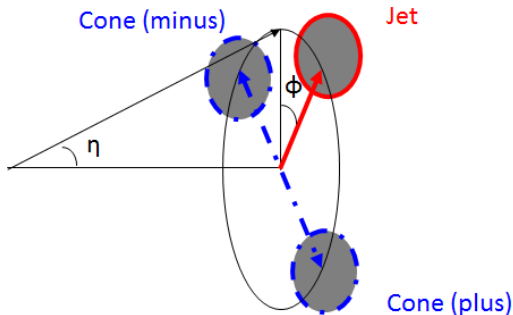
# Jet Reconstruction and Systematic Uncertainty Studies



- Charged tracks + electro-magnetic towers
- Anti- $k_T$  algorithm with  $R = 0.5$  for  $\sqrt{s} = 510$  GeV dataset
- PYTHIA + GEANT + Zero-bias events as embedding sample
  - Data-driven modified PYTHIA Perugia Tune
- Correct jet  $p_T$  and dijet  $M_{inv}$  from measured detector jets to PYTHIA parton jets
- Determine systematic uncertainties:
  - Comparing predicted jet  $A_{LL}$  between triggered detector jets and un-biased PYTHIA parton jets  $\rightarrow$  trigger bias and reconstruction uncertainty

# Underlying Event Correction to Jet Transverse Energy

- Two off-axis cones centered at  $\pm \frac{\pi}{2}$  away in  $\phi$  and the same  $\eta$  relative to a given jet are used to estimate underlying event for that jet ALICE, PRD 91, 112012.



- The underlying event correction on jet transverse momentum:  
$$dp_T = \frac{1}{2}(\rho_{plus} + \rho_{minus}) \times A_{jet}$$
- Sample  $\eta$  dependence of underlying events
- Allow to study the underlying event contribution to jet  $A_{LL}$

# Monte Carlo Tune Study

- Choose default Perugia 2012 tune with a smaller  $p_{T,0}$  scale parameter ( $P_{90} = 0.213$  default 0.24)

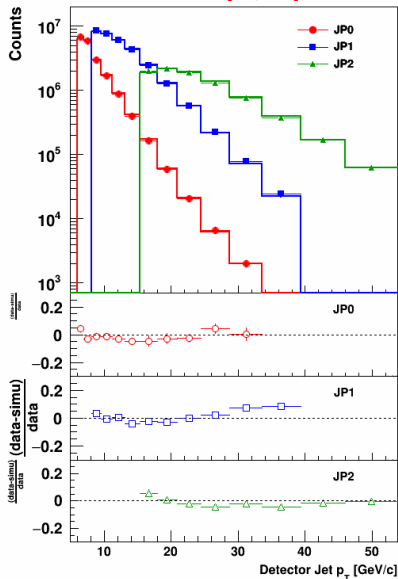
$$\sigma \sim \frac{1}{(p_T^2 + p_{T,0}^2)^2}$$

$$p_{T,0} = p_{T,ref} \times \left( \frac{\sqrt{s}}{\sqrt{s_{ref}}} \right)^{P_{90}}$$

- Reduce multiple parton interaction contribution
- Lead to better matching between PYTHIA simulation and previous STAR charged  $\pi^\pm$  spectrum measurements PLB 637, 161 and PRL 108, 072302
- Jet spectrum comparison for three jet patch triggers, JP0, JP1 and JP2

Markers: data and lines: simulation

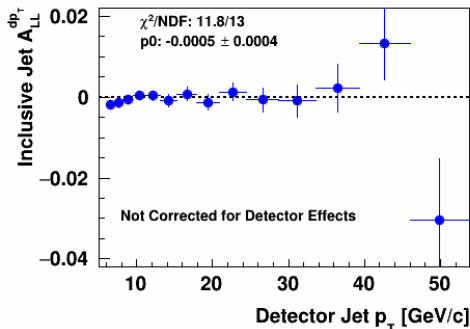
arXiv:1906.02740 [hep-ex]



# Effects of Underlying Events on Measured Jet $A_{LL}$

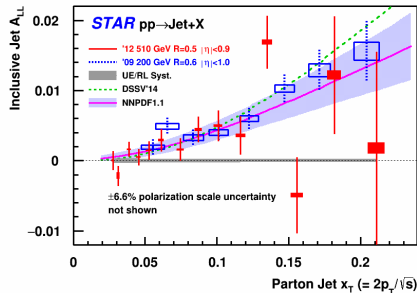
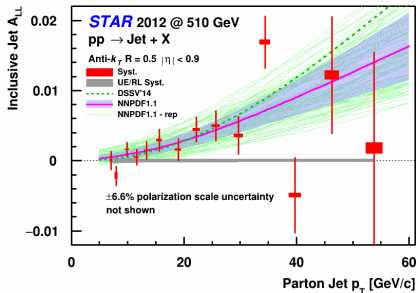
- Define underlying event correction  $dp_T$  asymmetry:

$$A_{LL}^{dp_T} = \frac{1}{P_A P_B} \frac{(\langle dp_T \rangle^{++} + \langle dp_T \rangle^{--}) - (\langle dp_T \rangle^{+-} + \langle dp_T \rangle^{-+})}{(\langle dp_T \rangle^{++} + \langle dp_T \rangle^{--}) + (\langle dp_T \rangle^{+-} + \langle dp_T \rangle^{-+})}$$

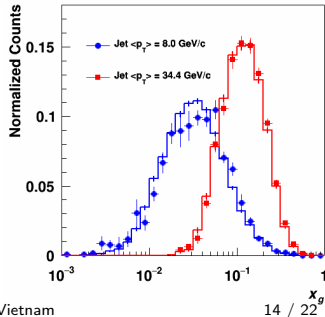


- Underlying event correction  $dp_T$  asymmetries are **consistent with zero**  
[arXiv:1906.02740 \[hep-ex\]](https://arxiv.org/abs/1906.02740)
- Underlying event contribution to measured jet  $A_{LL}$  is estimated to be  $\sim 10^{-4}$ ,  
assigned as an uncertainty

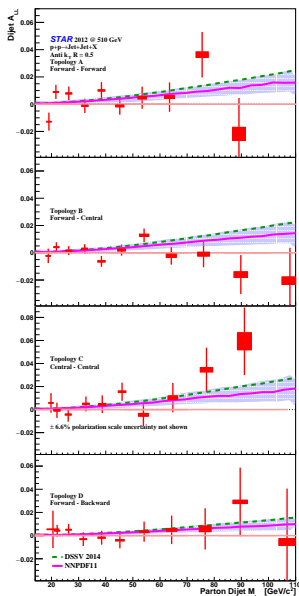
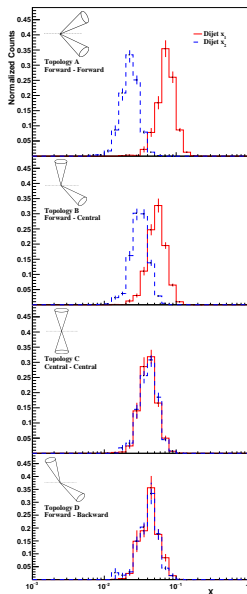
# STAR 510 GeV Inclusive Jet $A_{LL}$ Measurements



- Much reduced systematic uncertainty than the previous measurements at  $\sqrt{s} = 200$  GeV, [arXiv:1906.02740 \[hep-ex\]](https://arxiv.org/abs/1906.02740)
- Agree with recent polarized PDF predictions
- In the overlapping  $x_T = \frac{2p_T}{\sqrt{s}}$  region, both results agree well
- Allow to access  $x_g$  as low as 0.015



# STAR 510 GeV Dijet $A_{LL}$ Measurements



- Dijet  $A_{LL}$  vs. invariant mass for four  $\eta$  topologies, [arXiv:1906.02740 \[hep-ex\]](https://arxiv.org/abs/1906.02740)

**A/Forward-Forward:**

$$0.3 < |\eta_{3,4}| < 0.9$$

$$\eta_3 \cdot \eta_4 > 0$$

**B/Forward-Central:**

$$|\eta_{3,4}| < 0.3,$$

$$0.3 < |\eta_{3,4}| < 0.9$$

**C/Central-Central:**

$$|\eta_{3,4}| < 0.3$$

**D/Forward-Backward:**

$$0.3 < |\eta_{3,4}| < 0.9$$

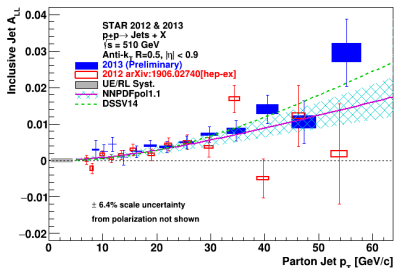
$$\eta_3 \cdot \eta_4 < 0$$

- Topology binning narrows the sampled  $x_g$  and the  $\cos\theta^*$  ranges

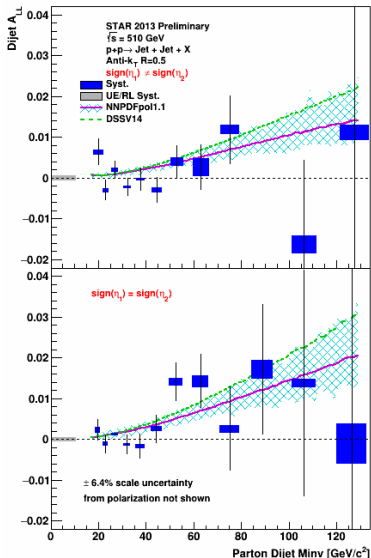
- Sampled  $x_g$  distributions much narrower than those from inclusive jets

# Inclusive and Dijet $A_{LL}$ from STAR 2013 510 GeV Data

- Preliminary inclusive jet (left) and dijet (right)  $A_{LL}$  from STAR 2013 510 GeV data, arXiv:1809.00923 [nucl-ex]

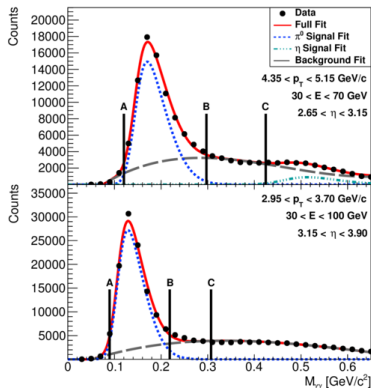


- Same procedure being applied as in 2012  $\sqrt{s} = 510$  GeV data
- The 2012 and 2013 results agree well
- Two  $\eta$  topologies for dijet  $A_{LL}$
- The study of the systematic uncertainty is underway for the final results

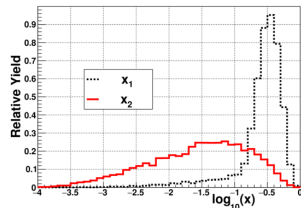
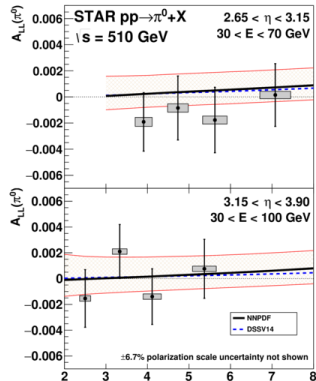




# STAR 510 GeV Forward $\pi^0$ $A_{LL}$



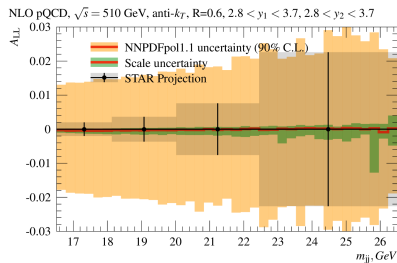
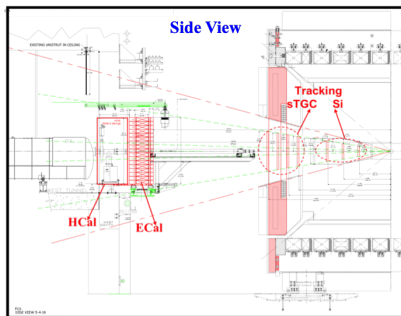
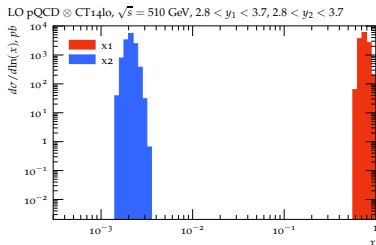
- $\pi^0$  reconstructed in STAR FMS PRD 98, 032013
- Measured  $A_{LL}$  is small, less than  $5 \times 10^{-3}$
- Allow to access  $x_g \sim 10^{-3}$



# STAR Forward Upgrade

- STAR is planning to install a Forward Calorimeter System (FCS), including an EMCal and a HCal, and a Forwarding Tracking System (FTS) in time for 2022 RHIC run
- Dijet measurements with one or both jets in the forward region ( $2.8 < \eta < 3.7$ ) will be one of the highlights of this upgrade
- With both jets in the FCS, it will provide gluon polarization at  $x_g \sim 10^{-3}$

STAR note: PSN0648

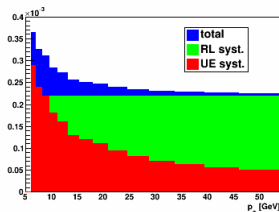


- STAR inclusive jet and dijet double-spin asymmetry measurements are unique to explore gluon polarization in the proton
- The 510 GeV results extend gluon polarization over  $x \sim 0.015$  to  $x \sim 0.2$ , [arXiv:1906.02740 \[hep-ex\]](#)
  - ① Inclusive jets will constrain the magnitude of the gluon polarization
  - ② Dijets will constrain the shape of  $\Delta g(x)$
- Inclusive jet and dijet  $A_{LL}$  are being studied from the 2013  $pp$  at  $\sqrt{s} = 510$  GeV
- Combined inclusive jet  $A_{LL}$  from the larger 2015 200 GeV and the smaller published 2009 data will improve the statistical precision by a factor of about 1.6
- The forward upgrade will provide new opportunities to probe low  $x \sim 10^{-3}$  gluon polarization where the current polarized PDF studies show large uncertainties



# Underlying Event Systematics on Jet $A_{LL}$

$$\delta A_{LL} = \frac{\int_{p_{T,min}-\langle dp_T \rangle \times A_{LL}^{dp_T}}^{p_{T,max}-\langle dp_T \rangle \times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T - \int_{p_{T,min}+\langle dp_T \rangle \times A_{LL}^{dp_T}}^{p_{T,max}+\langle dp_T \rangle \times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T}{\int_{p_{T,min}-\langle dp_T \rangle \times A_{LL}^{dp_T}}^{p_{T,max}-\langle dp_T \rangle \times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T + \int_{p_{T,min}+\langle dp_T \rangle \times A_{LL}^{dp_T}}^{p_{T,max}+\langle dp_T \rangle \times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T} \quad (1)$$



**Figure:** Underlying event systematic uncertainty on inclusive jet  $A_{LL}$  for 2012 510 GeV data compared with systematic uncertainty due to relative luminosity.

# STAR Charged $\pi^\pm$ Spectrum

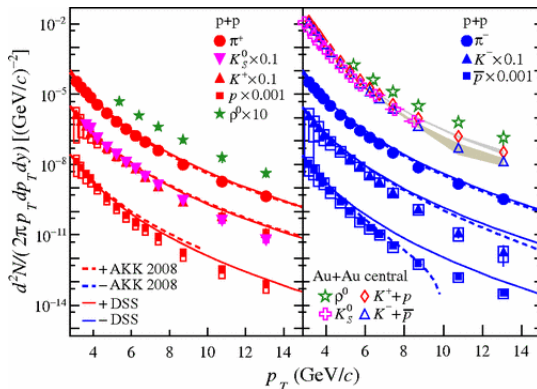


Figure: STAR charged  $\pi^\pm$  yields. PRL 108, 072302, 2012