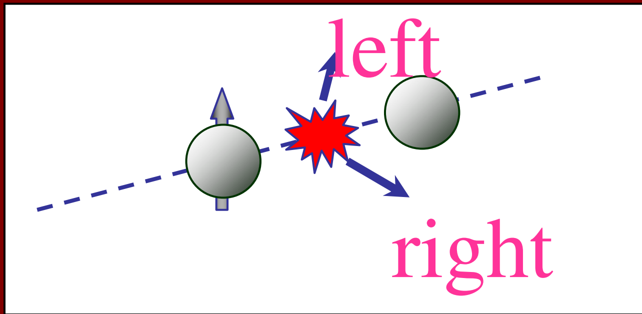
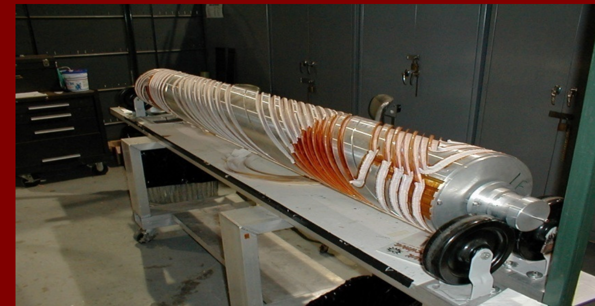
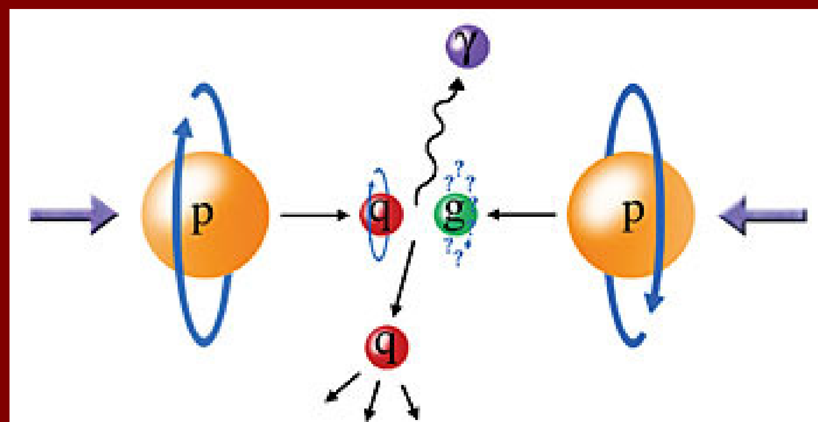




Spin in Hadron Reactions



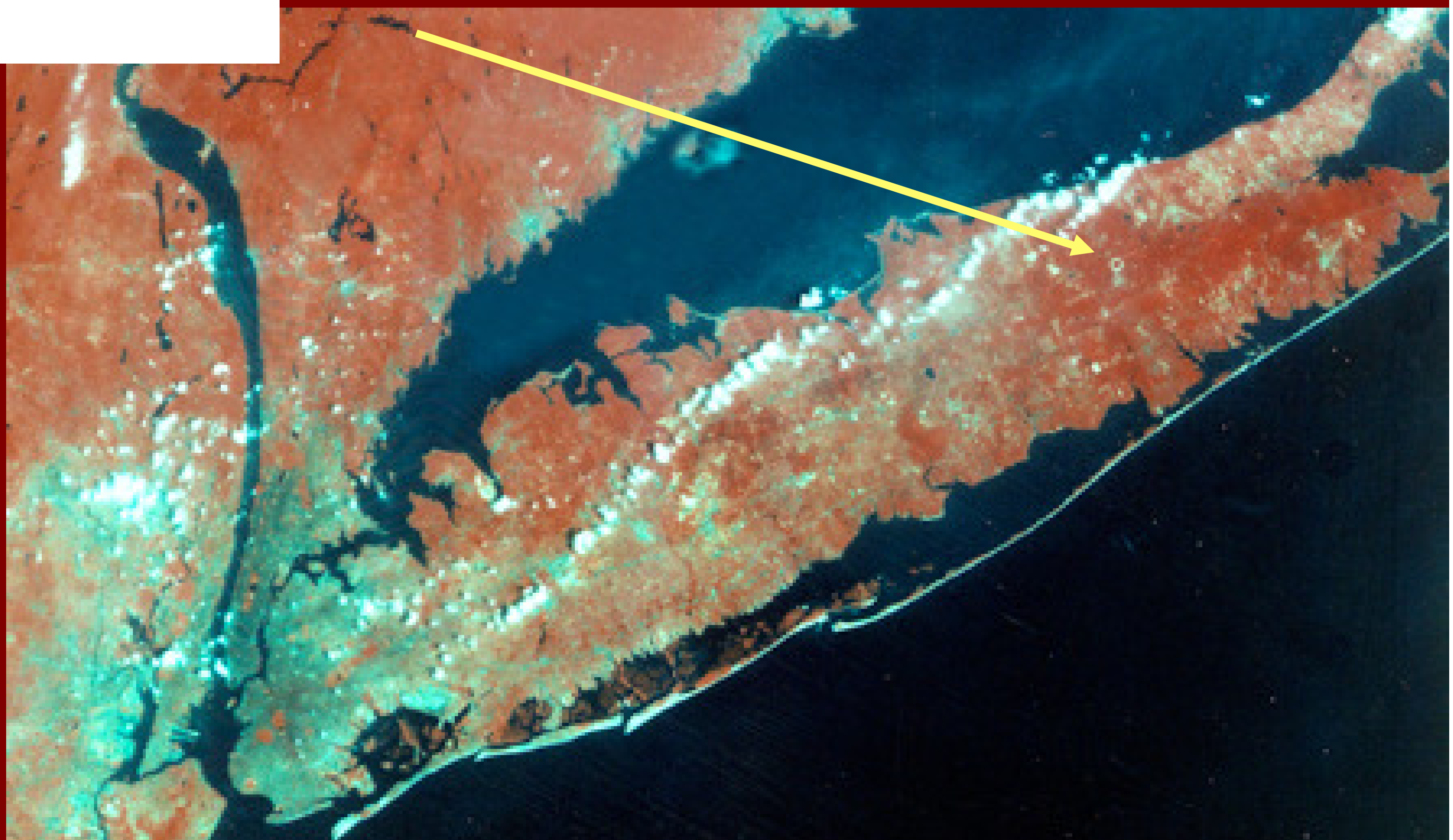
Christine Aidala
University of Massachusetts Amherst

SPIN 2008, University of Virginia

October 9, 2008

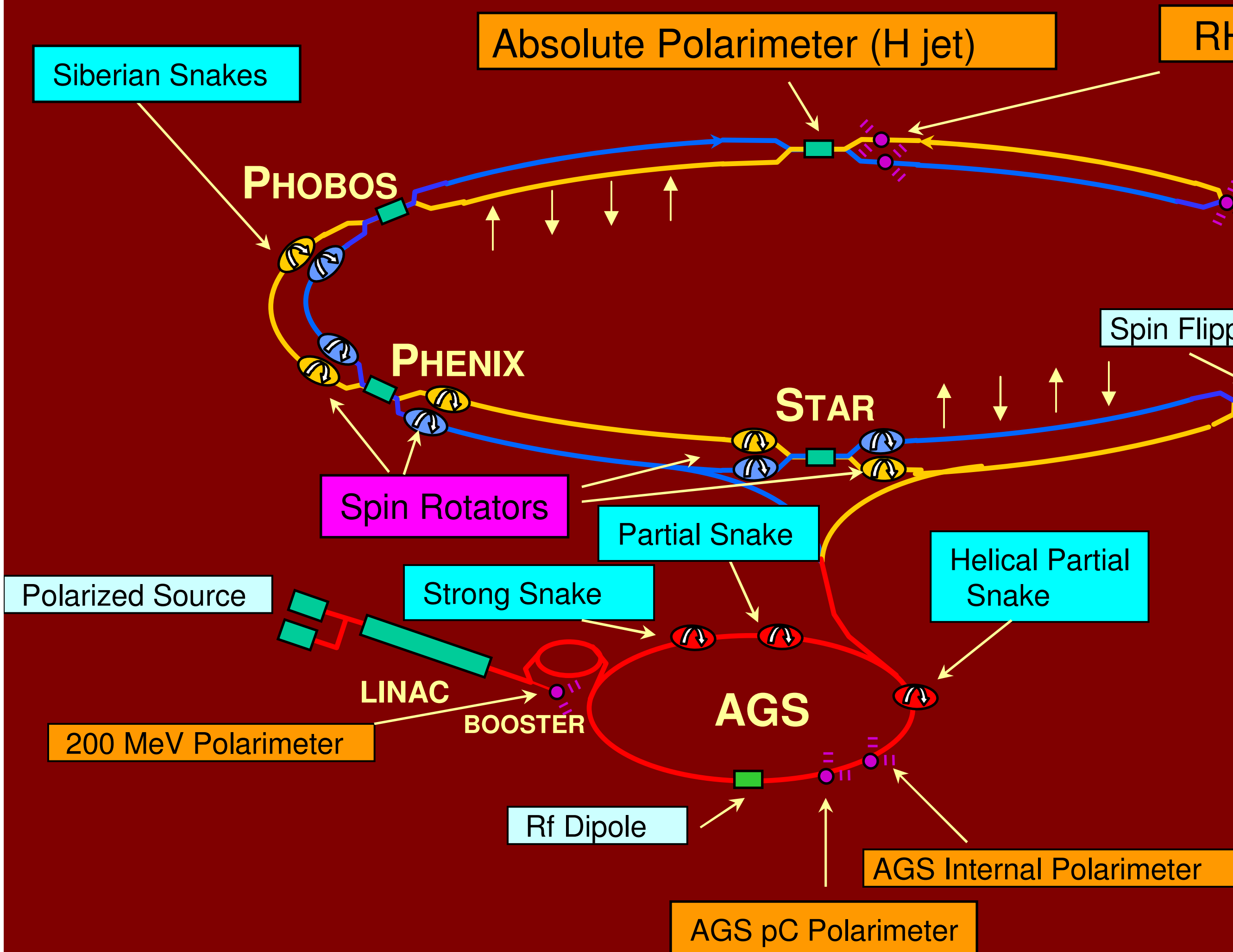
The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

BROOKHAVEN NATIONAL LABORATORY

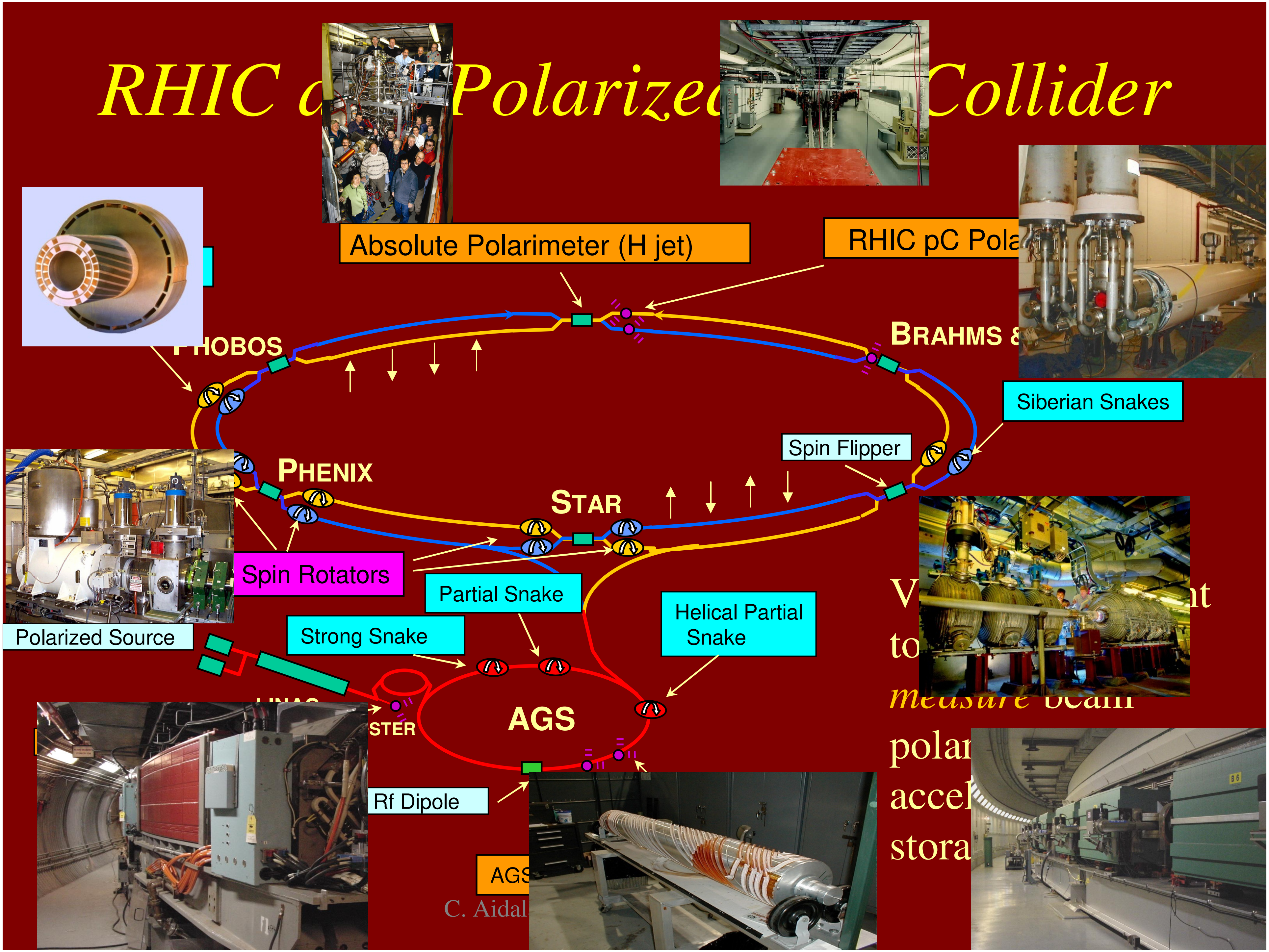


The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

RHIC as a Polarized p+p Collider



Various equipment to *maintain* and *measure* beam polarization through acceleration and storage



RHIC
Collider
Absolute Polarimeter (H jet)
PHENIX
STAR
Siberian Snakes
Spin Flipper
Spin Rotators
Partial Snake
Helical Partial Snake
Strong Snake
Polarized Source
AGS
Rf Dipole

Discovery!
Hyperon polarization

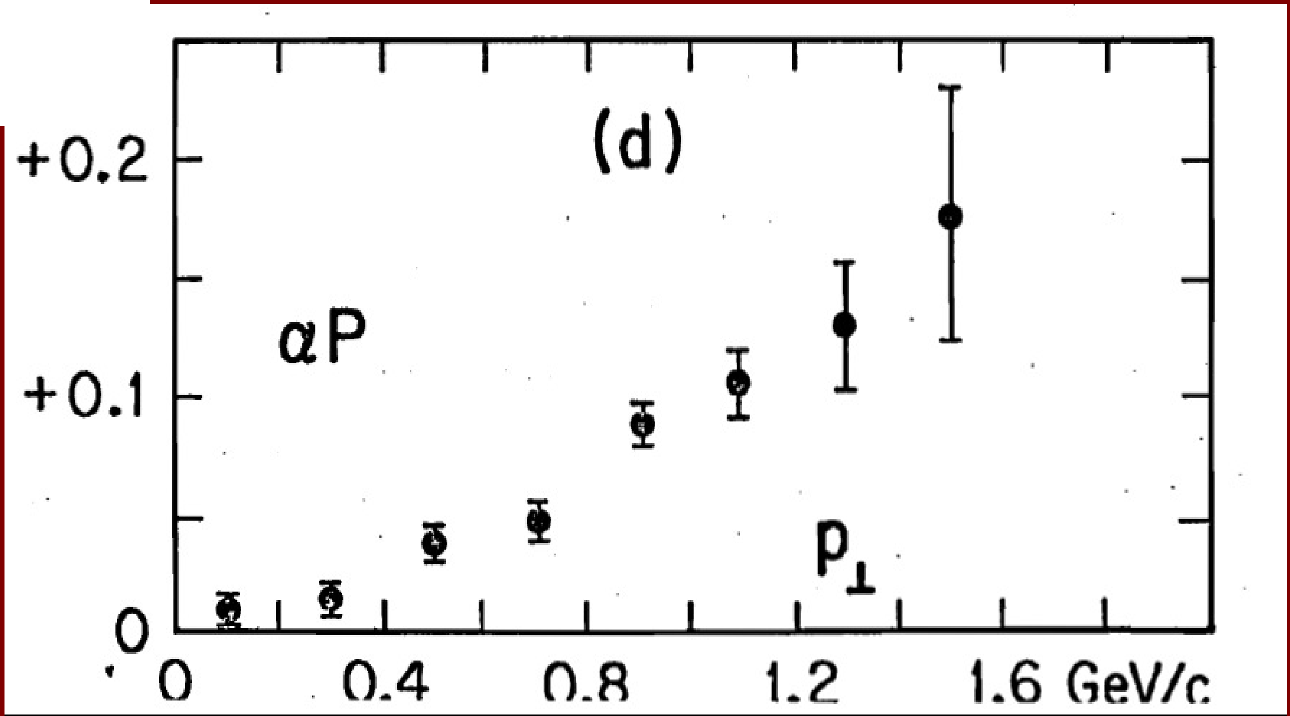
Λ^0 Hyperon Polarization

in Inclusive Production

by 300 GeV Protons on

Beryllium

G. Bunce et al., PRL36, 1113 (1976)
FNAL



Discovery!
Hyperon polarization

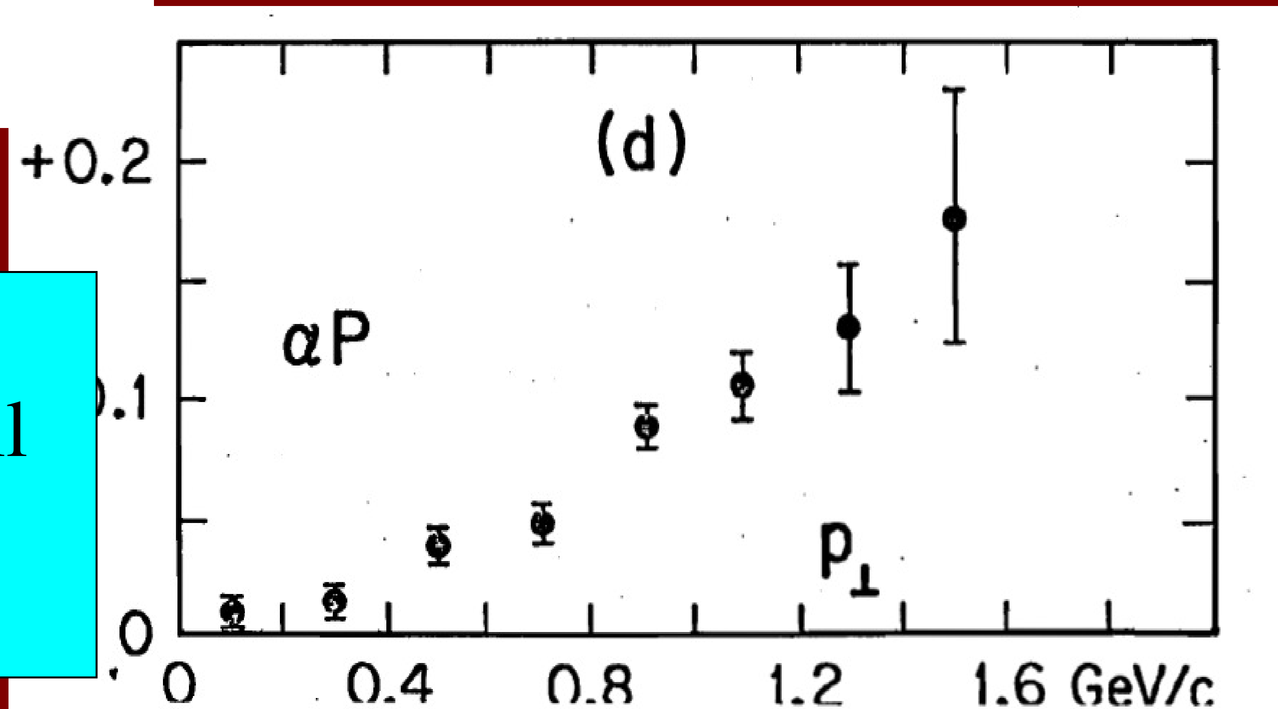
Λ° Hyperon Polarization

in Inclusive Production

by 300 GeV Protons on

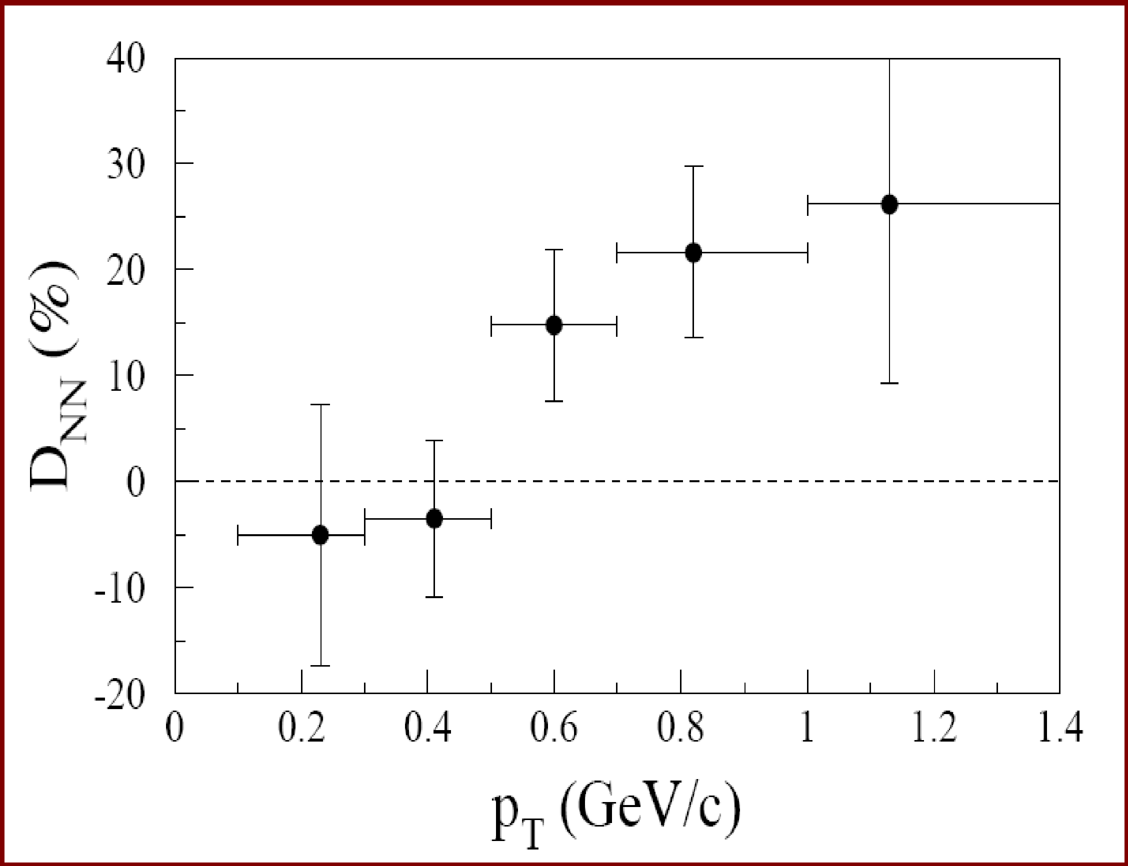
Beryllium

G. Bunce et al., PRL36, 1113 (1976)
FNAL



More than 30 years later, still not well understood!

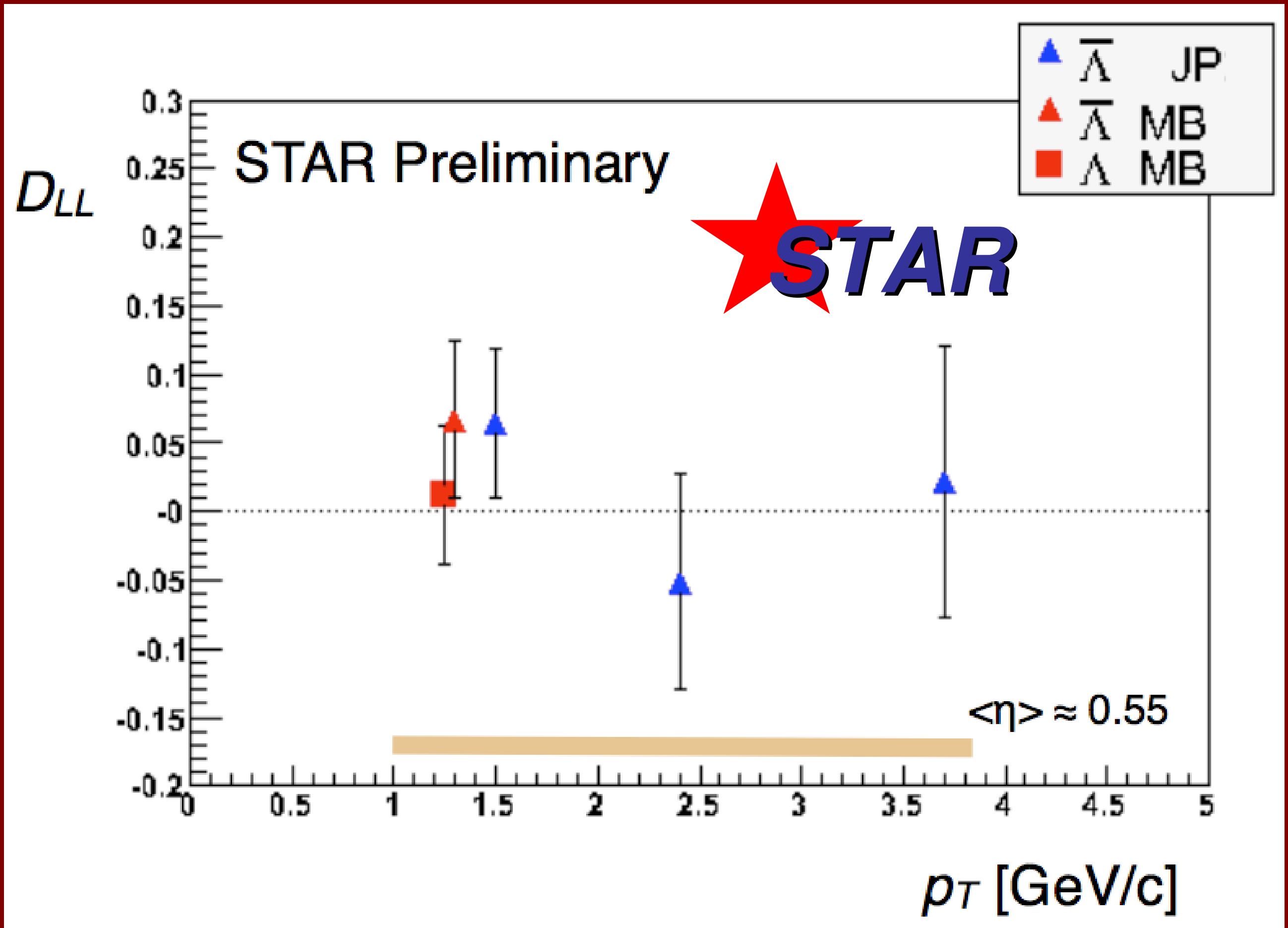
Polarized beams: Hyperon spin transfer measurements



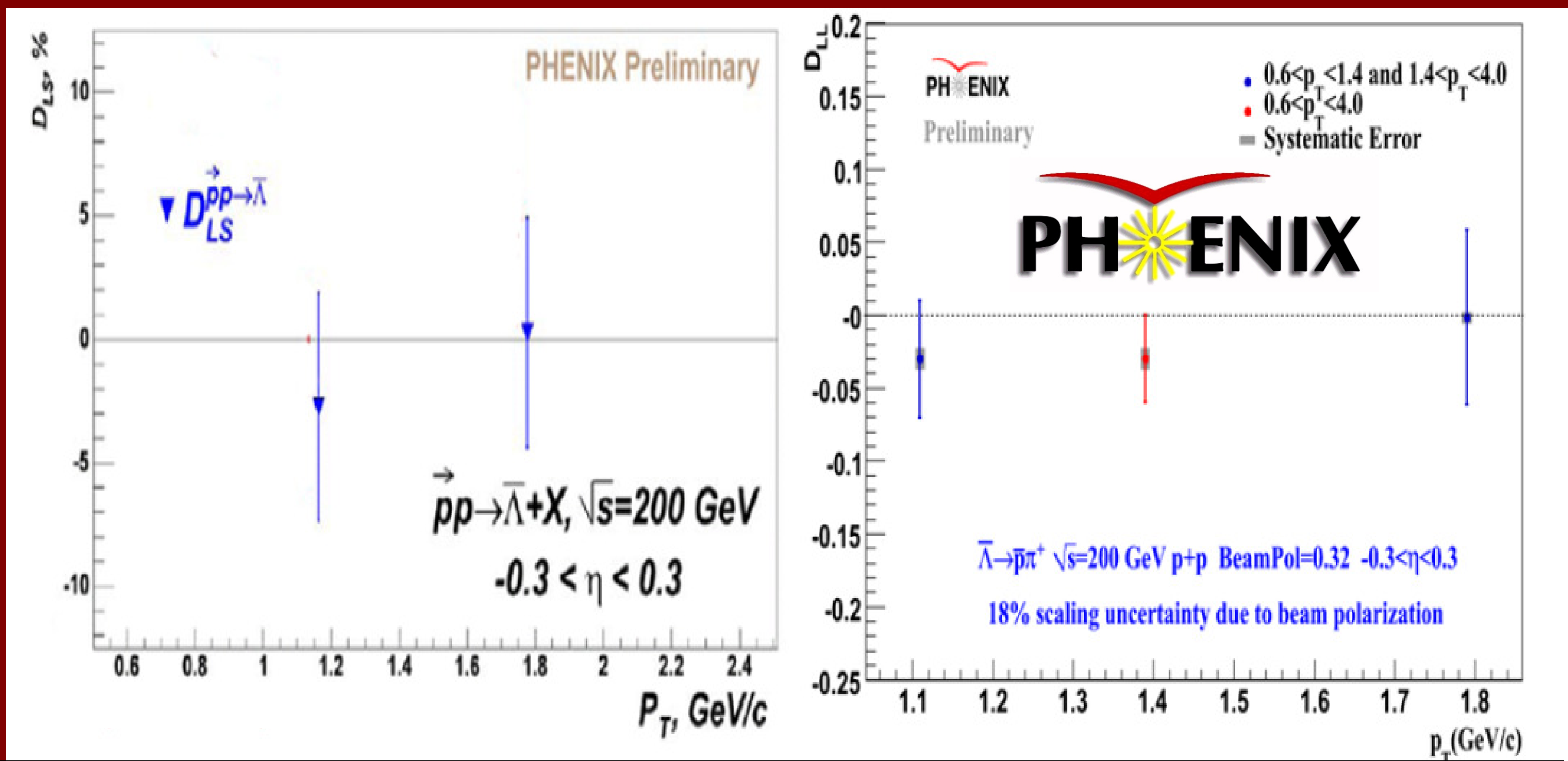
E704: Correlation found between transverse spin of initial-state proton and final-state lambda!

PRL78, 4003 (1997) – E704

Polarized beams: Hyperon spin transfer measurements



Polarized beams: Hyperon spin transfer measurements

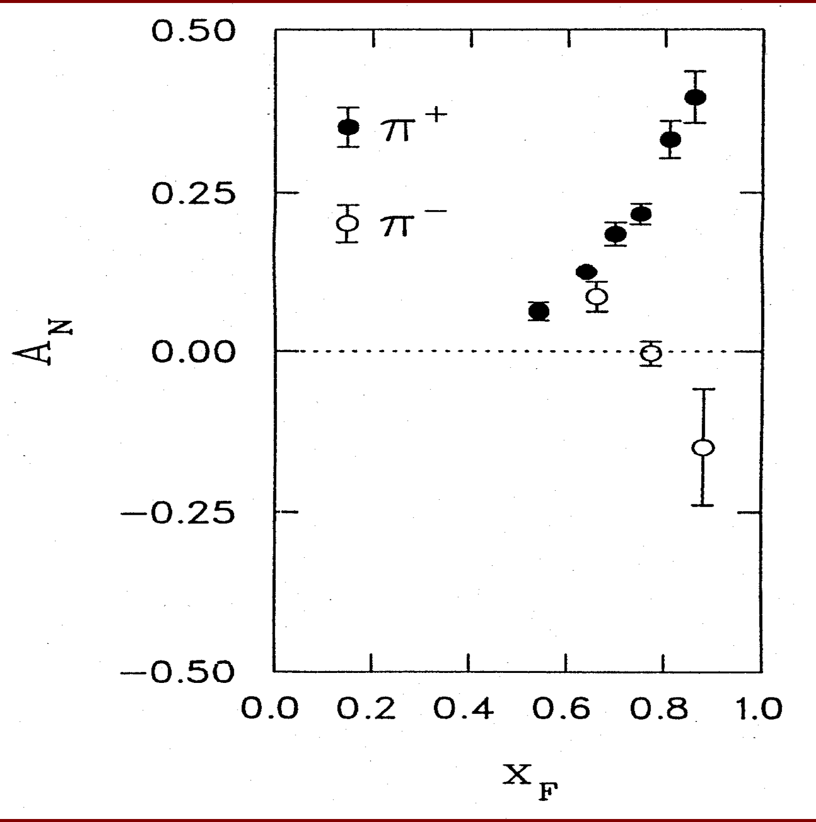


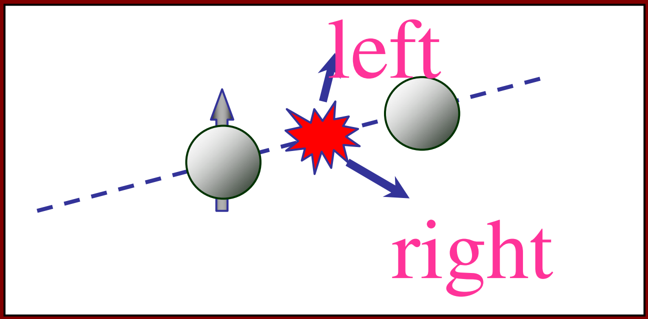
Spin transfers consistent with zero observed at RHIC with longitudinal polarization in the initial state. Transverse measurements still to come . . .

Discovery!
Large transverse single-spin asymmetries

Argonne ZGS, p_{beam} = 12 GeV/c

$$pp^{\uparrow} \rightarrow \pi X$$





W.H. Dragoset et al., PRL36, 929 (1976)

Transverse-momentum-dependent distributions and SSA's

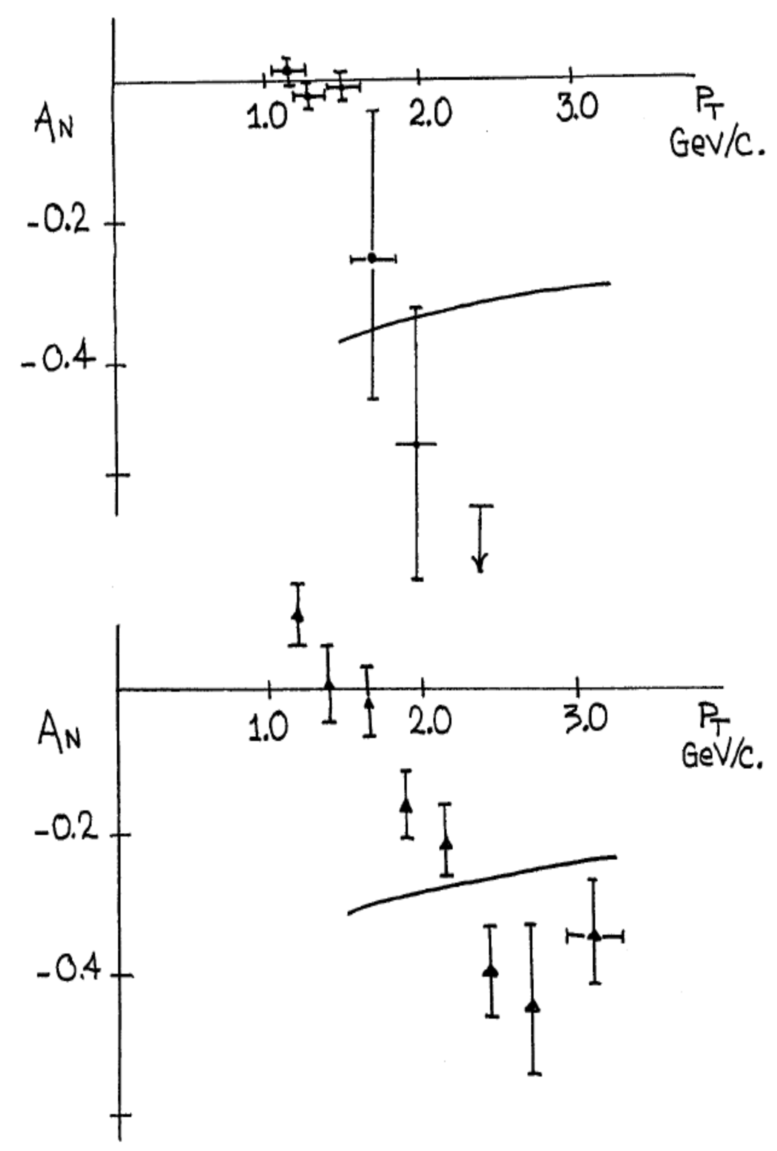
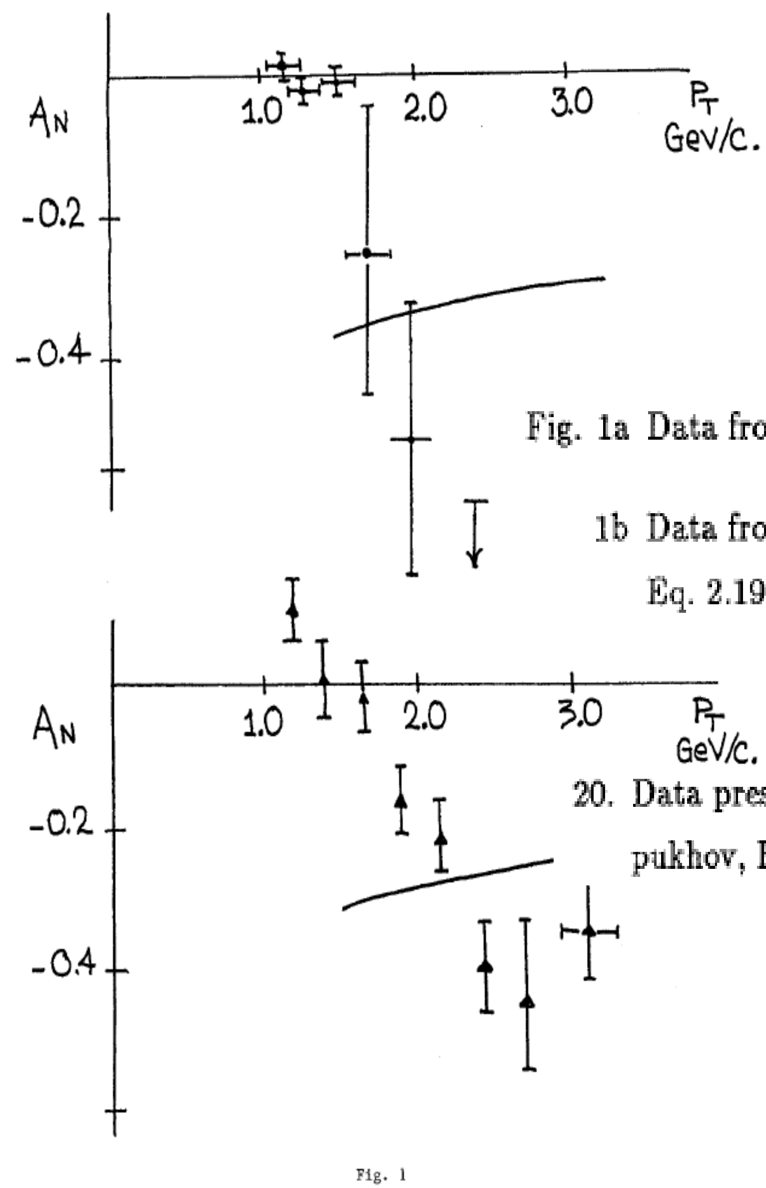


Fig. 1

1989: The "Sivers mechanism" is proposed in an attempt to understand the low-energy hadronic asymmetries.

D.W. Sivers, PRD41, 83 (1990)

Transverse-momentum-dependent distributions and SSA's



1989: The "Sivers mechanism" is proposed in an attempt to understand the low-energy hadronic asymmetries.

D.W. Sivers, PRD41, 83 (1990)

Fig. 1a Data from Ref. 19 on $pp\uparrow \rightarrow \pi^{\circ} X$ at $p_{\mathrm{LAB}} = 24\mathrm{GeV/c}$, $x_F \in (0, 0.1)$.

1b Data from Ref. 20 on $\pi^- p\uparrow \rightarrow \pi^{\circ} X$ at $p_{\mathrm{LAB}} = 40$ GeV/c, $x_F = 0.0$ The curve is from Eq. 2.19 with $\epsilon = 0.1$.

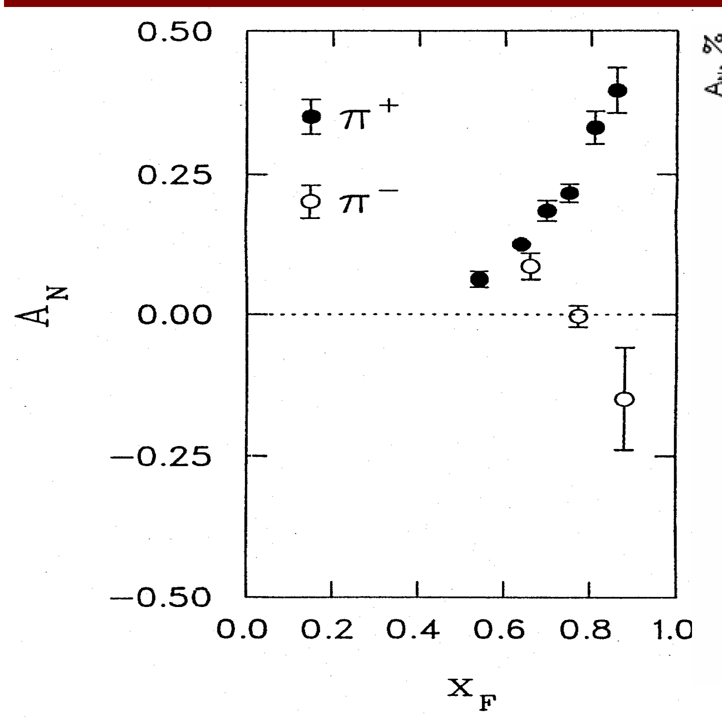
19. J. Antille *et al.*, Phys. Lett. **94B**, 523 (1980).

20. Data presented at the International Symposium on High Energy Spin Physics, Serpukhov, Protvino, 1986.

CERN

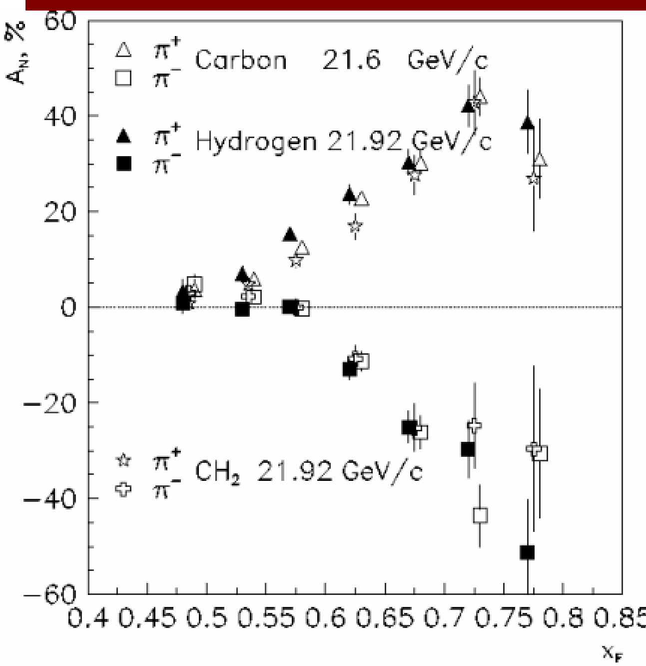
Transverse SSA's from low to high energies

ZGS 12 GeV beam



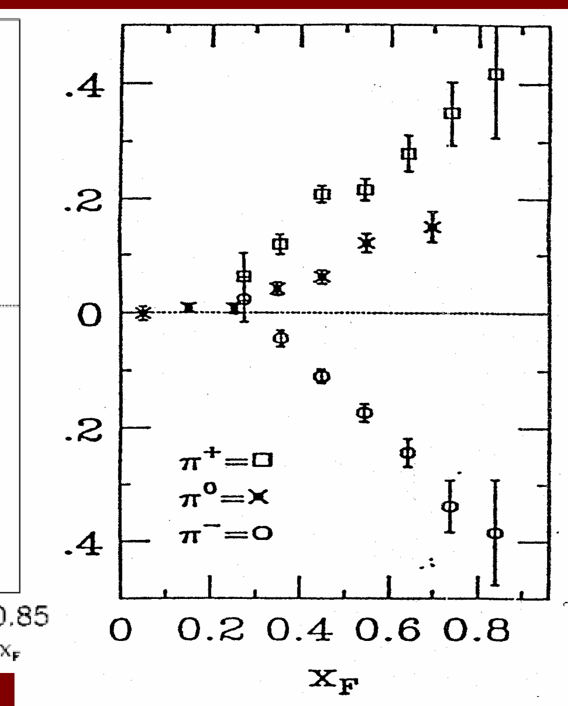
PRL36, 929 (1976)

AGS 22 GeV beam



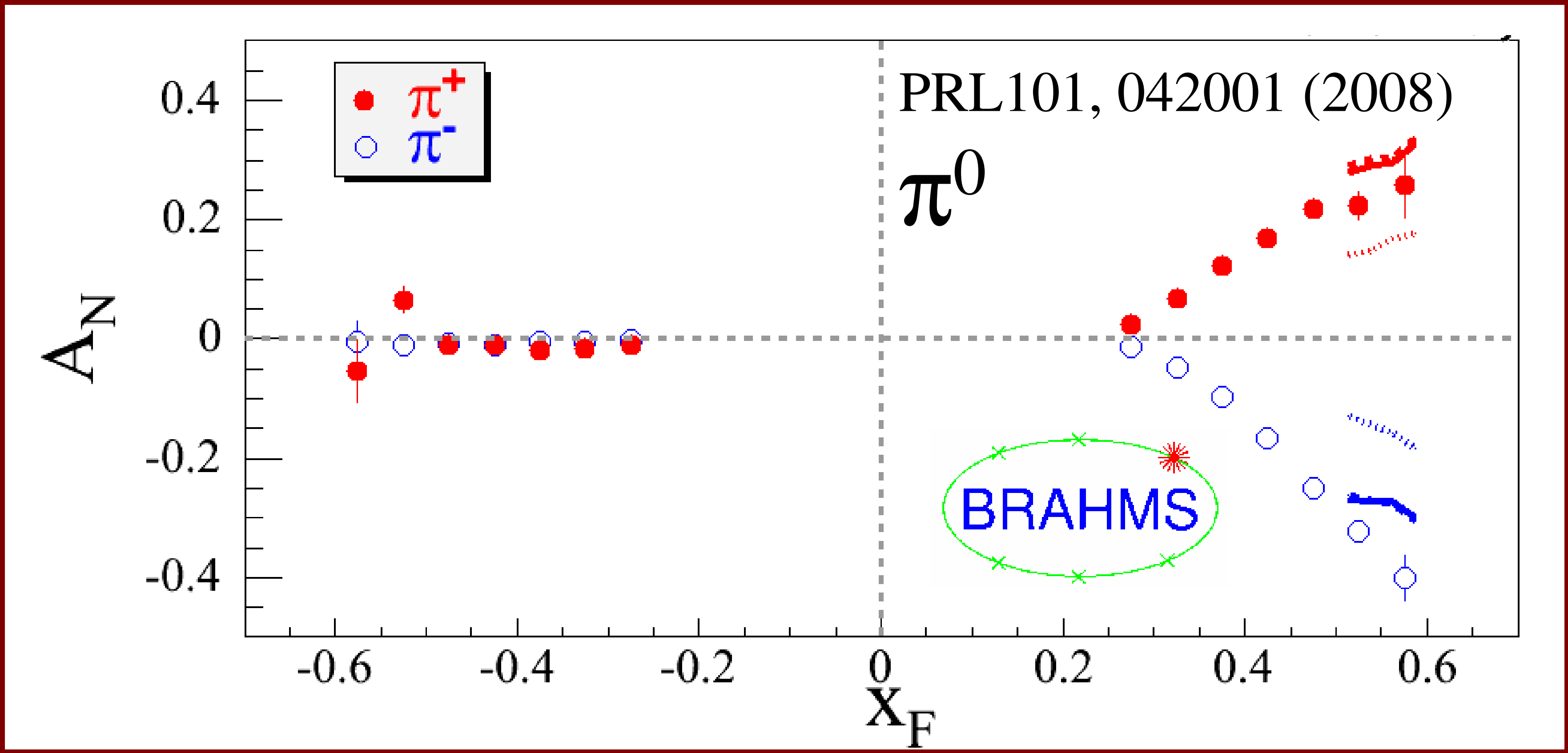
PRD65, 092008 (2002)

FNAL 200 GeV beam

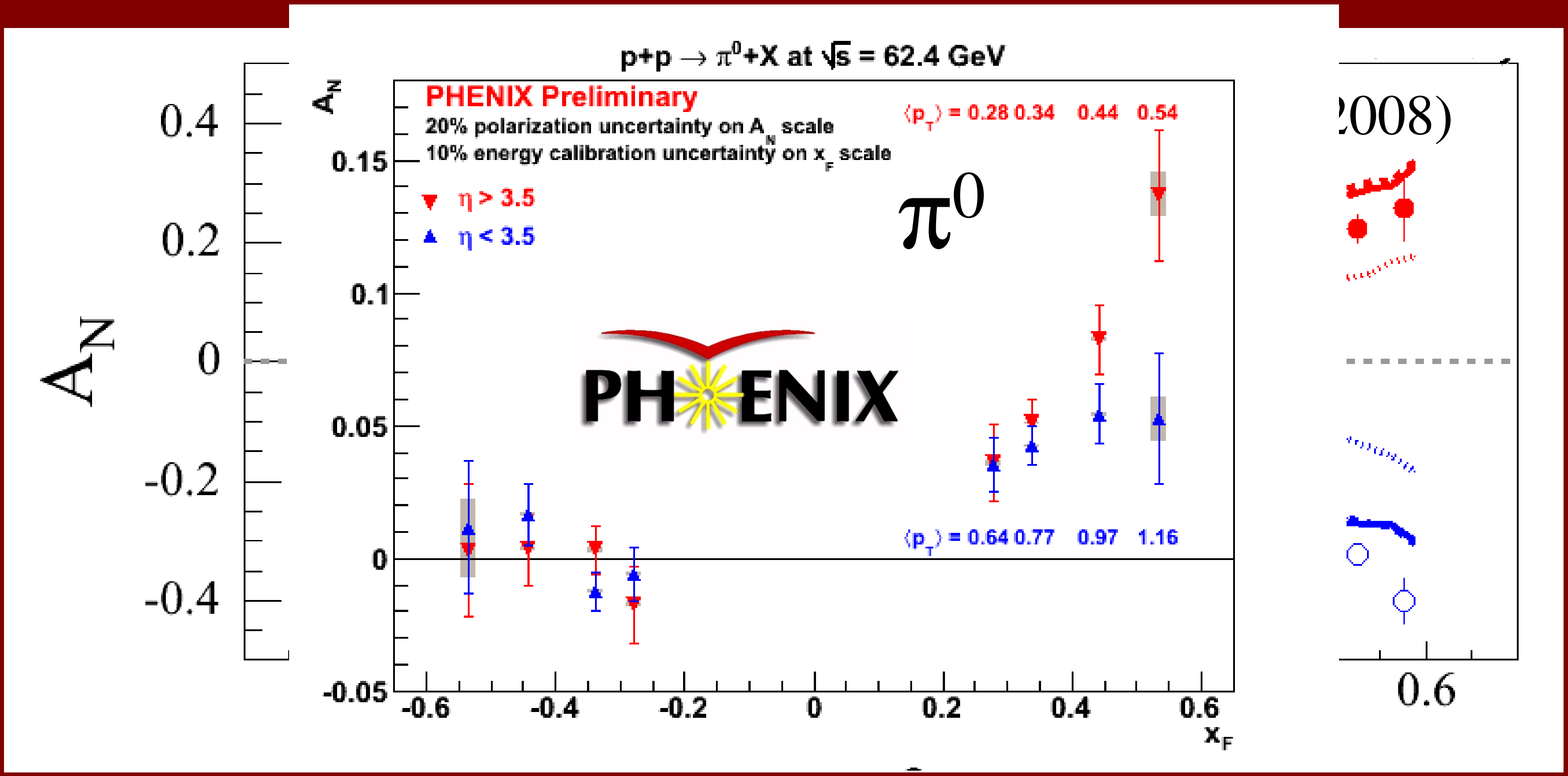


PLB261, 201 (1991)
PLB264, 462 (1991)

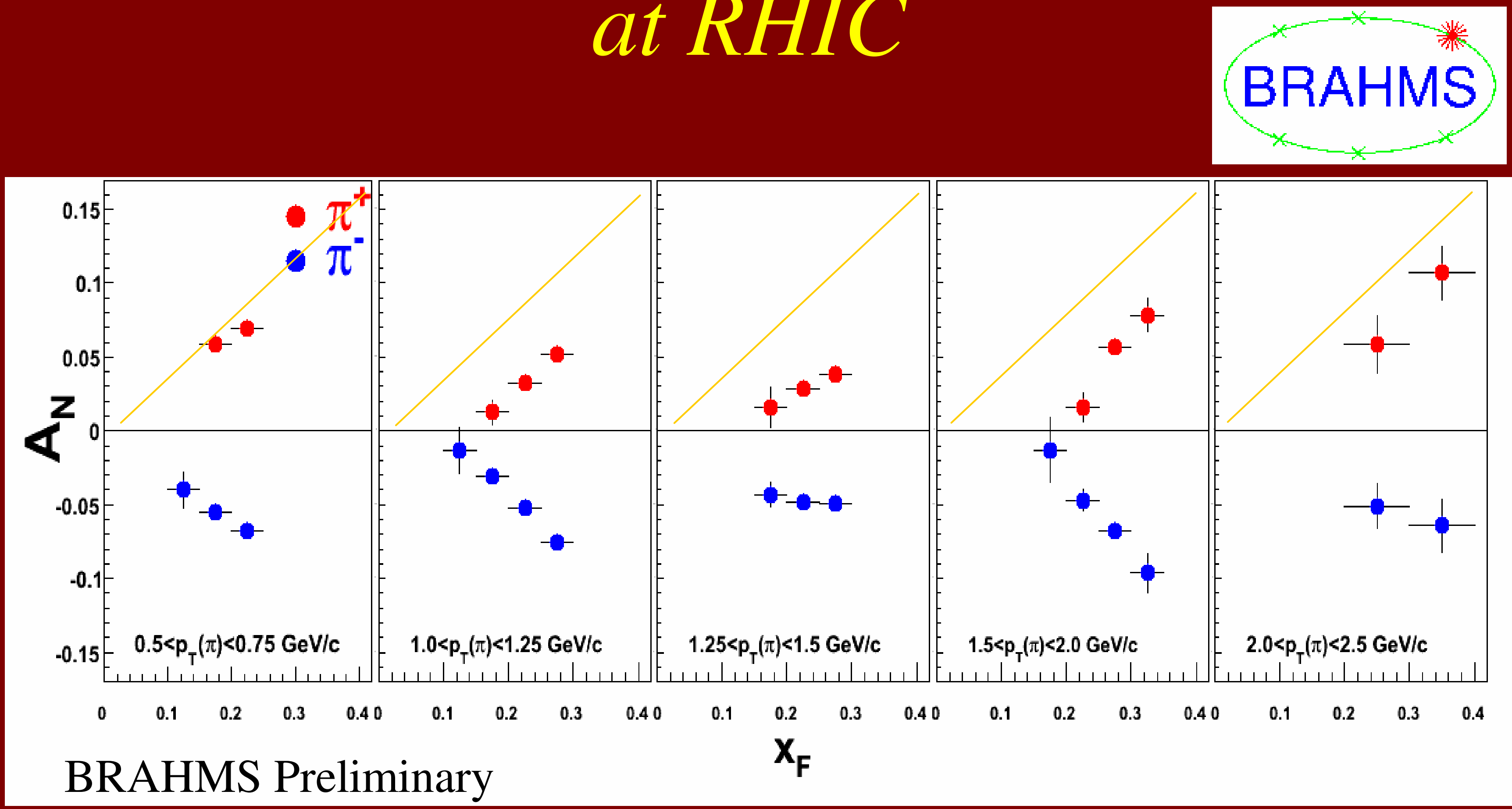
Transverse SSA's at $\sqrt{s}$ = 62.4 GeV at RHIC



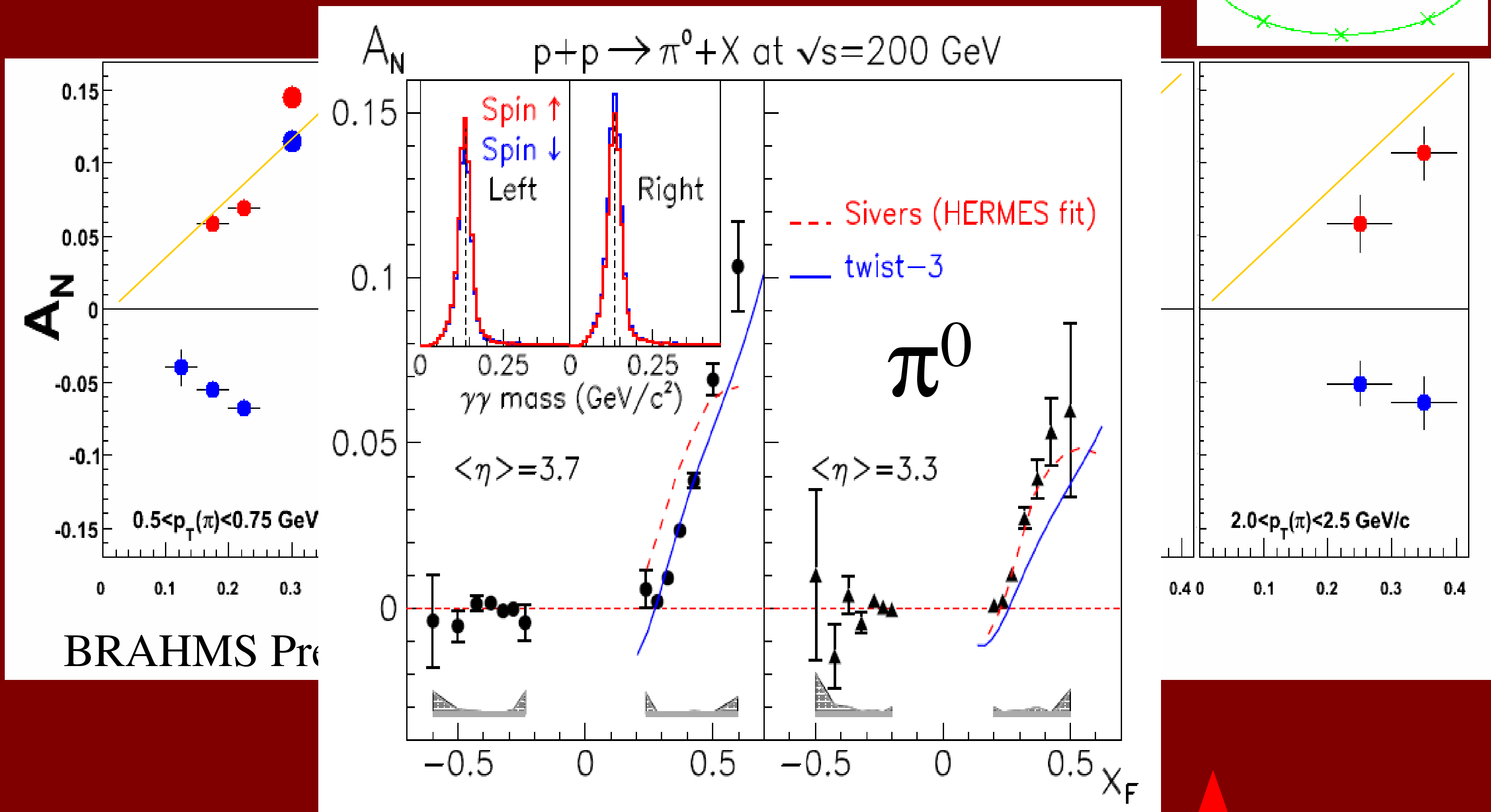
Transverse SSA's at √s = 62.4 GeV at RHIC



Transverse SSA's at √s = 200 GeV at RHIC

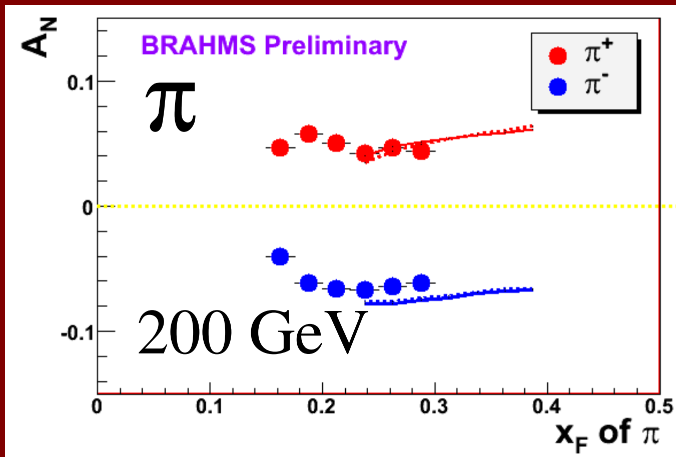


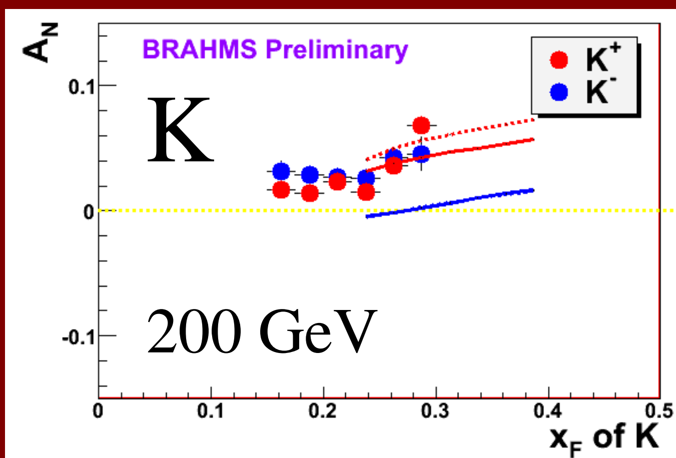
Transverse SSA's at $\sqrt{s}$ = 200 GeV at RHIC

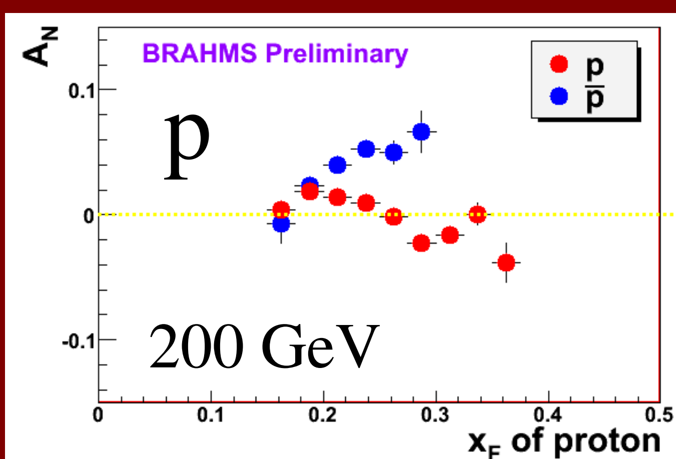


arXiv:0801.2990
Accepted by PRL

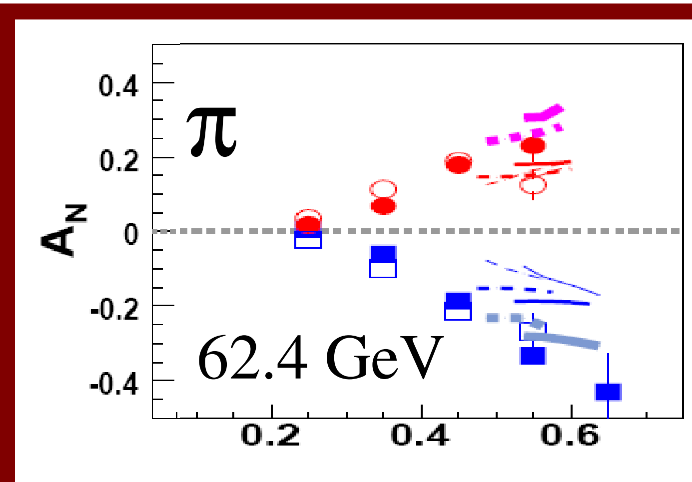
π, K, p at 200 and 62.4 GeV

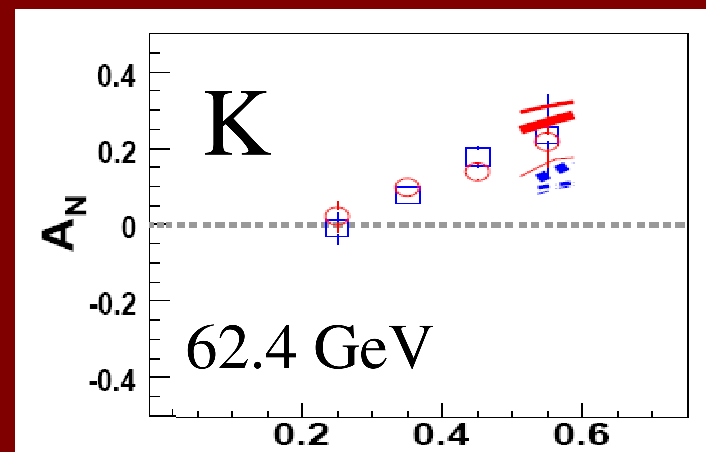


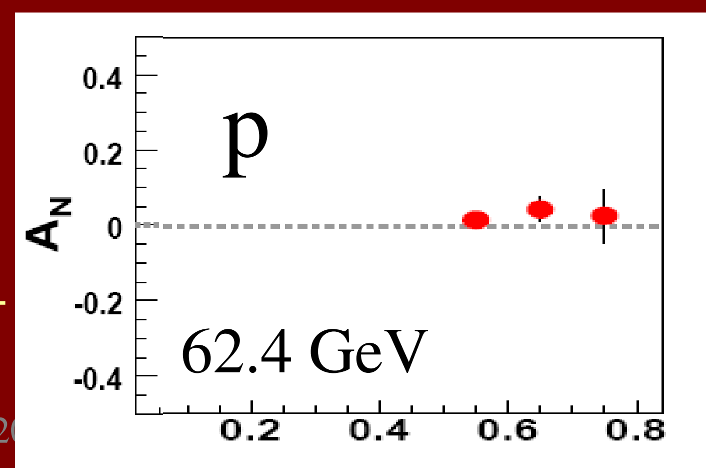




Note different scales





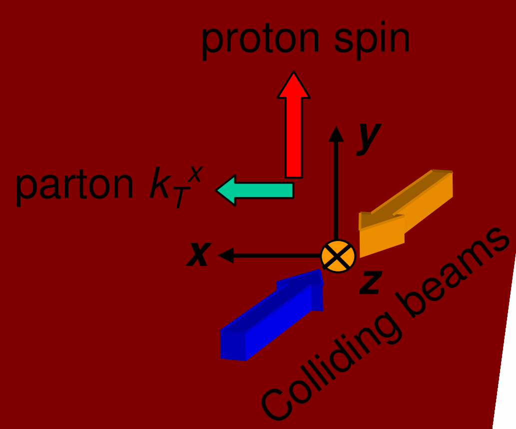


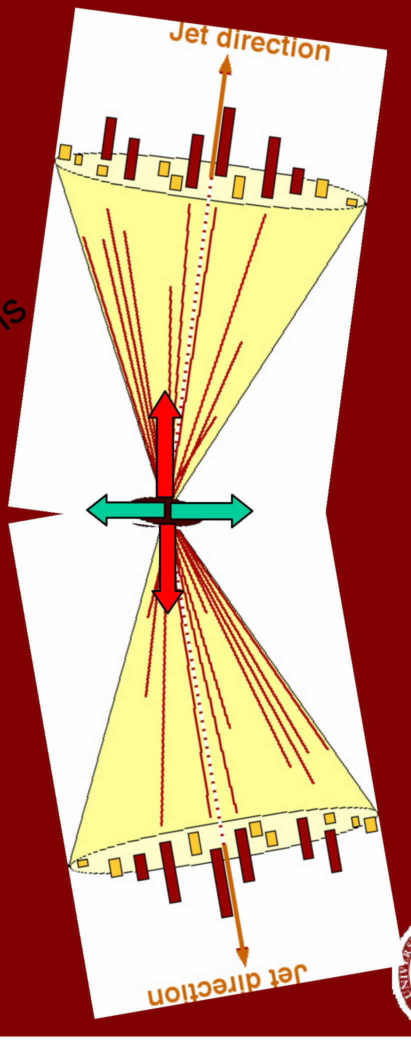
K- asymmetries underpredicted

Large antiproton asymmetry?? Unfortunately no 62.4 GeV measurement

Probing the Sivers Function via Dijets

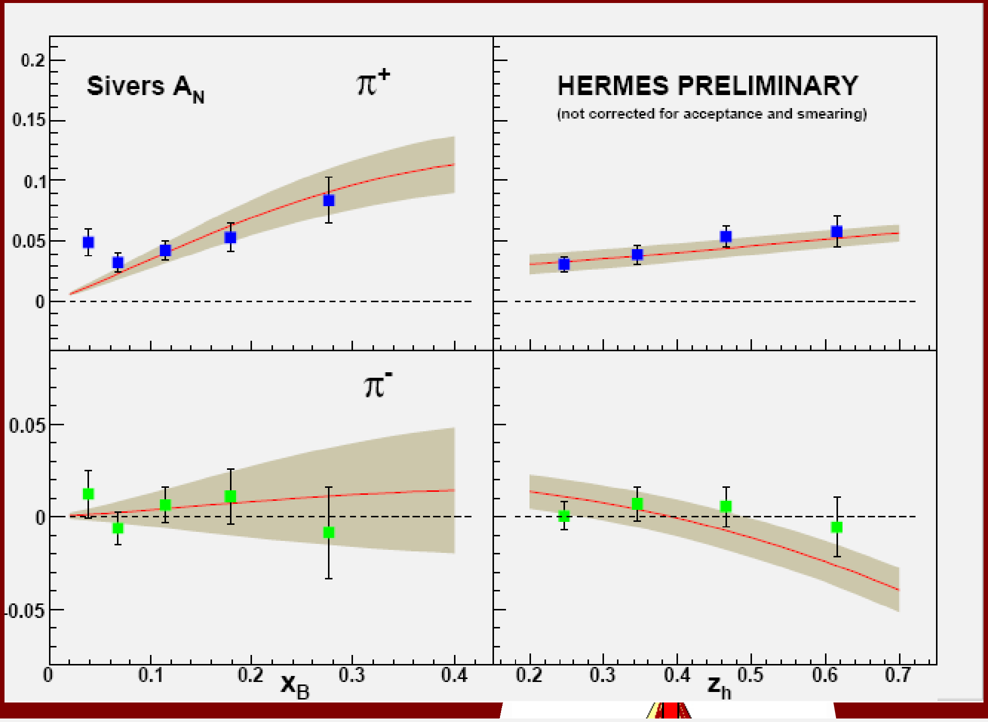
- Sivers effect in p+p ⇒ spin-dependent sideways boost to dijets, suggested by Boer & Vogelsang (PRD 69, 094025 (2004))
- 2005: Prediction by Vogelsang and Yuan for p+p, based on preliminary Sivers moments from HERMES



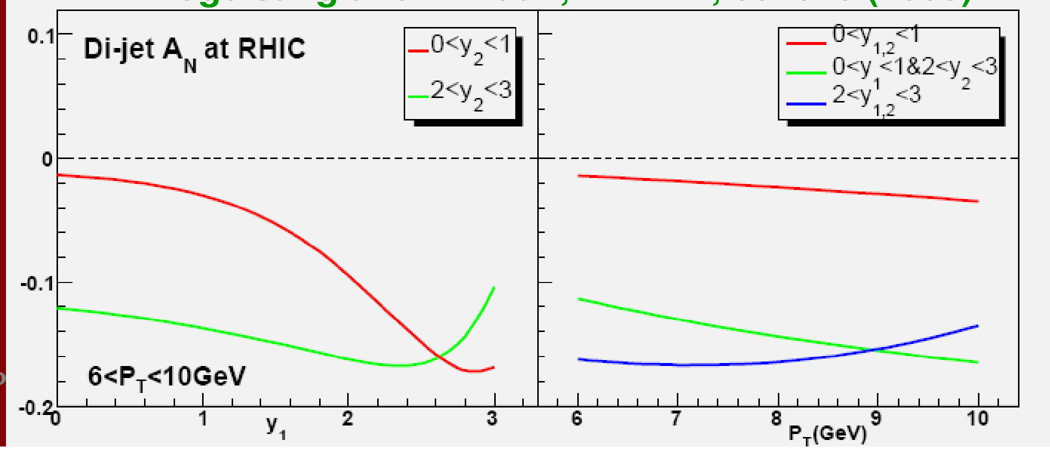


Probing the Sivers Function via Dijets

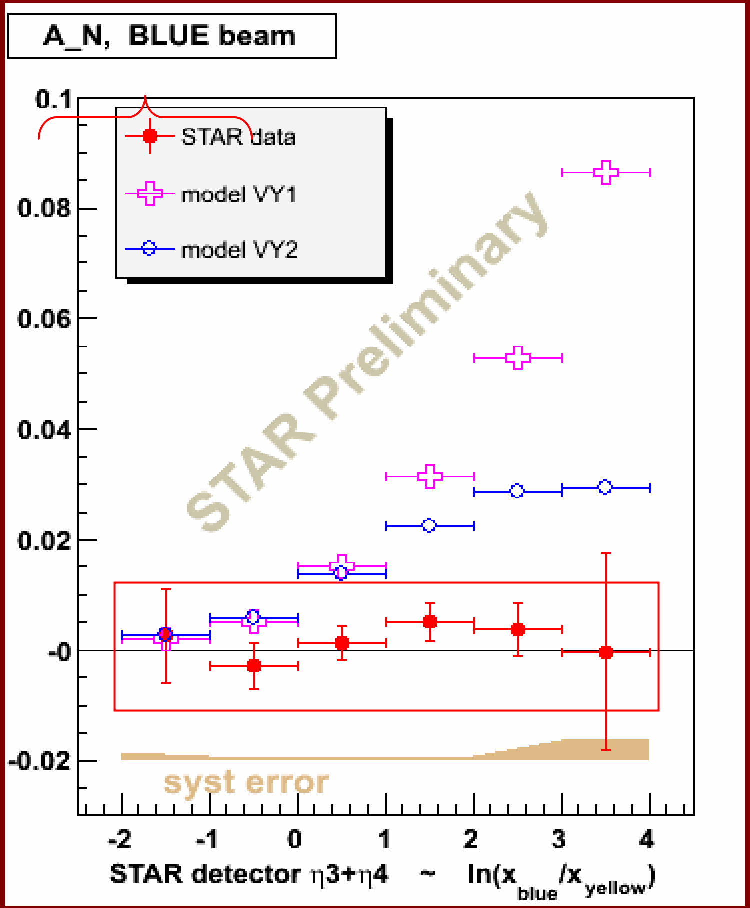
- Sivers effect in p+p ⇒ spin-dependent sideways boost to dijets, suggested by Boer & Vogelsang (PRD 69, 094025 (2004))
- 2005: Prediction by Vogelsang and Yuan for p+p, based on preliminary Sivers moments from HERMES



W. Vogelsang and F. Yuan, PRD 72, 054028 (2005).



Measured Sivers A_N for Dijets



Measured A_N consistent with zero ⇒ both quark and gluon Sivers effects much smaller in p+p → dijets than in HERMES SIDIS!!

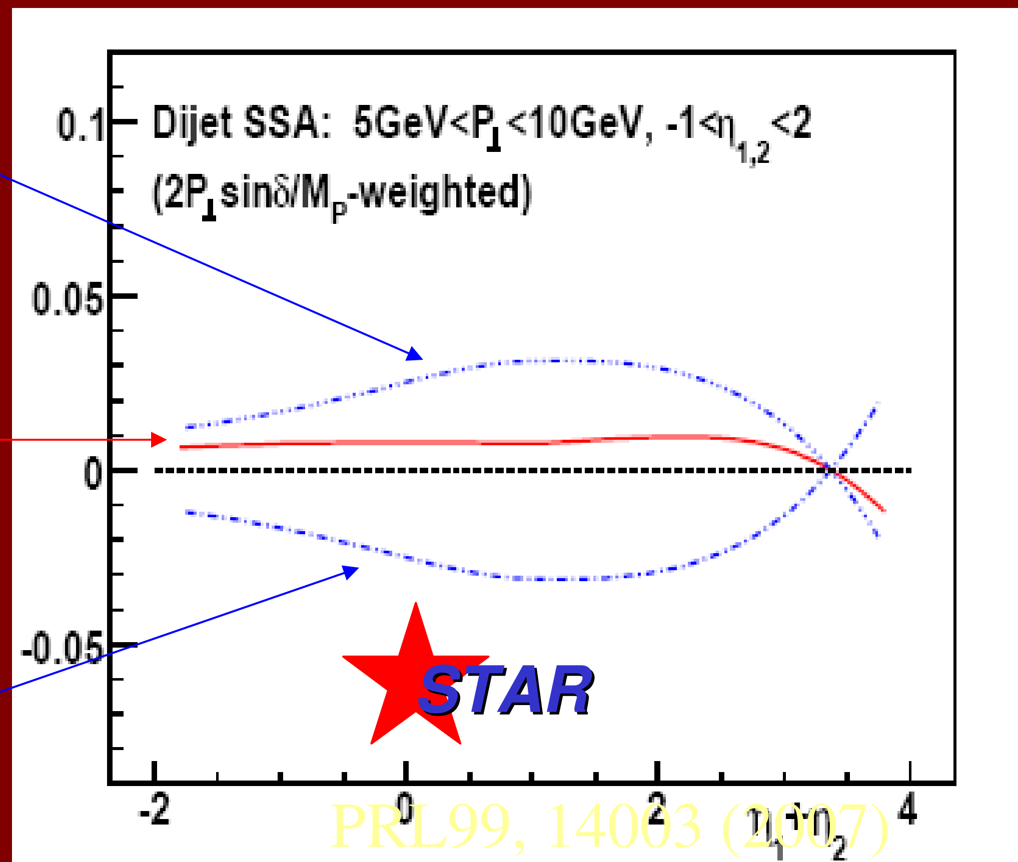
Calculations for p+p revisited!

Bomhof, Mulders, Vogelsang, Yuan: PRD75, 074019 (2007)

Prediction for dijet SSA if Sivers contributions were same as for SIDIS (FSI)

Initial- and final-state cancellations in p+p → jet+jet found to reduce expected dijet asymmetry at RHIC.

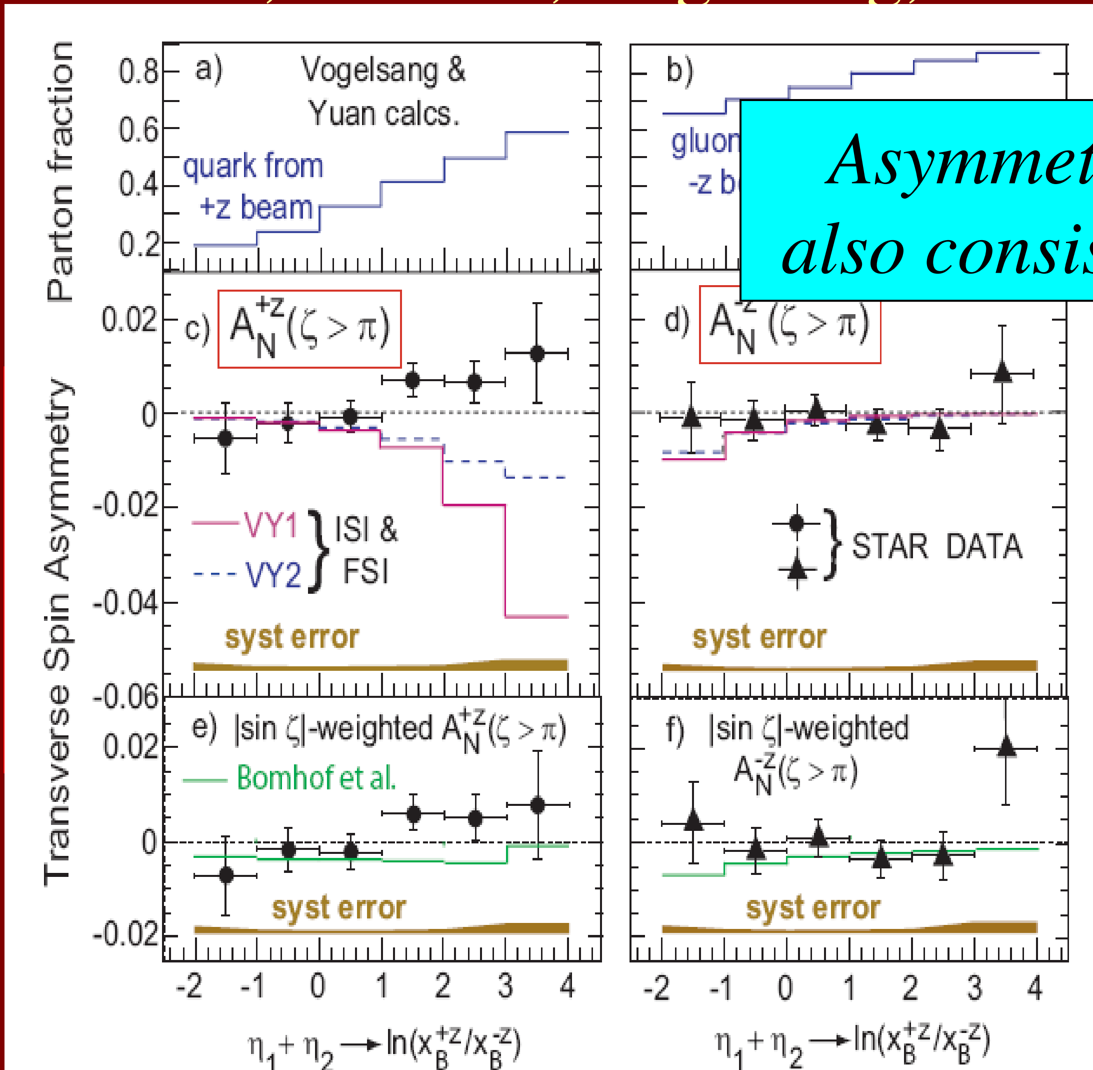
Prediction for dijet SSA if Sivers contributions were same as for Drell-Yan (ISI)



PRL99, 14003 (2007)

Calculations for p+p revisited!

Bomhof, Mulders, Vogelsang, Yuan: PRD75, 074019 (2007)

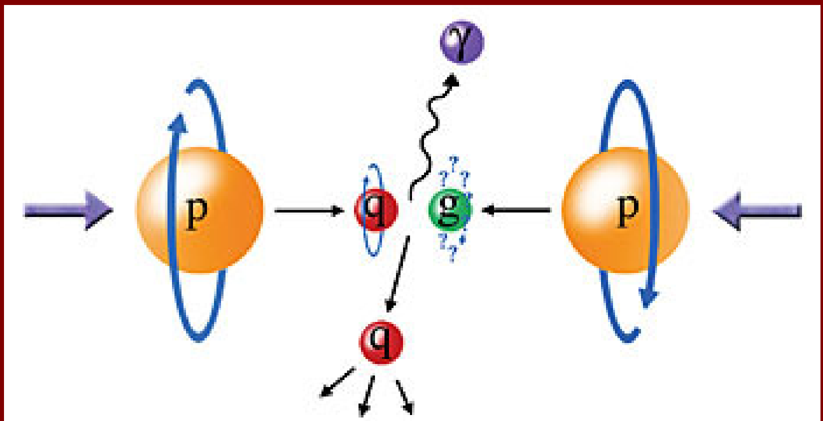


Asymmetries observed at STAR also consistent with SIDIS results!

STAR

PRL99, 14003 (2007)

Hadronic interactions and the helicity structure of the nucleon



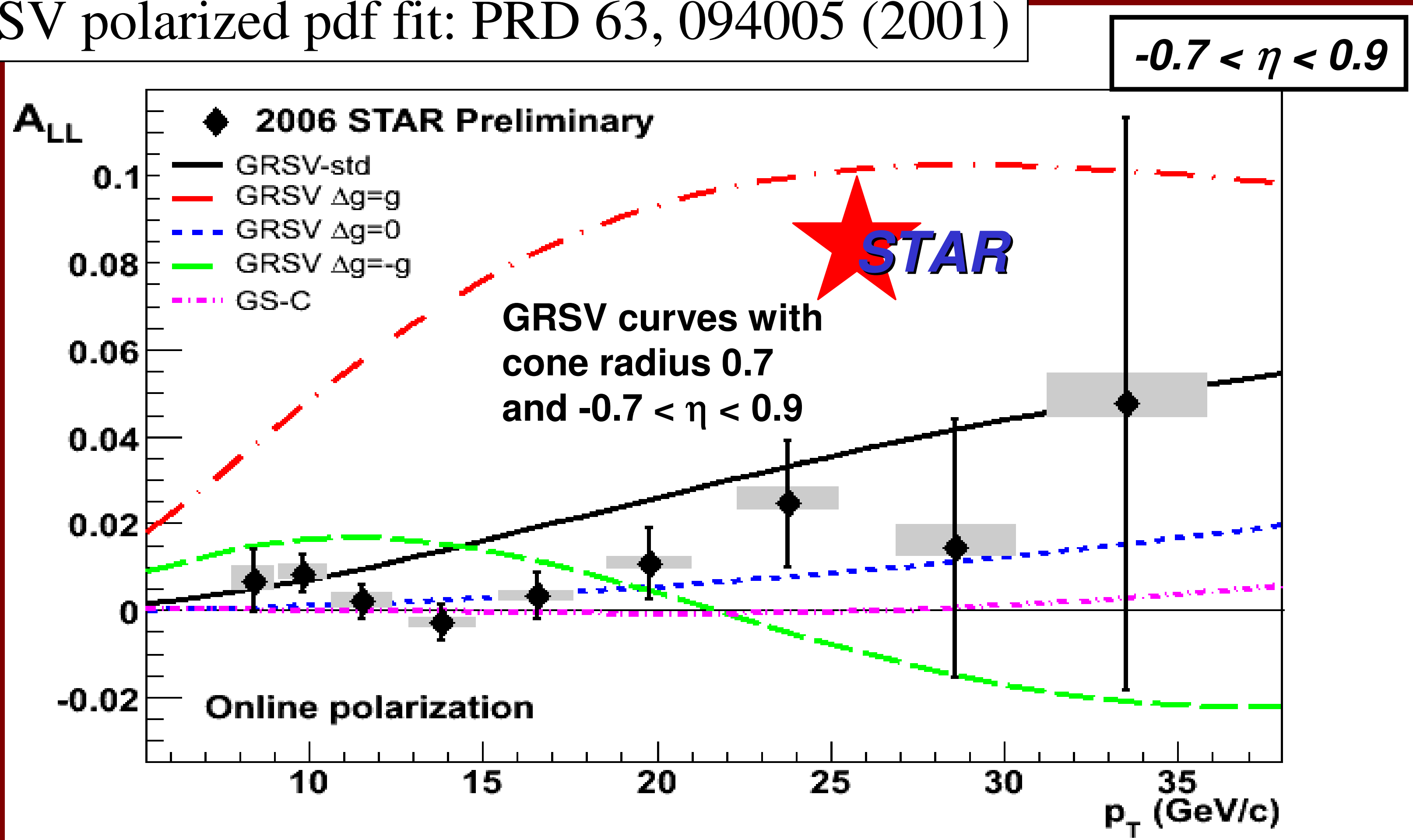
$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{1}{|P_1 P_2|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

$$\Delta\sigma(pp \to \pi^0 X) \propto \underbrace{\Delta q(x_1)}_{\text{DIS}} \otimes \underbrace{\Delta g(x_2)}_{?} \otimes \underbrace{\Delta\hat{\sigma}^{qg \to qg}(\hat{s})}_{\text{pQCD}} \otimes \underbrace{D_q^{\pi^0}(z)}_{\text{e+e-}}$$

Leading-order access to gluons → ΔG

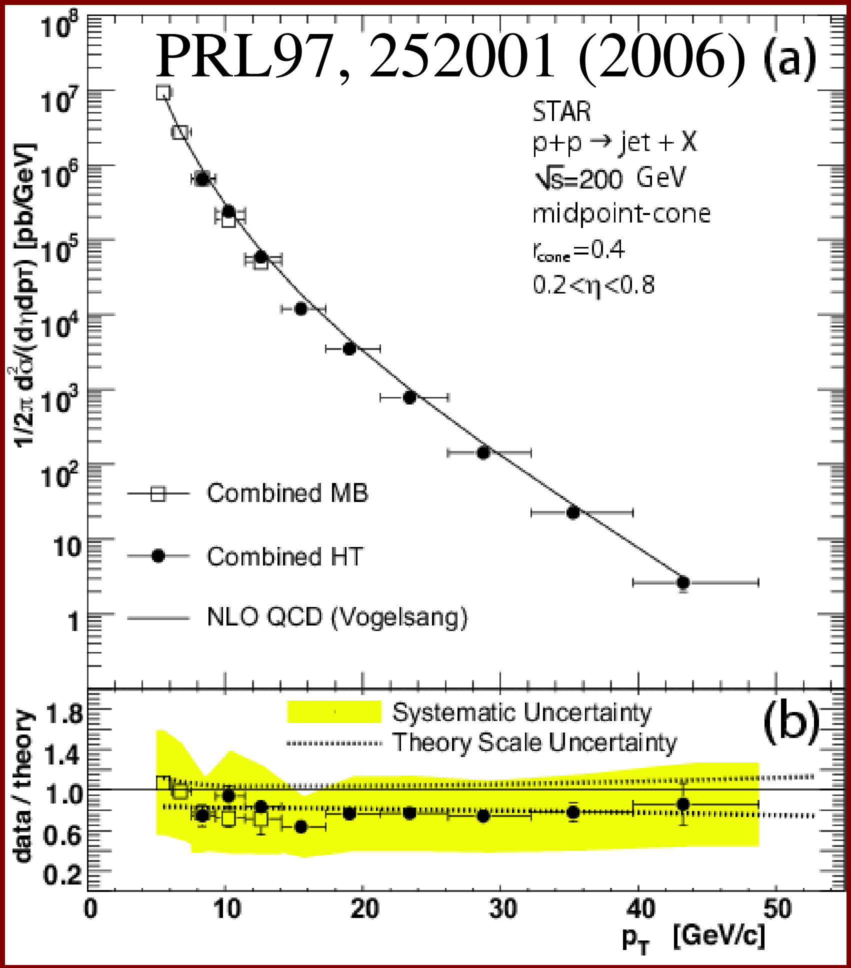
Inclusive jet production at 200 GeV

GRSV polarized pdf fit: PRD 63, 094005 (2001)

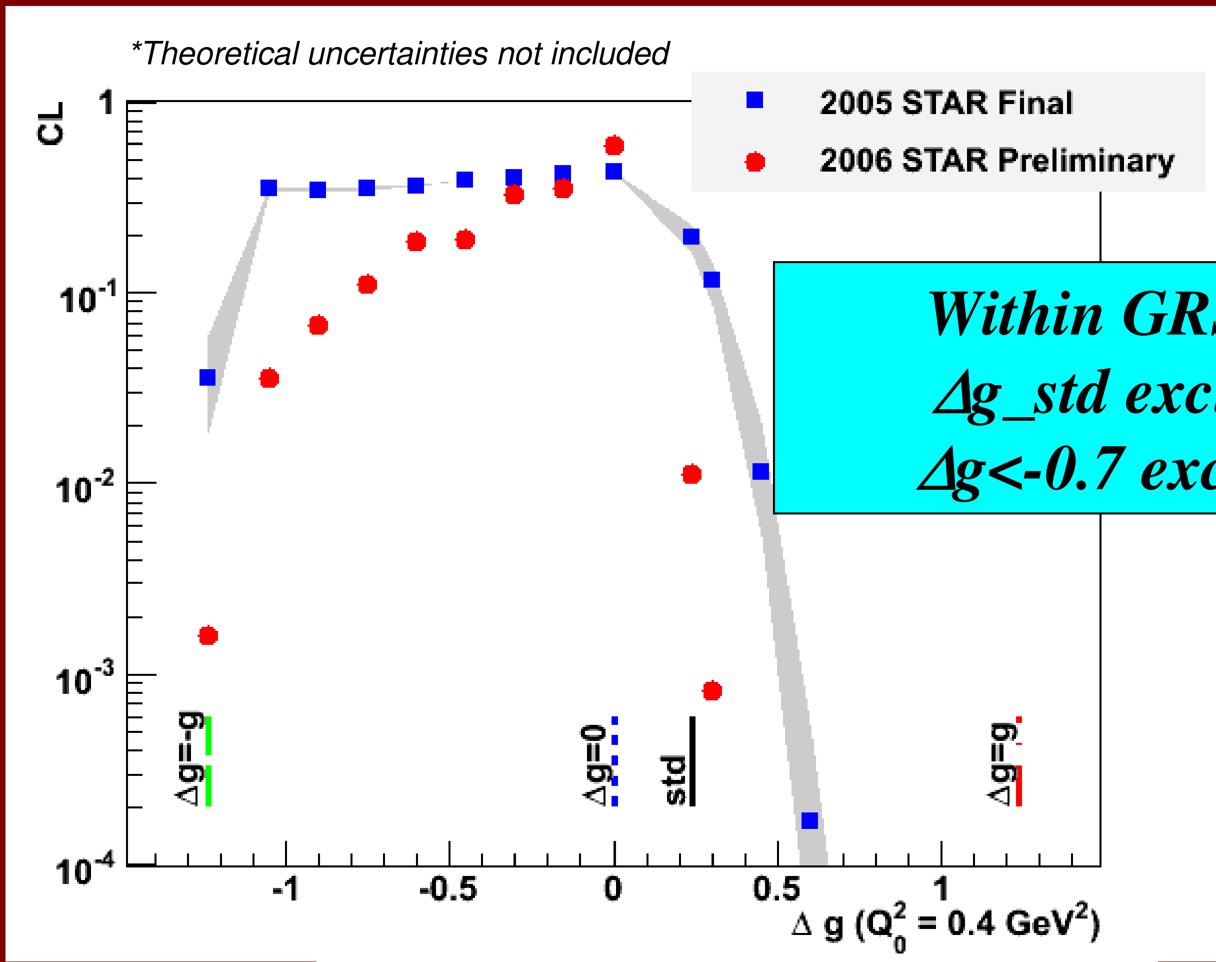


2005 jet data now published: PRL100, 232003 (2008)

Inclusive jet production at 200 GeV



Inclusive jet production at 200 GeV

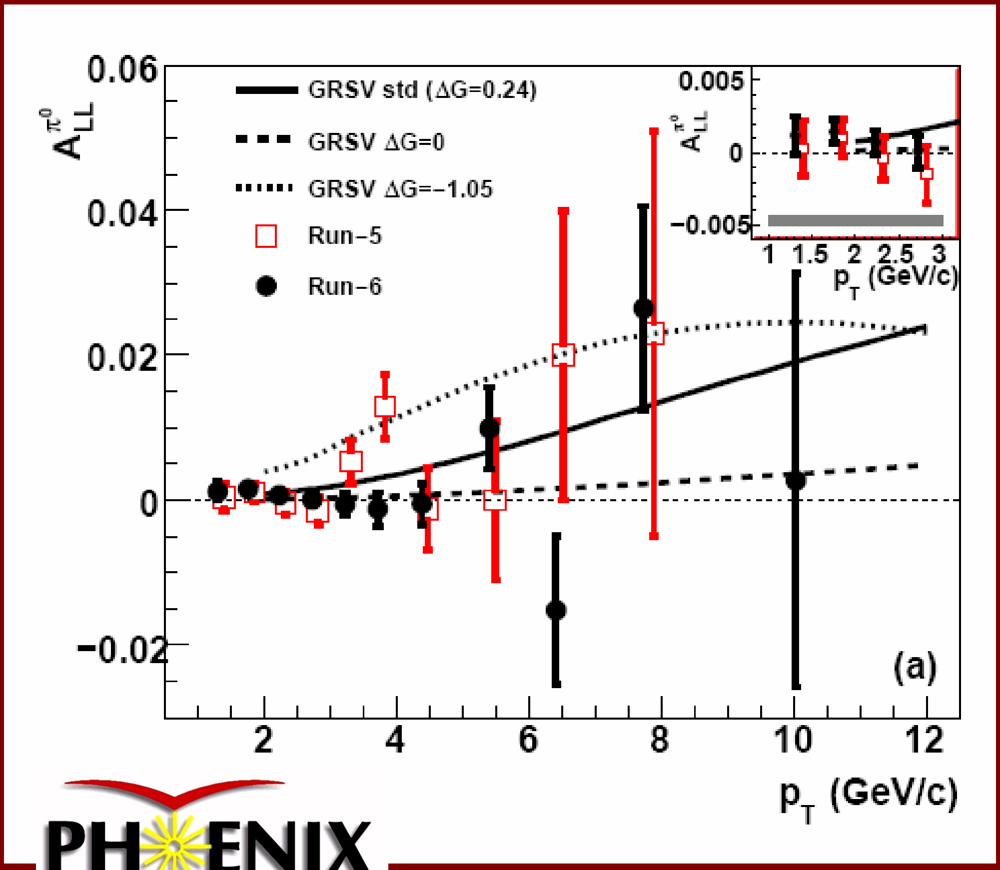


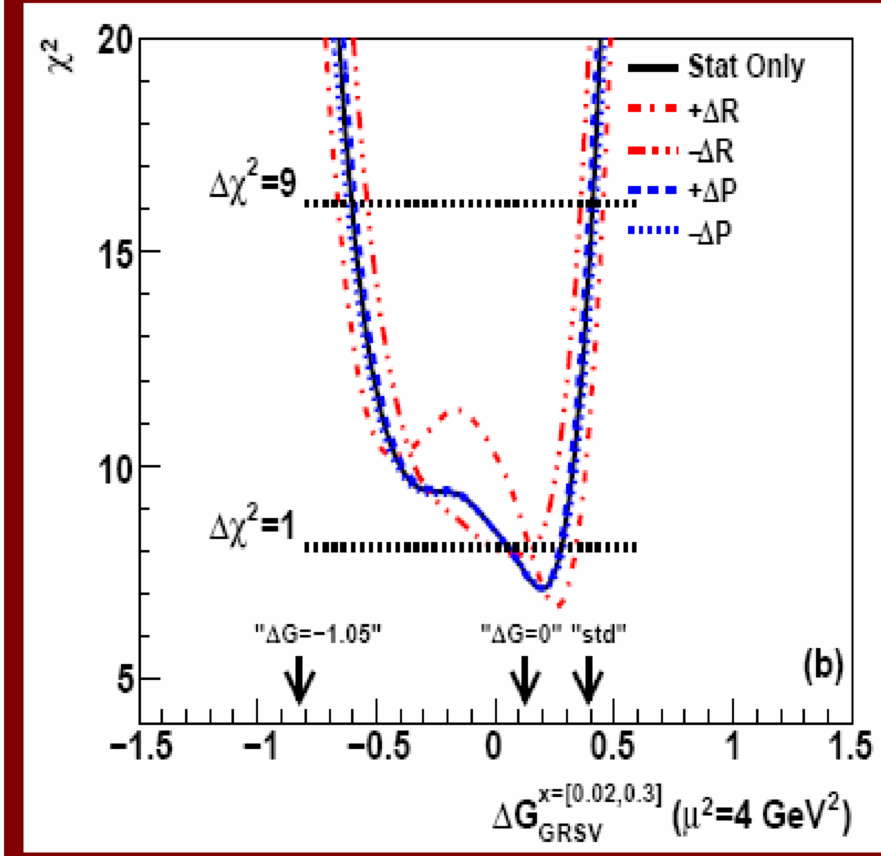
$-0.7 < \eta < 0.9$

Within GRSV framework:
Δg_std excluded with 99% CL
Δg<-0.7 excluded with 90% CL

Inclusive neutral pion production at 200 GeV

PRD76, 051106 (2007)

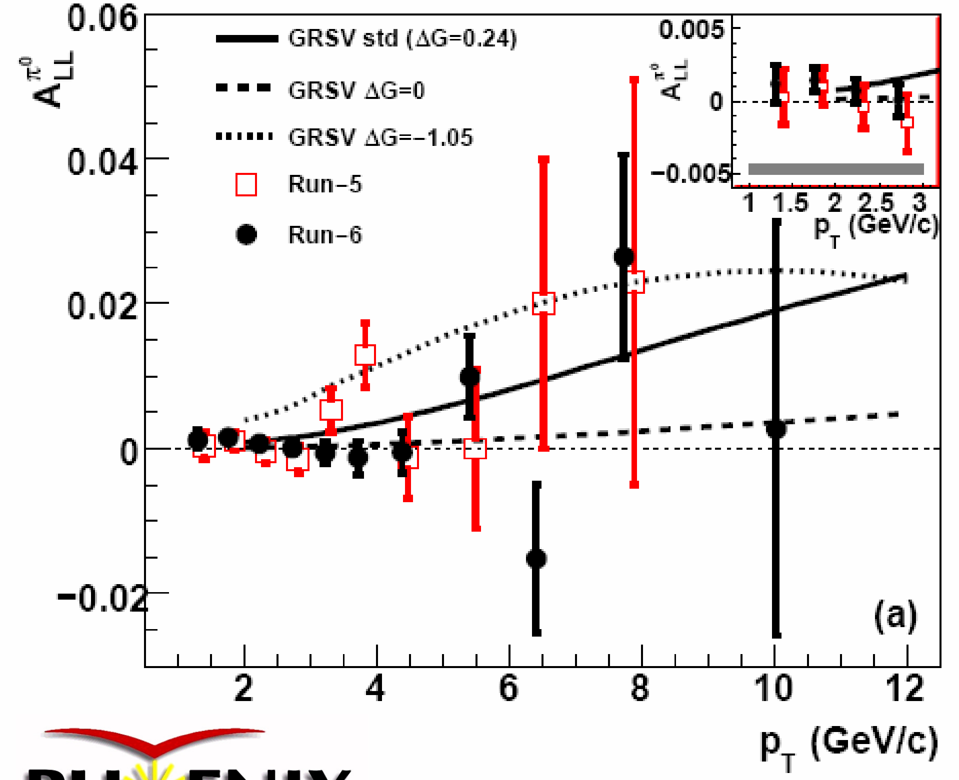




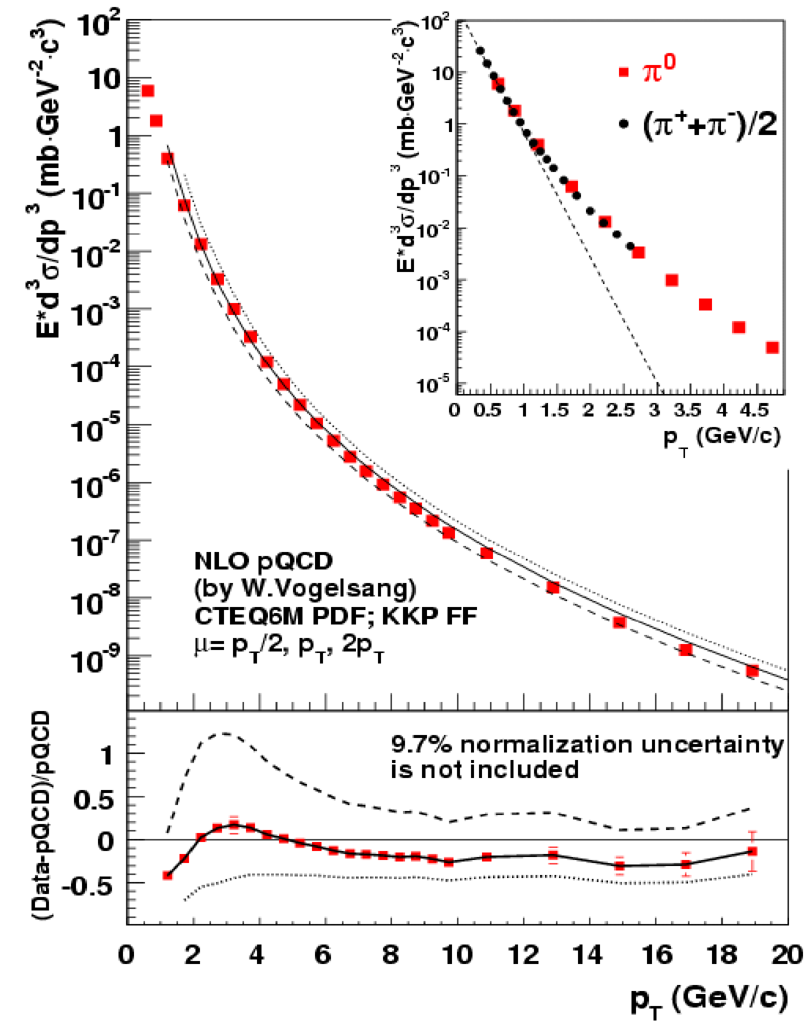
arXiv:0810.0694, submitted to PRL

Inclusive neutral pion production at 200 GeV

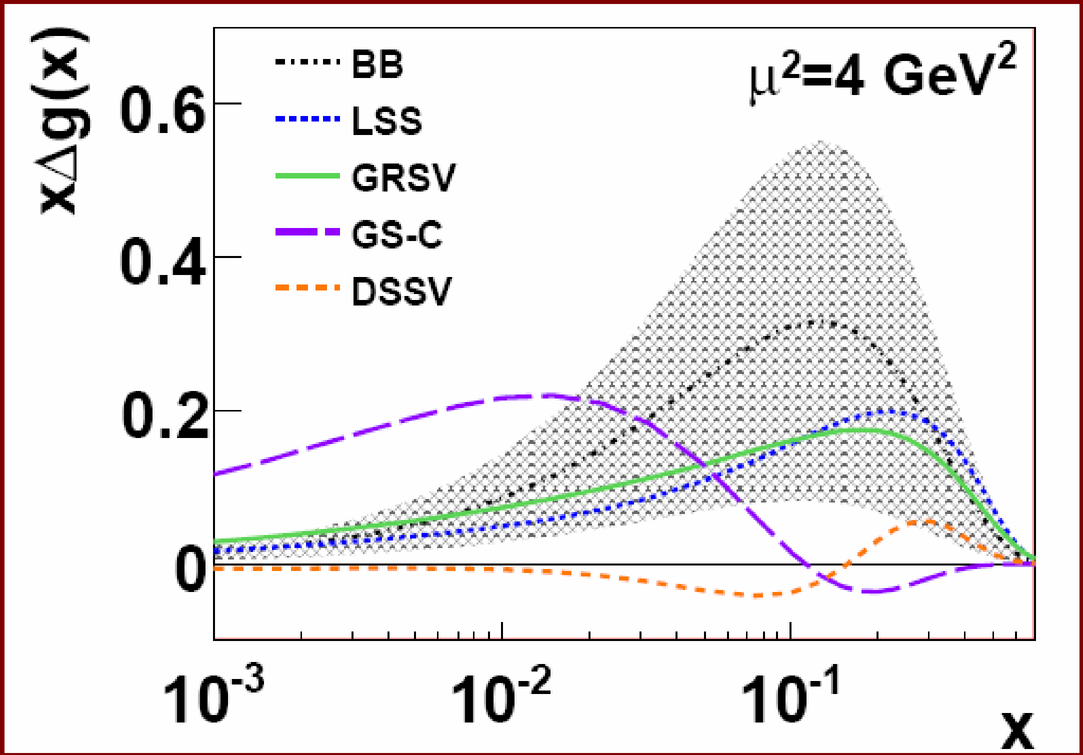
PRD76, 051106 (2007)



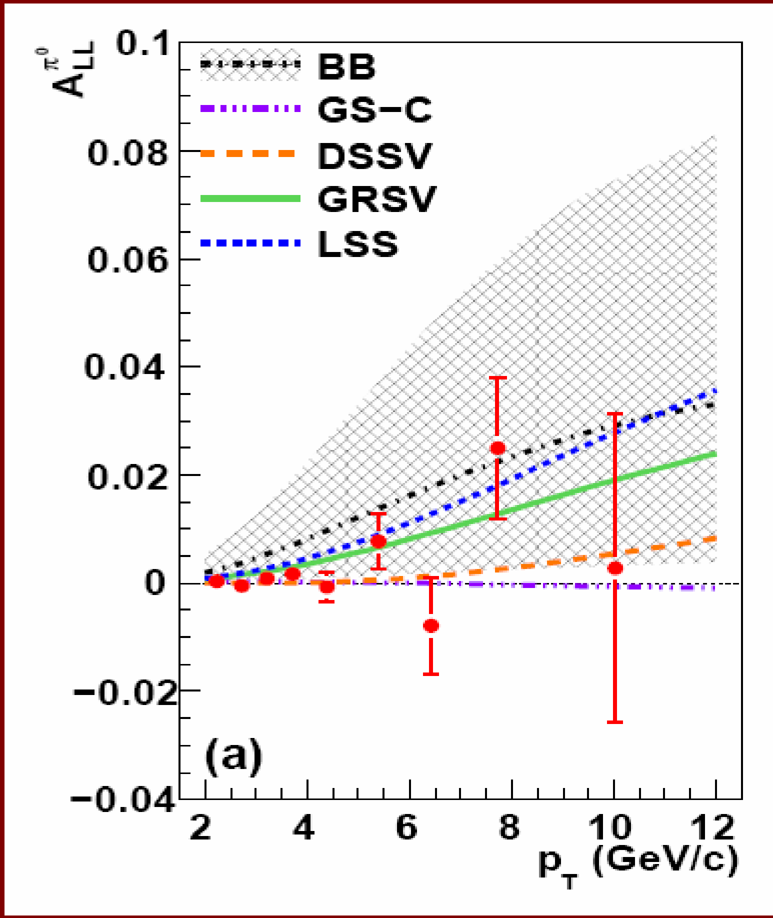
arXiv:0810.0694, submitted to PRL



π^0 A_{LL}: *Agreement with different parametrizations*



π^0 A_{LL}: *Agreement with different parametrizations*

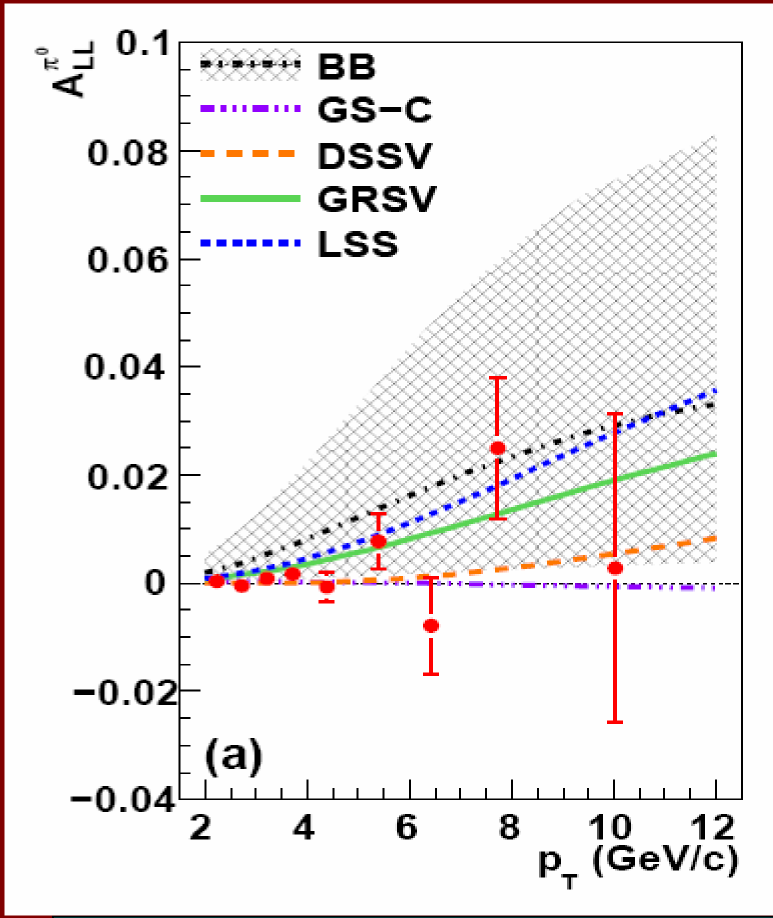


	Published best fit		
Group	$\Delta G^{[0,1]}$	$\Delta G^{[0.02,0.3]}$	χ^2
GS-C	0.95	0.18	8.3
DSSV	-0.05	-0.03	7.5
LSS	0.60	0.37	22.4
GRSV	0.67	0.38	14.8
BB	0.93	0.67	69.0

Small ΔG in our measured *x* region 0.02 to 0.3 gives small A_{LL} (DSSV and GS-C). Large ΔG gives comparatively larger A_{LL} .

arXiv:0810.0694, submitted to PRL

π^0 A_{LL}: *Agreement with different parametrizations*



	Published best fit		
Group	$\Delta G^{[0,1]}$	$\Delta G^{[0.02,0.3]}$	χ^2
GS-C	0.95	0.18	8.3
DSSV	-0.05	-0.03	7.5
LSS	0.60	0.37	22.4
GRSV	0.67	0.38	14.8
BB	0.93	0.67	69.0

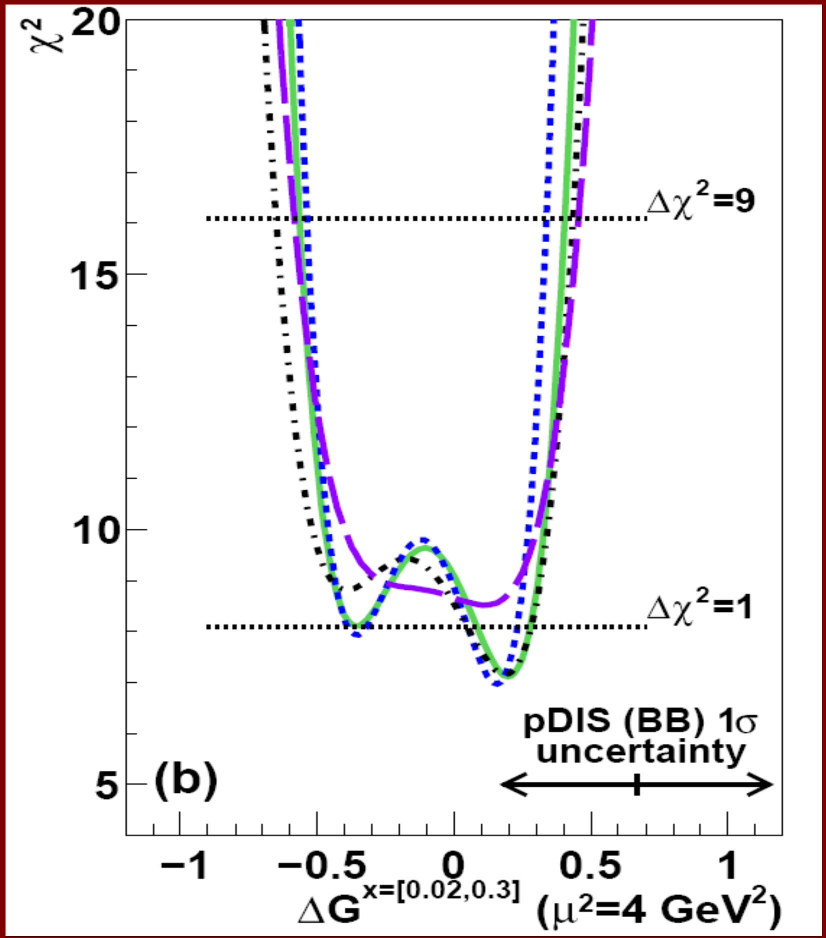
Small ΔG in our measured *x* region 0.02 to 0.3 gives small A_{LL} (DSSV and GS-C). Large ΔG gives comparatively larger A_{LL} .

Note small A_{LL} does not necessarily mean small ΔG in the full *x* range!

π^0 A_{LL}: *Agreement with different parametrizations*

For each parametrization, vary $\Delta G^{[0,1]}$ at the input scale while fixing $\Delta q(x)$ and the shape of $\Delta g(x)$, i.e. no refit to DIS data.

For range of shapes studied, current data relatively insensitive to shape in *x* region covered.

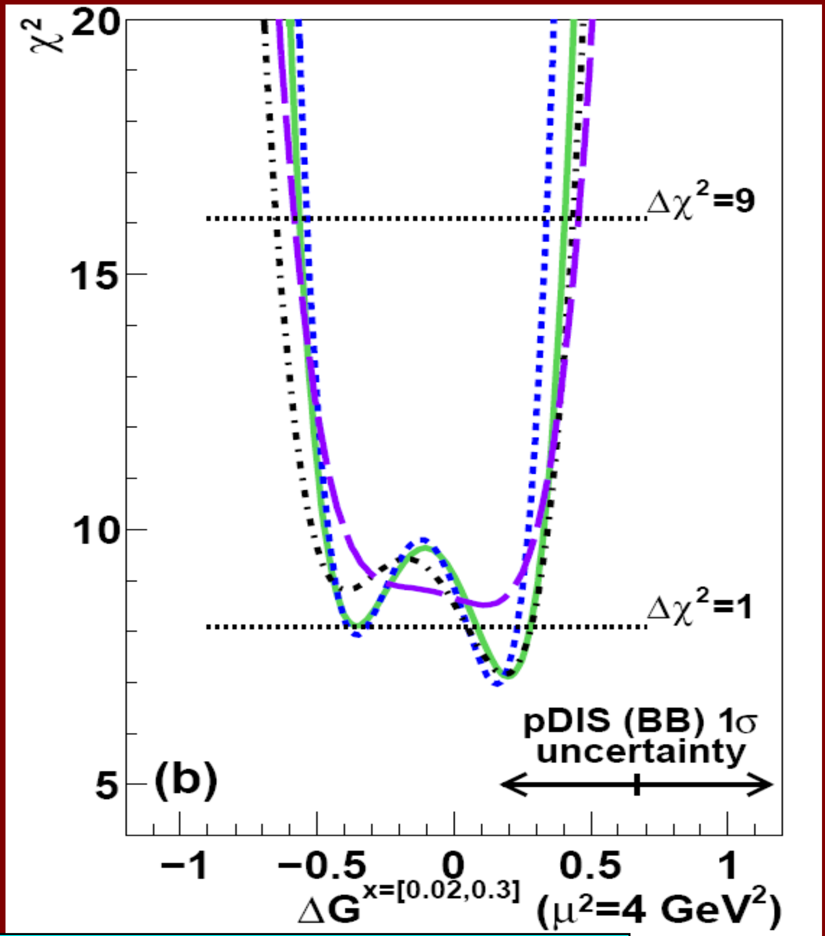


arXiv:0810.0694, submitted to PRL

π^0 A_{LL}: *Agreement with different parametrizations*

For each parametrization, vary $\Delta G^{[0,1]}$ at the input scale while fixing $\Delta q(x)$ and the shape of $\Delta g(x)$, i.e. no refit to DIS data.

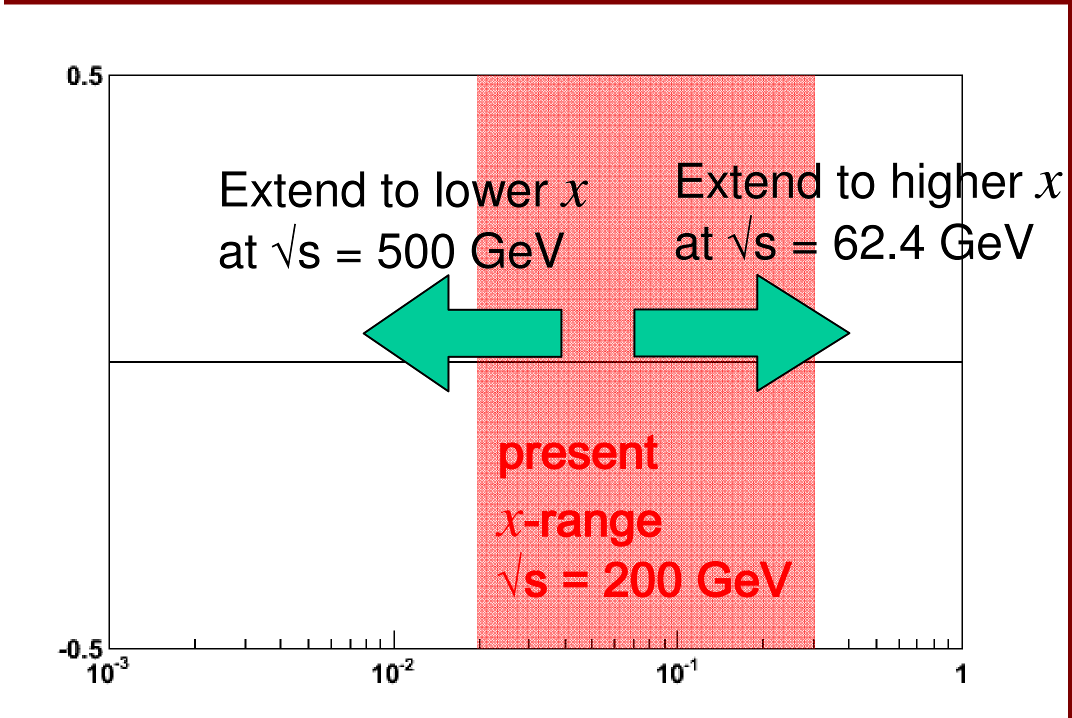
For range of shapes studied, current data relatively insensitive to shape in *x* region covered.



arXiv:0

Need to extend *x* range!

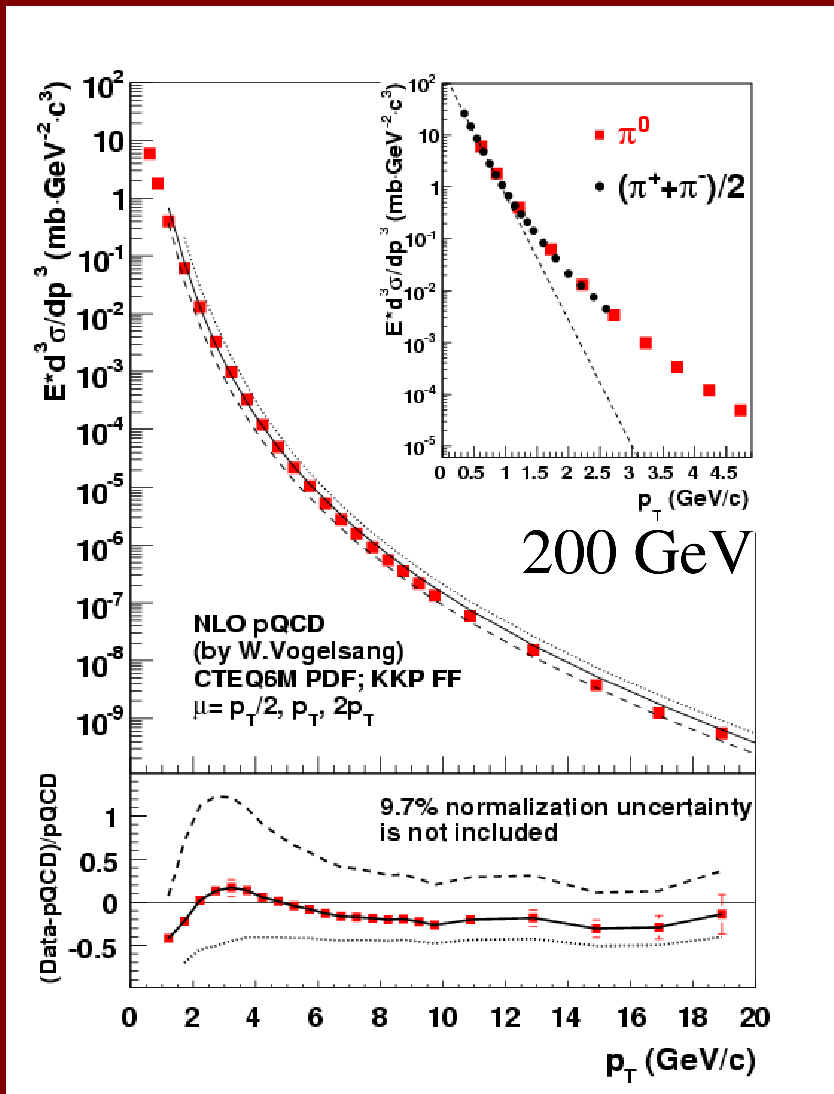
Extending x coverage

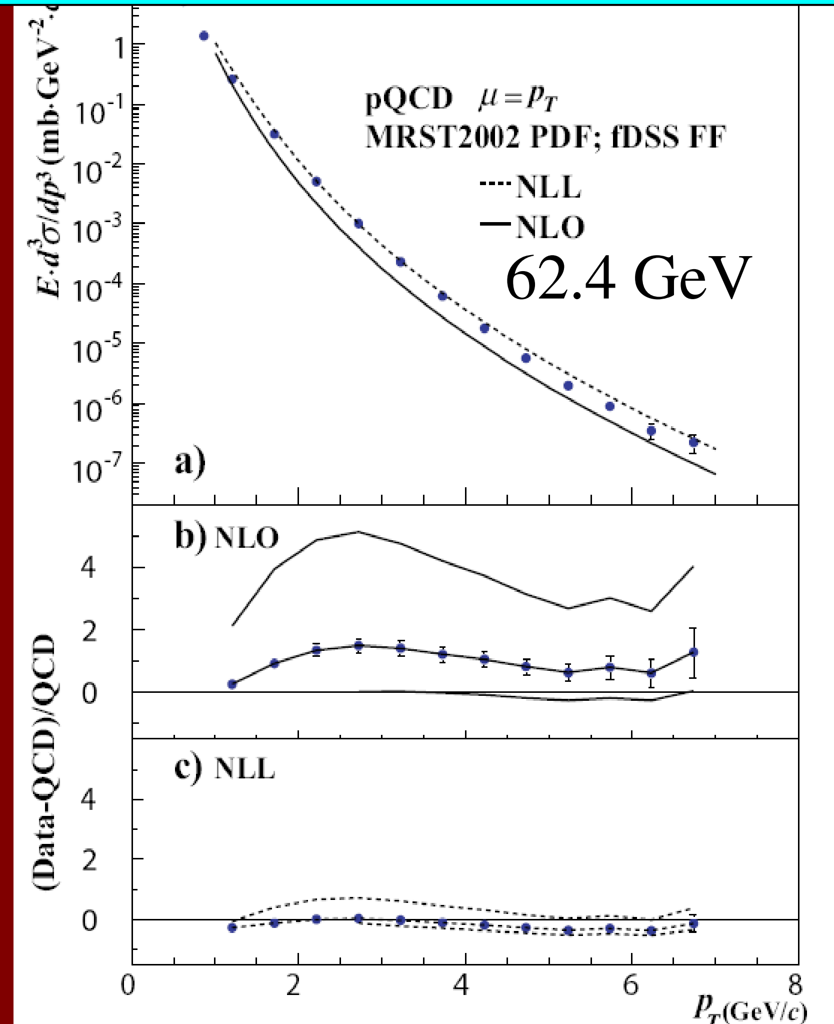


- Measure in different kinematic regions
  - e.g. forward vs. central
- Change center-of-mass energy
  - Most data so far at 200 GeV
  - Brief run in 2006 at 62.4 GeV
  - First 500 GeV data-taking planned for 2009!

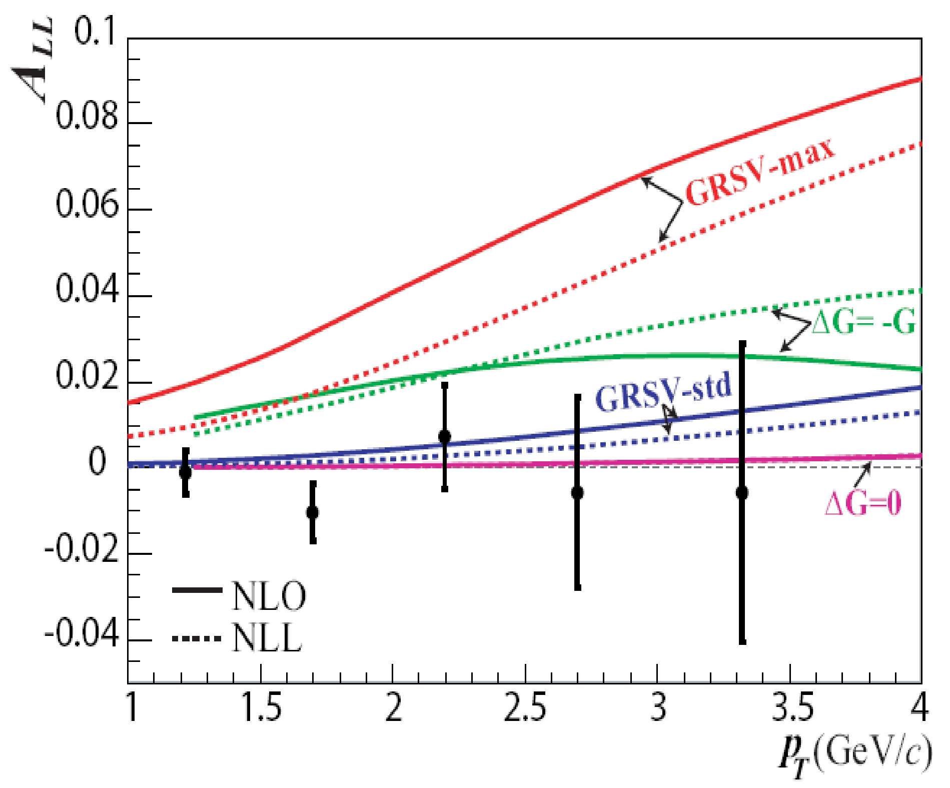
Extending x coverage

arXiv:0810.0701, submitted to PRD





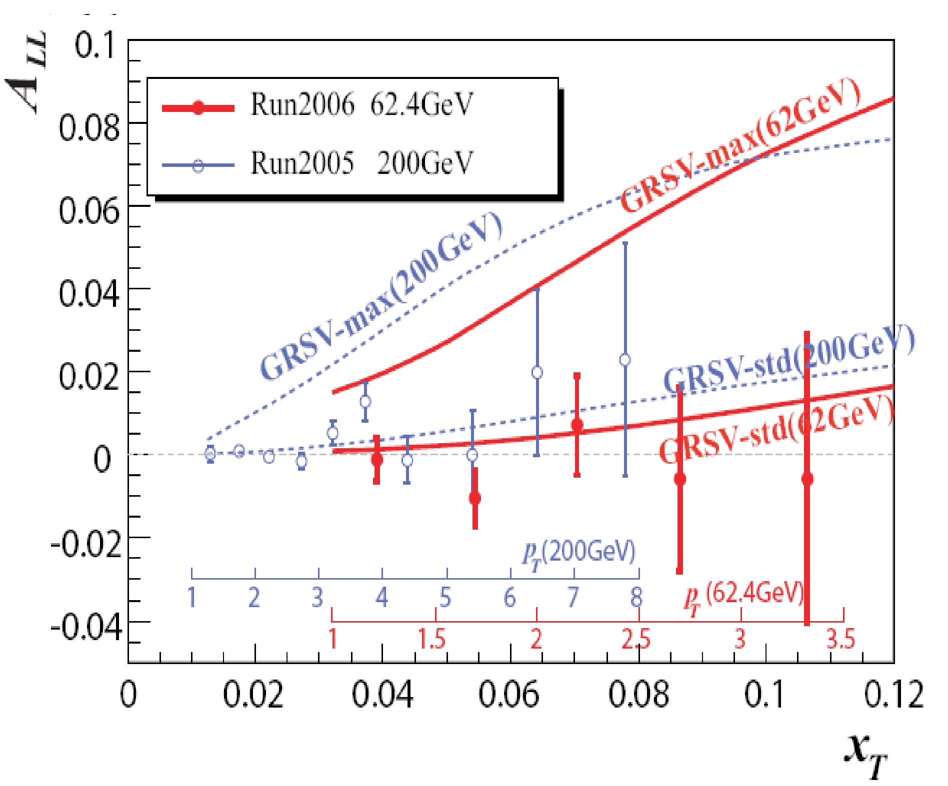
Neutral pion A_{LL} at 62.4 GeV



arXiv:0810.0701, submitted to PRD

Neutral pion A_{LL} at 62.4 GeV

$$x_T = \frac{2p_T}{\sqrt{s}}$$



Converting to x_T, can see significance of 62.4 GeV measurement (0.08 pb^{-1}) compared to published data from 2005 at 200 GeV (3.4 pb^{-1}).

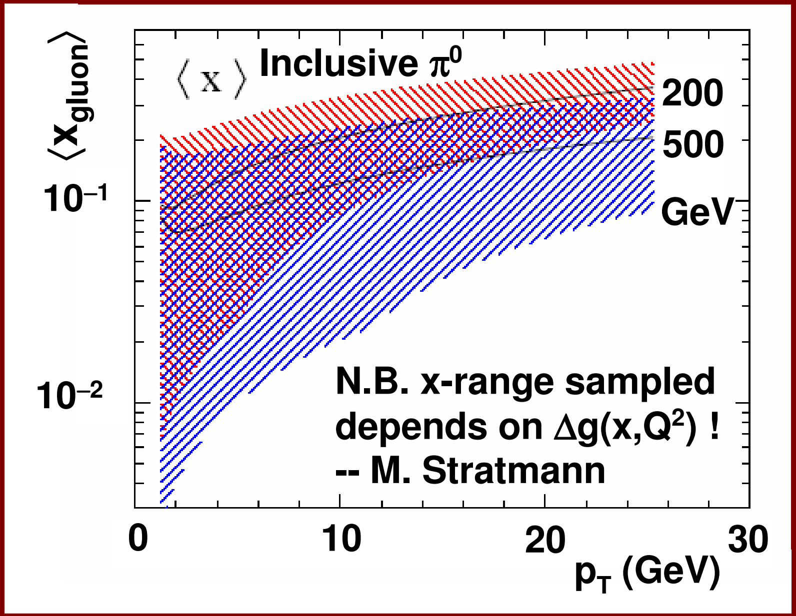
$$0.02 < x_{gluon} < 0.3 \quad (\sqrt{s} = 200\,\text{GeV})$$

$$0.06 < x_{gluon} < 0.4 \quad (\sqrt{s} = 62.4\,\text{GeV})$$

arXiv:0810.0701, submitted to PRD

Going beyond inclusive measurements

- Inclusive channels suffer from integration over x → model-dependent Δg extraction



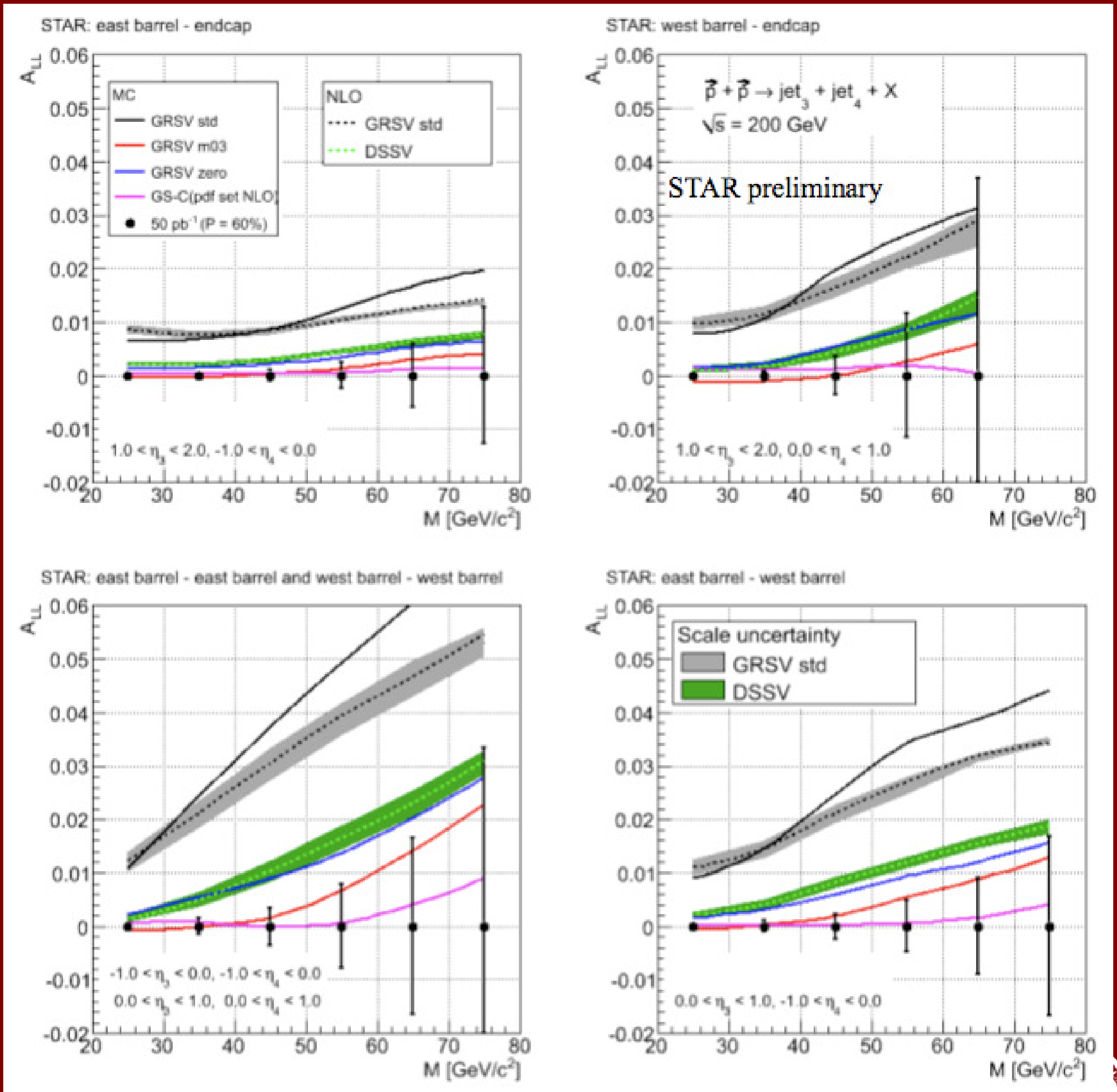
- Improved accelerator and detector performance will allow jet-jet and γ-jet coincidence measurements, placing better constraints on partonic kinematics

$$x_1 = \frac{x_T}{2}\left(e^{\eta_1} + e^{\eta_2}\right); \quad x_2 = \frac{x_T}{2}\left(e^{-\eta_1} + e^{-\eta_2}\right)$$

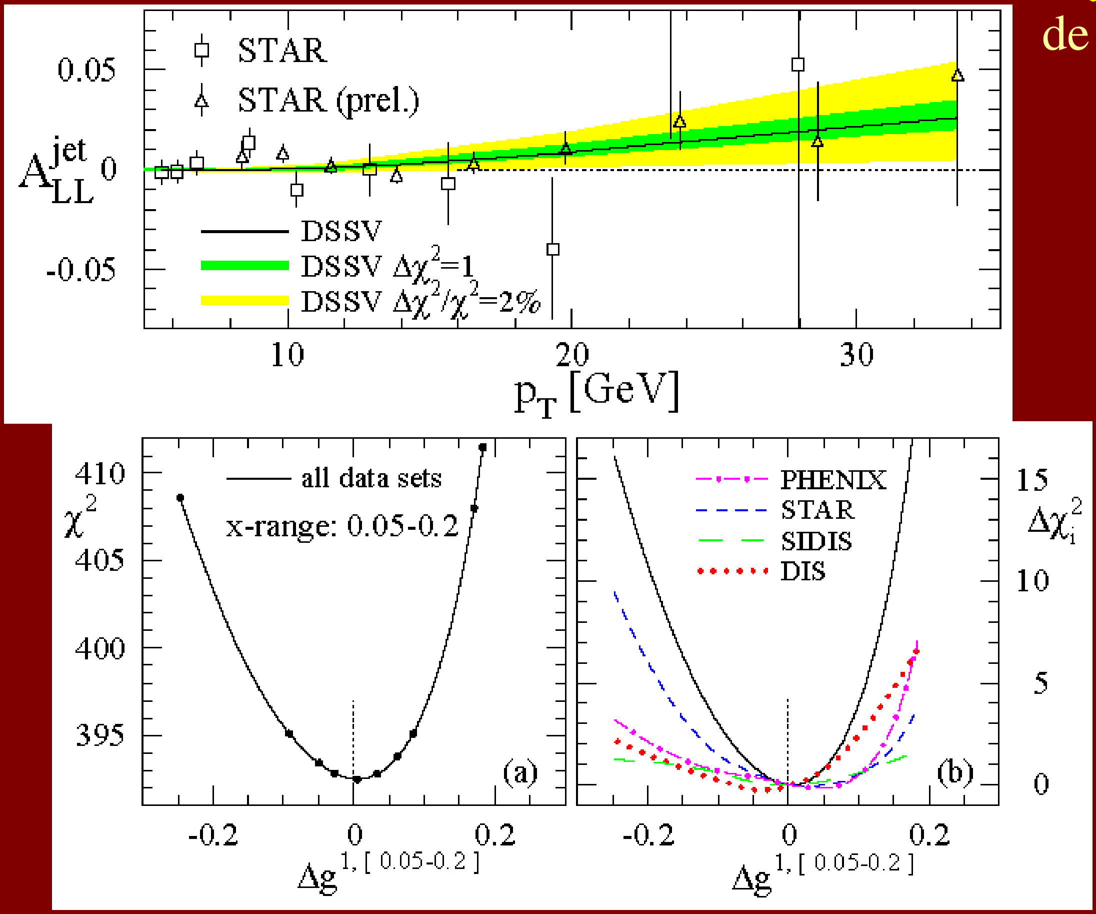
$$x_T \equiv \frac{2\,p_T}{\sqrt{s_{pp}}}$$

Going beyond inclusive measurements

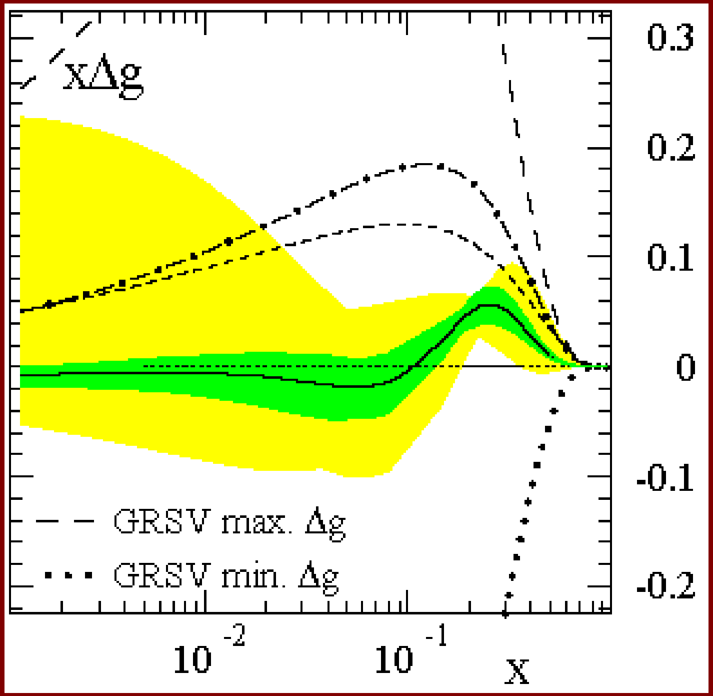
Dijet A_{LL} projections for 2009 run



Getting the full return on experimental efforts: Global analyses



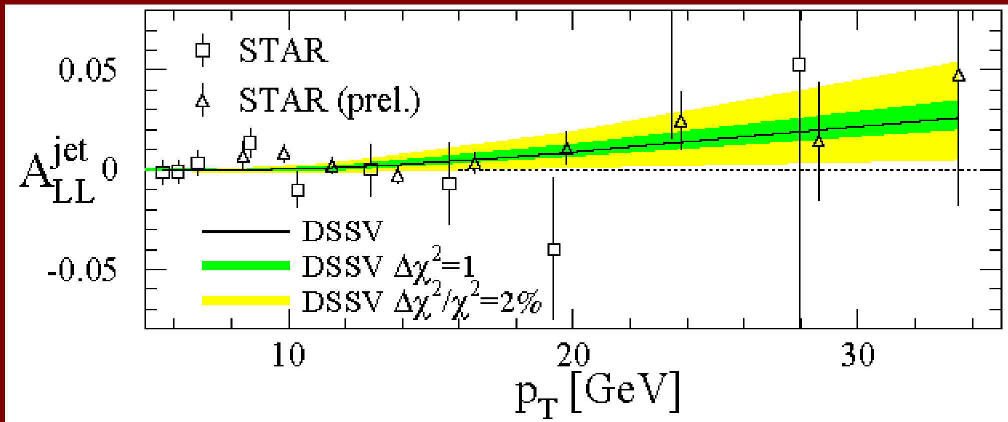
de Florian et al., PRL101, 072001 (2008)

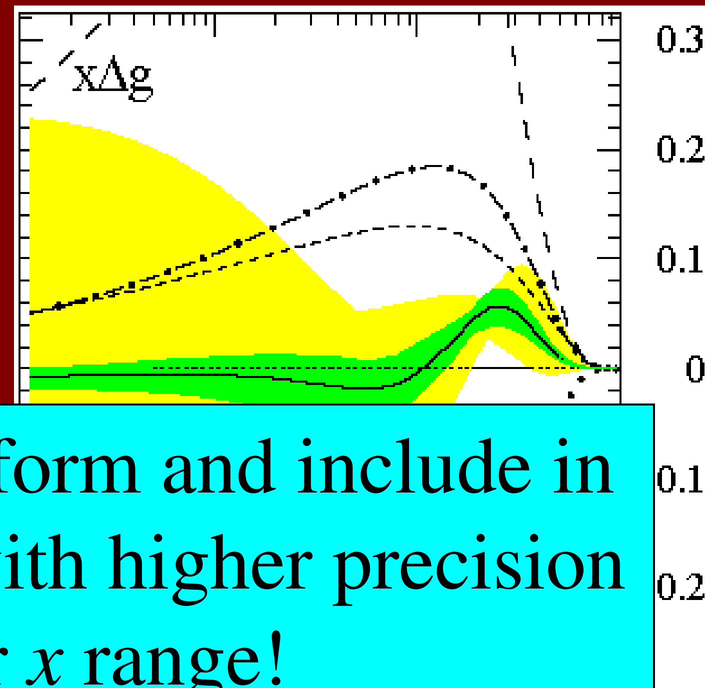


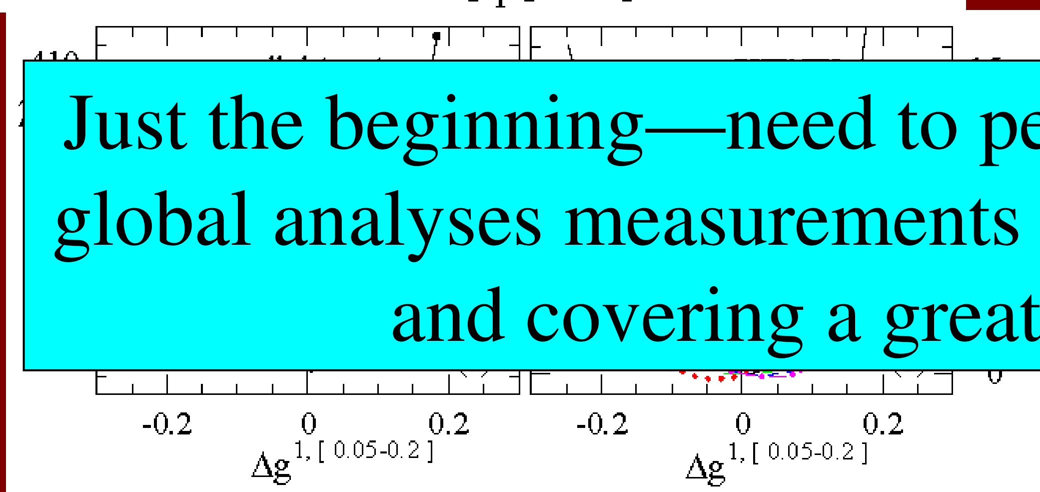
- The first global NLO analysis to include inclusive DIS, SIDIS, and RHIC p+p data on an equal footing
- Finds node in gluon distribution near $x \sim 0.1$

Getting the full return on experimental efforts: Global analyses

de Florian et al., PRL101, 072001 (2008)



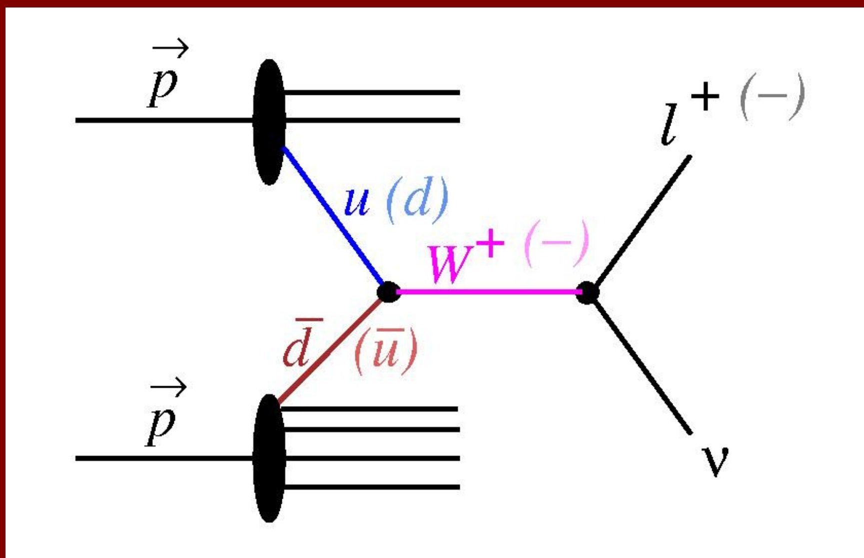




Just the beginning—need to perform and include in global analyses measurements with higher precision and covering a greater *x* range!

- The first global NLO analysis to include inclusive DIS, SIDIS, and RHIC p+p data on an equal footing
- Finds node in gluon distribution near $x \sim 0.1$

Access to flavor-separated quark and antiquark helicities via W production



$$A_L = \frac{1}{P}\frac{N^+/L^+ - N^-/L^-}{N^+/L^+ + N^-/L^-}$$

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

V-A coupling

Only L.H. u and R.H. d couple to W^+

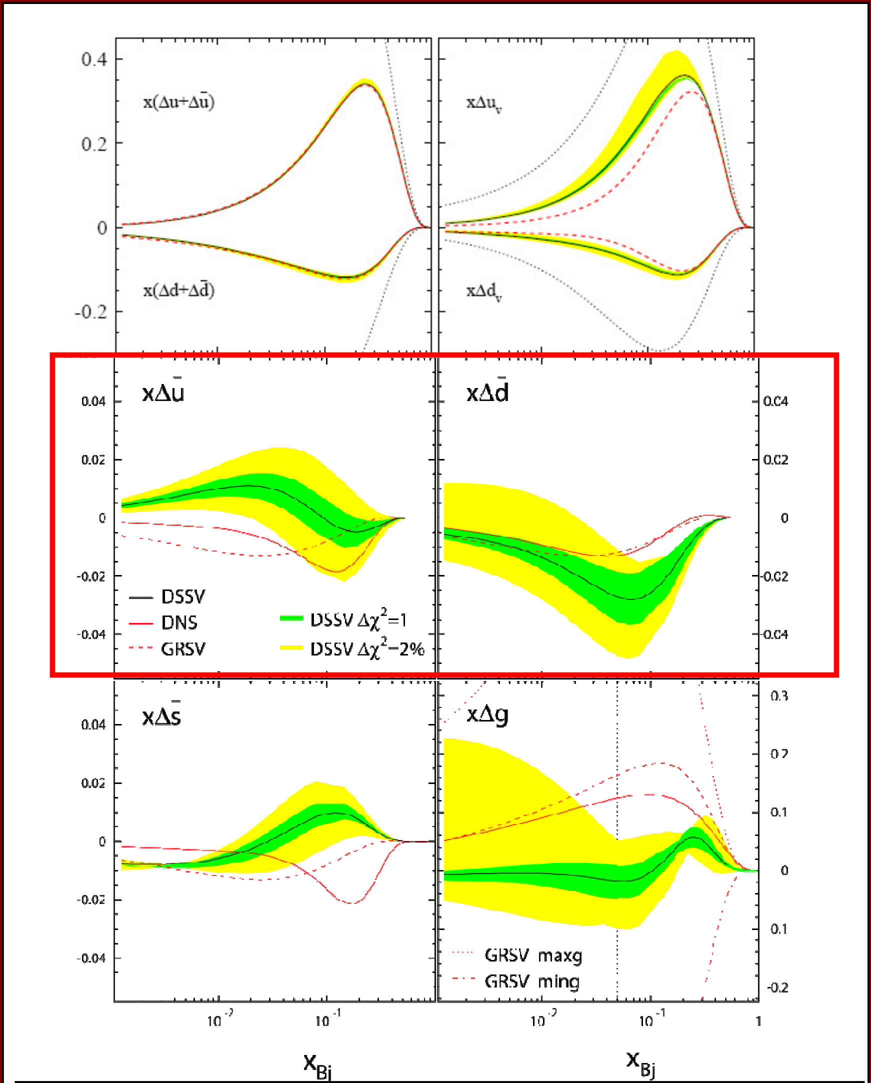
Likewise L.H. d and R.H. u to W^-

Only L.H. W's produced

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

44

Access to flavor-separated quark and antiquark helicities via W production



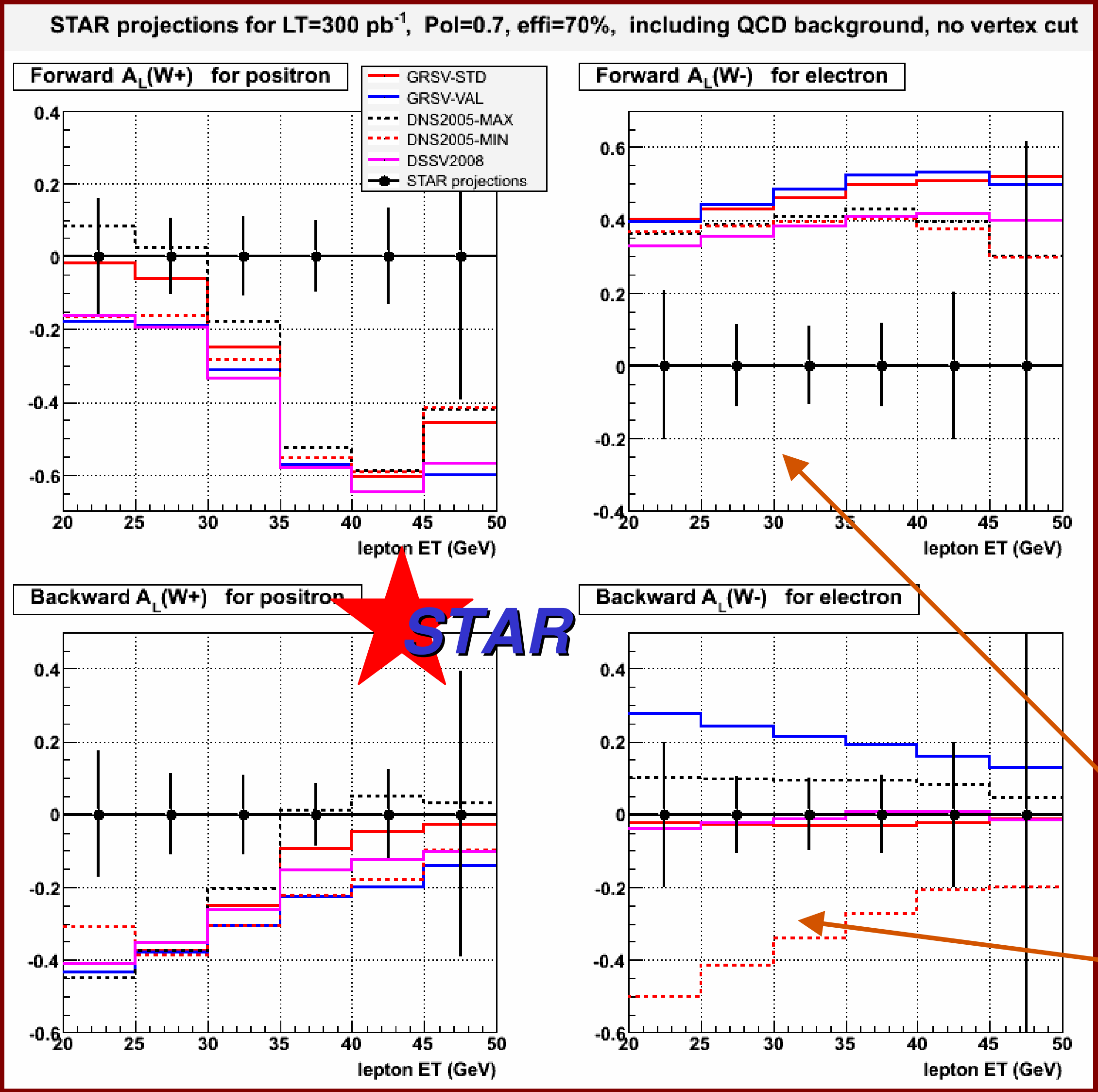
DSSV, PRL101, 072001 (2008)

$$A_L = \frac{1}{P}\frac{N^+/L^+ - N^-/L^-}{N^+/L^+ + N^-/L^-}$$

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

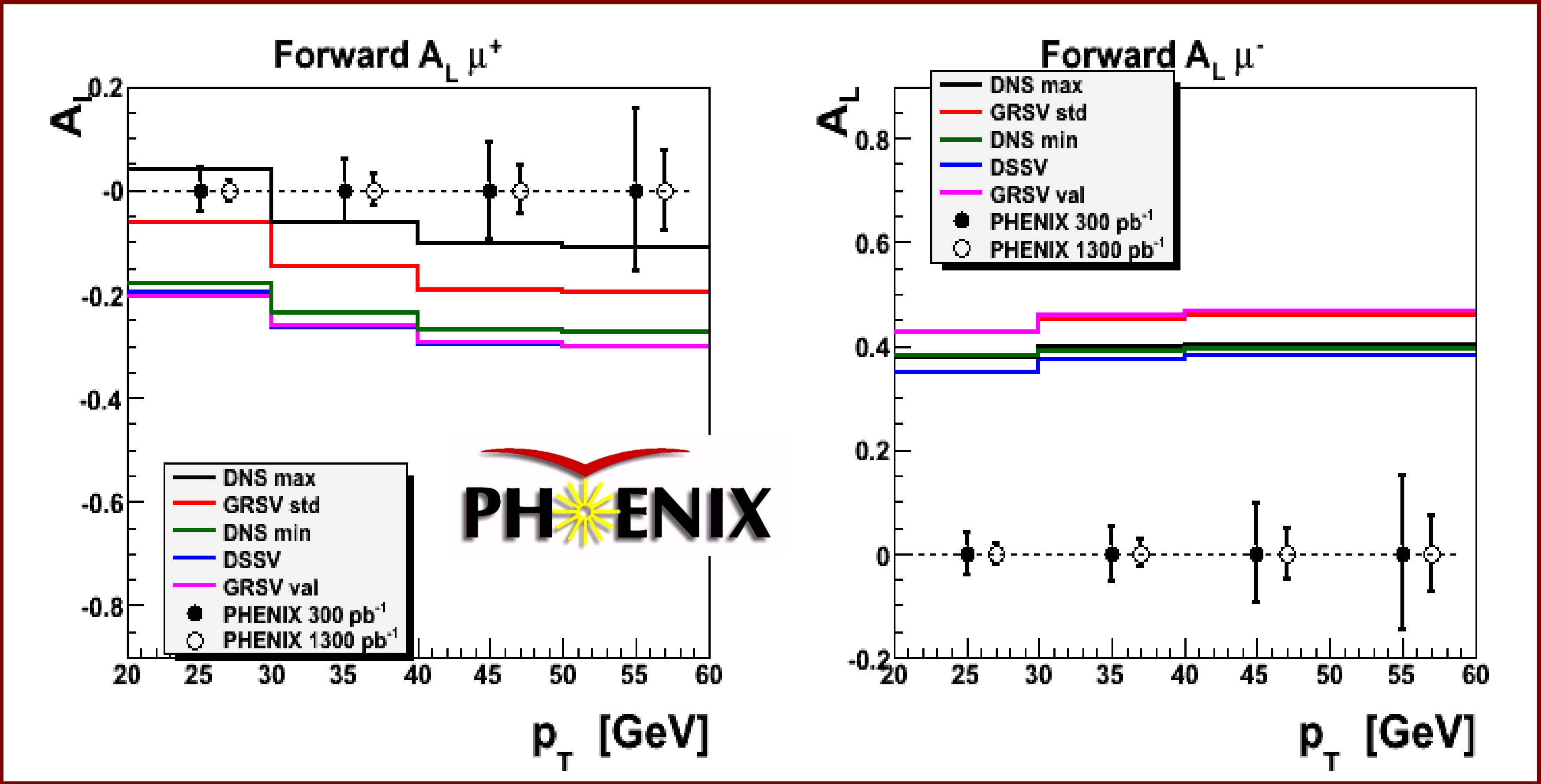
$$A_L^{W^-} \approx -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) - \bar{u}(x_1)d(x_2)}$$

Sensitivity projections vs. p_T

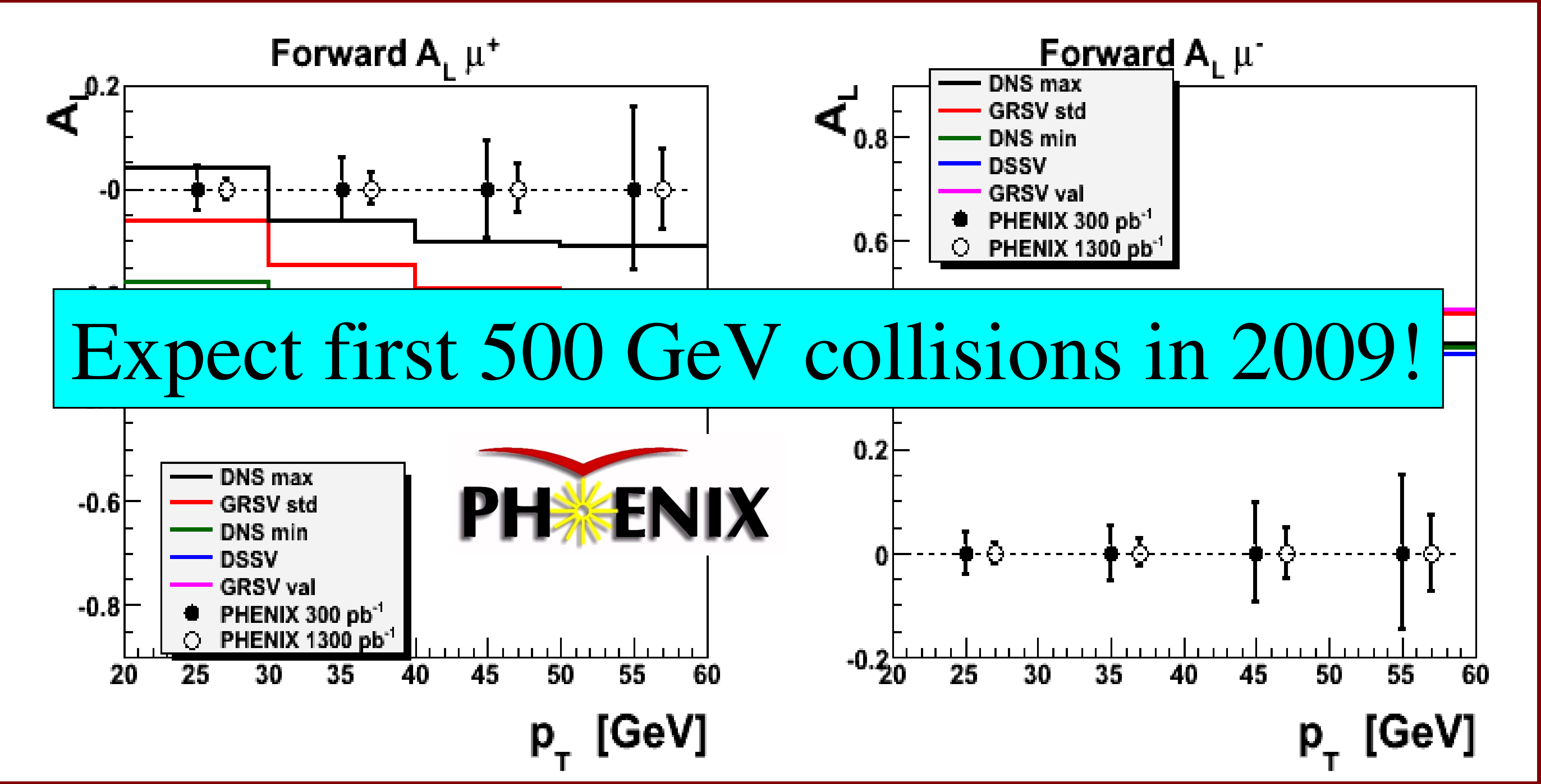


- $1 < \eta < 2$
- 300 pb^{-1}
- Realistic BG subtraction
- Recent PDFs ~representing current allowed $\Delta\bar{u}/\Delta\bar{d}$ range
- $\Delta\bar{d}$ and $\Delta\bar{u}$ isolated

Sensitivity projections vs. p_T



Sensitivity projections vs. p_T



Expect first 500 GeV collisions in 2009!

Conclusions

- Hadronic interactions have played and continue to play an integral role in the discovery and exploration of spin-dependent effects!
- RHIC, as a high-energy polarized proton collider, represents a landmark achievement in the field, having opened up a wealth of new opportunities
- Through global efforts, utilizing all the tools and techniques we have at our disposal, both theoretically and in different experimental systems, we can harness the full potential of hadronic reactions
  - The more we know from simpler systems, the more we can learn from increasingly complex ones!

"Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they might just ban such measurements altogether out of self-protection."

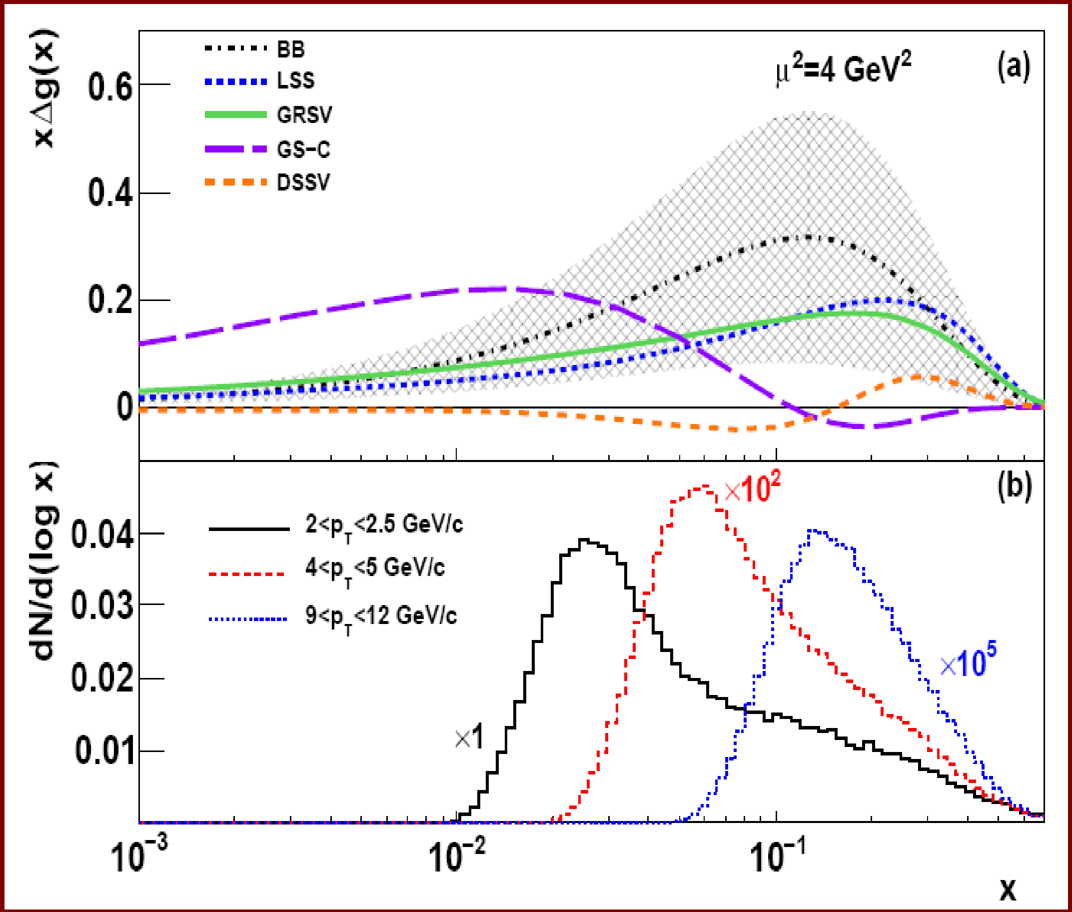
J.D. Bjorken

NATO Advanced Research Workshop on
QCD Hard Hadronic Processes
St. Croix, 1987

Extra slides

π^0 p_T vs. x_{gluon}

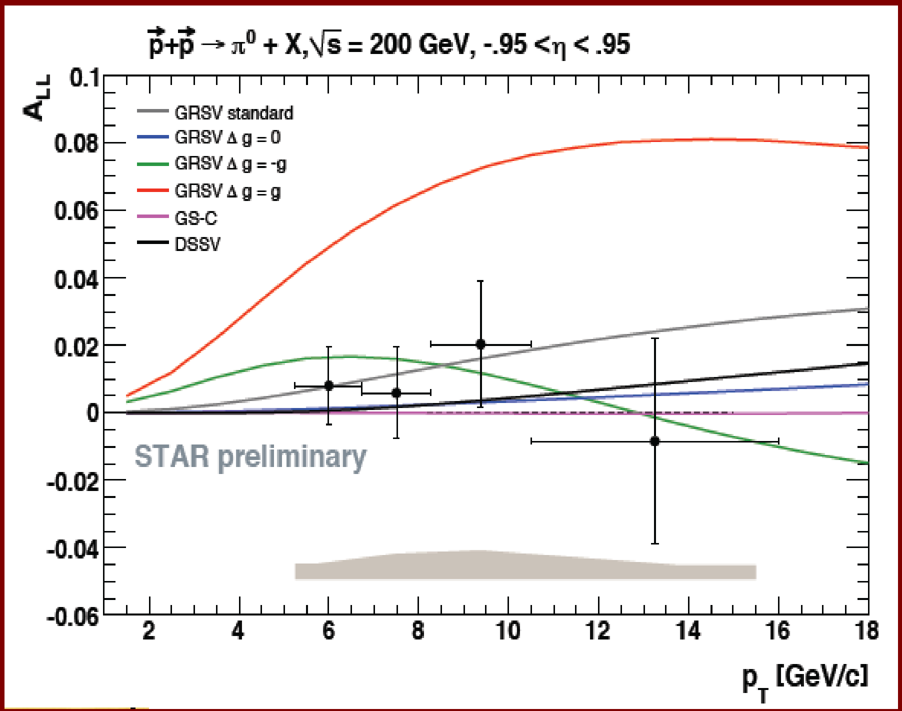
Based on simulation using NLO pQCD as input



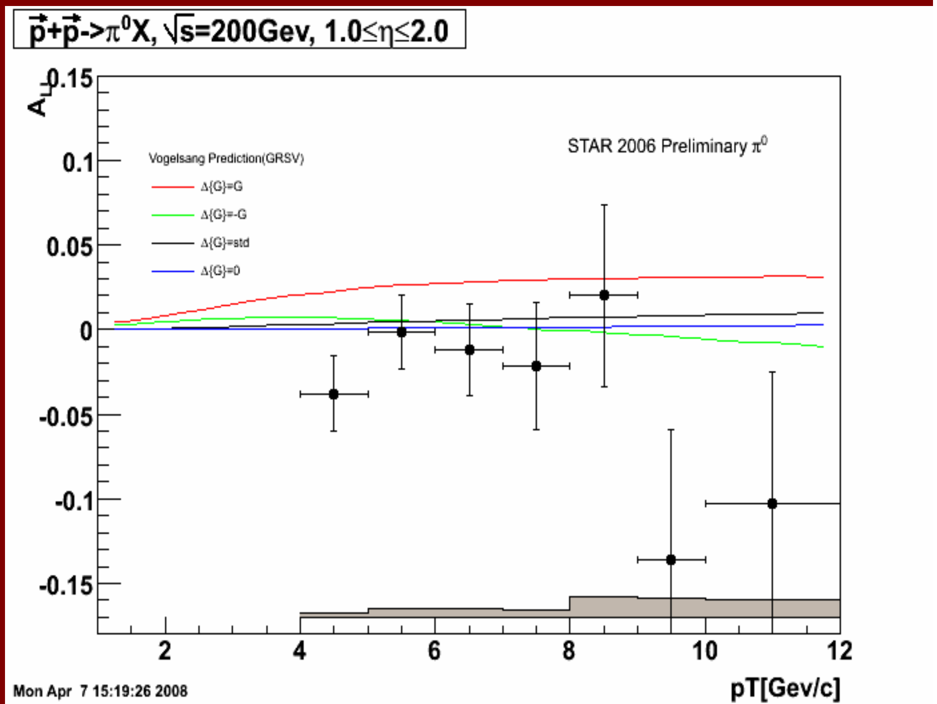
arXiv:0810.0694, submitted to PRL

Neutral pion A_{LL} at STAR

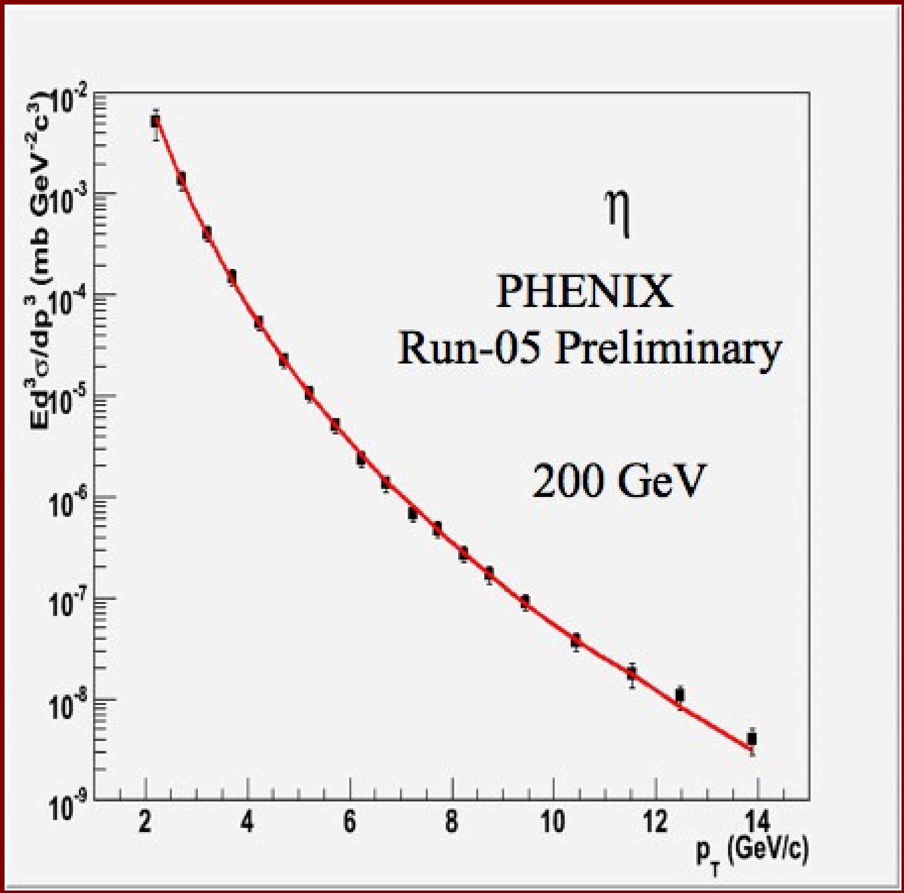
-0.95 < η < 0.95

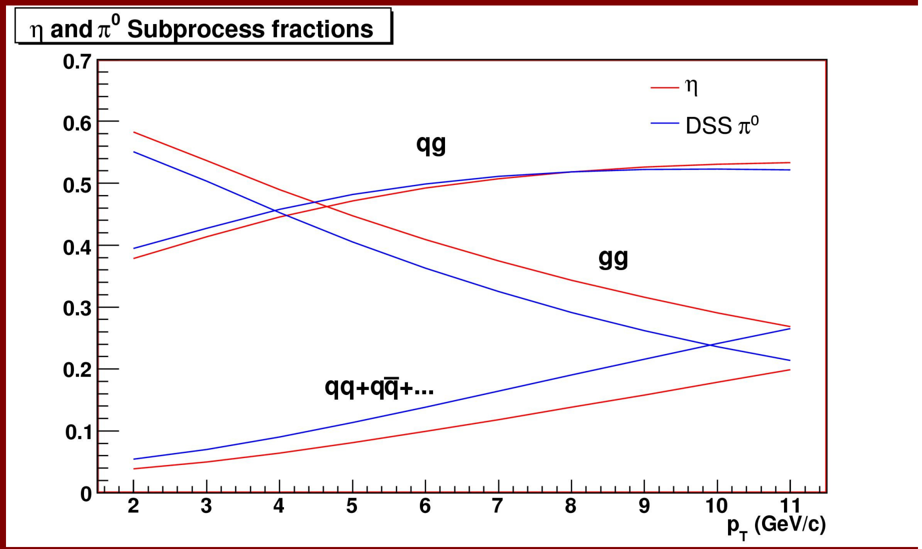


1.0 < η < 2.0



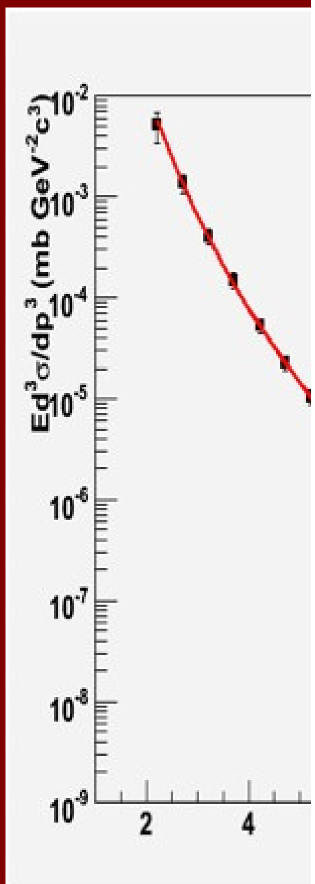
η A_{LL} at 200 GeV

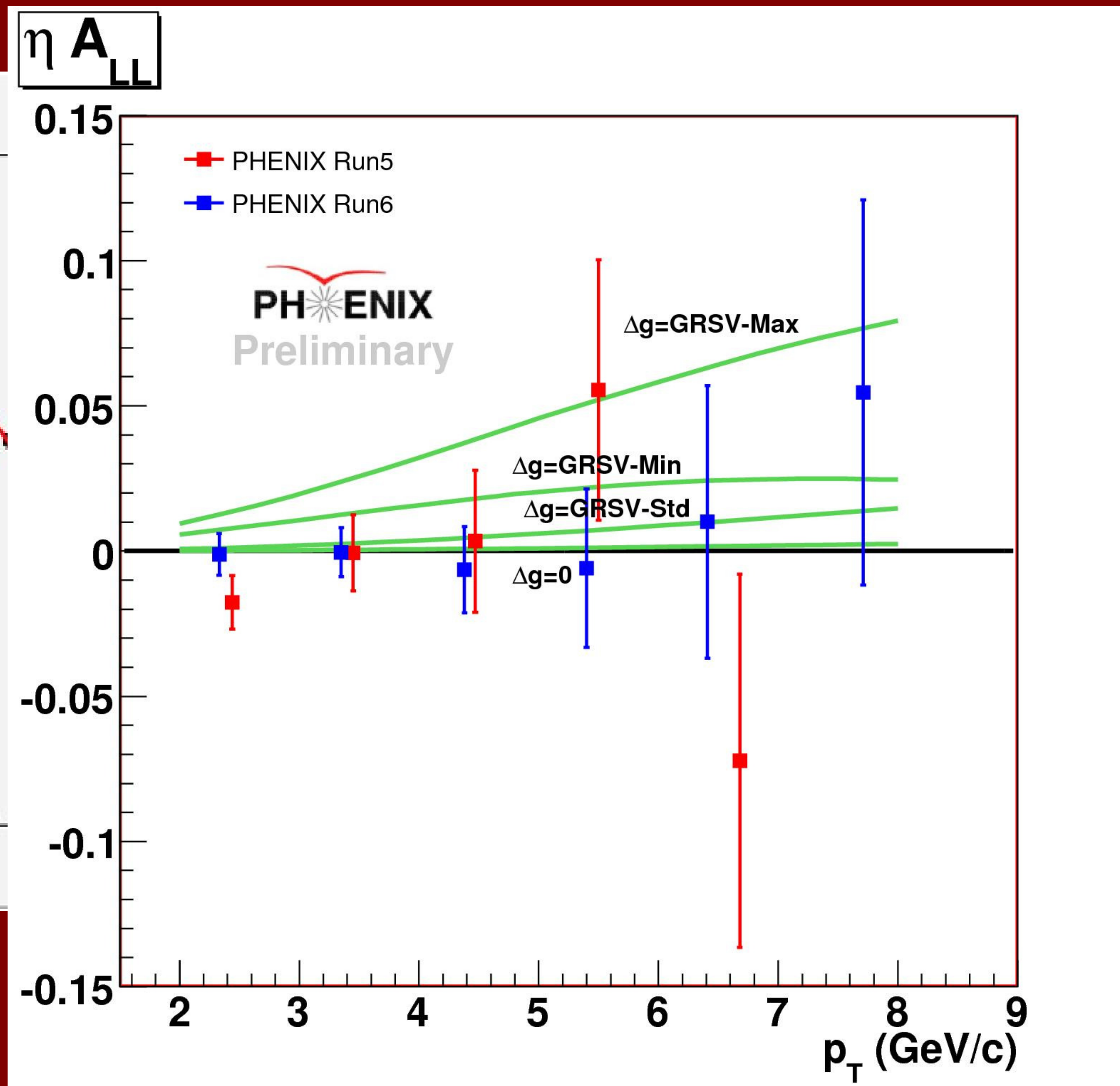


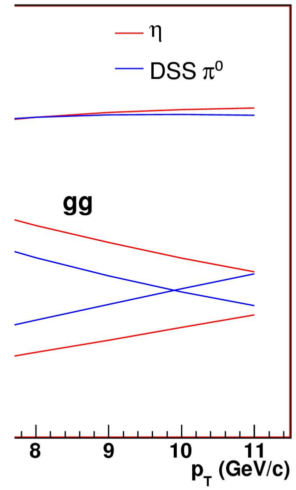


- ~1/2 as abundant as π^0
- 40% photon branching ratio
- Different wavefunction from π^0
- Stronger gluon/strange

η A_{LL} at 200 GeV



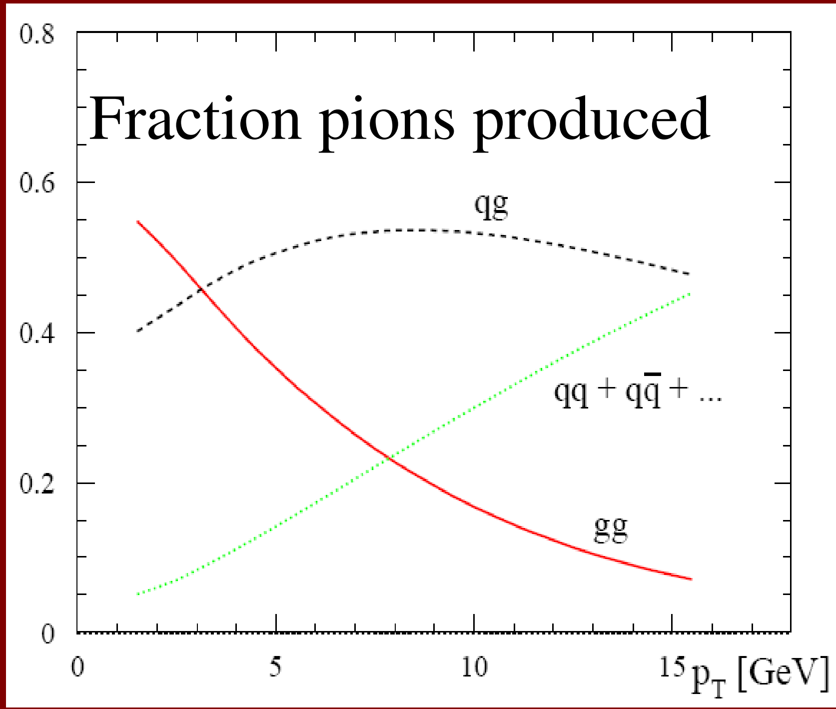




s π^0
ning ratio
ction from π^0
ange

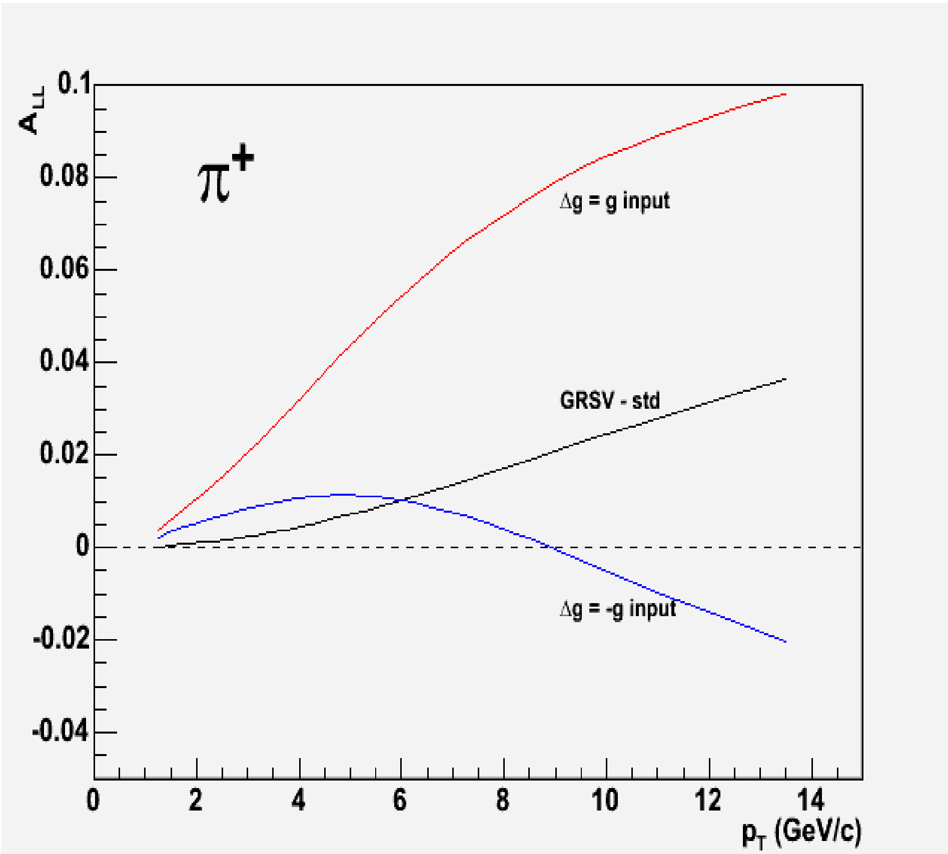
The Pion Isospin Triplet, A_{LL} and ΔG

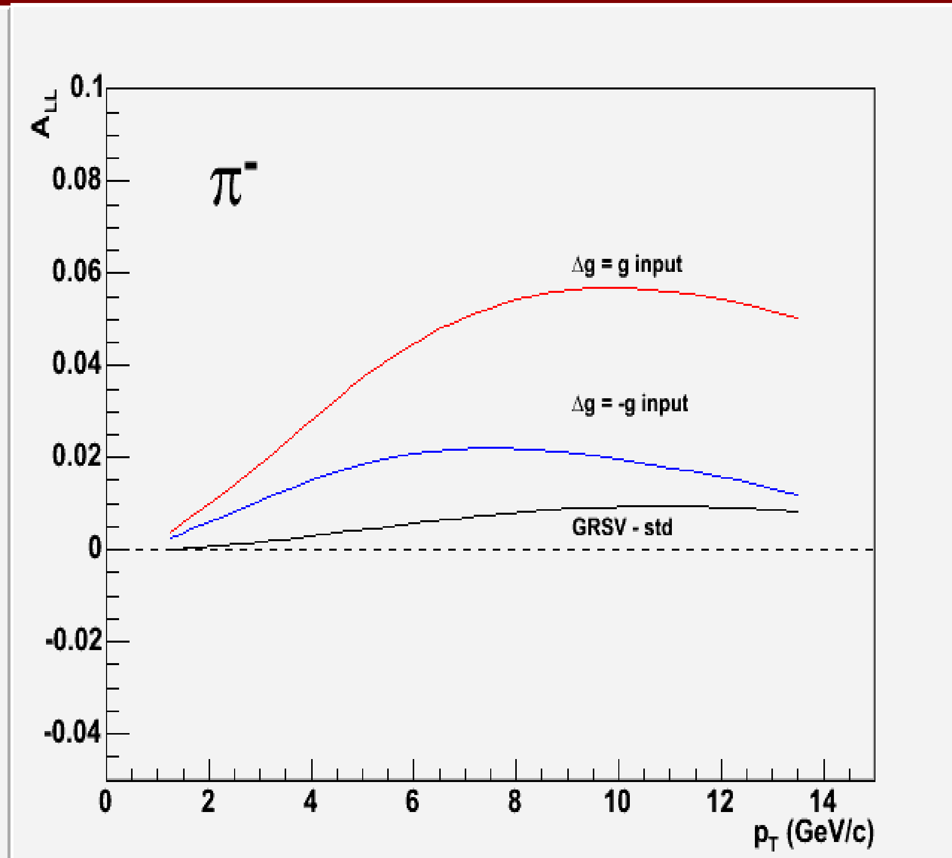
- At transverse momenta > ~5 GeV/c, midrapidity pions dominantly produced via qg scattering
- Tendency of π^+ $(u\bar{d})$ to fragment from an up quark and π^- $(d\bar{u})$ from a down quark and fact that Δu and Δd have opposite signs make A_{LL} of π^+ and π^- differ measurably
- Order of asymmetries of pion species can allow us to determine the sign of ΔG



$$\Delta G > 0 \Rightarrow A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$$

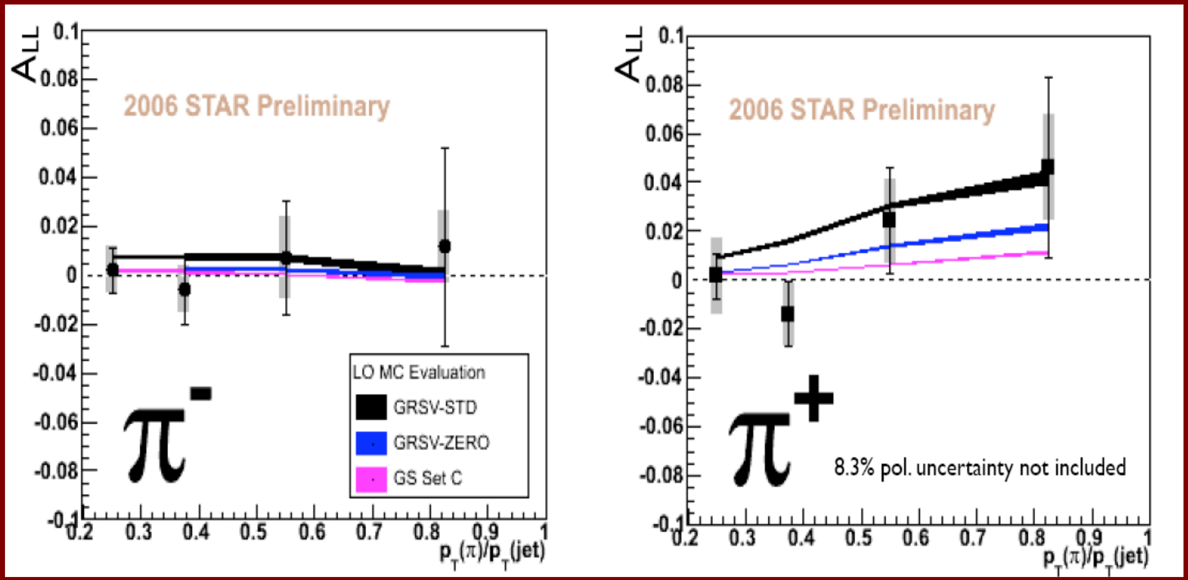
The Pion Isospin Triplet, A_{LL} and ΔG

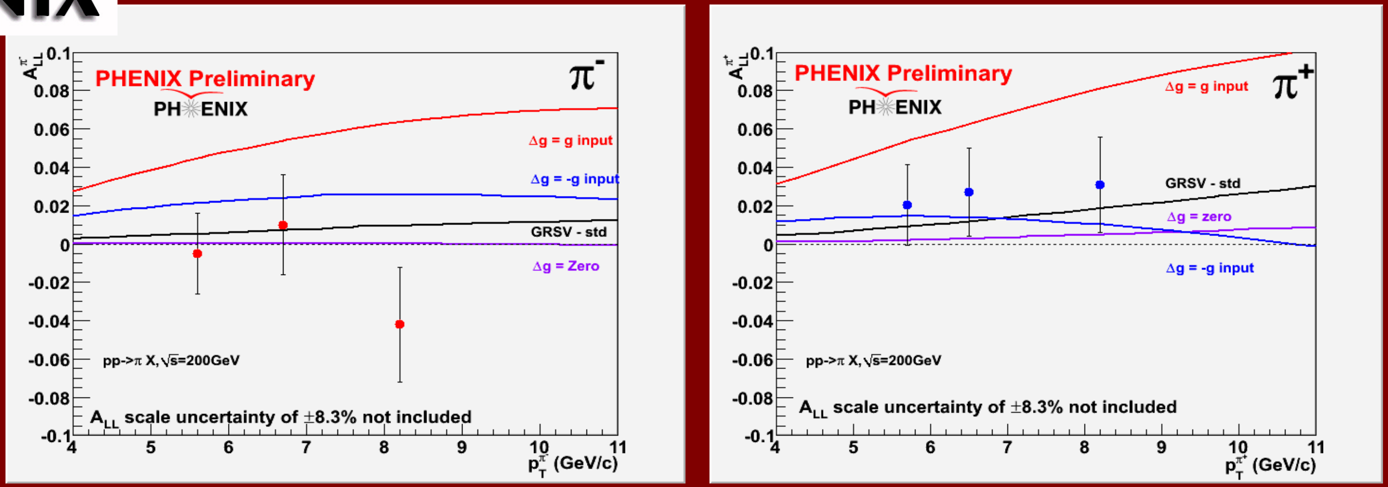




$$\Delta G > 0 \Rightarrow A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$$

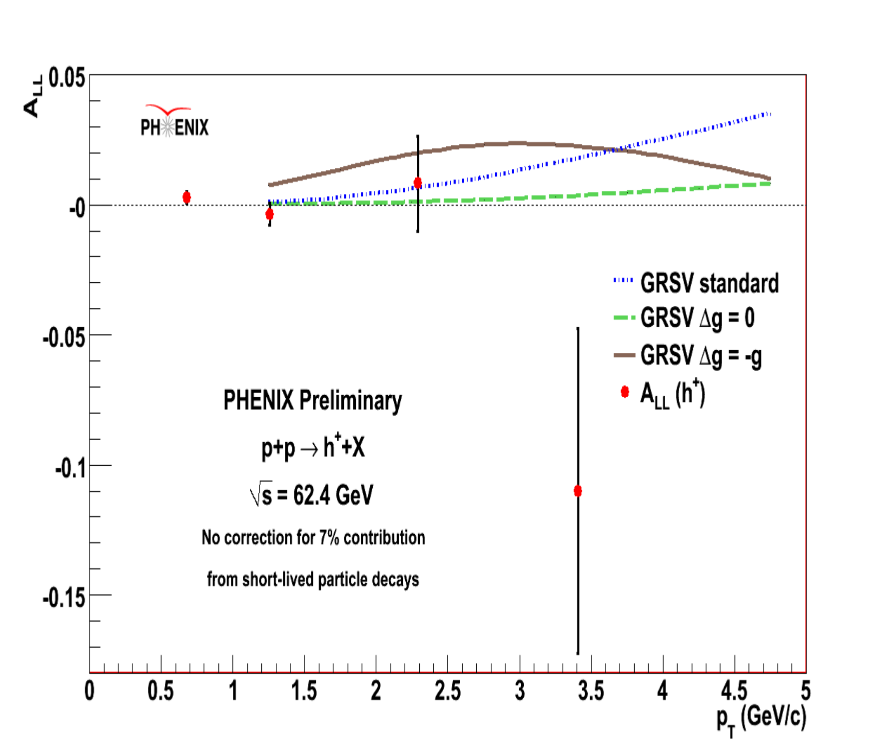
Charged pion A_{LL} at 200 GeV

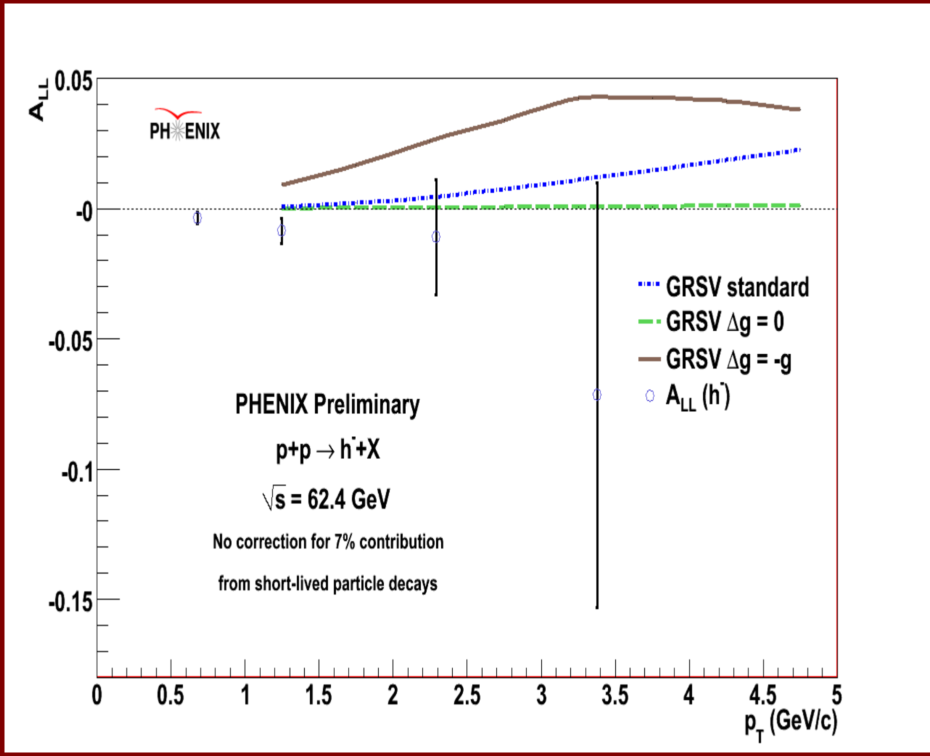




A_{LL} of non-identified charged hadrons at 62.4 GeV

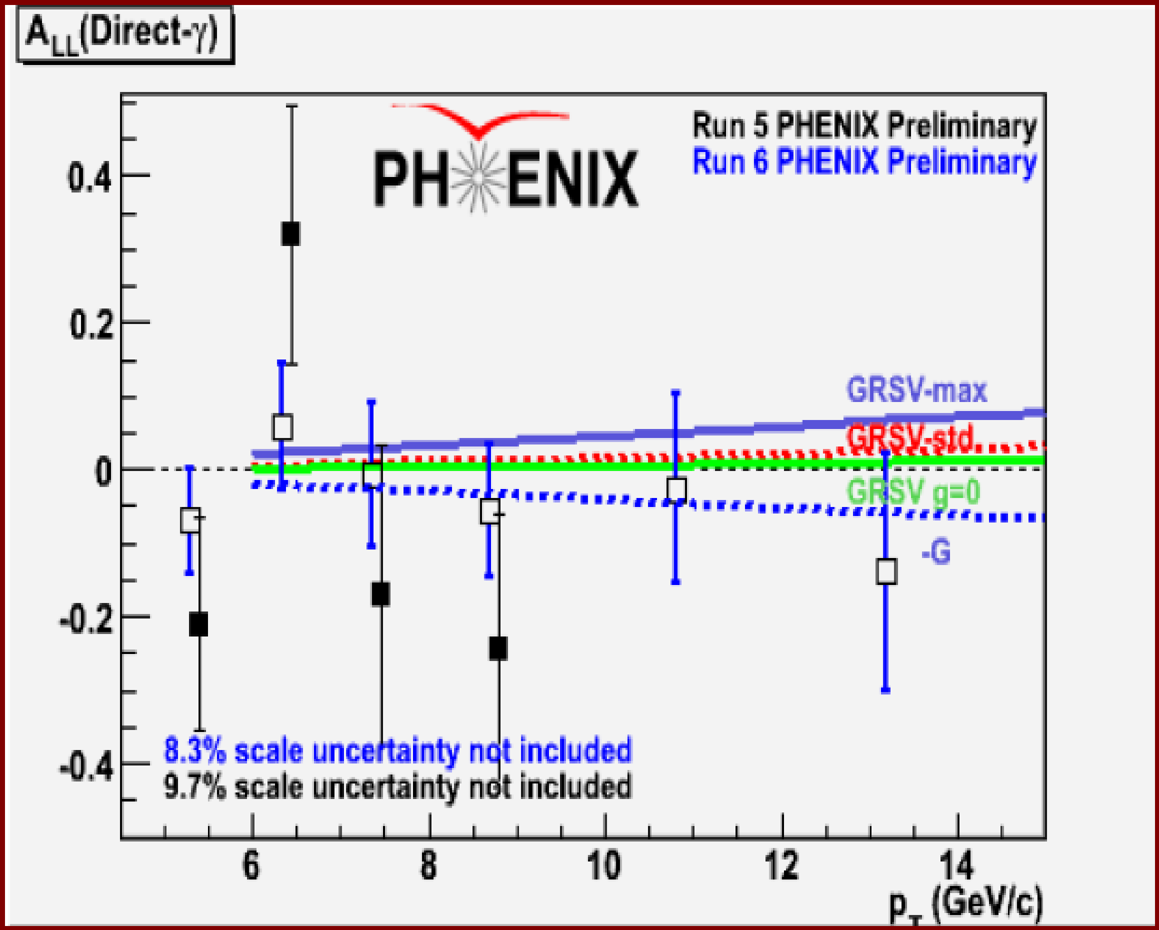
PHENIX Cross section measurement in progress!

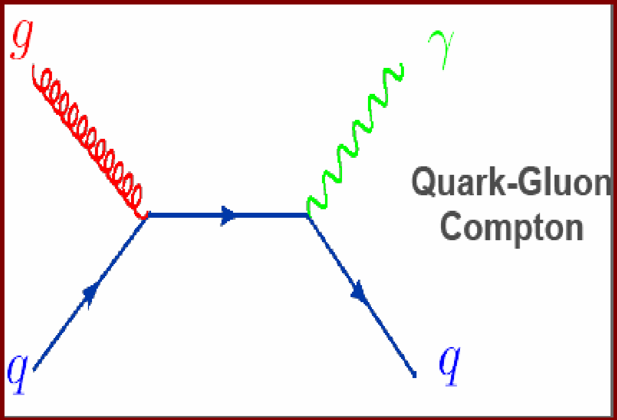




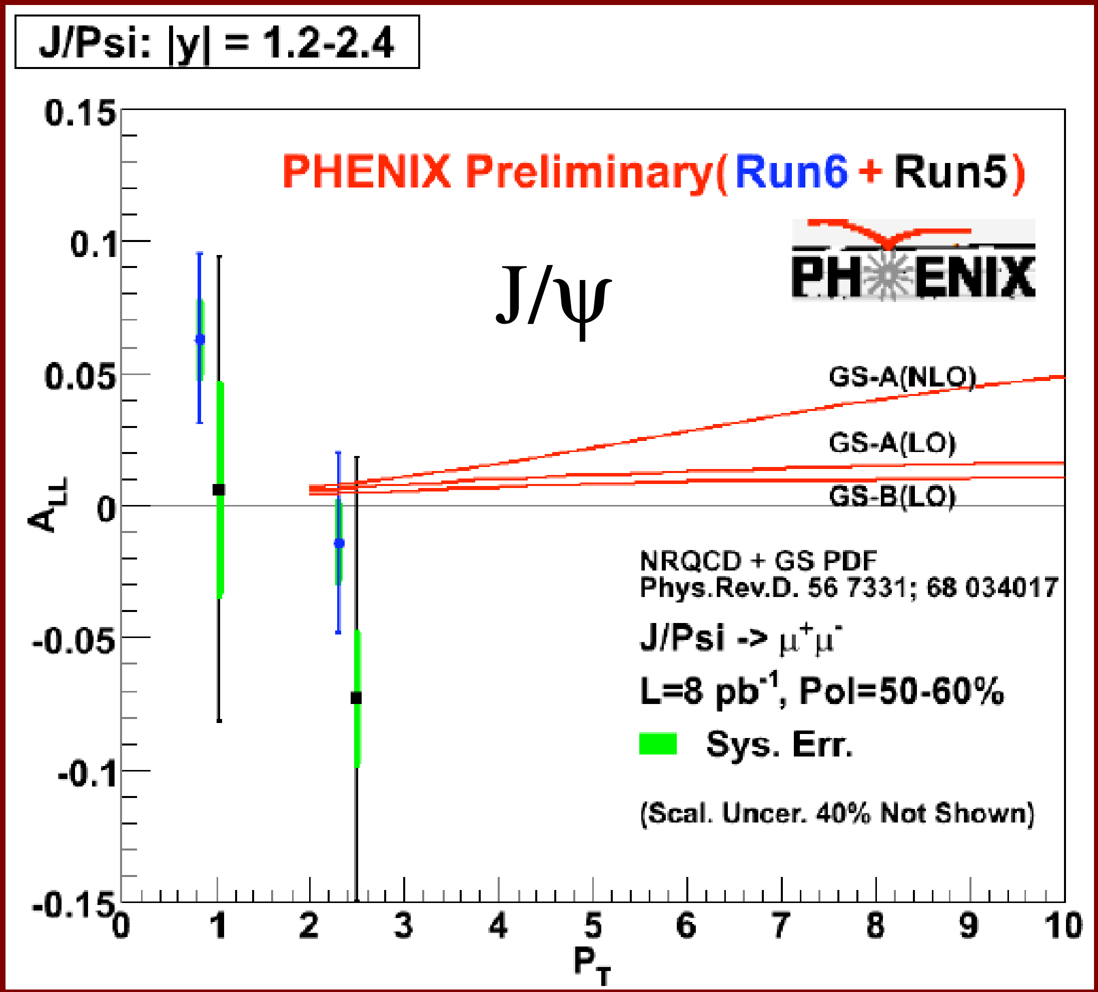
14% polarization uncertainty not included

A_{LL} of direct photons at 200 GeV

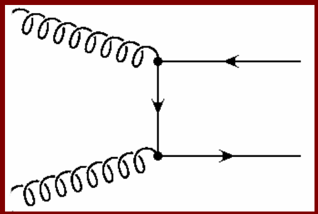




A_{LL} of J/ψ at $\sqrt{s}$=200 GeV



$$gg \rightarrow Q\bar{Q}$$



$$\propto \frac{\Delta g}{g} \frac{\Delta g}{g}$$

x_T *Scaling*

- x_T scaling—can parametrize cross sections for particle production in hadronic collisions by:

$$E\frac{d^3\sigma}{dp^3} \sim \left(\sqrt{s}\right)^{-n} F(x_T)$$

$$x_T = \frac{2p_T}{\sqrt{s}}, n = \text{constant}$$

- Lower energy has higher yield at fixed $\boldsymbol{x_T}$

$$L\int E\frac{d^3\sigma}{dp^3}dp_T = L\int E\frac{d^3\sigma}{dp^3}\frac{\sqrt{s}}{2}dx_T$$

$$\propto L\sqrt{s}^{-5.3}$$

x_T *Scaling*

- x_T scaling—can parametriz ross sections for particle produc n in hadronic collisions by:

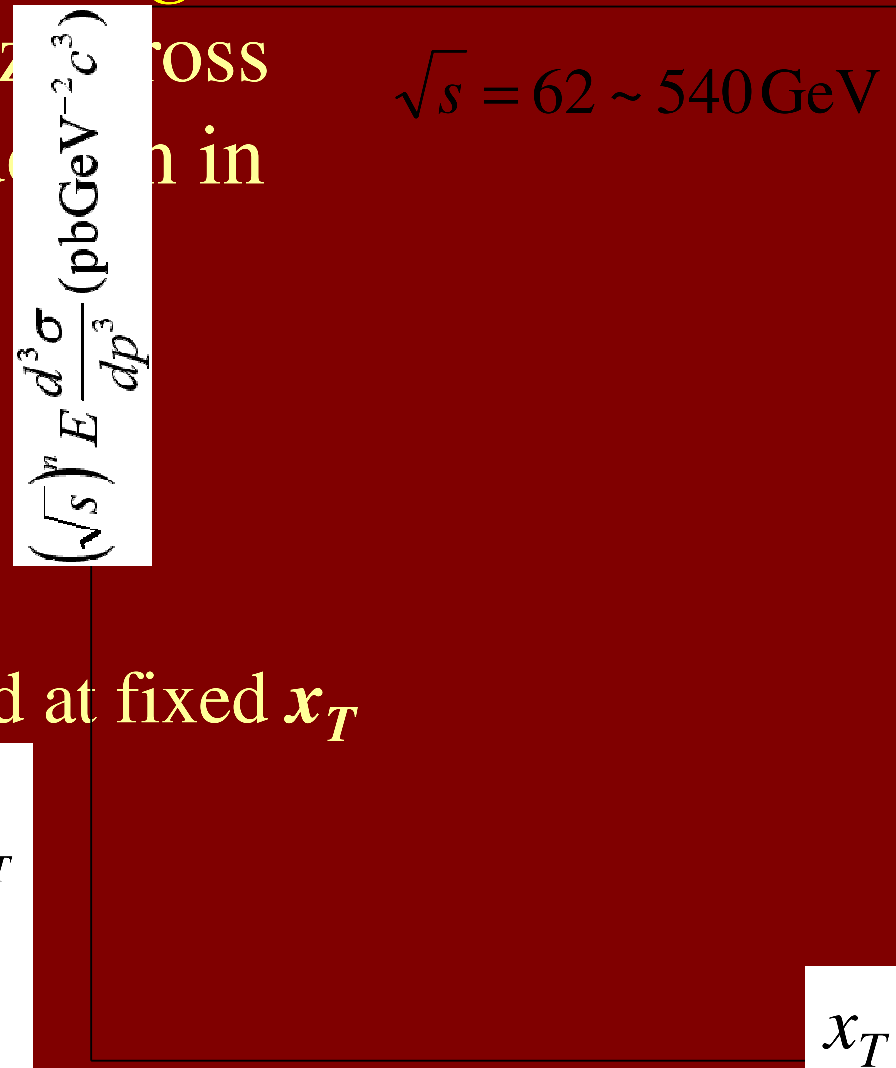
$$E\frac{d^3\sigma}{dp^3} \sim \left(\sqrt{s}\right)^{-n} F(x_T)$$

$$x_T = \frac{2p_T}{\sqrt{s}}, n = \text{constant}$$

- Lower energy has higher yield at fixed $\boldsymbol{x_T}$

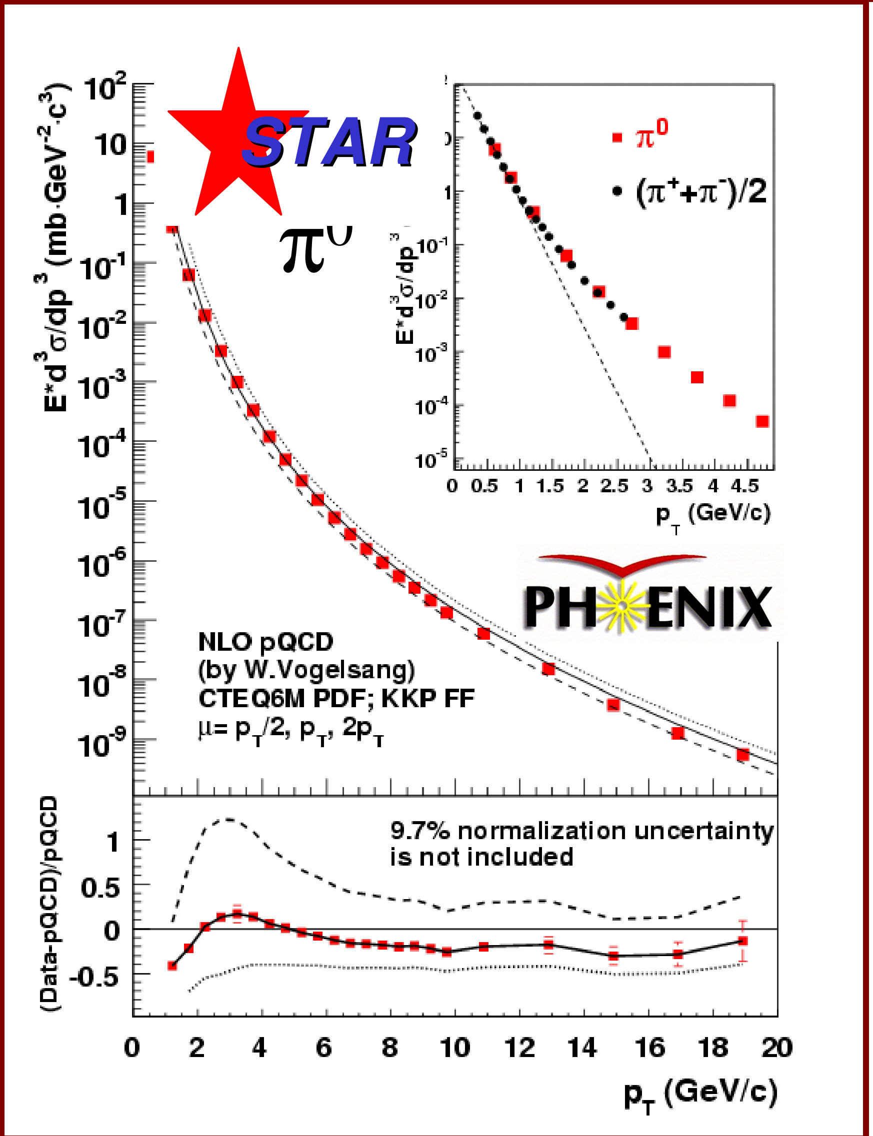
$$L\int E\frac{d^3\sigma}{dp^3}dp_T = L\int E\frac{d^3\sigma}{dp^3}\frac{\sqrt{s}}{2}dx_T$$

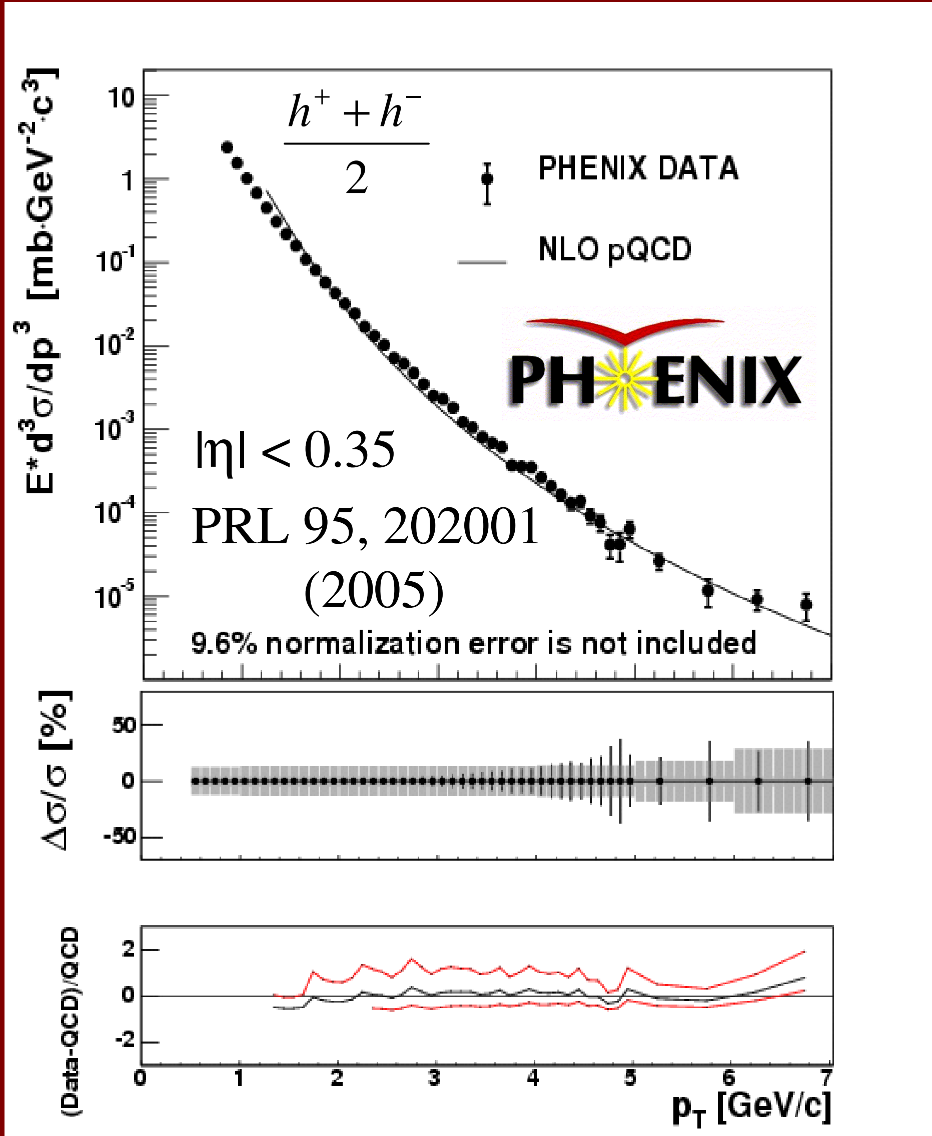
$$\propto L\sqrt{s}^{-5.3}$$



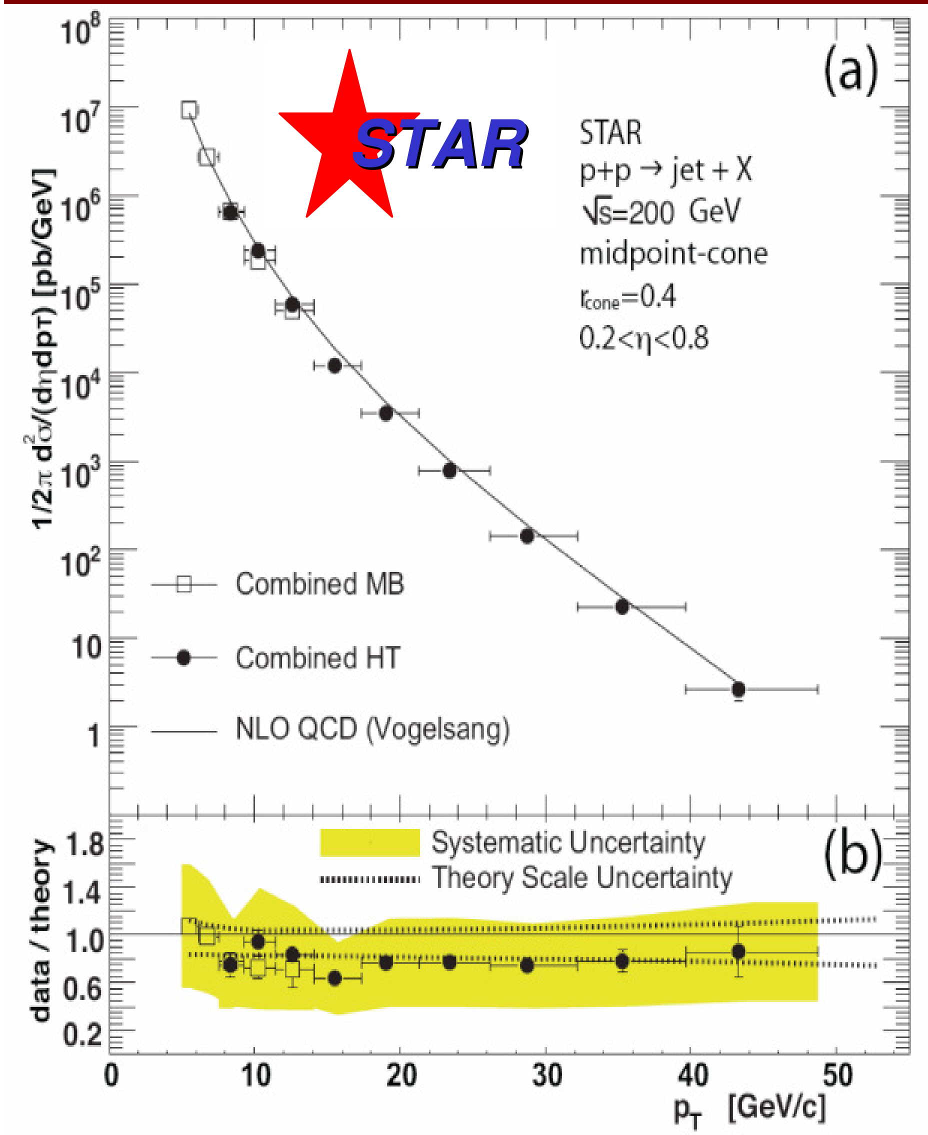
We can probe higher x_T with better statistics even with a short run at 62.4 GeV!! (compared to 200 GeV)

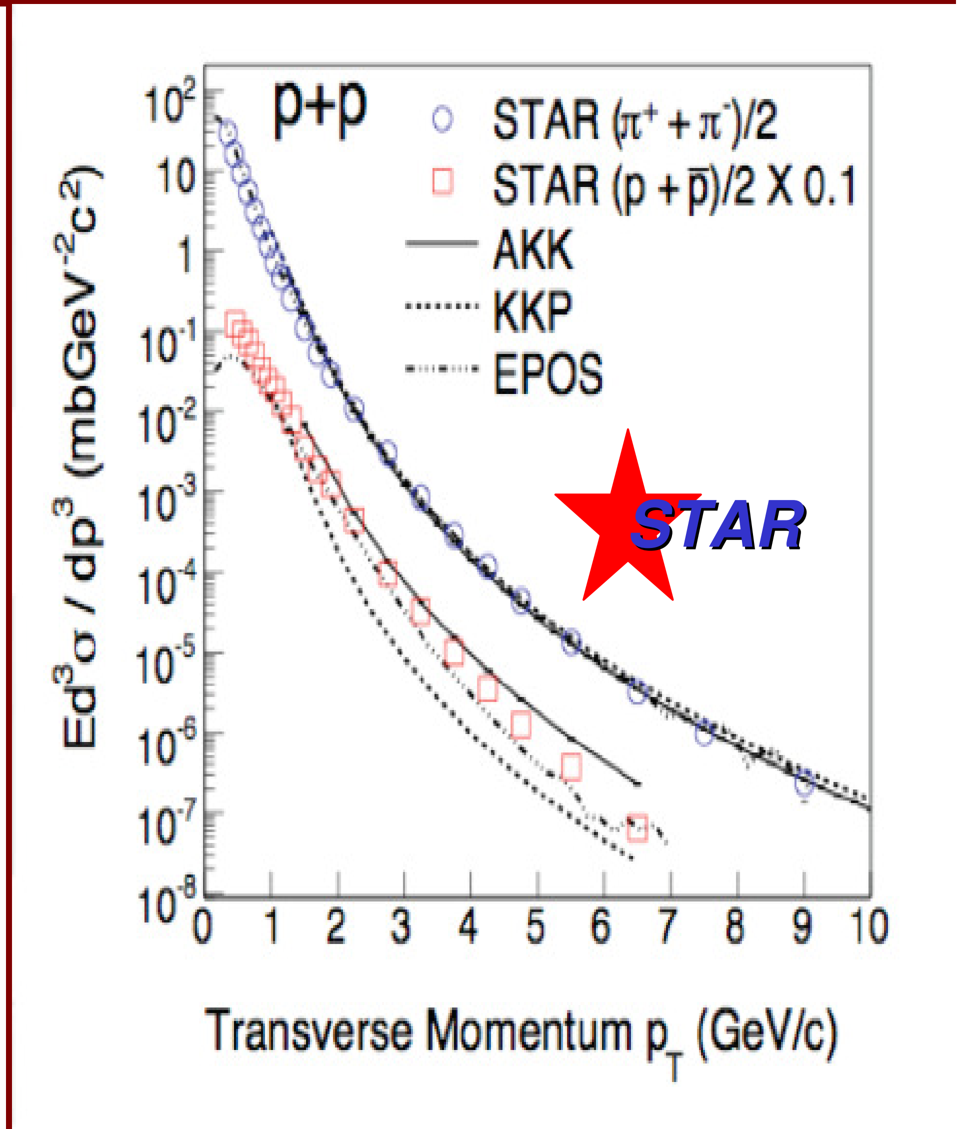
pQCD in Action at √s=200 GeV





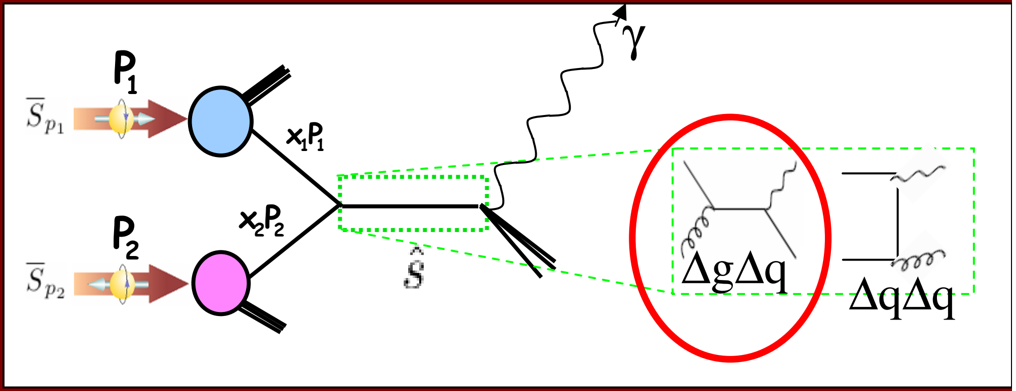
pQCD in Action at √s=200 GeV



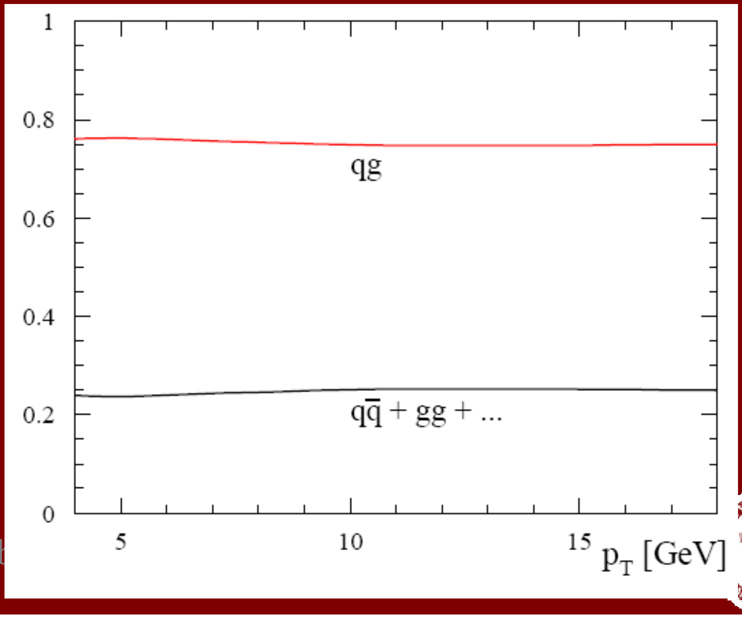


Prompt γ Production at √s=200 GeV

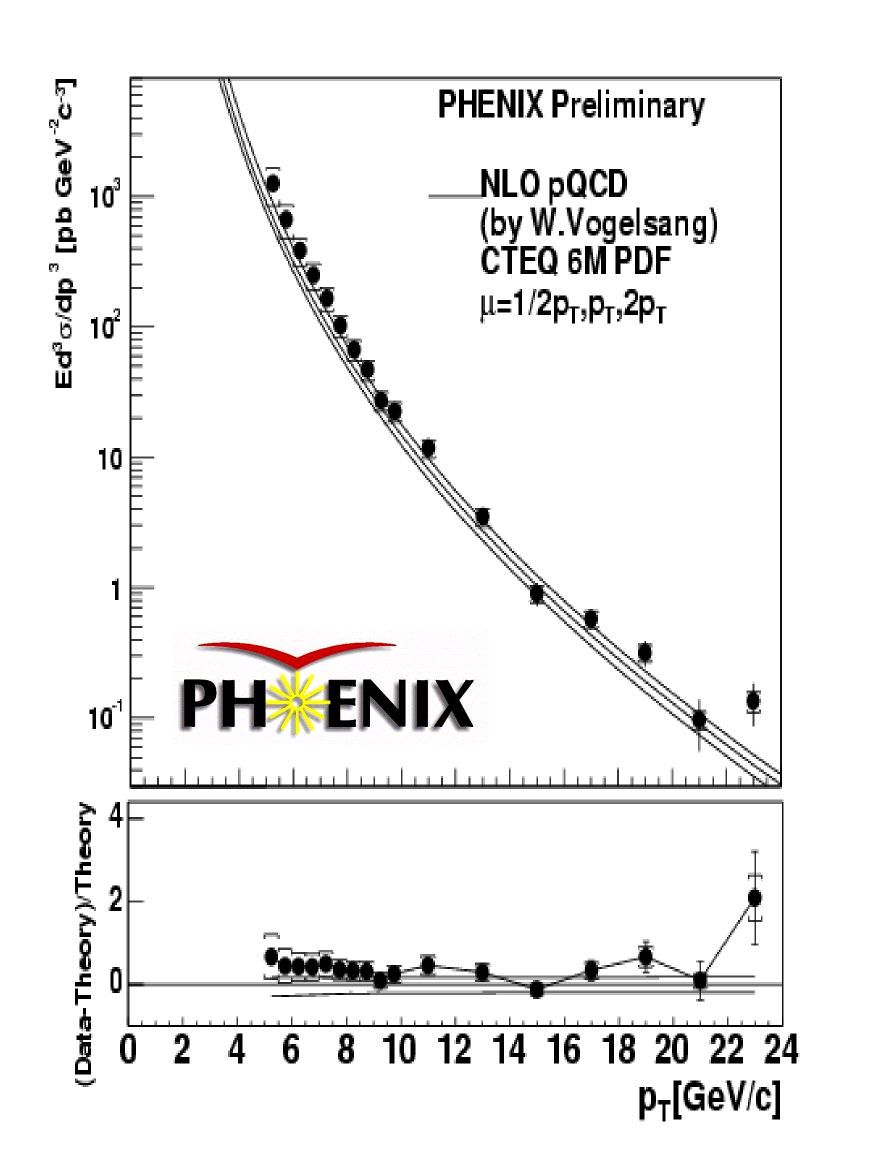
- Gluon Compton scattering dominates
  - At LO no fragmentation function
  - Small contribution from annihilation

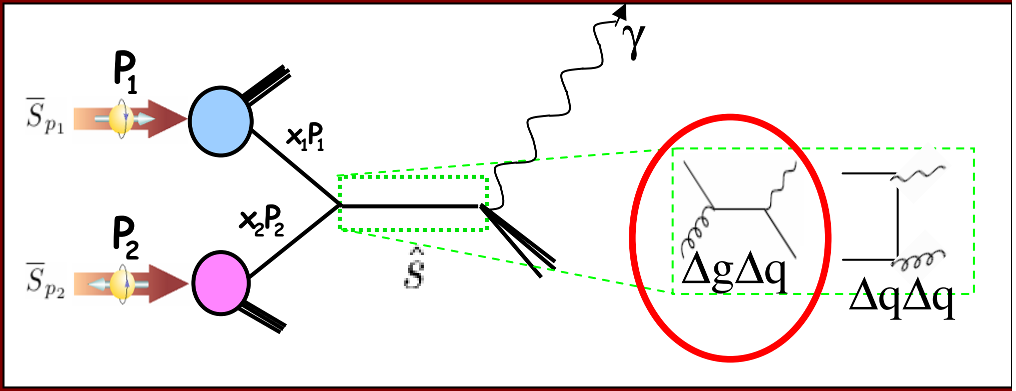


$$A_{LL} \propto \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta q(x_2)}{q(x_2)} \otimes \hat{a}_{LL}(gq \to \gamma q)$$

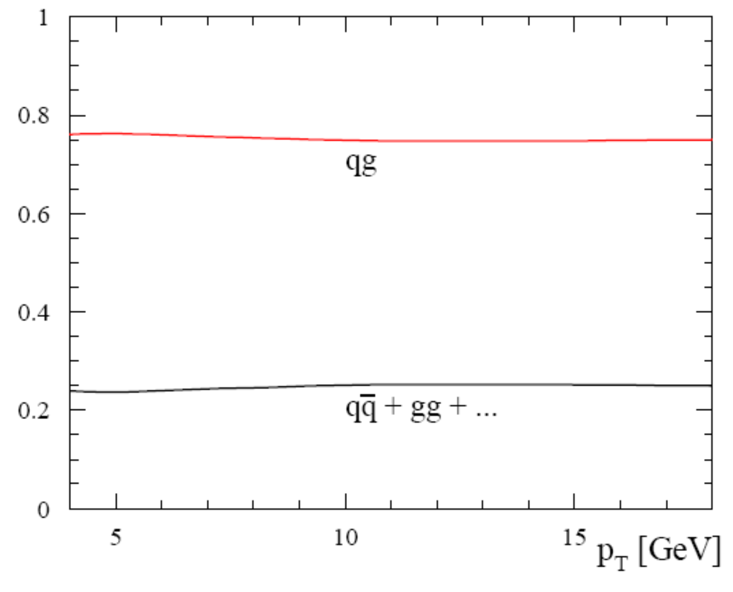


Prompt γ Production at √s=200 GeV

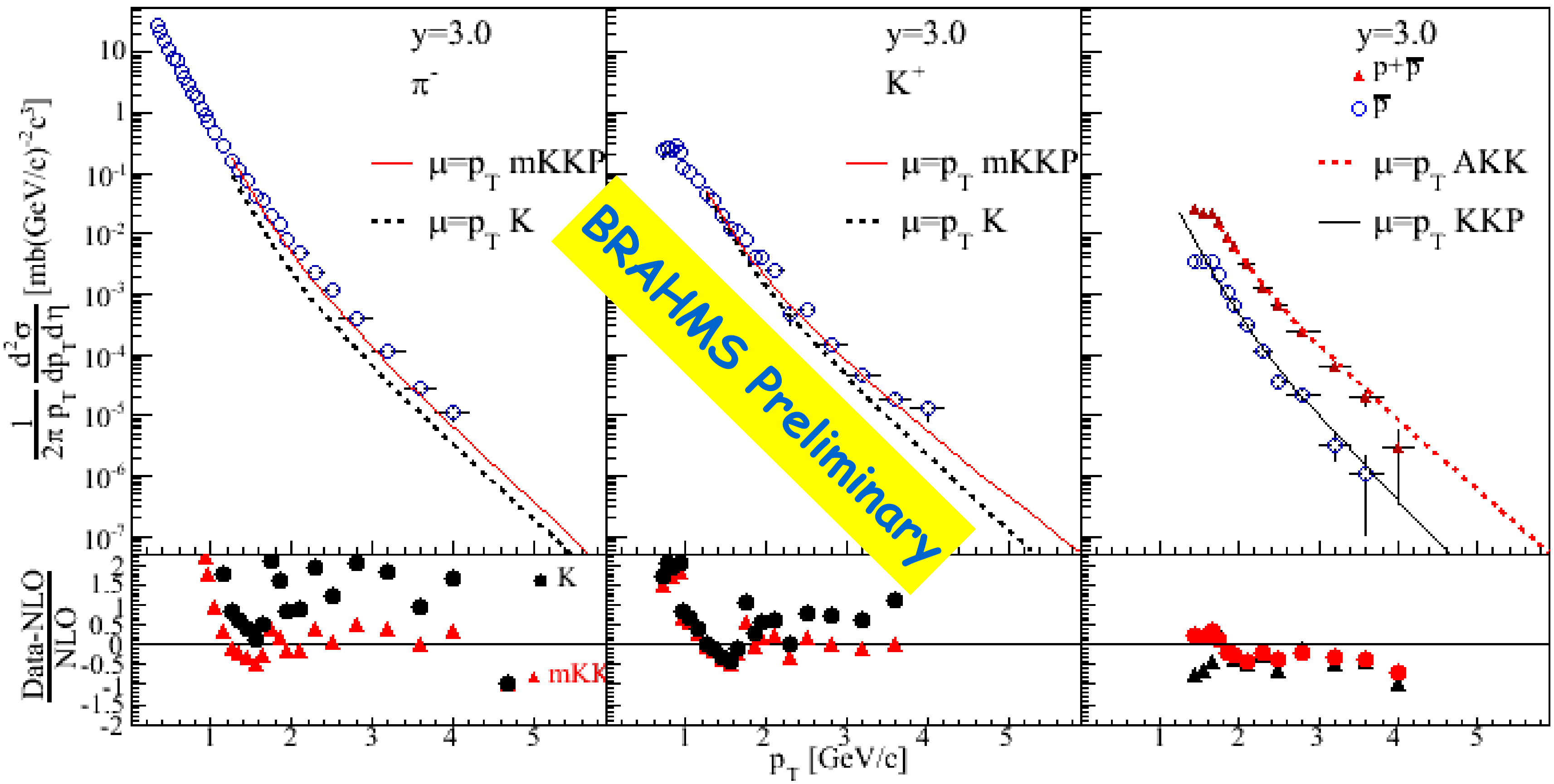




$$A_{LL} \propto \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta q(x_2)}{q(x_2)} \otimes \hat{a}_{LL}(gq \to \gamma q)$$

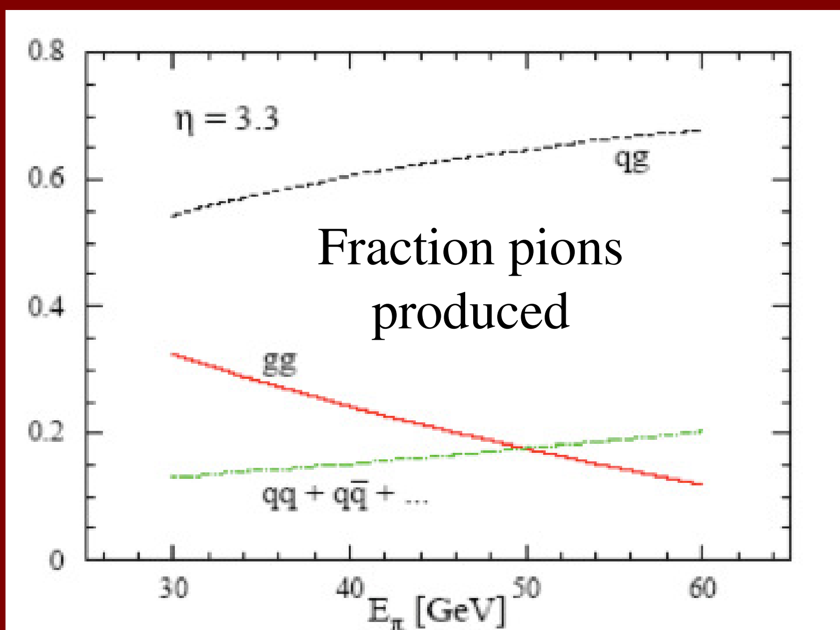


Forward Hadron Production at √s=200 GeV

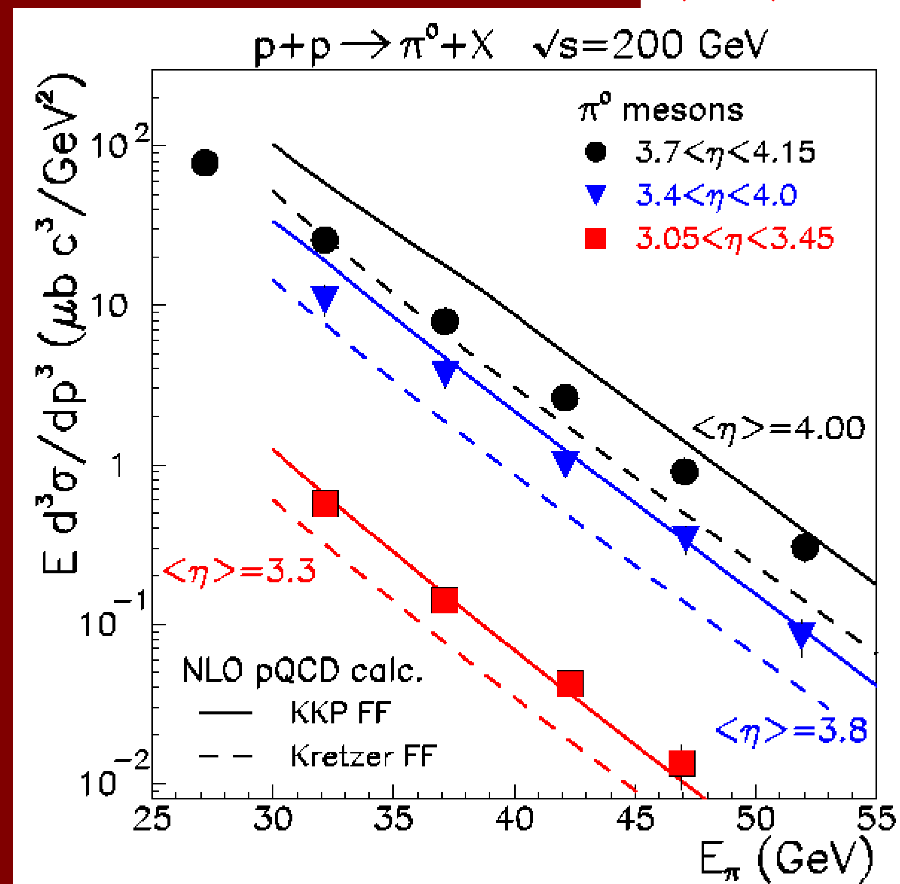


Forward Hadron Production at √s=200 GeV

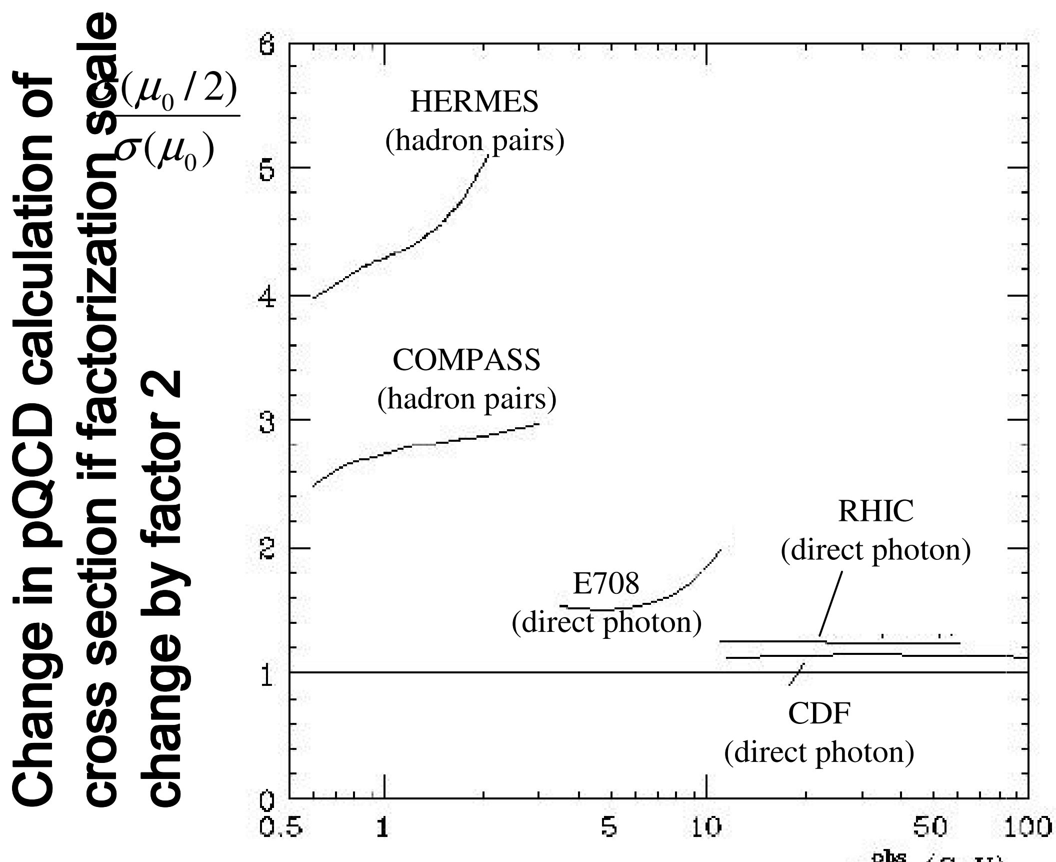
Good agreement between data and NLO pQCD at √s=200 GeV, even at larger rapidities



PRL 97 (2006) 152302



pQCD scale dependence at RHIC



Scale dependence benchmark:

Tevatron ~ 1.2
RHIC ~ 1.3
COMPASS ~ 2.5 – 3
HERMES ~ 4 – 5

→Scale dependence at RHIC is significantly reduced compared to fixed target polarized DIS.

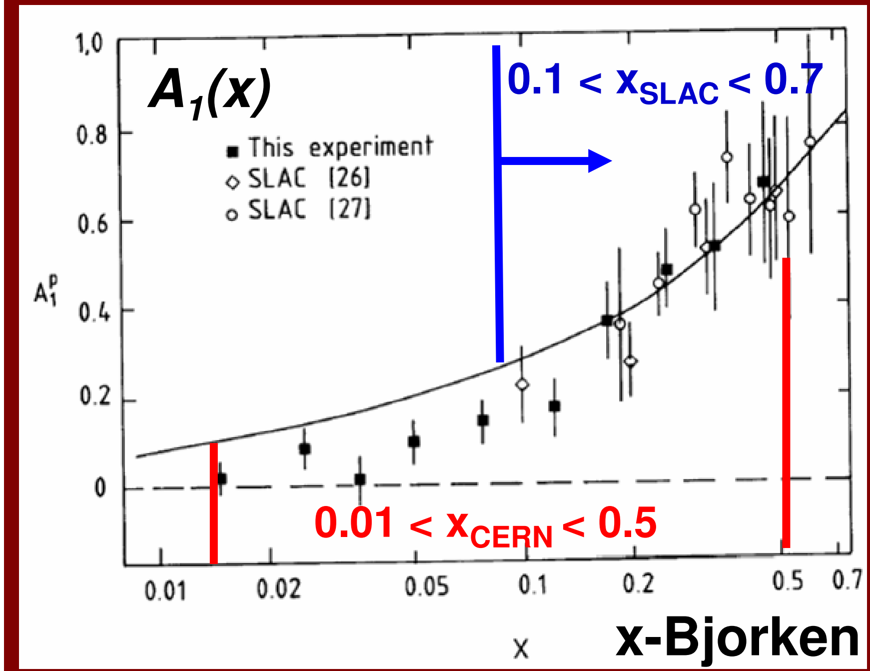
Conclusion: Extraction of spin dependent parton distributions is possible at RHIC using perturbative QCD ab initio: First spin structure experiments at collider energies!

Spin Crisis Came Out of a Low-x Measurement

SLAC: $0.10 < x_{SLAC} < 0.7$

CERN: $0.01 < x_{CERN} < 0.5$

$$\frac{1}{2} = \frac{1}{2} \cdot \Delta\Sigma + \Delta G + L_{G+q}$$



$$\Delta\Sigma_{SLAC+CERN} = 0.07 \pm 0.05 \pm 0.1$$

EMC (CERN), Phys.Lett.B206:364 (1988)
1349 citations in SPIRES!

⇨ **"Proton Spin Crisis"**

Spin Crisis Came Out of a Low-x Measurement

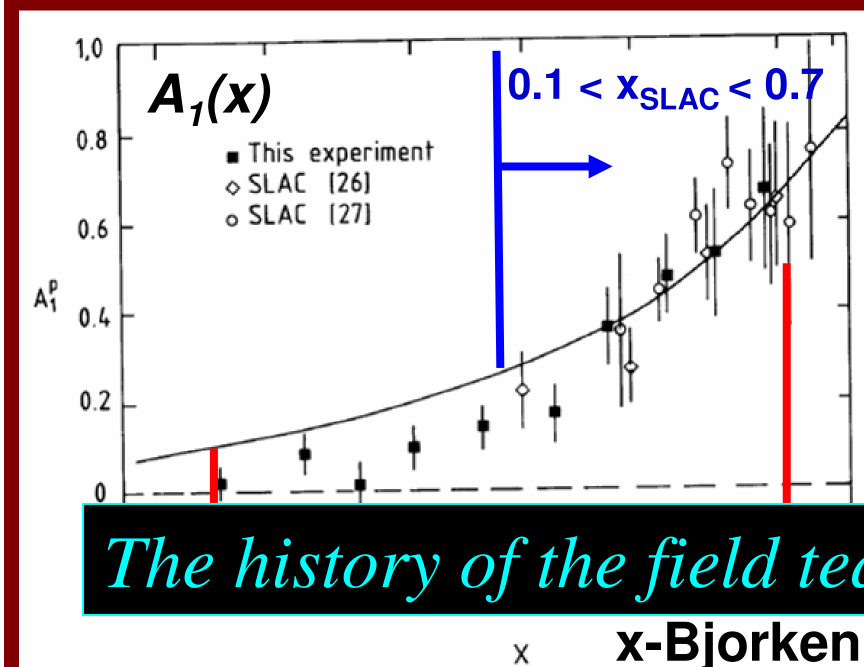
SLAC: $0.10 < x_{SLAC} < 0.$

CERN: $0.01 < x_{CERN} < 0.$

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

$\Delta\Sigma_{SLAC} \sim 0.6$ Quark-Parton Model expectation!

E130, Phys.Rev.Lett.51:1135 (1983)
415 citations

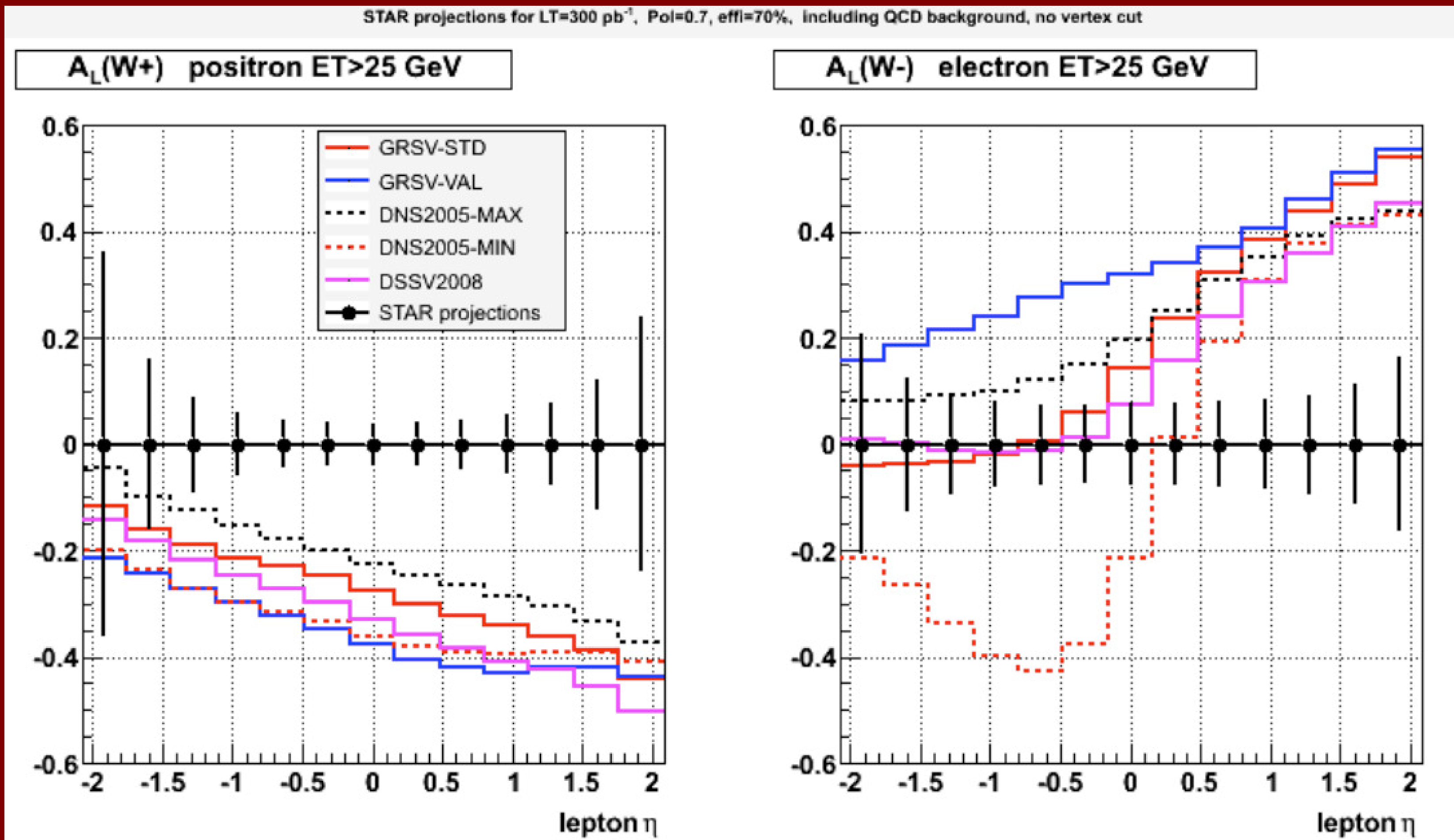


$$\Delta\Sigma_{SLAC+CERN} = 0.07 \pm 0.05 \pm 0.1$$

EMC (CERN), Phys.Lett.B206:364 (1988)
1349 citations in SPIRES!

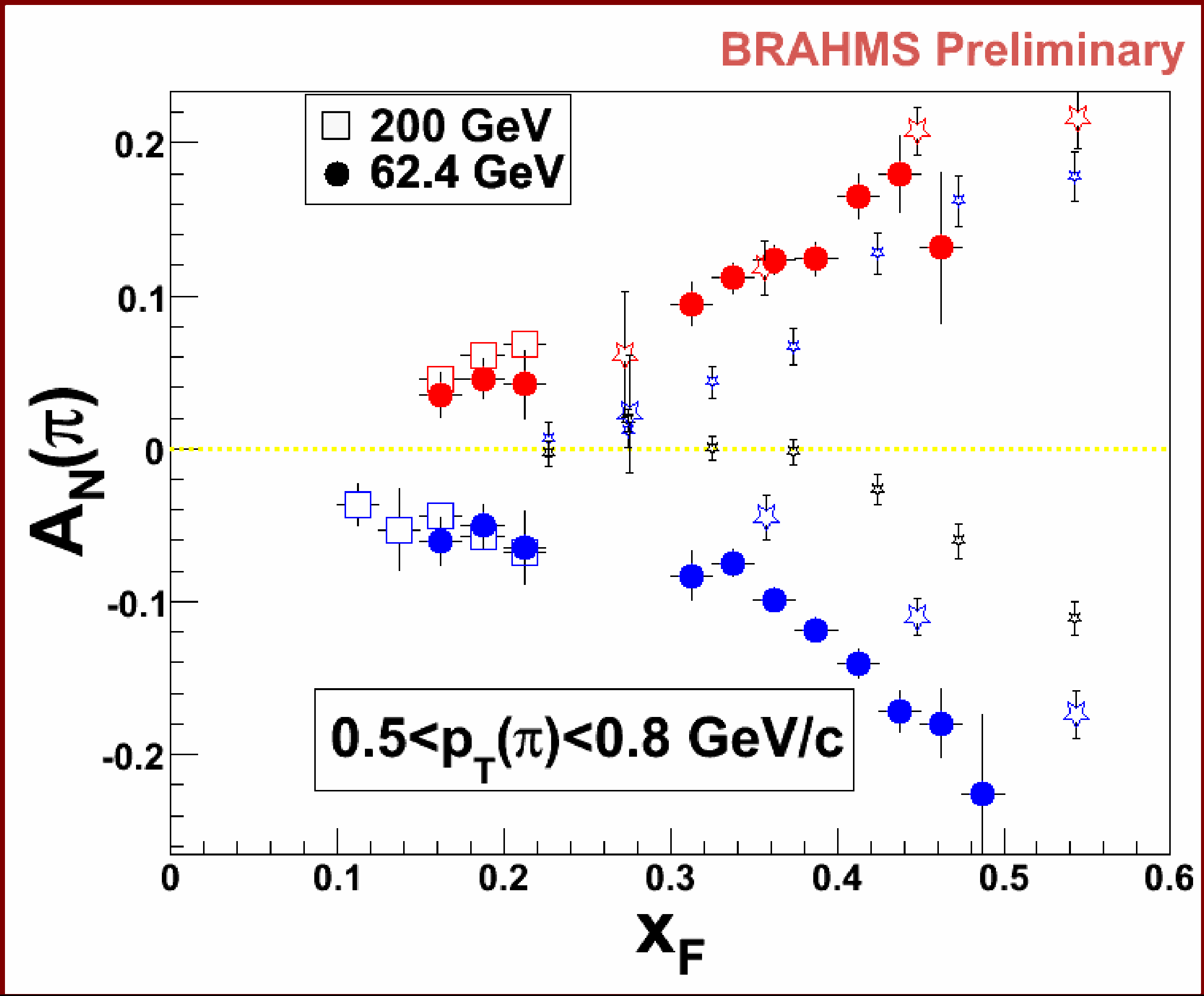
The history of the field teaches us that low x is important!

Sea Quark Helicities – Projections vs. η



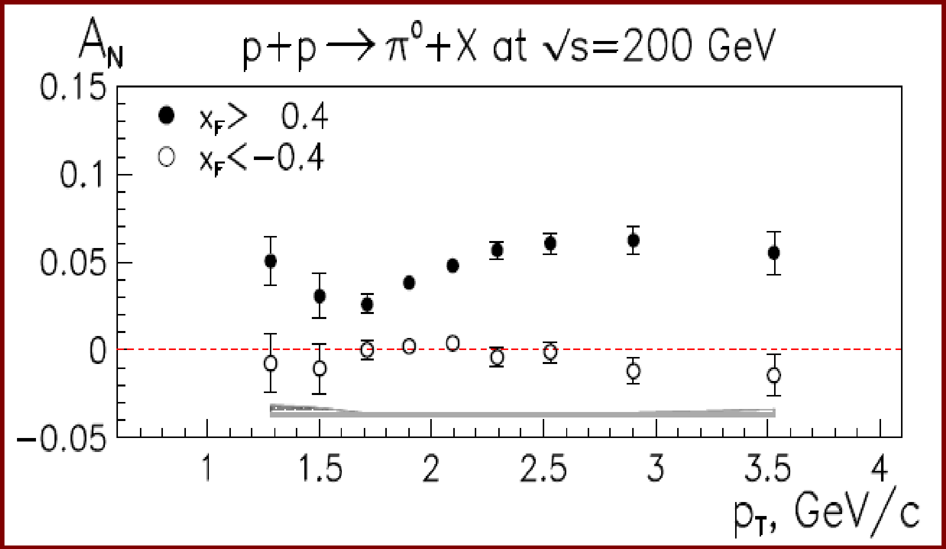
STAR

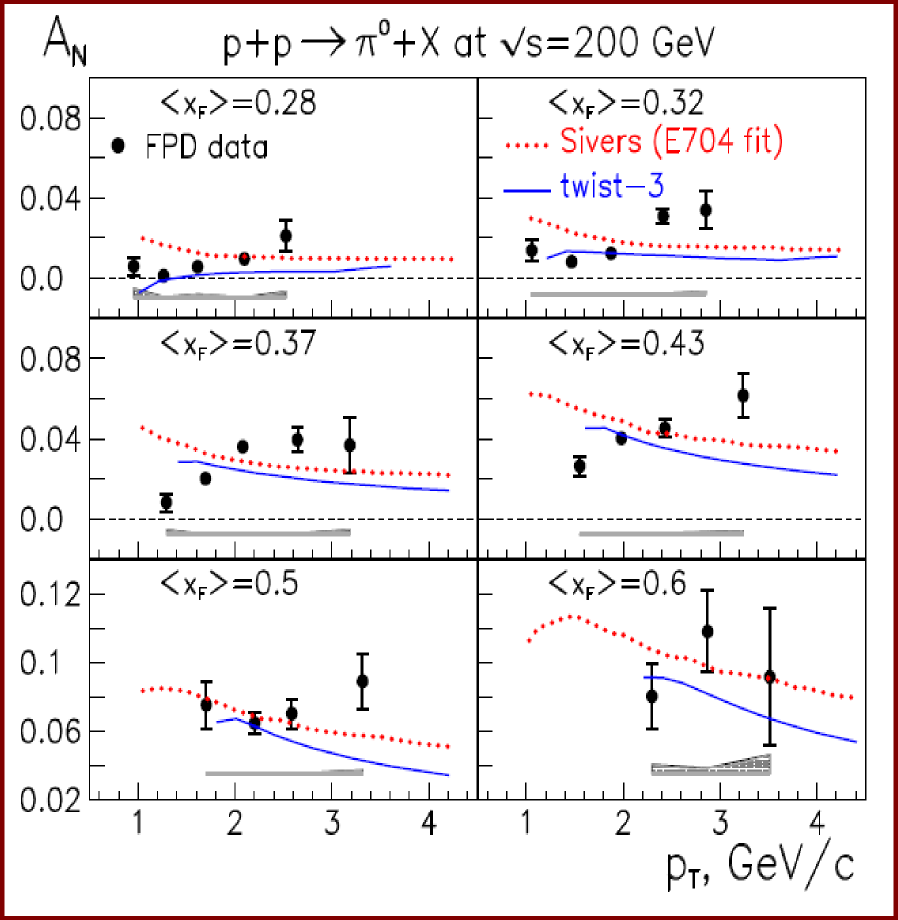
Unifying 62.4 and 200 GeV, BRAHMS + E704



E704 data – all p_T (small stars); p_T>0.7 GeV/c (large stars).

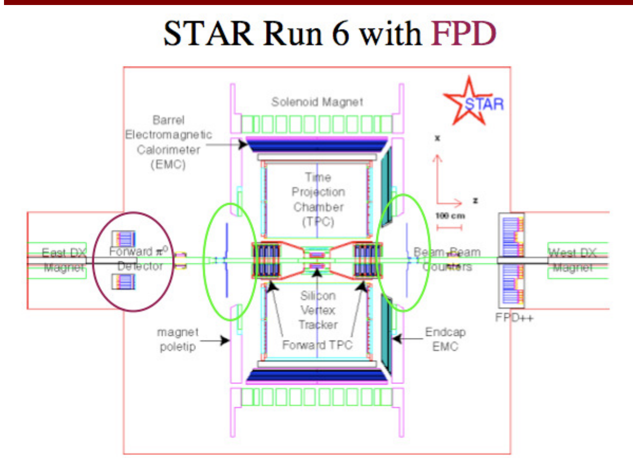
Forward π^0 A_N at 200 GeV: p_T dependence

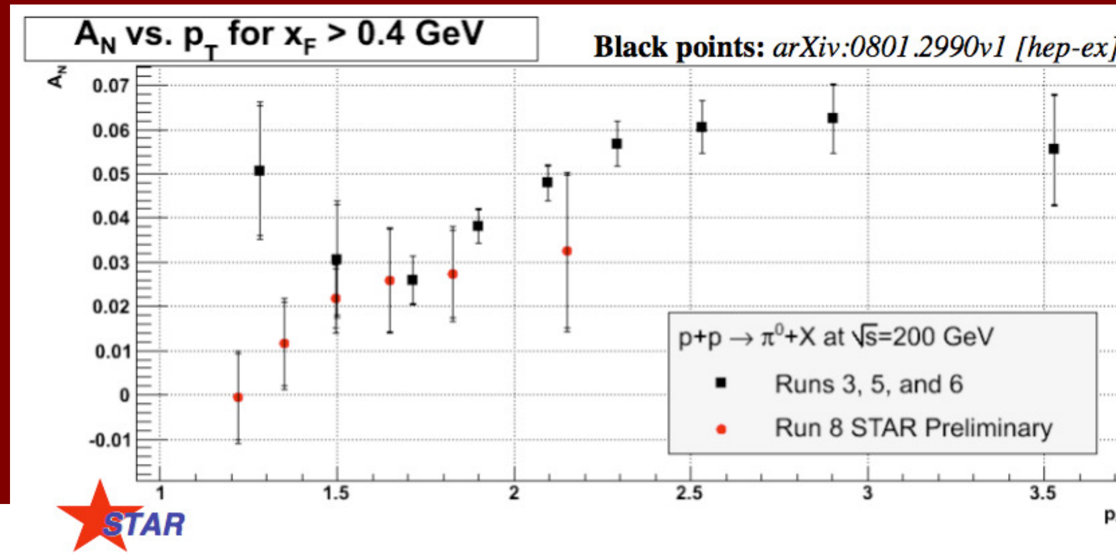


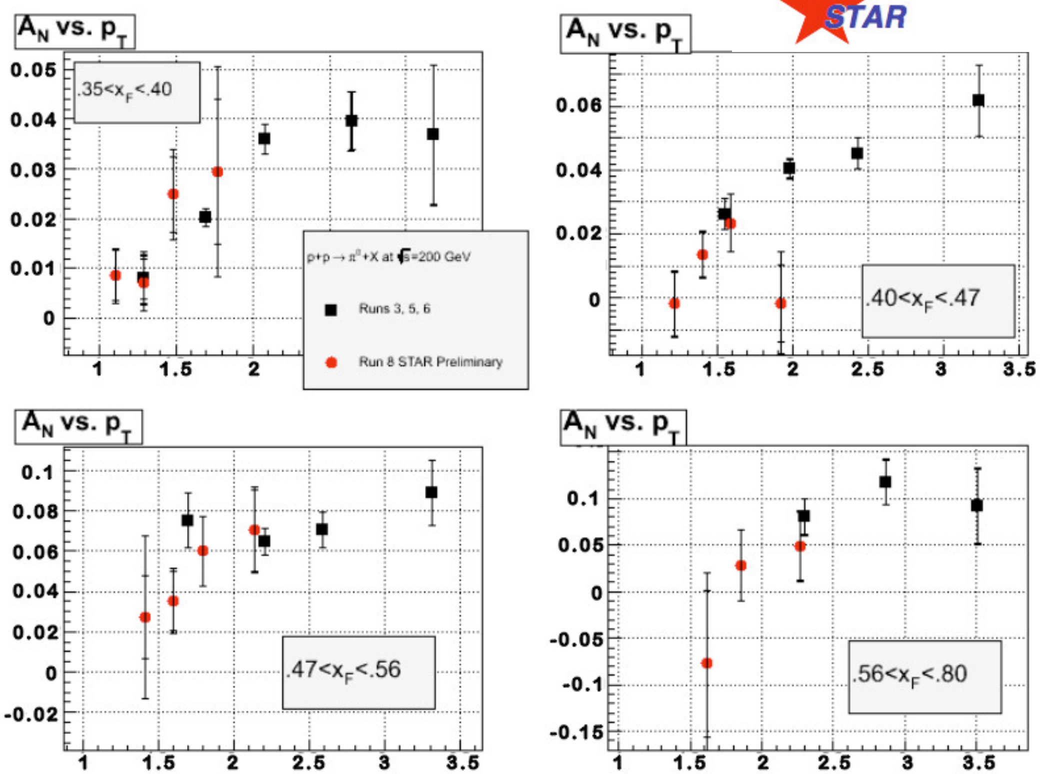


arXiv:0801.2990
Accepted by PRL

A_N at Forward Rapidity







First results from Run-08!

Attempting to Probe k_T from Orbital Motion

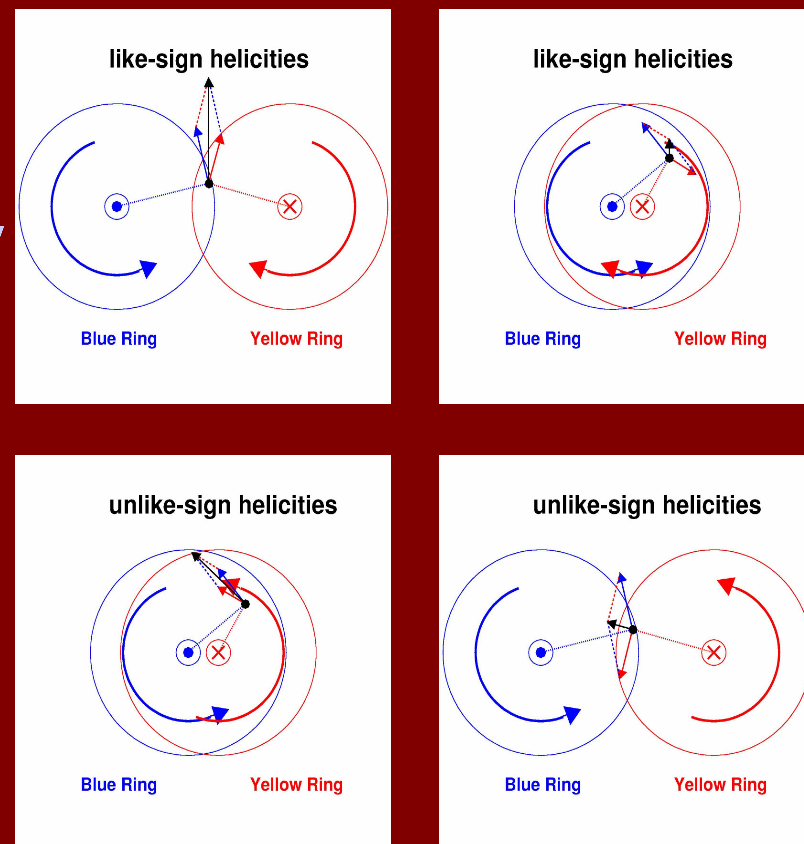
- Spin-correlated transverse momentum (orbital angular momentum) may contribute to jet k_T. (Meng Ta-chung et al., Phys. Rev. D40, 1989)
- Possible helicity dependence
- Would depend on (unmeasured) impact parameter, but may observe net effect after averaging over impact parameter

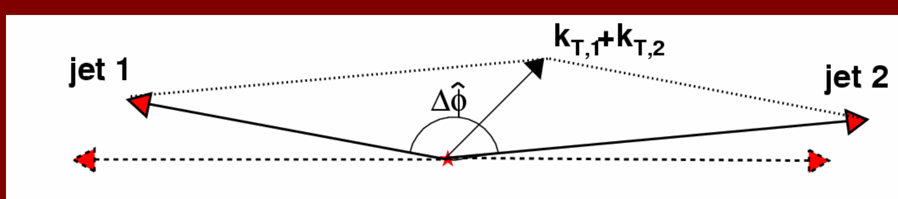
k_T larger

k_T smaller

Same helicity

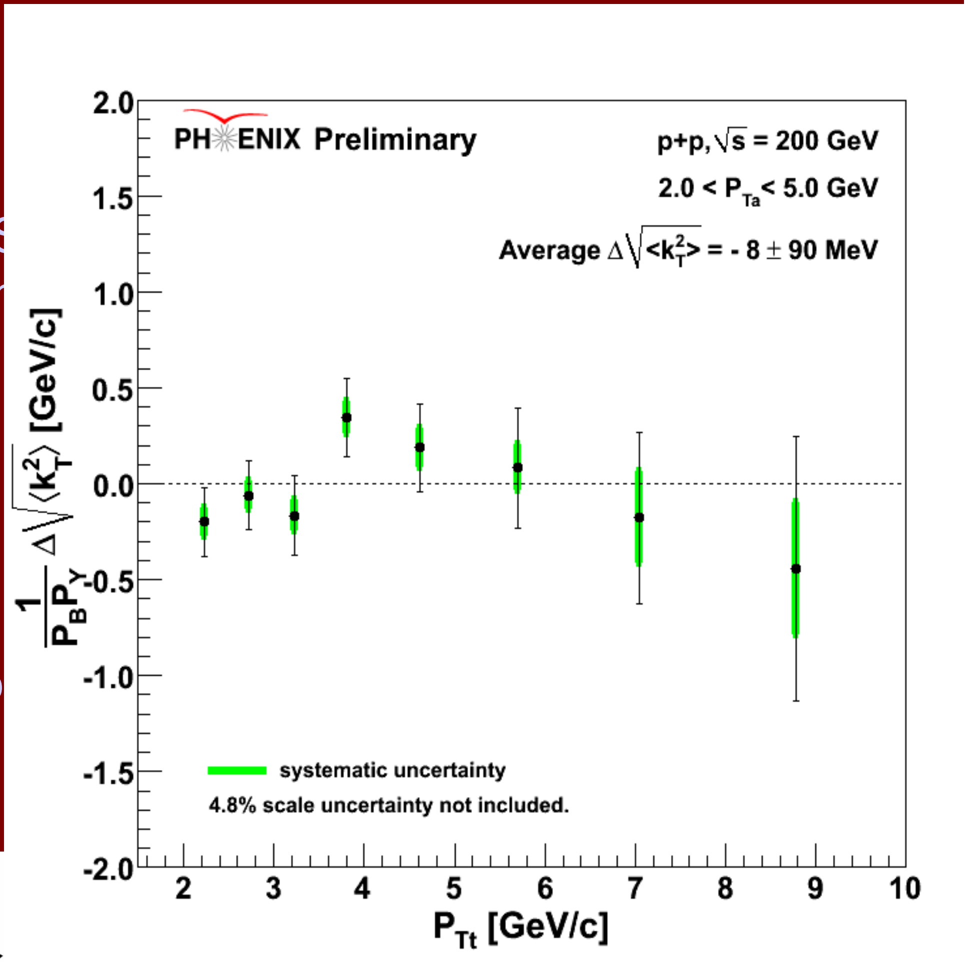
Opposite helicity

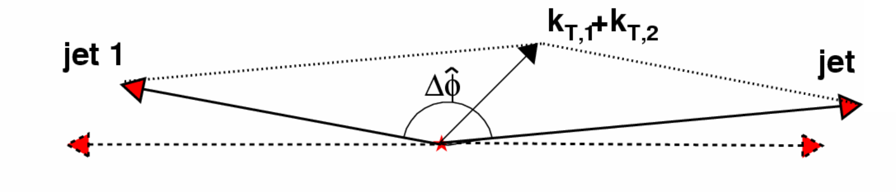




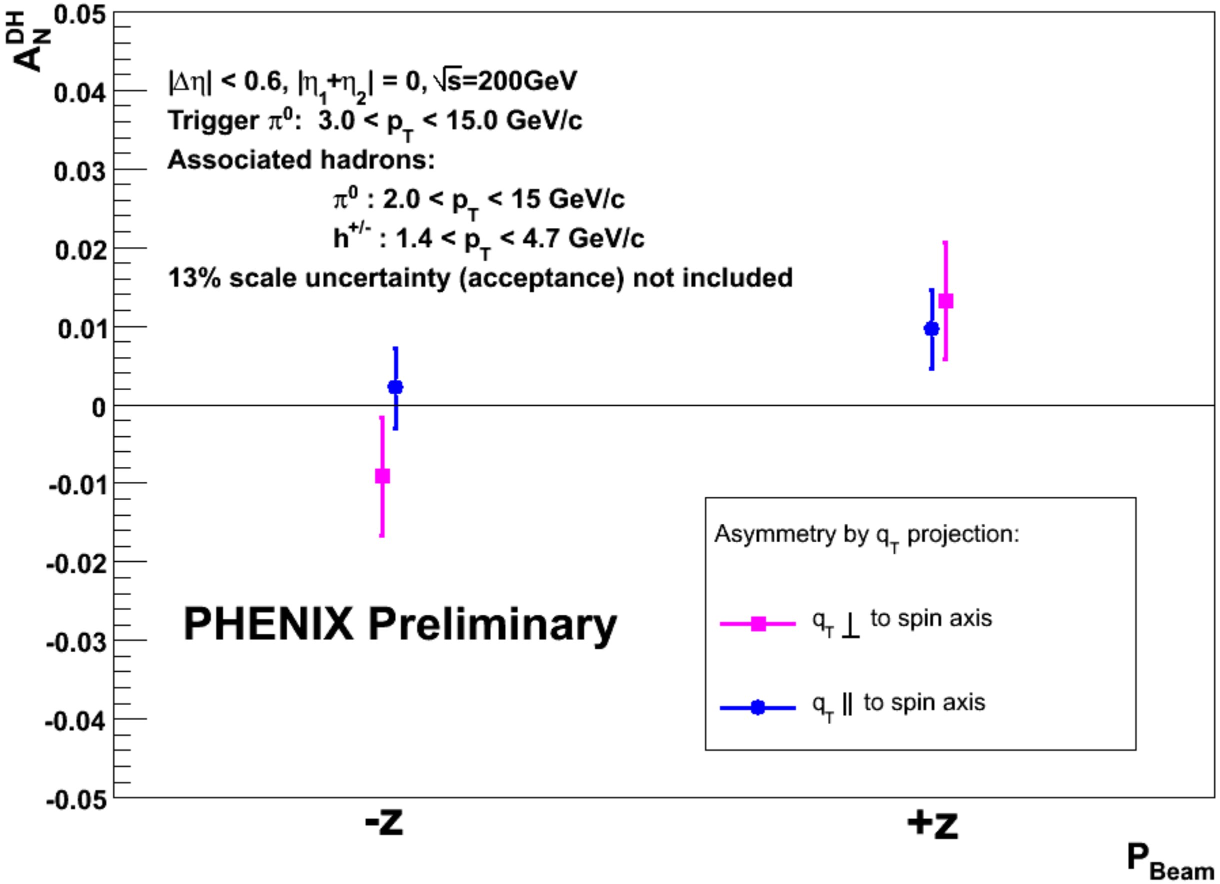
Attempting to Probe k_T from Orbital Motion

- Spin-correlated transverse momentum (orbital angular momentum) may contribute to jet k_T. (Meng Ta-chung et al., Phys. Rev. D40, 1989)
- Possible helicity dependence
- Would depend on (unmeasured) impact parameter, but may observe net effect after averaging over impact parameter





Sivers dihadrons from PHENIX



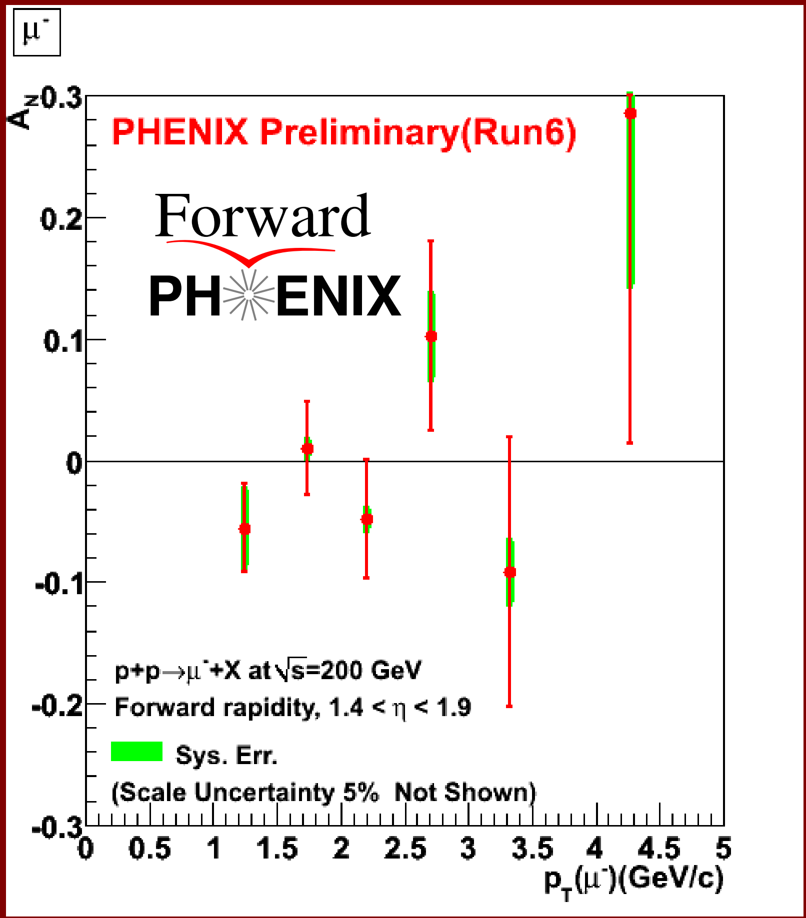
- $q_{T\perp}$ should show an asymmetry due to Sivers function.
- $q_{T||}$ should show no asymmetry, only for cross check.
- Measurement result: the asymmetry for $q_{T\perp}$ due to Sivers effect is consistent with zero.
- Fragmentation dilution factor is not included.

If an asymmetry is measured

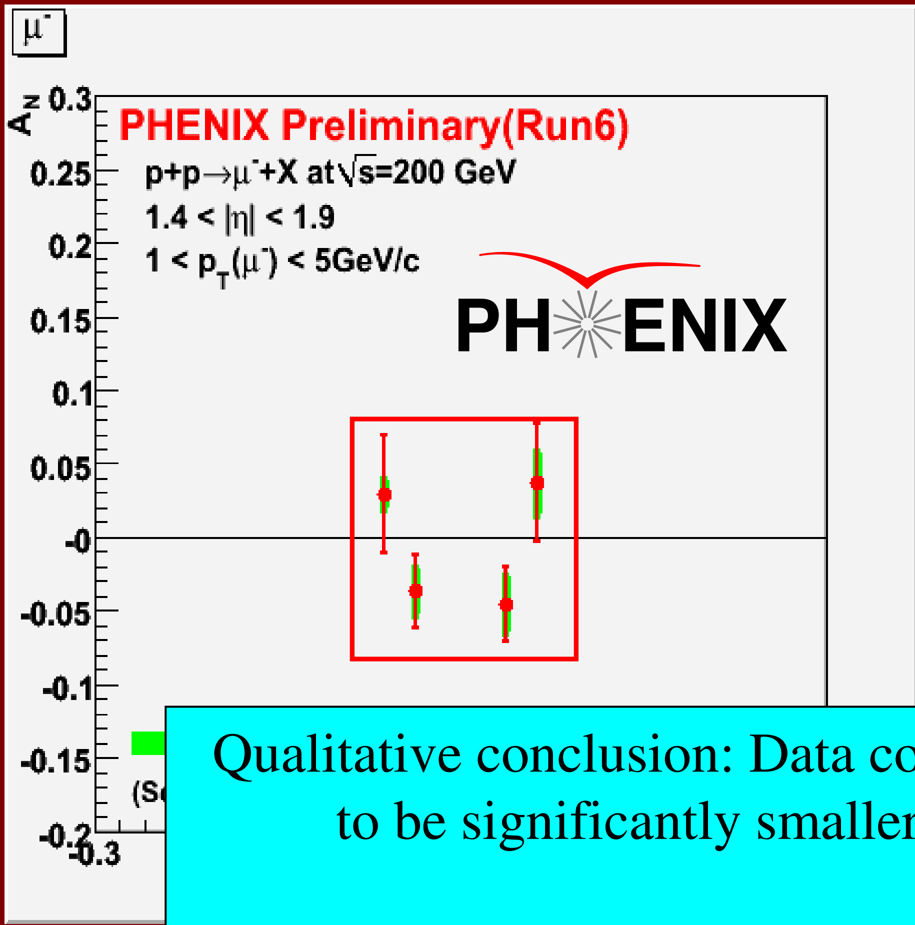
$$A_N \propto \vec{S}_T \bullet (\vec{P}_p \times \vec{k}_T) \Rightarrow A_N(P_{+z}) = -A_N(P_{-z}) \text{ for } q_{T\perp}$$

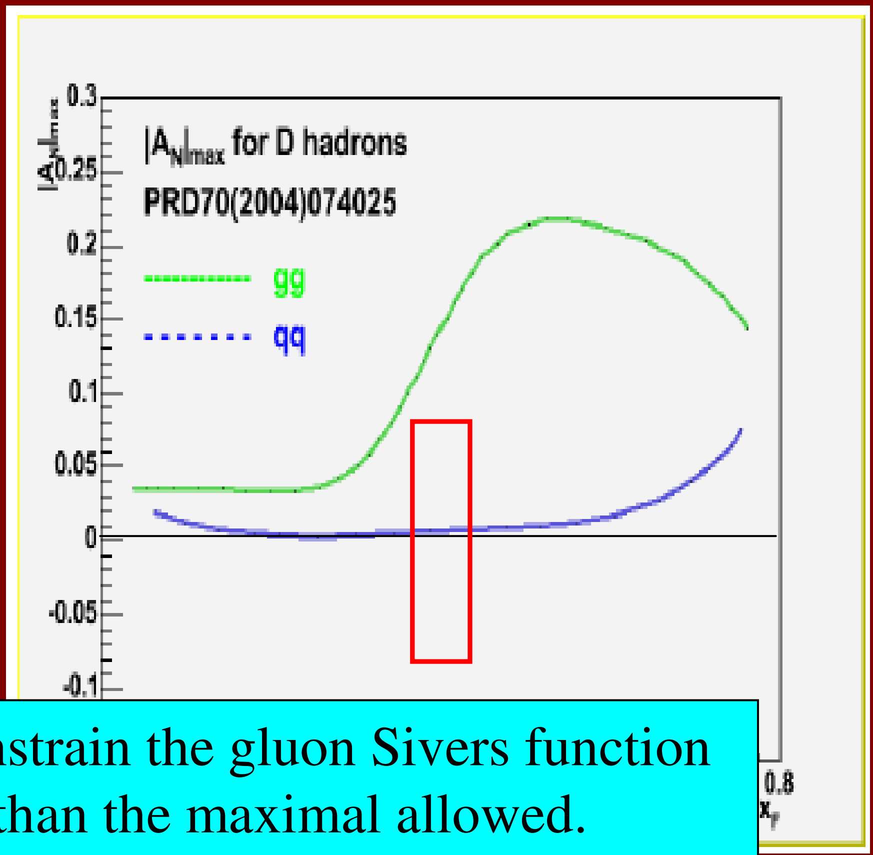
Heavy flavor single spin asymmetries

- Open charm single spin asymmetries sensitive to gluon Sivers function
  - Anselmino et al, PRD70, 074025 (2004)
- PHENIX data now available for A_N of prompt muons from heavy flavor decays



SSA of heavy flavor vs. x_F



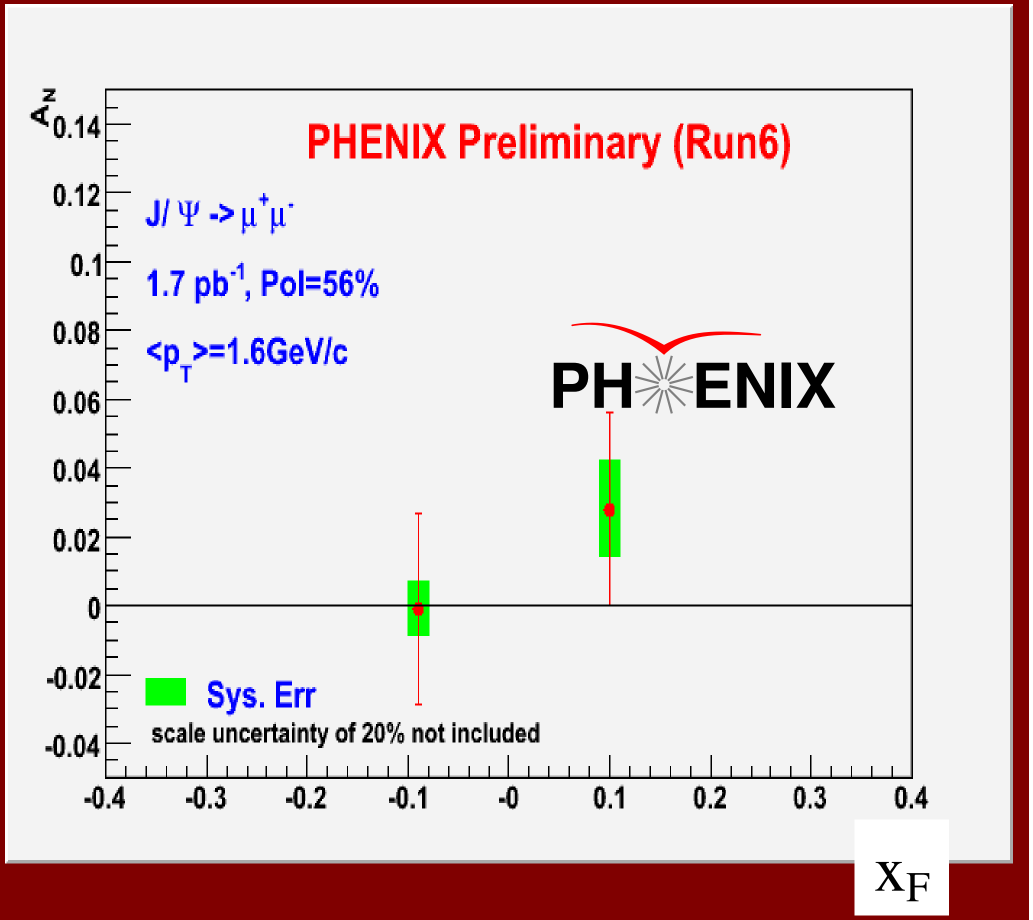


Qualitative conclusion: Data constrain the gluon Sivers function to be significantly smaller than the maximal allowed.

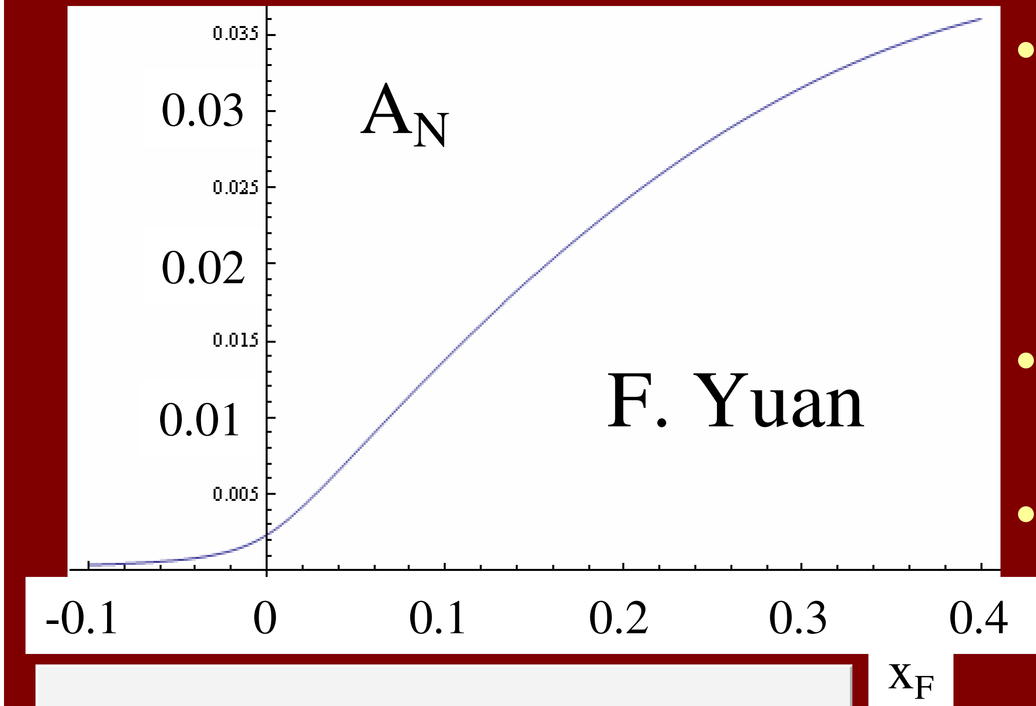
Translation between D meson and muon kinematics and estimate of charm vs. bottom components underway such that more quantitative comparison can be made in the future.

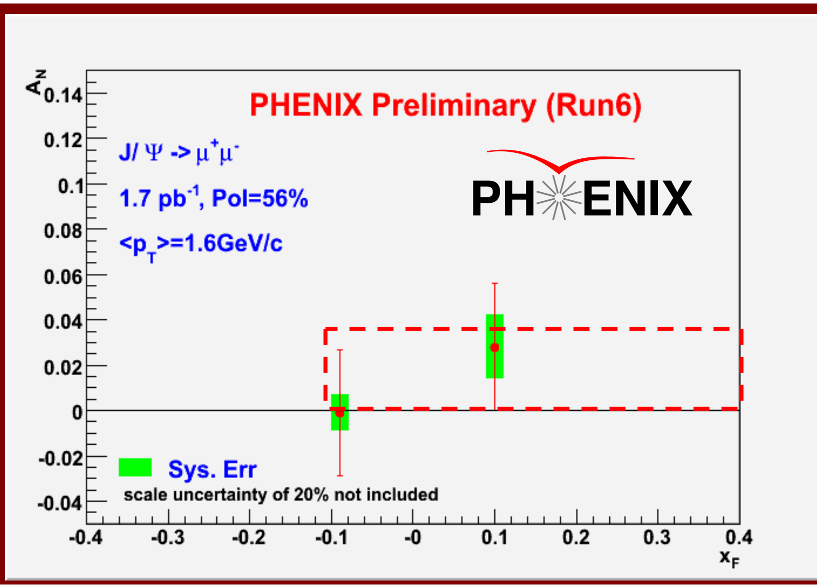
What about charmonium?

- J/ψ complicated by unknown production mechanism!
- Recent calculations for charmonium from F.Yuan, arXiv:0801.4357 [hep-ph]



New "rough" calculation for J/Ψ A_N at RHIC





- Assumed gluon Sivers function ~ 0.5 x(1-x) times unpolarized gluon distribution

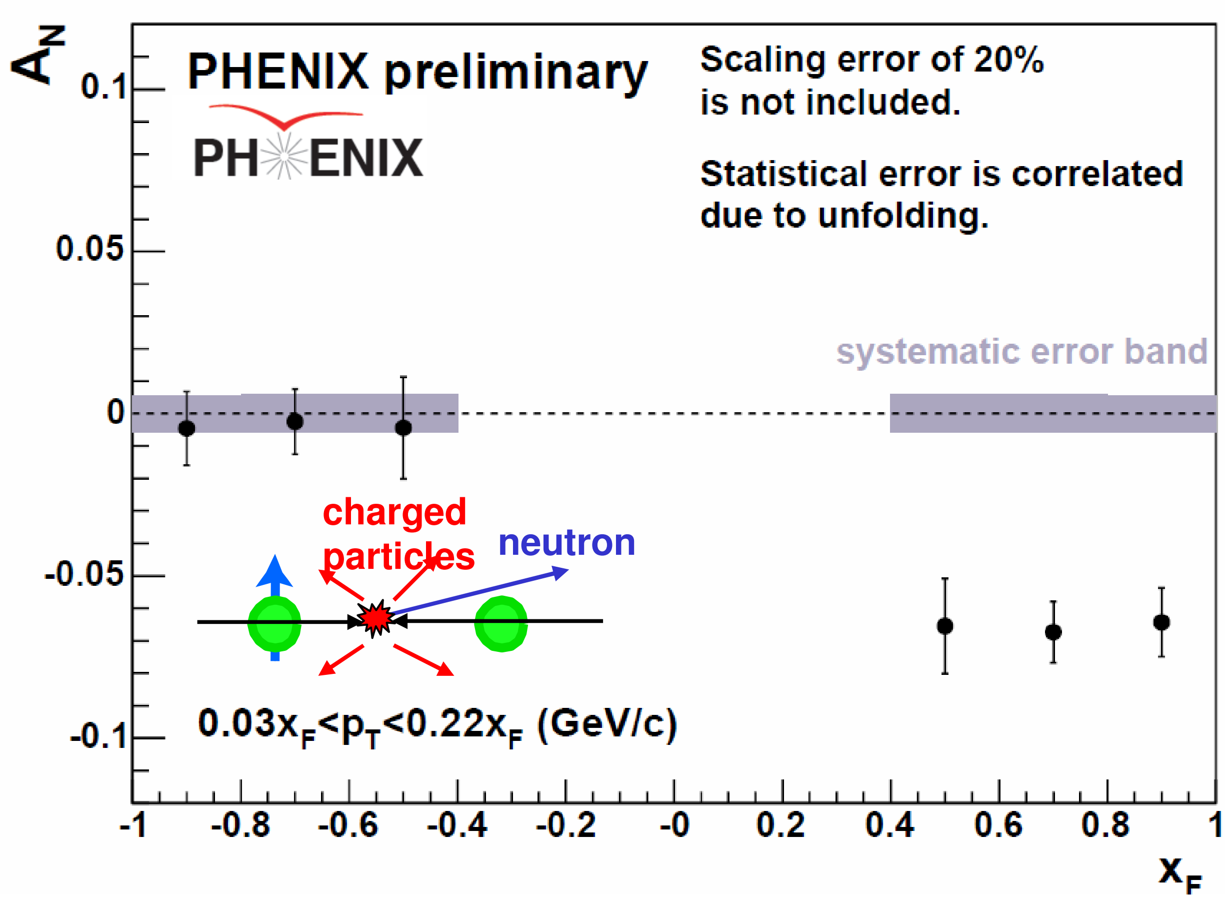
$$xG_{1T}^{\perp(1/2)}(x) \approx 0.5x(1-x)xG(x)$$

- Assumed 30% J/Ψ from χ_c decays
- No direct contributions!
  - Color-singlet is small in the cross section
  - Color-octet, FSI/ISI cancel out, SSA vanishes in the limit of $p_T \ll M_Q$
  - Origin of potential non-zero asymmetry is through χ_c!
- But beware: Production mechanism remains poorly understood!

Forward neutrons at √s=200 GeV at PHENIX

Large negative SSA observed for x_F>0, enhanced by requiring concidence with forward charged particles ("MinBias" trigger). No x_F dependence seen.

Neutron asymmetry x_F distribution with neutron trigger & MinBias



Mean p_T
(Estimated by simulation assuming ISR p_T dist.)

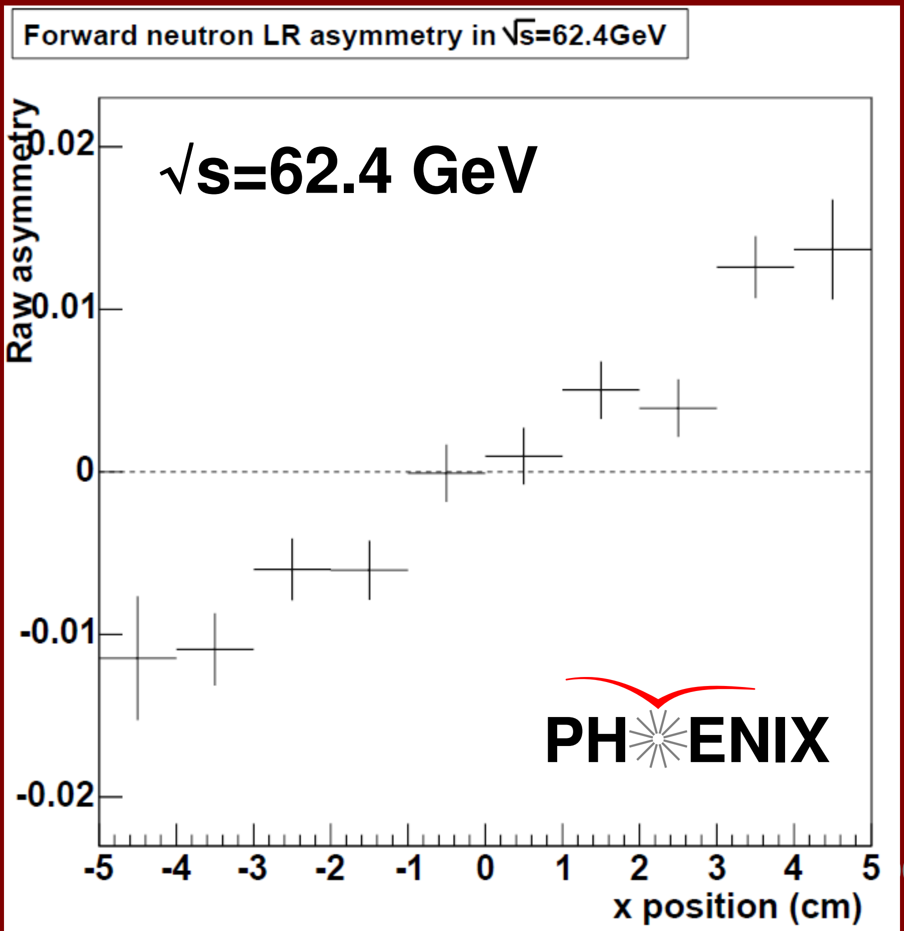
$0.4<\|x_F\|<0.6$	0.088 GeV/c
$0.6<\|x_F\|<0.8$	0.118 GeV/c
$0.8<\|x_F\|<1.0$	0.144 GeV/c

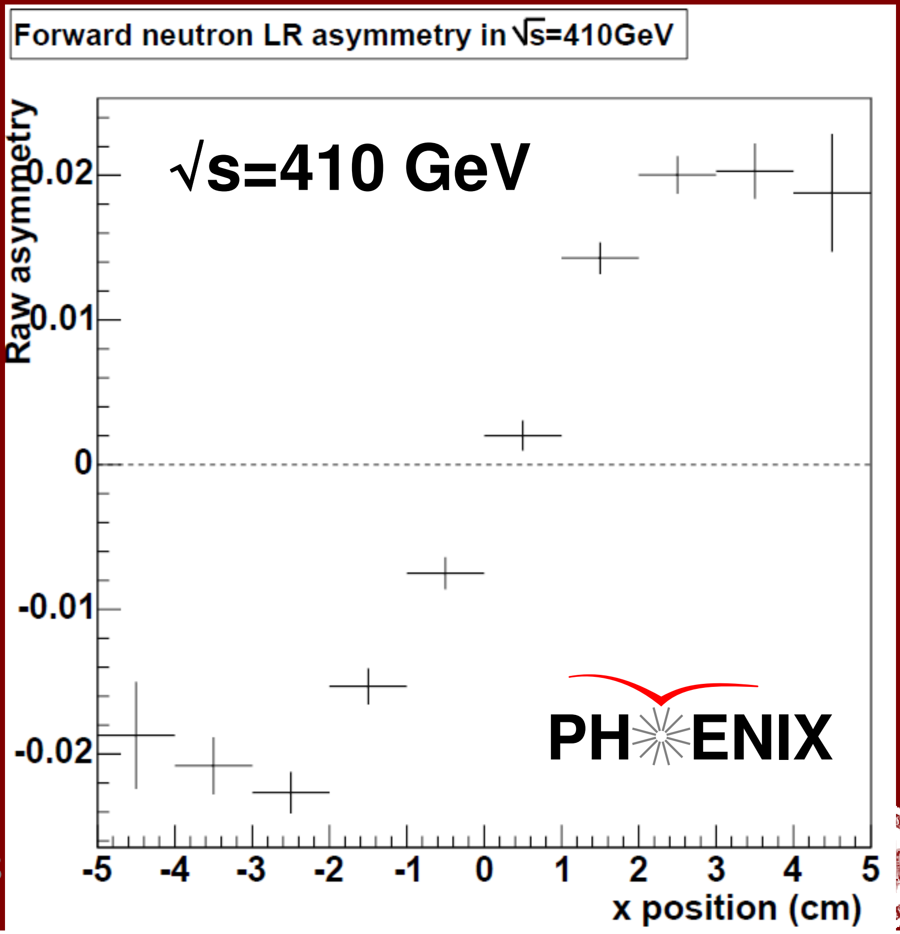
preliminary	A_N
Without MinBias	**-6.6 ±0.6 %**
With MinBias	**-8.3 ±0.4 %**

Forward neutrons at other energies

Significant forward neutron asymmetries observed down to 62.4 and up to 410 GeV!

$$A = \frac{N_+ - RN_-}{N_+ + RN_-}$$





Yesterday's discovery is today's calibration . . .

- Coulomb-nuclear interference and polarimetry at RHIC
  - Transverse SSA in elastic p+p and p+C scattering
- Transverse single-spin asymmetry in forward neutron production as local polarimetry at RHIC

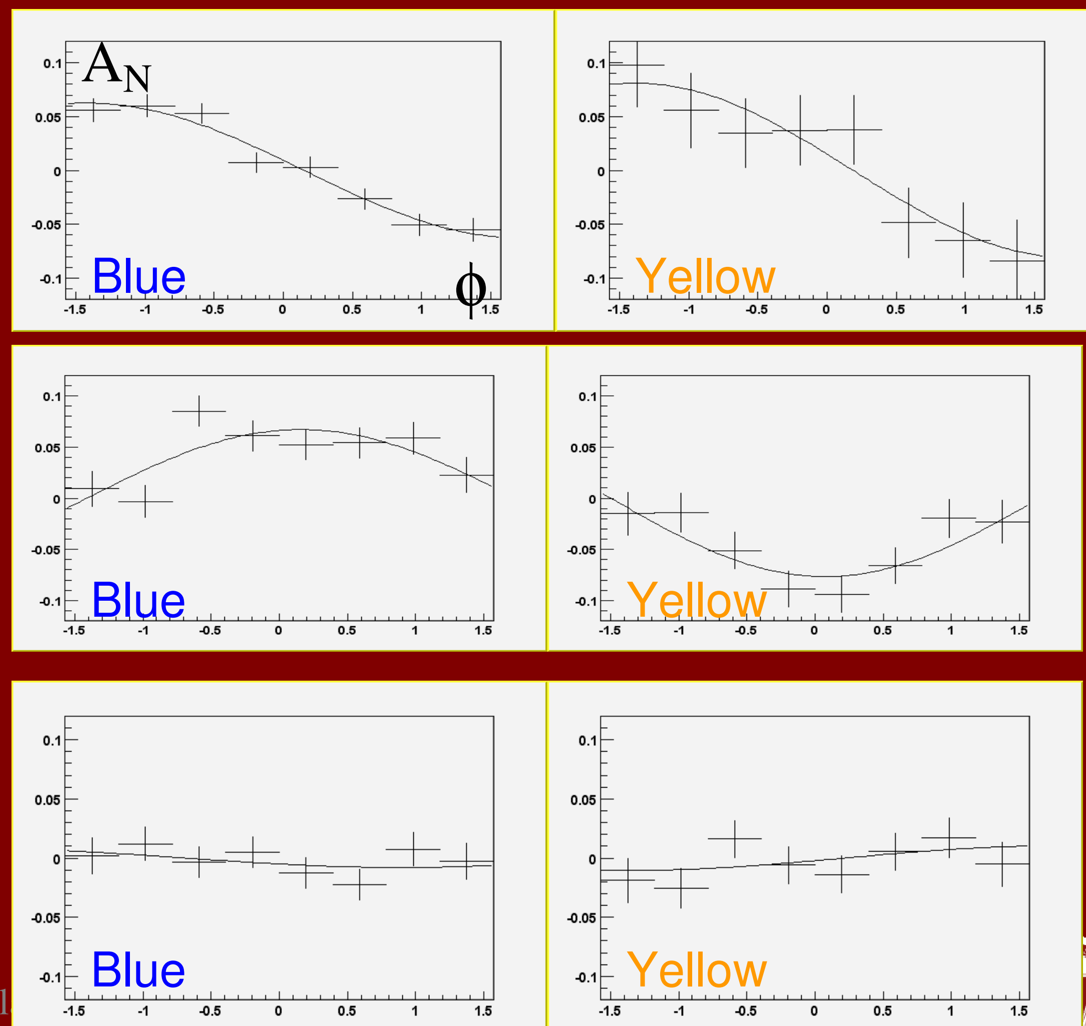
Yet note that forward neutron asymmetry still not understood at all!

Single-Spin Asymmetries for Local Polarimetry: Confirmation of Longitudinal Polarization

Spin Rotators OFF
Vertical polarization

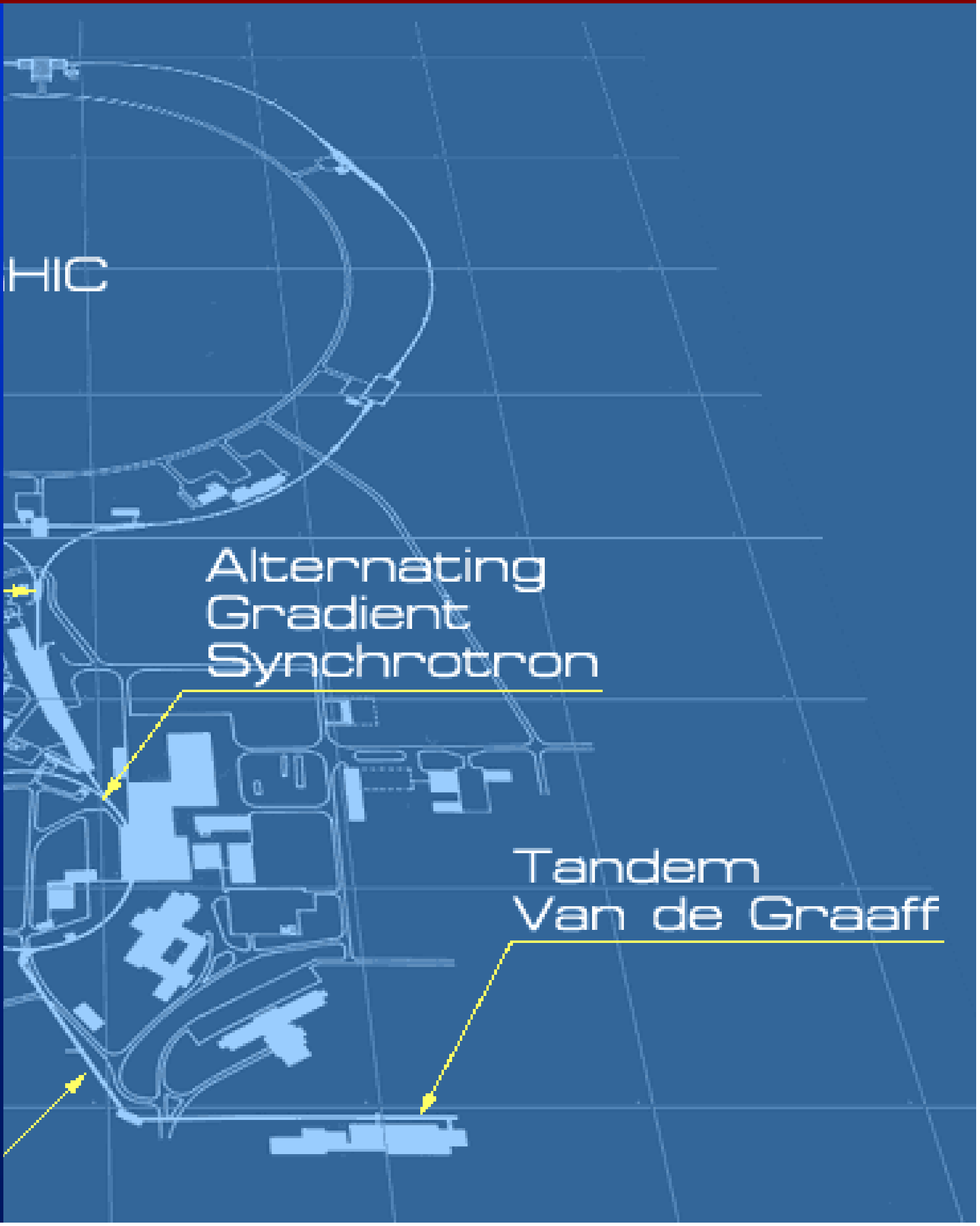
Spin Rotators ON
Current Reversed!
Radial polarization

Spin Rotators ON
Correct Current
Longitudinal polarization!



RHIC Specifications

- 3.83 km circumference
- Two independent rings
  - Up to 120 bunches/ring
  - 106 ns crossing time
- Energy:
  - ➔Up to 500 GeV for p+p
  - ➔Up to 200 GeV for Au+Au (per N+N collision)
- Luminosity
  - Au+Au: 2×10^{26} cm^{-2} s^{-1}
  - p+p : 2×10^{32} cm^{-2} s^{-1} (*<u>70% polarized</u>*)

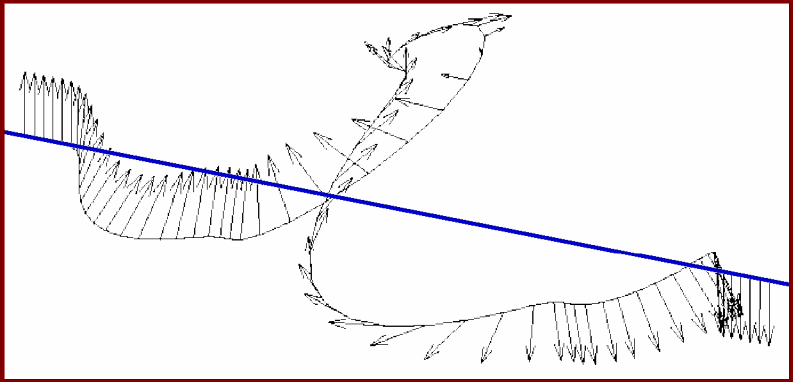


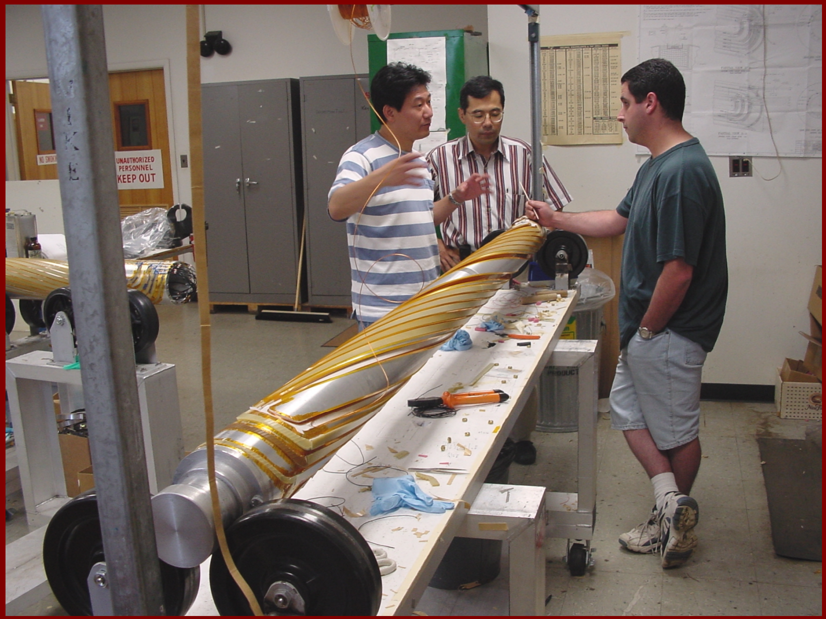
Polarized Collider Development

Parameter	Unit	2002	2003	2004	2005	**2006**
No. of bunches	--	55	55	56	106	**111**
bunch intensity	10^{11}	0.7	0.7	0.7	0.9	**1.4**
store energy	GeV	100	100	100	100	**100**
β^*	m	3	1	1	1	**1**
peak luminosity	$10^{30}cm^{-2}s^{-1}$	2	6	6	10	**35**
average luminosity	$10^{30}cm^{-2}s^{-1}$	1	4	4	6	**20**
Collision points	--	4	4	4	3	**2**
average polarization, store	%	15	27	46	50	**57**

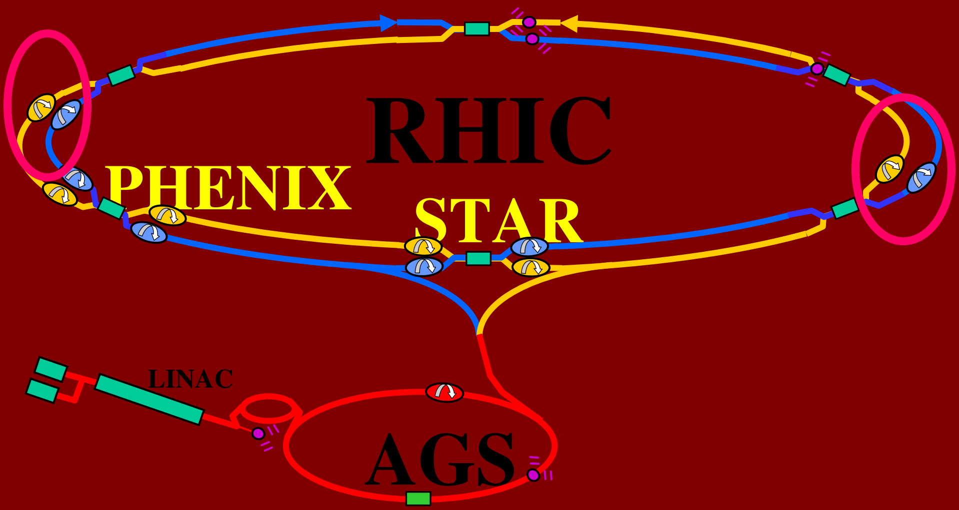
"Siberian Snakes" To Maintain Polarization

Effect of depolarizing resonances averaged out by rotating spin by 180 degrees on each turn



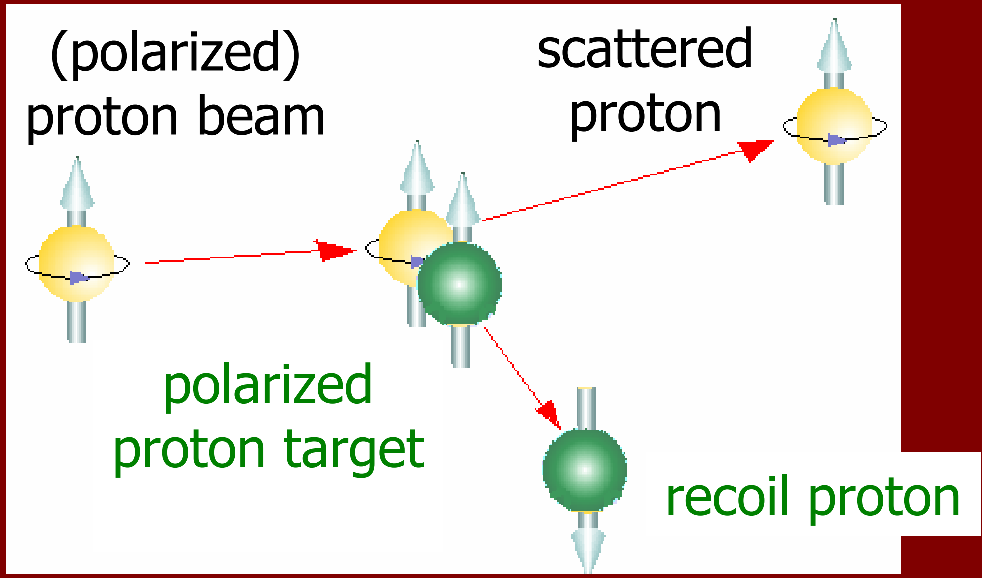


- 4 helical dipoles in each snake
- 2 snakes in each ring
    - axes orthogonal to each other



Hydrogen-Jet Polarimeter for Beams at Full Energy

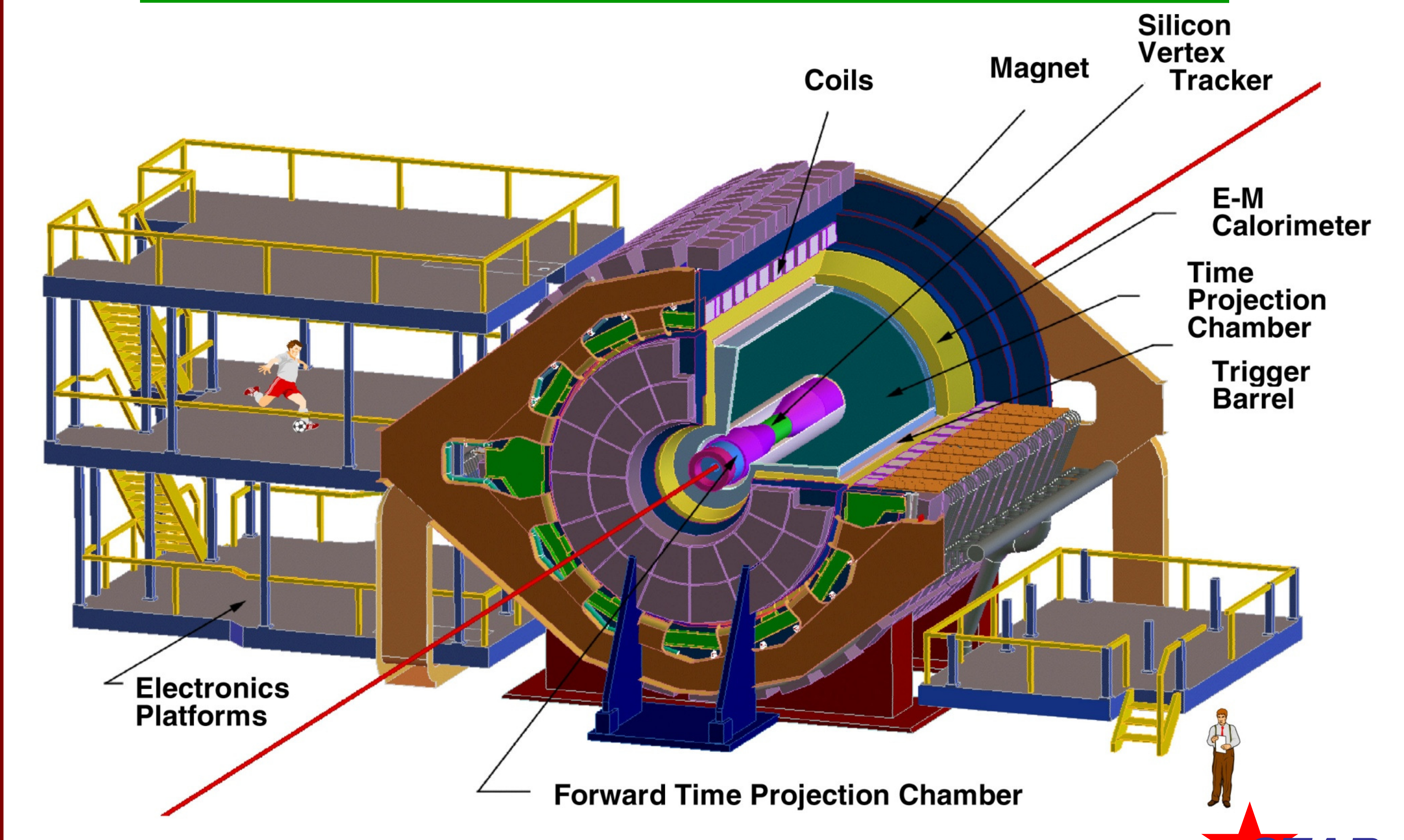
- Use transversely polarized hydrogen target and take advantage of transverse *single*-spin asymmetry in elastic proton-proton scattering
- Only consider single polarization at a time. Symmetric process!
  - Know polarization of your target
  - Measure analyzing power in scattering
  - Then use analyzing power to measure polarization of beam



$$A_N = \frac{1}{P_{\mathrm{target}}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$$P_{\mathrm{beam}} = \frac{1}{A_N} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

The STAR Detector at RHIC



PHENIX detector

- 2 central spectrometers
  - Track charged particles and detect electromagnetic processes

$|\eta| < 0.35$

$90^\circ + 90^\circ$ azimuth

- 2 forward muon spectrometers
  - Identify and track muons

$1.2 < |\eta| < 2.4$

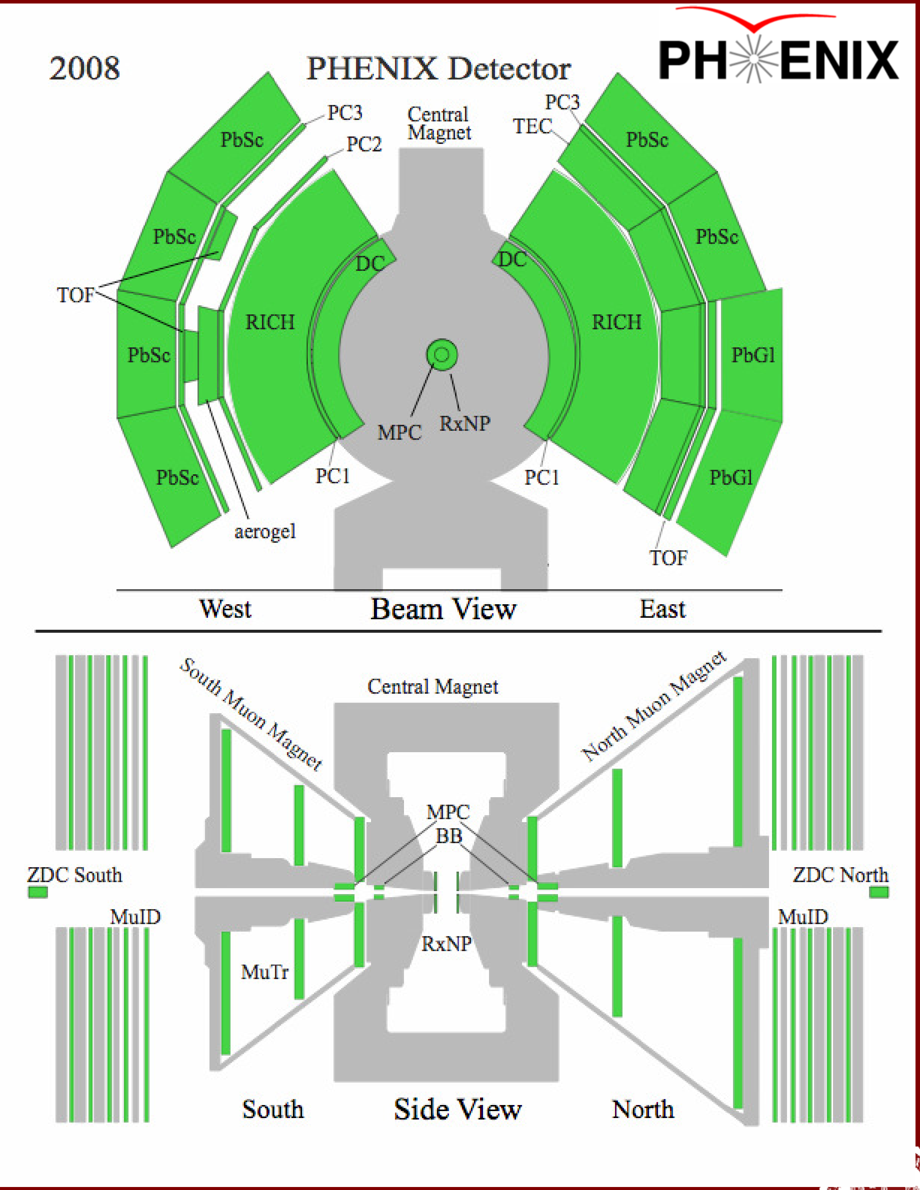
2π azimuth

- 2 forward calorimeters (as of 2007!)
  - Measure forward pions

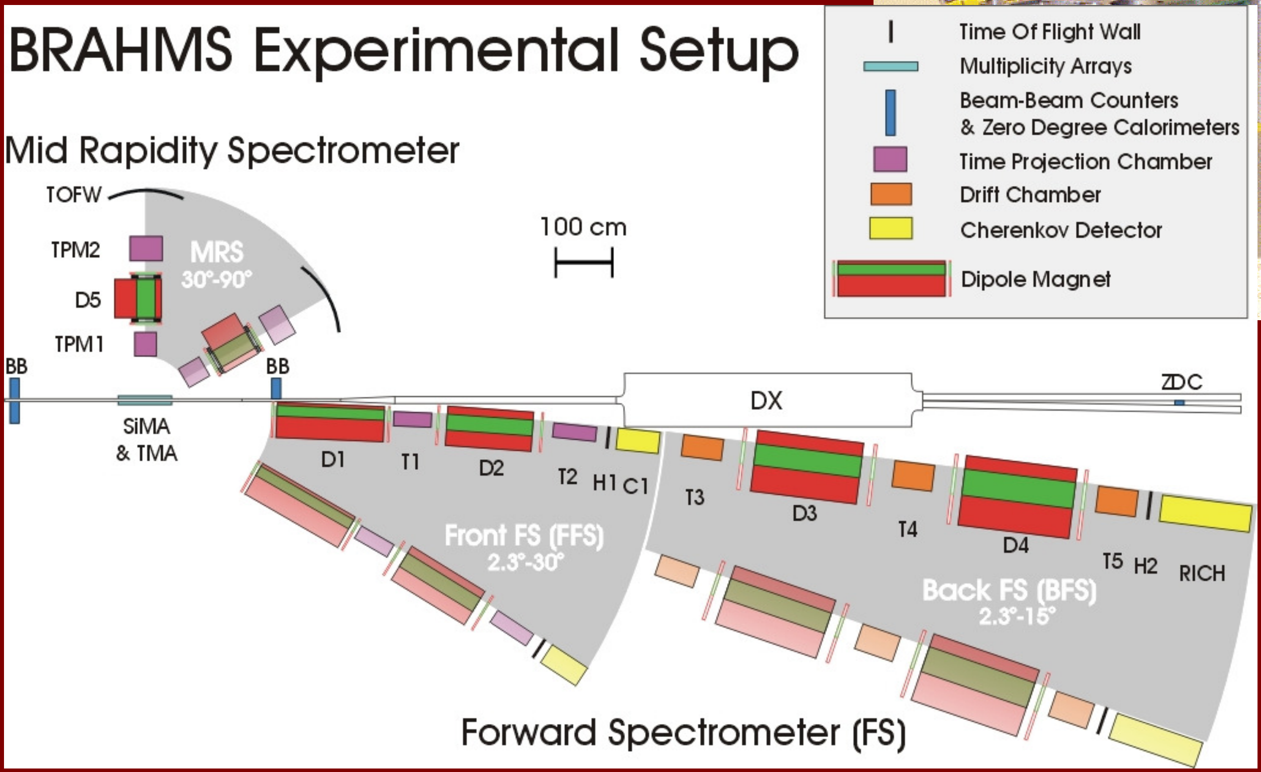
$3.1 < |\eta| < 3.7$

2π azimuth

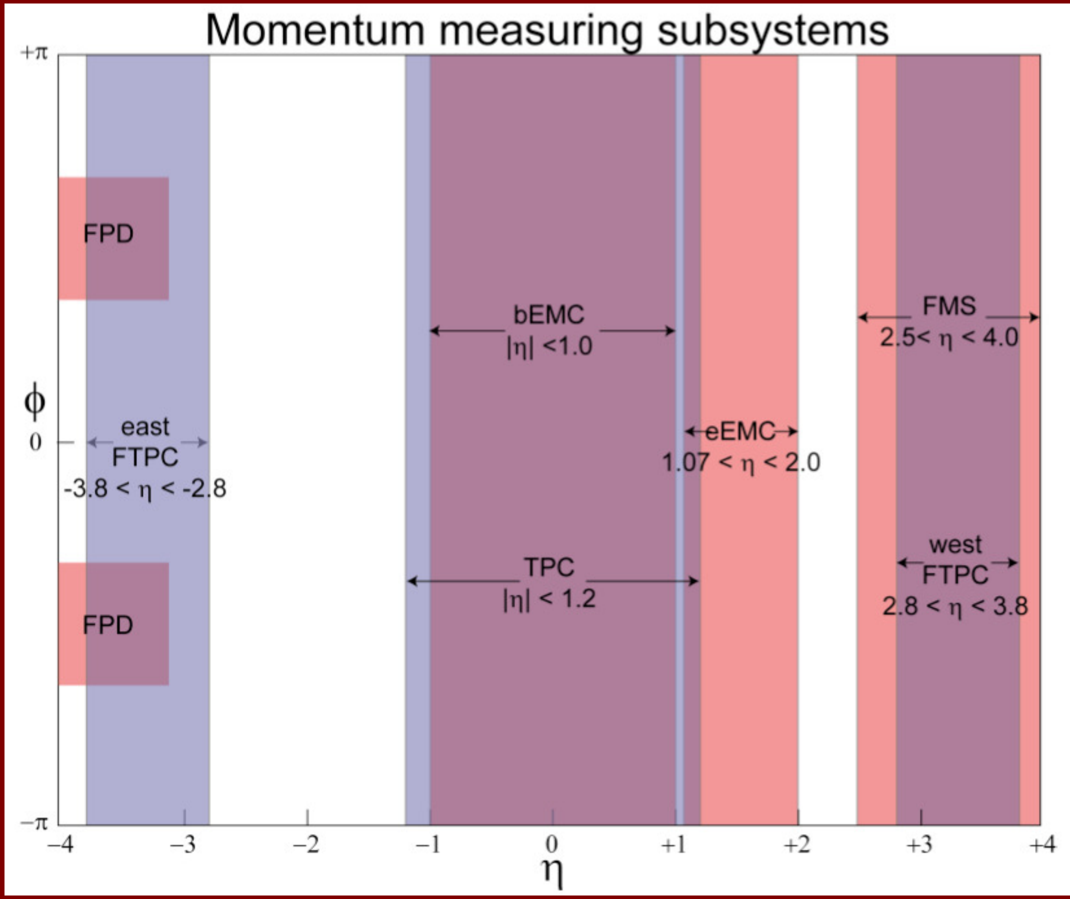
- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)



BRAHMS Detector



Forward Meson Spectrometer



20 times more acceptance than
previous forward calorimeters

STAR