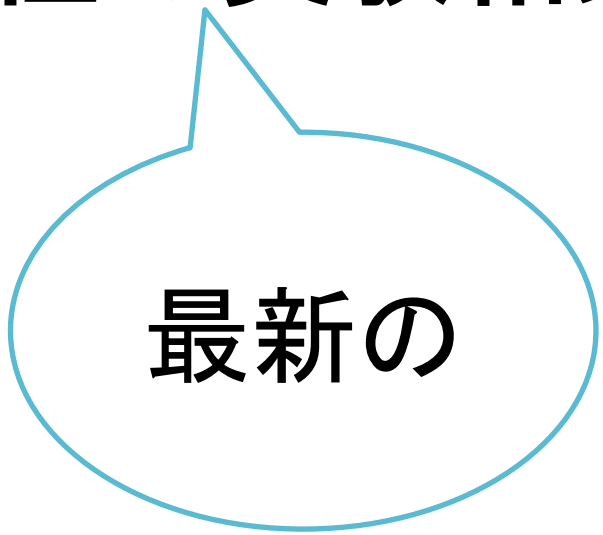
グルーオン偏極の実験結果



RIKEN/RBRC

Itaru Nakagawa

Longitudinal Spin Sum Rule

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

Quark+Sea Quark Spin

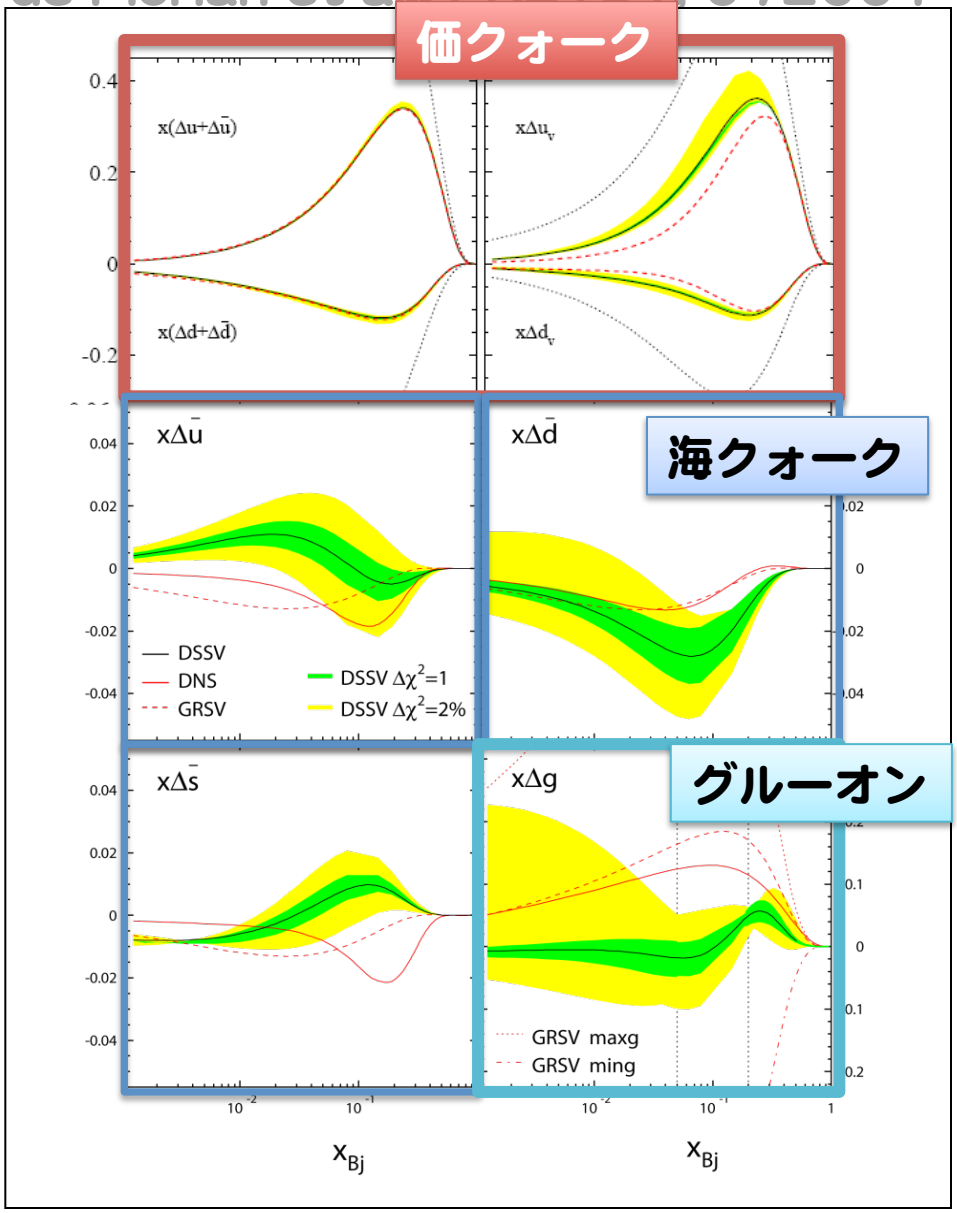
Gluon Spin

Orbital Angular Momentum

Not well measured yet!

グローバルなpQCD解析

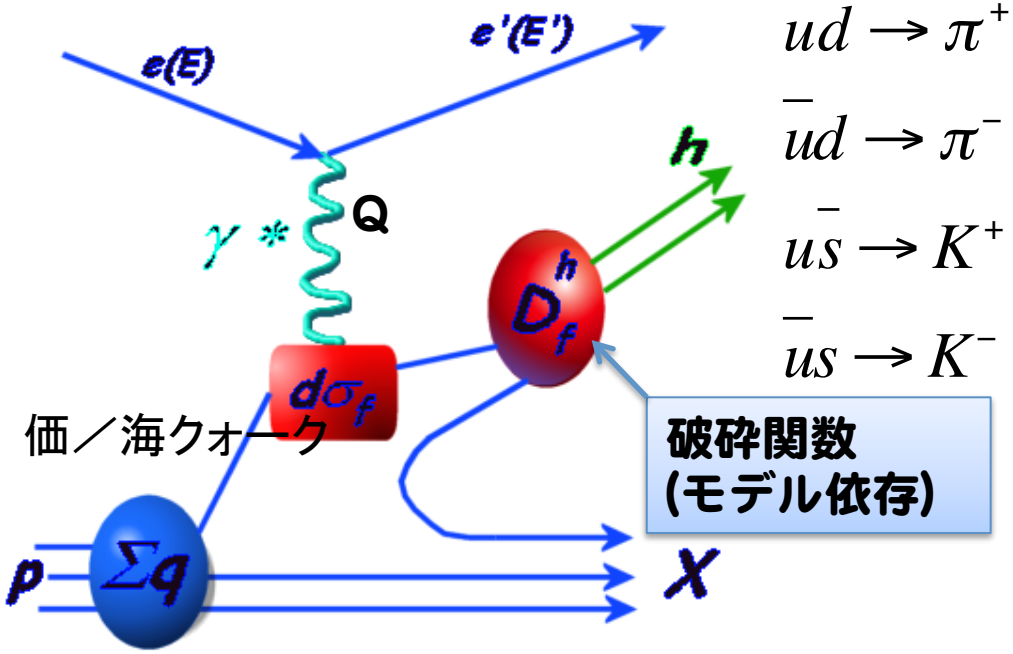
de Florian et al., PRL 101, 072001

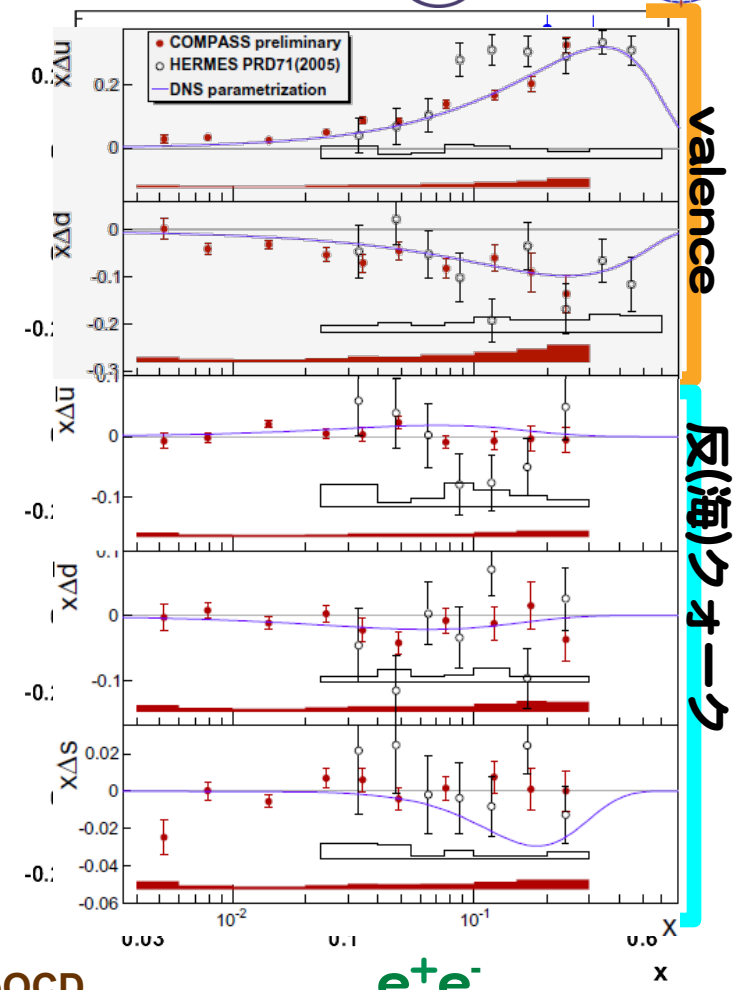


pQCD based theory fits
DIS/SIDS Data up to 2008

価クォーク
-> よくわかっている
海クォーク、グルーオン
-> まだよくわかっていない

偏極準非弾性散乱(SIDIS)



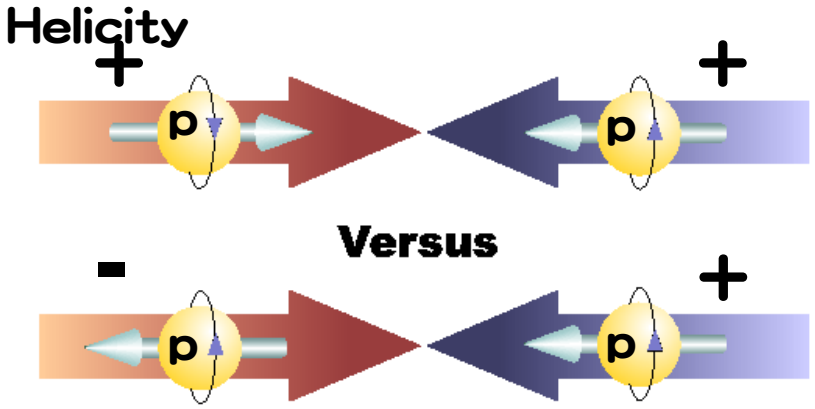


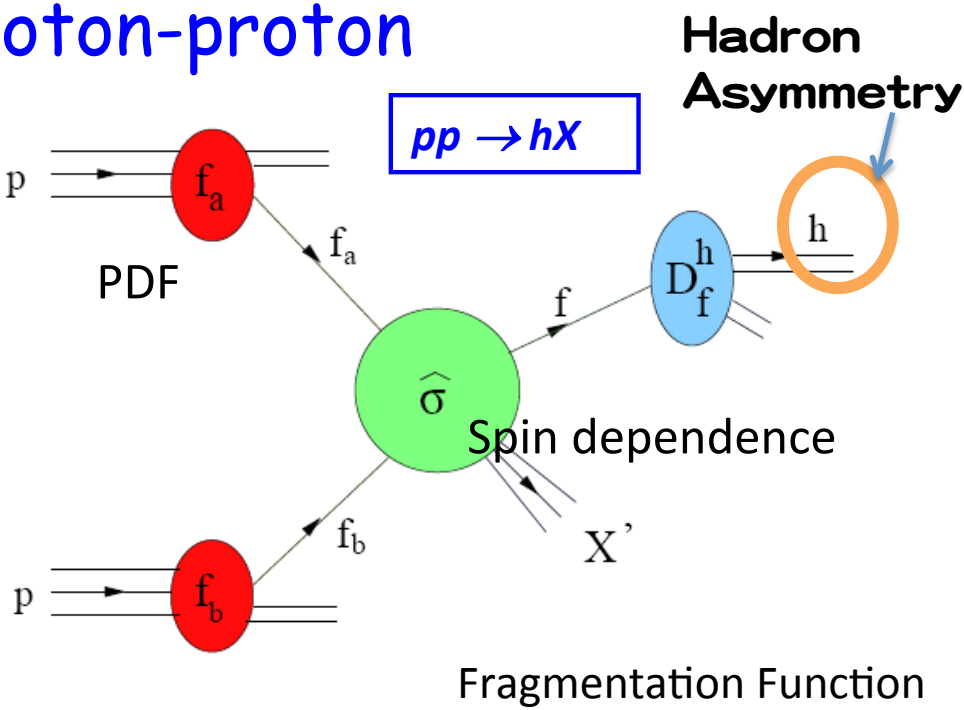
$$\frac{d^3\sigma^{\uparrow\downarrow}\left(pp^{\uparrow} \to \pi^+ X\right)}{dx_1 dx_2 dz} \propto q_i^{\uparrow}(x_1)\cdot q_j^{\downarrow}(x_2) \times \frac{d^3\hat{\sigma}^{\uparrow\downarrow}(q_i q_j \to q_k q_l)}{dx_1 dx_2} \times FF_{q_{k,l}}(z, k_T)$$

Proton Structure　pQCD　e^+e^-　$z=E_h/\nu$

Longitudinal Spin Structure

Longitudinally Polarized proton-proton

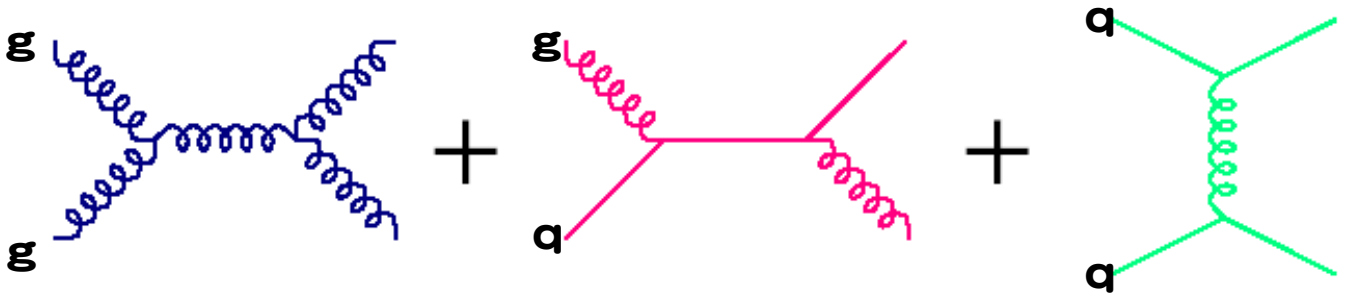




Helicity Asymmetry

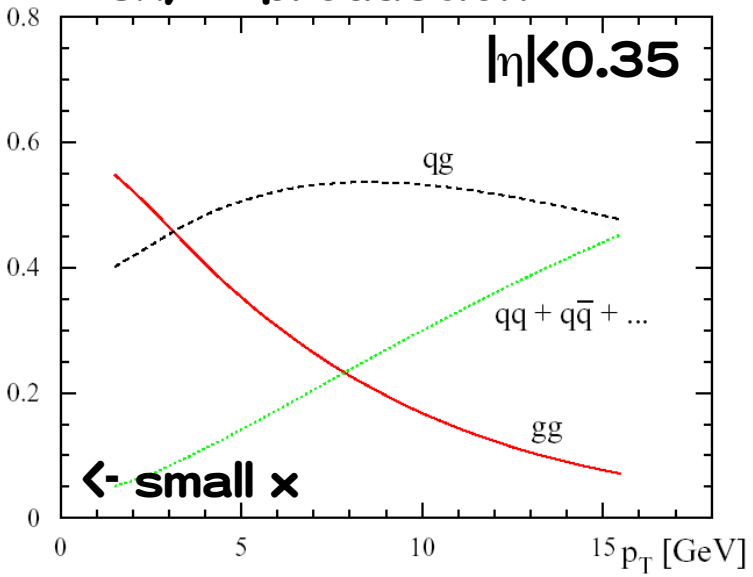
$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \cdot \hat{a}_{LL}^{f_a f_b \to fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \otimes D_f^h}$$

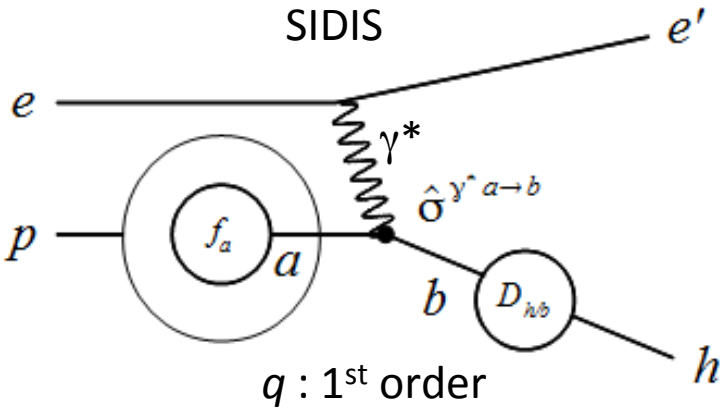
Subprocess of pp



$$A_{LL} \propto [\omega_{gg}]\Delta g\Delta g + [\omega_{gq}\Delta q]\Delta g + [\omega_{qq}\Delta q\Delta q]$$

ex) π^0 production

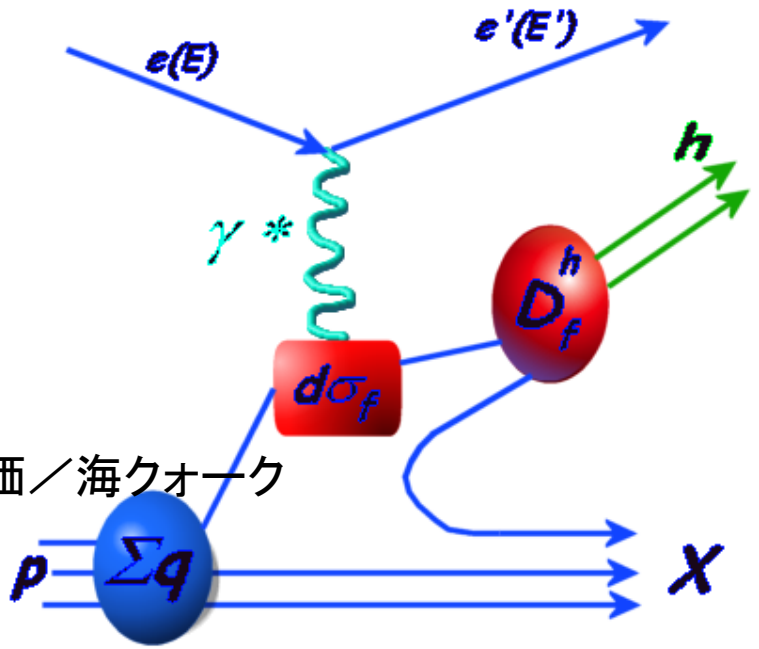




q : 1st order

Gluon is the major player compared to DIS/SIDIS

DISとproton-proton



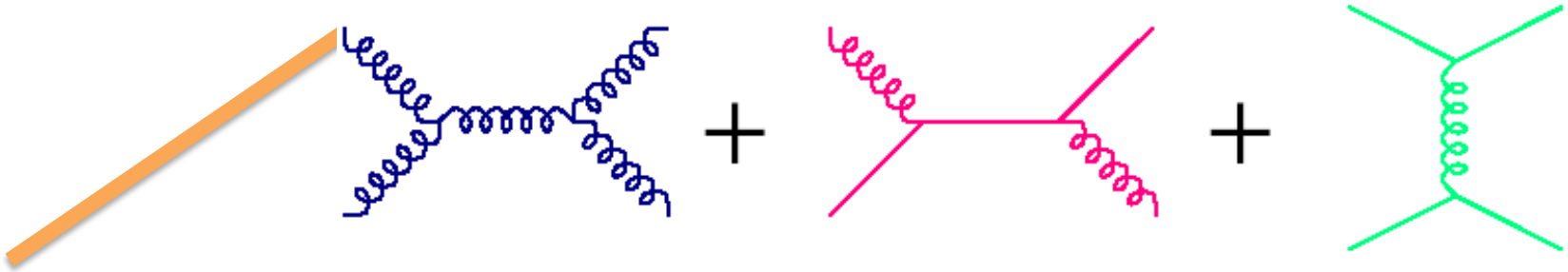
価／海クォーク

DIS

仮想光子と相互作用するのは価クォークまたは海クォーク

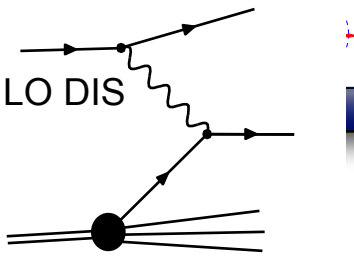
pp

素過程にはクォークもグルーオンも寄与する



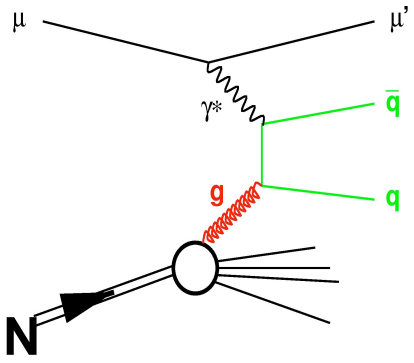
グルーオンに感度が高い

Direct gluon polarisation measurement via tagging PGF process



Non direct measurement of gluon polarisation - QCD fits

To select PGF process two methods are used @COMPASS:



- **Open-charm D meson production:**
  charm quark pairs produced in PGF, "clean" channel however with huge combinatorial background, low statistics but analysis less MC dependent

- **High transverse momentum hadron pairs production:**
  light quark pairs produced, high statistics but physical background; strongly model and MC dependent analysis, requires a very good agreement between data and MC

$$\sigma^{PGF} = G \otimes \hat{\sigma}^{PGF} \otimes H$$

$$\Delta\sigma^{PGF} = \Delta G \otimes \Delta\hat{\sigma}^{PGF} \otimes H$$

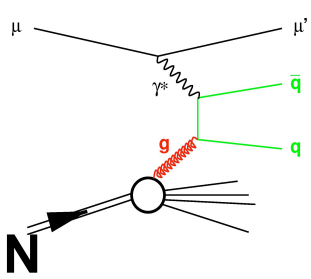
from MC

$$A \approx \frac{\Delta G}{G}(\bar{x}_G) < \hat{a}_{LL}^{PGF} >_G$$

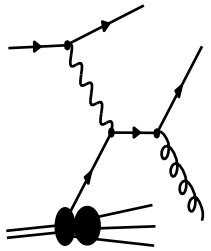
signal asymmetry from data

Large Q^2 : $Q^2 > 1$ (GeV/c)^2

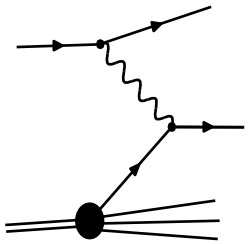
Physical model: three processes (LO QCD)



PGF



QCD-Compton



LO-DIS

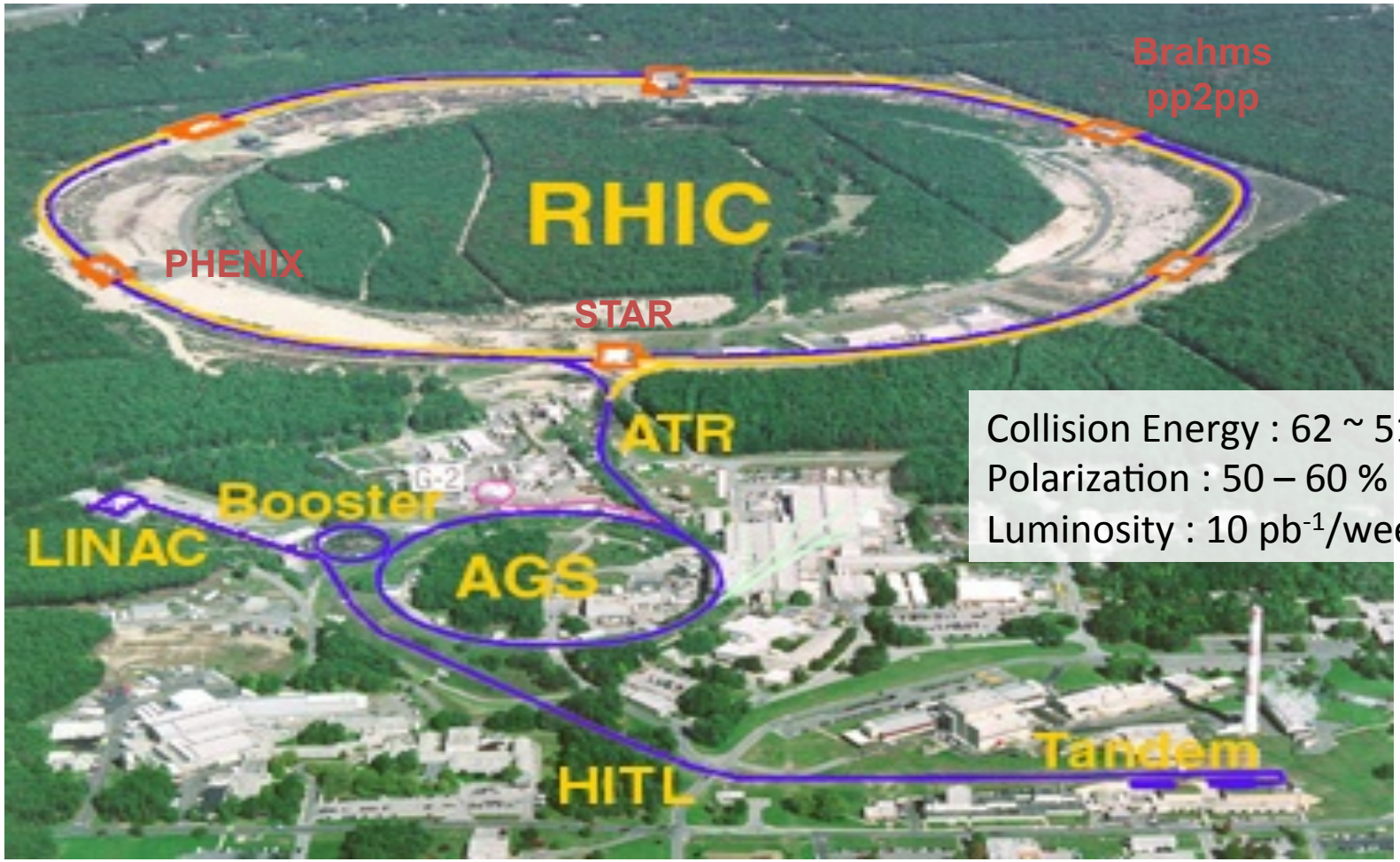
$$A_{LL}^{2h}(x_{Bj}) \approx \frac{\Delta G}{G}(x_G)\hat{a}_{LL}^{PGF} R_{PGF} + A_1^{LO}(x_C)\hat{a}_{LL}^{C} R_C + A_1^{LO}(x_{Bj}) D R_L$$

$$A_1^{LO} \equiv \frac{\sum_i e_i^2 \Delta q_i}{\sum_i e_i^2 q_i}$$

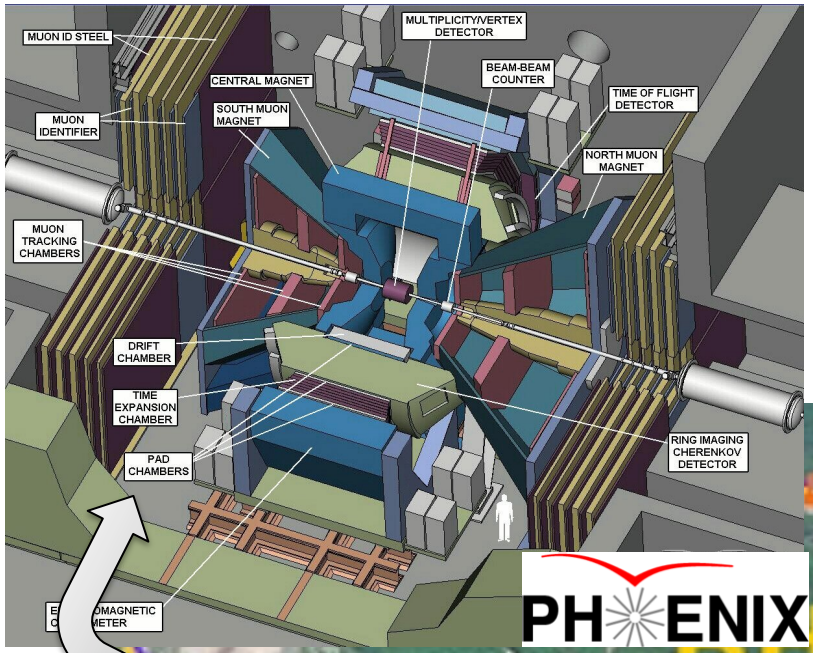
Same decomposition for inclusive sample to determine A_1^{LO}

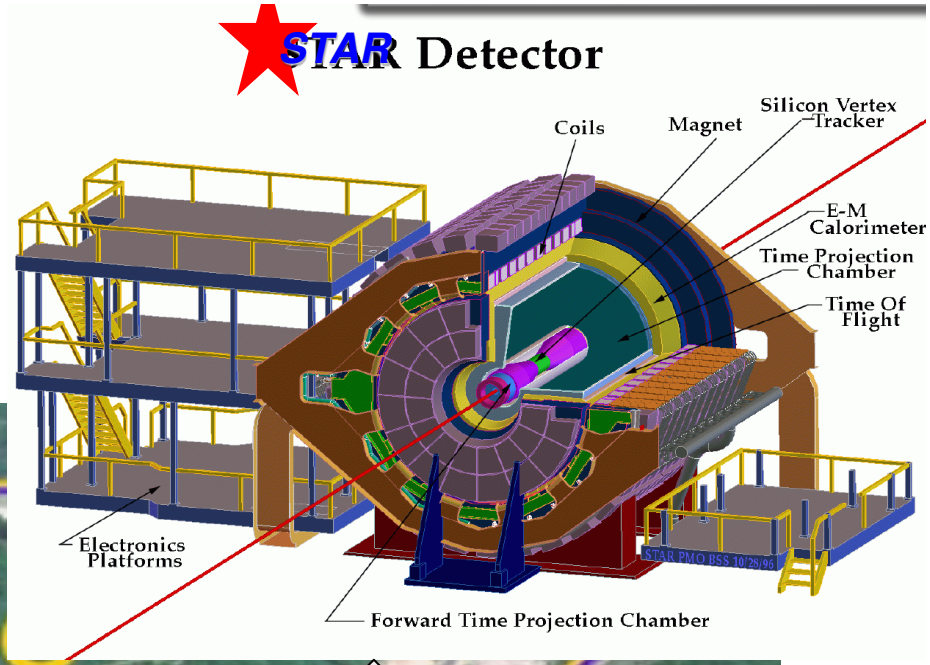
Optimization needed : “clean” (more PGF, “pure”) sample with limited statistics or less PGF populated but larger sample

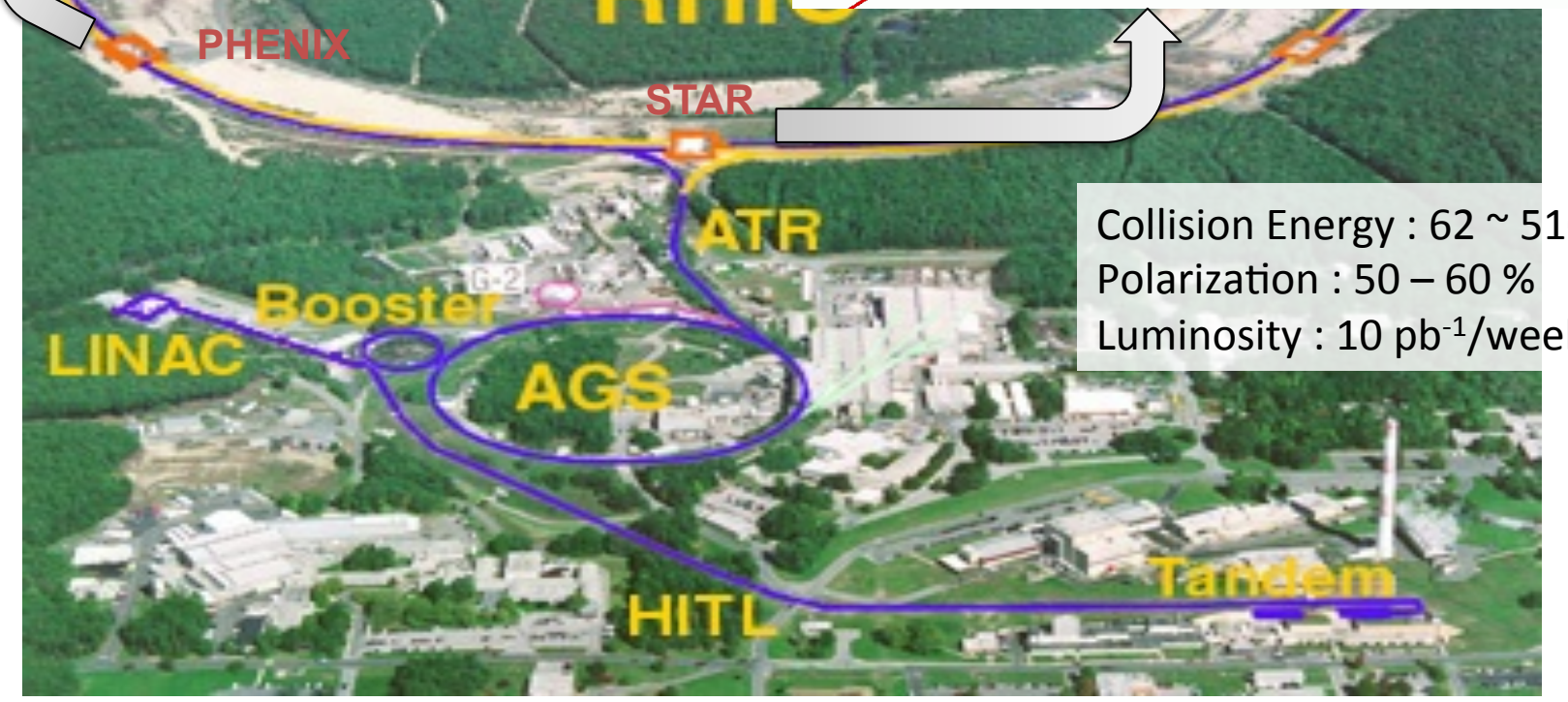
The Relativistic Heavy Ion Collider accelerator complex at Brookhaven National Laboratory



Collision Energy : 62 ~ 510 GeV
Polarization : 50 – 60 %
Luminosity : 10 pb^{-1}/week

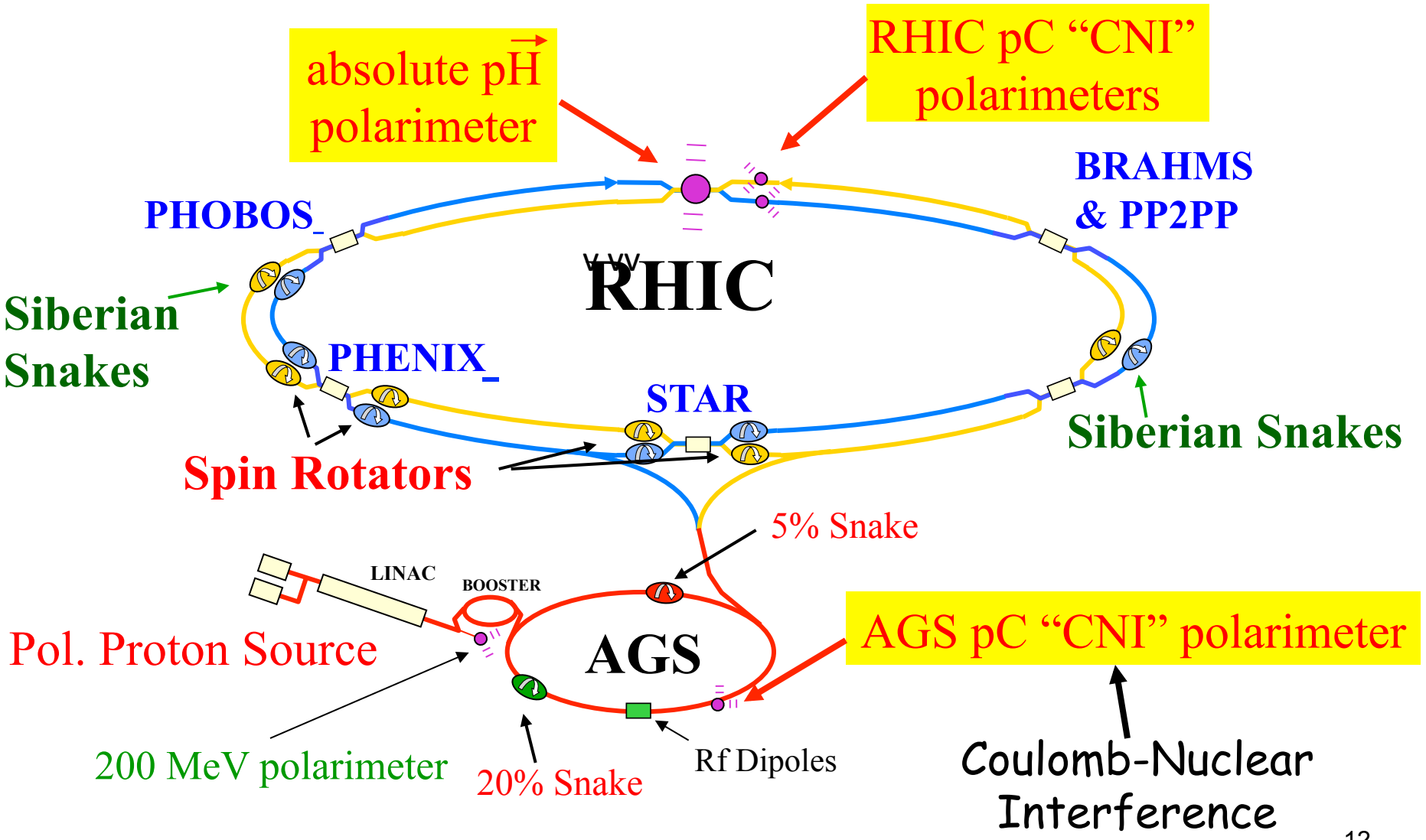




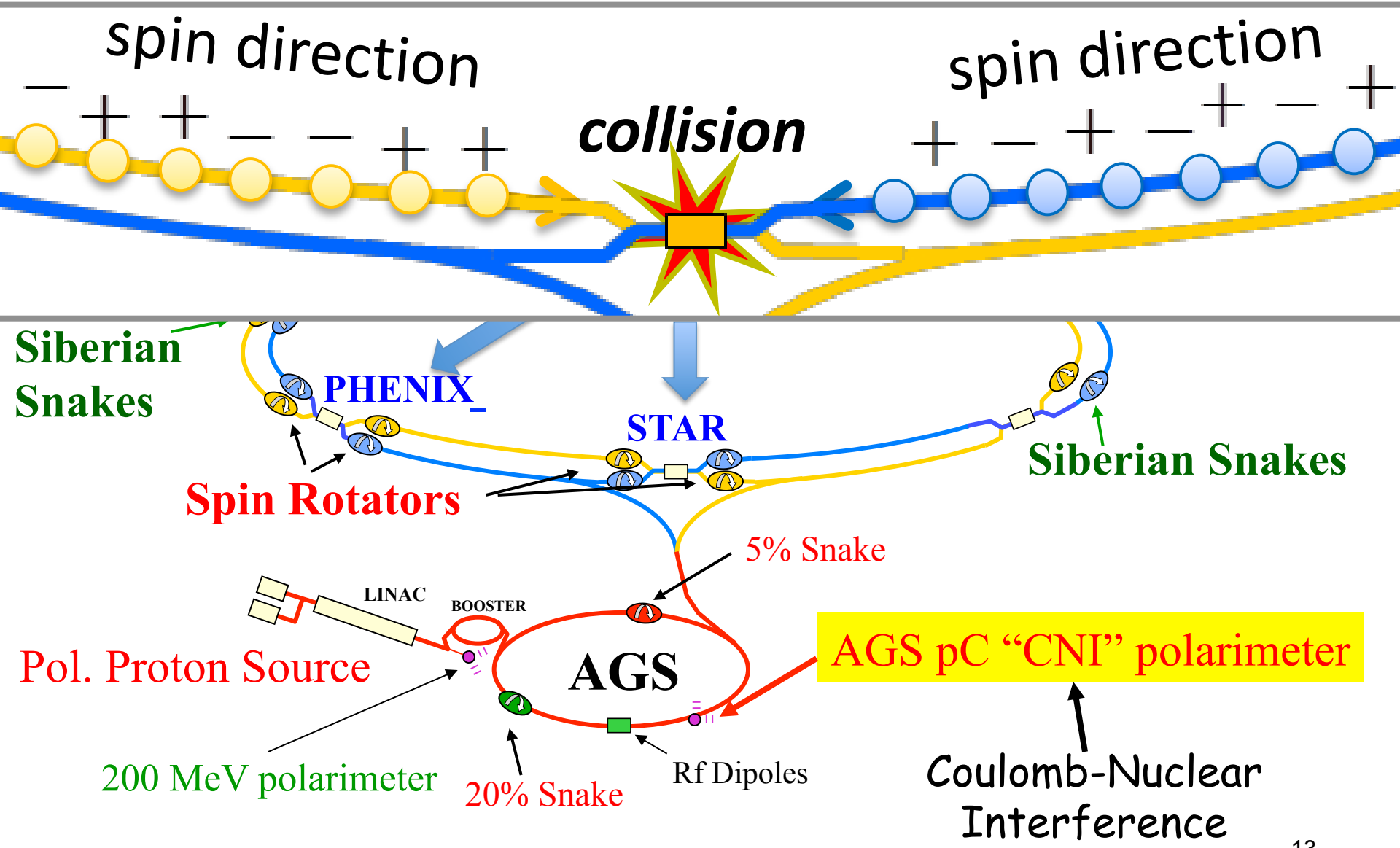


Collision Energy : 62 ~ 510 GeV
Polarization : 50 – 60 %
Luminosity : 10 pb^{-1}/week

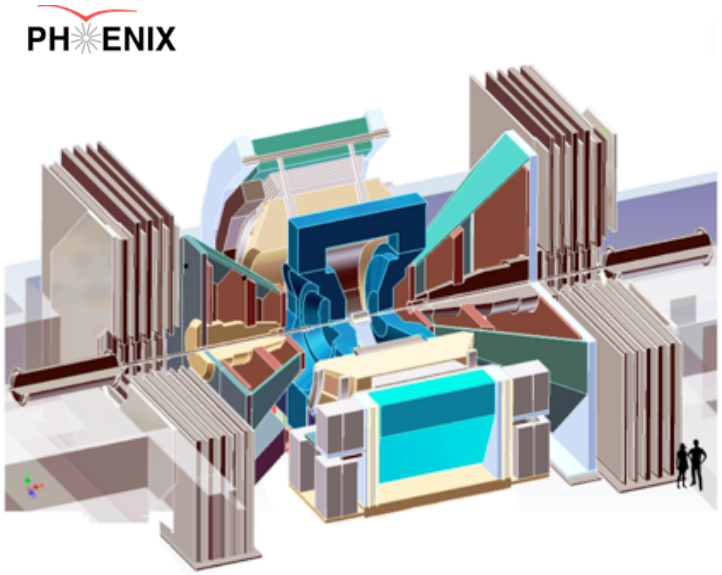
RHIC *p+p* accelerator complex



RHIC *p+p* accelerator complex

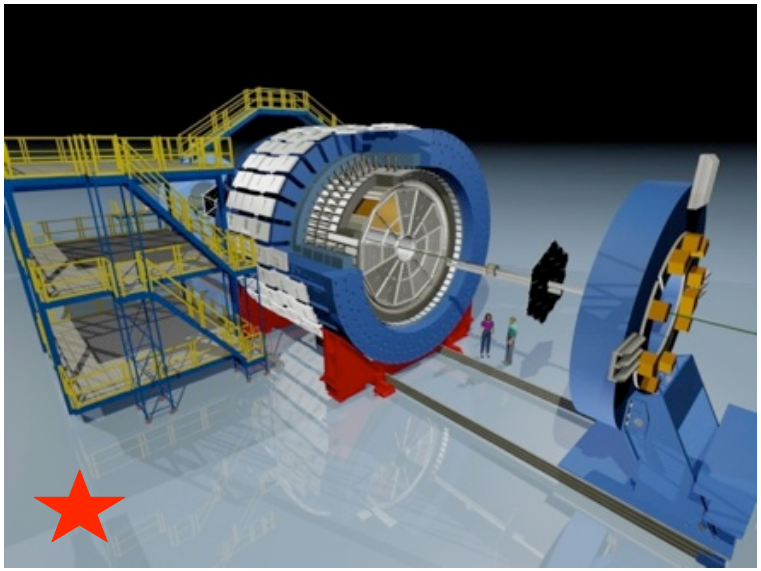


RHIC - The Current Main Experiments



PHENIX "DNA":

- high resolution and rate capabilities,
- central arms $|\eta|<0.35, \Delta\phi\sim\pi$ with key strengths for π^0 and η
- forward muon arms $1.2<|\eta|<2.4$



STAR "DNA":

large acceptance and low mass,

full acceptance and PID for $|\eta|< 1$, $\Delta\phi\sim2\pi$,

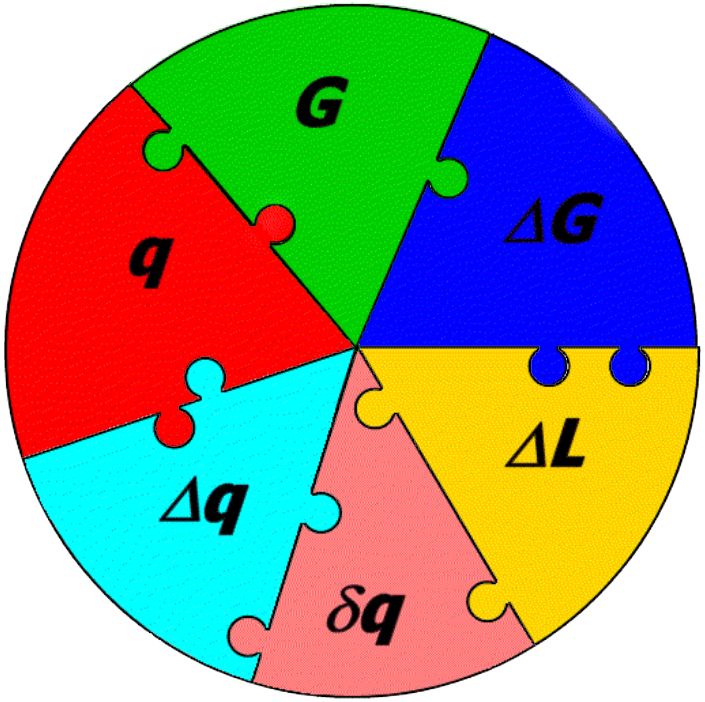
complemented with forward E.M. calorimetry

key strengths for jets and correlations

Vigorous ongoing upgrade programs, e.g. PHENIX FVTX, MPC-EX
STAR FMS-PS, Roman Pots

Slide from Renee Fatemi, Spin-2014

Highlights of RHIC Spin Program (Outline)



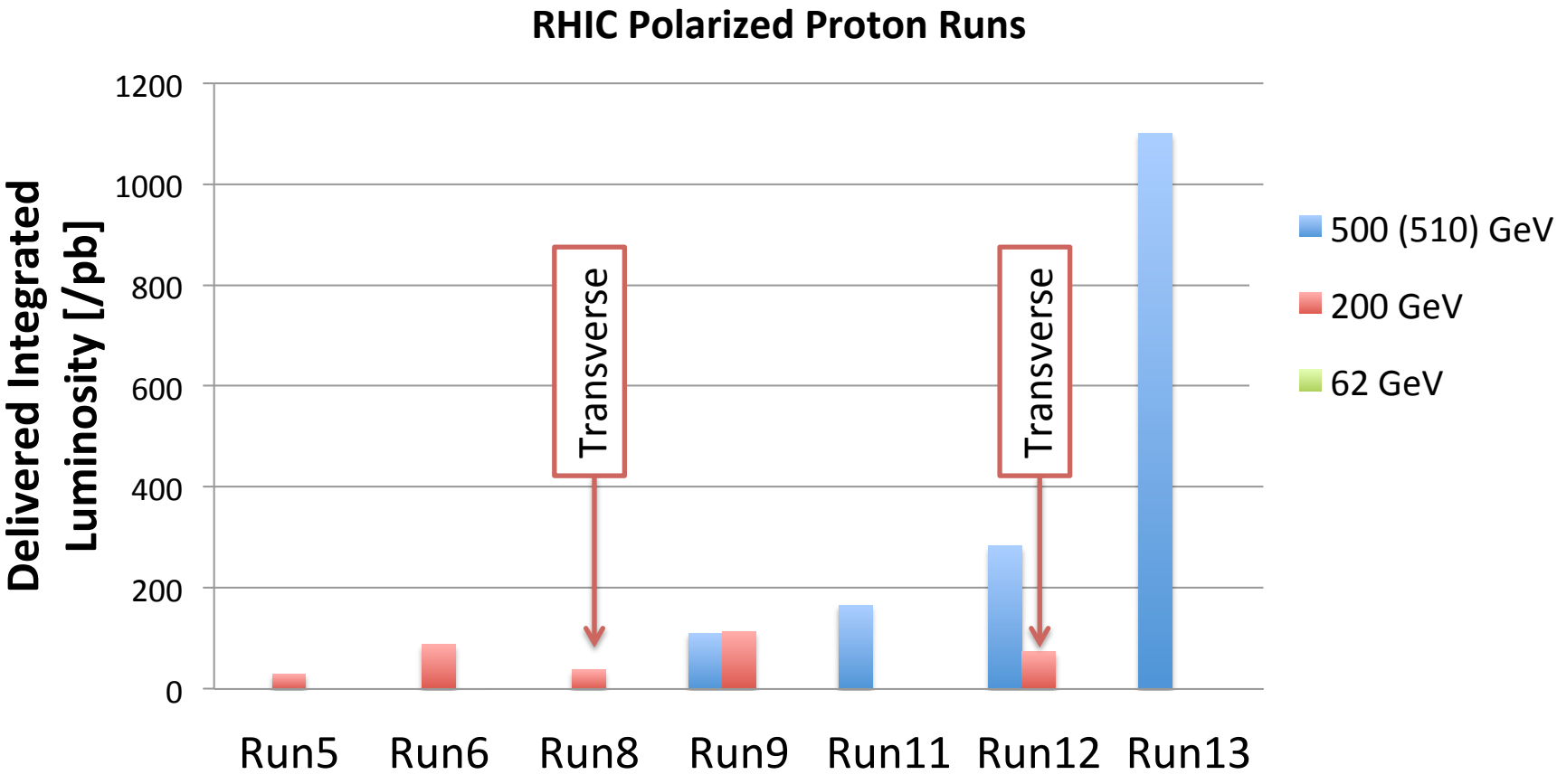
Spin Puzzle

Longitudinal Spin Structure
- **Gluon Spin** (this talk)
- **Sea Quark** (following talks)

Transverse Spin Structure
- Sivers Effect
- Collins Effect
- Higher Twist …

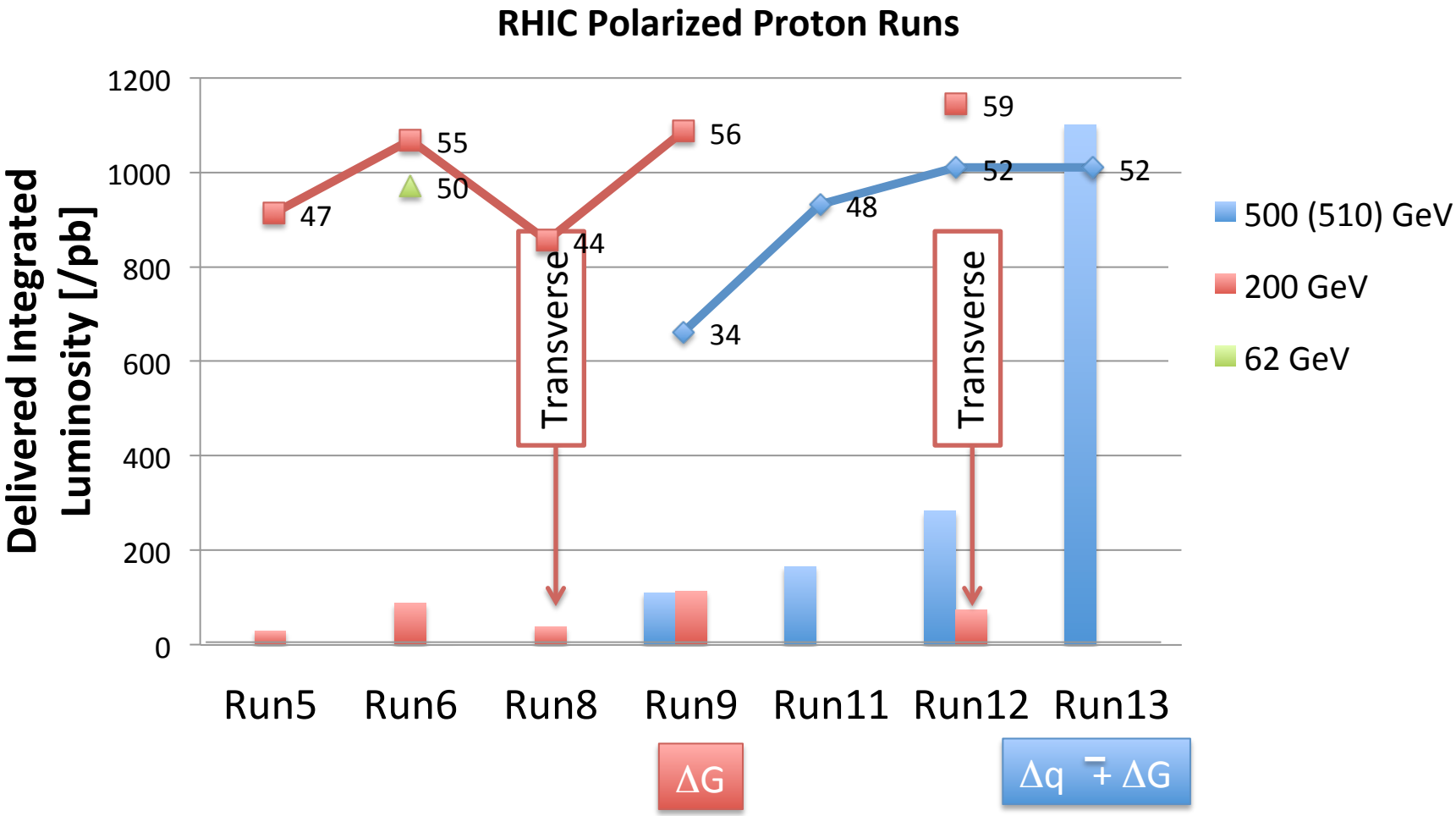
Future Upgrades

RHIC Polarized Spin Program

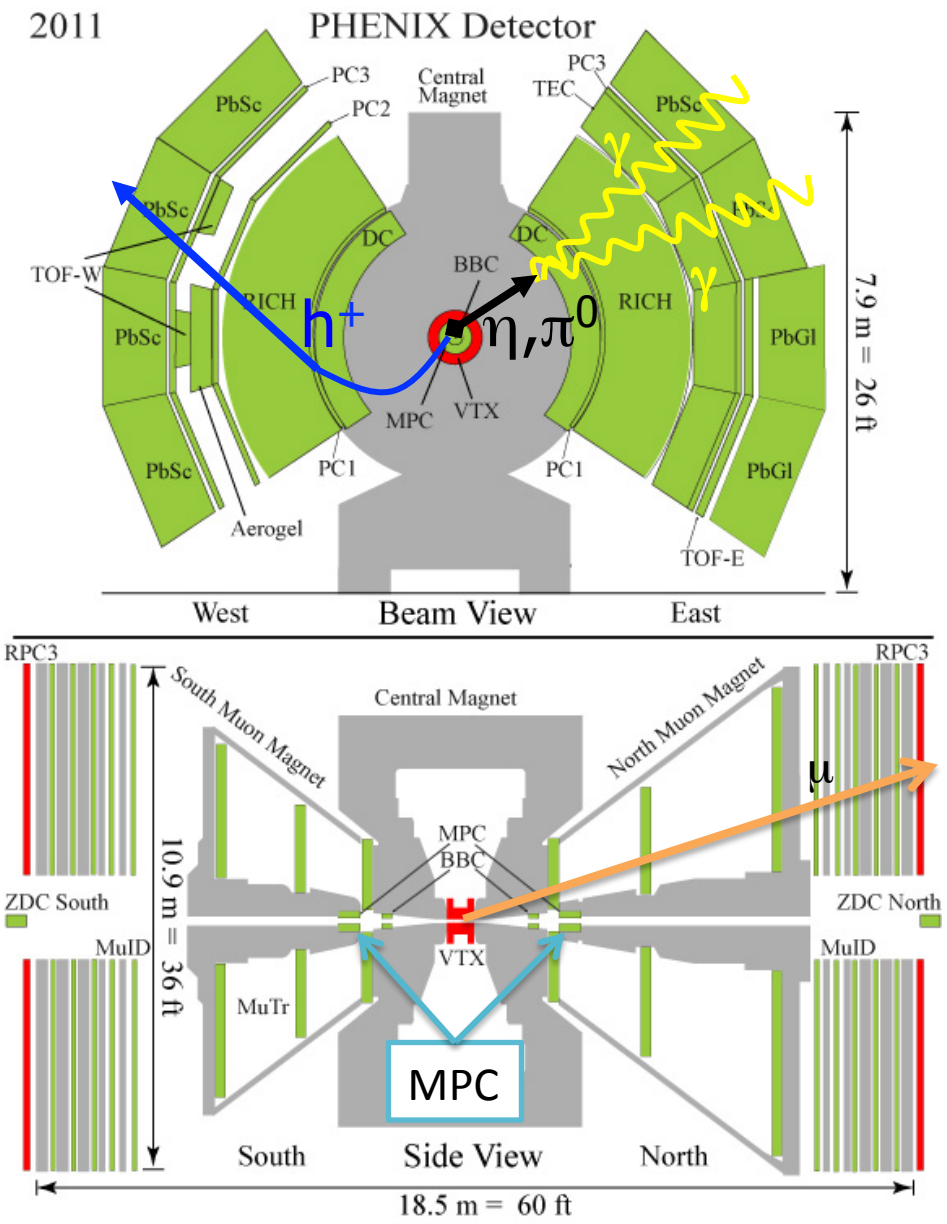


RHIC Polarized Spin Program

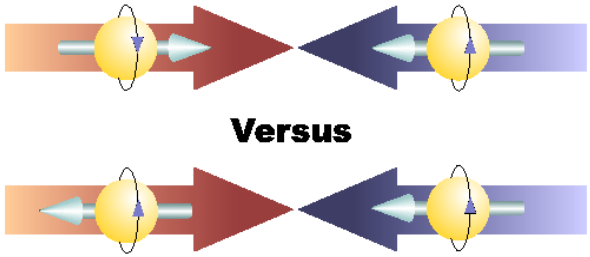
Beam Polarization



The PHENIX Detector



- Philosophy
  - high resolution & high-rate at the cost of acceptance
  - trigger for rare events
- Central Arms
  - $|\eta| < 0.35$, $\Delta\phi \sim \pi$
  - Momentum, Energy, PID
- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - Momentum (MuTr)
- Muon Piston Calorimeter
  - $3.1 < |\eta| < 3.9$



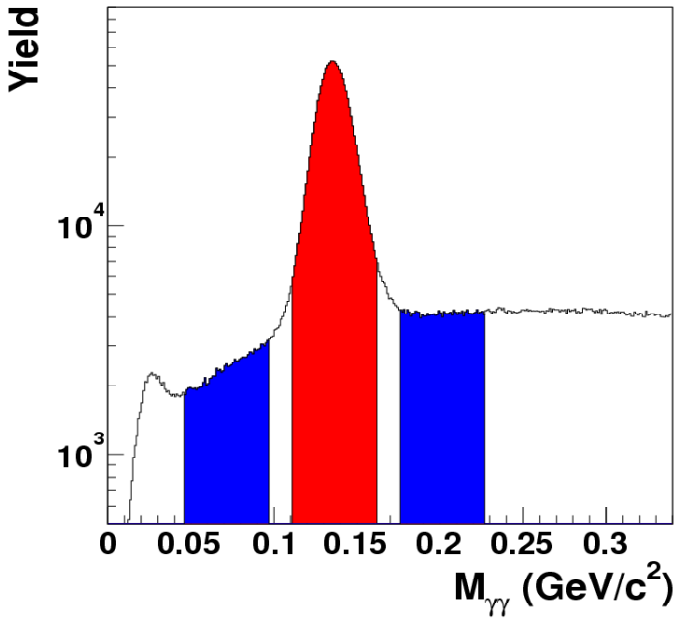
ΔG
DOUBLE HELICITY A_{LL} RESULTS

Probe	Advantage
π^0	Statistics
η	Different fragmentation
π^0 - π^0 correlation	Kinematic constraint
charged π	ΔG sign
heavy flavor decay e^-	Lower x, g-g dominant
MPC cluster	Lower x
Jet	Statistics (STAR)
Jet-Jet	Kinematics Constraint (STAR)

Central Arm π^0, η

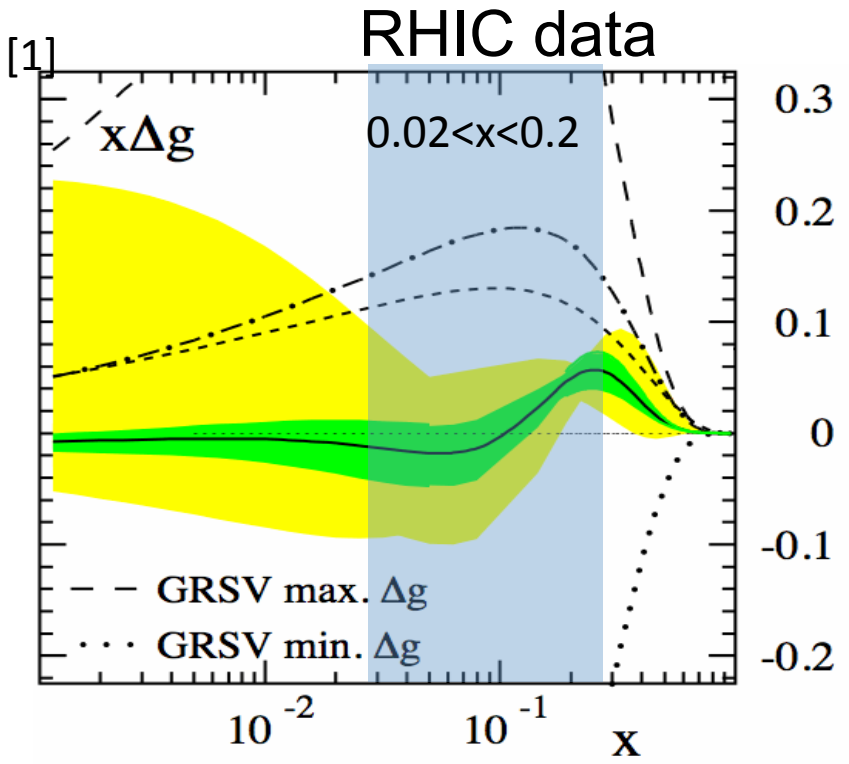
- Production cross section is high and from gluon interaction
- PHENIX EMCal trigger friendly
- Found in 2 photons invariant mass

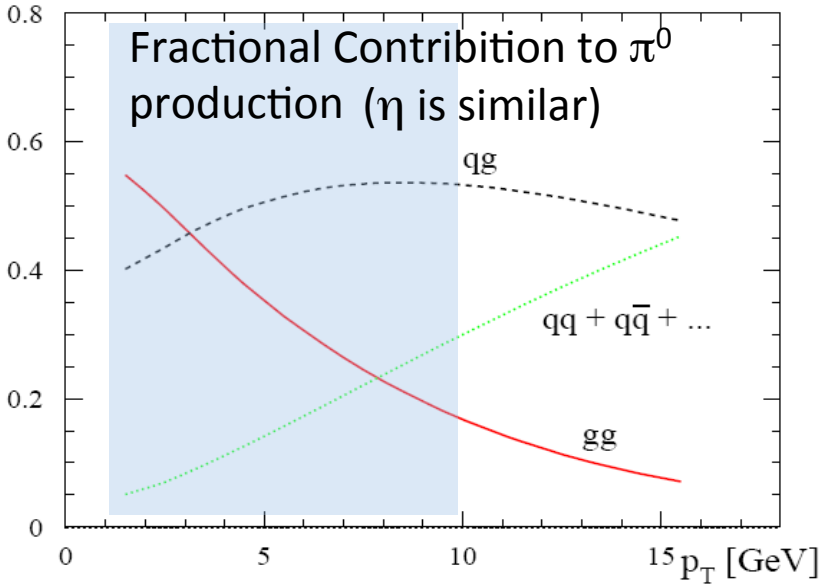
$$A_{LL}^{\pi 0} = \frac{A_{LL}^{\pi 0 + BG} - w_{BG} A_{LL}^{BG}}{1 - w_{BG}}$$



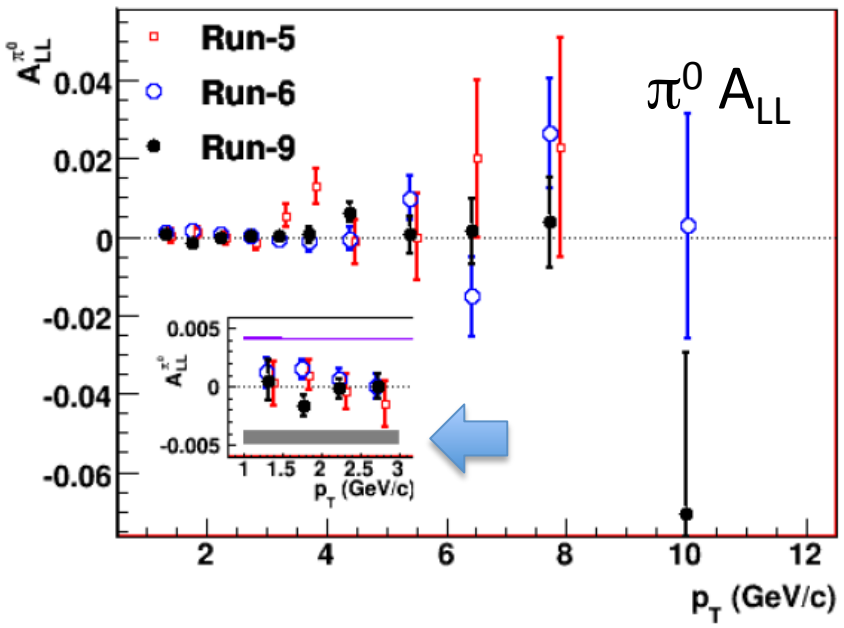
Phys. Rev. Lett. 101, 072001(2008)

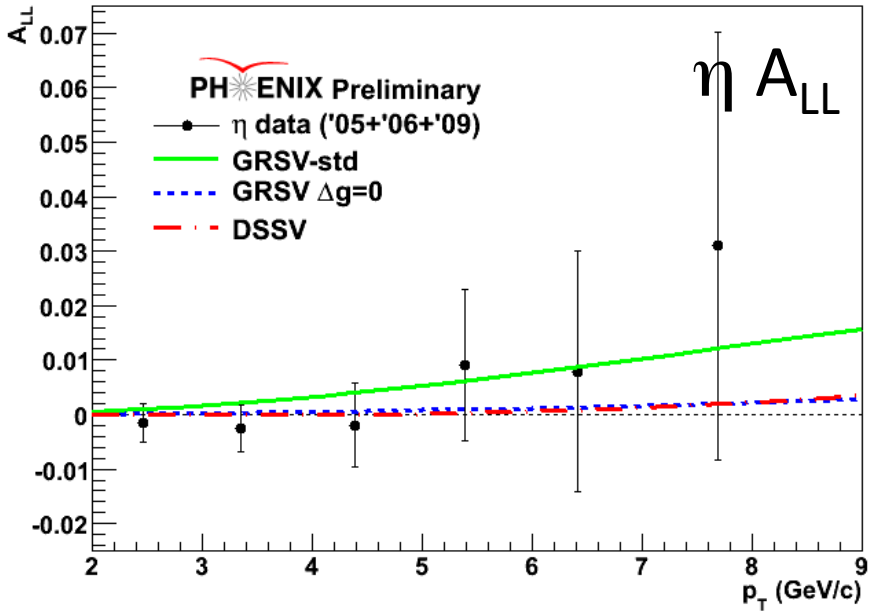
[1]





A_{LL} : Central Arm π^0, η





Statistically enriched observable

Need to control Systematic uncertainties (relative luminosity)

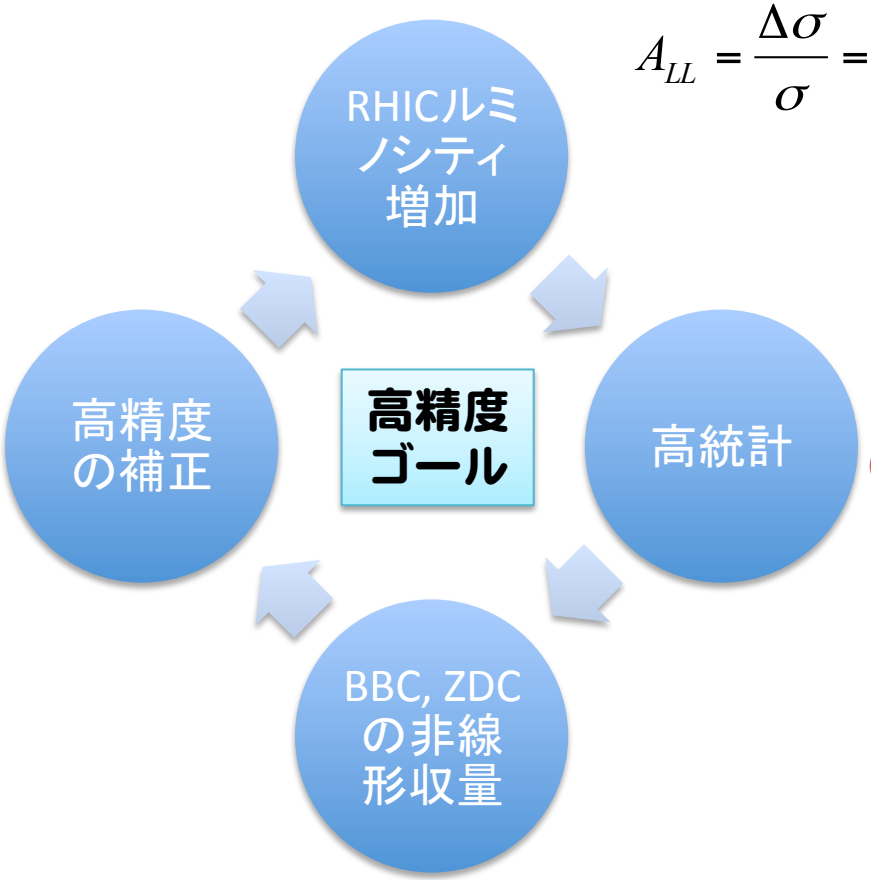
ΔG through

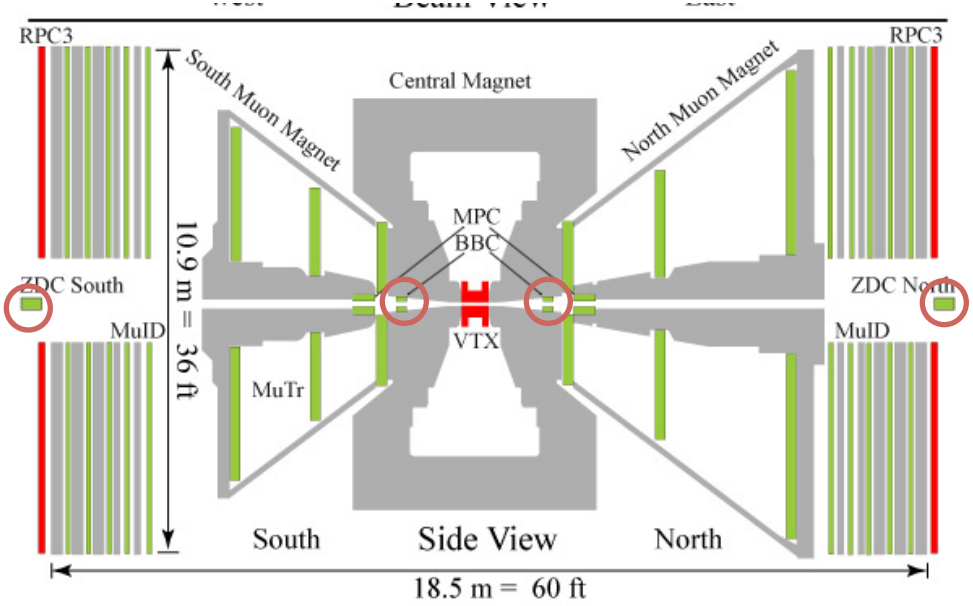
- a different flavor structure
- fragmentation function

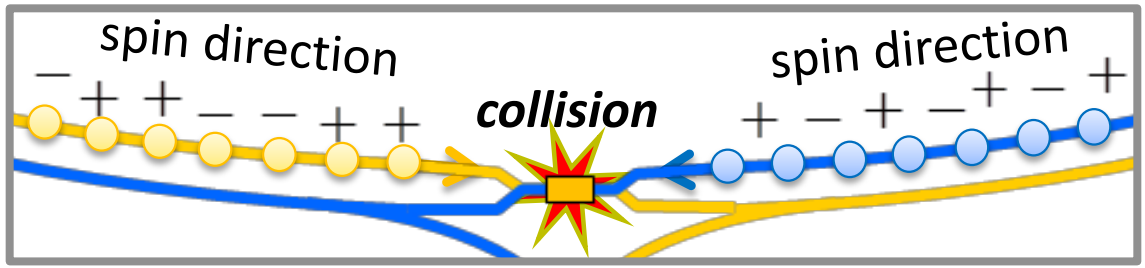
Statistically Challenging

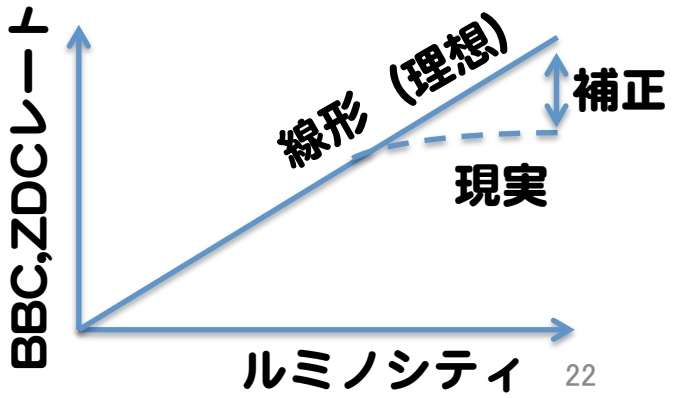
Relative Luminosity

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{1}{< P_B P_Y >} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}} \qquad R = \frac{L^{++}}{L^{+-}}$$



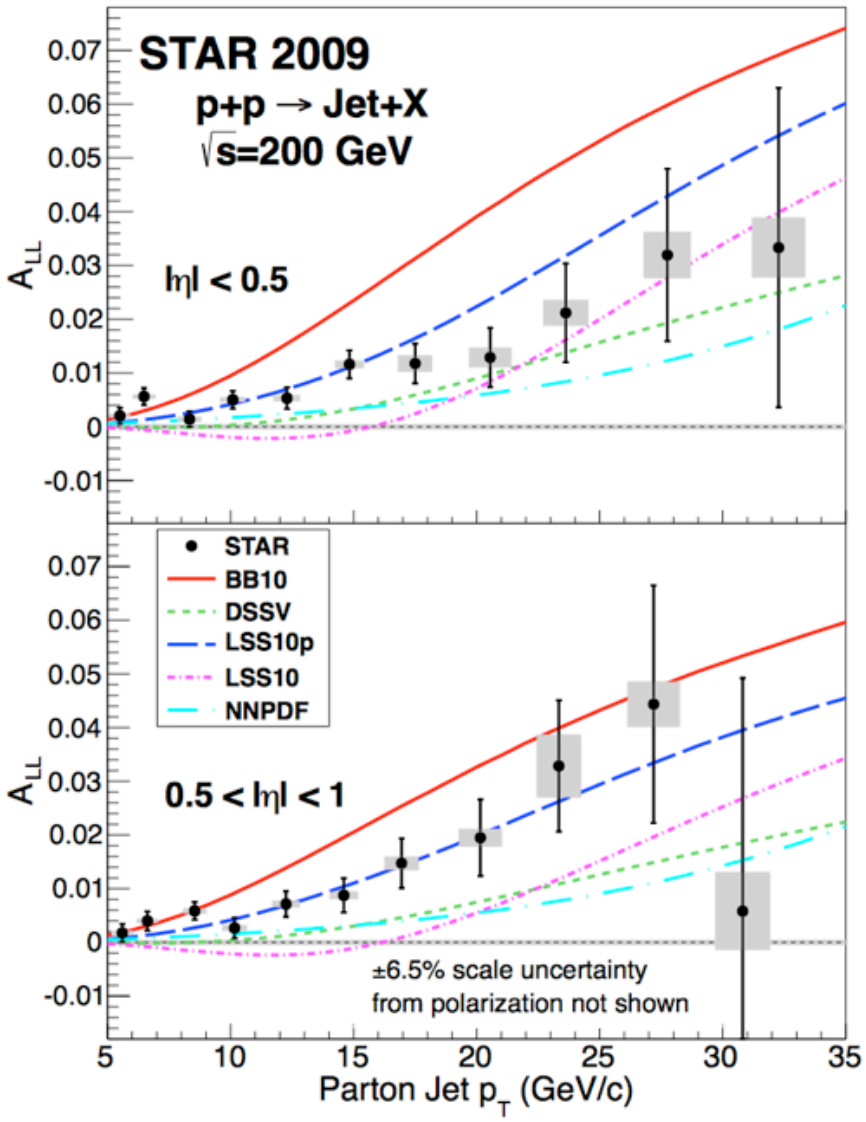


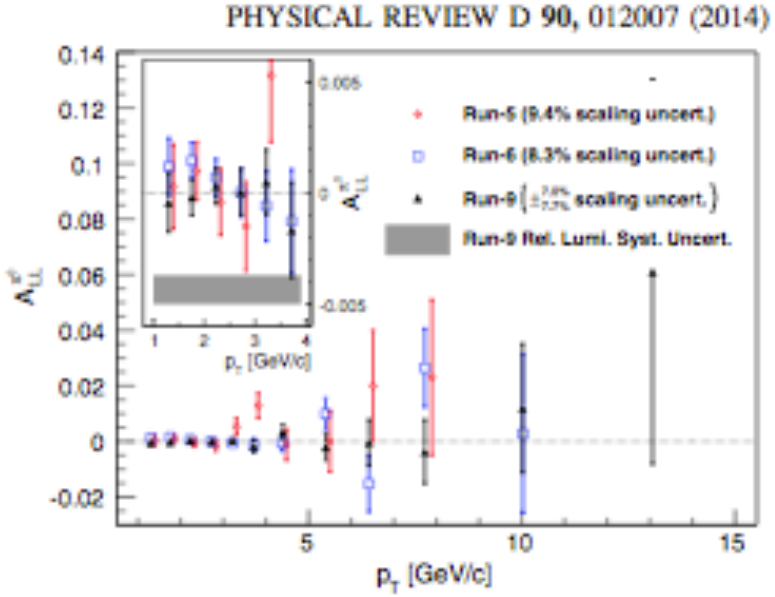


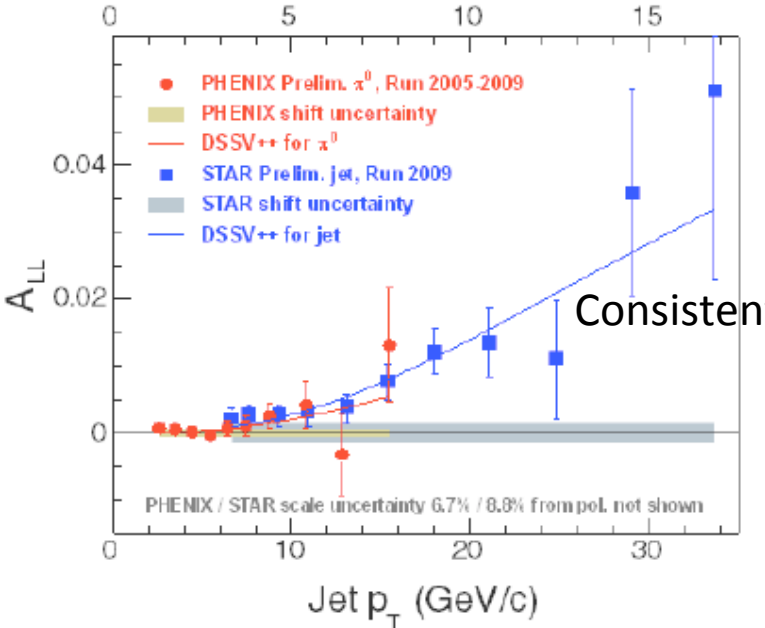


Run9 PHENIX π^0 and STAR Jet @ 200GeV

ArXiv:1405.5134







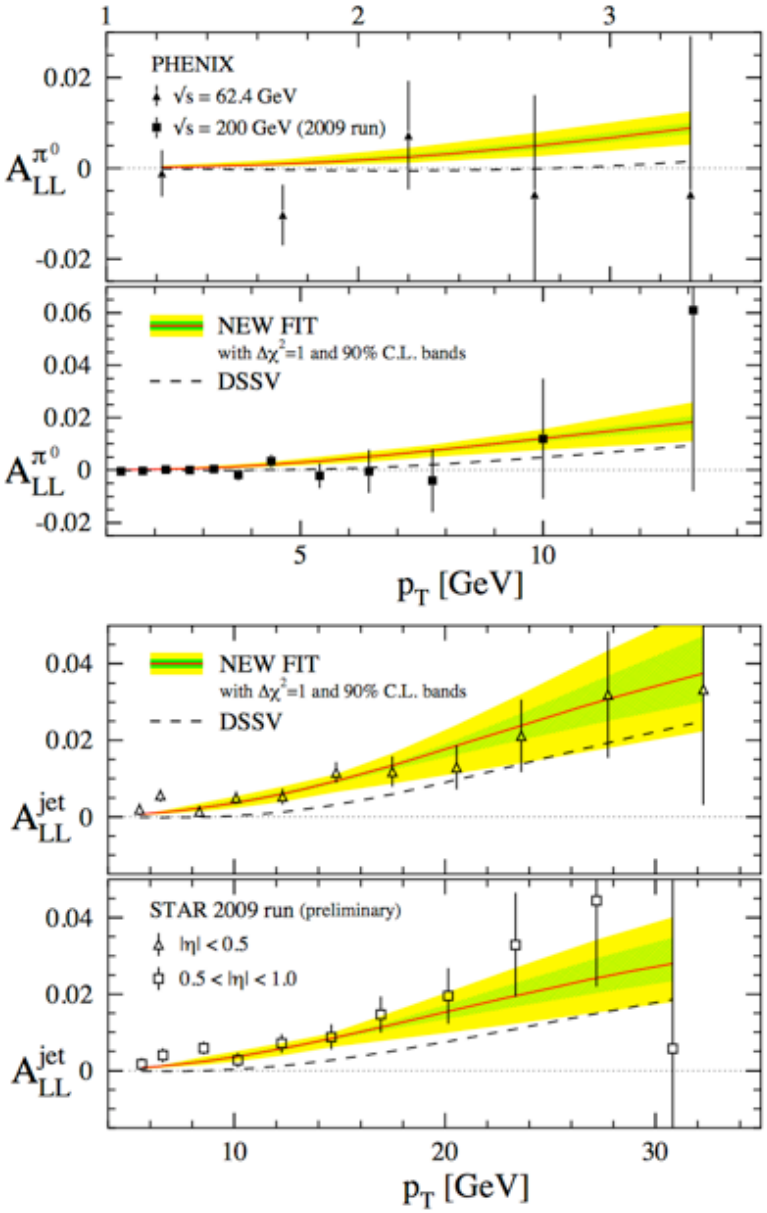
Consistent !

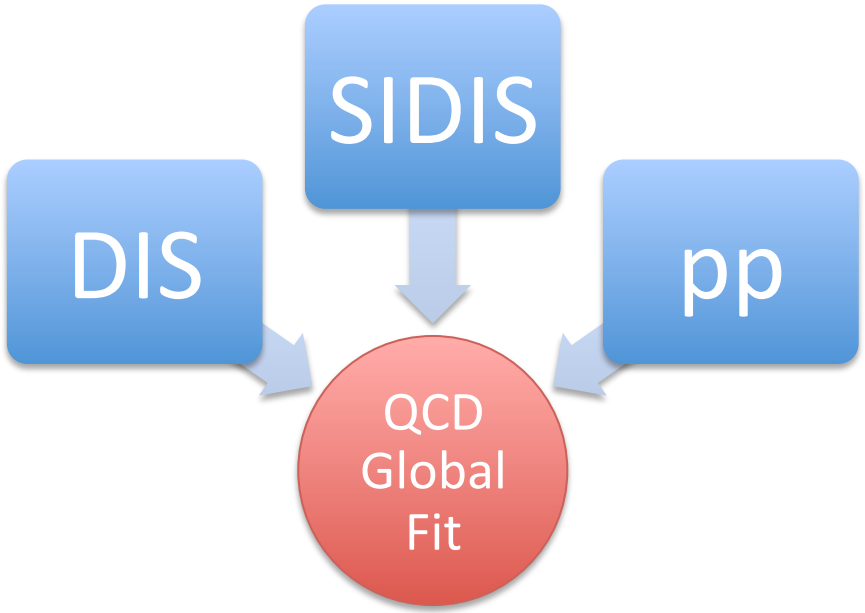
Global Fitting Models

Fit	Data sets	Parton Distributions	Uncertainties	Latest update
AAC08	DIS, π^0	Δu^+, Δd^+, Δs^+, Δg	Hessian $\Delta\chi^2 = 12.95$	[arXiv:0808.0413]
BB10	DIS	Δu^-, Δd^-, $\Delta \bar{q}$, Δg	Hessian $\Delta\chi^2 = 1$	[arXiv:1005.3113]
LSS10	DIS, SIDIS	Δu^+, Δd^+, $\Delta \bar{u}$, $\Delta \bar{d}$, $\Delta \bar{s}$, Δg	Hessian $\Delta\chi^2 = 1$	[arXiv:1010.0574]
JAM13	DIS	Δu^+, Δd^+, $\Delta \bar{u}$, $\Delta \bar{d}$, $\Delta \bar{s}$, Δg	Hessian $\Delta\chi^2 = 1$	[arXiv:1310.3734]
DSSV++	DIS, SIDIS, π^0, jets	Δu^+, Δd^+, $\Delta \bar{u}$, $\Delta \bar{d}$, $\Delta \bar{s}$, Δg	Hessian $\Delta\chi^2 = 1$ Lagr. mult. $\Delta\chi^2/\chi^2 = 2\%$	[arXiv:1404.4293]
NNPDFpol1.1	DIS, OC, $W^\pm$, jets	Δu^+, Δd^+, $\Delta \bar{u}$, $\Delta \bar{d}$, $\Delta \bar{s}$, Δg	Monte Carlo	[arXiv:1406.5539]

Global Fit Interpretation

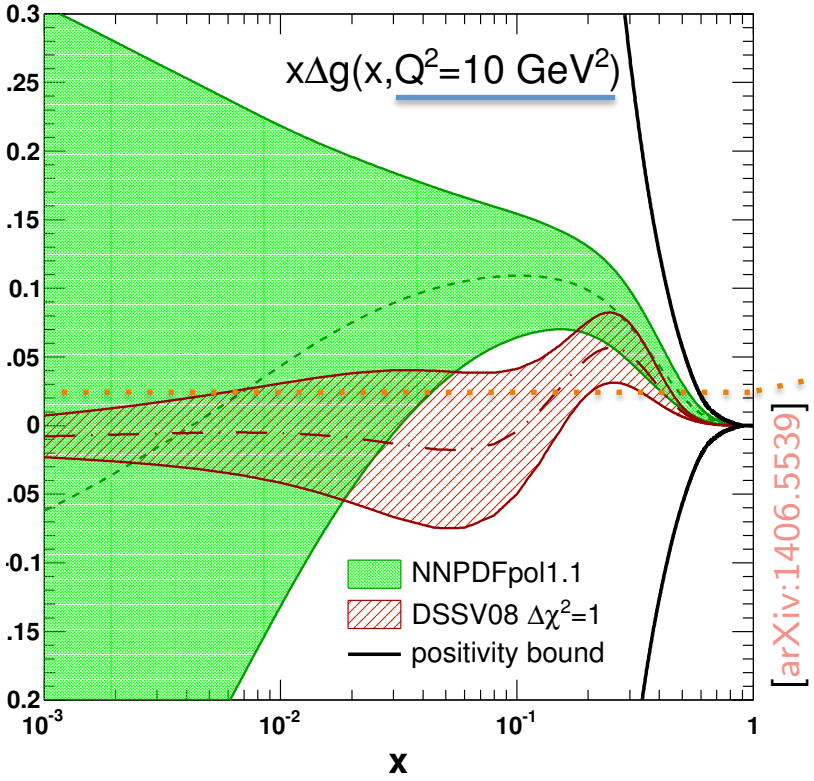
DSSV, Phys.Rev.Lett. 113, 012001



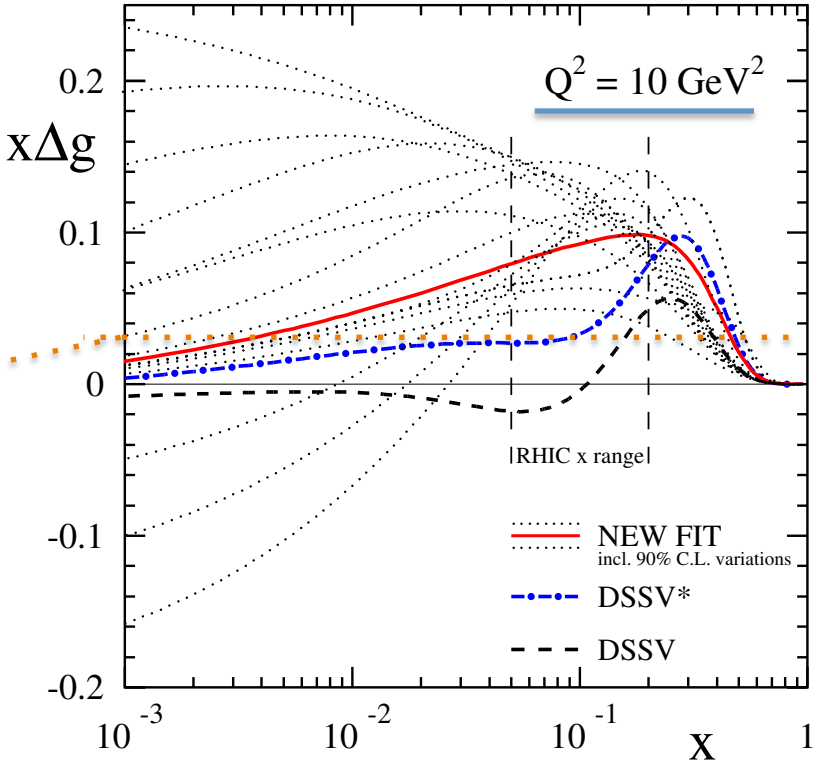


- DSSV (Excluding Run9 data)
- New Fit (DSSV++) (Including Run9 data)

Neural Network & DSSV



[arXiv:1406.5539]



PRL113,012001(2014)

NNPDFpol1.1: jet data ☑, π data ☒

$$\int_{-0.05}^{0.05} \Delta g(x)\,dx = 0.23 \pm 0.07$$

DSSV++: jet data ☑, π ☑

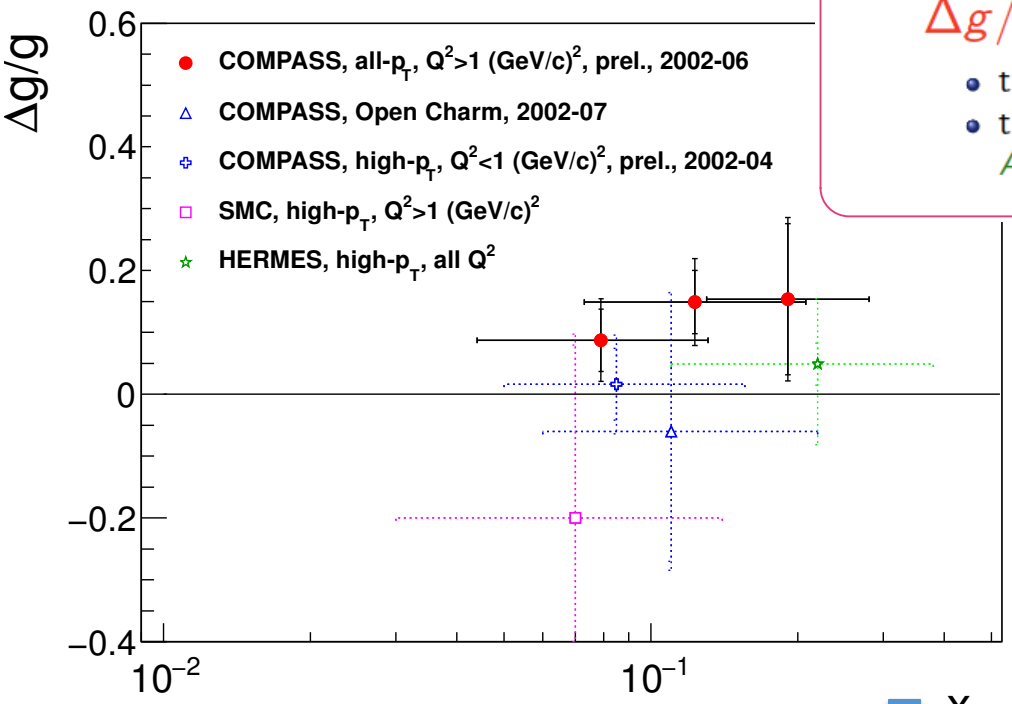
$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.1 \pm^{0.06}_{0.07}$$

- Both NNPDF and DSSV++ suggest positive gluon polarization
- They are quite consistent to each other!

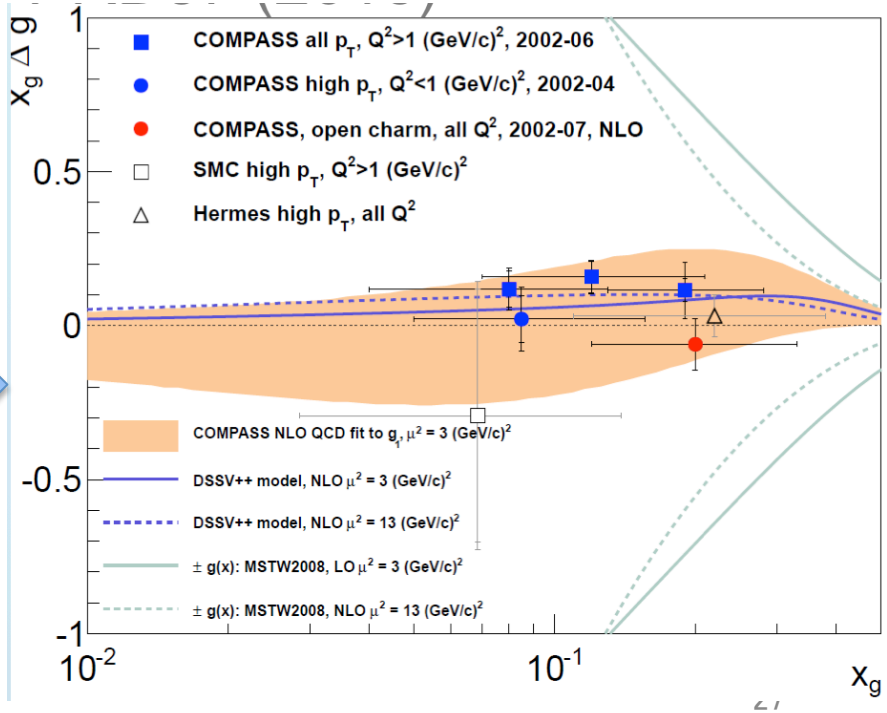
COMPASS High Q^2 Data

$\Delta g/g = 0.113 \pm 0.038 \pm 0.035$ (Preliminary)

- the scale, $\mu^2 =< Q^2 >\approx 3\ (\mathrm{GeV/c})^2$, and $< x_g >\approx 0.10$
- the result obtained under the assumption: $A_1^{QCDC}(x_C) = A_1^{LP}(x_{Bj})$ for $x_C = x_{Bj}$

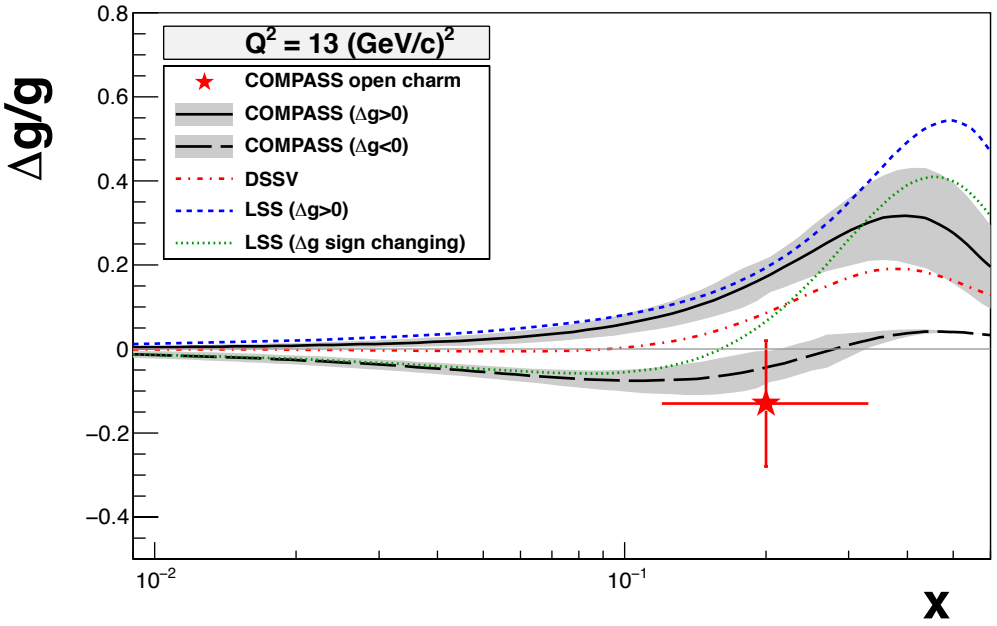


From K. Kurek, Spin2014



Consistent with DSSV++ for high Q^2 data

More Compass Results



Phys.Rev. D 87 (2013) 052018

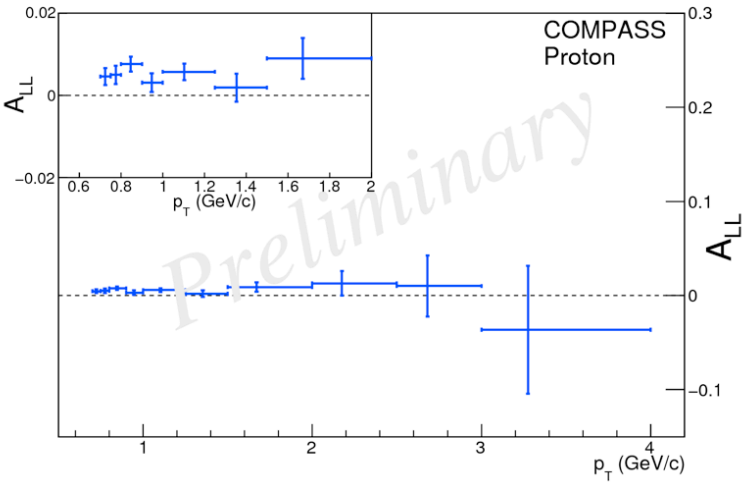
Not necessarily indication of positive gluon polarization (yet?)

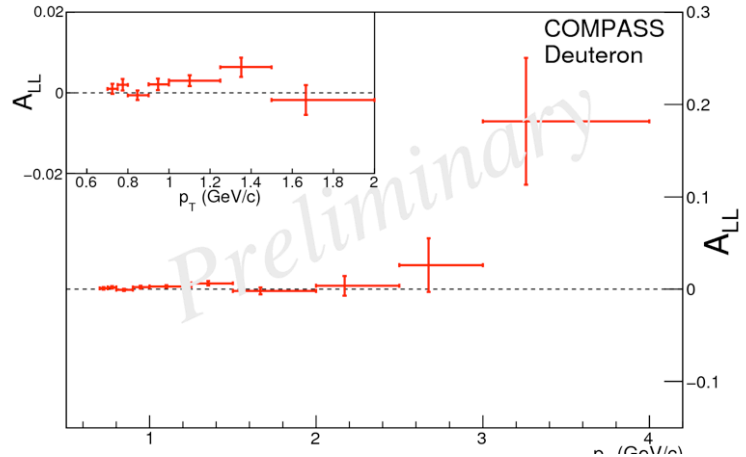
Preliminary results on asymmetries for low Q^2

more details:

DIS 2014: M. Levillain

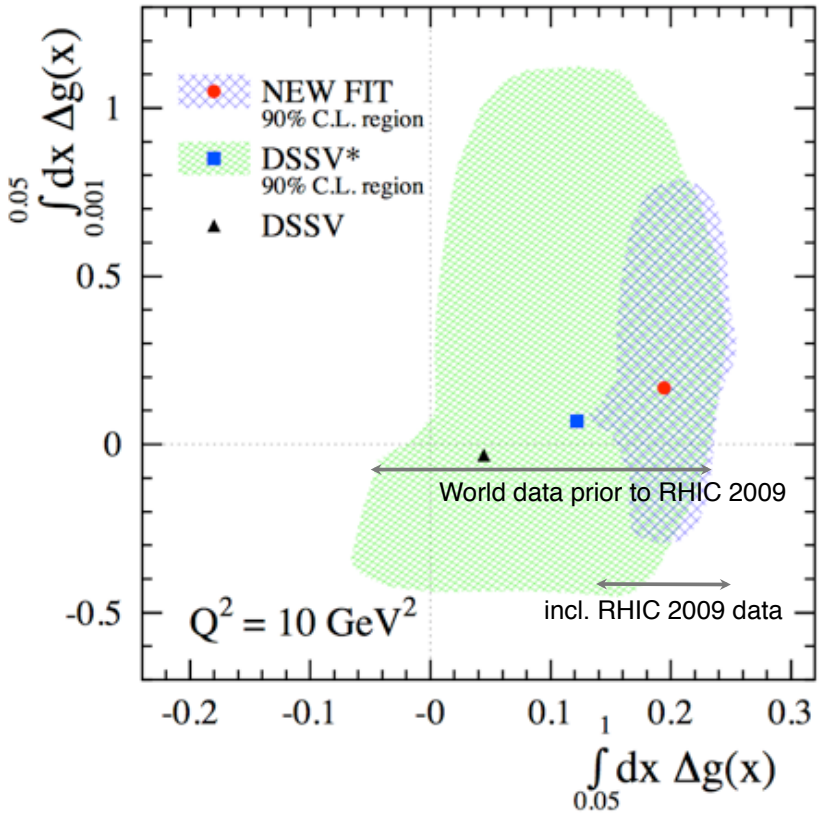
A. Nunes





Gluon Polarization at RHIC - What is next?

DSSV, Phys.Rev.Lett. 113, 012001



Extend sensitivity to *smaller* x_g

forward rapidity, $x_g \sim \exp(-\eta)$,

$\sqrt{s} = 500$ GeV data, $x_g \sim 1/\sqrt{s}$

Further *precision* from jet and neutral pion probes, and

from *complementary* probes

Slide from Renee Fatemi, Spin-2014

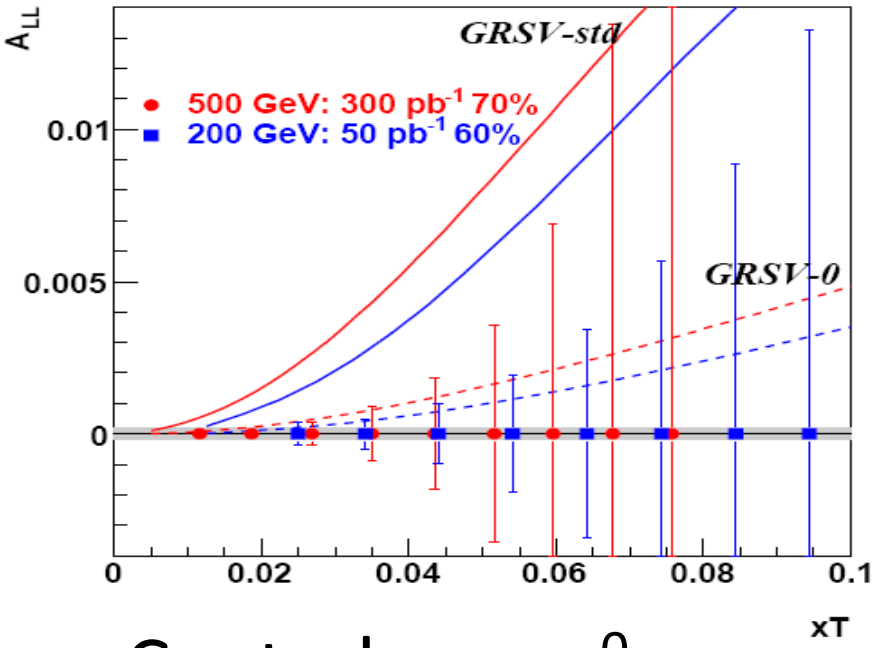
PHENIX central pi0 Preliminary

ΔG(X) AT 500GEV

ΔG @ 510 GeV

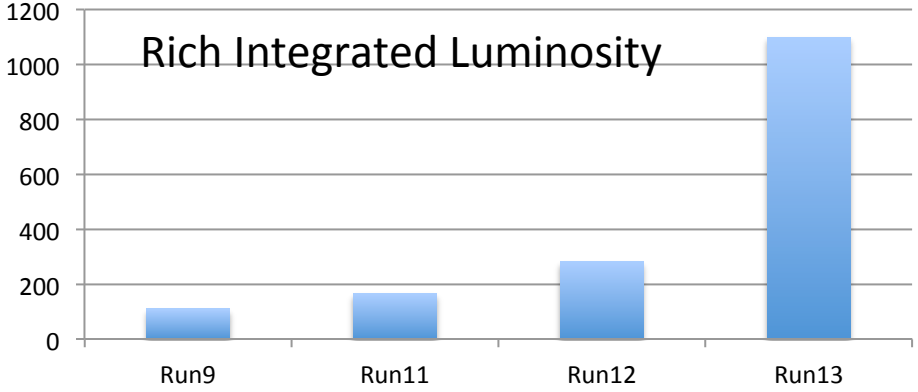
Access to smaller x region

Larger error @ overlapping x compared to 200GeV

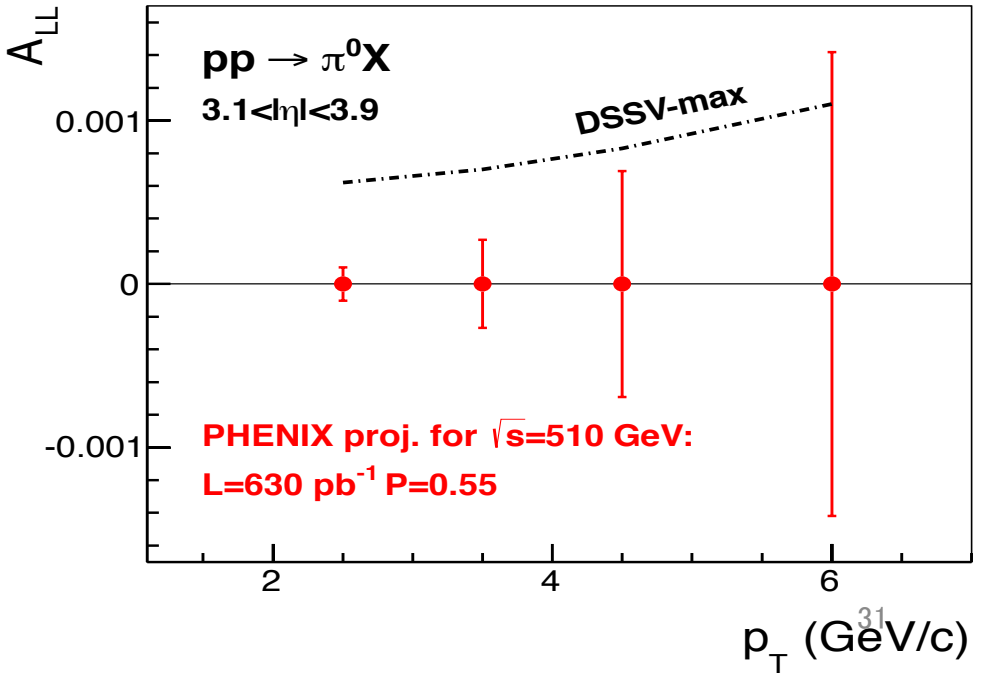


Central arm π^0

500 (510) GeV Integrated Luminosity (Delivered)



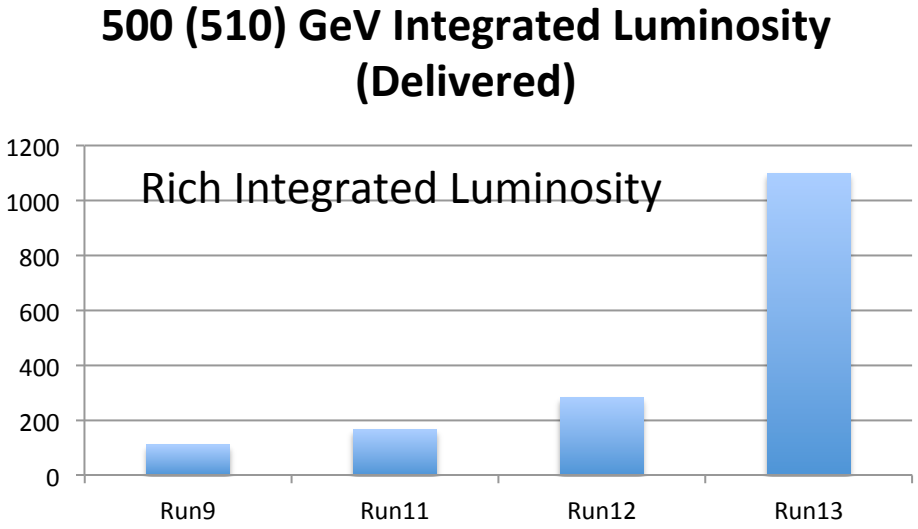
MPC π0 for ΔG at low x

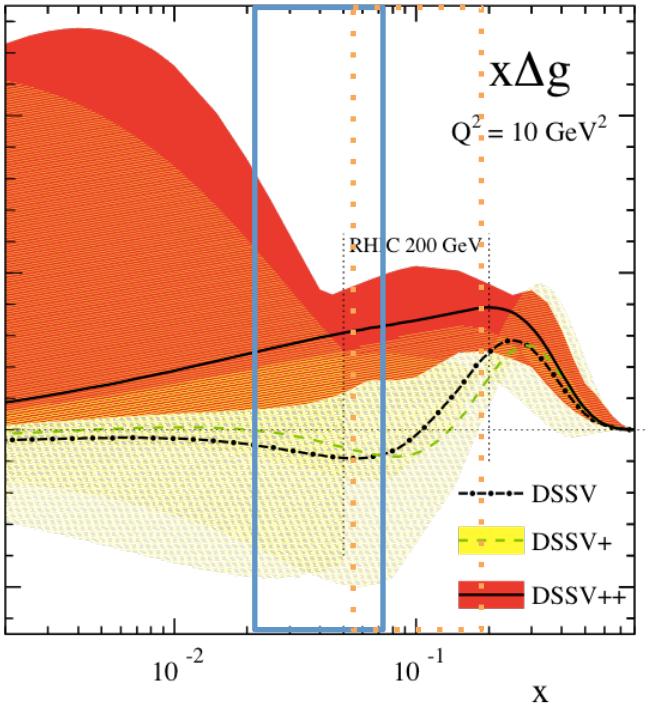


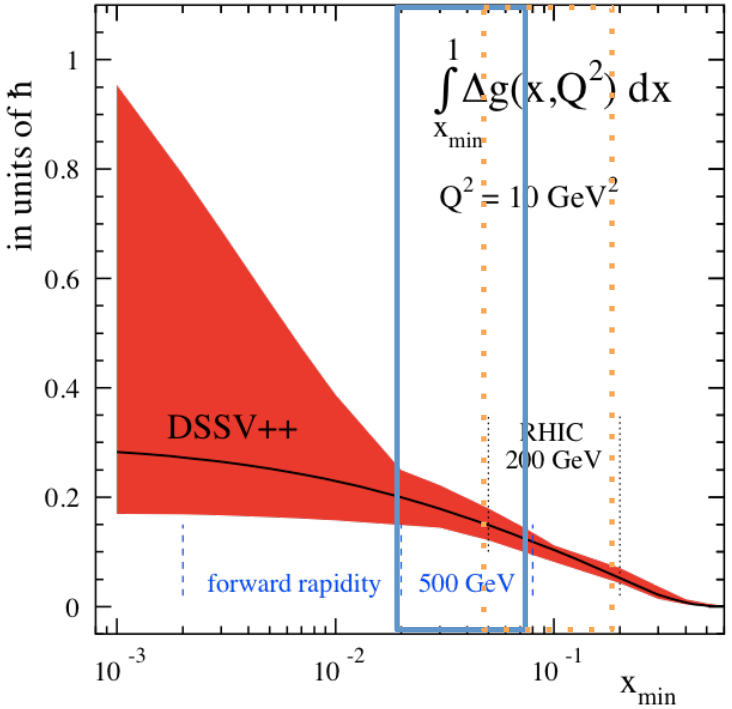
ΔG @ 510 GeV

Access to smaller x region

Larger error @ overlapping x compared to 200GeV

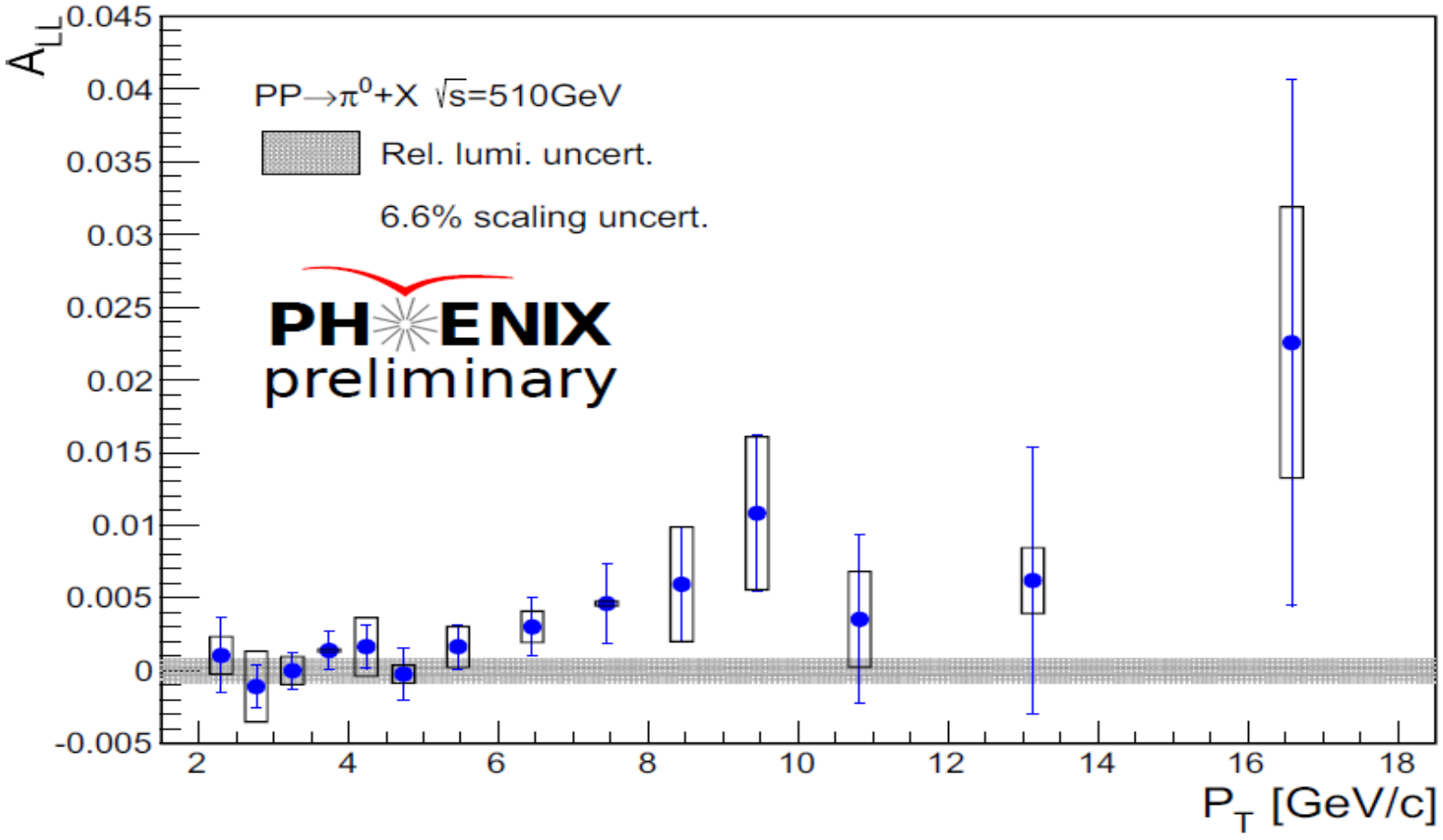






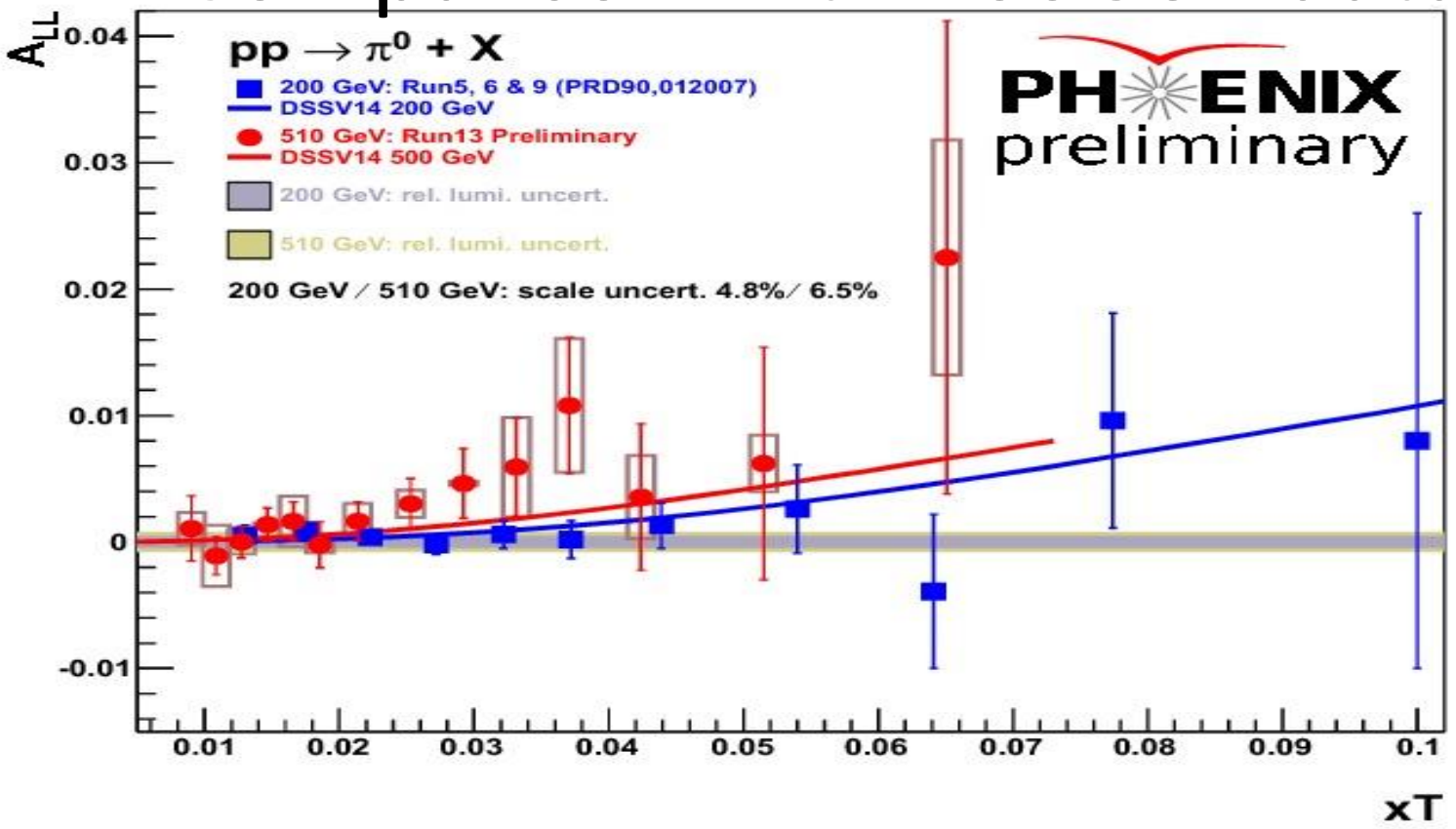
Central arm π^0

PHENIX Run13 π^0



Preliminary release in Spin2014 conference by Inseok Yoon (SNU/RIKEN)

Comparison with 200GeV data



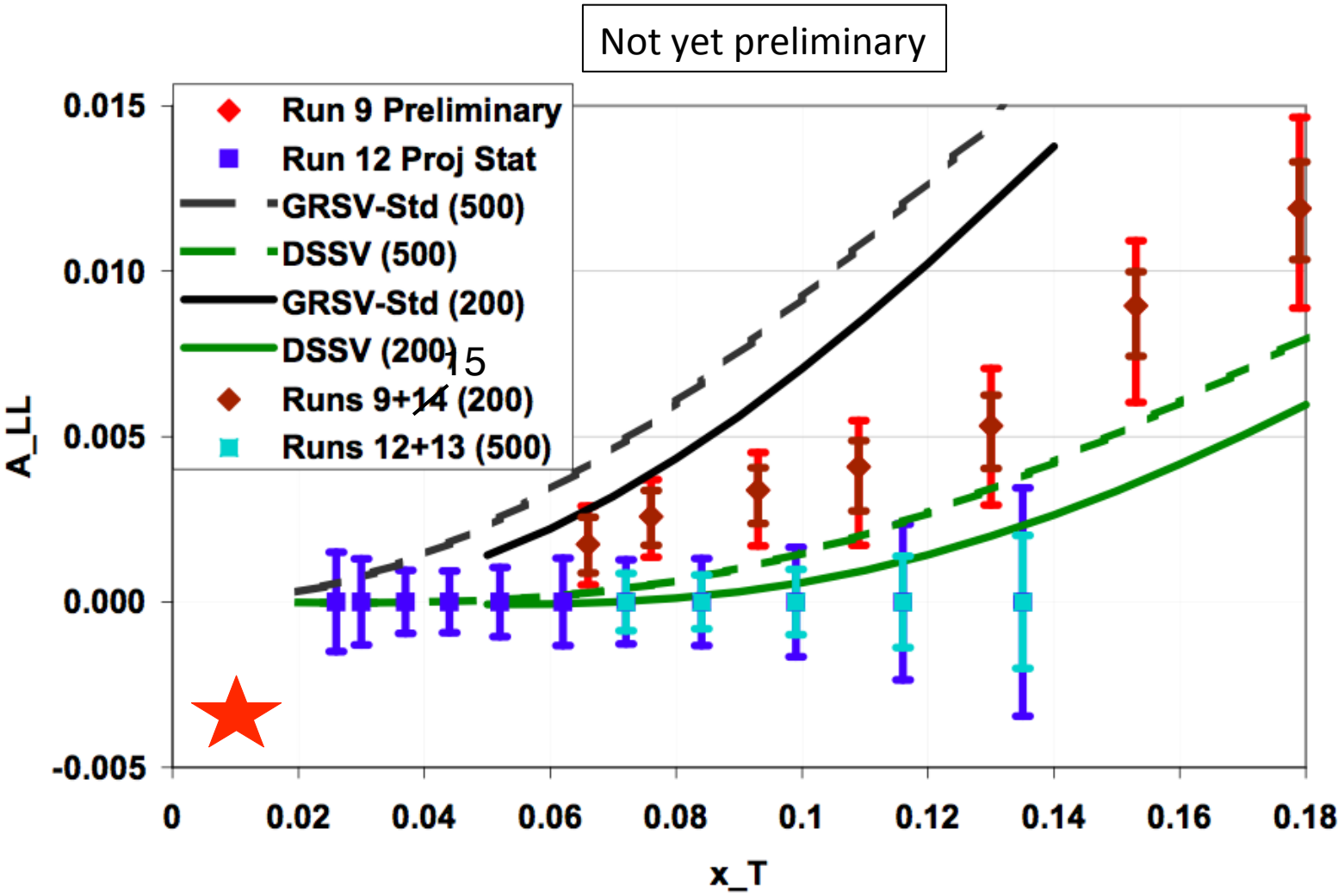
- Different scale and ths different size of asymmetries expected.
  Both of data and theory support it. Evolution effect?

$x_T = \frac{2P_T}{\sqrt{s}}$: approximate version of the average x.

Large positive asymmetry was observed. Consistent with latest positive ΔG results.

Slide from Inseok Yoon, Spin 2014

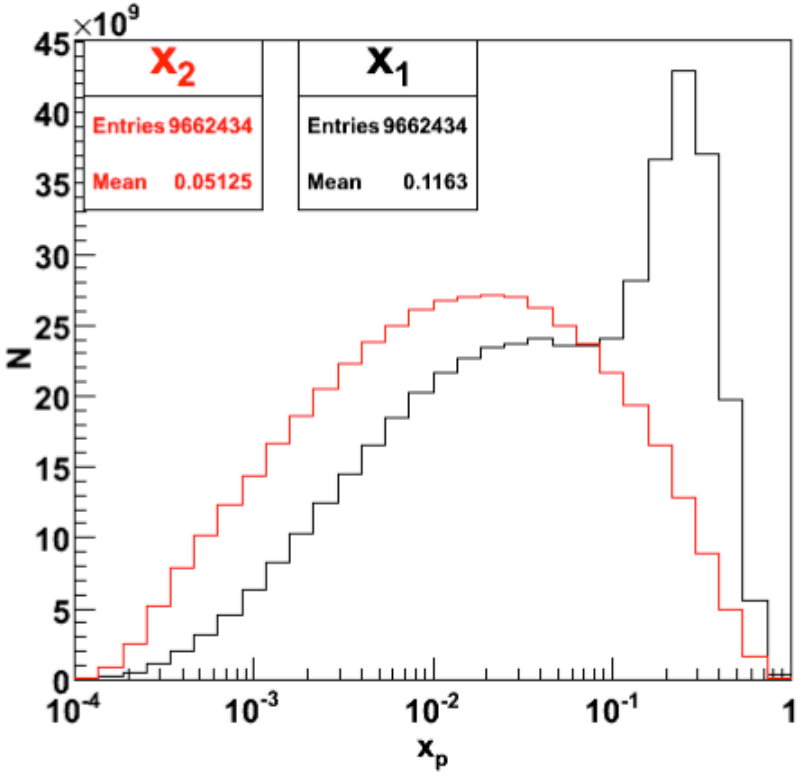
STAR inclusive Jet @ 500GeV



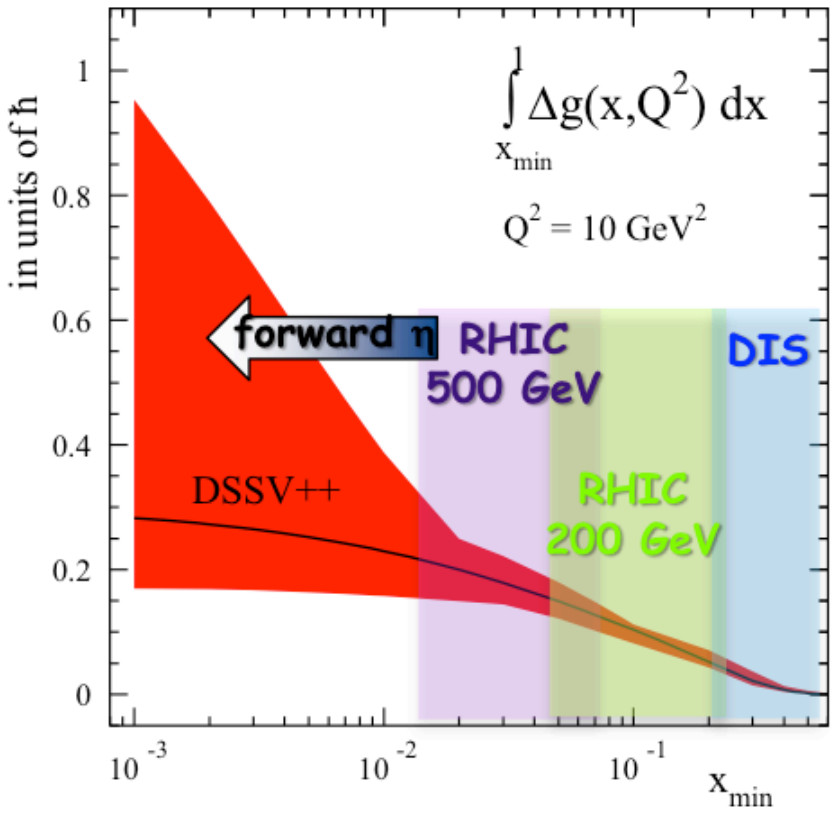
STAR pi0 @ 510 GeV Preliminary

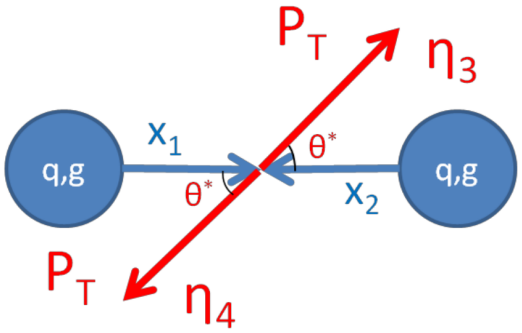
FORWARD MEASUREMENTS

Backward (Forward) Kinematics



Access even smaller x!



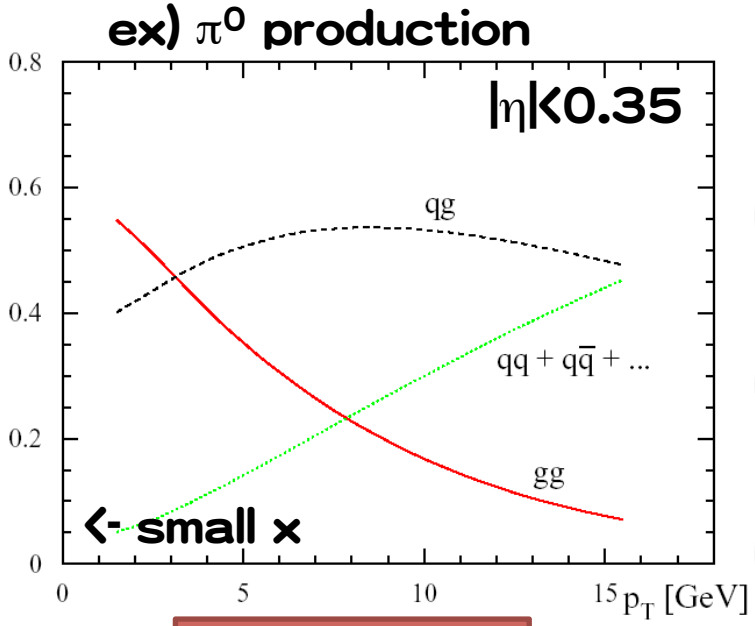


$$x_1 = \frac{p_T}{\sqrt{s}}\left(e^{\eta_3} + e^{\eta_4}\right)$$

$$x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-\eta_3} + e^{-\eta_4}\right)$$

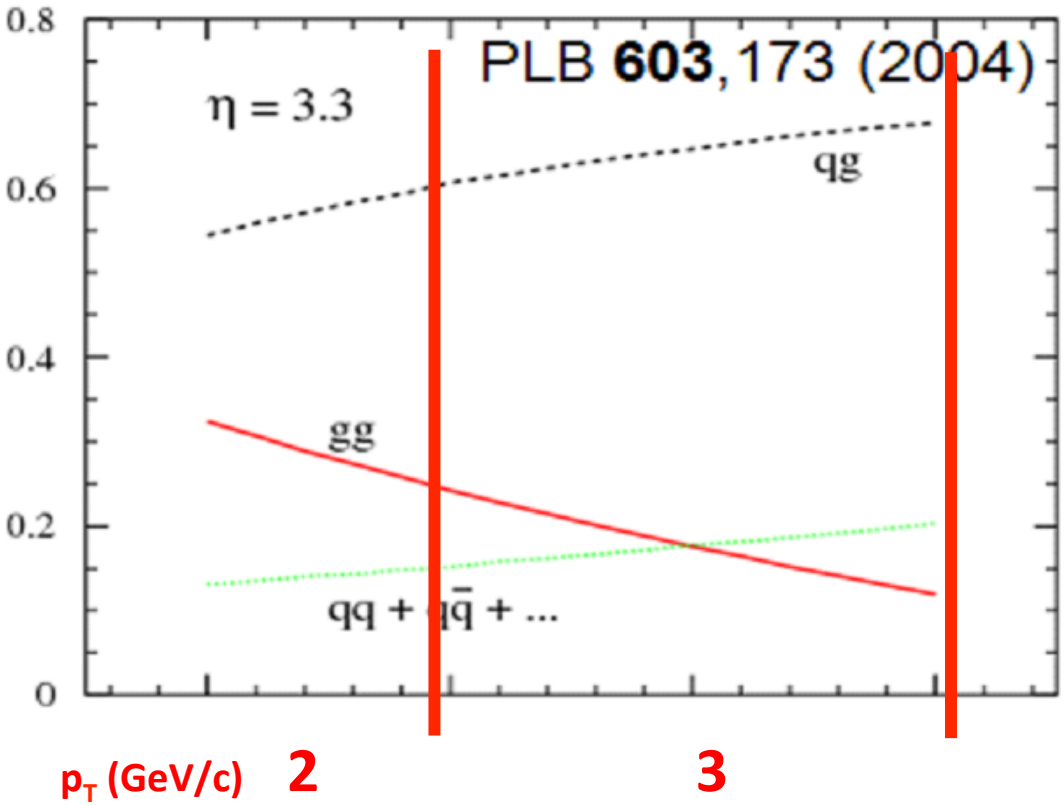
(leading-order x_1 and x_2 equations)

Sub-process in Forward



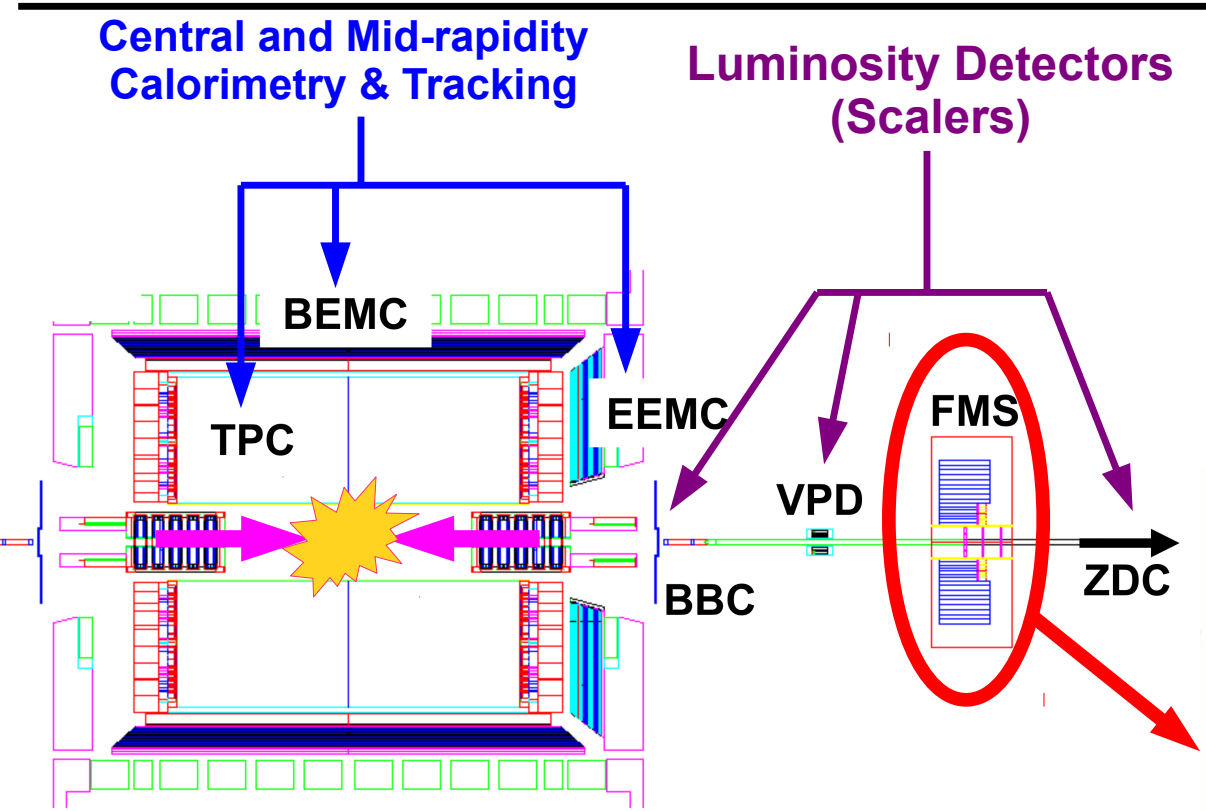
Central Rapidity

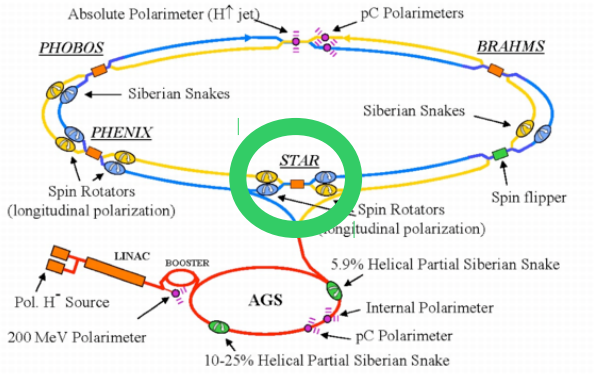
Central Rapidity

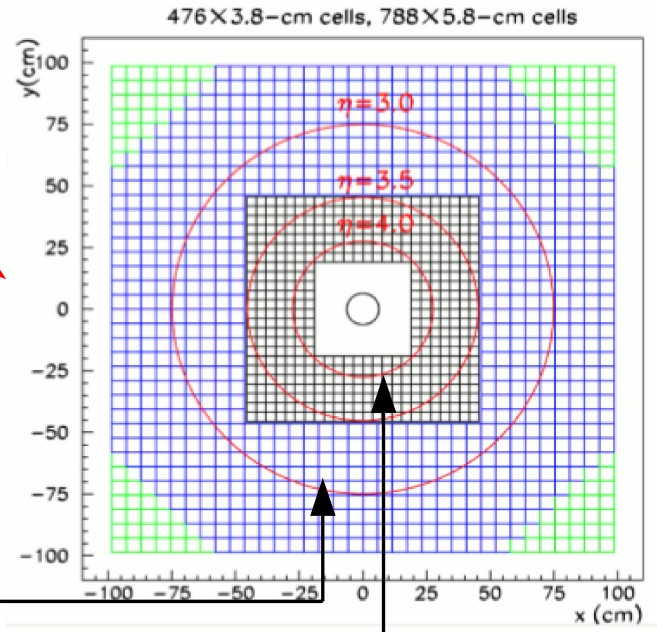


Quark-gluon dominates

Forward EM Calorimetry at STAR







PRIMARY FOCUS:

FMS – Forward Meson Spectrometer

- Forward pseudorapdity: **2.5 < η < 4**
- 1,264 **Lead-glass cells** coupled to photomultiplier tubes
  - Large (5.8 x 5.8 cm) outer cells (blue)
  - Small (3.8 x 3.8 cm) inner cells (black)
- Observes $\pi^0 \rightarrow \gamma+\gamma$ as 2 cluster events
- Forward observables → access to **low-x gluons**

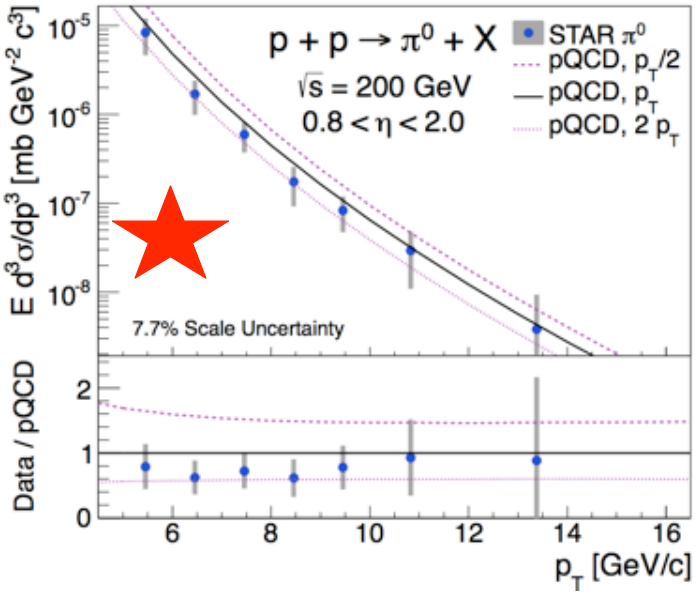
Slide from Christopher Dilks, Spin 2014

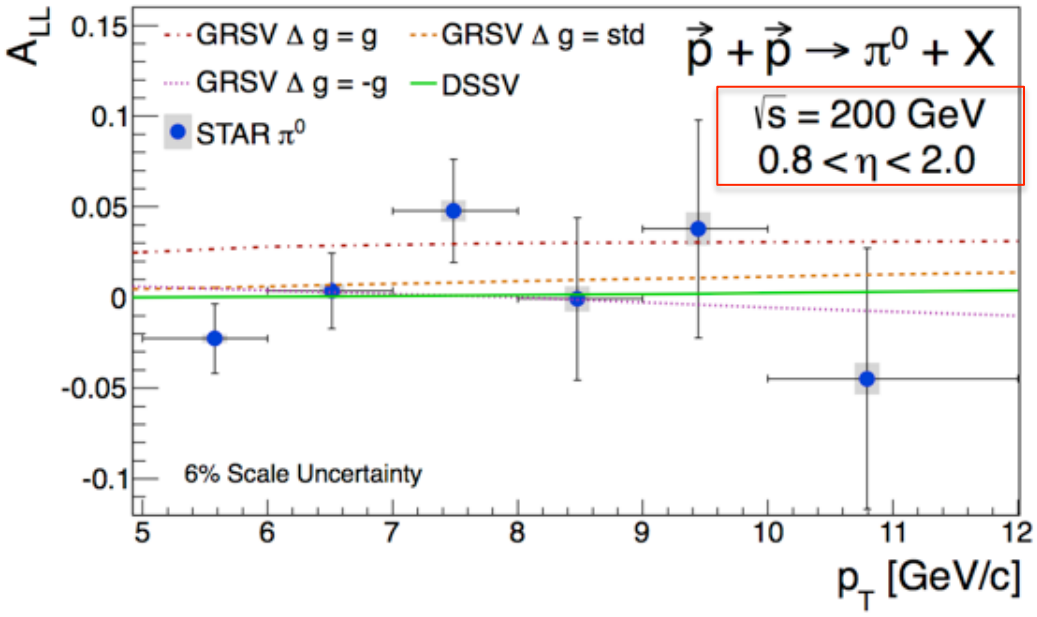
STAR Forward pi0

Gluon Polarization - other channels, smaller x_g

Initial neutral pion data, 4.8 pb^{-1} at $\sqrt{s}$ = 200 GeV, at more forward rapidity:

Phys.Rev. D89 (2014) 1, 012001

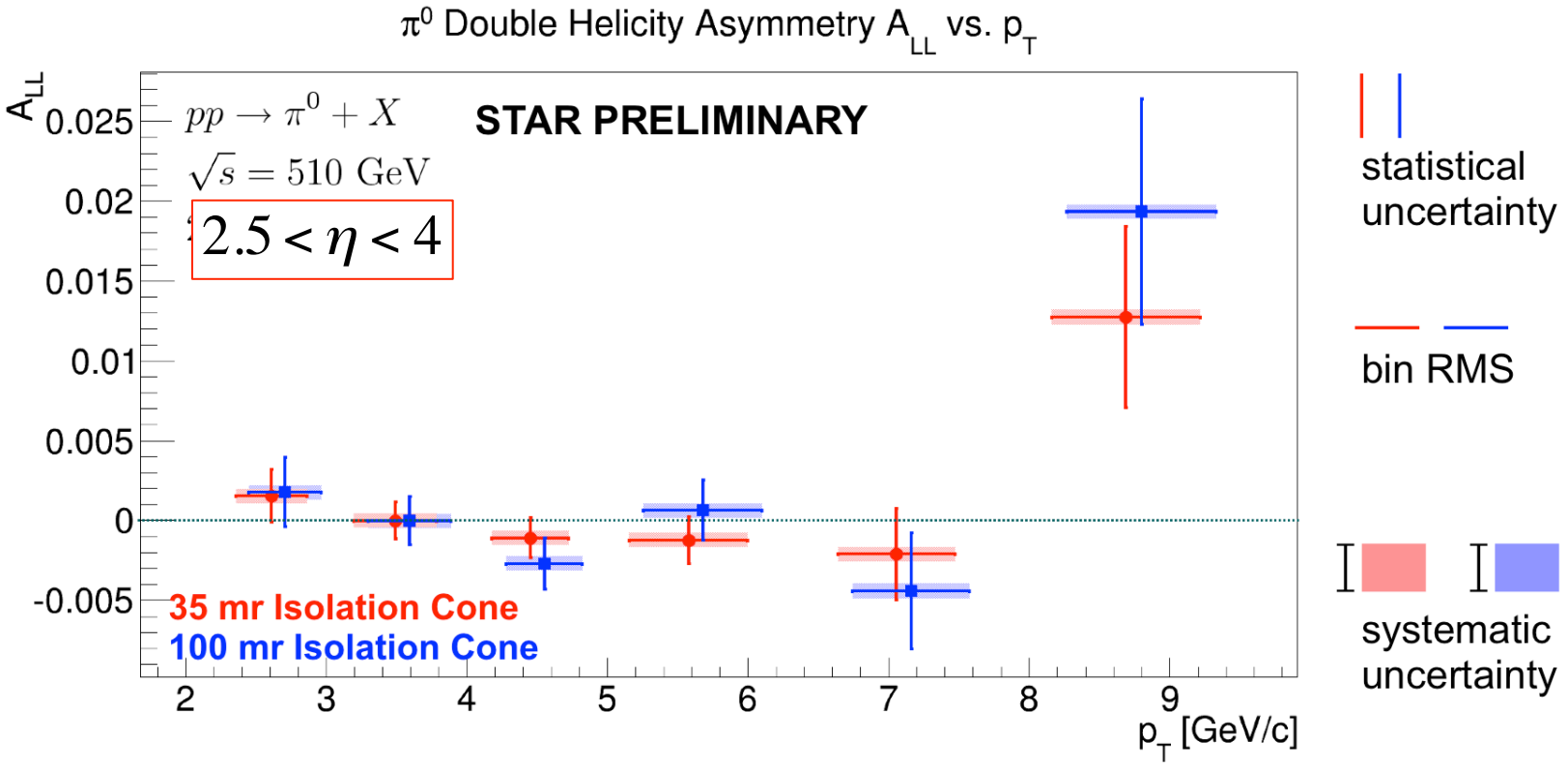




Proof-of-concept; needs further precision and $\sqrt{s}$ = 500 GeV and, eventually, upgrades.

Slide from Renee Fatemi, Spin-2014

Forward π^0 A_{LL} Measurement – p_T-Dependence



35 mr Constant Fit Result: $A_{LL} = -2.5 \times 10^{-4} \pm 6.5 \times 10^{-4}$

χ^2 / NDF = 7.8 / 5

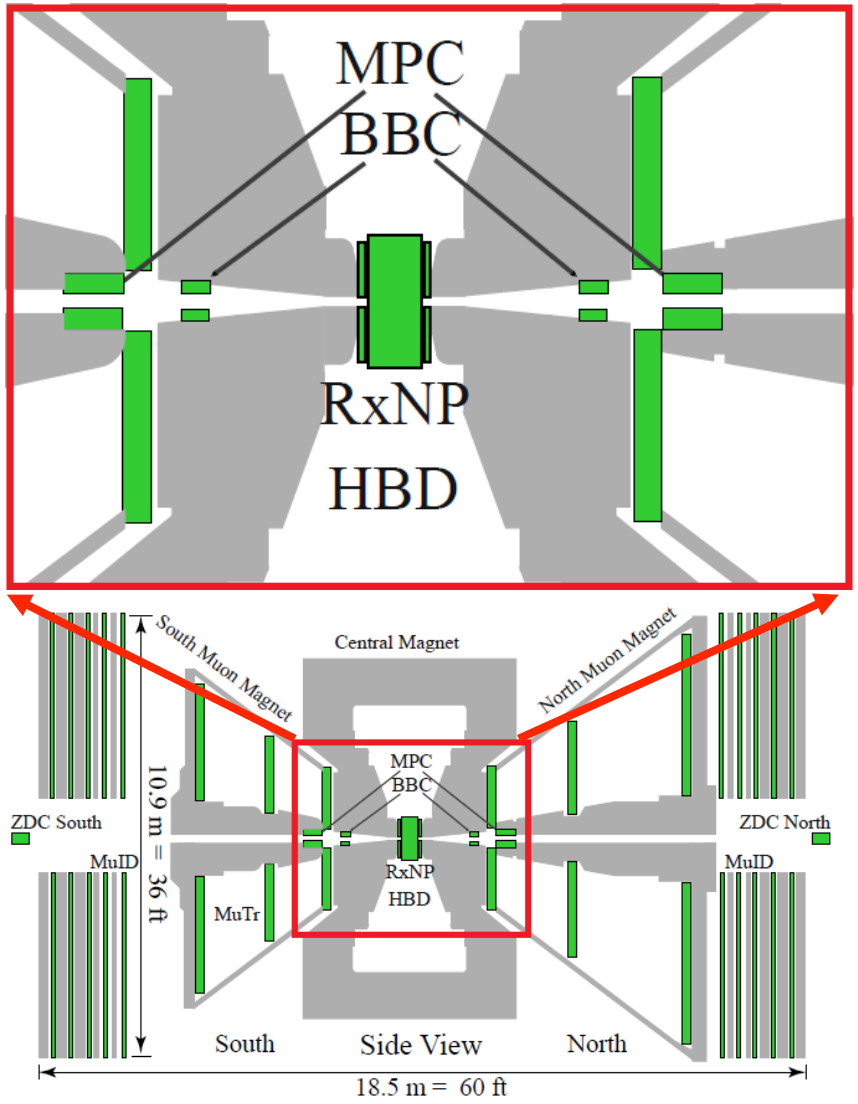
100 mr Constant Fit Result: $A_{LL} = -3.3 \times 10^{-4} \pm 8.4 \times 10^{-4}$

χ^2 / NDF = 12.5 / 5

* 100 mr points are offset by p_T + 0.1 GeV/c for visibility

Slide from Christopher Dilks, Spin 2014

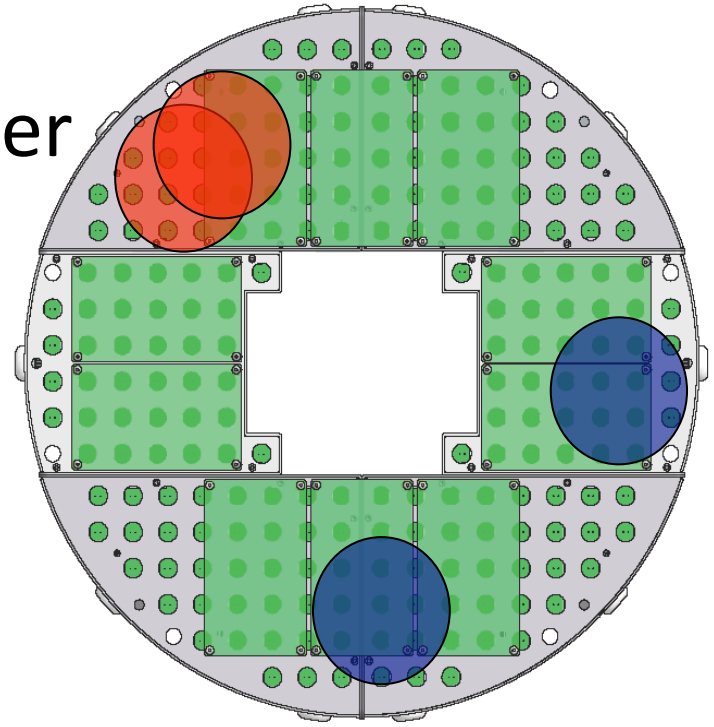
Exploring Lower-x by Forward MPC



Muon Piston Calorimeter
3.1<|η|<3.9

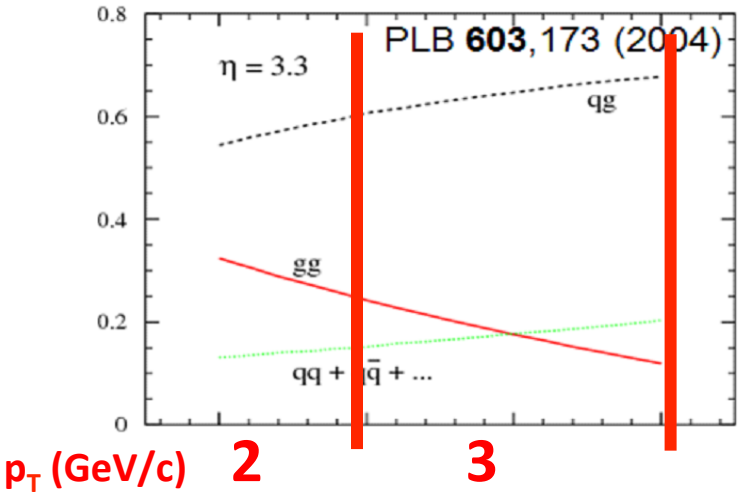
- **Low P_T Reconstructed π^0**
- **High PT Merged π^0**

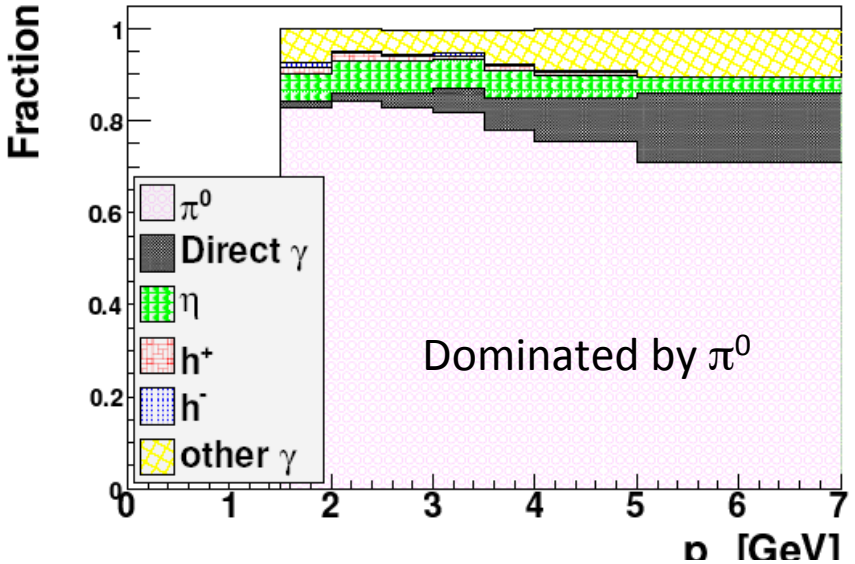
cluster

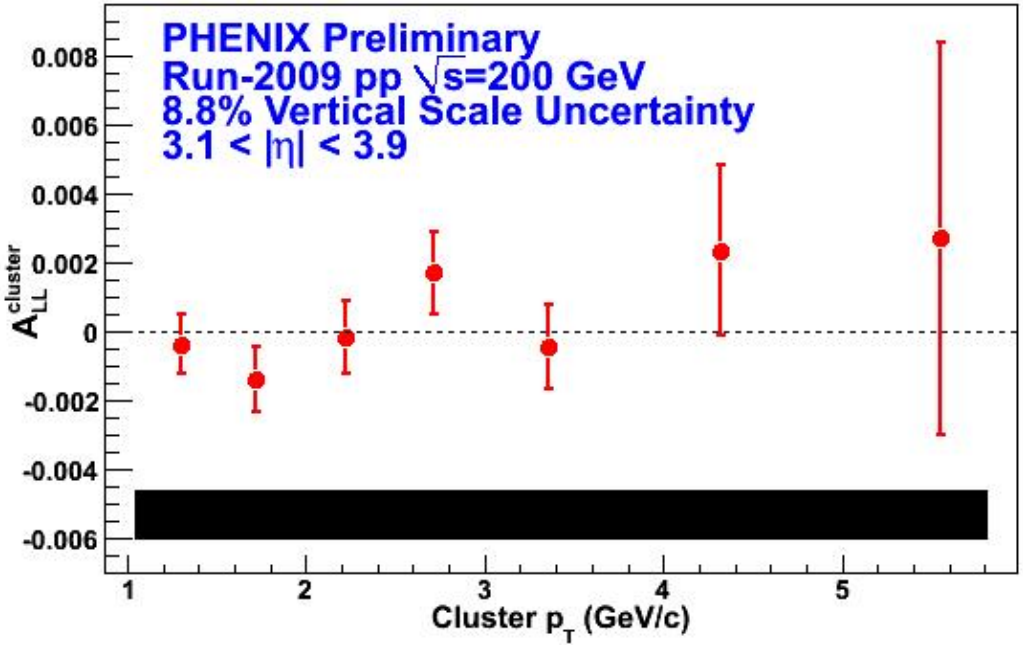


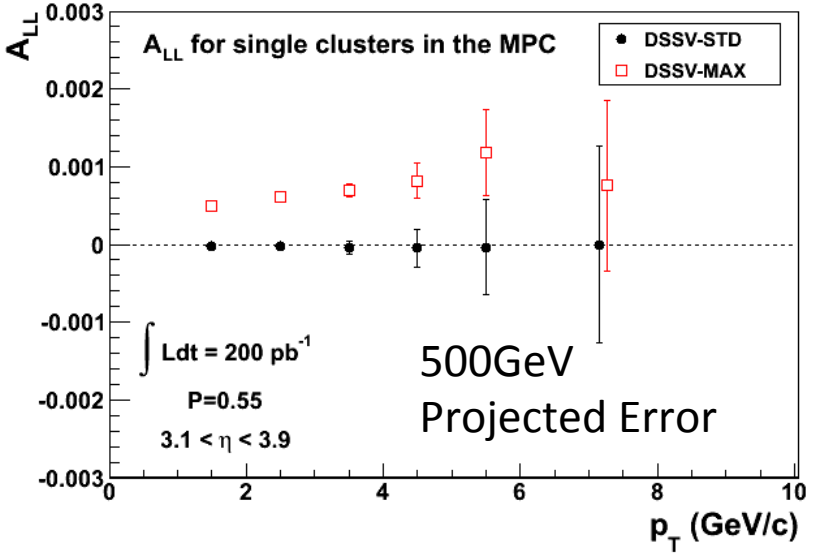
Range
0.05<x<0.2

Cluster A_{LL}


PLB 603,173 (2004)
η = 3.3
qg
gg
qq + q̄q̄ + ...
p_T (GeV/c)
2
3


Fraction
π⁰
Direct γ
η
h⁺
h⁻
other γ
Dominated by π⁰
p_T [GeV]


PHENIX Preliminary
Run-2009 pp √s=200 GeV
8.8% Vertical Scale Uncertainty
3.1 < |η| < 3.9
A_LL^cluster
Cluster p_T (GeV/c)


A_LL for single clusters in the MPC
DSSV-STD
DSSV-MAX
∫ Ldt = 200 pb⁻¹
P=0.55
3.1 < η < 3.9
500GeV
Projected Error
p_T (GeV/c)

Summary

- Good data sets available up to Run9 from PHENIX and STAR by now.
- Indicated positive ΔG in $0.05<x<0.2$ predicted by DSSV ++ and NNPDF @Q^2~10GeV
- Positive DG is consistent with COMPASS high-Q2 data (Q^2~3GeV).
- Still many observables are consistent with zero, but statistically not sufficient.
- New PHENIX 510GeV pi0 show positive ΔG
- Further 510GeV and forward measurements analysis are on going.