Longitudinal Spin Physics with the PHENIX Detector at RHIC

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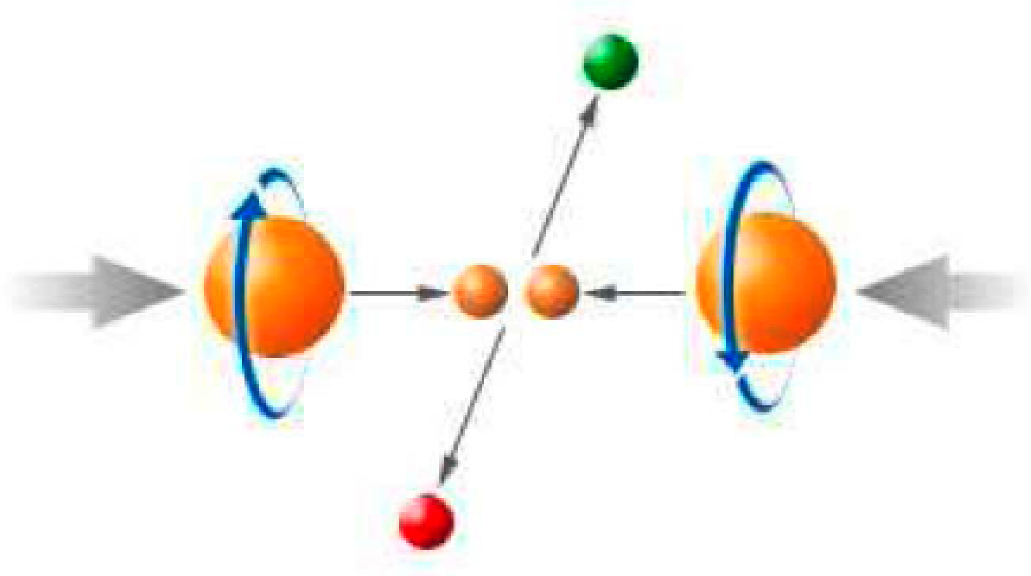
on behalf of the PHENIX Collaboration



Longitudinal Spin Physics Motivation and Goals

- Proton spin sum rule : $\frac{1}{2} = S_q + S_g + L_q + L_g$ (infinite momentum frame)
  $= \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$
- Roughly 50% of the momentum is carried by the quarks
- Relativistic quark models predict $\Delta\Sigma \approx 0.6 - 0.7$
- But experiments suggest $\Delta\Sigma \approx 0.25$, small in comparison $\Rightarrow$ perhaps Δg is large
- Spin structure poses a major challenge to our understanding
- Experiments can help through measurements of the polarized parton distribution functions :

$$\Delta f(x) = f_+(x) - f_-(x), \quad \text{as function of the momentum fraction } x$$
$$\Delta\Sigma = \int_0^1 \left[\Delta u(x) + \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{d}(x) + \Delta s(x) + \Delta\bar{s}(x)\right] dx$$
$$\Delta g = \int_0^1 g(x)dx$$

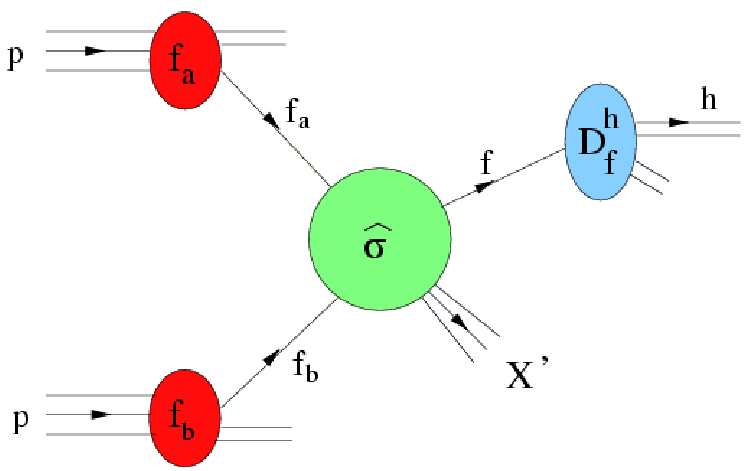
- How do the polarized PDFs behave as $x \to 0$, as $x \to 1$? Do they evolve as pQCD predicts?
- What are the relative contributions of the valence quarks, sea quarks, gluons? (Pauli principle suggests $\Delta\bar{u} > 0,\ \Delta\bar{d} < 0$)
- How do we deal with orbital angular momentum, transverse spin effects?
- Lab frame versus infinite momentum frame description of components

How do we extract Δg from inclusive polarized proton-proton collisions at RHIC ?

- Acquire sensitivity to Δg by measuring asymmetries in particle production from longitudinally polarized protons :

$$A_{LL}^{\pi^0} \equiv \frac{d\sigma(p_+p_+ \to \pi^0 X) - d\sigma(p_+p_- \to \pi^0 X)}{d\sigma(p_+p_+ \to \pi^0 X) + d\sigma(p_+p_- \to \pi^0 X)} \equiv \frac{d\Delta\sigma}{d\sigma}$$

$$= \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}, \quad R = \frac{L_{++}}{L_{+-}}$$



- To relate to Δg, can factorize pp collisions as convolution of :

  (i) (universal) parton densities $f_a(x_a)$, $f_b(x_b)$
  (ii) hard partonic cross section $\hat{\sigma}$
  (iii) fragmentation function $D_c^h(z)$

- Sensitive to gluon when a or b = gluon

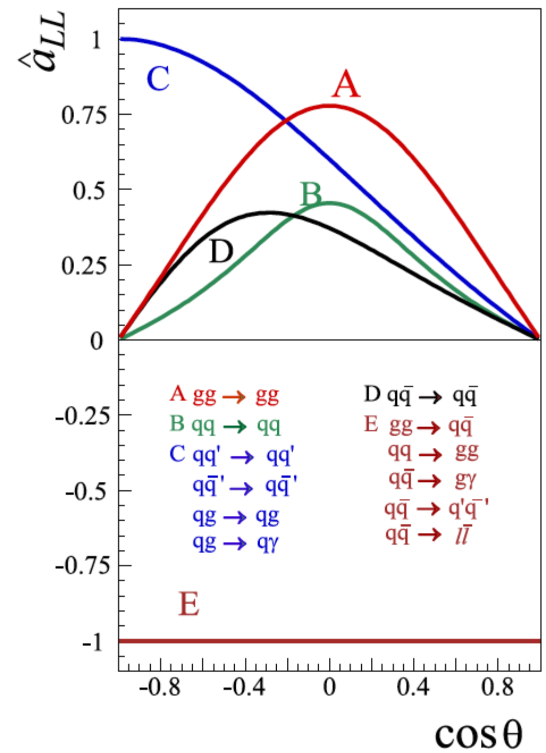
$$\frac{d\Delta\sigma^{\vec{p}\vec{p}\to\pi X}}{dp_T d\eta} = \sum_{abc} \int dx_a dx_b dz_c \, \Delta f_a(x_a, \mu_f) \, \Delta f_b(x_b, \mu_f) \times$$

$$\frac{d\Delta\hat{\sigma}^{ab\to cX}}{dp_T d\eta} \left(x_a P_a, x_b P_b, P_\pi / z_c, \mu_f, \mu'_{f'}, \mu_r\right) D_c^\pi \left(z_c, \mu'_f\right)$$

$$\text{where } d\Delta\hat{\sigma}^{ab\to cX} = d\hat{\sigma}^{ab\to cX} \times \hat{a}_{LL}^{ab\to cX}$$

How do we extract $\Delta g(x)$ from inclusive polarized pp collisions ?

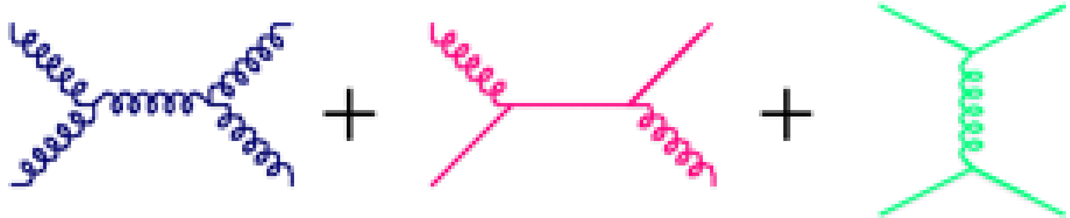
$$
d\Delta\sigma^{\vec{p}\vec{p}\to\pi X} = \sum_{abc}\int dx_a dx_b dz_c \, \Delta f_a(x_a,\mu_f)\, \Delta f_b(x_b,\mu_f) \times
d\hat{\sigma}^{ab\to cX}\left(x_a P_a, x_b P_b, P_\pi/z_c, \mu_f, \mu'_{f'}, \mu_r\right) \times
\hat{a}_{LL}^{ab\to cX} \times D_c^{\pi}\left(z_c, \mu'_f\right)
$$



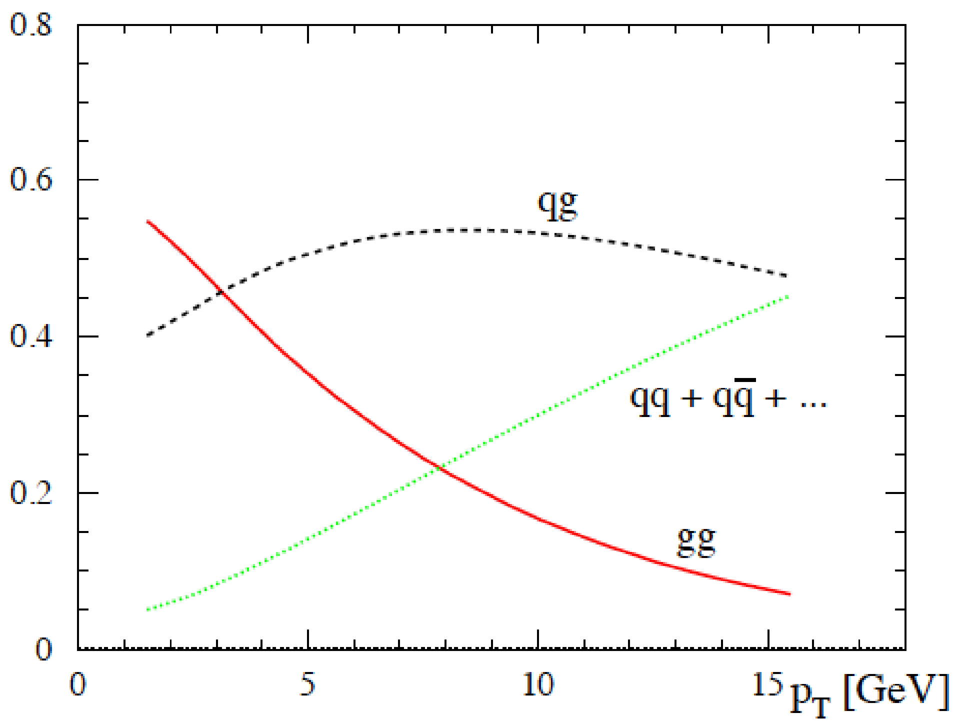
- pQCD framework is successful in describing unpolarized cross-sections (when power corrections, others small)
- pQCD framework can be used to extract $\Delta g(x)$ from polarized pp collisions
- Need to measure Δg through variety of channels, over range in x and momentum transfer
- Measuring momentum fractions x_a and/or x_b improves sensitivity to $\Delta g(x)$
- Final states such as γ and jet remove some complexity from fragmentation process
- Δg extracted will have some factorization/renormalization scale dependence

PHENIX Specialty : $A_{LL}(\vec{p}\vec{p} \rightarrow \pi^0 X)$

- PHENIX has excellent capabilities for triggering and identifying π^0
- A_{LL} of $\pi^0,\ \pi^{\pm}$ has contributions from $\Delta g \times \Delta g,\ \Delta g \times \Delta q$, and $\Delta q \times \Delta q$



Fractional contributions to π production at $\sqrt{s} = 200$ GeV

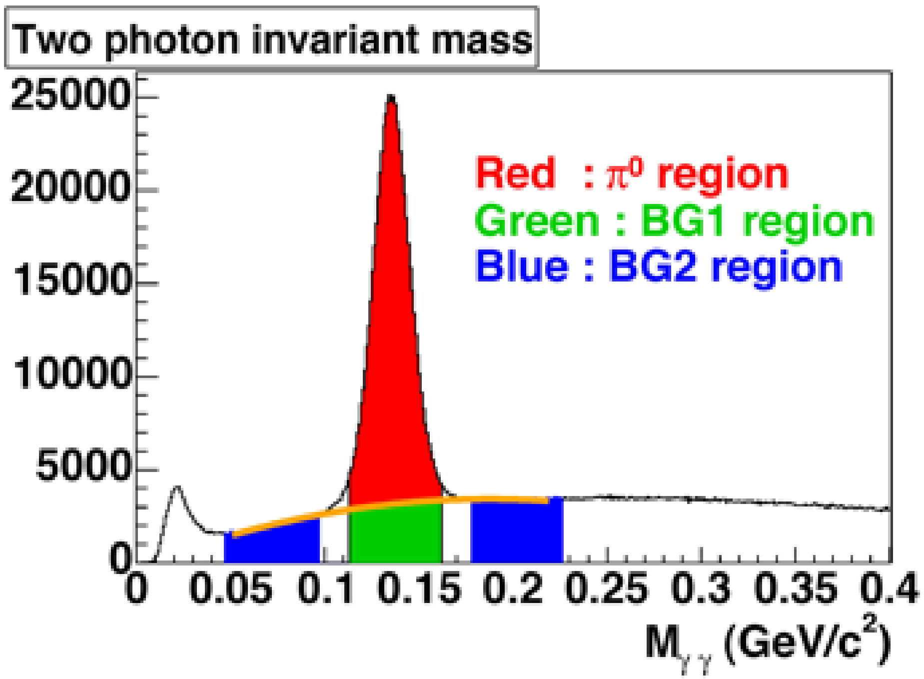


- At lower p_T ($<< 5$ GeV), A_{LL} of π depends on $(\Delta g)^2$
- Quark-gluon scattering starts to dominate for $p_T > 5$ GeV, linear dependence on $\Delta g(x)$

PHENIX Specialty : $A_{LL}(\vec{p}\vec{p} \rightarrow \pi^0 X)$

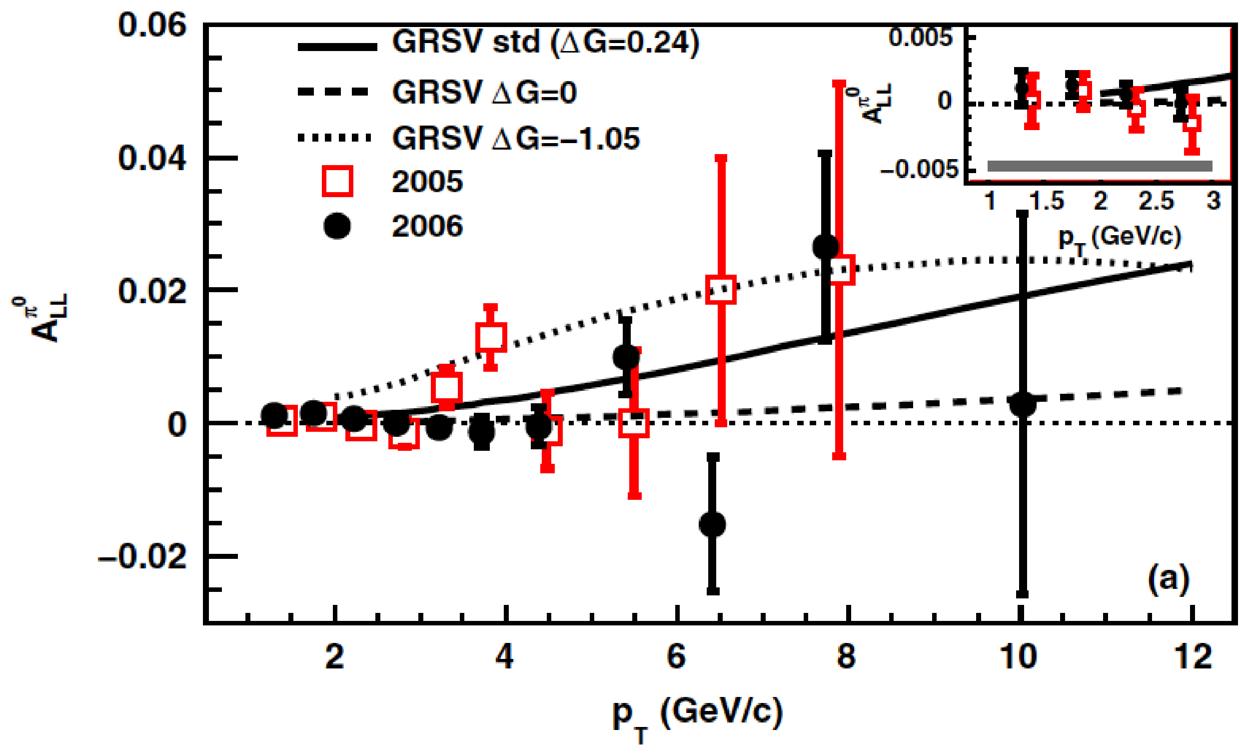
- Identify π^0 from 2γ invariant mass peak, extract background fraction, r, and asymmetry
- Construct :

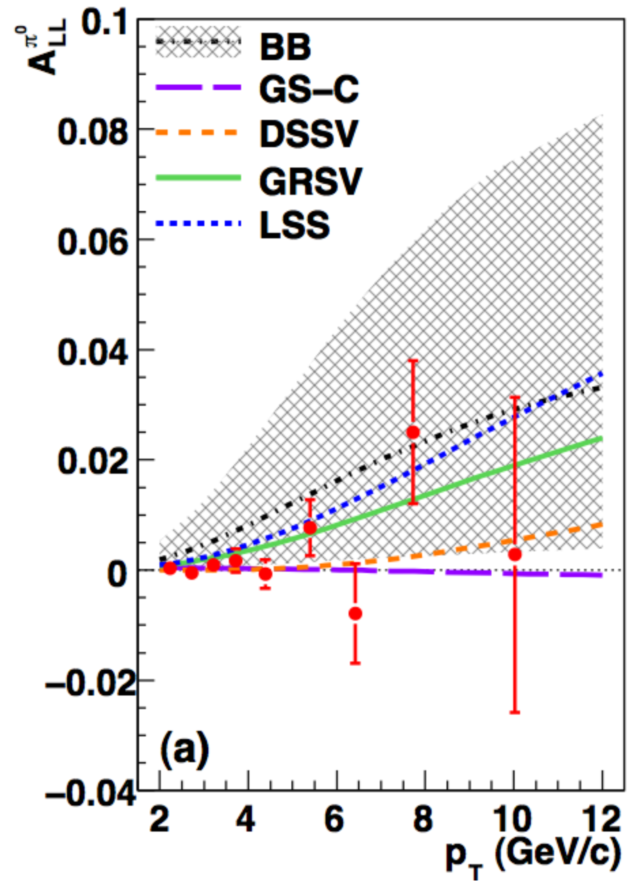
$$A_{LL}^{\pi^0} = \frac{A_{LL}^{\pi^0+BG} - rA_{LL}^{BG}}{1-r}$$



p_T Range	Run 6 Peak Yield (112-162 MeV)	Background Fraction
2.0-3.0 GeV	35 x 10^6 events	16%
5.0-6.0 GeV	380 K events	8 %
9.0-12.0 GeV	14 K events	6.3 %

PHENIX measurements of $A_{LL}(\vec{p}\vec{p} \rightarrow \pi^0 X)$ at $\sqrt{s}$=200 GeV

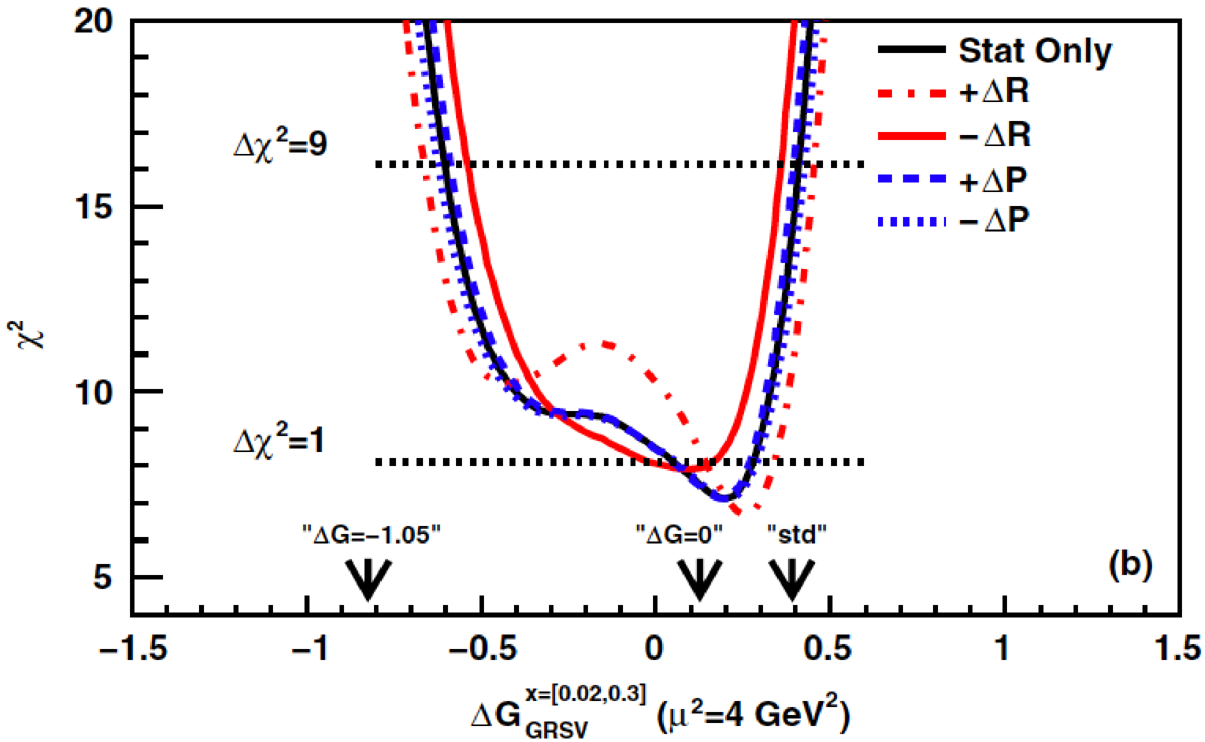




- Runs 5+6 $A_{LL}(pp \rightarrow \pi^0 X)$ at $\sqrt{s}$=200 GeV
- PHENIX PRL **103**, 012003 (2009)
- Uncertainties $< 1\%$ at $p_T < 5$ GeV (8.3% uncertainty in polarization not shown), $\delta R \approx\ 7 \times 10^{-4}$
- Asymmetries smaller than best-fits to DIS data $\Rightarrow$ smaller Δg

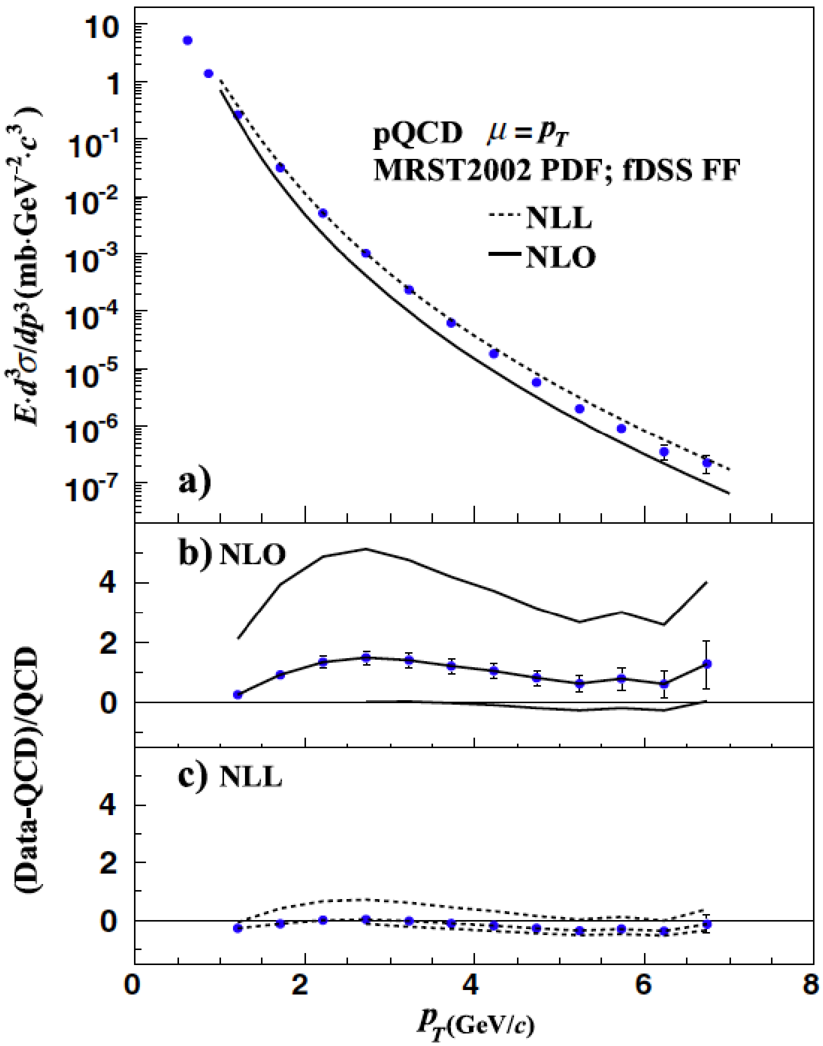
Model-dependent extraction of Δg from A_{LL}

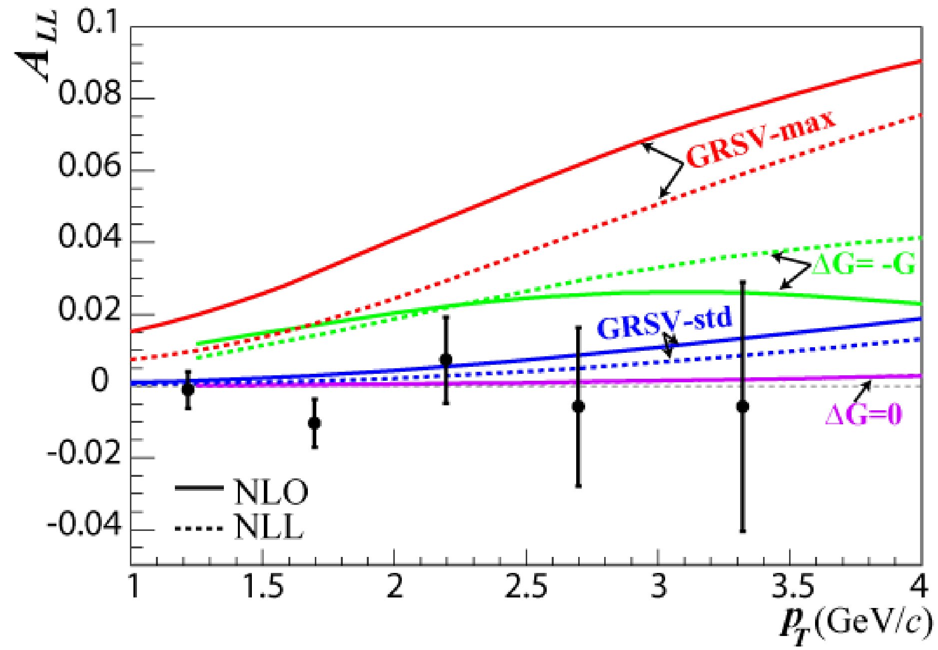
- Using constraint on $\int_0^1 \Delta g(x)dx$, fit polarized PDFs in GRSV functional form to pDIS data
- For each value of integral Δg, calculated $A_{LL}^{\pi^0}$ compared with measurement, extracted χ^2



- Polarization uncertainty not too important, relative luminosity uncertainty is important
- $\Delta g_{GRSV}^{[0.02,0.3]}(\mu^2 = 4\ \mathrm{GeV}^2) = 0.2 \pm 0.1 \pm 0.1\ (\Delta\chi^2 = 1)$
- $\Delta g_{GRSV}^{[0.02,0.3]}(\mu^2 = 4\ \mathrm{GeV}^2) = 0.2^{+0.2}_{-0.8} \pm 0.1\ \ (\Delta\chi^2 = 9)$
- Results favor a smaller Δg than pDIS data suggested, other functional forms for distribution : $-0.7 < \Delta g^{[0.02,0.3]} < 0.5$ for $\Delta\chi^2 = 9$
- Changes in scale $\mu = p_T,\ p_T/2,\ 2p_T$ yield additional uncertainty $\pm 0.1(^{+0.1}_{-0.4})$ for $\Delta\chi^2 = 1(9)$

PHENIX measurements of $A_{LL}(\vec{p}\vec{p} \to \pi^0 X)$ at $\sqrt{s}$=62.4



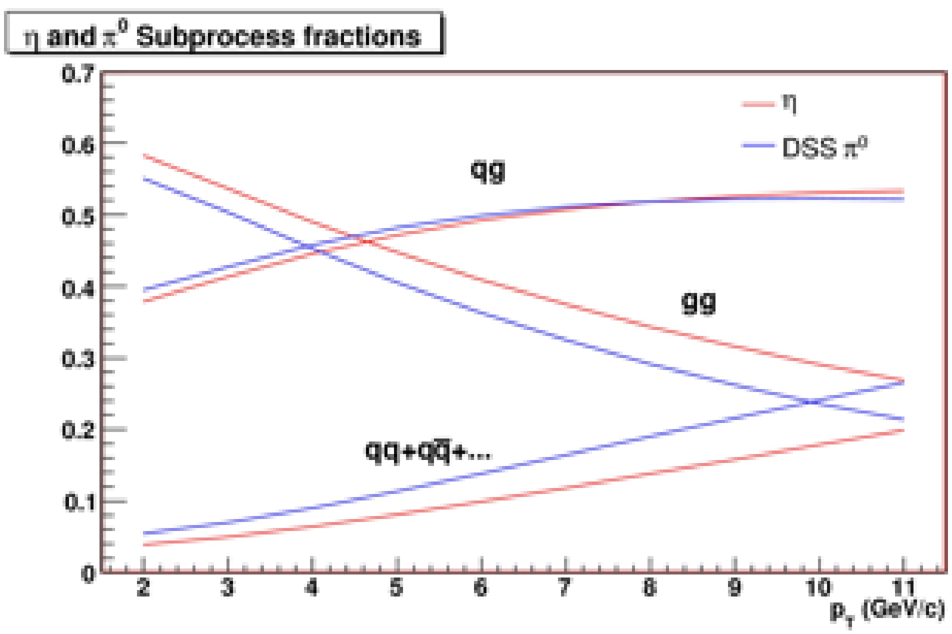


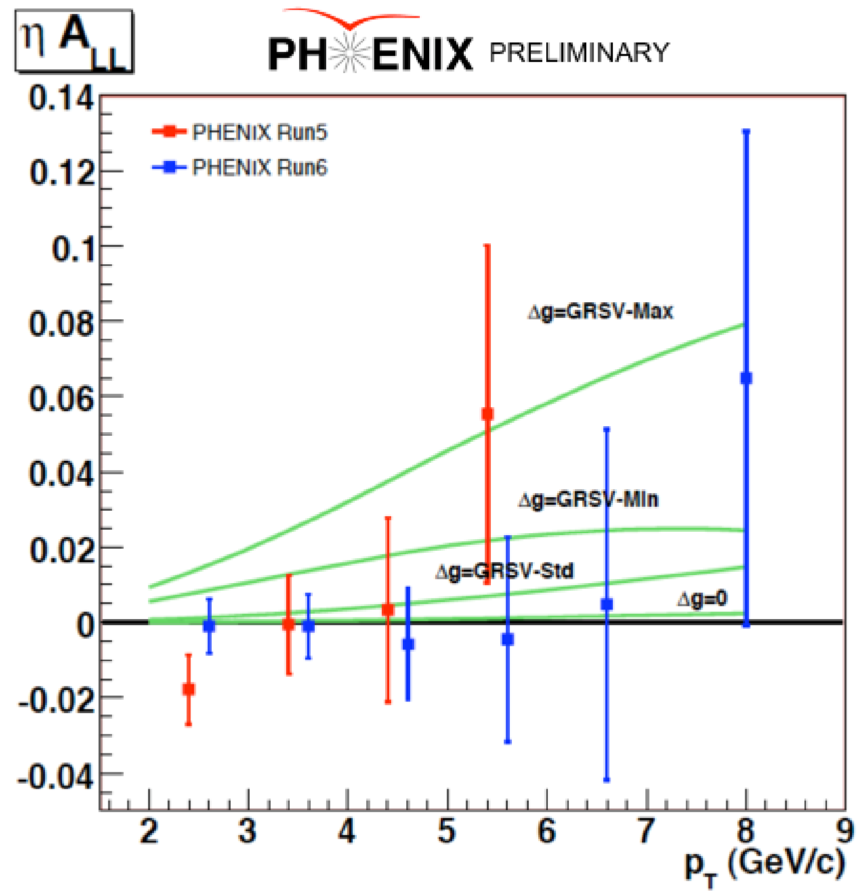
- Run 6 $d\sigma(pp \to \pi^0 X)$ at $\sqrt{s}$=62.4 GeV
- PHENIX PRD **79**, 012003 (2009)
- Cross section best described by NLL calculation

- Run 6 $A_{LL}(pp \to \pi^0 X)$ at $\sqrt{s}$=62.4 GeV
- PHENIX PRD **79**, 012003 (2009)
- Lower $\sqrt{s}$ accesses $\Delta g(x)$ at higher x
- Demonstrated need for NLL interpretation
- Not bad for 1 week of data!

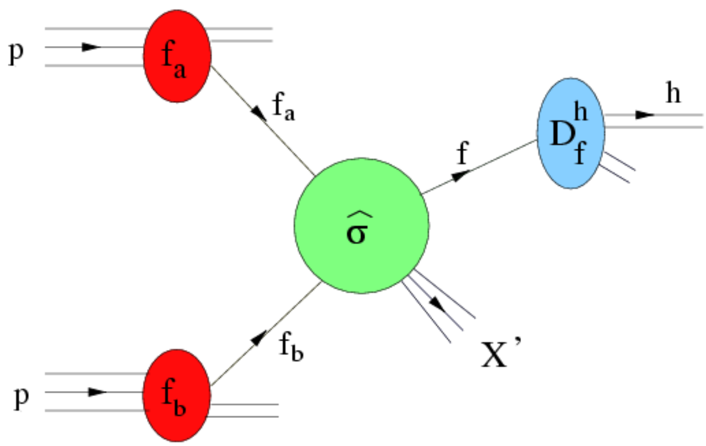
PHENIX measurements of $A_{LL}(\vec{p}\vec{p} \to \eta X)$ at $\sqrt{s}$=200 GeV

- PHENIX has measured $A_{LL}(\vec{p}\vec{p} \to \eta X)$ at $\sqrt{s}$=200 GeV
- $\eta = \left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)/\sqrt{6}$ different flavor content than π^0
- Detect $\eta \to 2\gamma$, similar to π^0 analysis
- Branching fraction 39.3%, but easier to identify at high p_T than π^0
- Sensitive to Δg, independent and complementary to $A_{LL}(\vec{p}\vec{p} \to \pi^0 X)$





- Measured double spin asymmetry $A_{LL}^{pp\rightarrow h^{\pm}X}$ at $\sqrt{s}$=62.4 and $A_{LL}^{pp\rightarrow \pi^{\pm}X}$ at $\sqrt{s}$=200 GeV
- Hadrons with $p_T \gtrsim$ few GeV/c produced dominantly by quark-gluon scattering
- Asymmetry measurement important because of leading order sensitivity to Δg



- $A_{LL}^{\pi} \propto \Delta g \otimes \sum_{q,\bar{q}} (\Delta q \otimes D_q^{\pi})$, where $\Delta u \approx 0.8$, $\Delta d \approx -0.40$
- $A_{LL}^{\pi+} \propto \Delta g \otimes \left(\Delta u \otimes D_u^{\pi+} + \Delta\bar{d} \otimes D_{\bar{d}}^{\pi+} \gg 0 \right)$
- $A_{LL}^{\pi-} \propto \Delta g \otimes \left(\Delta\bar{u} \otimes D_{\bar{u}}^{\pi-} + \Delta d \otimes D_{d}^{\pi-} \lesssim 0 \right)$

$\Rightarrow$ If $\Delta g > 0: \; A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$

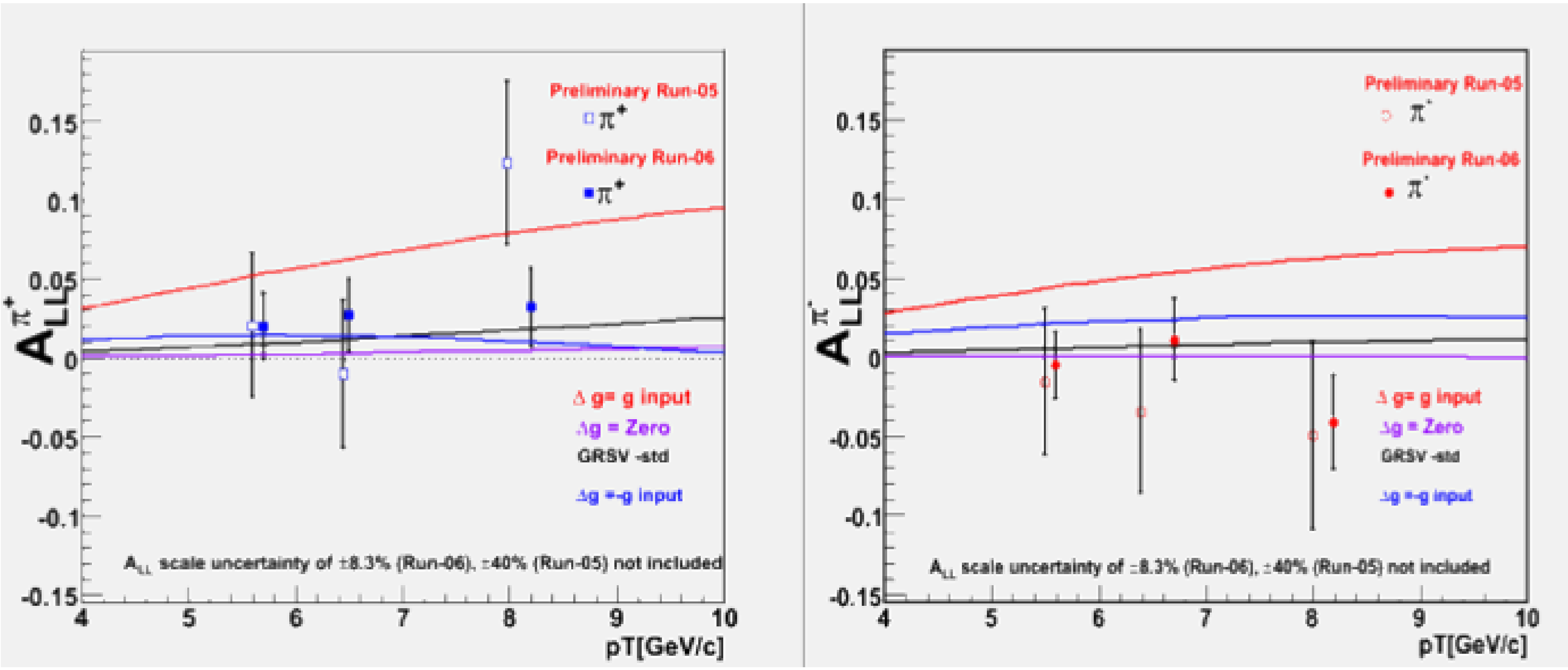
- Sensitive to sign of Δg

$\Rightarrow$ $A_{LL}^{\pi+}$ maximum analyzing power for Δg

- Comparison of $A_{LL}^{\pi^0}$ versus $A_{LL}^{h^{\pm}}$ may be sensitive to sign of Δg
- Probing Δg with different channels adds robustness to extraction of Δg

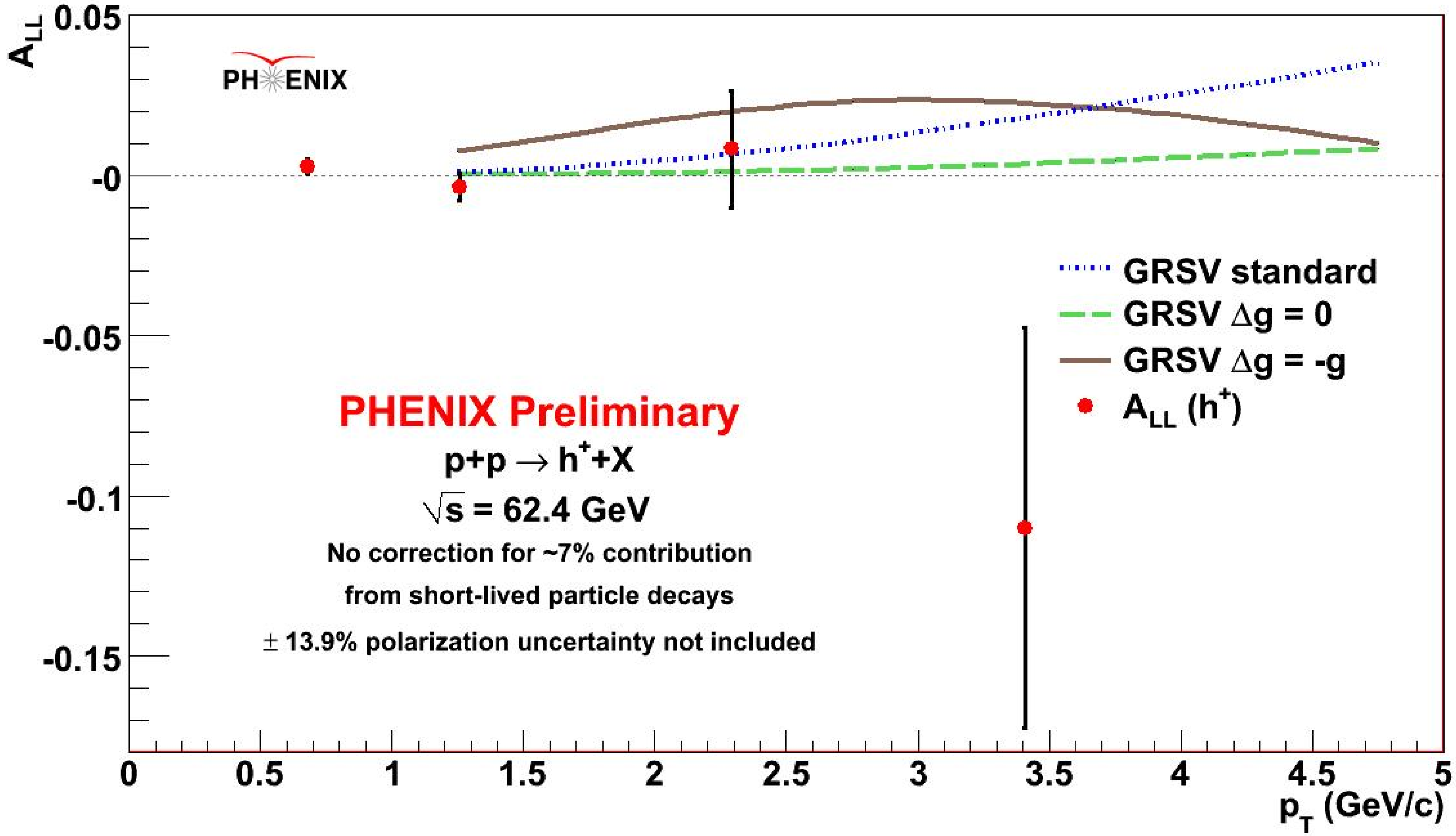
Experimental Results : A_{LL} of Charged Pions

- A_{LL} of charged pions with p_T from 5-12 GeV from pp collisions at $\sqrt{s}$=200 GeV
- Trigger on hadronic shower in EMCal, look for associated track and hit in RICH



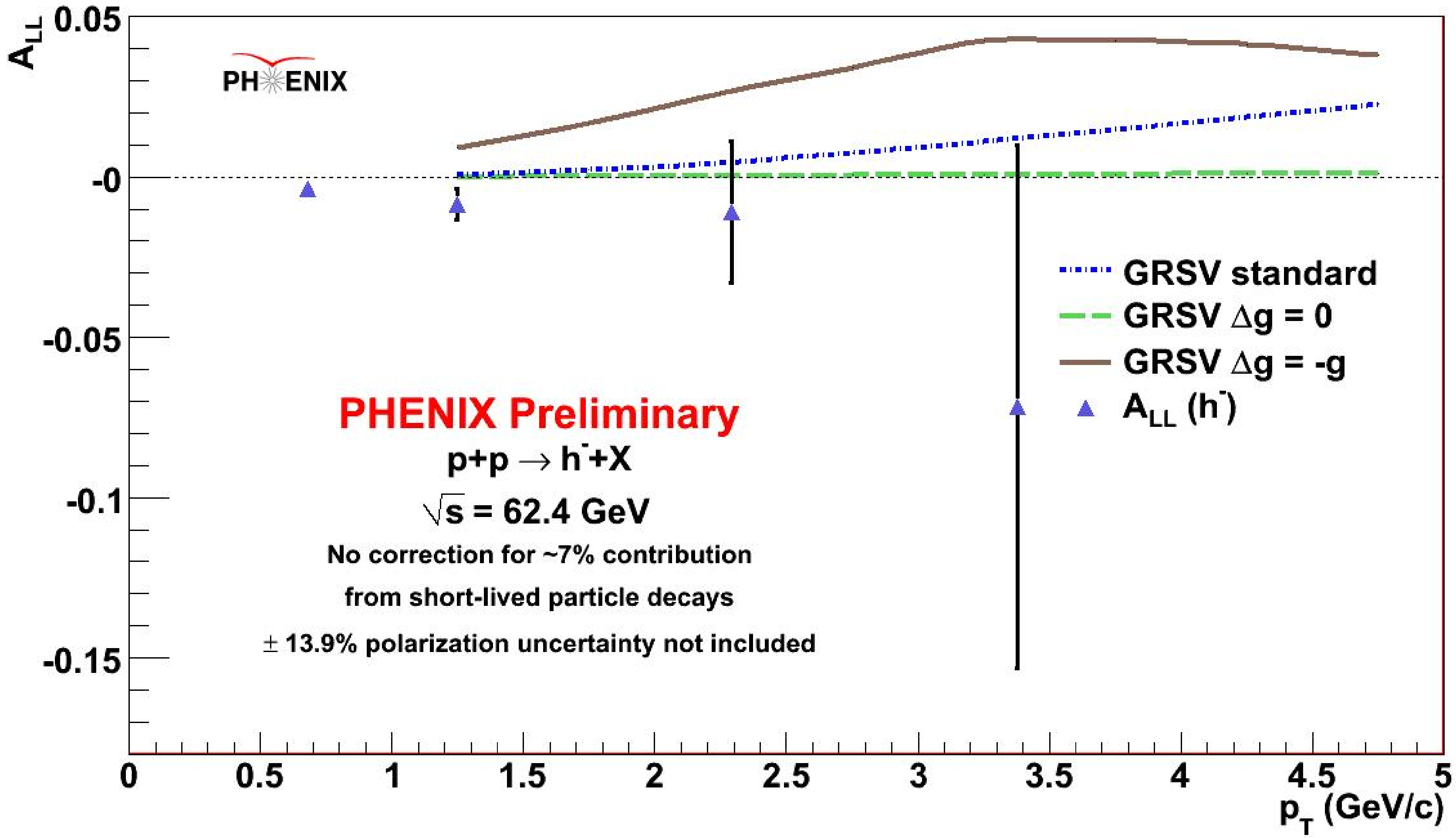
- Run 9 results will reduce statistical uncertainty, can look for ordering of asymmetry, sign of Δg

Results for A_{LL}^{h+} at $\sqrt{s}$=62.4 GeV and Comparison with GRSV Model Predictions



- GRSV model $\Delta g(x) = g(x)$ (not shown on plot) is > 0.1 at $p_T = 3.75$ GeV/c
- $\Delta g(x) = g(x)$ clearly excluded by the data, which favor smaller $\Delta g(x)$
- Not bad for $\approx$ 1 week of data!

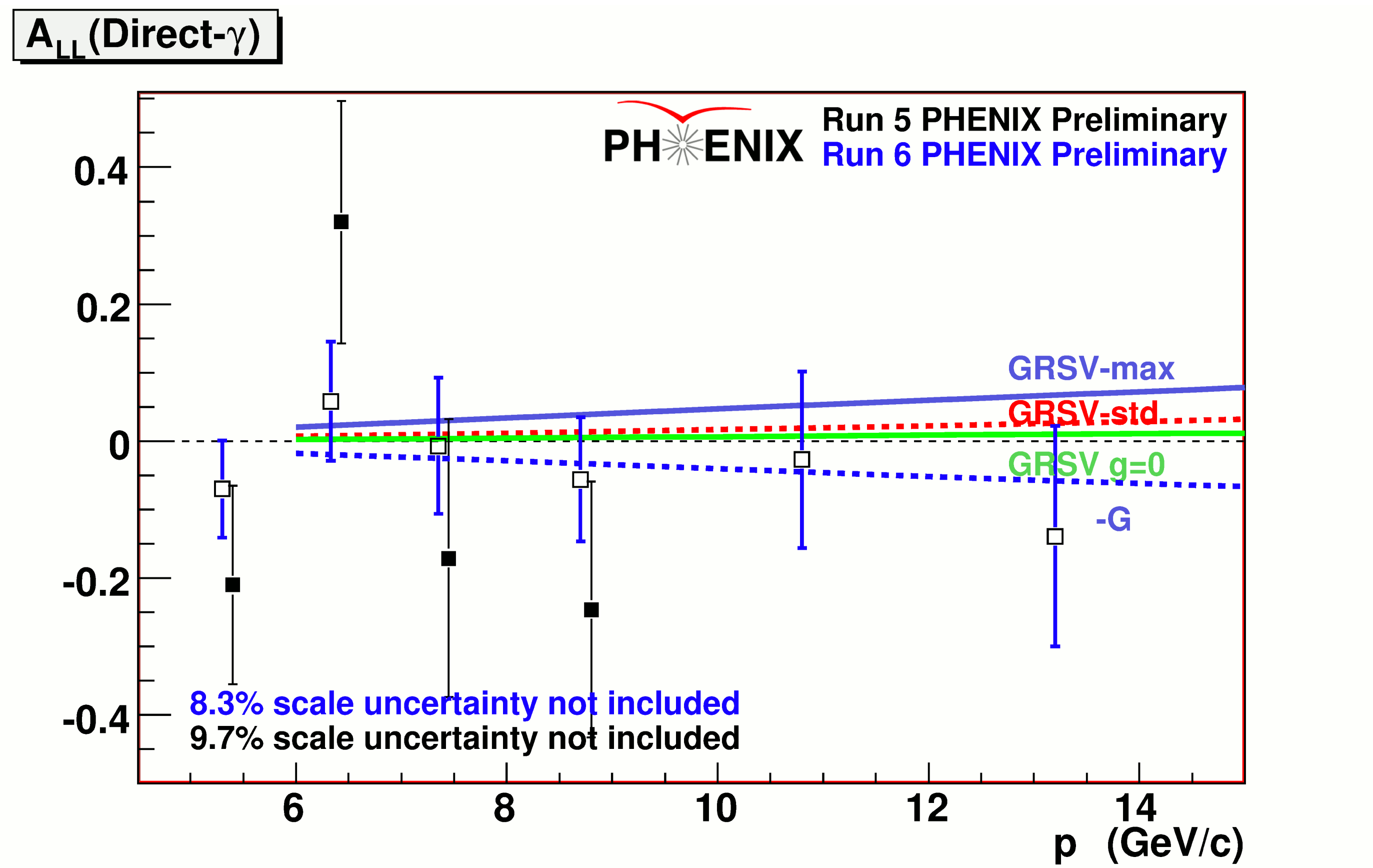
Results for A_{LL}^{h-} at $\sqrt{s}$=62.4 GeV and Comparison with GRSV Model Predictions

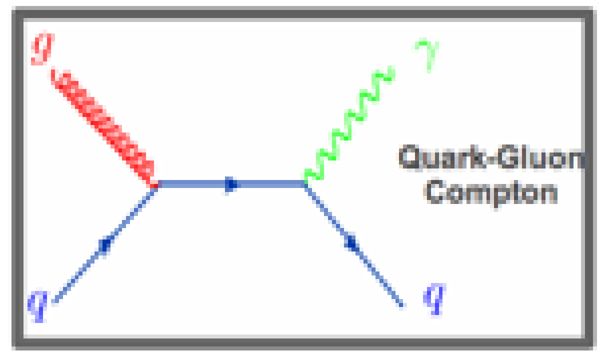


- Asymmetries predicted for A_{LL}^{h-} smaller than those for A_{LL}^{h+}
- Measured A_{LL}^{h-} small, consistent with zero, no ordering of asymmetries apparent
- GRSV model $\Delta g(x) = g(x)$ (not shown on plot) clearly excluded by the data

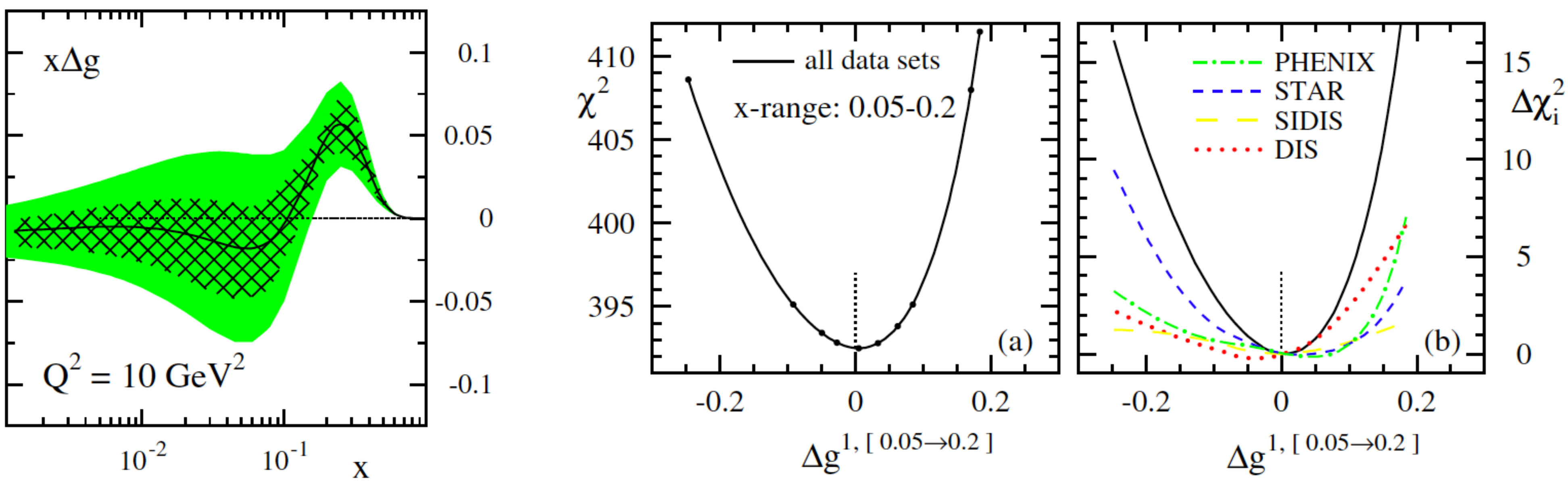
PHENIX measurement of A_{LL}(Direct-γ)

- Direct-γ production 75% dominated by $q + g \to q + \gamma$ (gluon-Compton process)
- Theoretically clean extraction of Δg from asymmetry data, large analyzing power, sensitive to sign of Δg, linear in Δg
- Small cross-section ($\approx$ 1 nb at p_T=5 GeV) $\Rightarrow$ need high luminosity and polarization
- Different experimental techniques than hadronic final states (isolation cut)





- Prior to start of RHIC spin program, $\Delta g = 1 - 2$ at scale of 1 GeV quite typical
  - Restored consistency between measured quark contribution to proton spin and rel. const. quark model predictions
  - Supported by a variety of models; QCD sum rules, QCD counting rules at large x and color coherence at low-x, ..,
- Major impact of program : such large values of Δg seem to be excluded
- Global analysis of D. De Florian, R. Sassot, M. Stratmanm and W. Vogelsang, Phys. Rev. D **80**, 034030 (2009) : integral of Δg from 0.05-0.2, using RHIC data, almost 0.



(From DSSV PRD 80, using $\Delta\chi^2$=1 from Lagrangian multiplier (hatched) and Hessian uncertainty estimates, and DSSV PRL **101**, 072001 (2008).)

Impact of RHIC Spin Program on Δg from DSSV, PRD 80, 034030 (2009)

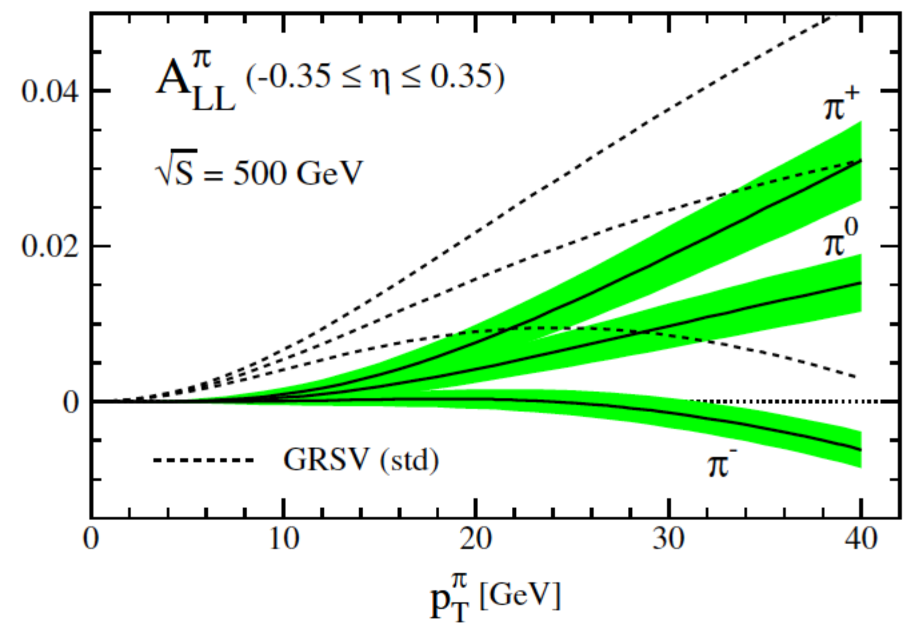
- Truncated integral at $Q^2 = 10\ GeV^2$, $\Delta g^{[0.001,1.0]} = 0.013^{+0.702}_{-0.314}$ $\Delta\chi^2/\chi^2 = 2\%$
- Truncated integral at $Q^2 = 10\ GeV^2$, $\Delta g^{[0.05,0.20]} = 0.005^{+0.129}_{-0.164}$ $\Delta\chi^2/\chi^2 = 2\%$

EXTRACTION OF SPIN-DEPENDENT PARTON DENSITIES ... PHYSICAL REVIEW D **80,** 034030 (2009)

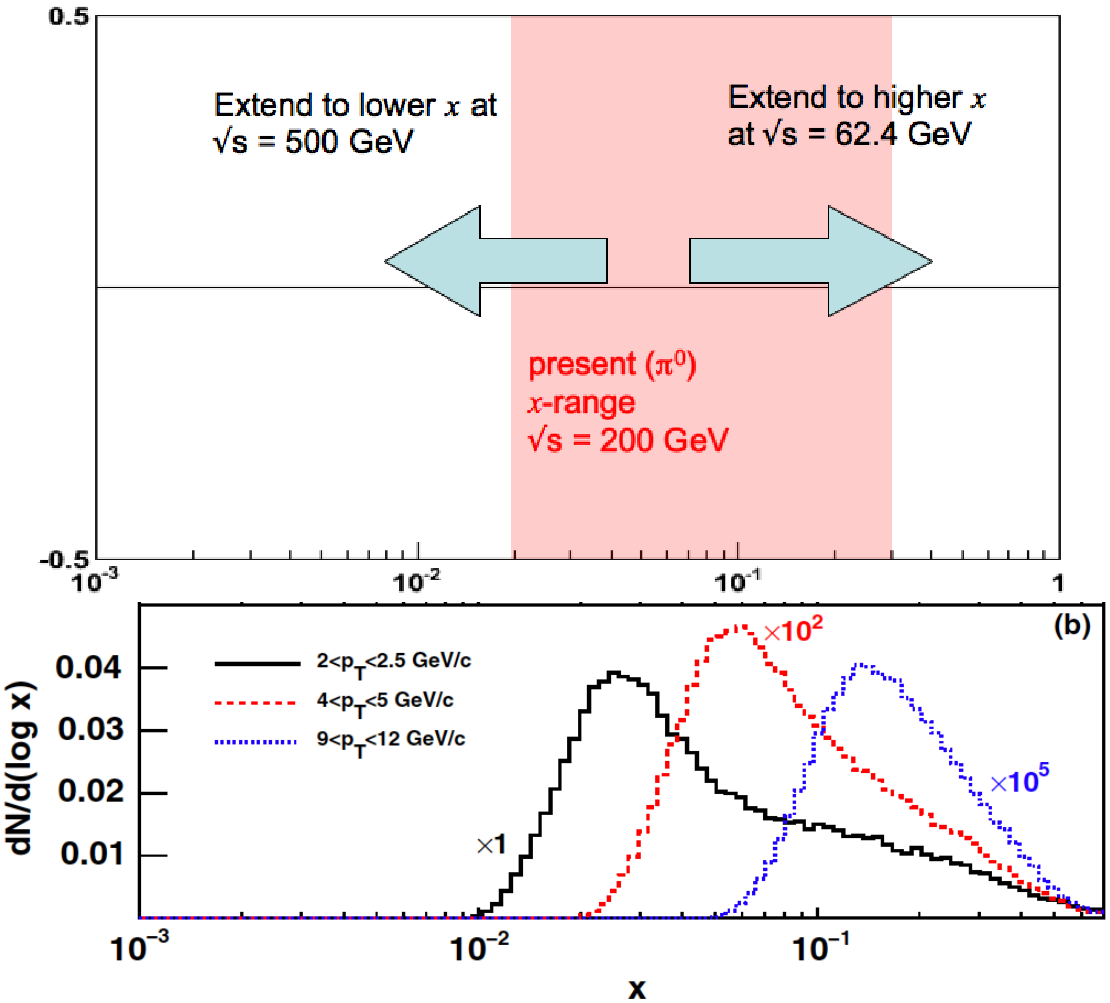
TABLE IV. Truncated first moments, $\Delta f_i^{1,[0.001\to 1]}$, and full ones, Δf_i^1, of our polarized PDFs at various Q^2.

x range in Eq. (35)	Q^2 [GeV^2]	$\Delta u + \Delta\bar{u}$	$\Delta d + \Delta\bar{d}$	$\Delta\bar{u}$	$\Delta\bar{d}$	$\Delta\bar{s}$	Δg	$\Delta\Sigma$
0.001–1.0	1	0.809	−0.417	0.034	−0.089	−0.006	−0.118	0.381
	4	0.798	−0.417	0.030	−0.090	−0.006	−0.035	0.369
	10	0.793	−0.416	0.028	−0.089	−0.006	0.013	0.366
	100	0.785	−0.412	0.026	−0.088	−0.005	0.117	0.363
0.0–1.0	1	0.817	−0.453	0.037	−0.112	−0.055	−0.118	0.255
	4	0.814	−0.456	0.036	−0.114	−0.056	−0.096	0.245
	10	0.813	−0.458	0.036	−0.115	−0.057	−0.084	0.242
	100	0.812	−0.459	0.036	−0.116	−0.058	−0.058	0.238

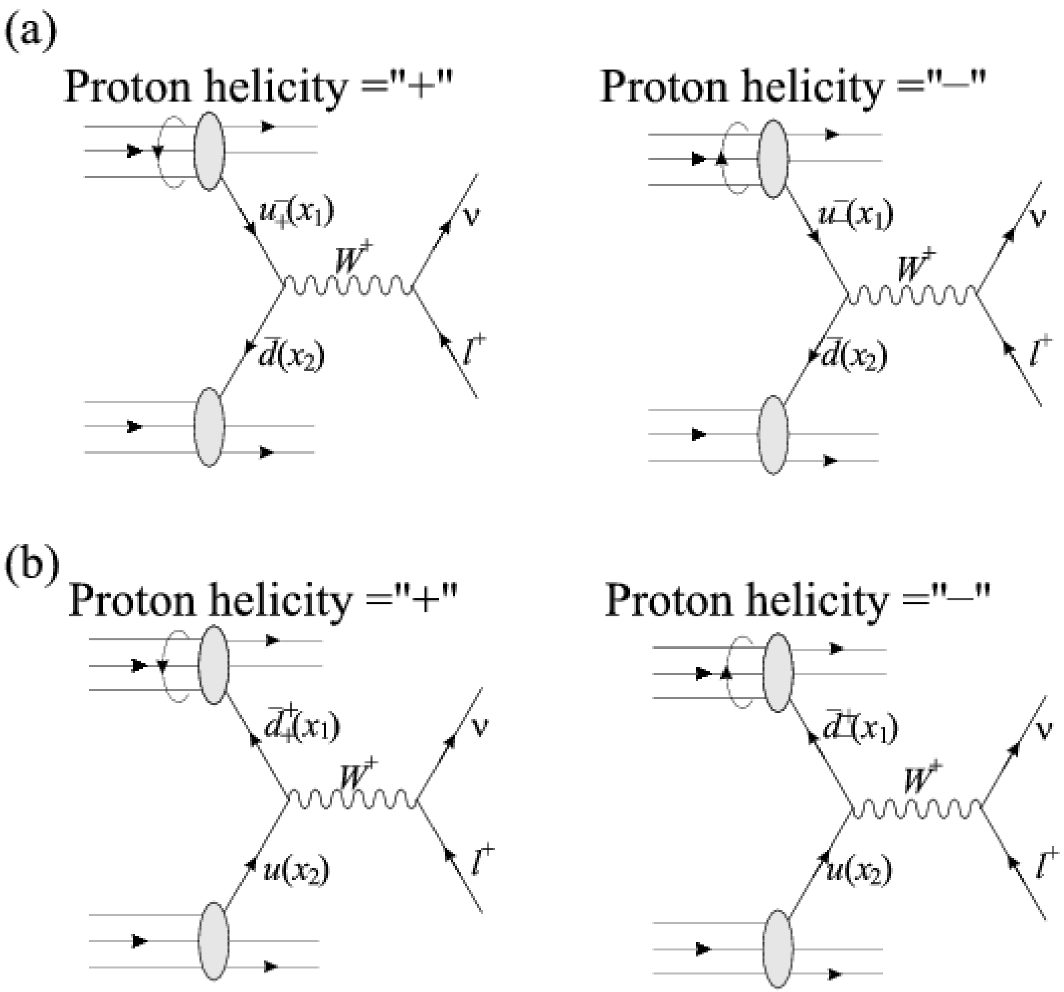
- Significant uncertainties arise in extrapolation to $x \to 0$, and from scale dependence
- Such analyses indicate need to constrain Δg at low x, but asymmetries small and difficult to measure (RL)



- Reduce statistical uncertainties in current x-range : more data, higher beam polarization, more channels ($\pi^{\pm}$, η, ...)
- Change collision energy to extend x range
- Move from inclusive measurements to those with sensitivity to parton kinematics : γ-jet, jet-jet, hadron-jet (particularly with detection in forward region) : $x_{1,2} = p_T\left(e^{\pm\eta_3} + e^{\pm\eta_4}\right)/\sqrt{s}$



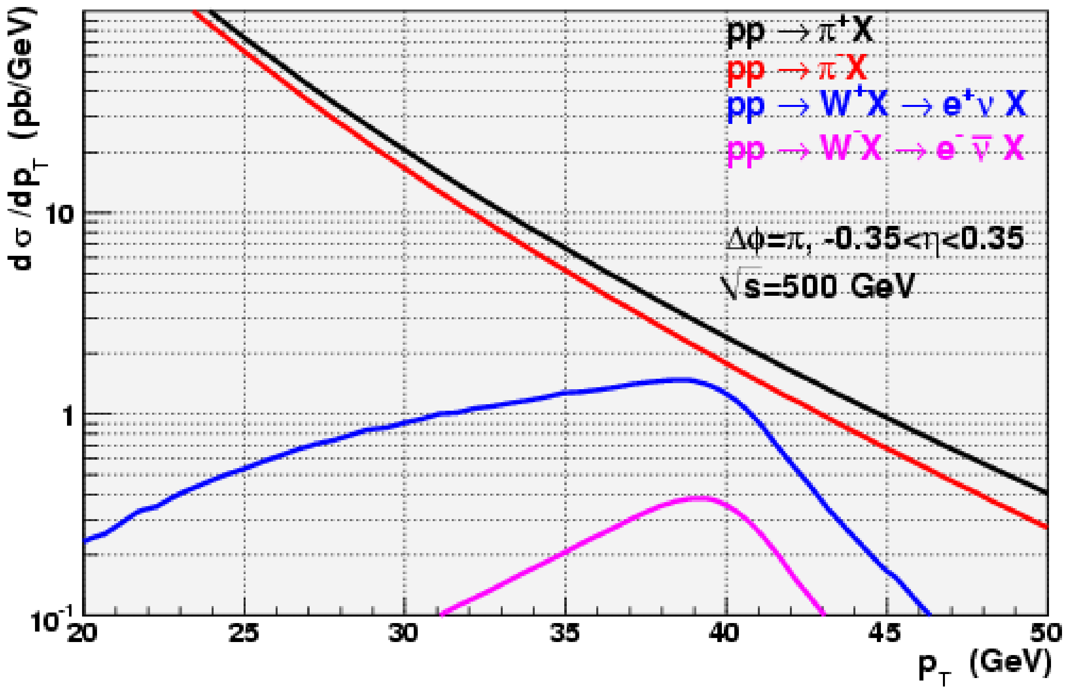
- Key measurements of the spin program : flavor separated $\Delta q(x)$ and $\Delta\bar{q}(x)$
- Semi-inclusive polarized DIS experiments (SMC, HERMES, COMPASS) have made such measurements
- STAR and PHENIX can do it exploiting parity violation in W production in polarized pp collisions - at high scale and independent of uncertainties in fragmentation functions
- Can also measure ratio $\bar{u}(x)/\bar{d}(x)$



(a) u always left-handed : Δu probed in polarized proton

(b) $\bar{d}$ always right-handed : $\Delta\bar{d}$ probed in polarized proton

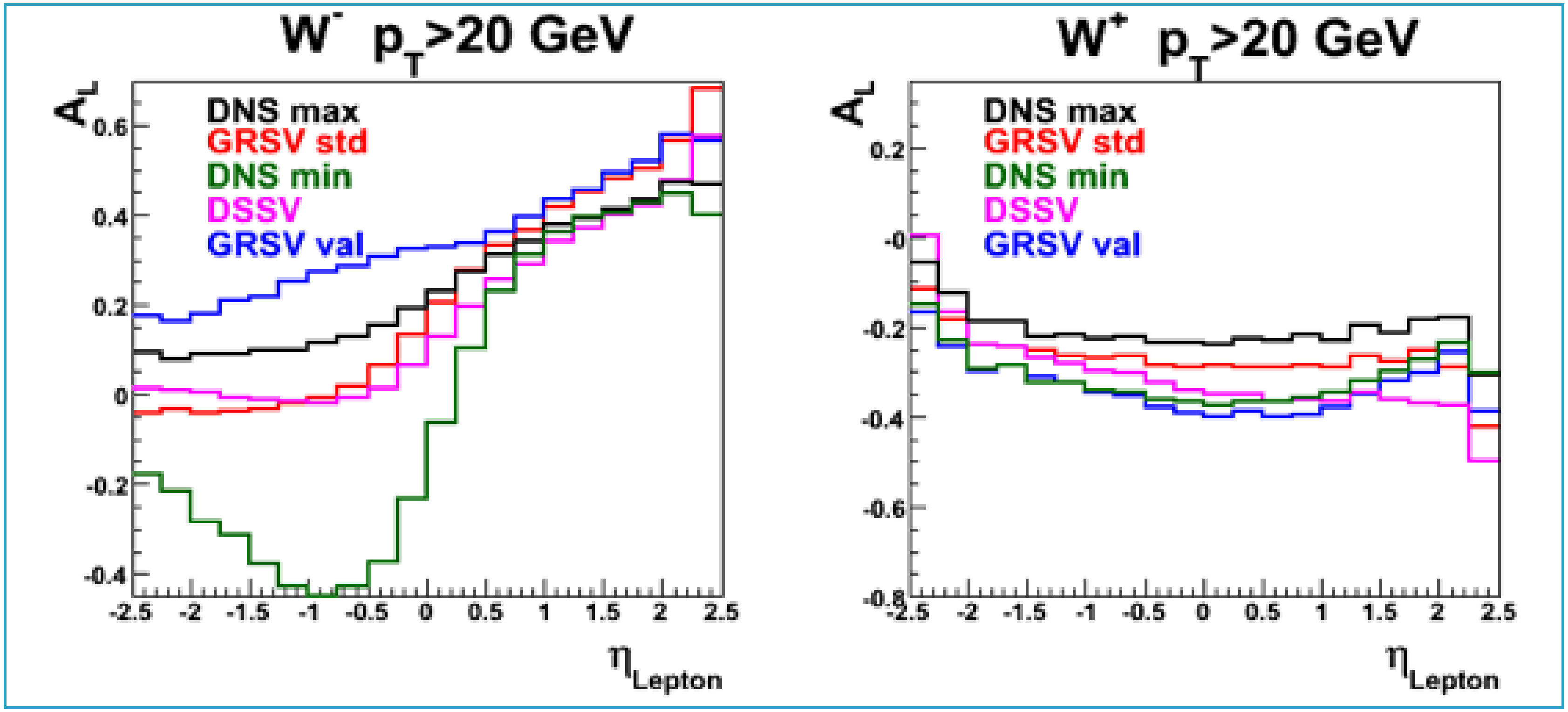
(From Bunce *et al.* Annu. Rev. Nucl. Part. Sci. **50** 525 (2000))



- W predictions from RHICBOS (Nadolsky and Yuan)
- $\pi^{\pm}$ predictions from W. Vogelsang + CTEQ6M
- Recorded 11 pb^{-1} at 35% polarization in Run 9 within PHENIX central arm acceptance
- Expect $\approx$ 200 e^+ with p_T >25 GeV from $pp \rightarrow W^+ \rightarrow e^+\nu_e$
- Expect $\approx$ 35 e^- with p_T >25 GeV from $pp \rightarrow W^- \rightarrow e^-\bar{\nu}_e$

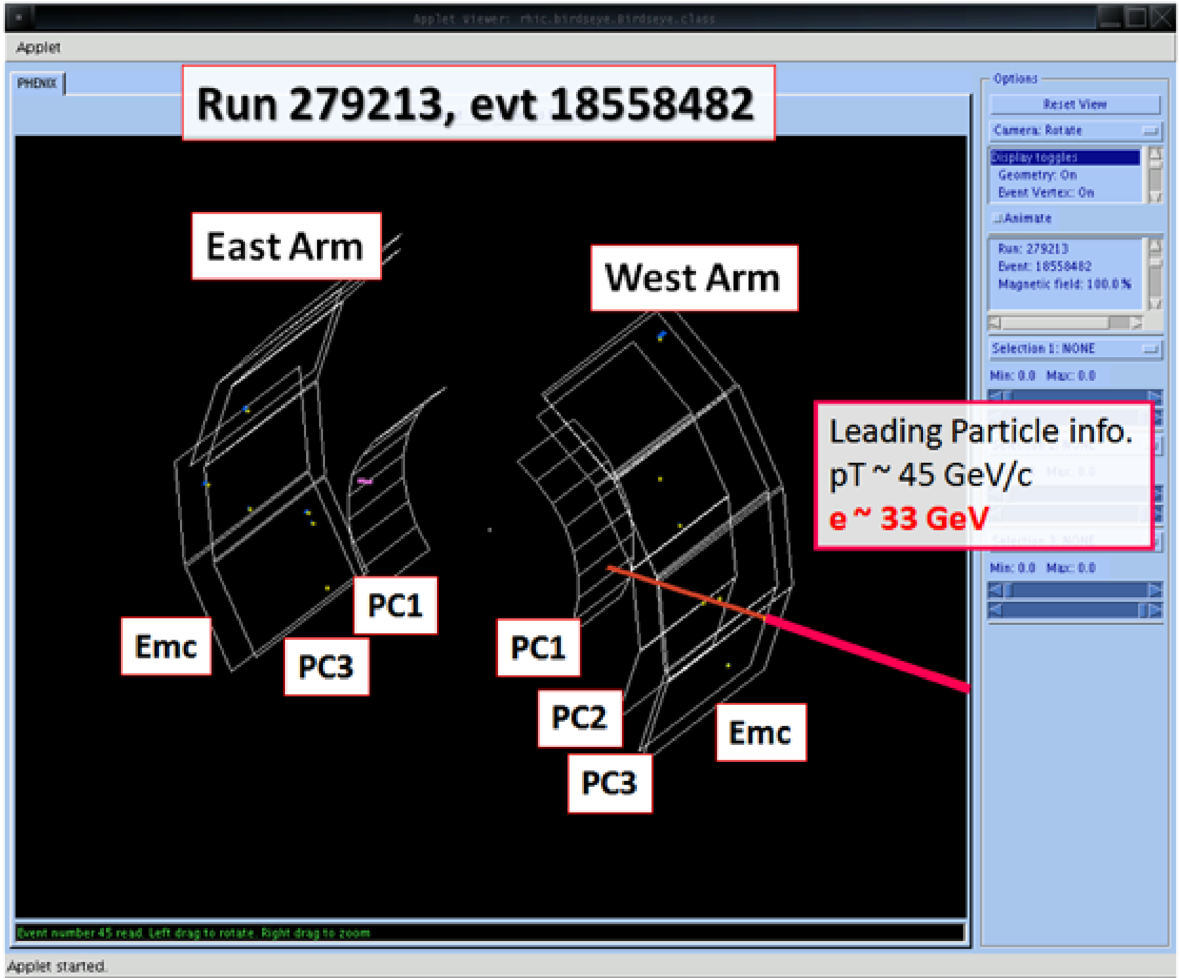
Analysis Approach

- Look for $>$ 25 GeV in EMCal with isolated charged track with high momentum, time of flight cut
- Momentum resolution poor, but good enough to distinguish e^+ from e^- at 2 σ
- Background from charged hadrons with hadronic shower in EMCal significant
- Other backgrounds : π^0 decay where one+ photon converts, charm/bottom decay, cosmics, accidentals
- Z→ e^+e^- roughly 6% background for W^+, 30% for W^-
- After cuts, expect $\delta A_L^{W+} \approx 0.3$



(From RHIC Spin Plan 2008)

- $W^- \; : \; : A_L \;\propto\; \Delta\bar{u}(x_1)d(x_2)(1-\cos\hat{\theta})^2 - \Delta d(x_1)\bar{d}(x_2)(1+\cos\hat{\theta})^2$
- $W^+ \; : \; : A_L \;\propto\; \Delta\bar{d}(x_1)u(x_2)(1+\cos\hat{\theta})^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\hat{\theta})^2$
- For W^+, $-0.35 < \eta_e < 0.35$, measure combination of $\Delta\bar{d}$ and Δu
- For W^-, $-0.35 < \eta_e < 0.35$, measure combination of $\Delta\bar{u}$ and Δd
- After cuts, anticipate $\delta A_L^{W+} \;\approx\; 0.3$. Eventually, should reach few percent
- Future measurements of $W^- \rightarrow \mu^-\bar{\nu}_\mu$ at $1.2 < |\eta_\mu| < 2.4$ separate contributions more cleanly : $\Delta\bar{u}(x_1)/u(x_1)$ at $\eta_\mu << 0$, and $-\Delta d(x_1)/d(x_1)$ at $\eta_\mu >> 0$



- W candidate event in PHENIX, after many years !
- Many more such events (of order 100), analysis underway
- Clear evidence for W signal above background
- After cuts, anticipate $\delta A_L^{W+} \approx 0.3$. Eventually, should reach few percent

Summary

- PHENIX and STAR now place tightest constraints on $\Delta g(x)$
- $\Delta g(x)$ small compared to expectations from pol. DIS in measured region ($0.05 < x < 0.2$)
- Evidence for Ws seen in PHENIX central arms, analysis underway for cross-section estimate, asymmetry
- Future upgrades (barrel and forward silicon vertex detectors, RPCs+muon trigger upgrade, calorimetry in forward region) will add greater acceptance, new physics channels
- In addition to $\sqrt{s} = 500$ GeV running in 2009, recorded ≈ 16 pb^{-1} at 55% polarization at $\sqrt{s} = 200$ GeV : best run so far