Current Status and Results of the PHENIX Spin Program at RHIC

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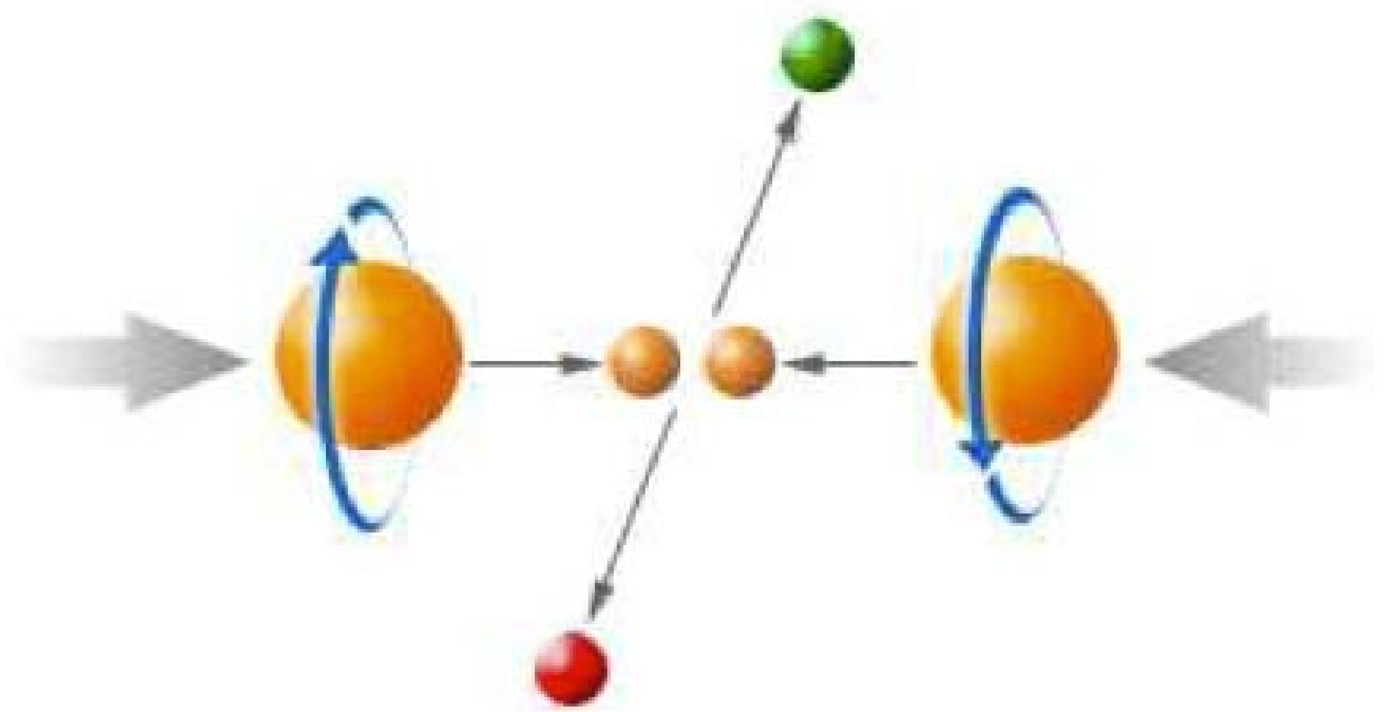
on behalf of the PHENIX Collaboration



Outline

- Motivation for Spin Physics at RHIC
- Introduction to RHIC Polarized Proton Accelerator
    - Polarized Source
    - pC Polarimeters
    - Hydrogen Gas Jet Target
- Introduction to PHENIX
    - PHENIX detectors
    - Local Polarimetry
    - Run History
- Physics Longitudinal Spin Analyses and Results
    - Neutral Pion A_{LL}, Direct Photons, Charged Pions, eta
- Determining the gluon contribution to spin of the proton
- Brief look at W physics potential at PHENIX
- Summary and Future Outlook

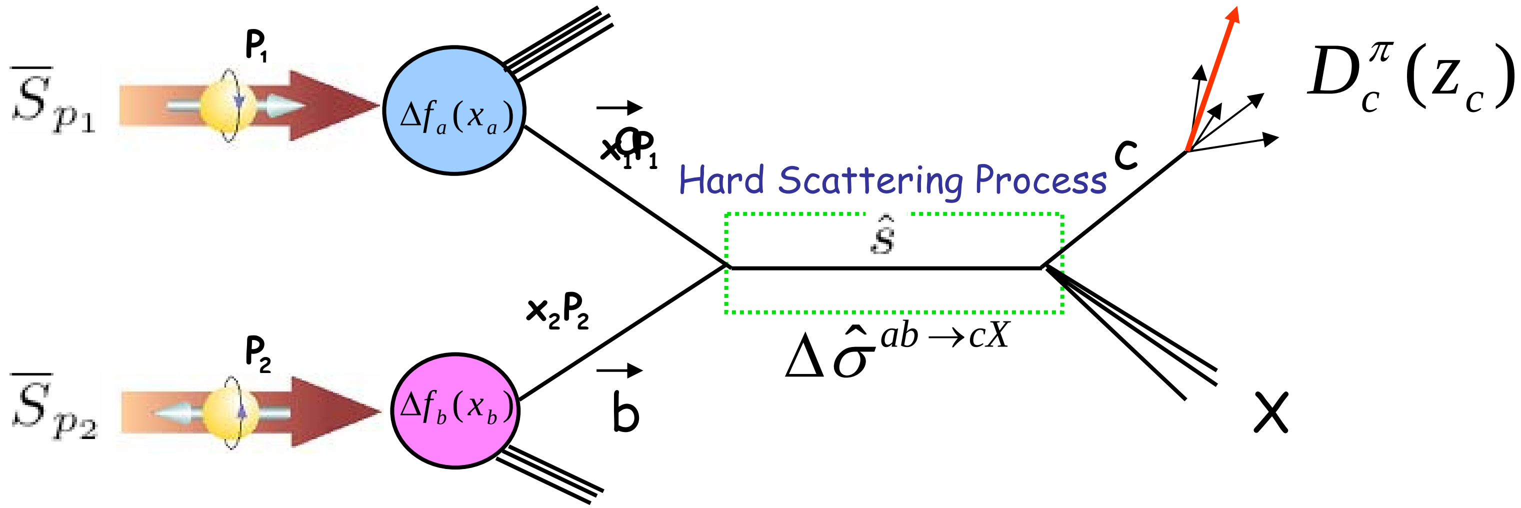
- Proton spin sum rule $\frac{1}{2} = \frac{1}{2}\Sigma\,(\Delta q + \Delta\bar{q}) + \Delta G + L_z$
  (recall $\Delta q(x) = q^{+}(x) - q^{-}(x)$, where x=momentum fraction carried by quark
- Polarized DIS experiments EMC, SMC, SLAC (E80,E130,E142-E155x), HERMES, COMPASS, JLab, suggest $\Sigma(\Delta q + \Delta\bar{q}) \approx 0.25$
- Gluon contribution $\Delta g(x)$ may be large, still largely unconstrained
- Δg accessible in pDIS from NLO pQCD analysis of scaling violations, from high p_T hadron pair production in photon-gluon fusion, open charm production

RHIC Spin Program will make 3 major contributions :

- Photons don't couple to gluons, but polarized hadron collisions can involve $\Delta g(x)$ at leading order, a new, direct approach to measuring $\Delta g(x)$
- RHIC Spin can run with transverse polarization : investigate transversity/ orbital angular momentum/quark-gluon correlations in the proton
- Parity violation in W production allows flavor separated measurements $\Delta u(x)$, $\Delta\bar{u}(x)$, $\Delta d(x)$, $\Delta\bar{d}(x)$ without detailed knowledge of fragmentation functions

RHIC Spin : Colliding beams of polarized partons

- Collide beams of polarized protons, 60+% polarization, $\sqrt{s}$ =62.4, 200, 500 GeV
- At high p_T, sqrt(s), can factorize as beams of polarized partons a,b



- Helicity conservation in cross-section $\Delta\sigma$(ab->cX) can imply large analyzing power for some processes
- Have sensitivity to polarized parton distributions, including gluon directly
- Different processes -> different combinations of a,b,cross-section
  --> can cross-check our results and interpretation

$$A_{LL} \approx \frac{\Delta a}{a} \otimes \frac{\Delta b}{b} \otimes \Delta\hat{\sigma}(\vec{a}+\vec{b} \to c + X)$$

- Collide two beams of protons, with helicities ++ and +- (or – and -+, or ...)
- Look in your detector to see if a particular particle is produced, say a π^0
- Number of π^0, N, detected depends on several factors :
  - The physics cross section of interest $E\frac{d^3\sigma^{\vec{p}\vec{p}\to\pi^0 X}}{dp^3}$
  - The intensity of the colliding beams (Luminosity $\mathcal{L}$) : $N = \sigma L$
  - The polarization of the beams
  - The angular coverage of the detector in θ and ϕ
  - The efficiency of your "trigger", detectors, data acquisition system, offline reconstruction efficiency,...

$$E\frac{d^3\sigma^{\vec{p}\vec{p}\to\pi^0 X}}{dp^3} = \frac{N}{L}\frac{1}{2\pi p_T}\frac{1}{\Delta p_T \Delta y}\frac{1}{\eta_{\rm trigger}}\frac{1}{\eta_{\rm reconstruction}}$$

- y called rapidity $y \approx -\log(\tan\theta/2)$
- Particles produced at 90° are at 0 rapidity, very forward or backwards have high rapidity
- Rapidity difference are relativistic invariants, and $x_{a,b} = \frac{2p_T}{\sqrt{s}}\exp(\pm y)$

$\Rightarrow$ If production angles of produced particles known, can infer original x, otherwise have to integrate over x

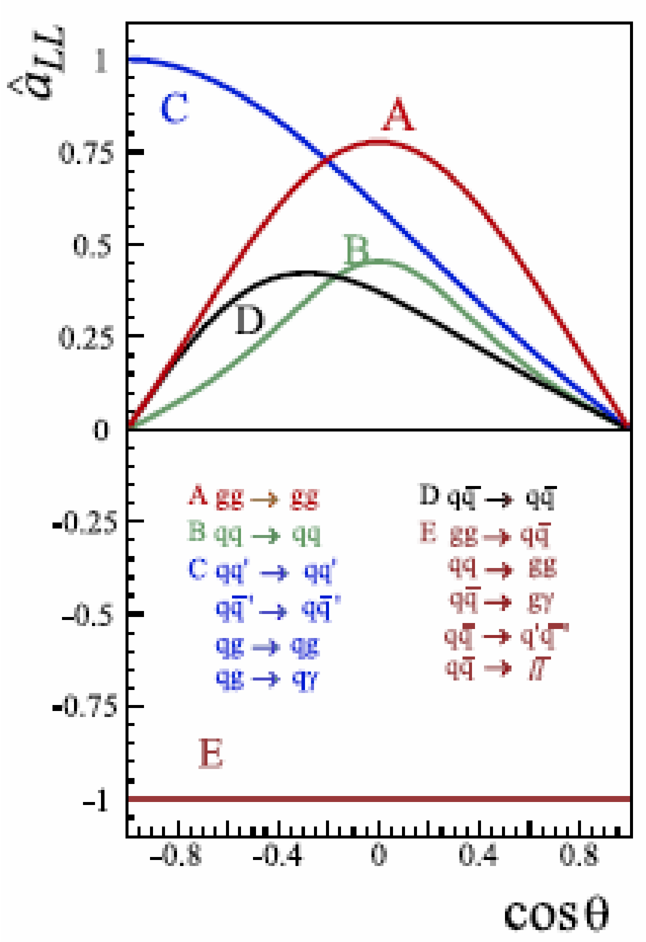
- Can form asymmetry A_{LL} in which detector attributes largely cancel

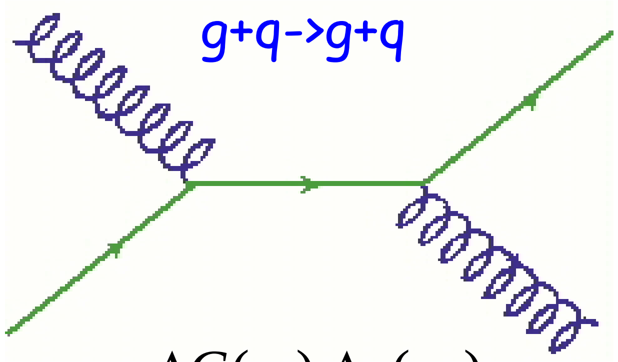
$$A_{LL} \equiv \frac{\frac{d\sigma^{++}}{dp_T} - \frac{d\sigma^{+-}}{dp_T}}{\frac{d\sigma^{++}}{dp_T} + \frac{d\sigma^{+-}}{dp_T}} = \frac{1}{P_1 P_2} \frac{N_{\pi^0}^{++}/L_{++} - N_{\pi^0}^{+-}/L_{+-}}{N_{\pi^0}^{++}/L_{++} + N_{\pi^0}^{+-}/L_{+-}}$$

- Need to measure polarizations $P_{1,2}$ of the beams
- Need to measure relative luminosity L_{++}/L_{+-}
- Need to measure particle yields, N, watch for spin-dependent asymmetries in triggers, etc.
- Repeat for other final state particles
- Combine all results in a "Global" analysis to extract Δg

- Probe gluons directly through gg, gq scattering
- High $\sqrt{s}$, high p_T permits clean pQCD interpretation
- Variety of final states : robust cross-checks on extraction of $\Delta g(x)$, probe different momentum fraction x_{gluon}
- Ability to run collider at different beam energies : access to different range of x_{gluon}

RHIC Spin : Colliding beams of polarized partons





$$A_{LL} = \frac{\Delta G(x_1)}{G(x_1)} \frac{\Delta q(x_2)}{q(x_2)} \hat{a}_{LL}$$

$$\approx \frac{\Delta G(x_1)}{G(x_1)} A_1^P(x_2) \hat{a}_{LL}$$

$$\approx \frac{\Delta G(x_1)}{G(x_1)} \times 0.3 \times 0.6$$

$$A_{LL} = \frac{1}{P^2} \frac{N_{++} - N_{+-}R}{N_{++} + N_{+-}R} \qquad R = \frac{L_{++}}{L_{+-}}$$

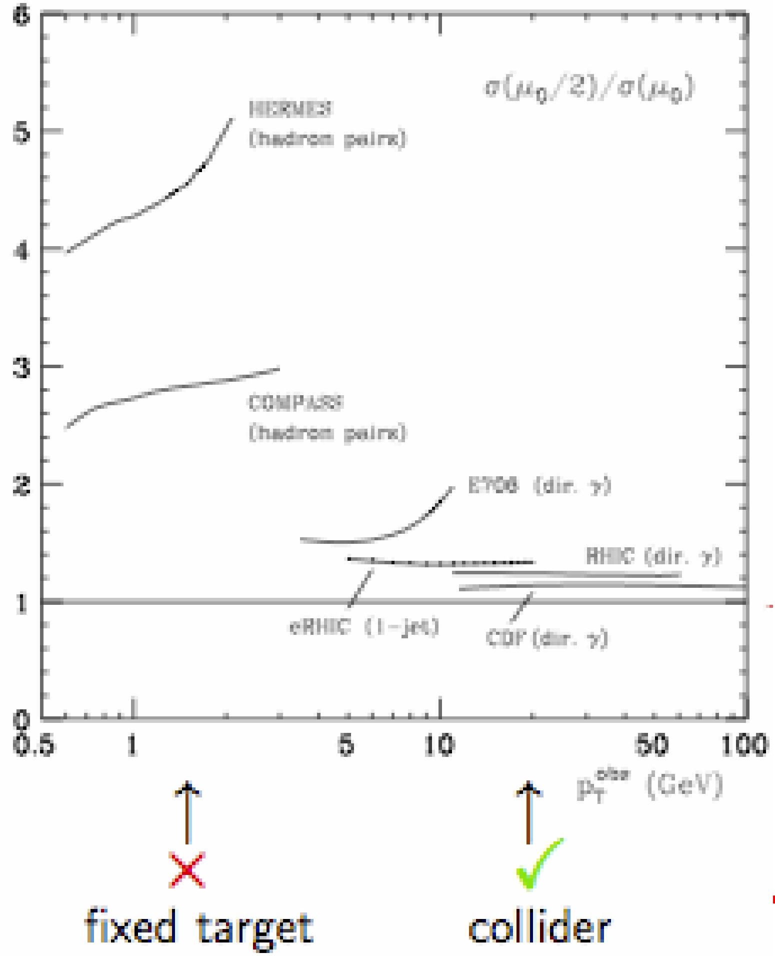
- Need to measure helicity dependent yields, N, Polarization, P, Relative Luminosity, R
- Expect asymmetries at small scattering angles to be tiny (small analyzing power)

RHIC Spin : Colliding beams of polarized partons

$$\frac{d\Delta\sigma^{\vec{p}\vec{p}\to\pi X}}{dp_T d\eta} = \sum_{abc}\int dx_a\, dx_b\, dz_c\, \Delta f_a(x_a,\mu_f)\,\Delta f_b(x_b,\mu_f)\, D_c^{\pi}(z_c,\mu_f')$$
$$\times \frac{d\Delta\hat{\sigma}^{ab\to cX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^{\pi}/z_c, \mu_f, \mu_f', \mu_r) + \mathcal{O}(\frac{\lambda}{p_T})^n$$

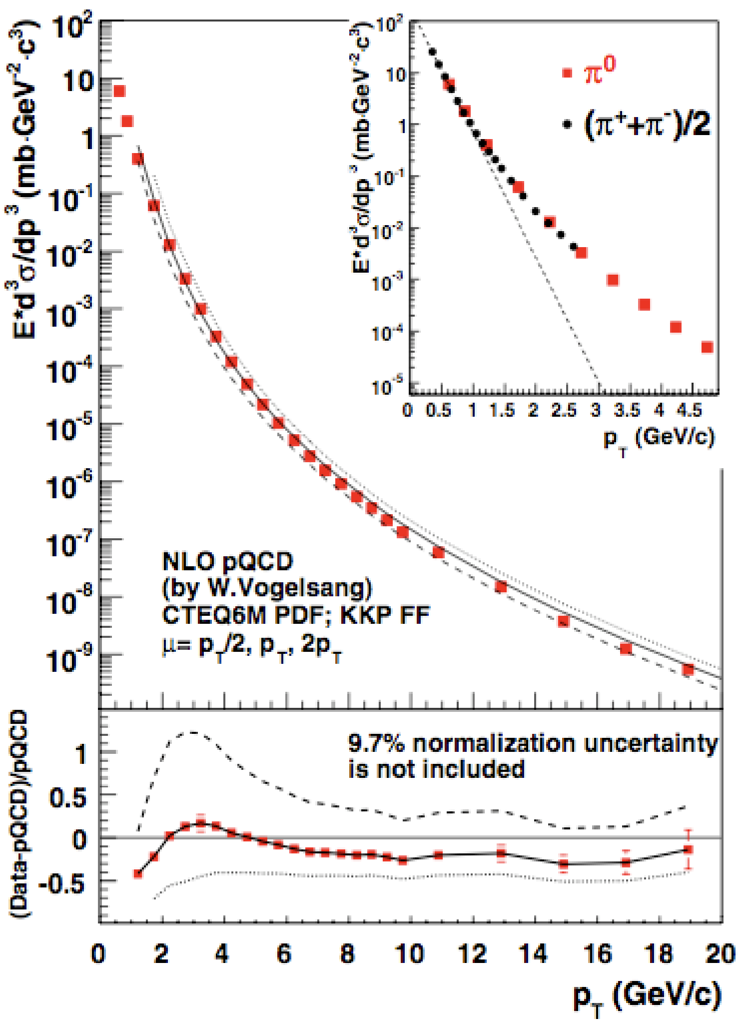
- Interpretation of results relies on pQCD
- high p_T and sqrt(s) help to reduce dependence on unphysical scales μ

 (M. Stratmann, W. Vogelsang)
- Important to show that this framework is reliable : to do that, see if pQCD can correctly predict cross-sections observed at RHIC sqrt(s), p_T

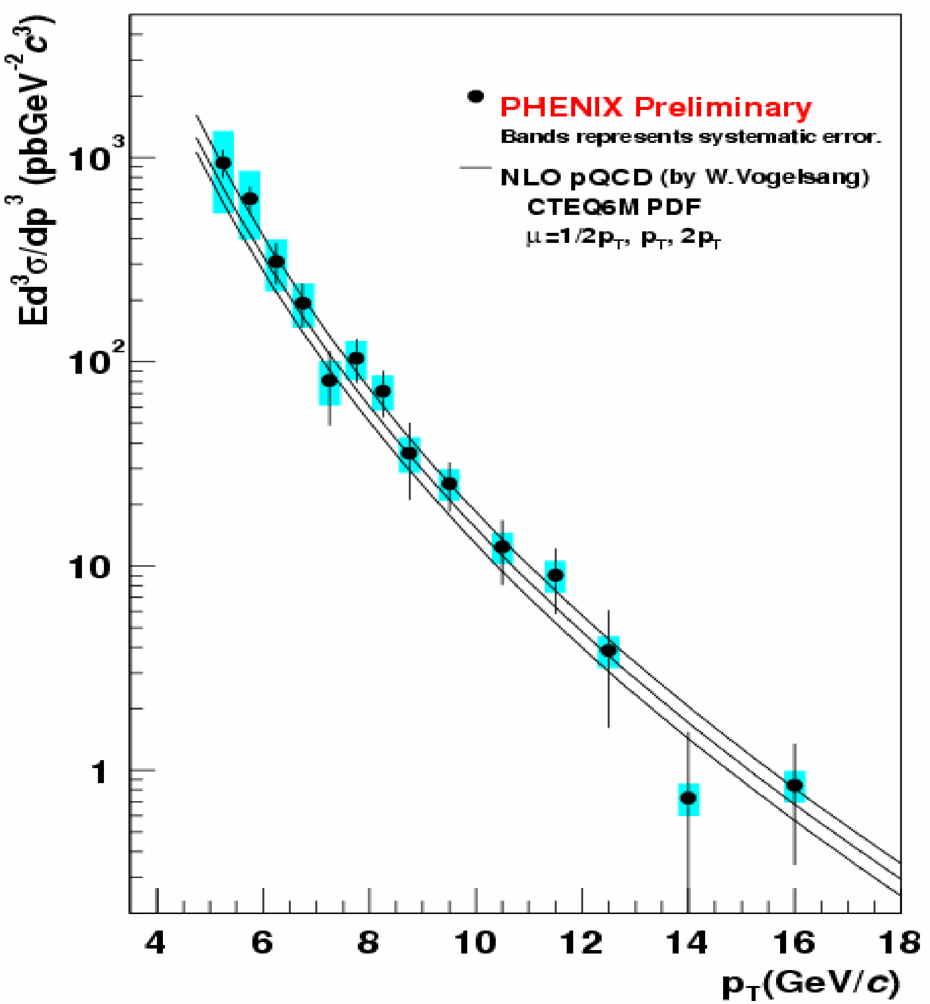


PHENIX (and STAR) data well described by pQCD

- π^0 cross-section at mid-rapidity well described by NLO pQCD
A.Adare et al, Phys.Rev.D76,051106(2007)

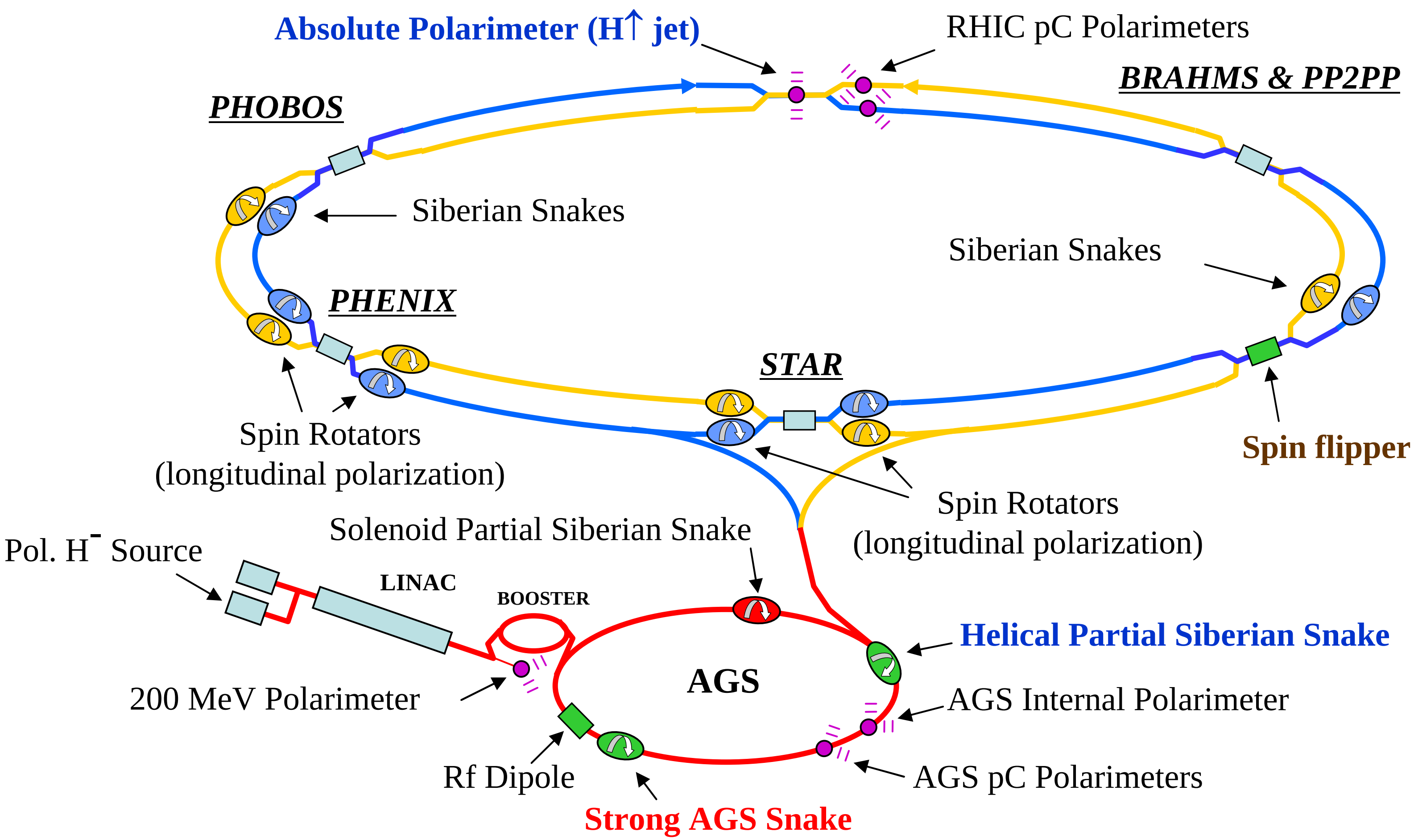


- γ cross-section at mid-rapidity well described by NLO pQCD

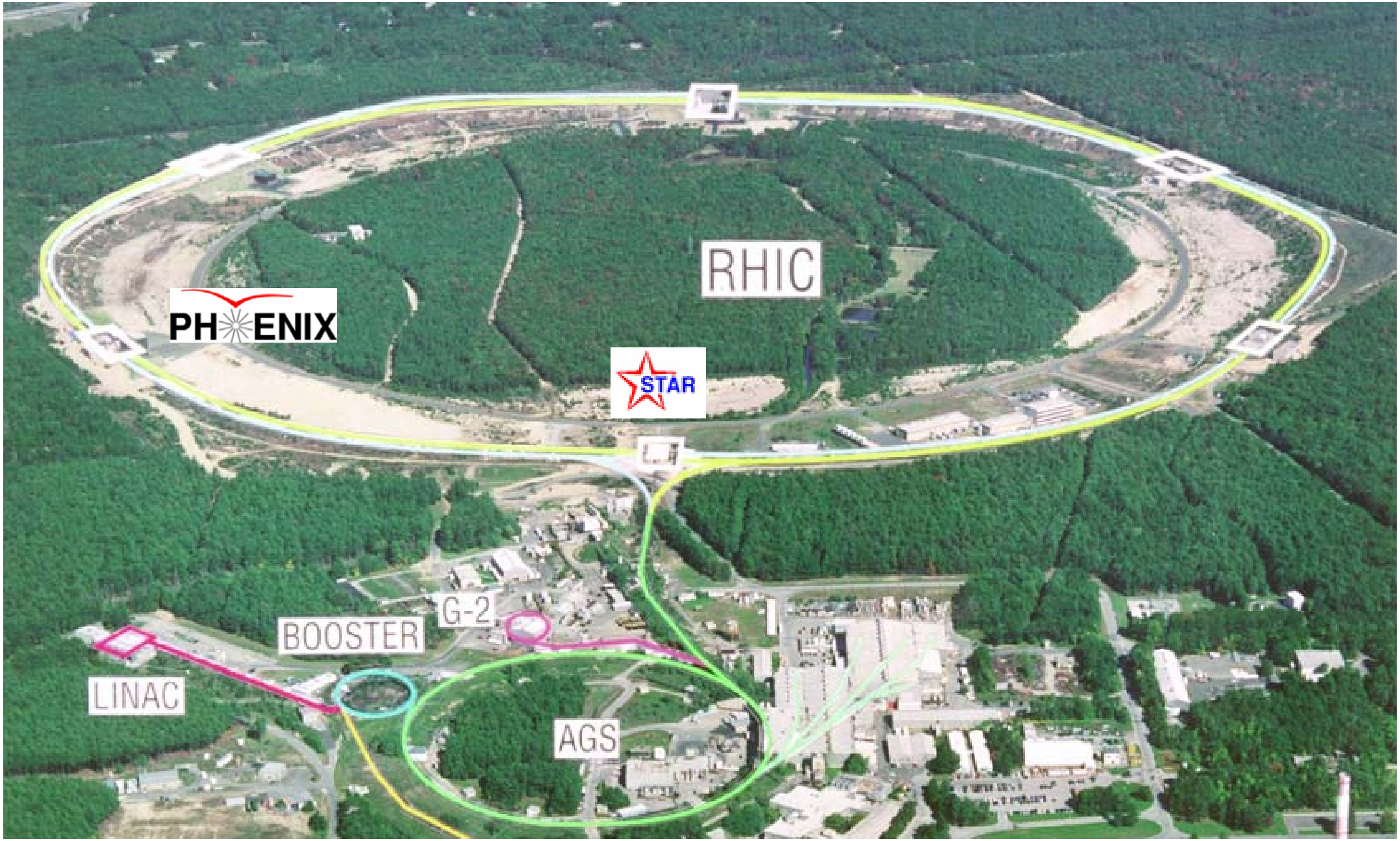


RHIC : The world's only polarized proton collider

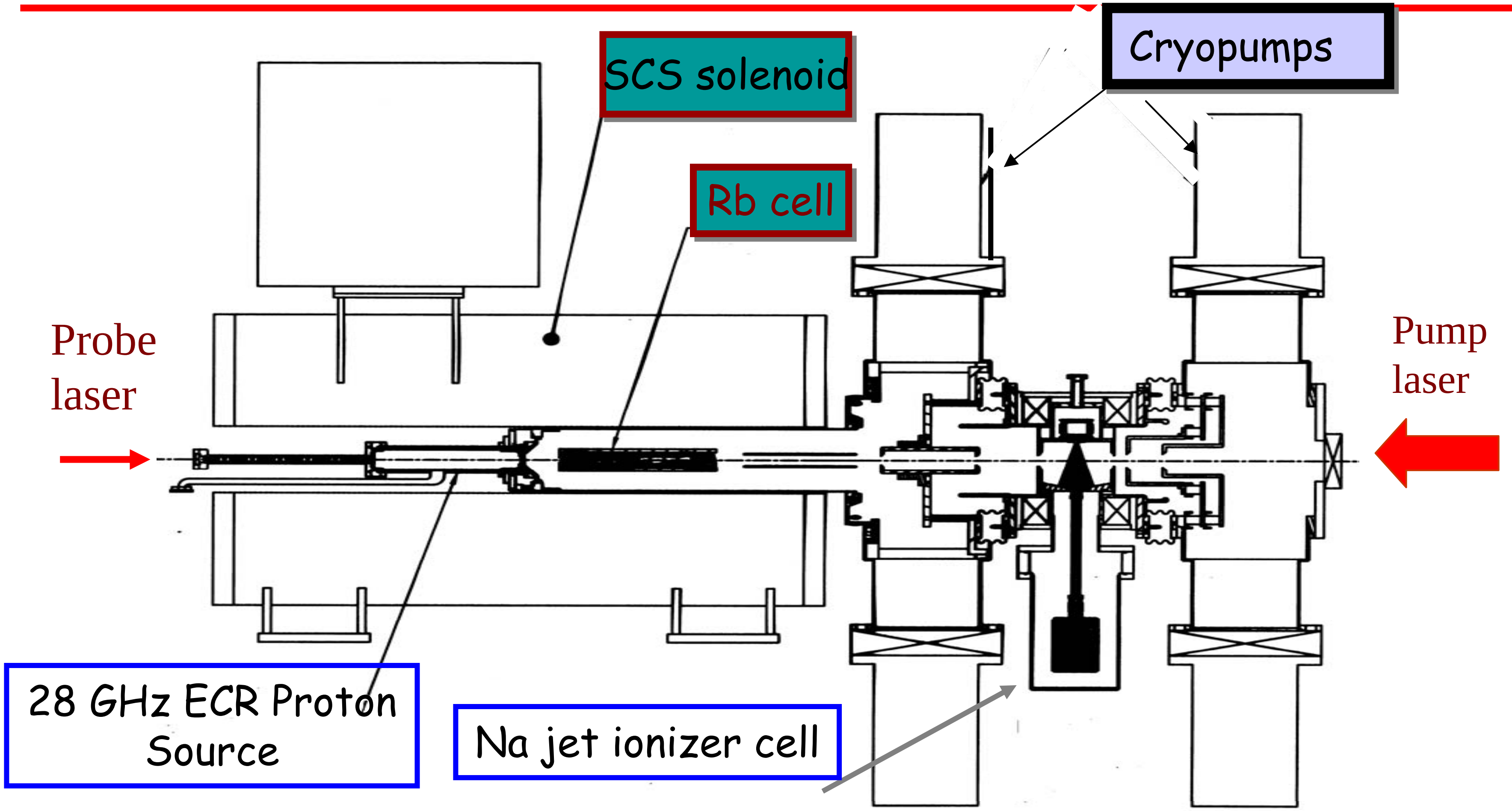
- Luminosity ~ few x10^{31} $cm^{-2}sec^{-1}$ at Sqrt(s) = 200 GeV, P ~ 60%
- Future : L ~ 2x10^{32} $cm^{-2}s^{-1}$, Sqrt(s)=500 GeV, P ~ 70%



RHIC : The world's only polarized proton collider



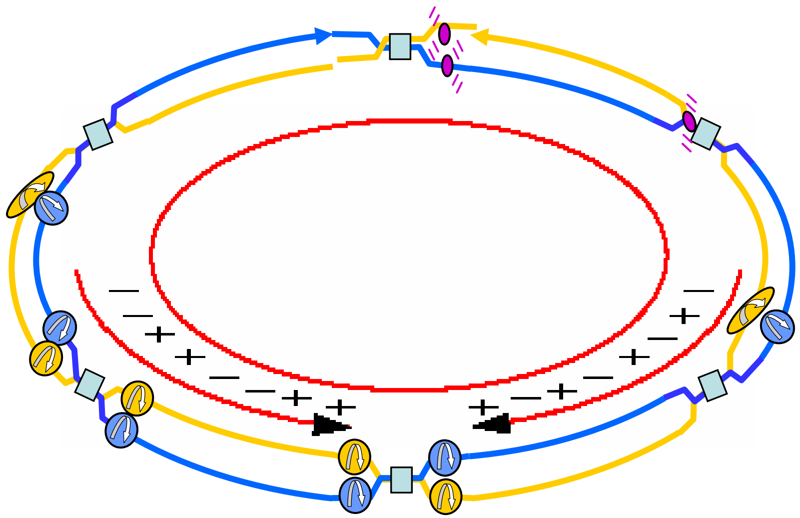
RHIC Optically Pumped Polarized Ion Source (OPPIS)



- Polarized proton blowtorch : 80+ % polarization, ~1 mA H^-, 200 microsecond pulses at 7.5 Hz -> 4×10^{11} protons at 200 MeV after RFQ and Linac (Anatoli Zelenski)

How the Bunches Collide in RHIC

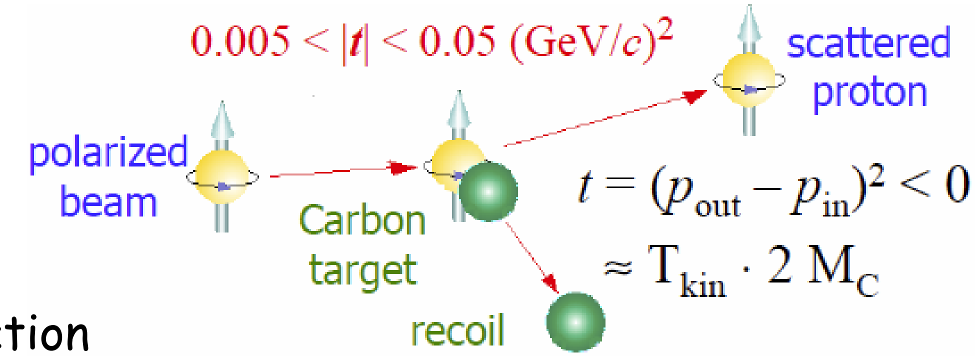
- Same bunches from each ring collide with each other at 78 kHz
- Spin pattern alternates with every bunch crossing (106.5 ns)
- Collecting ++,+-,--,-+ simultaneously (i.e. in same run) reduces systematics
- Possibility of developing false asymmetries are reduced
- 56 crossings in 2001-2004, up to 111 colliding pairs in 2006,2008
- bunch-by-bunch differences in luminosity and vertex distribution are investigated carefully

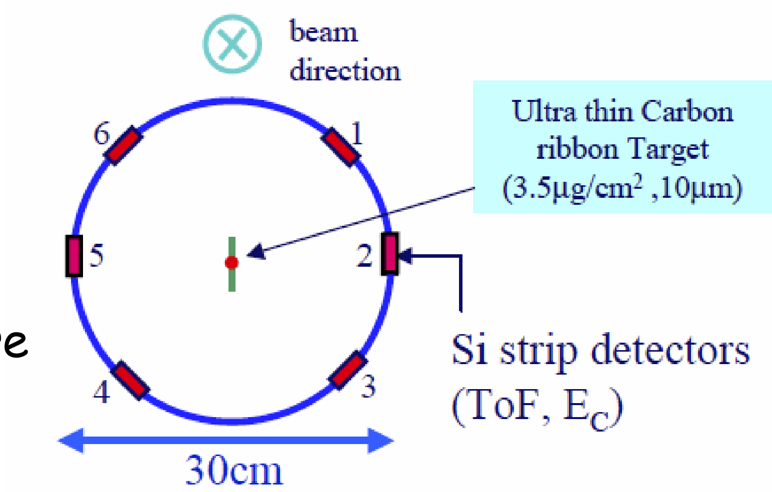


- Great Tools : Spins can be flipped and colliding pairs can be altered (still in commissioning phase)

Proton Beam Polarimetry : pC CNI Polarimeter

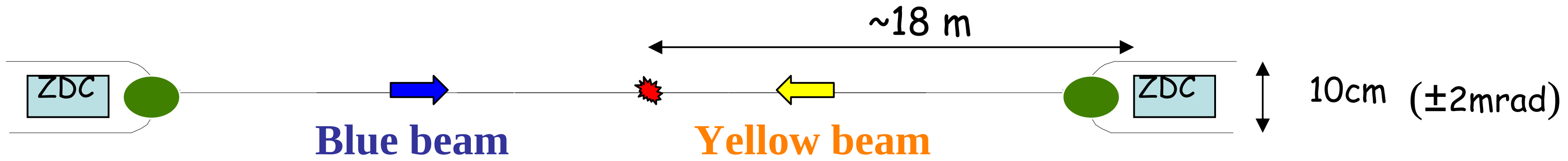
- CNI : analyzing power, A_N, from interference of hadronic non-spin flip and EM spin flip amplitudes
- In p-Carbon, $A_N \sim 1\text{-}2\%$
- Need 10^7 events - but cross section large - just takes a few minutes
- A_N absolute calibration from elastic *pp* scattering from polarized H gas jet target
- $$P_B = -\frac{1}{A_N}\frac{N_{Left} - N_{Right}}{N_{Left} + N_{Right}}$$
- P_B measured several times per store

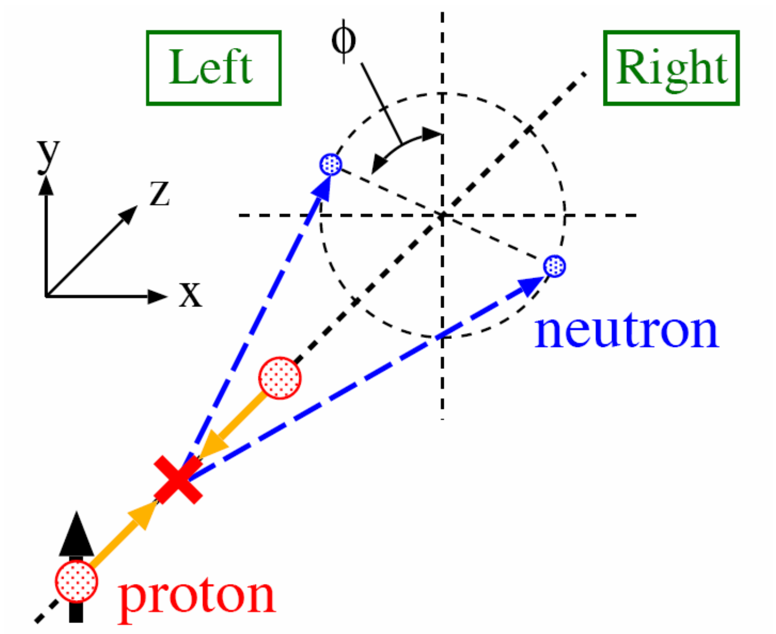


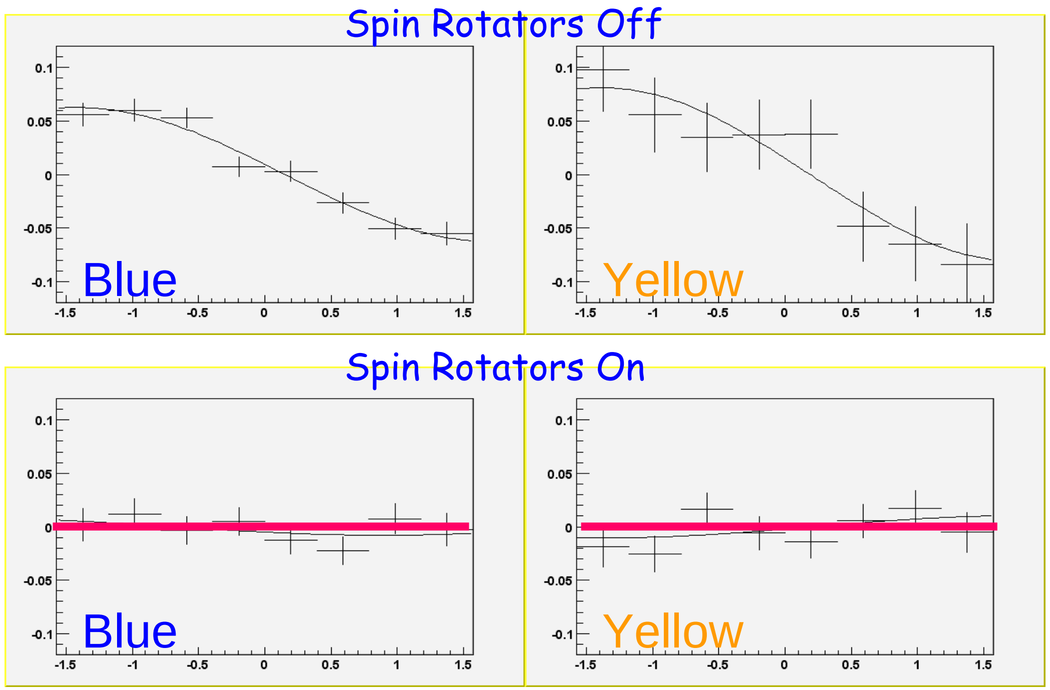


PHENIX Local Polarimeter

- Stable spin direction vertical - spin rotators enable longitudinal collisions
- PHENIX discovered analyzing power in neutron production at low p_T and high x_F in pp collisions at Sqrt(s)=200 GeV
- Neutrons identified in ZDC + Shower Max Detector







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PHENIX

14 Countries; 69 Institutions, more than 550 physicists

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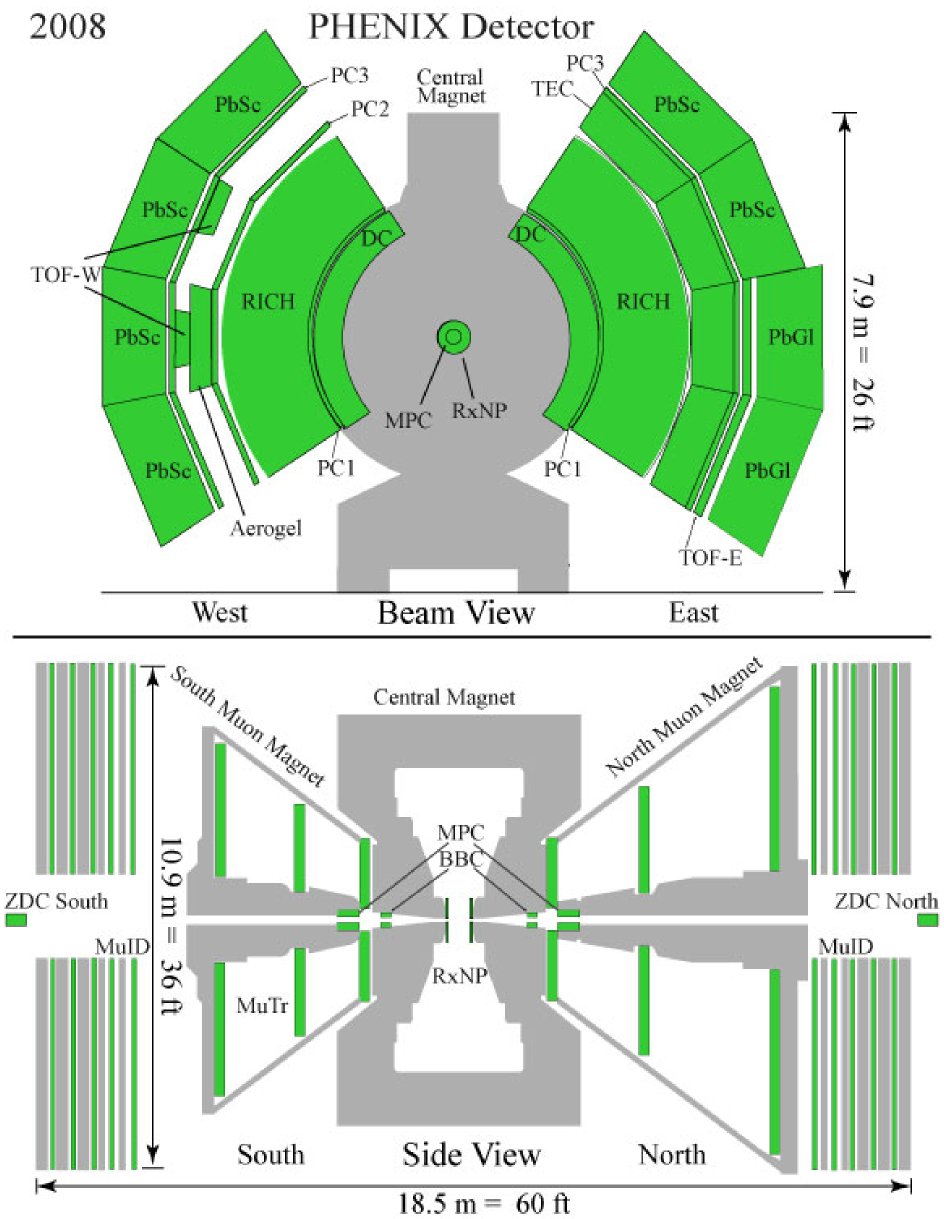
PHENIX Detector



π^0, η, γ detection

- Electromagnetic Calorimeter
  - PbSc, PbGl
  - High p_T photon trigger to collect π^0's, η's, γ's
  - Acceptance: $|\eta|<0.35$, $\phi = 2 \times \pi/2$
  - High granularity (~10*10mrad^2)

π^+/π^-

- Drift Chamber (DC) for Charged Tracks
- Ring Imaging Cherenkov Detector (RICH)
- High p_T charged pions (p_T>4.7 GeV).

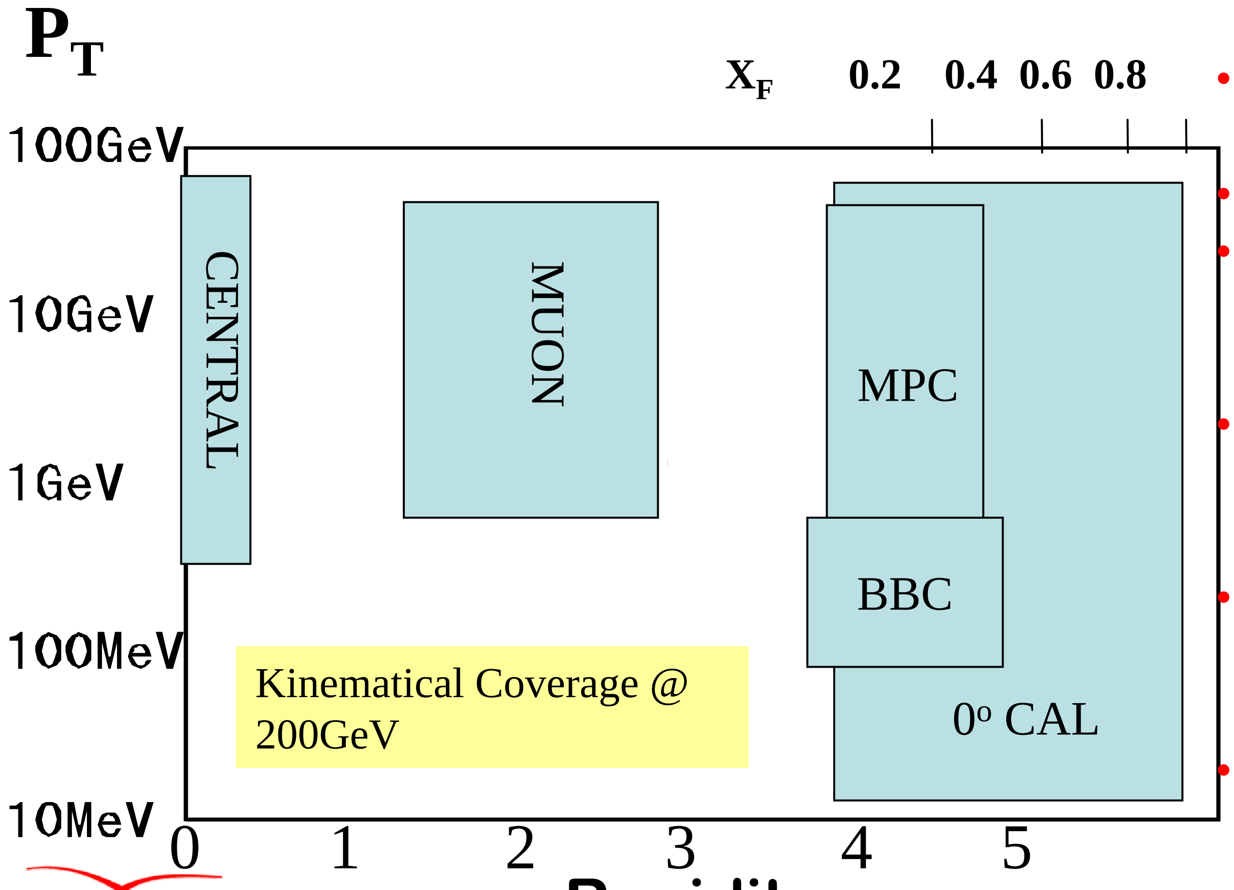
Relative Luminosity

- Beam Beam Counter (BBC)
  - Acceptance: 3.0< η<3.9
- Zero Degree Calorimeter (ZDC)
  - Acceptance: ±2 mrad

Local Polarimetry

- ZDC
- Shower Maximum Detector (SMD)

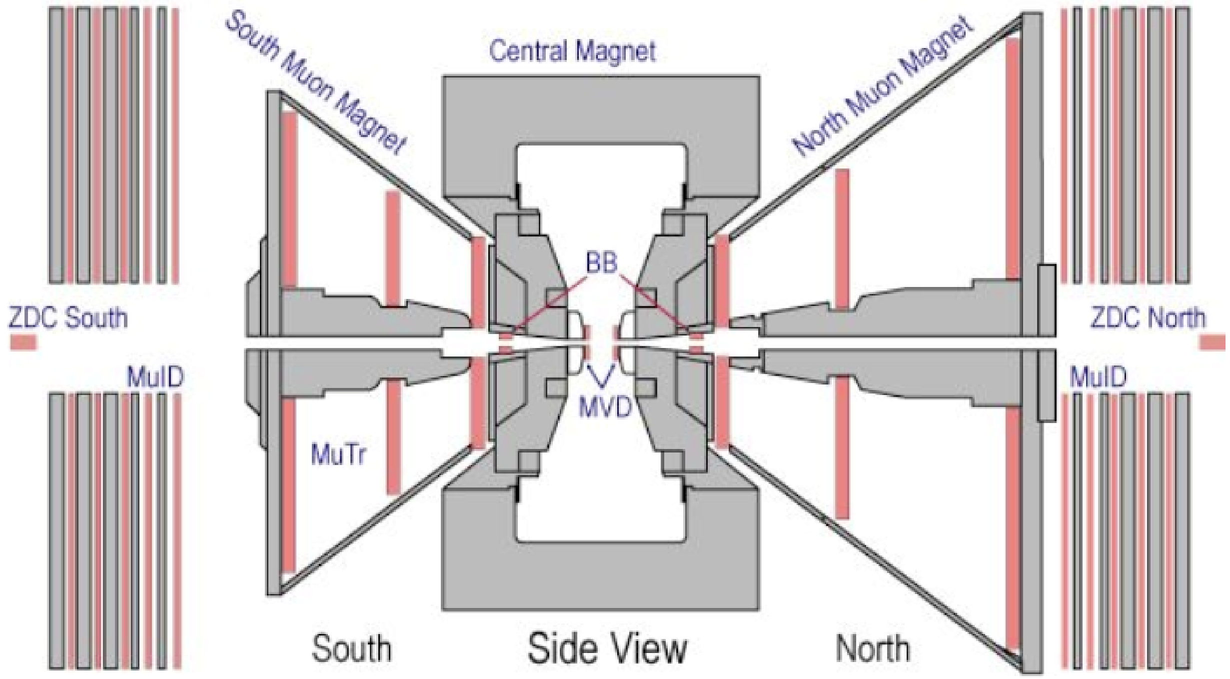
PHENIX Detector



- MPC : muon piston calorimeter
- Lead Tungstate
- detect π^0 in forward $3.1 < |\eta| < 3.65$
- Muon arms : $1.2 < |\eta| < 2.2$
- BBC : min. bias trigger, luminosity monitor
- ZDC : luminosity monitor, local polarimetry, sees photons, neutrons

- Modest coverage, but high granularity, good mass resolution, particle ID
- Excellent rate capability : 5000 Hz written to tape
- 32 different Level-1 triggers
- Coverage will improve significantly (see Atsushi Taketani's talk)

- Spray of particles from pp collisions yields coincidence in two Beam-Beam Counters (BBCs)
- Located at $\pm$1.44 m from interaction point, cover $\Delta\phi = 2\pi,\ 3.0 \leq |\eta| \leq 3.9$
- Average hit time is formed from PMTs in north and south BBC arms separately
- From difference of north and south BBC hit times can reconstruct z of vertex
- Central arm acceptance requires event vertex $|z|\ <\ 30$ cm, muon arms less restrictive
- Separate scalers for each colliding bunch pair measure collison rate for different helicity combinations
- Measure R with scalers attached to this minimum-bias trigger, $R = \frac{BBC_{++} + BBC_{--}}{BBC_{+-} + BBC_{-+}}$



PHENIX Polarized Proton Running History

Longitudinally Polarized Runs

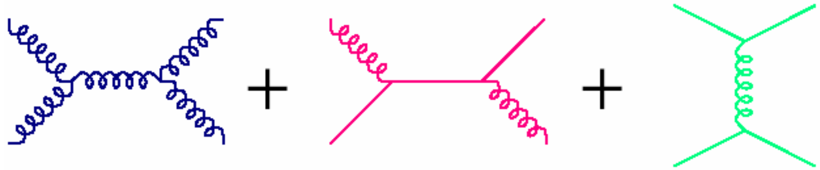
Year	$\sqrt{s}$ [GeV]	Recorded L	Pol [%]	FOM (P^4L)
2003 (Run 3)	200	.35 pb^{-1}	27	1.9 nb^{-1}
2004 (Run 4)	200	.12 pb^{-1}	40	3.1 nb^{-1}
2005 (Run 5)	200	3.4 pb^{-1}	49	200 nb^{-1}
2006 (Run 6)	62.4	.08 pb^{-1}	48	4.2 nb^{-1}
2006 (Run 6)	200	7.5 pb^{-1}	57	1100 nb^{-1}

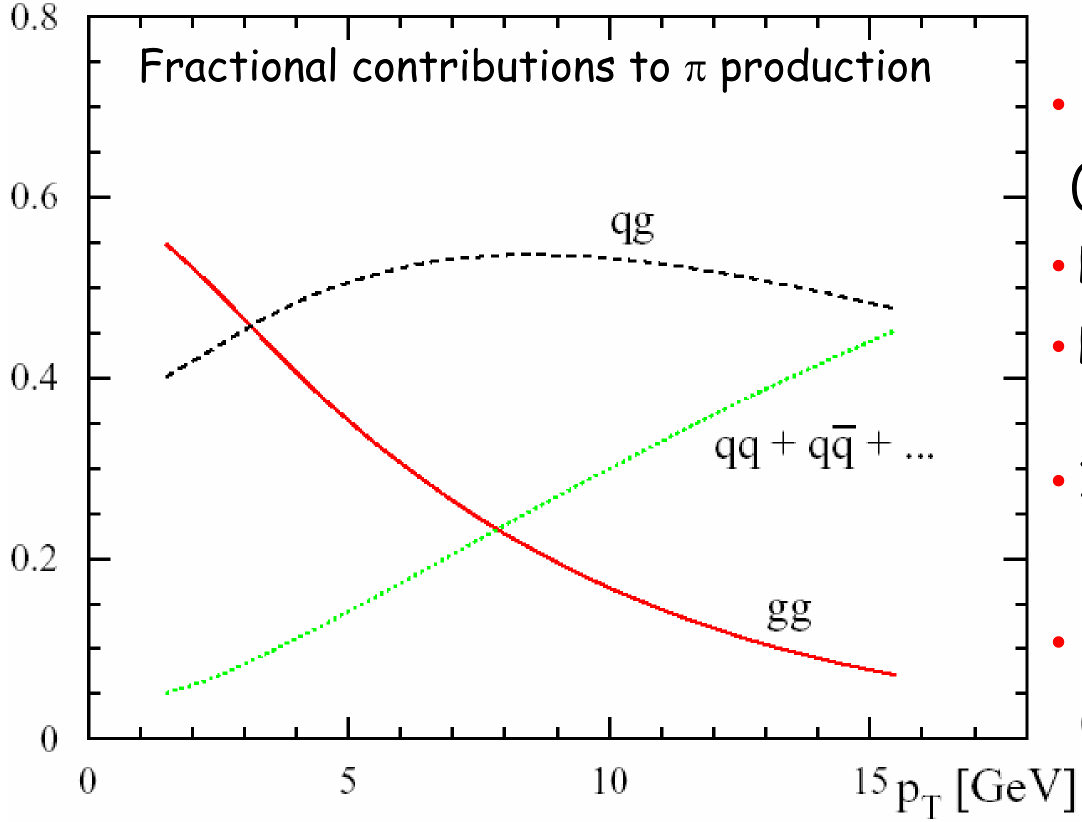
Transversely Polarized Runs

Year	$\sqrt{s}$ [GeV]	Recorded L	Pol [%]	FOM (P^2L)
2001 (Run 2)	200	.15 pb^{-1}	15	3.4 nb^{-1}
2005 (Run 5)	200	.16 pb^{-1}	47	38 nb^{-1}
2006 (Run 6)	62.4	.02 pb^{-1}	48	4.6 nb^{-1}
2006 (Run 6)	200	2.7 pb^{-1}	57	880 nb^{-1}
2008 (Run 8)	200	5.2 pb^{-1}	45	1000 nb^{-1}

Physics Results : A_{LL} of π^+, π^- at sqrt(s)=200 GeV

- A_{LL} of π has contributions from $\Delta g \times \Delta g$, $\Delta g \times \Delta q$, and $\Delta q \times \Delta q$ scattering

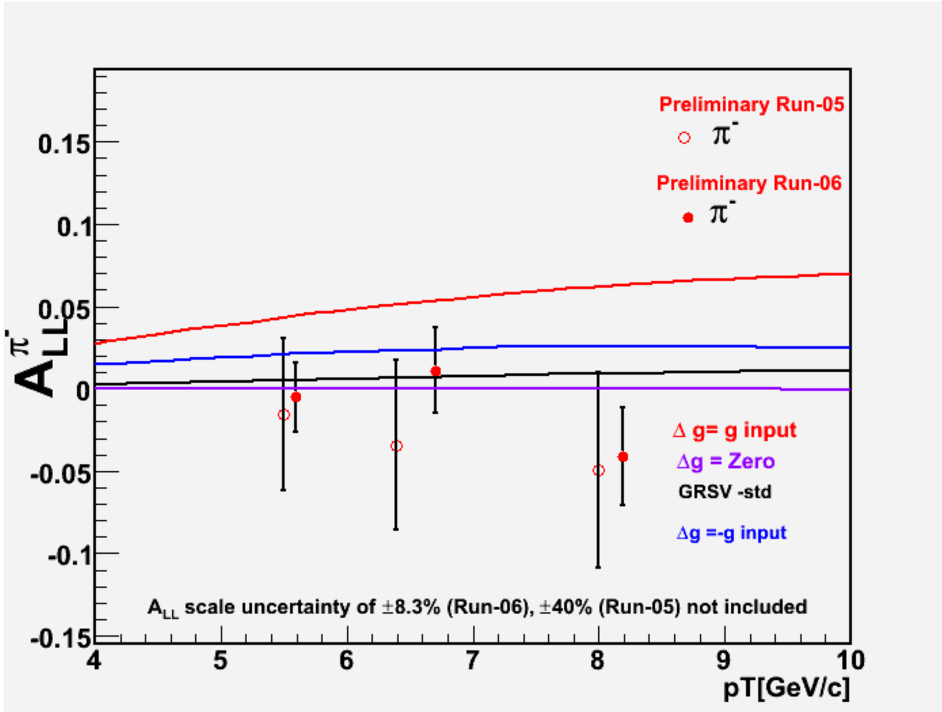




(From W. Vogelsang, M. Stratmann)

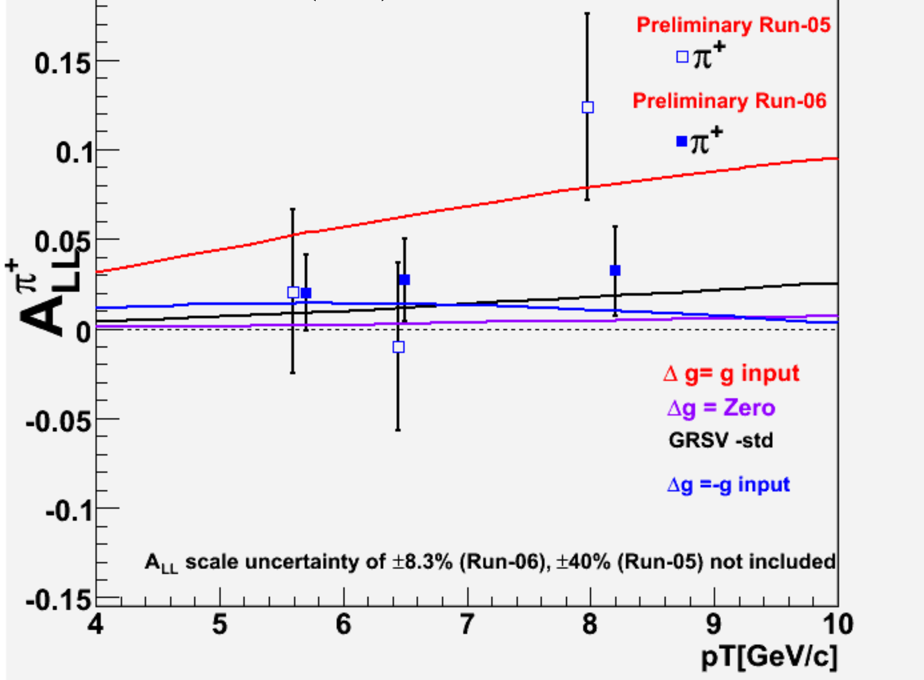
- Low p_T, A_{LL} of π depends on $(\Delta g)^2$ (insensitive to sign of $\Delta g(x)$)
- High p_T, A_{LL} of π depends on $\Delta g \times \Delta q$
- High p_T, $A_{LL} \propto \Delta g \left(\Delta u\, D_u^\pi + \Delta d\, D_d^\pi\right)$
- If $\Delta g > 0$, expect : $A_{LL}(\pi^+) > A_{LL}(\pi^0) > A_{LL}(\pi^-)$
- Maximum analyzing power for Δg using π^+

Physics Results : A_{LL} of π^+, π^- at sqrt(s)=200 GeV

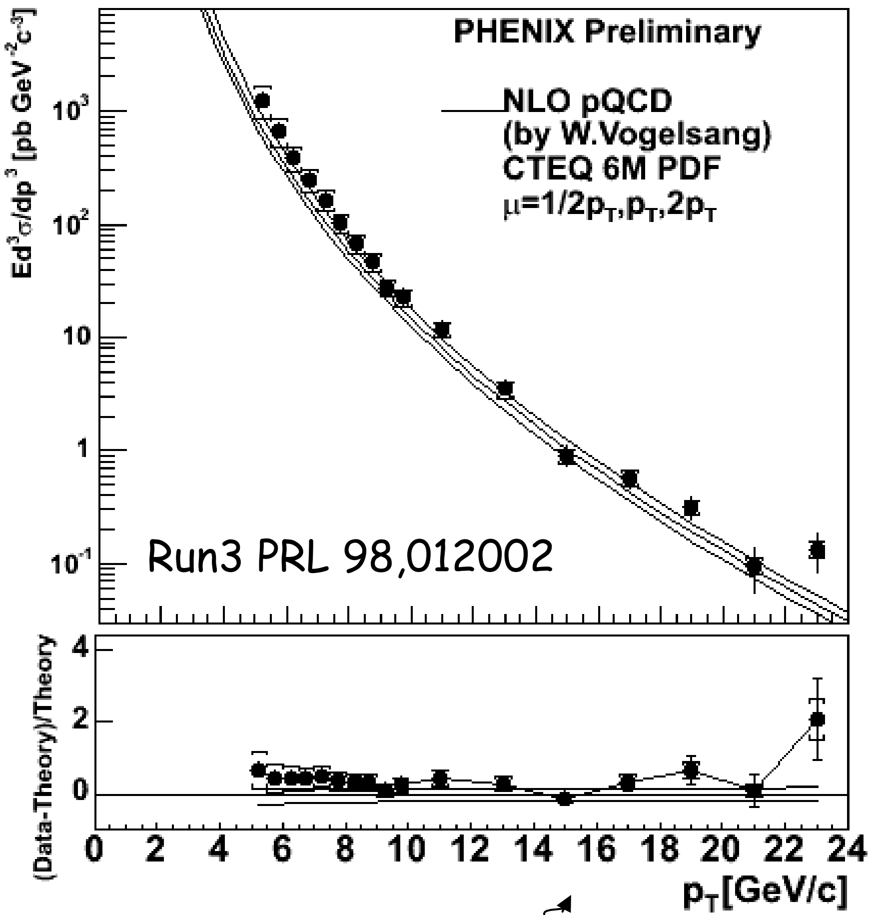


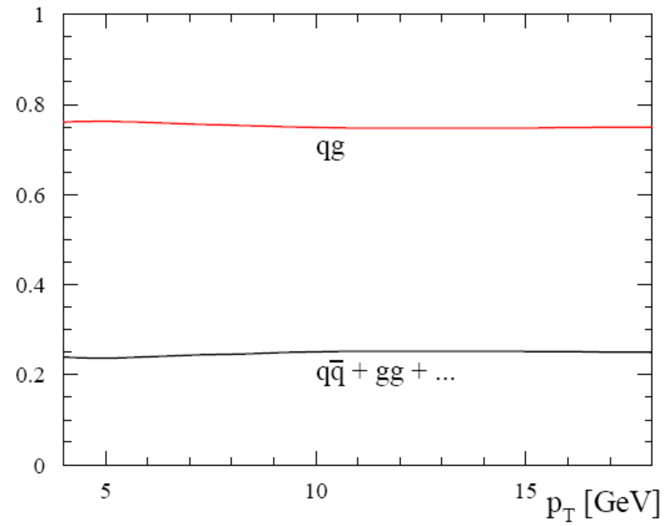
- Pions copiously produced
- Potential for high statistics
- Currently no trigger at PHENIX
- Cross section being extracted
- $\Delta G(Q^2=1) = 0.4$ in GRSV-std
- $\Delta G(Q^2=1) = 0.1$ in GRSV-0

(M. Glück, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. D 63, 094005 (2001))

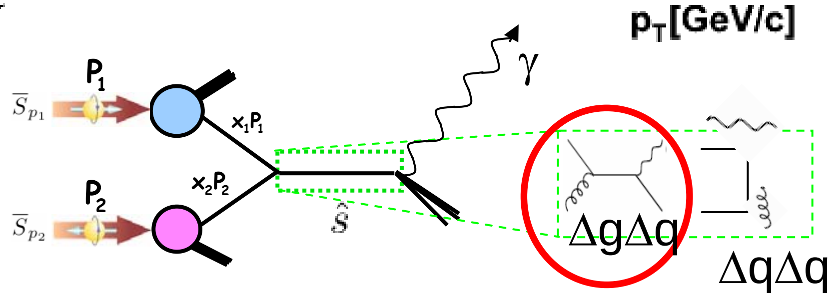


- Different fragmentation functions for π^+, π^0, π^- imply sensitivity to different quark flavors
- Consistency of Δg extracted from 3 independent π asymmetries good check on pQCD global analysis methods
- GRSV $\Delta g(x)=g(x)$ excluded



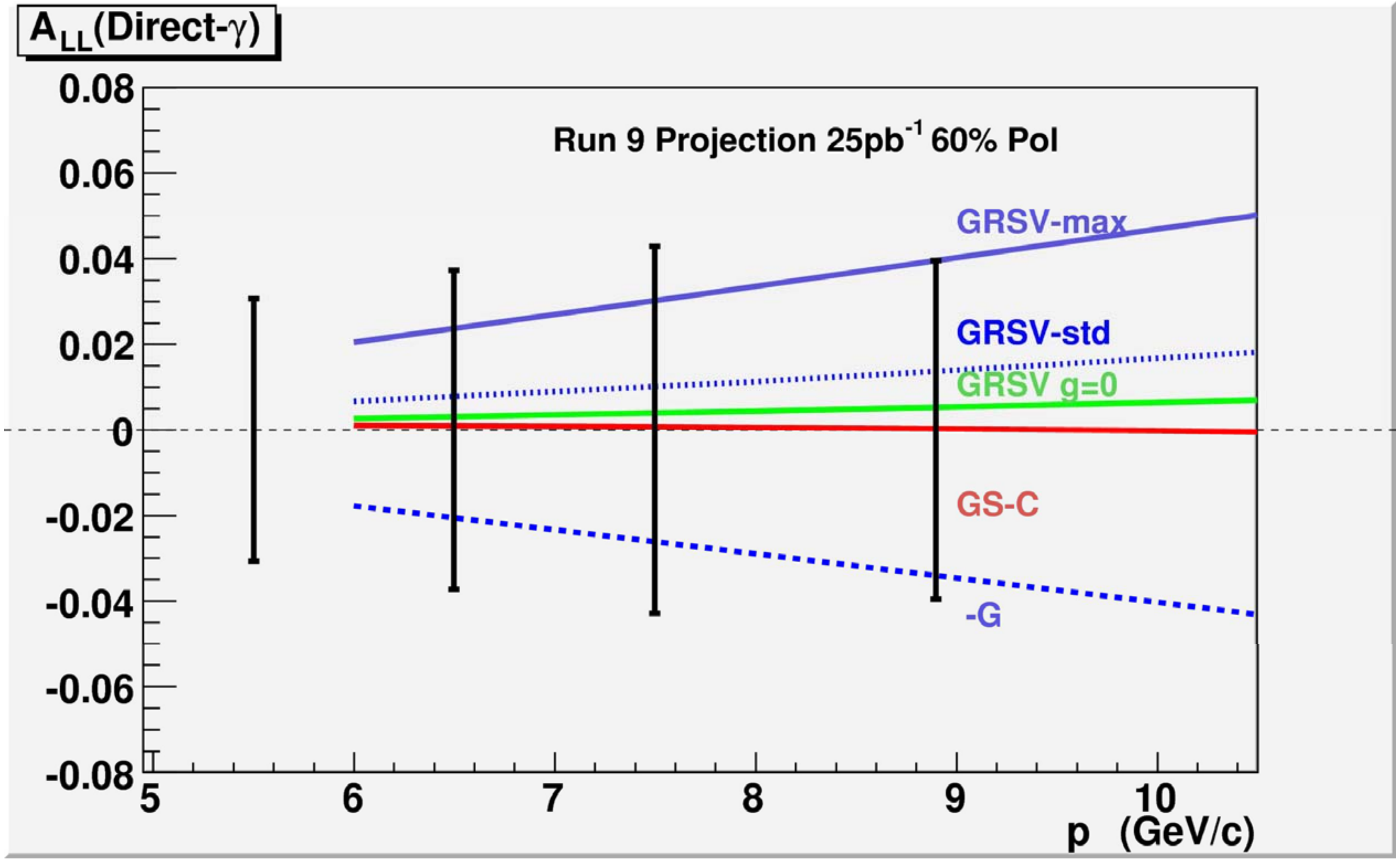


$$A_{LL} \propto \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta q(x_2)}{q(x_2)} \otimes \hat{a}_{LL}(gq \to \gamma q)$$



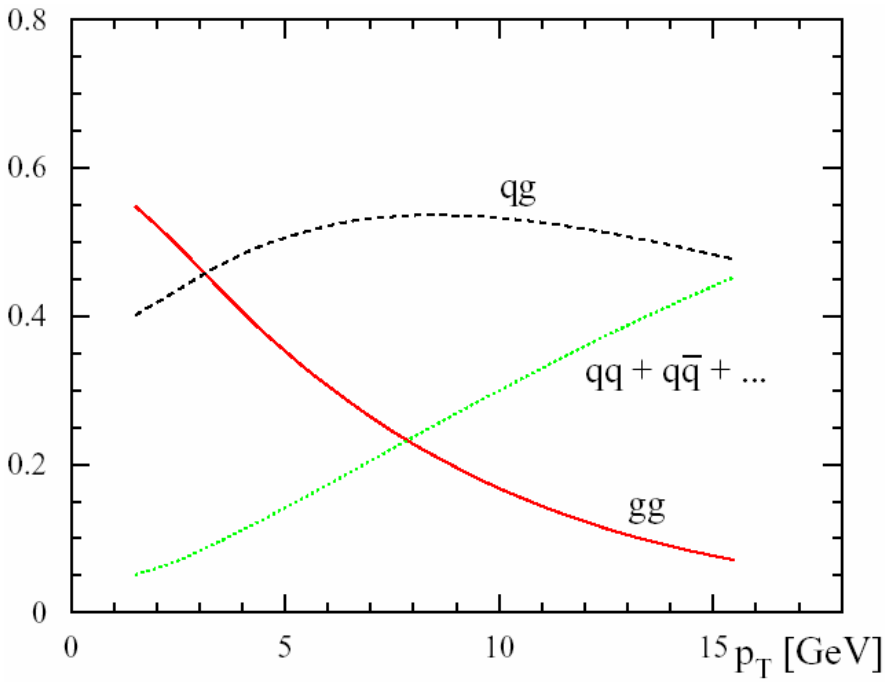
- Sensitive to sign and magnitude of Δg
- No convolution over fragmentation functions - theoretically clean
- A rare probe, poor statistics, large background from π^0, η etc. decays
- use isolation cut, works best at high p_T

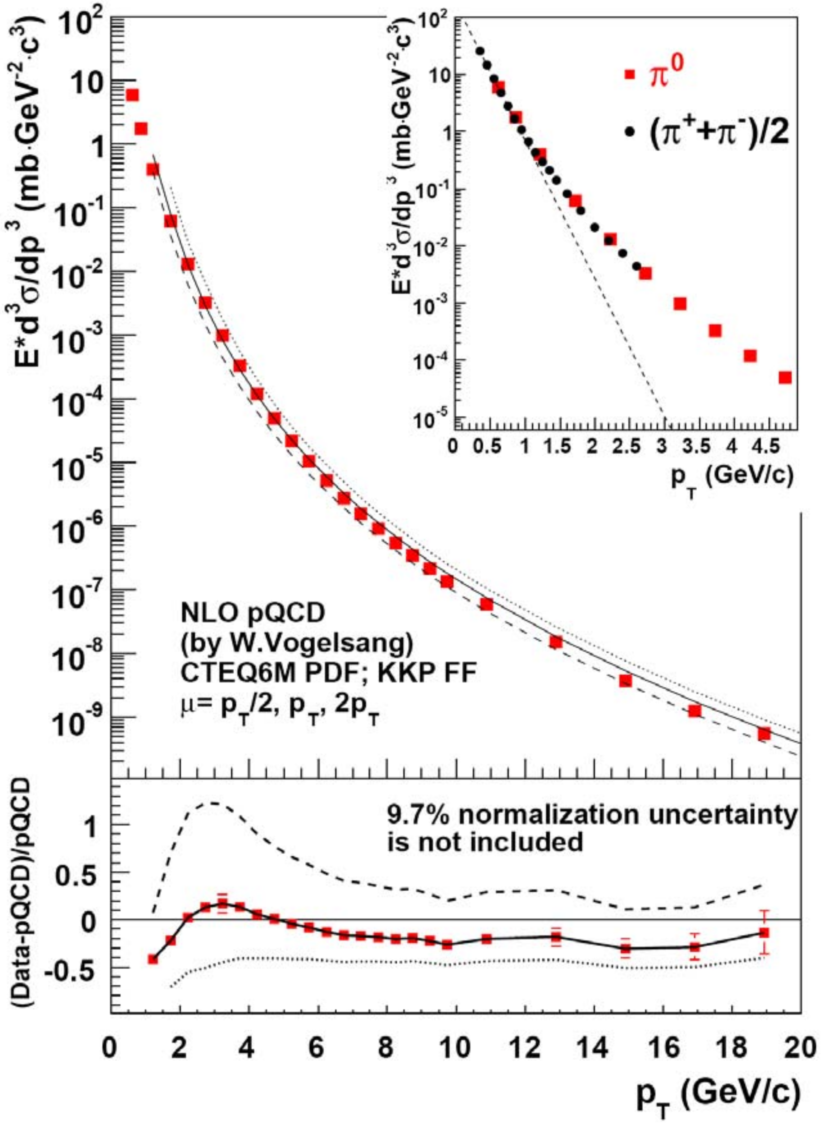
Anticipated Results : A_{LL} of Direct Photons at sqrt(s)=200 GeV



Physics Results : A_{LL} of π^0 at sqrt(s)=200 GeV

- π^0 produced in large quantities
- easy to trigger on, reconstruct
- detect two photons from $\pi^0 \rightarrow 2\gamma$
- pQCD predicts cross section well
- asymmetry sensitive to $\Delta g(x)$
- Run5/Run6 results included in recent DSSV global analysis of pol. PDFs





PRD 76,051106, PRL 91,241803

Physics Results : A_{LL} of π^0 at sqrt(s)=200 GeV

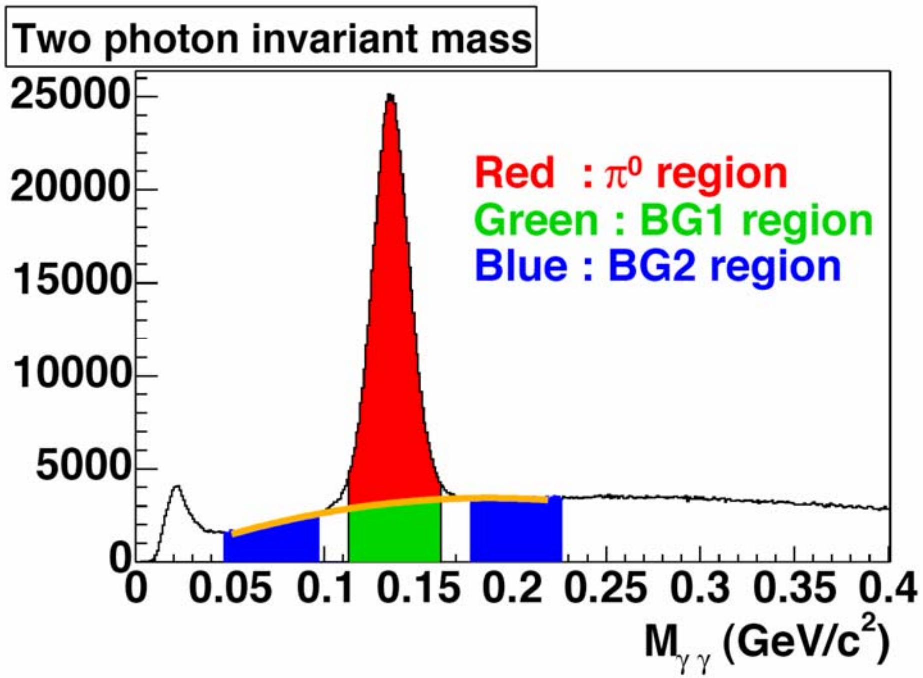
- Identify π^0 from 2γ invariant mass peak, extract A_{LL} (π^0 + BG1) and A_{LL}(BG2)

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P \cdot P} \cdot \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \text{where} R = \frac{L_{++}}{L_{+-}}$$

- Fit π^0 peak and get combinatorial background fraction

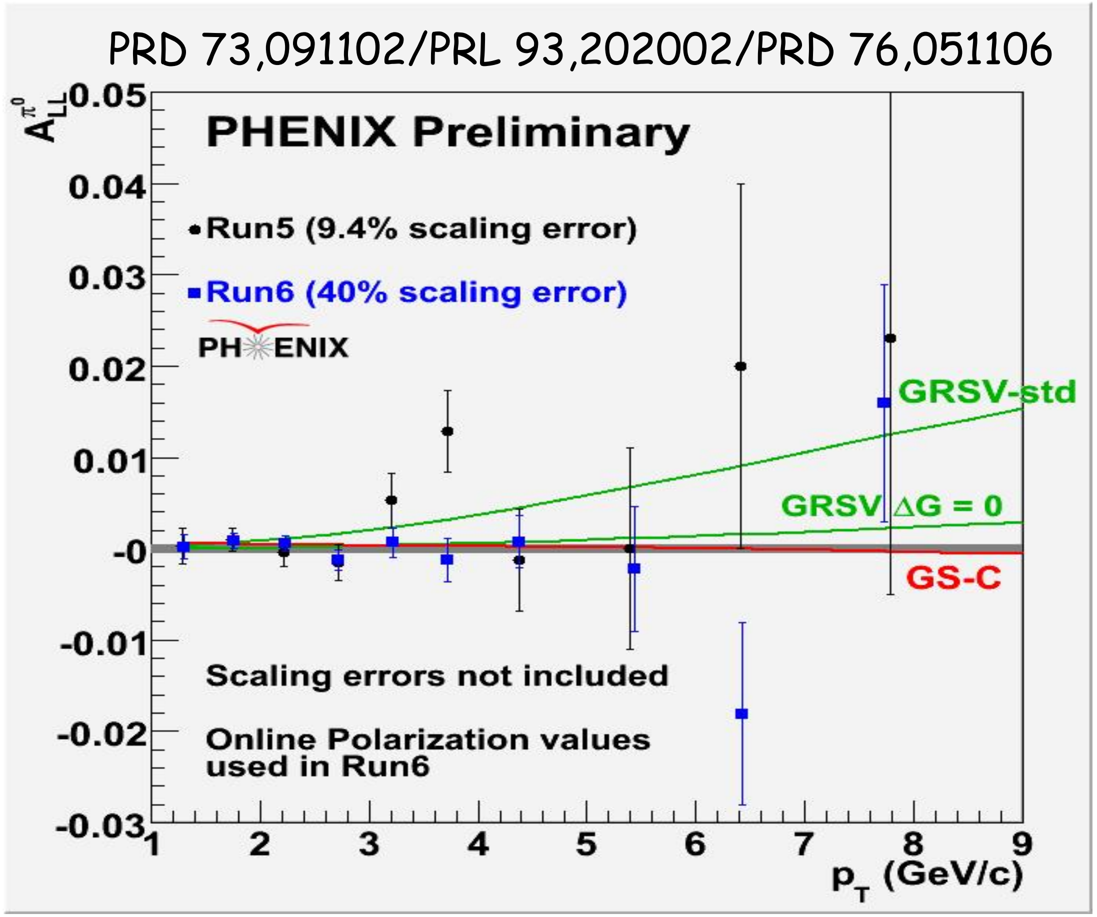
$$W_{BG} = 1 - W_{\pi^0} \quad \text{where} \quad W_{\pi^0} = \frac{\pi^0}{\pi^0 + BG1}$$

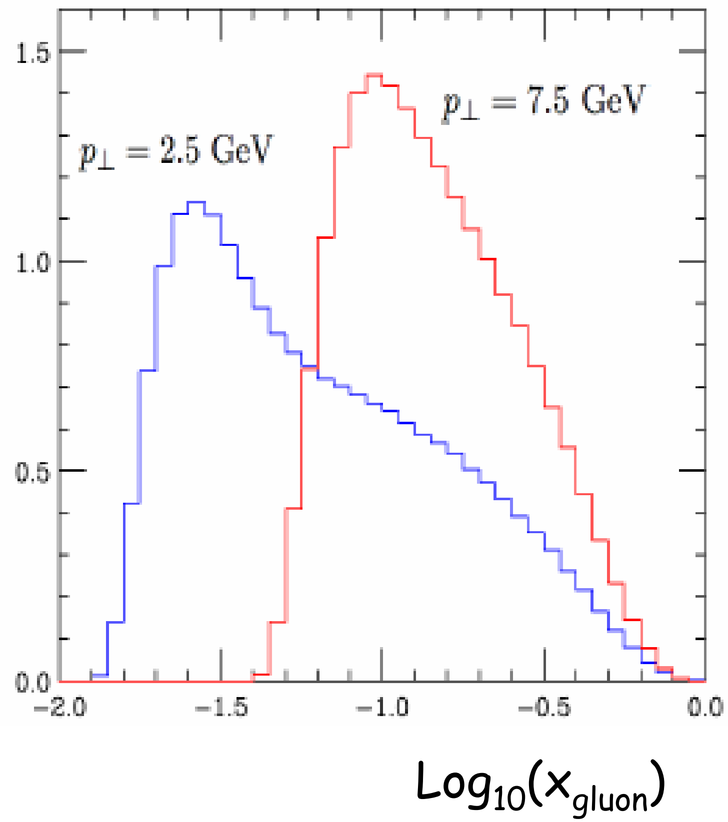
- Subtract A_{LL}(BG2) ~0, from A_{LL}(π^0 + BG1) to get A_{LL}(π^0)



p_T bin (GeV)	peak yield (112-162 MeV)	background yield (47-97 + 177-227 MeV)	background %
1.00-1.50	21081329	14336413	0.387
1.50-2.00	33609294	15705719	0.266
2.00-2.50	23655949	7264167	0.178
2.50-3.00	11656472	2515618	0.128
3.00-3.50	5165175	878295	0.102
3.50-4.00	2265137	334442	0.089
4.00-5.00	1515597	204589	0.082
5.00-6.00	380058	48938	0.080
6.00-7.00	117689	14651	0.078
7.00-9.00	61413	7335	0.077
9.00-12.00	14418	1540	0.063

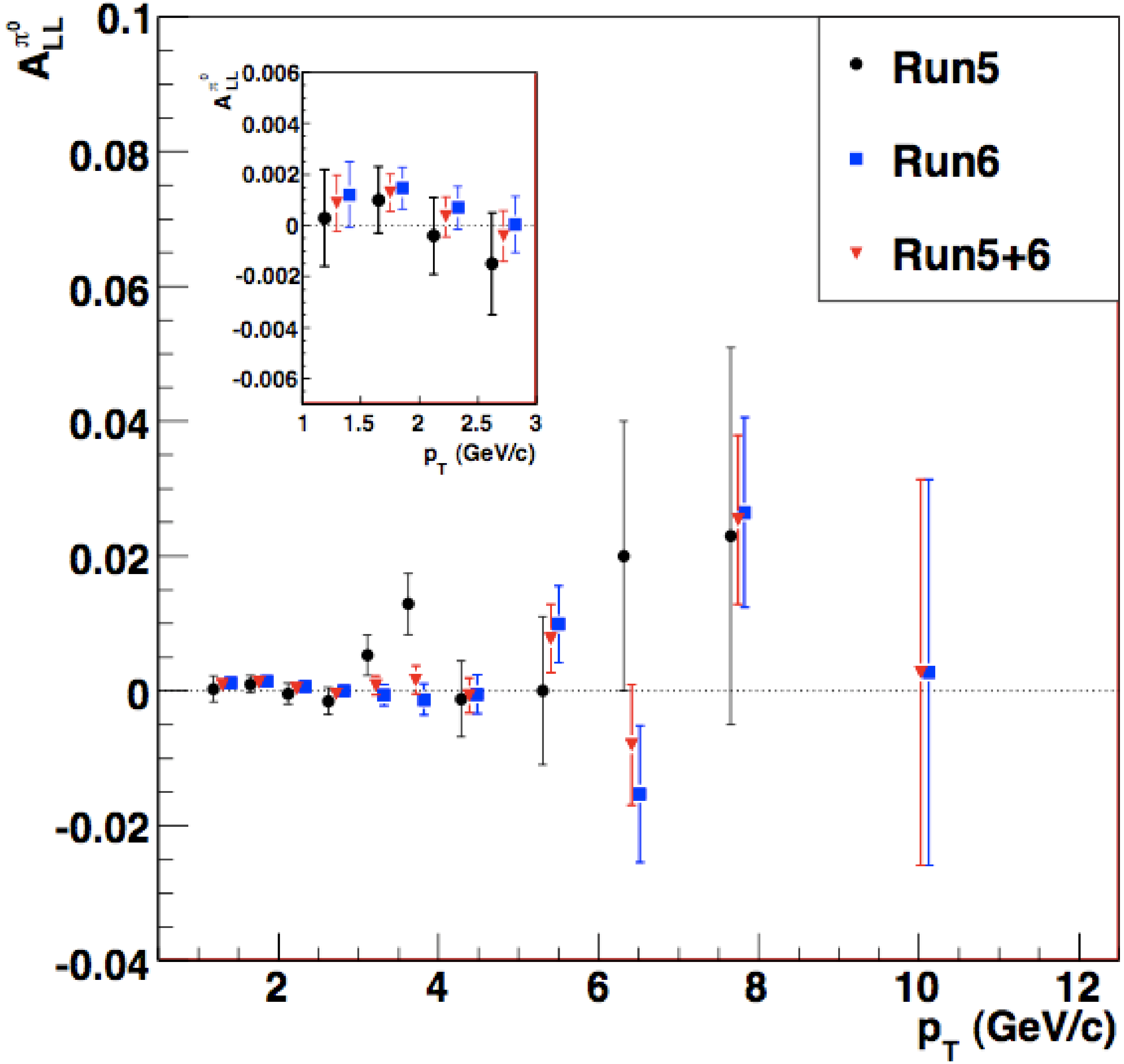
Physics Results : A_{LL} of π^0 at sqrt(s)=200 GeV



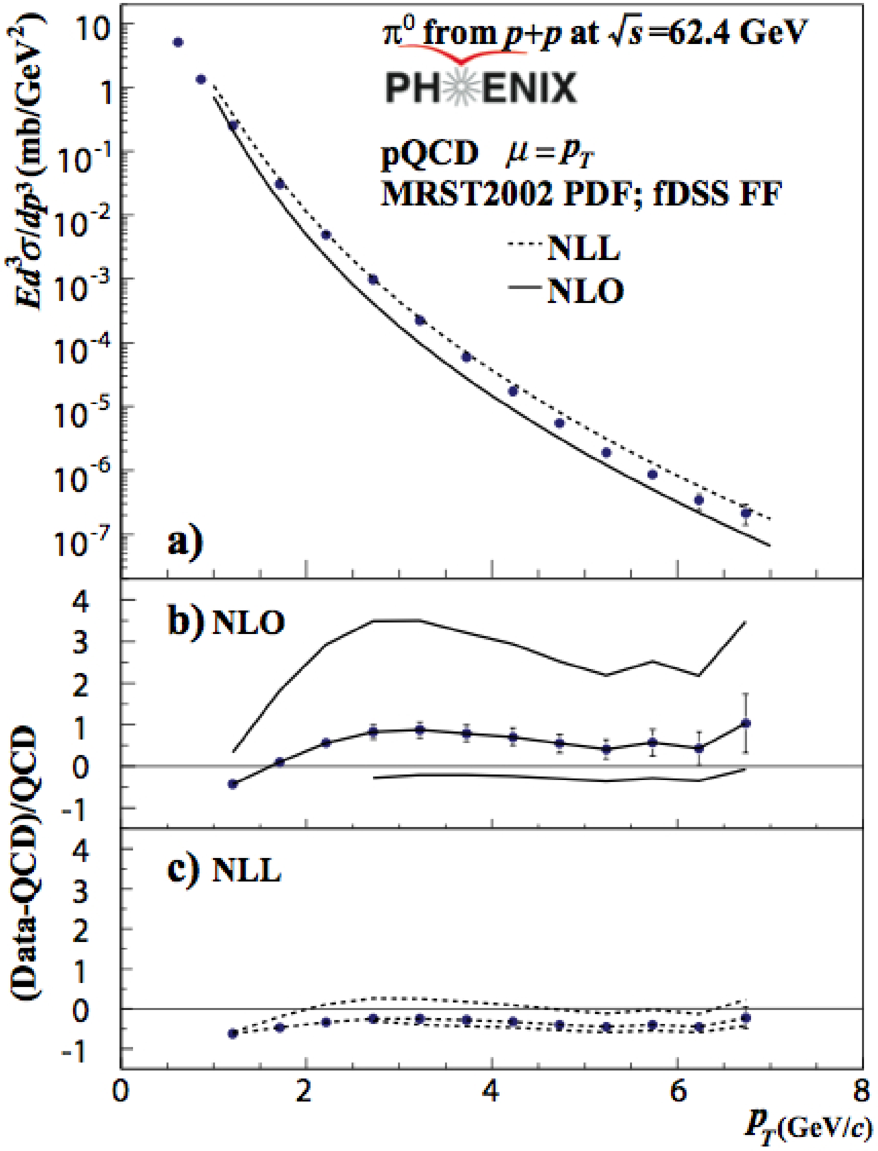


- Asymmetry involves gg, and qg scattering, acquire sensitivity to $\Delta g(x)$
- Statistics sufficient to distinguish GRSV-std from GRSV-0 models
- To interpret, note each p_T corresponds to wide, model-dependent range in x_{gluon}
- Inclusive channels not so sensitive to variation of $\Delta g(x)$ within measured x range

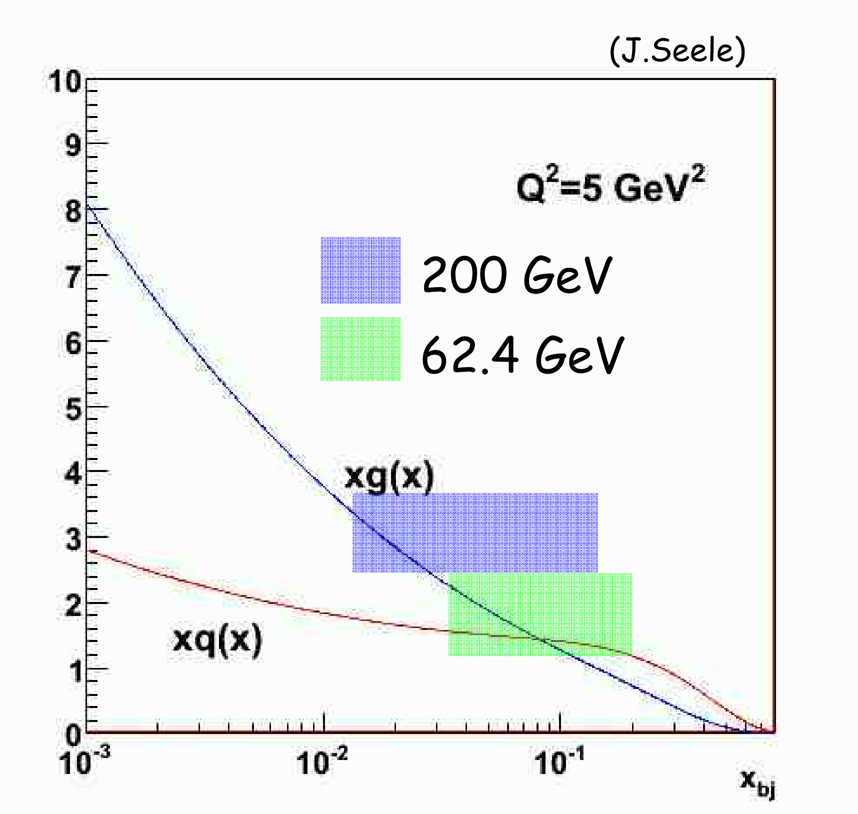
Physics Results : A_{LL} of π^0 at sqrt(s)=200 GeV



Physics Results : A_{LL} of π^0 at sqrt(s)=62.4 GeV

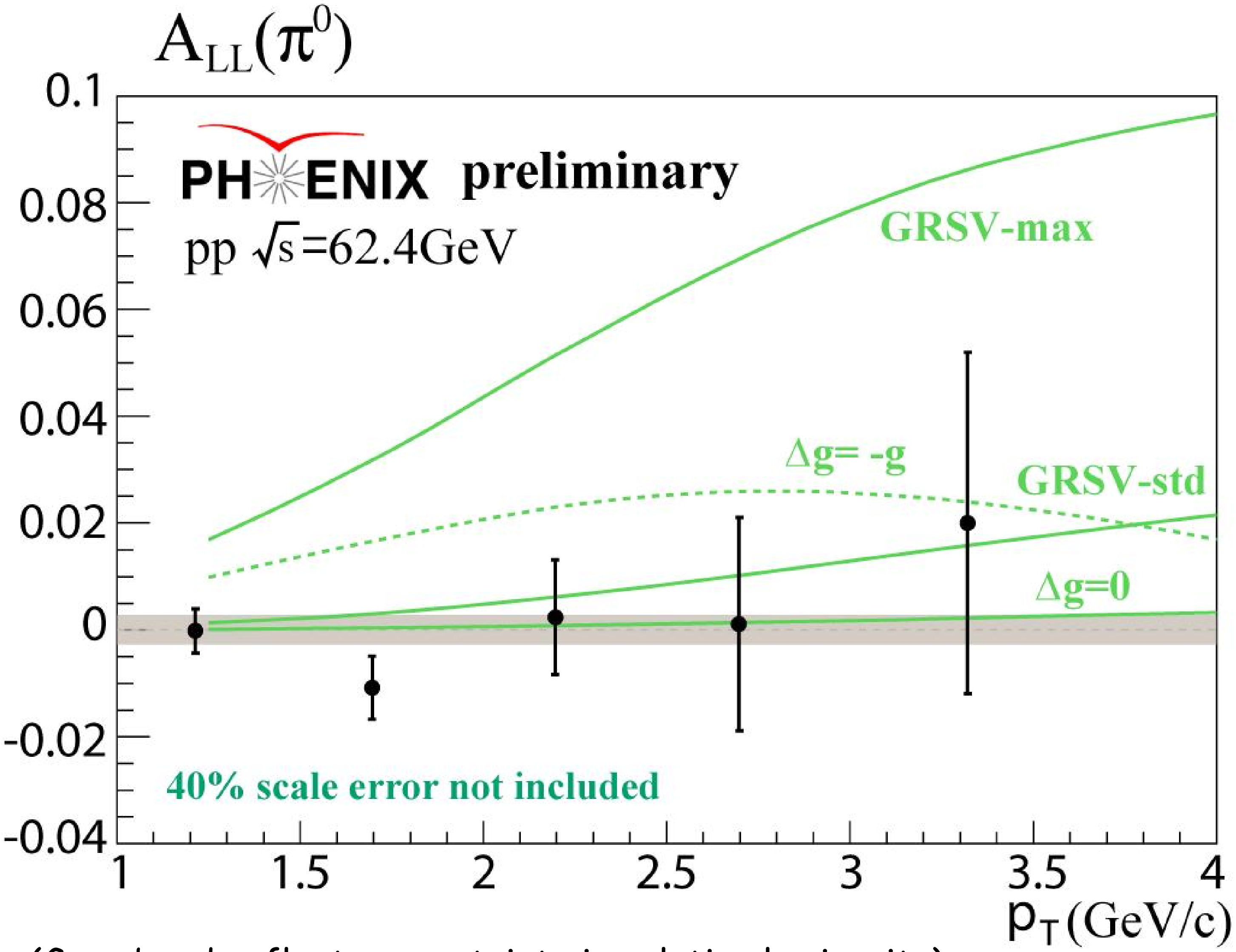


arXiv:0801.4555



- Cross-section described with NLL (Vogelsang et al.)
- Probes a higher range in x_b since $x \sim x_T = p_T$ / sqrt(s)/2, lower sqrt(s) probes higher x, and vice versa

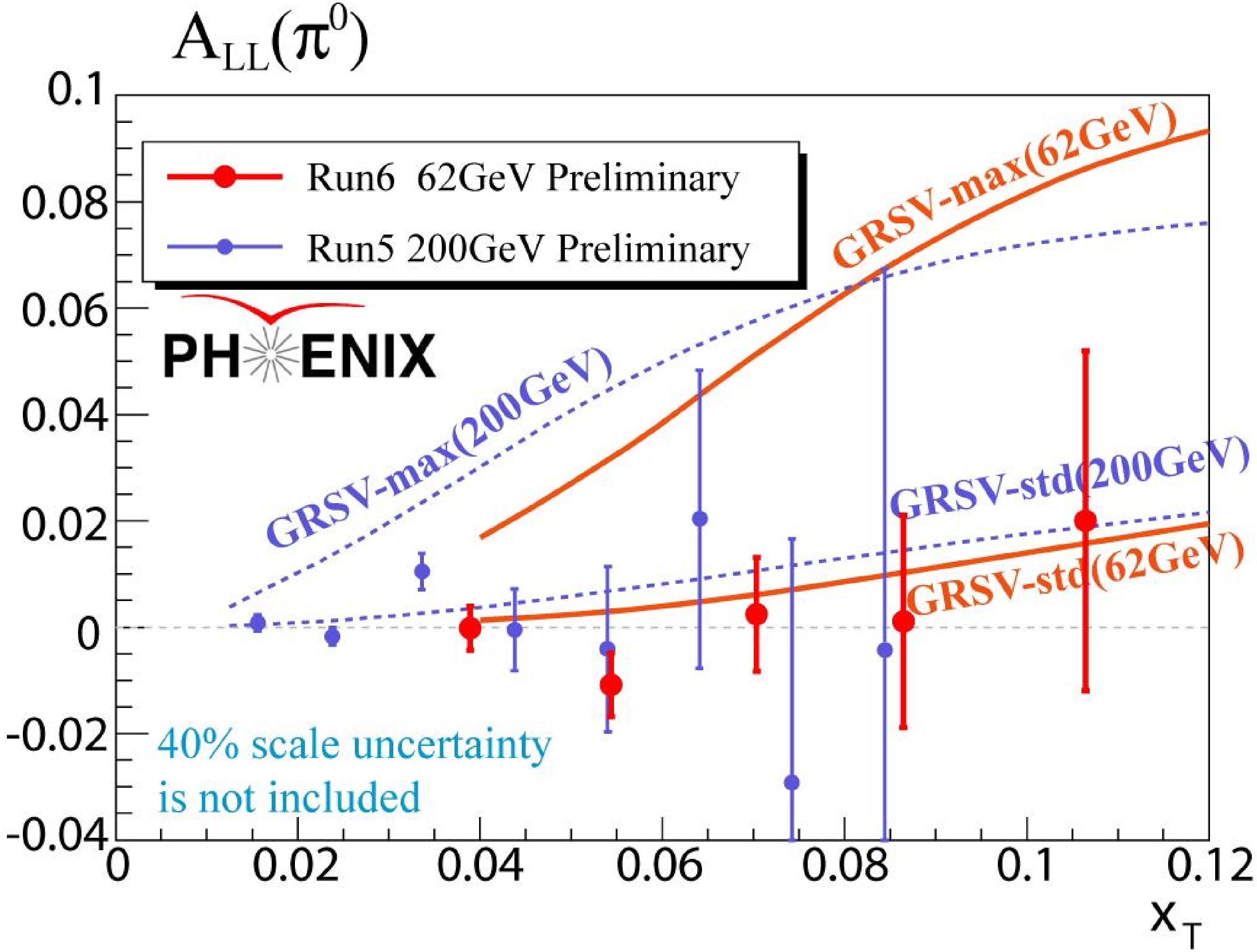
Physics Results : A_{LL} of π^0 at sqrt(s)=62.4 GeV



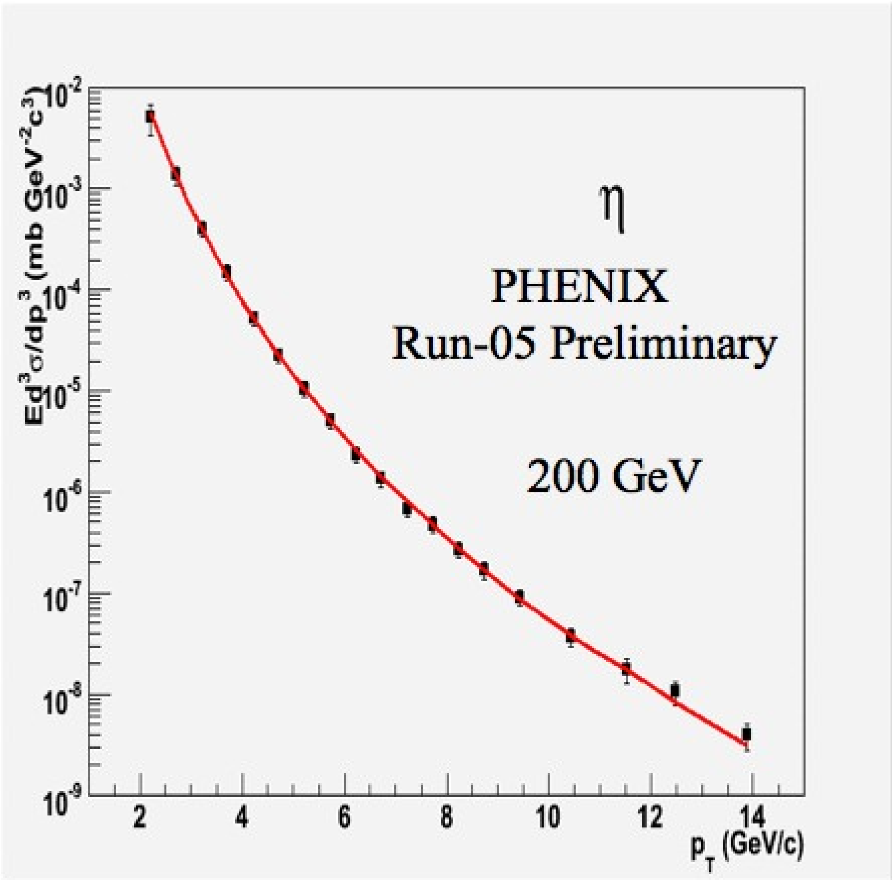
(Grey band reflects uncertainty in relative luminosity)

Physics Results : A_{LL} of π^0 at sqrt(s)=62.4 GeV

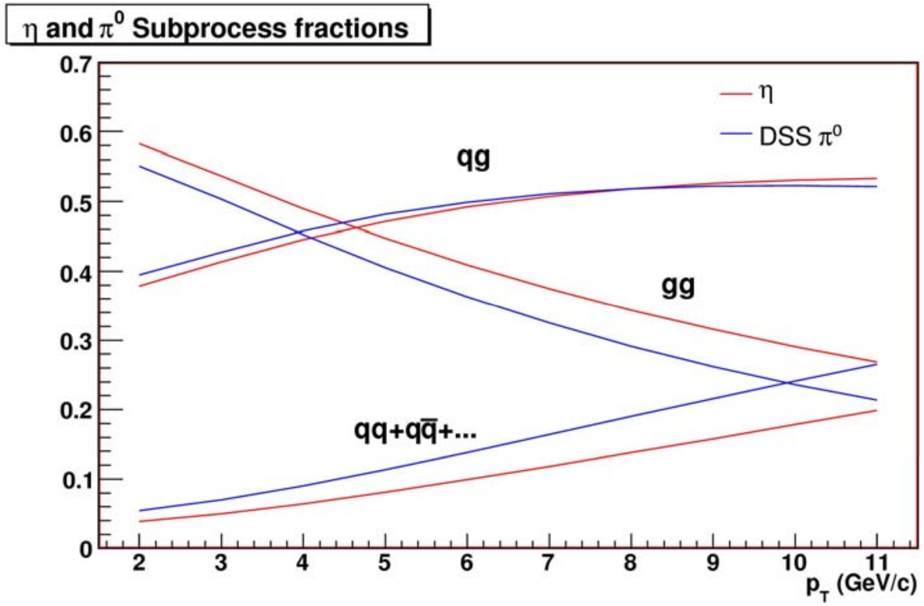
- $x_T = p_T$ / sqrt(s)/2, lower sqrt(s) probes higher x, and vice versa
- Run 5 200 GeV 2.7 pb^{-1}, Run 6 62.4 GeV 0.04 pb^{-1}



Physics Results : A_{LL} of η at sqrt(s)=200 GeV

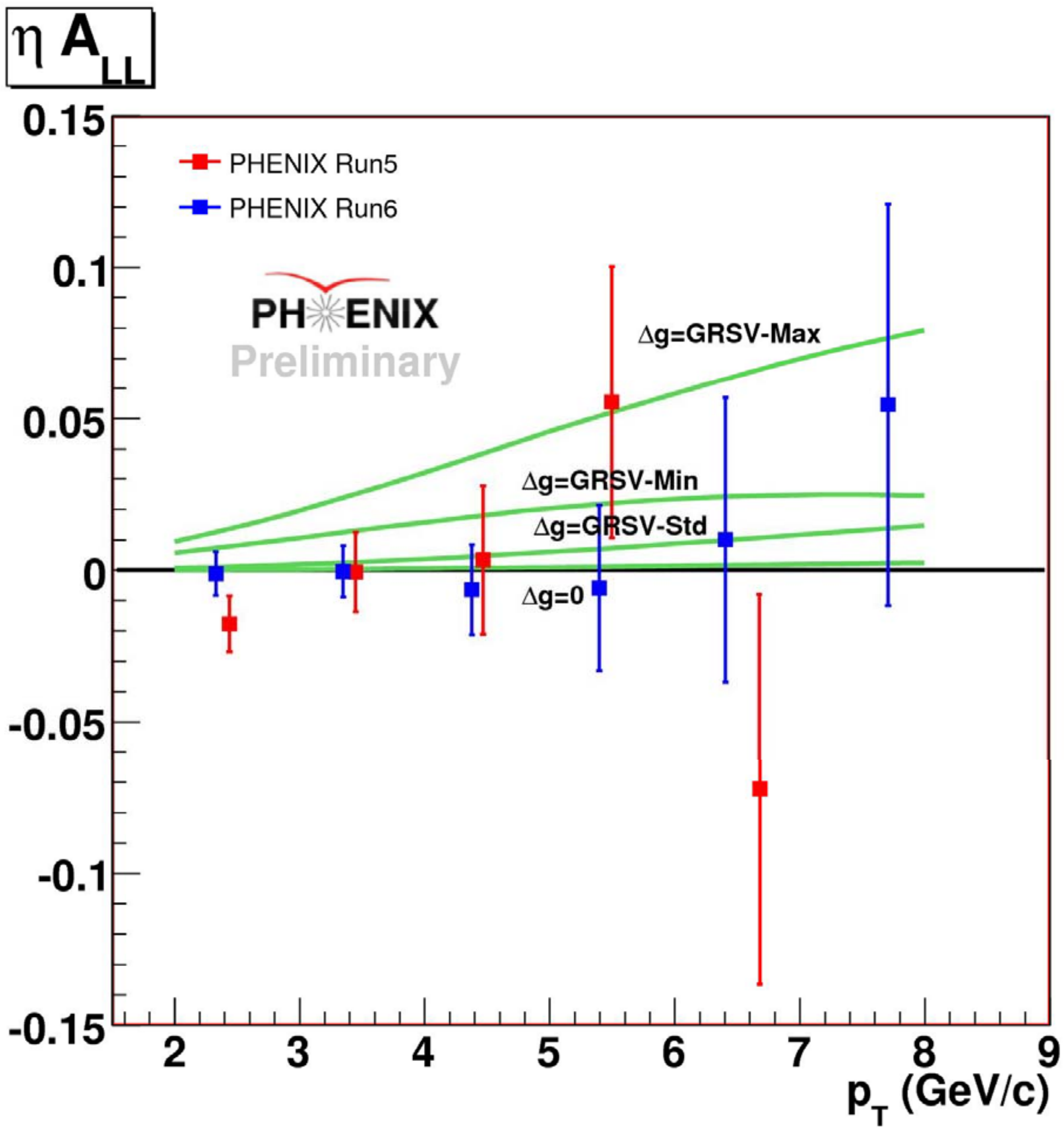


Run3 PRC 75,024909



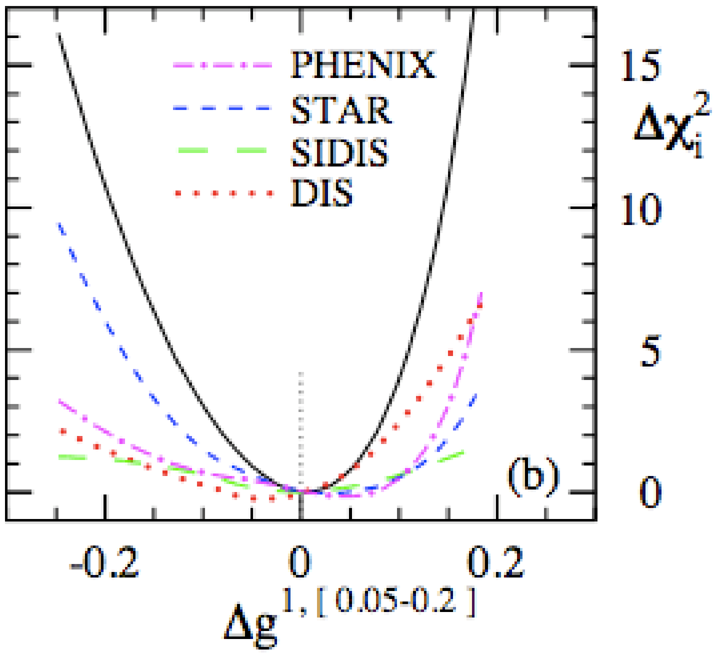
- Copiously produced, ~1/2 of π^0 yield
- Detect 40% which decay to diphotons
- Stronger coupling to gluon/strange
- Will be important at 500 GeV -photon merging at higher p_T

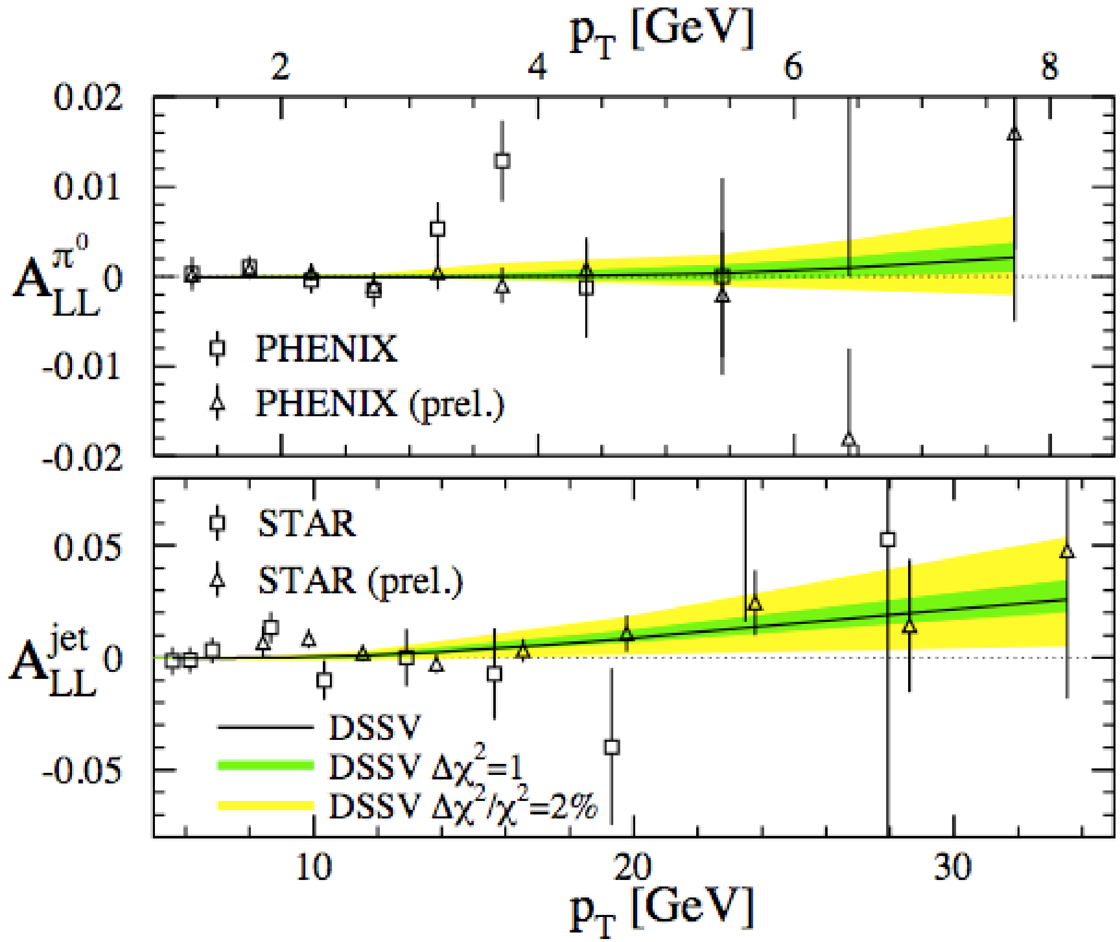
Physics Results : A_{LL} of η at sqrt(s)=200 GeV

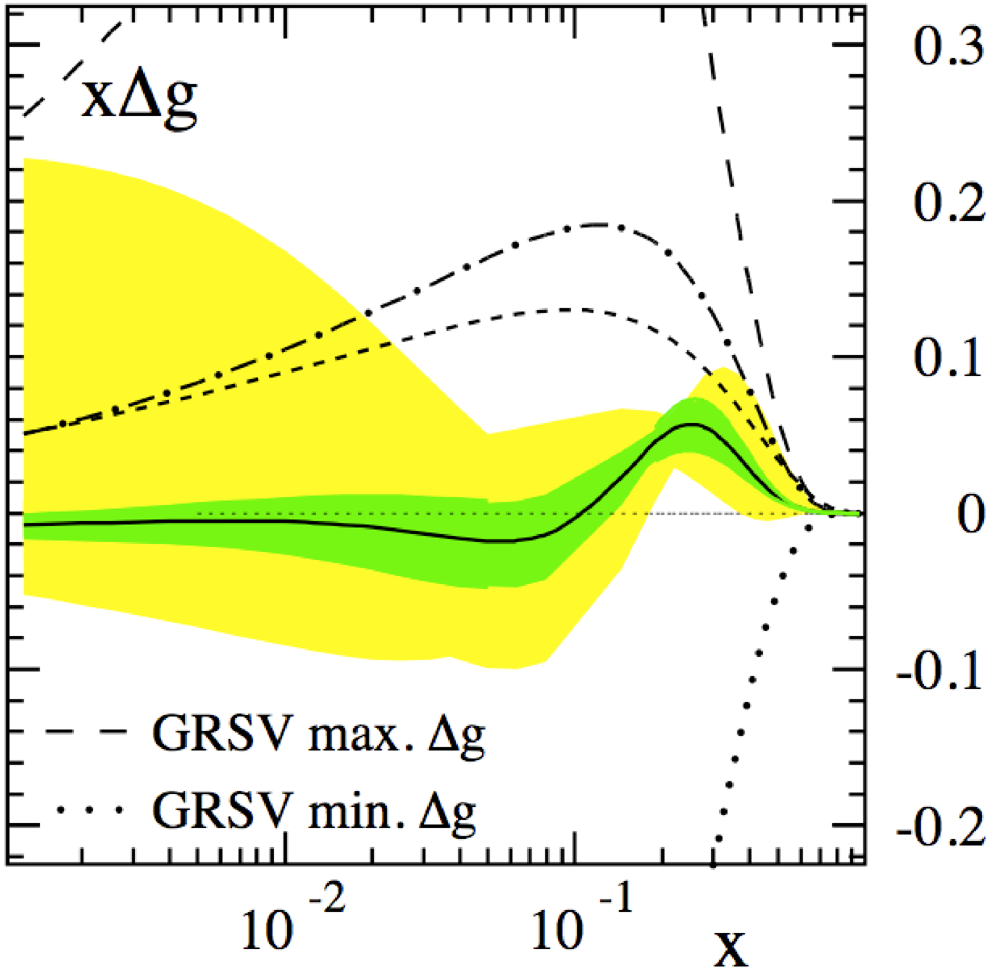


Physics Results : Implications of A_{LL} Measurements on $\Delta g(x)$

- RHIC results included for the first time in a global analysis (DSSV)
- $d\Delta\sigma = \sum_{ab} \int dx_a dx_b dz\, \Delta f_a(x_a,Q^2)\, \Delta f_b(x_b,Q^2)\, d\hat{\Delta}\sigma_{ab}(x_a,x_b,p_T,\alpha_s(Q^2))\, D_c^{\pi}(z,\mu)$
- D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, arXiv:0804.0422 [hep-ph]
- Used PHENIX $A_{LL}\ \pi^0$ and STAR A_{LL} inclusive jet in fits to $\Delta g(x)$ with DIS, semi-DIS
- Results show $\Delta g(x)$ small







(Green band $\Delta\chi^2$=1; Yellow band $\Delta\chi^2/\chi^2$=2%)

- $x\Delta g(x,Q^2) = Nx^{\alpha}(1-x)^{\beta}(1+\eta\, x)$

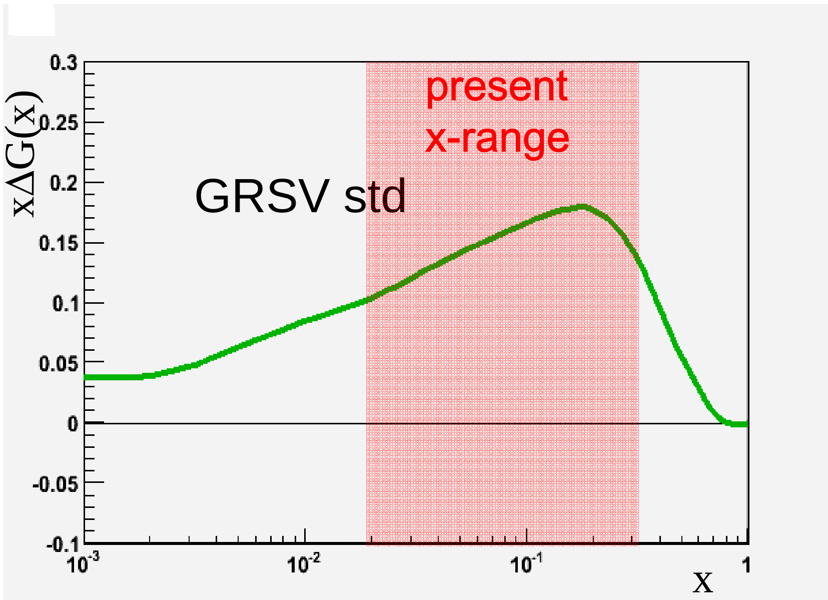
data prefer a node in $\Delta g(x)$ around x~0.1
future fits will allow different func.forms
$\Delta g(x)$ small, integral negative !
bulk of integral in unmeasured x<0.05 region, true for Gehrmann-Stirling C as well
important to measure at small x !!!

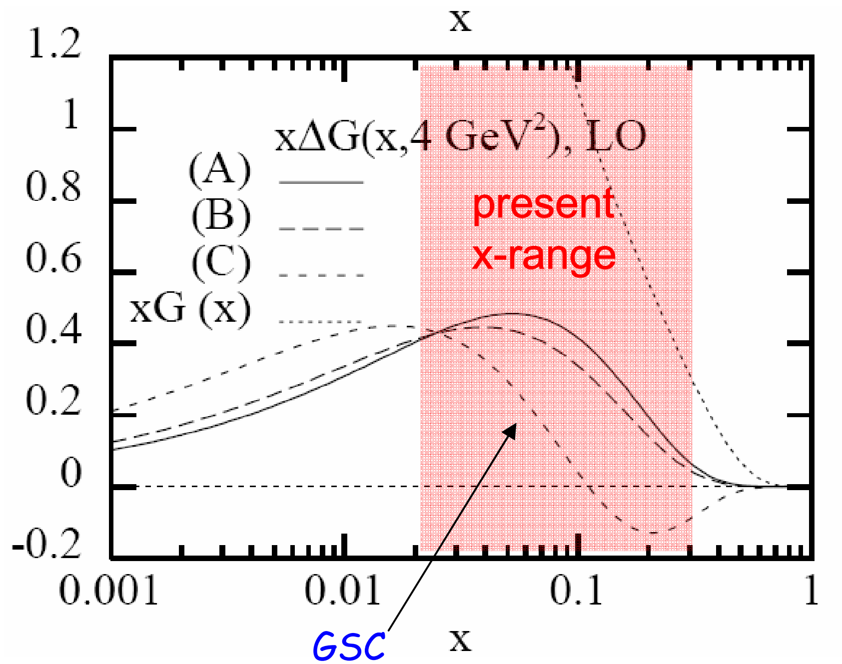
TABLE II: First moments $\Delta f_j^{1,[x_{\min}-1]}$ at $Q^2 = 10\,\mathrm{GeV}^2$.

	$x_{\min} = 0$	$x_{\min} = 0.001$	
	best fit	$\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
Δg	-0.084	$0.013\ ^{+0.106}_{-0.120}$	$0.013\ ^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

Importance of Determining $\Delta g(x)$ at low x

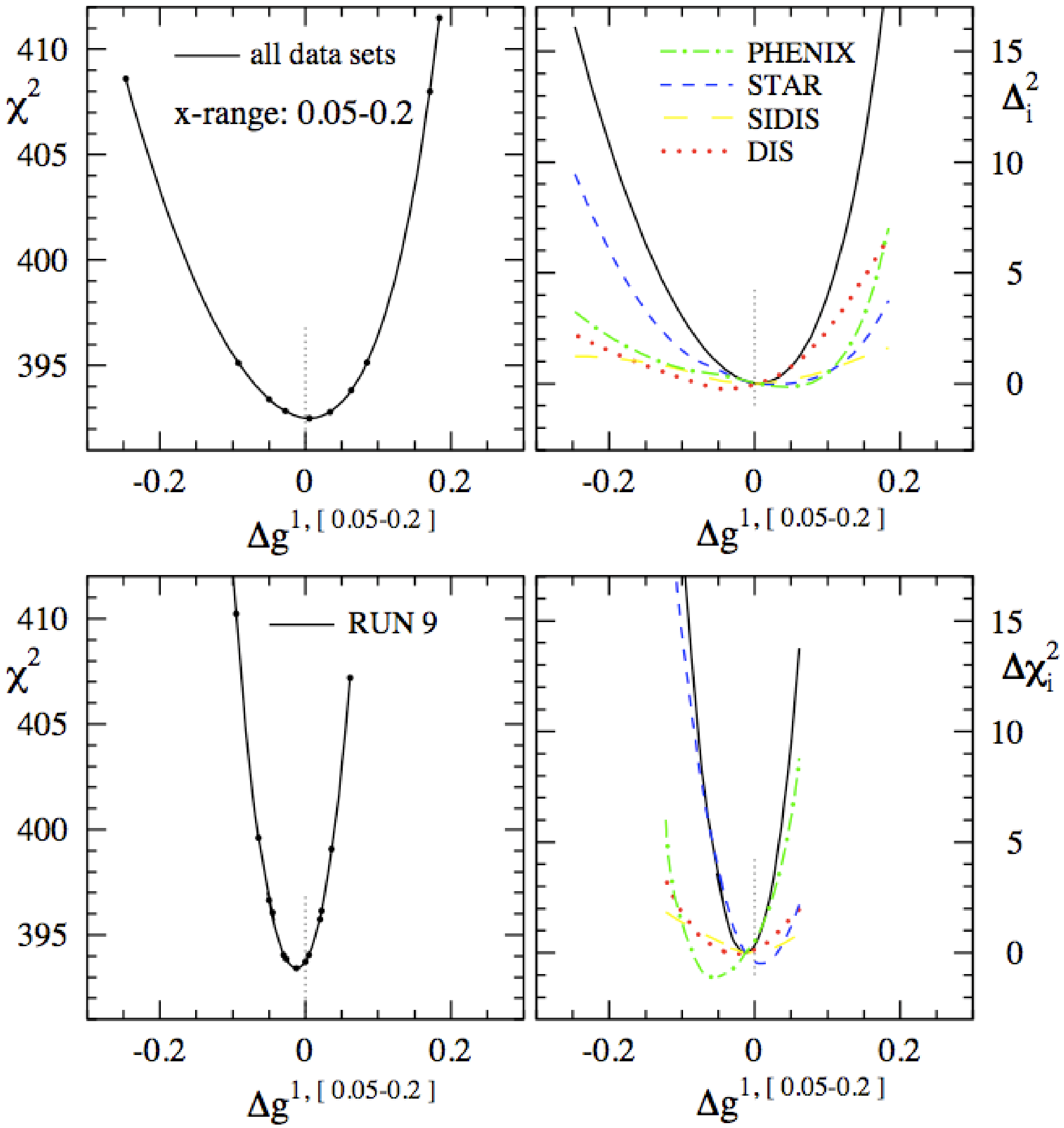
- The bulk of the first moment $\Delta G = \int_0^1 \Delta g(x)dx$ may be at low x
- Gehrmann-Stirling C : ΔG(x=0-->1) = 1, but ΔG(x=0.02-->0.3) ~ 0
- GRSV-0 : ΔG(x=0-->1) = 0, and ΔG(x=0.02-->0.3) ~ 0
- GRSV-std : ΔG(x=0-->1) = 0.4, and ΔG(x=0.02-->0.3) ~ 0.25
- DSSV : ΔG(x=0-->1) =-0.1, and ΔG(x=0.001--> 1) ~ 0.01





- Will need theoretical guidance to determine first moment
- Brodsky suggests Δg(x) ~ x g(x) at low x

Physics Results : Implications of A_{LL} Measurements on Δg

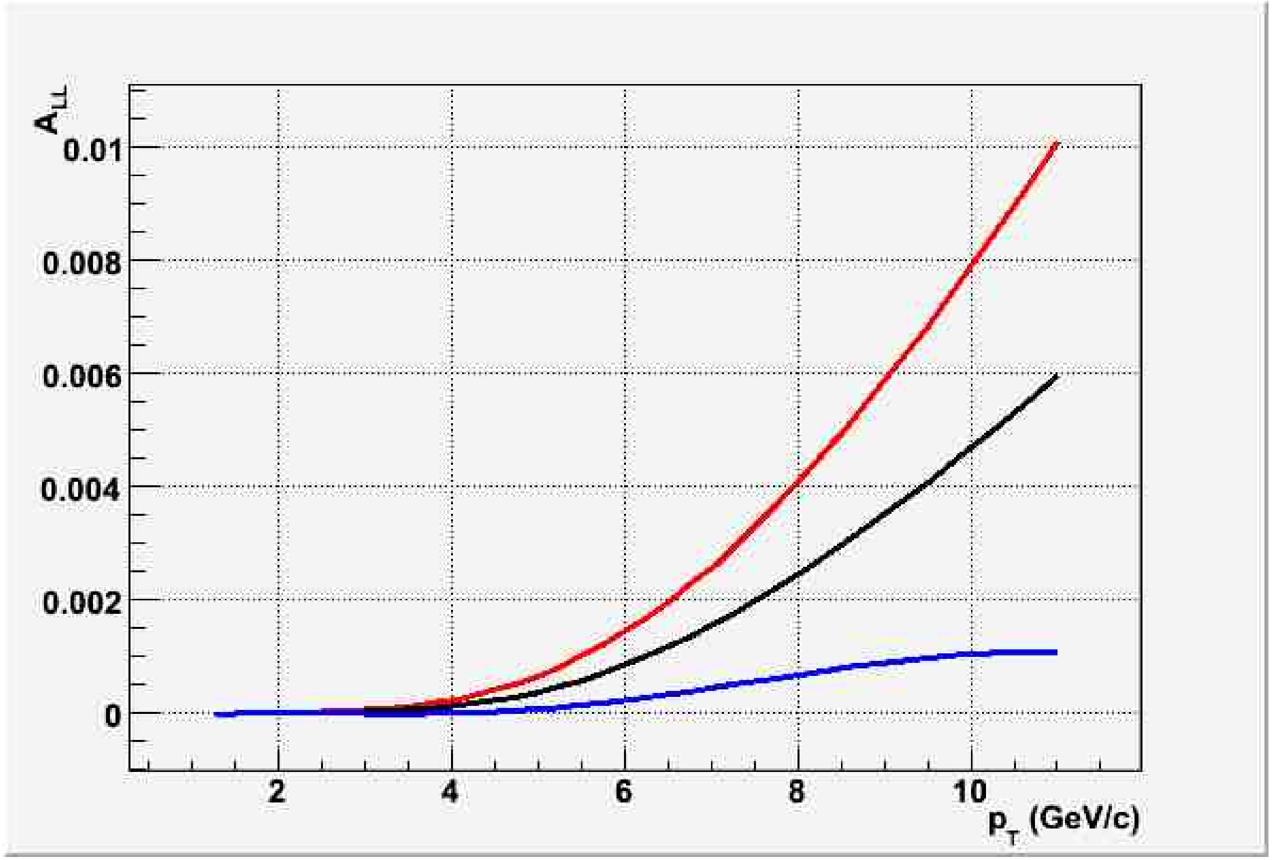


- Projected impact of Run 9 results
- Assume 25 pb^{-1} recorded, 60% pol
- A_{LL} statistical errors cut in 1/2
- Starting to see real progress in determining Δg

To Improve :

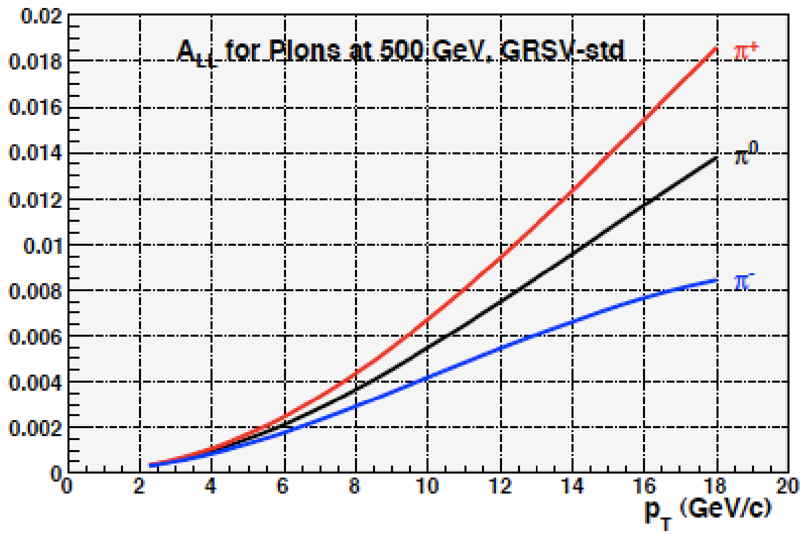
- need to go to lower x
  - run at 500 GeV
  - recall $x \sim p_T/\mathrm{sqrt}(s)$
  - should get factor 2.5 lower x
- Expand detector acceptance ($-0.35<\eta<0.35$, $\Delta\phi=\pi$) --> upgrades
- do correlation measurements (reconstruct partonic kinematics x_a, x_b)
- more running time !!!

Physics Results : Implications of A_{LL} Measurements on Δg



- A_{LL} π^+
- A_{LL} π^0
- A_{LL} π^-

- Using DSSV best fit to all data, can "predict" pion asymmetries
- Above plot (for 200 GeV cm energy) shows asymmetries very small
- Ordering A_{LL} $\pi^+ > \pi^0 > \pi^-$ since $\Delta g(x)$ mostly > 0 in x range probed by A_{LL} π
- Will need millions of events at $p_T > 6$ GeV/c to measure, several years



- Opportunity : At $\sqrt{s}$=500 GeV expect higher luminosity, will probe lower x (by factor 0.4)
- Cross-section higher at same p_T, corresponds to lower x hence smaller $\Delta q(x)/q(x)$, $\Delta g(x)/g(x)$
- Opportunity : Heavy flavor A_{LL} : can be measured at low p_T for lower x, but still describable by pQCD
- Challenge : Heavy flavor A_{LL} typically very small, 10^{-3}, sensitive to gg
- 2-particle Correlations : γ-jet, di-jet (forward-central,central-central), reconstruct parton kinematics, no FF
- $\eta = -\ln(\tan\theta/2)$, $x_1 = (p_T/\sqrt{s})(e^{+\eta_3} + e^{+\eta_4}), x_2 = (p_T/\sqrt{s})(e^{-\eta_3} + e^{-\eta_4})$
- Best x-resolution, help constrain functional form of $\Delta g(x)$?
- Correlation measurements : hadron-hadron (forward-central) : $\eta_1 \approx 0$, $|\eta_2| > 2$
- Probes $x_1 \gg x_2 \approx \text{few} \times 10^{-3}$, sensitive to $\Delta q(x_1)\Delta g(x_2)$, but asymmetries small

Long Term p-p Luminosity Projections

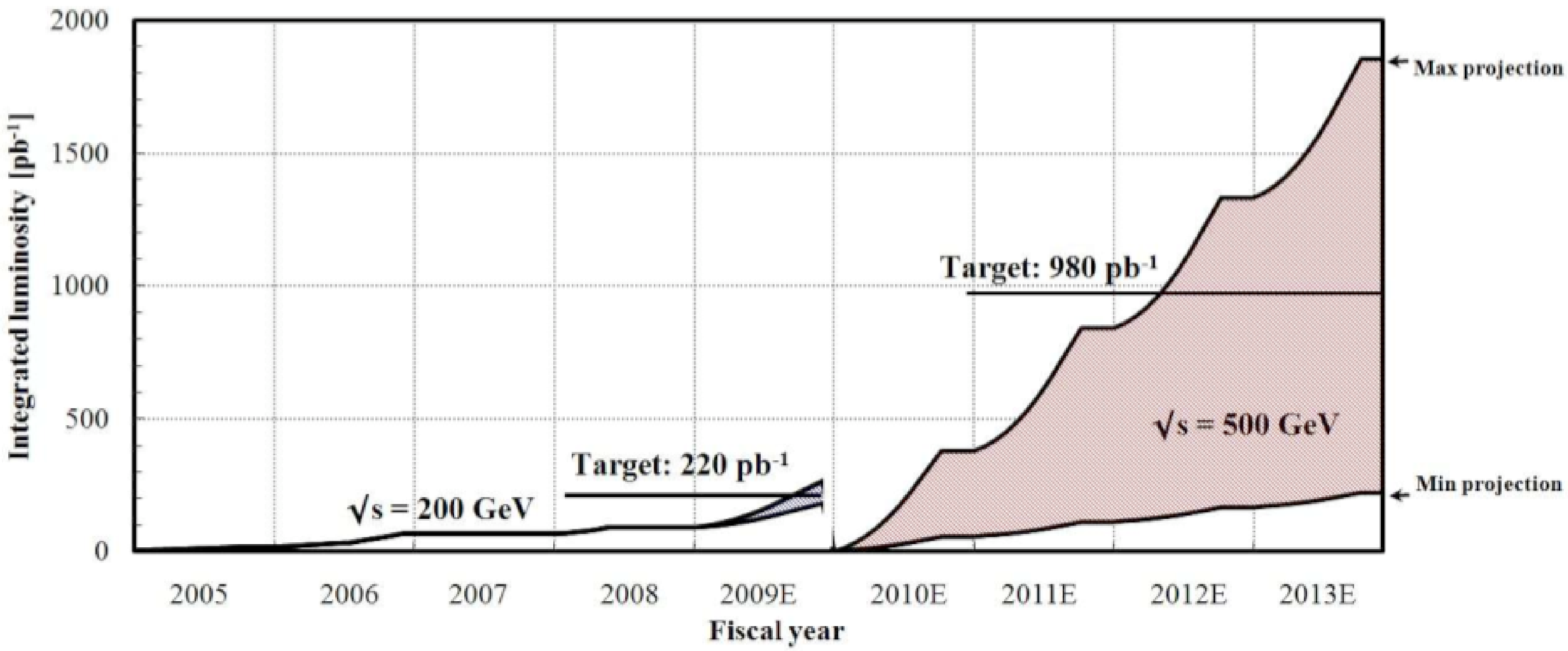
- With increased luminosity, run time, detector upgrades --> Best is yet to come !

Fiscal year		2006	2008	2009E	2010E	2011E	2012E	2013E
No of bunches	...	111	111	111	111	111	111	111
Protons/bunch, initial	10^{11}	1.4	1.5	1.8	1.9	2.0	2.0	2.0
Avg. beam current/ring	mA	187	205	250	264	280	280	280
β^*	m	1.0	1.0	0.8	0.7	0.6	0.6	0.5
Beam-beam parameter/IP	10^{-3}	5.6	4.9	6.1	7.4	7.5	7.5	7.5
Peak luminosity (200 GeV)	$10^{30}cm^{-2}s^{-1}$	28	35	63	96	121	129	137
Avg./peak luminosity	%	64	65	63	62	60	60	60
Avg. store luminosity (200 GeV)	$10^{30}cm^{-2}s^{-1}$	18	23	40	60	73	77	82
Time in store	%	46	60	60	60	60	60	60
Max luminosity/week (200 GeV)	pb^{-1}	6.5	7.5	14.5	21.6	26.4	28.0	29.8
Min luminosity/week (200 GeV)	pb^{-1}			7.5	7.5	7.5	7.5	7.5
Max luminosity/run (200 GeV)	pb^{-1}	46	19	130	150	180	200	210
Min luminosity/run (200 GeV)	pb^{-1}			70	50	50	50	50
Max luminosity/run (500 GeV)	pb^{-1}				375	450	500	525
Min luminosity/run (500 GeV)	pb^{-1}				125	125	125	125
AGS polarization, extraction, min/max	%	65[1]	55[1]	55/65	55/70	55/70	55/75	55/75
RHIC avg. store polarization, min/max	%	58	45	50/60	50/65	50/70	50/70	50/70

Long Term p-p Luminosity Projections : Best is yet to come

Table 3: Main hardware upgrades for RHIC Au-Au and p-p operation planned for FY 2009 to FY 2013.

	Au-Au	p-p
FY 2009	Blue longitudinal stochastic cooling Transverse stochastic cooling test	9 MHz rf system LEBT/MEBT modification
FY 2010	EBIS commissioning Transverse stochastic cooling, 1st plane 1st ring Transverse damper	Triplet vibration reduction
FY 2011	Transverse stochastic cooling, 1st plane 2nd ring	Electron lens 1st ring
FY 2012	56 MHz superconducting rf system (Transverse stochastic cooling, 2nd plane 1st ring)	56 MHz superconducting rf system Electron lens 2nd ring Polarized source upgrade
FY 2013	(Transverse stochastic cooling, 2nd plane 2nd ring)	



Relative Luminosity Measurement at PHENIX : Limiting Systematic?

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$
$$= \frac{1}{|\langle P_b P_y \rangle|} \cdot \frac{N_{++} - R \cdot N_{+-}}{N_{++} + R \cdot N_{+-}}; \quad R = \frac{L_{++}}{L_{+-}}$$
$$\frac{\partial A_{LL}}{\partial R}\delta R \approx \frac{1}{2|\langle P_b P_y \rangle|}\delta R$$

- To measure 1% asymmetry with $P_{beam} \approx 50\%$, need $\delta R < 10^{-3}$
- Higher polarization reduces sensitivity to uncertainty in R
- Order of magnitude requirement : $\delta R \leq \text{few} \times 10^{-4}$

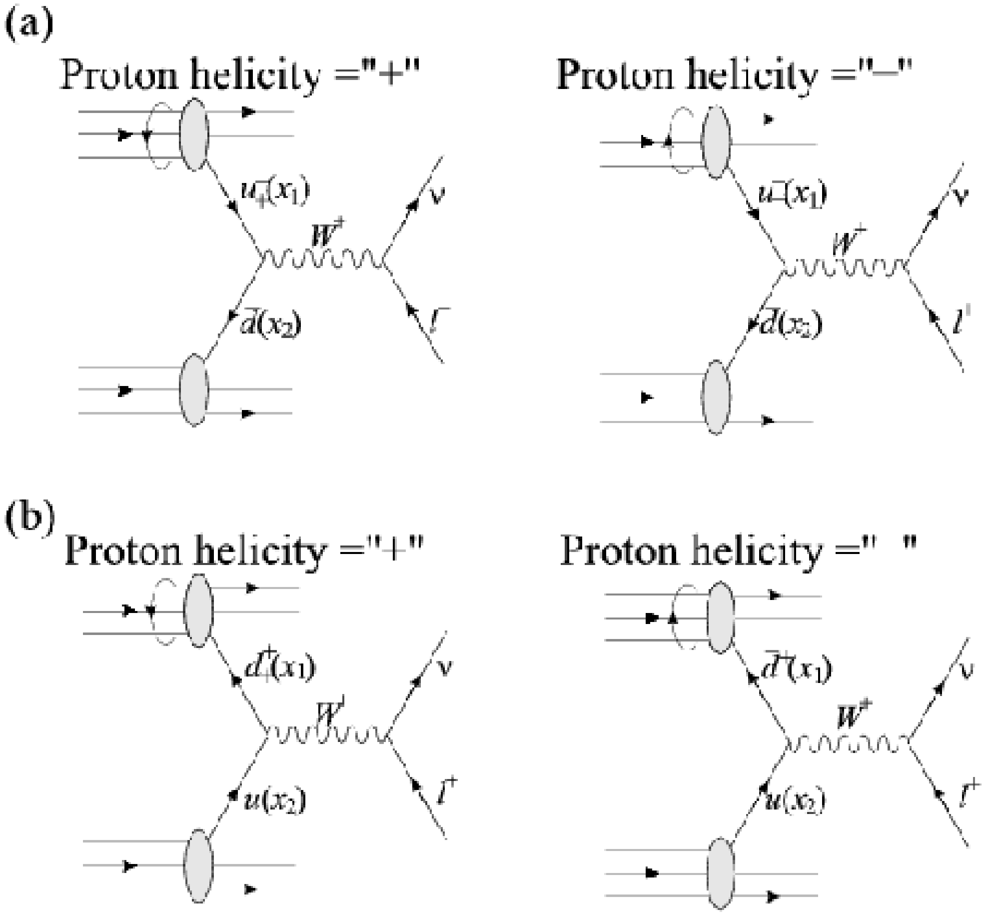
Upcoming Complications :

- At design luminosity, $\mathcal{L} = 2.0 \times 10^{32}$cm^{-2}s^{-1}, expect ≈ 1 pp collision/crossing
- 25 percent of all crossings may contain 2 or more pp collisions
- Our luminosity monitors can't reliably distinguish 1 from 2 collisions : we tend to undercount
- At high rates, we make mistakes reconstructing vertex, can trigger on two events outside of acceptance
- Some cancellation between the effects
- Have some good tools : spin flipper makes $R = 1$ by flipping all spins in 1 beam
- Can recog beams - change which bunches are colliding
- Ultimate systematic limit may be due to relative spin dependence in luminosity monitors BBC, ZDC

- Upcoming milestone : first Ws to be produced and detected at BNL in 2009 or 2010
- First recall importance of the measurements :

- Inclusive polarized DIS, $\Delta\sigma \propto e_q^2$, measures combination $\Delta q(x) + \Delta\bar{q}(x)$
- Semi-inclusive polarized DIS, $lp \rightarrow l'hX$, attempt to separate $\Delta q(x)$ from $\Delta\bar{q}(x)$,
  - requires knowledge of fragmentation functions
- W from polarized pp at RHIC can determine $\Delta q(x)$ and $\Delta\bar{q}(x)$ separately, no FF
- Thanks to RIKEN and current upgrades, 2 muon arms to detect $W \rightarrow \mu\nu$, 1.2< $|\eta_\mu|$ <2.2
- In the central arms, detect $W \rightarrow e\nu$, -0.35< $|\eta_e|$ <0.35
- Unpolarized ratio $\bar{d}(x)/\bar{u}(x)$ is large
- Is polarized ratio $\Delta\bar{d}(x)/\Delta\bar{u}(x)$ also large?
- This is great physics!

V-A Production of Ws



(a) Δu probed in the polarized proton (at top) : u always left-handed, independent of proton spin

(b) $\Delta \bar{d}$ probed in the polarized proton : $\bar{d}$ always right-handed, independent of proton spin

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

V-A Production of Ws

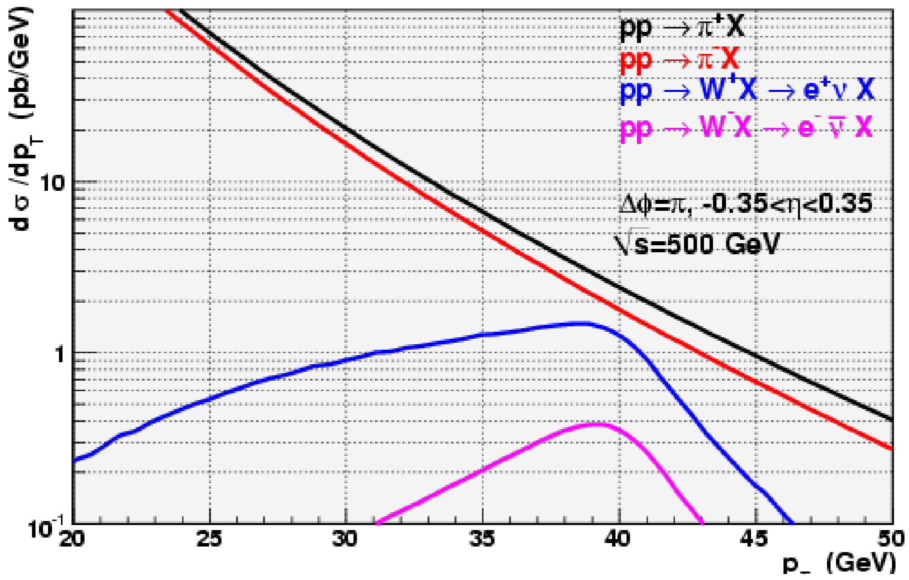
(Remember, need left-handed u, and right-handed $\bar{d}$ to make W^+)

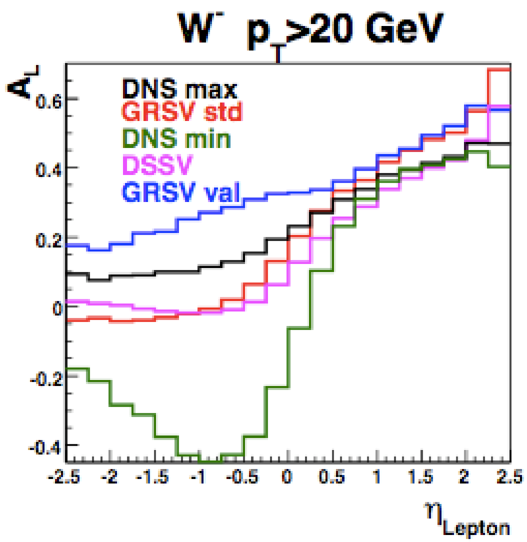
$$\begin{aligned}
\sigma_+^{W+} &\propto u^-(x_1)\bar{d}(x_2) + \bar{d}^+(x_1)u(x_2) \\
\sigma_-^{W+} &\propto u^+(x_1)\bar{d}(x_2) + \bar{d}^-(x_1)u(x_2) \\
\sigma_-^{W+} - \sigma_+^{W+} &\propto \Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)
\end{aligned}$$

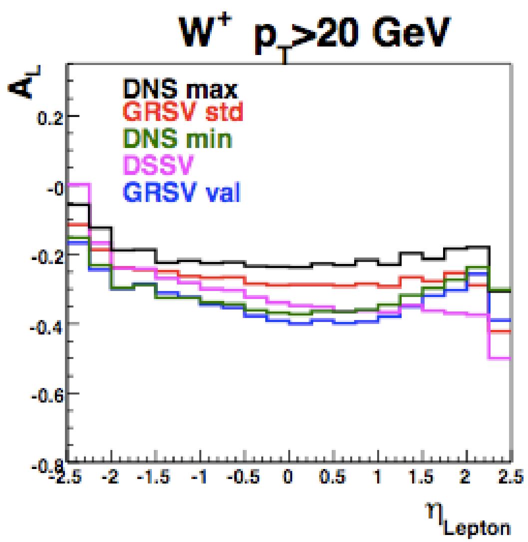
$$\begin{aligned}
A_L^W &= \frac{1}{P}\frac{N_-(W) - N_+(W)}{N_-(W) + N_+(W)} \\
A_L^{W+} &= \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \\
A_L^{W-} &= \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}
\end{aligned}$$

- At positive y_{W+}, $x_1 > x_2$, measure $\Delta u(x)/u(x)$
- At negative y_{W+}, $x_1 < x_2$, measure $-\Delta d(x)/d(x)$
- Expect *positive* asymmetries for $W^+ \to e^+\nu$
- Experimental observable will be lepton kinematics, not W kinematics

W Physics with the PHENIX Detector at RHIC







- W-->eν in central arms, 25 pb^{-1} for W^+, 4 pb^{-1} for W^- (RhicBos, Nadolsky and Yuan)
- Will need 1000 pb^{-1} delivered to get order 10K events
- Beat down QCD background with E/p, shower shape, isolation cuts
- Asymmetries reasonably large
- Expect to distinguish different polarized sea quark distributions
- x range overlaps with HERMES, but primarily at higher x

- Spin program well underway: have made measurements of A_{LL} of π^0, $\pi^\pm$, η
- Cross-sections for π, η, direct photon consistent with NLO pQCD
- Other measurements : single spin asymmetries, J/Ψ, helicity dependent k_T, spin transfer in Λ, ...

- First inclusion of pp data in global fits : extremely satisfying to see we are making progress
  - $\Delta g(x)$ is small, may have a node, first moment ≤ -0.1 !!!
- Collider luminosity is expected to improve significantly : bulk of data still to come
- Run 9 results should have twice the significance of Run 6, further constraining Δg
- Detector upgrades will add enormously to PHENIX acceptance
- Look forward to many new measurements with sensitivity to $\Delta g(x > \text{few} \times 10^{-3})$
- Challenge : asymmetries are small (need spin flipper to reduce δR)
- Treatment of low x extrapolation is open question (mostly for theorists?)
- Will determine $\bar{\Delta} q(x)$ distributions with upcoming W program
- Very interesting times ahead - but we really need luminosity/running time !