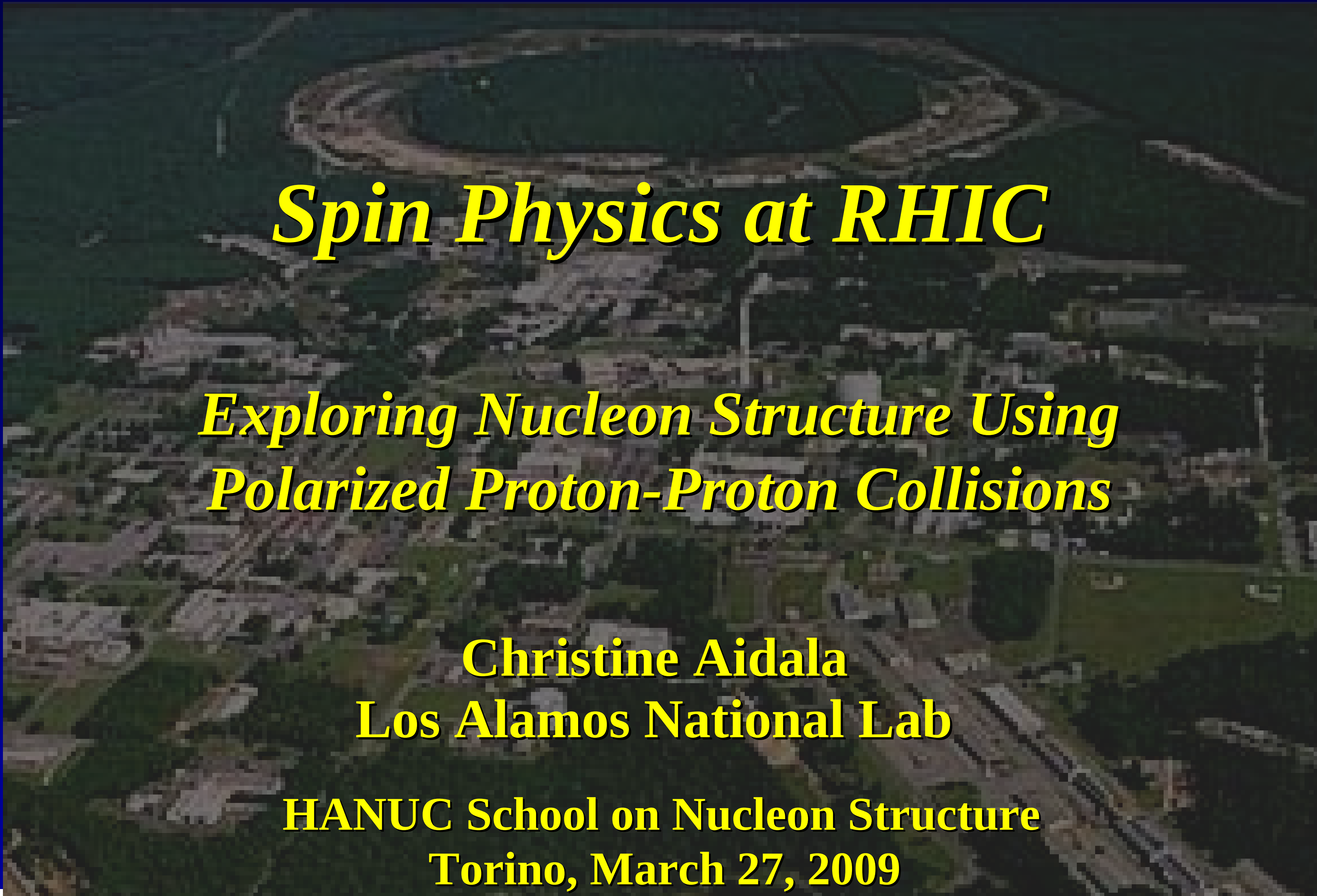


Spin Physics at RHIC

Exploring Nucleon Structure Using Polarized Proton-Proton Collisions

Christine Aidala
Los Alamos National Lab

HANUC School on Nucleon Structure
Torino, March 27, 2009

What is RHIC?

The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

New York City

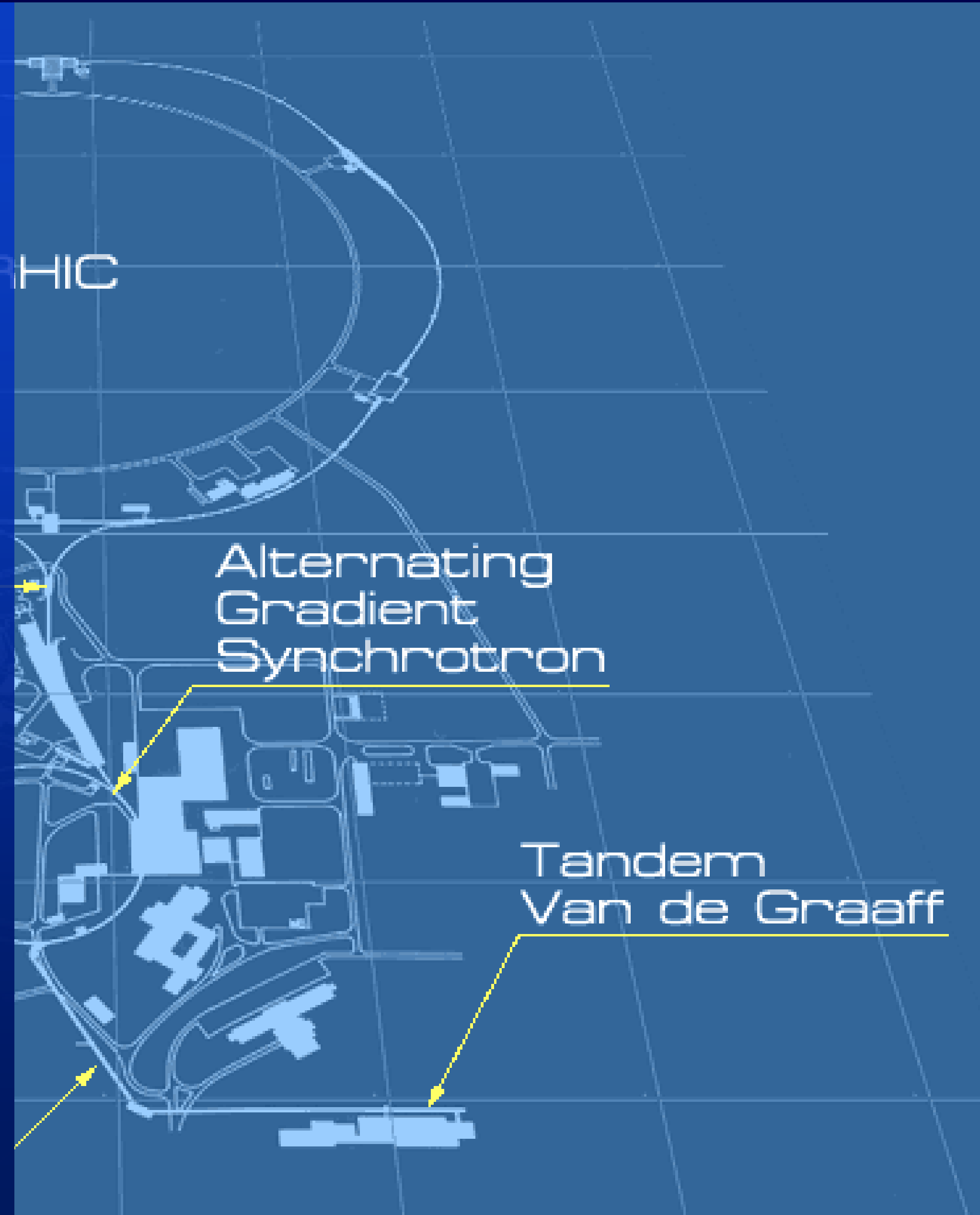
Overview of RHIC Physics

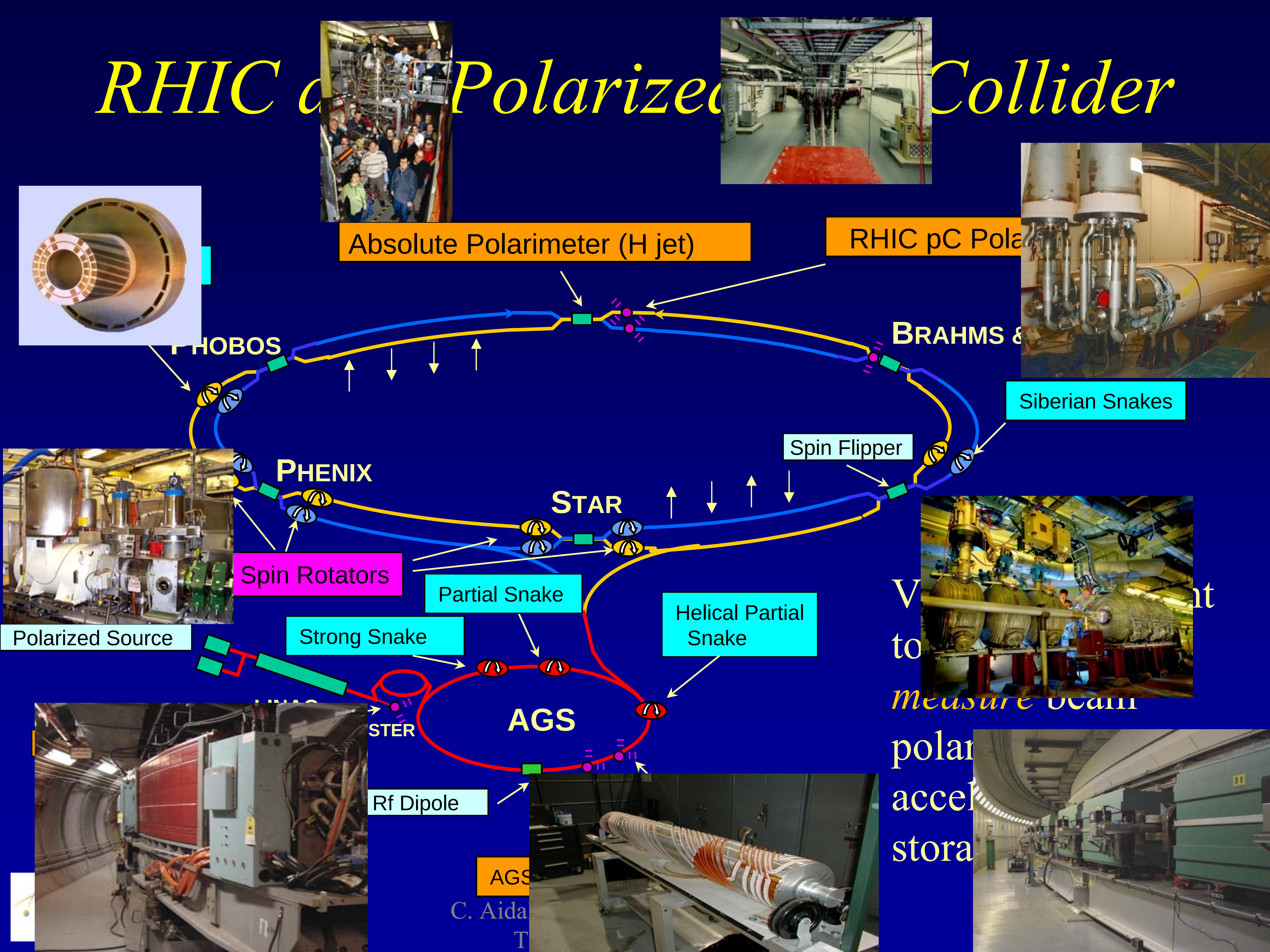
Broadest possible study of QCD in nucleus-nucleus ("heavy ion"), proton-nucleus, proton-proton collisions

- *Heavy ion physics*
    - Investigate nuclear matter under extreme conditions
    - Examine systematic variations with species and energy
- *Nucleon structure in a nuclear environment*
    - Nuclear dependence of pdf's
    - Gluon saturation physics
- ***Explore the spin of the proton***
    - In particular, contributions from
        - Gluon polarization (ΔG)
        - Sea-quark polarization $\left(\Delta\bar{u}, \Delta\bar{d}\right)$
        - Transversity distributions (δq)

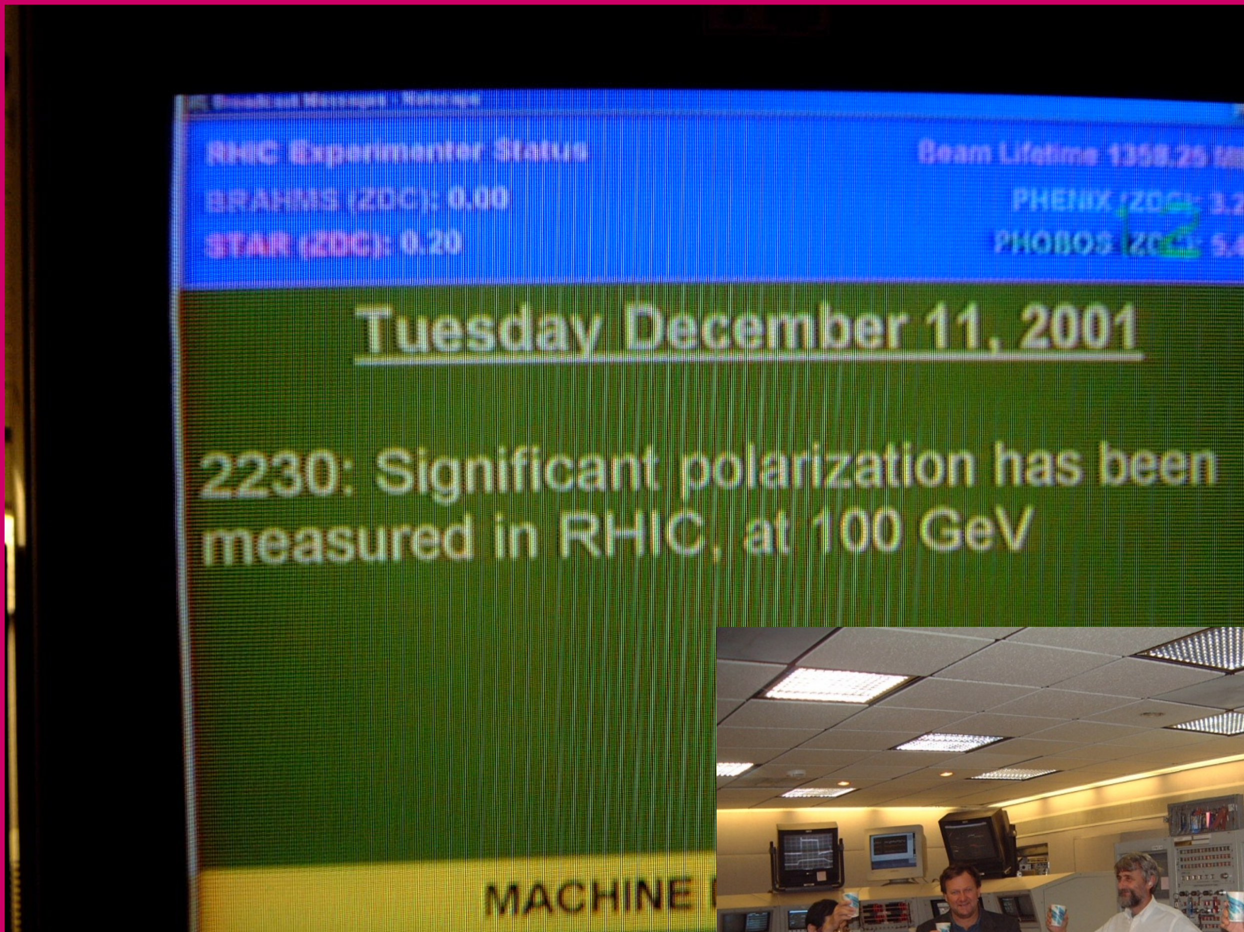
RHIC Collider Specifications

- 3.83 km circumference
- Two independent rings
  - Up to 120 bunches/ring
  - 106 ns crossing time
- Energy: (c.m.)
  - è 50 to 500 GeV for p+p
  - è 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>*)





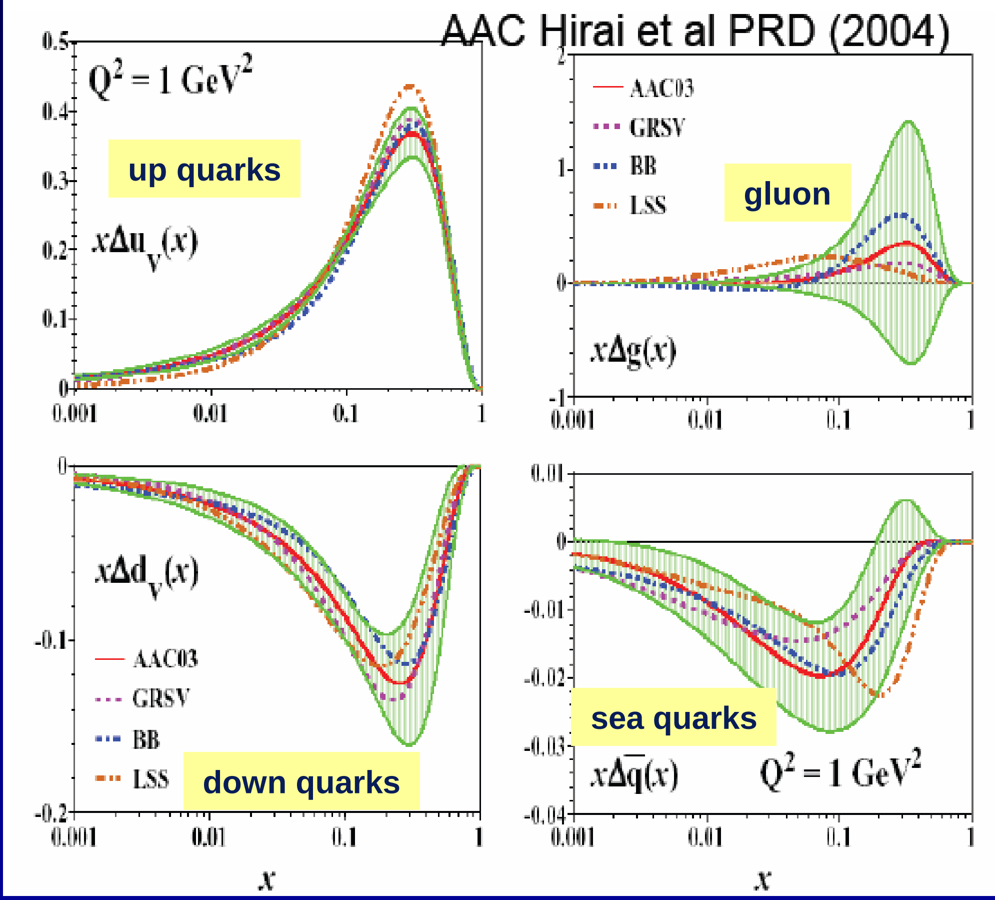
News to Celebrate



Why go through all the trouble to polarize the proton beams at RHIC?

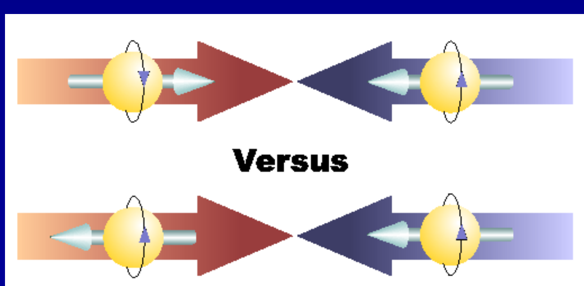
A Polarized Proton Collider: Opportunities . . .

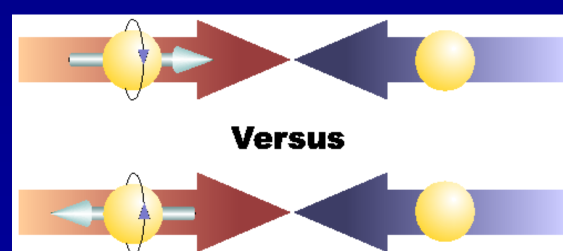
- Proton-proton collisions → Direct access to the gluons via gluon-quark, gluon-gluon scattering
  - Polarized gluon distribution not well known!
- High energy provided by a collider allows production of new probes, e.g. W bosons
  - Useful to probe flavor-separated polarized sea quarks
- High energy allows clean use of theoretical tools
  - Factorized perturbative quantum chromodynamics (pQCD)

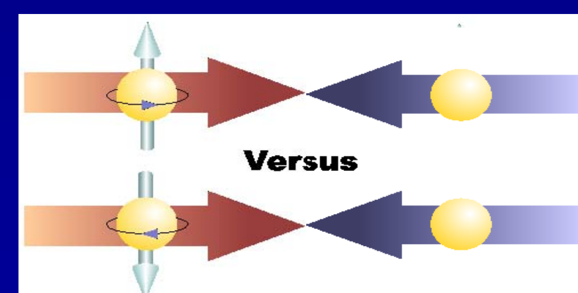


Proton Spin Structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π, Jets $A_{LL}(gg, gq \rightarrow \pi + X)$ Prompt Photons $A_{LL}(gq \rightarrow \gamma + X)$ Back-to-Back Correlations	**W Production** $A_L(u + \bar{d} \rightarrow W^+ \rightarrow \ell^+ + \nu_l)$ $A_L(\bar{u} + d \rightarrow W^- \rightarrow \ell^- + \bar{\nu}_l)$	**Transversity** **Transverse-momentum-dependent distributions** Single-Spin Asymmetries



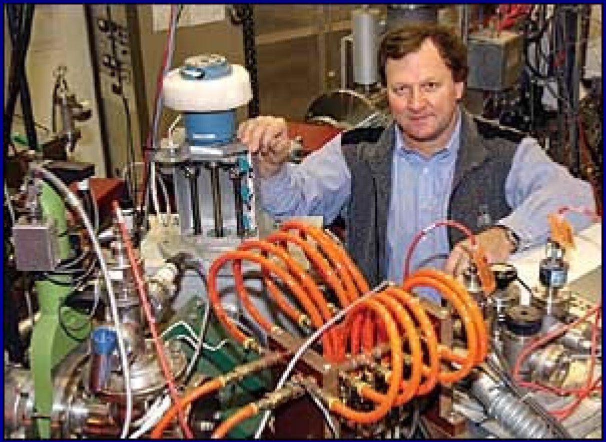




How do you polarize proton beams, try to maintain the polarization through acceleration up to hundreds of GeV, and know that you succeeded?

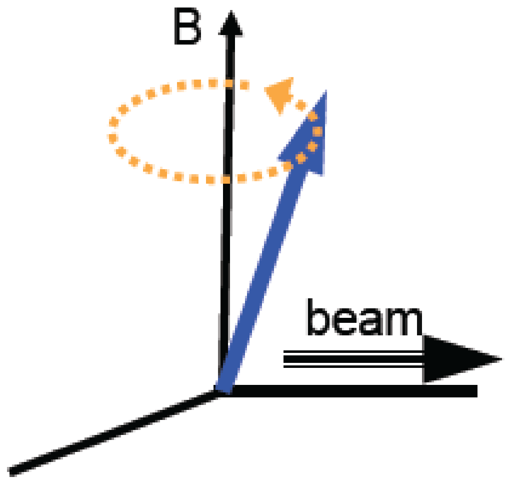
Polarized Source

- Optically pumped polarized H^- ion source (OPPIS)
- Polarization of 86-90% achieved!
- 0.5-1.0 mA current in routine operation (1.6 mA max)
- Start with primary proton beam of ~3.0 keV
- Polarized electron pick-up in optically pumped Rb vapor cell → H atom with polarized e-
- Transfer polarization to proton via hyperfine interaction (Sona transition)
- Negatively ionized in Na-jet vapor cell for subsequent acceleration



Spin motion in a circular accelerator

- In a perfect accelerator, spin vector precesses around its guiding field along the vertical direction



- Spin tune Q_s: number of precessions in one orbital revolution. In general,

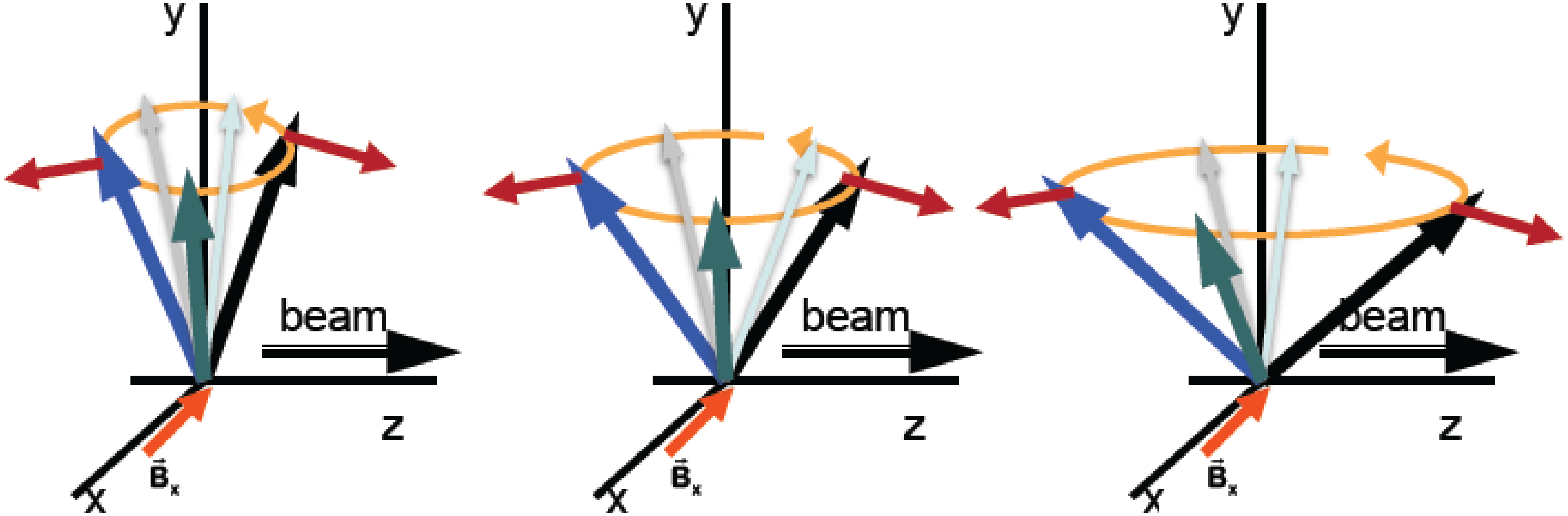
$$Q_s = G\gamma$$

From Mei Bai

BROOKHAVEN NATIONAL LABORATORY

Depolarizing mechanism in a synchrotron

- horizontal field kicks the spin vector away from its vertical direction, and can lead to polarization loss
  - dipole errors, misaligned qadrupoles, imperfect orbits
  - betatron oscillations
  - other multipole magnetic fields
  - other sources



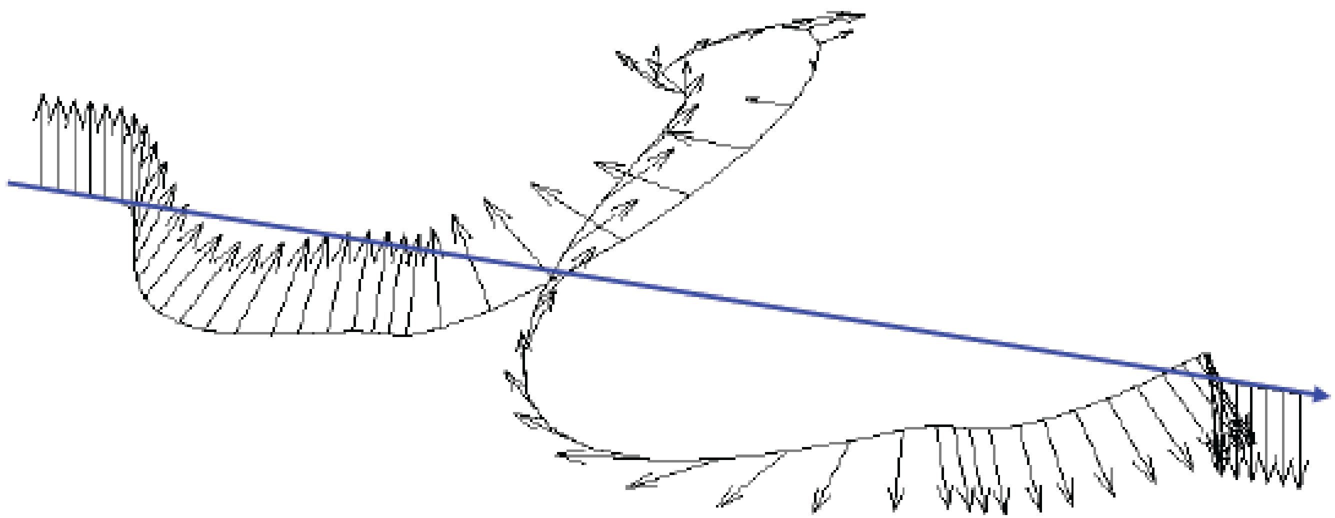
Initial

1st full betatron Oscillation period

2nd full betatron Oscillation period

Innovative polarized proton acceleration technique: Full Siberian snake

- First invented by Derbenev and Kondratenko from Novosibirsk in late 1976
- A group of dipole magnets with alternating horizontal and vertical dipole fields
- rotates spin vector by 180°



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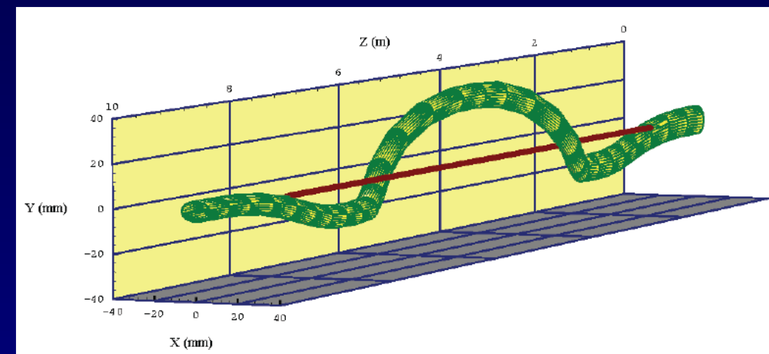
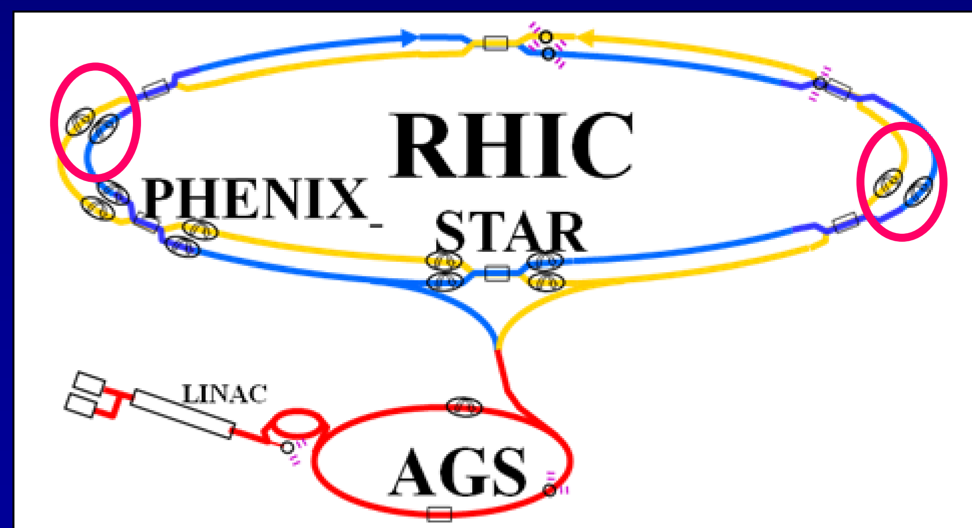
"Siberian Snakes" To Maintain Polarization

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





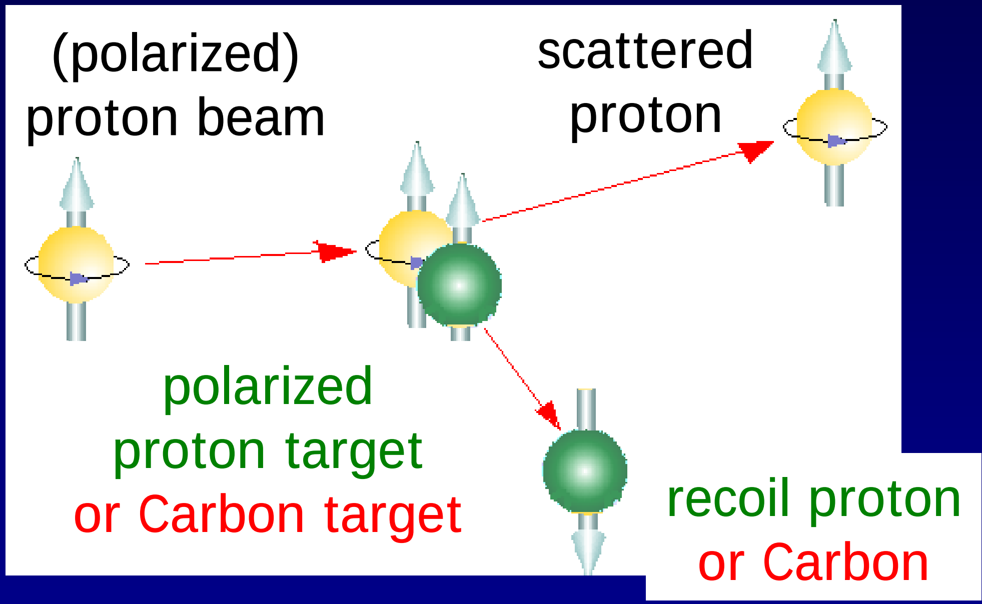
- 4 helical dipoles in each snake
- 2 snakes in each ring
    - axes orthogonal to each other

Did You Maintain Polarization?
RHIC Polarimetry

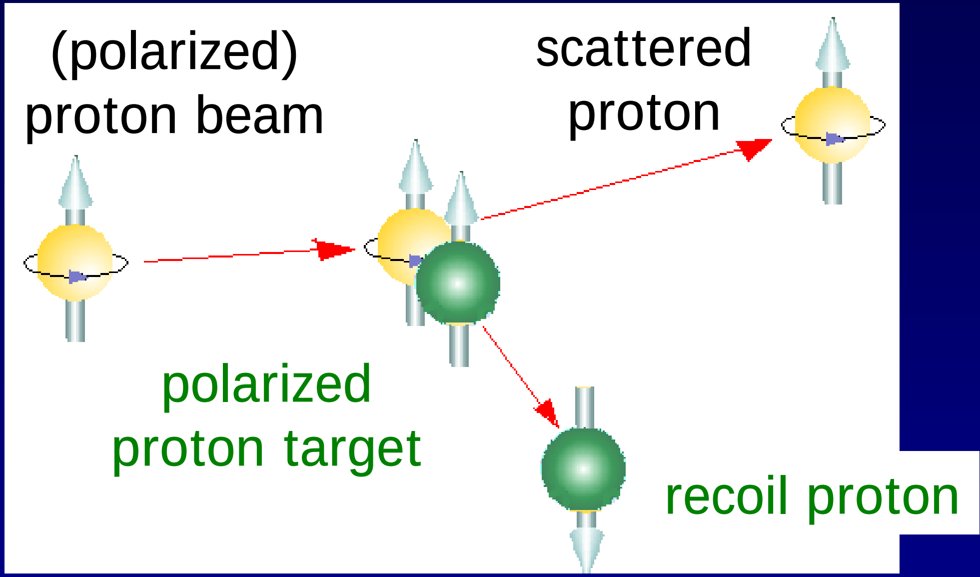
- Proton-carbon (pC) polarimeter
  - For *fast* measurements (< 10 s!) of beam polarization
  - Take several measurements during each fill
- Polarized hydrogen-jet polarimeter
  - Dedicated measurements (~weeks) to calibrate the pC polarimeter

Polarimetry (cont.)

- E950 experiment at AGS became RHIC pC polarimeter
  - Measure P_{beam} to ~30%
- H jet polarimeter designed to determine P_{beam} to 5%
  - Achieved uncertainty $\delta P/P$ of 4.2% in 2008!
- Both use asymmetries in processes that are already understood to determine the beam polarization



Hydrogen-Jet Polarimeter for Beams at Full Energy



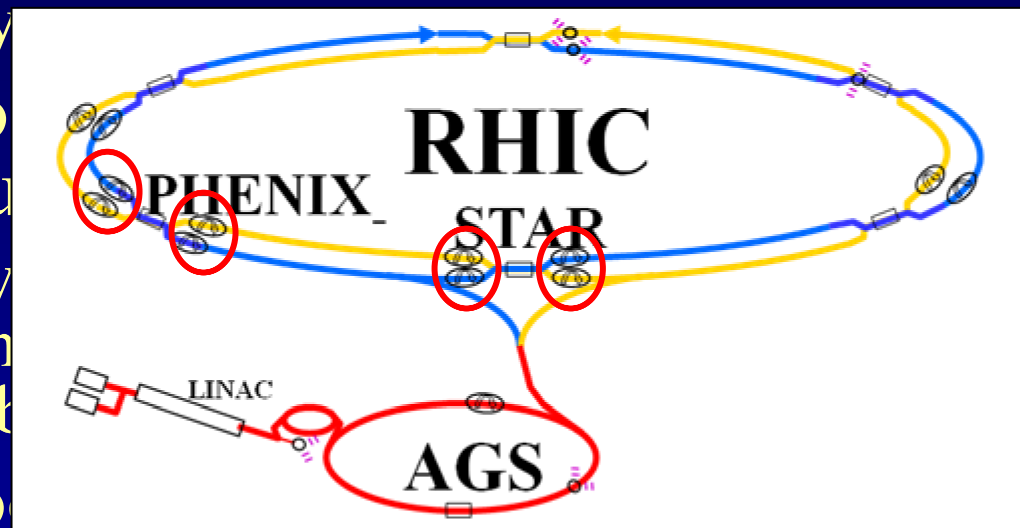
- Use transversely polarized hydrogen target and take advantage of transverse *single*-spin asymmetry in elastic proton-proton scattering
- Only consider single polarization at a time. ***Symmetric process!***
  - Know polarization of your target
  - Measure analyzing power in scattering
  - Then use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

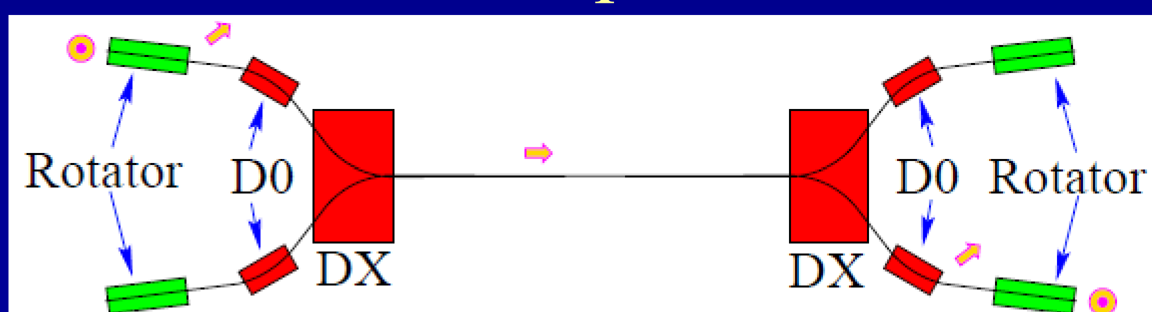
$$A_N = \frac{1}{P_{\text{target}}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

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

Controlling the Spin Direction for Experiments: Spin Rotator Magnets

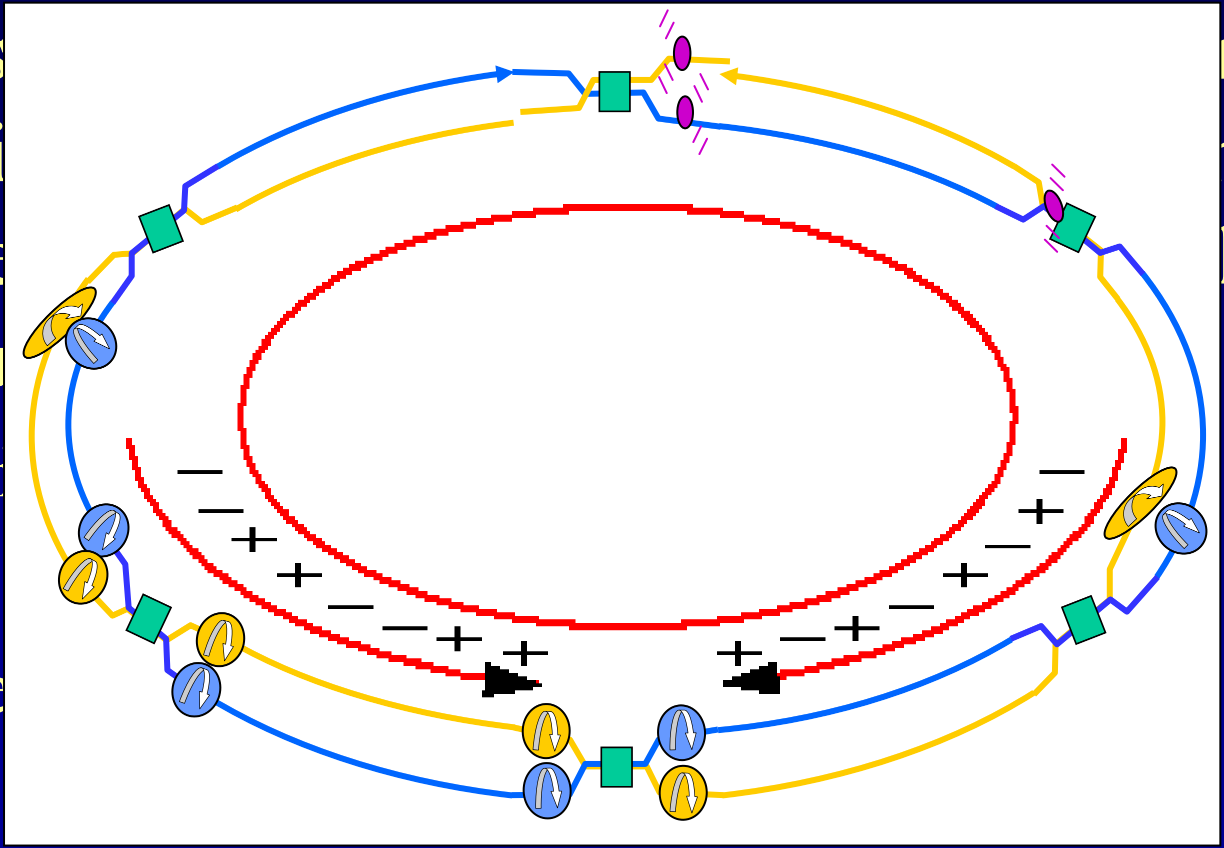
- Stable spin direction around the ring is vertical
  - Spin direction remains constant as direction of momentum changes continuously
- Spin rotator AC dipo direction for individu
  - One set rotates spin v before beam enters th it back to vertical as b
- Experiments can cho





Choosing Bunch-by-Bunch Spin Patterns to Control Systematics

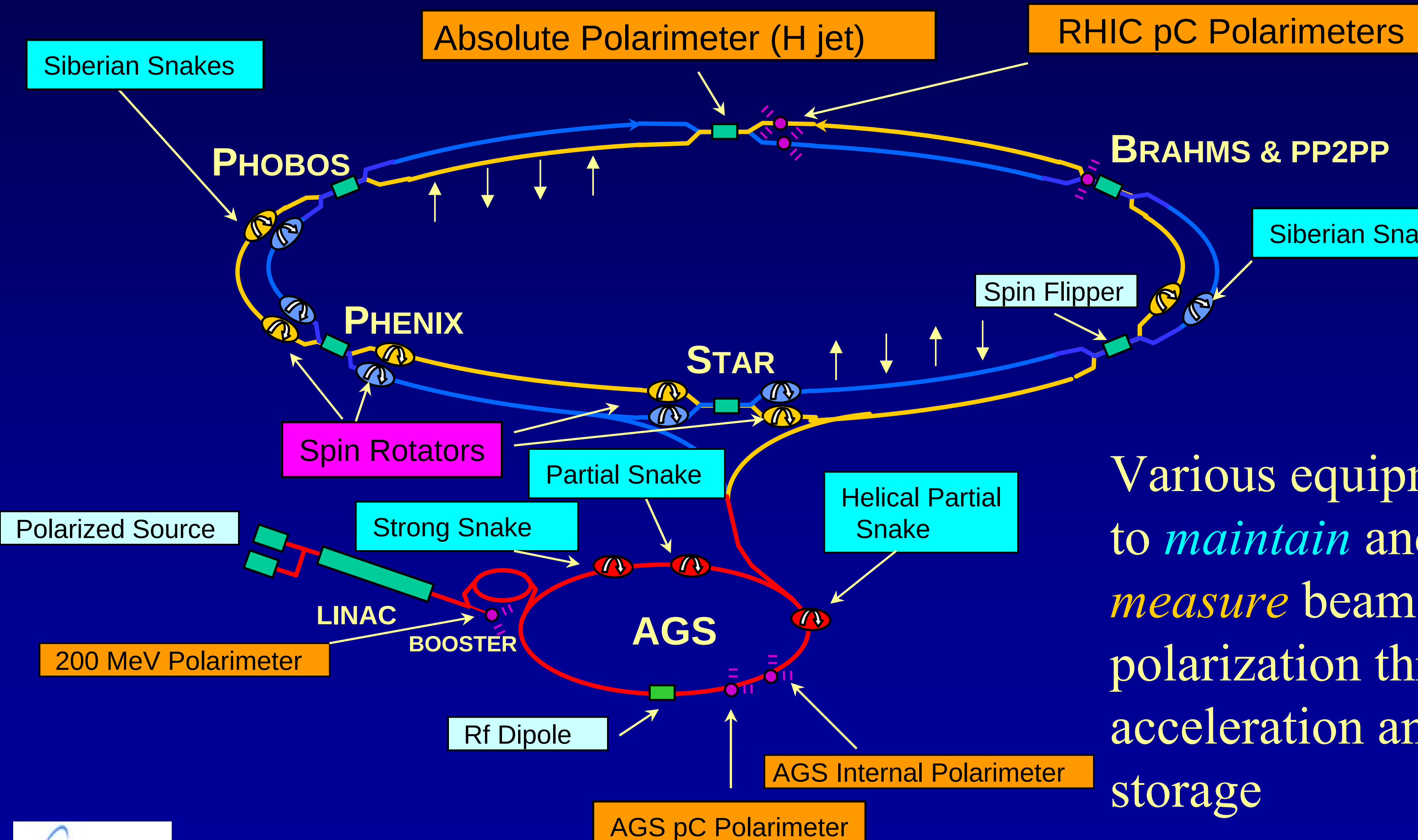
- Choos... n directi... ns to reduce... l measu...
  - Typi...
  - 106 ...
  - Like...



Spin Flipper for Further Control of Systematic Effects

- AC dipole magnet that "flips" spin of all protons in beam by 180 degrees
- Turn on, then off again to flip spins only once, e.g. halfway through a many-hour machine fill (unlike Siberian snakes, which must operate continuously to avoid depolarization of beam)
- Reduce possible effects due to bunch-by-bunch variations in polarization and luminosity
- Not yet fully commissioned—hasn't been needed, as other uncertainties have dominated measurements so far

RHIC as a Polarized p+p Collider



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

So how well does that all really work?

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**

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Performance Status

- Polarized source performance has exceeded design
- Polarimetry has exceeded design
- Highest polarization for 100 GeV beams achieved so far in RHIC ~65% (design 70%); Maximum achieved average polarization over many weeks 57%
  - Still working to improve further!
- Maximum average luminosity with high polarization 2×10^{31} cm^{-2} s^{-1} (design 2×10^{32})
  - Some trade-off between luminosity and polarization currently required in AGS
  - Still working to improve further!

Polarized Collisions at Different Energies

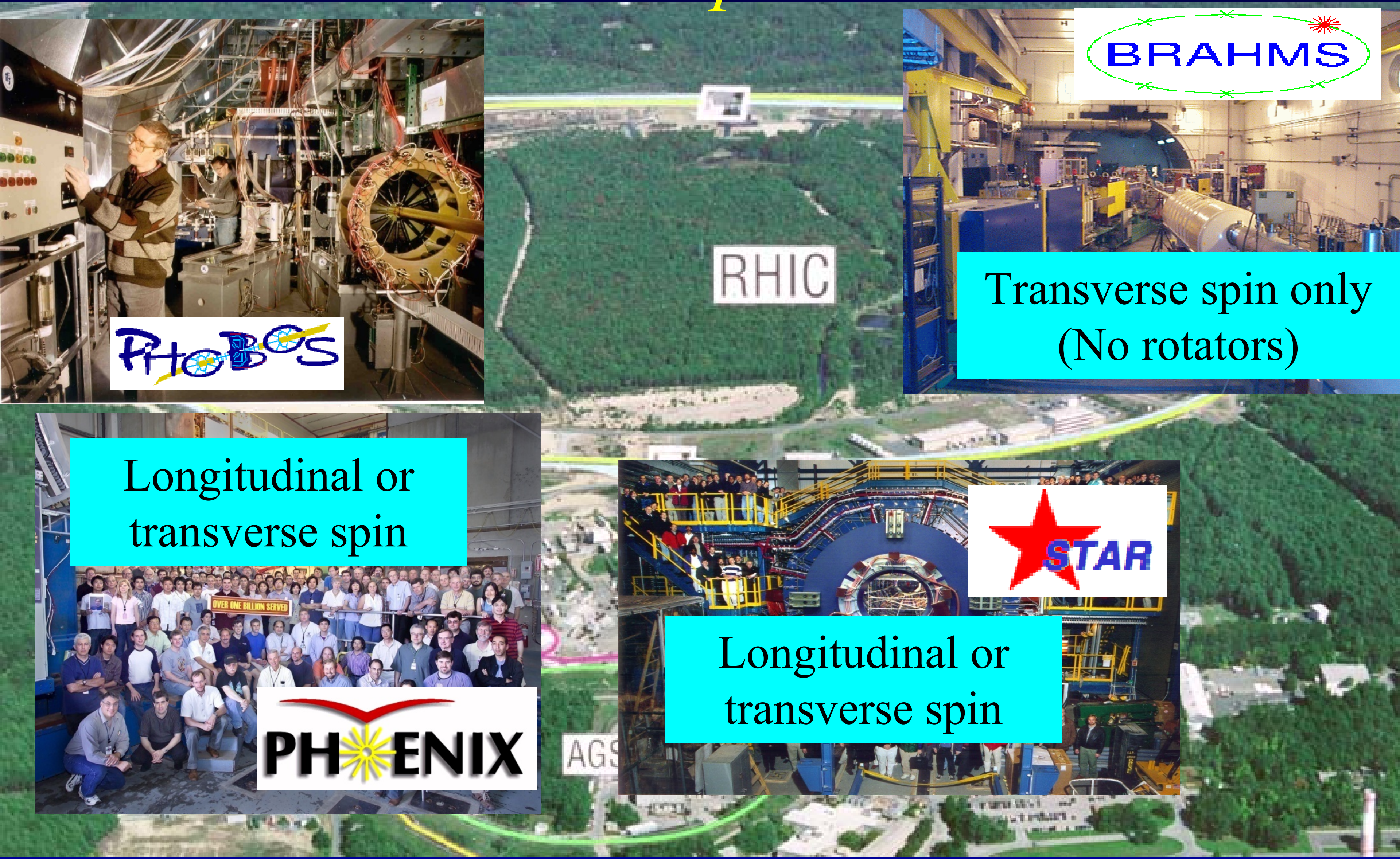
- Primary c.m. energy for polarized running has been 200 GeV
- Polarized data also taken at 62.4 GeV in 2006
  - Easier to maintain beam polarization at lower energies, since pass through fewer depolarizing resonances
- First 500 GeV running started this month!
  - Highest design energy!
  - Need to avoid polarization loss as pass through additional depolarizing resonances compared to 200 GeV
  - So far polarizations of up to ~40% observed according to proton-carbon polarimeter
    - (But note that pC polarimeter not yet calibrated at this energy—will need H-jet polarimeter to analyze several weeks of data)
  - An exciting start to the 500 GeV program!

Some Further Reading on Acceleration and Polarimetry of Polarized Protons

- "The RHIC Optically-Pumped Polarized H^- Ion Source"– A. Zelenski et al., Proceedings of International Workshop on Polarized Sources Targets and Polarimetry (PSTP 2007), AIP Conf. Proc. 990, p. 221, 2008.
- "Spin Dynamics and Snakes in Synchrotrons" – S.Y. Lee, World Scientific, 1997.
- "Accelerating Polarized Protons" – M. Bai, Lecture at 4^{th} Annual PHENIX Spinfest School, 2008. http://www.phenix.bnl.gov/WWW/physics/spin/spinfest/2008/Bai.pdf
- "Measurement of the analyzing power in pp elastic scattering in the peak CNI region at RHIC" – H. Okada et al., Phys. Lett. B638:450-454, 2006.

So we've got beams of polarized protons colliding at hundreds of GeV center-of-mass energy. How do we measure what comes out?

RHIC's Experiments



Transverse spin only (No rotators)

Longitudinal or transverse spin

Longitudinal or transverse spin

RHIC's Experiments

- Like most major collider facilities, (at least) two large, general-purpose detectors designed to take data over the full lifetime of the facility
  - STAR and PHENIX
- Two smaller experiments, both fully equipped from the beginning and designed to take data for the first several years
  - PHOBOS and BRAHMS
  - Both finished running by 2006
  - Both originally intended exclusively for heavy ion physics, but thanks to the interest and efforts of two BRAHMS collaborators, BRAHMS has performed some very nice transverse spin measurements as well!

The STAR Collaboration

U.S. Labs: Argonne, Lawrence Berkeley, and Brookhaven

U.S. Universities: UC Berkeley, UC Davis, UCLA, Carnegie Mellon, Creighton, CCNY, Indiana, Kent State, MSU, Ohio State, Old Dominion, Penn State, Purdue, Rice, Texas A&M, UT Austin, Washington, Wayne State, Valparaiso, Yale, MIT, Kentucky

Brazil: Universidade de Sao Paulo, Universidade Estadual de Campinas

China: HIT, IHEP, IOPP, USTC, ShanDong U., Tsinghua U., SINAP, IMP

Croatia: Zagreb University

Czech Republic: Institute of Nuclear Physics

England: U. of Birmingham

France: Institut de Recherches Subatomiques Strasbourg, SUBATECH

Germany: Max Planck Institute

India: IOP, Bhubaneswar, Jammu U., IIT-Mumbai, Panjab U., Rajasthan U., VECC

Netherlands: NIKHEF

Poland: Warsaw University of Technology

Russia: MEPHI, LPP/LHE JINR – Dubna, IHEP – Protvino, ITEP --Moscow

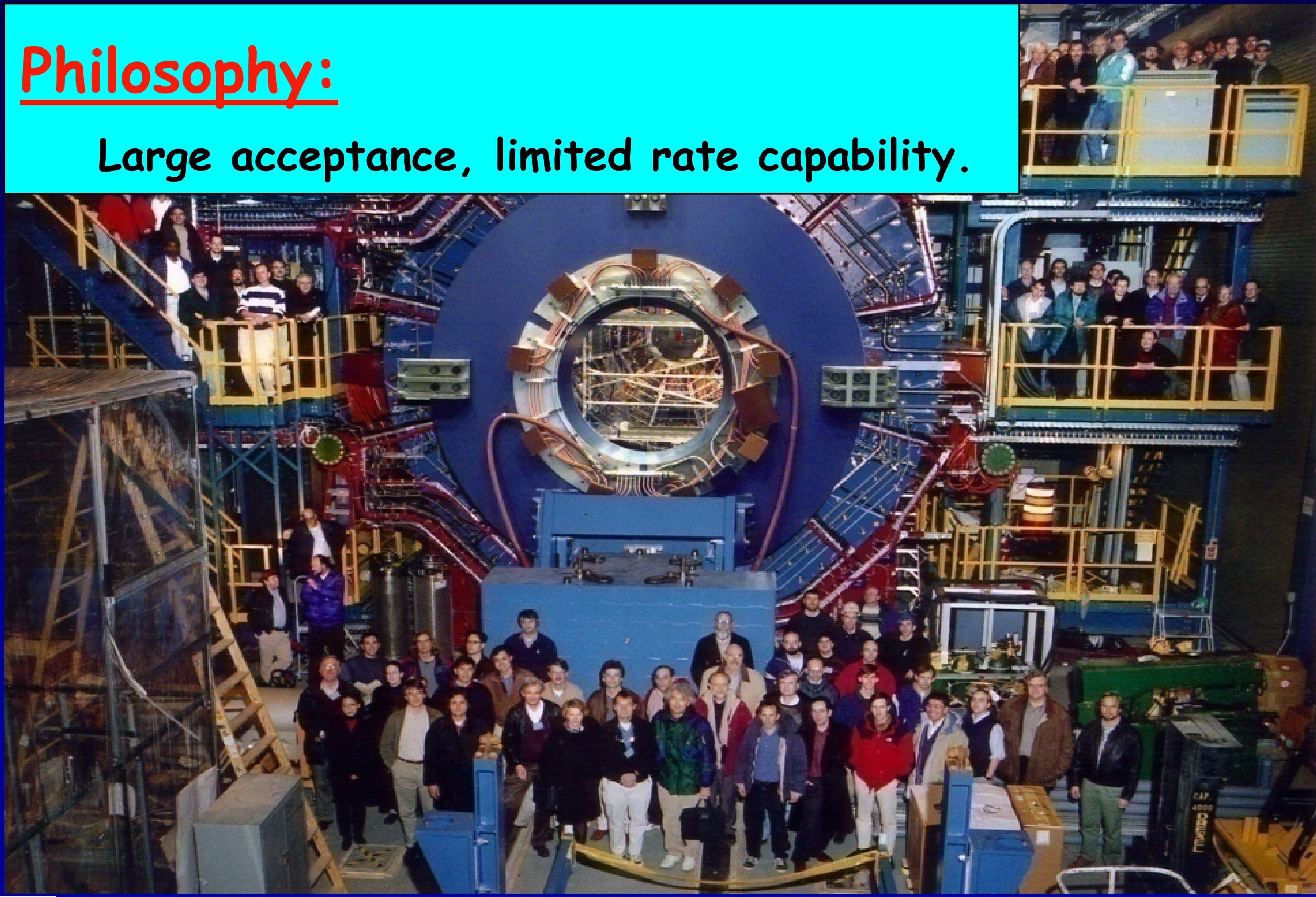
South Korea: KISTI, Pusan National University

12 countries
57 institutes
~550 scientists and engineers

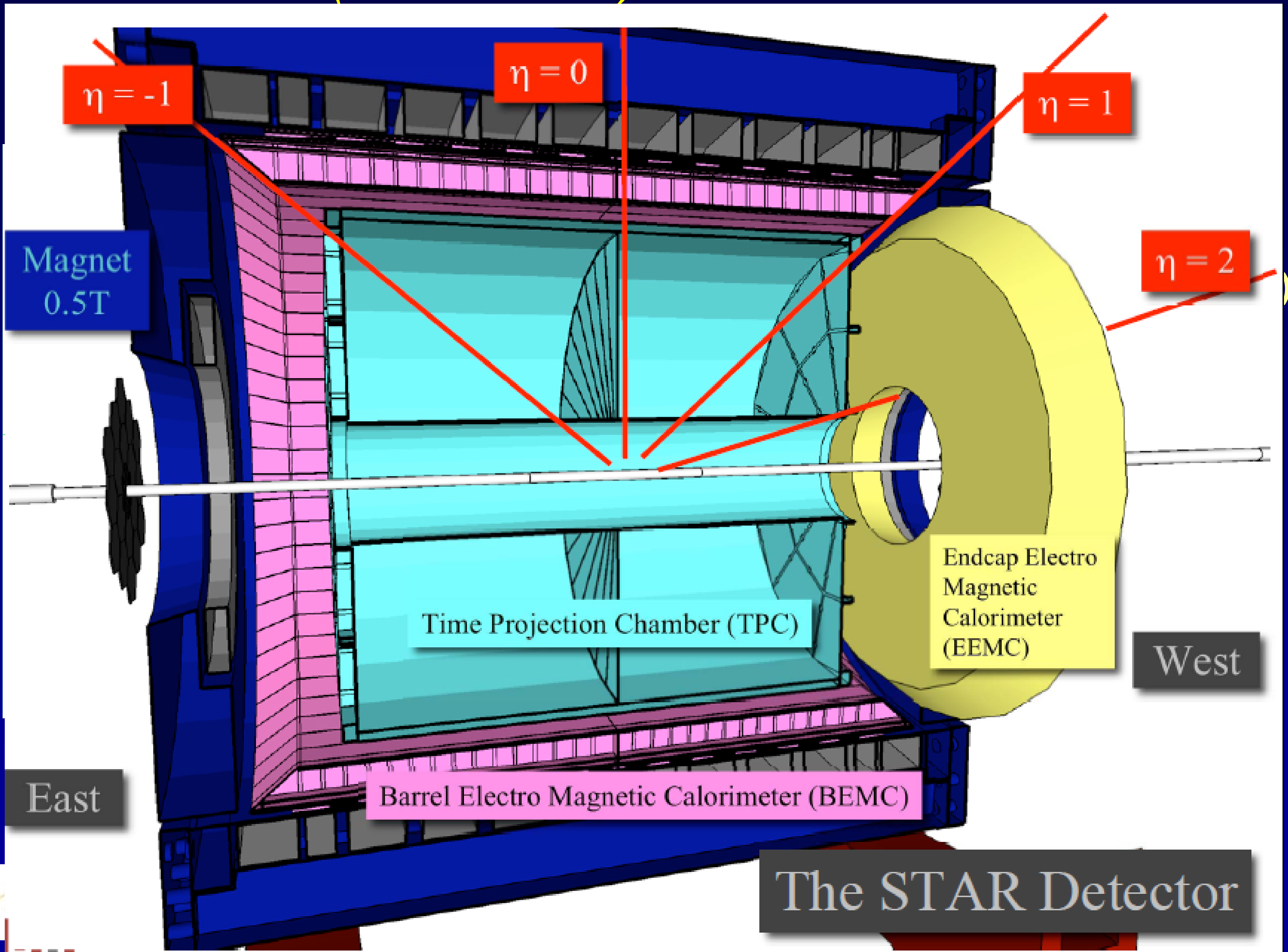
The STAR Detector

Philosophy:

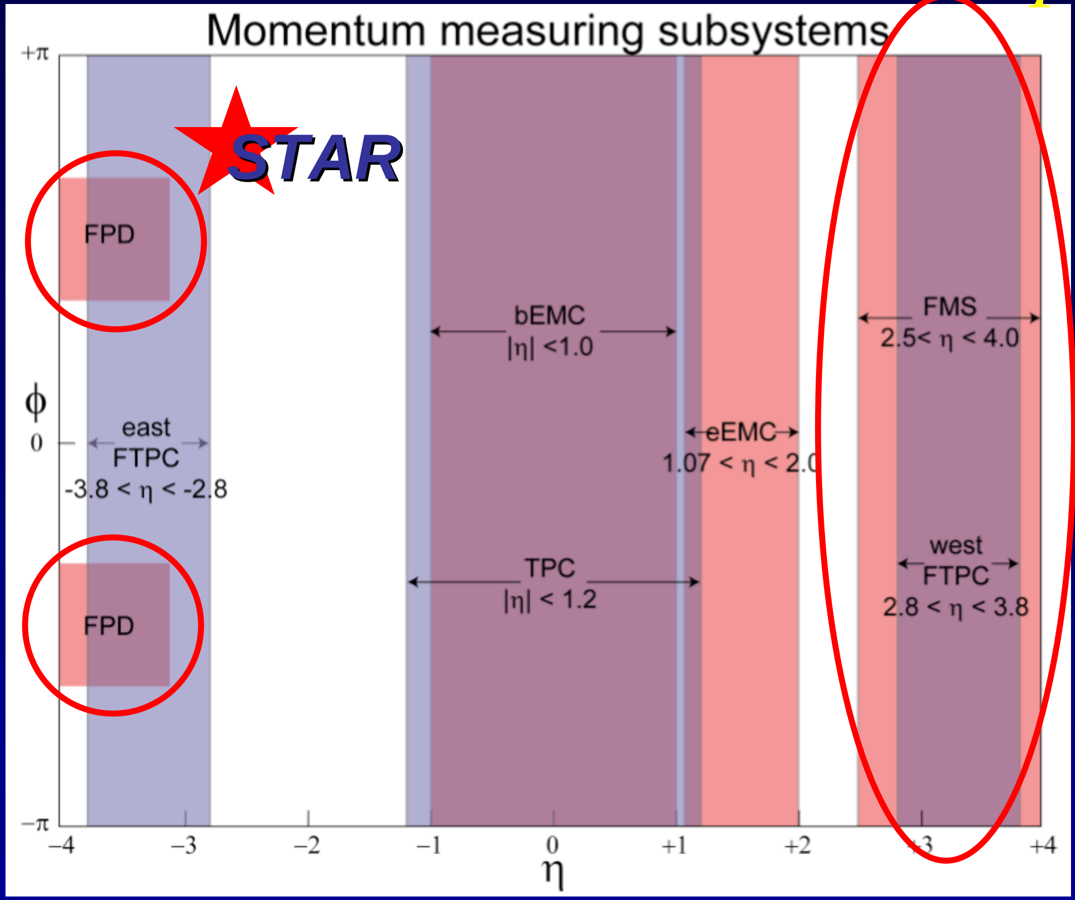
Large acceptance, limited rate capability.



The (Central) STAR Detector



STAR Forward Pion Detector and Forward Meson Spectrometer



FMS

FMS installed for 2008 run: 20 times more acceptance than previous STAR forward calorimeters!

The PHENIX Collaboration

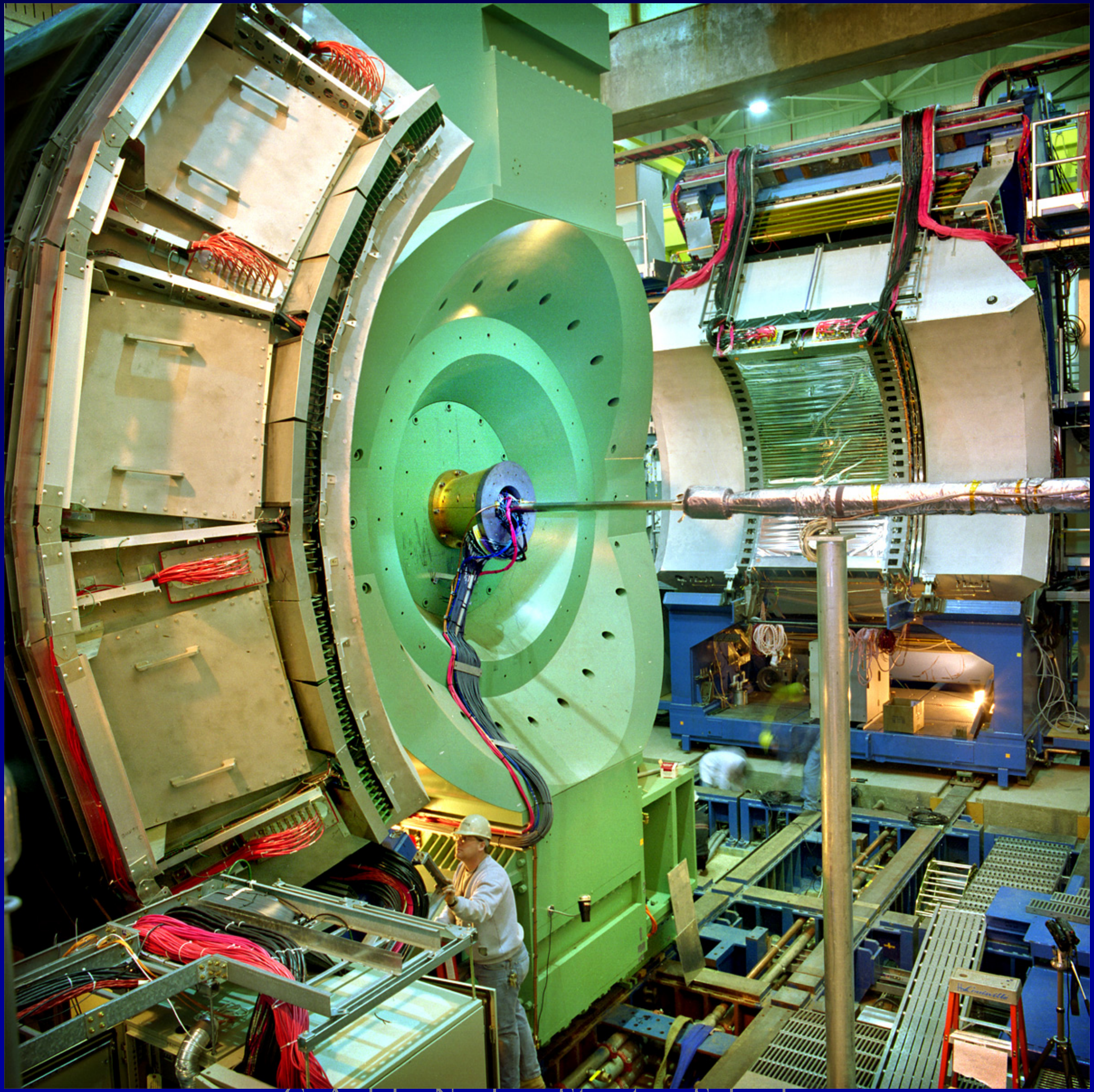
13 Countries; 62 Institutions; ~550 Participants

The PHENIX Detector

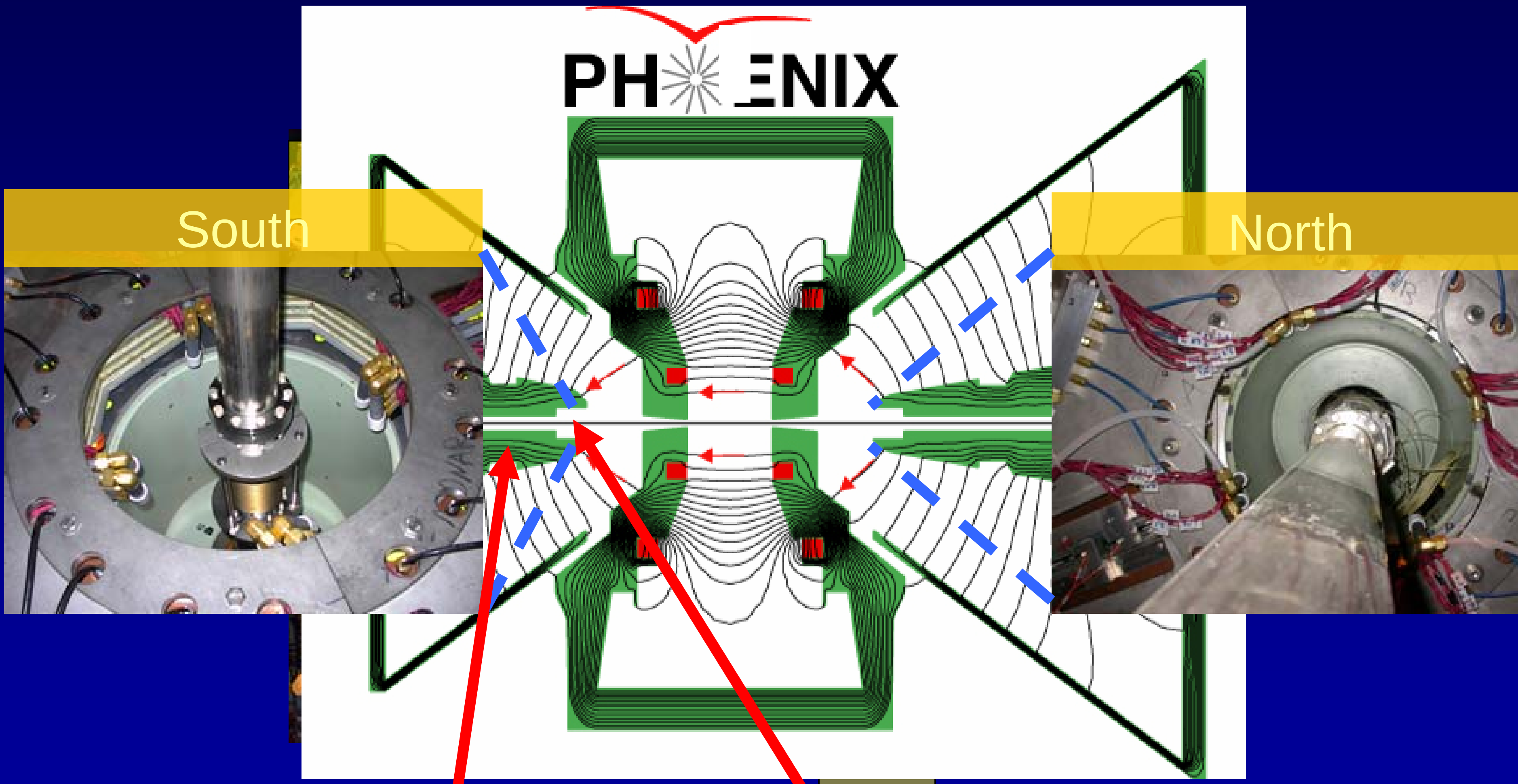
Philosophy:

High granularity, high rate capability to measure rare probes, but limited acceptance.

The PHENIX Detector



PHENIX Muon Piston Calorimeter: Filling in the Gaps!



Muon Piston

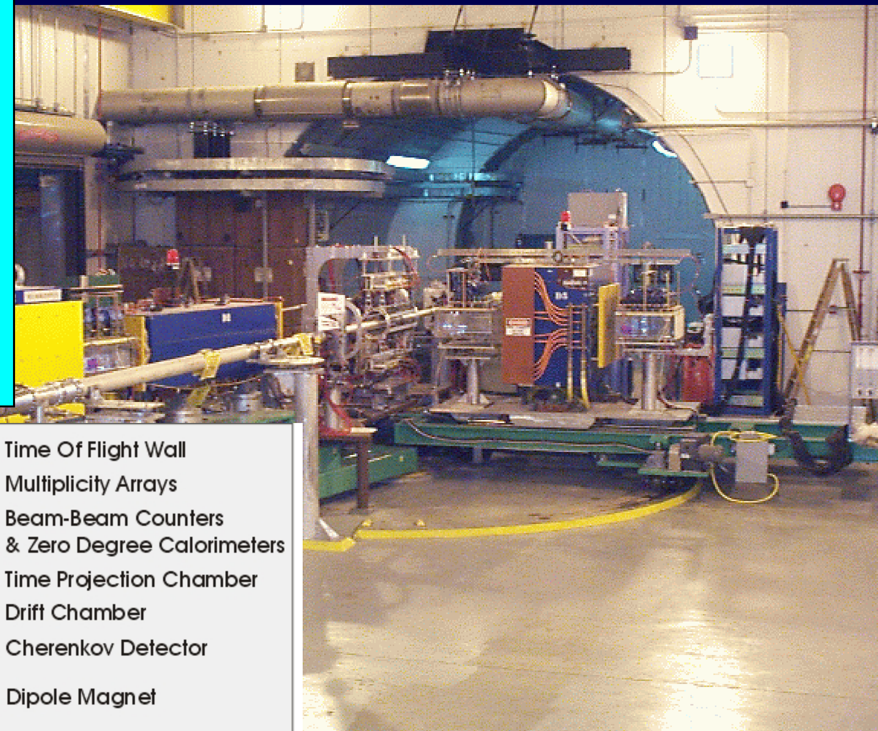
Muon Arms

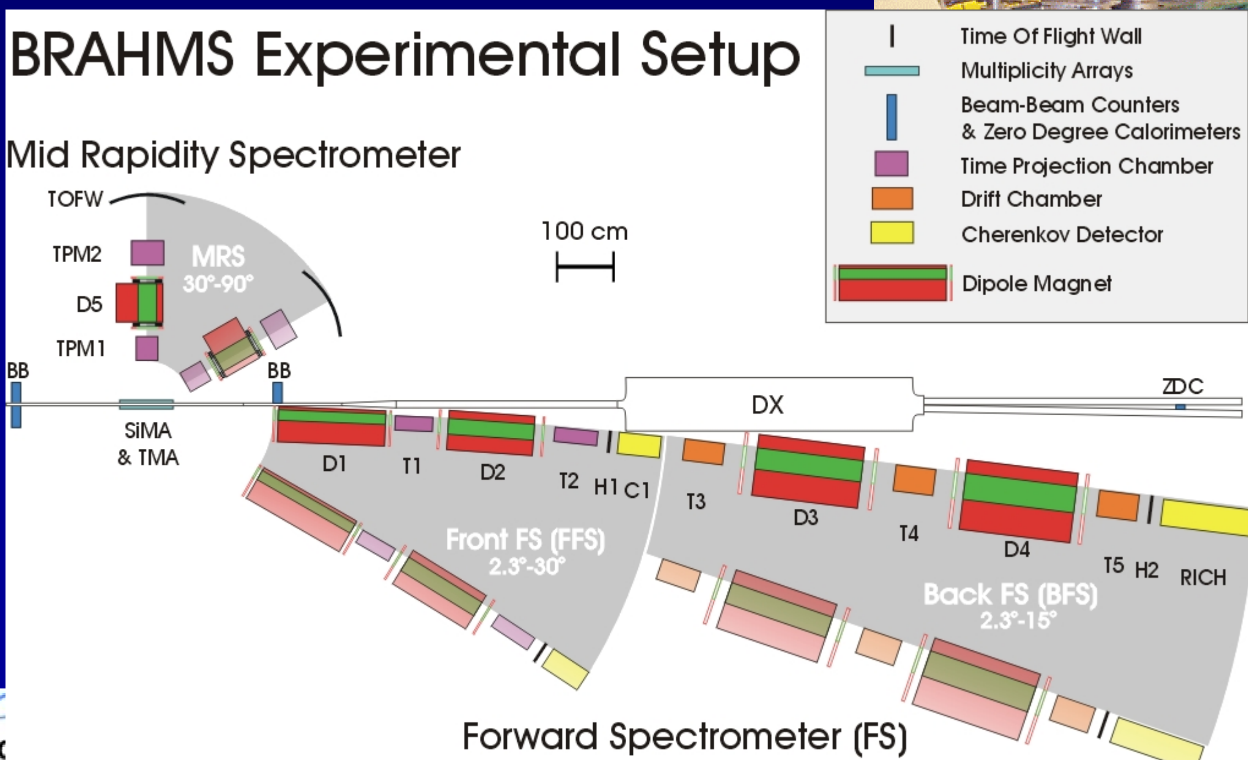
Muon Piston Hole

The BRAHMS Detector

Philosophy:

Small acceptance, movable spectrometer arms designed with good charged particle ID.

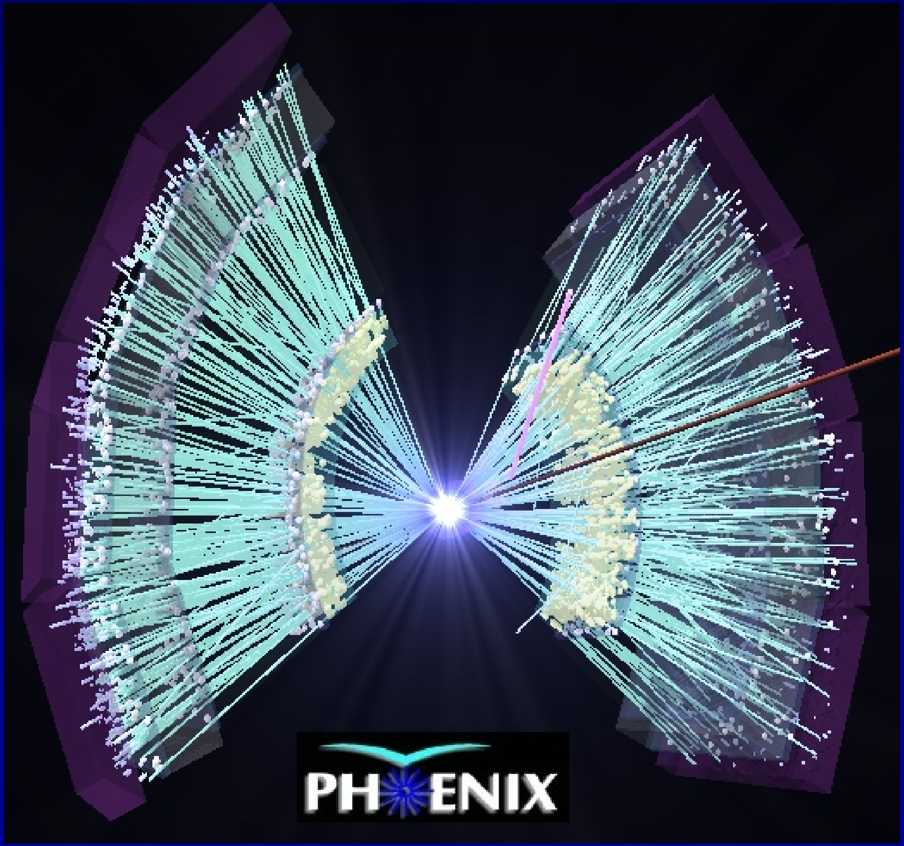


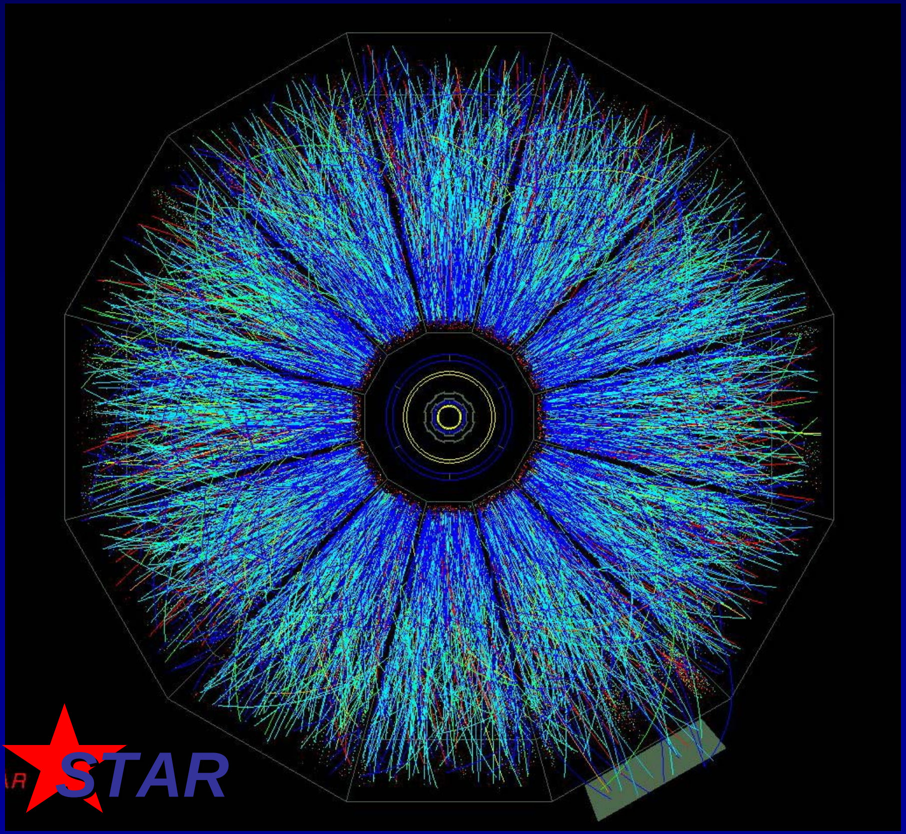


BRAHMS

Detectors Designed for High Multiplicities

Makes many things easy when you're studying p+p collisions!

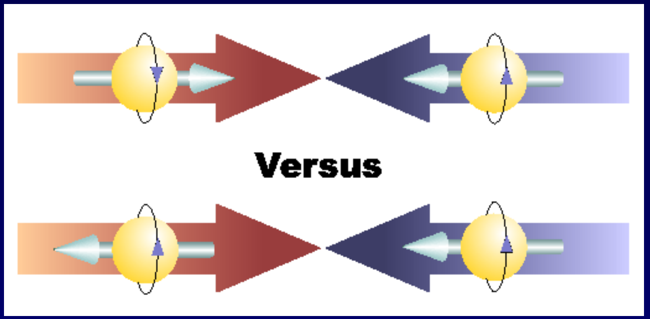




So what do we actually need to measure?

Spin Asymmetries

Example: Double-longitudinal asymmetry



- Difference in *spin-dependent* cross sections for particle production as a fraction of the *total* cross section
- Often shown as a percent, but note it's a *signed* quantity (from -1 to +1)

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{total}}$$

$$= \frac{1}{|P_1 P_2|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

$P_{1,2}$ = beam polarization
N = particle yield
L = luminosity
++ (+-) = same (opposite) helicity bunches

Relative Luminosity

- Combine yields from *different bunch crossings* to obtain asymmetries
- Important to know that relative luminosity between same-helicity and opposite-helicity bunch crossings is being counted correctly
- Don't get fooled by asymmetries in the luminosity detectors themselves!

Compare relative luminosity measurements from two different detectors situated in two different kinematic regions.
Beam-Beam Counter (BBC): quartz Cherenkov counter
Zero-Degree Calorimeter (ZDC): hadronic calorimeter

Relative Luminosity: Example Results From PHENIX Analysis of π^0 A_{LL}

- Uncertainty on A_{LL} due to relative luminosity (200 GeV data from 2006) $\delta A_{LL}=7\times10^{-4}$
  - Upper-limit estimation limited by ZDC statistics (30 times less than BBC statistics used in relative luminosity measurements)
- A_{LL} of BBC relative to ZDC consistent with 0 (<0.2%)
  - Strong indication that asymmetries seen by both detectors are zero (very different kinematical regions, different physics signals)
- Statistical uncertainties in lowest transverse momentum bins comparable to systematic uncertainties
  - Spin flipper will become important for next 200 GeV run!

Monitoring Spin Direction at Interaction Region

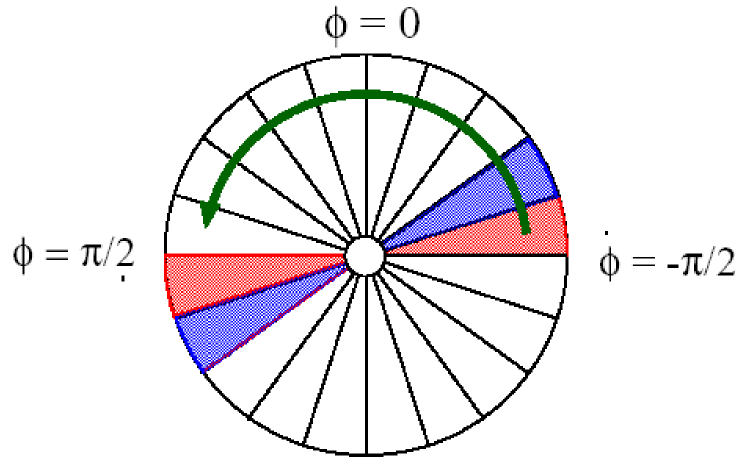
- Spin rotators outside the STAR and PHENIX interaction regions can be operated independently
- … al
-

Yesterday's discovery is today's calibration!
(Even when the physics behind yesterday's discovery still isn't well understood!!)

  – ~1% SSA in forward charged particle production

PHENIX Local Polarimeter

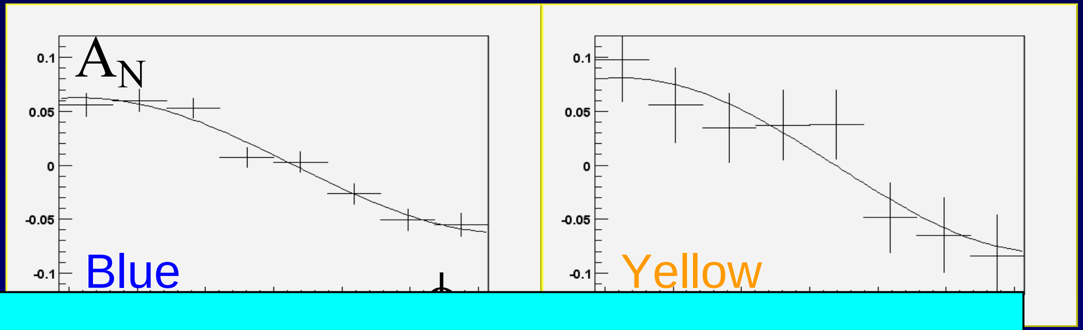
- ✓ Forward neutron transverse asymmetry (A_N) measurements
  - $A_N \sim -9\%$
- ✓ Shower Max Detector (position) + Zero-Degree Cal. (energy)



Vertical → $\phi \sim \pm\pi/2$
Radial → $\phi \sim 0, \pi$
Longitudinal → no asymmetry

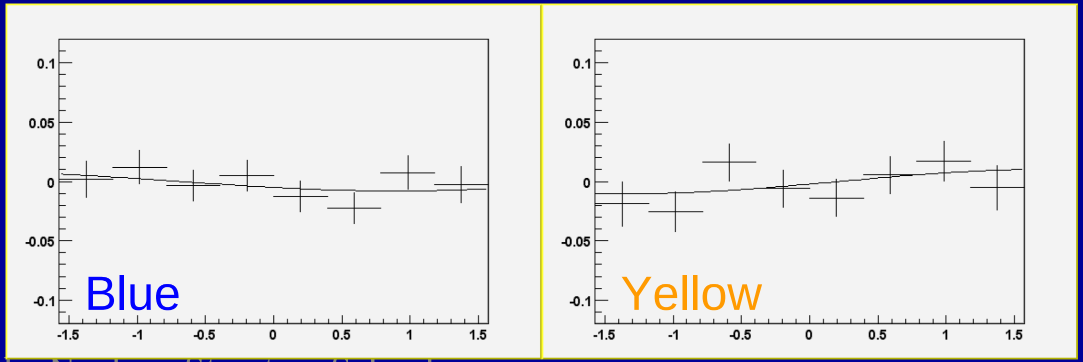
Neutron SSA for Local Polarimetry

Spin Rotators OFF
Vertical polarization



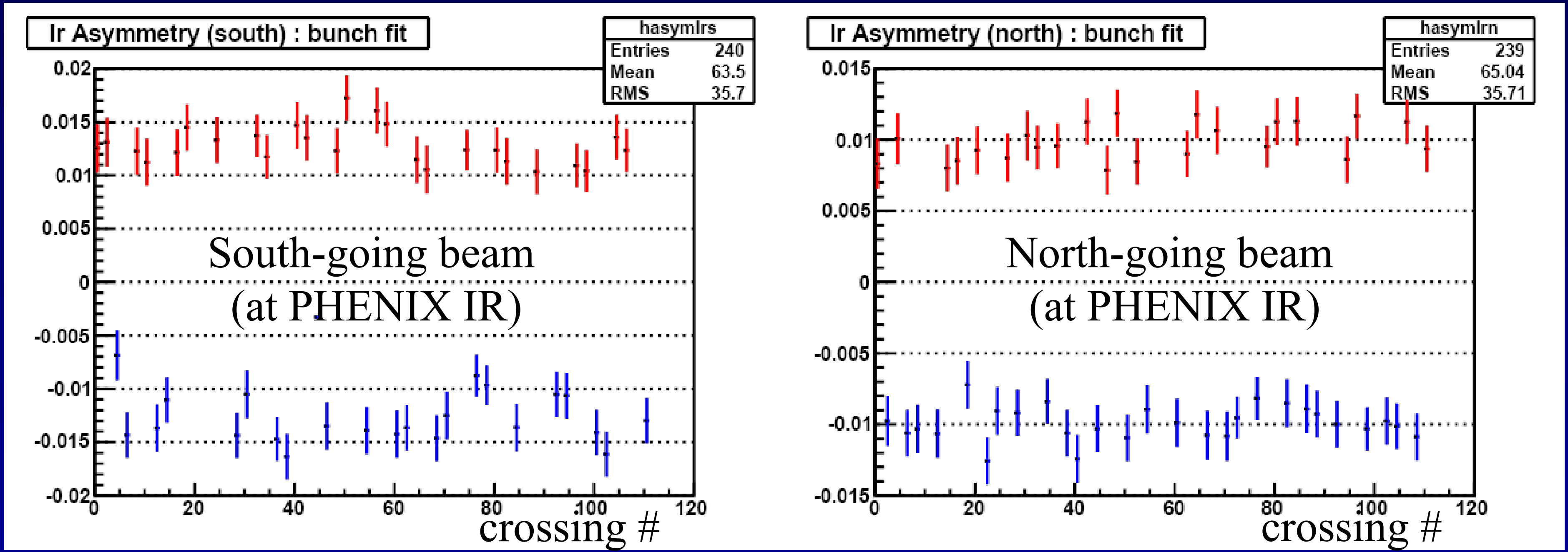
Allows measurement of any remaining component in an undesired direction

Spin Rotators ON
Longitudinal polarization



Bunch-by-Bunch Polarization Information

From ~10 minutes of 500 GeV commissioning data a few weeks ago!



With transverse polarization, use scalers to count raw left-right SSA in forward neutron production for each bunch crossing.

Measurement of *bunch-by-bunch variation* in polarization.

(Sign flip for bunches polarized vertically up vs. down.)

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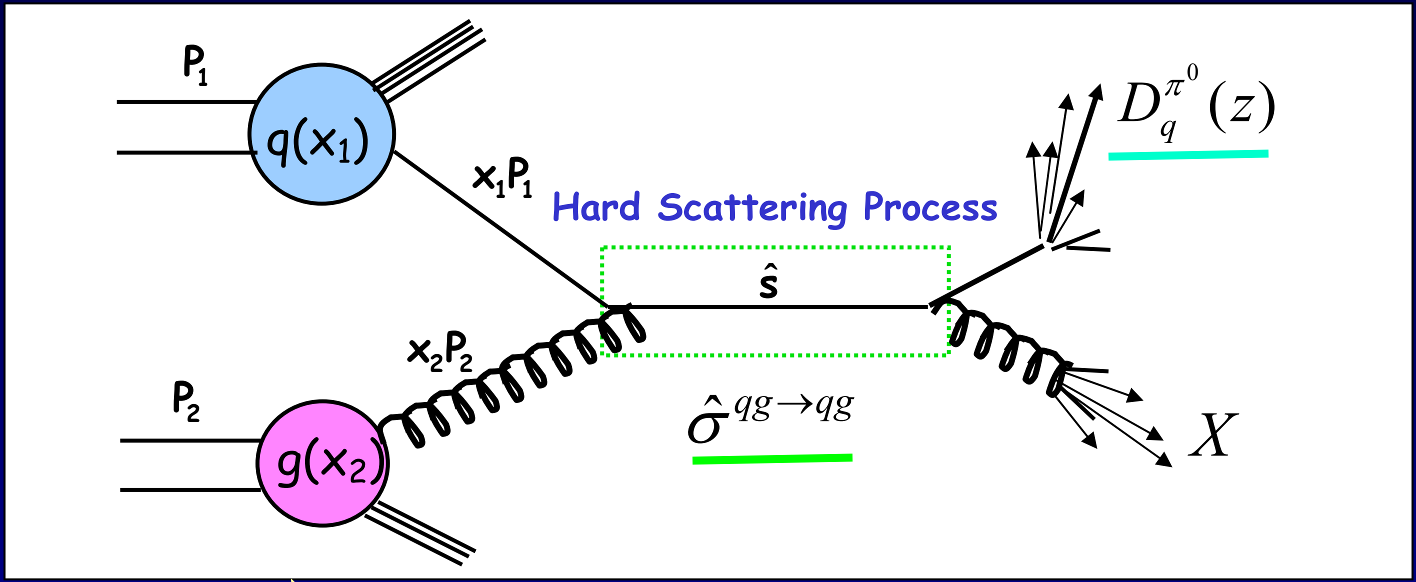
How are we going to be able to interpret our results?

Interpret Results Through ***Perturbative QCD***



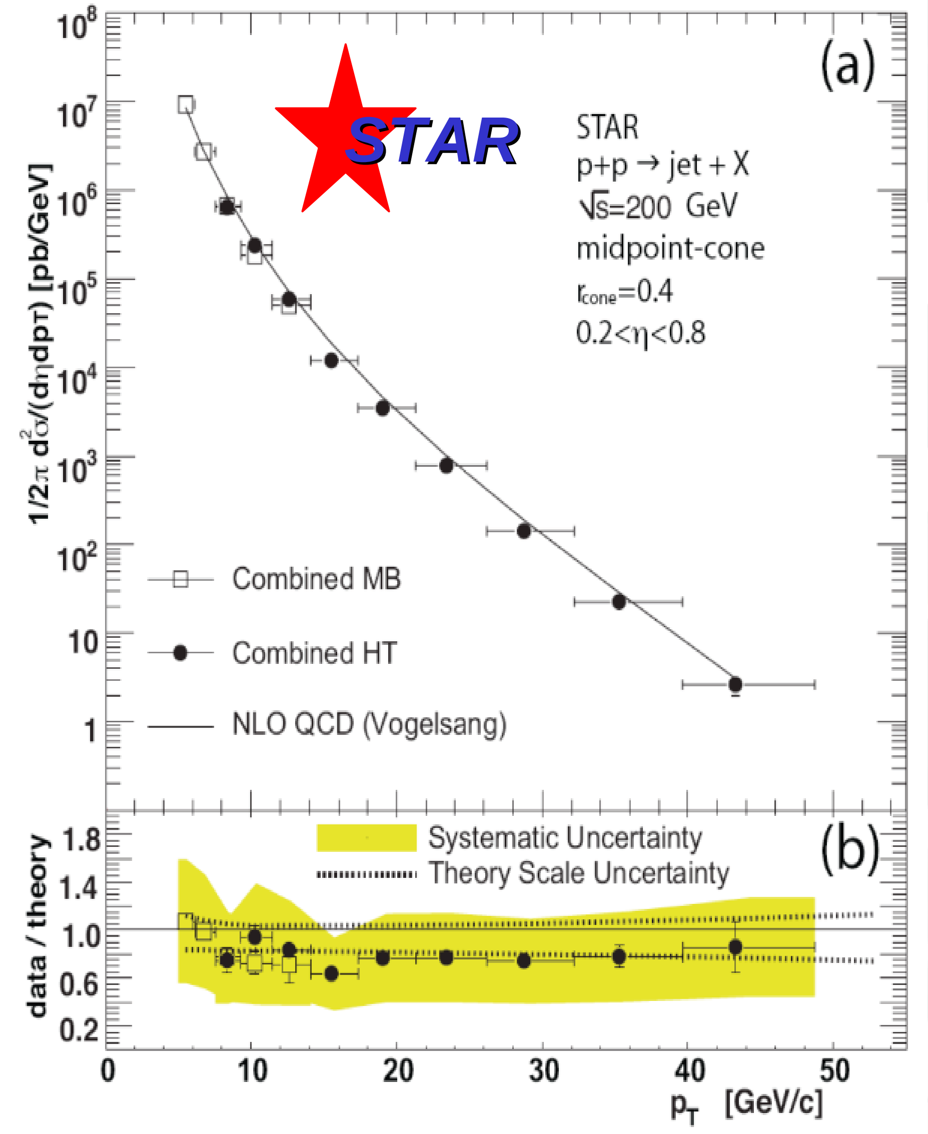
$$\sigma\left(pp \to \pi^0 X\right) \propto q(x_1) \otimes g(x_2) \otimes \hat{\sigma}^{qg\to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

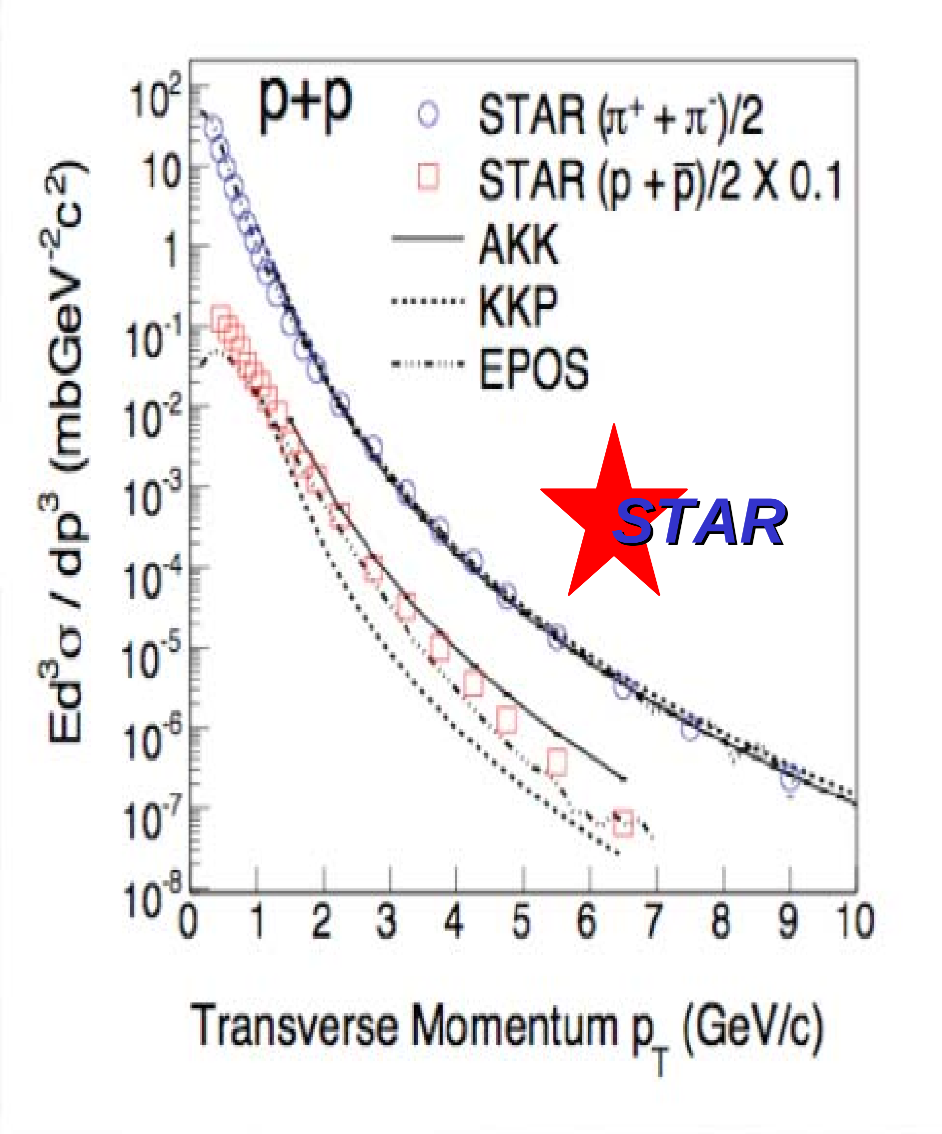
"Hard" probes have predictable rates given:

- Parton distribution functions (need experimental input)
- Partonic hard scattering rates (calculable in pQCD)
- Fragmentation functions (need experimental input)

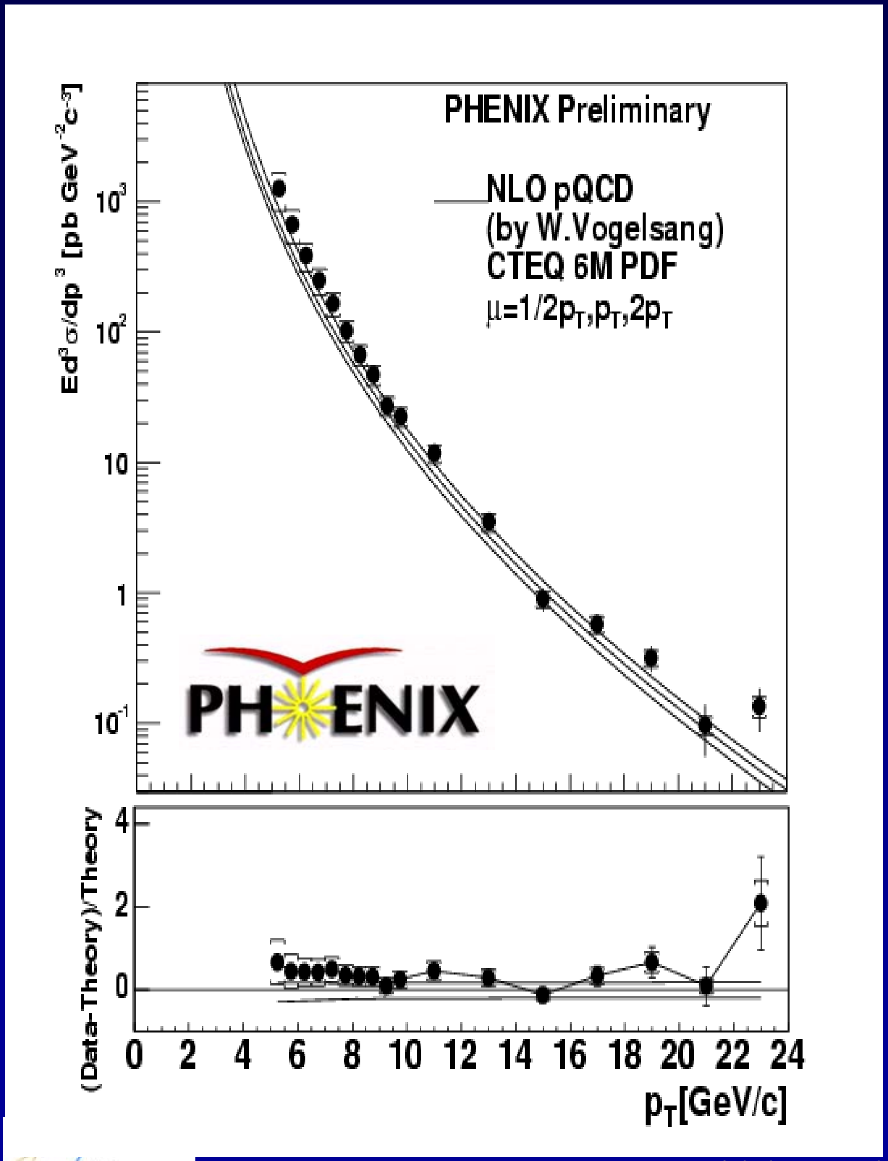
} Universality (Process independence)

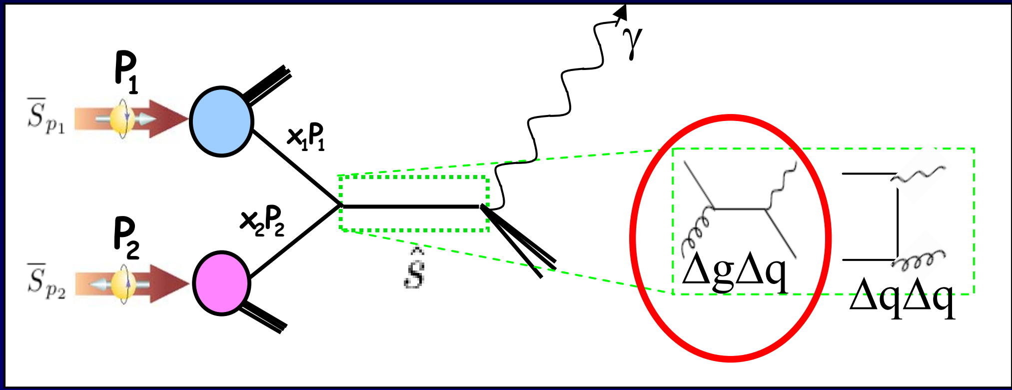
pQCD in Action at √s=200 GeV



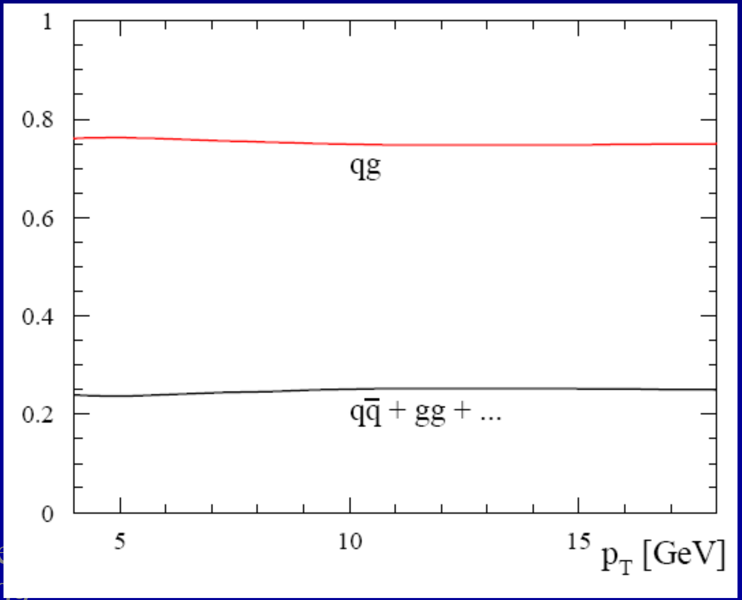


Prompt γ Production at √s=200 GeV



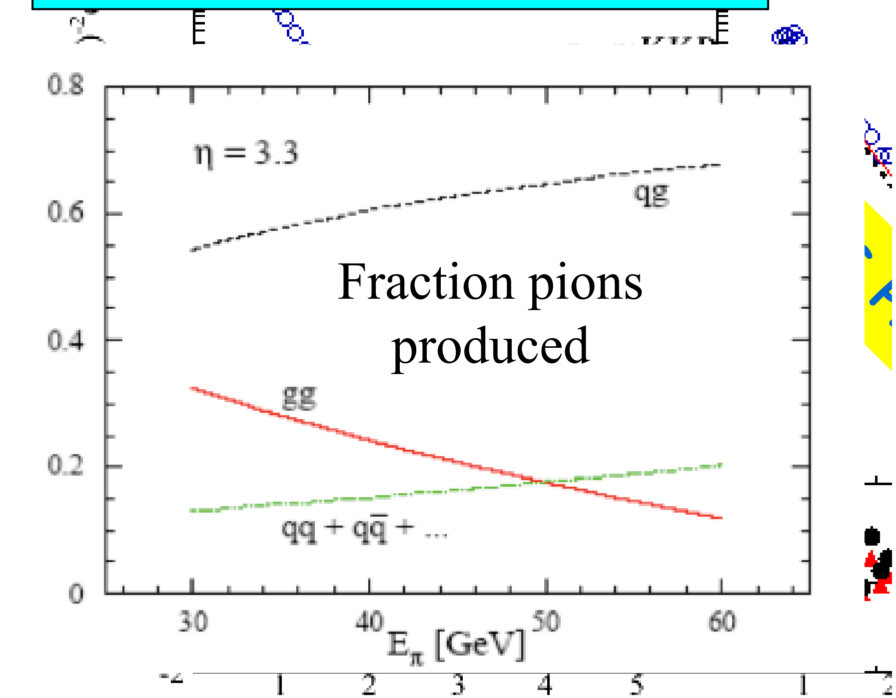


$$A_{LL} \propto \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta q(x_2)}{q(x_2)} \otimes \hat{a}_{LL}(gq \rightarrow \gamma q)$$

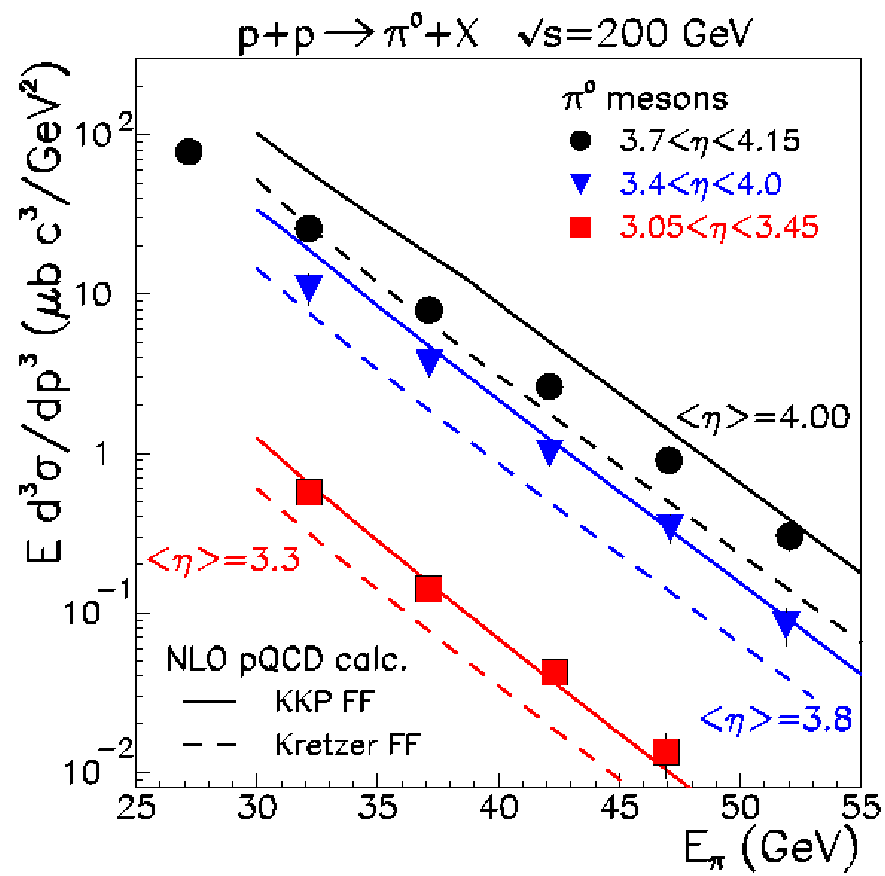


Forward Hadron Production at √s=200 GeV

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



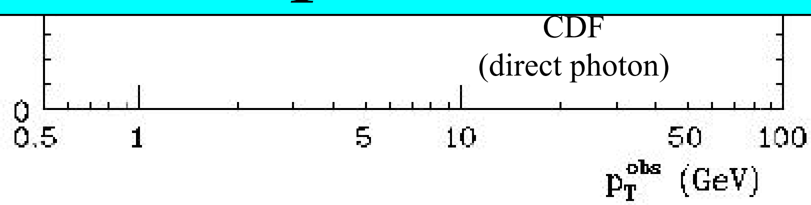
PRL 97 (2006) 152302



pQCD Scale Dependence at RHIC vs. Spin-Dependent DIS

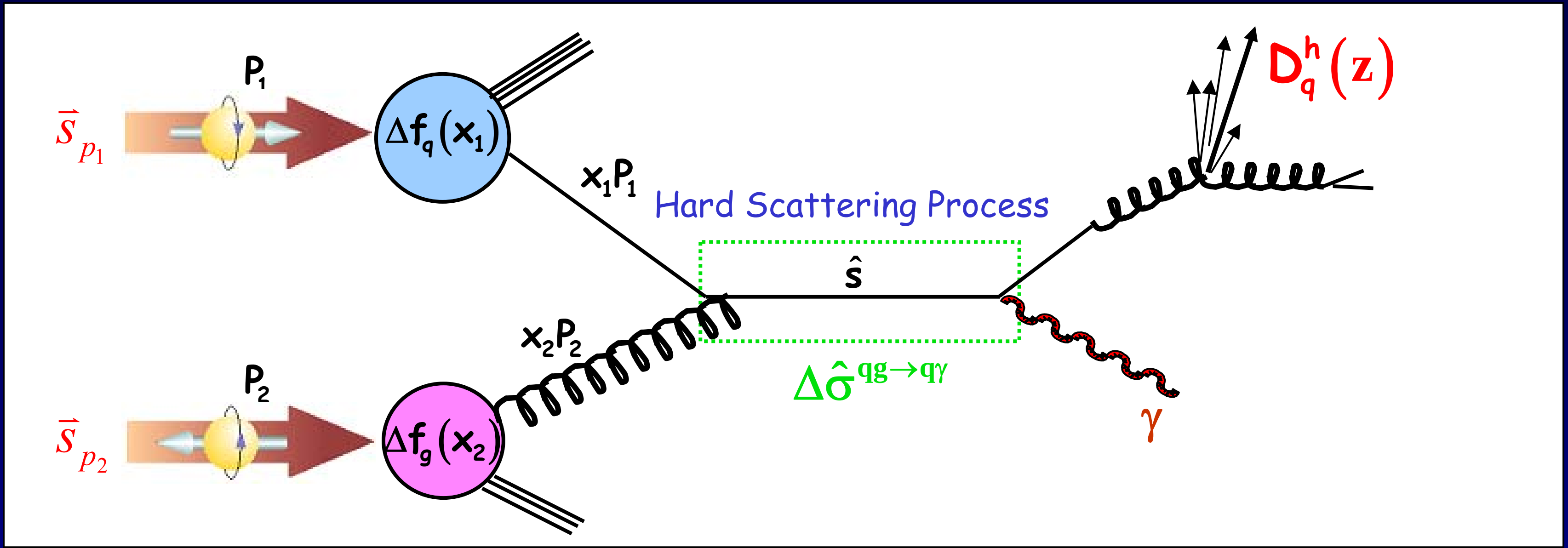
Change in pQCD calculation of cross section if factorization scale changed by factor 2

So pQCD describes polarization-averaged data at RHIC well, with (relatively) small dependence on the factorization and renormalization scales. How can pQCD be used to describe polarized data?



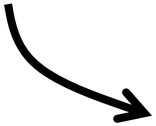
reduced compared to fixed-target polarized DIS, thanks to higher energy reached by a collider.

*Hard Scattering in **Polarized** p+p*



$$\Delta\sigma(pp\to\gamma X)\propto\Delta f_q(x_1)\otimes\Delta f_g(x_2)\otimes\Delta\hat{\sigma}^{qg\to q\gamma}(\hat{s})$$

$$A_{LL}=\frac{\sigma^{\uparrow\uparrow}-\sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow}+\sigma^{\uparrow\downarrow}}\equiv\frac{\Delta\sigma}{\sigma}=\hat{a}_{LL}(qg\to q\gamma)\otimes\frac{\Delta g(x_1)}{g(x_1)}\otimes\frac{\Delta q(x_2)}{q(x_2)}$$

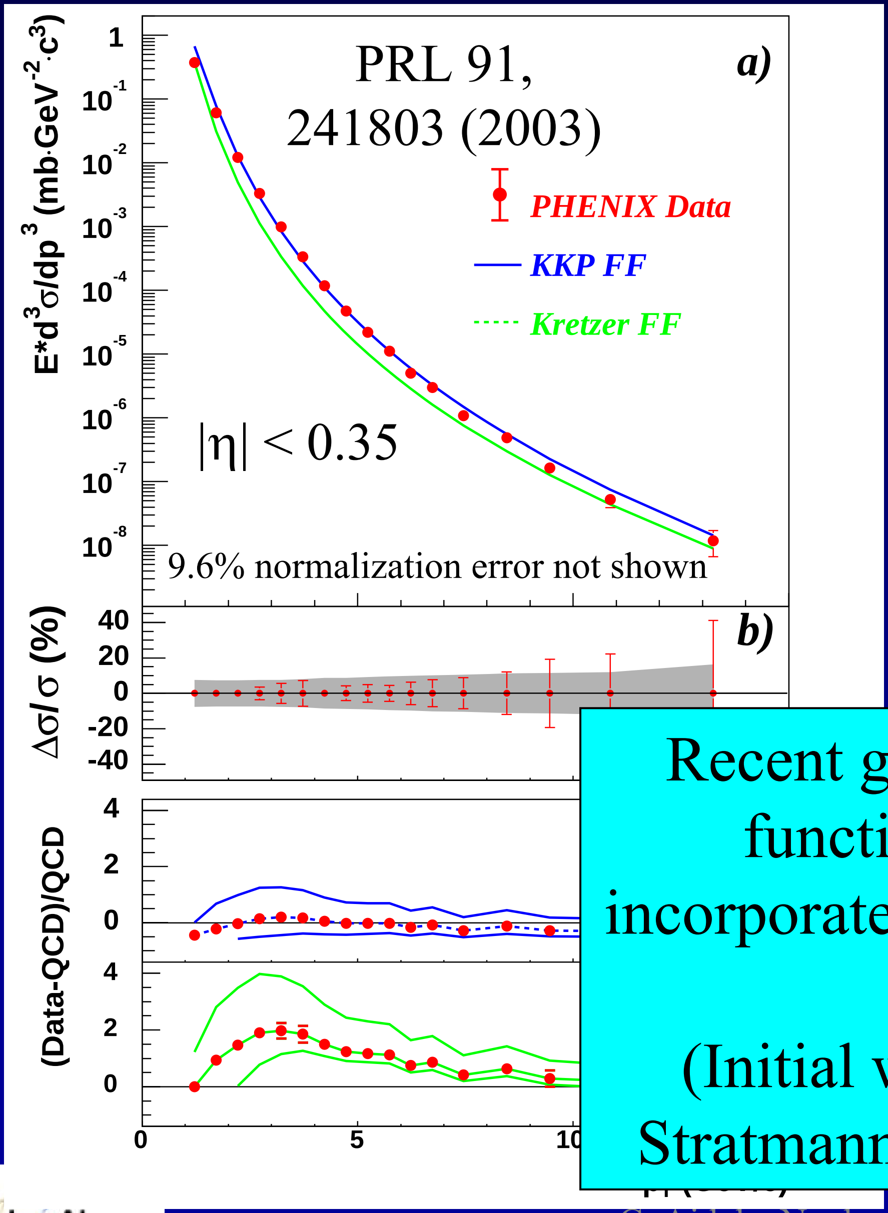


$\Delta\hat{\sigma}/\hat{\sigma}$

Proton-Proton Collisions: A Complex System

- Can only learn from p+p results in conjunction with information from simpler systems!
  - Many subprocesses contribute to (e.g.) inclusive hadron production in p+p collisions—couldn't disentangle them with p+p data alone
  - (A few processes are simpler, e.g. Drell-Yan)
- Most knowledge of pdf's from DIS
- Most knowledge of FF's from e+e-
- Once you have reasonably constrained pdf's and/or FF's, can use p+p data to further refine those constraints

Example: PHENIX π^0 Cross Section from 2002 Run



- NLO pQCD calculation
  - PDF: CTEQ5M
  - Fragmentation functions:
    - Kniehl-Kramer-Potter (KKP)
    - Kretzer

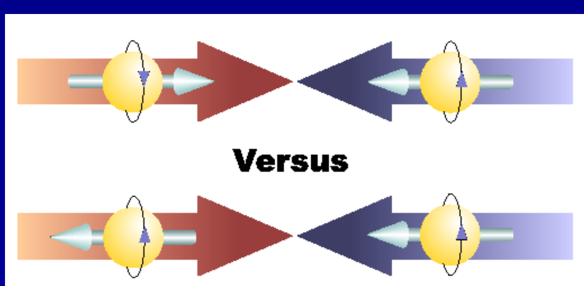
Spectrum constrained gluon → π fragmentation function!

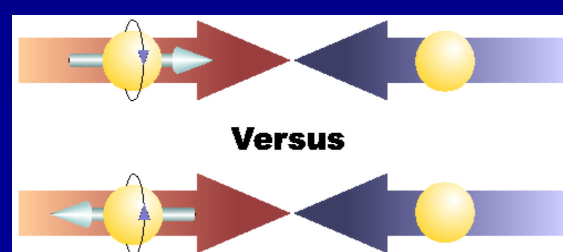
Recent global analyses of fragmentation functions (FF's) have been able to incorporate not only world e+e- data but also SIDIS and p+p data!
(Initial work by de Florian, Sassot, and Stratmann, Phys. Rev. D75:114010, 2007)

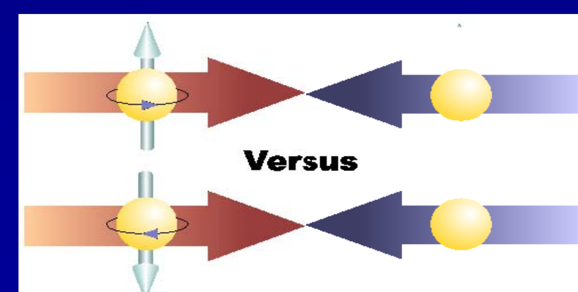
And now for some (spin-dependent) results!

Proton Spin Structure at RHIC

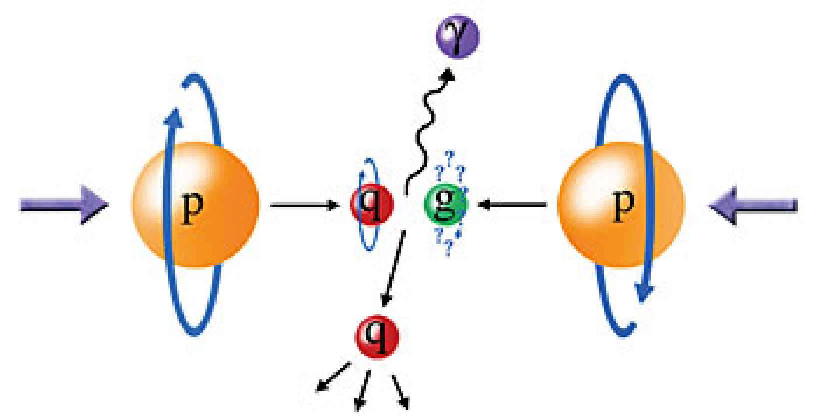
Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π, Jets $A_{LL}(gg, gq \to \pi + X)$ Prompt Photons $A_{LL}(gq \to \gamma + X)$ Back-to-Back Correlations	**W Production** $A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$ $A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	**Transversity** **Transverse-momentum-dependent distributions** Single-Spin Asymmetries







Probing $\Delta g(x)$ Through Polarized p+p Collisions



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

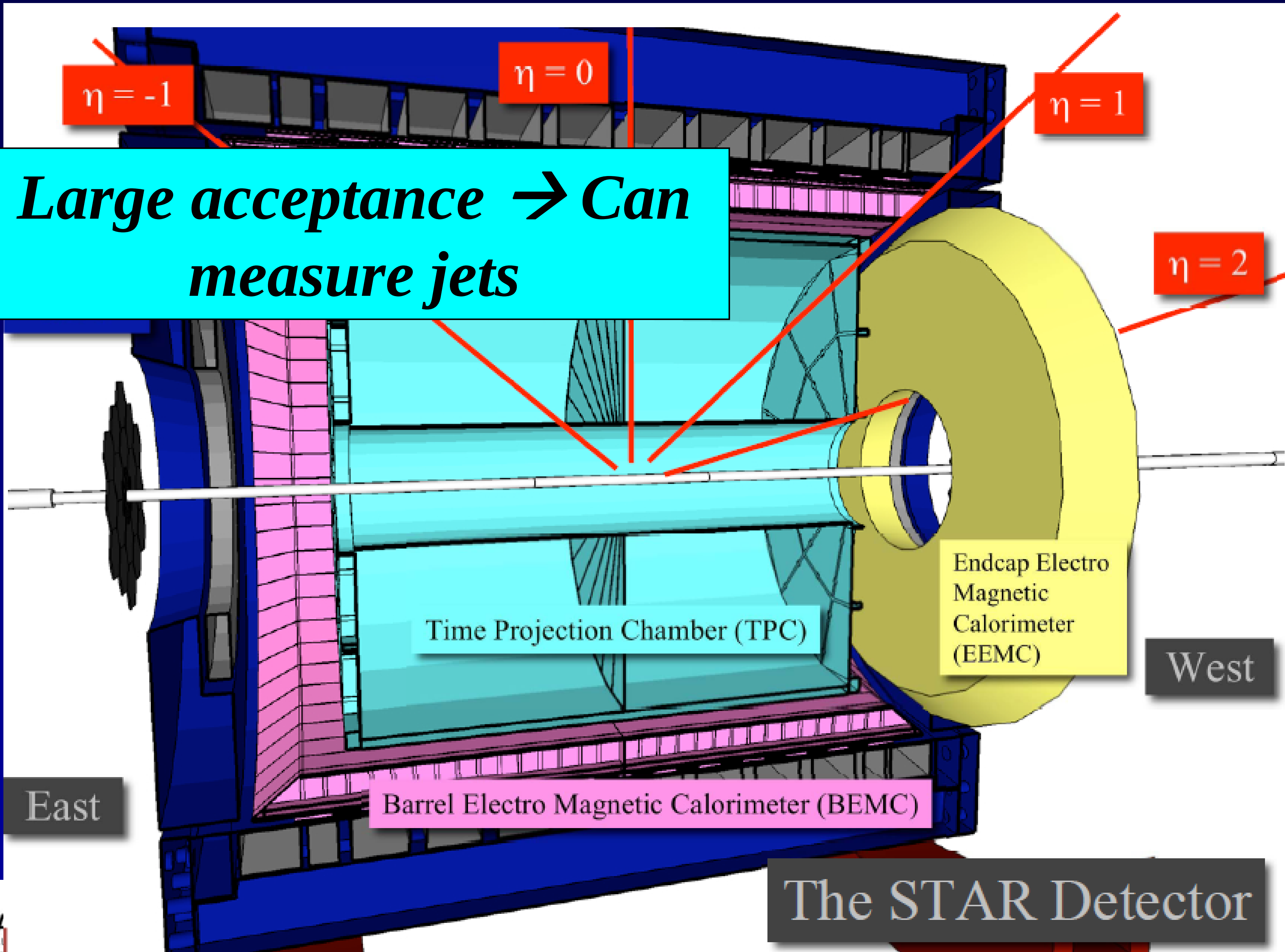
$$\Delta\sigma(pp \to \pi^0 X) \propto \Delta q(x_1) \otimes \Delta g(x_2) \otimes \Delta\hat{\sigma}^{qg \to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

DIS ? pQCD e+e-

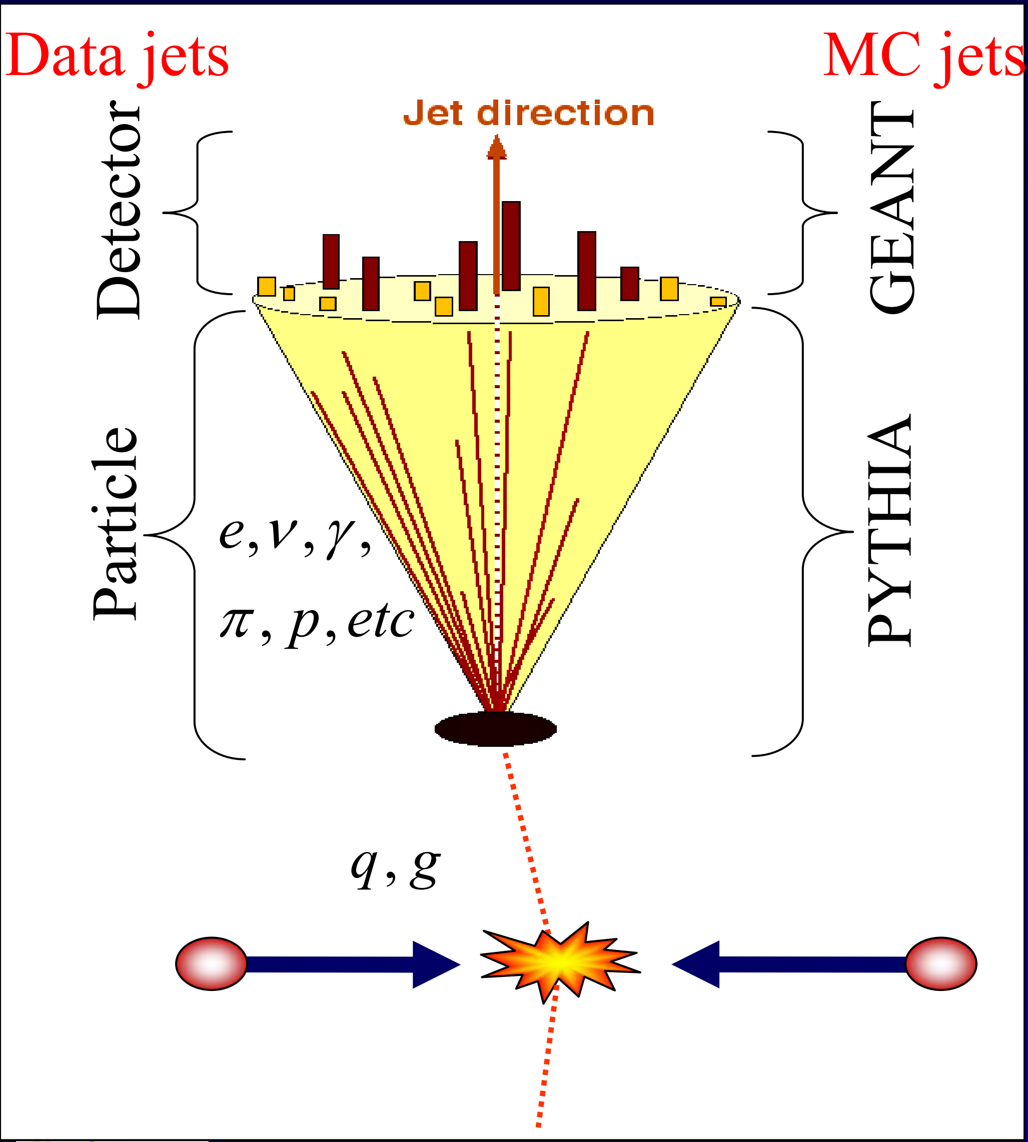
Leading-order access to gluons → ΔG

The STAR Detector

Large acceptance → Can measure jets



Jet Reconstruction in STAR

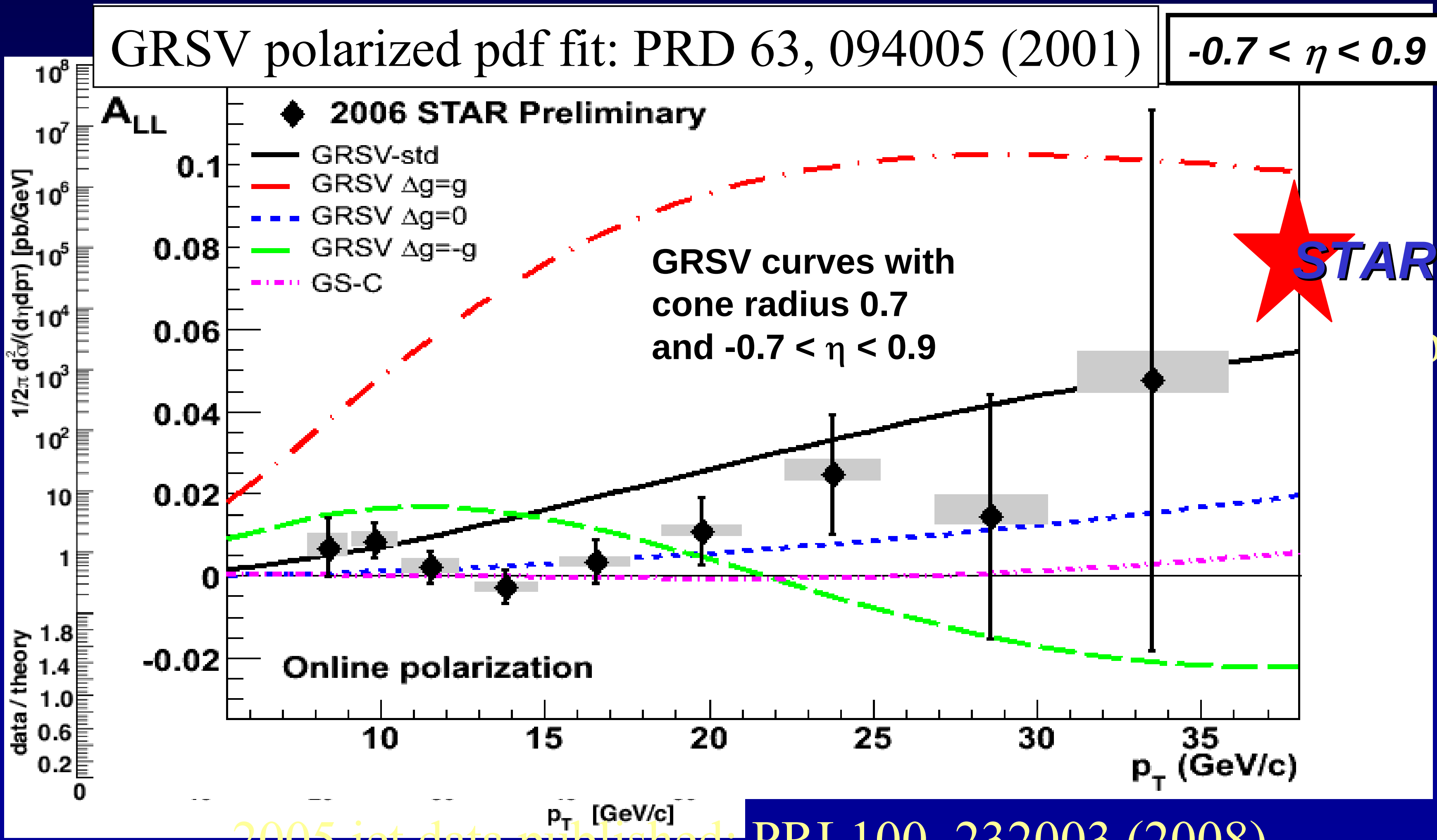


Midpoint cone algorithm
(Adapted from TeVatron II – hep-ex/0005012)

- Seed energy = 0.5 GeV
  - Cone radius in η-ϕ
  - R=0.4 with $0.2 < \eta < 0.8$ (2005)
  - R=0.7 with $-0.7 < \eta < 0.9$ (2006)
- Splitting/merging fraction f=0.5

Use PYTHIA + GEANT to quantify detector response

Inclusive Jet Production at 200 GeV



2005 jet data published: PRL100, 232003 (2008)

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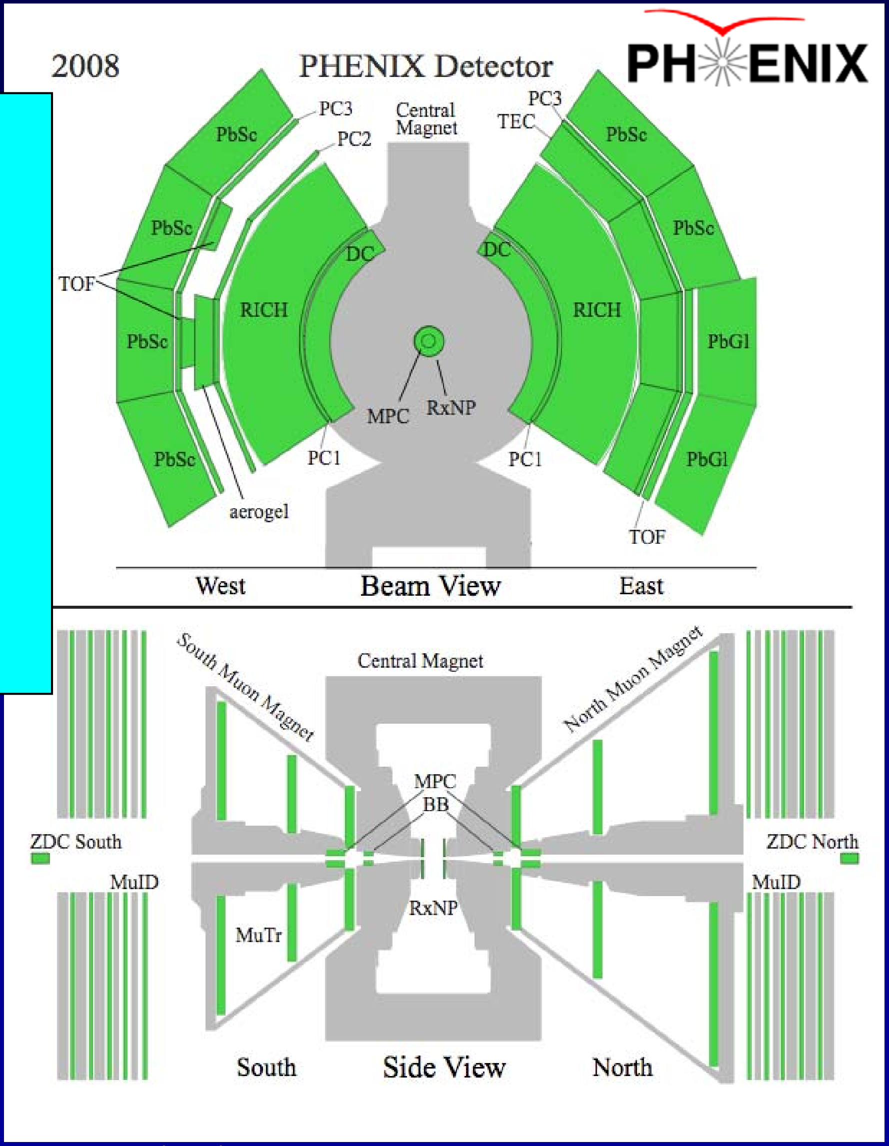
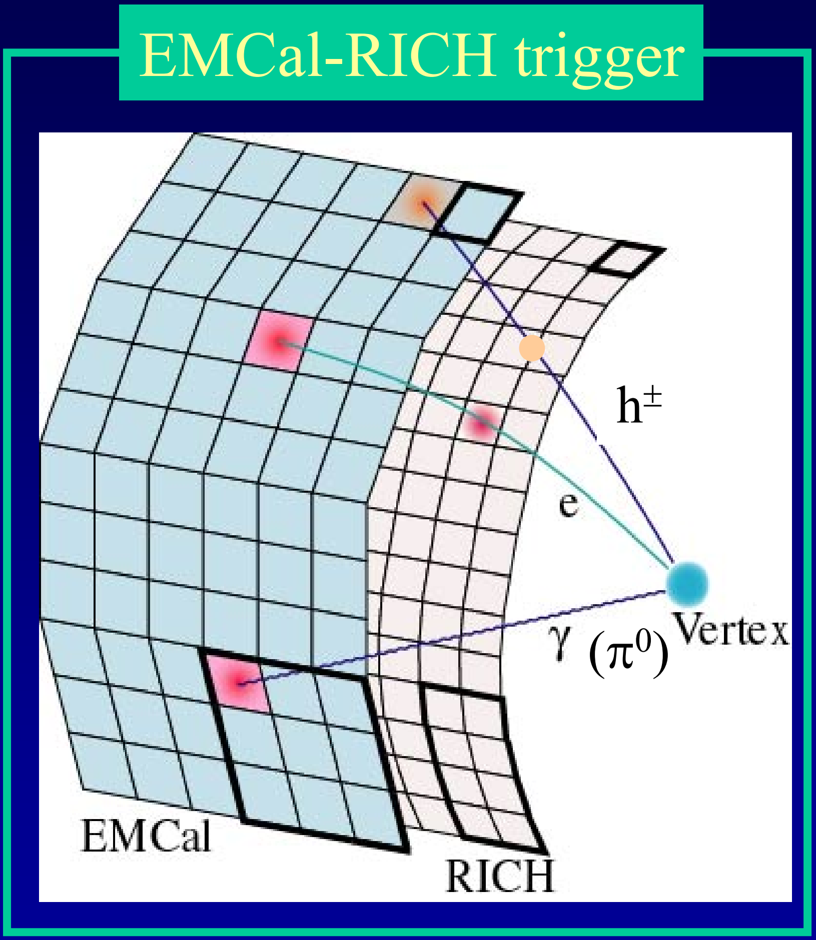
The PHENIX Detector

Limited acceptance → Measure inclusive hadrons

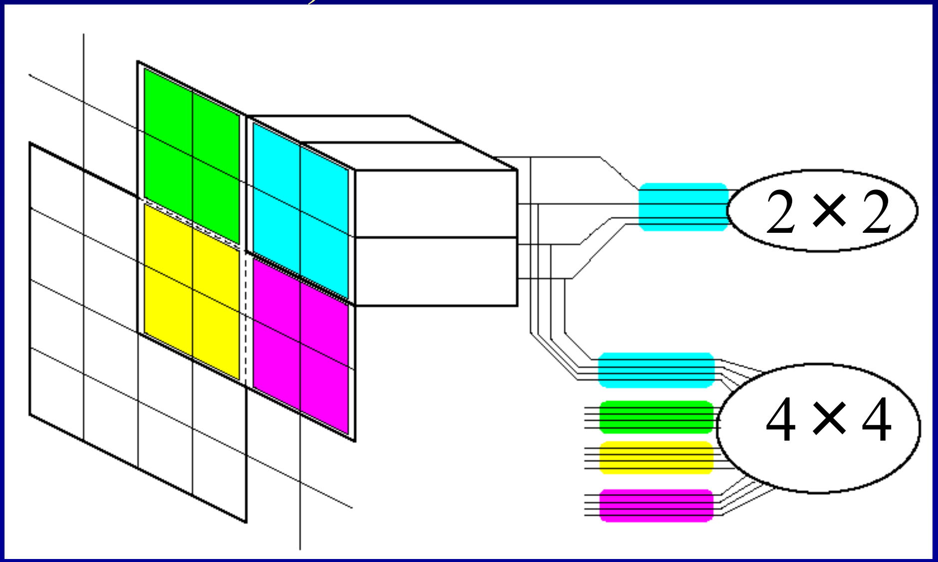
Ability for fast triggering on electromagnetic energy: $\pi^0 \rightarrow \gamma\gamma$ a convenient probe



PHENIX High-Energy EMCal Trigger

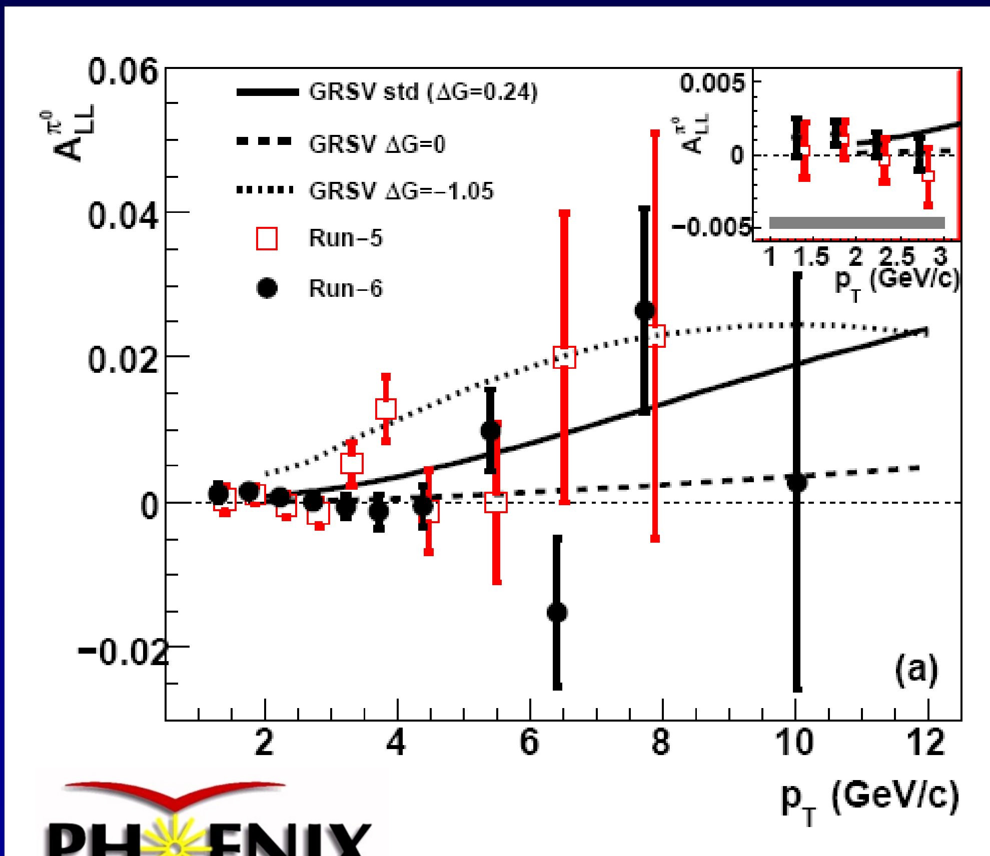


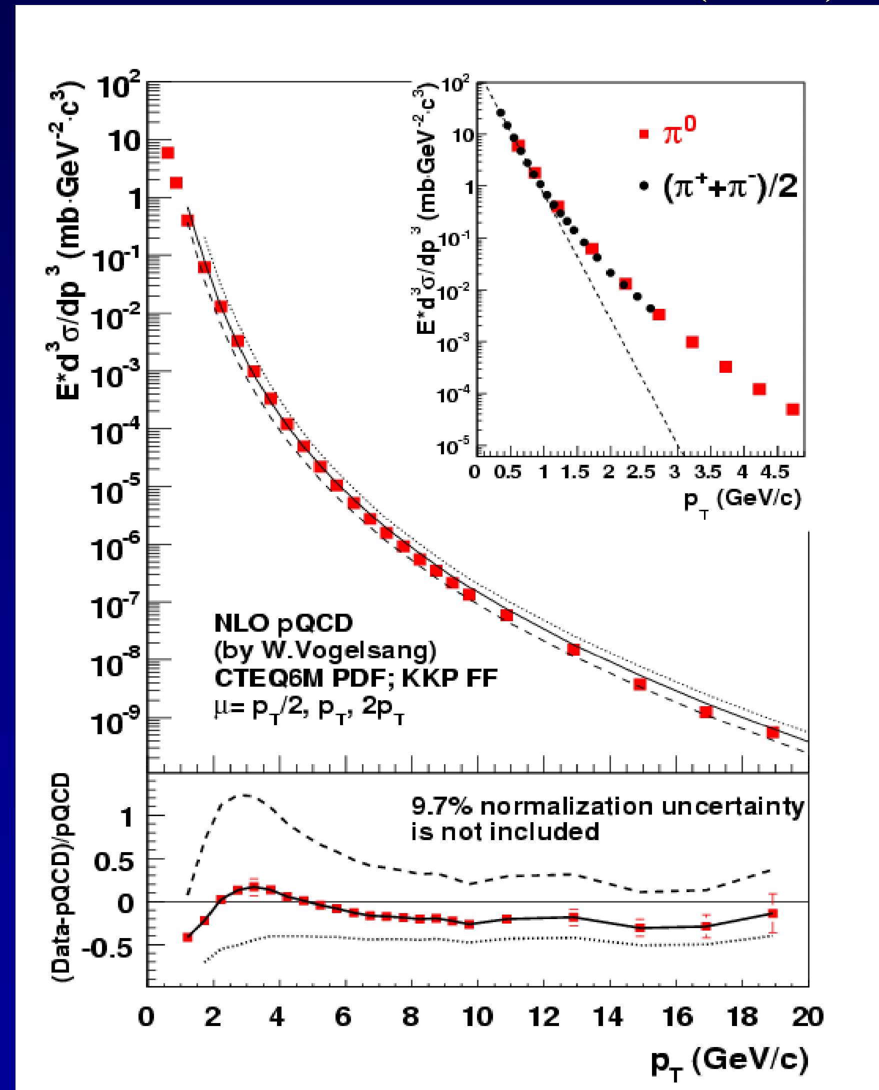
- EMCal part has two sums to collect photon shower
  - 2 × 2 tower non-overlapping sum (1 threshold at 0.8 GeV)
  - 4 × 4 tower overlapping sum (3 thresholds possible—lowest at 1.4 GeV)



Inclusive Neutral Pion Production at 200 GeV

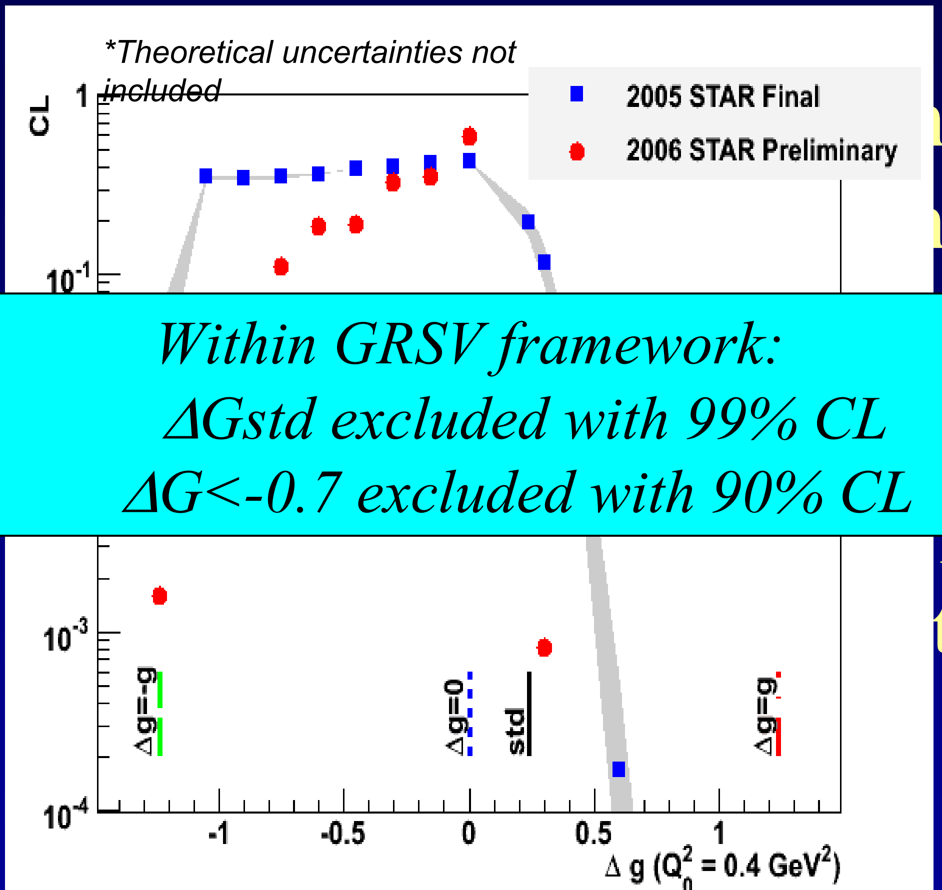
PRD76, 051106 (2007)





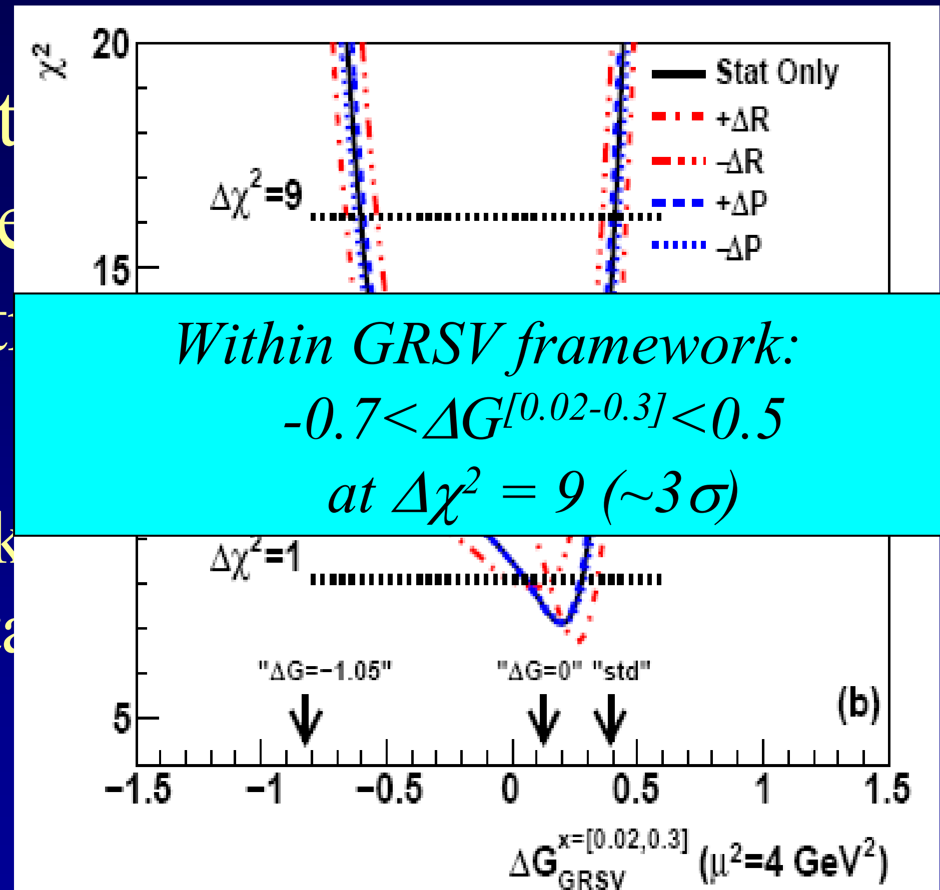
arXiv:0810.0694, submitted to PRL

How Can We Learn about ΔG from Jet and π^0 A_{LL} Measurements at RHIC?



Within GRSV framework:
ΔGstd excluded with 99% CL
ΔG<-0.7 excluded with 90% CL

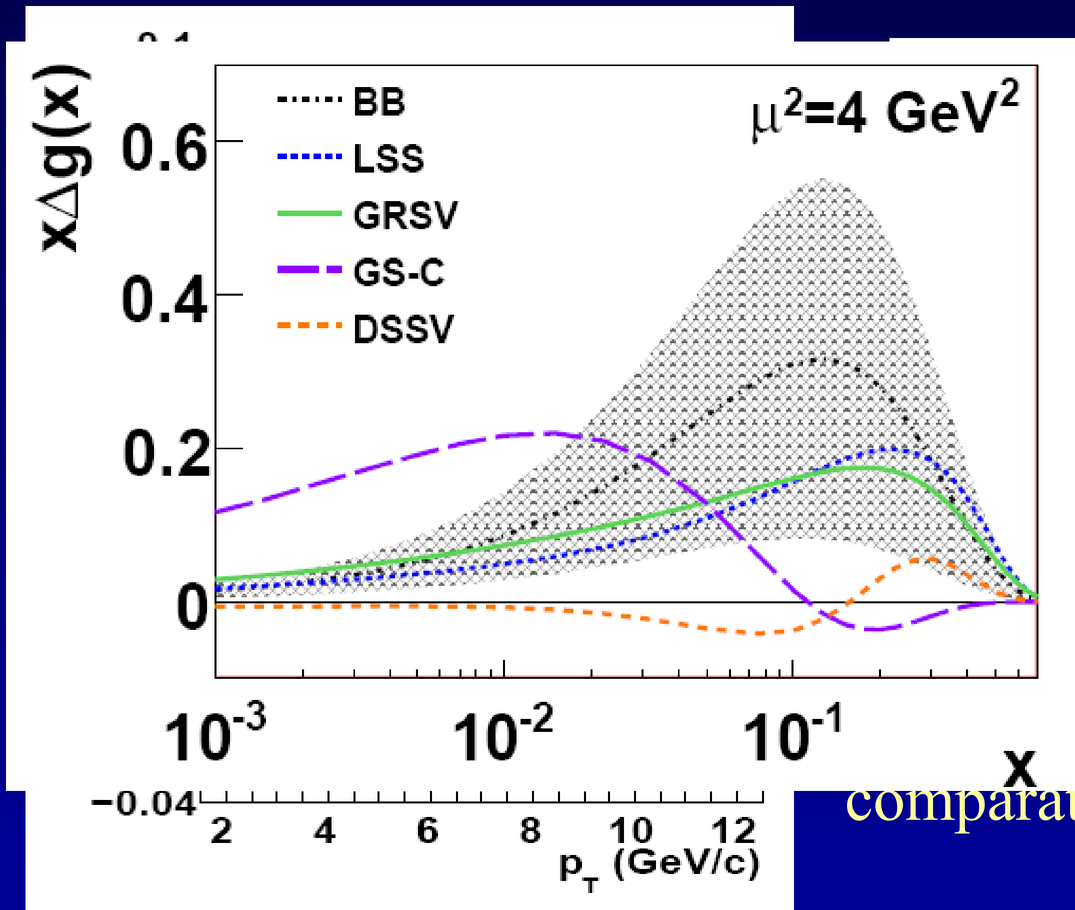
STAR: Confidence Level for agreement of jet data with different values of ΔG within GRSV framework



Within GRSV framework:
$-0.7 < \Delta G^{[0.02-0.3]} < 0.5$
at $\Delta\chi^2 = 9$ *(~3σ)*

PHENIX: χ^2 for agreement of pion data with different values of ΔG within GRSV framework

Comparing to Different Parametrizations



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

G in our measured *x* region
3 gives small A_{LL} (DSSV
C). Large ΔG gives
comparatively larger A_{LL} .

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

But How Do You Know x_{gluon} in p+p Collisions?

Different p_T bins correspond to different (overlapping) ranges in x—not as
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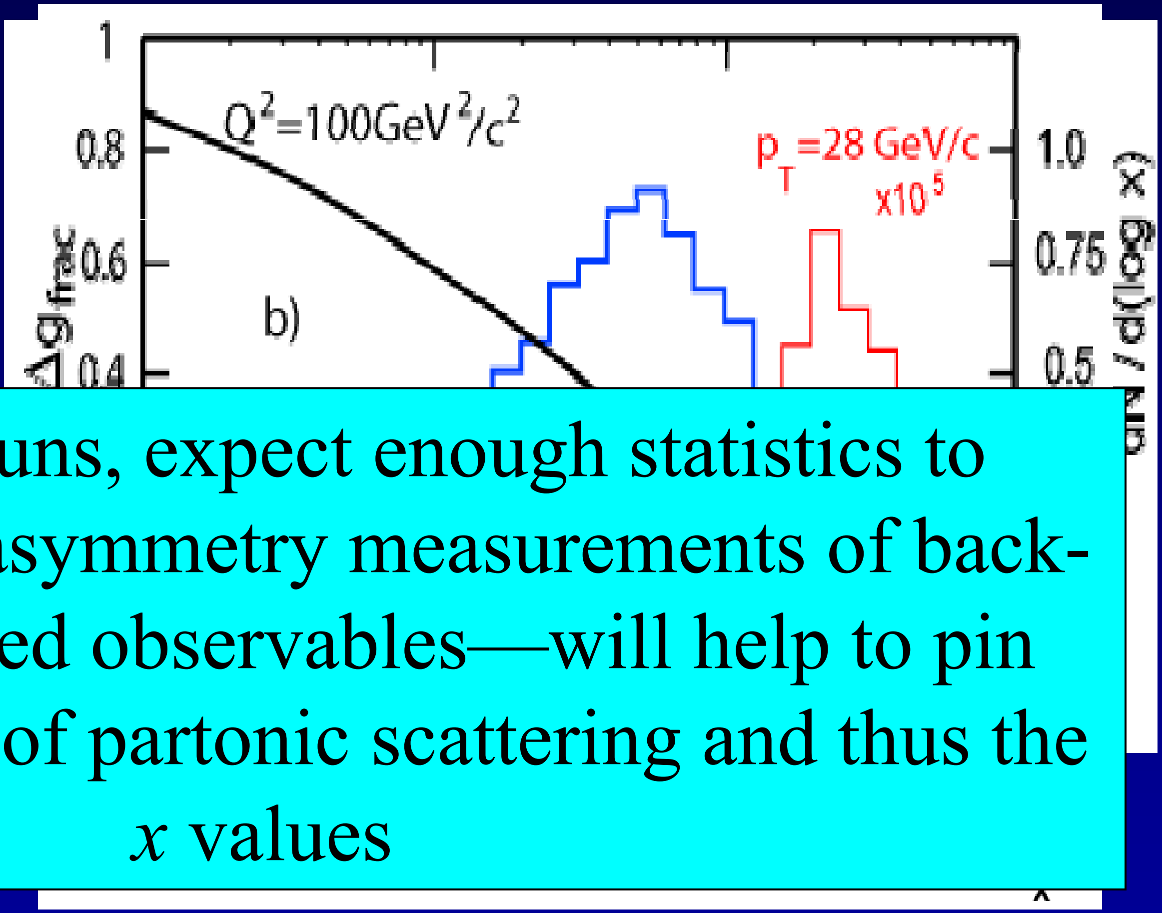


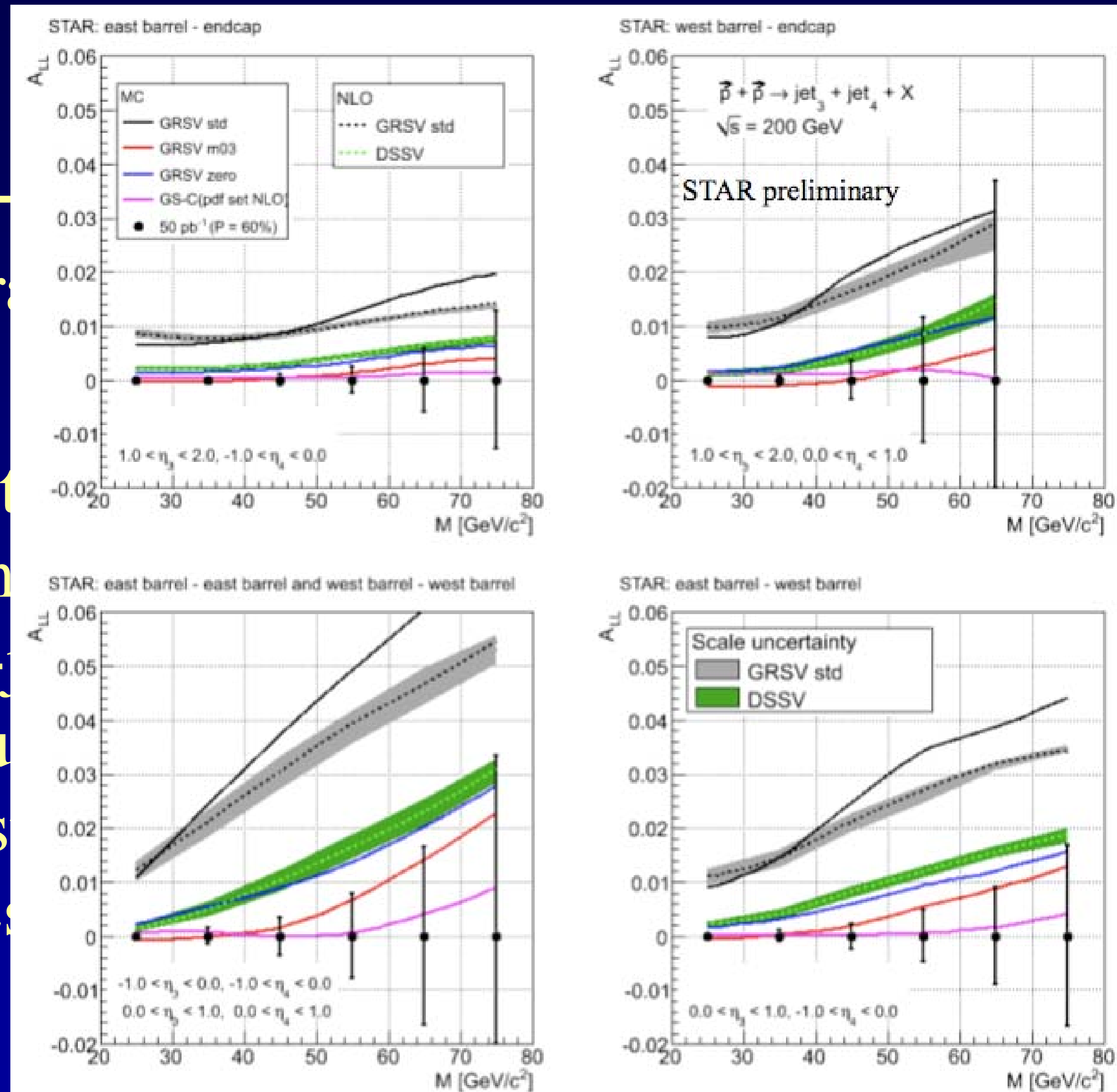
In upcoming runs, expect enough statistics to perform helicity asymmetry measurements of back-to-back correlated observables—will help to pin down kinematics of partonic scattering and thus the *x* values

Going Beyond Inclusive Measurements

- Inclusive channels
  integration over x –
  dependent ΔG extr

Dijet A_{LL} projections
for 2009 run

- Improved accelerat
  detector performan
  allow jet-jet and γ-j
  coi   ce measu
  placing better cons
  partonic kinematics

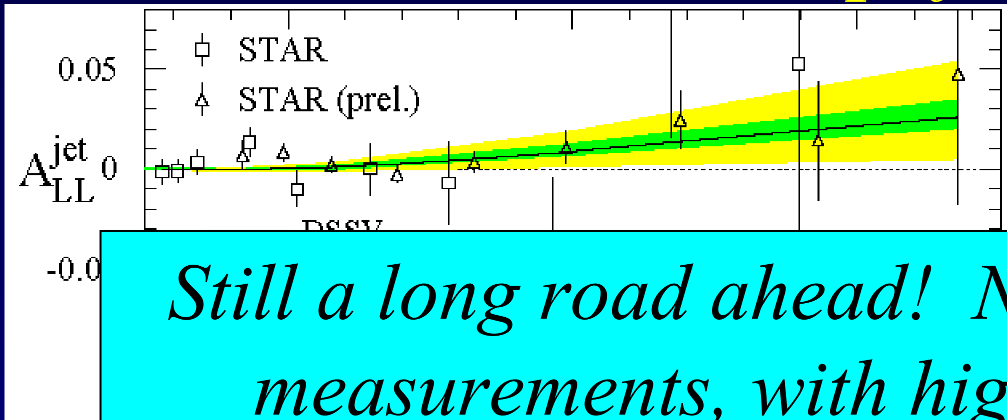


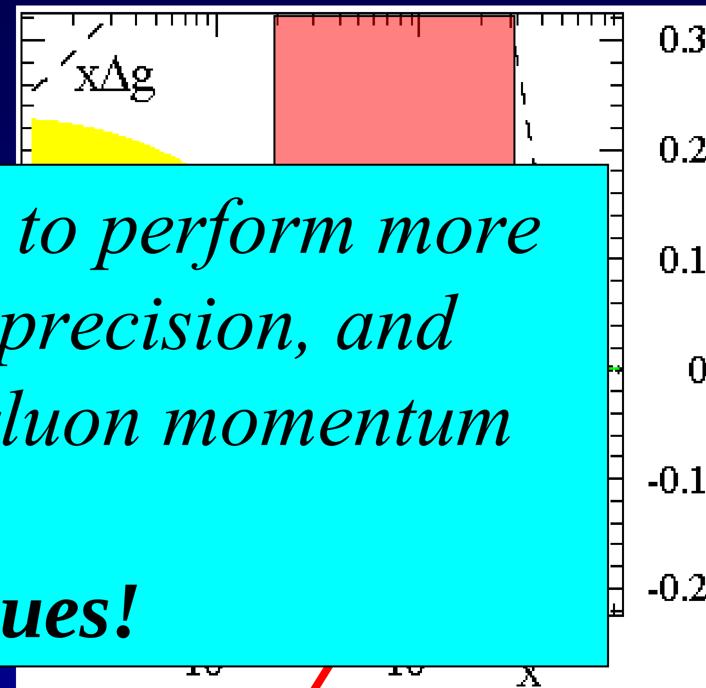
How Can We Learn about ΔG from Jet and π^0 A_{LL} Measurements at RHIC?

- One way: compare points from individual experimental measurements to pQCD calculations of asymmetry which assume different values for ΔG
  - Typically use fixed quark helicity distributions (from a fit to polarized DIS data)
- Another (better!) way: fit the p+p data simultaneously with all other world data

Getting the Full Return on Experimental Efforts: Global pdf Analyses

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





Still a long road ahead! Need to perform more measurements, with higher precision, and covering a greater range in gluon momentum fraction.

Spin crisis continues!

- T
  (
  s
  a
- Truncated moment of $\Delta g(x)$ at moderate x found to be small
- Best fit finds node in gluon distribution near $x \sim 0.1$
  - Not prohibited, but not so intuitive . . .

x range covered by current RHIC measurements at 200 GeV

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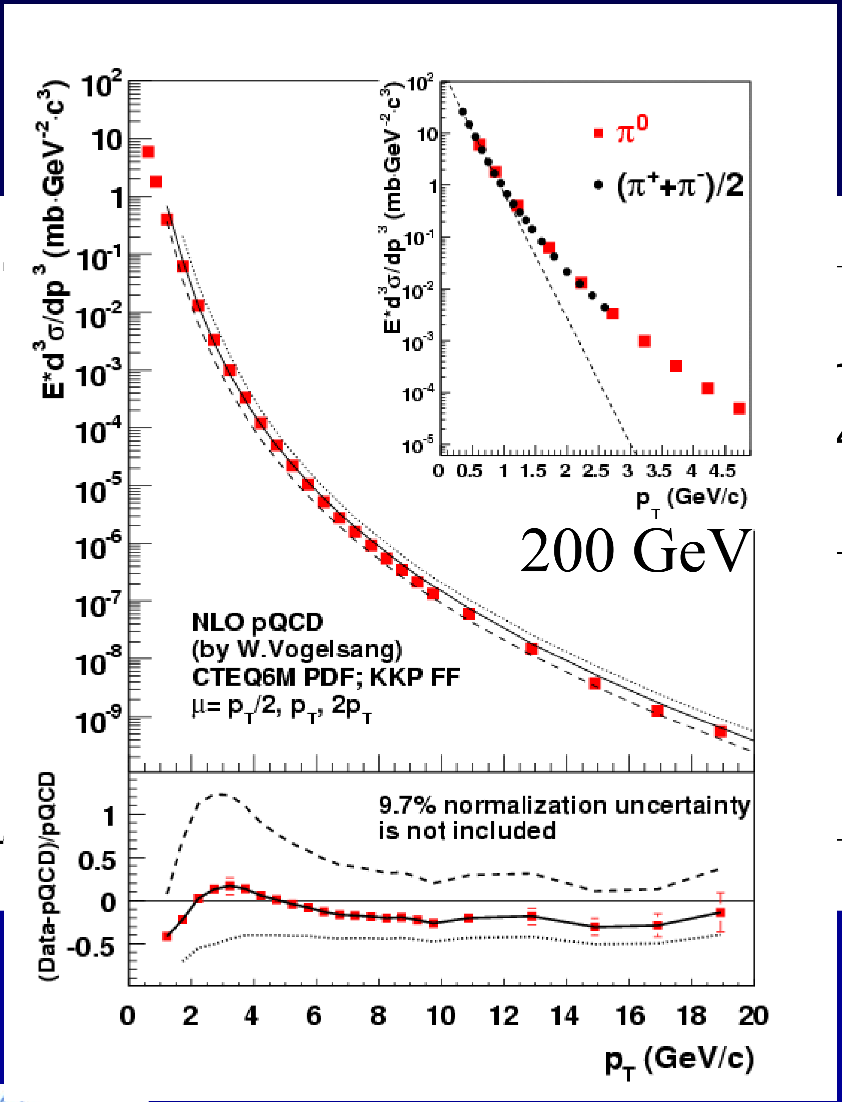
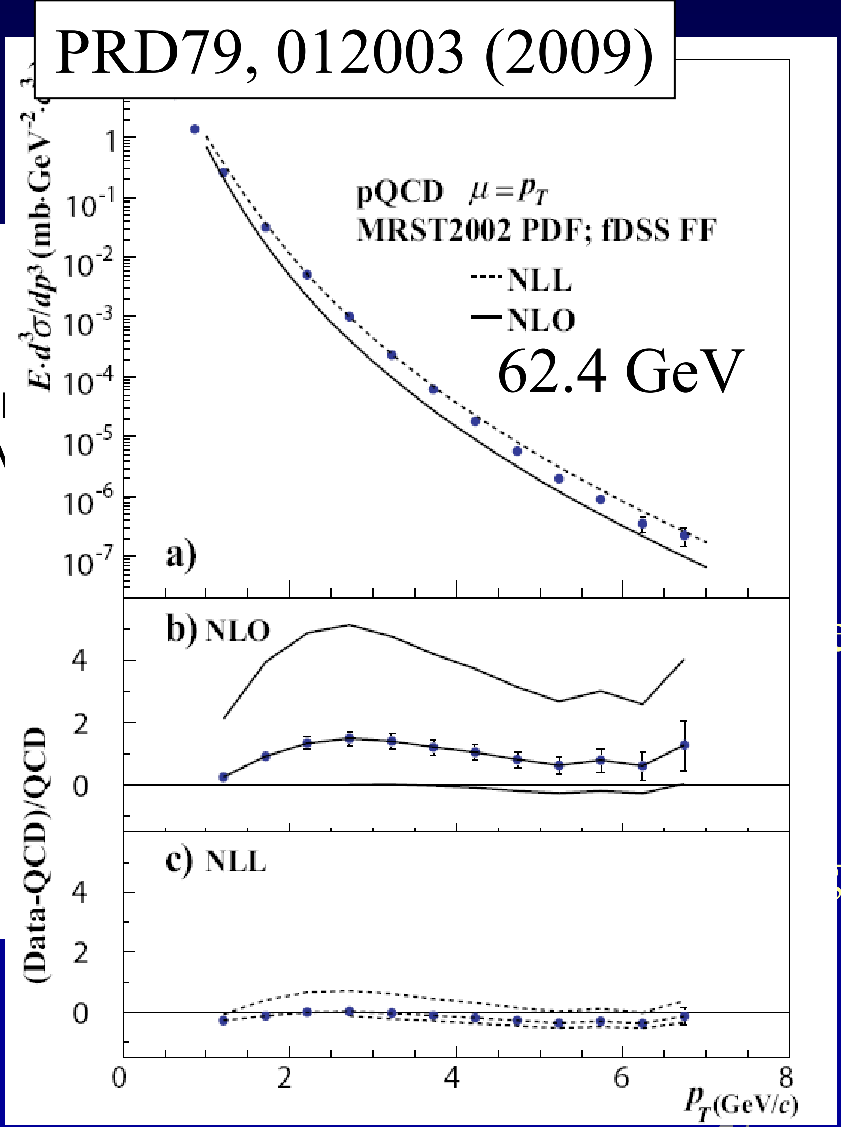
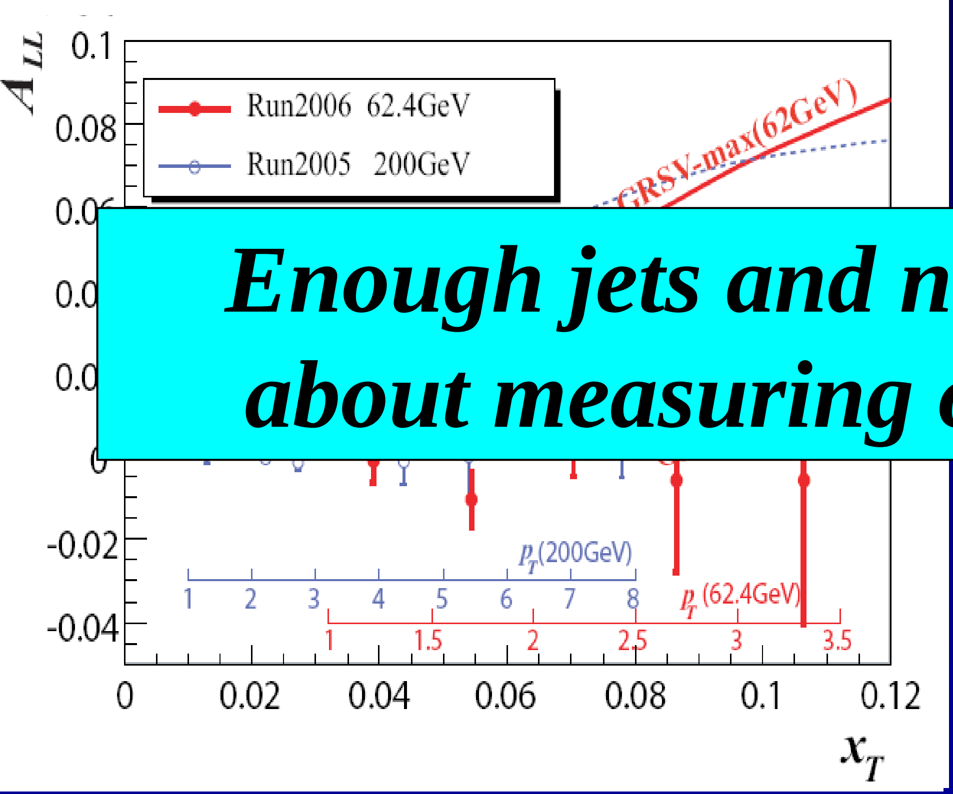
Extending x Coverage





Neutral Pion A_{LL} at 62.4 GeV

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



Converting to x_T, can see

Enough jets and neutral pions! How about measuring other observables?

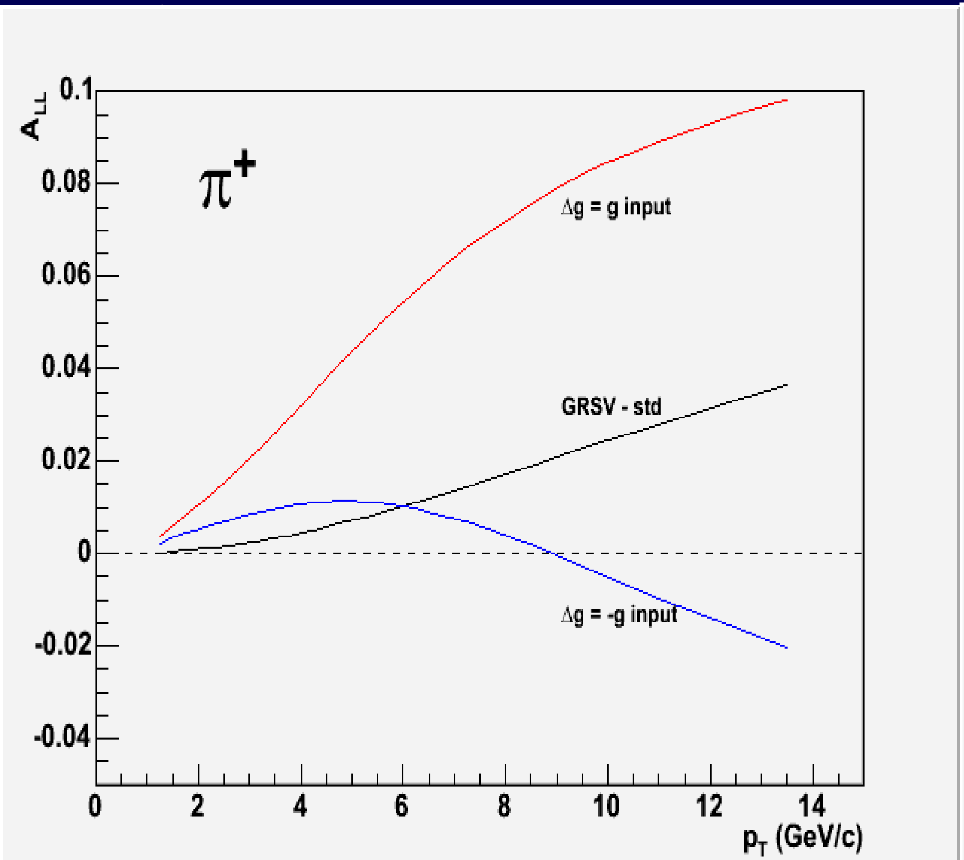
2005 at 200 GeV (3.4 pb^{-1}).

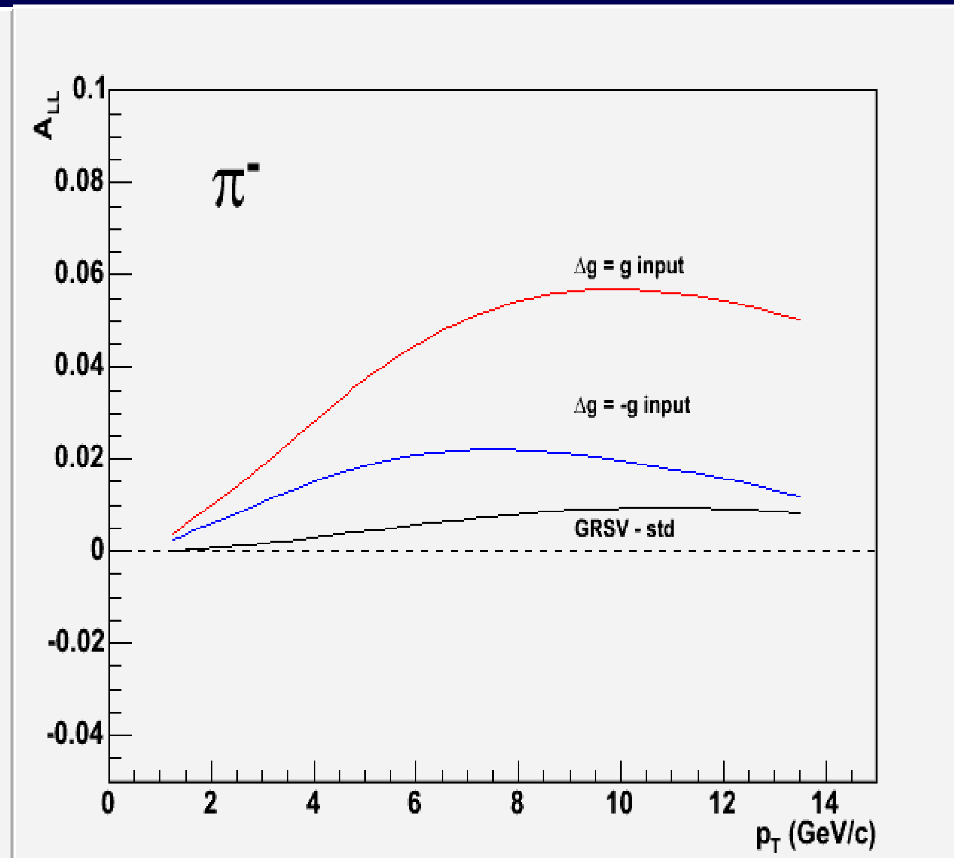
$$0.02 < x_{gluon} < 0.3 \quad (\sqrt{s} = 200\,\text{GeV})$$

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

PRD79, 012003 (2009)

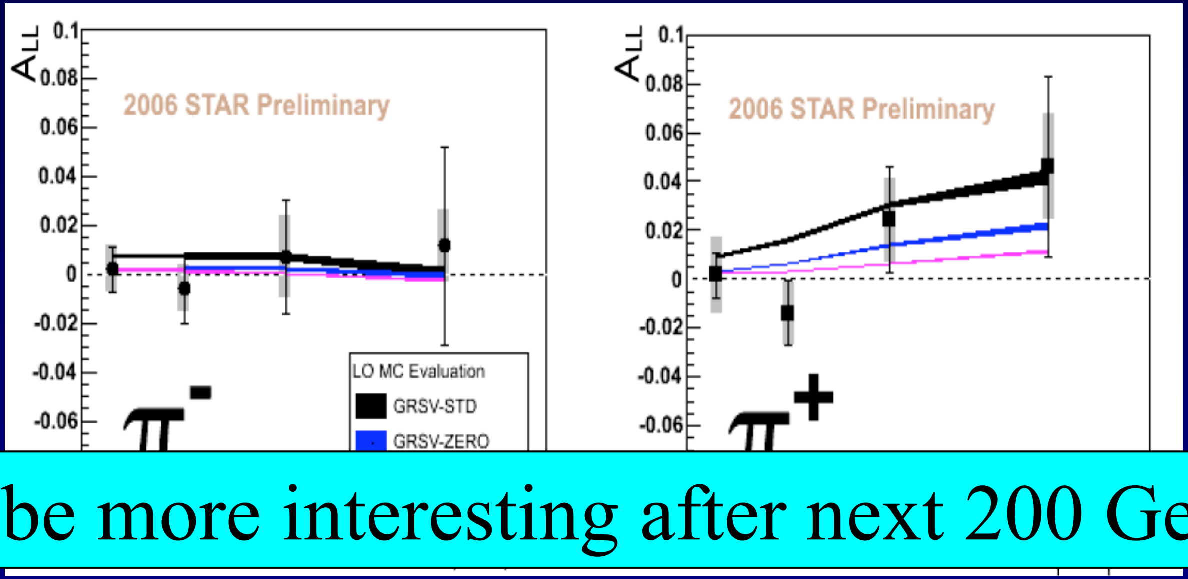
The Pion Isospin Triplet, A_{LL} and ΔG



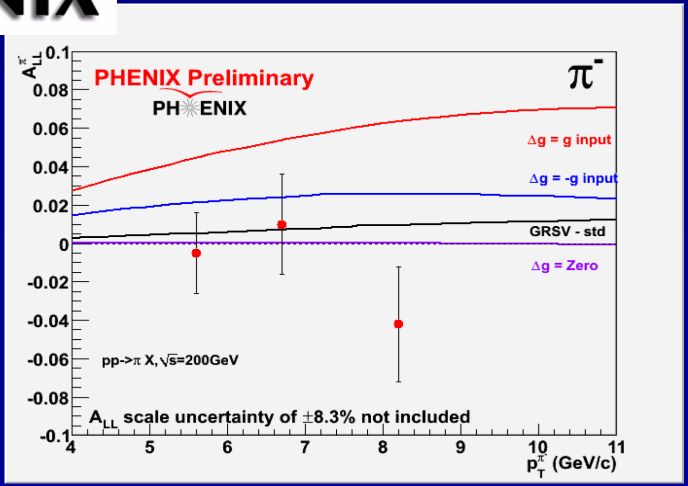


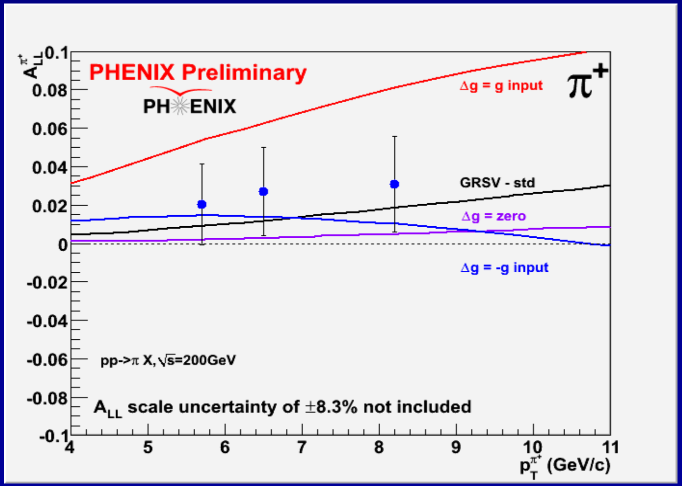
$$\Delta G > 0 \Rightarrow A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$$

Charged pion A_{LL} at 200 GeV



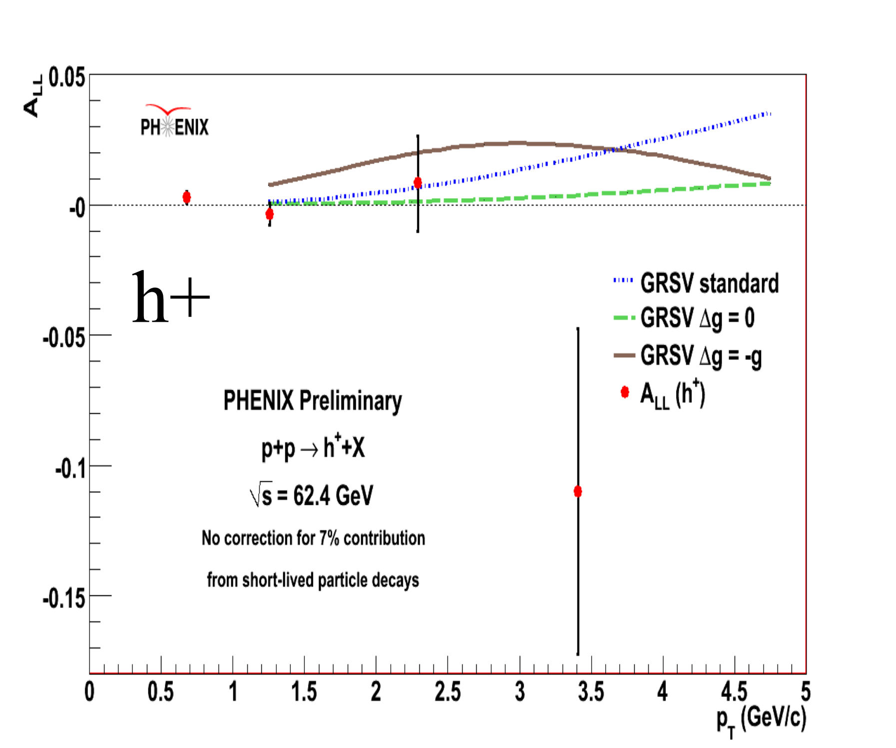
Should be more interesting after next 200 GeV run!

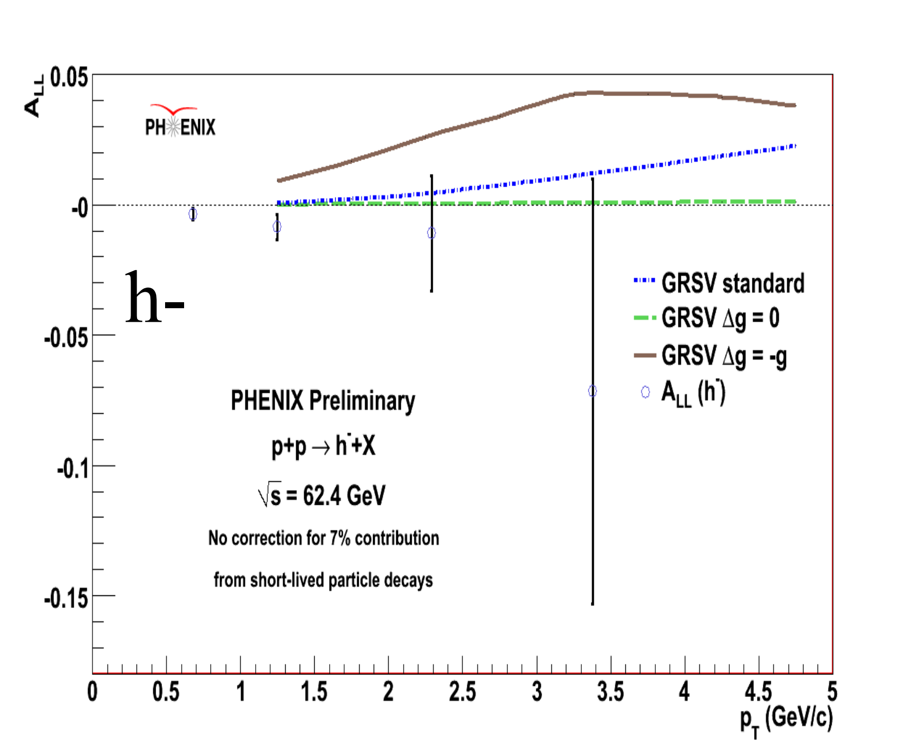




A_{LL} of Non-Identified Charged Hadrons at 62.4 GeV

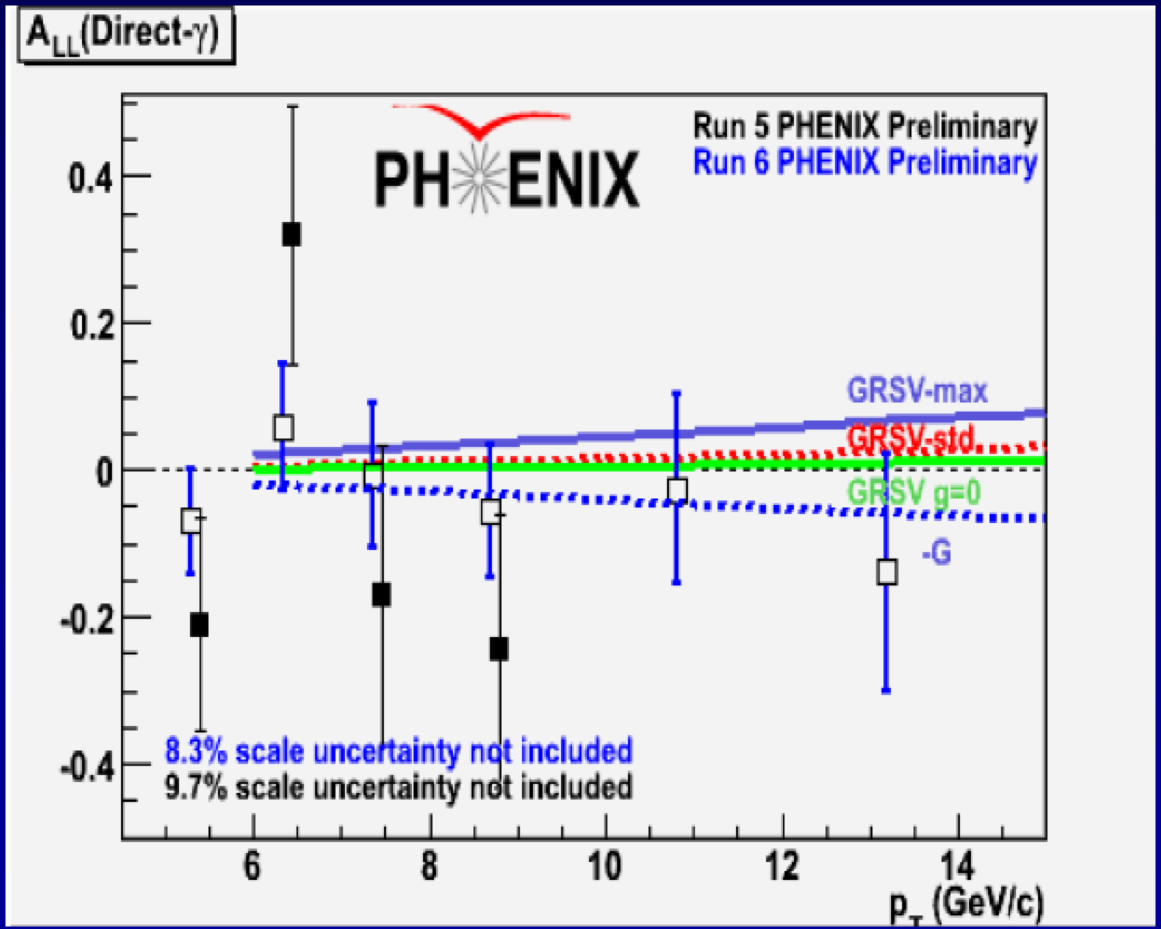
As for identified charged pions, expect sensitivity to sign of gluon spin.
Cross section measurement in progress!
(Another check of applicability of NLO and/or NLL at this energy)

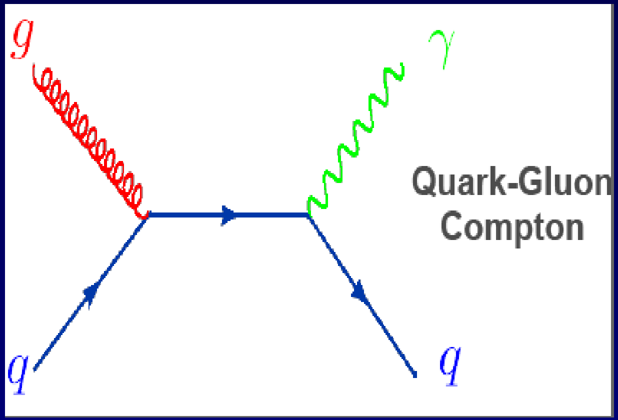




14% polarization uncertainty not included

A_{LL} of Direct Photons at 200 GeV



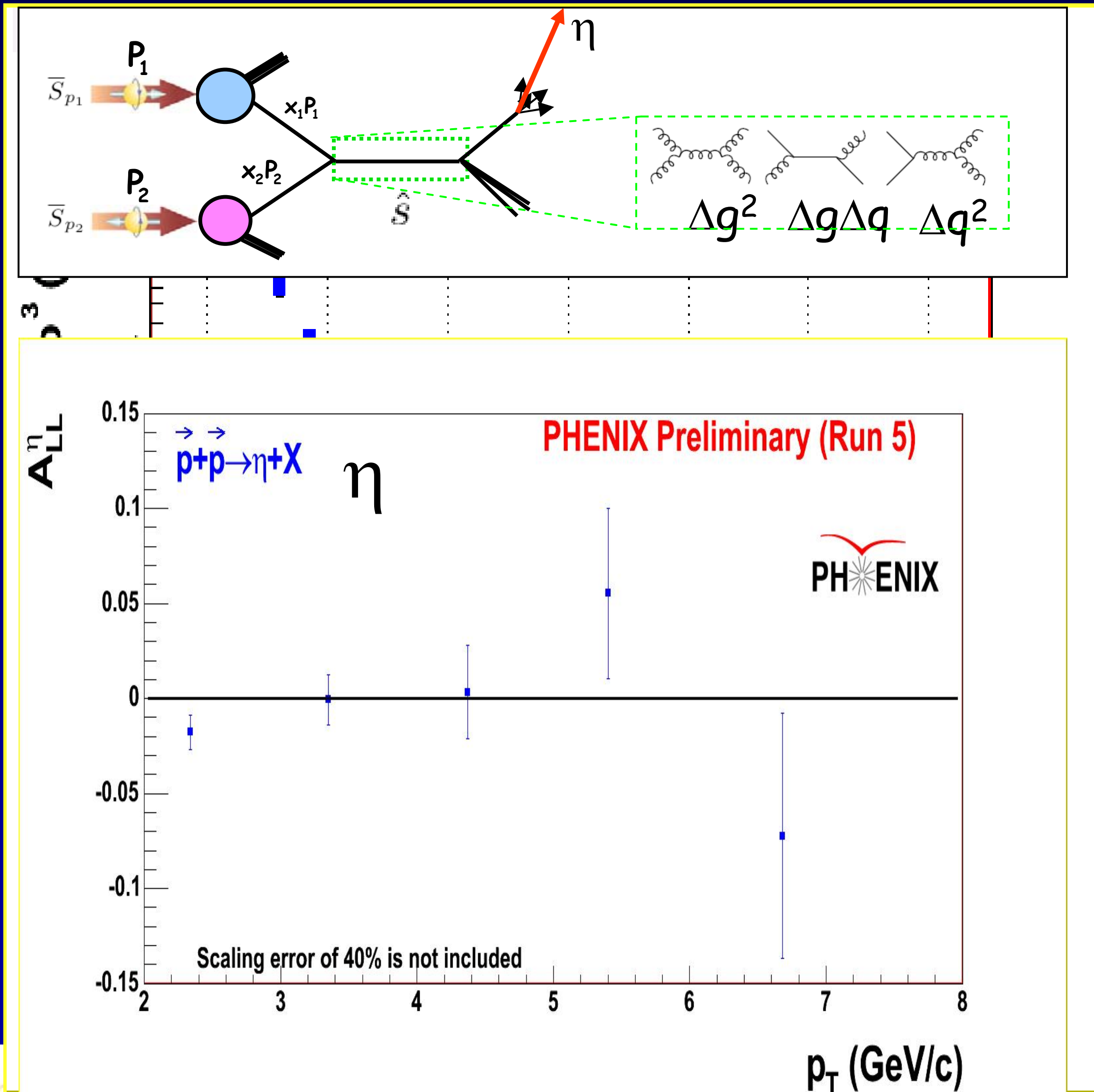


Theoretically clean channel—few partonic processes contribute, and no dependence on fragmentation functions—but small production cross section!!

Fragmentation Functions (FF's): Improving Our Input for Inclusive Hadronic Probes

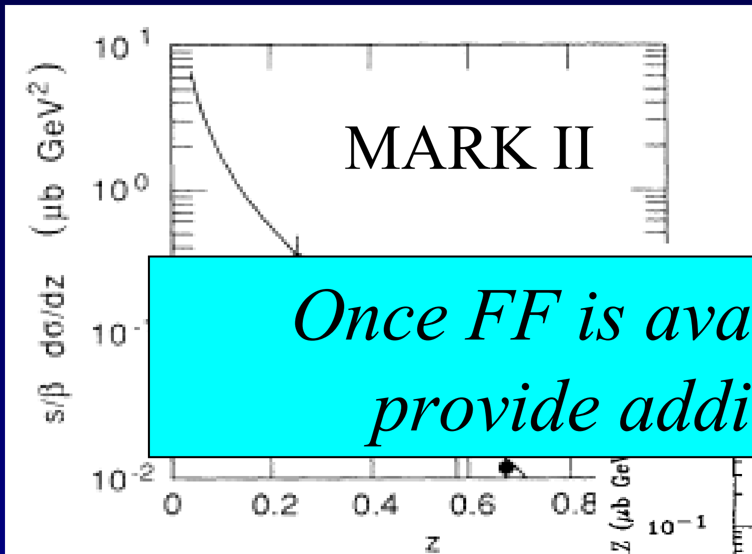
- FF's not directly calculable from theory—need to be measured and fitted experimentally (like pdf's)
- The better we know the FF's, the tighter constraints we can put on the polarized parton distribution functions!
- Traditionally from e+e- data—clean system!
- Framework recently developed to extract FF's using all available data from *deep-inelastic scattering and hadronic collisions* as well as e+e-
  - de Florian, Sassot, Stratmann: PRD75:114010 (2007)

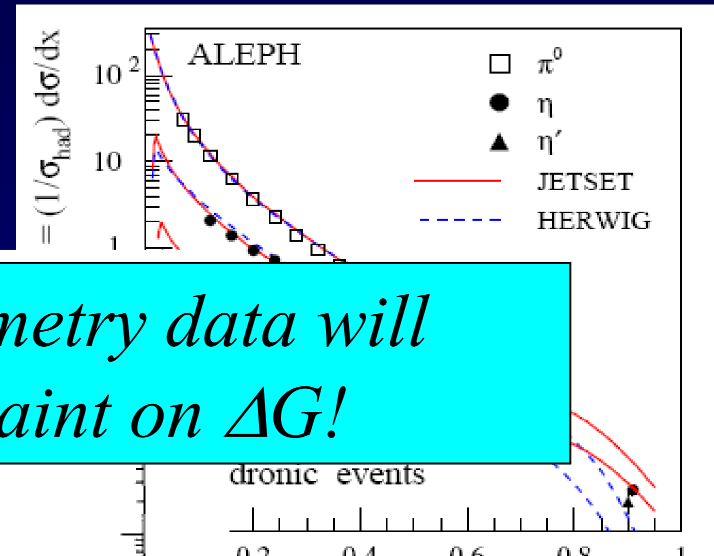
An Example:
Cross Section and A_{LL} of η Meson



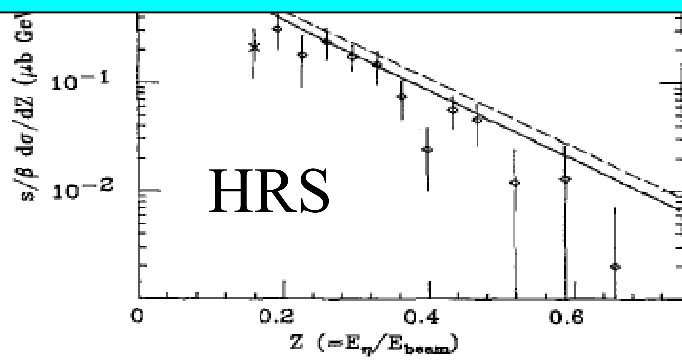
η relatively abundant ($\eta/\pi^0 \sim 0.5$) and easy to measure via decay to two photons, but fragmentation function not available in the literature! No theoretical comparisons possible to extract information on ΔG. . .

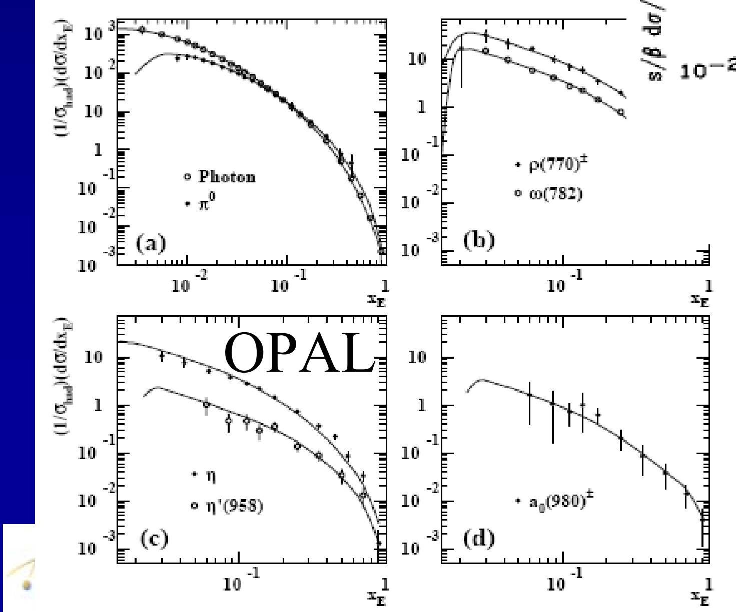
Parametrizing the η FF Using e+e- and PHENIX p+p Data

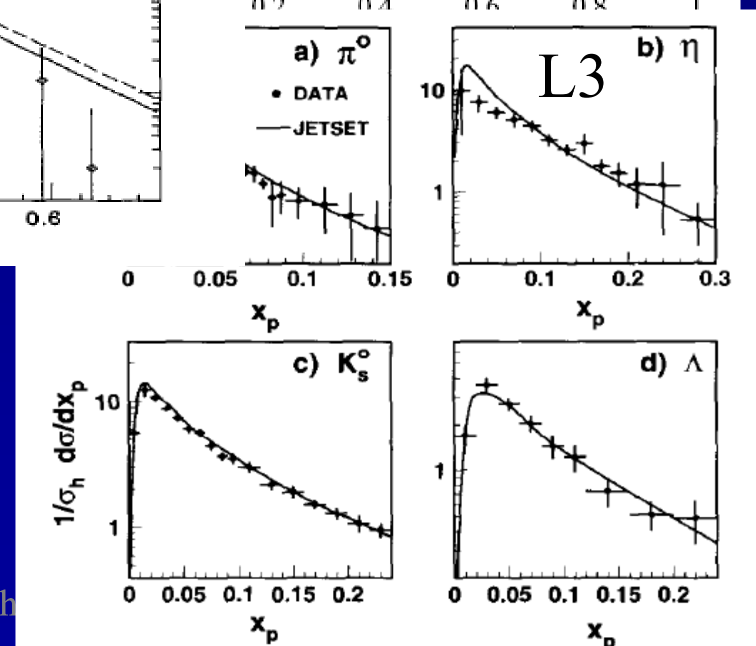




Once FF is available, asymmetry data will provide additional constraint on ΔG!

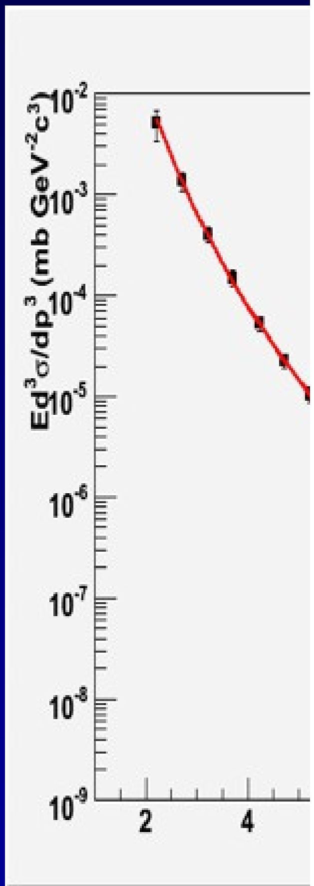


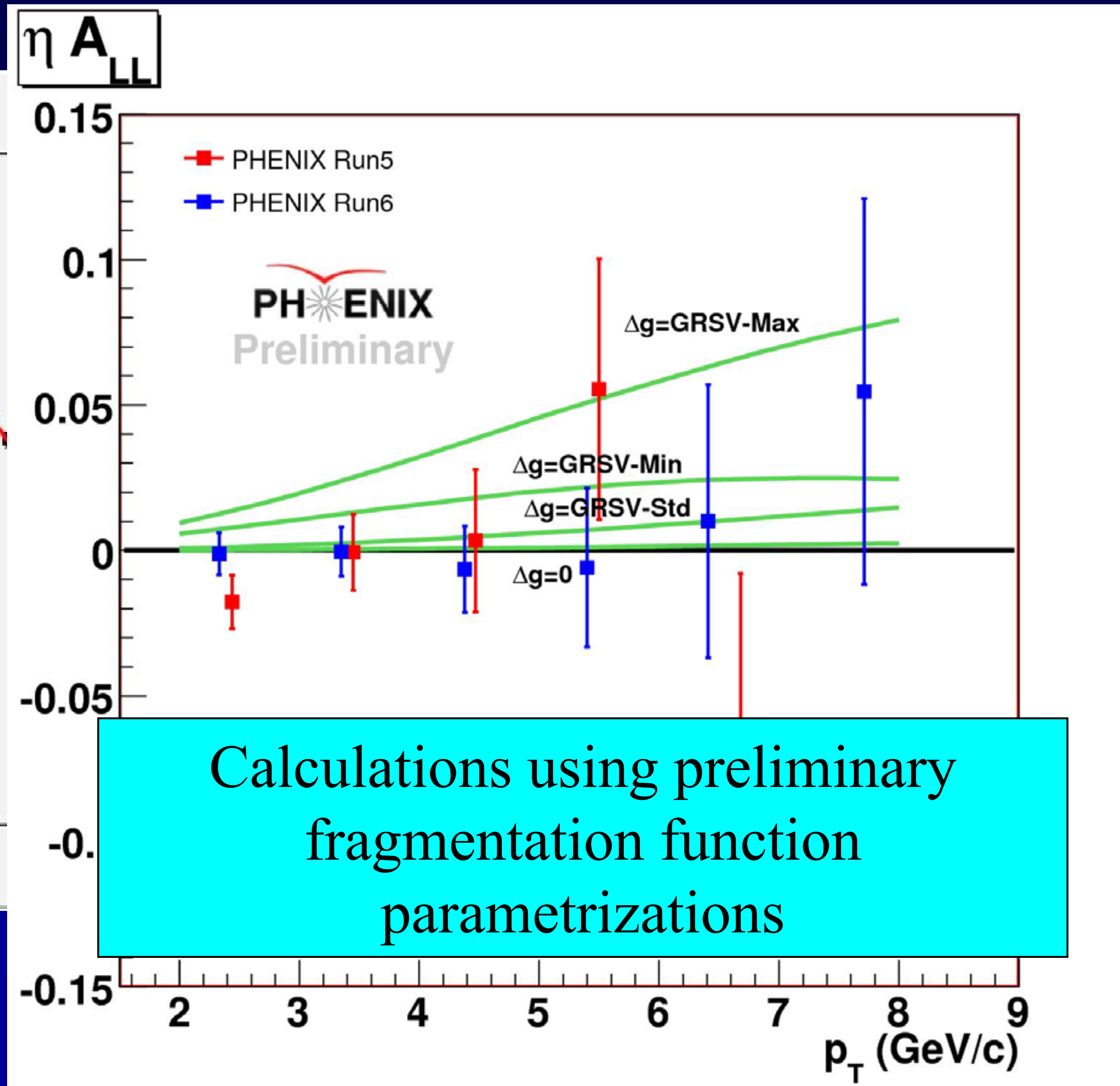


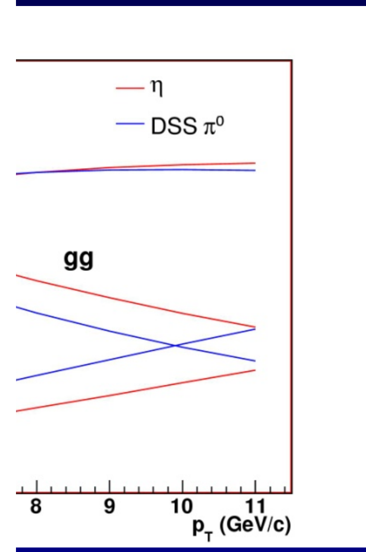


CA, J. Seele, M. Stratmann

$\eta\ A_{LL}$ at 200 GeV







Calculations using preliminary fragmentation function parametrizations

s π^0
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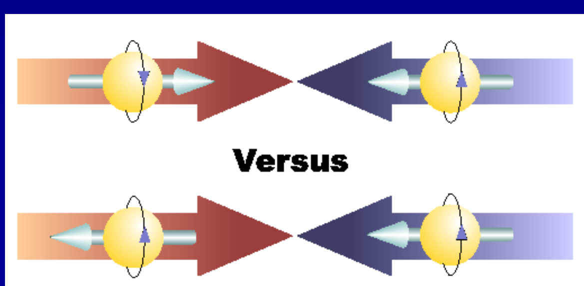
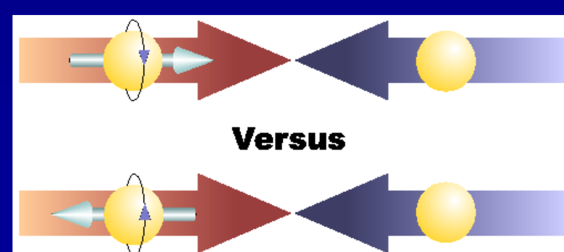
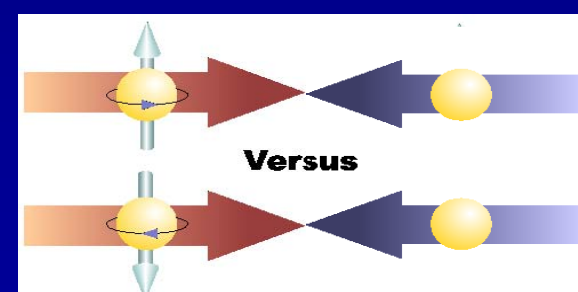
Proton Spin Structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π, Jets $A_{LL}(gg, gq \to \pi + X)$ Prompt Photons $A_{LL}(gq \to \gamma + X)$ Back-to-Back Correlations	**W Production** $A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$ $A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	**Transversity** **Transverse-momentum-dependent distributions** Single-Spin Asymmetries





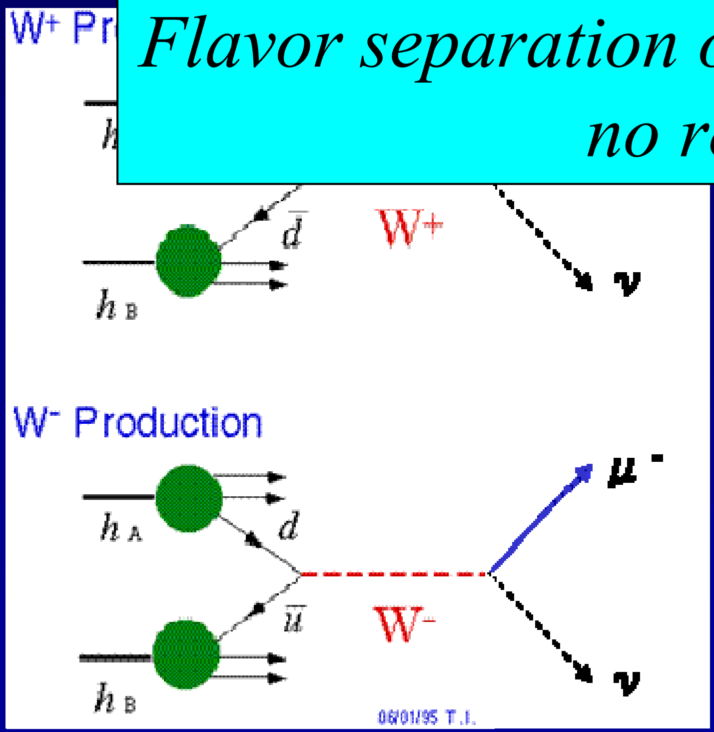


Flavor-Separated Sea Quark Polarizations Through W Production

$$\Delta q(x), \Delta\bar{q}(x)$$

$$A_L^{W^+} \approx \frac{\Delta u(x_1, M_W^2)}{u(x_1, M_W^2)}, \; x_1 > x_2 \;\; (y_W >> 0)$$

0)

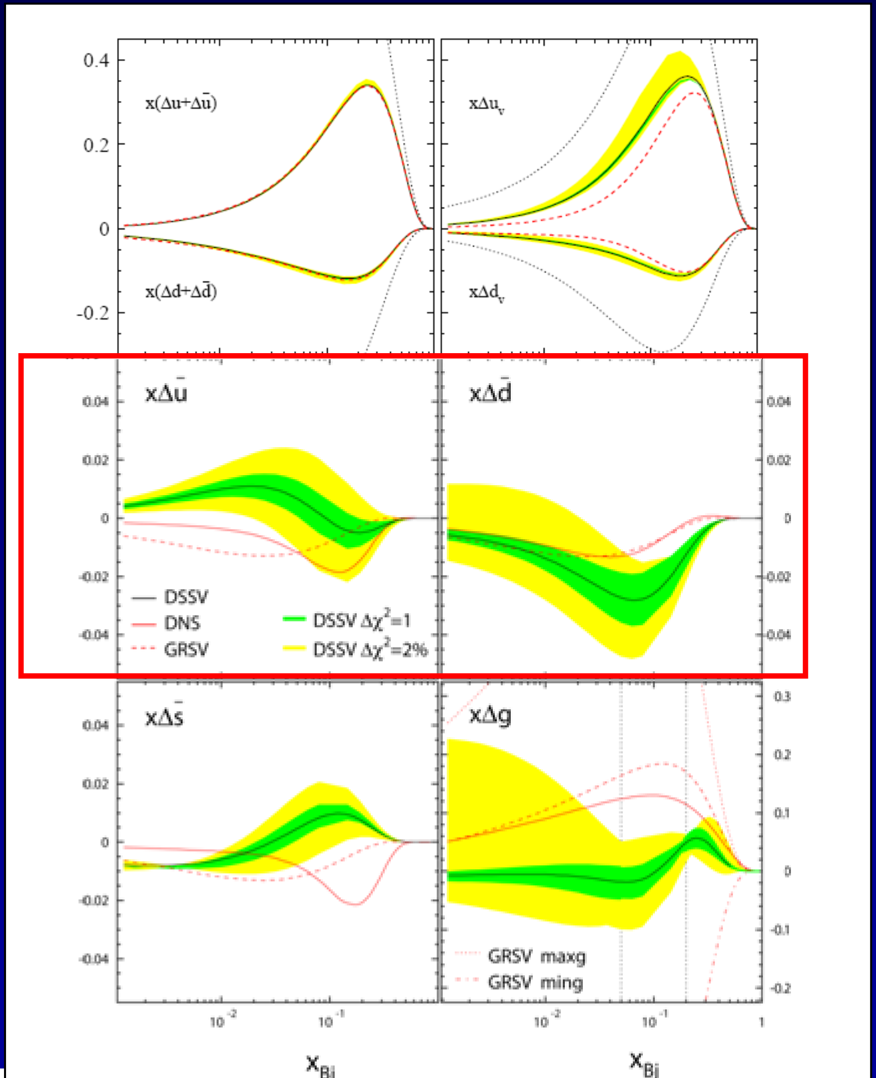


Flavor separation of the polarized sea quarks with no reliance on FF's!

For W- interchange u and d

Parity violation of the weak interaction in combination with control over the proton spin orientation gives access to the *flavor* spin structure of the proton!

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



DSSV, PRL101, 072001 (2008)

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

Latest global fit to helicity distributions: Still relatively large uncertainties on helicity distributions of anti-up and anti-down quarks!

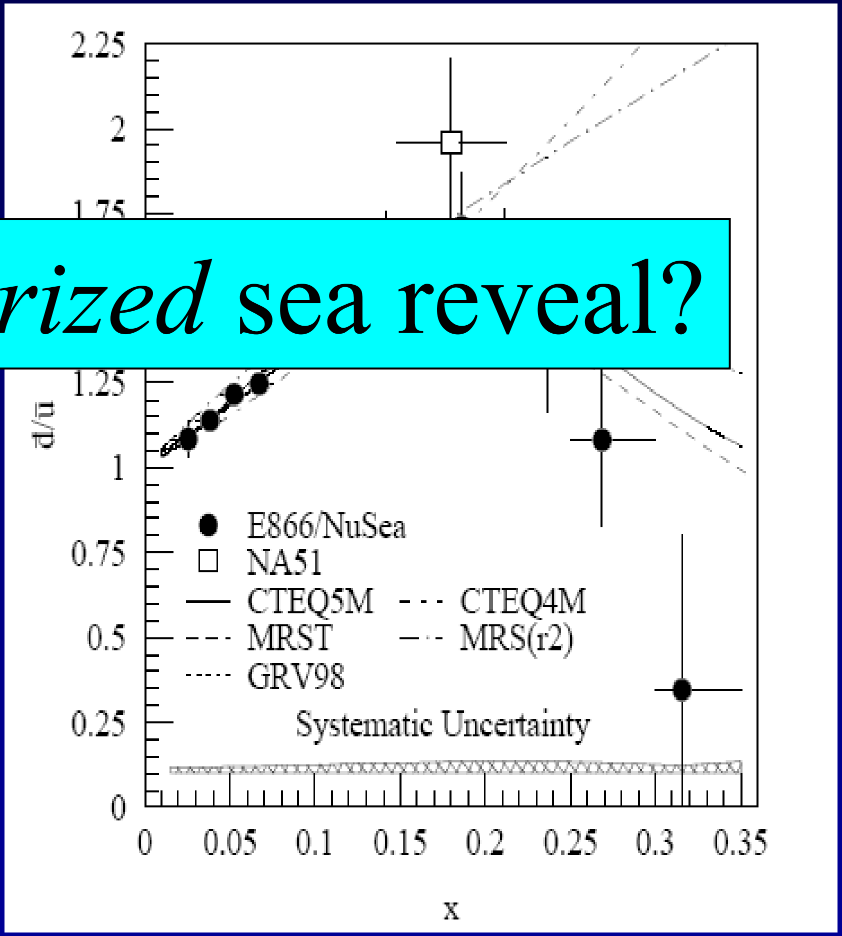
Flavor Asymmetry in the Unpolarized Sea (Discovered in Hadronic Collisions!)

- Fermilab Experiment 866 used proton-hydrogen and pr
co
nucleon structure via the Drell-Yan process

What will the *polarized* sea reveal?

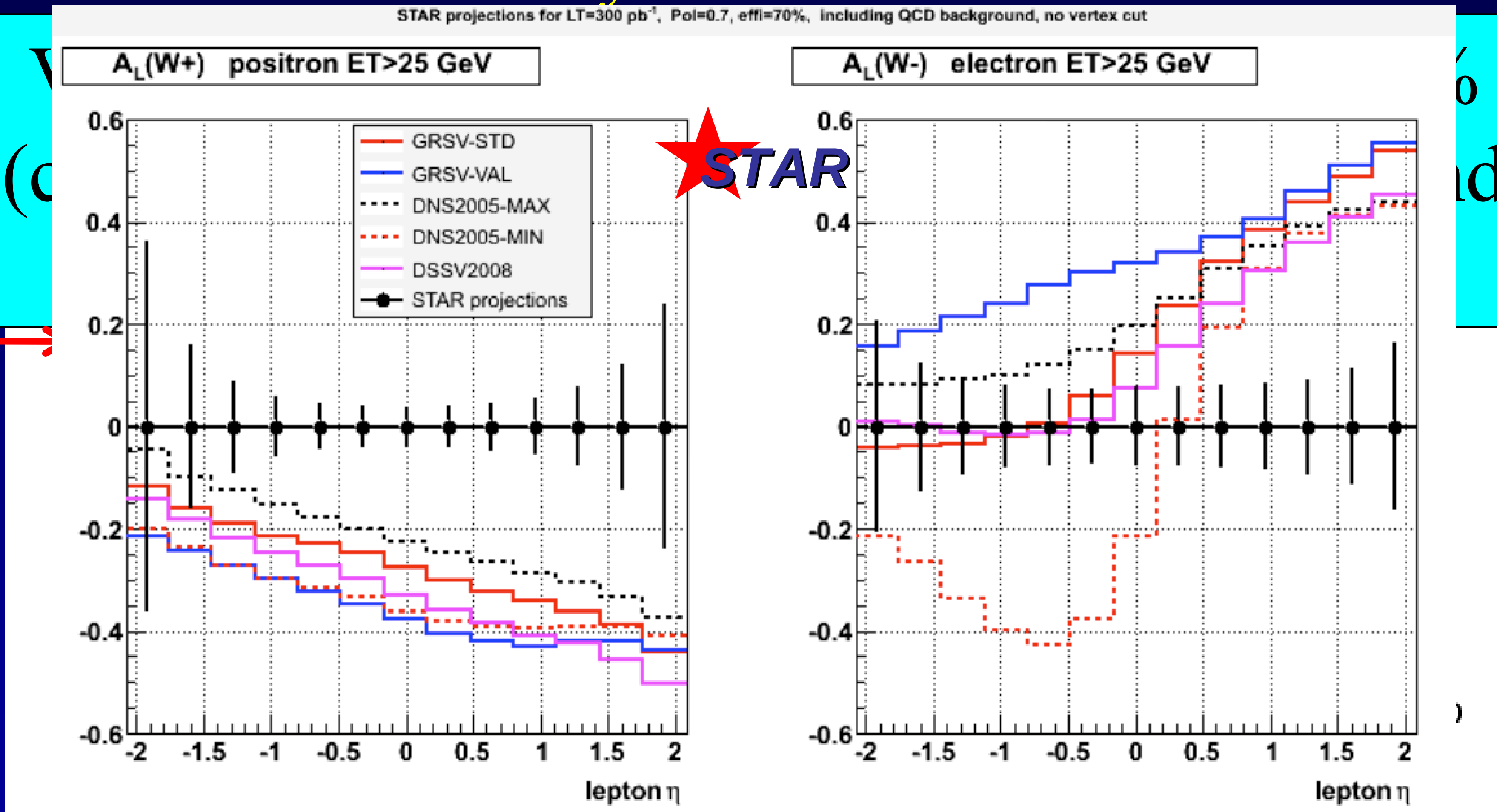
$$q + \bar{q} \rightarrow \mu^{+} + \mu^{-}$$

- Anti-up/anti-down asymmetry in the quark sea, with an unexpected x behavior!



PRD64, 052002 (2001)

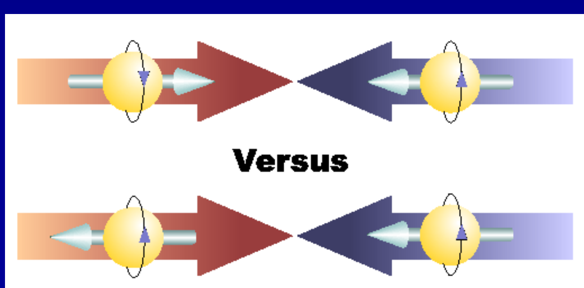
Some Expectations for W Asymmetries

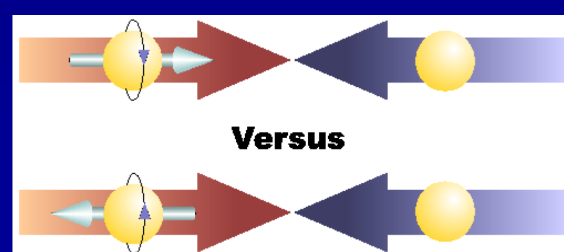


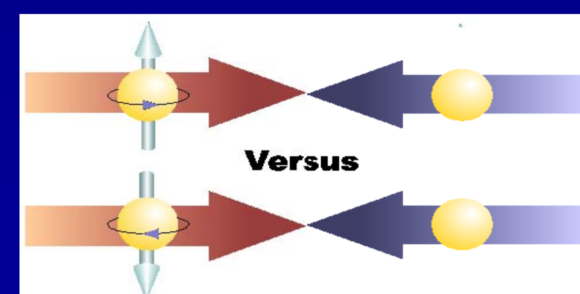
First 500 GeV data-taking started this month!

Proton Spin Structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π, Jets $A_{LL}(gg, gq \to \pi + X)$ Prompt Photons $A_{LL}(gq \to \gamma + X)$ Back-to-Back Correlations	**W Production** $A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$ $A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	**Transversity** **Transverse-momentum-dependent distributions** Single-Spin Asymmetries



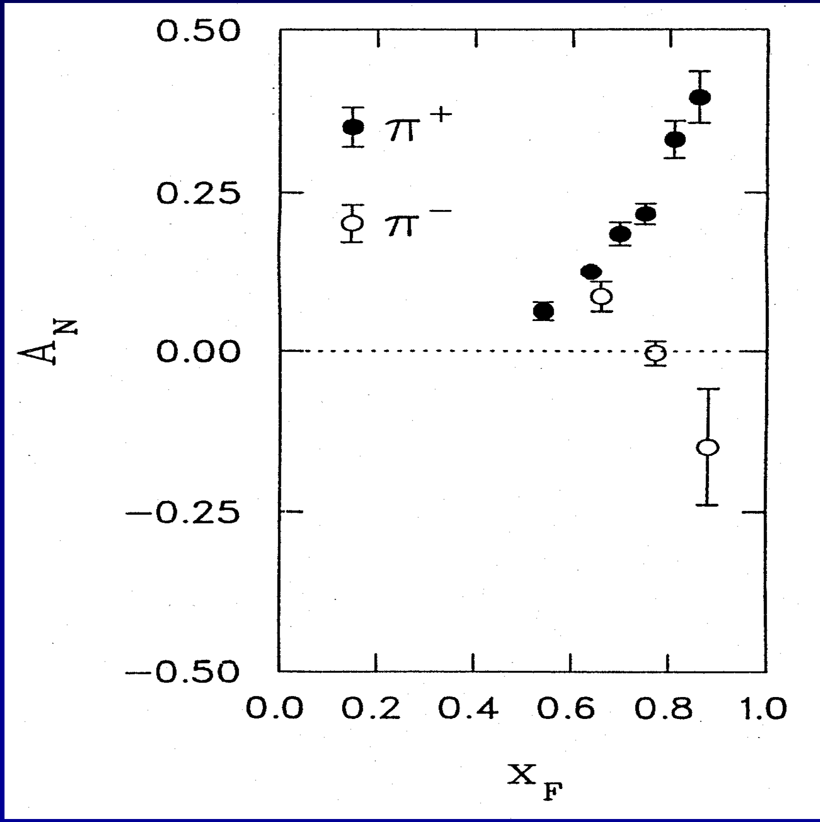


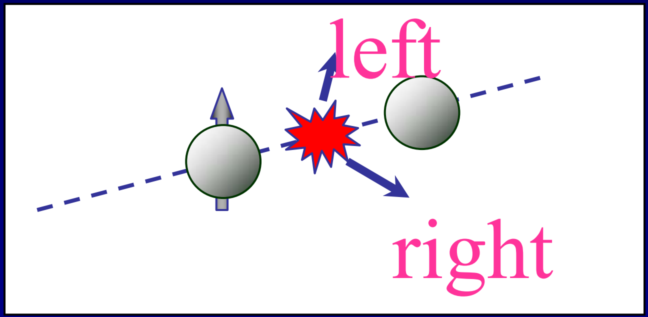


1976: Discovery in p+p Collisions! Large Transverse Single-Spin Asymmetries

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

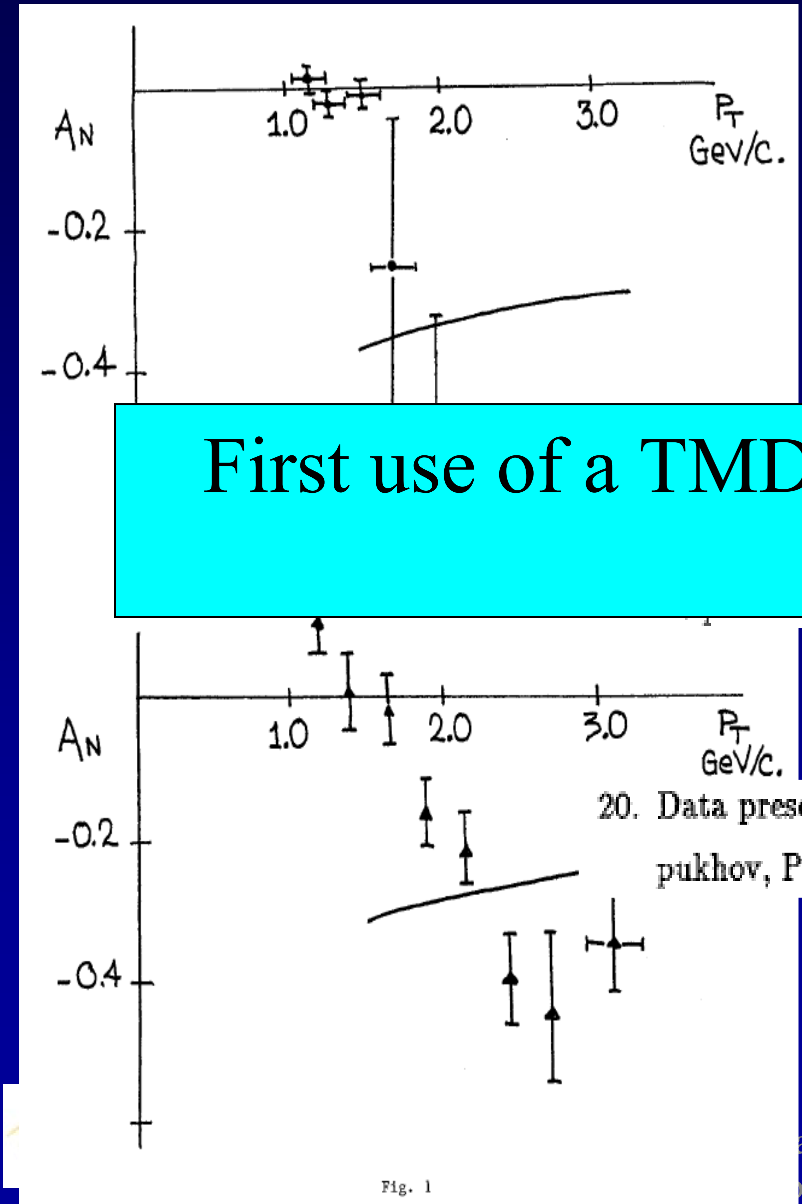
$$pp^{\uparrow} \rightarrow \pi X$$





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

Transverse-Momentum-Dependent Distributions and SSA's



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

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

First use of a TMD to try to explain transverse SSA's!

is from

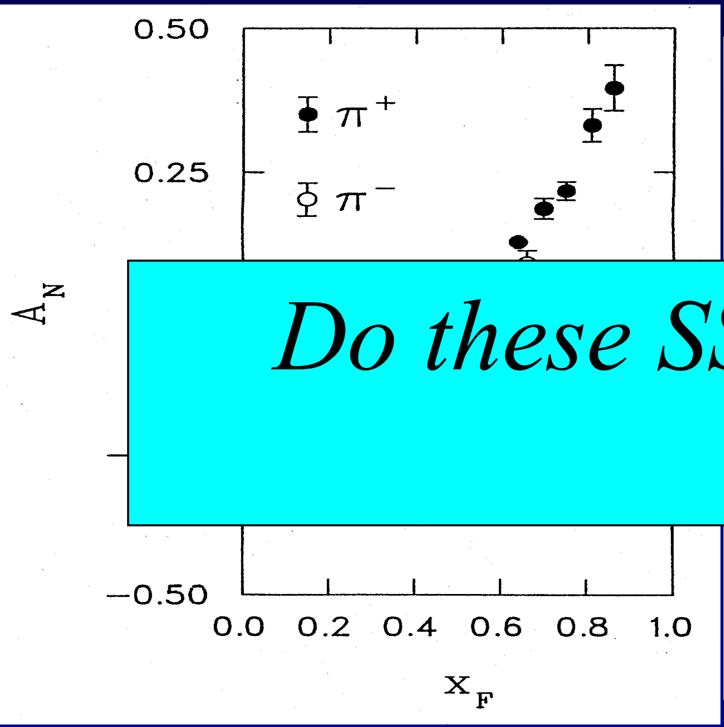
19. J. Antille *et al.*, Phys. Lett. **94B**, 523 (1980).

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

CERN

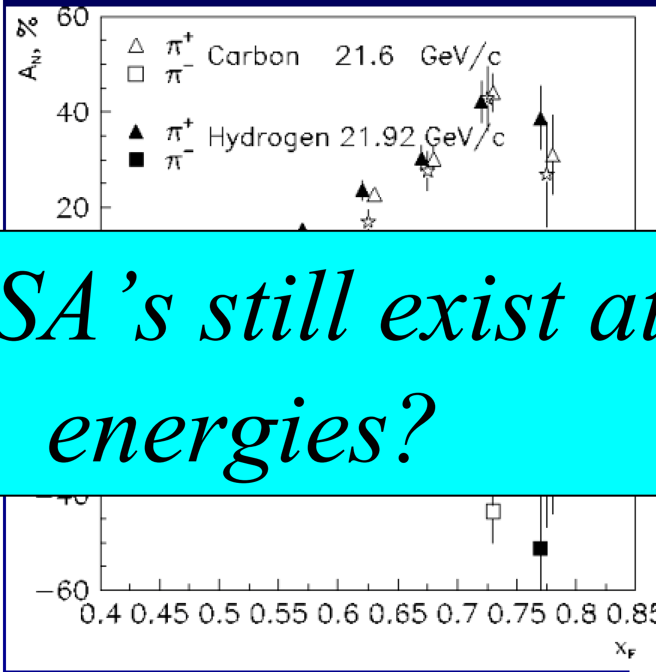
Transverse SSA's from Low to High Energies

Argonne √s=4.9 GeV



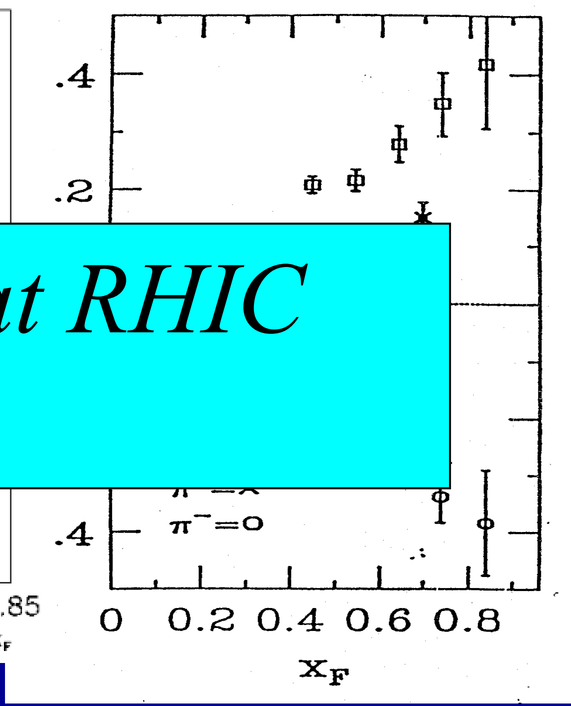
PRL36, 929 (1976)

BNL √s=6.6 GeV



PRD65, 092008 (2002)

FNAL √s=19.4 GeV



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

Do these SSA's still exist at RHIC energies?

$$x_F = 2p_{long}/\sqrt{s}$$

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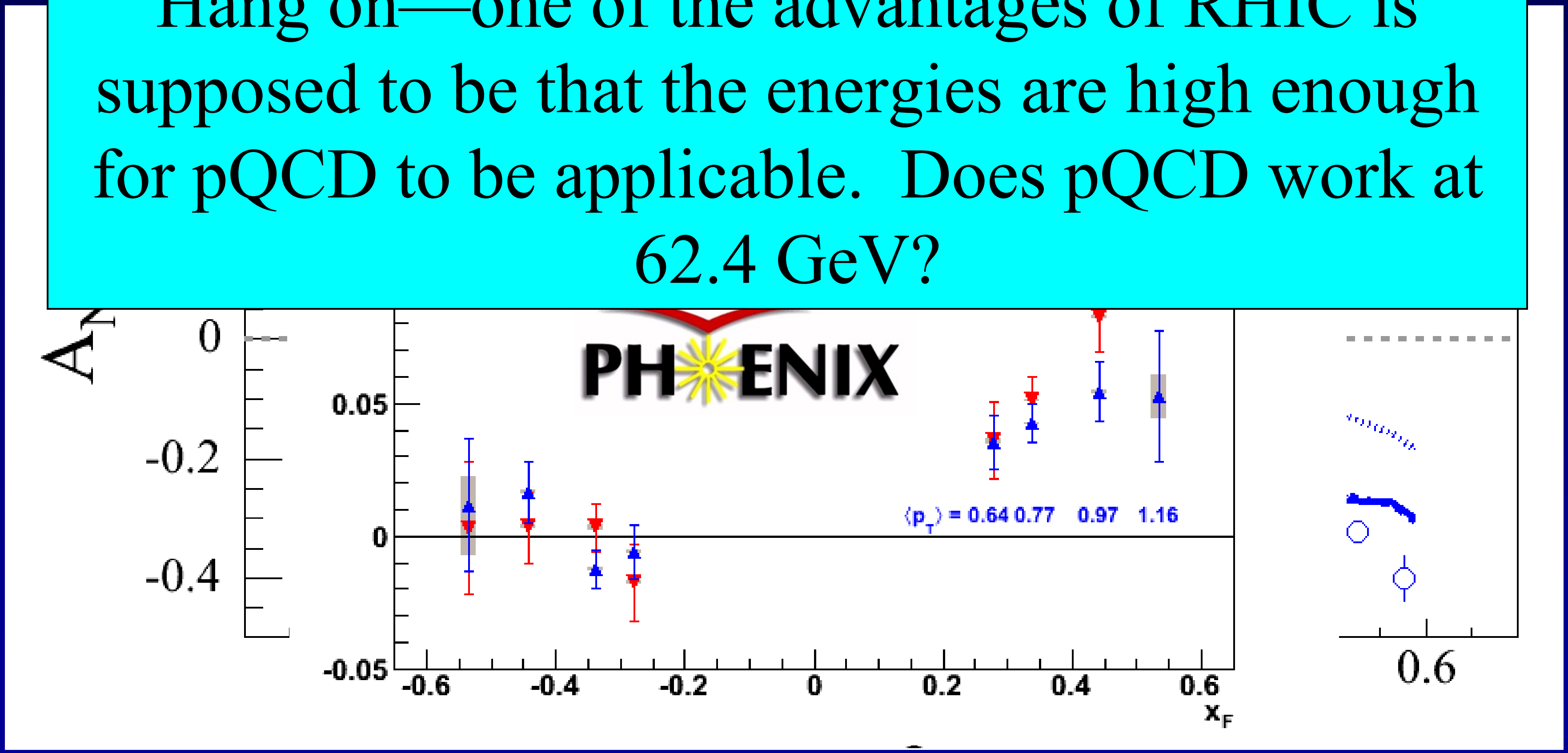
Yes! Transverse SSA's at $\sqrt{s}$ = 62.4 GeV at RHIC

Hang on—one of the advantages of RHIC is supposed to be that the energies are high enough for pQCD to be applicable. Does pQCD work at 62.4 GeV?

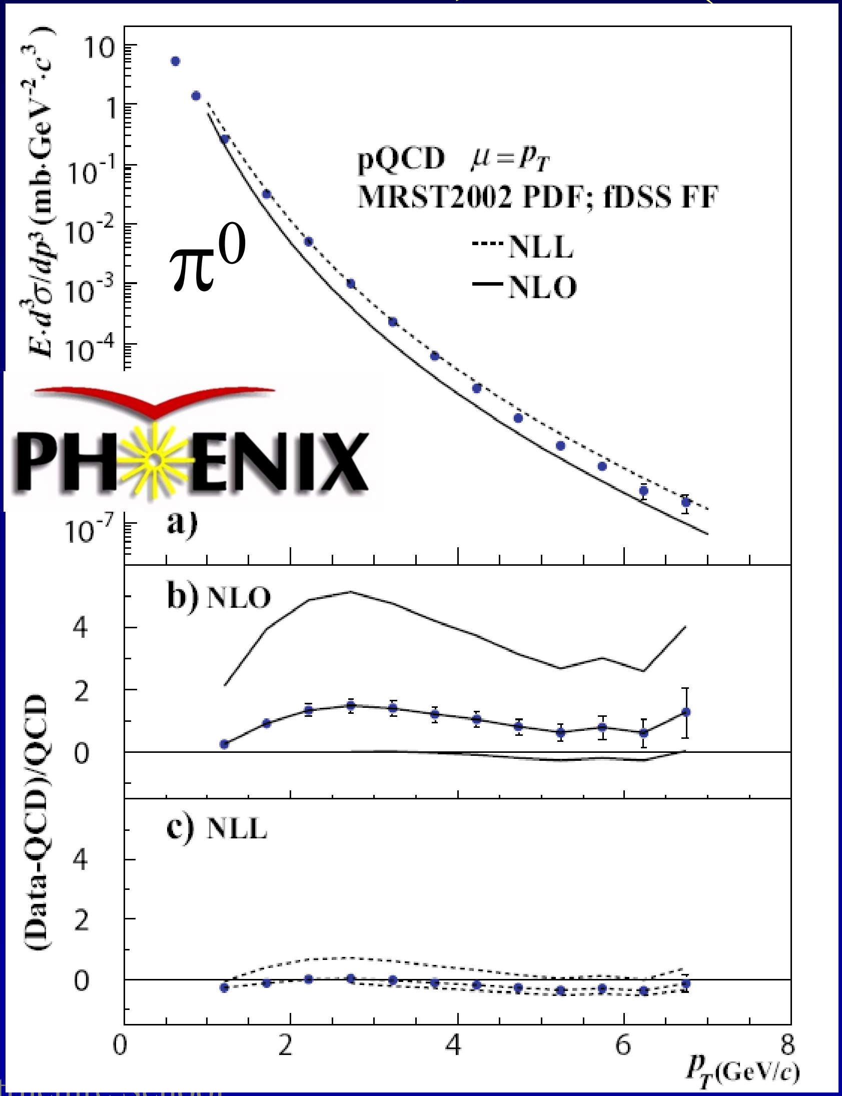


Same behavior of three pion species as at lower energies

62.4 GeV: Comparison to pQCD at Midrapidity

PRD79, 012003 (2009)

- pQCD in good agreement with neutral pion cross section at midrapidity
- Some indication that next-to-leading log (NLL) corrections may be applicable



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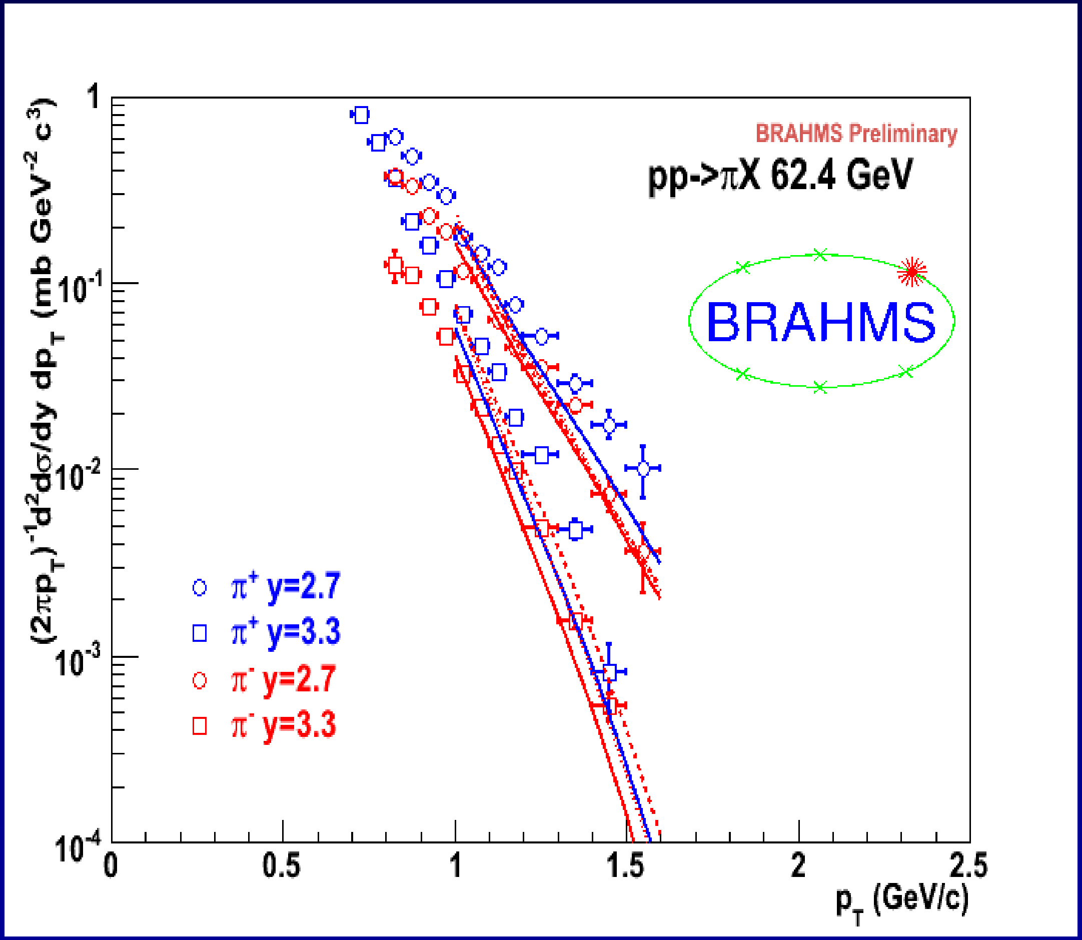
62.4 GeV: Comparison to pQCD at Forward Rapidities—Pions

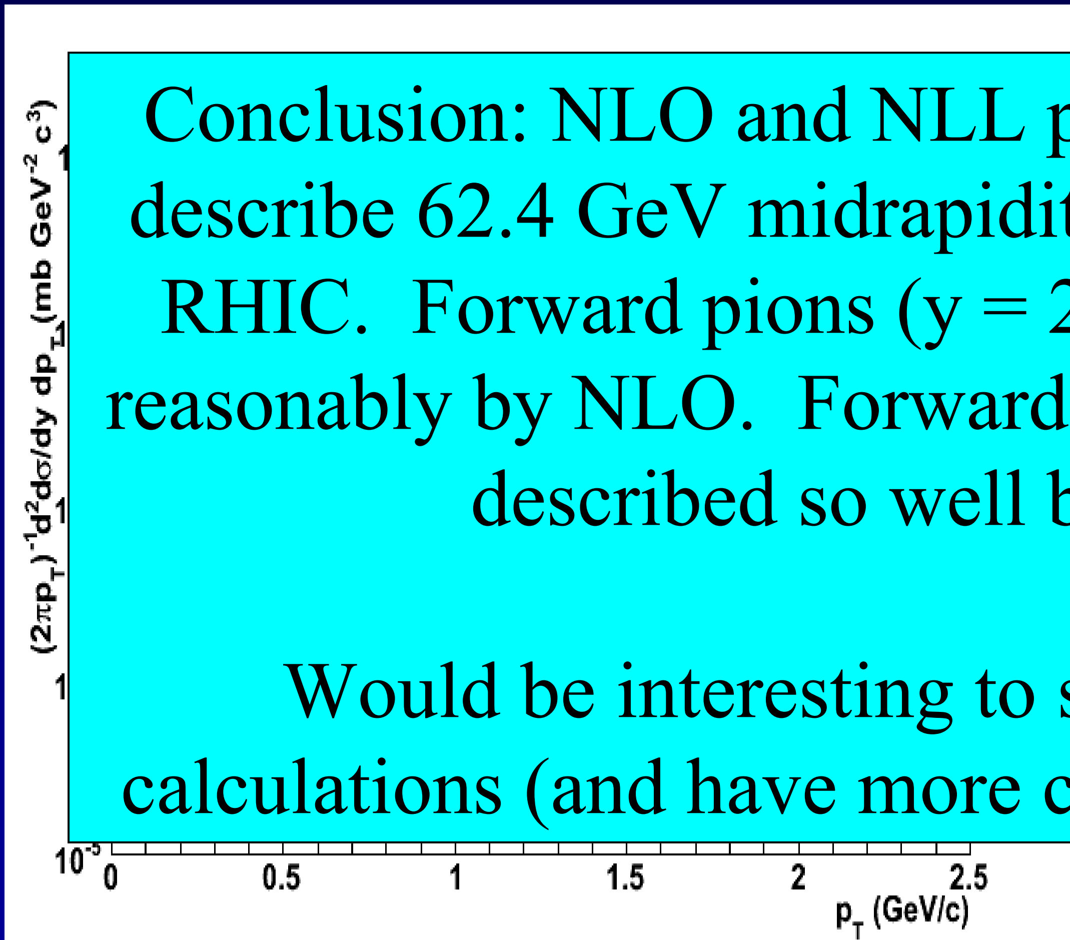


Comparison of NLO pQCD calculations with BRAHMS π data at high rapidity. The calculations are for a scale factor of $\mu = p_T$, KKP (solid) and DSS (dashed) with CTEQ5 and CTEQ6.5.

Surprisingly good description of data, in apparent disagreement with earlier analysis of ISR π^0 data at 53 GeV.

Still not so bad!

62.4 GeV: Comparison to pQCD at Forward Rapidities—Kaons



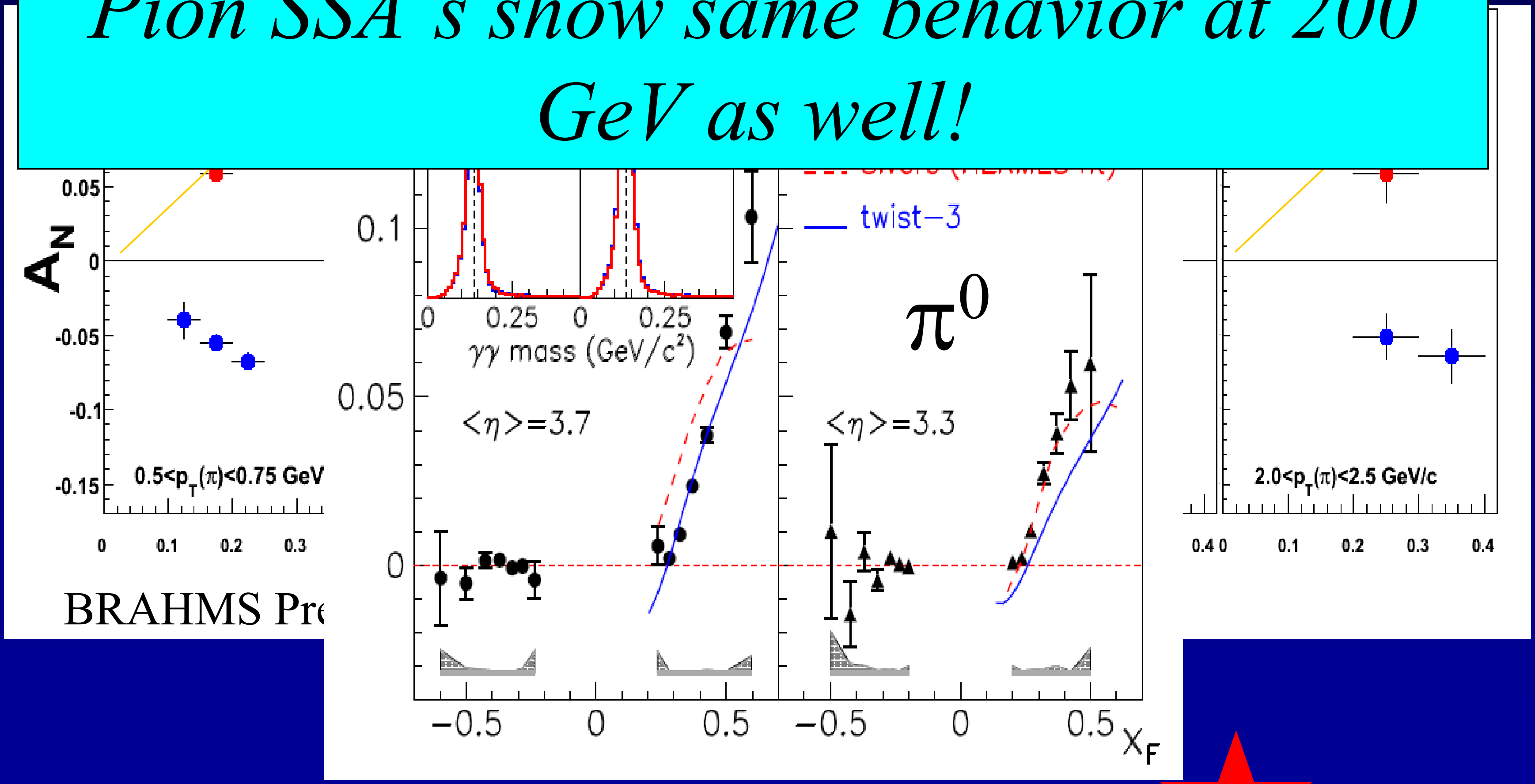
Conclusion: NLO and NLL pQCD calculations describe 62.4 GeV midrapidity pion data well at RHIC. Forward pions (y = 2.7, 3.3) described reasonably by NLO. Forward kaons (y = 3.2) not described so well by NLO.

Would be interesting to see more NLL calculations (and have more cross section data!).

K^+: Not bad!
K^-: Hmm…

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

Pion SSA's show same behavior at 200 GeV as well!



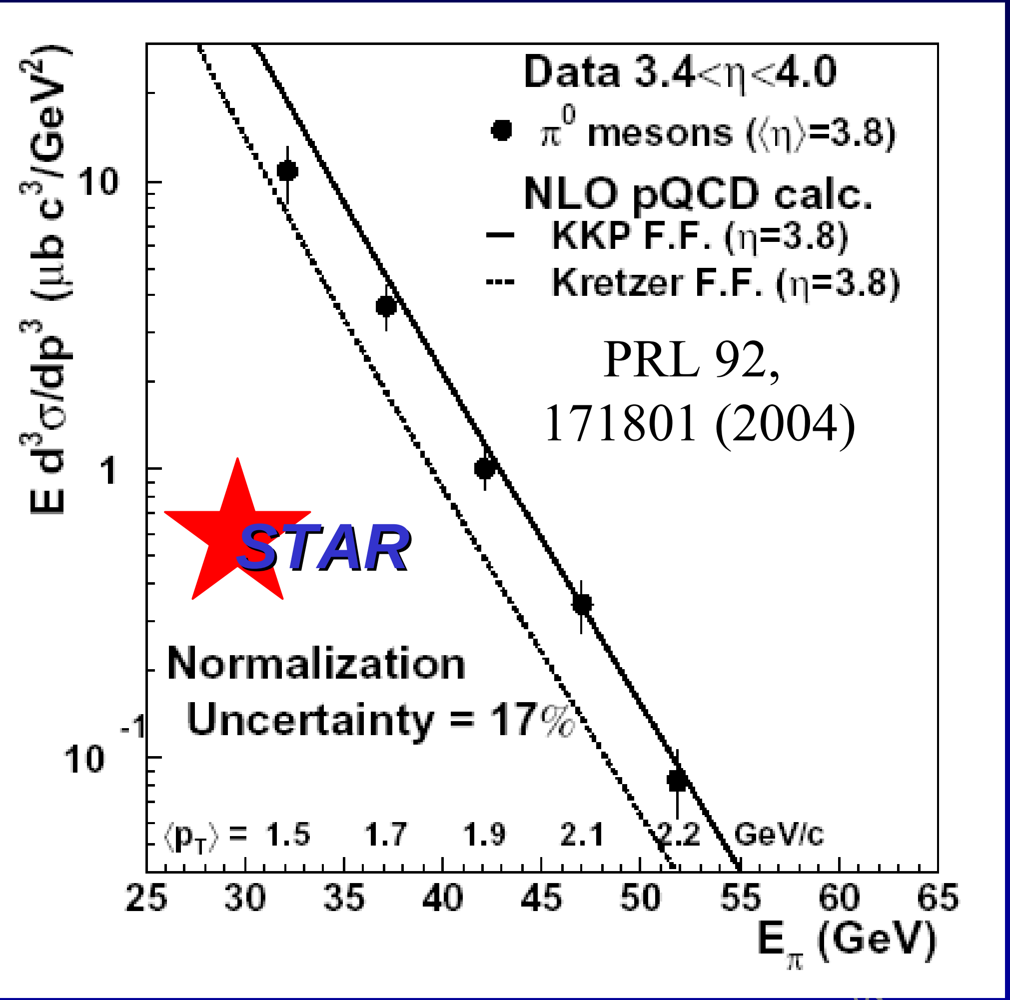
arXiv:0801.2990

Accepted by PRL

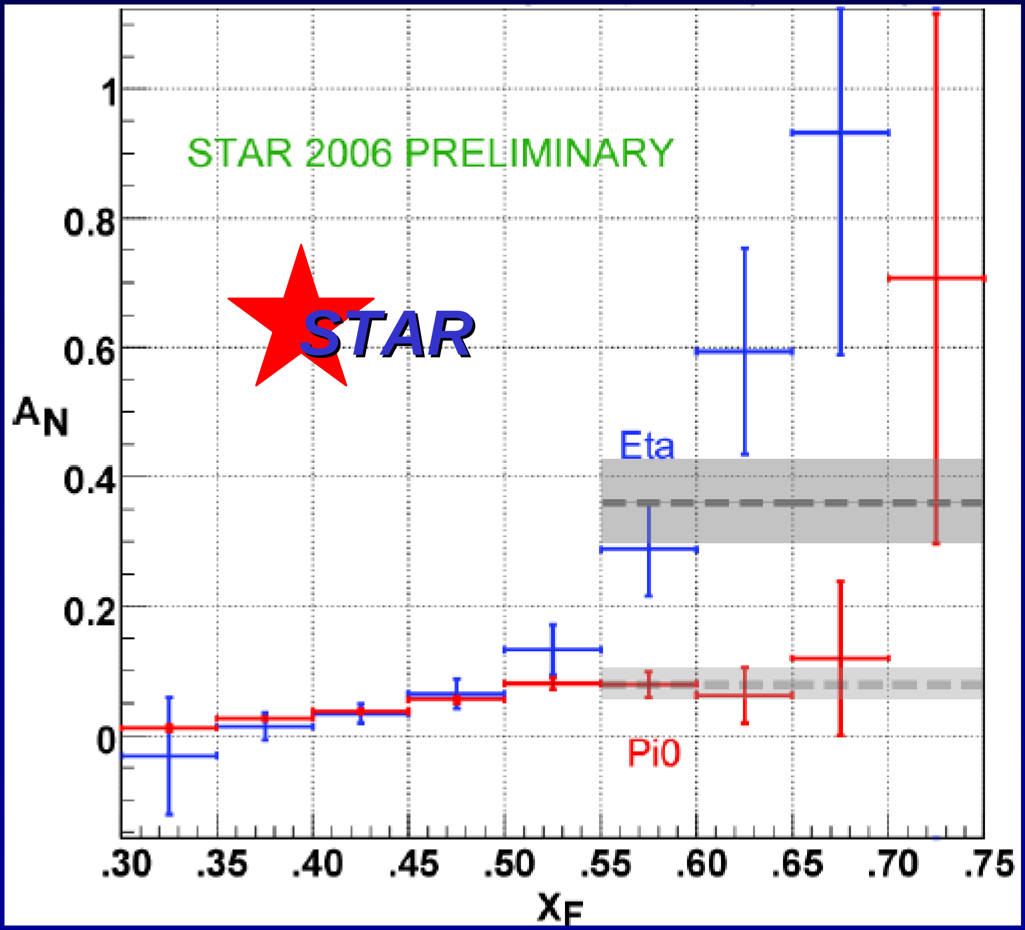
200 GeV: Comparison to pQCD at Forward Rapidity

STAR, 3.4 < η < 4.0

- NLO calculation describes data well within uncertainties due to fragmentation functions
  - (Note that more recent FF's now available)



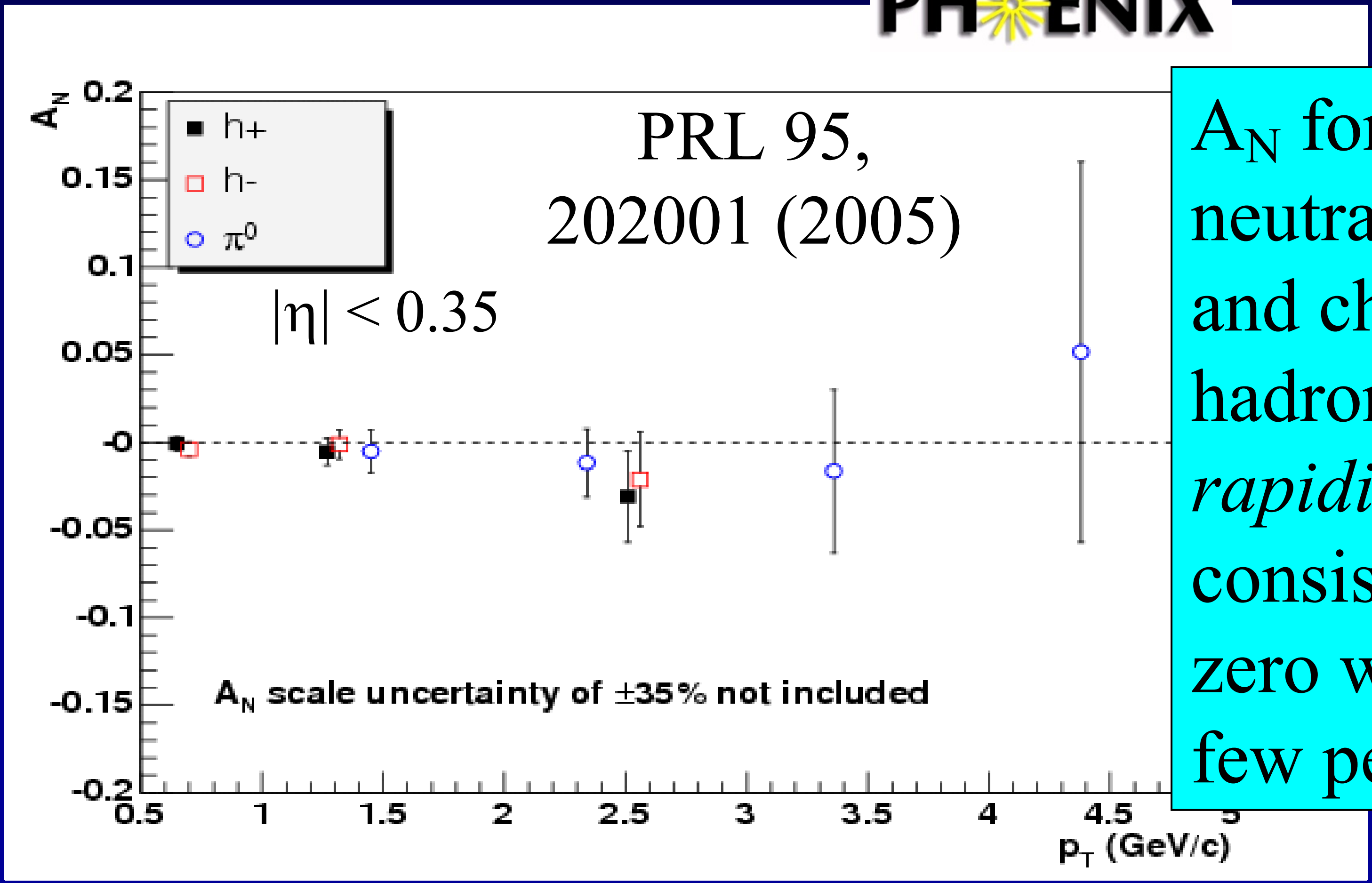
Transverse SSA of Eta Meson at 200 GeV



Eta asymmetry larger than neutral pion SSA! Why??

PHENIX will be able to make a similar measurement, thanks to recently added forward calorimeter.

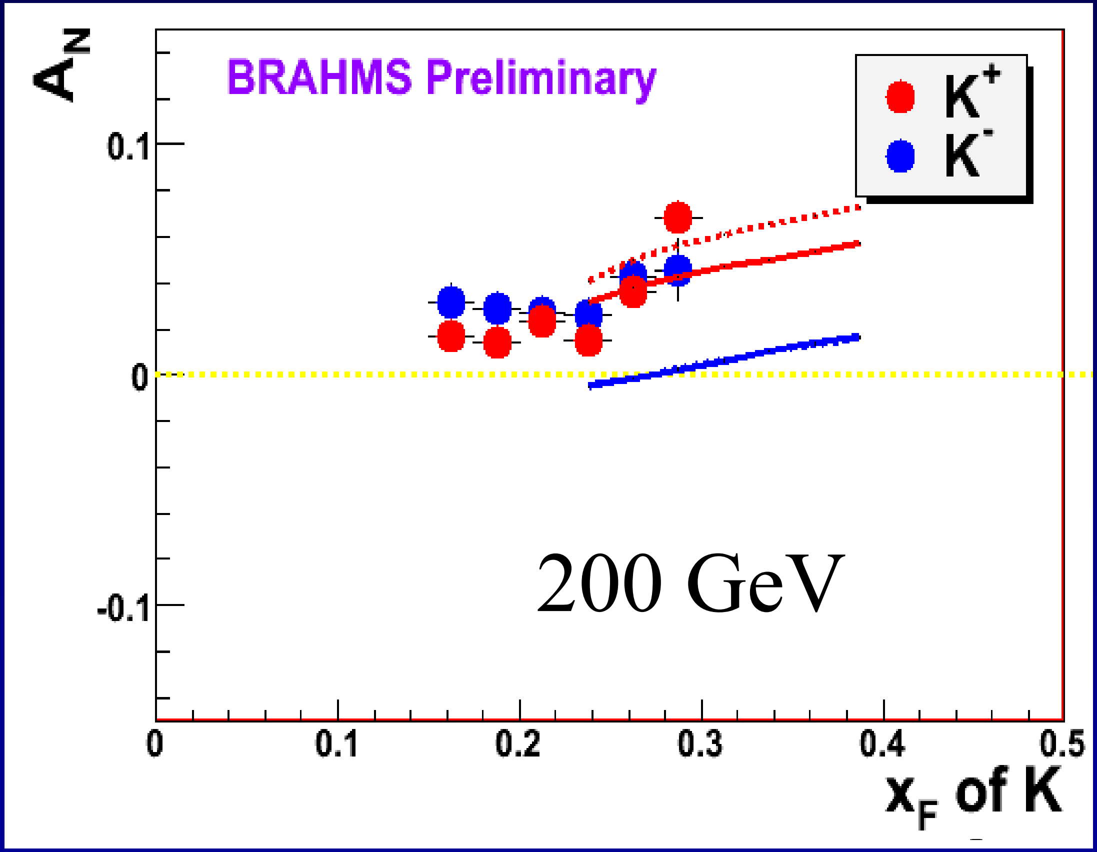
A_N of Midrapidity Neutral Pions



A_N for both neutral pions and charged hadrons at *mid-rapidity* consistent with zero within a few percent.

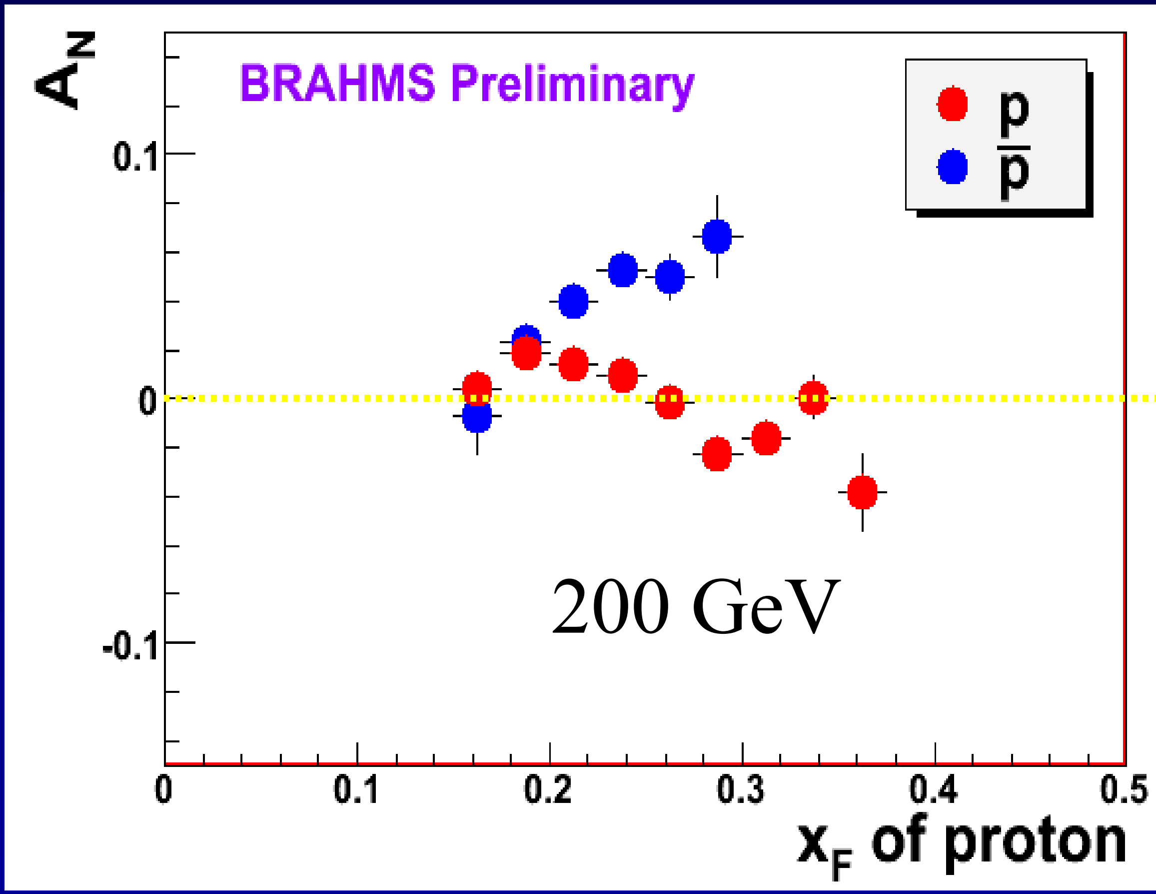
Forward Kaon SSA's

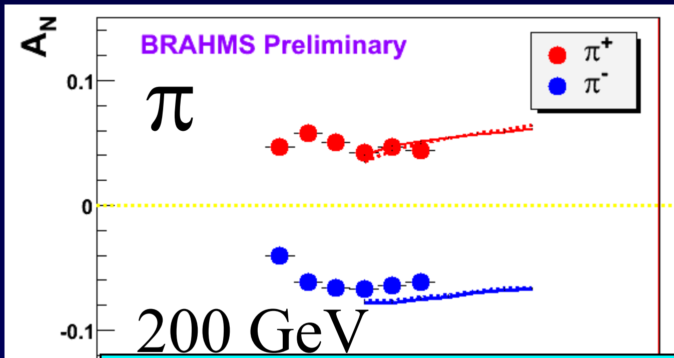
- Unlike mirror symmetry of charged pions, charged pion SSA's both positive, and of same magnitude. Why?? Theory predicts same signs, but not same magnitude.



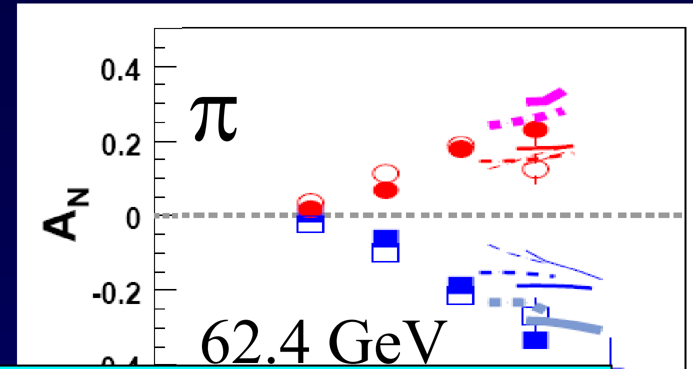
Forward Proton SSA's

- Proton asymmetry consistent with zero
- But non-zero antiproton asymmetry!!
- Unfortunately, no measurement available for antiprotons at 62.4 GeV

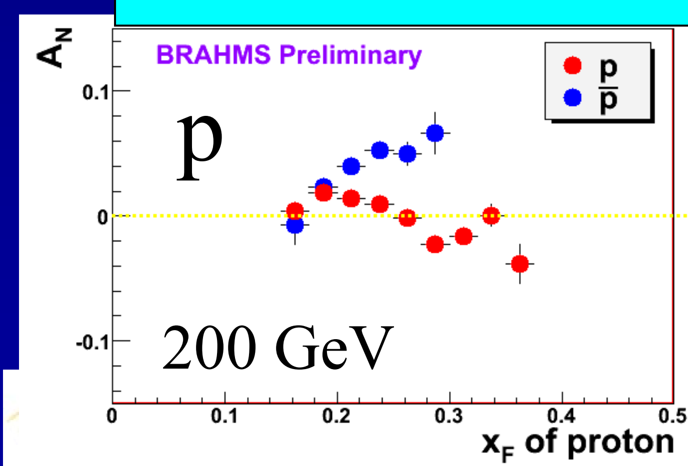




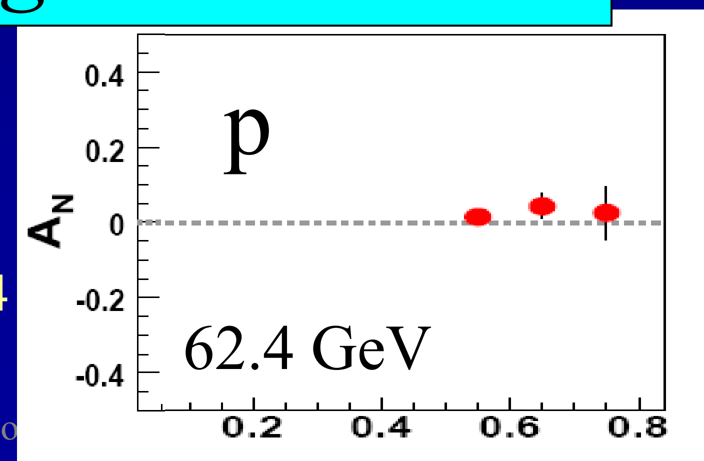
π, K, p
at 200 and
62.4 GeV



Signs and magnitudes of pion SSA's suggest a valence quark effect.
Kaon and (anti-)proton (and eta?) SSA's seem to contradict this!
Further measurements of great interest!

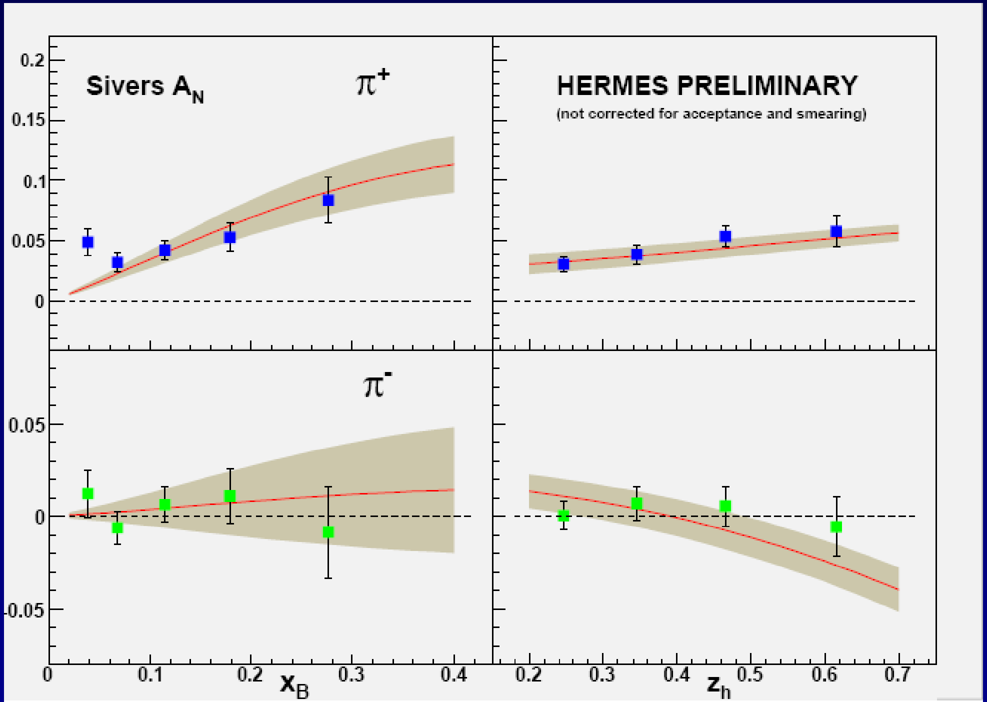


Large antiproton asymmetry??
Unfortunately no 62.4 GeV measurement

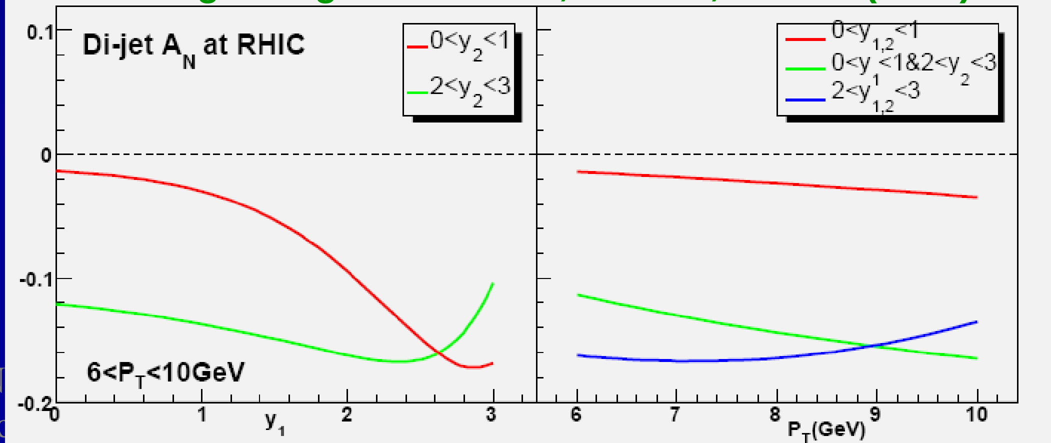


Probing the Sivers Function via Dijets

- Sivers effect in p+p $\Rightarrow$ 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).



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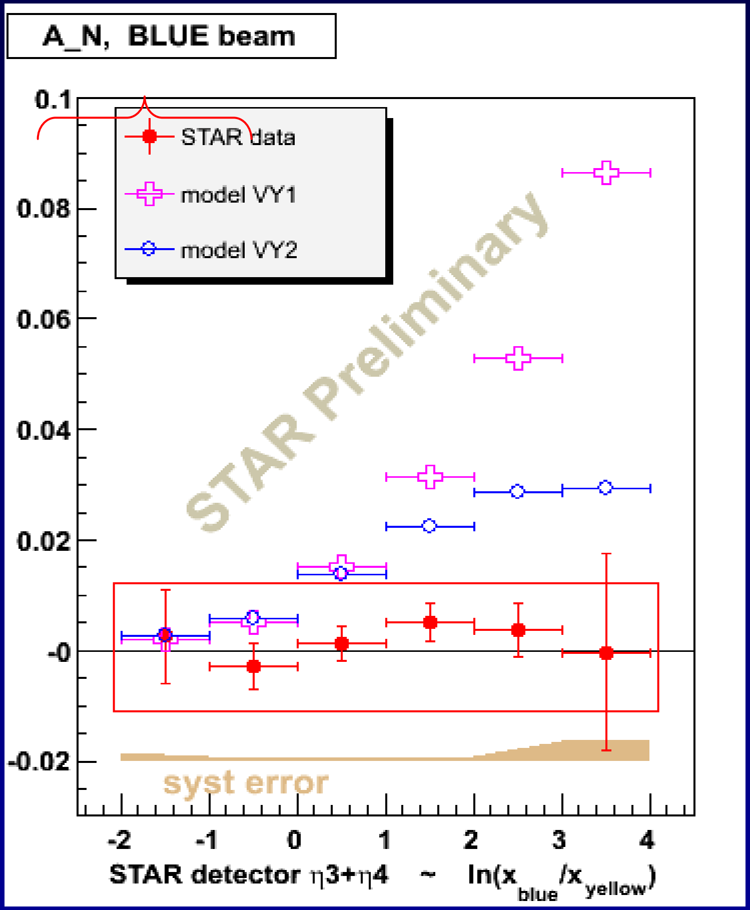
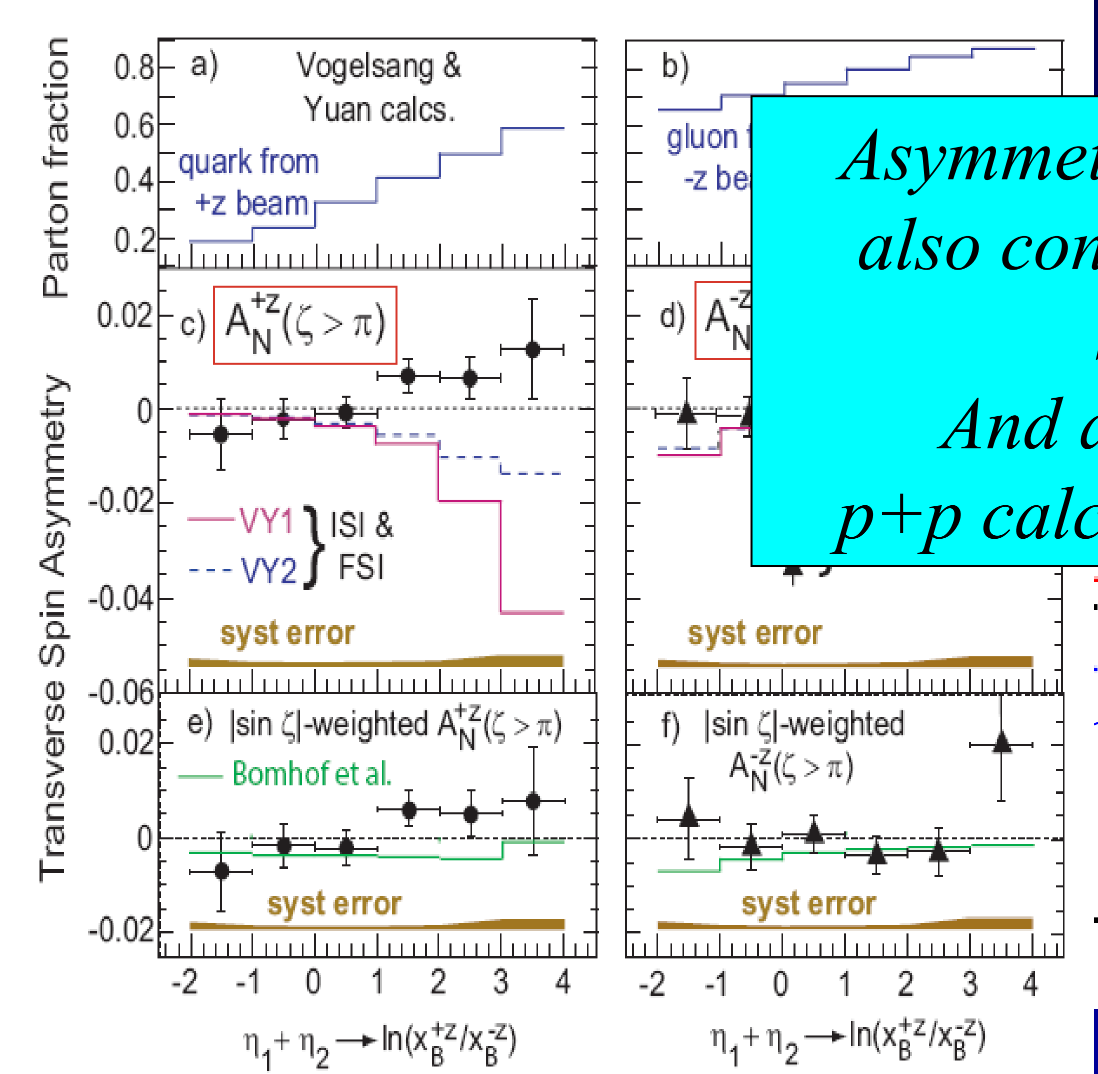
Measured Sivers A_N for Dijets



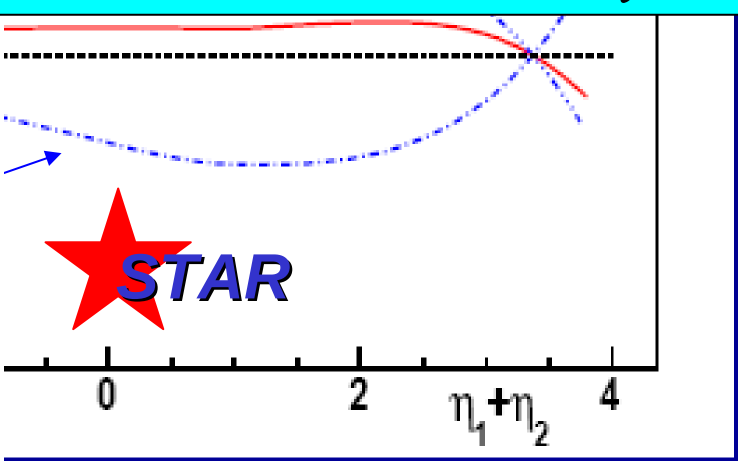
Measured A_N consistent with zero ⇒ both quark and gluon Sivers effects much smaller in p+p → dijets than in HERMES SIDIS!!

Calculations for p+p Revisited!

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

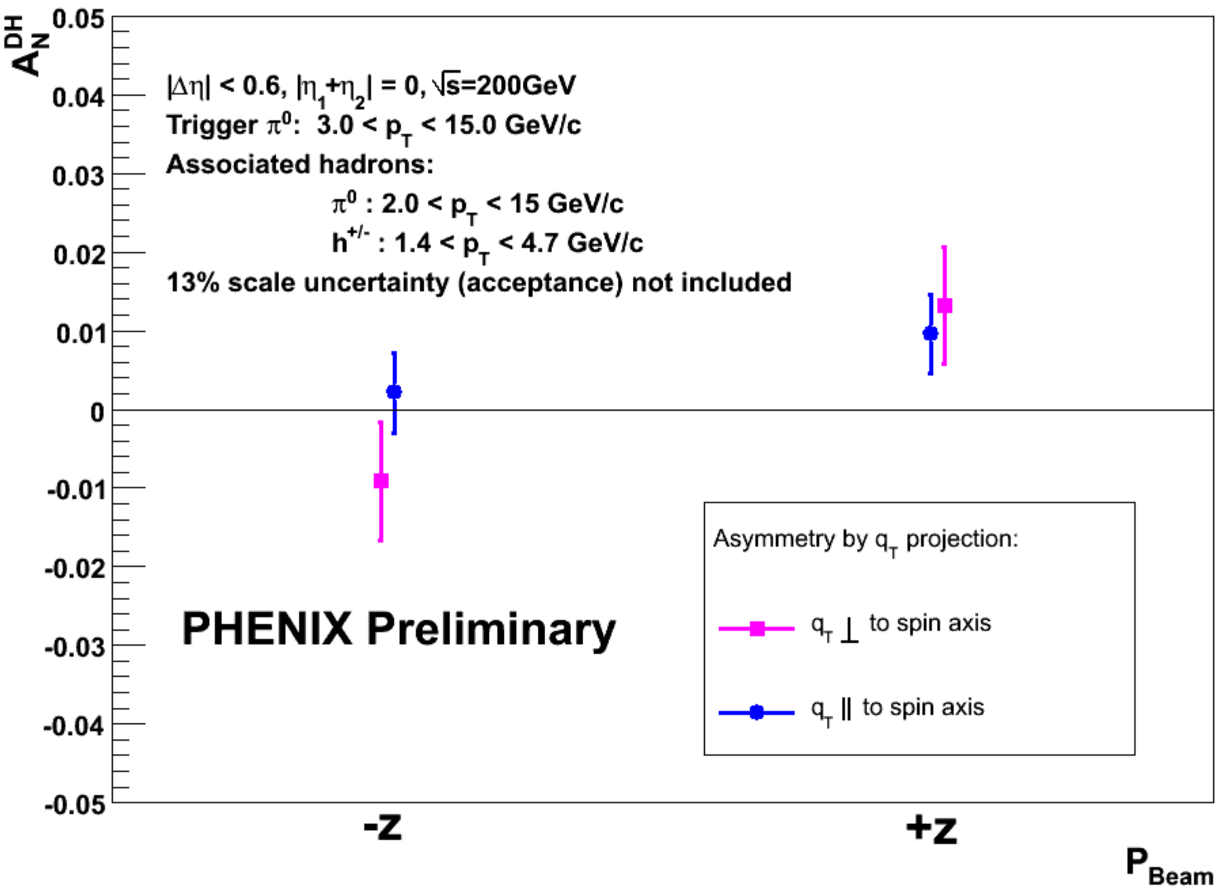


Asymmetries observed at STAR also consistent with HERMES SIDIS results!
And a healthy reminder:
p+p calculations can be tricky!



PRL99, 14003 (2007)

Sivers Dihadrons from PHENIX

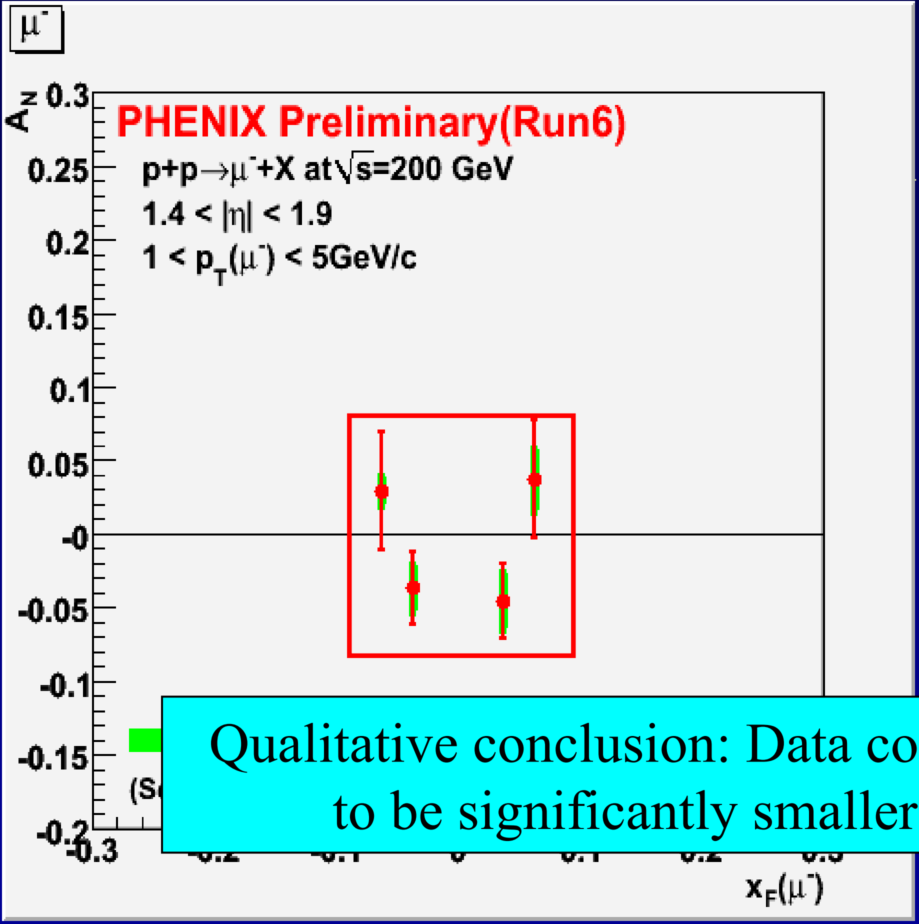


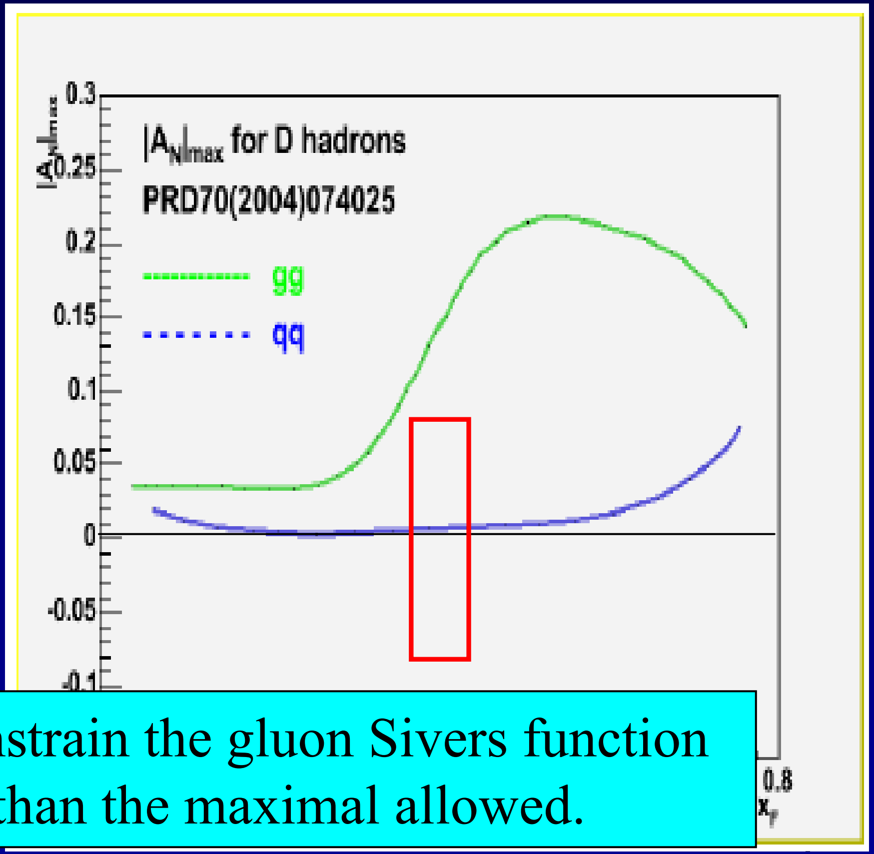
- $q_{T\perp}$ could show an asymmetry due to Sivers function.
- $q_{T||}$ should show no asymmetry, only for cross check.
- Result: asymmetry for $q_{T\perp}$ due to Sivers effect is smaller than ~1%. Consistent with STAR.
- Fragmentation dilution factor is not included.

If an asymmetry is measured

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

SSA of Heavy Flavor: Another Way to Isolate Sivers Effect in p+p





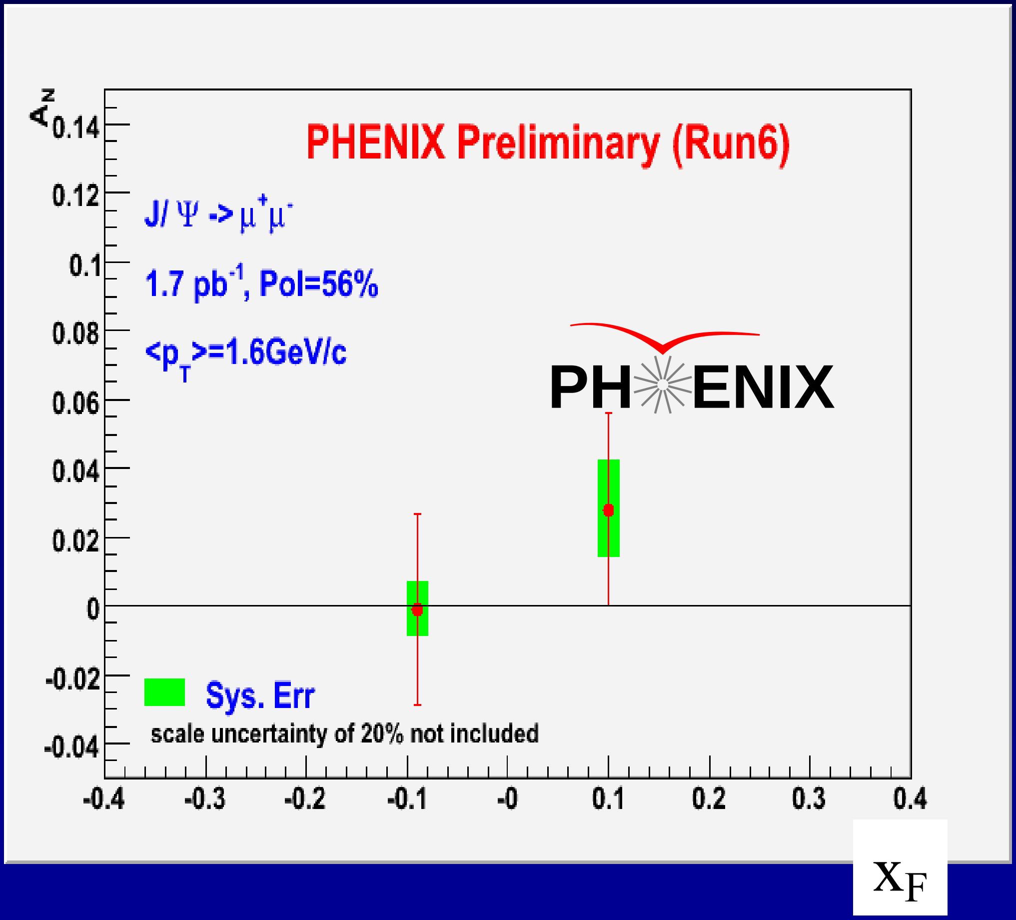
Qualitative conclusion: Data constrain the gluon Sivers function to be significantly smaller than the maximal allowed.

Data: Prompt muons from charm and bottom

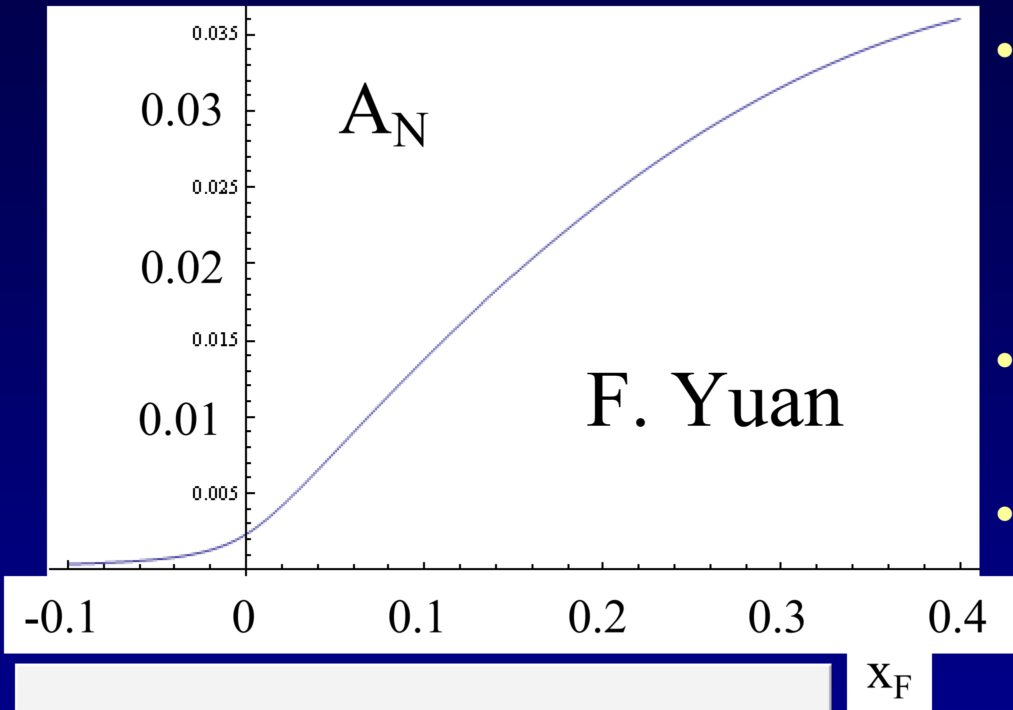
Calculations: D mesons

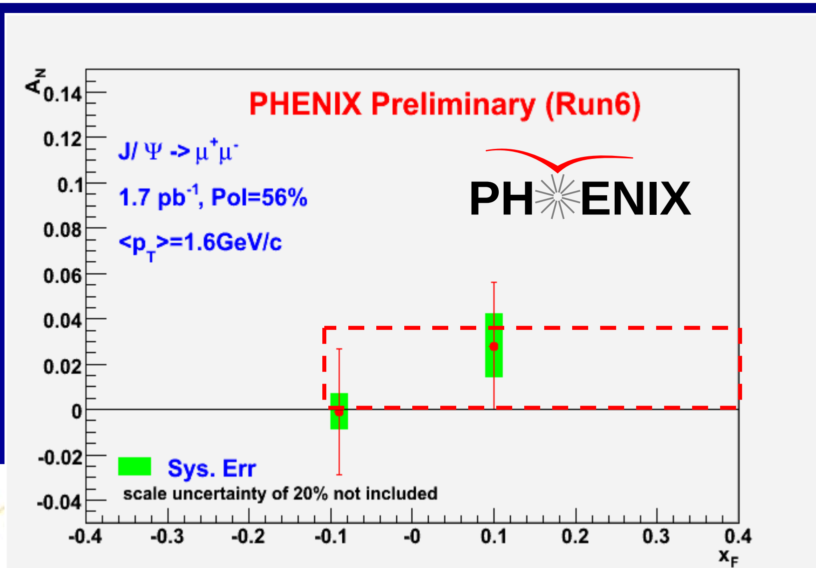
What About Charmonium?

- J/ψ complicated by unknown production mechanism!
- Recent calculations for transverse SSA of charmonium from F.Yuan, PRD78, 014024 (2008)
- → Asymmetry itself may provide insight into production mechanism!
  - In addition to evidence from J/Ψ polarization and rapidity dependence of cross section



"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!

Measuring Transversity in p+p

Drell-Yan

Drell-Yan in p+p (as opposed to p+pbar) requires high luminosities! We don't expect results from RHIC for a while . . .

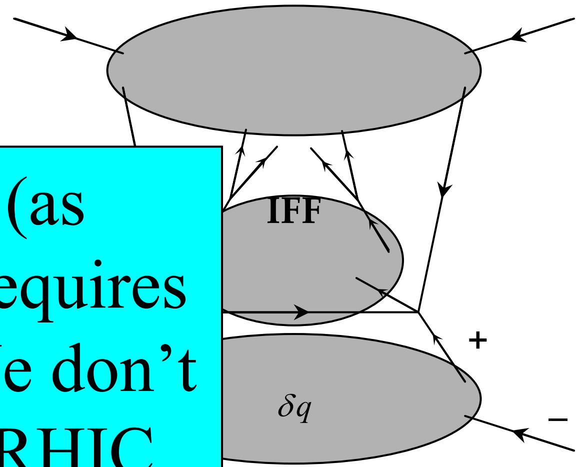
$$A_{TT} = \frac{\ldots}{\sigma^{\uparrow\uparrow}+\sigma^{\uparrow\downarrow}}$$

$$p^{\uparrow}p^{\uparrow}(\overline{p}^{\uparrow}) \rightarrow l^{+}l^{-}X$$

$$A_{TT} \propto \delta q \otimes \delta\overline{q}(\delta q)$$

RHIC, FAIR

Interference FF



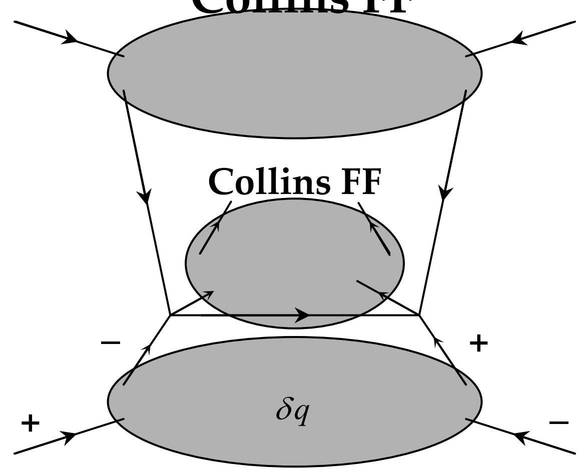
$$A_{UT} = \frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}}$$

$$pp^{\uparrow} \rightarrow hhX$$

$$A_{UT} \propto \delta q \otimes H_1^{\square}$$

RHIC

Collins FF



$$A_{UT} = \frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}}$$

$$pp^{\uparrow} \rightarrow hX$$

$$A_{UT} \propto \delta q \otimes H_1^{\perp}$$

RHIC

Probing Transversity via the Collins FF

- With STAR Forward Meson Spectrometer installed for 2008 … will be able to measure spin-correlated azimuthal distribution of neutral pions around jet axis—isolates the Collins asymmetry!

STAR FMS

Preliminary results expected soon!

Probing Transversity via the Interference Fragmentation Function

Physics asymmetry

$$A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{\sigma_{UT}}{\sigma_{UU}}$$

$$d\sigma_{UU} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \int \frac{dx_a dx_b}{4\pi^2 z_c} f_1^a(x_a)\, f_1^b(x_b) \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} D_{1,oo}(\bar{z}_c, M_C^2)$$

Unpolarized quark distribution
Known from DIS

Transversity
to be extracted

Hard scattering cross section
from pQCD

IFF + Di-hadron FF
to be measured in e+e-

$$d\sigma_{UT} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \frac{|\mathbf{R}_C|}{M_C} |\mathbf{S}_{BT}| \sin(\phi_{S_B} - \phi_{R_C}) \int \frac{dx_a dx_b}{16\pi z_c} f_1^a(x_a)\, h_1^b(x_b) \frac{d\Delta\hat{\sigma}_{ab^{\uparrow}\to c^{\uparrow}d}}{d\hat{t}} H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)$$

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Why Di-hadron (IFF) SSA at RHIC

- Di-hadron vs single hadron
  - *Collinear* factorization; no concerns about validity of factorization theorem for k_T-dependent distributions (only proven for Drell-Yan in p+p)
  - No model uncertainties due to k_T dependence of FF or pdf
  - No need to separate effects like Sivers/Collins effects in single hadron measurement (isolates transversity x IFF)
  - Completely independent measurement sensitive to transversity
- Di-hadron measurement in fixed target vs. collider
  - At higher scale
    - sub-leading twist effects suppressed
    - factorization assumption better justified

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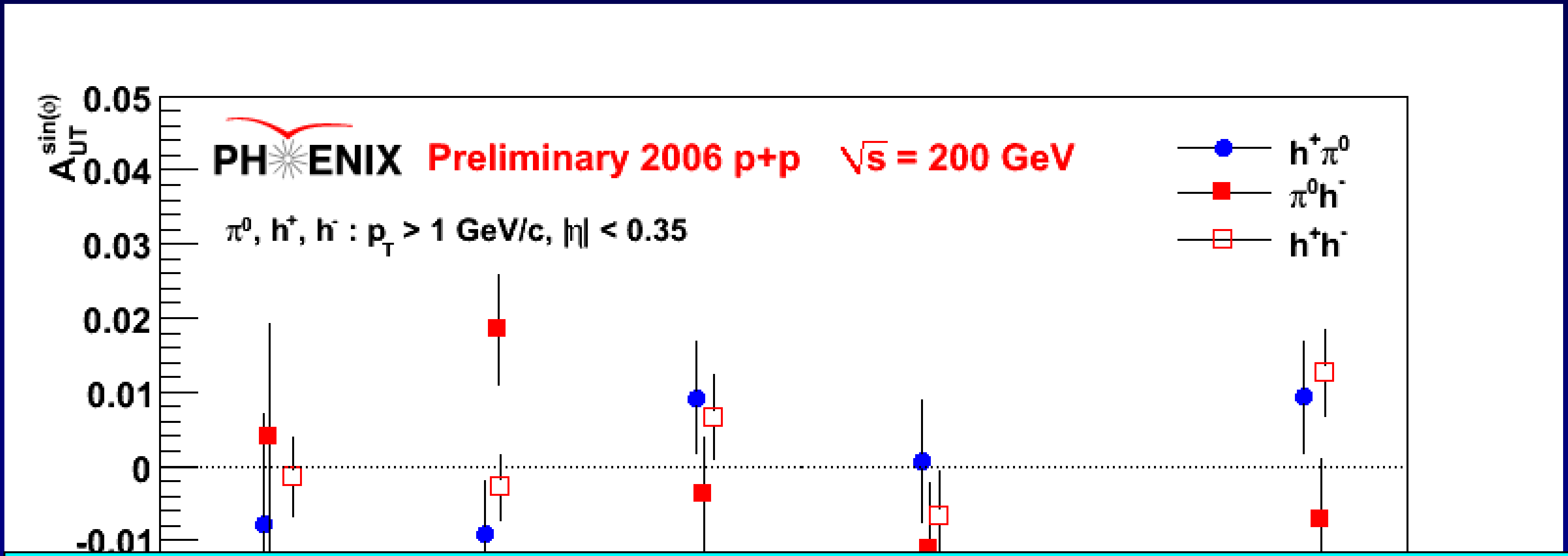
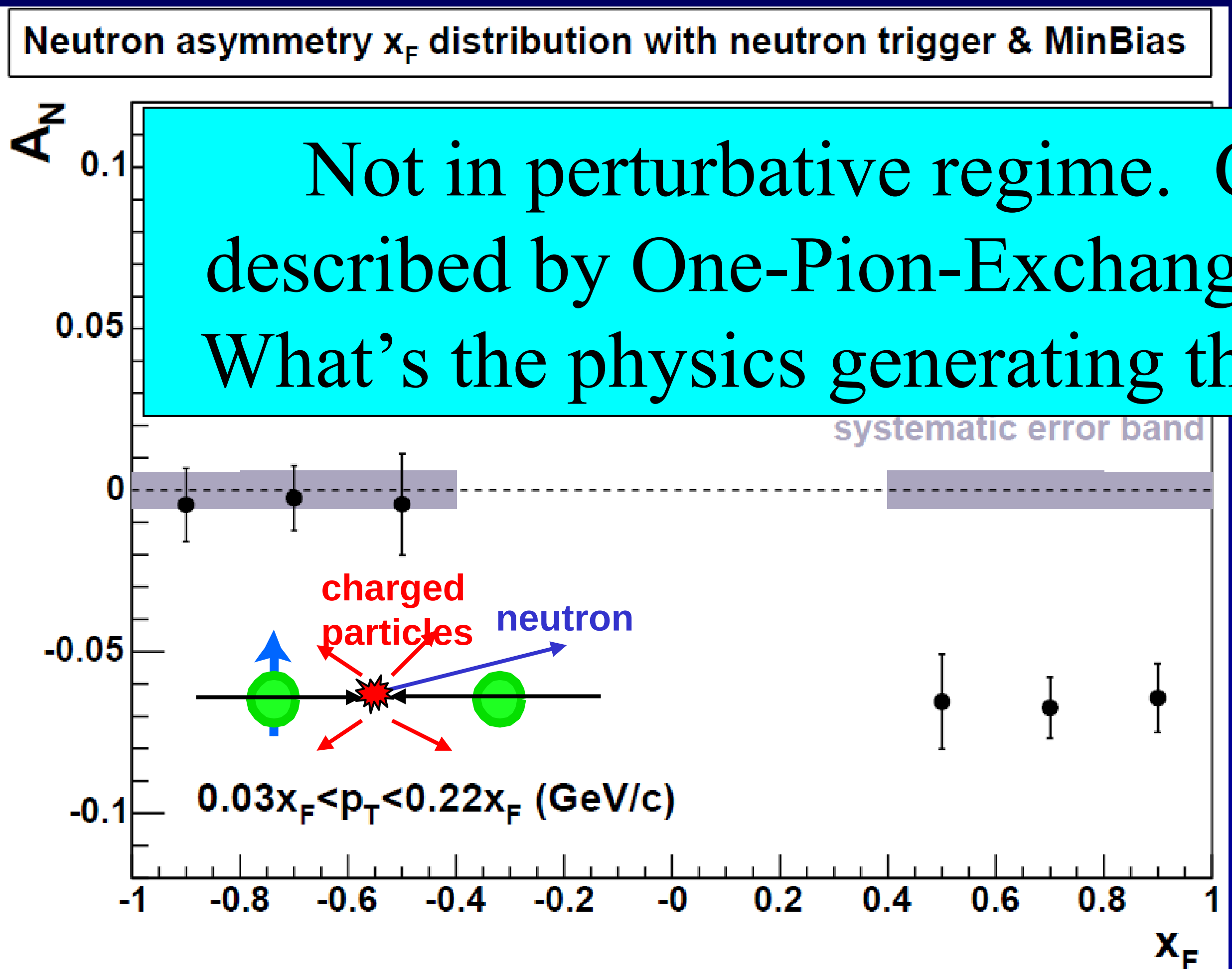
Probing Transversity via the Interference Fragmentation Function



Waiting for BELLE to release Interference and unpolarized di-hadron FF results to be able to learn anything about transversity from p+p measurement!

Another Non-Zero Transverse SSA: Forward Neutrons at $\sqrt{s}$=200 GeV

Large negative SSA discovered in 2002! Observed for $x_F>0$, enhanced by requiring concidence with forward charged particles ("MinBias" trigger). No x_F dependence seen.



Not in perturbative regime. Cross section described by One-Pion-Exchange (OPE) model. What's the physics generating this asymmetry??

Mean p_T
on
)
eV/c
eV/c
eV/c

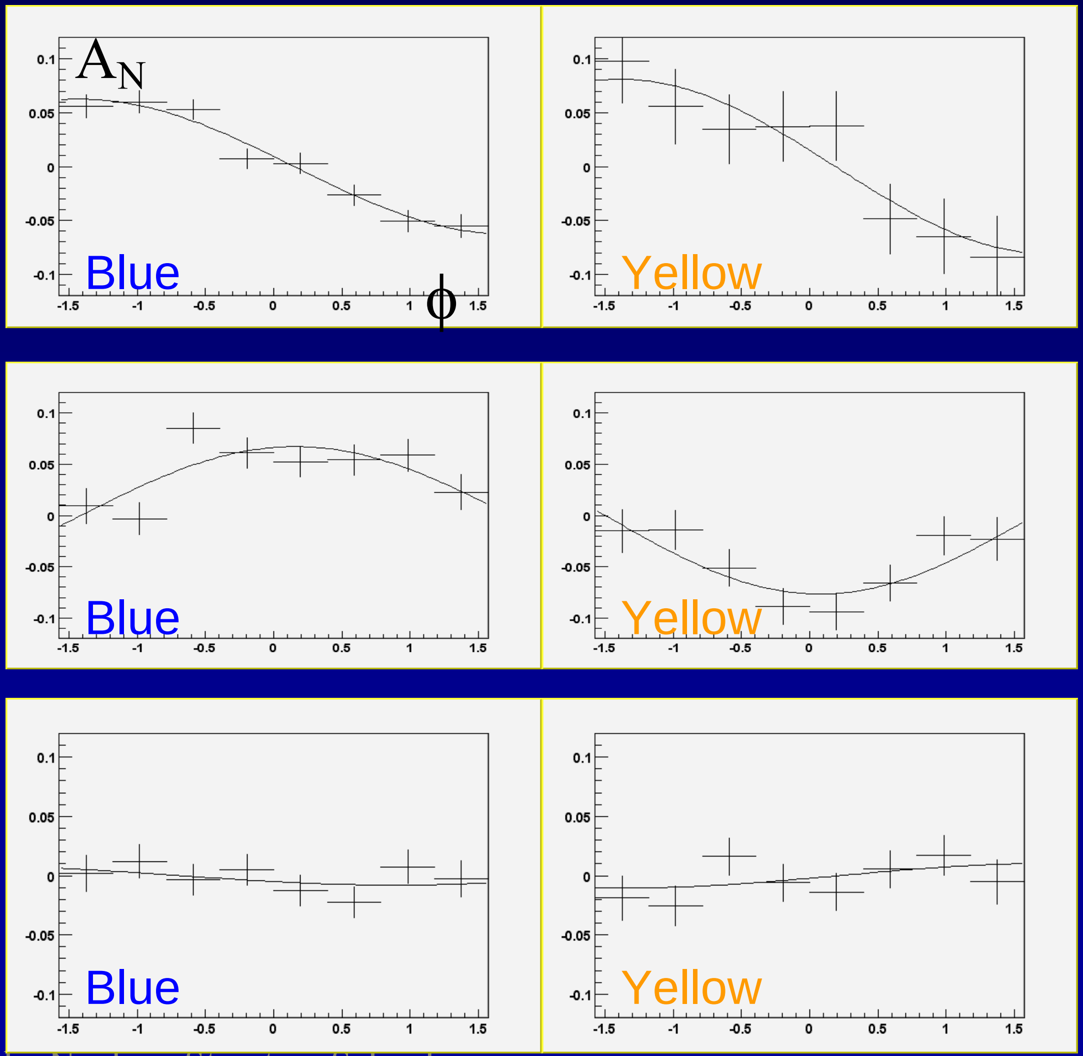
preliminary	A_N
Without MinBias	-6.6 ±0.6 %
With MinBias	-8.3 ±0.4 %

Recall: Use Neutron SSA for Local Polarimetry, Even If Don't Understand the Physics!

Spin Rotators OFF
Vertical polarization

Spin Rotators ON
Radial polarization

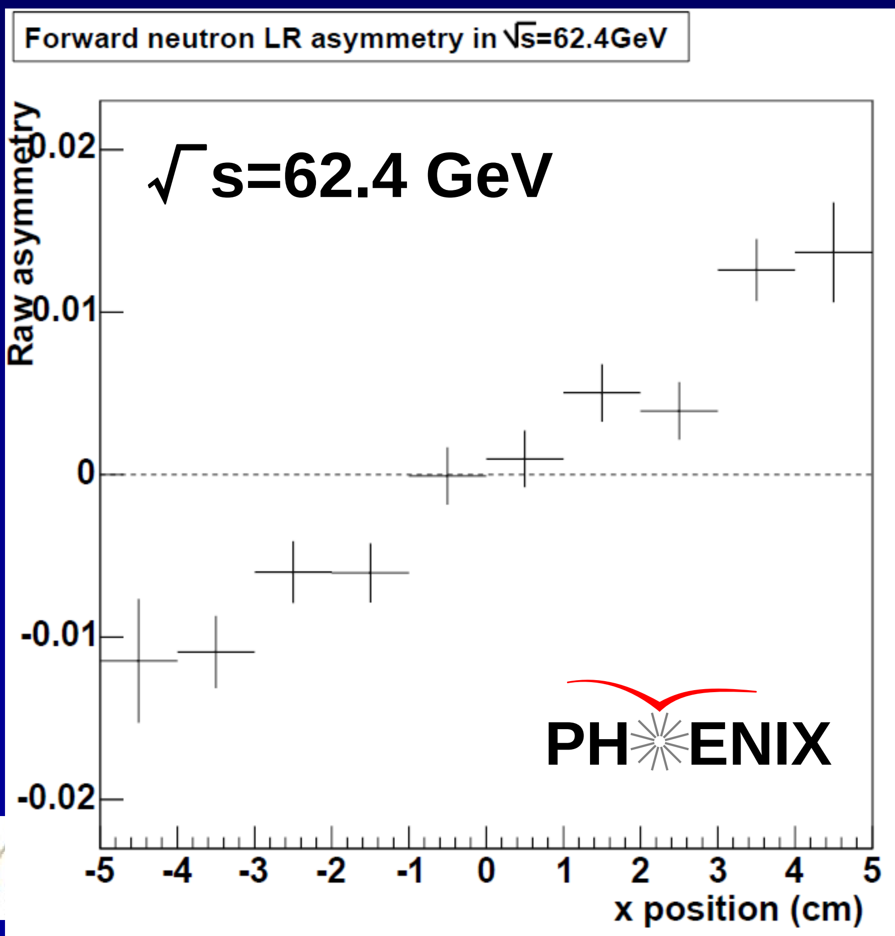
Spin Rotators ON
Longitudinal polarization

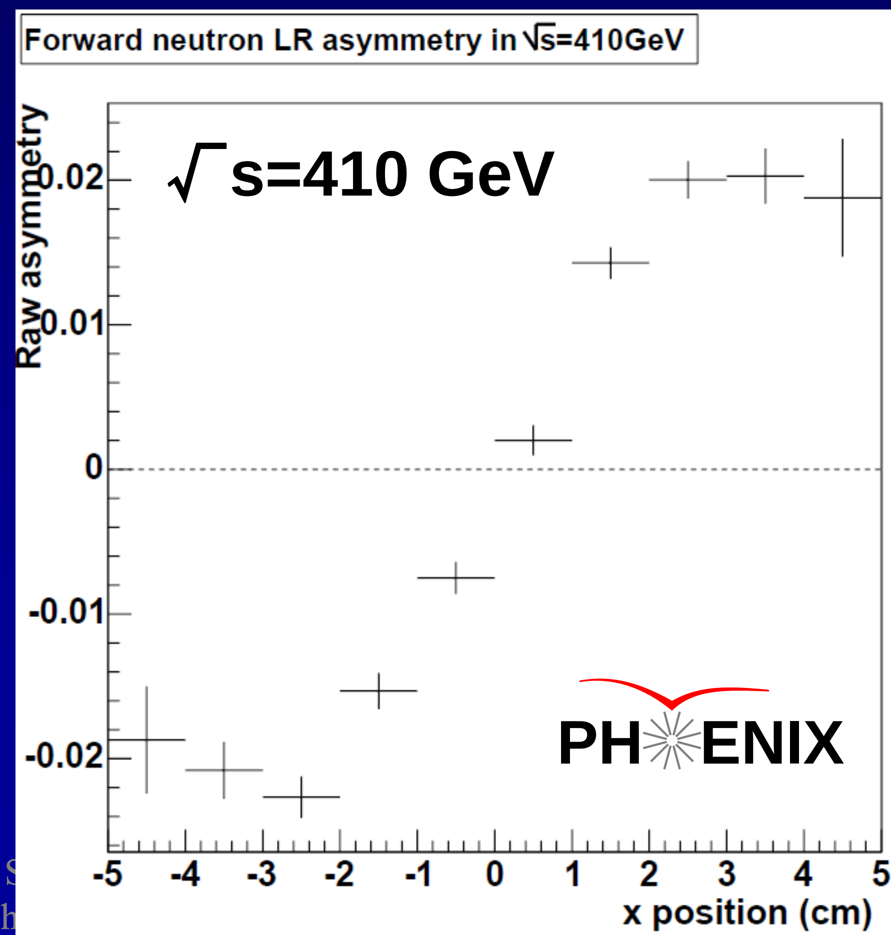


Forward Neutron SSA at Other Energies

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

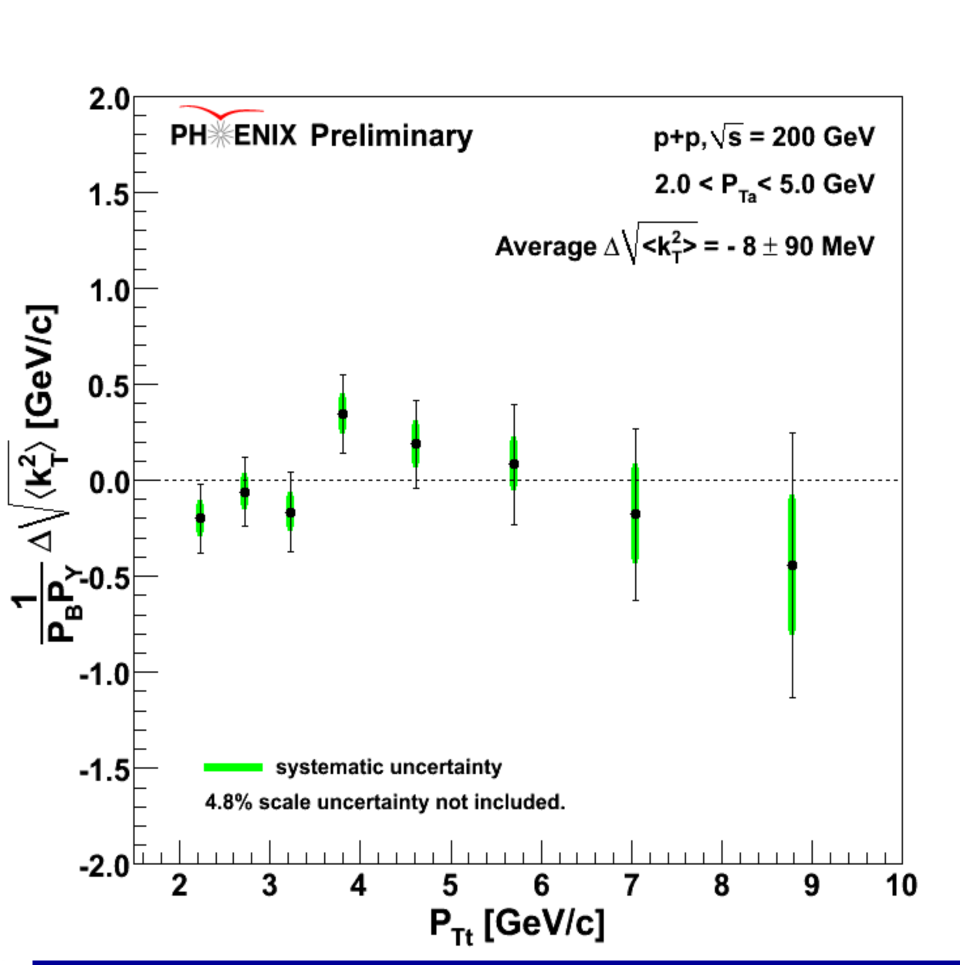
$$A = \frac{N_+ - RN_-}{N_+ + RN_-}$$

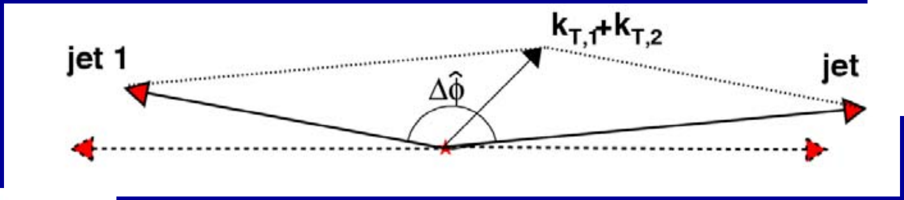




An Exploratory Measurement: Attempting to Probe k_T from Orbital Motion

- 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





Summary and Conclusions I

- Polarization of proton beams at RHIC has opened up many new opportunities to study proton spin structure!
- Polarized collider → higher energies → new probes (W's), cleaner theoretical interpretation
- Hadronic interactions → direct access to gluons
- Within x range of ~0.02-0.4 probed so far, gluon spin contribution to the spin of the proton measured to be significantly smaller than what's "missing" according to measurements of the quark spin contribution

Summary and Conclusions II

- 500 GeV program—just started this month!
  - Extend x reach down to ~0.002 for gluon spin measurements

RHIC one among several facilities working to piece together a comprehensive picture of the structure of the nucleon, a basic building block of everyday matter.

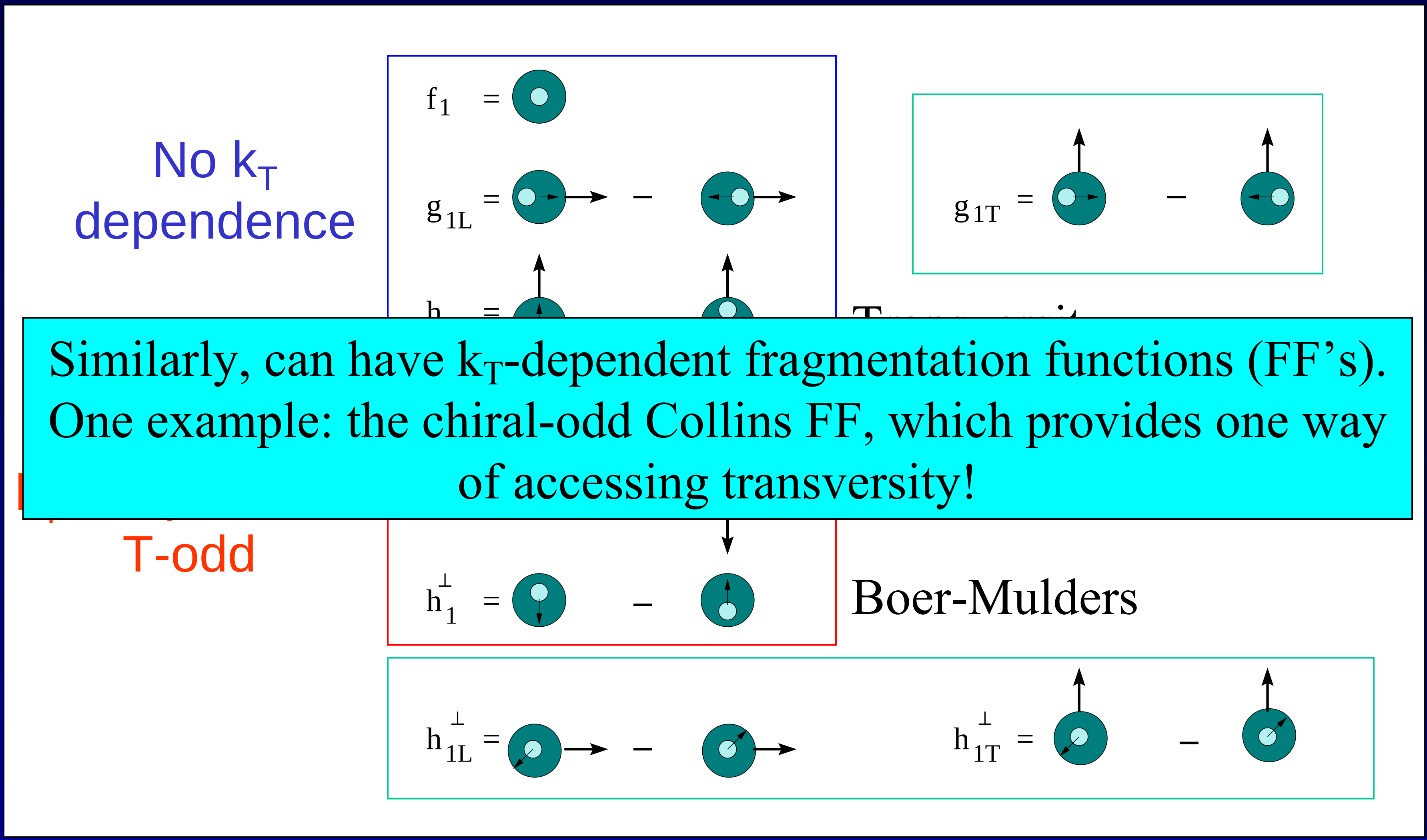
past ~7 years have effectively opened up a new

Looking forward to many more years of data and progress in our understanding!

  - Ideas for new measurements in p+p being generated rapidly!

Additional Material

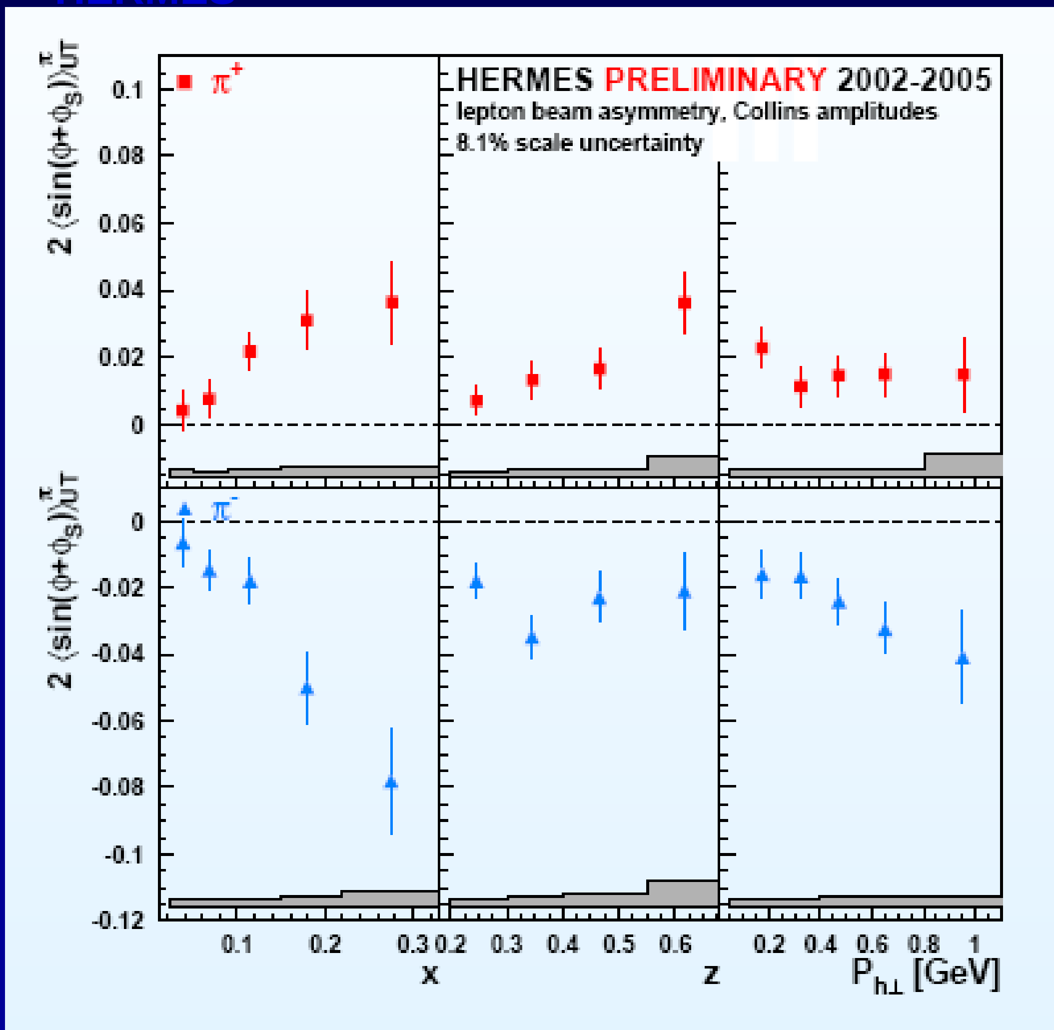
Quark Distribution Functions



Similarly, can have k_T-dependent fragmentation functions (FF's). One example: the chiral-odd Collins FF, which provides one way of accessing transversity!

First Observation of the Collins Effect in Polarized Deep Inelastic Electron-Proton Scattering

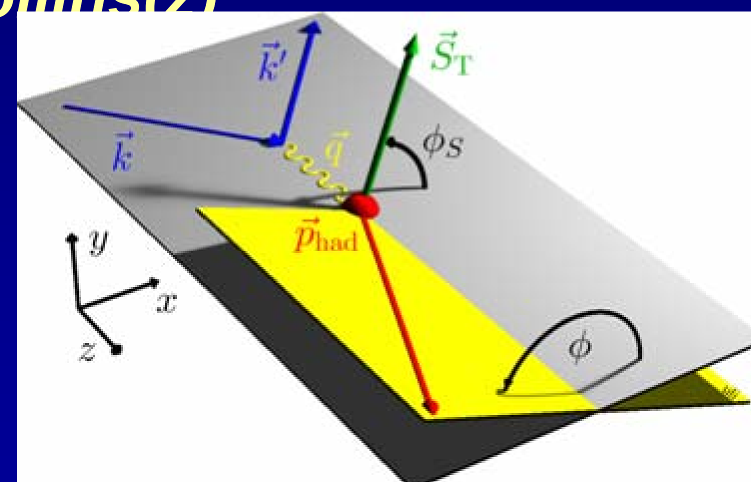
HERMES



Collins Asymmetries in semi-inclusive deep inelastic scattering

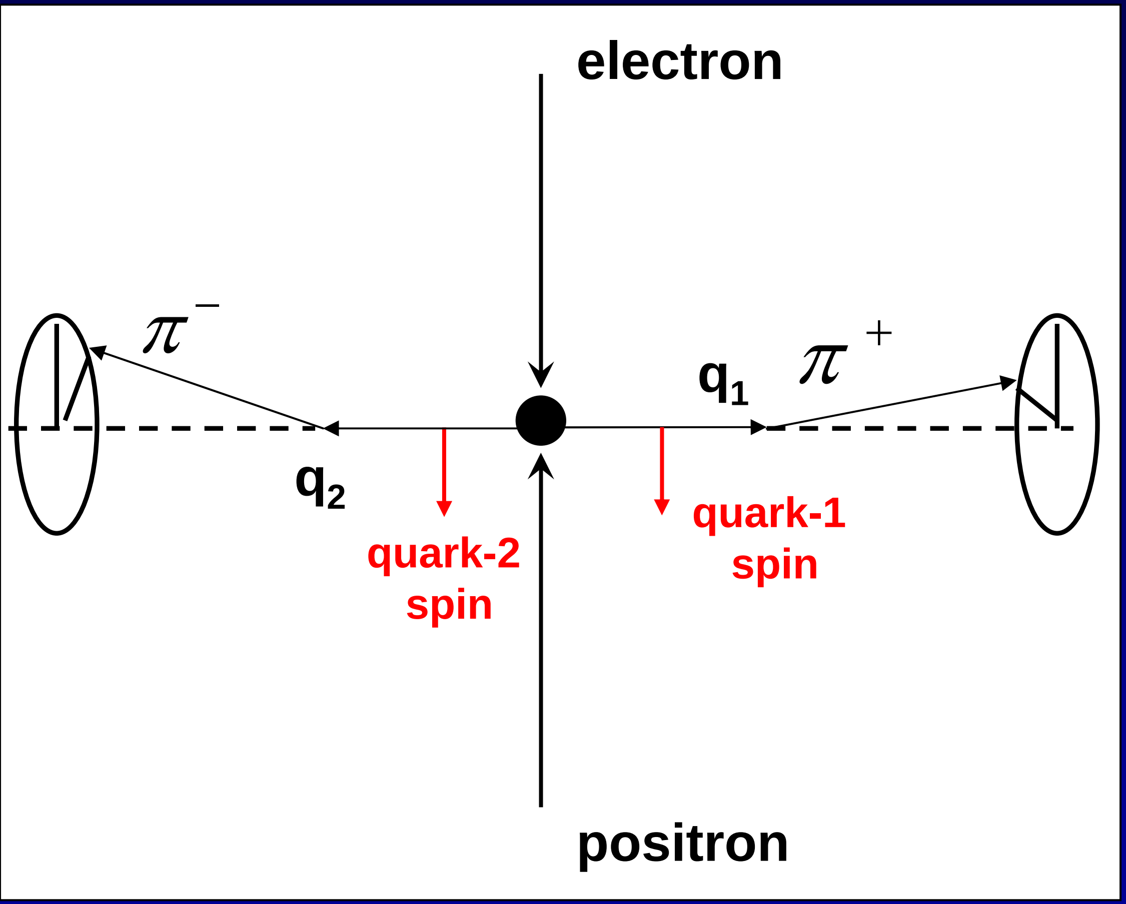
$e+p \rightarrow e + \pi + X$

~ Transversity (x) x Collins(z)



$A_{UT} \sin(\phi+\phi_S)$

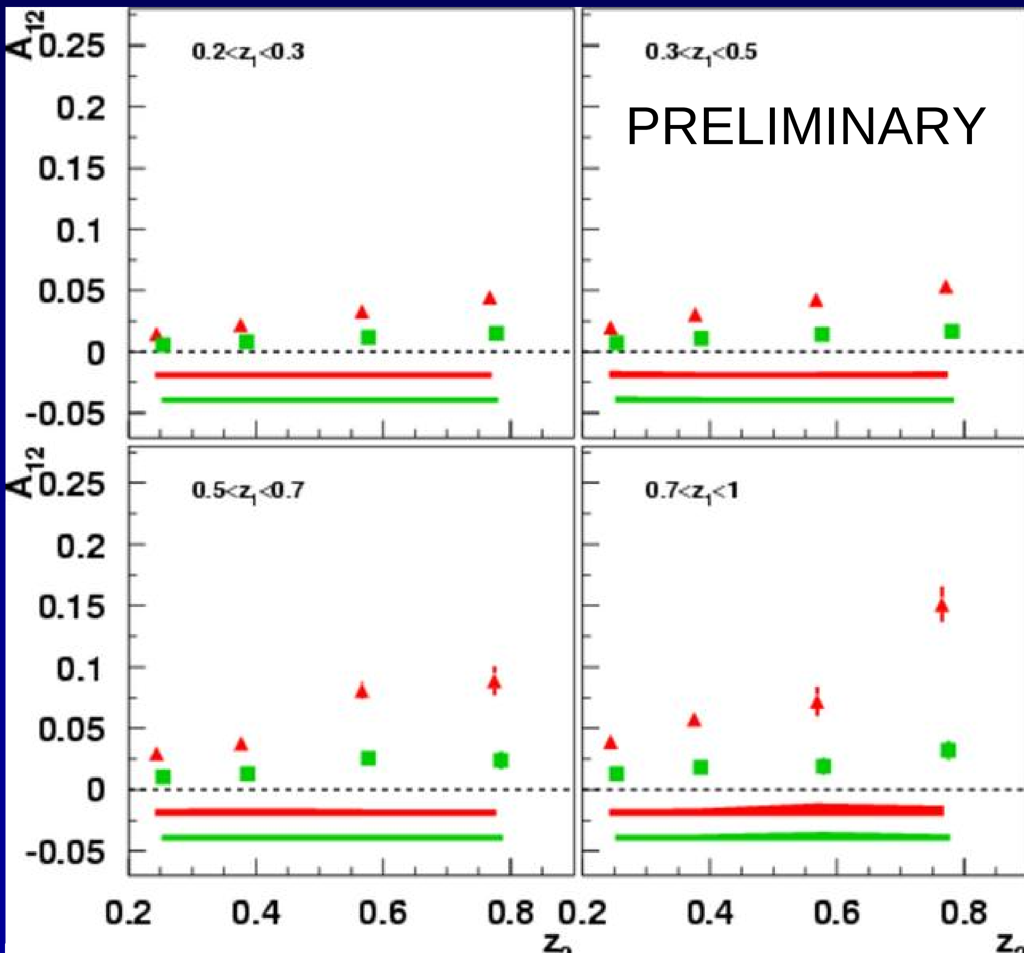
The Collins Effect Must be Present In e^+e^- Annihilation into Quarks!



Collins effect in e+e-
Quark fragmentation
will lead to effects
in di-hadron correlation
measurements!

Observation of the Collins Effect in e^+e^- Annihilation with Belle

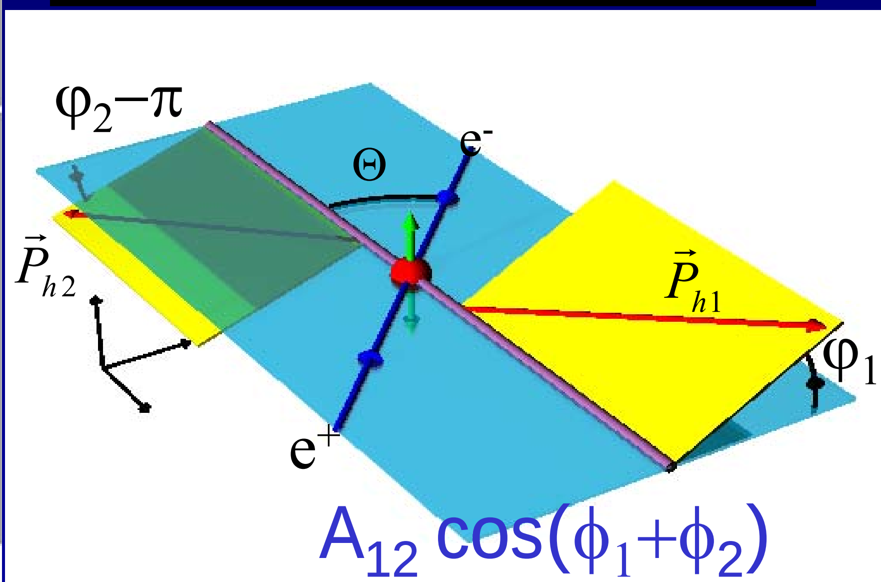
Belle (UIUC/RBRC) group



Collins Asymmetries in e^+e^- annihilation into hadrons

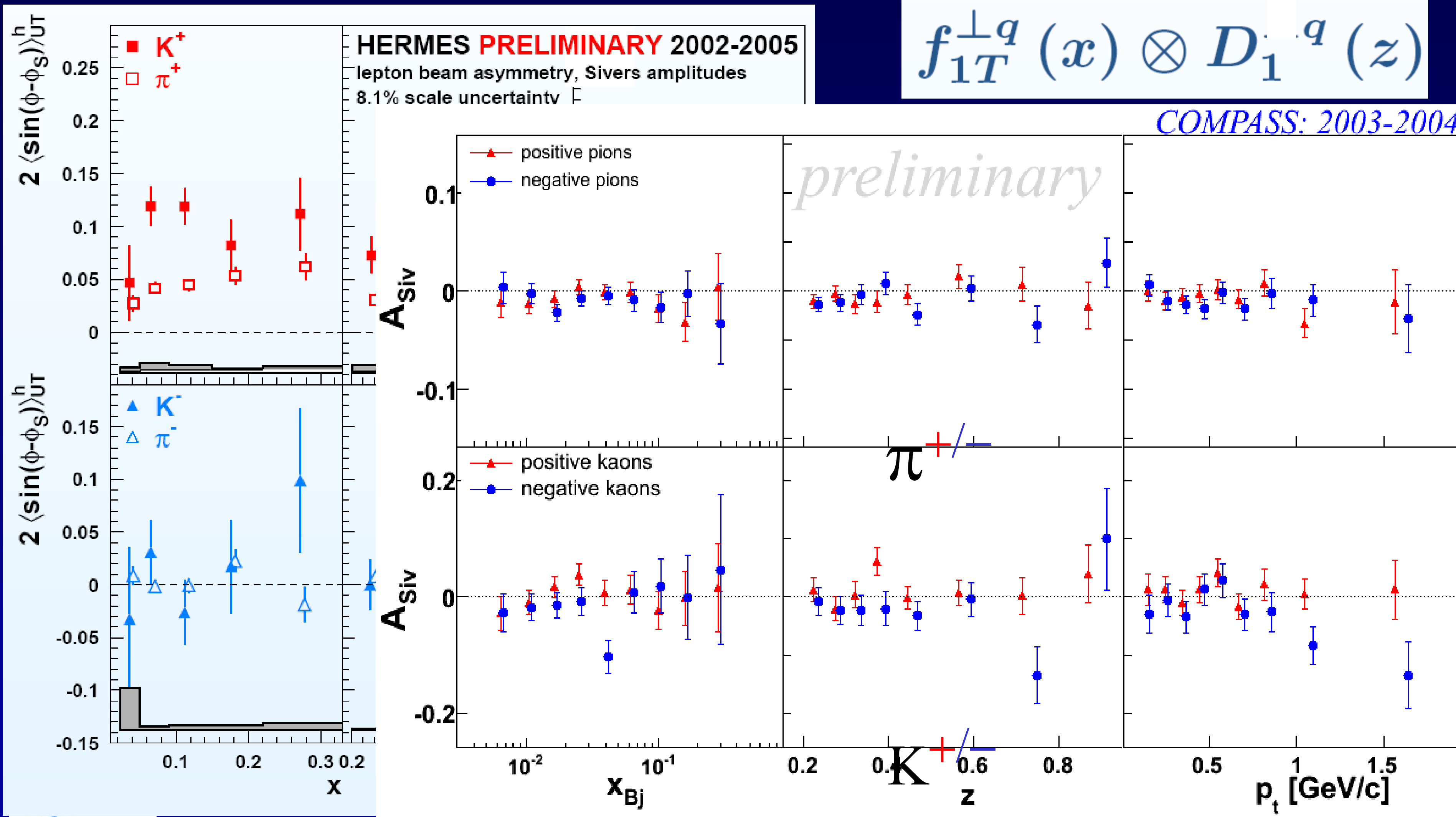
$e^+ + e^- \rightarrow \pi^+ + \pi^- + X$

$\sim$ *Collins(z_1) x Collins (z_2)*



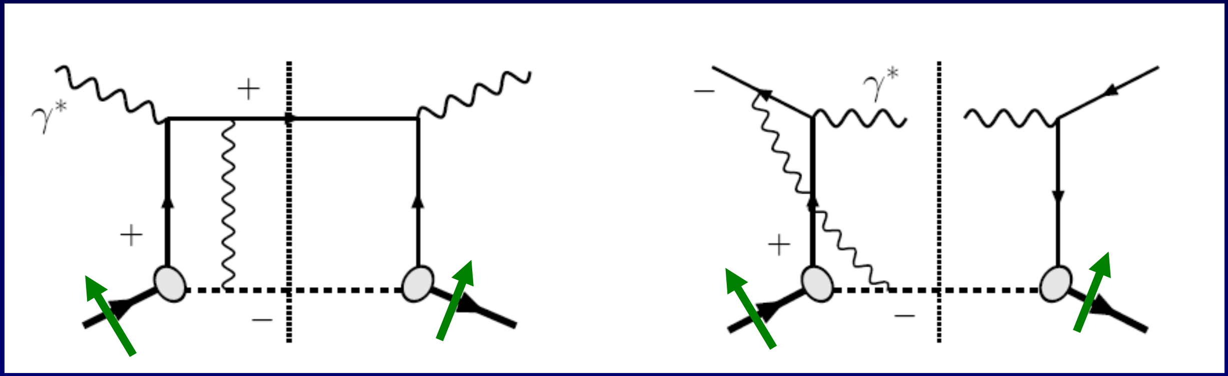
Sivers Asymmetries at HERMES and COMPASS

$$f_{1T}^{\perp q}(x) \otimes D_1^{q}(z)$$



Non-universality of Sivers Asymmetries: Unique Prediction of Gauge Theory!

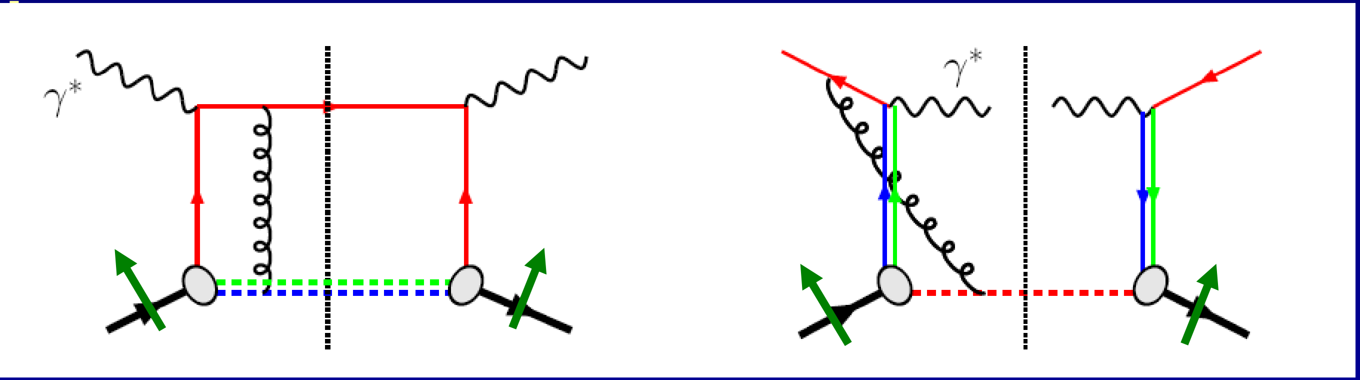
Simple QED example:



DIS: attractive

Drell-Yan: repulsive

Same in QCD:



As a result:

$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

x_T *Scaling*

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

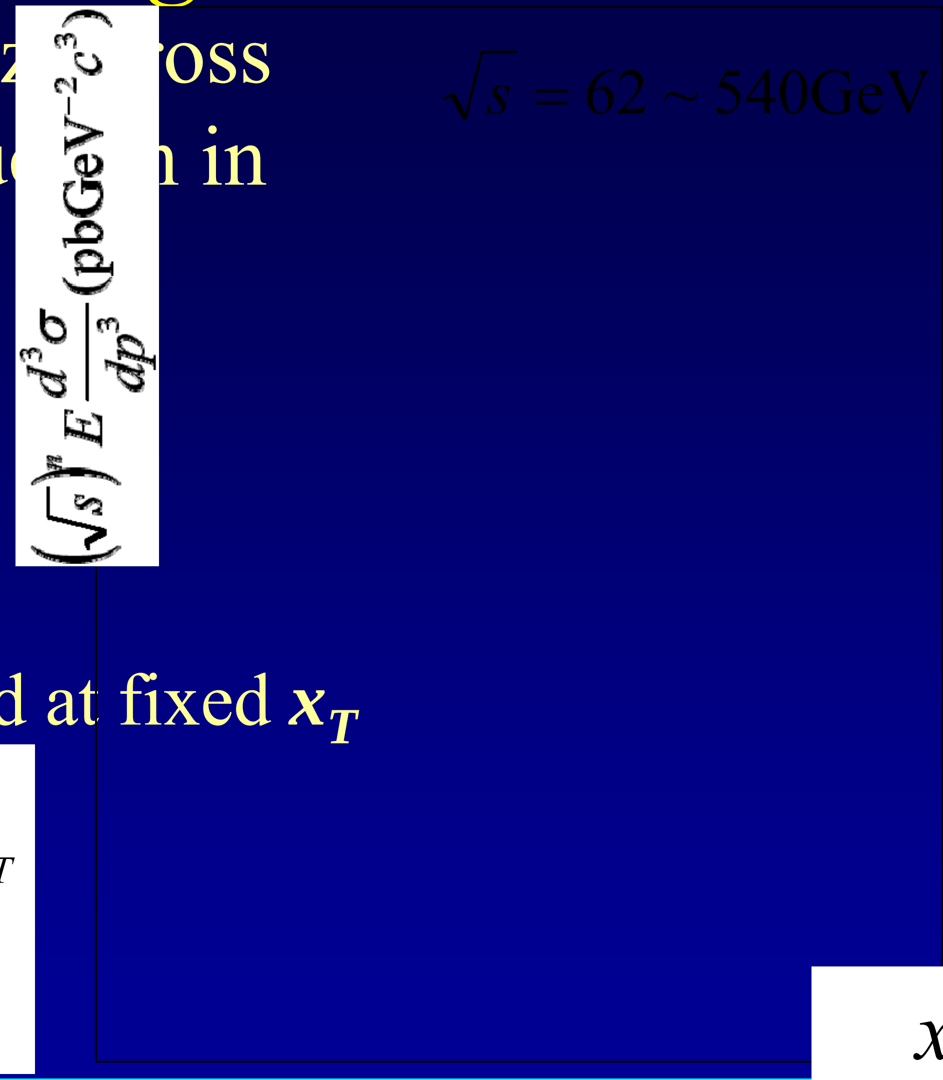
$$E\frac{d^3\sigma}{dp^3} \sim \left(\sqrt{s}\right)^{-n} F(x_T)$$

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

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

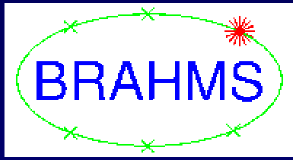
$$L\int E\frac{d^3\sigma}{dp^3}dp_T = L\int E\frac{d^3\sigma}{dp^3}\frac{\sqrt{s}}{2}dx_T$$

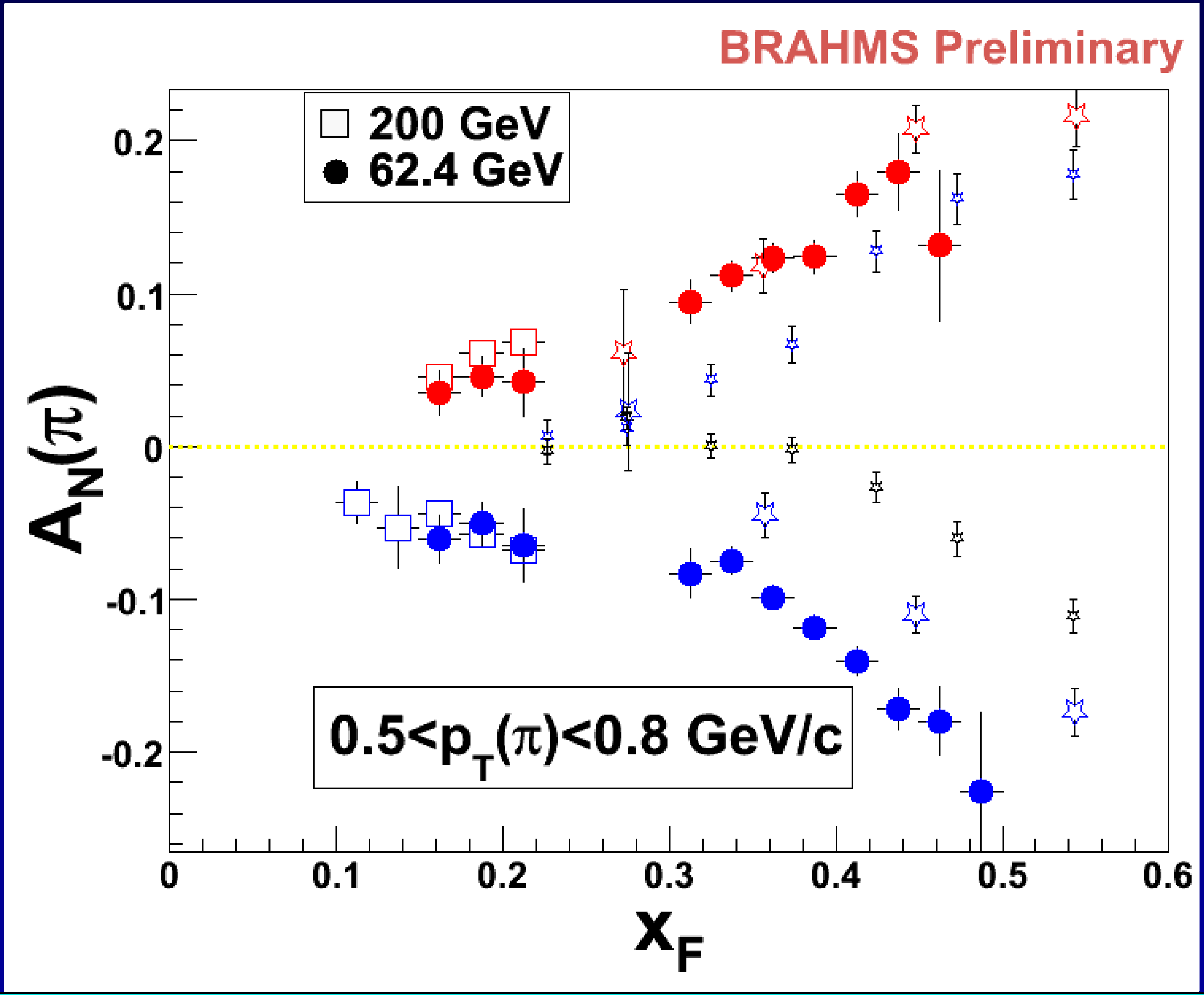
$$\propto L\sqrt{s}^{-5.3}$$



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

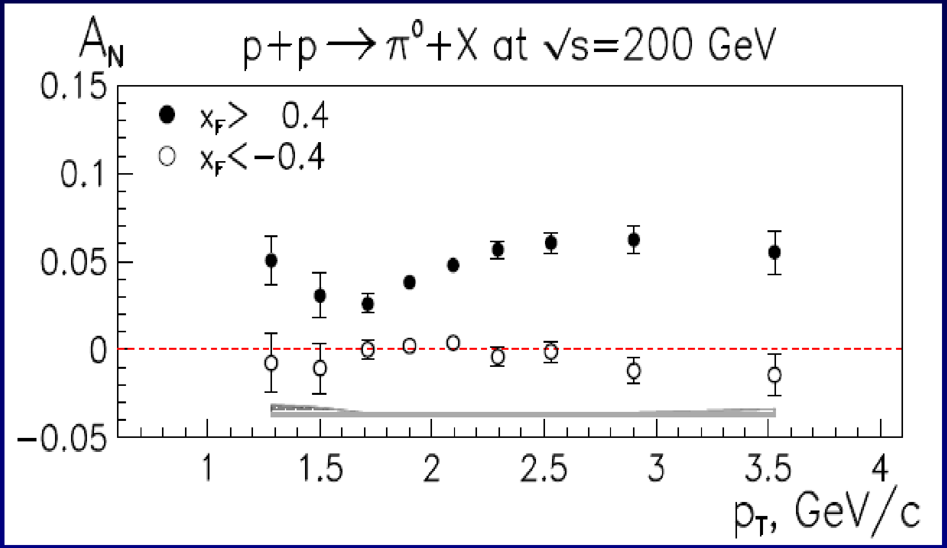
Unifying 62.4 and 200 GeV, BRAHMS + E704

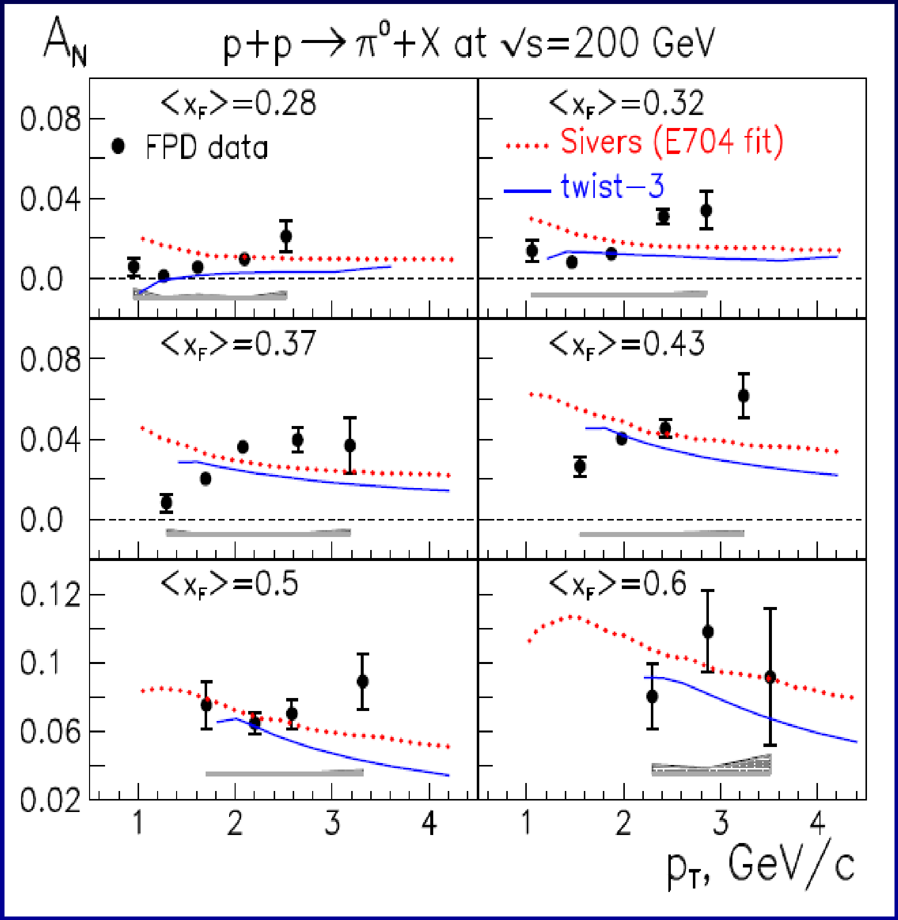




E704 data – all p_T (small stars); p_T>0.7 GeV/c (large stars).

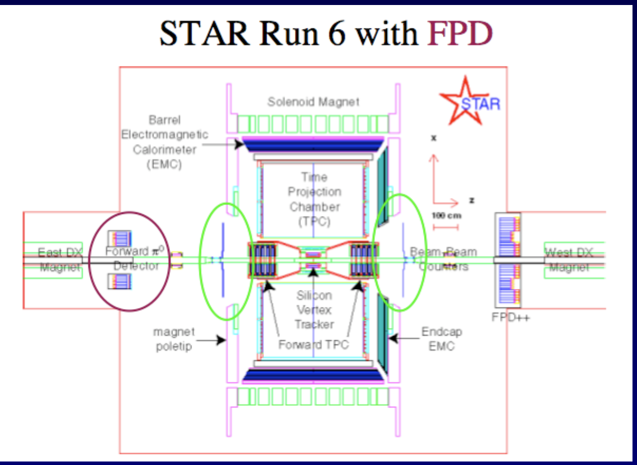
Forward π^0 A_N at 200 GeV: p_T dependence

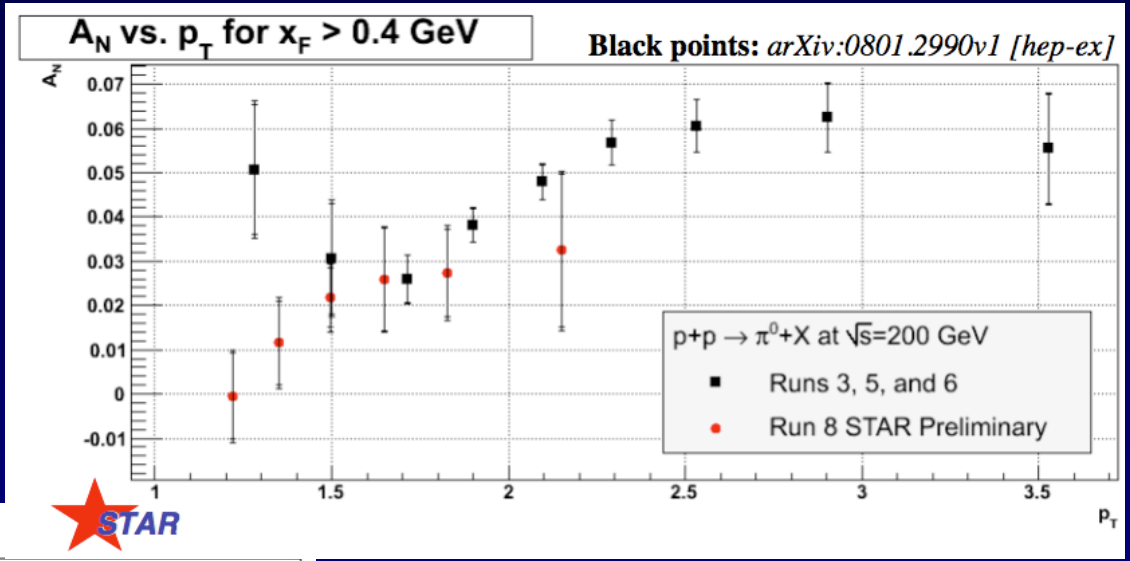


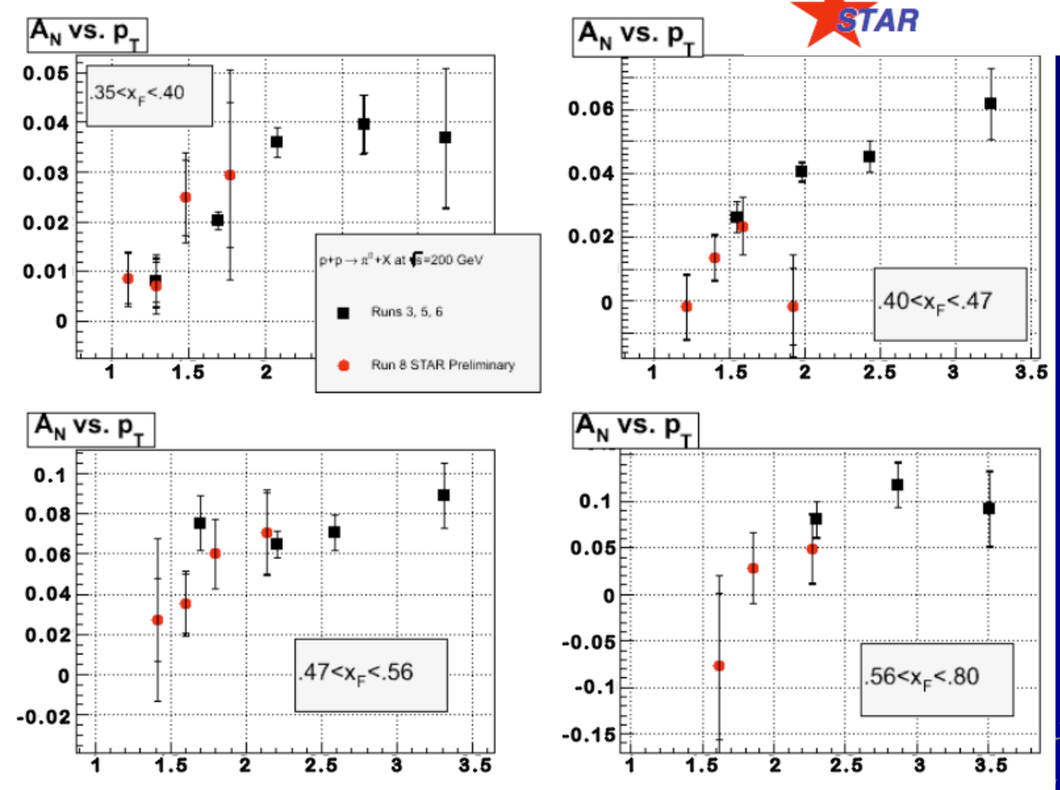


arXiv:0801.2990
Accepted by PRL

A_N at Forward Rapidity



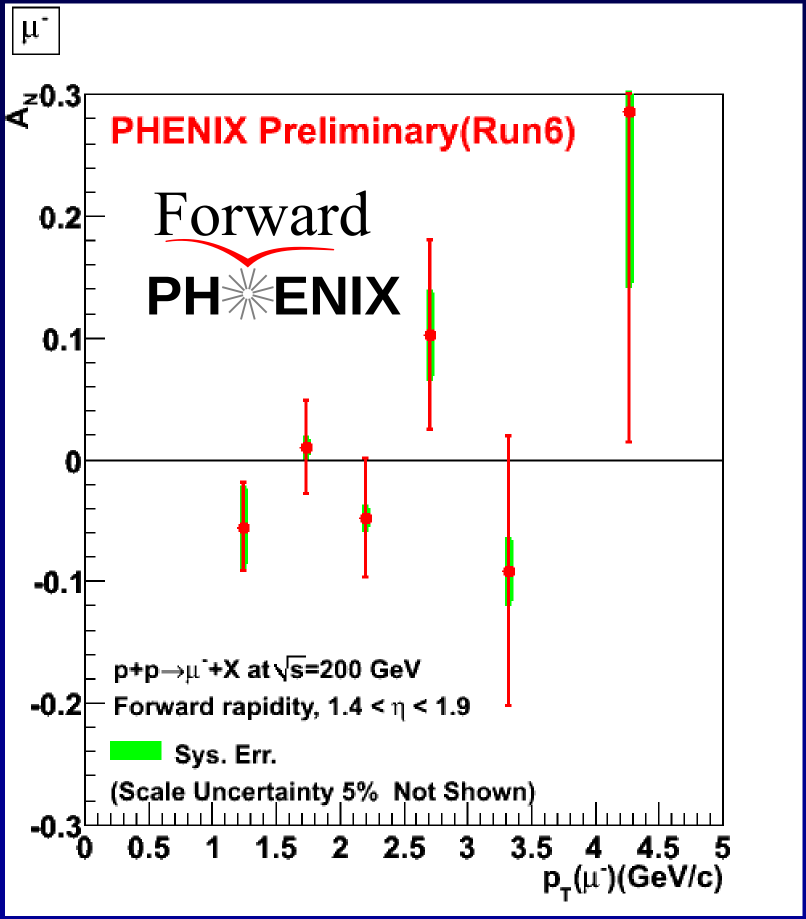




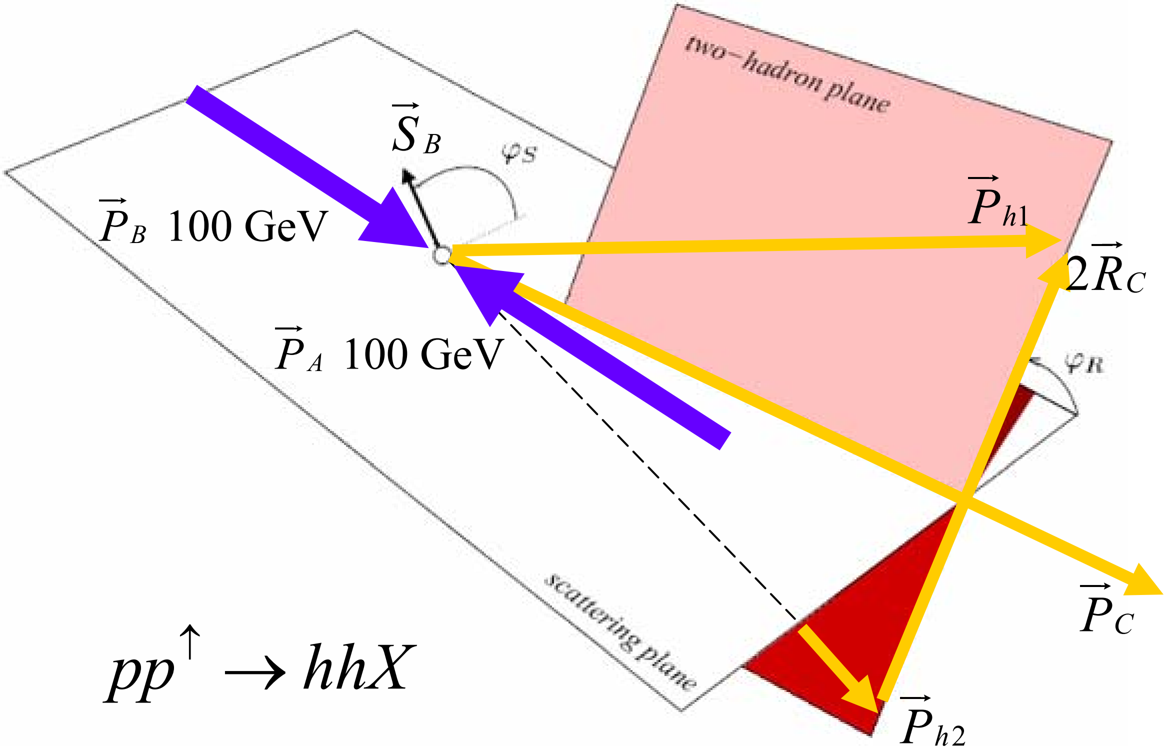
First results from Run-08!

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



Definition of Vectors and Angles for IFF Measurement in PHENIX



$pp^{\uparrow} \rightarrow hhX$

p+p c.m.s. = lab frame

$\vec{P}_A, \vec{P}_B$: momenta of protons

$\vec{P}_{h1}, \vec{P}_{h2}$: momenta of hadrons

$\vec{P}_C = \vec{P}_{h1} + \vec{P}_{h2}$

$\vec{R}_C = (\vec{P}_{h1} - \vec{P}_{h2})/2$

$\vec{S}_B$: proton spin orientation

hadron plane: $\vec{P}_{h1}, \vec{P}_{h2}$

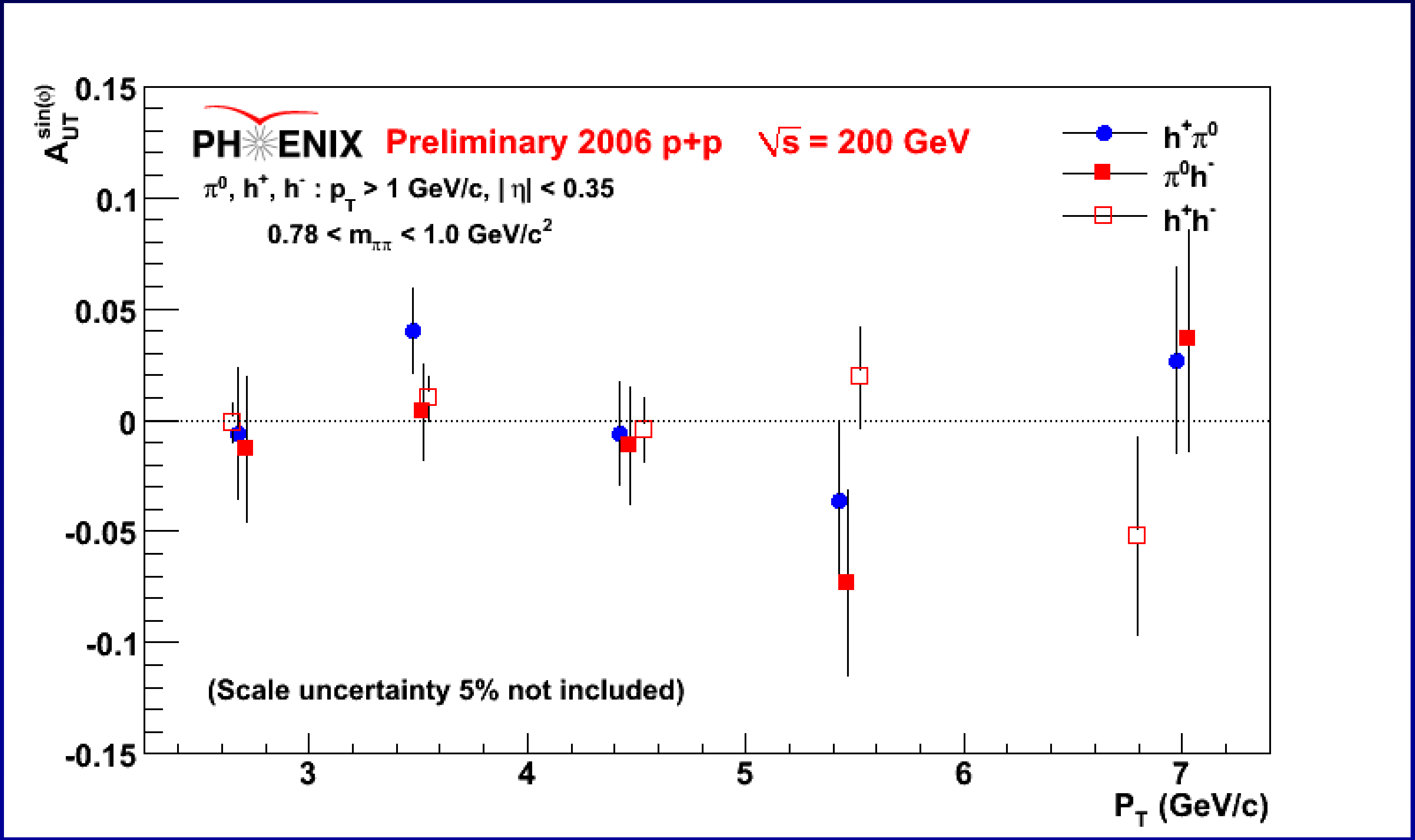
scattering plane: $\vec{P}_C, \vec{P}_B$

ϕ_R : from scattering plane to hadron plane

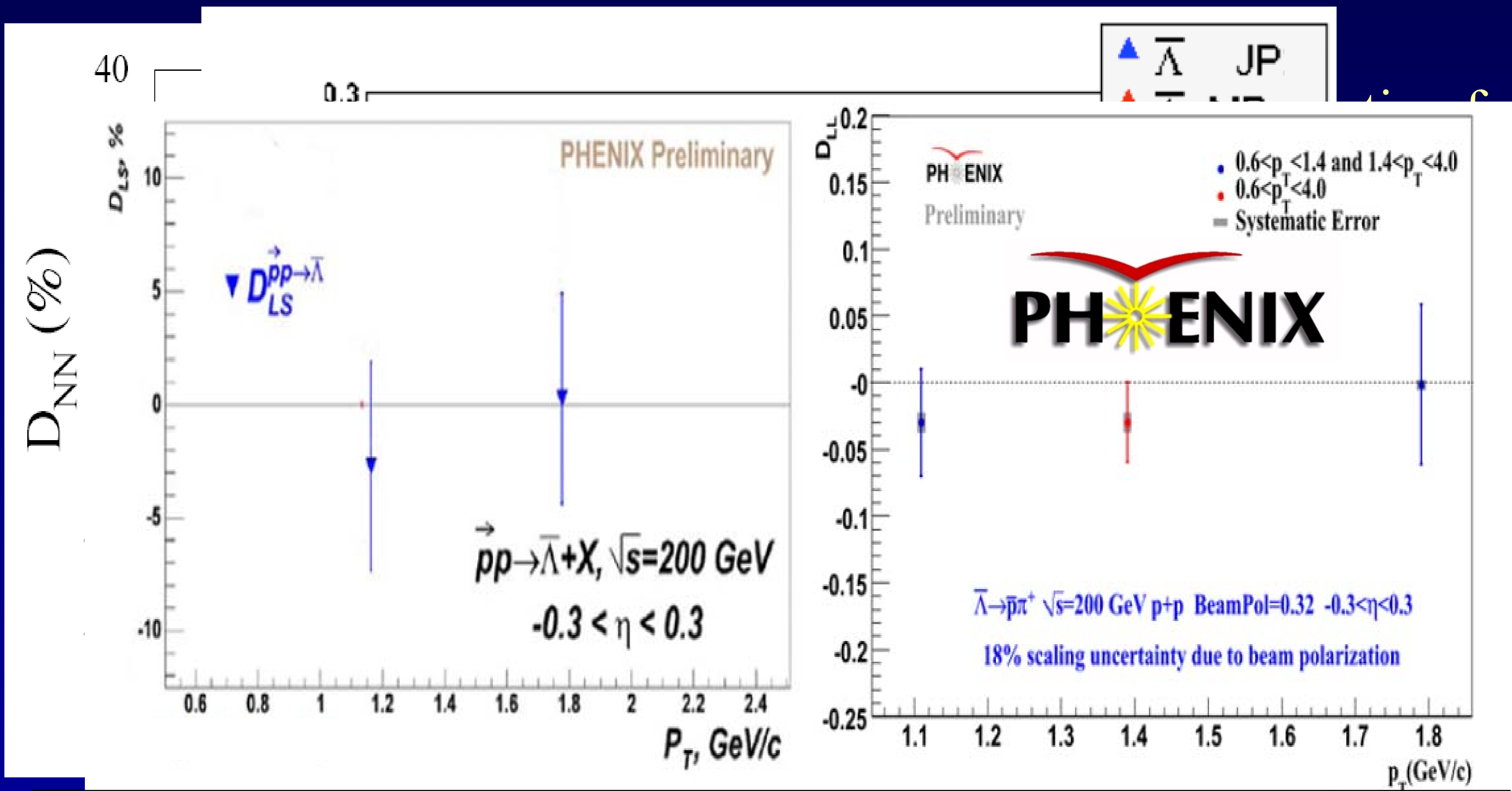
ϕ_S : from polarization vector to scattering plane

Bacchetta and Radici, PRD70, 094032 (2004)

p_T Dependence of Interference Fragmentation Function Asymmetry



Polarized beams: Hyperon spin transfer measurements

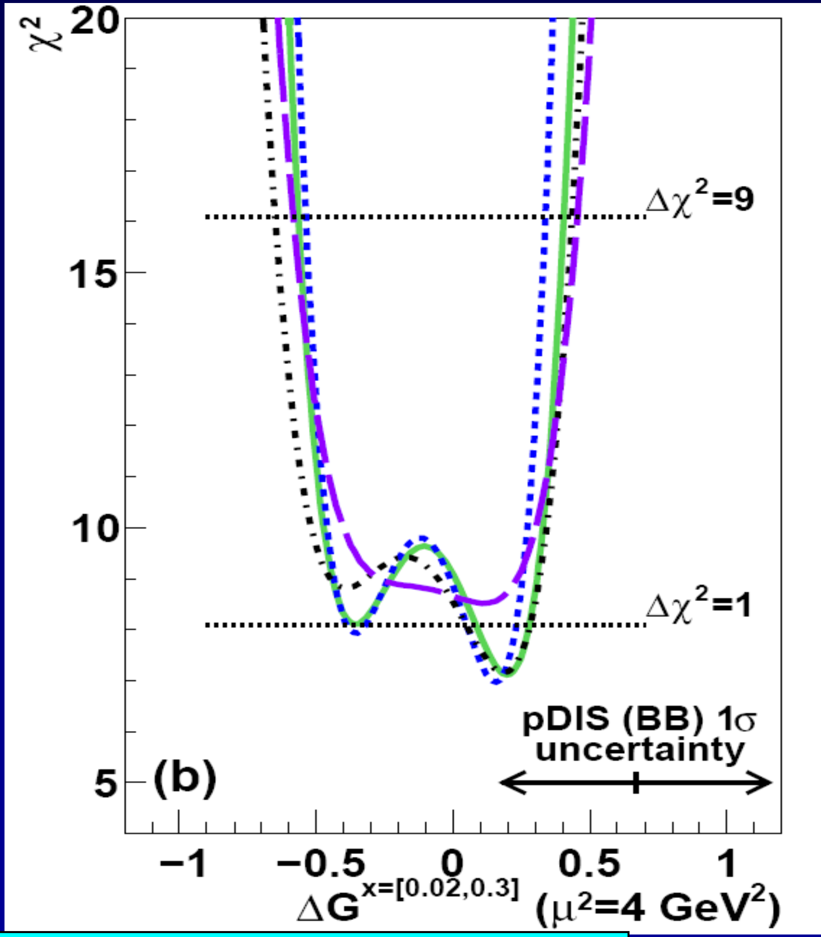


Spin transfers consistent with zero observed at RHIC with longitudinal polarization in the initial state. Transverse measurements still to come . . .

PHENIX 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!

Neutral pion A_{LL} at STAR

$-0.95 < \eta < 0.95$ 				$1.0 < \eta < 2.0$