RHIC Spin Program

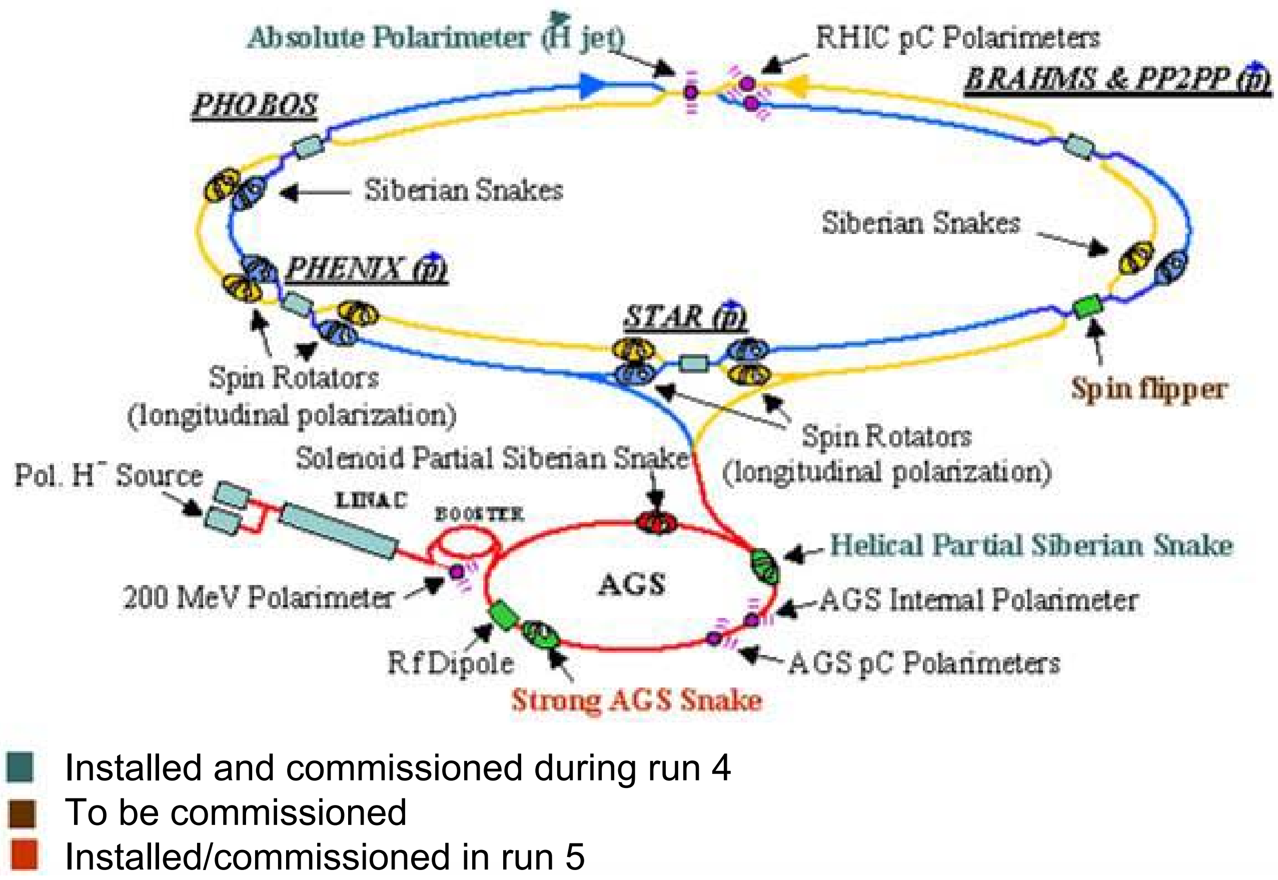
OUTLINE

- Goals of RHIC Spin Program
- Tests of applicability of pQCD framework
- Status of longitudinal spin asymmetry measurements
- Transverse single spin effects in p+p collisions at $\sqrt{s}$=200 GeV

L.C. Bland
DOE Review of Medium Energy Physics
Washington 11 May 2006

BROOKHAVEN
NATIONAL LABORATORY

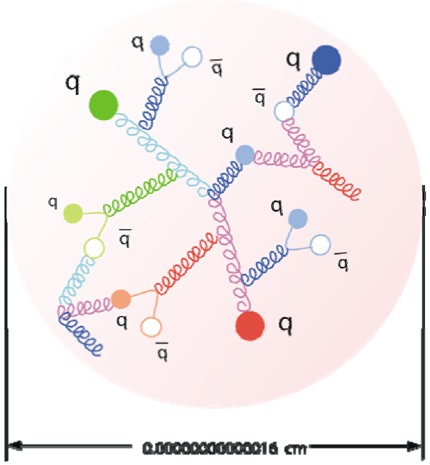
RHIC pp accelerator complex



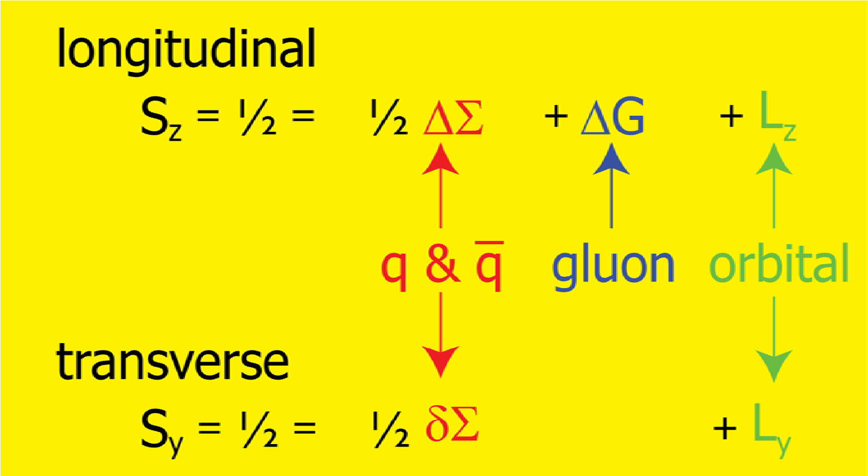
Developments for runs 2 (1/02), 3 (3/03 → 5/03) and 4 (4/04 → 5/04)

- Helical dipole snake magnets
- CNI polarimeters in RHIC,AGS
  → fast feedback
- β*=1m operataion
- spin rotators → longitudinal polarization
- polarized atomic hydrogen jet target

Motivation for RHIC Spin Program



The proton and neutron are the building blocks of atomic nuclei. We know they are built from quarks, antiquarks and gluons. The proton and neutron have fundamental properties of *mass* and *intrinsic spin*.



longitudinal

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

q & $\bar{q}$ gluon orbital

transverse

$S_y = \frac{1}{2} = \quad \frac{1}{2}\delta\Sigma \quad + L_y$

Where is the spin of the proton?

Goals of RHIC spin program

Present Milestones and Plans

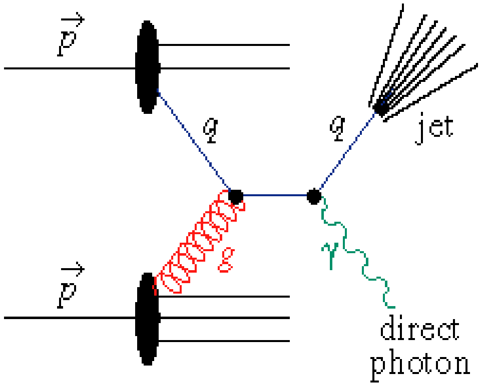
- *Direct measurement* of polarized gluon distribution (ΔG) *using multiple probes*

- Direct measurement of flavor identified *anti-quark polarization* using *parity violating production of* $W^{\pm}$

- *Transverse spin:* Transversity ($\delta\Sigma$) & transverse spin effects with connections to orbital angular momentum (L_y)

Methods to Address Spin Structure at RHIC

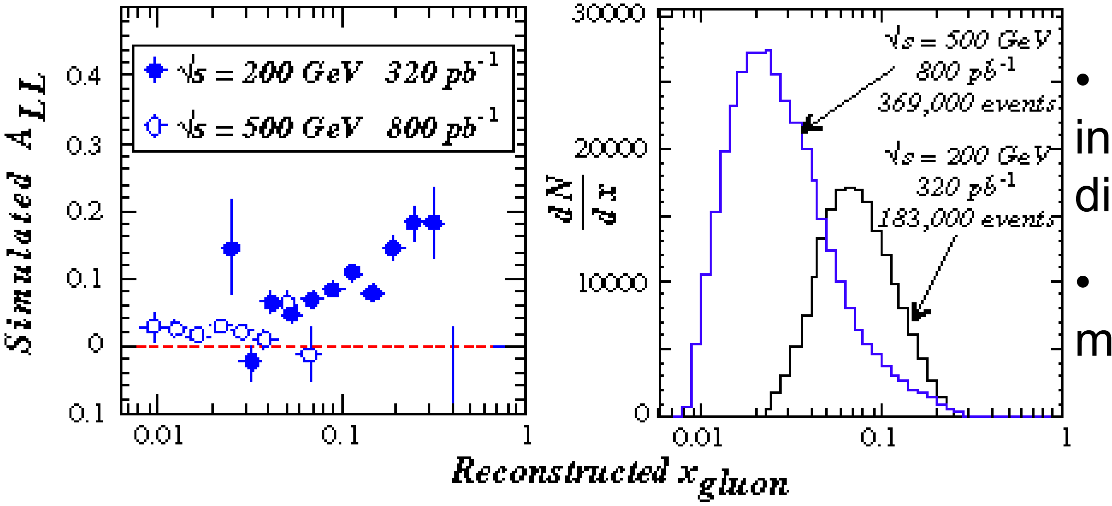
In the perturbative QCD picture, the measured 2-spin A_{LL} for particles produced in polarized p+p collisions at RHIC is interpreted as using polarized quarks from one proton to probe the gluon polarization from the other proton.



Quark-Gluon Compton scattering

$$\vec{p} + \vec{p} \rightarrow \gamma\,(+\,jet) + X$$

$$\vec{p}\,\vec{p} \rightarrow \gamma + jet + X$$



- *Inclusive production* ⇒ convolution integral with contributions from q,g with different momentum fractions (x).
- *Away-side correlations* ⇒ constrain momentum fractions of contributing q,g

Interpret measured asymmetry within leading-order pQCD

$$A_{LL} = \overbrace{P_{part.\,1}\;P_{part.\,2}}^{\text{parton pol'ns.}}\quad \hat{a}_{LL} = \underbrace{\overbrace{\frac{\Delta f_1}{f_1}\;\frac{\Delta f_2}{f_2}}^{\text{pol struct fncs.}}}_{\text{unpol struct fncs.}}\;\hat{a}_{LL}(\hat{s},\hat{t},\hat{u}) \xrightarrow[\text{QCD Compton}]{} \boxed{\frac{\Delta G(x_g)}{G(x_g)}}\;A_1^p(x_q)\;\hat{a}_{LL}$$

Measured in polarized deep-inelastic scattering

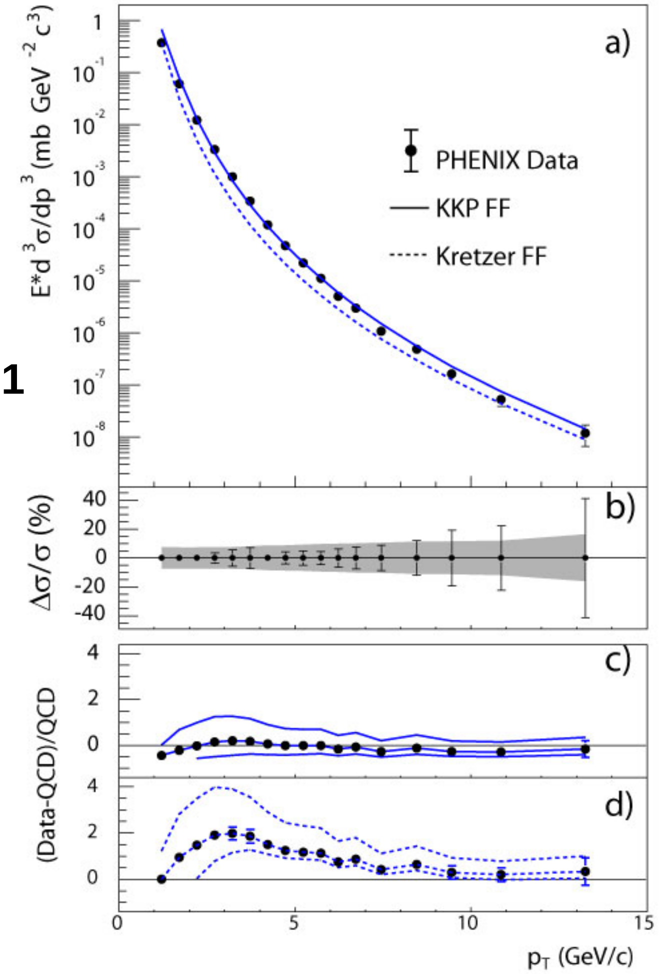
pQCD result for specific process

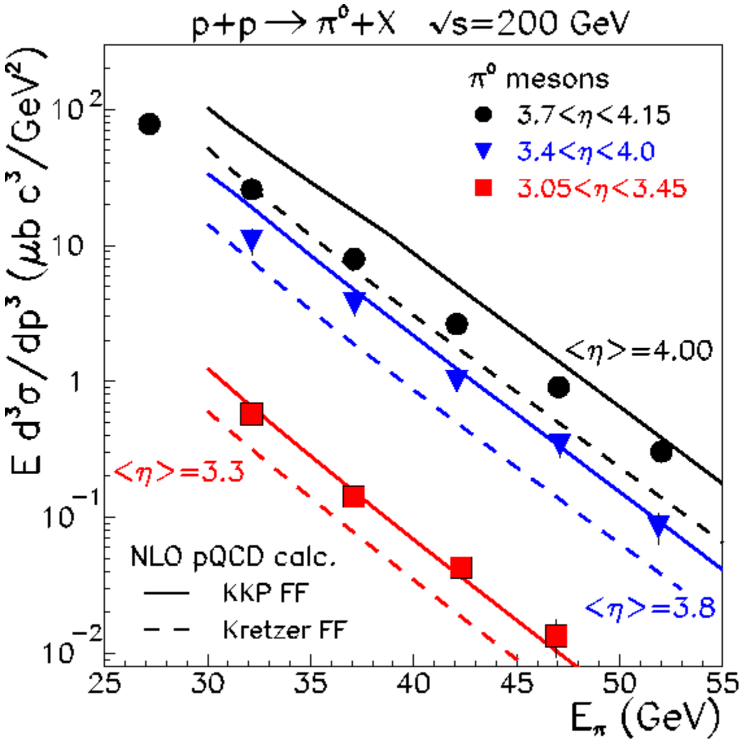
gluon polarization

Does pQCD describe particle production at RHIC?

Compare cross sections measured for $p+p\rightarrow\pi^0$ +X at $\sqrt{s}$=200 GeV
to next-to-leading order pQCD calculations

S.S. Adler *et al.* (PHENIX), PRL **91** (2003) 241803





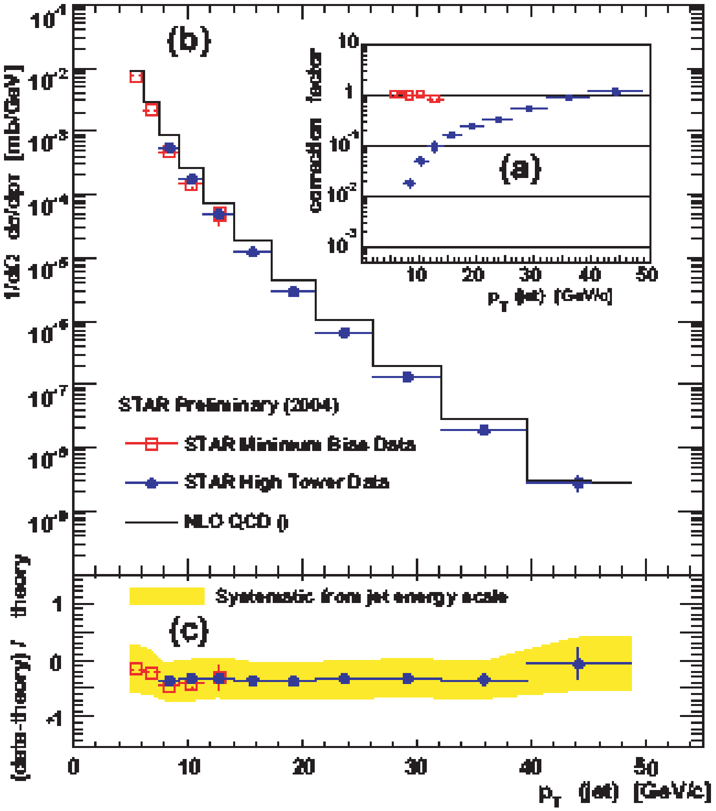
J. Adams *et al.* (STAR), PRL **92** (2004) 171801; and submitted to PRL [nucl-ex/0602011]

Particle production cross sections agree with NLO pQCD down to p_T~2 GeV/c over a wide range, 0 < η < 3.8, of pseudorapidity (η = -ln tan θ/2).

Does pQCD describe particle production at RHIC?

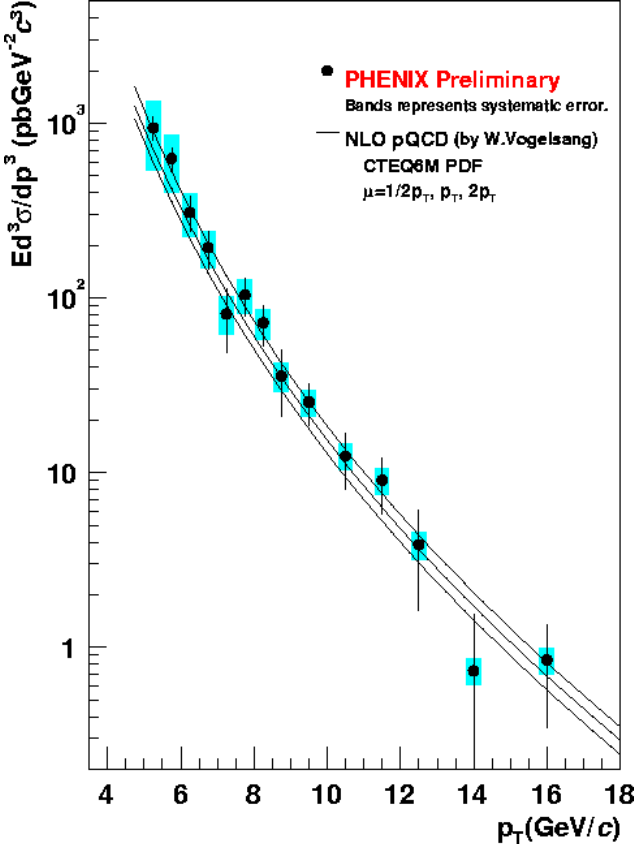
Production of jets and photons at midrapidity for √s=200 GeV

jet production



M.Miller (for STAR) PANIC2005
[hep-ex/0604001]

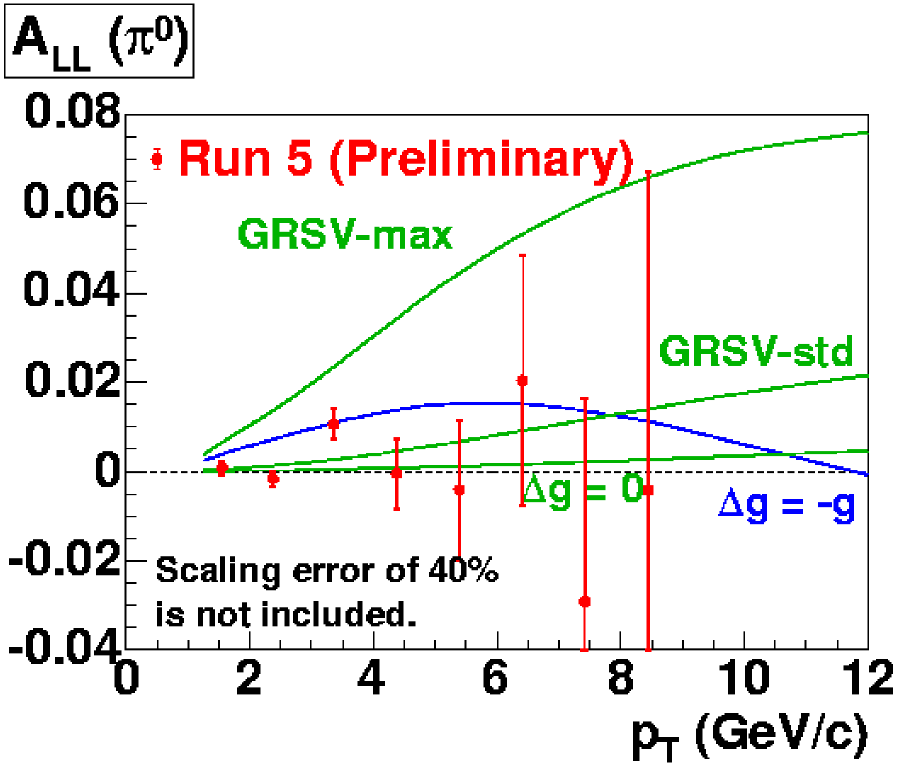
γ production



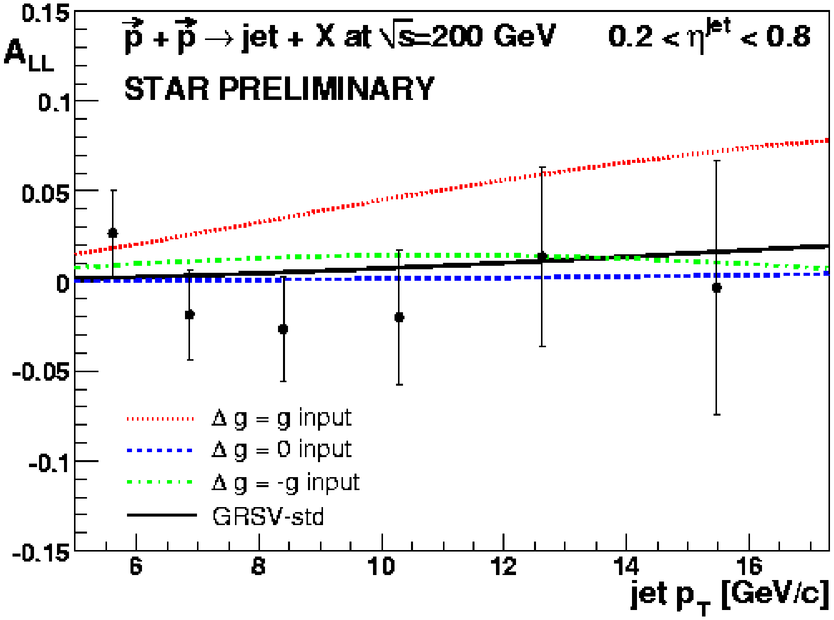
K.Okada (for PHENIX)
SPIN2004 [hep-ex/0512040]

NLO pQCD is a robust framework for understanding spin observables at RHIC energies.

A_{LL} for π^0 and jet production



K.Boyle (for PHENIX) PANIC2005

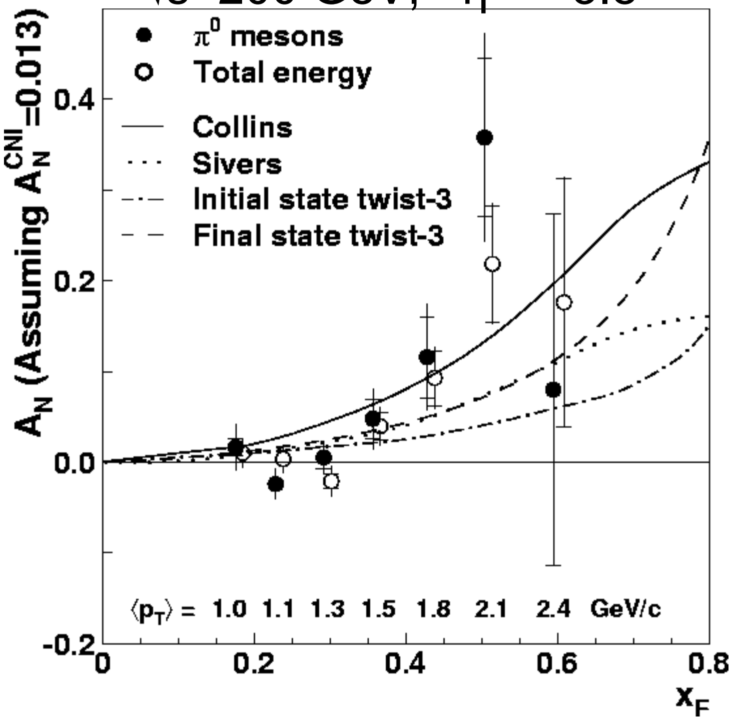


J.Kiryluk (for STAR) PANIC2005
[hep-ex/0512040]

Precision of preliminary results available to date rule out maximal gluon polarization

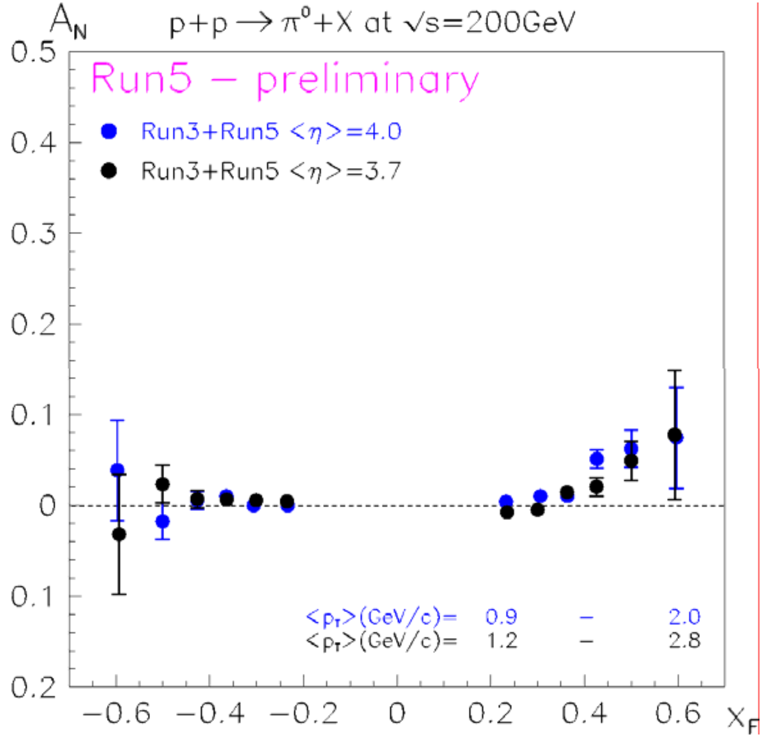
Spin Effects at Large Rapidity

$\sqrt{s}$=200 GeV, <η> = 3.8



STAR collaboration Phys. Rev. Lett. **92** (2004) 171801

Spin effects initially observed in RHIC run 2 confirmed by higher statistics measurements in runs 3,5.



D. Morozov, for STAR [hep-ex/0512013]

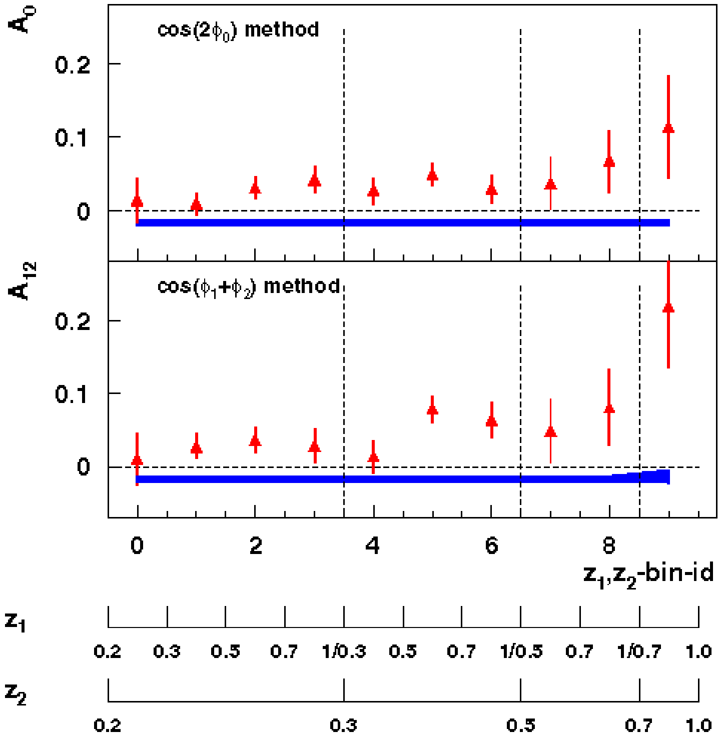
Similar to result from E704 experiment ($\sqrt{s}$=20 GeV, $0.5 < p_T < 2.0$ GeV/c)

Can be described by several models available as predictions:

- Qiu and Sterman (initial state) / Koike (final state): twist-3 pQCD calculations, multi-parton correlations
- Sivers: spin and $k_\perp$ correlation in parton distribution functions (initial state)
- Collins/Heppelmann: spin and $k_\perp$ correlation in fragmentation function (final state)

Transverse Spin

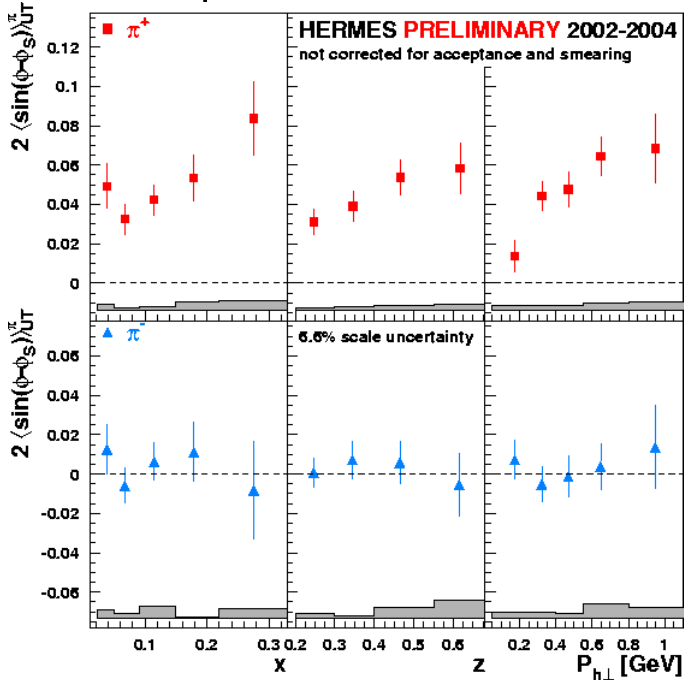
Recent experimental/theoretical developments ⇒ require new RHIC milestone



$e^+e^- \rightarrow$ di-hadron +X, √s=10.52 GeV, azimuthal asymmetries

⇒ Collins fragmentation function

Belle collaboration, submitted to PRL [hep-ex/0507063]



Semi-inclusive deep-inelastic scattering from transversely polarized proton target

⇒ non-zero Collins effect

⇒ non-zero Sivers effect

HERMES collaboration, [hep-ex/0507013]

⇒ Probe orbital angular momentum (Sivers effect) and transversity (Collins effect) via transverse single spin asymmetries in particle production at RHIC

RHIC Spin – Plans and Status

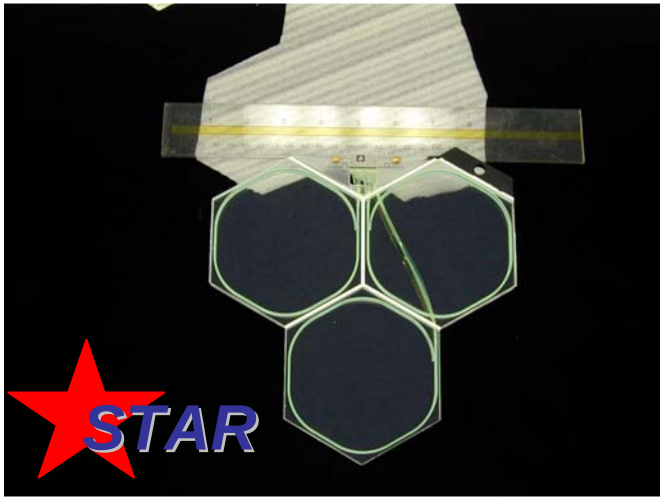
Summary

- RHIC spin, a world unique polarized proton collider, is addressing fundamental aspects of proton spin structure.
- Measured cross sections for particle production at RHIC energies agree with NLO pQCD down to p_T~2 GeV/c $\Rightarrow$ sound theoretical basis for understanding spin effects.
- First preliminary results for A_{LL} measured for π^0 and jet production rule out maximal gluon polarization. Improved precision, and A_{LL} for direct photon production, will determine gluon contribution to proton spin.
- Non-zero transverse single-spin effects are observed for π^0 production at large rapidity for p+p collisions at $\sqrt{s}$ = 200 GeV. Dynamical origin, and sensitivity to transversity and/or orbital motion, can be established by measurements with improved instrumentation at large rapidity.

Plans for Forward Particle Production and Spin Asymmetry Measurements at STAR

OUTLINE

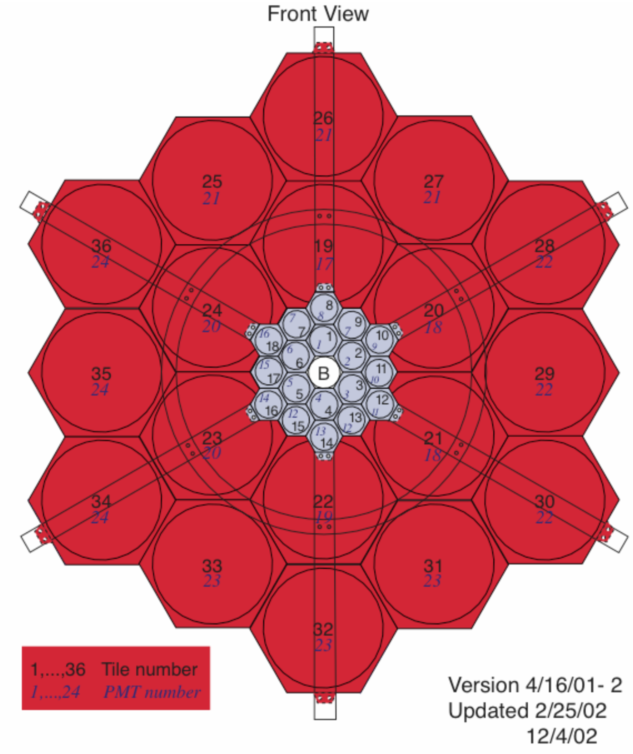
- Contributions of BNL STAR spin group
- Physics motivations for Forward Meson Spectrometer
- Plans for ongoing RHIC run 6 and beyond



Beam Beam Counter

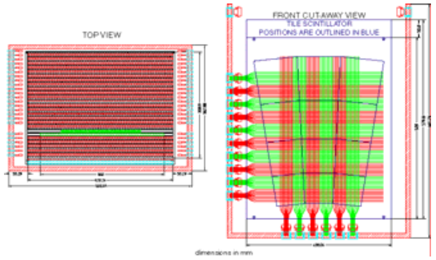
Scintillator annuli tiled by 1cm thick hex tiles with fiber-optic light collection (2.5<|η|<5)

- Feed back to RHIC for p+p collision tuning at STAR
- Measure relative luminosity ~10^{-3} level
- Measure absolute luminosity ~ 15% level
- Minimum bias trigger (covers ~50% of total σ)
- Measure multiplicity at forward rapidity
- A_N for forward charged particles ⇒ local polarimeter

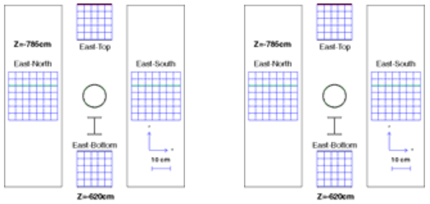


STAR Forward Calorimetry

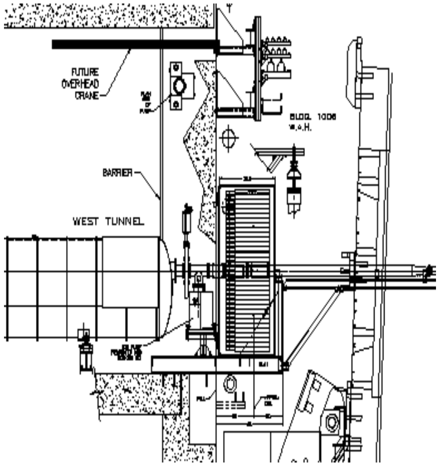
Recent History and Plans

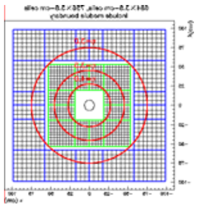


- Prototype FPD proposal Dec 2000
  - Approved March 2001
  - Run 2 polarized proton data (published 2004 spin asymmetry and cross section)



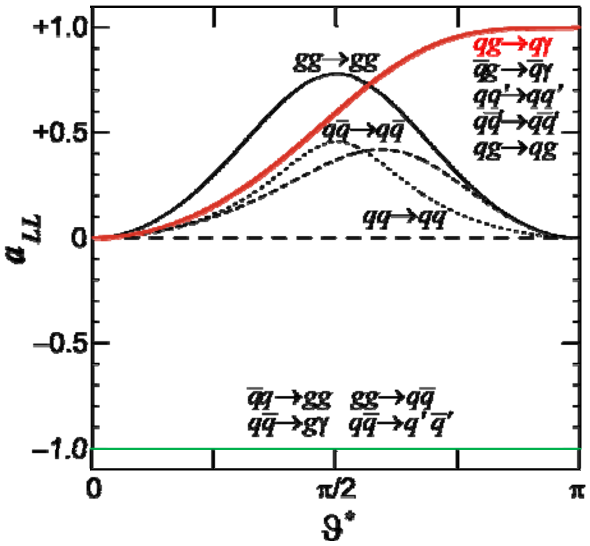
- FPD proposal June 2002
  - Review July 2002
  - Run 3 data pp dAu (Preliminary A_n Results)

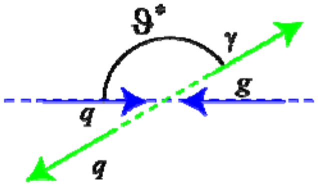




- FMS Proposal: Complete Forward EM Coverage (**hep-ex/0502040).**

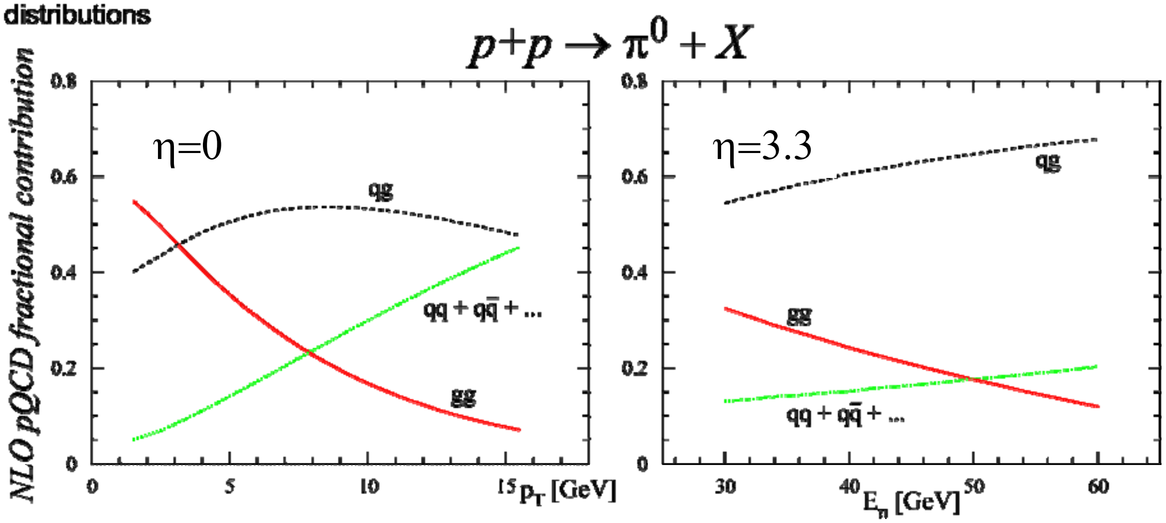
Importance of rapidity for spin physics





pQCD partonic
2-spin asymmetry
angular distributions

Large rapidity γ production optimizes sensitivity to gluon polarization via QCD Compton backscattering



Large rapidity ⇒ large Feynman x

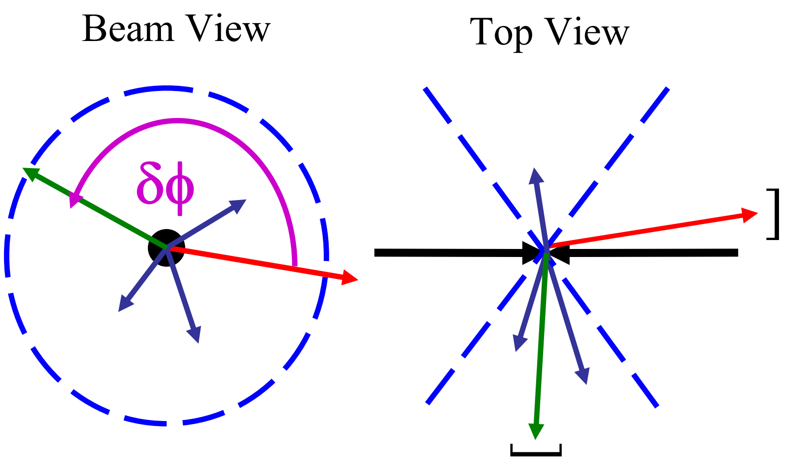
- changes subprocess admixture relative to midrapidity
- emphasis on large–Bjorken–x quarks probing low–Bjorken–x gluons

Issues –

- dominance of beam fragmentation at low √s ⇒ addressed by σ at RHIC energies
- what is sufficient p_T?

Back-to-back Azimuthal Correlations with large $\Delta\eta$

Is forward production from partonic scattering?



Trigger by forward π^0

- **$E_\pi > 25$ GeV**
- **$\langle\eta_\pi\rangle = 4$**

Midrapidity *h*$^\pm$ tracks in TPC

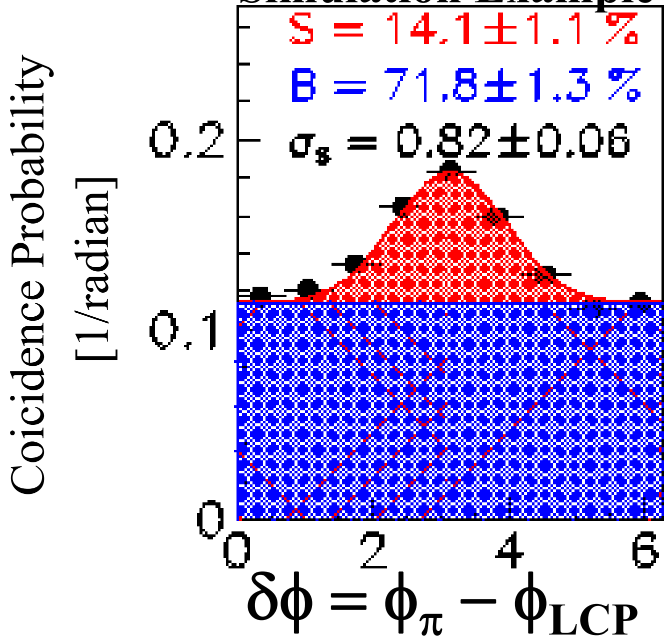
- **$-0.75 < \eta < +0.75$**

Leading Charged Particle(LCP)

- **$p_T > 0.5$ GeV/c**

Fit $\delta\phi = \phi_\pi - \phi_{LCP}$ normalized distributions and with Gaussian+constant

Simulation Example

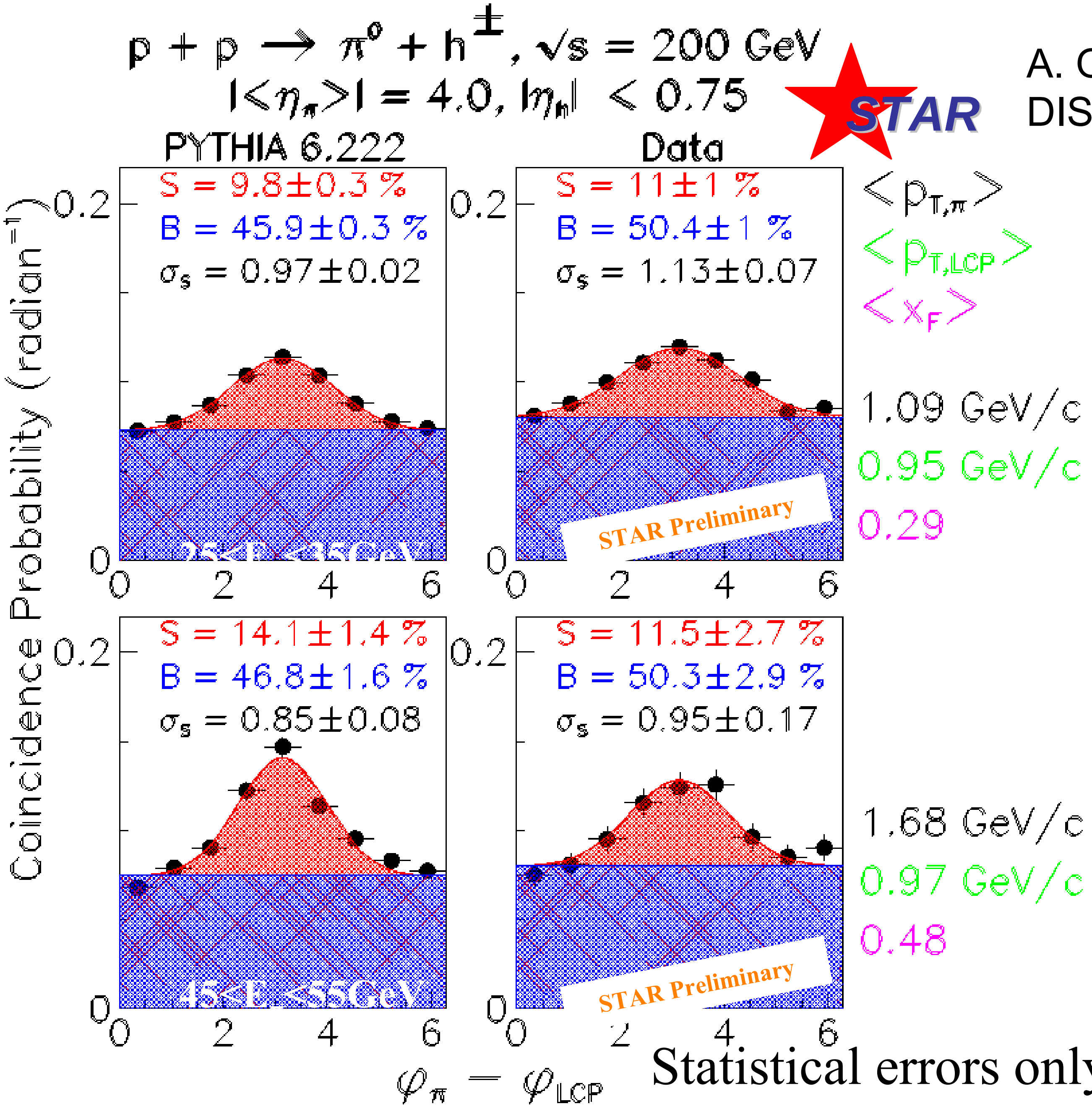


S = Probability of "correlated" event under Gaussian

B = Probability of "un-correlated" event under constant

σ_s = Width of Gaussian

A. Ogawa (for STAR), DIS04 [nucl-ex/0408004]



Statistical errors only

PYTHIA (with detector effects) predicts

- "S" grows with $<x_F>$ and $<p_{T,\pi}>$
- "σ_s" decrease with $<x_F>$ and $<p_{T,\pi}>$

PYTHIA prediction agrees with p+p data

Larger k_T from multi-gluon emission required to fit data

Plans for Future Large Rapidity Studies

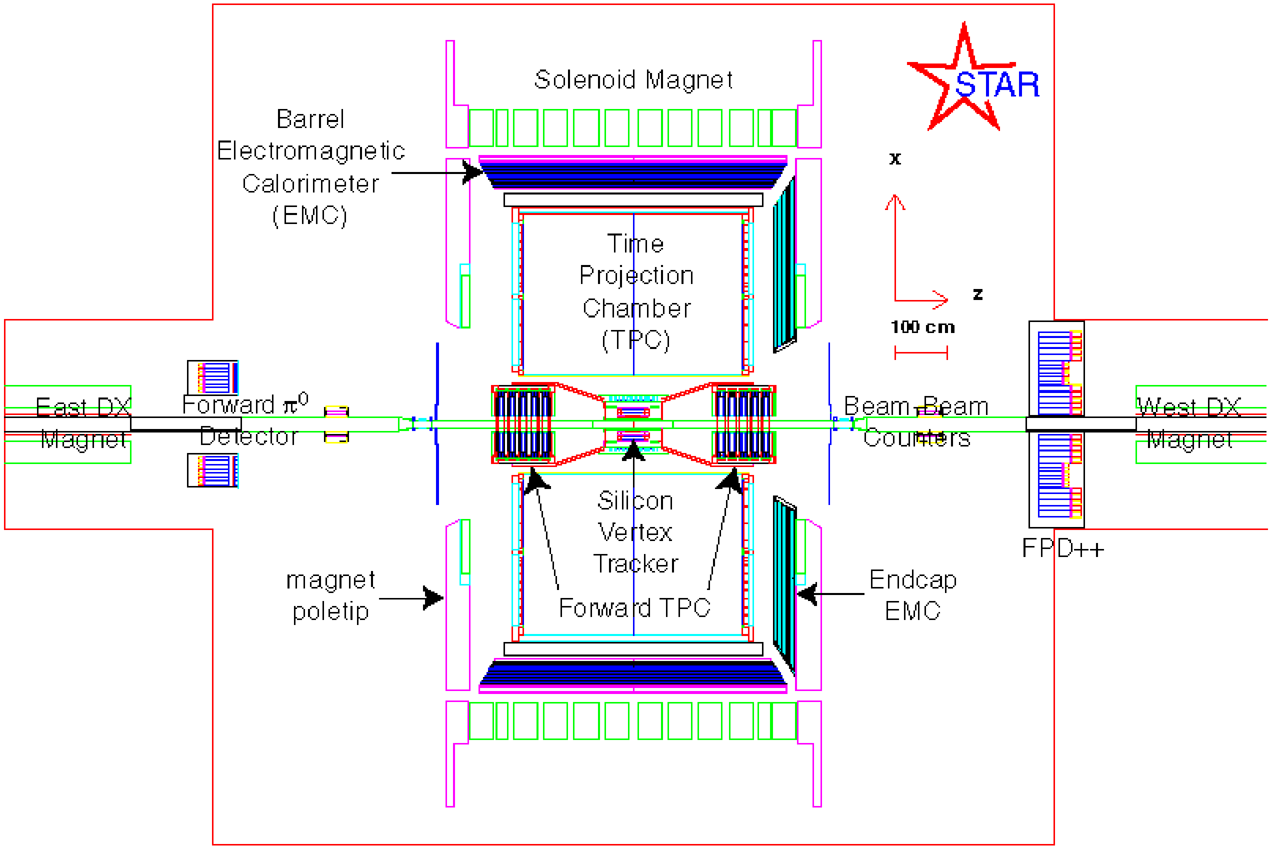
STAR Forward Meson Spectrometer (FMS)

- STAR Forward Meson Spectrometer (FMS) planned for installation by RHIC run 7
- STAR Forward Pion Detector upgrade (FPD++) underway as an engineering test of the FMS during RHIC run 6

⇒ Disentangle the dynamical origins to transverse SSA in p+p collisions via measurements of A_N for

- ➢ jet-like events
- ➢ direct photon production

STAR Configuration for Run 6

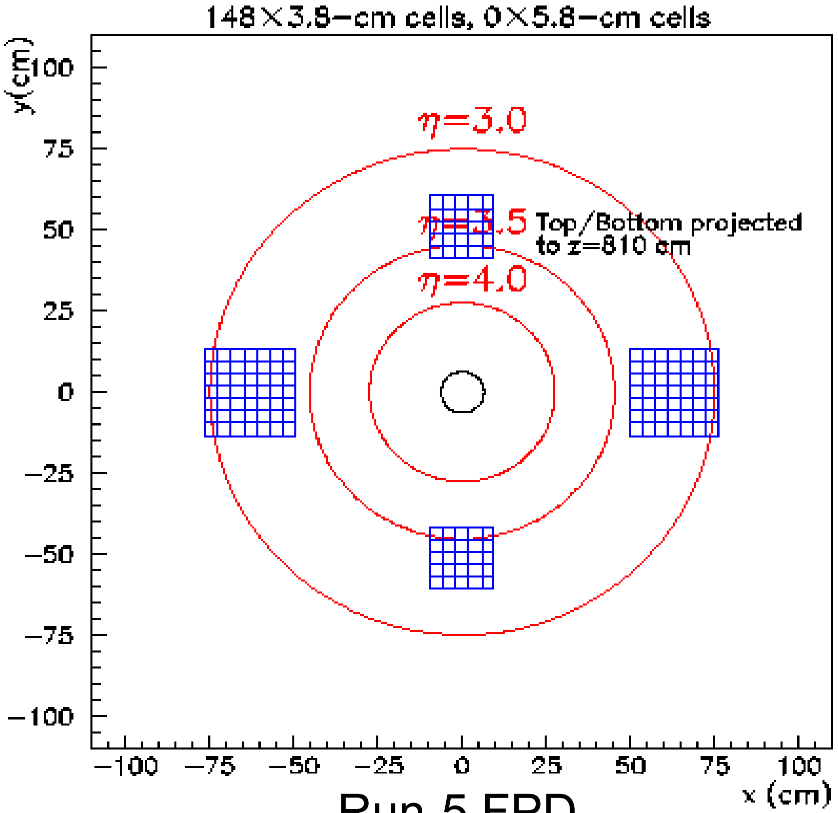


- TPC: $-1.0 < \eta < 1.0$
- FTPC: $2.8 < |\eta| < 3.8$
- BBC : $2.2 < |\eta| < 5.0$
- EEMC: $1 < \eta < 2$
- BEMC: $-1 < \eta < 1$
- FPD: $|\eta| \sim 4.0$ & ~ 3.7

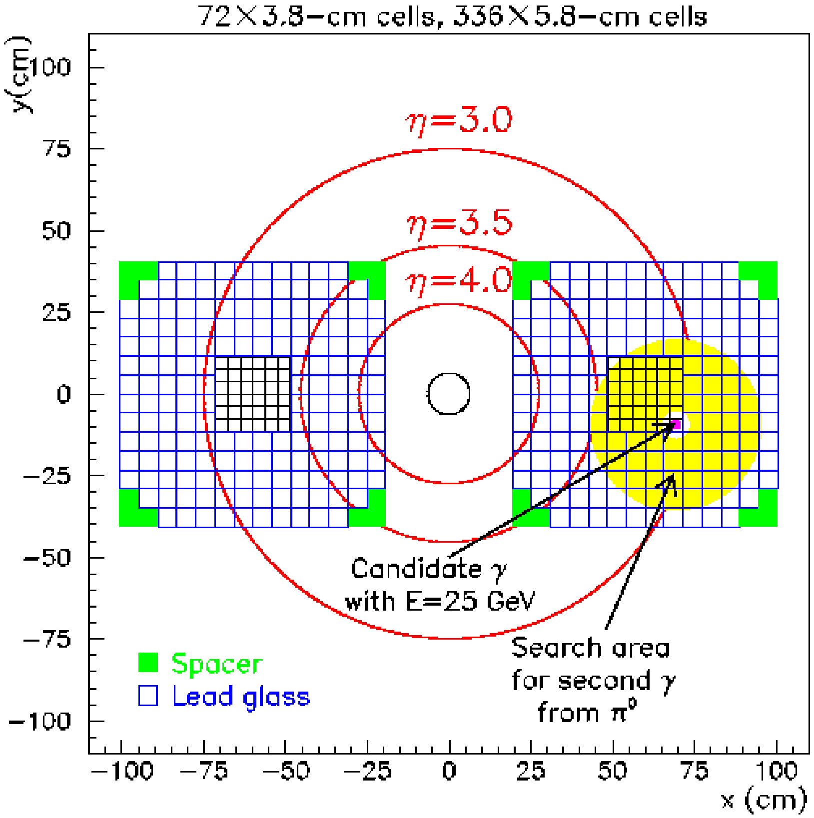
STAR characterized by azimuthally complete acceptance over broad range of pseudorapidity.

FPD++ Physics for Run6

We have staged a large version of the FPD to prove our ability to detect jet-like events, direct photons, etc. with the STAR FMS



Run-5 FPD



The center annulus of the run-6 FPD++ is similar to arrays used to measure forward π^0 SSA. The FPD++ annulus is surrounded by additional calorimetry to increase the acceptance for jet-like events and direct γ events.

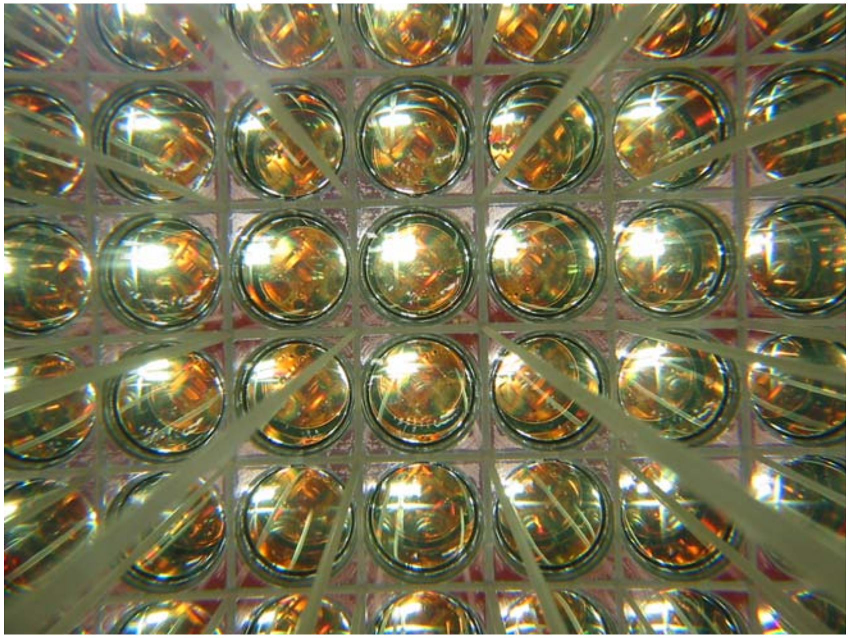
New FMS Calorimeter
Lead Glass From FNAL E831

804 cells of 5.8cm×5.8cm×60cm

Schott F2 lead glass

Loaded On a Rental Truck for Trip To BNL

Students prepare cells at test Lab at BNL



Individual lead glass detectors are prepared and tested prior to installation in the calorimeter. In total, 13 students have been involved to date in this work since May, 2005.

Student Participation

Stony Brook University Undergraduate Research and Creative Activity (URECA)

STONY BROOK
STATE UNIVERSITY OF NEW YORK

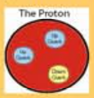
A High-Energy Detector for Spin Physics at RHIC

Jonathan Langdon, Christopher Miller, Nicholas Zachariou
Brookhaven National Laboratory
Leslie Bland

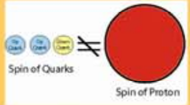
BROOKHAVEN
NATIONAL LABORATORY

Theory-

The proton is a not a elementary particle because it's composed of three quarks.



The proton also has an intrinsic property called spin with a value of 1/2h. One would think the sum of the spins from the three component quarks would equal the net spin of the proton, BUT past experiments disprove this asseration.

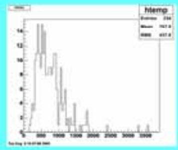


Therefore, a new detector at the STAR experiment, containing hundreds of individual lead glass cells, will investigate the origins of the proton's spin more extensively.
Our task consists of refurbishing and testing these lead glass cells for the detector.

Testing-

Inside a single lead glass detector →

Particle enters → Particle Compton scatters off lead atoms and produces light → Light is Recorded at Phototube



The first picture shows the phototube optics inside the lead glass. This observation makes sure that the lead glass was not damaged from radiation, and it determines whether the connection between the phototube and the glass is good (air bubbles in the connection might change our results)

A number of tests of the phototube properties, including gain, IV curves, and frequency dependence (The two plots are shown above). All these tests determine the optimum way to stack the detector, while discarding all the bad cells.

Refurbishing-

Step 1:

In the cleaning stage, a thorough shinning of the lead glass surface is done using alcohol.

→

Step 2:

During wrapping, the detector is neatly wrapped with Mylar Foil. This increase the reflection coefficient of the glass

→

Step 3:

The end of the lead glass is tapped over like a Christmas present. This finishes the wrapping stage.

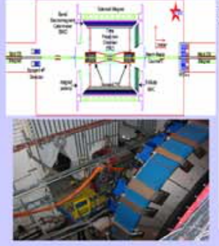
→

Step 4:

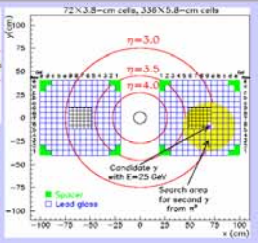
Measurements of the lead glass are recorded. This includes the thickness of the cell in several different positions

Detector-

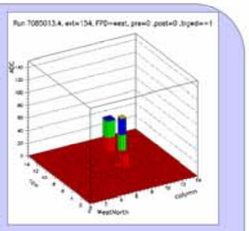
This is the test detector for the future 1500 cell calorimeter. As you can see, each of the lead glass detectors are compactly stacked.



This is where the detector is located in the STAR experiment. A beam of particles collide in the center, which produces a whole bunch of particles for the detector to observe.



When a pion (an elementary particle) enters the middle sections, the whole detector "opens up" (triggers, taking only useful data) and an energy measurement is made.

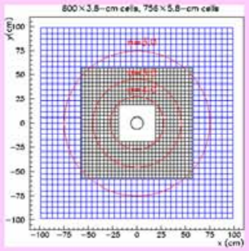


This is a 3D graph of a single measurement made from the detector. Each of these pillars represent the energy in a single lead glass cell. The spin measurement is made when this energy distribution is analyzed.

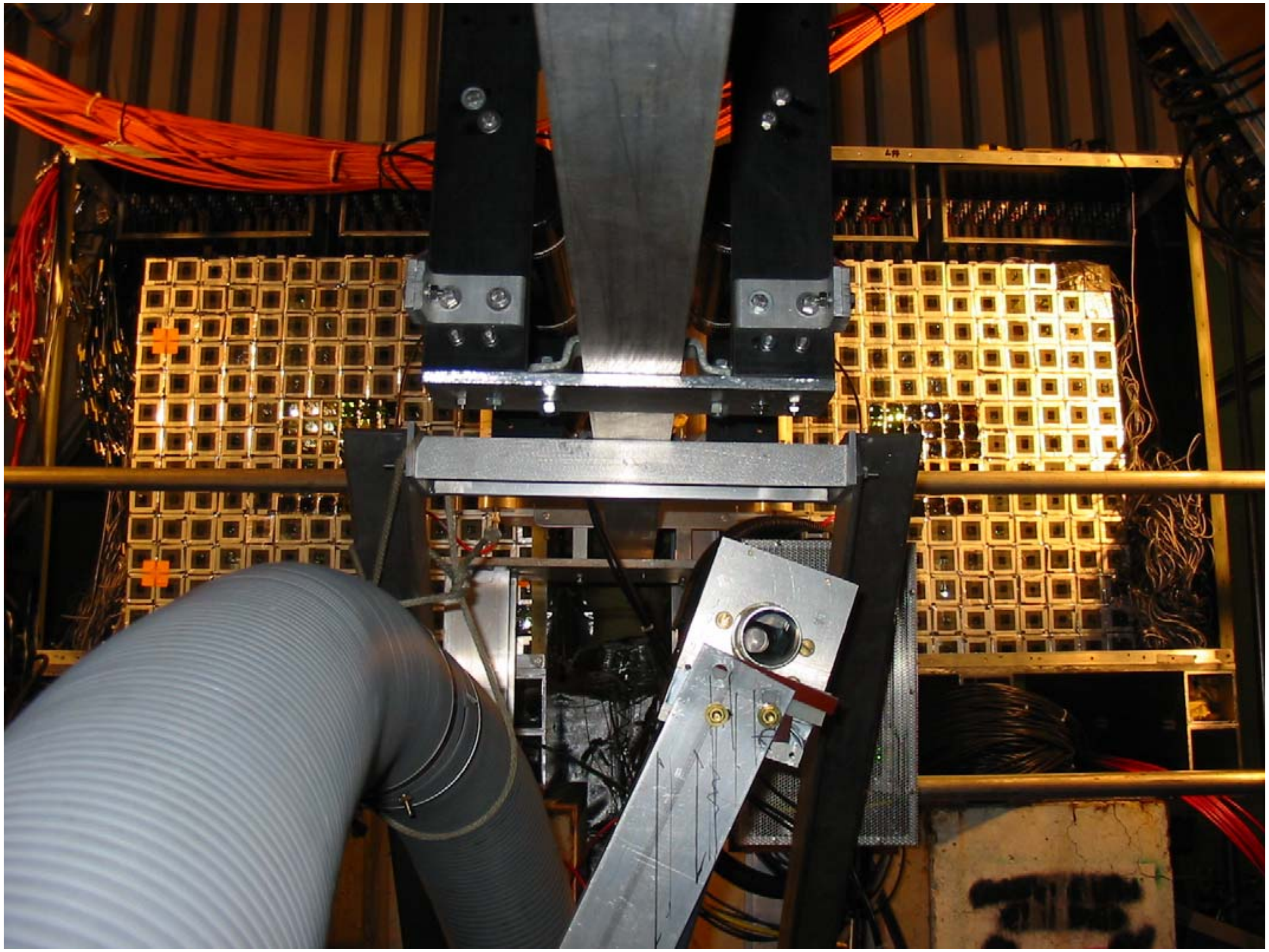
Goals-

We will prepare and test more cells for the future "1500 hundred cell calorimeter", which will provide a bigger area for the spin measurement (The picture is located to the right).

In the end, this calorimeter will allow us to further understand the spin properties of the proton.



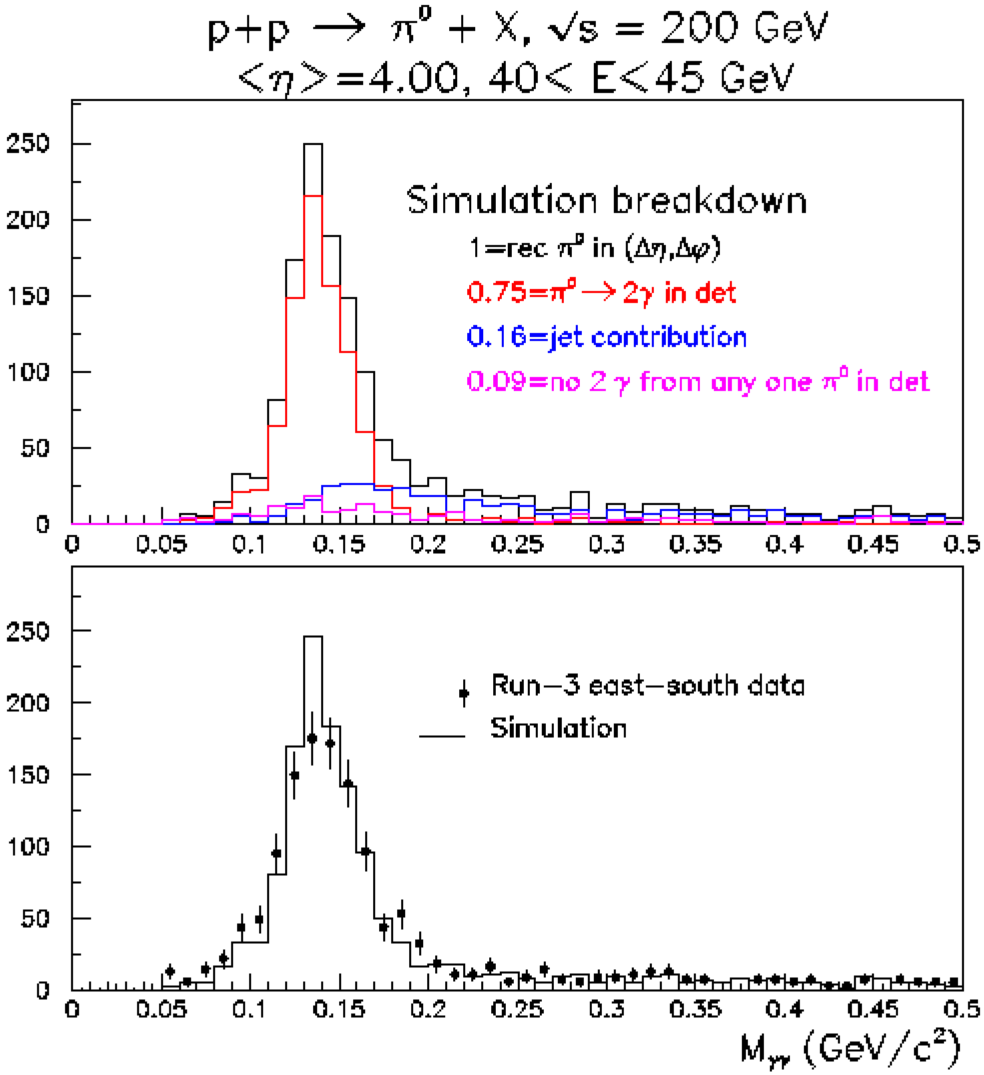
Completed FPD++



Provides left/right symmetric calorimeters for detection of jet-like events

Jet-Like Events

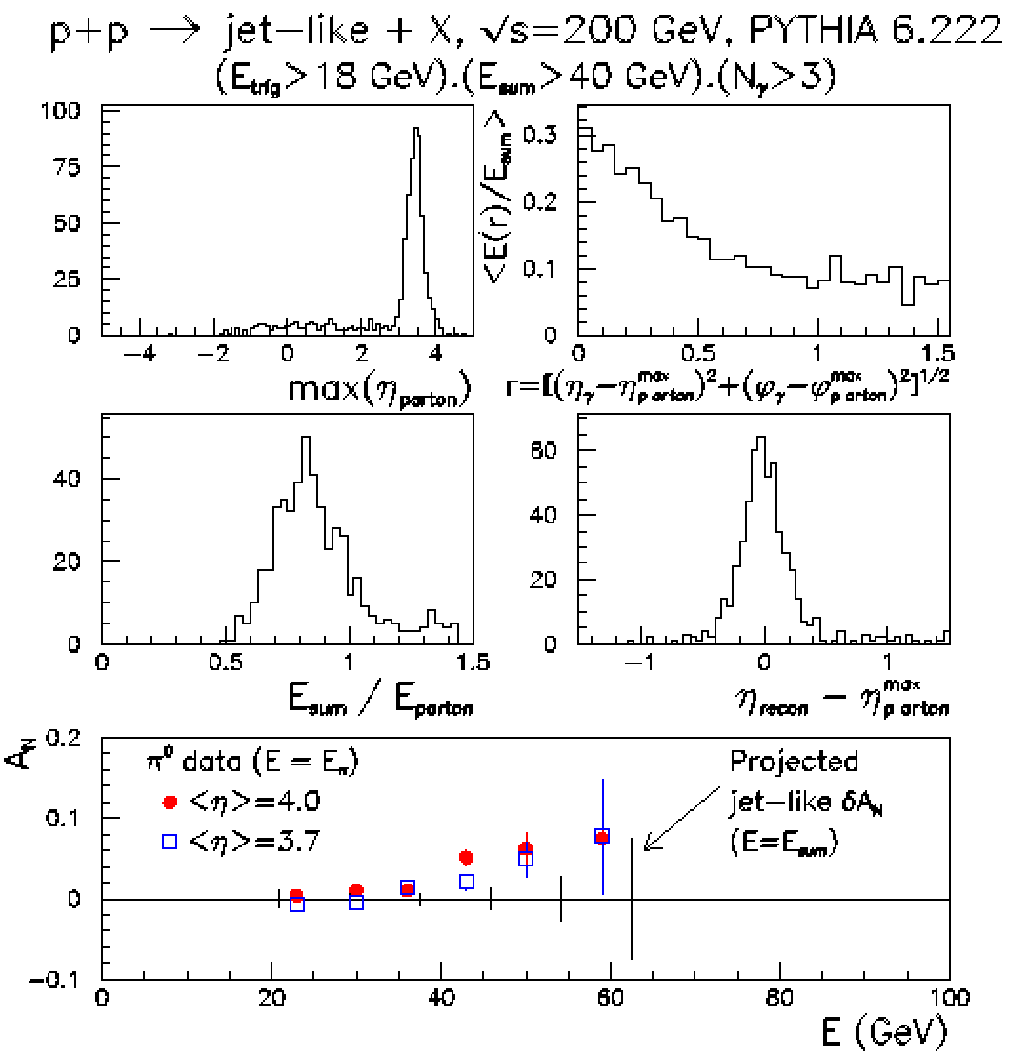
- Is the single spin asymmetry observed for π^0 also present for the jet the π^0 comes from?
- Answer discriminates between Sivers and Collins contributions
- Trigger on energy in small cells, reconstruct π^0 and measure the energy in the entire FPD++
- Average over the Collins angle and define a new x_F for the event, then measure analyzing power versus x_F



Expect that jet-like events are ~15% of π^0 events

Jet spin asymmetry

L.C. Bland [hep-ex/0602012]



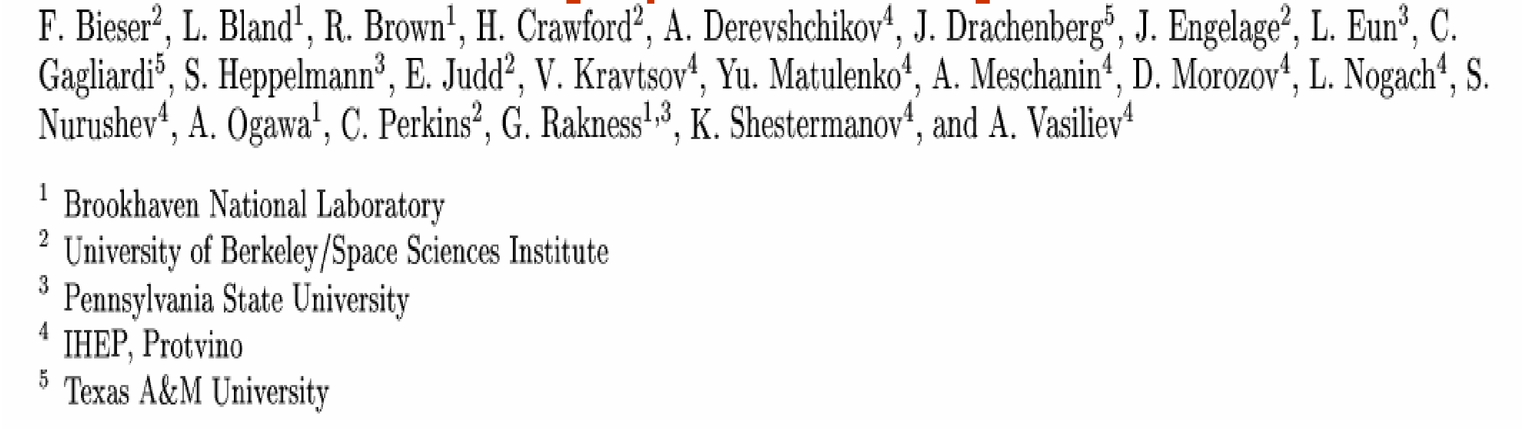
- N_γ>3 requirement should allow π^0–π^0 analysis
- (upper left) for each event, examine PYTHIA record for final-state hard scattered partons ⇒ event selection chooses jet-like events.
- (upper right) event-averaged correlation between photon energy and distance in η,ϕ space from thrust axis ⇒ events are expected to exhibit similar jet characteristics as found at $\eta\approx0$
- (middle) multi-photon final states enable reconstruction of parent parton kinematics via momentum sum of observed photons.
- (bottom) projected statistical accuracy for data sample having 5 pb^{-1} and 50% beam polarization.

Azimuthal symmetry of FPD++ around thrust axis, selected by E_{trig} condition, enables

- integration over the Collins angle ⇒ isolating the Sivers effect, or
- dependence on the Collins angle ⇒ isolating the Collins/Heppelmann effect

Three Highlighted Objectives In STAR Forward Meson Spectrometer Proposal

[hep-ex/0502040]



F. Bieser[2], L. Bland[1], R. Brown[1], H. Crawford[2], A. Derevshchikov[4], J. Drachenberg[5], J. Engelage[2], L. Eun[3], C. Gagliardi[5], S. Heppelmann[3], E. Judd[2], V. Kravtsov[4], Yu. Matulenko[4], A. Meschanin[4], D. Morozov[4], L. Nogach[4], S. Nurushev[4], A. Ogawa[1], C. Perkins[2], G. Rakness[1,3], K. Shestermanov[4], and A. Vasiliev[4]

[1] Brookhaven National Laboratory
[2] University of Berkeley/Space Sciences Institute
[3] Pennsylvania State University
[4] IHEP, Protvino
[5] Texas A&M University

1. A **$d(p)+Au\rightarrow\pi^0\pi^0+X$** measurement of the **parton model gluon density distributions $xg(x)$** in **gold nuclei** for **$0.001< x <0.1$**. For $0.01<x<0.1$, this measurement tests the universality of the gluon distribution.

   DOE milestone

2. Characterization of correlated pion cross sections as a function of Q^2 ($p_T{}^2$) to search for the onset of **gluon saturation effects** associated with **macroscopic gluon fields. (again d-Au)**
3. Measurements with **transversely polarized protons** that are expected to **resolve the origin of the large transverse spin asymmetries** in reactions for **forward π^0 production. (polarized pp)**

New Physics at high gluon density

1. **Shadowing**. Gluons hiding behind other gluons. Modification of g(x) in nuclei. Modified distributions needed by codes that hope to calculate energy density after heavy ion collision.

2. **Saturation Physics**. New phenomena associated with large gluon density.
   - Coherent gluon contributions.
   - Macroscopic gluon fields.
   - Higher twist effects.
   - “Color Glass Condensate”

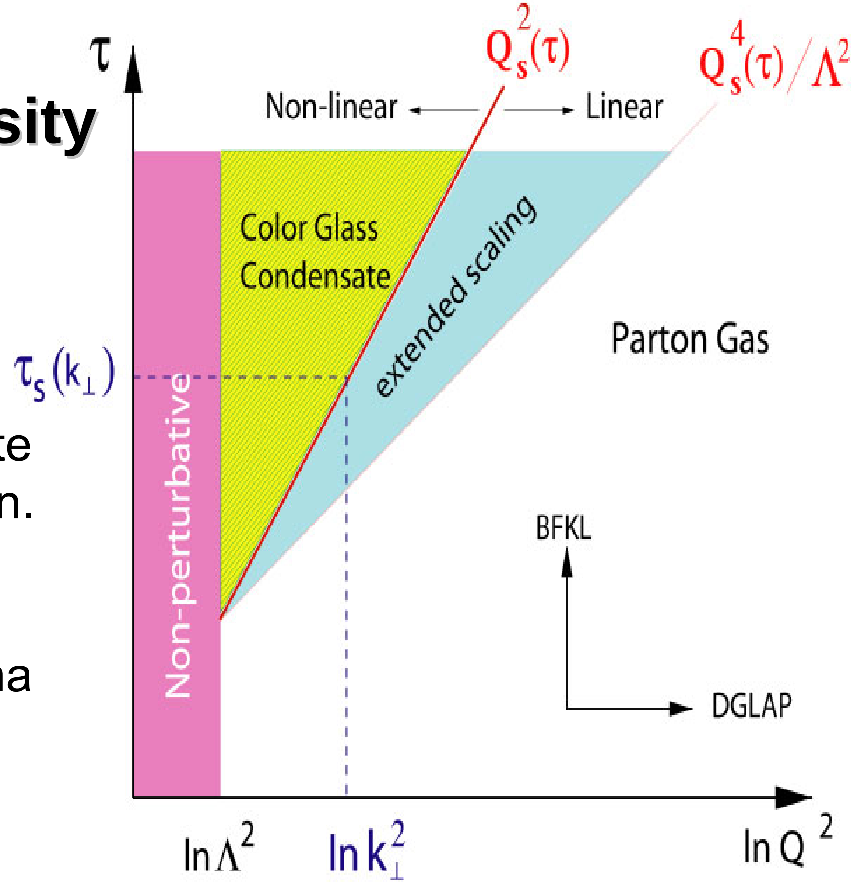
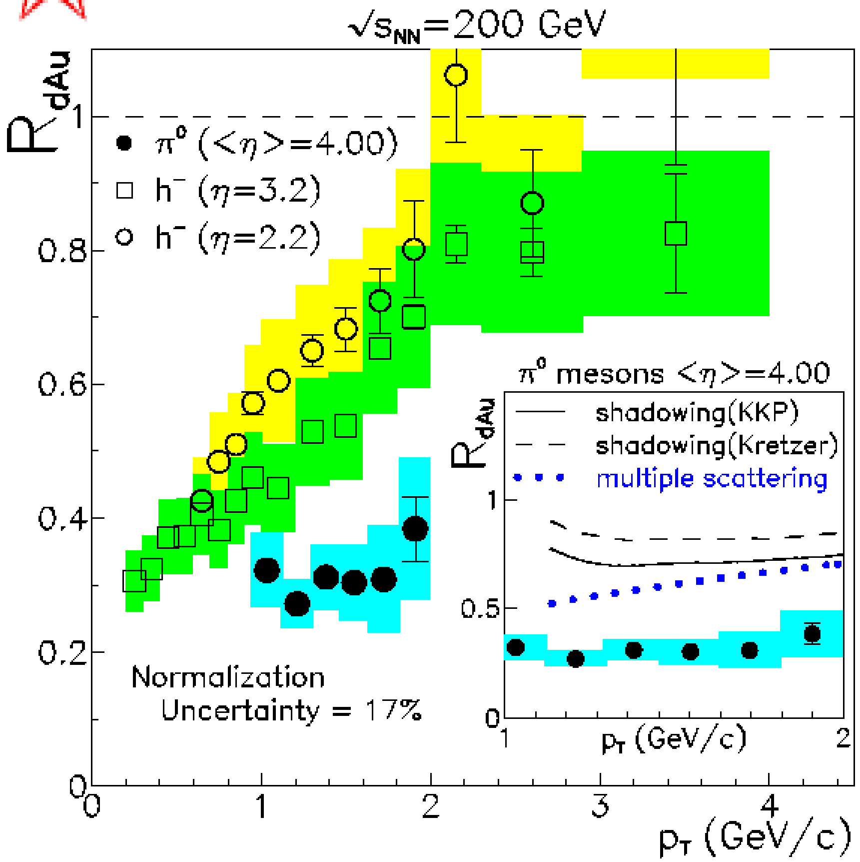


Figure 3 Diagram showing the boundary between possible “phase” regions in the τ=ln(1/x) vs ln Q^2 plane

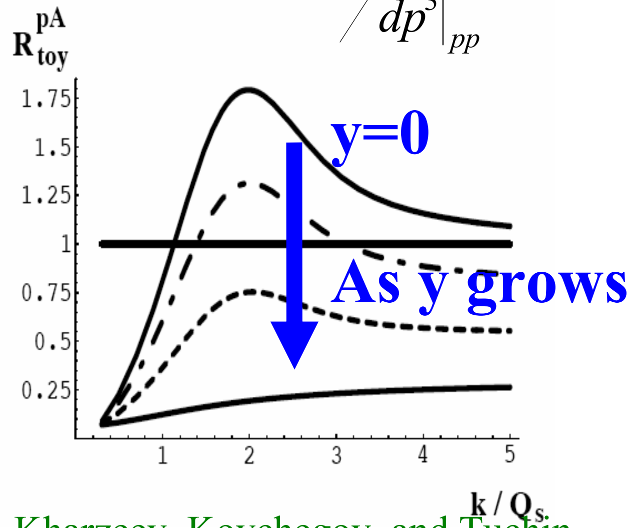
Edmond Iancu and Raju Venugopalan, review for Quark Gluon Plasma 3, R.C. Hwa and X.-N. Wang (eds.), World Scientific, 2003 [hep-ph/0303204].

η Dependence of R_{dAu}



STAR collaboration, submitted to PRL [nucl-ex/0602011]

$$R_{dAu} = \frac{\sigma_{pp}^{inelastic}}{\langle N_{binary}\rangle \sigma_{dAu}^{inelastic}} \frac{\left. Ed^3\sigma \middle/ dp^3 \right|_{dAu}}{\left. Ed^3\sigma \middle/ dp^3 \right|_{pp}} \approx \frac{1}{2\times 197}\frac{\sigma_{dAu}}{\sigma_{pp}}$$



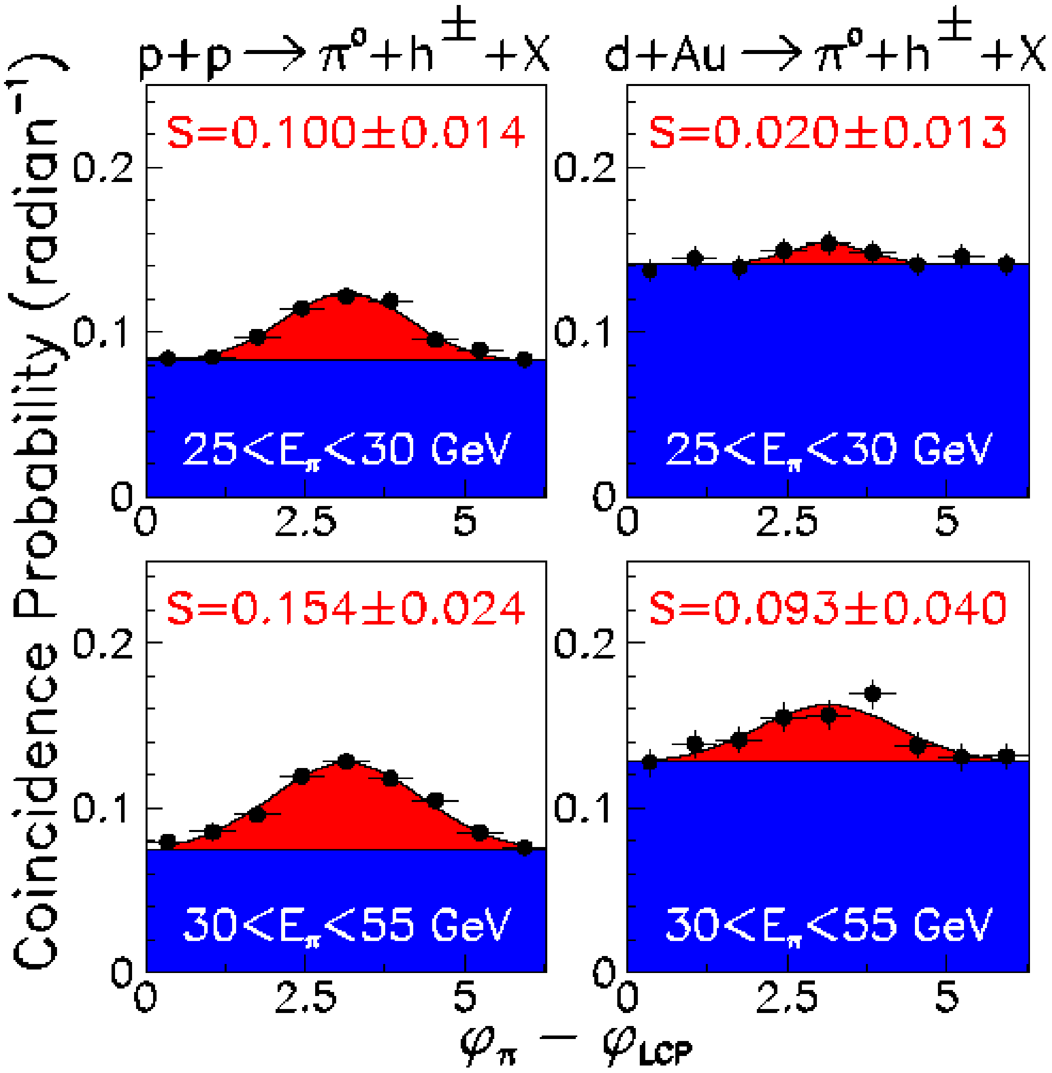
Kharzeev, Kovchegov, and Tuchin, Phys. Rev. D **68** , 094013 (2003)

See also J. Jalilian-Marian, Nucl. Phys. **A739**, 319 (2004)

- From **isospin** considerations, p + p → h⁻ is expected to be suppressed relative to d + nucleon → h⁻ at large η [Guzey, Strikman and Vogelsang, Phys. Lett. B **603**, 173 (2004)]
- Observe **significant rapidity dependence** similar to expectations from a “toy model” of R_{pA} within the Color Glass Condensate framework.

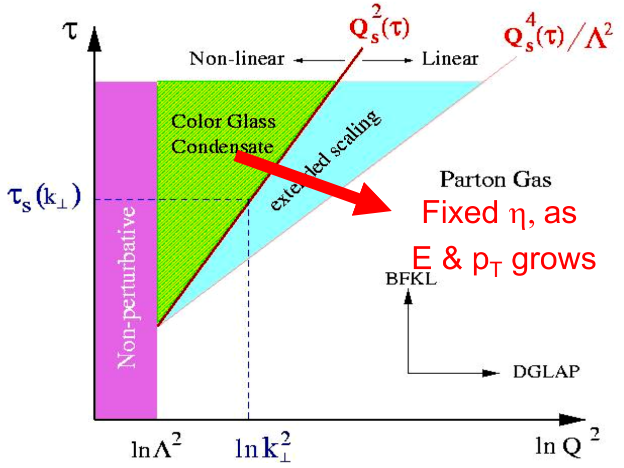
Forward + mid-rapidity correlations in d+Au

nucl-ex/0602011



- are suppressed at small $<x_F>$ and $<p_{T,\pi}>$

consistent with CGC picture



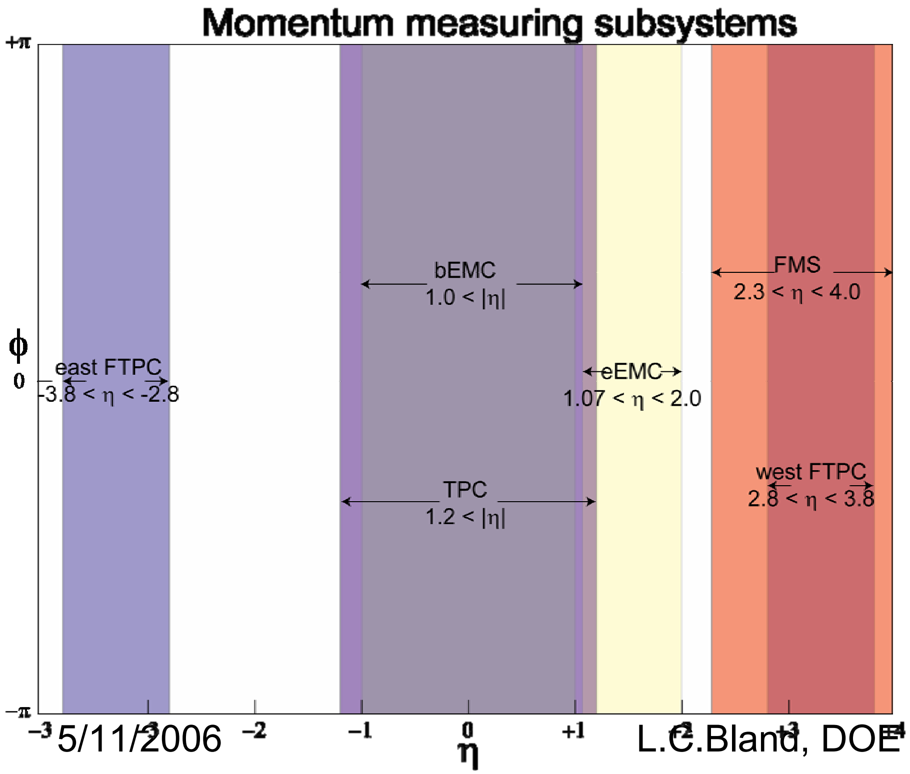
Fixed η, as E & p_T grows

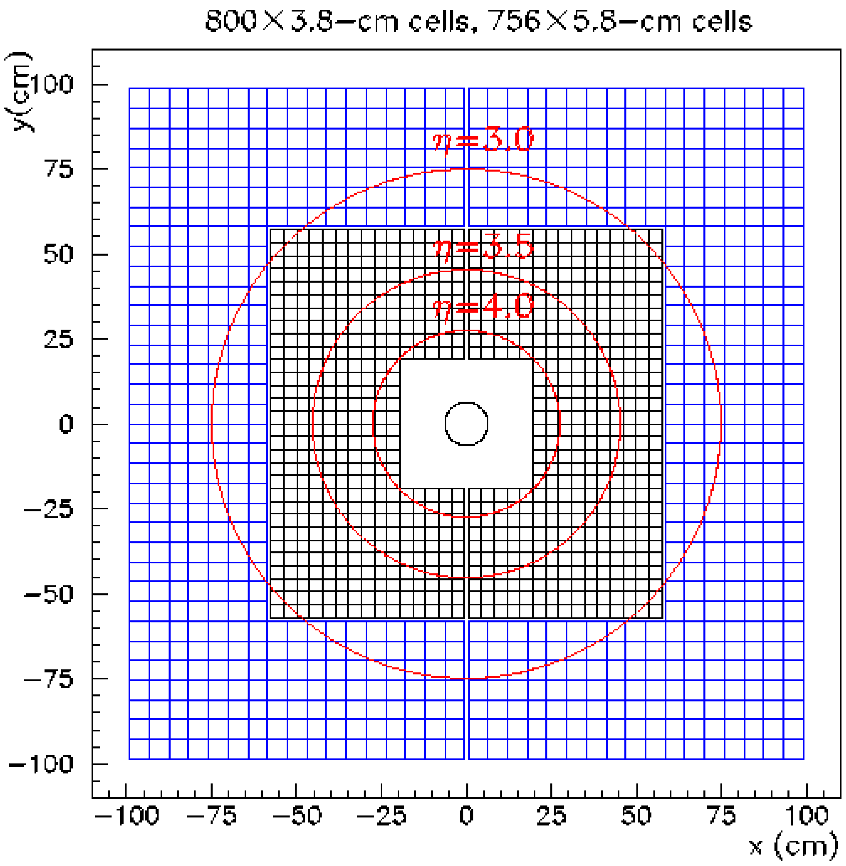
- are similar in d+Au and p+p at larger $<x_F>$ and $<p_{T,\pi}>$

as expected by HIJING

Forward Meson Spectrometer for Run 7

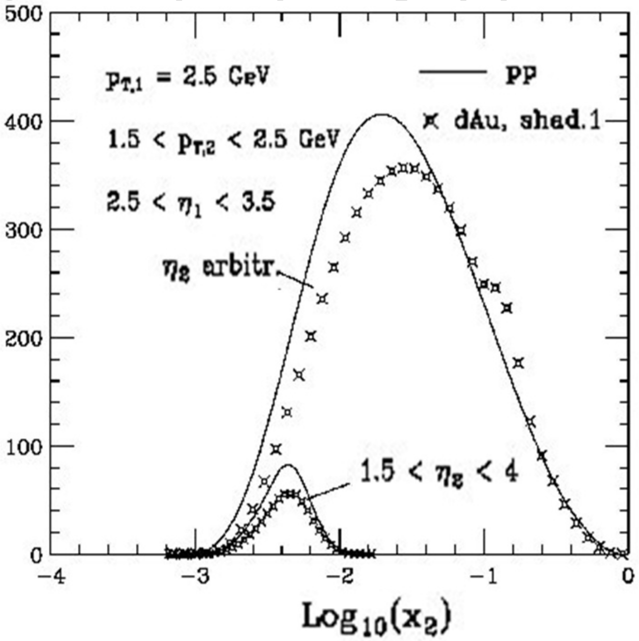
- FMS will provide full azimuthal coverage for range $2.5 \le \eta \le 4.0$
- broad acceptance in x_F-p_T plane for inclusive $\gamma,\pi^0,\omega,K^0,\ldots$ production in p+p and d(p)+Au
- broad acceptance for $\gamma-\pi^0$ and $\pi^0-\pi^0$ from forward jet pairs to probe low-x gluon density in p+p and d(p)+Au collisions



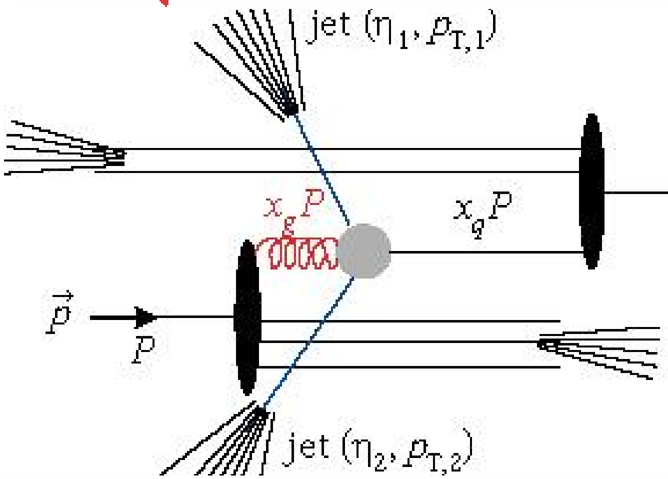


Run-7 FMS as seen from STAR interaction point

Frankfurt, Guzey and Strikman,
J. Phys. G27 (2001) R23 [hep-ph/0010248].

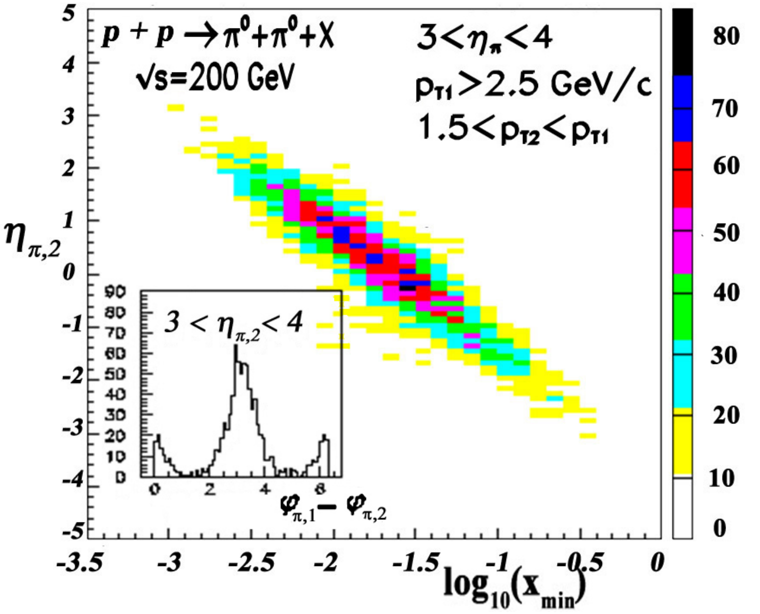


$$x_+ \approx \frac{p_T}{\sqrt{s}}\left(e^{+\eta_1}+e^{+\eta_2}\right)\xrightarrow[\eta_1>>\eta_2]{} x_F$$



$$x_- \approx \frac{p_T}{\sqrt{s}}\left(e^{-\eta_1}+e^{-\eta_2}\right)\xrightarrow[\eta_1>>\eta_2]{} x_F e^{-(\eta_1+\eta_2)}$$

- constrain x value of gluon probed by high-x quark by *detection of second hadron* serving as jet surrogate
- span broad pseudorapidity range (-1<η<+4) for second hadron ⇒ span broad range of x_{gluon}
- provide sensitivity to higher p_T for forward π^0 ⇒ reduce 2→3 (inelastic) parton process contributions thereby reducing uncorrelated background in Δϕ correlation.



Pythia Simulation

BNL STAR Spin Group

Staff: L. Bland, A. Ogawa, 1 additional staff (2006/7);
2 additional post docs (2006/7; 2007/8)

Four-year plan (2007-2010)

2007 – complete FMS; measure gluon density in gold nucleus via d+Au collisions.

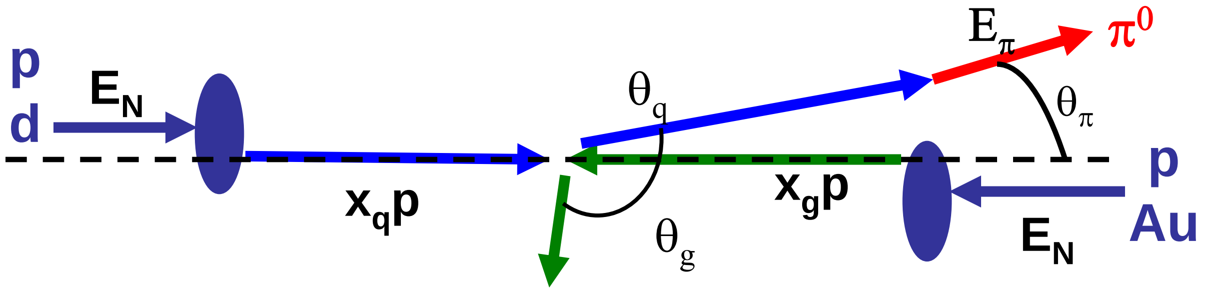
2008 – measure transverse spin asymmetries for π^0–π^0 correlations.

2009 – complete A_{LL} measurements for prompt photon production, γ-jet and γ-hadron correlations at $\sqrt{s}$ = 200 GeV to probe $\Delta g(x)$; transverse spin asymmetries for inclusive production at $\sqrt{s}$ = 500 GeV.

2010 – A_{LL} measurements for prompt photon production at $\sqrt{s}$ = 500 GeV.

Backups

Forward π^0 production in hadron collider



$$Q^2 \sim p_T^2 \qquad x_F \approx \frac{2E_\pi}{\sqrt{s}}$$

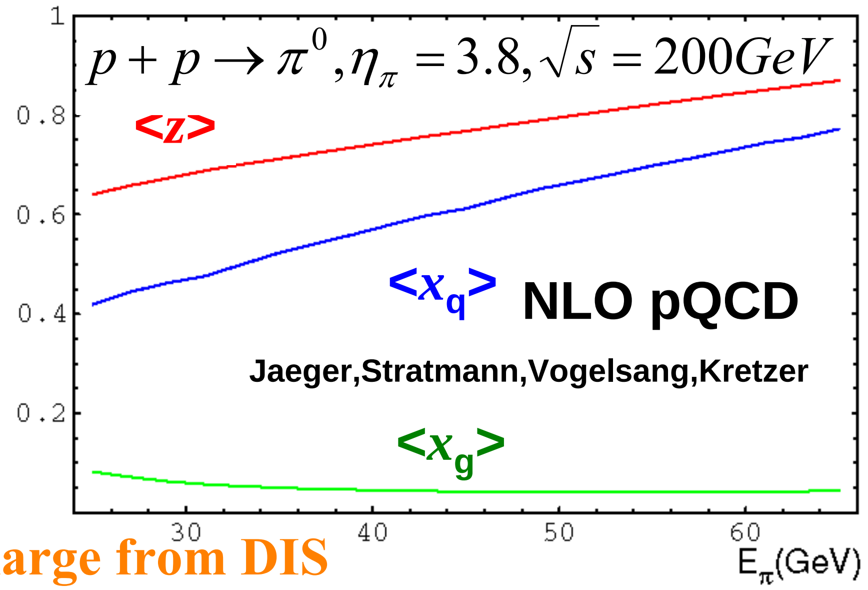
$$\sqrt{s} = 2E_N \qquad z = \frac{E_\pi}{E_q}$$

$$\eta = -\ln(\tan(\frac{\theta}{2}))$$

$$x_q \approx x_F / \langle z \rangle \qquad x_g \approx \frac{p_T}{\sqrt{s}} e^{-\eta_g}$$

(collinear approx.)

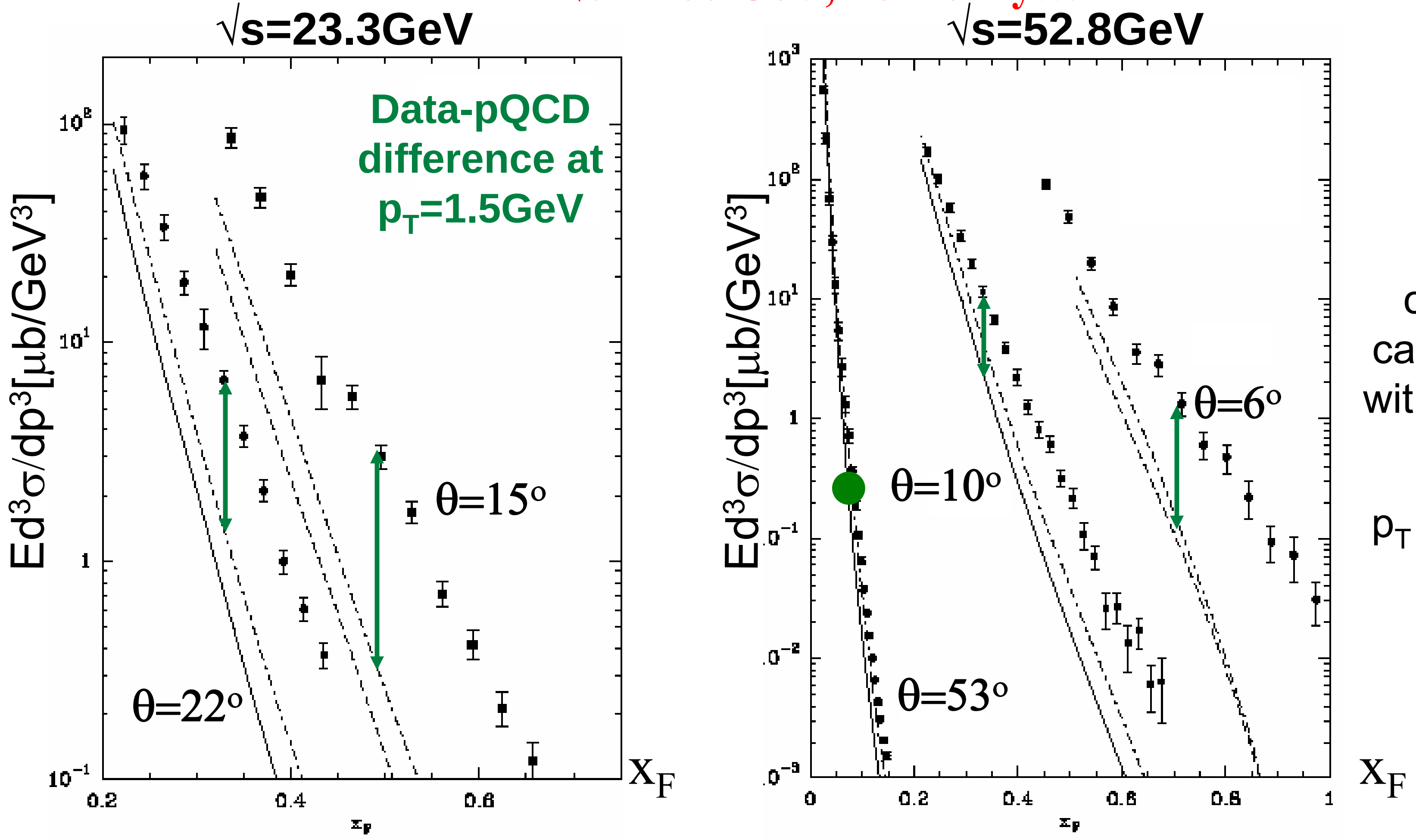
- **Large rapidity π production (η_π~4) probes asymmetric partonic collisions**



- Mostly **high-*x* valence quark** + **low-*x* gluon**
  - **$0.3 < x_q < 0.7$**
  - **$0.001 < x_g < 0.1$**
- <*z*> nearly constant and high 0.7 ~ 0.8
- **Large-*x* quark polarization is known to be large from DIS**
- **Directly couple to gluons ⇒ probe of low *x* gluons**

But, do we understand forward π^0 production in p + p?

At $\sqrt{s} < 200$ GeV, not really…



Data-pQCD difference at p_T=1.5GeV

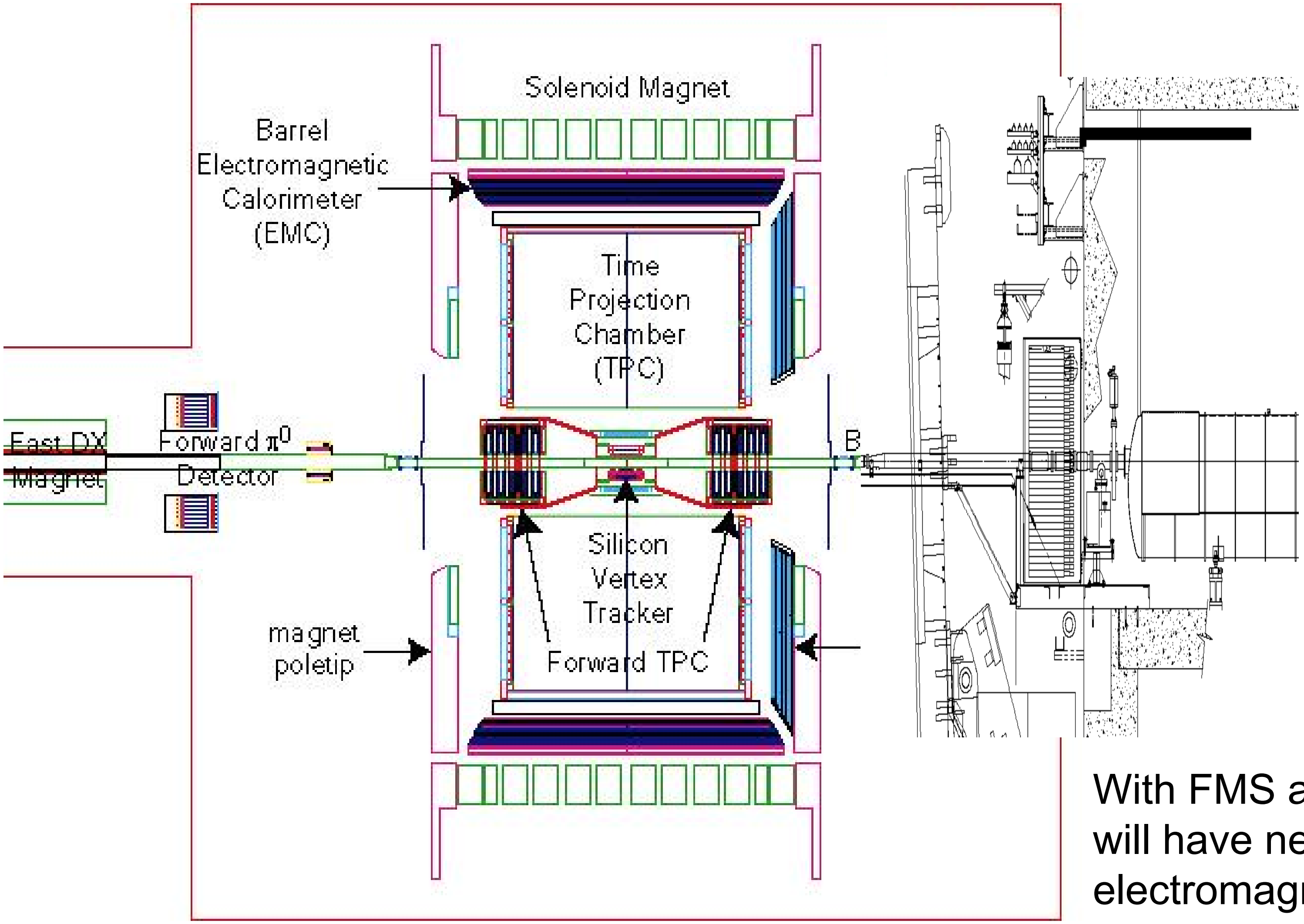
2 NLO collinear calculations with different scale:

p_T and $p_T/2$

Bourrely and Soffer (hep-ph/0311110, Data references therein): NLO pQCD calculations underpredict the data at $\sqrt{s} < 200$ GeV (ISR and fixed target)

$\sigma_{data}/\sigma_{pQCD}$ appears to be function of θ, $\sqrt{s}$ in addition to p_T

STAR detector layout with FMS



TPC: $-1.0 < \eta < 1.0$

FTPC: $2.8 < |\eta| < 3.8$

BBC : $2.2 < |\eta| < 5.0$

EEMC:$1 < \eta < 2$

BEMC:$-1 < \eta < 1$

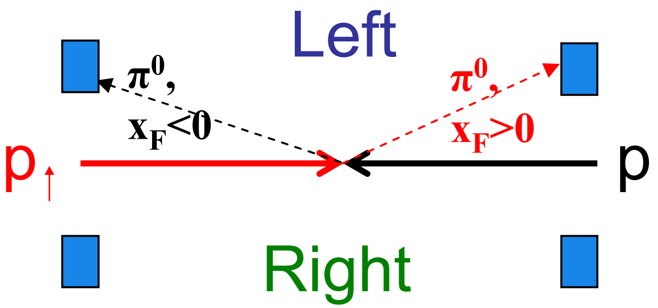
FMS: $2.5<\eta< 4.0$

With FMS addition, STAR will have nearly contiguous electromagnetic calorimetry for $-1 < \eta < 4$

Spin Effects

Definitions of Measurements

Transverse Single Spin Asymmetries



positive A_N: more π^0 going left to polarized beam

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

- $d\sigma^{\uparrow(\downarrow)}$ – differential cross section of π^0 when incoming proton has spin up(down)

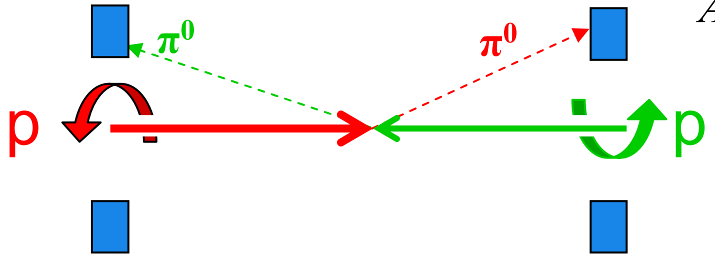
- Single-arm calorimeter:

$$A_N = \frac{1}{P_{Beam}} \cdot \left(\frac{N^\uparrow - RN^\downarrow}{N^\uparrow + RN^\downarrow} \right) \qquad R = \frac{L^\uparrow}{L^\downarrow}$$

R – relative luminosity (by BBC)

P_{beam} – beam polarization

Longitudinal Two Spin Asymmetries



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

- $d\sigma_{++(+-)}$ – differential cross section of π^0 when incoming protons have equal(opposite) helicity

- Single-arm calorimeter:

$$A_{LL} = \frac{1}{P^2_{Beam}} \cdot \left(\frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \right) \qquad R = \frac{L_{++}}{L_{+-}}$$

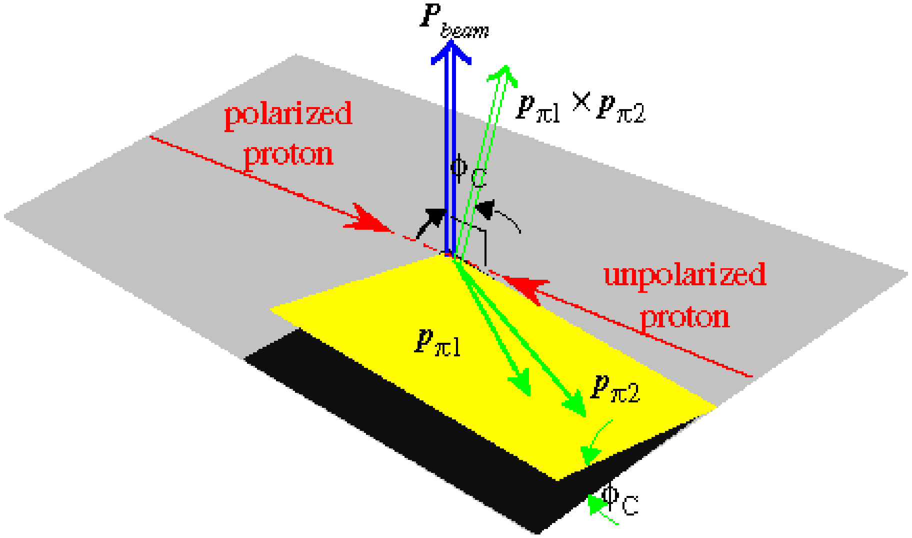
R – relative luminosity (by BBC)

P_{beam} – beam polarization

Disentangling Dynamics of Single Spin Asymmetries

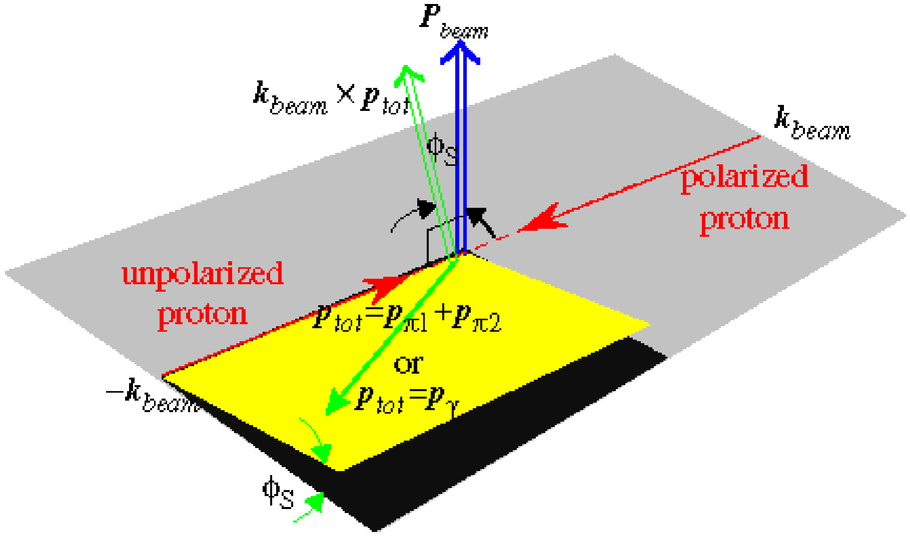
Spin-dependent particle correlations

Collins/Hepplemann mechanism requires transversity and spin-dependent fragmentation



$$D_{\pi/q}(z,\mathbf{k}_\pi^\perp,\mathbf{s}_q) = \hat{D}_{\pi/q}(z,k_\pi^\perp) + \frac{1}{2}\Delta^N D_{\pi/q}(z,k_\pi^\perp)\frac{\mathbf{s}_q\cdot(\mathbf{p}_q\times\mathbf{k}_\pi^\perp)}{\left|\mathbf{p}_q\times\mathbf{k}_\pi^\perp\right|}$$

Sivers mechanism asymmetry is present for forward jet or γ



$$f_q(x,\mathbf{k}_q^\perp,\mathbf{S}_P) = f_q(x,k_q^\perp) + \frac{1}{2}\Delta_q^N f_q(x,k_q^\perp)\frac{\mathbf{S}_P\cdot(\mathbf{P}_p\times\mathbf{k}_q^\perp)}{\left|\mathbf{S}_P\right|\left|\mathbf{P}_P\right|\left|\mathbf{k}_q^\perp\right|}$$

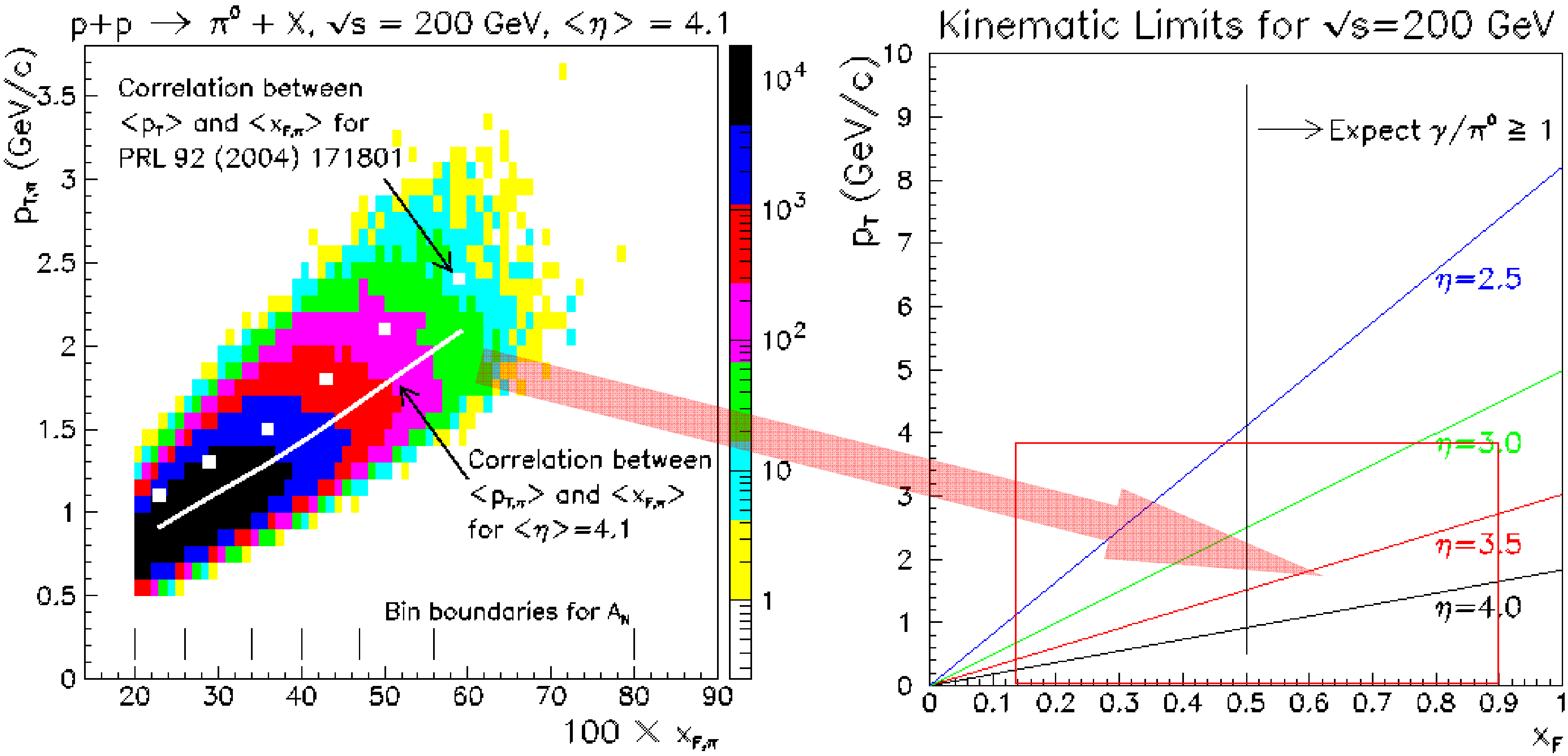
Large acceptance of FMS will enable disentangling dynamics of spin asymmetries

Basic physics Goals

Ideas to be tested using FPD++ in RHIC run 6

- Prototype for FMS (planned completion for RHIC run 7)
- Discriminate dynamical origin of the forward A_N
  - Measurement of jetlike events and A_N for those
    - Similar to FPD (left/right symmetric) but with larger active area
    - Measure shape of forward jet
  - Measure direct photons cross section, possibly A_N, requiring separation of π^0 and direct gamma
- Continue the study of π^0 asymmetry in pp
- other

x_F and p_T range of FPD data



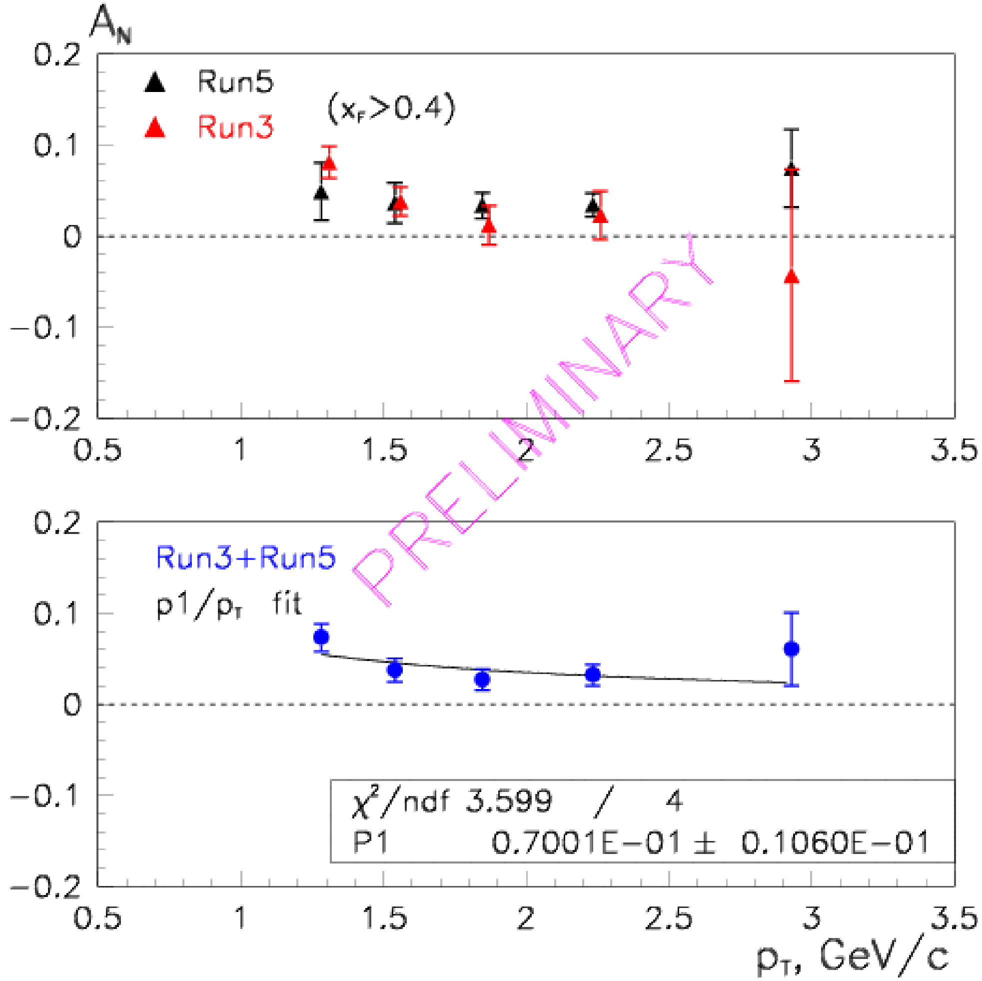
$A_N(p_T)$ from run3+run5 at √s=200 GeV

- Combined statistics from run3 and run5 with $x_F>0.4$

- There is evidence that analyzing power at $x_F>0.4$ decreases with increasing p_T

- To do: systematics study

Uses online beam polarization values



Time/luminosity dependent

d calibration

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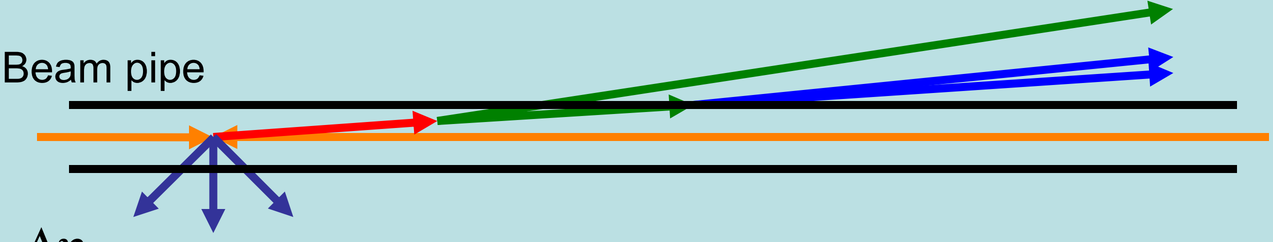
on

V

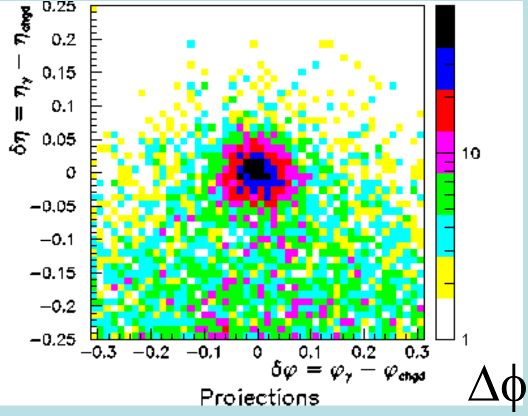
FTPC-FPD matching

Photon conversion in beam pipe

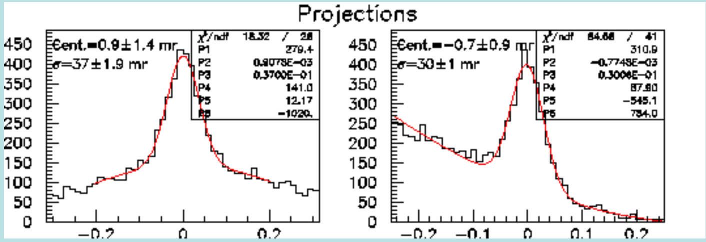
$p + p \rightarrow \pi^0\ (+ X) \rightarrow \gamma\ (+ \gamma) \rightarrow e^+ e^-$



Δη

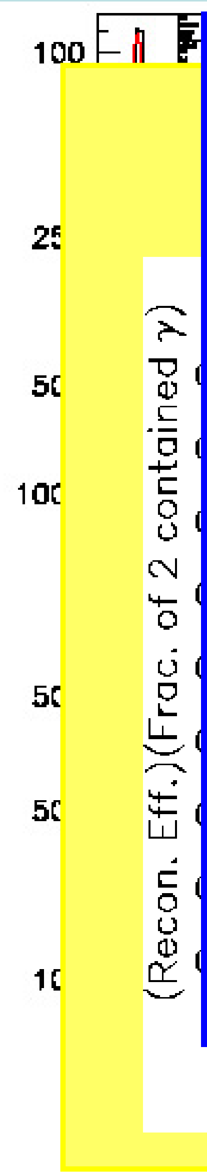


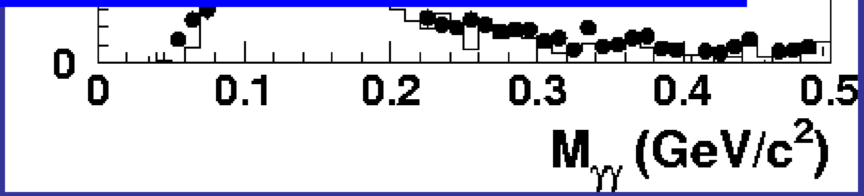
Δϕ



Δϕ Δη

⇒ FPD position known relative to STAR





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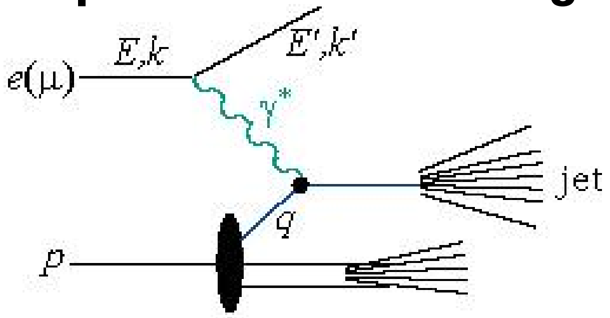
2nd mom

Why Consider Forward Physics at a Collider?

Kinematics

Deep inelastic scattering

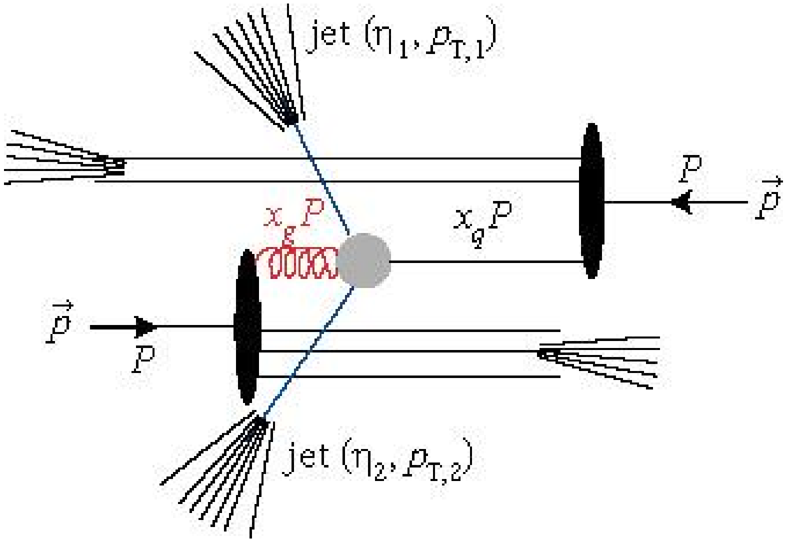


$$Q^2 = 2(EE' - \vec{k}\cdot\vec{k}')$$

$$\nu = E - E'$$

$$x = Q^2/2M\nu$$

Hard scattering hadroproduction



Can Bjorken x values be selected in hard scattering?

Assume:

1. Initial partons are collinear
2. Partonic interaction is elastic

$\Rightarrow p_{T,1} \approx p_{T,2}$

$$\Rightarrow \quad x_q \approx p_T/\sqrt{s}\,(\,e^{+\eta_1} + e^{+\eta_2}\,)$$

$$x_g \approx p_T/\sqrt{s}\,(\,e^{-\eta_1} + e^{-\eta_2}\,)$$

Studying pseudorapidity, η=-ln(tanθ/2), dependence of particle production probes parton distributions at different Bjorken x values and involves different admixtures of gg, qg and qq' subprocesses.

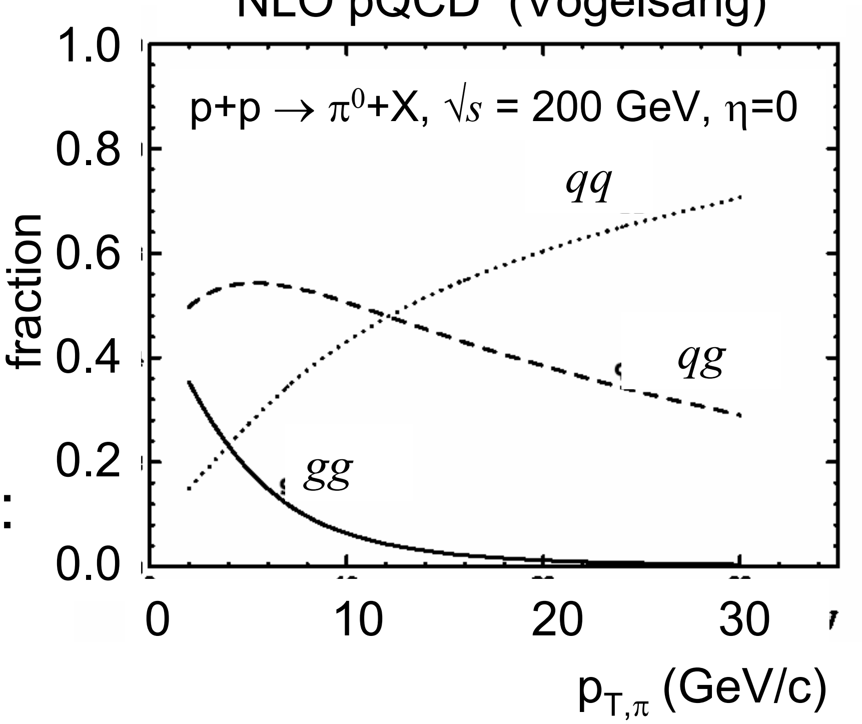
Simple Kinematic Limits

Mid-rapidity particle detection:

$\eta_1 \approx 0$ and $\langle \eta_2 \rangle \approx 0$

$$\Rightarrow x_q \approx x_g \approx x_T = 2\, p_T / \sqrt{s}$$

NLO pQCD (Vogelsang)



Large-rapidity particle detection:

$\eta_1 >> \eta_2$

$$\Rightarrow x_q \approx x_T\, e^{\eta_1} \approx x_F \text{ (Feynman } x\text{), and}$$

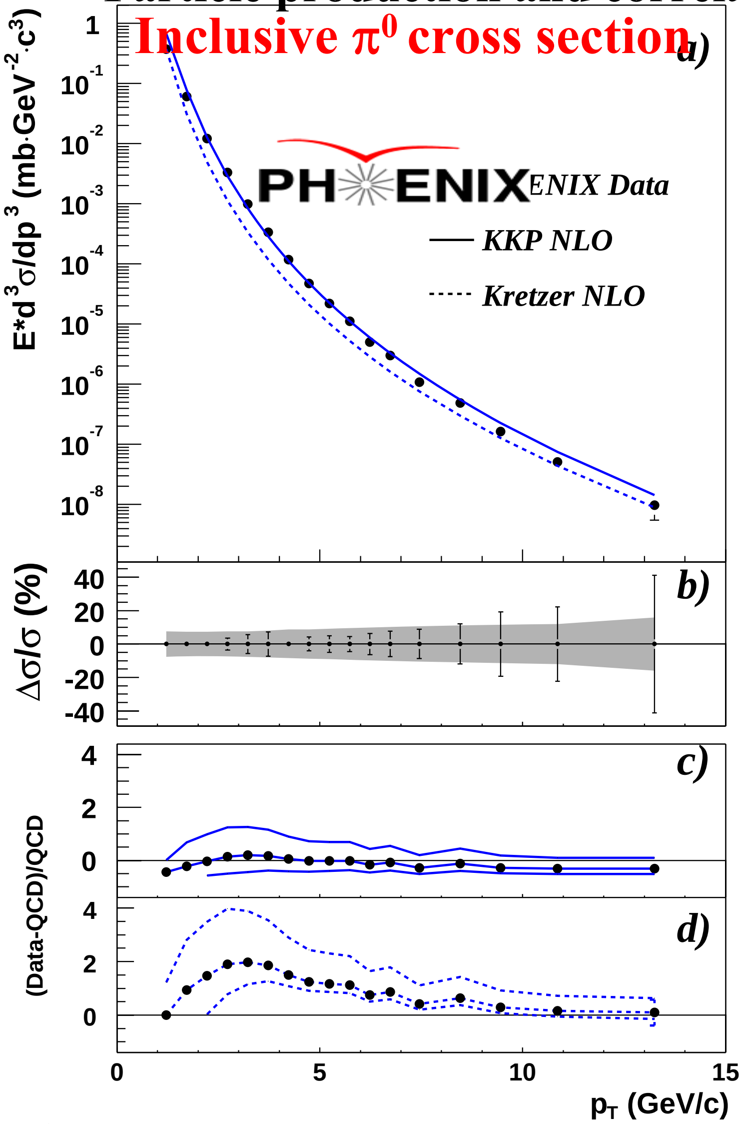
$$x_g \approx x_F\, e^{-(\eta_1 + \eta_2)}$$

⇒ Large rapidity particle production and correlations involving large rapidity particle probes low-x parton distributions using valence quarks

How can one infer the dynamics of particle production?

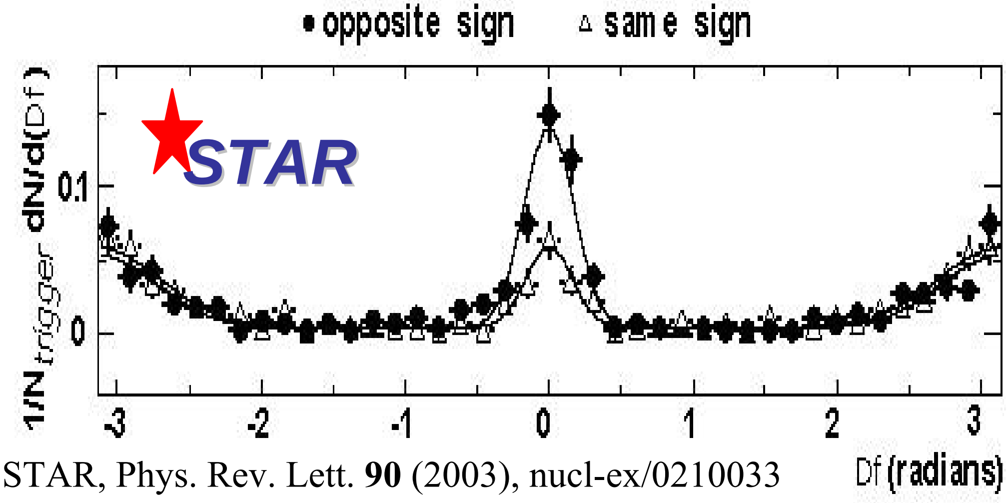
Particle production and correlations near $\eta \approx 0$ in p+p collisions at $\sqrt{s}$ = 200 GeV

Inclusive π^0 cross section



Phys. Rev. Lett. 91, 241803 (2003)
hep-ex/0304038

Two particle correlations ($h^{\pm}$)

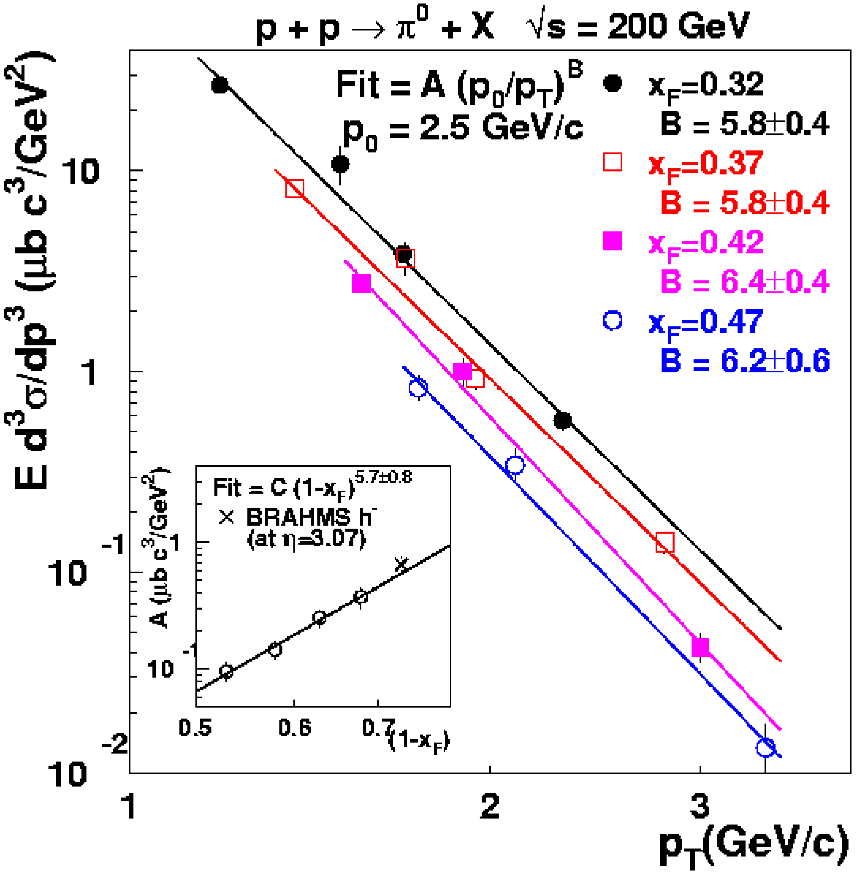


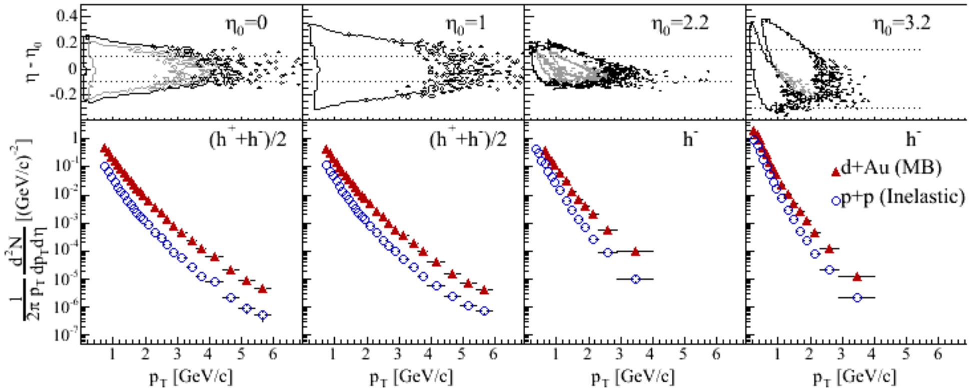
STAR, Phys. Rev. Lett. **90** (2003), nucl-ex/0210033

At $\sqrt{s}$ = 200GeV and **mid-rapidity**, both **NLO pQCD** and **PYTHIA** explains p+p data well, down to p_T~1GeV/c, consistent with partonic origin

Do they work for forward rapidity?

Towards establishing consistency between FPD (π^0)/BRAHMS(h^-)



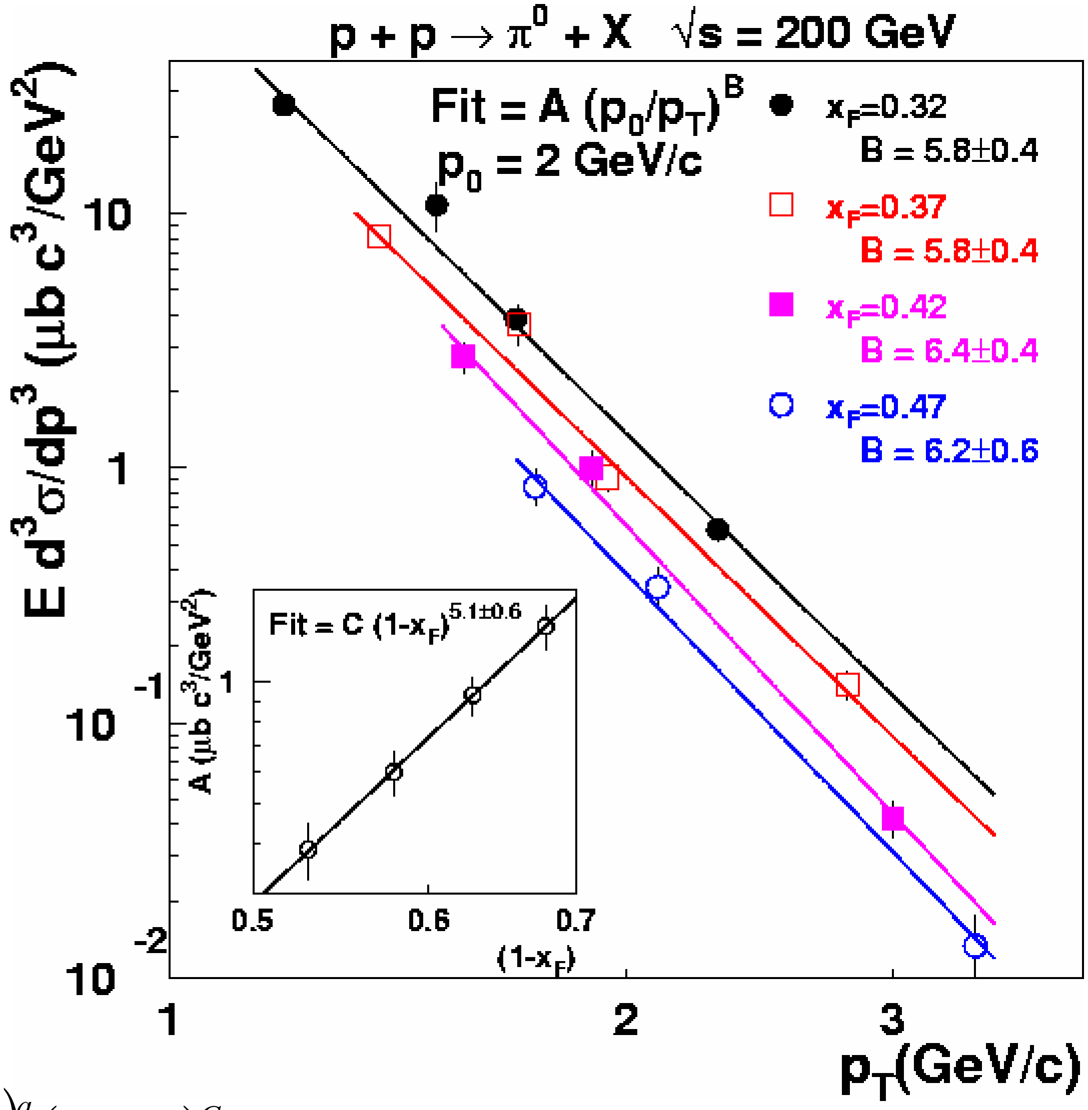


Extrapolate x_F dependence at p_T=2.5 GeV/c to compare with BRAHMS h^- data. Issues to consider:

- $\langle\eta\rangle$ of BRAHMS data for $2.3<p_T<2.9$ GeV/c bin. From Fig. 1 of PRL 94 (2005) 032301 take $\langle\eta\rangle$=3.07 ⇒ $\langle x_F\rangle$=0.27
- π^-/h^- ratio?

Results appear consistent but have insufficient accuracy to establish p+p→π^-/π^0 isospin effects

STAR-FPD
Cross Sections



Similar to ISR analysis
J. Singh, et al Nucl. Phys.
B140 (1978) 189.

$$E\frac{d^3\sigma}{dp^3} \propto (1-x_F)^C\, p_T^{\ -B}$$
$$C \approx 5$$
$$B \approx 6$$

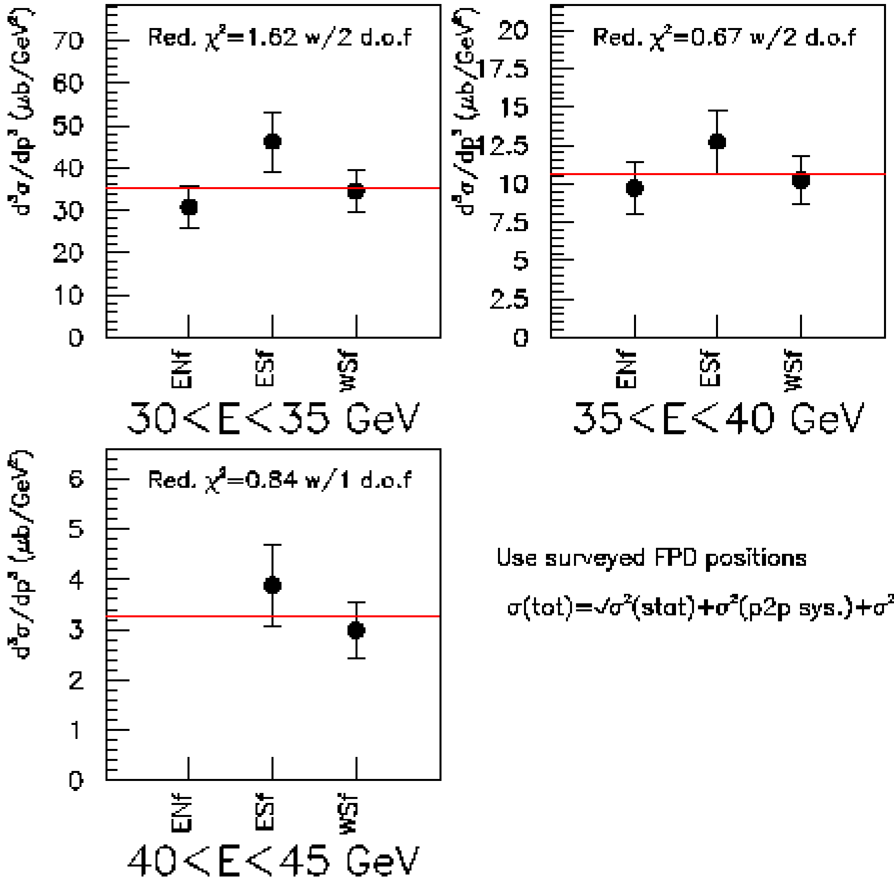
Expect QCD scaling of form:

$$E\frac{d^3\sigma}{dp^3} \propto x_T^{-a}(1-x_F)^C\, p_T^{-n} = \left(\sqrt{s}/2\right)^a (1-x_F)^C\, p_T^{-n-a} \Rightarrow B = n+a$$

$\Rightarrow$ Require $\sqrt{s}$ dependence to disentangle p_T and x_T dependence

Systematics

Exclude all points with < 100 counts



Use surveyed FPD positions

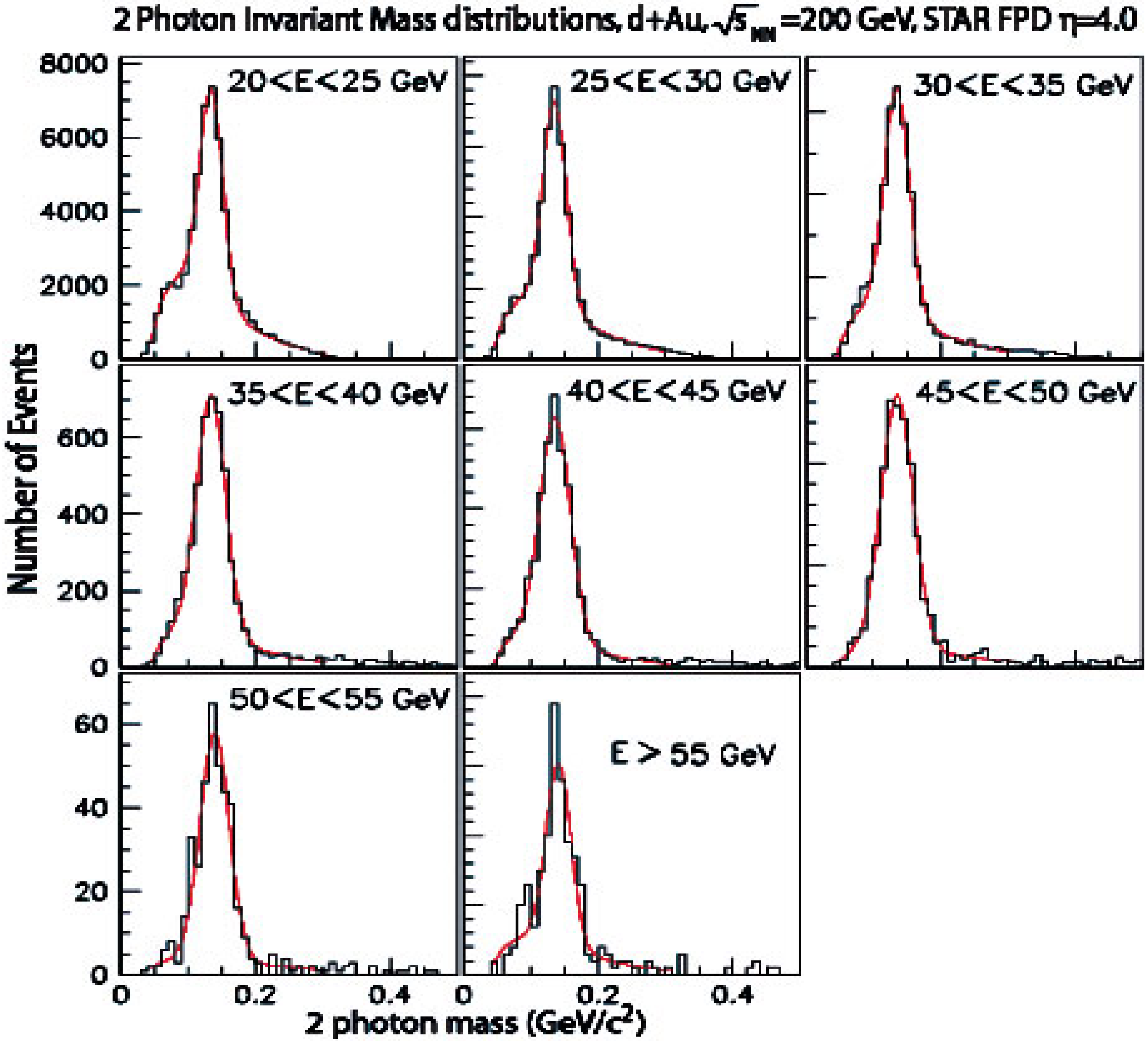
$\sigma(\text{tot})=\sqrt{\sigma^2(\text{stat})+\sigma^2(\text{p2p sys.})+\sigma^2(\Delta\eta)}$

Measurements utilizing independent calorimeters consistent within uncertainties

Systematics:

- Normalization uncertainty = 16%:
  - position uncertainty (dominant)
- Energy dependent uncertainty = 13% - 27%:
  - energy calibration to 1% (dominant)
  - background/bin migration correction
  - kinematical constraints

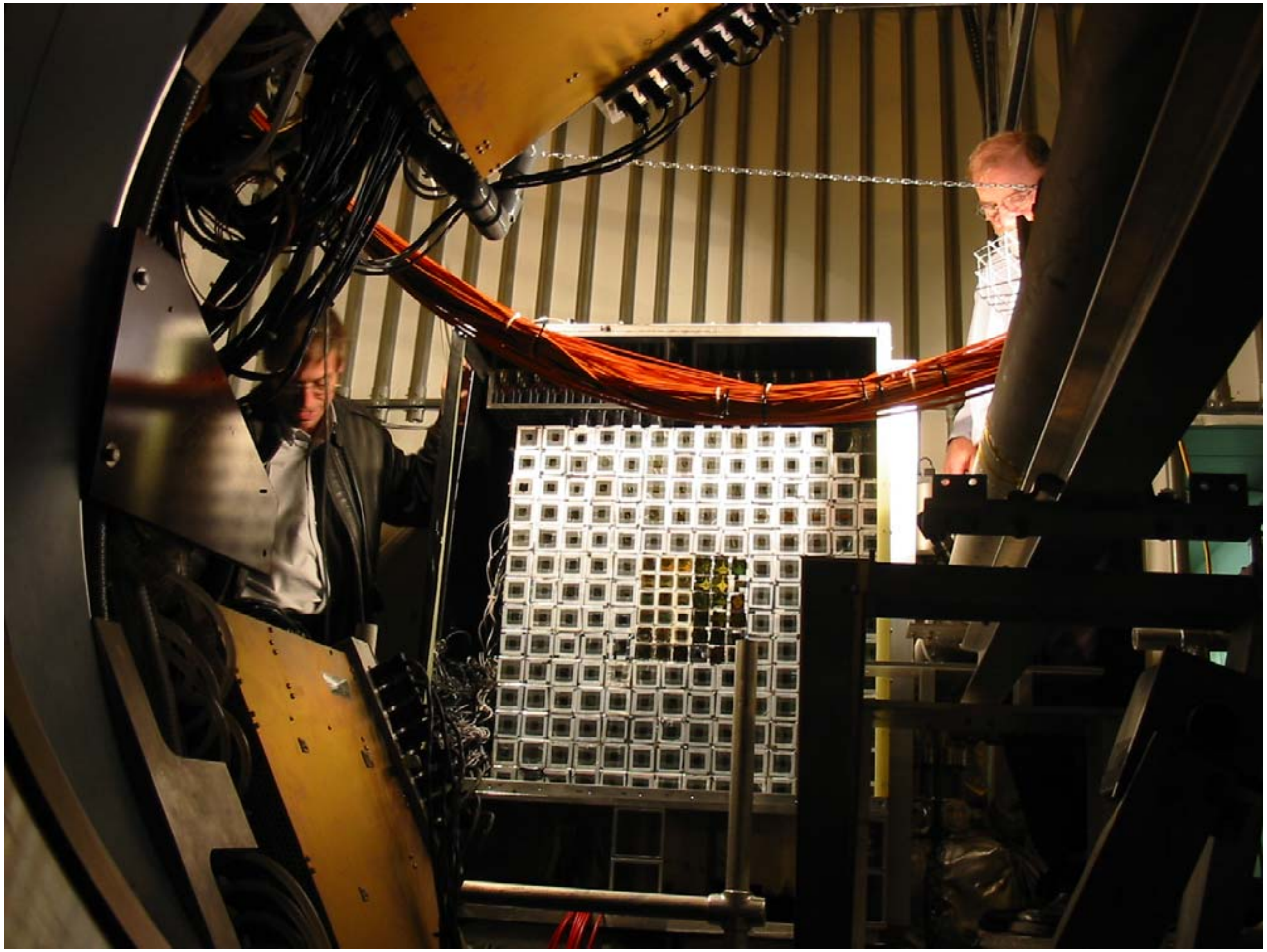
FPD Detector and π^o reconstruction



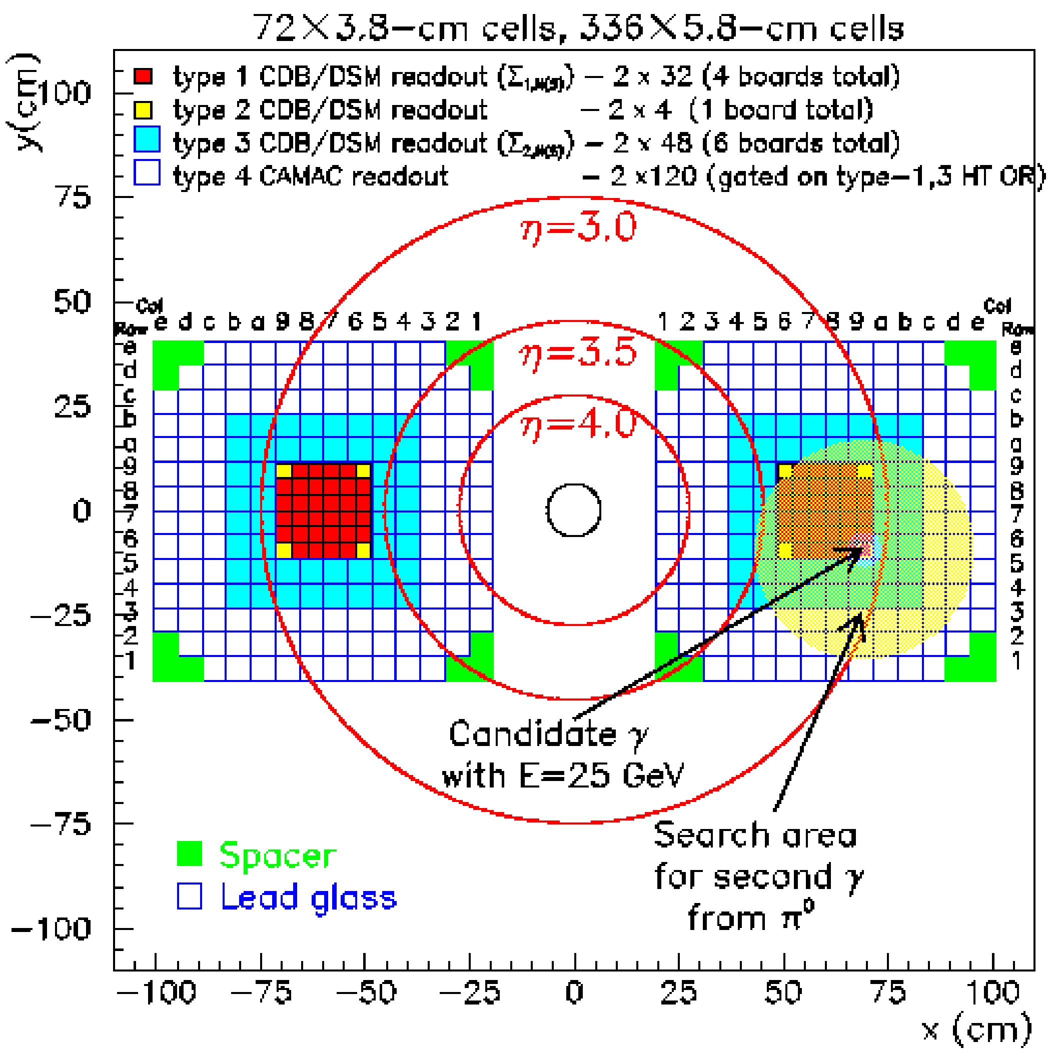
- robust di-photon reconstructions with FPD in d+Au collisions on deuteron beam side.
- average number of photons reconstructed increases by 0.5 compared to p+p data.

Status report

- Calorimeter cells for free thanks to FNAL / U.Col. and Protvino
- Cells were refurbished and tested at BNL
- South calorimeter in place on new FMS platform, readout electronics in place and tested
- *In situ* cell-by-cell tests followed installation



Planned readout



- Trigger on summed energy

E_{trig} is energy sum from only the small cells of one calorimeter

- Determine total energy for event

E_{sum} is the energy sum from all cells of one calorimeter

- Photon and π^0 finding will be based on existing FPD software

⇒ Reconstruct photon multiplicity (N_γ); π^0,… invariant mass; etc.

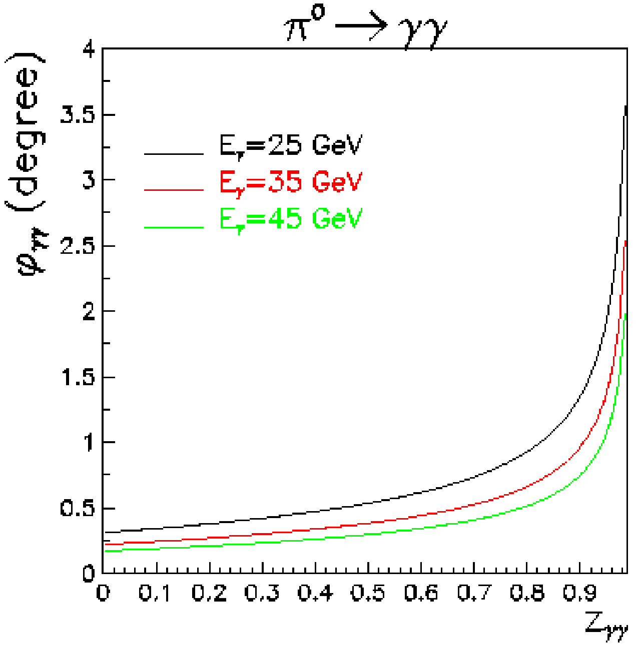
How do we detect direct photons?

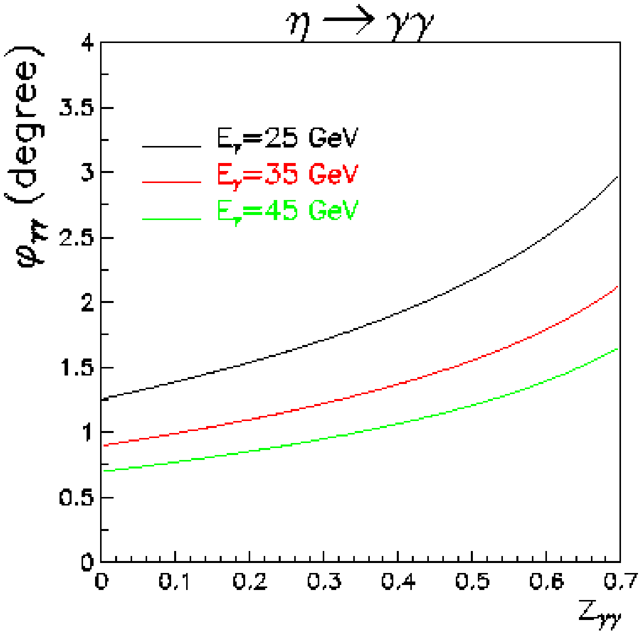
Isolate photons by having sensitivity to partner in decay of known particles:

$\pi^0 \to \gamma\gamma$	M=0.135 GeV	BR=98.8%
$K^0 \to \pi^0\pi^0 \to \gamma\gamma\ \gamma\gamma$	0.497	31%
$\eta \to \gamma\gamma$	0.547	39%
$\omega \to \pi^0\gamma \to \gamma\gamma\ \gamma$	0.782	8.9%

Detailed simulations underway

Where do decay partners go?





di-photon parameters

$z_{\gamma\gamma} = |E_1-E_2|/(E_1+E_2)$

$\phi_{\gamma\gamma}$ = opening angle

$M_m = 0.135\ \mathrm{GeV}/c^2\ (\pi^0)$

$M_m=0.548\ \mathrm{GeV}/c^2\ (\eta)$

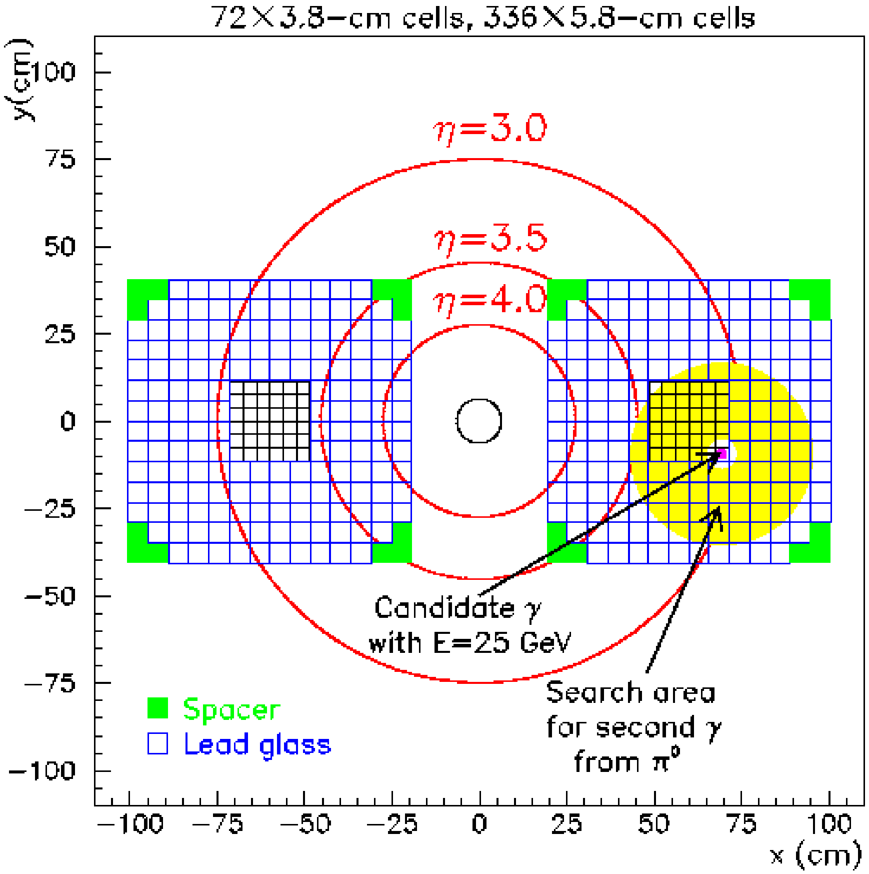
for candidate photon with $E_1 = E_\gamma$,

$$E_2 = \frac{1-z_{\gamma\gamma}}{1+z_{\gamma\gamma}} E_\gamma, \text{ gives the energy of second photon}$$

$$\sin\frac{\phi_{\gamma\gamma}^{\max}}{2} = \frac{M_m c^2}{2E_\gamma}\sqrt{\frac{1+z_{\gamma\gamma}}{1-z_{\gamma\gamma}}},\quad \sin\frac{\phi_{\gamma\gamma}^{\min}}{2} = \frac{M_m c^2}{E_1+E_2} = \frac{1}{\gamma_m}\ \text{ give max and min opening angle}$$

- Gain sensitivity to direct photons by ensuring we have high probability to catch decay partners
- This means we need dynamic range, because photon energies get low (~0.25 GeV), and sufficient area (typical opening angles are only a few degrees at our η ranges).

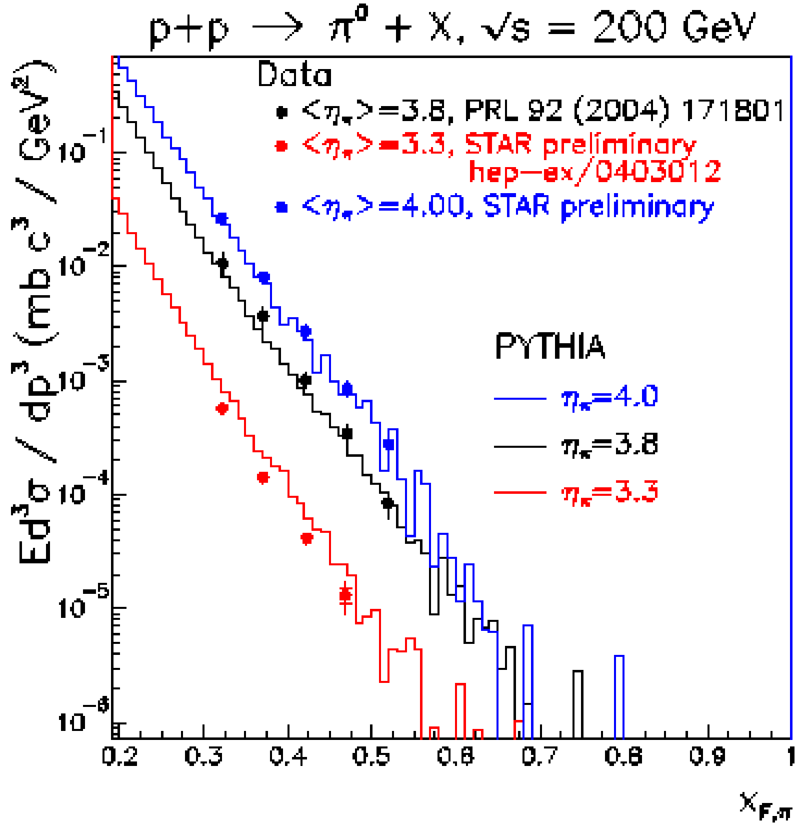
Sample decays on FPD++



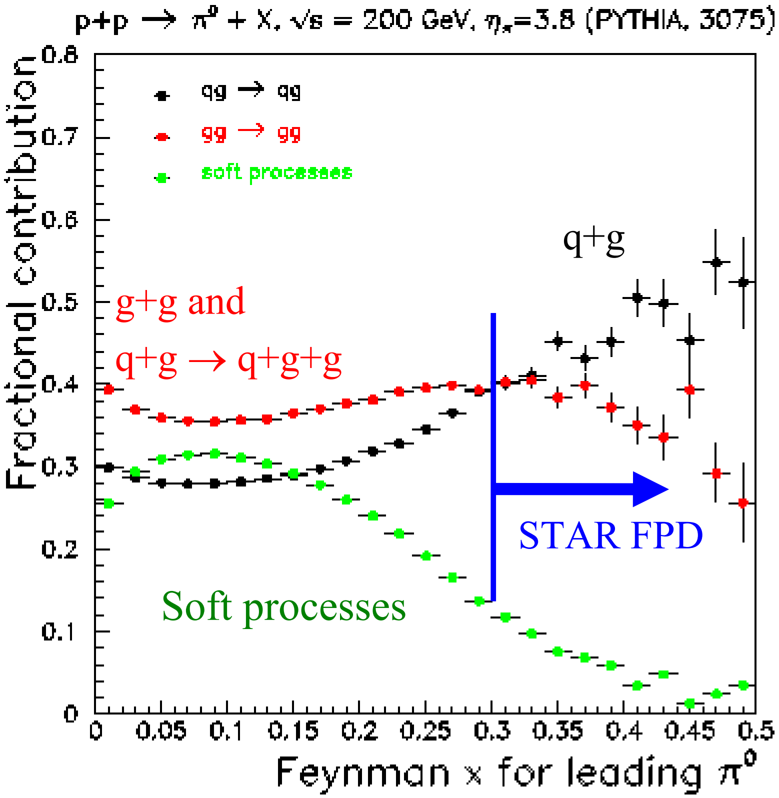
With FPD++ module size and electronic dynamic range, have >95% probability of detecting second photon from π^0 decay.

PYTHIA: a guide to the physics

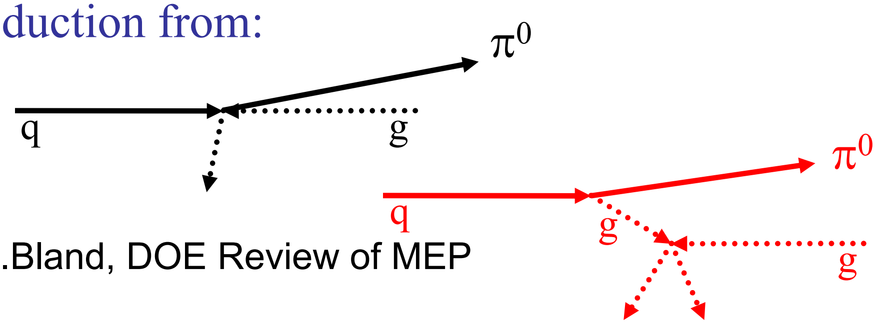
Forward Inclusive π^0 Cross-Section:



Subprocesses involved:



- PYTHIA ***prediction*** agrees well with the inclusive π^0 cross section at $\eta \sim 3\text{-}4$
- Dominant sources of large x_F π^0 production from:
- $q + g \rightarrow q + g$ **(2→2)** $\rightarrow \pi^0 + X$
- $q + g \rightarrow q + g + g$ **(2→3)** $\rightarrow \pi^0 + X$



d+Au → π^0+π^0+X, pseudorapidity correlations with forward π^0

HIJIING 1.381 Simulations

- increased p_T for forward π^0 over run-3 results is expected to reduce the background in $\Delta\phi$ correlation
- detection of π^0 in interval $-1<\eta<+1$ correlated with forward π^0 ($3<\eta<4$) is expected to probe $0.01<x_{\text{gluon}}<0.1$ ⇒ provides a universality test of nuclear gluon distribution determined from DIS
- detection of π^0 in interval $1<\eta<4$ correlated with forward π^0 ($3<\eta<4$) is expected to probe $0.001<x_{\text{gluon}}<0.01$ ⇒ smallest x range until eRHIC
- at d+Au interaction rates achieved at the end of run-3 (R_{int}~30 kHz), expect 9,700±200 (5,600±140) π^0–π^0 coincident events that probe $0.001<x_{\text{gluon}}<0.01$ for "no shadowing" ("shadowing") scenarios.