Measurements of Single Transverse Spin Asymmetries in √s=200 GeV pp Collisions at STAR

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For STAR

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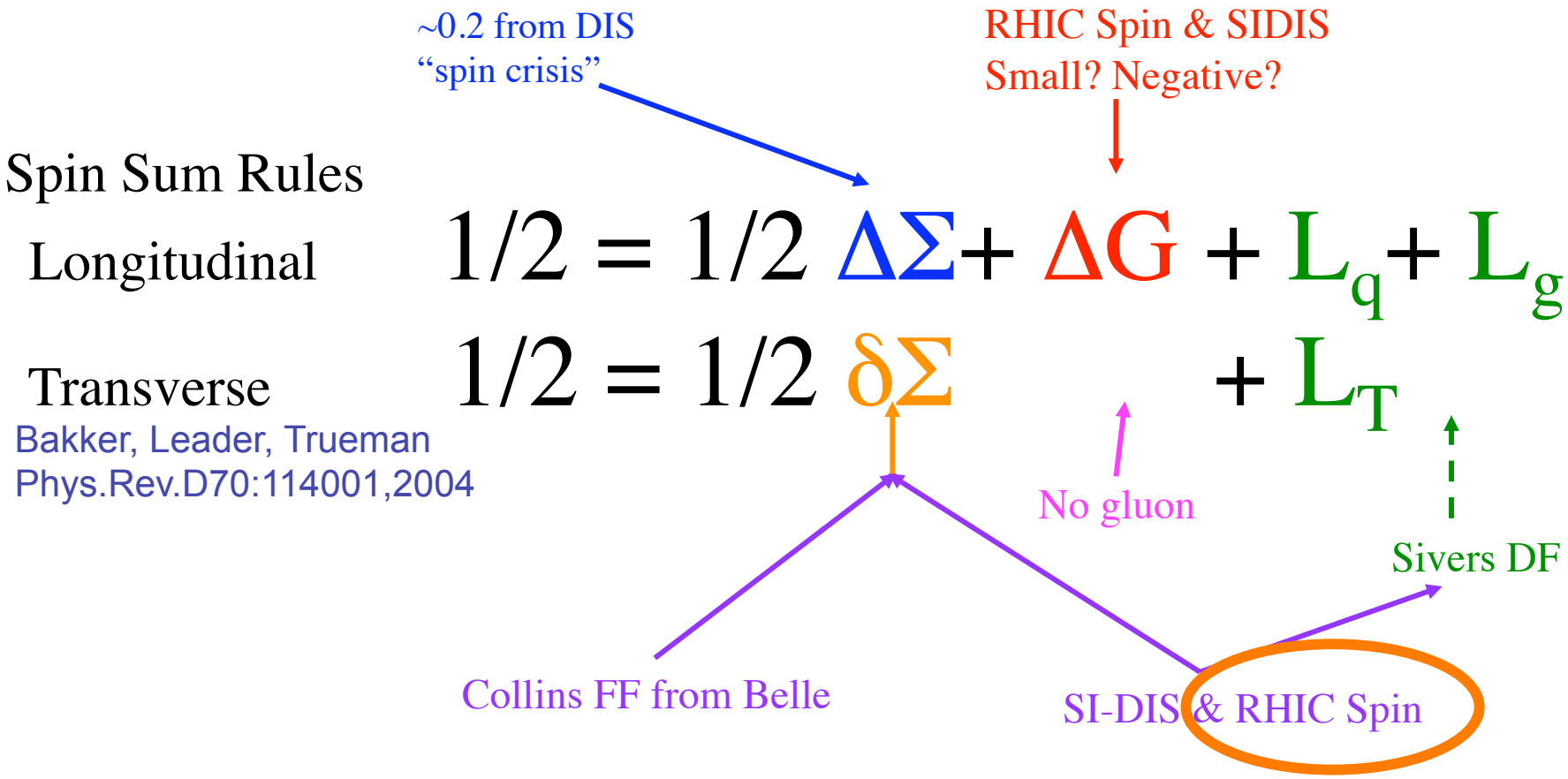
Outline

- Introduction
- RHIC – STAR – Forward Calorimeters
- Inclusive π^0 A_N results
- Going beyond inclusive π^0
- Future plans
- Summary

The Nucleon Spin Puzzle



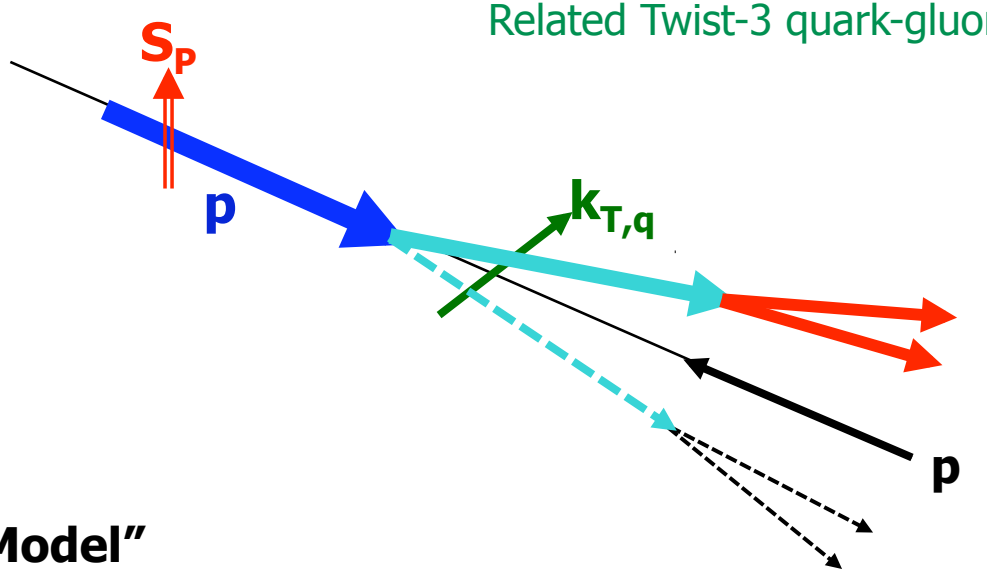
Collins Fragmentation Function ?
Can we use it as a probe for Transversity?
Sivers Distribution Function ?

Sivers Effect

Phys Rev D41 (1990) 83; 43 (1991) 261

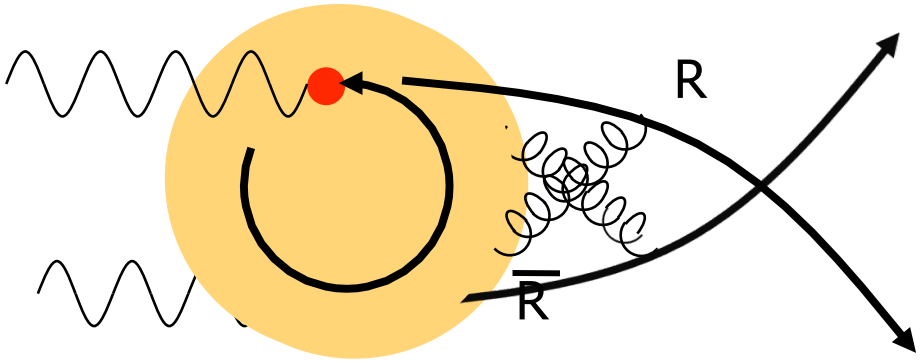
Correlation between nucleon spin and parton k_T

Related Twist-3 quark-gluon correlation at initial state



"QCD Lens Model"

Red Shift + Attractive Final State Interaction



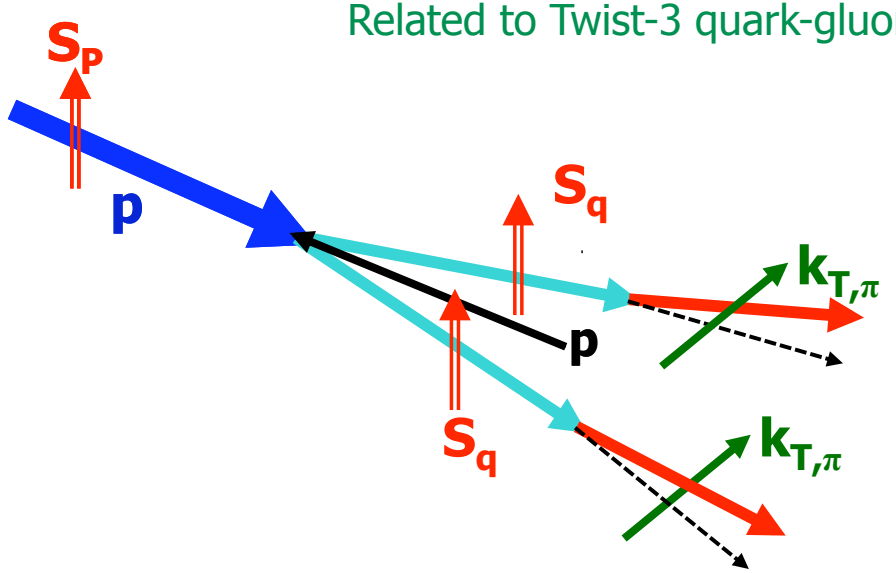
If there is no orbital angular momentum, Sivers effect would be zero!

Transversity and Collins Effect

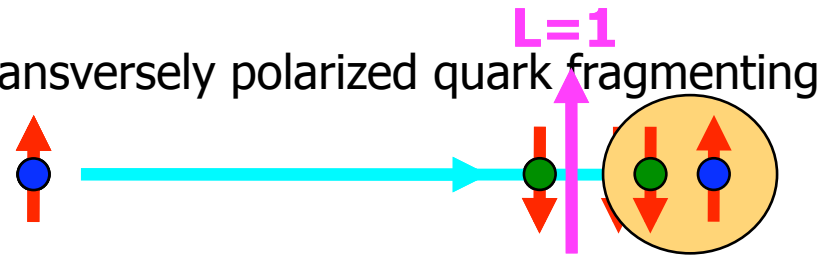
Nucl Phys B396 (1993) 161

Transversity (quark polarization) * asymmetry in the jet fragmentation

Related to Twist-3 quark-gluon correlation at final state



Artru model

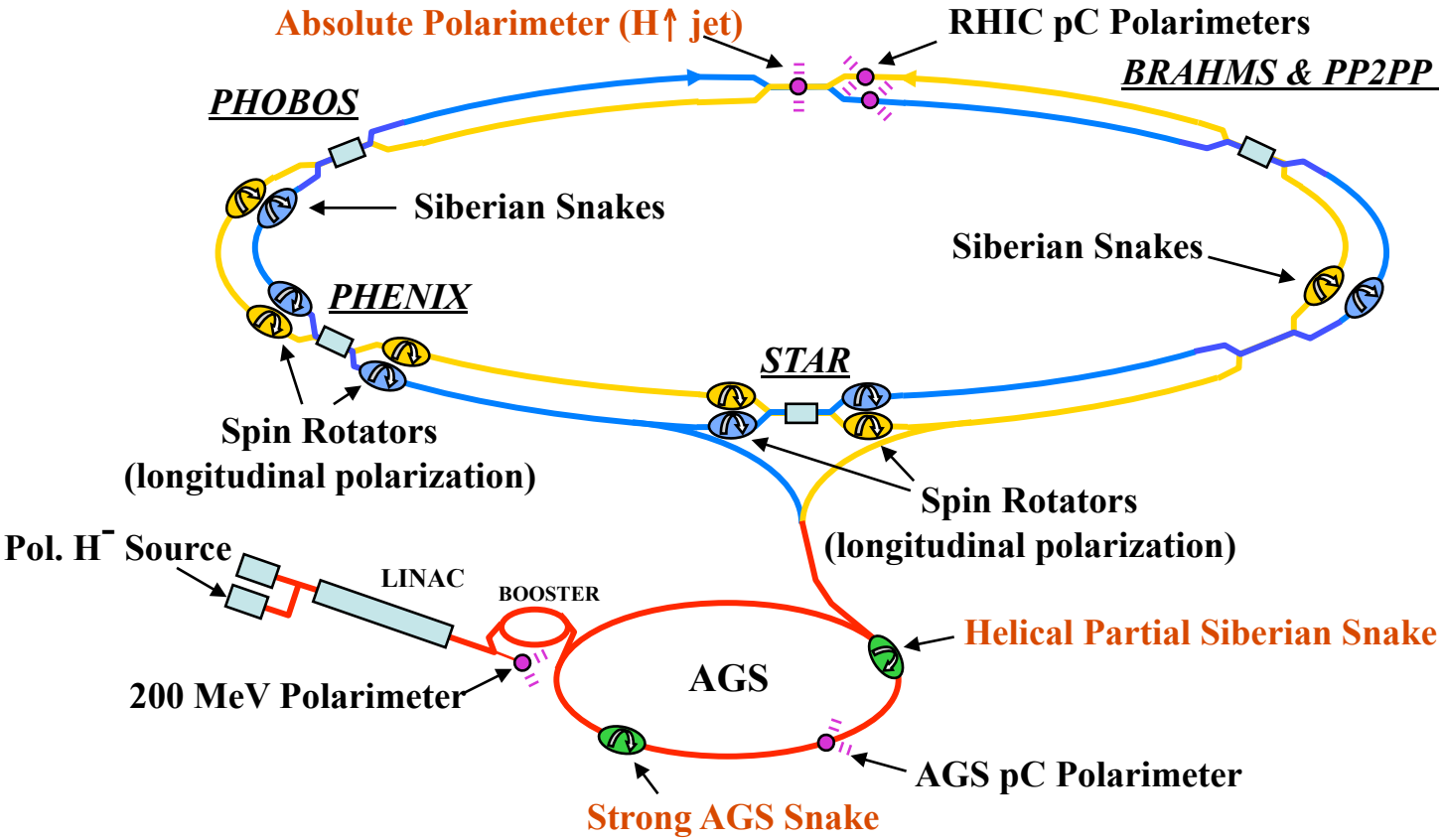


Quark pair creation with vacuum quantum numbers ($^3P_0$)

Pion going into screen

Collins FF can be used as a probe for Transversity

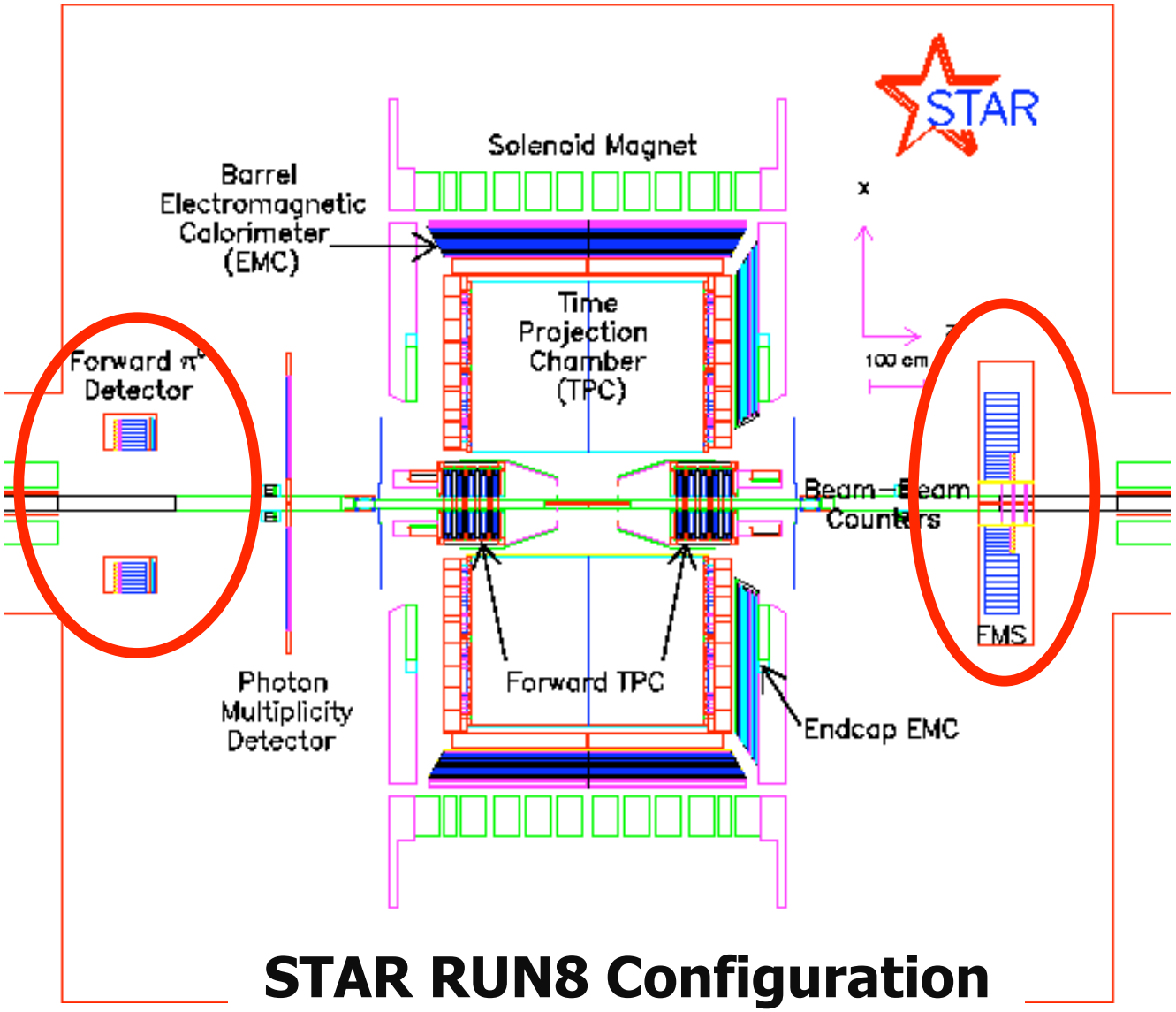
RHIC - First and only Polarized pp Collider



RHIC pp runs with transverse spin

Run2	L=0.35/pb	P=15%	Prototype FPD
Run3	L=1.0/pb	P=25%	FPD
Run5	L=0.1/pb	P=50%	FPD
Run6	L=6.8/pb	P=60%	FPD++
Run8	L~7.8/pb	P=45%	FMS & FPD

STAR Detector and Physics



STAR RUN8 Configuration

TPC: $-1.0 < \eta < 1.0$

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

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

EEMC: $1 < \eta < 2$

BEMC: $-1 < \eta < 1$

Run2-6

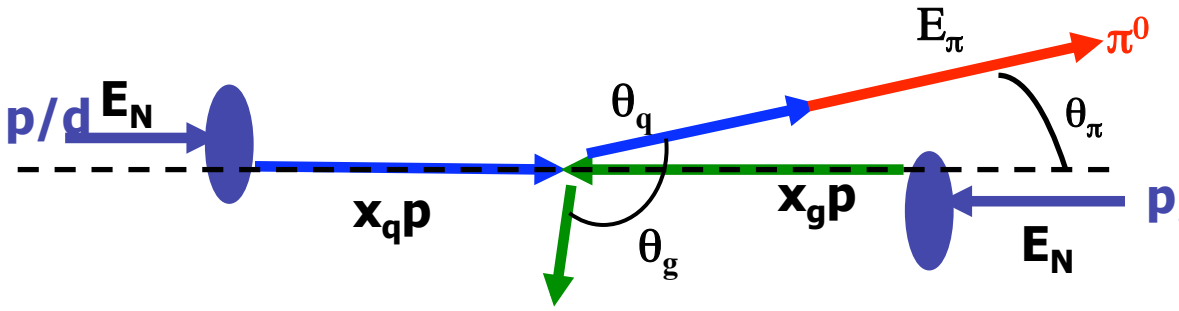
FPD/FPD++:

$\eta \sim 3.3 - 4.1$

Run8

FMS : $2.5 < \eta < 4.1$

Why forward in a hadron collider is interesting?



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

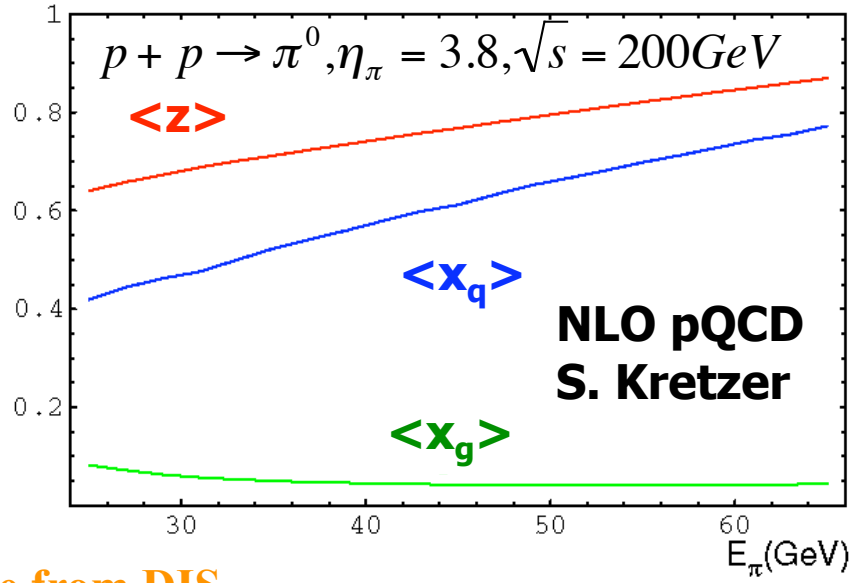
$$\sqrt{s} = 2E_N$$

$$\eta = -\ln(\tan(\frac{\theta}{2})) \qquad z = \frac{E_\pi}{E_q}$$

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

(colinear 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 ~ 0.8**

- **Large-x quark polarization is known to be large from DIS**
- **Directly couple to gluons = A probe of low x gluons**

Forward Meson Spectrometer (FMS)

Three Highlighted Objectives In FMS Proposal
(not exclusive)

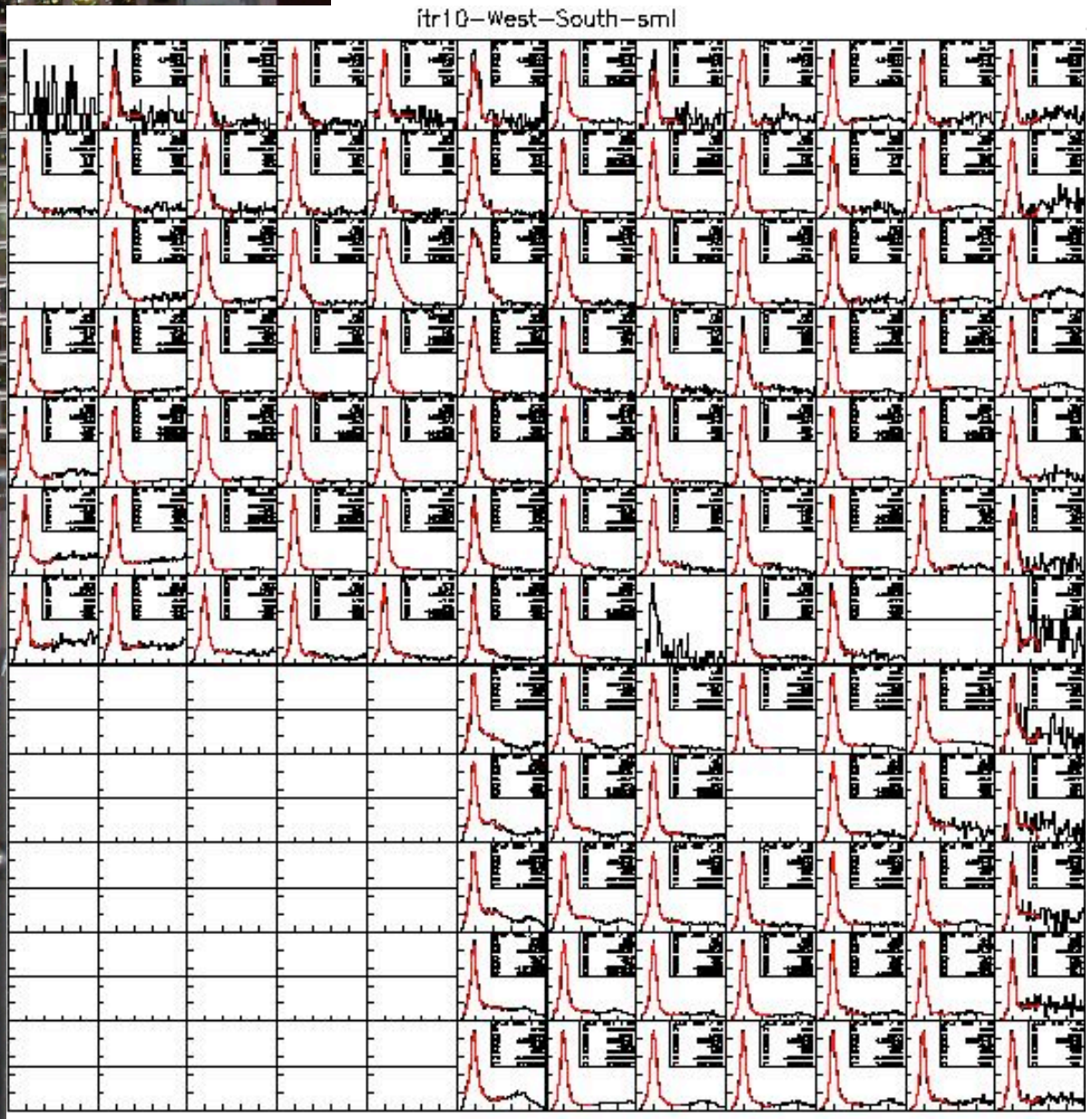
hep-ex/0502040

1. A **d(p)+Au→$\pi^0\pi^0$+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.

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)**

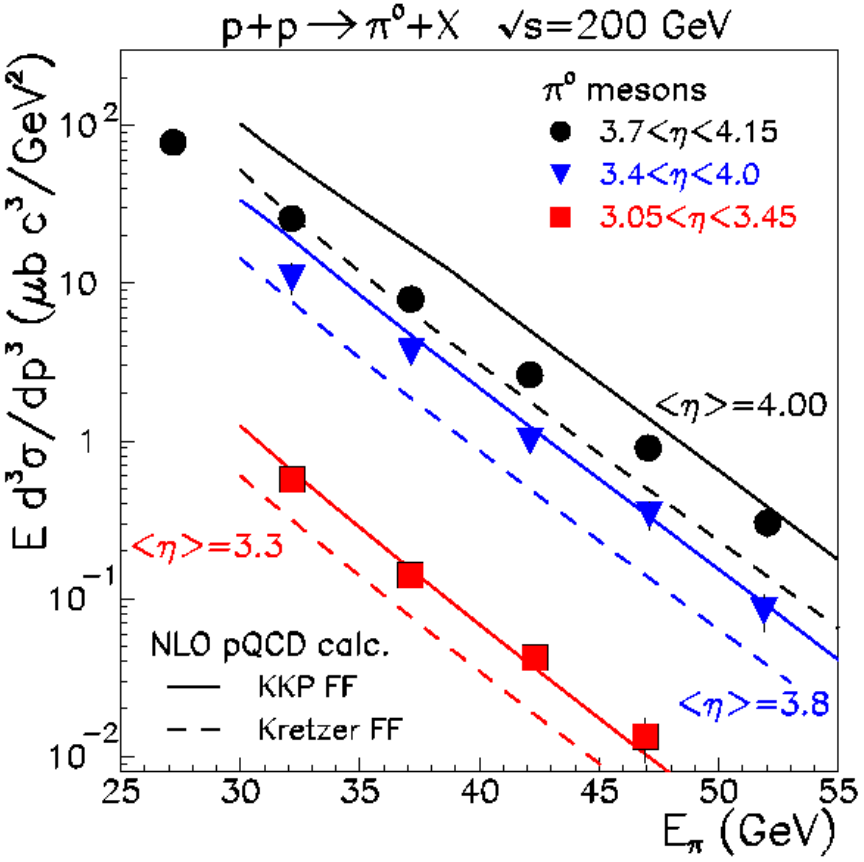
3. Measurements with **transversely polarized protons** that are expected to **resolve the origin of the large transverse spin asymmetries** in reactions for **forward π^0 production.** **(polarized pp)**

ctrometer for Run8

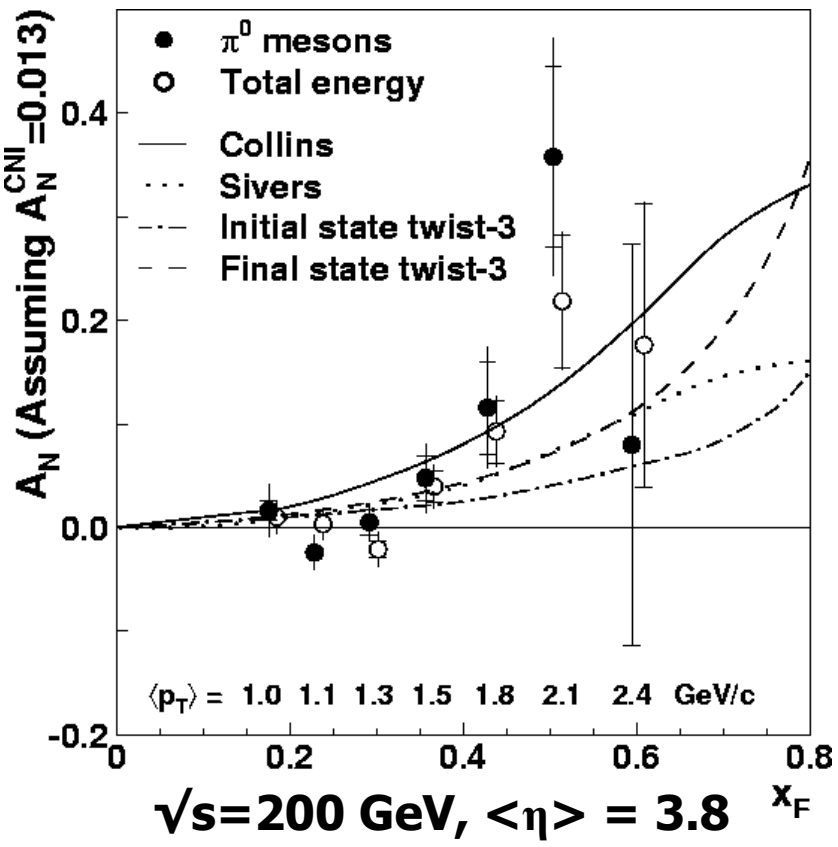


Measurements at STAR FPD (run2-3)

PRL 97, 152302 (2006)



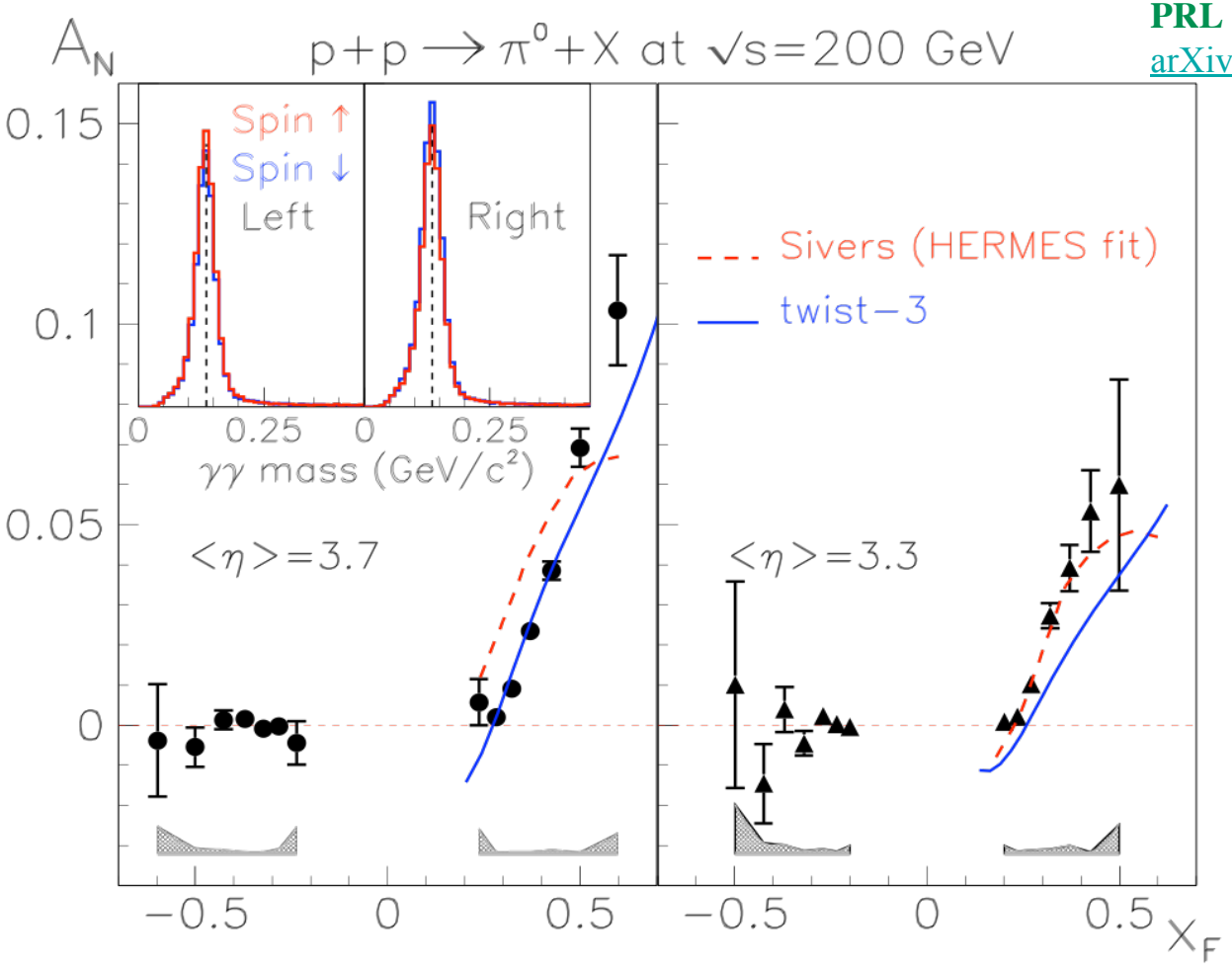
PRL 92, 171801 (2004)



Cross-section is consistent with NLO pQCD calculations

Asymmetry revealed at lower energies persists at √s=200 GeV

π^0 A_N at $\sqrt{s}$=200 GeV : x_F-dep (Run6)



PRL 101, 222001 (2008)
arXiv:0801.2990v1 [hep-ex]

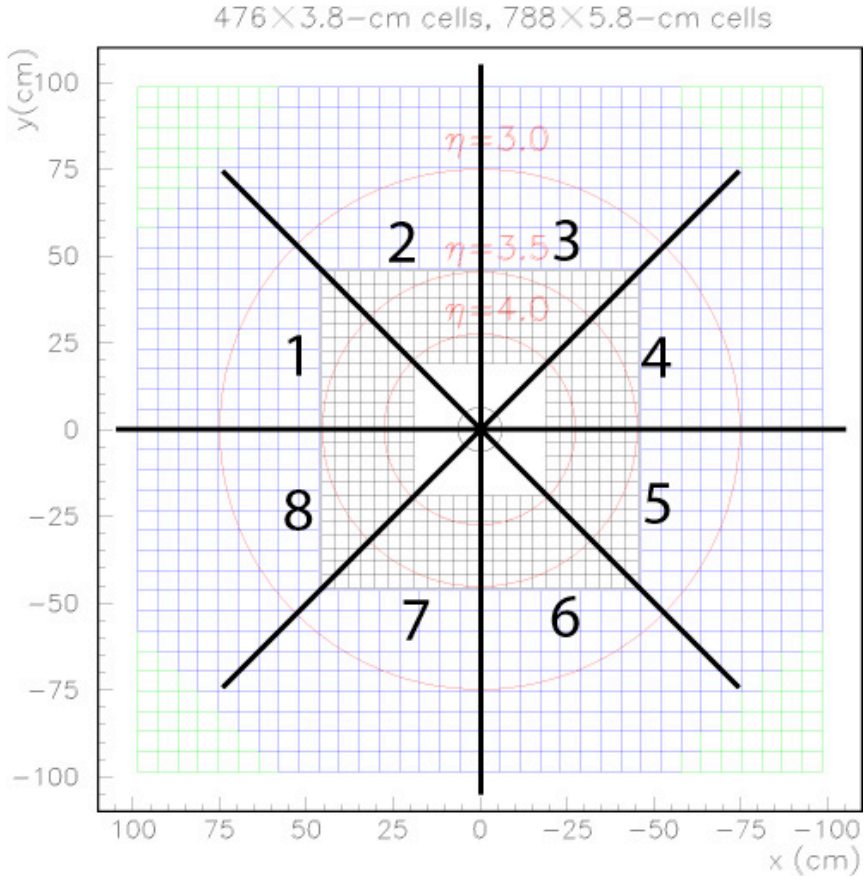
A_N at positive x_F grows with increasing x_F

Fits to SIDIS (HERMES) is consistent with data

U. D'Alesio, F. Murgia
Phys. Rev. D 70, 074009 (2004)
arXiv:hep-ph/0712.4240

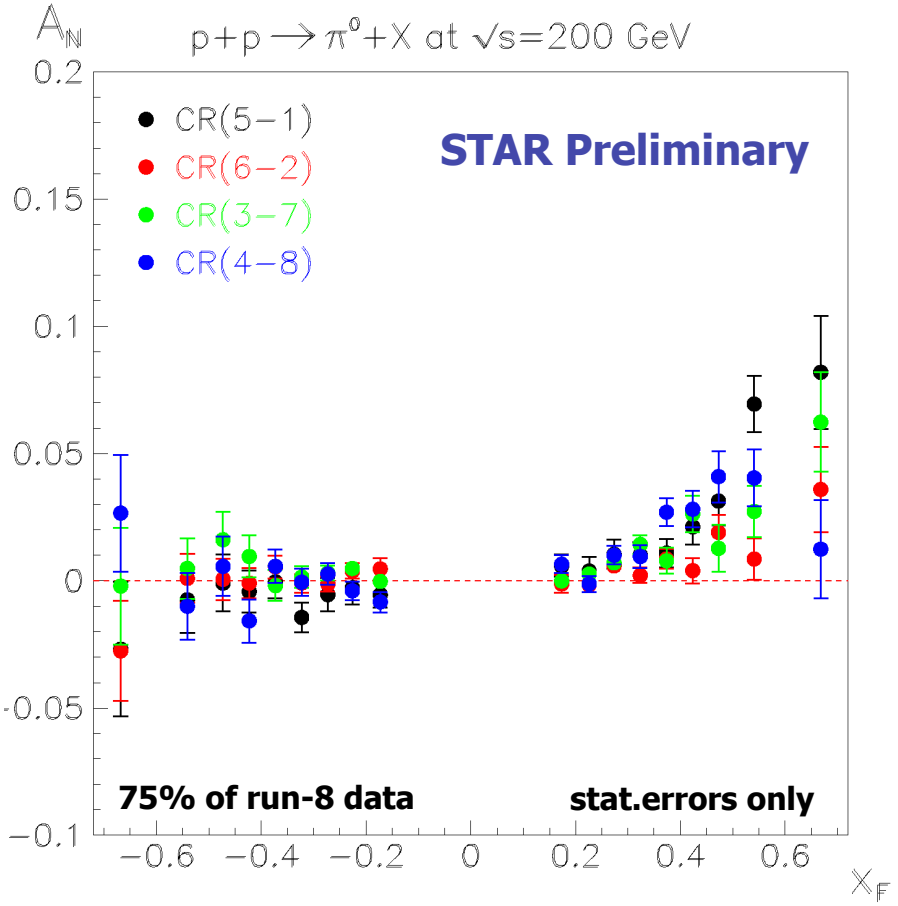
C. Kouvaris, J. Qiu, W. Vogelsang, F. Yuan,
Phys. Rev. D 74, 114013 (2006).

First look at FMS Run8 data



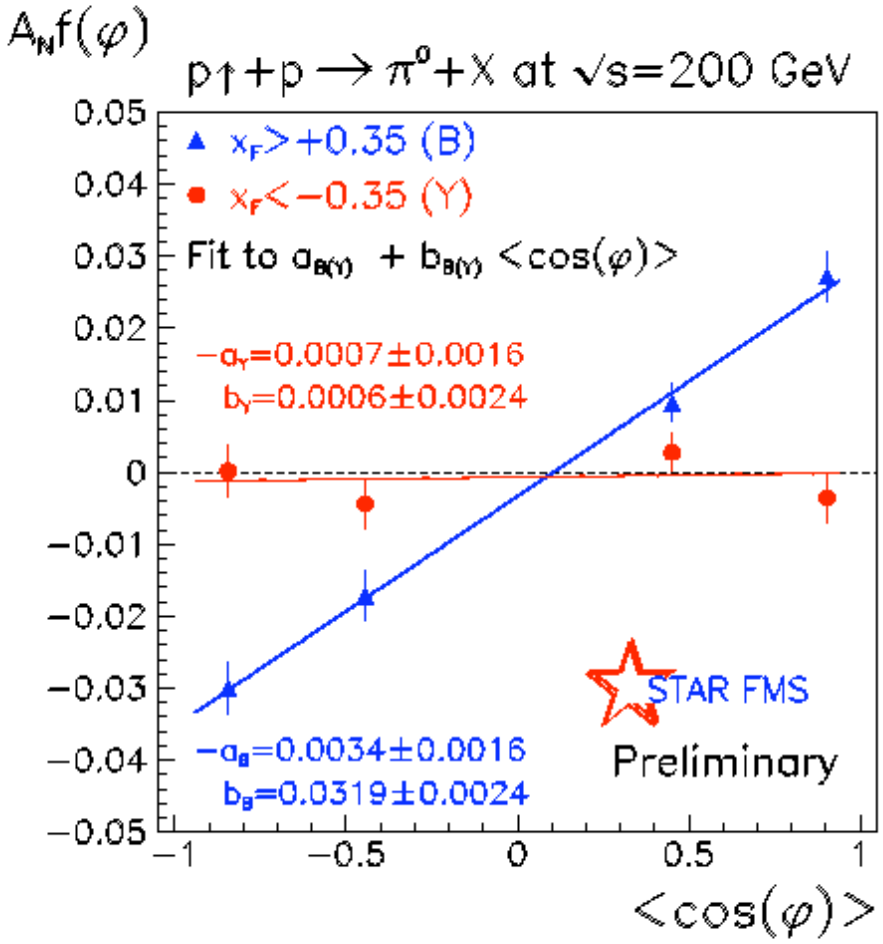
Octant subdivision of FMS for inclusive π^0 spin sorting.

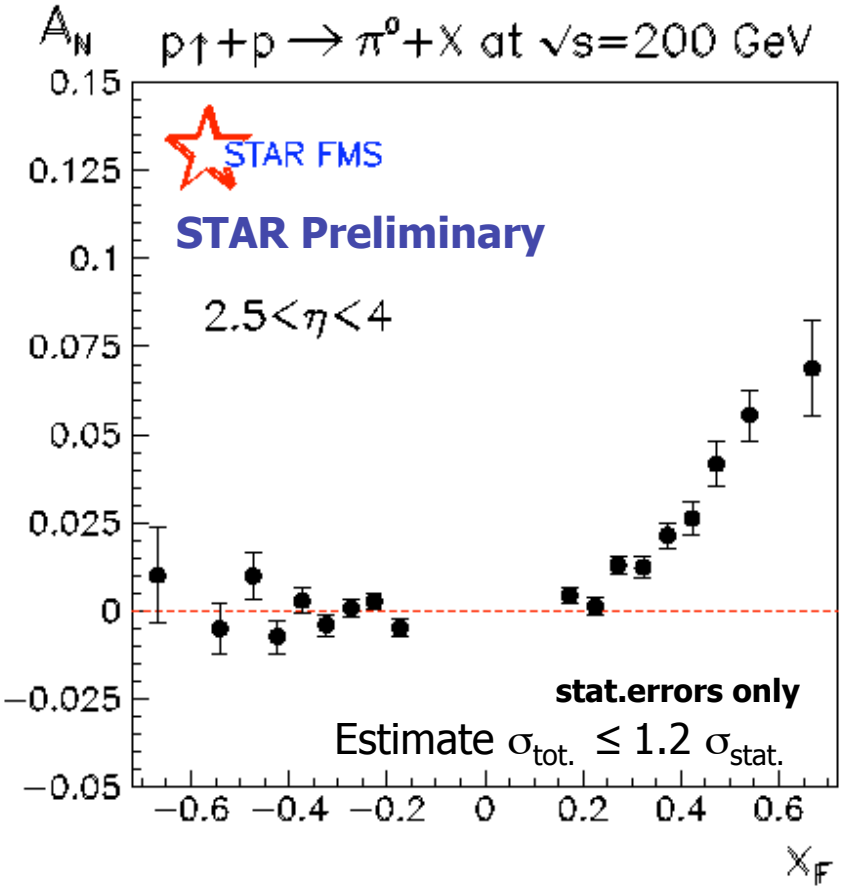
A_N <cosϕ>



- **Systematic errors being evaluated**
- **First estimate $\sigma_{tot.} \leq 1.2\ \sigma_{stat.}$**

First look at Run8 FMS data

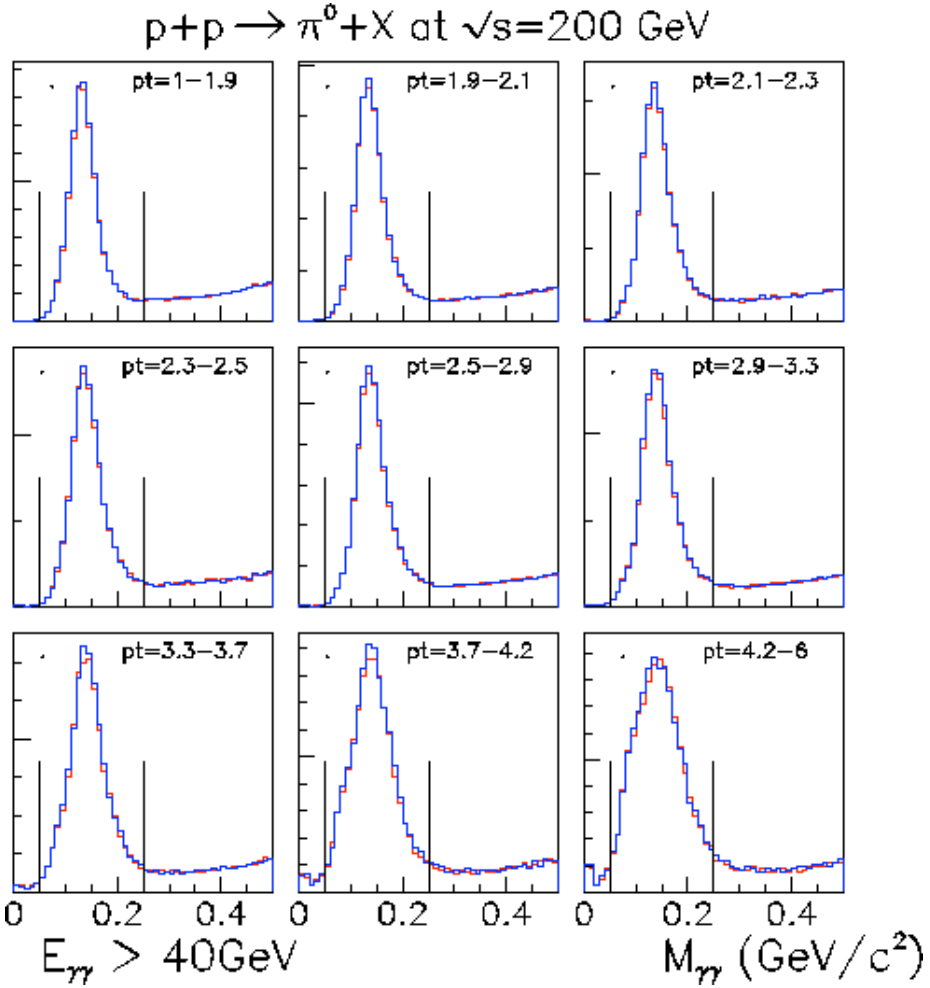


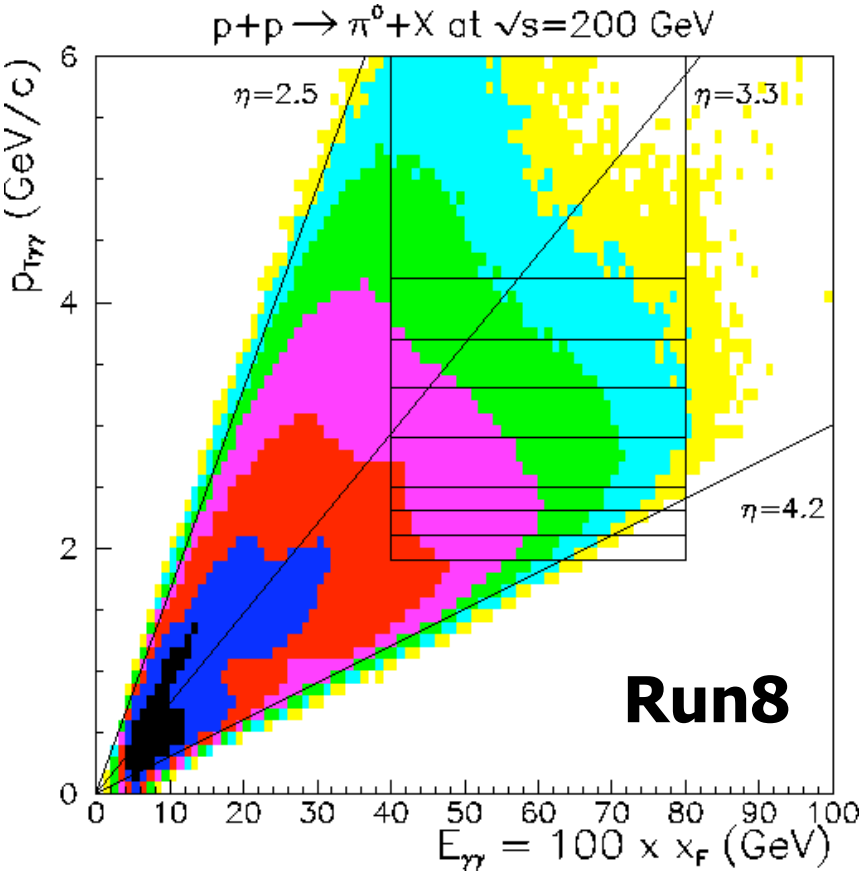


- **Azimuthal dependence appears to be as expected**
- **A_N comparable to prior measurements**

arXiv:0901.2828 (Nokola Poljack – SPIN08)

π^0 A_N at $\sqrt{s}$=200 GeV : p_T-dependence

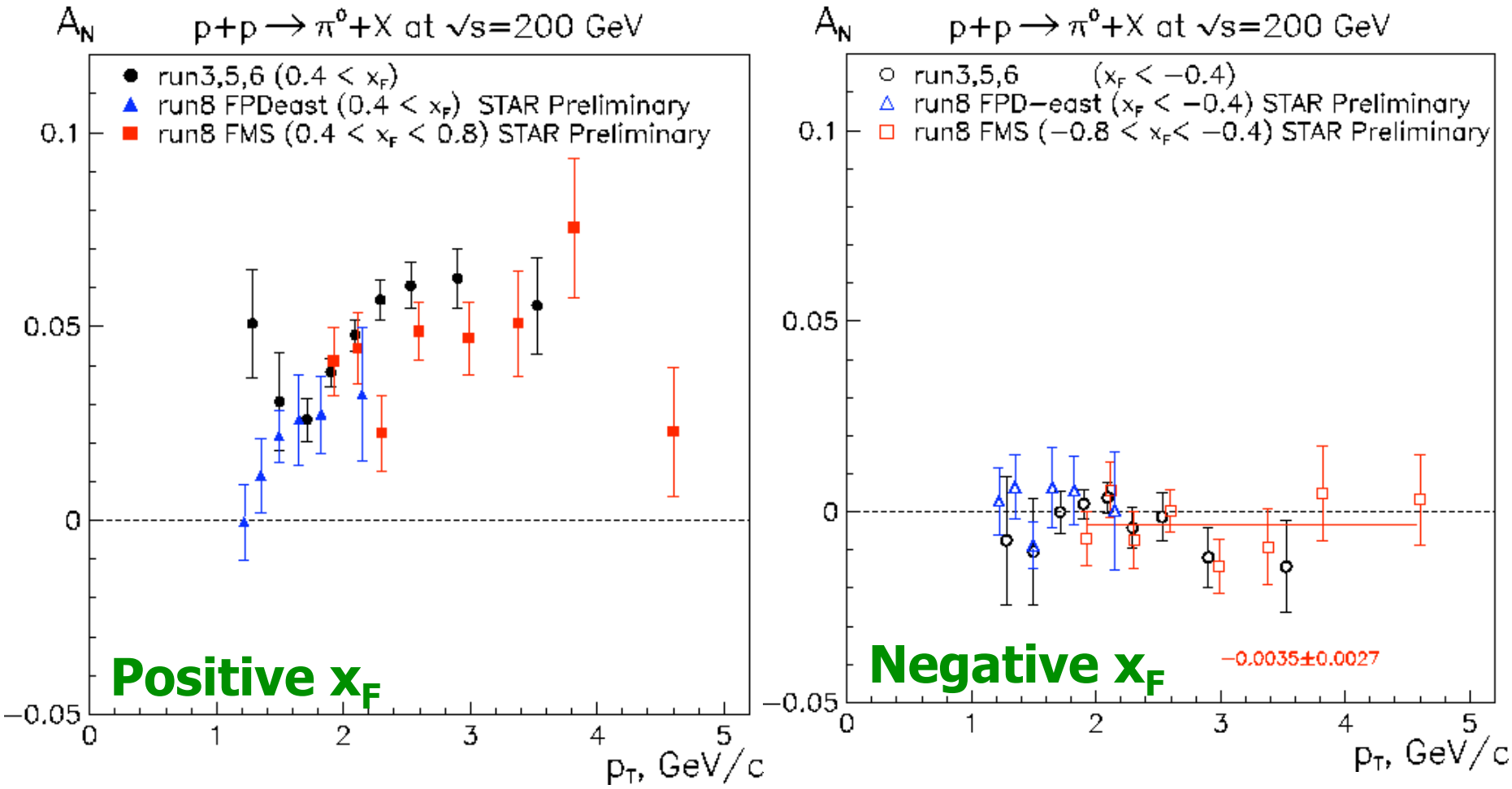




F.o.M = LP^2 Run8 < Run6

FMS reaches p_T ~ 6GeV/c

π^0 A_N at $\sqrt{s}$=200 GeV : p_T-dependence



Needs more transverse spin running

Indication of Positive A_N persists up to p_T~5GeV

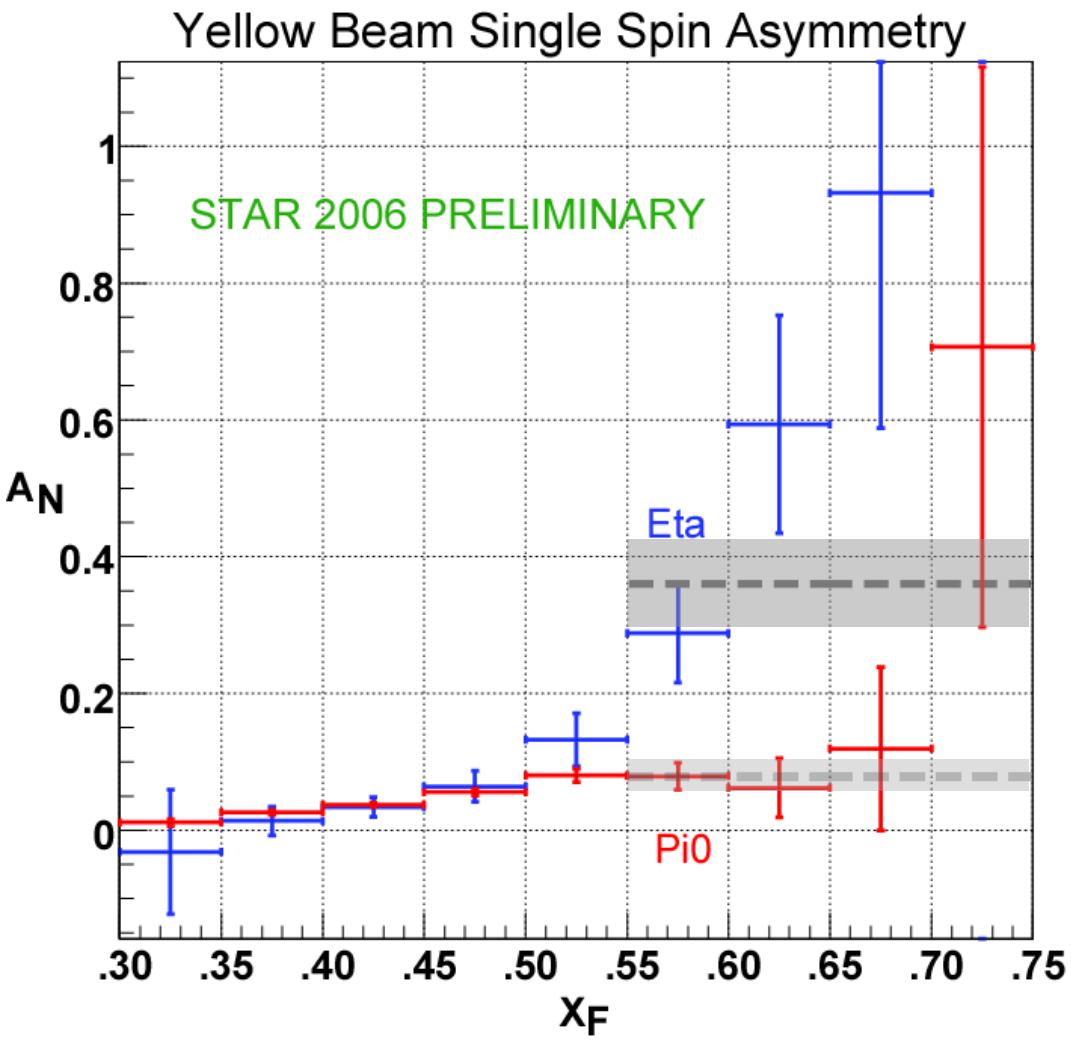
Negative x_F consistent with zero

Run8 FPD east result : arXiv:0901.2763 (James Drachenberg– SPIN08)

Going Beyond Inclusive pi0

DIS	
Inclusive DIS	Not sensitive
Semi-Inclusive DIS	Collins, Sivers and more
PP	
Inclusive pi0 production in pp	Collins and Sivers are mixed
Heavier mesons? Spin-1 mesons?	Qualitative expectation (No prediction)
Direct Photons	Sivers
"Semi-Inclusive" pp	
• p+p -> jet -> hadron + rest of jet	Collins x Transversity
• p+p -> di-hadron (near side)	Collins x Transversity (or Interference FF)
• p+p -> jet	Sivers
• p+p -> di-jet, di-hadron (away side)	Sivers
• p+p -> l+l (DY)	Sivers

A_N for Eta mass region (Run6 FPD)



1. N_{photon} = 2
2. Center Cut (η and ϕ)
3. Pi0 or Eta mass cuts
4. Average Yellow Beam Polarization = 56%

$0.55<x_{F<}0.75$

$\langle A_N \rangle \eta = 0.36 +/- 0.06$
$\langle A_N \rangle \pi = 0.08 +/- 0.02$

The asymmetry in the η mass region @ $x_F>0.55$ is greater than 5 sigma above zero, and about 4 sigma above the asymmetry in the π^0 mass region.

arXiv:0905.2840 (Steve Heppelmann – DIS08)

First look at Eta mass region in FMS

2 photon Mass Distributions in four Pseudo-Rapidity Y Regions (Preliminary Energy Calibration)

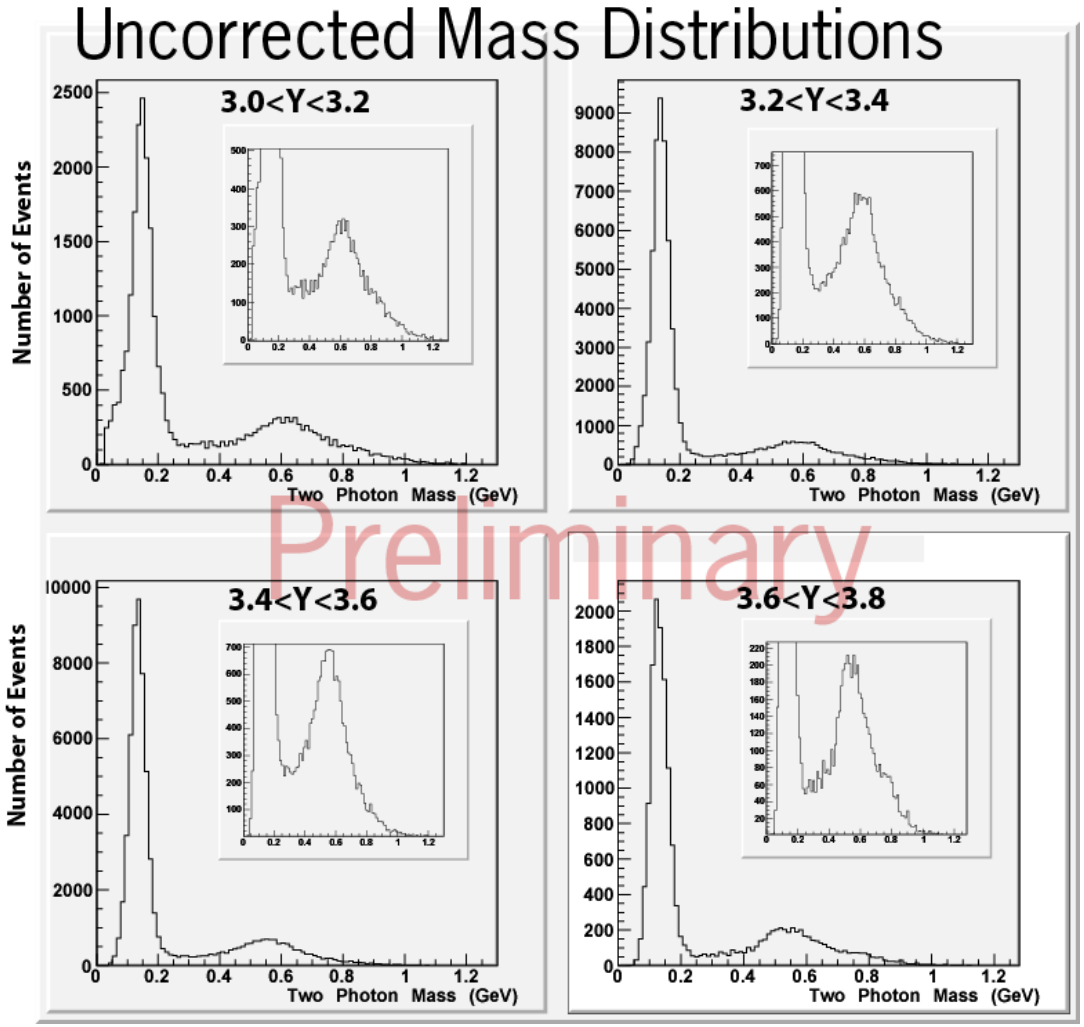
Event Selection

2 Photons within cone

$$\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.85$$

$P_{t\,\Upsilon} > 2$ GeV/c
$Z_{\Upsilon} < .7$

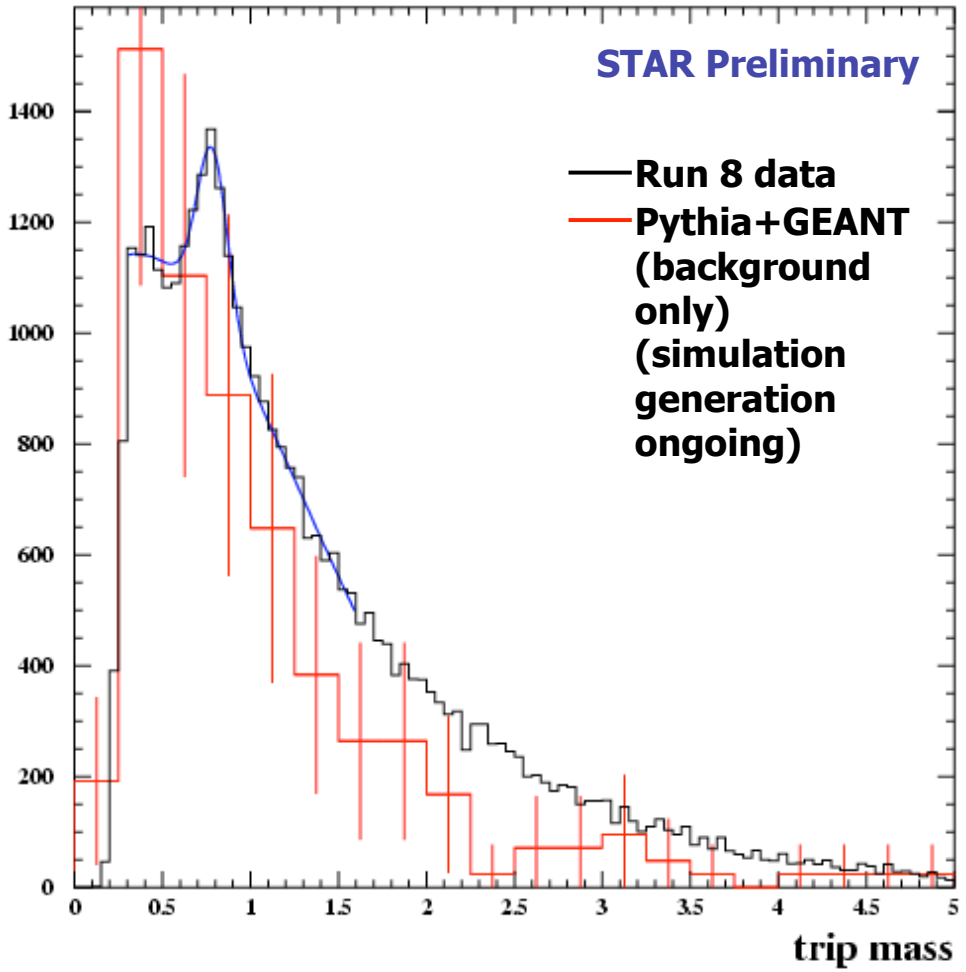
- Mass differences?
- Isospin differences?
- Role of Strangeness?



First look at Triple photons : spin1 ω

3 photon events to look for $\omega \rightarrow \pi^0\gamma$ (BR= 8.9%)

- **P_T(triplet)>2.5 GeV/c**
- **E(triplet)>30 GeV**
- **P_T(photon cluster)>1.5 GeV/c**
- **$P_T(\pi^0)$>1 GeV/c**



Background only MC

Run8 FMS data

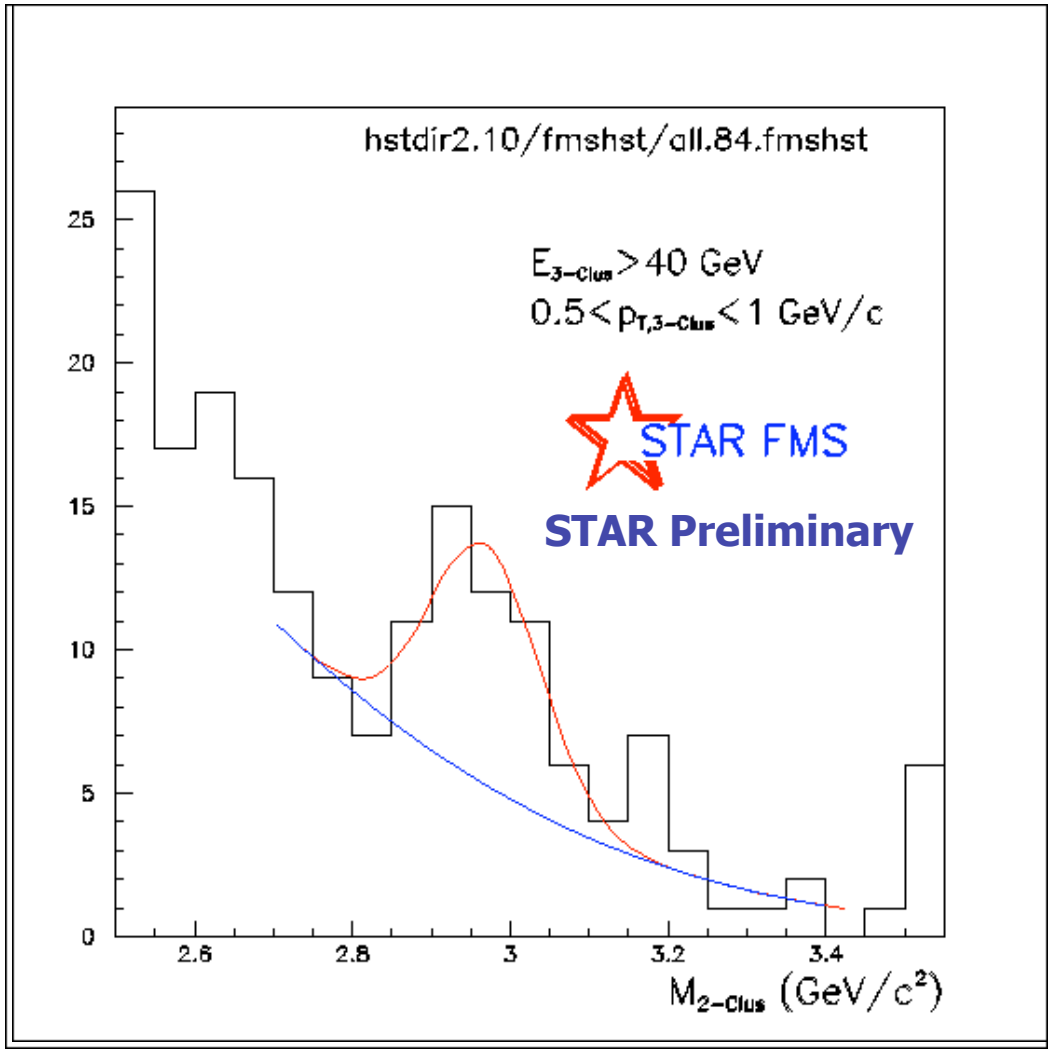
Fit is gaussian + P3

μ=0.784±0.008 GeV
σ=0.087±0.009 GeV
Scale=1339±135 Events

Significant (10σ) $\omega \rightarrow \pi^0\gamma$ signal seen in the data.

Comparison to dAu
Spin-1 meson A_N

First look at three clusters : Xc→J/ψ



- **Reconstructed invariant mass of candidate**

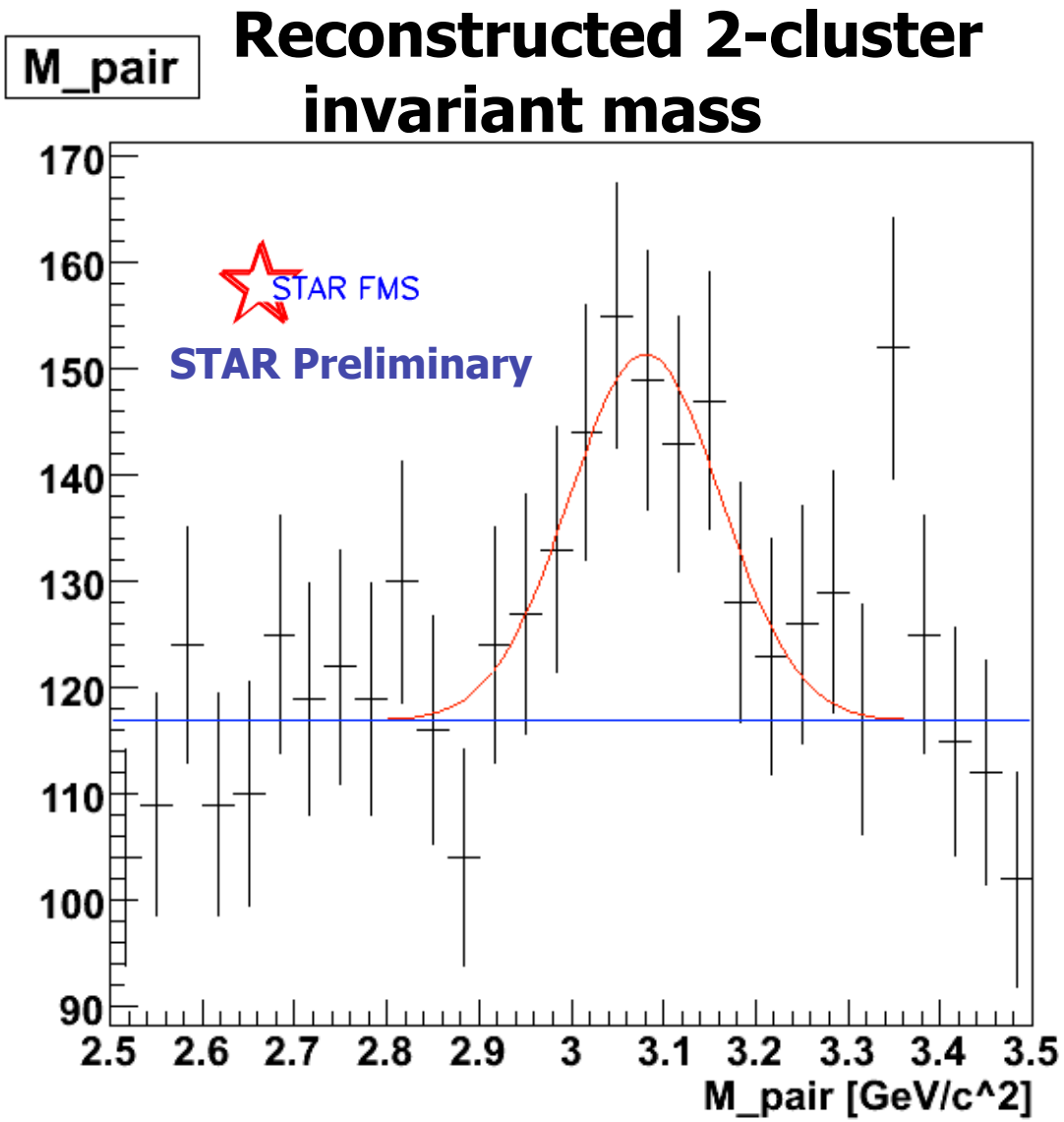
  $\chi_c \rightarrow J/\psi + \gamma$ events

  - **Peak Counts = 8.40 ± 2.88**
    - **2.9 σ Significance**
  - **μ = 2.97 ± 0.025 GeV**
  - **σ = 0.070 ± 0.025 GeV**
  - **χ^2/d.o.f. = 0.7 with 14 points fit.**

- **Significance depends on background model**
- **2.9 σ significance with currently estimated background.**

First look at two clusters : J/Ψ

Benchmark for DY



Fit with Gaussian + Offset

Gaussian Fit Parameters:

- $\mu = 3.080 \pm 0.020$ GeV/c^2
- $\sigma = 0.082 \pm 0.026$ GeV/c^2
- χ^2/d.o.f. = 20.83/26
- Significance from fit
  - 4.5 σ

Cuts Applied:

- E_pair > 60.0 GeV
- $Z_{\gamma\gamma} < 0.7$
- Isolation Radius:
  - 0.4 Eta-Phi
- p_T_cluster > 1.0 GeV/c

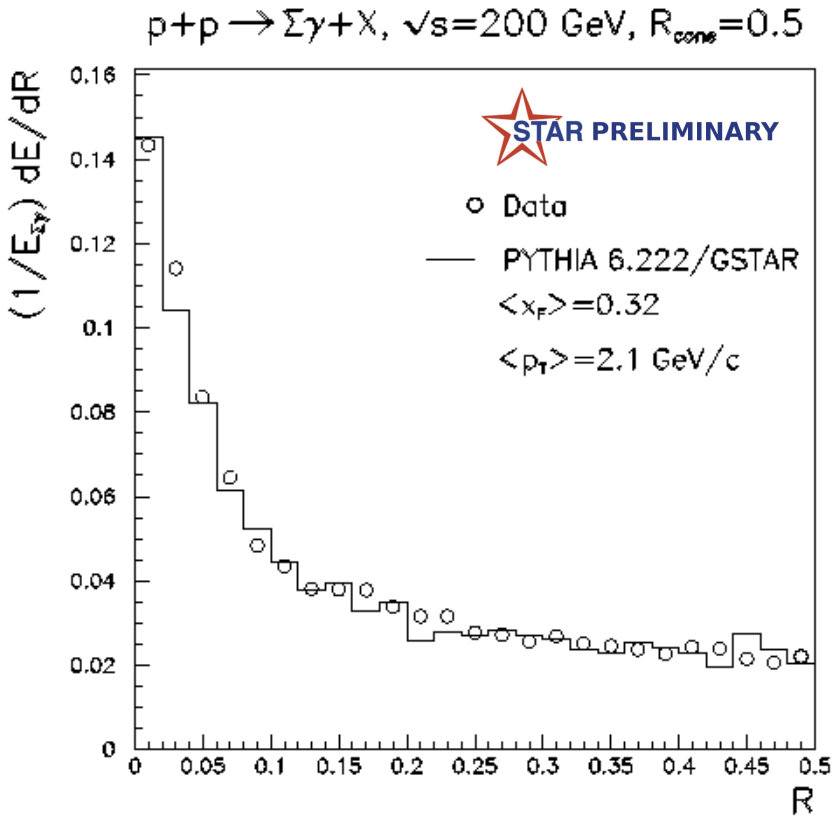
First high x_F J/Ψ measurement at collider

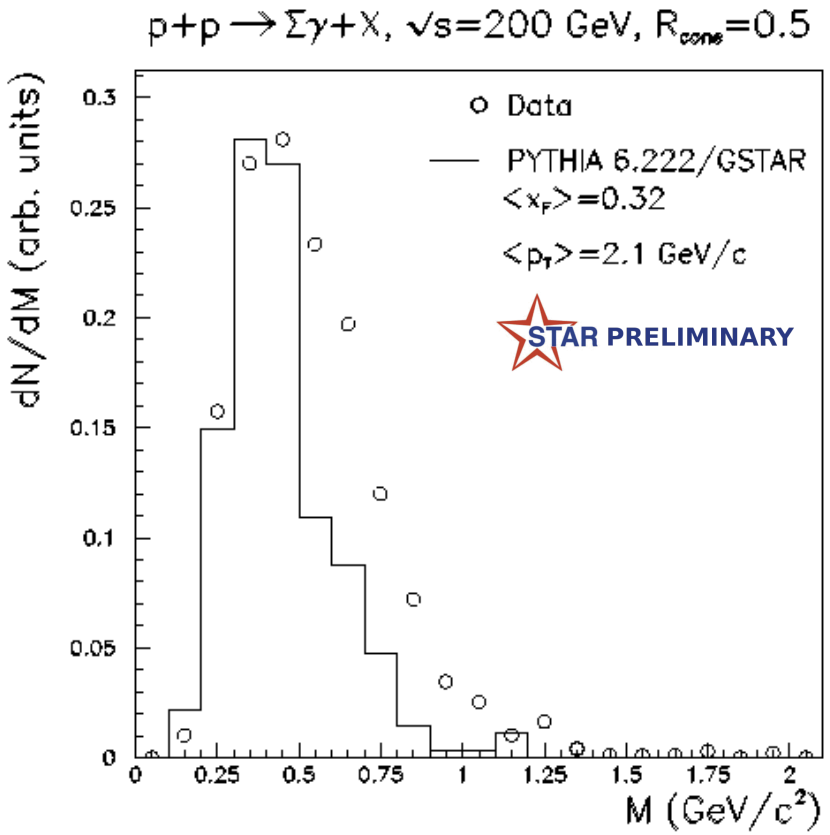
First look at "jet-like" events

Event selection done with:

- **>15 detectors with energy > 0.4GeV in the event (no single pions in the event)**
- **cone radius = 0.5 (eta-phi space)**
- **"Jet-like" $p_T > 1$ GeV/c ; $x_F > 0.2$**
- **2 perimeter fiducial volume cut (small/large cells)**

A_N^{jet} is only sensitive to Sivers
Hadron correlation with in jet for Collins effect



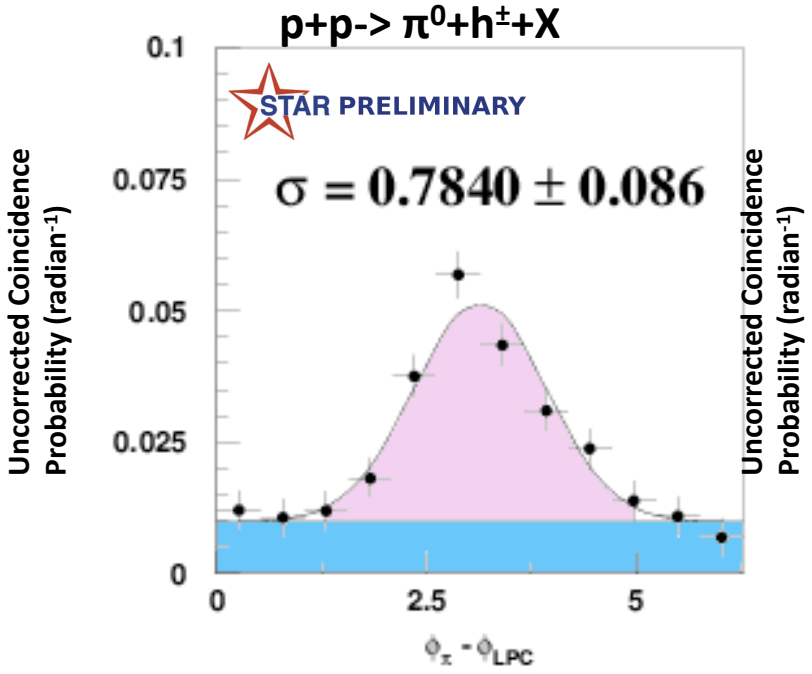


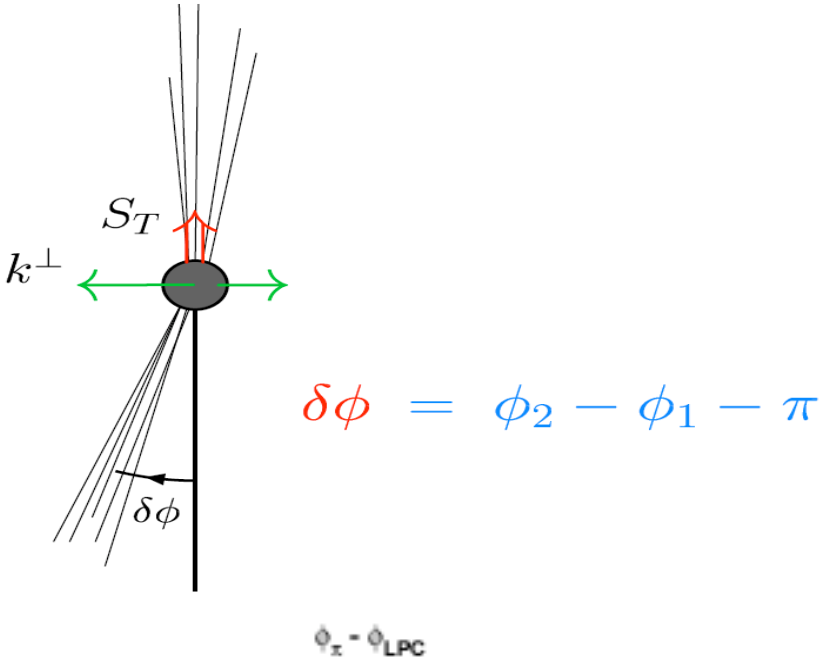
arXiv:0901.2828 (Nokola Poljack – SPIN08)

Forward pi0 (FMS) – Mid-rapidity(TPC & BEMC) Azimuthal Correlations

pQCD inspired "GSV cuts" (Guzey, Strikman and Vogelsang, hep-ph/0407201):

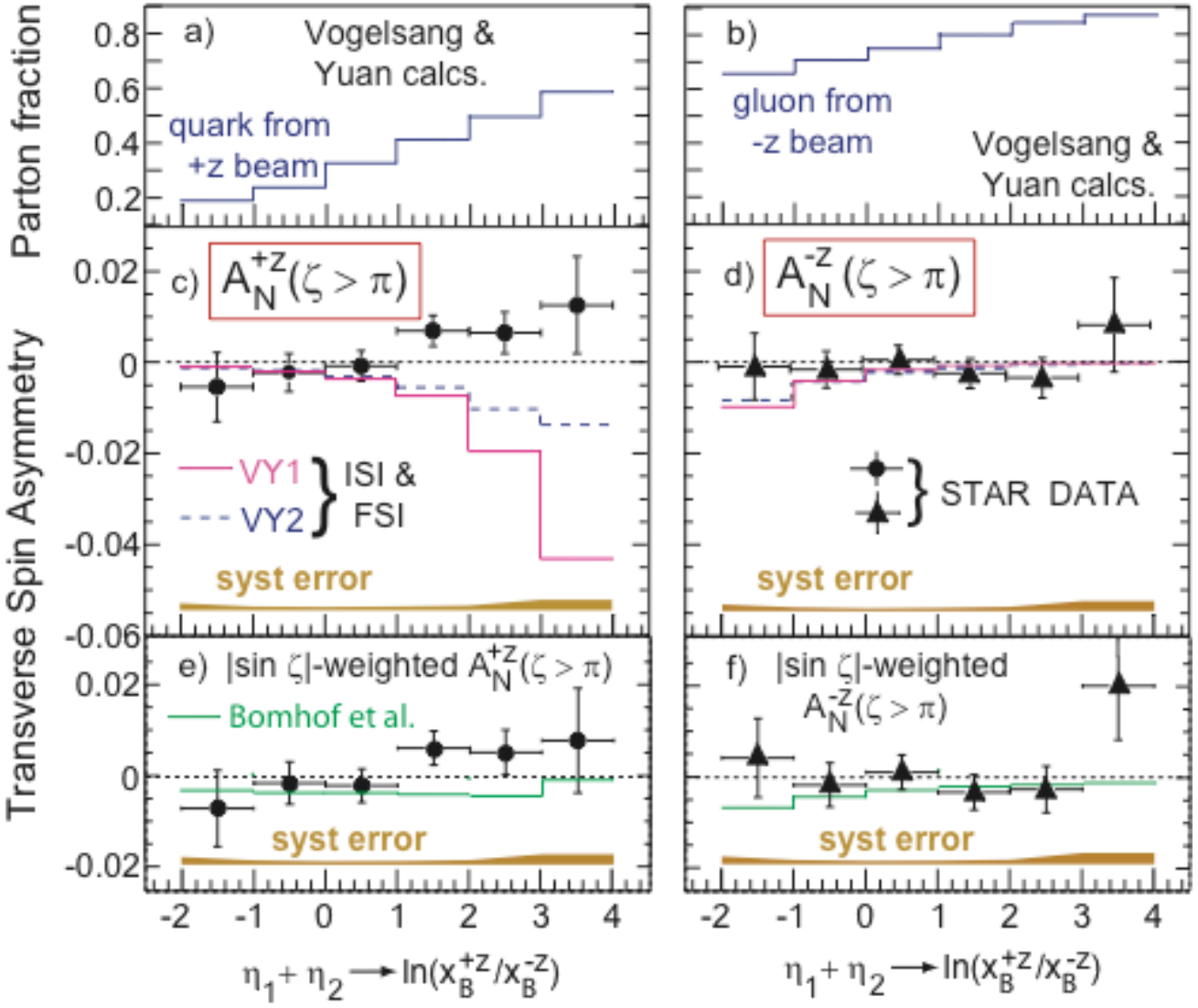
- $|\eta_{TPC}| < 0.9$; $2.8 < \eta_{FMS} < 3.8$;
- $2.5\text{GeV} < p_T^{(FMS)}$
- $1.5\text{GeV} < p_T^{(TPC)} < p_T^{(FMS)}$;
- $|z_{\gamma\gamma FMS}| < 0.7$; $0.07 < M_{\gamma\gamma} < 0.30$ GeV ;
- only leading particle considered , corrected for pile-up
- as proposed in hep-ex/0502040





- **Possible back-to-back di-jet/di-hadron Sivers measurements**
- **Low-x / gluon saturation study**
- **Step towards transverse spin forward photon-jet**

Measured Sivers A_N for mid-rapidity Di-jets



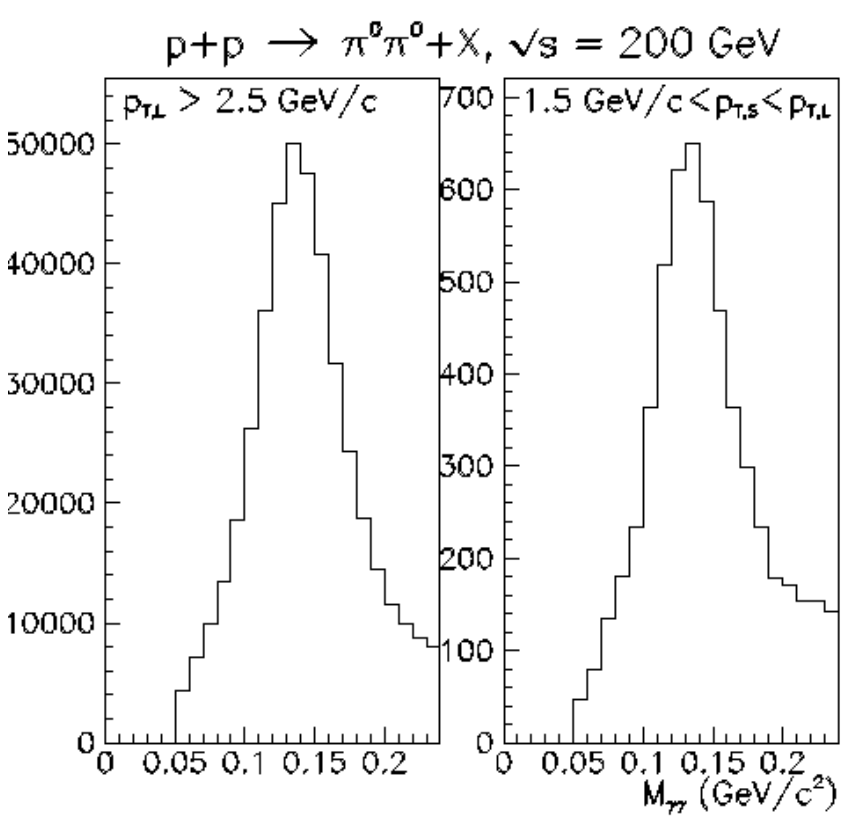
STAR A_N all consistent with zero

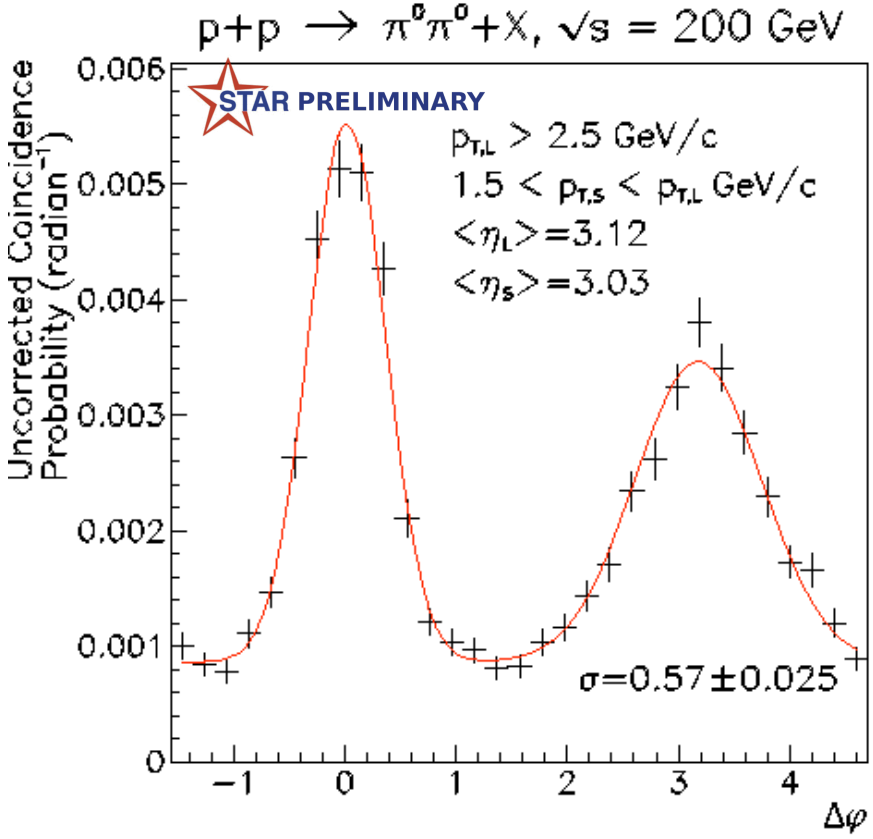
⇒

both net high-*x* parton and low-*x* gluon Sivers effects ~10x smaller in pp di-jets than SIDIS quark Sivers asym.!

Same measurement but at forward where $A_N^{\pi 0}$ is none zero

Forward pi0 (FMS) – Forward pi0(FMS) Azimuthal Correlations



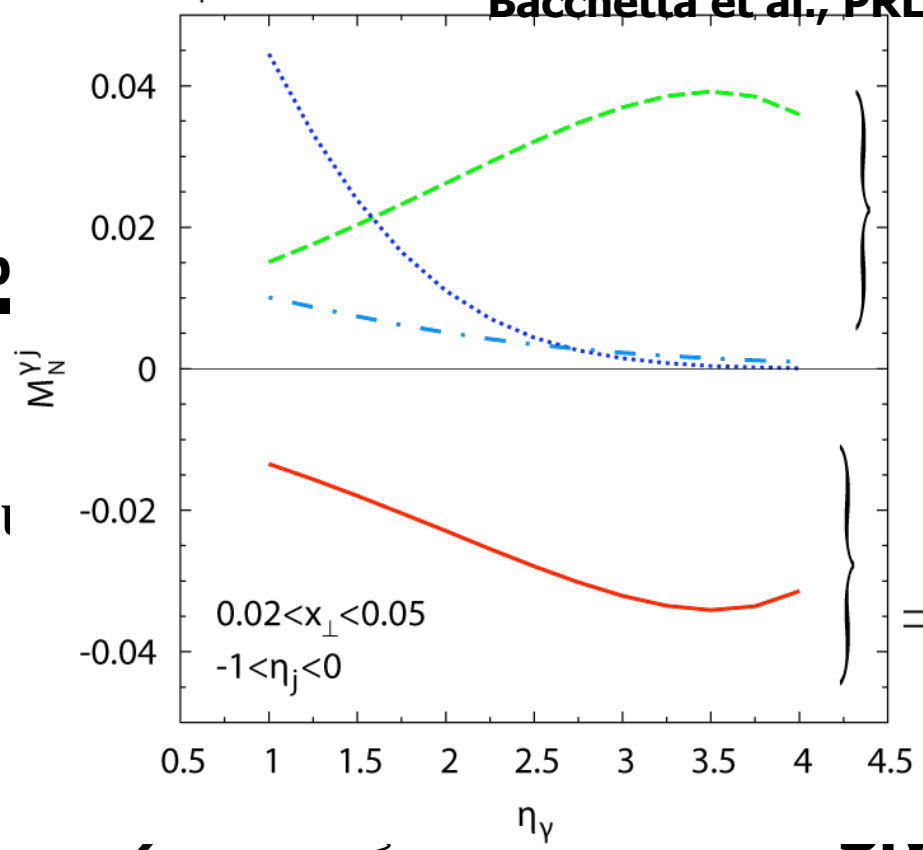


- Possible back-to-back di-jet/di-hadron Sivers measurement
- Possible near-side hadron correlation for Collins fragmentation function/Interference fragmentation function + Transversity
- Low-x / gluon saturation study – accessing lowest x_{Bj}^{gluon}

"Special" universality (breaking) of Sivers-F

$p_{\uparrow}+p \rightarrow \gamma+jet+X$, $\sqrt{s}=200$ GeV

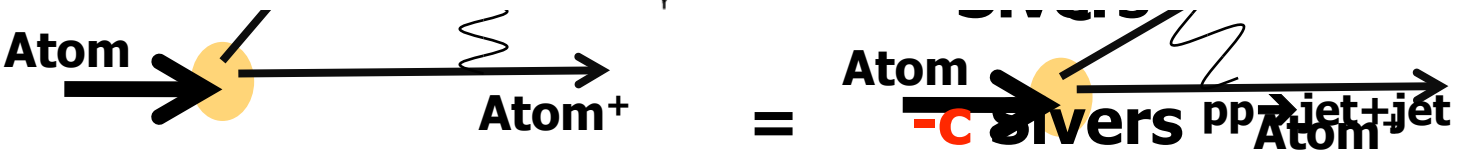
Bacchetta et al., PRL 99, 212002



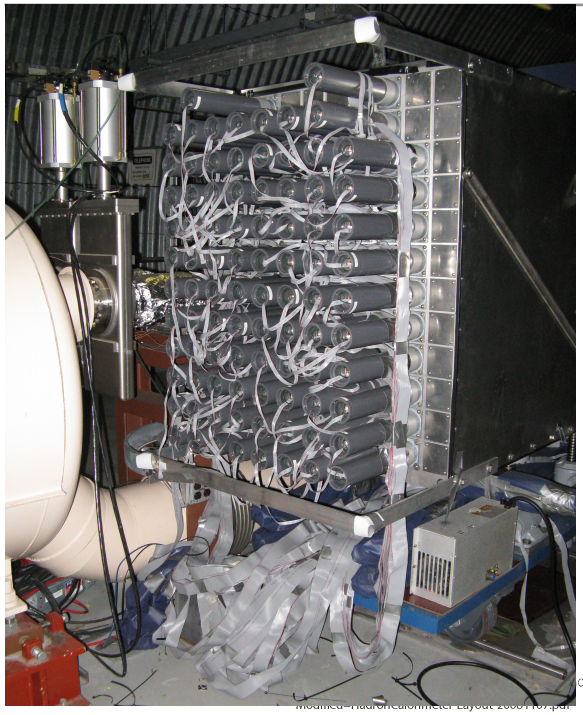
Conventional calculations

Color-charge interactions
⇒ sign change

QED Analogu



Forward Hadron Calorimeter (FHC)

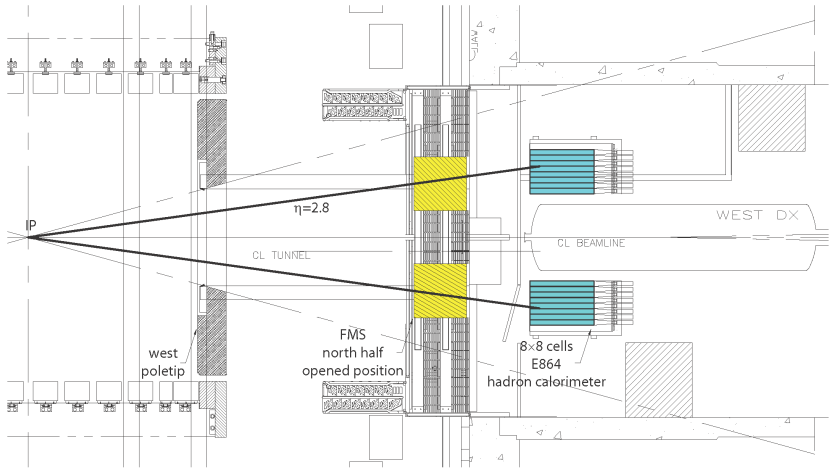


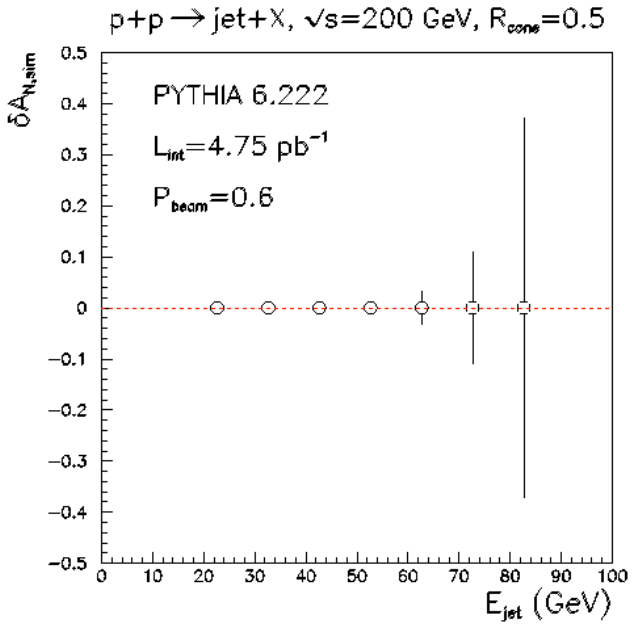
Real jet physics with FMS + FHC

Lambda, Photon (isolation)

BNL-AGS-E864 hadron calorimeter detectors Refurbished and used by PHOBOS

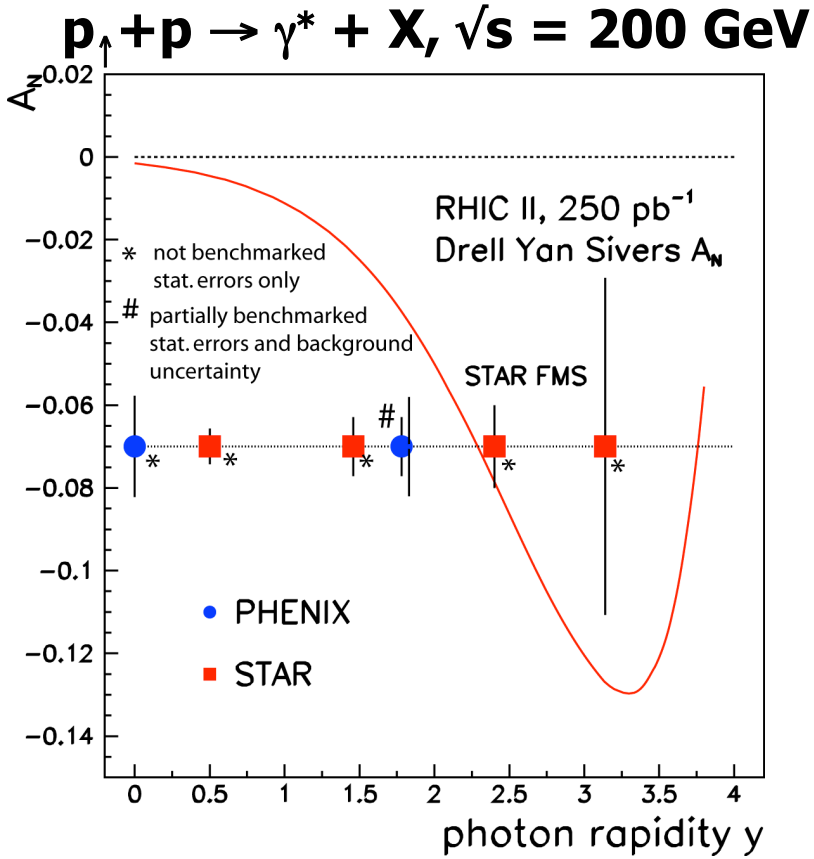
Estimated statistical precision for uncertainty in analyzing power for $p_{\uparrow}+p \rightarrow jet + X$ at $\sqrt{s}$ = 200 GeV.





Transverse Spin Asymmetries for the DY Process

http://spin.riken.bnl.gov/rsc/write-up/dy-final.pdf



Two 10-week runs in 2015 and 2016

with RHIC-II luminosity

detector upgrades (charge sign measurement at forward)

FMS Summary and Outlook

- **Forward Meson Spectrometer (FMS) is constructed & took data in run8!**

  Low-x physics (Can we see Gluon saturation? CGC?)

  New results at higher p_T for inclusive π^0

  Separate Sivers from Collins effects
  "Jet-like" events and π^0-π^0 correlations
  Near and away side jet-π^0 correlations

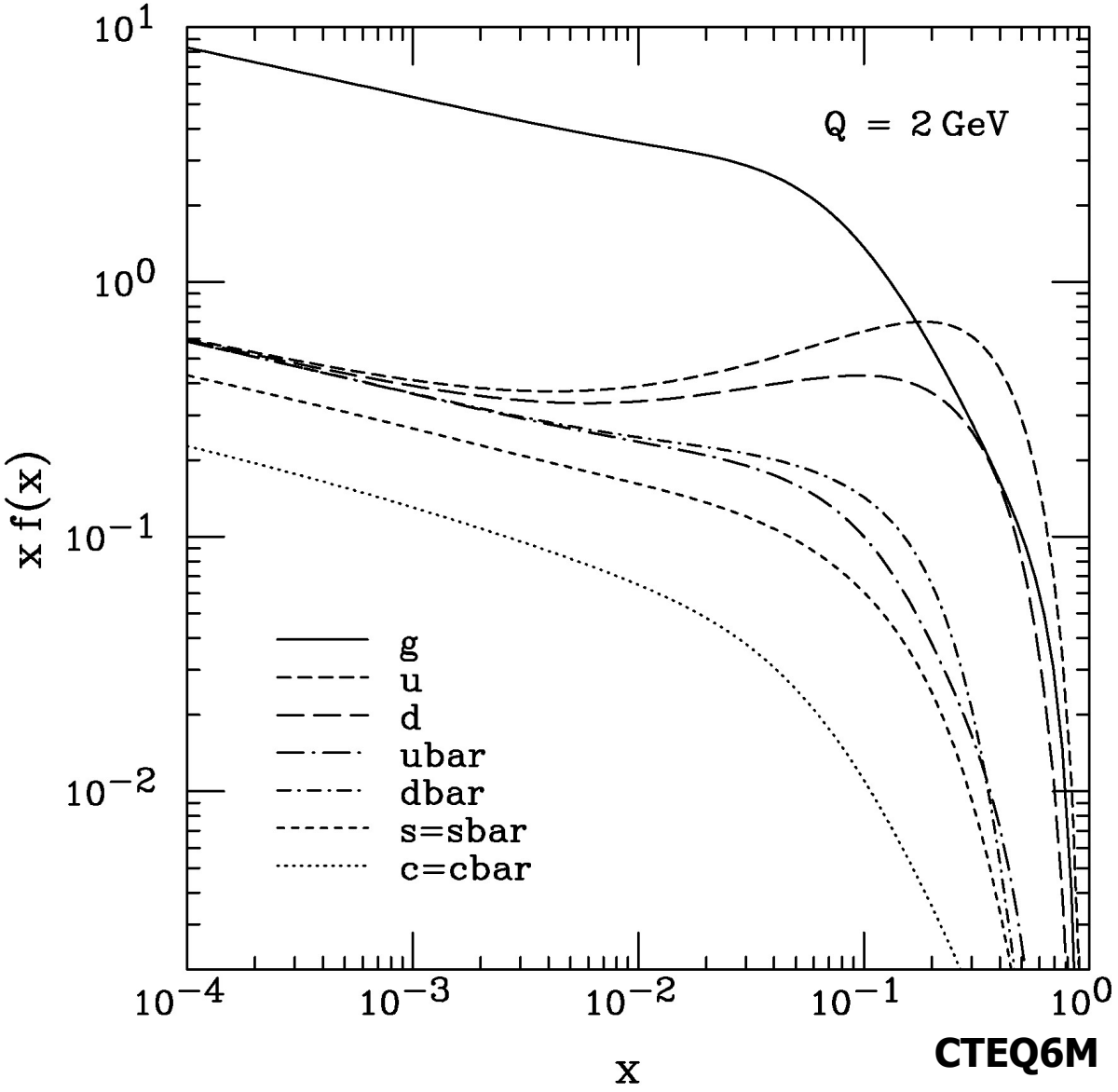
  Heavier mesons : Eta, ω, J/Ψ…

- **Direct Photon + Jet to test "sign change" of Sivers function**
- **Longitudinal spin at forward – run9**
- **Forward Hadron Calorimeter (FHC) behind FMS – run11**
- **DY - RHIC2 era**

End of talk

Quark and Gluon Distribution Function

Gluon DF cannot keep rising forever



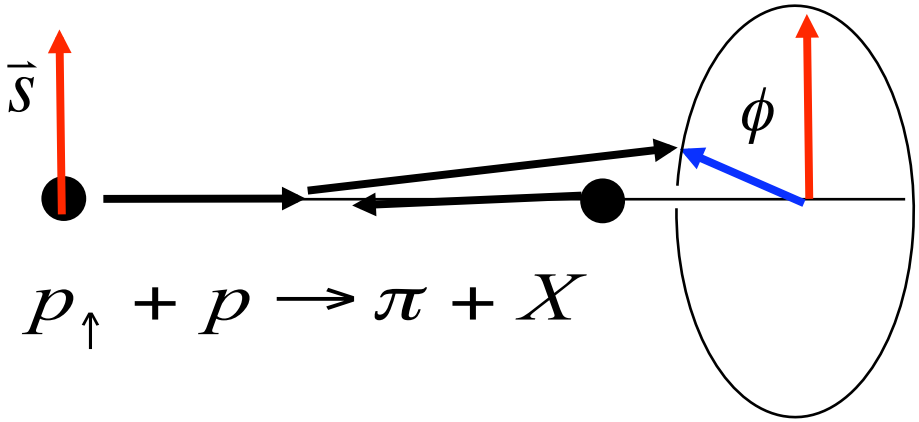
$$\int_0^1 x[u(x) + d(x)....]dx \sim 0.5$$

~50% of nucleon momentum is carried by quarks

$$\int_0^1 xg(x)dx \sim 0.5$$

~50% is by gluons

Another Spin Puzzle
Single Transverse Spin Asymmetry (A_N) in hadron collisions

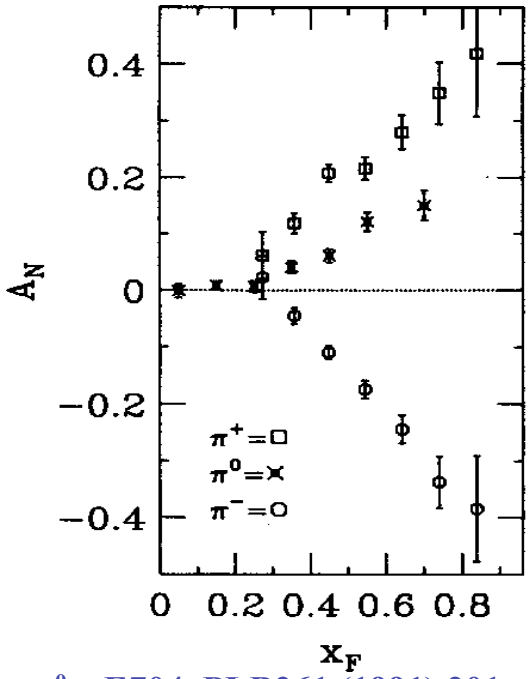


$$p_\uparrow + p \rightarrow \pi + X$$

$$\sigma = \sigma_0(1 + PA_N \sin\phi)$$

$$A_N = \frac{1}{P}\frac{N^{left} - N^{right}}{N^{left} + N^{right}}$$

√s=20 GeV, p_T=0.5-2.0 GeV/c



π^0 – E704, PLB261 (1991) 201.
$\pi^{+/-}$ - E704, PLB264 (1991) 462.

Kane, Pumplin, Repko PRL 41 1689 (1978)

$$A_N \sim \frac{m_q \alpha_s}{p_T} \sim 0.001$$

A_N is expected to be very small in pQCD
at leading twist and with collinear factorization

Twist-3 effect

k_T factorization &
Transverse Momentum Dependent (TMD) PDF

The Nucleon Spin Puzzle

~0.2 from DIS
"spin crisis"

RHIC Spin & SIDIS

GPD

Spin Sum Rules

Longitudinal $1/2 = 1/2\ \Delta\Sigma + \Delta G + L_L$

Transverse $1/2 = 1/2\ \delta\Sigma + L_T$

Bakker, Leader, Trueman
Phys.Rev.D70:114001,2004

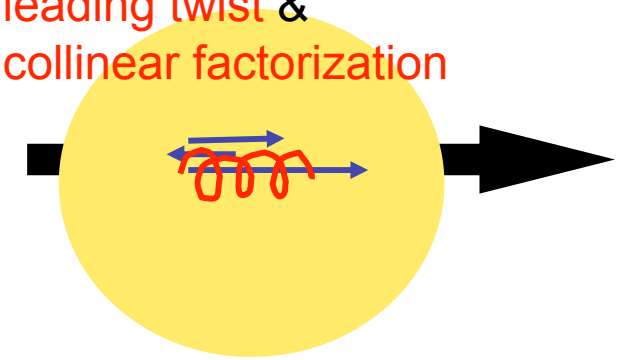
No gluon

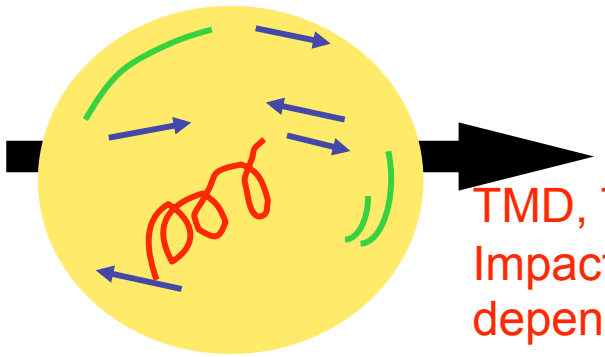
Sivers DF

Collins FF from Belle

SI-DIS & RHIC Spin

leading twist &
collinear factorization

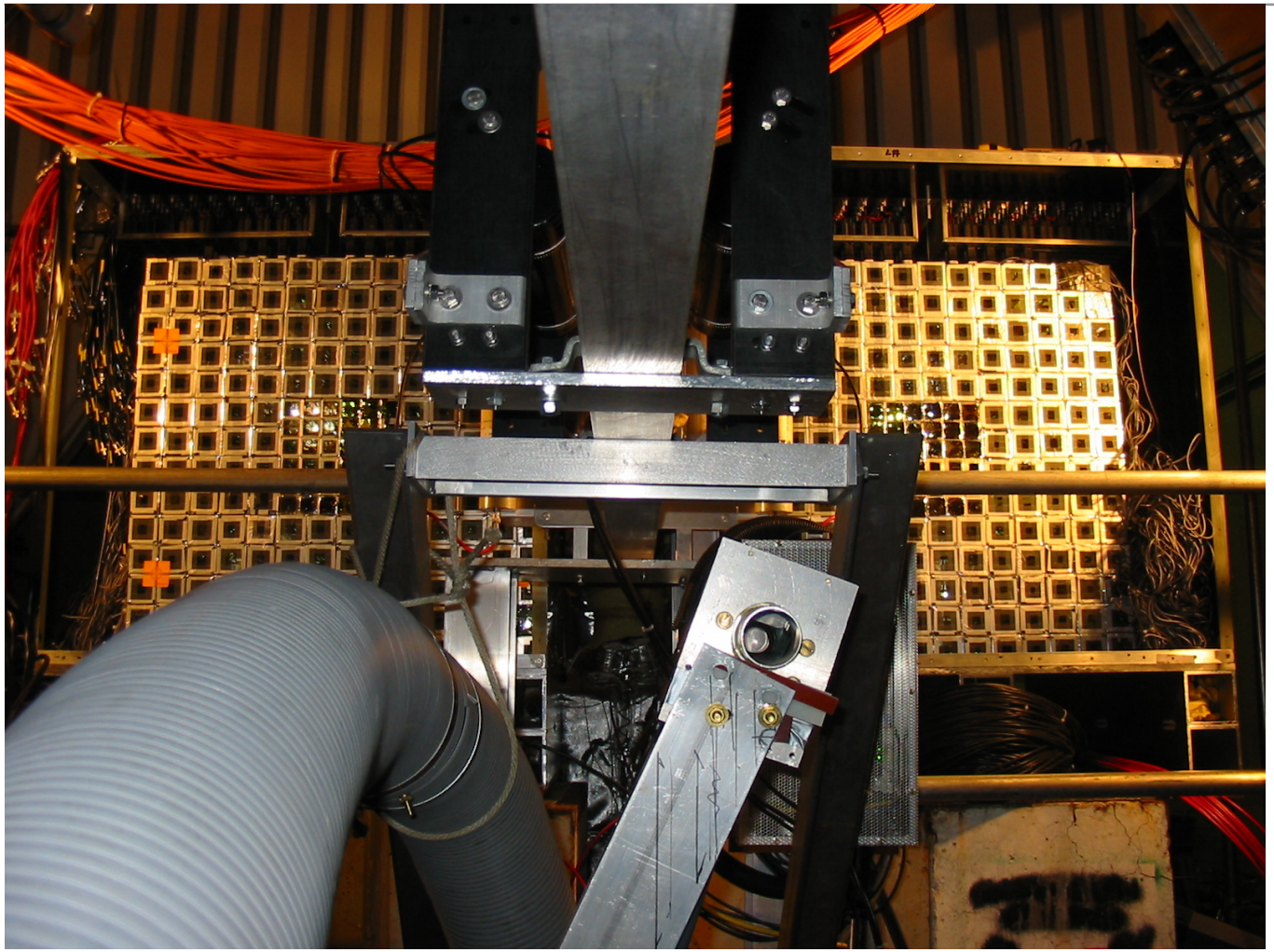




TMD, Twist-3 CF, GPD,
Impact parameter
dependent PDF, etc

Collinear & leading twist is too simplified picture to understand spin of nucleons

STAR Forward Pion Detector (FPD)



Run6

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++/FPD:

$\eta \sim 3.3 - 4.1$

FPD++: engineering test of the Forward Meson Spectrometer