Parton Dynamics at PHENIX

Joe Osborn

University of Michigan

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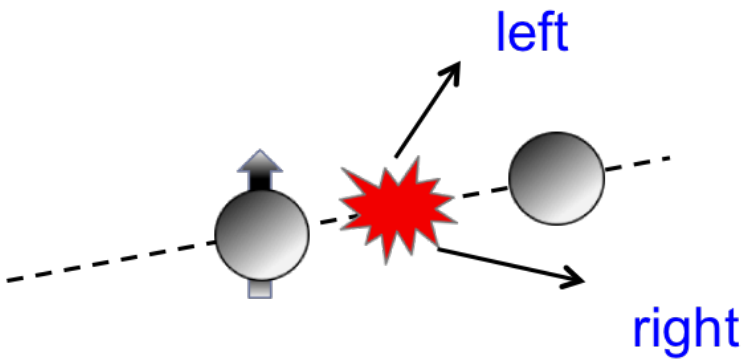
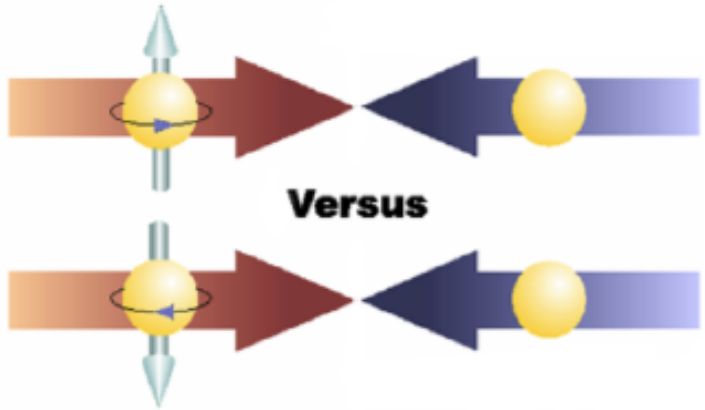
Outline

- Motivation for studying parton dynamics
- Intrinsic partonic transverse momentum
- New upgrade MPC-EX at PHENIX
- Summary

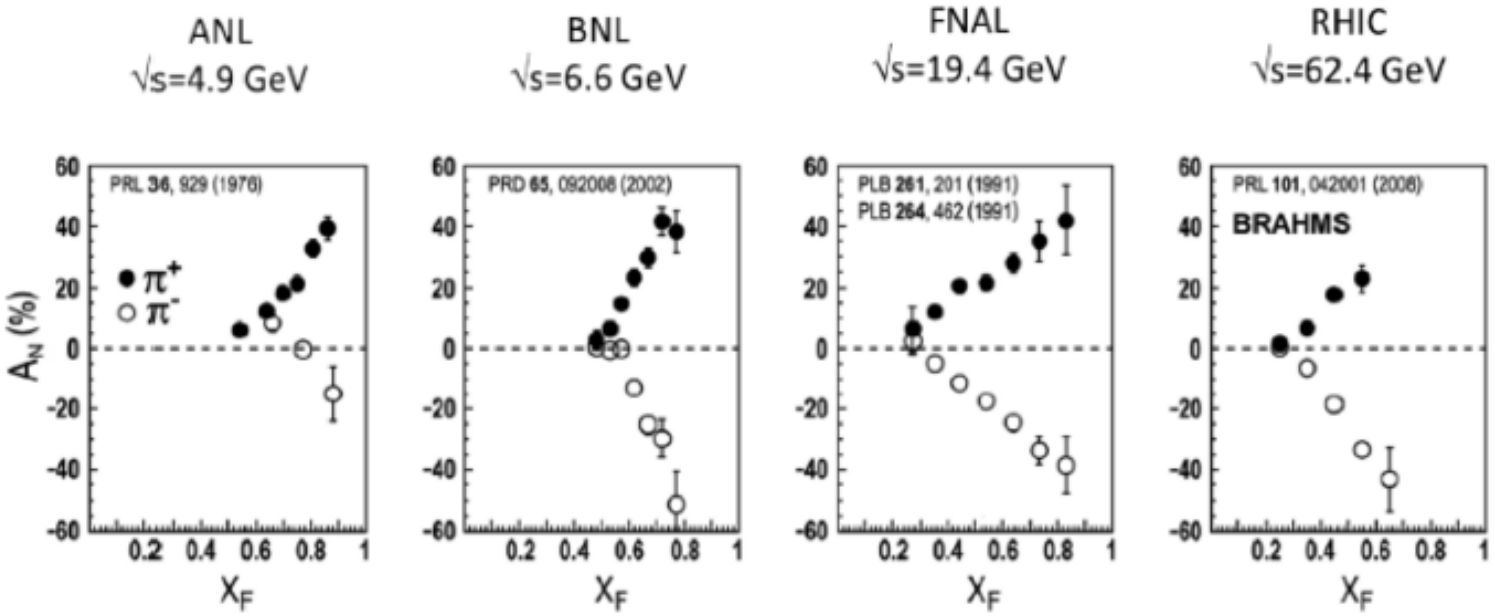
Transverse Single Spin Asymmetries

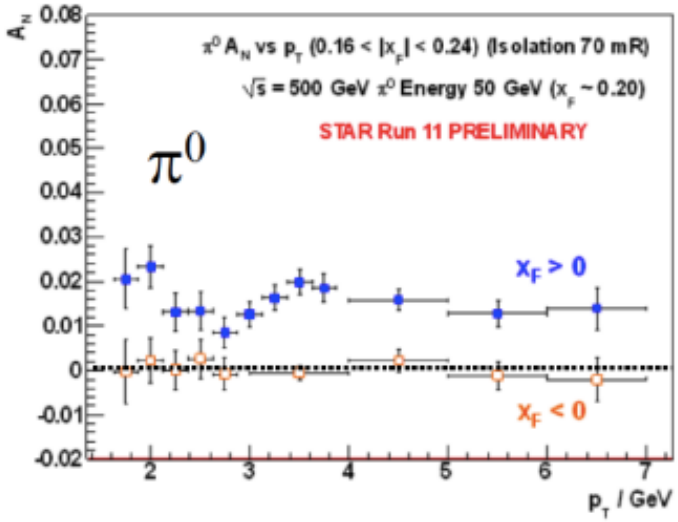
- Large asymmetries observed in polarized $p + p$
- pQCD prediction very small, $\approx 0.1\%$
- Non-perturbative effects
- Frontier in QCD... Finally have the theoretical abilities to study parton dynamics!





Transverse Single Spin Asymmetries





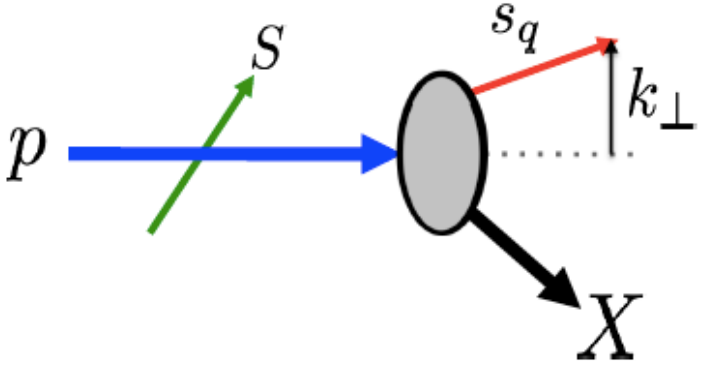
$$x_F = \frac{2p_L}{\sqrt{s}}$$

- Asymmetry huge over broad range of $\sqrt{s}$
- Non-zero even at $Q^2 \approx 49$ $[\mathrm{GeV/c}]^2$ and $\sqrt{s} = 500$ GeV

Initial vs. Final State Effects

Initial-state effects:
(e.g.) Sivers transverse-momentum-dependent parton distribution function

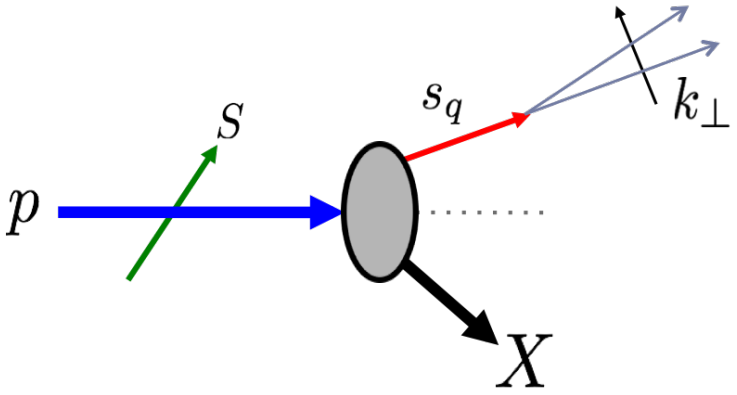
$$f_{1T}^{\perp}(x, k_{\perp}^2) \cdot D_q^h(z)$$



Correlation between proton-spin and quark orbital angular momentum

Final-state effects:
(e.g.) Collins transverse-momentum-dependent fragmentation function

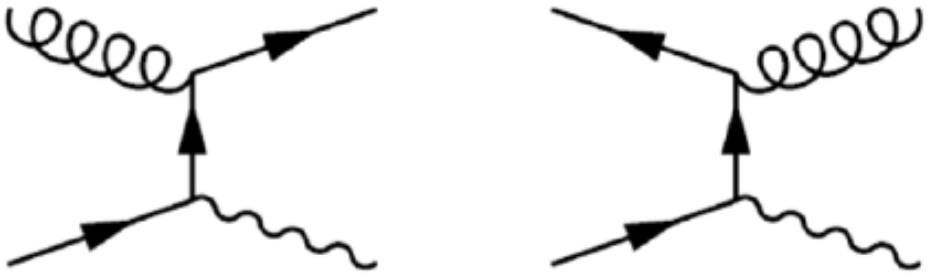
$$h(x) \cdot D_q^{\perp}(z, k_{\perp}^2)$$



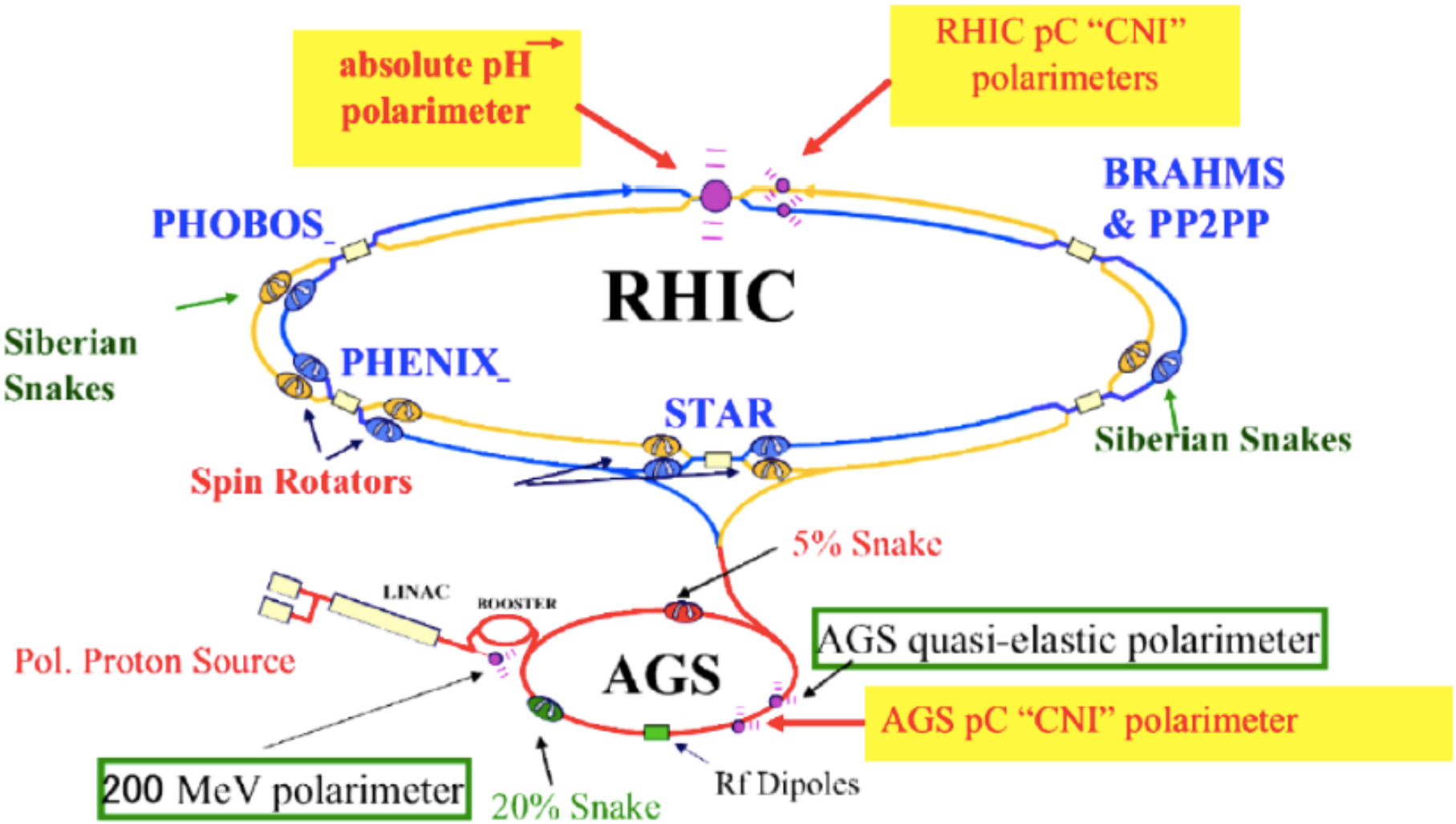
Correlation between final-state quark spin and hadron orbital angular momentum

Direct Photons

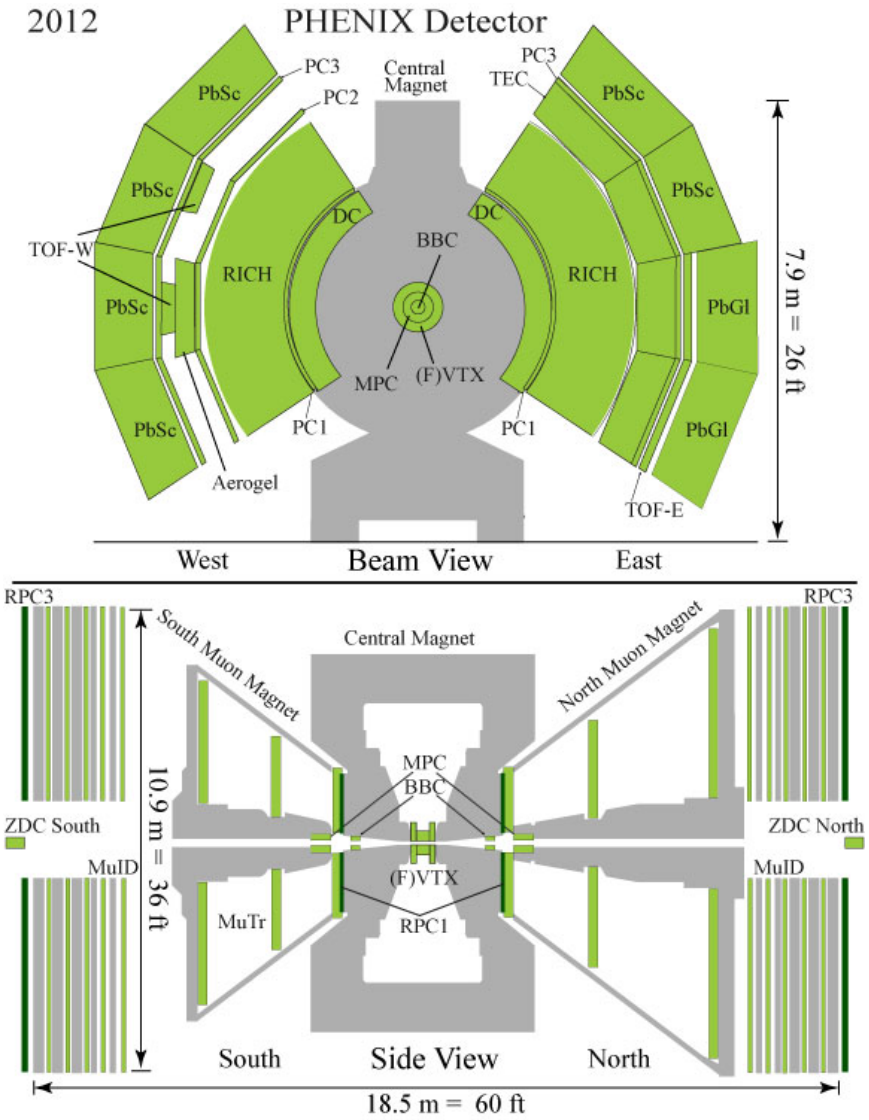
- In order to isolate initial-state from final-state, look for direct photons
- Therefore can gain access to non-perturbative initial-state effects!
- Understanding initial-state effects is (one of) the goals of the MPC-EX and PHENIX spin program



RHIC

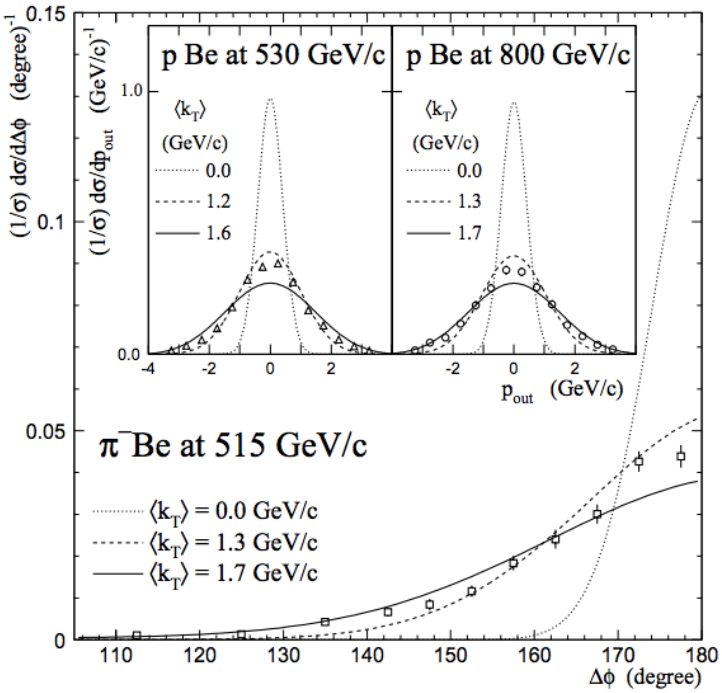

absolute pH polarimeter
RHIC pC "CNI" polarimeters
BRAHMS & PP2PP
PHOBOS
RHIC
Siberian Snakes
PHENIX
STAR
Siberian Snakes
Spin Rotators
5% Snake
LINAC
BOOSTER
Pol. Proton Source
AGS
AGS quasi-elastic polarimeter
AGS pC "CNI" polarimeter
200 MeV polarimeter
20% Snake
Rf Dipoles

PHENIX

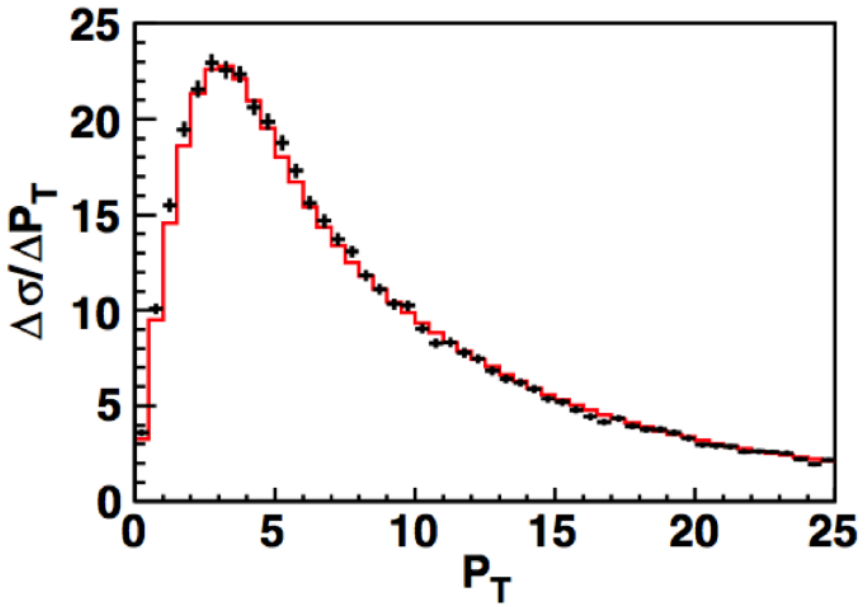


- Central arms ($|\eta| \leq 0.35$)
  - EMCal
  - Drift Chamber
- Forward arms ($3.1 < |\eta| < 3.8$)
  - MPC EMCal
  - New MPC-EX preshower

Intrinsic Partonic Transverse Momentum



PRL 81, 2642

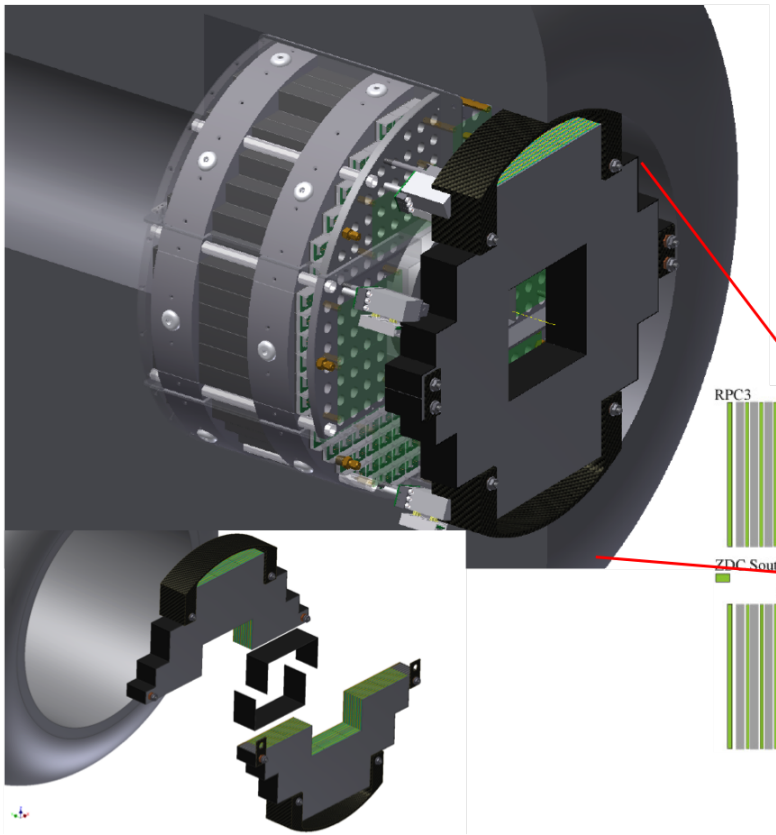


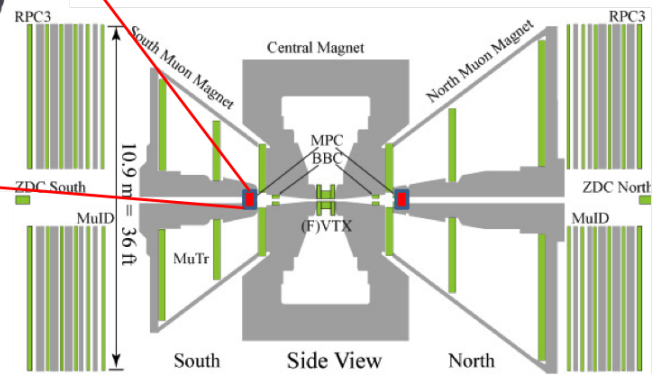
PRD 86, 052010 (2012)

- Angular correlations between direct photons and away side hadrons gives access to intrinsic k_T
- Drell-Yan Z boson cross section from CDF shows non-perturbative effects at low p_T
- Ongoing work to measure at $\sqrt{s} = 510$ GeV at PHENIX

MPC-EX Preshower Detector

- At forward directions, where spin-momentum effects are known to be large, $\pi^0 \to \gamma\gamma$ background to direct photons very large
- At PHENIX, solution is adding pre-shower MPC-EX to existing calorimeter MPC



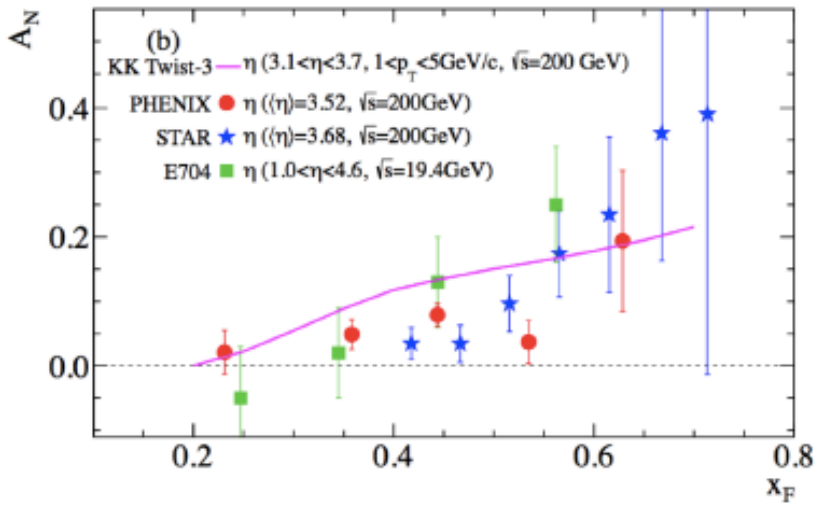


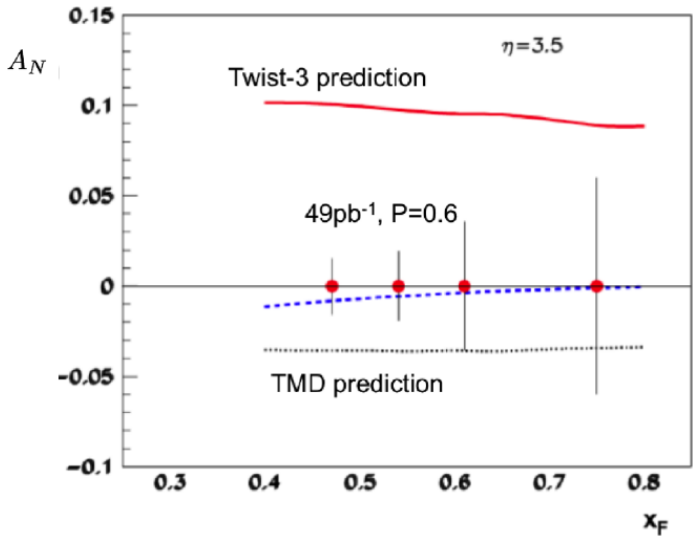
- π^0 reconstruction up to 80 GeV due to increased 2 photon resolution

Spin-Momentum Correlations with the MPC-EX

- Transverse single-spin asymmetry measurements
  - π^0 up to $x_F \approx 0.8$
  - η up to $x_F \approx 0.95$
  - Direct photons enabled by increased background rejection
- MPC-EX status
  - MPC-EX just finished collecting data for the first time this summer in $\sqrt{s} = 200$ GeV collisions
    - $p^{\uparrow} + p$ ($\sim$60 pb^{-1})
    - $p^{\uparrow} + Au$ ($\sim$205 nb^{-1})
    - $p^{\uparrow} + Al$ ($\sim$450 nb^{-1})
  - Analysis efforts underway now!

PRD 90, 072008





PRD 83, 094001 (2011)

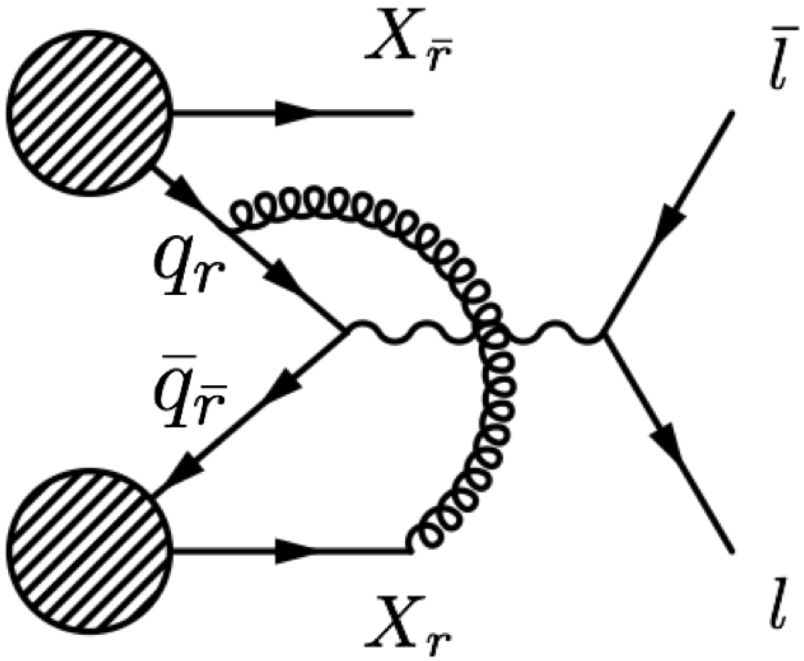
Summary

- Parton dynamics a new frontier in QCD!
- Strong spin-momentum correlations lead to large asymmetries, in particular in forward region
- Intrinsic partonic transverse momentum measured, ongoing work to measure at higher $\sqrt{s}$ at PHENIX
- New pre-shower MPC-EX aims to better understand origins of large asymmetries

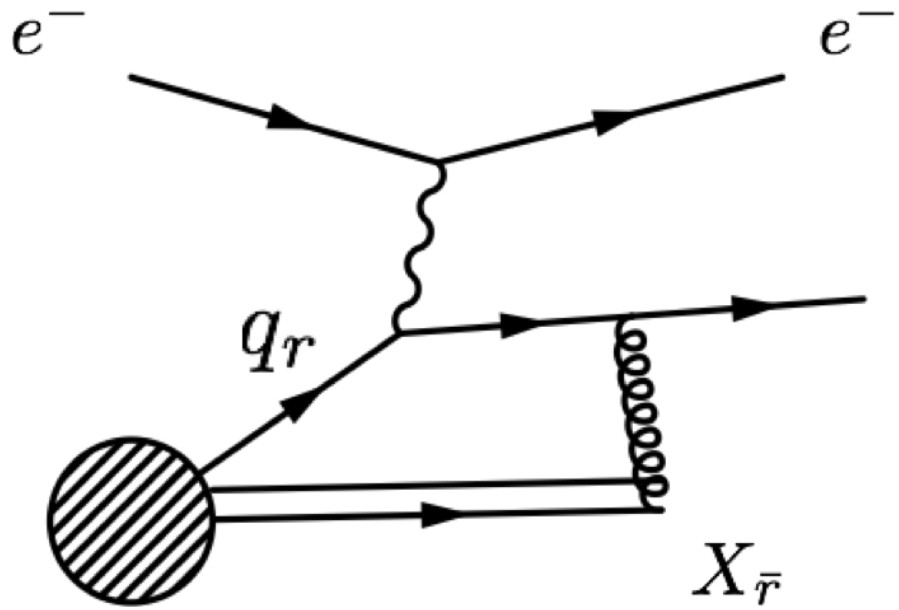
BACK UP

Sivers Function Universal?

Drell Yan



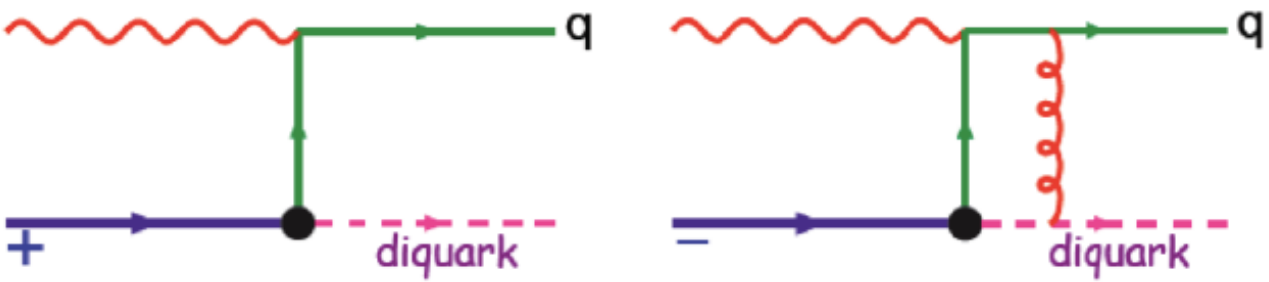
SIDIS



Sivers Sign Change

gauge links have physical consequences;
quark models for non vanishing Sivers function,

SIDIS final state interactions



Brodsky, Hwang, Schmidt, PL B530 (2002) 99 - Collins, PL B536 (2002) 43

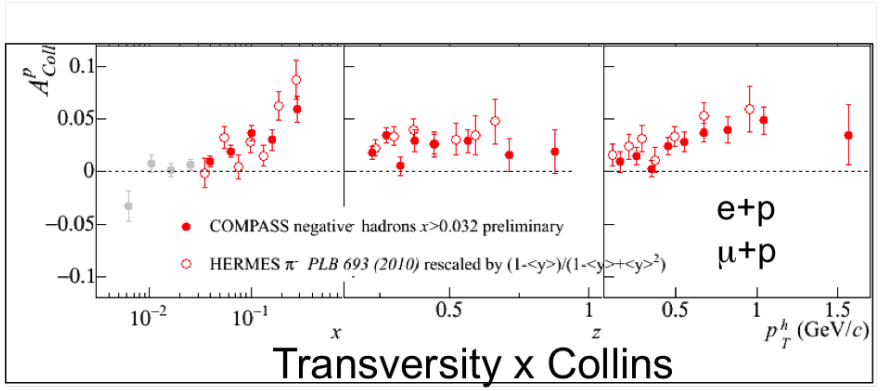
An earlier proof that the Sivers asymmetry vanishes because of time-reversal invariance is invalidated by the path-ordered exponential of the gluon field in the operator definition of parton densities. Instead, the time-reversal argument shows that the Sivers asymmetry is reversed in sign in hadron-induced hard processes (e.g., Drell-Yan), thereby violating naive universality of parton densities. Previous phenomenology with time-reversal-odd parton densities is therefore validated.

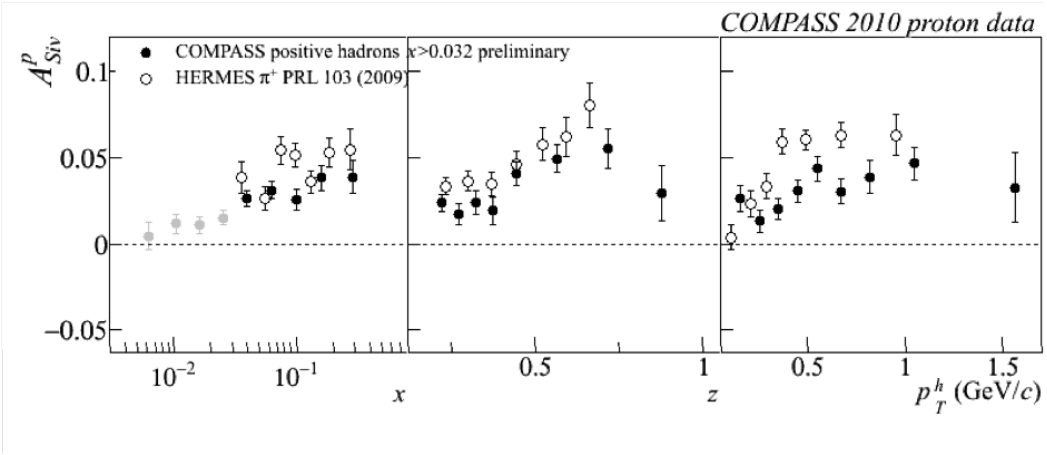
$$[f_{1T}^{q\perp}]_{\rm SIDIS} = -[f_{1T}^{q\perp}]_{\rm DY}$$

Figure from M. Anselmino, Transversity 2014

TMDs in SIDIS

- Measurements of Sivers and Collins Function in SIDIS at HERMES and COMPASS
- No measurements in $p + p$ (yet)





Twist-3 and TMD

- TMDs
  - One momentum scale to probe nonperturbative transverse momentum

$$Q_1 \sim \lambda_{QCD}$$

  - One momentum scale to ensure pQCD

$$Q_2 \gg \lambda_{QCD}$$

  - Example in SIDIS

$$\lambda_{QCD}^2 \lesssim p_{h\perp}^2 \ll Q^2$$

- Collinear PDFs/FFs (twist-3)
  - One observed energy scale

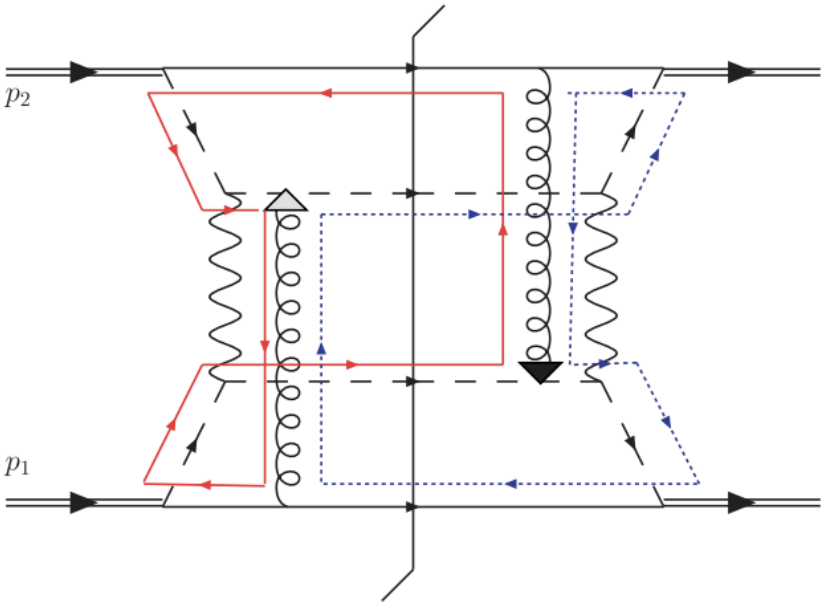
$$Q_1 \gg \lambda_{QCD}$$

  - Collinear PDFs/FFs

$$f(x, Q^2)$$

  - Integrated over parton transverse momenta

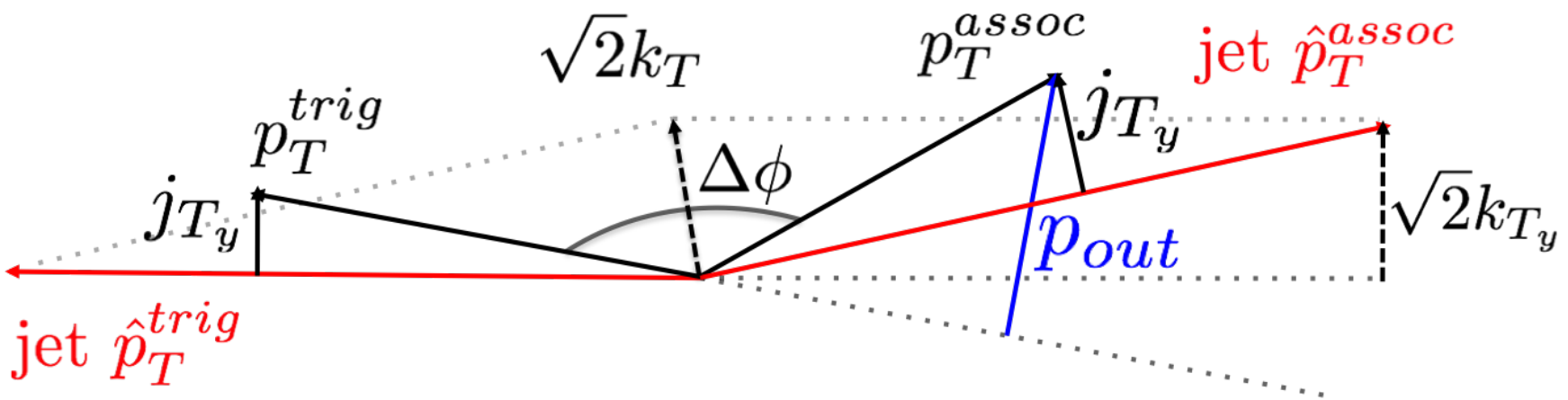
TMD-Factorization Breaking and Color Entanglement



PRD 81, 094006

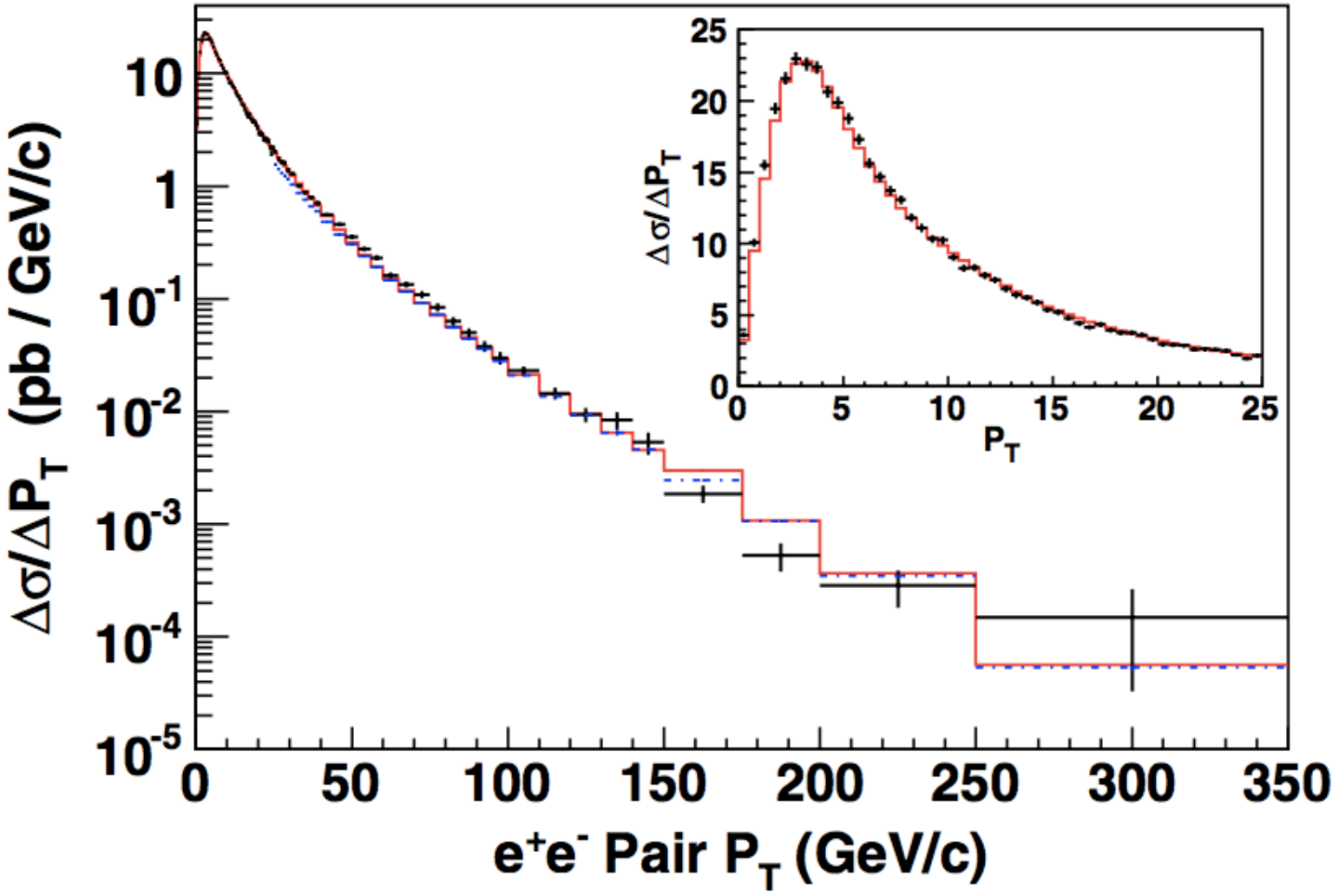
- Color entanglement predicted in 2010 if quark transverse momentum taken into account
- Quarks correlated across protons, similar to quantum entanglement
- Large asymmetries a color entanglement effect?

Intrinsic Partonic Transverse Momentum



- Need baseline measurement to understand intrinsic partonic transverse momentum
- Direct photon replaces jet p_T^{trig}
- Measure $\Delta\phi$ correlations with direct photon and associated charged hadrons

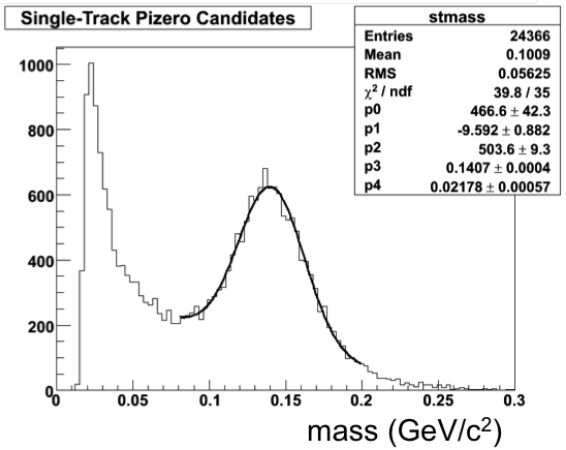
CDF Z Cross Section

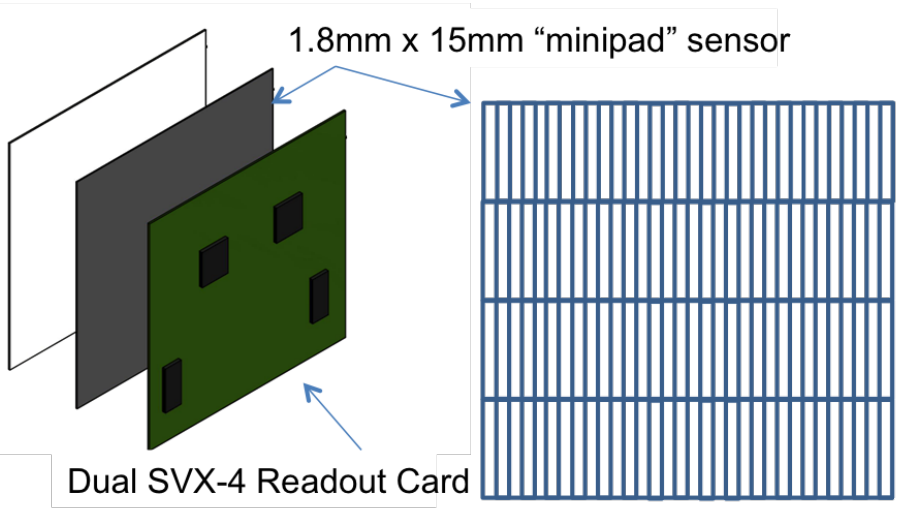


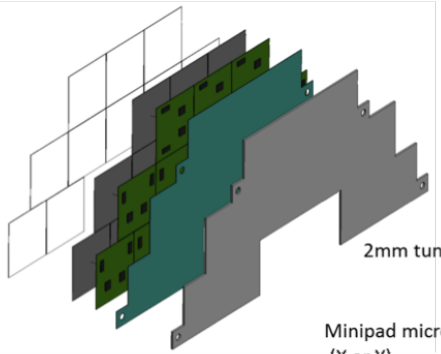
MPC-EX Minipad Sensors

Detector elements are Si "minipad" detectors, one per tungsten gap, oriented in X and Y (alternating layers).

π^0 mesons reconstructed in p+p jet events (E>20GeV)







Cross-Section View: