Parton Dynamics in High Energy Proton-Proton Collisions at PHENIX

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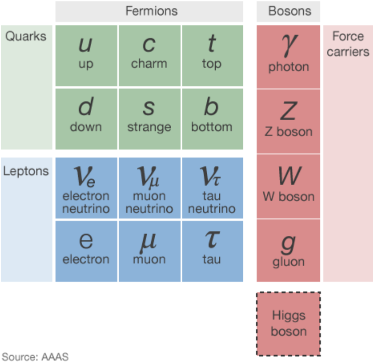
PGSS Seminar

July 8 2015

Outline

- Quantum Chromodynamics
- Nucleon Landscape
- Transverse partonic motion
- Relativistic Heavy Ion Collider and PHENIX Experiment
- MPC-EX detector upgrade

The Standard Model

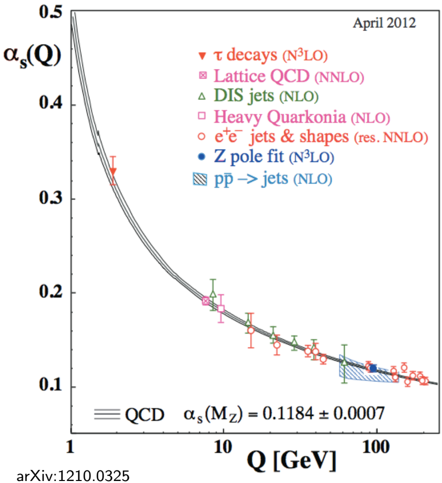


Source: AAAS

- 4 forces in physics
  - Weak
  - Electric
  - Gravitational
  - Strong
- Quarks and gluons interact strongly
- Quantum Chromodynamics

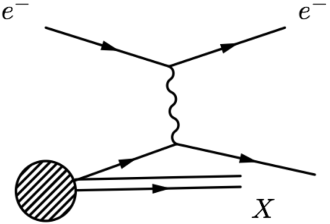
QCD

- Proton structure
  - Quarks
  - Gluons
- Asymptotic Freedom
- Confinement
- Color charge
- Self coupling gluon
- How do we look inside the proton?



arXiv:1210.0325

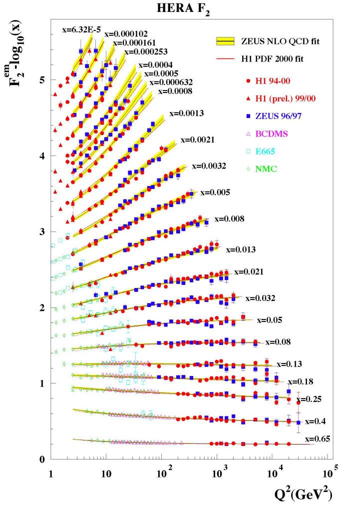
Electron Scattering: A clean channel



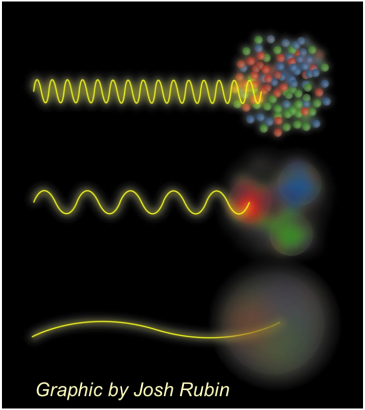
- Deep Inelastic Scattering (DIS) revealed inner structure to proton
- Structure at low momentum fraction x

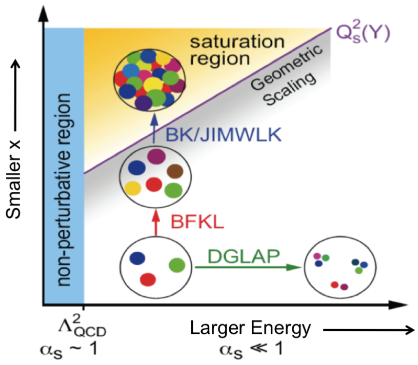
$$x = \frac{p_{quark}}{p_{proton}}$$

$$Q^2 = -q^2 = (p_1 - p_3)^2$$

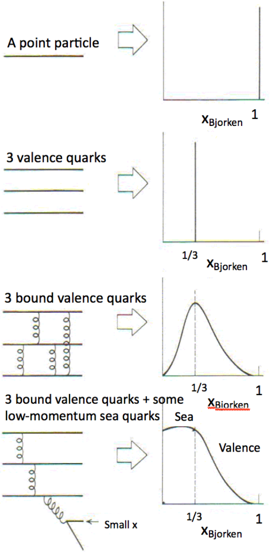


Nucleon Landscape

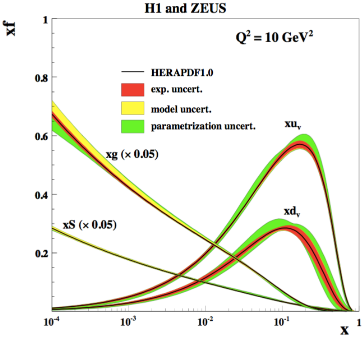




Parton Distribution Functions



- Non-perturbative functions
- Require experimental input, can't just calculate!

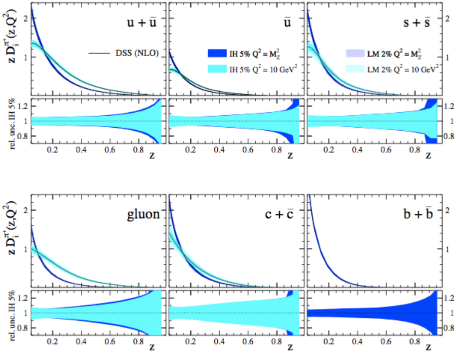


arXiv:hep-ex/0911.884

Fragmentation Functions

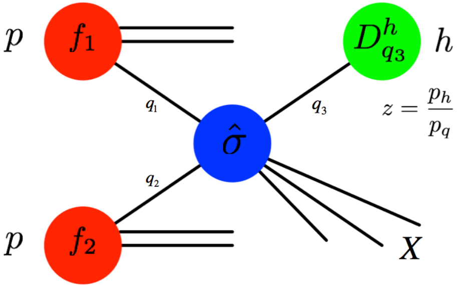
- Similar theoretical footing with Parton Distribution Functions
- Non-perturbative functions
- Probability of a quark fragmenting to a particular hadron

$$z = \frac{p_{hadron}}{p_{quark}}$$



arXiv:1209.3240

QCD Factorization



- Non-perturbative (long scale) parton distribution functions f_1, f_2 and fragmentation functions $D^h_{q_3}$
- Perturbative (short scale) calculable partonic hard scattering cross section $\hat{\sigma}$
- Convolution of three gives total cross section

$$\sigma \propto f_{q_1}(x_2, Q^2) \otimes f_{q_2}(x_2, Q^2) \otimes \hat{\sigma}_{q_1 q_2 \to q_3} \otimes D^h_{q_3}(z_{q_3}, Q^2)$$

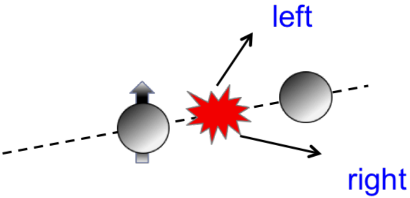
So what?

- We seem to have a good understanding of what's going on in the proton, right?
- Parton distrbution functions describe initial partonic states
- Fragmentation functions describe final hadronizing states
- Theorists calculate partonic hard scattering cross section in perturbative QCD
- The convolution of these three things gives us our cross section
- So, let's pack up and go home. QCD good to go!

Transverse Single Spin Asymmetries (TSSA)

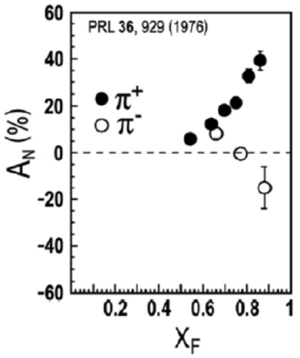
- Observable that we measure
- Measure final state particles
  - π^0
  - η

$$A_N(\phi) = \frac{\sigma^{\uparrow}(\phi) - \sigma^{\downarrow}(\phi)}{\sigma^{\uparrow}(\phi) + \sigma^{\downarrow}(\phi)}$$



Transverse Single Spin Asymmetries

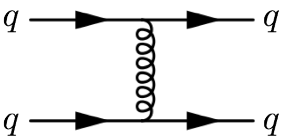
QCD Experiment



$$\sqrt{s} = 4.9\ \text{GeV}$$

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

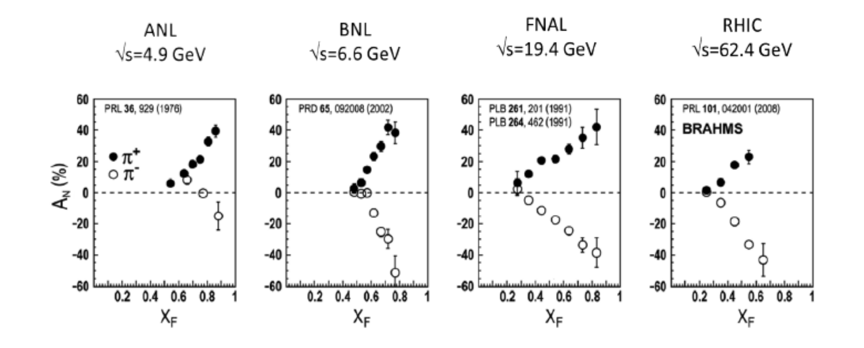
Perturbative QCD Calculation



$$A_N \propto \frac{m_q}{\sqrt{s}} \approx 0.1\%$$

Kane,Pumplin,Repko (1978)

What about in REAL perturbative QCD Regime?



- Asymmetry survives well into perturbative QCD regime
- Perturbative QCD wrong??

Figure by Christine Aidala

Transverse Momentum Dependent Parton Distribution Functions

- Perturbative QCD not wrong, just need to look deeper...
- What about transverse motion of quarks?
- Traditional parton distribution functions only consider collinear quark motion

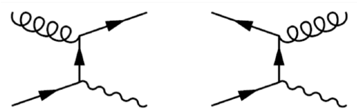
- Transverse Momentum Dependent parton distribution function proposed by Dennis Sivers in 1991
  - Relation between inital state L_q and S_p?

$$f(x, Q^2) \rightarrow f(x, k_T; Q^2)$$

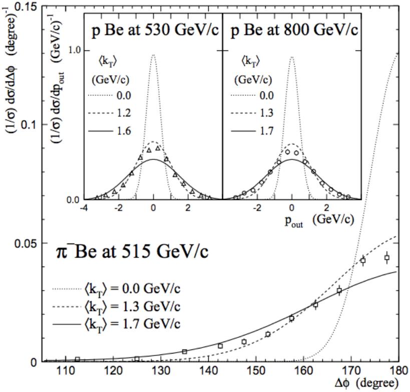
- Transverse Momentum Dependent Fragmentation Function proposed by John Collins in 1993
  - Relation between final state S_q and L_h?

$$D_q^h(z, Q^2) \rightarrow D_z^h(z, p_T; Q^2)$$

Intrinsic Transverse Momentum

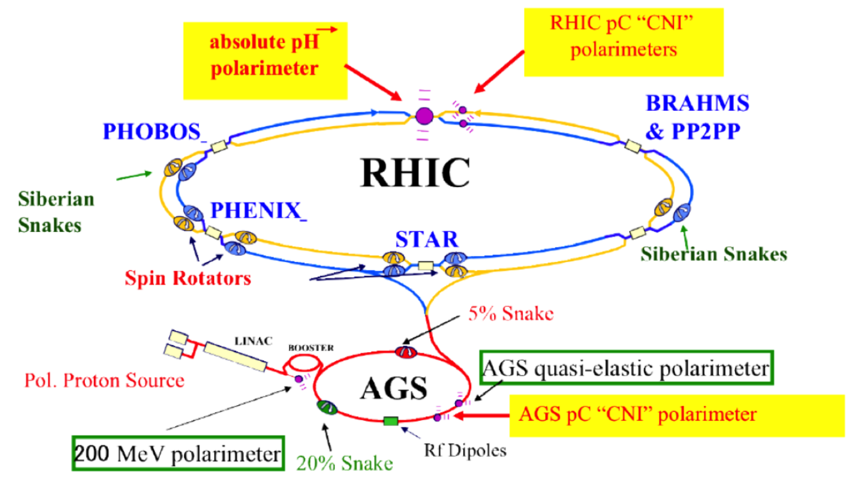


- Two leading order processes above give photon+jet
- At leading order photon+jet emerge exactly back to back
- Smearing of away side jet indicates intrinsic partonic k_T

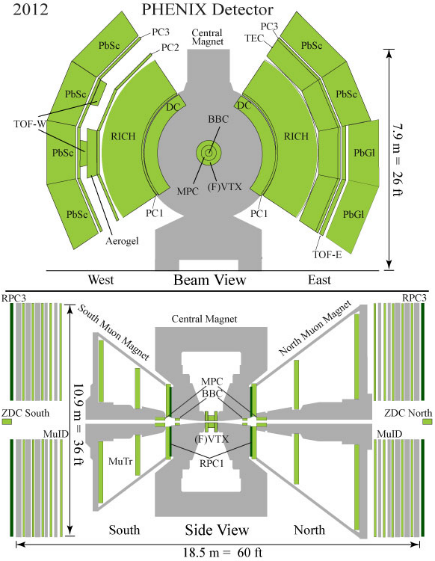


PRL 81,2642

Relativistic Heavy Ion Collider (RHIC)



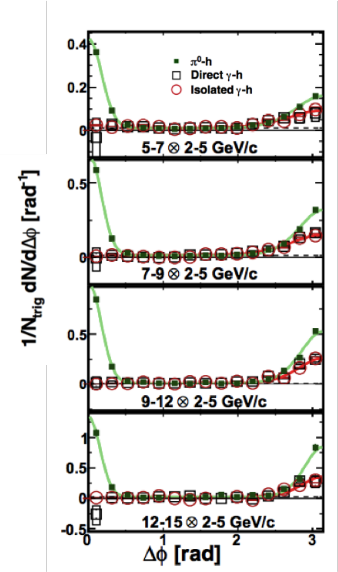
PHENIX



- Mid-rapidity ($|\eta| < 0.35$)
  - EMCal
  - Charged Particle Tracking
- Forward rapidity ($3.1 < |\eta| < 3.8$)
  - MPC
  - New upgrade MPC-EX

PHENIX Central Arms

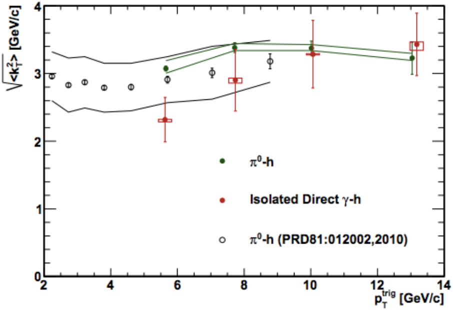
- Central arm calorimetry gives access to direct photon production
- Correlations analyzed in both $p+p$ and $Au+Au$ collisions



PRD 82, 072001

PHENIX Central Arms

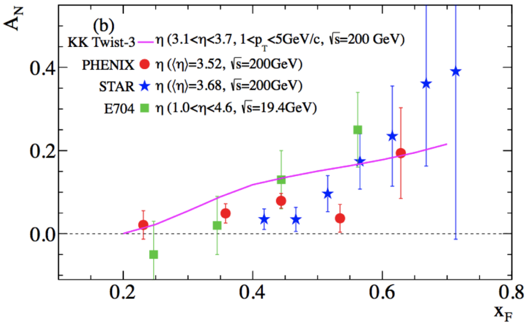
- PHENIX results at $\sqrt{s} = 200$ GeV
- Direct photon and π^0 triggers consistent



PRD 82, 072001

PHENIX Forward Calorimetry

- Effects from spin momentum correlations are known to be large in forward region
- In 2007 PHENIX installed MPC at $3.1 < |\eta| < 3.8$

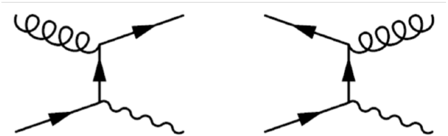


PRD 90, 072008

What Now?

- Evidence accumulated for partonic transverse dynamics abundant
- Where do we go from here?
- We want to better understand the underlying mechanisms that result in these transverse effects
- Problem: How do we differentiate initial state effects of transverse momentum from messy final state hadronization effects?

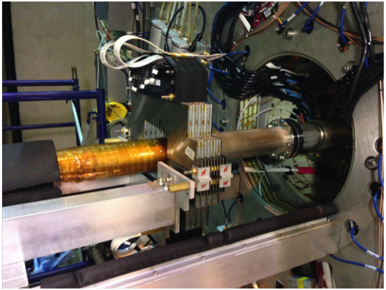
The Golden Channel



- Direct photons aptly named "the golden channel"
- Come directly from hard scattering $\rightarrow$ Contain partonic information
- No color charge $\rightarrow$ No hadronization effects!
- Problem: Background due to $\pi^0 \rightarrow \gamma\gamma$

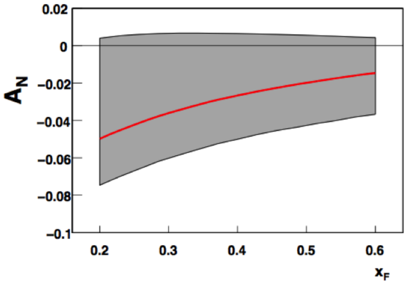
MPC-EX

- Solution: A pre-shower extension to the existing MPC, cleverly named the MPC-EX
- Allows for π^0 reconstruction up to 80 GeV
- Thus, much higher background rejection



MPC-EX

- Many measurements to make!
  - π^0 and η transverse single spin asymmetry over large x_F range
  - Direct photon transverse single spin asymmetry
- MPC-EX just finished taking first data set
- $\sqrt{s} = 200$ GeV transversely polarized $p + p$ and $p + Au$ runs



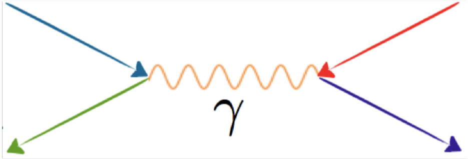
Summary

- The most basic building block of matter is actually pretty complicated!
  - 3 valence quark picture only accurate in certain momentum regimes
  - Partons carry some intrinsic transverse momentum
  - On top of that, incredibly large spin momentum correlations are seen
- PHENIX experiment at RHIC
  - RHIC has unique capability to polarize proton beams
  - PHENIX calorimetry in place to measure effects from partonic dynamics
- MPC-EX
  - New pre-shower detector to improve π^0 detection and rejection for direct photons
  - Just finished taking data for first time!

Thank You!

Back Up

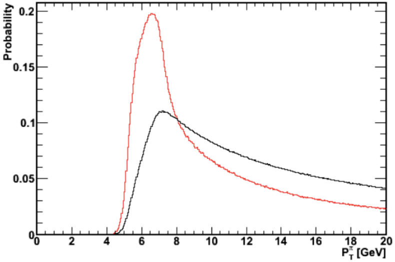
Measuring Fragmentation Functions



$$\sigma^{e^+e^-\to hX} \propto \sum \sigma^{e^+e^-\to q\bar{q}} \times (D_q^h + D_{\bar{q}}^H)$$

Statistical Subtraction Method

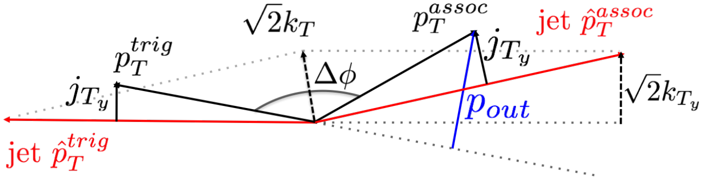
$$Y^{iso}_{direct} = \frac{1}{R^{iso}_{\gamma} - 1}\left(R^{iso}_{\gamma} Y^{iso}_{inclusive-tag} - Y^{iso}_{decay}\right)$$



$$R^{iso}_{\gamma} = \frac{R_{\gamma}}{(1-\epsilon^{tag}_{decay})(1-\epsilon^{niso}_{decay})} \frac{N_{inclusive} - N_{tag} - N_{isolated}}{N_{inclusive}}$$

$$\epsilon^{decay}_{tag} = \frac{N^{tag}_{decay}}{N_{inc}} R_{\gamma}$$

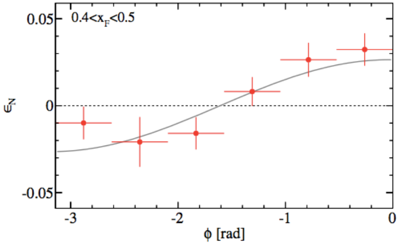
$$\epsilon^{niso}_{decay} = \left(1 + \frac{\sum_{\pi} P^{rem-tag}(p^{\gamma}_{T}, p^{\pi}_{T}) N^{iso}_{\pi}}{\sum_{\pi} P^{rem-tag}(p^{\gamma}_{T}, p^{\pi}_{T}) N^{niso}_{\pi}}\right)^{-1}$$



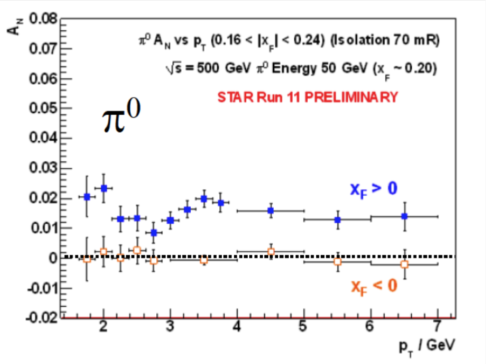
TSSA Methods

$$A_N = \frac{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} - \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} + \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}$$

- Measure particle production as a function of azimuthal angle and polarization of beam



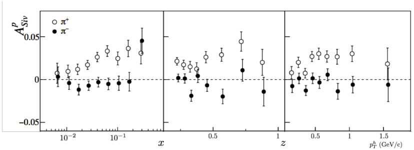
Keep goin' up



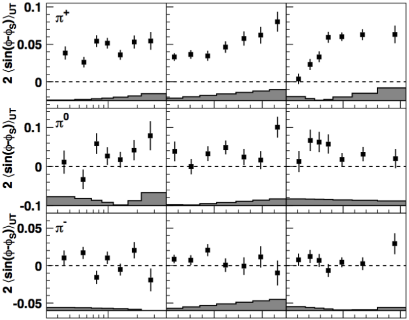
- Asymmetry still non-zero even at $\sqrt{s} = 500$ GeV
- Well into perturbative QCD regime
- Perturbative QCD wrong??

TMDs

- Measurements of Sivers Function in Semi-Inclusive Deep Inelastic Scattering (SIDIS) at COMPASS (below) and HERMES (right)
- Non-zero!
- No measurements in $p+p$ (yet)



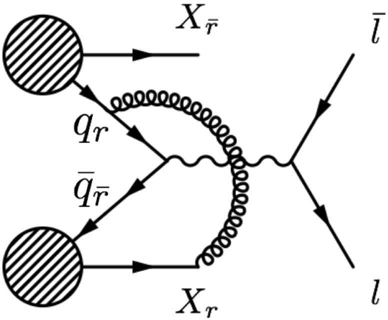
arXiv: 1408.4405



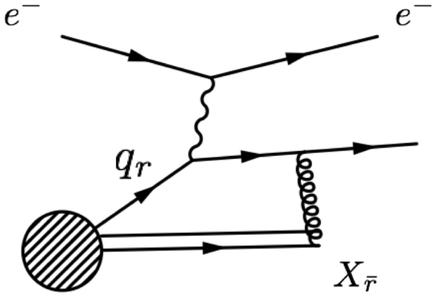
PRL 103, 152002

Universal Functions?

Drell Yan



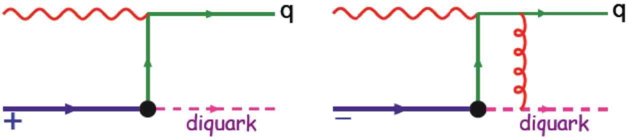
SIDIS



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

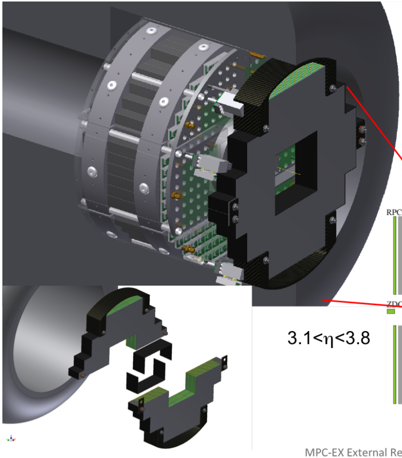
An earlier proof that the Sivers asymmetry vanishes because of time-reversal invariance is invalidated by the path-ordered exponential of the gluon field in the operator definition of parton densities. Instead, the time-reversal argument shows that the Sivers asymmetry is reversed in sign in hadron-induced 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

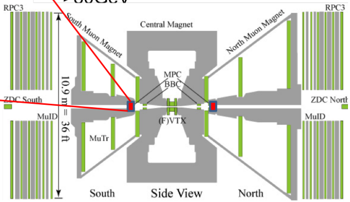
MPC-EX Detector

The MPC-EX Detector



A combined charged particle tracker and EM preshower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

- π^0 rejection (direct photons)
- π^0 reconstruction out to >80GeV



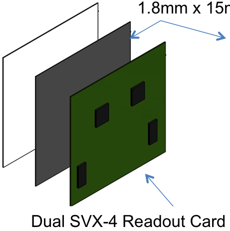
$3.1<\eta<3.8$

MPC-EX External Review

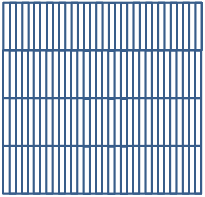
MPC-EX Hardware

Minipad Sensors

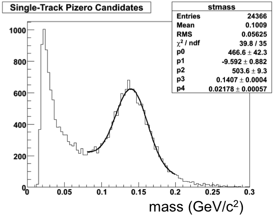
Detector elements are Si “minipad” detectors, one per tungsten gap, oriented in X and Y (alternating layers).



1.8mm x 15mm “minipad” sensor

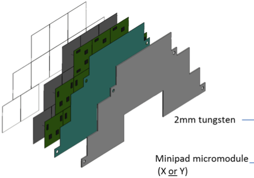


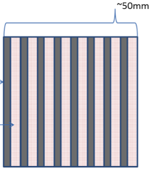
π^0 mesons reconstructed in p+p jet events (E>20GeV)



More detail in talks from D. Lynch,
A. Sukhanov and S. Campbell

Cross-Section View:





MPC-EX External Review