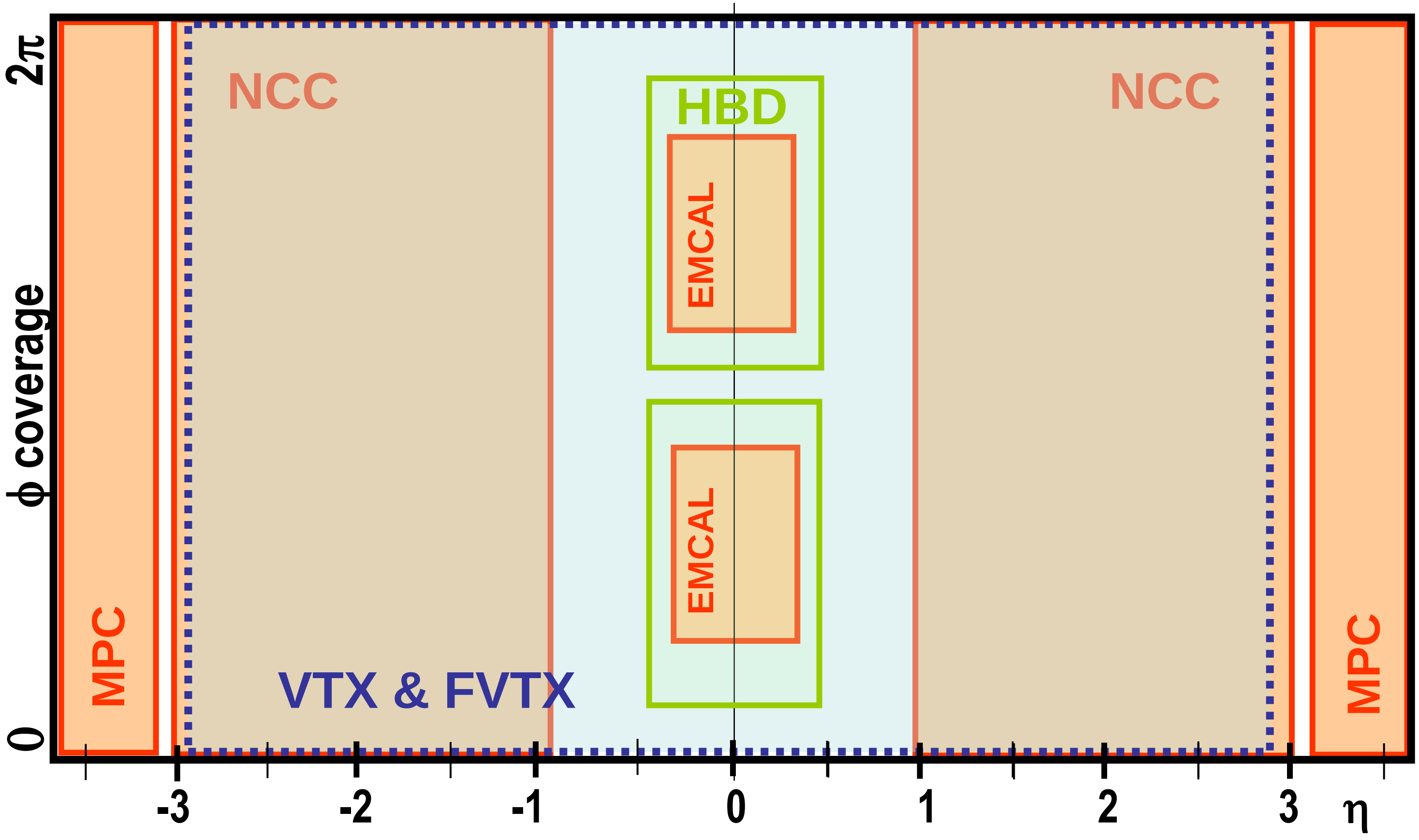
Physics of the MPC

Mickey Chiu

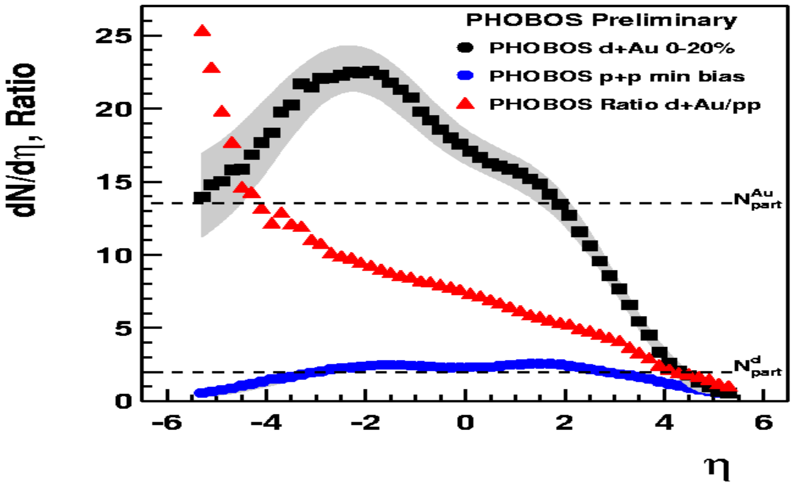
BNL

Future PHENIX Acceptance

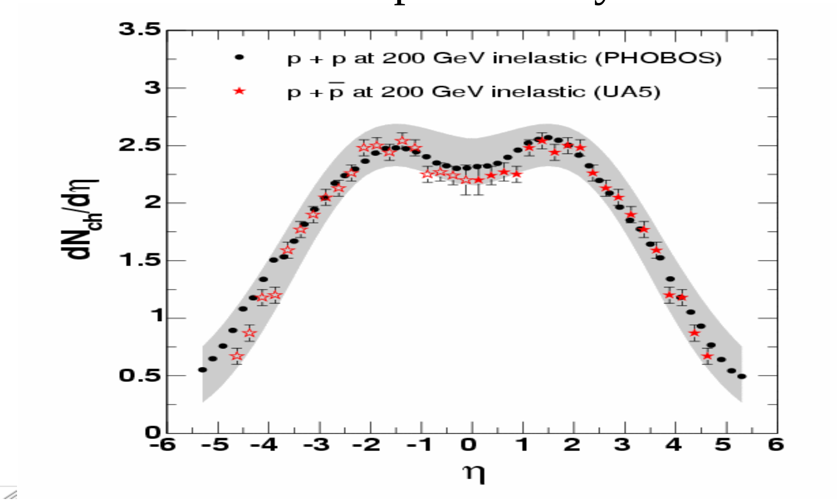


- History – PHENIX is a small acceptance, high rate, rare probes (photons, J/Psi, etc.) detector
- Future – Add acceptance plus add some new capabilities (hadron blind, displaced vertex)
- MPC, by virtue of it's location at forward rapidities, adds access to new areas, such as lower x (gluon saturated region?), higher x (valence region), even though it is a physically small detector.

Au+Au, p+p, d+Au Landscape



PHOBOS preliminary



MPC

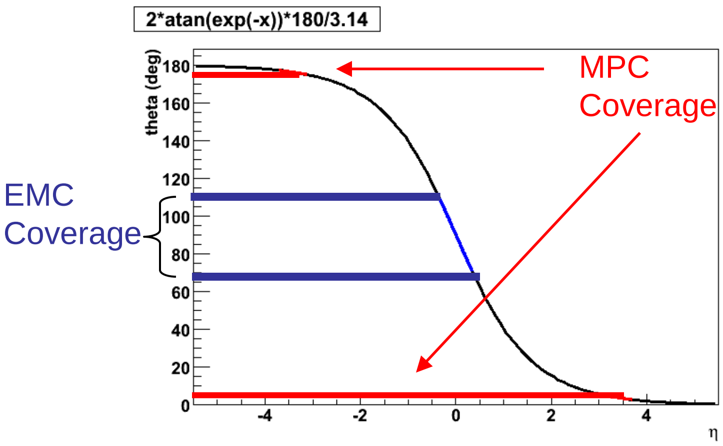
$2° < \theta < 5°$

$\sim 1000 \text{ cm}^2$

EMC

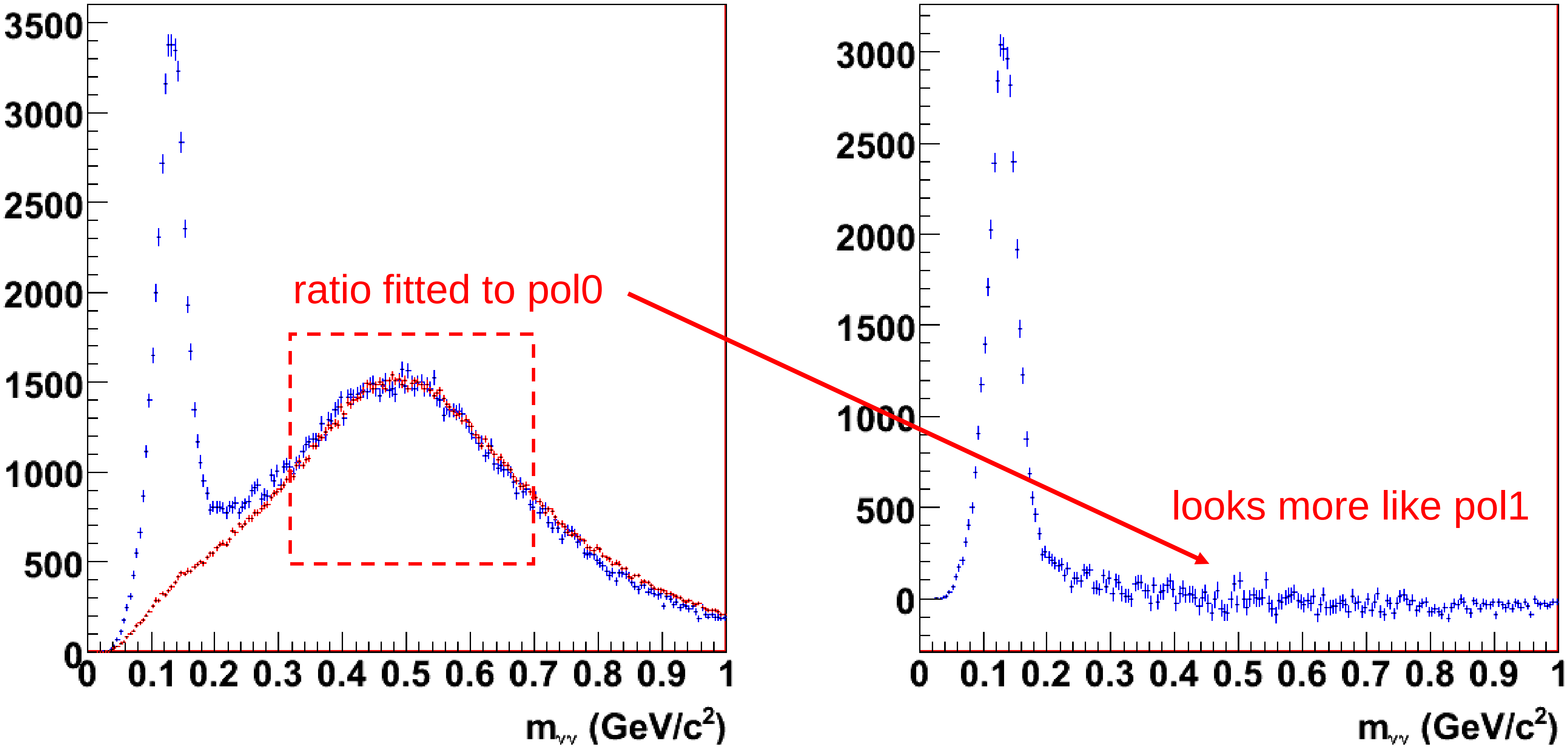
$70° < \theta < 110°$

$0.6 \times 10^6 \text{ cm}^2$



- Direct pi0 Reconstruction in p+p, d+Au possible
  - But not in Au+Au
  - Reduced to global observables, like E_T, RP
- Positives:
  - Energies are higher by boost, $E = m_T\cosh(y) \sim m_T e^y/2$ for y large
    - Easier to measure
  - Particles/tower larger – MIP "easy"

MPC π^0 mass peak

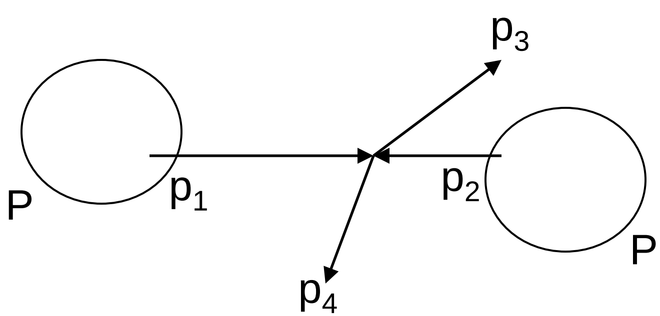


integrated over phi

example for one (out of four) polarization states

scaled mixed event background

2→2 Hard Scattering (LO)



Simply Elastic Scattering!

Initial State:

$$p_1 = (x_1 P, 0, 0, x_1 P)$$
$$p_2 = (x_2 P, 0, 0, -x_2 P)$$

Final State:

$$p_3 = (E_3, p_T, p_{3,z})$$
$$p_4 = (E_4, -p_T, p_{4,z})$$

$$p_z = m_T \sinh y$$
$$E = m_T \cosh y$$

$$(x_1 - x_2)P = E_{3,z} + E_{4,z} = \frac{m_T}{2}(e^{y_3} - e^{-y_3} + e^{y_4} - e^{-y_4})$$
$$(x_1 + x_2)P = p_{3,z} + p_{4,z} = \frac{m_T}{2}(e^{y_3} + e^{-y_3} + e^{y_4} + e^{-y_4})$$

$$x_1 = \frac{m_T}{P}(e^{y_3} + e^{y_4})$$
$$x_2 = \frac{m_T}{P}(e^{-y_3} + e^{-y_4})$$

Special Cases:

a. y_3 forward, y_4 mid-rapidity (MPC-EMC)

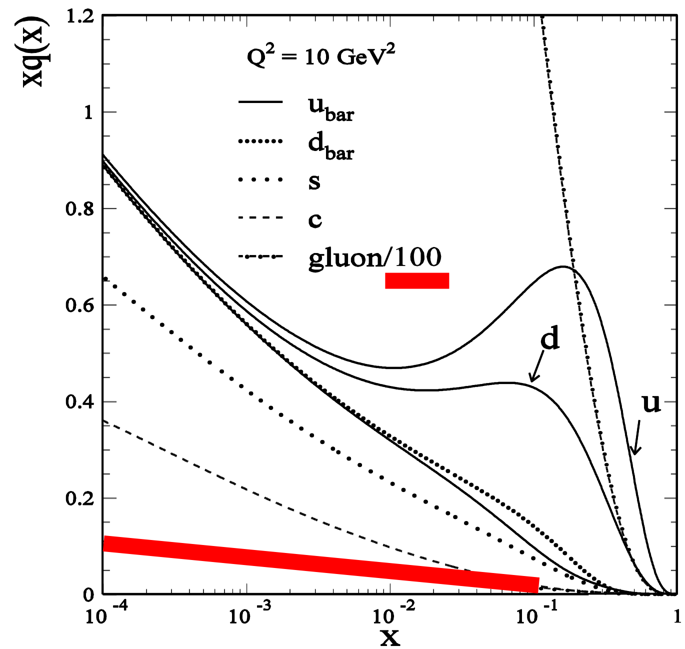
$$x_1 = \frac{m_T}{P}(e^{y_3} + e^{y_4}) \qquad x_2 = \frac{m_T}{P} e^{-y_4}$$

b. y_3, y_4 both forward (MPC-MPC)

$$x_1 = \frac{m_T}{P}(e^{y_3} + e^{y_4}) \qquad x_2 \approx 0$$

a. y_3 forward, y_4 backwards (MPC.S-MPC.N)

$$x_1 \approx \frac{m_T}{P} e^{y_3} \qquad x_2 \approx \frac{m_T}{P} e^{-y_4}$$



Nucleon Spin Physics

•protons … e of
QCD, ar … f.
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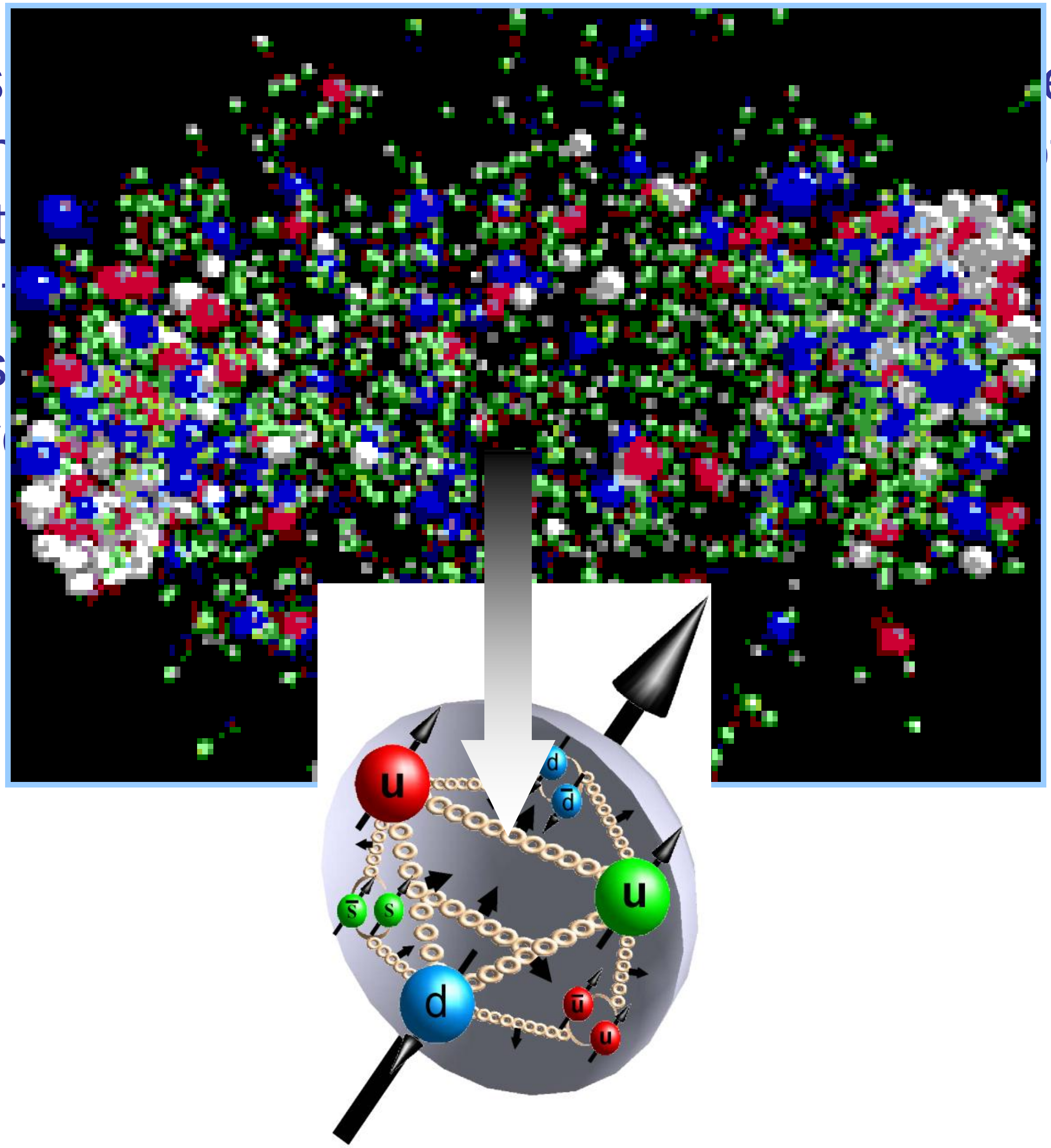
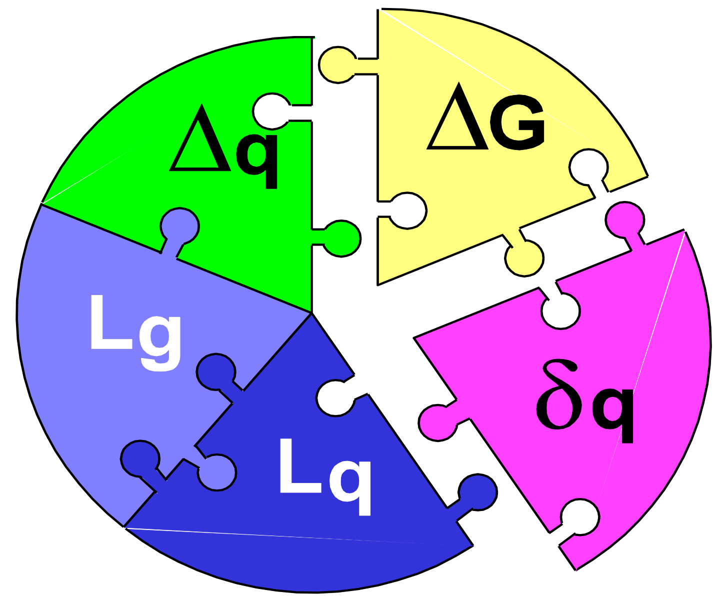


The Spin Structure of the Proton

- From NLO-QCD analysis of DIS measurements
  $\Delta\Sigma \approx 0.2$ (but has evolved to 0.3)
  $\Delta G = 1.0 \pm 1.2$ → probably small?
- quark polarization $\Delta q(x)$
  → first 5-flavor separation from HERMES
- transversity $\delta q(x)$
  → a new window on quark spin
  → azimuthal asymmetries from HERMES and JLab
  → Collins fn measured at Belle
  → future: flavor decomposition
- gluon polarization $\Delta G(x)$
  → RHIC-spin and COMPASS started providing answers!
- GPD's and TMDs and High Twist?
  → orbital angular momentum?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



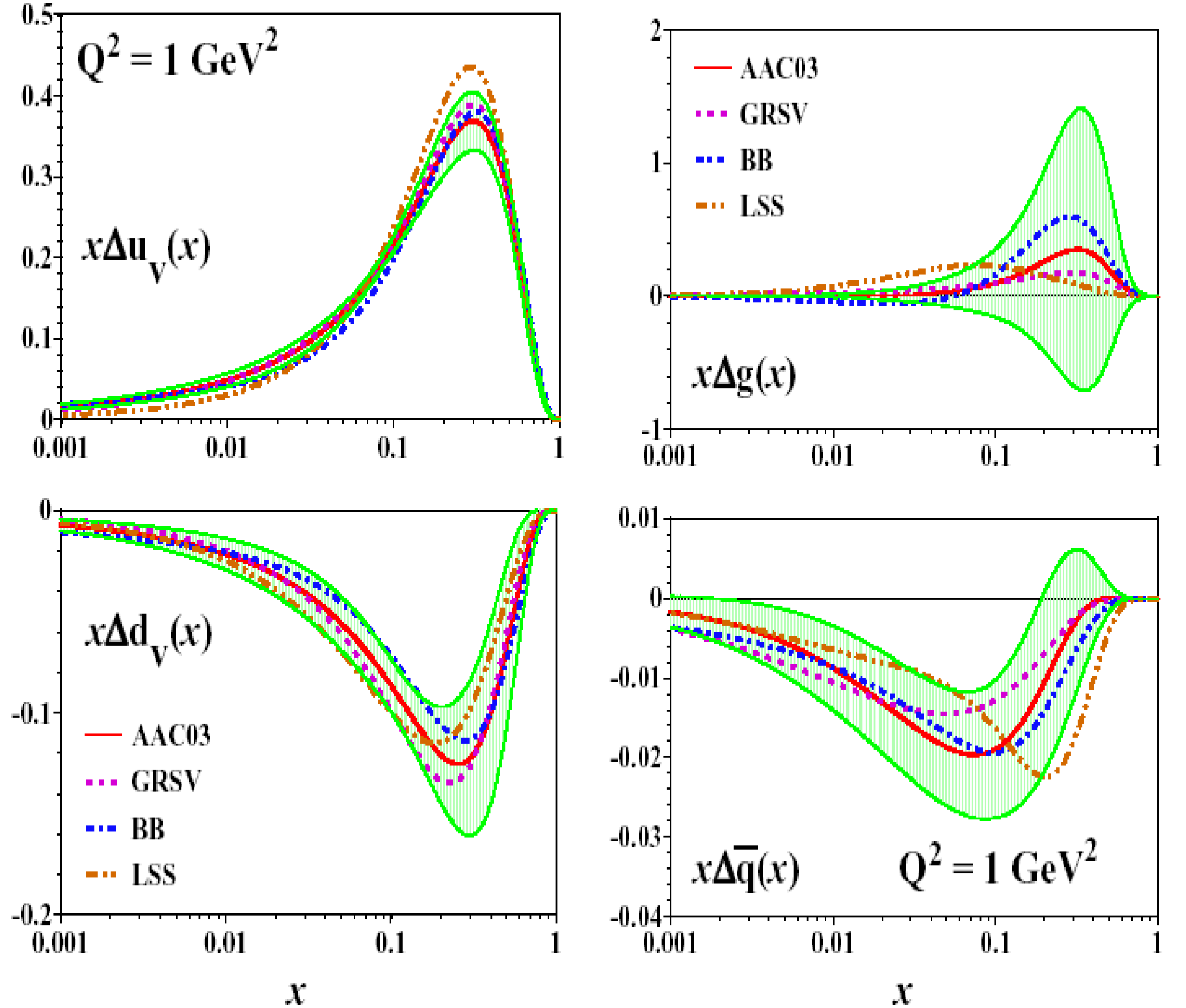
We want to solve this puzzle! → need large range in x and Q^2 and high luminosity for precision!

Polarised PDF

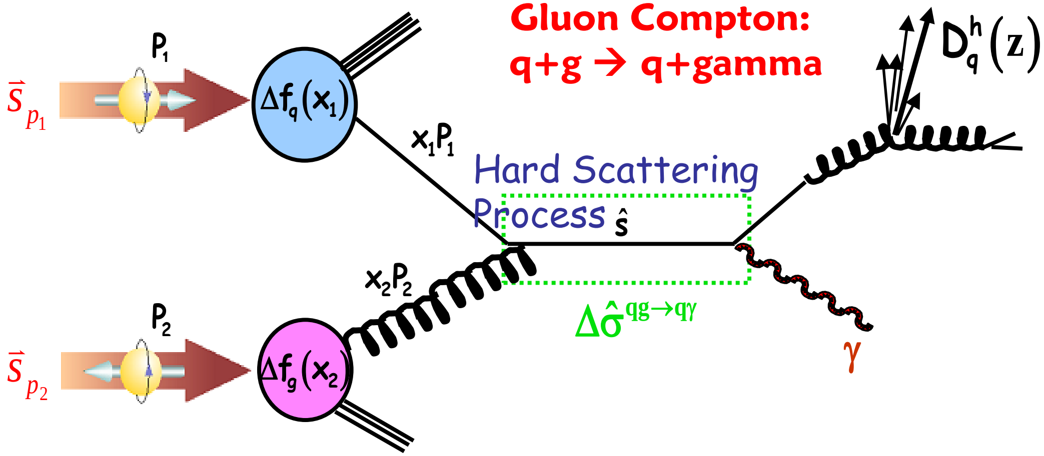
Asymmetry Analysis Collaboration

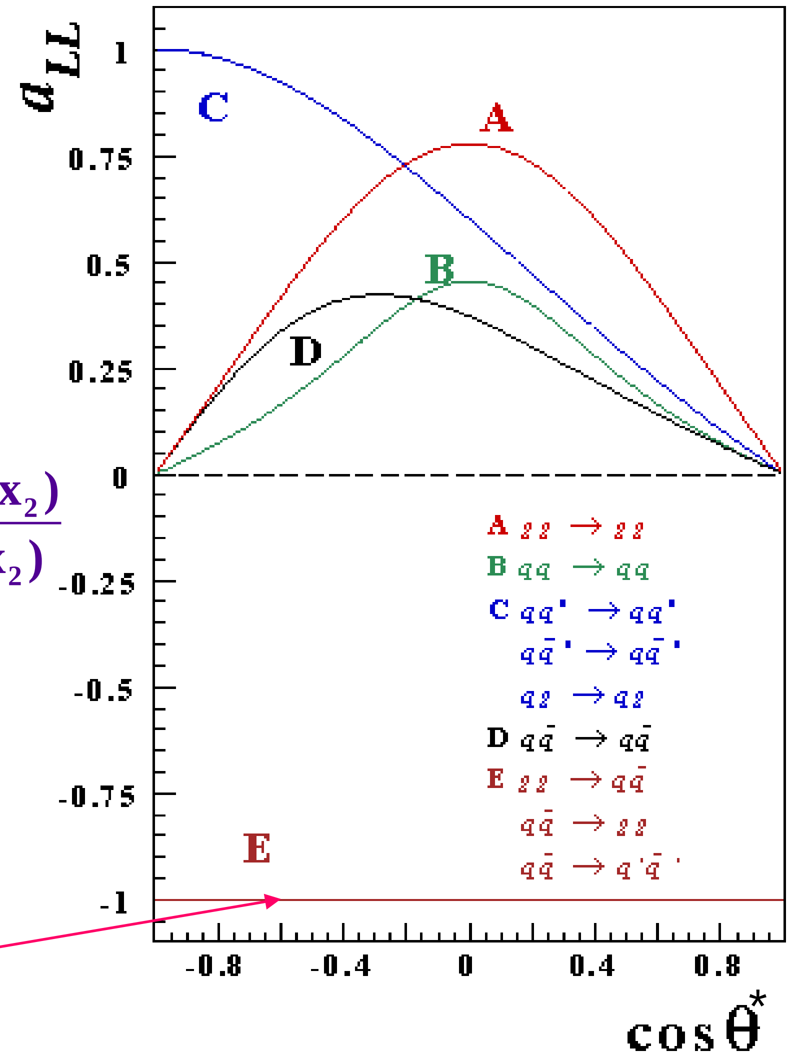
M. Hirai, S. Kumano and N. Saito, PRD (2004)

- Valence Dist's are determined well
- Sea Dist' is poorly constrained
- Gluon can be either >0, =0, <0



Scattering in polarized p+p



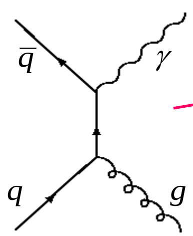


$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \equiv \frac{\Delta\sigma}{\sigma} = \hat{a}_{LL}(qg \to q\gamma) \otimes \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta q(x_2)}{q(x_2)}$$

where $\hat{a}_{LL} = \frac{\Delta\hat{\sigma}}{\hat{\sigma}} = \frac{\hat{\sigma}^{\uparrow\uparrow} - \hat{\sigma}^{\uparrow\downarrow}}{\hat{\sigma}^{\uparrow\uparrow} + \hat{\sigma}^{\uparrow\downarrow}}$ $\qquad \hat{\sigma} = \sigma^{qg\to q\gamma}$

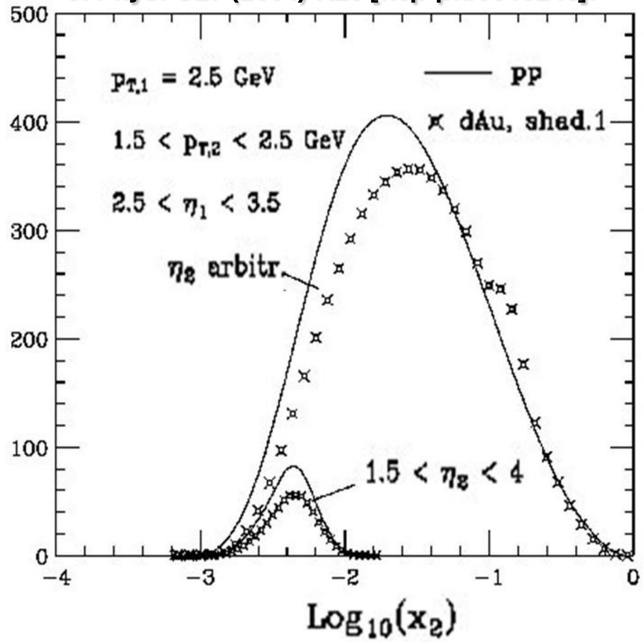
And much the same for other processes…

Annihilation:
$q+\bar{q}$ → g + gamma

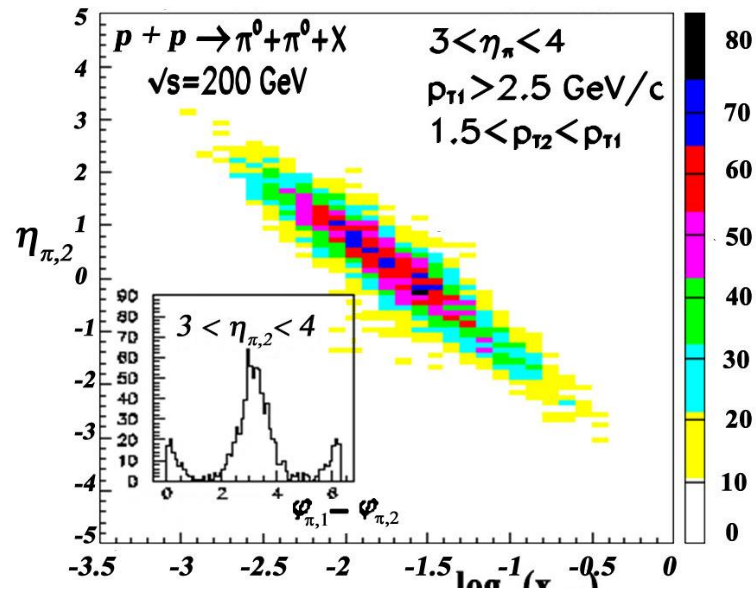


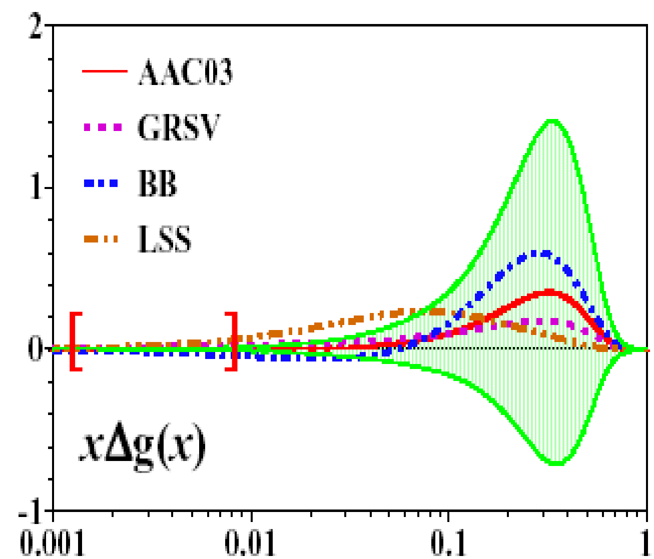
Di-Hadron A_{LL}*: Constraining x values

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



STAR Pythia Simulation



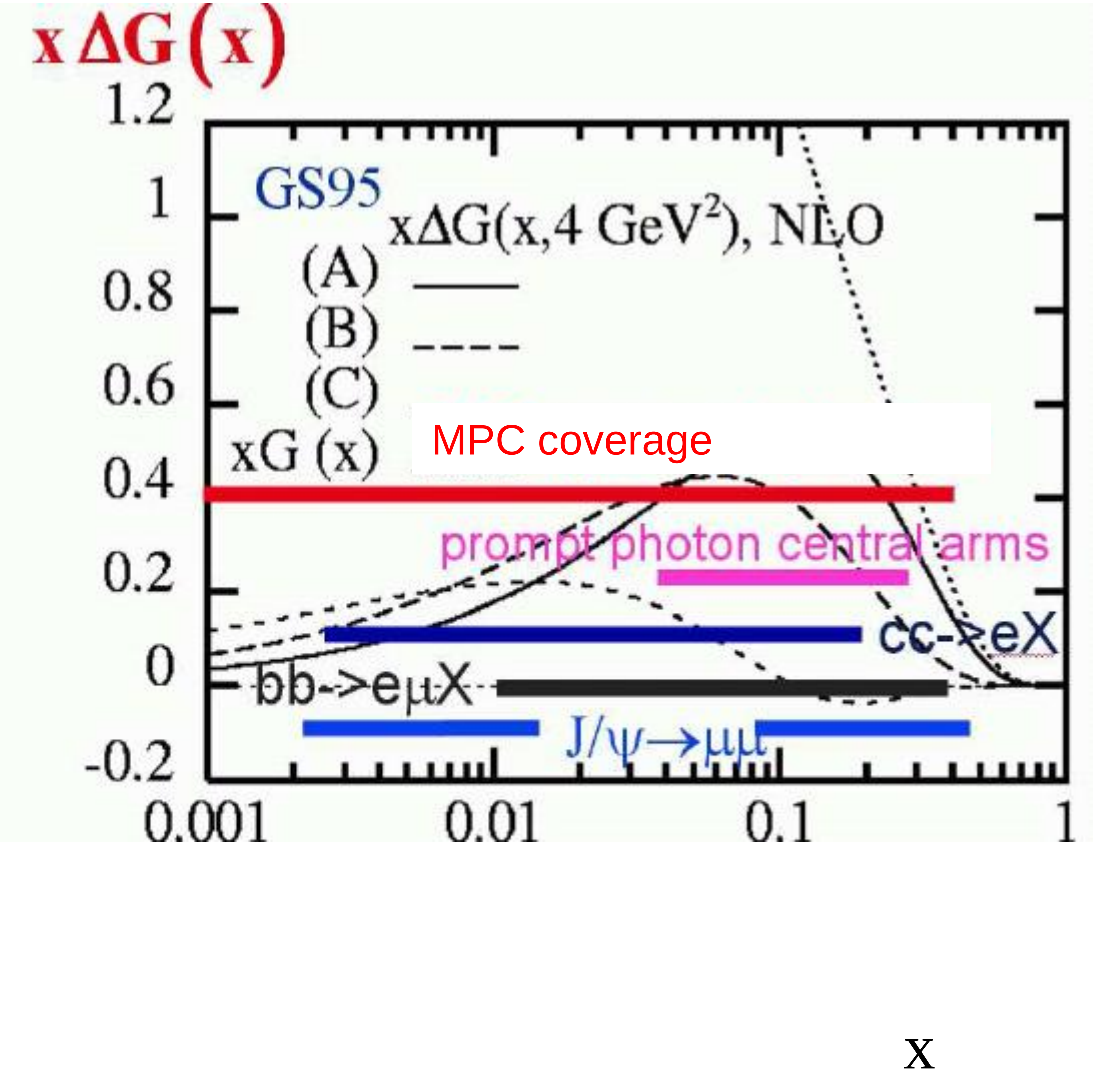


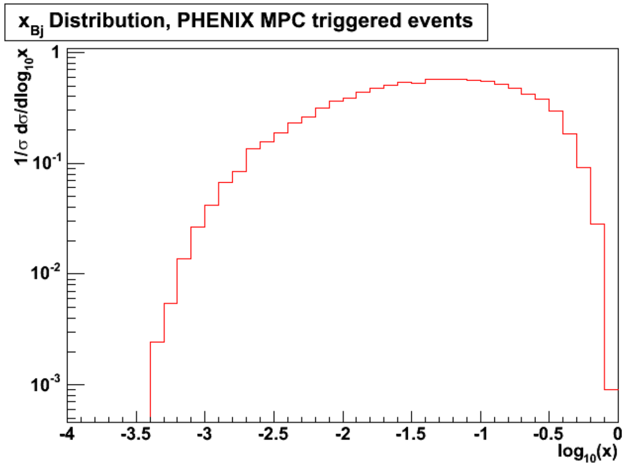
- constrain x value of gluon probed by high-x quark by *detection of second hadron* serving as jet surrogate.
- span broad pseudorapidity range for second hadron ⇒ span broad range of x_{gluon}

*J. Koster Thesis

MPC Reach for ΔG at low x

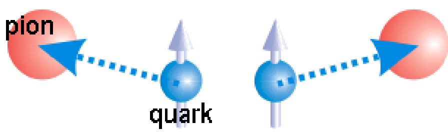
- Reminder:
  - Measurements at moderate x at SLAC on the quark structure functions were consistent with the QPM
  - Low-x measurements from CERN showed that this was not the case, i.e. it lead to the “spin crisis”
  - Recent (2005) results at even lower x from COMPASS moved ΔΣ from 0.25 to 0.3



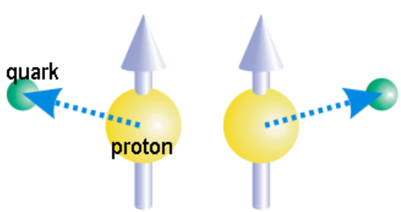


Single Transverse Spin Asymmetries

- Fermilab E-704 reported Large Asymmetries A_N
- Could be explained as
  - Transversity x Spin-dep fragmentation (Collins effect),

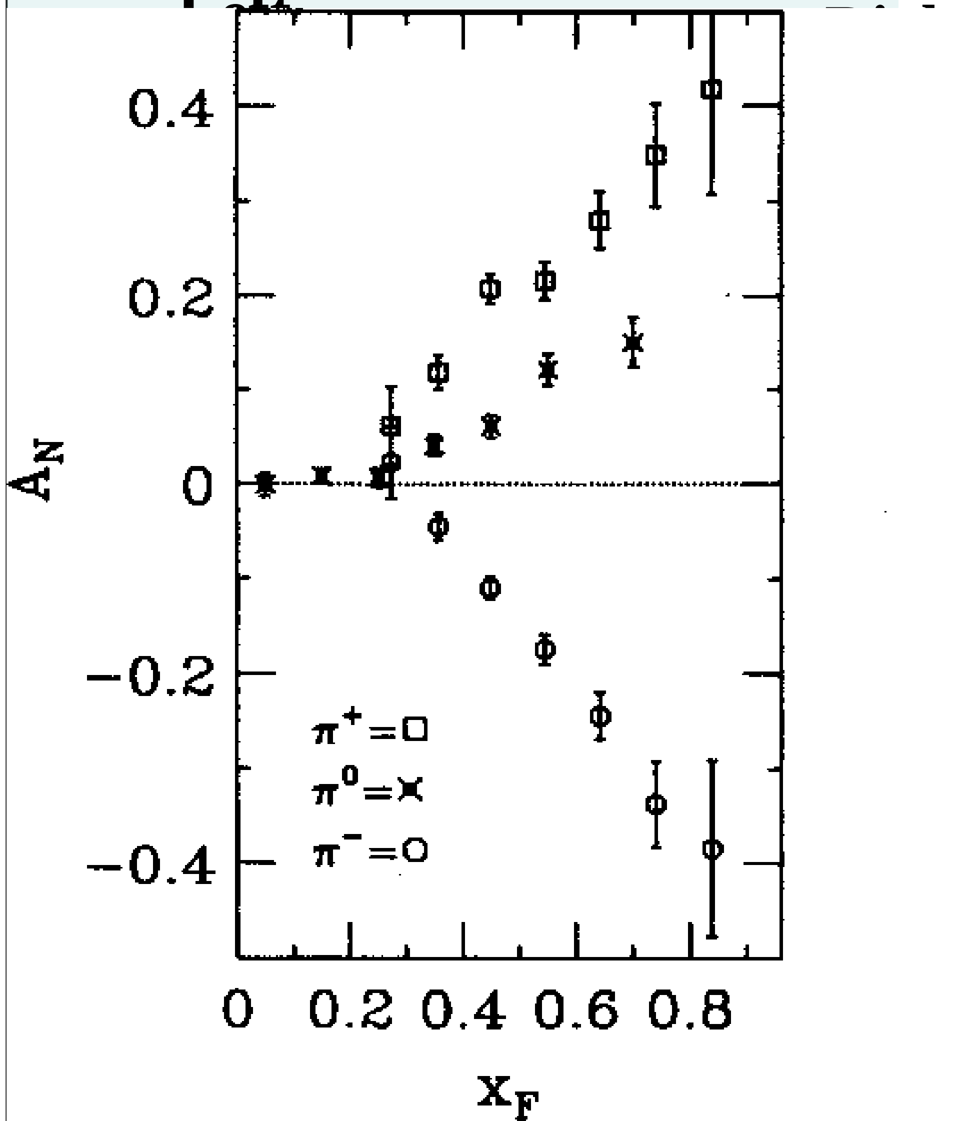


  - Intrinsic-k_T imbalance (Sivers effect) , or



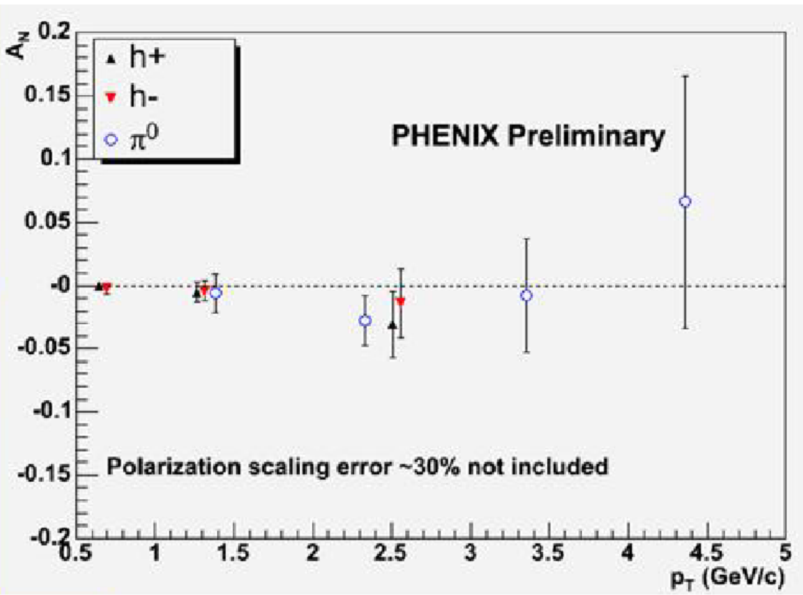
  - Twist-3 (Qiu-Sterman, Koike)
  - Or combination of above

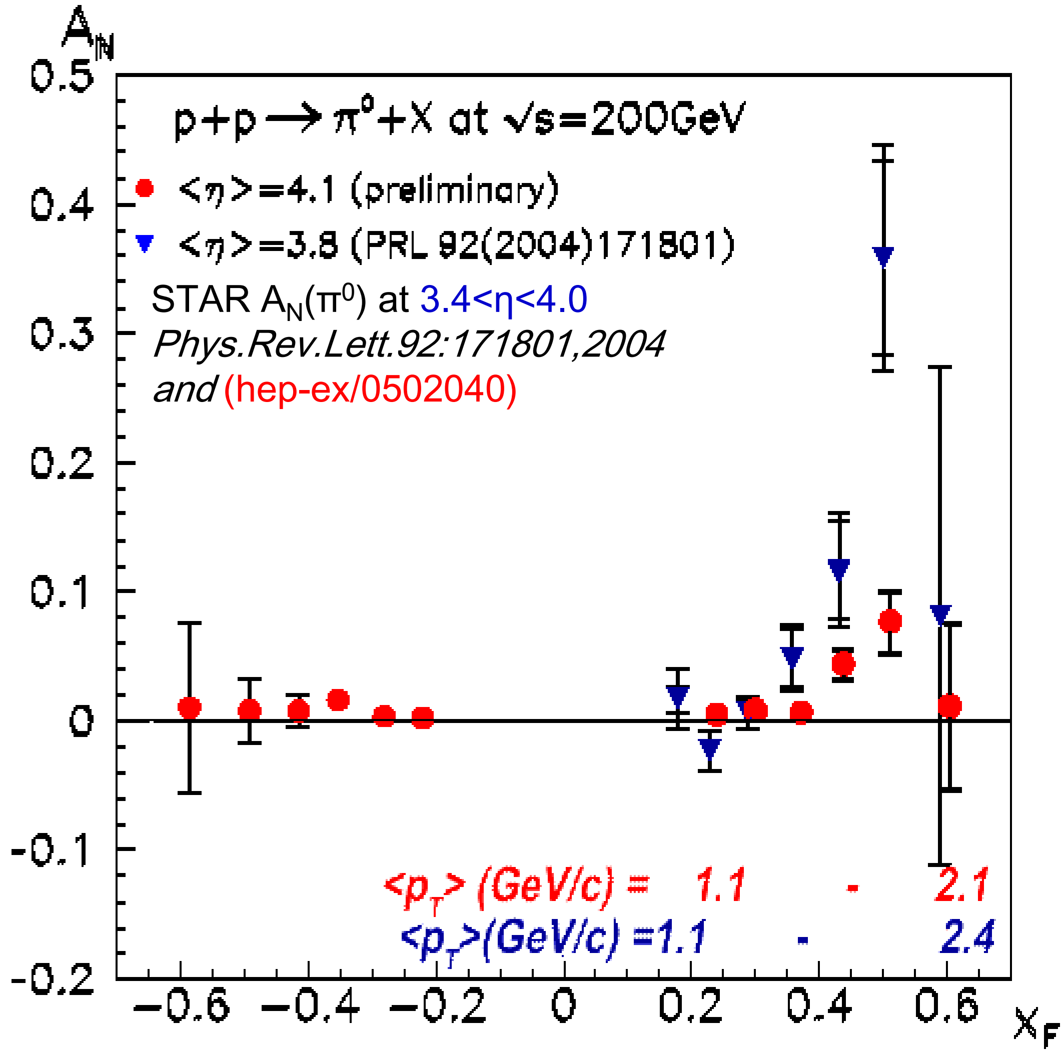
$pp \to \pi X$ at $\sqrt{s} = 19.4\,\mathrm{GeV}$



First A_N Results from PHENIX and STAR

PHENIX $A_N(\pi^0)$ and $A_N(\pi^0)$, |η|<0.35
Phys.Rev.Lett.95:202001,2005





In PHENIX:

Aidala, Bauer, Makdisi, Okada, Perdekamp

Also identified charged particle (pi,K,p) AN

Naïve LO, Leading Twist, pQCD Result

In this note we have pointed out that the asymmetry off a polarized target, and the transverse polarization of a produced quark in $e^+e^- \to q\bar{q}$, or in $qq \to qq$ at large p_T, or in leptoproduction, should all be calculable perturbatively in QCD. The result is zero for $m_q = 0$ and is numerically small if we calculate $m_q/\sqrt{s}$ corrections for light quarks. We discuss how to test the predictions. At least for the cases when P is small, tests should be available soon in large-p_T production [where currently $P(\Lambda) = 25\%$ for $p_T \gtrsim 2$ GeV/c], and e^+e^- reactions. While fragmentation effects could dilute polarizations, they cannot (by parity considerations) induce polarization. Consequently, observation of significant polarizations in the above reactions would contradict either QCD or its applicability.

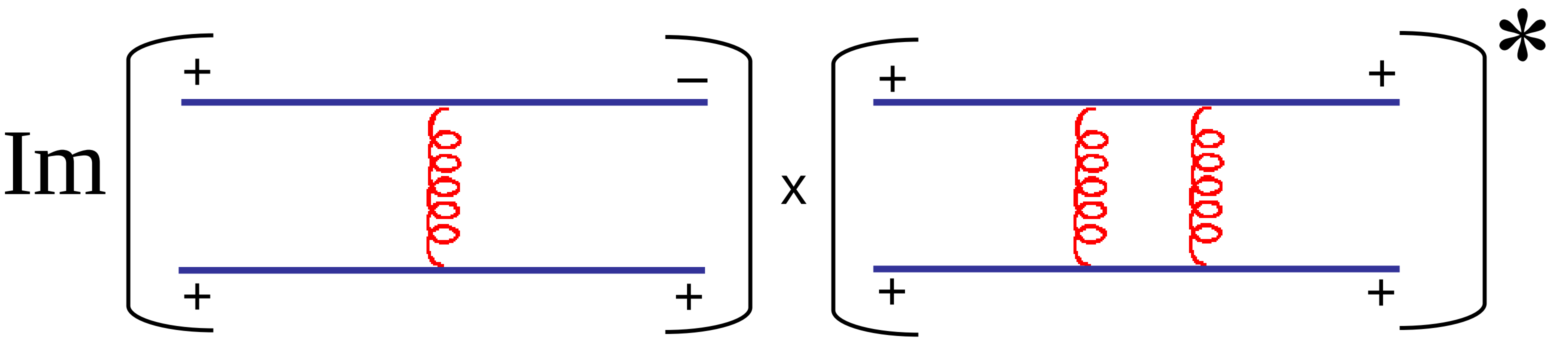
Kane, Pumpkin and Repko PRL 41 1978

$$A_N \propto \frac{m_q}{\sqrt{s}} \quad \text{example, } \mathrm{m_q} = 3MeV, \sqrt{s} = 20GeV, A_N \approx 10^{-4}$$

Helicity violation term due to finite quark masses

Single spin asymmetries at partonic level. Example: $qq' \to qq'$

$A_N \neq 0$ needs helicity flip + relative phase

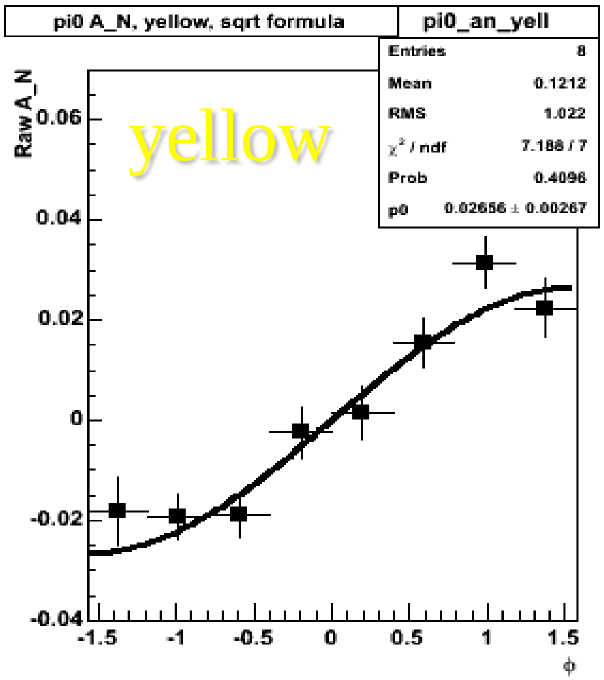


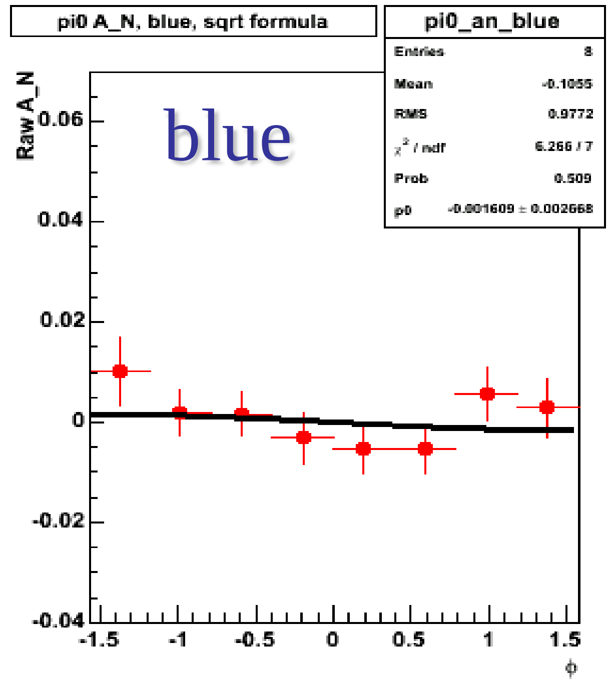
QED and QCD interactions conserve helicity, up to corrections $O(m_q / E)$

$$A_N \propto \frac{m_q}{E}\alpha_s$$ at quark level

but large SSA observed at hadron level!

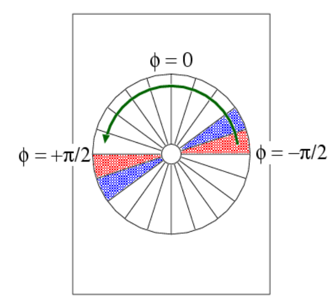
MPC Square root asymmetries in 62 GeV p↑+p





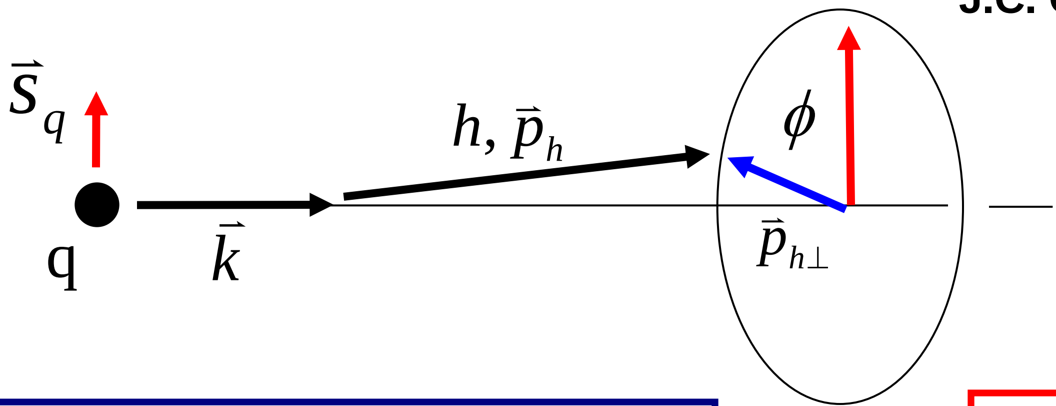
- Asymmetry seen in yellow beam (positive x_F), but not in blue (negative xF)

$$\varepsilon = \frac{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} \cdot N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} \cdot N_R^{\uparrow}}}$$



Collins Effect in Quark Fragmentation

J.C. Collins, Nucl. Phys. B396, 161(1993)



$\vec{k}$	: Quark Momentum
$\vec{s}_q$	: Quark Spin
$\vec{p}_h$	: Hadron Momentum

Collins Effect:
Fragmentation of a quark with transverse Spin into a hadron *h* with the following azimuthal distribution:

$$\propto \left(\vec{k} \times \vec{p}_h\right) \cdot \vec{s}_q$$

$$\propto \sin\phi$$

D^h_q is the probability to find a hadron with momentum z_1 and transverse momentum p_{hT}:

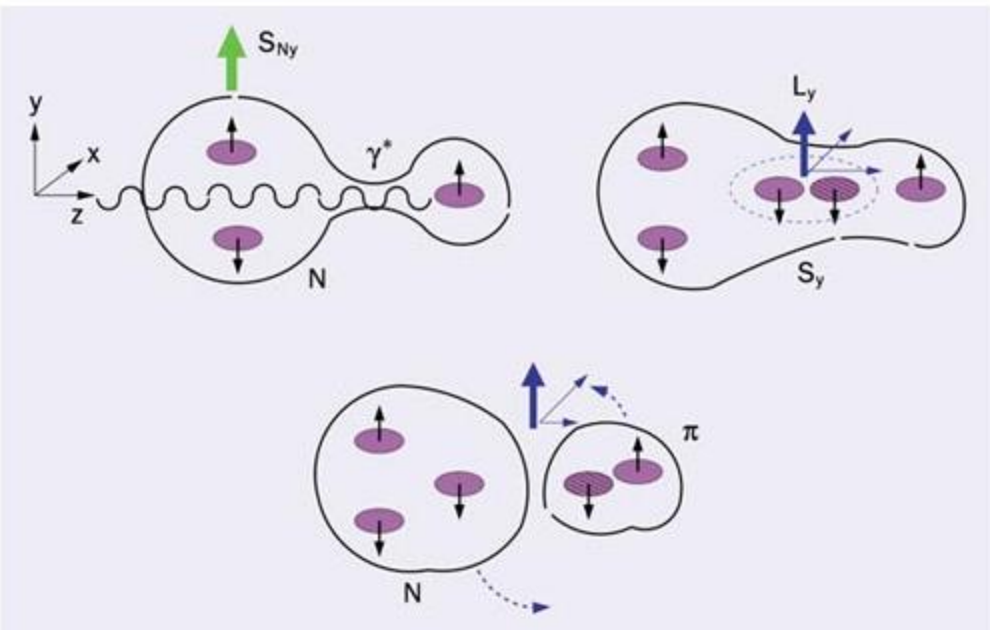
$$D^h_{q^\uparrow}(z, \vec{p}_{h\perp}) = D_1^{q,h}(z) + H_1^{\perp q,h}(z, p^2_{h\perp}) \frac{\left(\hat{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q}{zM_h}$$

unpolarized FF **Collins FF**

Artru Model for Collins Fragmentation

A simple model to illustrate that spin-orbital angular momentum coupling can lead to left right asymmetries in spin-dependent fragmentation:

http://cerncourier.com/main/article/44/8/19/1



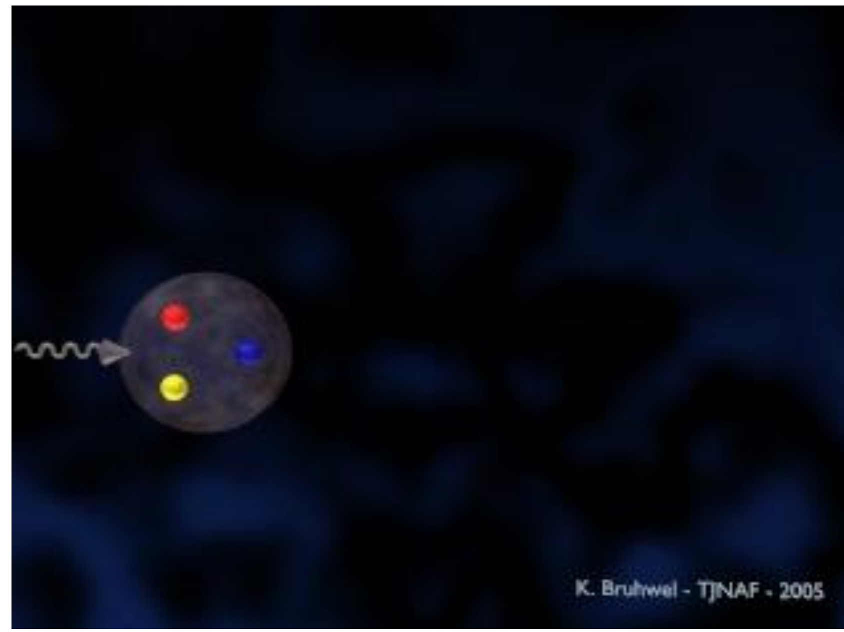
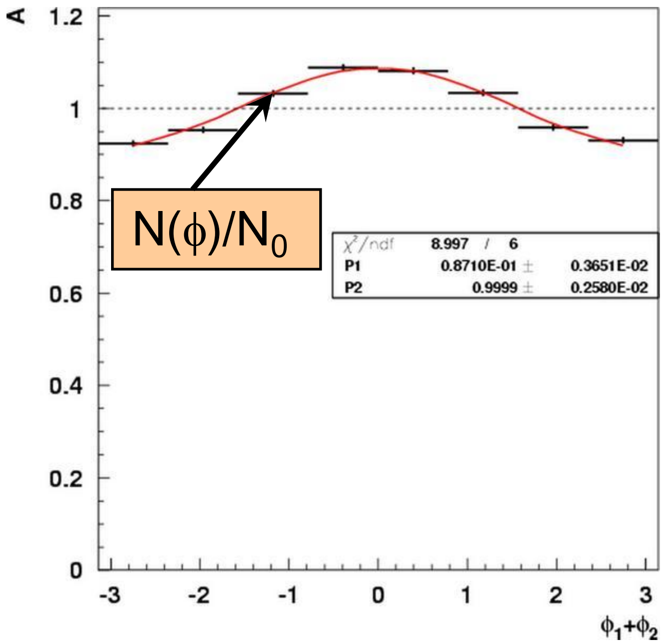


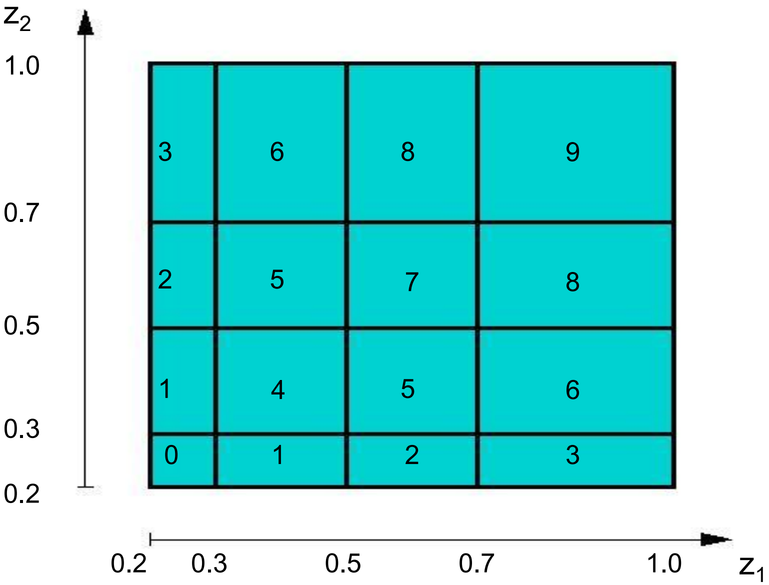
Fig. 1. The Collins effect in a sketch suggested by Xavier Artru of Orsay in the context of the Lund fragmentation model. A virtual photon hits a valence quark at the end of a flux tube; the flux tube stretches and eventually breaks down; a quark-antiquark pair is created in the $^3P_0$ state with the quantum numbers $J^P = 0^+$ of vacuum, i.e. with orbital angular momentum L_y = 1 and spin S_y = -1; the pair rotates in space and colour around the breaking point; a pion is formed and deviated upward by this rotation, while the residual hadron is deviated downward.

Belle: Azimuthal Correlation in 10 $(z_1 - z_2)$ Quark-Momentum Bins

Azimuthal Distribution of Hadron-Pairs



Bins in Quark Momentum



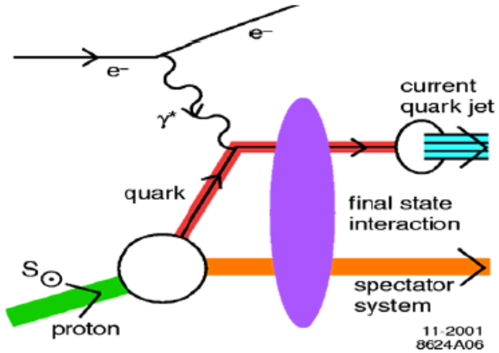
$$\frac{N(\phi)}{N_0} = \frac{aD_1\overline{D_1} + cos(2\phi)\left(bH_1\overline{H_1} + cD_1\overline{D_1}\right)}{aD_1\overline{D_1}} = P2 + P1\cos(2\phi)$$

D_1: Spin averaged Fragmentation Function

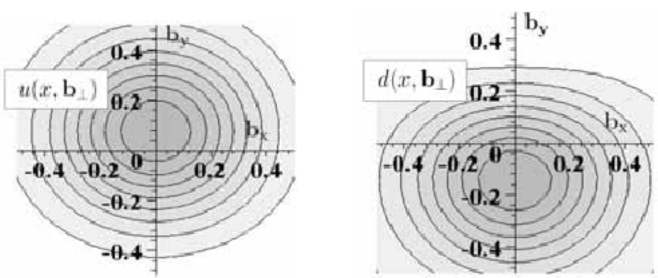
H_1: Collins Fragmentation Function

Sivers Effect: Final State Interaction

Sivers effect is an interference with a final state interaction of quark with spectator system.

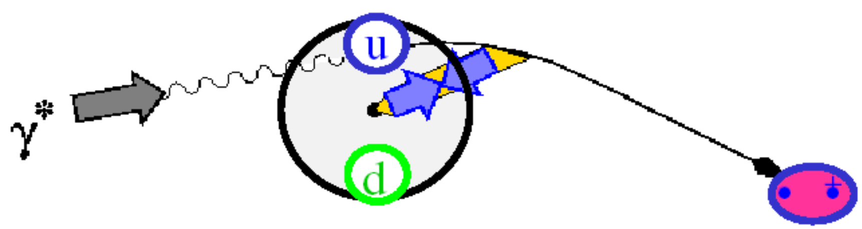


(Int.J.Mod.Phys.A18:1327-1334,2003)



(Nucl.Phys. A735 (2004) 185-199)

Can be understood as soft-gluon exchange in final state.



Final state soft gluons ?

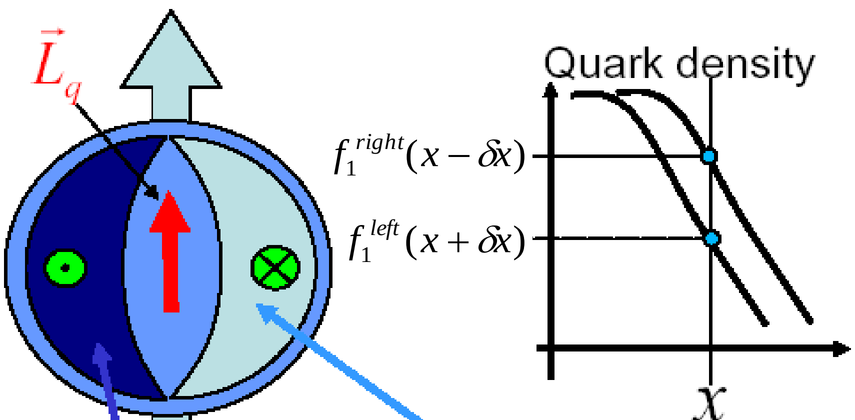
➔ What happens to factorization and universality ??

Sivers: Connection to Orbital Angular Momentum?

The Sivers function is unpolarized quark distribution function in the transversely polarized nucleon.

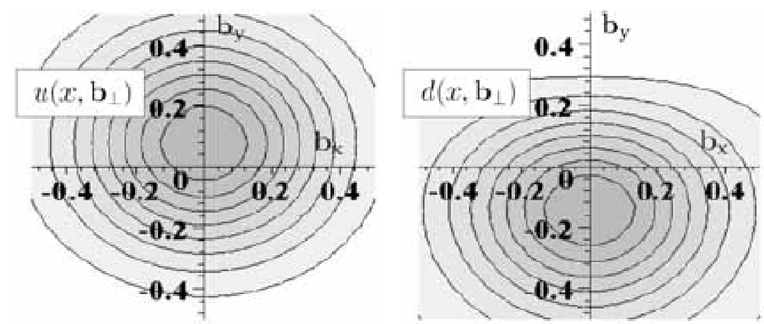
Semi-classical picture :

If quarks have L_q , probability to find quark which carries momentum fraction of "x" is different between left & right sides in the nucleon (viewed from virtual photon).



$f_1^{Left}(x) < f_1^{Right}(x)$

x_q is blue/red shifted!

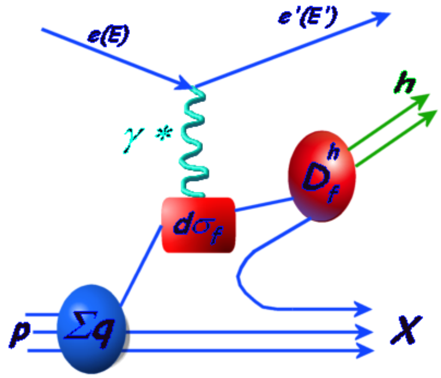


M. Burkardt
(Nucl.Phys. A735 (2004) 185-199)

➔ Sivers function can be viewed an impact-parameter dependent PDF.

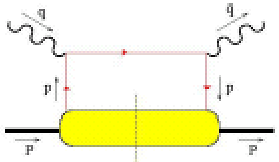
Mechanism for Observed Transverse-Spin Effects

1) Spin-Orbit Effects in the Proton Itself

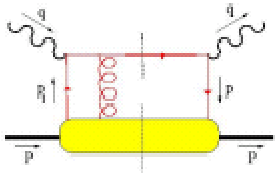


$$d\sigma^h \sim \Sigma e_q^2 q(x)\, d\sigma_f\, D_f^h(z)$$

Sivers distribution

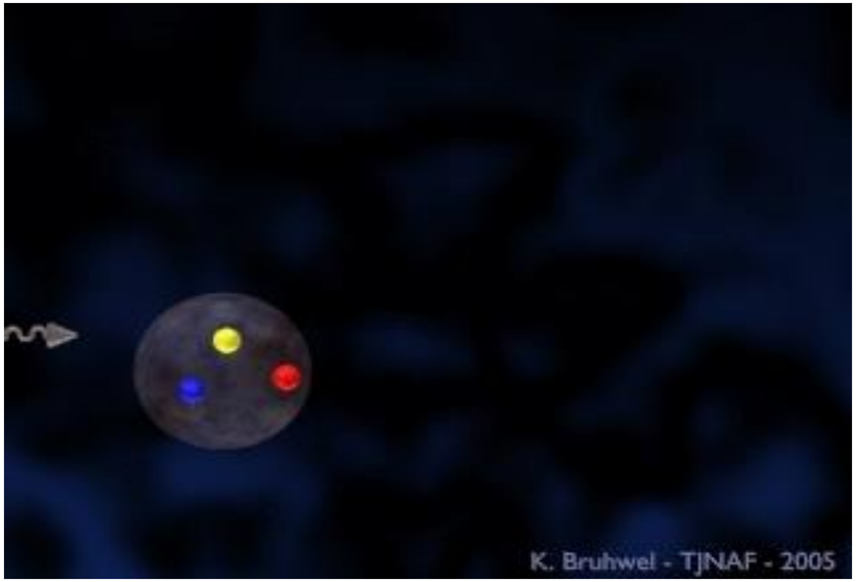


interferes with



(soft gluons)

to establish leading-twist Sivers distribution required

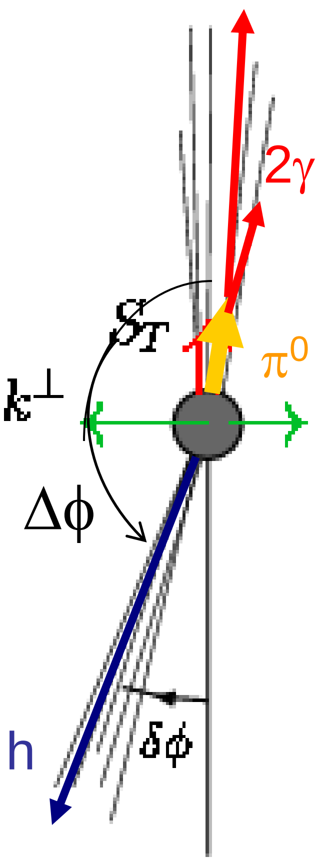


It's there (HERMES)?

Sivers Fcn from Back2Back Analysis

Boer and Vogelsang, Phys.Rev.D69:094025,2004, hep-ph/0312320

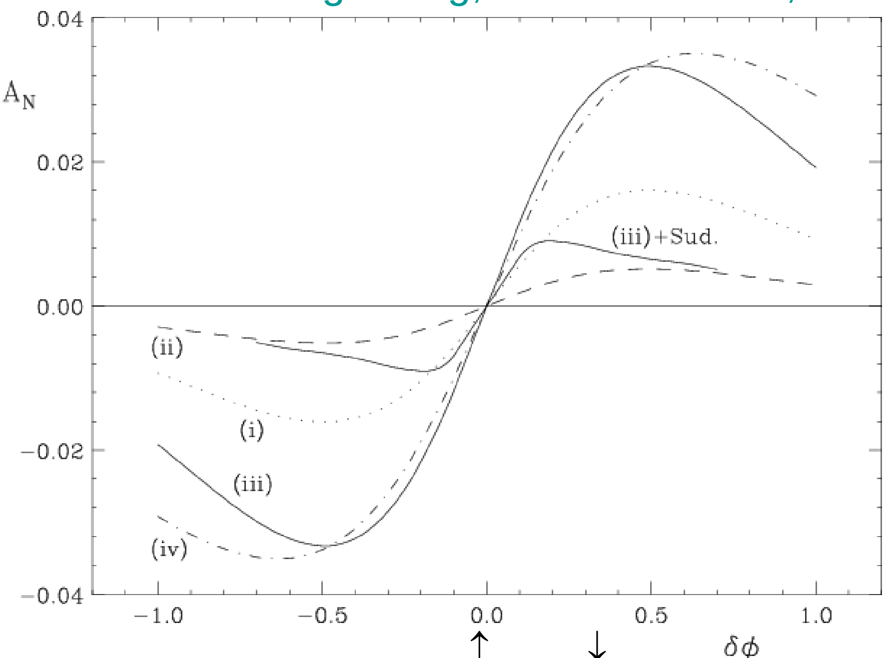
$$\hat{f}(x,k_T,S_T) = f(x,k_T) + \frac{1}{2}\Delta^N f(x,k_T)\frac{S_T\cdot(P\times k_T)}{|S_T||P||k_T|}$$



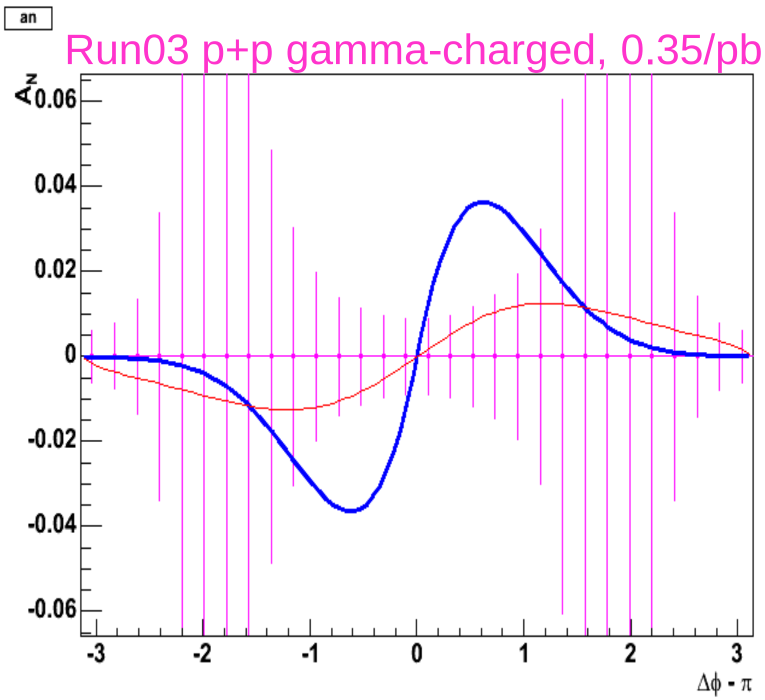
- Non-Zero Sivers function means that there is a left/right asymmetry in the k_T of the partons in the nucleon
    - For a positive Siver's function, there will be net parton k_T to the left (relative to direction of proton, assuming spin direction is up).
- Boer and Vogelsang find that this parton asymmetry will lead to an asymmetry in the $\delta\phi$ distribution of back-to-back jets
    - There should be more jets to the left (as in picture to the left).
- Should also be able to see this effect with fragments of jets, and not just with fully reconstructed jets?
    - Take some jet trigger particle along S_T axis (either aligned or anti-aligned to S_T)
    - Trigger doesn't have to be a leading particle, but does have to be a good jet proxy
    - Then look at $\delta\phi$ distribution of away side particles

Unpolarized Results from Run03 p+p

Boer and Vogelsang, PRD69:094025,2004



Run03 p+p gamma-charged, 0.35/pb



•Asymmetry $$A_N \equiv \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- •numerator is difference between aligned and anti-aligned δϕ dist's, where aligned means trigger jet and spin in same direction
- •denominator is simply unpolarized δϕ distribution

•On left are some theoretical guesses on expected magnitude of AN from Siver's

•On right are gamma-charged hadron δϕ dist's from Run03 p+p

- •2.25 GeV gamma's as jet trigger, 0.6-4.0 GeV charged hadrons to map out jet shape
- •Dotted lines are schematic effect on away side δϕ dist due to Siver's Fn (not to scale)

Hermes Sivers

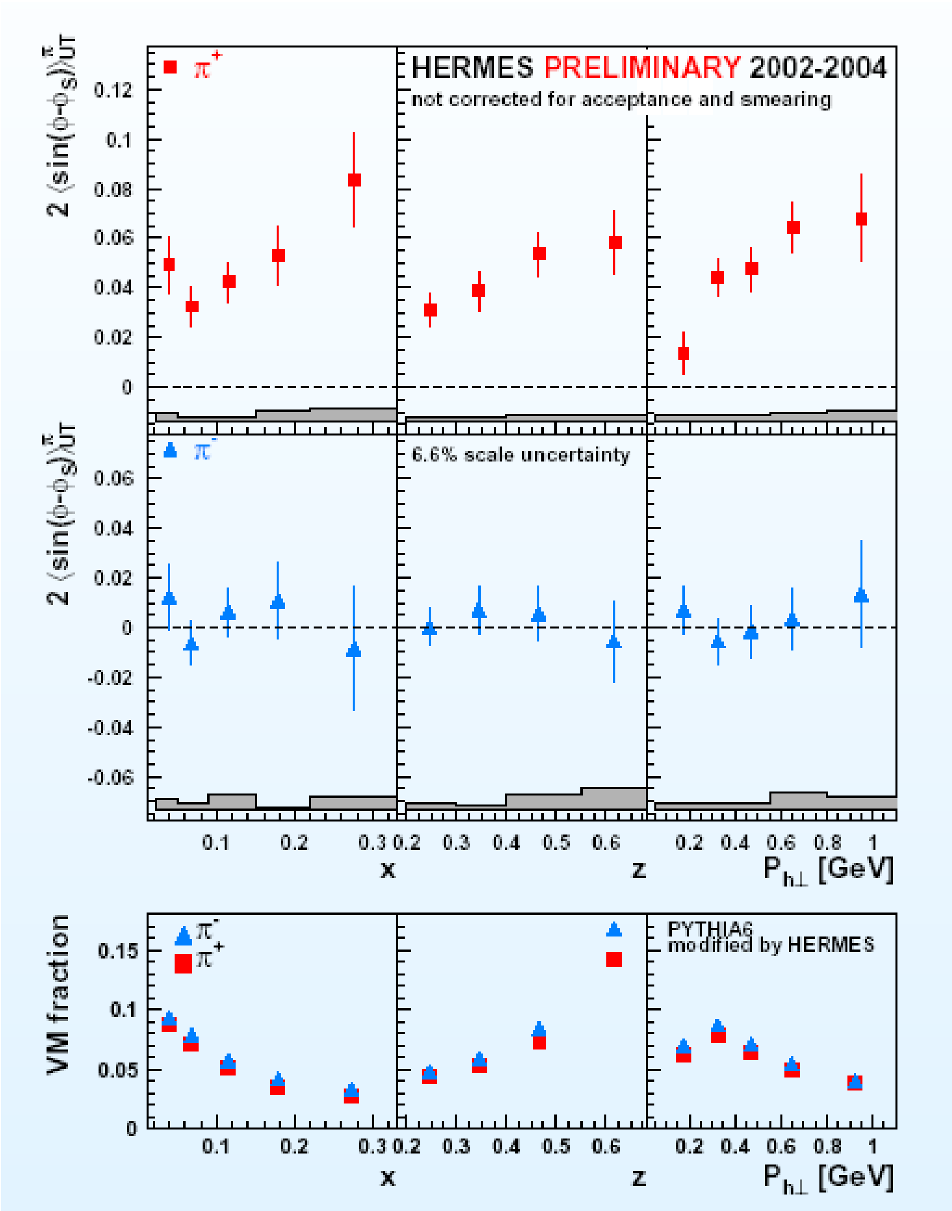
$$l\, N^{\uparrow} \rightarrow l\, \pi\, X$$

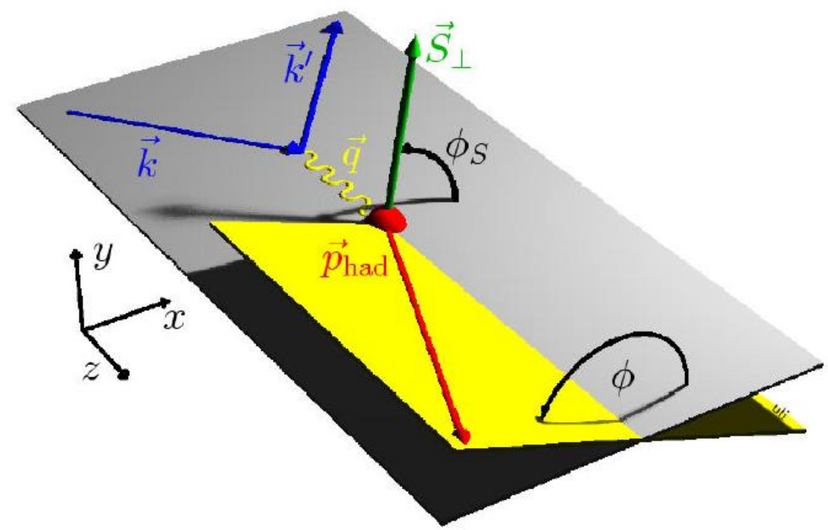
"Sivers moment"

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

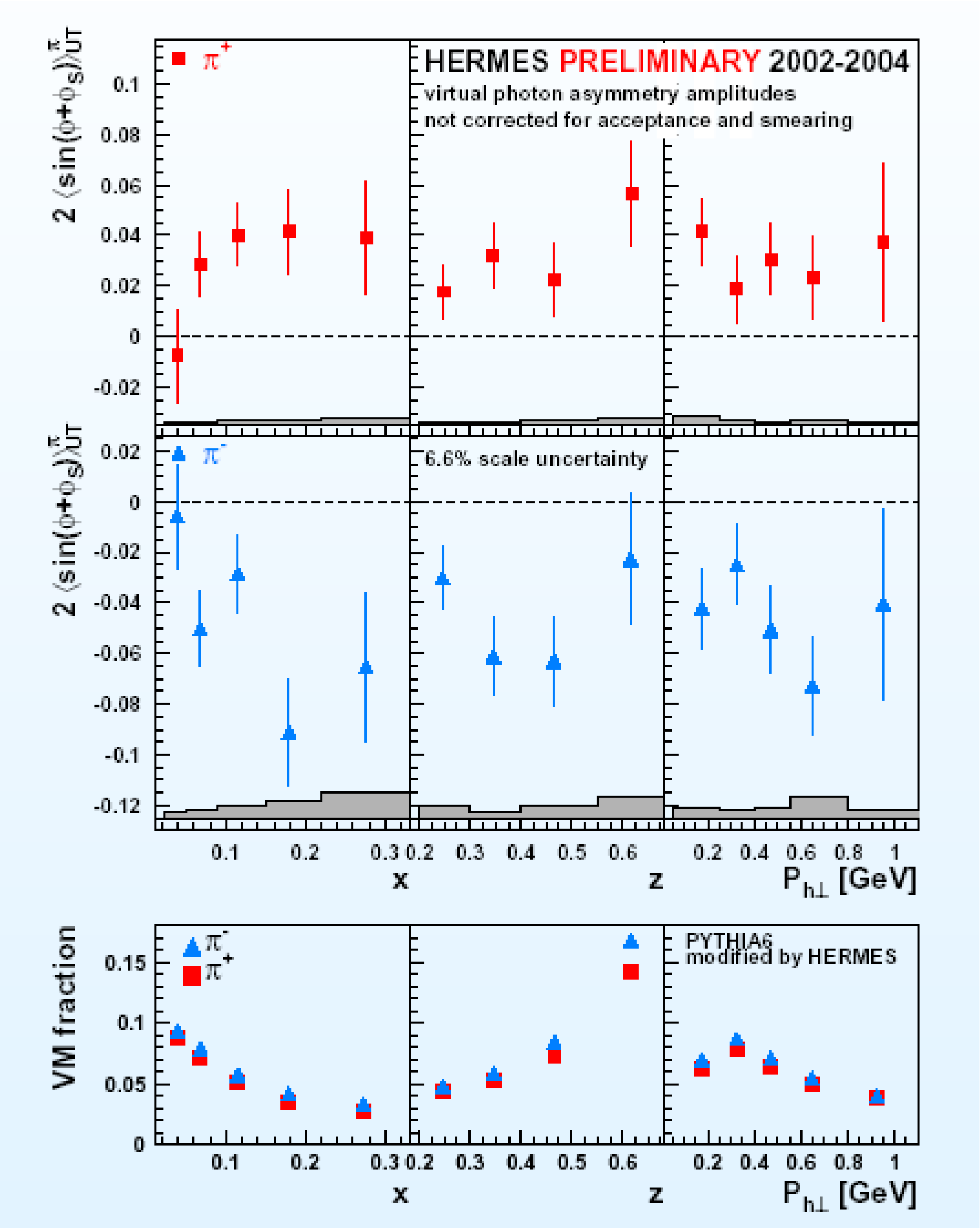
$$2\langle \sin(\Phi - \Phi_S) \rangle = A_{UT}^{\sin(\Phi - \Phi_S)}$$

$$\equiv 2 \frac{\int d\Phi\, d\Phi_S (d\sigma^{\uparrow} - d\sigma^{\downarrow}) \sin(\Phi - \Phi_S)}{\int d\Phi\, d\Phi_S (d\sigma^{\uparrow} + d\sigma^{\downarrow})}$$





Hermes Collins



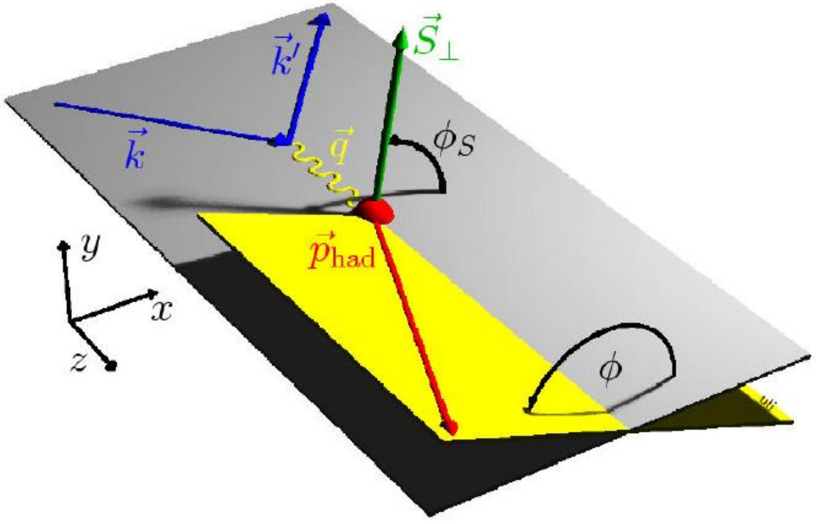
$$l\, N^{\uparrow} \rightarrow l\, \pi\, X$$

"Collins moment"

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

$$2\langle \sin(\Phi + \Phi_S) \rangle = A_{UT}^{\sin(\Phi+\Phi_S)}$$

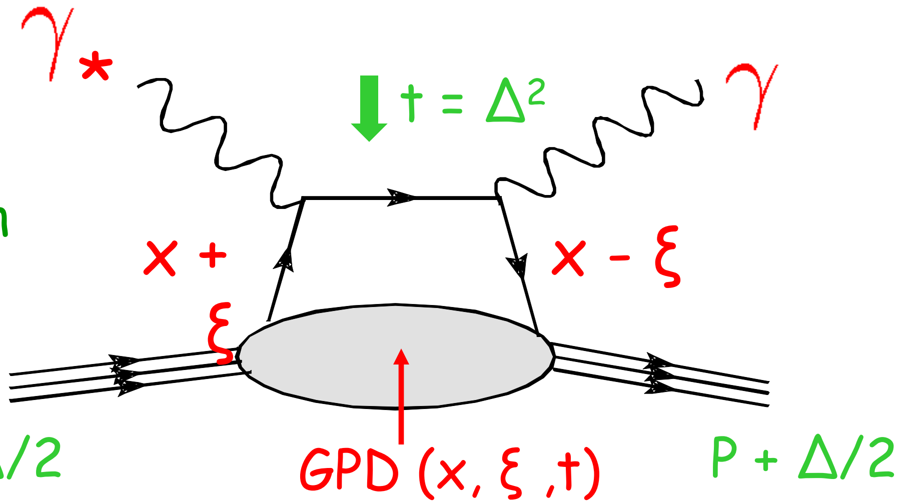
$$\equiv 2 \frac{\int d\Phi\, d\Phi_S (d\sigma^{\uparrow} - d\sigma^{\downarrow}) \sin(\Phi + \Phi_S)}{\int d\Phi\, d\Phi_S (d\sigma^{\uparrow} + d\sigma^{\downarrow})}$$



Generalized Parton Distributions

➡ Q_{hard}^2 large

Ji , Radyushkin (1996)



low -t process : $-t \ll Q_{hard}^2$

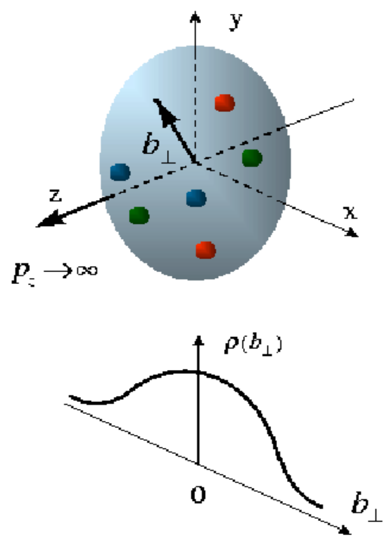
(x + ξ) and (x - ξ) : longitudinal momentum fractions of quarks

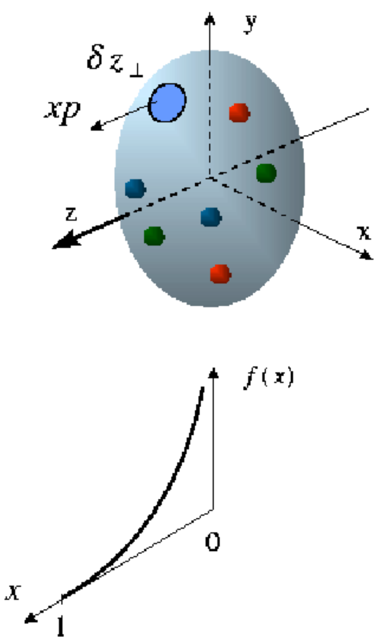
➡ at large Q^2 : QCD factorization theorem ➡ hard exclusive process can be described by 4 transitions (GPDs) :

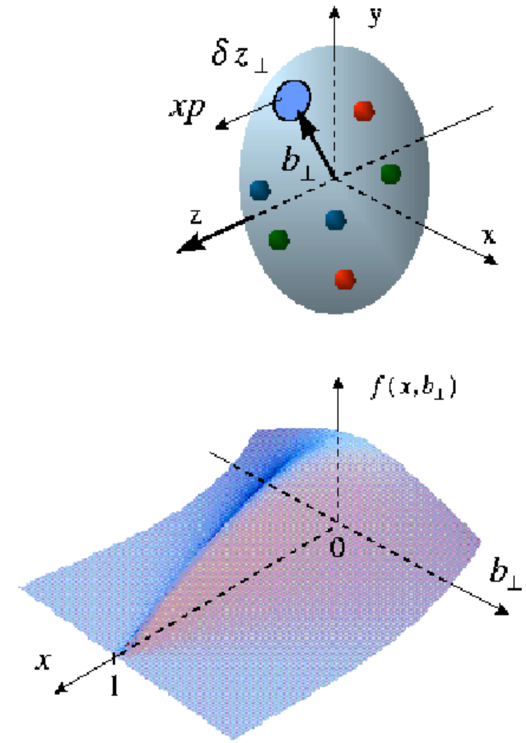
Vector : $H(x, \xi, t)$ Axial-Vector : $\tilde{H}(x, \xi, t)$

Tensor : $E(x, \xi, t)$ Pseudoscalar : $\tilde{E}(x, \xi, t)$

Generalized Parton Distributions yield 3-dim quark structure of nucleon







Elastic Scattering

transverse quark distribution in Coordinate space

DIS

longitudinal quark distribution in momentum space

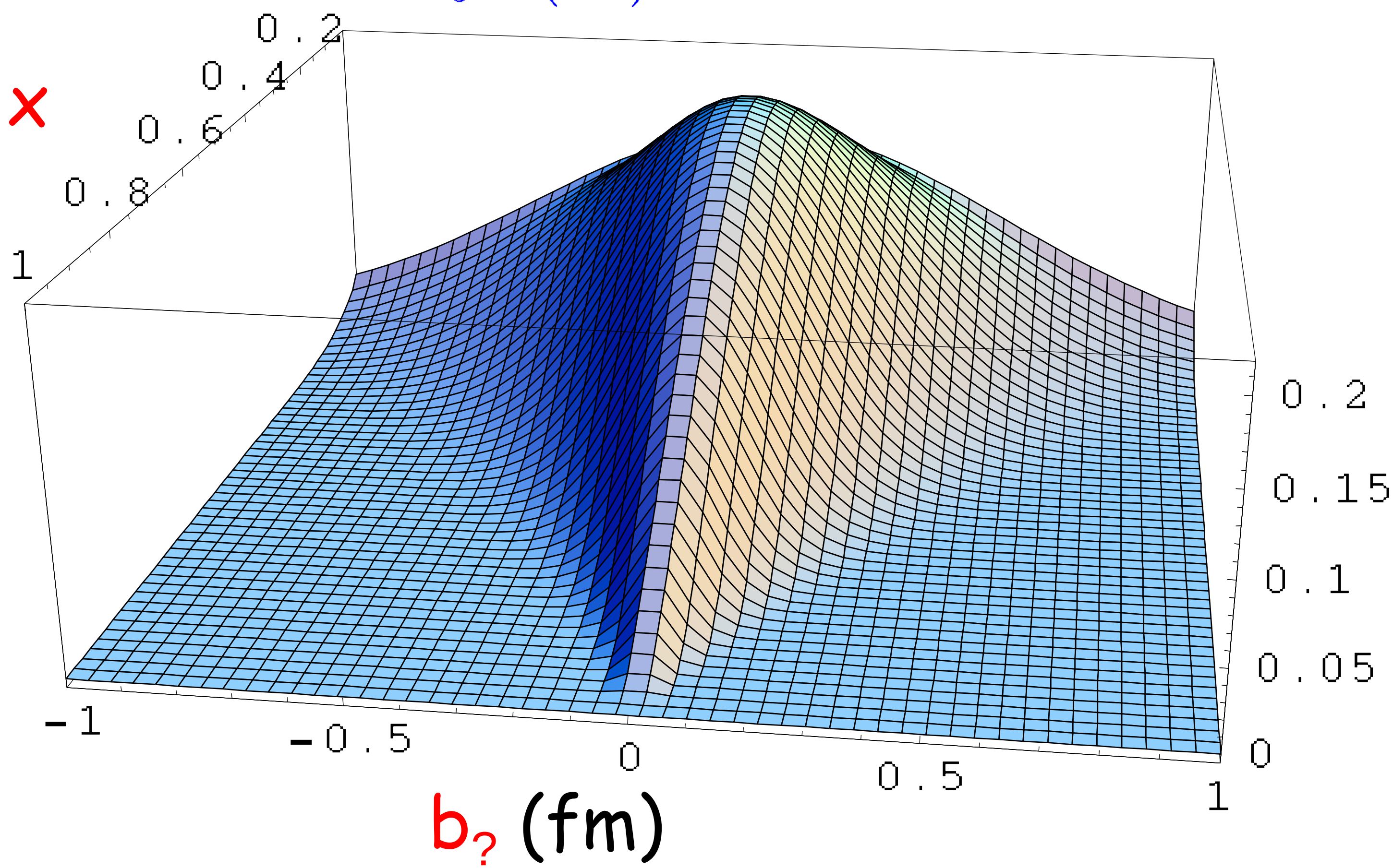
DES (GPDs)

Fully-correlated quark distribution in both coordinate and momentum space

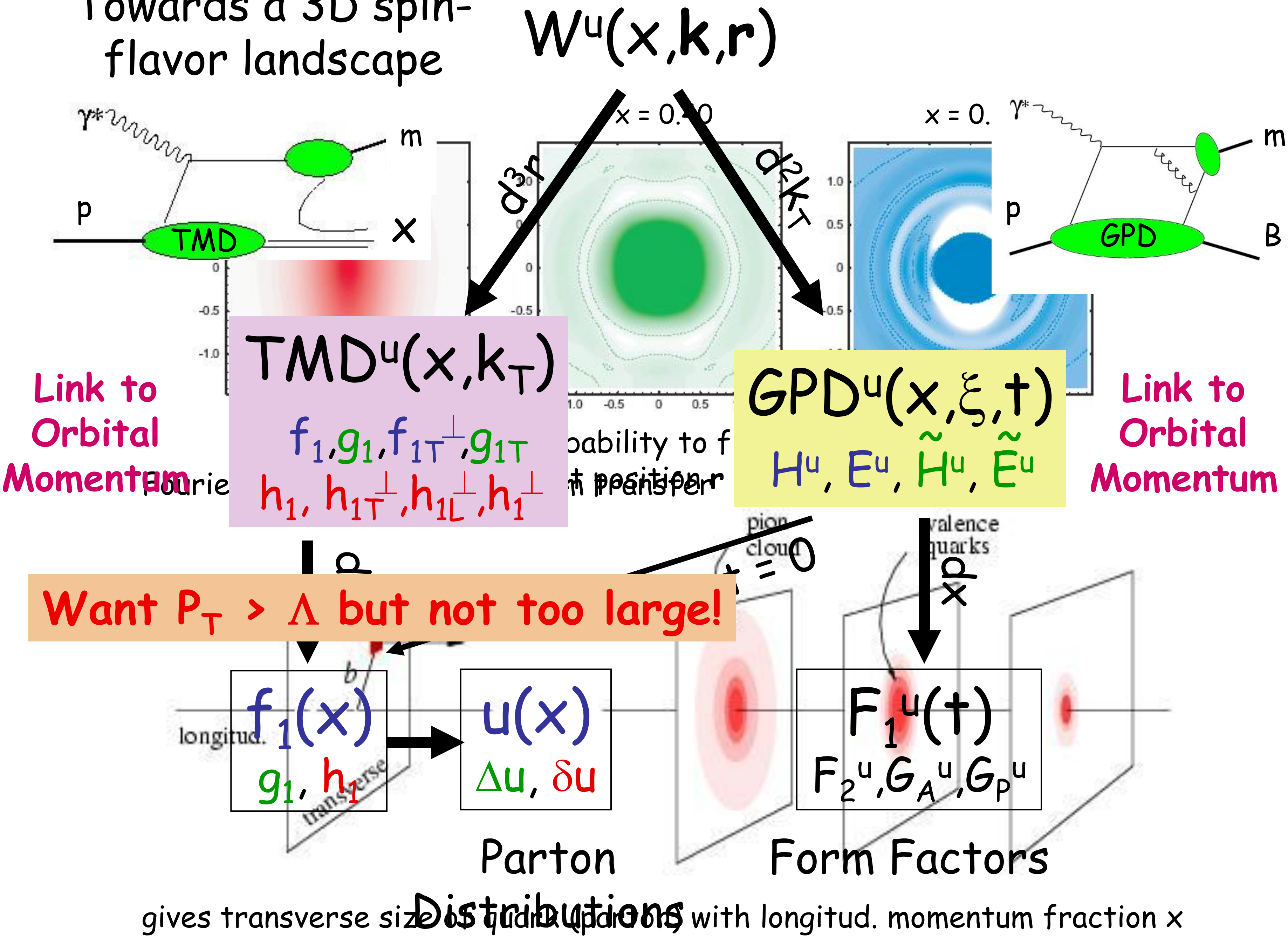
GPDs : transverse image of the nucleon (tomography)

$H^u(x, b_?)$

$$H^q(x, \mathbf{b}_\perp) = \int \frac{d^2 \mathbf{\Delta}_\perp}{(2\pi)^2} e^{i \mathbf{b}_\perp \cdot \mathbf{\Delta}_\perp} H^q(x, \xi = 0, -{\mathbf{\Delta}_\perp}^2)$$



Towards a 3D spin-flavor landscape

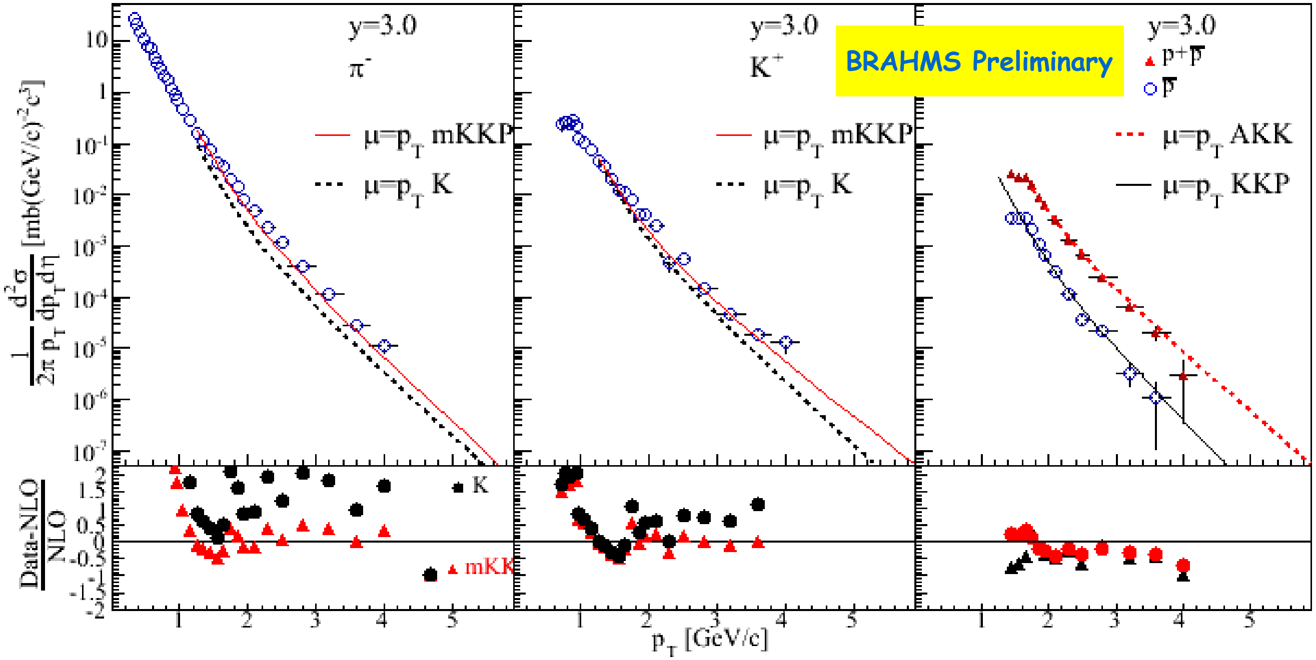


Spin is challenging ....

Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they might just ban such measurements altogether out of self-protection.

J.D. Bjorken
St. Croix, 1987

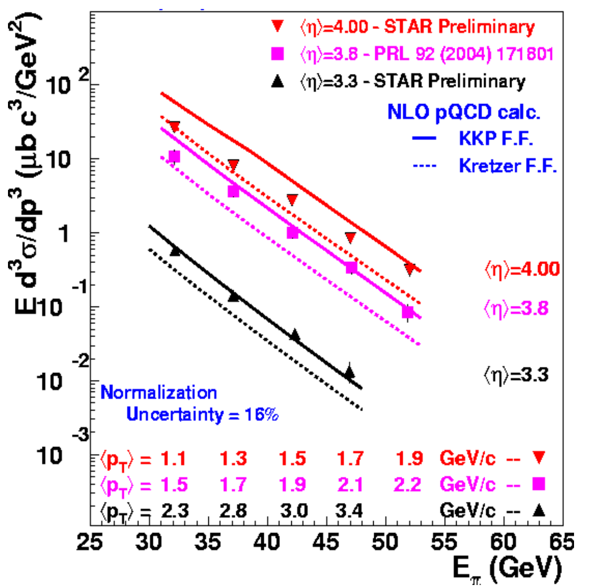
Cross-sections at RHIC, Forward Rapidities



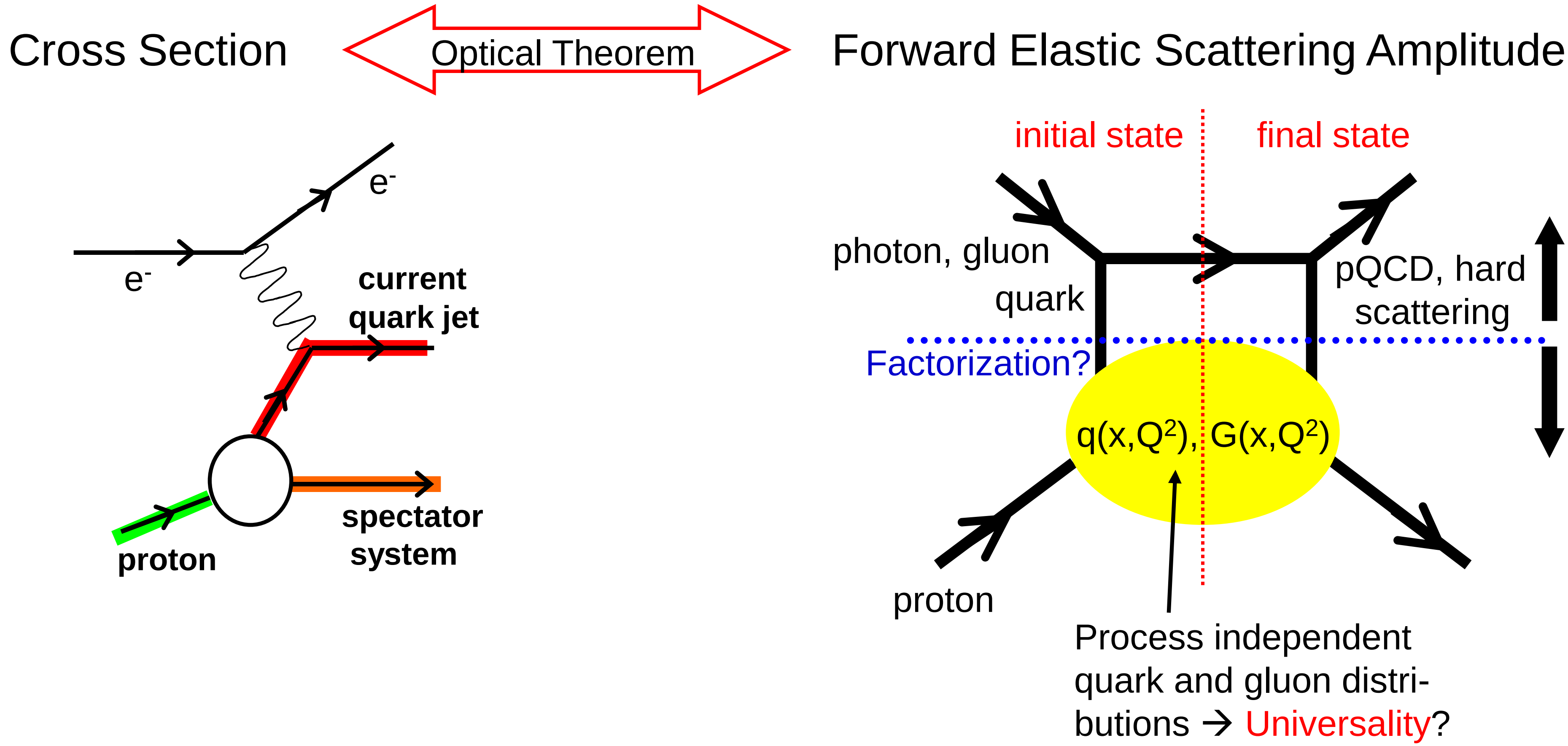
•Cross-sections generally described well by NLO pQCD at √s = 200 GeV and forward rapidities

•Are we in a situation where in unpolarized the theory is relatively well understood, but the polarized gives surprises?

- •Potentially we are in a region where the polarized data gives us new information about QCD, in a region where one can have quantitative theoretical understanding of the effects, and not just phenomenology.



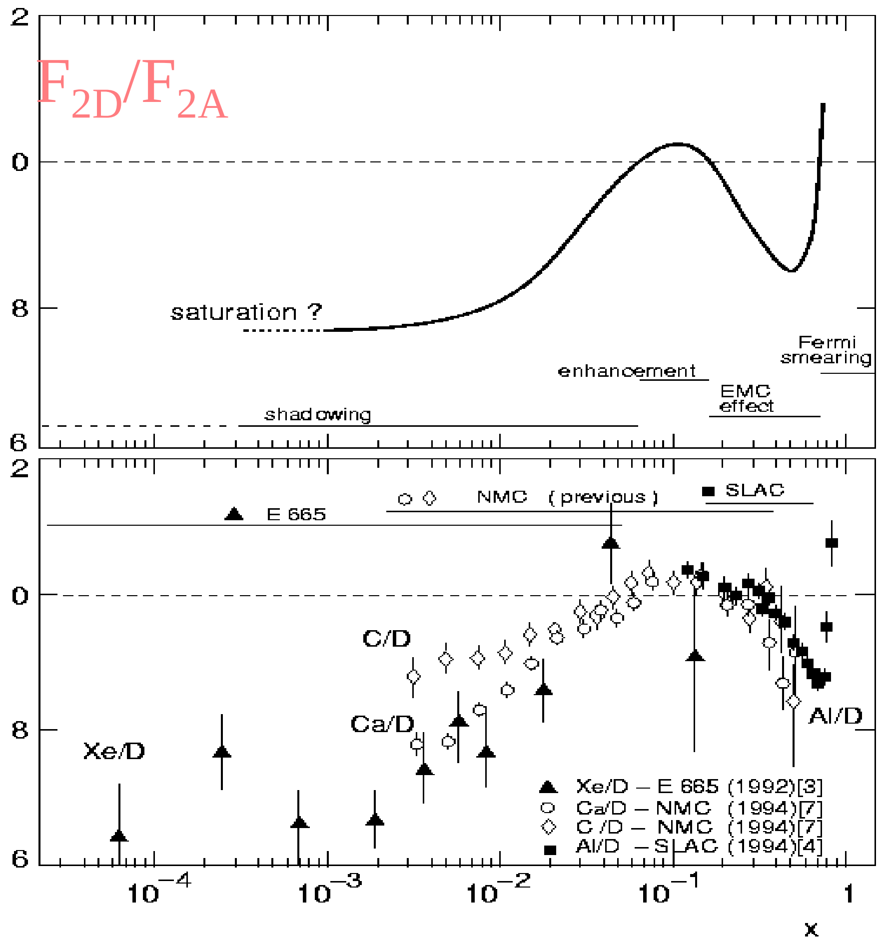
Optical Theorem in Hard Scattering



The imaginary part of the forward elastic scattering amplitude is equal to the total cross-section, ie, the lost cross-section in elastic scatters is equal to cross-secton of inelastic scatters.

Cold Nuclear Structure (d+Au)

Observation that structure functions are altered in nuclei stunned much of the HEP community ~25 years ago



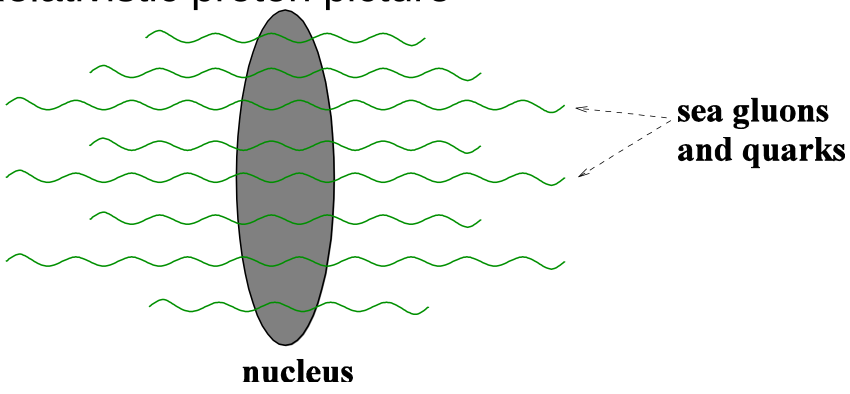
Regions of:

- Fermi smearing
- EMC effect
- Enhancement
- Shadowing
- Saturation?

Regions of shadowing and saturation mostly around Q^2 ~1 GeV^2

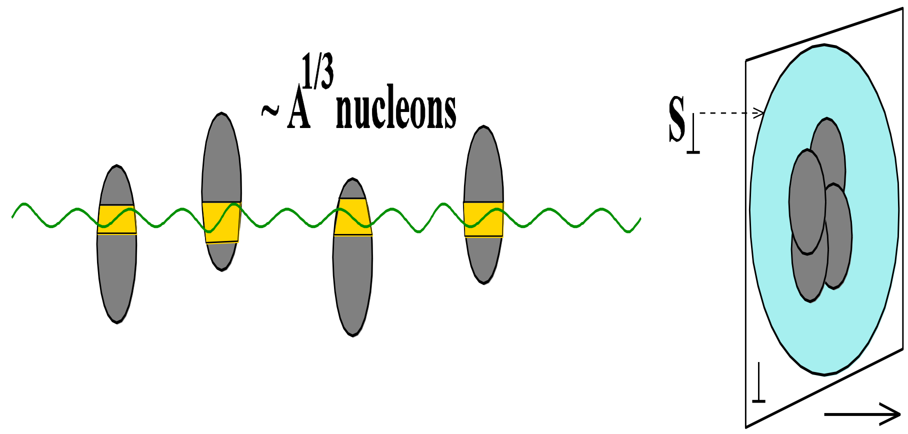
Saturation picture in nuclei

Relativistic proton picture



$$l_{coh} \sim \frac{1}{k_+} \sim \frac{1}{x_{Bj}\ p_+} \sim \frac{1}{x_{Bj}\ m_N}$$

(In rest frame of proton)

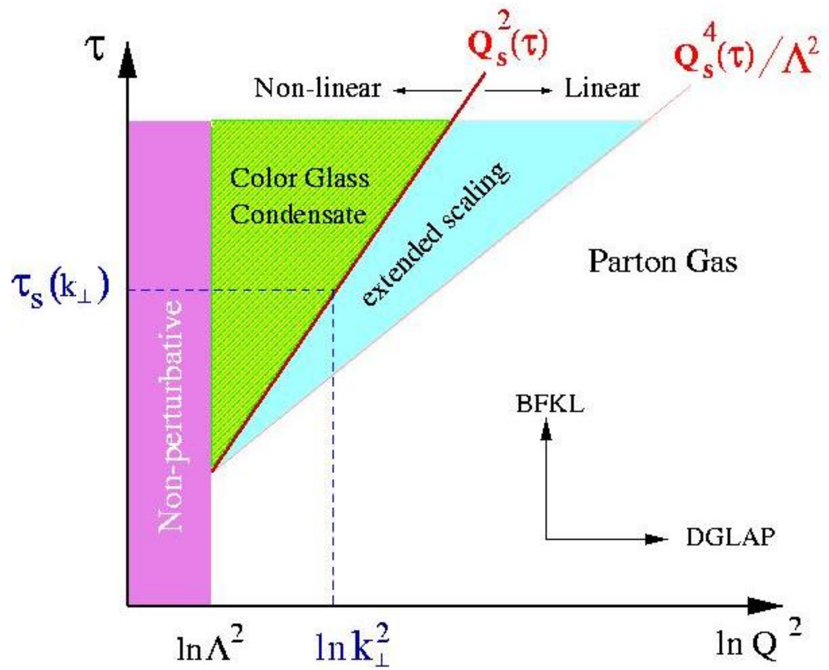


Nucleus picture

- Transverse area of a parton ~ $1/Q^2$
- Cross section parton-probe : $\sigma \sim \alpha_s/Q^2$
- Partons start to overlap when $S_A \sim N_A \sigma$
- The parton density saturates
- Saturation scale : $Q_s^2 \sim \alpha_s(Q_s^2) N_A/\pi R_A^2 \sim A^{1/3}$
- At saturation N_{parton} is proportional to $1/\alpha_s$
- Q_s^2 is proportional to the density of participating nucleons; larger for heavy nuclei.

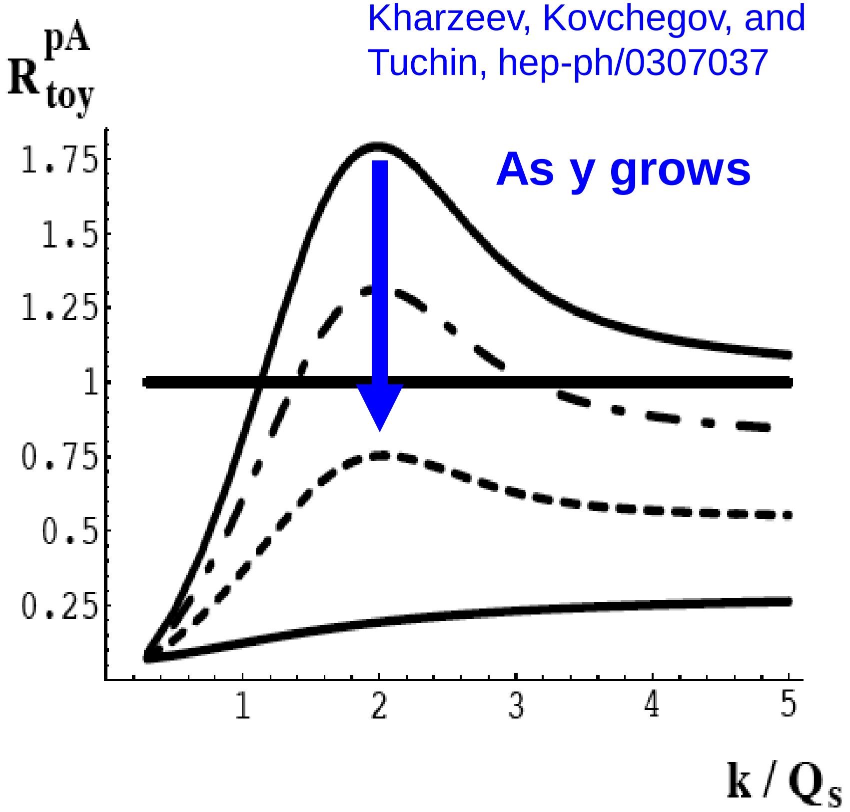
Expectations for a color glass condensate

$\tau = \ln\left(\frac{1}{x}\right)$ τ related to rapidity of produced hadrons.



Iancu and Venugopalan, hep-ph/0303204

Kharzeev, Kovchegov, and Tuchin, hep-ph/0307037

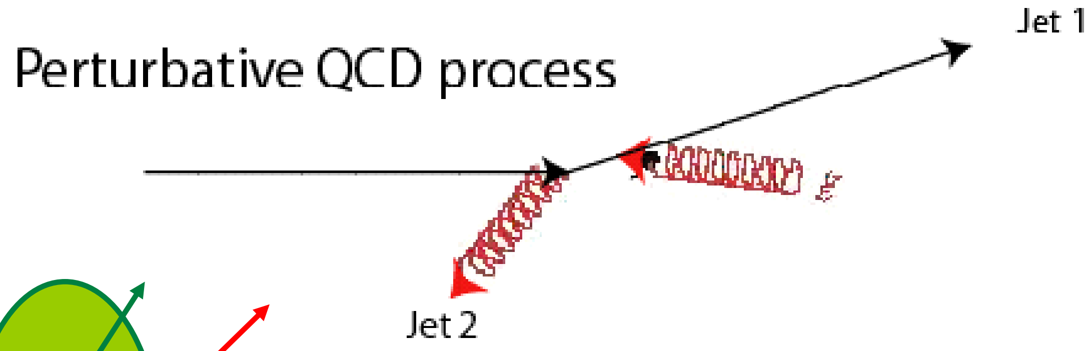


Are the forward d+Au results evidence for **gluon saturation at RHIC energies**?

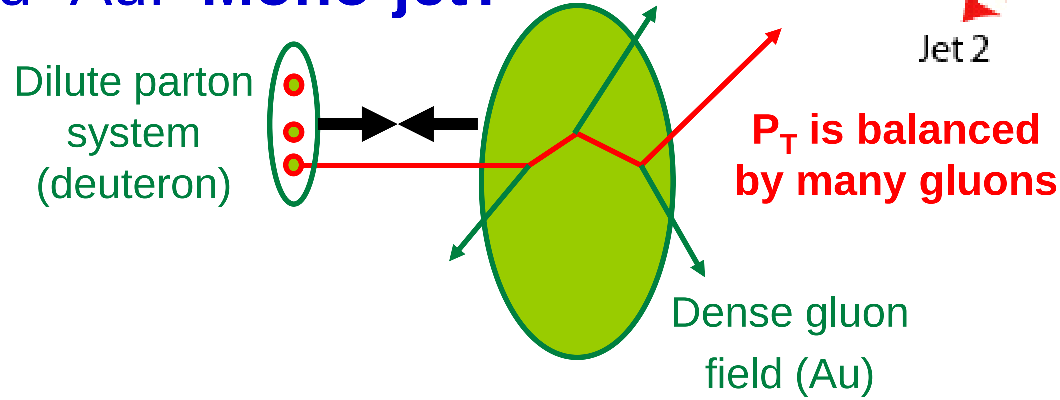
Not clear. Need more data, and more observables.

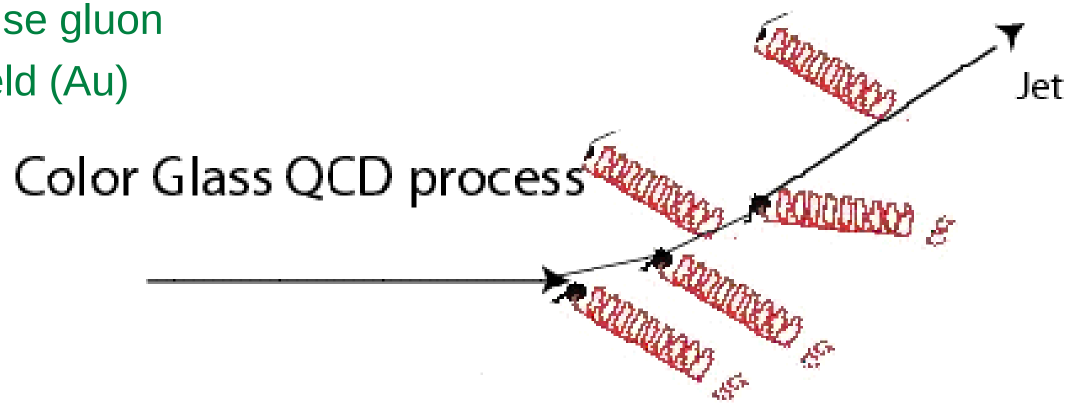
Any difference between p+p and d+Au?

p+p: **Di-jet**



d+Au: **Mono-jet?**

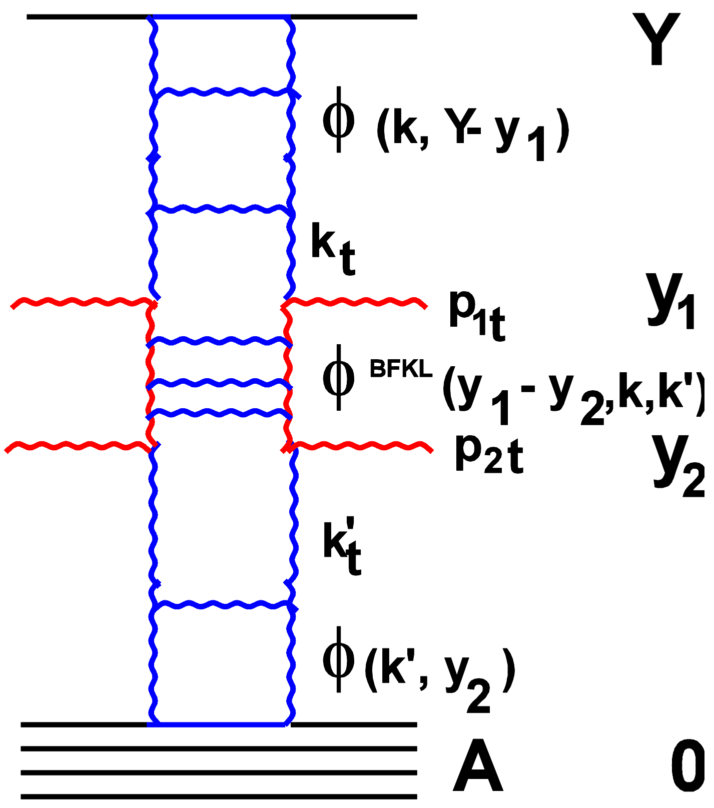


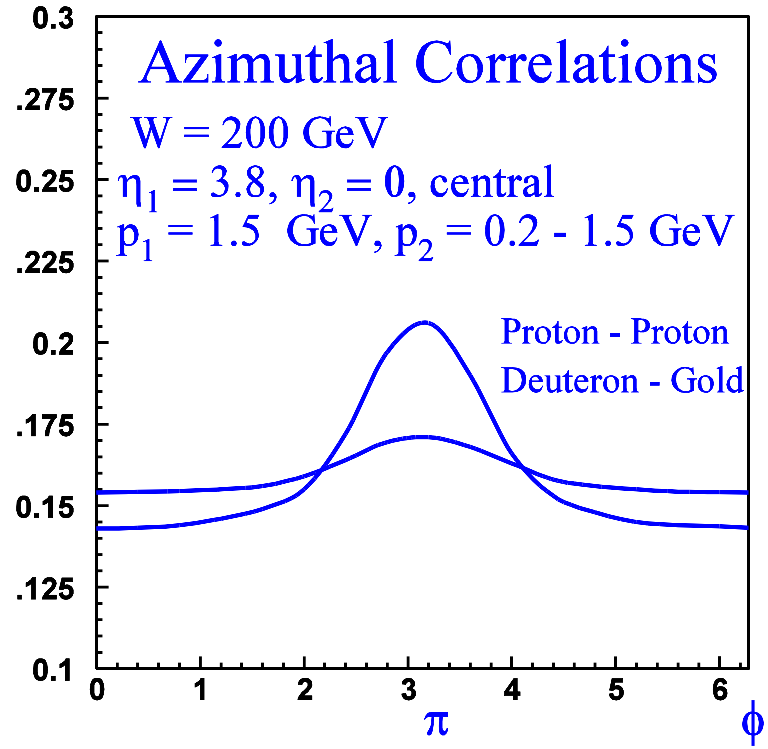


Kharzeev, Levin, McLerran (NPA748, 627)

Color glass condensate predicts that the **back-to-back correlation** from p+p **should be suppressed**

Back-to-back correlations with the color glass



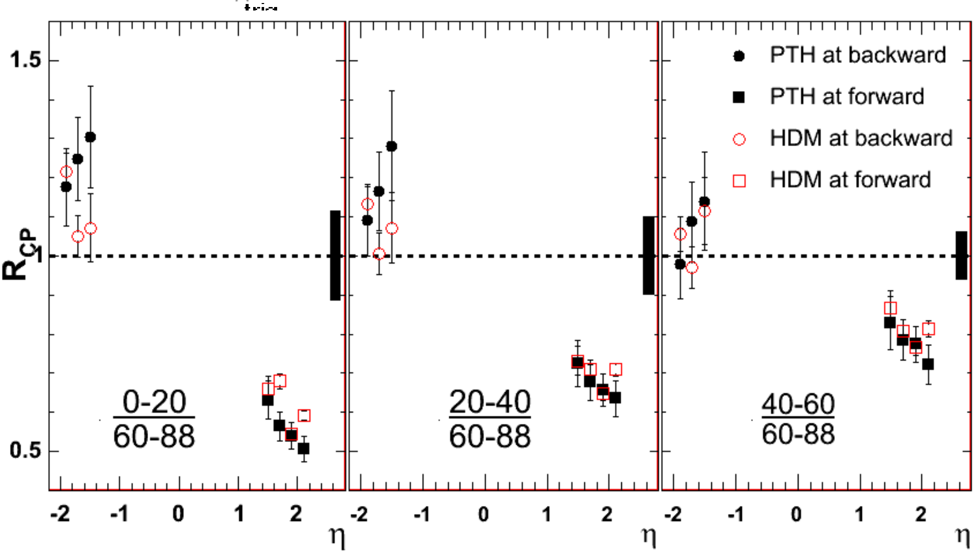


The evolution between the jets makes the correlations disappear.

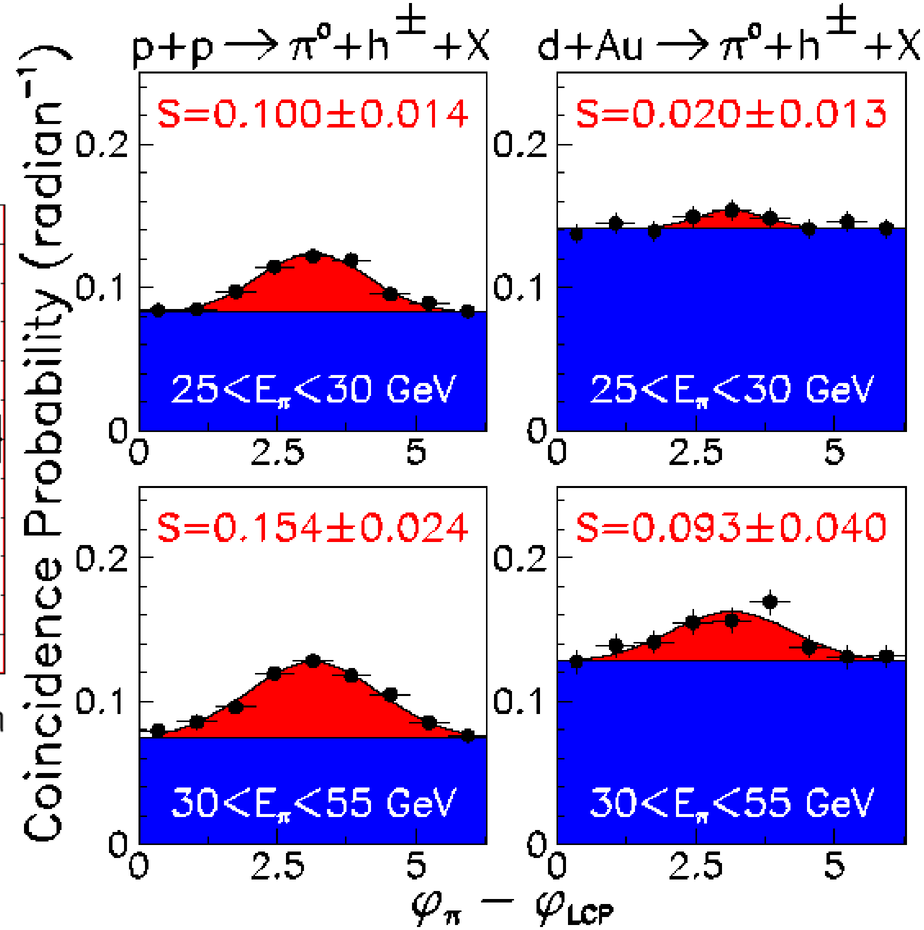
(Kharzeev, Levin, and McLerran, NP A748, 627)

Forward-midrapidity correlations in d+Au

PHENIX PRL 94, 082302



STAR PRL 97, 152302

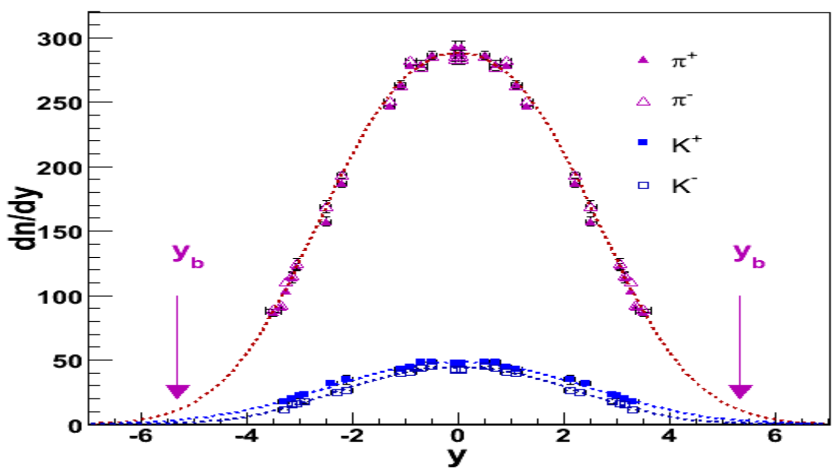


π^0: $|\langle\eta\rangle| = 4.0$
$h^{\pm}$: $|\eta| < 0.75$
$p_T > 0.5$ GeV/c

- PHENIX doesn't see any changes for $\langle x_g \rangle \sim 0.015$
- STAR might see suppression for $\langle x_g \rangle \sim 0.006$

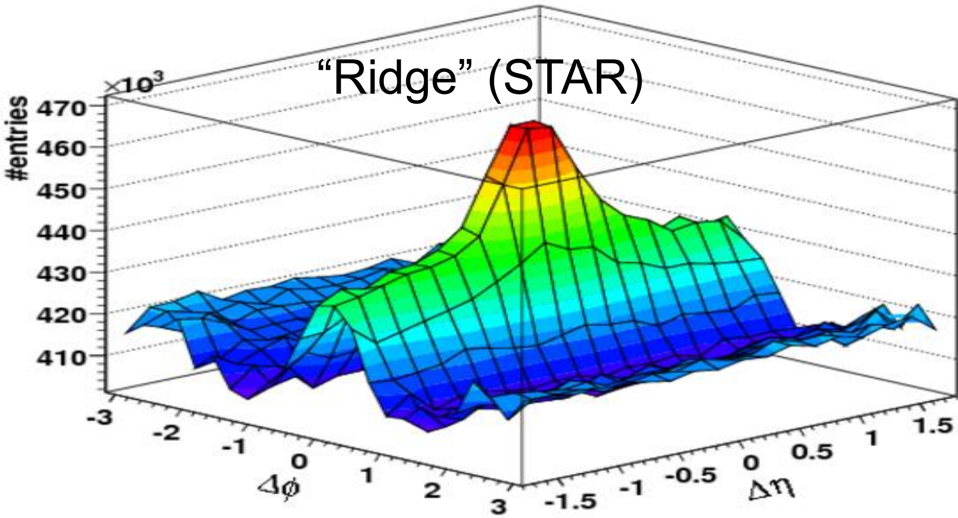
The MPC in Heavy Ion Physics

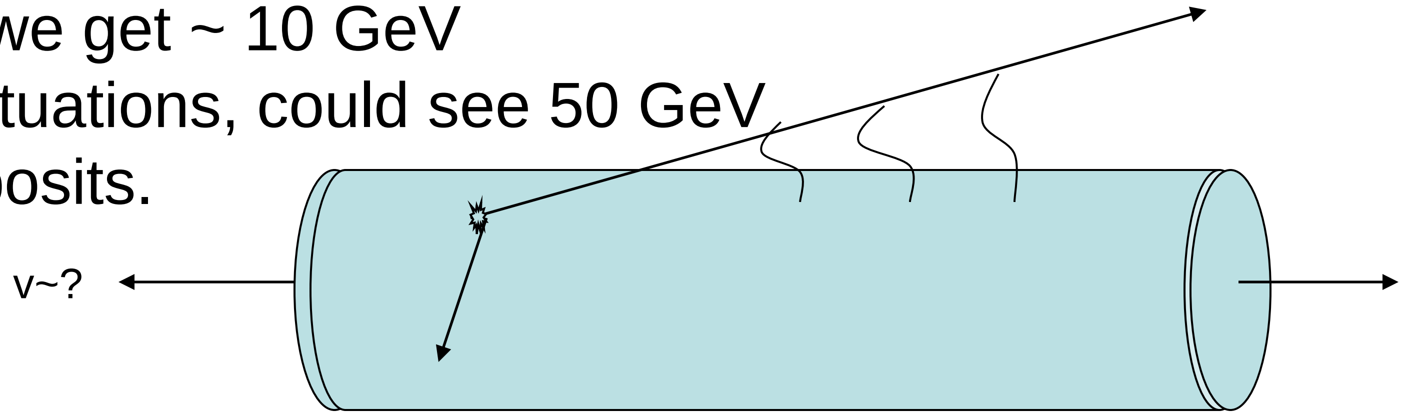
- Due to extremely high occupancies in the forward region, MPC capabilities are vastly reduced in Au+Au.
    - Possibly one could do something in peripheral collisions, but due to need to reduce HV to not saturate, resolution (due to noise) is reduced.
- Reaction plane (RP) contribution
    - Sees neutral particles missed by BBC – adds to resolution
    - Can use E_T (p_T) weighted values to determine RP
- Forward E_T
    - Can this help to distinguish between Bjorken vs. Landau expansion?



Jet Correlations with MPC?

- Need Large $\Delta\eta$ to study ridge
- MPC Covers $\Delta\eta$ ~ 2.7 to 4.0
  - Potentially already beyond the where the ridge ends?
- Can be done using central arm trigger and MPC energy flow.
- OR, perhaps with a trigger tower in the MPC: expect ~100 GeV/tower in central Au+Au, so we get ~ 10 GeV fluctuations, could see 50 GeV deposits.





Conclusions