Recent Experimental Results on QCD Factorization Breaking of Nonperturbative Functions

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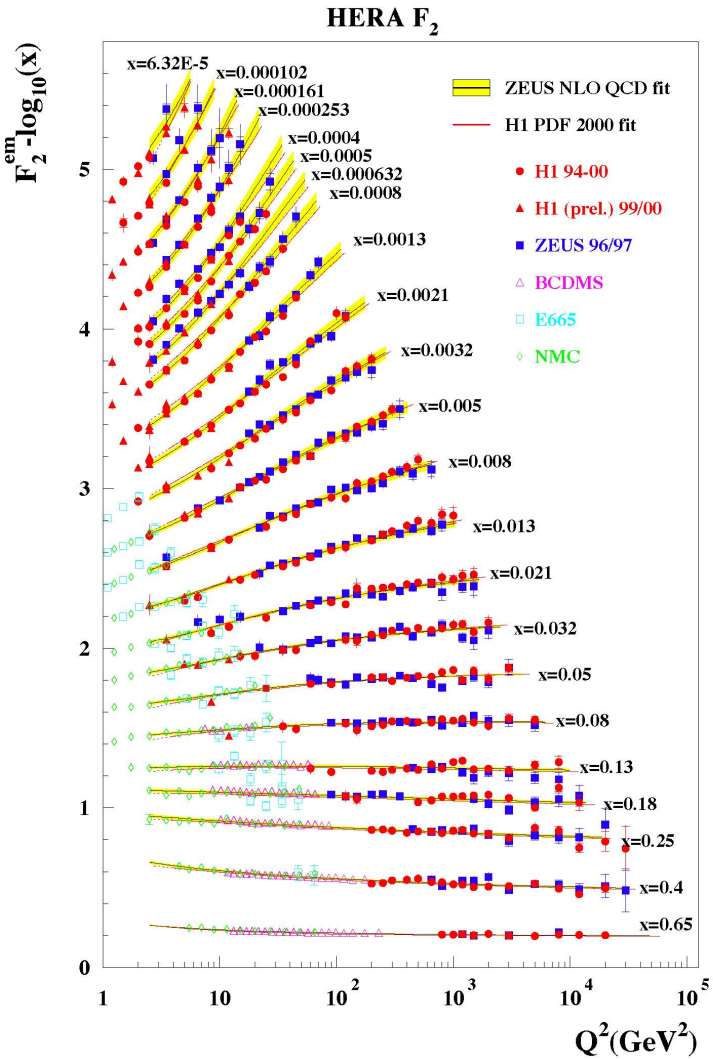
Outline

- Why study the 3-D structure of nucleon
- Physics in the transverse momentum dependent framework
- RHIC, PHENIX, and two particle angular correlations
- Recent results on factorization breaking
- Future factorization breaking measurements

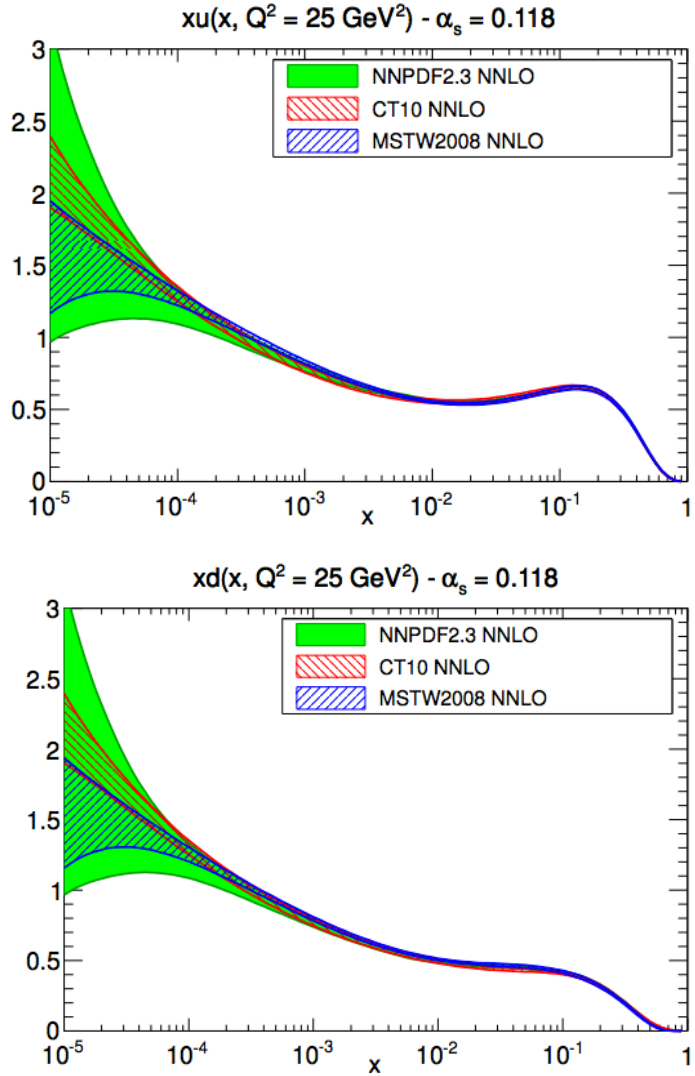
Mapping the Structure of the Proton

- Historically have used semi-inclusive deep-inelastic-scattering (SIDIS) and Drell-Yan (DY) as probes of hadron structure
- SIDIS measurements showed there is structure to the proton
- Longitudinal structure of proton in terms of $x = p_{\text{quark}}/p_{\text{proton}}$
- Well mapped out over large range of x and Q^2



1-D Structure

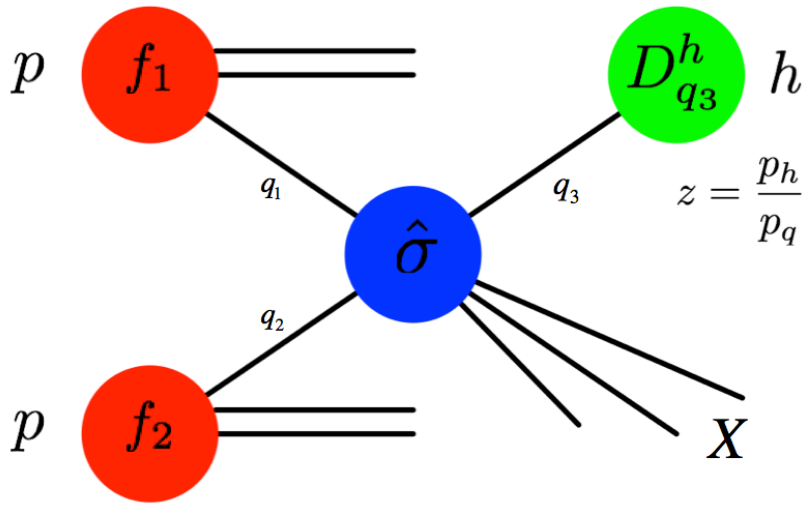
- Collected data has led to incredible precision for partonic structure of nucleons in the longitudinal direction!
- Collinear parton distribution functions (PDFs) are very well constrained over 4 orders of magnitude in x



Figures taken from http://nnpdf.hepforge.org

QCD Cross Sections

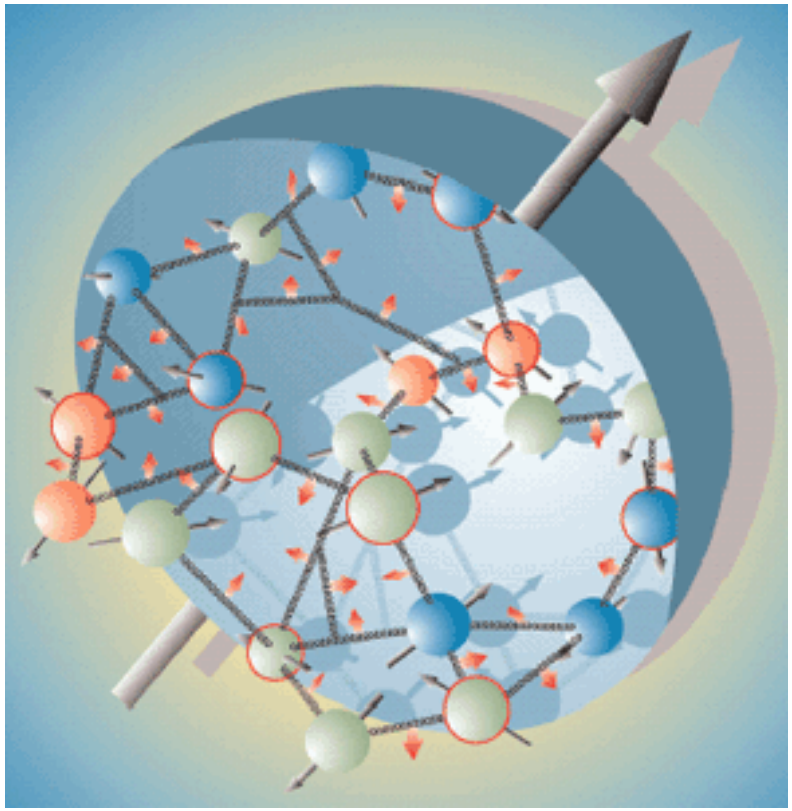
- To account for bound state nature of hadrons, cross sections are factorized
- Nonperturbative parton distribution and fragmentation functions (PDFs and FFs) are used to describe the individual partons within a hadron
- Functions are *nonperturbative*, must be constrained by data!
- Taken to be process independent and uncorrelated



$$\sigma = f_1(x, Q^2) \otimes f_2(x, Q^2) \otimes \frac{d\hat{\sigma}}{dt} \otimes D_q^h(z, Q^2)$$

Multidimensional Proton Structure

- What does the bound-state proton look like in terms of the quarks and gluons inside it?
  - Position
  - Momentum
  - Spin
  - Flavor
  - Charge
  - Color (!)
- What about transverse momentum degrees of freedom?



1D vs. 3D Nonperturbative Functions

- Historically nonperturbative functions are approximated as only dependent on the collinear momentum fraction x
- In reality there must be transverse structure due to the confined nature of the partons and the additional possibility of gluon radiation
- The unintegrated k_T distributions are explicitly dependent on transverse momentum

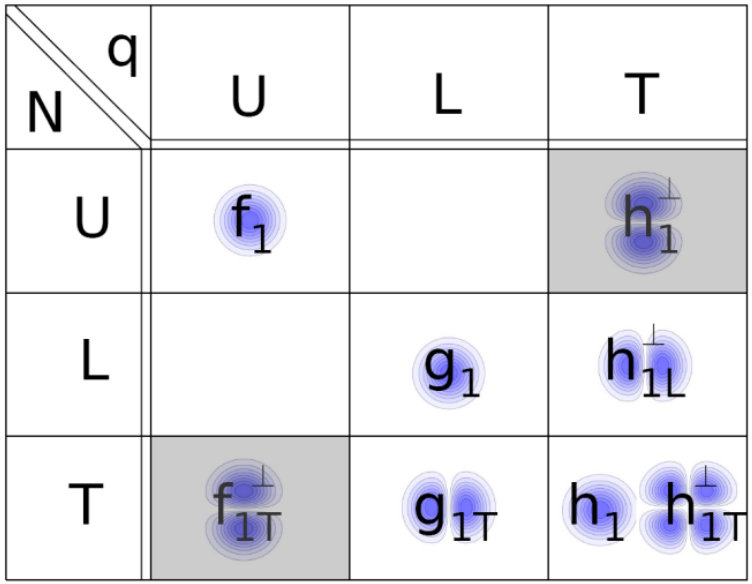
$$\text{Parton Distribution Functions: } f(x) \to f(x, k_T)$$

$$\text{Fragmentation Functions: } D(z) \to D(z, j_T)$$

- We can also add spin into the picture...

Transverse-Momentum-Dependent PDF Zoo

Transverse-Momentum-Dependent (TMD) PDFs



N - Nucleon
q - Quark
U - Unpolarized
L - Longitudinally polarized
T - Transversely polarized

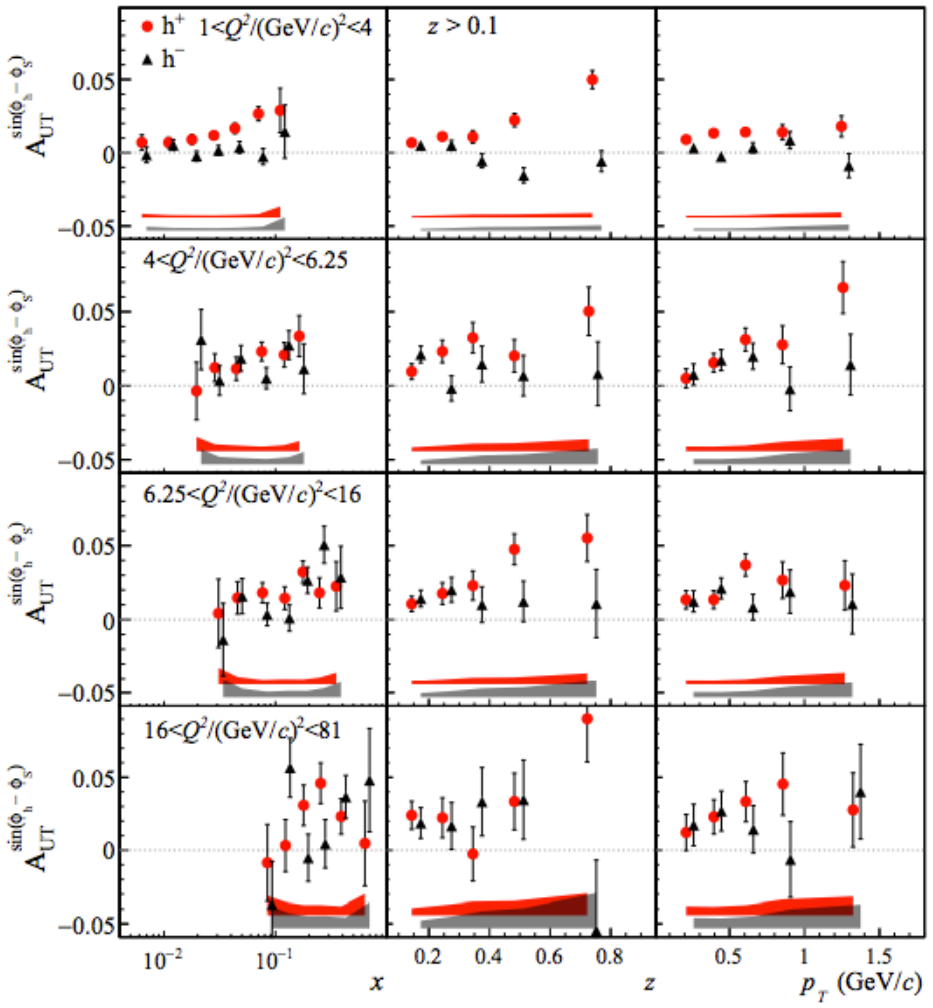
- 8 TMD PDFs at twist-2 describing transverse partonic structure, spin-spin, and spin-momentum *correlations!*

Image taken from Alexei Prokudin Spin 2016

Transverse-Momentum-Dependent Functions in Nature

- Many transverse-momentum-dependent PDFs and FFs correlate spin with momentum
- Beginning to really explore partonic correlations within the nucleon! New era of nucleon structure
- Are these correlations really present in nature? Absolutely!

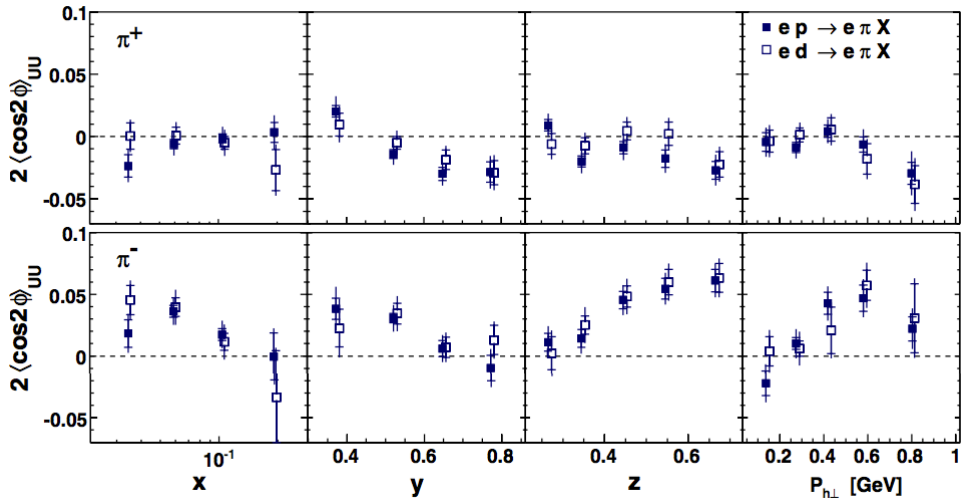
Sivers TMD PDF



arXiv:1609.07374, COMPASS at CERN

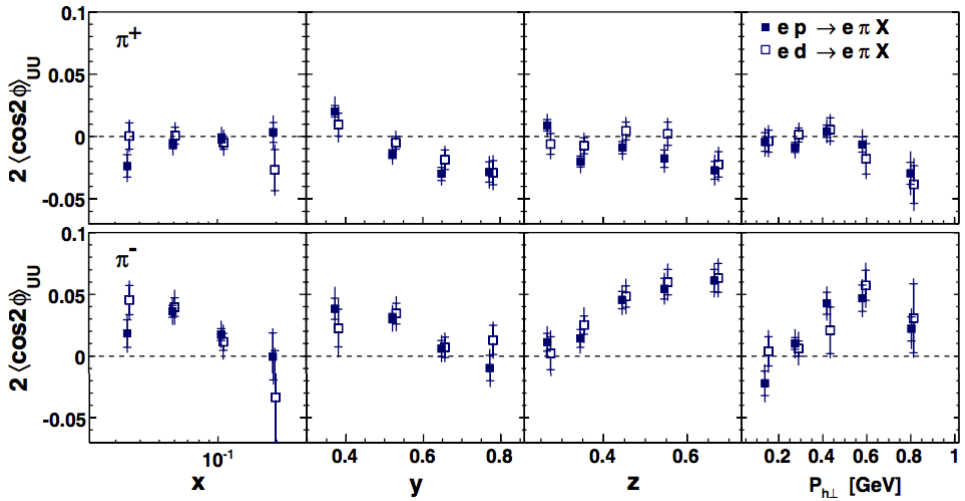
Transverse-Momentum-Dependent Functions in Nature

Boer Mulders TMD PDF

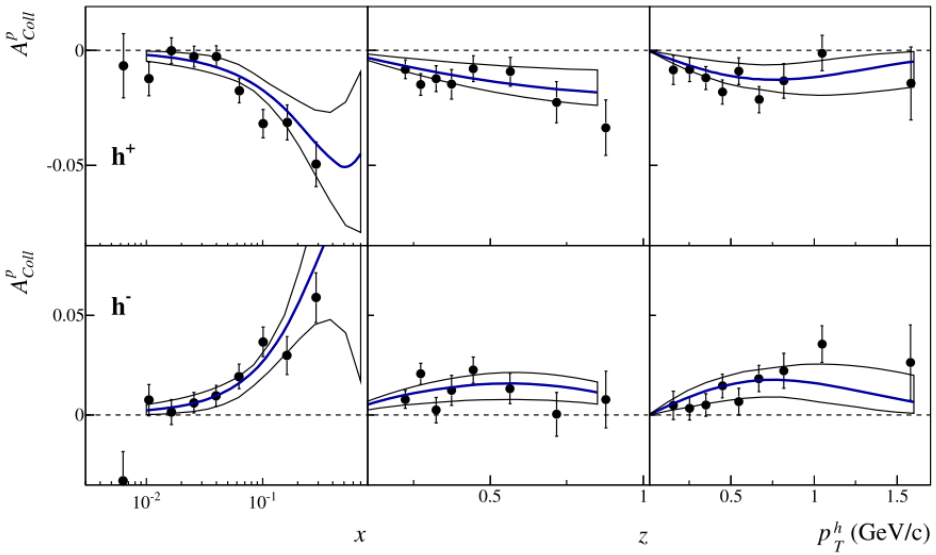


PRD 87, 012010(2013), HERMES at HERA

Transverse-Momentum-Dependent Functions in Nature

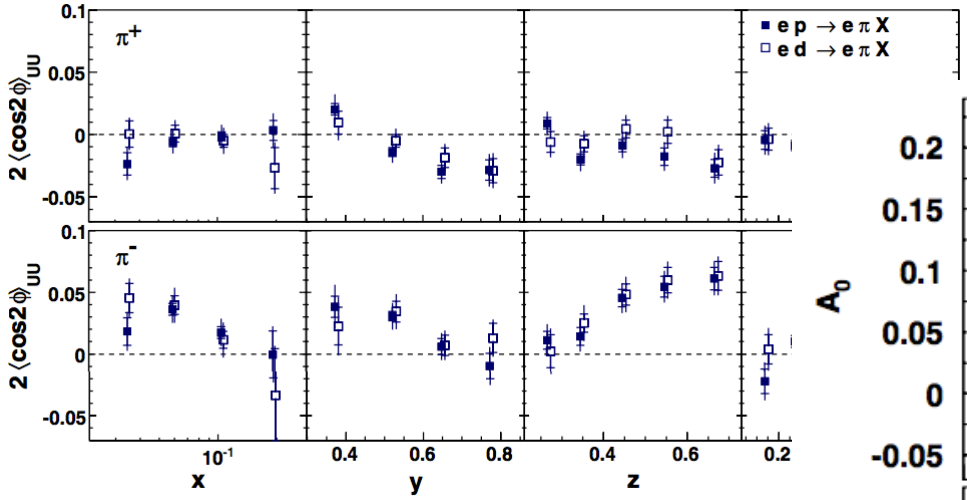


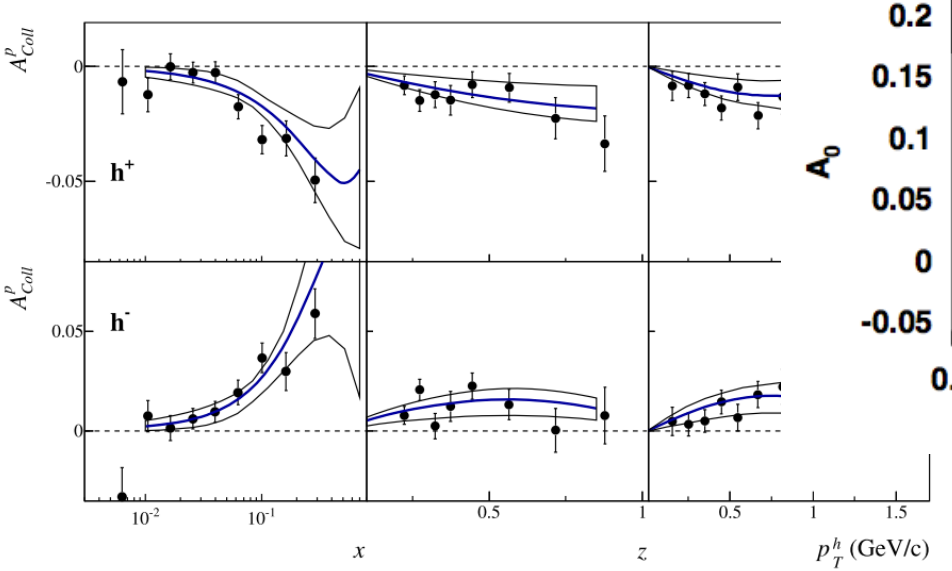
Transversity TMD PDF



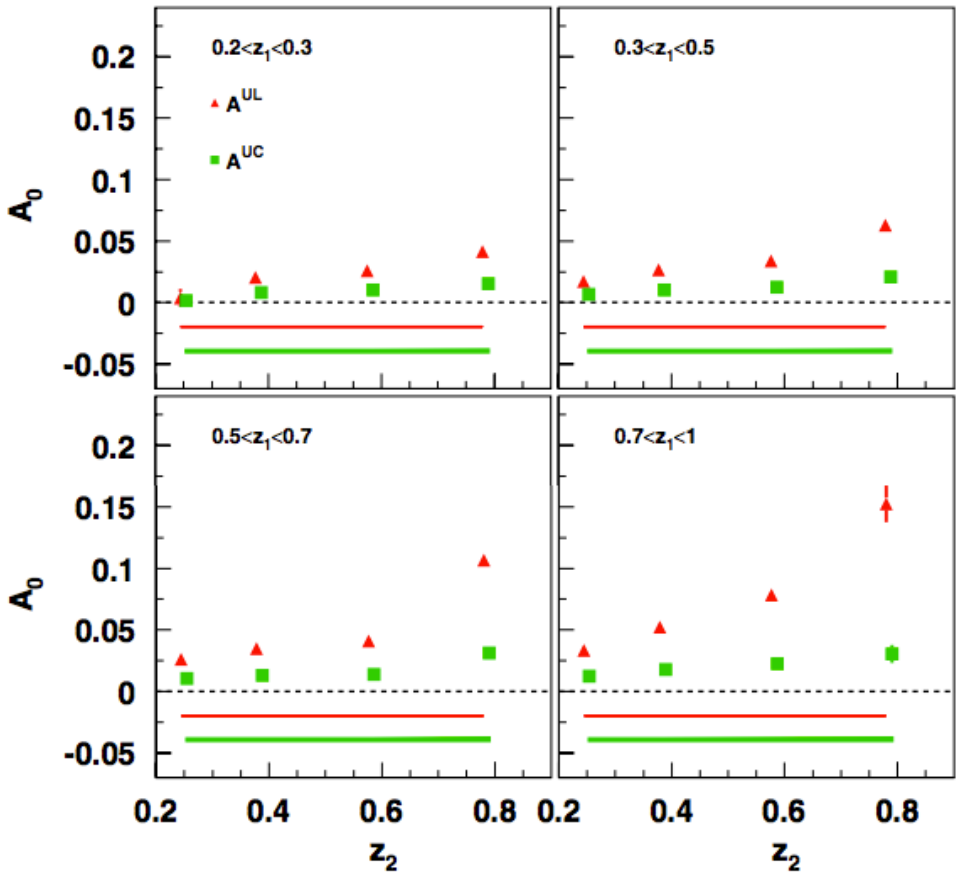
PLB 717, (2012) 376, COMPASS at CERN

Transverse-Momentum-Dependent Functions in Nature





PRD 78, 032011 (2008), Belle at KEK



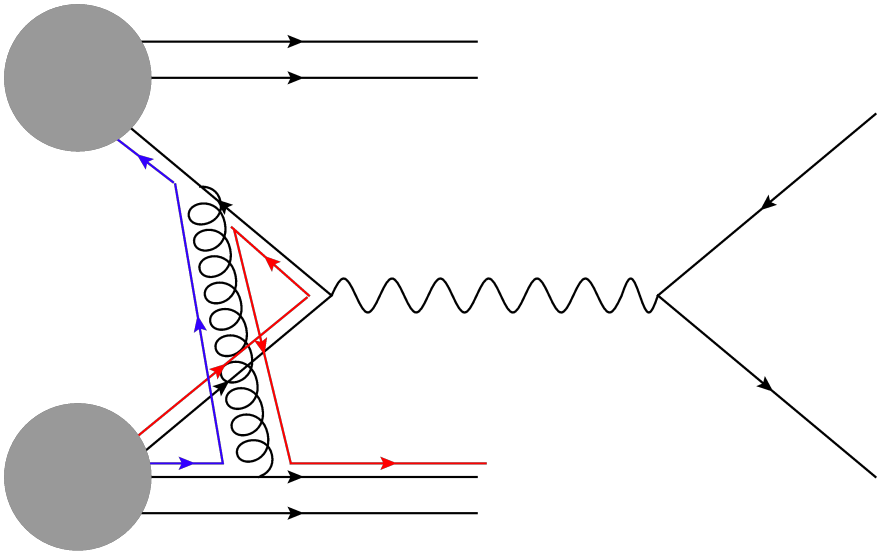
Collins TMD FF

Transverse-Momentum-Dependent Phenomenology

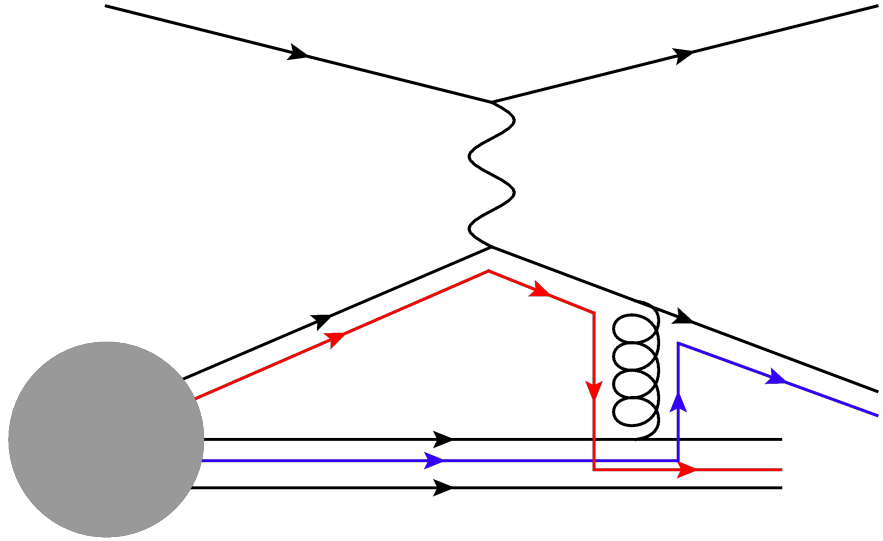
- In the collinear framework, nonperturbative functions are taken to be uncorrelated, universal, process independent functions
- In the transverse-momentum-dependent framework, it has been necessary to re-check these assumptions
- This has led to very interesting predictions...

Universality in Transverse-Momentum-Dependent Functions

Drell-Yan



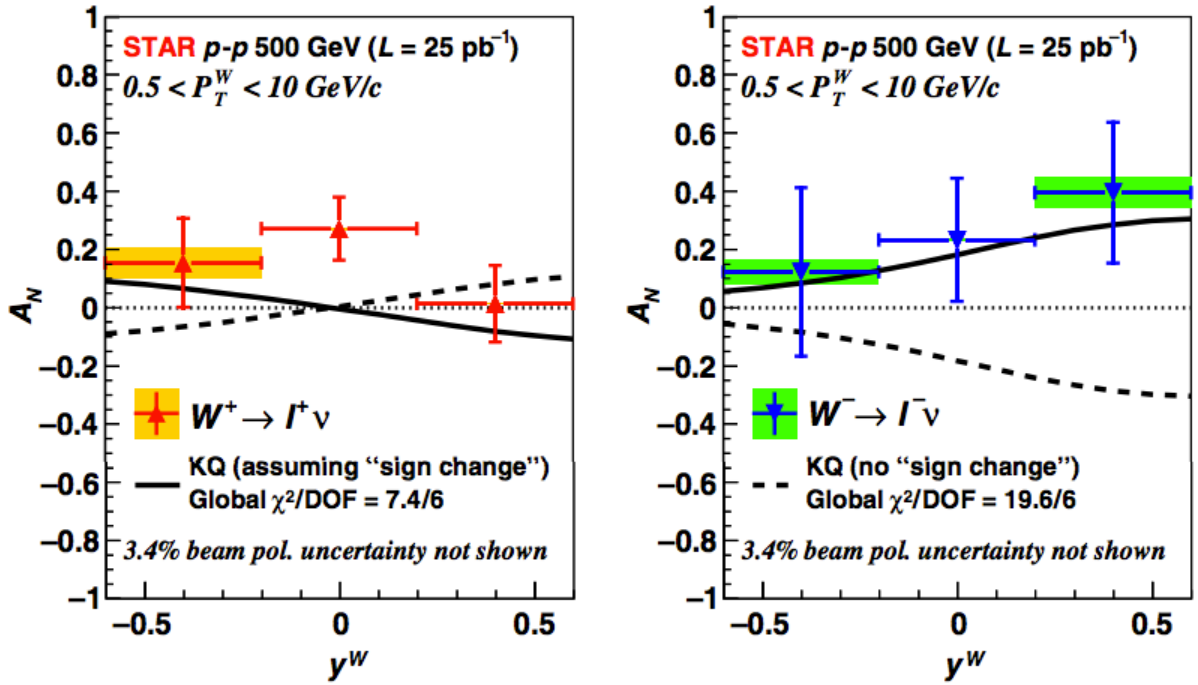
Semi-Inclusive DIS



- Sign change in Sivers transverse-momentum-dependent PDF predicted due to initial-state vs. final-state gluon exchange with proton remnants between Drell-Yan and semi-inclusive DIS: process dependent PDF!
- Factorization of transverse-momentum-dependent PDFs and fragmentation functions still predicted to hold in these QED processes

First Measurement of Possible Modified Universality

- Semi-inclusive DIS Sivers asymmetries have been measured, e.g. by HERMES and COMPASS collaborations
- First measurement of Drell-Yan type process from STAR at RHIC!
- Data support prediction of process dependent transverse-momentum-dependent PDF



PRL 116, 132301(2016)

Factorization of Transverse-Momentum-Dependent Functions

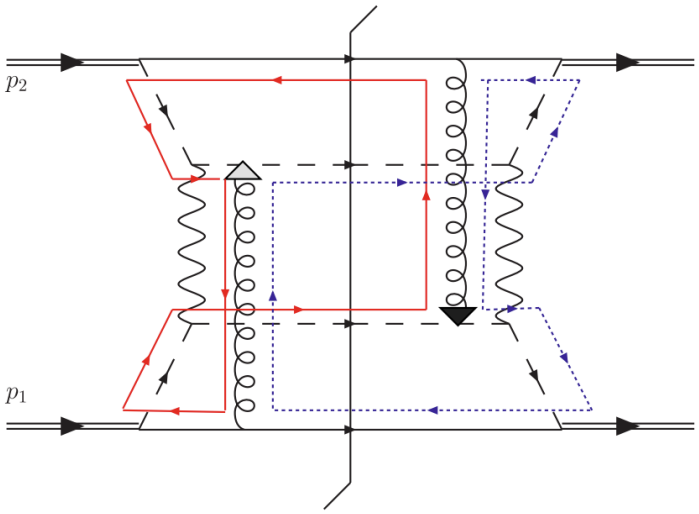
- Factorization is still predicted to hold in semi-inclusive DIS and Drell-Yan

$$\sigma = f_1(x, k_T, Q^2) \otimes f_2(x, k_T, Q^2) \otimes \frac{d\hat{\sigma}}{dt} \otimes D_q^h(z, j_T, Q^2)$$

- What about leading-order QCD processes where a colored quark or gluon is exchanged?
- Color present in both the initial and final state - therefore soft gluon exchange possible in both the initial and final state

Factorization of Transverse-Momentum-Dependent Functions

- Factorization breaking predicted in a transverse-momentum-dependent (TMD) framework for $p + p \rightarrow h_1 + h_2$ (PRD 81, 094006 (2010))
- TMD nonperturbative functions no longer defined - partons are quantum mechanically correlated across colliding hadrons!
- Consequence of soft gluon exchanges in both the initial and final state

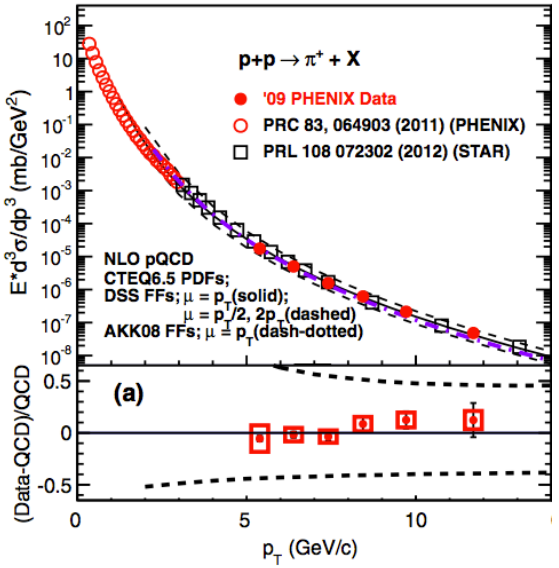


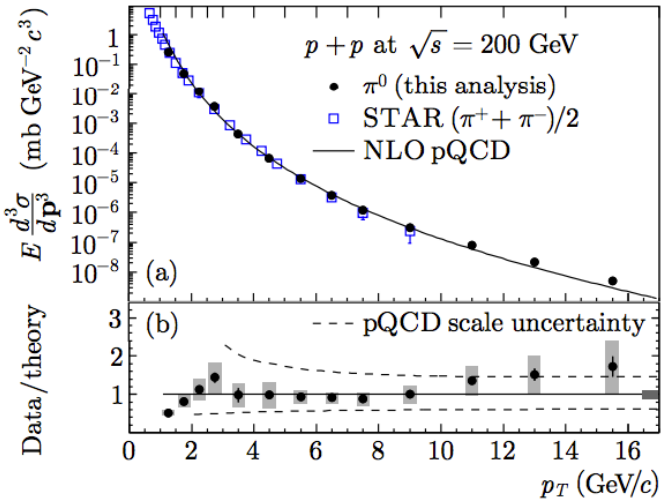
- Predicted modified universality of certain TMD PDFs and factorization breaking from same physical process - consequences of color flow in action!
- Consequence of QCD as a non-Abelian gauge theory

Looking for Factorization Breaking

- An obvious way to look for effects is by comparing measurement to a calculation which assumes factorization
- Problem: calculations require good knowledge of the transverse-momentum-dependent nonperturbative functions. Collinear pQCD calculations still have ∼10-40% errors
- What about observing change of functions with the hard scattering scale?

PRD 91, 032001 (2015)

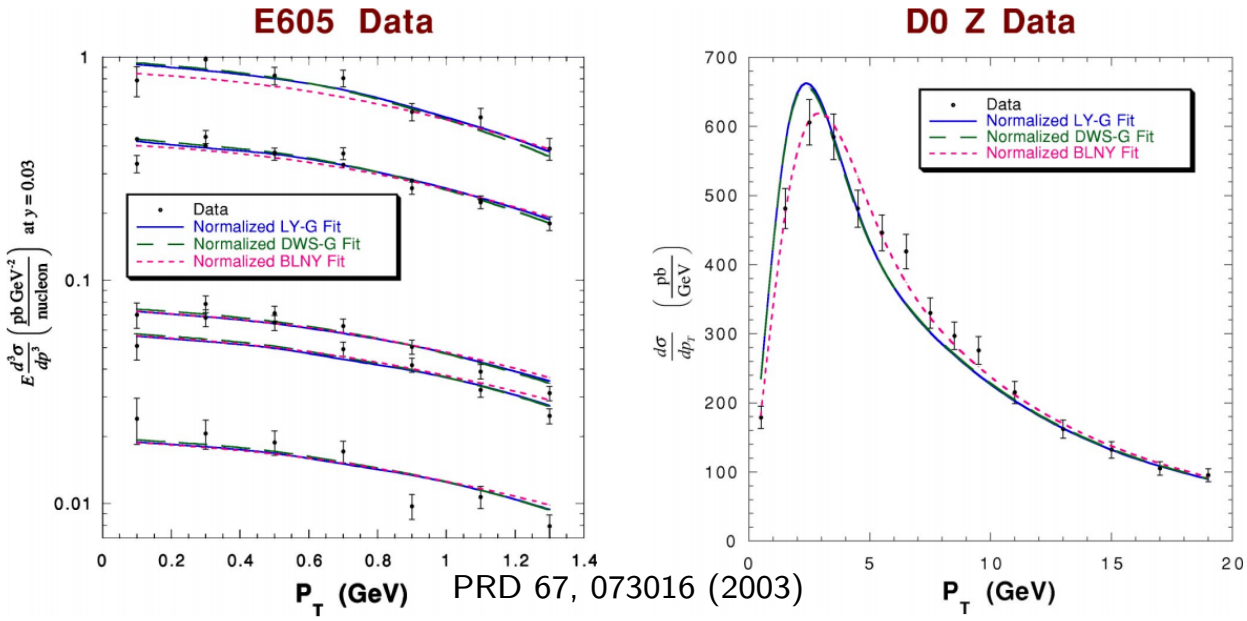




PRD 80, 111108 (2009)

Collins-Soper-Sterman (CSS) Evolution

- CSS evolution first published in 1985. Similar to DGLAP evolution equation, but includes small transverse momentum scale
- Has been used to successfully describe global Drell-Yan and Tevatron Z^0 cross sections
- Clear qualitative prediction - momentum widths sensitive to nonperturbative transverse momentum increase with increasing hard scale
- Due to increased phase space for hard gluon radiation

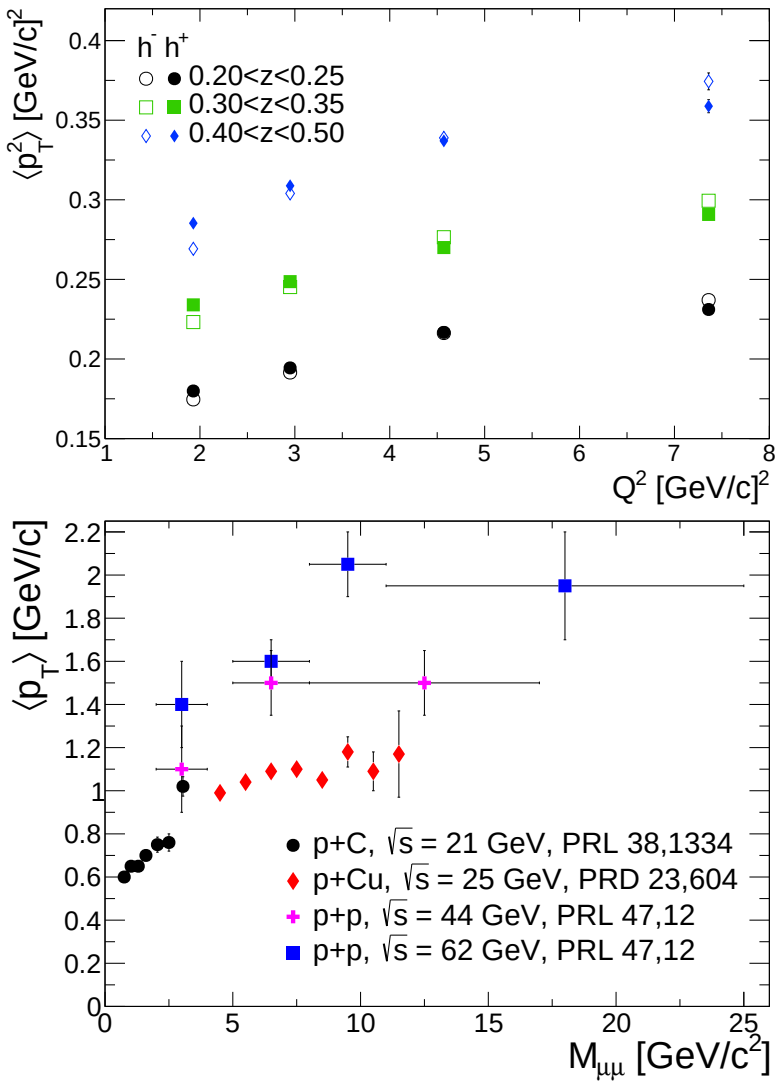


PRD 67, 073016 (2003)

Drell-Yan/Z and Semi-Inclusive DIS in CSS Evolution

- Measurements show that Drell-Yan and semi-inclusive DIS follow theoretical prediction - widths rise with hard scattering scale
- The theoretical evolution prediction comes directly out of the derivation for transverse-momentum-dependent factorization

SIDIS - Eur. Phys. J. C(2013) 73,2531

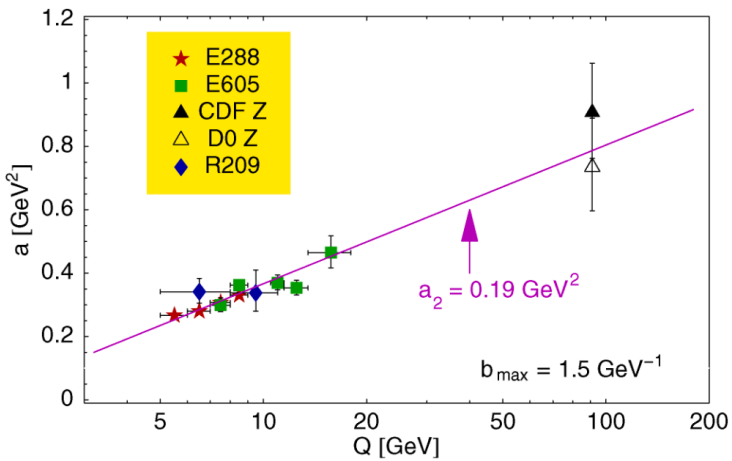


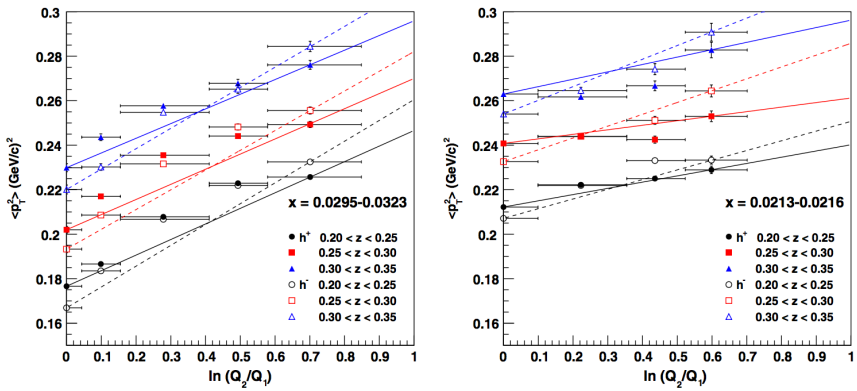
FNAL fixed target DY

Drell-Yan/Z and Semi-Inclusive DIS in CSS Evolution

- Phenomenological studies confirm that Drell-Yan and semi-inclusive DIS follow theoretical prediction
- The evolution prediction comes directly out of the derivation for transverse-momentum-dependent (TMD) factorization
  - If TMD factorization, then CSS evolution. If not CSS evolution, then not TMD factorization!
- Drell-Yan and semi-inclusive DIS clearly follow theoretical prediction

DY/Z - PLB 633, 710 (2006)

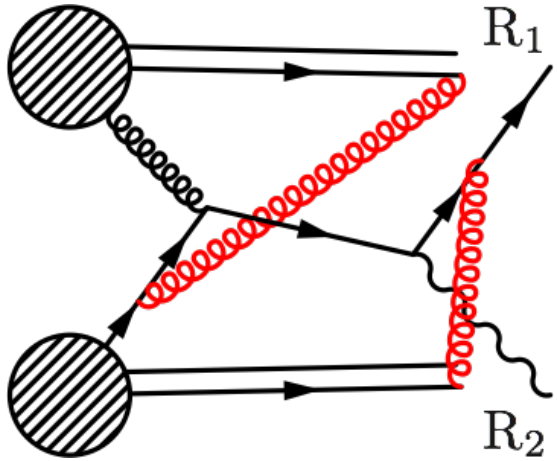


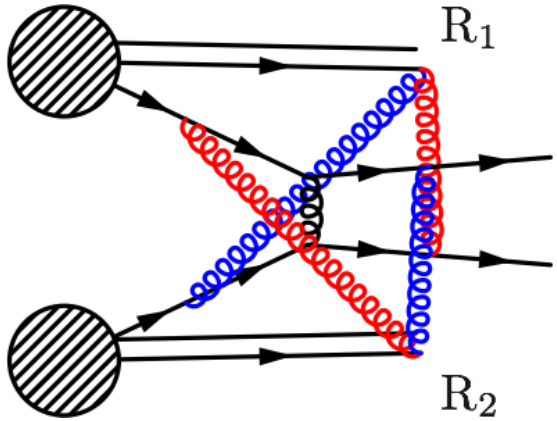


SIDIS - PRD 89, 094002 (2014)

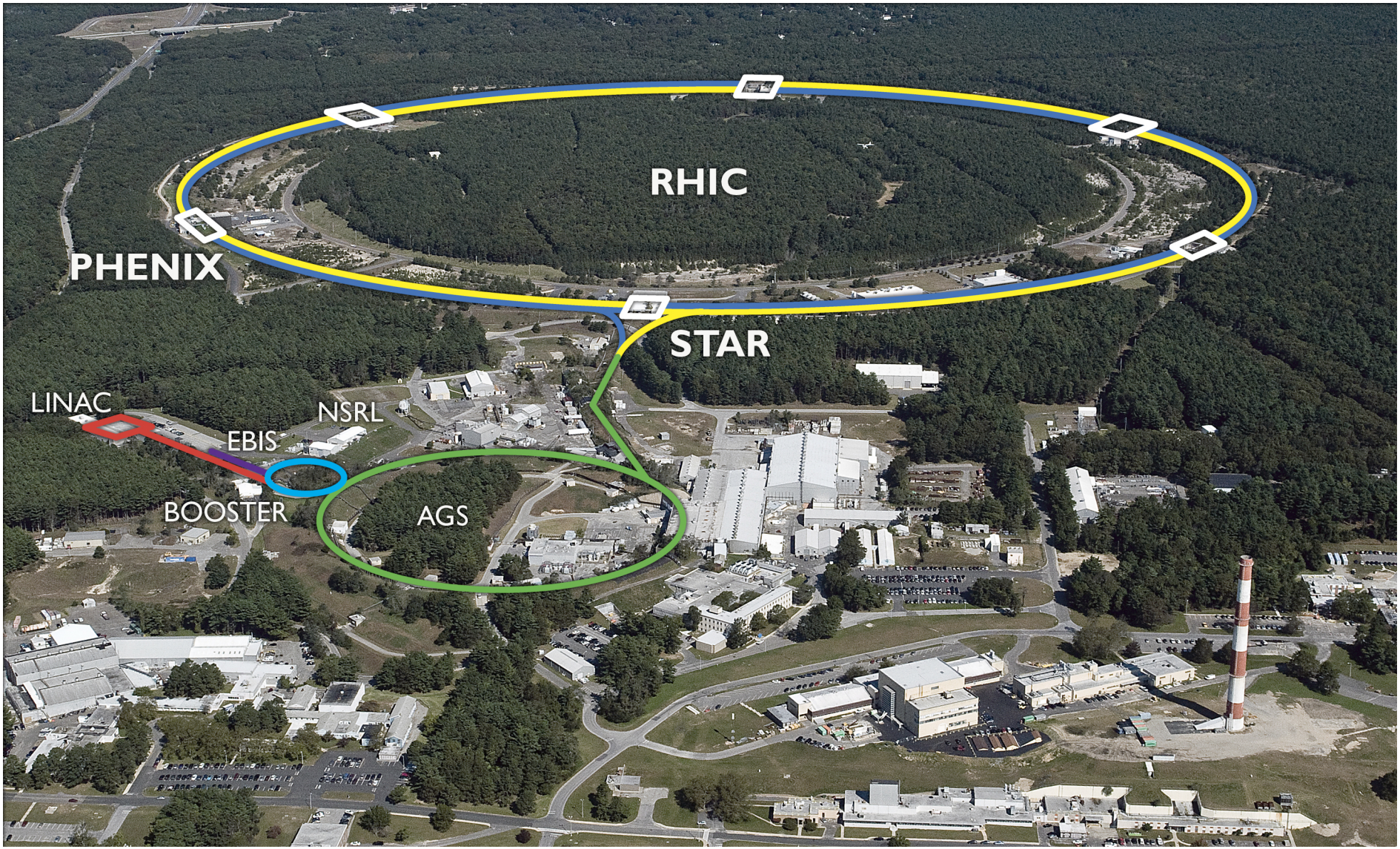
Direct Photons and Dihadrons

- Direct photon-hadron and dihadron correlations both predicted to be sensitive to factorization breaking effects in PHENIX
- Assuming factorization, direct photon-hadrons probe three nonperturbative functions, while dihadrons probe four
- Direct photons offer one less avenue for gluon exchange in the final-state: fewer/different effects?



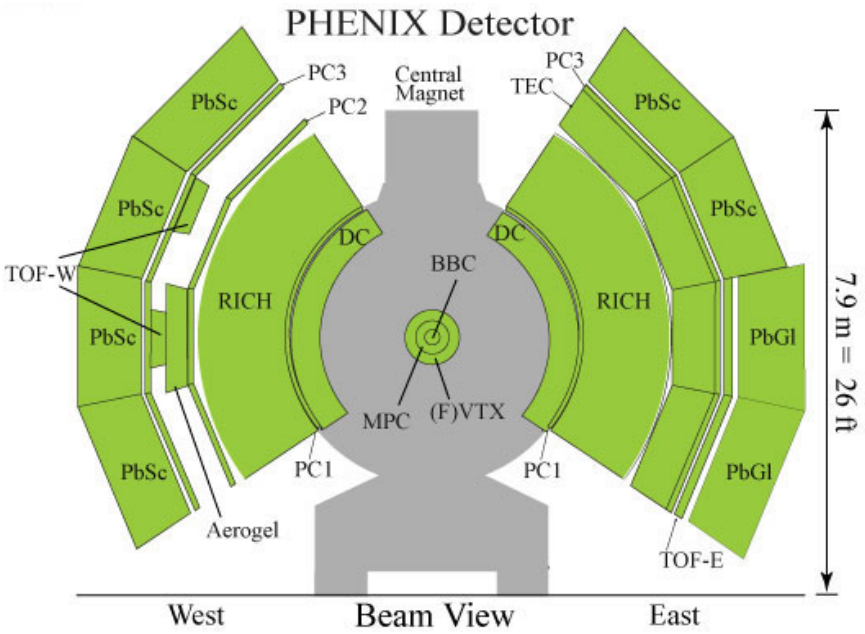


Relativistic Heavy Ion Collider - RHIC at Brookhaven National Laboratory



PHENIX Detector

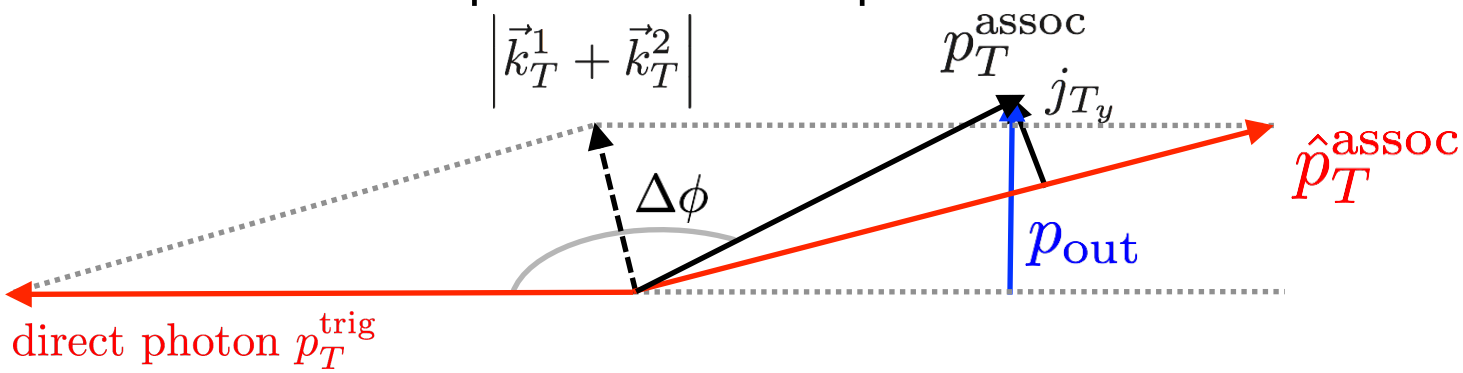
- PHENIX central arms
  - $\Delta\phi \sim \pi$
  - $|\eta|$ <0.35
- Electromagnetic Calorimeter (PbSc/PbGl) provides isolated direct photon and $\pi^0 \to \gamma\gamma$ detection
- Drift Chamber (DC) and Pad Chambers (PC) provide nonidentified charged hadron detection



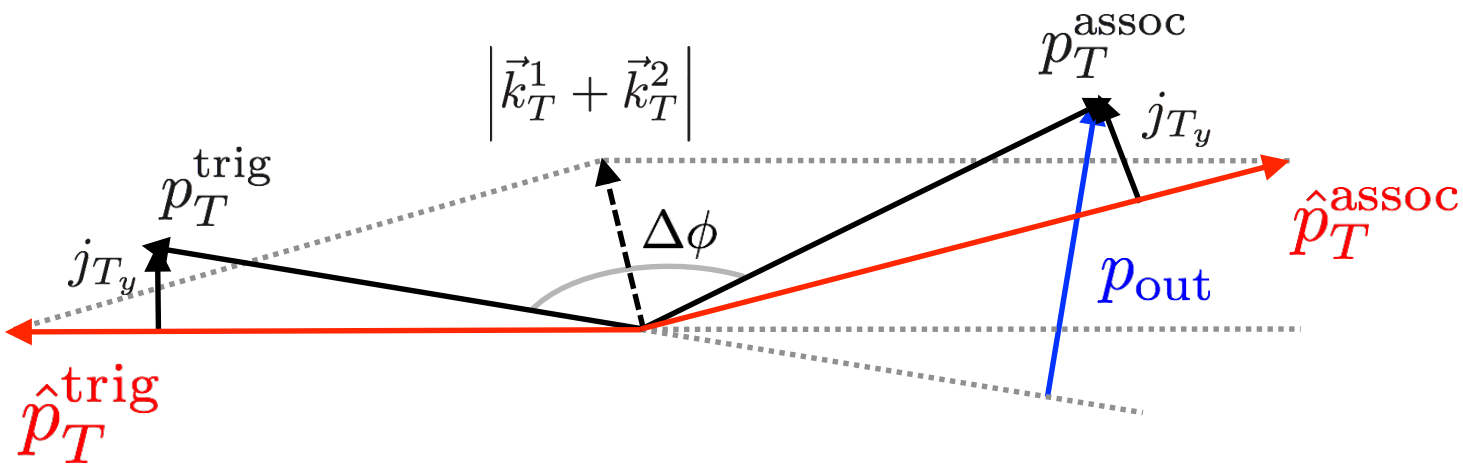
- New results from 2012/2013 $\sqrt{s}$=510 GeV p+p runs

Angular Correlation Observables

Direct photon-hadron production

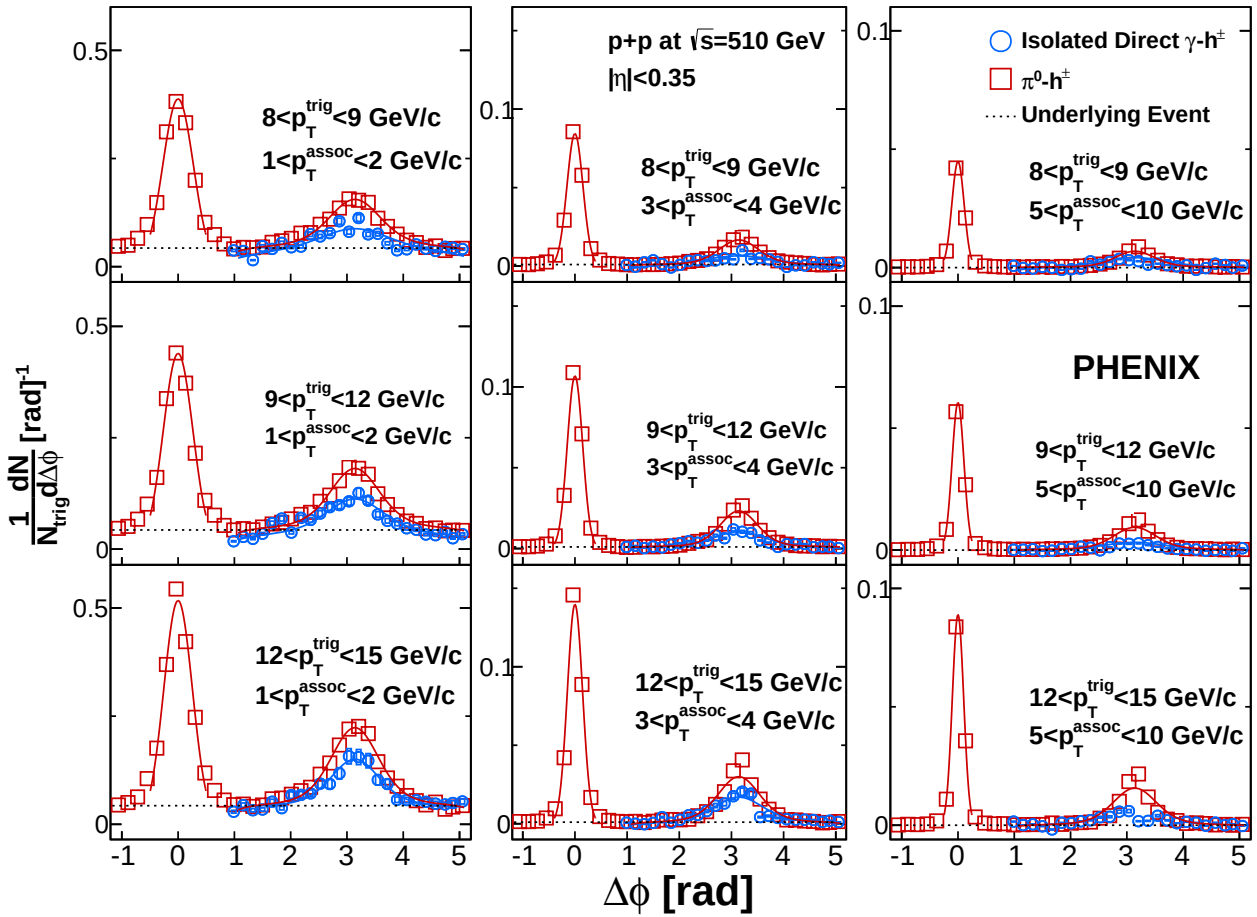


Dihadron production



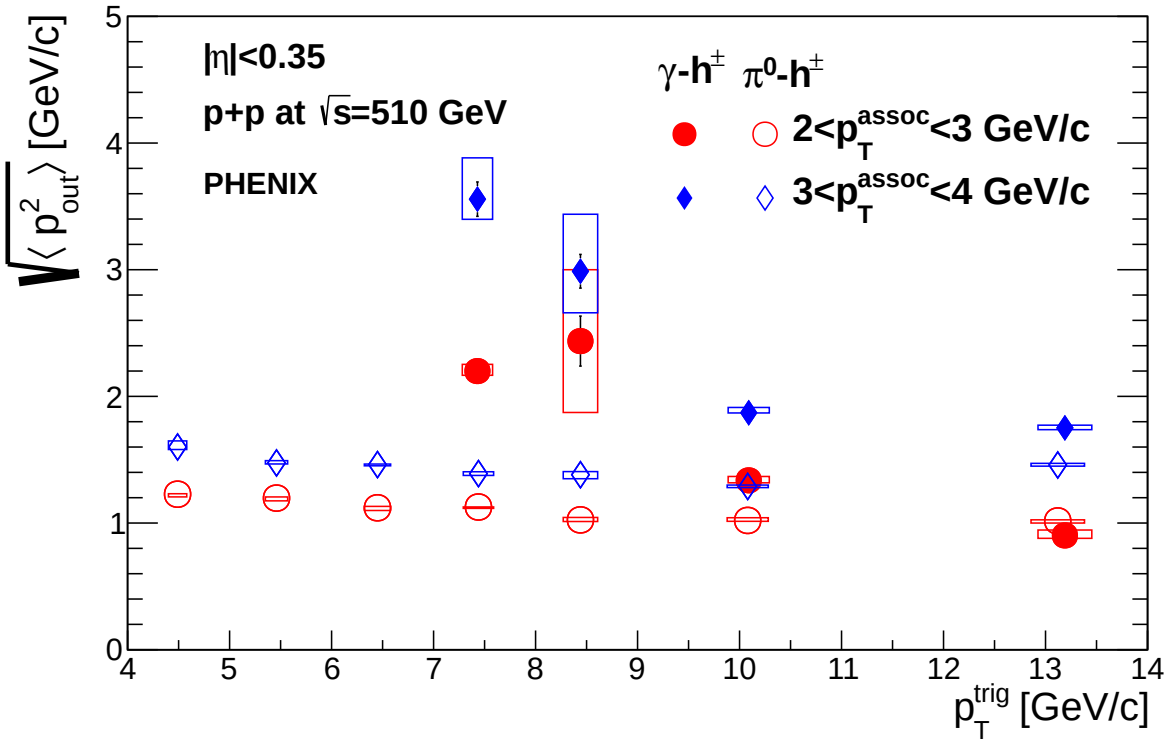
$$p_{out} = p_T^{assoc} \sin \Delta\phi$$

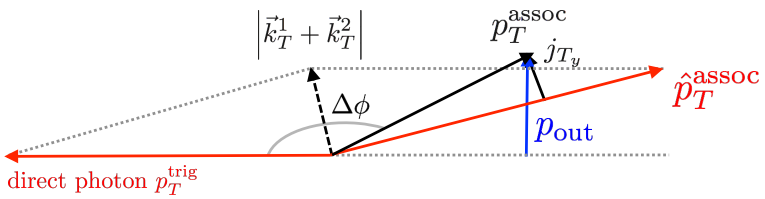
$\Delta\phi$ Correlations for π^0-h$^{\pm}$ and Direct γ-h$^{\pm}$



- Two jet structure visible for π^0-h$^{\pm}$, isolation cut on near side for direct γ-h$^{\pm}$
- Direct γ-h$^{\pm}$ probes smaller jet energy due to emerging from hard scattering at LO

$\sqrt{\langle p_{out}^2 \rangle}$ Extracted from Fits to $\Delta\phi$ Correlations

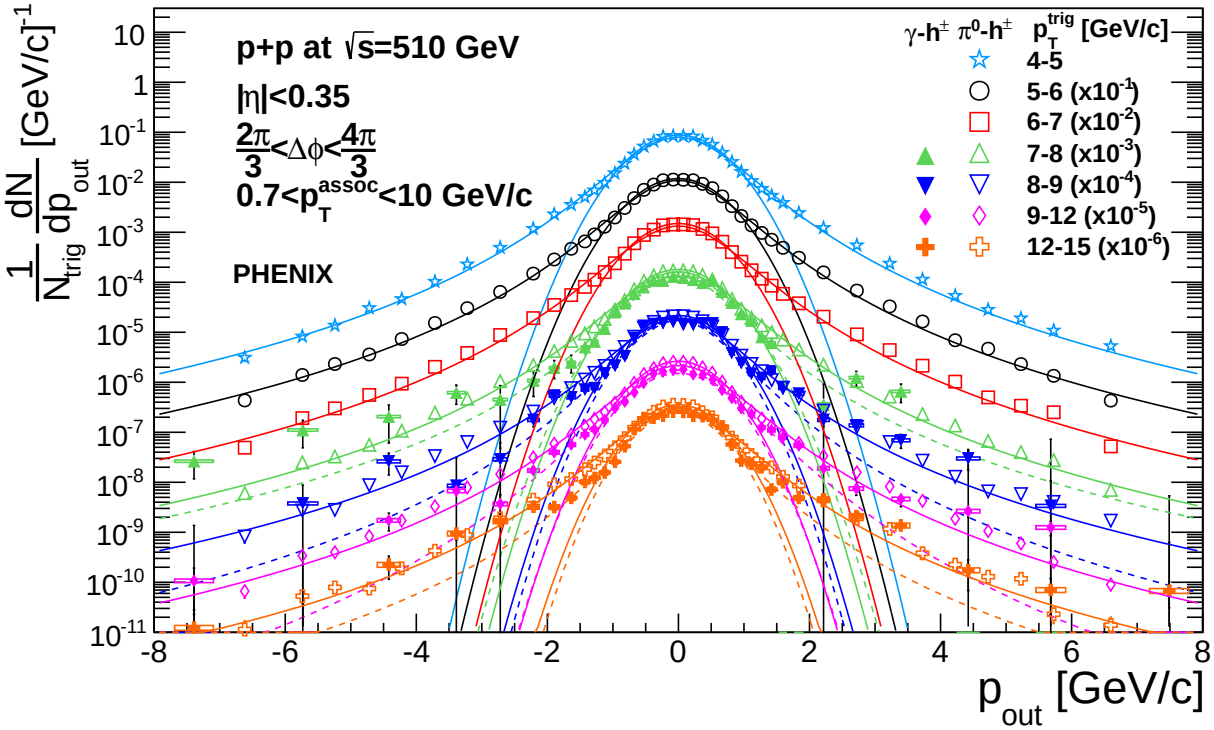




- $\sqrt{\langle p_{out}^2 \rangle}$ characterizes away-side jet width in momentum space
- Decreases with hard scattering scale p_T^{trig}, opposite of semi-inclusive DIS and Drell-Yan!
- Sensitive to perturbative and nonperturbative k_T and j_T; fits are to entire away-side jet

p_{out} Distributions

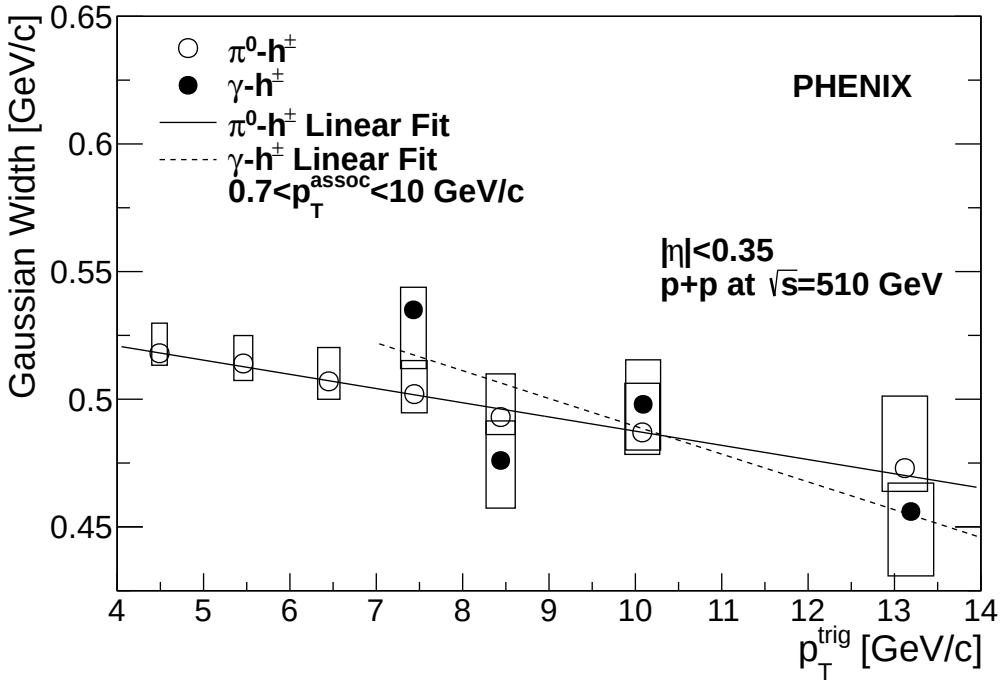
- p_{out} shows two distinct regions: Gaussian and power law
- Gaussian fits clearly fail past ~1.3 GeV/c
- Indicates transition from nonperturbative to perturbative k_T and j_T



- Note: Curves are Kaplan and Gaussian fits, not calculations!!

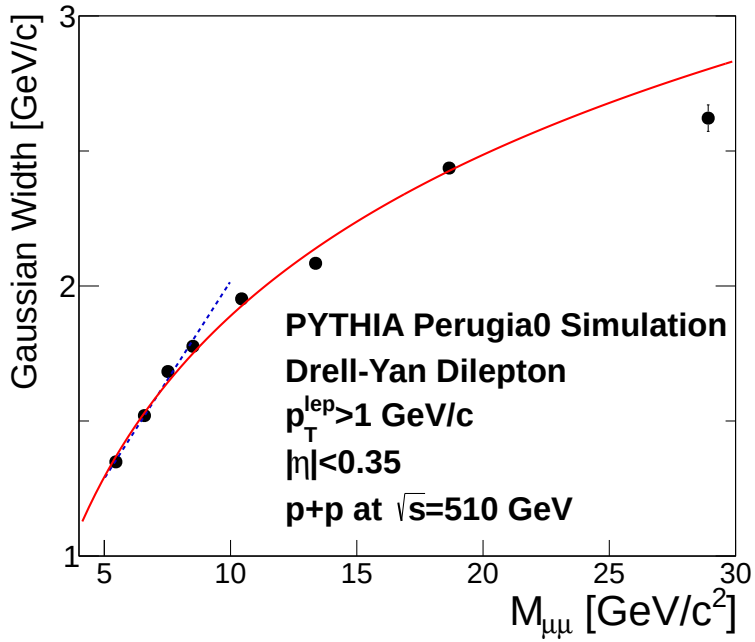
Gaussian Widths of p_{out}

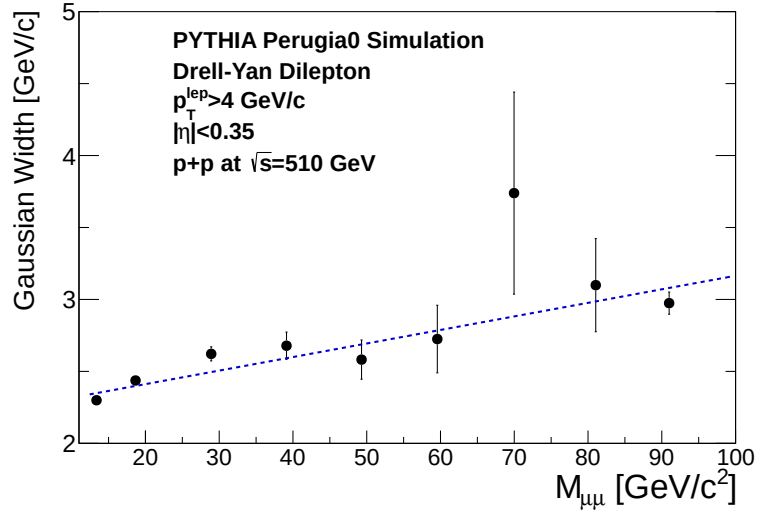
- Extract Gaussian widths of p_{out} vs. p_T^{trig}, hard scattering scale
- Sensitive to *only* nonperturbative k_T and j_T in the nearly back-to-back region $\Delta\phi \sim \pi$
- Gaussian widths decrease with p_T^{trig} also, consistent with $\sqrt{\langle p_{out}^2 \rangle}$ and opposite of semi-inclusive DIS and Drell-Yan!



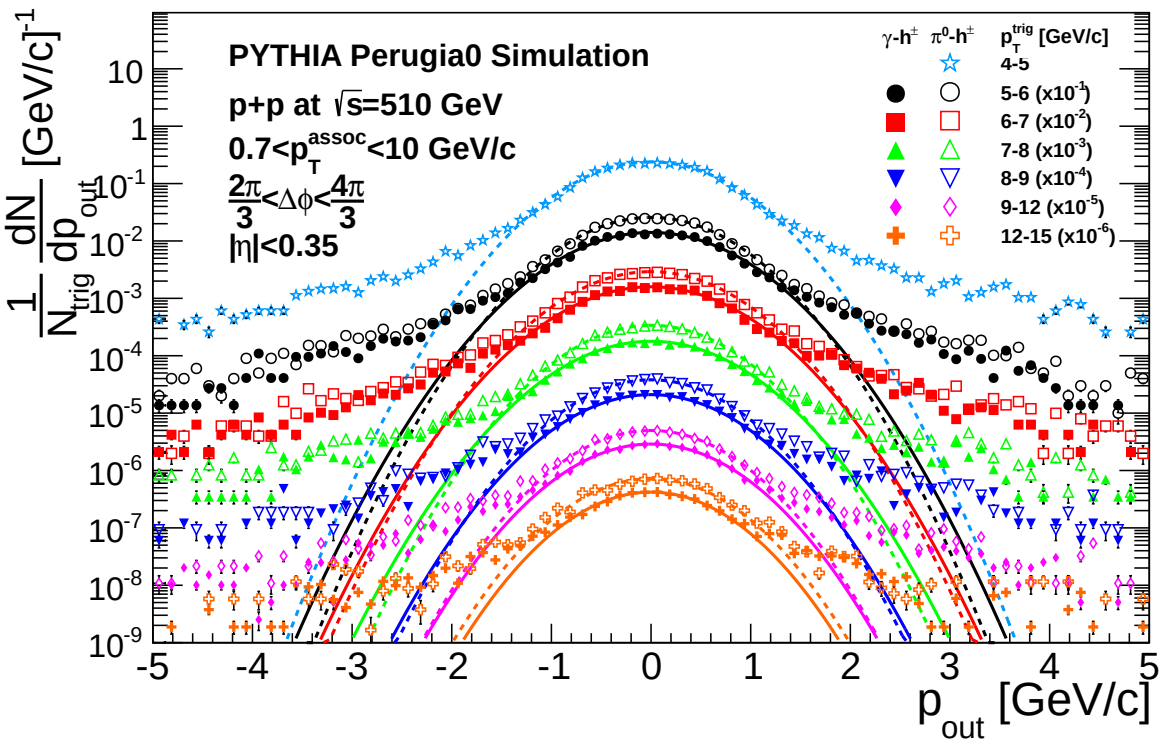
PYTHIA p+p Event Simulation

- To make a comparison, used PYTHIA event generator simulation
- PYTHIA reproduces expectation from CSS evolution in Drell-Yan over large range of $M_{\mu\mu}$





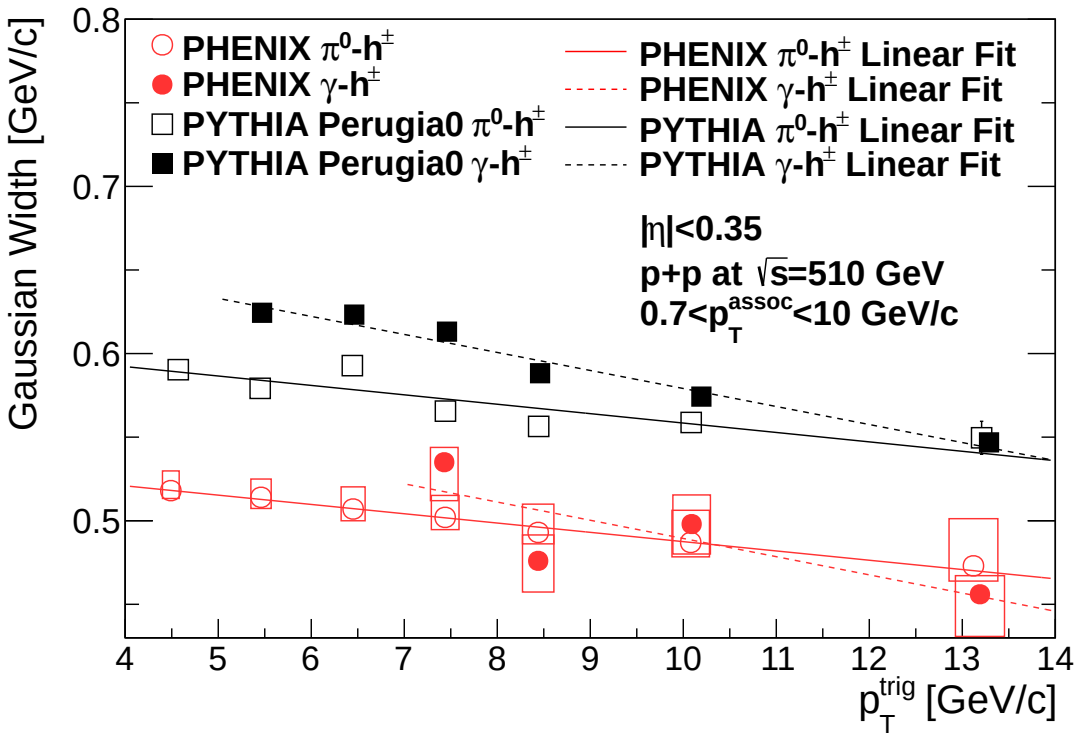
PYTHIA Event Simulation



- Can construct p_{out} distributions for direct photons and dihadrons in PYTHIA as well for direct comparison
- PYTHIA replicates the nonperturbative to perturbative transition in the p_{out} distributions

PYTHIA Event Simulation

- PYTHIA also replicates the negative slope of the gaussian widths in $\gamma-$hadron and π^0-hadron!
- Magnitudes of widths from PYTHIA show $\sim$15% difference from data despite slope being replicated



PYTHIA Simulation

- WHY does PYTHIA replicate both increasing behavior in $p+p \rightarrow \ell\bar{\ell}$ and decreasing behavior in $p+p \rightarrow$h+X??
- Unlike analytical pQCD calculation, PYTHIA forces all particles to color neutralize in the event, including remnants
- PYTHIA allows initial and final state soft gluon exchanges!
- PYTHIA authors confirm that it is plausible that PYTHIA would be sensitive to such effects

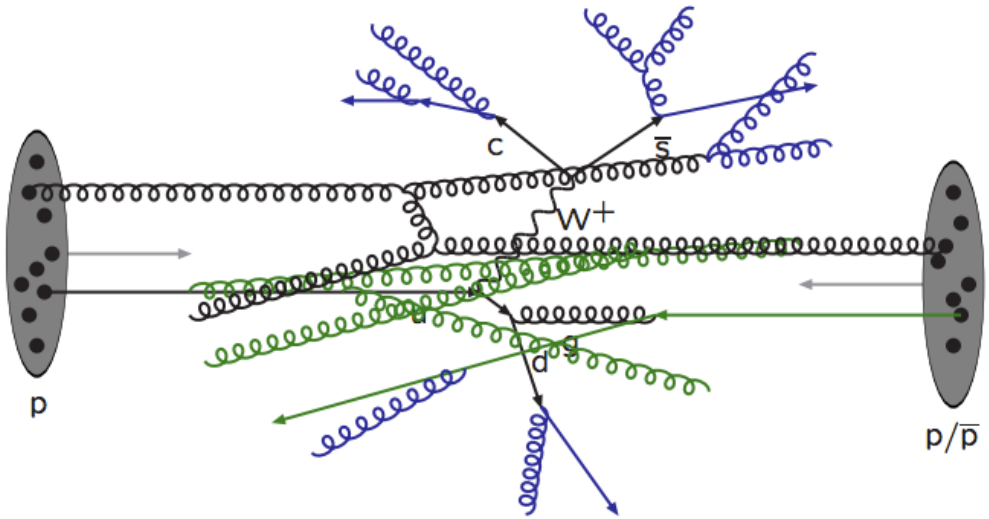
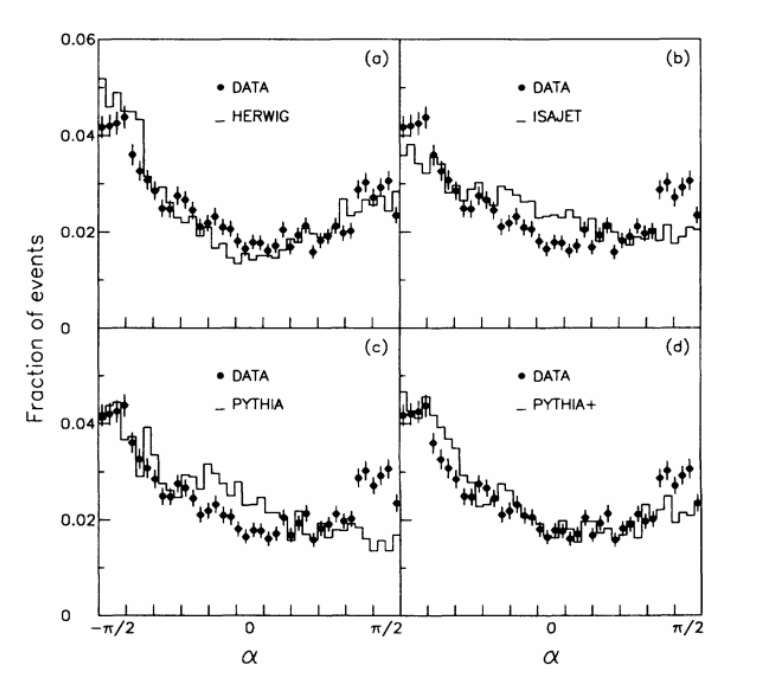


Image taken from http://home.thep.lu.se/ torbjorn/talks/karlsruhe10a.pdf

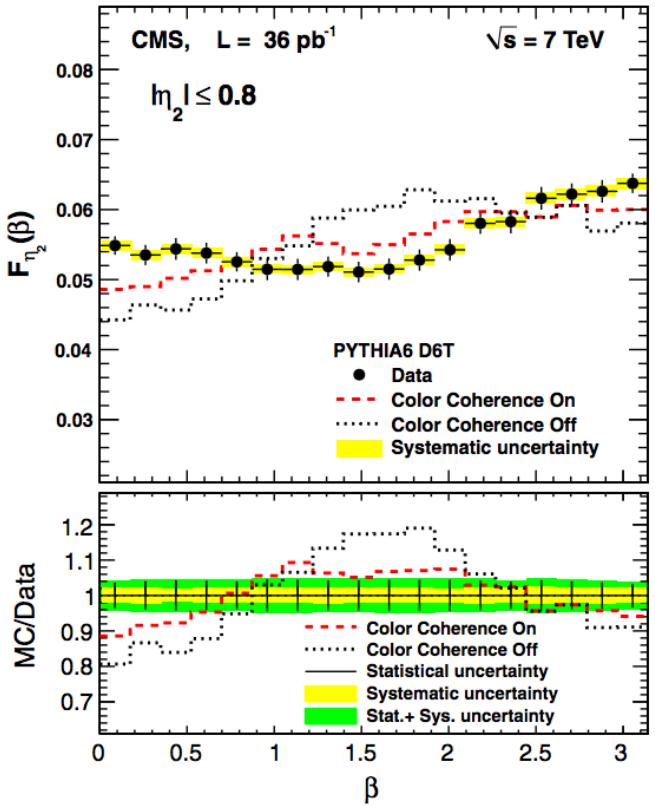
Relations to Other QCD Studies?

- Color coherence studies at the Tevatron



Phys. Rev. D 50, 5562 (1994) (CDF)
Phys. Lett. B 414, 419-427 (1997) (D0)

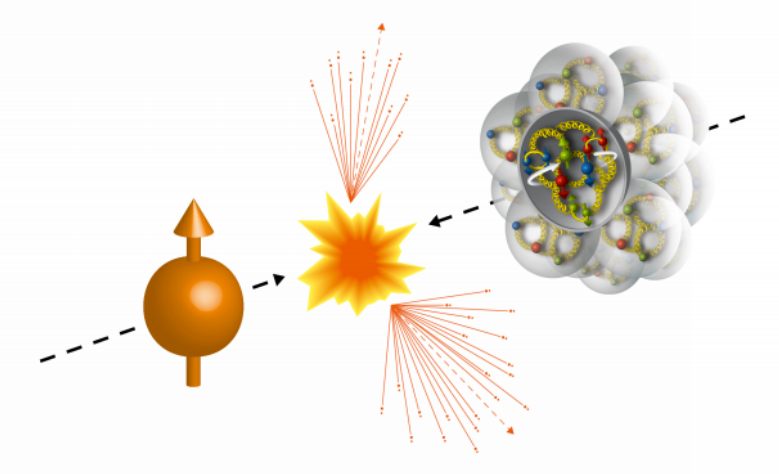
- Color coherence studies at the LHC



Eur. Phys. J. C74 (2014) no.6,2901

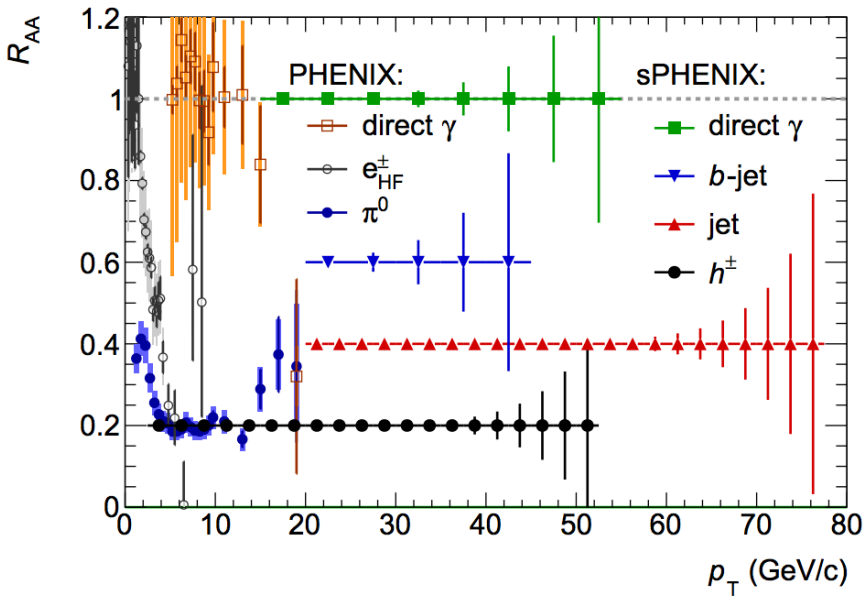
Future Measurements

- Recent RHIC run in 2015 delivered one of the most unique data sets to PHENIX and STAR
- RHIC collided $p^{\uparrow}+p$, $p^{\uparrow}+$Au, and $p^{\uparrow}+$Al at $\sqrt{s} = 200$ GeV
- PHENIX recorded $\sim$10x the amount of $\sqrt{s} = 200$ GeV data from previous analysis
- Possibility to compare $p+p$ at $\sqrt{s} = 200$ and 510 GeV

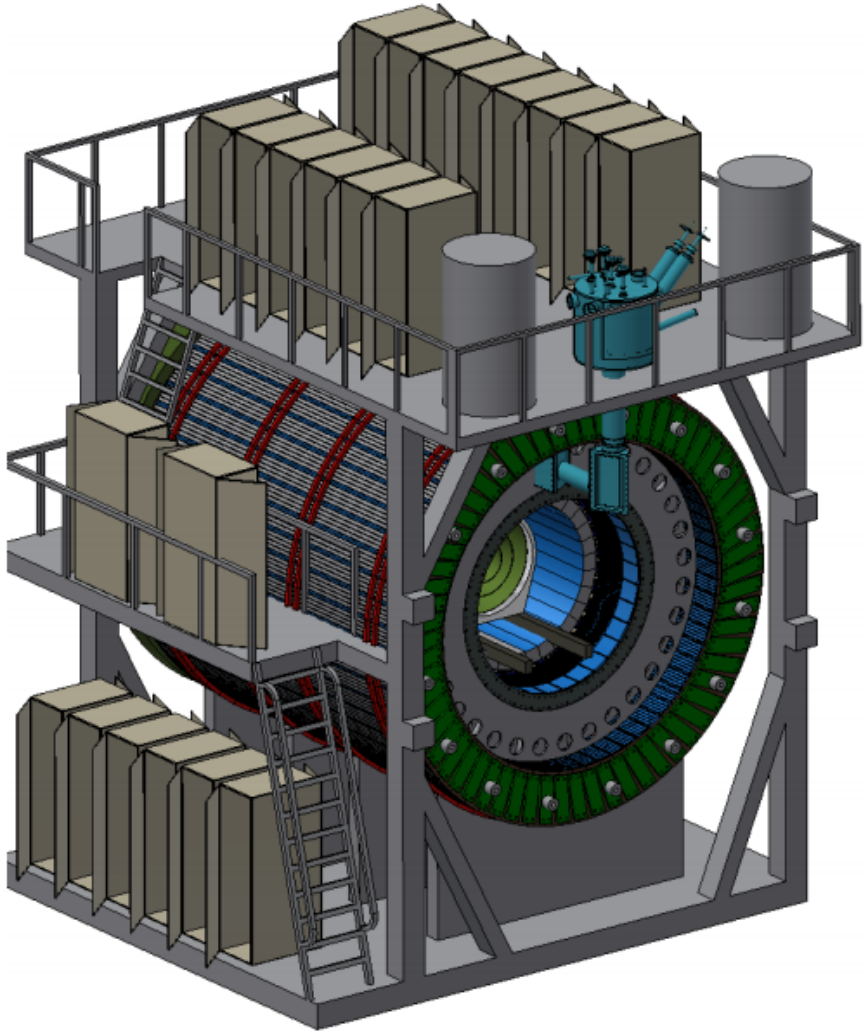


- Possibility to compare $p+p$ to $p+$A (stronger gluon fields in nucleus??)
- Does transverse spin change anything??

Future Measurements - sPHENIX



- Future detector at RHIC, sPHENIX, has been proposed
- Dedicated jet detector at RHIC
- Golden measurement - γ-jet
- Allows full kinematic event reconstruction



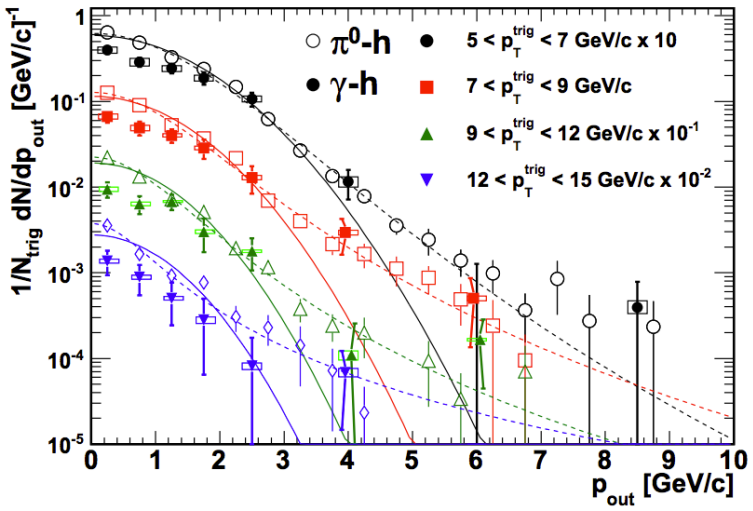
Conclusions

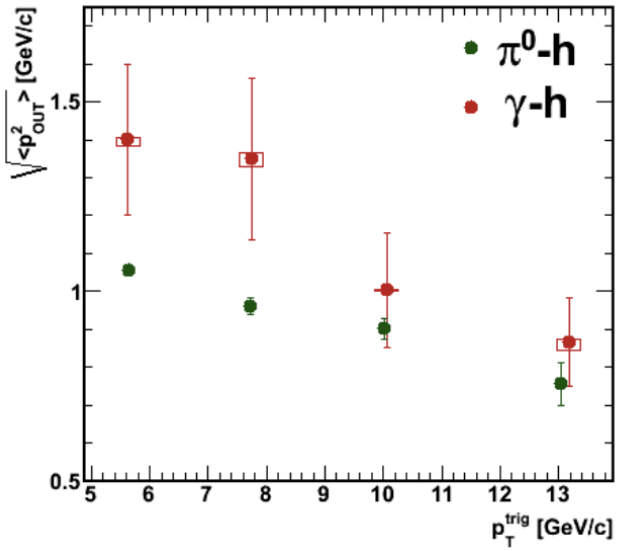
- Extending the knowledge of nucleon structure from 1 dimension to 3 dimensions (and more!)
- Transverse-momentum-dependent nucleon structure offers a richer description of the nucleon with many interesting phenomenological predictions
- Factorization breaking has been predicted in hadronic collisions where a final-state hadron is measured in a transverse-momentum-dependent framework
- PHENIX has just released the first measurement studying these predicted effects - arXiv:1609.04769
- Data show the opposite evolution trend in the nonperturbative momentum widths from semi-inclusive DIS and Drell-Yan, where factorization is predicted to hold
- More measurements planned in the future... stay tuned!

Back Up

$\sqrt{s}$=200 GeV Results from PHENIX

- Previous PHENIX result at $\sqrt{s}$=200 GeV with larger errors (Phys. Rev. D 82, 072001 (2010))
- Next step: analyze recent Run 15 $\sqrt{s}$=200 GeV p+p and p+A data from RHIC!
- 6x luminosity in Run 15 p+p, as well as first result from p+A
- Can also look at transverse spin dependence in Run 15!

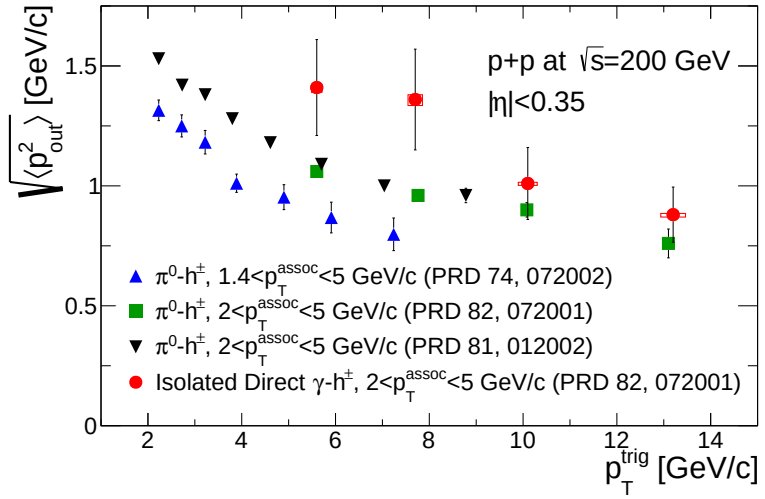


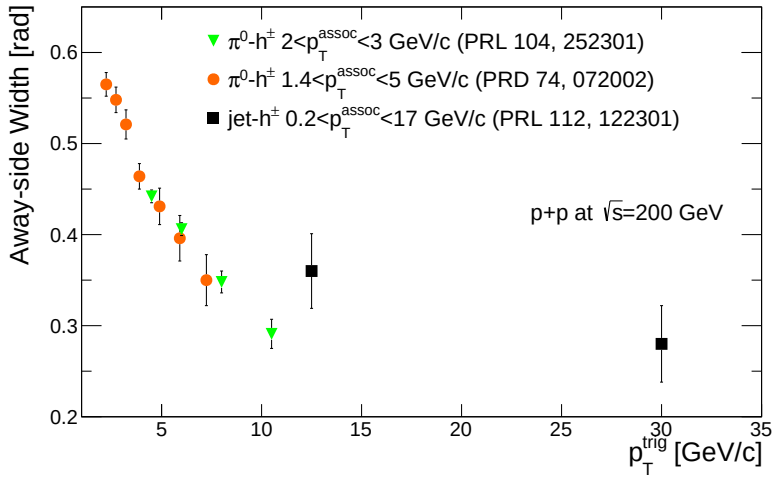


$$2 < p_T^{assoc} < 5$$

$\sqrt{s}$=200 GeV Results from RHIC

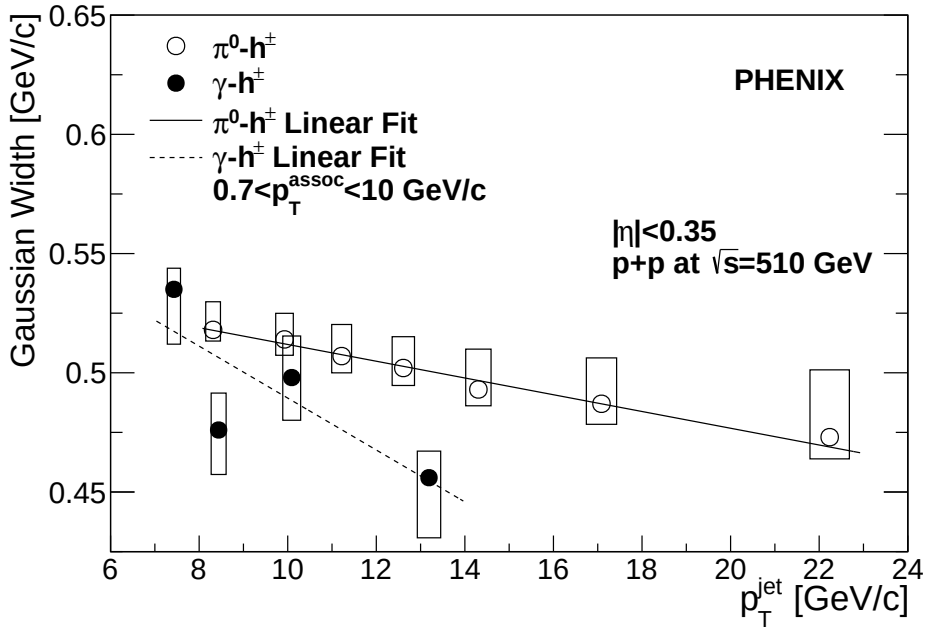
- Previous PHENIX result at $\sqrt{s}$=200 GeV to lower p_T^{trig} (PRD 81, 012002 (2010))
- Shows $\sqrt{\langle p_{out}^2 \rangle}$ over lower range of p_T^{trig}
- Also can plot away-side width in angular space - same trend over large range of p_T^{trig}



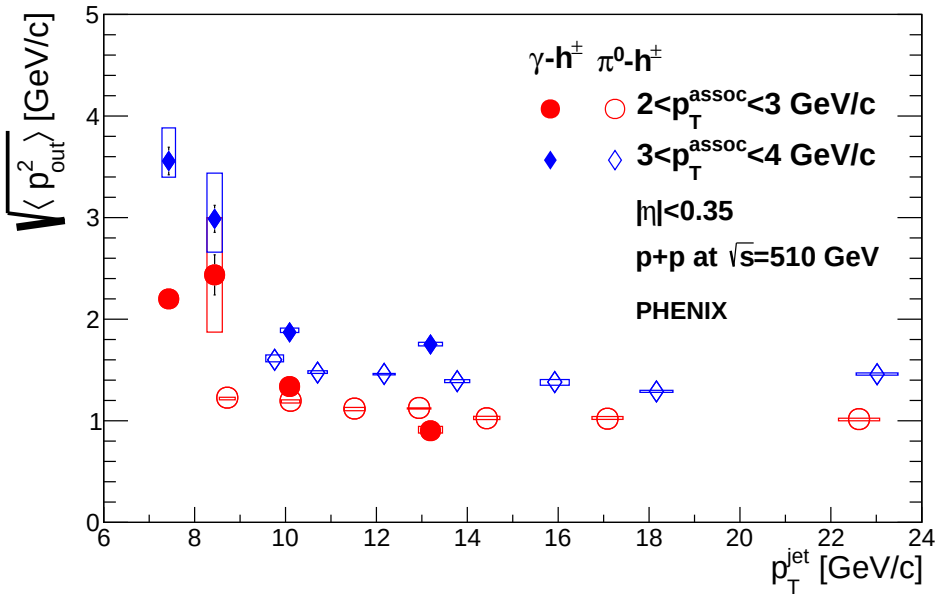


$\langle z_T \rangle$ with Gaussian Widths

- $\langle z_T \rangle$ p_T^{trig} correction was also applied to Gaussian widths vs. p_T^{trig}
- $\langle z_T \rangle$ more or less amounts to a scale factor of 2 difference in the slope

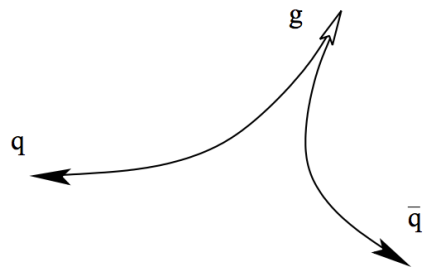


$\sqrt{\langle p_{out}^2 \rangle}$ vs. p_T^{jet}



- Examined $\sqrt{\langle p_{out}^2 \rangle}$ as a function of p_T^{jet} as well
- $p_T^{jet} = p_T^{trig}$ for direct photons
- $p_T^{jet} = p_T^{trig} / \langle z_T \rangle$ for π^0s, with $\langle z_T \rangle$ estimated using PYTHIA
  - $\langle z_T \rangle = \frac{p_T^{trig}}{\hat{p}_T^{trig}}$
- The $\sqrt{\langle p_{out}^2 \rangle}$ distributions almost form a continuous function?

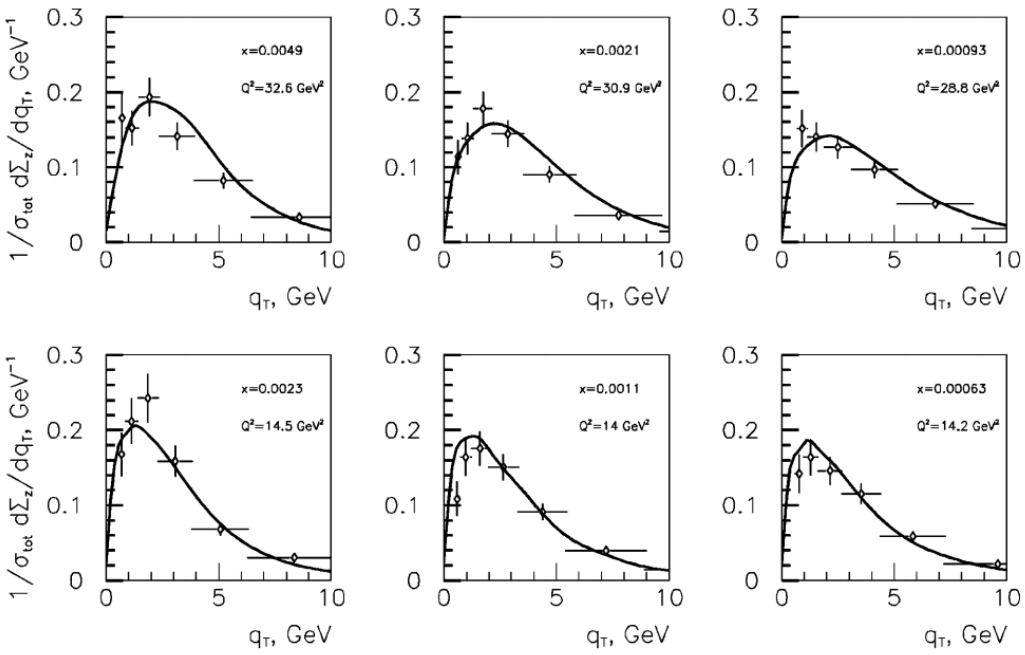
More about Color Coherence



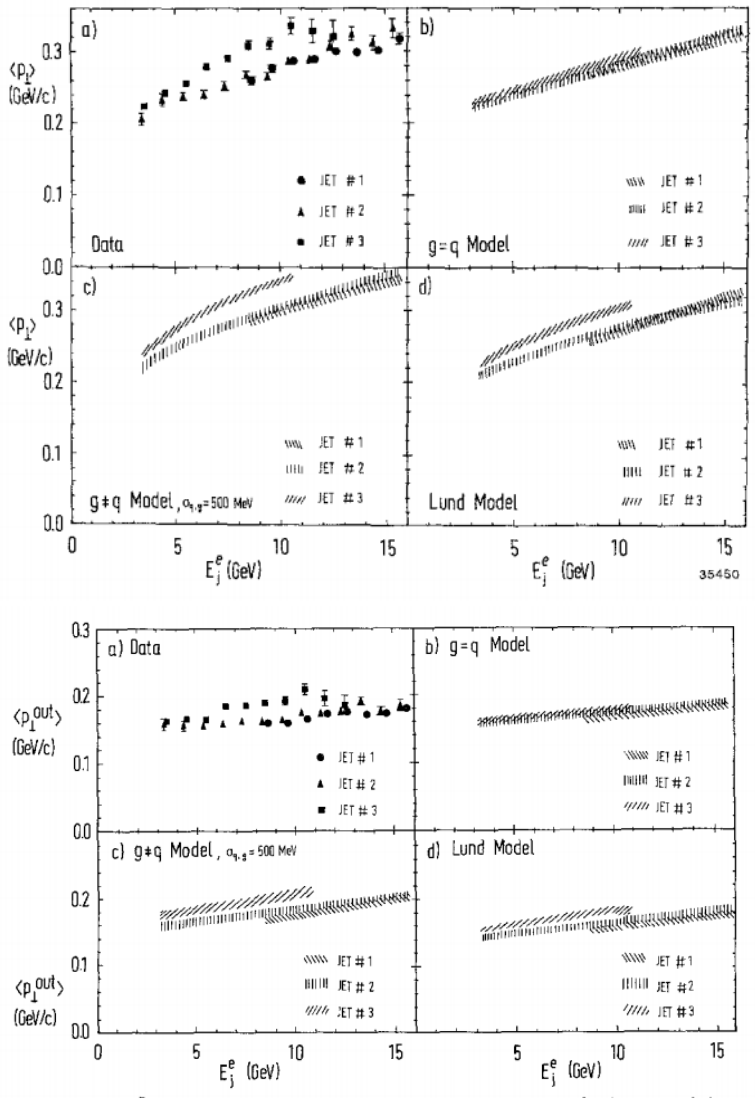
- Radiation "drags" color away from vertex
- Destructive interference occurs away from emitted gluons
- Soft radiation inhibited in certain areas
- Leads to certain regions of phase space where gluons constructively or destructively interfere

- See the following references
  - Phys. Rev. D 50,5562 (1994)
  - Phys. Lett. B 414 (1997) 419-427
  - Dokshitzer, Yuri. *Basics of Perturbative QCD* (Editions Frontieres, 1991) Chapters 4,5,9

SIDIS and e^+e^- Annihilation Momentum Widths



PRD 61, 014003



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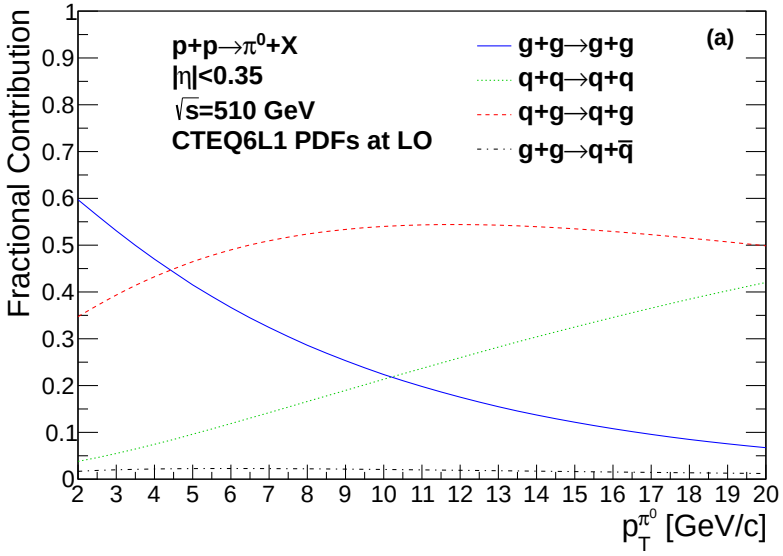
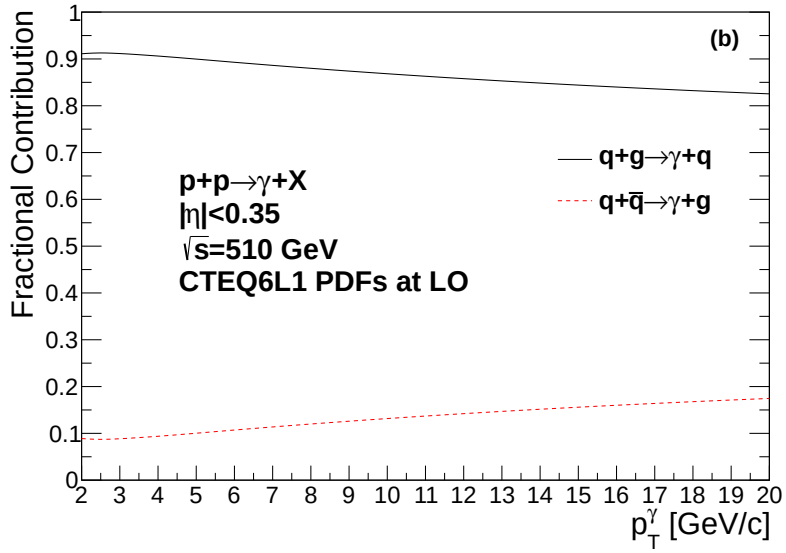
Partonic Contributions to Processes at LO



- π^0 contribution changes from gluon dominated at low p_T to mix of quark and gluons at high p_T

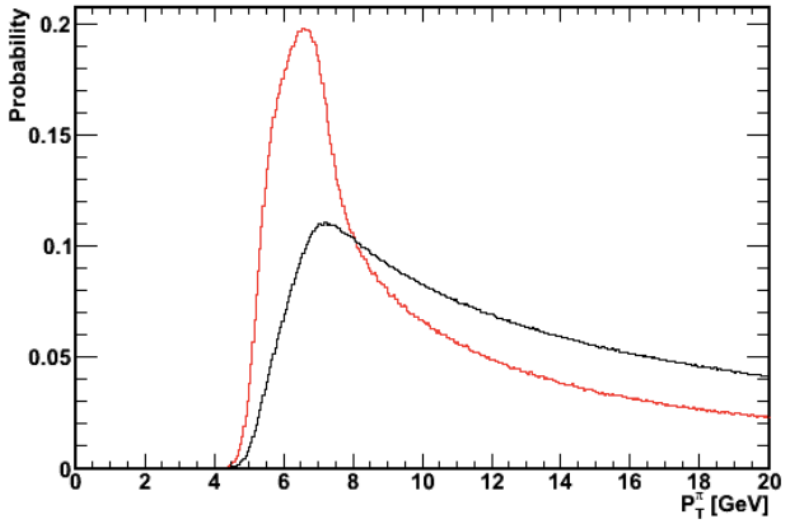


- Direct photon contribution dominated by QCD Compton scattering at all p_T
- NLO corrections small at midrapidity (Phys. Lett. B 140,87)

Analysis Methods

- Correlated $\pi^0-h^{\pm}$ or isolated $\gamma-h^{\pm}$ are collected and corrected with:
  - Charged hadron efficiency
  - Acceptance correction
- Direct photons undergo additional statistical subtraction to remove decay photon background, estimated with Monte Carlo probability functions
- Isolation and tagging cuts remove decay photon background and NLO fragmentation photons

Probability for a π^0 to decay to a photon which could not be tagged with $5 < p_T < 7$ GeV/c in PHENIX

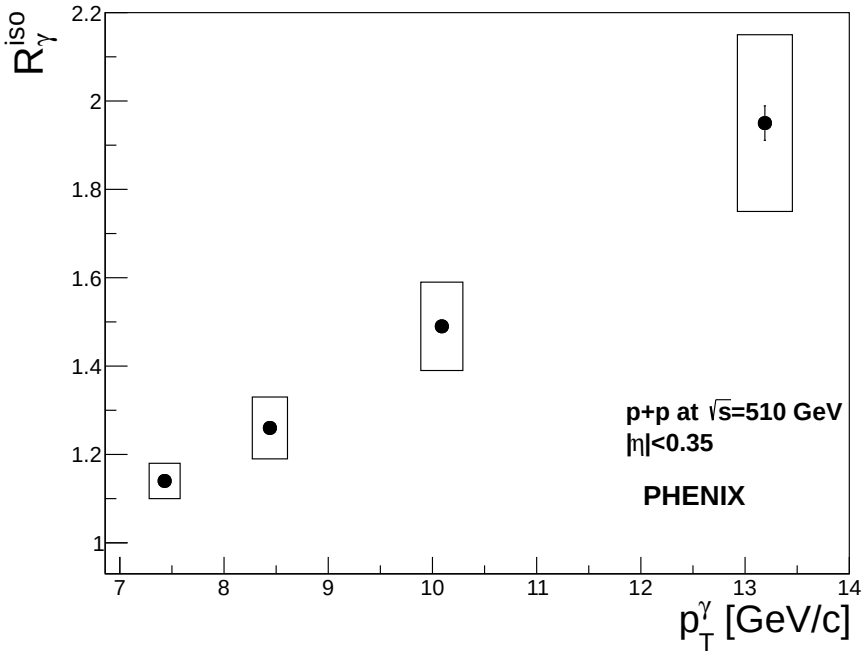


$$Y_{dir}^{iso} = \frac{1}{R_{\gamma}^{iso} - 1}\left(R_{\gamma}^{iso} Y_{inc}^{iso} - Y_{dec}^{iso}\right)$$

PRD 82,072001 (2010)
PRC 80,024908 (2009)

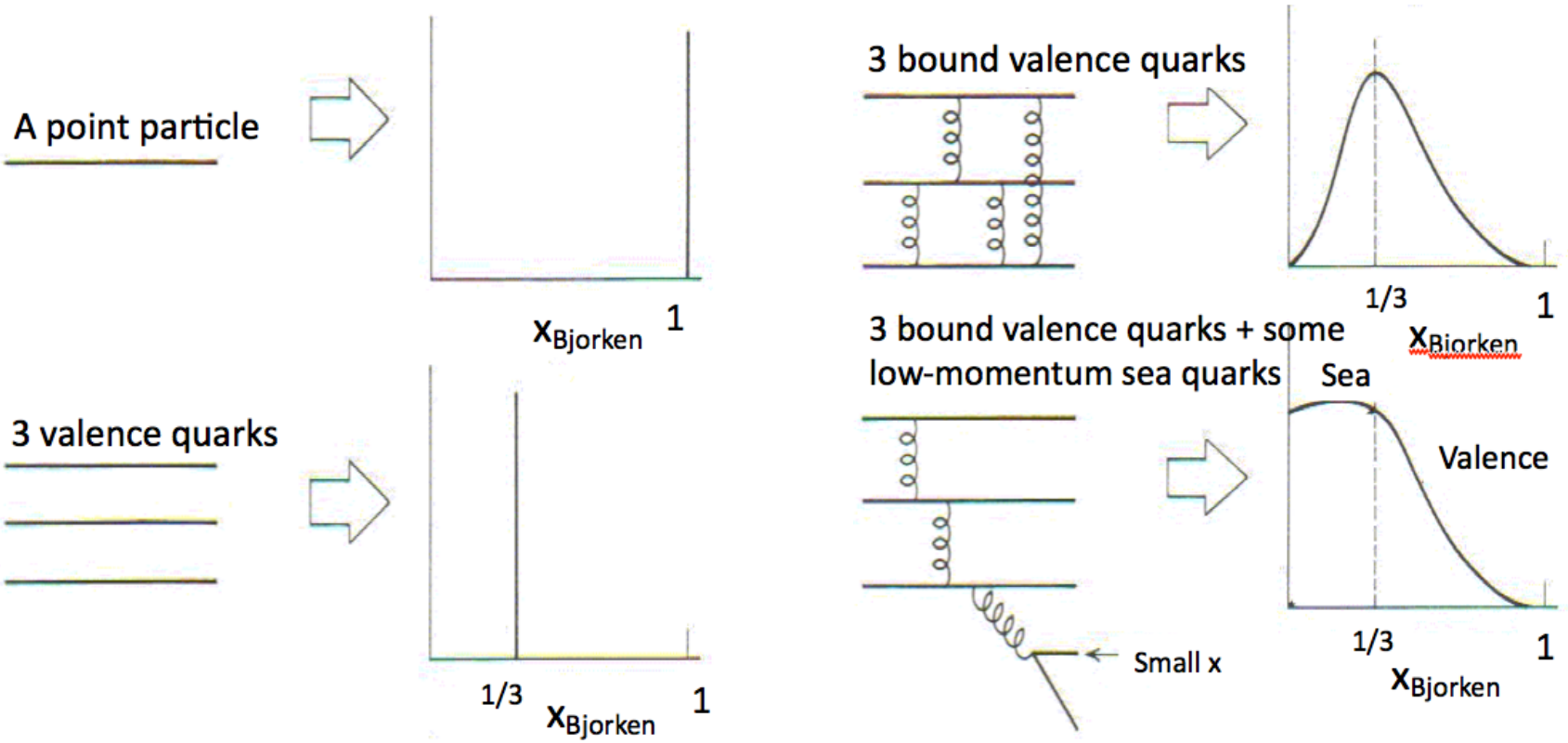
R_γ^{iso} Measurement at $\sqrt{s}$=510 GeV

- R_γ^{iso} measured for statistical subtraction of isolated decay photon contribution
- R_γ measured in PHENIX and corrected by tagging and isolation efficiencies
- R_γ^{iso} >1 indicates isolated direct photon production



$$R_\gamma^{iso} = \frac{R_\gamma}{(1-\epsilon_{dec}^{tag})(1-\epsilon_{dec}^{niso})} \frac{N_{inc}^{iso}}{N_{inc}}$$

PDF Review


A point particle
$x_{Bjorken}$
1
3 valence quarks
1/3
$x_{Bjorken}$
1
3 bound valence quarks
1/3
1
$x_{Bjorken}$
3 bound valence quarks + some low-momentum sea quarks
Sea
Valence
Small x
1/3
1
$x_{Bjorken}$