Recent Experimental Results on QCD Factorization Breaking of Nonperturbative Functions

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Based on work in arXiv:1609.04769, submitted to Phys. Rev. D

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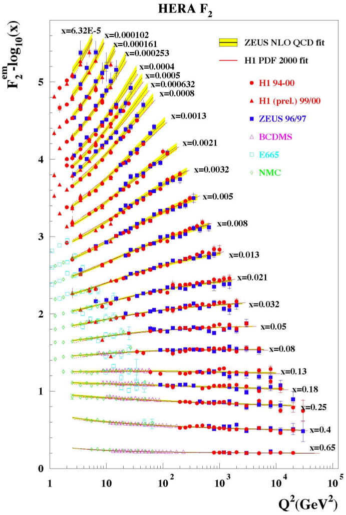
Outline

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

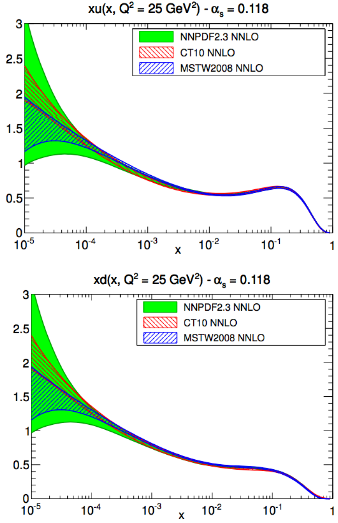
Mapping the Structure of the Proton

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



1-D Structure

- This has led to incredible precision for partonic structure of nucleons in the longitudinal direction!
- Collinear parton distribution functions (PDFs) are very well constrained
- What about other degrees of freedom?



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

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 (!)
- Significant work has gone into understanding 1-D longitudinal momentum structure. What about transverse momentum?

1D vs. 3D Nonperturbative Functions

- Historically PDFs and FFs 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

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

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

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

Transverse-Momentum-Dependent PDF and FF Zoo

Transverse-Momentum-Dependent (TMD) PDFs

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Transverse-Momentum-Dependent (TMD) FFs

N \ q	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$H_{1T}^\perp$	G_{1T}	H_1 $H_{1T}^\perp$

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

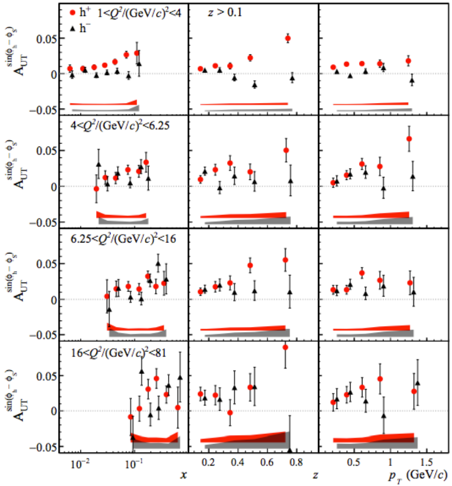
Images taken from Alexei Prokudin Spin 2016

Long Island beach in 1D

Long Island beach in 3D

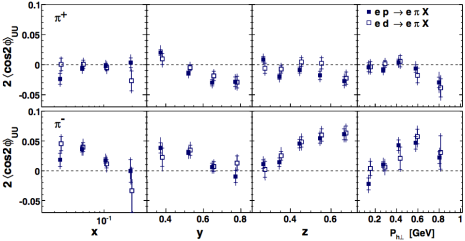
Transverse-Momentum-Dependent Functions in Nature

- Many TMD PDFs and TMD FFs correlate spin with momentum
- Beginning to really explore partonic correlations within the nucleon! New era of nucleon structure
- Are these correlations really there?



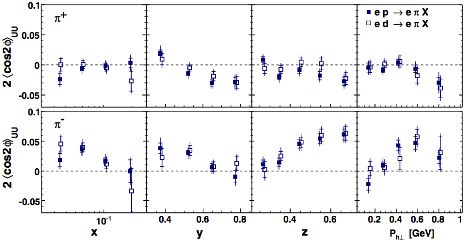
arXiv:1609.07374

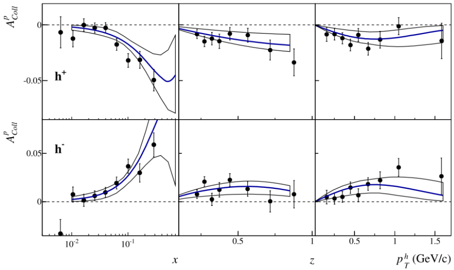
Transverse-Momentum-Dependent Functions in Nature



PRD 87, 012010(2013)

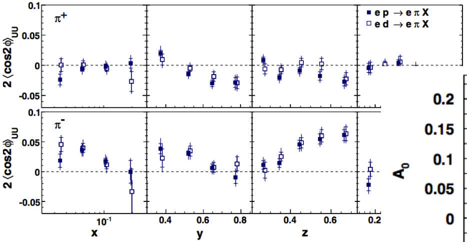
Transverse-Momentum-Dependent Functions in Nature



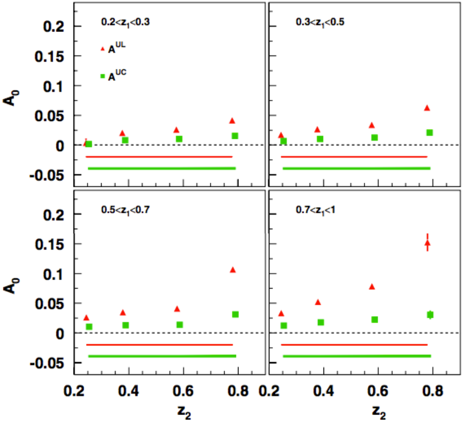


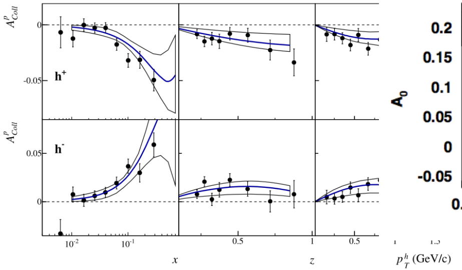
PLB 717, (2012) 376

Transverse-Momentum-Dependent Functions in Nature



PRD 78, 032011 (2008)





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Transverse-Momentum-Dependent Functions in Nature

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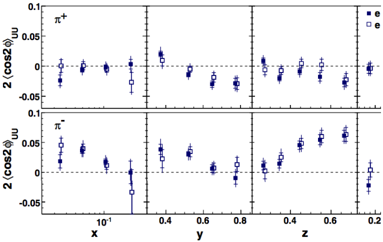
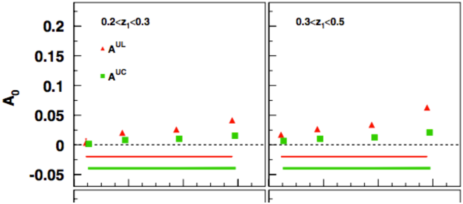
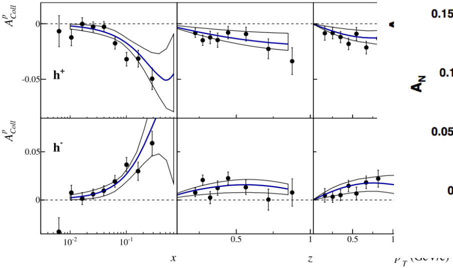
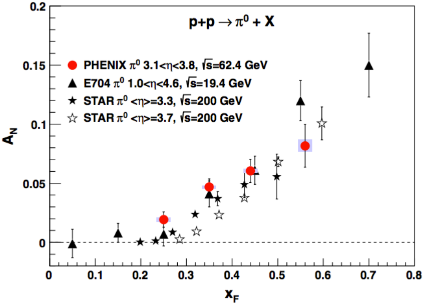








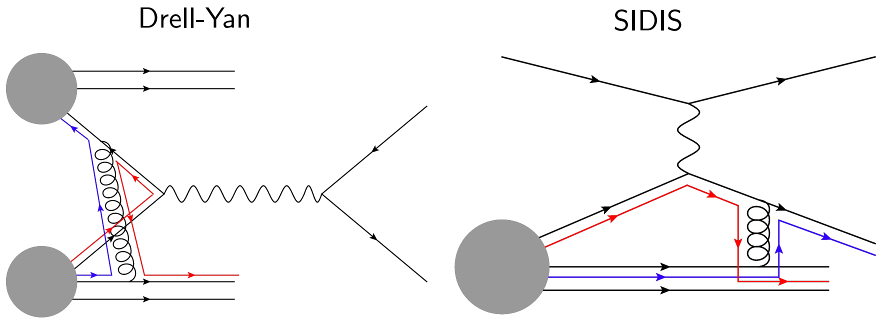
PRD 90, 012006 (2014)

PLB 717, (2012) 376

Transverse-Momentum-Dependent Phenomenology

- In the collinear framework, PDFs and FFs are taken to be universal, process independent functions
- In the TMD framework, it has been necessary to re-check these assumptions
- This has led to very interesting predictions...

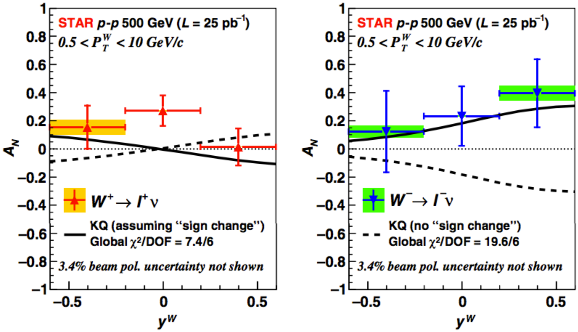
Universality in Transverse-Momentum-Dependent Functions



- Sign change in Sivers TMD PDF predicted due to initial-state vs. final-state gluon exchange with proton remnants between DY and SIDIS: modified universality of TMD PDF!
- Factorization of TMD PDFs and TMD FFs still predicted to hold in these QED processes

First Measurement of Possible Modified Universality

- SIDIS Sivers asymmetries have been measured, e.g. by HERMES and COMPASS
- First measurement of DY type process from STAR at RHIC!
- Hints at sign change if TMD evolution effects are small



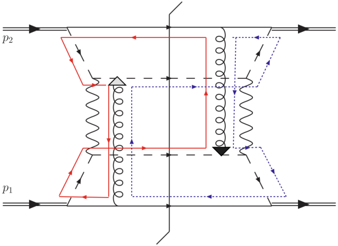
PRL 116, 132301(2016)

Factorization of Transverse-Momentum-Dependent Functions

- Factorization is still predicted to hold in SIDIS and DY
- 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 TMD framework for $p + p \rightarrow h_1 + h_2$ (PRD 81, 094006 (2010))
- TMD PDFs and FFs no longer defined - partons are quantum mechanically correlated across bound state hadrons!
- Consequence of soft gluon exchanges in both the initial and final state

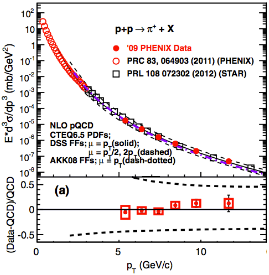


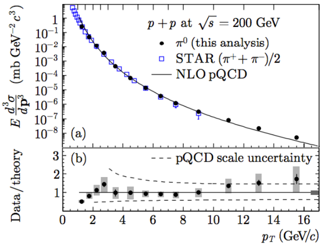
- Predicted modified universality of certain TMD PDFs and factorization breaking from same physical process - consequences of color flow in action!

Unique Quality of RHIC and PHENIX/STAR

- Can *only* study this effect in hadronic collisions
- RHIC ideal since initial-state k_T not too large
- Additionally PHENIX/STAR detectors can measure to small p_T

PRD 91, 032001 (2015)



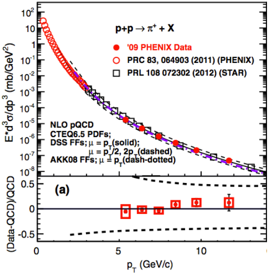


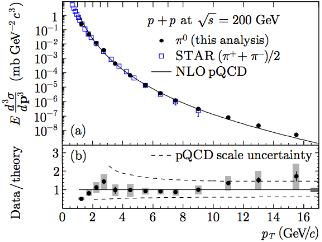
PRD 80, 111108 (2009)

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 nonperturbative TMD PDFs and TMD FFs. Collinear pQCD calculations still have ∼10-40% errors
- What about using TMD evolution??

PRD 91, 032001 (2015)

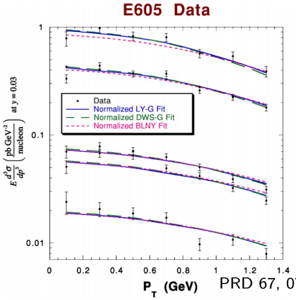




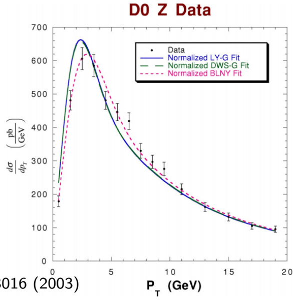
PRD 80, 111108 (2009)

Collins-Soper-Sterman (CSS) Evolution

- CSS evolution first published in 1985
- Has been used to successfully describe FNAL DY (E605) 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



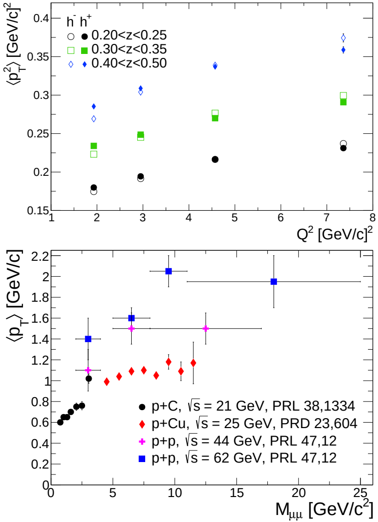
PRD 67, 073016 (2003)



DY/Z and SIDIS in CSS Evolution

- Measurements show that DY and SIDIS follow prediction of CSS evolution
- The CSS evolution equation comes directly out of the derivation for TMD factorization

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

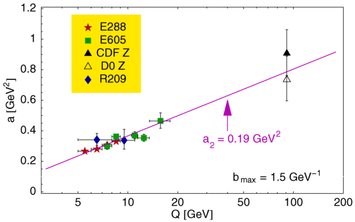


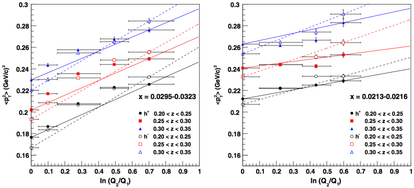
FNAL fixed target DY

DY/Z and SIDIS in CSS Evolution

- Phenomenological studies confirm that DY and SIDIS follow CSS evolution
- The CSS evolution equation comes directly out of the derivation for TMD factorization
- DY and SIDIS clearly follow prediction

DY/Z - PLB 633, 710 (2006)

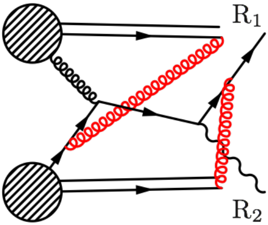


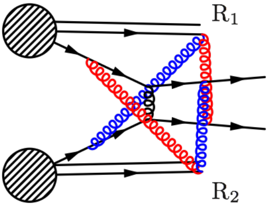


SIDIS - PRD 89, 094002 (2014)

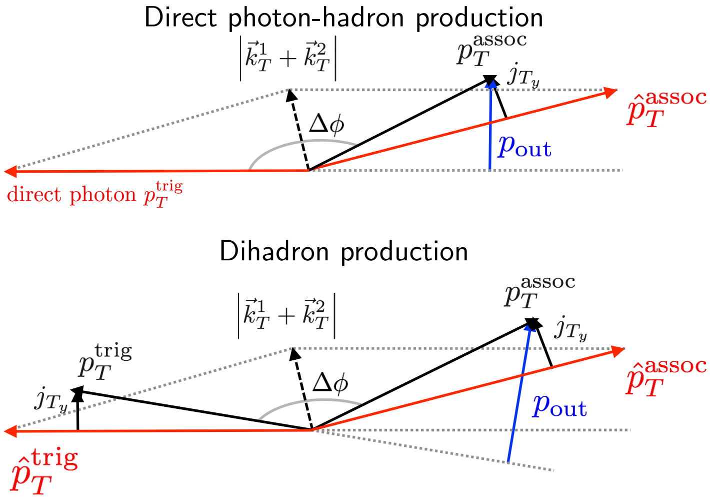
Direct Photons and Dihadrons

- 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?





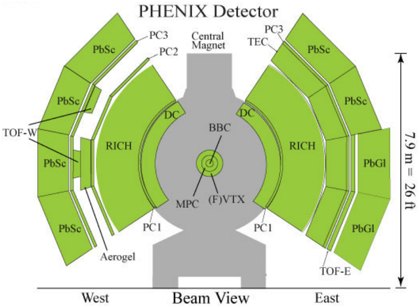
Angular Correlation Observables



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

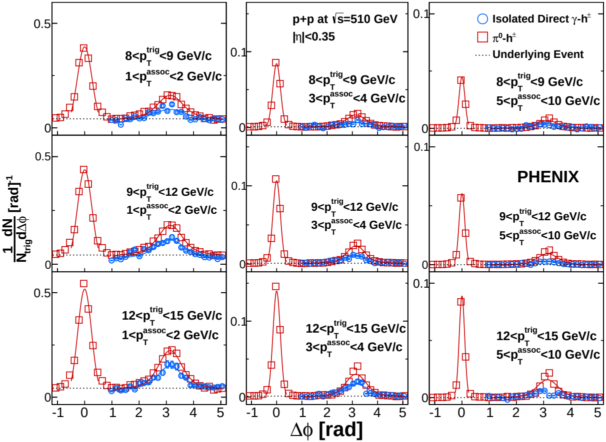
PHENIX Detector

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



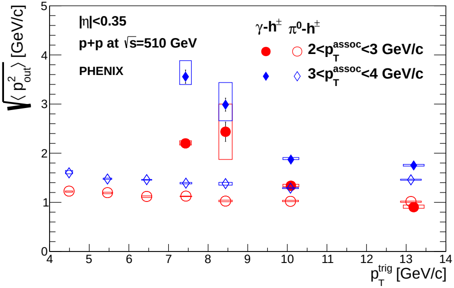
- New results from 2012/2013 $\sqrt{s}$=510 GeV p+p runs

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



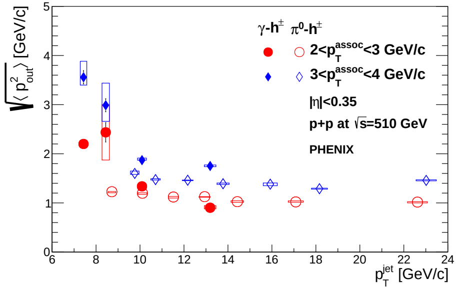
- Two jet structure visible for π^0-h$^\pm$, isolation cut on near side for direct γ-h$^\pm$
- Direct γ-h$^\pm$ probes smaller jet energy due to emerging from hard scattering at LO

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



- $\sqrt{\langle p_{out}^2 \rangle}$ characterizes away-side jet width in momentum space
- Decreases with hard scale, opposite of SIDIS and DY!
- Sensitive to perturbative and nonperturbative k_T and j_T; fits are to entire away-side jet

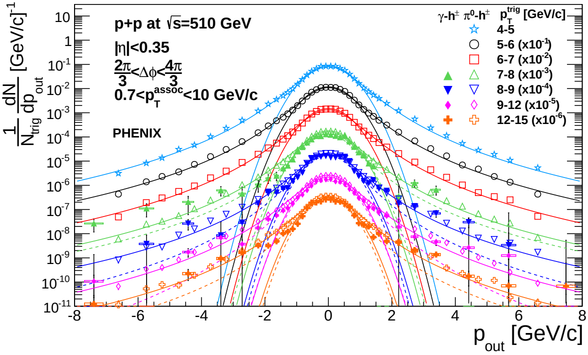
$\sqrt{\langle p_{out}^2 \rangle}$ vs. p_T^{jet}



- 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?

p_{out} Distributions

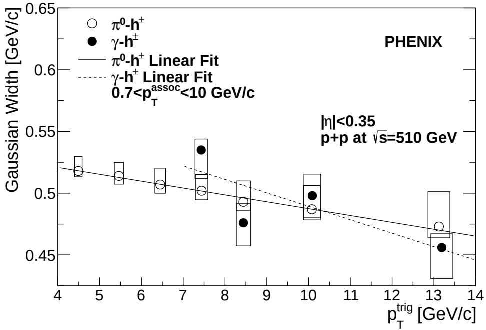
- p_{out} shows two distinct regions: Gaussian and power law
- Gaussian fits clearly fail past ∼1.3 GeV/c
- Indicates transition from nonperturbative to perturbative k_T and j_T



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

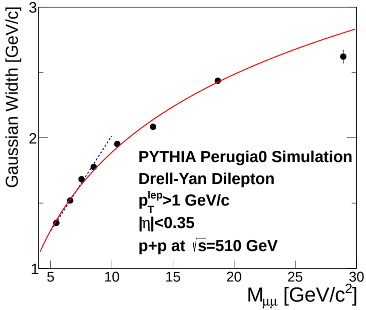
Gaussian Widths of p_{out}

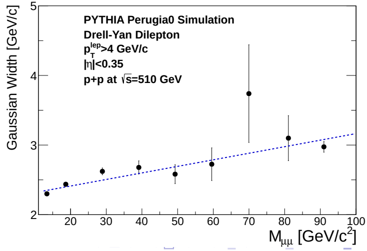
- Extract Gaussian widths of p_{out} vs. p_T^{trig}
- Sensitive to *only* nonperturbative k_T and j_T in the nearly back-to-back region $\Delta\phi \sim \pi$
- Gaussian widths decrease with p_T^{trig} also, consistent with $\sqrt{\langle p_{out}^2 \rangle}$ and opposite of SIDIS and DY!



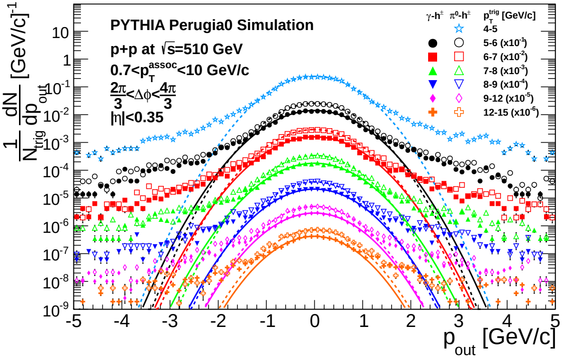
PYTHIA Simulation

- To make a comparison, used PYTHIA simulation
- Chose Perugia0 tune since it was tuned to low p_T Z Boson data from the Tevatron
- Should describe Drell-Yan reasonably well
- PYTHIA reproduces expectation from CSS evolution in Drell-Yan over large range of $M_{\mu\mu}$





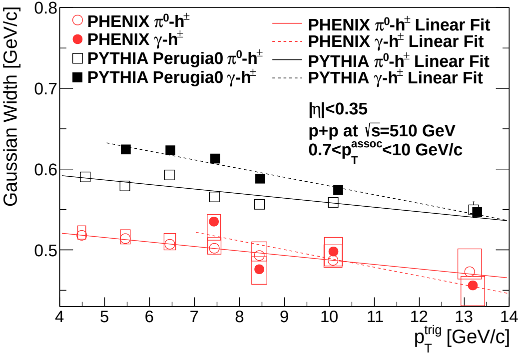
PYTHIA Simulation



- Can construct p_{out} distributions for direct photons and dihadrons in PYTHIA as well using Perugia0 tune for direct comparison
- PYTHIA replicates the nonperturbative to perturbative transition in the p_{out} distributions

PYTHIA Simulation

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



- Decreasing trend does not depend on choice of tune (several were tested)

PYTHIA Simulation

- WHY does PYTHIA replicate both DY and p+p $\rightarrow$h+X??
- Unlike a standard pQCD calculation, PYTHIA forces all particles to color neutralize in the event, including remnants
- PYTHIA allows initial and final state soft gluon exchanges, as well as initial and final state interactions!
- People from Lund group confirm that it is plausible that PYTHIA would be sensitive to such effects

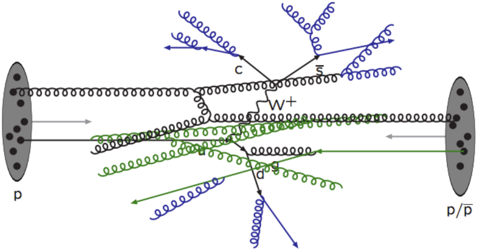


Image taken from http://home.thep.lu.se/ torbjorn/talks/karlsruhe10a.pdf

Relations to Other QCD Studies?

- Factorization breaking in heavy ions from CMS: PRC 92,034911 (2015)

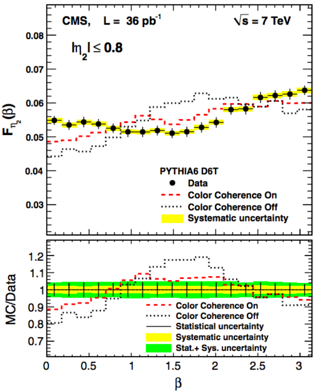
$$\frac{dN^{\rm pair}}{d\Delta\phi} \propto 1+2\sum_n V_{n\Delta}\cos(n\Delta\phi)$$

CMS finds that

$$V_{n\Delta} \neq v_n^a v_n^b$$

where v^a and v^b are the single-particle flow harmonics for a pair of particles

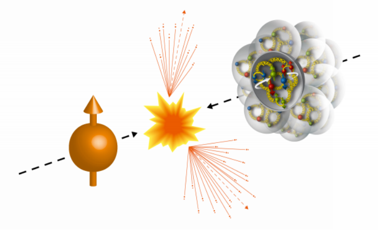
- Color coherence studies at the Tevatron and LHC



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

Future Measurements

- Recent RHIC Run-15 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 ~10x the amount of $\sqrt{s} = 200$ GeV data from previous analysis
- Possibility to compare $p+p$ at $\sqrt{s} = 200$ and 510 GeV (TMD evolution)



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

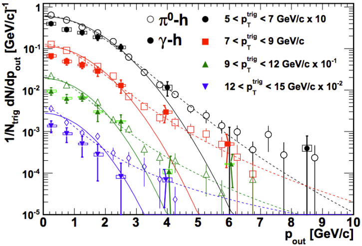
Conclusions

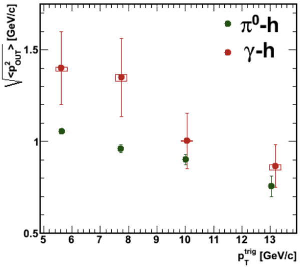
- Extending the knowledge of nucleon structure from 1 dimension to 3 dimensions (and more!)
- Transverse-momentum-dependent nucleon structure offers a richer description of the nucleon with many interesting phenomenological predictions
- Factorization breaking has been predicted in hadronic collisions 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 SIDIS and DY, 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!

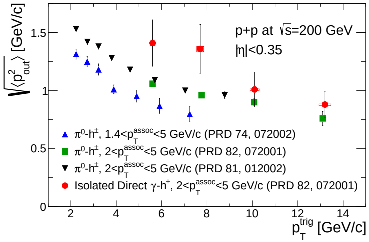


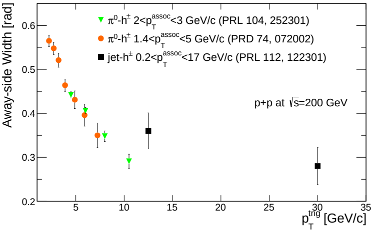


$2 < p_T^{assoc} < 5$

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

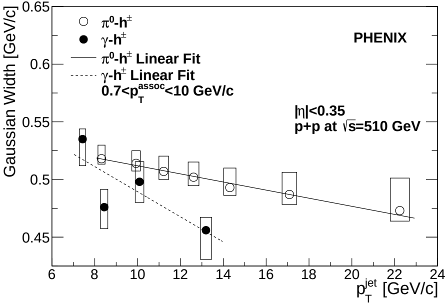
- Previous PHENIX result at $\sqrt{s}$=200 GeV to lower p_T^{trig} (PRD 81, 012002 (2010))
- Shows $\sqrt{\langle p_{out}^2 \rangle}$ over lower range of p_T^{trig}
- Also can plot away-side width in angular space - same trend over large range of p_T^{trig}



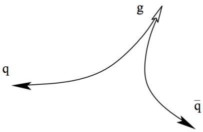


$\langle z_T \rangle$ with Gaussian Widths

- $\langle z_T \rangle$ 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



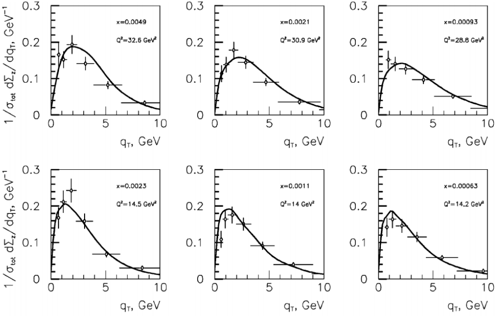
More about Color Coherence



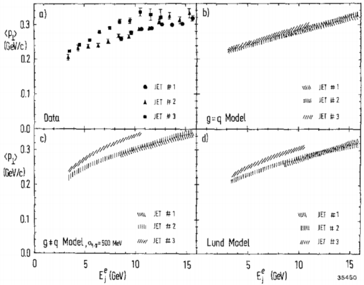
- Radiation "drags" color away from vertex
- Destructive interference occurs away from emitted gluons
- Soft radiation inhibited in certain areas
- Leads to certain regions of phase space where gluons constructively or destructively interfere

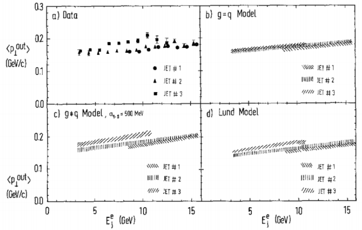
- See the following references
  - Phys. Rev. D 50,5562 (1994)
  - Phys. Lett. B 414 (1997) 419-427
  - Dokshitzer, Yuri. *Basics of Perturbative QCD* (Editions Frontieres, 1991) Chapters 4,5,9

SIDIS and e^+e^- Annihilation Momentum Widths



PRD 61, 014003





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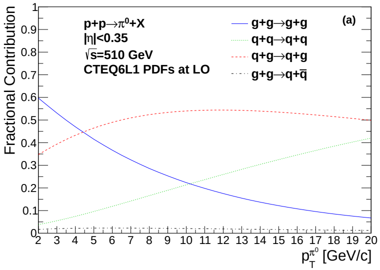
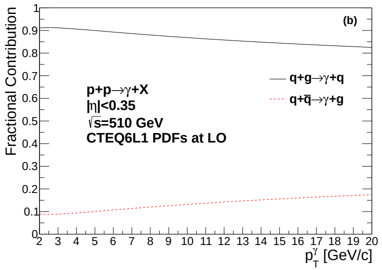
Partonic Contributions to Processes at LO





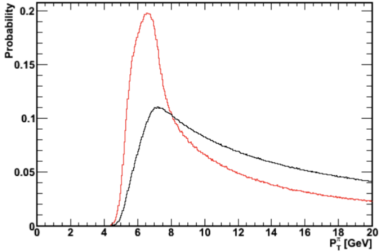
- π^0 contribution changes from gluon dominated at low p_T to mix of quark and gluons at high p_T

- 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 π^0−h$^\pm$ or isolated γ−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

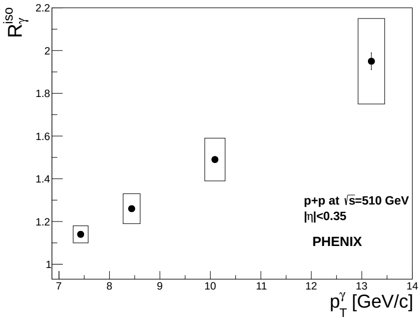


$$Y_{dir}^{iso} = \frac{1}{R_\gamma^{iso} - 1}\left(R_\gamma^{iso} Y_{inc}^{iso} - Y_{dec}^{iso}\right)$$

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
- $R_\gamma^{iso} > 1$ indicates isolated direct photon production



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