Effects from QCD color flow in proton-proton and proton-nucleus collisions

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University of Michigan

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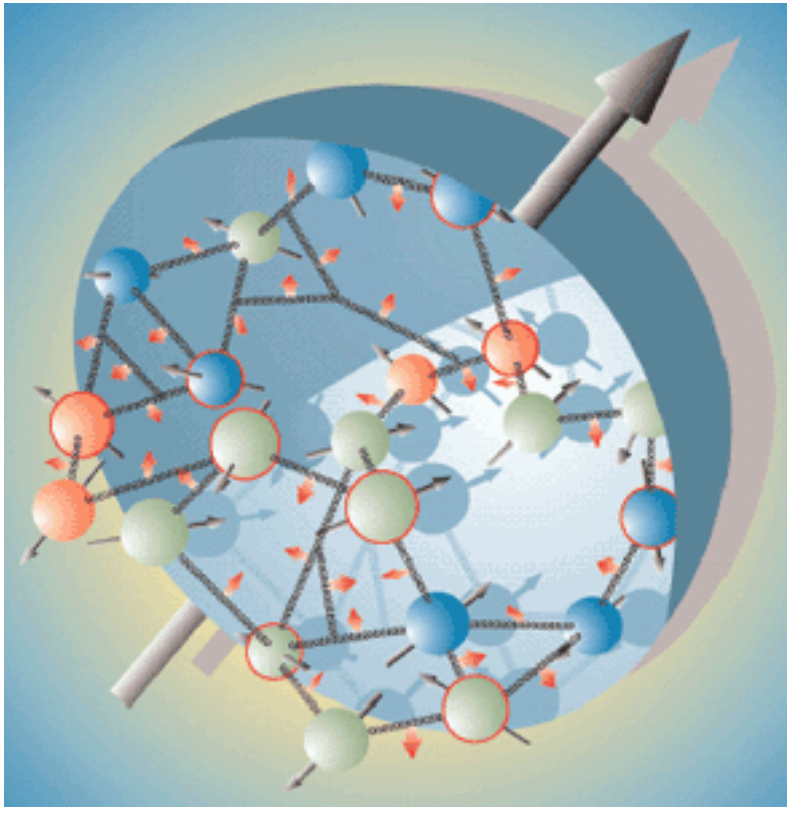
U.S. DEPARTMENT OF ENERGY | Office of Science

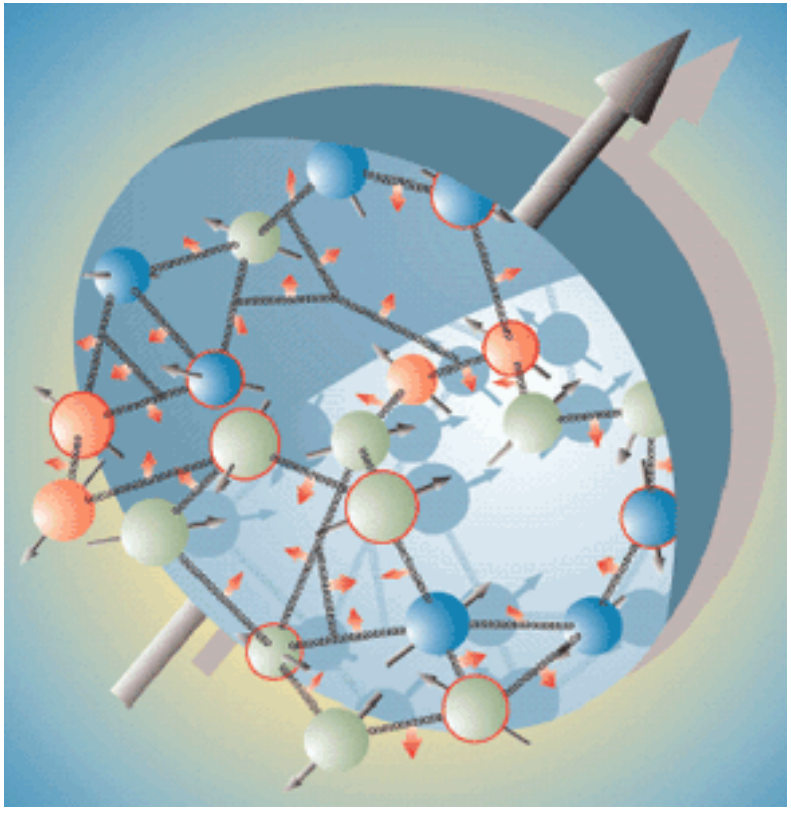
Quantum Chromodynamics

- QCD is the fundamental gauge theory describing the strong force
- Written in terms of quark and gluon (parton) degrees of freedom



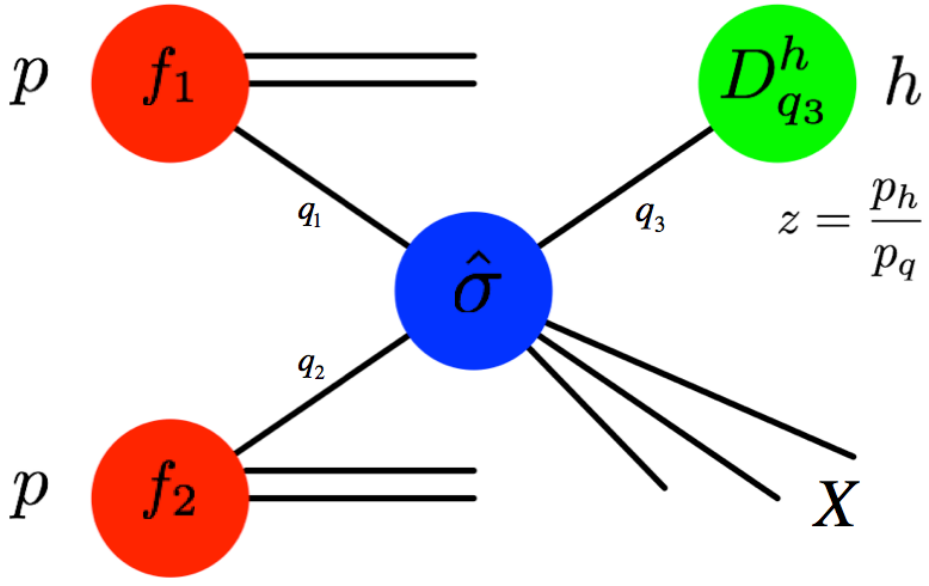
Quantum Chromodynamics

- QCD is the fundamental gauge theory describing the strong force
- Written in terms of quark and gluon (parton) degrees of freedom
- But we can only directly observe combinations of partons in the laboratory!
- Confinement and the non-Abelian nature of QCD: gluon self coupling and color charge



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



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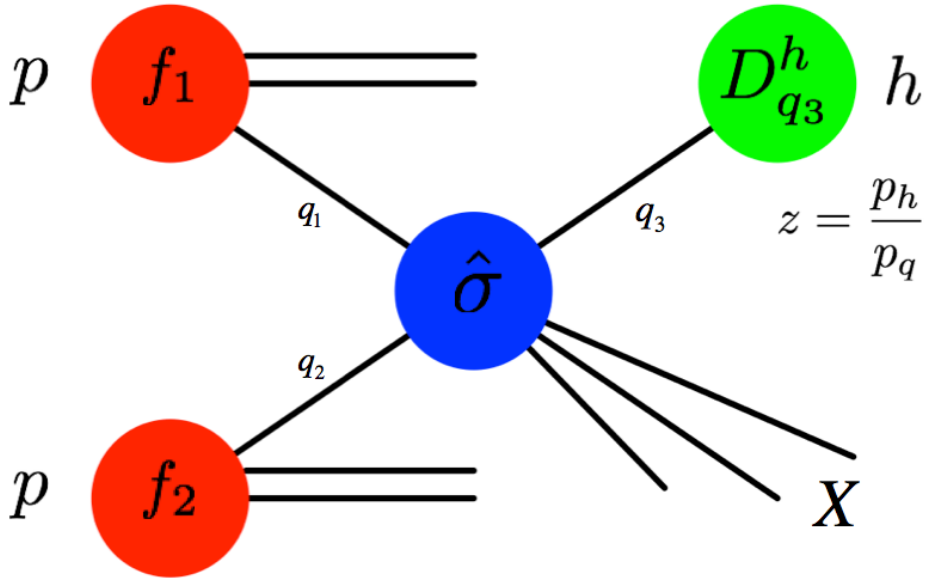

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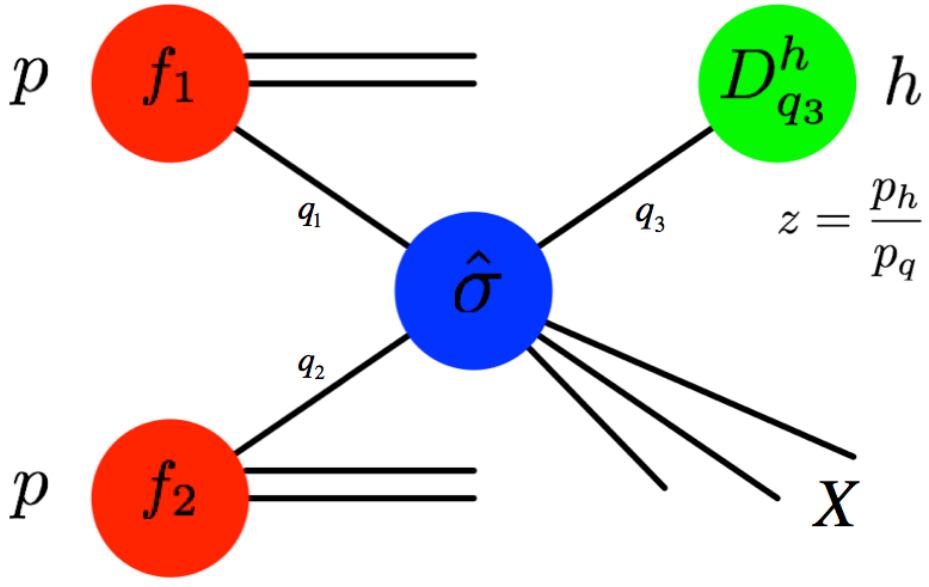
- Taken to be process independent and uncorrelated



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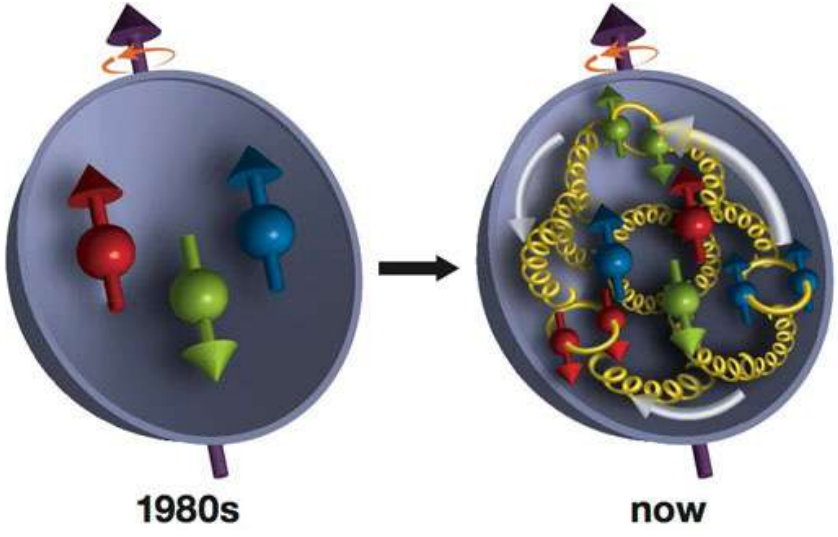
The Proton Multidimensionally

- Historically, the structure of the proton has been approximated as only dependent on the collinear momentum fraction x
- The last two decades have seen QCD move from a static to dynamic picture of the proton



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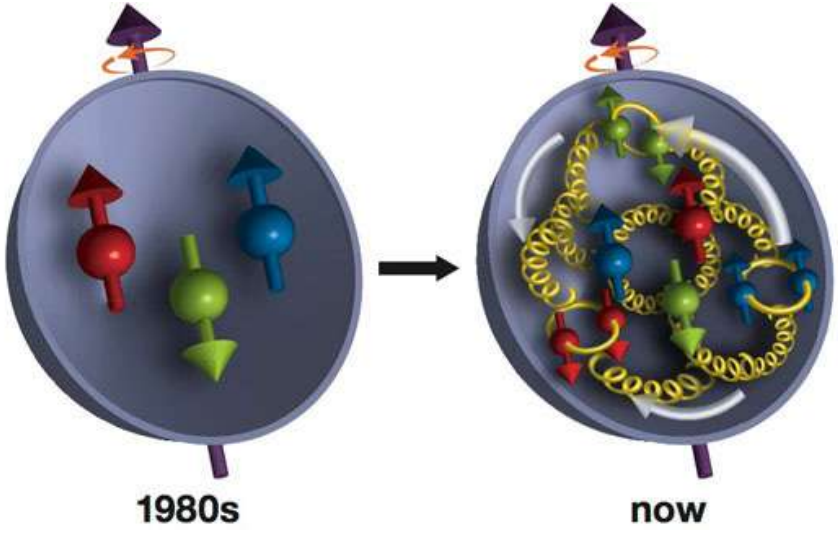

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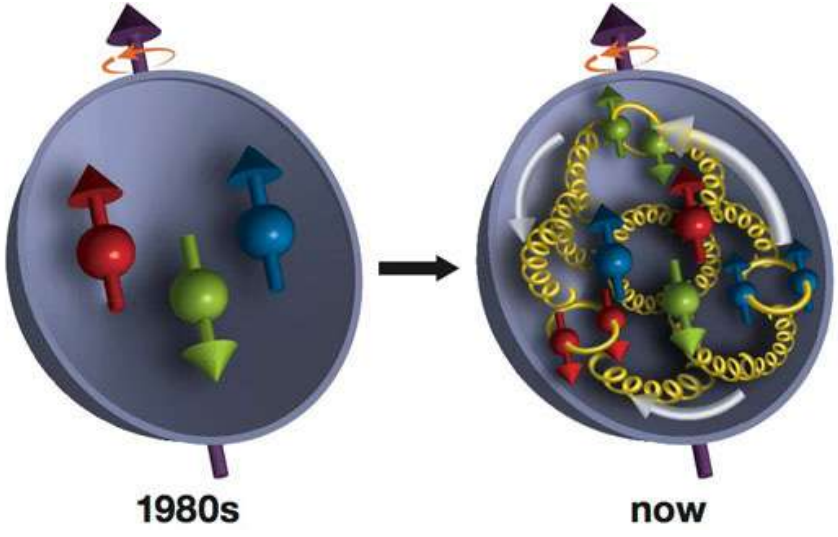

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  - Flavor
  - Momentum (3D)
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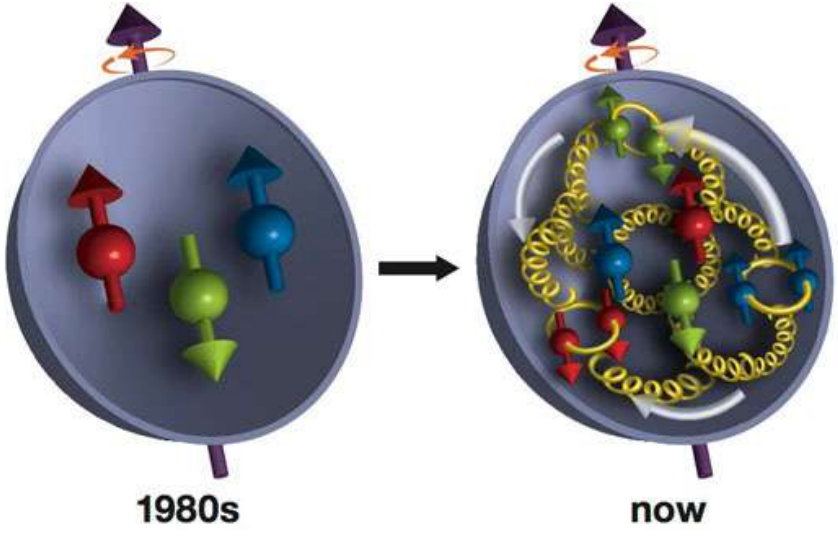

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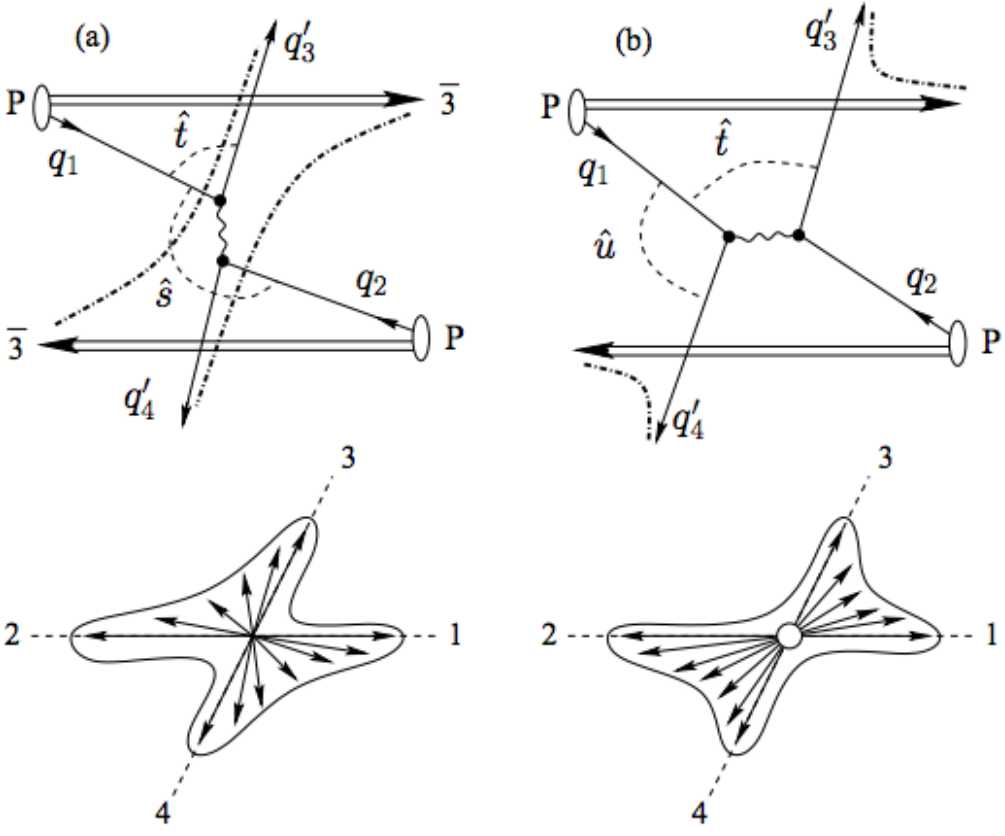
Color Coherence

- Color flow through hard processes leads to certain regions of particle production in hadronic collisions



Y. Dokshitzer. Basics of Perturbative QCD, 1991

Color Coherence

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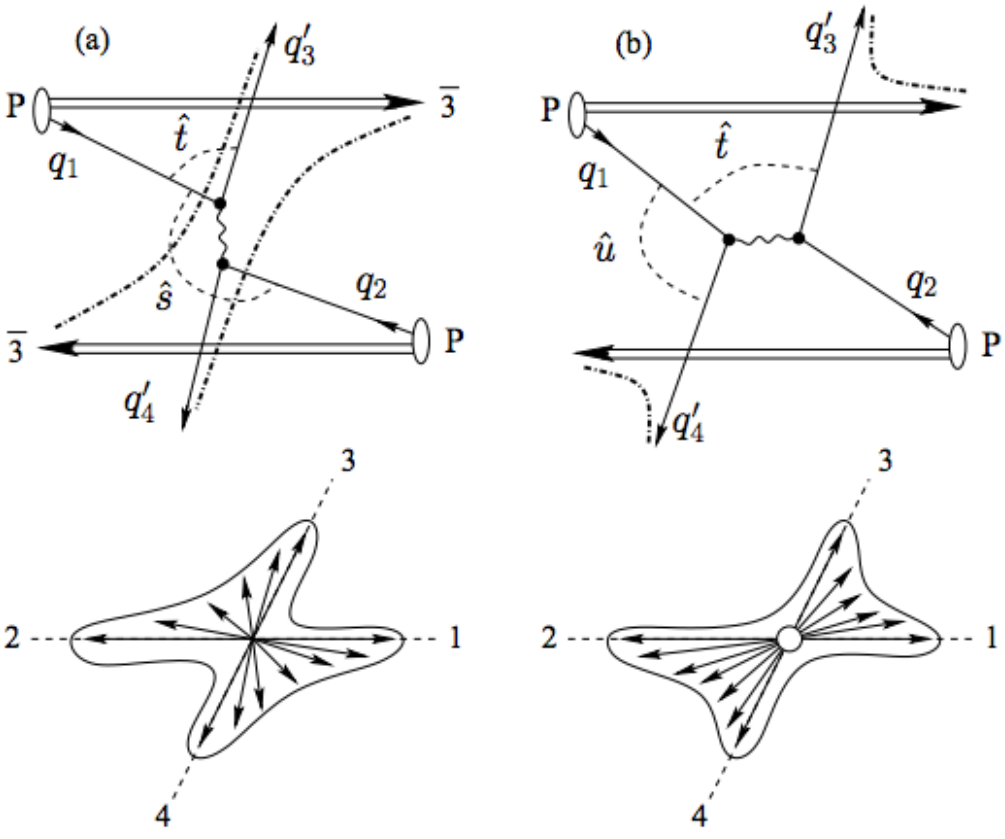

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Color Coherence

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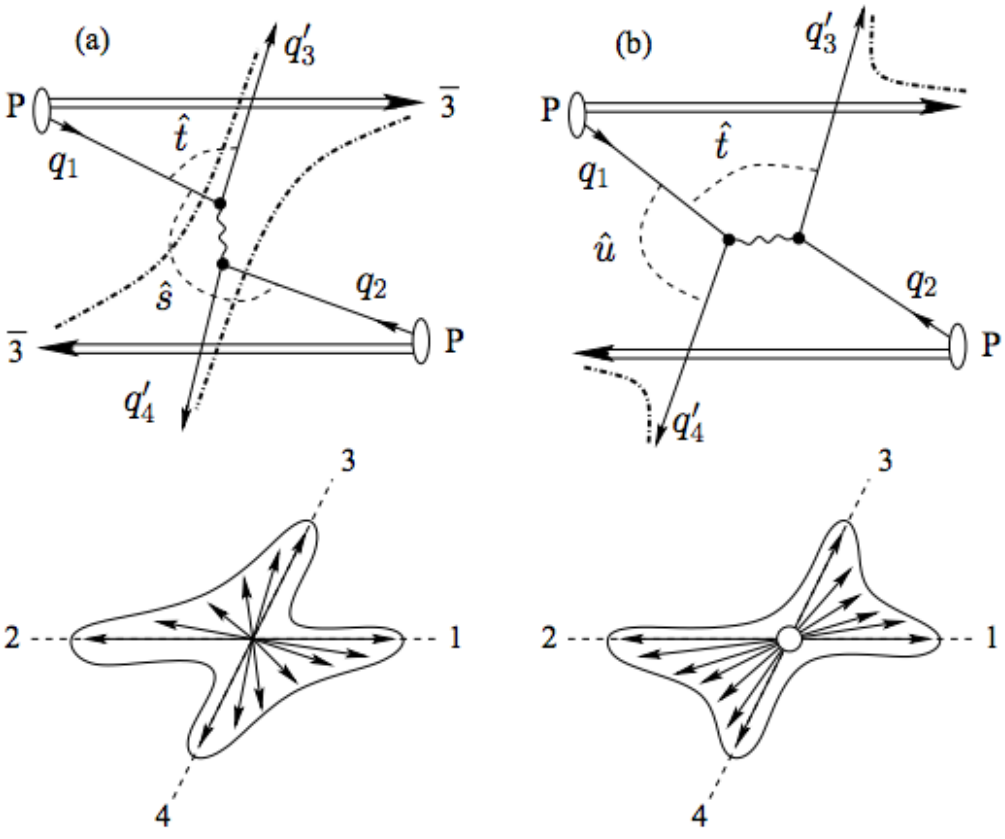
- Color connects hard scattered partons with remnants of other proton
- Color connections lead to destructive gluon interferences $\rightarrow$ depletions in hadron production



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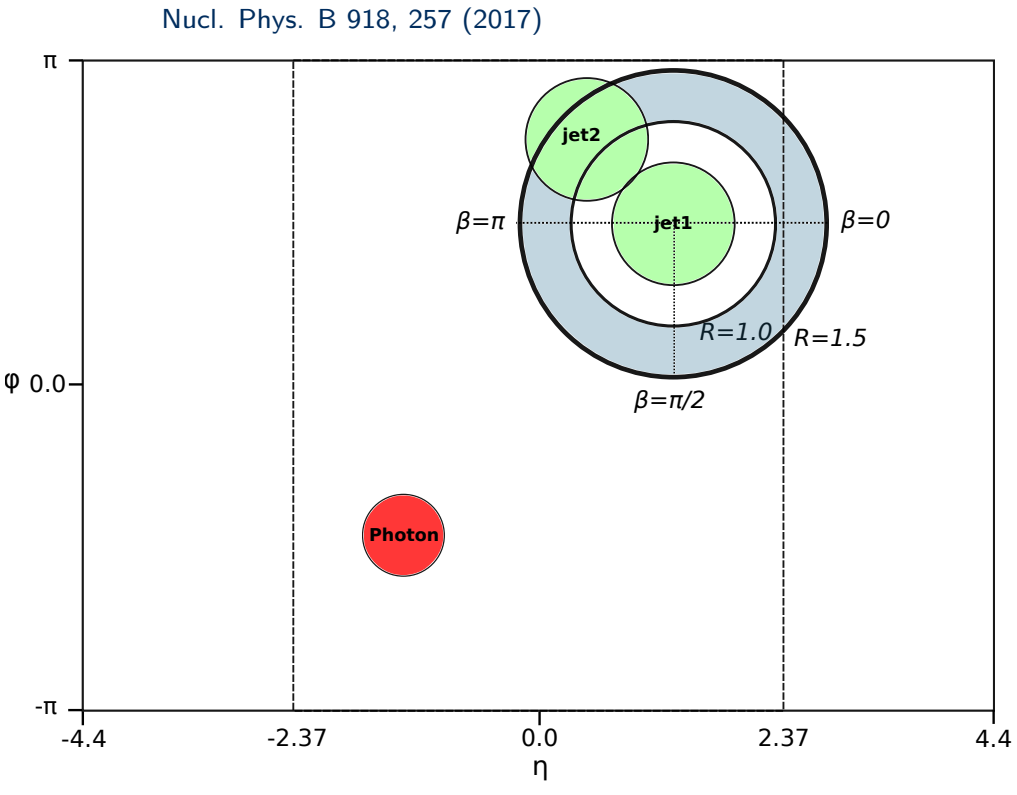
Color Coherence Measurements



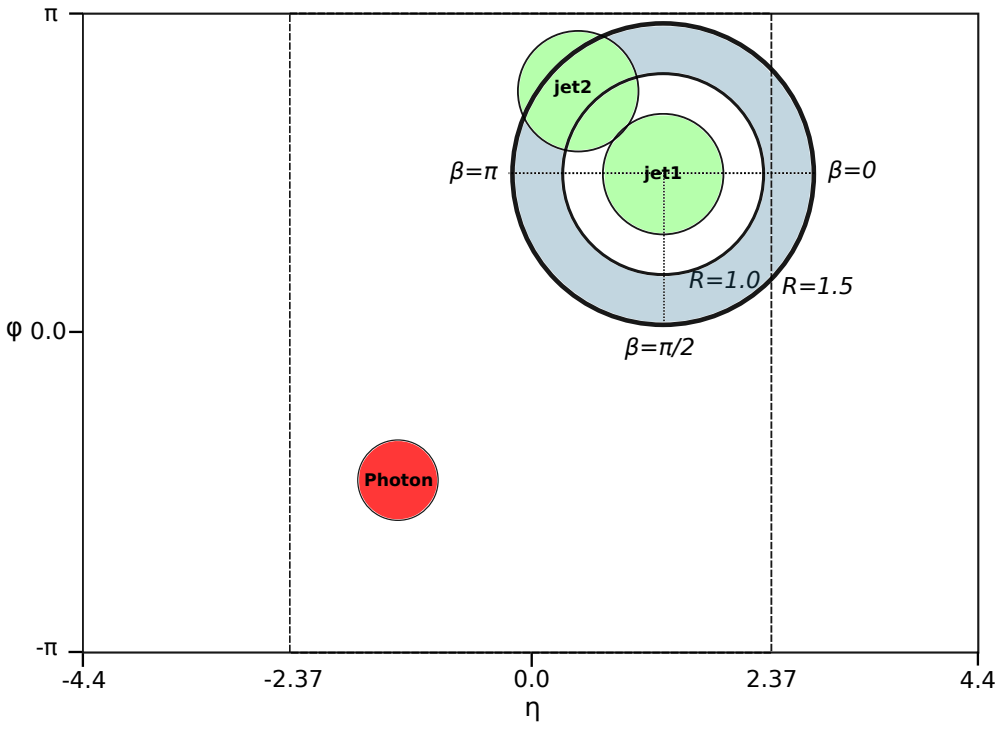
- Color coherence measurements study:

$$\beta = \tan^{-1} \frac{\Delta\phi_{21}}{\text{sign}(\eta_1)\Delta\eta_{21}}$$

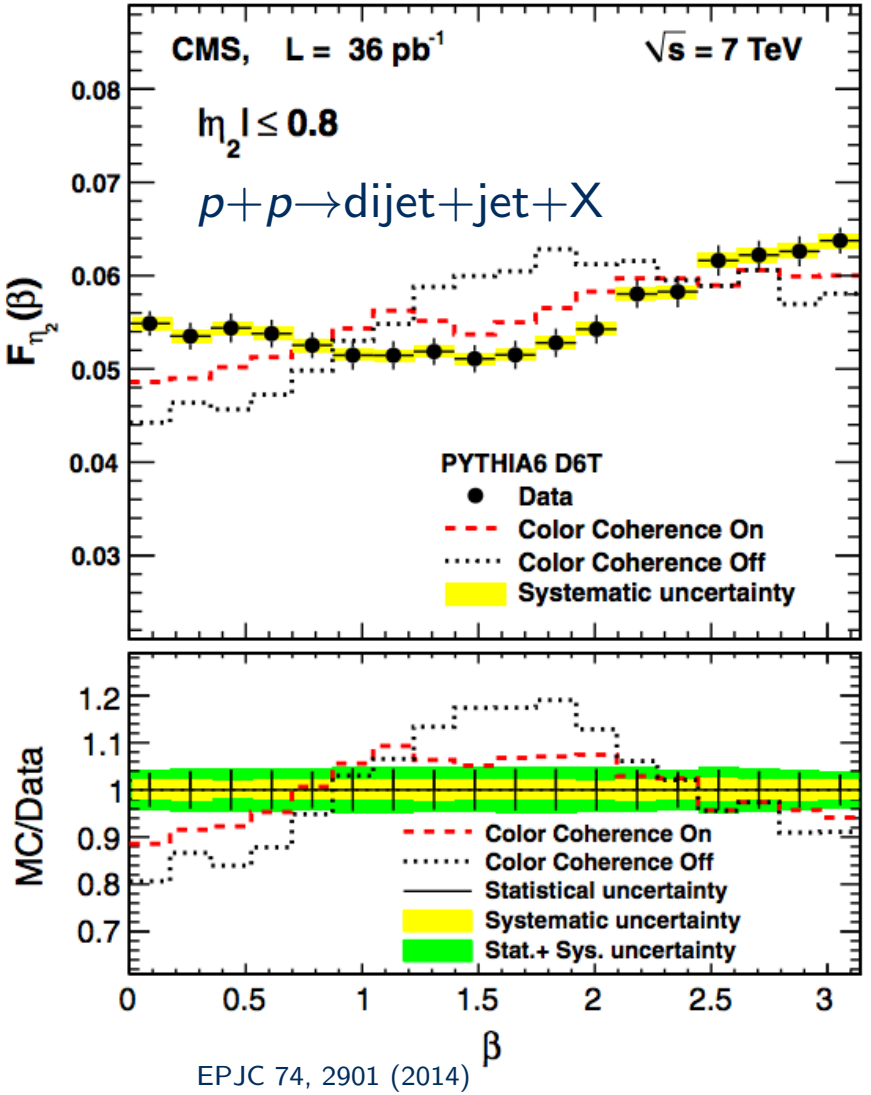
- Angle in (η, ϕ) space between sub-leading hard-scattered jet and gluon initiated jet
- $\beta = 0$ points to the beam closer to jet 1 in (η, ϕ) space
- $\beta = \pi$ points to the beam farther from jet 1 in (η, ϕ) space

Color Coherence Measurements

Nucl. Phys. B 918, 257 (2017)



- Third jet more likely to be found at $\beta = 0$, $\beta = \pi$, i.e. similar ϕ but large η gap (remnant activity high!)



EPJC 74, 2901 (2014)

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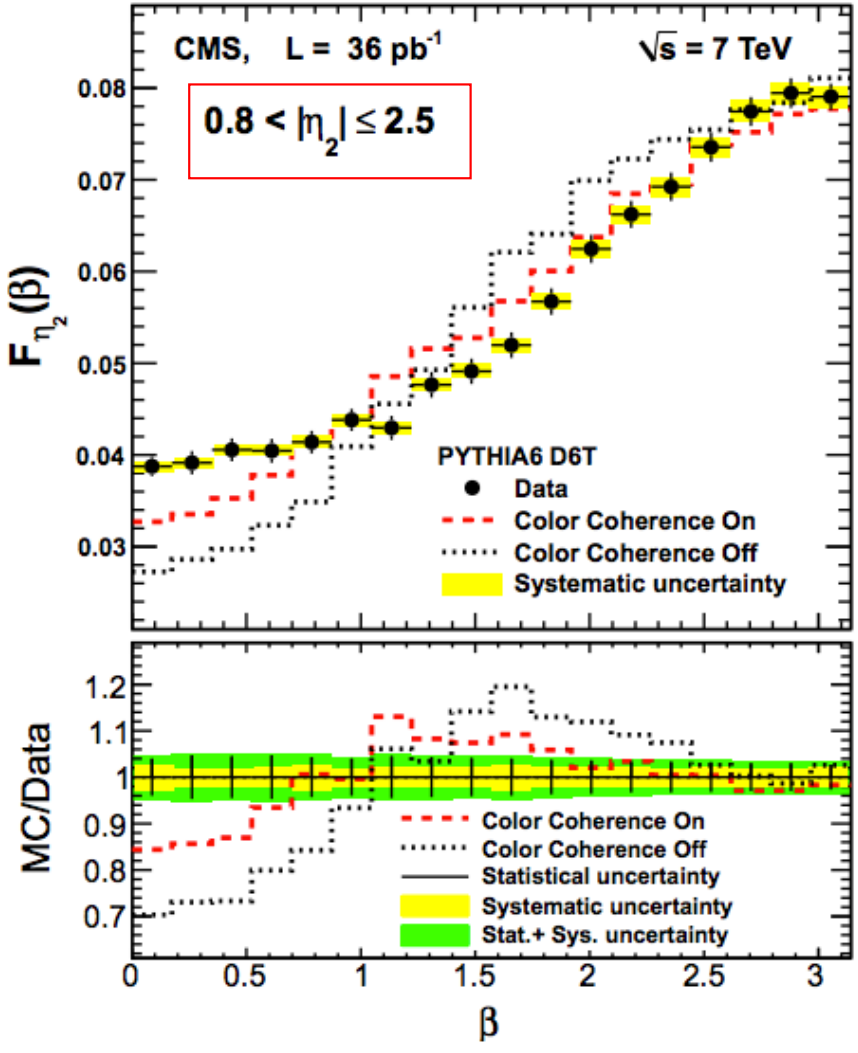

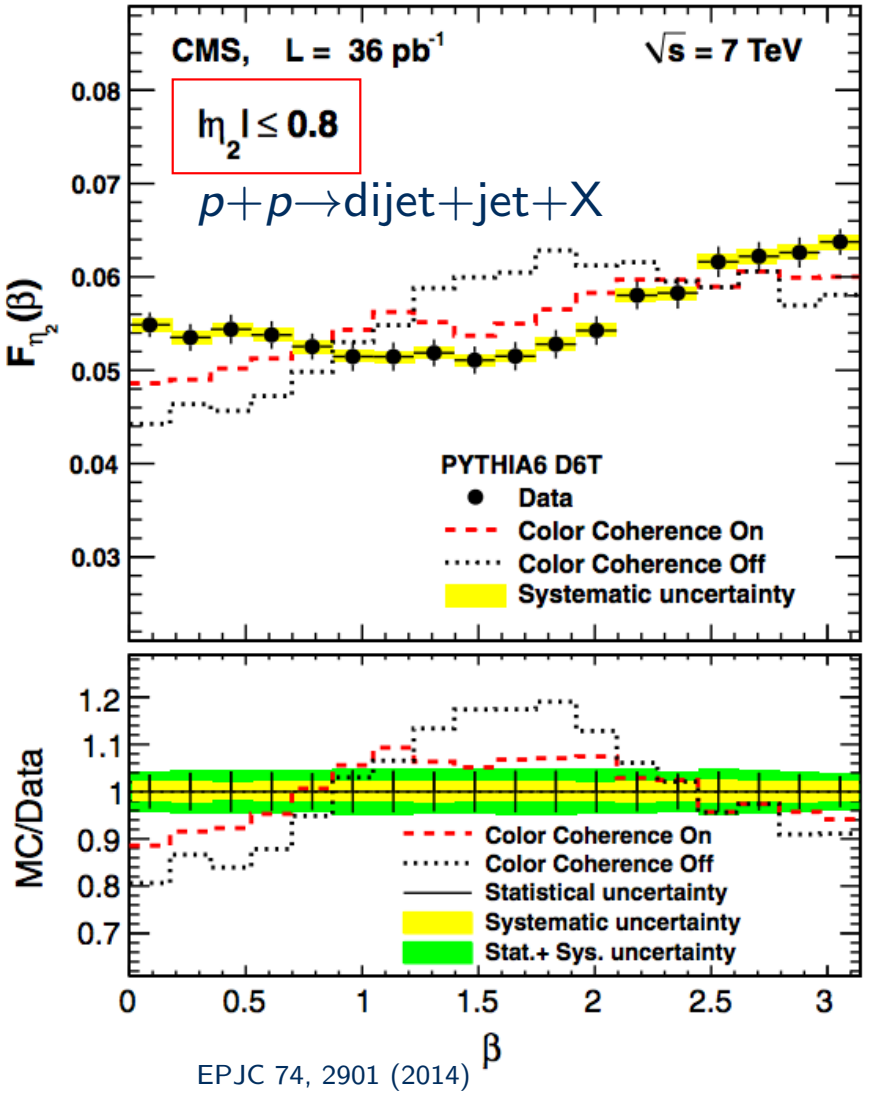

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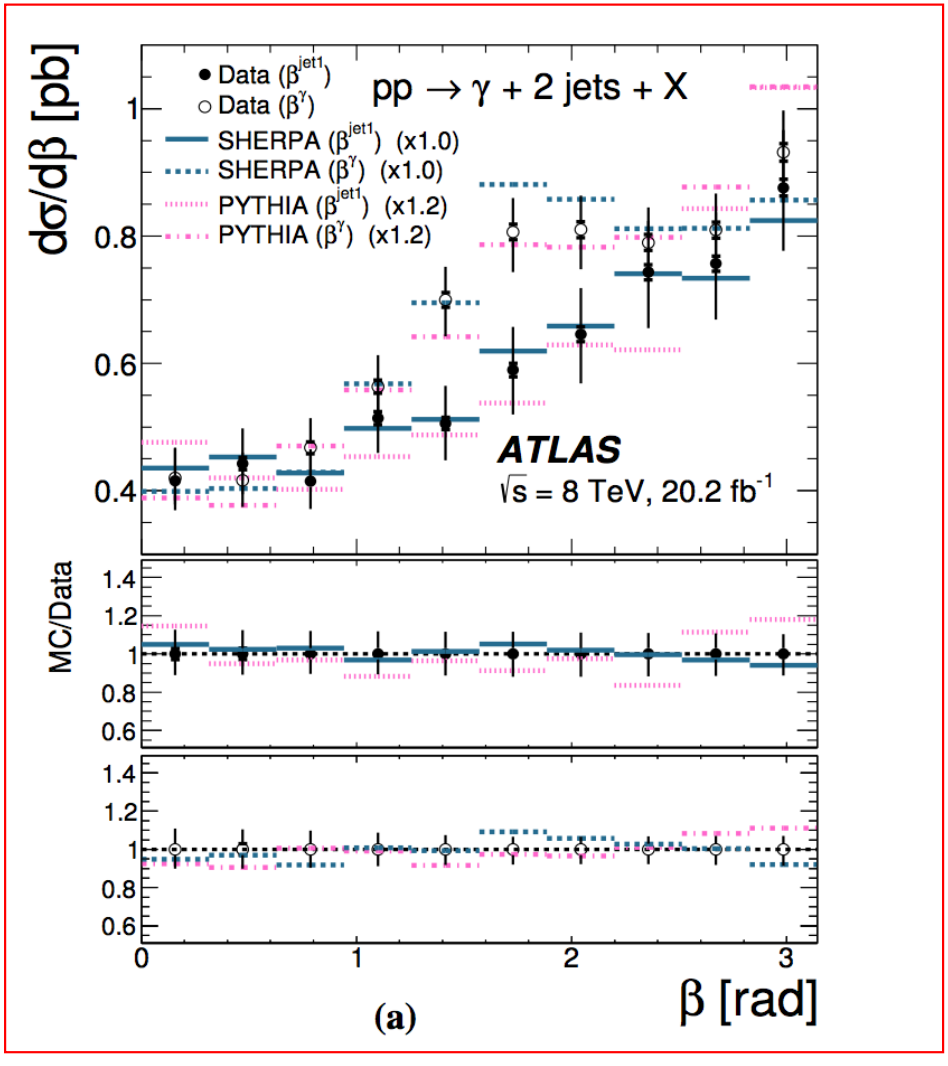
- Even stronger correlation to opposite beam at forward rapidities!

Color Coherence Measurements



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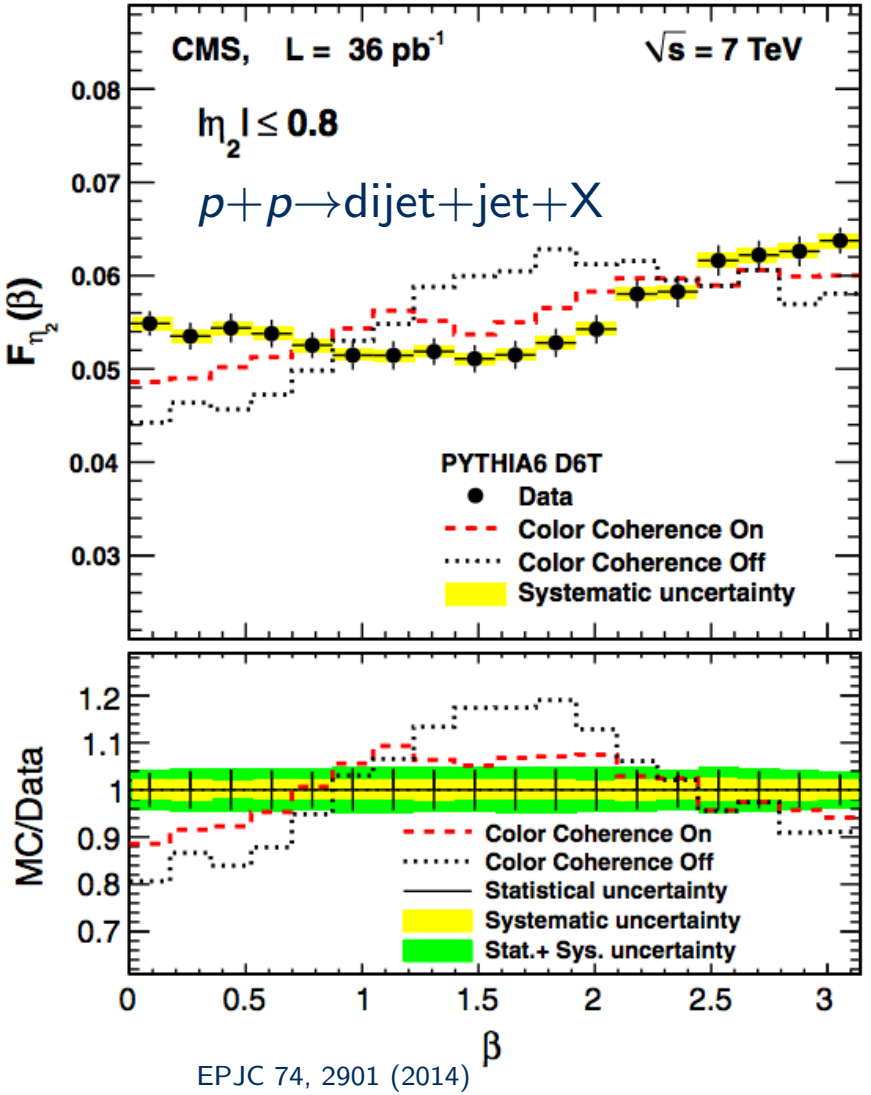
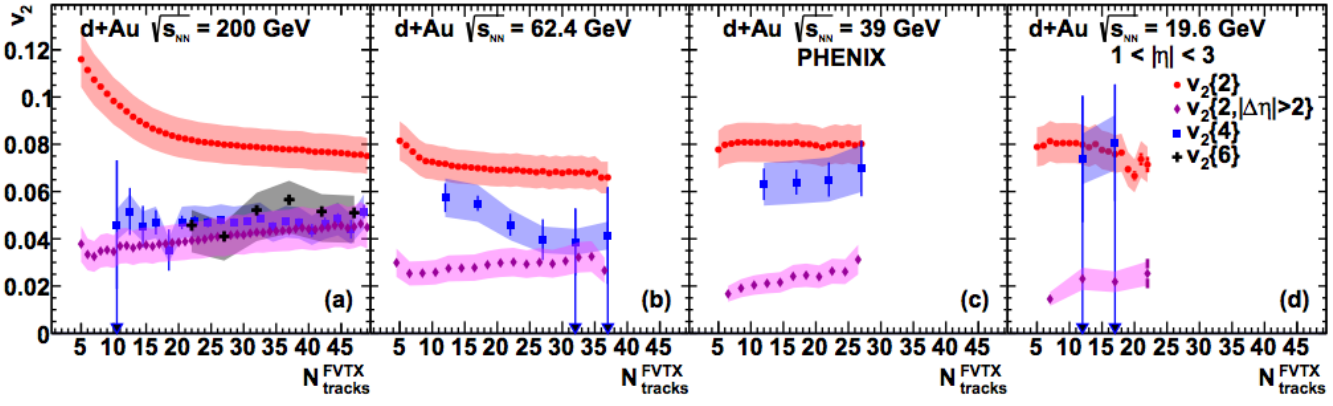


EPJC 74, 2901 (2014)

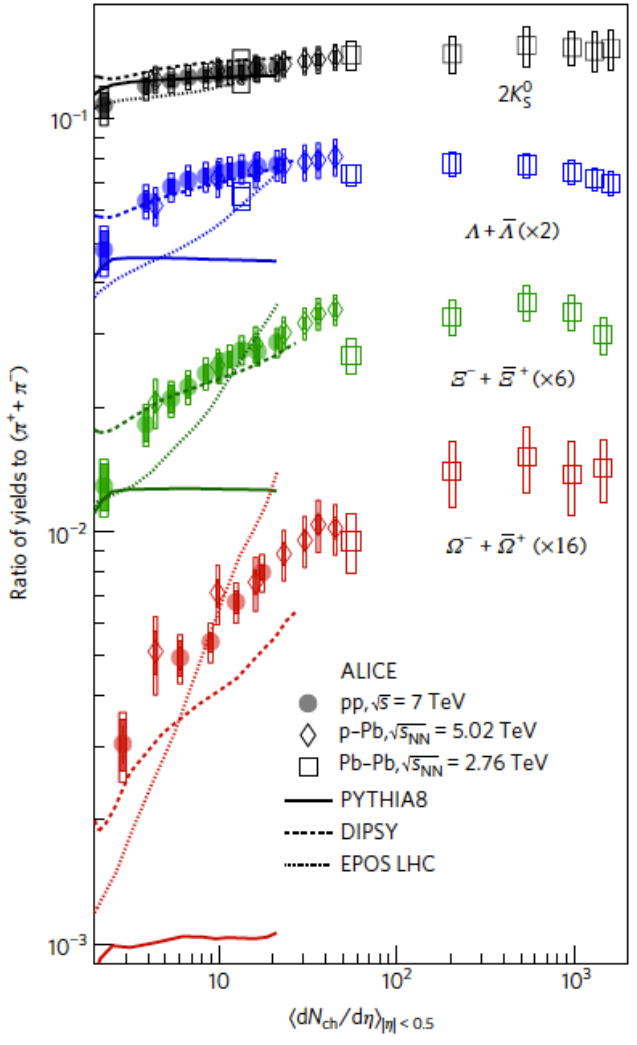
- Even stronger correlation to opposite beam when using $\gamma-$jet!

Relation to High Multiplicity?

- Surprising results from RHIC and LHC show novel phenomena in high multiplicity p+p and p+A
- What role does color play in these measurements?
- Color coherence measurements also probing (parton) long range η correlations

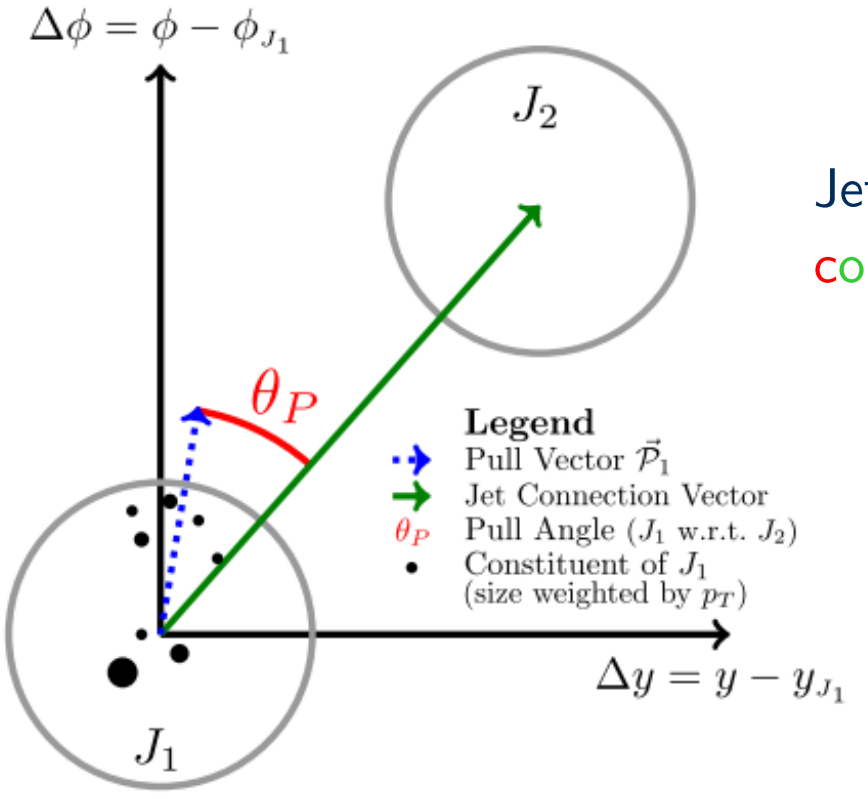


PRL 120, 062302 (2018)



Nature Phys. 13 (2017) 535-539

Jet Substructure

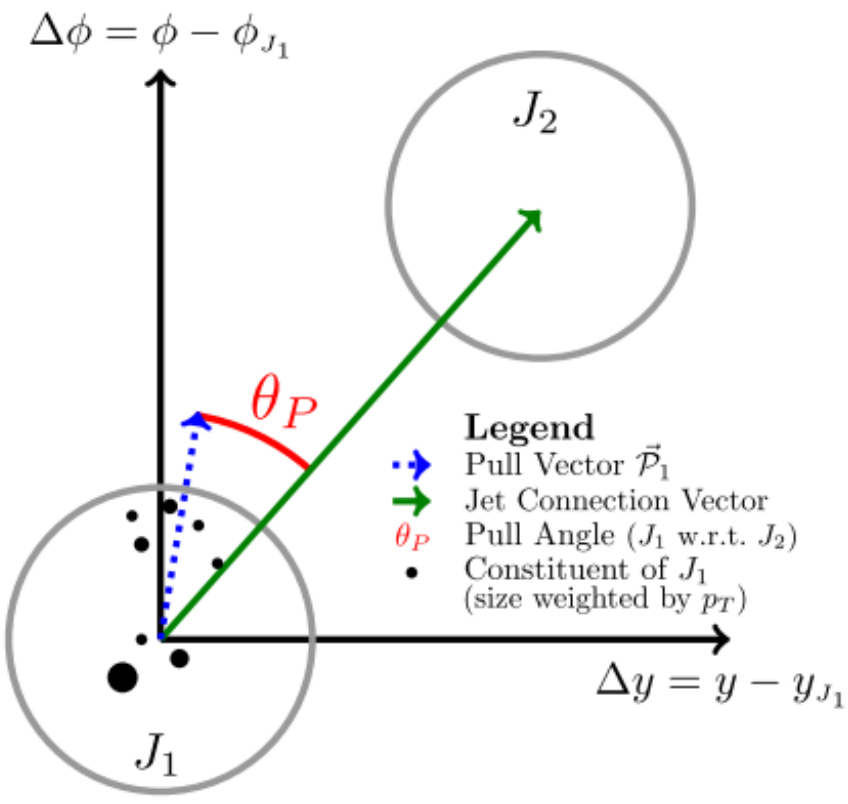


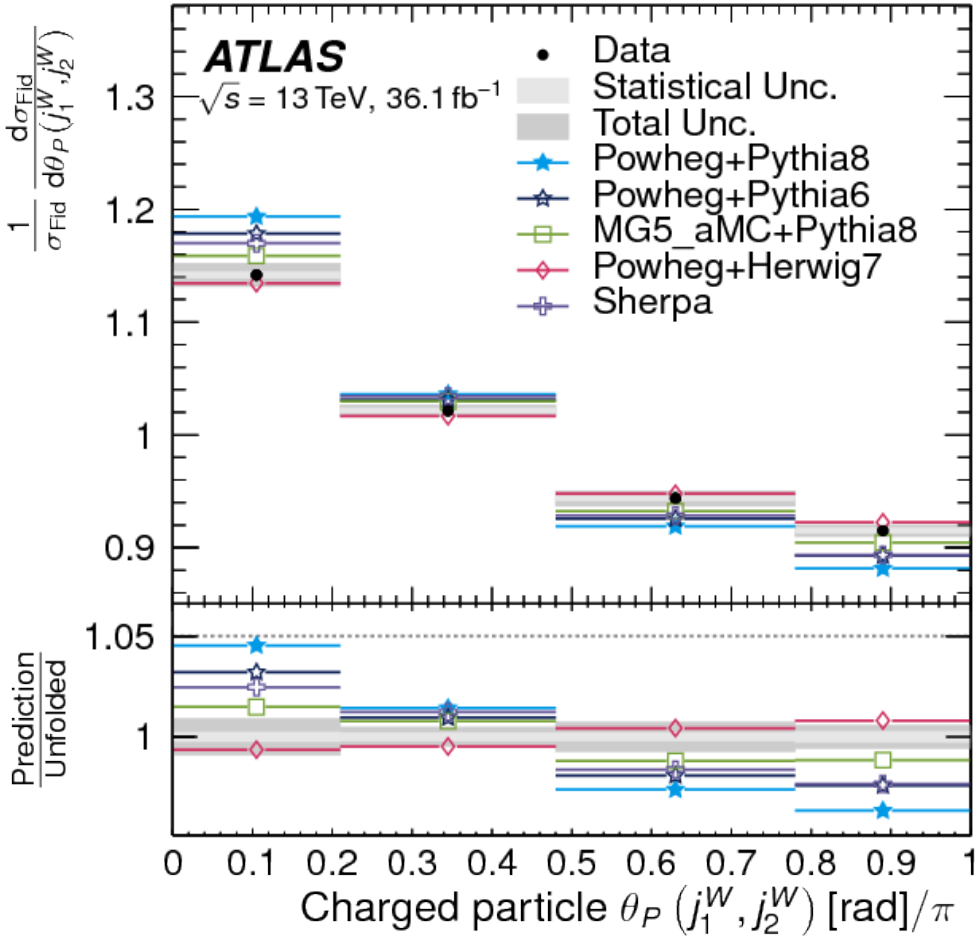
Jet-pull vector predicted to be sensitive to color connections (PRL 105, 022001 (2010))

$$\vec{\mathcal{P}}(j) = \sum_{i \epsilon j} \frac{\left|\vec{\Delta r}_i\right| \cdot p_T^i}{p_T^j} \vec{\Delta r}_i$$

- Absence of color connection - θ_p expected to be distributed uniformly
- Color connection - θ_p expected to preferentially lie along jet connection vector $\theta_p \sim 0$

Jet Substructure





arXiv:1805.02935

- Jet pull angle preferentially $\sim 0 \rightarrow$ color connections
- Color affects radiation patterns within jets

Multidifferential observables are revealing the effects of color flow in $p+p$ collisions

1D vs. 3D Nonperturbative Functions

- 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

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

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

$$\sigma = f_{q/h}(x, k_T, Q^2) \otimes \frac{d\hat{\sigma}}{dt} \otimes D_{q/h}(z, j_t, Q^2)$$

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$$\Longrightarrow \Lambda_{QCD} \lesssim k_T \ll Q$$

$\Longrightarrow$ Multi-scale observables necessary!

Transverse-Momentum-Dependent Phenomenology

- In the collinear framework, nonperturbative functions are taken to be uncorrelated, universal, process independent functions
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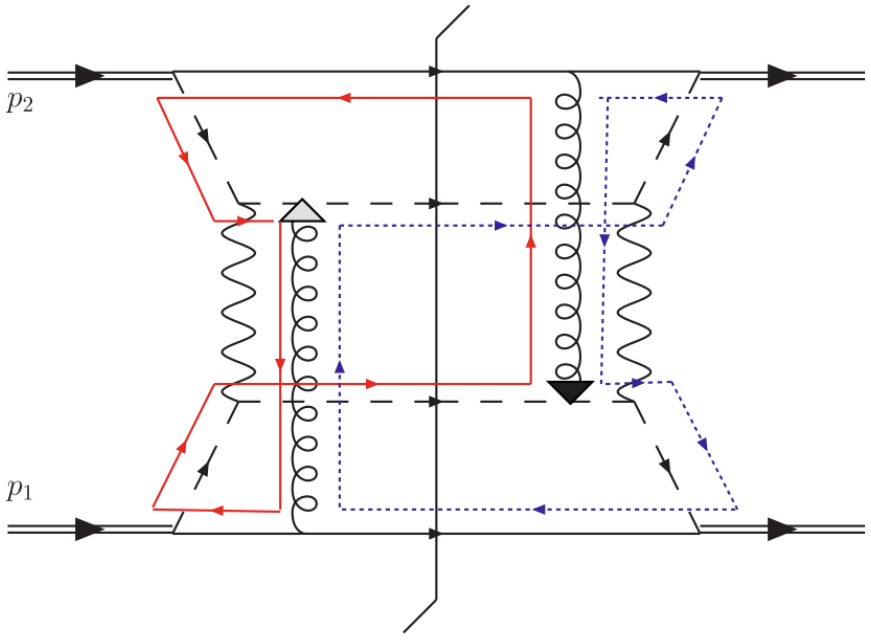
Transverse-Momentum-Dependent Phenomenology

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

Factorization Breaking of TMD Functions

- Factorization breaking predicted in a transverse-momentum-dependent (TMD) framework for $p + p \to h_1 + h_2$ (PRD 81, 094006 (2010))
- TMD nonperturbative functions no longer defined - partons are quantum mechanically correlated via color across colliding hadrons!



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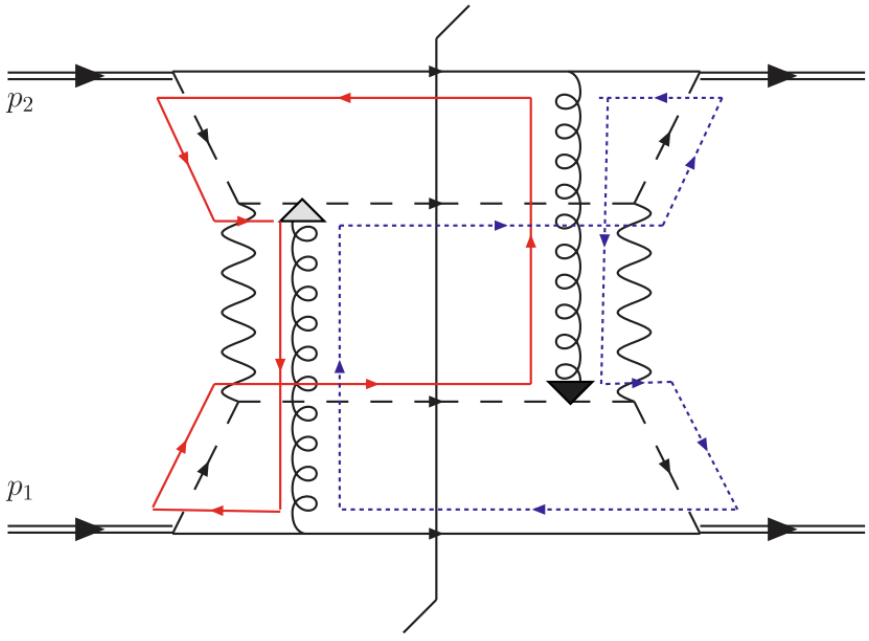

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$$\downarrow$$

$$\sigma \stackrel{?}{=} CF(x_1, x_2, k_{T_1}, k_{T_2}, z_1, z_2, j_{T_1}, j_{T_2}) \otimes \frac{d\hat{\sigma}}{dt}$$

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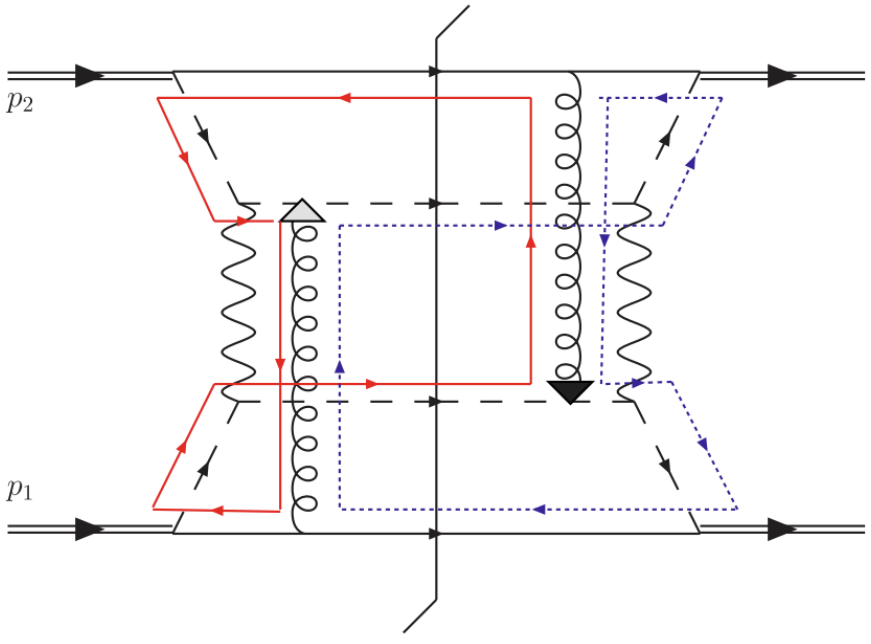

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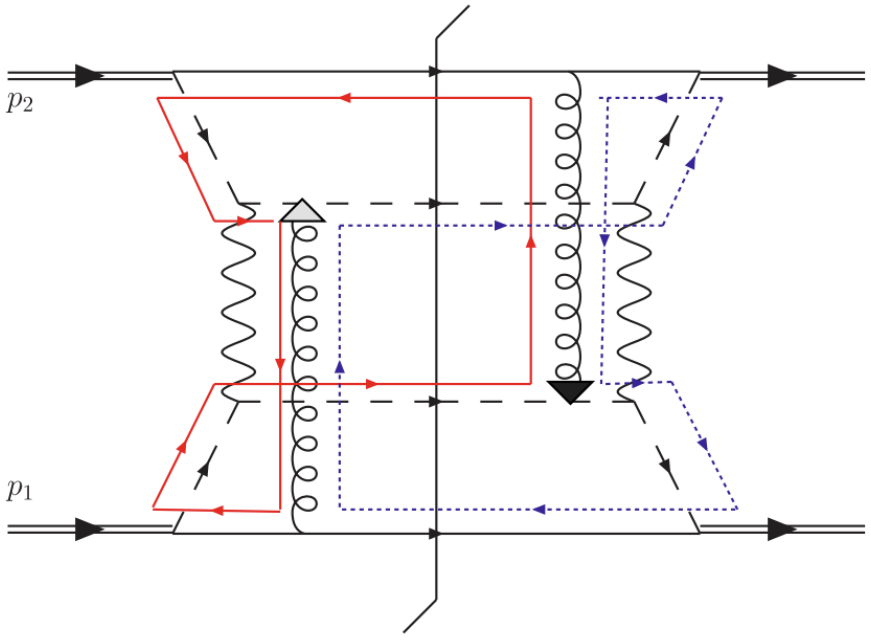
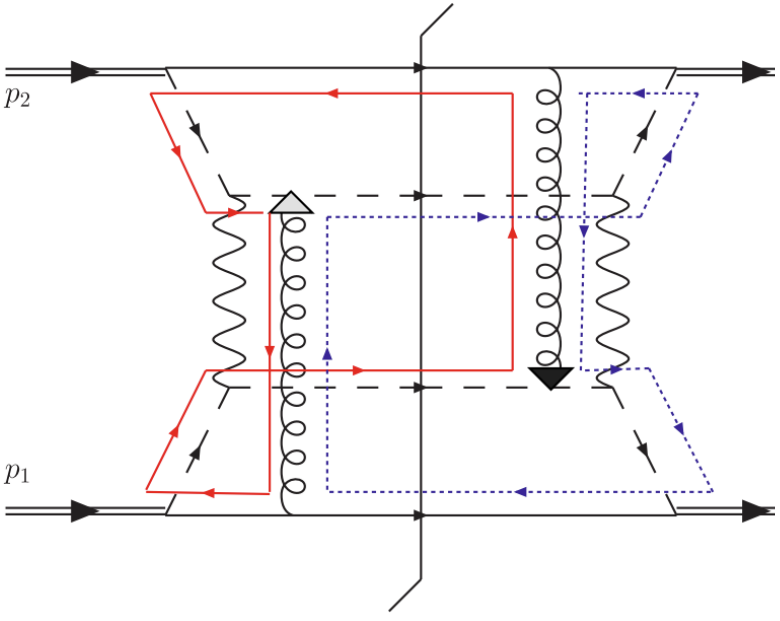


- Consequence of QCD as a non-Abelian gauge theory

Color Entanglement and Color Coherence

Color entanglement



PRD 81, 094006 (2010)

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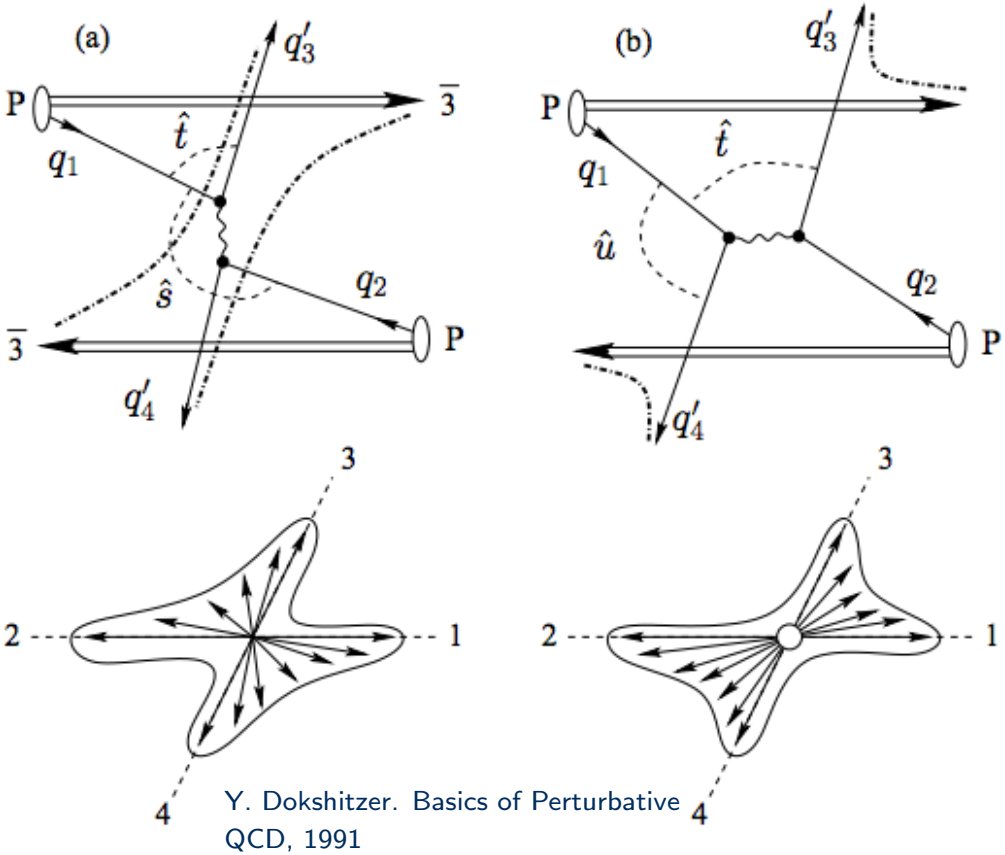


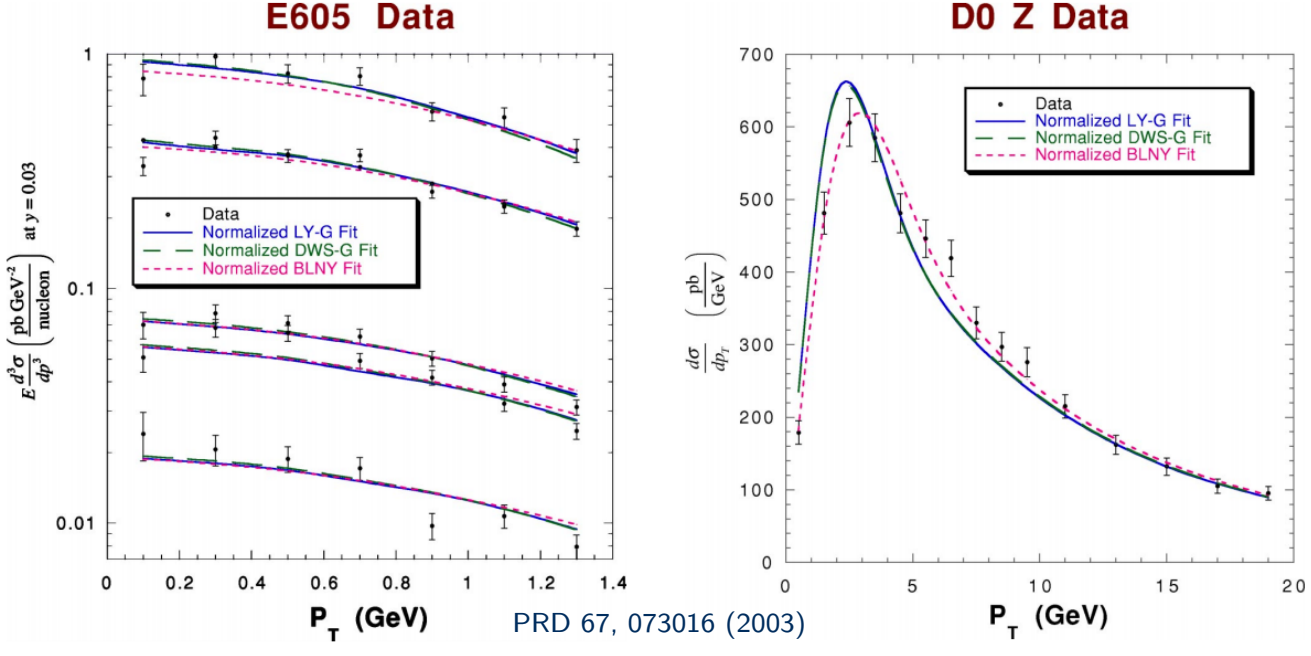
Y. Dokshitzer. Basics of Perturbative QCD, 1991

- The same underlying QCD phenomena at play - color leads to nonperturbative consequences

How can we search for effects from TMD color entanglement?

Collins-Soper-Sterman (CSS) Evolution with Q^2

- 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



PRD 67, 073016 (2003)

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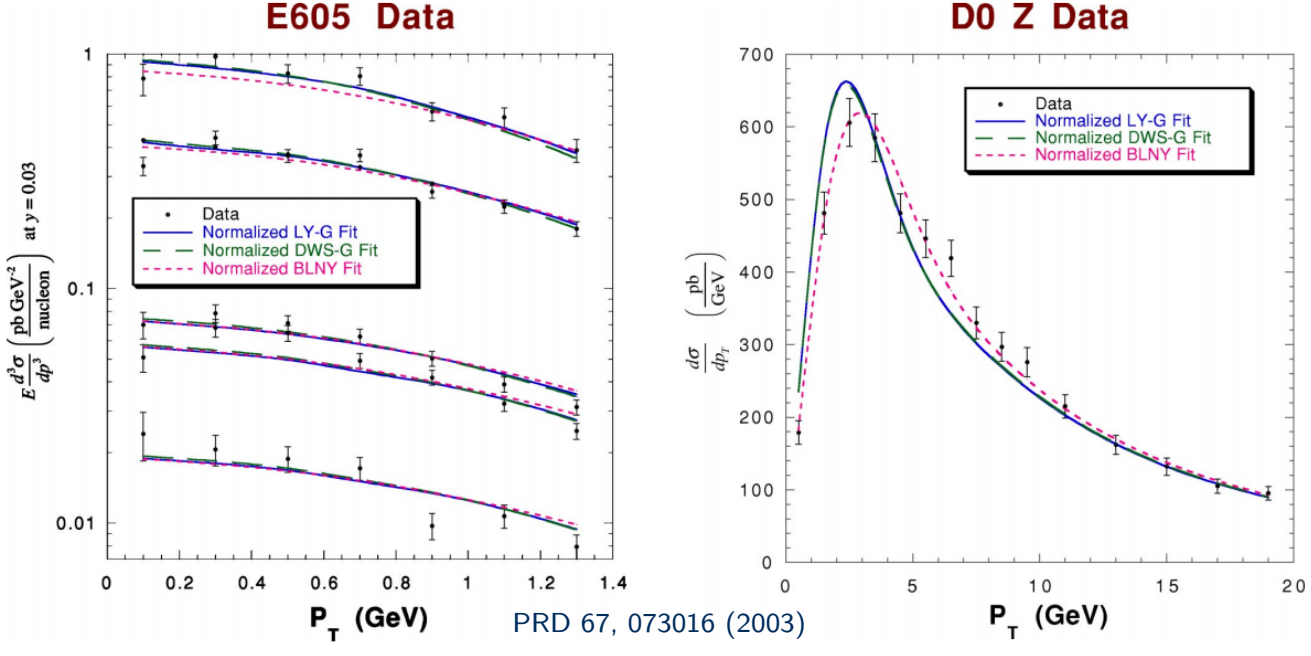
- Clear qualitative prediction - momentum widths sensitive to nonperturbative transverse momentum increase with increasing hard scale
- Due to increased phase space for gluon radiation



PRD 67, 073016 (2003)

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

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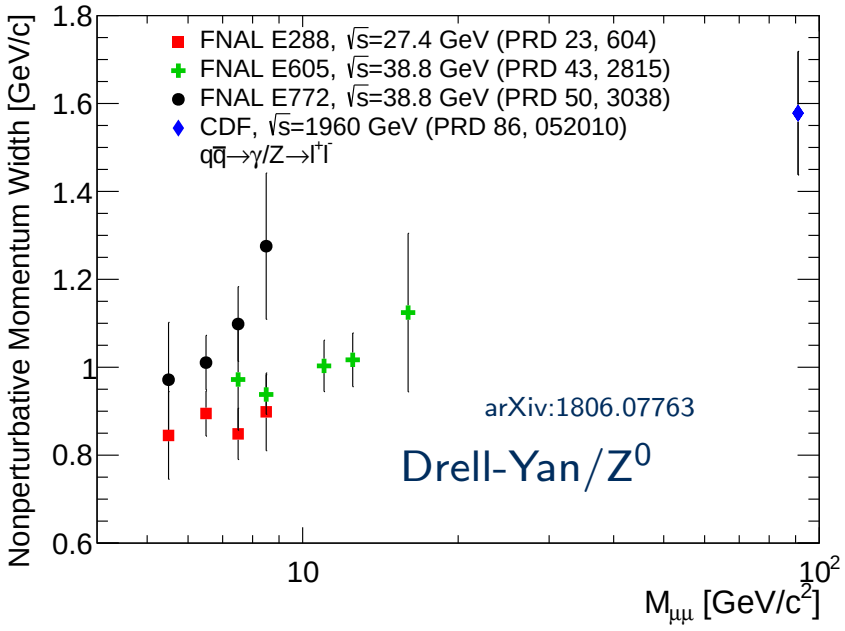

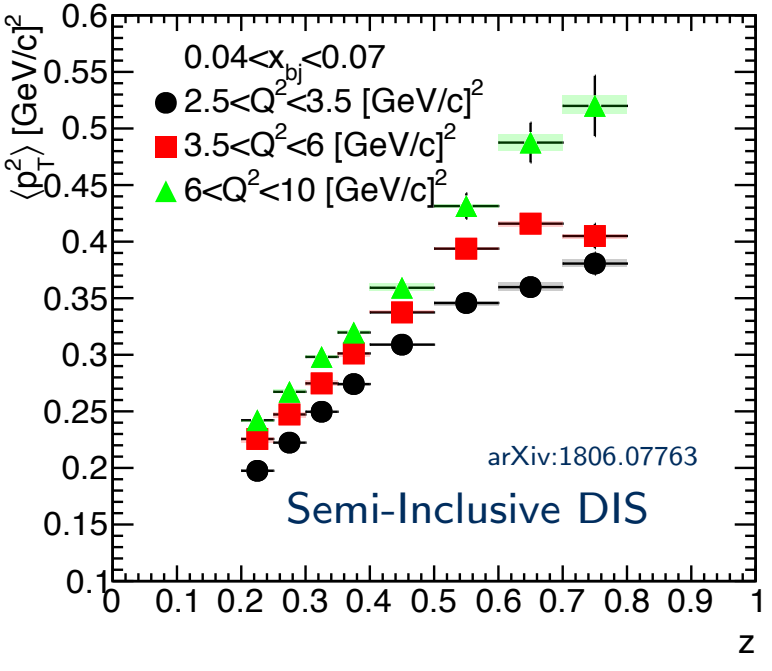

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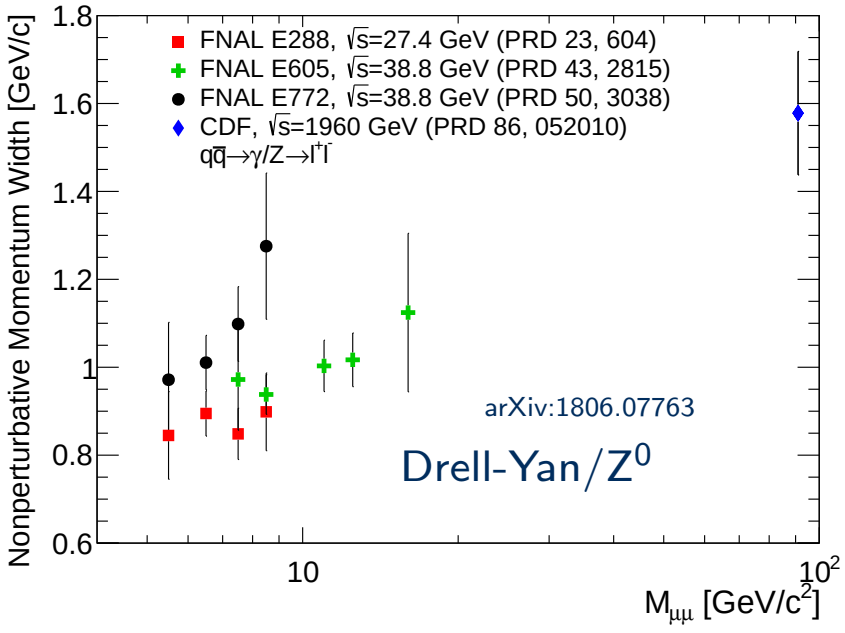

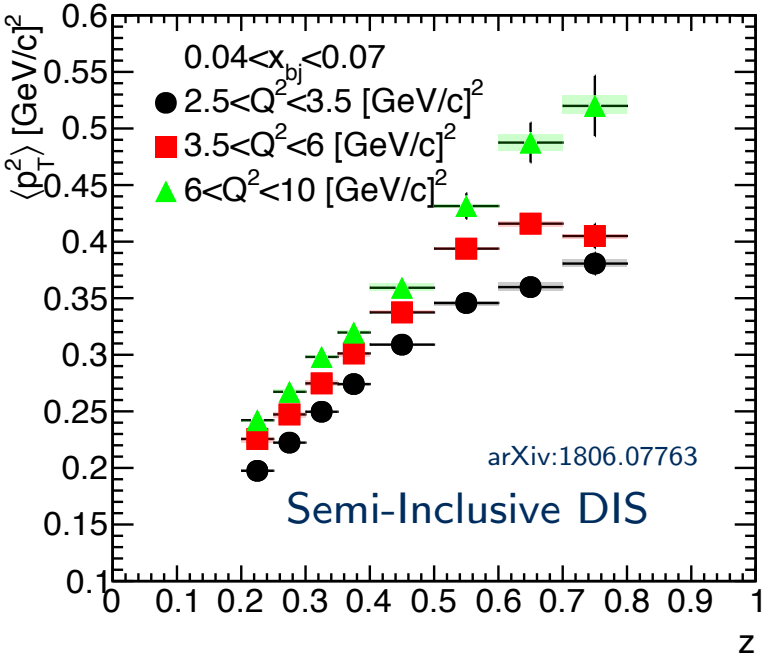

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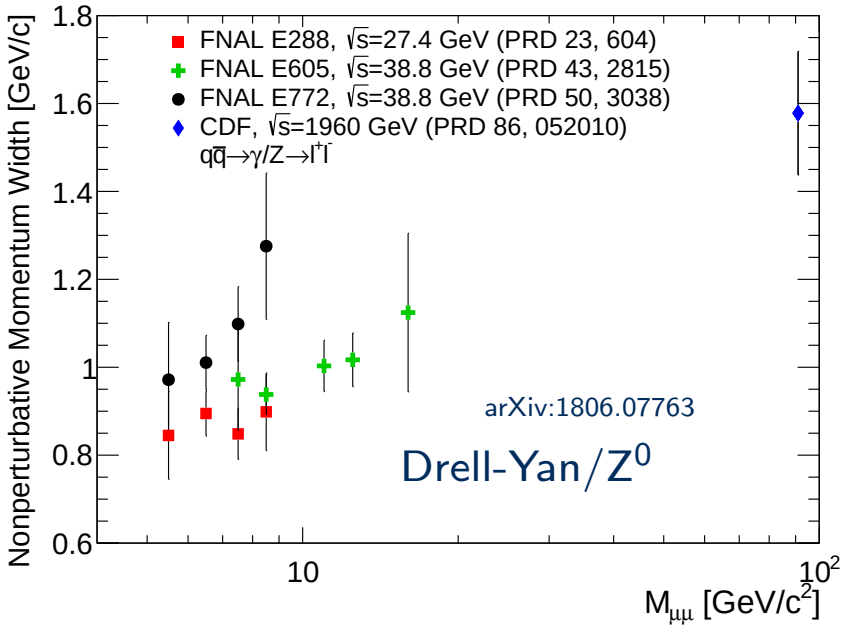
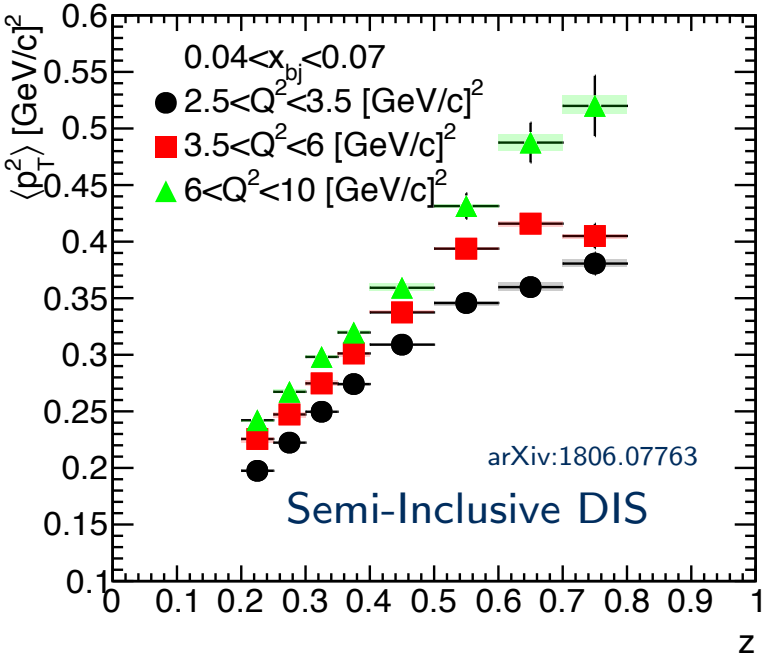
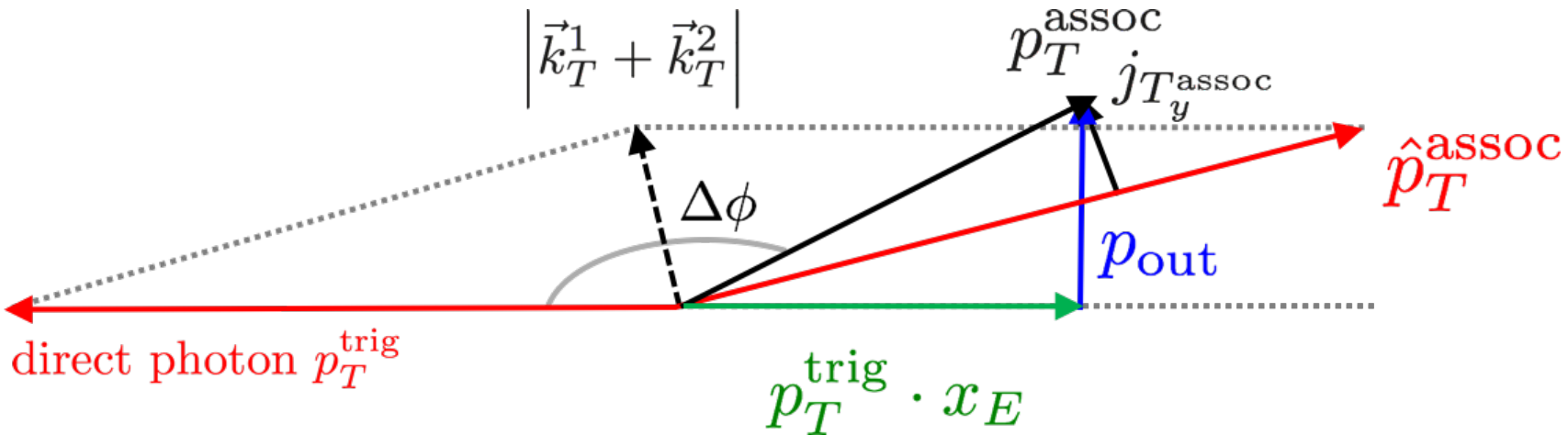
- The evolution prediction comes directly out of the derivation for transverse-momentum-dependent (TMD) factorization
  - If TMD factorization, then CSS evolution. If not CSS evolution, then not TMD factorization!



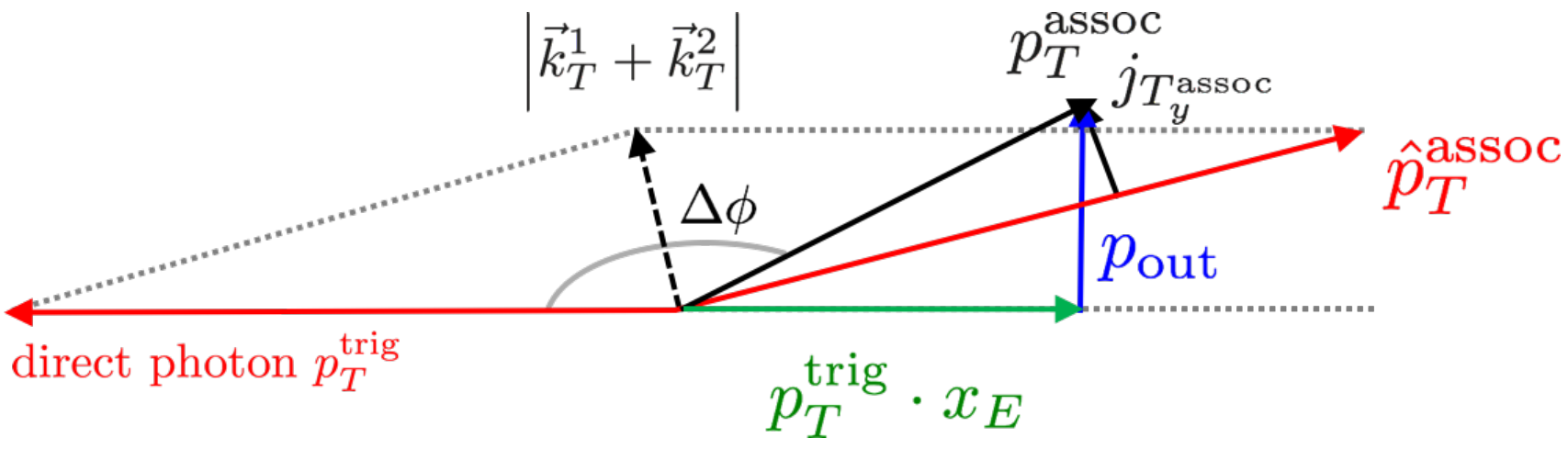


Observables To Probe Entanglement



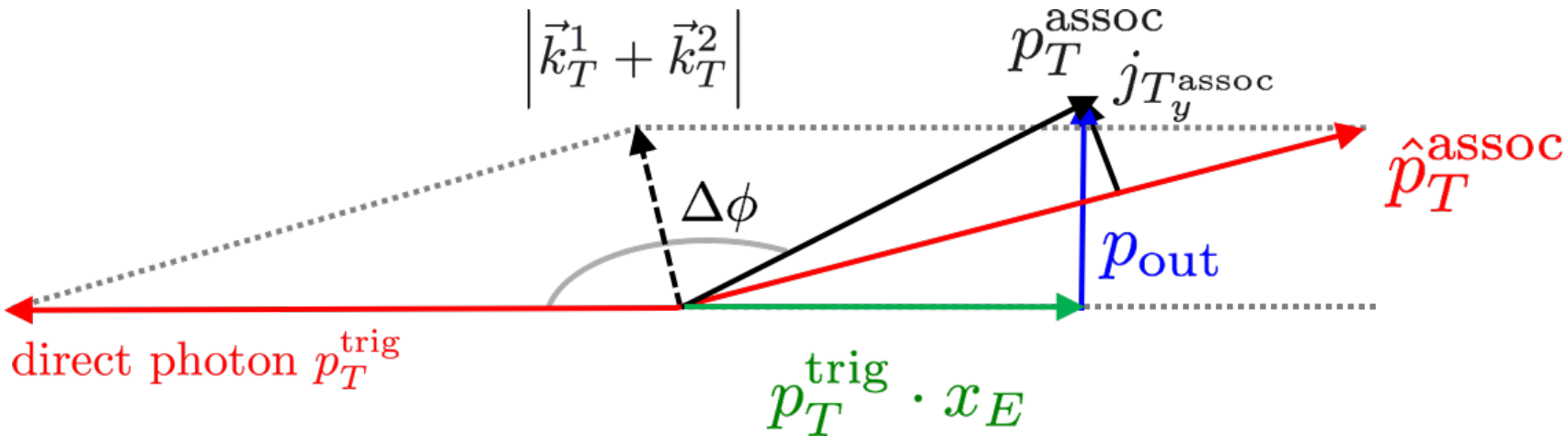
- To probe color entanglement effects, an observable must have color in the initial and final state

Observables To Probe Entanglement



- To probe color entanglement effects, an observable must have color in the initial and final state
  - Can use $p + p \to \gamma + \text{h}^{\pm} + X$ or $p + p \to \text{h}^{\pm} + \text{h}^{\pm} + X$

Observables To Probe Entanglement



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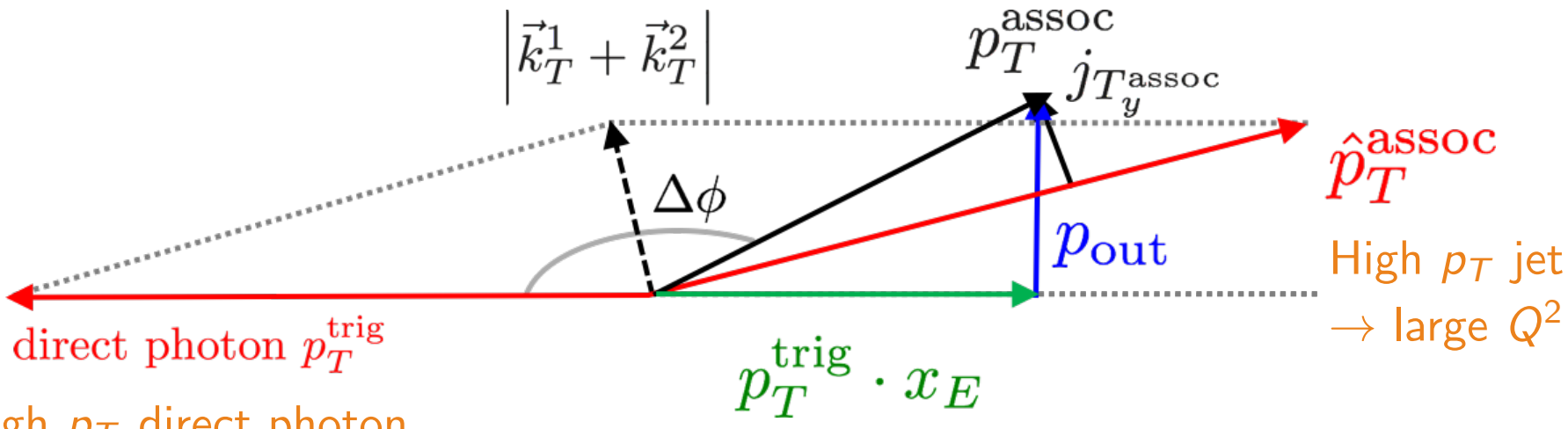

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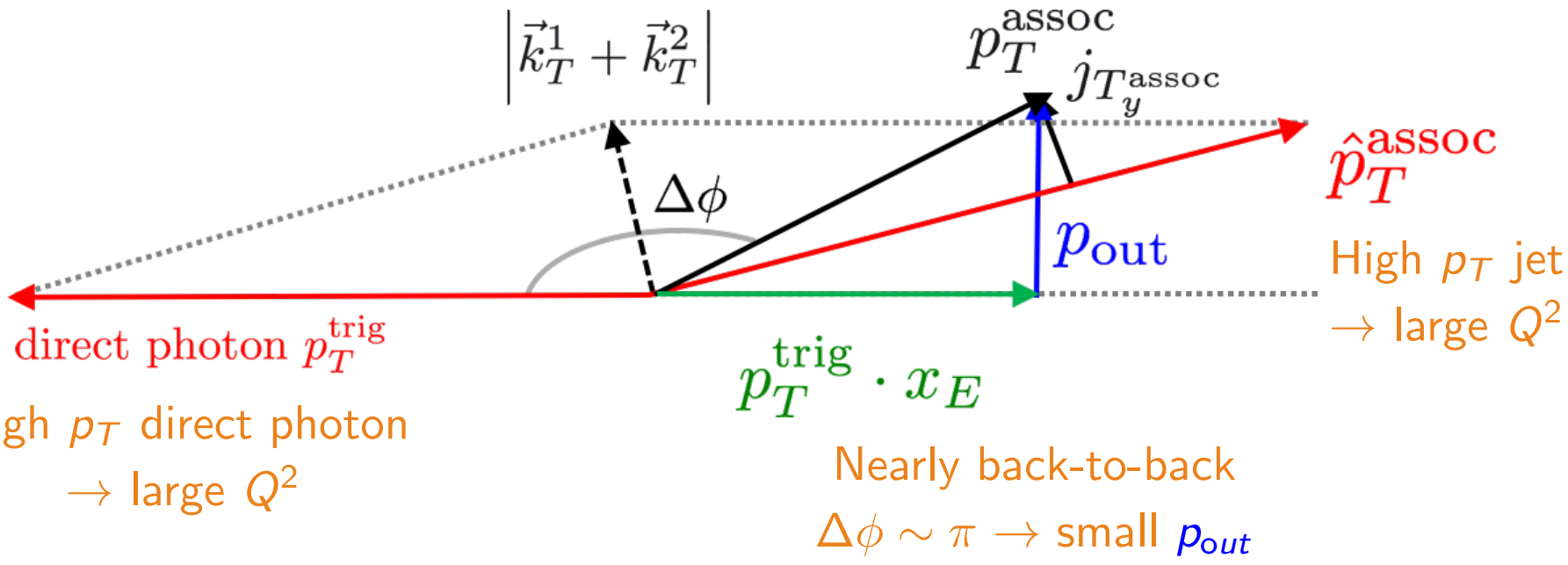

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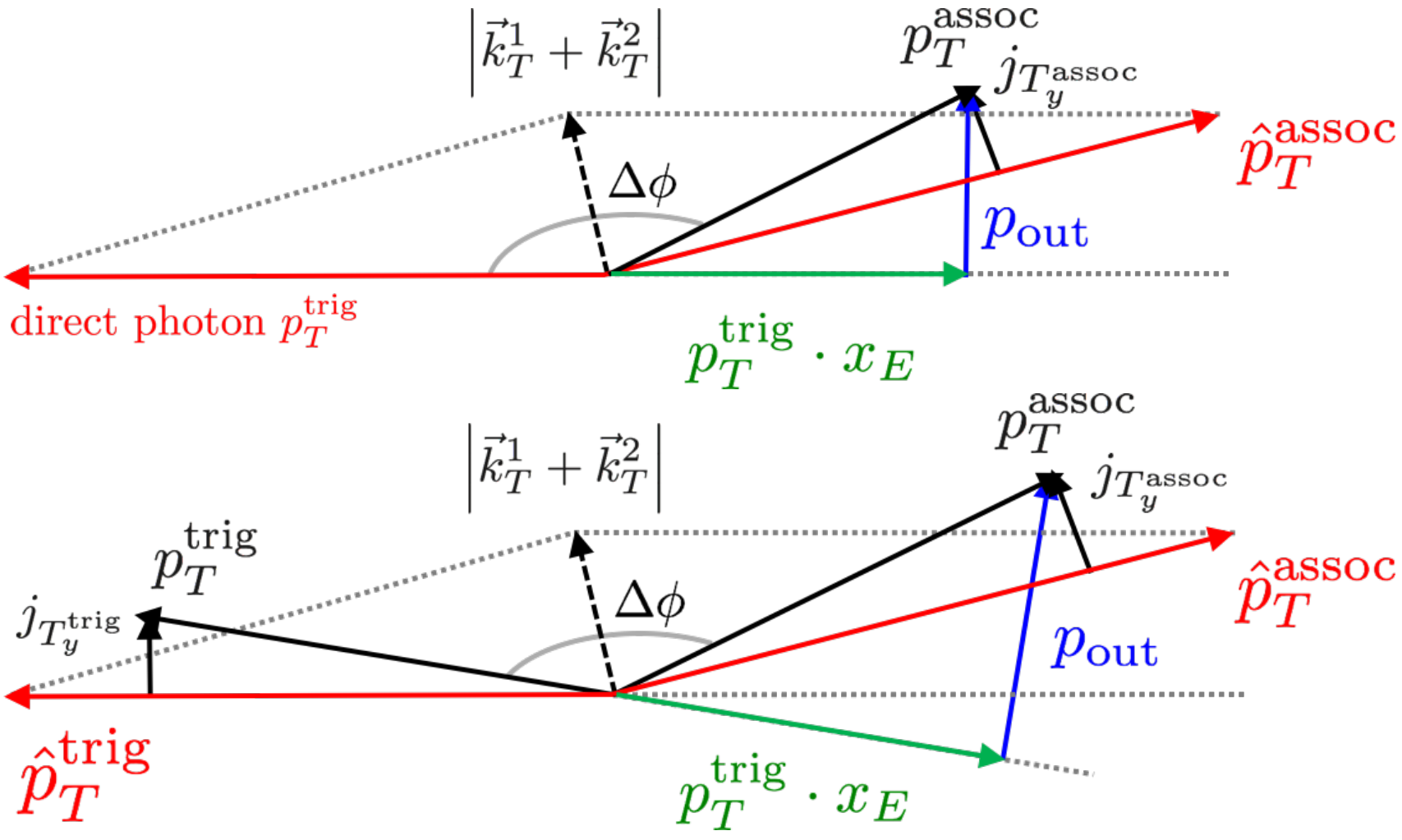
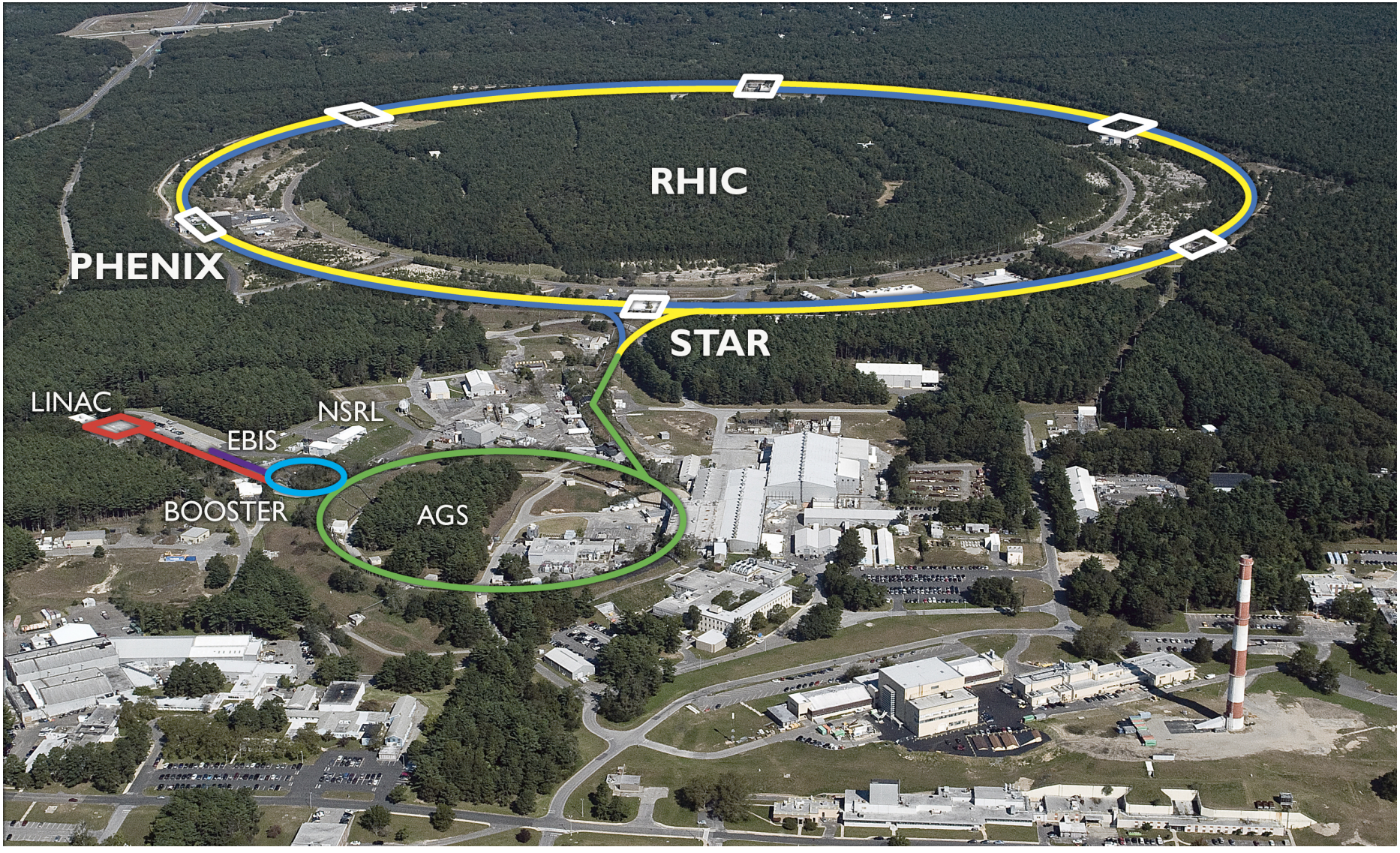


Relativistic Heavy Ion Collider - RHIC at Brookhaven National Laboratory



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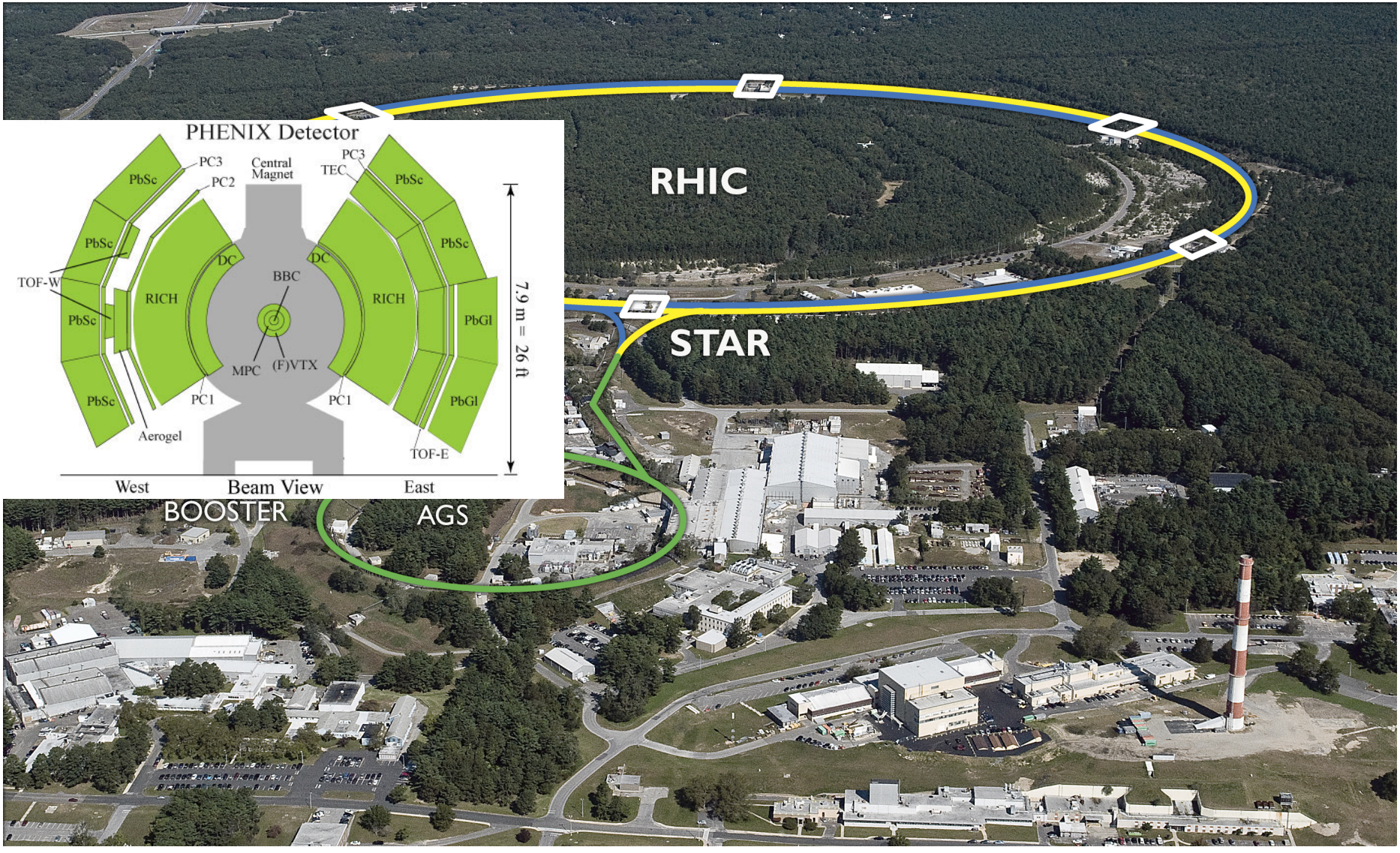
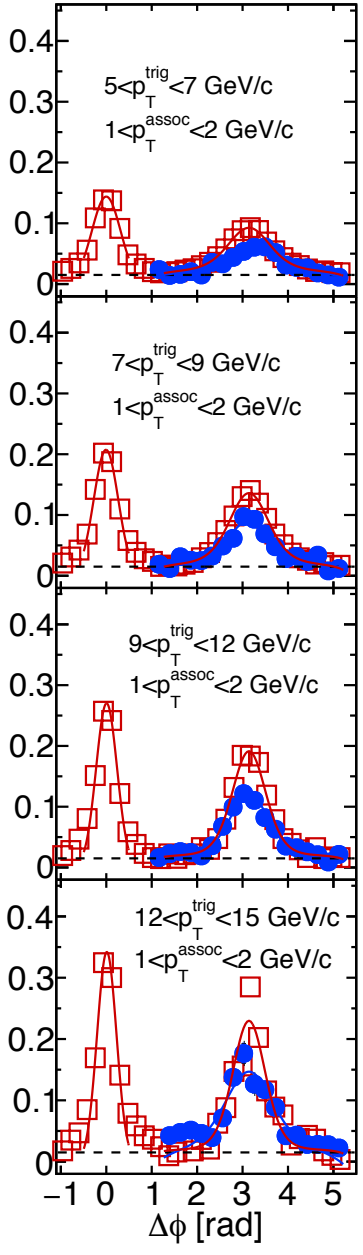


$\Delta\phi$ Correlations for $\pi^0 - h^{\pm}$ and Direct $\gamma - h^{\pm}$

$$\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi}\,[rad]^{-1}$$



arXiv:1805.02450

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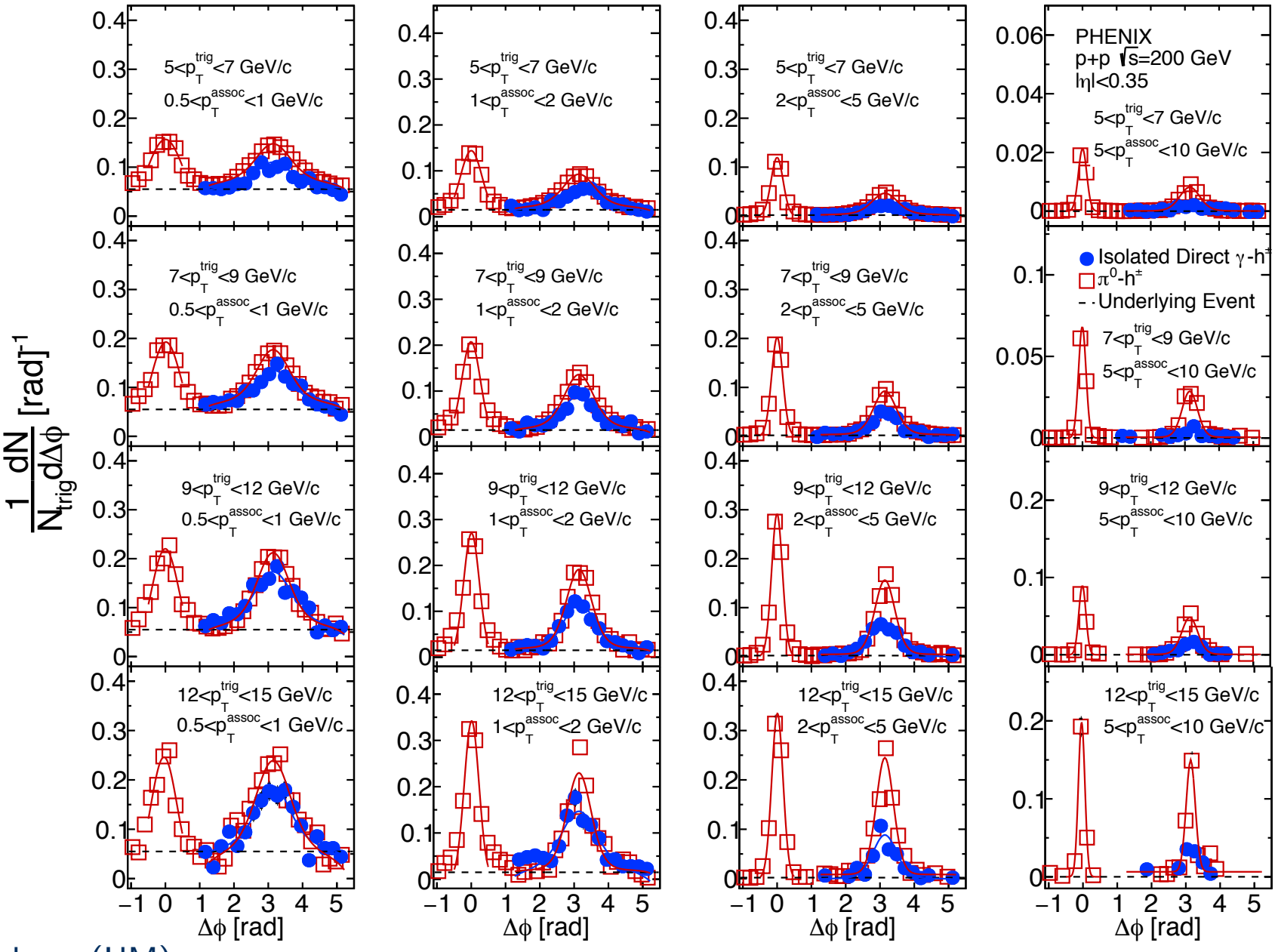
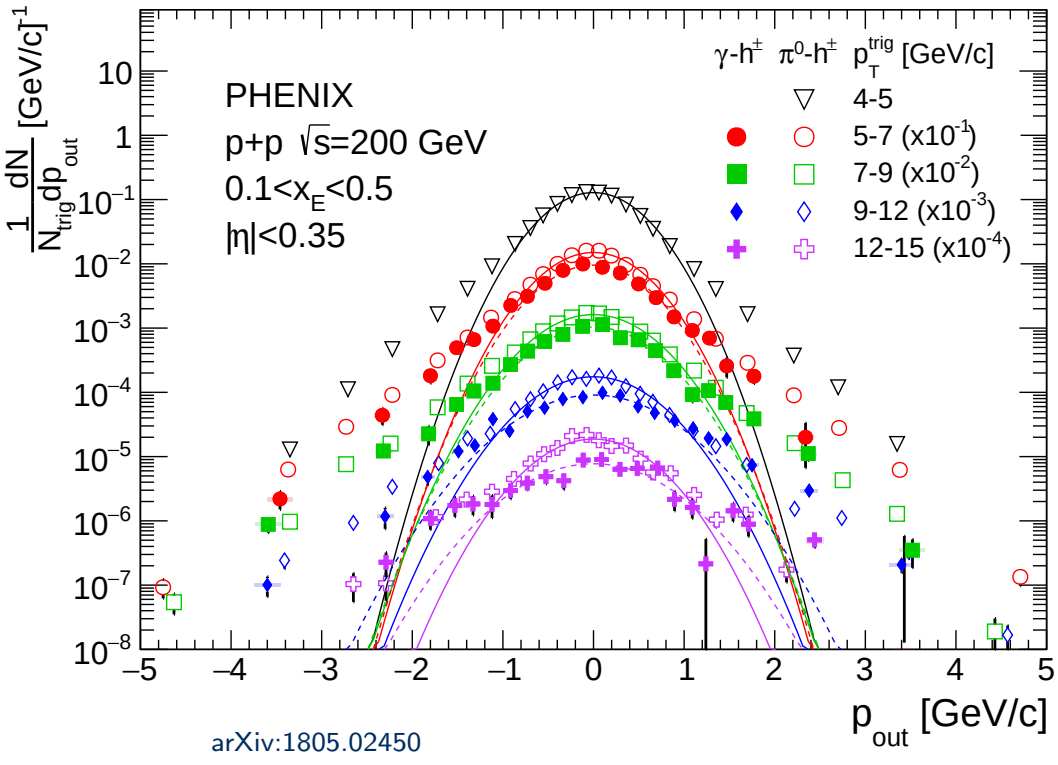


arXiv:1805.02450

Measurements of p_{out} Distributions in $p+p \rightarrow$ hadrons



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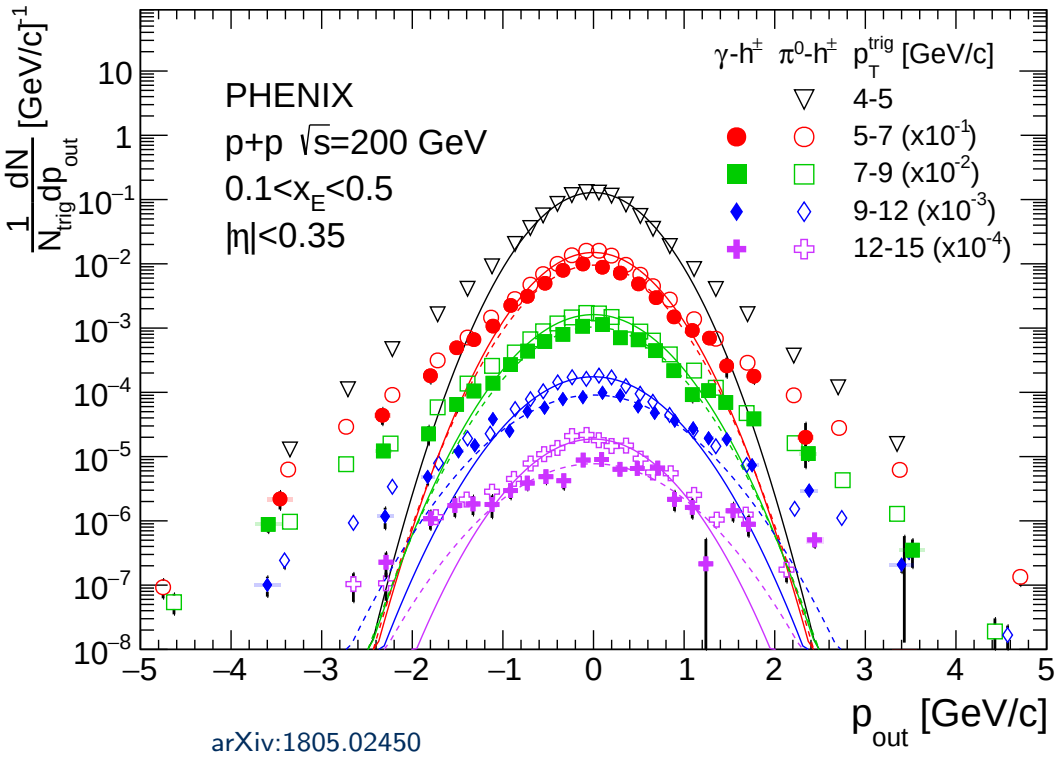

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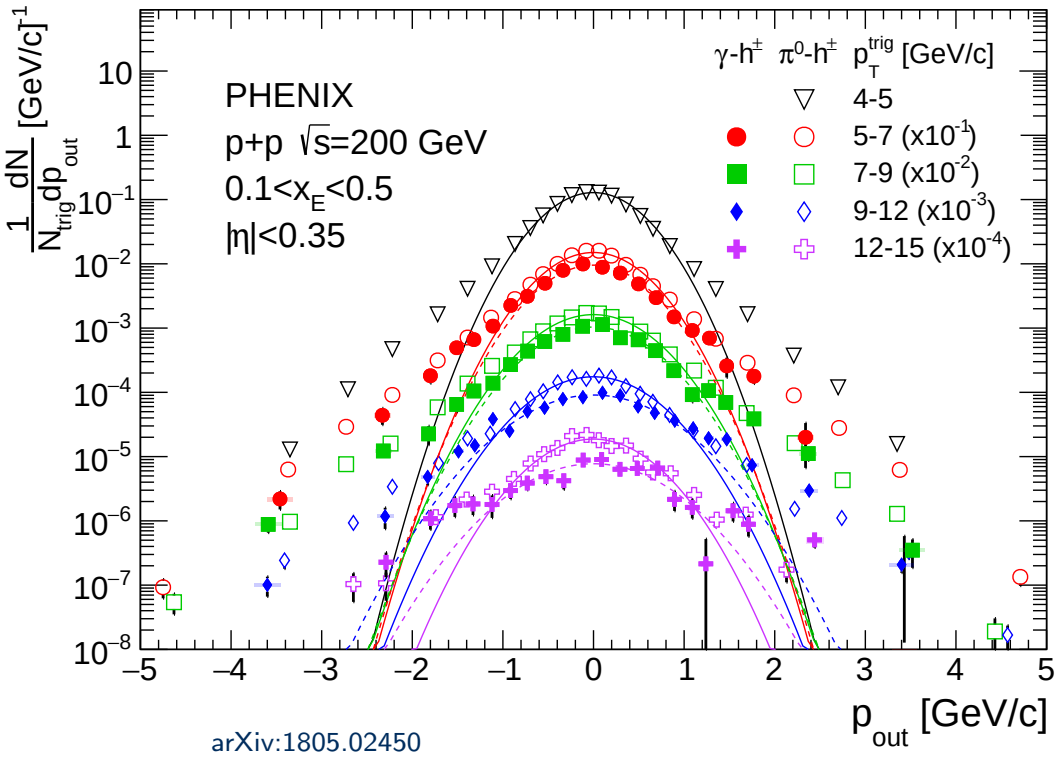
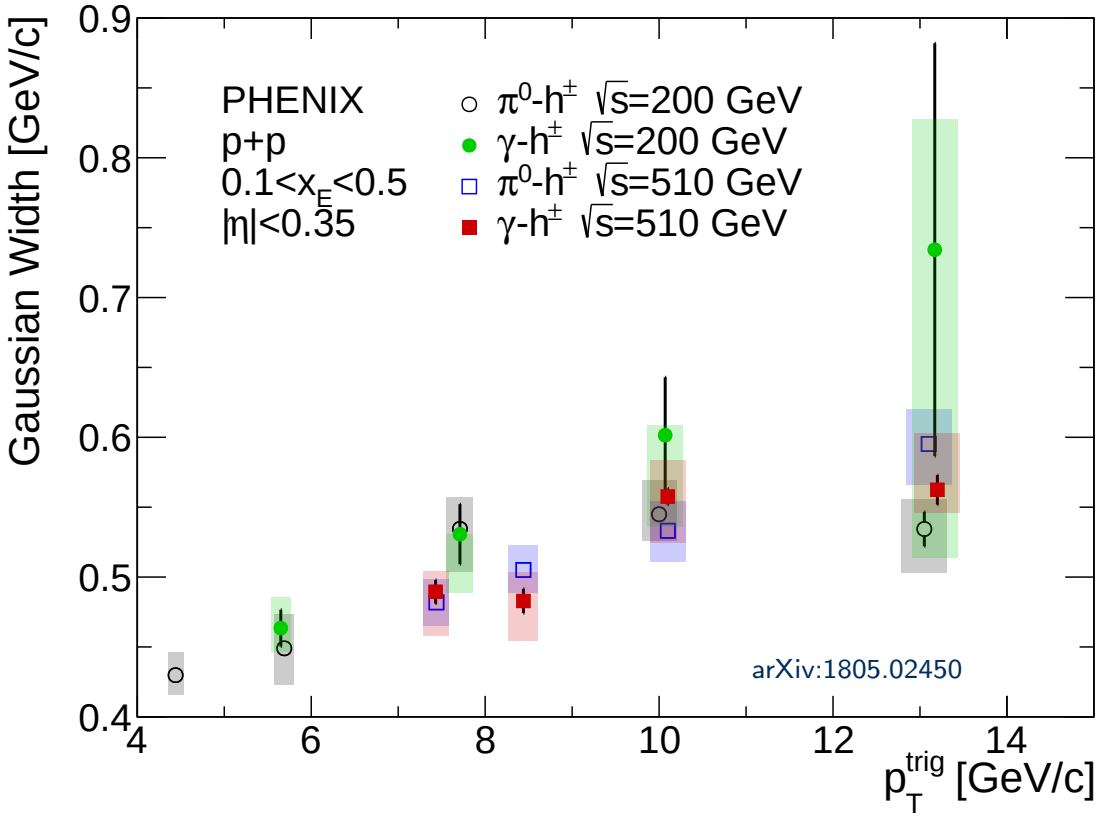


- Two distinct regions:
  - Gaussian at small p_{out}
  - Power law at large p_{out}
- Indicates TMD observable - $\Lambda_{QCD} \lesssim p_{out} \ll p_T^{\text{trig}}$
- Can characterize any potential color effects by studying width evolution as a function of p_T^{trig}

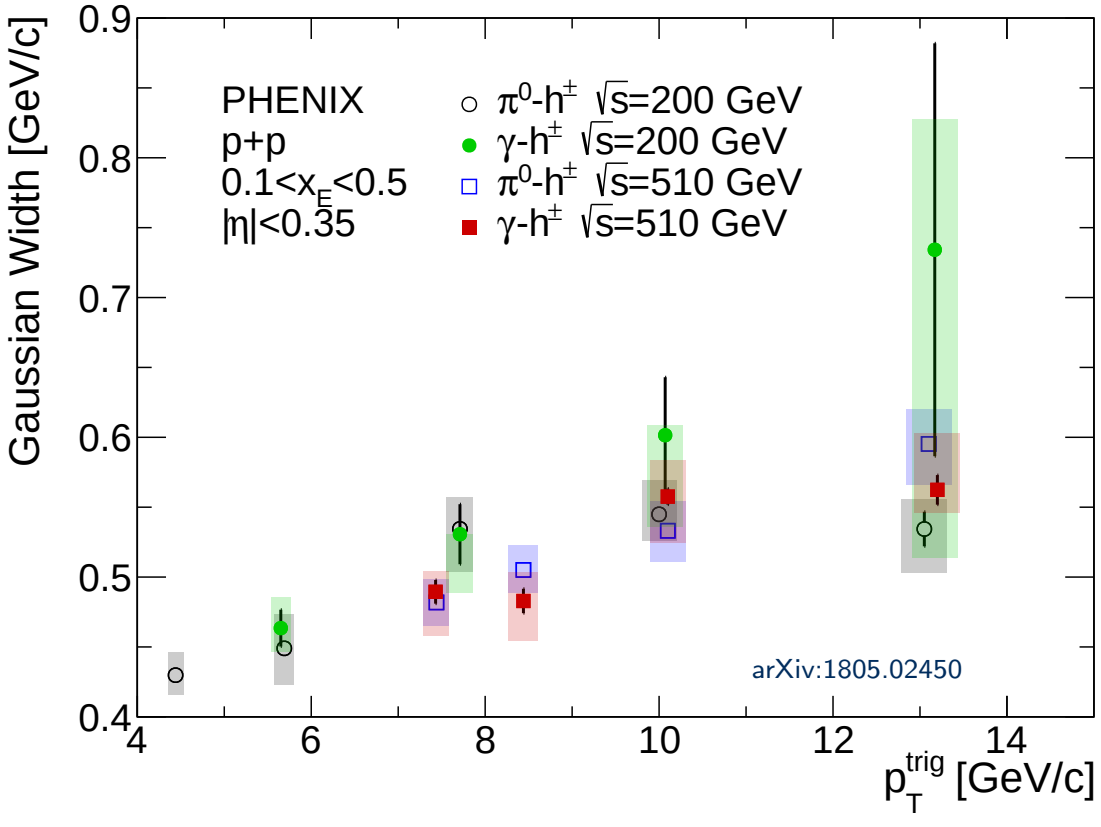
Gaussian Width of p_{out} Evolution in p+$p \rightarrow$ hadrons

- Away-side Gaussian widths shown as a function of p_T^{trig} at $\sqrt{s} = 200$ and 510 GeV



Gaussian Width of p_{out} Evolution in $p+p \rightarrow$ hadrons

- Away-side Gaussian widths shown as a function of p_T^{trig} at $\sqrt{s} = 200$ and 510 GeV
- Qualitatively similar behavior to Drell-Yan and semi-inclusive DIS interactions where color entanglement is not predicted



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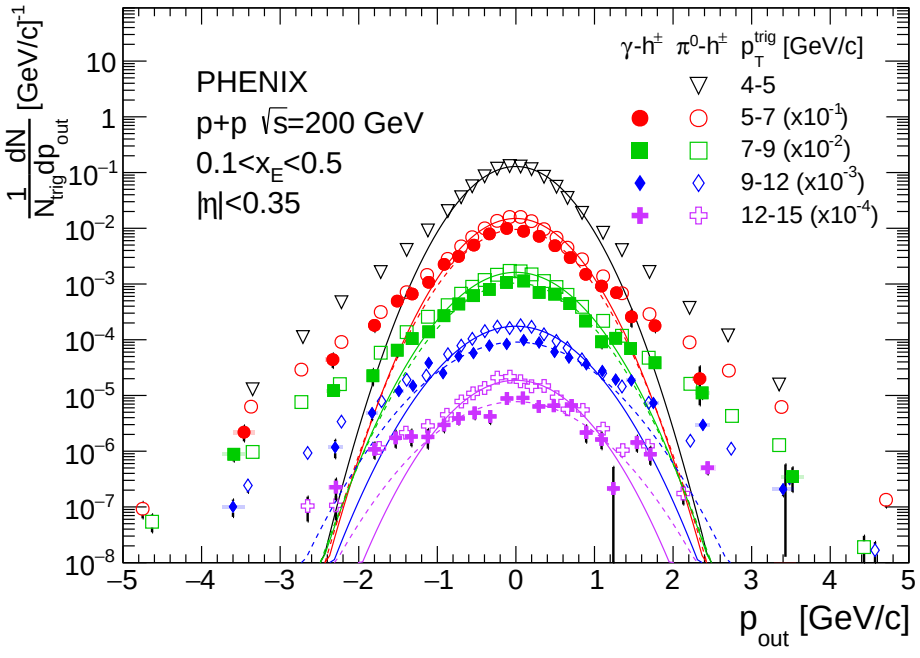

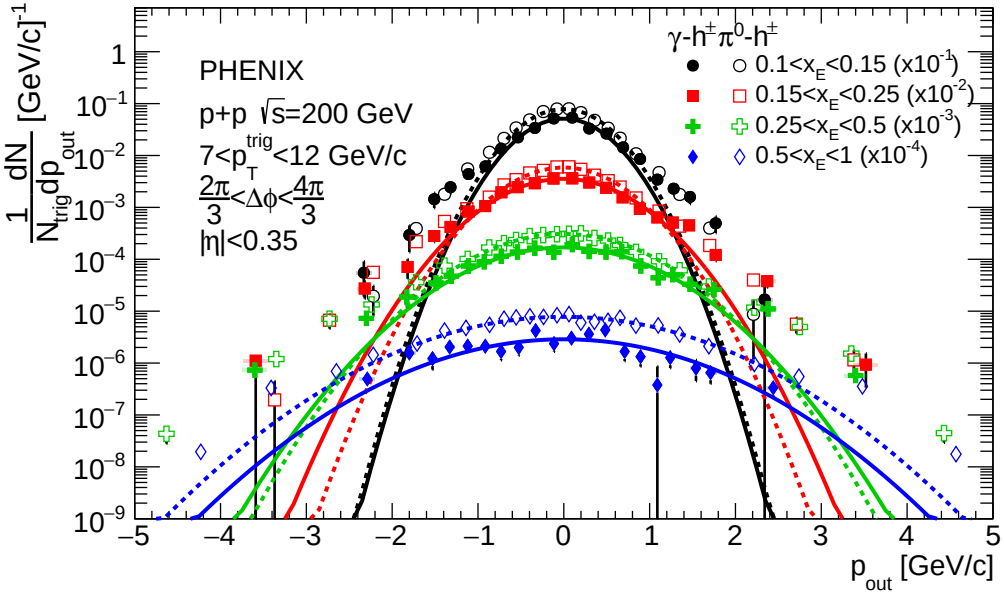

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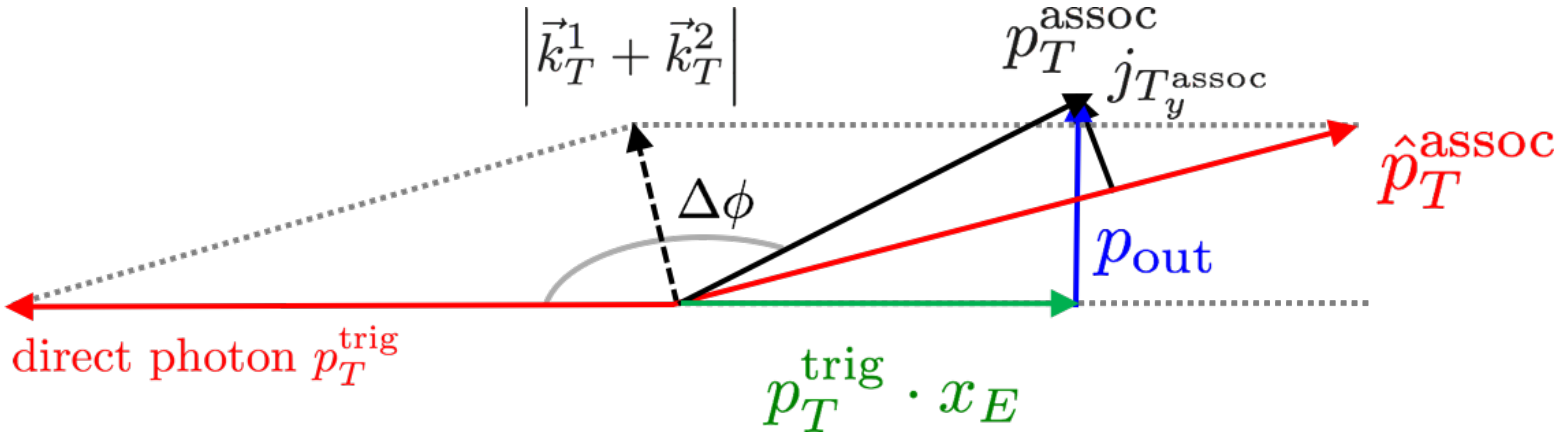
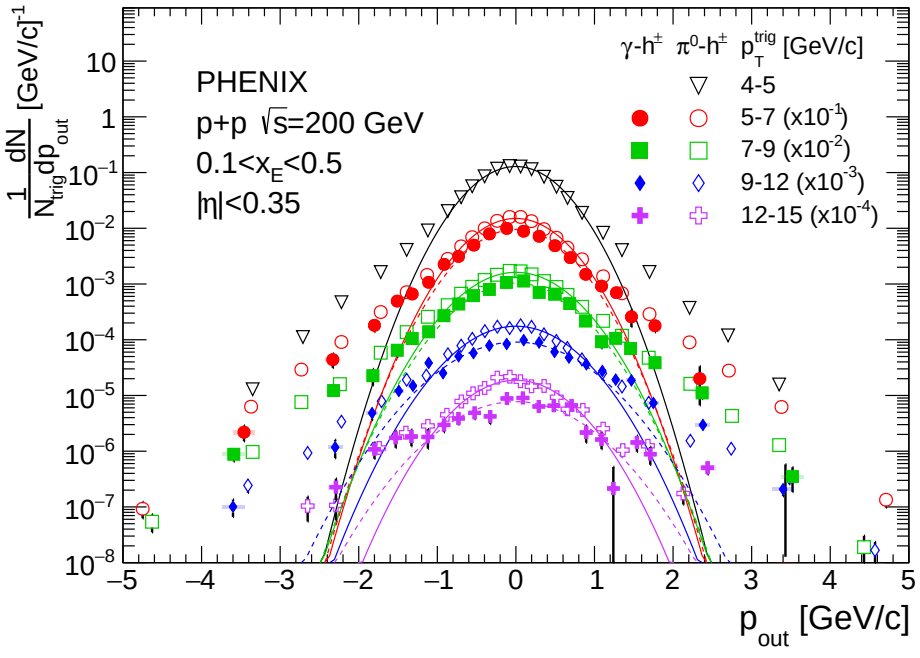
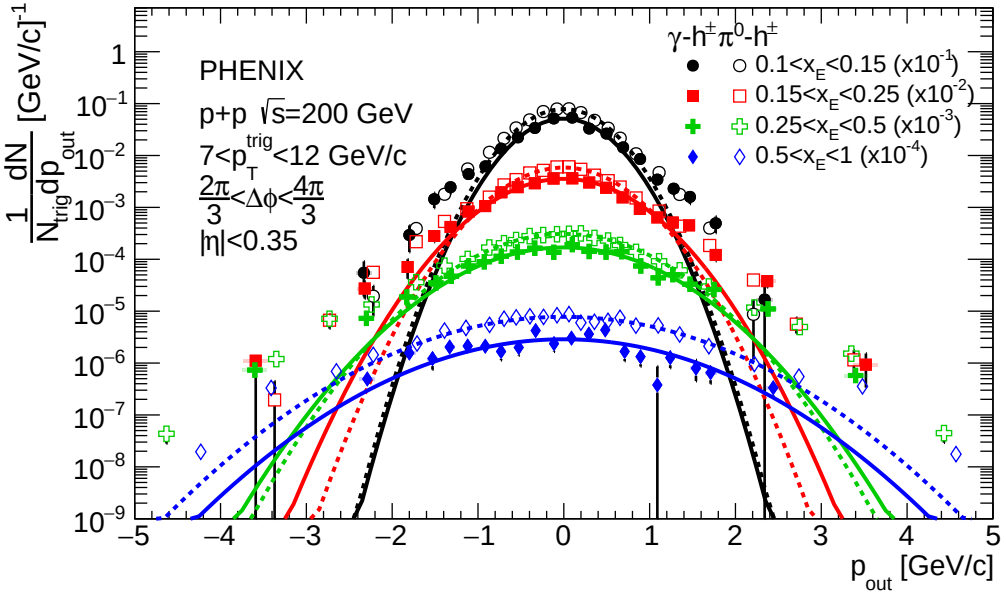


Measurements of p_{out} Distributions in $p+p \rightarrow$ hadrons



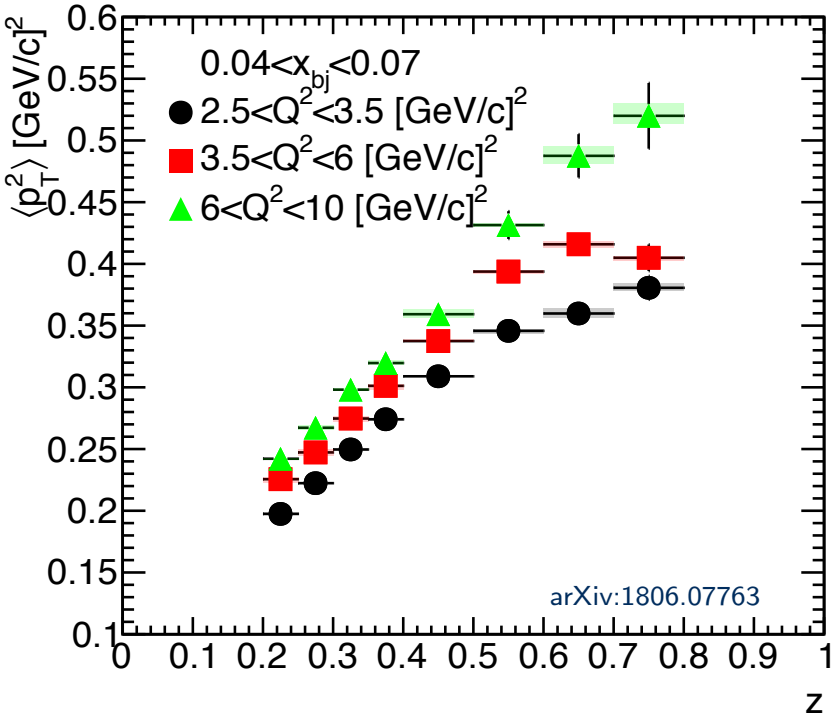


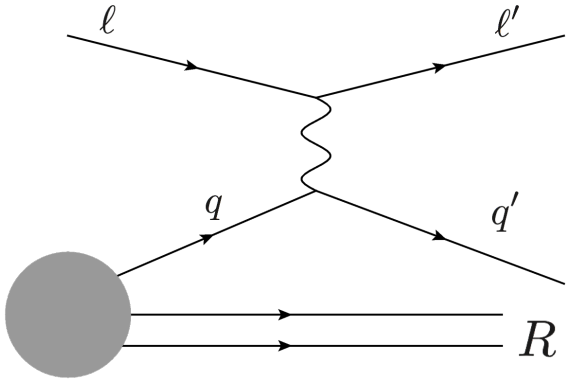
arXiv:1805.02450

- Measure p_{out} as a function of p_T^{trig} or x_E
- Multidifferential precision QCD measurements!

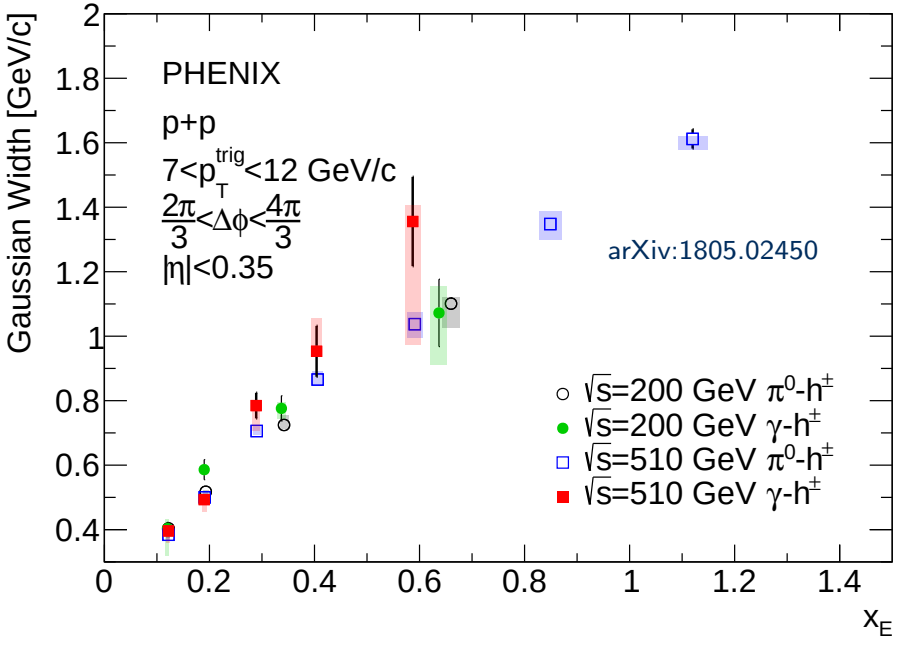
Comparing SIDIS and $p+p \rightarrow$ hadrons

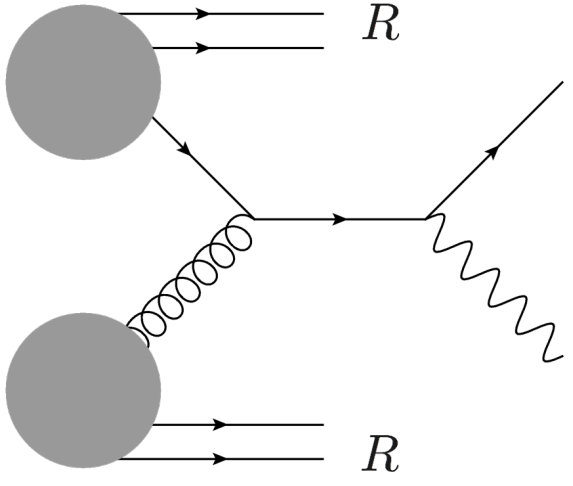
SIDIS





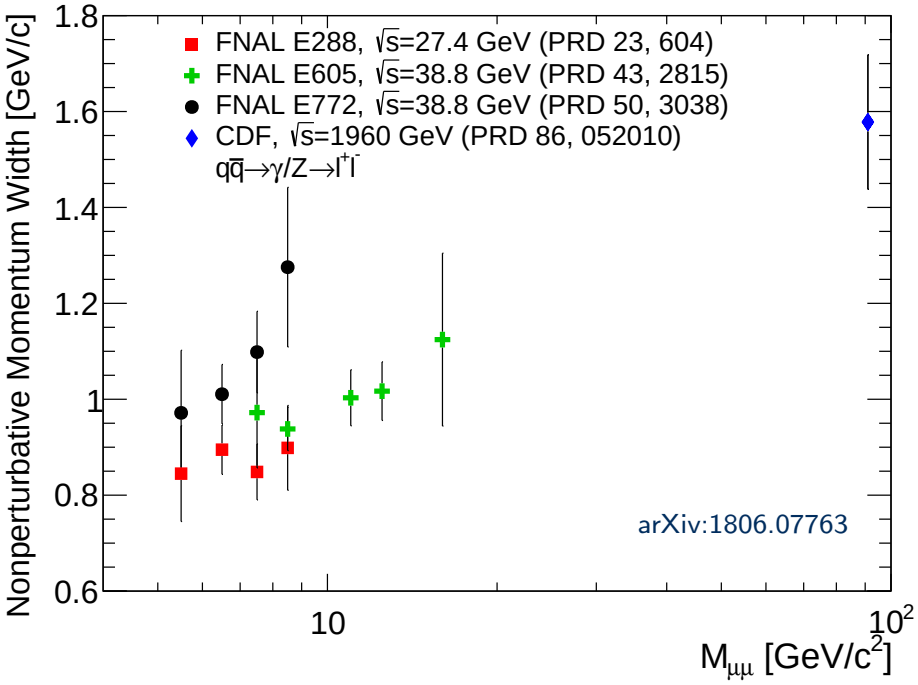
$p+p \rightarrow$ hadrons

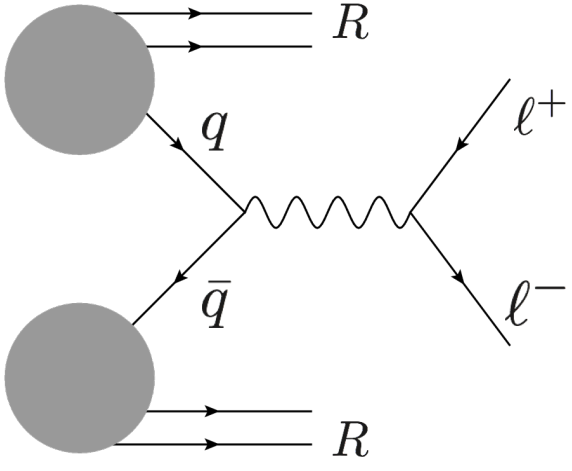




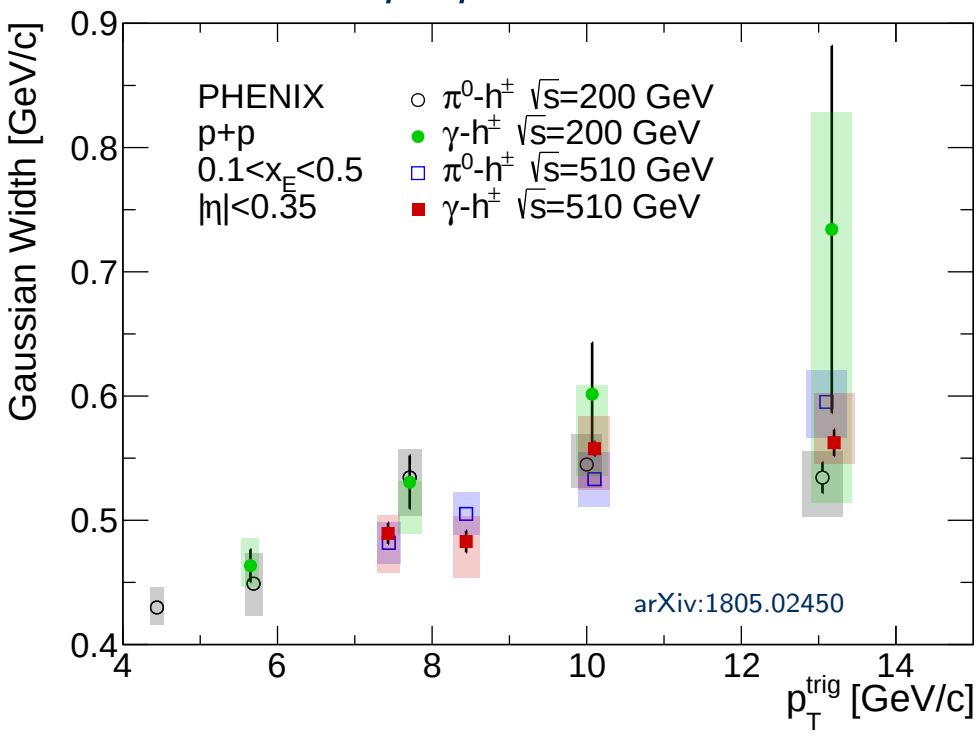
Comparing Drell-Yan and $p+p \rightarrow$ hadrons

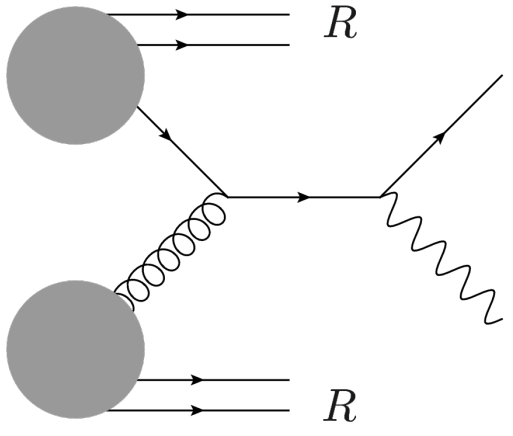
Drell-Yan





$p+p \rightarrow$ hadrons





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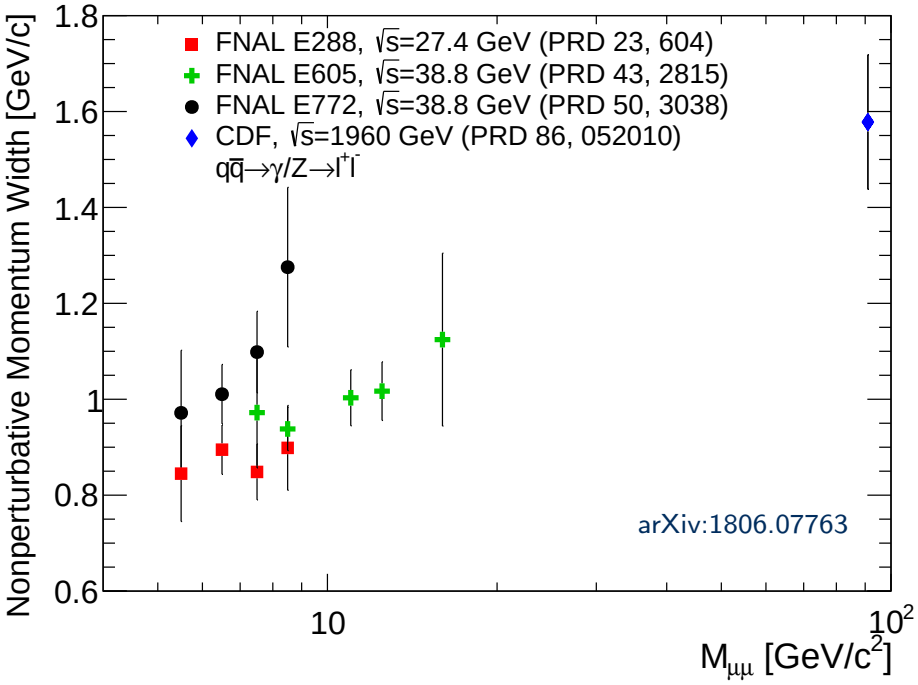
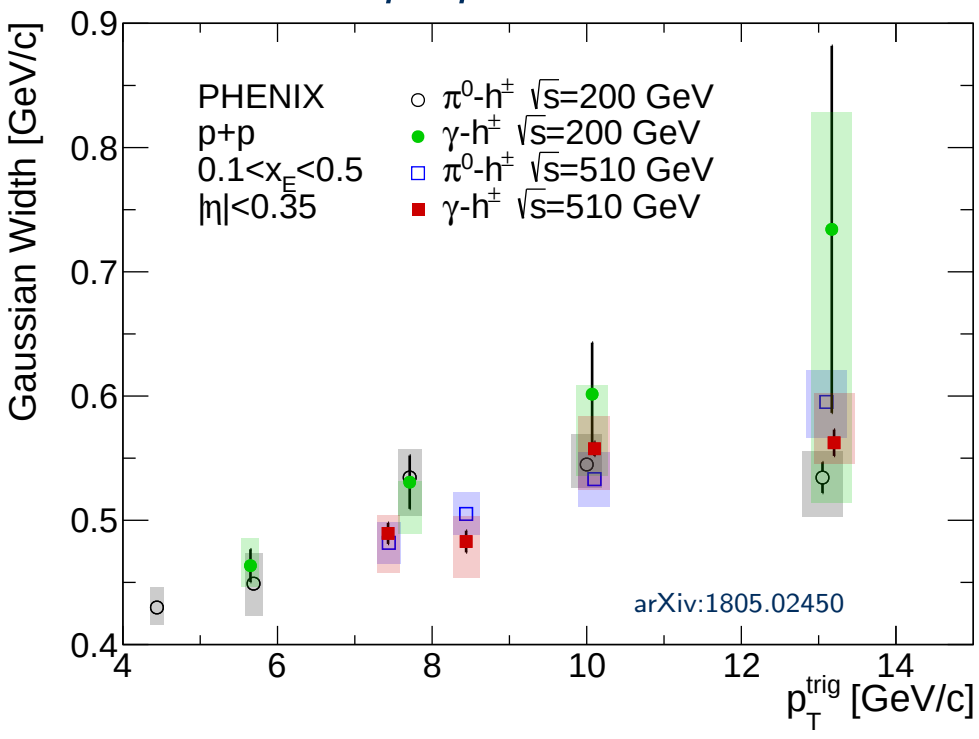


$p+p \rightarrow$ hadrons

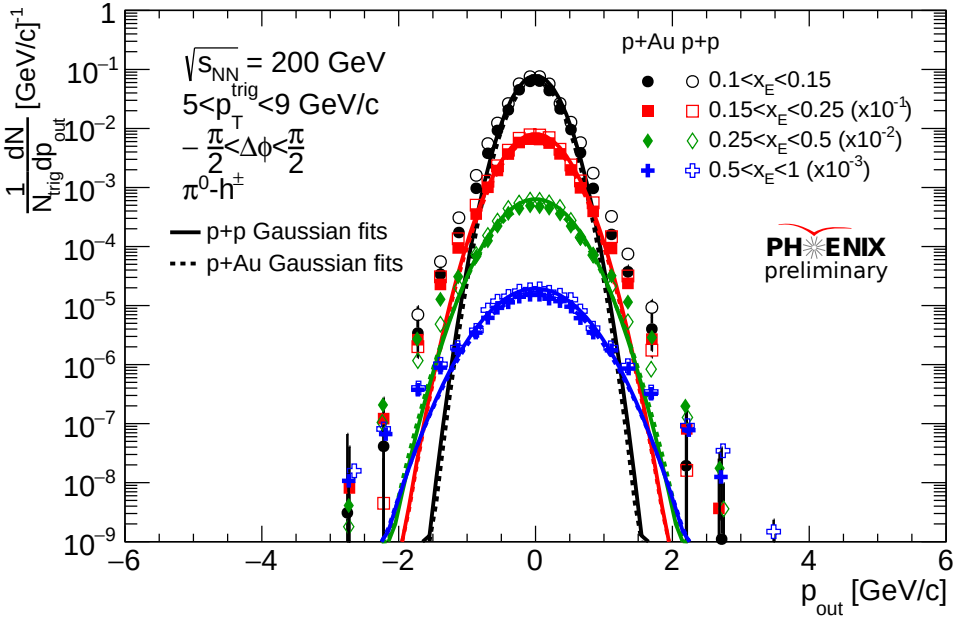


- Since qualitative behavior is similar, calculations needed to compare transverse-momentum-dependent evolution rates in different processes
- Drell-Yan/SIDIS (no color entanglement predicted) and $p+p \rightarrow$ hadrons (color entanglement predicted) may exhibit different magnitudes, evolution rates, etc.

What about proton-nucleus collisions, where there can be more QCD interactions?

Extending Color Studies to p+A

- Dihadrons give additional QCD interactions in p+A collisions compared to direct photon-hadrons
- Measure the p_{out} distributions on both the near-side and away-side in p+p and p+A to compare



Near-side

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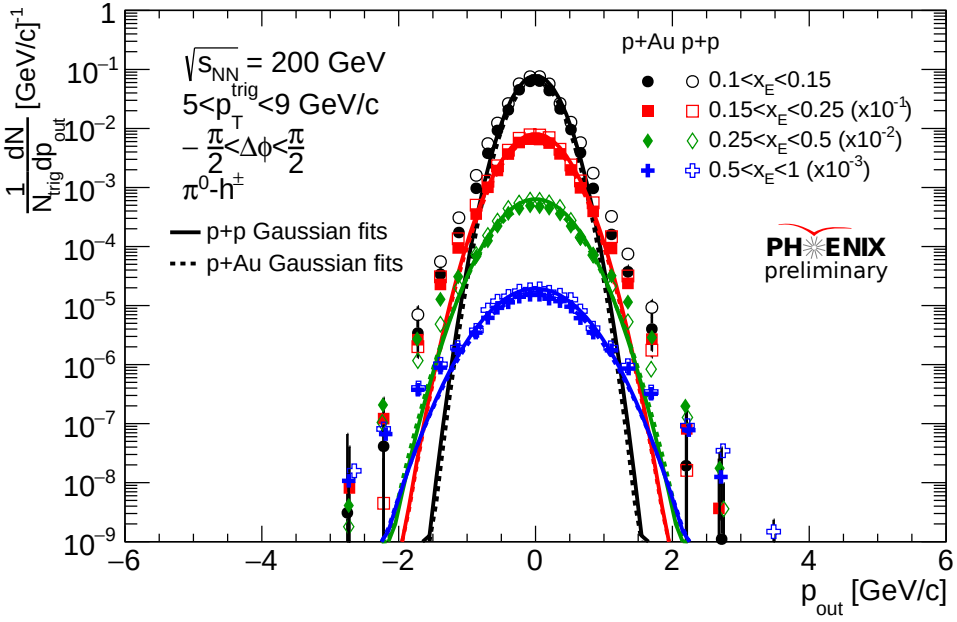
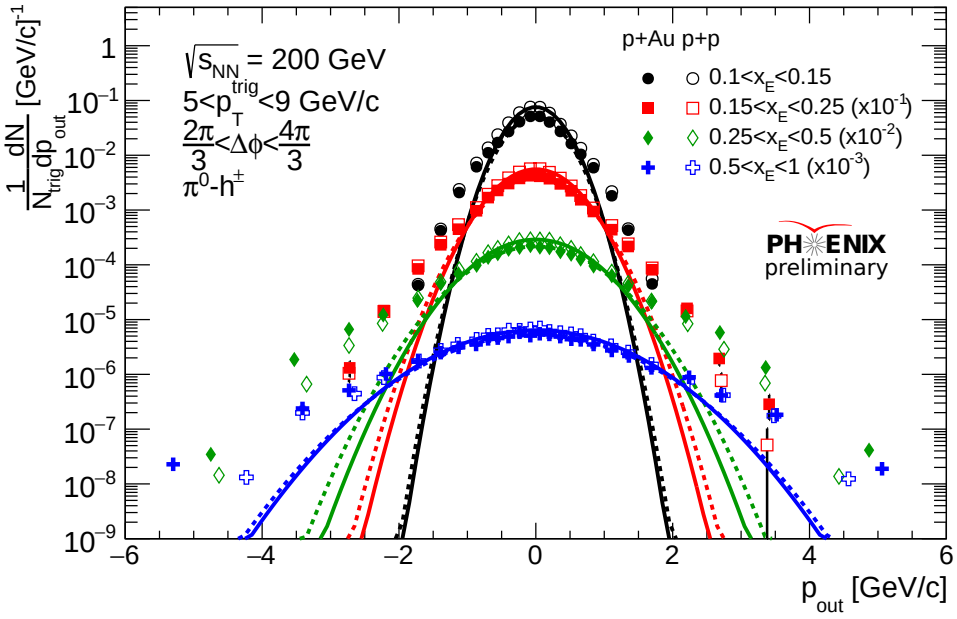
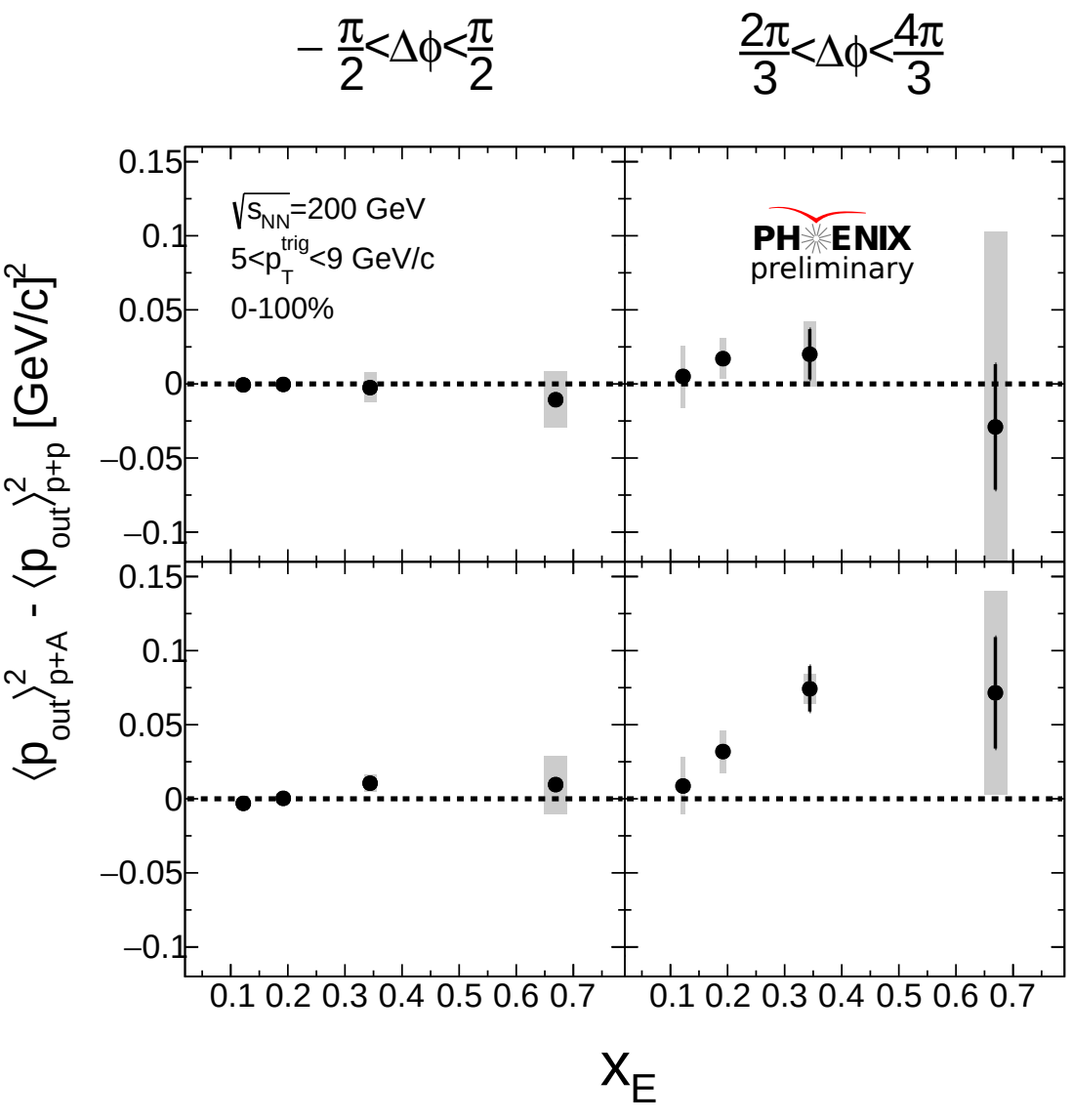


Near-side



Far-side

Nonperturbative Transverse Momentum Broadening in p+A



- Measure squared Gaussian width in p+A minus p+p

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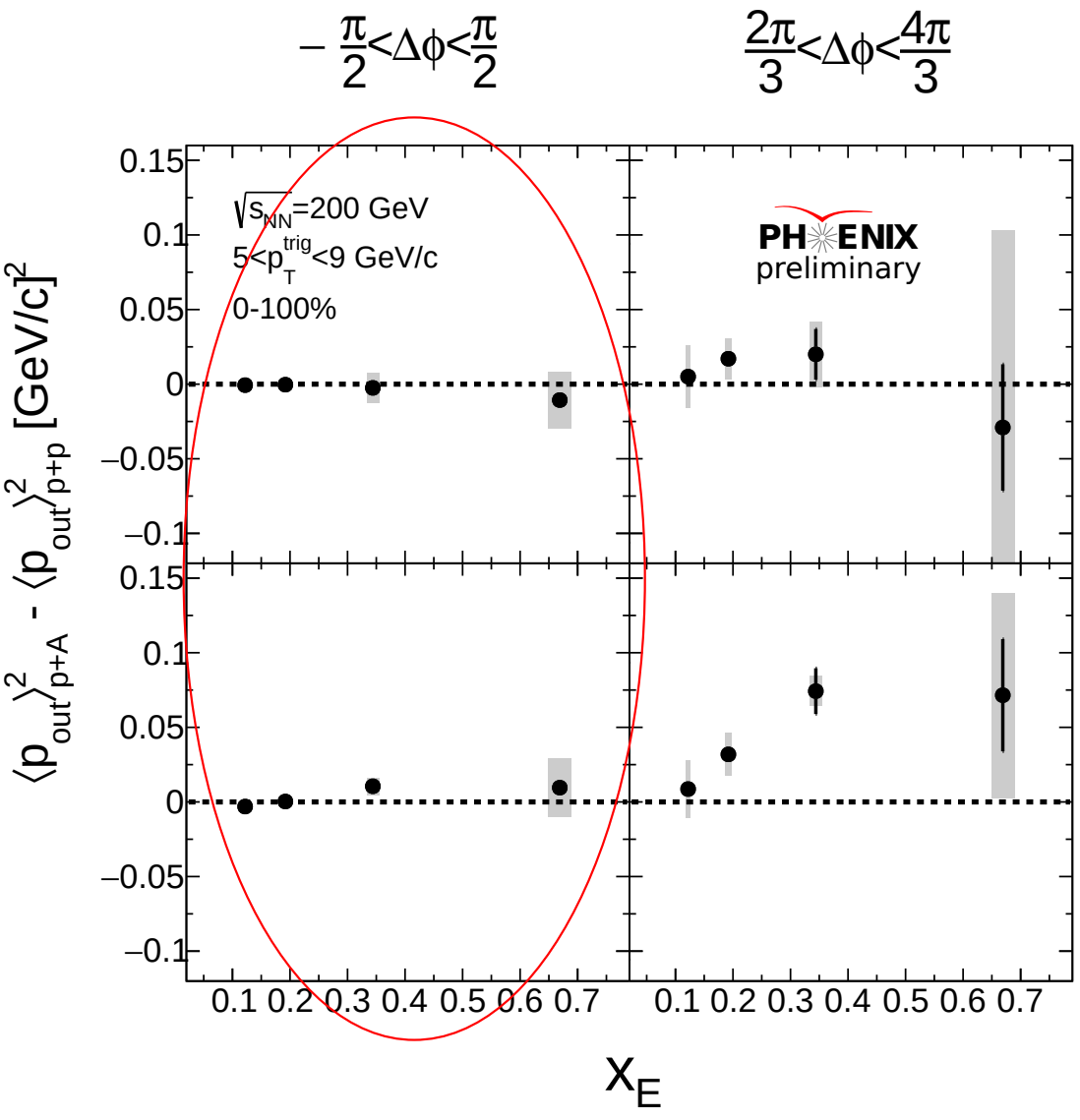

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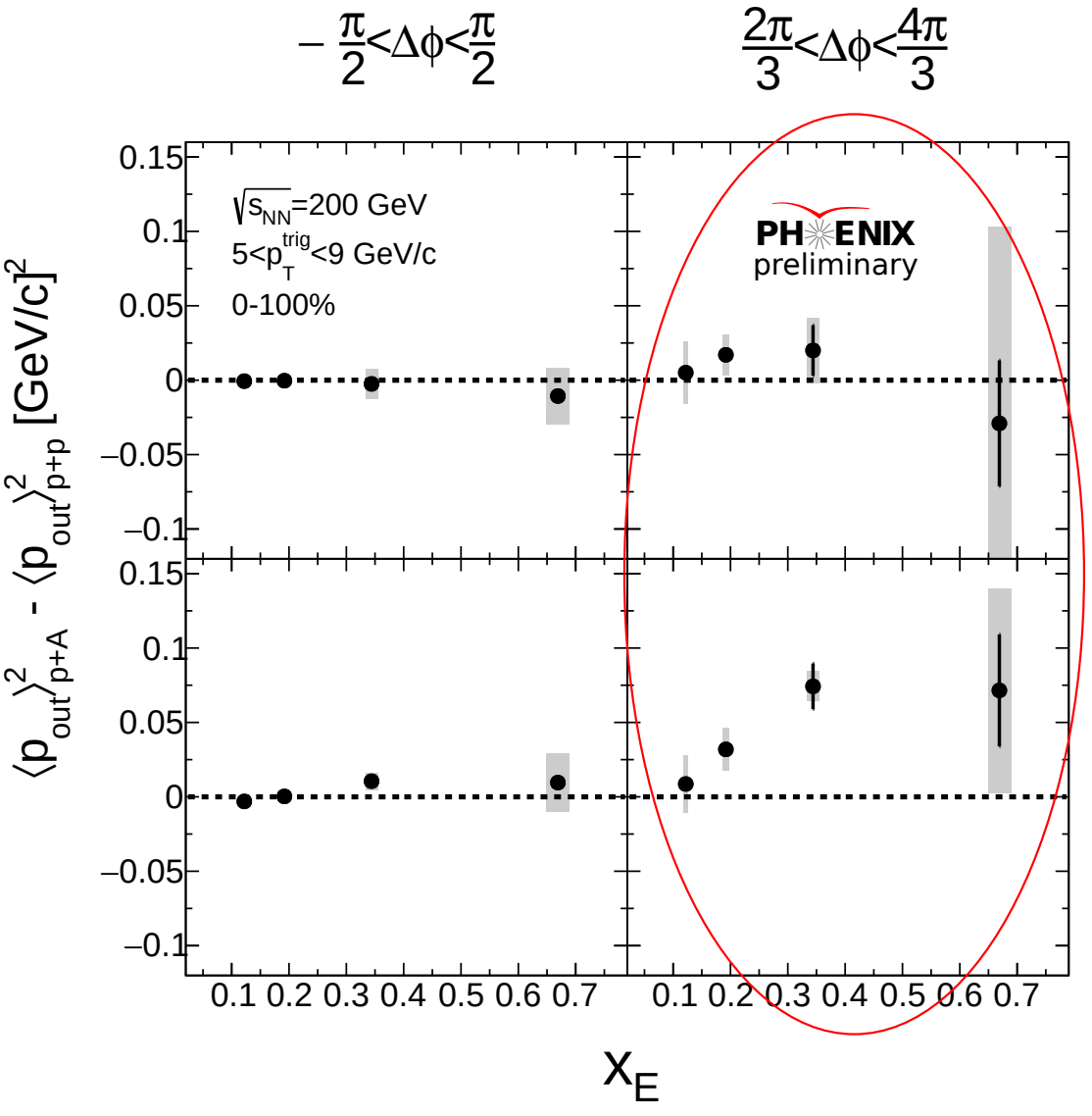
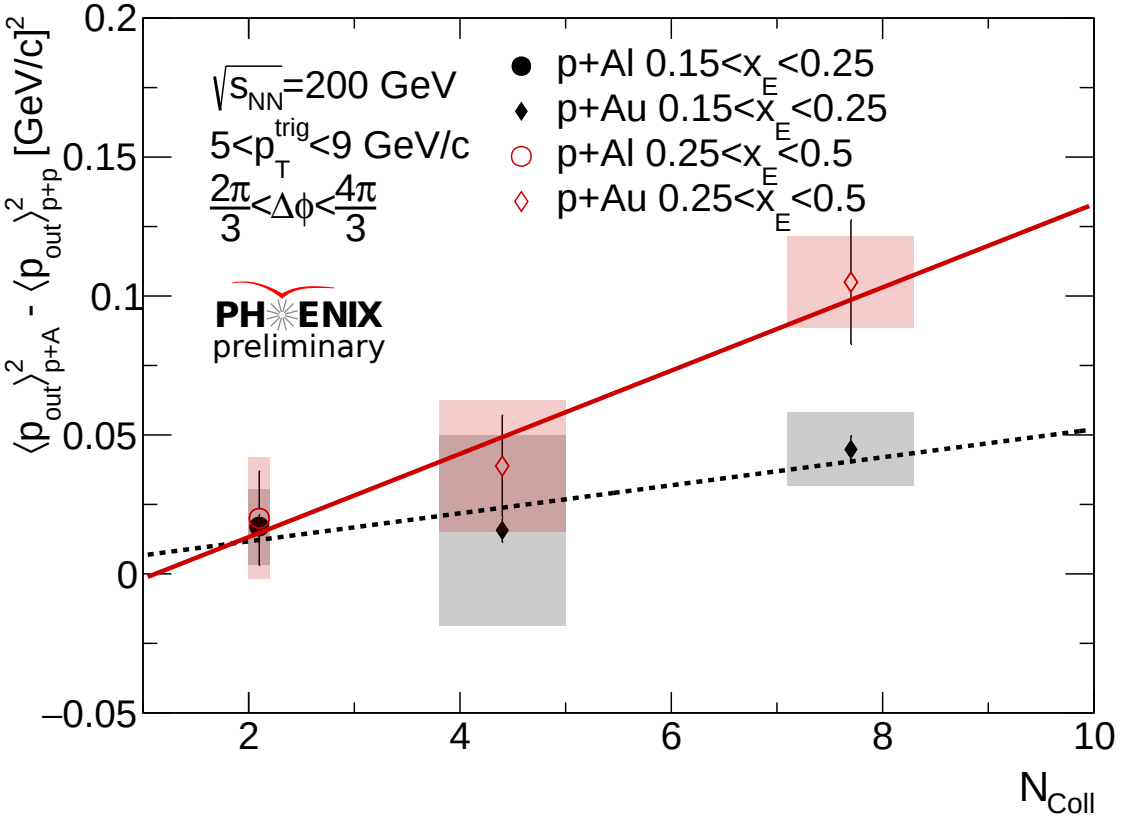


- Measure squared Gaussian width in p+A minus p+p
- No significant near-side transverse momentum broadening
- Nonzero away-side nonperturbative transverse momentum broadening in p+A

Broadening as a Function of N_{coll}



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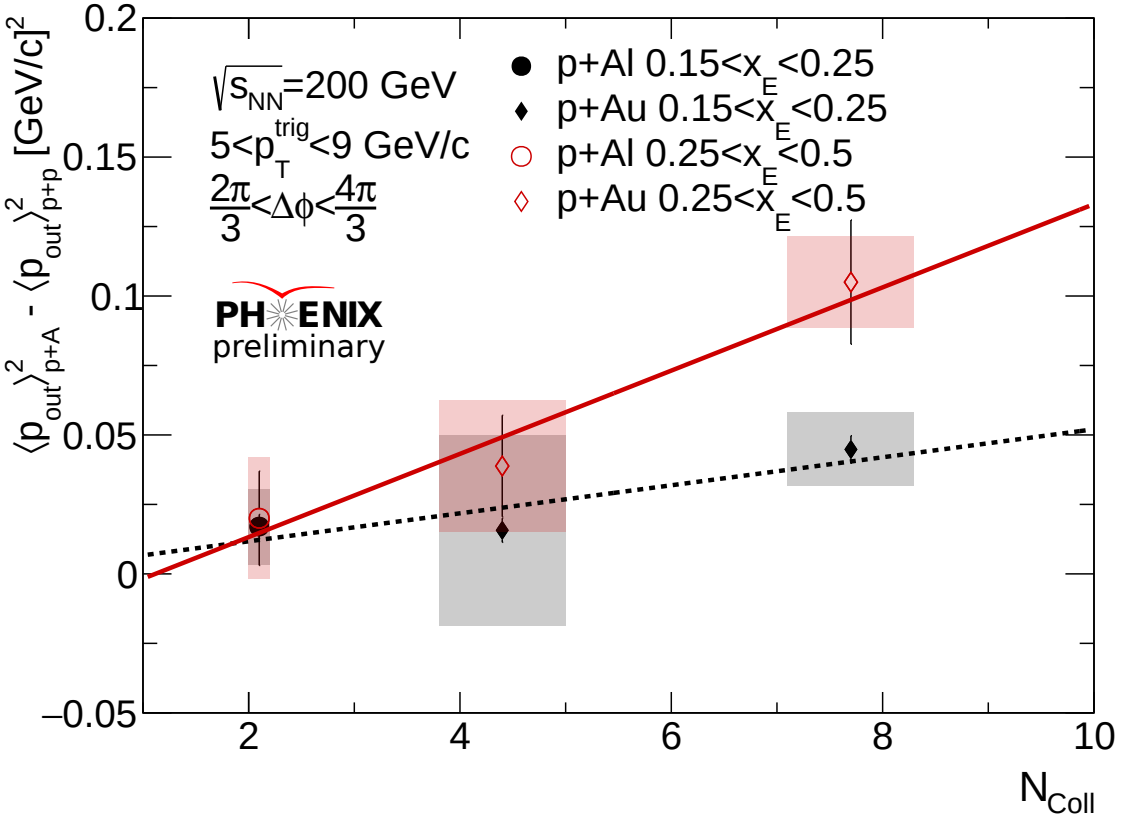

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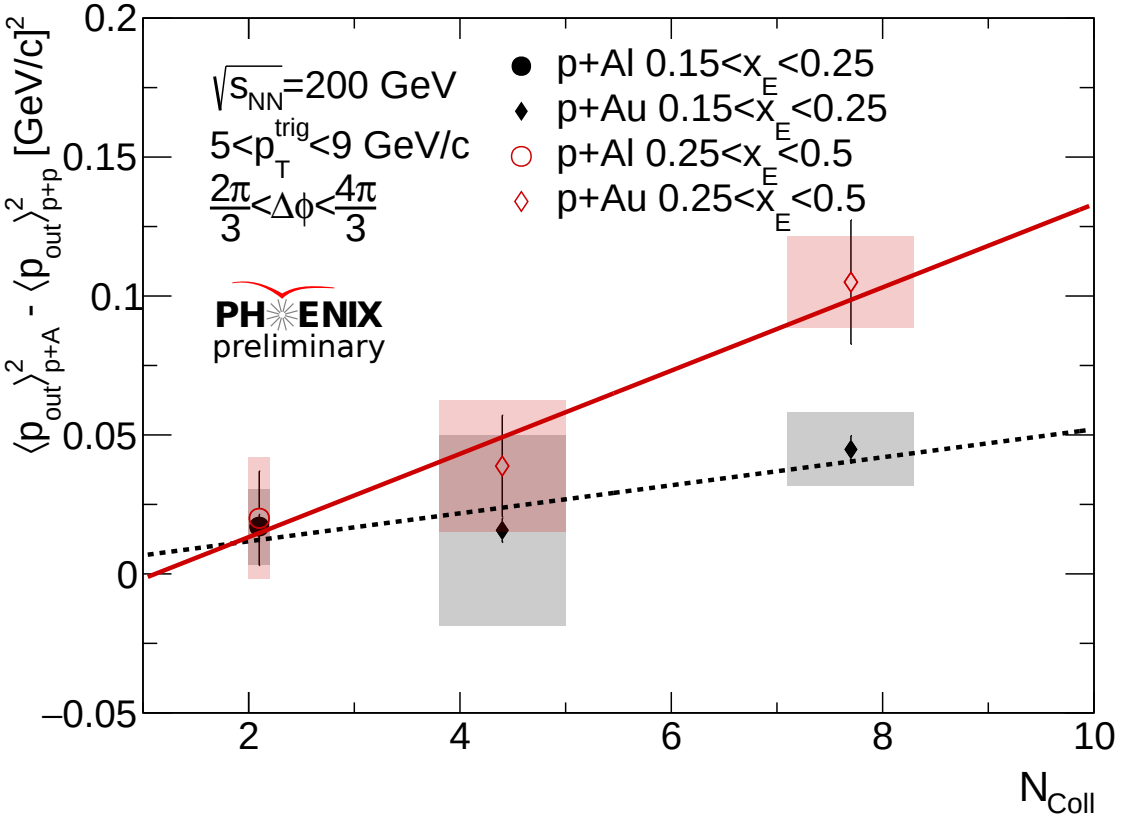

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  - ...

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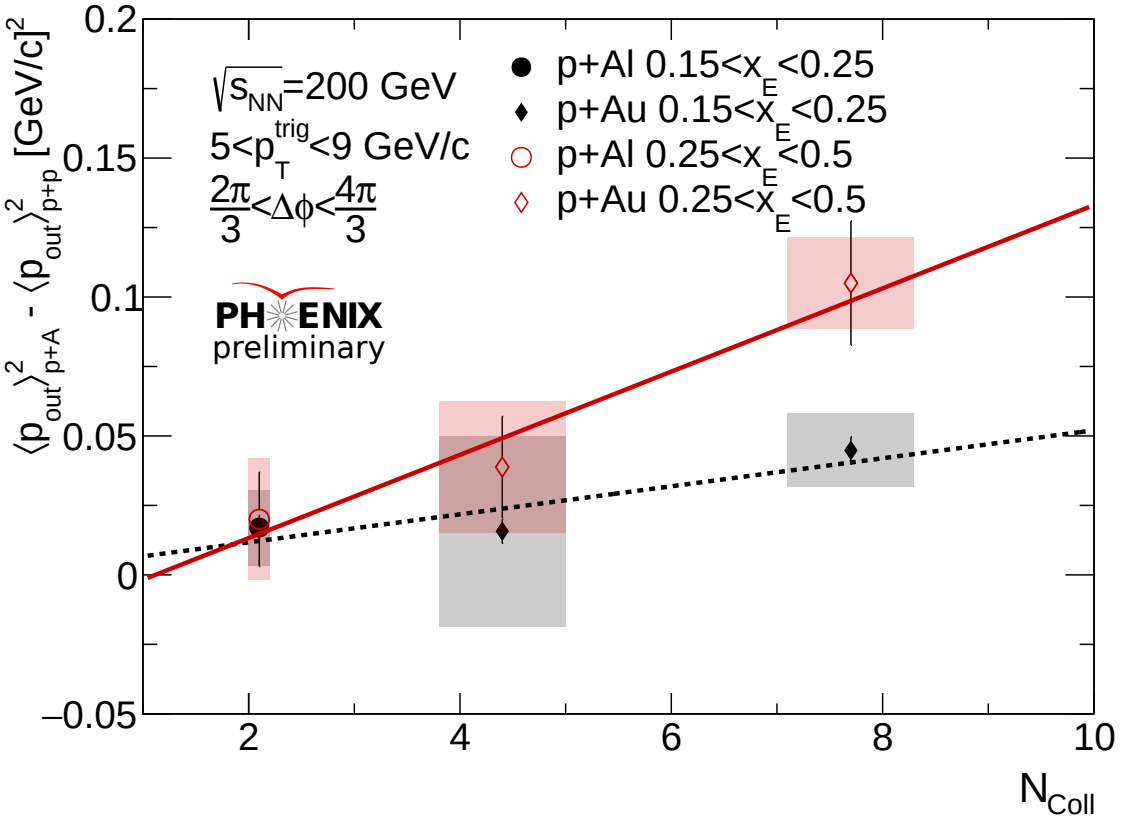

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  - ...

- To be submitted for publication soon, stay tuned!

Future Color Entanglement Measurements

- Color entanglement interactions require color in the initial and final states
- Crucial to make measurements at RHIC and LHC for interpreting future Electron-Ion Collider data!

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- Crucial to make measurements at RHIC and LHC for interpreting future Electron-Ion Collider data!
- Golden channel: γ/Z^0-jet $\rightarrow$ parton dynamics can be determined at leading order
- Need high p_T processes which still have sensitivity to the nonperturbative physics

Conclusions

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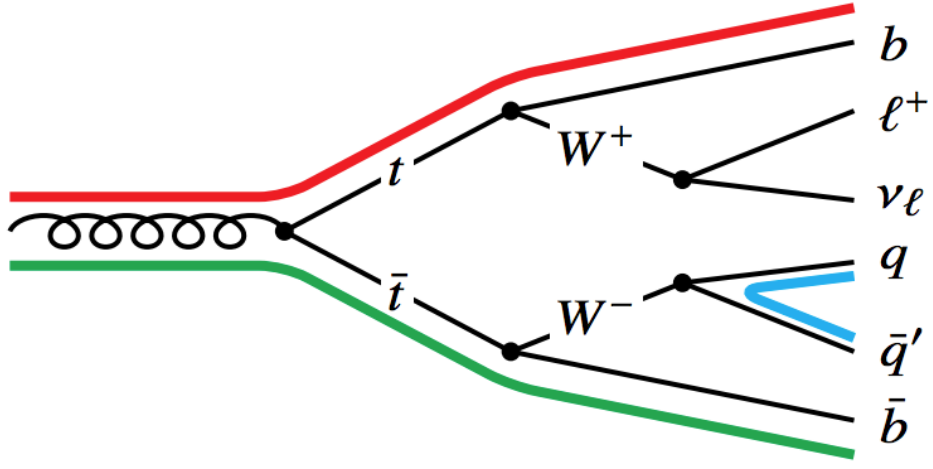
- Dihadron correlations in p+A collisions exhibit path length dependence, sensitive to color, energy loss, and more
- Future measurements at sPHENIX and LHCb will continue to probe color effects
- Synthesizing information from many different collision systems is joining historically separate fields - it's all QCD!

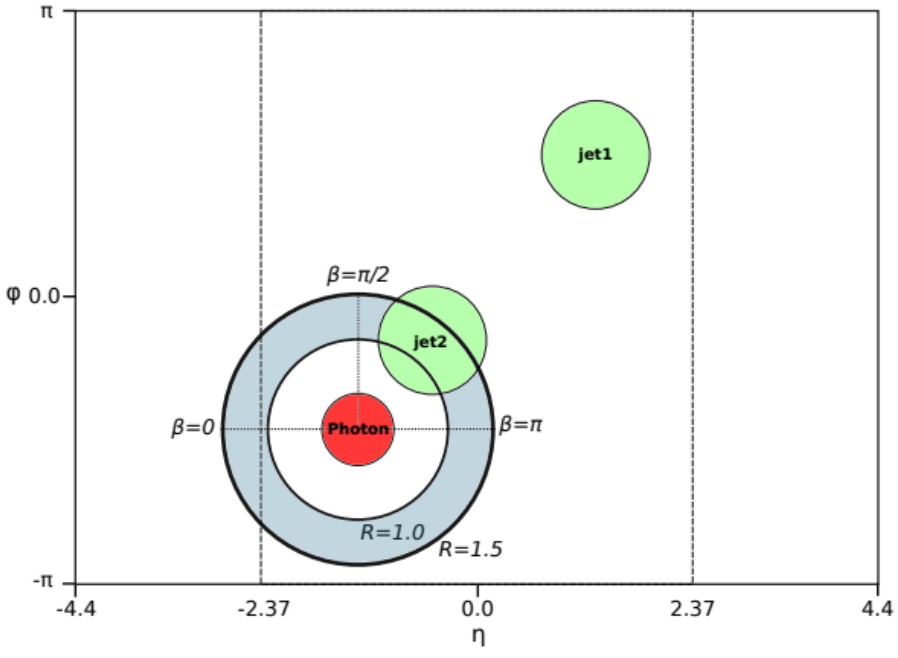
Back up

$t\bar{t}$ Color Topology

- Example $t\bar{t}$ color topology
- $t\bar{t}$ are color connected via gluon splitting
- Hadronizing quarks from W decays can also be color connected



β_γ Definition



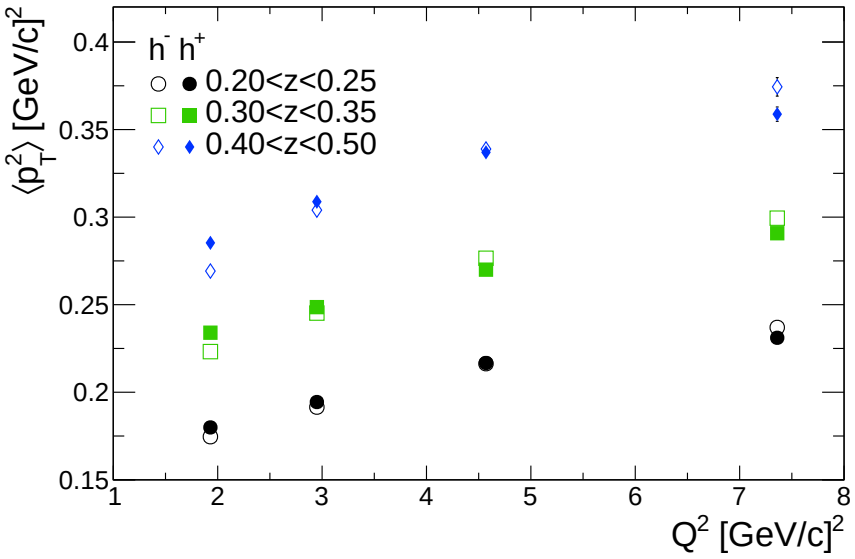
- ATLAS collaboration also measures β_γ, defined in a similar way to β_{jet}

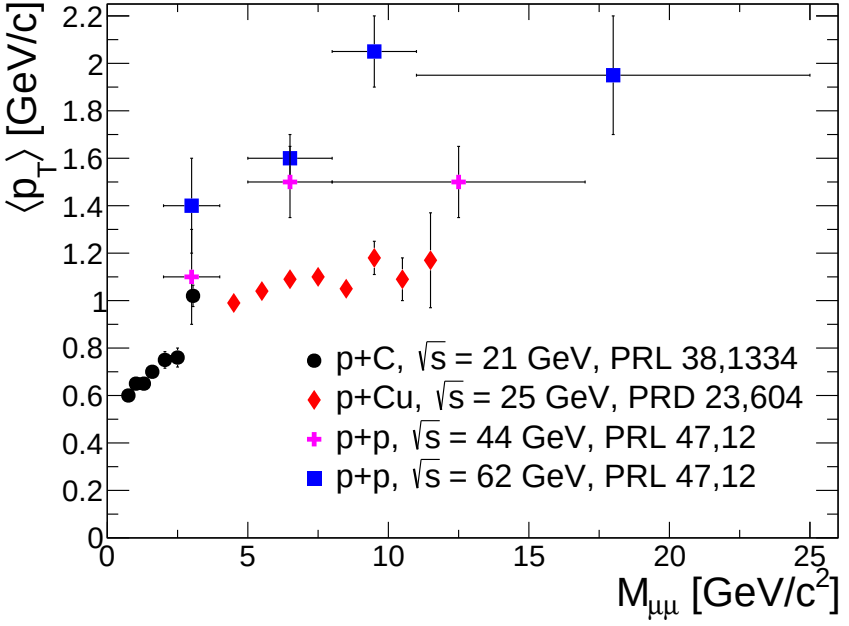
$$\beta^\gamma = \tan^{-1} \frac{|\phi^{jet2} - \phi^\gamma|}{\text{sign}(\eta^\gamma) \cdot (\eta^{jet2} - \eta^\gamma)}$$

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

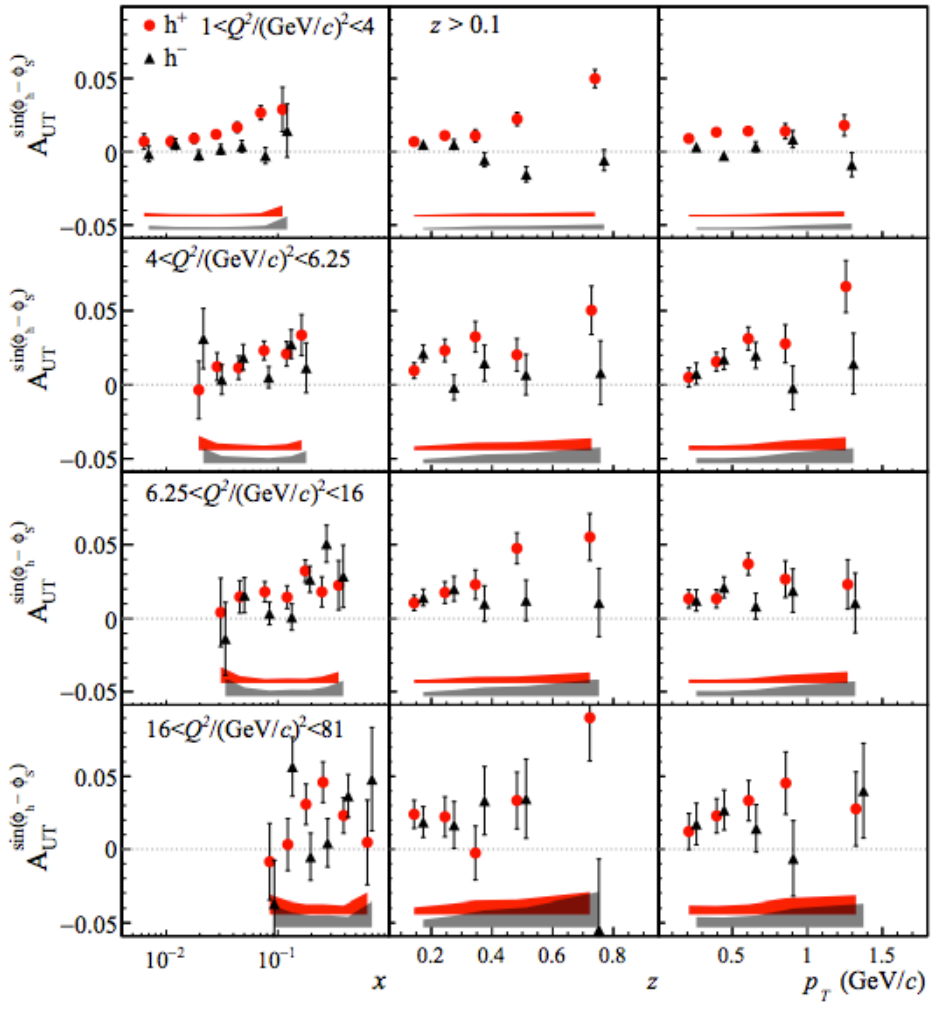




FNAL fixed target DY

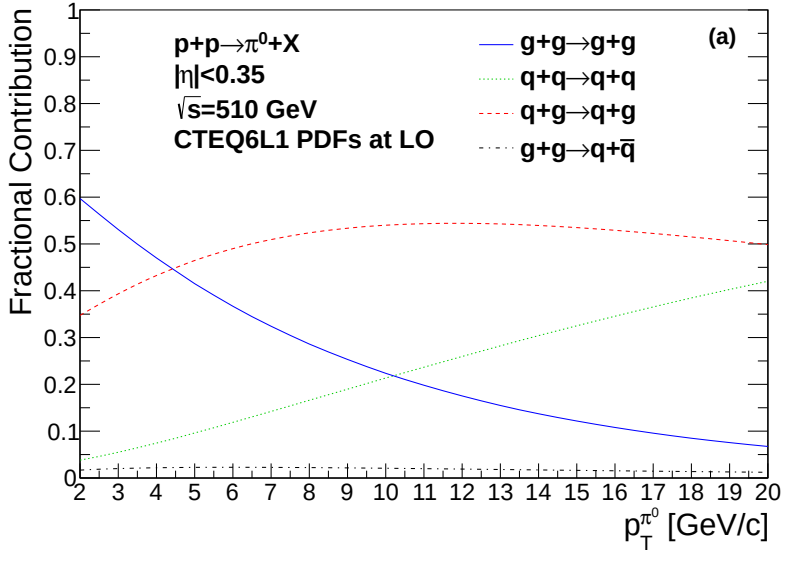
SIDIS Sivers Measurement

- SIDIS Sivers measurement shows ∼5% asymmetries
- Smaller than the asymmetries measured in hadronic collisions
- SIDIS only sensitive to final-state effects from gluon exchanges

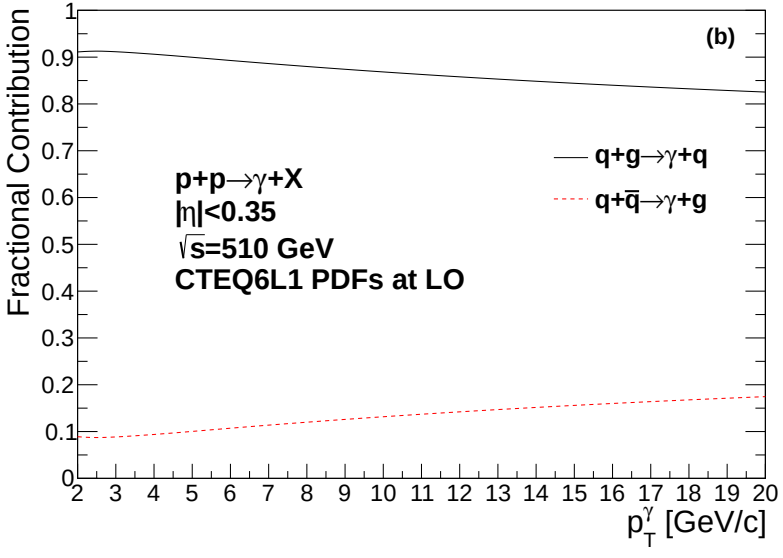


Phys. Lett. B770 (2017) 138-145

Partonic Contributions to Processes at LO

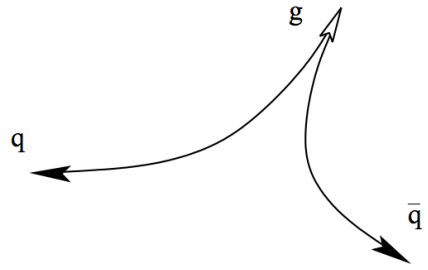


- π^0 contribution changes from gluon dominated at low p_T to mix of quark and gluons at high p_T



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

More about Color Coherence



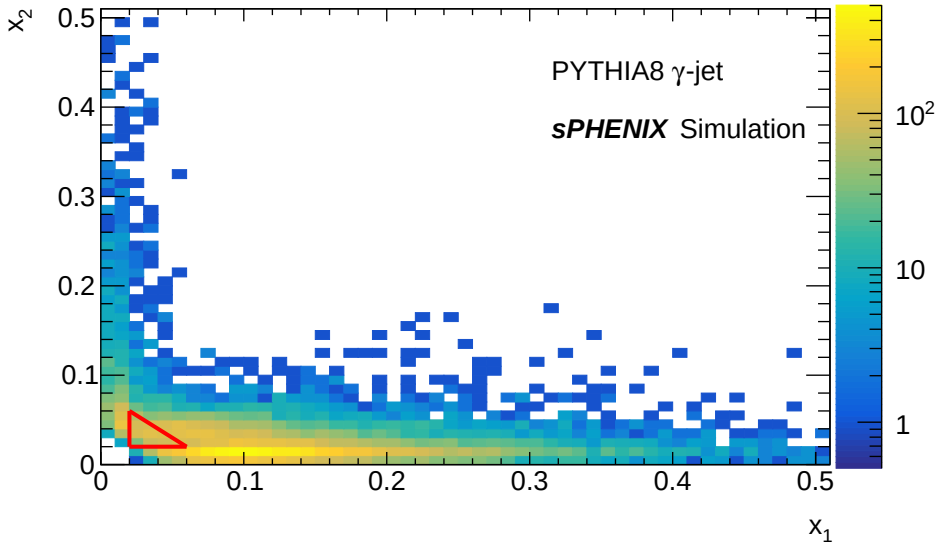
- Radiation "drags" color away from vertex
- Destructive interference occurs away from emitted gluons
- Soft radiation inhibited in certain areas
- Leads to certain regions of phase space where gluons constructively or destructively interfere

- 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

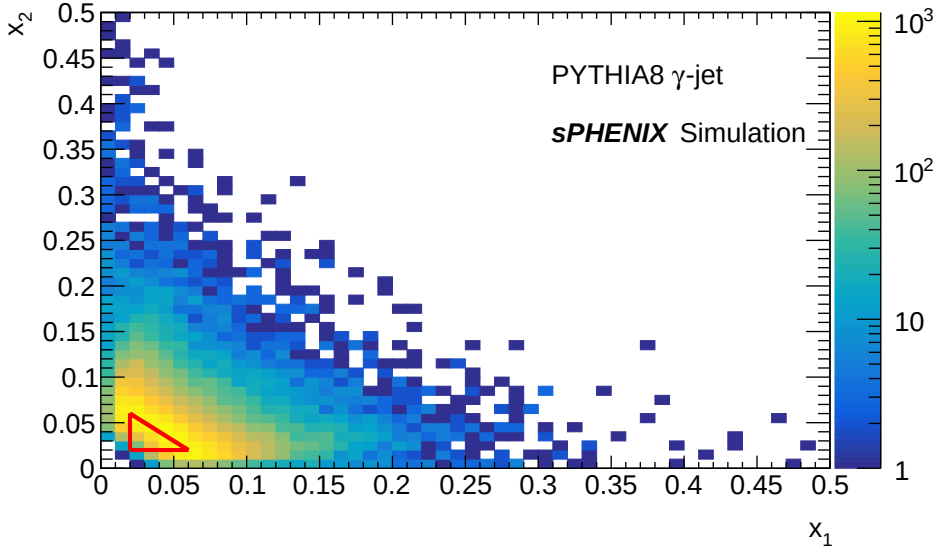
Extending PHENIX Kinematic Reach

- Central-forward (top) and central-central (bottom) γ-jet x_1,x_2 reach at $\sqrt{s} =$ 510 GeV. Red triangle indicates x_1-x_2 reach of PHENIX PRD 95, 072002 (2017)

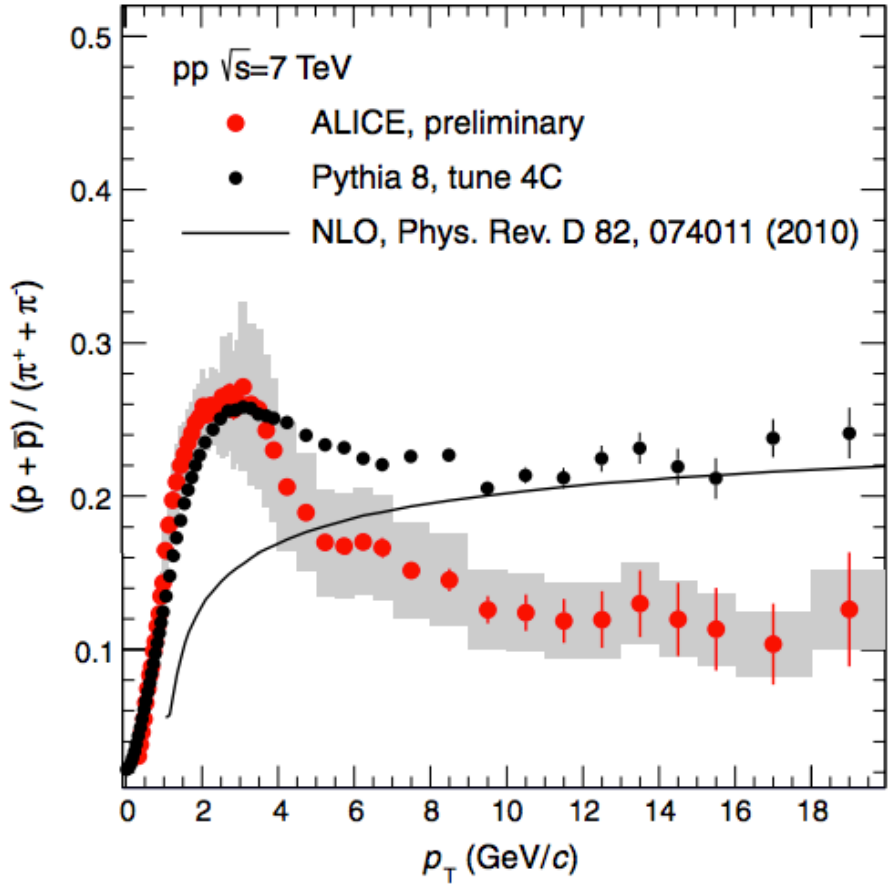
Central-Forward γ-jet



Central-Central γ-jet



Color Leads to v_2 Fourier Harmonic in PYTHIA

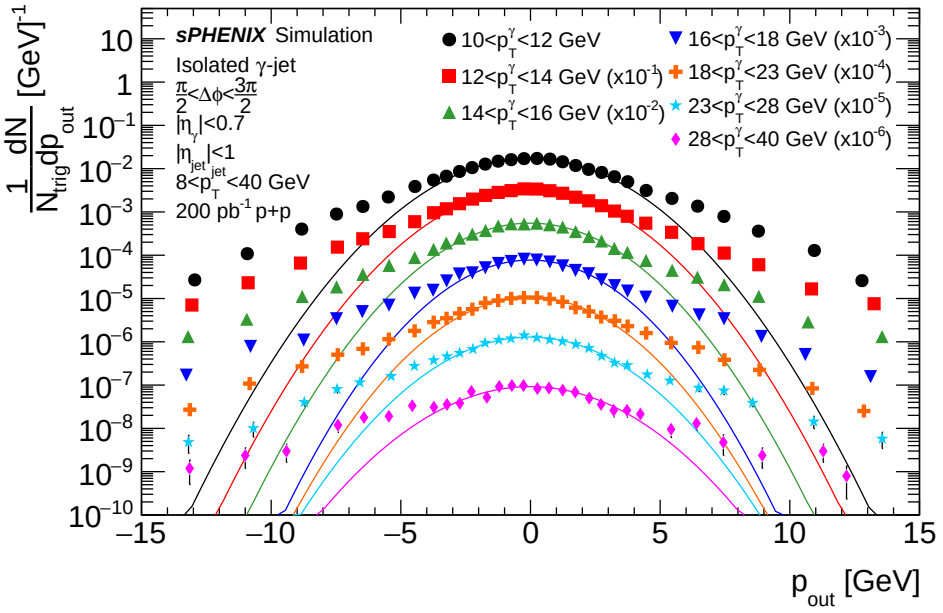


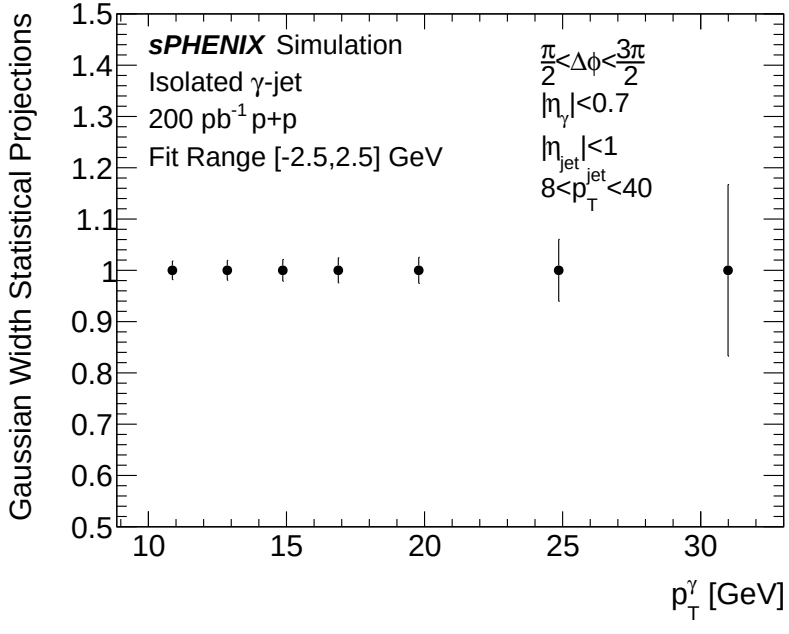
PRL 111, 042001 (2013)

- Color reconnection mechanisms within PYTHIA exhibit similar characteristics to measured Fourier harmonics in p+p
- Can color coherence generate long range eta correlations and PID radial flow patterns?
- Multiple partonic interactions are necessarily color connected

Estimated γ-jet Statistical Precision

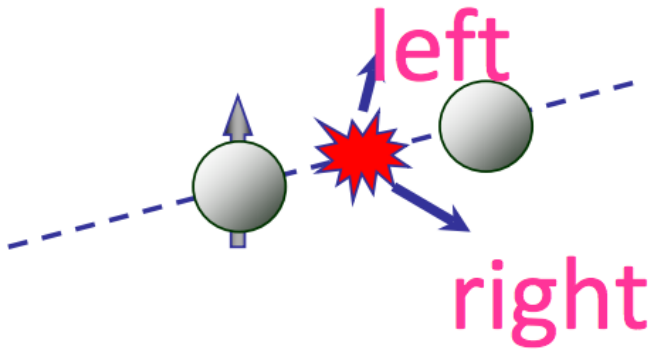
- $\gamma-$jet is the ideal channel - limits color flow possibilities with sensitivity to only k_T
- RHIC kinematics important - need high p_T processes which still have sensitivity to the nonperturbative physics
- sPHENIX will have excellent statistical precision for γ-jet at RHIC *for the first time*
- Will extend PRD 95, 072002 (2017) to study x dependence as well as role of fragmentation with tracking capabilities

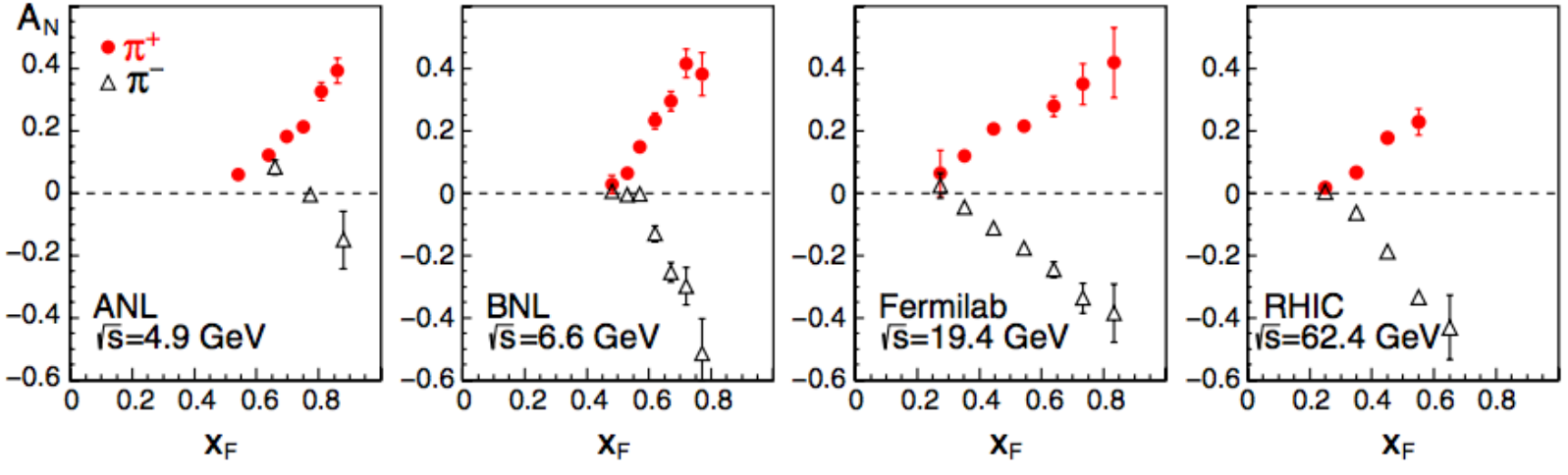




Relation to Huge Transverse Single Spin Asymmetries?

- Transverse single spin asymmetries show up to 40% left-right asymmetry in p+p collisions
- Only ∼5% in semi-inclusive DIS
- Effects from color contributing?

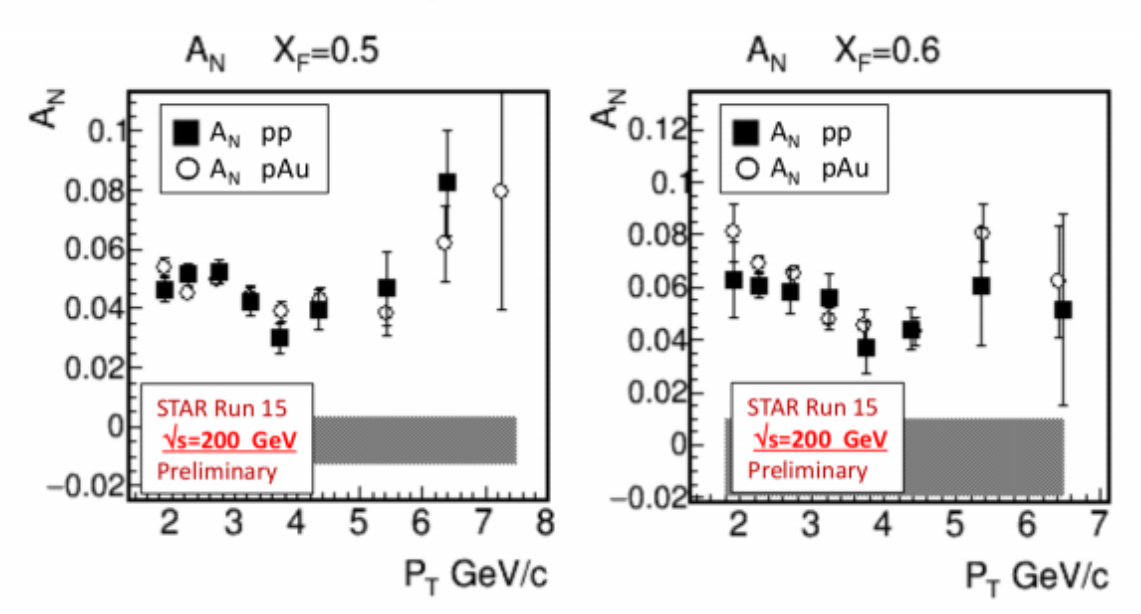




Rev. Mod. Phys. 85, 655 (2013)

Relation to Huge Transverse Single Spin Asymmetries?

- Transverse single spin asymmetries are perturbatively predicted to go to 0 with increasing p_T
- Nonzero ($\sim$7%) asymmetries have been measured up to $p_T \sim 7$ GeV
- Transverse single spin asymmetries seem to not follow perturbative evolution as well
- Do correlations follow expectation of magnitudes for perturbative evolution? Calculations necessary...



Transverse-Momentum-Dependent PDF Zoo

Transverse-Momentum-Dependent (TMD) PDFs

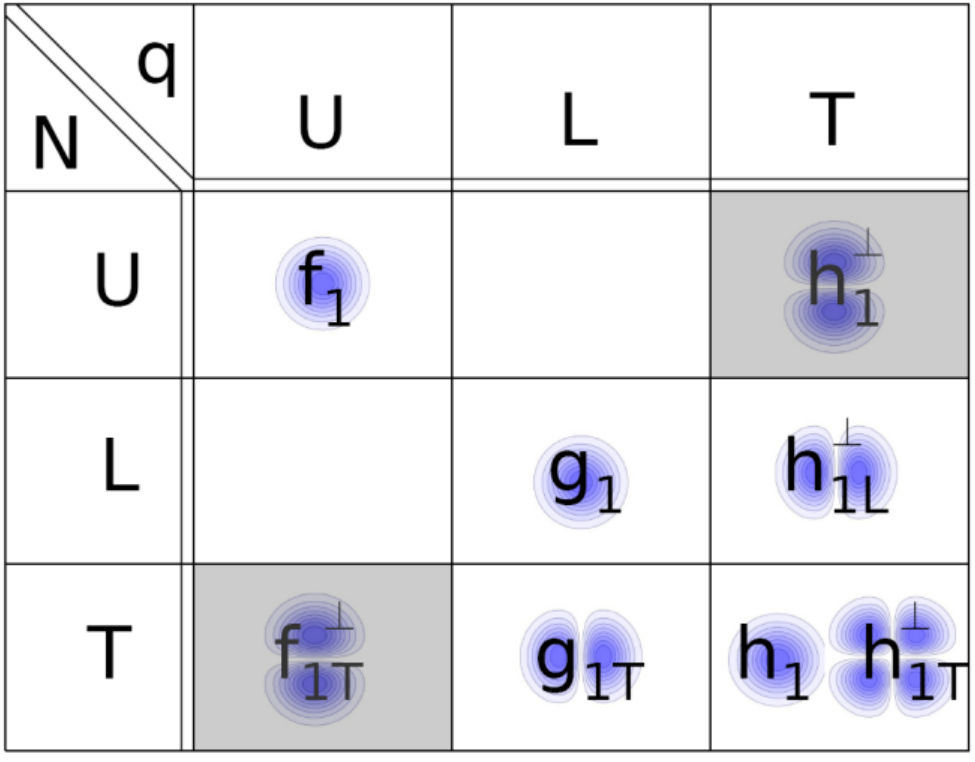


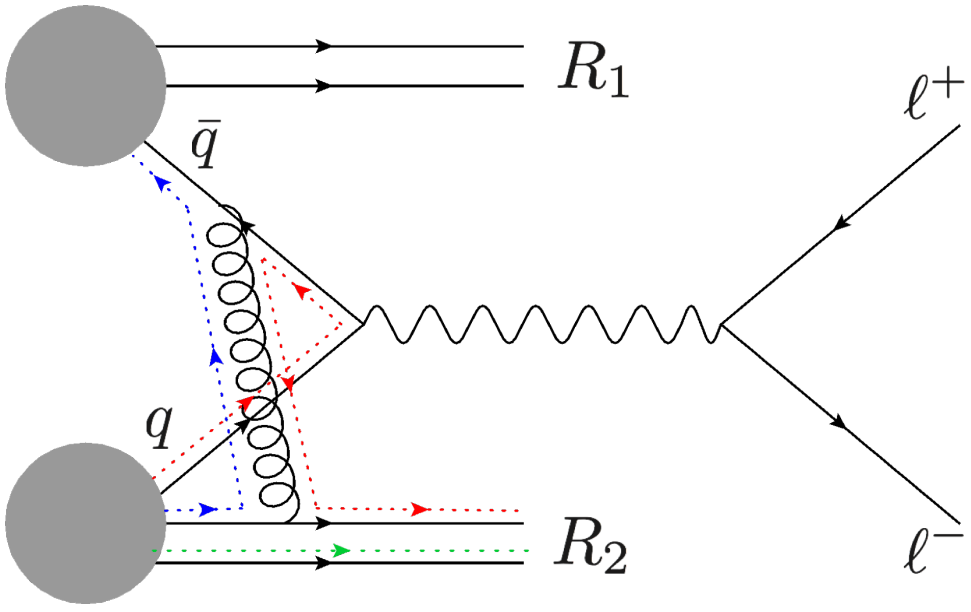
Image taken from Alexei Prokudin Spin 2016

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

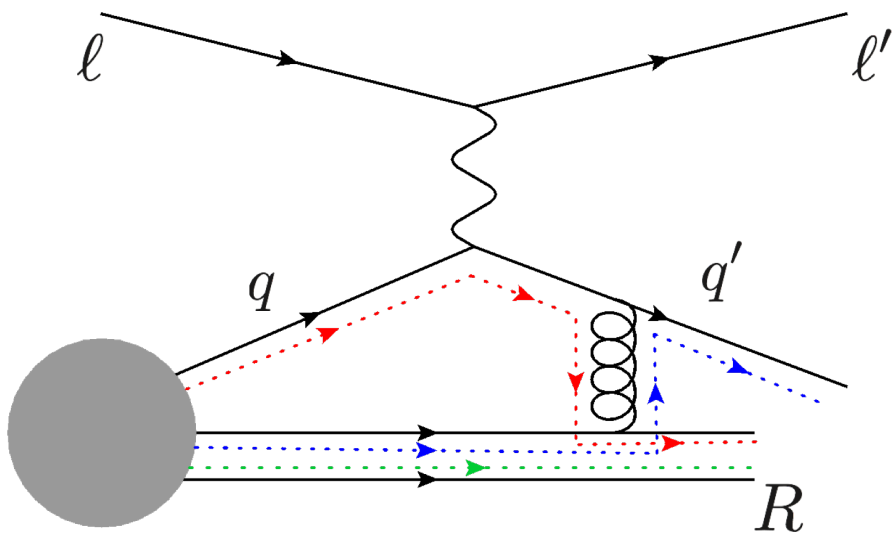
- 8 TMD PDFs describing transverse partonic structure, spin-spin, and spin-momentum *correlations!*

Universality in Transverse-Momentum-Dependent Functions

Drell-Yan: $q + \bar{q} \to \ell^+ + \ell^-$



Semi-Inclusive DIS: $e^- + p \to e^- + h$

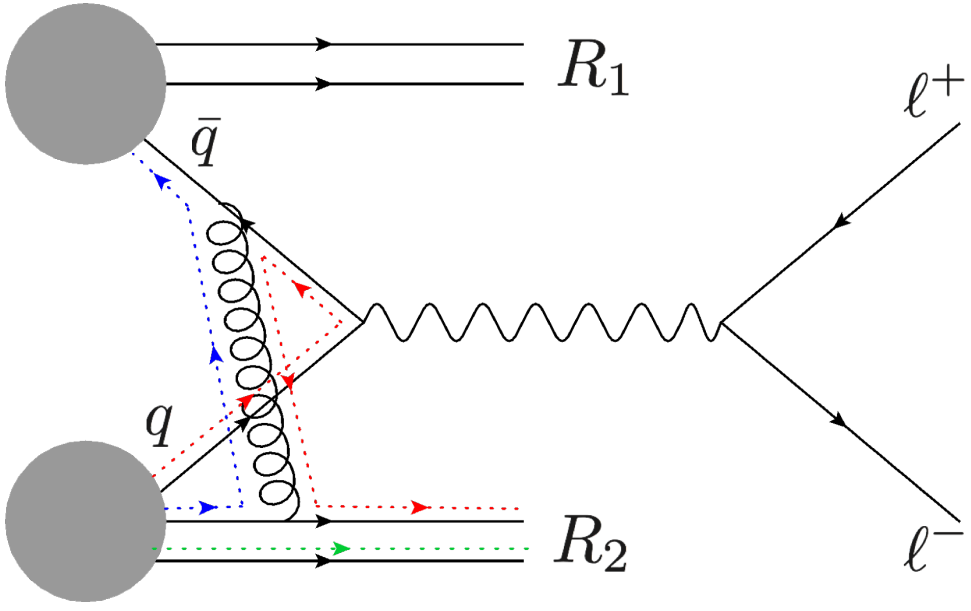


- Sign change in parity-time odd transverse-momentum-dependent PDFs predicted due to initial-state vs. final-state gluon exchange with proton remnants in different processes!

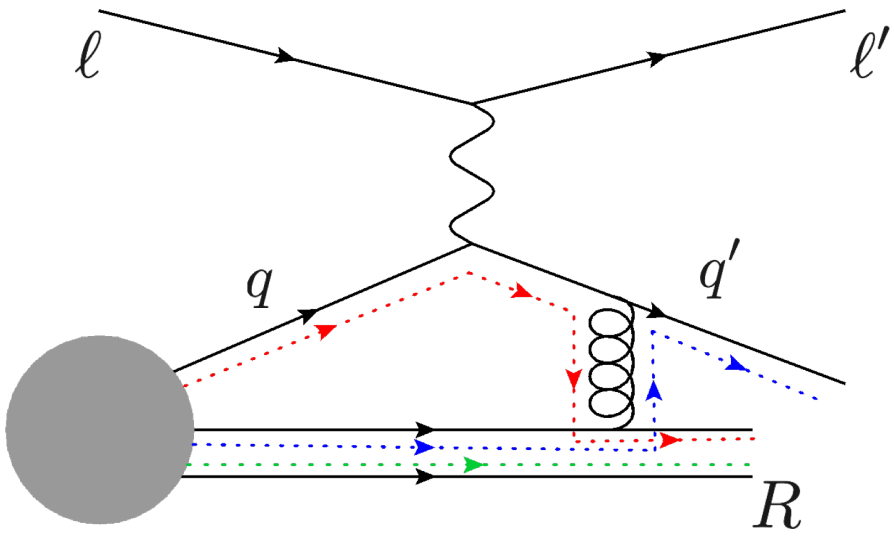
$$f_{1T}^{\perp}(x, k_T, Q^2)|_{\mathrm{DY}} = -f_{1T}^{\perp}(x, k_T, Q^2)|_{\mathrm{SIDIS}}$$

Universality in Transverse-Momentum-Dependent Functions

Drell-Yan: $q + \bar{q} \to \ell^+ + \ell^-$



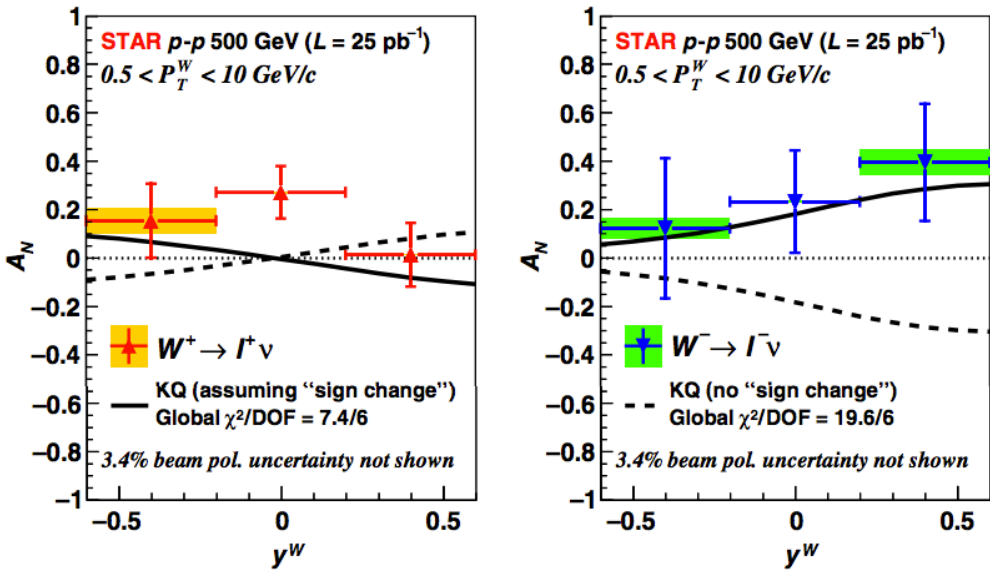
Semi-Inclusive DIS: $e^- + p \to e^- + h$



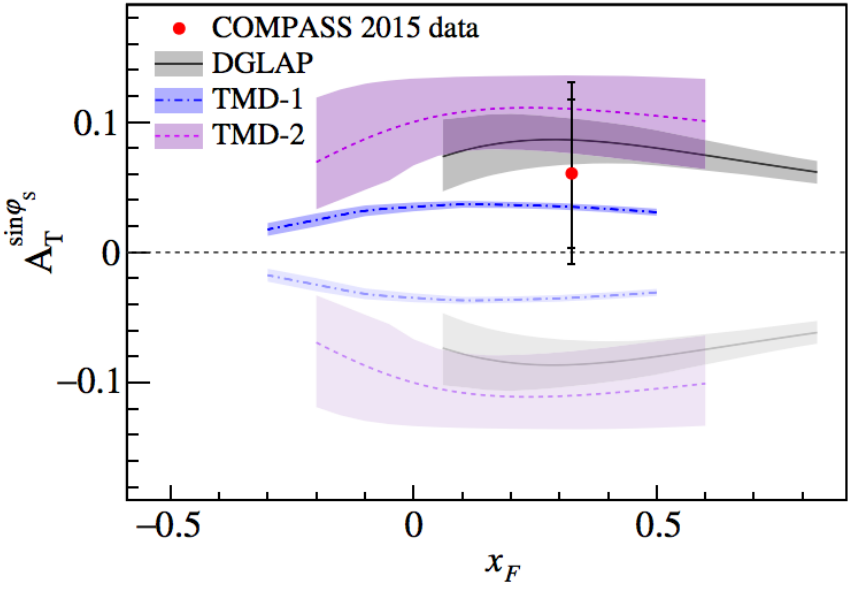
- Sign change in parity-time odd transverse-momentum-dependent PDFs predicted due to initial-state vs. final-state gluon exchange with proton remnants in different processes!
- Factorization of transverse-momentum-dependent PDFs and fragmentation functions still predicted to hold in these QED processes

First Measurement of Possible Modified Universality

- Semi-inclusive DIS Sivers asymmetries have been measured, e.g. by HERMES and COMPASS collaborations
- First measurements of Drell-Yan (type) processes just recently reported
- Data support prediction of process dependent transverse-momentum-dependent PDF (although still statistically limited)



PRL 116, 132301(2016)



PRL 119, 112002 (2017)