Transverse-Momentum-Dependent Distributions and Color Entanglement in QCD

Lecture 5 – TMD factorization, Aharonov-Bohm, and Color Entanglement II

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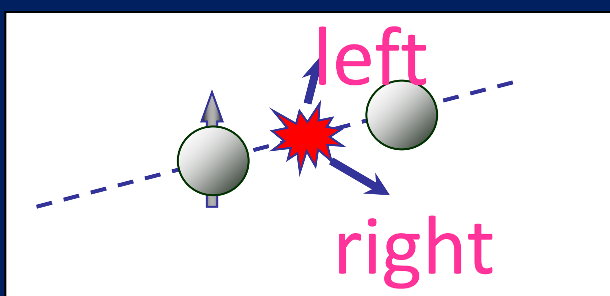
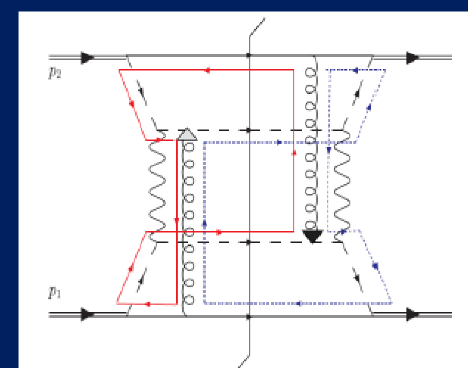
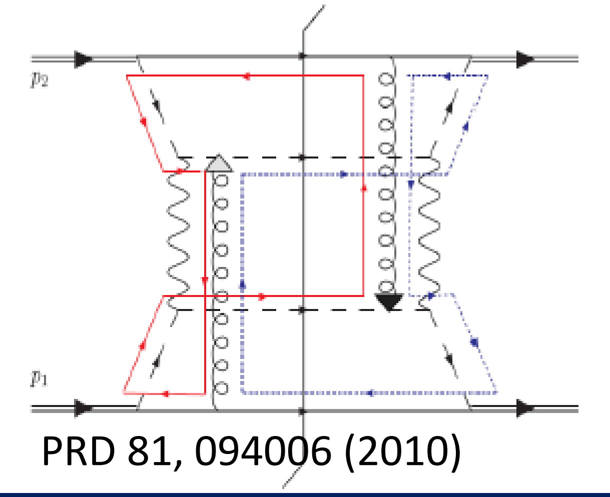




Hampton University Graduate Studies Program
Jefferson Lab
June 2016

Recall: Color entanglement

- 2010: Rogers and Mulders predict *color entanglement* in processes involving p+p production of hadrons if parton transverse momentum taken into account
- Quarks become correlated *across* the two protons
- Consequence of QCD specifically as a ***non-Abelian*** gauge theory!
- Again, can't use gauge transform to get rid of gluons being exchanged

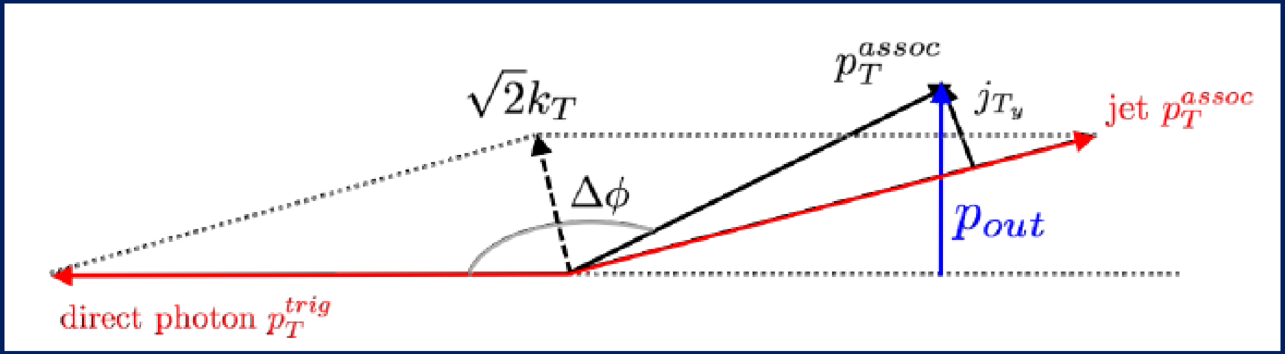


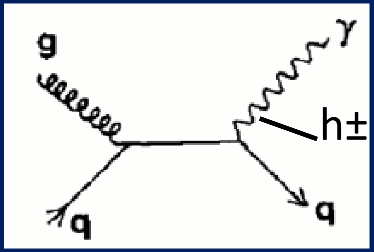
PRD 81, 094006 (2010)

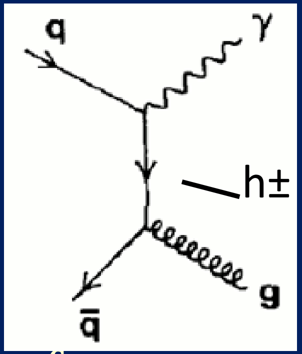
$$p + p \to h_1 + h_2 + X$$

Color flow can't be described as flow in the two gluons separately. Requires *simultaneous* presence of both.

Recall the observables: Direct photon – hadron correlations in p+p

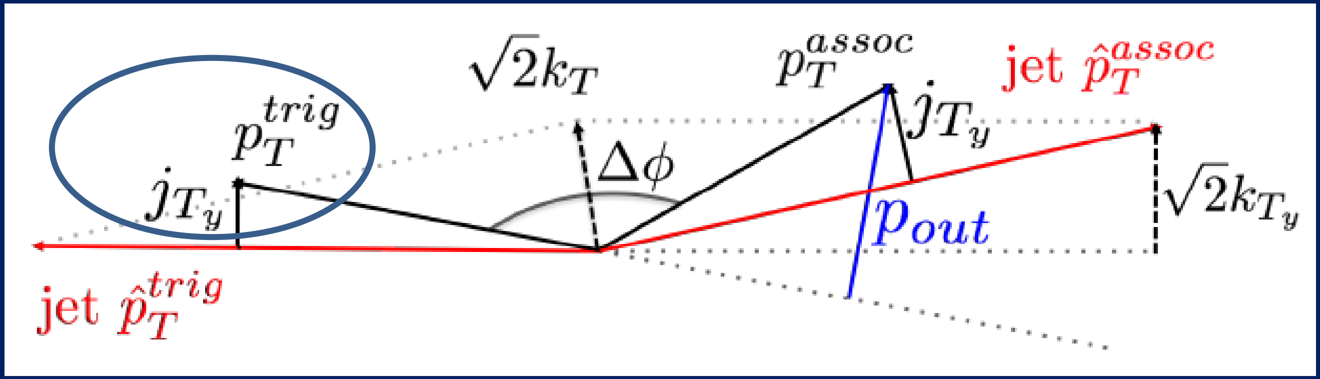






- "Direct" photon – produced directly in hard scattering
- ~85% quark-gluon Compton scattering (top diagram) in our kinematics
- Measure out-of-plane momentum component p_{out} of one particle with respect to other
- Unpolarized – effects predicted for polarized and unpolarized; more data available for unpolarized

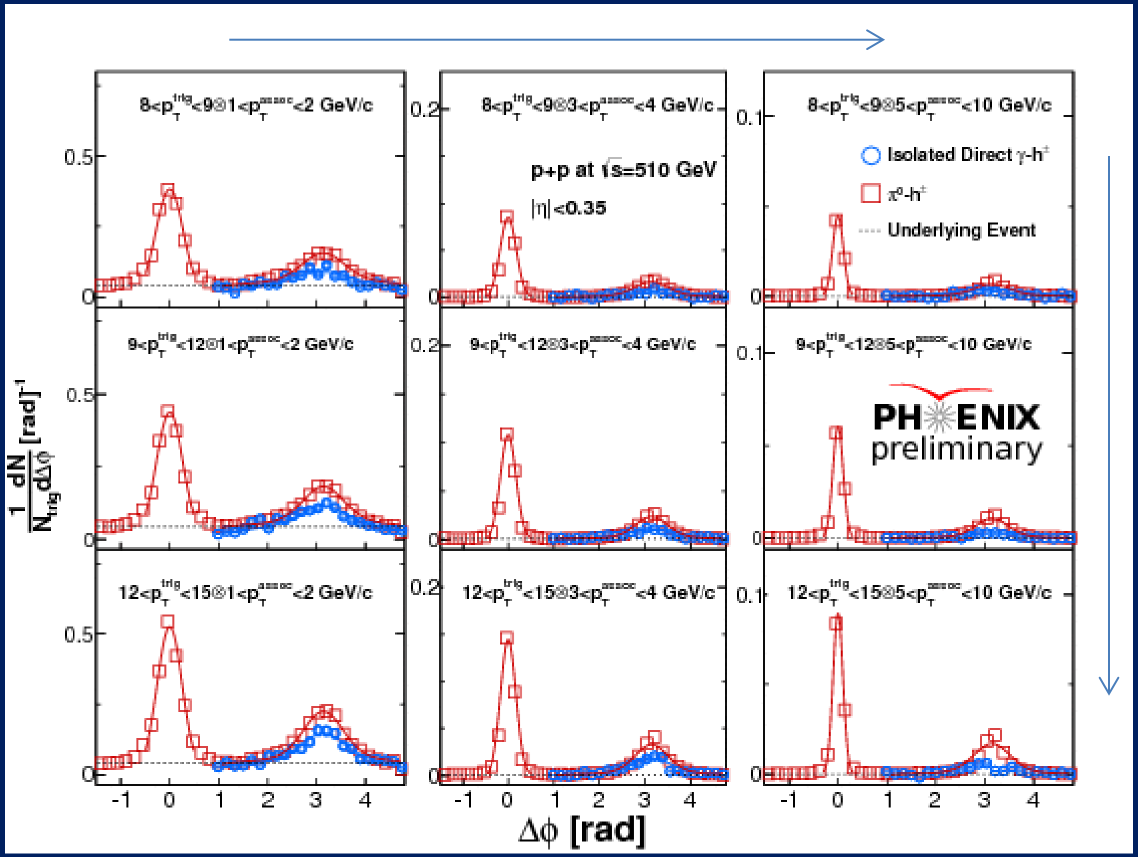
Also π^0 – hadron correlations in p+p



- Additional place for gluon to attach in π^0 – charged hadron correlations compared to direct photon – charged hadron correlations
- Additional nonperturbative transverse momentum from pion fragmentation
- Both measurements at $\sqrt{s}$ = 510 GeV, midrapidity

Two-particle azimuthal angular correlations

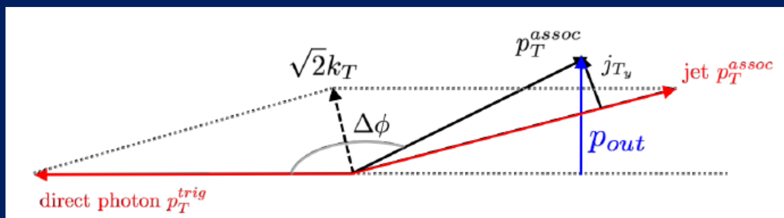
Associated charged hadron p_T increasing

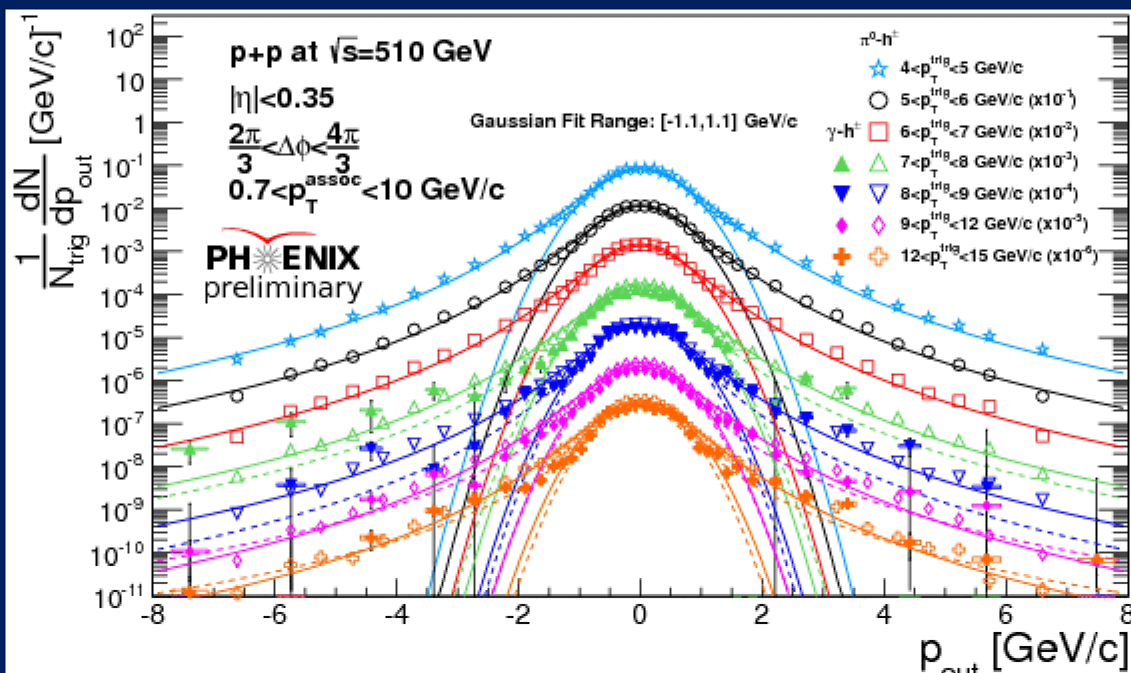


Trigger photon or pion p_T increasing

- Angular distribution of "associated" charged hadrons around a "trigger" photon or π^0
- Two-jet structure seen for pion-hadron correlations
- Away-side jet structure seen for direct photon – hadron correlations
  - Isolation cut on near side
- Trigger particle p_T shown here ranges from 8-15 GeV/c → hard scale

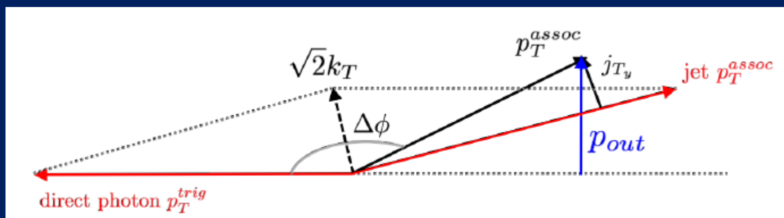
Out-of-plane momentum component distributions

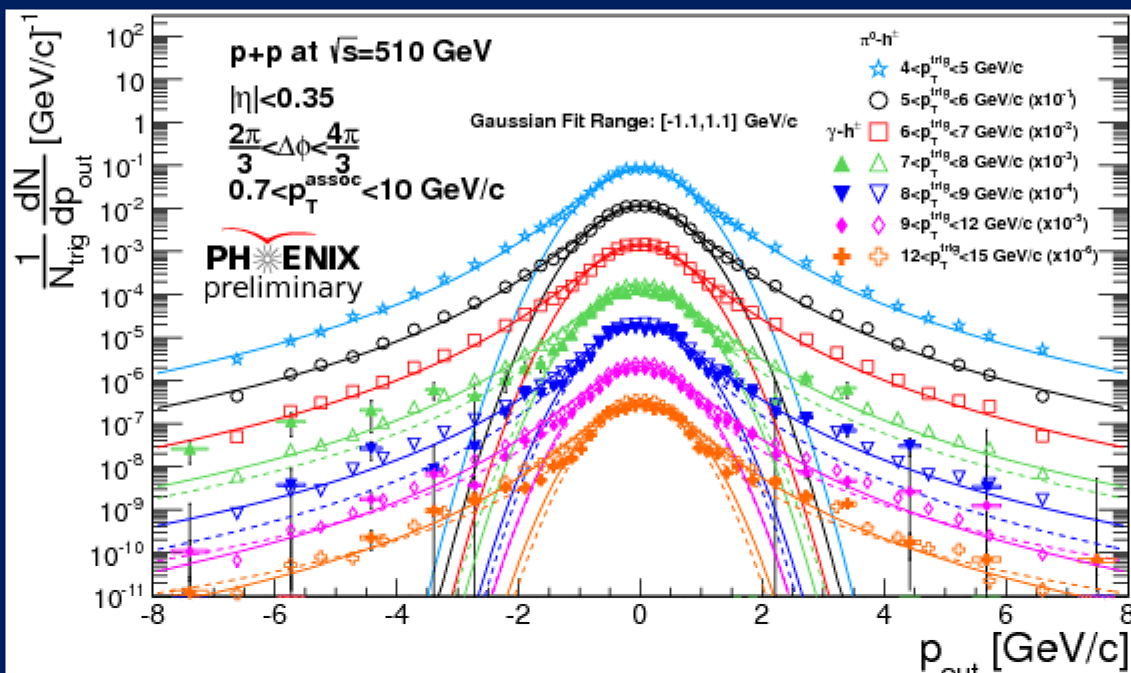




- Out-of-plane momentum distribution for charged hadrons in the away-side peak
- Associated charged hadron p_T from 0.7-10 GeV/c
  - Underlying event (hadrons not associated with jet structure) statistically subtracted
- Different colors for different photon or pion p_T bins, ranging from 4-15 GeV/c
- Open points for pion-hadron correlations
- Filled points for photon-hadron correlations

Out-of-plane momentum component distributions





- Clear two-component distribution observed
  - Gaussian around $p_{out} = 0$ → sensitive to nonperturbative transverse momentum
  - Power law tails → due to perturbative gluon radiation
- Curves are fits, not calculations

How to search for color entanglement?

- The original idea (2010):
  - Compare our p_{out} distributions to calculations for the same process *assuming no entanglement*, and look for deviations in the shape and/or magnitude

- Difficulties with that idea:
  - No calculations available
  - If someone did perform calculations, they'd depend on parameterizations of TMD pdfs and FFs
    - TMD pdfs, even in unpolarized case here, still have very large uncertainties
    - Unpolarized TMD FF parameterizations not yet available
    - TMD phenomenology still in very early stages! Quantitative comparisons would likely be inconclusive

Look instead at evolution

- New idea that came out of discussions with Ted Rogers and John Collins in 2015 – Look at *evolution* of nonperturbative transverse momentum widths with hard scale
  - Don't need any TMD calculations or phenomenology, so don't have to worry about uncertainties on distributions extracted from factorized processes
  - Just look for *qualitatively* different behavior

- The Collins-Soper evolution equation comes directly out of the derivation of TMD factorization, so if factorization is broken, CSS evolution not expected
  - Collins, arXiv:1212.5974

Collins-Soper-Sterman evolution

- See Lecture 4 by Markus Diehl for more theoretical details
- Collinear evolution in hard scale Q described by DGLAP equations
- TMD evolution in hard scale Q described instead by Collins-Soper-Sterman evolution
  - Collins and Soper, NPB193, 381 (1981), Err. B213, 545 (1983); Collins and Soper, NPB194, 445 (1982); Collins, Soper, and Sterman, NPB250, 199 (1985)
  - Modernized and improved version of same method: Collins, *Foundations of Pertubative QCD*, 2011

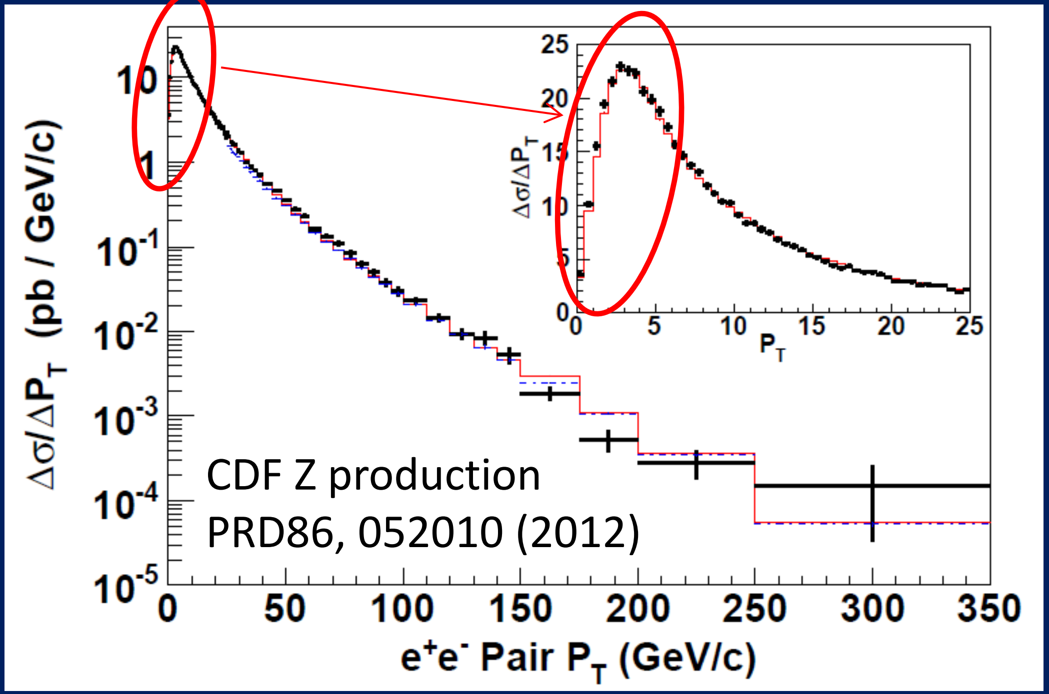
TMD factorization and evolution were worked out in the 1980s?

- Yes! TMD pdfs and FFs describing *spin-momentum correlations* were developed in 1990s, but in 1980s there was already interest in role of nonperturbative transverse momentum effects in unpolarized processes

- Focus, however, was *not* on understanding nucleon structure, but rather on treating particle production in high energy collisions down to low transverse momenta
  - E.g. Drell-Yan, Z, and W boson cross sections differential in p_T

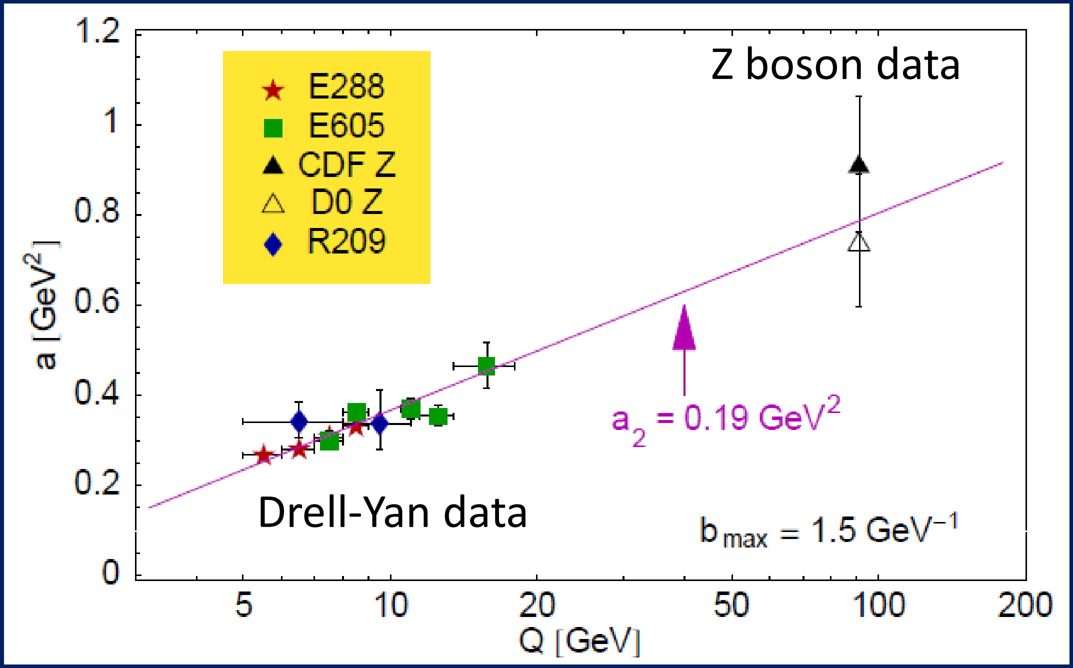
Collins-Soper-Sterman framework to treat Z boson at low p_T

- p_T of Z in circled region due to nonperturbative k_T of annihilating quark and antiquark
- Perturbatively generated tail then extends to 350 GeV
- Early CSS work focused on treating this nonperturbative transverse momentum, not on nucleon structure



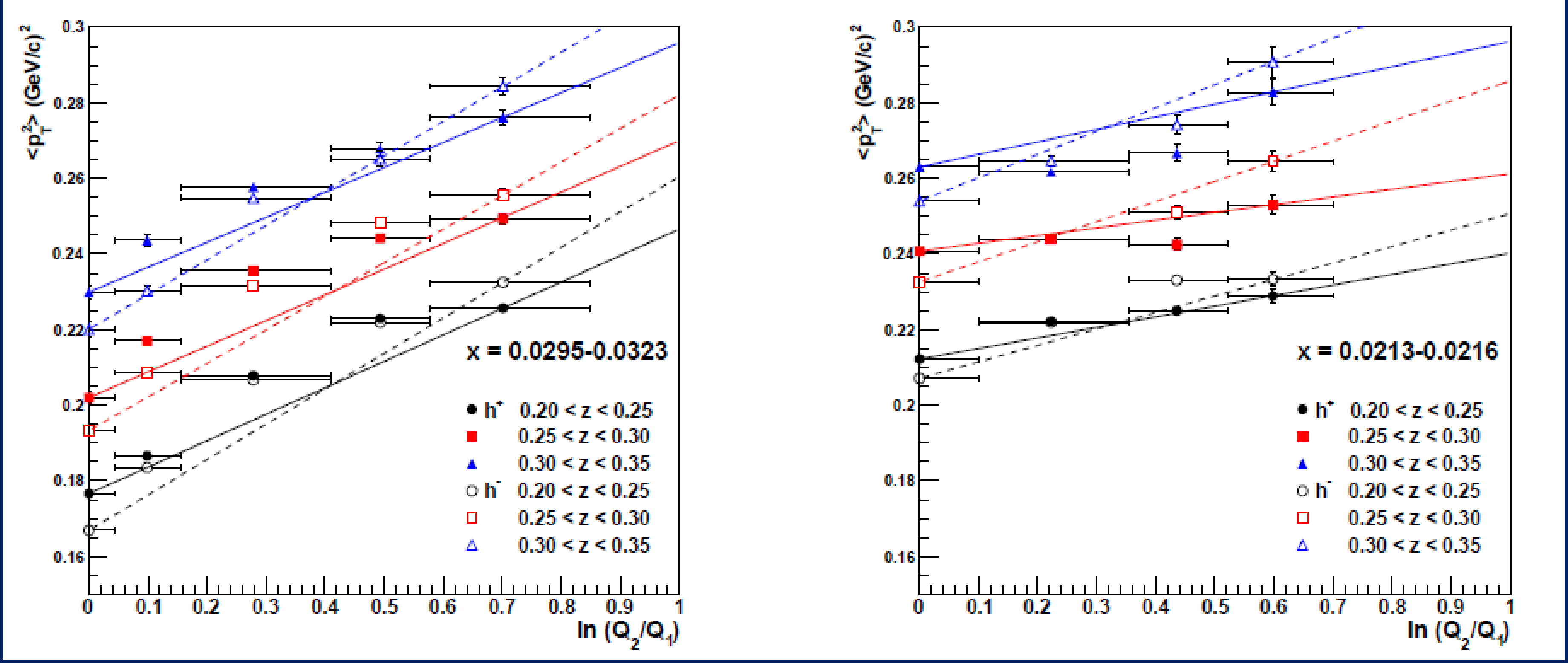
CSS evolution predicts nonperturbative transverse momentum widths increase with Q

- Can be understood intuitively as broadening of phase space for gluon radiation
- Confirmed experimentally



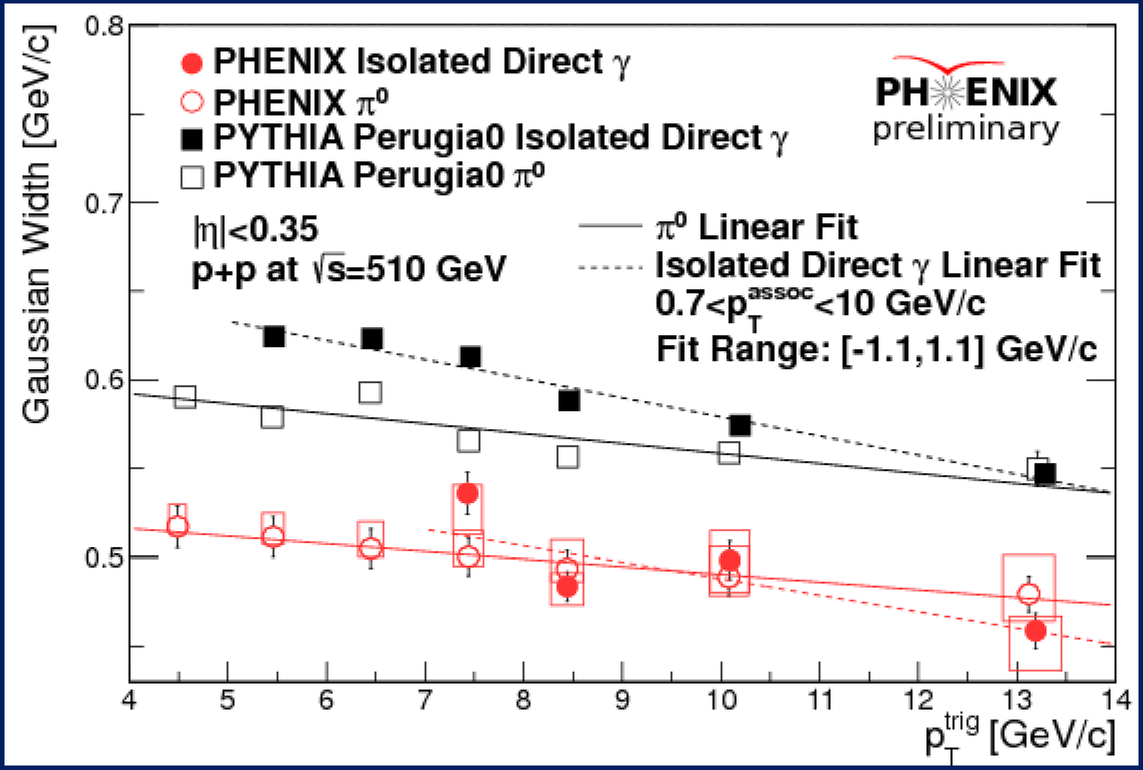
Konychev + Nadolsky, PLB633, 710 (2006)

Broadening with hard scale also confirmed experimentally in SIDIS data



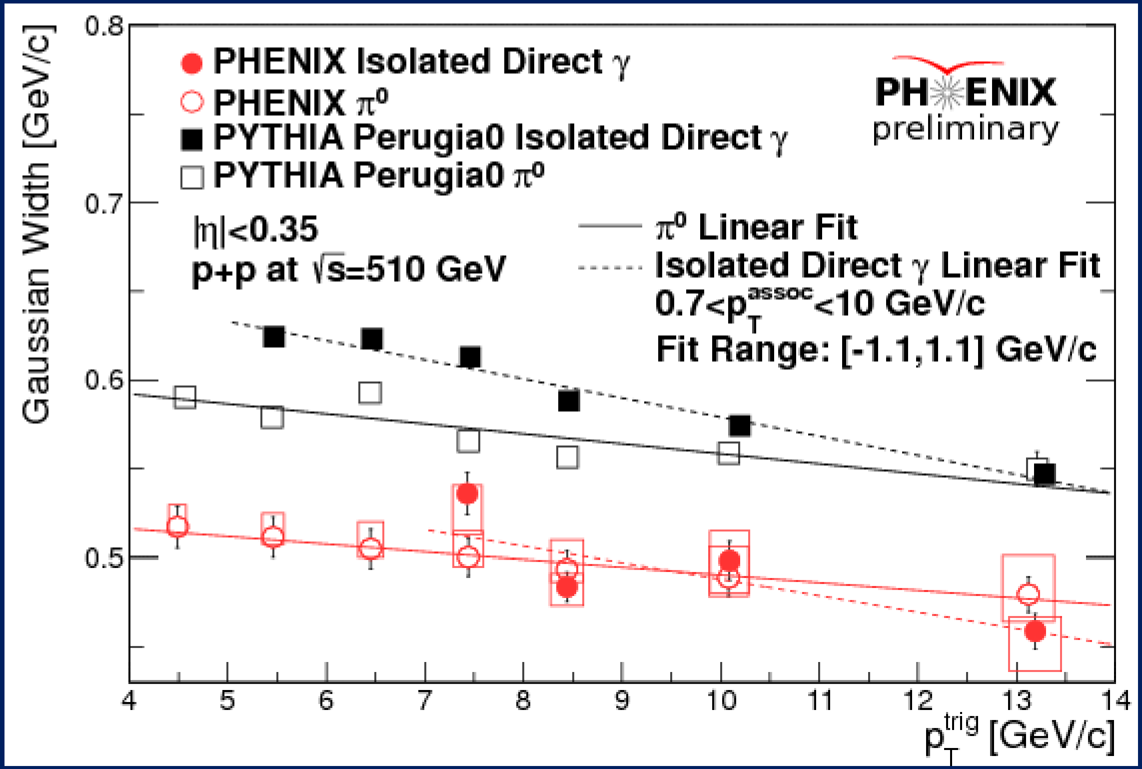
CAA, Field, Gamberg, Rogers, PRD89, 094002 (2014)
Data from COMPASS, EPJ C73, 2531 (2013)

p+p data: Widths decrease as function of hard scale!



- Clear *qualitative* deviation from CSS evolution!

p+p data: Widths decrease as function of hard scale!



- *And* PYTHIA simulations also show decreasing widths, with slopes for photon-hadron and pion-hadron correlations matching data ~perfectly!
- Absolute widths ~15-20% wider

pQCD calculations versus PYTHIA Monte Carlo

- Does PYTHIA include color entanglement effects??

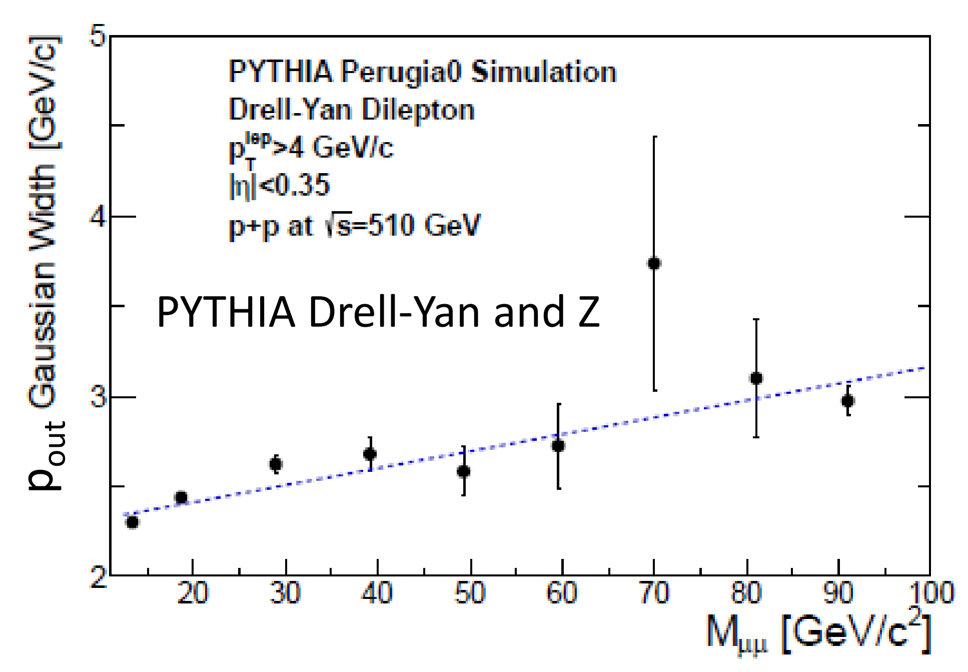
- While PYTHIA certainly doesn't include analytical factorization breaking effects because it assumes collinear factorization, in contrast to a collinear pQCD calculation it does include initial- and final-state interactions. After a parton interacts, the remnants of the two protons are free to interact with other objects in the collision, and *every* object in the interaction is forced to color neutralize

- Factorization breaking effects are predicted in photon-hadron and dihadron correlations due to the possibility of gluon exchange between partons involved in the hard scattering and proton remnants in both the initial and final states

- Plausible that PYTHIA sensitive to factorization breaking effects!

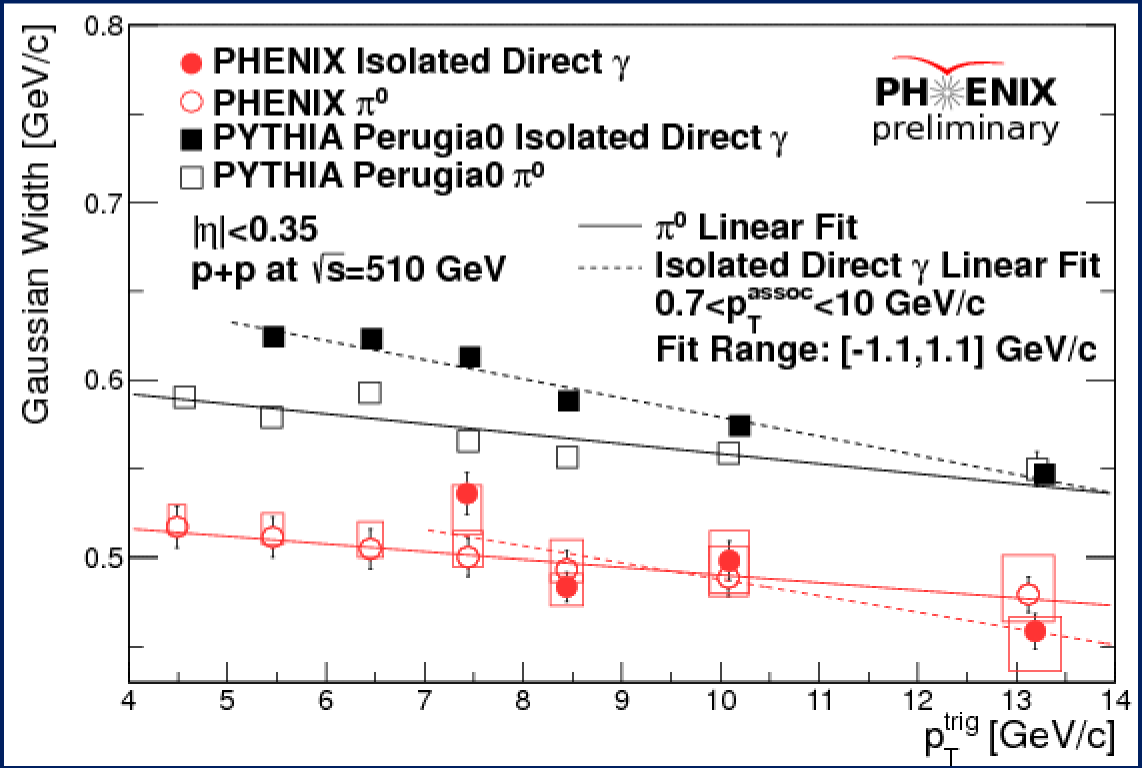
Sanity check: Simulated p_{out} widths for Drell-Yan and Z production

- No measured Drell-Yan or Z data as function of out-of-plane momentum component
  - No reason to look at p_{out} when can look at full p_T of pair
- Try to make more direct comparison to our observable – look at *simulated* D-Y and Z p_{out} distributions, fit Gaussian regions, plot Gaussian widths as function of hard scale



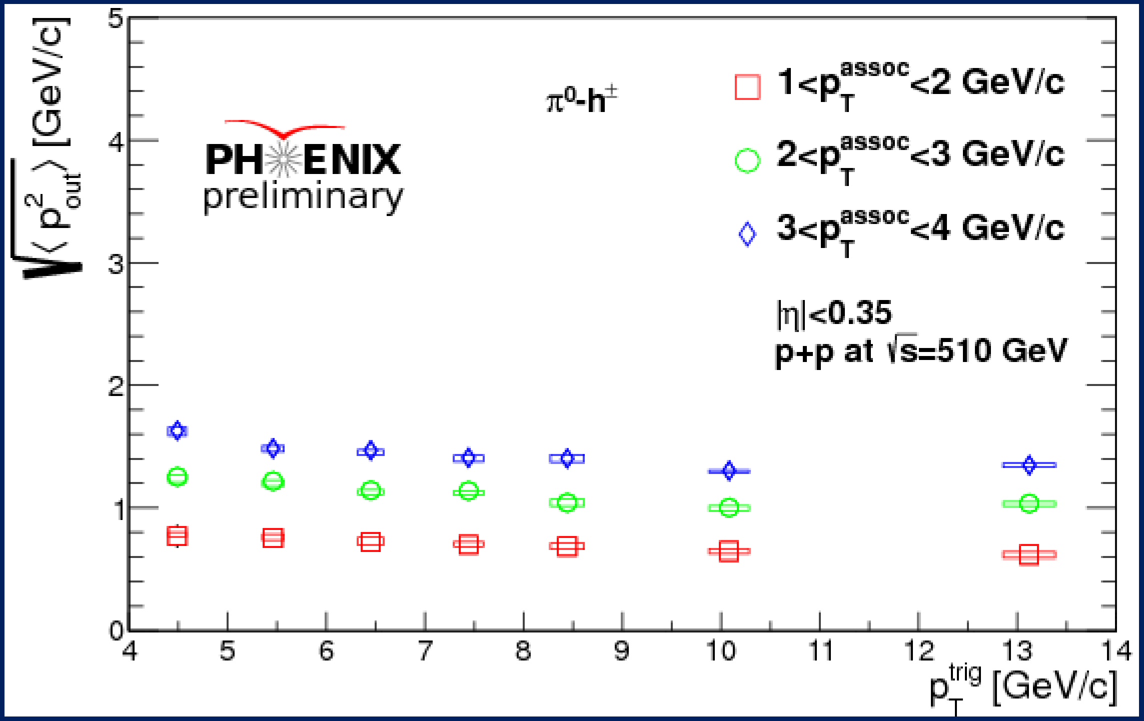
Widths increase as expected from CSS evolution

PYTHIA provides a way forward?



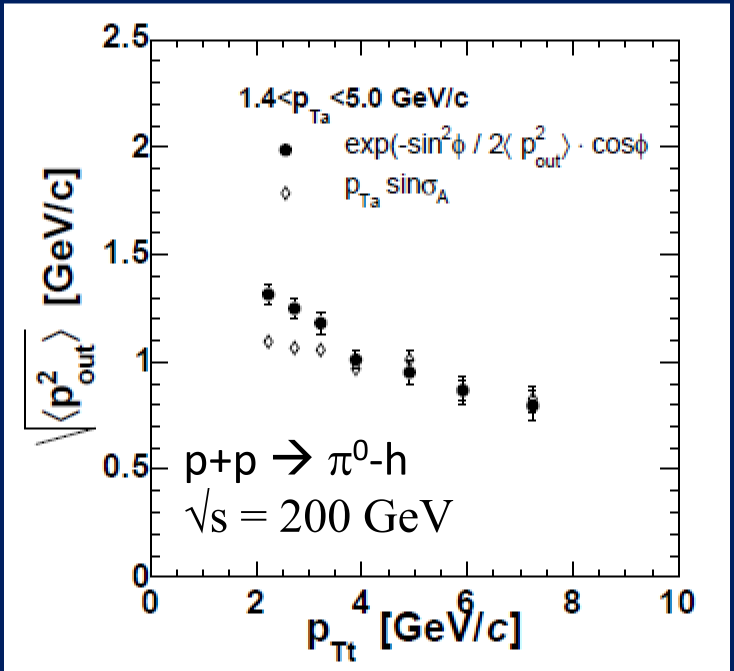
- If it's color-entangled partons across colliding protons, currently have *no* idea how to formulate the novel nonperturbative correlation functions
- Given that PYTHIA reproduces decreasing widths strikingly accurately, offers potential path forward to trying to understand what's going on

Alternative measure of nonperturbative transverse momentum: RMS p_{out}

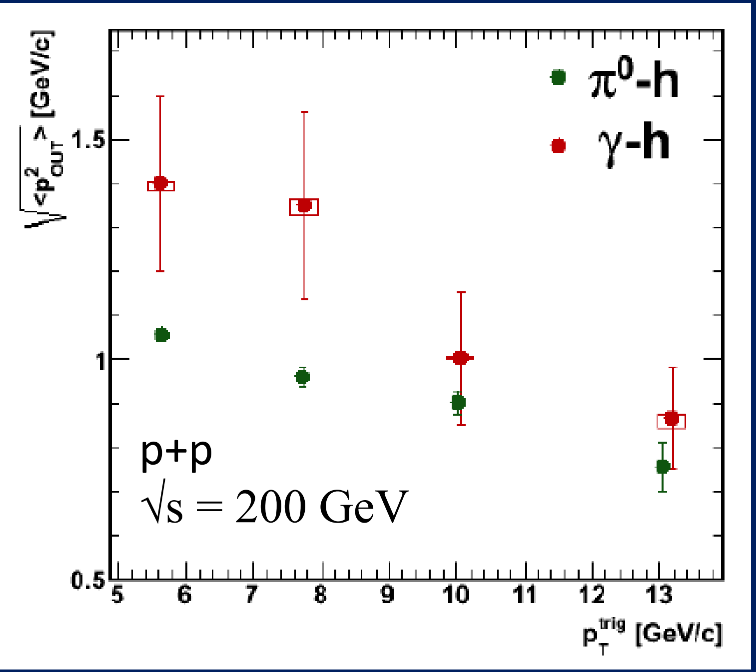


- Get via fit to away-side peak in $\Delta\phi$ distributions – see PRD82, 072001 (2010)
- Gives dependence on hard scale for each associated hadron p_T bin separately
  - All (modestly) decreasing with hard scale

This was actually observed previously!



PHENIX, PRD74, 072002 (2006)



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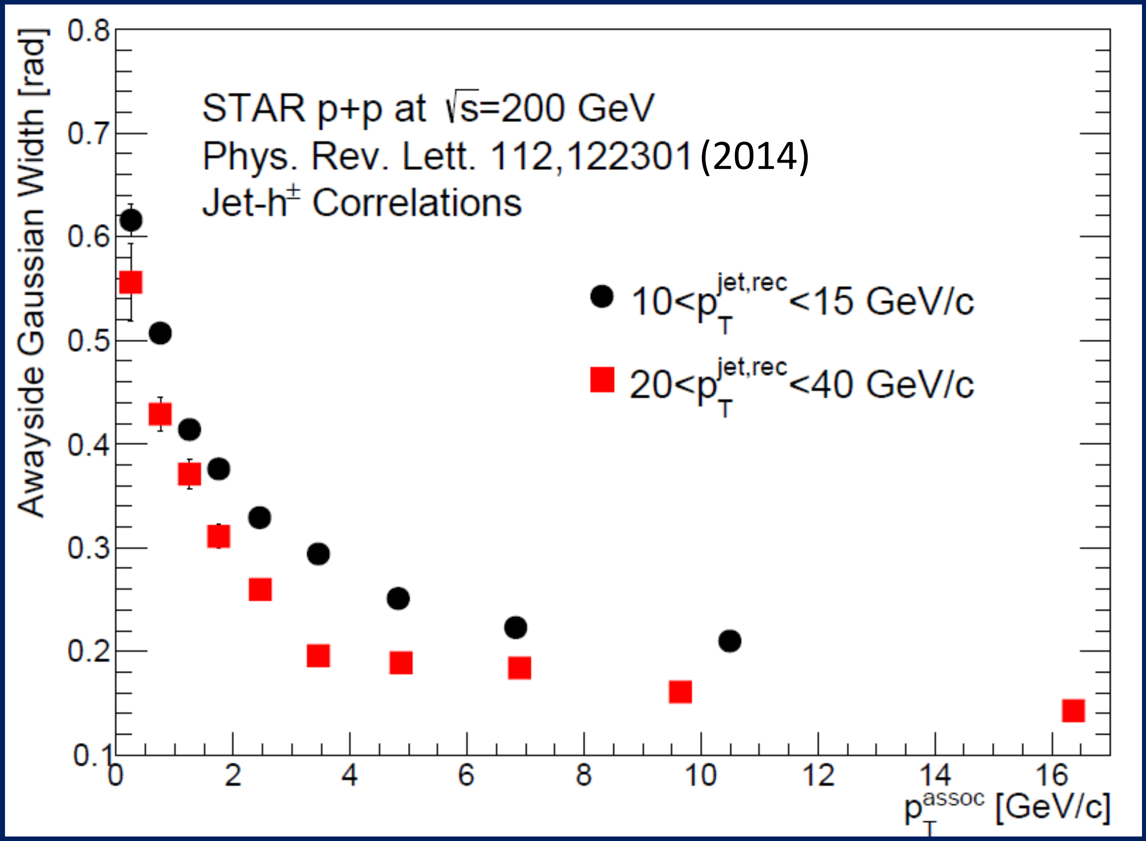
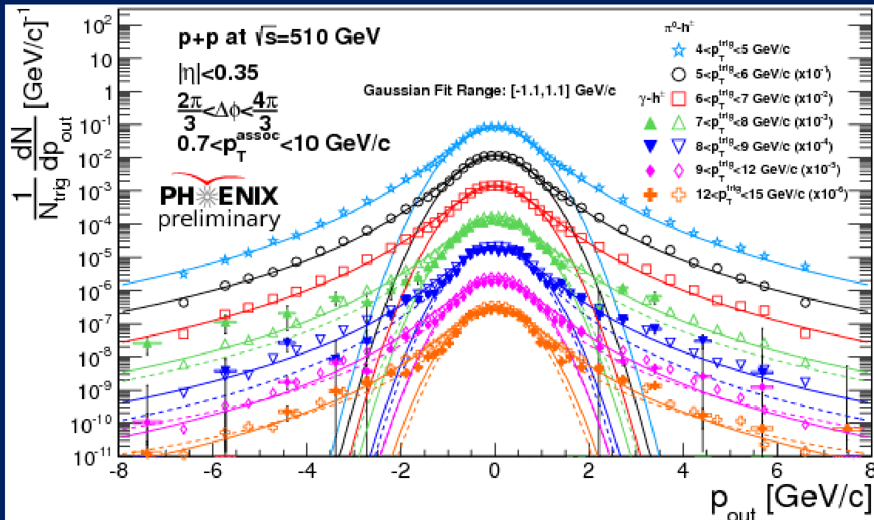
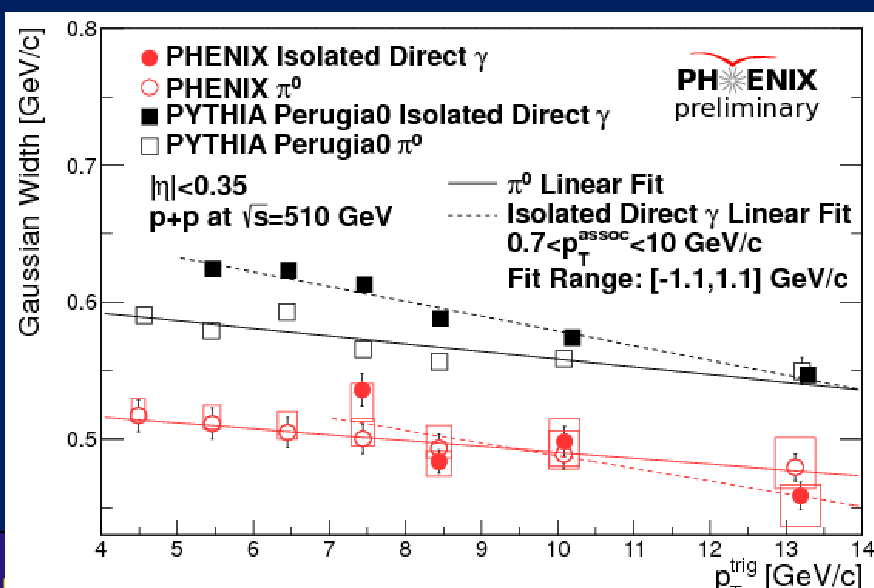


- Width of away side (related to RMS p_{out}) smaller for larger hard scale (squares) than smaller hard scale (circles), for every associated hadron p_T bin

- Motivated by completely different physics—reference for modification of dijet-like events in heavy ion collisions
  - Not previously considered with respect to TMD factorization breaking!

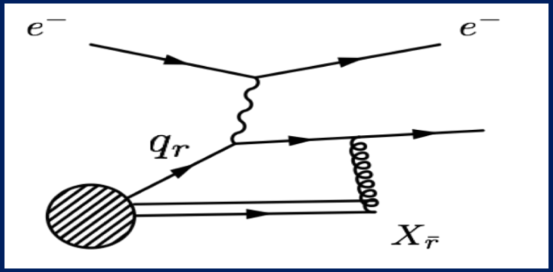
Color entanglement?

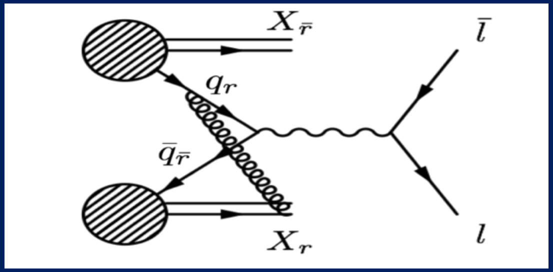


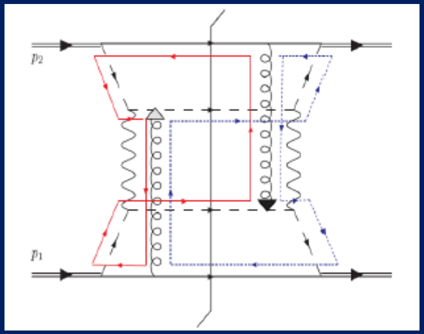


- Nonperturbative transverse momentum widths don't follow CSS evolution, and CSS evolution comes directly from TMD factorization derivation
- Decreasing widths reproduced in PYTHIA, in which gluon exchange between partons involved in hard scattering and remnants occurs
- Certainly suggestive! But so far can't rule out other (unknown) possible effects
- Getting some sense (from PYTHIA?) of what drives the decrease would boost confidence in drawing a conclusion

Summary: Lecture 5





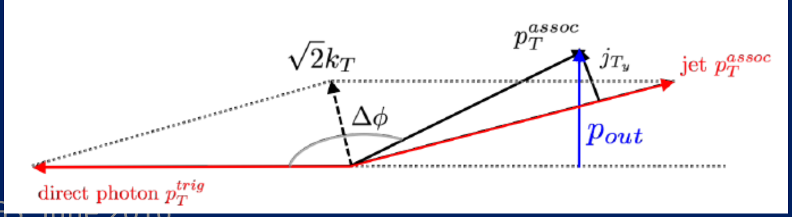


- Increasing focus on *interactions* in QCD
- Gradually shifting to think about QCD systems in new ways, focusing on topics/ideas/concepts long familiar to the world of condensed matter physics
  - All sorts of correlations within systems
  - Quantum mechanical phase interference effects
  - Quantum entangled systems
- Gaining greater appreciation for QCD in its full glory as a non-Abelian, gauge-invariant quantum field theory

Extra

Observables in Drell-Yan/Z versus p+p to hadrons

- p_T of Drell-Yan lepton pair or of Z boson already gives access to (summed) initial-state nonperturbative partonic transverse momentum
- Recall: In p+p to hadrons don't have exact 2-to-2 partonic kinematics, as you do in Drell-Yan or Z production
- Out-of-plane momentum component p_{out} for photon-hadron (or dihadron) production in p+p—don't know fragmentation momentum fraction *z*



Magnetic and electric A-B effects; Type-I and Type-II A-B effects

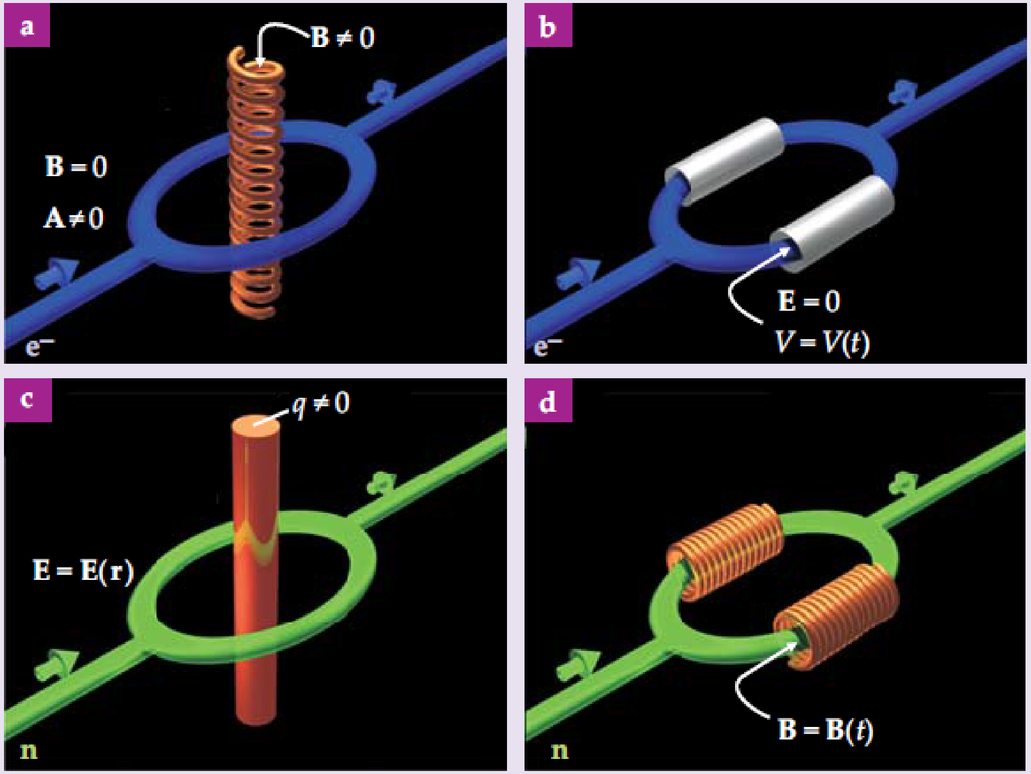
Box 1. Types and duals

Physics Today, September 2009

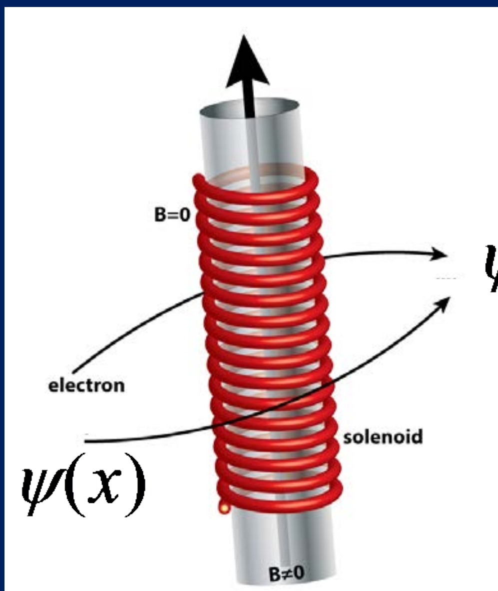
The original magnetic and electric Aharonov–Bohm effects (panels a and b) are type I effects in the sense that in an ideal experiment, the electron sees no **B** or **E** fields, though it does traverse different potentials **A** and *V*. In their respective dual effects—the Aharonov–Casher effect (panel c) and the so-called neutron-scalar AB effect (panel d)—polarized neutrons (neutral particles with magnetic dipole moments) replace unpolarized electrons, and electrostatic configurations change places with solenoids.[10] In panel c, a neutron interferometer encloses a line of charge, and in panel d, neutrons pass through pulsed solenoids. These duals are classified as type II effects because the neutron must traverse a nonvanishing **E** or **B** field.

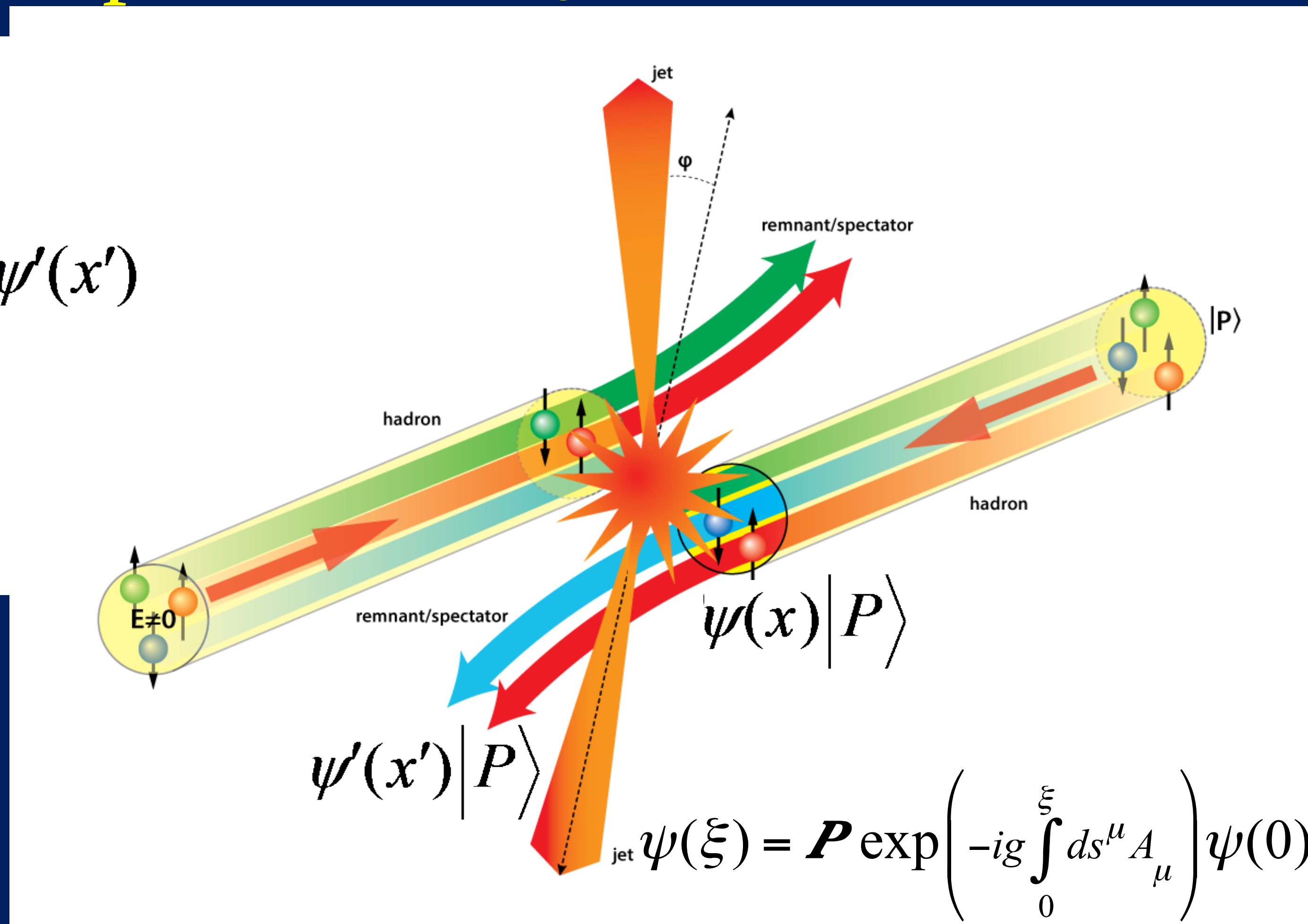
In either case, to acquire an AB phase shift, the electron or neutron must pass through a region of nonzero electromagnetic potential. That quantum mechanical result seems to elevate the status of the potentials to a physical reality absent from classical electromagnetism. Yakir Aharonov has pointed out that the potentials do overdetermine the experimental outcome; the phase shift need only be known modulo 2π. An alternative view is that the original magnetic AB effect shows electromagnetic fields acting nonlocally.[1]

For type II effects, the wavepackets can plow straight through force fields, and forces are allowed in the interaction. But the AB interpretation requires that the emerging wavepackets not be deflected or delayed in any way. Quantum mechanical descriptions generally circumvent the notion of forces. But one can use here an operational definition of forces that might be mimicking an AB effect: If the interaction has produced no deflection or delay, there were no forces.



Opportunities to see color-induced phases in QCD



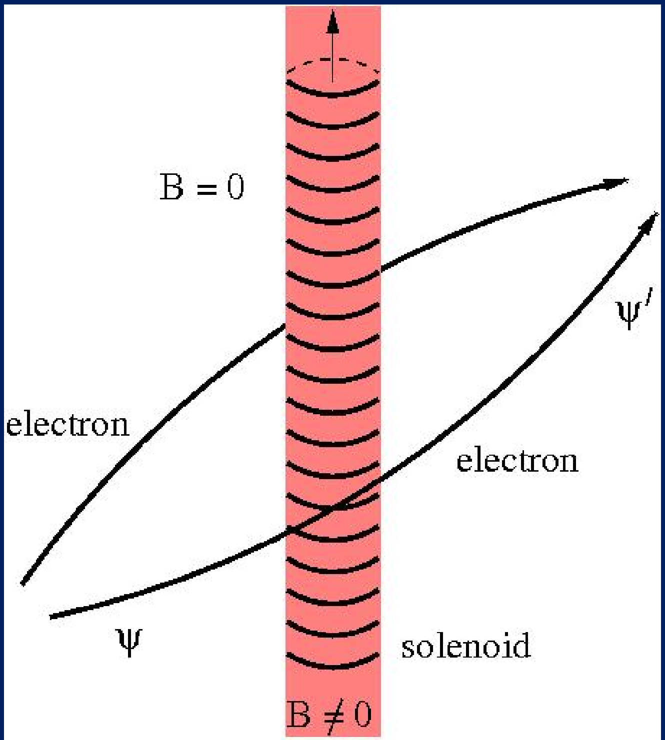


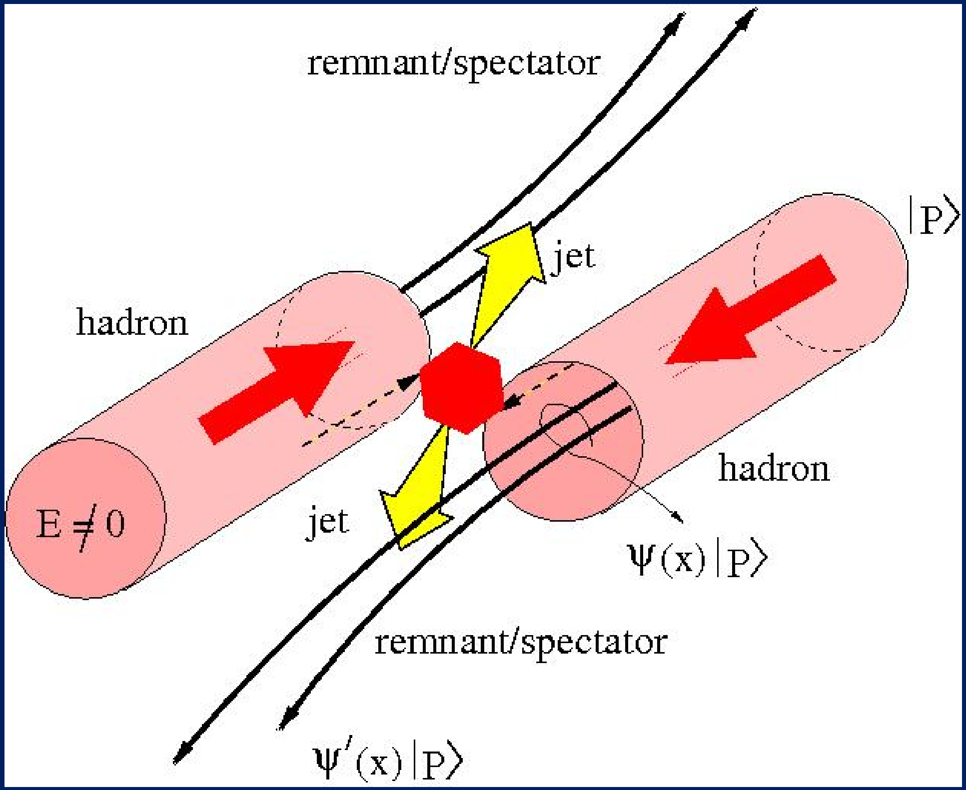
Slide from P. Mulders

Figures by Kees Huyser

Featuring: phases in gauge theories

Slide from P. Mulders



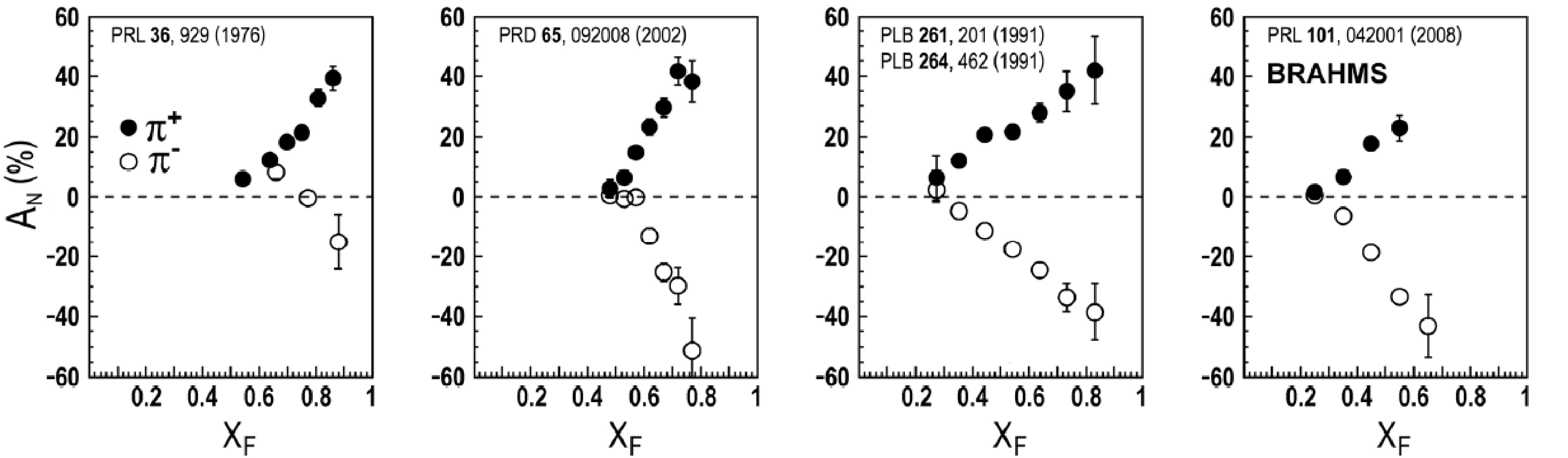


$$\psi' = P\, e^{ie\int ds.A}\, \psi$$

$$\psi_i(x)\big|P\big\rangle = P\, e^{-ig\int_x^{x'} ds_\mu A^\mu}\, \psi_i(x')\big|P\big\rangle$$

But what about proton-proton collisions?

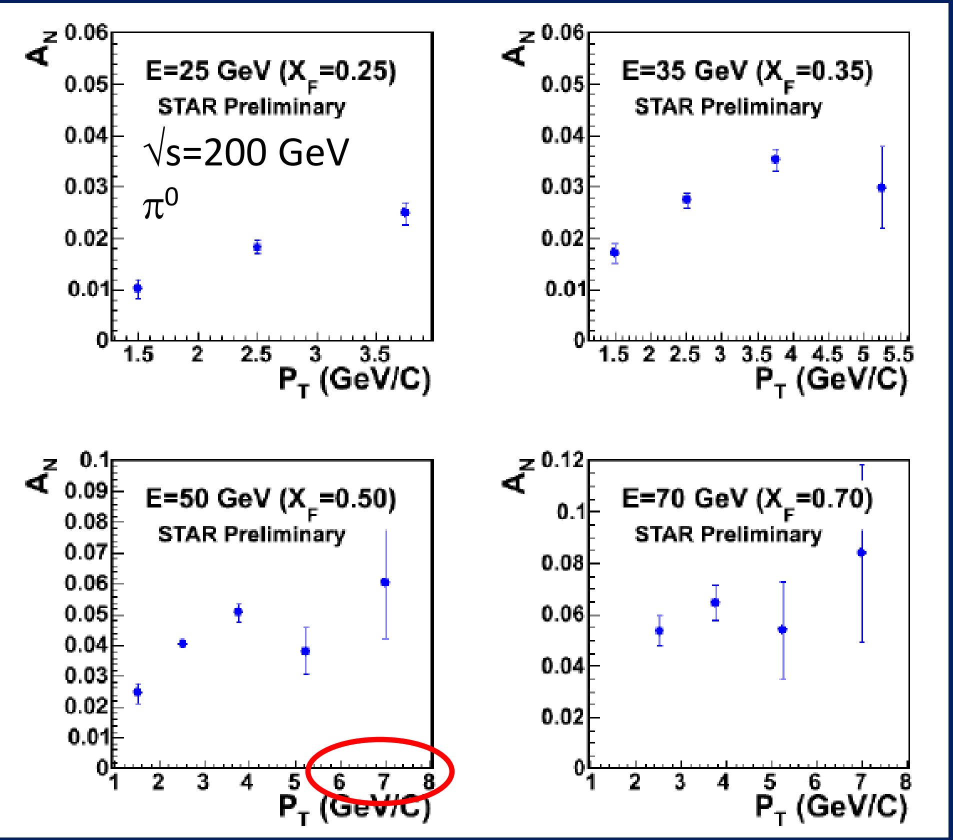
ANL	BNL	FNAL	RHIC
$\sqrt{s}$=4.9 GeV	$\sqrt{s}$=6.6 GeV	$\sqrt{s}$=19.4 GeV	$\sqrt{s}$=62.4 GeV



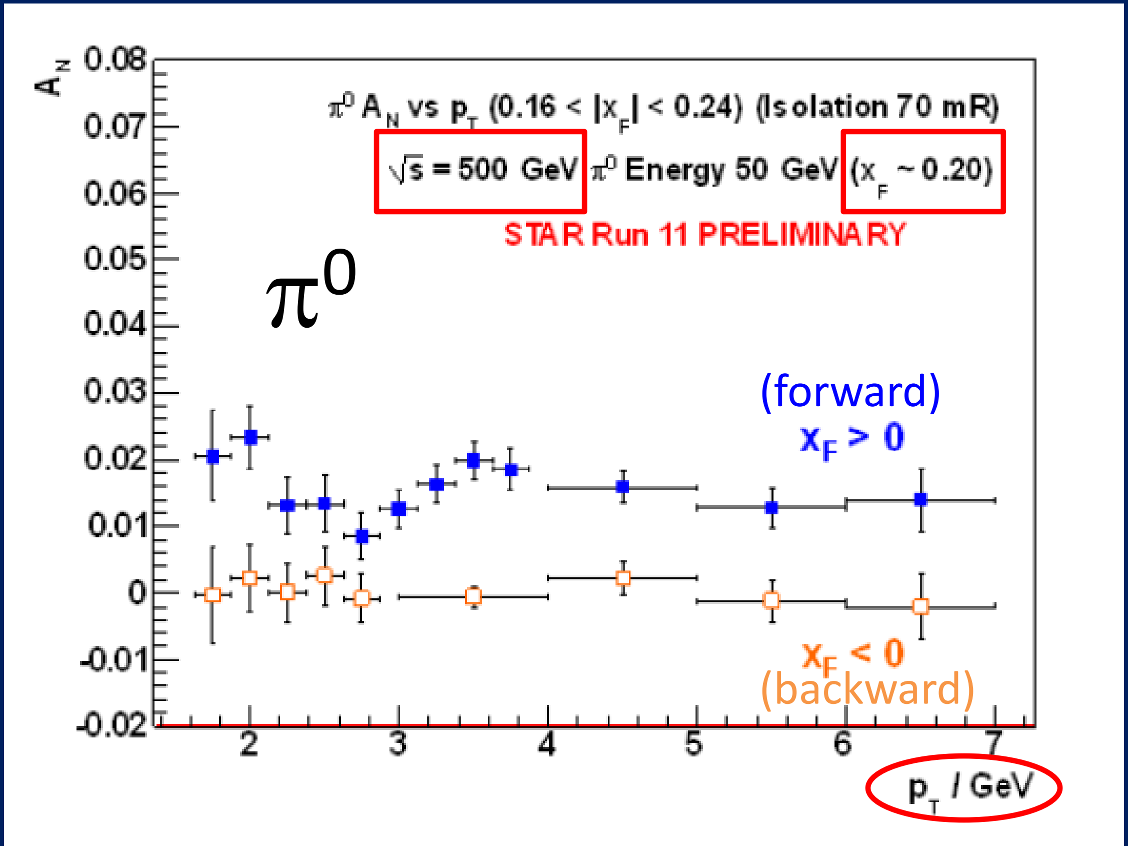
Strikingly similar effects across energies!
→ Continuum between nonperturbative/nonpartonic and perturbative/partonic descriptions of this <u>nonperturbative</u> structure?

Transverse single-spin asymmetry in $p+p \rightarrow hadron + X$: Only measure one momentum scale

- For high enough p_T of produced hadron (>1-2 GeV) have hard scale, so can apply perturbative calculations
  - Clear nonzero asymmetries out to 8 GeV → $Q^2 \sim 64$ GeV^2
- Can have contributions from initial-state and final-state effects
- Inclusive measurement—don't measure the combination of a hard plus a nonperturbative momentum scale required to (directly) apply TMD framework in pQCD calculations

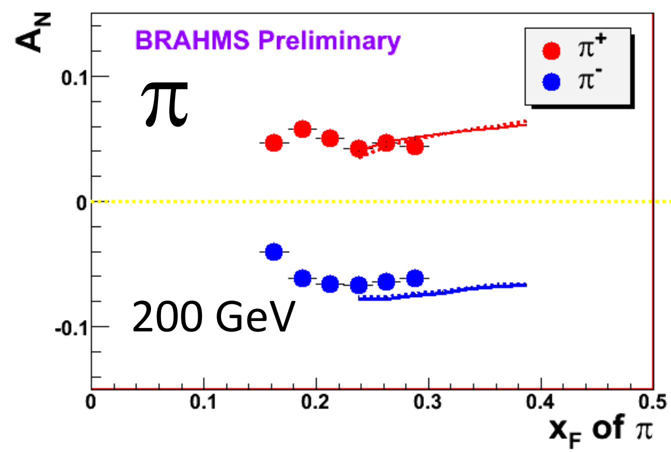


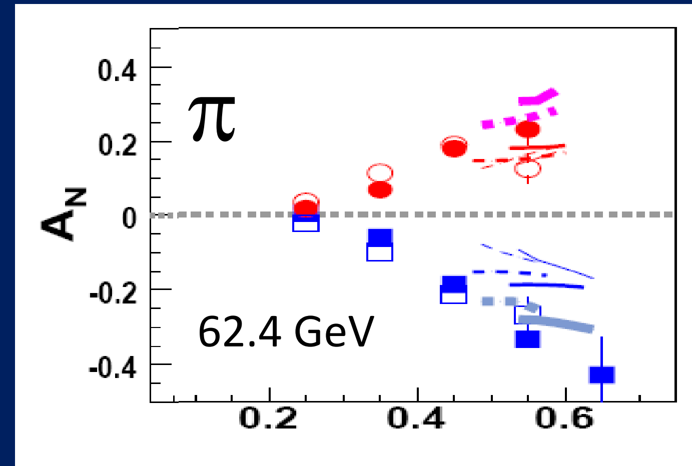
Single-spin asymmetries in transversely polarized p+p collisions



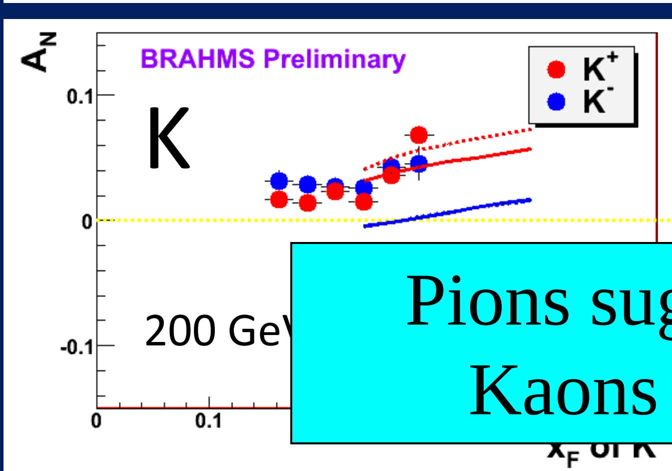
- Effects persist to kinematic regimes where perturbative QCD techniques clearly apply
- p_T = 7 GeV
  → $Q^2 \sim 49$ GeV^2!

π, K, p at 200 and 62.4 GeV

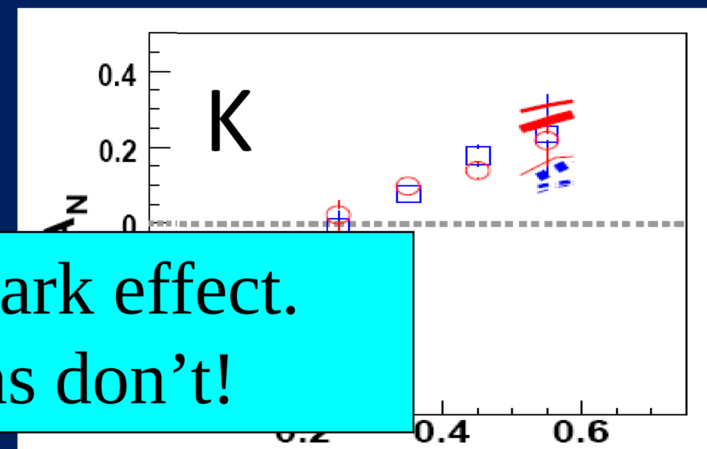




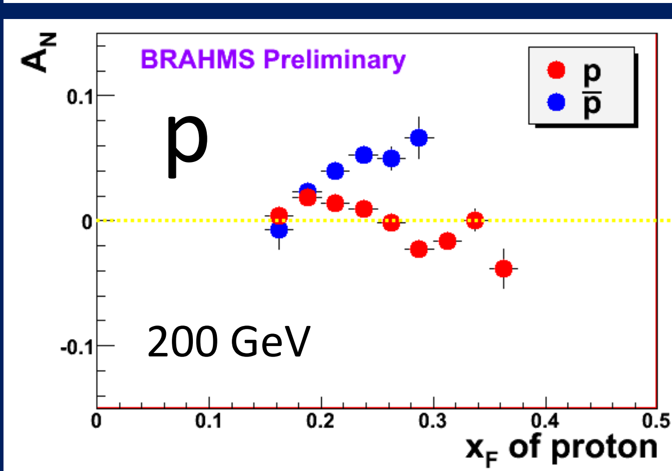
Note different scales



K- asymmetries underpredicted



Pions suggest valence quark effect.
Kaons and (anti)protons don't!



Large antiproton asymmetry??
Unfortunately no 62.4 GeV measurement