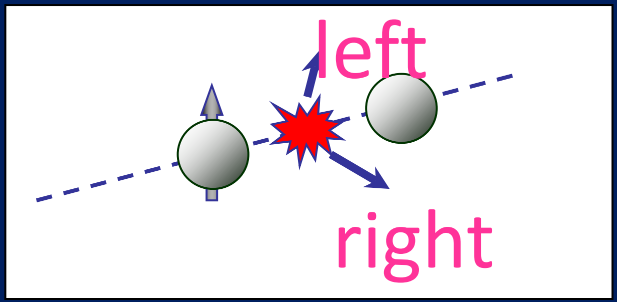
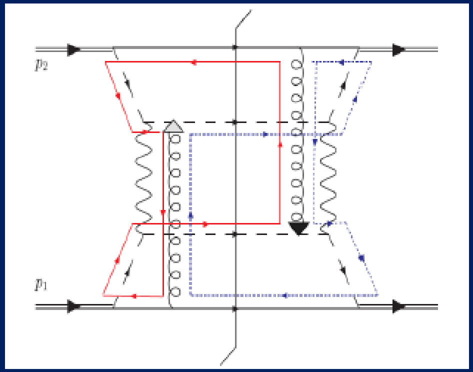
Transverse-Momentum-Dependent Distributions and Color Entanglement in QCD

Lecture 4 – TMD factorization, Aharonov-Bohm, and Color Entanglement I

Christine A. Aidala

University of Michigan





Hampton University Graduate Studies Program
Jefferson Lab
June 2016

But first – response to a question

- On Friday there was a question about why there are no TMD pdfs for longitudinally polarized parton within unpolarized nucleon, or unpolarized parton within longitudinally polarized nucleon
- Recall single-spin spin-momentum correlations in the initial state (i.e. TMD pdfs) can be written as triple vector products: $\boxed{S \cdot (p_{boost} \times k_T)}$

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 $h_{1T}^{\perp}$

- For longitudinally polarized nucleon or parton, spin is parallel to boost axis, so triple product is zero

Not just QCD systems

- In the business of nuclear physics, you study your systems via scattering processes
  - Scattering process typically treated as a tool

- In recent years, QCD processes themselves becoming a focus, in addition to QCD systems

"The good life is a process, not a state of being."
– Carl Rogers (20th century American psychologist)

Recall: “Naïve-T-odd” (PT-odd) spin-momentum correlations require phase interference

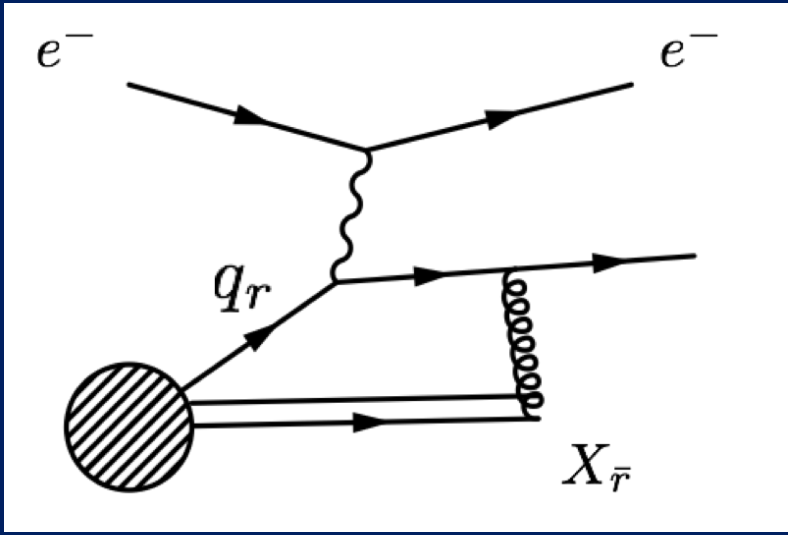
- Sivers and Boer-Mulders TMD pdfs odd under “naïve-time-reversal” (actually a PT transformation)

- 1990 – Proposed by D.W. Sivers – PRD41, 83 (1990)
- 1993 – Claimed forbidden by J.C. Collins – NPB396, 161 (1993)

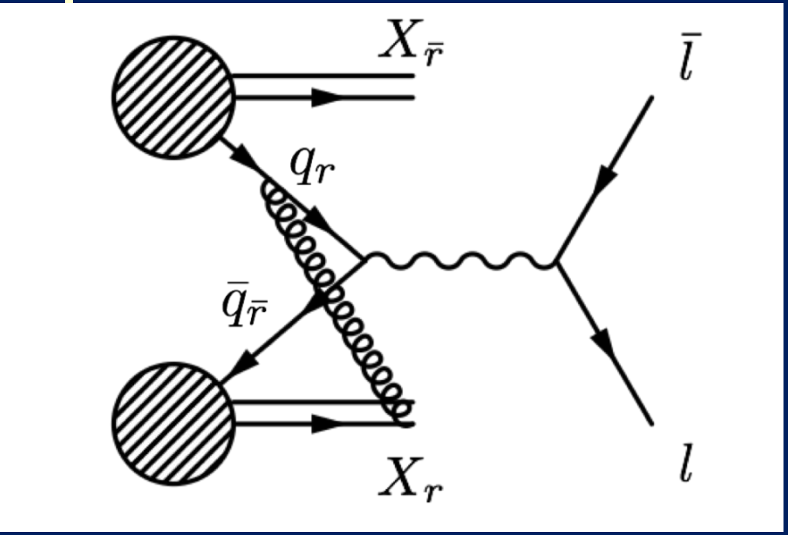
- 2002 – Demonstrated nonvanishing by Brodsky, Hwang, Schmidt if *phase interference effects due to color interactions* present – PLB530, 99 (2002)
- 2002 – J.C. Collins realizes that this implies a relative sign difference between PT-odd TMD pdfs with color interactions in the initial vs. the final state – PLB536, 43 (2002)
  - Sparked dramatic increase in interest in the field – 95 citations of Sivers paper 1990-2002, 814 more (total 909) 2002-now!
- 2004 – Measurement of nonzero Sivers asymmetry in SIDIS by HERMES → these interactions are indeed taking place – PRL94, 012002 (2005)

Modified universality of certain transverse-momentum-dependent pdfs: Color in action!

Deep-inelastic lepton-nucleon scattering:
Attractive final-state interactions



Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions



As a result, get *opposite sign* for the Sivers transverse-momentum-dependent pdf when measure in semi-inclusive DIS versus Drell-Yan: *process-dependent* pdf! (Collins 2002)

Figures by J.D. Osborn

Recall: Modified universality of PT-odd TMD pdfs

- Gluon exchange between a parton involved in the hard scattering and a remnant can (and presumably does) always take place

- What's special about processes involving PT-odd TMD pdfs: *Can't get rid of such gluon exchanges via a gauge transformation*

An intuitive (if hand-waving) picture

- Look at the gluon exchange as setting up a field, through which a colored quark (SIDIS) or anticolored antiquark (Drell-Yan) passes
  - It could also be an antiquark in SIDIS, or the quark in Drell-Yan. What matters is the color relation between the parton involved in the hard scattering and the remnant with which the gluon exchange occurs
- The field carries spin information
- The field also has a spatial extent
- Passage of the quark or antiquark will be “with” or “against” the spin, depending on where it passes
- These different paths lead to different phase shifts, which then produce the interference leading to the nonzero spin-momentum correlation
- The phase shifts and resulting interference are different for the different color relations (SIDIS vs. Drell-Yan), leading to an overall relative minus sign associated with the (interaction plus the) PT-odd TMD pdf

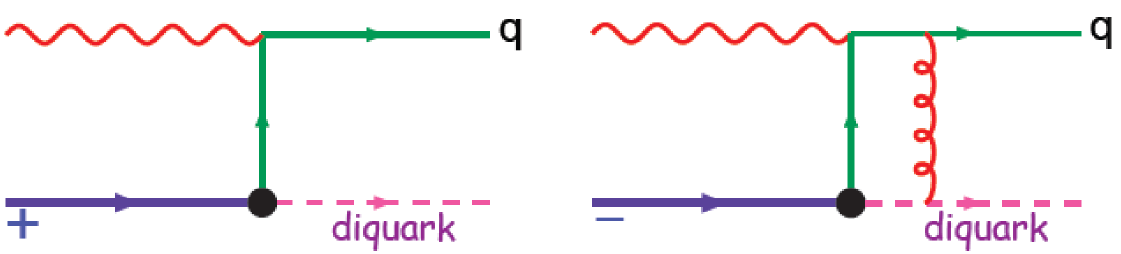
Modified universality requires full QCD: Gauge-invariant quantum field theory

We have ignored here the subtleties needed to make this a gauge invariant definition: an appropriate path ordered exponential of the gluon field is needed [18].

From 1993 claim by J.C. Collins that processes involving PT-odd TMD pdfs must vanish

gauge links have physical consequences;
quark models for non vanishing Sivers function,

SIDIS final state interactions



Brodsky, Hwang, Schmidt, PL B530 (2002) 99 - Collins, PL B536 (2002) 43

An earlier proof that the Sivers asymmetry vanishes because of time-reversal invariance is invalidated by the path-ordered exponential of the gluon field in the operator definition of parton densities. Instead, the time-reversal argument shows that the Sivers asymmetry is reversed in sign in hadron-induced hard processes (e.g., Drell-Yan), thereby violating naive universality of parton densities. Previous phenomenology with time-reversal-odd parton densities is therefore validated.

$$[f_{1T}^{q\perp}]_{\text{SIDIS}} = -[f_{1T}^{q\perp}]_{\text{DY}}$$

Slide from M. Anselmino, Transversity 2014

Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

Wikipedia:

“The Aharonov–Bohm effect is important conceptually because it bears on three issues apparent in the recasting of (Maxwell's) classical electromagnetic theory as a gauge theory, which before the advent of quantum mechanics could be argued to be a mathematical reformulation with no physical consequences. The Aharonov–Bohm thought experiments and their experimental realization imply that the issues were not just philosophical.

The three issues are:

- whether potentials are "physical" or just a convenient tool for calculating force fields;
- whether action principles are fundamental;
- the principle of locality.”

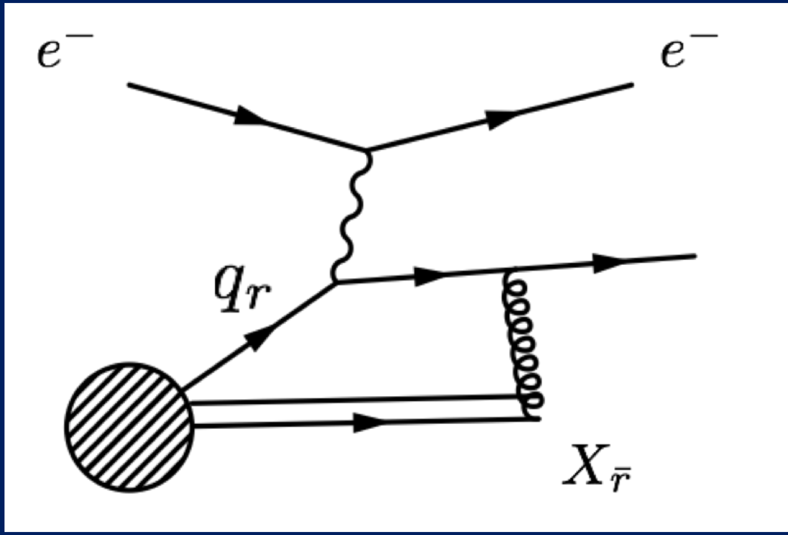
Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

Physics Today, September 2009 :
The Aharonov–Bohm effects: Variations on a subtle theme,
by Herman Batelaan and Akira Tonomura.

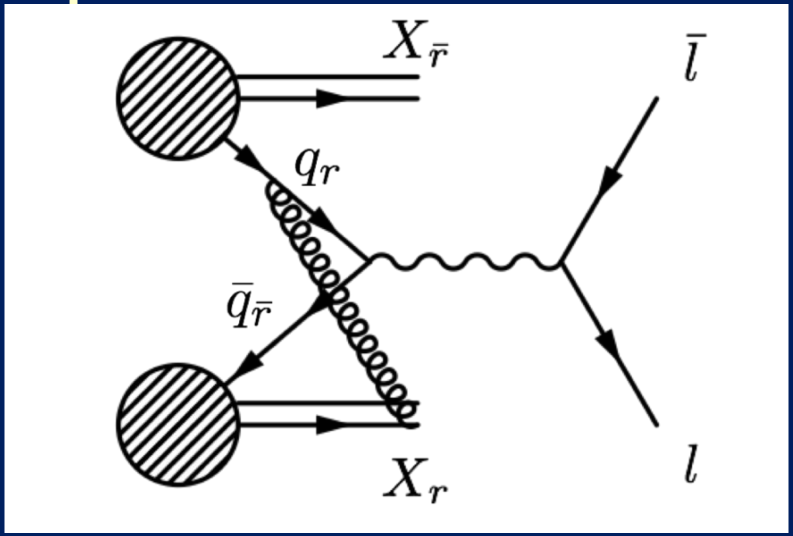
"Aharonov stresses that the arguments that led to the prediction of the various electromagnetic AB effects apply equally well to any other gauge-invariant quantum theory. In the standard model of particle physics, the strong and weak nuclear interactions are also described by gauge-invariant theories. So one may expect that particle-physics experimenters will be looking for new AB effects in new domains."

Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm effect in QCD!!

Deep-inelastic lepton-nucleon scattering:
Attractive final-state interactions



Quark-antiquark annihilation to leptons:
Repulsive initial-state interactions



Phase shifts due to the potential
See e.g. Pijlman, hep-ph/0604226 or Sivers, arXiv:1109.2521

Figures by J.D. Osborn

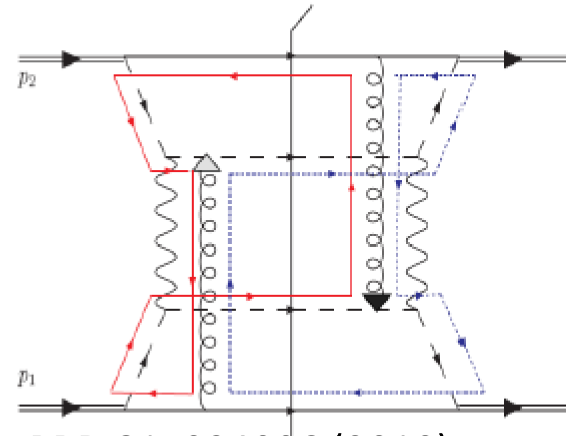
Recall: SIDIS and Drell-Yan are QED processes involving hadrons

- Simplicity of these two processes: Abelian vs. non-Abelian nature of the gauge group doesn't play a major qualitative role

- BUT: In QCD expect additional, new effects due to specific non-Abelian nature of the gauge group

QCD Aharonov-Bohm effect: 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



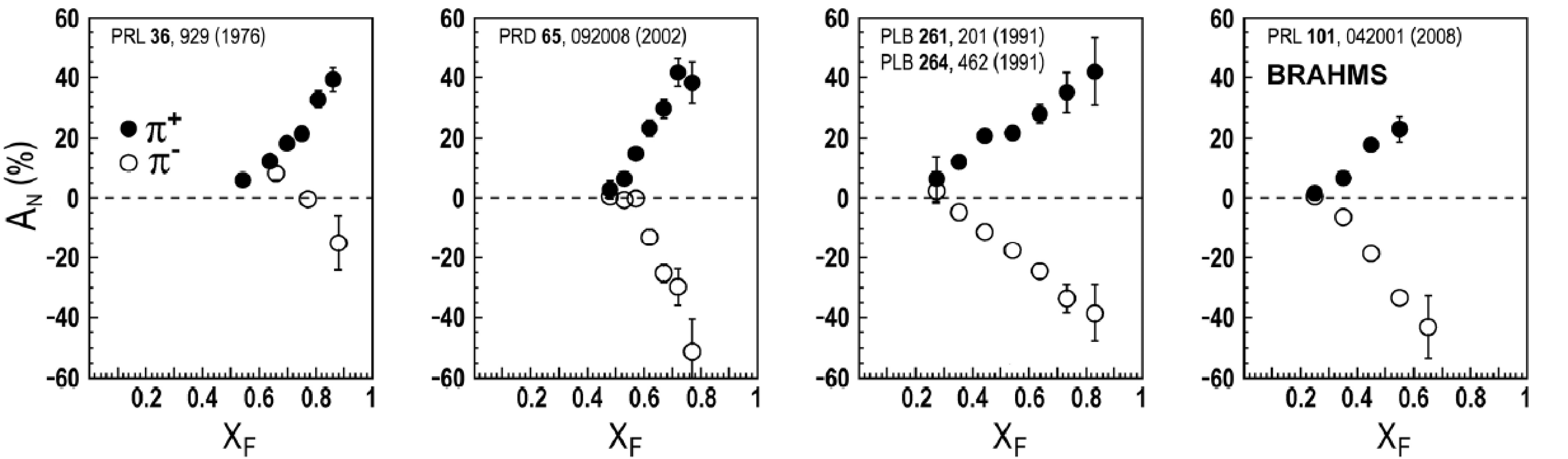
PRD 81, 094006 (2010)

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

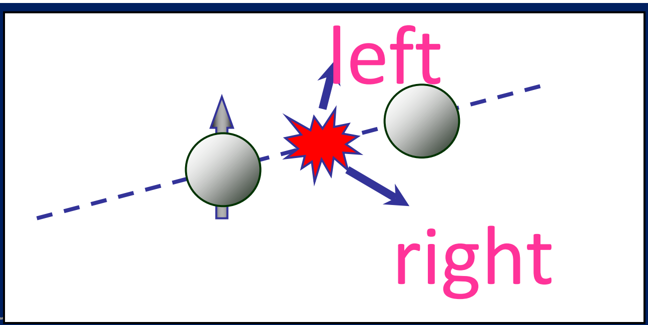
Color flow can't be described as flow in the two gluons separately. Requires *simultaneous* presence of both.

Huge *spin asymmetries in p+p → hadrons: Does color entanglement play a role??*

ANL	BNL	FNAL	RHIC
√s=4.9 GeV	√s=6.6 GeV	√s=19.4 GeV	√s=62.4 GeV



$$x_F = 2p_{long} / \sqrt{s}$$



Terminology

- “TMD factorization breaking”
- “Color entanglement”
- “Correlated partons across colliding protons”

- All refer to same predicted phenomenon

Entanglement

- Consider familiar case of spins of two-electron system
- Non-entangled cases, e.g.

$$|\uparrow\rangle\,|\downarrow\rangle$$

$$|\uparrow\rangle\,|\downarrow\rangle + |\downarrow\rangle\,|\downarrow\rangle = (|\uparrow\rangle + |\downarrow\rangle)|\downarrow\rangle$$

- Entangled cases, e.g.

$$|\uparrow\rangle\,|\uparrow\rangle + |\downarrow\rangle\,|\downarrow\rangle$$

$$|\uparrow\rangle\,|\downarrow\rangle - |\downarrow\rangle\,|\uparrow\rangle$$

- In entangled cases the two spins are correlated
  - Don't factorize from one another
  - Any interactions are with the two-electron system as a whole

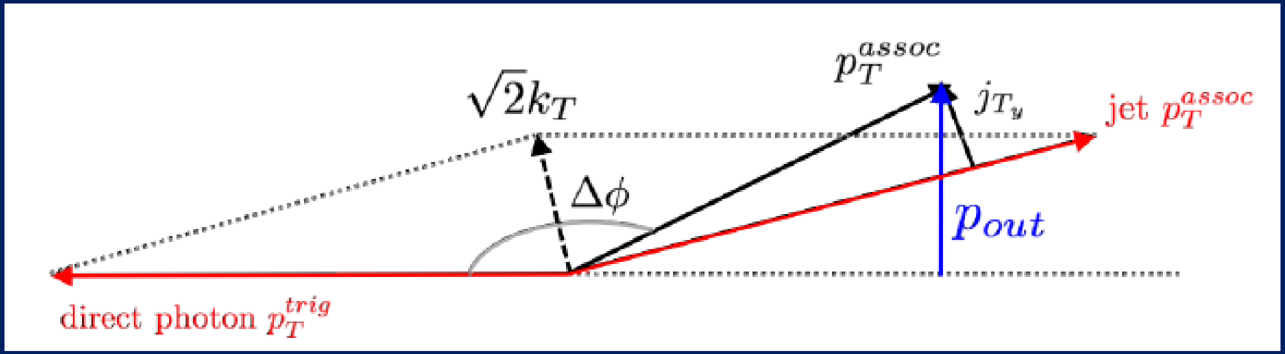
Factorization and factorization breaking

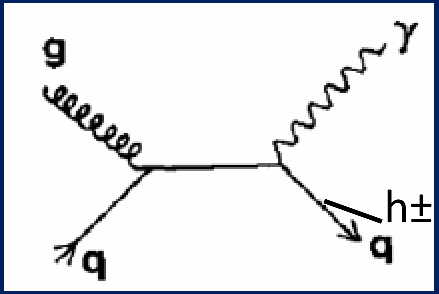
- Factorization generally refers to two things in QCD processes with a hard scale
  - Factorization of short-distance (i.e. perturbative) from long-distance (i.e. nonperturbative) physics
  - Factorization of nonperturbative functions from one another, e.g. into separate pdfs and FFs for each hadron involved in a process
- Factorization of short-distance from long-distance physics believed to hold
- Factorization of nonperturbative functions predicted to be broken in TMD processes involving p+p → hadrons
  - Would need e.g. a single nonperturbative function to describe correlated partons in the two protons

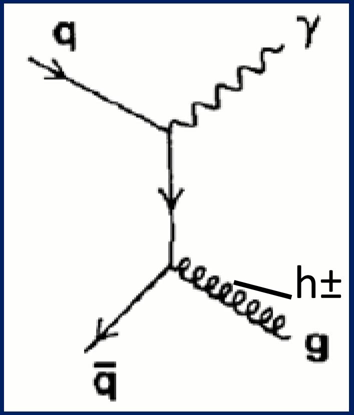
How can we search for color entanglement effects?

- Need processes where gluons can be exchanged in *both* initial and final states
  - Hadron-hadron collisions
  - At least one hadron in the final state (gluon can be exchanged with remnant of initial-state hadron)
- Need processes sensitive to nonperturbative transverse momentum

Direct photon – hadron correlations in p+p

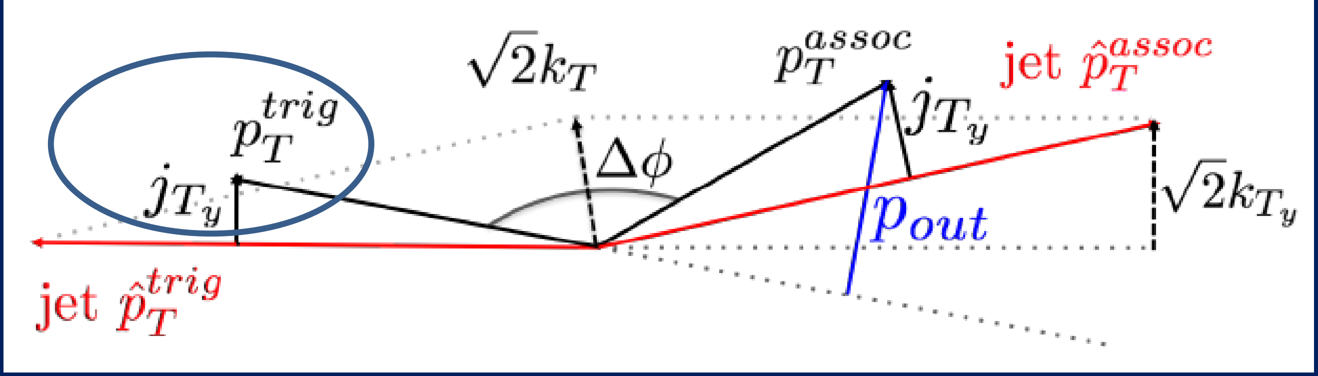






- "Direct" photon – produced directly in hard scattering
- ~85% quark-gluon Compton scattering (top diagram) in our kinematics
- Measure out-of-plane momentum component p_{out} of one particle with respect to other
- Unpolarized – effects predicted for polarized and unpolarized; more data available for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

Also π^0 – hadron correlations in p+p

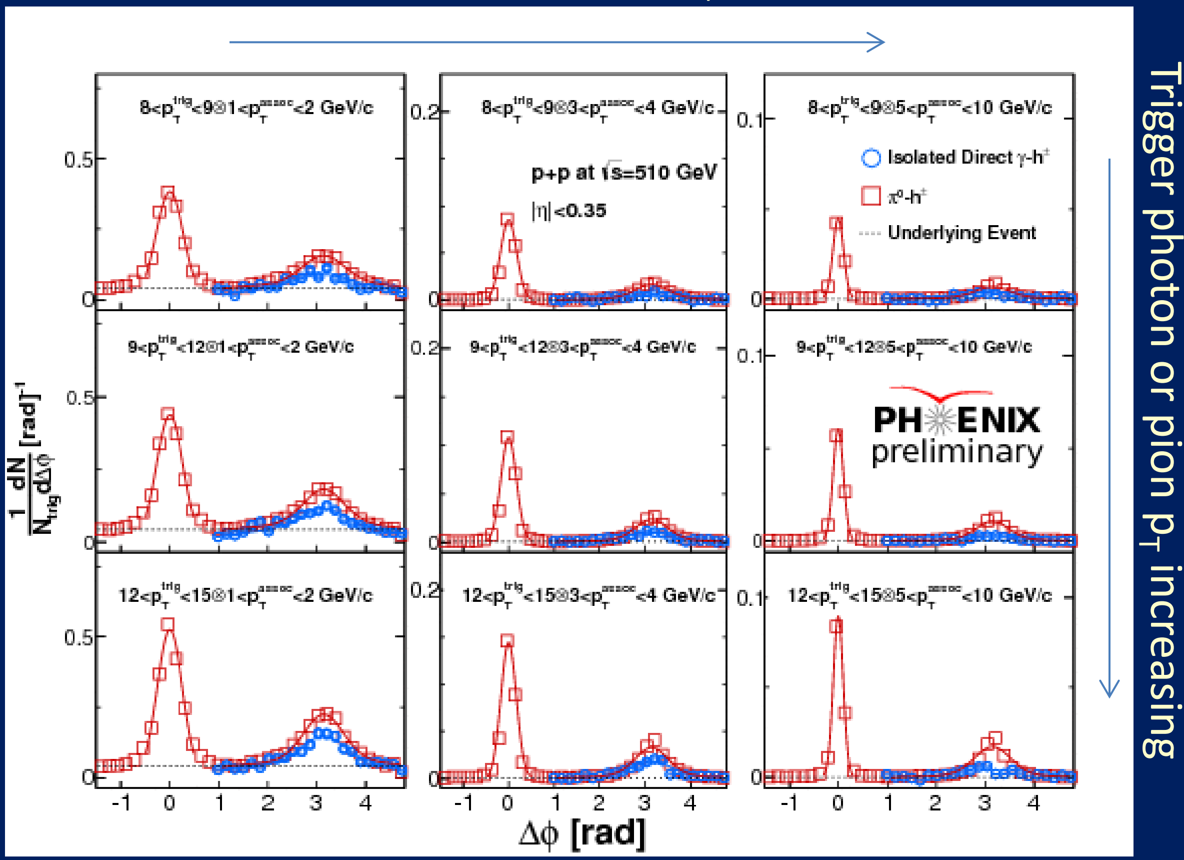


- Additional place for gluon to attach in π^0 – charged hadron correlations compared to direct photon – charged hadron correlations
- Additional nonperturbative transverse momentum from pion fragmentation

- Both measurements at $\sqrt{s}$ = 510 GeV, midrapidity

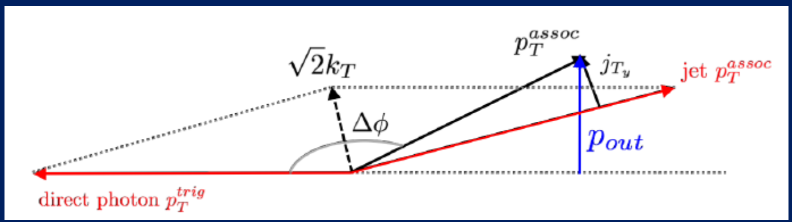
Two-particle azimuthal angular correlations

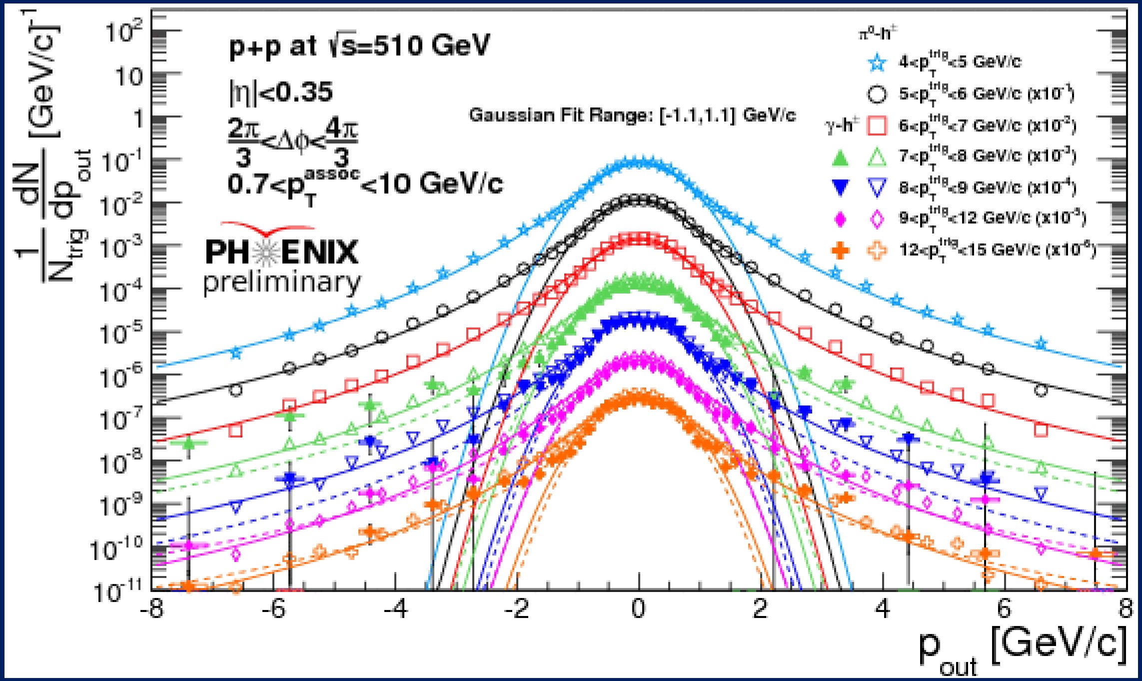
Associated charged hadron p_T increasing



- 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

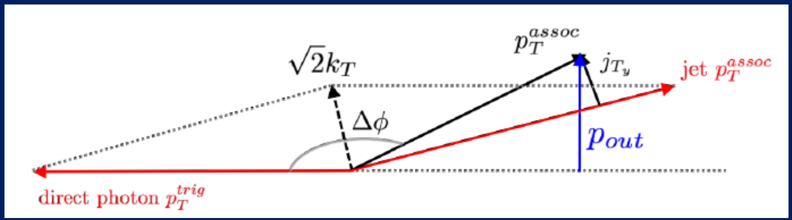
Out-of-plane momentum component distributions

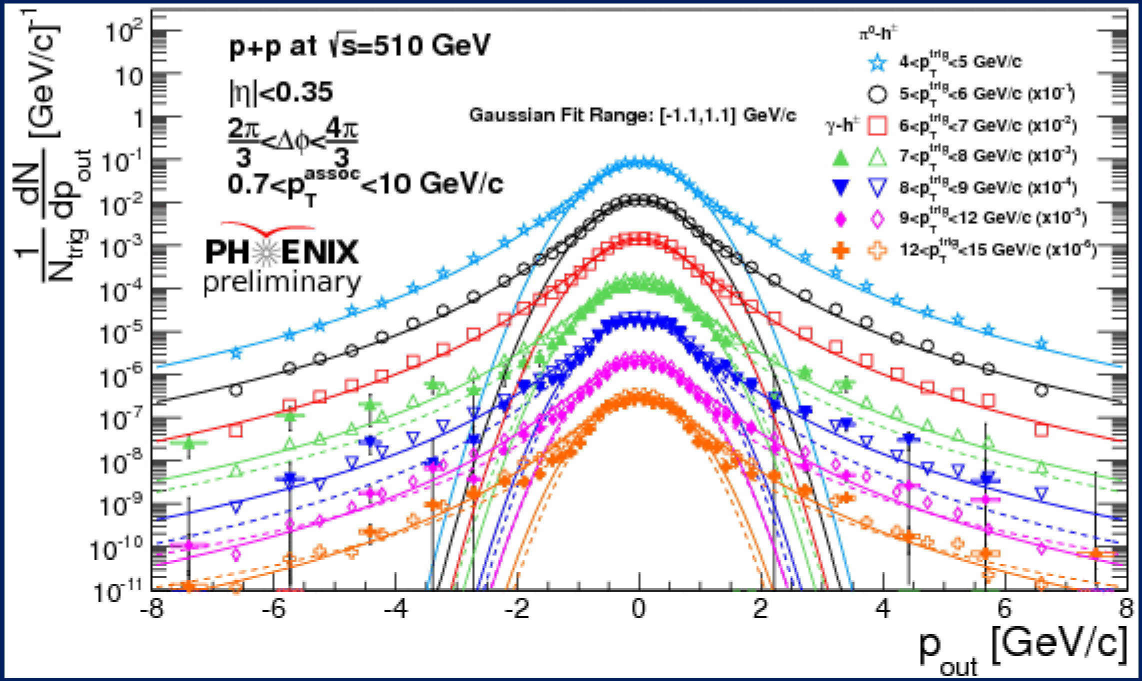




- Out-of-plane momentum distribution for charged hadrons in the away-side peak
- Associated charged hadron p_T from 0.7-10 GeV/c
  - Underlying event (hadrons not associated with jet structure) statistically subtracted
- Different colors for different photon or pion p_T bins, ranging from 4-15 GeV/c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

Now what?

- Okay, so we've measured a hard-scattering observable in p+p → hadrons sensitive to nonperturbative transverse momentum
- How can we look for evidence of color entanglement effects??
- Will examine *evolution* of the nonperturbative Gaussian widths with the hard scale and look for deviations from Collins-Soper-Sterman evolution
- To be continued in Lecture 5 . . .

Summary: Lecture 4

- *Processes and interactions* in QCD are becoming a focus in their own right, independent of their use as tools to study hadron structure
- Studies related to transverse-momentum-dependent pdfs and FFs are bringing to light fundamental aspects of QCD as a gauge-invariant quantum field theory, and specifically as a non-Abelian one

Extra

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

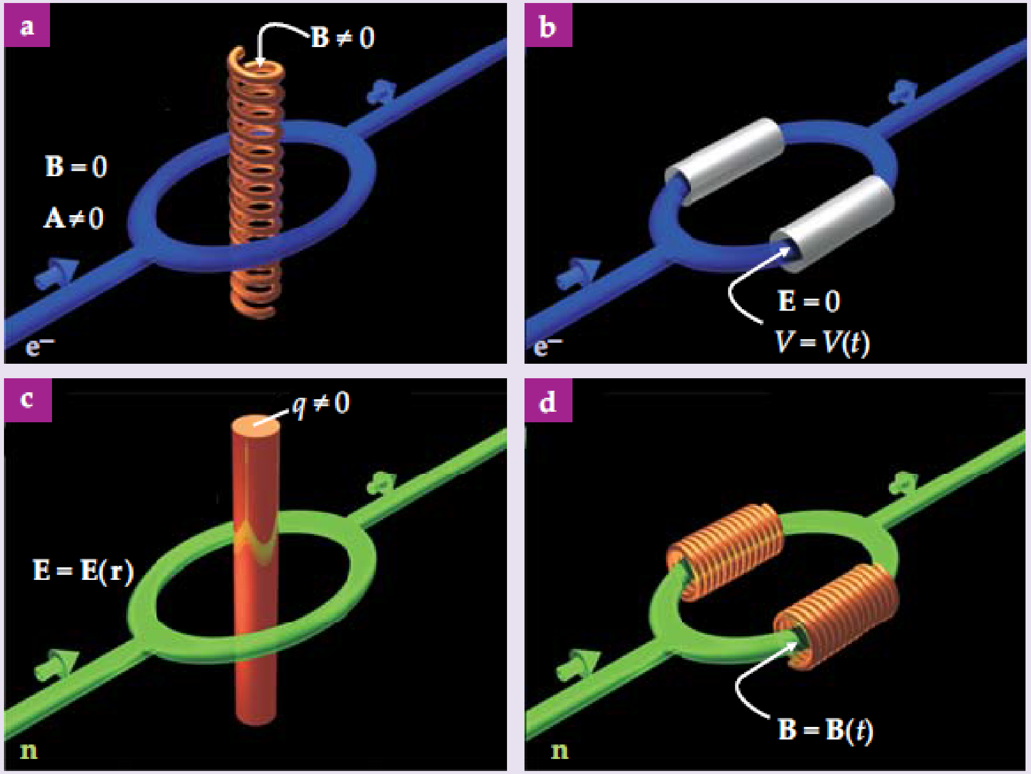
Box 1. Types and duals

Physics Today, September 2009

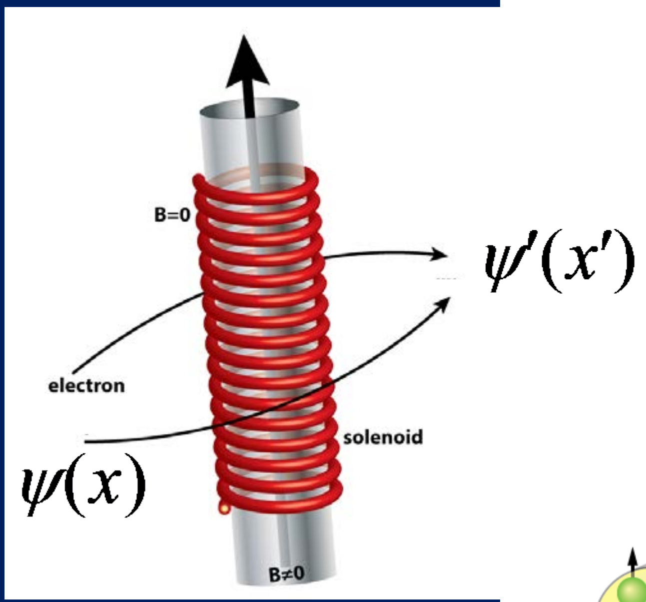
The original magnetic and electric Aharonov–Bohm effects (panels a and b) are type I effects in the sense that in an ideal experiment, the electron sees no **B** or **E** fields, though it does traverse different potentials **A** and *V*. In their respective dual effects—the Aharonov–Casher effect (panel 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.

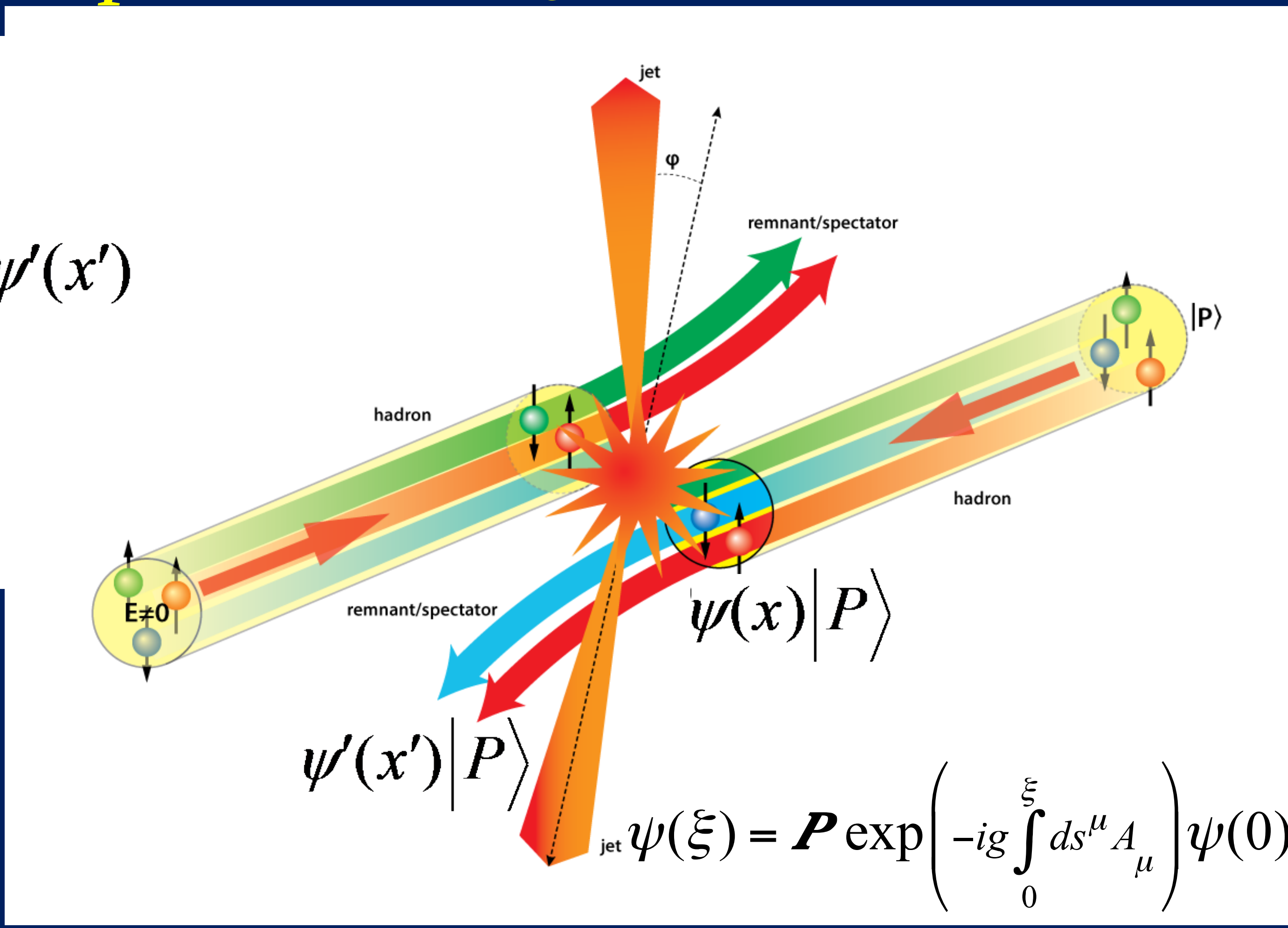
In either case, to acquire an AB phase shift, the electron or neutron must pass through a region of nonzero electromagnetic potential. That quantum mechanical result seems to elevate the status of the potentials to a physical reality absent from classical electromagnetism. Yakir Aharonov has pointed 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



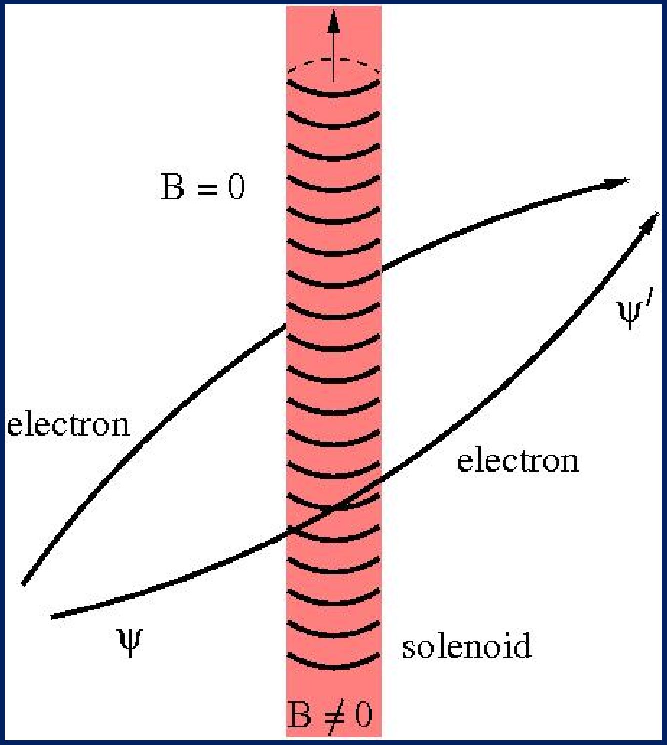


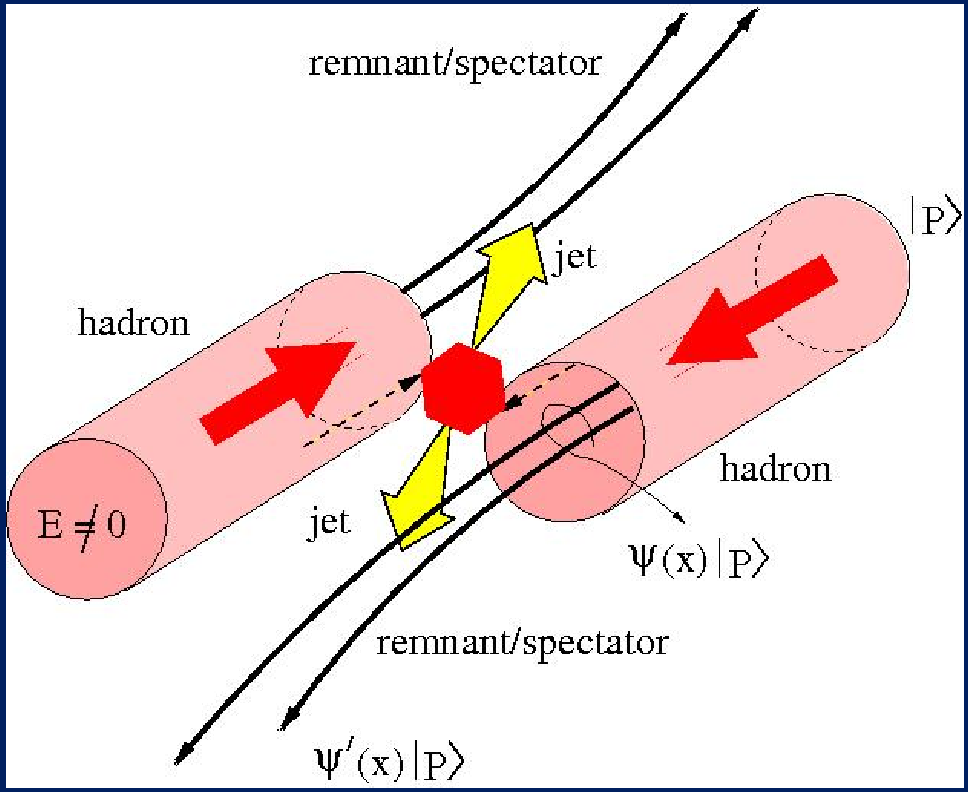
Slide from P. Mulders

Figures by Kees Huyser

Featuring: phases in gauge theories

Slide from P. Mulders





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

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