Transverse-Momentum-Dependent Distributions and Color Entanglement in QCD

Lecture 1 - Introduction

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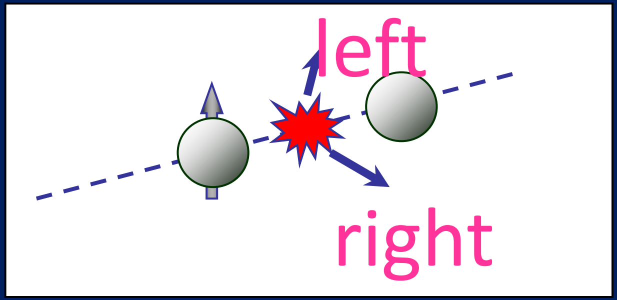

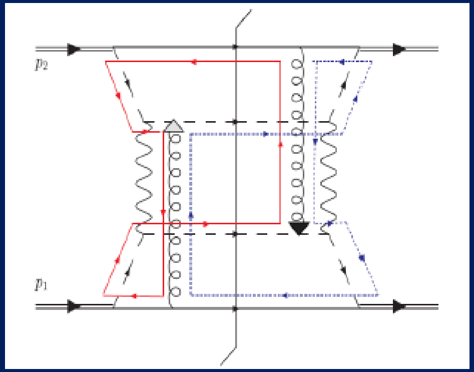

Hampton University Graduate Studies Program
Jefferson Lab
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How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?

How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?

Mapping out the partonic structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

Vast majority of past four decades focused on *1-dimensional* momentum structure! Since 1990s starting to consider transverse components . . .

Mapping out the partonic structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

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- *Color*

Polarized protons first studied in 1980s. How angular momentum of quarks and gluons add up still not well understood!

Mapping out the partonic structure of the proton

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Early measurements of flavor distributions in valence region. Flavor structure at lower momentum fractions still yielding surprises!

Mapping out the partonic structure of the proton

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Theoretical and experimental concepts to describe and access position only born in mid-1990s. Pioneering measurements over past decade.

Mapping out the partonic structure of the proton

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

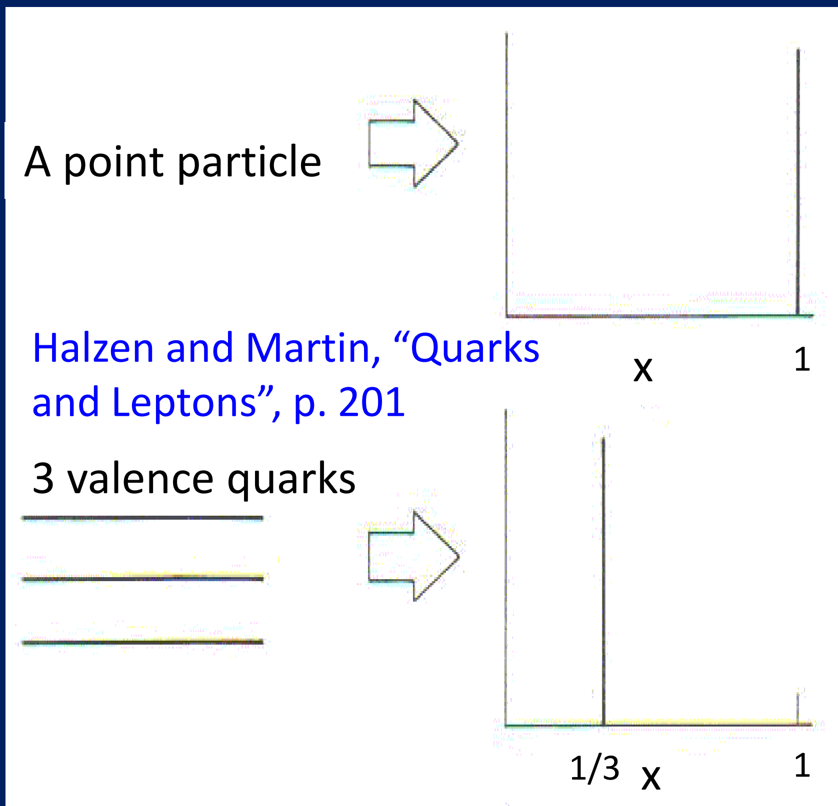
Accounted for theoretically from beginning of QCD, but more detailed, potentially observable effects of color have come to forefront in last few years . . .

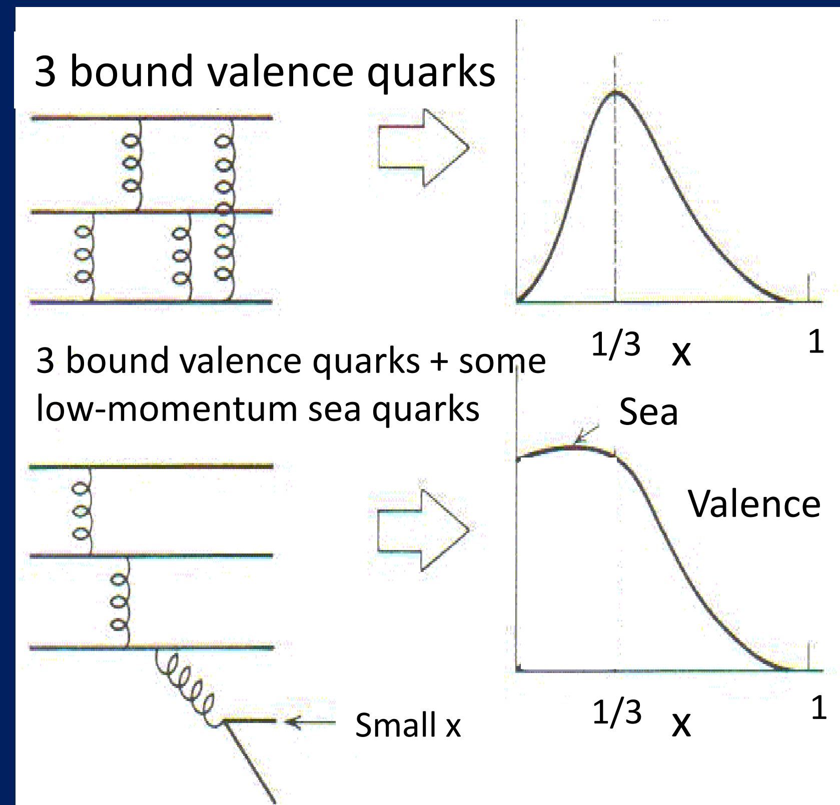
Outline of lectures

1. Introduction; collinear and TMD proton structure and hadronization; some history
2. TMDs and proton structure; measurements; collinear twist-3 and multiparton correlations; sea quarks
3. Processes and experimental facilities
4. TMD factorization, Aharonov-Bohm, and color entanglement I
5. TMD factorization, Aharonov-Bohm, and color entanglement II
6. Connections to other subfields of QCD; summary and outlook

Ways to describe proton structure: Review of unpolarized, collinear pdfs

What momentum fraction would the scattering particle carry if the proton were made of …

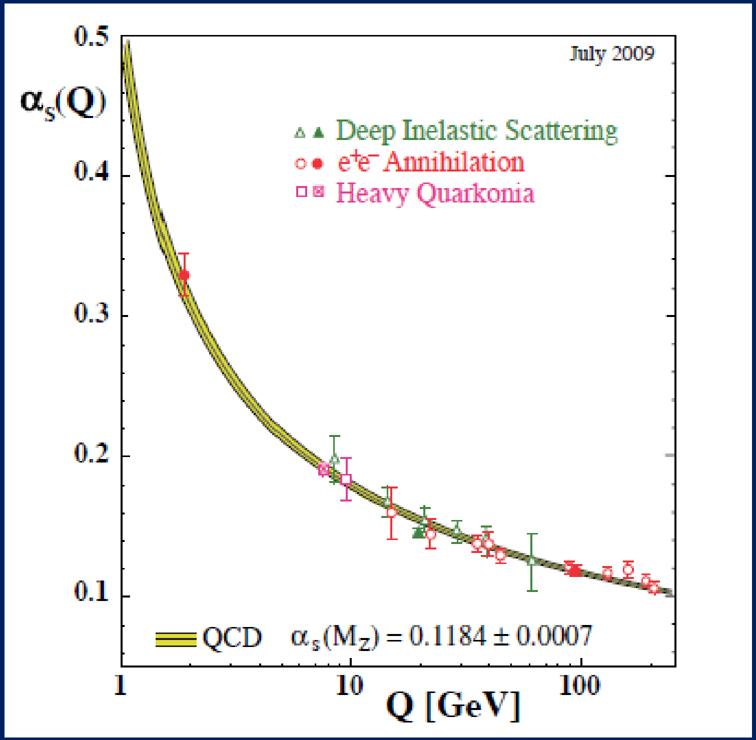




- Don’t take into account polarization of proton or parton
- Integrate over partonic transverse momentum within proton

Review: Perturbative QCD

- Take advantage of running of the strong coupling constant with energy (*asymptotic freedom*)—weak coupling at high energies (short distances)
- Perturbative expansion as in quantum electrodynamics (but many more diagrams due to gluon self-coupling!!)



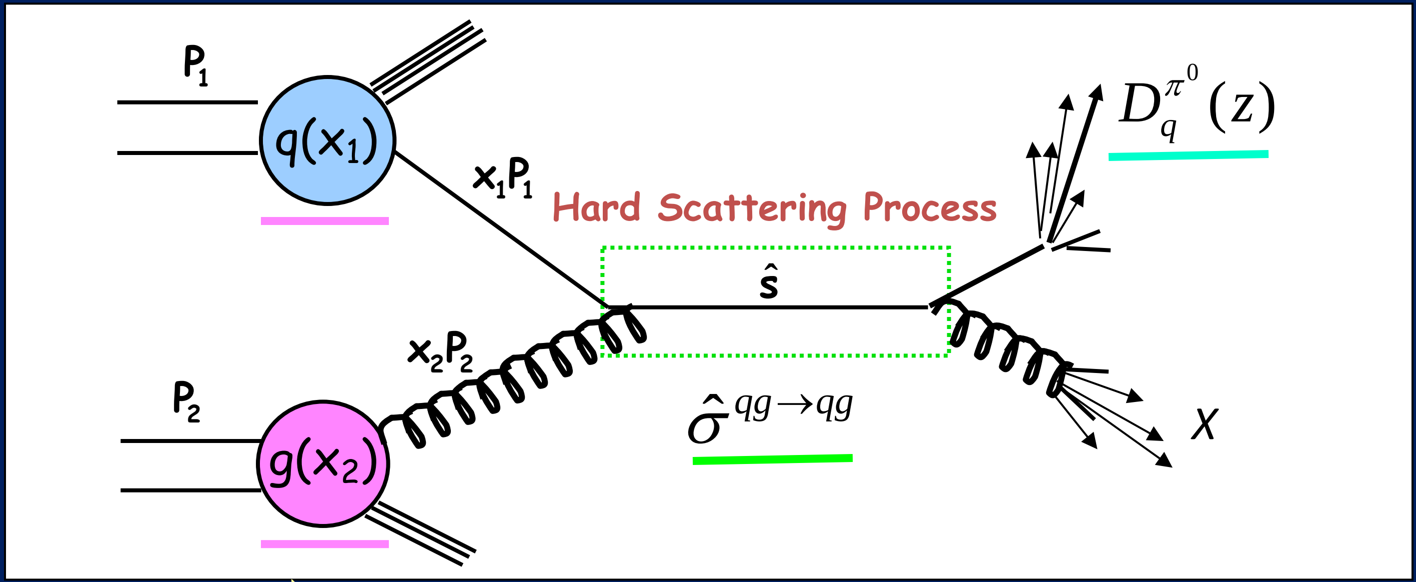
Importantly: Perturbative QCD provides a rigorous way of relating the fundamental field theory—in terms of ***quarks and gluons****—to a variety of physical observables—in terms of* ***hadrons***

Review: Factorization and universality in perturbative QCD

- Systematically *factorize* short- and long-distance physics—observable physical QCD processes always involve at least one long-distance scale (confinement)
  - Short-distance (high-energy) scale required to apply perturbative techniques
- Long-distance (i.e. nonperturbative) functions need to be *universal* in order to be portable across calculations for many processes

Measure nonperturbative pdfs and fragmentation functions (FFs) in many scattering systems over a wide kinematic range
→ constrain by performing *simultaneous fits to world data.*
See lectures by Amanda Cooper-Sarkar

Pdfs and FFs in pQCD calculations of observables



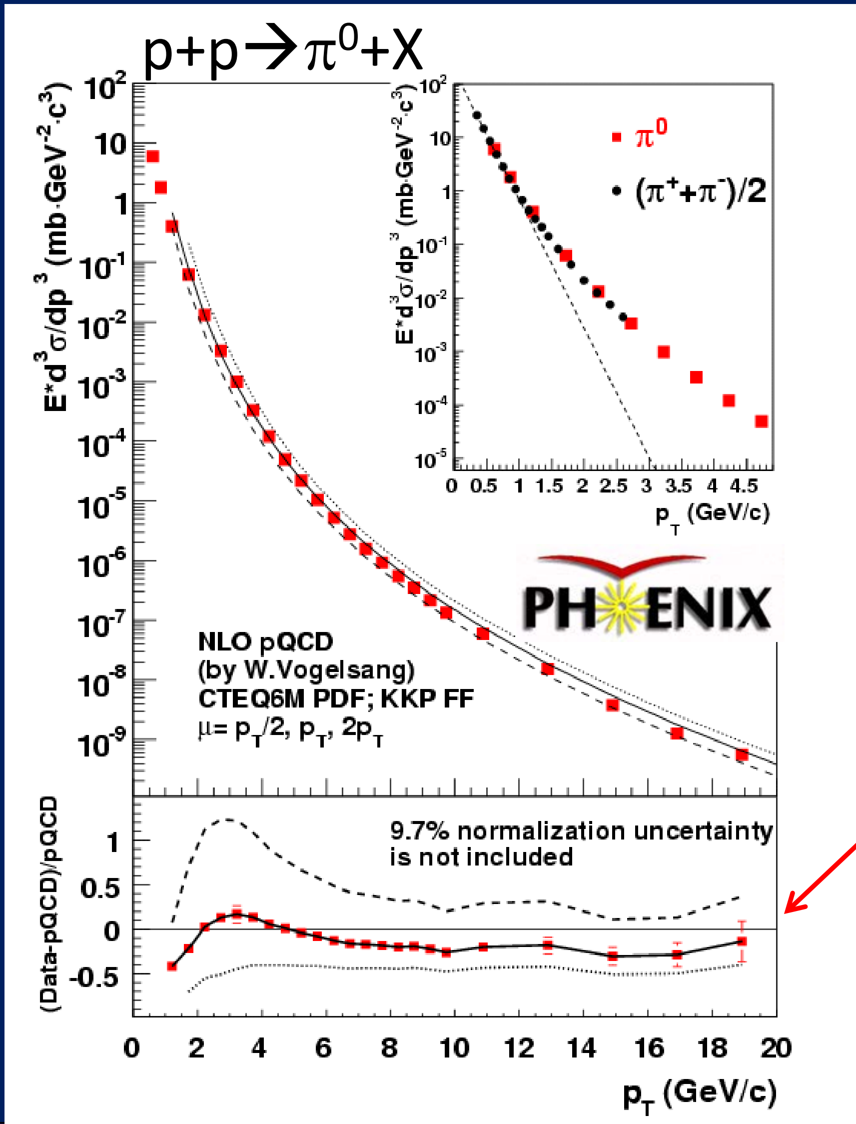
$$\sigma\left(pp \to \pi^0 X\right) \propto q(x_1) \otimes g(x_2) \otimes \hat{\sigma}^{qg\to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

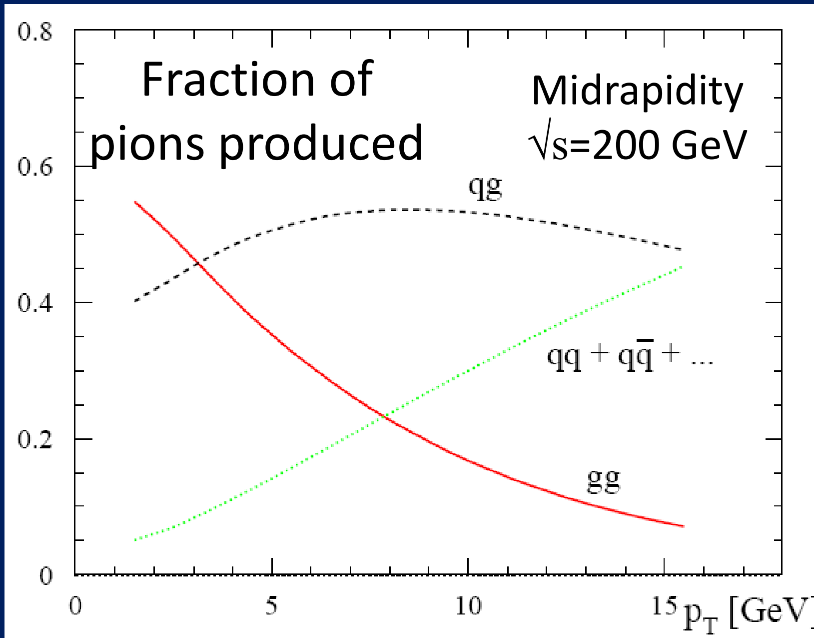
High-energy processes have predictable rates given:

- Partonic hard scattering rates (calculable in pQCD)
- Parton distribution functions (experiment)
- Fragmentation functions (experiment)

} **Universal non-perturbative factors**

pQCD in action at $\sqrt{s}=200$ GeV





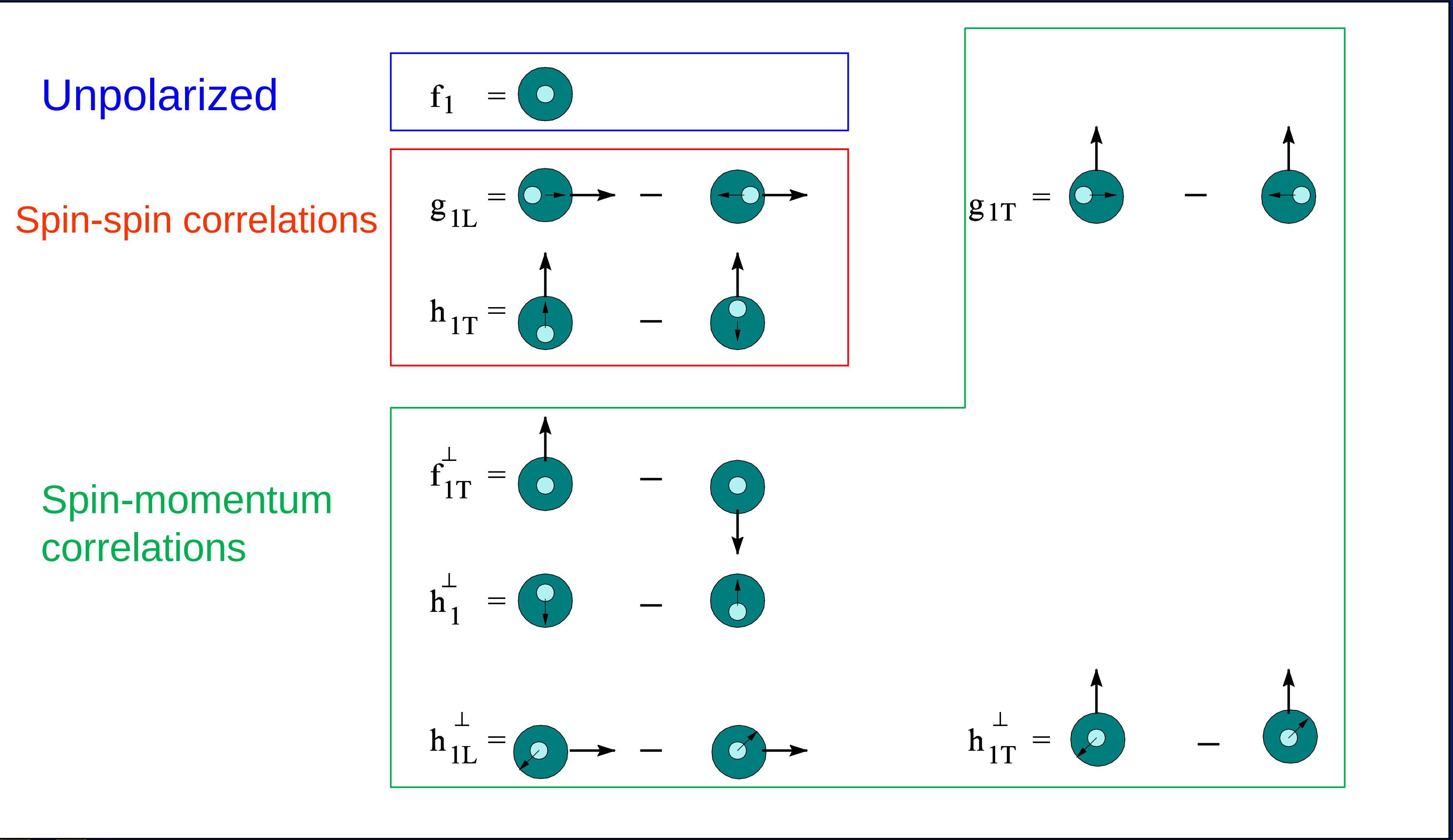
Systematic uncertainty on calculation due to factorization, renormalization, and fragmentation scale dependence. All three scales taken as equal and varied from $p_T/2$ to $2p_T$. See lectures by Markus Diehl.

Cross section prediction varies by tens of percent here.

Complementary scattering systems

- Learn from p+p results in conjunction with information from simpler systems
  - Many subprocesses contribute to (e.g.) inclusive hadron production in p+p collisions—couldn't disentangle them with p+p data alone
  - (A few processes are simpler, e.g. Drell-Yan)
- Most knowledge of pdfs from DIS
- Most knowledge of FFs from e+e-
- Note that Drell-Yan, DIS, and e+e- are all *QED* processes involving hadrons
- Once you have reasonably constrained pdfs and/or FFs, can use p+p data to further refine those constraints
  - Hadronic collisions have been important in constraining *gluons*—interact at leading order. E.g. pion production results on previous page have improved constraints on gluon → pion FFs
  - Hadronic collisions also open up opportunities to explore unique aspects of QCD! More in Lectures 4 and 5 . . .
- More on complementary processes and experimental facilities in Lecture 3 . . .

Beyond unpolarized, collinear pdfs: Spin-spin and spin-momentum correlations in QCD bound states



Twist-2 transverse-momentum-dependent pdfs

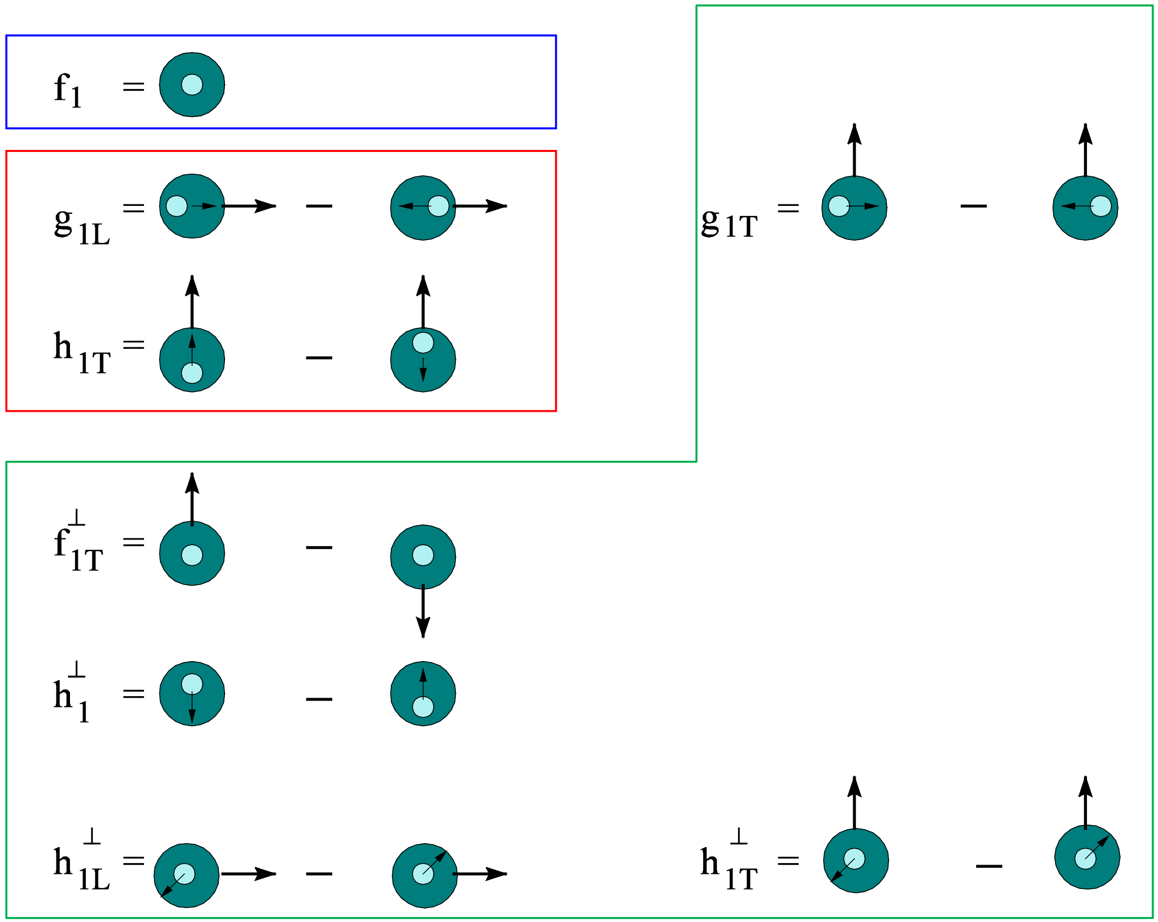
Can keep transverse momentum dependence (more info than collinear), but survive if you do integrate over k_T

Unpolarized

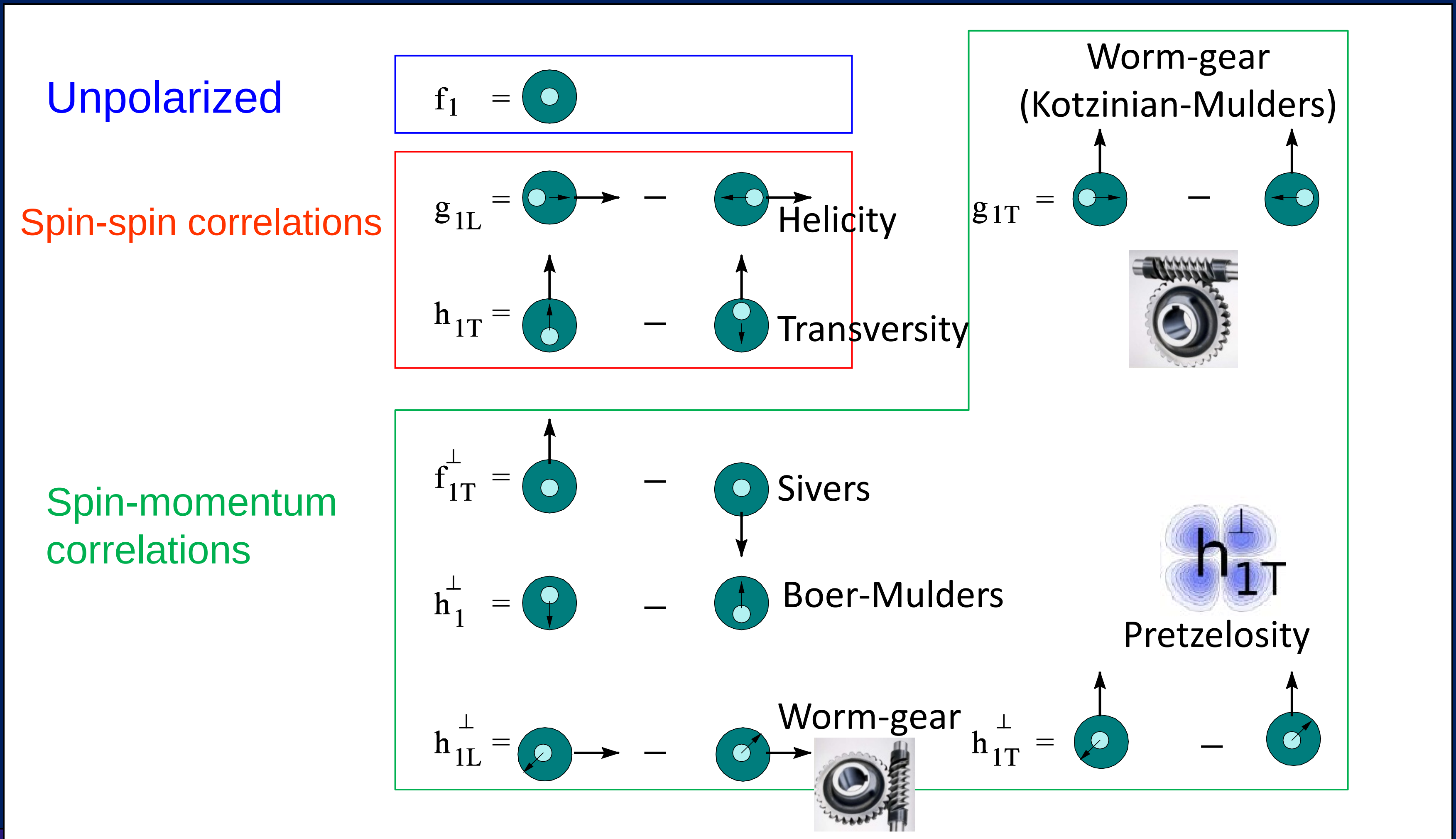
Spin-spin correlations

Spin-momentum correlations

Vanish if integrate over k_T, no collinear counterparts



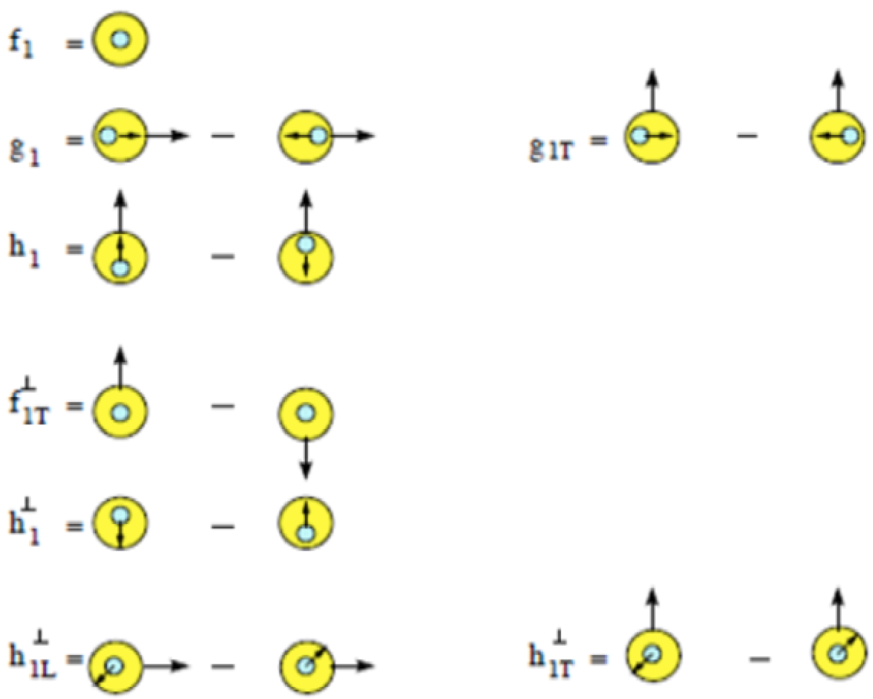
Twist-2 transverse-momentum-dependent pdfs



Twist-2 transverse-momentum-dependent pdfs

U = unpolarized L = longitudinally polarized T = transversely polarized

N = nucleon q = quark



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

Spin-spin correlations in terms of helicity

Elastic proton-quark scattering

(related to inelastic scattering through optical theorem)

Three independent pdfs corresponding to following helicity states in scattering:

$$
\begin{array}{ccccc}
\frac{1}{2} & \frac{1}{2} & \longrightarrow & \frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & -\frac{1}{2} & \longrightarrow & \frac{1}{2} & -\frac{1}{2} \\
\frac{1}{2} & -\frac{1}{2} & \longrightarrow & -\frac{1}{2} & \frac{1}{2}
\end{array}
$$

Helicity basis not "natural" for transversity

Corresponds to difference in probability of scattering off of transversely polarized quark within transversely polarized proton with quark spin parallel vs. antiparallel to proton's

Take linear combinations to form familiar collinear pdfs:

$$
\begin{array}{ll}
q \longleftrightarrow \left(\frac{1}{2}\ \frac{1}{2} \rightarrow \frac{1}{2}\ \frac{1}{2}\right) + \left(\frac{1}{2}\ -\frac{1}{2} \rightarrow \frac{1}{2}\ -\frac{1}{2}\right) & \text{Helicity average (unpolarized pdf)} \\
\Delta q \longleftrightarrow \left(\frac{1}{2}\ \frac{1}{2} \rightarrow \frac{1}{2}\ \frac{1}{2}\right) - \left(\frac{1}{2}\ -\frac{1}{2} \rightarrow \frac{1}{2}\ -\frac{1}{2}\right) & \text{Helicity difference (helicity pdf)} \\
\boxed{\delta q \longleftrightarrow \left(\frac{1}{2}\ -\frac{1}{2} \rightarrow -\frac{1}{2}\ \frac{1}{2}\right)} & \text{Helicity flip (transversity pdf)}
\end{array}
$$

Spin-spin correlations (collinear or TMD): Helicity vs. transverse spin structure

- Transverse spin structure of the proton cannot be deduced from helicity structure
  - Spatial rotations and Lorentz boosts don't commute
  - Relationship between longitudinal and transverse structure provides information on the relativistic nature of partons in the proton
  - Even collinear transverse spin structure (transversity) should thus be linked to parton k_T
    - I haven't dug into this yet myself to try to understand it better . . .

TMD pdfs: Some properties

- Pdfs involving transversely polarized quarks are chiral-odd—can only be observed experimentally in conjunction with a second chiral-odd function
  - Another pdf or a FF
  - Transversity, Boer-Mulders, pretzelosity, one of the worm gears (all the ‘h’ TMD pdfs)
- TMD pdfs involving a single spin vector are “naïve-time-reversal-odd,” i.e. PT-odd
  - Sivers and Boer-Mulders
- What about TMD pdfs for gluons?
  - Gluons massless—can’t have helicity-flip states, i.e. transversely polarized gluons
  - However, can have TMDs for linearly polarized gluons, similar to linearly polarized photons—not extensively explored yet
  - Unpolarized and longitudinally polarized TMD pdfs no problem for gluons

Transverse single-spin asymmetries

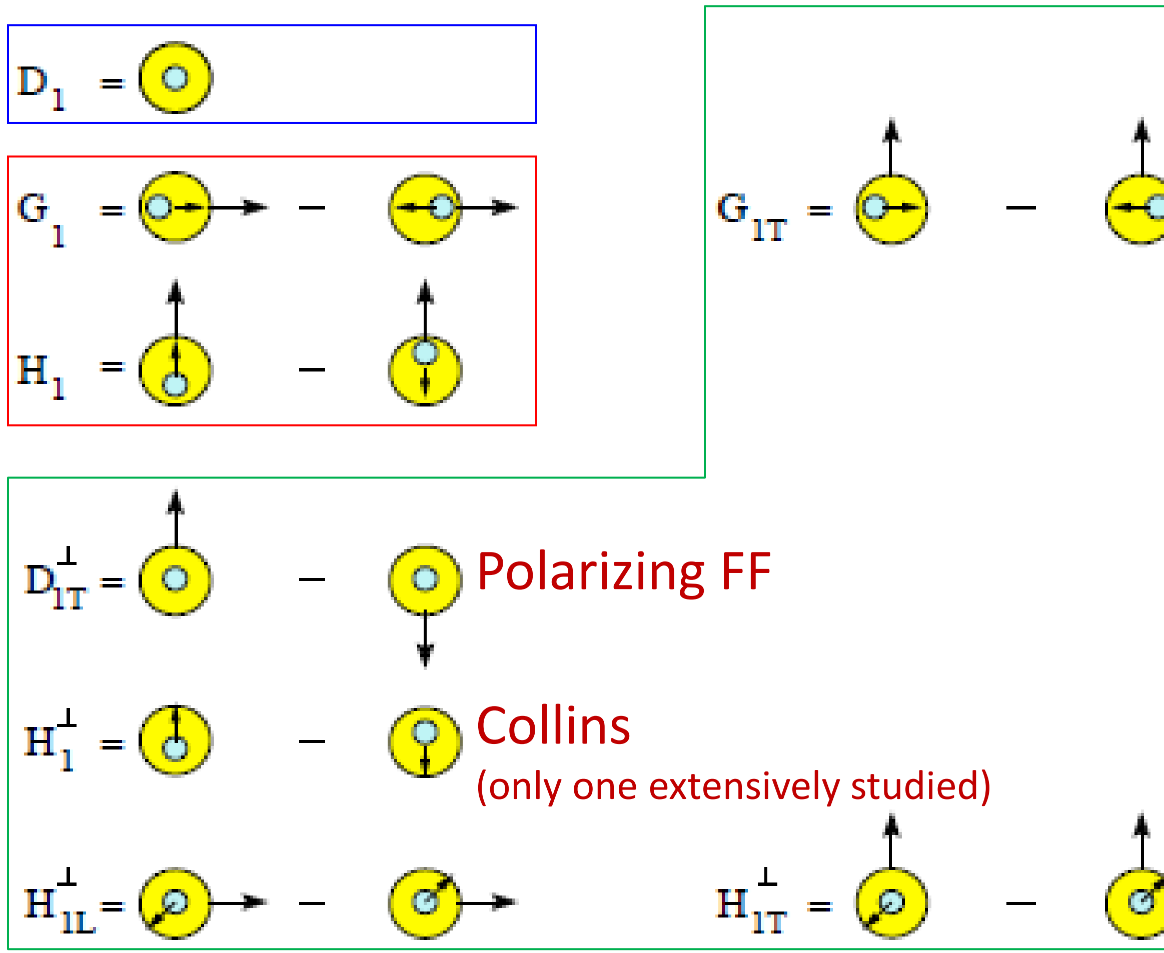
- General form for transverse single-spin asymmetries: $S \cdot \left(p_1 \times p_2\right)$
  - Collinear momenta would produce no effect
  - Thus importance of transverse momentum dependence
- Spin could be of initial proton, struck quark, fragmenting quark, produced hadron
- Possible momenta include initial proton momentum, final-state particle or jet momentum, k_T of parton within proton, j_T of final-state particle with respect to jet axis
- Lots of combinations possible!

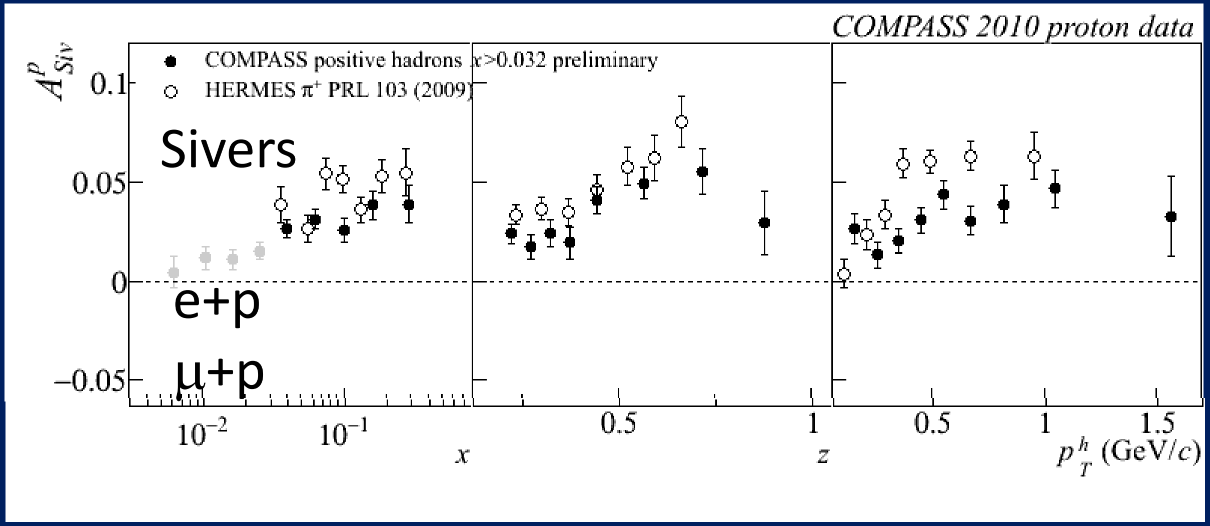
Twist-2 transverse-momentum-dependent FFs

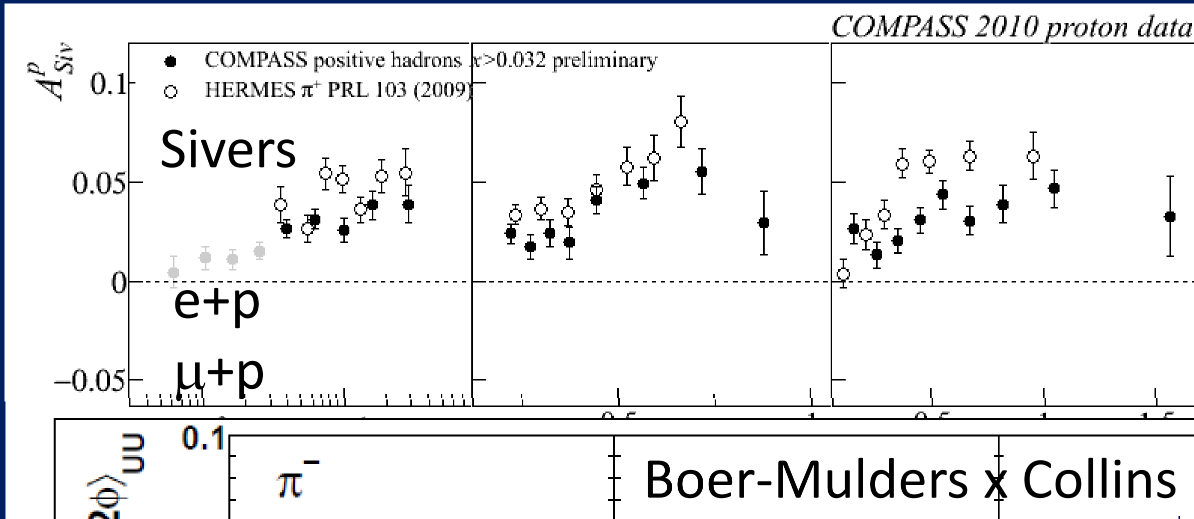
Unpolarized

Spin-spin correlations

Spin-momentum correlations




COMPASS 2010 proton data
A^p_{Siv}
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
0.1
0.05
0
−0.05
10^{-2}
10^{-1}
x
0.5
1
z
0.5
1
1.5
p^h_T (GeV/c)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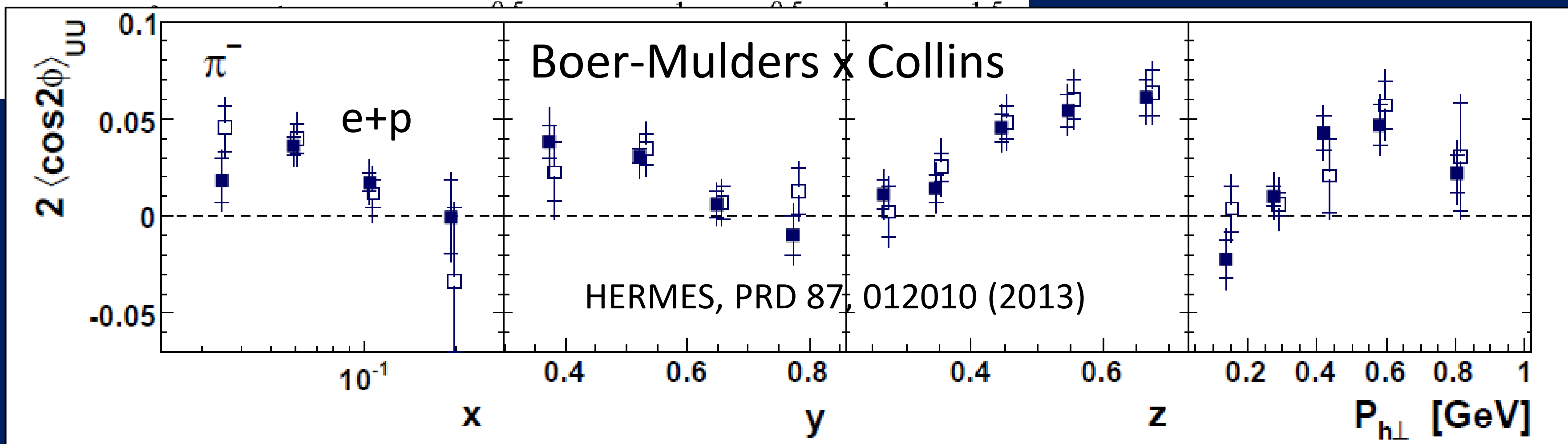
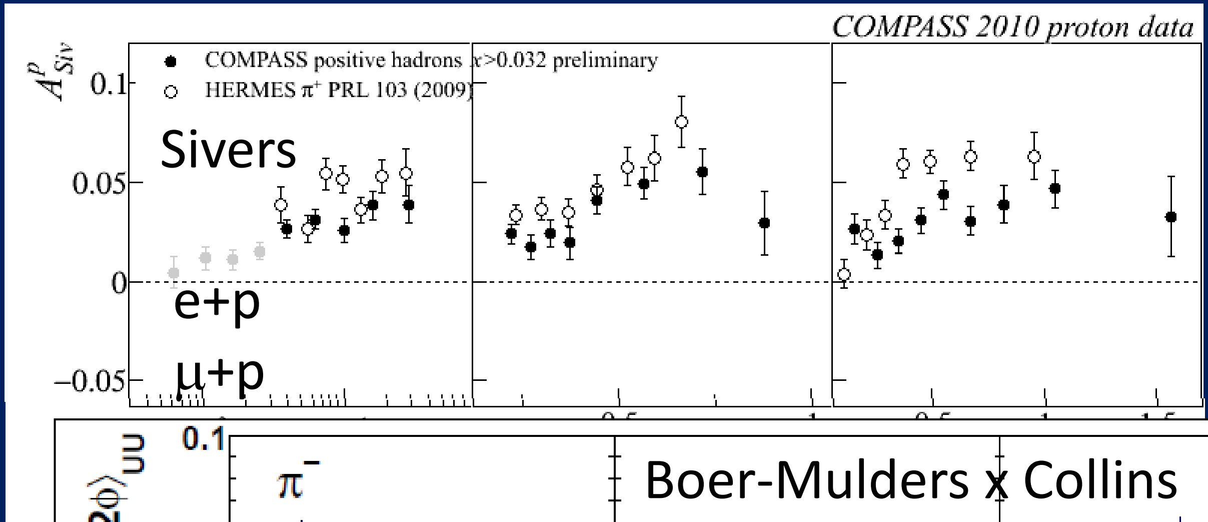

2 ⟨cos2φ⟩UU
0.1
0.05
0
-0.05
π−
e+p
Boer-Mulders x Collins
HERMES, PRD 87, 012010 (2013)
10-1
0.4
0.6
0.8
0.4
0.6
0.2
0.4
0.6
0.8
1
x
y
z
Ph⊥ [GeV]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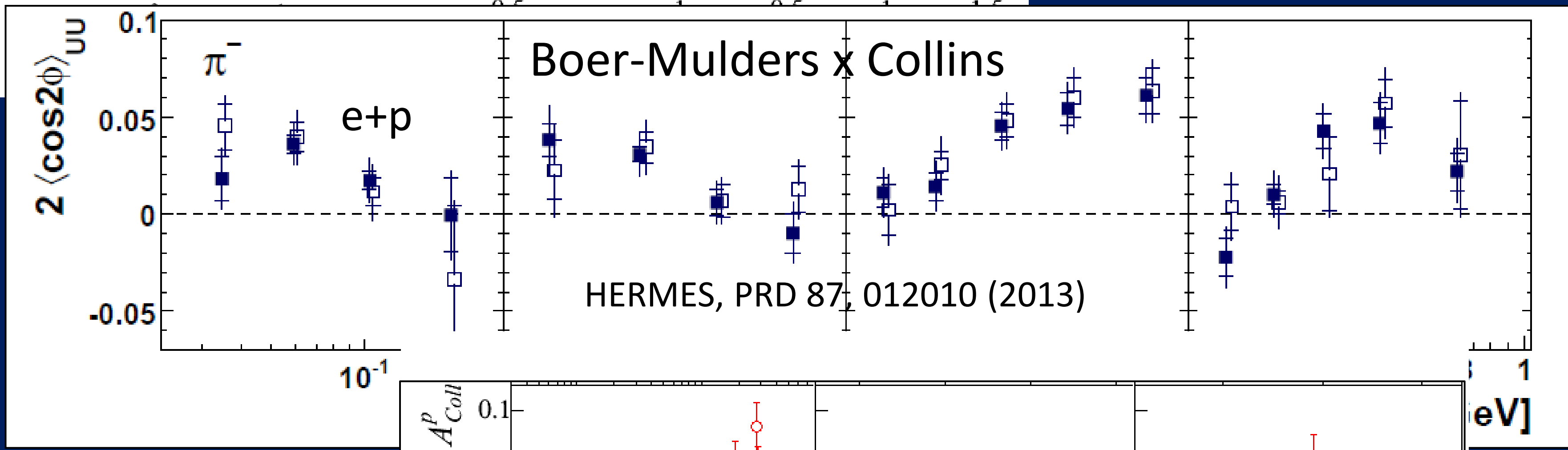
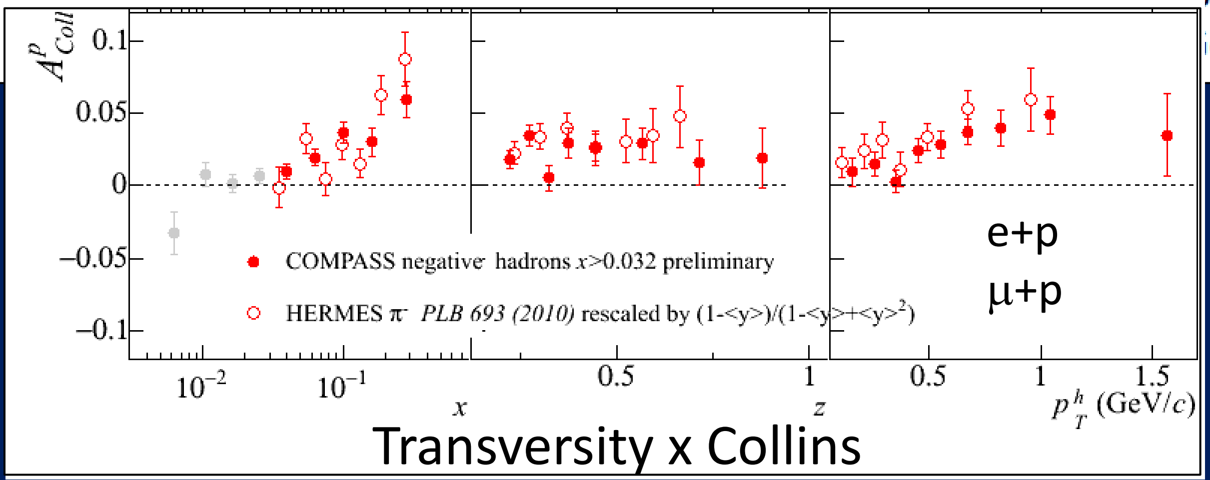
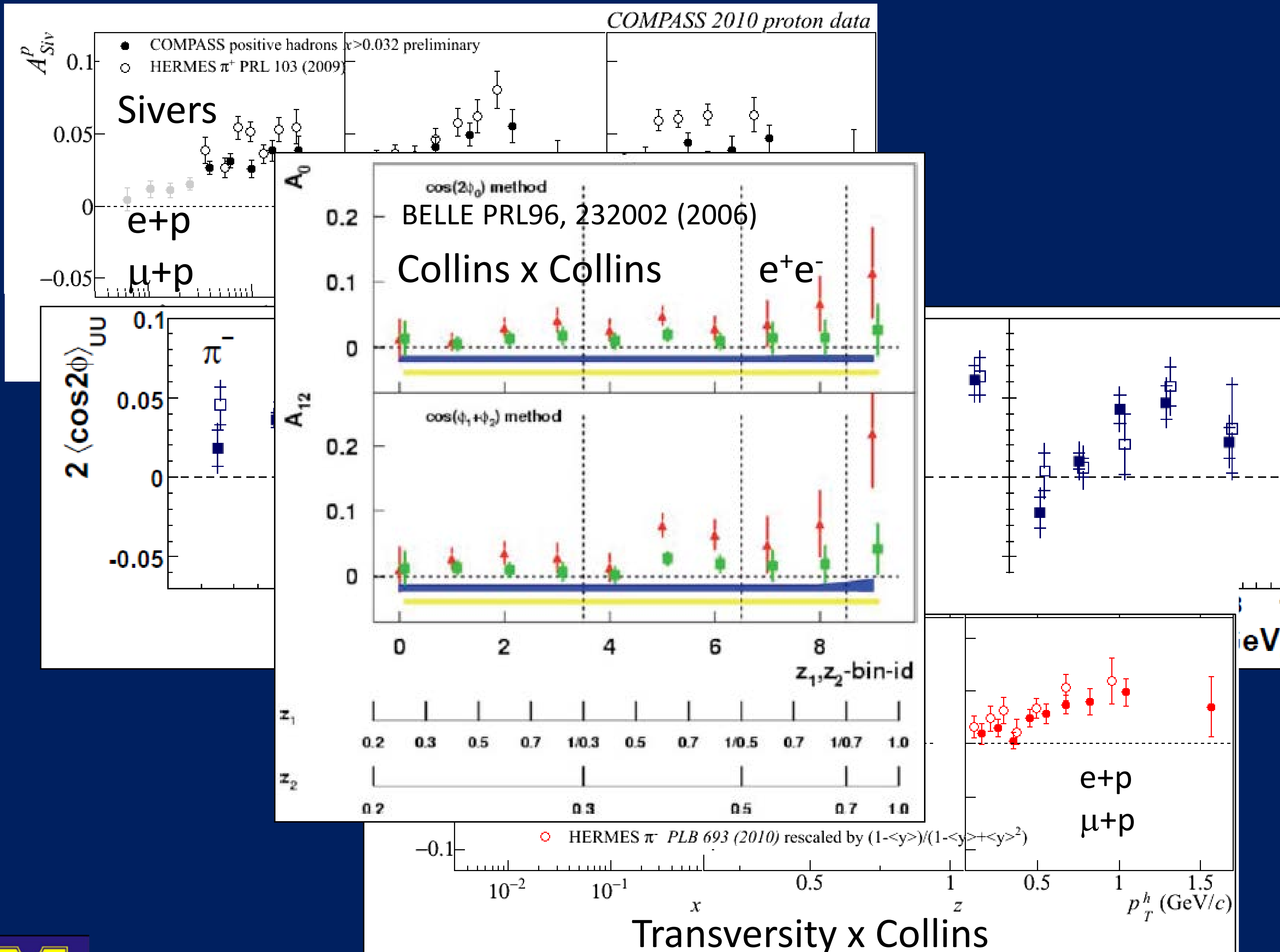
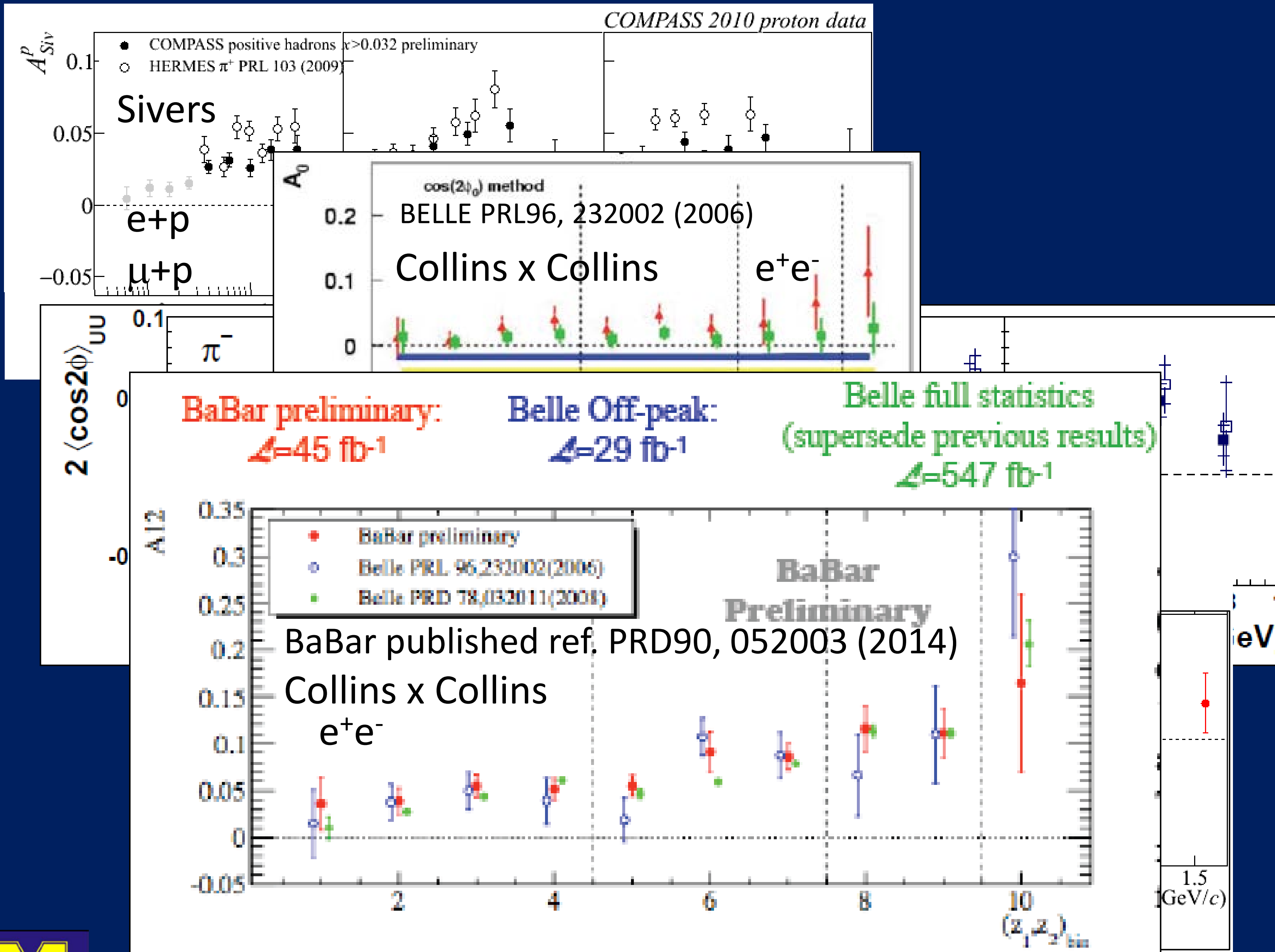
Sivers
e+p
μ+p


π−
e+p
Boer-Mulders x Collins
HERMES, PRD 87, 012010 (2013)


COMPASS negative hadrons x>0.032 preliminary
HERMES π− PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>²)
e+p
μ+p
Transversity x Collins


COMPASS 2010 proton data
COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
A^p_{Siv}
BELLE PRL96, 232002 (2006)
Collins x Collins
e+e-
cos(2φ0) method
cos(φ1+φ2) method
A0
A12
z1,z2-bin-id
π-
2 ⟨cos2φ⟩UU
HERMES π- PLB 693 (2010) rescaled by (1-<y>)/(1-<y>+<y>2)
e+p
μ+p
x
z
p_T^h (GeV/c)
Transversity x Collins


COMPASS 2010 proton data
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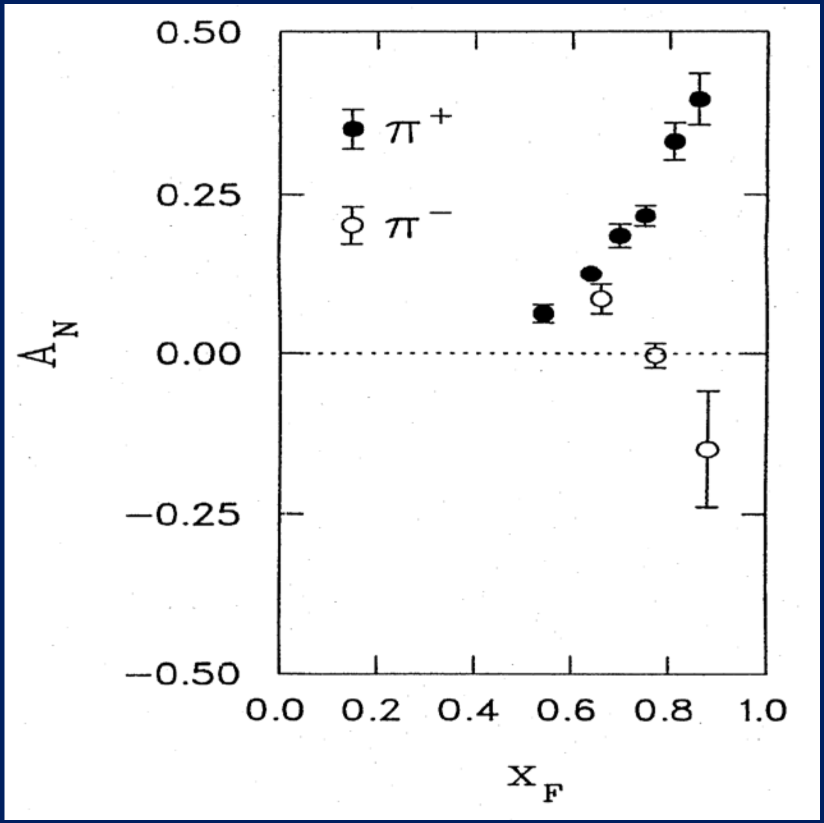
HERMES π+ PRL 103 (2009)
Sivers
e+p
μ+p
cos(2φ0) method
BELLE PRL96, 232002 (2006)
Collins x Collins
e+e-
BaBar preliminary:
L=45 fb-1
Belle Off-peak:
L=29 fb-1
Belle full statistics
(supersede previous results)
L=547 fb-1
BaBar preliminary
Belle PRL 96,232002(2006)
Belle PRD 78,032011(2008)
BaBar Preliminary
BaBar published ref. PRD90, 052003 (2014)
Collins x Collins
e+e-
A12
(z1,z2)bin

Some history of spin-momentum correlations and TMD functions: 1976 discovery in p+p collisions

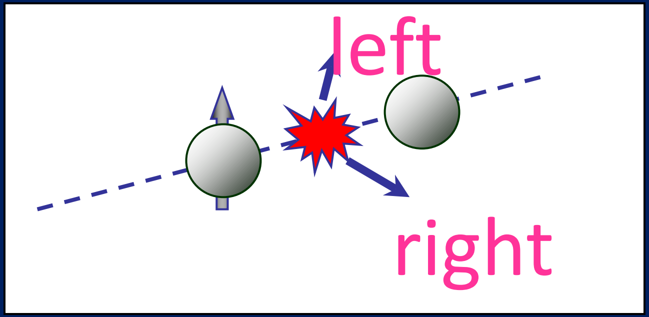
Argonne √s=4.9 GeV



W.H. Dragoset et al., PRL36, 929 (1976)

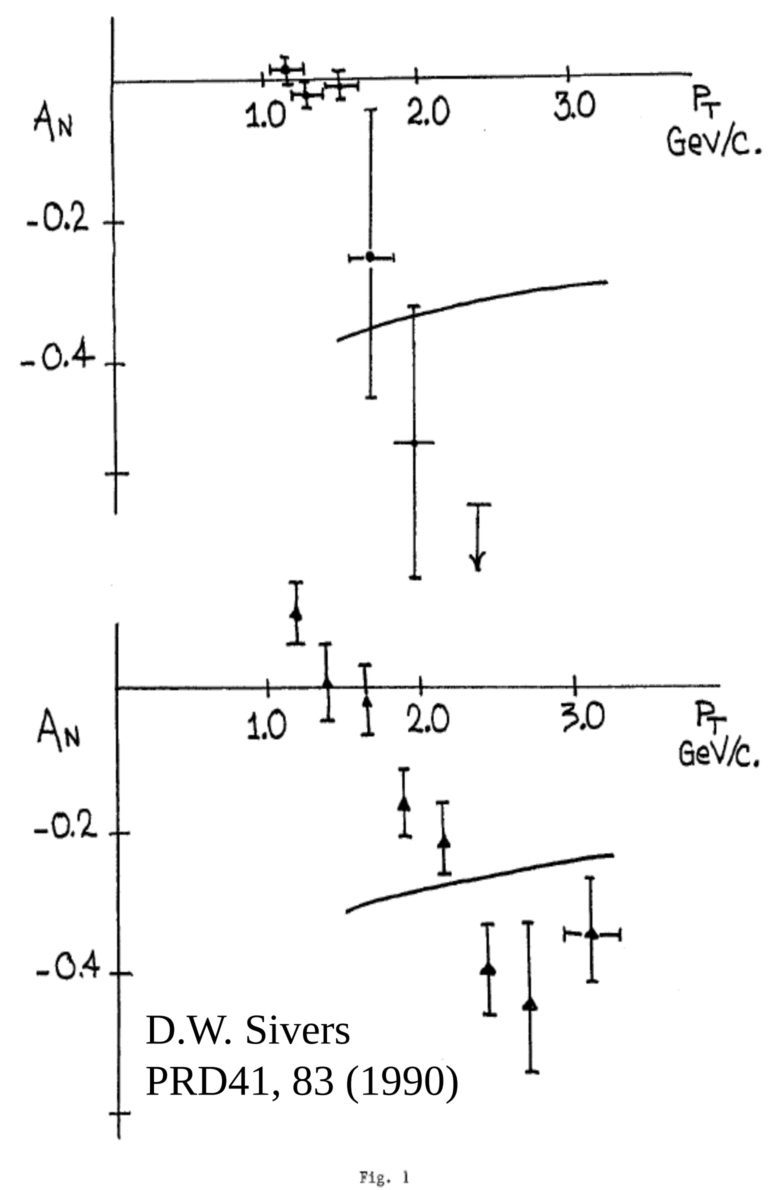
Charged pions produced preferentially on one or the other side with respect to the transversely polarized beam direction—by up to 40%!!

Had to wait more than a decade for the birth of a new subfield in order to explore the possibilities . . .



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

Transverse-momentum-dependent distributions and single-spin asymmetries



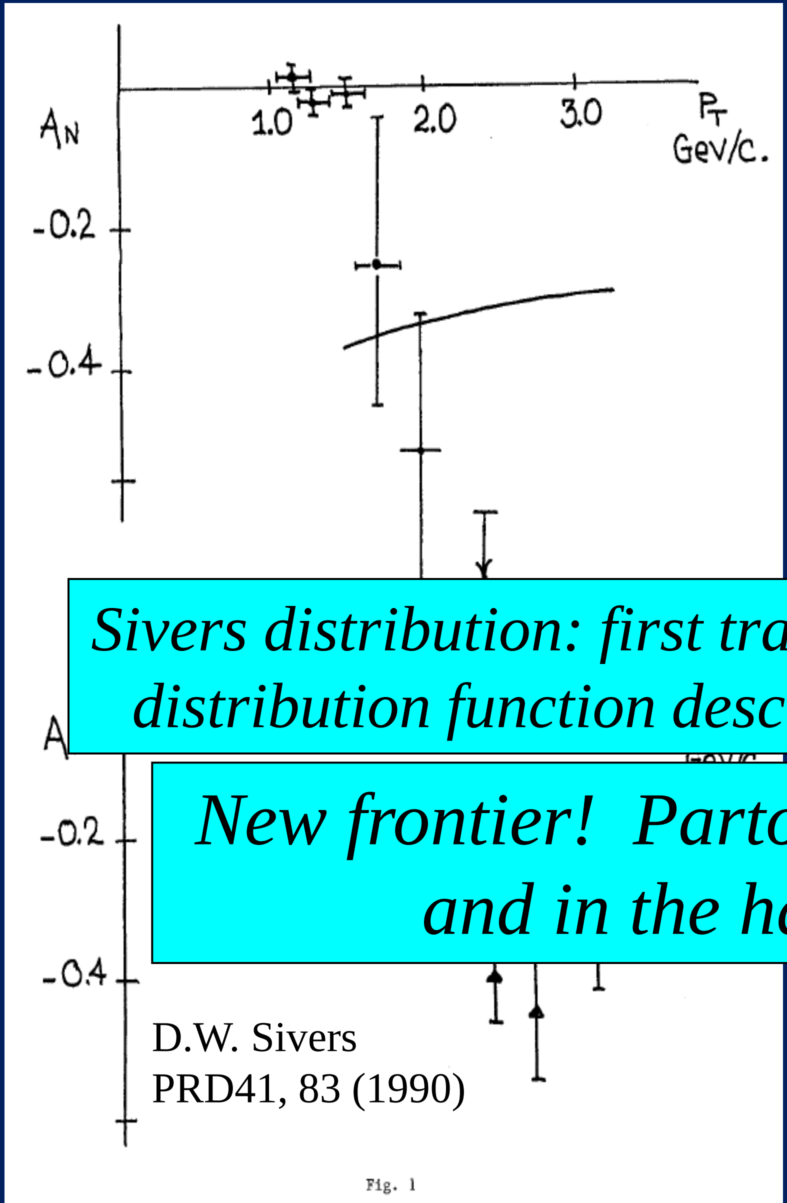
D.W. Sivers
PRD41, 83 (1990)

- 1990: "Sivers mechanism" proposed in attempt to understand observed asymmetries
- Departed from traditional *collinear* factorization assumption in pQCD and proposed correlation between the *intrinsic transverse motion* of the quarks and gluons and the proton's spin

$$\boxed{S \cdot (p_1 \times p_2)}$$

Spin and momenta of partons and/or hadrons

Transverse-momentum-dependent distributions and single-spin asymmetries



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Sivers distribution: first transverse-momentum-dependent parton distribution function describing a spin-momentum correlation

New frontier! Parton ***dynamics*** *inside hadrons, and in the hadronization process*

$$S \cdot (p_1 \times p_2)$$

Spin and momenta of partons and/or hadrons

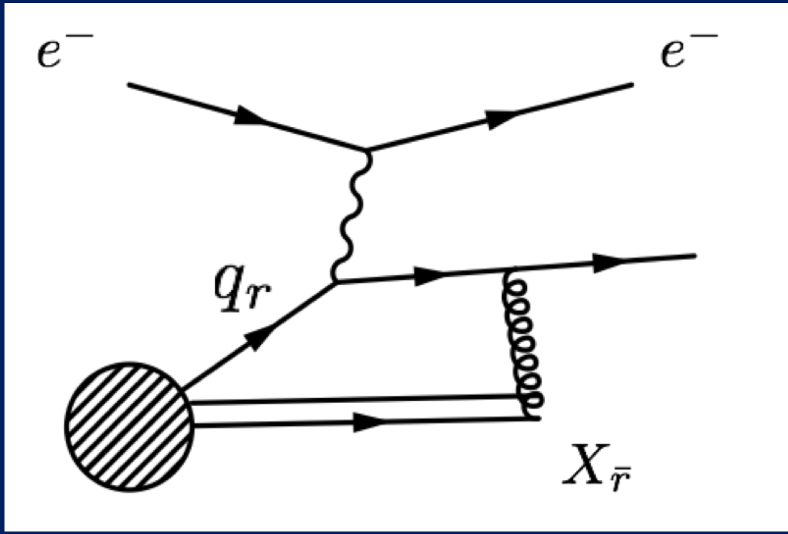
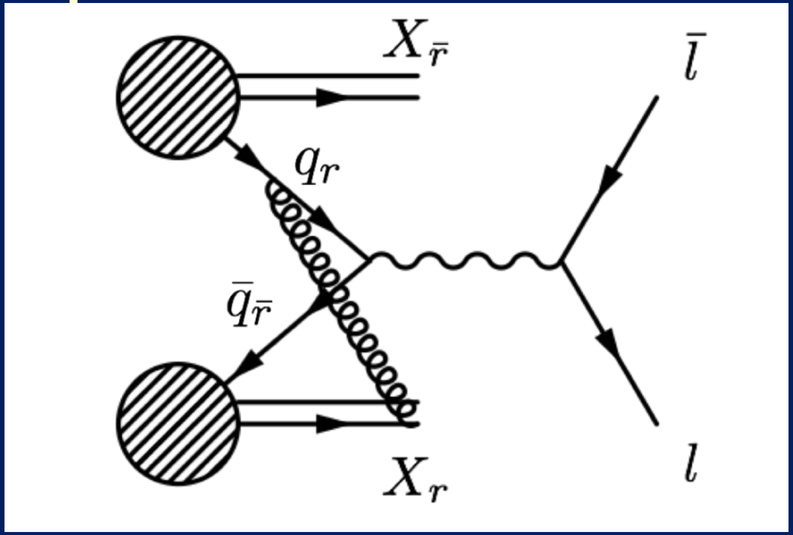
“Naïve-T-odd” (PT-odd) spin-momentum correlations require phase interference

- Some spin-momentum correlation functions odd under “naïve-time-reversal” (actually a PT transformation)

- 1990 – Proposed by D.W. Sivers
- 1993 – Claimed forbidden by J.C. Collins

- 2002 – Demonstrated nonvanishing by Brodsky, Hwang, Schmidt if *phase interference effects due to color interactions* present
- 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
  - Sparked dramatic increase in interest in the field
- 2004 – Measurement of nonzero Sivers asymmetry in SIDIS by HERMES

Modified universality of certain transverse-momentum-dependent distributions: 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

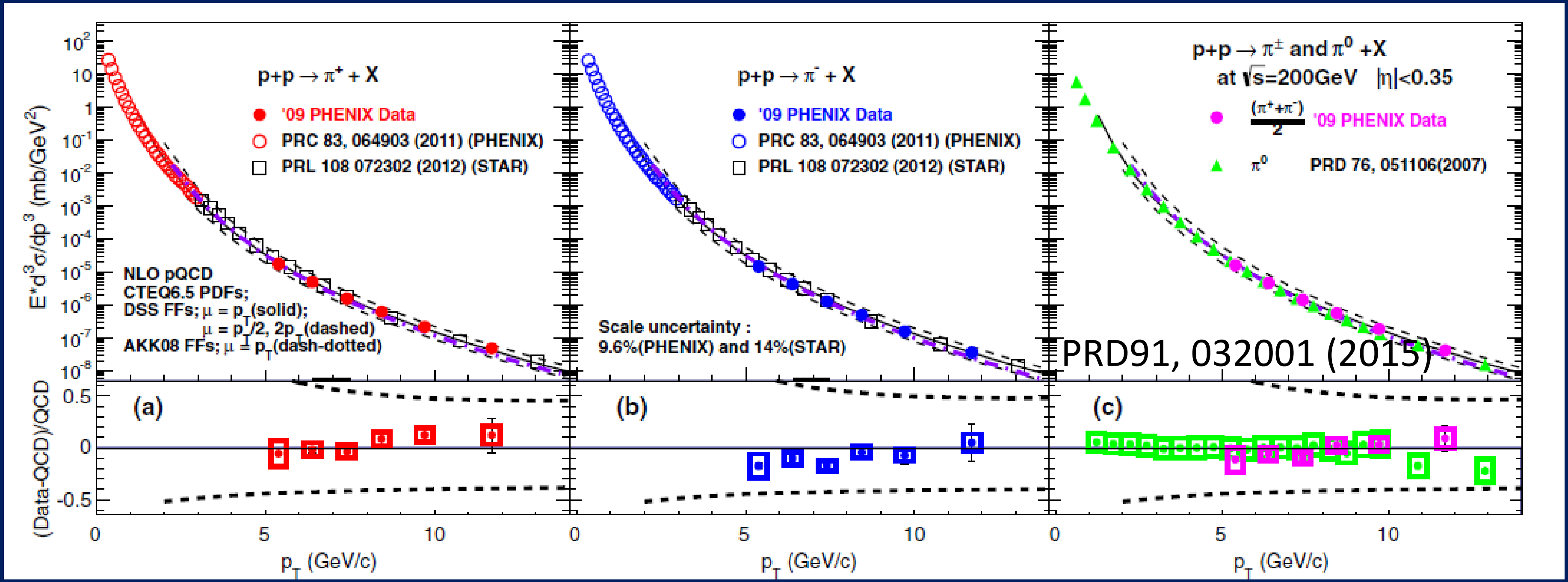
Modified universality of PT-odd TMD pdfs

- 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*
- Experimental evidence from SIDIS for a nonzero Sivers pdf already confirms that such gluon exchanges are taking place
- Still waiting for a definitive polarized Drell-Yan measurement to compare to SIDIS. More in Lectures 2 and 3 . . .

Hadronization, collinear and TMD: Recent advances

- Not as far along as nucleon structure—less of a focus in earlier years
- Recent advances via
  - Spin-momentum (and spin-spin) correlations in FFs
  - Multiparton correlations in hadronization—interference effects between hadronization from (q+g) and only a quark, or (g+g) and only a gluon. See Lecture 2
  - Looking at interference effects of multiple hadrons coming from a single parton
  - Hadronization in nuclear environment

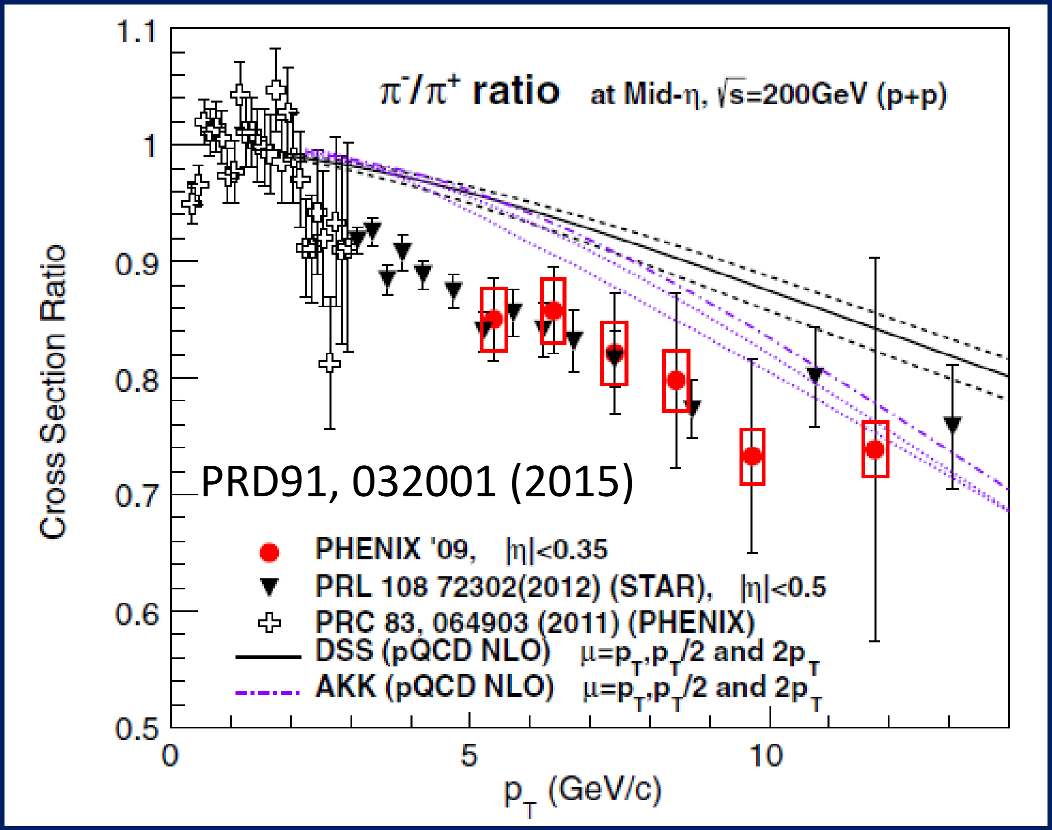
Inclusive pion production in 200 GeV p+p



Easiest hadron to produce—lots of data. Where are we?

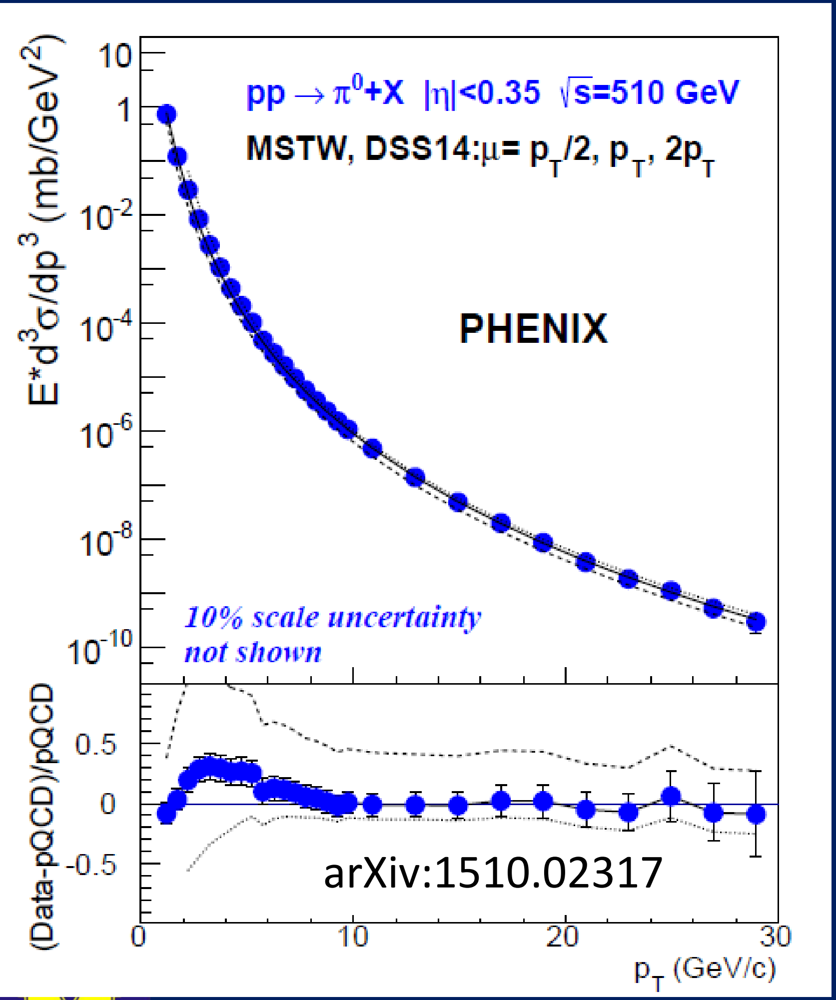
- Data points themselves 10-14% normalization uncertainty.
- NLO pQCD calculations within ~+-20% for scale choice of p_T, p_T ~5-15 GeV/c.
- Scale uncertainties ~+-50% for scale choice from $p_T/2$ to $2p_T$. "Good" agreement.

Charged pion ratio, 200 GeV p+p



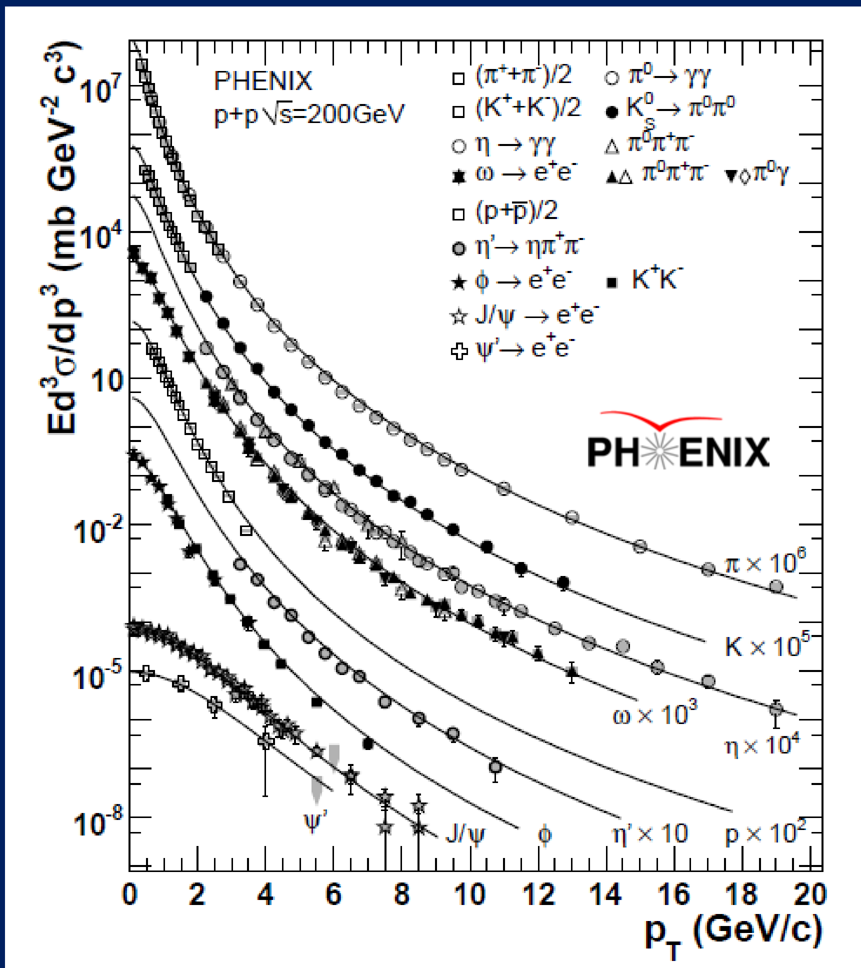
- Measured π-/π+ *ratio* significantly below NLO calculations for p_T ~3-10 GeV/c
  - Data: Normalization uncertainties on cross sections cancel *completely*
  - Calculation: Scale uncertainty greatly reduced
- More powerful constraint to fit ratio directly—just starting to be done

Scale uncertainty remains large for single-particle p+p cross sections even for $\sqrt{s}$ =510 GeV and p_T up to 30 GeV



- Good agreement with NLO, but variation up to ~10-20% for scale choice p_T
- Scale uncertainty ~+50%, -20%
- Measured π-/π+ ratio at 200 GeV within ~15% of NLO calculation, but less "good" because of greatly reduced scale uncertainties
  - Evidently other uncertainties relevant
- What are most appropriate uncertainties to use in each case?

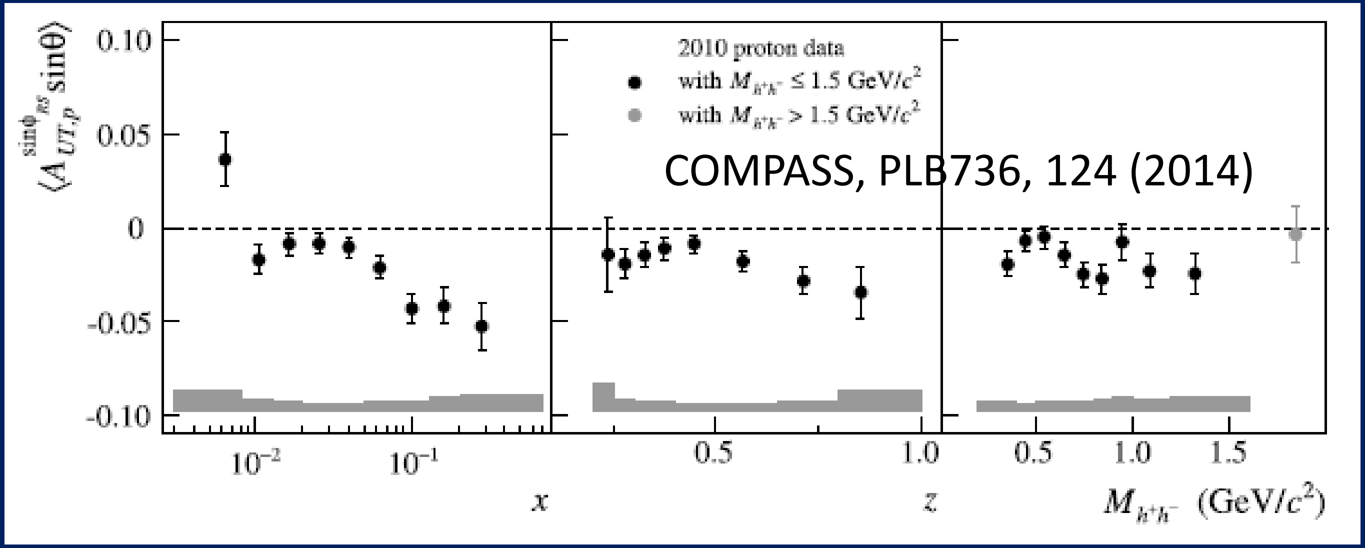
Eventually even more global global fits?
(for "traditional" FFs in "vacuum")



PRD83, 052004 (2011)

- Perform FF parameterizations for even more particles simultaneously?
  - Will constrain relative normalizations well!
  - Eventually simultaneous pdf and FF extractions
- Can we learn by comparing similar mass states? E.g. about gluon FFs?
  - Is a gluon any more or less likely to fragment into a kaon vs. an eta? Eta' vs. phi vs. proton?

Looking at multiple hadrons from the same parton: Dihadron interference FF



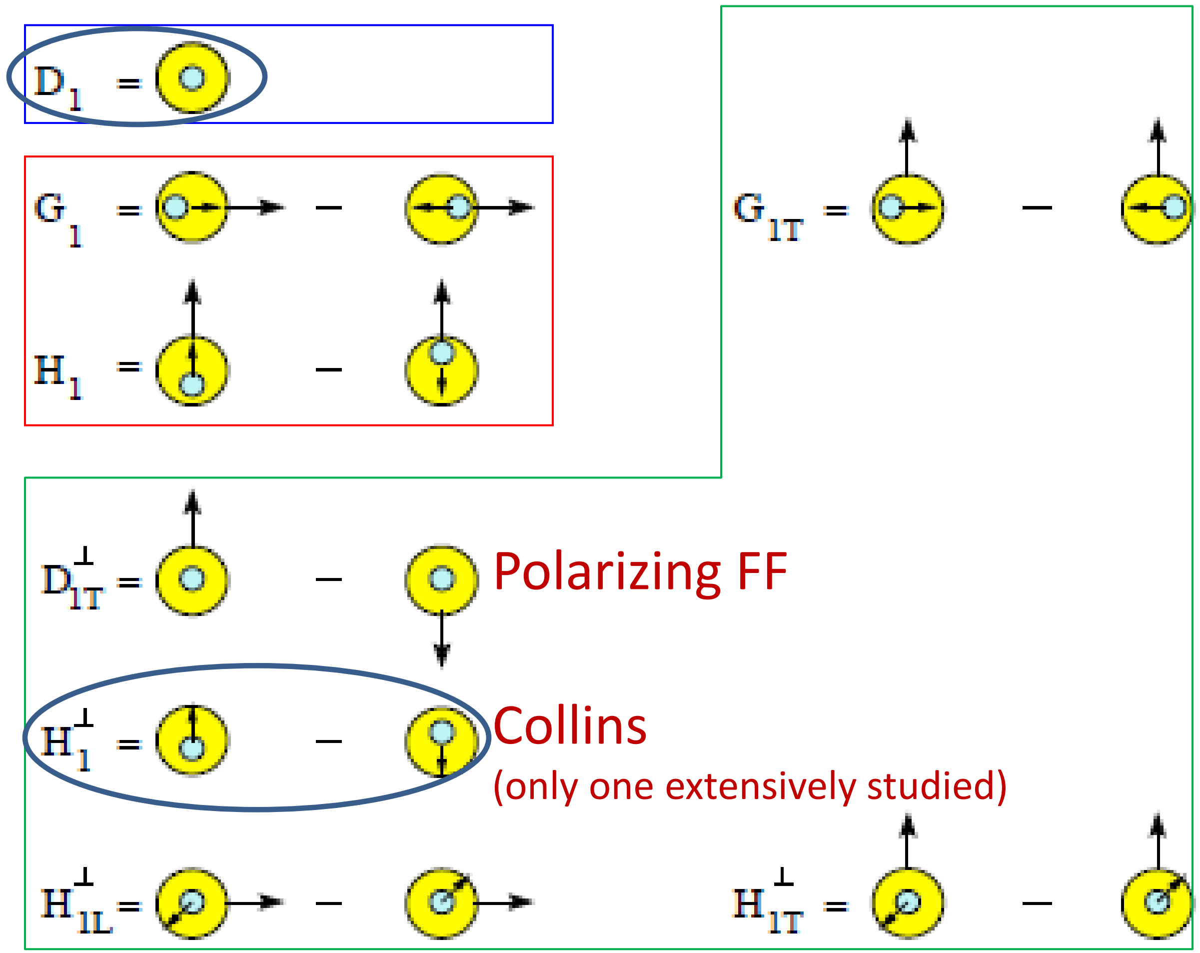
- Pion pair hadronizes from same quark; correlation between quark transverse spin and angular distribution of pair
  - collinear
  - chiral-odd—can measure in conjunction with another chiral-odd function
  - Clear nonzero effects in e+e- and semi-inclusive DIS
  - Transversity x IFF in SIDIS shown here

Twist-2 transverse-momentum-dependent FFs

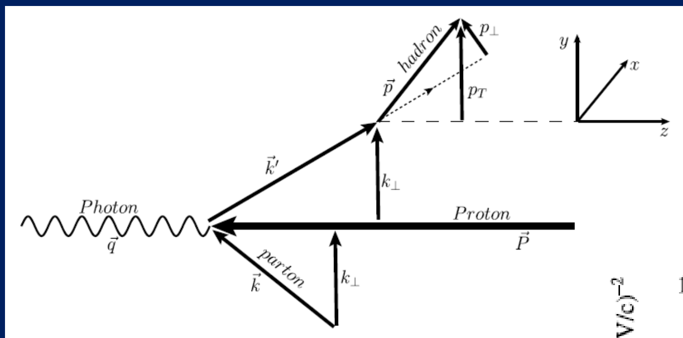
Unpolarized

Spin-spin correlations

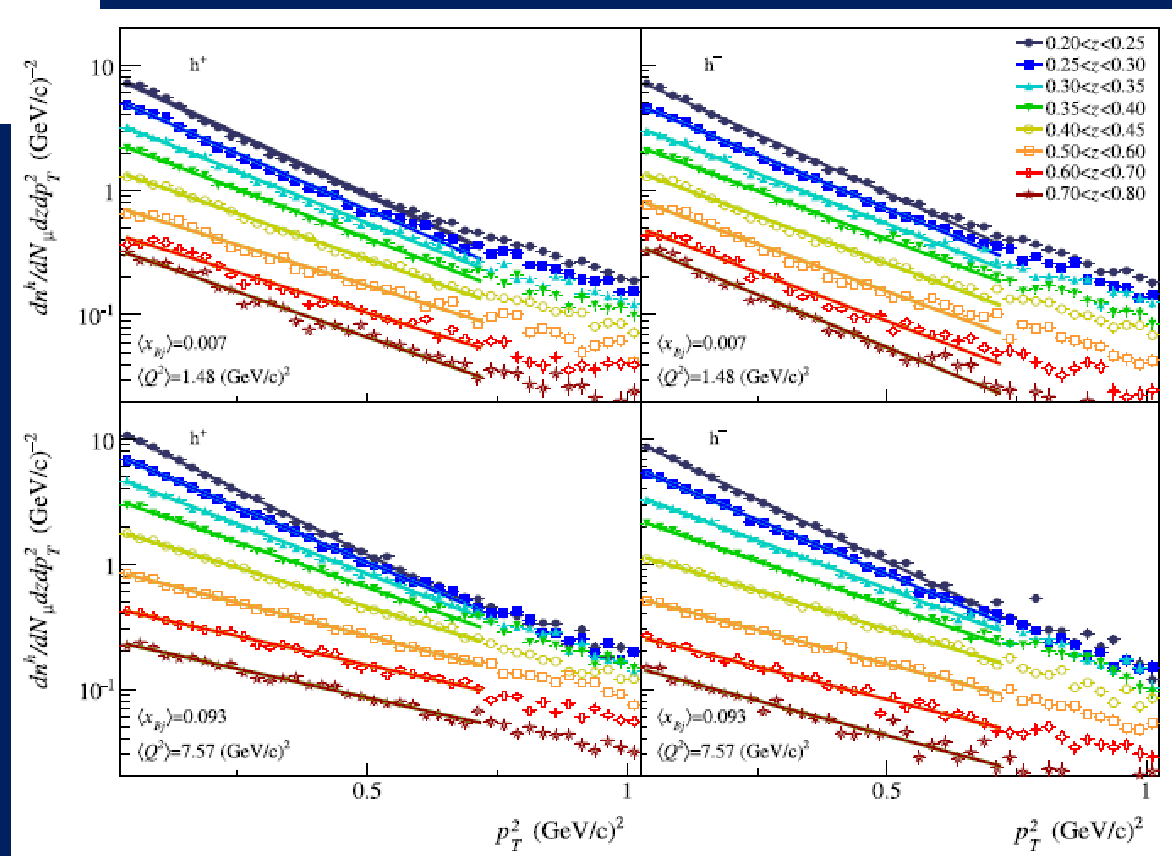
Spin-momentum correlations



Semi-inclusive DIS TMD multiplicities

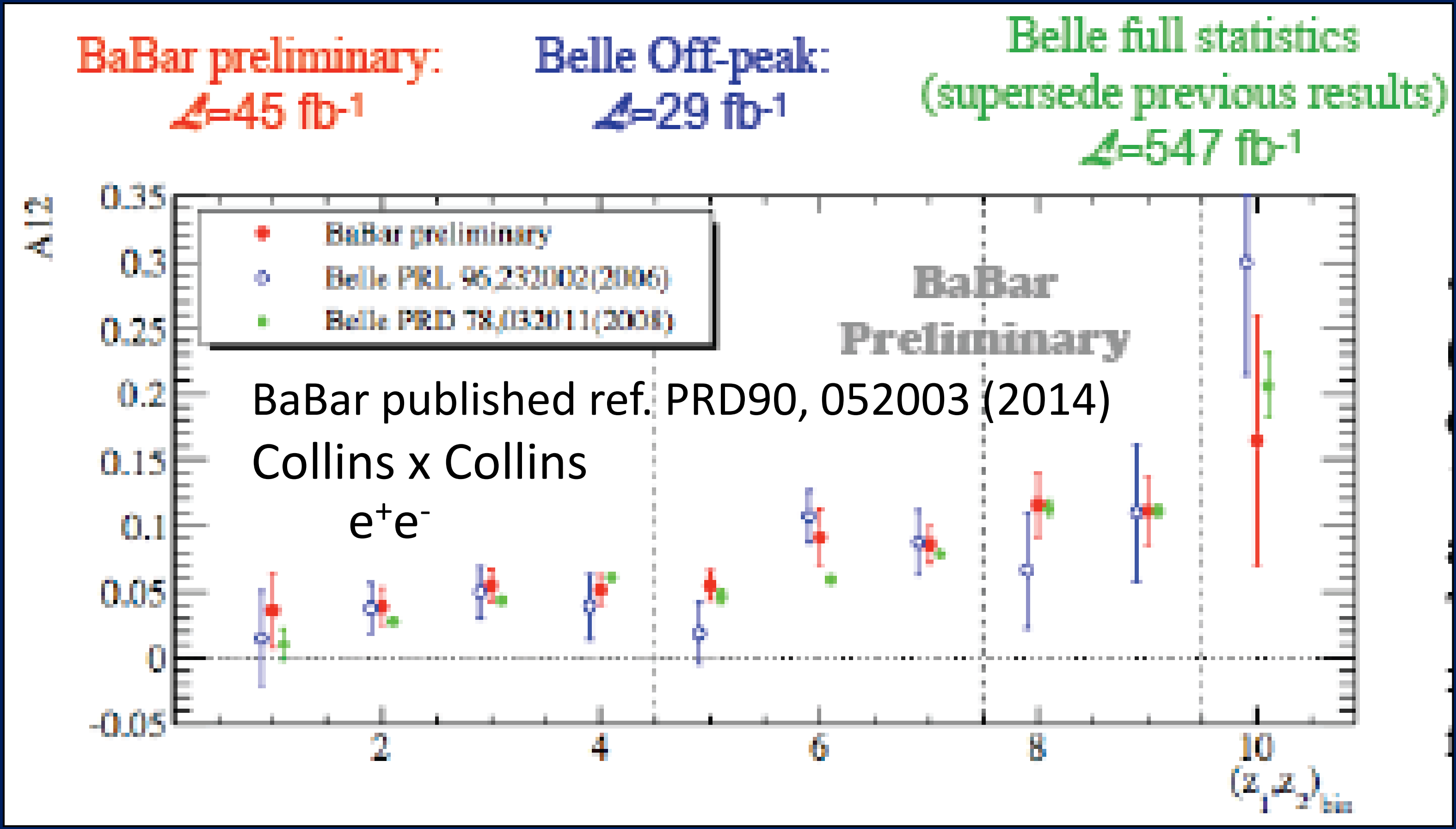


COMPASS, EPJ C73, 2531 (2013)



Nonidentified h+, h- multidifferential in p_T^2, x, z, Q^2

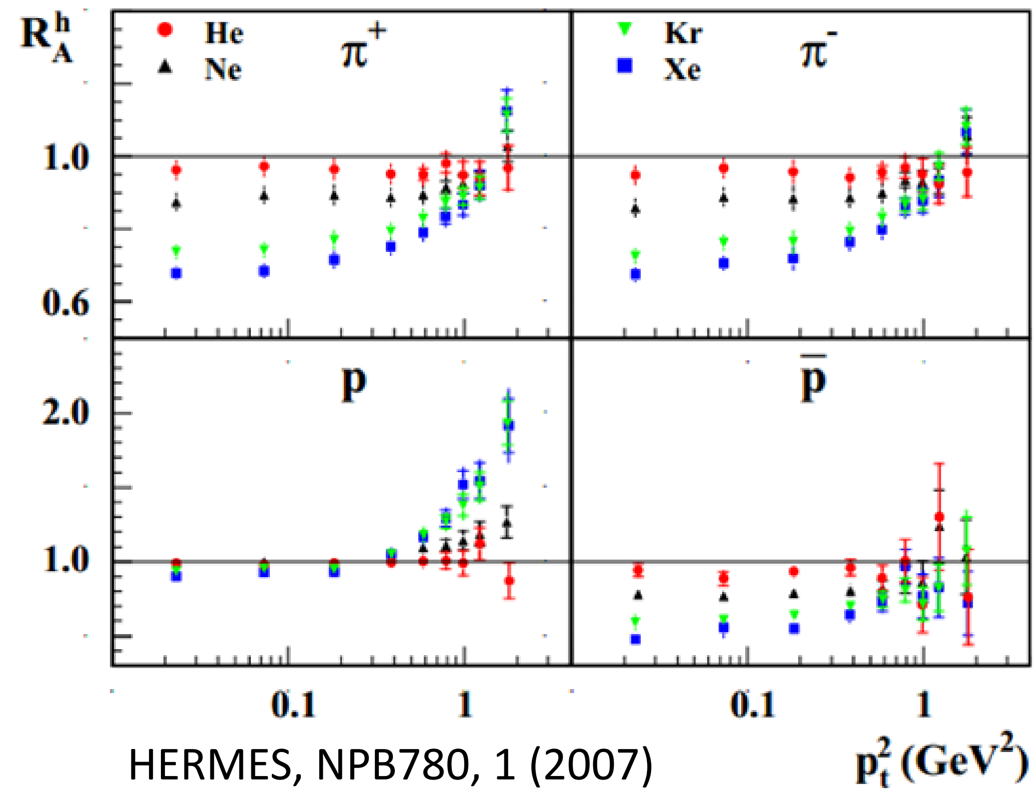
TMD spin-momentum correlation in hadronization: Collins FF



Measured for pions in e+e- by BELLE and BaBar: 5-20% effect

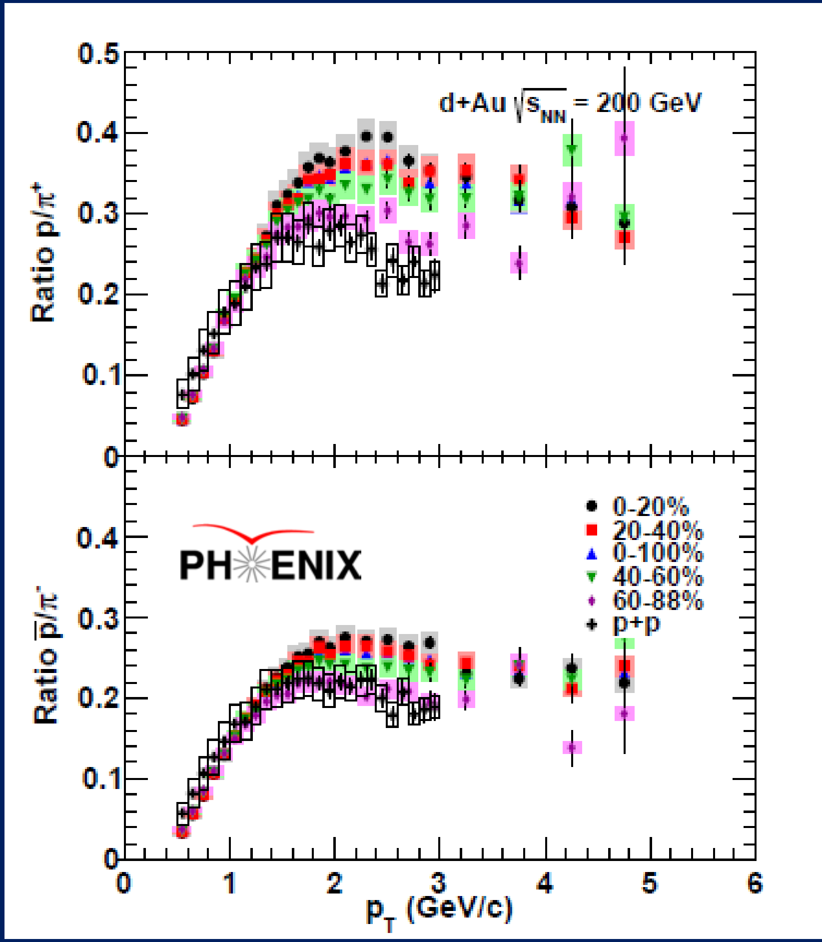
Hadronization in higher-density partonic environments: Nuclear SIDIS

- Nuclear modification of particle production
- Enhancement of protons compared to pions in e+A with respect to scaled e+p



HERMES, NPB780, 1 (2007)

Hadronization in higher-density partonic environments: d+Au compared to p+p



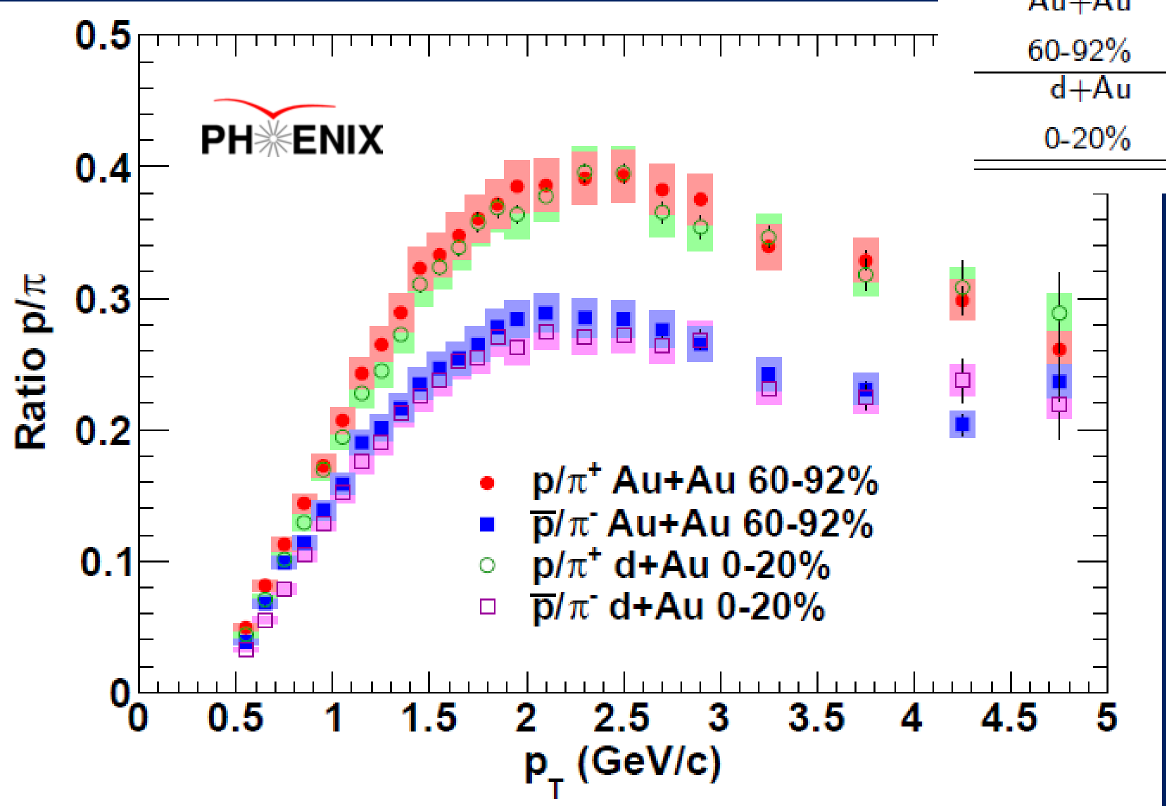
PRC88, 024906 (2013)

- d+Au data for identified charged hadrons in bins of centrality (degree of overlap of colliding nuclei—smaller percentiles are more overlapping)
- Ratio of protons to pions increases with greater overlap
- New hadron production mechanism enabled by presence of additional partons/nucleons
  - Parton recombination?

Comparing proton-to-pion ratio in central d+Au with peripheral Au+Au

N_{coll} - # of binary nucleon-nucleon collisions
N_{part} - # of participating nucleons

Centrality	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$
Au+Au 60-92%	14.8 ± 3.0	14.7 ± 2.9
d+Au 0-20%	15.1 ± 1.0	15.3 ± 0.8

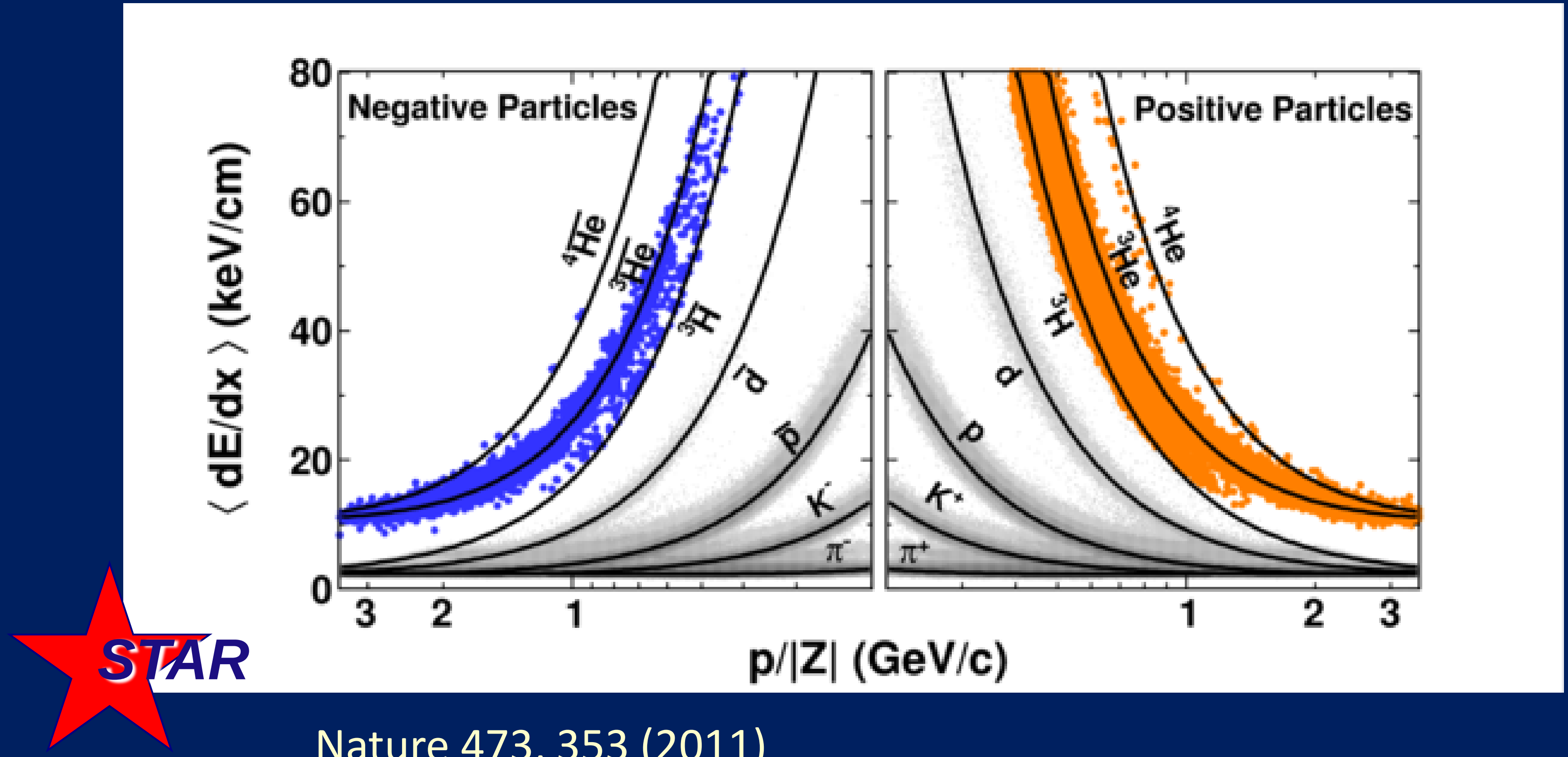


PRC88, 024906 (2013)

Both shape and magnitude identical for ~same number of nucleons involved!

Suggests common mechanism(s) for baryon production in the two systems

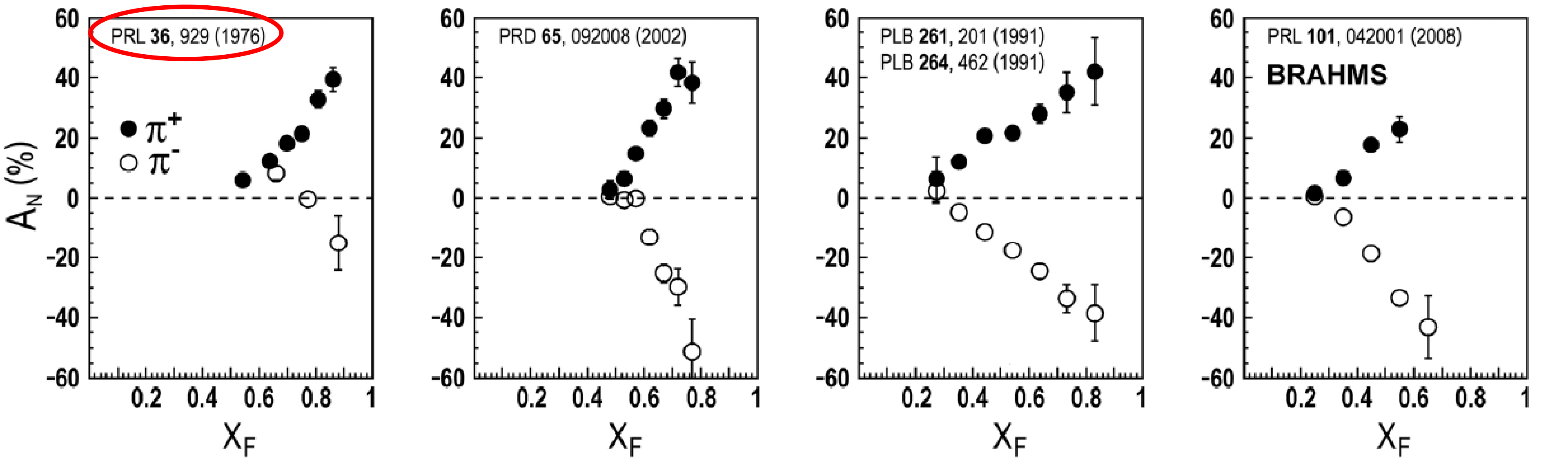
Bound states of hadronic bound states: Creating nuclei!



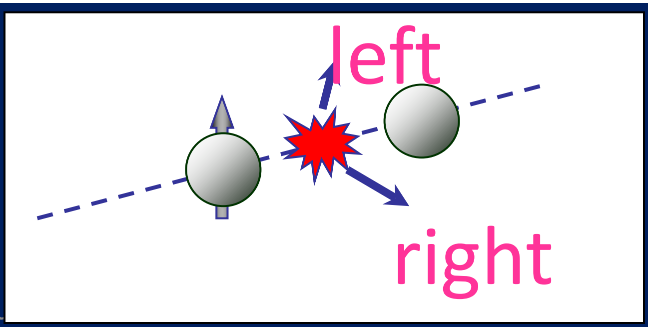
Nature 473, 353 (2011)

Back to spin-momentum correlations: What about the original p+p → hadrons?

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



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



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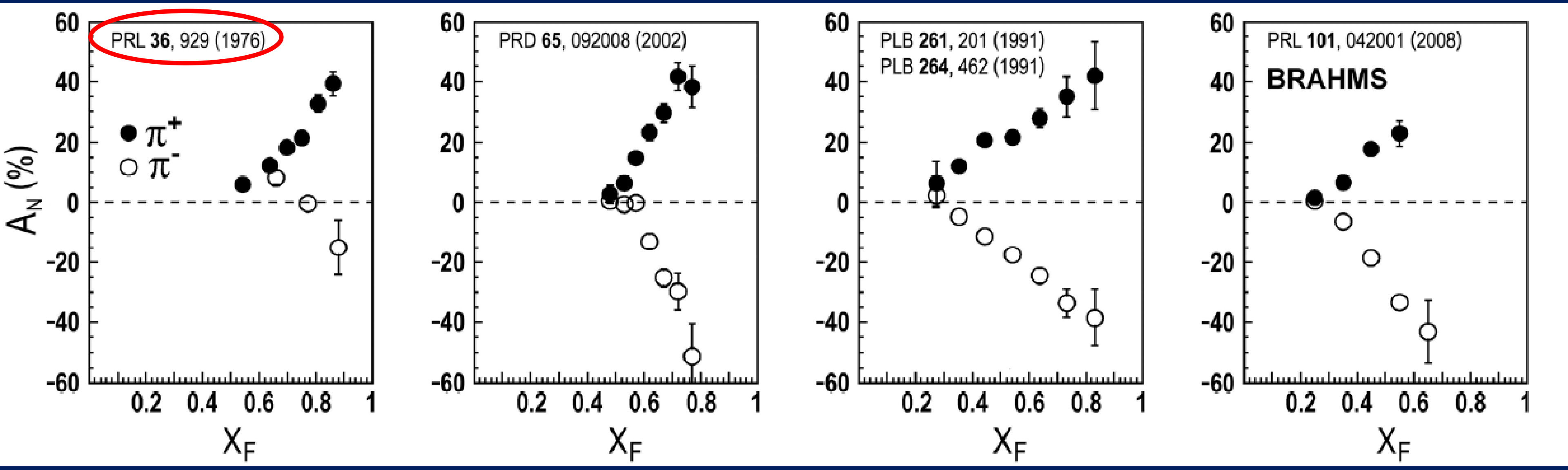
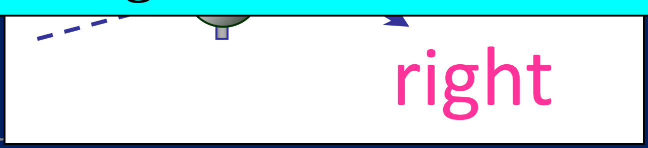


Experimentally confirmed numerous times, with strikingly similar effects across energies!



p+p → hadron + X: Challenging to interpret

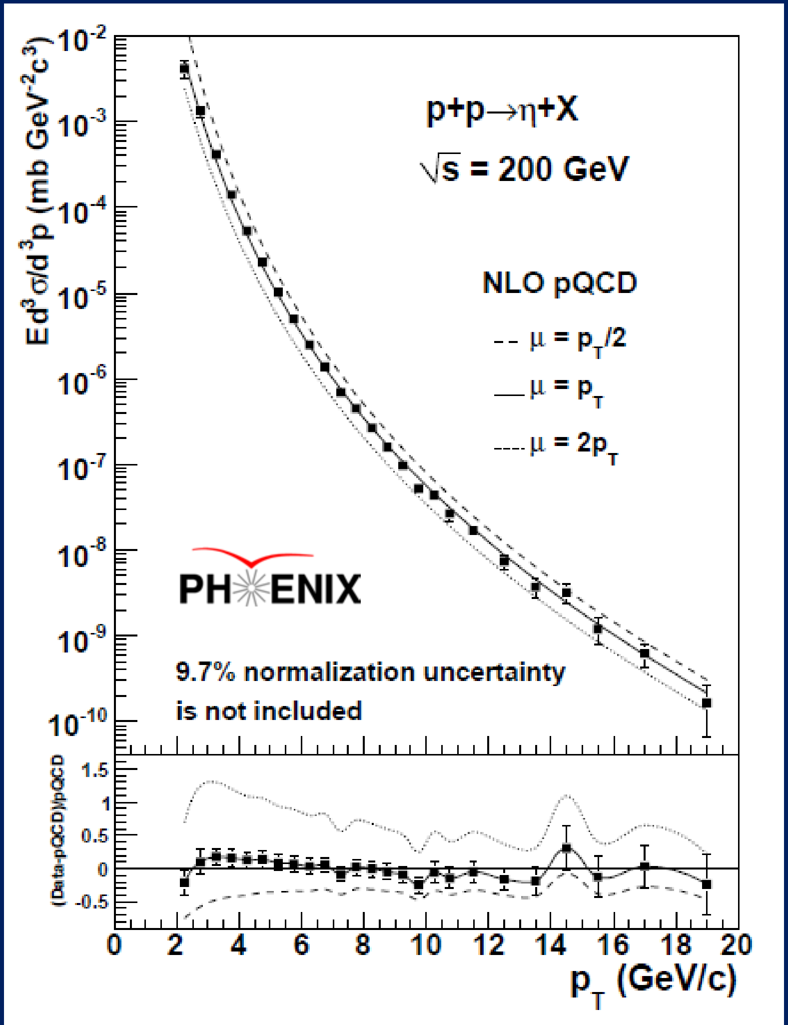
- Always huge effects!
- But in p+p → pion +X don't have enough information to separate initial-state (proton structure) from final-state (hadronization) effects
- Inclusive measurement—don't measure the combination of a hard plus a nonperturbative momentum scale required to (directly) apply TMD framework in pQCD calculations
- More in later lectures . . .

Summary: Lecture 1

- Transverse-momentum-dependent distributions have extended our knowledge of partons within QCD bound states and the process of hadronization, highlighting parton *dynamics*
- Working with TMD functions has furthermore brought to light fundamental aspects of QCD related to *color interactions*
- While nucleon structure has been a focus over the past ~40 years, increasing attention is starting to be paid to hadronization

Extra

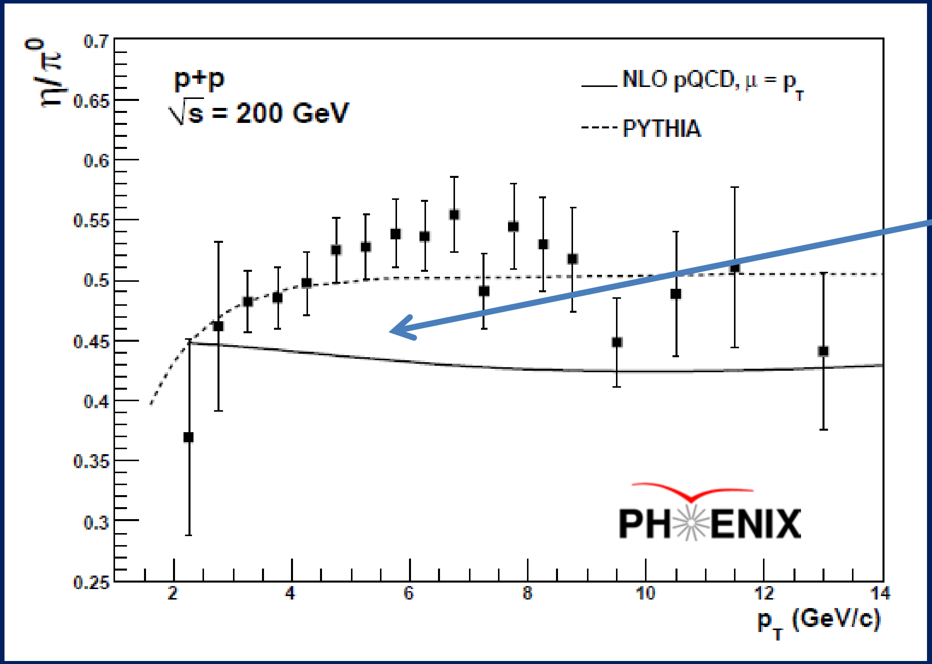
Eta mesons in 200 GeV p+p



PRD83, 032001 (2011)

- Cross section data used in FF fit

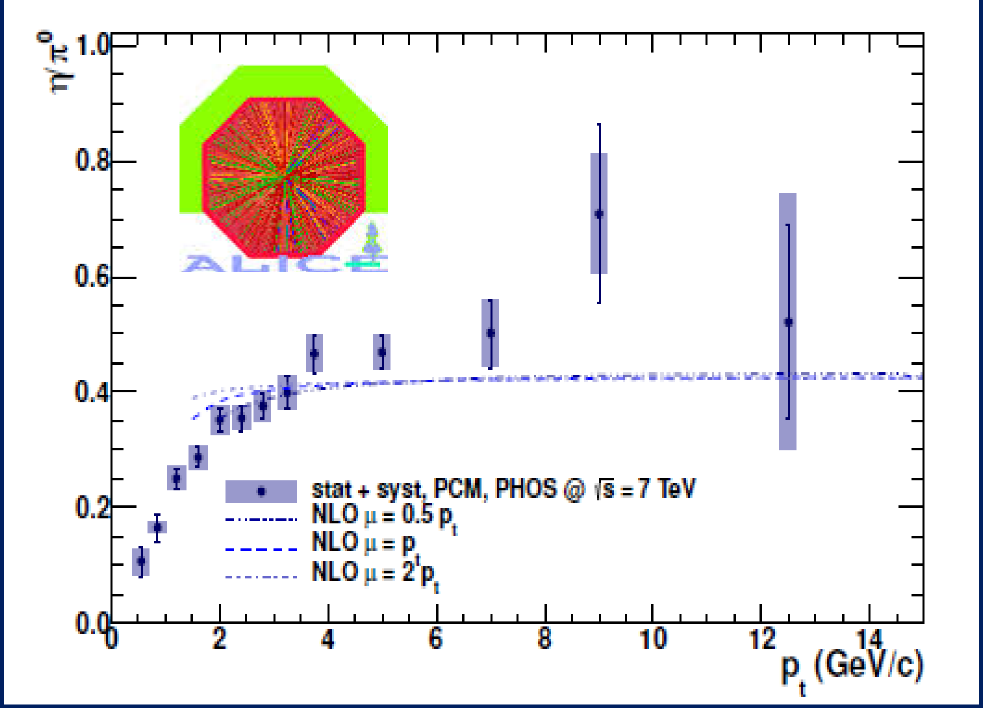
Eta mesons in 200 GeV p+p



- Cross section data used in FF fit
- NLO calculation for η/π^0 ratio ~15% too low (no uncertainties shown)
- PHENIX eta data and (earlier but consistent) π^0 data were used in respective FF fits, but in π^0 fit, PHENIX data normalization scaled within uncertainty in one direction, and in eta fit, scaled in other direction
- Again, fitting ratio directly would provide stronger constraint

PRD83, 032001 (2011)

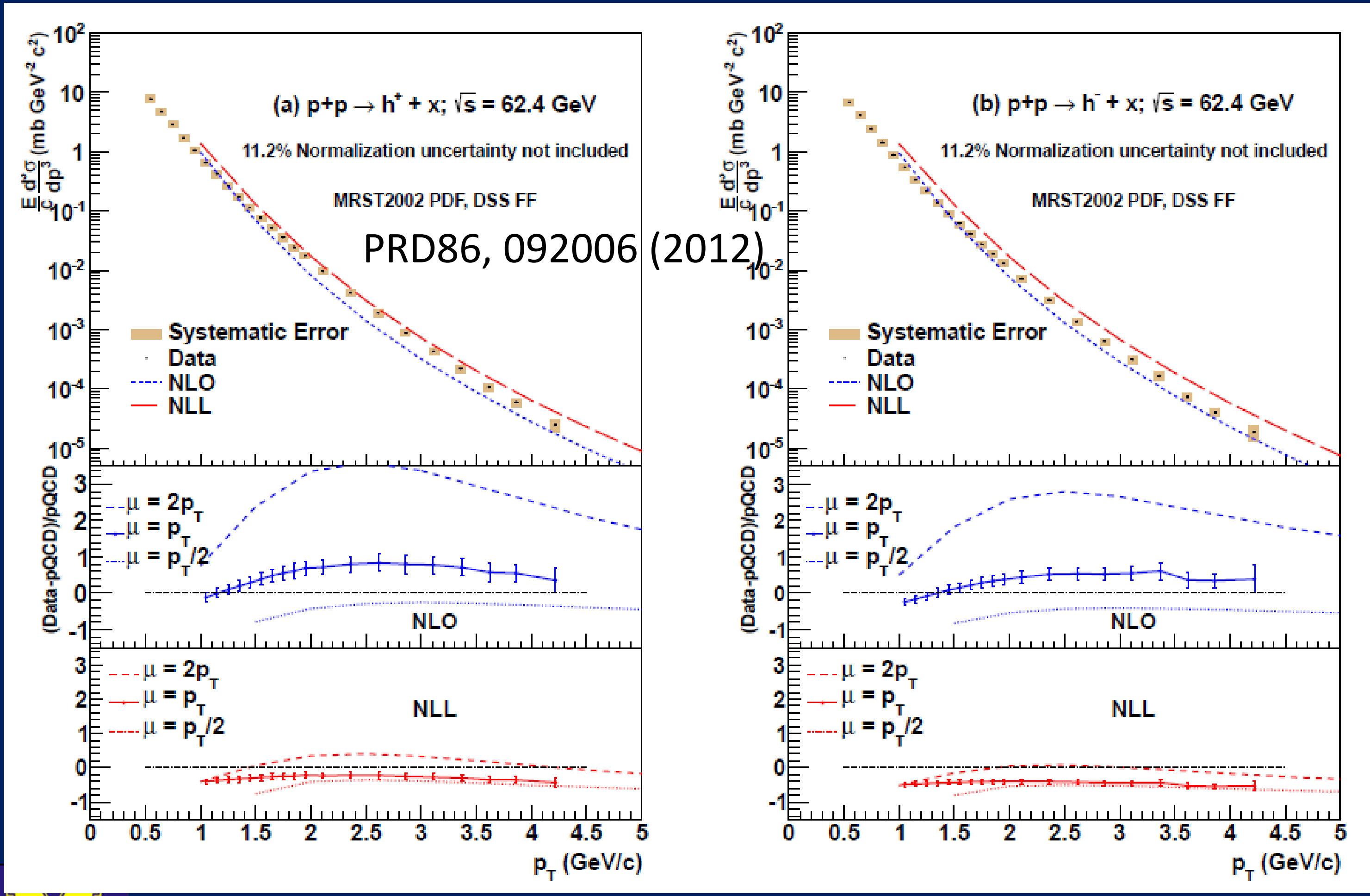
ALICE η/π^0 ratio, p+p at 7 TeV



PLB717, 152 (2012)

- Same p_T range as PHENIX data
- Calculated ratio again below data
- Scale uncertainty on NLO calculation shown (nearly cancels!)

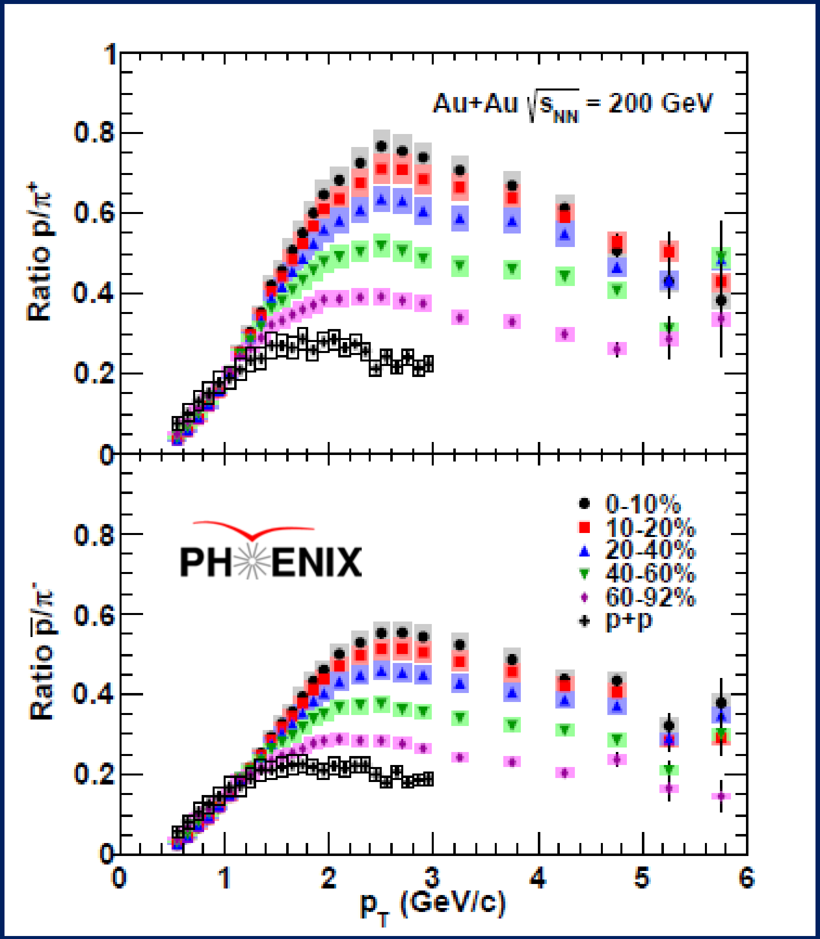
Midrapidity charge-separated hadrons in 62.4 GeV p+p: Reining in scale uncertainties with NLL resummation



PRD86, 092006 (2012)

Useful when appropriate …

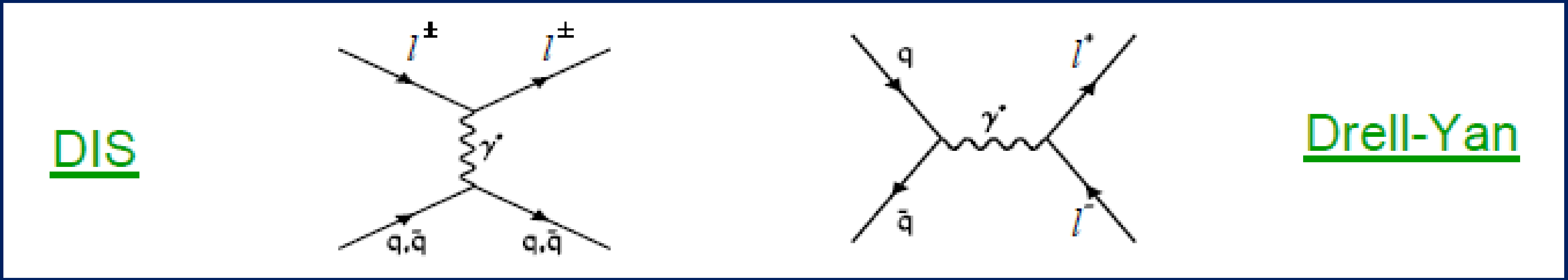
Centrality-dependent baryon enhancement in d+Au compared to p+p



- Precision d+Au data for identified charged hadrons in bins of centrality
- New hadron production mechanism enabled by presence of additional partons/ nucleons
  - Parton recombination?
- Strong centrality dependence despite small range of N_{part} and N_{coll} values in d+Au
- Well-known centrality-dependent baryon enhancement in Au+Au

PRC88, 024906 (2013)

Complementarity of Drell-Yan and DIS



- Both deep-inelastic lepton-nucleon scattering (DIS) and quark-antiquark annihilation to leptons (Drell-Yan process) are tools to probe the quark and antiquark structure of hadrons