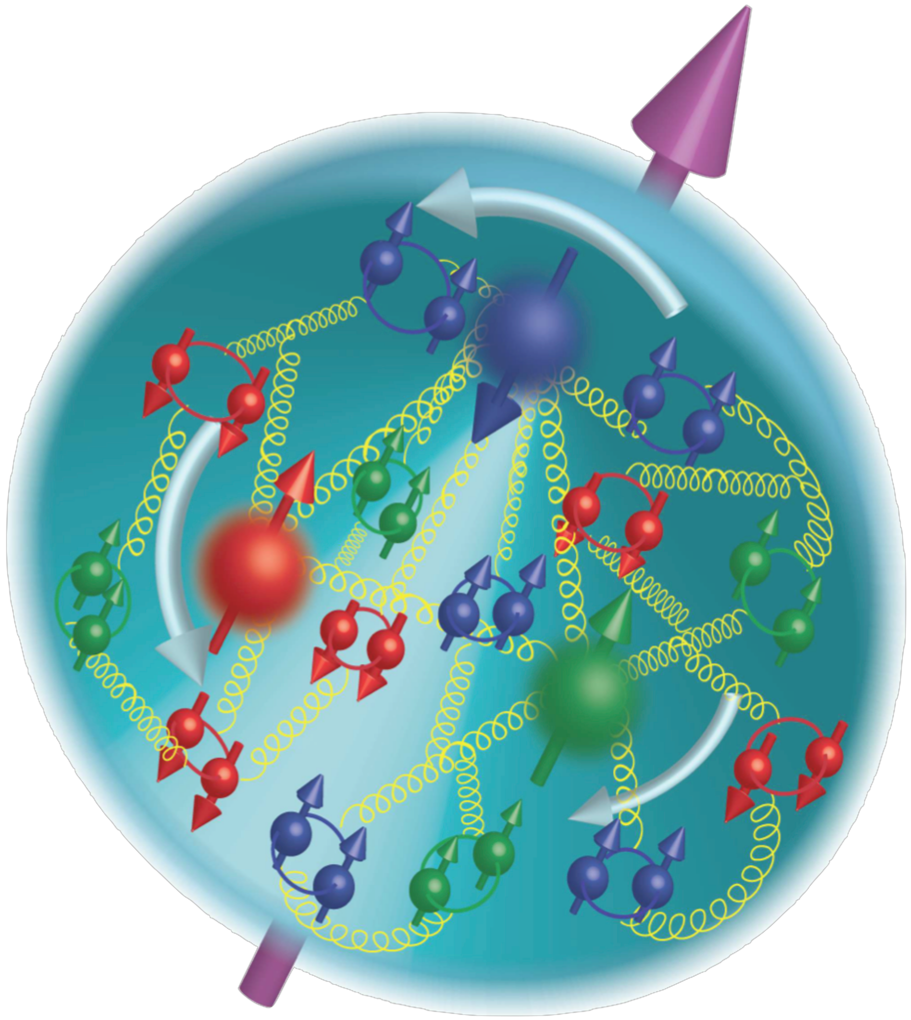
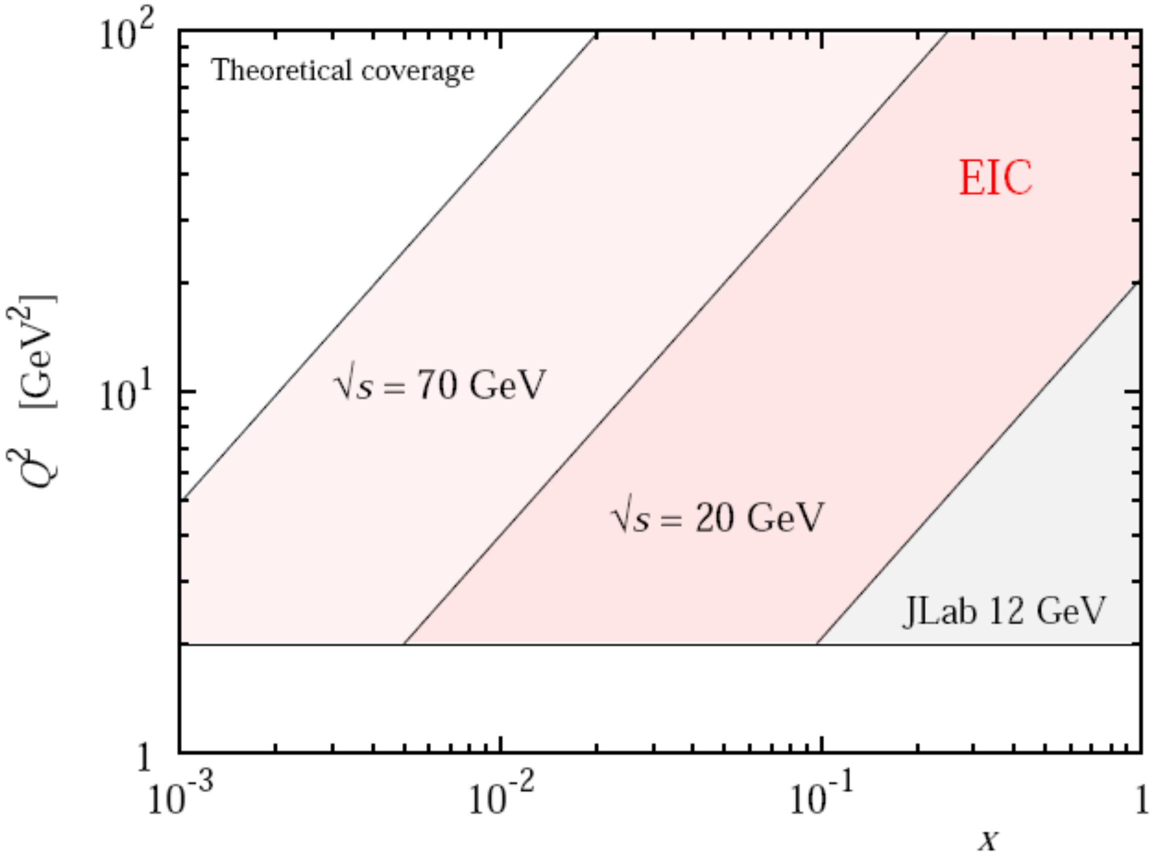
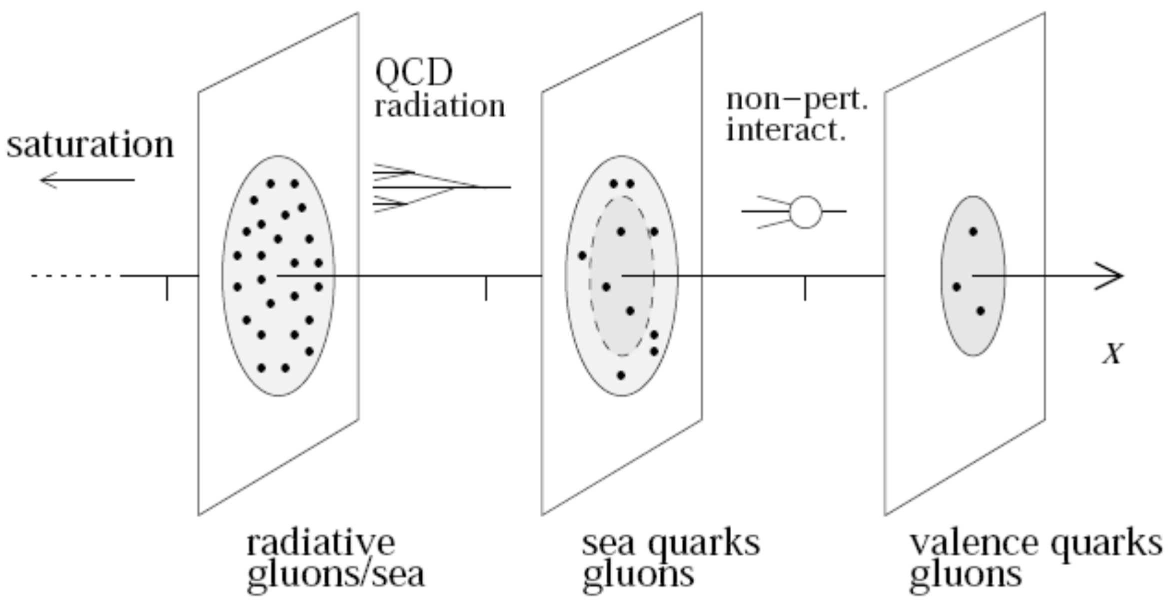


AN OVERVIEW OF TMDs

Alexei Prokudin

NUCLEON LANDSCAPE





Nucleon is a many body dynamical system of quarks and gluons

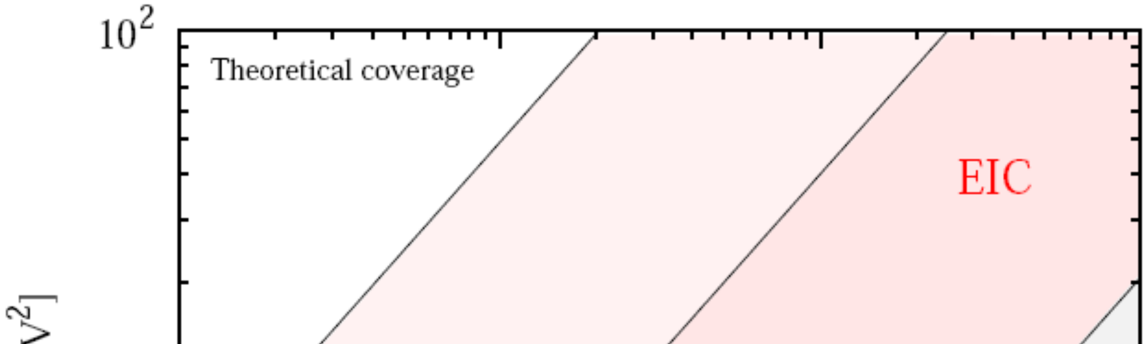
By changing x we probe different aspects of nucleon wave function

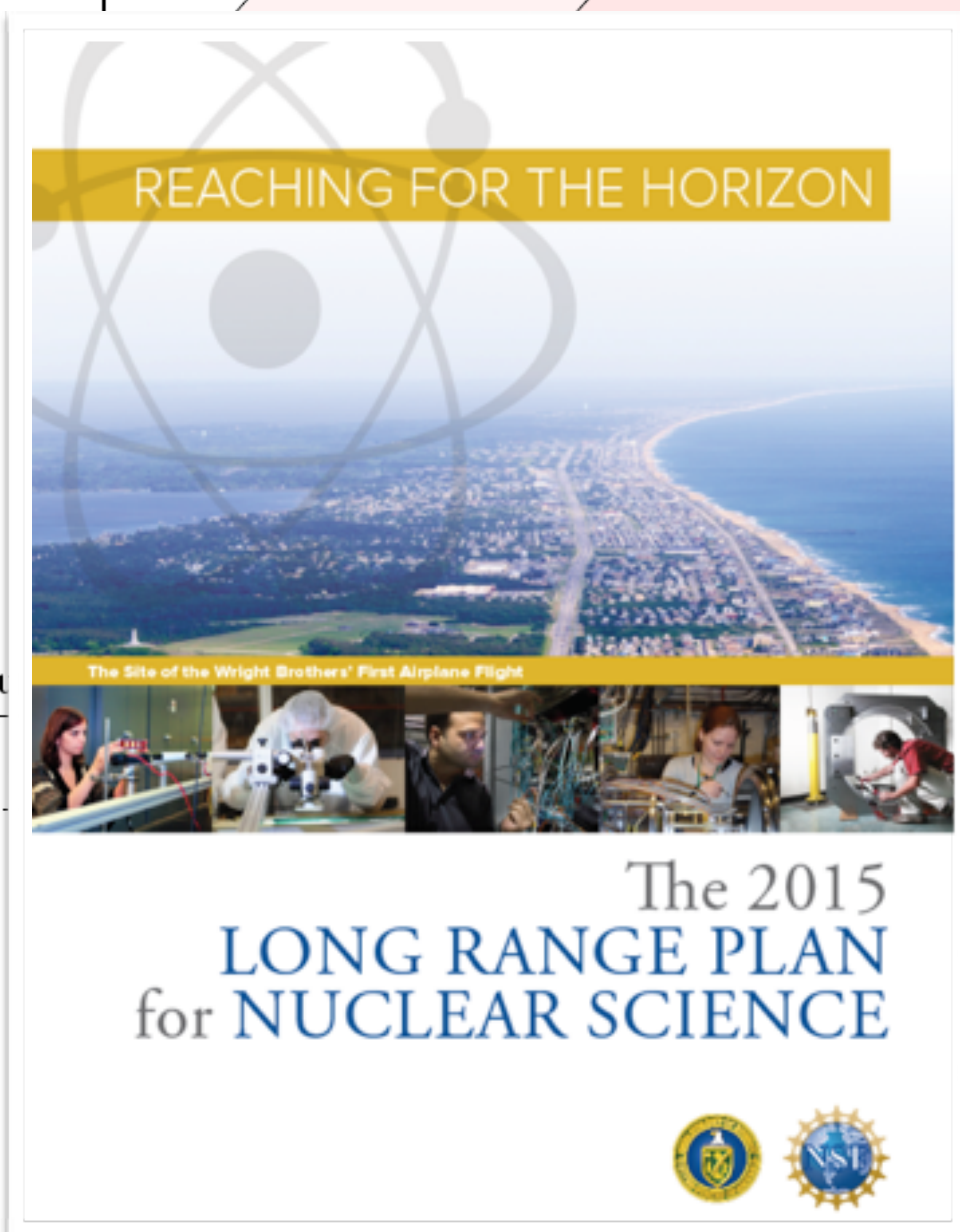
How partons move and how they are distributed in space is one of the directions of development of nuclear physics

Technically such information is encoded into Generalised Parton Distributions (GPDs) and Transverse Momentum Dependent distributions (TMDs)

These distributions are also referred to as 3D (three-dimensional) distributions

NUCLEON LANDSCAPE





Nucleon is a many body dynamical system of quarks and gluons

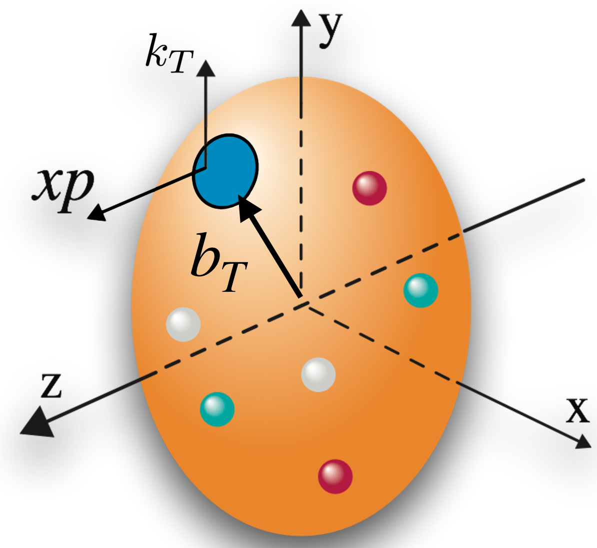
By changing x we probe different aspects of nucleon wave function

How partons move and how they are distributed in space is one of the directions of development of nuclear physics

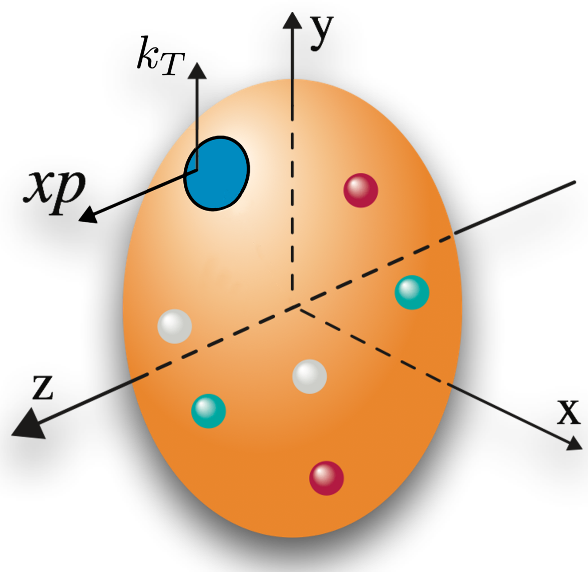
Technically such information is encoded

Understanding the structure of hadrons in terms of QCD's partons (quarks and gluons) is one of the central goals of 2015 NSAC Long-Range Plan

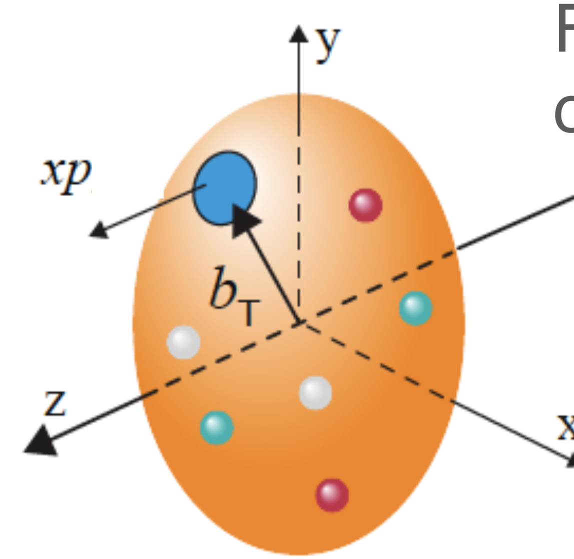
Wigner distributions (Fourier transform of GTMDs = Generalized Transverse Momentum Distributions)



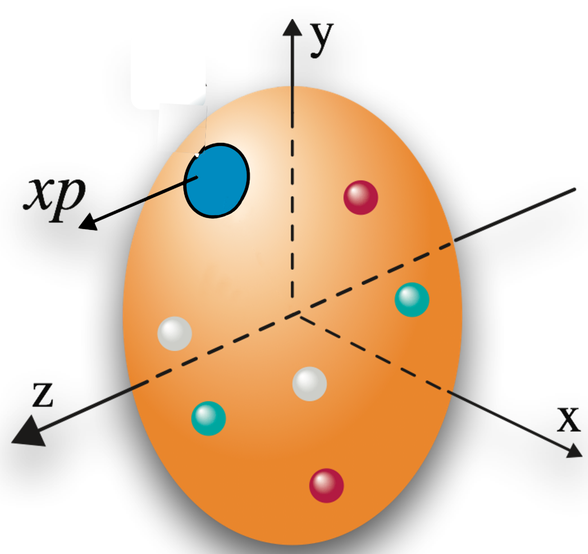
TMDs



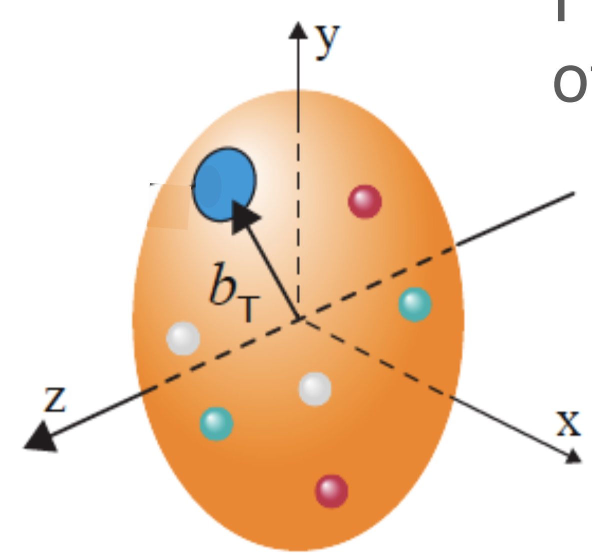
Fourier transform of GPDs



PDFs



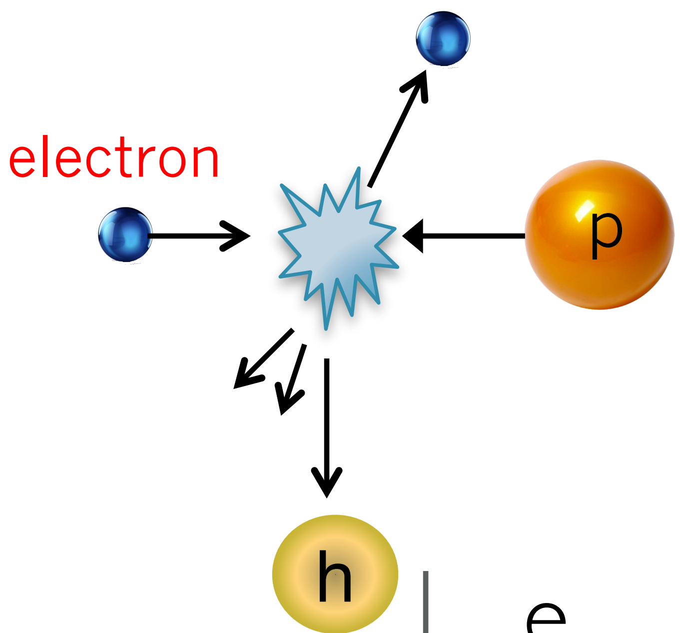
Fourier transform of Form Factors

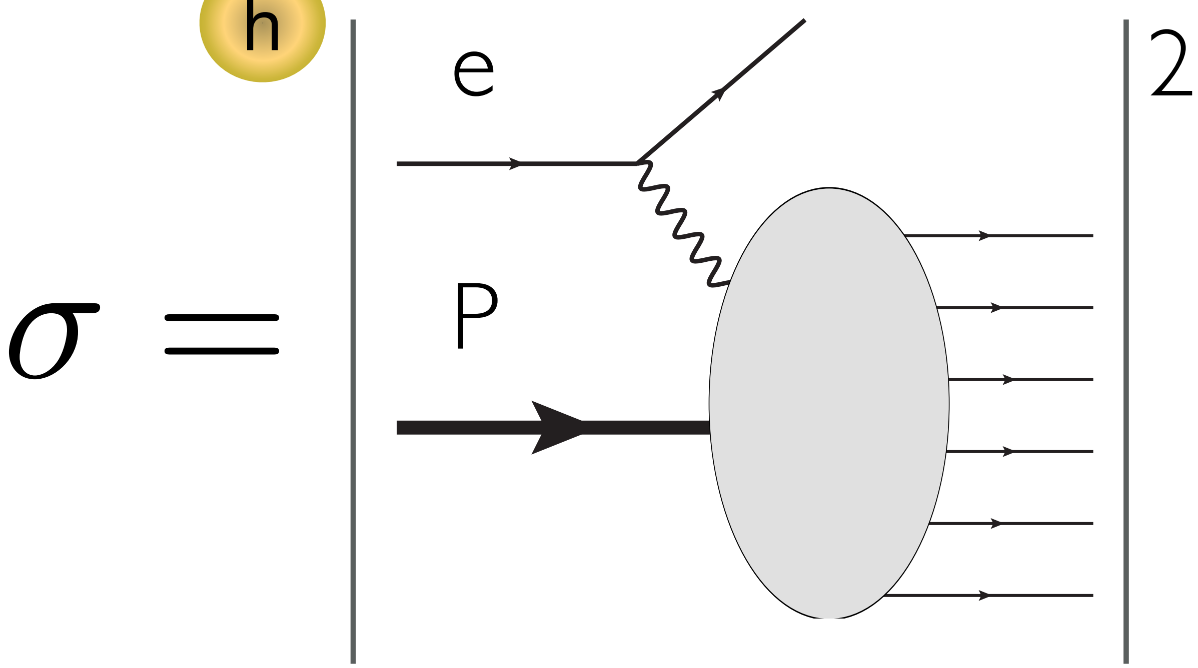


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

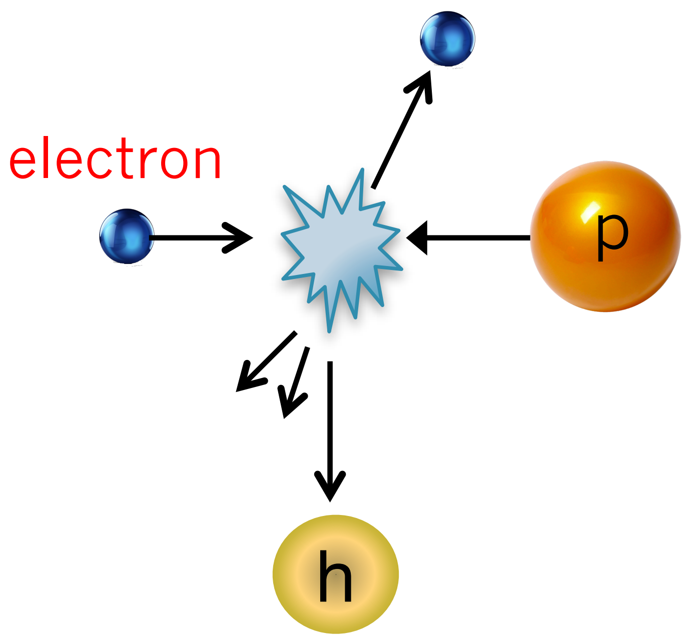
QCD FACTORIZATION IS THE KEY!

We need a probe to “see” quarks and gluons

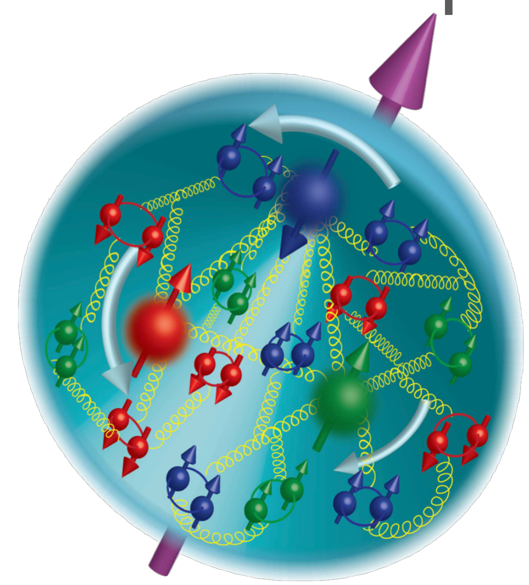




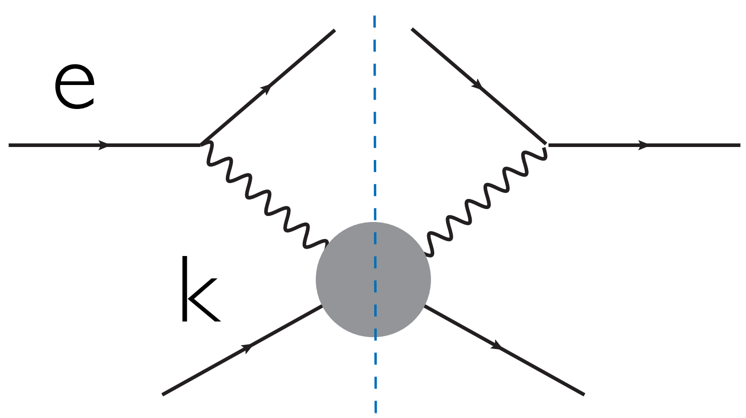
QCD FACTORIZATION IS THE KEY!



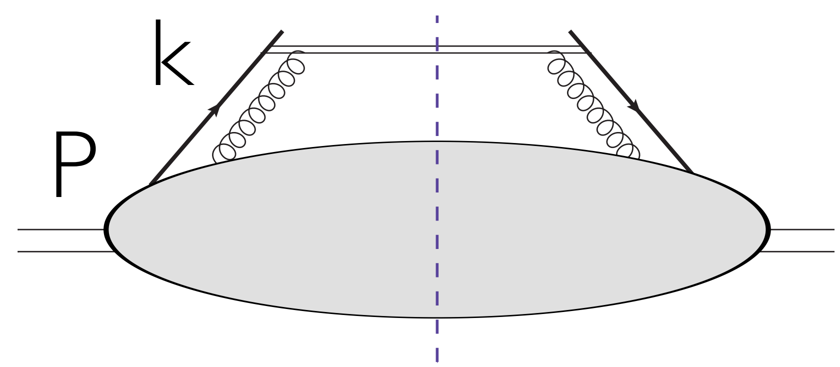
We need a probe to “see” quarks and gluons



$\sigma \approx$



$\otimes$

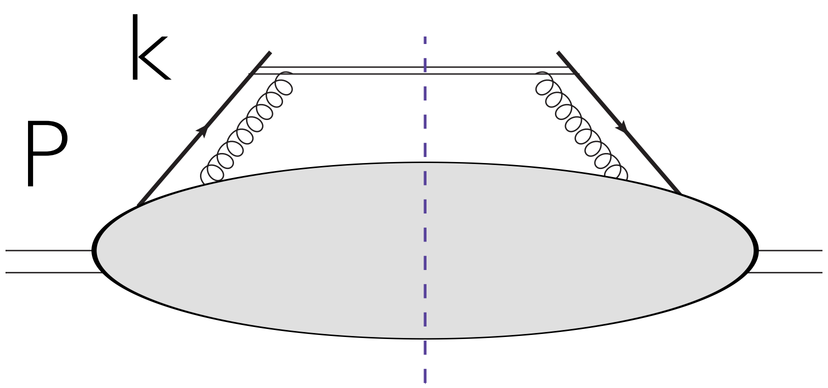


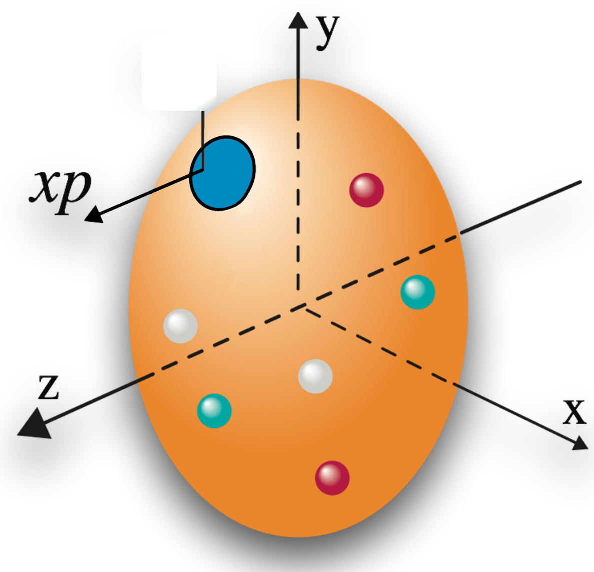
$+\mathcal{O}\left(\frac{M}{Q}\right)$

Factorization Probe Structure Power corrections

HADRON'S PARTONIC STRUCTURE

Collinear Parton Distribution Functions





$f_{q/P}(x)$

longitudinal

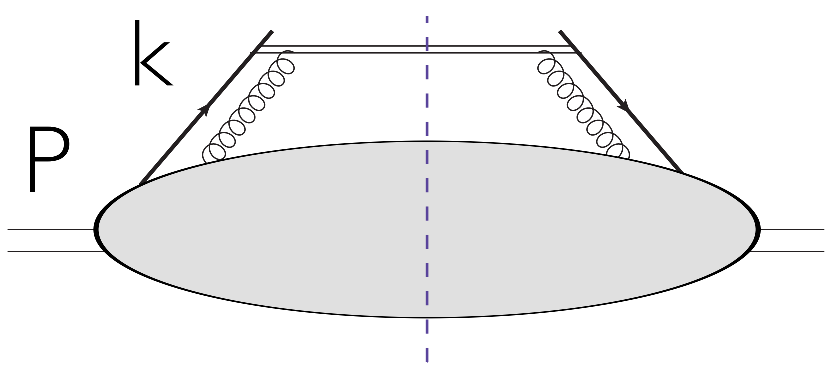
Probability density to find a quark with a momentum fraction x

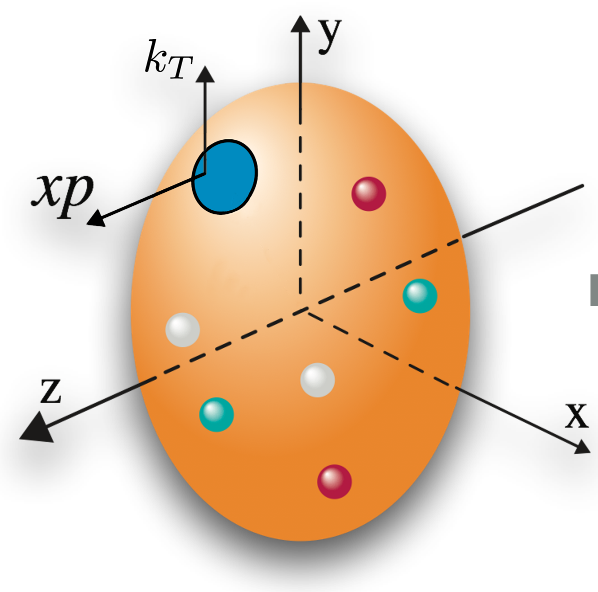
Hard probe resolves the particle nature of partons, but is not sensitive to hadron's structure at ~fm distances.

HADRON'S PARTONIC STRUCTURE

To study the physics of *confined motion of quarks and gluons* inside of the proton one needs a new type "hard probe" with two scales.

Transverse Momentum Dependent functions





$$f_{q/P}(x, k_T)$$

longitudinal & transverse

One large scale (Q) sensitive to particle nature of quark and gluons

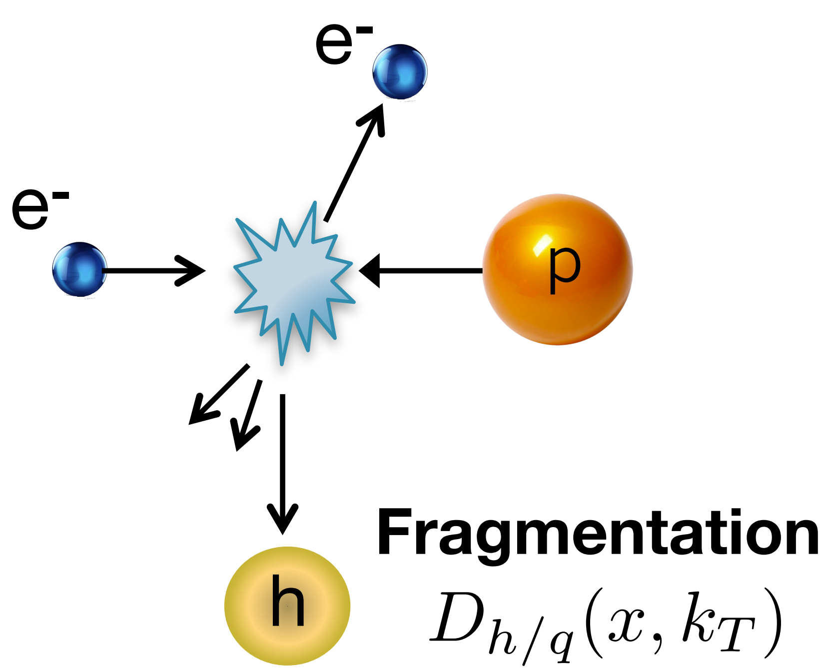
One small scale (k_T) *sensitive to how QCD bounds partons* and to the detailed structure at ~fm distances.

The confined motion (k_T dependence) is encoded in TMDs

QCD factorization is proven for a number of processes

Semi-Inclusive DIS

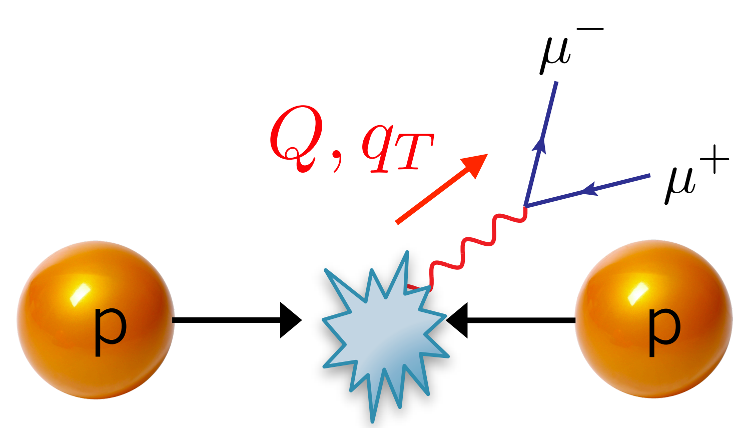
$$\sigma \sim f_{q/P}(x,k_T)D_{h/q}(x,k_T)$$



Meng, Olness, Soper (1992)
Ji, Ma, Yuan (2005)
Idilbi, Ji, Ma, Yuan (2004)
Collins (2011)

Drell-Yan

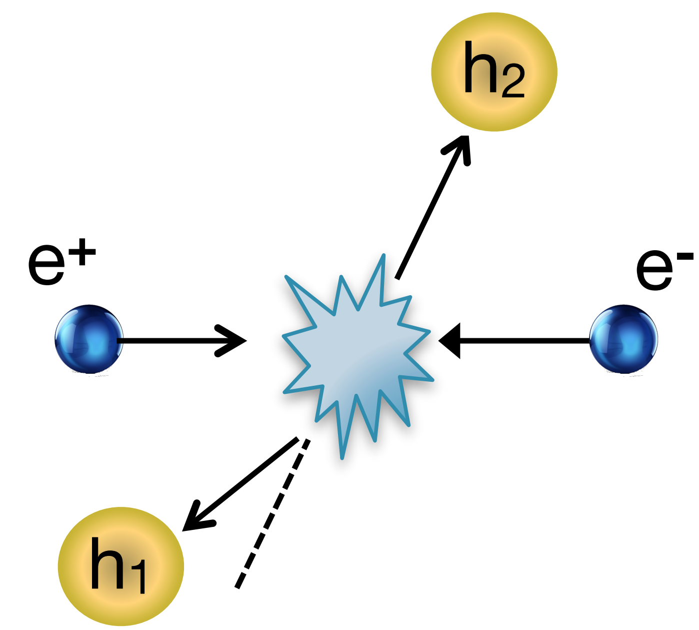
$$\sigma \sim f_{q/P}(x,k_T)f_{q/P}(x,k_T)$$



Collins, Soper, Sterman (1985)
Ji, Ma, Yuan (2004)
Collins (2011)

Dihadron in e^+e^-

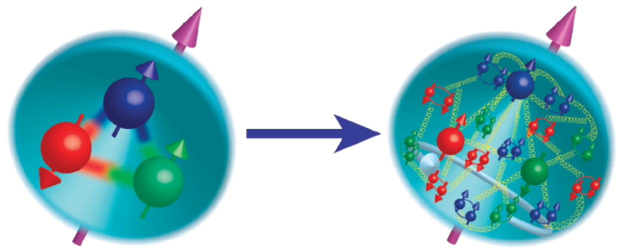
$$\sigma \sim D_{h_1/q}(x,k_T)D_{h_2/q}(x,k_T)$$



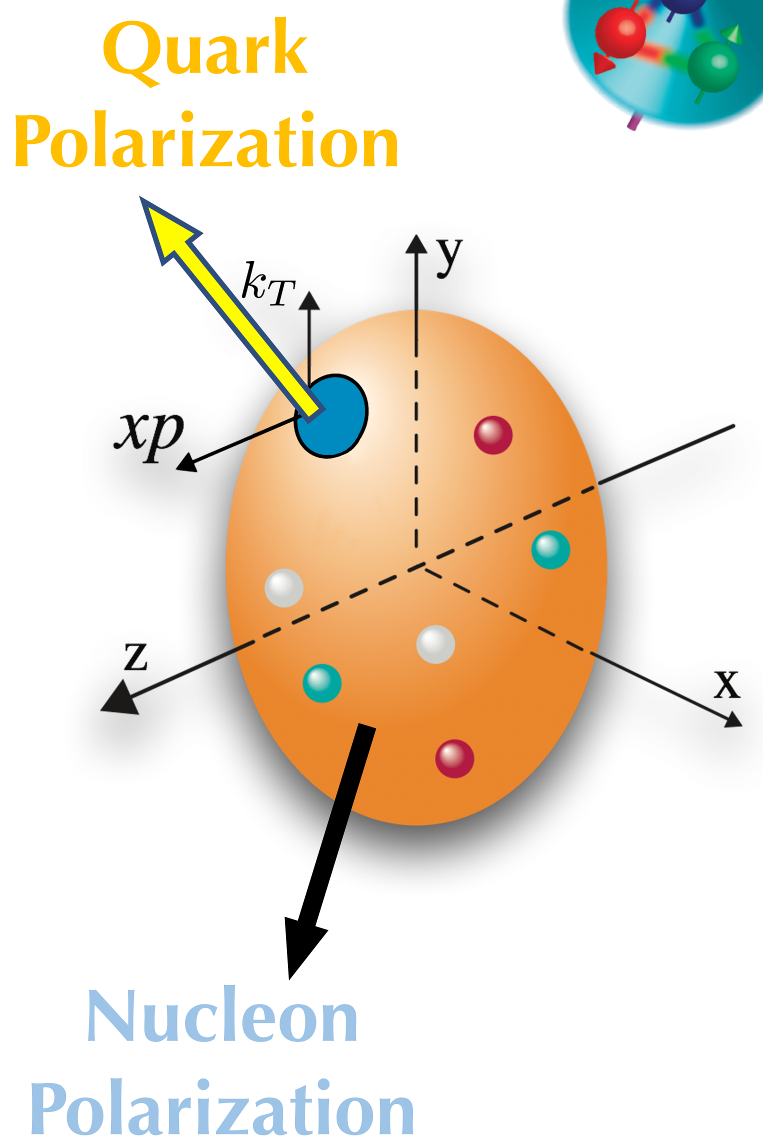
Collins, Soper (1983)
Collins (2011)

Small scale → $q_T \ll Q$ ← Large scale

Our understanding of hadron evolves: TMDs with Polarization



Nucleon emerges as a strongly interacting, relativistic bound state of quarks and gluons

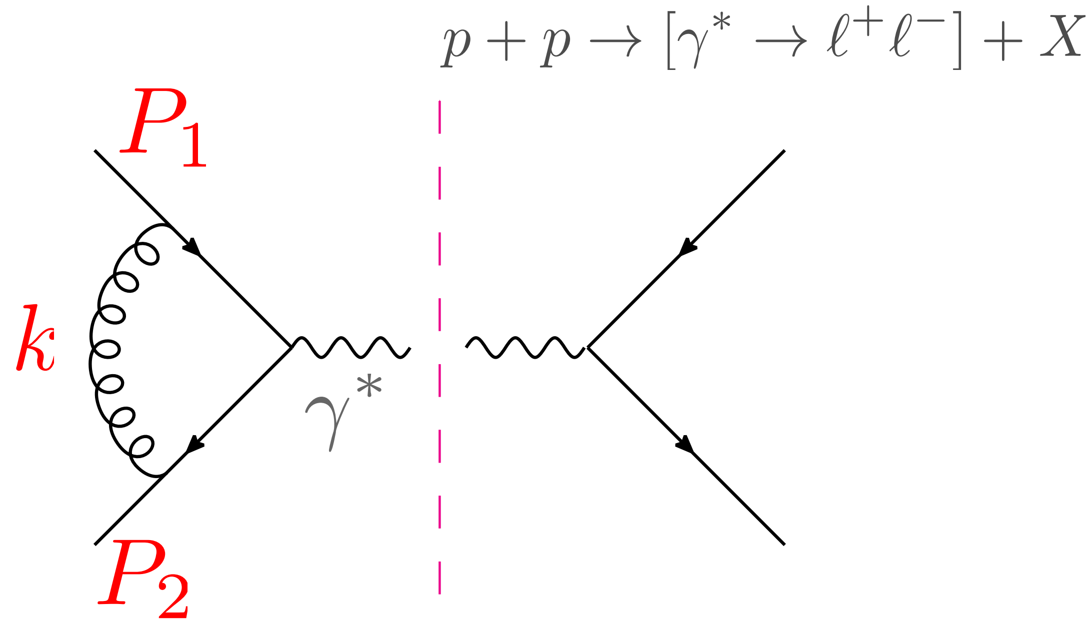


		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$		$h_1^{\perp}(x,k_T^2)$ - *Boer-Mulders*
	L		$g_1(x,k_T^2)$ - *Helicity*	$h_{1L}^{\perp}(x,k_T^2)$ -
	T	$f_{1T}^{\perp}(x,k_T^2)$ - *Sivers*	$g_{1T}(x,k_T^2)$ -	$h_1(x,k_T^2)$ - *Transversity* $h_{1T}^{\perp}(x,k_T^2)$ - *Pretzelosity*

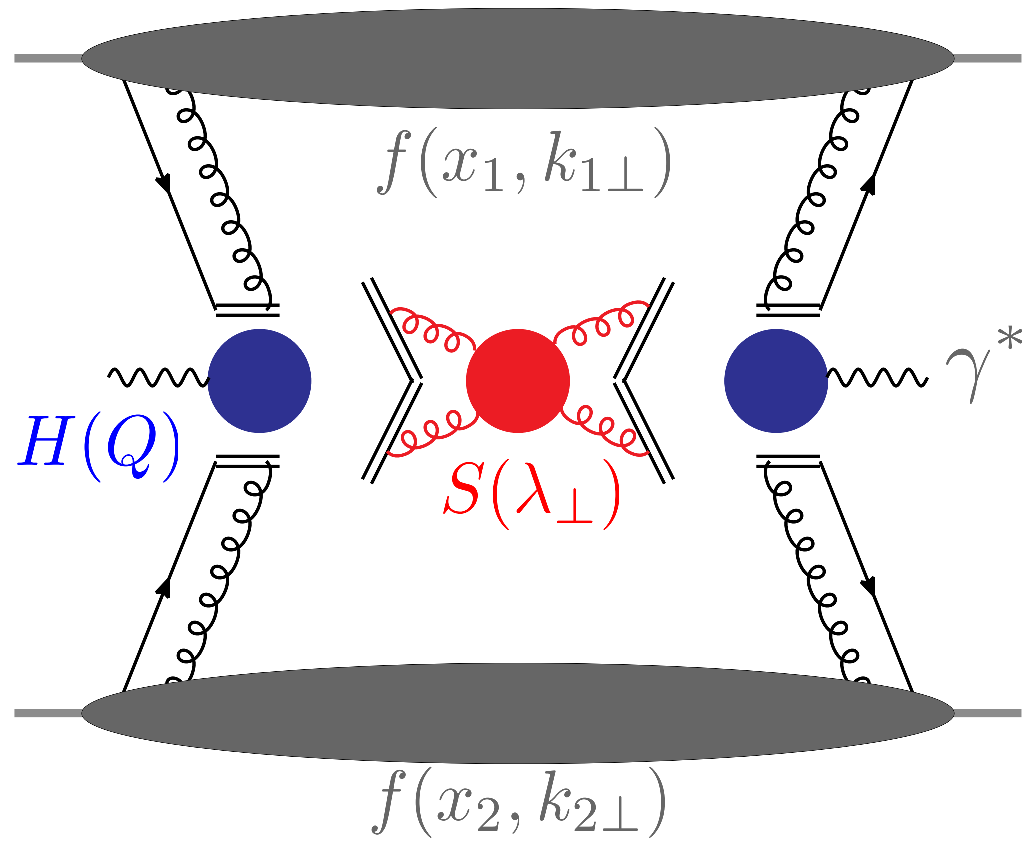
Analogous tables for:

- Gluons $f_1 \to f_1^g$ etc
- Fragmentation functions
- Nuclear targets $S \neq \frac{1}{2}$

TMD FACTORIZATION



Factorization of regions:
(1) k//P_1, (2) k//P_2, (3) k soft, (4) k hard



$$F(x,b) = f(x,b)\sqrt{S(b)}$$

$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} = \int \frac{d^2 b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) F(x_1, b) F(x_2, b)$$

$$\mu \frac{d}{d\mu} \ln f_q(x, \vec{b}_T, \mu, \zeta) = \gamma_\mu^q(\mu, \zeta)$$

$$\zeta \frac{d}{d\zeta} \ln f_q(x, \vec{b}_T, \mu, \zeta) = \gamma_\zeta^q(\mu, b_T)$$

Collins-Soper Equations

μ = renormalization scale

ζ = Collins-Soper parameter

TMD FACTORIZATION

Collins, Soper, Sterman (85), Collins (11), Rogers, Collins (15)

$$F(x, k_\perp; Q) = \frac{1}{(2\pi)^2} \int d^2 b e^{ik_\perp \cdot b} F(x, b; Q) = \frac{1}{2\pi} \int_0^\infty db\, b J_0(k_\perp b) F(x, b; Q)$$

$$F(x, b; Q) \approx C \otimes F(x, c/b^*) \times \exp\left\{ -\int_{c/b^*}^{Q} \frac{d\mu}{\mu} \left(A \ln \frac{Q^2}{\mu^2} + B \right) \right\} \times \exp\left(-S_{\text{non-pert}}(b, Q) \right)$$

OPE/collinear part

transverse part, Sudakov FF

- The evolution is complicated as one evolves in 2 dimensions
- The presence of a non-perturbative evolution kernel makes calculations more involved
- Theoretical constraints exist on both non-perturbative shape of TMD and the non-perturbative kernel of evolution

✓ **Non-perturbative: fitted from data**

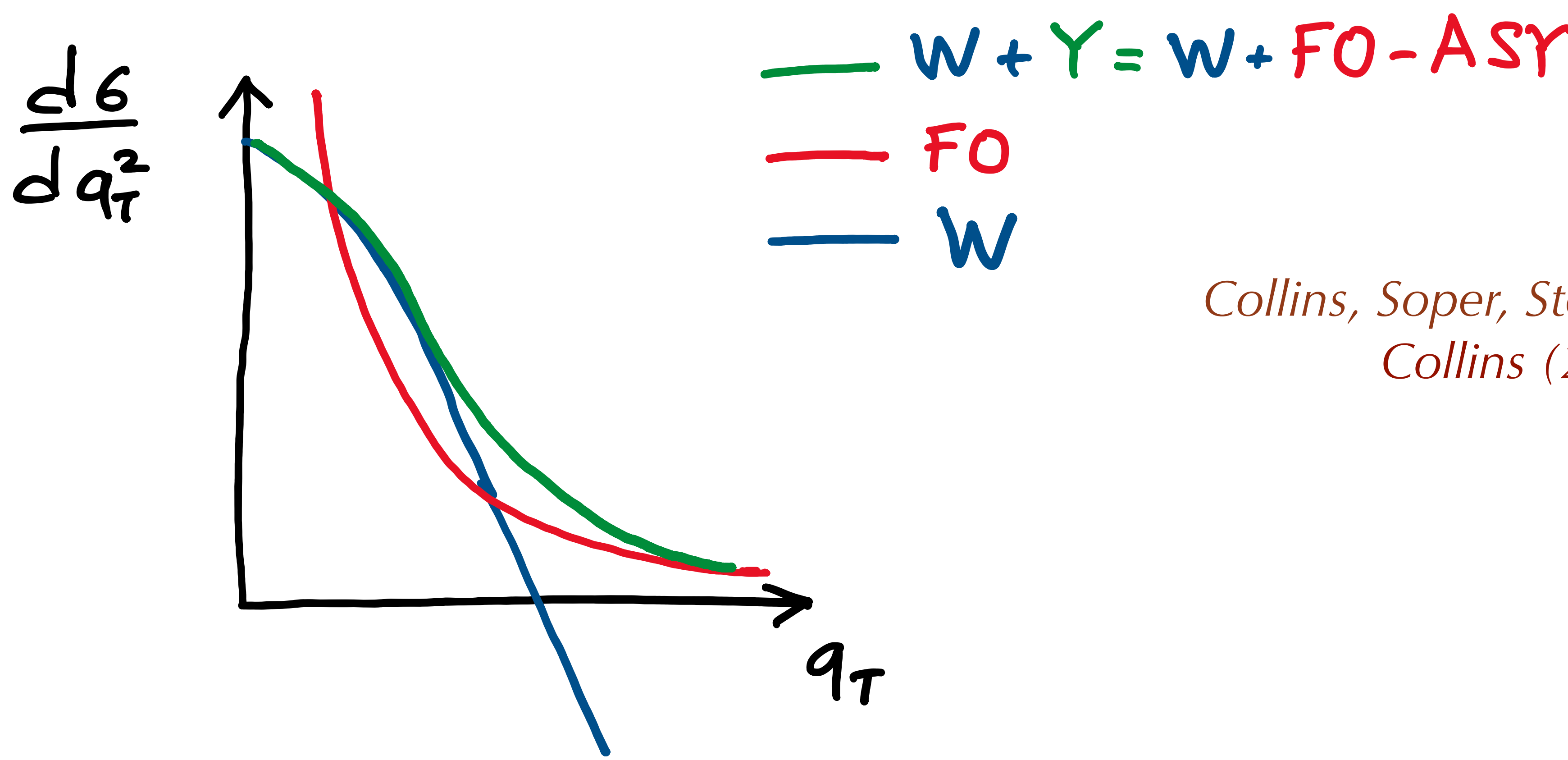
✓ The key ingredient – ln(Q) piece is spin-independent

✓ Non-perturbative shape of TMDs is to be extracted from data

✓ One can use information from models or ab-initio calculations, such as lattice QCD: shape of TMDs, non-perturbative kernel.

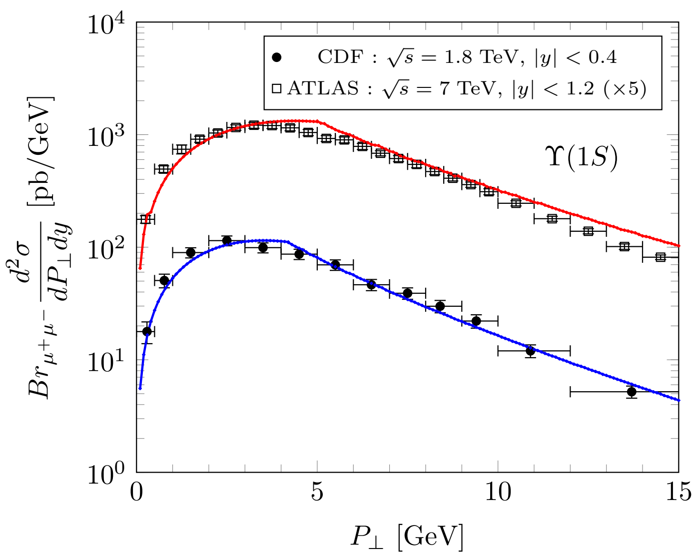
TMD FACTORIZATION AND CSS

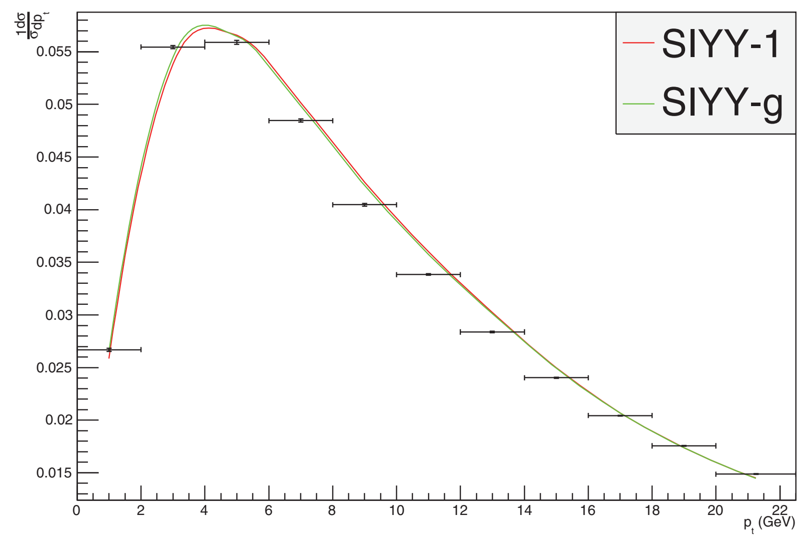
- TMD factorization organizes a differential in q_T cross section as a convolution of TMD functions (W term) in the region of applicability of TMD factorization $q_T \ll Q$
- CSS formalism provides a W+Y method to make the cross section accurate in a wide region of q_T by adding a Y term, which is a difference of a Fixed Order calculation in collinear approximation and its asymptotic expansion $q_T \to 0$
- At some large $q_T \sim Q$ calculation is switched to a Fixed Order

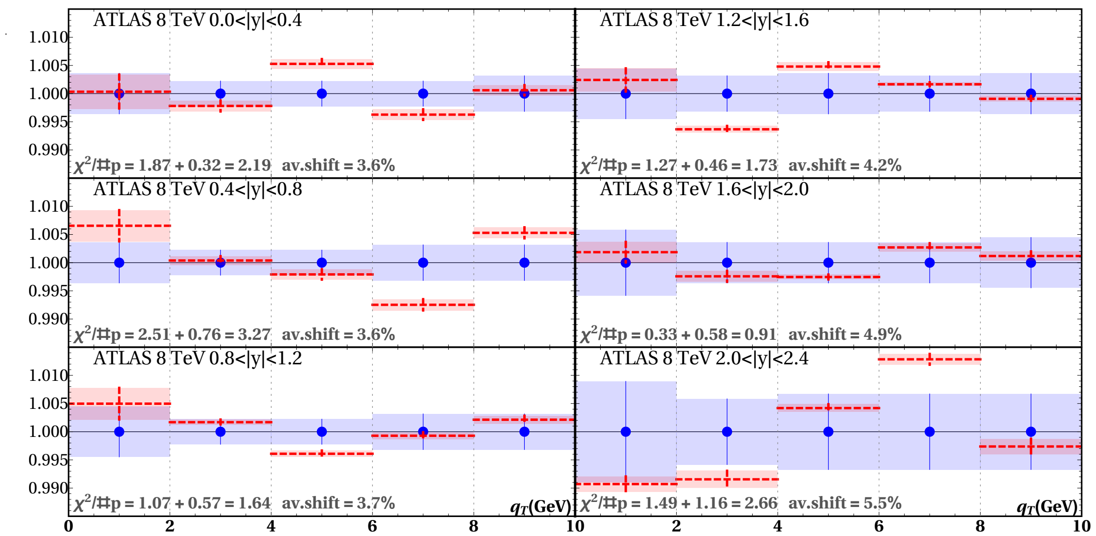


Collins, Soper, Sterman (1985)
Collins (2011)

SUCCESS OF TMD FACTORIZATION PREDICTIVE POWER







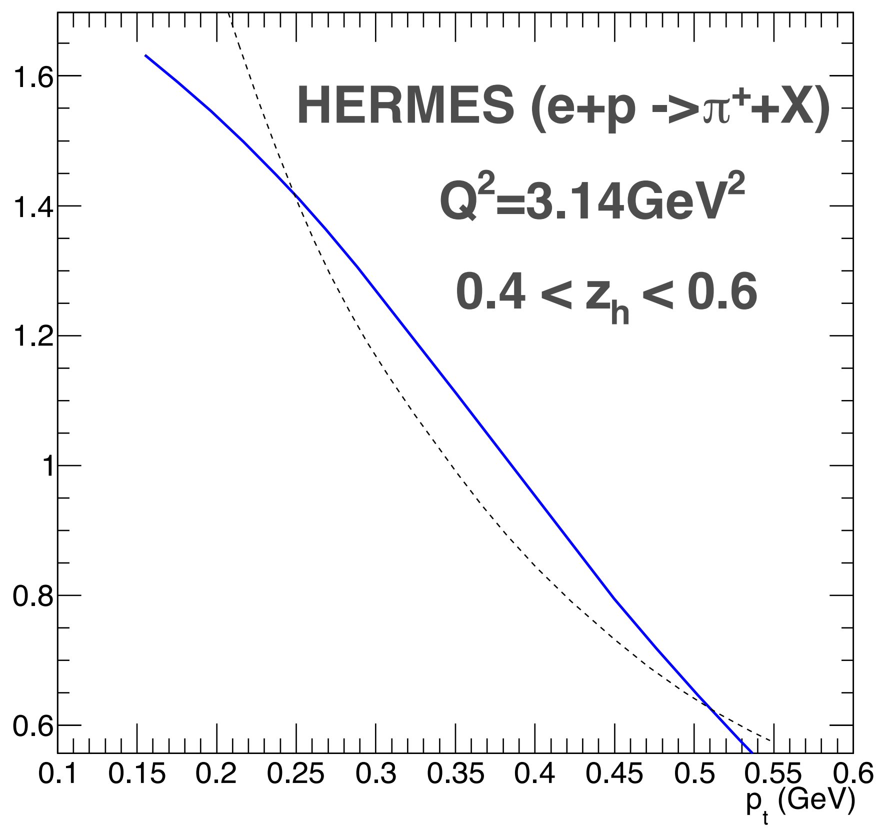
Qiu, Watanabe arXiv:1710.06928 *Sun, Isaacson, Yuan, Yuan arXiv:1406.3073* *Bertone, Scimemi, Vladimirov arXiv:1902.08474*

Upsilon production

Z boson production at the LHC

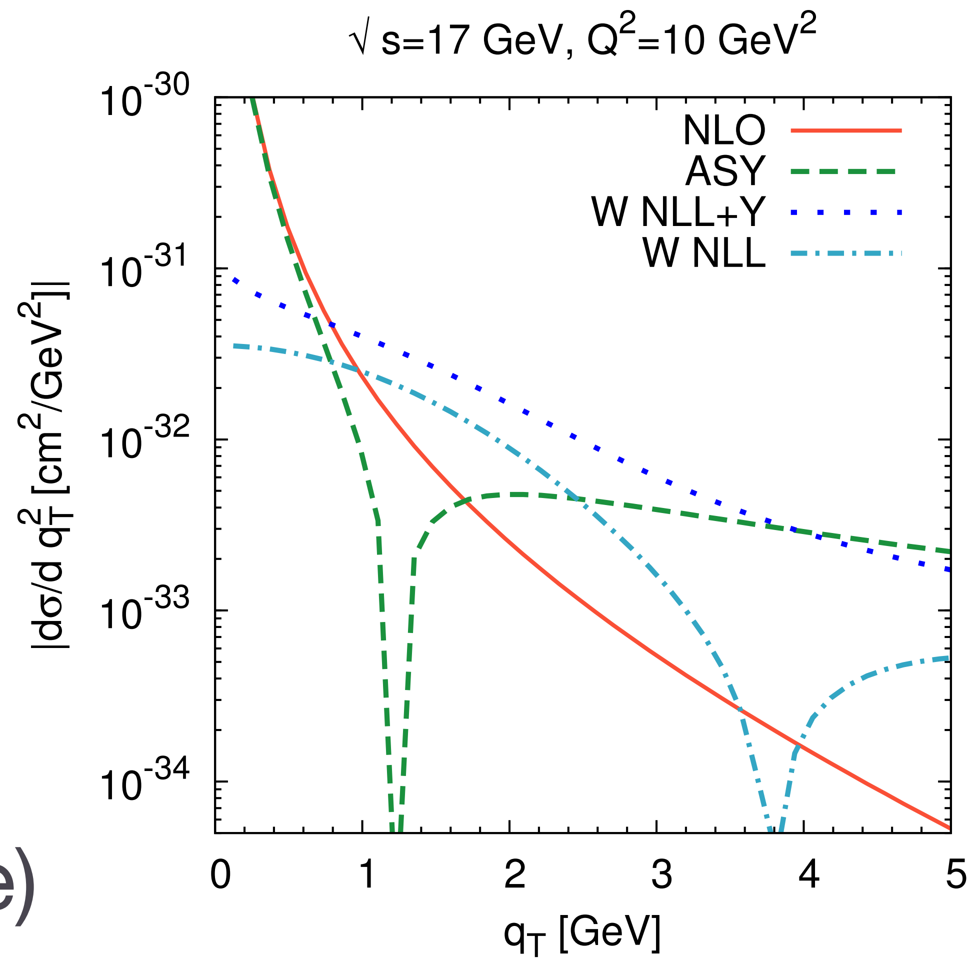
- TMD factorization (with an appropriate matching to collinear results) aims at an accurate description (and prediction) of a differential in q_T cross section in a wide range of q_T
- LHC results at 7 and 13 TeV are accurately predicted from fits of lower energies

"PROBLEMS" OF TMD FACTORIZATION AT LOW Q



W (solid line) and Y terms (dashed line)

Sun, Isaacson, Yuan, Yuan arXiv:1406.3073



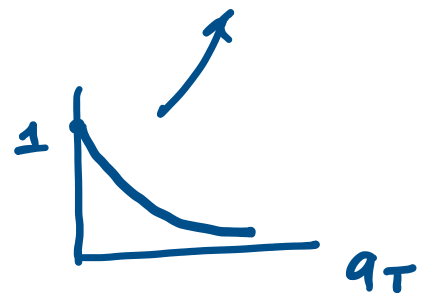
Boglione, Gonzalez, Melis, AP arXiv:1412.1383

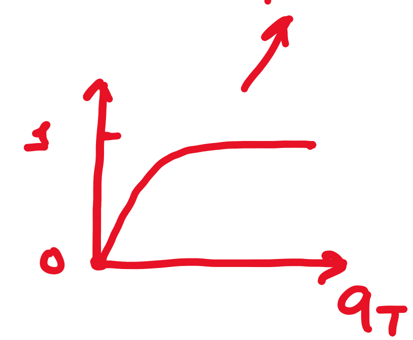
- At low Q the Y term becomes unreasonably large (larger than the W term) in the region of the maximal validity of TMD factorization (cross section should be given by W with a small error)
- W term changes sign at a different qT compared to ASY, making matching problematic
- The reason: Y=FO-ASY has constant terms that do not depend on q_T and may be large compared to W if cross section itself is small

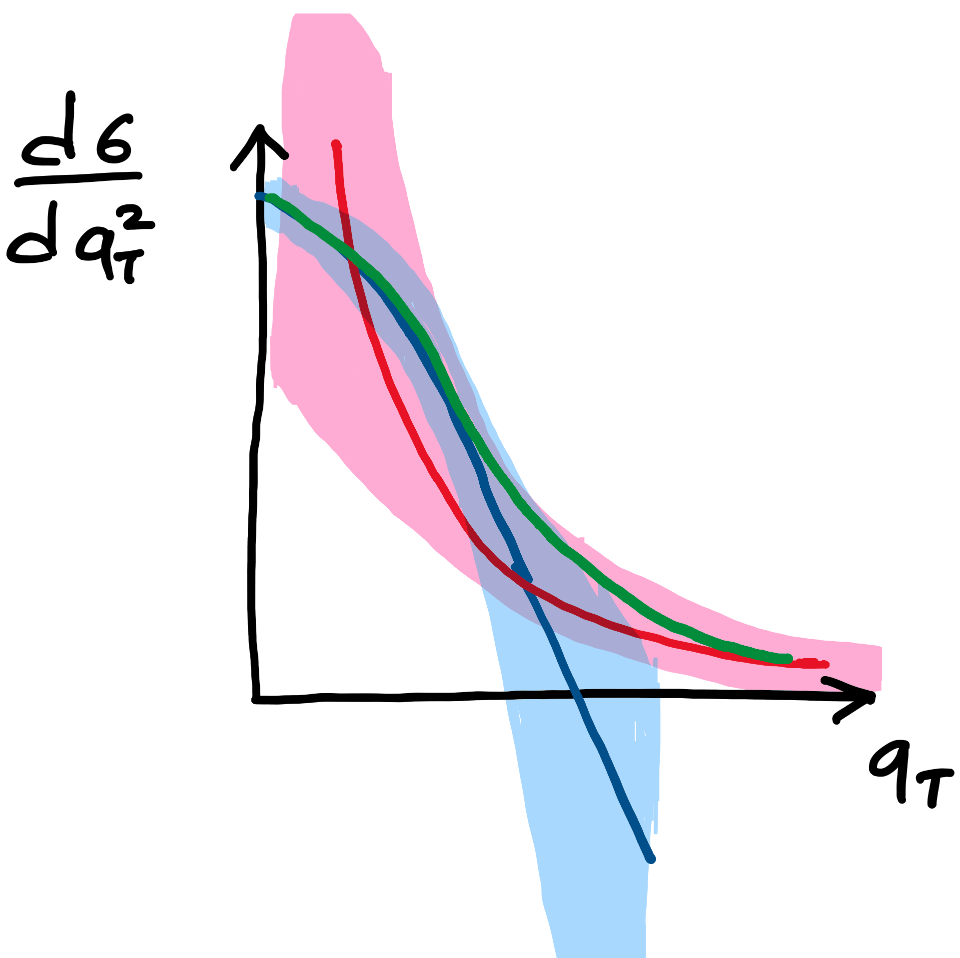
POSSIBLE RESOLUTION: ACCOUNT FOR THE ERRORS OF FACTORIZATION

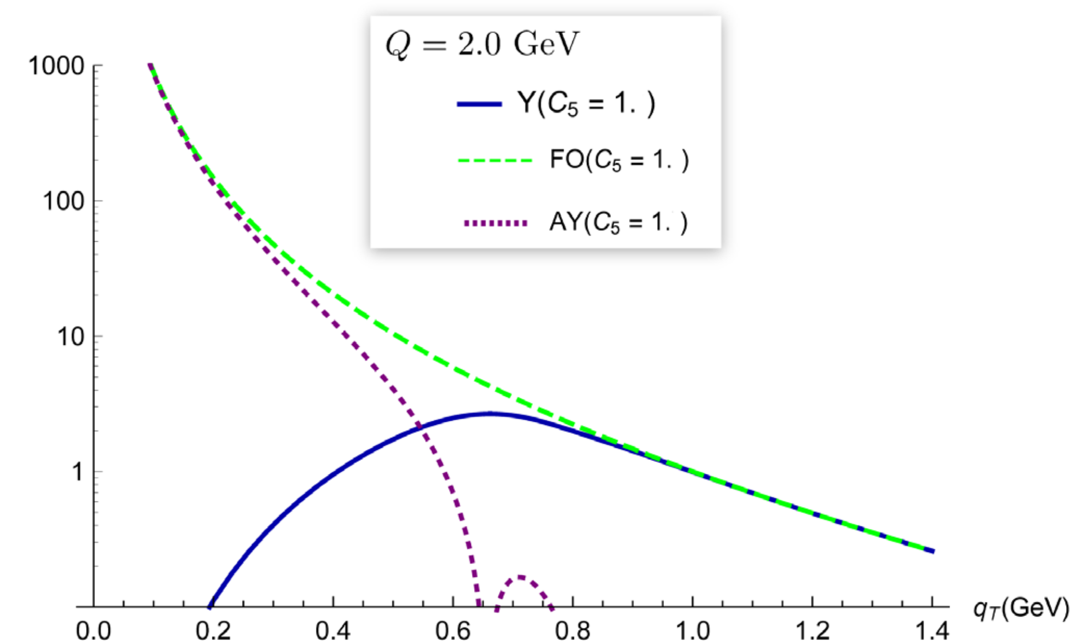
It is all about the theoretical errors: modify W and Y=FO-ASY preserving the overall precision

$$W + \text{FO-ASY} \rightarrow W \cdot \Xi(q_T) + (\text{FO-ASY}) \cdot \chi(q_T)$$





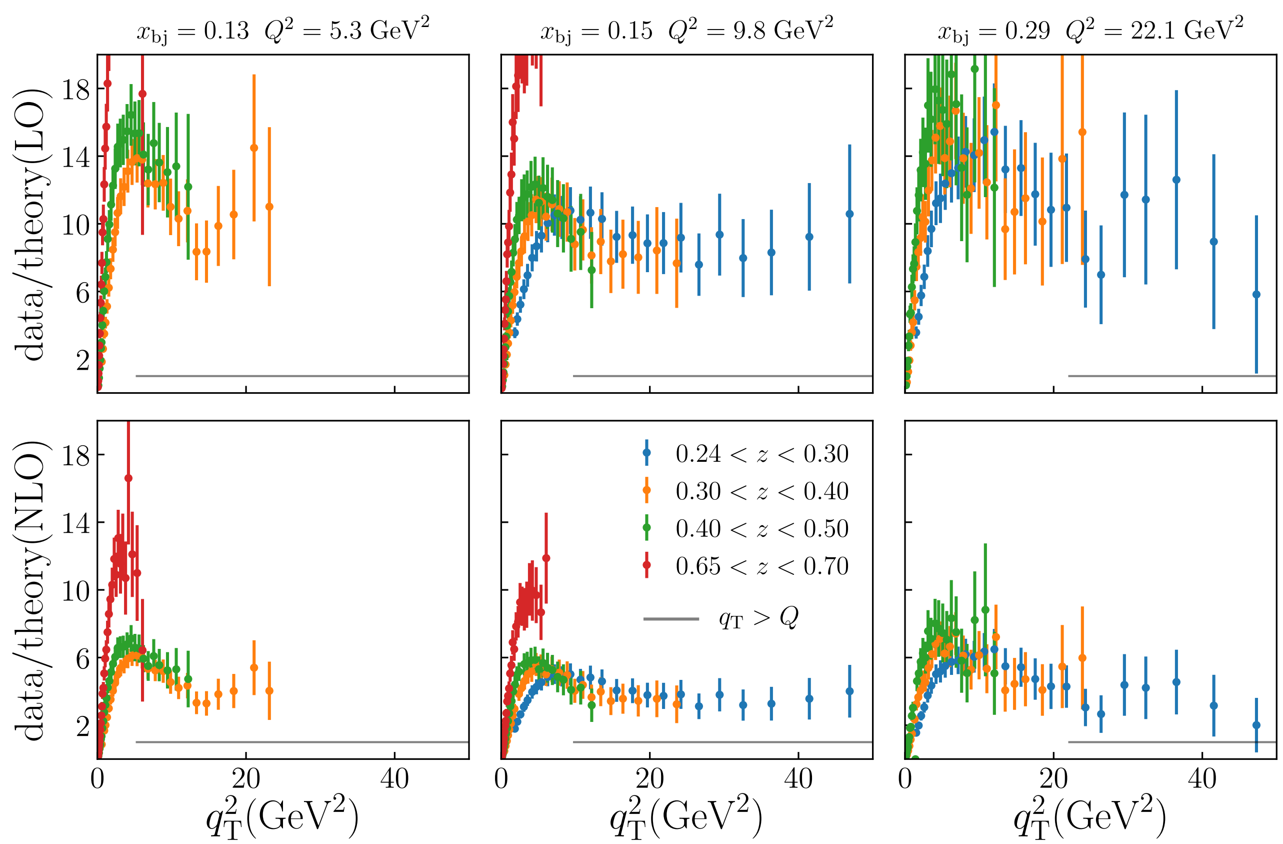




Collins, Gamberg, AP, Rogers, Sato, Wang arXiv:1605.00671

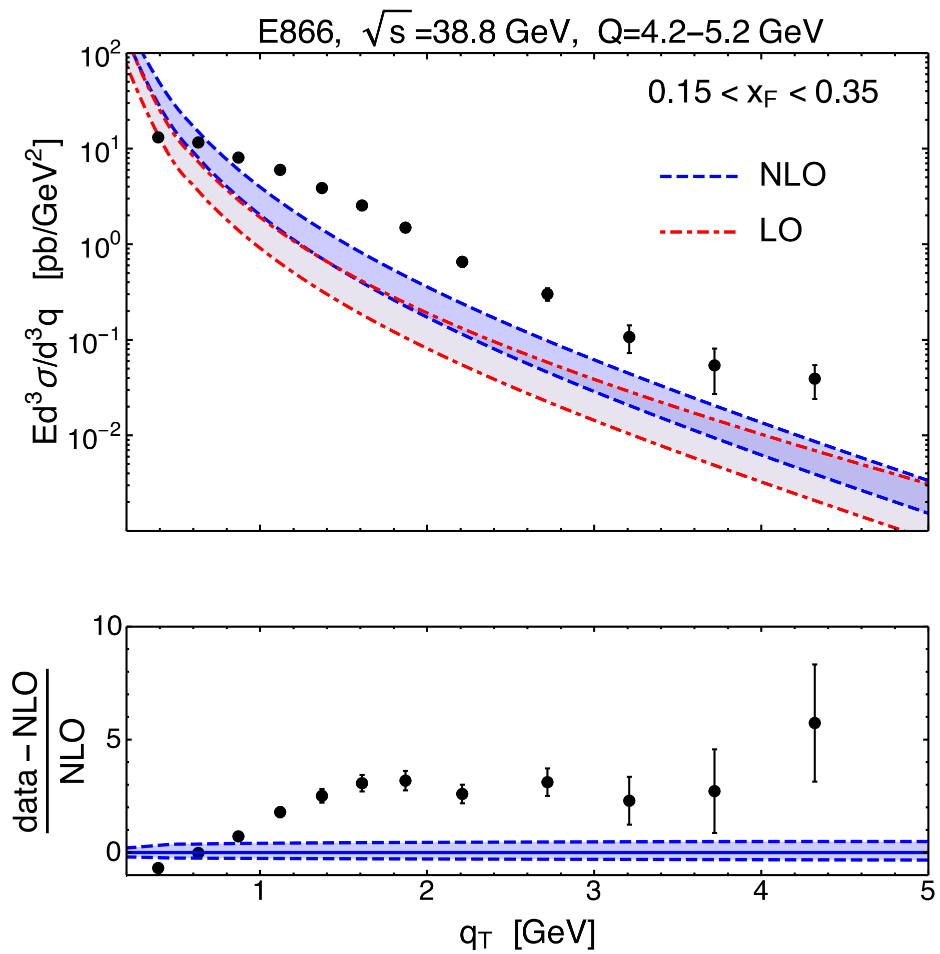
PROBLEMS WITH HIGH TRANSVERSE MOMENTUM

SIDIS



Gonzalez, Rogers, Sato, Wang arXiv:1808.04396

Drell-Yan

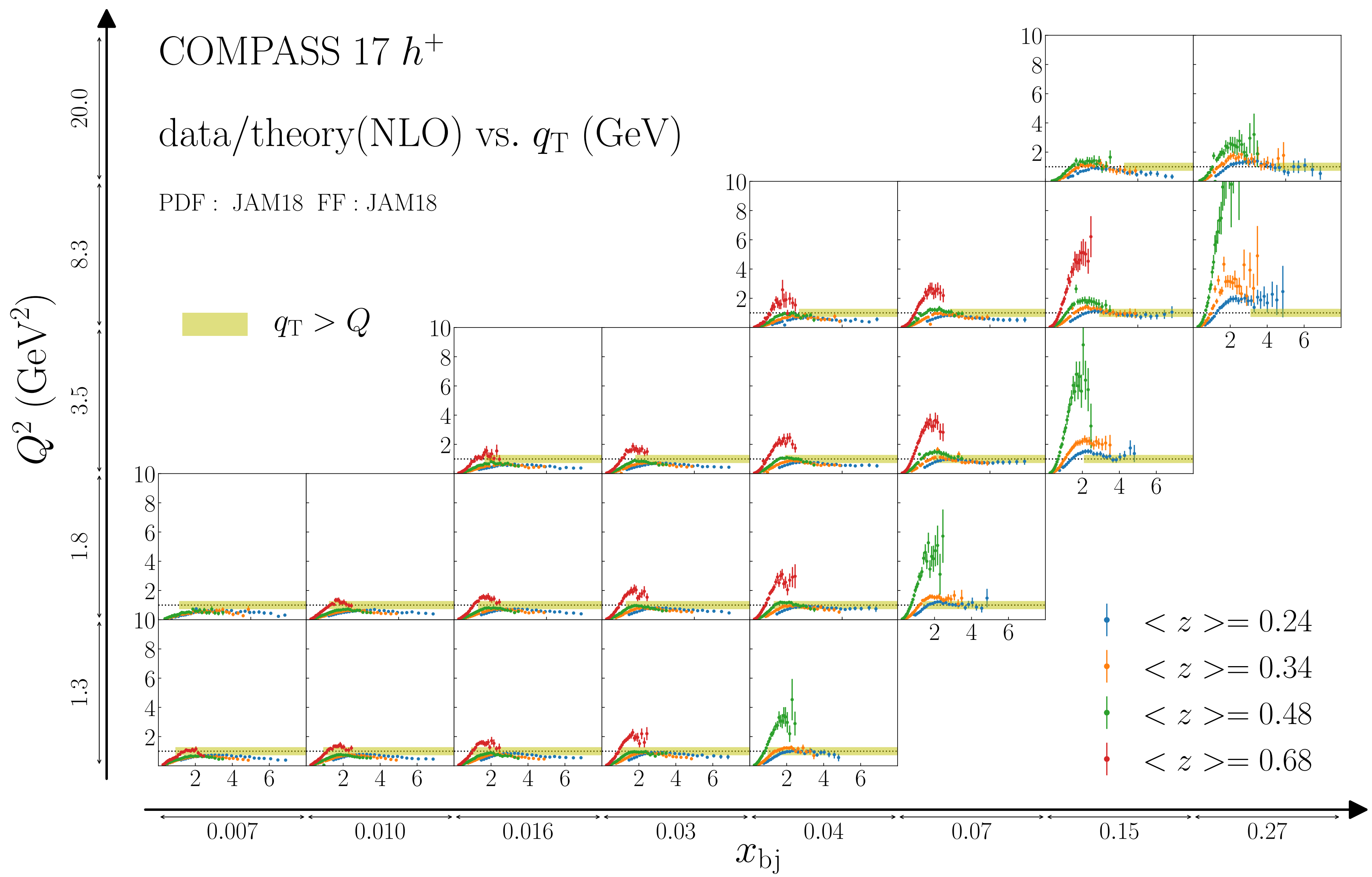


Bacchetta, Bozzi, Lambertsen, Piacenza, Steiglechner, Vogelsang, arXiv:1901.06916

At high q_T, the collinear formalism should be valid, but large discrepancies are observed

PROBLEMS WITH HIGH TRANSVERSE MOMENTUM

Gonzalez-Hernandez, Rogers, Sato, Wang arXiv:1808.04396

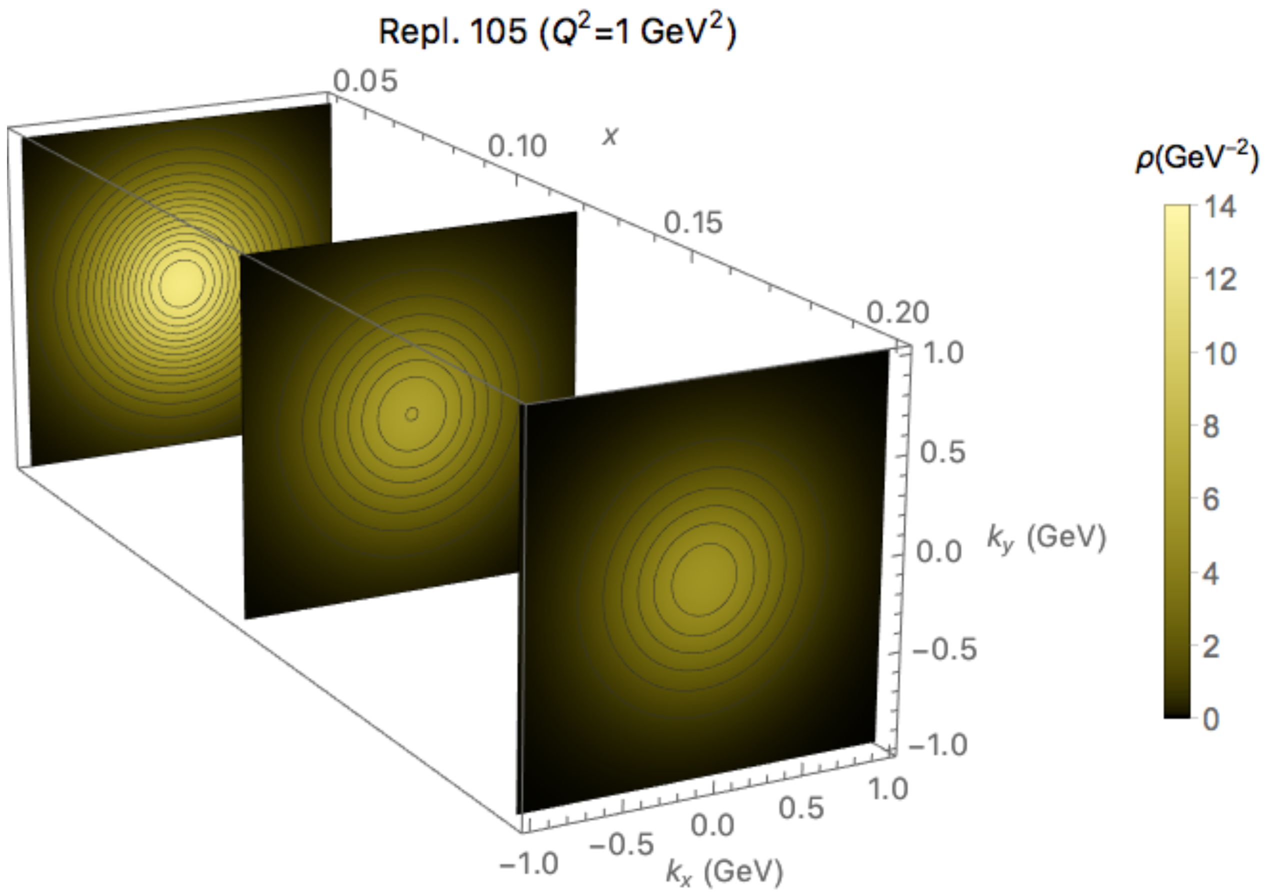


The discrepancies could be largely resolved by sharply modifying the gluon collinear fragmentation function

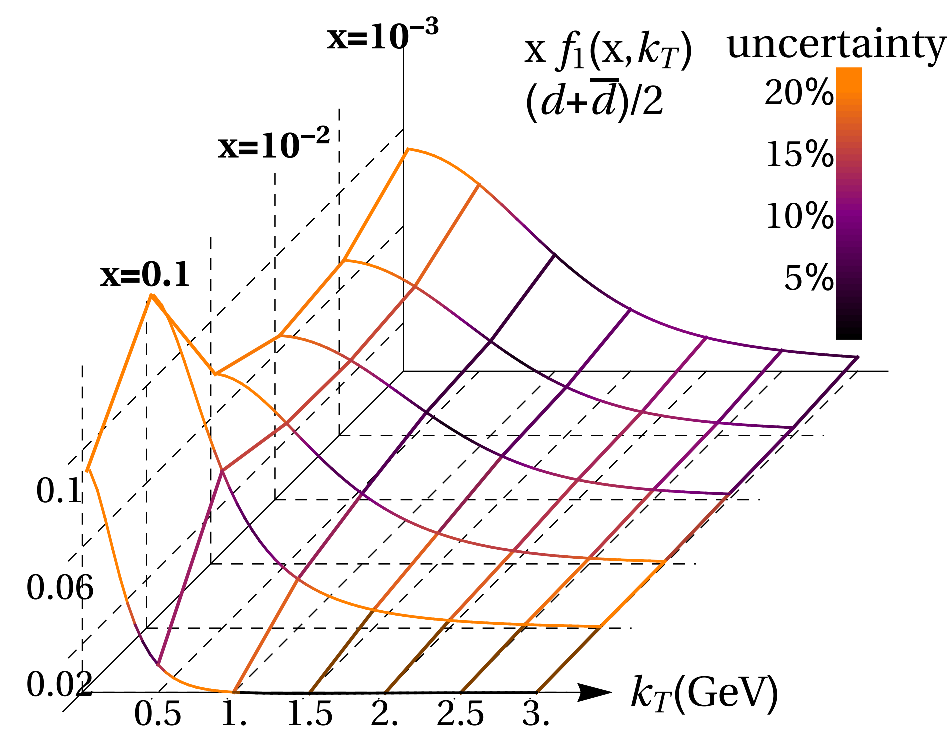
TMD FITS OF UNPOLARIZED DATA

	Framework	W+Y	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	W	✘	✘	✔	✔	98
QZ 2001 hep-ph/0506225	NLO-NLL	W+Y	✘	✘	✔	✔	28 (?)
RESBOS resbos@msu	NLO-NNLL	W+Y	✘	✘	✔	✔	>100 (?)
Pavia 2013 arXiv:1309.3507	LO	W	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO	W	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	W	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	W	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
SIYY 2014 arXiv:1406.3073	NLO-NLL	W+Y	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	W	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	W	✘	✘	✔	✔	309
BSV 2019 arXiv:1902.08474	NNLO-NNLL	W	✘	✘	✔	✔	457

3D DISTRIBUTIONS EXTRACTED FROM DATA



Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

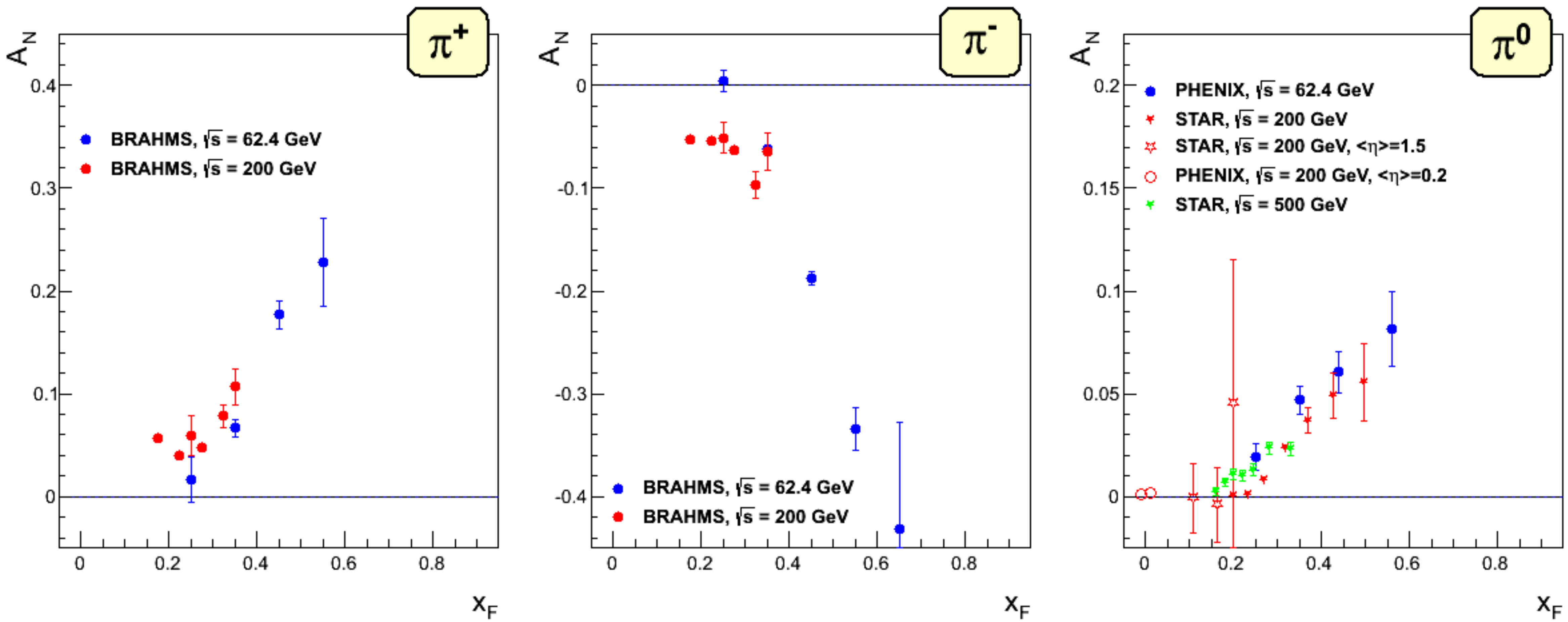


Bertone, Scimemi, Vladimirov, arXiv:1902.08474

CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

Asymmetry survives with growing collision energy

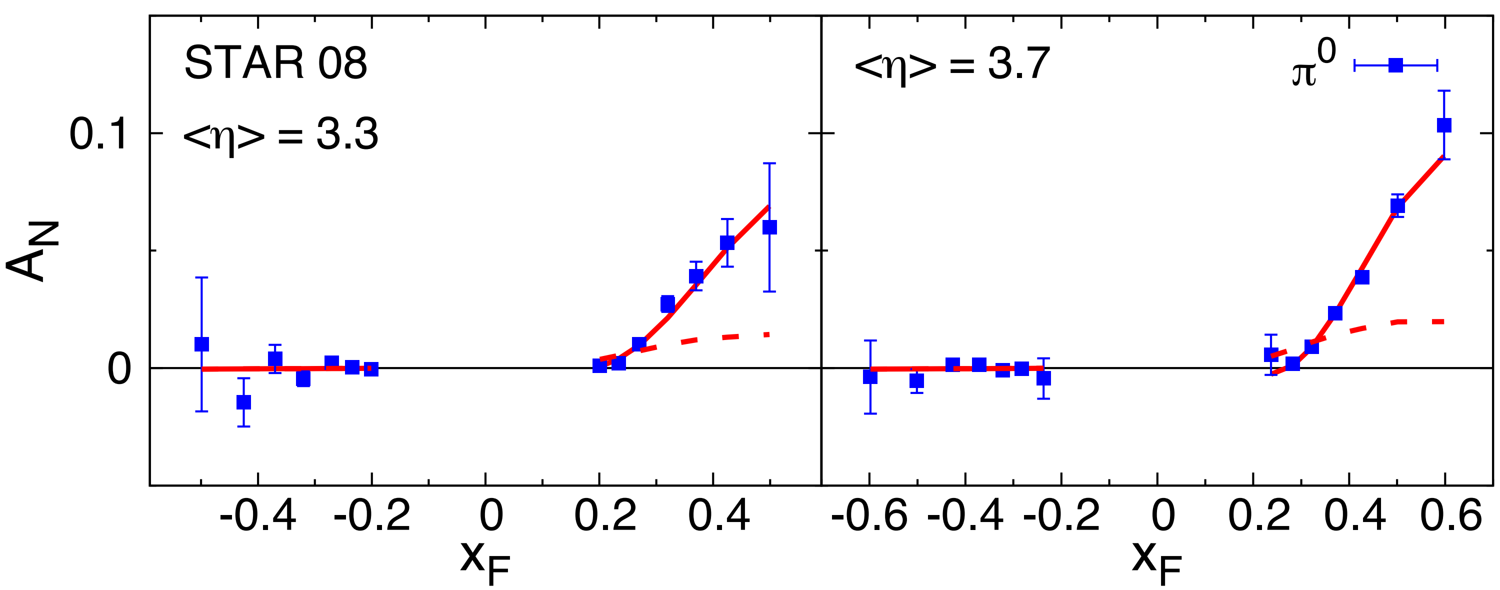
RHIC: STAR, BRAHMS, PHENIX



"The RHIC SPIN Program: Achievements and Future Opportunities", Aschenauer et al (15)

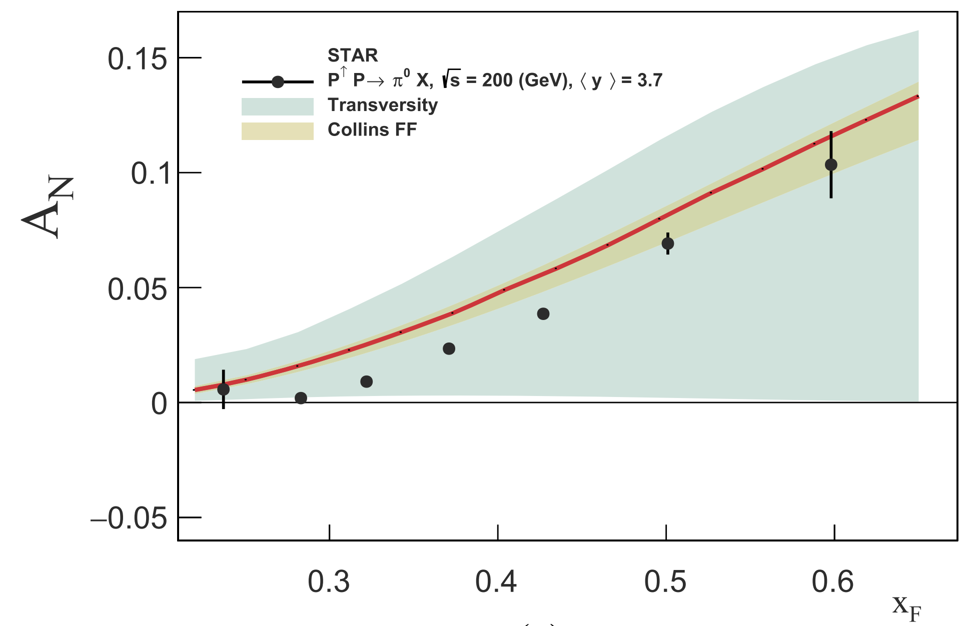
TOWARDS THE SOLUTION OF 40 YEAR OLD PUZZLE

Kanazawa, Koike, Metz, Pitonyak PRD 89 (2014)



Explanation using fit of twist-3 fragmentation functions

Gamberg, Kang, Pitonyak, Prokudin PLB 770 (2017)



Prediction of A_N at STAR using only SIDIS and e^+e^- data information only

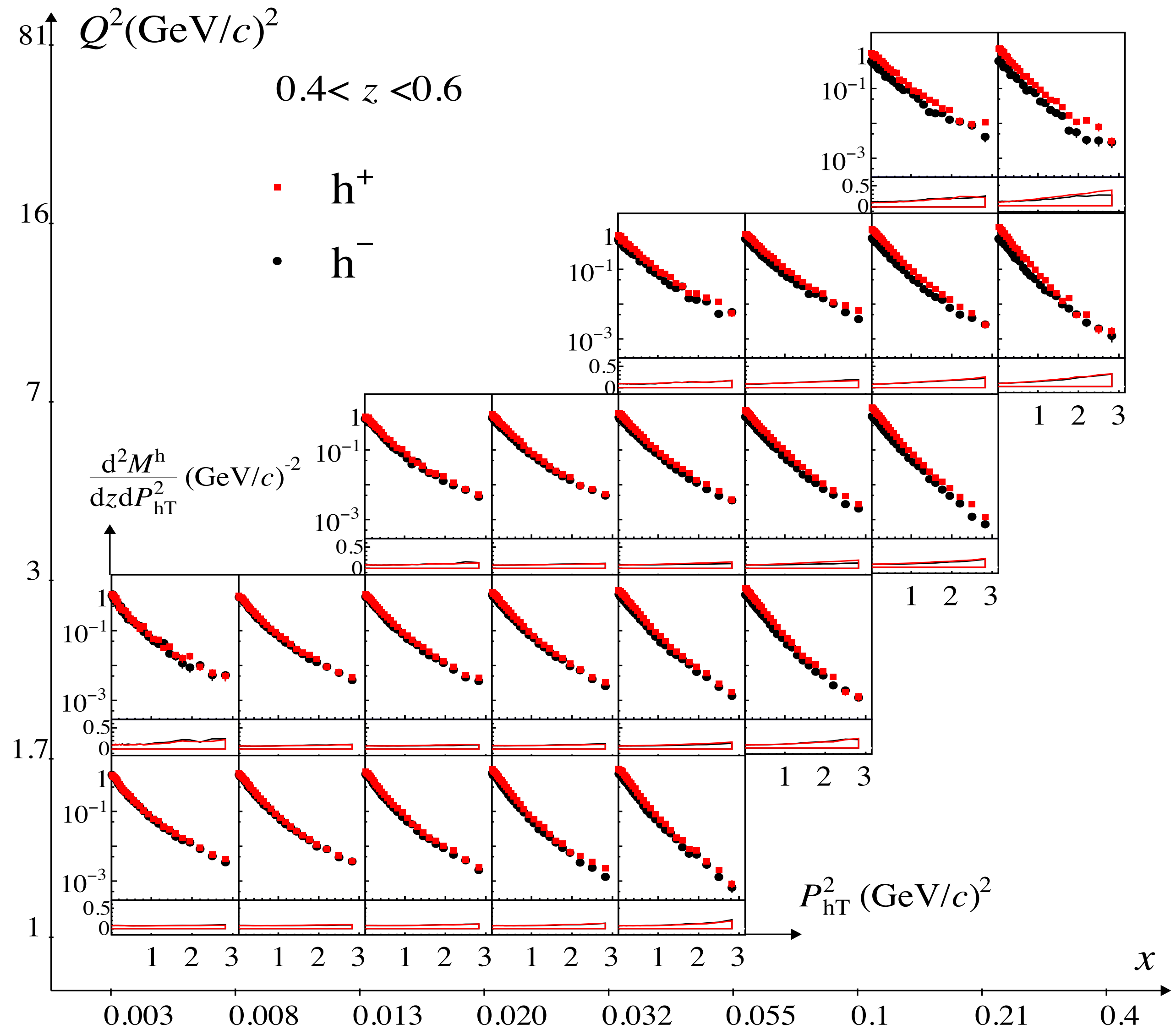
Fast progress in TMD determinations is taking place,
but still many open questions

As TMDs are known better and better,
they can be used to improve high-energy
precision measurements

THE FUTURE

NEW DATA FROM COMPASS AND JLAB

Multidimensional binning

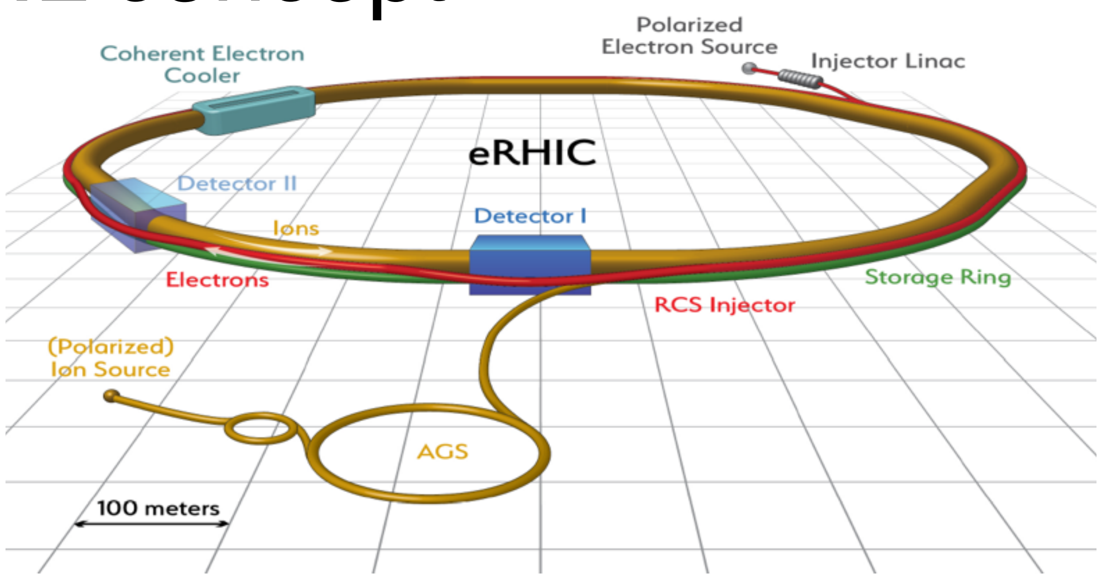


COMPASS Collab., arXiv:1709.07374

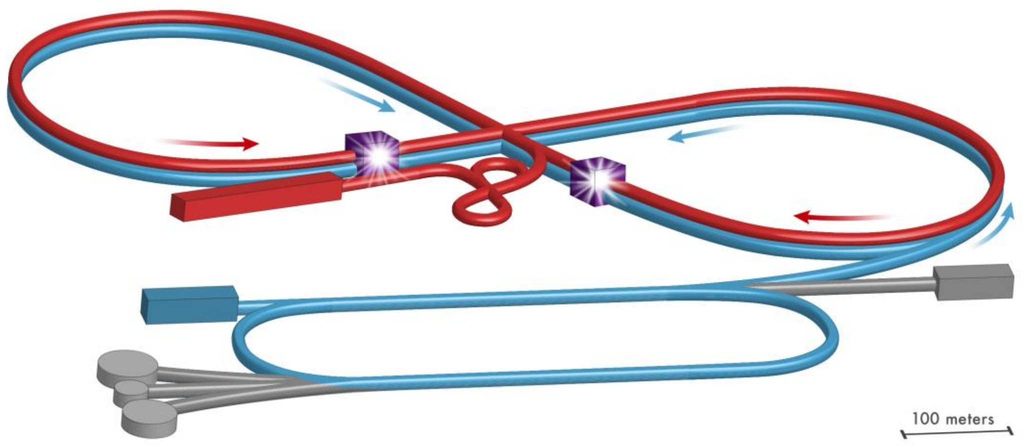
COMPASS is in “full swing” mode. JLAB 12 data are going to follow.

THE ELECTRON-ION COLLIDER PROJECT

BNL concept



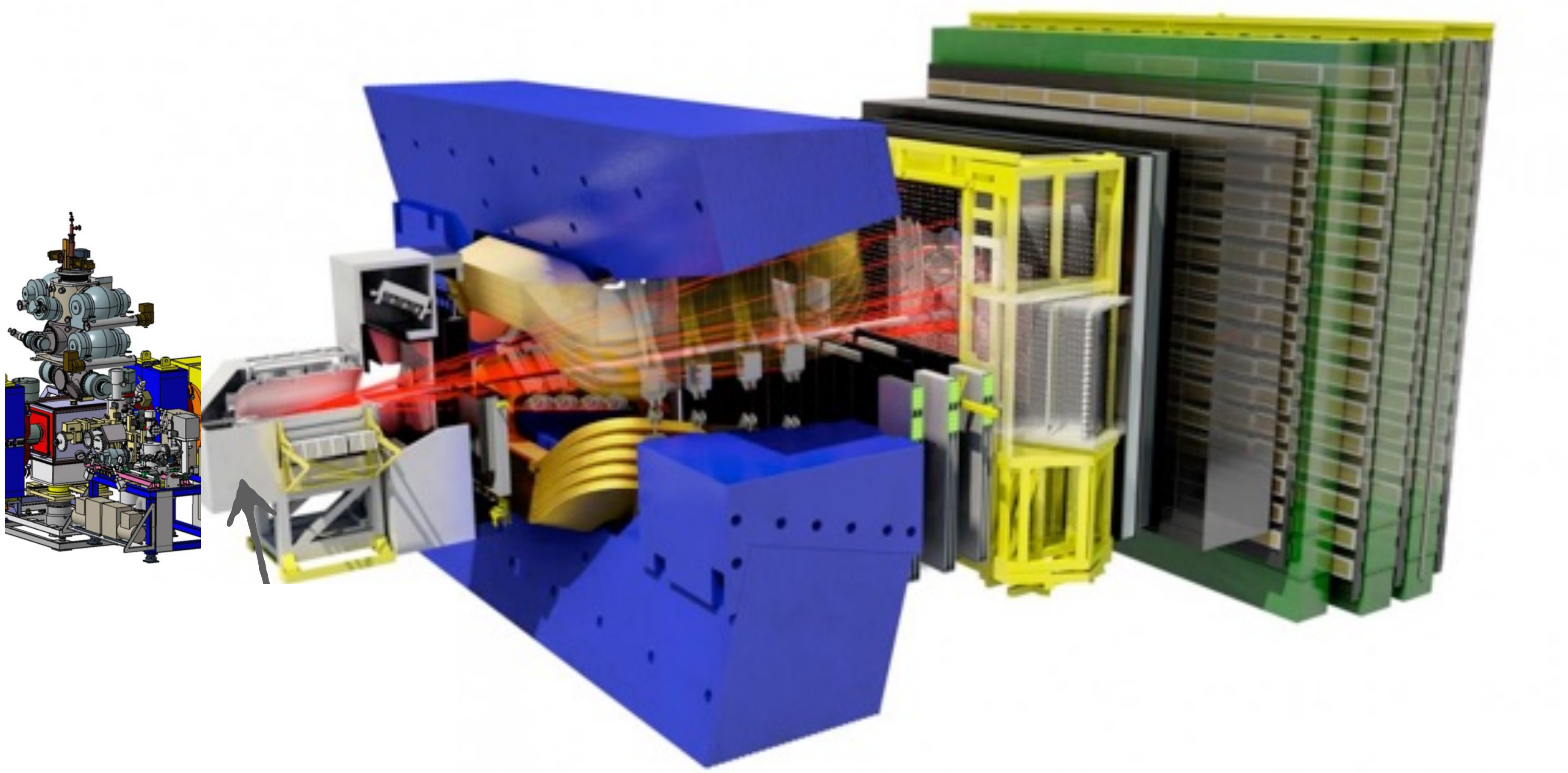
JLab concept



- High luminosity: (10^{34} cm^{-2} s^{-1})
- Variable CM energy: 20-100 GeV
- Polarized beams
- Protons and other nuclei

LHCb FIXED TARGET, INCLUDING POLARIZATION

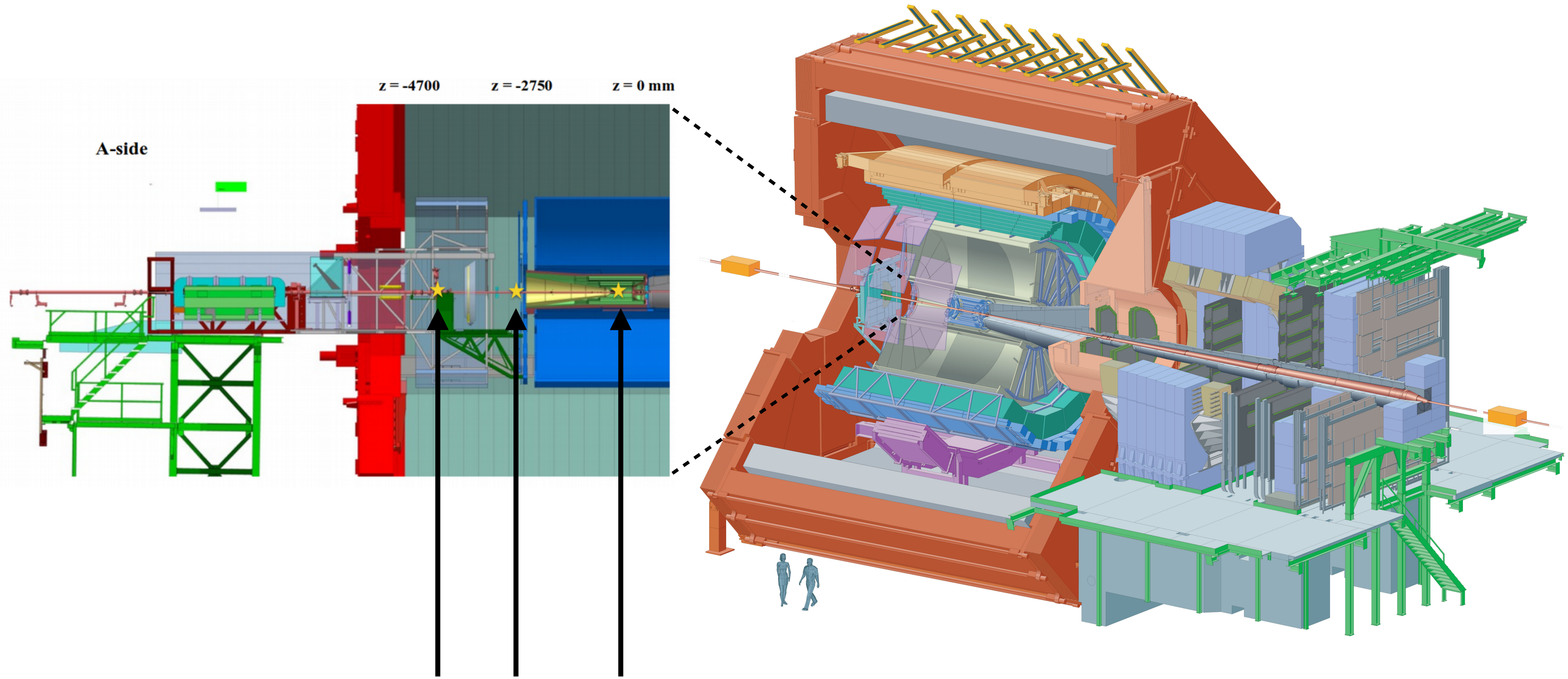
https://indico.cern.ch/event/755856/



Polarised target

ALICE FIXED TARGET

https://indico.cern.ch/event/755856/



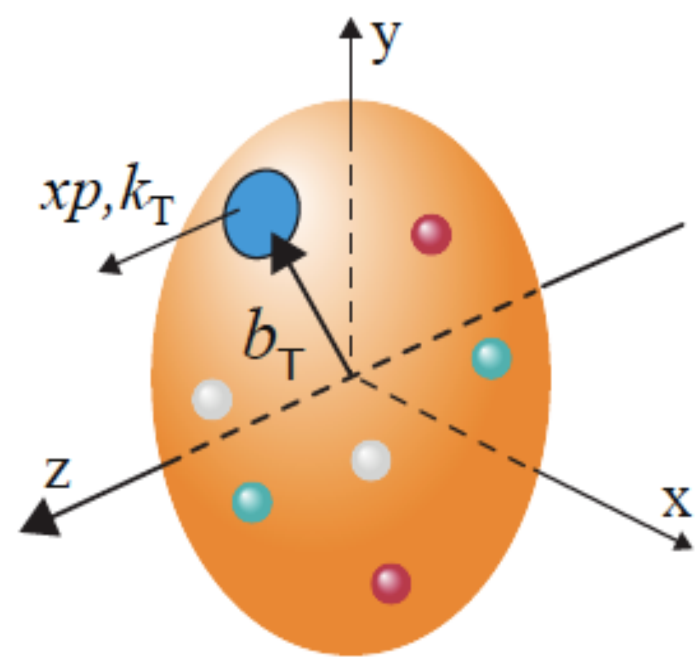
Possible fixed-target positioning

THEORETICAL AND PHENOMENOLOGICAL DEVELOPMENT

- Strengthen the theoretical foundations of TMD physics
- New ways to access TMDs, GPDs, Wigner distributions
- Connect low-x, large-x formalisms. Relate TMD and collinear physics
- New ways to view quantum entanglement, confinement?
- Develop fast software for global analysis of hadron structure
- Produce extensive TMDs from global fitting data
- Make results available to the community

What is the 2D confined transverse motion of quarks and gluons inside a proton?

How to identify universal proton structure properties from measured k_T-dependence?



How does the confined motion change along with probing x, Q^2?

Can we extract QCD color force responsible for the confined motion?

How is the motion correlated with macroscopic proton properties, as well as microscopic parton properties, such as the spin?