Hadron structure - from 1D to 3D

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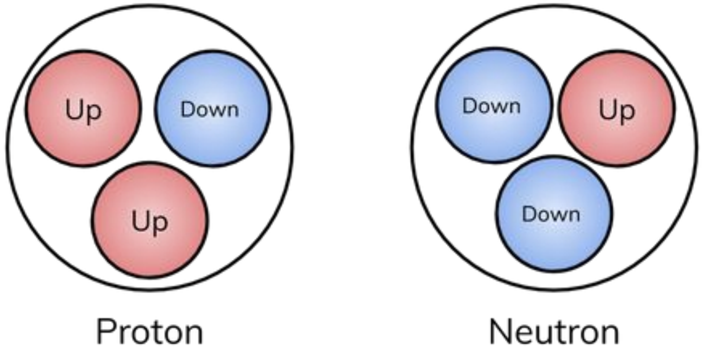
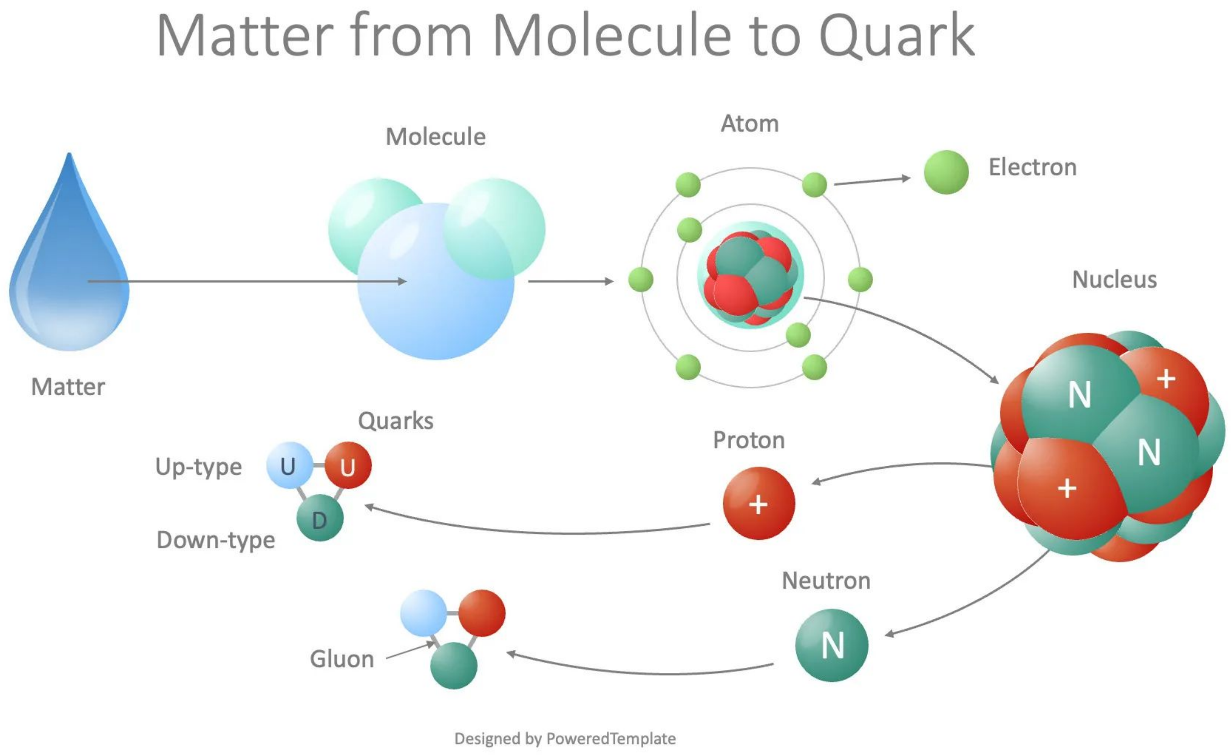
Motivation

Proton structure:

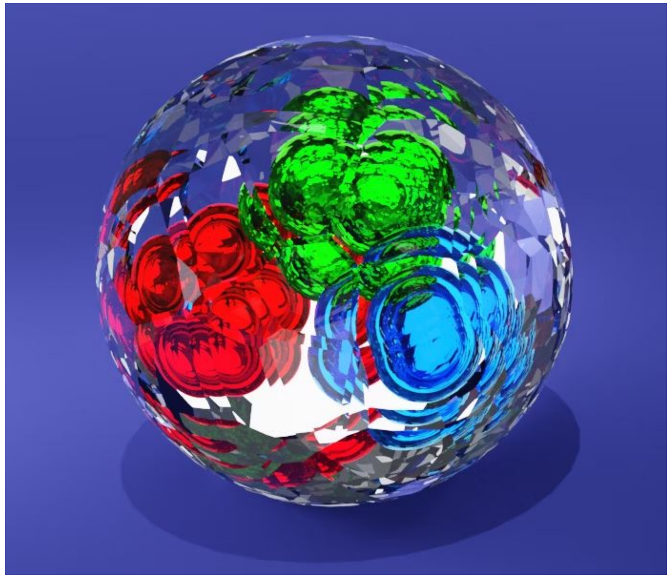
- **Mass**: how do quarks (2.3~4.8 MeV) and gluons make up the mass of proton (938 MeV)?
- **Spin**: how do quarks and gluons make up the proton spin of ½?

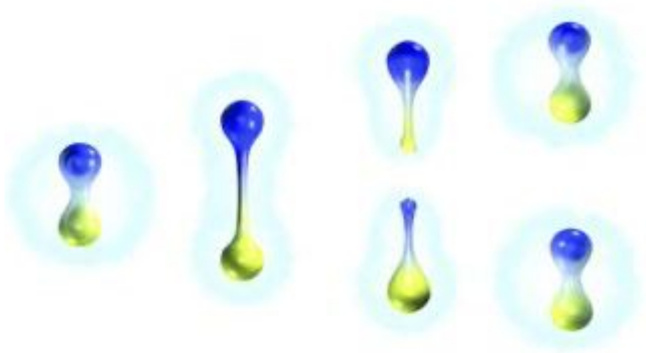


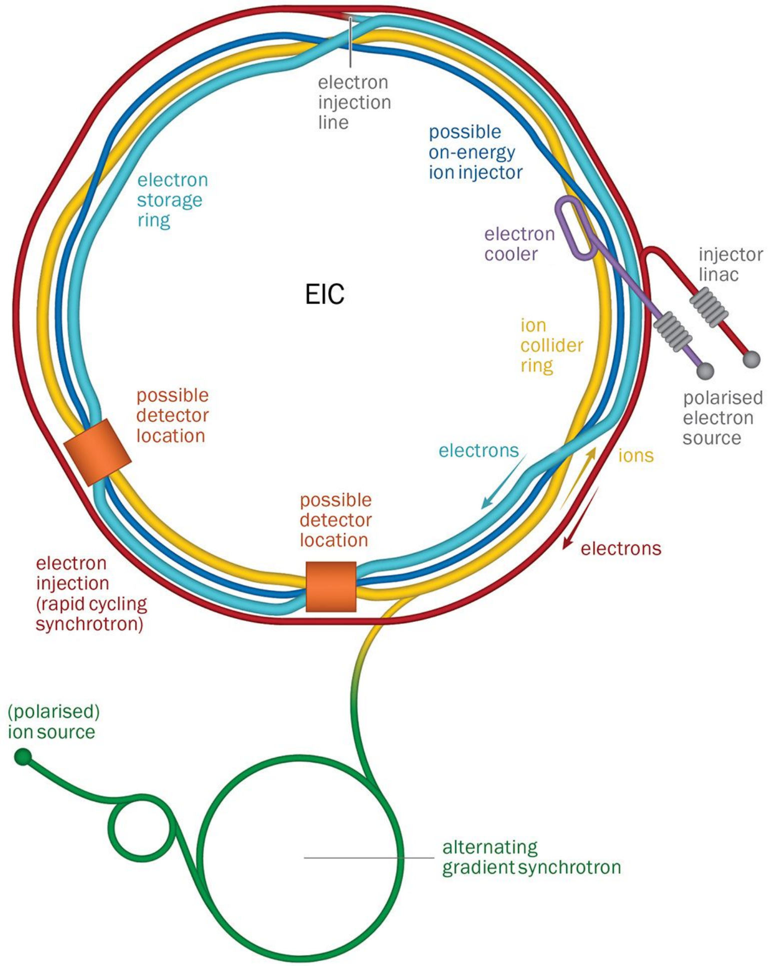


Probe proton structure

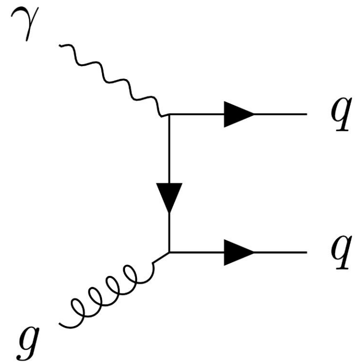
- Confinement: extraction of information is indirect
- High energy collision: send in a probe and measure the outcome

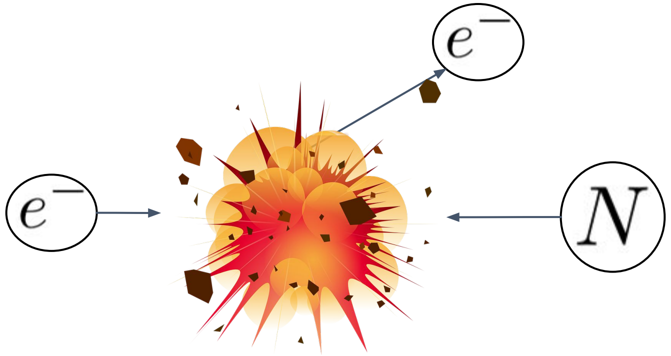




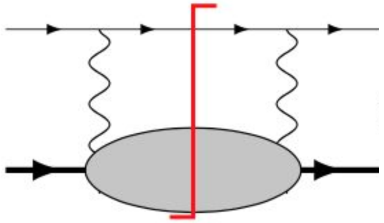


Deep-inelastic scattering (DIS)



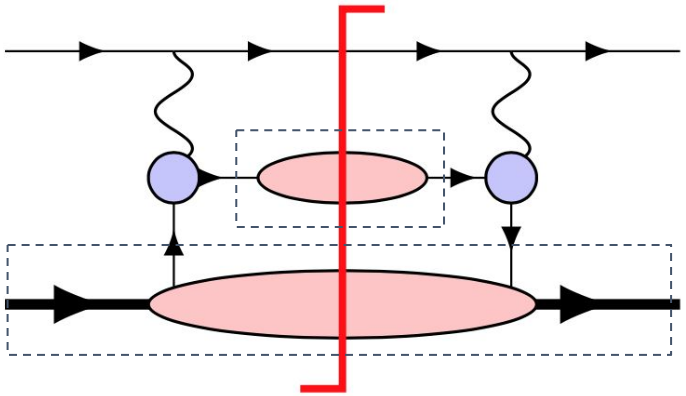


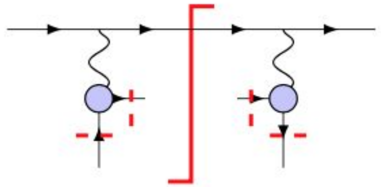
$$E' \frac{\mathrm{d}\sigma}{\mathrm{d}^3 l'}$$



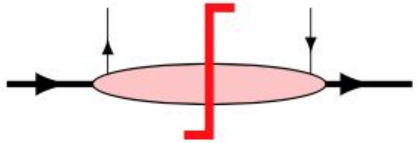
Approximations

$Q^2 \gg m^2$





Collision dependent factor



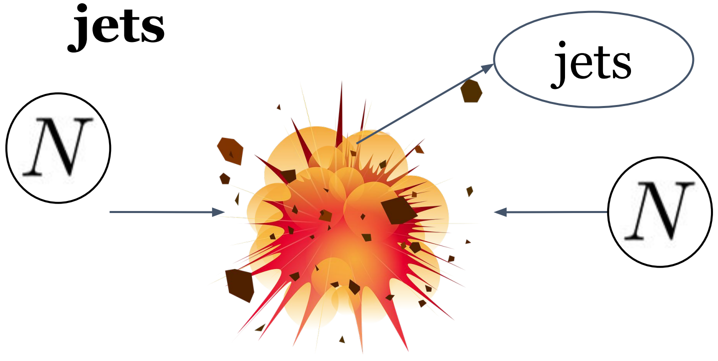
Internal structure

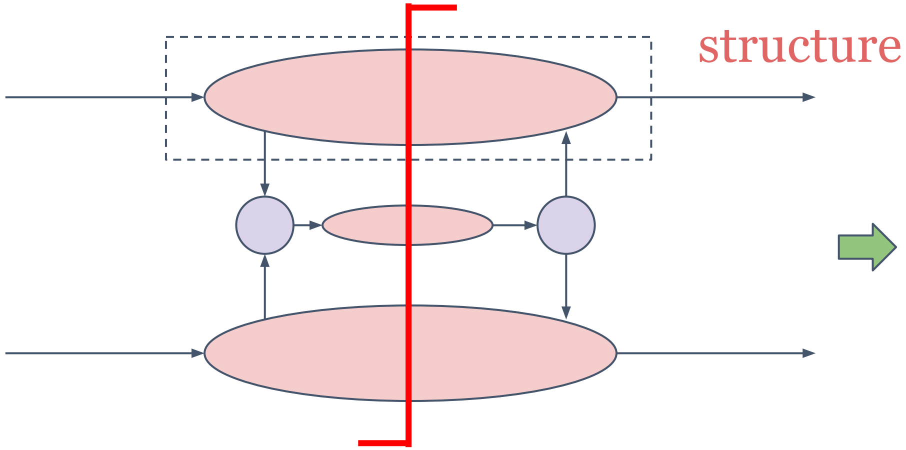
$$\sum_i \int_x^1 \frac{\mathrm{d}\xi}{\xi} H_i(\xi)\, f_i\left(\frac{x}{\xi}\right) + \mathcal{O}\left(\frac{m^2}{Q^2}\right)$$

Error of approximations

Jets and Drell-Yan

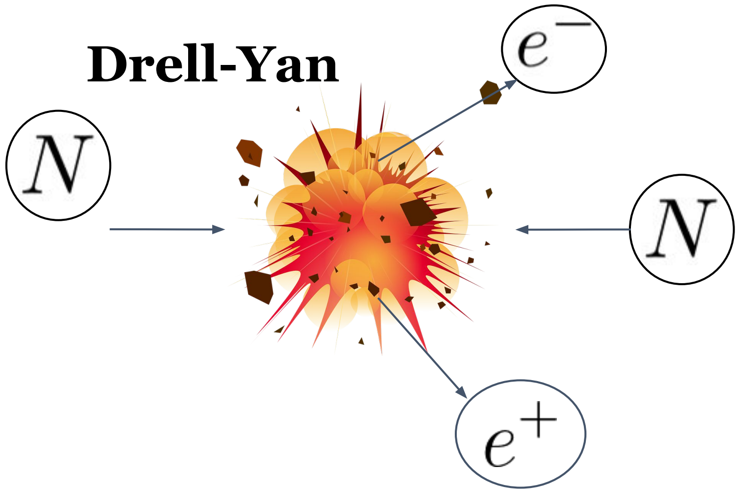
jets

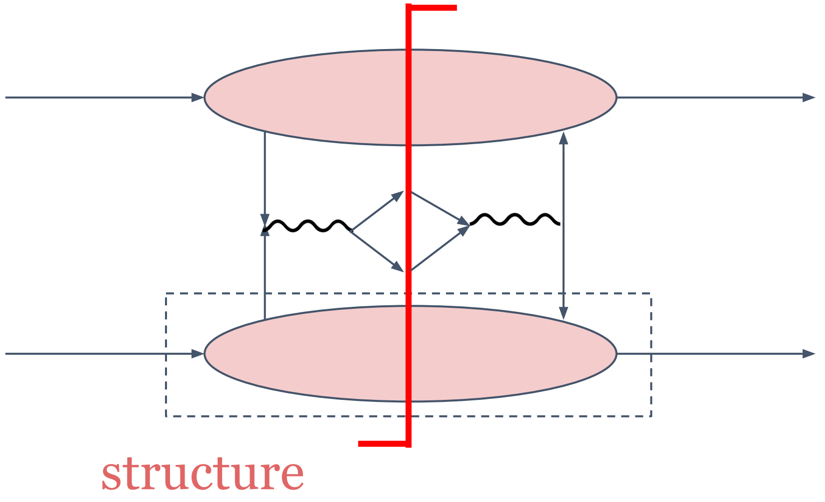




$$d\sigma^{\text{jets}} = \sum_{i,j} H_{ij}^{\text{jets}} \otimes f_i \otimes f_j$$

Drell-Yan

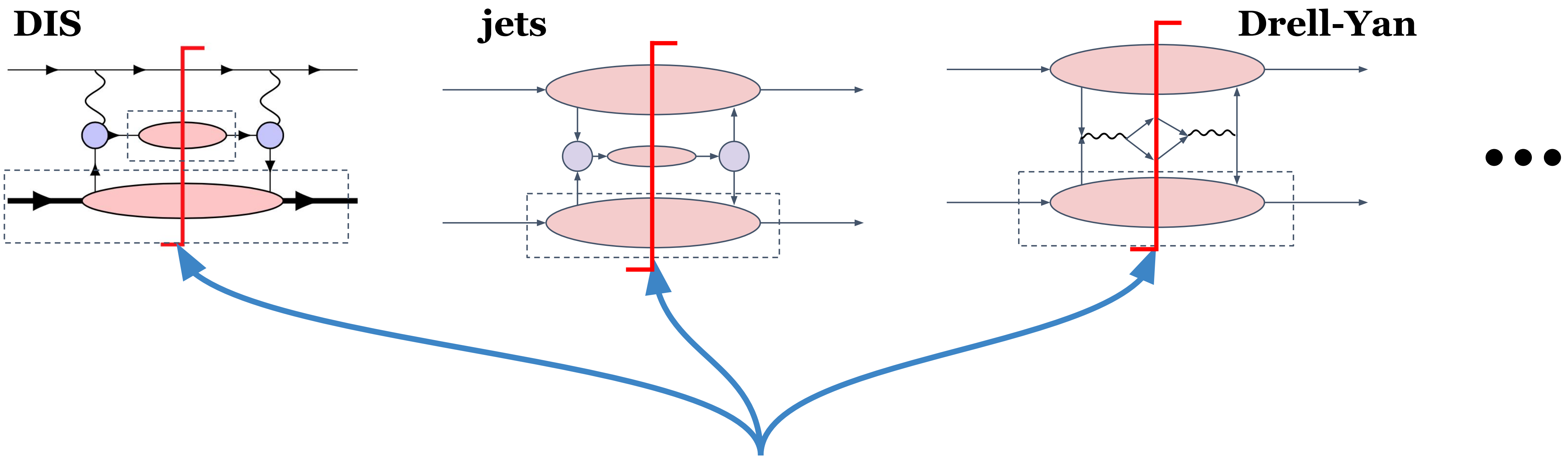




$$d\sigma^{\text{DY}} = \sum_{i,j} H_{ij}^{\text{DY}} \otimes f_i \otimes f_j$$

and many more...

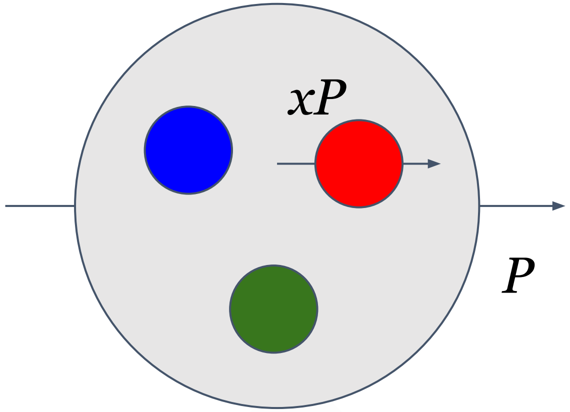
Universality

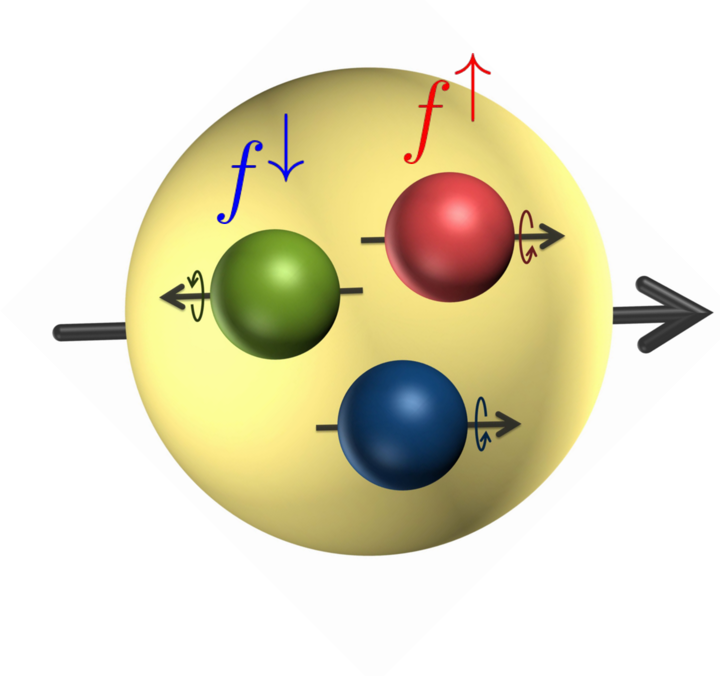


cross sections described by
universal nonperturbative
functions, *e.g.*, PDFs

Parton distribution functions - 1D

- Probability to find a quark ***i*** or a gluon ***g*** in a hadron ***h*** carrying a fraction x of the hadron's momentum.
- A function of x ($0<x<1$) and μ (factorization scale), flavor of partons.
- spin-averaged (unpolarized): $\boldsymbol{f} = \boldsymbol{f}^{\uparrow} + \boldsymbol{f}^{\downarrow}$
- spin-dependent (polarized): $\boldsymbol{\Delta f} = \boldsymbol{f}^{\uparrow} - \boldsymbol{f}^{\downarrow}$

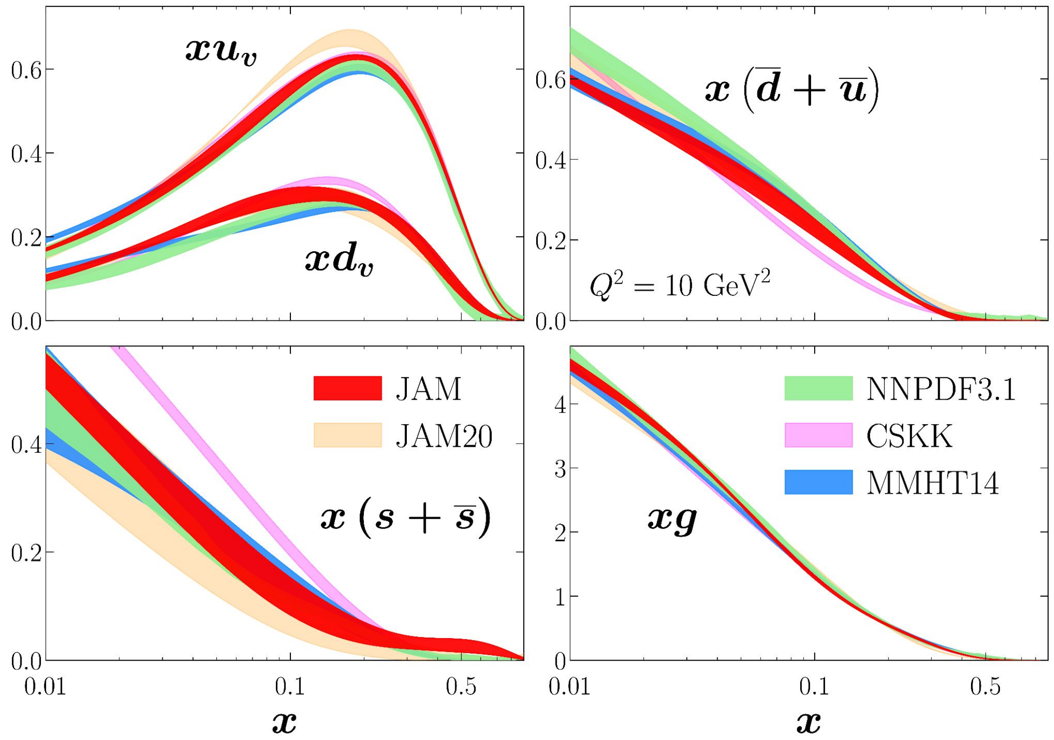


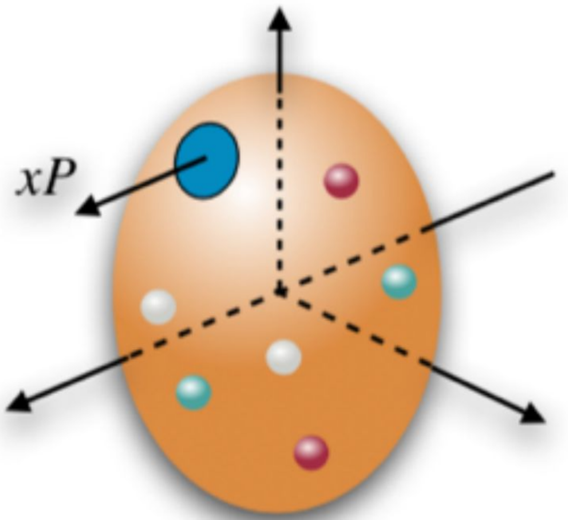


Porton 1D structure

- 1D unpolarized parton distribution functions (PDFs)
  - probability of finding a parton inside a proton with momentum fraction *x*

- $u_v = u - u$-bar
- $d_v = d - d$-bar
- sea: u-bar, d-bar, s, s-bar…

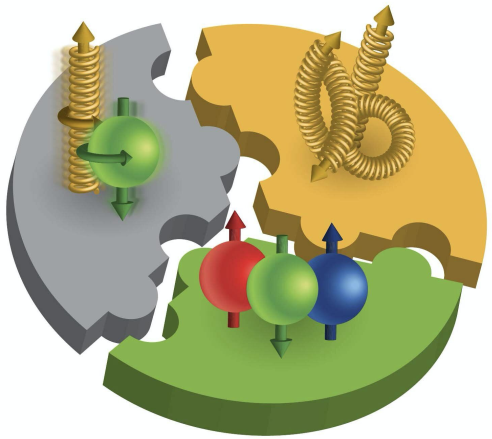




Zhou, Sato & Melnitchouk, 2201.02075

What about the spin structure?

Porton 1D structure - spin dependent



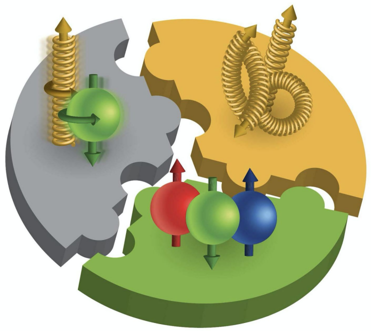
What is the decomposition of the proton spin?

- current extraction of $\Delta\Sigma$ is around 0.3 (contribution from quarks)
- spin can be extracted from parton distribution functions (PDFs)
- orbital angular momentum can be extracted from GPDs

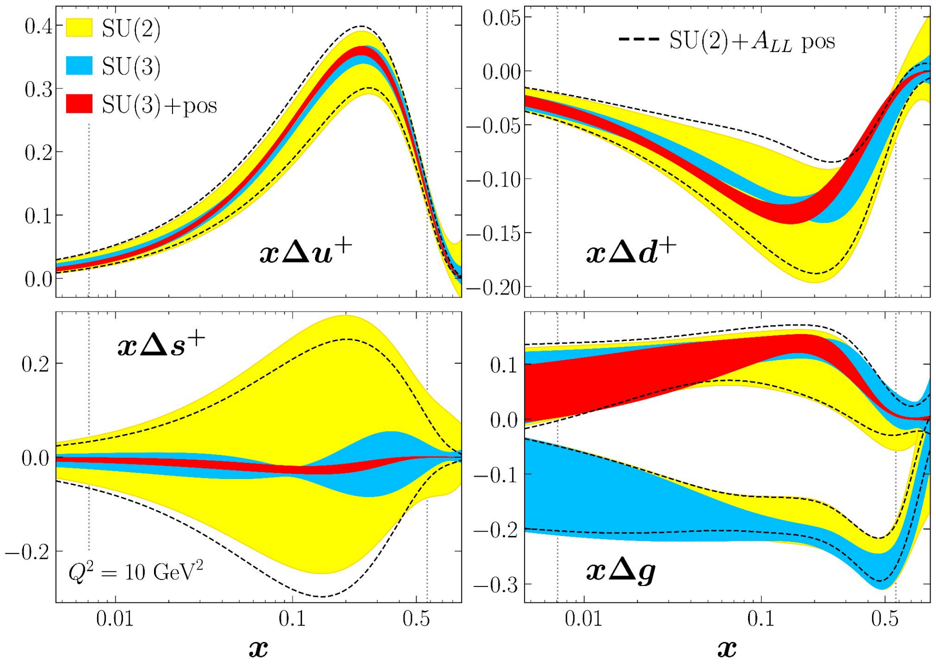
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

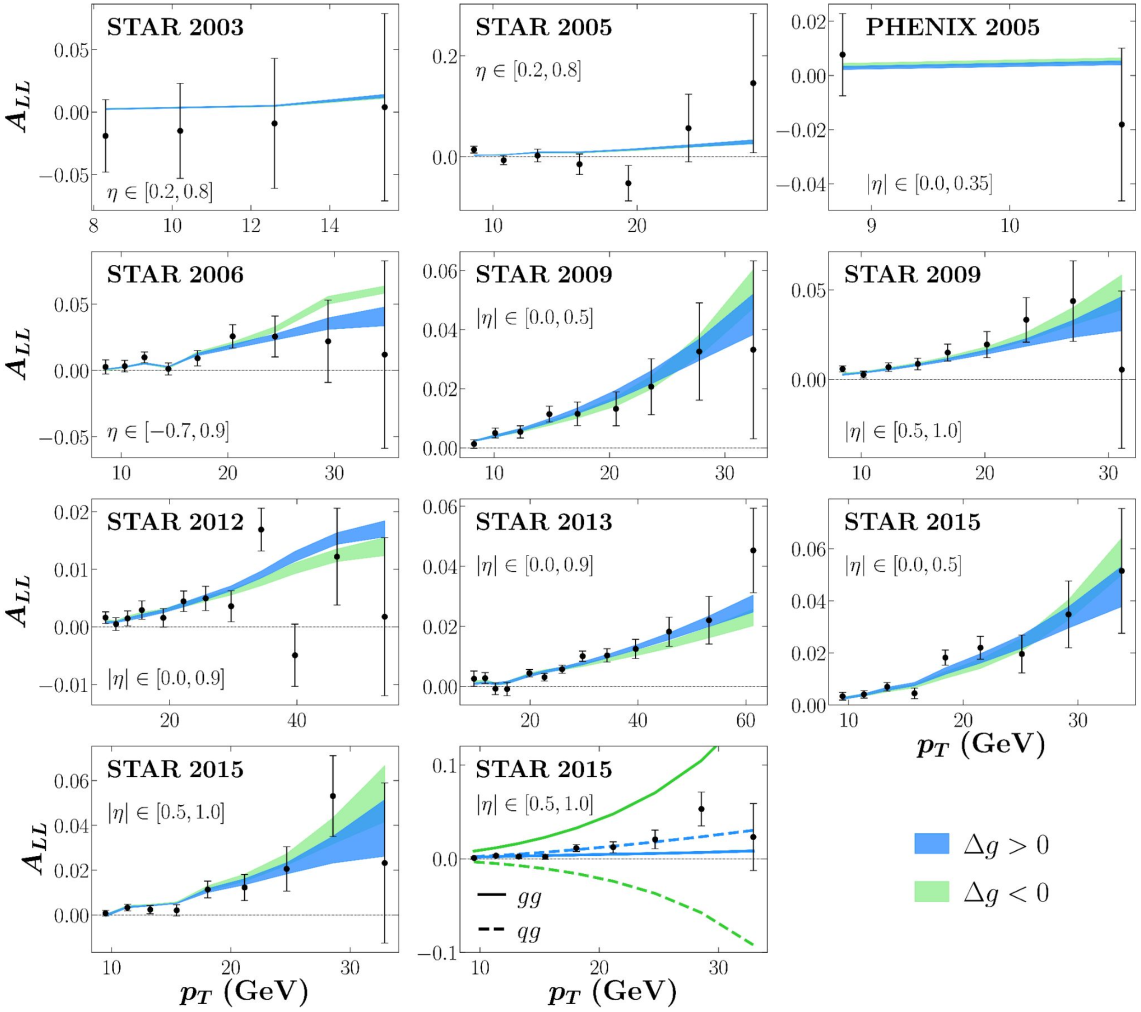
Gluon polarization - sign?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$



- 1D helicity distribution
  - STAR experiment *pp*→jet is sensitive to *Δg*
  - *Δg* gives the gluon contribution to proton spin

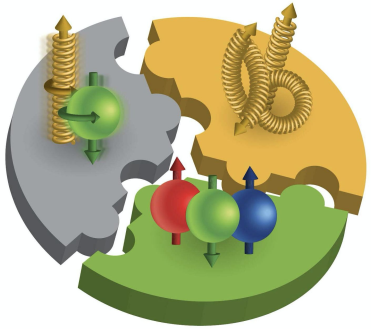




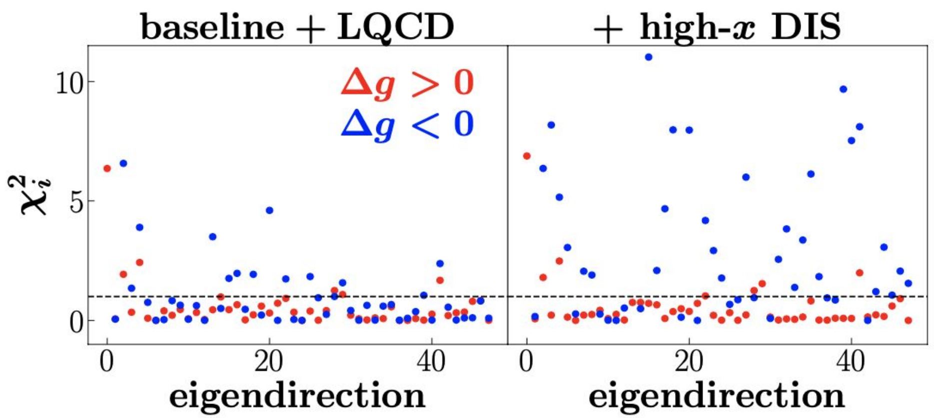
Zhou, Sato & Melnitchouk, 2201.02075

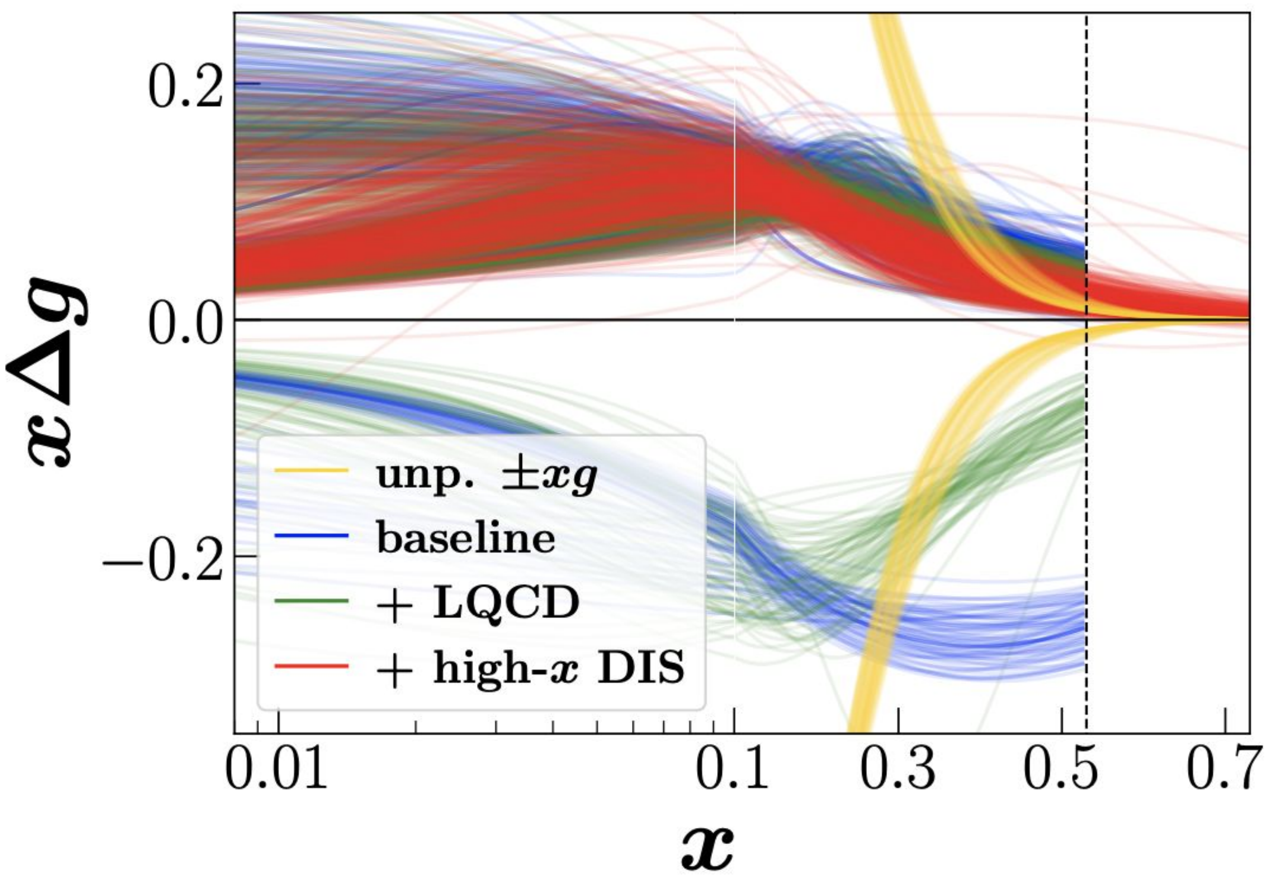
Gluon polarization - sign?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$



- 1D helicity distribution
  - negative gluon ruled out with Lattice & high-x data





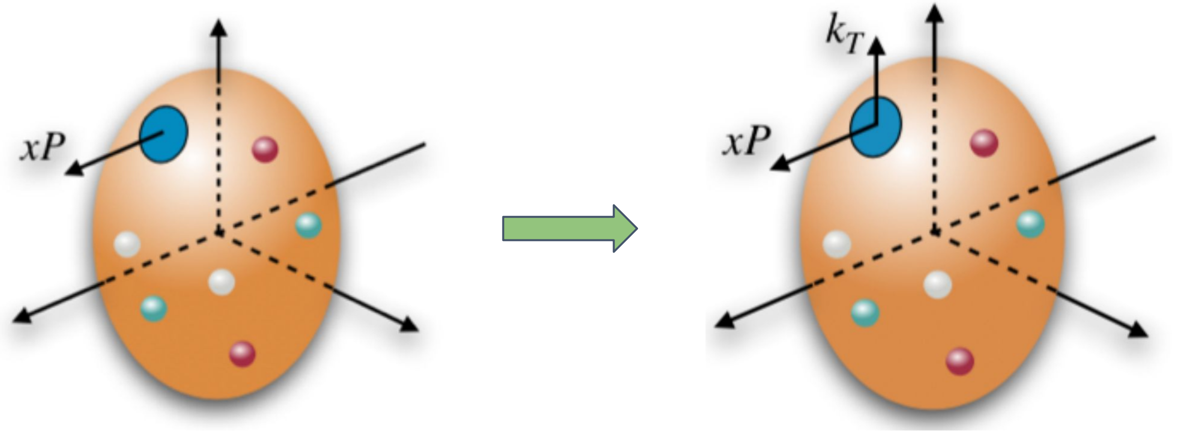
Hunt-Smith, Cocuzza, et al, 2403.08117

Proton structure in 3D

3D structure of hadrons

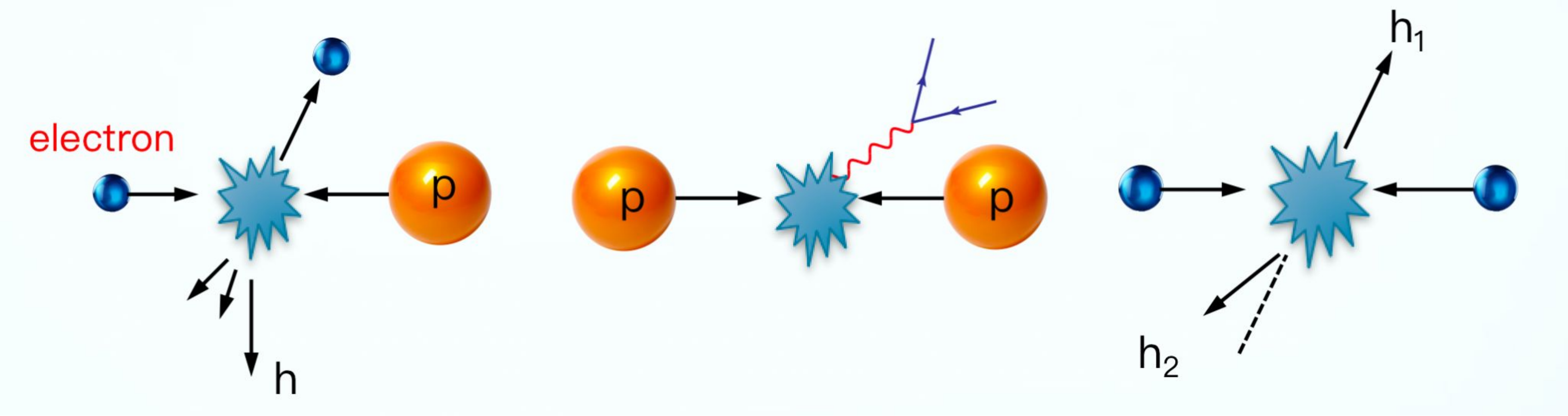
Beyond 1D:

- TMD: transverse momentum dependence (3D structure in momentum space)
- GPD: generalized parton distributions (3D structure in position space)



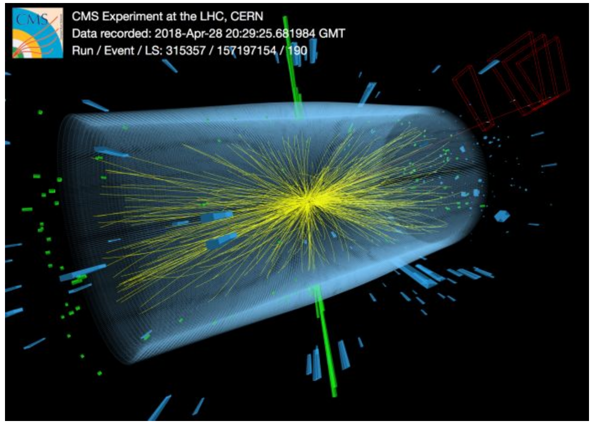
Processes to extract TMDs

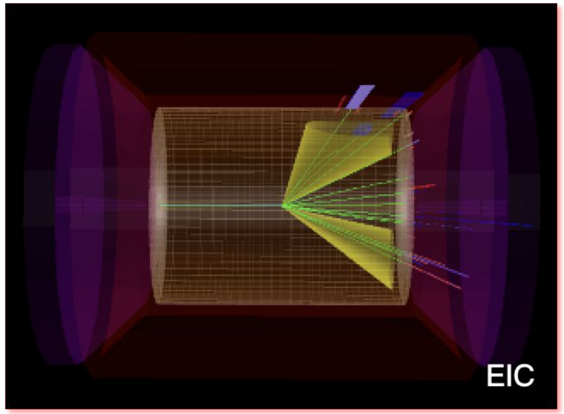
- Standard processes: SIDIS, Drell-Yan, e^+e^-



- Focus of this talk: jets for

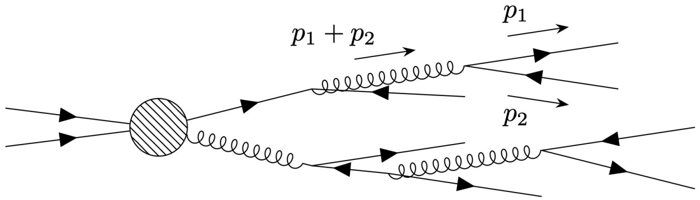
  3D imaging



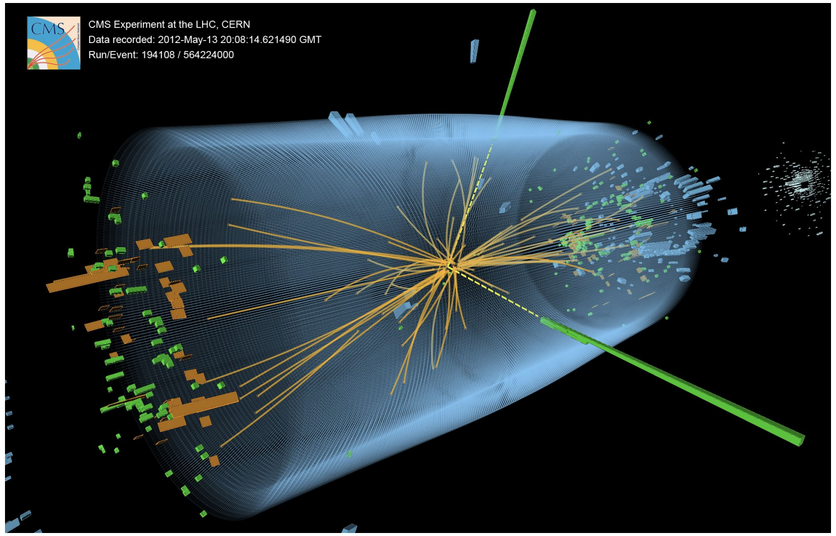


Jets as probes of hadron structure

- A jet is collimated spray of hadrons in high-energy particle reactions.
- Jets are manifestations of collinear enhancement.
- Probes hadron structure (PDFs) without needing to know about details of hadronization (fragmentation functions), in contrast to SIDIS.
- Jets are defined up to specific clustering algorithms (cone, k_T, anti-k_T...).



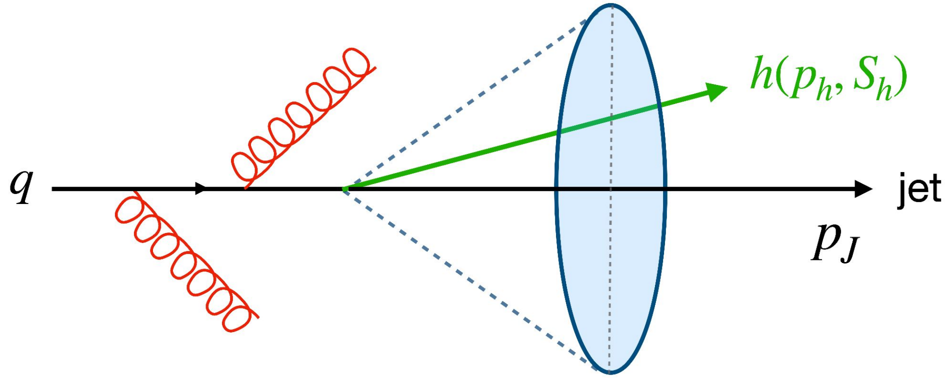
$$\frac{1}{(p_1 + p_2)^2} = \frac{1}{2E_1E_2\,(1 - \cos\theta)}$$



Jet substructure

Suppose one measures a hadron that is produced within the jet, one can measure:

- collinear momentum fraction z_h distribution
- hadron transverse momentum $\boldsymbol{j}_\perp$ with respect to jet axis (sensitive to TMD FFs)

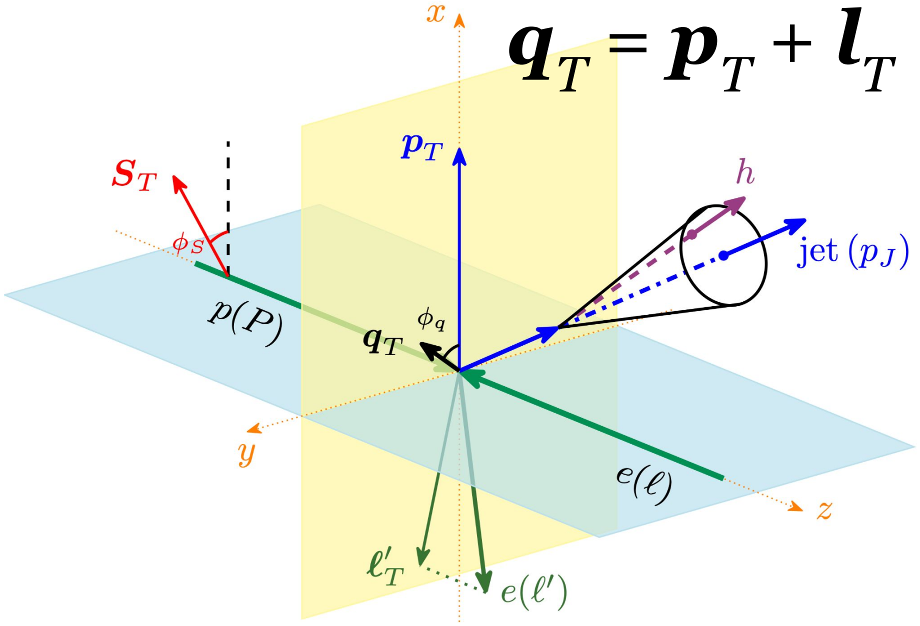


Kang, Xing, Zhao and **Zhou**, 2311.00672

Exclusive jet production

- Momentum imbalance $\boldsymbol{q}_T$: sensitive to initial-state TMD distributions
- Hadron $\boldsymbol{j}_\perp$: sensitive to TMD FFs

$$\boldsymbol{q}_T = \boldsymbol{p}_T + \boldsymbol{l}_T$$

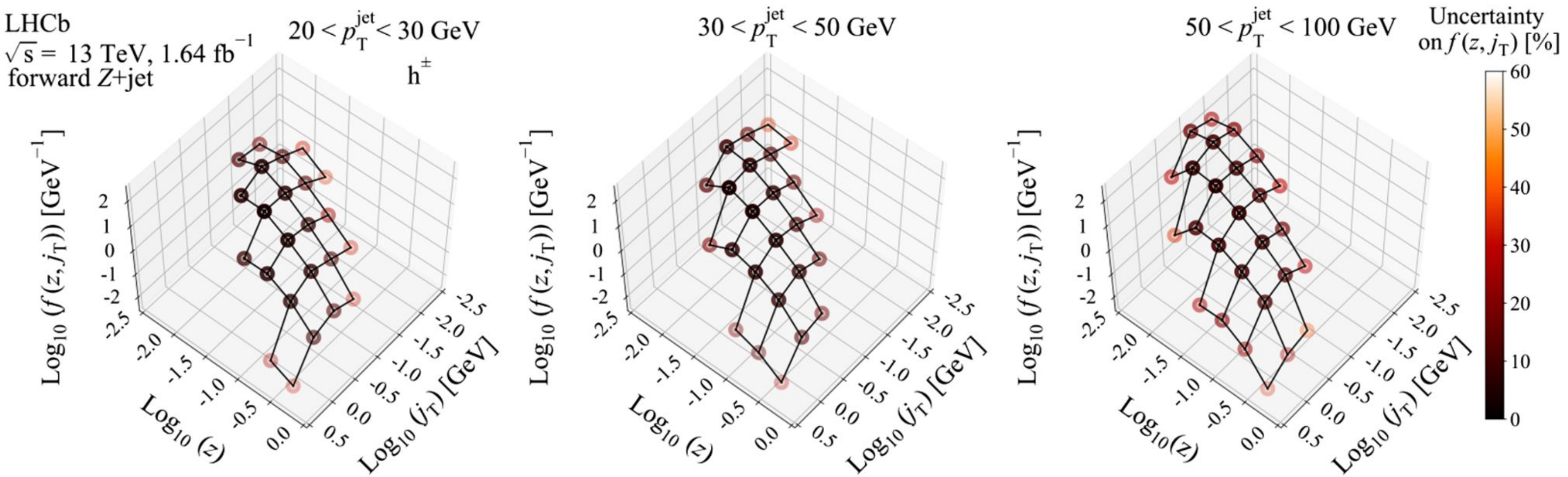


$$\frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}\mathcal{PS}} = \int \frac{\mathrm{d}^2\boldsymbol{b}}{(2\pi)^2} e^{-i\boldsymbol{q}_T\cdot\boldsymbol{b}} \tilde{f}_a^{q/p}(x_a, b) \tilde{f}_b^{q/p}(x_b, b)$$
$$\times \widetilde{S}_{n\bar{n}n_J}(\boldsymbol{b}) \widetilde{S}^{cs}_{n_J}(\boldsymbol{b}, R) H_{ab\to cZ}(p_T, m_Z) J_c(p_{JT}R)$$

- Kang, Lee, Shao & Zhao: 2106.15624
- Kang, Lee, Xing, Zhao & Zhou: 2411.XXXX

Exclusive jet production: $pp \to Z + \text{jet}(h)$

- Recent measurement by LHCb (2208.11691)
- First time differential in both z_h and $\boldsymbol{j}_\perp$ (proposed in 1906.07187)



Exclusive jet production: $pp \to Z + \text{jet}(h)$

- **Fragmentation functions** (2101.04664, 2202.03372)
- Data included: e^+e^-, SIDIS, polarized SIDIS

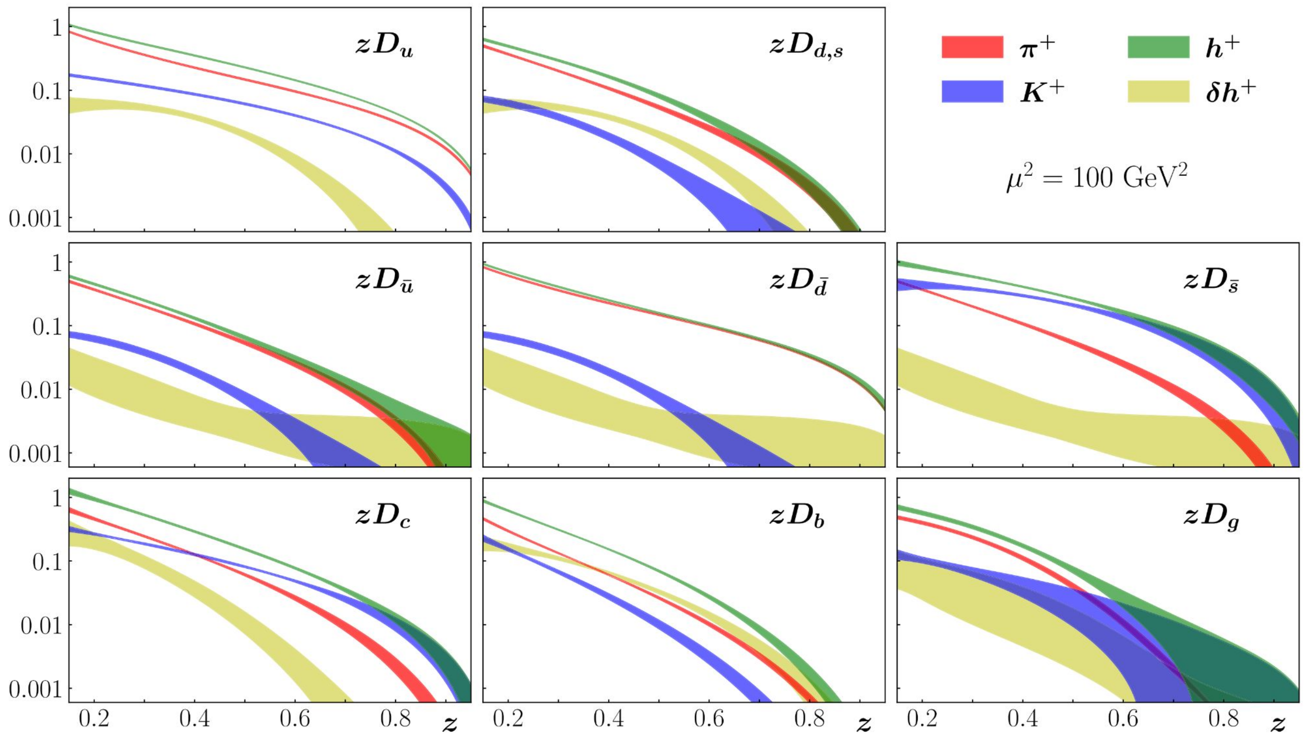
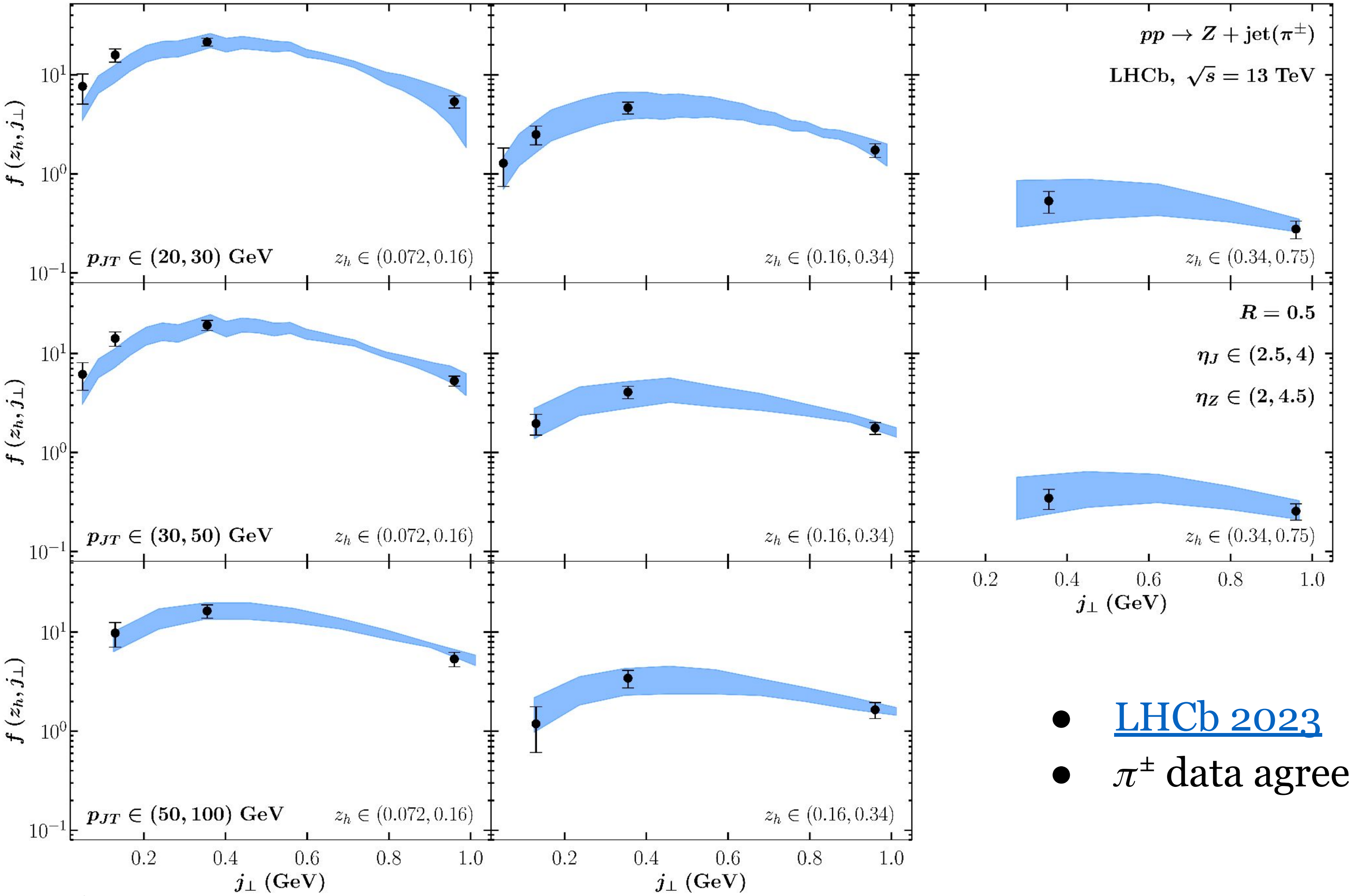


TABLE I. Summary of χ^2 values per number of points N_{dat} for the various datasets used in this analysis.

Process	N_{dat}	χ^2/N_{dat}
Polarized		
Inclusive DIS	365	0.95
SIDIS (π^+, π^-)	64	1.05
SIDIS (K^+, K^-)	57	0.42
SIDIS (h^+, h^-)	110	0.95
Inclusive jets	83	0.84
STAR $W^\pm$	12	0.65
PHENIX $W^\pm/Z$	6	0.50
Total	**697**	**0.89**
Unpolarized		
Inclusive DIS	3908	1.17
SIDIS (π^+, π^-)	498	0.94
SIDIS (K^+, K^-)	494	1.31
SIDIS (h^+, h^-)	498	0.71
Inclusive jets	198	1.28
Drell-Yan	205	1.21
W/Z production	153	1.01
Total	**5954**	**1.12**
SIA $(\pi^\pm)$	231	0.91
SIA $(K^\pm)$	213	0.70
SIA $(h^\pm)$	120	1.07
Total	**7215**	**1.08**

Exclusive jet production: $pp \to Z + \text{jet}(h)$

$\pi^{\pm}$

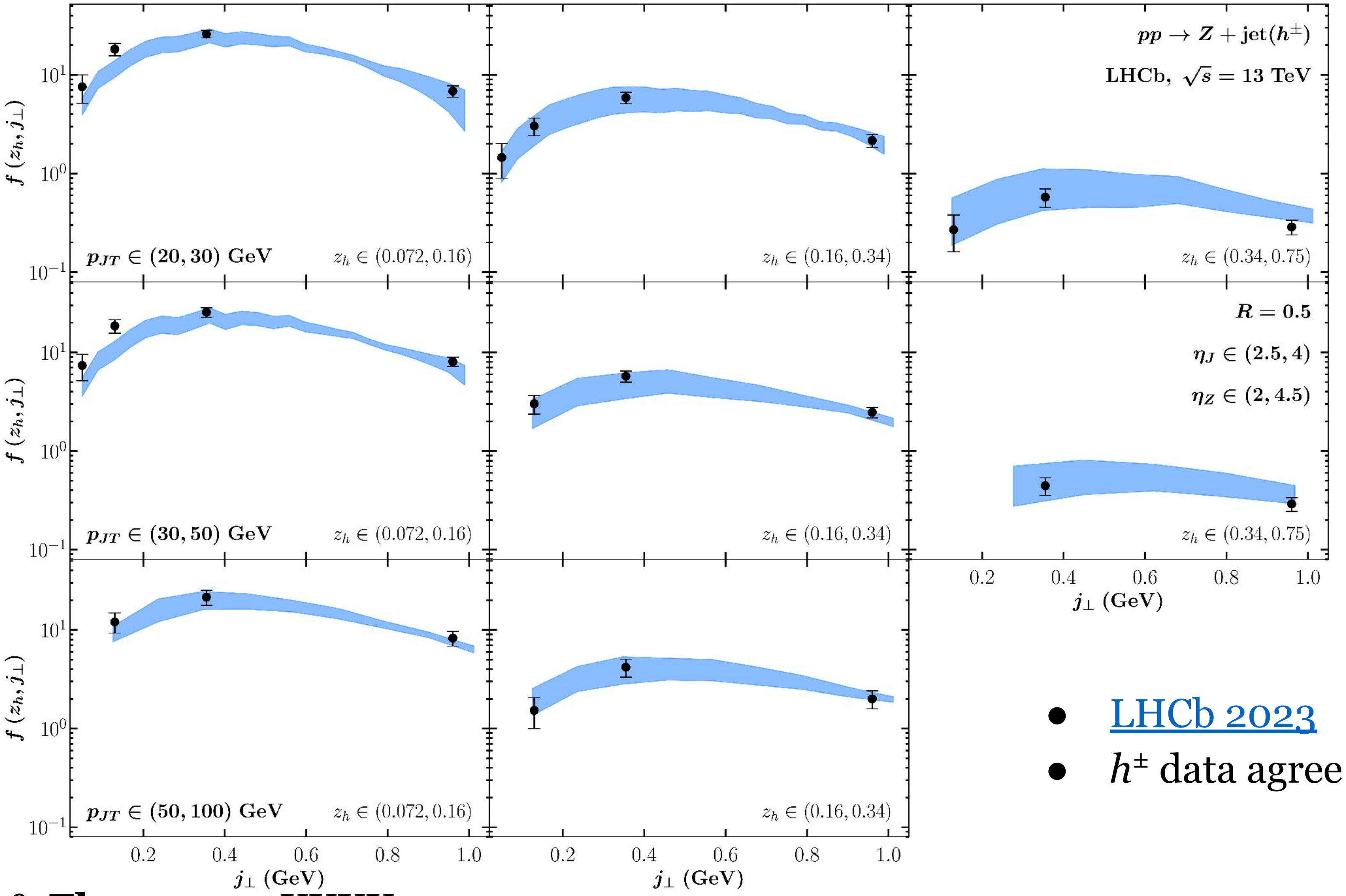


- LHCb 2023
- $\pi^{\pm}$ data agree very well ✓

Kang, Lee, Xing, Zhao & **Zhou**: 2411.XXXX

Exclusive jet production: $pp \to Z + \text{jet}(h)$

$h^{\pm}$



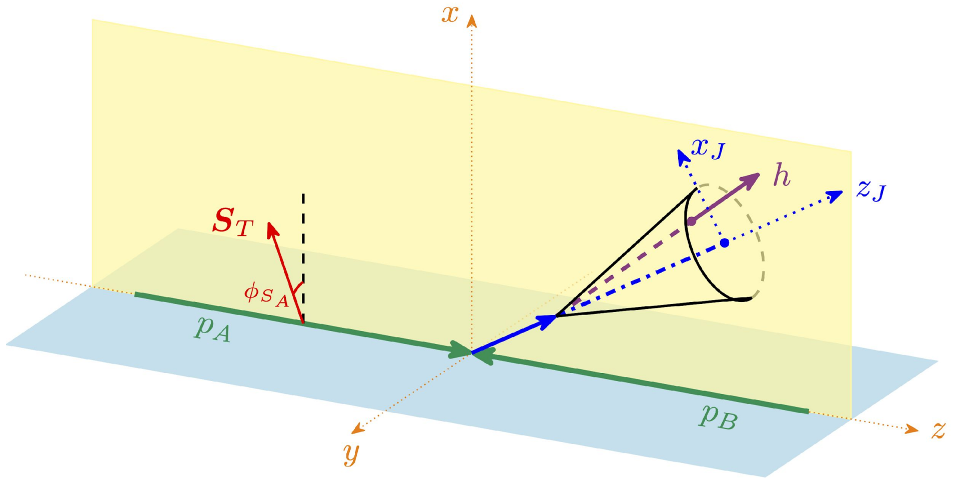
- LHCb 2023
- $h^{\pm}$ data agree very well ✓

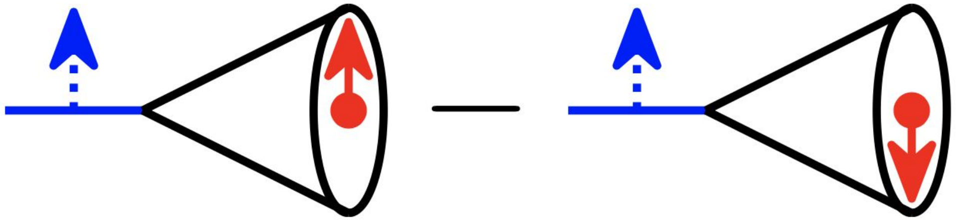
Kang, Lee, Xing, Zhao & **Zhou**: 2403.XXXX

Single inclusive jet production

- Collinear PDFs: only one scale p_T is measured.
- TMD FFs: when hadron transverse momentum distribution is measured.

Kang, Ringer & Vitev: 16; Dai, Kim & Leibovich: 16; Kaufmann, Mukherjee & Vogelsang: 15



$\mathcal{H}_1 =$ 

$$\frac{d\sigma^{pp\to \text{jet}(h)+X}}{dp_T\, d\eta\, dz_h} \propto f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{D}_1^{h/c}(z, z_h, p_T R, \mu),$$

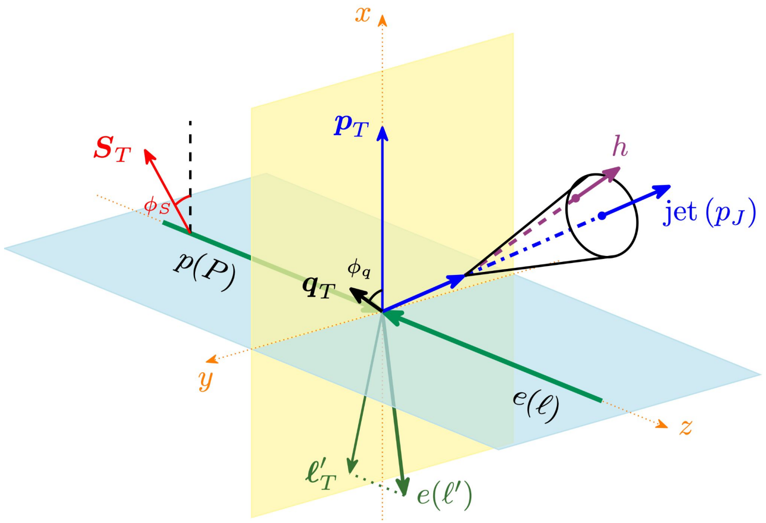
$$\frac{d\sigma^{pp\to \text{jet}(h)+X}}{dp_T\, d\eta\, dz_h\, d^2\boldsymbol{j}_\perp} \propto f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_1^{h/c}(z, z_h, \boldsymbol{j}_\perp, p_T R, \mu, \zeta_J),$$

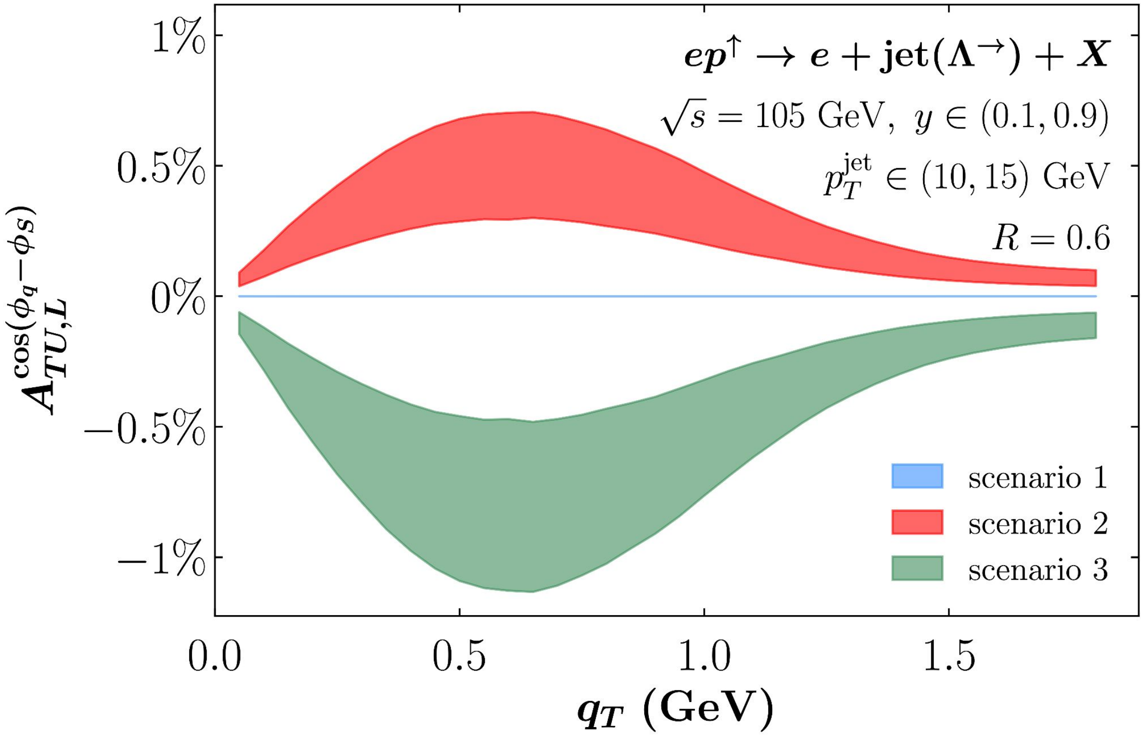
- z_h: large momentum fraction of hadron v.s. jet
- $\boldsymbol{j}_\perp$: hadron transverse momentum w.r.t. jet axis

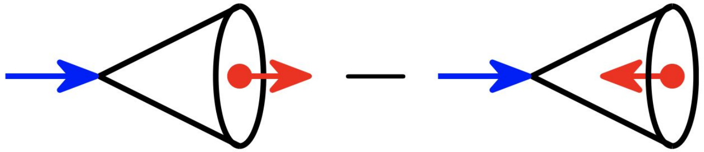
Exclusive jet production: $ep \rightarrow e + \text{jet}(h)$

- worm-gear function
- longitudinally polarized FFs

$$A_{TU,L}(z_h, j_\perp) \equiv \frac{\hat{\sigma}_0 H \mathscr{G}_{1L} \widetilde{g}_{1T} \overline{S}_{\text{global}} \overline{S}_{\text{cs}}}{\hat{\sigma}_0 H \mathscr{D}_1 \widetilde{f}_1 \overline{S}_{\text{global}} \overline{S}_{\text{cs}}}$$





$\Delta \mathscr{G}_q^h =$ 

Kang, Xing, Zhao and **Zhou**, 2311.00672

Relation between TMD FFs and TMD FJFs

If you measure both z_h and $\boldsymbol{j}_\perp$

Leading Quark TMDFFs — Hadron Spin — Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		D_1 = Unpolarized		$H_1^\perp$ = − Collins
Polarized Hadrons	L		G_1 = − Helicity	$H_{1L}^\perp$ = −
Polarized Hadrons	T	$D_{1T}^\perp$ = − Polarizing FF	$G_{1T}^\perp$ = −	H_1 = − Transversity $H_{1T}^\perp$ = −

[TMD handbook, 2304.03302](https://arxiv.org/abs/2304.03302)

		Quark polarization		
		U	L	T
Hadron polarization	U	$\mathcal{D}_1$ =		$\mathcal{H}_1^\perp$ = −
Hadron polarization	L		$\mathcal{G}_{1L}$ = −	$\mathcal{H}_{1L}^\perp$ = −
Hadron polarization	T	$\mathcal{D}_{1T}^\perp$ = −	$\mathcal{G}_{1T}$ = −	$\mathcal{H}_1$ = − $\mathcal{H}_{1T}^\perp$ = −

[Kang, Xing, Zhao and **Zhou**, 2311.00672](https://arxiv.org/abs/2311.00672)

How do we connect them?

Summary

- Hadron 1D structure:
    - unpolarized PDFs – proton collinear momentum distribution
    - polarized PDFs – proton spin decomposition
- Hadron 3D structure:
    - transverse momentum dependent distributions – more detailed mapping of hadron structure
    - jet substructure – polarization opens up a wide range of possibilities

Thanks for your attention!