

# TMDs, GPDs and GTMDs

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December 2, IJCLab, Orsay, France

# Preliminary words

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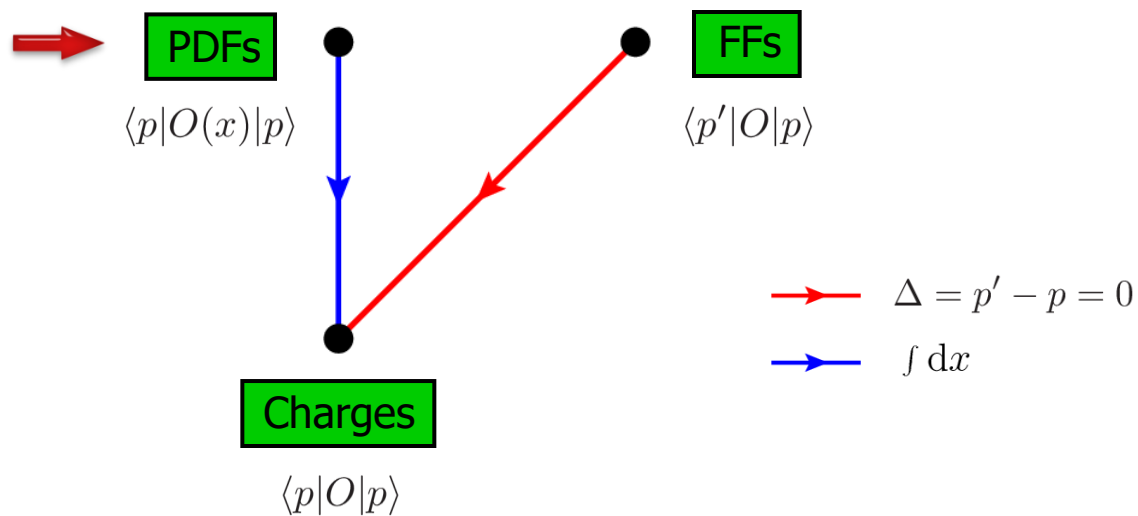
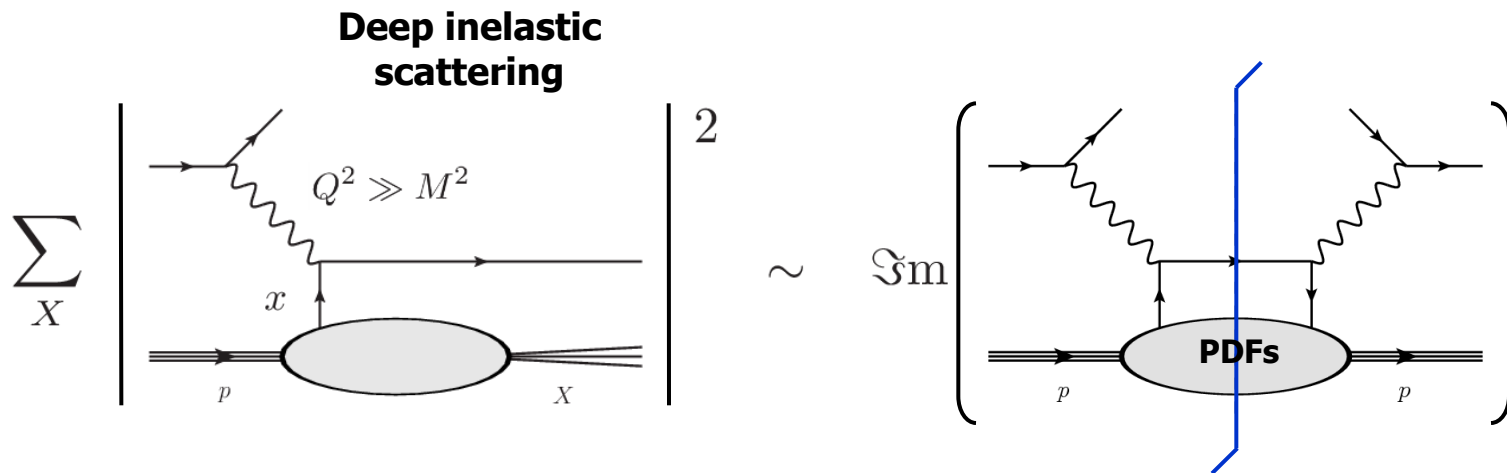
**This is a last-minute talk**

**I am no LHC expert**

**I apologize for the non-exhaustive, superficial, biased overview  
and for any misrepresentation**

**I am grateful to [Shohini Bhattacharya](#) and [Charlotte Van Hulse](#)  
for their kind help!**

# Parton distribution zoo

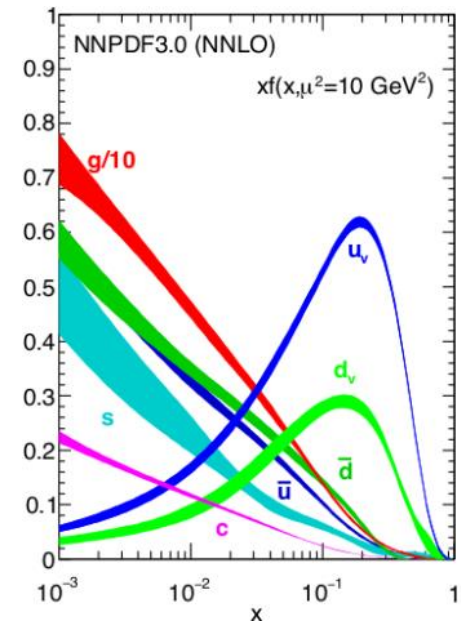
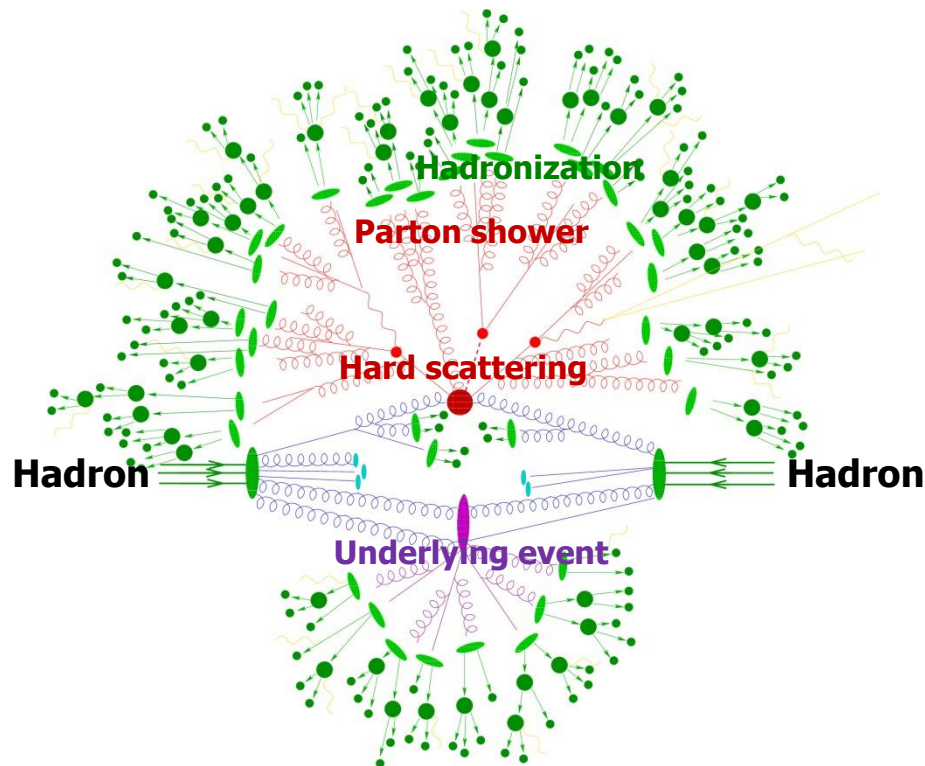


# Parton distribution functions

## 1D picture of the hadron structure

At the LHC :

- Key input to describe/study high-energy collisions
- High-energy data used to constrain/study hadron structure



# Parton distribution functions

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**Numerous aspects have been addressed in this conference**

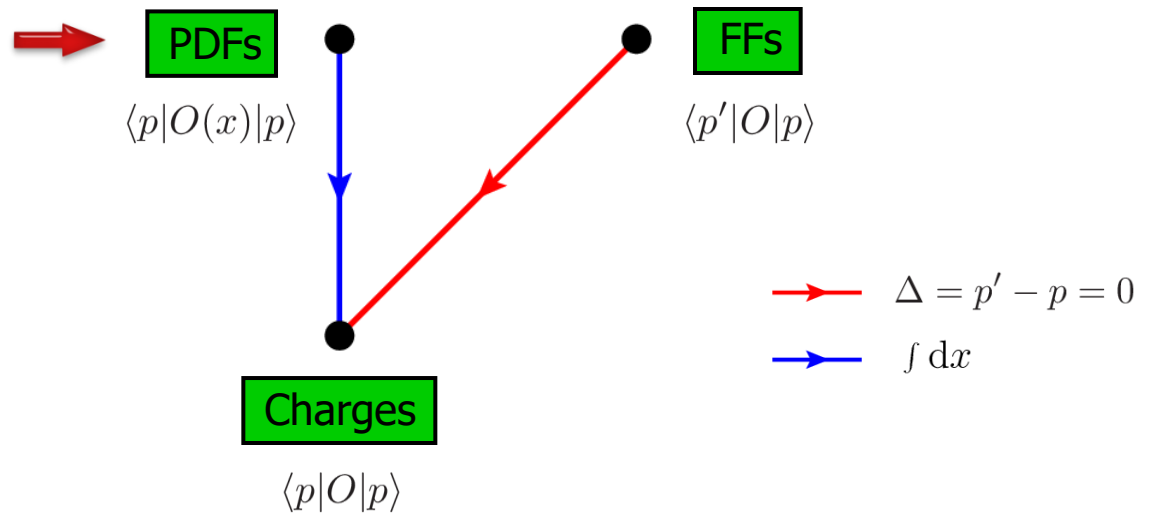
**From e.g. **WG7: Parton tomography from 1D to 5D****

- **Dijet production** (Le Mahieu, Hatta)
- **Quarkonium production** (Ferreiro, Guzey, Matyja)
- **PDFs fits and uncertainties** (Cruz Martinez, Kassabov-Zaharieva, Newman, Silveti)
- **Intrinsic charm and heavy flavors** (Maciula, Magni, Mattioli)
- **Nuclear PDFs** (Boente Garcia, Paakkinnen)
- **Double PDFs and MPI** (Gaunt)
- **Low-x and gluon saturation** (Caucal)
- **Fragmentation and hadronization** (Volkel)
- **Photon induced and proton-nucleus collisions** (Manna)

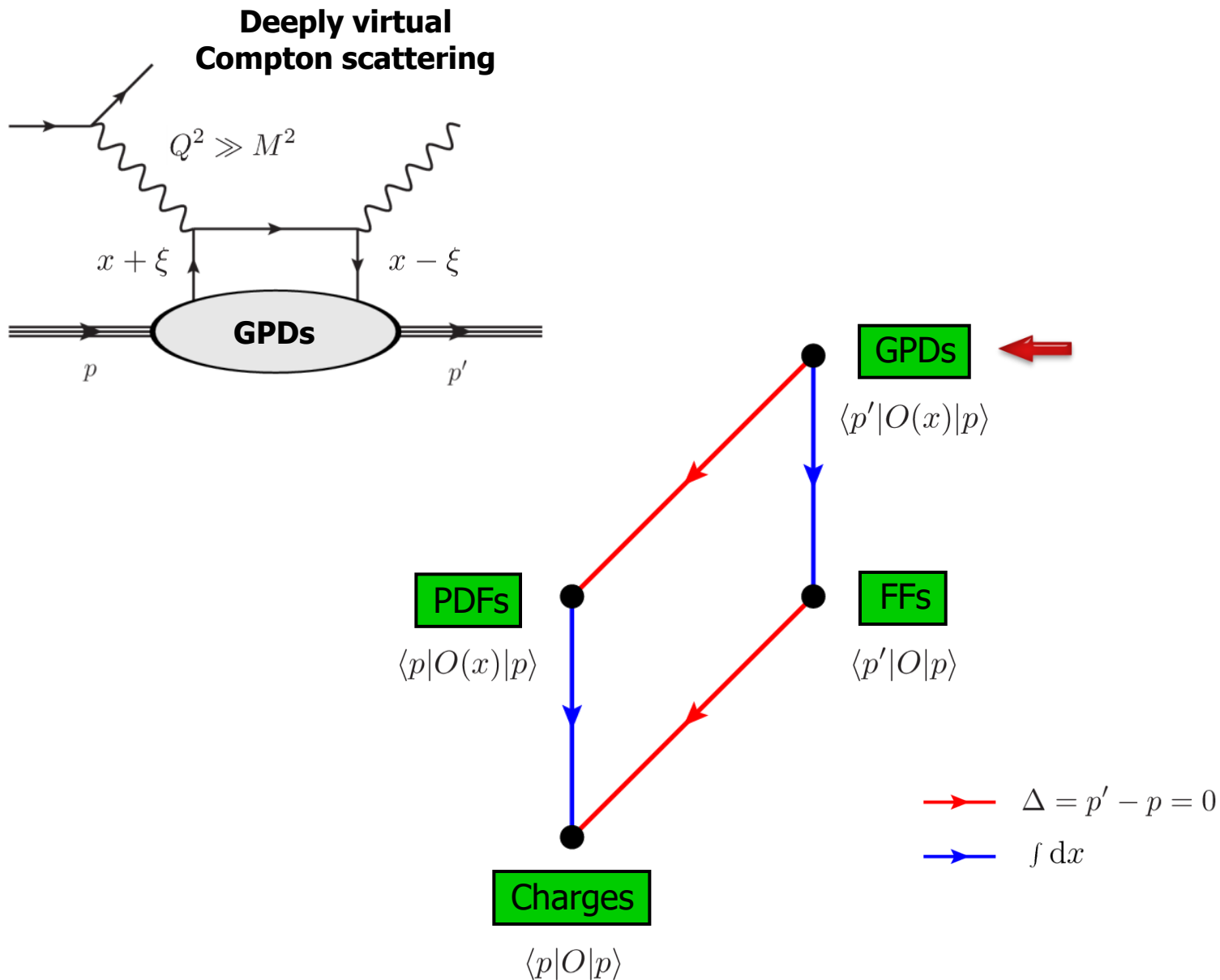
**A fixed-target experiment@LHC would provide key information in the high-x region !** [Hadjidakis *et al.* (2021)]

# Parton distribution zoo

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# Parton distribution zoo



# Generalized parton distributions

$$\Delta = p' - p \quad \xi = -\frac{\Delta^+}{(p' + p)^+}$$

## 1+2D picture of the hadron structure

[Burkardt (2003)]

$$\text{GPD}(x, \Delta = 0) = \text{PDF}(x)$$

$$\int dx x^n \text{GPD}(x, \Delta) = \sum_k \xi^k \text{GFF}(\Delta^2)$$

$n = 0$       **Electromagnetic FFs**

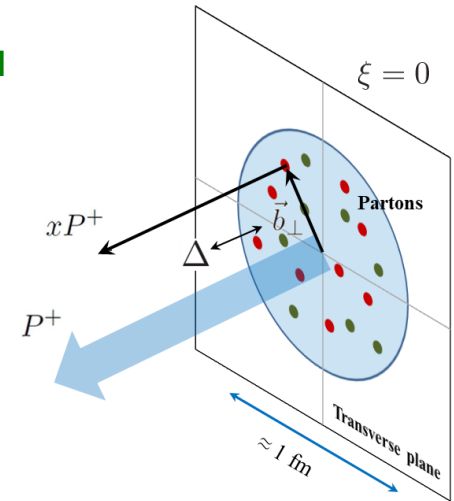
$n = 1$       **Gravitational FFs**

[Ji (1996)]

[Polyakov (2003)]

[Polyakov, Schweitzer (2018)]

Key to study mass, spin and pressure



$$T^{\mu\nu} = \begin{bmatrix} \text{Energy density } T_{00} & T_{01} & T_{02} & T_{03} \\ T_{10} & T_{11} & T_{12} & T_{13} \\ T_{20} & T_{21} & T_{22} & T_{23} \\ T_{30} & T_{31} & T_{32} & T_{33} \end{bmatrix}$$

Labels for the matrix elements:

- $T_{00}$ : Energy density
- $T_{01}, T_{02}, T_{03}$ : Momentum density
- $T_{10}, T_{20}, T_{30}$ : Energy flux
- $T_{11}, T_{12}, T_{13}, T_{21}, T_{22}, T_{23}, T_{31}, T_{32}, T_{33}$ : Momentum flux
- Off-diagonal elements (e.g.,  $T_{12}, T_{21}$ ): Shear stress
- Diagonal elements (e.g.,  $T_{11}, T_{22}, T_{33}$ ): Normal stress (pressure)

Can be used to : • probe parton orbital angular momentum (Riberdy)

• model double PDFs

[Diehl, Ostermeier, Schaefer (2011)]

[Diehl, Gaunt (2018)]

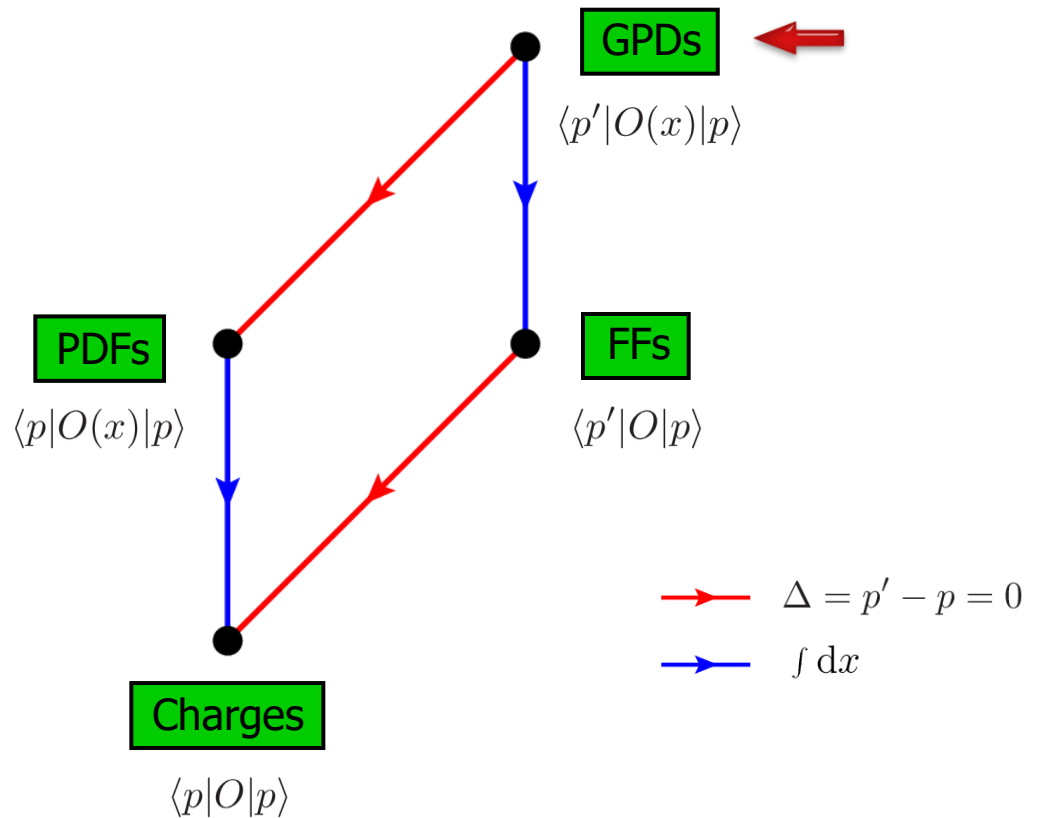
Some GPDs could be measured in UPCs through exclusive photoproduction of a  $\gamma$ -meson pair

[Duplancic *et al.*, 2209.05380]

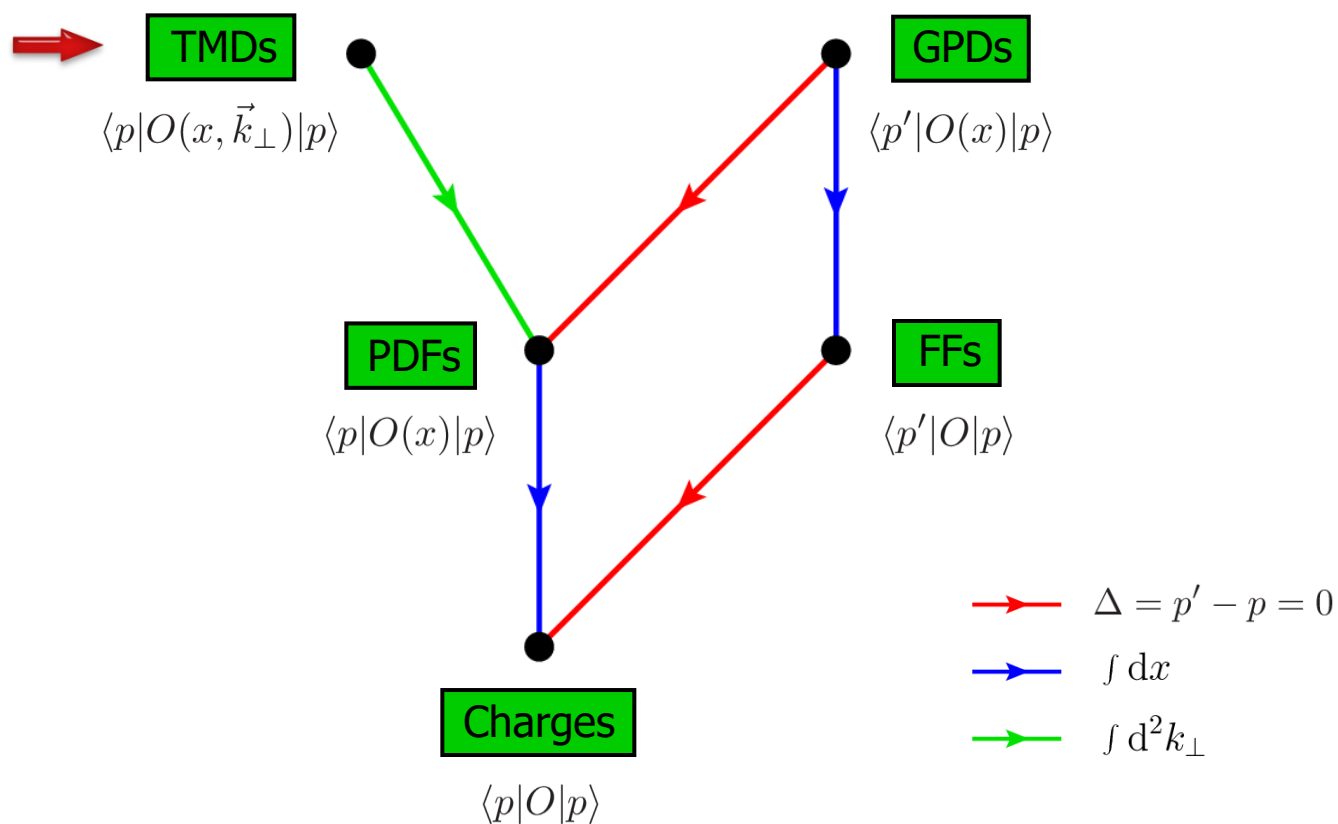
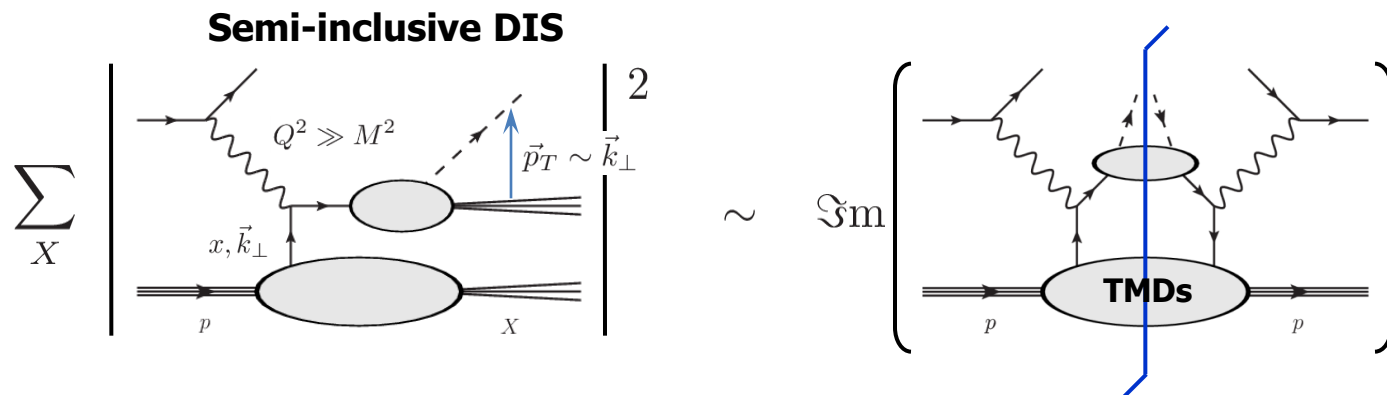


# Parton distribution zoo

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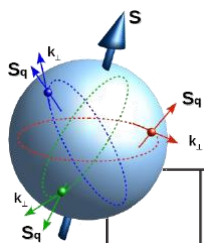


# Parton distribution zoo



# Transverse momentum distributions

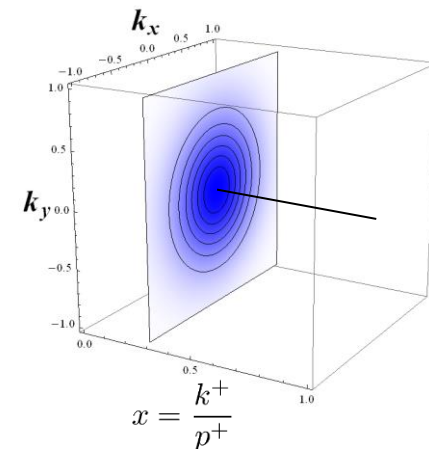
## 3D picture of the hadron structure



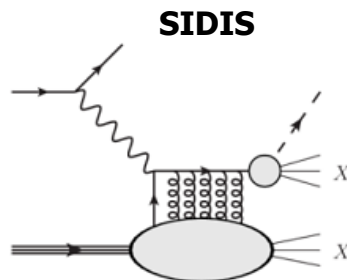
Quark polarization

Nucleon polarization

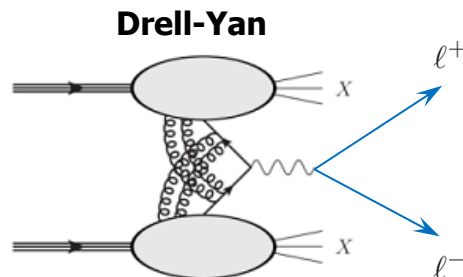
	$U$	$T_x$	$T_y$	$L$
$U$	$f_1$	$\frac{k_y}{M} h_1^\perp$	$-\frac{k_x}{M} h_1^\perp$	
$T_x$	$\frac{k_y}{M} f_{1T}^\perp$	$h_1 + \frac{k_x^2 - k_y^2}{2M^2} h_{1T}^\perp$	$\frac{k_x k_y}{M^2} h_{1T}^\perp$	$\frac{k_x}{M} g_{1T}$
$T_y$	$-\frac{k_x}{M} f_{1T}^\perp$	$\frac{k_x k_y}{M^2} h_{1T}^\perp$	$h_1 - \frac{k_x^2 - k_y^2}{2M^2} h_{1T}^\perp$	$\frac{k_y}{M} g_{1T}$
$L$		$\frac{k_x}{M} h_{1L}^\perp$	$\frac{k_y}{M} h_{1L}^\perp$	$g_{1L}$



Changes sign under ISI  $\leftrightarrow$  FSI (naive T-odd)



FSI



ISI

$$\frac{d\sigma}{d\Omega} \sim 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi$$

**Gluon TMDs** (Celiberto)

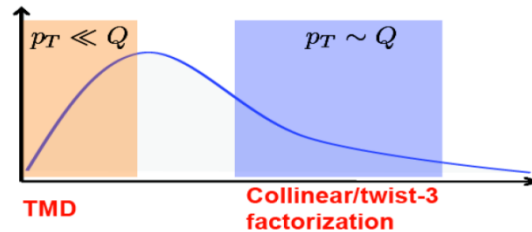
# Transverse momentum distributions

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**Violations of Lam-Tung relations  $1 - \lambda = 2\nu$  as a signature of parton transverse momentum**

[Boer (1999)]  
[Peng, Chang, McClellan, Teryaev (2016)]  
[Motyka, Sadzikowski, Stebel (2017)]

**Sensitivity to TMDs in low- $p_T$  spectrum of Z and W**



[Hautmann, Scimemi, Vladimirov (2020)]  
[Gutierrez-Reyes, Lelal-Gomez, Scimemi (2020)]

**Quarkonium-pair production as a probe of unpolarized and linearly polarized gluon TMDs, including TMD evolution effects**

[Scarpa, Boer, Echevarria, Lansberg, Pisano, Schlegel (2020)]

**Prospects for quarkonium studies at the high-luminosity LHC**

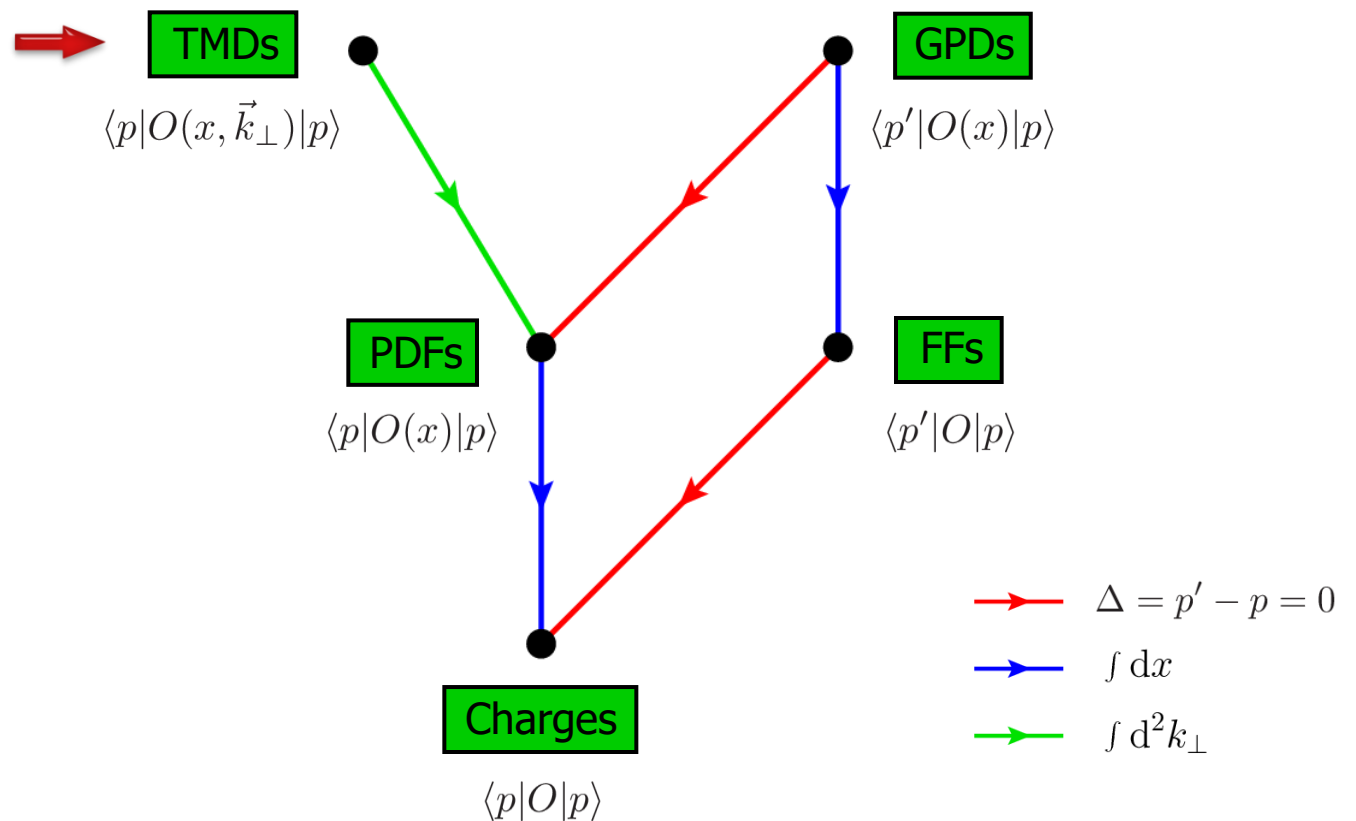
[Chapon *et al.* (2022)]

**LHCSpin project (polarized fixed target at LHCb)**

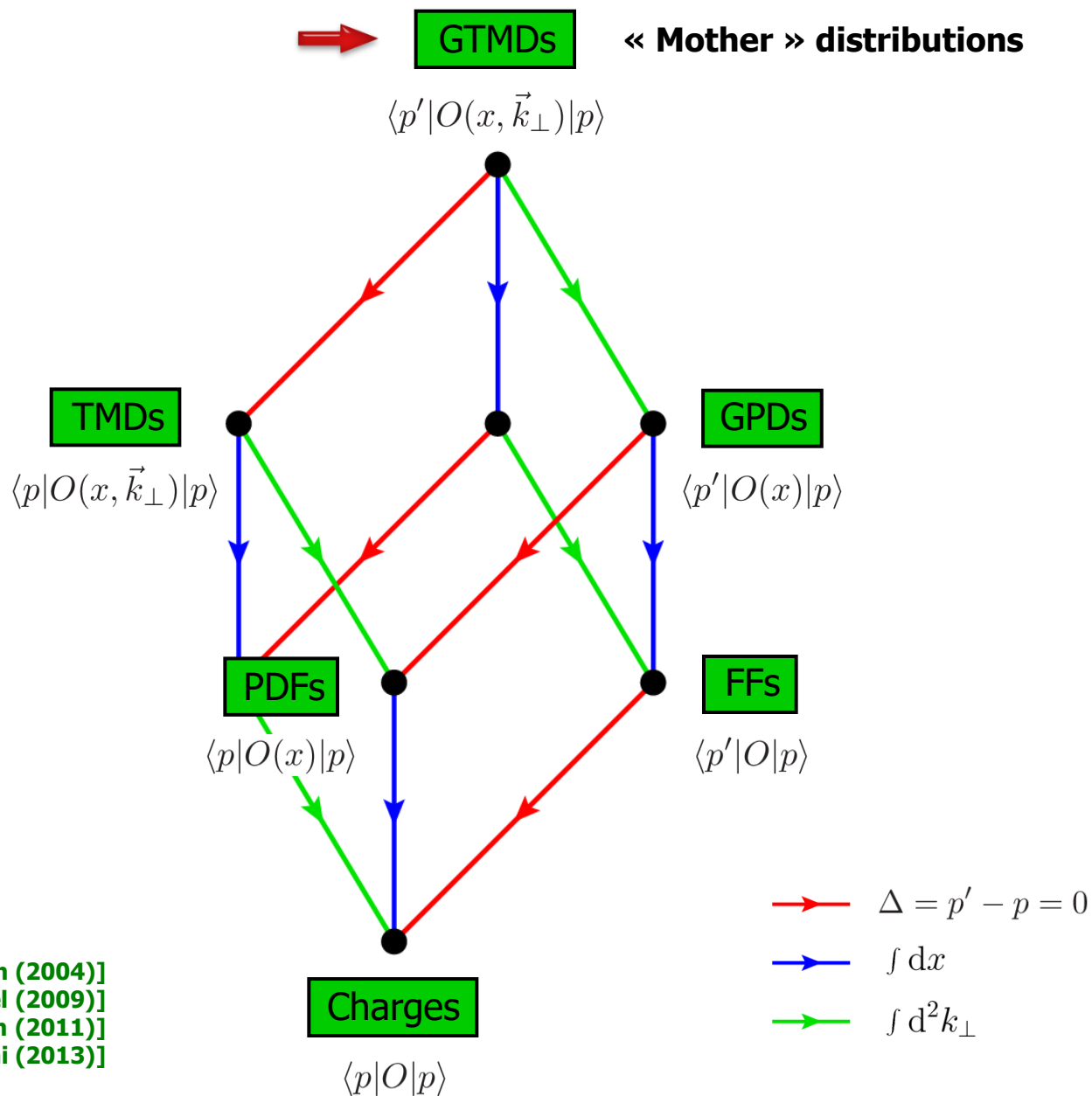
[Aidala *et al.*, 1901.08002]  
[D'Alesio, Murgia, Pisano, Rajesh (2019)]

# Parton distribution zoo

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# Parton distribution zoo



[Belitsky, Ji, Yuan (2004)]  
 [Meissner, Metz, Schlegel (2009)]  
 [Lorcé, Pasquini, Vanderhaeghen (2011)]  
 [Lorcé, Pasquini (2013)]

# Generalized TMDs

## 3+2D picture of the hadron structure

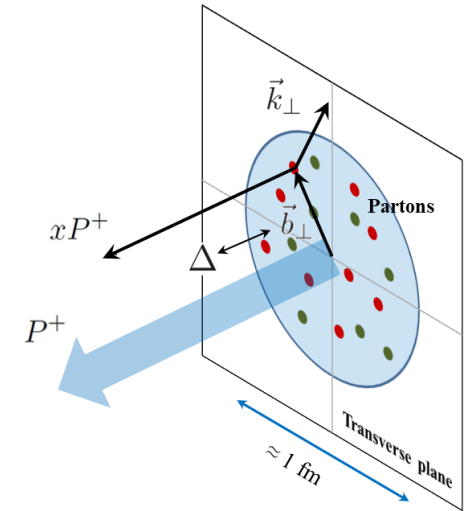
$$\text{WD}(x, \vec{k}_\perp, \vec{b}_\perp) \sim \mathcal{F} [\text{GTMD}(x, k_\perp, \Delta)]$$

Phase-space or  
Wigner distributions

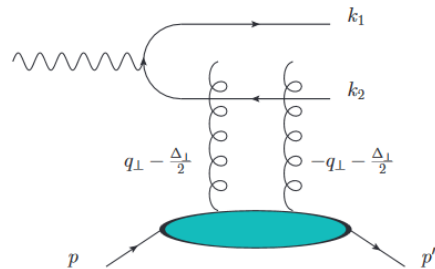
[Belitsky, Ji, Yuan (2004)]  
[Lorcé, Pasquini (2011)]

$$L_z = \int dx d^2k_\perp d^2b_\perp (\vec{b}_\perp \times \vec{k}_\perp) \text{WD}(x, \vec{k}_\perp, \vec{b}_\perp)$$

[Lorcé, Pasquini (2011)]  
[Hatta (2012)]  
[Ji, Xiong, Yuan (2013)]



## Gluon GTMDs could be accessed at LHC via exclusive production of



- **double quarkonium**

[Bhattacharya, Metz, Ojha, Tsai, Zhou (2022)]

- **diffractive dijet in UPCs**

[Hagiwara *et al.* (2017)]

(Le Mahieu, Hatta)

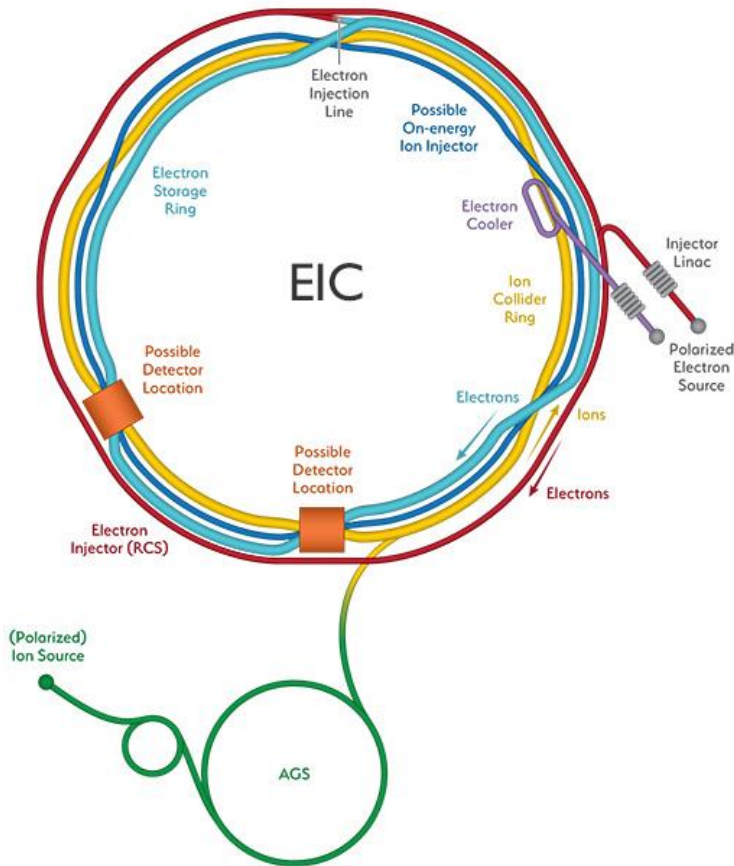
## Encouraging first attempt at measuring azimuthal correlations within exclusive dijets in $\gamma$ -Pb collisions

[CMS Collaboration, 2205.00045]

# Last words

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## Nice complementarity between LHC and EIC@BNL



## LHC

- Large  $Q^2$  lever arm (TMD evolution)
- W/Z production (quark TMDs)
- Small-x region
- Mostly (semi)inclusive

## EIC

- ep and eA processes
- Polarization
- High luminosity ( $\sim$ HERA  $10^{2-3}$ )
- Intermediate and high-x region
- Many possible exclusive channels