Large Transverse Momentum in SIDIS

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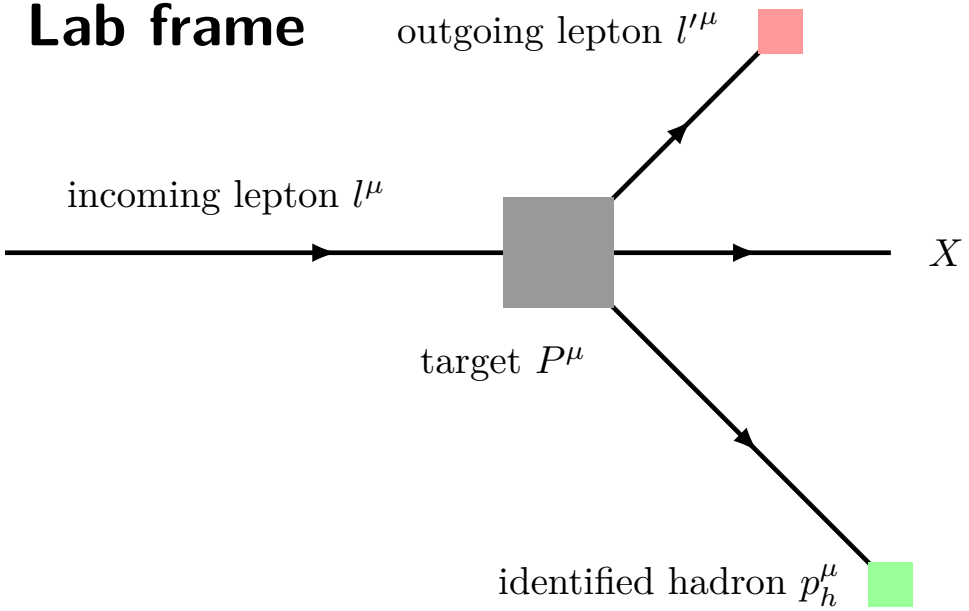
In collaboration with:

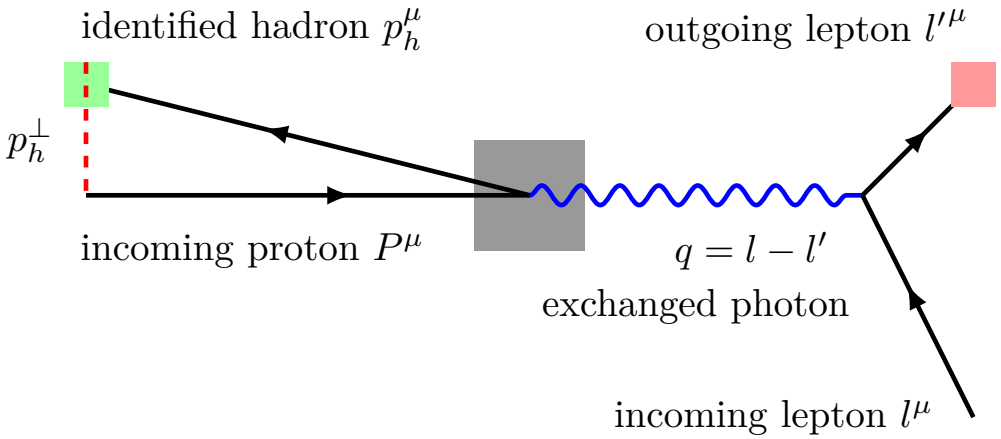
- O. Gonzalez
- T. Rogers
- B. Wang

Semi inclusive deep inelastic scattering (SIDIS)

Lab frame

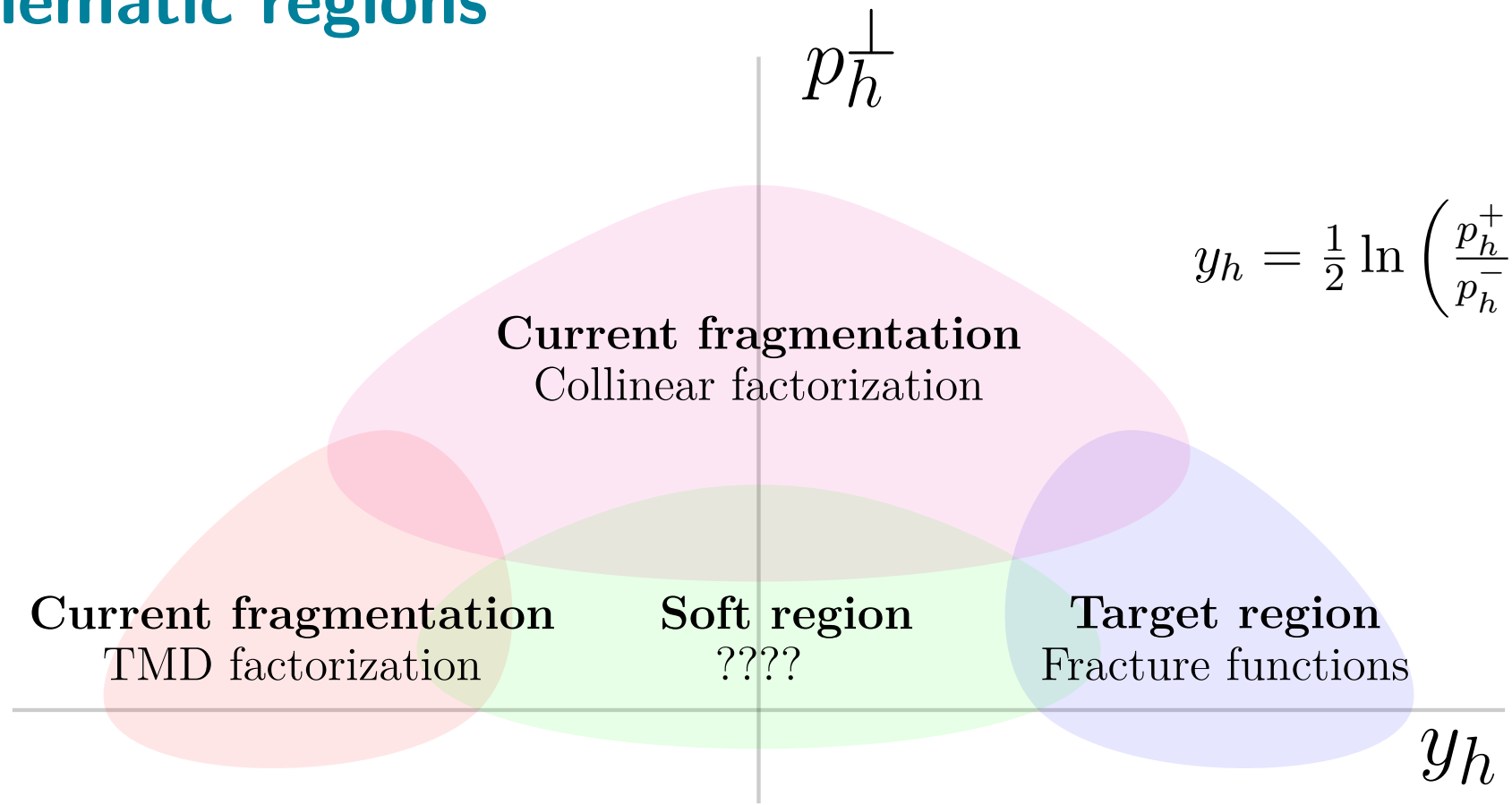


Breit frame



Key question :
How is $p_h^{\perp}$ generated at short distances?

Kinematic regions

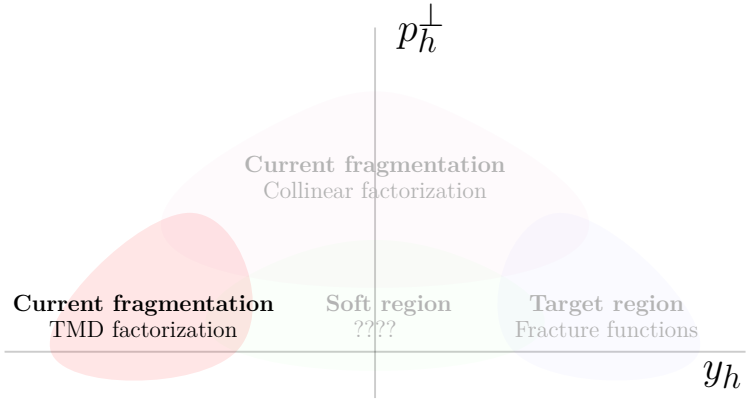


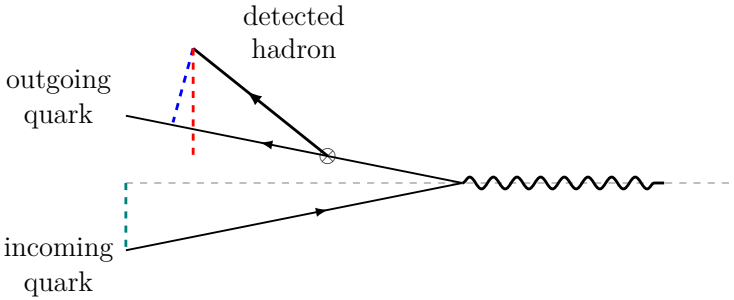
- **Different regions** are sensitive to distinct physical mechanisms

Factorization in the current region

small transverse momentum

W

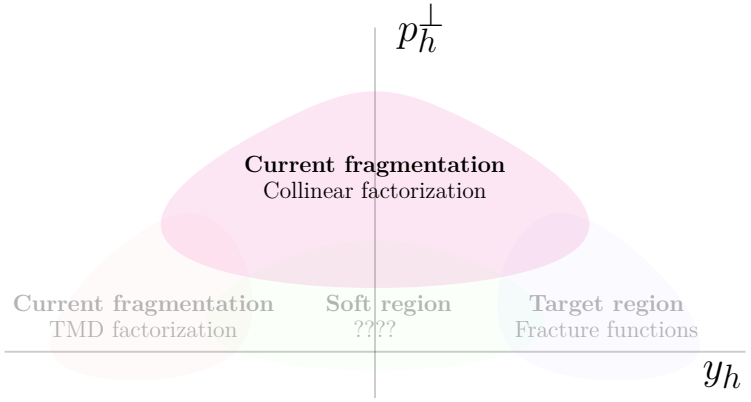


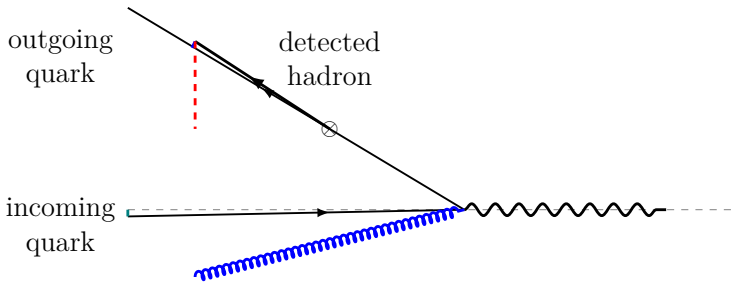


$$f_1(\xi, k_\perp),\ d_1(\zeta, k_\perp)$$

large transverse momentum

FO



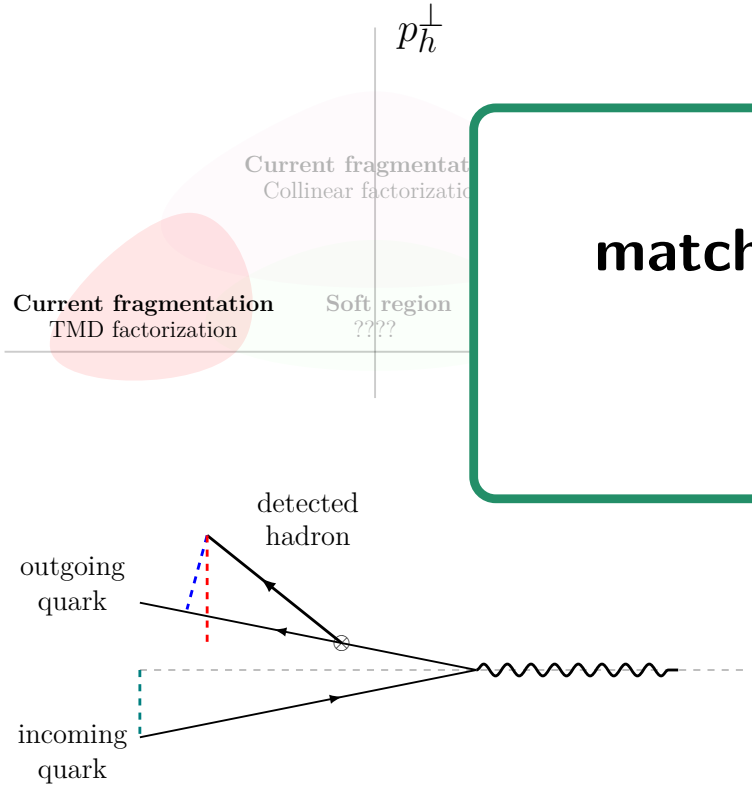


$$f_1(\xi),\ d_1(\zeta)$$

Factorization in the current region

small transverse momentum

W



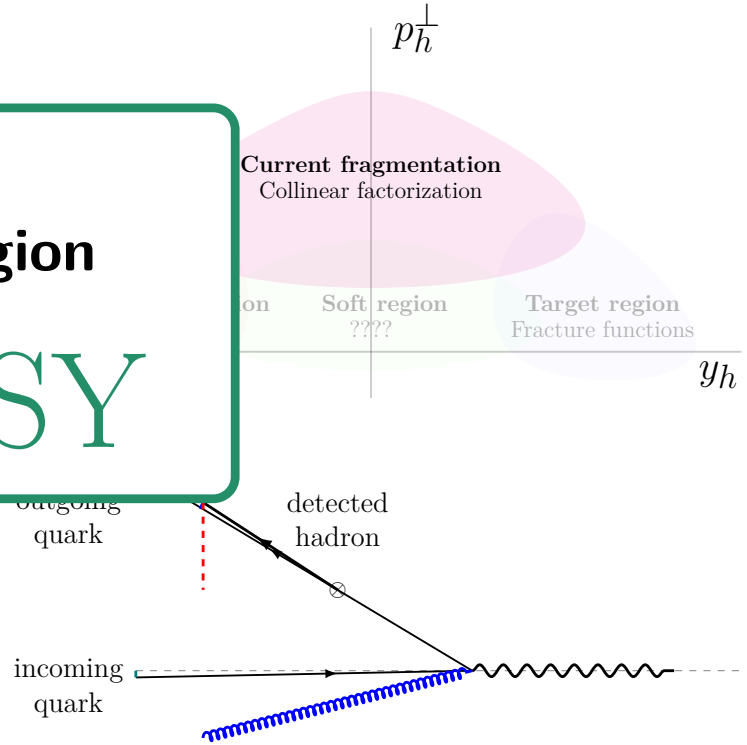
$$f_1(\xi, k_\perp),\ d_1(\zeta, k_\perp)$$

matching region

ASY

large transverse momentum

FO



$$f_1(\xi),\ d_1(\zeta)$$

Factorization in the current region

$$\frac{d\sigma}{dx dQ^2 dz dp_h^\perp} = \mathrm{W} + \mathrm{FO} - \mathrm{ASY} + \mathcal{O}(m^2/Q^2)$$

- Scale separation $\rightarrow q_\mathrm{T}/Q$ $\qquad q_\mathrm{T} = p_h^\perp/z, \qquad z = \dfrac{P \cdot p_h}{P \cdot q}$
- Limits

$$\frac{d\sigma}{dx dQ^2 dz dp_h^\perp} \sim \mathrm{W} \quad \text{for } q_\mathrm{T} \ll Q$$

$$\sim \mathrm{FO} \quad \text{for } q_\mathrm{T} \geq Q$$

Phenomenology

- In theory

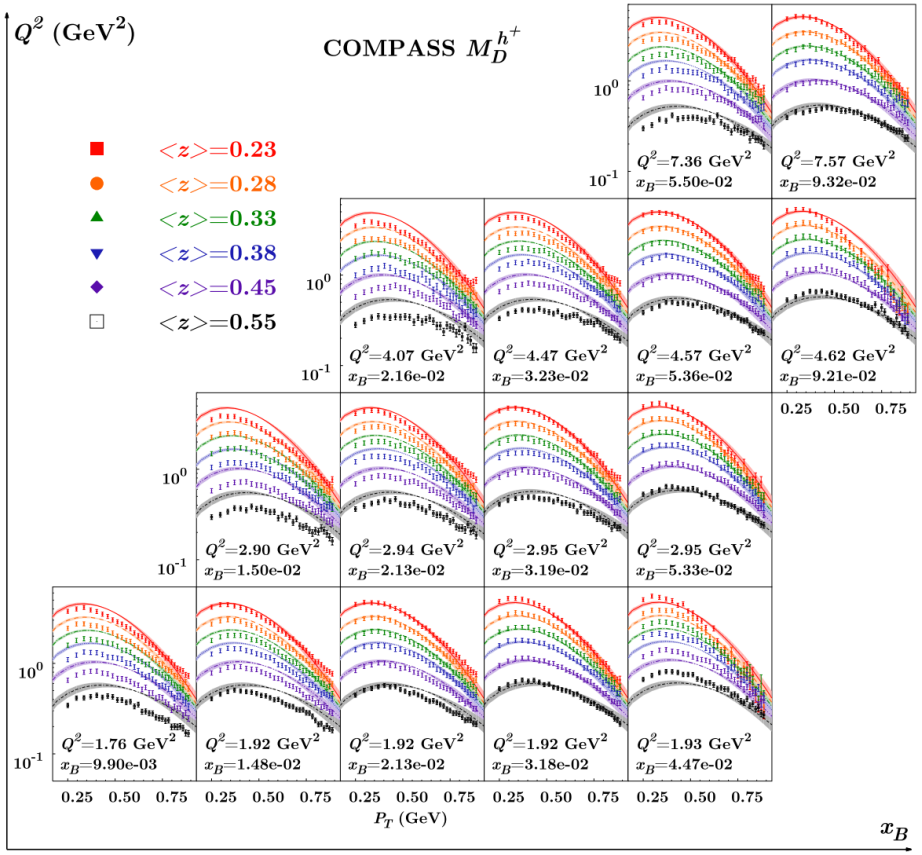
$$\frac{d\sigma}{dx dQ^2 dz dp_h^\perp} = \mathrm{W} + \mathrm{FO} - \mathrm{ASY} + \mathcal{O}(m^2/Q^2)$$

- In practice

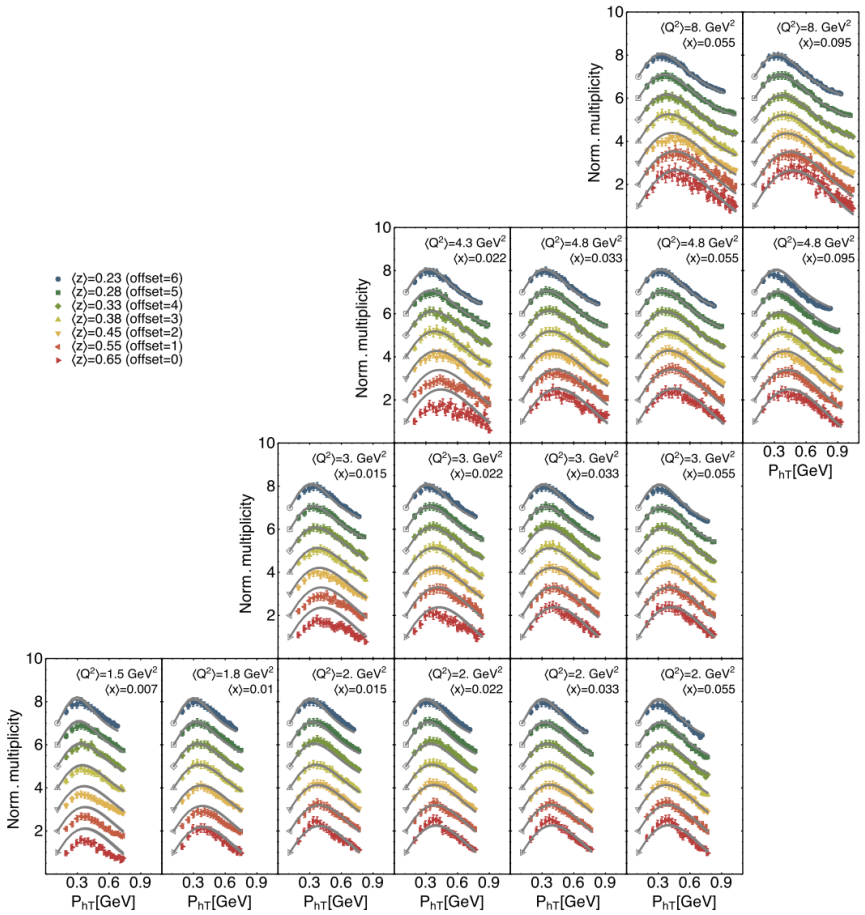
$$\frac{d\sigma}{dx dQ^2 dz dp_h^\perp} \sim \mathrm{W}$$

State-of-the-art phenomenology

Anselmino et al



Bacchetta et al



- These analyzes used only W (Gaussian, CSS)
- Samples with $q_T/Q \sim 1.63$ has been included
- **BUT TMDs are only valid for $q_T/Q \ll 1$!**

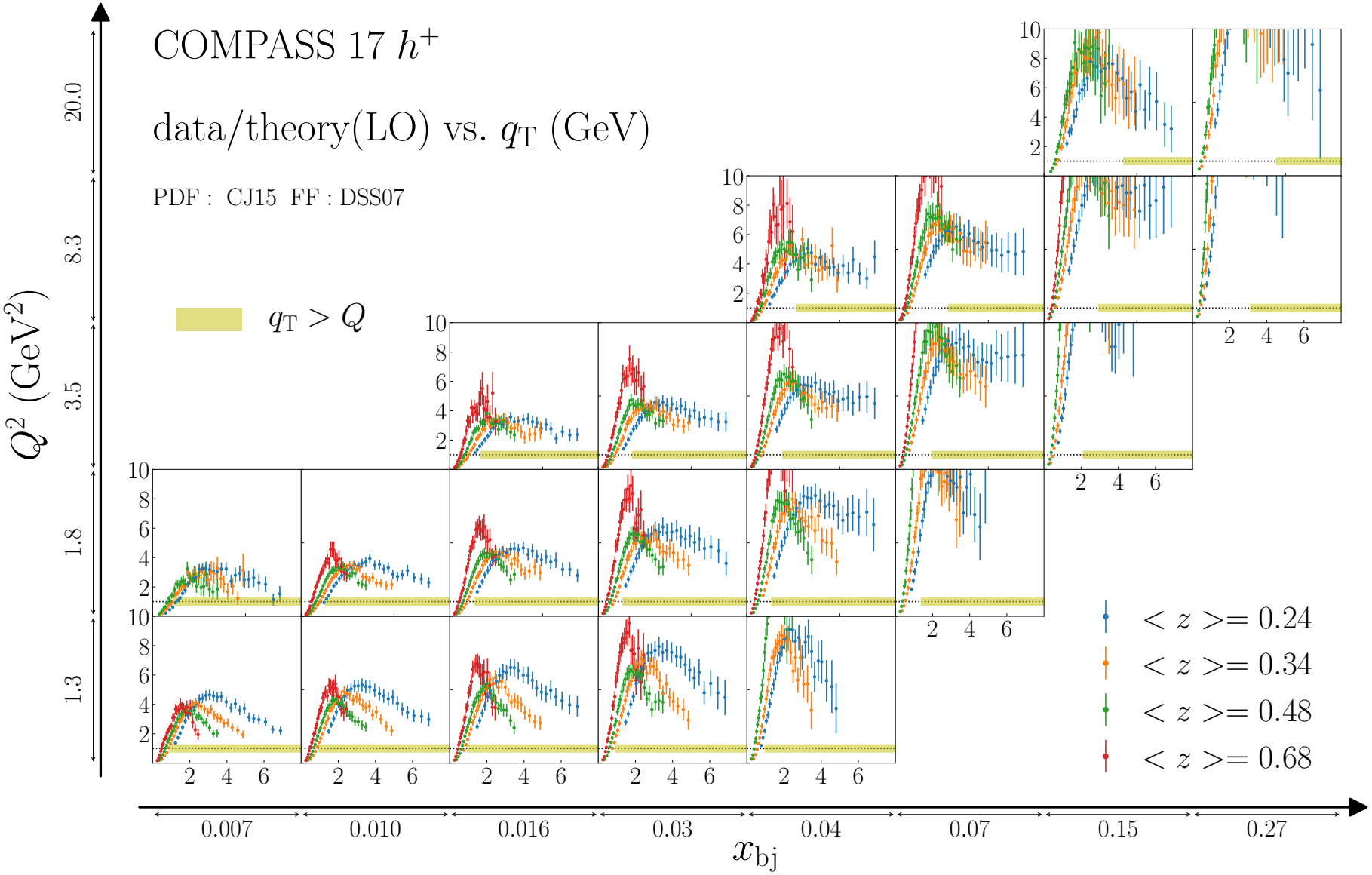
What happens if we use FO?

- At LO:

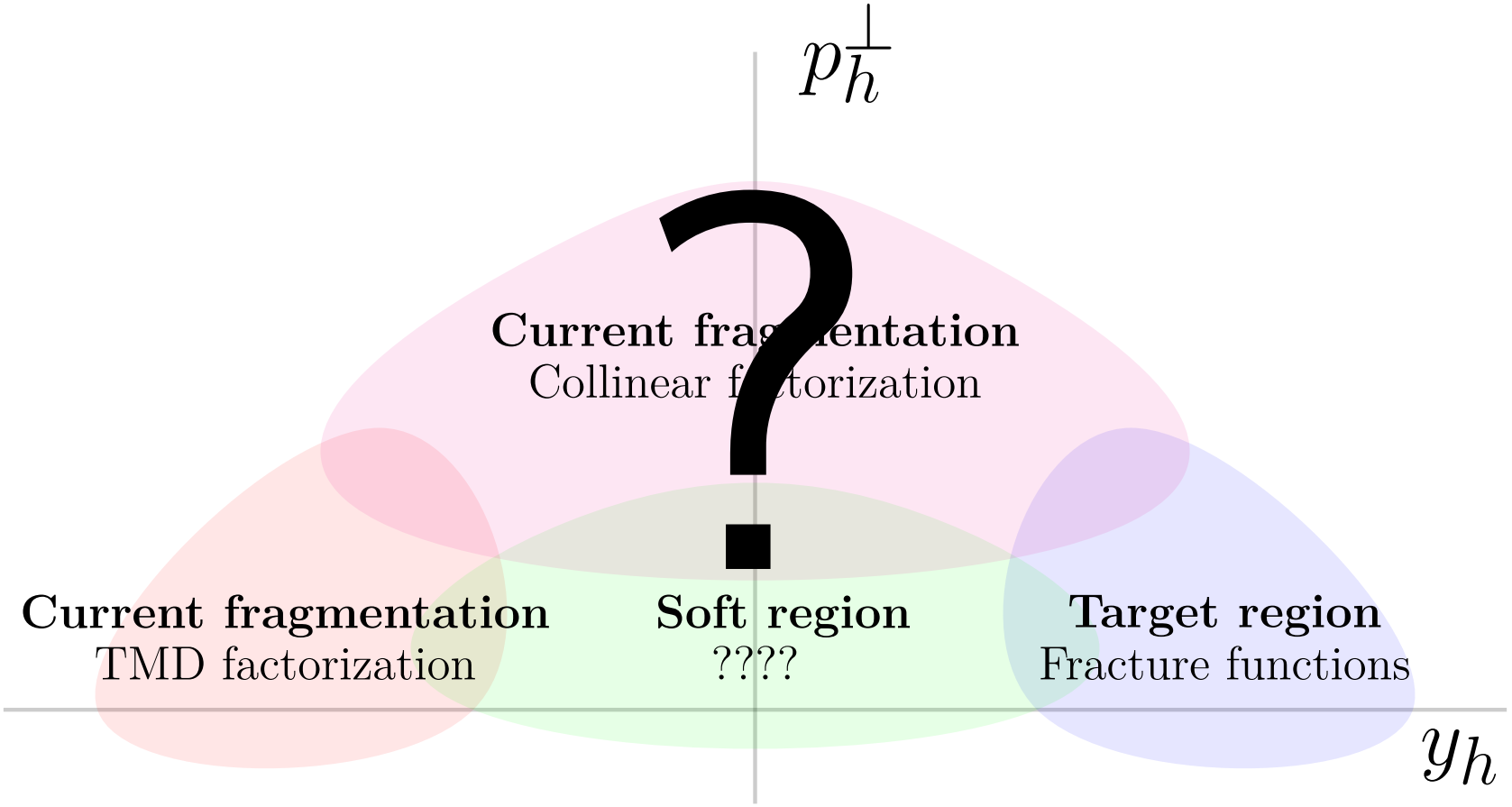
$$\mathrm{FO} = \sum_q e_q^2 \int_{\frac{q_T^2}{Q^2}\frac{xz}{1-z}+x}^{1} \frac{d\xi}{\xi - x} f_q(\xi,\mu)\ d_q(\zeta(\xi),\mu)\ H(\xi)$$

- For collinear distributions we use
  - PDFs: CJ15
  - FFs: DSS07

FO @ LO predictions (DSS07)



The large p_{T} puzzle



- Revisit charged hadron FFs
- Include NLO corrections

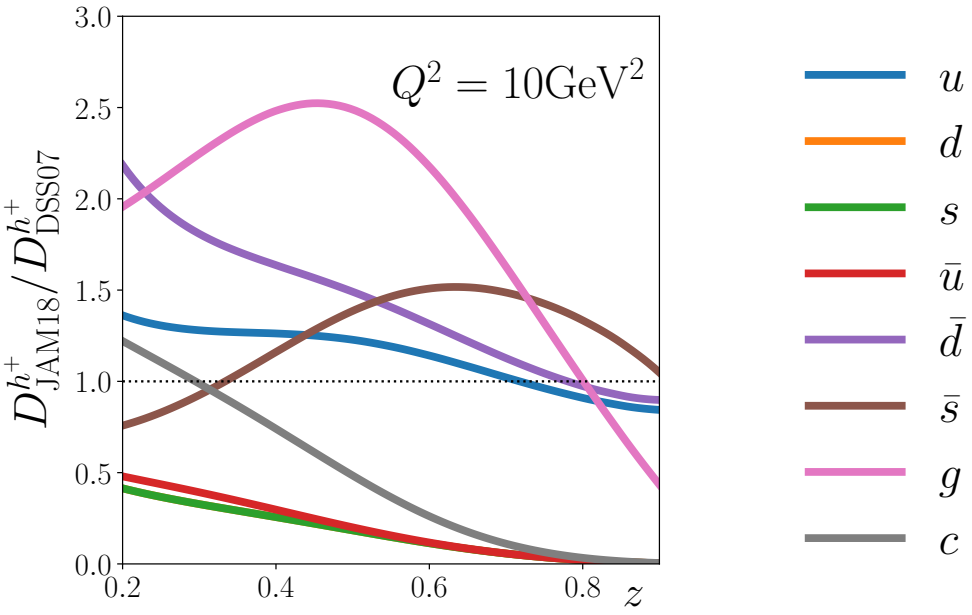
Revisiting charged hadron FFs (in JAM)

- For q_{T} integrated cross section @ NLO:

$$\frac{d\sigma}{dx dQ^2 dz} = \sum_q H_q \otimes f_q \otimes d_q(x, z)$$

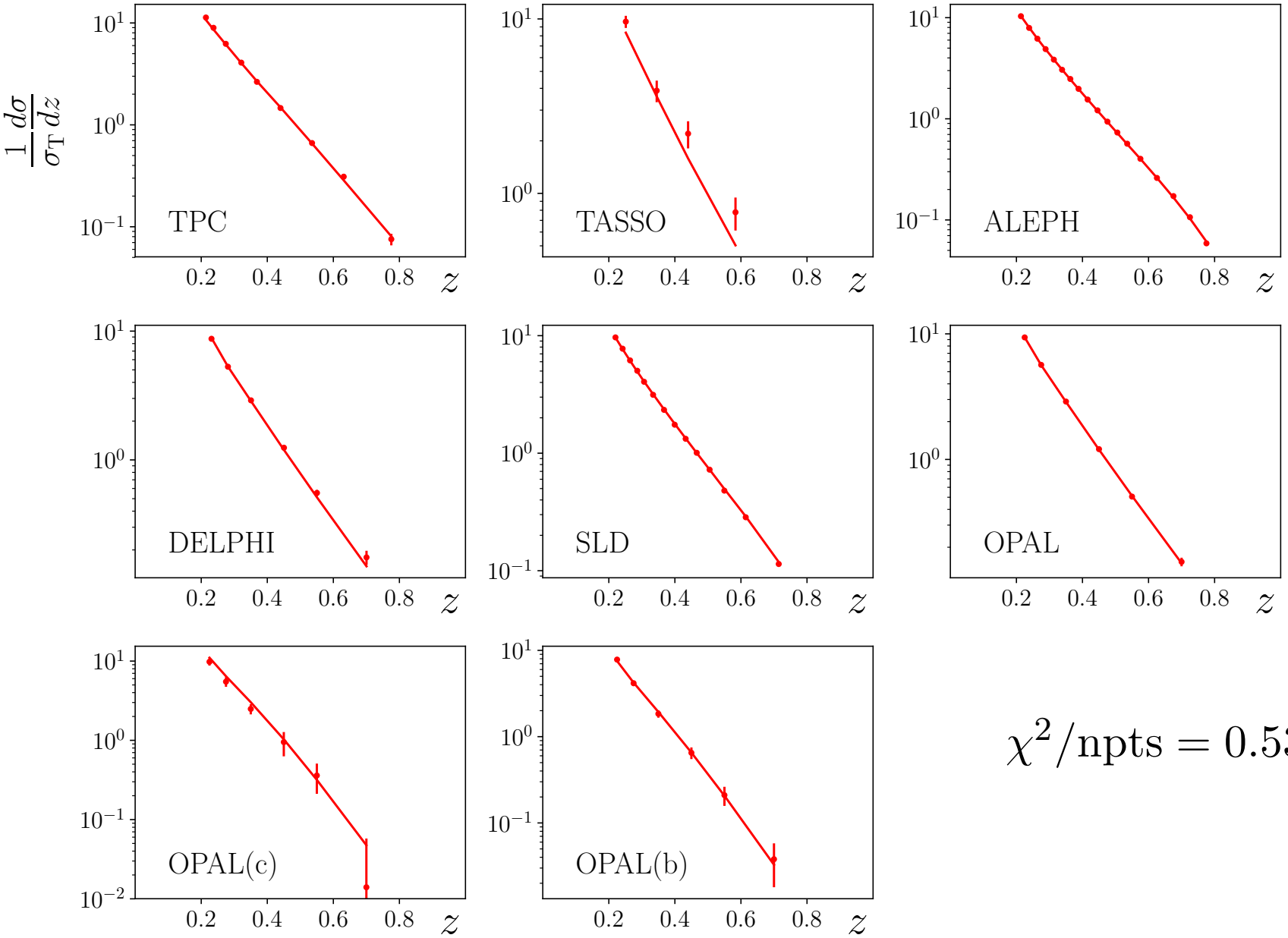
- Data sets:
  - SIDIS(h^+, h^-) q_{T} integrated data from COMPASS
  - $e^+e^- \to h^\pm + X$ (work with the $0.2 < z < 0.8$ samples)
  - PDFs: JAM18

Revisiting charged hadron FFs (in JAM)



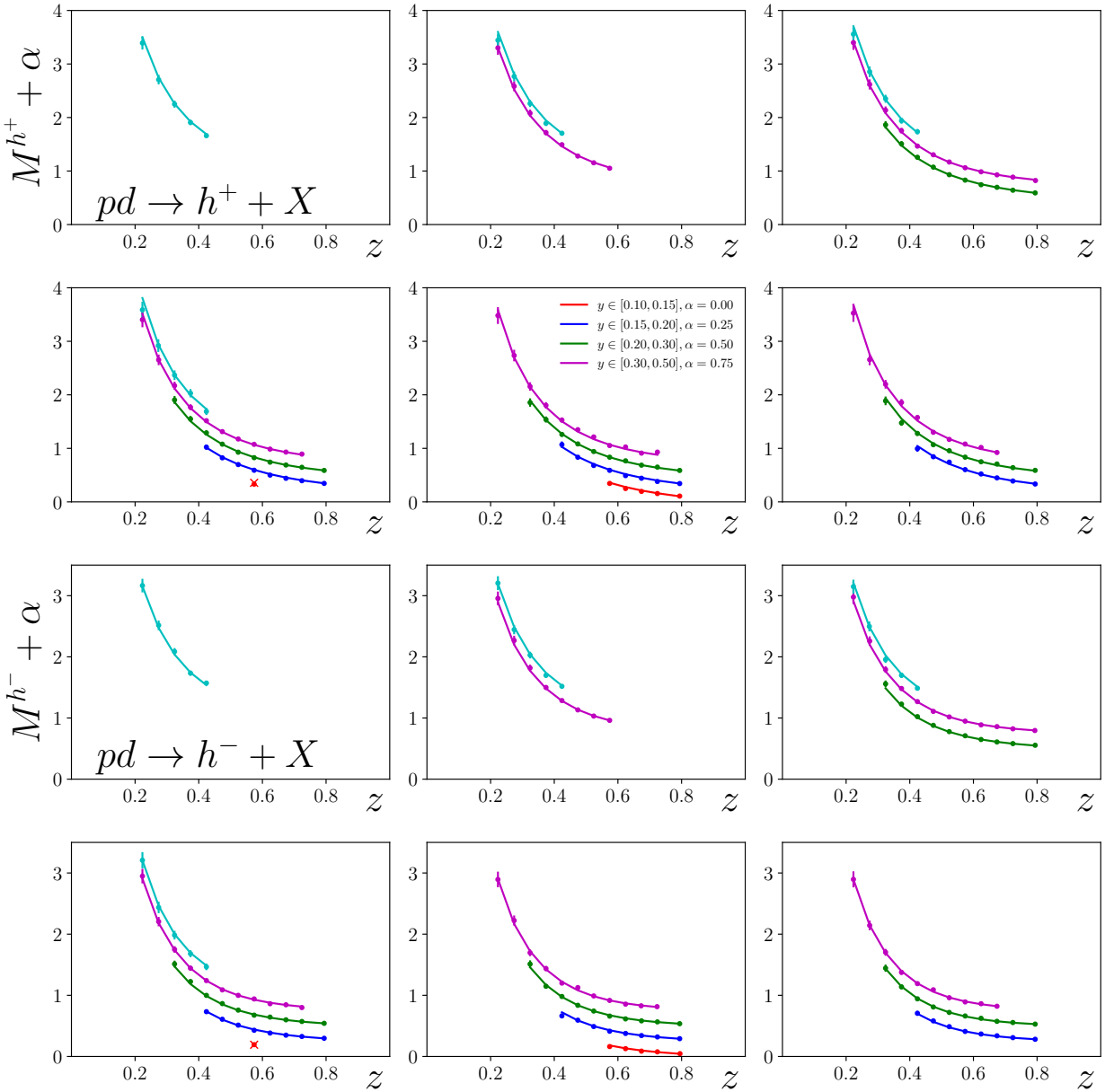
- The gluon fragmentation is significantly different $\rightarrow$ recently observed by the NNPDF

Revisiting charged hadron FFs (in JAM)



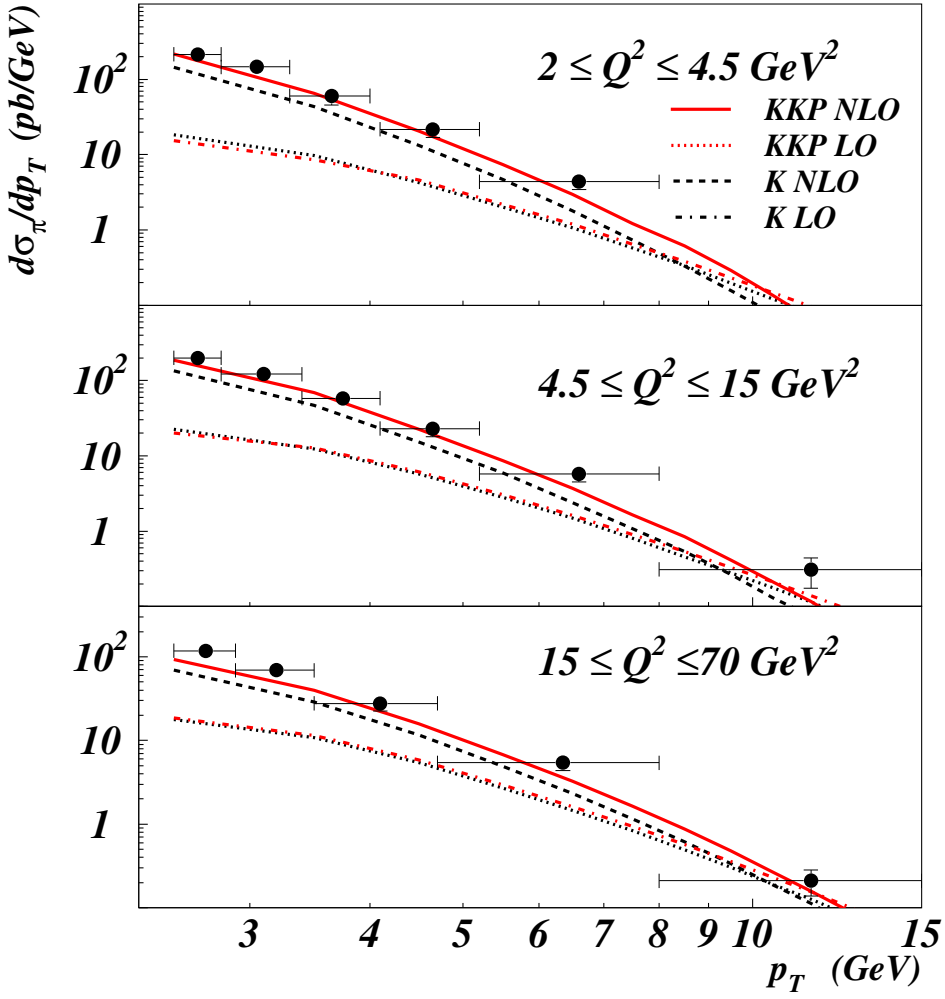
$$\chi^2/\text{npts} = 0.53$$

Revisiting charged hadron FFs (in JAM)



$\chi^2/\text{npts} = 0.48$

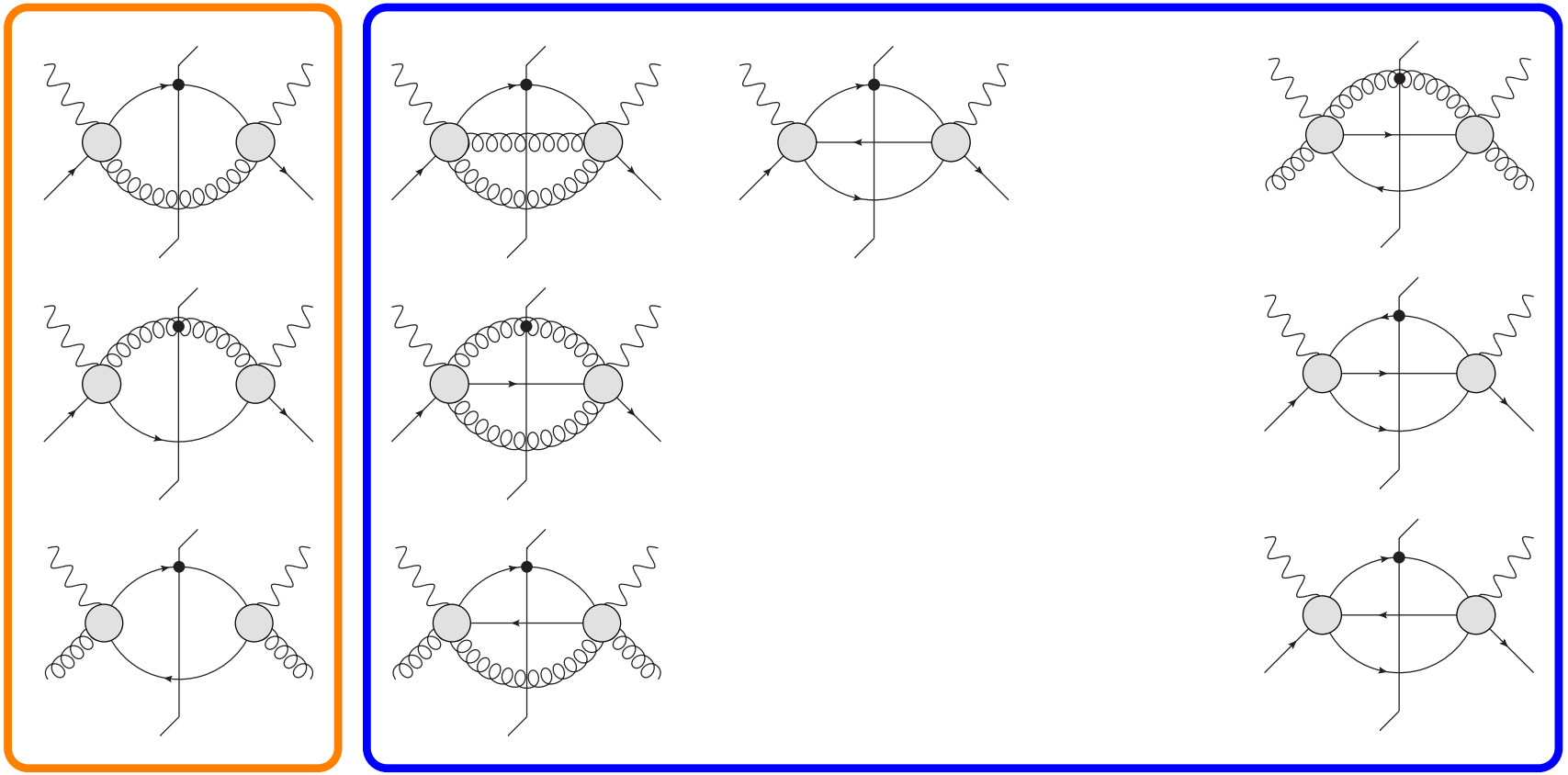
order α_S^2 corrections to FO



- There are strong indications that order α_S^2 corrections are very important
- An order of magnitude of corrections at small p_T.
- As a sanity check, we need to have an independent calculation

Daleo,et al. (2005)
PRD.71.034013

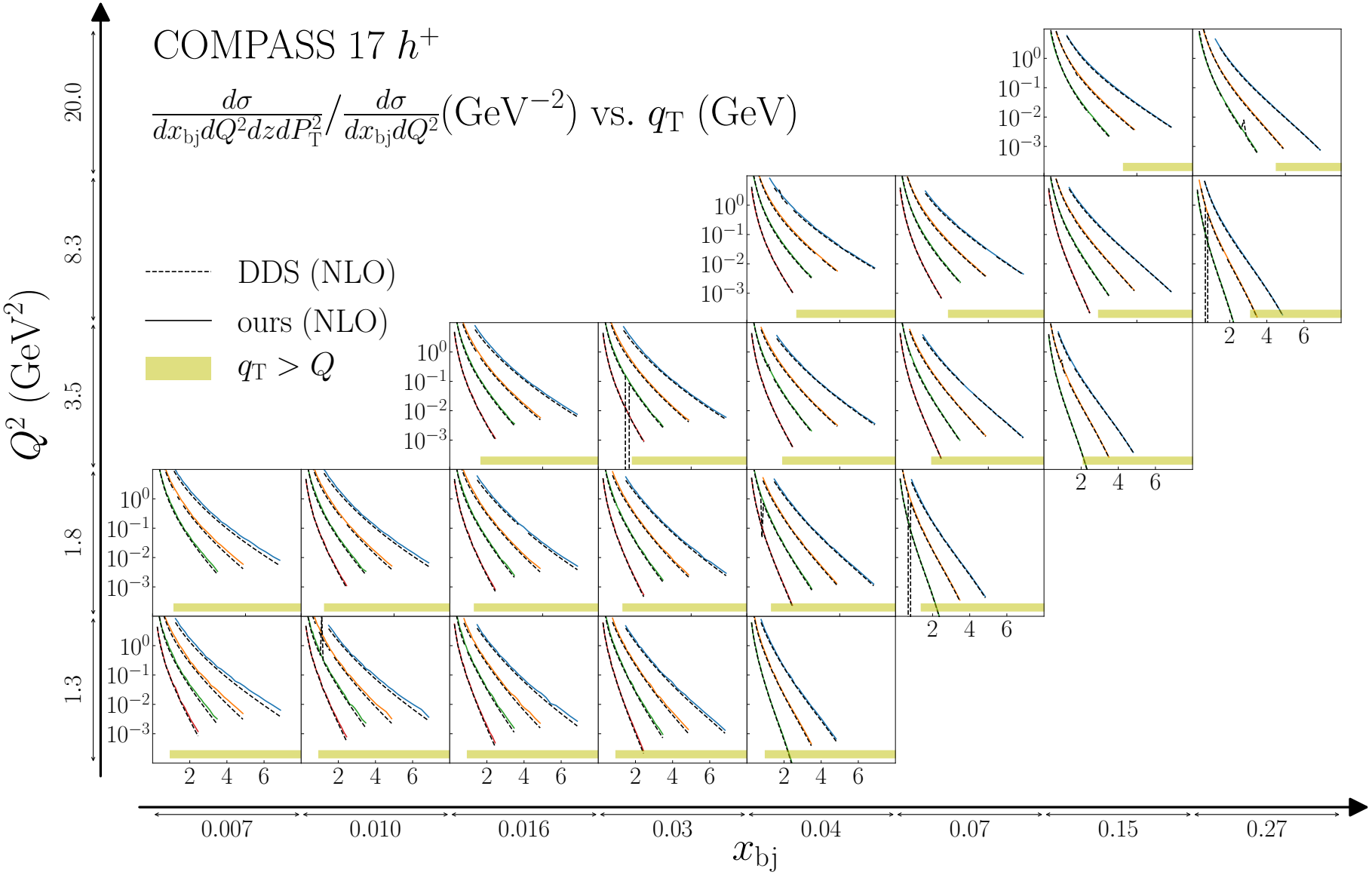
order α_S^2 corrections to FO



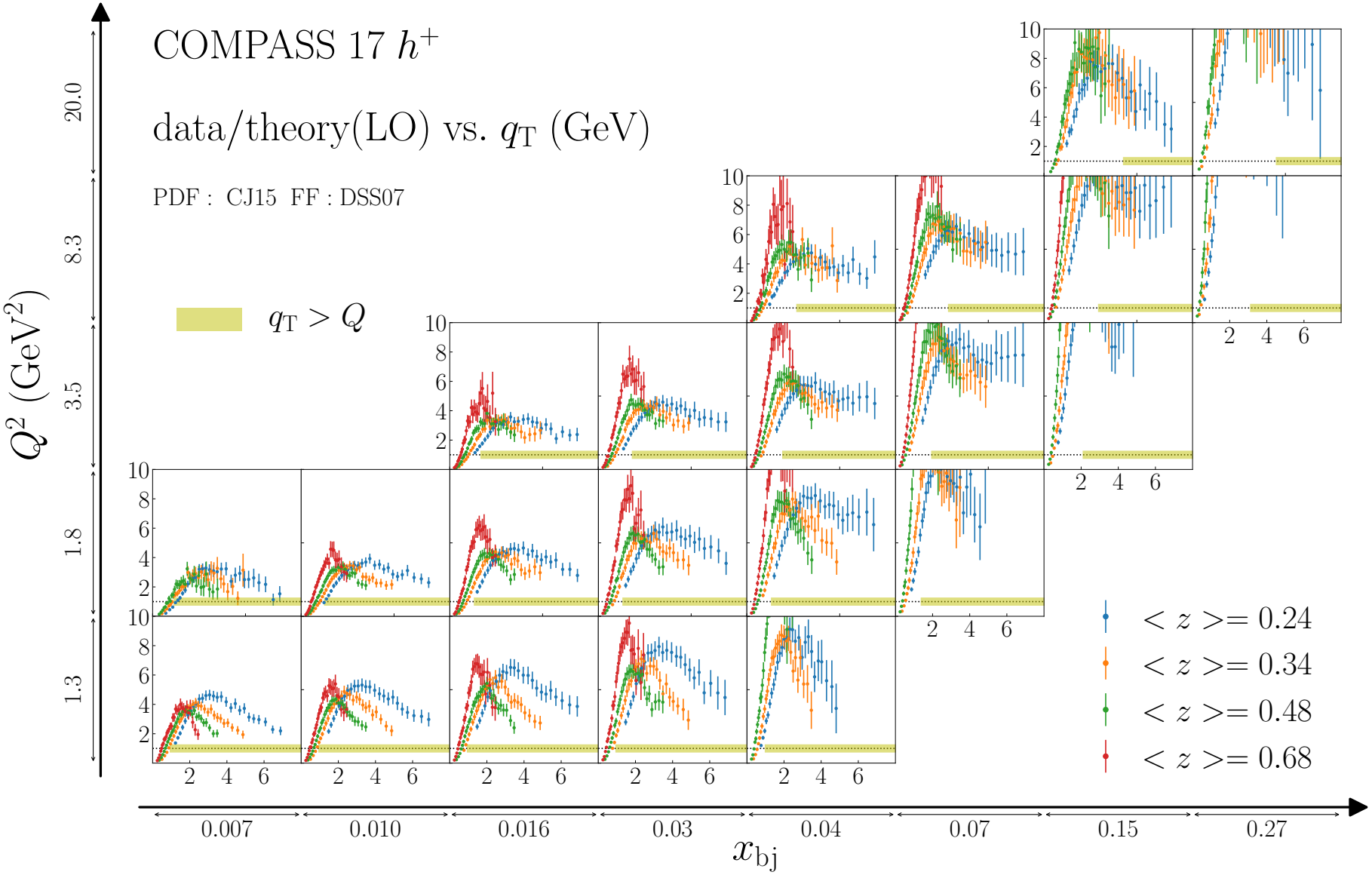
Born/Virtual Real

- ✓ Compute $2 \to 2$ virtual graphs (Passarino-Veltman)
- ✓ Compute $2 \to 3$ real graphs (analytic integration)
- ✓ Cancel double and single IR poles

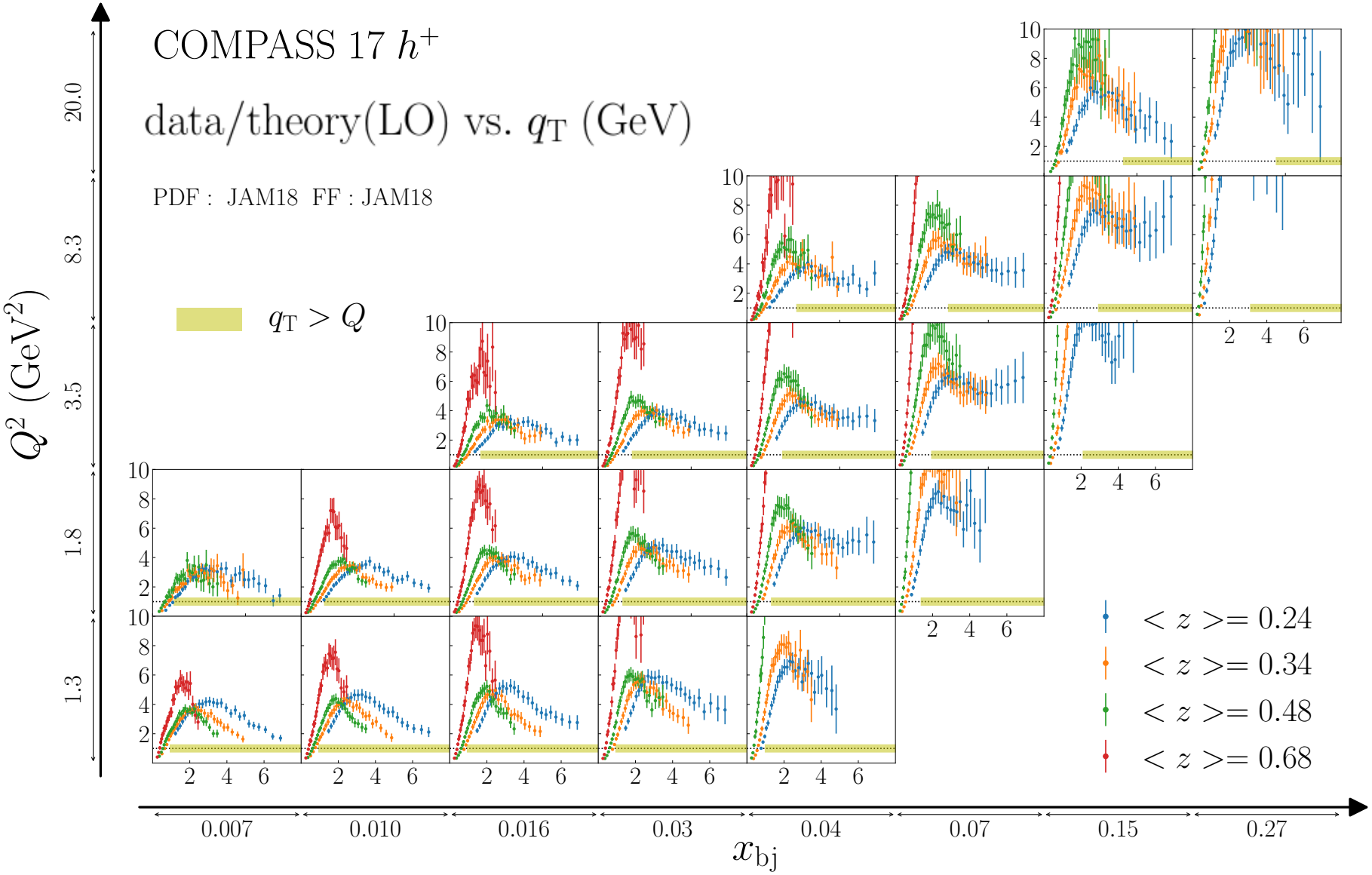
FO @ NLO benchmark



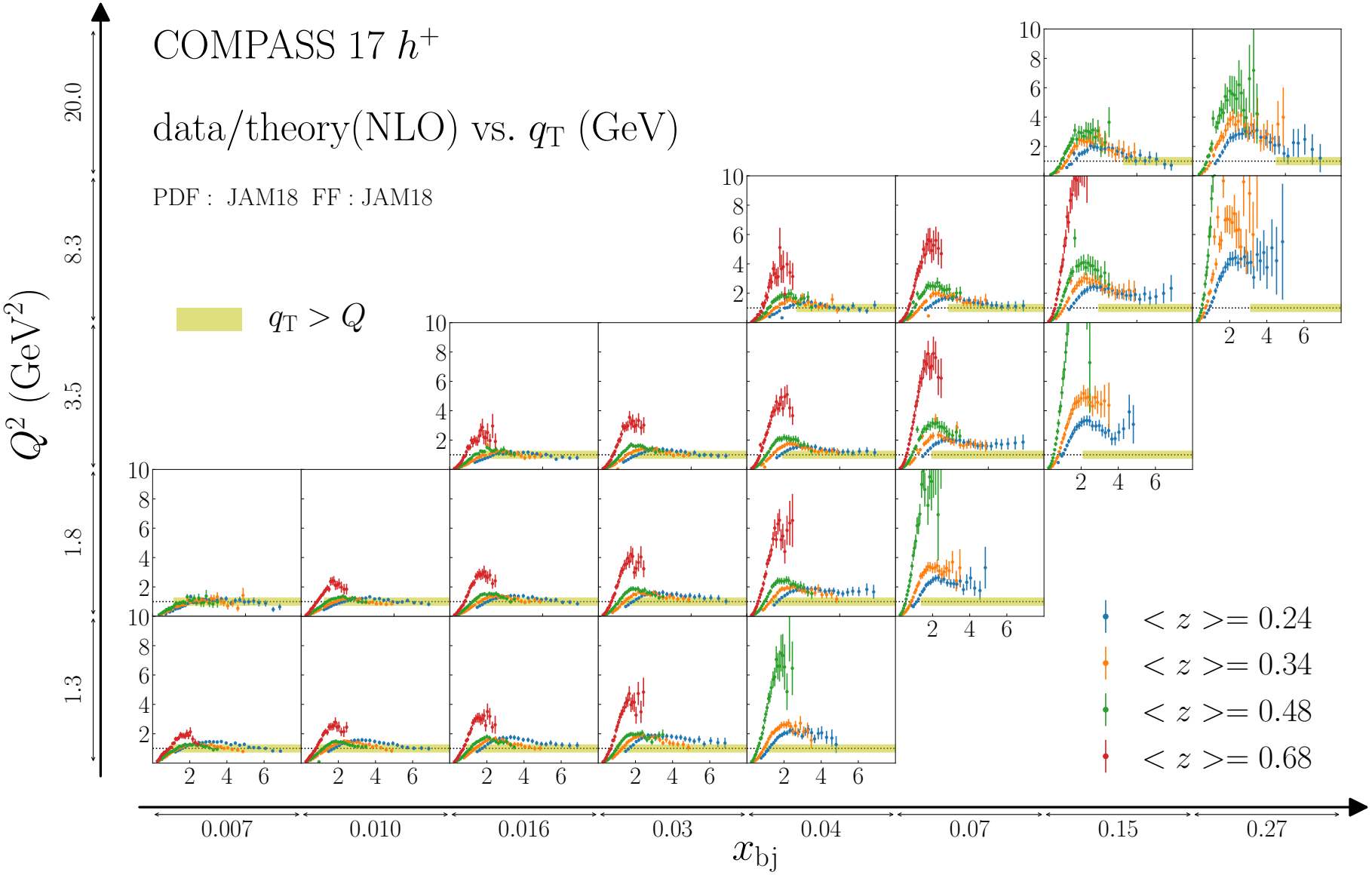
FO @ LO predictions (DSS07)



FO @ LO predictions (JAM18)



FO @ NLO (JAM18 FFs)



Summary and outlook

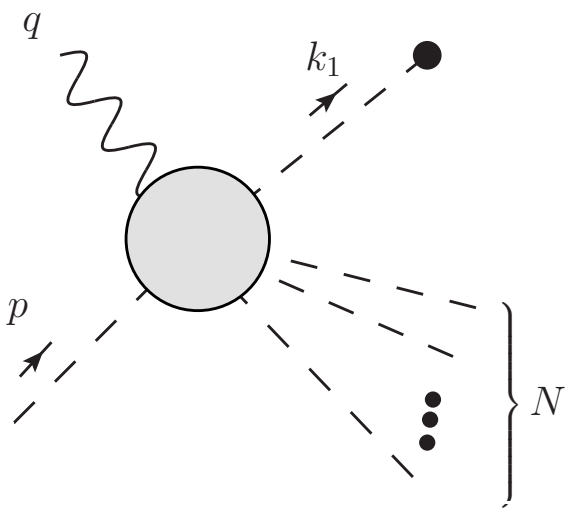
$$\frac{d\sigma}{dx\ dy\ d\Psi\ dz\ d\phi_h\ dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sum_{i=1}^{18} F_i(x,z,Q^2,P_{hT}^2)\beta_i$$

F_i	Standard label	β_i
F_1	$F_{UU,T}$	1
F_2	$F_{UU,L}$	ε
F_3	F_{LL}	$S_{\|\|}\lambda_e\sqrt{1-\varepsilon^2}$
F_4	$F_{UT}^{\sin(\phi_h+\phi_S)}$	$\|\vec{S}_\perp\|\varepsilon\sin(\phi_h+\phi_S)$
F_5	$F_{UT,T}^{\sin(\phi_h-\phi_S)}$	$\|\vec{S}_\perp\|\sin(\phi_h-\phi_S)$
F_6	$F_{UT,L}^{\sin(\phi_h-\phi_S)}$	$\|\vec{S}_\perp\|\varepsilon\sin(\phi_h-\phi_S)$
F_7	$F_{UU}^{\cos 2\phi_h}$	$\varepsilon\ \cos(2\phi_h)$
F_8	$F_{UT}^{\sin(3\phi_h-\psi_S)}$	$\|\vec{S}_\perp\|\varepsilon\sin(3\phi_h-\phi_S)$
F_9	$F_{LT}^{\cos(\phi_h-\phi_S)}$	$\|\vec{S}_\perp\|\lambda_e\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)$
F_{10}	$F_{UL}^{\sin\ 2\phi_h}$	$S_{\|\|}\varepsilon\sin(2\phi_h)$
F_{11}	$F_{LT}^{\cos\phi_S}$	$\|\vec{S}_\perp\|\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S$
F_{12}	$F_{LL}^{\cos\phi_h}$	$S_{\|\|}\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h$
F_{13}	$F_{LT}^{\cos(2\phi_h-\phi_S)}$	$\|\vec{S}_\perp\|\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)$
F_{14}	$F_{UL}^{\sin\phi_h}$	$S_{\|\|}\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h$
F_{15}	$F_{LU}^{\sin\phi_h}$	$\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h$
F_{16}	$F_{UU}^{\cos\phi_h}$	$\sqrt{2\varepsilon(1+\varepsilon)}\ \cos\phi_h$
F_{17}	$F_{UT}^{\sin\phi_S}$	$\|\vec{S}_\perp\|\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S$
F_{18}	$F_{UT}^{\sin(2\phi_h-\phi_S)}$	$\|\vec{S}_\perp\|\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)$

- The apparent disagreement between data and FO can be resolved by tunning FFs+NLO
- Maybe it might be possibility to describe F_{UU} in the full W + FO − ASY
- This is important as all the structure functions that are typically provided in a form of asymmetries $A_i = F_i/F_{UU}$

backup

Why $q_{\rm T}/Q$? (J. Gonzalez-Hernandes, T.C Rogers, NS, B. Wang)



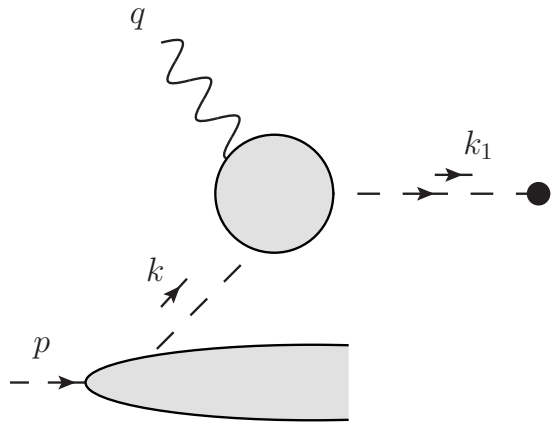
- Lets define

$$k \equiv k_1 - q$$

- Propagators in the blob

$$\frac{1}{k^2 + O(\Lambda^2_{\rm QCD})}, \qquad \frac{1}{k^2 + O(Q^2)}$$

- Two extreme regions
  - $|k^2| \sim \Lambda^2_{\rm QCD} \to k$ is part of PDF
  - $|k^2| \sim Q^2 \to k$ is part of hard blob



- $|k^2|/Q^2$ is the relevant Lorentz invariant measure of transverse momentum size

Why q_{T}/Q ? (J. Gonzalez-Hernandes, T.C Rogers, NS, B. Wang)

- In terms of partonic variables

$$\left|\frac{k^2}{Q^2}\right| = (1-\hat{z}) + \hat{z}\frac{q_{\mathrm{T}}^2}{Q^2}$$

- For $q_T < Q$ one can write

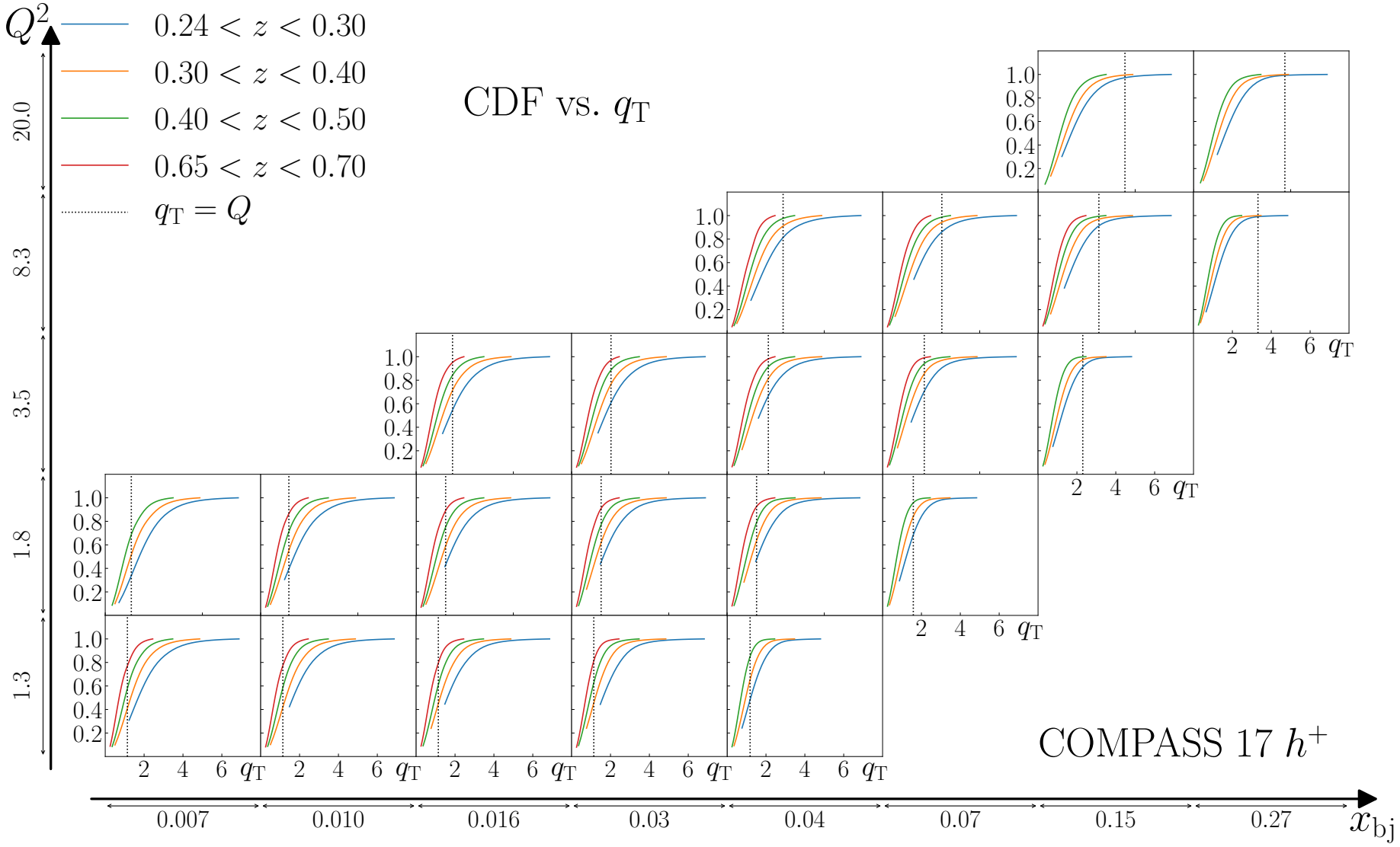
$$\frac{q_{\mathrm{T}}^2}{Q^2} < \left|\frac{k^2}{Q^2}\right| < 1 - z\left(1 - \frac{q_{\mathrm{T}}^2}{Q^2}\right)$$

- One can conclude that
  - $q_{\mathrm{T}} \ll Q$ signals the onset of TMD region
  - $q_{\mathrm{T}} \sim Q$ signals the large transverse momentum region

Question

- How important is the P_{T} tail for the integrated SIDIS multiplicities?

- Consider the cumulative distribution function (CDF)

$$\mathrm{CDF} = \int_0^{P_{\mathrm{T}}^2} dP_{\mathrm{T}}^2 \frac{1}{M(x,z)} \frac{dM}{dP_{\mathrm{T}}^2}(x,z,P_{\mathrm{T}}^2)$$

From q_{T} differential to q_{T} integrated