Understanding the large transverse momentum spectrum in SIDIS

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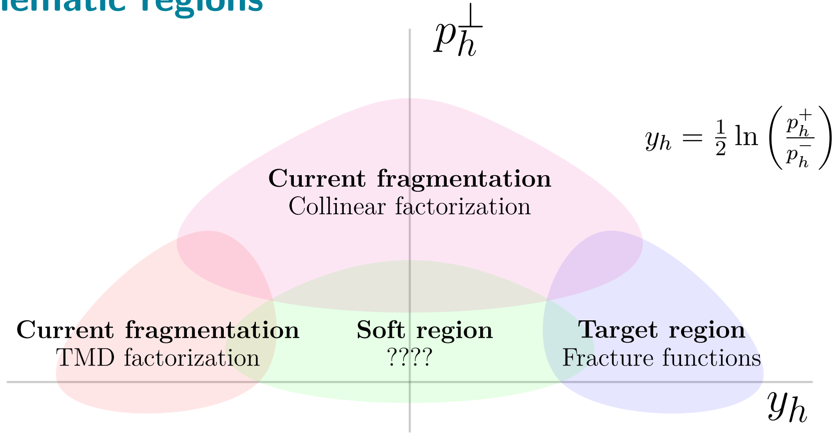
Jefferson Lab Angular Momentum Collaboration

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Kinematic regions of SIDIS

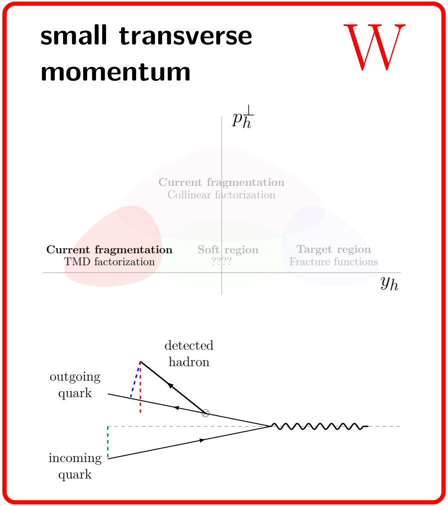
Kinematic regions

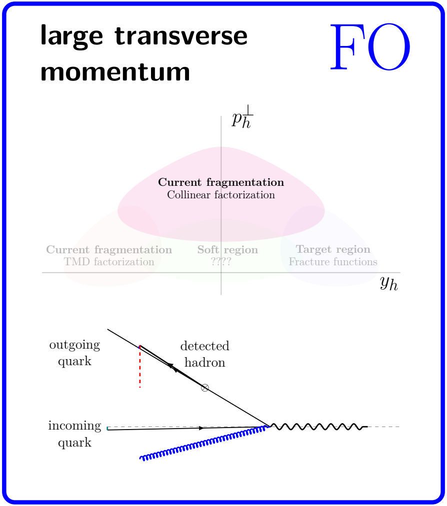


- **Different regions** are sensitive to distinct physical mechanisms

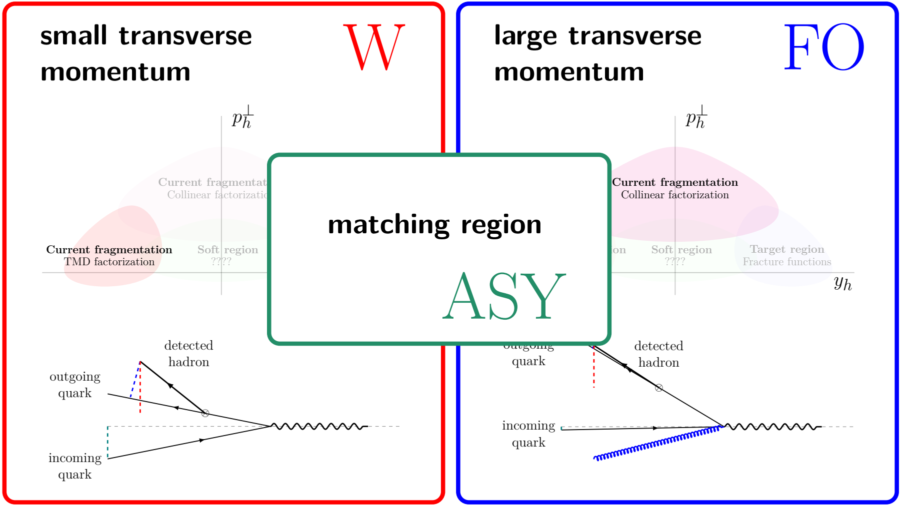
Theory of current fragmentation

Theory framework for current fragmentation





Theory framework for current fragmentation



Theory framework for current fragmentation

- The formulation of is based on a scale separation governed by the ratio

$$q_{\mathrm{T}}/Q$$

- where

$$z = \frac{P \cdot p_h}{P \cdot q}, \qquad q_{\mathrm{T}} = p_h^{\perp}/z$$

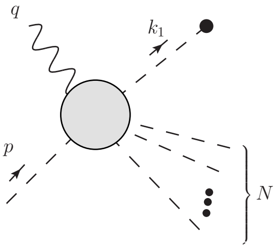
- The cross section is built as

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

$$\sim \mathrm{W} \quad \text{for } q_{\mathrm{T}} \ll Q$$

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

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



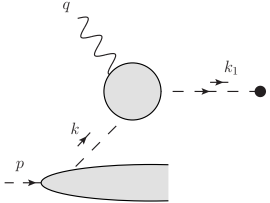
- Lets define

$$k \equiv k_1 - q$$

- Propagators in the blob

$$\frac{1}{k^2 + O(\Lambda_{\mathrm{QCD}}^2)}, \qquad \frac{1}{k^2 + O(Q^2)}$$

- Two extreme regions
  - $|k^2| \sim \Lambda_{\mathrm{QCD}}^2 \rightarrow k$ is part of PDF
  - $|k^2| \sim Q^2 \rightarrow k$ 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

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

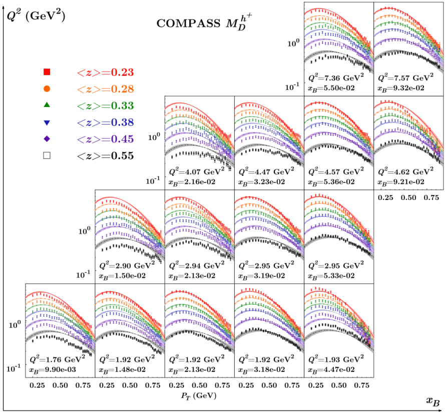
- For $q_T < Q$ one can write

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

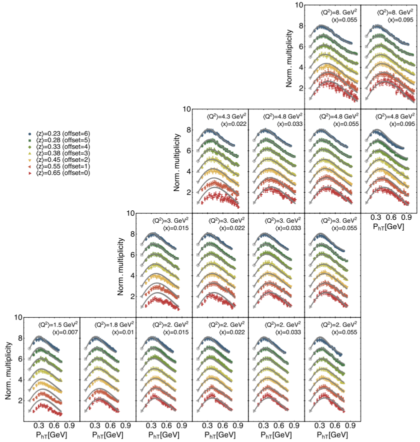
- One can conclude that
  - $q_{\mathrm{T}} \ll Q$ signals the onset of TMD region
  - $q_{\mathrm{T}} \sim Q$ signals the large transverse momentum region

Phenomenology

Existing phenomenology



Anselmino et al



Bacchetta et al

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

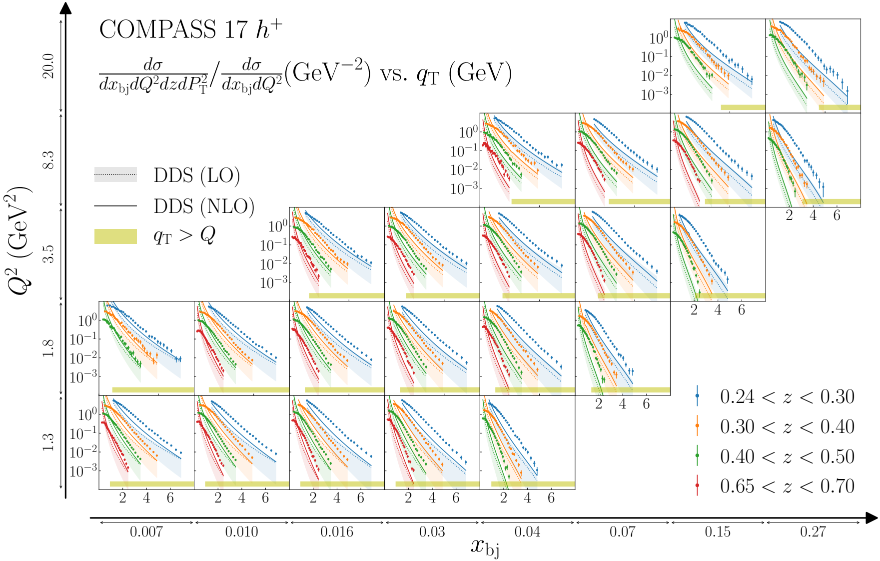
Large p_{T} SIDIS phenomenology

- At LO:

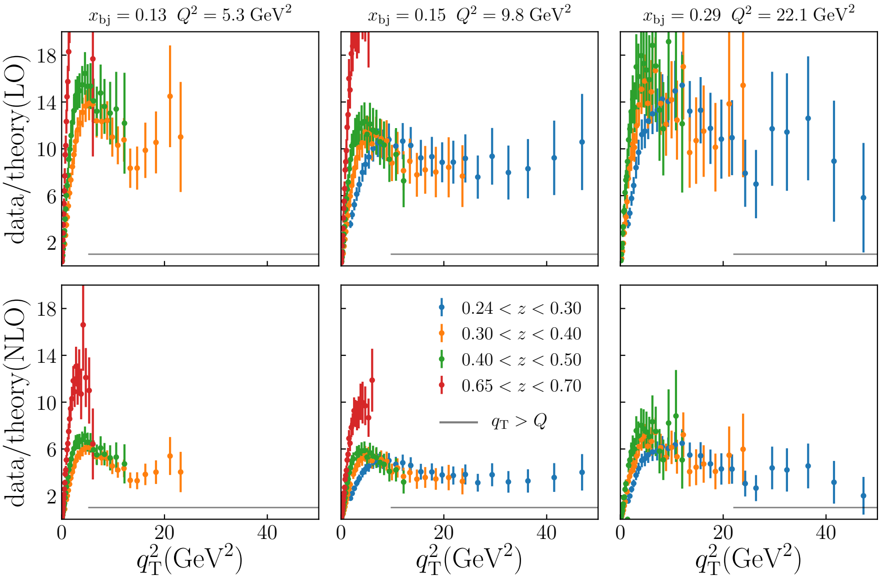
$$\frac{d\sigma}{dx dQ^2 dz dp_{\mathrm{T}}} \sim \sum_q e_q^2 \int_{\frac{q_{\mathrm{T}}^2}{Q^2}\frac{xz}{1-z}+x}^{1} \frac{d\xi}{\xi - x} f_q(\xi,\mu)\; d_q(\zeta(\xi),\mu)\; H(\xi)$$

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

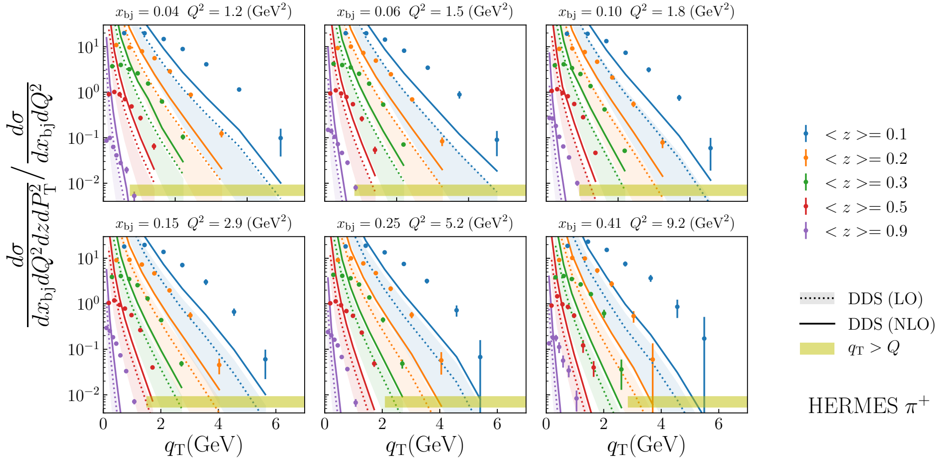
COMPASS: $l + d \to l' + h^+ + X$



COMPASS: $l + d \to l' + h^+ + X$



HERMES: $l + p \to l' + \pi^+ + X$



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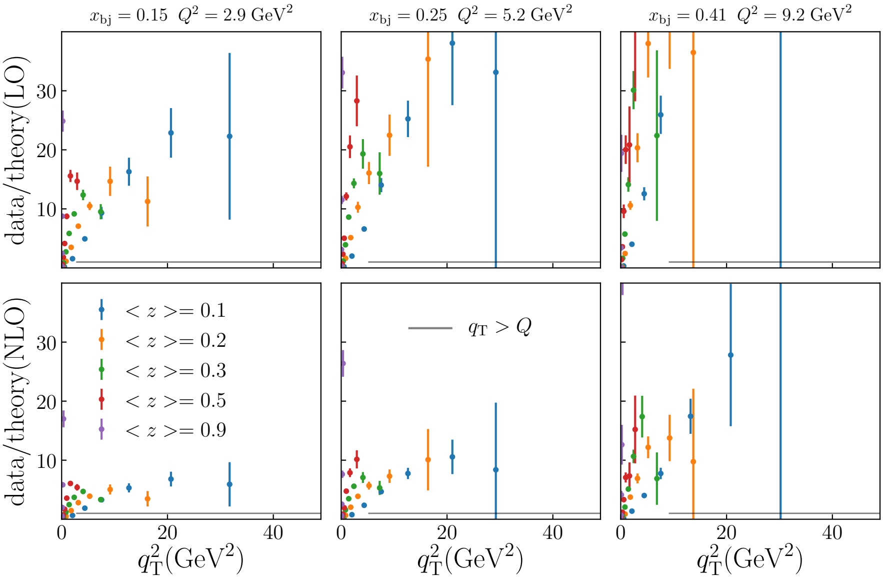
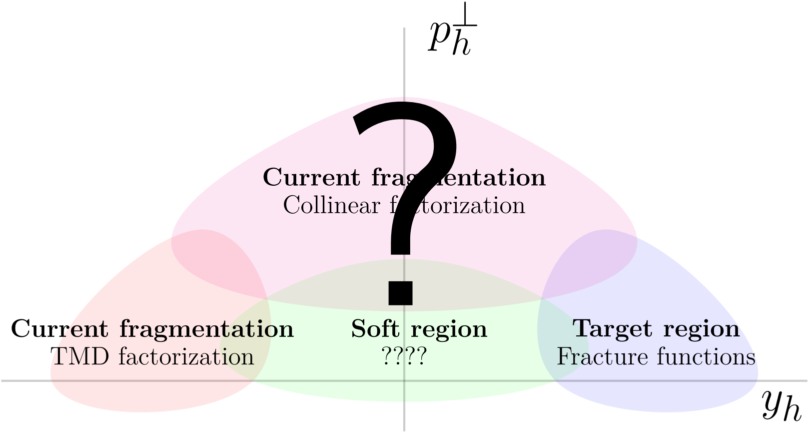


The large p_{T} puzzle



- What are we missing?
- **perturtative parts** : power corrections, threshold corrections
- **non-perturbative parts** : PDFs, FFs

The role of non perturbative input

- For p_{T} integrated @ LO:

$$\frac{d\sigma}{dxdQ^2dz} \sim \sum_q e_q^2 f_q(x,\mu)\ d_q(z,\mu)$$

- For p_{T} differential @ LO:

$$\frac{d\sigma}{dxdQ^2dzdp_{\mathrm{T}}} \sim \sum_q e_q^2 \int_{\frac{q_{\mathrm{T}}^2}{Q^2}\frac{xz}{1-z}+x}^{1} \frac{d\xi}{\xi - x} f_q(\xi,\mu)\ d_q(\zeta(\xi),\mu)\ H(\xi)$$

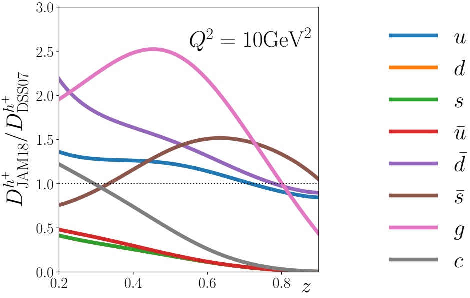
- Note:

- gluon PDFs/FFs **are involved** in p_{T} differential but not in the integrated case
- For p_{T} differential, the q_{T} factor in the integrand provides point-by-point in q_{T} constraints on PDF/FF
- The p_{T} spectrum is **very sensitive** to the shape of PDF/FF

Revisiting charged hadron FFs (in JAM)

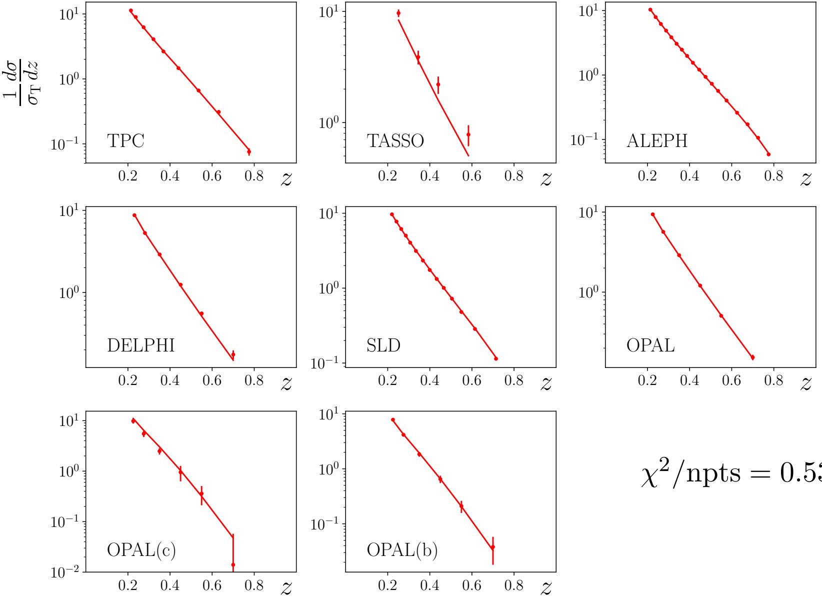
Revisiting charged hadron FFs (in JAM)

- 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 (see my talk at spin physics in nuclear reactions and nuclei)
- Extracted FFs:



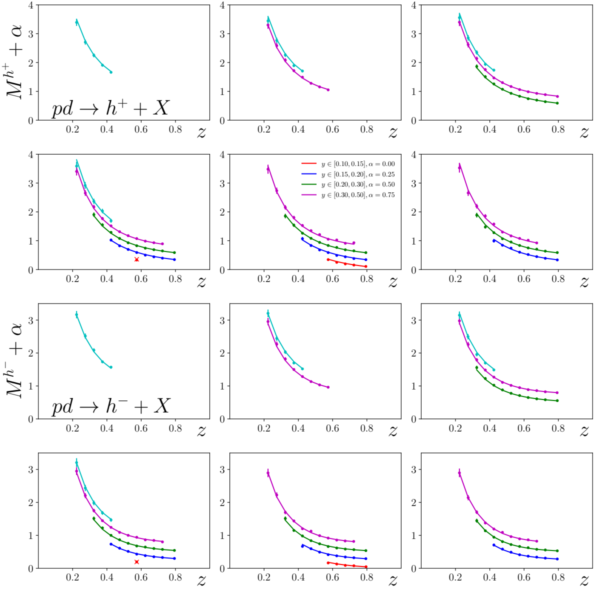
- The gluon fragmentation is significantly different $\to$ recently observed by the NNPDF

Revisiting charged hadron FFs (in JAM)



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

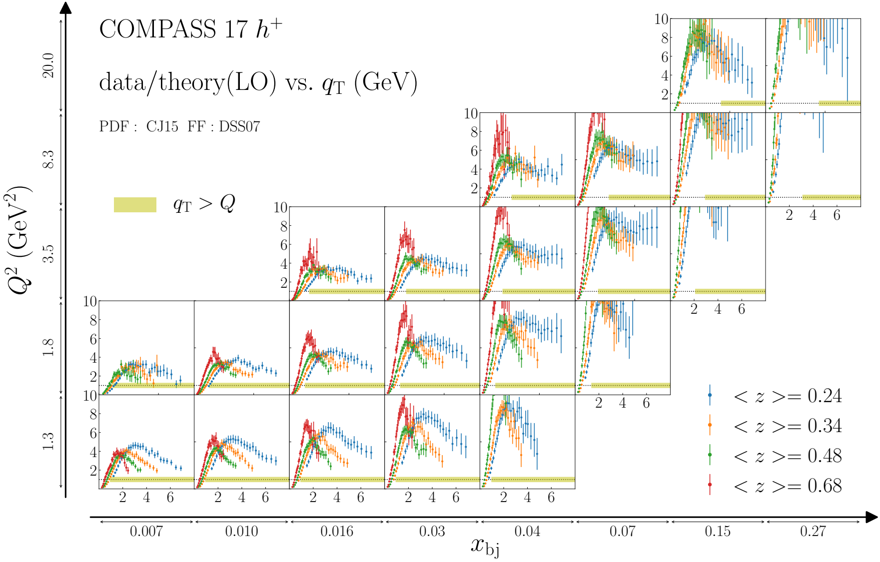
Revisiting charged hadron FFs (in JAM)



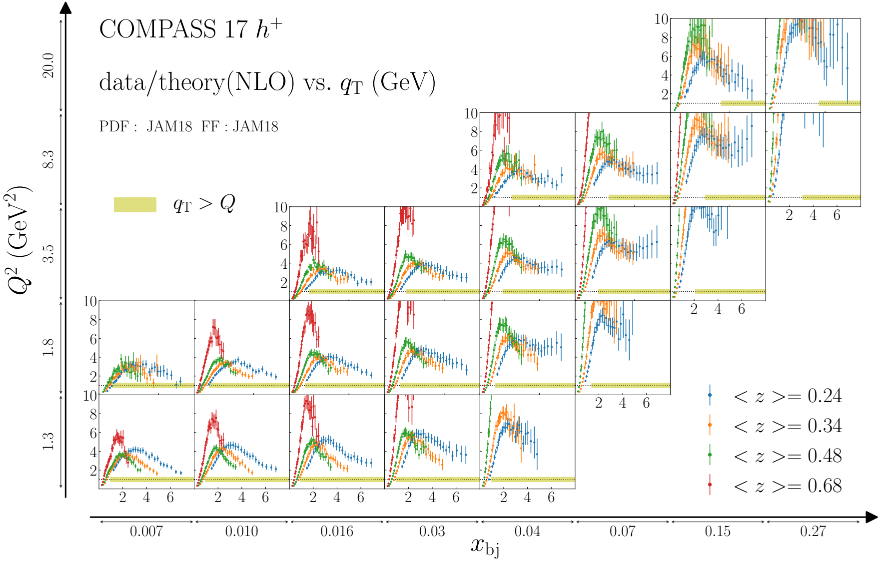
$$\chi^2/\text{npts} = 0.48$$

New predictions for the SIDIS q_{T} spectrum

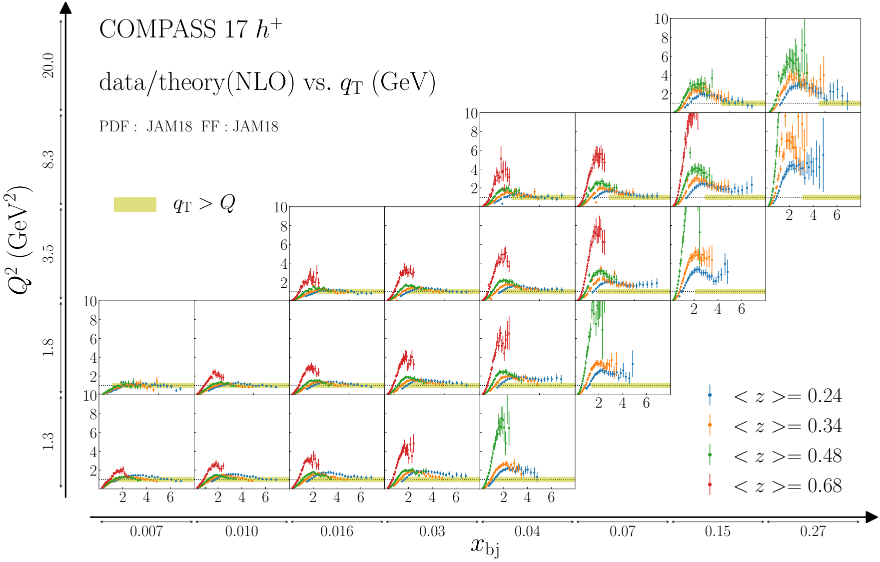
Old predictions (DSS07) @ LO



New predictions (JAM18) @ LO



New predictions (JAM18) @ NLO (DDS)



Lessons

- It is possible to restore the predictive power of pQCD for the SIDIS large p_{T} by retunning the FFs
- Conversely the large q_{T} SIDIS spectrum can be used constrain more accurately FFs in particular the gluon
- These results opens up the possibility to for the first time start the TMD phenomenology within the full $W + Y$

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
- It provides for the first time the possibility to describe F_{UU} in the full $\mathrm{W}+\mathrm{FO}-\mathrm{ASY}$
- This is important as all the structure functions that are typically provided in a form of asymmetries $A_i = F_i/F_{UU}$