SIDIS: challenges at low energies and opportunities at EIC

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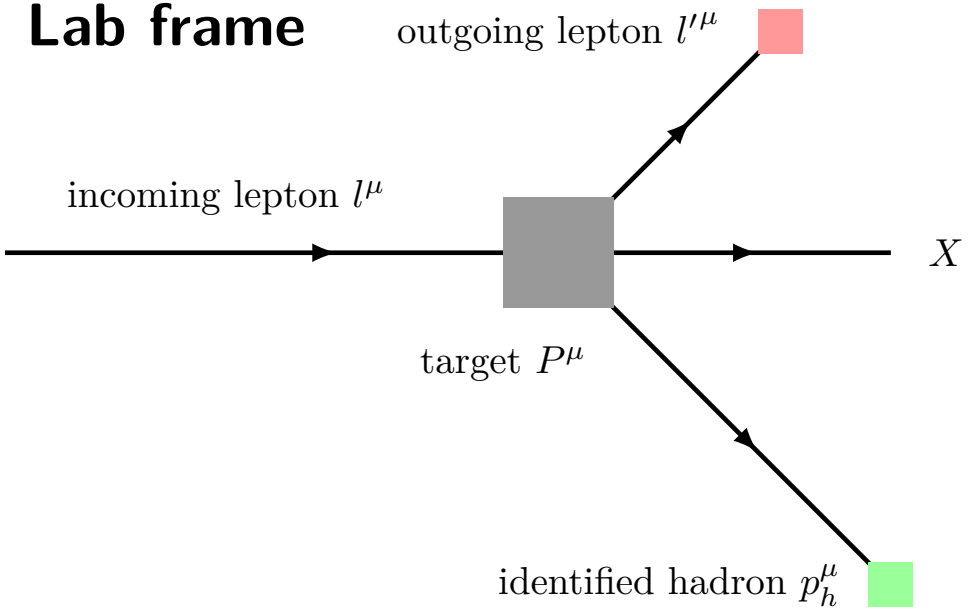
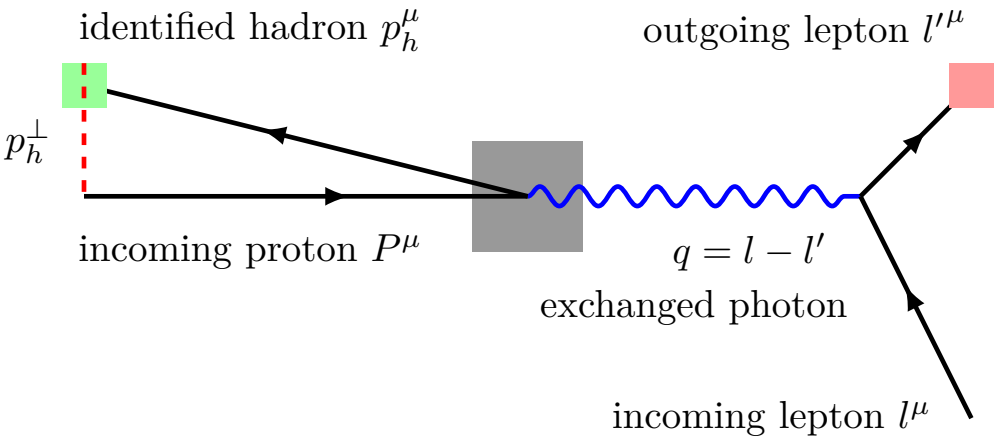
Semi inclusive deep inelastic scattering (SIDIS)

Lab frame



Breit frame



- Process is dominated by one photon exchange with large virtuality $Q^2 \gg \lambda_{\mathrm{QCD}}$
- **Key question** : How is $p_h^{\perp}$ generated at short distances?

Semi inclusive deep inelastic scattering (SIDIS)

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

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}	$F_{LT}^{\cos\phi_S}$	$\|\vec{S}_\perp\|\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S$
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F_{14}	$F_{UL}^{\sin\phi_h}$	$S_{\|\|}\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h$
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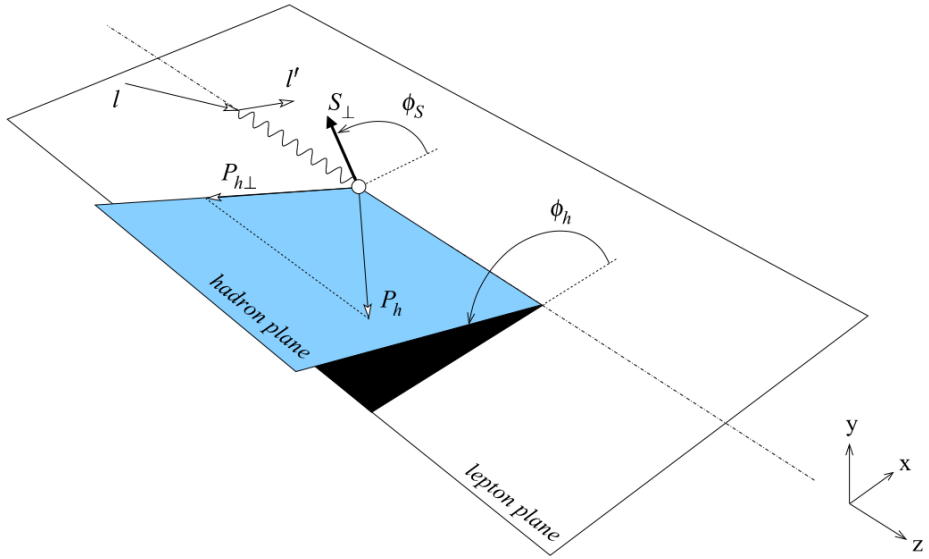
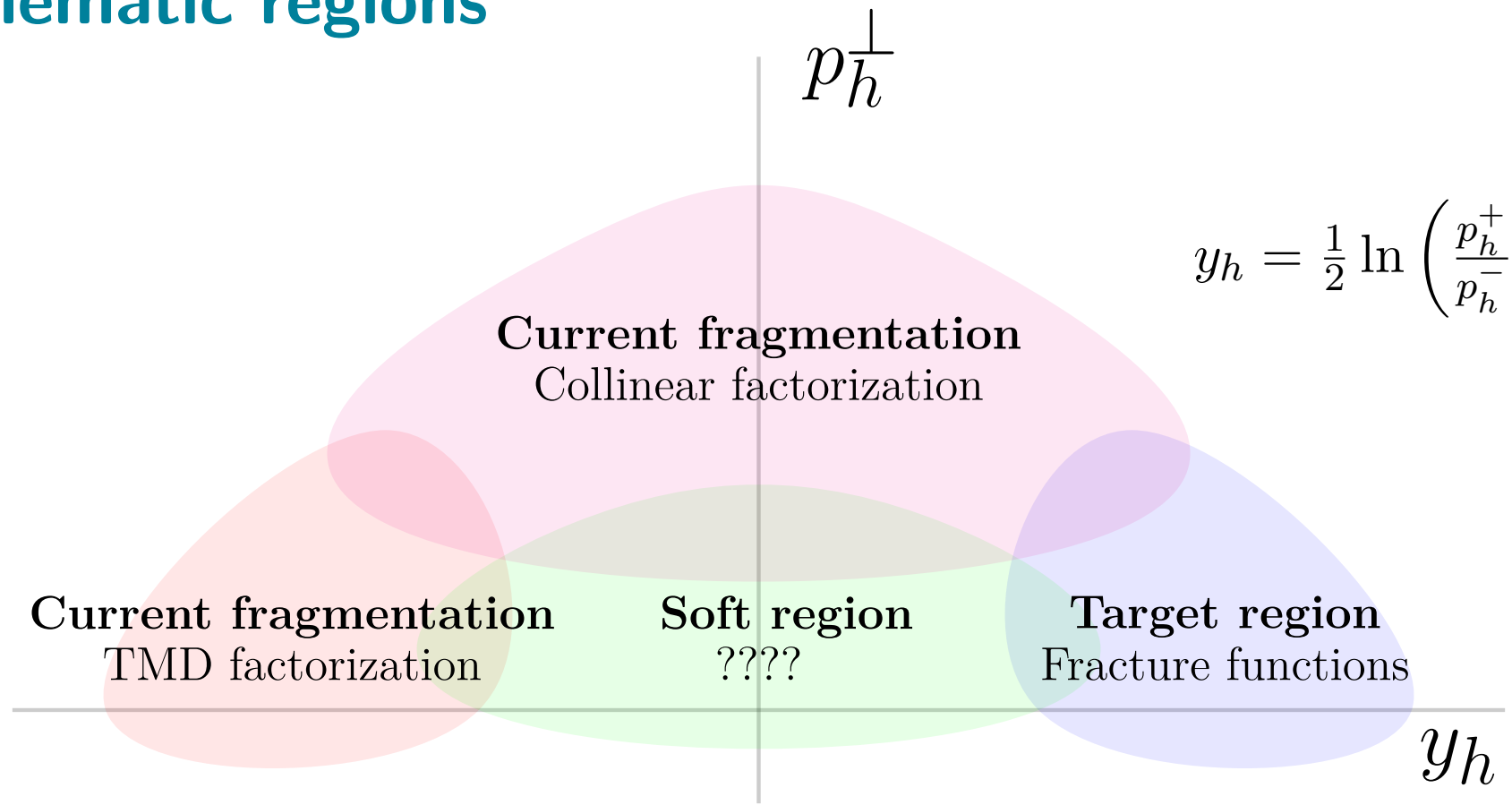


Bacchetta et al (2007)

Kinematic regions



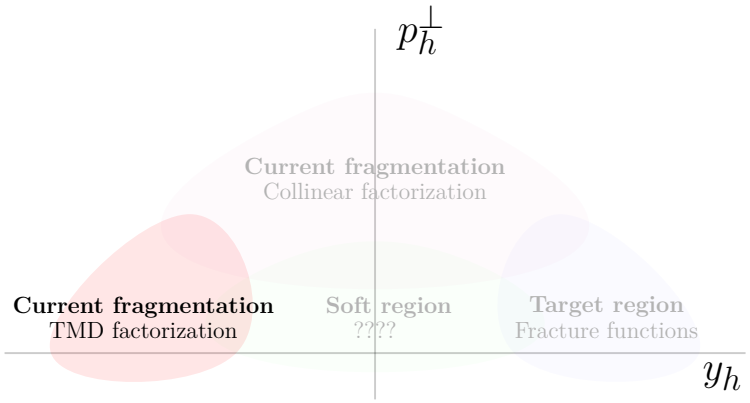
- Different regions are sensitive to distinct physical mechanisms
- They encodes different aspects of nucleon structure and hadronization
- The **challenge** is to have a solid understanding of all the regions

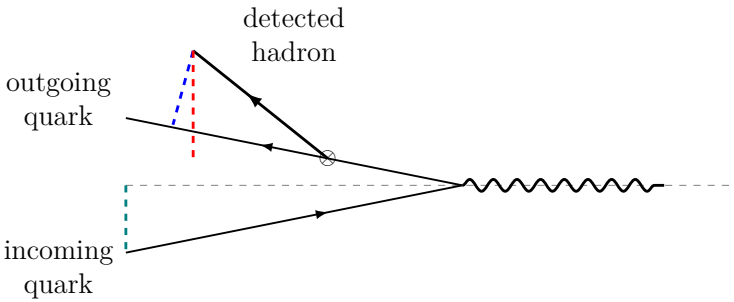
Theory framework for current fragmentation

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

small transverse momentum

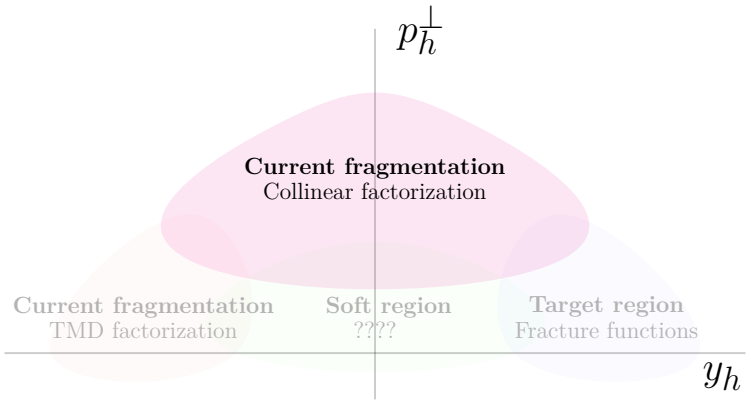
W

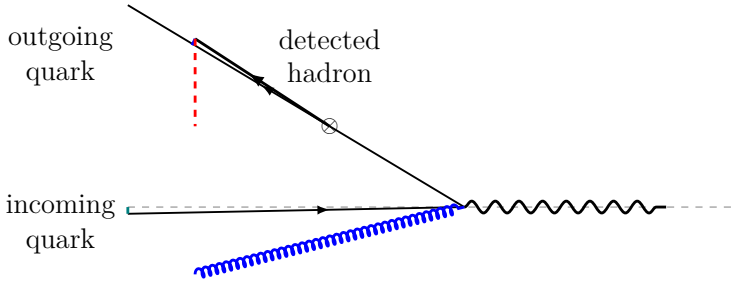




large transverse momentum

FO





What determines small or large transverse momentum ?

- The formulation of $\mathrm{W} + \mathrm{FO} - \mathrm{ASY}$ is based on a scale separation governed by the ratio

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

- It $q_{\mathrm{T}}/Q << 1$ then

$$\sigma \simeq \mathrm{W} \quad \mathrm{FO} - \mathrm{ASY} \simeq 0$$

- It $q_{\mathrm{T}}/Q \geq 1$ then

$$\sigma \simeq \mathrm{FO} \quad \mathrm{W} - \mathrm{ASY} \simeq 0$$

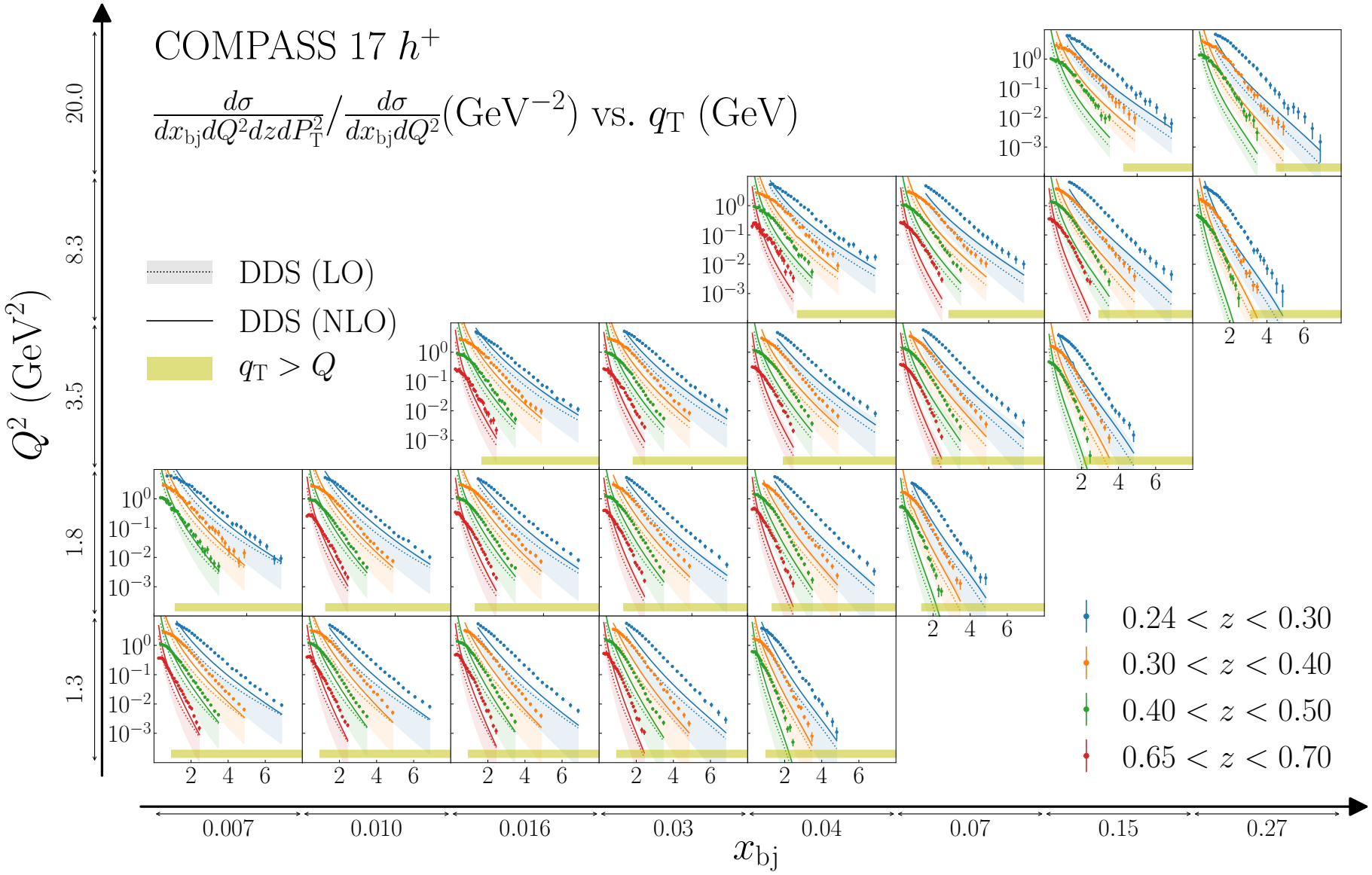
$$z = \frac{P \cdot p_h}{P \cdot q}$$

$$q_{\mathrm{T}} = p_h^{\perp}/z$$

Status of p_{T} dependent SIDIS phenomenology

- Most of p_{T} dependent SIDIS data has been studied using only $\mathrm{W} \rightarrow$ TMD distributions
- Little attention has been paid to incorporate FO in the analyzes
- FO is computed using collinear factorization with existing PDFs (CJ15) and FFs (DSS)

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



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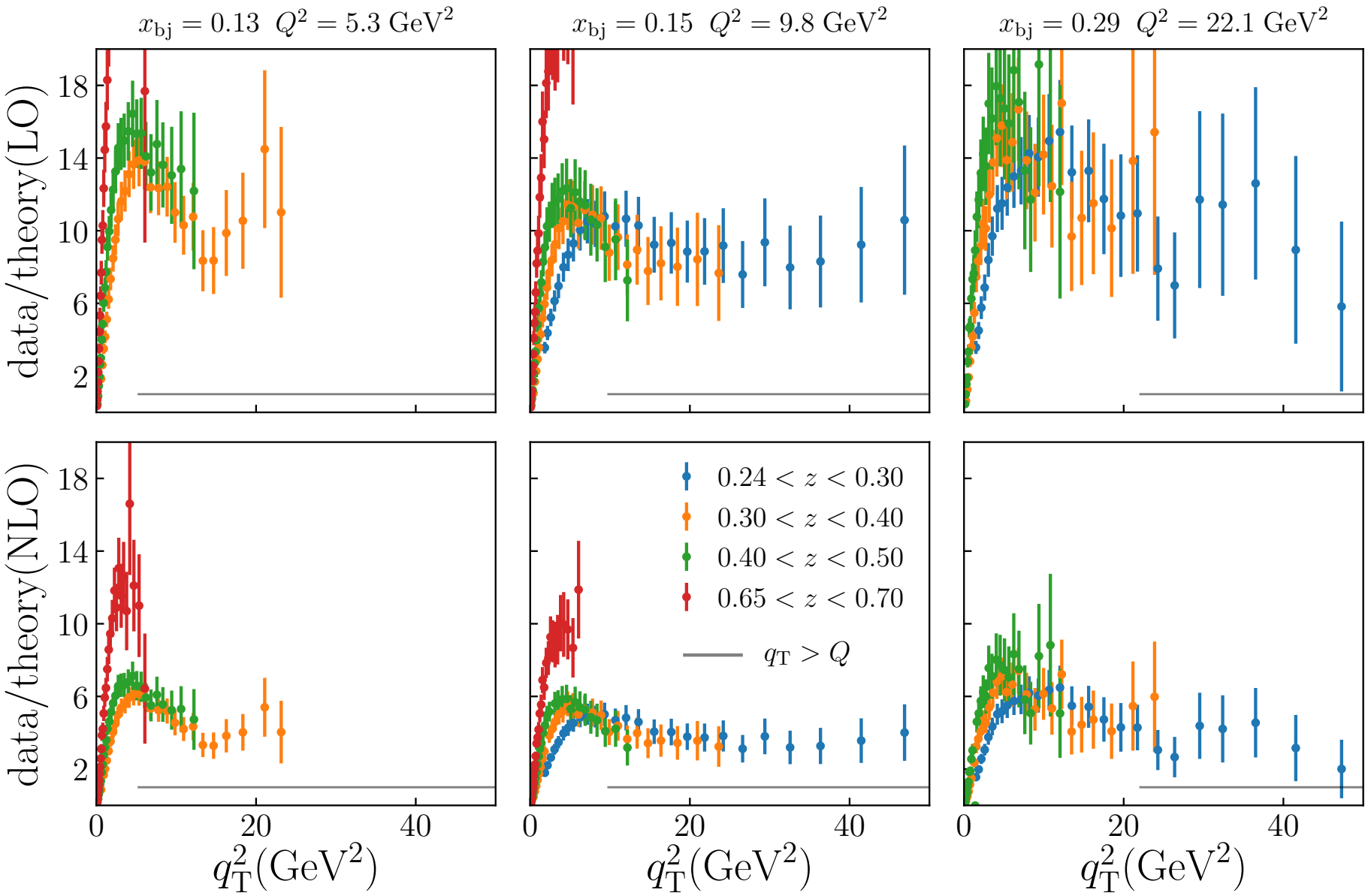
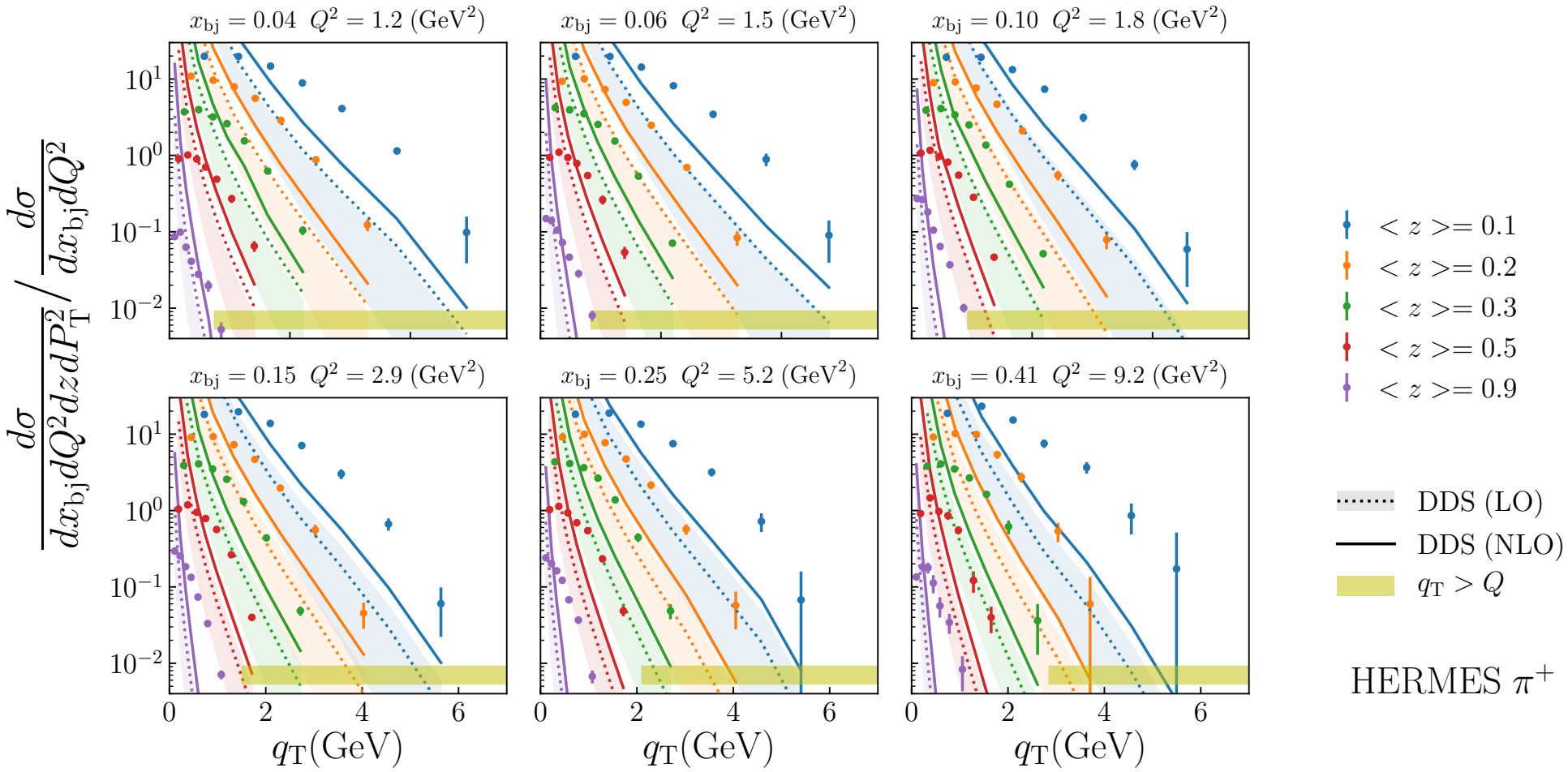


HERMES: $l + p \to l' + \pi^+ + X$



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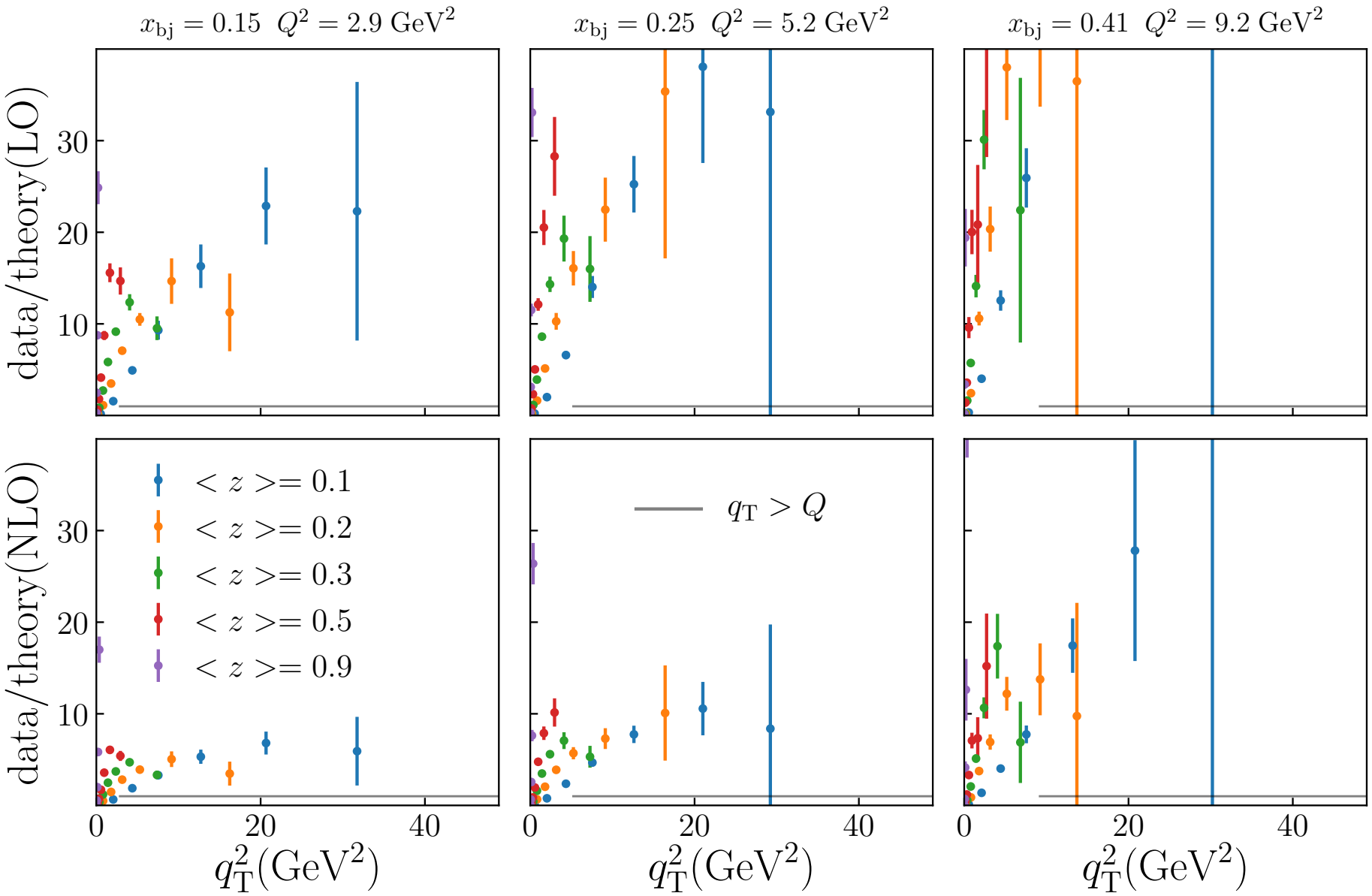
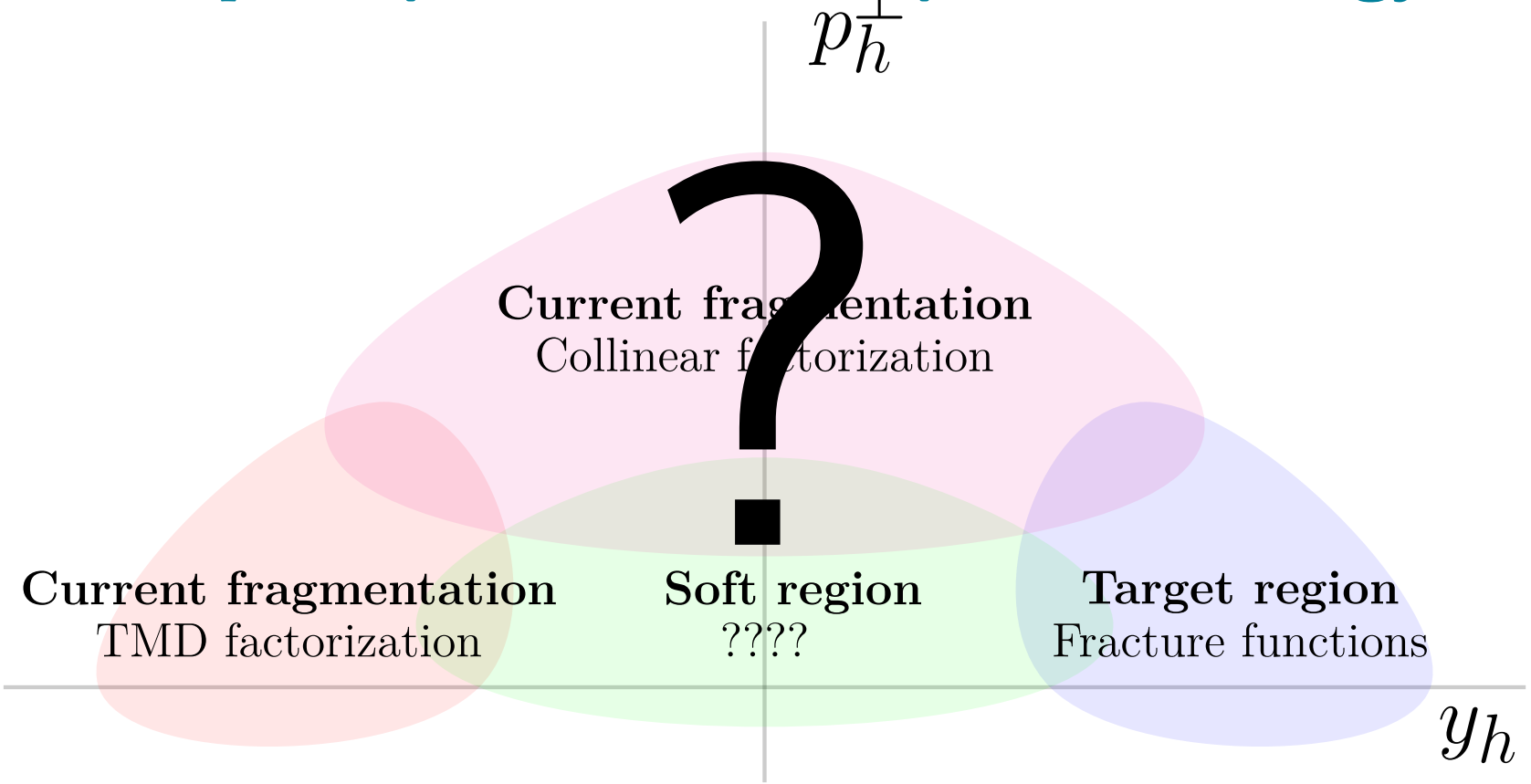


Status of p_{T} dependent SIDIS phenomenology



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

SIDIS in collinear factorization

- For p_{T} integrated @ LO:

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

- For p_{T} differential @ LO:

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

- 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
- Lets try a **global analysis** of PDF+FF using these data!

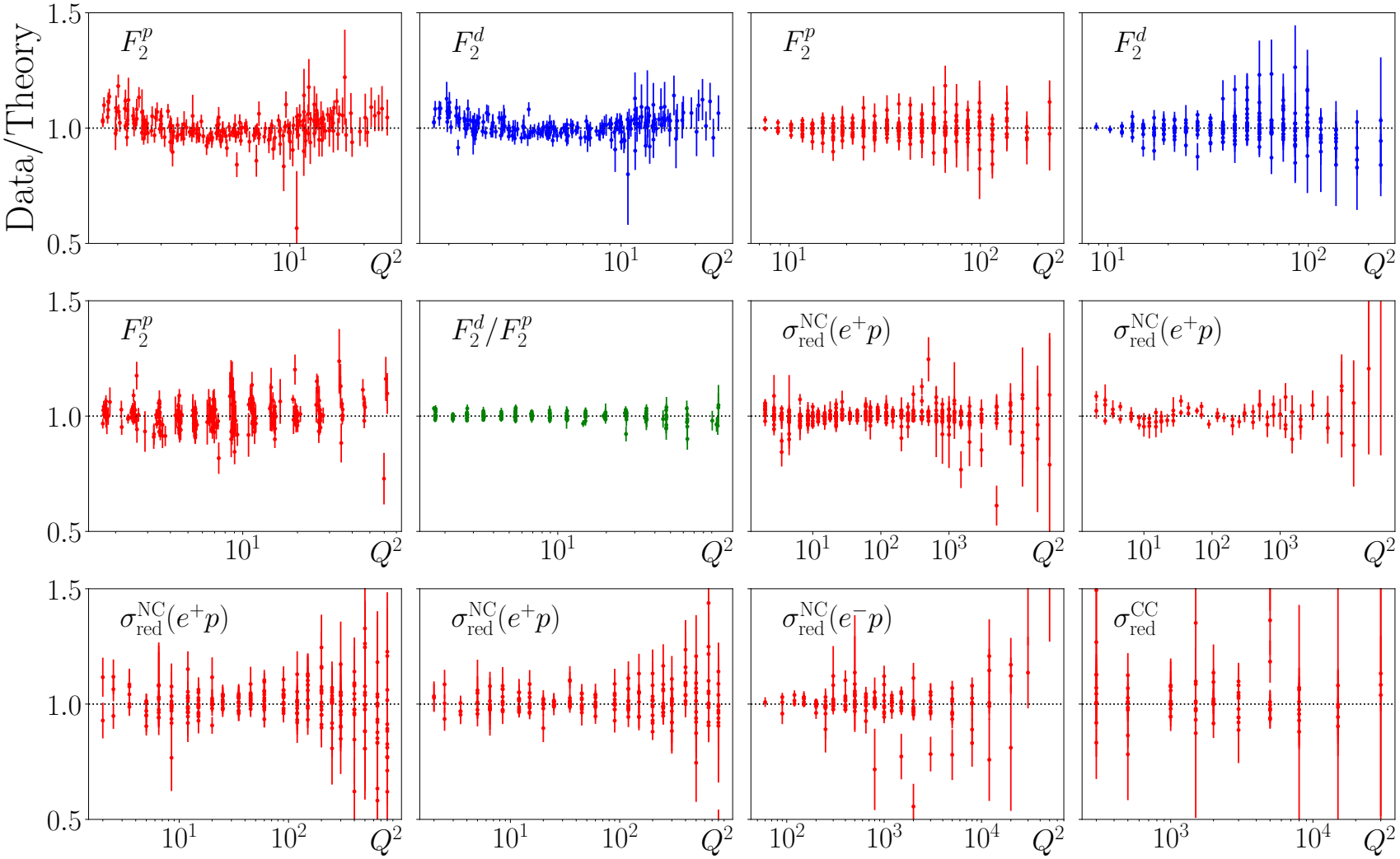
The global analysis I: the data sets

- constraints on PDFs
  - **DIS**: SLAC, BCDMS, NMC, HERA (NC, CC)
  - **DY**: E866 pp, pd

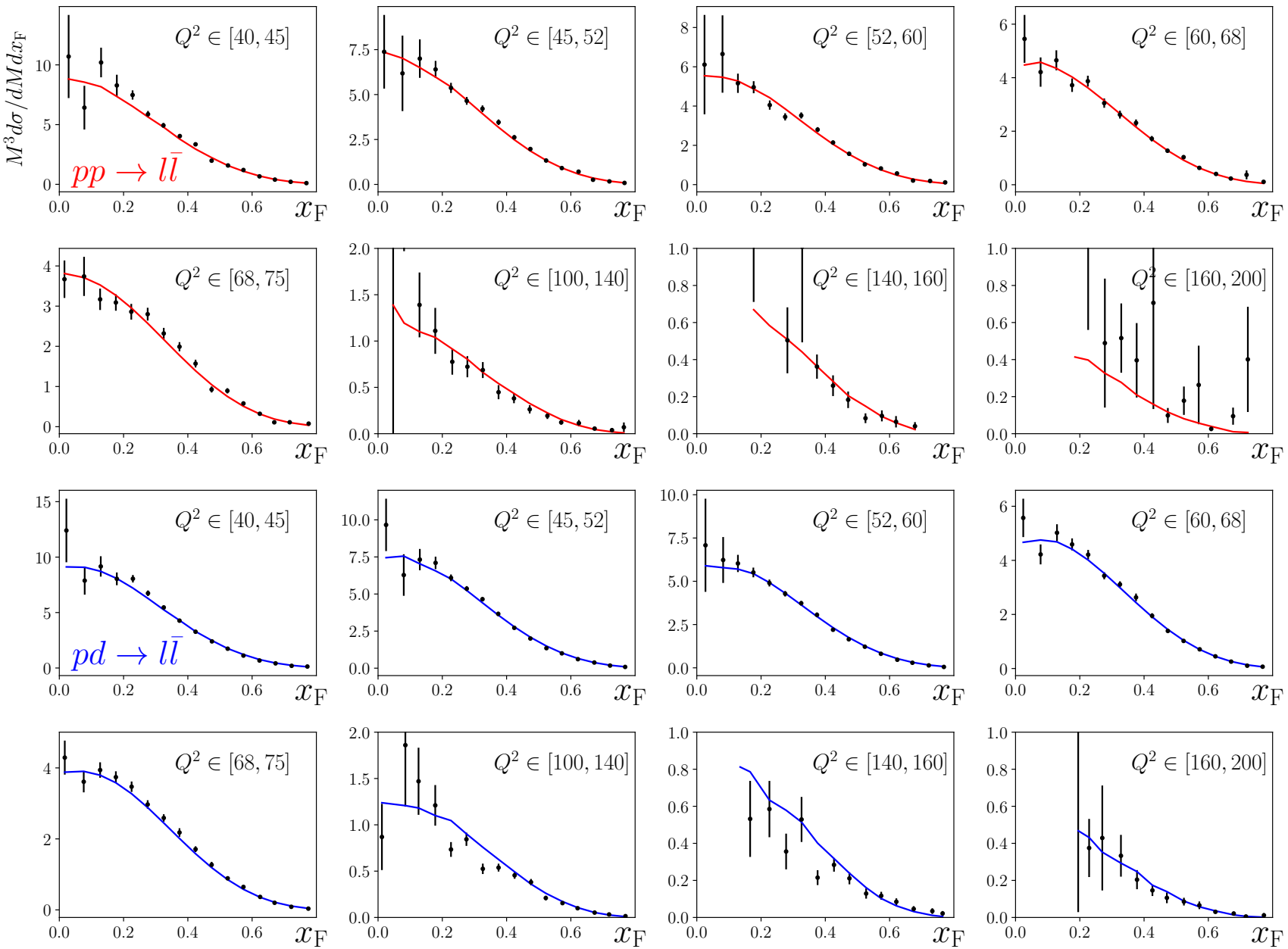
- constraints on FFs
  - **SIA** $\pi^{\pm}$: TASSO, TPC, TPC(c), TPC(b), TOPAZ, SLD, SLD(c), SLD(b), ALEPH, OPAL , OPAL(c), OPAL(b), DELPHI, DELPHI(b), BABAR, BELLE, ARGUS

- constraints on PDFs and FFs
  - **SIDIS** p_{T} dependent: HERMES π^{+}, π^{-}
  - **SIDIS** p_{T} integrated: COMPASS π^{+}, π^{-}

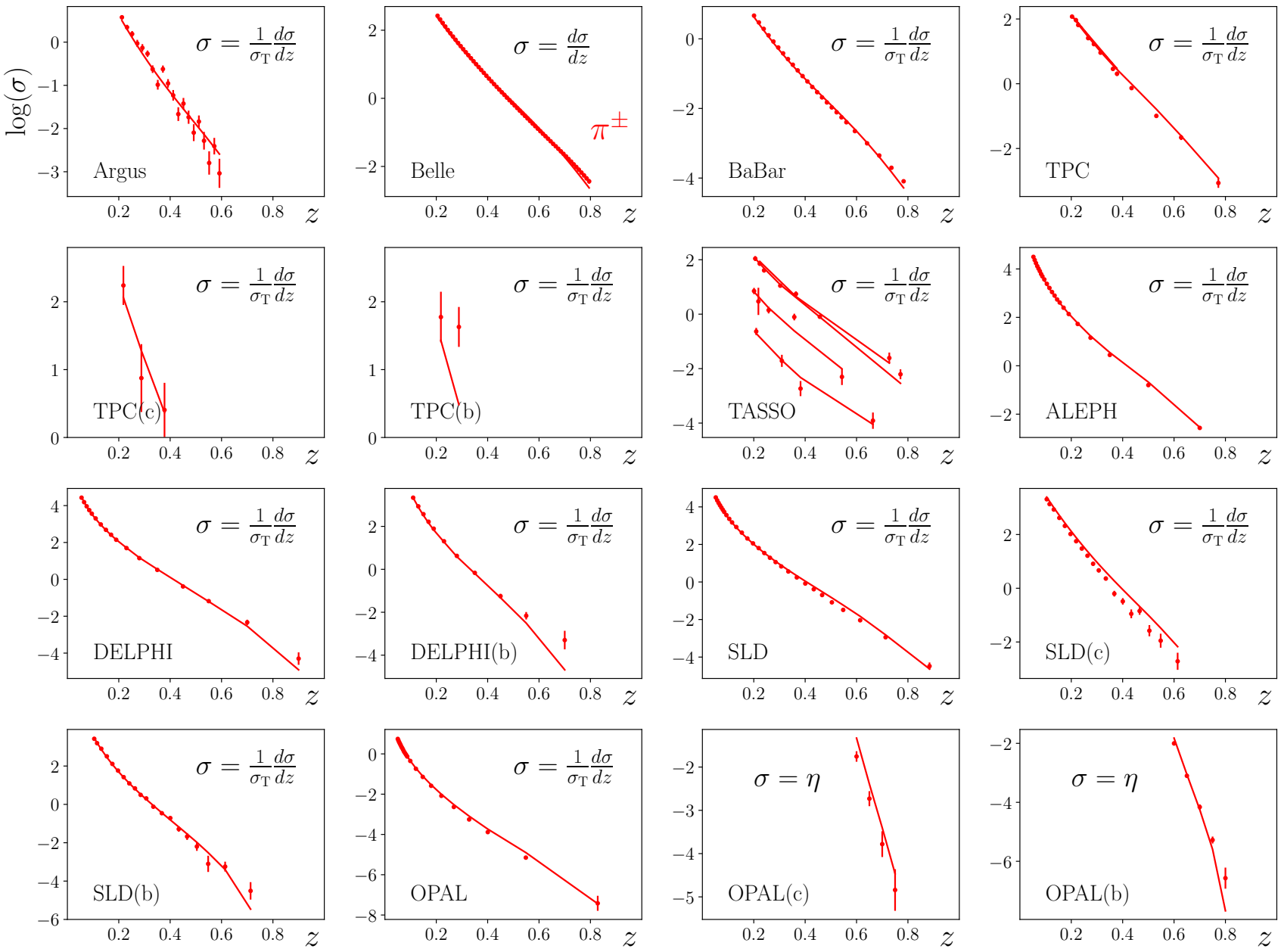
The global analysis I: DIS results



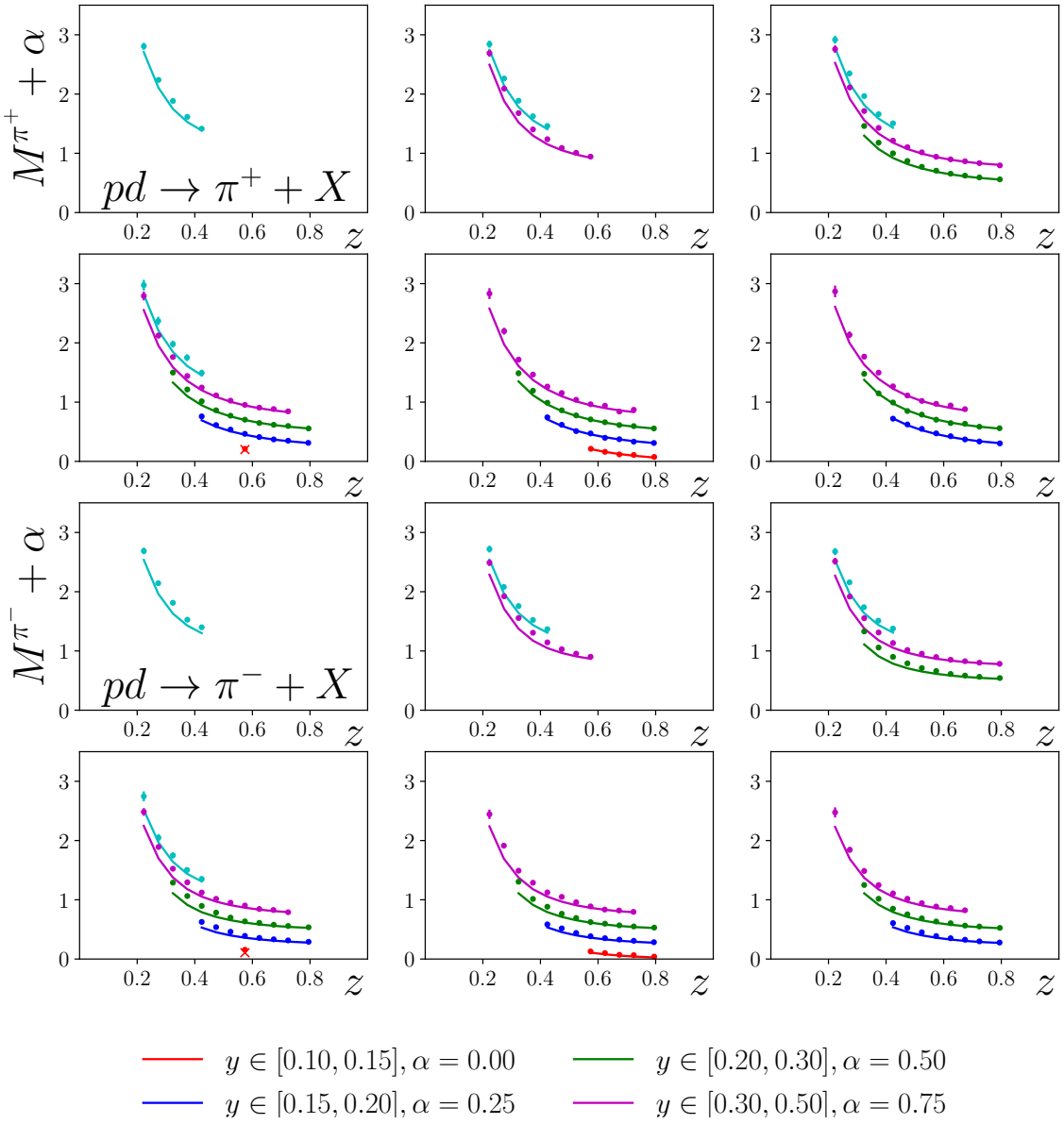
The global analysis I: DY results



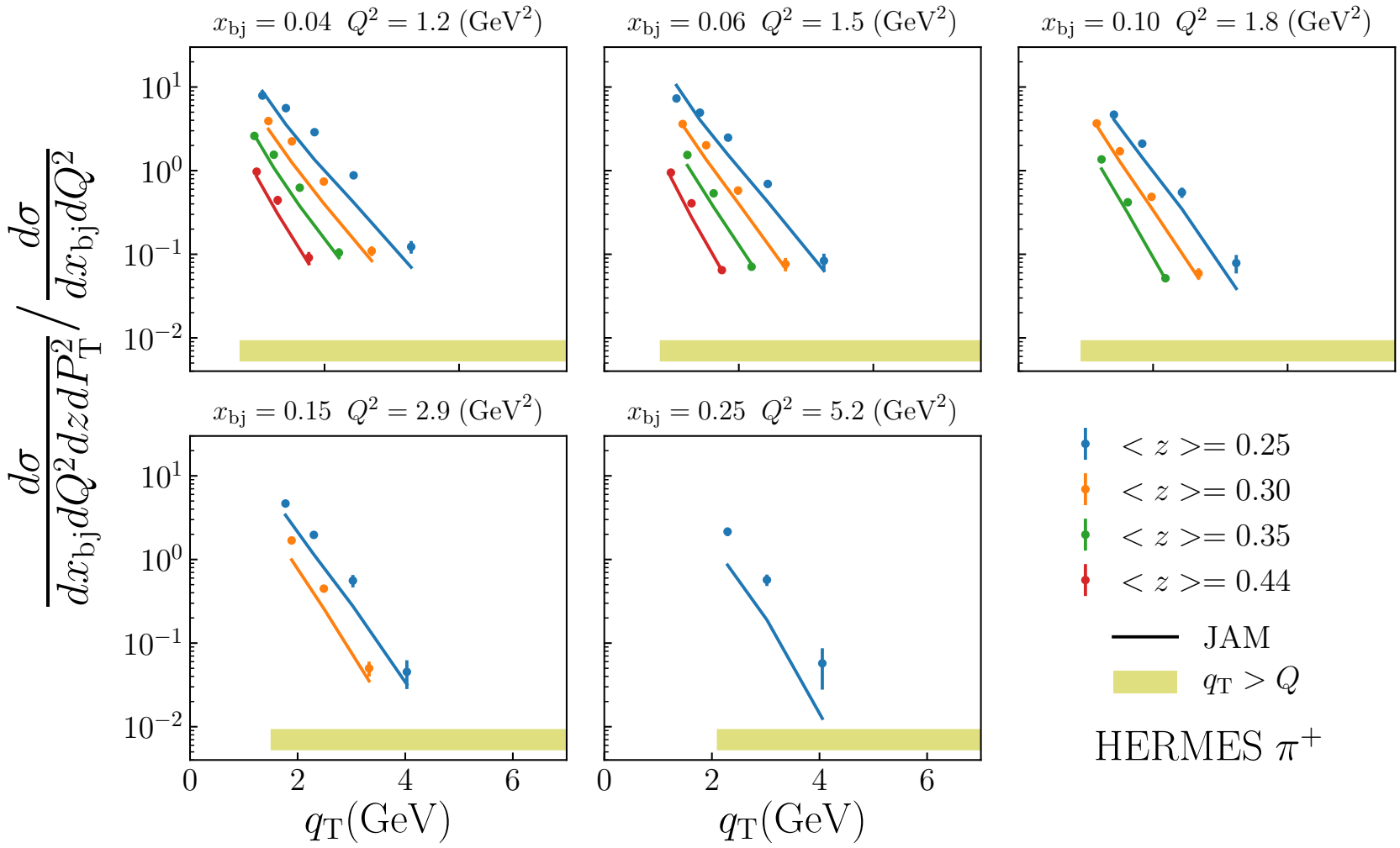
The global analysis I: SIA results



The global analysis I: SIDIS q_{T} integrated

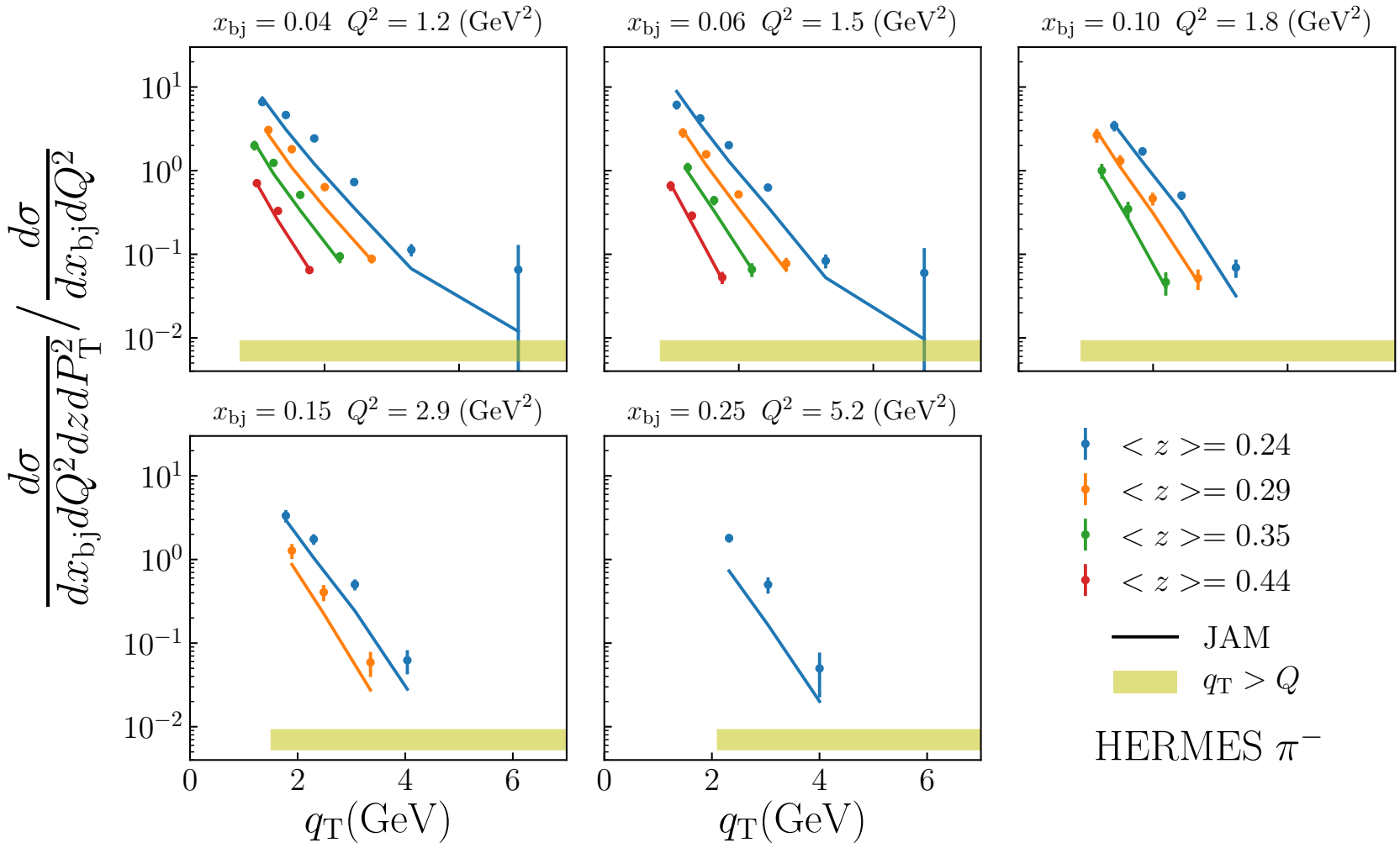


The global analysis I: SIDIS q_{T} dependent



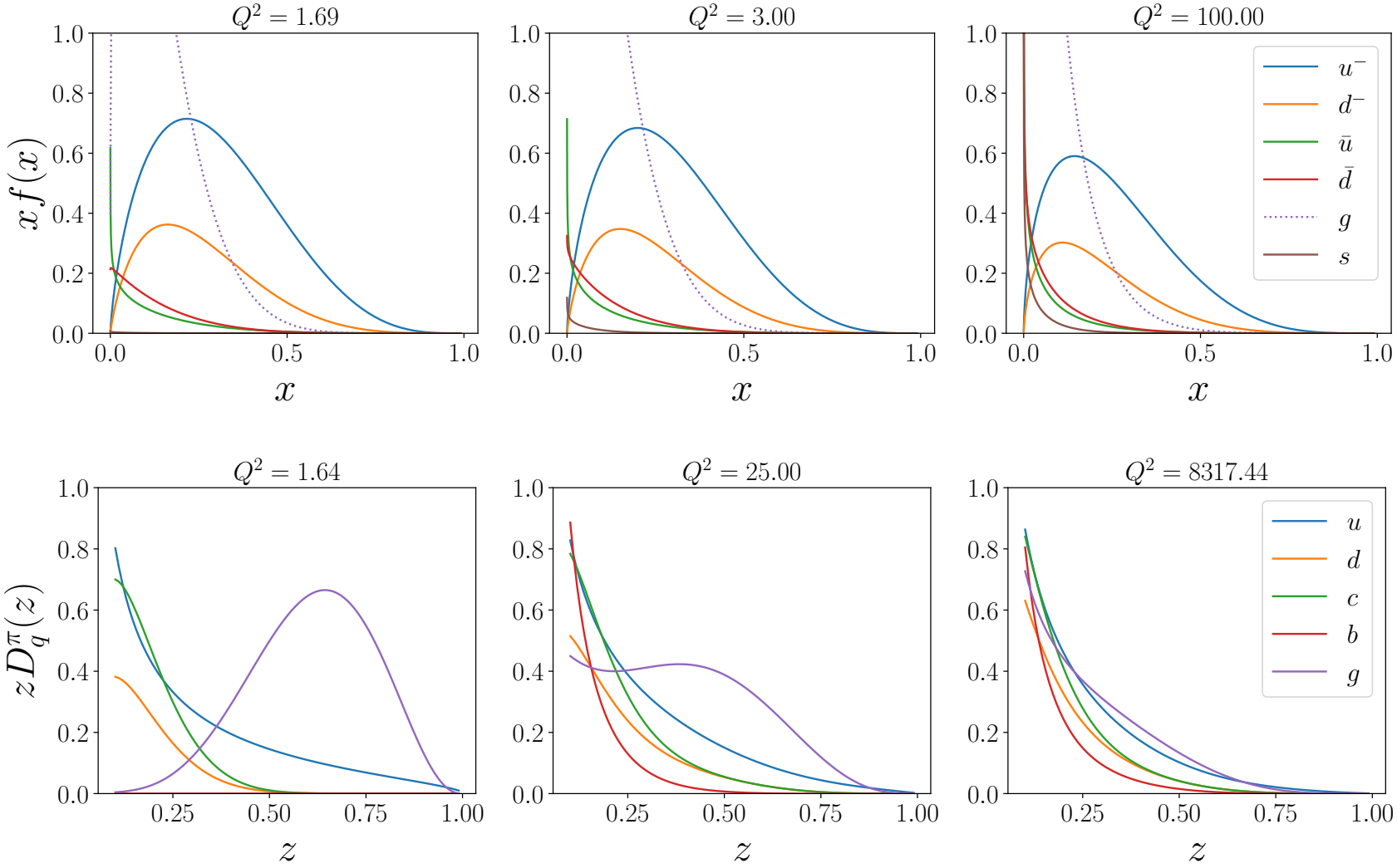
- $q_{\mathrm{T}}/Q > 1$ cut has been imposed

The global analysis I: SIDIS q_{T} dependent



- $q_{\mathrm{T}}/Q > 1$ cut has been imposed

The global analysis I: PDFs and FFs



- Gluon FFs peaks at much larger z

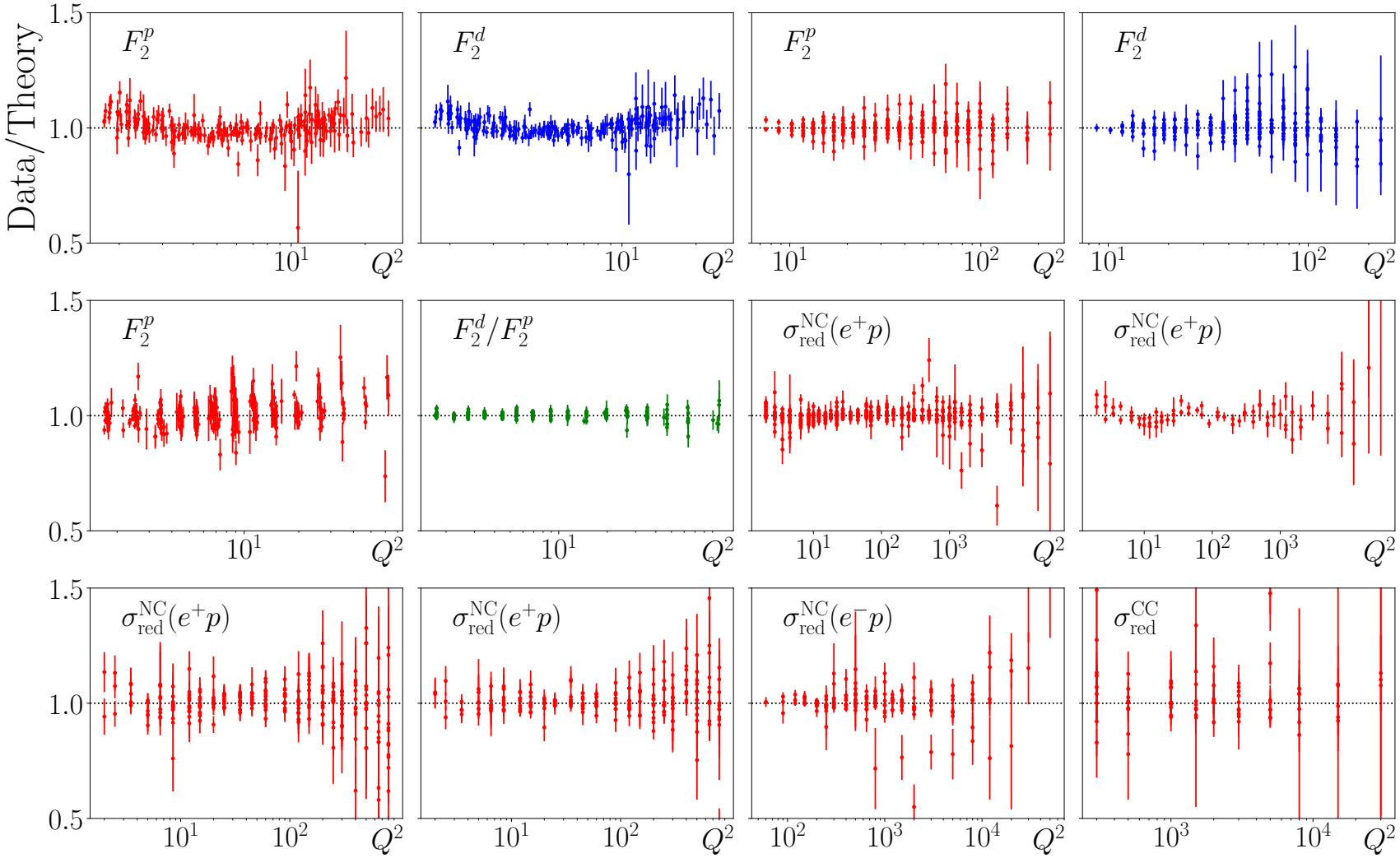
The global analysis II: the data sets

- constraints on PDFs
  - **DIS**: SLAC, BCDMS, NMC, HERA (NC, CC)
  - **DY**: E866 pp, pd

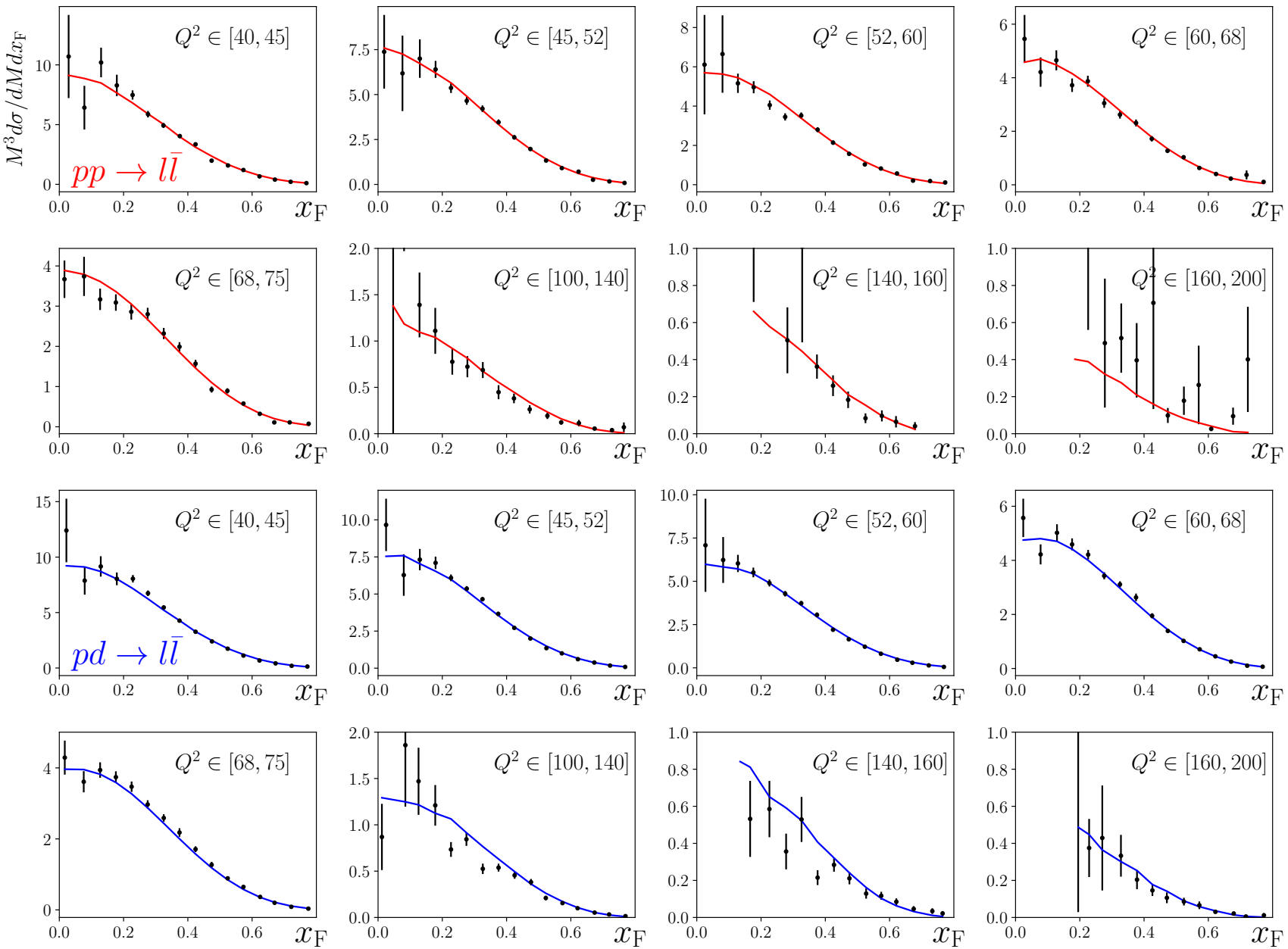
- constraints on FFs
  - **SIA**: TASSO, TPC, TOPAZ, SLD, ALEPH, DELPHI

- constraints on PDFs and FFs
  - **SIDIS** p_{T} dependent: COMPASS h^+, h^-

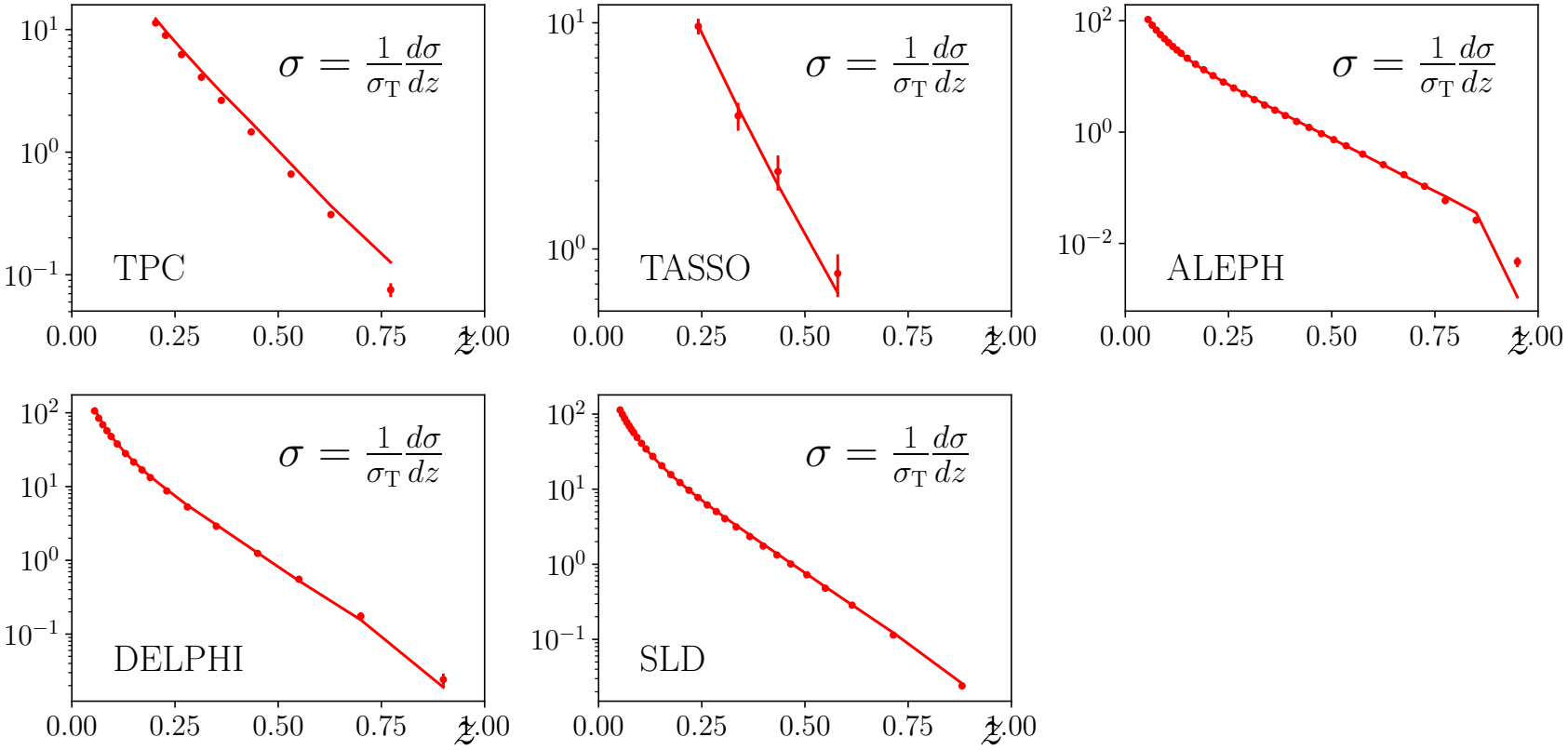
The global analysis II: DIS results



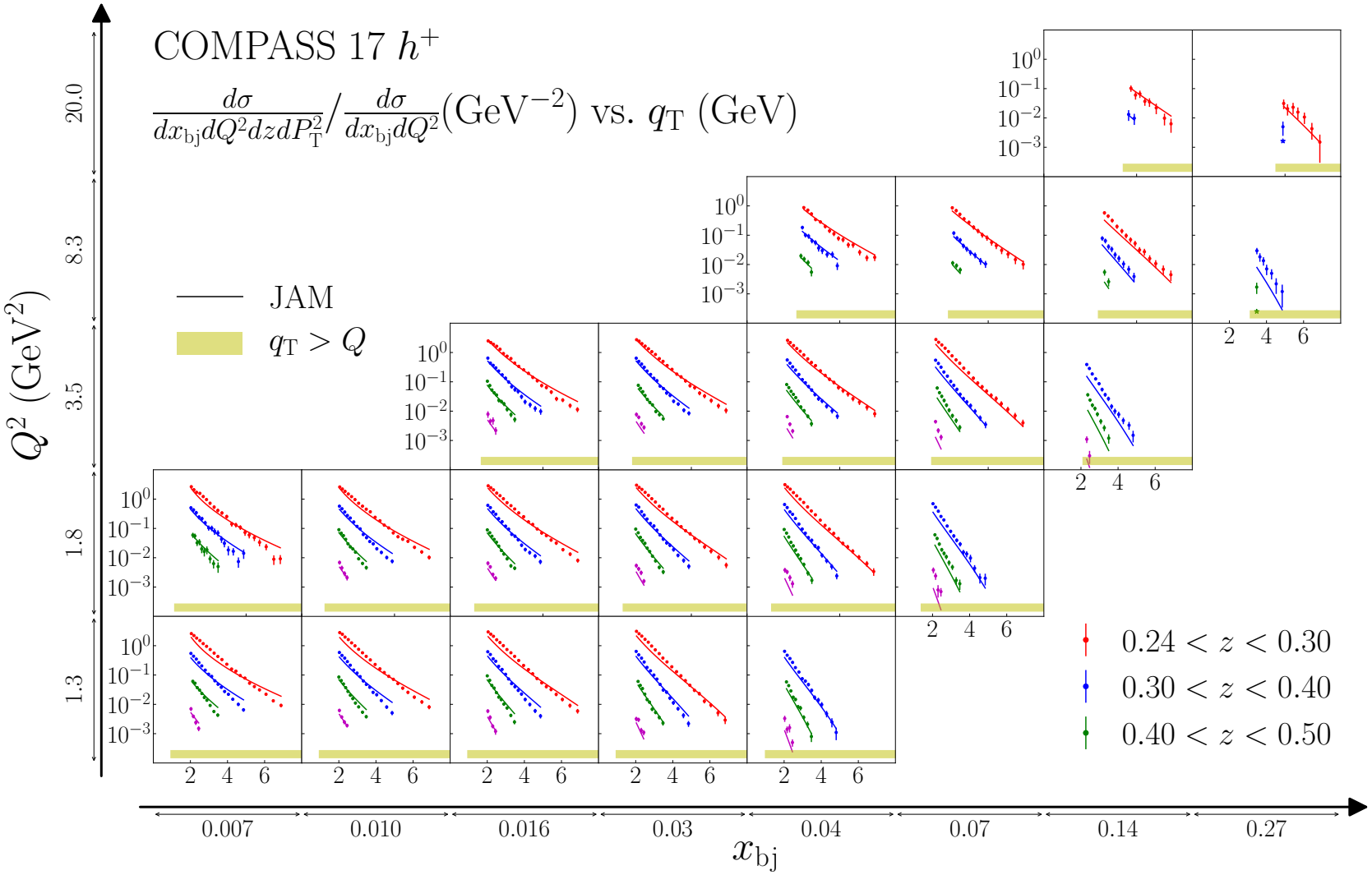
The global analysis II: DY results



The global analysis II: SIA ($h^{\pm}$) results



The global analysis II: SIDIS q_{T} dependent



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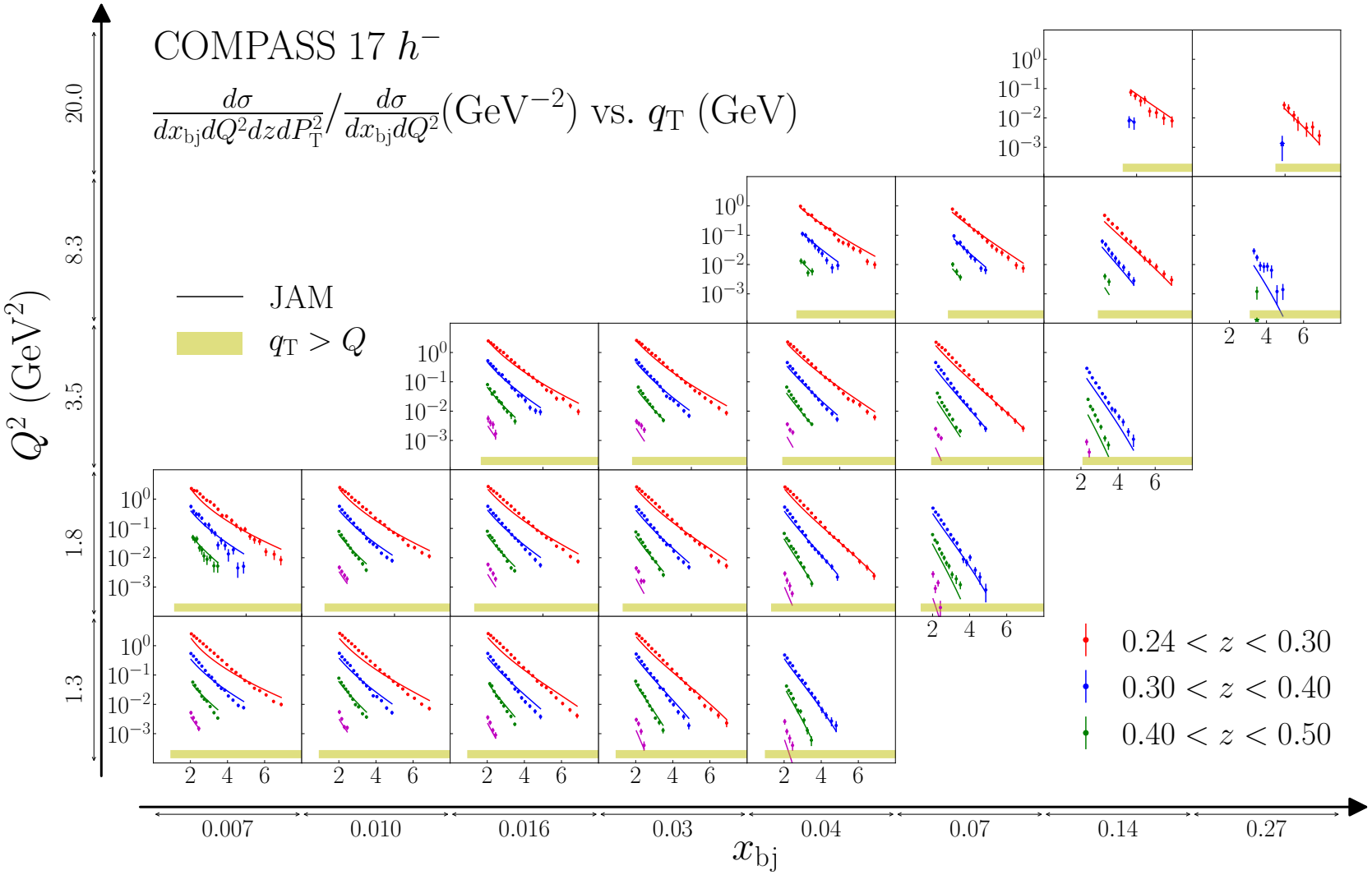
The global analysis II: SIDIS q_{T} dependent



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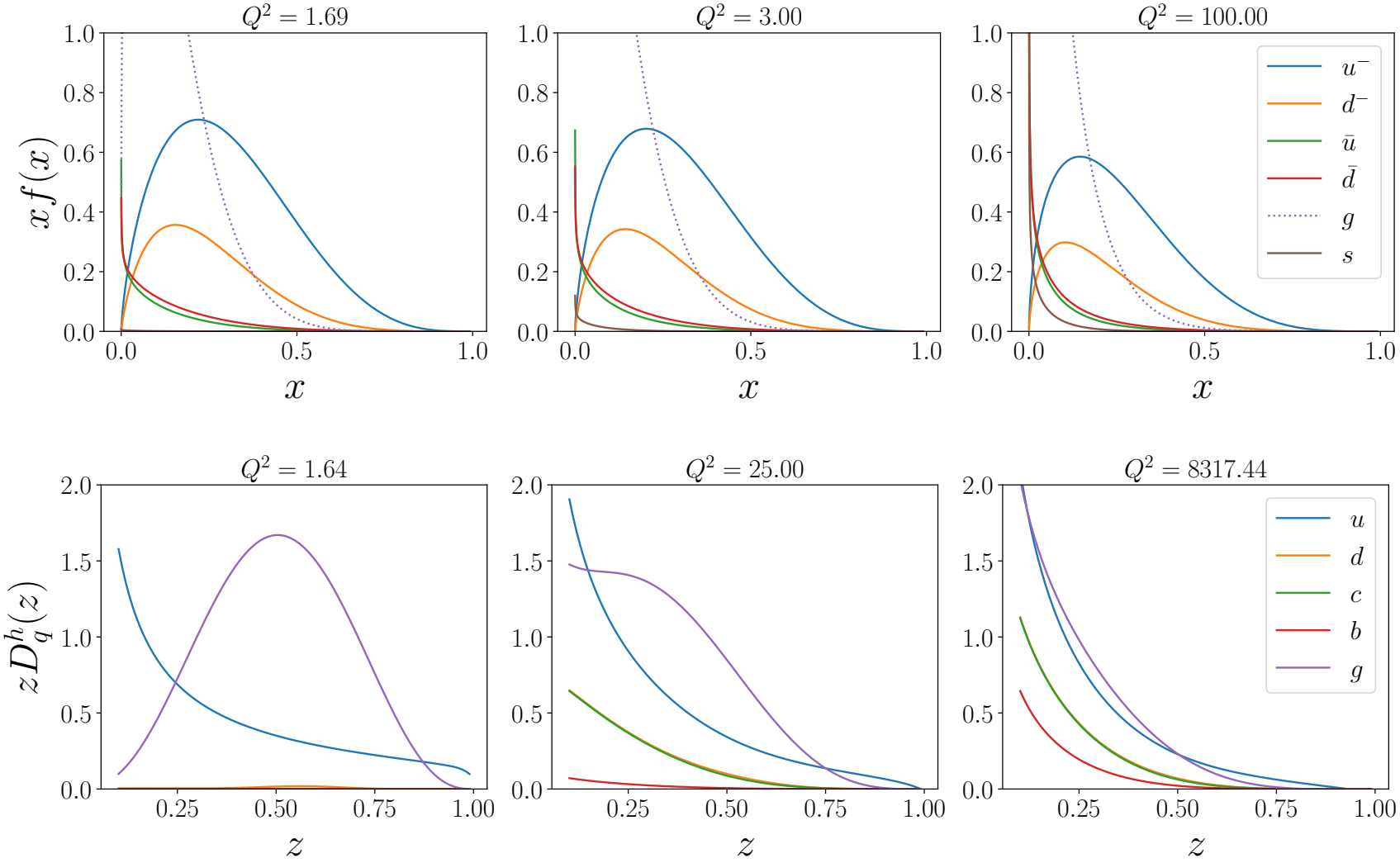
The global analysis II: PDFs and FFs



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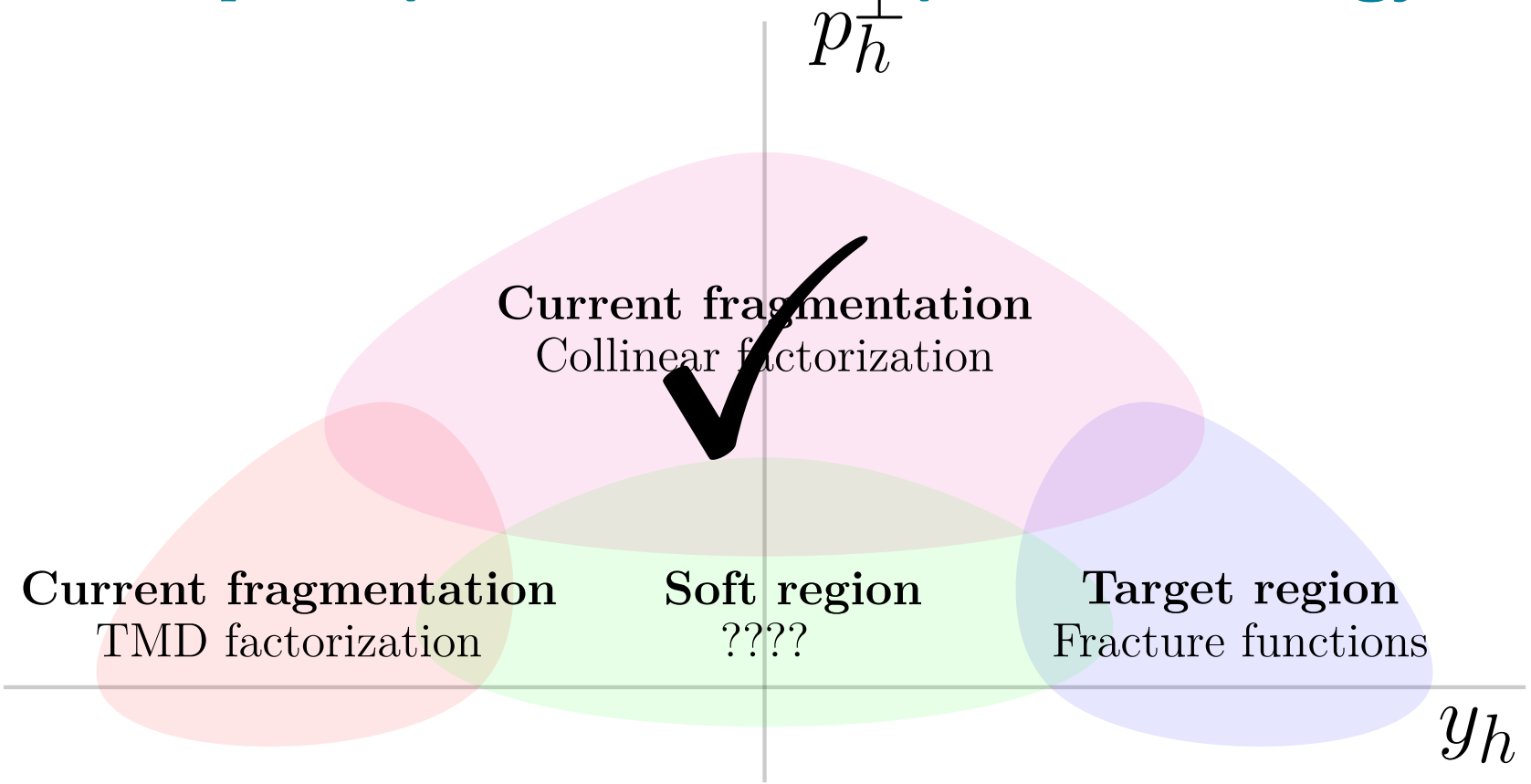
Status of p_{T} dependent SIDIS phenomenology



- **Lessons:**
- SIDIS q_{T} spectrum offers new constraints on FFs
- TMD analyses must include simultaneous analysis of the collinear distributions $\rightarrow$ **JAM**

Summary and outlook

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

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- 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 are typically provided in a form of asymmetries $A_i = F_i/F_{UU}$