

On the reconstruction of SIDIS observables in the Breit frame

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Structure of the proton

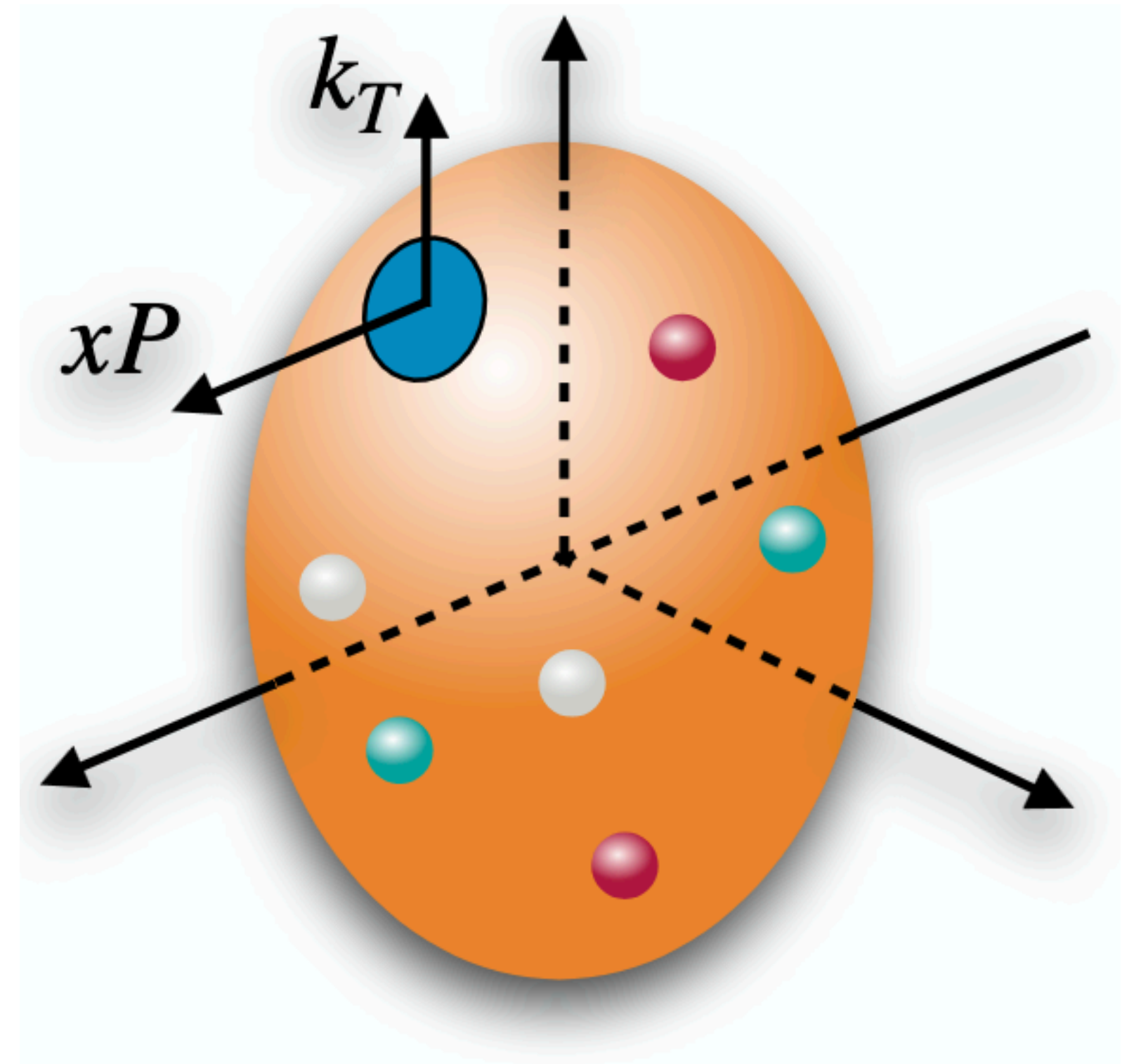
What is the proton's non-perturbative structure?

→ Encoded by

- 1) Collinear Parton Distribution Functions (PDFs)
- 2) Transverse Momentum Distributions (TMDs)
- 3) ... and more not discussed here

→ OPE: $f_{i/P}(x, b_T) = [C \otimes f_{i/P}(x)] E(\mu, \zeta) f_{NP}$

Hadron femtography has been a rich field of investigation for 50 years!

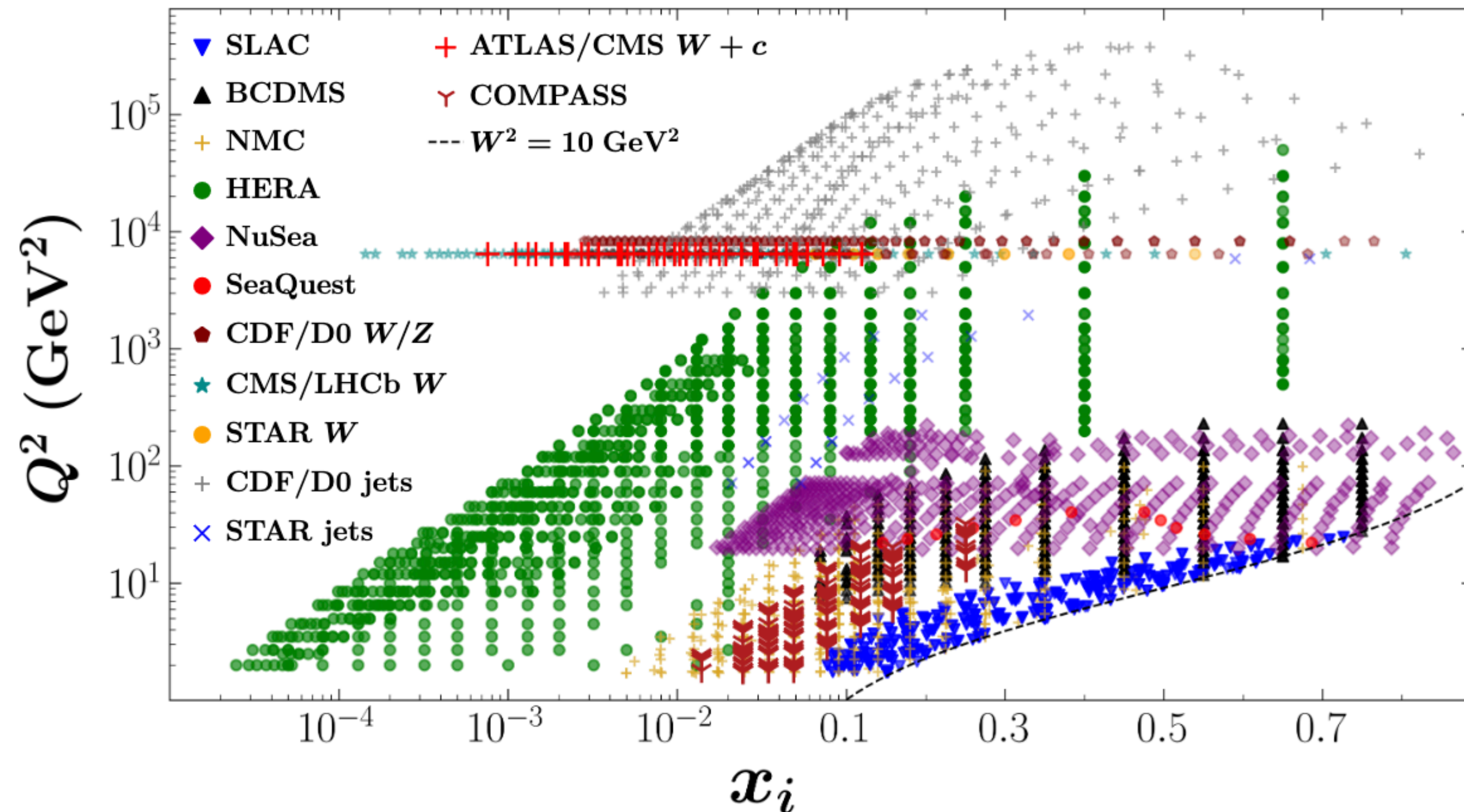


$$f_{i/P}(x, k_T; \mu^2, \zeta) \xrightarrow{\int d^2\mathbf{k}_T} f_{i/P}(x; \mu^2)$$

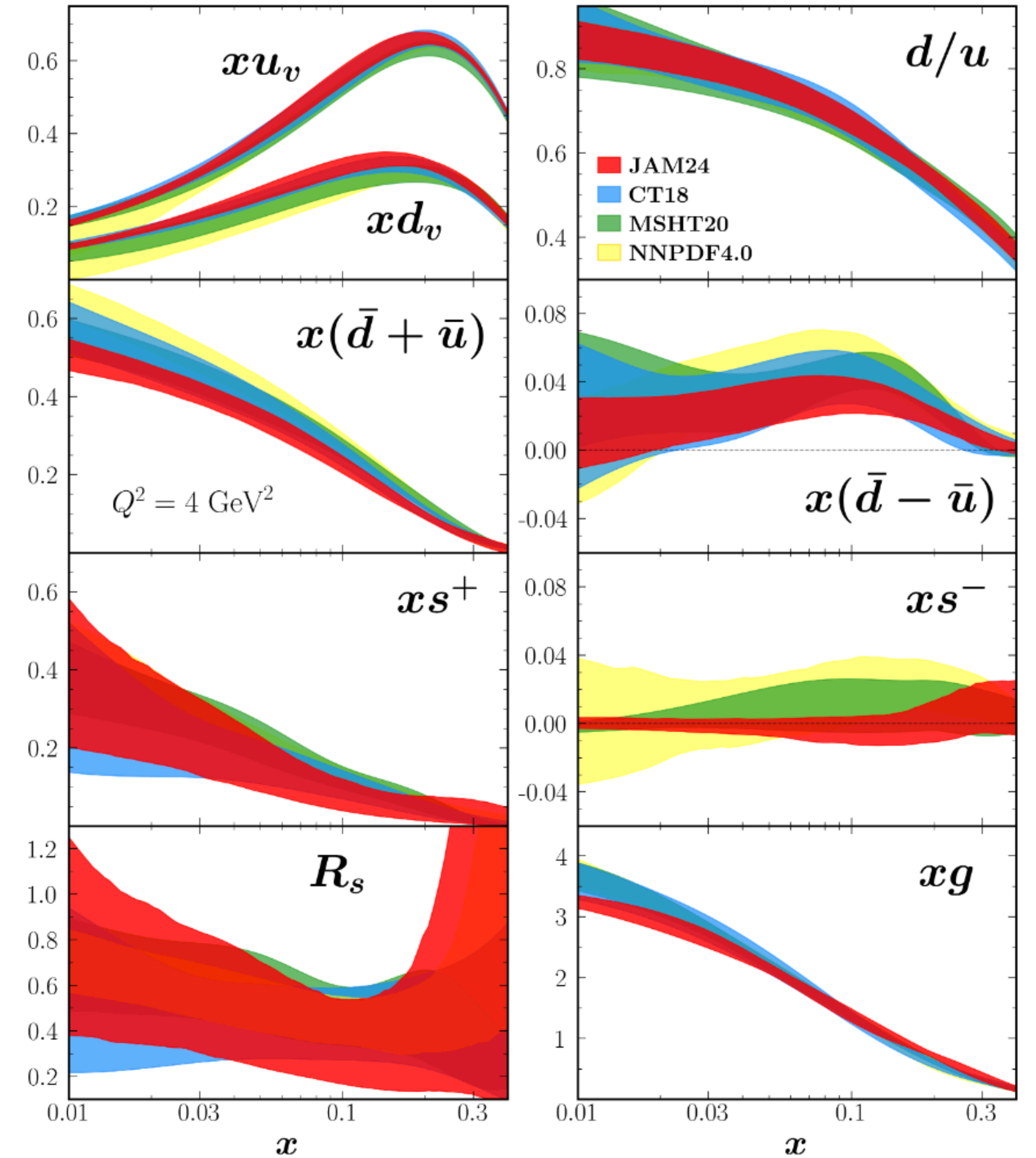
State of PDF global analysis

→ Universality and factorization

*Extensive study of PDFs by many groups
and lots of data*



Anderson, Sato, Melnitchouk, arXiv:2501.00665v2 [hep-ph] (2025)



State of PDF global analysis

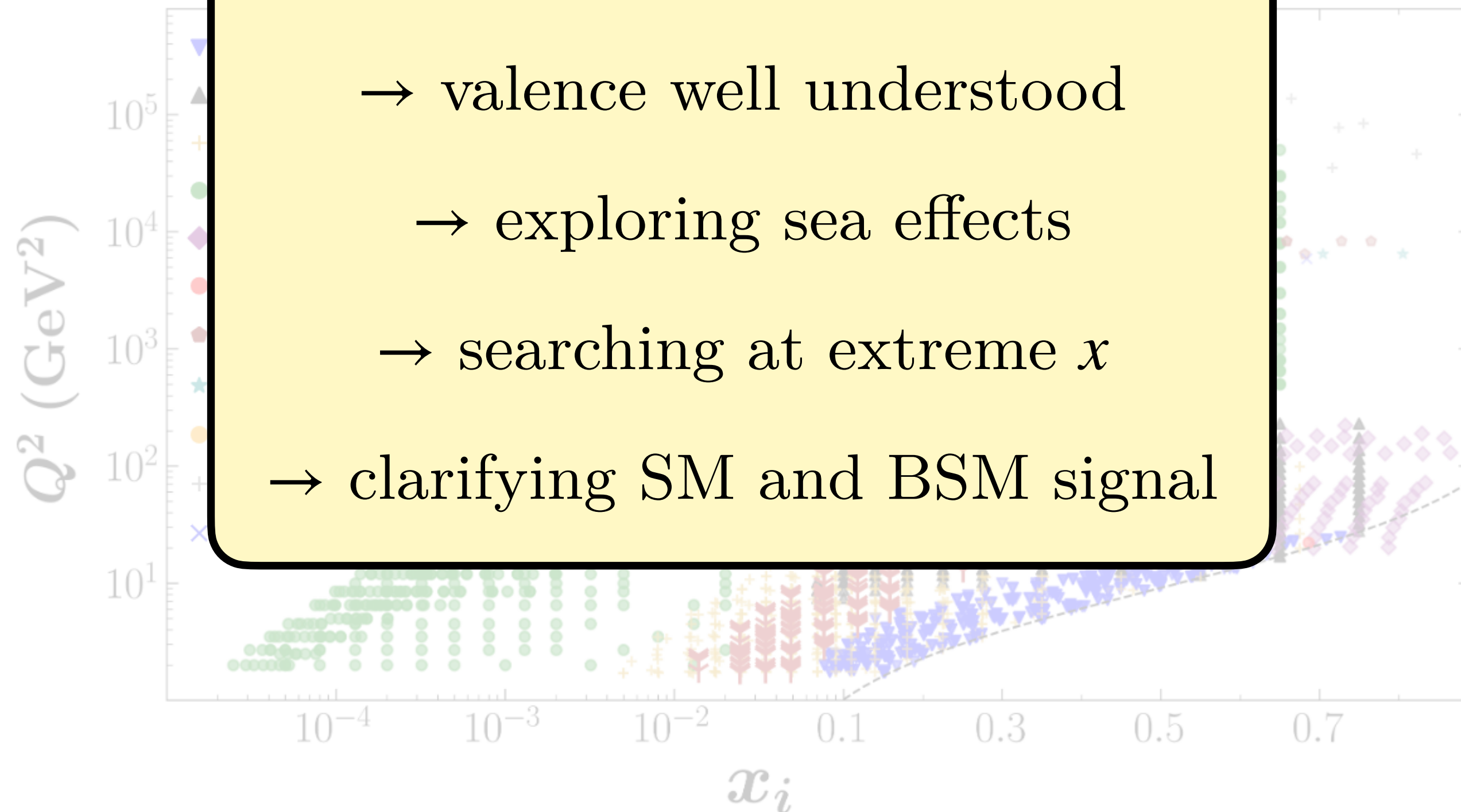
Aiming for precision:

→ valence well understood

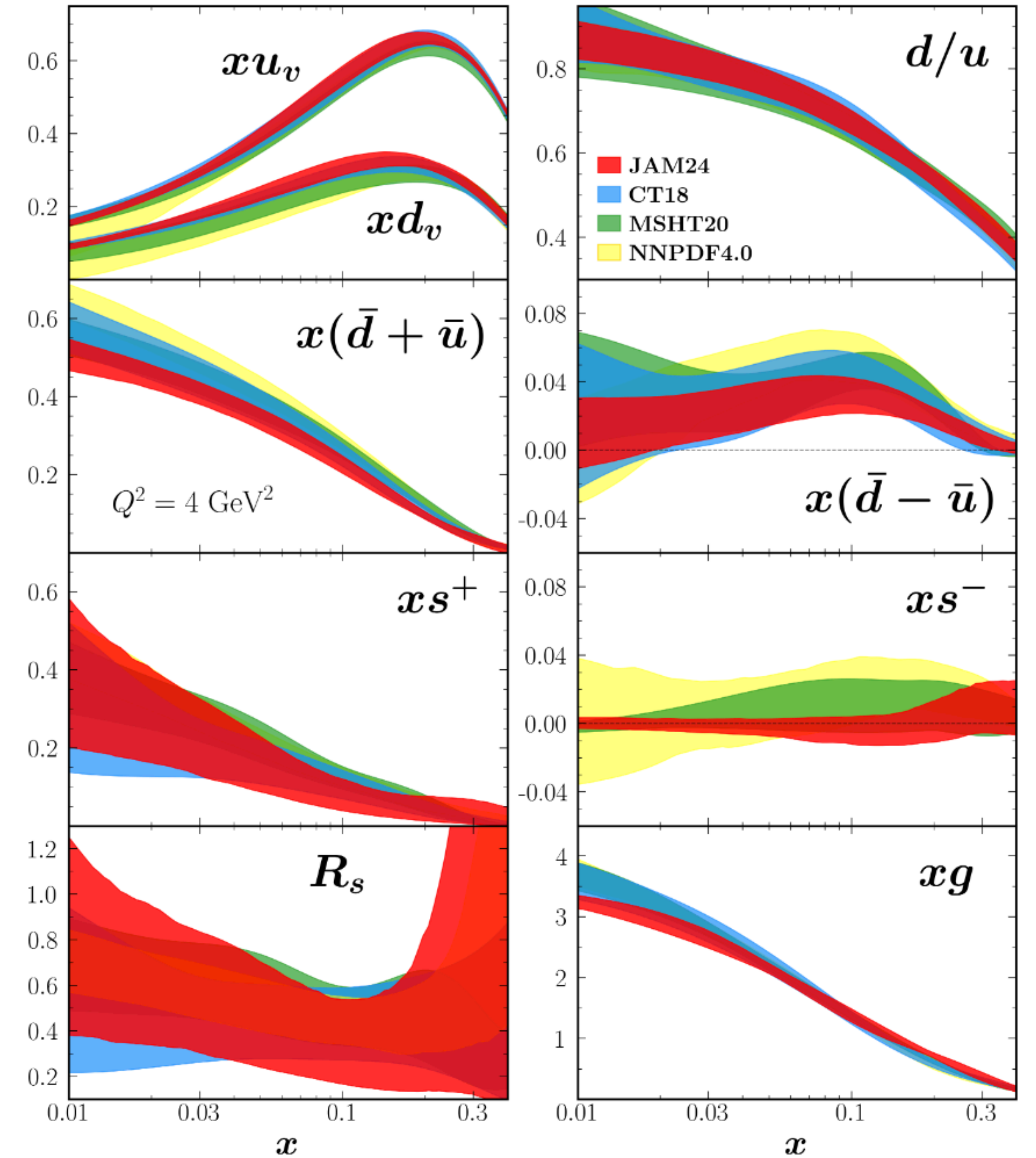
→ exploring sea effects

→ searching at extreme x

→ clarifying SM and BSM signal



Anderson, Sato, Melnitchouk, arXiv:2501.00665v2 [hep-ph] (2025)

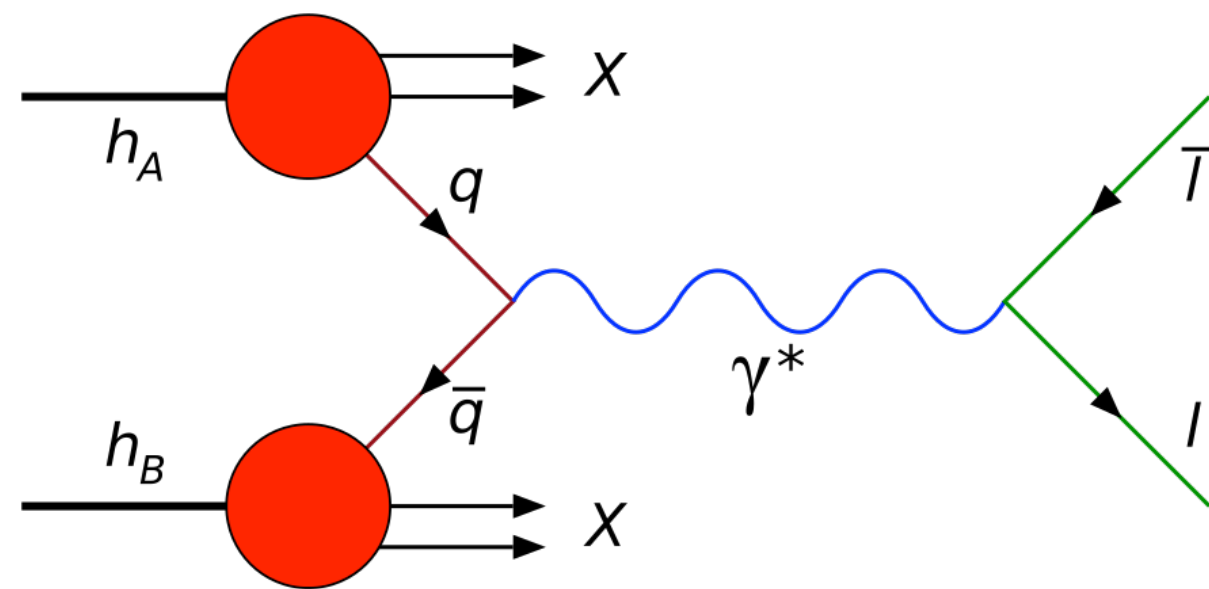


State of TMD global analysis

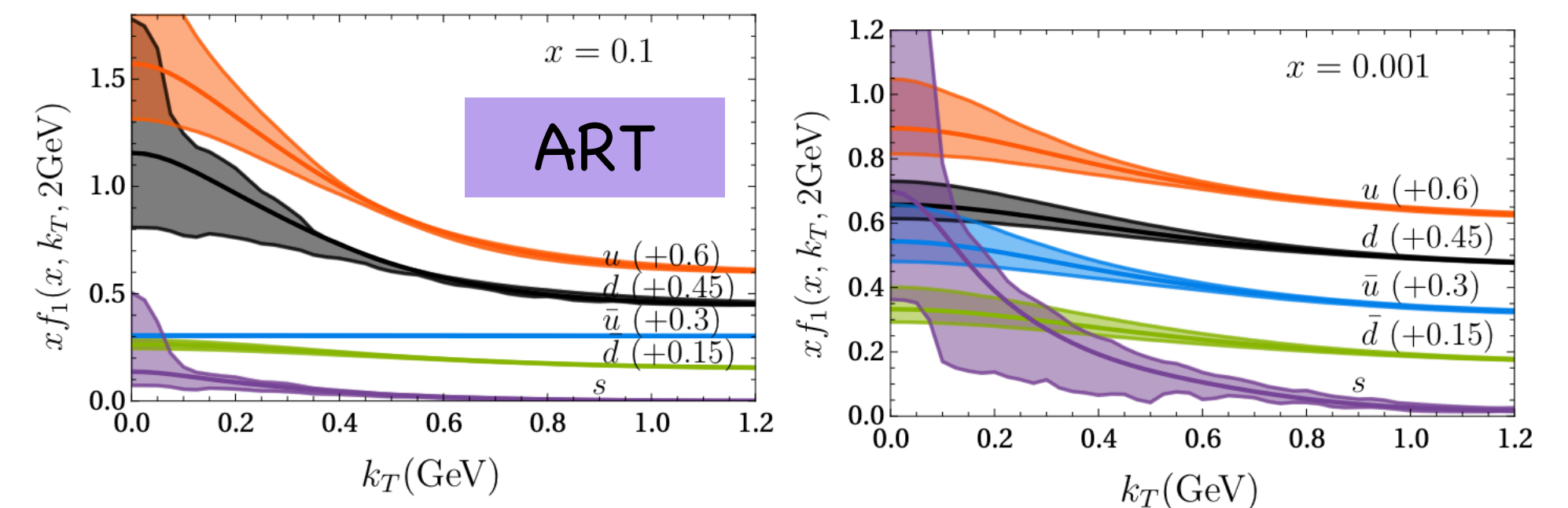
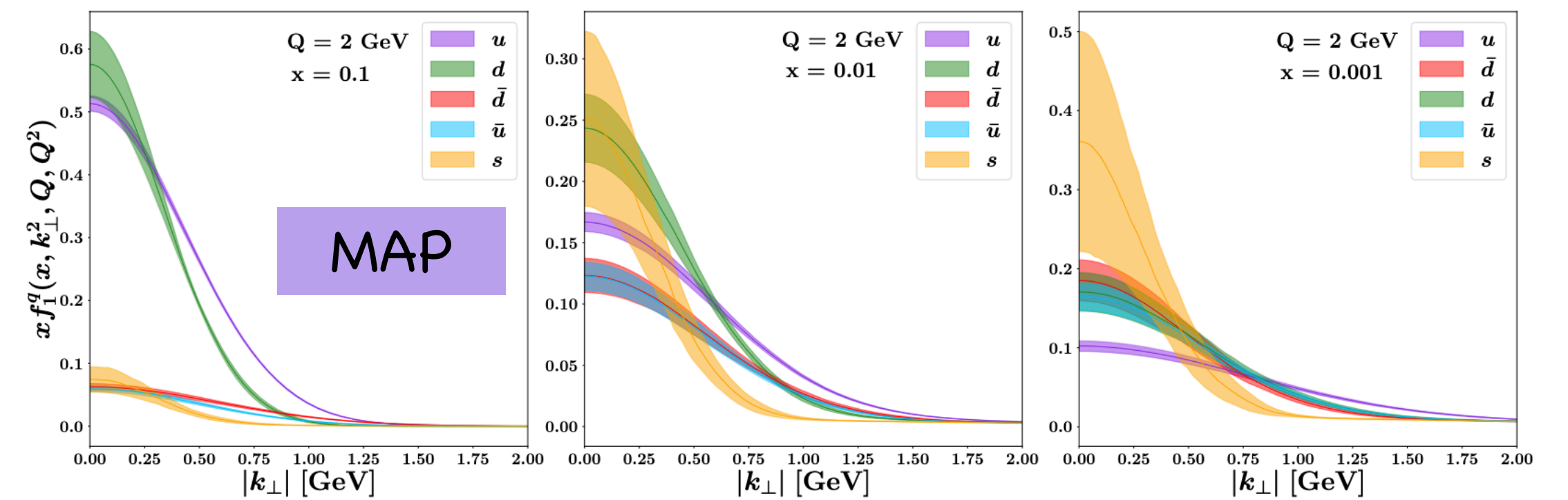
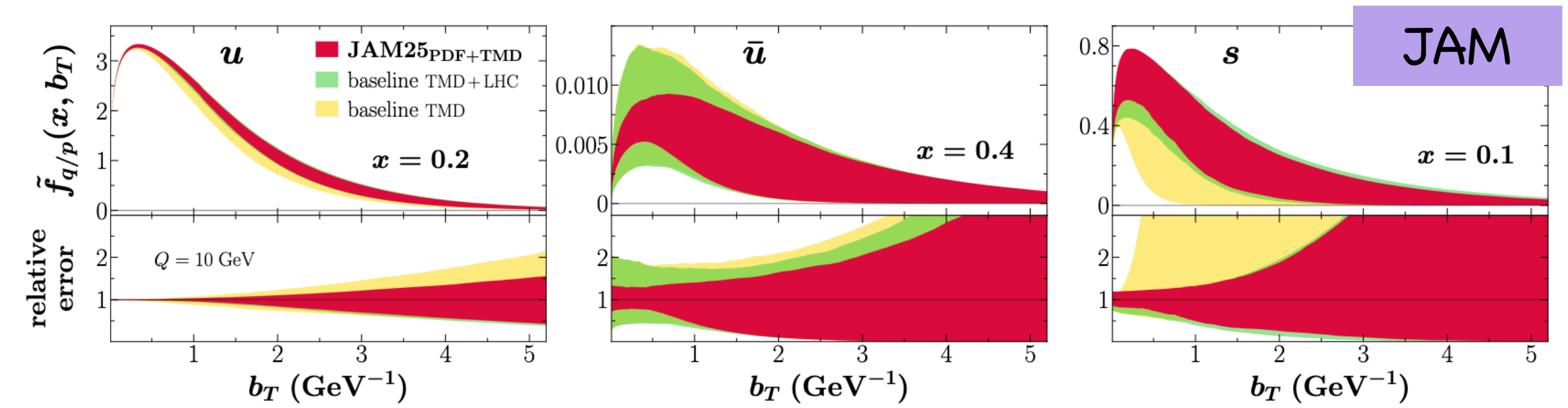
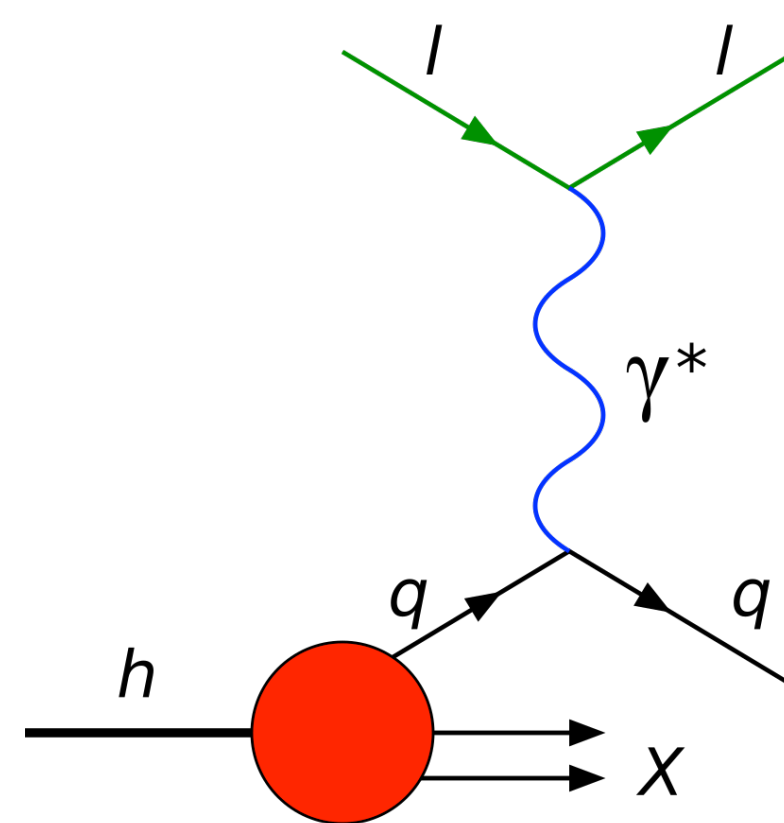
→ Universality* and factorization

TMDs of more “recent” interest

Drell-Yan



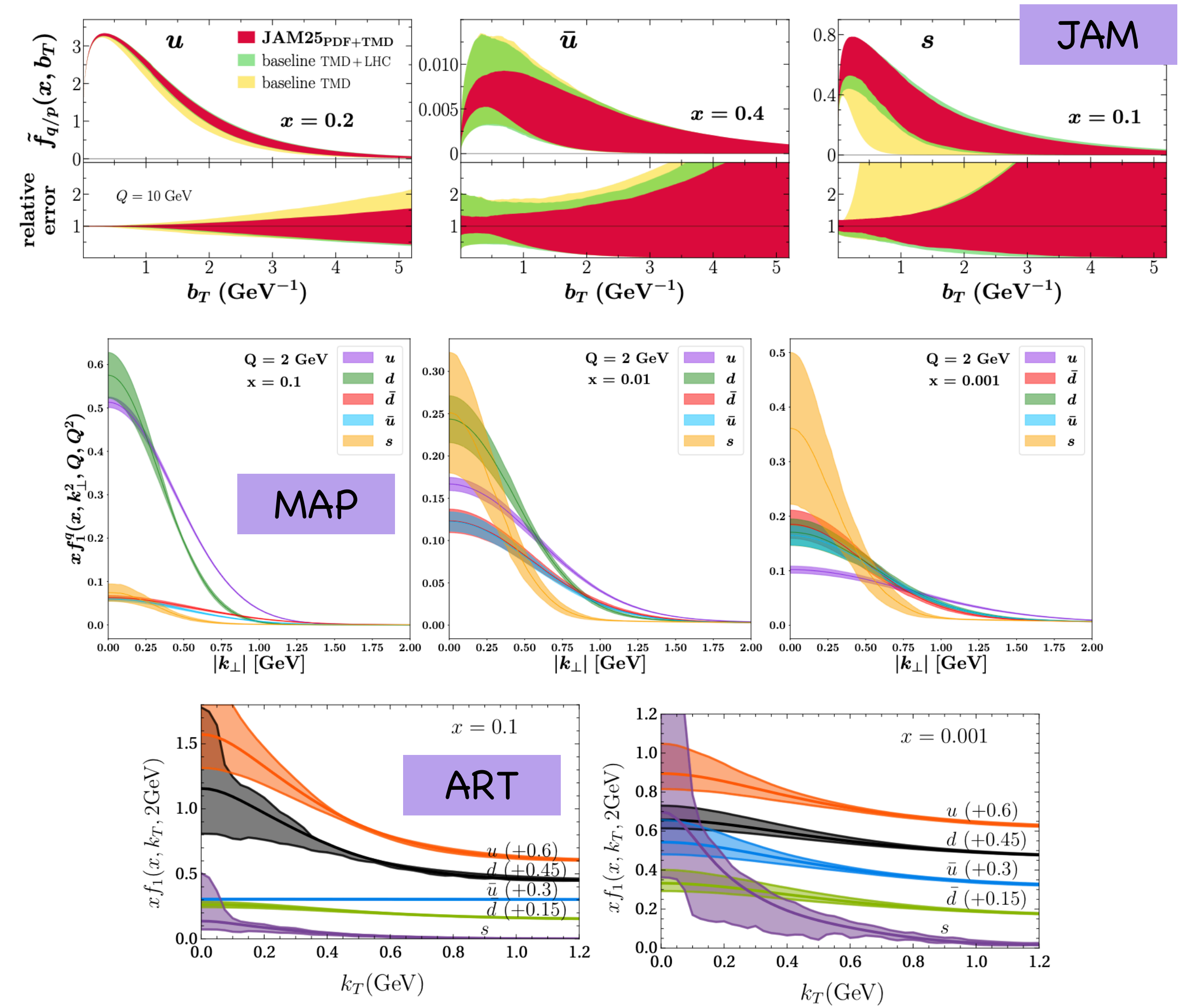
SIDIS



State of TMD global analysis

Aiming for understanding:

- 1-2 decades of modern analyses
- ironing out methodology
- refining theory descriptions
- exploring PDF/TMD consistency

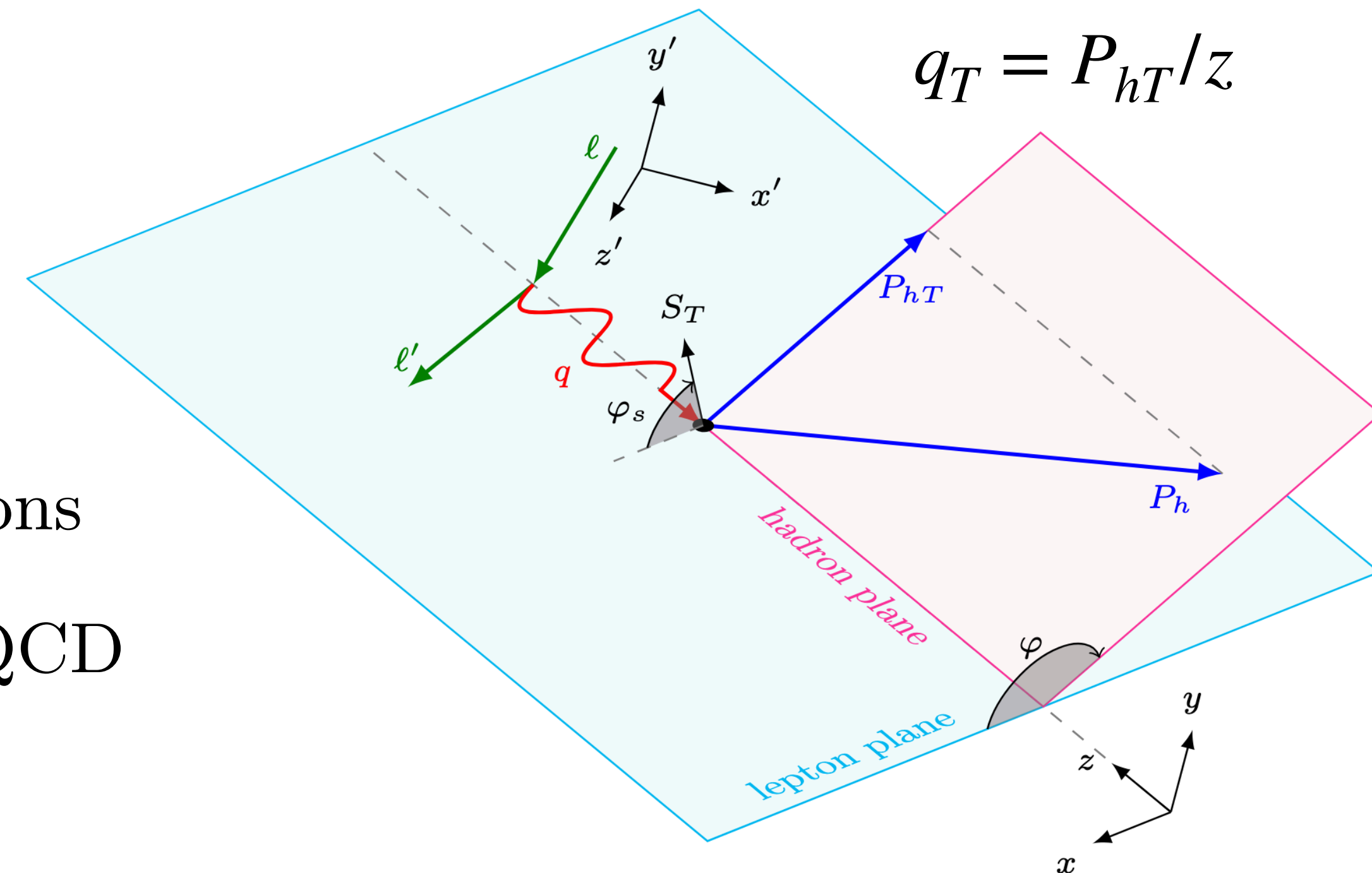


SIDIS basics

$$\frac{d\sigma}{dx dy dz dq_T^2 d\varphi} = \frac{\alpha^2 y}{Q^2(1-\varepsilon)} \left[F_{UU,T} + \varepsilon F_{UU,L} - \sqrt{2\varepsilon(1+\varepsilon)} F_{UU}^{\cos\varphi} \cos\varphi + \varepsilon F_{UU}^{\cos 2\varphi} \cos 2\varphi \right]$$

Observation of final-state hadron*

- Enhanced flavor separation
- Unique correlations encoded in azimuthal modulations
- Bridge between hadron structure, hadronization, pQCD



CSS construction

$$\frac{d\sigma}{dx dy dz dq_T^2 d\varphi} = \frac{\alpha^2 y}{Q^2(1-\varepsilon)} \left[F_{UU,T} + \varepsilon F_{UU,L} - \sqrt{2\varepsilon(1+\varepsilon)} F_{UU}^{\cos\varphi} \cos\varphi + \varepsilon F_{UU}^{\cos 2\varphi} \cos 2\varphi \right]$$

$$F^{(W)} = C[\omega_{T/L} f_1 D_1]$$

$$F^{(ASY)} = \lim_{q_T/Q \rightarrow \infty} F_{UU,T/L}^{(W)} \approx \lim_{q_T/Q \rightarrow 0} F_{UU,T/L}^{(FO)}$$

$$F^{(FO)} = \frac{1}{Q^2} \frac{\alpha_s}{(2\pi z)^2} \sum_{ij} C_{UU,T/L}^{(ij)} \otimes f_{i/P} \otimes D_{h/lj}$$



TMDs



PDFs

SIDIS in global analysis

$$\frac{d\sigma}{dx dy dz dq_T^2 d\varphi} = \frac{\alpha^2 y}{Q^2(1-\varepsilon)} \left[F_{UU,T} + \varepsilon F_{UU,L} - \sqrt{2\varepsilon(1+\varepsilon)} F_{UU}^{\cos\varphi} \cos\varphi + \varepsilon F_{UU}^{\cos 2\varphi} \cos 2\varphi \right]$$

No modern global analysis with full SIDIS

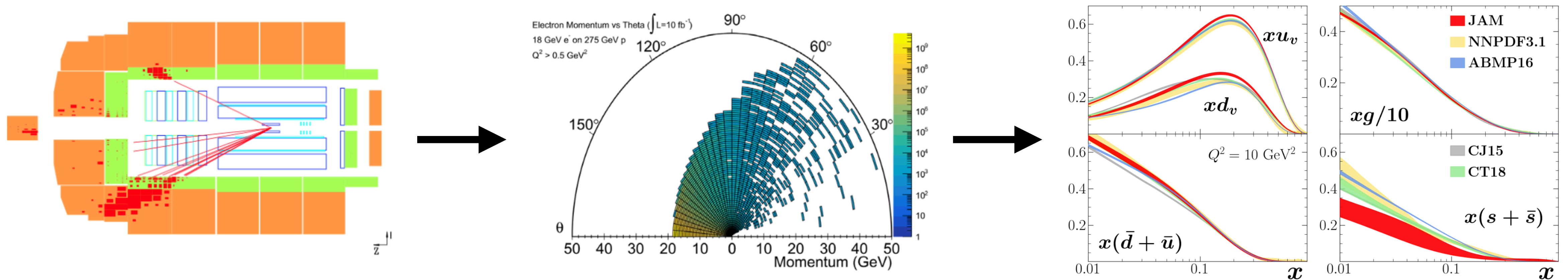
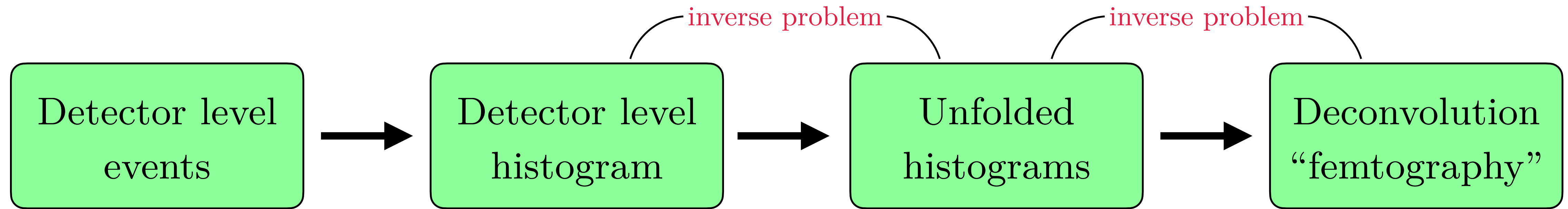
→ TMDs: keep only small- q_T data

→ PDFs: integrate over q_T (z -dependent)

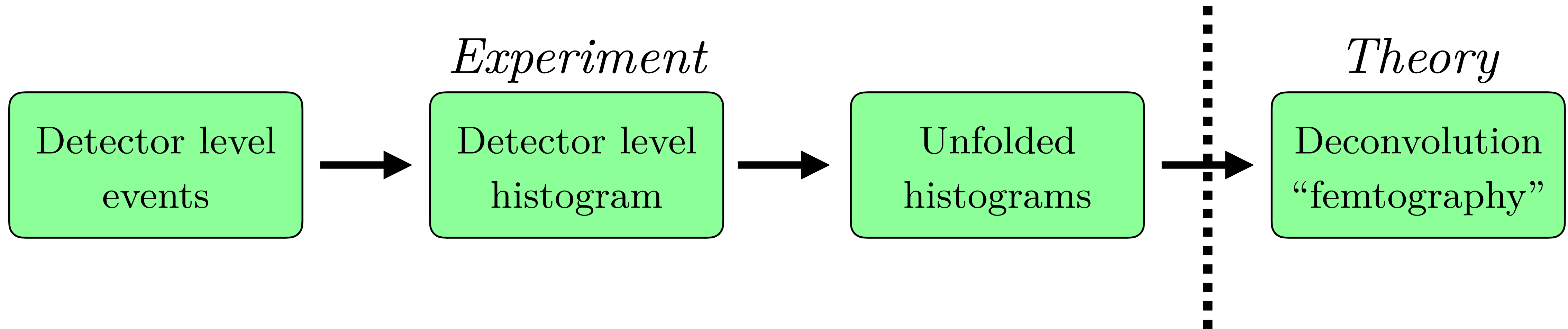
Should move toward using full q_T information & machinery!



Standard data packaging pipeline



Standard data packaging pipeline



$$\left\langle \frac{d\sigma}{d\Phi} \right\rangle = \int_{\mathcal{V}} d\Phi \frac{d\sigma}{d\Phi} A(\Phi) / \int_{\mathcal{V}} d\Phi A(\Phi)$$
$$\stackrel{?}{\approx} \frac{1}{V_{\text{bin}}} \int_{\mathcal{V}} d\Phi \frac{d\sigma}{d\Phi} \rightarrow \frac{d\sigma}{d\Phi}$$

Fundamental objects: binned observables

→ arbitrary binning choice

→ detector effects coupled with physics

→ how does this scale with increasing dimensionality?

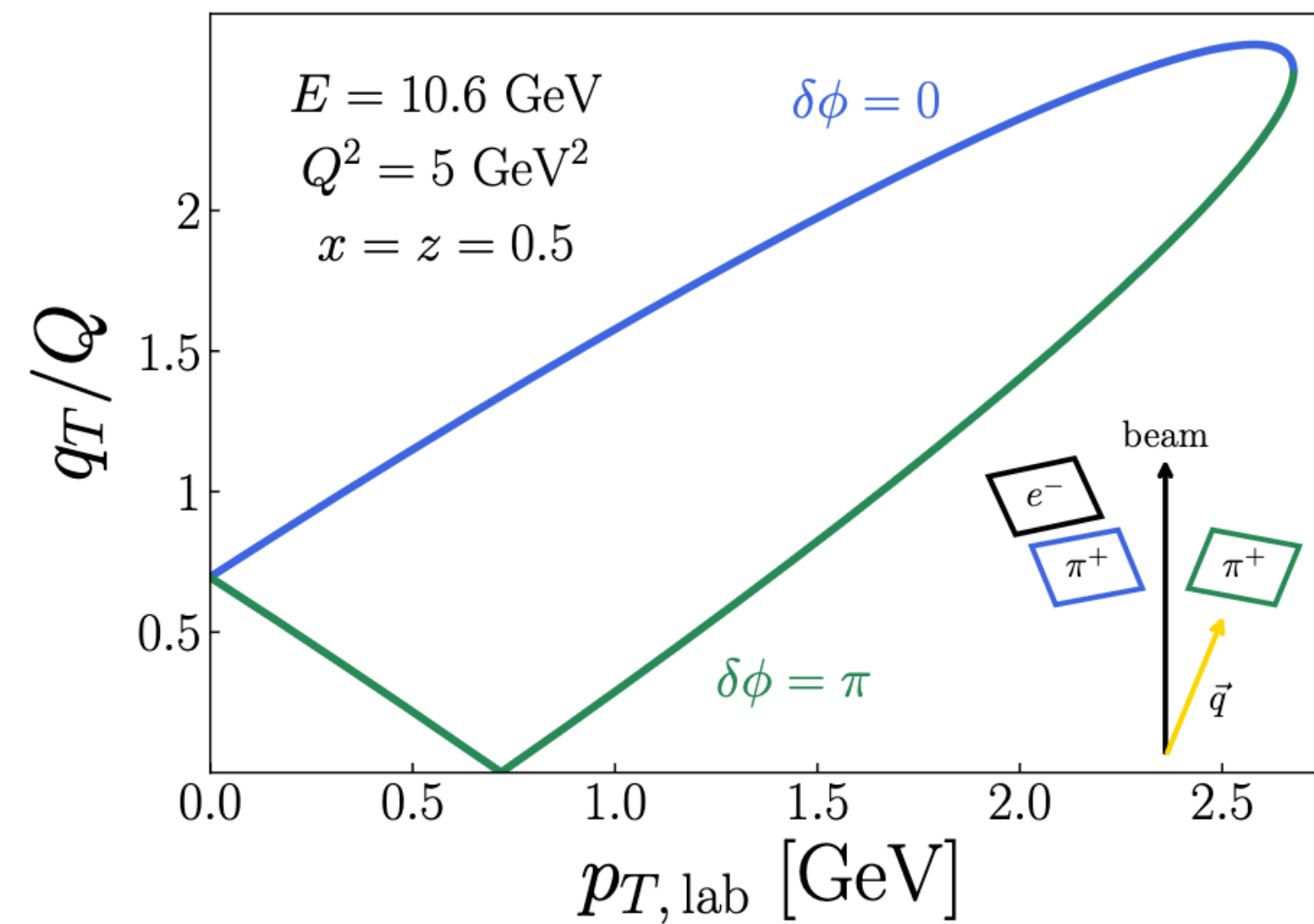
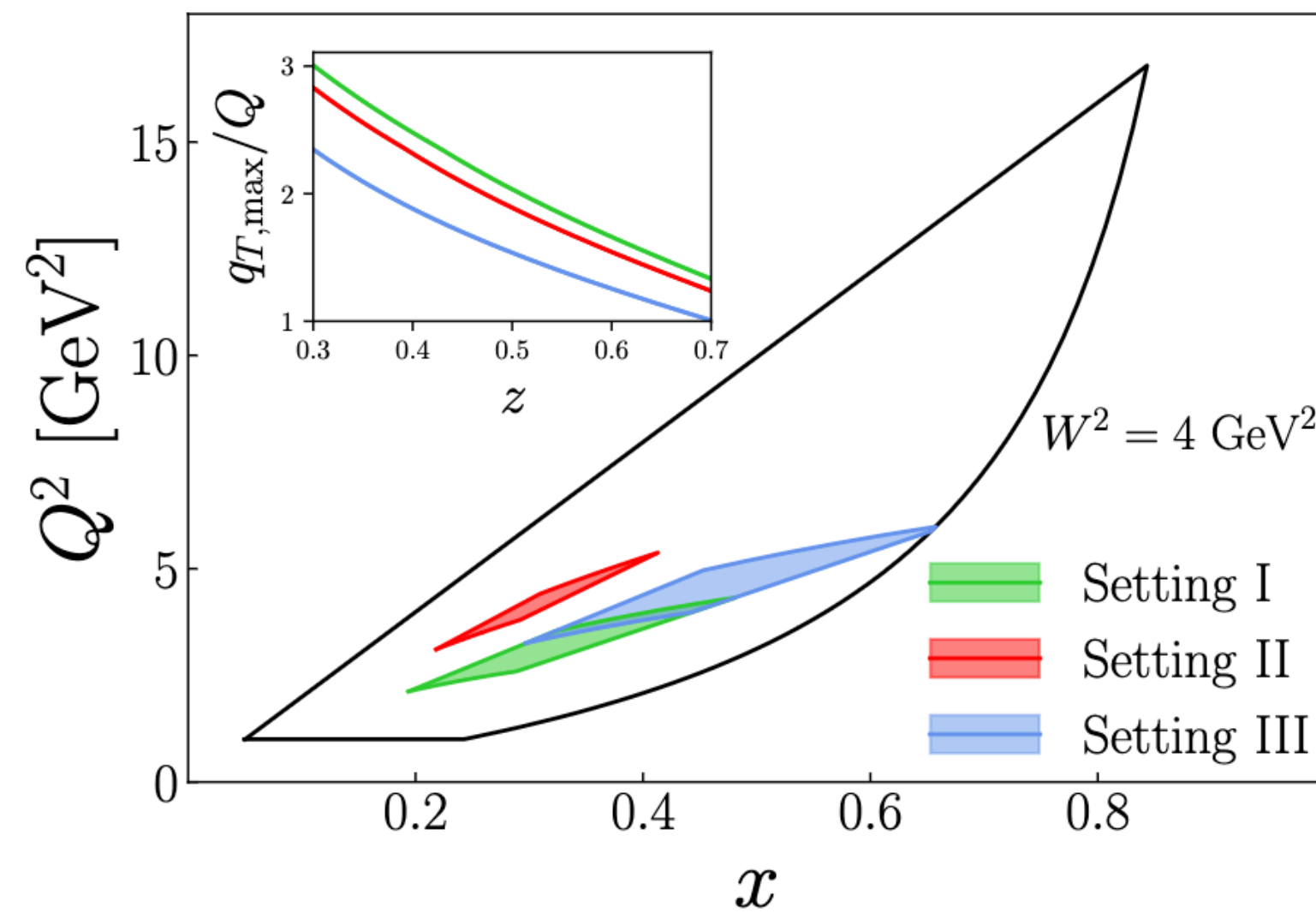
Hall C at JLab: a case study

Ongoing experimental program

E12-09-002, E12-09-017,
E12-13-007, E12-06-104,
PR12-23-014

Flavor, transverse momentum, and azimuthal dependence of charged pion multiplicities in SIDIS with 10.6 GeV electrons

Bosted *et al.*, arXiv:2510.03562v2 [hep-ex] (2025)



→ spectrometer measurements

→ high luminosity

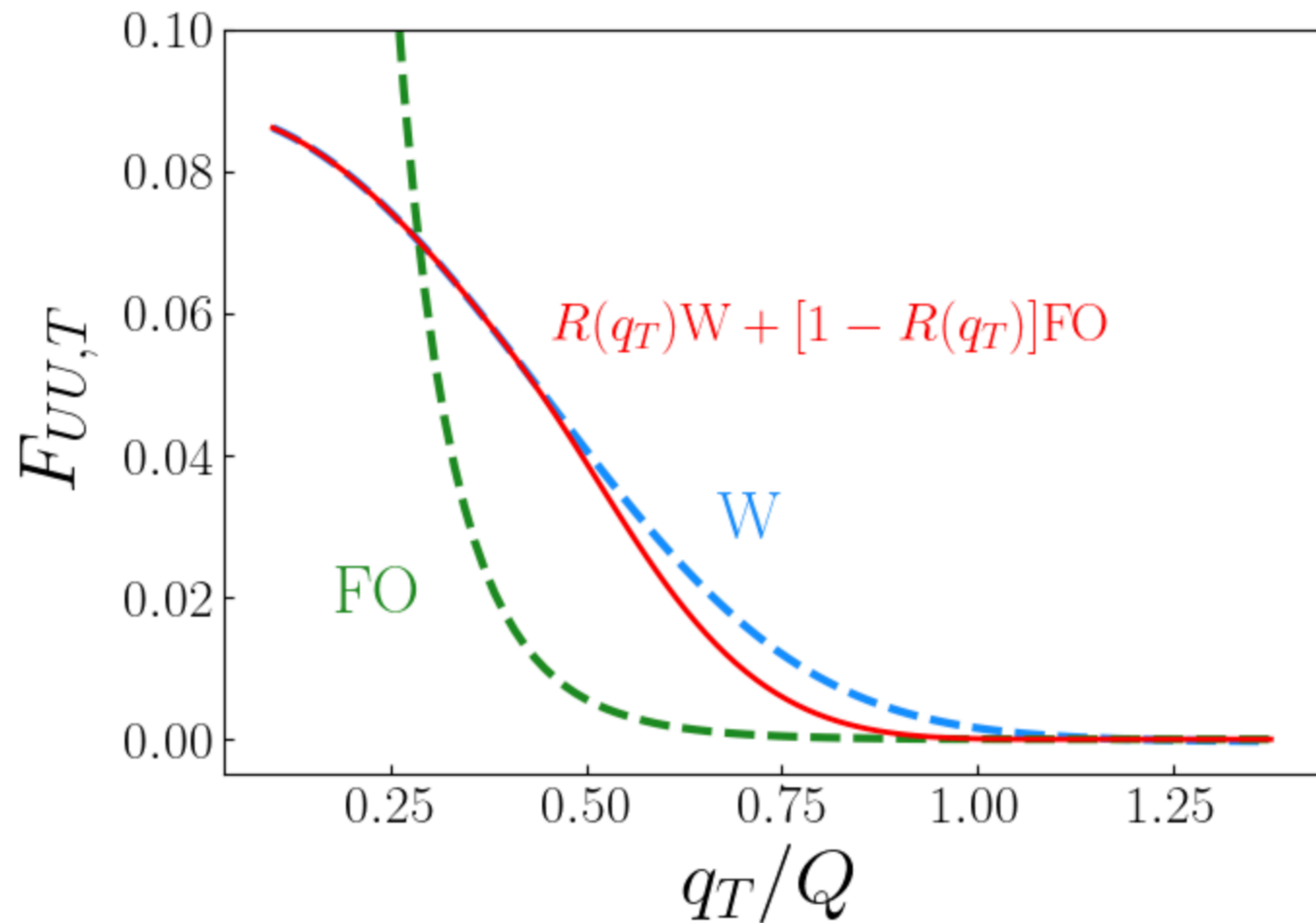
→ non-trivial

1) lab & Breit frame relation

2) phase space constraints

Case study setup

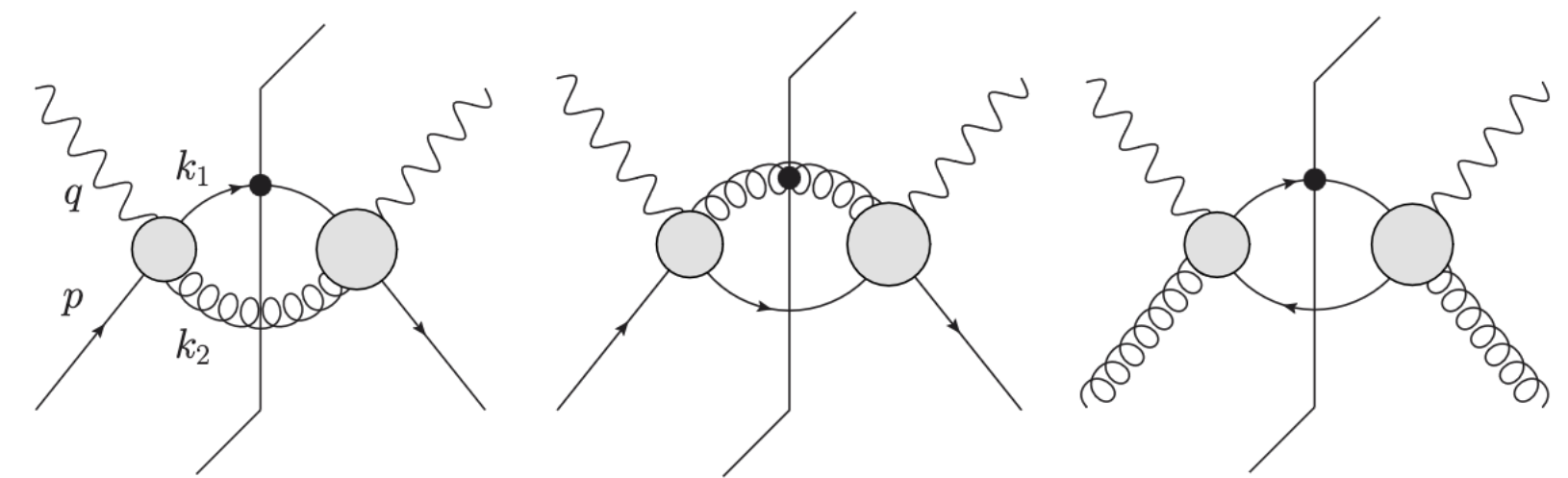
Goal: closure test for observable reconstruction



→ W term with GPM (only $F_{UU,T}$)

$$F_{UU,T} = \sum_a x e_a^2 f_{a/N}(x, Q^2) D_{h/a}(z, Q^2) \frac{\exp\left(-\frac{z^2 q_T^2}{z^2 \langle p_T^2 \rangle + \langle P_T^2 \rangle}\right)}{\pi\left(z^2 \langle p_T^2 \rangle + \langle P_T^2 \rangle\right)}$$

→ FO at LO (all structures)



Anselmino *et al.*, arXiv:1312.6261 [hep-ph] (2013)

Bacchetta, Boer, Diehl, Mulders arXiv:0803.0227 [hep-ph] (2008)

→ transition function to interpolate regions

Case study setup

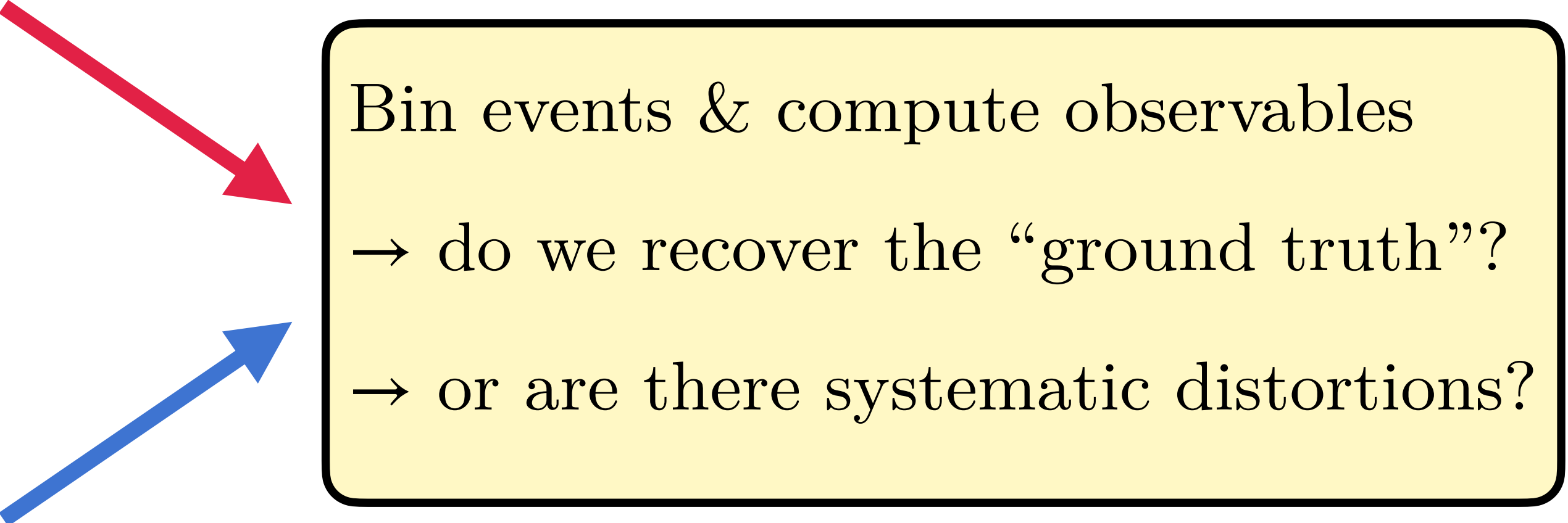
Goal: closure test for observable reconstruction

Generate events

- electron: (x, Q^2) spectrometer bin
- pions: $0.3 < z < 0.7$, 4π coverage

Make pion cuts

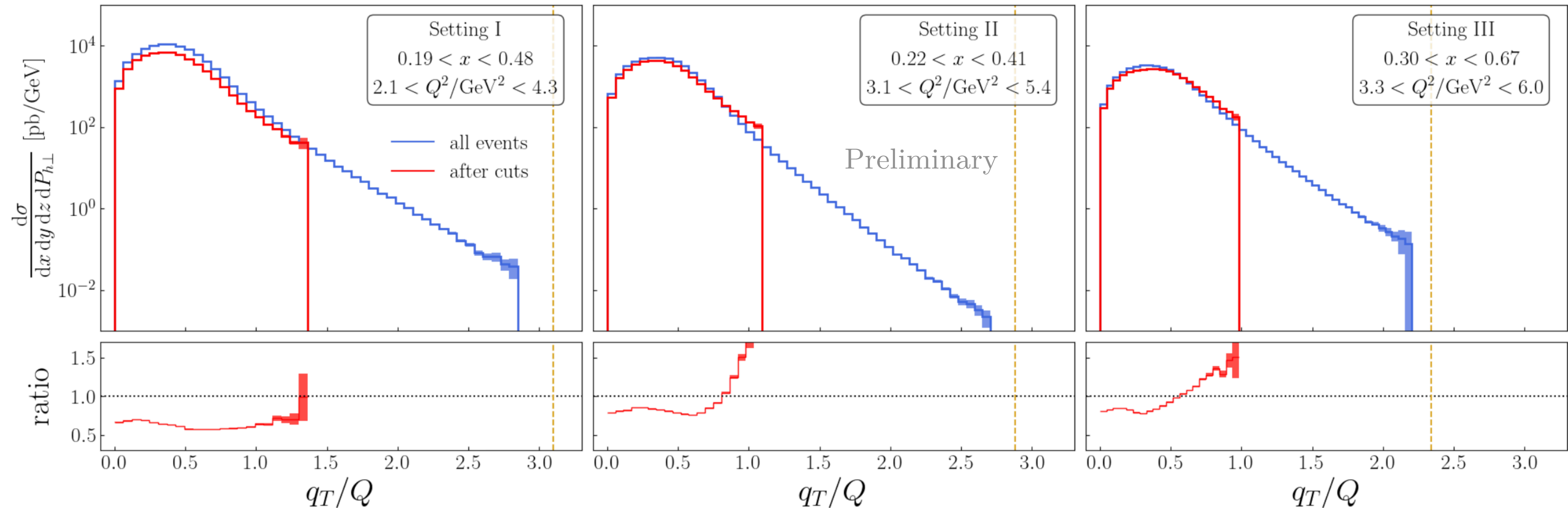
- pions: corresponding spectrometer coverage



Bin events & compute observables

- do we recover the “ground truth”?
- or are there systematic distortions?

The q_T spectrum



$$\frac{d\sigma}{d\Phi} \neq \int_{\mathcal{V}} d\Phi \frac{d\sigma}{d\Phi} A(\Phi) / \int_{\mathcal{V}} d\Phi A(\Phi)$$



Cross section and acceptance don't trivially factorize in Breit frame!

Observing a trend

MAP (solid — “ground truth”)

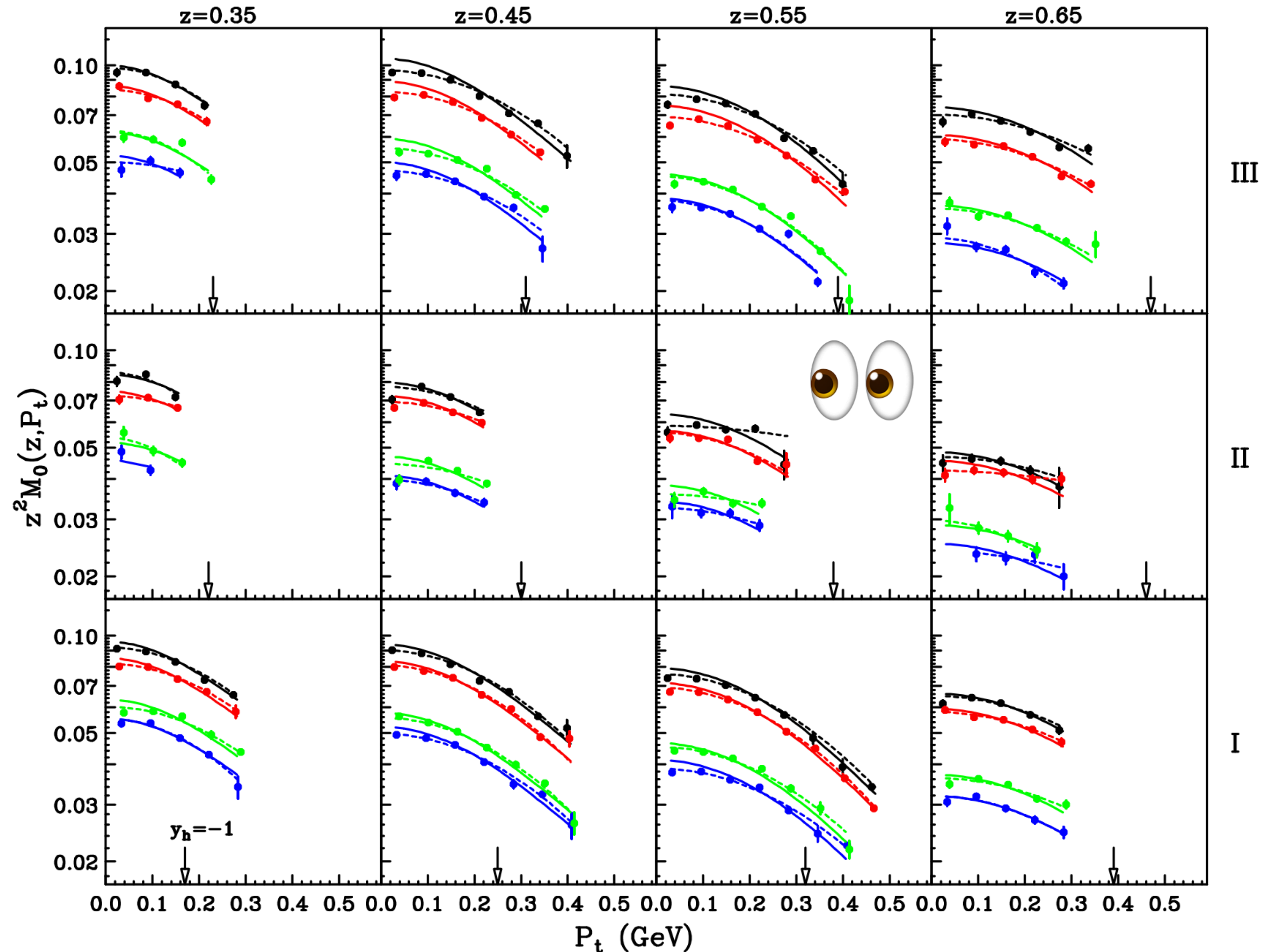
Hall C (dashed — reconstructed)

→ black: $p \rightarrow \pi^+$

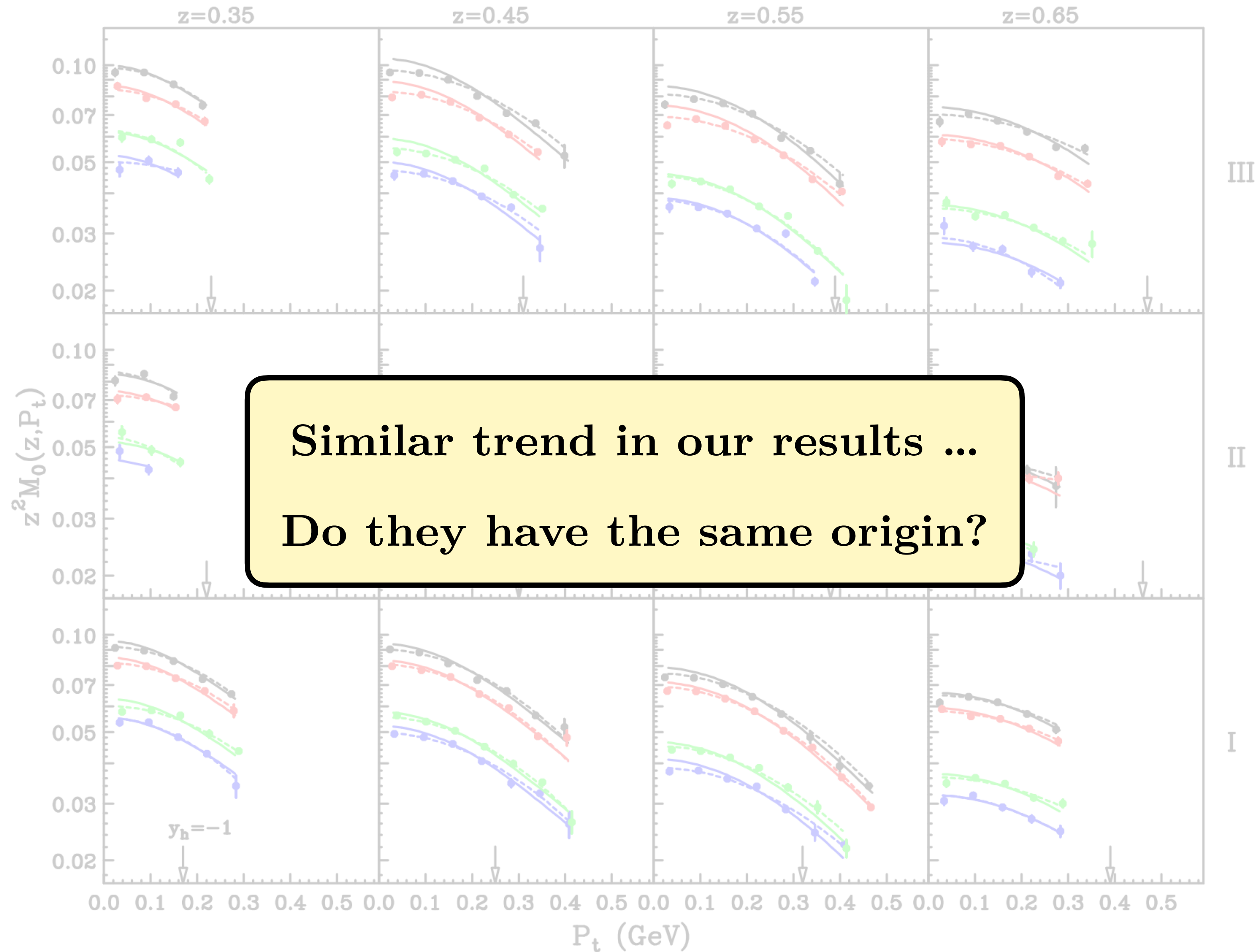
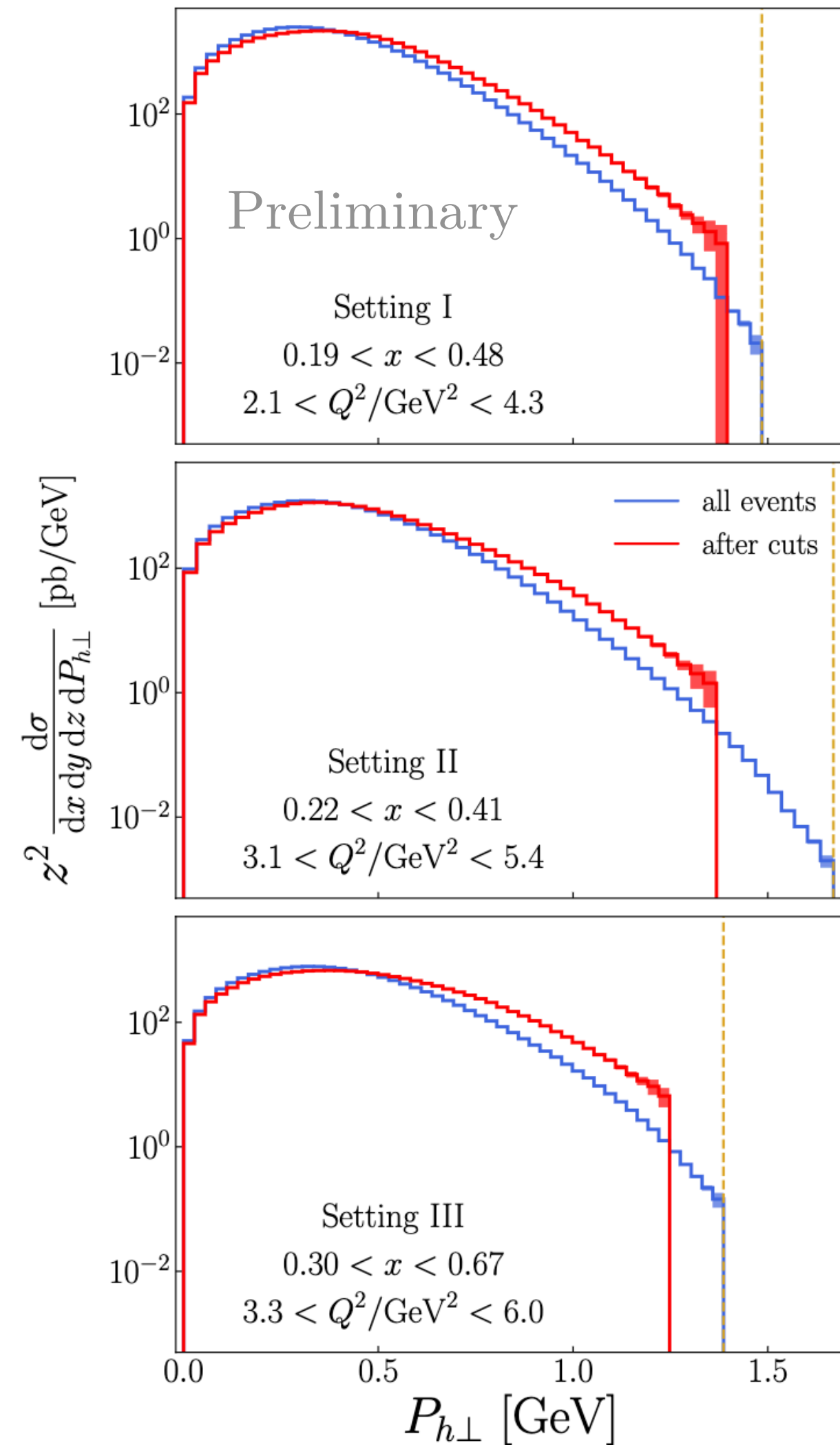
Measurements across $P_{h\perp}$

→ start smaller

→ fall off slower than MAP

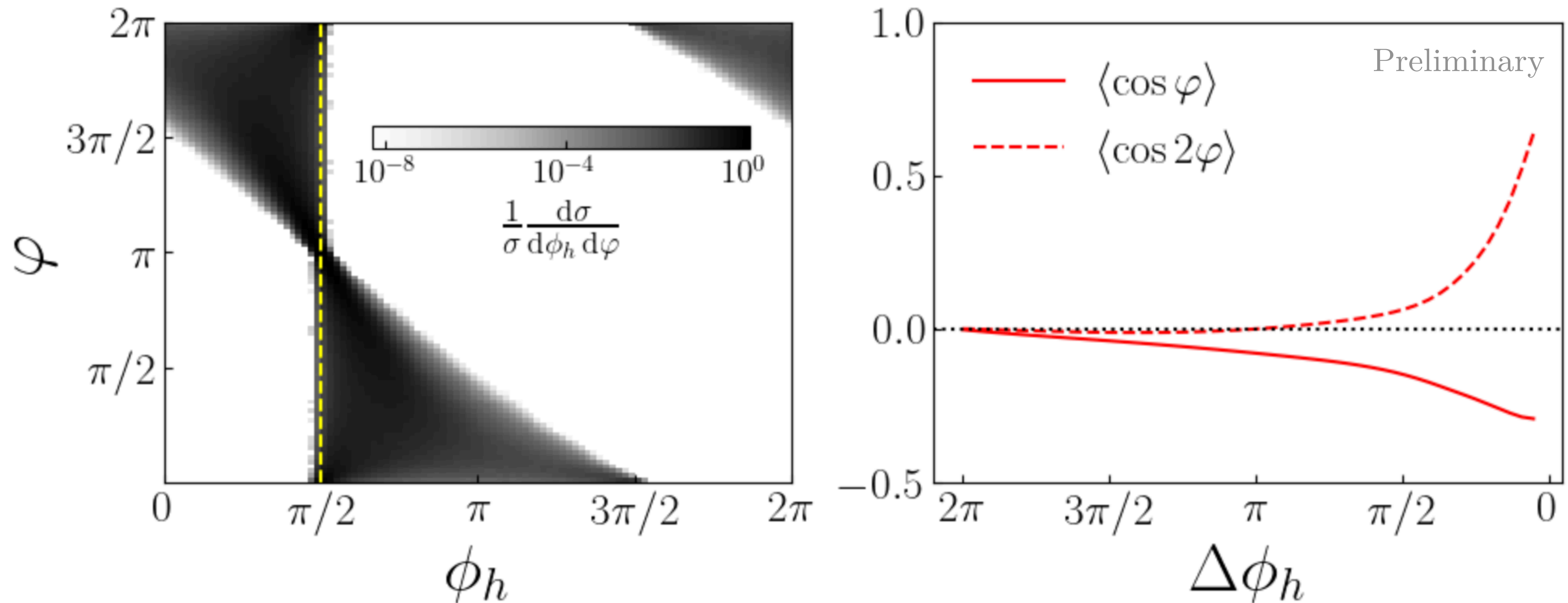


Observing a trend



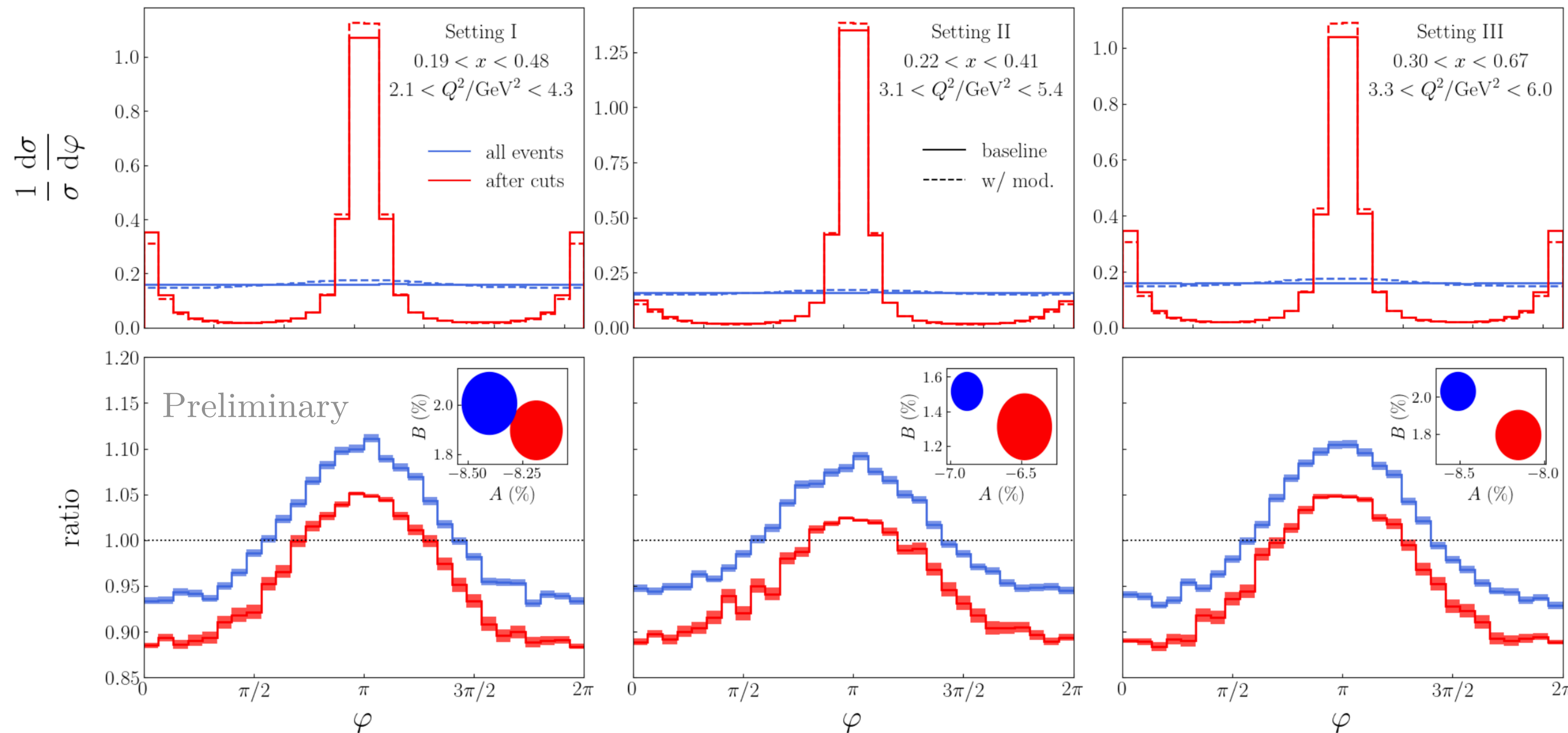
Similar trend in our results ...
 Do they have the same origin?

Azimuthal modulations



Acceptance induces arbitrary angular modulations in cross section ...

Azimuthal modulations



Solid: no modulation

Dashed: with modulation



Fit ratios to form

$$r = c + A \cos \varphi + B \cos 2\varphi$$



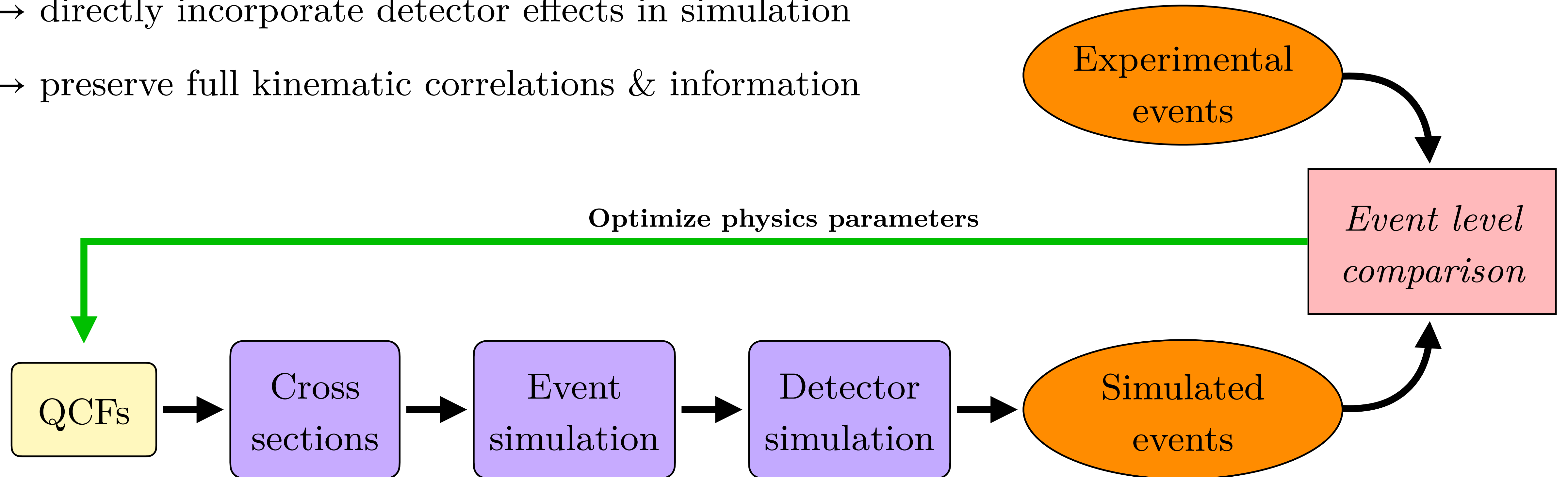
Closure test fails here

Simulation based inference

Essential problem: acceptance mixes non-trivially with cross section

Event-level analysis:

- directly incorporate detector effects in simulation
- preserve full kinematic correlations & information



Looking forward

SIDIS offers a rich physics landscape for future global analyses

→ indispensable probe of collinear & transverse proton structure

→ lots of challenges in formal/phenomenological description of q_T spectrum

This work:

→ demonstrated difficulty in reconstructing fundamental observables with non-trivial acceptance

→ Future — perform closure test with SBI & move toward event-level global analysis