(Our own) thoughts on TMDs

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Outline

Pavel's e-mail questions:

1. What will be known about the TMD structure of hadrons in **5, 10, and 15 years from now**?

2. How will **our own research** contribute to the progress in understanding of TMDs?

3. What **critical physics questions** must be solved to make progress?

4. What **experimental measurements** can provide incisive information?

5. What will be necessary to **extend TMD formalisms** to new scattering processes?

6. How will we understand the interplay of **perturbative** and **non-perturbative** QCD effects?

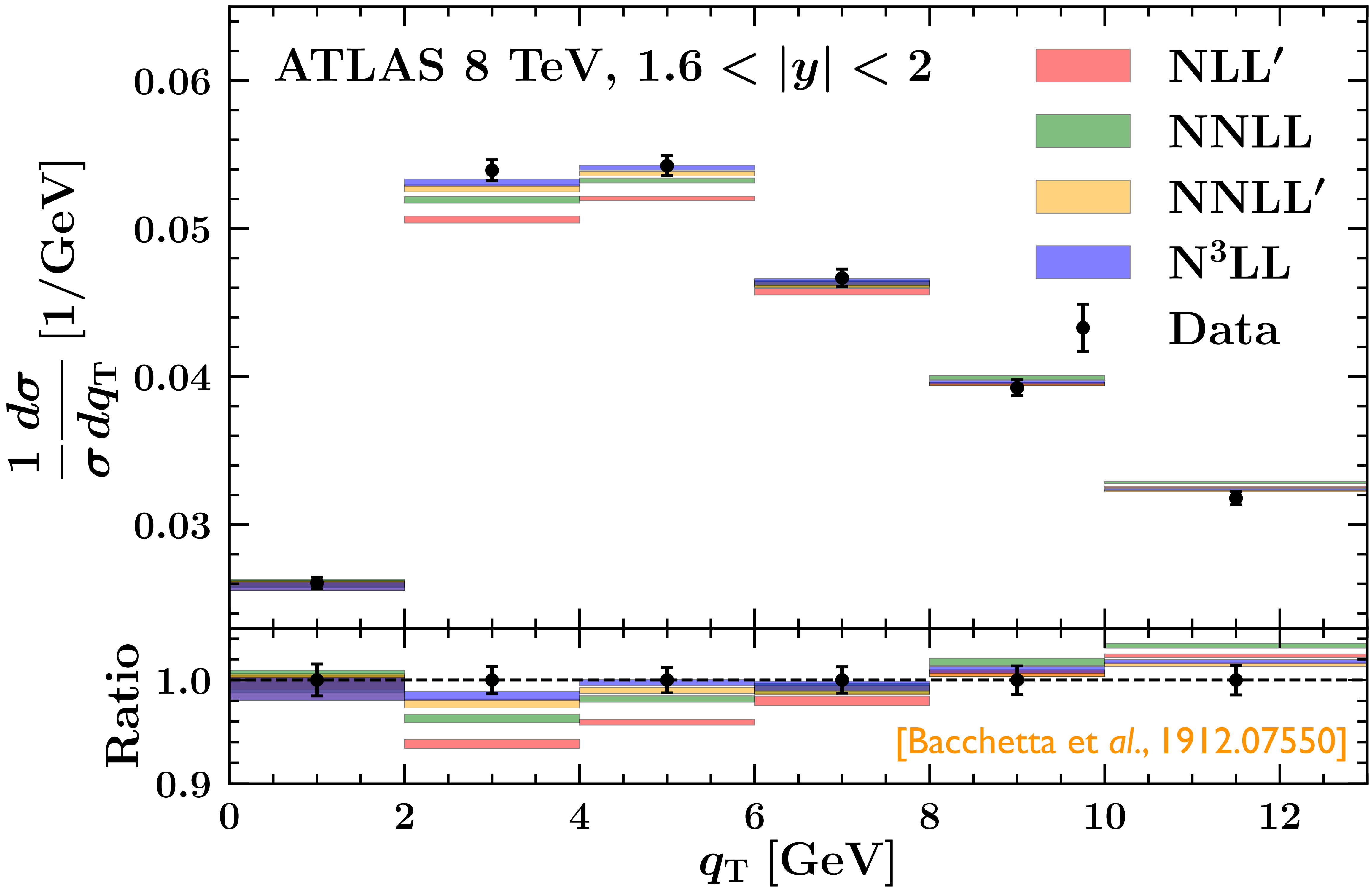
7. How can the **QCD community** help with addressing these questions?

1) 5, 10, and 15 years from now

- Perhaps the hardest question, our answer is “we just don’t know”.
- We can try to *guess* based on our view of the current research directions.
- Next 5 years:
  - establishment of **TMD precision determinations**,
  - better exploitation of the **LHC** data (it started less than two years ago),
  - better **separation** between non-perturbative evolution and “intrinsic k_T”,
  - TMD **flavour** dependence.
- Next 10 year:
  - **gluon** TMD?
  - precision physics with **polarised TMDs**?
- Next 15 years:
  - the EIC will kick in and will surely impact TMDs, hard to foresee how though.
  - great potential to unravel hadron structure (TMD : EIC $\stackrel{?}{=}$ PDF : HERA).
  - Nuclear TMDs?

2) Our own research

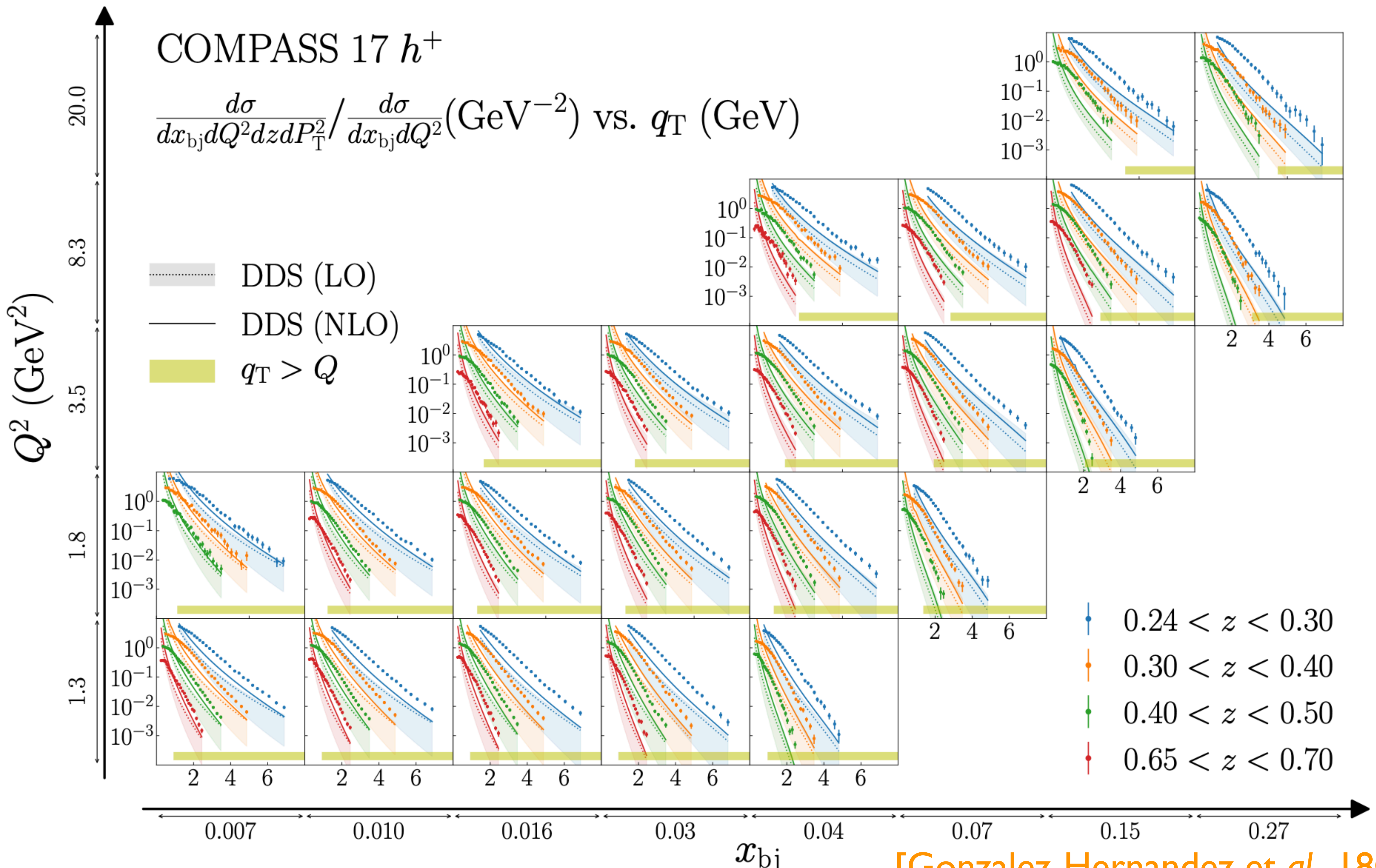
- A fit of **TMD PDFs** on Drell-Yan world data up N³LL accuracy:



- Now working on SIDIS data and thus TMD FFs.

3) Critical physics questions

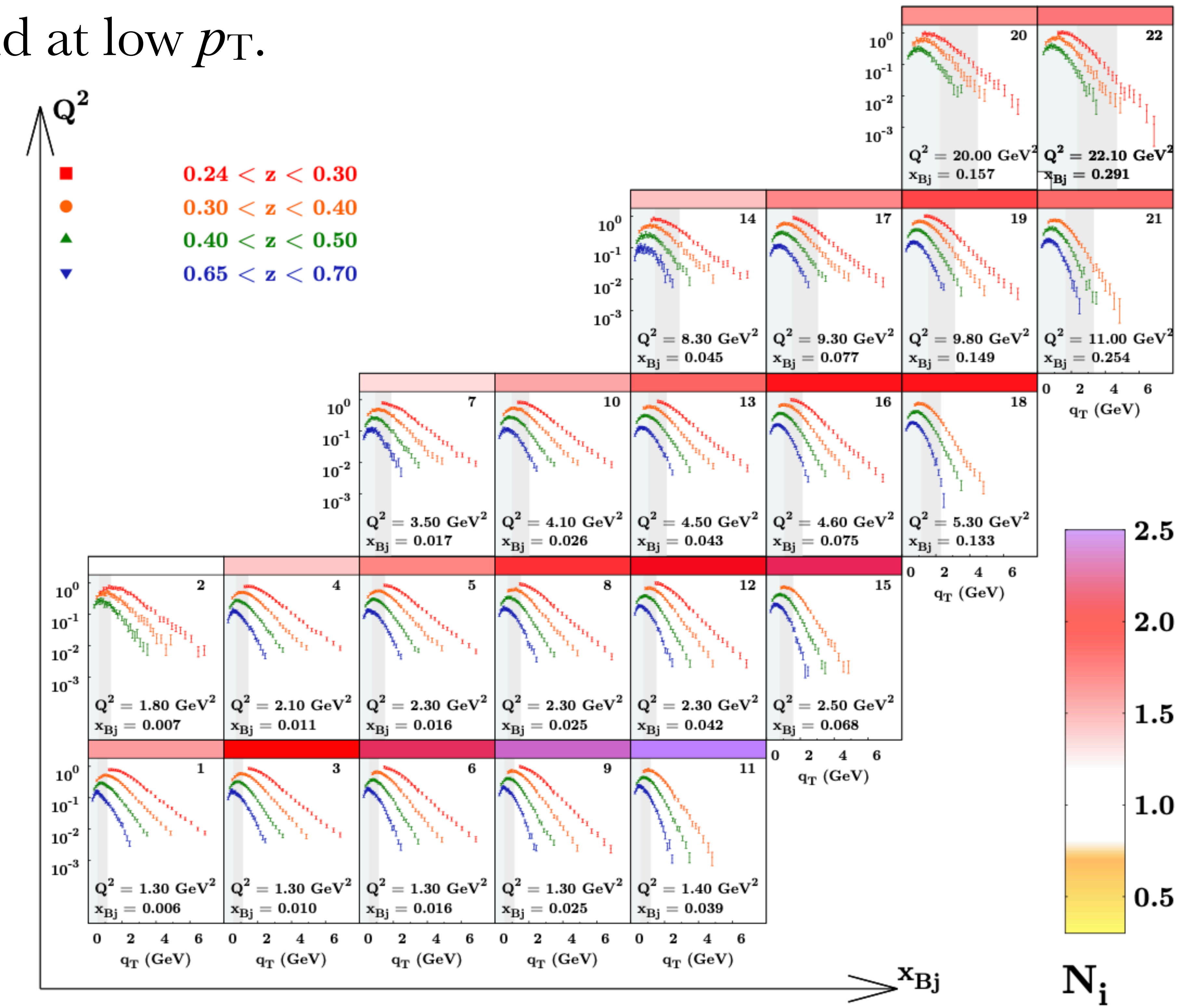
- SIDIS data from HERMES and COMPASS case is a still-standing issue:
  - at high p_T…



[Gonzalez-Hernandez et *al.*, 1808.04396]

3) Critical physics questions

- SIDIS data from HERMES and COMPASS case is a still-standing issue:
  - … and at low p_T.

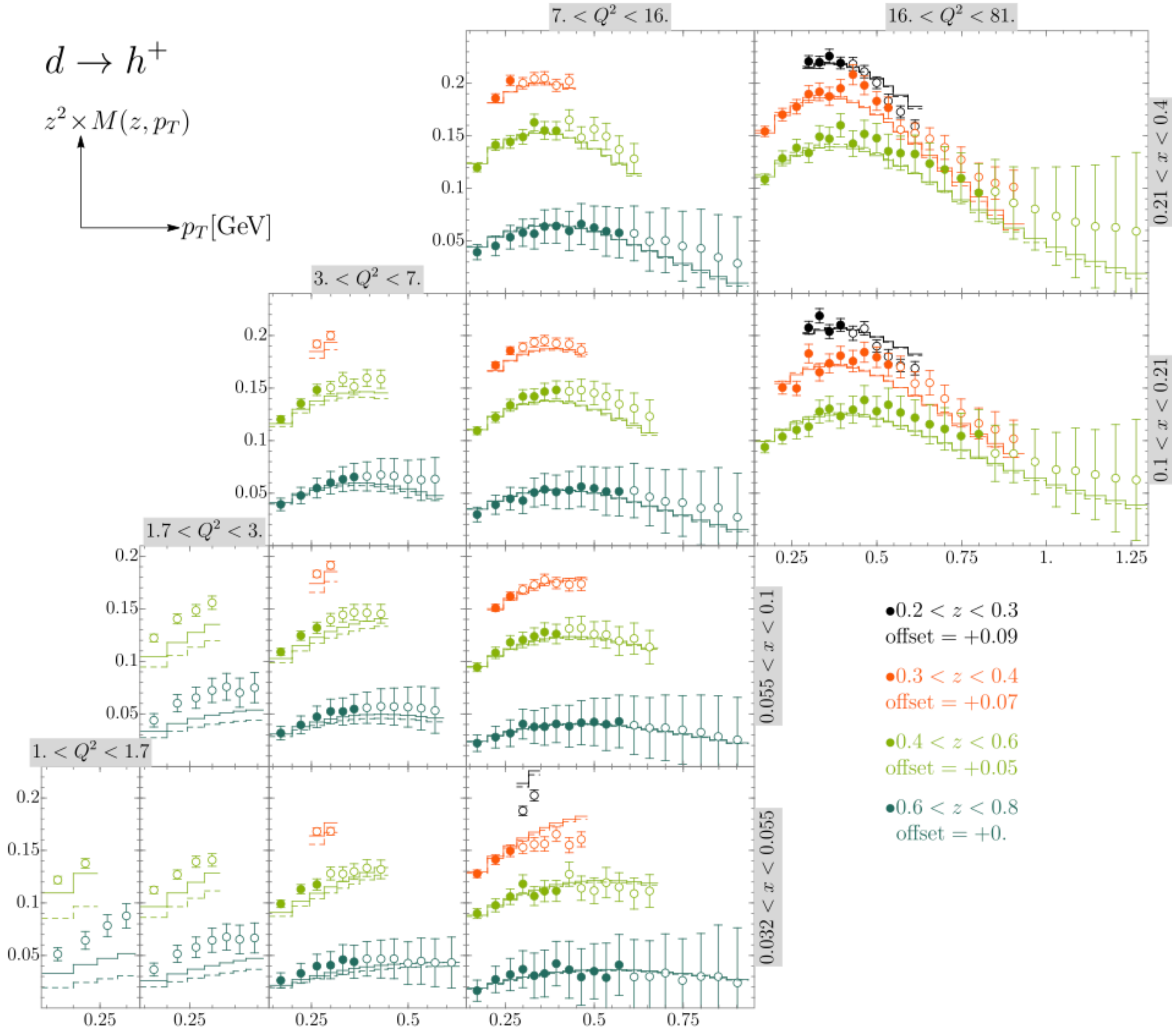


[Gonzalez-Hernandez et *al*., PoS(DIS2019)176]

see also [F. Piacenza, 2020, Ph.D. Thesis]

3) Critical physics questions

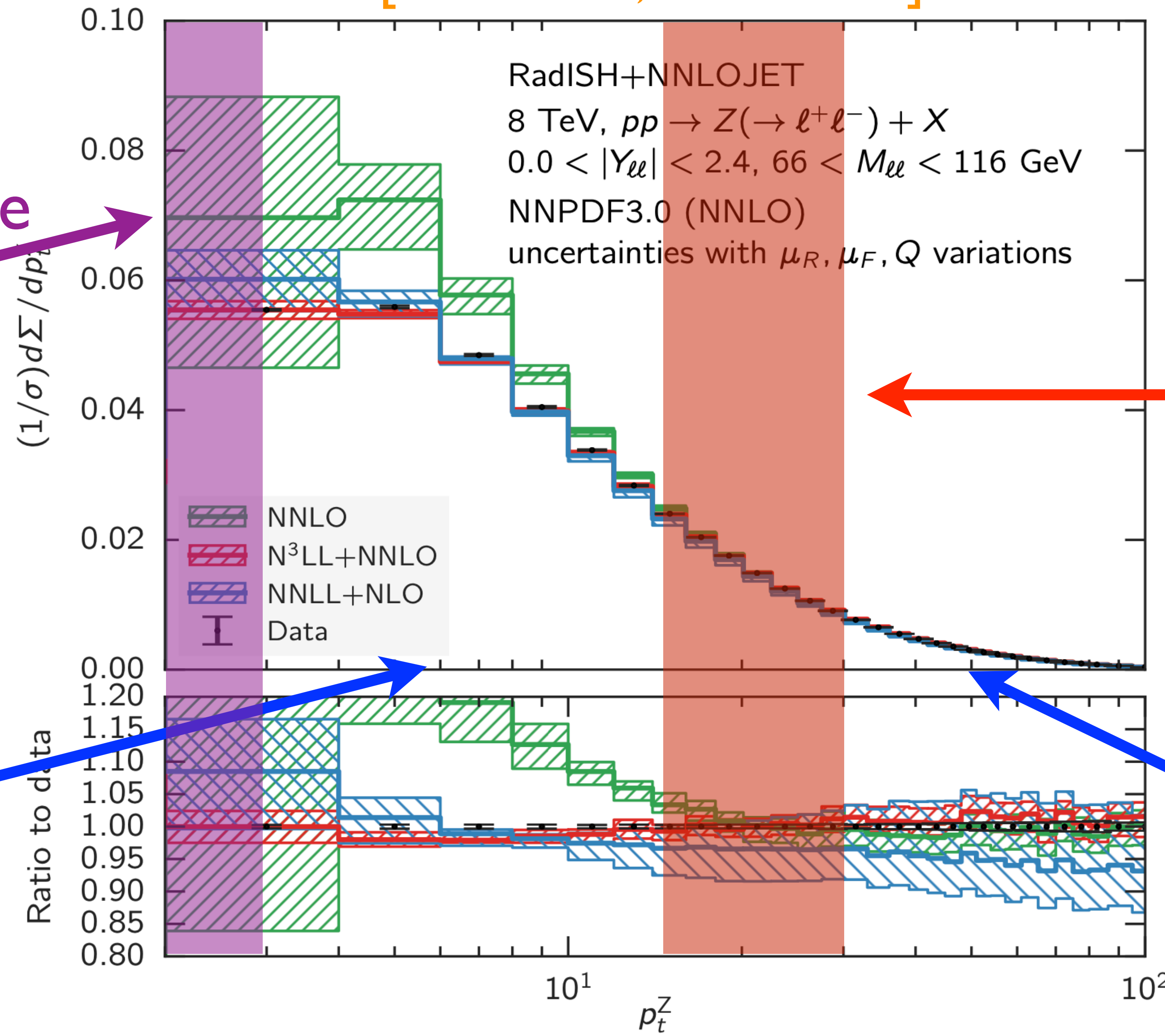
- SIDIS data from HERMES and COMPASS case is a still-standing issue:
  - no problem found by Scimemi and Vladimirov at low p_T. [1912.06532]



3) Critical physics questions

- **Matching** between TMD and collinear factorisations:

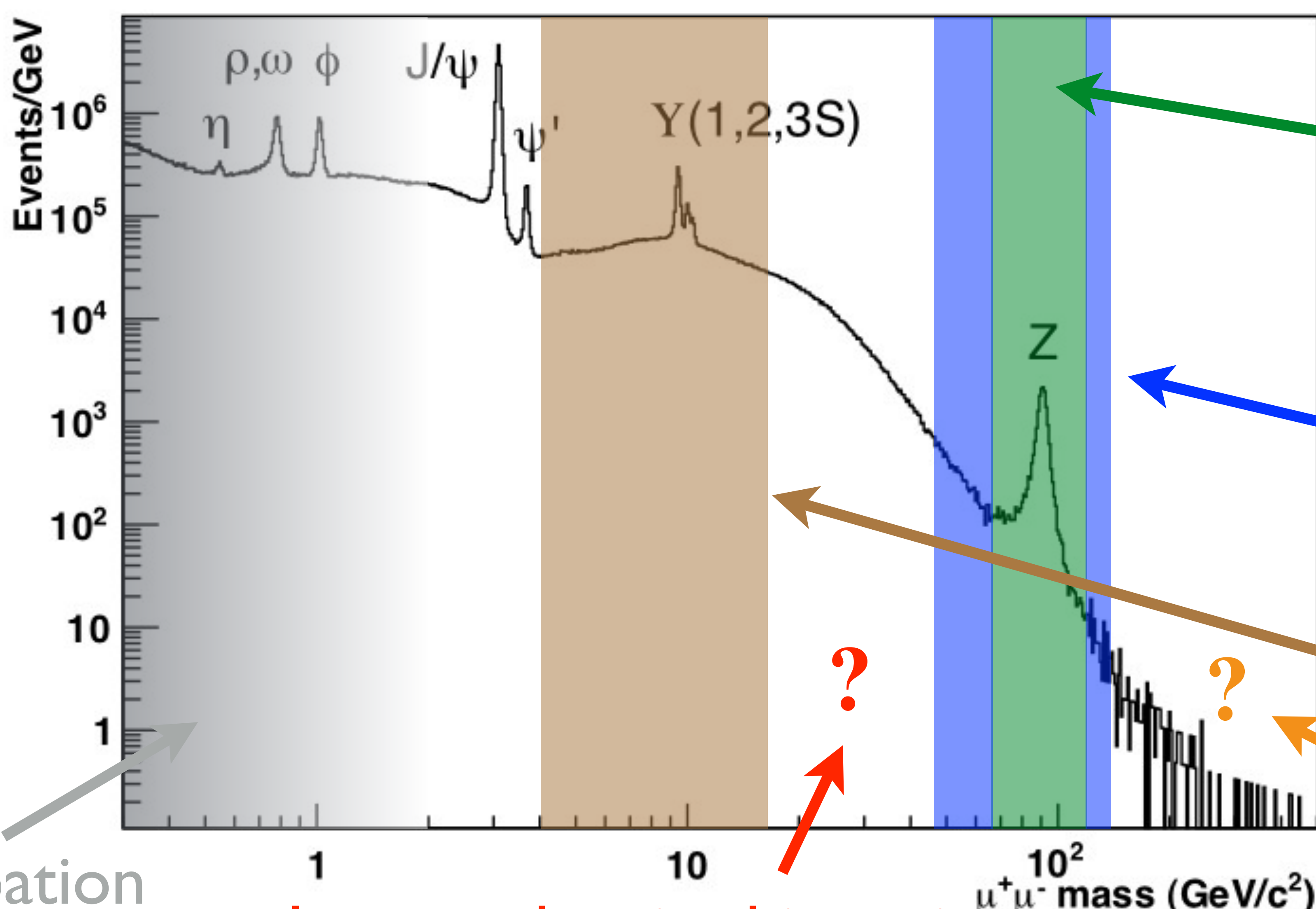
[Bizon et *al.*, 1805.05916]



- Well-understood procedure at the LHC energies where usually $Q \gg \Lambda_{\rm QCD}$:
  - clear separation of TMD and collinear, non-perturbative confined to very low $q_{\rm T}$.
- Not so much so for current (and future) SIDIS data due to smaller Q:
  - need to *identify* and *study* the transition region.

4) Experimental measurements

- TMD factorisation applies for $q_T \ll Q$:
  - if $q_T \gg \Lambda_{QCD}$, TMDs ~ collinear distributions (times a perturbative matching),
  - the region $q_T \simeq \Lambda_{QCD}$ is relevant for hadron structure, no matter how large Q,
  - As Q increases the cross section drops and low q_T becomes hard to access.



Precise data from the LHC and Tevatron

Less precise data from the LHC that extends to low q_T

Some poor old fixed-target data

Perturbation theory breaking and resonances

Low-q_T data in this region absent but would be very welcome!

Is $q_T \simeq \Lambda_{QCD}$ attainable with good precision here?

4) Experimental measurements

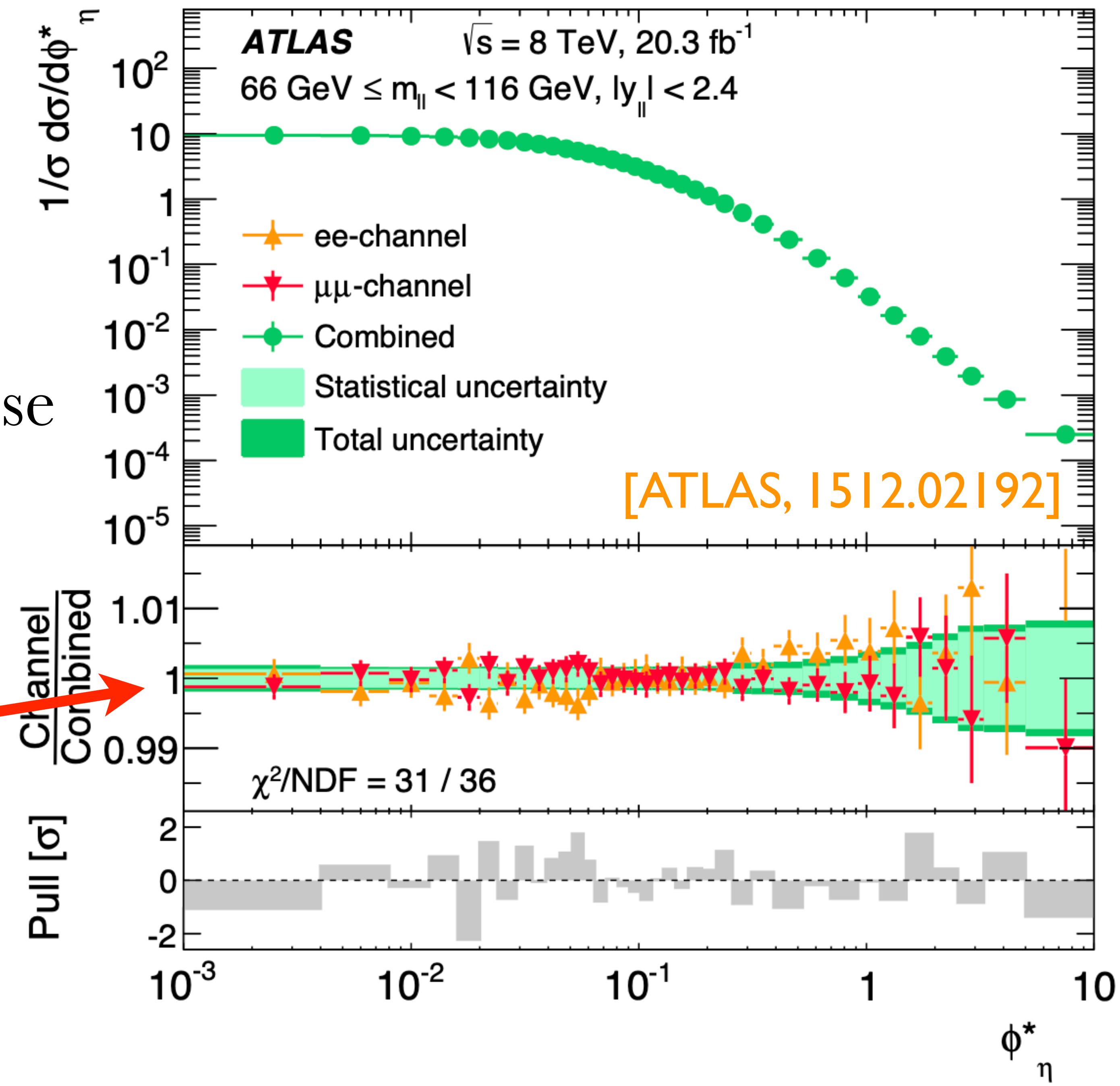
- Observables other than the q_T of the vector boson can be considered.
- An example that we are currently considering is φ^*:

$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi_\ell}{2}\right)\sqrt{1-\tanh^2\left(\frac{\Delta\eta_\ell}{2}\right)}$$

[Banfi et *al.*, 1009.1580]

- Experimentally very clean because it only involves angles.

Insanely precise!



- Since small φ^* is mapped onto small q_T, this observable is expected to carry important information on hadron structure.

5) Extend TMD formalisms

- TMD factorisation has been proven for:
  - inclusive Drell-Yan production,
  - semi-inclusive deep-inelastic scattering,
  - inclusive e^+e^- annihilation into two hadrons.
- Generalised TMD factorisation **breaking** has instead been proven for:

$$H_1 + H_2 \to H_3 + H_4 + X$$

[Rogers and Mulders, 1001.2977]
[Collins and Qiu, 0705.2141]
[Collins, 0708.4410]

- How about?

$$H_1 + H_2 \to H_3 + \gamma^*/Z + X$$
$$e + H_1 \to H_2 + H_3 + X$$

- Understanding factorisation breaking effects is important to exploit data.

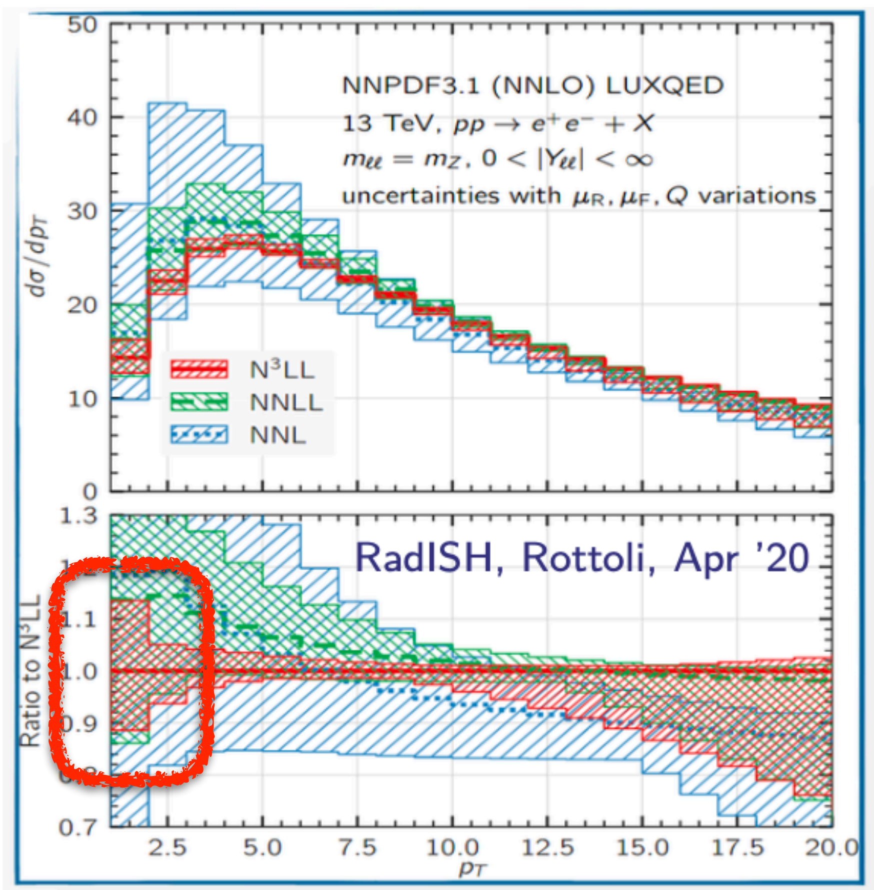
- Quarkonium (J/ψ, η_c,etc.) production is also receiving attention:

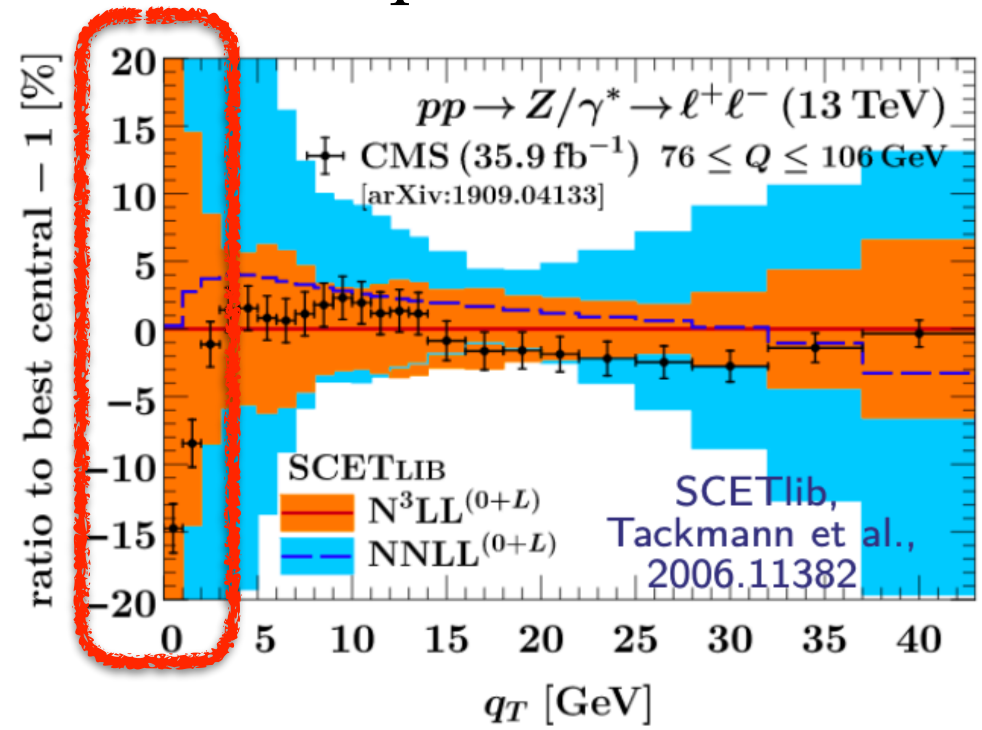
e.g. [Echevarria, 1907.06494]

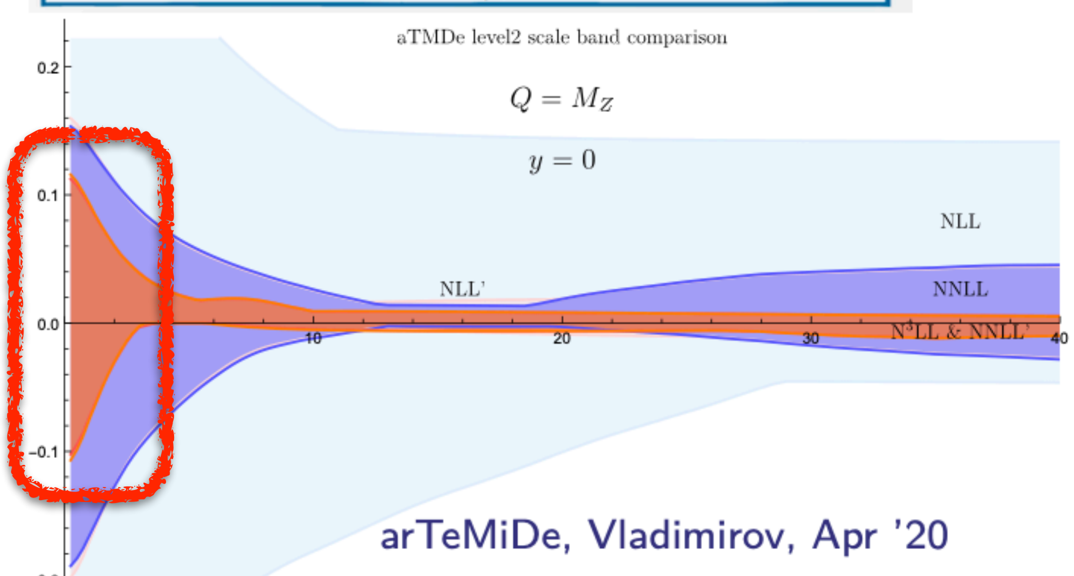
  - important for the gluon TMD,
  - appropriate factorisation theorems are necessary.

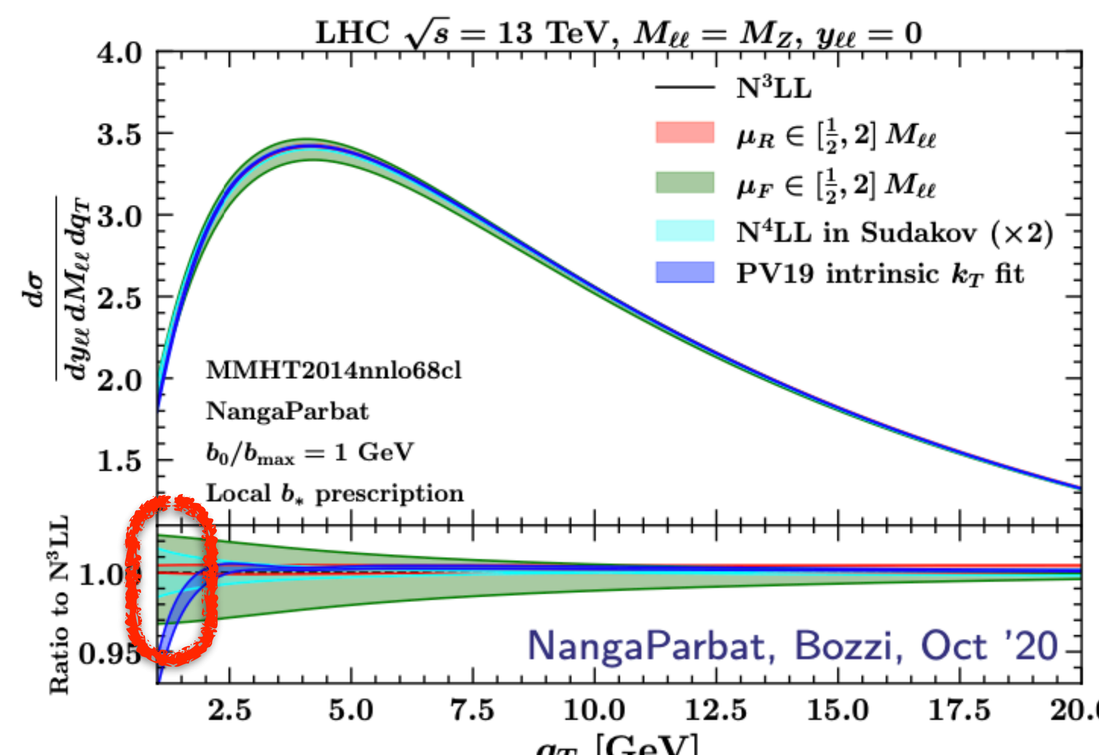
6) Interplay of Pert. and NP

- Understanding of **theoretical uncertainties** is crucial to achieve a reliable extraction of the non-perturbative components from data.









[T. Cridge, last EWWG general meeting]

7) QCD community

- Let us behave as a **coherent** community:
  - more communication between low- and high-energy communities,

$$\sigma = \underbrace{\hat{\sigma}}_{\text{high energy}} \otimes \underbrace{f}_{\text{low energy}}$$

  - more communication between collinear and TMD communities,
  - much to be learned on the hadron structure from the **GPD** approach.