Lecture 2: Phenomenological aspects of Drell-Yan and Higgs production

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Outline

- Historical importance of Drell-Yan production:
  - the discovery of charm, bottom, and Z/W weak bosons.
- Modern phenomenological implications of Drell-Yan production:
  - constraints on PDFs and the mass of the W boson,
  - importance of higher-order corrections,
  - resummation at work.
- Higgs production:
  - $gg \to H + X$ at fixed order and resummed,
  - some phenomenological implications of $gg \to H + X \to \gamma\gamma + X$

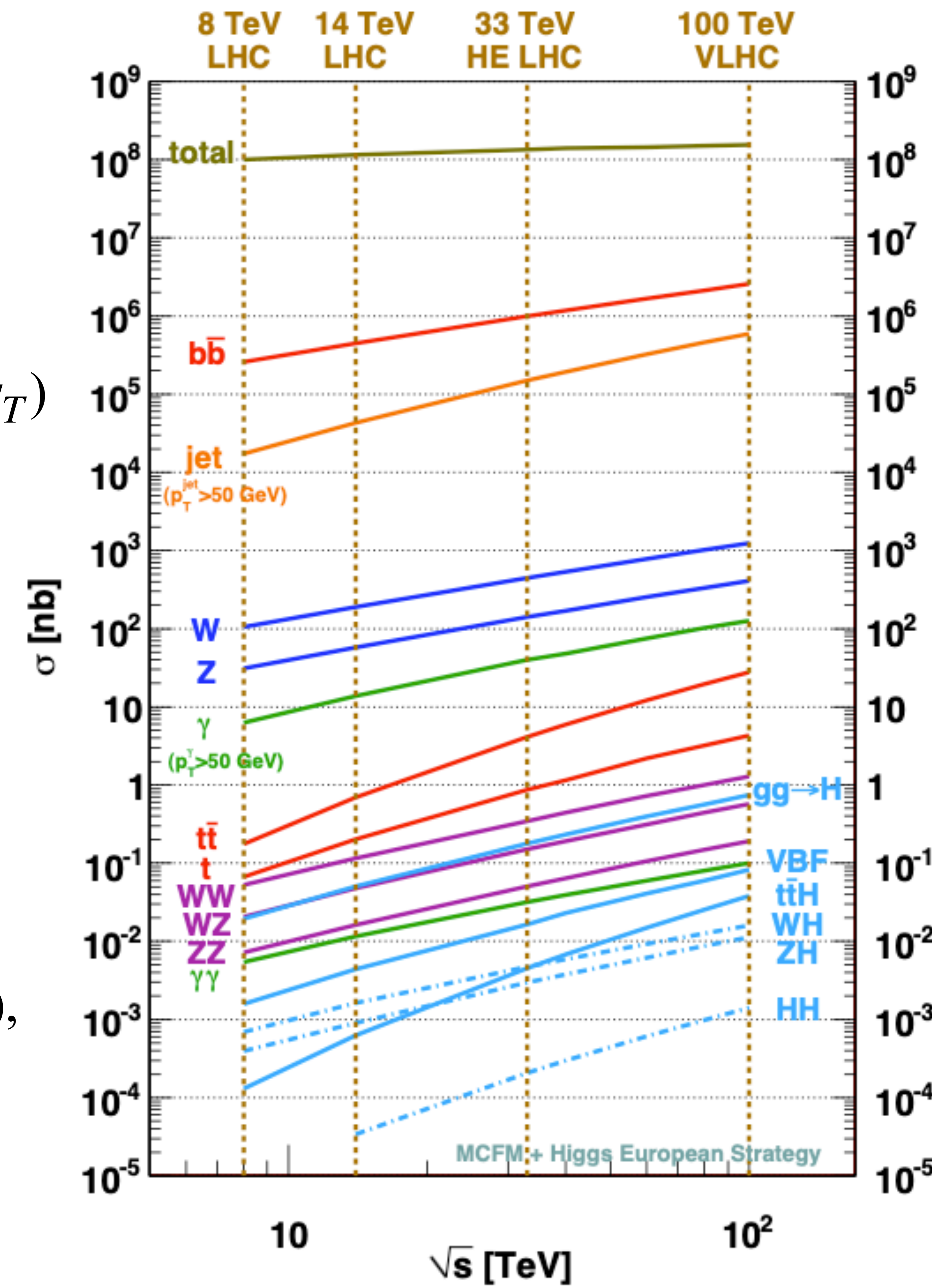
How much Drell-Yan and Higgs?

Drell-Yan production (Z and W):

- large cross section,
- clean final states (leptons and missing E_T),
- an additional jet (*e.g.* for measuring the q_T) leaves the cross section large,
- ~30(10)% of W(Z)'s decay leptonically,
- this all allows for precise measurements.
- theoretically well-understood.

Higgs production:

- cross section much smaller ($gg \to H$ largest),
- harder to measure,
- harder to extract information.



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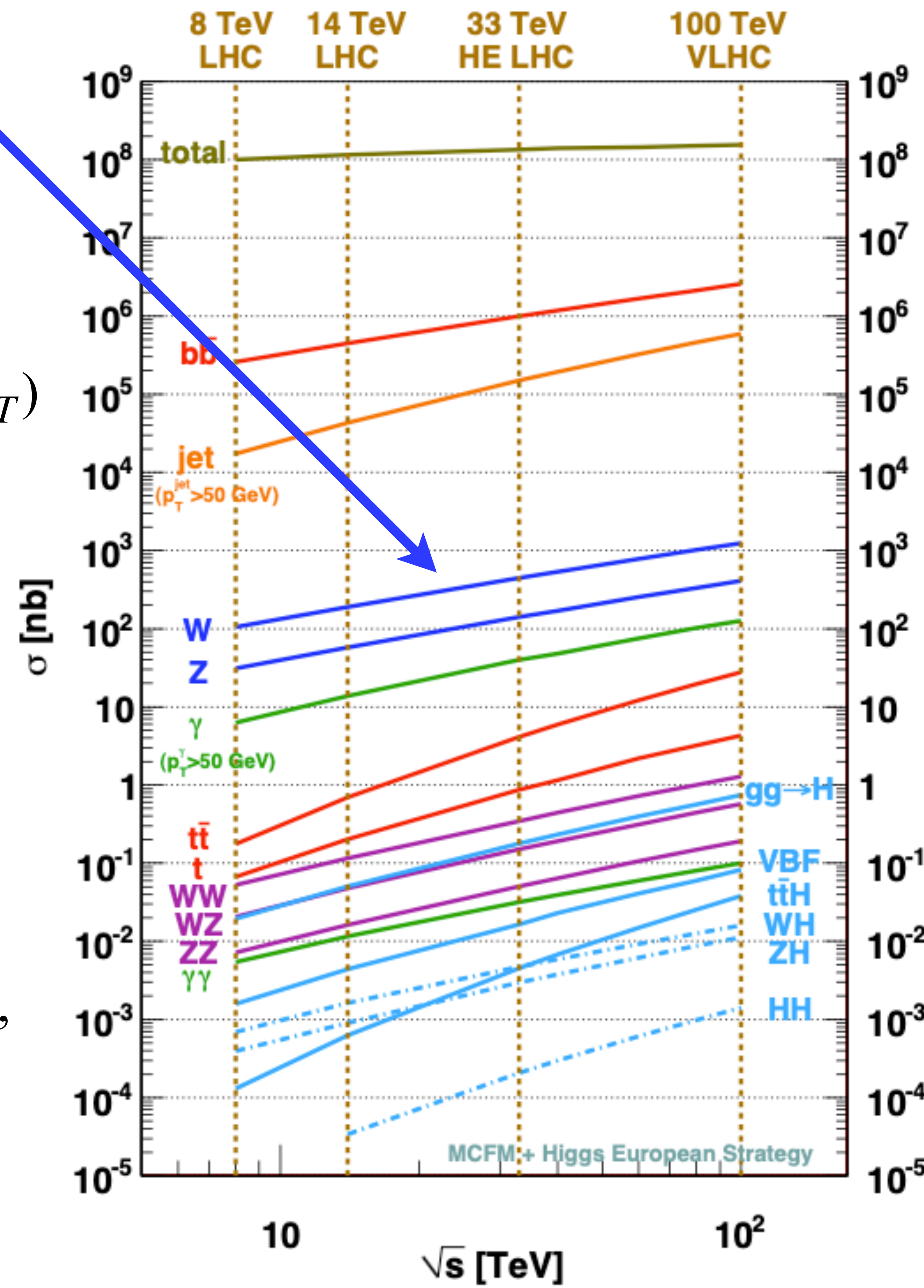

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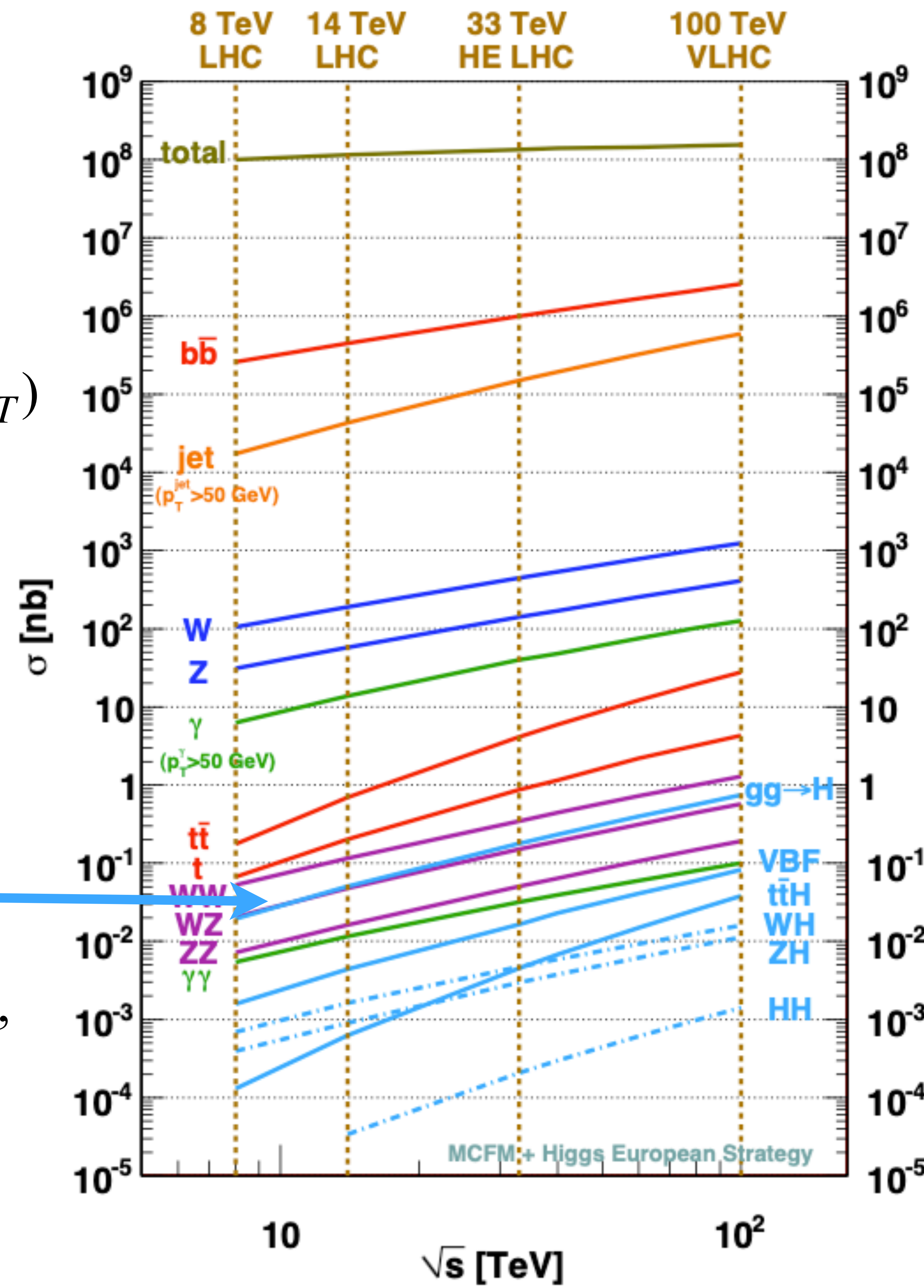
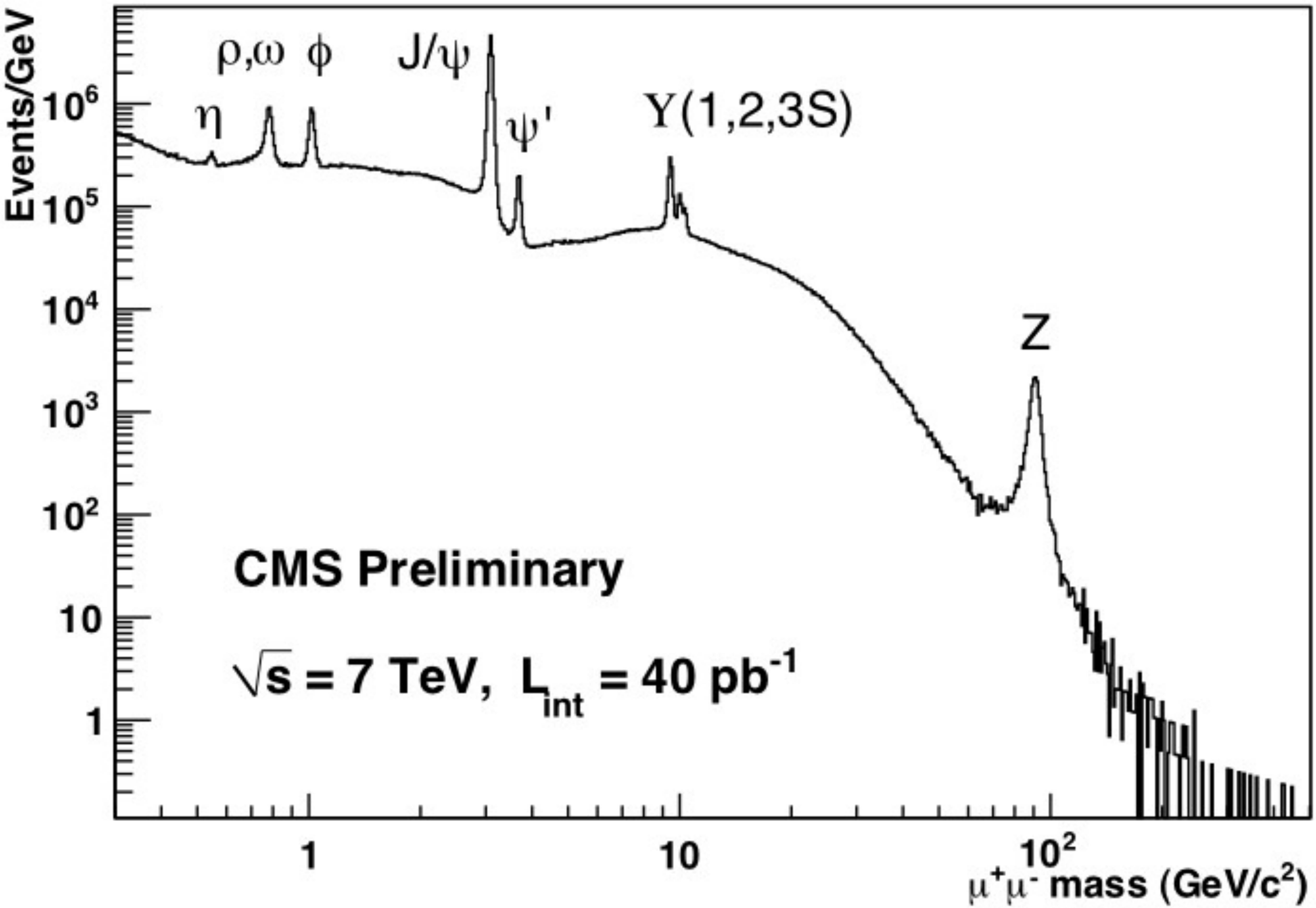


The Drell-Yan mass spectrum



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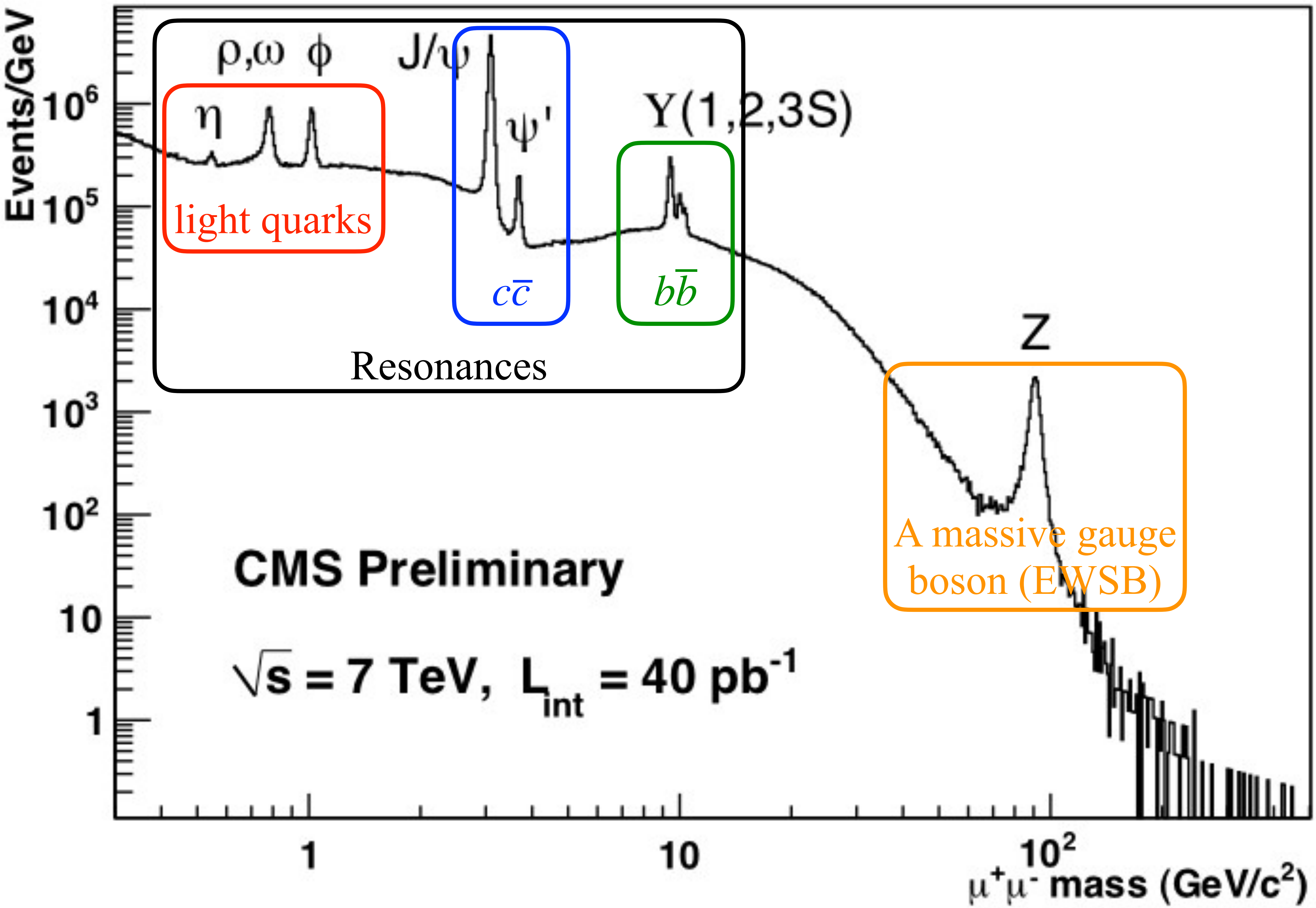
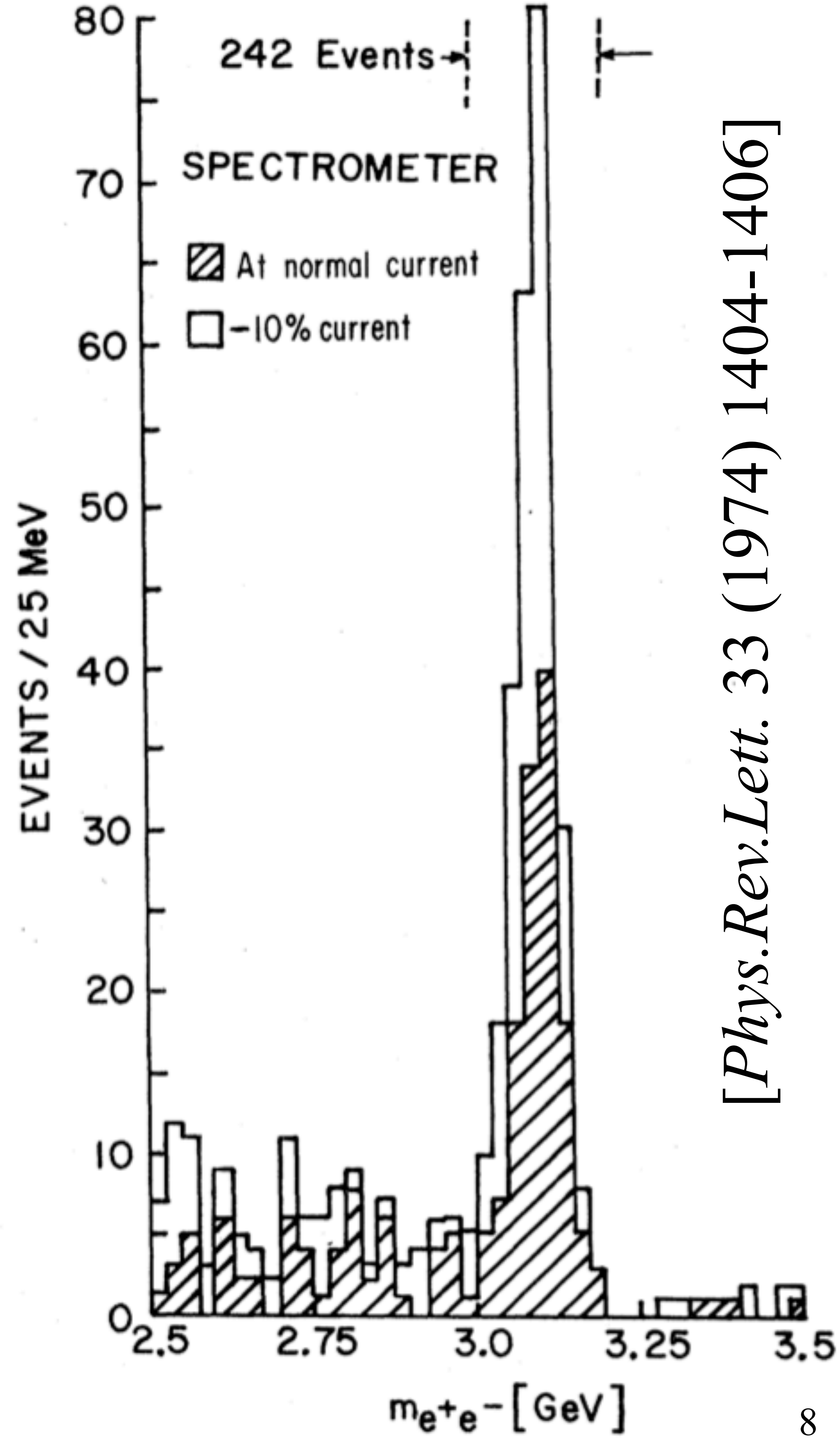


The discovery of the charm: the J/ψ

In 1970, Glashow, Iliopoulos and Maiani (GIM) postulated the existence of a new quark favour: the **charm quark** [*Phys.Rev.D* 2 (1970) 1285-1292]:

- originally conceived to explain the suppression of FCNC processes (they only occur at one loop),
- on top of u, d, and s, GIM introduced a **4th quark** flavour to complete the second generation of quarks.
- Like other quarks, the charm can form bound states (**resonances**).
- In 1974, the BNL observed a very narrow resonance at $m_{e^+e^-} = 3.1$ GeV in the invariant mass of the electron pair in p+Be $\to e^+ + e^- + X$ (**Drell-Yan**): the $J(J/\psi)$ hadron was observed for the fist time and thus the charm discovered.
- The valence structure of the J/ψ is $c\bar{c}$. Therefore, the mass of the J/ψ suggests $m_c \sim 1.5$ GeV. The current PDG value is $m_c(m_c) = 1.27 \pm 0.02$ GeV.

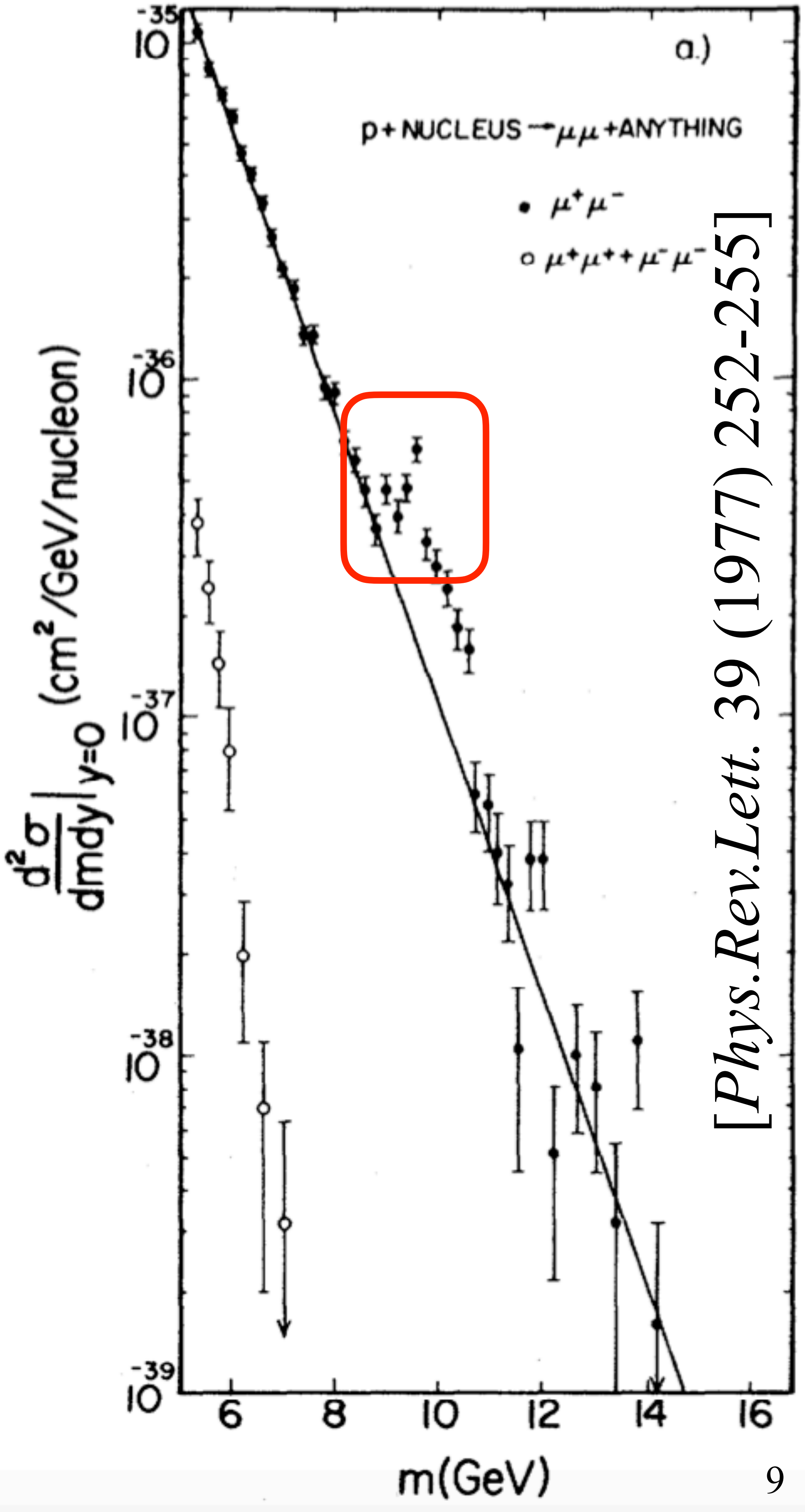


[*Phys.Rev.Lett.* 33 (1974) 1404-1406]

The discovery of the bottom: the Υ

In 1977, the E288 experiment at Fermilab observed a resonance at $m_{\mu^+\mu^-} = 9.5$ GeV in the invariant mass of the muon pair in $p+(\mathrm{Cu, Pt}) \to \mu^+ + \mu^- + X$ (**Drell-Yan**): the Υ hadron was observed for the first time and the **bottom** (or **beauty**) discovered.

- The valence structure of the Υ is $b\bar{b}$. Therefore, the mass of the Υ suggests $m_b \sim 4.7$ GeV. The current PDG value is $m_b(m_b) = 4.18^{+0.03}_{-0.02}$ GeV.
- The existence of a fifth quark flavour immediately triggered the hypothesis of a **sixth quark**, the **top**, to complete the third quark generation.
- The top quark was discovered later in 1995 at Fermilab by the the **Tevatron** experiments CDF and D0.
- The presence of a third family and the consequent 3×3 mixing matrix (CKM) between up- and down-type quarks introduced the possibility of **CP violation** in the Standard Model.

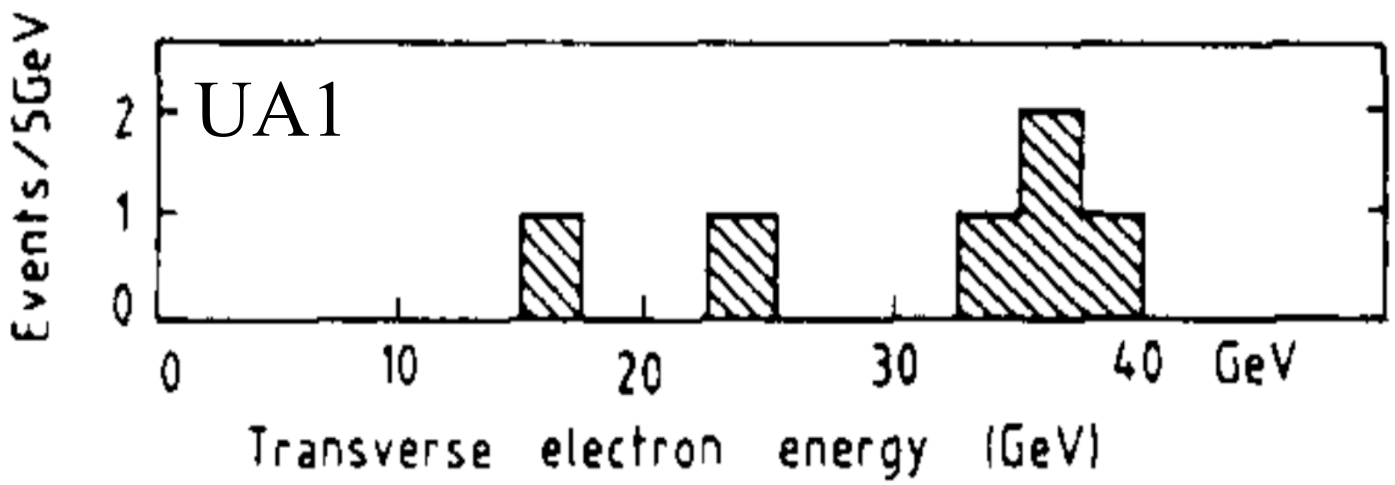


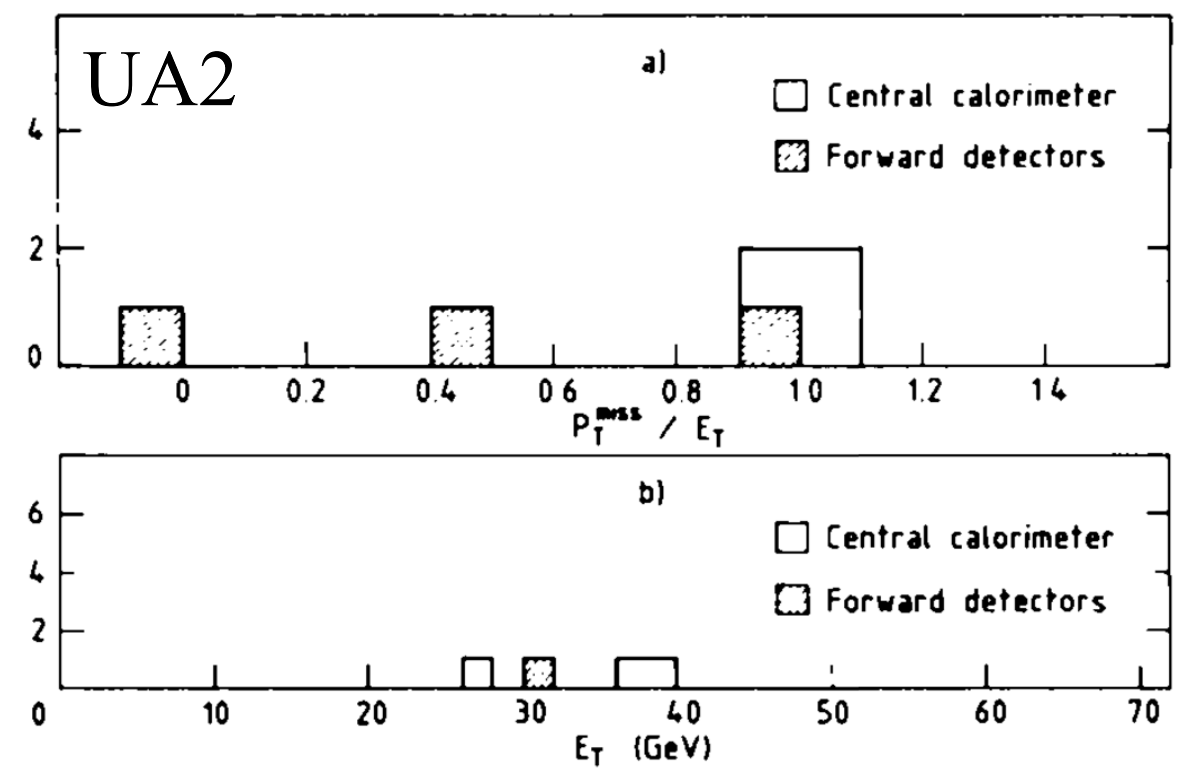
[*Phys.Rev.Lett.* 39 (1977) 252-255]

The discovery of the Z and W bosons

The massive Z and W are perhaps the most direct manifestation of the **spontaneous breaking** of the $SU(2)_L$ gauge symmetry of the standard model:

- In 1983 both the UA1 [*Phys. Lett.* B 122, 103 (1983)] and the UA2 [*Phys. Lett.* B 122 476 (1983)] experiments at the S$p\overline{p}$S collider at CERN announced the discovery of the $\mathbf{W}^{\pm}$ bosons in $p\overline{p} \to e^{\pm}\nu_e(\overline{\nu}_e) + X$ collisions (**charged-current Drell-Yan**) with mass around 80 GeV.





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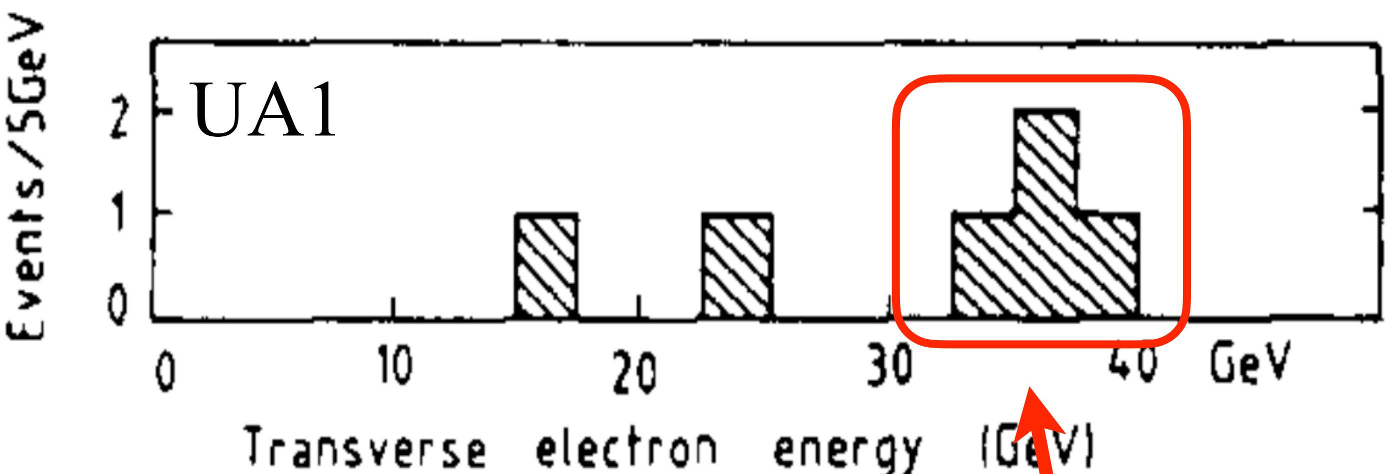

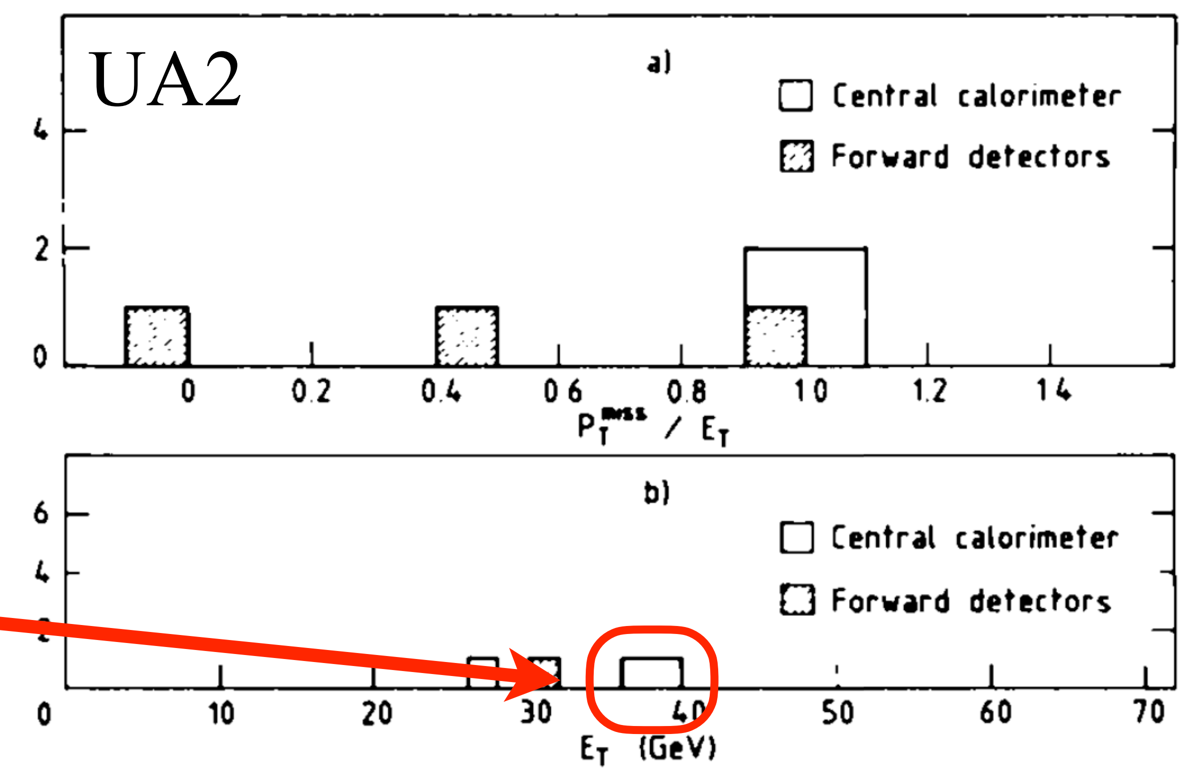

Jacobian peak
at $E_T = M_W/2$

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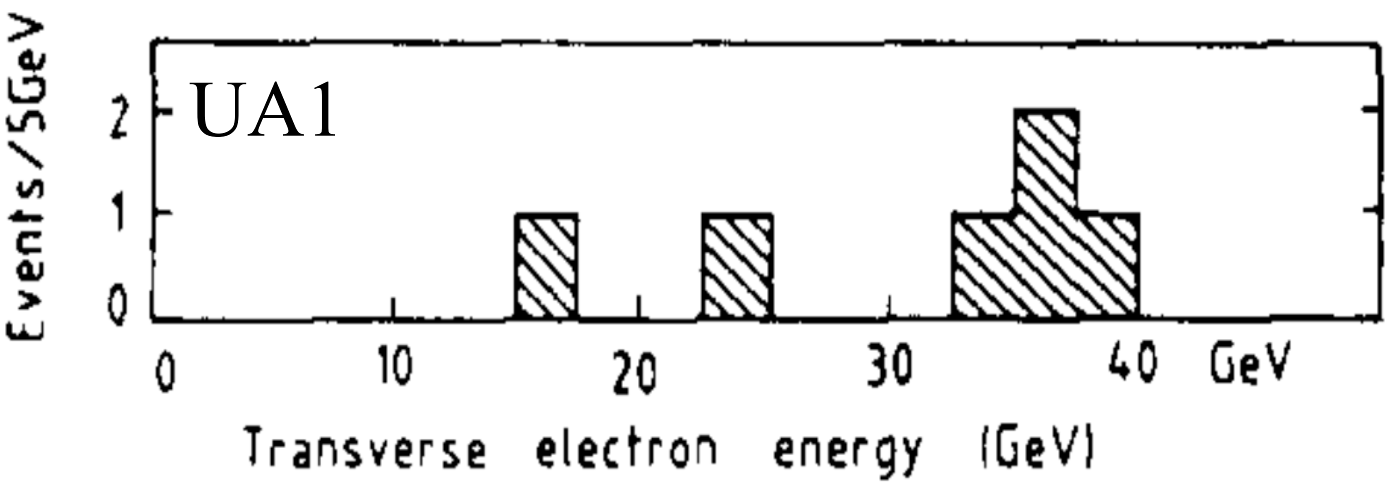
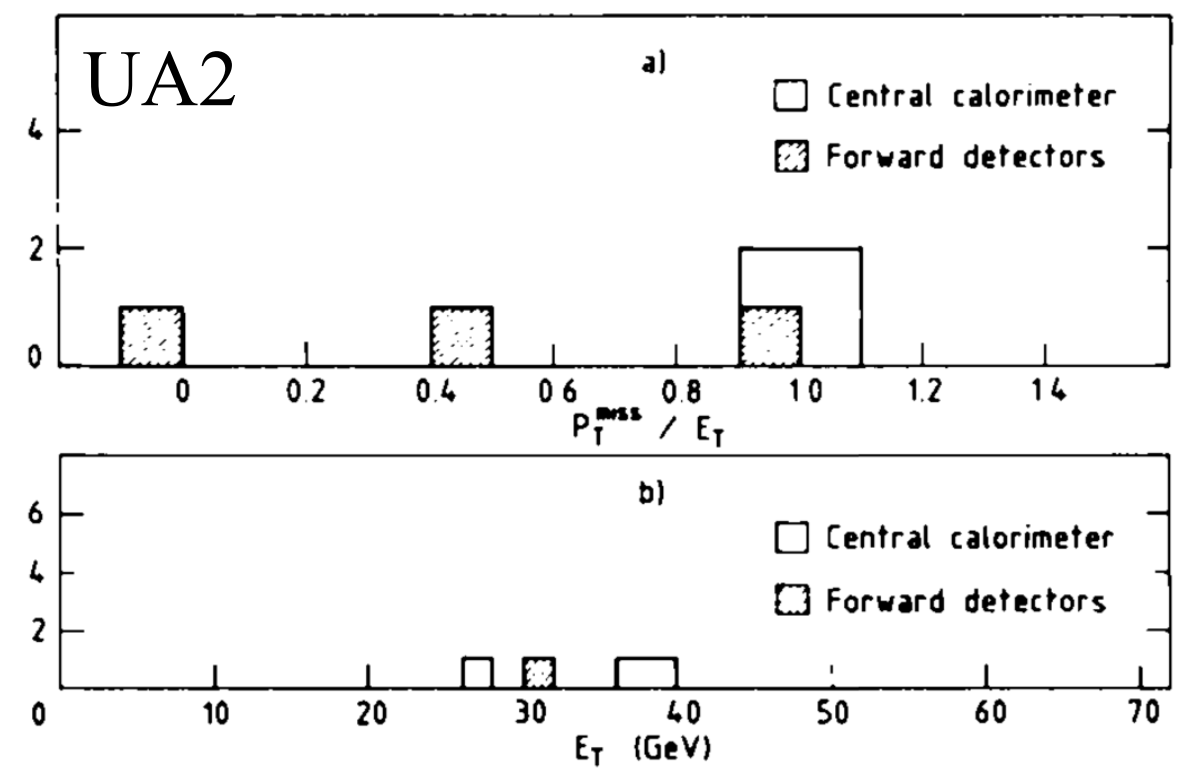
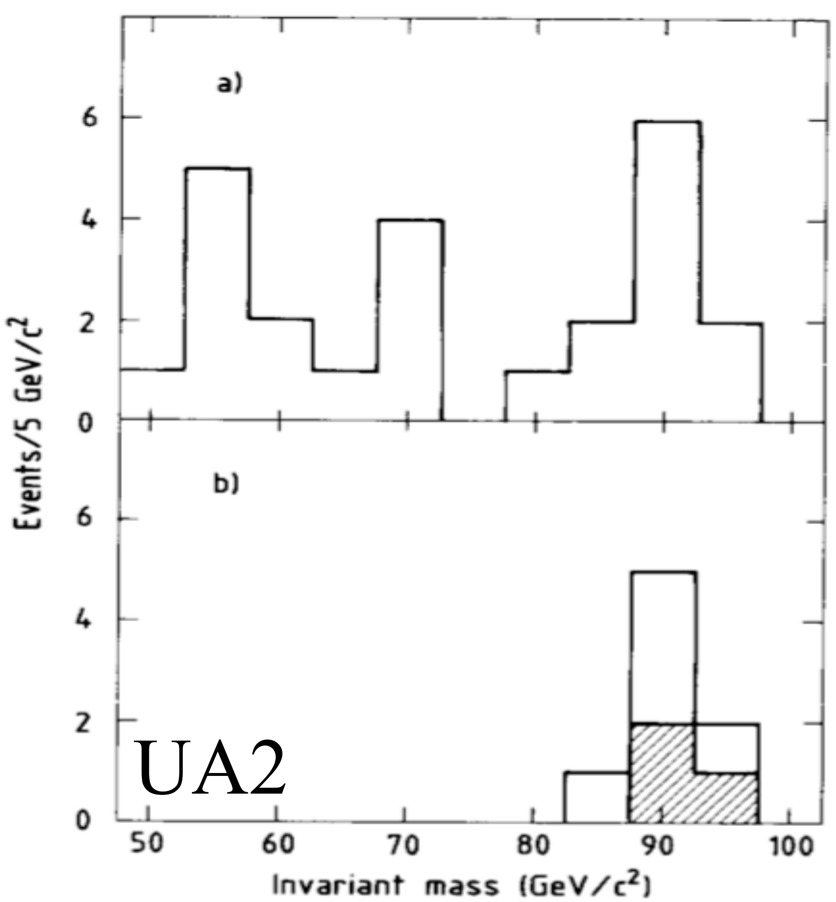


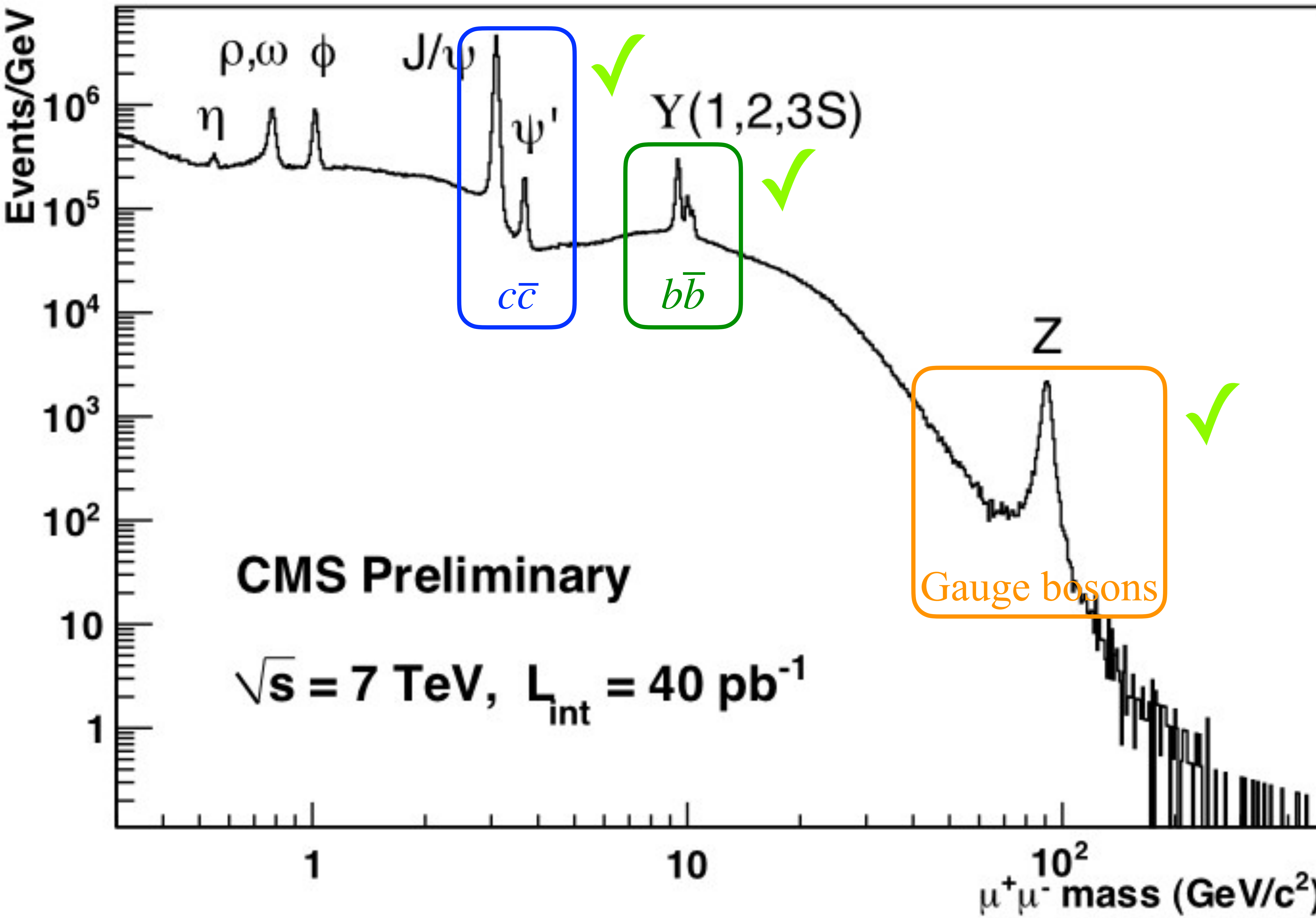




- The same year the same collaborations announced the discovery of the **Z** boson in $p\overline{p} \to e^{+}e^{-} + X$ (**neutral current Drell-Yan**) (UA1 [*Phys*. *Lett*. B 126, 398 (1983)] and UA2 [*Phys*. *Lett*. B 129, 130 (1983)).

- UA2 obtained a remarkably precise determination of the Z mass: $M_Z = 91.9 \pm 1.3 \pm 1.4$ GeV (PDG: $M_Z = 91.1876 \pm 0.0021$ GeV)

The Drell-Yan mass spectrum for discovery



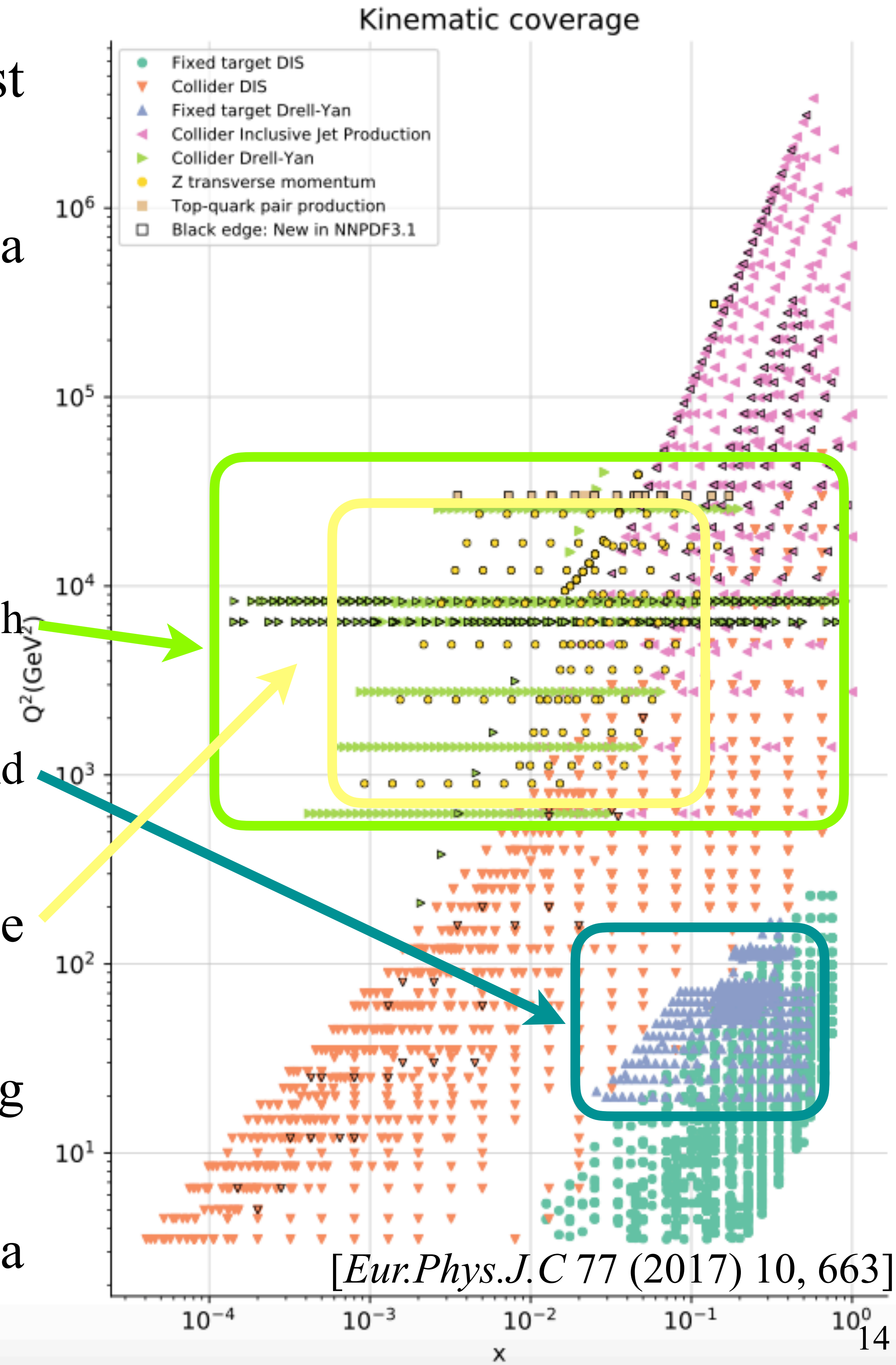
Drell-Yan in PDF determinations

Drell-Yan (both Z and W) is amongst the most important processes in **PDF determinations**:

- as opposite to DIS, Drell-Yan gives access to a larger variety of quark PDF combinations:
  - this enables **flavour/antiflavour separation**.
- very wide **kinematic coverage**:
  - collider data, placed at higher energies can reach values of x as low as 10^{-4},
  - fixed-target data is placed at lower scales and probes quark PDFs higher values of x.

Can you tell why fixed-order experiments probe larger values of x?

- The q_T distribution of the Z gives access to the **gluon PDF**.
- The precision of the modern data is a driving force in PDF determinations:
  - LHC data as well as new fixed-target data from Fermilab (SeaQuest).



[*Eur.Phys.J.C* 77 (2017) 10, 663]

Fixed-target Drell-Yan and sea PDFs

Very recently the SeaQuest (E906) experiment at Fermilab has released data for the ratio of cross sections σ_{pd}/σ_{pp} [*Nature* 590 (2021) 7847, 561-565].

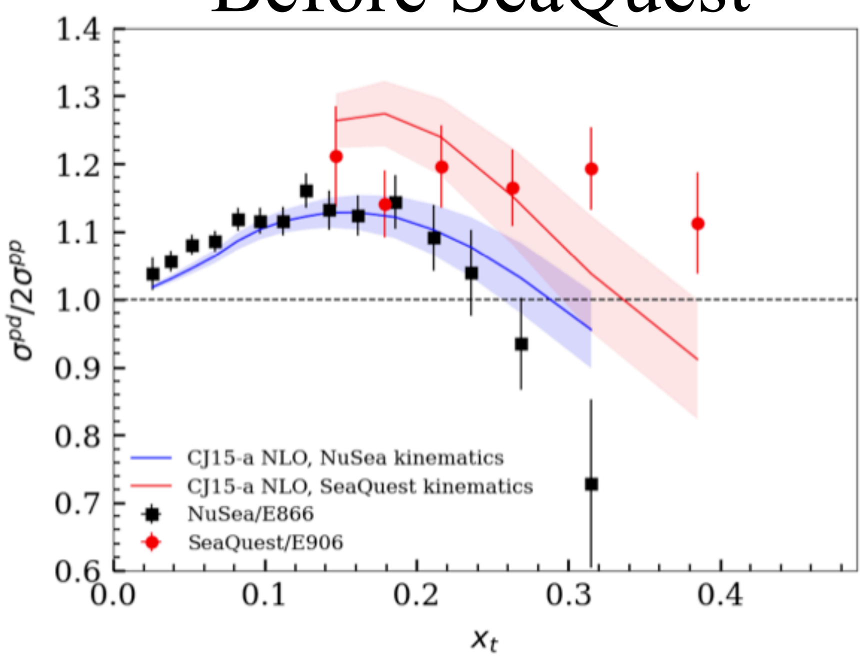
This ratio is **sensitive to the ratio of sea quark PDFs**:

$$\boxed{\frac{\sigma_{pd}}{\sigma_{pp}} \simeq 1 + \frac{\bar{d}(x)}{\bar{u}(x)}}$$

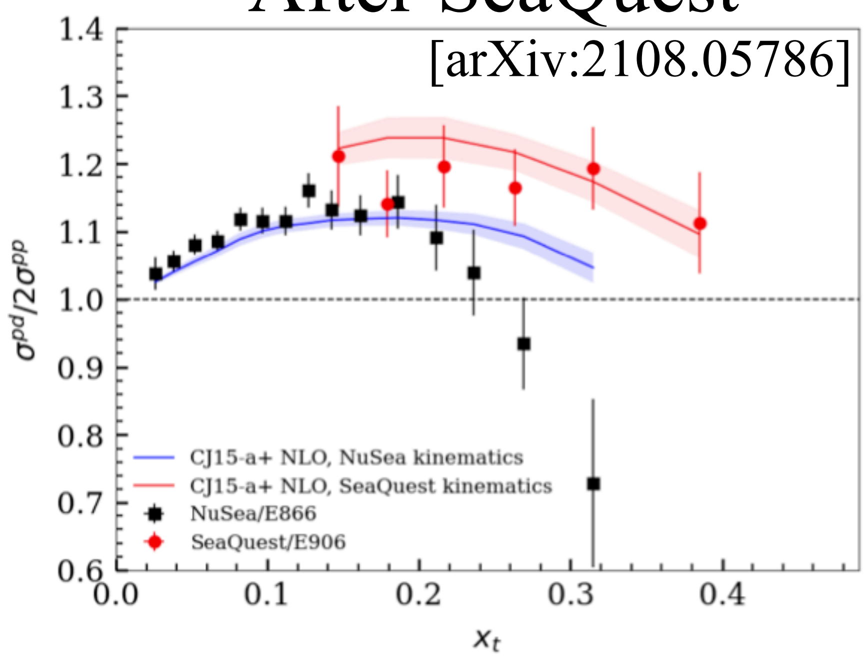
Can you derive this relation?

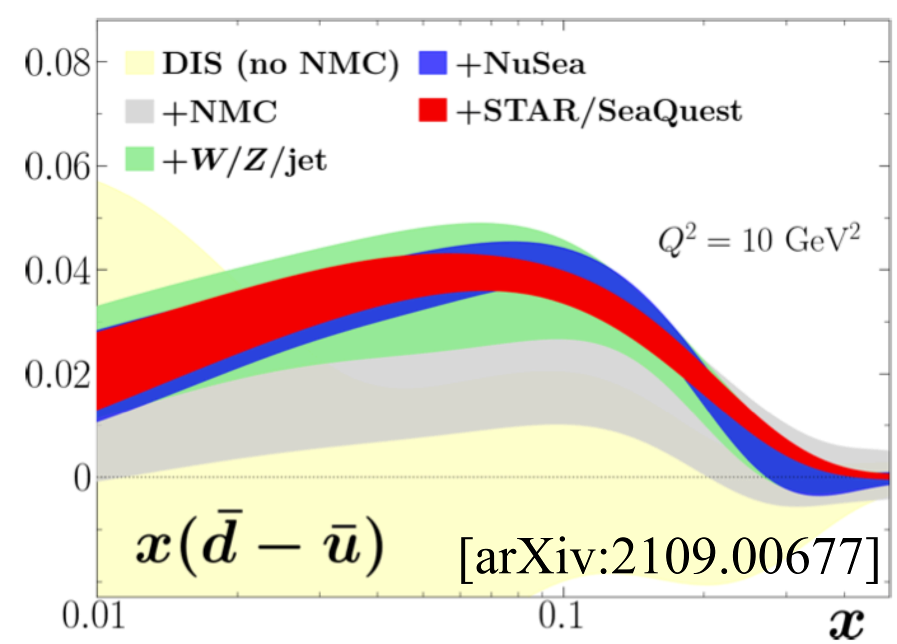
Being a fixed-target experiment, **large values of *x*** are probed giving us access to the sea quark PDFs in a region that is presently **poorly known**.

Before SeaQuest



After SeaQuest





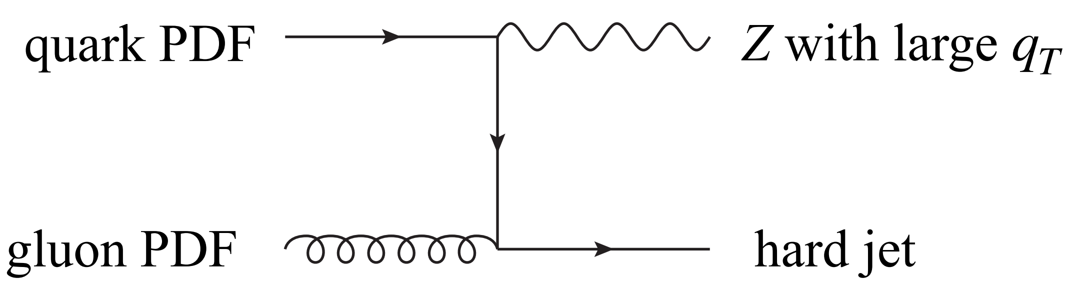
Significant impact on the $\bar{u}$ and $\bar{d}$ PDFs at large x.

Currently unresolved tension with the older NuSea (E866) data.

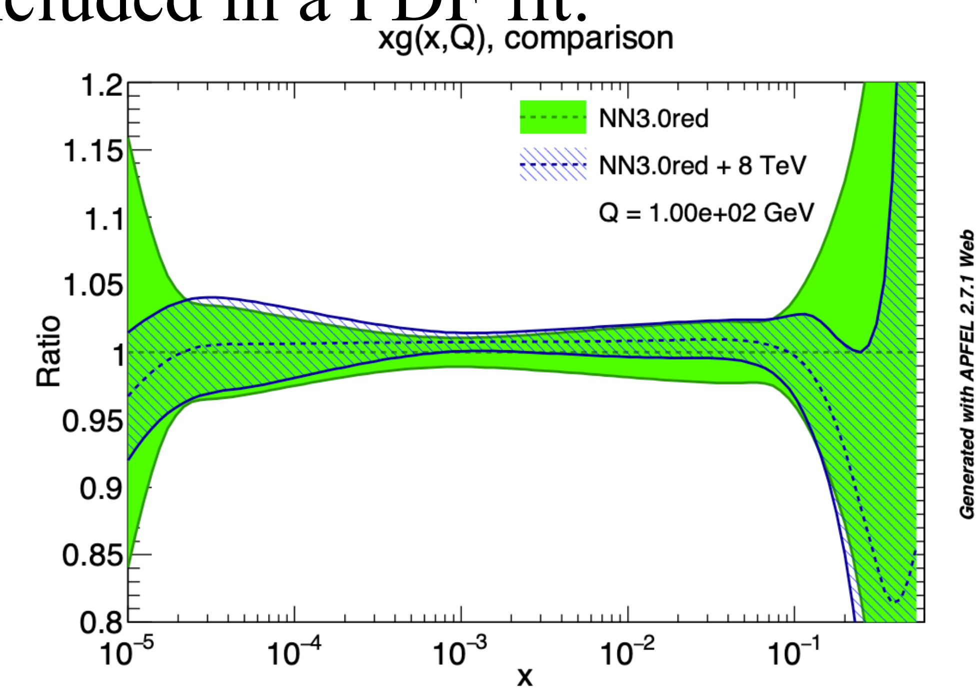
Drell-Yan q_T distribution and the gluon PDF

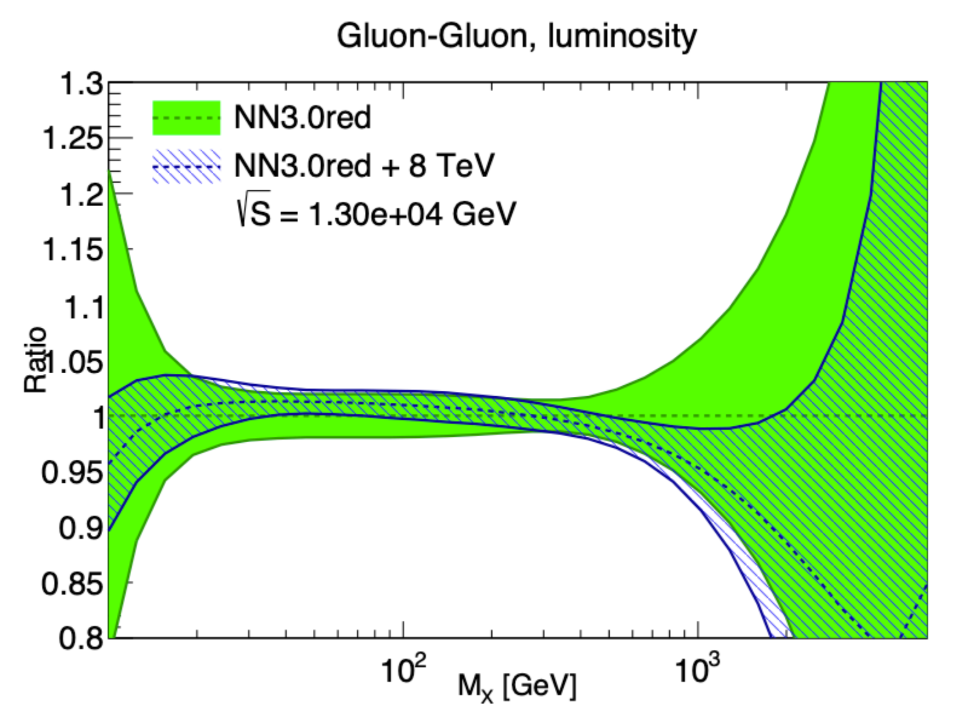
The q_T of the Z boson allows us to constraint the collinear gluon PDF:

- as we have seen in the previous lecture, collinear factorisation is reliable for $q_T \simeq Q$.
- In order for the Z to have a large q_T, it needs an object to recoil against. This is typically a jet. As a consequence, the relevant process is $pp \to Z + j + X$.
- One of the leading-order partonic cross sections contributing to this process is:



In [*JHEP* 07 (2017) 130] the ATLAS 8 TeV data for the q_T of the Z with $q_T > 30$ GeV have been included in a PDF fit:

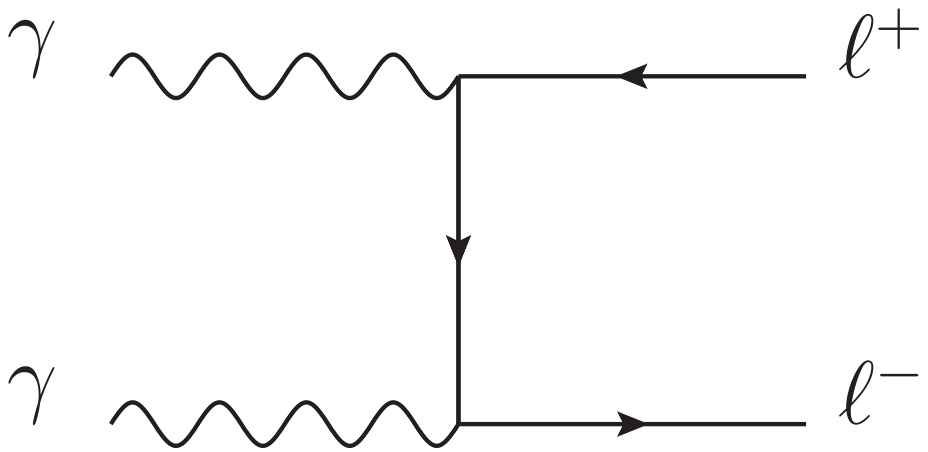




The impact on the gluon PDF is **significant**.

The photon PDF of the proton

If we promote the **photon** to be a **parton**, *i.e.* we allow the photon to contribute to the proton structure, then we need to allow for a **photon PDF**.



Therefore, Drell-Yan production regarded as the production of a lepton pair receives contribution also from the **photon** already at the **leading order**.

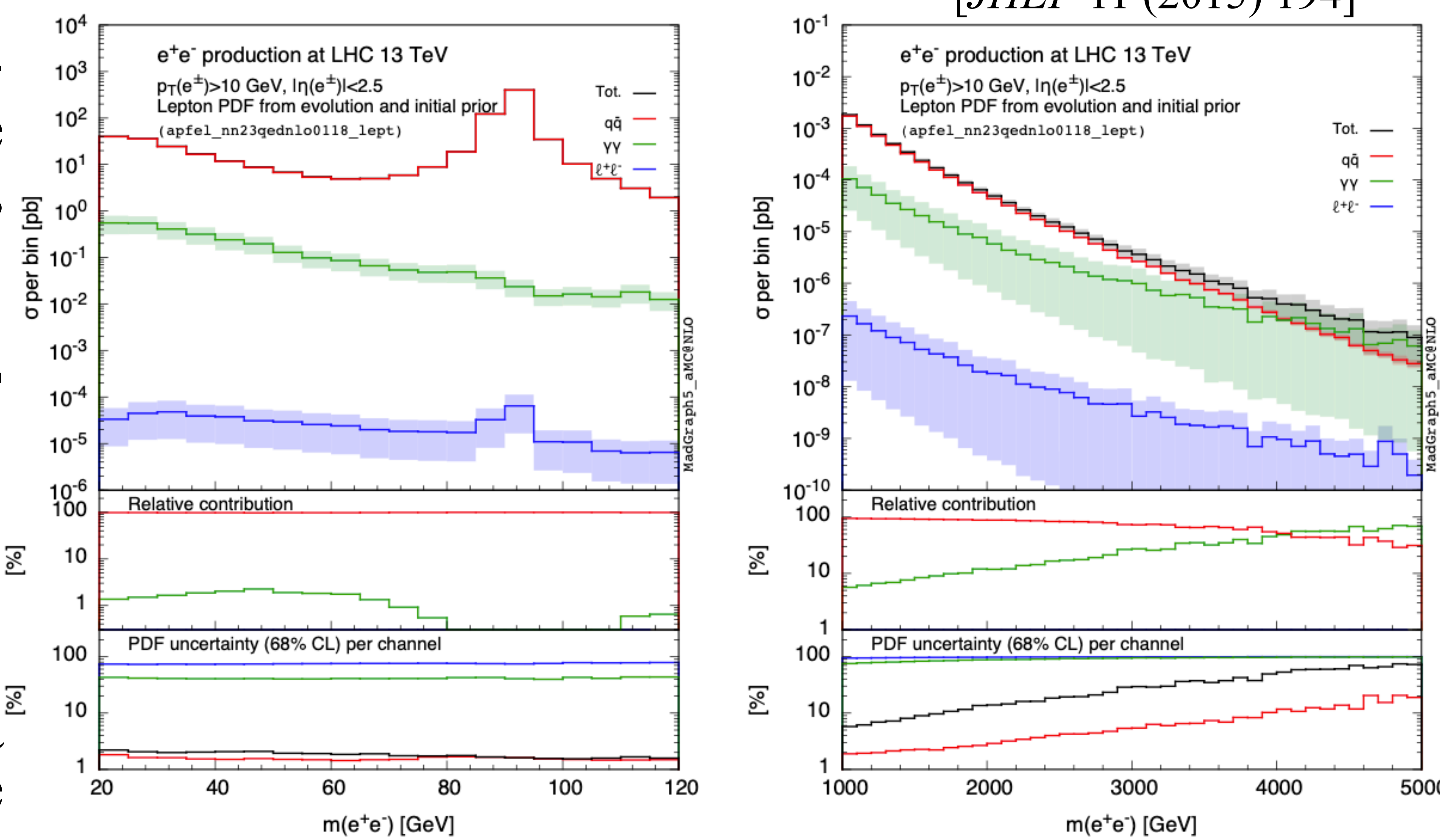
At small and middle lepton-pair invariant masses $m_{\ell\ell}$ the photon-initiated contribution is suppressed by the photon PDF.

At high $m_{\ell\ell}$ the photon PDF becomes relatively larger:

- probing large x.

High-mass Drell-Yan data enables us to determine the photon PDF.

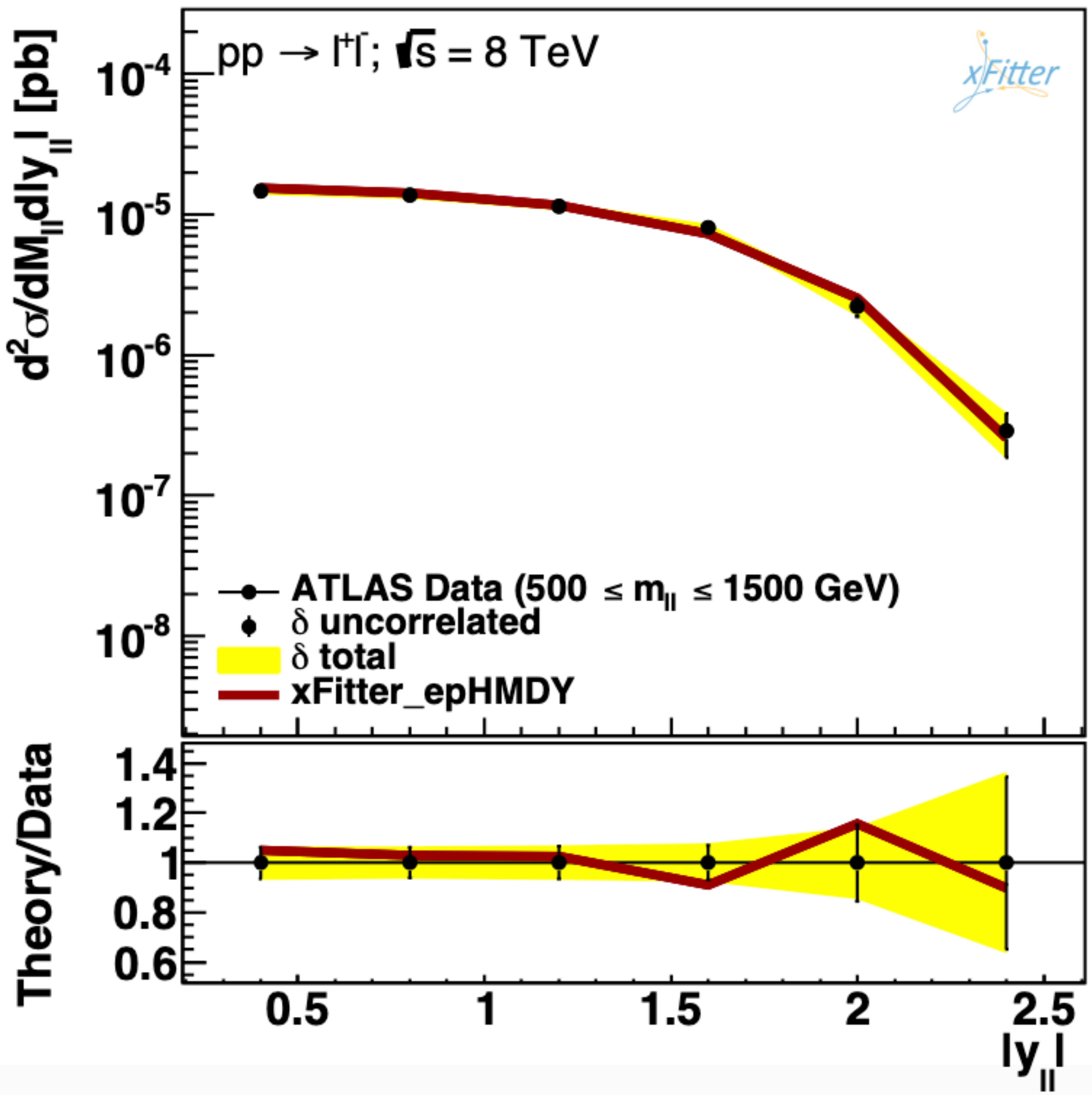
[*JHEP* 11 (2015) 194]

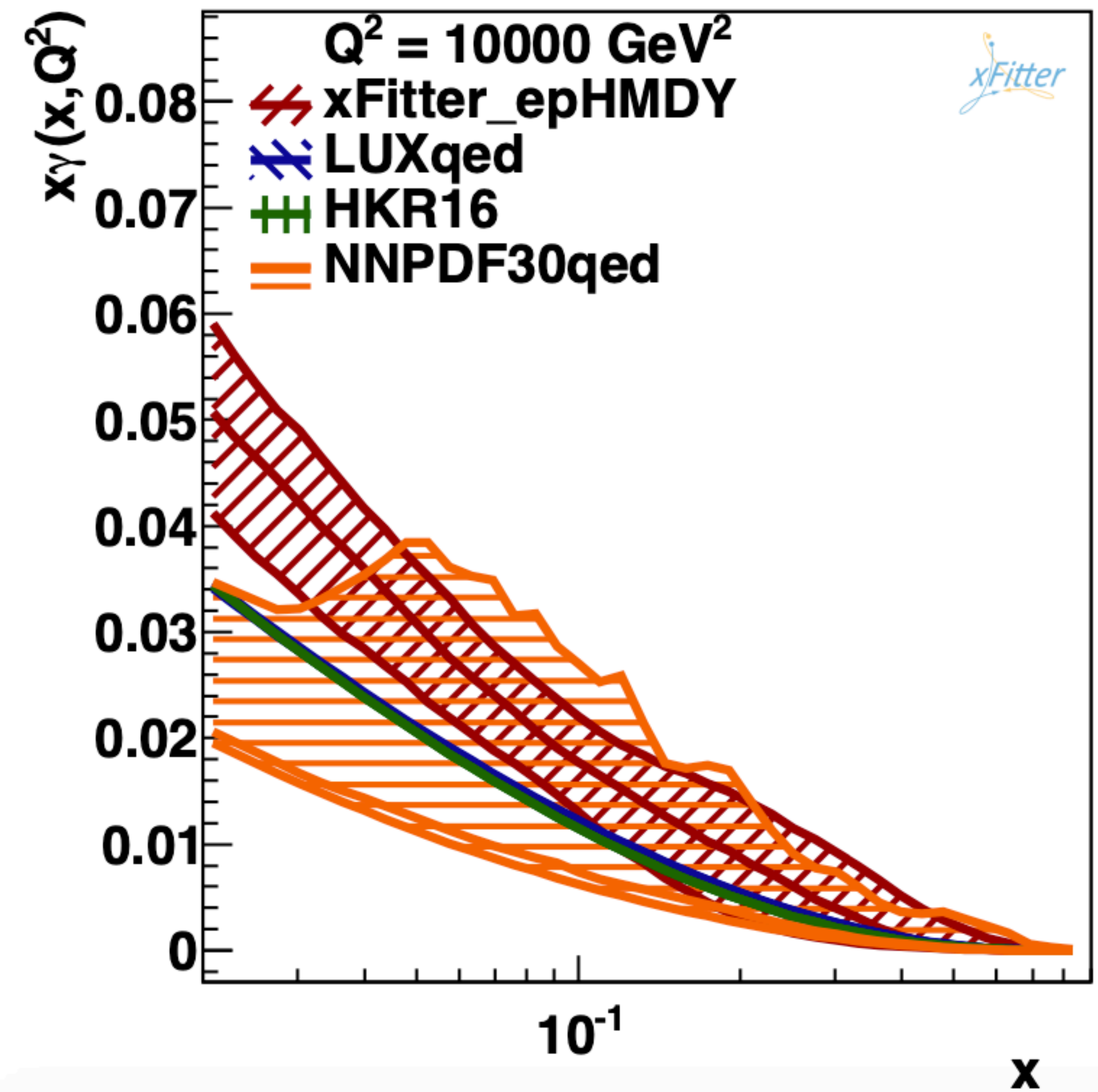


The photon PDF of the proton

In [*Eur.Phys.J.C* 77 (2017) 6, 400] the high-mass ATLAS 8 TeV data was used to extract the photon PDF:

- QED/EW effects included up to NLO.

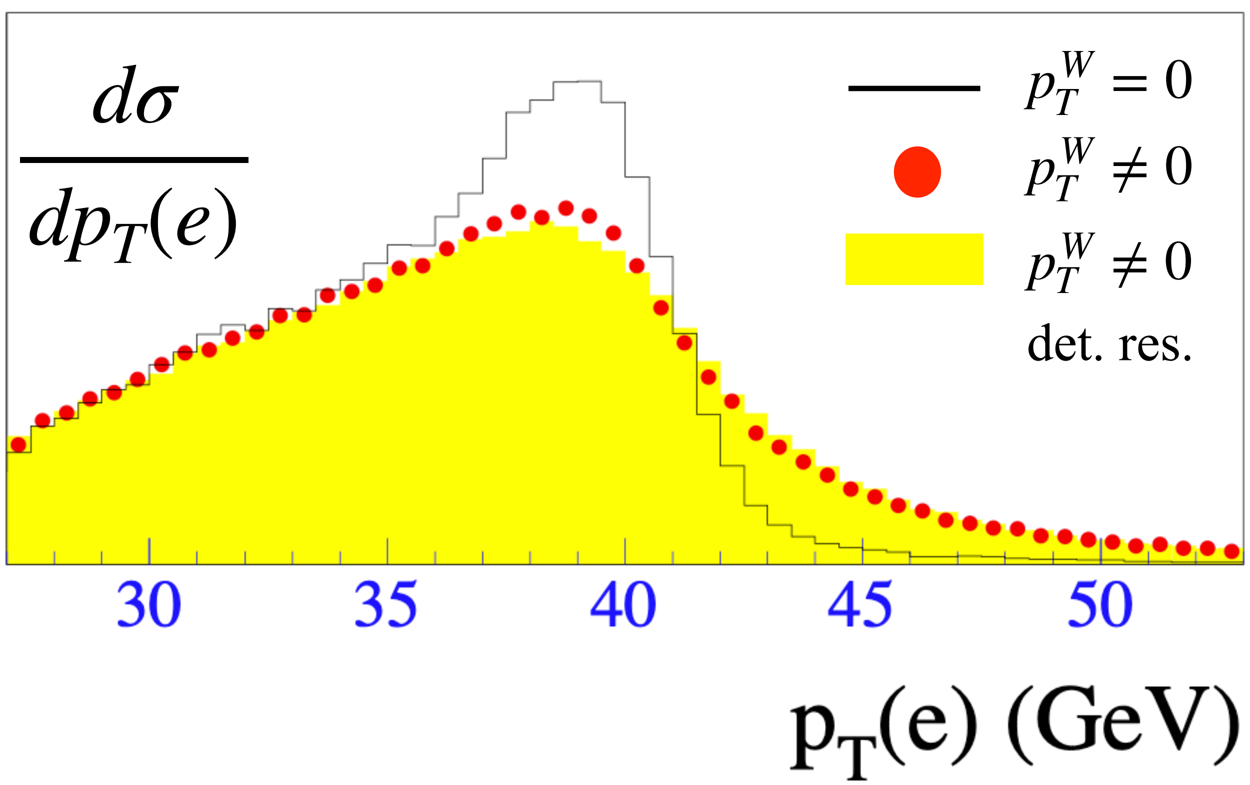


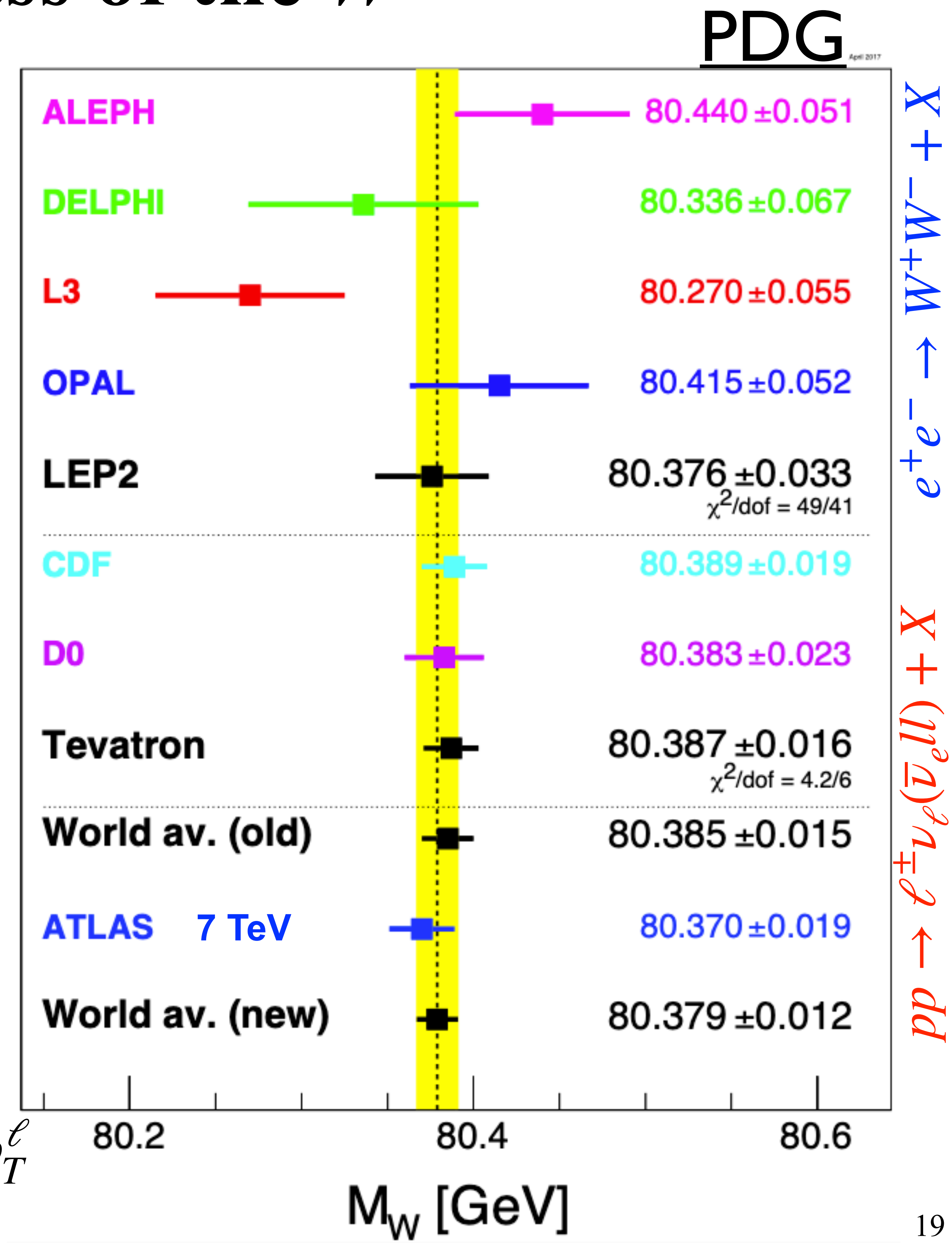


The mass of the W

A precise measurement of the W mass would not only provide a strong test of the Standard Model but would also allow us to constrain **possible extensions** to it.

The most precise measurements of the W mass is achieved by fitting the p_T^ℓ and m_T in Drell-Yan production $pp \to W^\pm + X \to \ell^\pm \nu_\ell(\bar{\nu}_\ell) + X$.

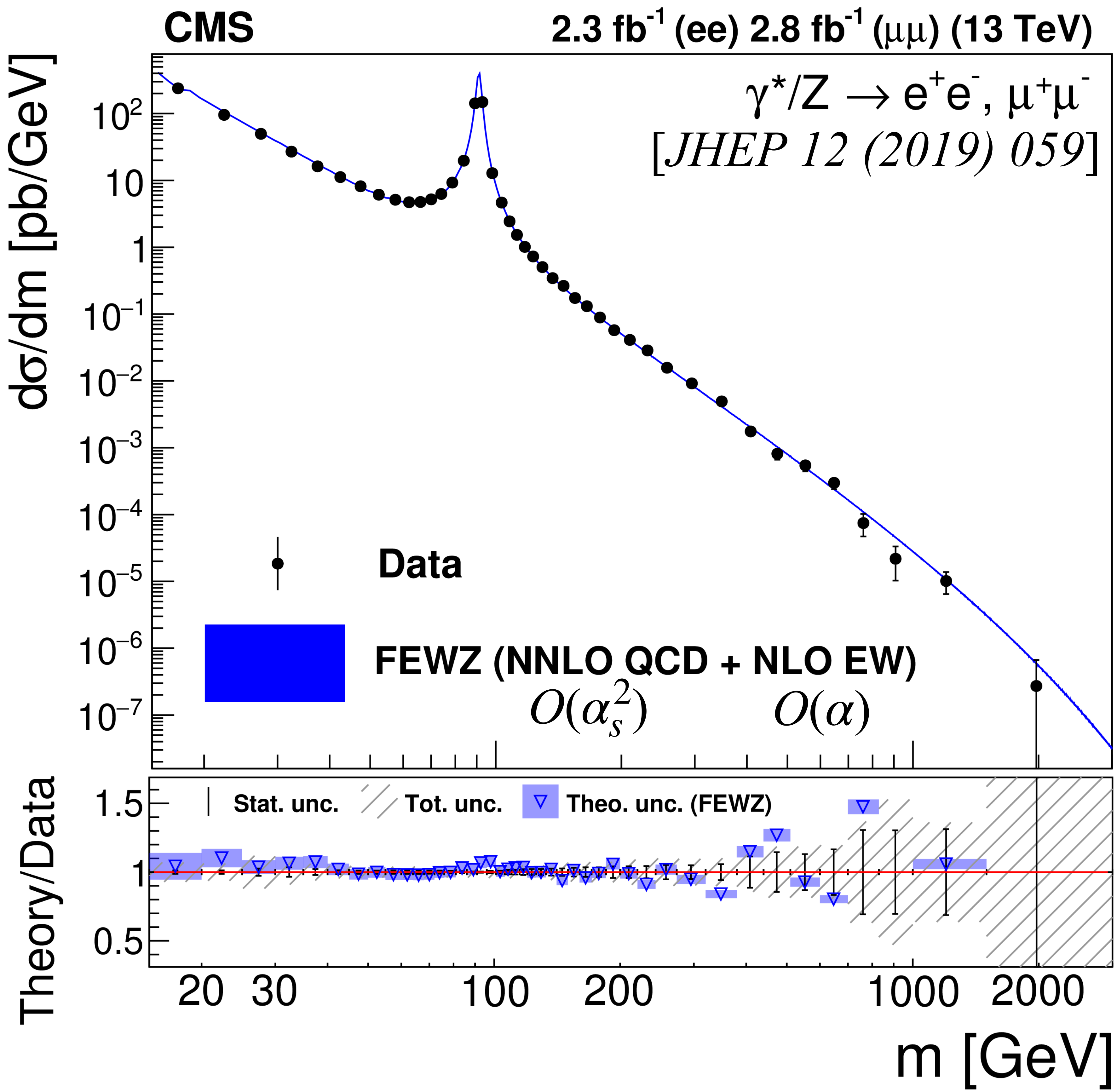




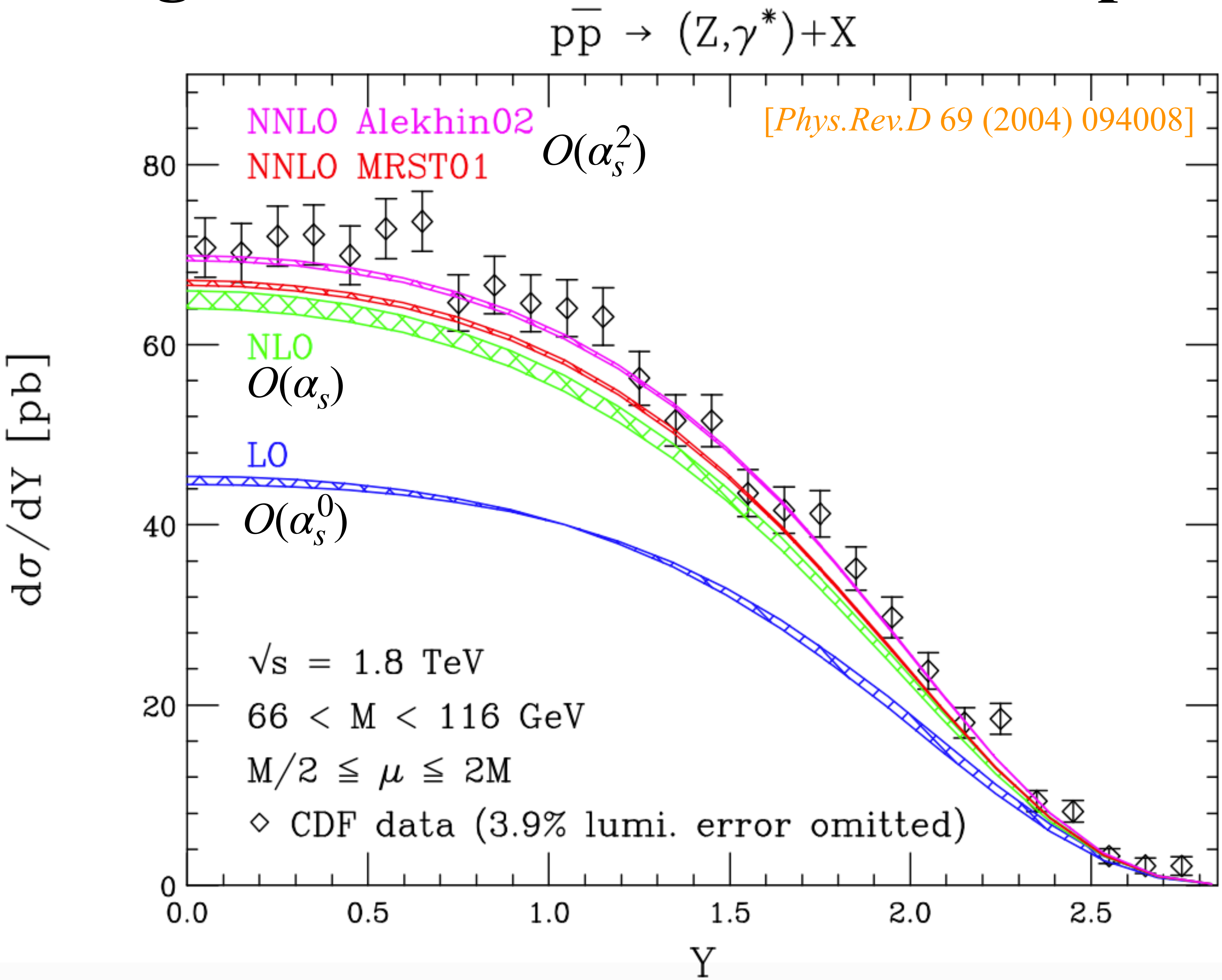
Important to model p_T^W to estimate p_T^ℓ and thus measure M_W.

Higher-order corrections: the mass spectrum

Our current understanding of the invariant mass spectrum in Drell-Yan is very good.



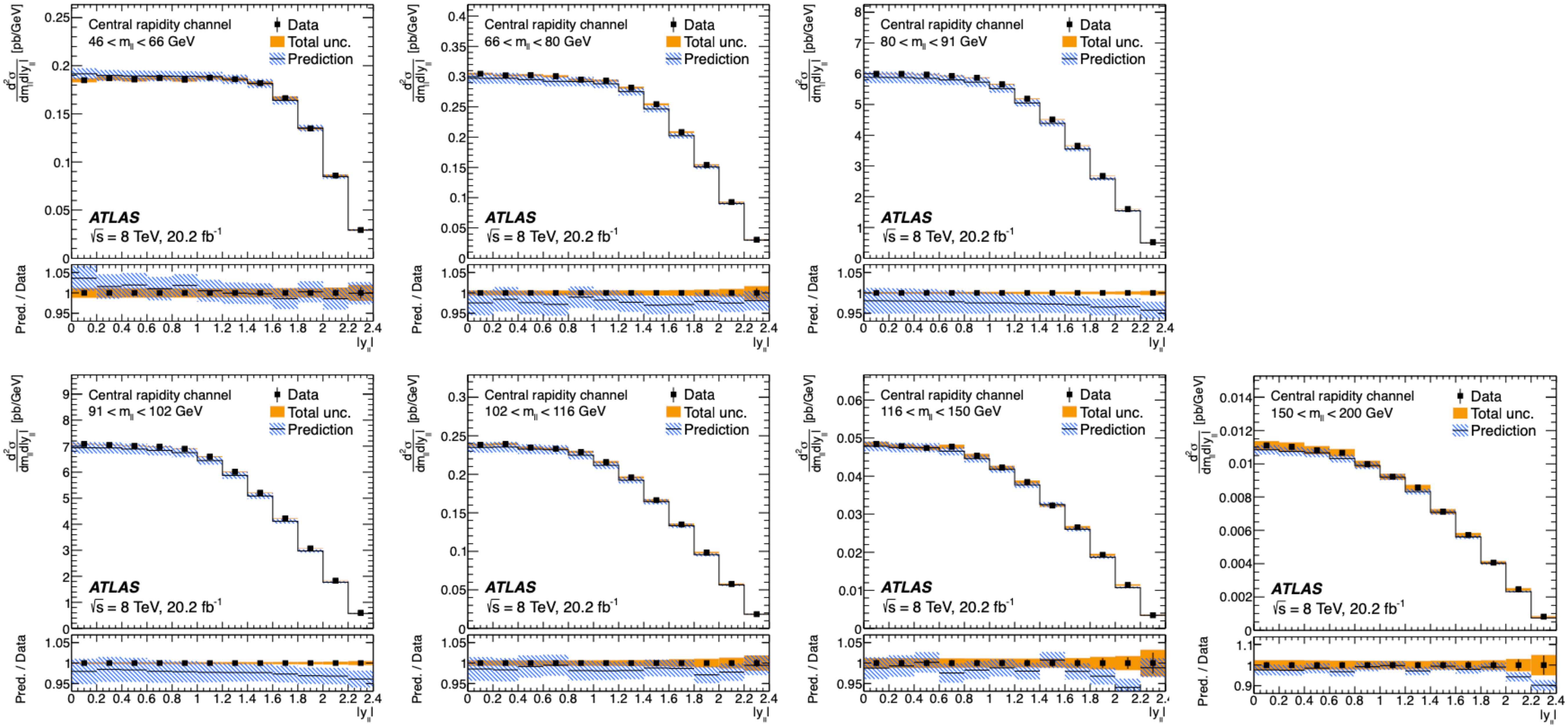
Higher-order corrections: the rapidity



NNLO corrections significantly improve the agreement with data.

Higher-order corrections: the rapidity

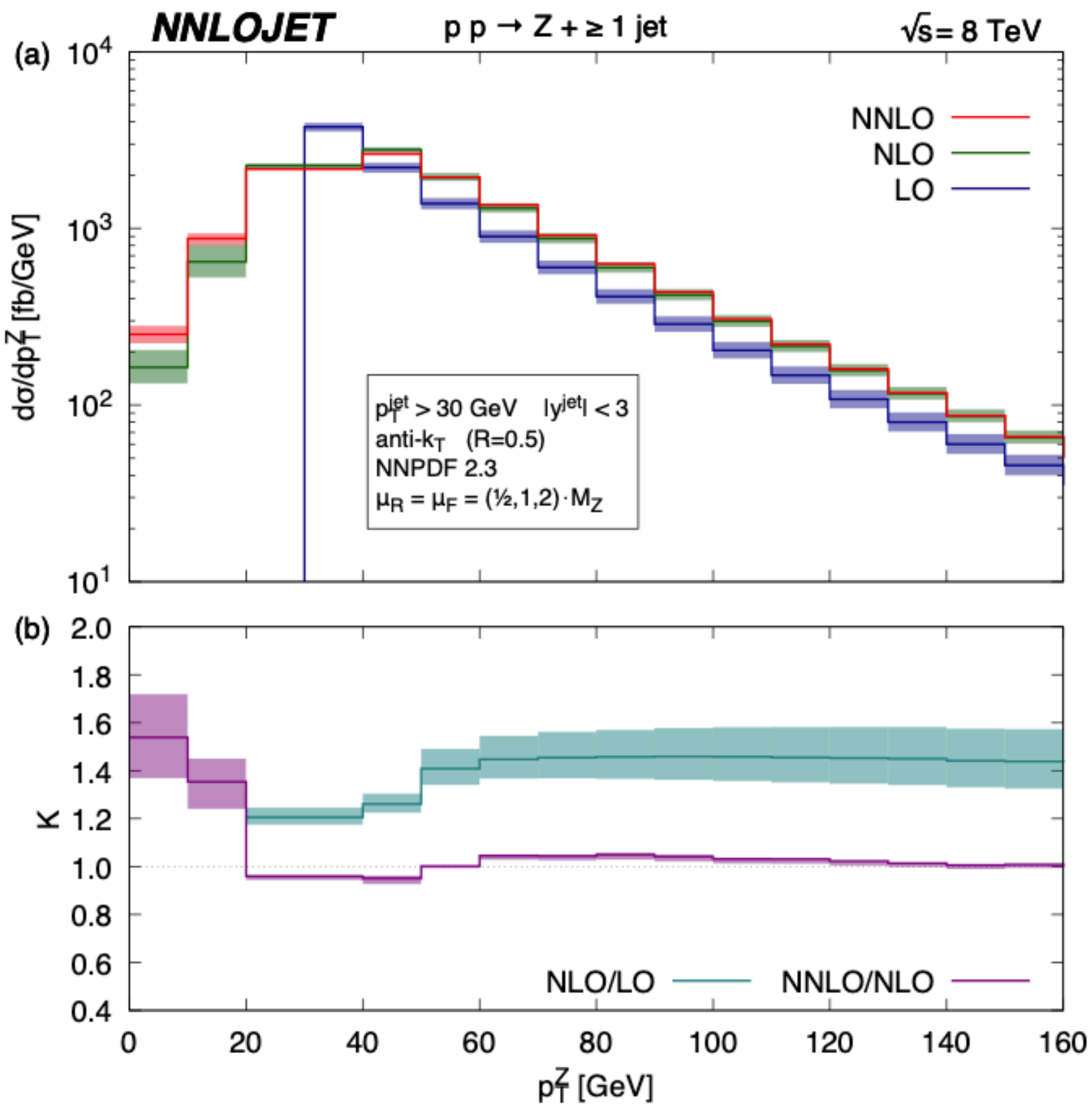
[JHEP 12 (2017) 059]

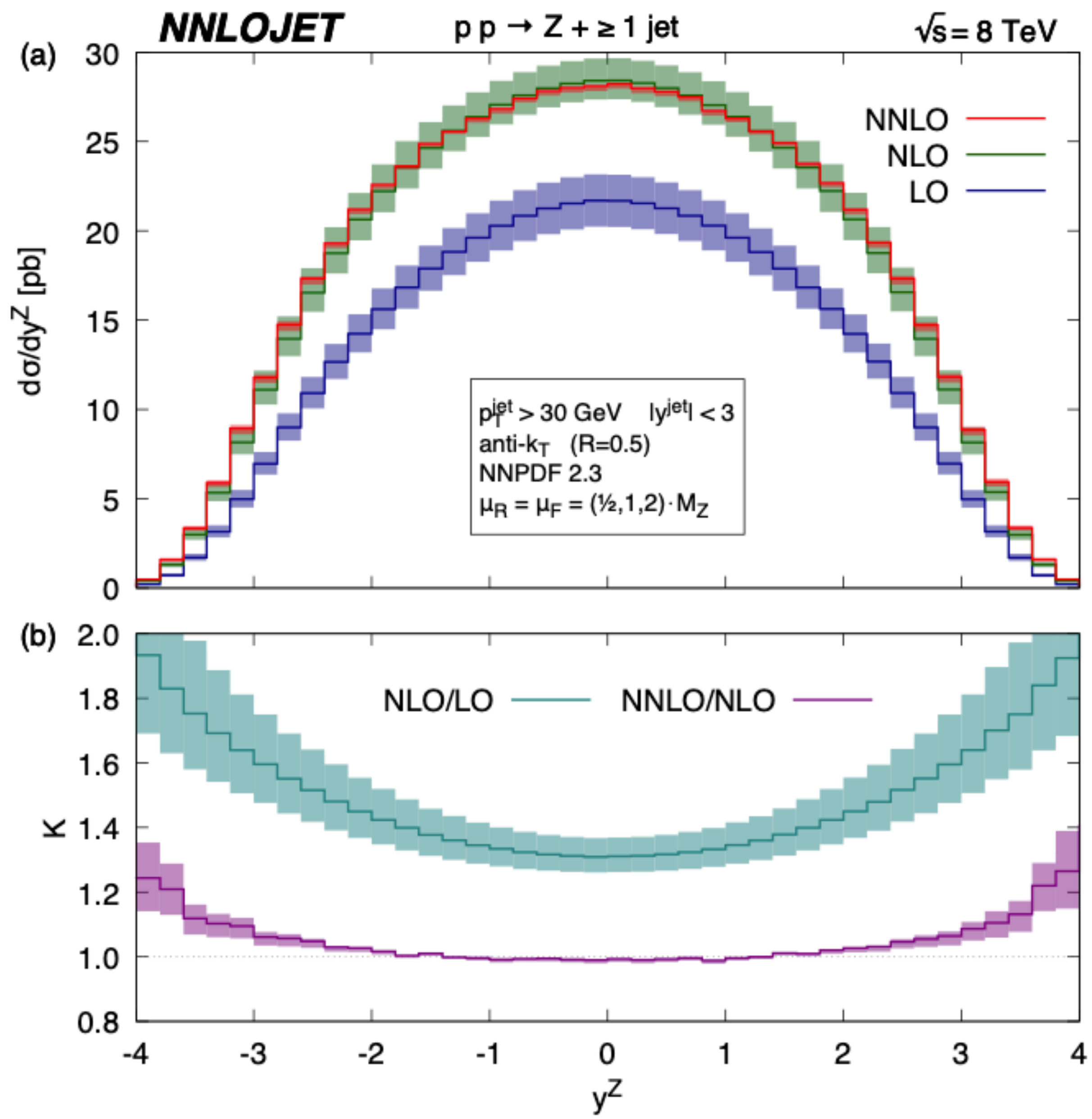


- NNLO + NLO EW predictions.
- Very good agreement between data and theory also in lower and higher invariant mass bins.

Higher-order corrections: q_T distribution

The fully differential NNLO (*i.e.* $O(\alpha_s^3)$) corrections to the cross section for $pp \to Z$+jet was presented in [*Phys. Rev. Lett.* 117 (2016) 2, 022001]. This calculation allows us to compute the q_T of the Z to NNLO accuracy.





NNLO corrections are moderate but significant in the fixed-order domain ($q_\mathrm{T} \sim Q$, $y \sim 1$):

- improve the agreement with data (see next slide).

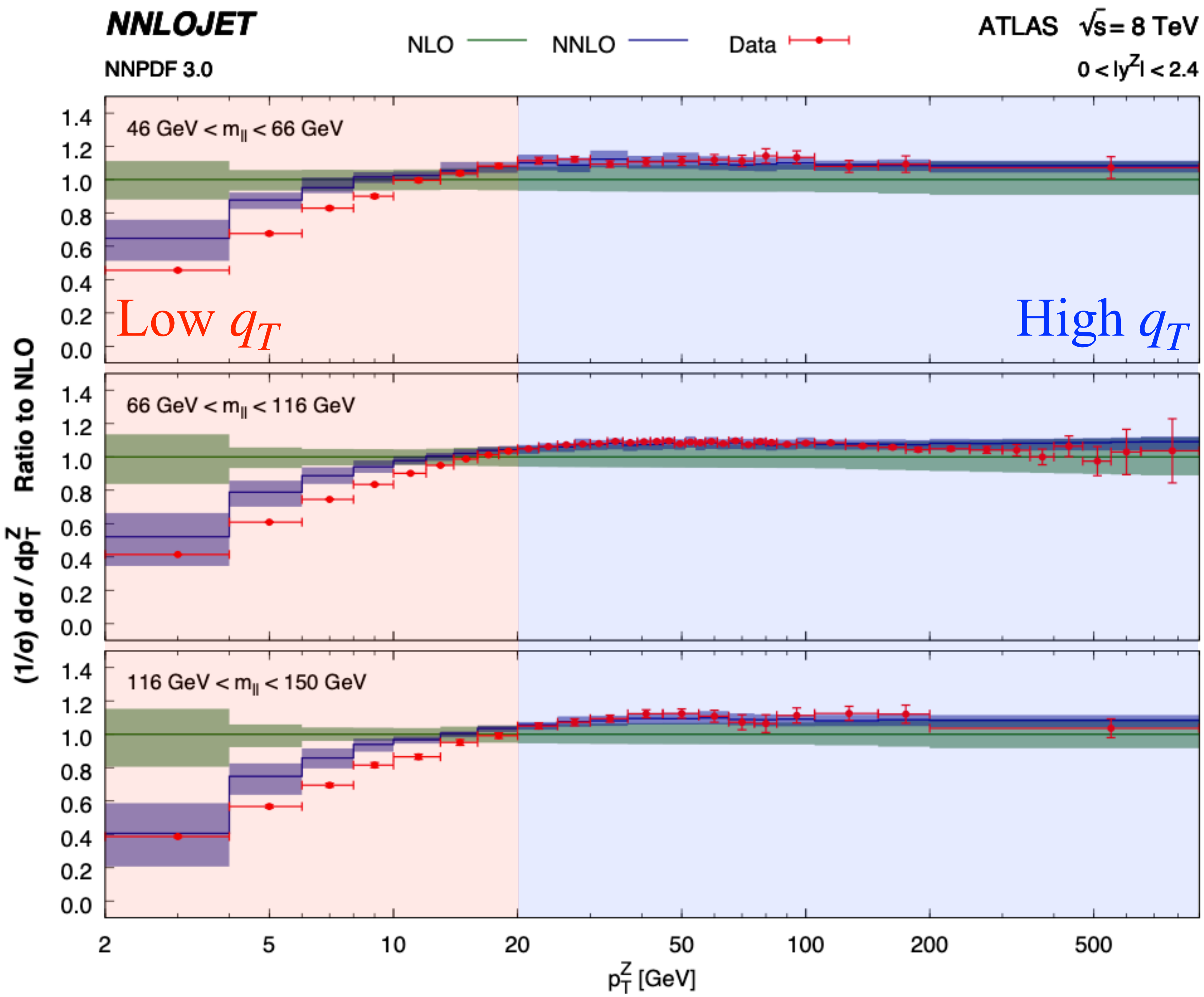
Can you guess what happens if y becomes very large?

Sizeable reduction of scale uncertainties except (as expected) at low q_T and large rapidity.

Higher-order corrections: q_T distribution

NNLO corrections improve the agreement with data all across the board:

- for $q_{\mathrm{T}} \sim Q$ the agreement with data is now excellent,
- for $q_{\mathrm{T}} \ll Q$, NNLO partly captures the double-log behaviour and provides qualitative improvements in the description of the shape of the data: **resummation still needed**.



Resummation of the q_T distribution

In order to exploit q_T resummation at $q_T \ll Q$ and still benefit of the fixed-order calculation at $q_T \sim Q$, one needs to adopt a matched procedure like CSS:

$$\frac{d\sigma}{dQ\,dy\,dq_T} = \boxed{W(Q, y, q_T)} + \boxed{Y(Q, y, q_T)}$$

Resummation of $\alpha_s^n \ln^{2n-1}(Q/q_T)$ — Power corrections of $(q_T/Q)^m$

We know how to compute W (see previous lecture), how do we compute Y?

We know that Y contains powers of $(q_T\,/\,Q)$ *only*:

- W contains **all the logarithmically enhanced terms** resummed up to some order:

$$W^{\mathrm{N}^l\mathrm{LL}}(Q, y, q_T) = \frac{1}{q_T} \sum_{m=0}^{l} \sum_{n=\lfloor m/2 \rfloor}^{\infty} W^{[m,n]} \alpha_s^n \ln^{2n-m-1}\left(\frac{Q}{q_T}\right)$$

- The N^{p}LO fixed-order calculation contains **log terms** *and* power corrections **up to** α_s^{p+1}:

$$\mathrm{FO}^{\mathrm{N}^p\mathrm{LO}}(Q, y, q_T) = \frac{1}{q_T} \sum_{n=1}^{p+1} \alpha_s^n \sum_{k=1}^{2n-1} F^{[k,n]} \ln^k\left(\frac{Q}{q_T}\right) + \text{power corrections}$$

- The log terms of W up to α_s^{p+1} have to match those in FO, it follows that:

$$\mathrm{FO}^{\mathrm{N}^p\mathrm{LO}}(Q, y, q_T) - \left[W^{\mathrm{N}^l\mathrm{LL}}(Q, y, q_T)\right]_{\text{exp. to } O(\alpha_s^{p+1})} = \text{power corrections} = Y(Q, y, q_T)$$

- Th implementation of the **additive** matching. Others exist.

Can you think of any alternative matching procedure?

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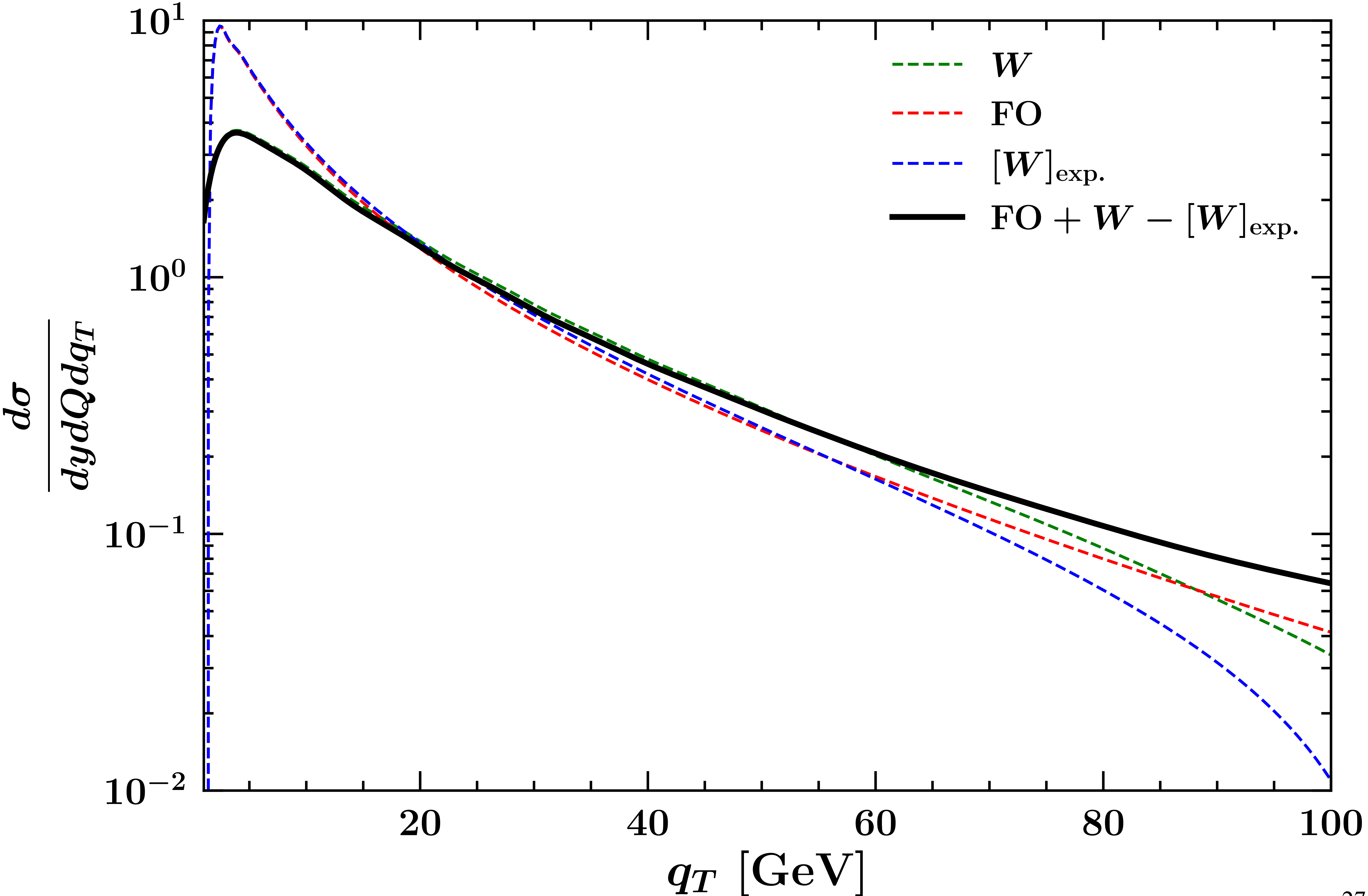

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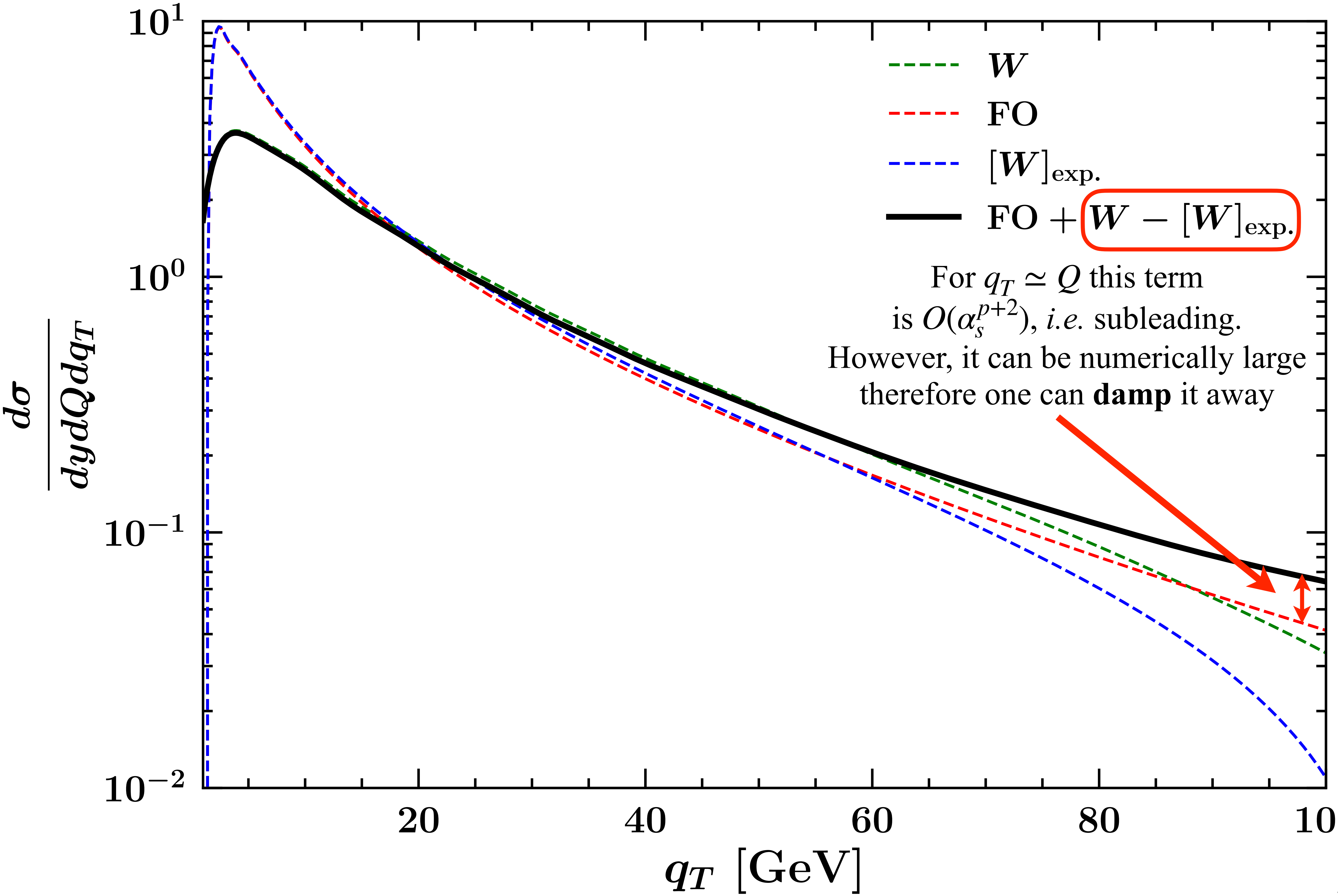
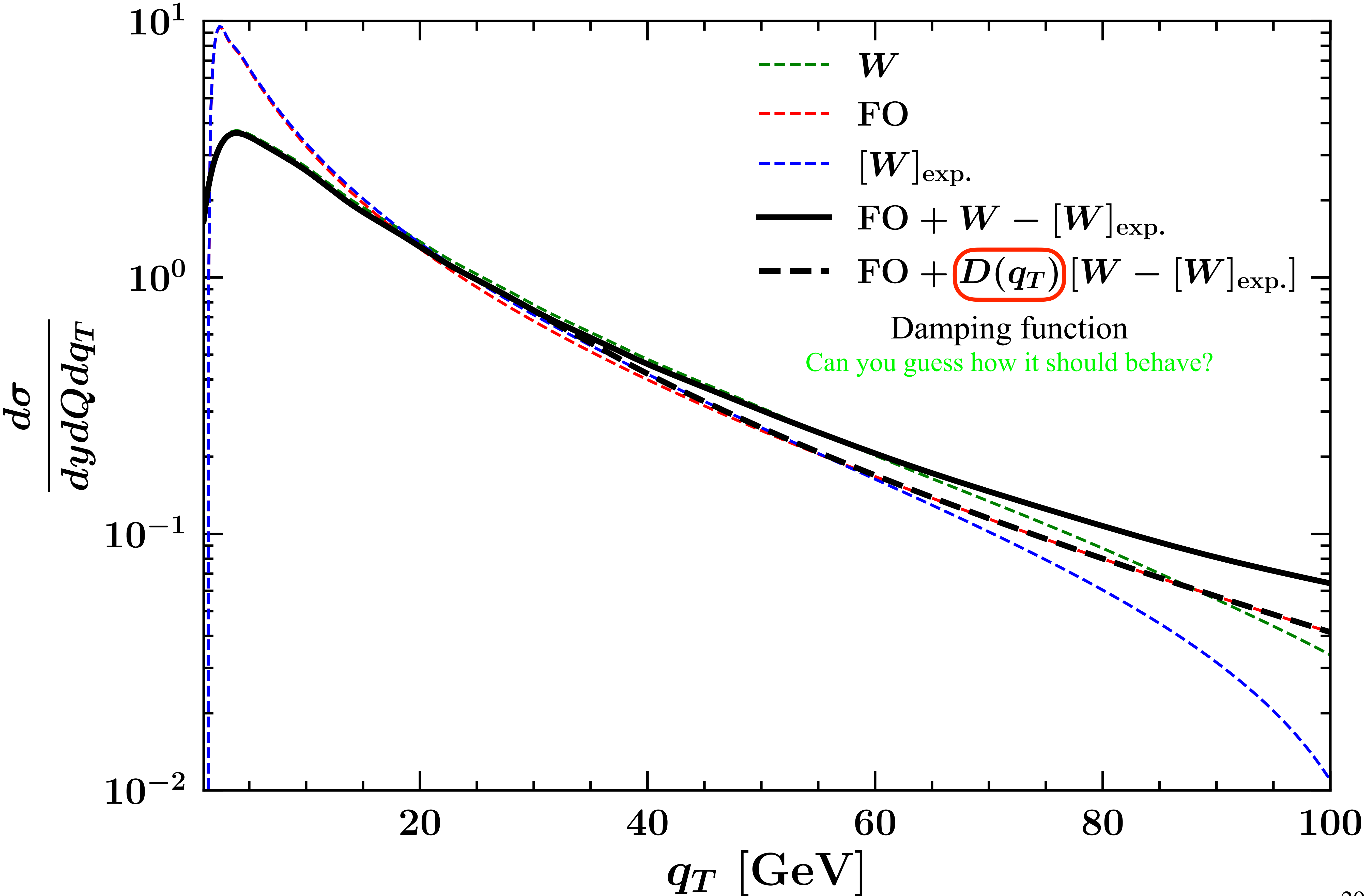
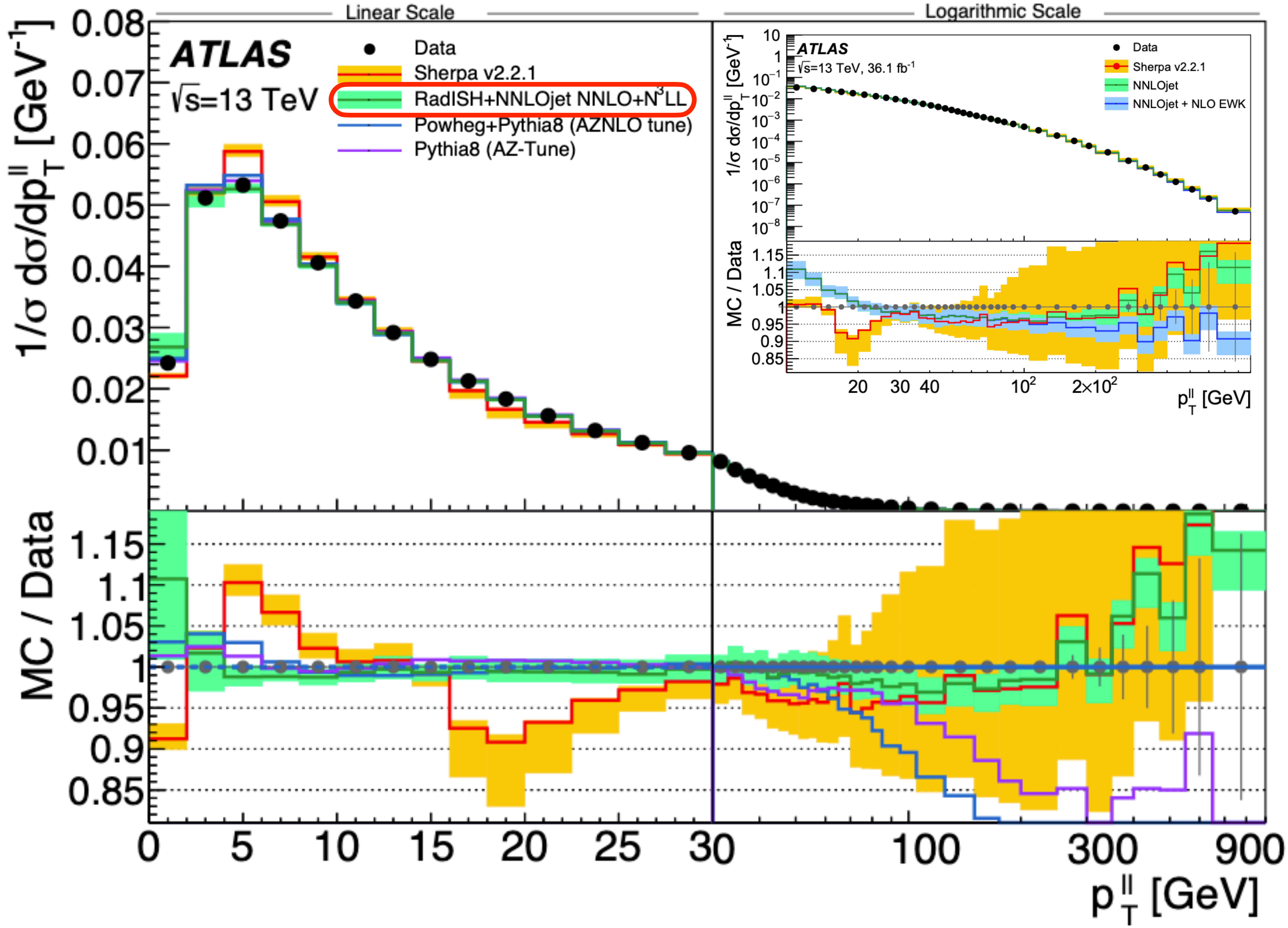


Resummation of the q_T distribution

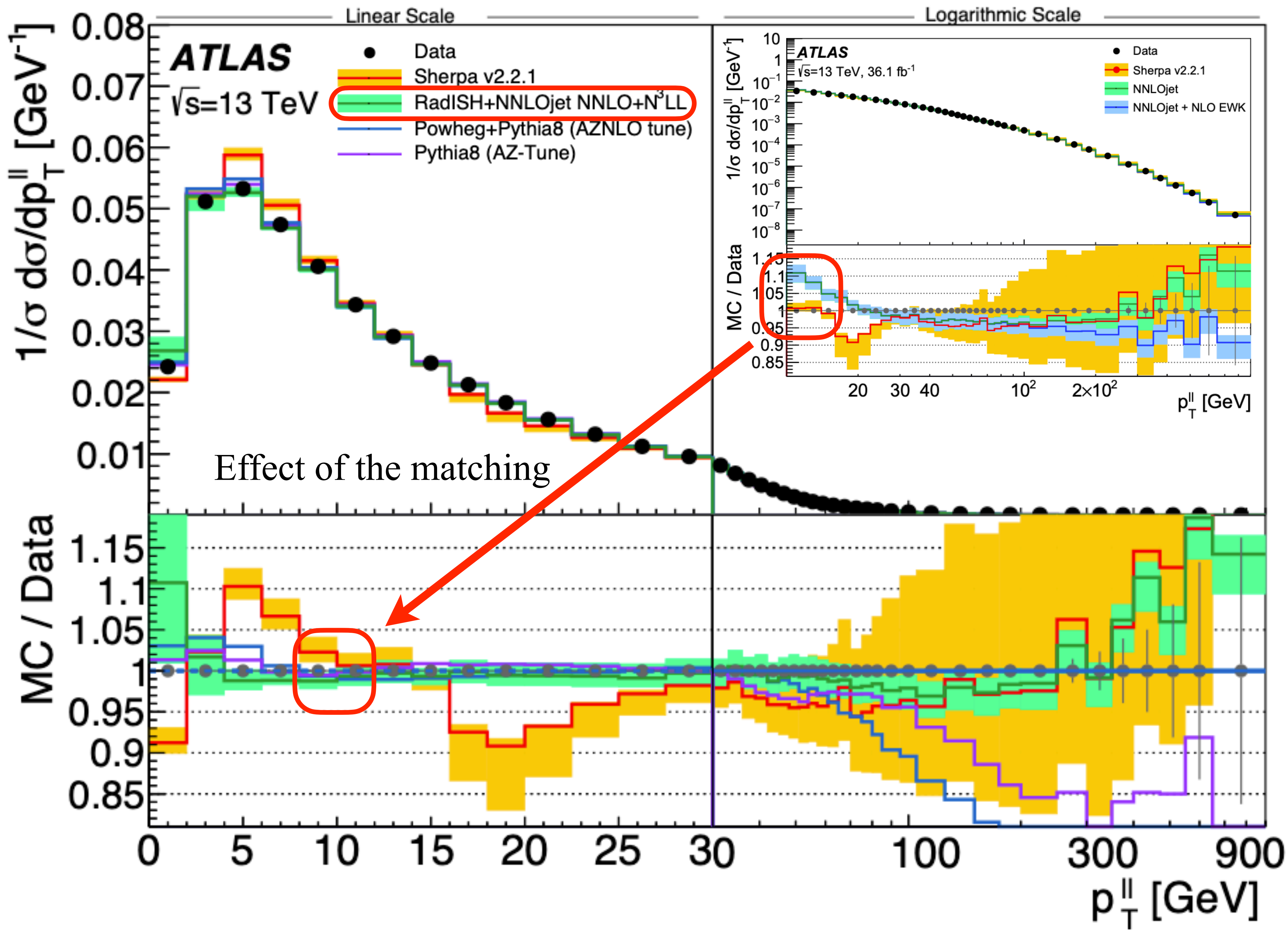


Resummation of the q_T distribution



RadISH + NNLOjet implements the matching procedure described below (except that the matching is **multiplicative** rather than additive [*JHEP* 12 (2018) 132]. Can you tell what is the difference?).

Resummation of the q_T distribution



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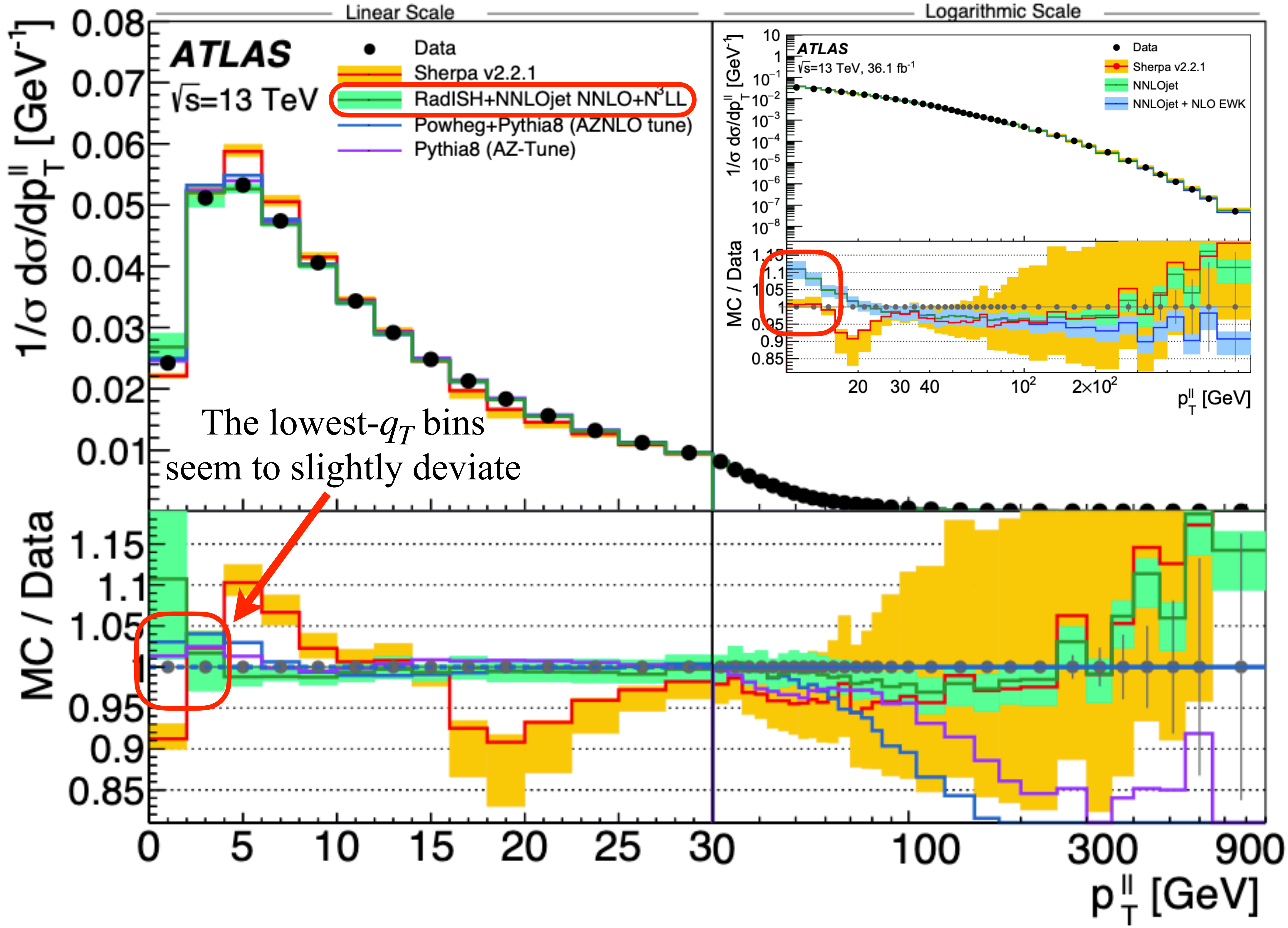
Resummation of the q_T distribution



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Non-perturbative effects in q_T distributions

As mentioned in the previous lecture, for $q_T \lesssim 1$ GeV non-perturbative effects, related to α_s becoming large and eventually hitting the Landau pole, become important.

The TMD view on q_T resummation allowed for a transparent way of parameterising non-perturbative effects into a function that can determined through fits to data (like PDFs).

A Little reminder:

$$\frac{d\sigma}{dQ^2 dy dq_T^2} = \frac{2\pi\alpha_{\rm em}^2}{3sQ^2 N_c} \sum_q H_{ab}(\alpha_s(Q)) \int_0^\infty db\, b J_0\left(b q_T\right) F_a\left(x_1, b; Q, Q^2\right) F_b\left(x_2, b; Q, Q^2\right)$$

do this trick:

$$b_*(b) = \frac{b}{\sqrt{1 + b^2/b_{\rm max}^2}} \qquad F\left(x, b; \mu, \zeta\right) = \left[\frac{F\left(x, b; \mu, \zeta\right)}{F\left(x, b_*(b); \mu, \zeta\right)}\right] F\left(x, b_*(b); \mu, \zeta\right) = f_{\rm NP}(x, b, \zeta) F\left(x, b_*(b); \mu, \zeta\right)$$

so that:

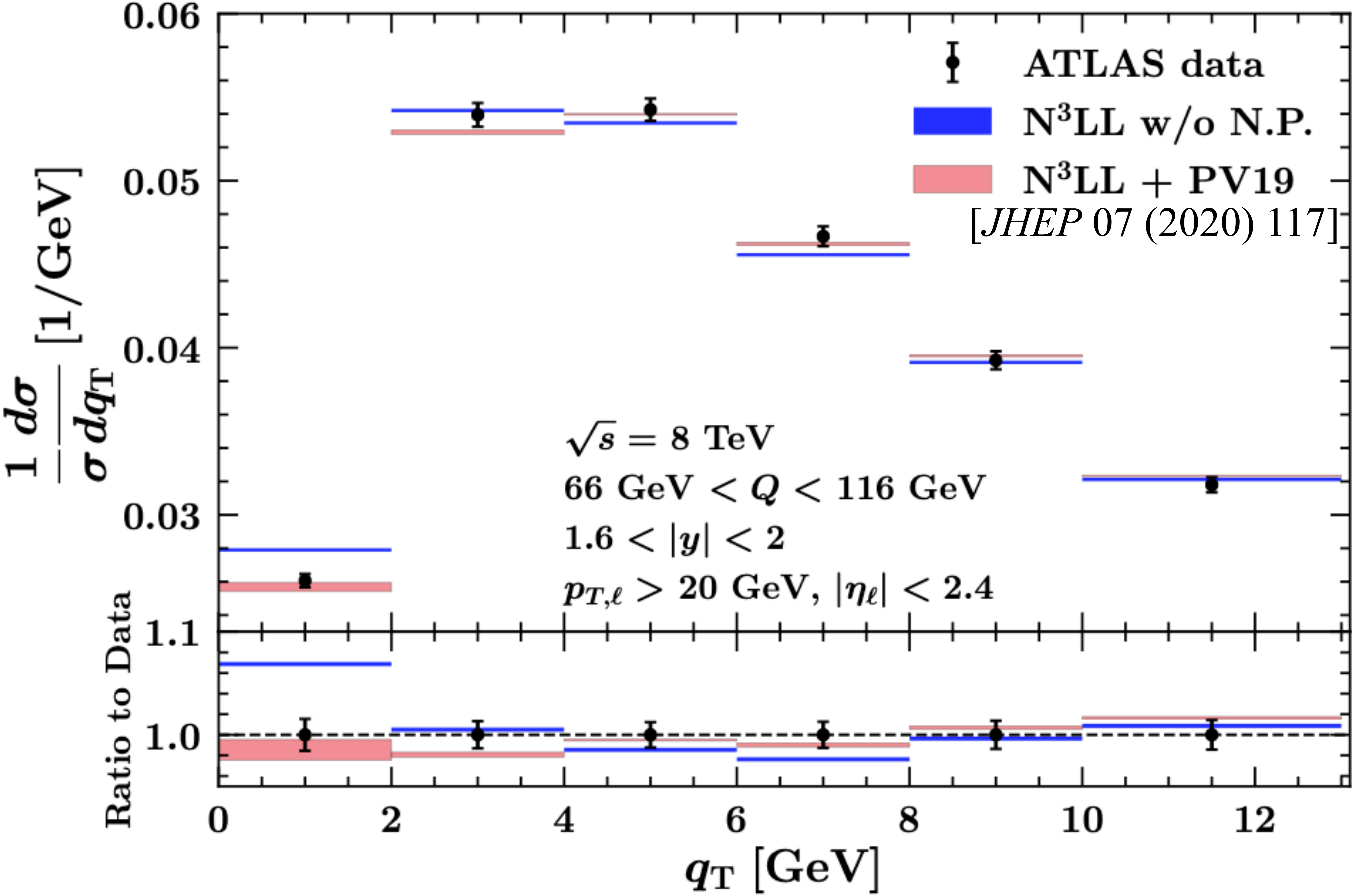
$$\begin{aligned} \frac{d\sigma}{dQ^2 dy dq_T^2} &= \frac{2\pi\alpha_{\rm em}^2}{3sQ^2 N_c} \sum_q H_{ab}(\alpha_s(Q)) \int_0^\infty db\, b J_0\left(b q_T\right) f_{\rm NP}\left(x_1, b, Q^2\right) f_{\rm NP}\left(x_2, b, Q^2\right) \\ &\times \quad F_a\left(x_1, b_*(b); Q, Q^2\right) F_b\left(x_2, b_*(b); Q, Q^2\right) \end{aligned}$$

take small q_T data that, parameterise $f_{\rm NP}$, *e.g.*:

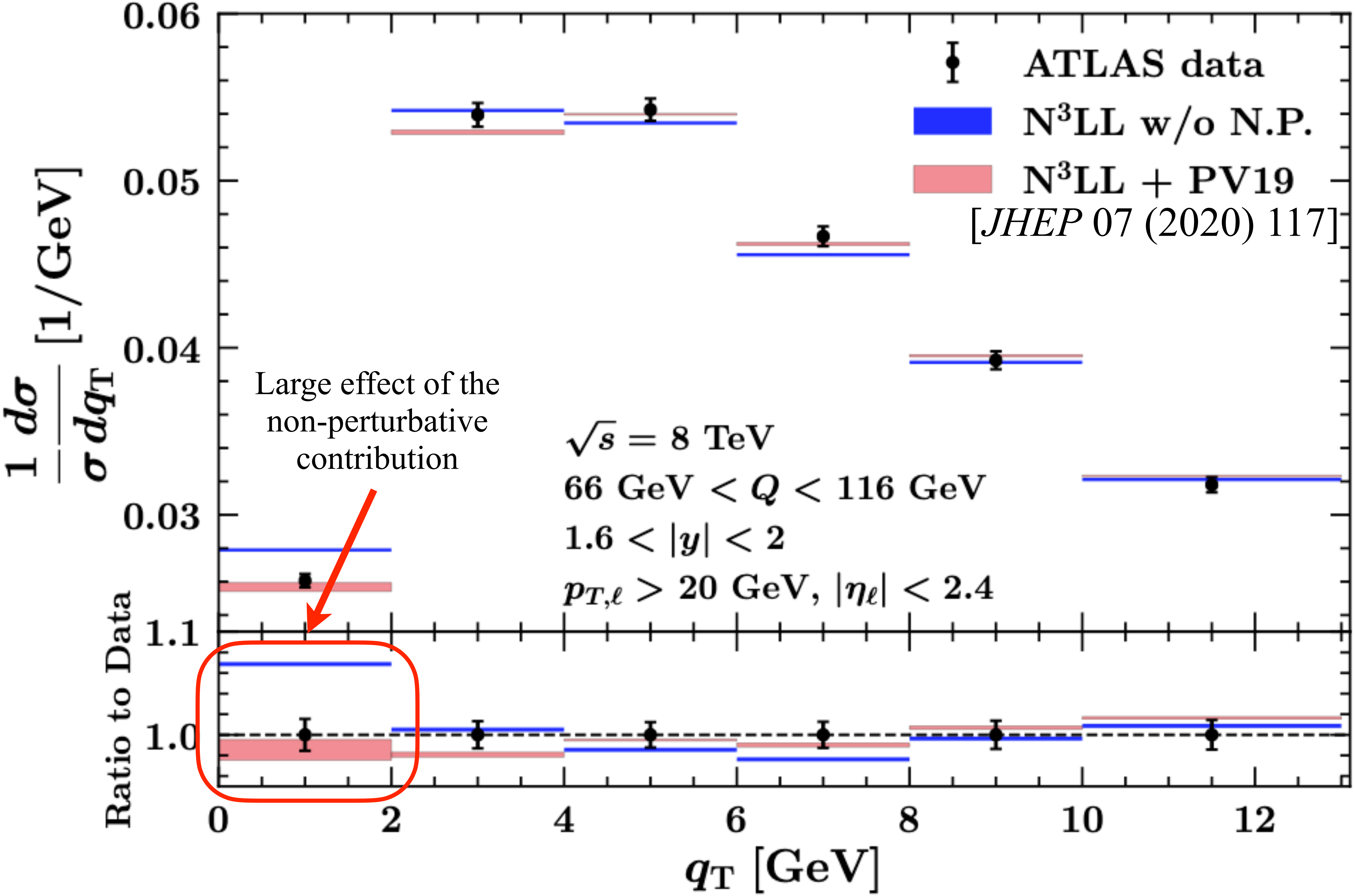
$$f_{\rm NP}(x, b, \zeta) = \exp\left[g_1(b) \ln\left(\frac{\zeta}{Q_0^2}\right) + g_2(x, b)\right]$$

and determine it through a fit.

Non-perturbative effects in q_T distributions



Non-perturbative effects in q_T distributions

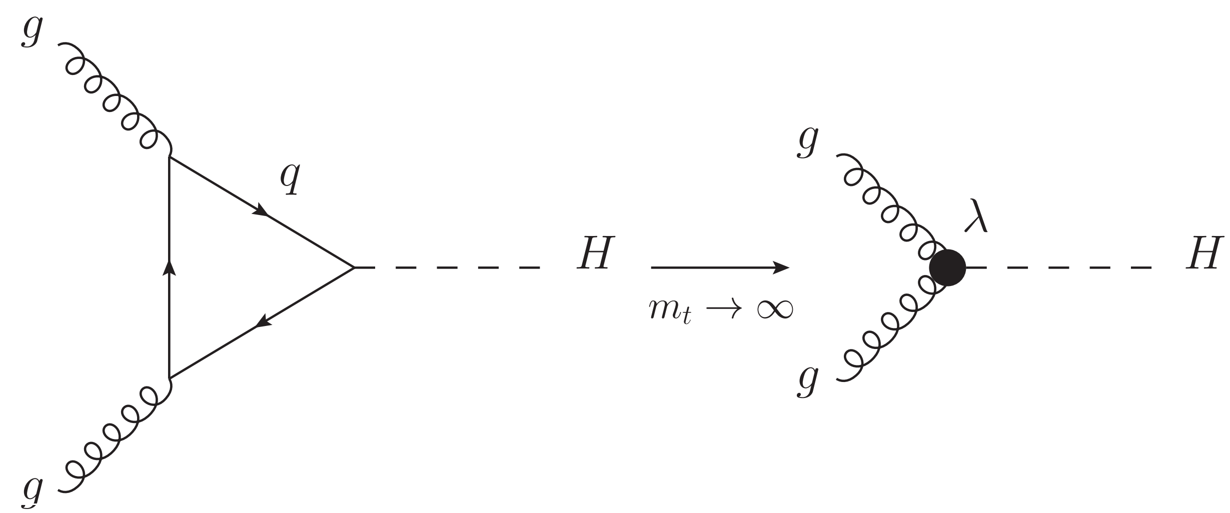


Inclusive Higgs production in $gg \to H$

The main reason why inclusive Higgs production in gluon fusion fits this discussion is that, like Drell-Yan production, the final state is a **colour singlet**.

As a consequence, factorisation (collinear and TMD) works just as well as for Drell-Yan.

The parallel is made particularly transparent in **the** $m_t \to \infty$ **limit** in which top-quark loops can be integrated out. As a consequence:



which amounts to introducing an additional term in the ($n_f = 5$) QCD Lagrangian:

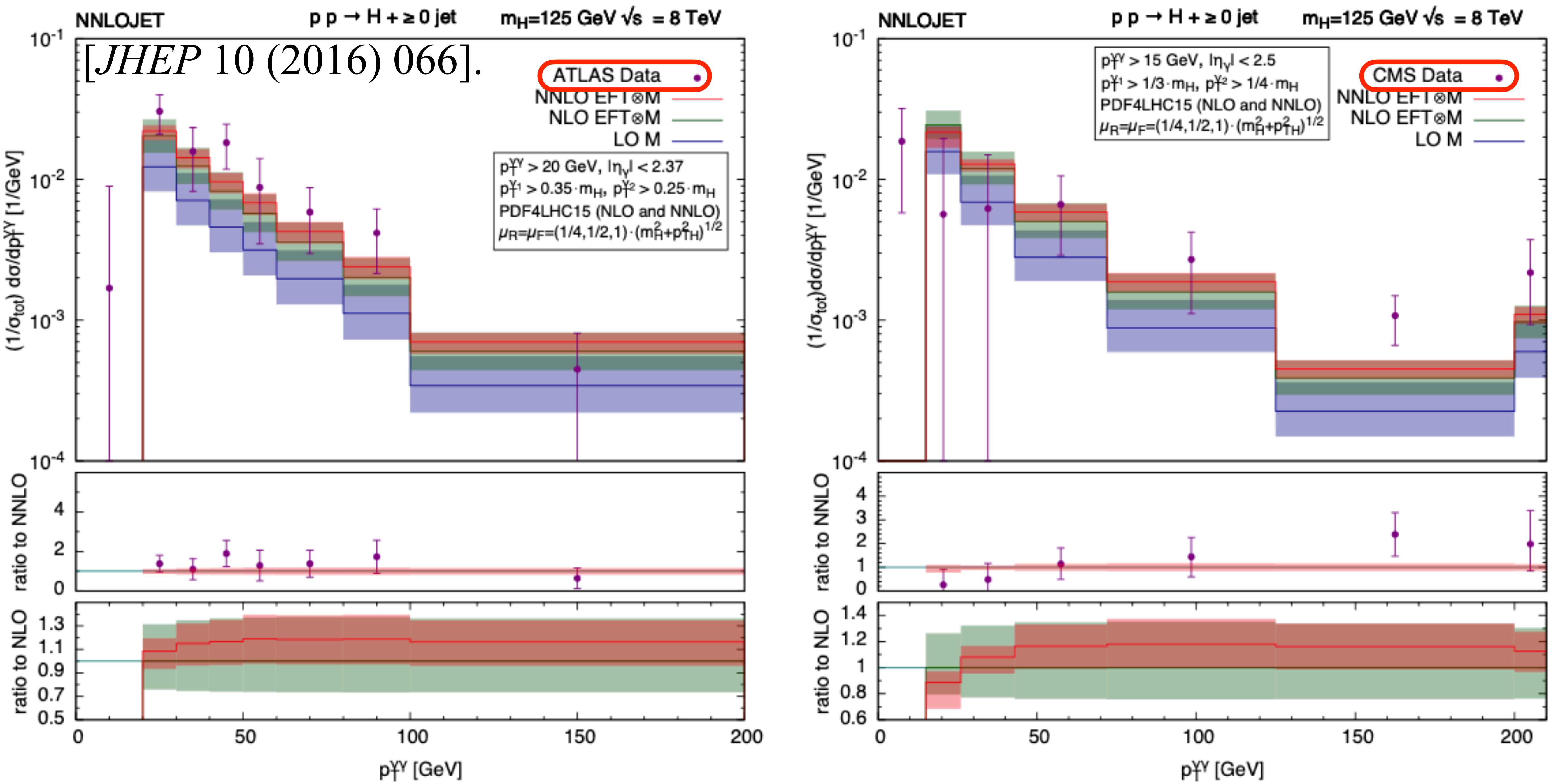
$$\mathcal{L}_{gg\to H} = -\frac{\lambda}{4} G^{\mu\nu} G_{\mu\nu} H$$

thus making higher-order perturbative calculations more convenient.

The effective coupling $\lambda = \mathcal{O}(\alpha_s^2)$ receives perturbative corrections that are currently known to NNLO [Nucl. Phys. B510 (1998) 61–87]. The partonic cross sections for $pp \to H + j + X$ are also know to NNLO accuracy (*e.g.* [*JHEP* 10 (2016) 066]).

This enables a **full NNLO calculation** of the q_T of the Higgs for $q_T \sim M_H$.

Inclusive Higgs production in $gg \to H$



[*JHEP* 10 (2016) 066].

A comparison at the level of normalised cross sections between theoretical predictions and the ATLAS and CMS data for $pp \to H + X \to \gamma\gamma + X$ is reassuring:

- higher-order corrections seem to get closer to the data,
- substantial theory-uncertainty reduction going from LO to NNLO,
- **data** accuracy though is still **not very competitive**.

Inclusive Higgs production in $gg \to H$

Let us briefly explore what happens at **low** q_T.

Remarkably, the CSS and TMD-factorisation formulas apply (almost) out of the box:

- the only change w.r.t. Drell-Yan is replacing quarks with gluons.

$$
\begin{aligned}
\frac{d\sigma^{\mathrm{CSS}}_{gg\to H+X}}{dy\,dq_T^2} \quad &\propto \quad H_{qq\to H}(\alpha_s(M_H)) \int_0^\infty db\, b J_0(bq_T) \\
&\times \quad \sum_i \int_{x_1}^1 \frac{dy_1}{y_1} C_{gi}(y_1, \alpha_s(\mu_b)) f_i\left(\frac{x_1}{y_1}, \mu_b\right) \\
&\times \quad \sum_j \int_{x_2}^1 \frac{dy_2}{y_2} C_{gj}(y_2, \alpha_s(\mu_b)) f_j\left(\frac{x_2}{y_2}, \mu_b\right) \\
&\times \quad \exp\left\{-\int_{\mu_b^2}^{M_H^2} \frac{d\mu^2}{\mu^2}\left[A_g(\alpha_s(\mu)) \ln\left(\frac{M_H^2}{\mu^2}\right) + B_g(\alpha_s(\mu))\right]\right\} \\
&+ \quad Y(y, q_T) \\
&\propto \quad \underbrace{H_{qq\to H}(\alpha_s(M_H)) \int_0^\infty db\, b J_0(bq_T) F_g(x_1, b, M_H, M_H^2) F_g(x_1, b, M_H, M_H^2)}_{W(y,q_T)} + Y(y, q_T)
\end{aligned}
$$

In this form, the formula assumes that the gluons are **unpolarised**:

- f_i are the collinear unpolarised PDFs,
- F_g is the TMD unpolarised **gluon** distribution.

Inclusive Higgs production in $gg \to H$

However, it turns out that also **linearly** polarised gluons contribute to the cross section:

- if b is small enough, the linearly polarised gluon distribution can be matched onto the unpolarised gluon PDF:

$$h_1^\perp(x, b, \mu_b, \mu_b^2) \underset{b \ll \Lambda_{QCD}^{-1}}{=} \sum_i \int_x^1 \frac{dy}{y} G_{gi}(y, \alpha(\mu_b)) f_i\left(\frac{x}{y}, \mu_b\right)$$

- In fact, TMD factorisation introduces a new (non-perturbative) TMD distribution: the so-called **Boer-Mulders TMD** $h_1^\perp$ that parameterises the distribution of a linearly polarised gluon inside an unpolarised hadron.

- The net result is that the factorisation formular is modified as follows:

$$\frac{d\sigma^{\text{CSS}}_{gg\to H+X}}{dydq_T^2} \quad \to \quad \frac{d\sigma^{\text{CSS}}_{gg\to H+X}}{dydq_T^2} + (C \to G)$$

$$\propto \quad H_{qq\to H}(\alpha_s(M_H))\left[\int_0^\infty db\, b J_0(bq_T) F_g(x_1, b, M_H, M_H^2) F_g(x_1, b, M_H, M_H^2)\right.$$

$$+ \quad \left.\int_0^\infty db\, b J_2(bq_T) h_1^\perp(x_1, b, M_H, M_H^2) h_1^\perp(x_1, b, M_H, M_H^2)\right] + Y(y, q_T)$$

The TMD form allows one to introduce a non-perturbative component for $b \gtrsim \Lambda_{\text{QCD}}^{-1}$:

$$h_1^\perp(x, b; \mu, \zeta) = \left[\frac{h_1^\perp(x, b; \mu, \zeta)}{h_1^\perp(x, b_*(b); \mu, \zeta)}\right] h_1^\perp(x, b_*(b); \mu, \zeta) = f_{\text{NP}}^\perp(x, b, \zeta) h_1^\perp(x, b_*(b); \mu, \zeta)$$

Inclusive Higgs production in $gg \to H$

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$$\frac{d\sigma^{\rm CSS}_{gg\to H+X}}{dy dq_T^2} \quad \to \quad \boxed{\frac{d\sigma^{\rm CSS}_{gg\to H+X}}{dy dq_T^2}} + \boxed{(C \to G)}$$

Unpolarised contribution

$$\propto \quad H_{qq\to H}(\alpha_s(M_H))\left[\int_0^\infty db\, b J_0(bq_T) \boxed{F_g(x_1, b, M_H, M_H^2) F_g(x_1, b, M_H, M_H^2)}\right.$$

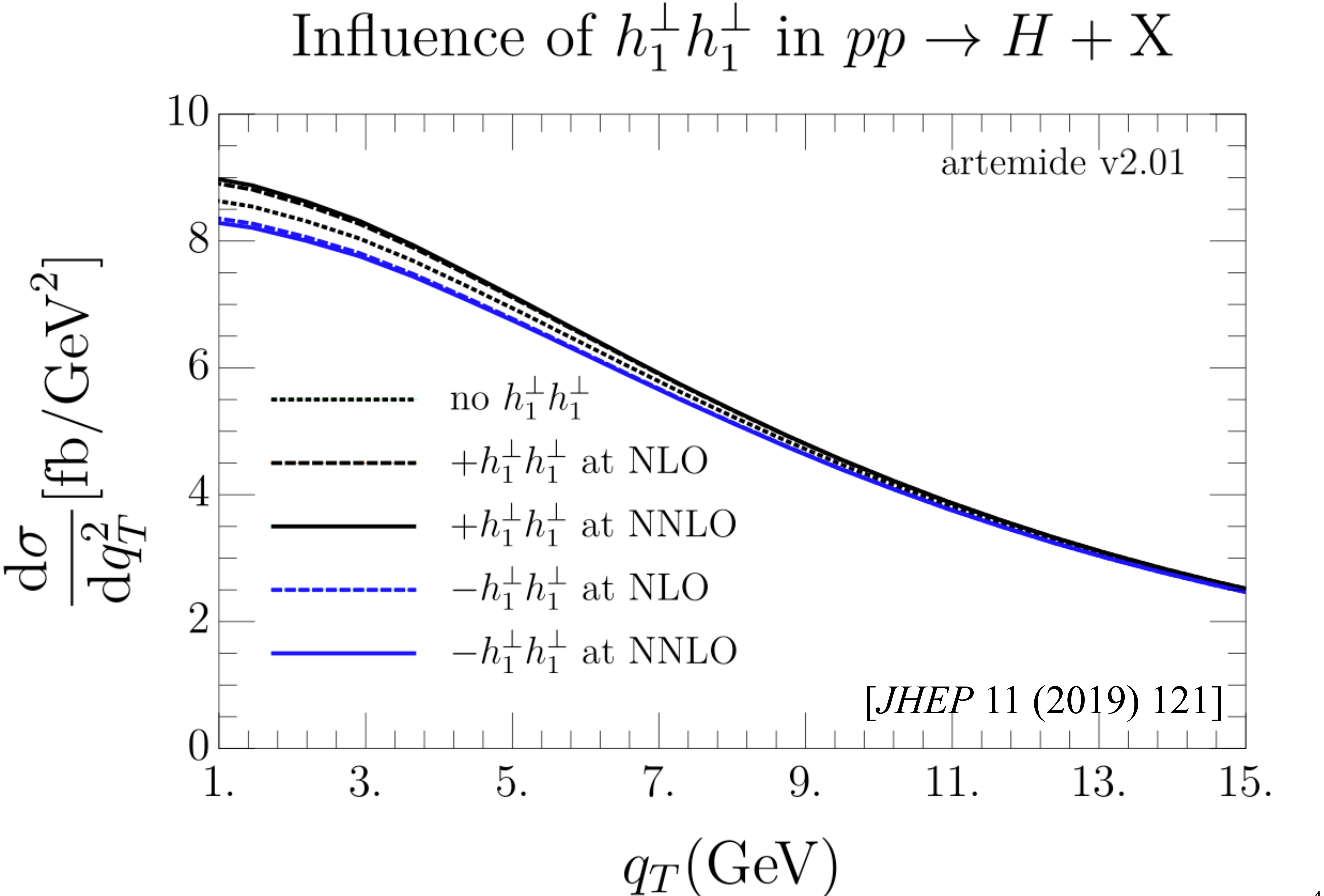
Linearly polarised contribution

$$\left. + \quad \int_0^\infty db\, b J_2(bq_T) \boxed{h_1^\perp(x_1, b, M_H, M_H^2) h_1^\perp(x_1, b, M_H, M_H^2)}\right] + Y(y, q_T)$$

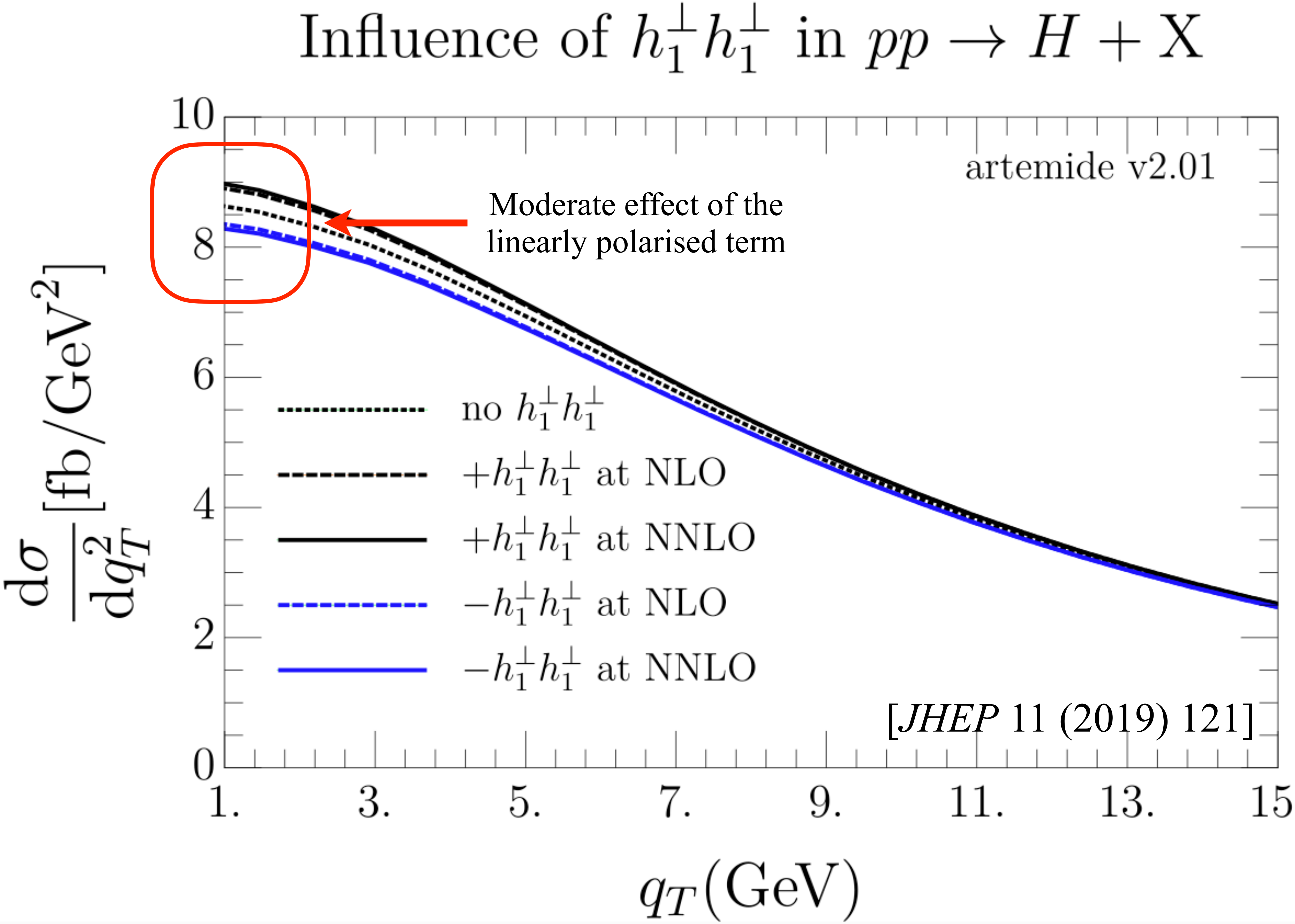
The TMD form allows one to introduce a non-perturbative component for $b \gtrsim \Lambda_{\rm QCD}^{-1}$:

$$h_1^\perp(x, b; \mu, \zeta) = \left[\frac{h_1^\perp(x, b; \mu, \zeta)}{h_1^\perp(x, b_*(b); \mu, \zeta)}\right] h_1^\perp(x, b_*(b); \mu, \zeta) = f_{\rm NP}^\perp(x, b, \zeta) h_1^\perp(x, b_*(b); \mu, \zeta)$$

Inclusive Higgs production in $gg \to H$

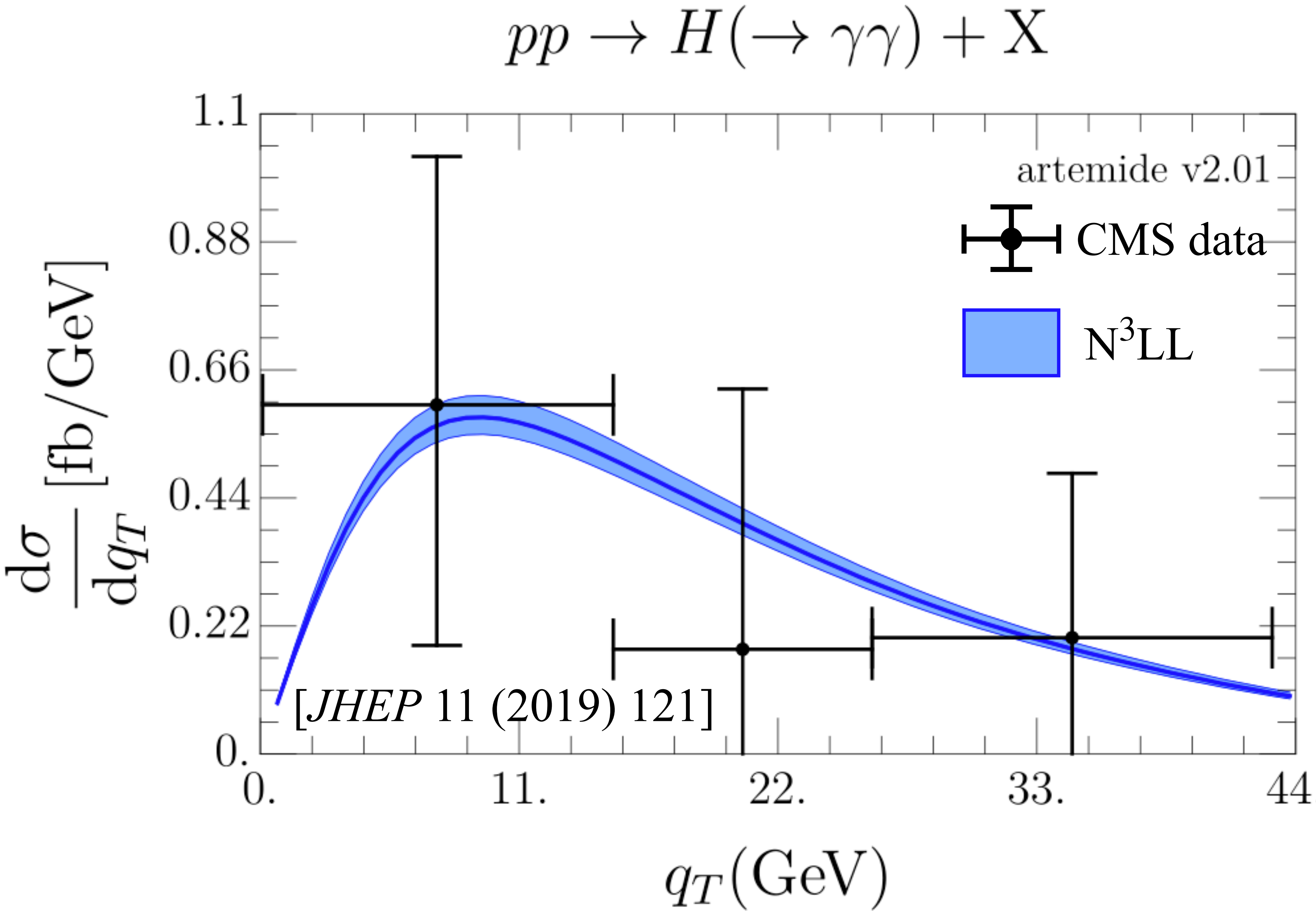


Inclusive Higgs production in $gg \to H$



Inclusive Higgs production in $gg \to H$

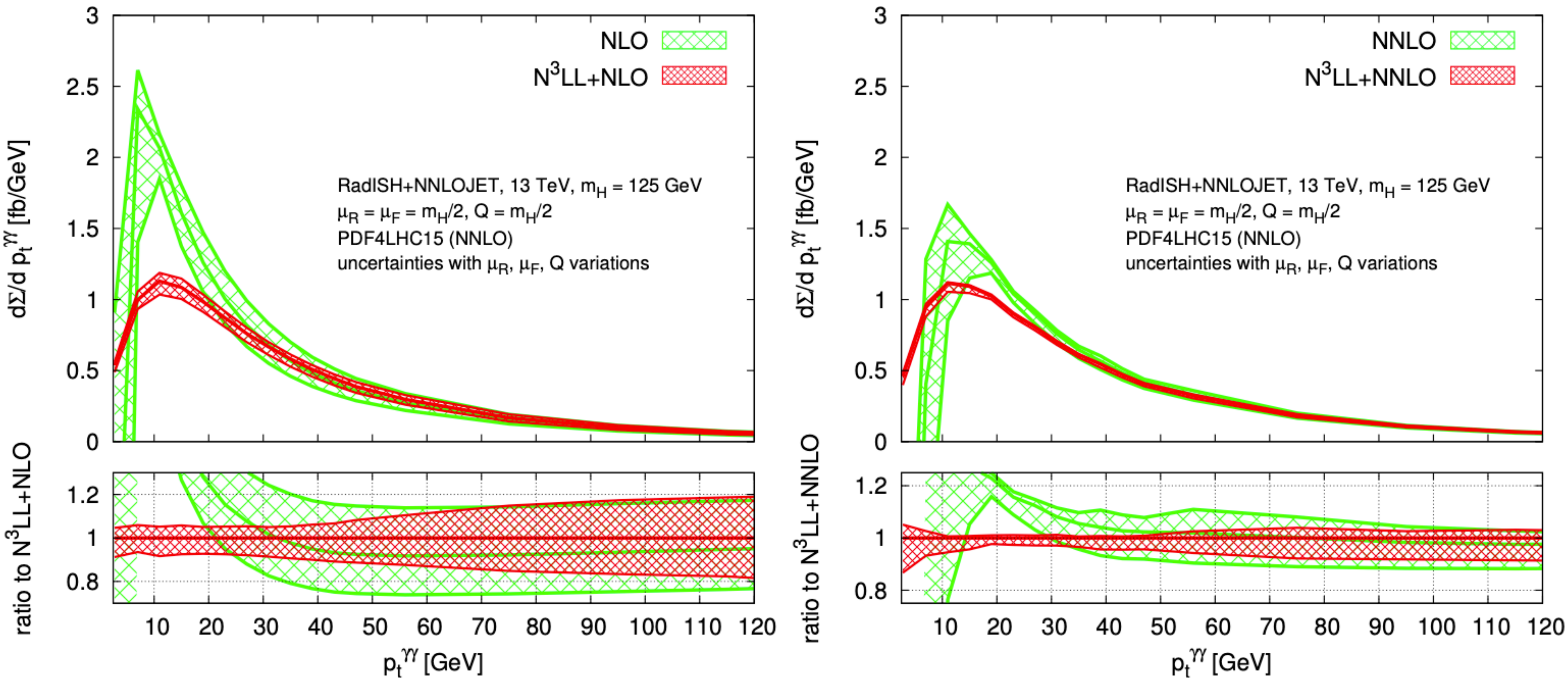
One can attempt to assess how well predictions (including linearly-polarised gluons) at low-q_T compare to the LHC Higgs-production data:



Unfortunately, current data does not allow to say much on the accuracy of the formalism as well as on the TMD gluon distributions.

Inclusive Higgs production in $gg \to H$

A carefully study of the Higgs q_T matching the resummed calculation with the fixed-order one for $pp \to H + X \to \gamma\gamma + X$ was done in [*JHEP* 12 (2018) 132] with realistic cuts on the photons:



Expected patterns:

- unreliability of the fixed-order calculation at low $p_T^{\gamma\gamma}$ (NLO (left) vs. NNLO (right)),
- reduction of the theoretical uncertainties going from NLO to NNLO,
- dominance of the resummation at low $p_T^{\gamma\gamma}$ in the matched calculation.

That’s all folks!
Thank you!