The impact of TMDs on LHC physics

giuseppe bozzi
university of pavia

Sar WorS 2021

September 6th, 2021

TMD structure

$$
\begin{aligned}
F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) &= \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) && : A \\
&\times \exp\left\{ K(b_*; \mu_b) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'} \right] \right\} && : B \\
&\times \exp\left\{ g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}} \right\} && : C
\end{aligned}
$$

TMD structure

$$F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) = \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) \qquad : A$$

$$\times \quad \exp\left\{ K(b_*; \mu_b) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'} \right] \right\} \qquad : B$$

$$\times \quad \exp\left\{ g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}} \right\} \qquad : C$$

- matching to collinear PDF at $b_T \ll 1/\Lambda_{QCD}$
- **perturbative**

TMD structure

$$F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) = \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) \qquad : A$$

$$\times \exp\left\{ K(b_*; \mu_b) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'} \right] \right\} \qquad : B$$

$$\times \exp\left\{ g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}} \right\} \qquad : C$$

- matching to collinear PDF at $b_T \ll 1/\Lambda_{QCD}$
- **perturbative**

- CS and RGE evolution to large b_T
- **perturbative**

TMD structure

$$F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) = \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) \quad : A$$

$$\times \exp\left\{ K(b_*; \mu_b) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'} \right] \right\} \quad : B$$

$$\times \exp\left\{ g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}} \right\} \quad : C$$

$$\left(\mu_b = 2e^{-\gamma_E}/b_*\right)$$

- matching to collinear PDF at $b_T \ll 1/\Lambda_{QCD}$
- **perturbative**

- CS and RGE evolution to large b_T
- **perturbative**

- b_* prescription to avoid Landau pole
- f_{NP} “parametrises” the **non-perturbative** transverse modes
- **fit** f_{NP} to data

Perturbative accuracy

Accuracy	H and C	K and γ_F	γ_K	PDF and α_s evolution
LL	0	-	1	-
NLL	0	1	2	LO
NNLL	1	2	3	NLO
N^3LL	2	3	4	NNLO

Perturbative accuracy

Accuracy	H and C	K and γ_F	γ_K	PDF and α_s evolution
LL	0	-	1	-
NLL	0	1	2	LO
NLL'	1	1	2	NLO
NNLL	1	2	3	NLO
NNLL'	2	2	3	NNLO
N^3LL	2	3	4	NNLO

Perturbative accuracy

Accuracy	H and C	K and γ_F	γ_K	PDF and α_s evolution
LL	0	-	1	-
NLL	0	1	2	LO
NLL'	1	1	2	NLO
NNLL	1	2	3	NLO
NNLL'	2	2	3	NNLO
N^3LL	2	3	4	NNLO

NLL $\quad C^0 \quad$ $$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$$

Perturbative accuracy

Accuracy	H and C	K and γ_F	γ_K	PDF and α_s evolution
LL	0	-	1	-
NLL	0	1	2	LO
NLL'	1	1	2	NLO
NNLL	1	2	3	NLO
NNLL'	2	2	3	NNLO
N^3LL	2	3	4	NNLO

$$\text{NLL} \qquad C^0 \qquad \alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$$

$$\text{NLL'} \qquad \left(C^0 + \alpha_S C^1\right) \qquad \alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$$

Perturbative accuracy

Accuracy	H and C	K and γ_F	γ_K	PDF and α_s evolution
LL	0	-	1	-
NLL	0	1	2	LO
NLL'	1	1	2	NLO
NNLL	1	2	3	NLO
NNLL'	2	2	3	NNLO
N^3LL	2	3	4	NNLO

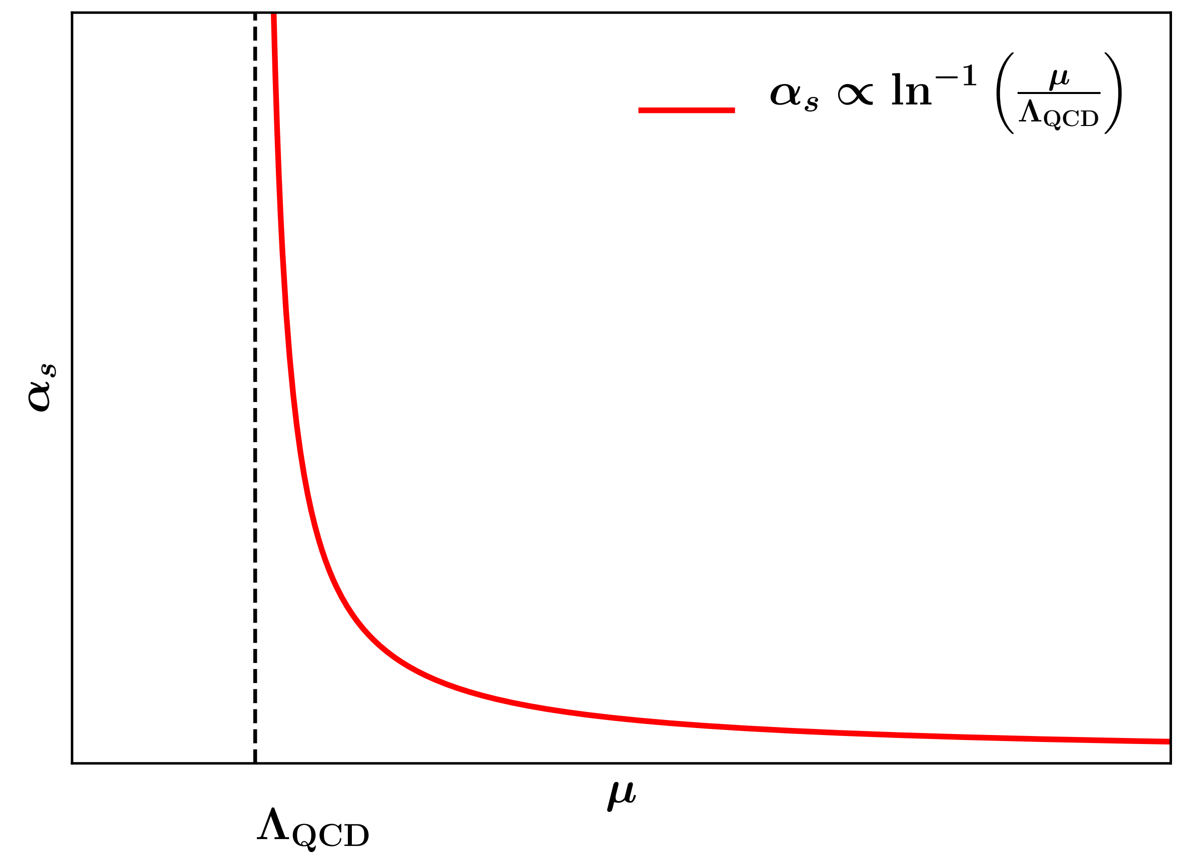
NLL $\quad C^0 \quad \alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$

NLL' $\quad \left(C^0 + \alpha_S C^1\right) \quad \alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$

same logarithmic accuracy (difference = NNLL)

Non-perturbative: b* and f_{NP}

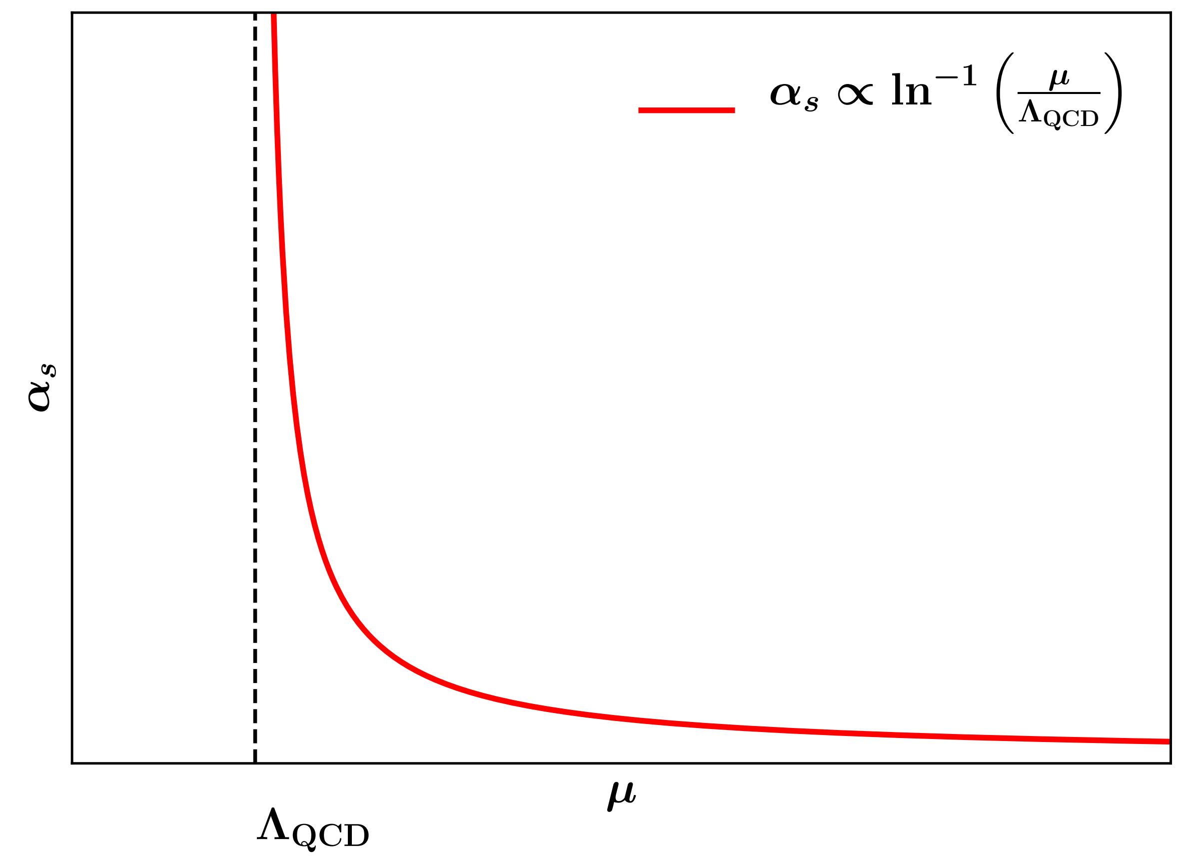
$\alpha_s(\mu_b) = \alpha\left(\frac{2e^{-\gamma_E}}{b}\right) \gg 1$ for large b values



Non-perturbative: b* and f_{NP}

$\alpha_s(\mu_b) = \alpha\left(\frac{2e^{-\gamma_E}}{b}\right) \gg 1$ for large b values

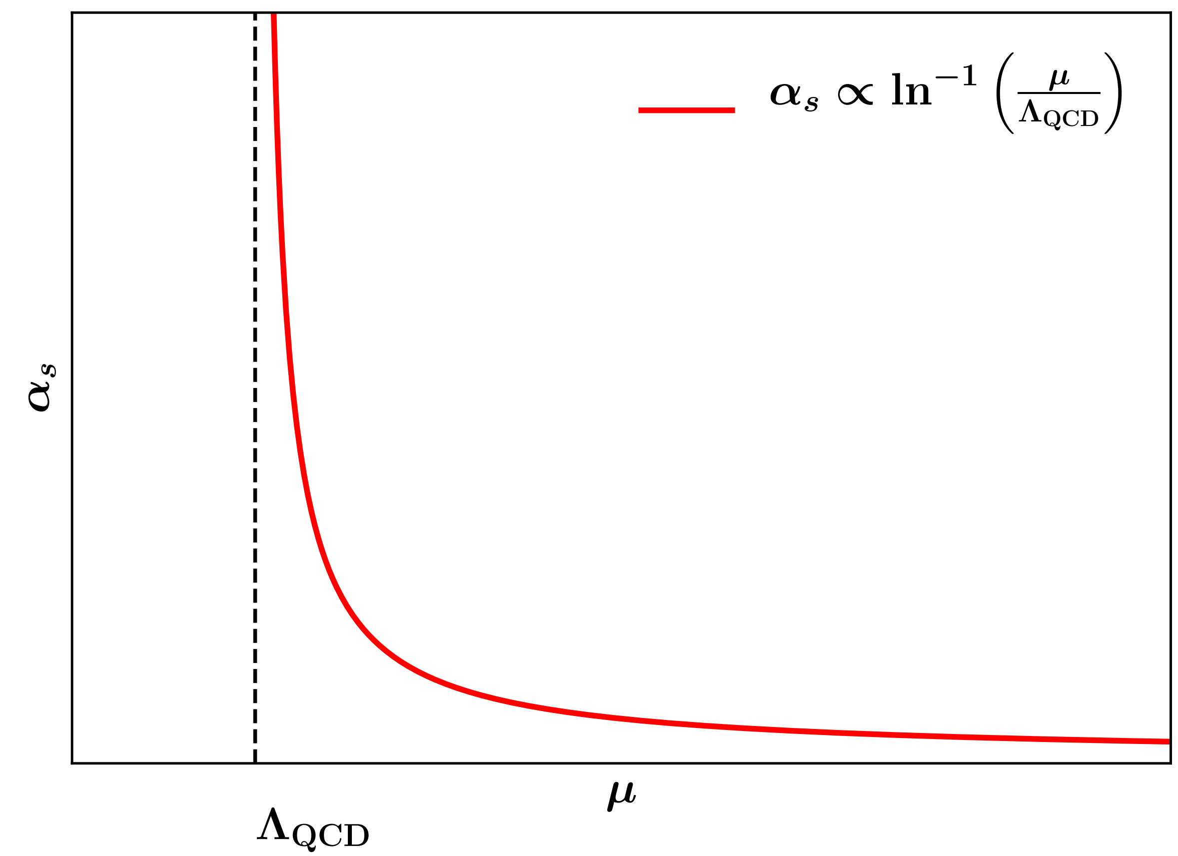
b*-prescription
to avoid Landau pole at Λ_{QCD}



Non-perturbative: b* and f_{NP}

$\alpha_s(\mu_b) = \alpha\left(\frac{2e^{-\gamma_E}}{b}\right) \gg 1$ for large b values

b*-prescription
to avoid Landau pole at Λ_{QCD}

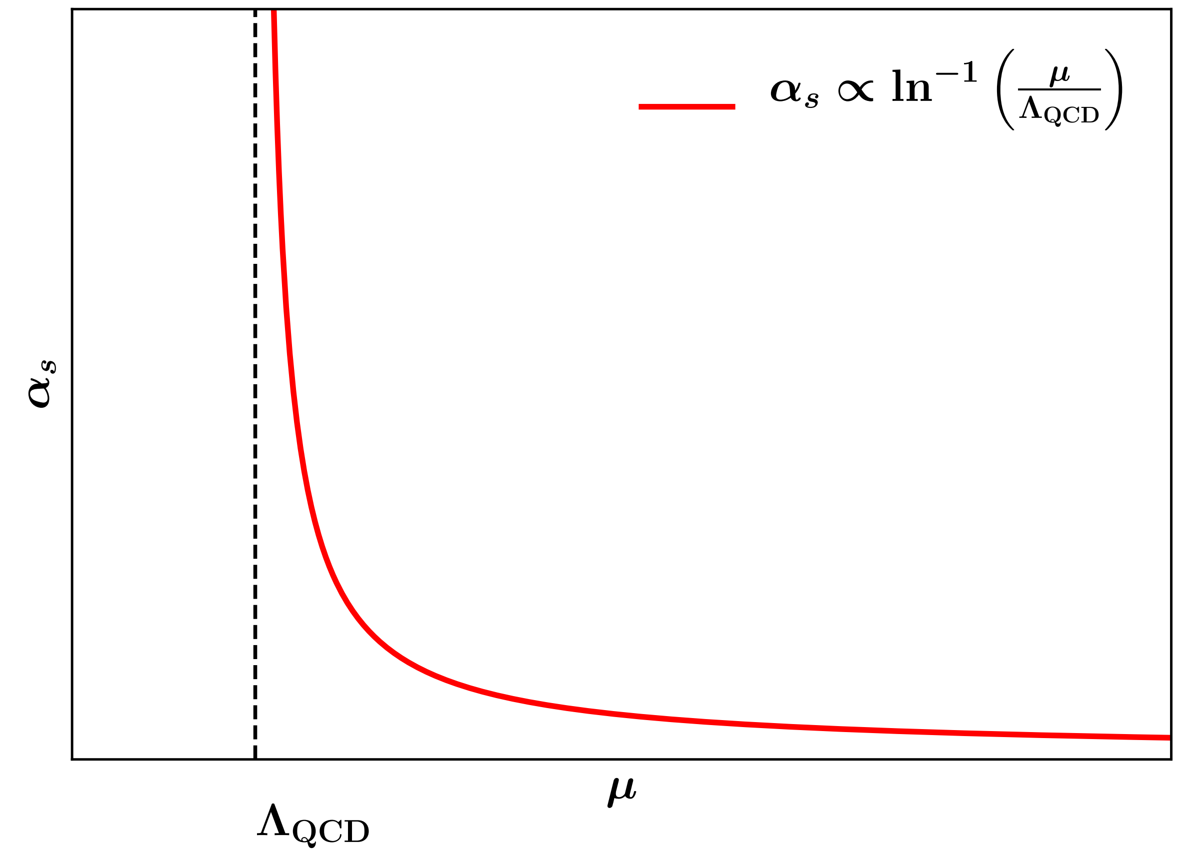


$$F(x,b;\mu,\zeta) = \left[\frac{F(x,b;\mu,\zeta)}{F(x,b_*(b);\mu,\zeta)}\right] F(x,b_*(b);\mu,\zeta)$$

Non-perturbative: b* and f_{NP}

$\alpha_s(\mu_b) = \alpha\left(\frac{2e^{-\gamma_E}}{b}\right) \gg 1$ for large b values

b*-prescription
to avoid Landau pole at Λ_{QCD}



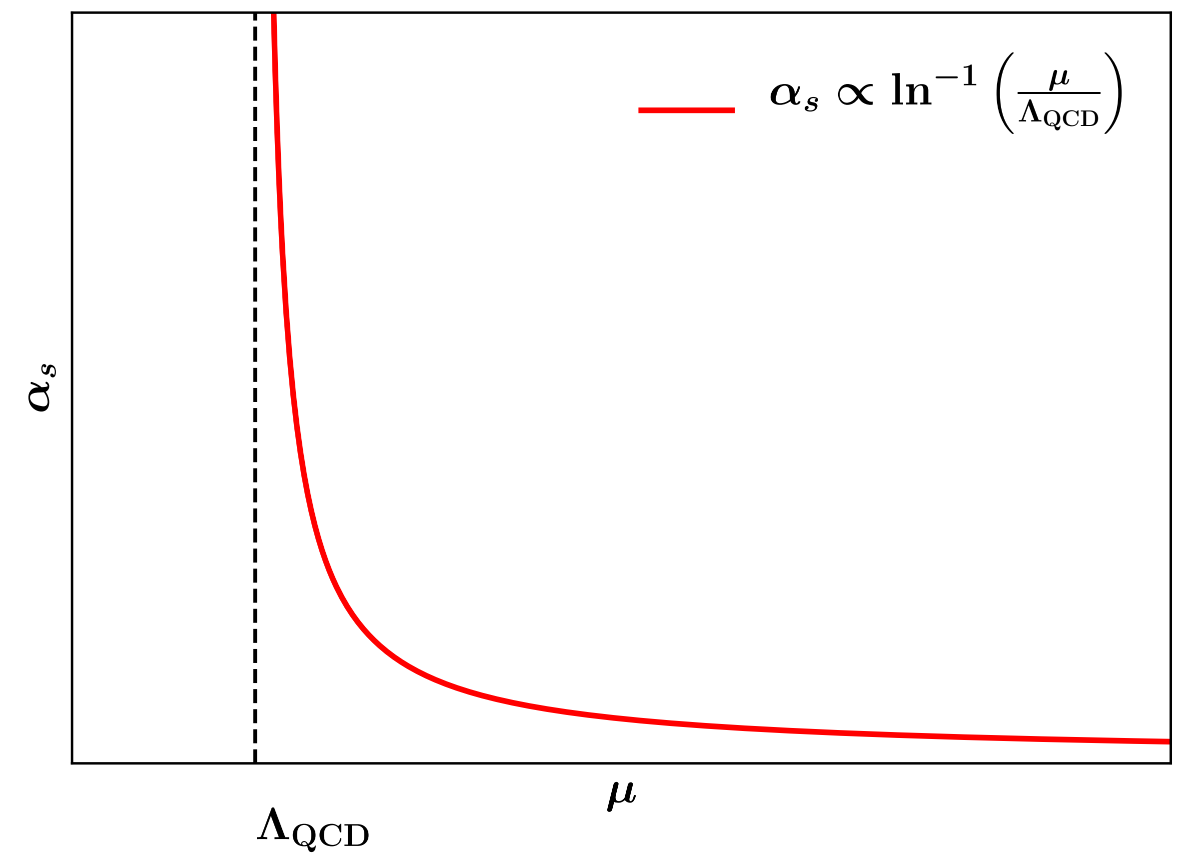
fNP

$$F(x,b;\mu,\zeta) = \left[\frac{F(x,b;\mu,\zeta)}{F(x,b_*(b);\mu,\zeta)}\right] F(x,b_*(b);\mu,\zeta)$$

Non-perturbative: b* and f_{NP}

$\alpha_s(\mu_b) = \alpha\left(\frac{2e^{-\gamma_E}}{b}\right) \gg 1$ for large b values

b*-prescription
to avoid Landau pole at Λ_{QCD}



f_{NP}

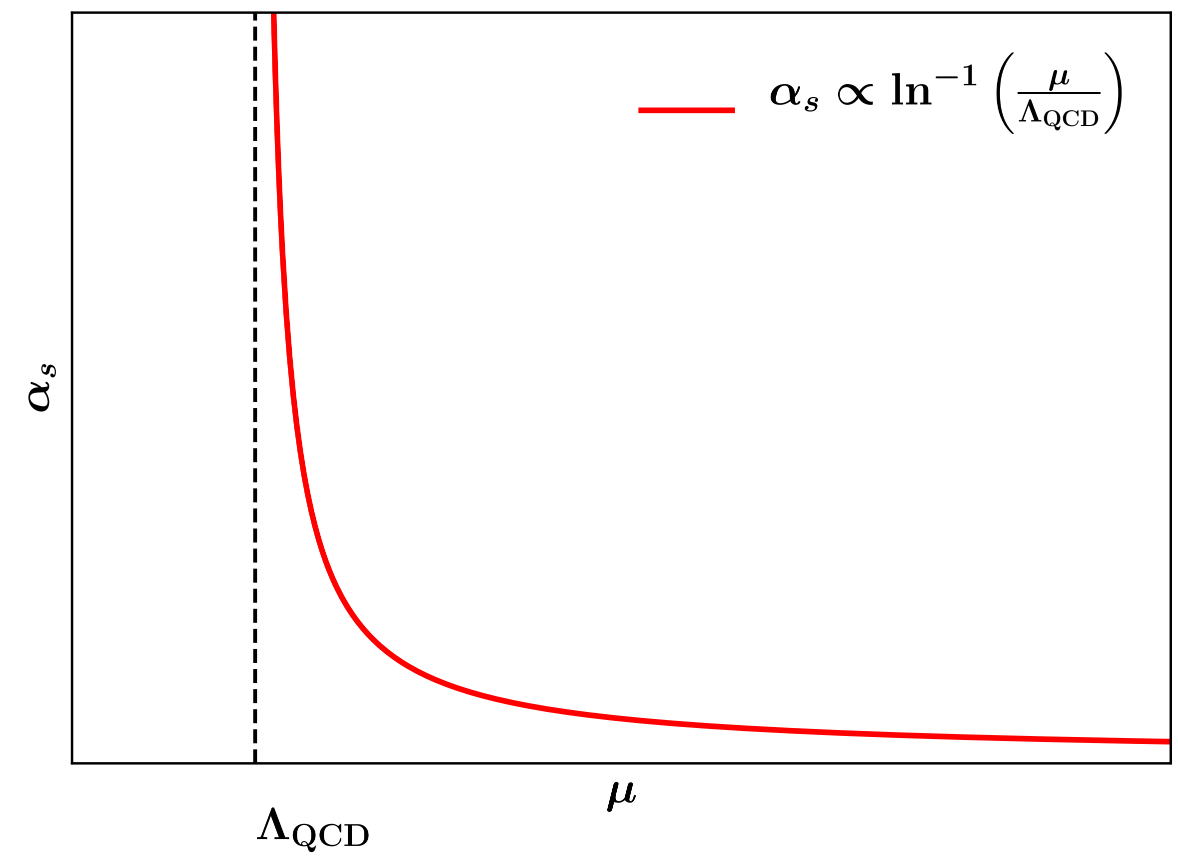
$$F(x, b; \mu, \zeta) = \left[\frac{F(x,b;\mu,\zeta)}{F(x,b_*(b);\mu,\zeta)}\right] F(x, b_*(b); \mu, \zeta)$$

- NP is unavoidable: intrinsically tied to regularisation procedure

Non-perturbative: b* and f_{NP}

$\alpha_s(\mu_b) = \alpha\left(\frac{2e^{-\gamma_E}}{b}\right) \gg 1$ for large b values

b*-prescription
to avoid Landau pole at Λ_{QCD}



f_{NP}

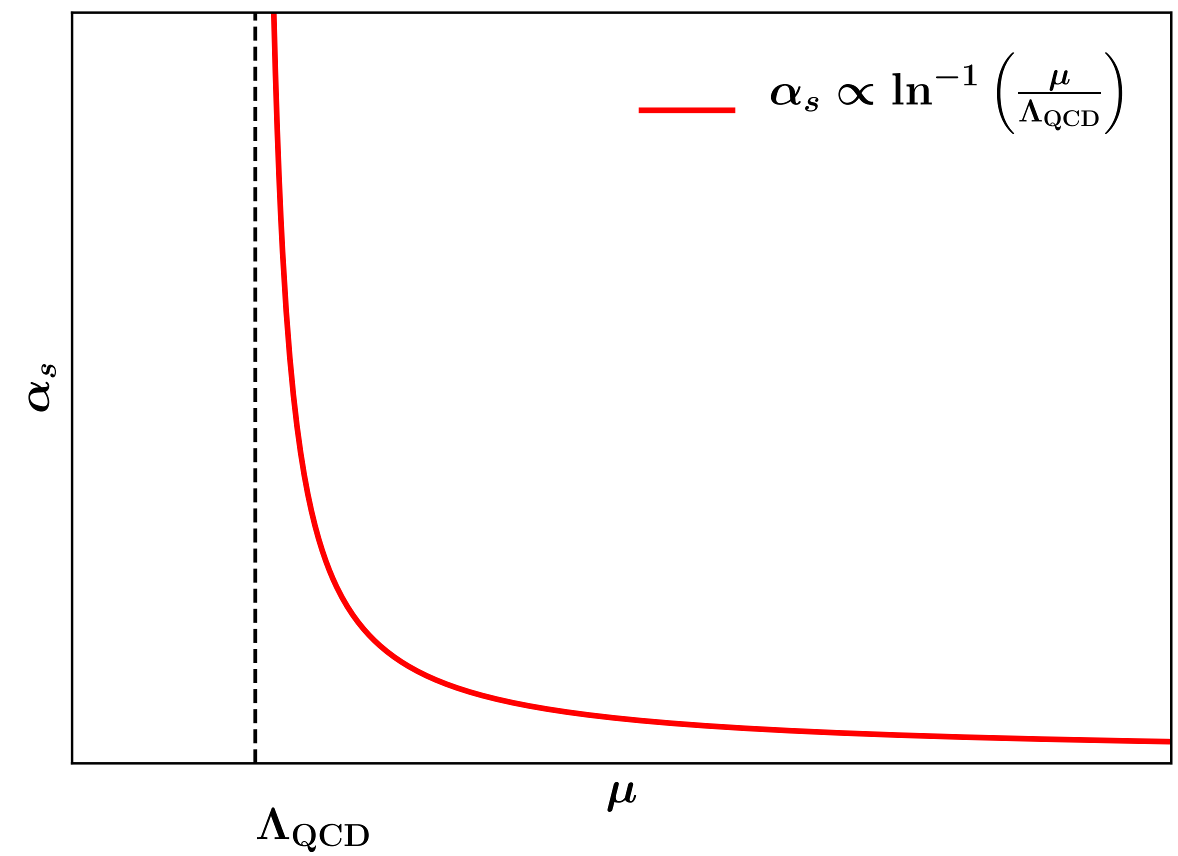
$$F(x,b;\mu,\zeta) = \left[\frac{F(x,b;\mu,\zeta)}{F(x,b_*(b);\mu,\zeta)}\right] F(x,b_*(b);\mu,\zeta)$$

- NP is unavoidable: intrinsically tied to regularisation procedure
- There is not a universal form factor: NP depends on details of b*

Non-perturbative: b* and f_{NP}

$\alpha_s(\mu_b) = \alpha\left(\frac{2e^{-\gamma_E}}{b}\right) \gg 1$ for large b values

b*-prescription
to avoid Landau pole at Λ_{QCD}



f_{NP}

$$F(x,b;\mu,\zeta) = \left[\frac{F(x,b;\mu,\zeta)}{F(x,b_*(b);\mu,\zeta)}\right] F(x,b_*(b);\mu,\zeta)$$

- NP is <u>unavoidable</u>: intrinsically tied to regularisation procedure
- <u>There is not a universal form factor</u>: NP depends on details of b*
- f_{NP} determined through a fit to experimental data

Other formalisms

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \overset{\text{TMD}}{\propto} H \times F_1 \times F_2 + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

Other formalisms

$$\overset{q_T-\text{res.}}{\underset{\text{PB}}{\propto}} \quad e^{2S}\left[f_1 \otimes \mathcal{H} \otimes f_2\right]$$

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \quad \overset{\text{TMD}}{\propto} \quad H \times F_1 \times F_2 \qquad + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

Other formalisms

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \quad \overset{q_T-\text{res.}}{\underset{\text{PB}}{\propto}} \quad e^{2S}\left[f_1 \otimes \mathcal{H} \otimes f_2\right]$$

$$\overset{\text{TMD}}{\propto} \quad H \times F_1 \times F_2 \quad + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

$$\overset{\text{SCET}}{\propto} \quad H \times B_1 \times B_2 \times S$$

Other formalisms

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \overset{q_T-\text{res.}}{\underset{\text{PB}}{\propto}} e^{2S}\left[f_1 \otimes \mathcal{H} \otimes f_2\right]$$

$$\overset{\text{TMD}}{\propto} H \times F_1 \times F_2 \qquad + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

$$\overset{\text{SCET}}{\propto} H \times B_1 \times B_2 \times S$$

- Dictionary:

$$\mathcal{H} = H C_1 C_2$$

$$F_i = e^S C_i \otimes f_i$$

$$F_i = \sqrt{S} \times B_i$$

Other formalisms

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \overset{q_T-\text{res.}}{\underset{\text{PB}}{\propto}} e^{2S}\left[f_1 \otimes \mathcal{H} \otimes f_2\right]$$

$$\overset{\text{TMD}}{\propto} H \times F_1 \times F_2 \qquad + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

$$\overset{\text{SCET}}{\propto} H \times B_1 \times B_2 \times S$$

- Dictionary:

$$\mathcal{H} = H C_1 C_2$$

$$F_i = e^S C_i \otimes f_i$$

$$F_i = \sqrt{S} \times B_i$$

- All **equivalent** for factorising processes such as DY @ LHC energies

Codes

- SCETlib
  [https://confluence.desy.de/display/scetlib]
- CuTe
  [https://cute.hepforge.org]

} SCET

- DYRes/DYTURBO
  [https://gitlab.cern.ch/DYdevel/DYTURBO]
- ReSolve
  [https://github.com/fkhorad/reSolve]

} q_T - res.

- RadISH
  [https://arxiv.org/pdf/1705.09127.pdf]
- PB-TMD
  [https://arxiv.org/pdf/1906.00919.pdf]

} PB

- NangaParbat
  [https://github.com/vbertone/NangaParbat]
- arTeMiDe
  [https://teorica.fis.ucm.es/artemide/]

} TMD

Codes

- SCETlib
  [https://confluence.desy.de/display/scetlib]
- CuTe
  [https://cute.hepforge.org]

} SCET

- DYRes/DYTURBO
  [https://gitlab.cern.ch/DYdevel/DYTURBO]
- ReSolve
  [https://github.com/fkhorad/reSolve]

} q_T - res.

- RadISH
  [https://arxiv.org/pdf/1705.09127.pdf]
- PB-TMD
  [https://arxiv.org/pdf/1906.00919.pdf]

} PB

- NangaParbat
  [https://github.com/vbertone/NangaParbat]
- arTeMiDe
  [https://teorica.fis.ucm.es/artemide/]

} TMD

Basic ingredients common to all codes

Main differences:

- working space: b_T or q_T
- pert.: PDF evolution, scale variation, matching with f.o.
- non-pert.: treatment of Landau pole, intrinsic-k_T

Codes

- SCETlib
  [https://confluence.desy.de/display/scetlib]
- CuTe
  [https://cute.hepforge.org]

} SCET

- DYRes/DYTURBO
  [https://gitlab.cern.ch/DYdevel/DYTURBO]
- ReSolve
  [https://github.com/fkhorad/reSolve]

} q_T - res.

- RadISH
  [https://arxiv.org/pdf/1705.09127.pdf]
- PB-TMD
  [https://arxiv.org/pdf/1906.00919.pdf]

} PB

- NangaParbat
  [https://github.com/vbertone/NangaParbat]
- arTeMiDe
  [https://teorica.fis.ucm.es/artemide/]

} TMD

Basic ingredients common to all codes

Main differences:

- working space: b_T or q_T
- pert.: PDF evolution, scale variation, matching with f.o.
- non-pert.: treatment of Landau pole, intrinsic-k_T

↓

LHC EWWG "Benchmark"
i.e., compare

- accuracy (easy)
- differences (hard)
- uncertainties (harder)

Codes

- SCETlib
  [https://confluence.desy.de/display/scetlib]
- CuTe
  [https://cute.hepforge.org]

} SCET

- DYRes/DYTURBO
  [https://gitlab.cern.ch/DYdevel/DYTURBO]
- ReSolve
  [https://github.com/fkhorad/reSolve]

} q_T - res.

- RadISH
  [https://arxiv.org/pdf/1705.09127.pdf]
- PB-TMD
  [https://arxiv.org/pdf/1906.00919.pdf]

} PB

- NangaParbat
  [https://github.com/vbertone/NangaParbat]
- arTeMiDe
  [https://teorica.fis.ucm.es/artemide/]

} TMD

Basic ingredients common to all codes

Main differences:

- working space: b_T or q_T
- pert.: PDF evolution, scale variation, matching with f.o.
- non-pert.: treatment of Landau pole, intrinsic-k_T

↓

LHC EWWG "Benchmark"
i.e., compare

- accuracy (easy)
- differences (hard)
- uncertainties (harder)

Structure of Yellow Report

Resummed predictions of the transverse momentum distribution of Drell–Yan lepton pairs in proton-proton collisions at the LHC

Insert your name and institutional address[a]

[a] *World*

Abstract

Placeholder

Keywords: Drell–Yan, Resummation, LHC

Contents

1 **1. Introduction**

*Corresponding authors

Structure of Yellow Report

Level 1

- $\frac{d\sigma}{dQdydq_T}$ for Z/γ^* @ 13 TeV (focus on $Q = m_Z, y = 0$)
- Only resummed piece
- Only "canonical" logs: $L = \log(Q^2 b^2 / b_0^2)$
- Fixed (hard) scale Q
- Same PDFs, α_s, EW parameters, no lepton cuts
- No NP: different regularisation but common b_{max}

Resummed predictions of the transverse momentum distribution of Drell–Yan lepton pairs in proton-proton collisions at the LHC

Insert your name and institutional address[a]

[a] *World*

Abstract

Placeholder

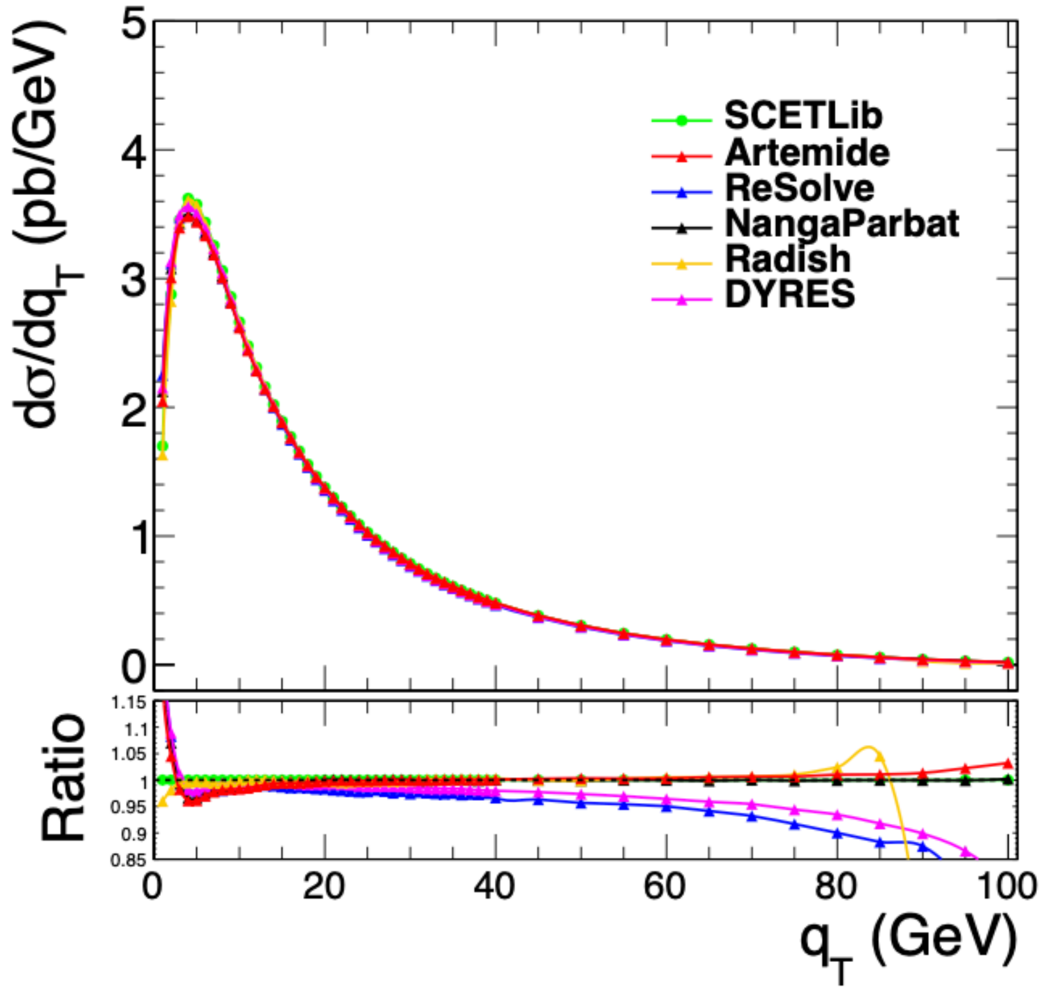
Keywords: Drell–Yan, Resummation, LHC

Contents

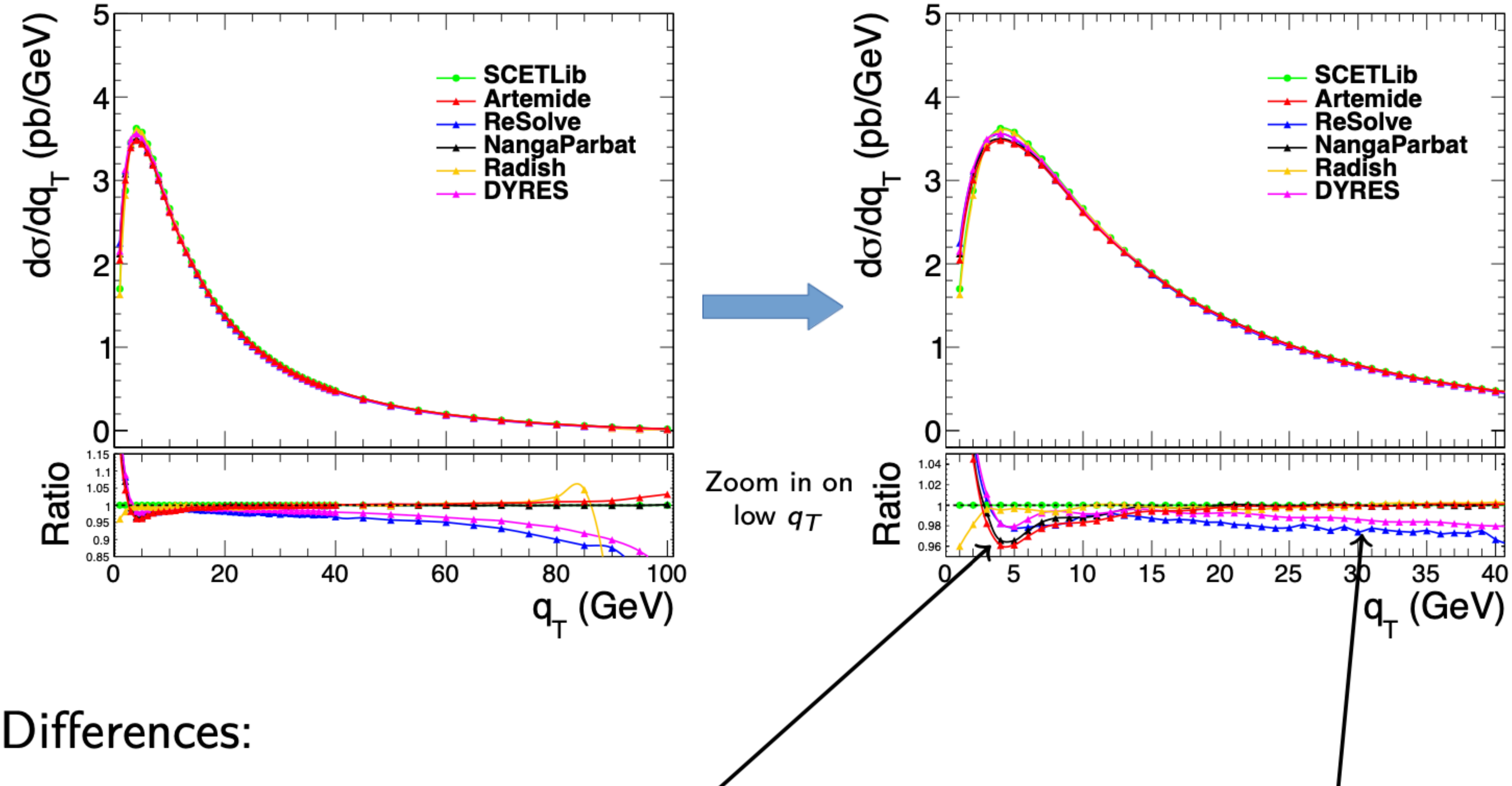
*Corresponding authors

1 **1. Introduction**

Level 1 - NNLL' differences



Level 1 - NNLL' differences



Differences:

- Small differences at low q_T.
- q_T resummation codes show differences at intermediate - high q_T.

Level 1 - Global vs. local b*

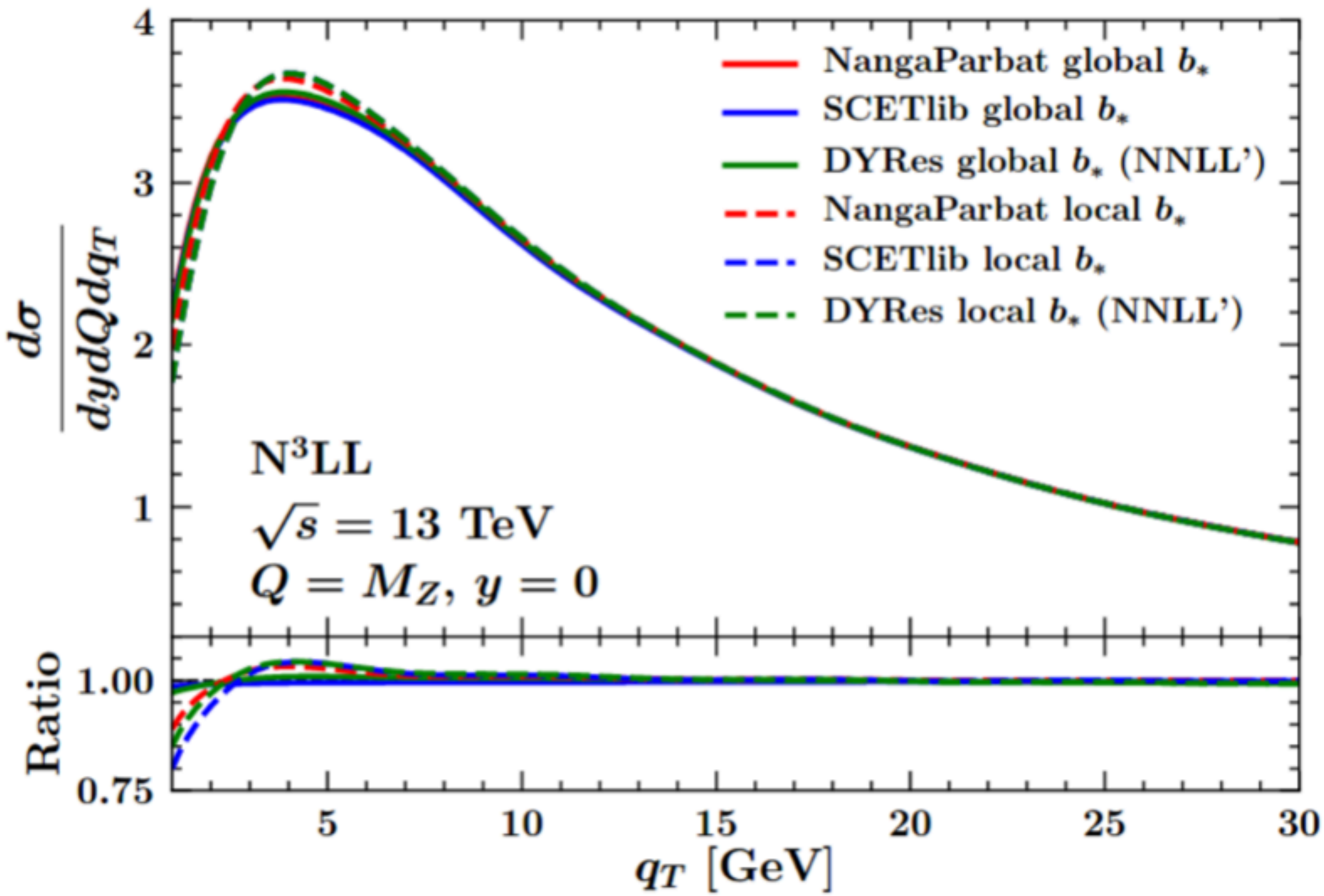
- Different implementations of b^* prescription: <u>global</u> vs. <u>local</u>
  local = replace $b \to b^*$ only in α_s and PDF but not logs

- affects low-q_T end of spectrum

Level 1 - Global vs. local b*

- Different implementations of b^* prescription: global vs. local
  local = replace $b \to b^*$ only in α_s and PDF but not logs

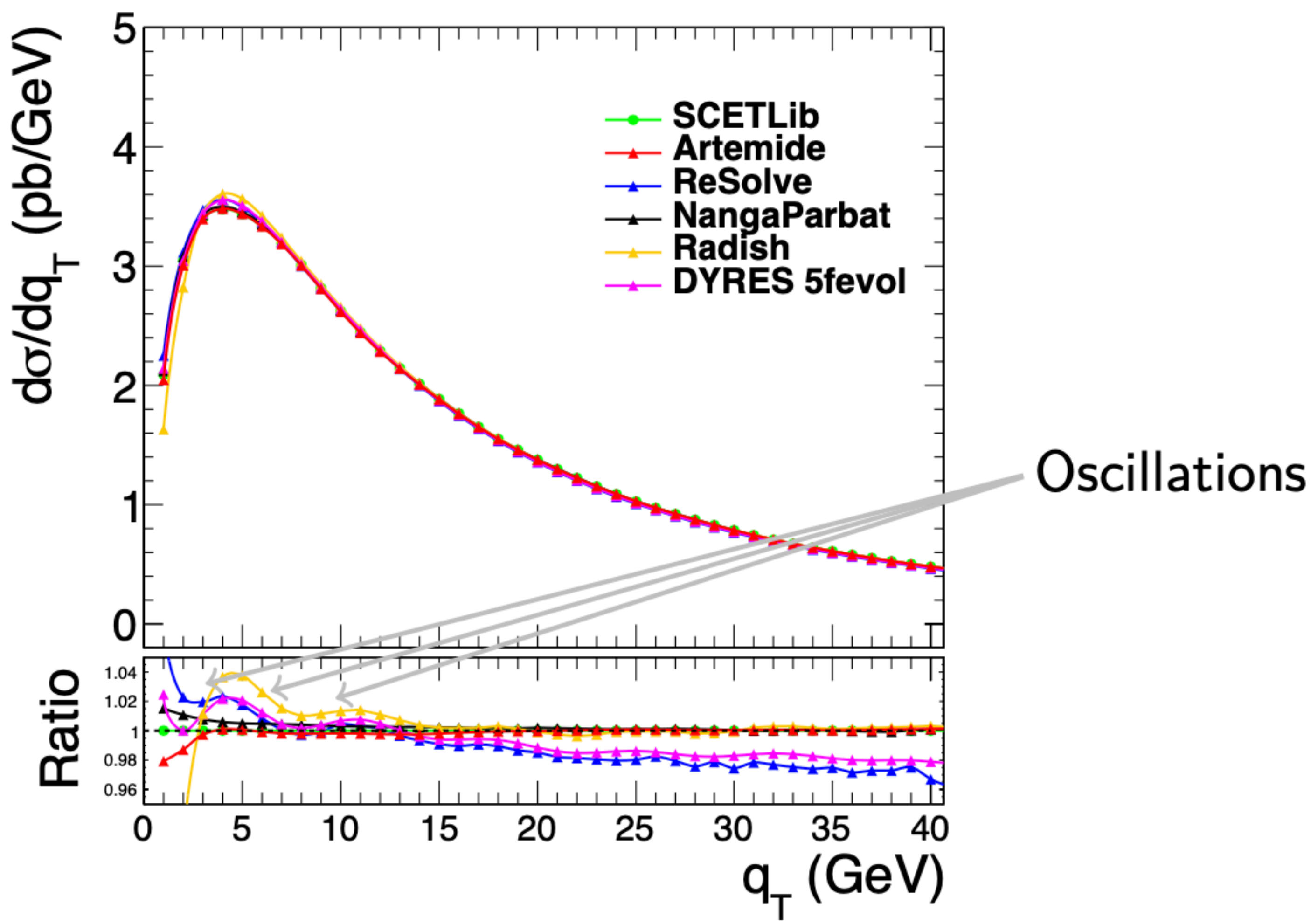
- affects low-q_T end of spectrum



Level 1 - PDF evolution

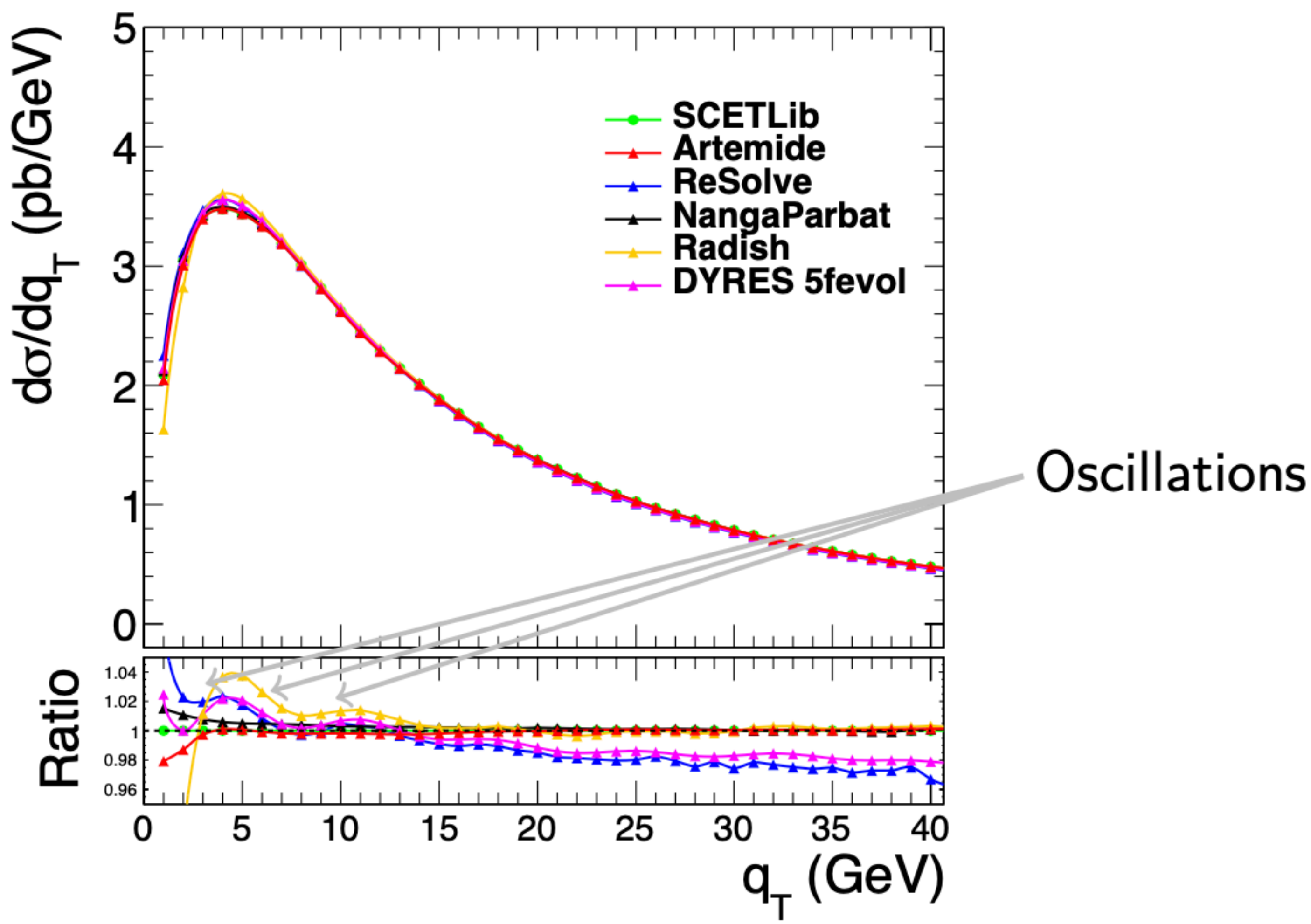
Level 1 - PDF evolution

- <u>Coherent</u> small oscillations in ratios: why?



Level 1 - PDF evolution

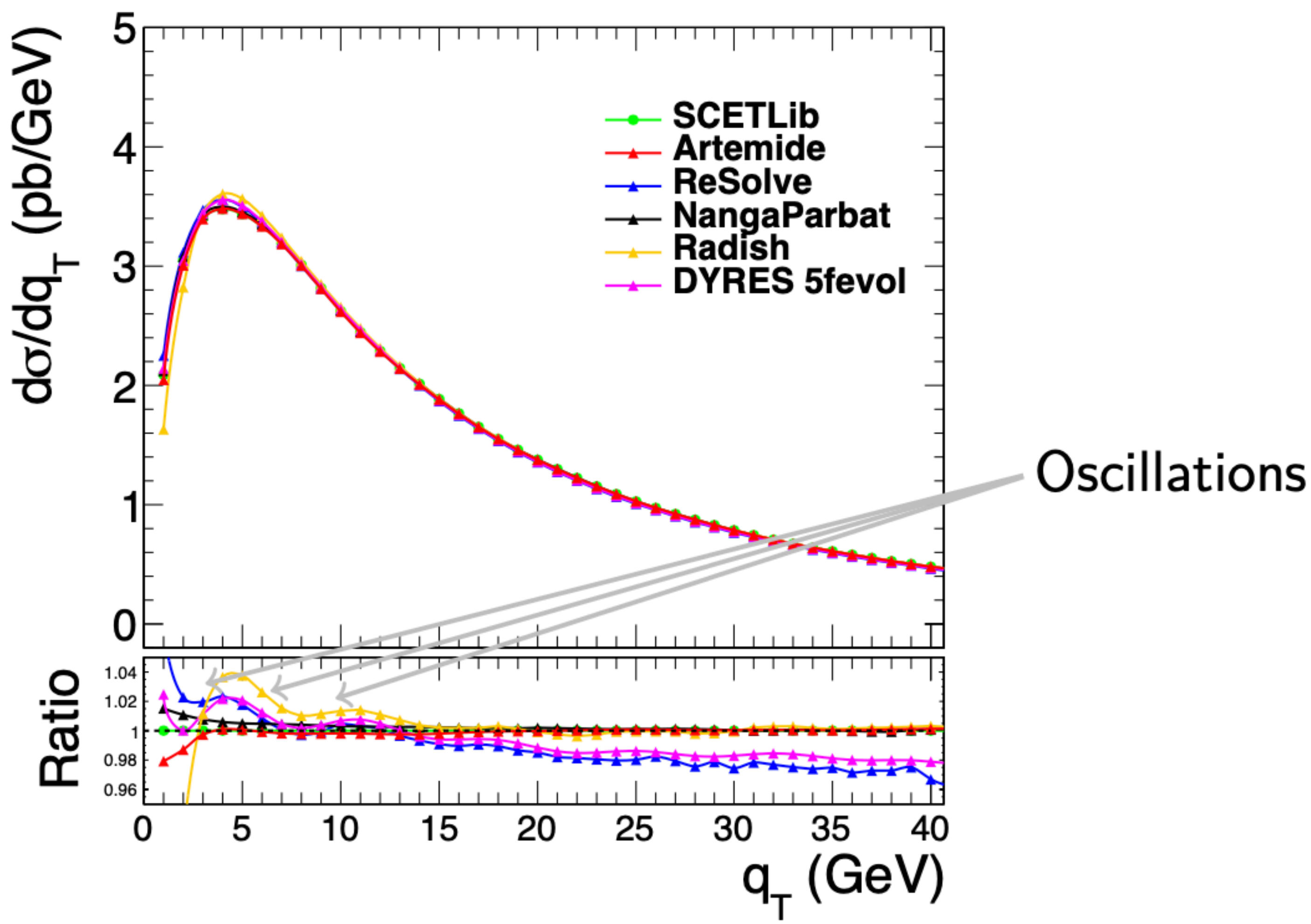
- Coherent small oscillations in ratios: why?
- reSolve, DYTurbo: backward evolution in Mellin space, no thresholds
- SCETlib, NangaParbat, arTeMiDe: LHAPDF evolution, thresholds

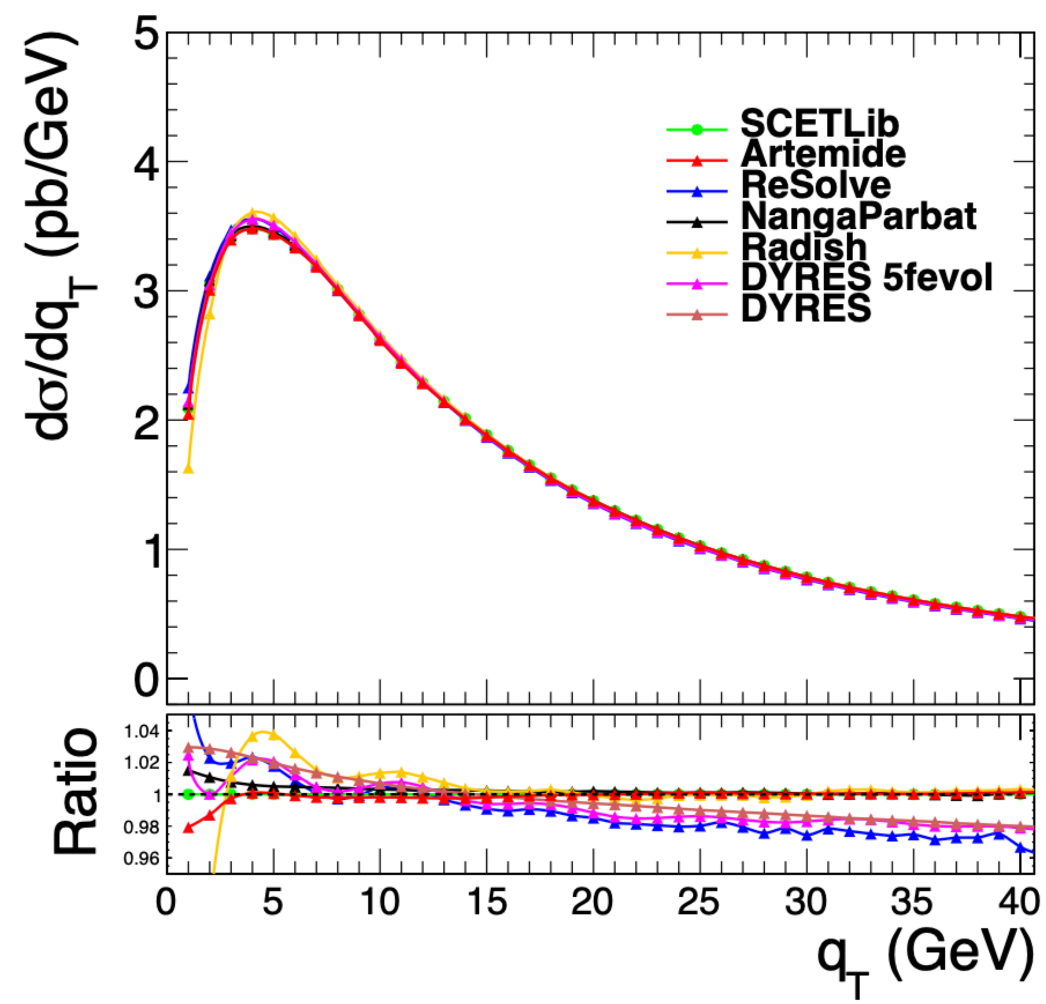


Level 1 - PDF evolution

- Coherent small oscillations in ratios: why?
- reSolve, DYTurbo: backward evolution in Mellin space, no thresholds
- SCETlib, NangaParbat, arTeMiDe: LHAPDF evolution, thresholds

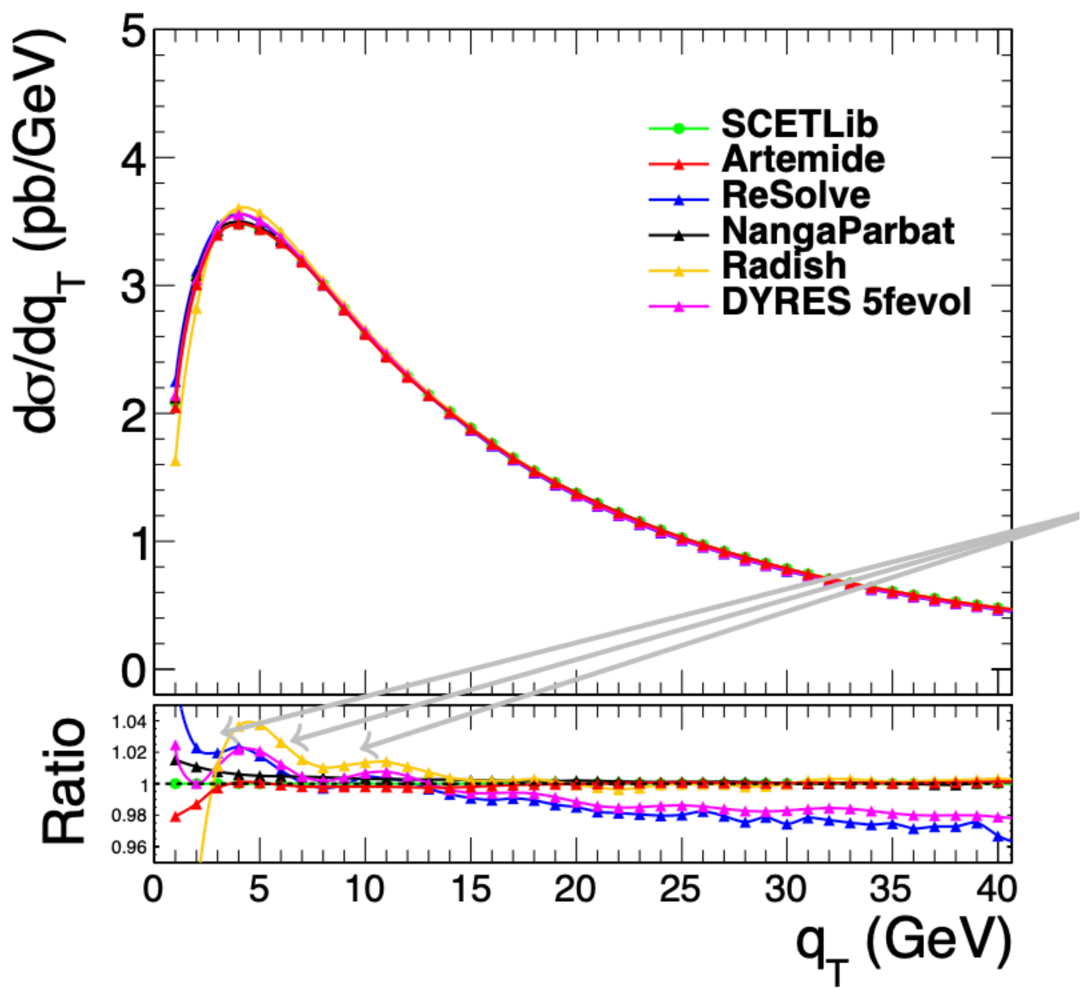
Oscillations removed in DYTurbo plus LHAPDF



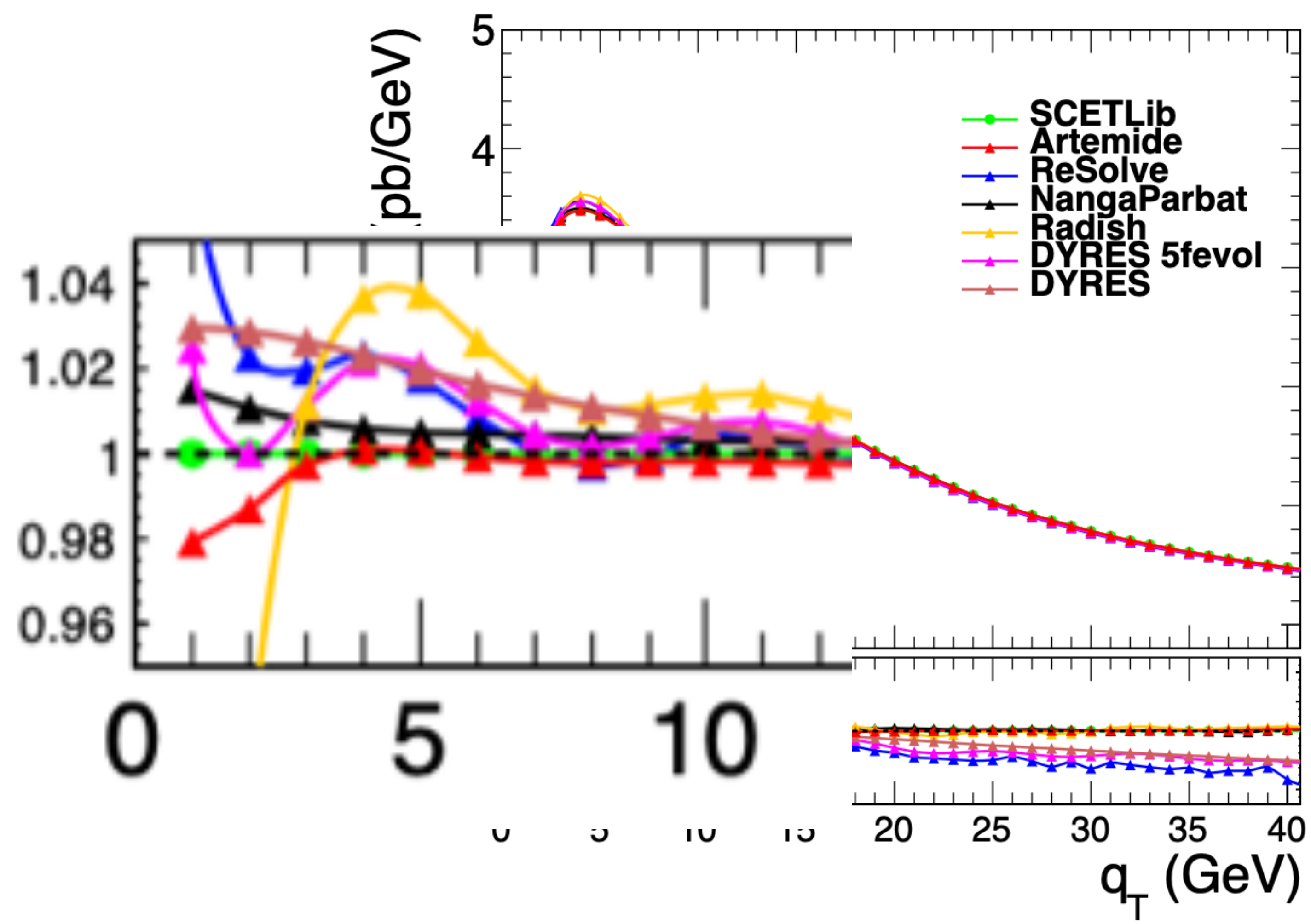


Level 1 - PDF evolution

- Coherent small oscillations in ratios: why?
- reSolve, DYTurbo: backward evolution in Mellin space, no thresholds
- SCETlib, NangaParbat, arTeMiDe: LHAPDF evolution, thresholds



Oscillations removed in DYTurbo plus LHAPDF



Level 1 - intermediate q_T

$$\frac{d\sigma}{dq_{\mathbf{T}}} \sim H(Q)S(Q,\mu_b)\left[C(\mu_b)\otimes f(\mu_b)\right]^{2}$$

Level 1 - intermediate q_T

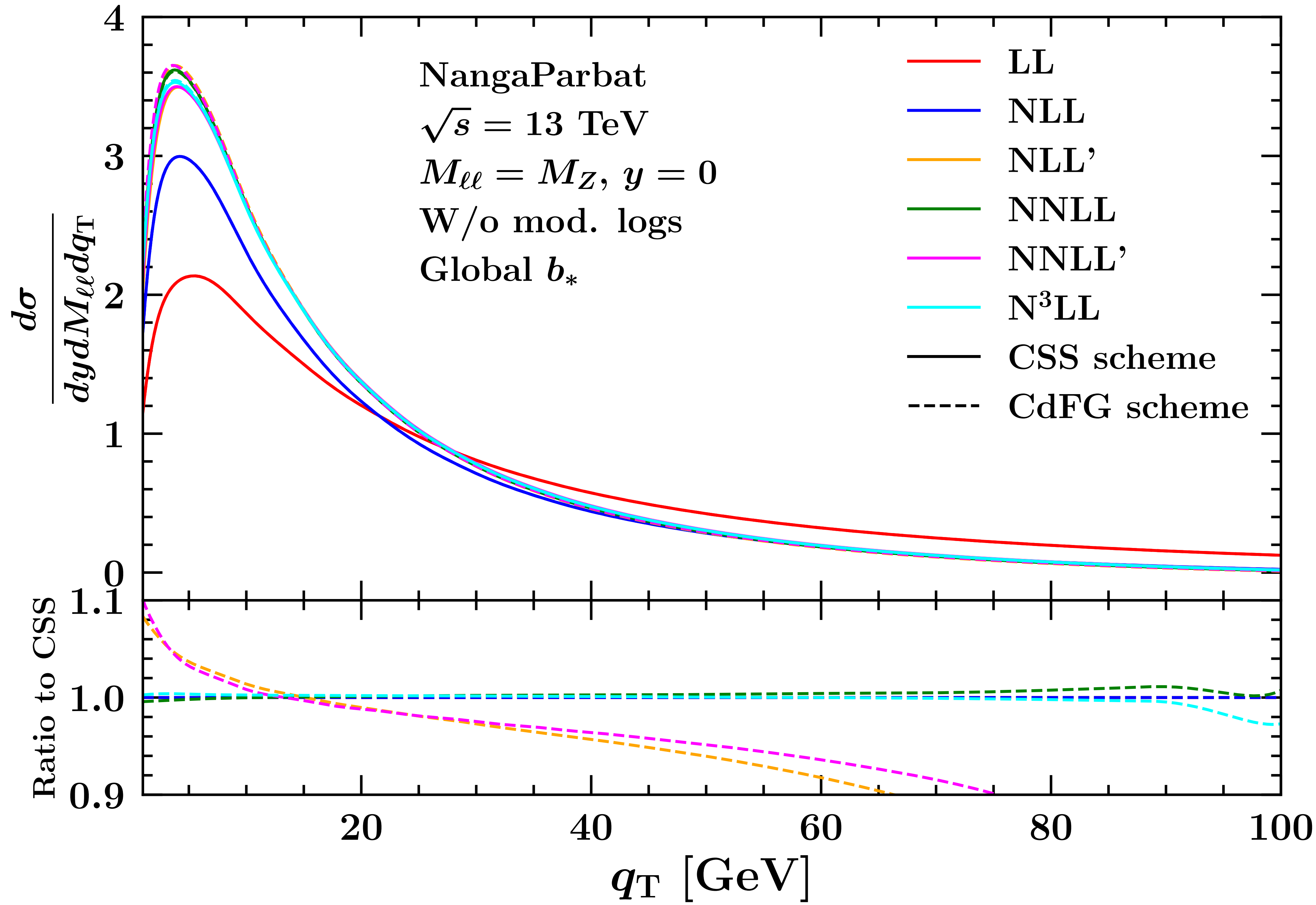
$$\frac{d\boldsymbol{\sigma}}{d\boldsymbol{q}_{\mathbf{T}}} \sim \boldsymbol{H}(\boldsymbol{Q})\boldsymbol{S}(\boldsymbol{Q},\boldsymbol{\mu_b})\left[\boldsymbol{C}(\boldsymbol{\mu_b})\otimes\boldsymbol{f}(\boldsymbol{\mu_b})\right]^{\mathbf{2}}$$

- "Resummation scheme" dependence: freedom to redefine each factor

Level 1 - intermediate q_T

$$\frac{d\sigma}{dq_T} \sim H(Q)S(Q,\mu_b)\left[C(\mu_b)\otimes f(\mu_b)\right]^2$$

- "Resummation scheme" dependence: freedom to redefine each factor



Structure of Yellow Report

Resummed predictions of the transverse momentum distribution of Drell–Yan lepton pairs in proton-proton collisions at the LHC

Insert your name and institutional address[a]

[a] *World*

Abstract

Placeholder

Keywords: Drell–Yan, Resummation, LHC

Contents

1. Introduction

*Corresponding authors

Structure of Yellow Report

Resummed predictions of the transverse momentum distribution of Drell–Yan lepton pairs in proton-proton collisions at the LHC

Insert your name and institutional address[a]

[a] *World*

Abstract

Placeholder

Keywords: Drell–Yan, Resummation, LHC

Contents

*Correspo...

Level 2

- Still only resummed piece, no NP, no lepton cuts
- Modified logs $L = \log(Q^2 b^2 / b_0^2 + 1)$ (or equivalent)
- Choose own scales (i.e. $\mu_{res} = m_Z/2,\ m_Z,\ \dots$)
- Scale variation: hard, since it requires a careful "mapping" of different scales in different formalisms

1. Introduction

Level 2 - Scale variation

Level 2 - Scale variation

- Several sources of theoretical uncertainties
- Estimate through scale variation, BUT:

Level 2 - Scale variation

- Several sources of theoretical uncertainties
- Estimate through scale variation, BUT:
  - PB & q_T - resummation: μ_r, μ_f, μ_{res}

Level 2 - Scale variation

- Several sources of theoretical uncertainties
- Estimate through scale variation, BUT:
  - PB & q_T - resummation: μ_r, μ_f, μ_{res}
  - TMD: $(\mu_0, \zeta_0) \rightarrow (\mu, \zeta)$ (effectively reduce to 2 in DY case)

Level 2 - Scale variation

- Several sources of theoretical uncertainties
- Estimate through scale variation, BUT:
  - PB & q_T - resummation: μ_r, μ_f, μ_{res}
  - TMD: $(\mu_0, \zeta_0) \to (\mu, \zeta)$ (effectively reduce to 2 in DY case)
  - SCET: $(\mu_i, \nu_i) \to (\mu_f, \nu_f)$ for **each** of the B, H, S functions

Level 2 - Scale variation

- Several sources of theoretical uncertainties
- Estimate through scale variation, BUT:
  - PB & q_T - resummation: μ_r, μ_f, μ_{res}
  - TMD: $(\mu_0, \zeta_0) \to (\mu, \zeta)$ (effectively reduce to 2 in DY case)
  - SCET: $(\mu_i, \nu_i) \to (\mu_f, \nu_f)$ for **each** of the B, H, S functions
- Each scale has its own "central" value
- How to compare different scale variations in different formalisms?

Example: TMD vs. q_T scales

Example: TMD vs. q_T scales

- The **factorisation scale $\boldsymbol{\mu_F}$** present in q_T resummation is absent in the TMD formalism:

Example: TMD vs. q_T scales

- The **factorisation scale** $\boldsymbol{\mu_F}$ present in q_T resummation is absent in the TMD formalism:
  - TMD: PDFs are computed at the low scale $\boldsymbol{\mu_0}$ (varied around $\boldsymbol{\mu_\mathbf{b}}$)

Example: TMD vs. q_T scales

- The **factorisation scale** $\boldsymbol{\mu_F}$ present in q_T resummation is absent in the TMD formalism:
  - TMD: PDFs are computed at the low scale $\boldsymbol{\mu_0}$ (varied around $\boldsymbol{\mu_b}$)
  - q_T - res.: PDFs are evolved from *exactly* $\boldsymbol{\mu_b}$ up to $\boldsymbol{\mu_F}$ (varied around $\boldsymbol{Q}$)

Example: TMD vs. q_T scales

- The **factorisation scale** $\boldsymbol{\mu_F}$ present in q_T resummation is absent in the TMD formalism:
  - TMD: PDFs are computed at the low scale $\boldsymbol{\mu_0}$ (varied around $\boldsymbol{\mu_b}$)
  - q_T - res.: PDFs are evolved from *exactly* $\boldsymbol{\mu_b}$ up to $\boldsymbol{\mu_F}$ (varied around $\boldsymbol{Q}$)
  - variations of $\boldsymbol{\mu_0}$ are typically much larger than variations of $\boldsymbol{\mu_F}$ because at the energies relevant to the benchmark $\boldsymbol{\alpha_s(\mu_0) \gg \alpha_s(\mu_F)}$

Example: TMD vs. q_T scales

- The **factorisation scale μ_F** present in q_T resummation is absent in the TMD formalism:
  - TMD: PDFs are computed at the low scale μ_0 (varied around μ_b)
  - q_T - res.: PDFs are evolved from *exactly* μ_b up to μ_F (varied around Q)
  - variations of μ_0 are typically much larger than variations of μ_F because at the energies relevant to the benchmark $\alpha_s(\mu_0) \gg \alpha_s(\mu_F)$
- A careful (and not trivial) comparison of the Sudakov integral in the two formalisms suggests that the **renormalisation scale μ_R** in q_T resummation is to be (partly) identified with the scale μ in the TMD formalism

Example: TMD vs. q_T scales

Example: TMD vs. q_T scales

- In q_T - resummation, the Sudakov is computed analytically and written in terms of the **functions g_n**:

$$\int_{\mu_b}^{Q} \frac{d\mu'}{\mu'} \left[A(\alpha_s(\mu')) \ln\left(\frac{Q}{\mu'}\right) + B(\alpha_s(\mu')) \right] = L g_0(\alpha_s L) + \sum_{n=1}^{\infty} \alpha_s^{n-1} g_n(\alpha_s L)$$

$$= L g_0(\alpha_s L) + \sum_{n=1}^{k} \alpha_s^{n-1} g_n(\alpha_s L) + \mathcal{O}(\alpha_s^{k+n} L^n)$$

Example: TMD vs. q_T scales

- In q_T - resummation, the Sudakov is computed analytically and written in terms of the **functions g_n**:

$$\int_{\mu_b}^{Q} \frac{d\mu'}{\mu'} \left[A(\alpha_s(\mu')) \ln\left(\frac{Q}{\mu'}\right) + B(\alpha_s(\mu')) \right] = L g_0(\alpha_s L) + \sum_{n=1}^{\infty} \alpha_s^{n-1} g_n(\alpha_s L)$$

$$= L g_0(\alpha_s L) + \sum_{n=1}^{k} \alpha_s^{n-1} g_n(\alpha_s L) + \mathcal{O}(\alpha_s^{k+n} L^n)$$

- The series in the r.h.s. is **truncated** according to the log accuracy and the **resummation scale** μ_{res} is introduced as follows:

$$L = \ln\left(\frac{Q}{\mu_b}\right) = \ln\left(\frac{\mu_{res}}{\mu_b}\right) + \ln\left(\frac{Q}{\mu_{res}}\right)$$

The explicit μ_{res} dependence gives an estimate of missing subleading logs

Example: TMD vs. q_T scales

- In q_T - resummation, the Sudakov is computed analytically and written in terms of the **functions g_n**:

$$\int_{\mu_b}^{Q} \frac{d\mu'}{\mu'} \left[A(\alpha_s(\mu')) \ln\left(\frac{Q}{\mu'}\right) + B(\alpha_s(\mu')) \right] = L g_0(\alpha_s L) + \sum_{n=1}^{\infty} \alpha_s^{n-1} g_n(\alpha_s L)$$

$$= L g_0(\alpha_s L) + \sum_{n=1}^{k} \alpha_s^{n-1} g_n(\alpha_s L) + \mathcal{O}(\alpha_s^{k+n} L^n)$$

- The series in the r.h.s. is **truncated** according to the log accuracy and the **resummation scale** μ_{res} is introduced as follows:

$$L = \ln\left(\frac{Q}{\mu_b}\right) = \ln\left(\frac{\mu_{res}}{\mu_b}\right) + \ln\left(\frac{Q}{\mu_{res}}\right)$$

  The explicit μ_{res} dependence gives an estimate of missing subleading logs

- If the Sudakov is computed exactly, no resummation scale appears:
  - this is what we do in NangaParbat by computing the integral numerically
  - therefore, we have **no resummation scale dependence**

Estimate of uncertainties

Estimate of uncertainties

- Theoretical uncertainty estimate on **N^{3}LL**:

Estimate of uncertainties

- Theoretical uncertainty estimate on **N^3LL**:
  - estimate of subleading logarithmic corrections by including N^4LL corrections in the Sudakov (**mimicking resummation scale variations**),

Estimate of uncertainties

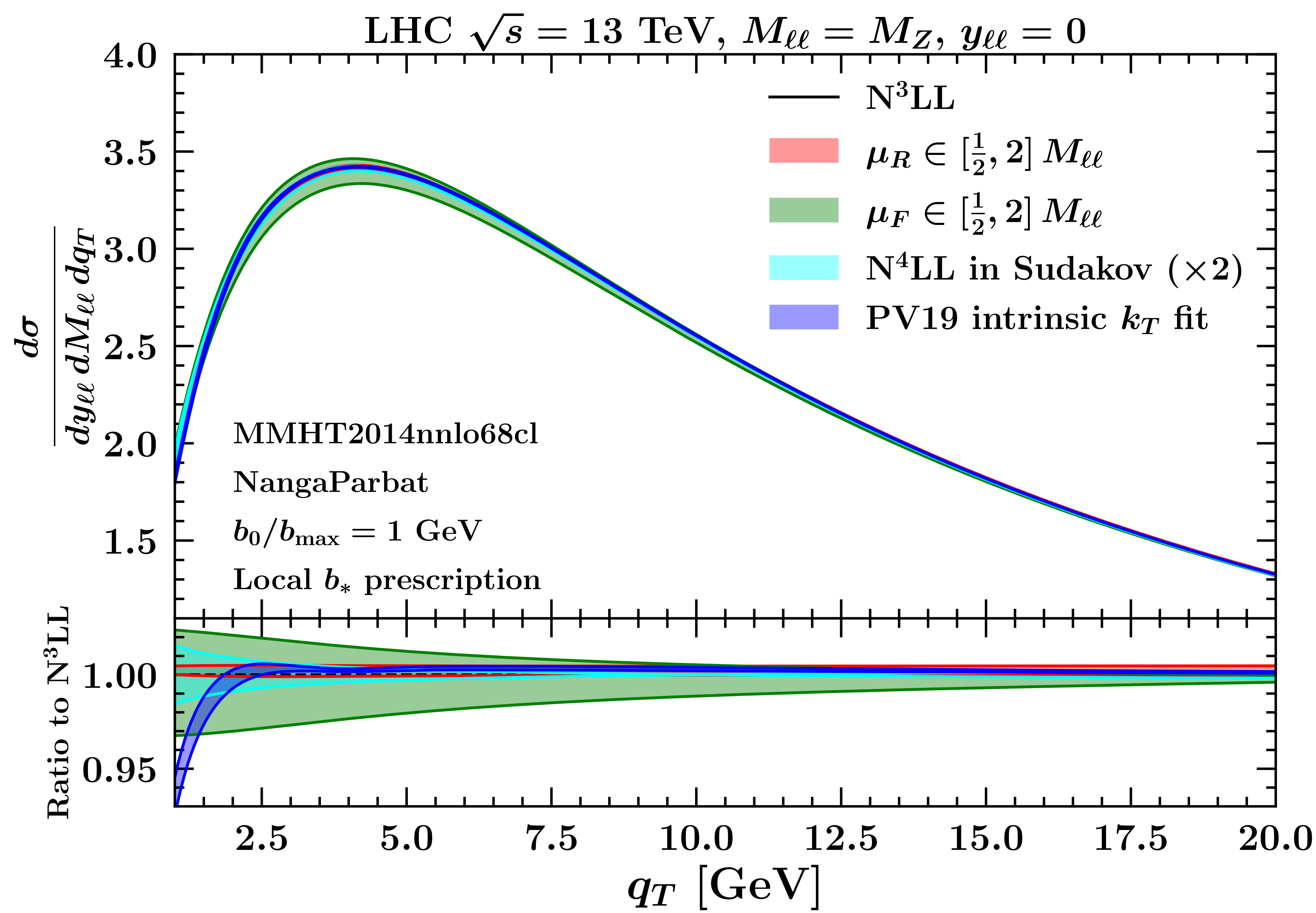
- Theoretical uncertainty estimate on **N^3LL**:
  - estimate of subleading logarithmic corrections by including N^4LL corrections in the Sudakov (**mimicking resummation scale variations**),
  - variations of μ_r and μ_f by a factor 2 up and down w.r.t. $\boldsymbol{M_{ll}}$,

Estimate of uncertainties

- Theoretical uncertainty estimate on **N^{3}LL**:
  - estimate of subleading logarithmic corrections by including N^{4}LL corrections in the Sudakov (**mimicking resummation scale variations**),
    [G. Das, S.-O. Moch, A. Vogt, arXiv:1912.12920]
  - variations of μ_r and μ_f by a factor 2 up and down w.r.t. M_{ll},
  - inclusion of non-perturbative effects as determined in the **PV19** fit.
    [A. Bacchetta *et al.*, arXiv:1912.07550]

Estimate of uncertainties

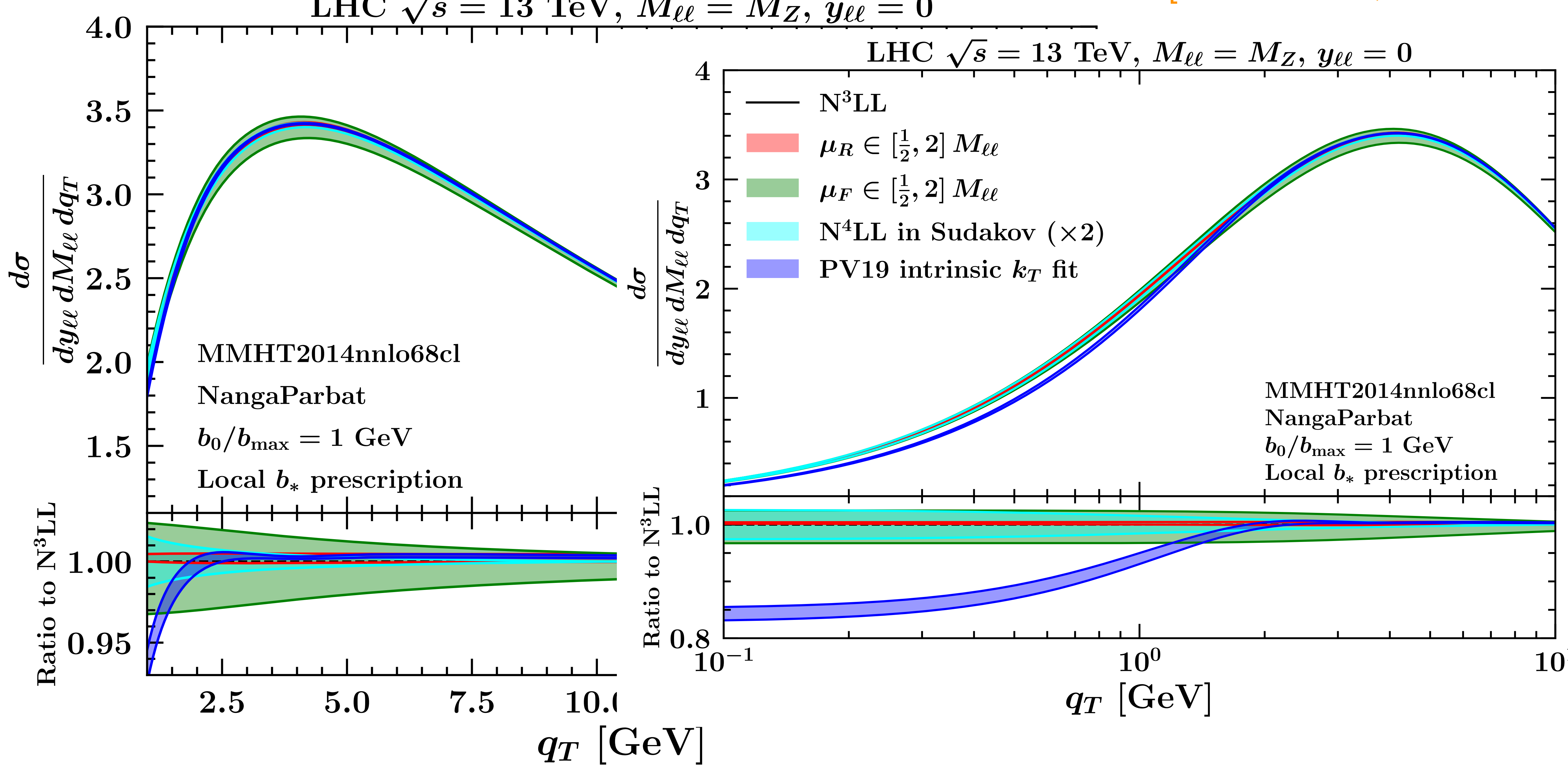
- Theoretical uncertainty estimate on **N³LL**:
  - estimate of subleading logarithmic corrections by including N⁴LL corrections in the Sudakov (**mimicking resummation scale variations**),
    [G. Das, S.-O. Moch, A. Vogt, arXiv:1912.12920]
  - variations of μ_r and μ_f by a factor 2 up and down w.r.t. $\boldsymbol{M_{ll}}$,
  - inclusion of non-perturbative effects as determined in the **PV19** fit.
    [A. Bacchetta *et al.*, arXiv:1912.07550]



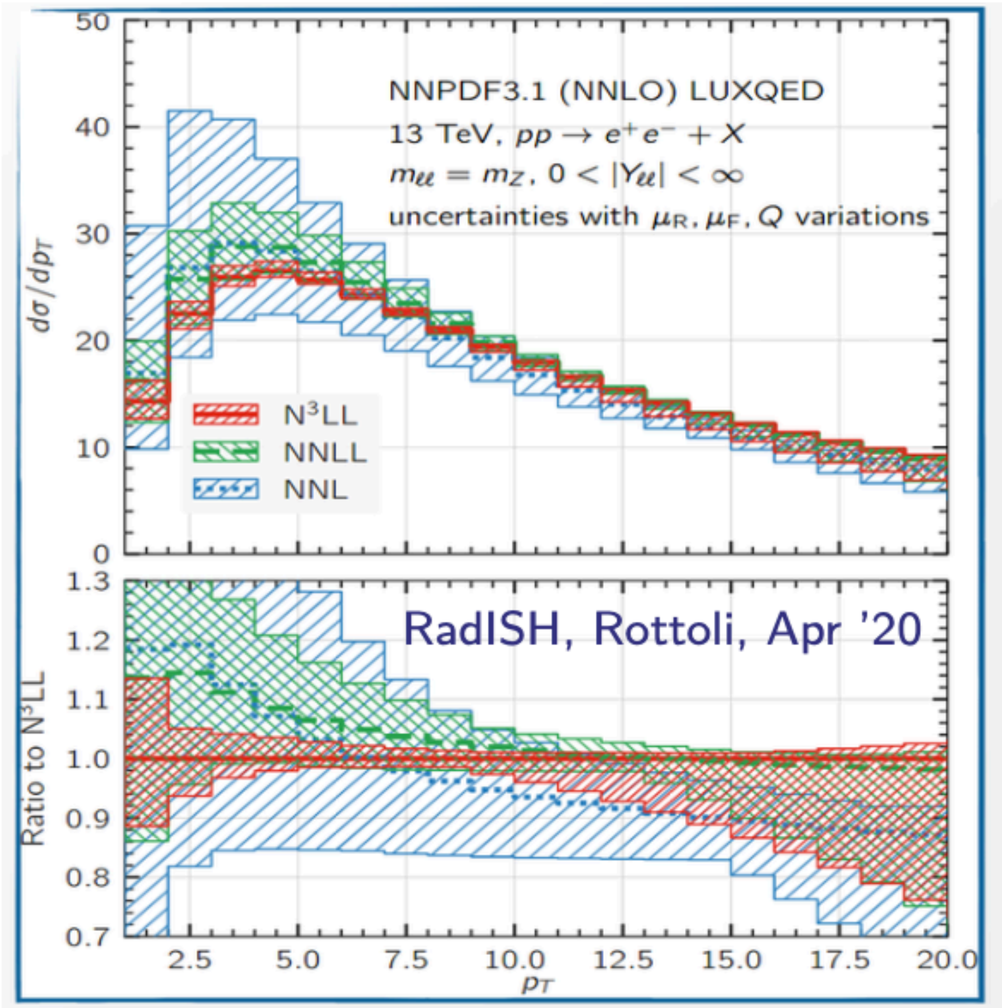
Estimate of uncertainties

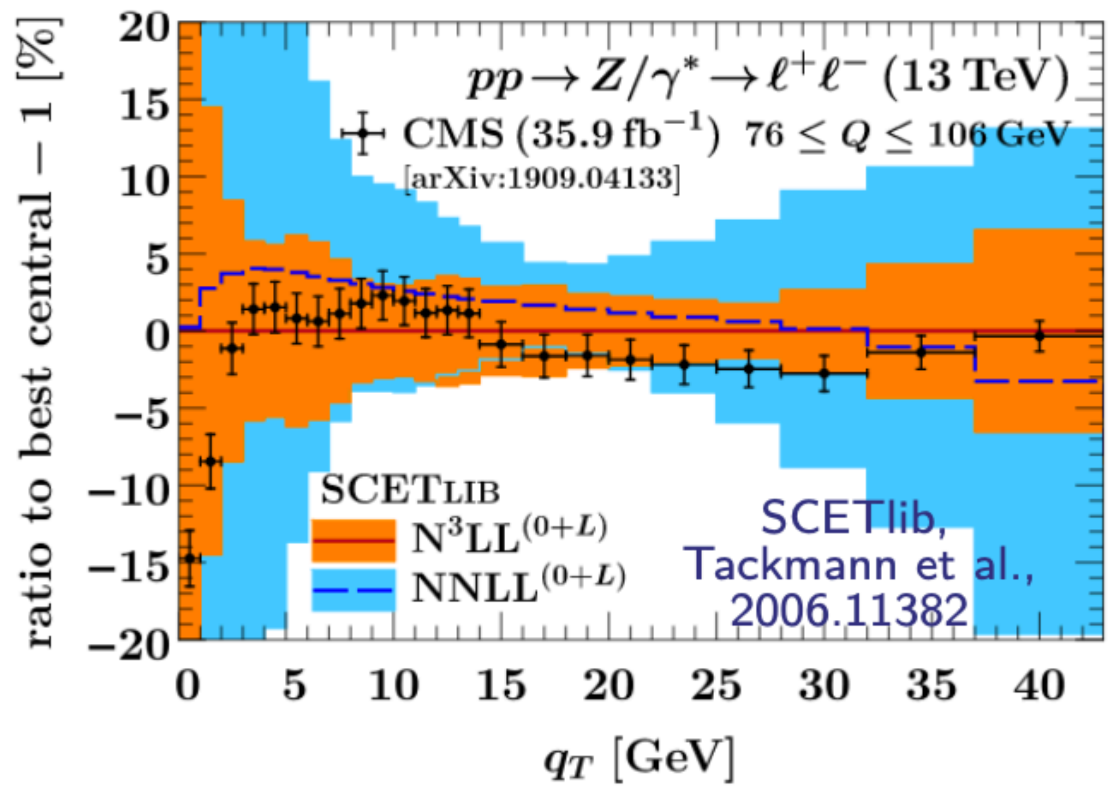
- Theoretical uncertainty estimate on **N³LL**:
  - estimate of subleading logarithmic corrections by including N⁴LL corrections in the Sudakov (**mimicking resummation scale variations**), [G. Das, S.-O. Moch, A. Vogt, arXiv:1912.12920]
  - variations of μ_r and μ_f by a factor 2 up and down w.r.t. $\boldsymbol{M_{ll}}$,
  - inclusion of non-perturbative effects as determined in the **PV19** fit.

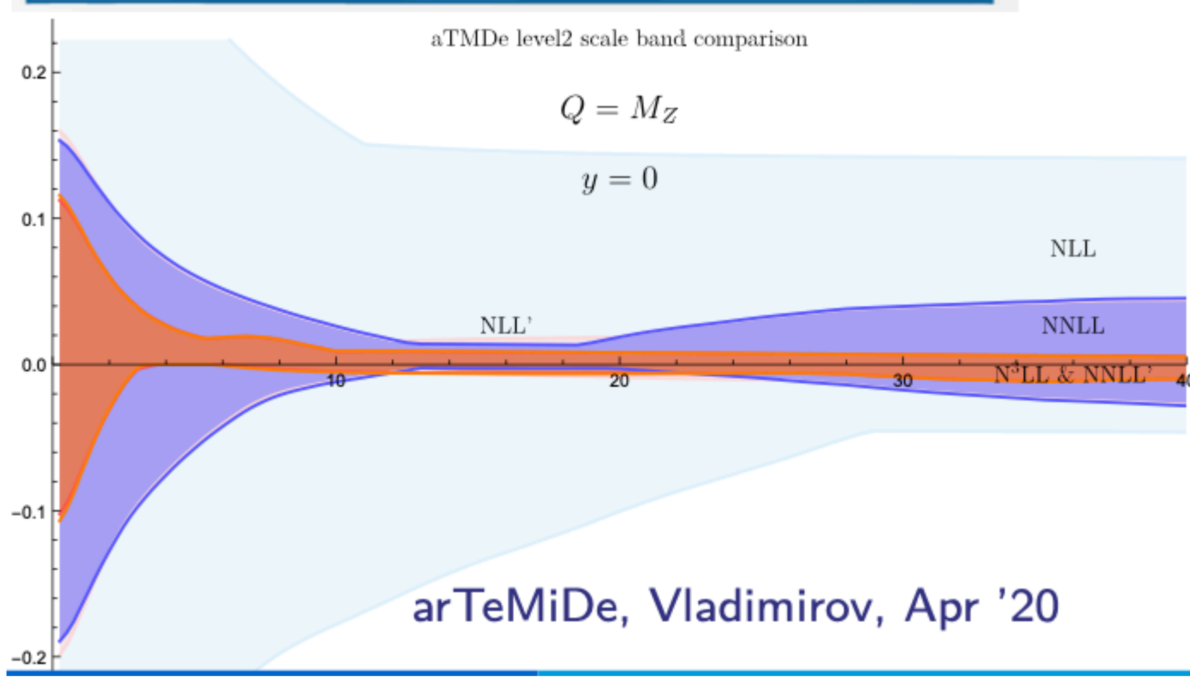
[A. Bacchetta *et al.*, arXiv:1912.07550]

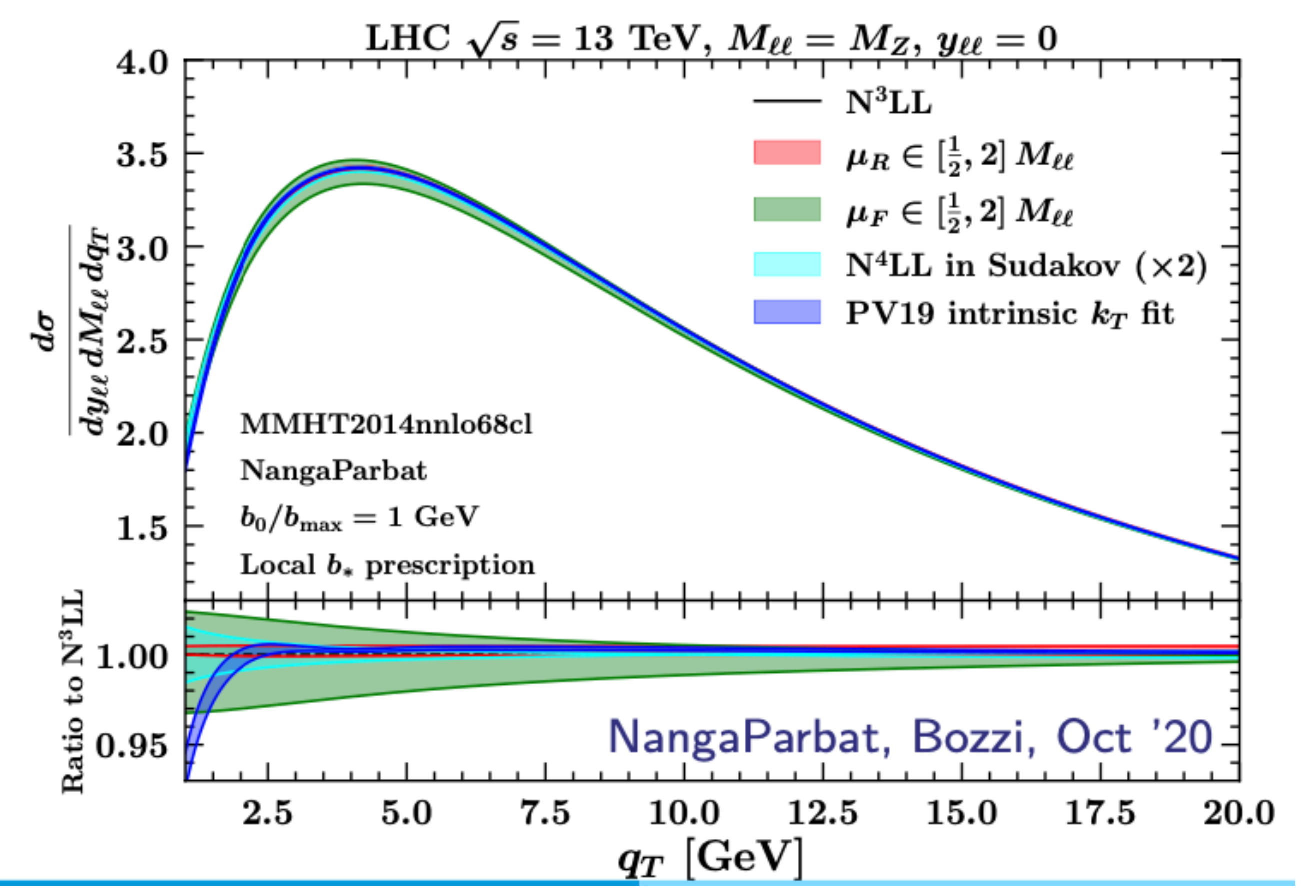


Estimate of uncertainties









Structure of Yellow Report

Resummed predictions of the transverse momentum distribution of Drell–Yan lepton pairs in proton-proton collisions at the LHC

Insert your name and institutional address[a]

[a] *World*

Abstract

Placeholder

Keywords: Drell–Yan, Resummation, LHC

Contents

1. Introduction

*Corresponding authors

Structure of Yellow Report

Level 3

- matching with fixed order (full q_T - spectrum)
- Each group uses its own matching formalisms
- Introduce matching uncertainty in addition to perturbative ones
- Still a (lot of) work in progress…

Resummed predictions of the transverse momentum distribution of Drell–Yan lepton pairs in proton-proton collisions at the LHC

Insert your name and institutional address[a]

[a] *World*

Abstract

Placeholder

Keywords: Drell–Yan, Resummation, LHC

Contents

1. Introduction

*Corresponding authors

Structure of Yellow Report

Level 3

- matching with fixed order (full q_T - spectrum)
- Each group uses its own matching formalisms
- Introduce matching uncertainty in addition to perturbative ones
- Still a (lot of) work in progress…
- Bonus track: **Level 3.5!**
  Contribution of intrinsic-k_T (TMD only)
  (Pseudo-data fit?)

Resummed predictions of the transverse momentum distribution of Drell–Yan lepton pairs in proton-proton collisions at the LHC

Insert your name and institutional address[a]

[a]*World*

Abstract

Placeholder

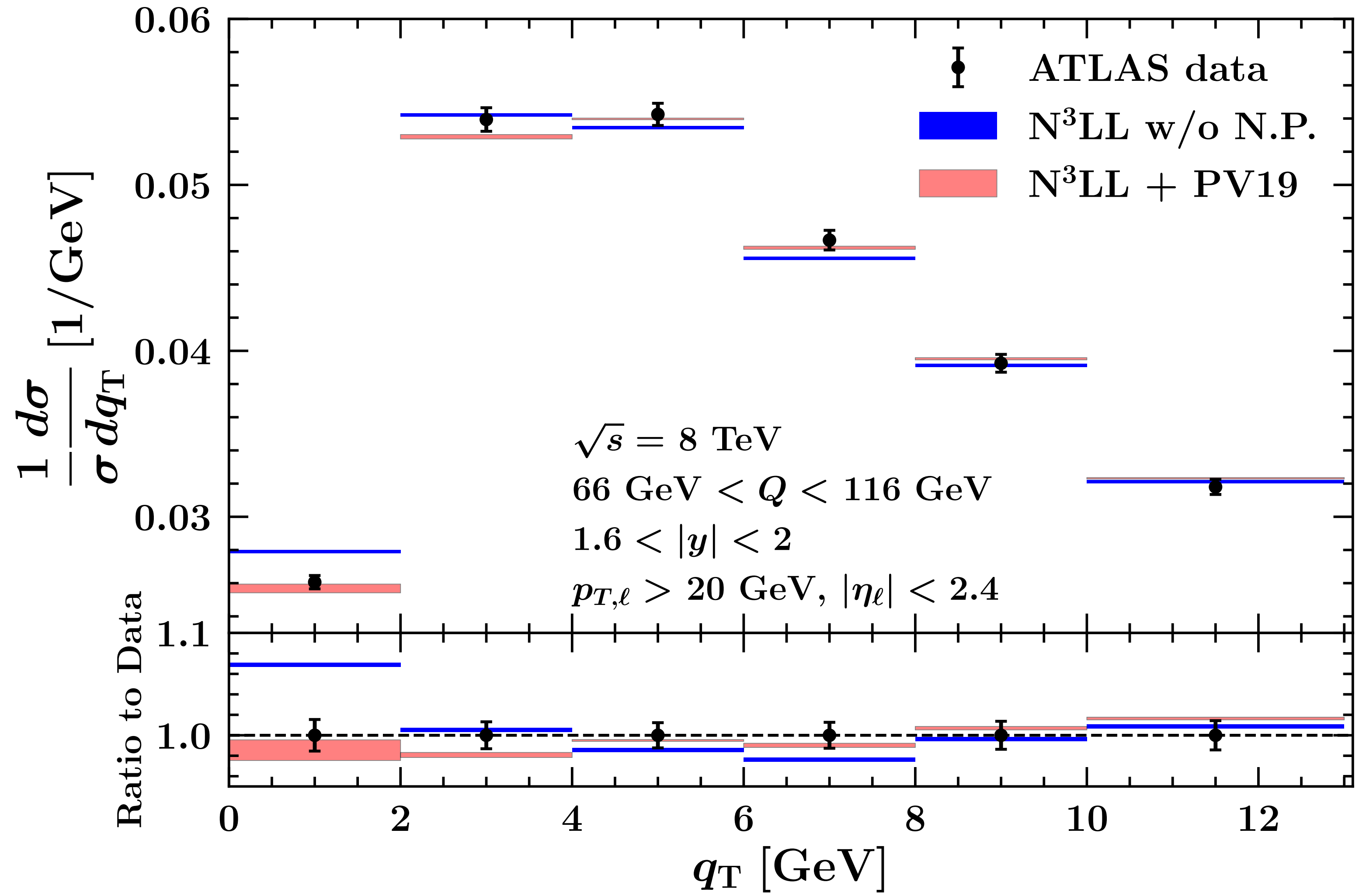
Keywords: Drell–Yan, Resummation, LHC

Contents

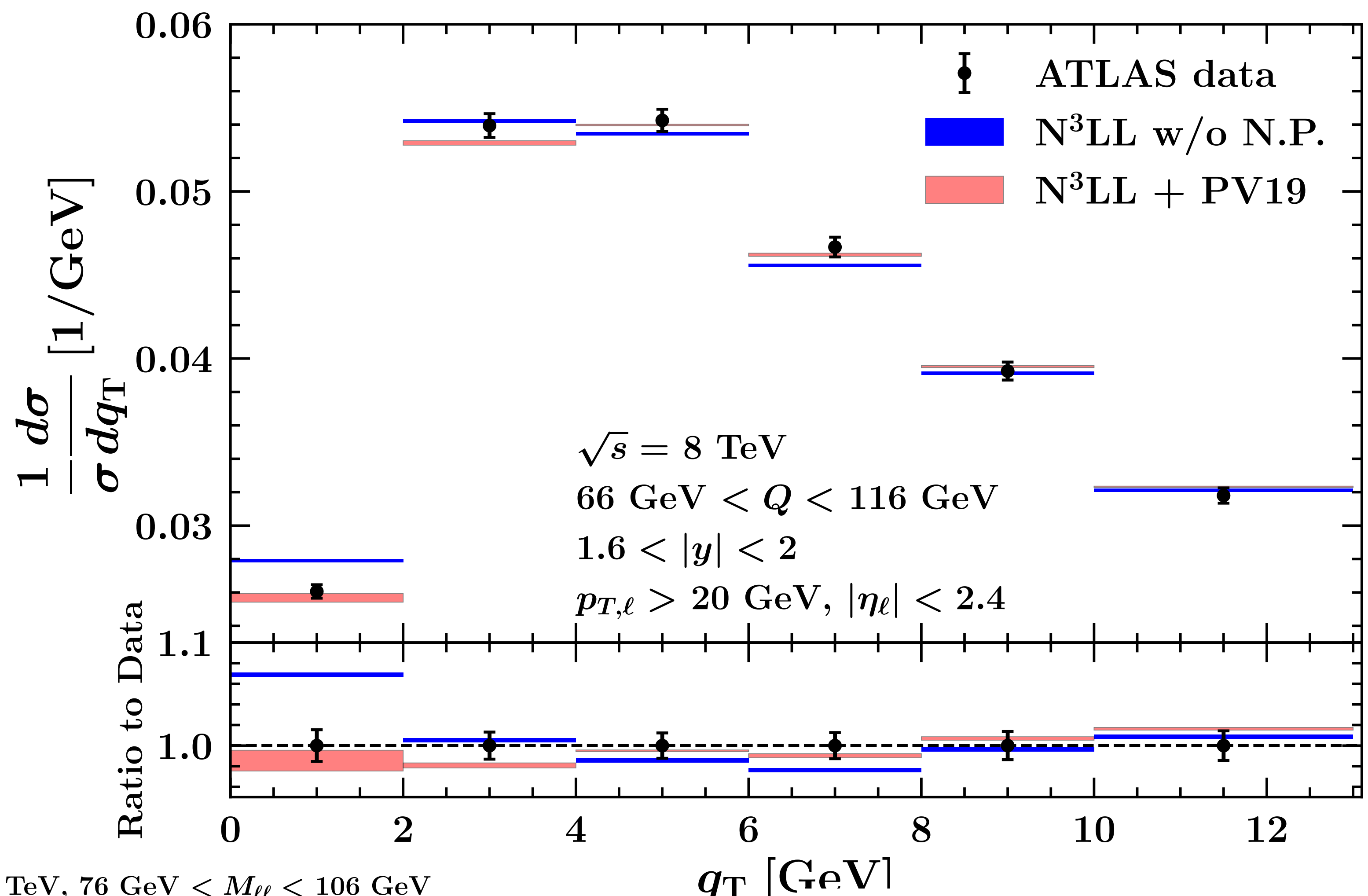
1 **1. Introduction**

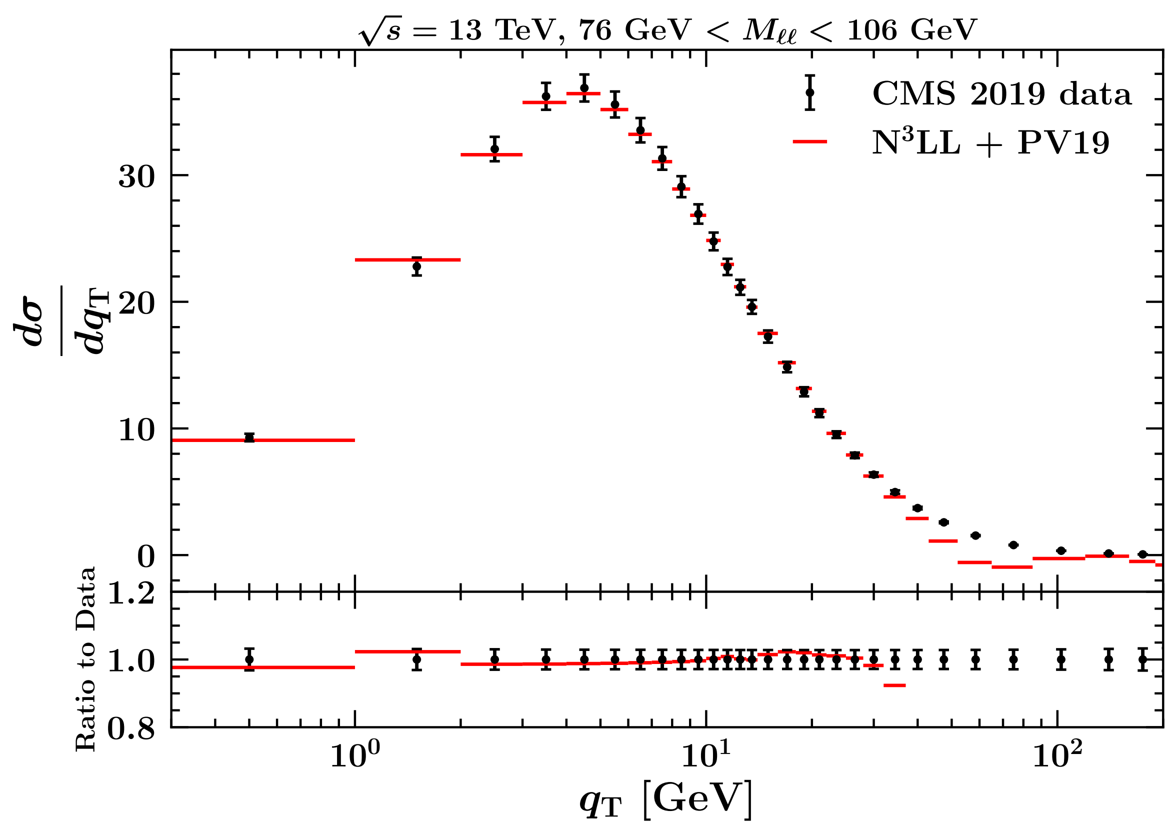
*Corresponding authors

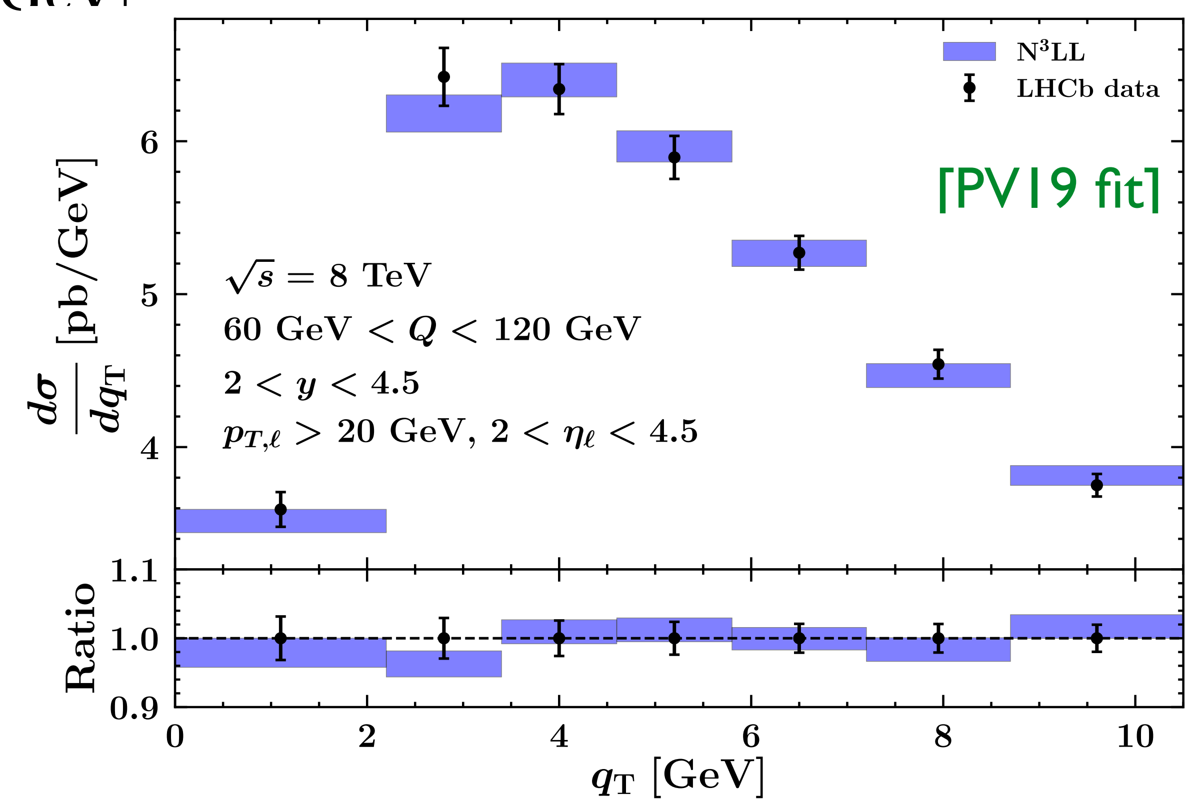
Impact on DY data @ LHC



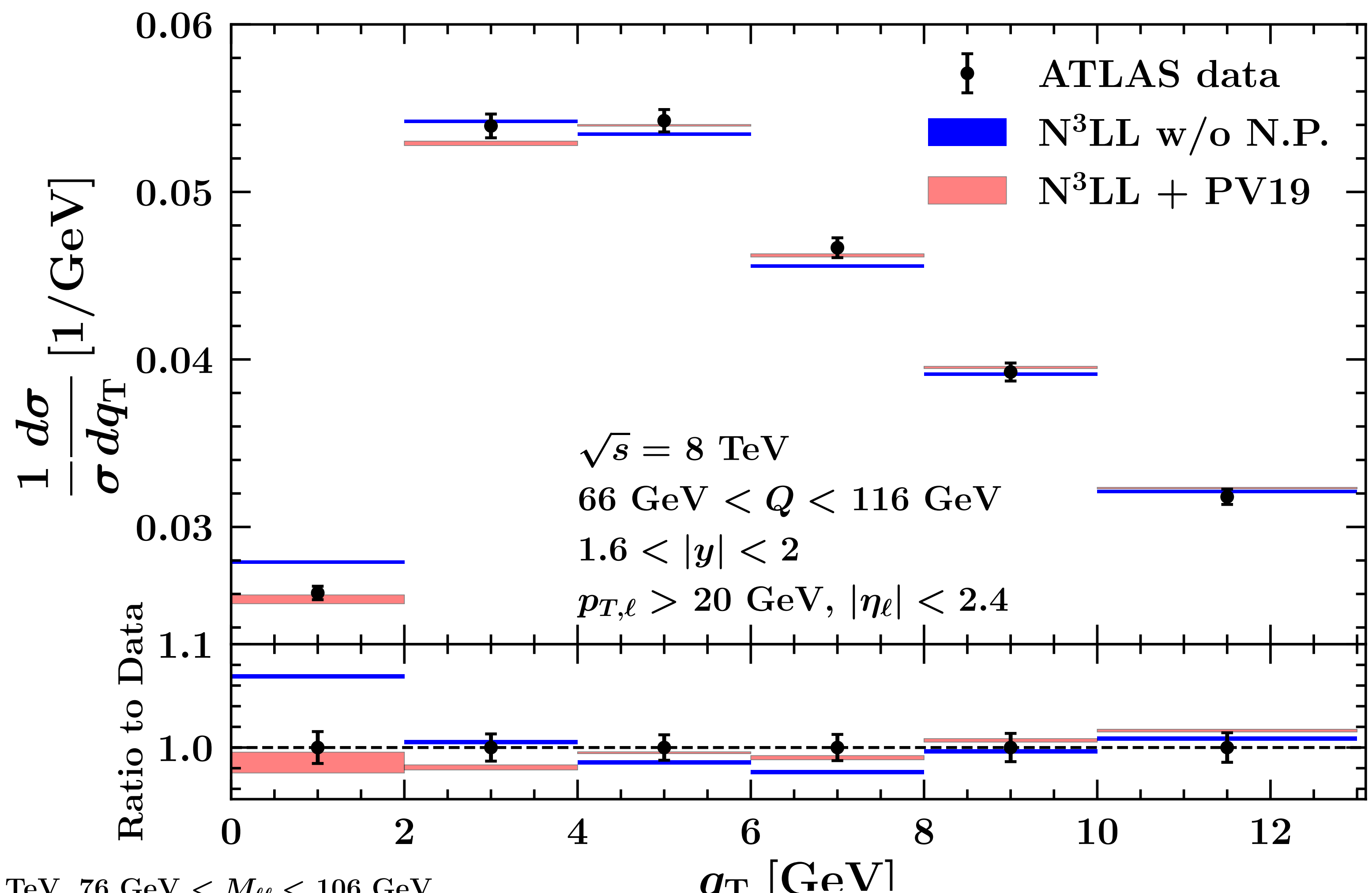
Impact on DY data @ LHC

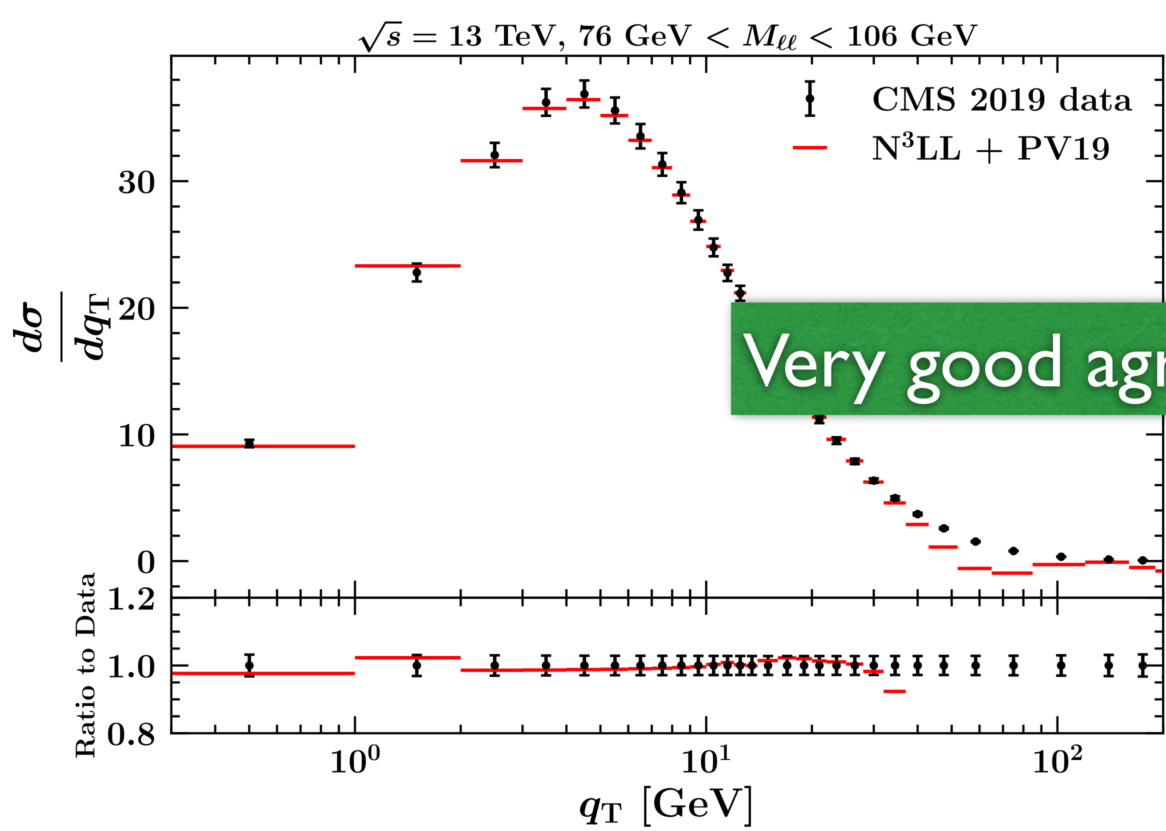


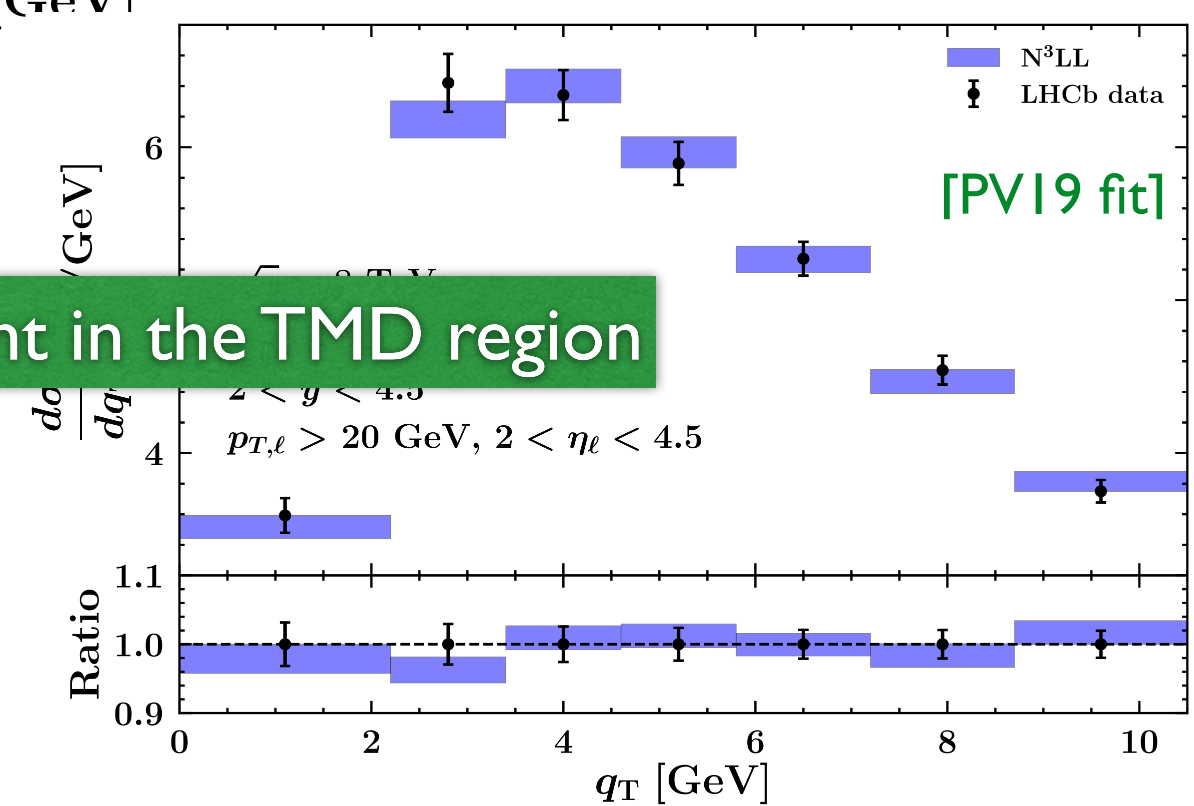




Impact on DY data @ LHC

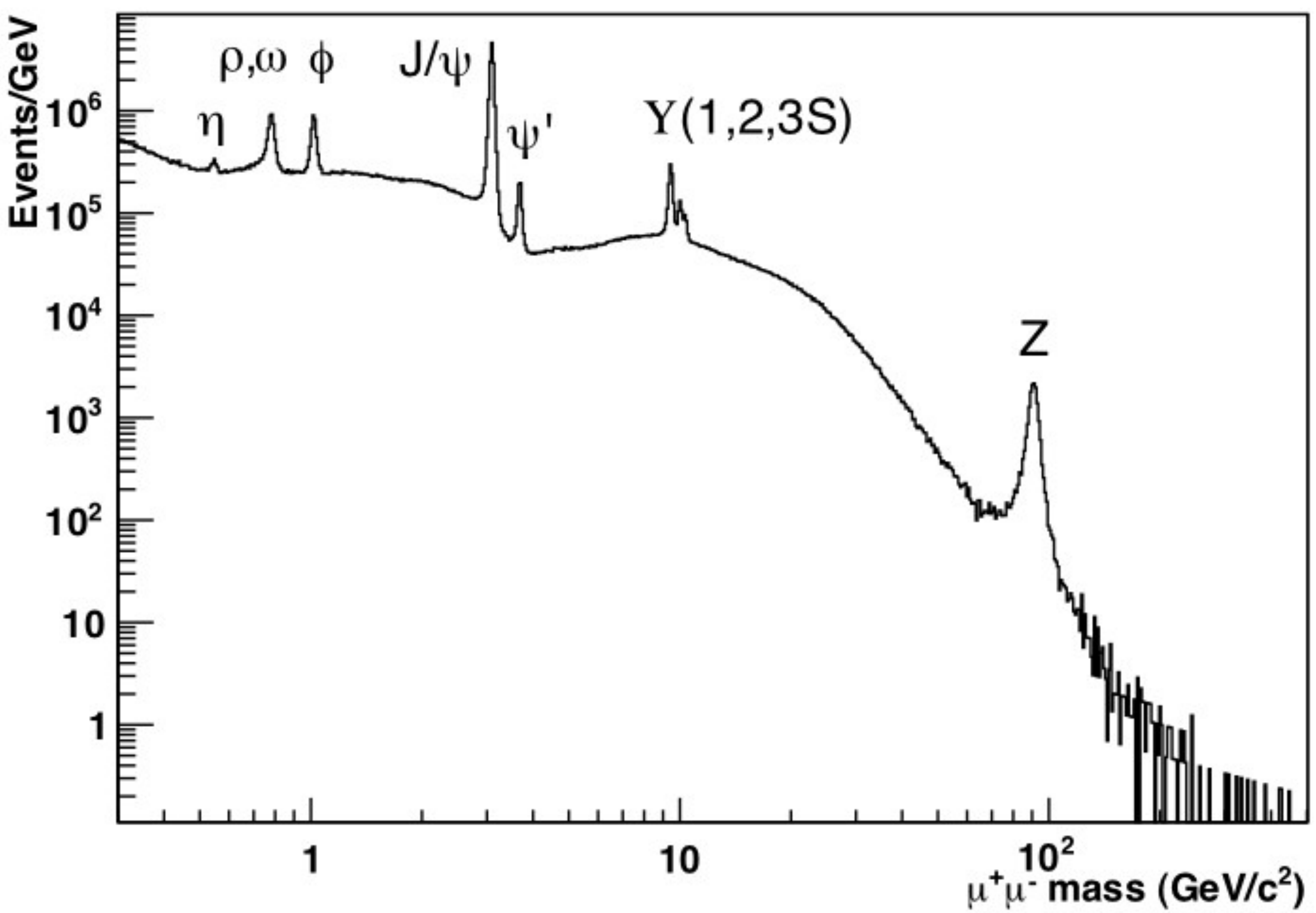






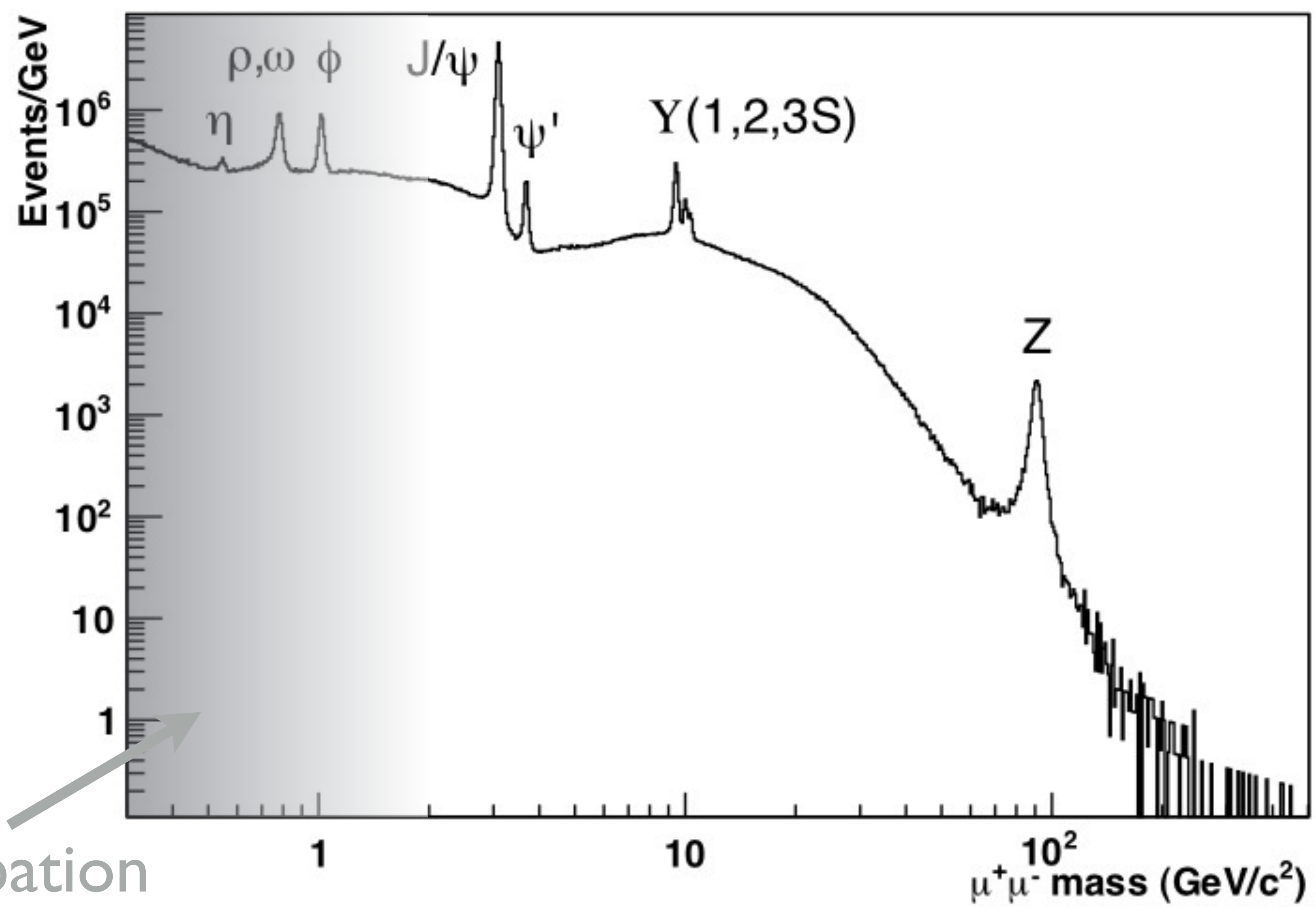
Very good agreement in the TMD region

What we need



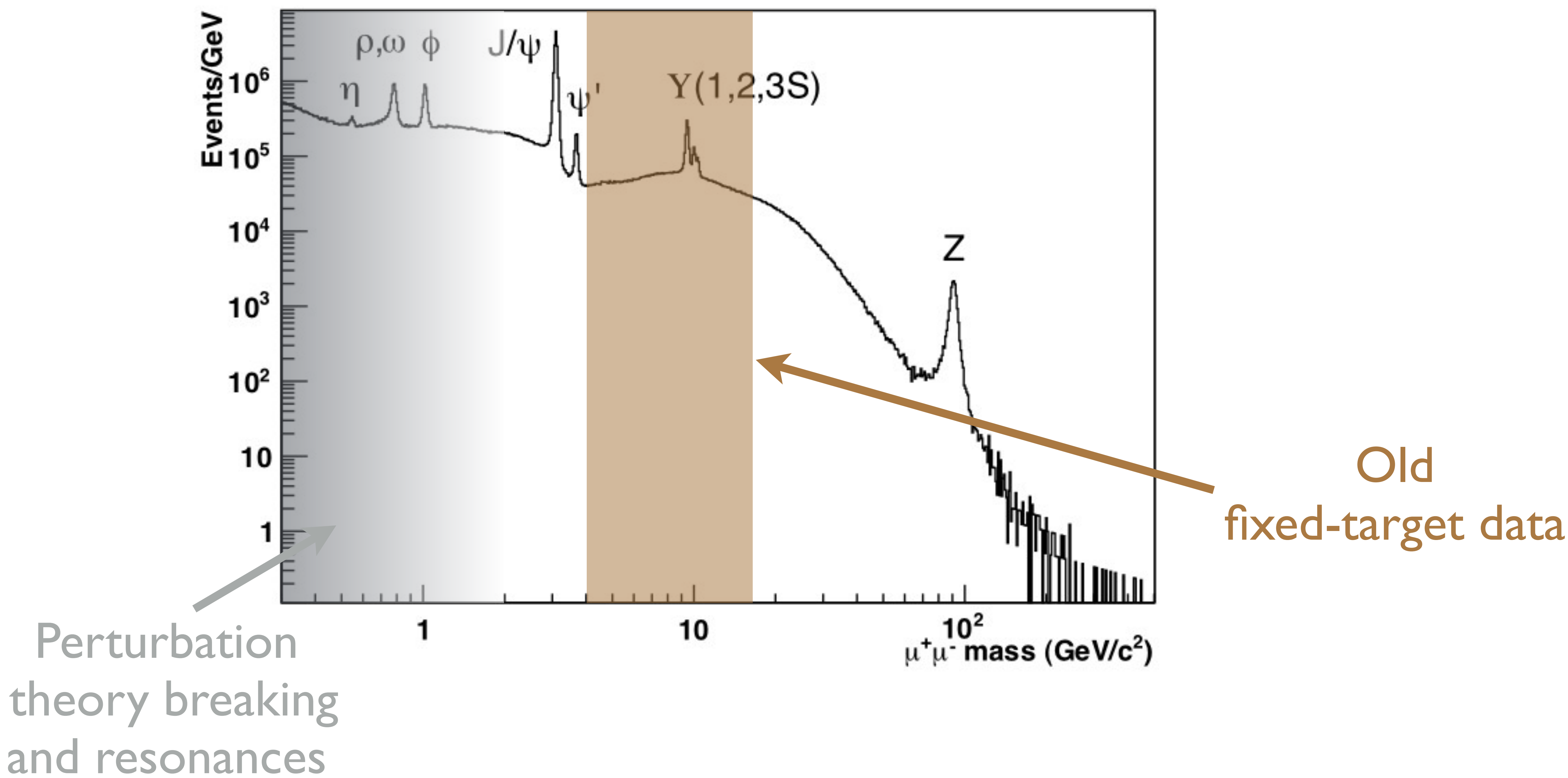
Events/GeV
10^6
10^5
10^4
10^3
10^2
10
1
η
ρ,ω
φ
J/ψ
ψ'
Υ(1,2,3S)
Z
1
10
10^2
$\mu^+\mu^-$ mass (GeV/c^2)

What we need



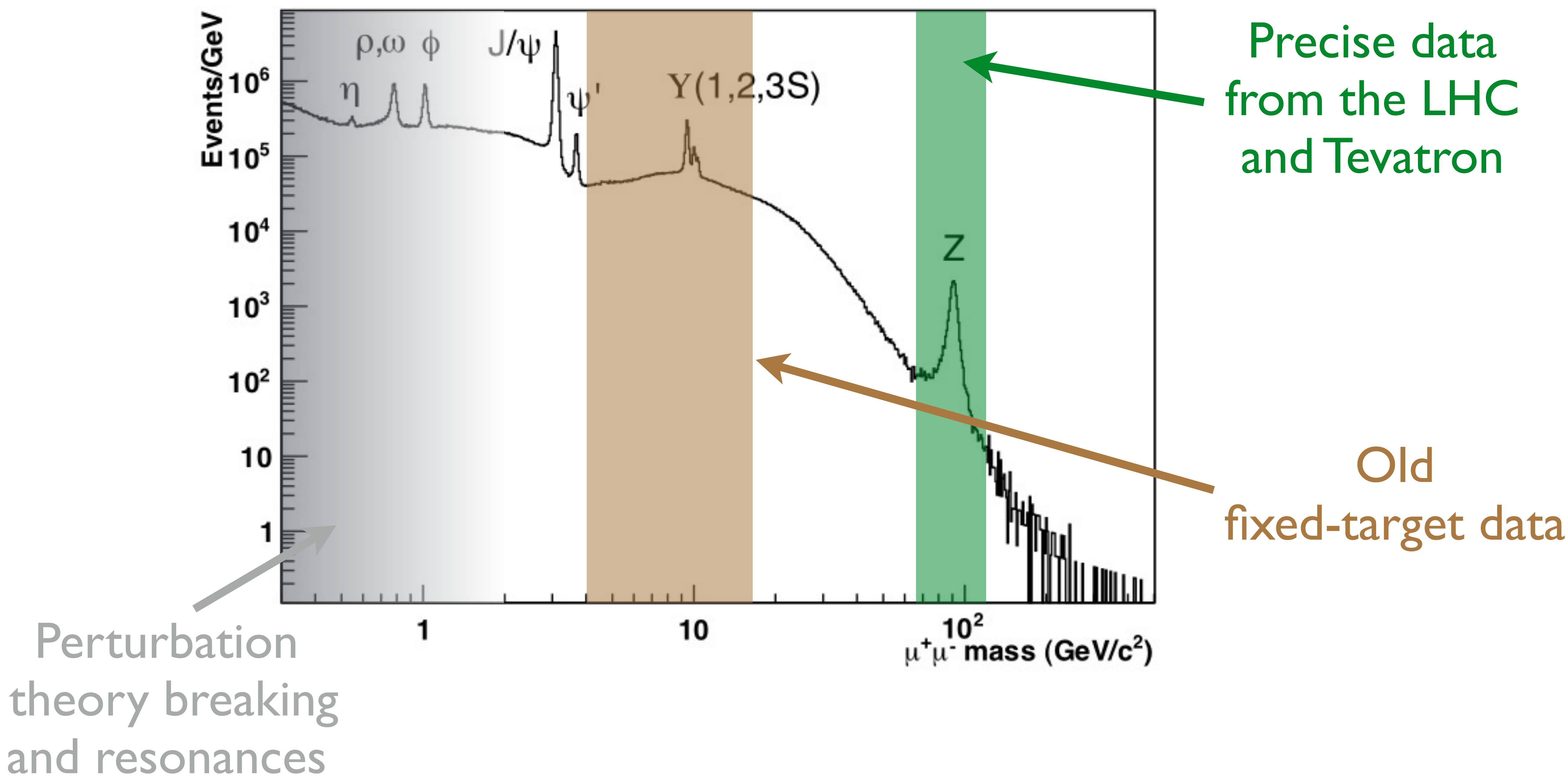
Perturbation theory breaking and resonances

What we need

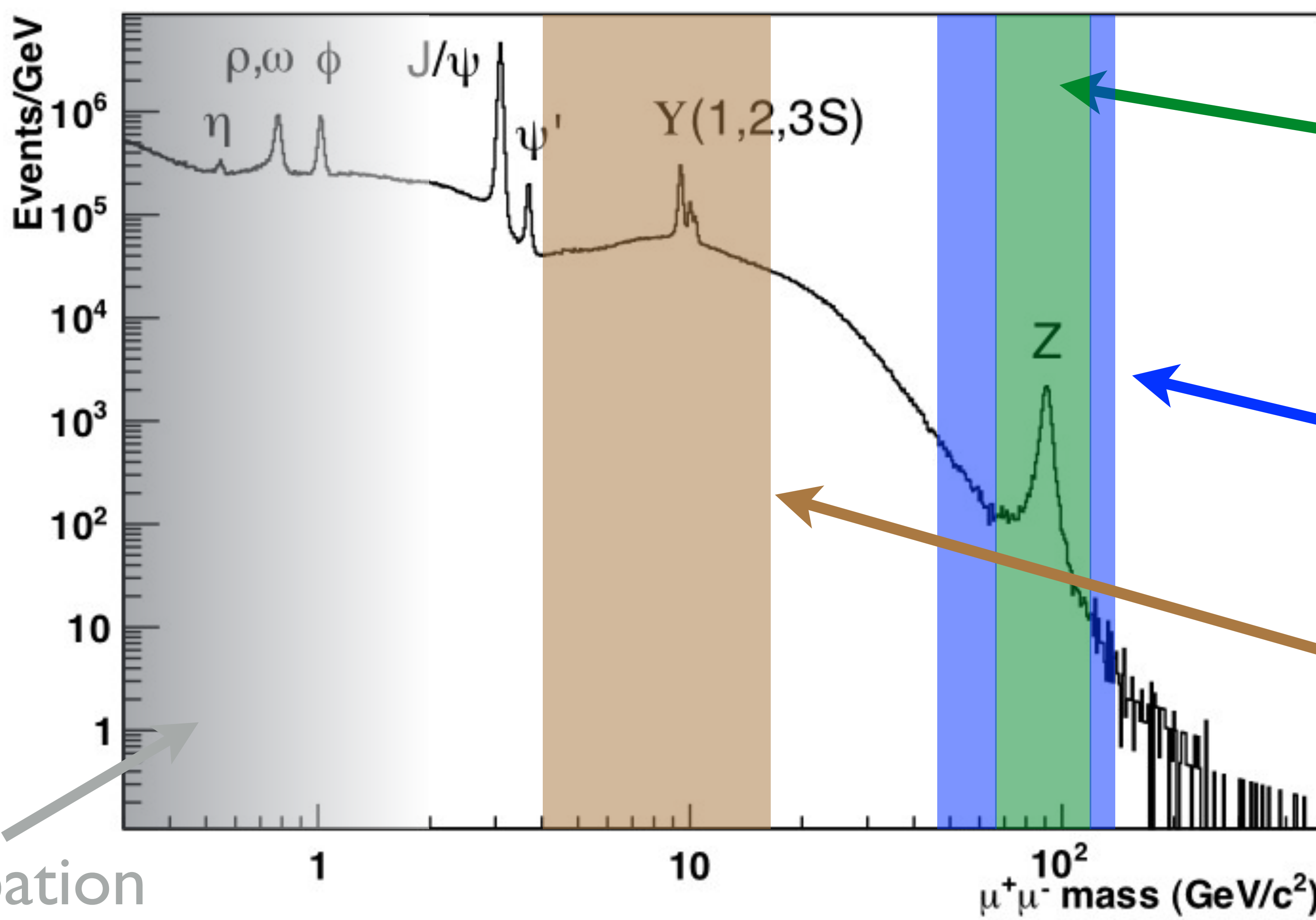


Events/GeV
10^6
10^5
10^4
10^3
10^2
10
1
ρ,ω ϕ
J/ψ
η
ψ'
Υ(1,2,3S)
Z
1
10
10^2
$\mu^+\mu^-$ mass (GeV/c^2)
Old
fixed-target data
Perturbation
theory breaking
and resonances

What we need


Events/GeV
10^6
10^5
10^4
10^3
10^2
10
1
η
ρ,ω
φ
J/ψ
ψ'
Υ(1,2,3S)
Z
1
10
10^2
$\mu^+\mu^-$ mass (GeV/c^2)
Precise data
from the LHC
and Tevatron
Old
fixed-target data
Perturbation
theory breaking
and resonances

What we need



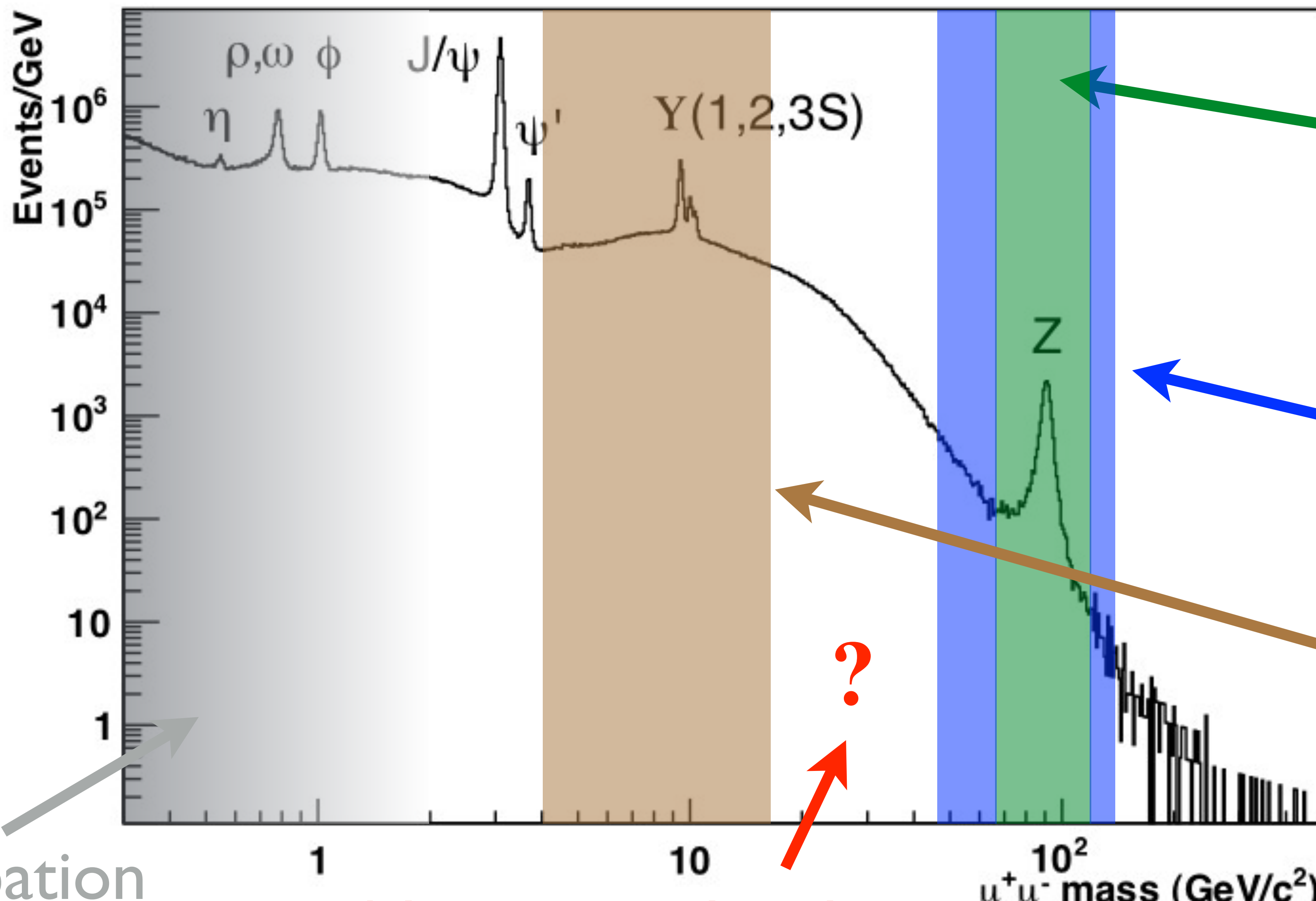
Precise data from the LHC and Tevatron

Less precise data from the LHC that extends to low q_T

Old fixed-target data

Perturbation theory breaking and resonances

What we need



Precise data from the LHC and Tevatron

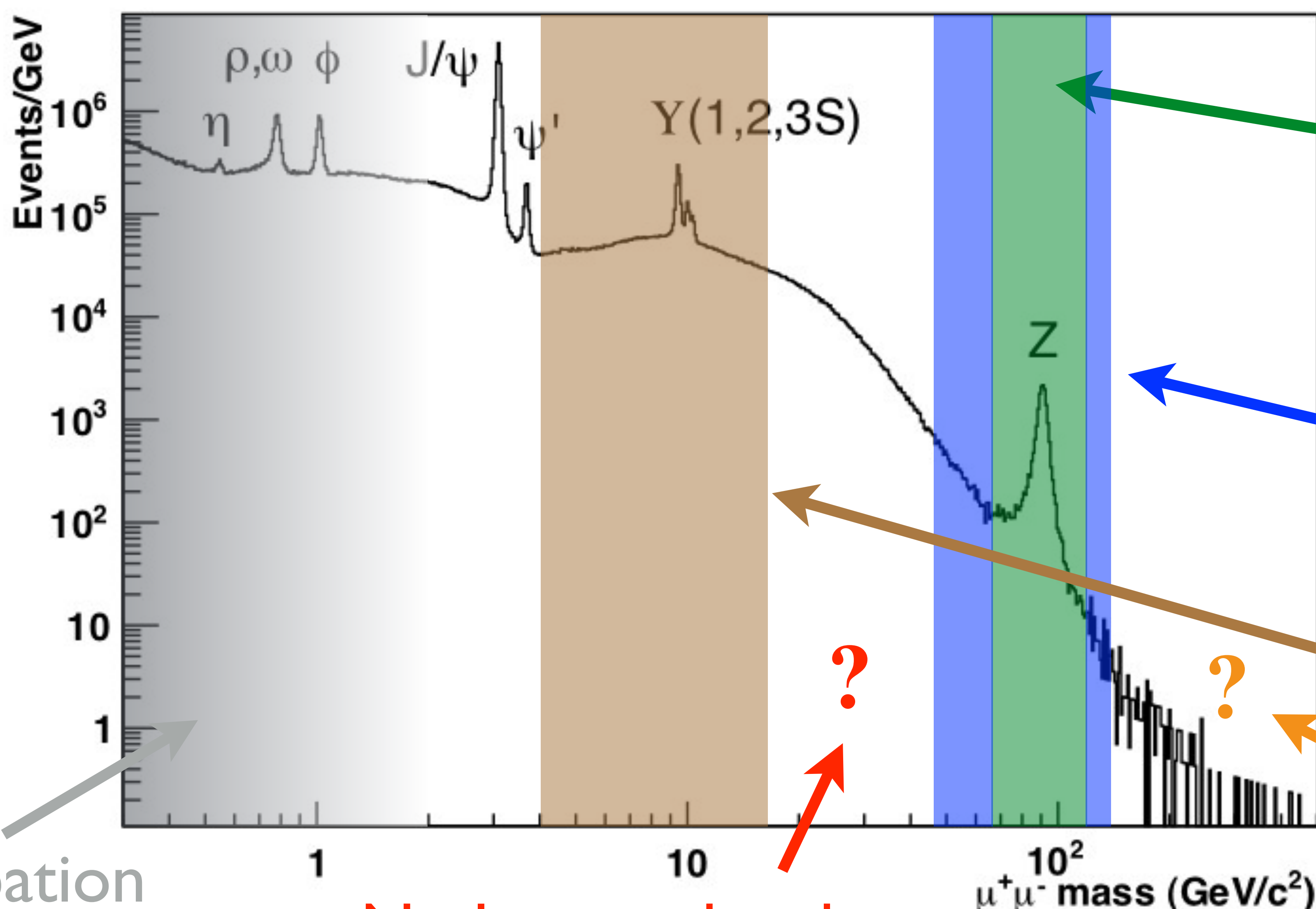
Less precise data from the LHC that extends to low q_T

Old fixed-target data

Perturbation theory breaking and resonances

No low-q_T data here but would be very welcome!

What we need



Precise data from the LHC and Tevatron

Less precise data from the LHC that extends to low q_T

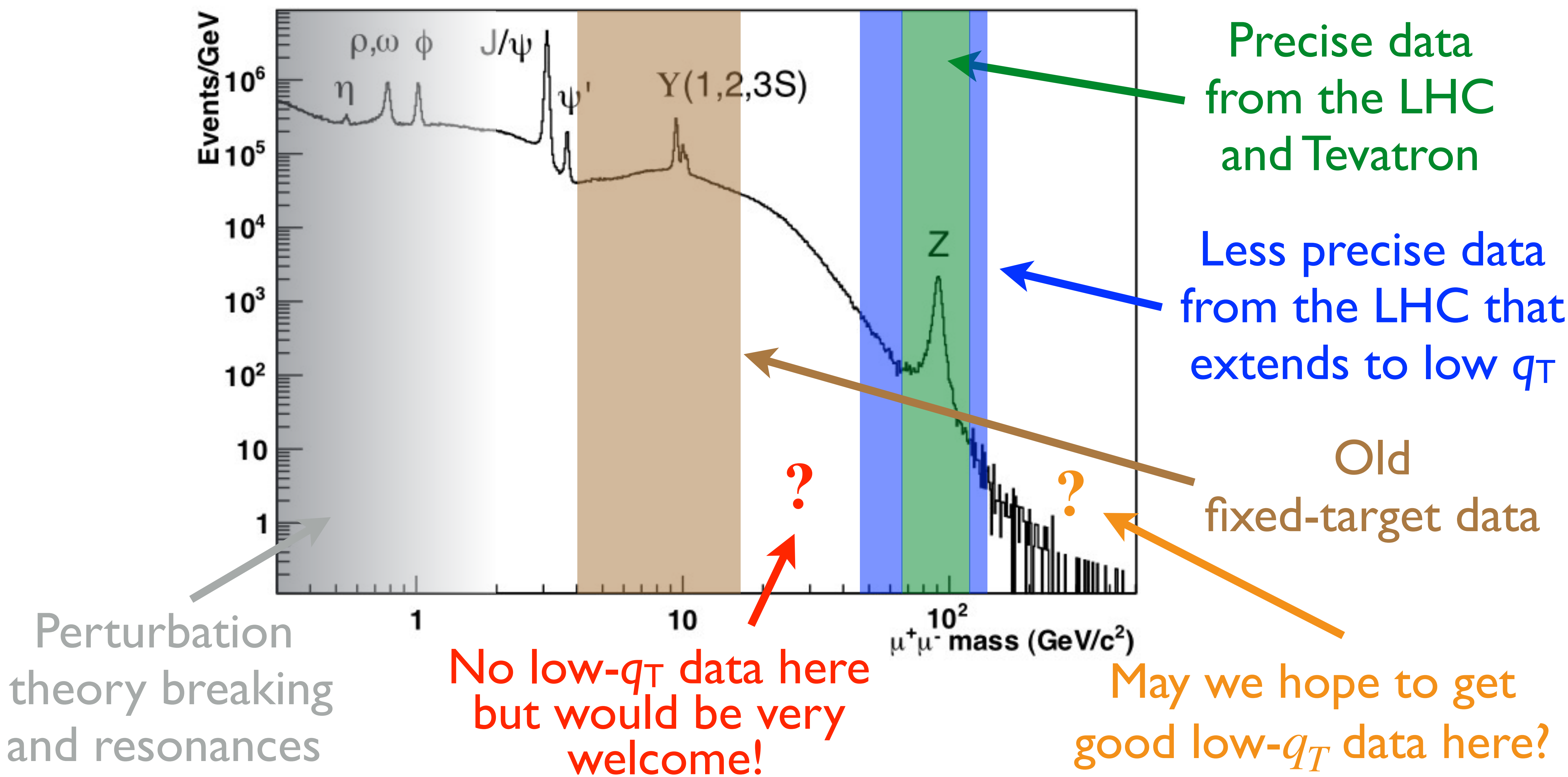
Old fixed-target data

Perturbation theory breaking and resonances

No low-q_T data here but would be very welcome!

May we hope to get good low-q_T data here?

What we need



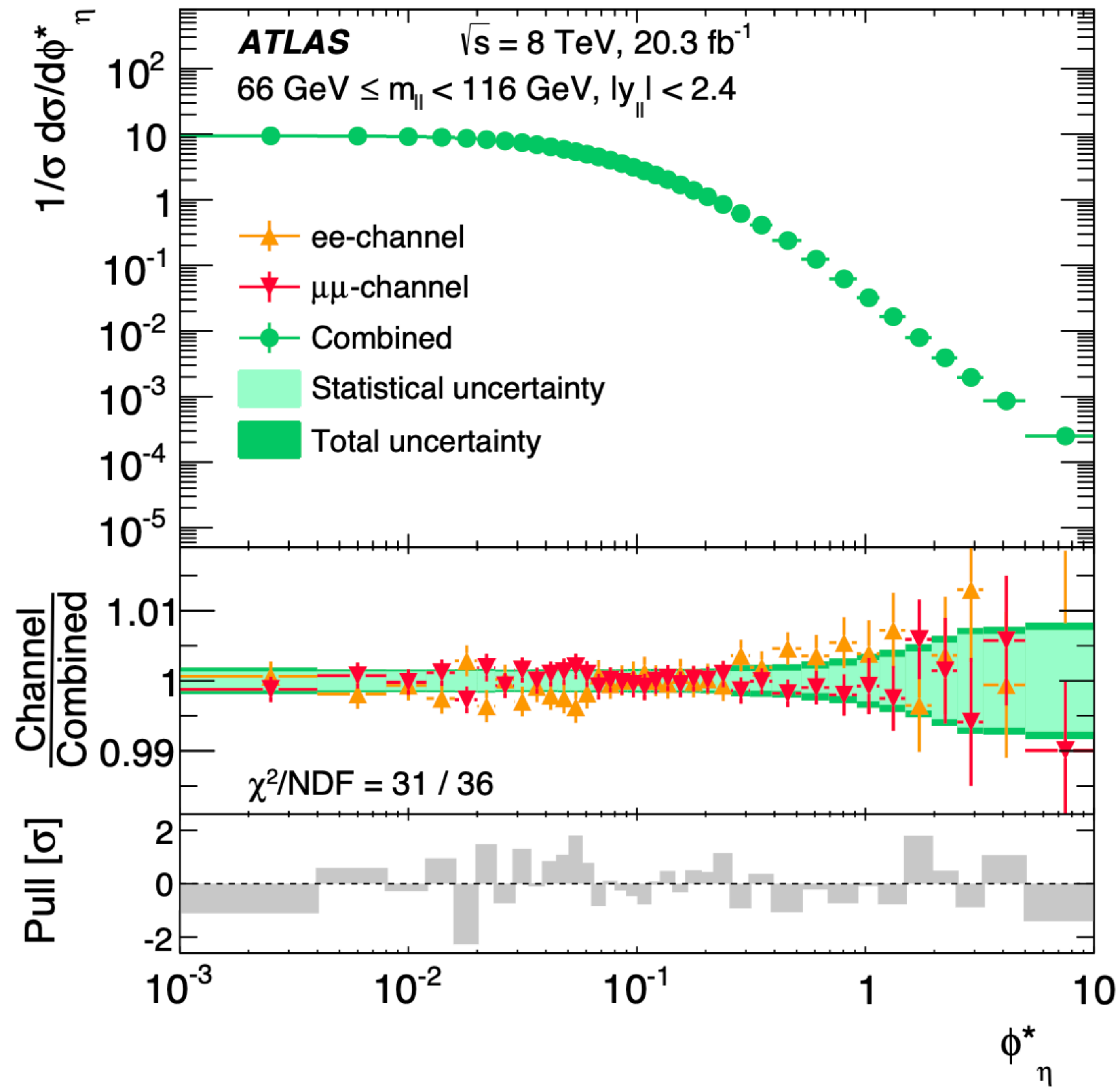
- Need as many (low-q_T + y-binned) data as possible!

Challenging measurements

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

[Banfi *et al.*, 1009.1580]

[ATLAS, 1512.02192]



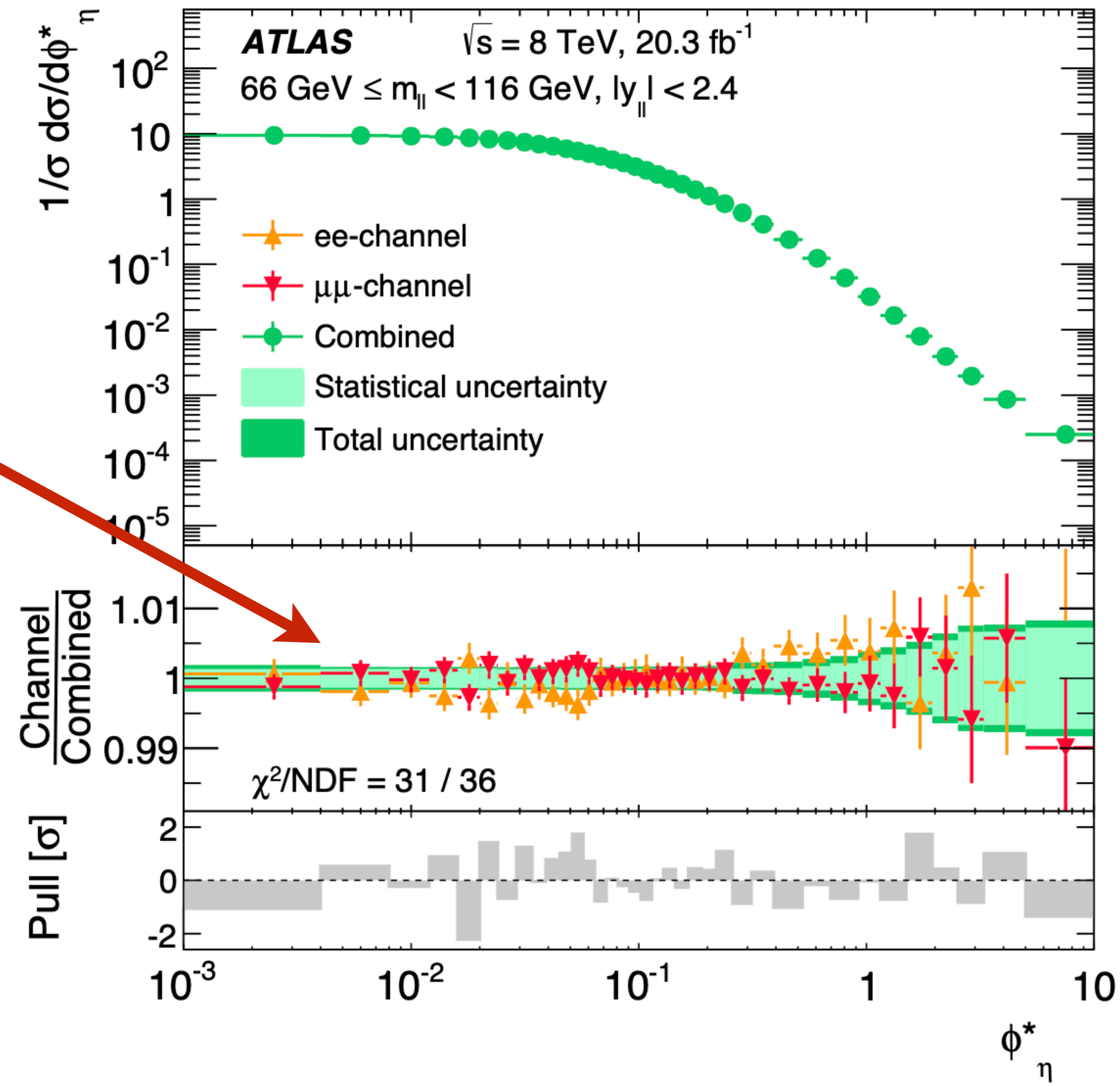
Challenging measurements

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

[Banfi et *al.*, 1009.1580]

- Only angles: insanely precise!

[ATLAS, 1512.02192]



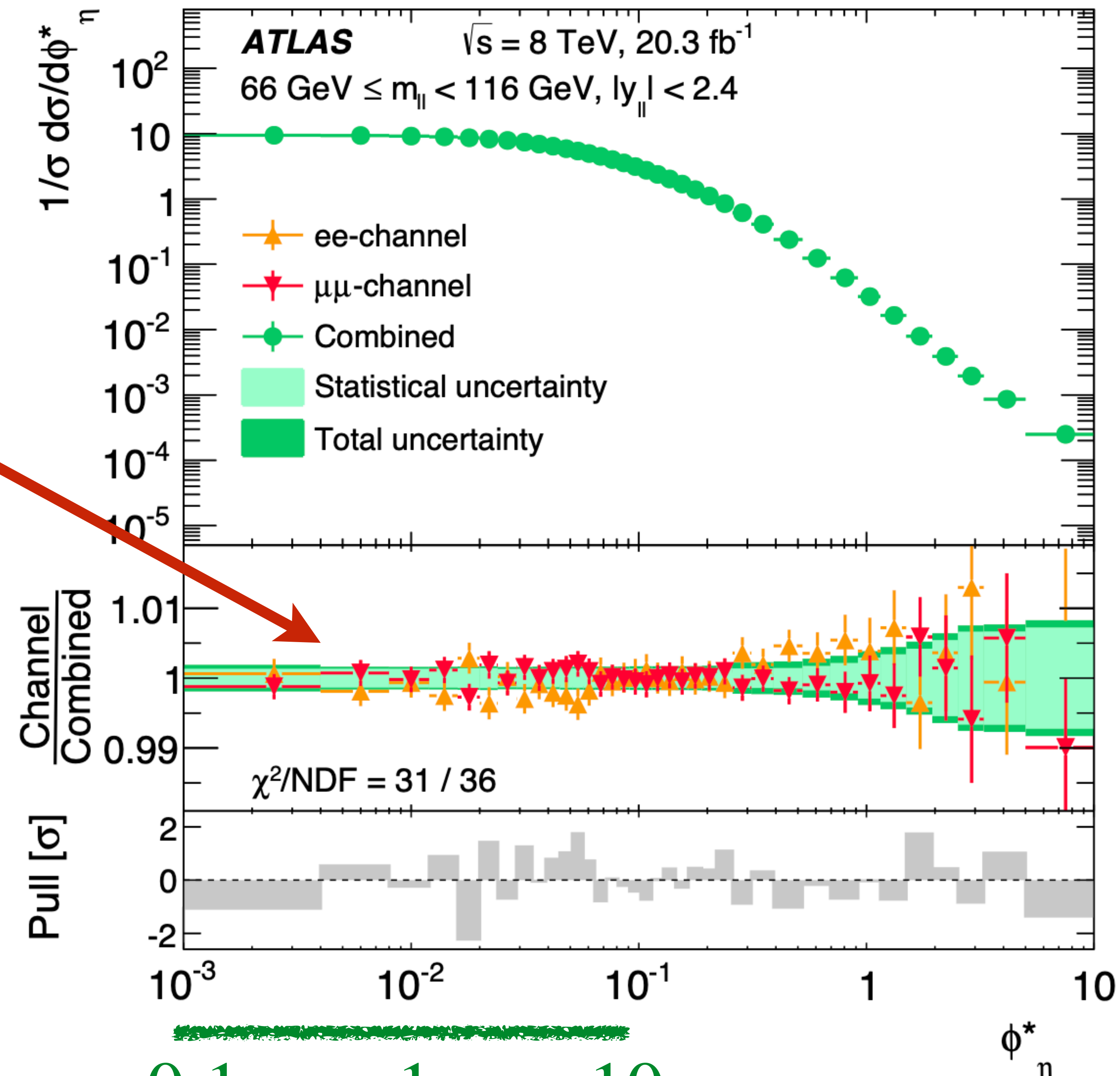
Challenging measurements

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

[Banfi et *al.*, 1009.1580]

[ATLAS, 1512.02192]

- Only angles: insanely precise!
- $\phi^*_\eta \approx \dfrac{q_T}{M}$



$q_T \approx 0.1 \quad 1 \quad 10$

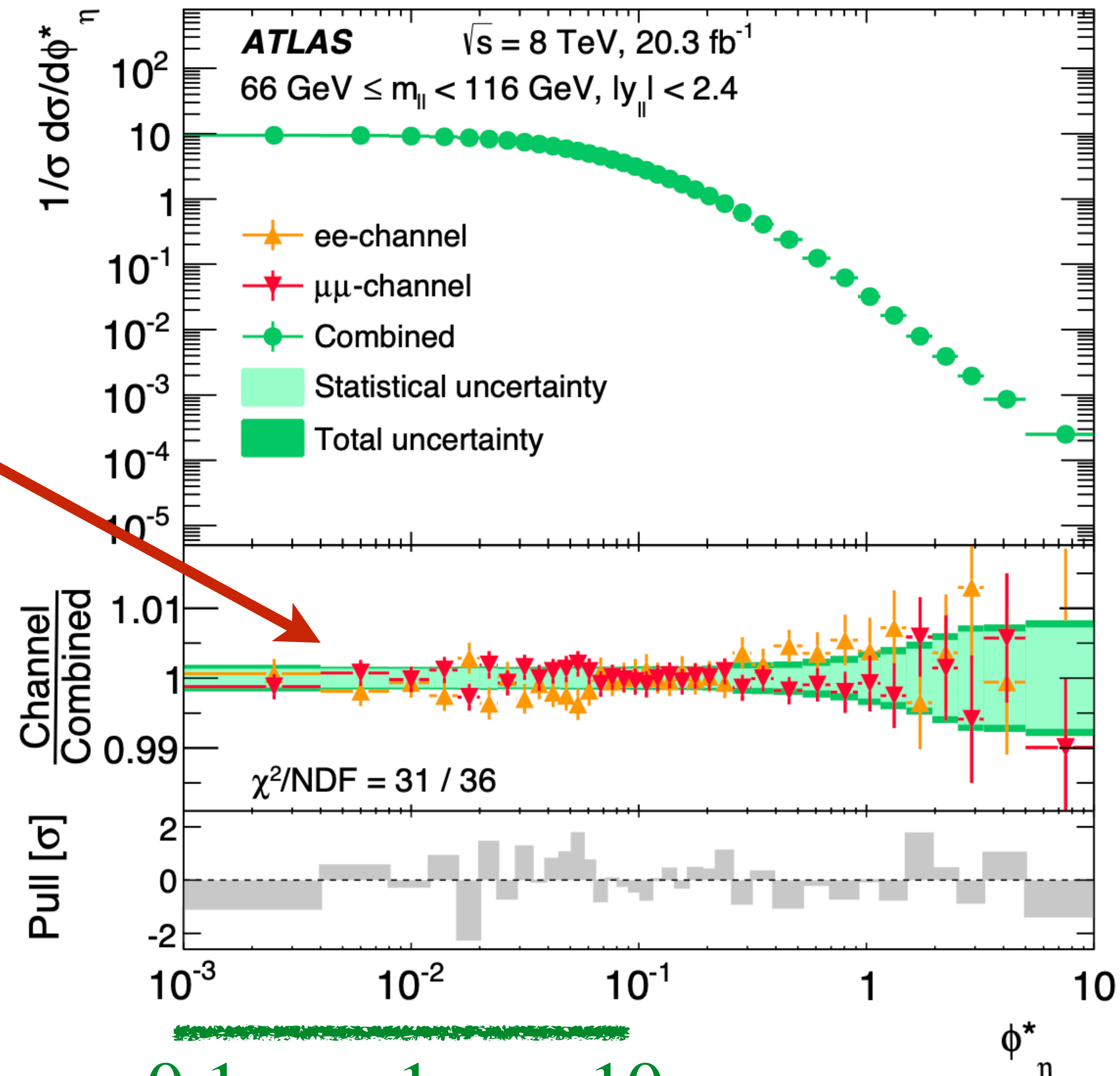
Challenging measurements

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

[Banfi *et al.*, 1009.1580]

- Only angles: insanely precise!
- $\phi^*_\eta \approx \dfrac{q_T}{M}$
- definitely relevant for hadron structure

[ATLAS, 1512.02192]



$q_T \approx 0.1 \quad 1 \quad 10$

Challenging measurements

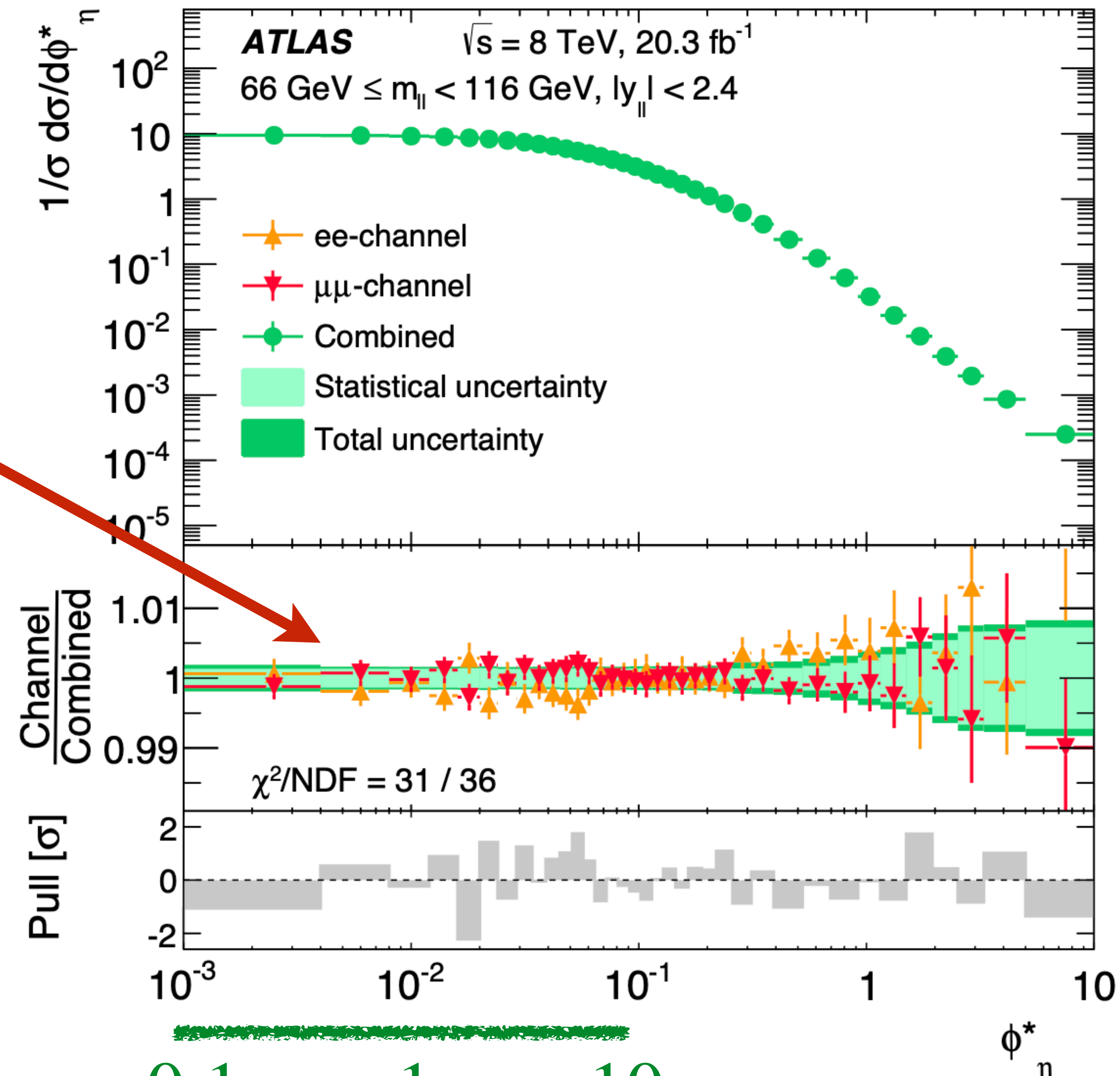
$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi_\ell}{2}\right)\sqrt{1-\tanh^2\left(\frac{\Delta\eta_\ell}{2}\right)}$$

[Banfi et *al.*, 1009.1580]

- Only angles: insanely precise!
- $\phi^*_\eta \approx \frac{q_T}{M}$
- definitely relevant for hadron structure

- it might be interesting to check shape variation with rapidity and m_{ll} at low ϕ^*_η (TMD (x, Q^2)-dependence)

[ATLAS, 1512.02192]



$q_T \approx 0.1 \quad 1 \quad 10$

W mass measurements

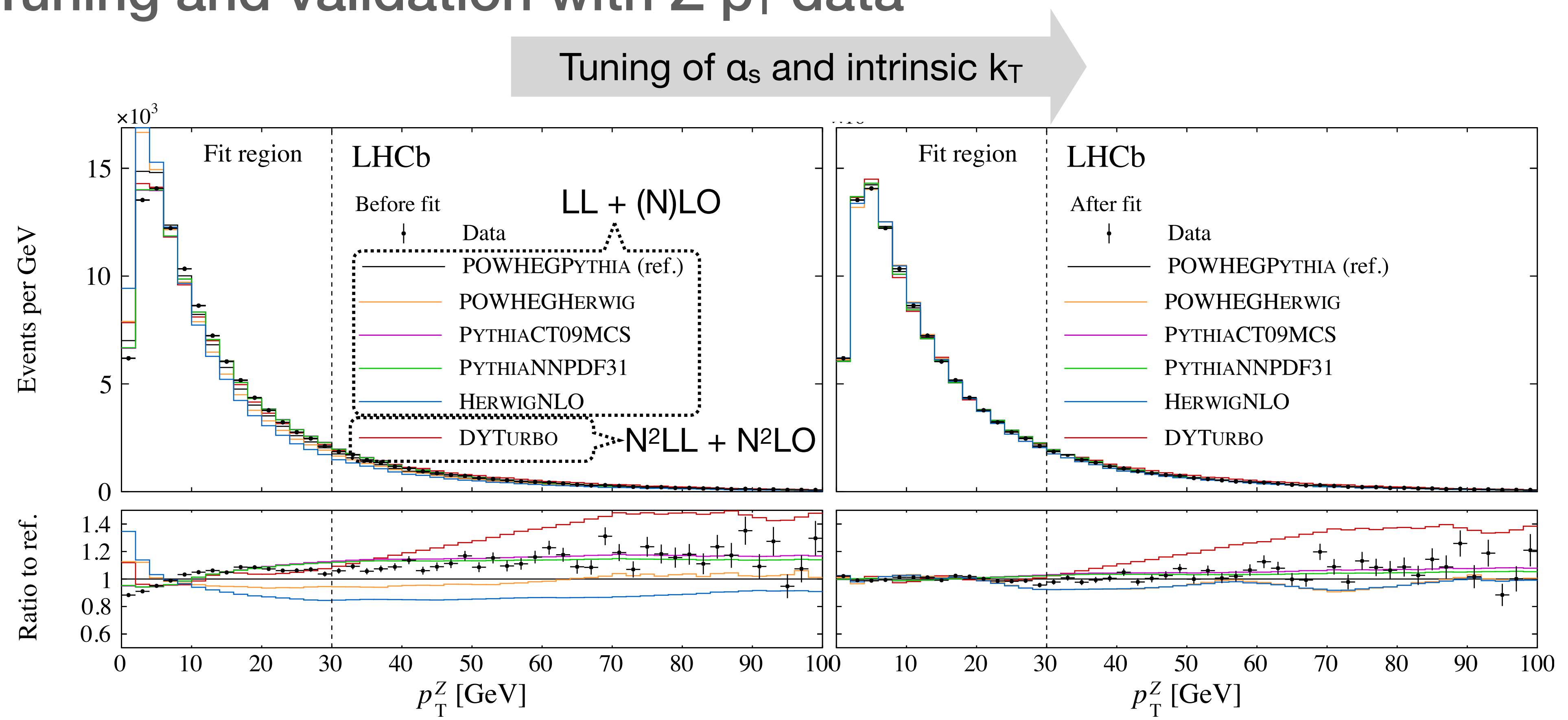
W mass measurements

- $p_{Tl} \leftarrow q_{TW} \leftarrow$ resummation + intrinsic-k_T

W mass measurements

- $p_{Tl} \leftarrow q_{TW} \leftarrow$ resummation + intrinsic-k_T
- <u>All analyses assume flavour-independence</u>

Tuning and validation with Z p_T data



DYTurbo (at N²LL+N²LO) does *OK* out-of-the-box for $p_T < 30$ GeV.

Varied success with the event generators, but they can still be tuned…

[M.Vesterinen, CERN seminar, June 2021]

POWHEGPythia gives the best description after tuning and is therefore the basis of our central model.

⚠️Would the resulting predictions of W p_T distribution be reliable?

W mass measurements

W mass measurements

- But we already know that it might be a relevant effect!

W mass measurements

- But we already know that it might be a relevant effect!

  flavour-dependent widths

Set	u_v	d_v	u_s	d_s	s
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
5	0.42	0.38	0.29	0.57	0.27
6	0.40	0.52	0.46	0.54	0.21
7	0.22	0.21	0.40	0.46	0.49
8	0.53	0.31	0.59	0.54	0.33
9	0.46	0.46	0.58	0.40	0.28

W mass measurements

- But we already know that it might be a relevant effect!

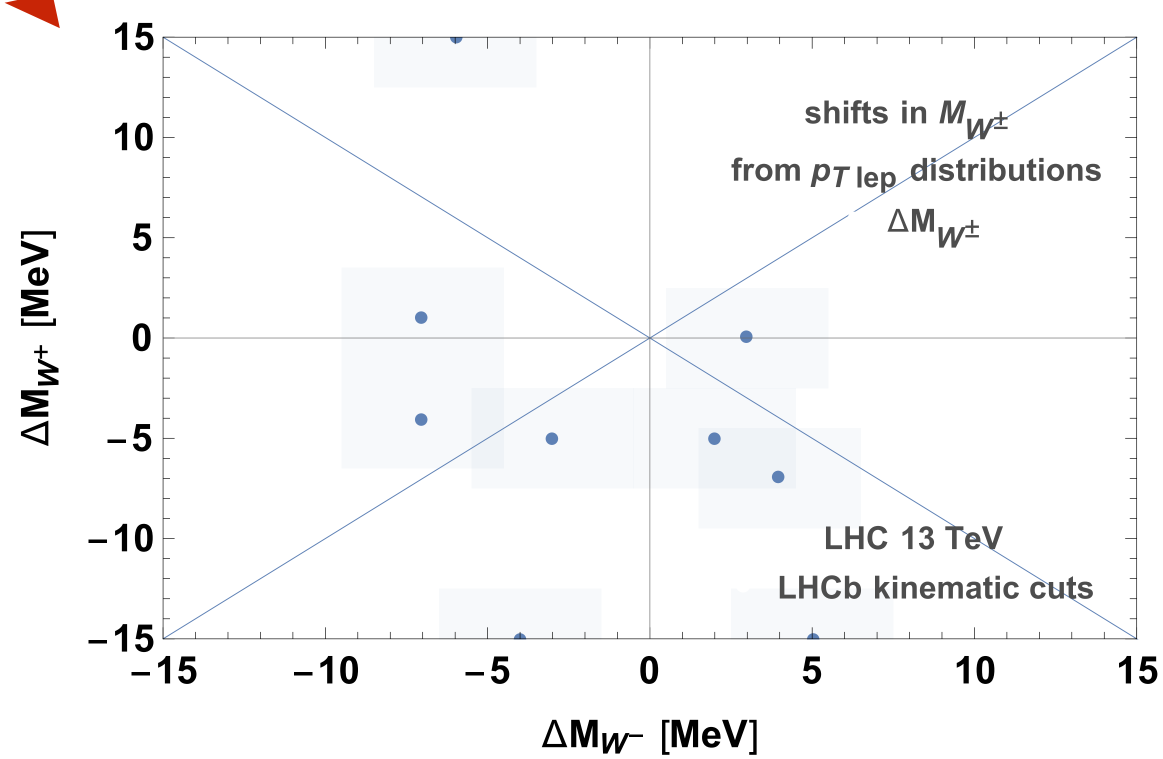
flavour-dependent widths

Set	u_v	d_v	u_s	d_s	s
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
5	0.42	0.38	0.29	0.57	0.27
6	0.40	0.52	0.46	0.54	0.21
7	0.22	0.21	0.40	0.46	0.49
8	0.53	0.31	0.59	0.54	0.33
9	0.46	0.46	0.58	0.40	0.28

W mass shifts

	ΔM_{W^+}			ΔM_{W^-}		
Set	m_T	$p_{T\ell}$	$p_{T\nu}$	m_T	$p_{T\ell}$	$p_{T\nu}$
1	-1	-5	7	-1	-3	8
2	-1	-15	6	0	5	10
3	-1	1	8	-1	-7	5
4	-1	-15	6	0	-4	5
5	-1	-4	6	-1	-7	5
6	-1	-5	7	0	2	9
7	-1	-15	6	-1	-6	5
8	-1	0	8	0	3	10
9	-1	-7	7	0	4	10

TABLE II: LHCb 13 TeV



[Bacchetta et al., 1807.02101]

Outlook

Outlook

- **TMD precision era has started!** In the next few years we expect:

Outlook

- **TMD precision era has started!** In the next few years we expect:
    - better exploitation of LHC data

Outlook

- **TMD precision era has started!** In the next few years we expect:
  - better exploitation of LHC data
  - increasingly accurate TMD fits

Outlook

- **TMD precision era has started!** In the next few years we expect:
  - better exploitation of LHC data
  - increasingly accurate TMD fits
  - relevant role of hadron structure in precision EW at the LHC

Outlook

- **TMD precision era has started!** In the next few years we expect:
    - better exploitation of LHC data
    - increasingly accurate TMD fits
    - relevant role of hadron structure in precision EW at the LHC
    - TMD flavour dependence

Outlook

- **TMD precision era has started!** In the next few years we expect:
    - better exploitation of LHC data
    - increasingly accurate TMD fits
    - relevant role of hadron structure in precision EW at the LHC
    - TMD flavour dependence
- More interaction needed between collinear and TMD communities

Outlook

- **TMD precision era has started!** In the next few years we expect:
  - better exploitation of LHC data
  - increasingly accurate TMD fits
  - relevant role of hadron structure in precision EW at the LHC
  - TMD flavour dependence
- More interaction needed between collinear and TMD communities
- **Keep promoting TMDs at the LHC!**

Outlook

- **TMD precision era has started!** In the next few years we expect:
    - better exploitation of LHC data
    - increasingly accurate TMD fits
    - relevant role of hadron structure in precision EW at the LHC
    - TMD flavour dependence
- More interaction needed between collinear and TMD communities
- **Keep promoting TMDs at the LHC!**

Outlook

- **TMD precision era has started!** In the next few years we expect:
  - better exploitation of LHC data
  - increasingly accurate TMD fits
  - relevant role of hadron structure in precision EW at the LHC
  - TMD flavour dependence
- More interaction needed between collinear and TMD communities
- **Keep promoting TMDs at the LHC!**

Backup slides

Resummation scheme

- Let us start from CSS factorisation:

$$\frac{d\sigma}{dq_T} \sim H(Q)S(Q,\mu_b)\left[C(\mu_b)\otimes f(\mu_b)\right]^2$$

- Arbitrary "perturbative" function: $h(\mu) \equiv h(\alpha_s(\mu)) = \sum_{n=0}^{\infty} \alpha_s^n(\mu) h^{(n)}$

$$\frac{d\ln h(\mu)}{d\ln\mu} = \frac{d\alpha_s(\mu)}{d\ln\mu}\frac{d\ln h(\mu)}{d\alpha_s} = \beta(\alpha_s(\mu))[h(\mu)]^{-1}\frac{dh(\mu)}{d\alpha_s} \Rightarrow h(Q) = \exp\left[\int_{\mu_b}^{Q}\frac{d\mu}{\mu}\beta(\alpha_s(\mu))[h(\mu)]^{-1}\frac{dh(\mu)}{d\alpha_s}\right]h(\mu_b)$$

- so that:

$$\begin{aligned}\frac{d\sigma}{dq_T} &\sim h(Q)[h(Q)]^{-1}H(Q)S(Q,\mu_b)\left[C(\mu_b)\otimes f(\mu_b)\right]^2 \\ &= \underbrace{[h(Q)]^{-1}H(Q)}_{\widetilde{H}(Q)}\underbrace{S(Q,\mu_b)\exp\left[\int_{\mu_b}^{Q}\frac{d\mu}{\mu}\beta(\alpha_s(\mu))[h(\mu)]^{-1}\frac{dh}{d\alpha_s}\right]}_{\widetilde{S}(Q,\mu_b)}\left[\underbrace{\sqrt{h(\mu_b)}C(\mu_b)}_{\widetilde{C}(\mu_b)}\otimes f(\mu_b)\right]^2\end{aligned}$$

- Choosing $h = H$ defines the Catani-de Florian-Grazzini (CdFG) scheme:

$$\begin{aligned}\widetilde{C}_{ij}^{(0)}(x) &= C_{ij}^{(0)}(x) = \delta_{ij}\delta(1-x) & \widetilde{B}^{(0)} &= B^{(0)} \\ \widetilde{C}_{ij}^{(1)}(x) &= C_{ij}^{(1)}(x) + \frac{1}{2}H^{(1)}\delta_{ij}\delta(1-x) & \widetilde{B}^{(1)} &= B^{(1)} + \beta_0 H^{(1)} \\ \widetilde{C}^{(2)}(x) &= C_{ij}^{(2)}(x) + \frac{1}{2}H^{(1)}C_{ij}^{(1)}(x) + \frac{1}{2}\left[H^{(2)} - \frac{1}{4}(H^{(1)})^2\right]\delta_{ij}\delta(1-x) & \widetilde{B}^{(2)} &= B^{(2)} + \beta_1 H^{(1)} + 2\beta_0\left[H^{(2)} - \frac{1}{2}(H^{(1)})^2\right]\end{aligned}$$

- Enough up to N^3LL.

TMD scale variations

- TMD factorisation allows one to obtain the **evolution equations**:

$$\begin{cases} \dfrac{d\ln F}{d\ln\mu} = \gamma(\mu,\zeta) \\[2ex] \dfrac{d\ln F}{d\ln\sqrt{\zeta}} = K(\mu) \end{cases}, \qquad \frac{d^2\ln F}{d\ln\mu\, d\ln\sqrt{\zeta}} = \begin{cases} \dfrac{d\gamma}{d\ln\sqrt{\zeta}} \\[2ex] \dfrac{dK}{d\ln\mu} \end{cases} = \gamma_K(\alpha_s(\mu))$$

- To solve these equations we need to fix **two pairs of (*i.e.* four) scales**:
  - **initial** scales: (μ_0, ζ_0)
  - **final** scales: (μ, ζ)
- The solution is **unique** and reads:

$$F(\mu,\zeta) = R\left[(\mu,\zeta)\leftarrow(\mu_0,\zeta_0)\right] F(\mu_0,\zeta_0)$$

$$R\left[(\mu,\zeta)\leftarrow(\mu_0,\zeta_0)\right] = \exp\left\{K(\mu_0)\ln\frac{\sqrt{\zeta}}{\sqrt{\zeta_0}} + \int_{\mu_0}^{\mu}\frac{d\mu'}{\mu'}\left[\gamma_F(\alpha_s(\mu')) - \gamma_K(\alpha_s(\mu'))\ln\frac{\sqrt{\zeta}}{\mu'}\right]\right\}$$

- The question is: **how do we choose these four scales?**

TMD scale variations

- A sensible choice of the scales is important to **allow perturbation theory to be reliable**:
  - **no large unresummed logarithms** should be introduced,
  - each scale has to be set in the **vicinity of its natural (central) value**,
  - scale variations (within a reasonable range) give an estimate of HO corrs.
- In TMD factorisation ($q_T \ll Q$) for DY the relevant scales are $\boldsymbol{q_T}$ and $\boldsymbol{Q}$:
  - natural to expect $\mu_0 \sim \sqrt{\zeta_0} \sim q_T \sim b_T^{-1}$ and $\mu \sim \sqrt{\zeta} \sim Q$
- In fact, it turns out that (in the $\overline{\text{MS}}$ scheme) the **central scales** are:

$$\mu_0 = \sqrt{\zeta_0} = \frac{2e^{-\gamma_E}}{b_T} \equiv \mu_b \quad \text{and} \quad \mu = \sqrt{\zeta} = Q$$

- This choice **nullifies** all unresummed logs. One should thus consider:

$$\mu_0 = C_i^{(1)} \mu_b, \quad \sqrt{\zeta_0} = C_i^{(2)} \mu_b, \quad \mu = C_f^{(1)} Q, \quad \sqrt{\zeta} = C_f^{(2)} Q,$$

TMD scale variations

- To reason why variations of ζ have **no effect** is that:

$$\frac{d\sigma}{dq_T} \propto H\left(\frac{\mu}{Q}\right) F_1(\mu,\zeta_1)F_2(\mu,\zeta_2) \quad \text{with} \quad \boxed{\zeta_1\zeta_2 \overset{!}{=} Q^4}$$

- It is easy to see that:

$$F_1(\mu,\zeta_1)F_2(\mu,\zeta_2) = \underbrace{R\left[(\mu,\zeta_1)\leftarrow(\mu_0,\zeta_0)\right] R\left[(\mu,\zeta_2)\leftarrow(\mu_0,\zeta_0)\right]}_{f(\zeta_1\zeta_2)\,=\,f(Q^4)} F_1(\mu_0,\zeta_0)F_2(\mu_0,\zeta_0)$$

- The single dependence on ζ_1 and ζ_2 **drops** in the combination:
  - we choose $\zeta_1 = \zeta_2 = Q^2$ but any other choice such that $\zeta_1\zeta_2 = Q^4$ is **identical**.
- In addition, in NangaParbat we have chosen to set $\mu_0 = \sqrt{\zeta_0}$:
  - not strictly necessary but **probably a conservative choice**.
- At the end of the day, we have **two scales** to be varied:

$$\boxed{\mu_0 = \sqrt{\zeta_0} = C_i\mu_b \quad \text{and} \quad \mu = C_f Q}$$