REF, Pavia, 27 November 2019

Extraction of TMDs from Drell-Yan data

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3DSPIN MAPPING THE PROTON IN 3D

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Pavia 2019 TMD fit

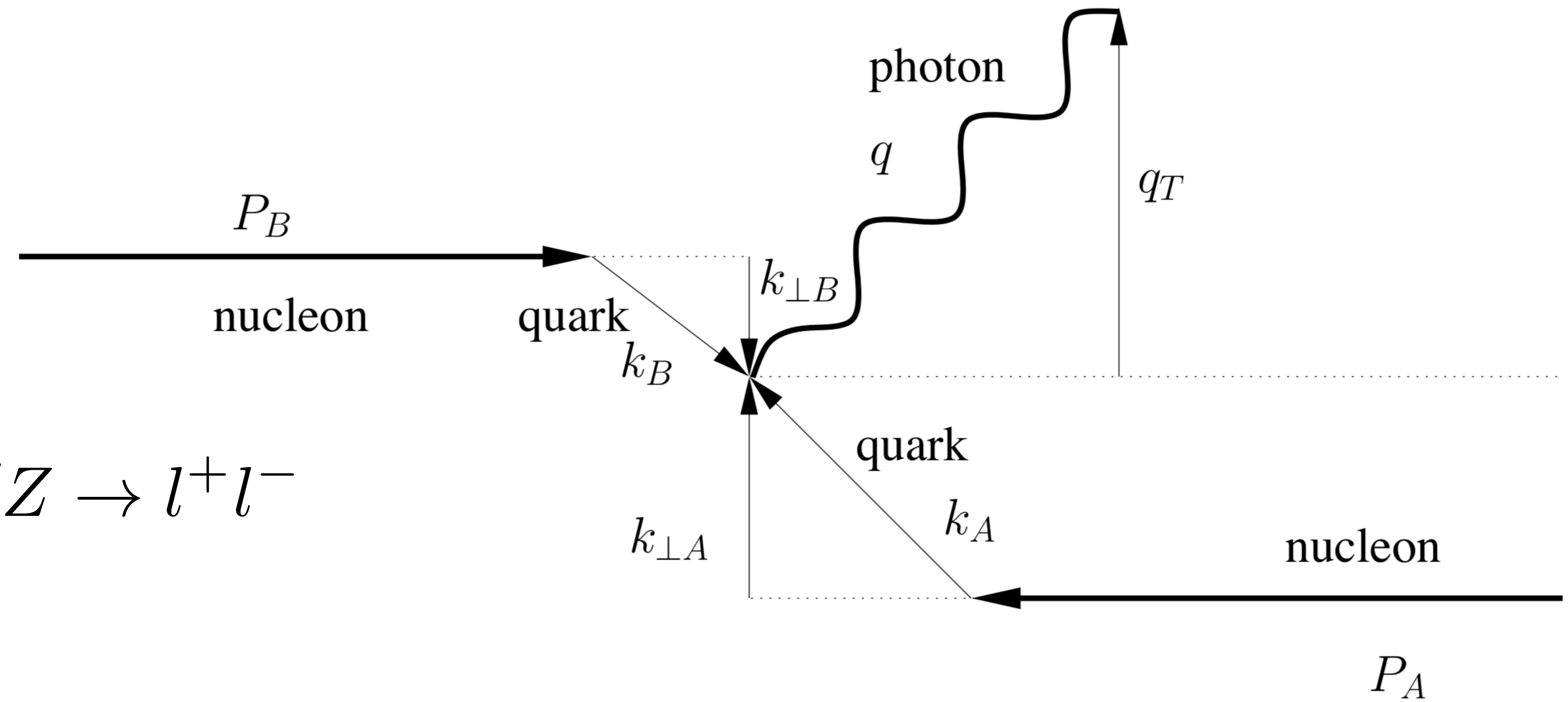
perturbative accuracy
up to
N3LL

Drell-Yan
LHC data

NO
normalisation
coefficients

$\chi^2 = 1.07$

TMD factorisation



Drell-Yan

$N(P_A) + N(P_B) \to \gamma^*/Z \to l^+l^-$

for $q_T \ll Q$ **fixed logarithmic accuracy**

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} = \sigma_0 H(Q,\mu) \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} x_1 F_q(x_1, \mathbf{b}; \mu, \zeta_1) x_2 F_{\bar{q}}(x_2, \mathbf{b}; \mu, \zeta_2)$$

Logarithmic accuracy

$$\frac{d\sigma}{dq_T} \propto H(Q,\mu) \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} F_q(x_1,\mathbf{b};\mu) F_{\bar{q}}(x_2,\mathbf{b};\mu)$$

hard factor

matching coefficients

collinear PDF

$$F(x,\mathbf{b};\mu) = \sum_j \left(C_j \otimes f^j\right)(x,b_*;\mu_b) e^{R(b_*;\mu_b,\mu)} f_{\rm NP}(x,b)$$

Sudakov form factor

Logarithmic accuracy

$$\frac{d\sigma}{dq_T} \propto H(Q,\mu) \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} F_q(x_1,\mathbf{b};\mu) F_{\bar{q}}(x_2,\mathbf{b};\mu)$$

hard factor

matching coefficients

collinear PDF

non perturbative function

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hard factor

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Sudakov form factor

perturbative expansion in $\alpha_s(\mu)$

resummation of

$$L = \ln \frac{Q^2}{\mu_b^2}$$

define logarithmic ordering

Logarithmic accuracy

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

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

$$\times f_{\rm NP}(x, b, \zeta).$$

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

b* prescription

$$\left(\frac{d\sigma}{dq_T}\right) \propto \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} F_q(x_1,\mathbf{b}) F_{\bar{q}}(x_2,\mathbf{b})$$

when b_T becomes large

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

invalidates perturbative calculations

need to use some prescription,

$b_{\max}$

b* prescription

$$\left(\frac{d\sigma}{dq_T}\right) \propto \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} F_q(x_1, \mathbf{b}) F_{\bar{q}}(x_2, \mathbf{b})$$

when b_T becomes large

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

invalidates perturbative calculations

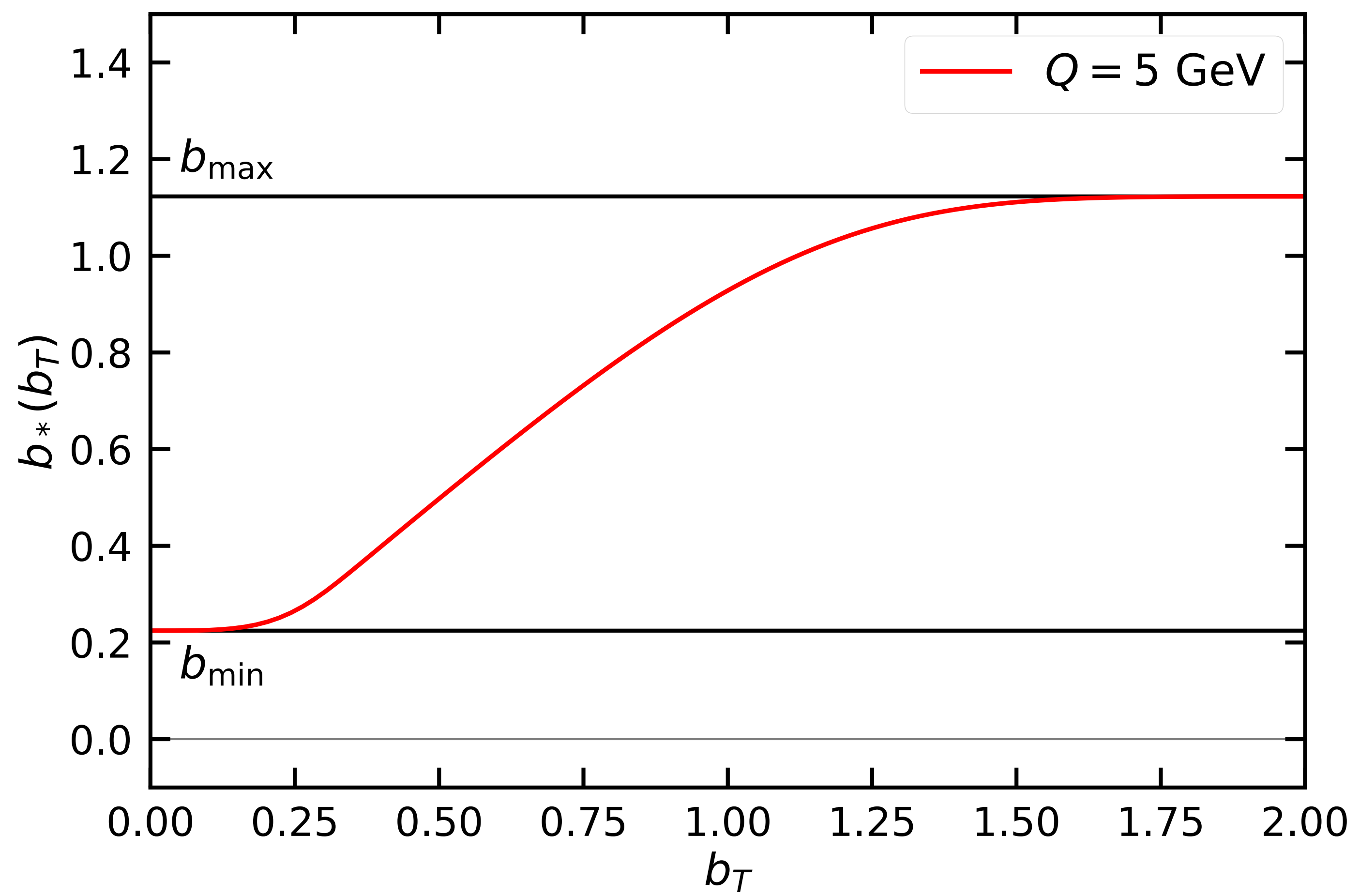
$\Rightarrow b_{\max}$

b-min choice

$$b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = 2e^{-\gamma_E}/Q$$

$$b_*(b) = b_{\max}\left(\frac{1-\exp\left(-\frac{b^4}{b^4_{\max}}\right)}{1-\exp\left(-\frac{b^4}{b^4_{\min}}\right)}\right)^{\frac{1}{4}}$$



Non perturbative function

perturbative

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

non perturbative

$$f_{\rm NP}(x,b,\zeta)$$

fit to data

depends on the choice of b*-prescription

Non perturbative function

QGaussian **Gaussian**

$$f_{\mathrm{NP}}(x, b, \zeta) = \left[\frac{1-\lambda}{1+g_1(x)\frac{b^2}{4}} + \lambda \exp\left(-g_{1,B}(x)\frac{b^2}{4}\right)\right]$$

$$\times \quad \exp\left[-\left(g_2 + g_{2B} b^2\right) \log\left(\frac{\zeta}{Q_0^2}\right) \frac{b^2}{4}\right]$$

Non perturbative function

$$f_{\mathrm{NP}}(x,b,\zeta) = \left[\frac{1-\lambda}{1+g_1(x)\frac{b^2}{4}} + \lambda \exp\left(-g_{1,B}(x)\frac{b^2}{4}\right)\right]$$

$$\times \quad \exp\left[-\left(g_2 + g_{2B} b^2\right) \log\left(\frac{\zeta}{Q_0^2}\right)\frac{b^2}{4}\right]$$

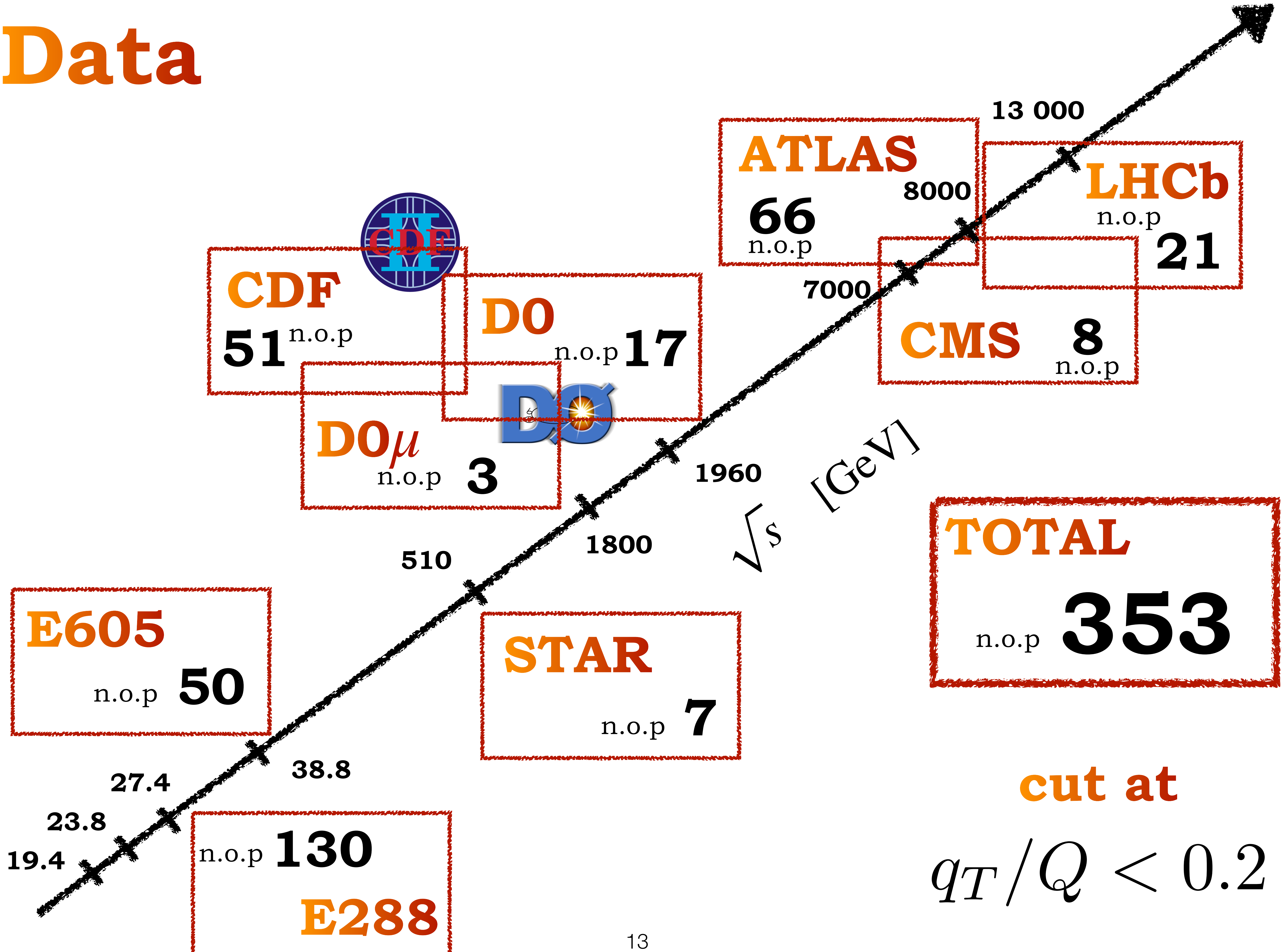
x-dependence

$$g_1(x) = \frac{N_1}{x\sigma}\exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{x}{\alpha}\right)\right]$$

9 parameters

$$g_{1,B}(x) = \frac{N_{1B}}{x\sigma_B}\exp\left[-\frac{1}{2\sigma_B^2}\ln^2\left(\frac{x}{\alpha_B}\right)\right]$$

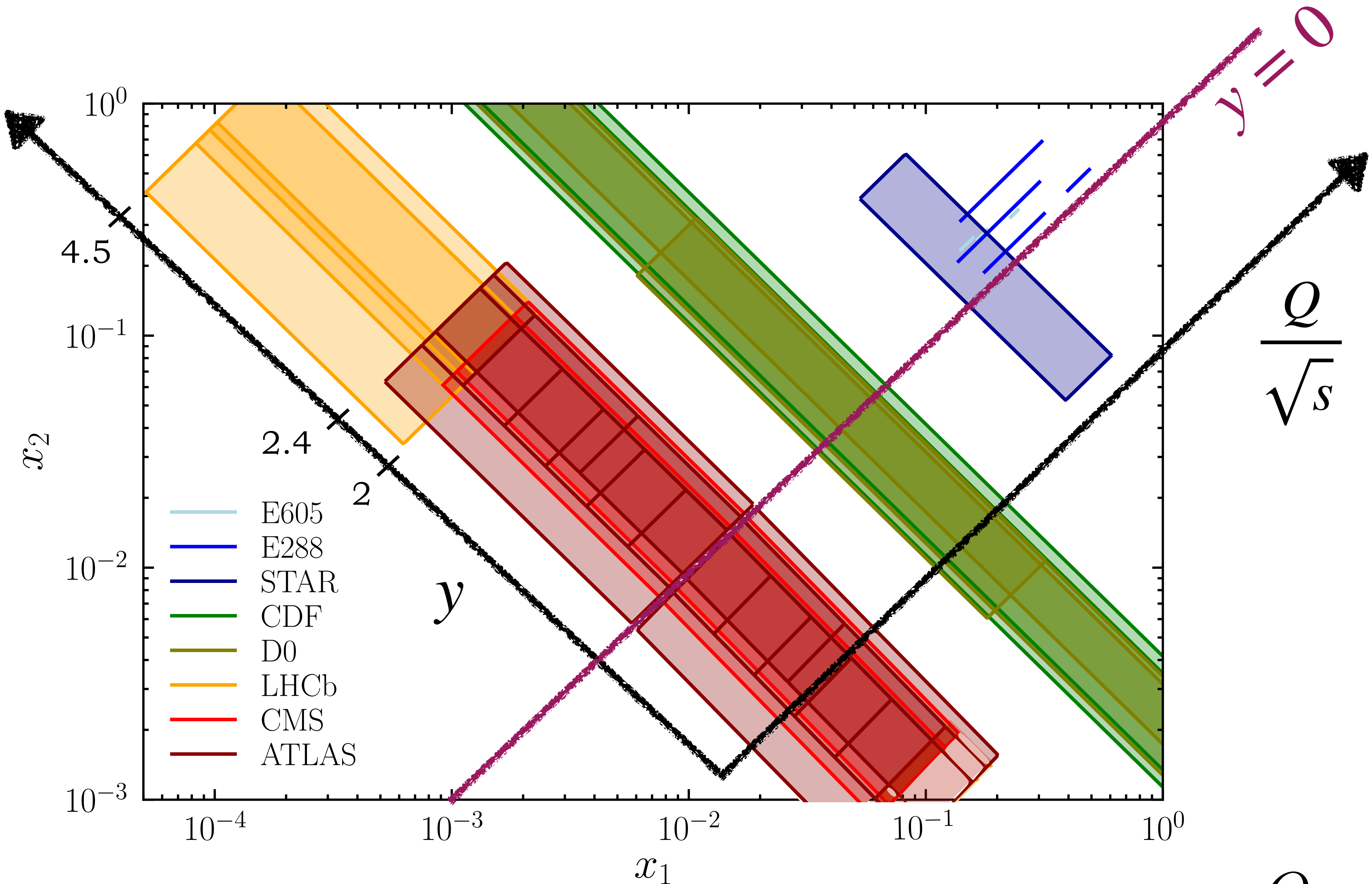
Data



cut at

$$q_T/Q < 0.2$$

x, Q, y coverage



$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y}$$

Experimental uncertainties

$$m_i \pm \sigma_{i,\mathrm{stat}} \pm \sigma_{i,\mathrm{unc}} \pm \sigma^{(1)}_{i,\mathrm{corr}} \pm \cdots \pm \sigma^{(k)}_{i,\mathrm{corr}}$$

uncorrelated | **correlated**

shifted prediction

$$\bar{t}_i = t_i + d_i$$

nuisance parameters

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{m_i - \bar{t}_i}{s_i} \right)^2 + \sum_{\alpha=1}^{k} \lambda_\alpha^2$$

uncorrelated contribution | penalty term

Bertone, Scimemi, Vladimirov
arXiv:1902.08474

Experimental uncertainties

$$m_i \pm \sigma_{i,\mathrm{stat}} \pm \sigma_{i,\mathrm{unc}} \pm \sigma_{i,\mathrm{corr}}^{(1)} \pm \cdots \pm \sigma_{i,\mathrm{corr}}^{(k)}$$

uncorrelated **correlated**

shifted prediction $\bar{t}_i = t_i + d_i$

nuisance parameters

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{m_i - \bar{t}_i}{s_i} \right)^2 + \sum_{\alpha=1}^{k} \lambda_\alpha^2$$

uncorrelated contribution penalty term

we also included **PDF errors** **MMHT2014nnlo**

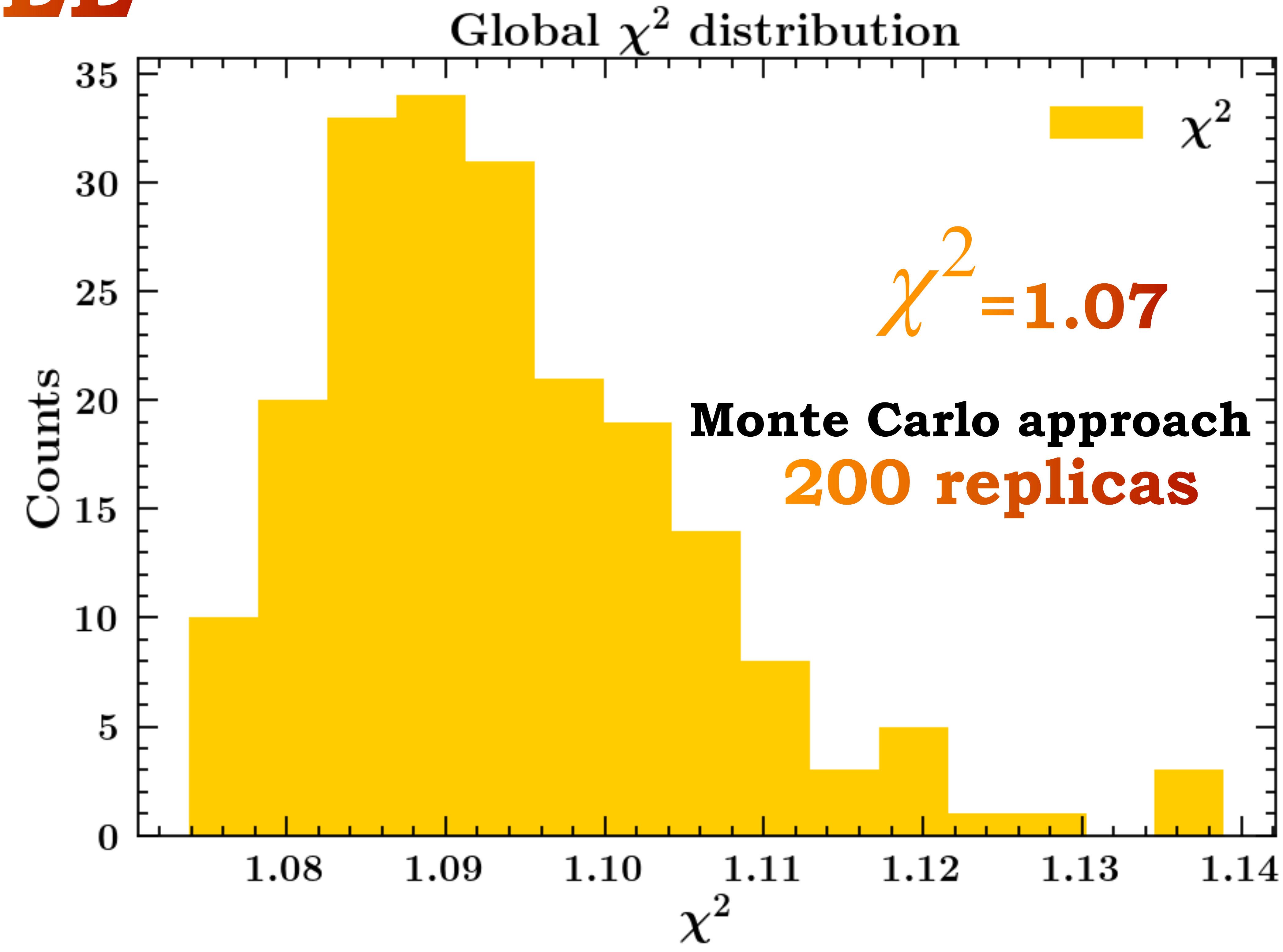
Fit quality
perturbative convergence

also observed by Bertone, Scimemi, Vladimirov
arXiv:1902.08474

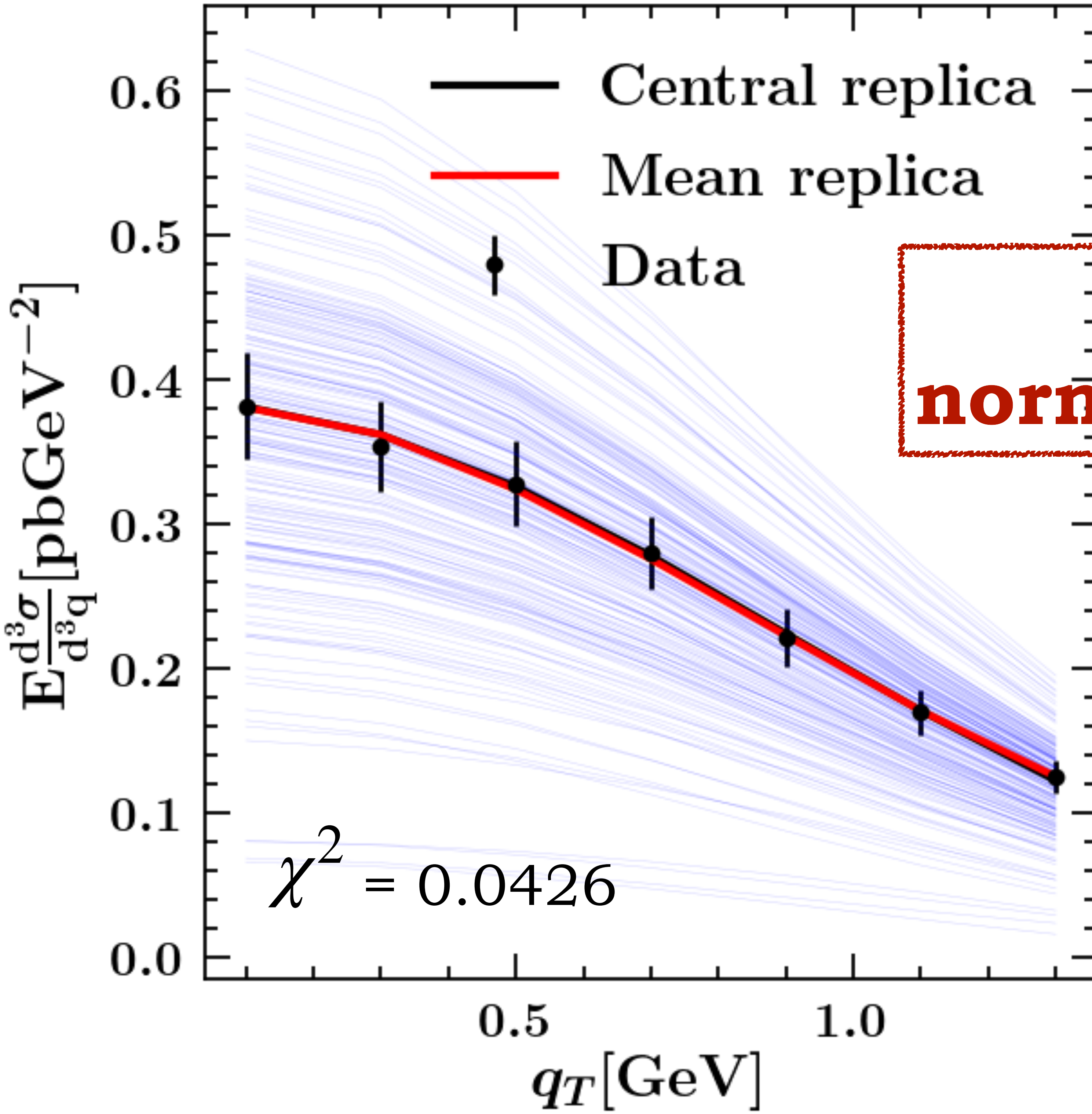
Order	NLL’	NNLL	NNLL’	N3LL
χ_0^2 / n.d.p.	3.2628	1.6686	1.1465	**1.0705**

Global χ^2 as a function of the perturbative accuracy

Fit properties N3LL



Pavia 2019
N3LL



E288

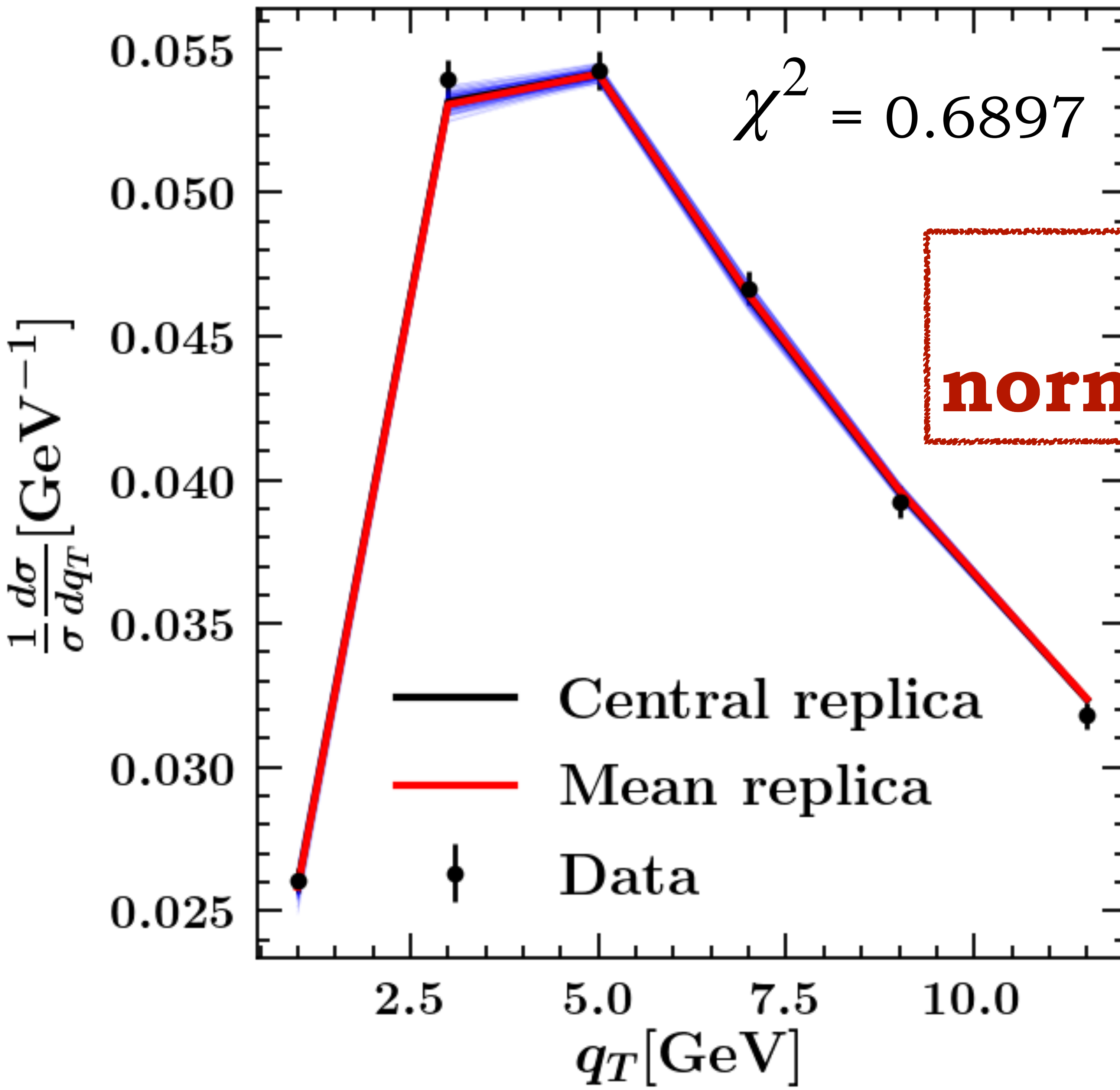
NO normalisation

$\sqrt{s}$ = 27.4 GeV

7<Q<8

Pavia 2019
N3LL

ATLAS 8 TeV
1.6 < |y| < 2

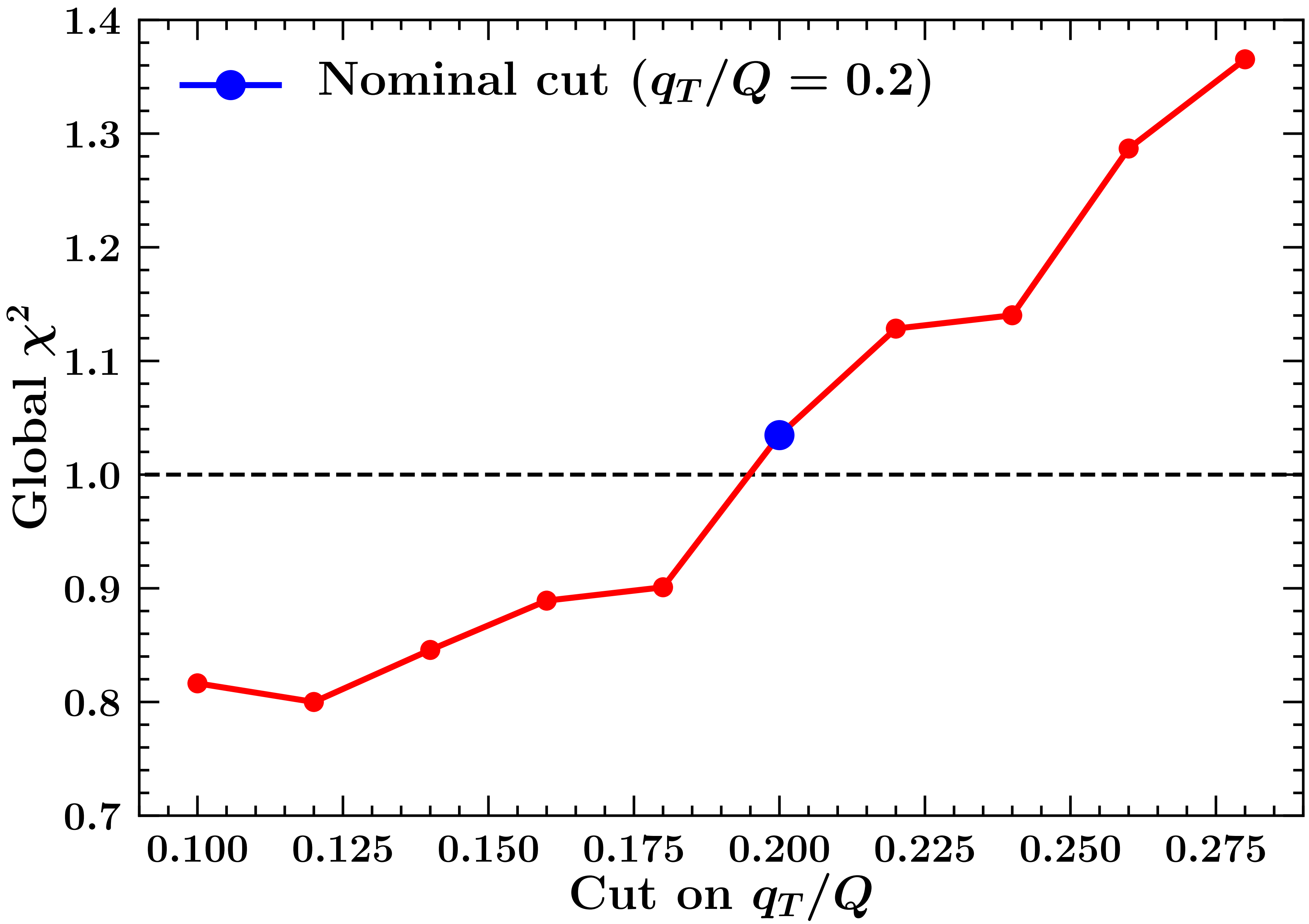


NO normalisation

lepton cuts

on the final-state leptons

Cut on q_T/Q



Nominal cut ($q_T/Q = 0.2$)
Global χ^2
Cut on q_T/Q
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.100
0.125
0.150
0.175
0.200
0.225
0.250
0.275

NangaParbat

Nanga Parbat: a TMD fitting framework

Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

Download

will be **publicly available**

You can obtain NangaParbat directly from the github repository:

based on APFEL++ to extract **TMD PDFs** and **FFs**

Conclusions

- Current precision of data requires the most accurate calculations

  └── perturbative convergence **N3LL**

- A sound treatment of **uncertainties** is also required

  └── correlated systematics,
  PDFs uncertainties

- **Simultaneous** description of low- and high-energy data with

  NO normalisation coefficients

Backup

TMDs
factorisation

$$\frac{d\sigma}{dQ\,dy\,dq_T} = \frac{16\pi\alpha^2 q_T \mathcal{P}}{9Q^3} H(Q,\mu) \sum_q c_q(Q) \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} x_1 F_q(x_1,\mathbf{b};\mu,\zeta_1) x_2 F_{\bar{q}}(x_2,\mathbf{b};\mu,\zeta_2)$$

$$F_f(x,\mathbf{b};\mu,\zeta) = \sum_j \left(C_{f/j} \otimes f^j\right)(x,b_*;\mu_b)\, e^{R(b_*;\mu_b,\mu)} f_{\mathrm{NP}}(x,b,\zeta)$$

scales

$$\mu = Q \qquad\qquad \zeta_1 = \zeta_2 = Q^2$$

TMDs

factorises as hard
and longitudinal non-perturbative

matching to the
collinear region

$b_T \ll 1/\Lambda_{QCD}$

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

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

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

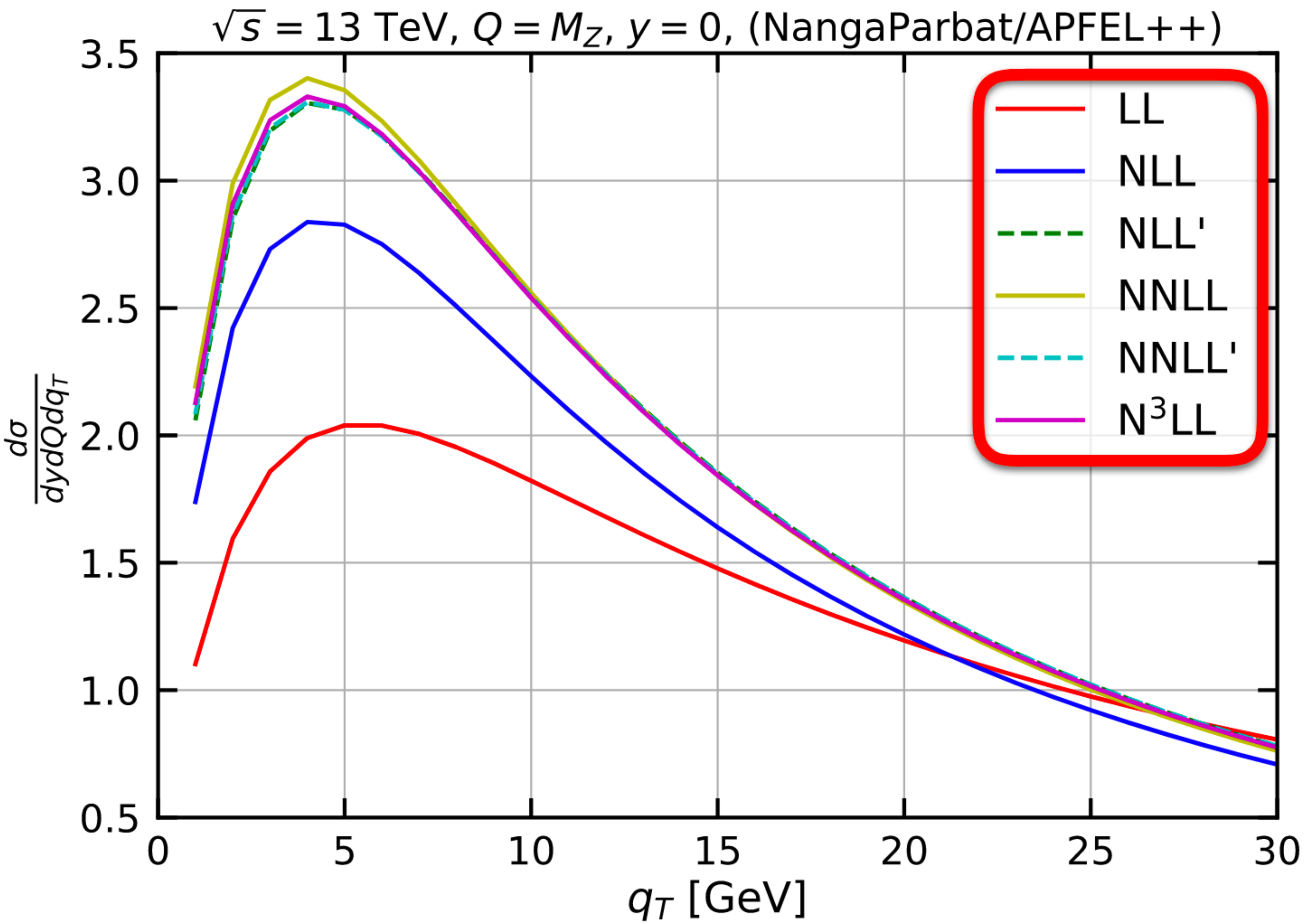
CS and RGE
evolution

non perturbative
transverse content

parametrised
and **fitted to data**

slide from V. Bertone

Higher-order corrections
comparison of different orders



Mathematical tools

integrations

$$\sigma = \int_{Q_{\min}}^{Q_{\max}} dQ \int_{y_{\min}}^{y_{\max}} dy \int_{q_{T,\min}}^{q_{T,\max}} dq_T \left[\frac{d\sigma}{dQ dy dq_T} \right]$$

no narrow-width approximation

integration over the range in boson rapidity

integration over bins in q_T

lepton cuts

on the final-state leptons

Lepton cuts

on the final-state leptons

η lepton rapidity

ATLAS

$|\eta| \leq 2.4$

CMS

$|\eta| \leq 2.1$

LHCb

$2 \leq |\eta| \leq 4.5$

$$p_t \geq 20 \quad \text{GeV}$$

phase-space reduction factor

$$\mathcal{P}(Q, y, q_T) = \frac{\displaystyle\int_{\text{fid. reg.}} d\Omega \quad g_\perp^{\mu\nu} L_{\mu\nu}}{\displaystyle\int d\Omega \quad g_\perp^{\mu\nu} L_{\mu\nu}}$$

Experimental uncertainties

$$m_i \pm \sigma_{i,\text{stat}} \pm \sigma_{i,\text{unc}} \pm \sigma_{i,\text{corr}}^{(1)} \pm \cdots \pm \sigma_{i,\text{corr}}^{(k)}$$

uncorrelated **correlated**

additive multiplicative

$$\chi^2 = \sum_{i,j=1}^{n} (m_i - t_i)\, V_{ij}^{-1}\, (m_j - t_j)$$

$$\sigma_{i,\text{corr}}^{(l)} \equiv \delta_{i,\text{corr}}^{(l)} m_i$$

covariance matrix

$$V_{ij} = s_i^2 \delta_{ij} + \left(\sum_{l=1}^{k_a} \delta_{i,\text{add}}^{(l)} \delta_{j,\text{add}}^{(l)} + \sum_{l=1}^{k_m} \delta_{i,\text{mult}}^{(l)} \delta_{j,\text{mult}}^{(l)} \right) m_i m_j$$

Bertone, Scimemi, Vladimirov
arXiv:1902.08474

Chisquare

systematic shift

$$d_i = \sum_{\alpha=1}^{k} \lambda_\alpha \sigma_{i,\mathrm{corr}}^{(\alpha)}$$

$$\frac{\partial \chi^2}{\partial \lambda_\alpha} = 0$$

nuisance parameters

$$\bar{t}_i = t_i + d_i$$ shifted prediction

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{m_i - \bar{t}_i}{s_i} \right)^2 + \sum_{\alpha=1}^{k} \lambda_\alpha^2$$

recover the form of
the uncorrelated definition

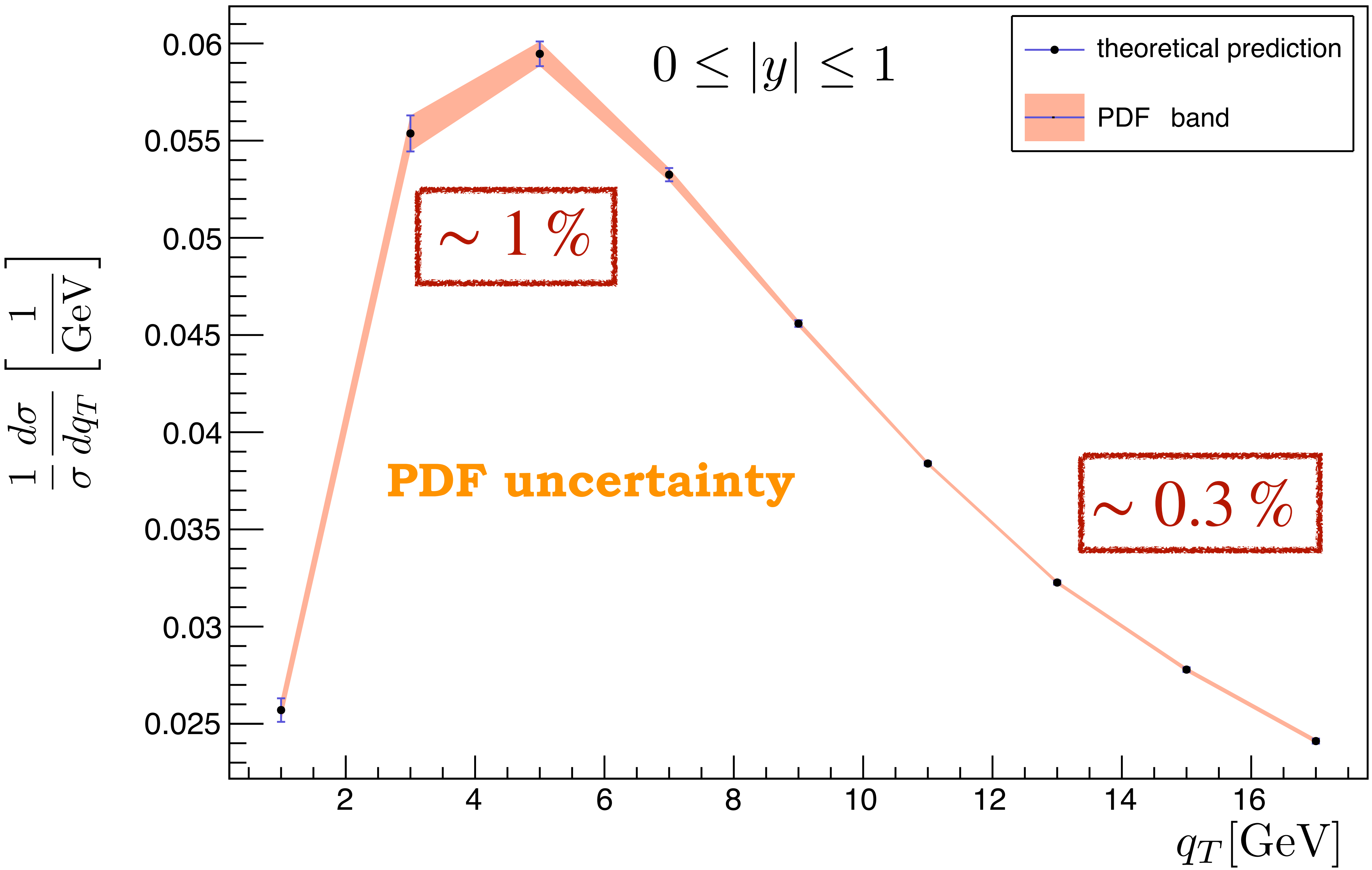
penalty term

Hessian method

MMHT2014@nlo

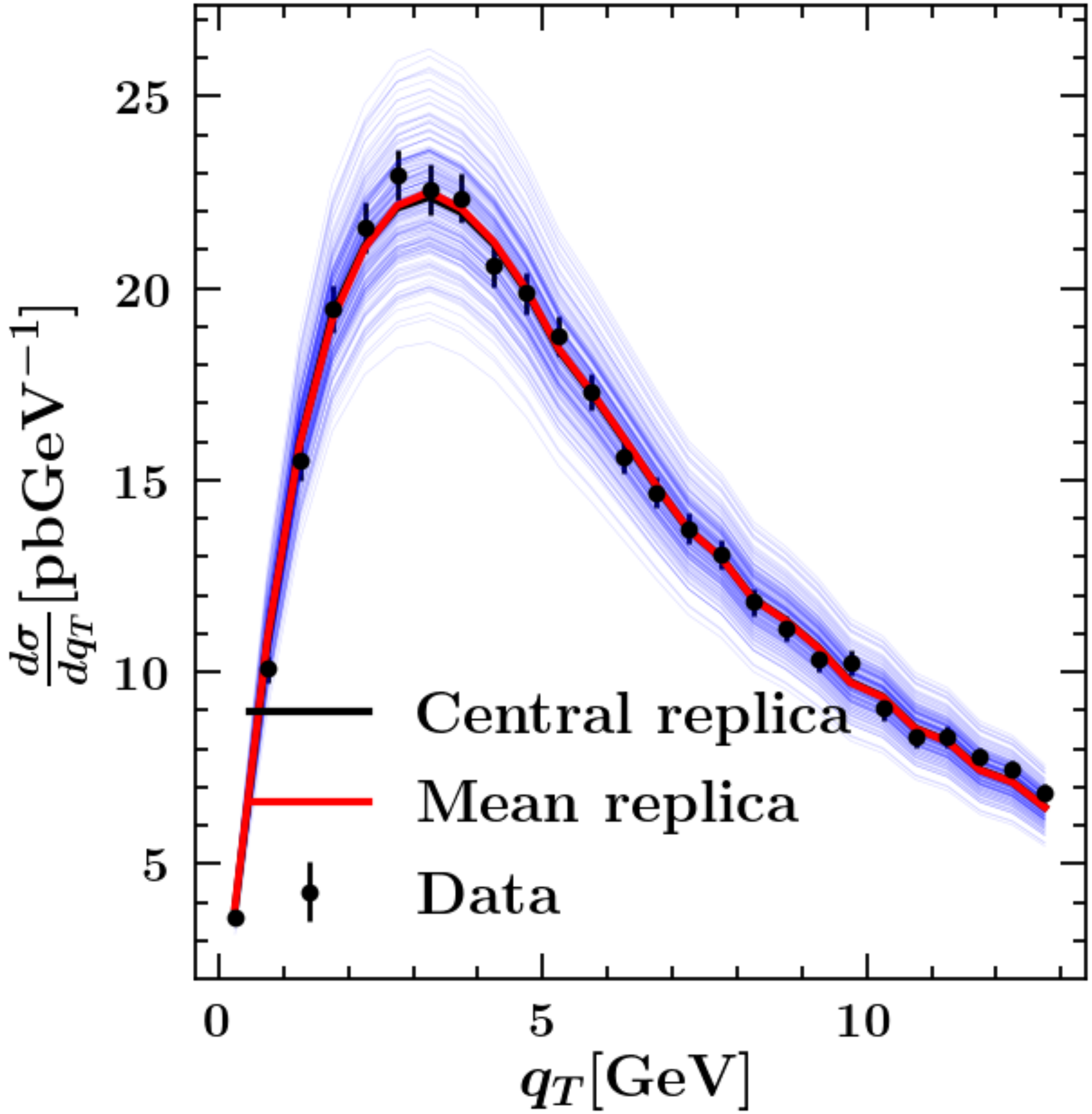
NNLL

[ATLAS 7 TeV]



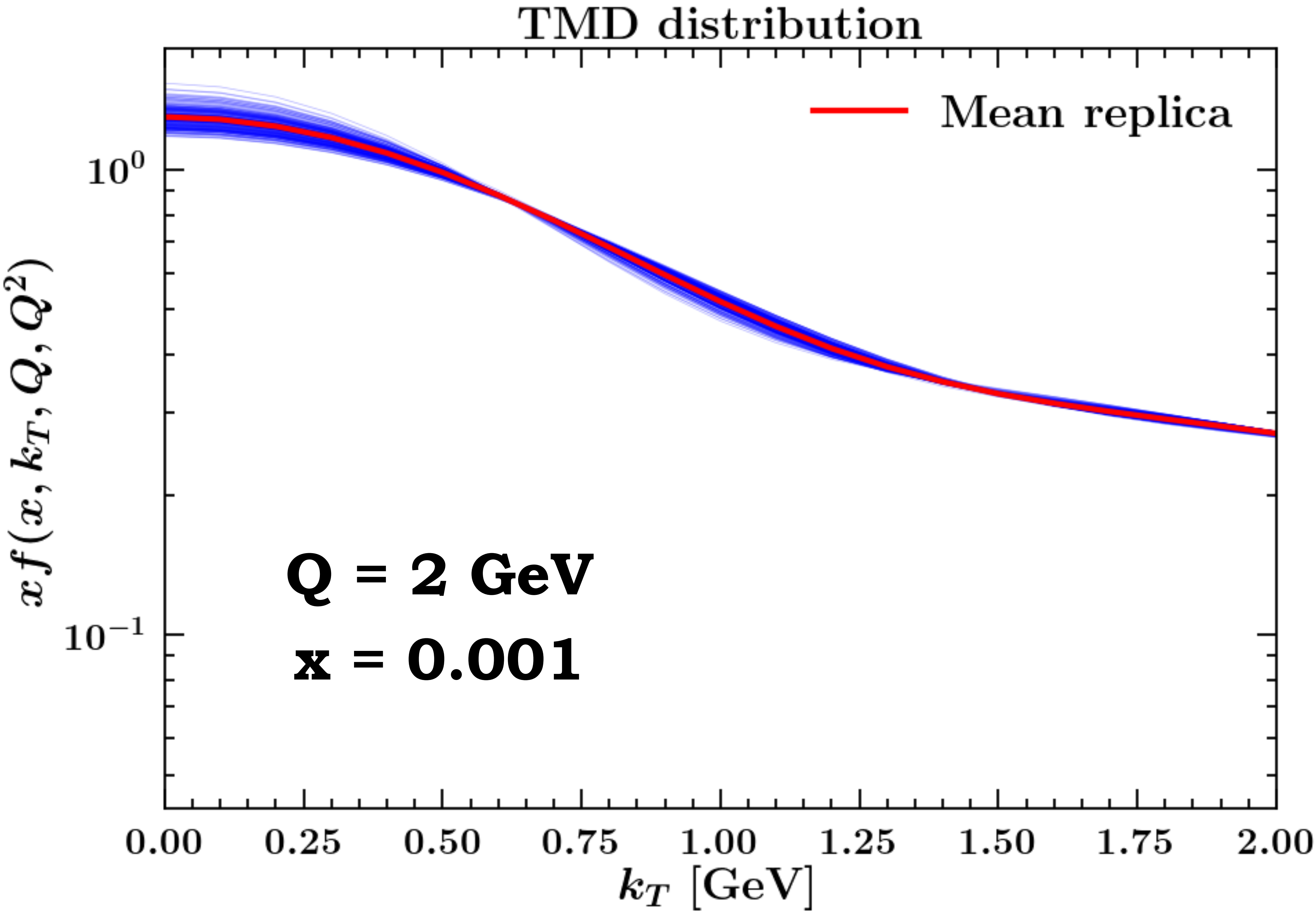
Pavia 2019

N3LL

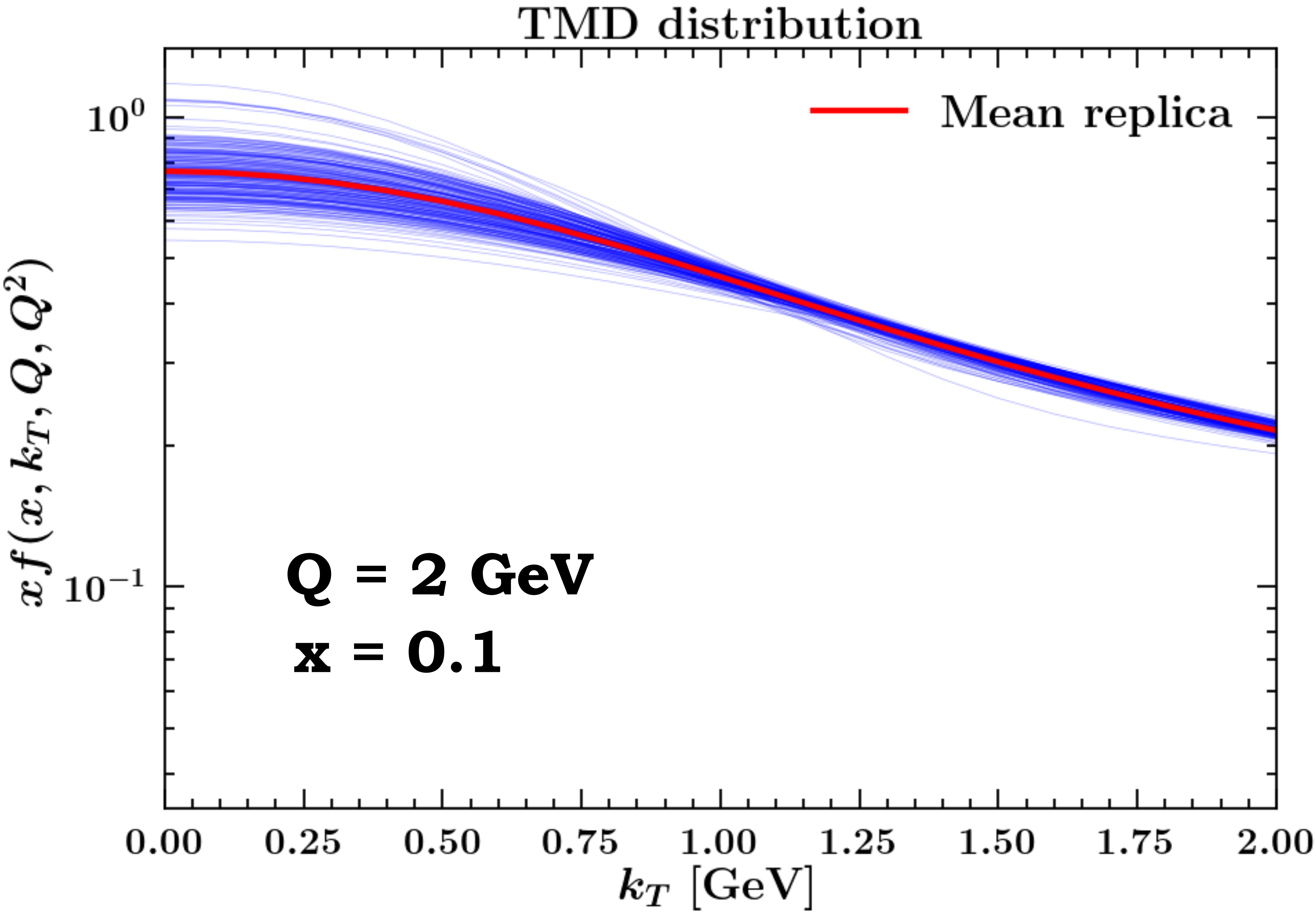


CDF Run II

TMDs in k_T space



TMDs in k_T space



Pavia 2017
global fit

Bacchetta, Delcarro, Pisano, Radici, Signori
arXiv:1703.10157

NLL

with normalisation coefficients

BSV 2019
Drell-Yan fit

Bertone, Scimemi, Vladimirov
arXiv:1902.08474

NNLL'

different framework