Università degli Studi di Milano

INFN Istituto Nazionale di Fisica Nucleare

MW determination at hadron colliders: update from the Milan meeting, proposal of a new observable

Alessandro Vicini
Università di Milano and INFN Milano

Orsay, February 23rd 2023

based on: L.Rottoli, P.Torrielli, AV, arXiv:2301.04059

Precision calculations for Drell-Yan processes, Milano November 21-22 2022

https://indico.cern.ch/event/1194218/

1/3 of the 38 registered participants age<35

Precision calculations for Drell-Yan processes / Programme — Monday, 21 November 2022

Monday, 21 November 2022

Description of the Drell-Yan kinematical distributions: QCD results - V10 room, settore didattico (09:25 - 13:00)

time	[id] title	presenter
09:30	[12] Welcome	VICINI, Alessandro
09:35	[1] Fixed-order QCD prediction of Drell-Yan observables	CHEN, Xuan
10:15	[2] QCD resummation effects on Drell-Yan observables	NEUMANN, Tobias
11:00	Coffee break	
11:15	[4] MW determination at hadron collides: theoretical uncertainties from PDFs and QCD modelling	BOZZI, Giuseppe

Lunch break - V10 room, settore didattico (13:00 - 14:30)

Description of Drell-Yan kinematical distributions: EW and mixed EW-QCD corrections - V10 room, settore didattico (14:30 - 18:40)

time	[id] title	presenter
15:10	[11] Bottom quark effects in the ptZ spectrum and the MW determination	BAGNASCHI, Emanuele Angelo ZARO, Marco
16:10	[8] Electroweak corrections to Drell-Yan processes and MW determination	CHIESA, Mauro
17:10	[9] Mixed QCD-EW corrections and MW determination	RONTSCH, Raoul Horst

Precision calculations for Drell-Yan processes / Programme — Tuesday, 22 November 2022

Tuesday, 22 November 2022

Fitting methodologies - V10 room, settore didattico (09:30 - 13:00)

time	[id] title	presenter
09:30	[5] Summary of the CDF procedures	NEUMANN, Tobias
10:30	[7] Comments on the determination of a model parameter from kinematical distributions	BAGNASCHI, Emanuele Angelo
11:30	[3] The ptW/ptZ ratio and the MW determination	FERRERA, Giancarlo FERRERA, Giancarlo
12:30	[13] Concluding remarks	VICINI, Alessandro

Discussion on the theoretical uncertainties on MW - V10 room, settore didattico (14:30 - 17:30)

time	[id] title	presenter
14:30	[10] Free discussions	ALL

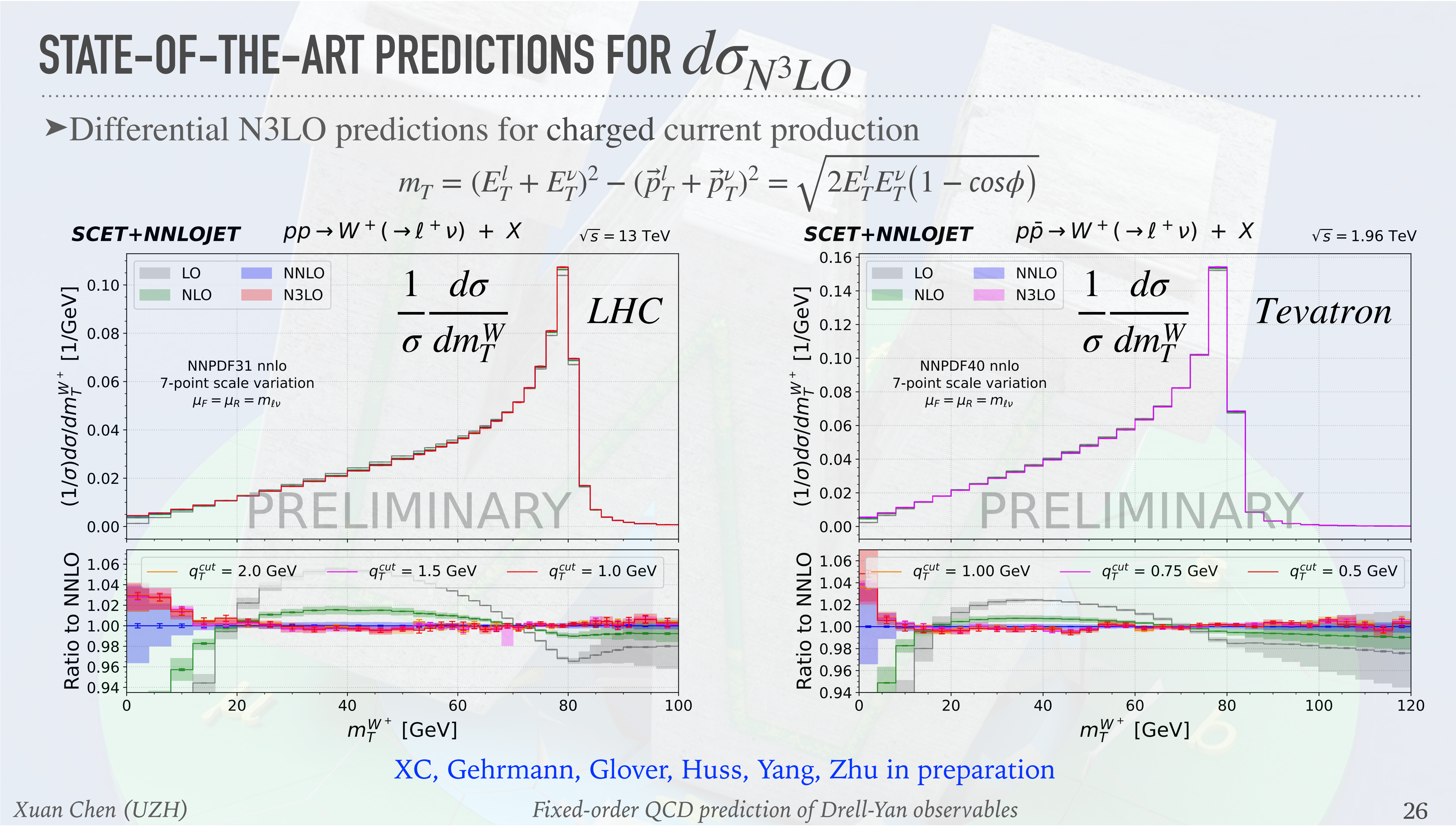
What is the status of the precision calculations for the Drell-Yan processes?

How can an improvement in the precision of the predictions impact the precision determination of m_W ?

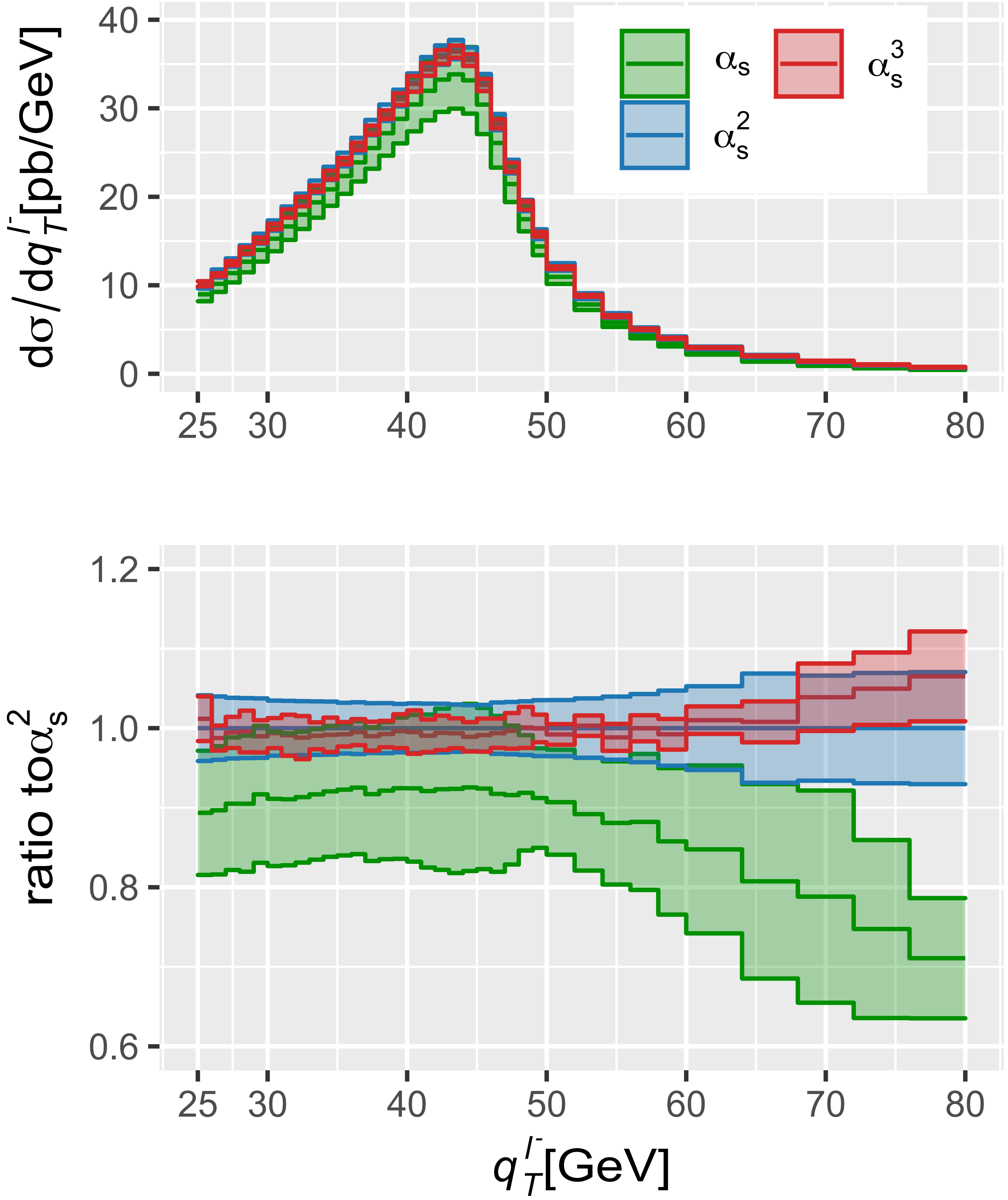
Marginal discussion about the PDF problem, focus mostly on the recent perturbative calculations

Precision calculations for Drell-Yan processes, Milano November 21-22 2022

X.Chen

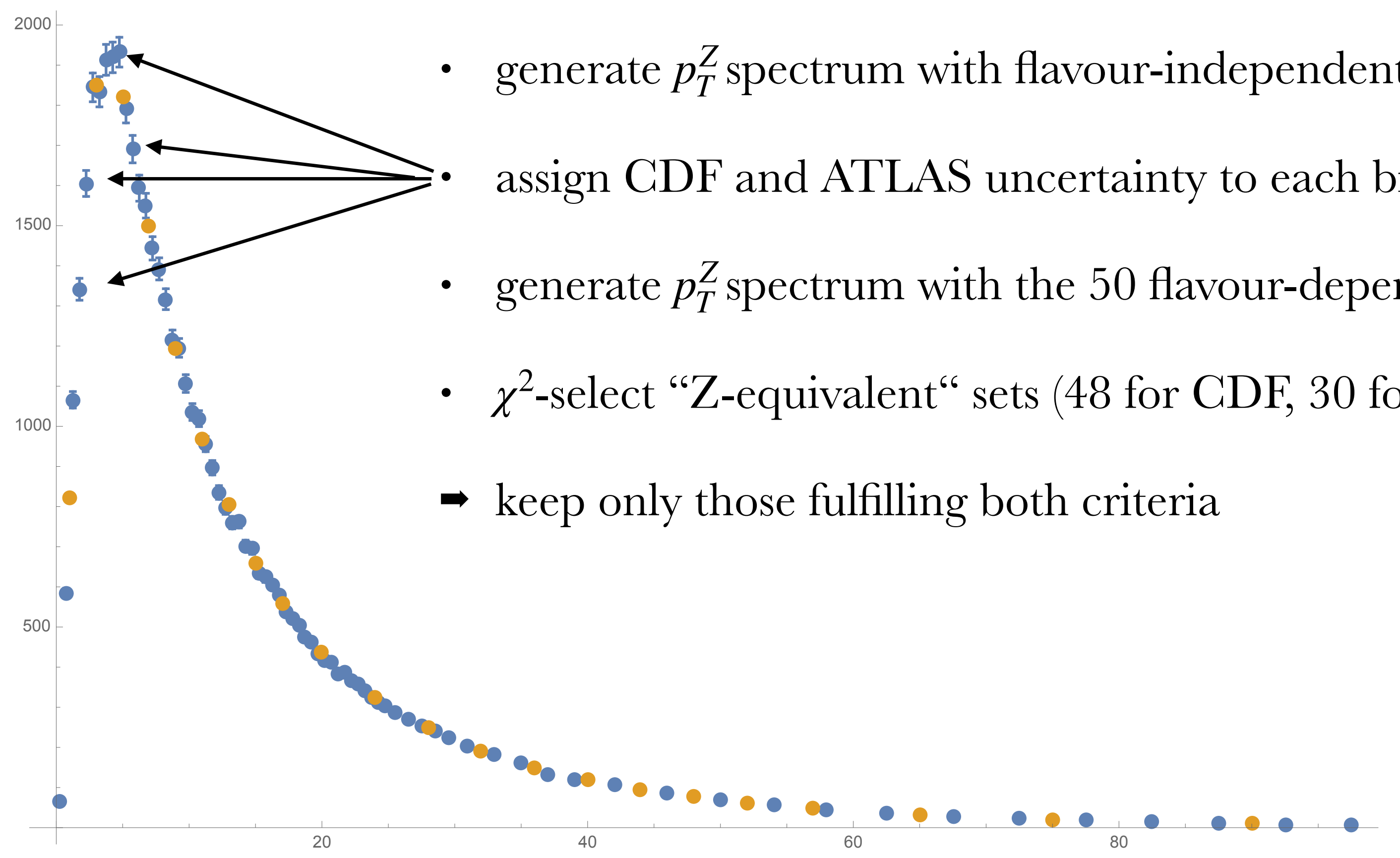


T.Neumann



"Z-equivalent" sets

G.Bozzi



- generate p_T^Z spectrum with flavour-independent set
- assign CDF and ATLAS uncertainty to each bin
- generate p_T^Z spectrum with the 50 flavour-dependent sets
- χ^2-select "Z-equivalent" sets (48 for CDF, 30 for ATLAS)
- ➡ keep only those fulfilling both criteria

Bacchetta, Bozzi, Radici, Ritzmann, Signori
PLB 788, 542 (2019)

Several observables include now third order corrections in α_s

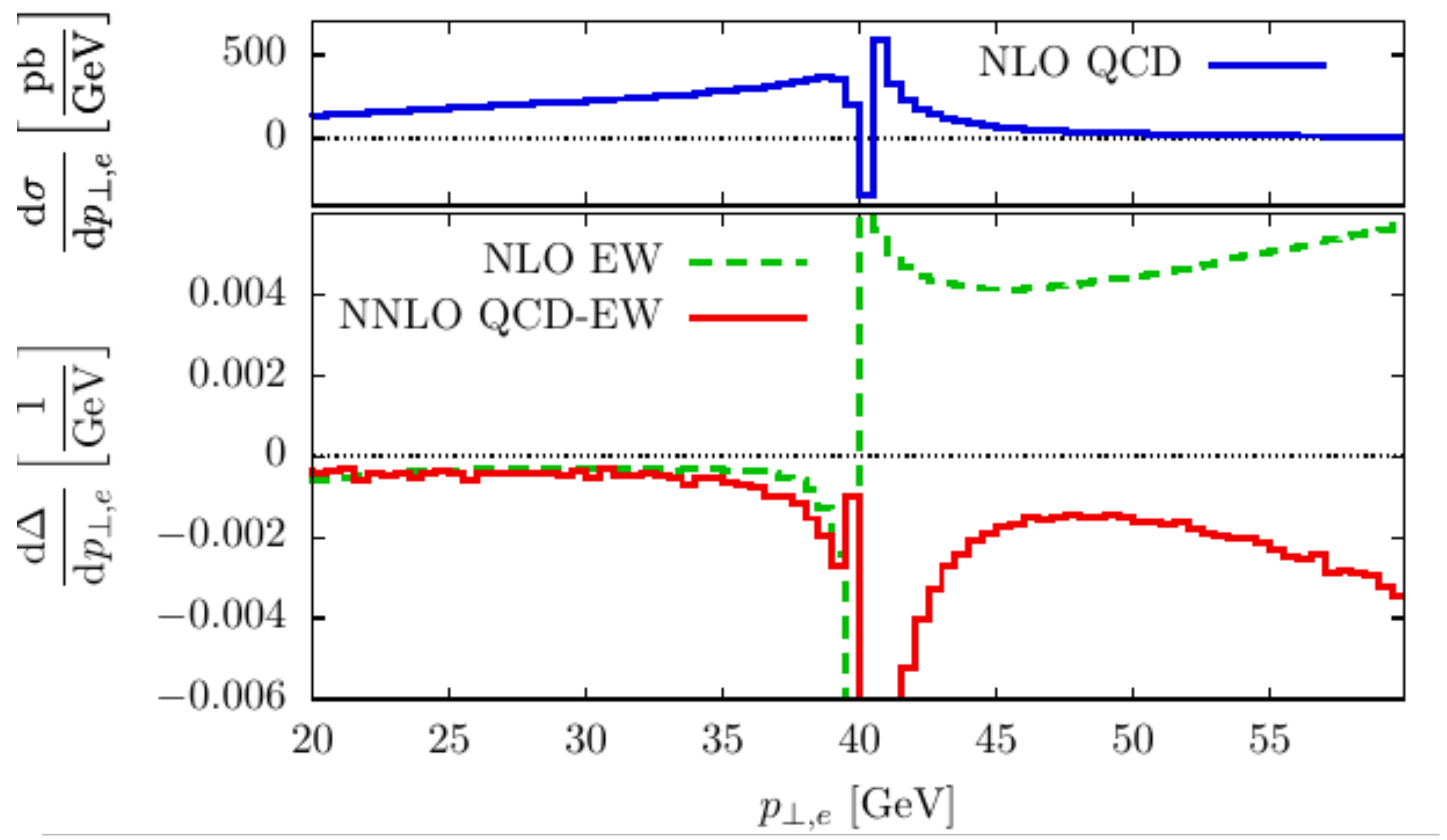
The non-perturbative contributions can be studied in a more constrained theoretical framework

Precision calculations for Drell-Yan processes, Milano November 21-22 2022

M.Chiesa

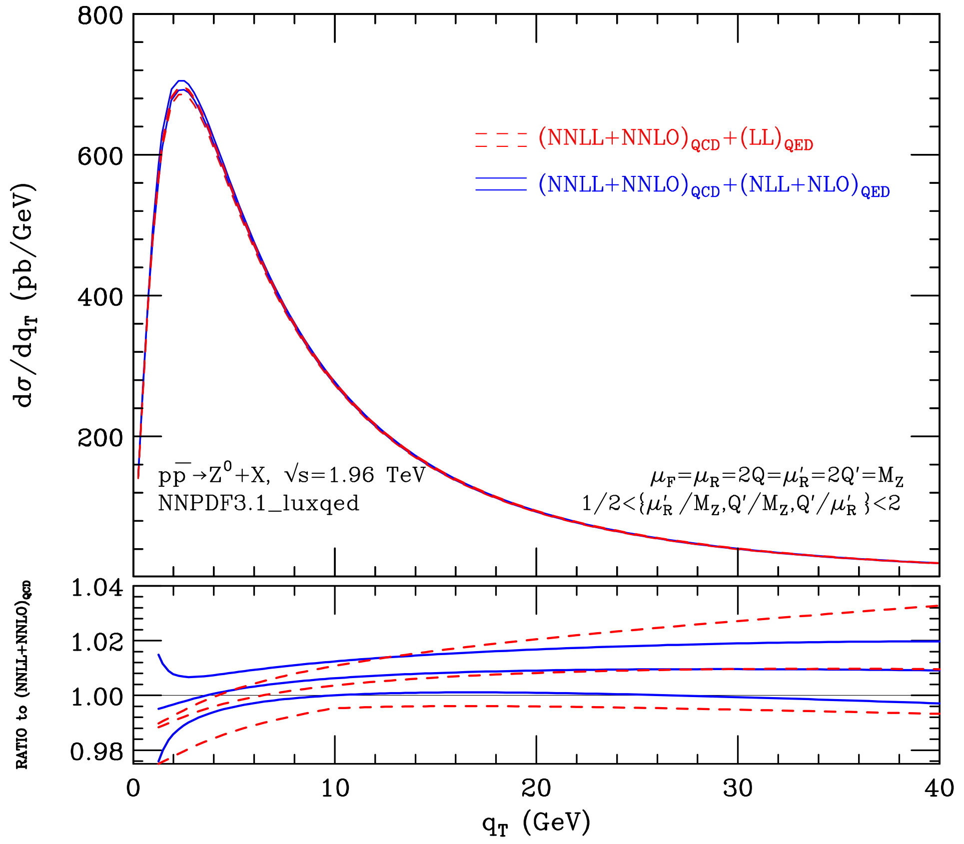
- approximated factorized mixed QCD-EW corrections VS $\alpha\alpha_S$ corrections: theory uncertainties in MC generators at NLO QCD+NLO EW matched to QED and QCD PS
- estimate of QED, weak, and mixed corrections: how do they change when changing the IS QCD modeling? (use different shower MCs, different tunes,...)
- uncertainties from QED PS (H.O. qed): comparing other QED showers
- impact of pair radiation: possible interplay with IS QCD modeling
- estimate of missing NNLO EW corrections: input parameter scheme variations? Interplay with QCD? Other possible estimates?

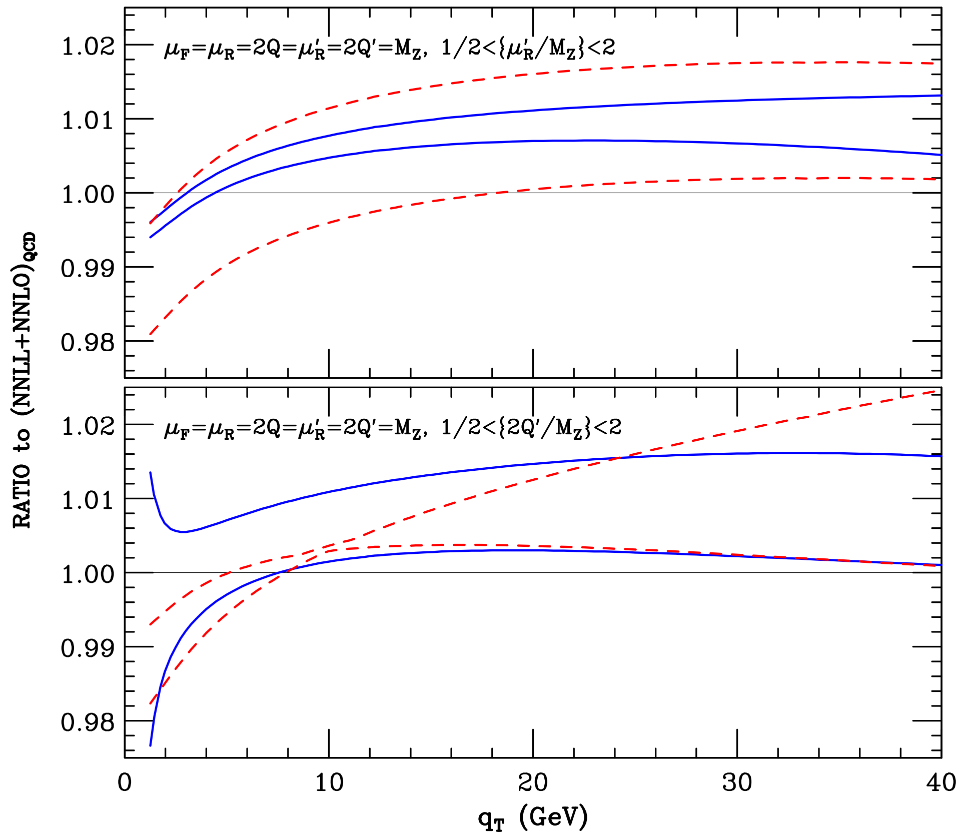
R.Röntsch



G.Ferrera

Combined QED and QCD q_T resummation for Z production at the Tevatron [Cieri,G.F.,Sborlini ('18)]





The impact of purely EW corrections can be better understood

The mixed QCD-EW corrections play an important role closely entangled with the modelling of the QCD contributions

Precision calculations for Drell-Yan processes, Milano November 21-22 2022

- The theoretical progress in the prediction of the kinematical distributions must be matched with a corresponding progress in the procedures adopted to determine m_W from the distributions

- The transfer of such progress to the generation of events is still an issue for the highest precision

- Similar discussions at the workshop "GEARING UP FOR HIGH-PRECISION LHC PHYSICS" https://www.munich-iapbp.de/hp-lhc-physics2022

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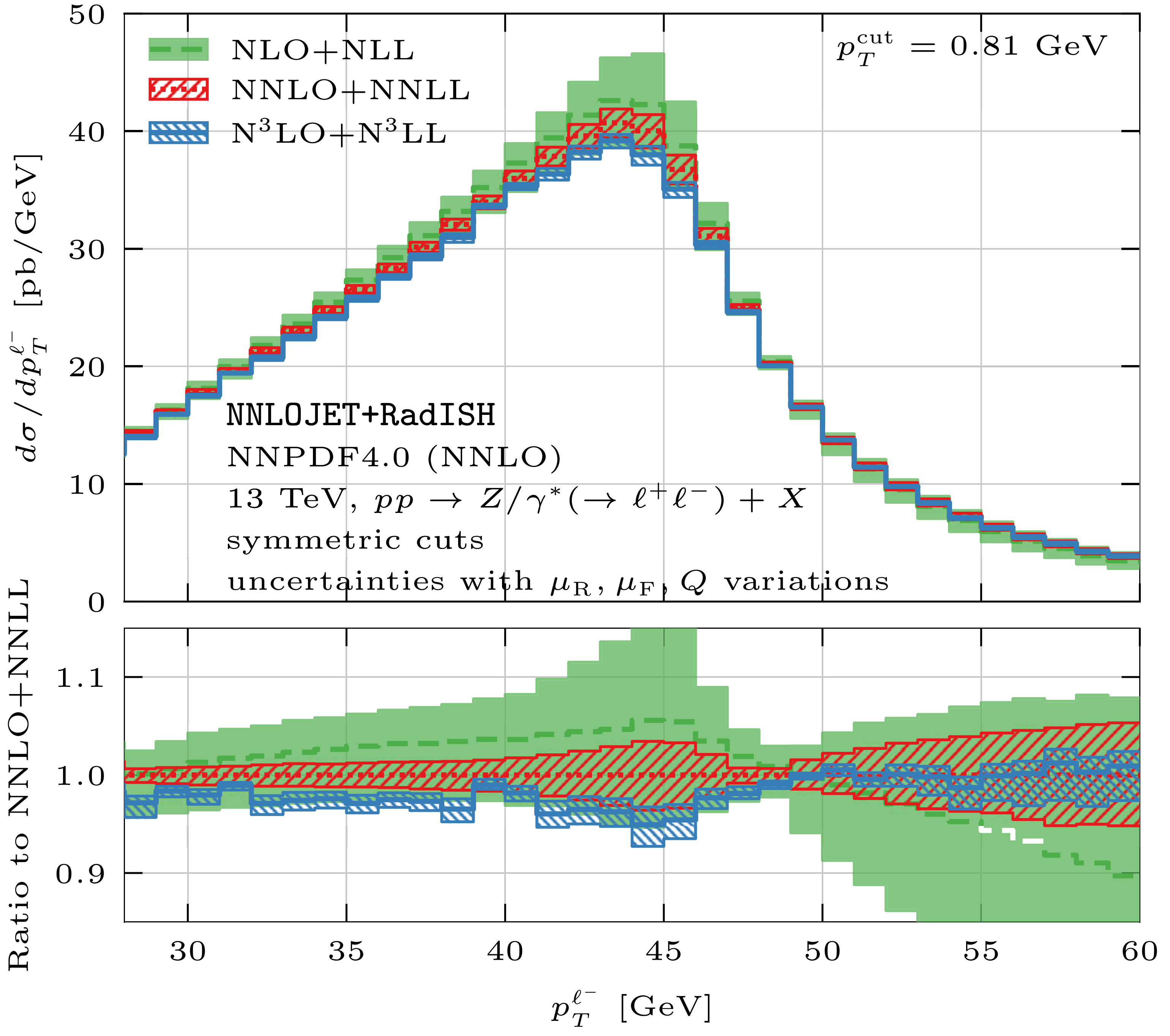
Template fitting: description of the single lepton transverse momentum distribution

The template fitting procedure is acceptable if the data are described by the theoretical distribution with high quality

X.Chen, T.Gehrmann, N.Glover, A.Huss, P.Monni, E.Re, L.Rottoli, P.Torrielli, arXiv:2203.01565



Scale variation of the N3LO+N3LL prediction for ptlep provides a set of equally good templates
but the width of the uncertainty band is at the few percent level
a factor 10 larger than the naive estimate would require !

$\longrightarrow$ data driven approach

a Monte Carlo event generator is tuned to the data in NCDY ($p_\perp^Z$)

$\downarrow$

the same parameters are then used to prepare the CCDY templates

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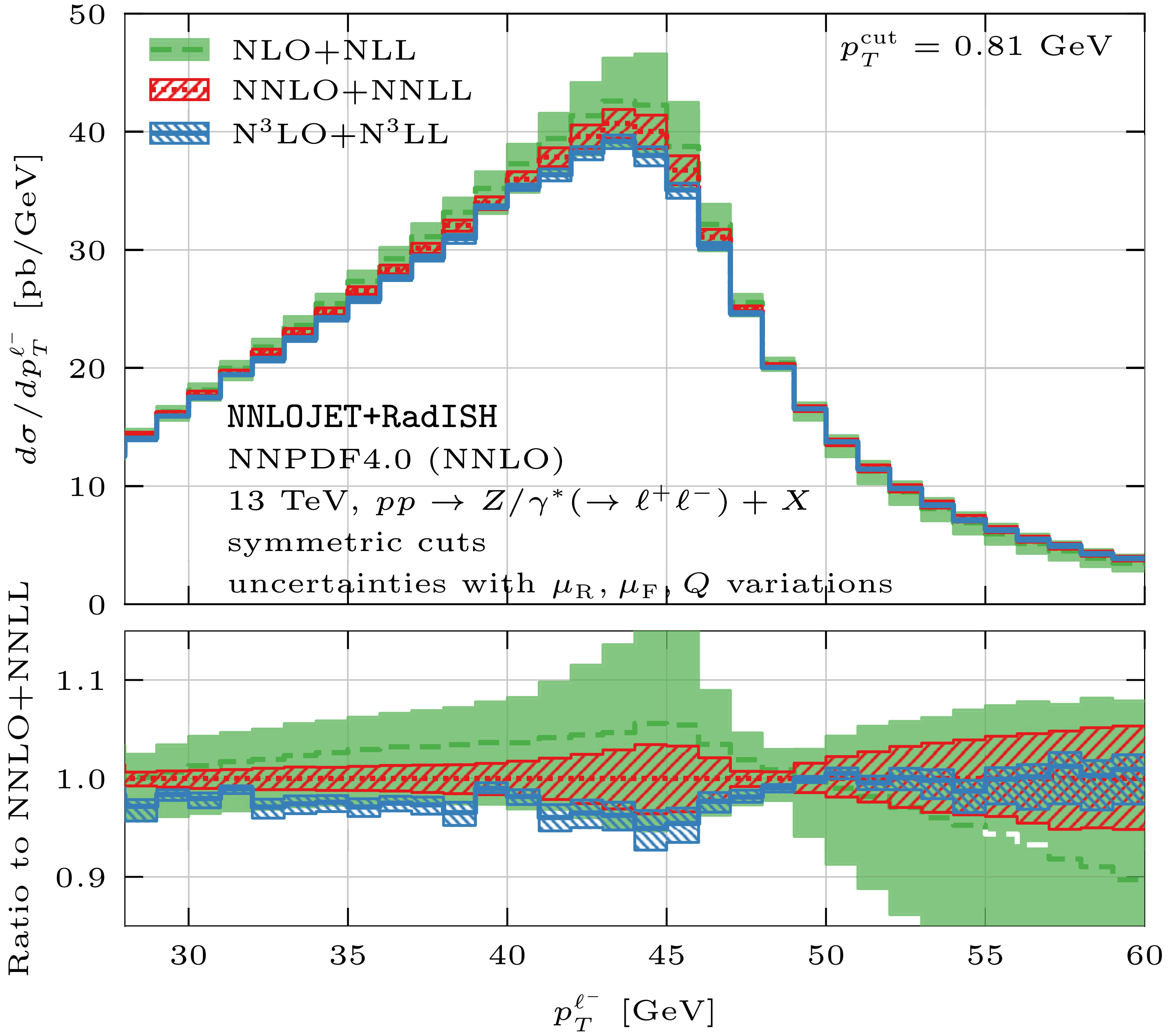

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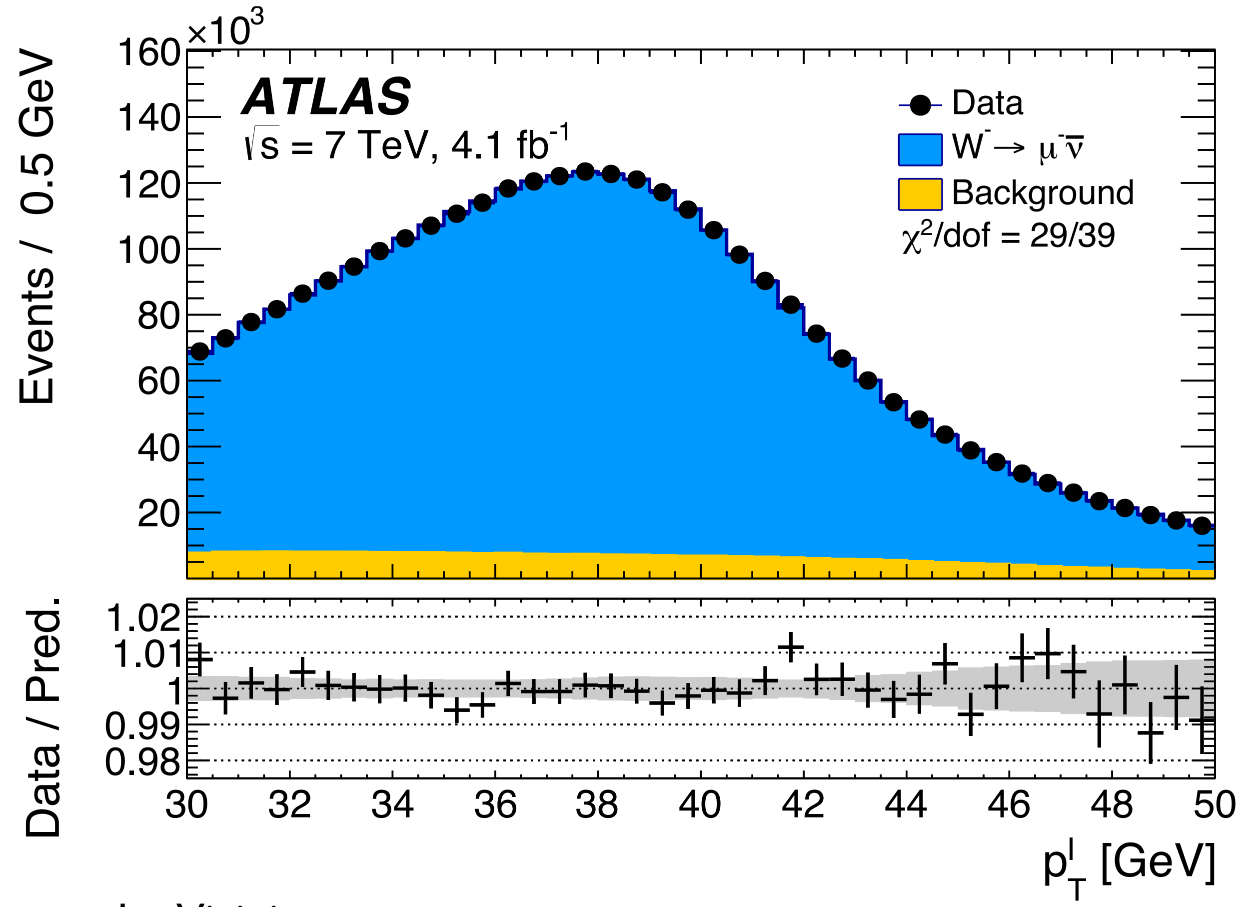
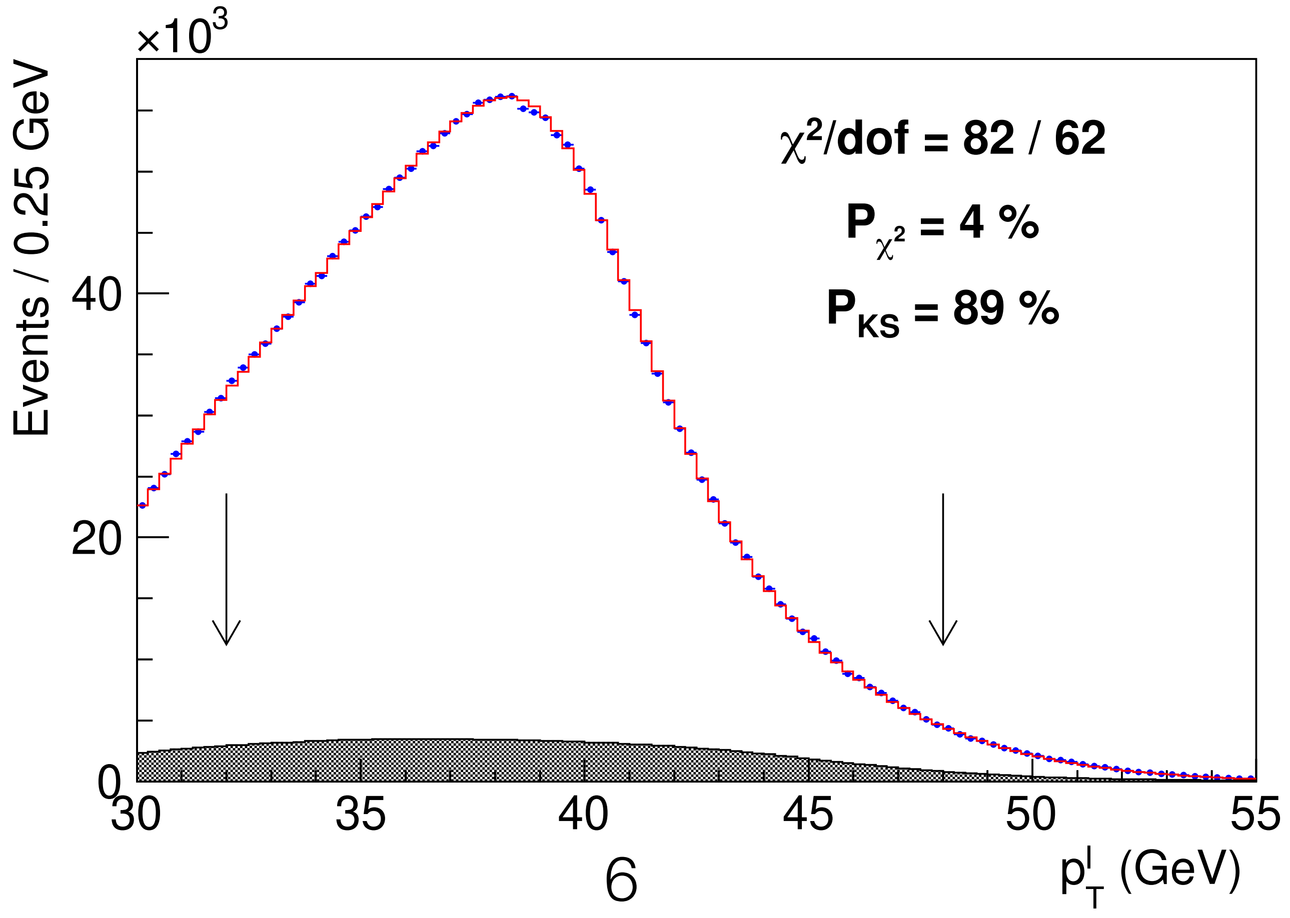
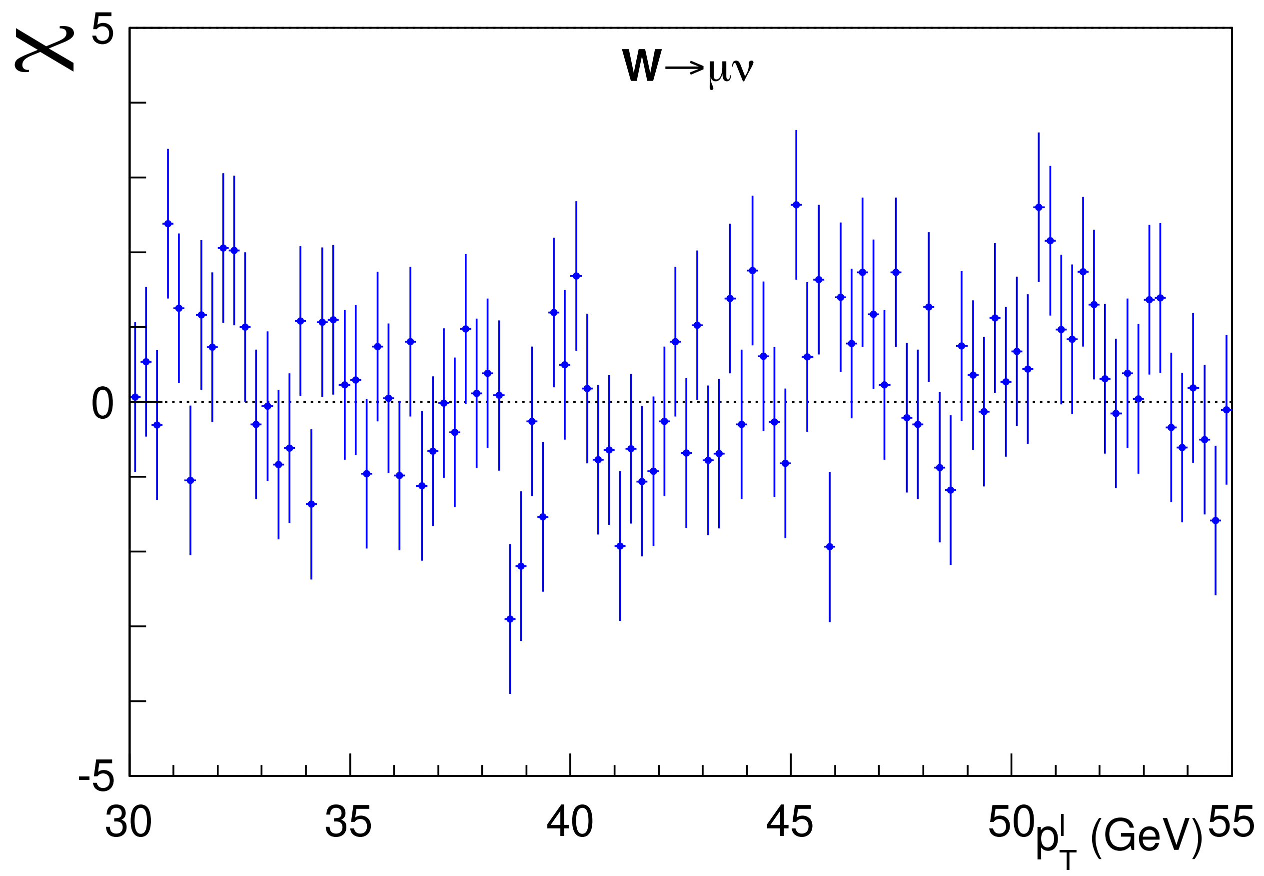
Eur.Phys.J.C 78 (2018) 2, 110, *Eur.Phys.J.C* 78 (2018) 11, 898 (erratum)



CDF collaboration, Scince 376, 170-176 (2022)





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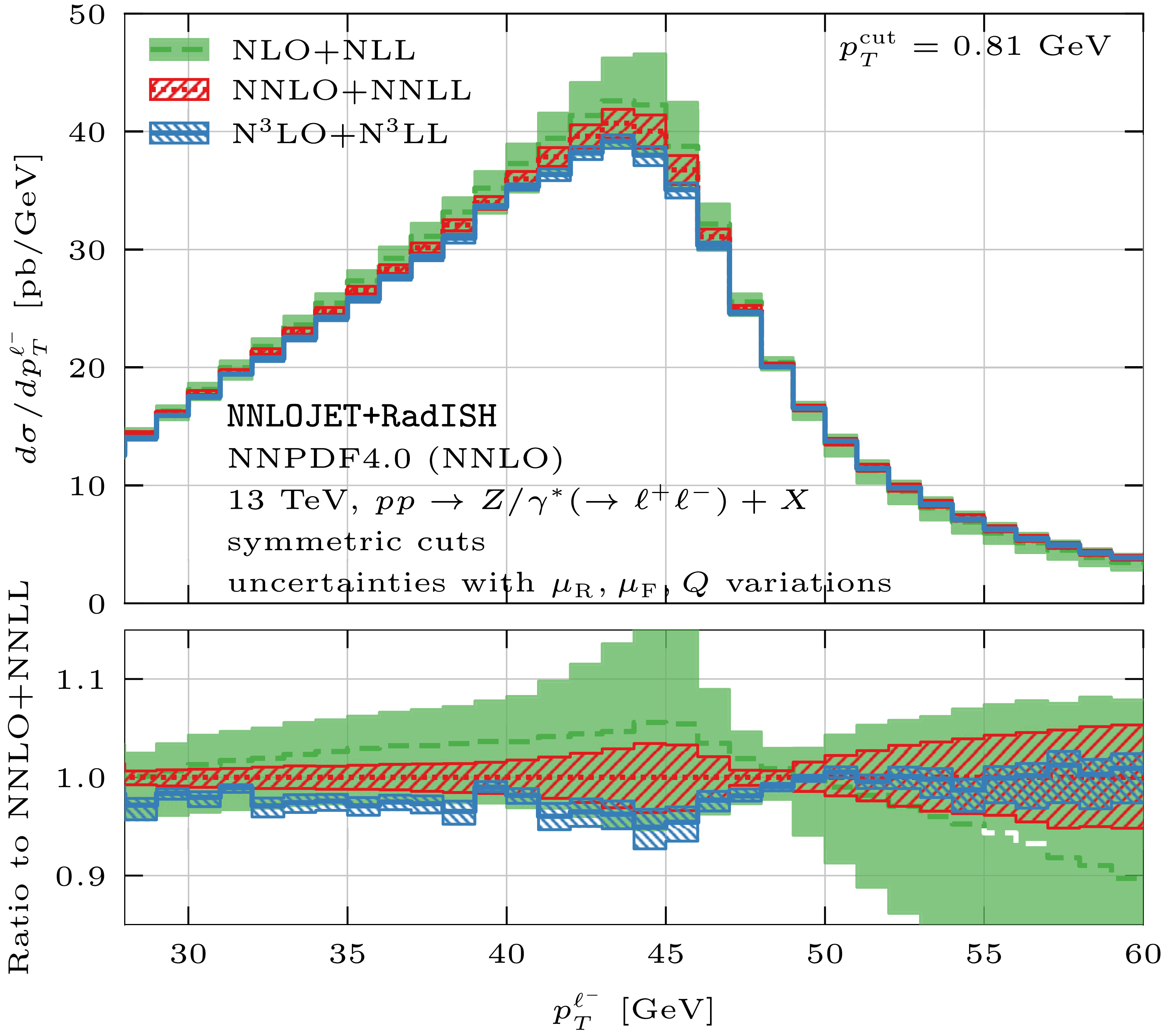

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→ data driven approach

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↓

the same parameters are then used to prepare the CCDY templates

What are the limitations of the transfer of information from NCDY to CCDY ?

Comments on the data driven approach

- The Monte Carlo event generators typically have NLO+(N)LL QCD perturbative accuracy
  $\rightarrow$ they might require a reweighing factor to match the data larger than a code N3LO+N3LL

- The tuning to the data should be done in association to QCD scale variations
  $\rightarrow$ starting from different pQCD scale choices, we can achieve by construction the same description of NCDY
  with different reweighing functions
  but
  we should check how the different alternatives behave when applied to CCDY

- The tuning assumes that the missing factor taken from the data is universal, i.e. identical for NCDY and CCDY
  but
  several elements of difference:
  - masses and phase-space factors, acceptances
  - different electric charges (QED corrections)
  - different initial states ($\rightarrow$ PDFs, heavy quarks effects)

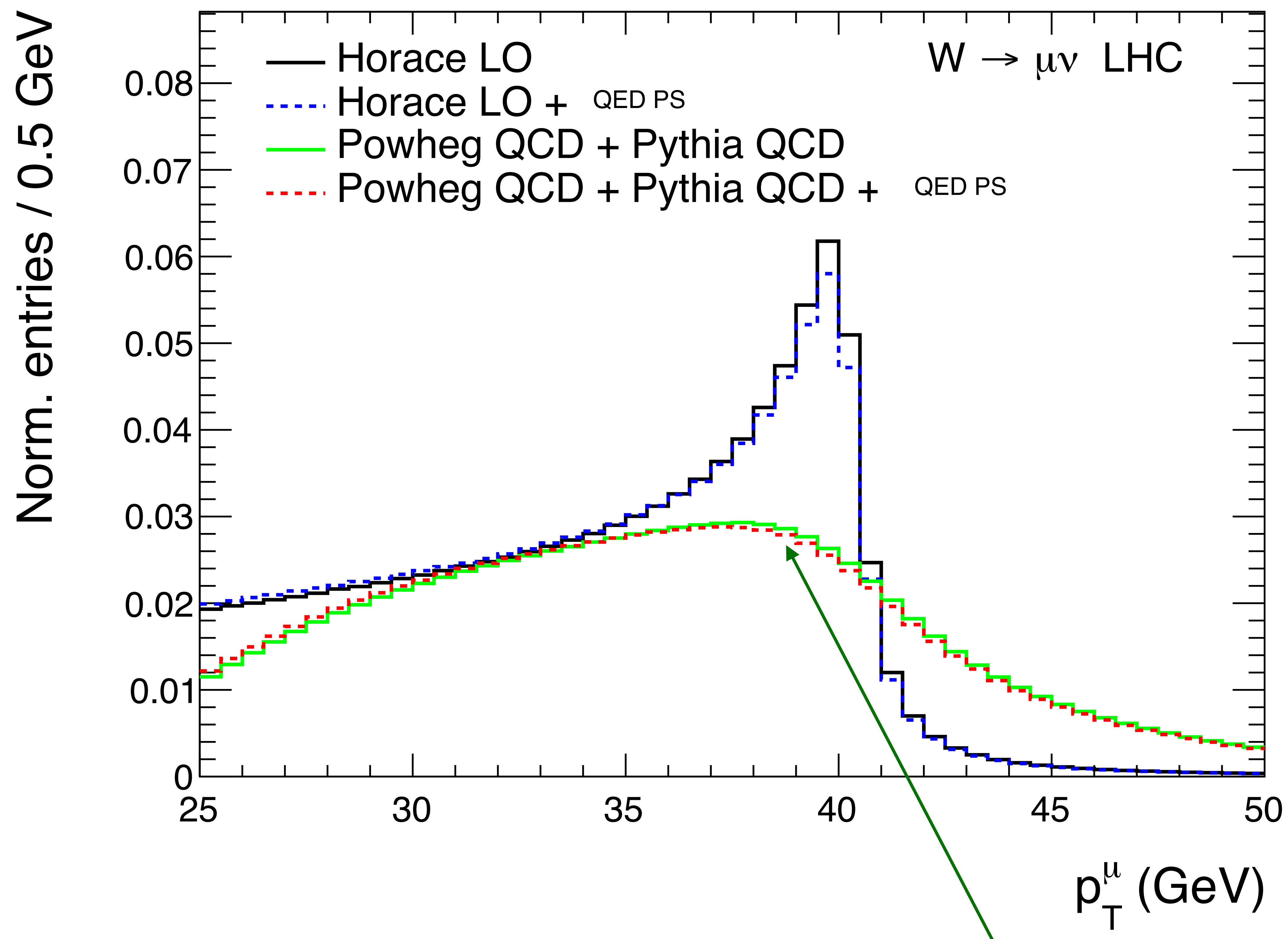
- The tuning assumes that the reweighing factor derived from $p_\perp^Z$
  applies equally well to the $p_\perp^W$ and to the lepton transverse momentum in CCDY

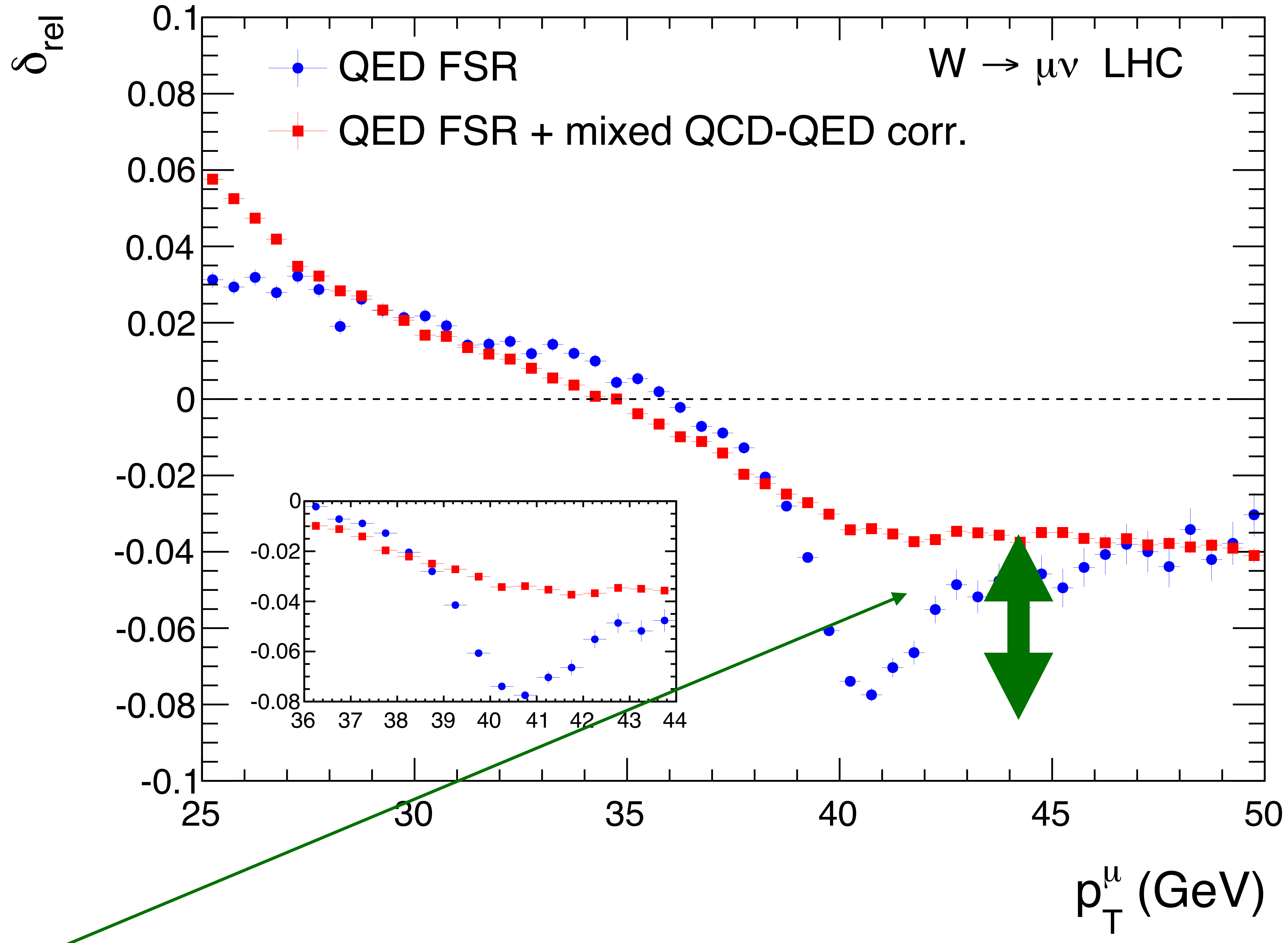
- It is possible that BSM physics is reabsorbed in the tuning

- The interpretation of the fitted value is not necessarily the SM lagrangian parameter

Interplay of QCD and QED corrections

C.Carloni Calame, M.Chiesa, H.Martinez, G.Montagna, O.Nicrosini, F.Piccinini, AV, arXiv:1612.02841





- very large impact of initial-state QCD radiation on the ptlep distribution
- large radiative corrections due to QED final state radiation at the jacobian peak
- very large interplay of QCD and QED corrections redefining the precise shape of the jacobian peak

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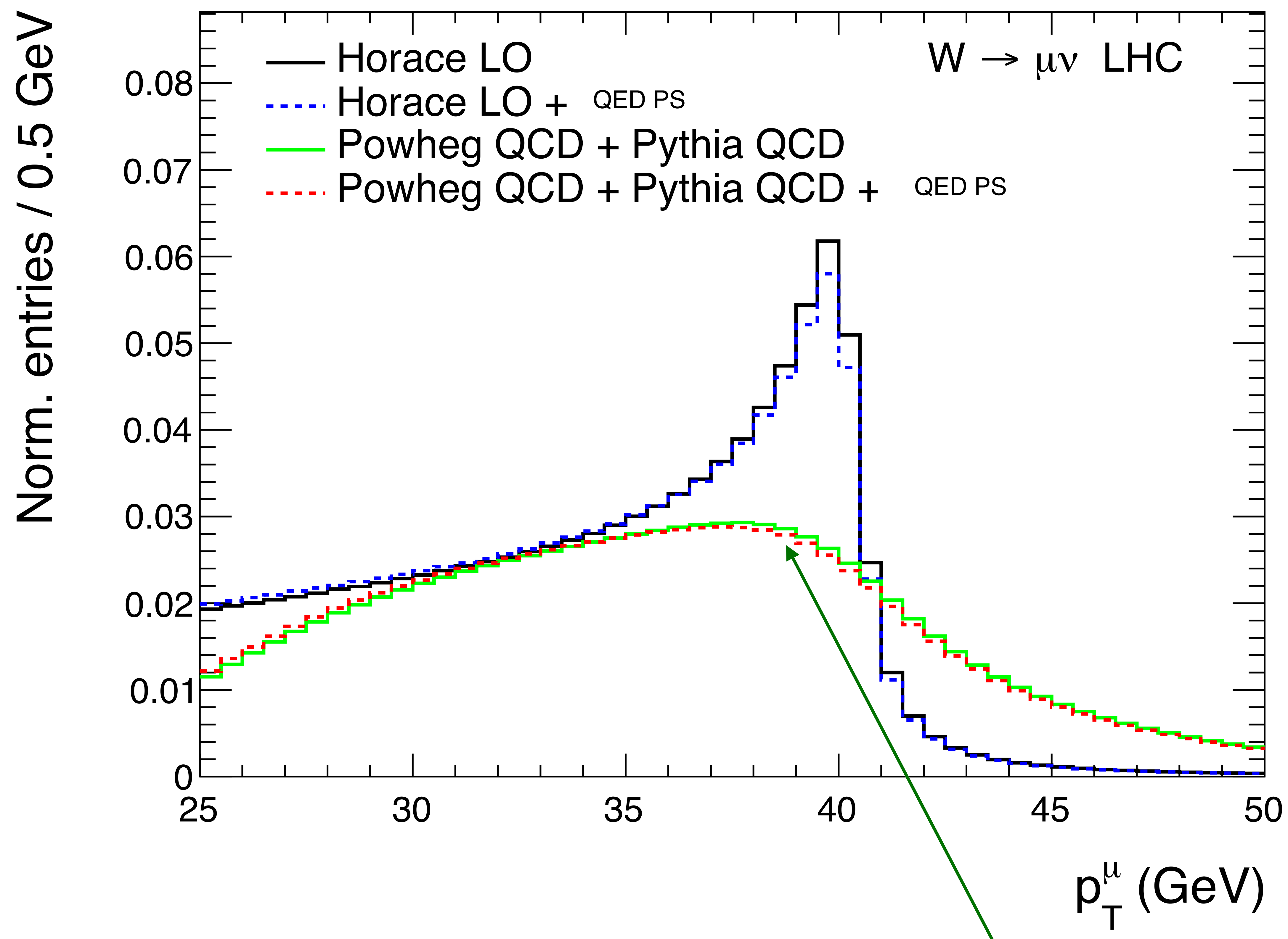

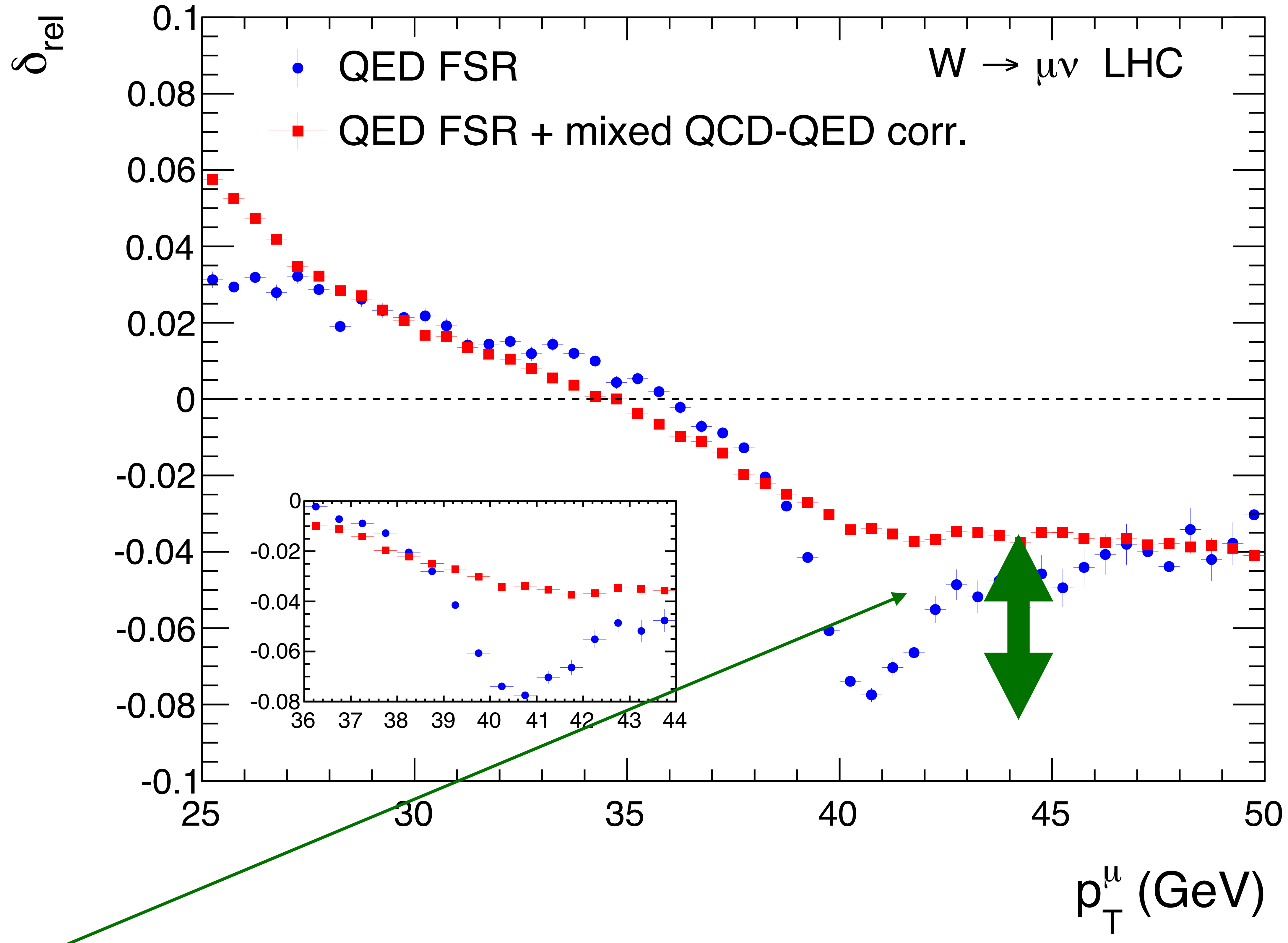

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NLO-QCD + QCDPS + QEDPS is the lowest order meaningful approximation of this observable

the precise size of the mixed QCDxQED corrections (and uncertainties) depends on the choice for the QCD modelling

Comments on the χ^2 minimisation in the template fit

$$\chi^2 = (\vec{d} - \vec{t})^T \cdot C^{-1} \cdot (\vec{d} - \vec{t}) \qquad C = \Sigma_{stat} + \Sigma_{syst,exp} + \Sigma_{MC} + \Sigma_{PDF} + \Sigma_{syst,th}$$

The $\Sigma_{syst,th}$ contribution to the covariance matrix is never included, because of the non-statistical nature of theory uncertainties

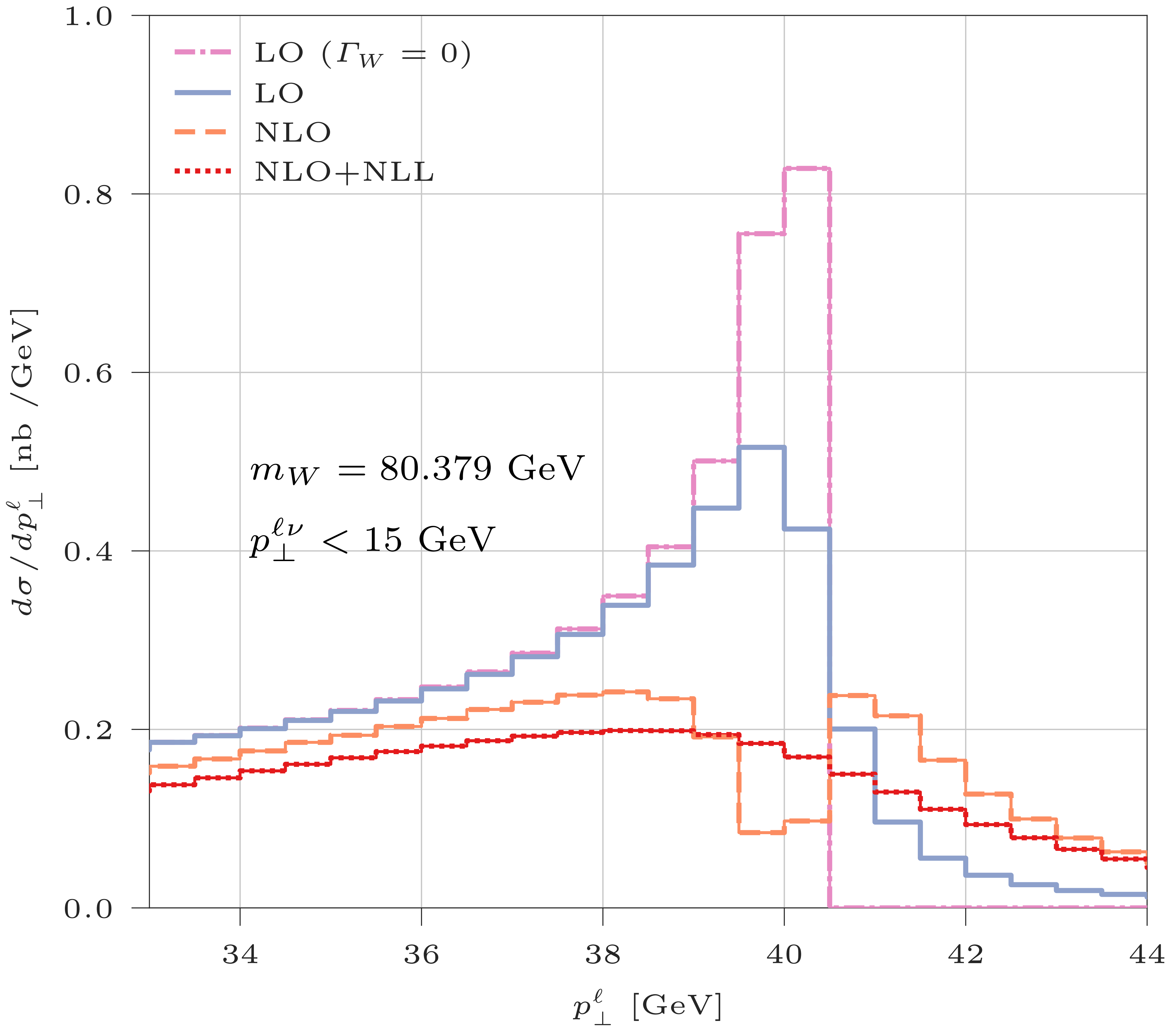
The χ^2 minimisation leads to sensible and stable results when the deviation of the data from the templates is comparable to the size of the eigenvalues of the covariance matrix
but
the lepton transverse momentum distribution receives very large corrections in QCD, much larger than 0.1% ;
the absence of $\Sigma_{syst,th}$ makes it impossible to assign a "sensible" contribution to the χ^2, e.g. when applying scale variations (instability of the χ^2 minimisation)

$\rightarrow$ the data driven approach remains the only way to pursue a template fit approach
at the price of losing the possibility to study the theoretical uncertainties on the modelling

MW from a jacobian asymmetry

LR, PT, AV, arXiv:2301.04059

The lepton transverse momentum distribution in charged-current Drell-Yan



The lepton transverse momentum distribution has a jacobian peak induced by the factor $1/\sqrt{1-\frac{s}{4p_\perp^2}}$.

When studying the W resonance region, the peak appears at $p_\perp \sim \frac{m_W}{2}$

Kinematical end point at $\frac{m_W}{2}$ at LO

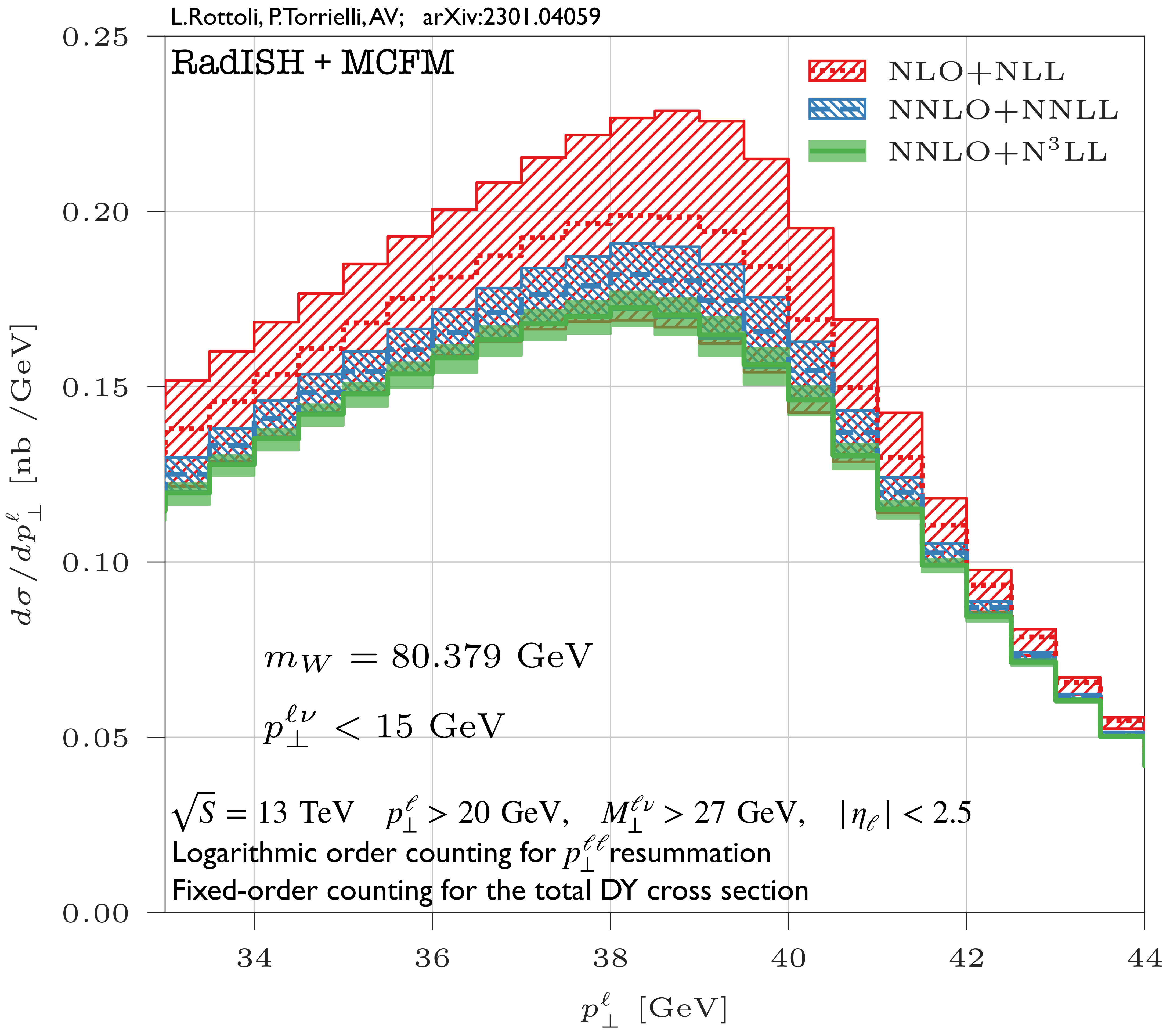
The decay width allows to populate the upper tail of the distribution

Sensitivity to soft radiation $\rightarrow$ double peak at NLO-QCD

The QCD-ISR leading log resummation broadens the distribution and cures the sensitivity to soft radiation at the jacobian peak.

The presence of an end point is the source of specific sensitivity to m_W

The lepton transverse momentum distribution in charged-current Drell-Yan



Impressive progress in QCD calculations

X.Chen, T.Gehrmann, N.Glover, A.Huss, P.Monni, E.Re, L.Rottoli, P.Torrielli, arXiv:2203.01565
X.Chen, T.Gehrmann, N.Glover, A.Huss, T.yang, H.Zhu, arXiv: 2205.11426
J.Campbell, T.Neumann, arXiv:2207.07056

Uncertainty band based on canonical scale variations

$$\mu_{R,F} = \xi_{R,F}\sqrt{(M^{\ell\nu})^2 + (p_\perp^{\ell\nu})^2}\,, \quad \mu_Q = \xi_Q M^{\ell\nu}$$

$\xi_{R,F} \in (1/2,1,2)$ excluding ratios=4 (7 variations)

$(\xi_R, \xi_F) = (1,1)$ and $\xi_Q = (1/4,1)$ (2 variations)

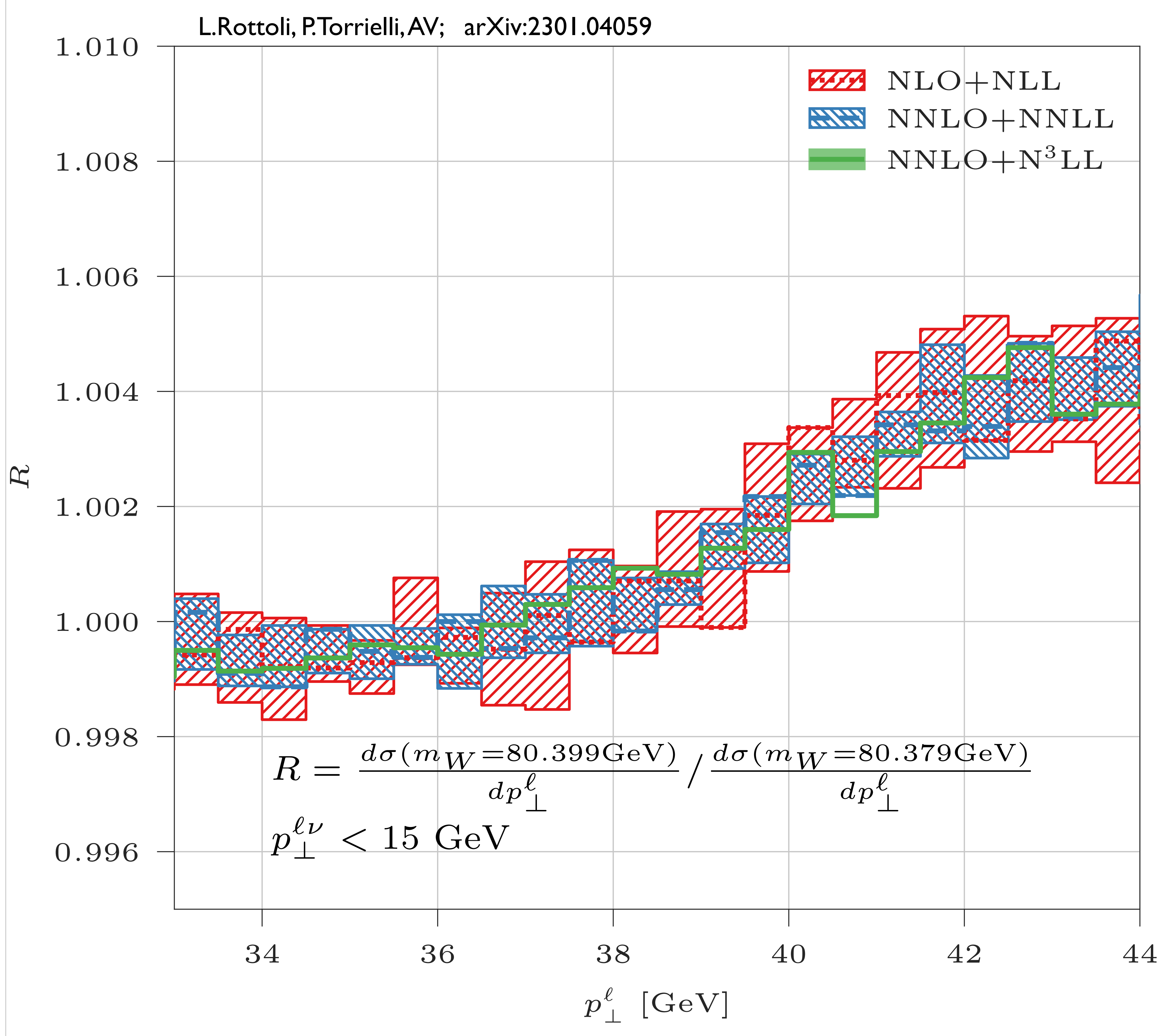
At NNLO+N3LL, residual ±2% uncertainty

The peak of the distribution is located at $p_\perp \sim 38.5$ GeV

The point of maximal sensitivity is shifted by :

- $\Gamma_W/2$ compared to the nominal value $m_W/2$
- the effect of resummed QCD radiation

Sensitivity to the W boson mass: independence from QCD approximation



The determination of m_W requires the possibility to appreciate the distortion of the distribution induced by 2 different mass hypotheses

A shift by $\Delta m_W = 20$ MeV distorts the distribution at few per mille level

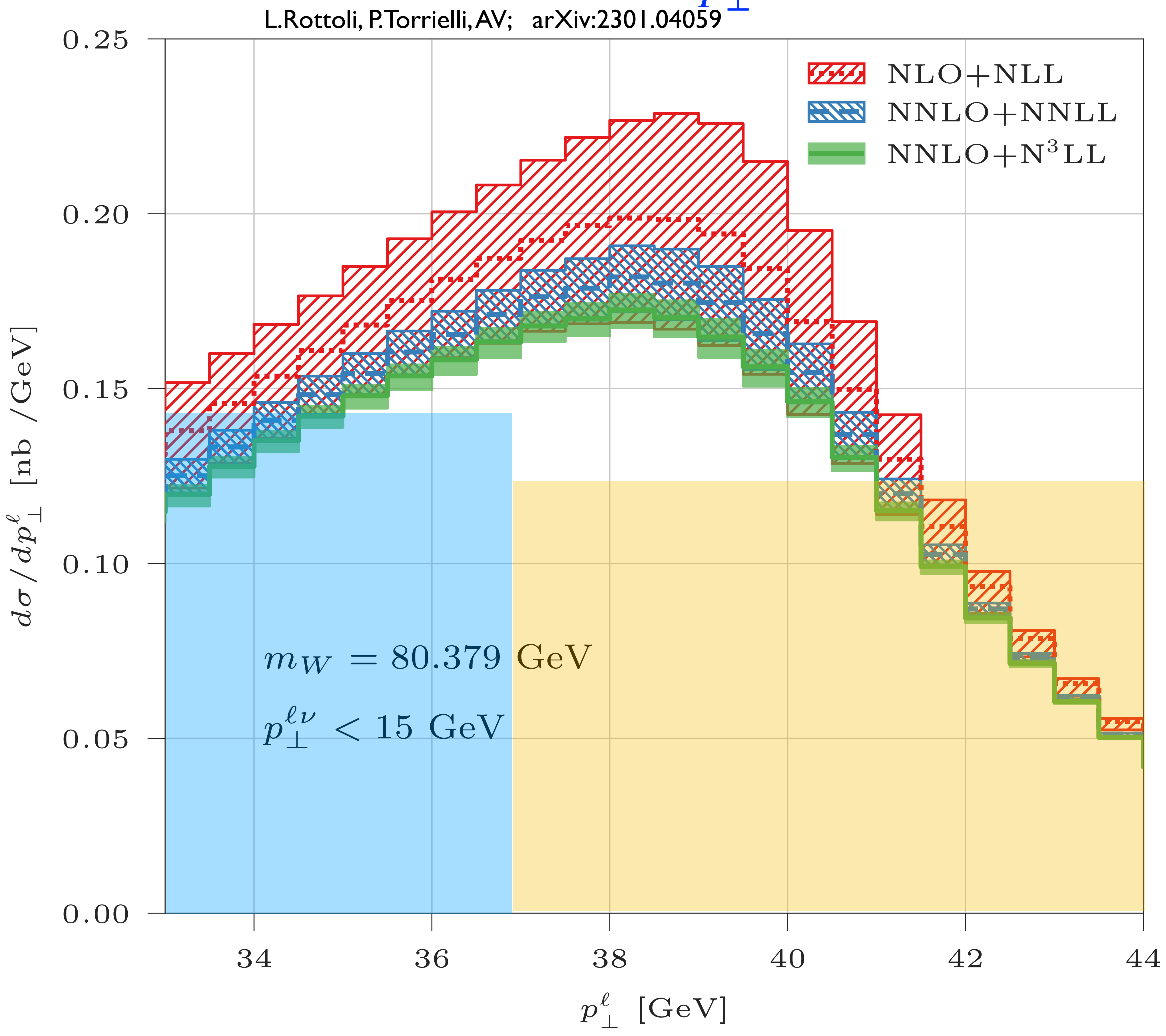
In pure QCD,
the distortion is independent of the QCD approximation or scale choice

The process can be factorized in production (with QCD effects)
times propagation and decay of the W boson.
The sensitivity to m_W stems from the propagation and decay part

The sensitivity to m_W is independent of the QCD approximation
The central value and the uncertainty on m_W instead do depend
on the QCD approximation

The study of the covariance matrix for m_W variations shows that one specific combination of bins carries the bulk of the sensitivity to m_W $\longrightarrow$ following this indication, we design a new observable

The jacobian asymmetry $\mathscr{A}_{p_\perp^\ell}$



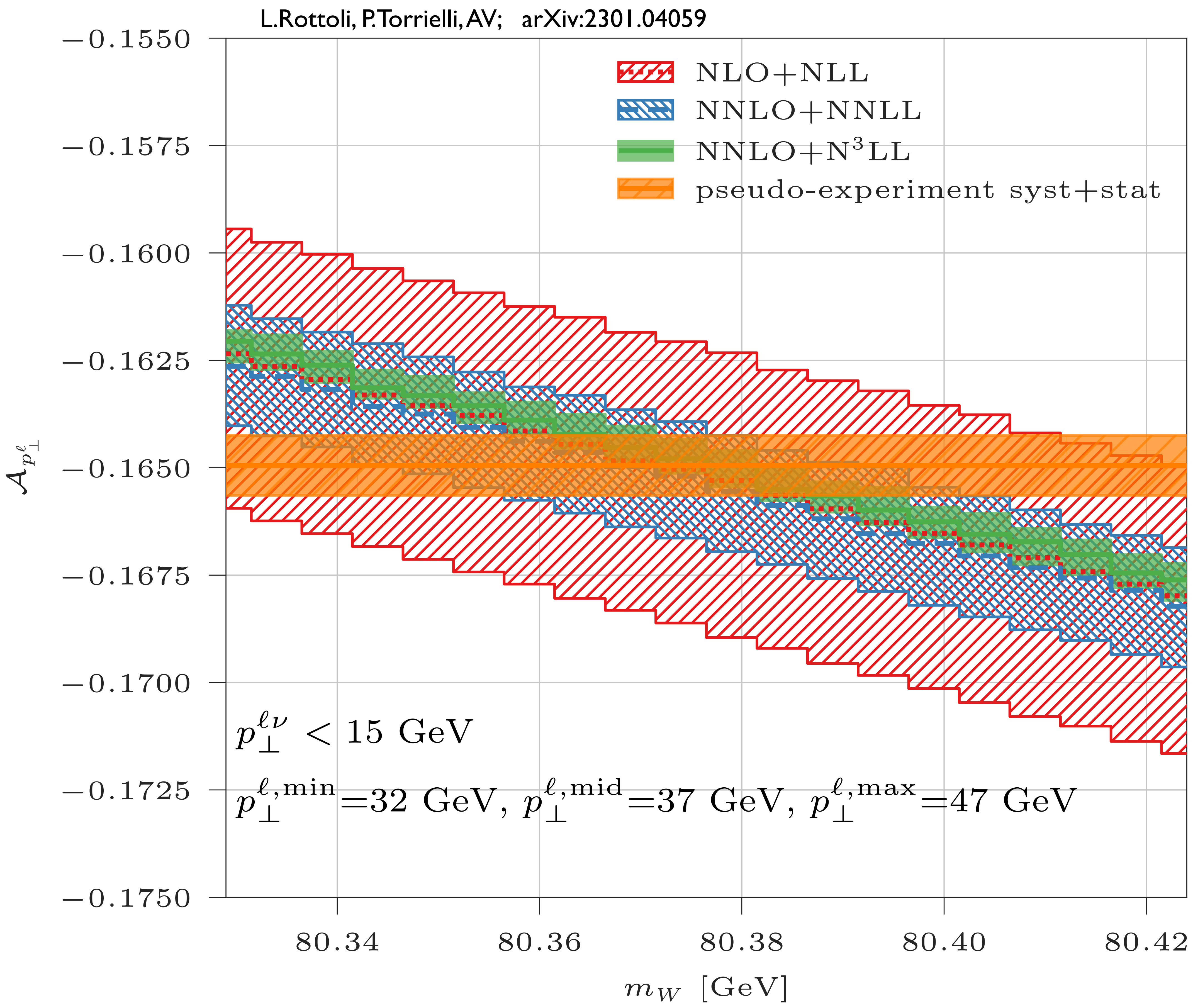
$$L_{p_\perp^\ell} \equiv \int_{p_\perp^{\ell,\min}}^{p_\perp^{\ell,\mathrm{mid}}} dp_\perp^\ell \frac{d\sigma}{dp_\perp^\ell}, \qquad U_{p_\perp^\ell} \equiv \int_{p_\perp^{\ell,\mathrm{mid}}}^{p_\perp^{\ell,\max}} dp_\perp^\ell \frac{d\sigma}{dp_\perp^\ell}$$

$$\mathcal{A}_{p_\perp^\ell}(p_\perp^{\ell,\min}, p_\perp^{\ell,\mathrm{mid}}, p_\perp^{\ell,\max}) \equiv \frac{L_{p_\perp^\ell} - U_{p_\perp^\ell}}{L_{p_\perp^\ell} + U_{p_\perp^\ell}}$$

The asymmetry is an observable (i.e. it is measurable via counting): its value is one single scalar number
It depends only on the edges of the two defining bins

Increasing m_W shifts the position of the peak to the right $\rightarrow$ Events migrate from the blue to the orange bin
$\rightarrow$ The asymmetry decreases

The jacobian asymmetry $\mathcal{A}_{p_\perp^\ell}$ as a function of MW



The asymmetry $\mathcal{A}_{p_\perp}$ has a linear dependence on m_W,
stemming from the linear dependence on the end-point position

The slope of the asymmetry expresses the sensitivity to m_W,
in a given setup $(p_\perp^{\ell,min}, p_\perp^{\ell,mid}, p_\perp^{\ell,max})$

The slope is the same with every QCD approximation
(factorization of QCD effects, perturbative and non-perturbative)

The "large" size of the two bins $\mathcal{O}(5-10)$ GeV leads to
- small statistical errors
- excellent stability of the QCD results (inclusive quantity)
- ease to unfold the data to particle level (m_W combination)

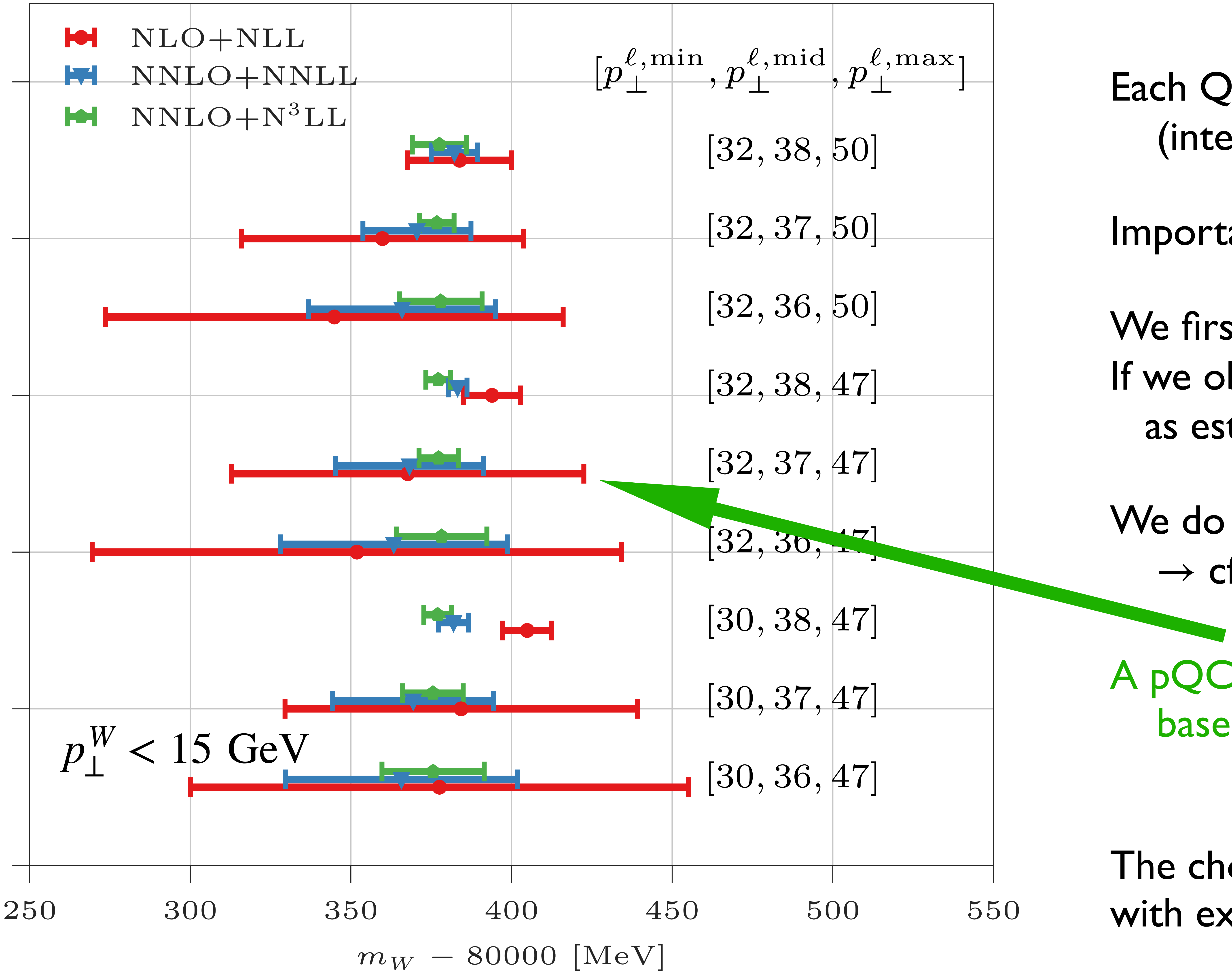
The experimental value and the theoretical predictions can be directly compared (m_W from the intersection of two lines)

The main systematics on the two fiducial cross sections is related to the lepton momentum scale resolution
A determination at the ± 15 MeV level from the experimental side seems possible

MW determination as a function of the $\mathscr{A}_{p_\perp^\ell}$ parameters

as pseudo-experimental value we choose the NNLO+N3LL result with $m_W = 80.379$

L.Rottoli, P.Torrielli, AV; arXiv:2301.04059



Each QCD scale-variations band determines an m_W interval (intersection with the central experimental line)

Important role of the N3LL corrections

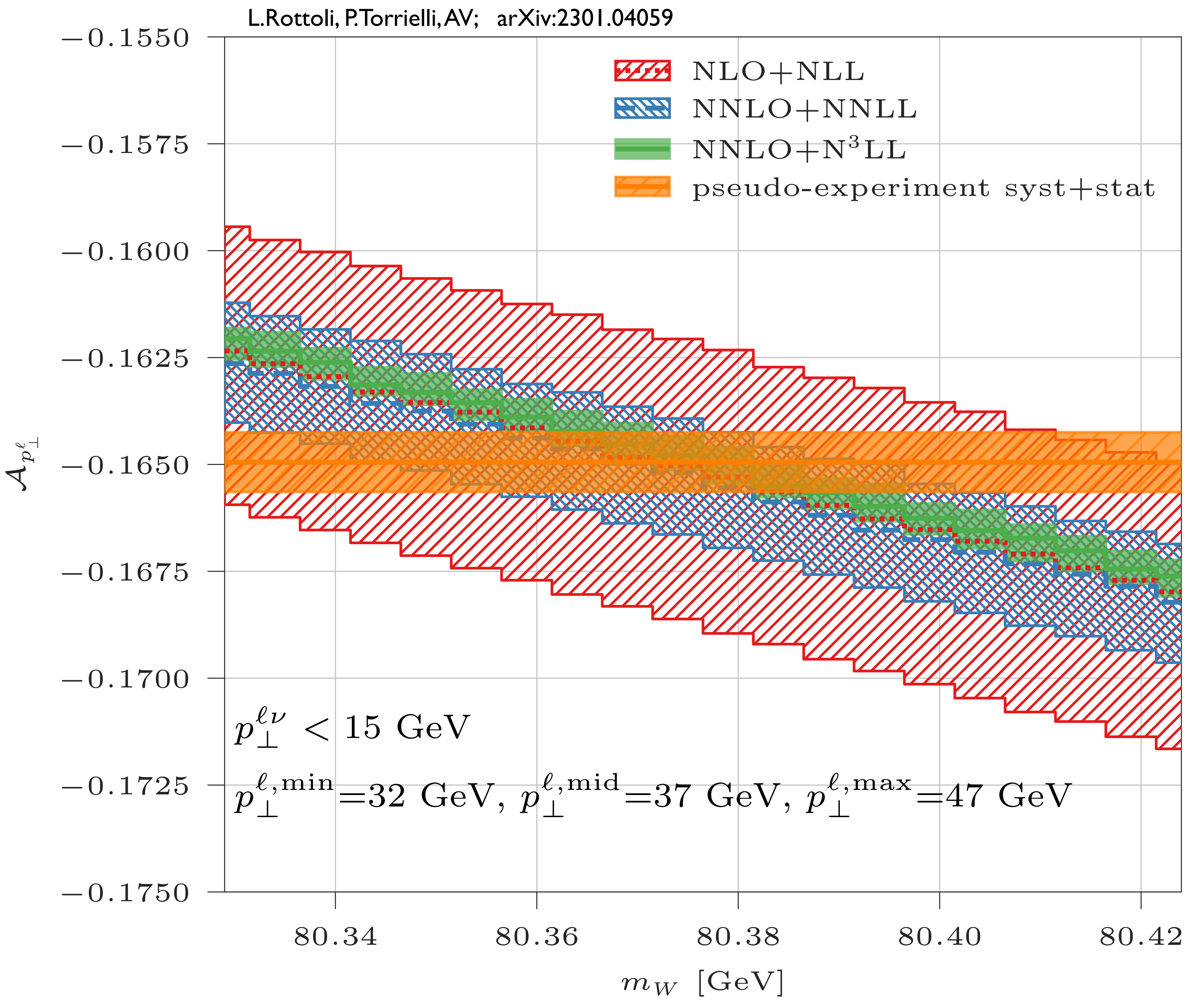
We first check the convergence order-by-order.
If we observe it, then we take the size of the m_W interval as estimator of the residual pQCD uncertainty

We do not trust the scale variations alone
→ cfr the choice with $p_\perp^{\ell,mid} = 38$ GeV

A pQCD uncertainty at the ± 5 MeV level is achievable based on CCDY data alone

The choice of the midpoint is important to identify two regions with excellent QCD convergence

What's missing?



The excellent convergence in pQCD of the asymmetry $\mathscr{A}_{p_\perp}$ is the best possible starting point to discuss

- the impact on the central m_W value of
  - missing perturbative corrections (QED, QCDxEW)
  - non-perturbative effects

$\rightarrow$ each effect yields a vertical offset of $\mathscr{A}_{p_\perp^\ell} \rightarrow m_W$ shift
QED corrections might also change the slope

$\rightarrow$ the non-perturbative effects are a refinement of the study
- impact on top of NNLO+N3LL is expected moderate
- not a necessary element as in the template fit case

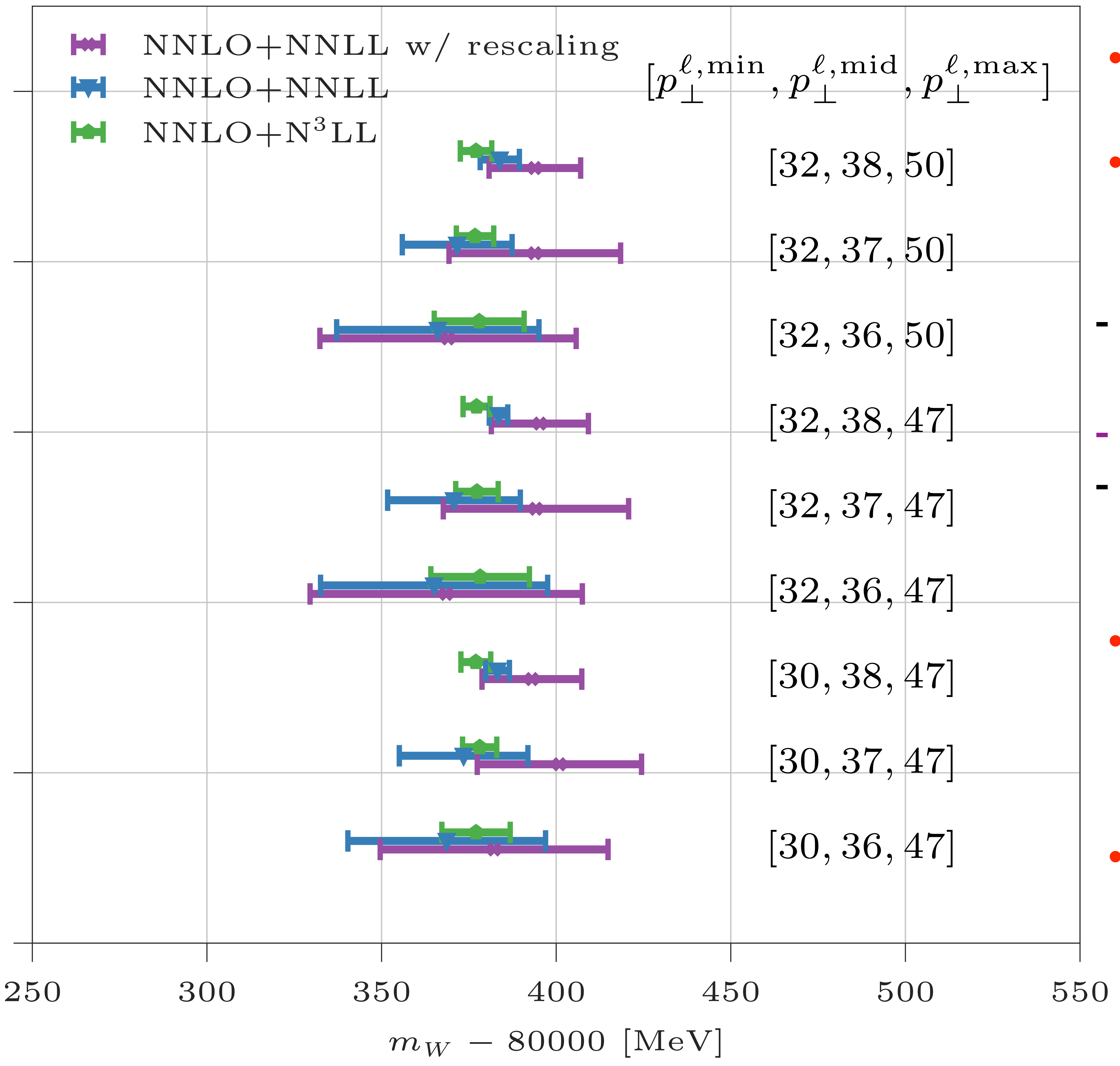
- the propagation of the uncertainties

$\rightarrow$ the linearity of the dependence on m_W allows an easy propagation of each uncertainty source

Two items of central relevance are the intrinsic $k_\perp$ of the initial state partons (non-perturbative effects)
the proton collinear PDFs

Information transfer from NCDY to CCDY :   a validation exercise

L.Rottoli, P.Torrielli, AV;   arXiv:2301.04059



- NNLO+N3LL with central scales is our MC truth = pseudodata both for NCDY and CCDY
- we take NNLO+NNLL as theory model

- for different scale choices we compute the reweighing functions from NNLO+NNLL to the $p_\perp^Z$ pseudodata
- we then use the same reweighing functions in CCDY at NNLO+NNLL
- we compare the reweighed results and the CCDY pseudo data

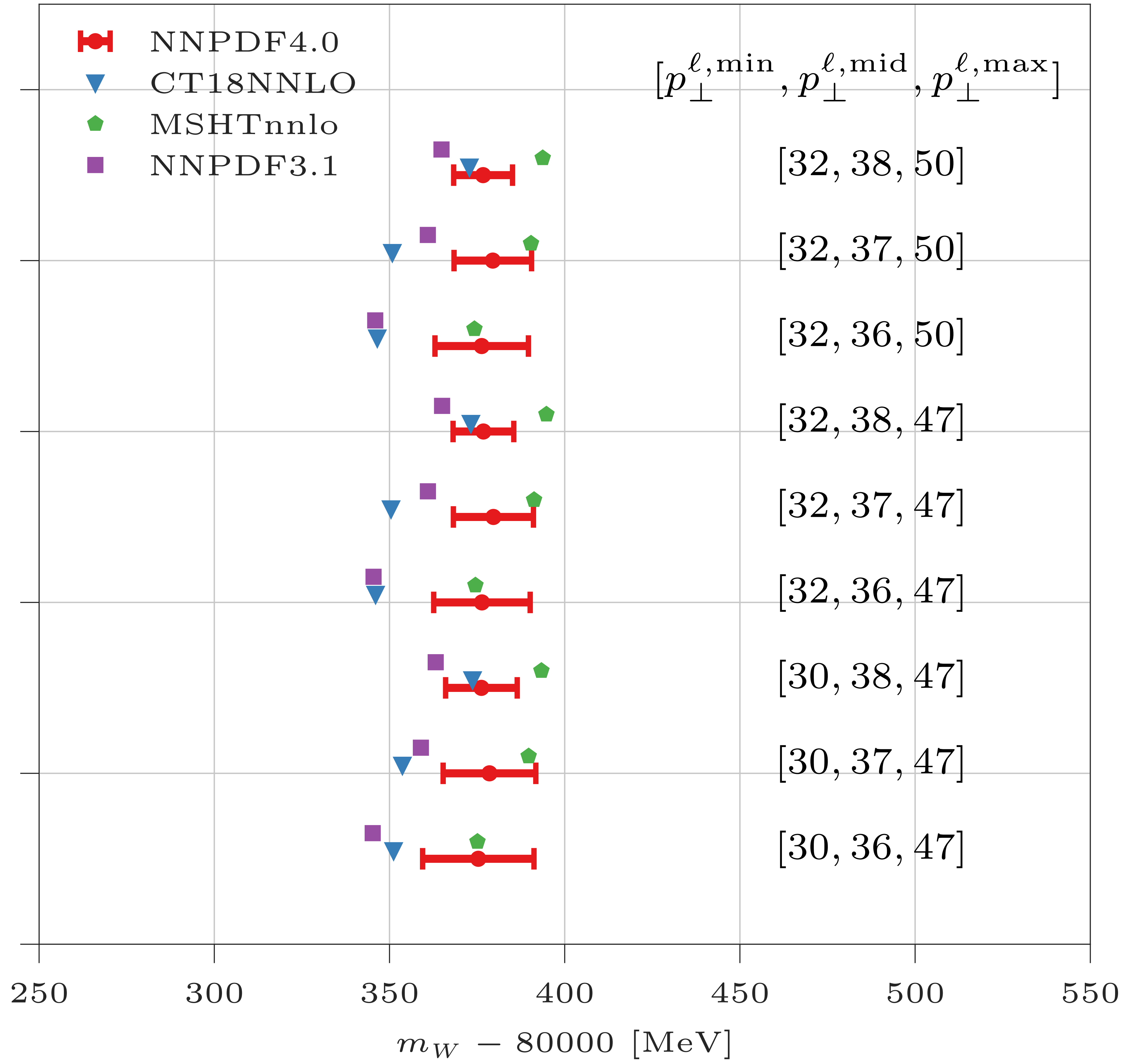
- the $p_\perp^W$ and $p_\perp^\ell$ distributions obtained with reweighing show an improvement (get very close to the CCDY pseudodata), but still maintain some shape differences

- the pQCD uncertainty on m_W estimated with or without reweighing is of similar size (in our case the NNLO+NNLL QCD uncertainty)

→ usage of the highest available perturbative order is recommended to minimize the systematics in the transfer from Z to W

PDF uncertainties

L.Rottoli, P.Torrielli, AV; arXiv:2301.04059



- the PDF uncertainties on m_W are evaluated in a conservative way using the 100 replicae of the NNPDF4.0 - NLO set
  $\rightarrow \delta m_W^{PDF} = \pm 11$ MeV
- the spread of the central values of CT18NNLO, MSHTnnlo, NNPDF4.0 if of ~ 30 MeV
- this size of the uncertainty is expected:
  $\mathscr{A}_{p_\perp^\ell}$ is one single observable, particularly sensitive to PDF variations

$\rightarrow$ more information is needed to mitigate this problem

1) in situ profiling
(e.g. use additional bins of the $p_\perp^\ell$ distribution)

2) combination of results in different rapidity acceptance regions
(e.g. LHCb combined with ATLAS/CMS)

3) combination of results for W^+ and W^-

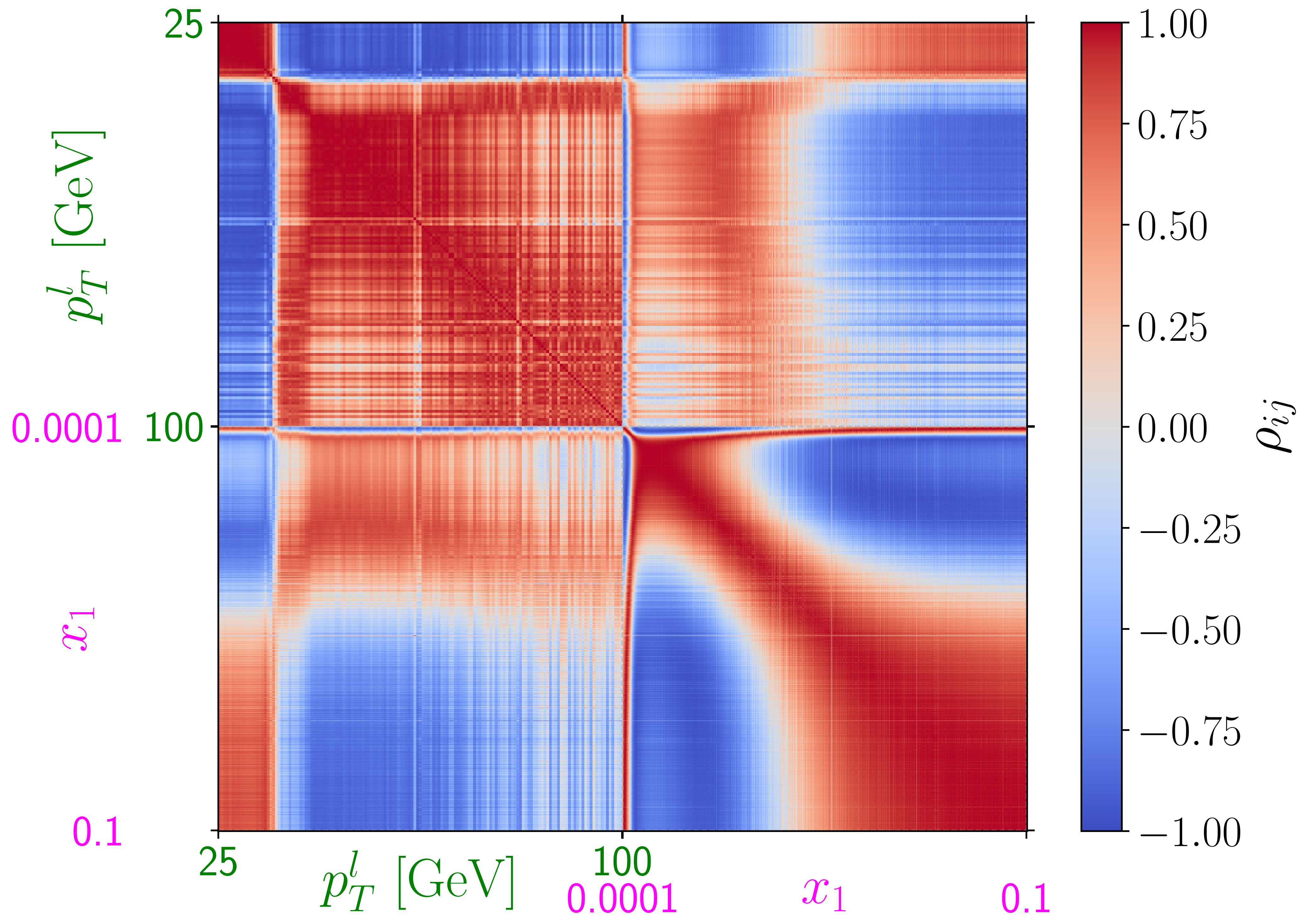
PDF uncertainty on MW: exploiting the theoretical constraints

E.Bagnaschi, AV, Phys.Rev.Lett.126 (2021) 4, 041801

all PDF replicas are correlated because the parton densities are developed in the same QCD framework
1) obey sum rules, 2) satisfy DGLAP equations, 3) are based on the same data set

the "unitarity constraint" of each parton density affects the parton-parton luminosities, which, convoluted with the partonic xsec, in turn affect the hadron-level xsec

$$\rho_{ij} = \frac{\langle \left(\mathcal{O}_i - \langle \mathcal{O}_i \rangle_{PDF}\right)\left(\mathcal{O}_j - \langle \mathcal{O}_j \rangle_{PDF}\right)\rangle_{PDF}}{\sigma_i \sigma_j}$$



The uncertainty of PDF origin can be reduced to the few MeV level

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E.Bagnaschi, AV, Phys.Rev.Lett.126 (2021) 4, 041801

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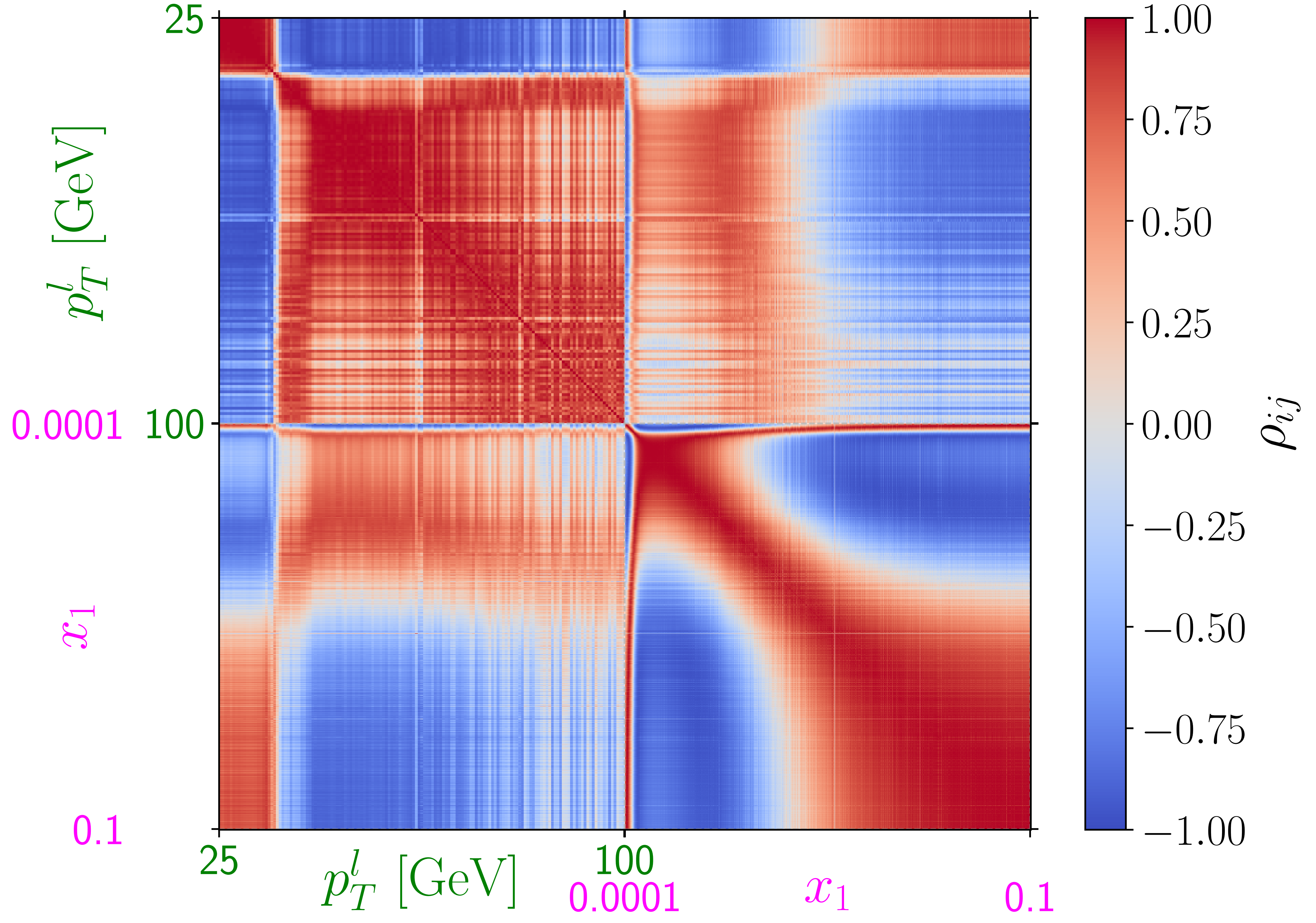


$$\chi^2_{k,\,min} = \sum_{r,s \in bins} \left(\mathcal{T}_{0,k} - \mathcal{D}^{exp}\right)_r C^{-1}_{rs} \left(\mathcal{T}_{0,k} - \mathcal{D}^{exp}\right)_s$$

$$C = \Sigma_{PDF} + \Sigma_{stat} + \Sigma_{MC} + \Sigma_{exp\,syst}$$ total covariance

Inserting the information about PDFs in the covariance matrix leads to a profiling action "in situ", given by the data themselves

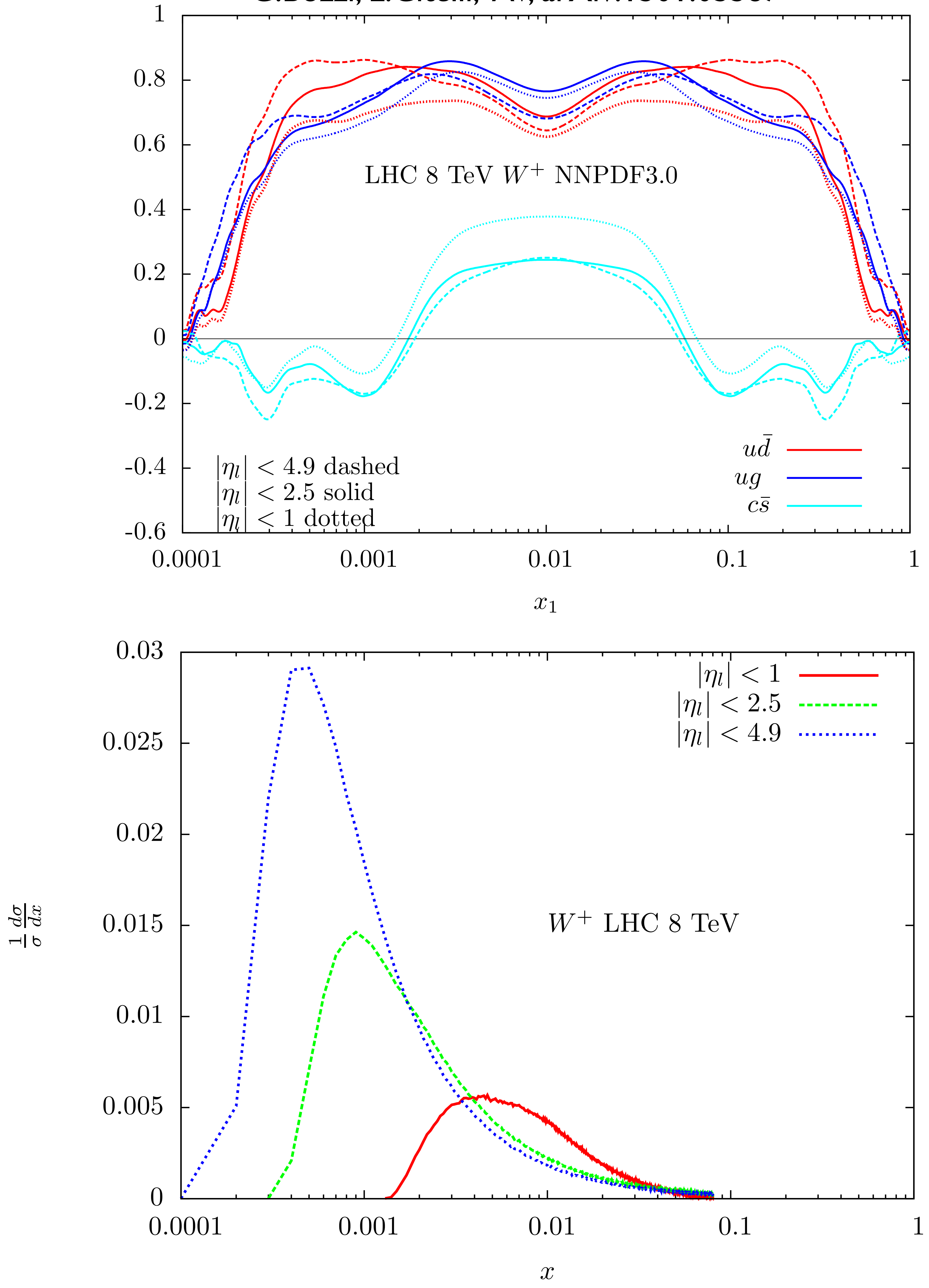
the PDF uncertainty can be reduced to the few MeV level thanks to the strong anti correlated behaviour of the two tails of $p_\perp^\ell$

The uncertainty of PDF origin can be reduced to the few MeV level

PDF rapidity correlations

LHCb can provide a crucial contribution
to constrain the PDF uncertainties

G.Bozzi, L.Citelli, AV, arXiv:1501.05587



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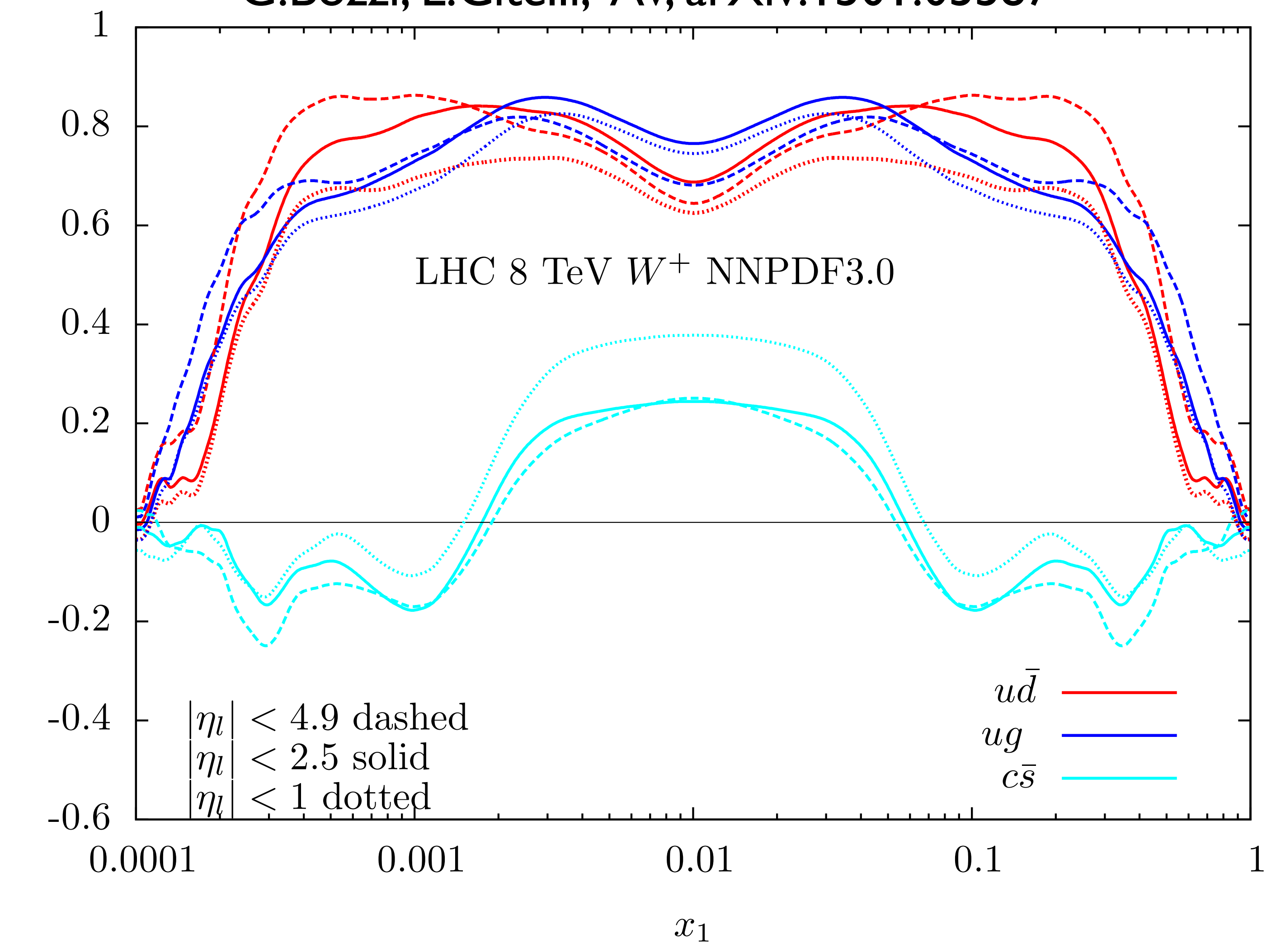
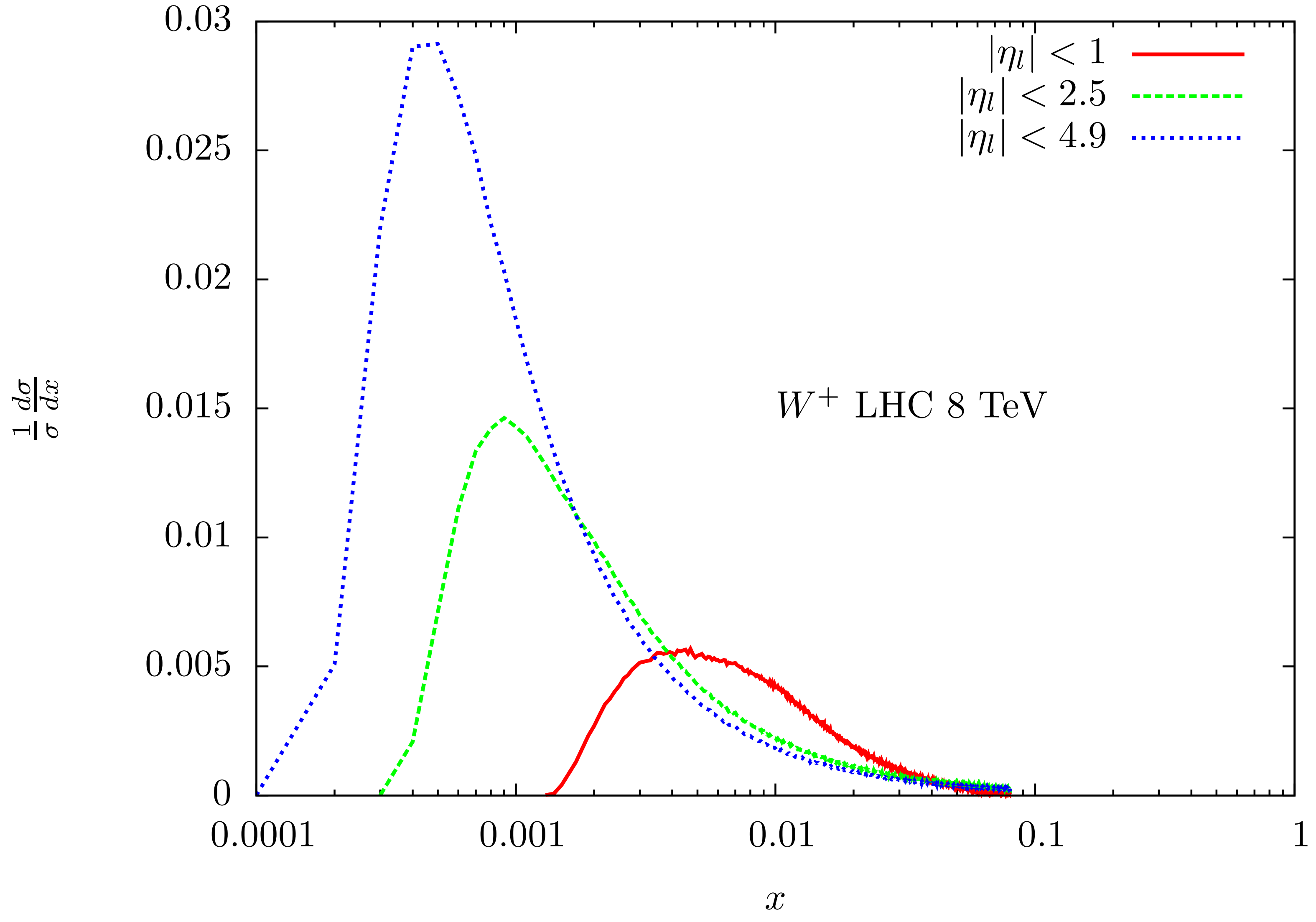
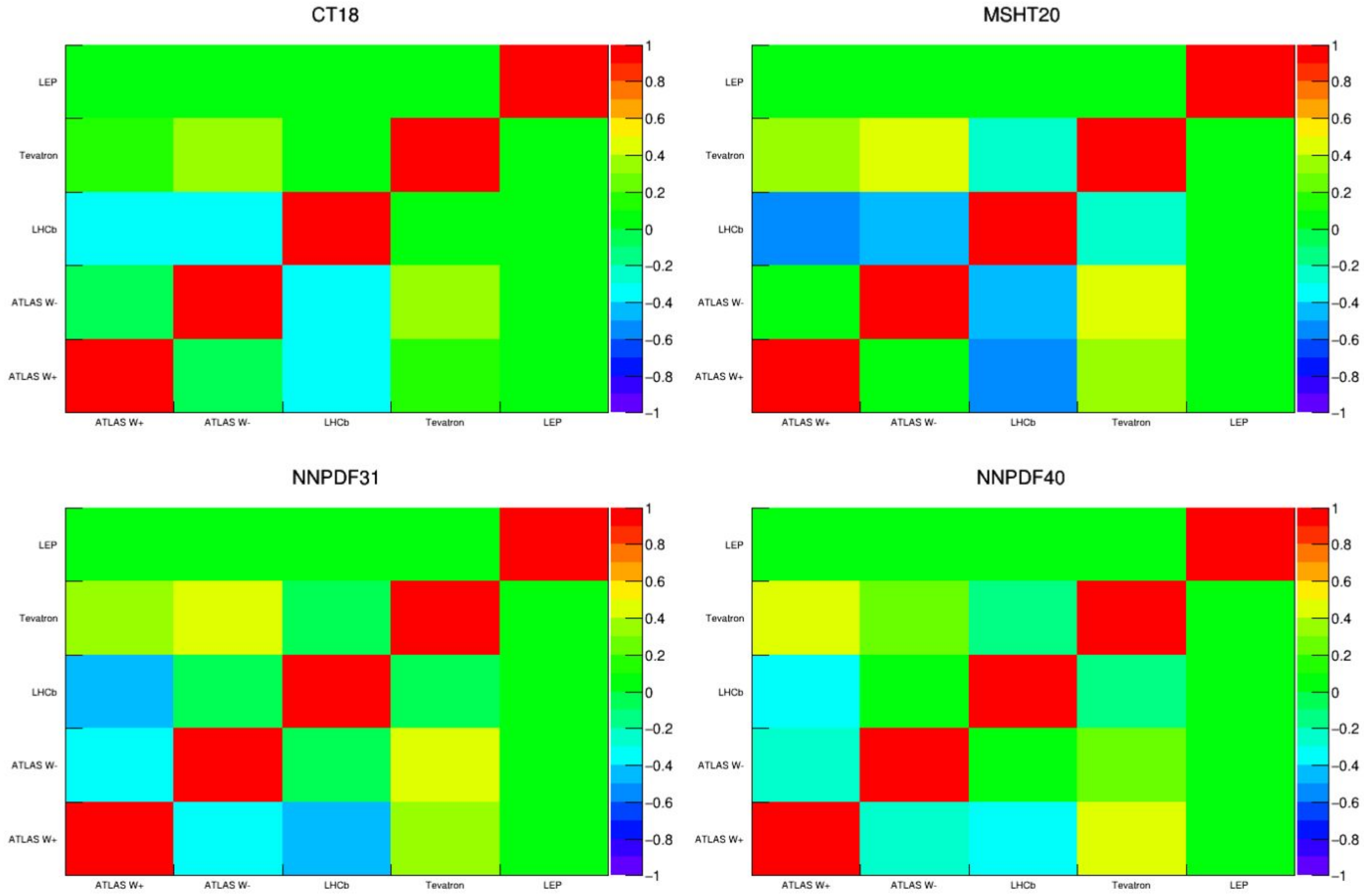




Detailed study in the [Tevatron-LHC W-boson mass Combination Working Group]

The anticorrelation of the LHCb results helps reducing the total PDF uncertainty



plot from Jan Kretschmar's talk at the EW WG general meeting (November 16th 2022)

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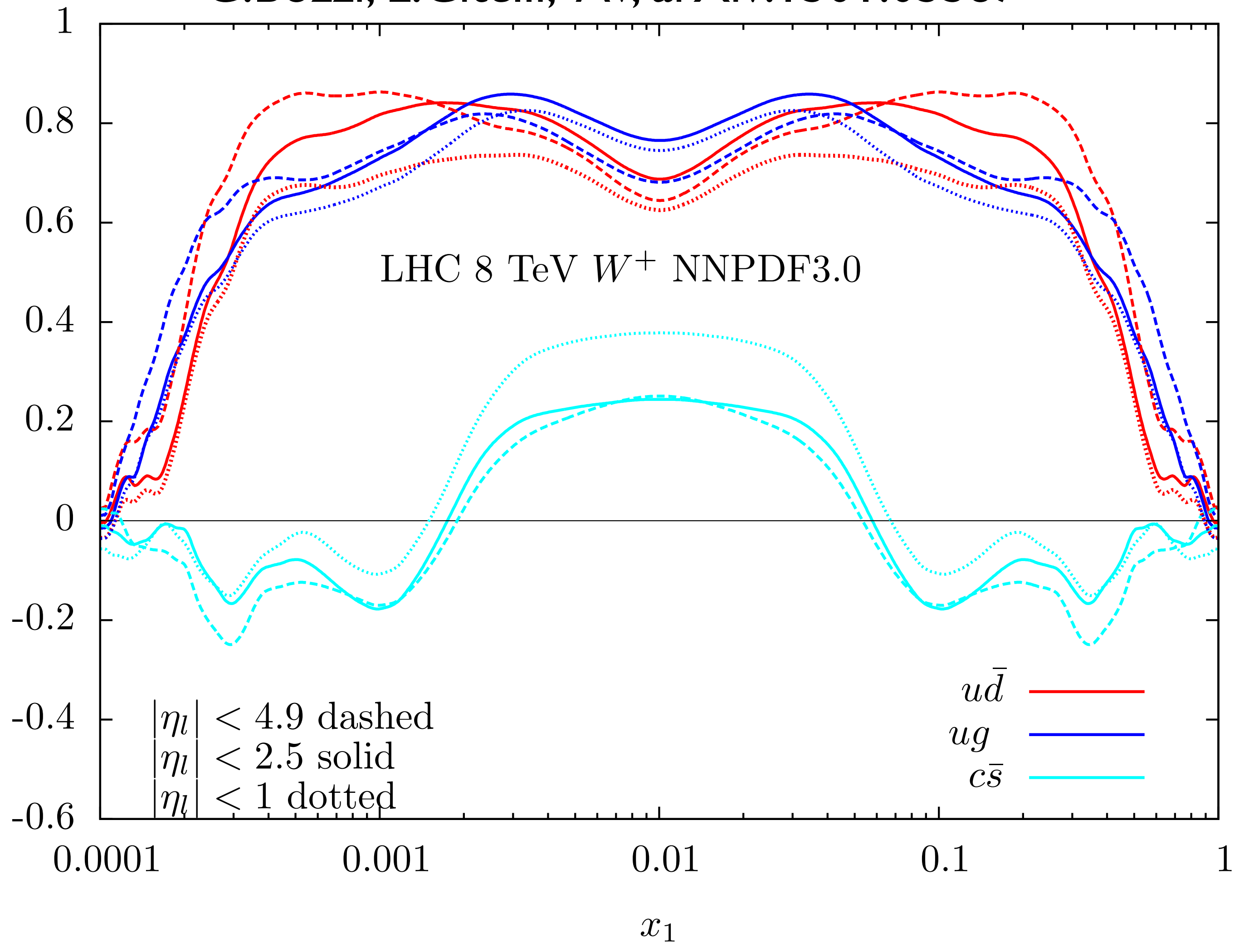

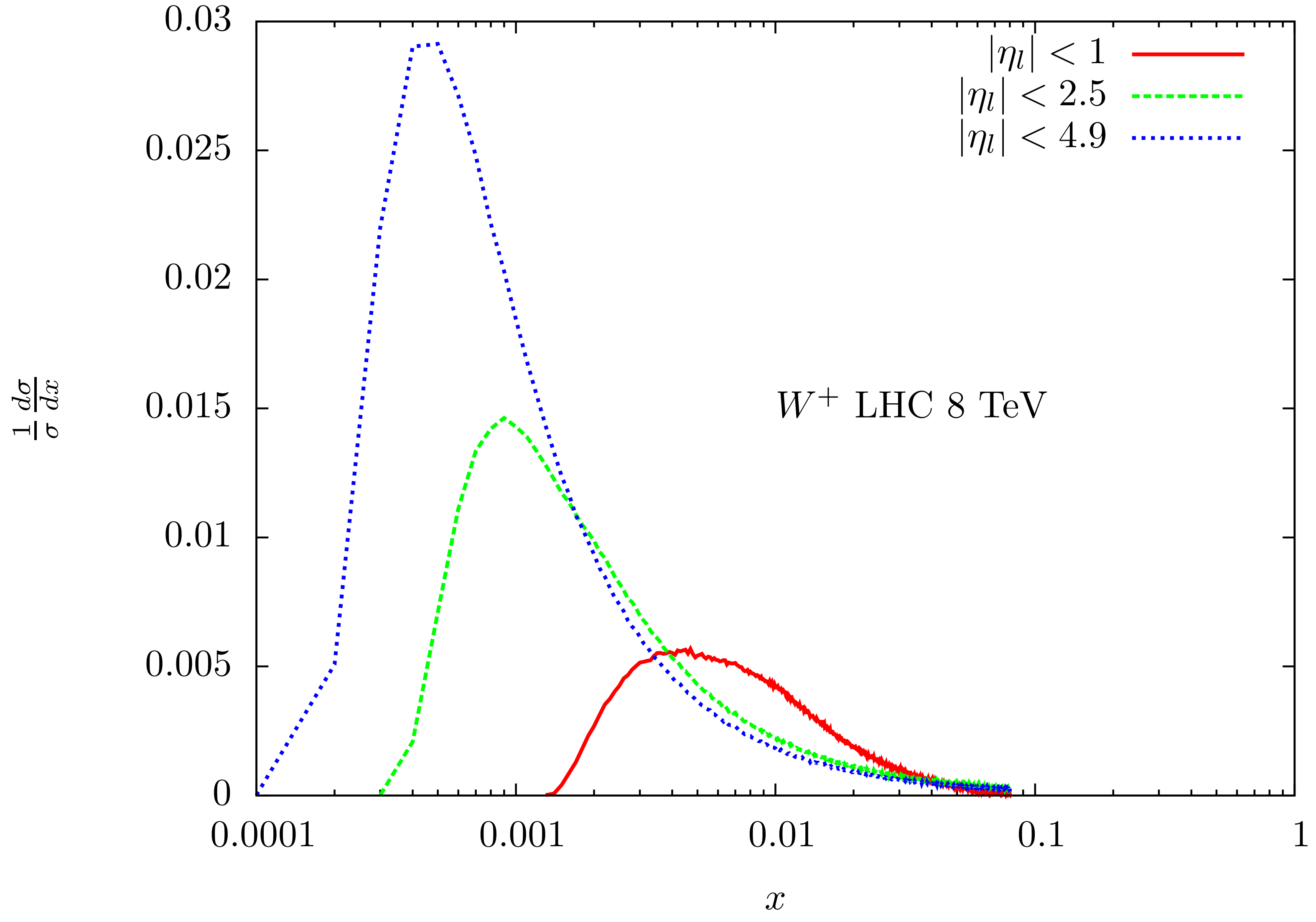

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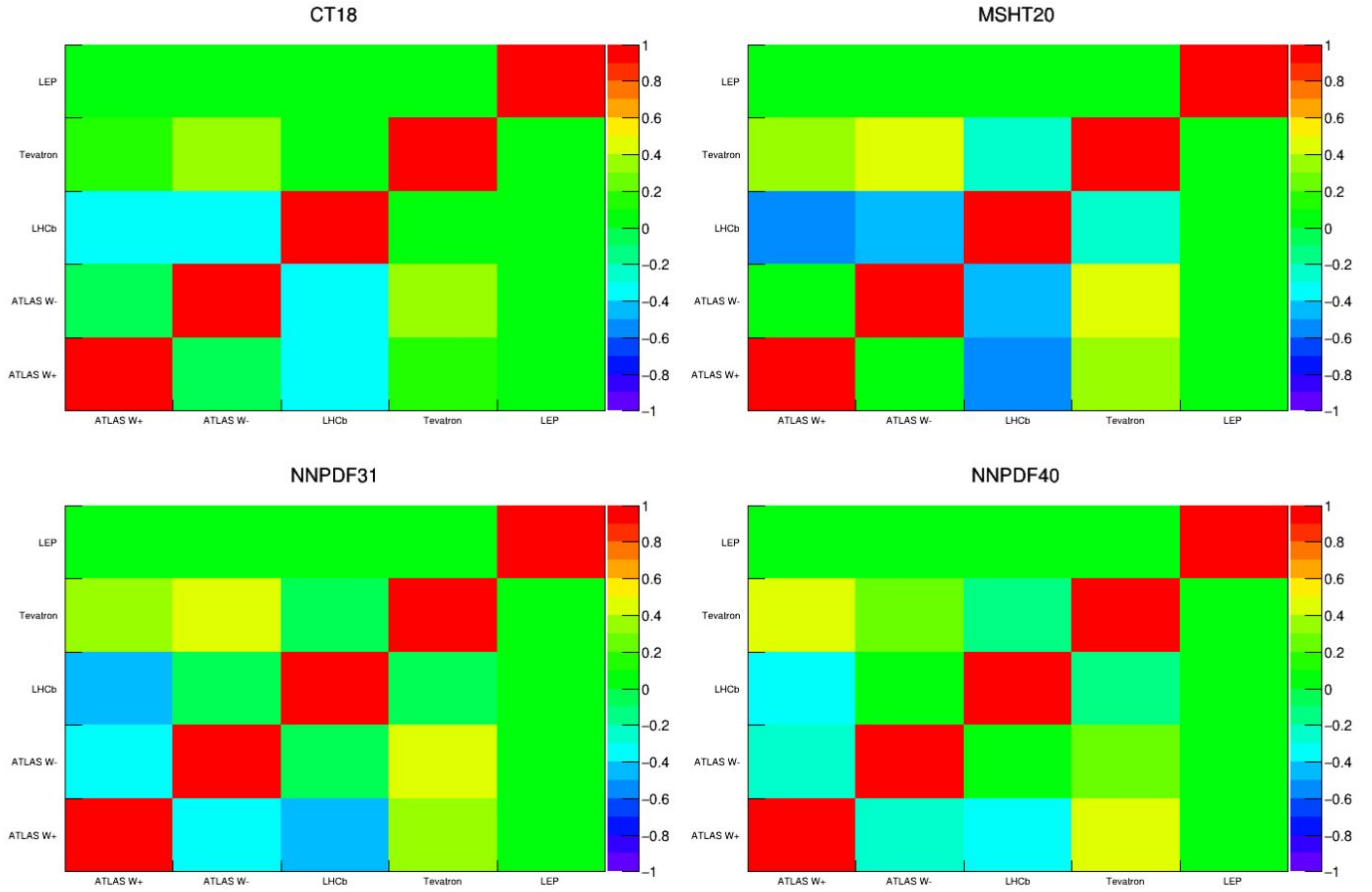

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In progress: impact of the combination of m_W determinations obtained with $\mathscr{A}_{p_\perp^\ell}$ in the LHCb and in the ATLAS/CMS regions

Conclusions

- The asymmetry $\mathscr{A}_{p_\perp^\ell}$ can contribute to understand and refine the methodologies needed for the m_W determination

  - excellent pQCD convergence
  - large linear dependence on m_W $\rightarrow$ sensitivity for a precision measurement
  - defined in terms of large fiducial cross sections
  - possibility to unfold the data to particle level $\rightarrow$ simplicity in a global combination

- A key feature of the $\mathscr{A}_{p_\perp^\ell}$ is the simplification of the discussion of the individual items contributing to the total error.

- The study of the $\mathscr{A}_{p_\perp^\ell}$ at all the LHC experiments, differential in the lepton pseudorapidity can provide a strong reduction factor of the PDF uncertainty on m_W

- A useful tuning of non-perturbative parameters should be done on top of the NNLO+N3LL predictions Can such a study replace a PYTHIA tune ?

- The analogous quantity in the NCDY case can be used to determine m_Z , testing the quality of the QCD modelling with the cross check of the value obtained from the lepton-pair invariant mass distribution

In progress: a complete phenomenological study, including all the available SM radiative corrections

Backup

Information available in the $p_\perp^\ell$ distribution

- The diagonalization of the covariance matrix w.r.t. m_W variations yields N linear combinations of the primary bins

  The first combination is very close to the asymmetry $\mathscr{A}_{p_\perp^\ell}$, is very sensitive to m_W, has low pQCD uncertainty

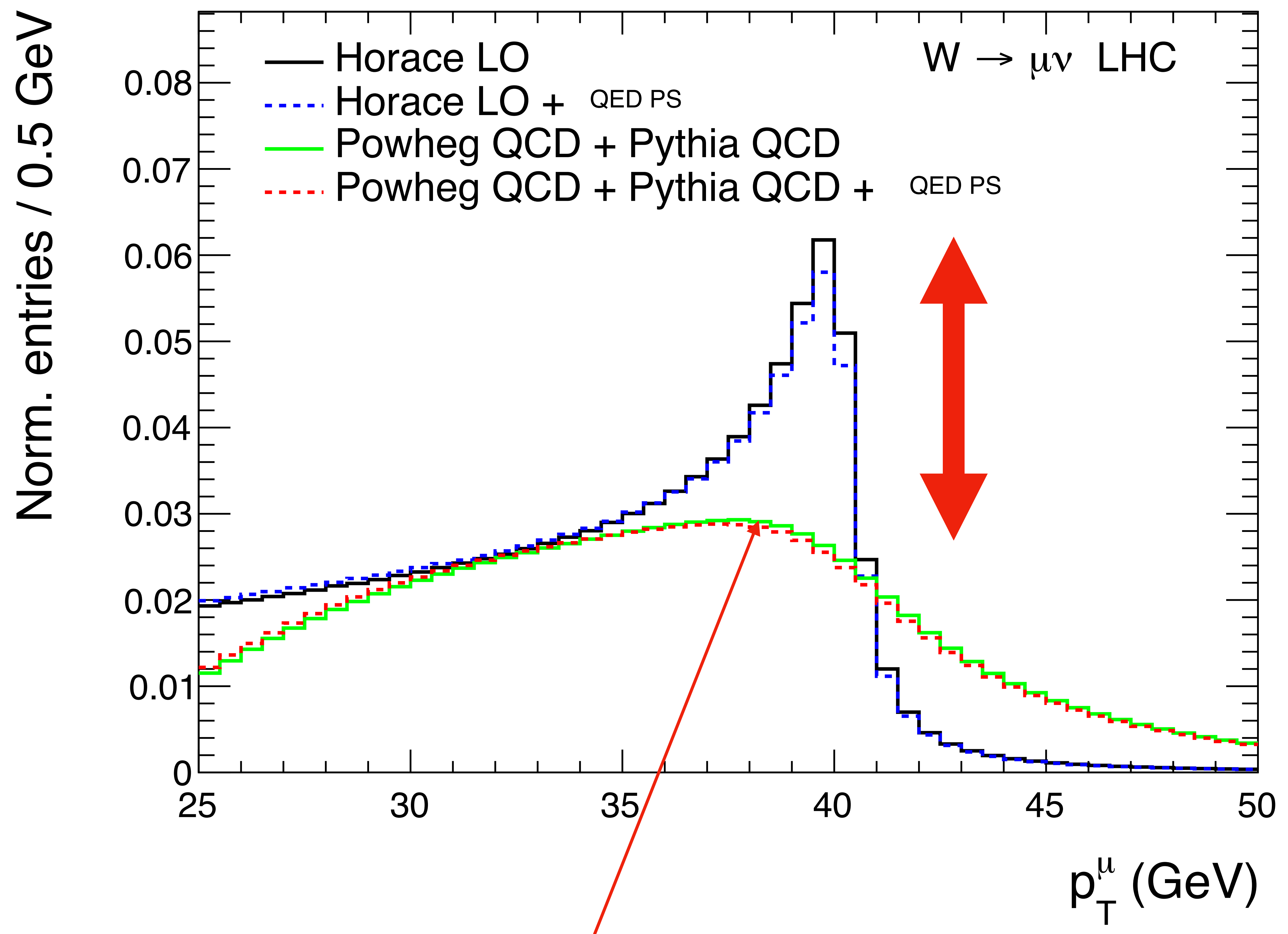
  The other combinations have a weaker sensitivity to m_W and are affected by larger QCD uncertainties (check in progress)

- The final combination of the N m_W independent determinations should be weighed by the respective QCD uncertainties
  if the latter had a statistical meaning

- Only a detailed numerical analysis can decide whether keeping only the asymmetry $\mathscr{A}_{p_\perp^\ell}$ is
  a loss of information or a reduction of "QCD noise"

Basic ingredients of the simulation tools needed for the MW determination

C.Carloni Calame, M.Chiesa, H.Martinez, G.Montagna, O.Nicrosini, F.Piccinini, AV, arXiv:1612.02841



- very large impact of initial-state QCD radiation on the ptlep distribution
- large radiative corrections due to QED final state radiation at the jacobian peak
- very large interplay of QCD and QED corrections redefining the precise shape of the jacobian peak

26

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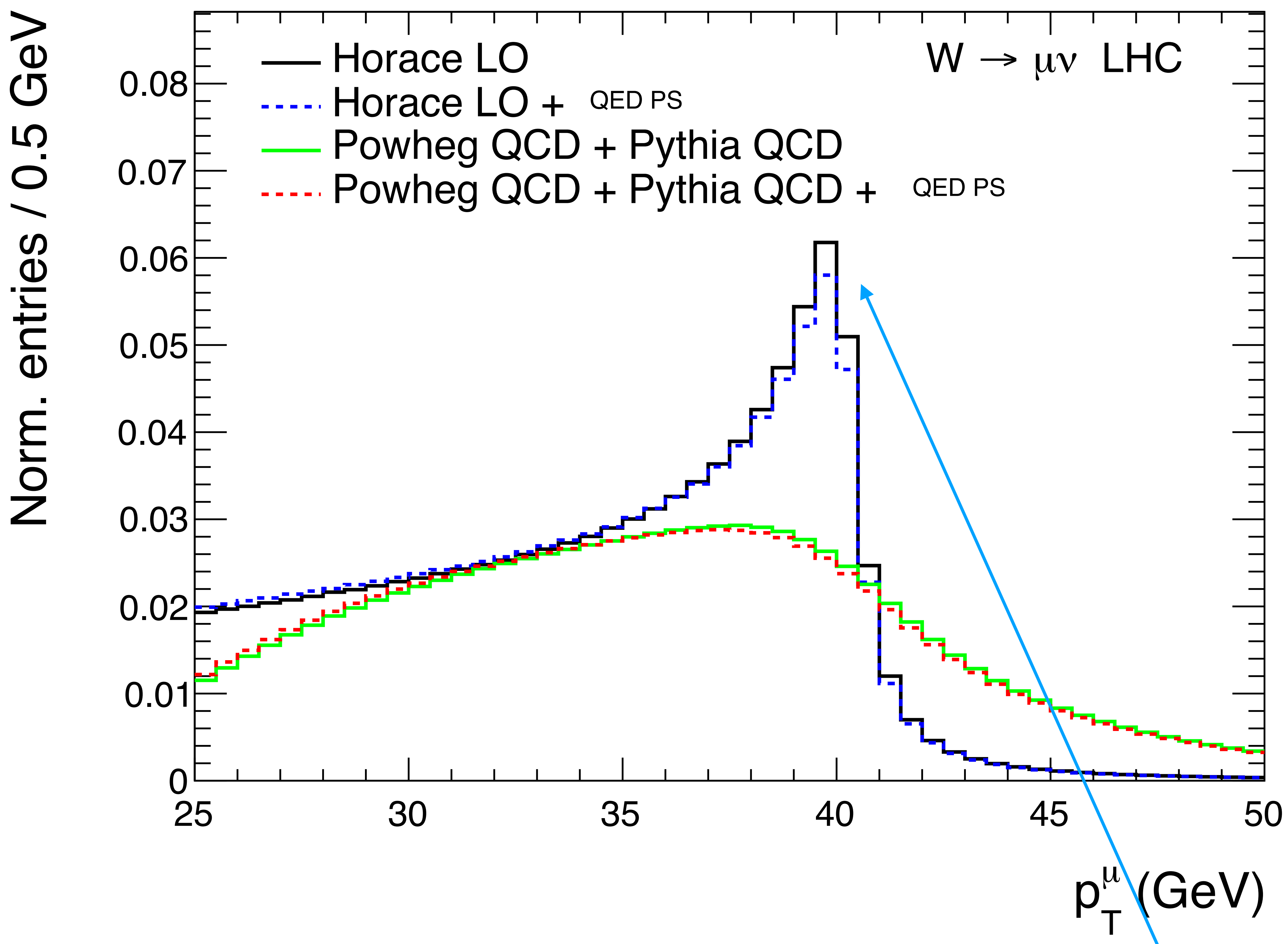

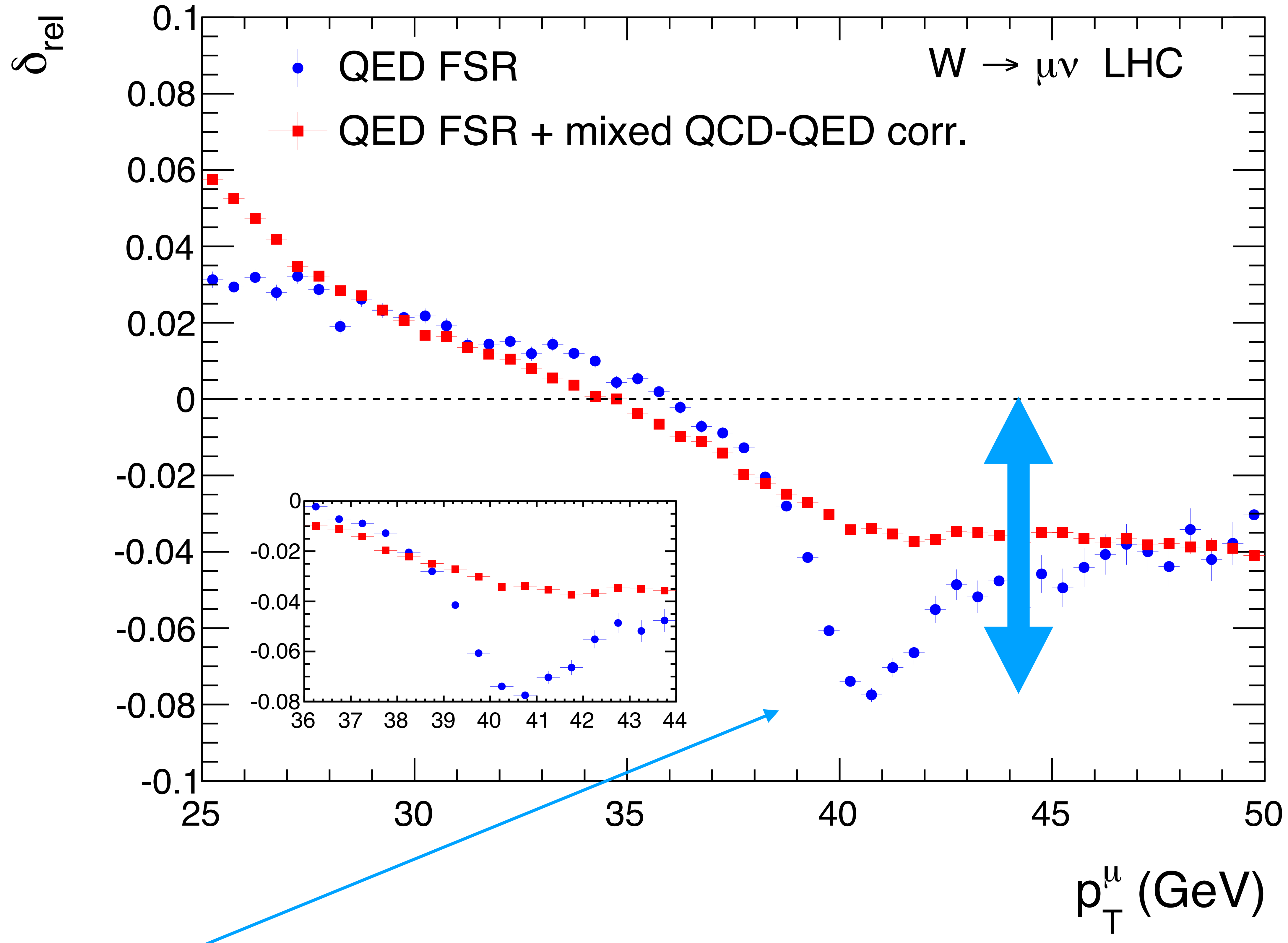

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Impact of EW and mixed QCDxEW corrections on MW

C.Carloni Calame, M.Chiesa, H.Martinez, G.Montagna, O.Nicrosini, F.Piccinini, AV, arXiv:1612.02841

$pp \to W^+$, $\sqrt{s} = 14$ TeV		M_W shifts (MeV)			
Templates accuracy: LO		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$	
Pseudo–data accuracy		M_T	p_T^ℓ	M_T	p_T^ℓ
1	HORACE only FSR-LL at $\mathcal{O}(\alpha)$	-94±1	-104±1	-204±1	-230±2
2	HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
3	HORACE NLO-EW with QED shower	-90±1	-94±1	-177±1	-190±2
4	HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1
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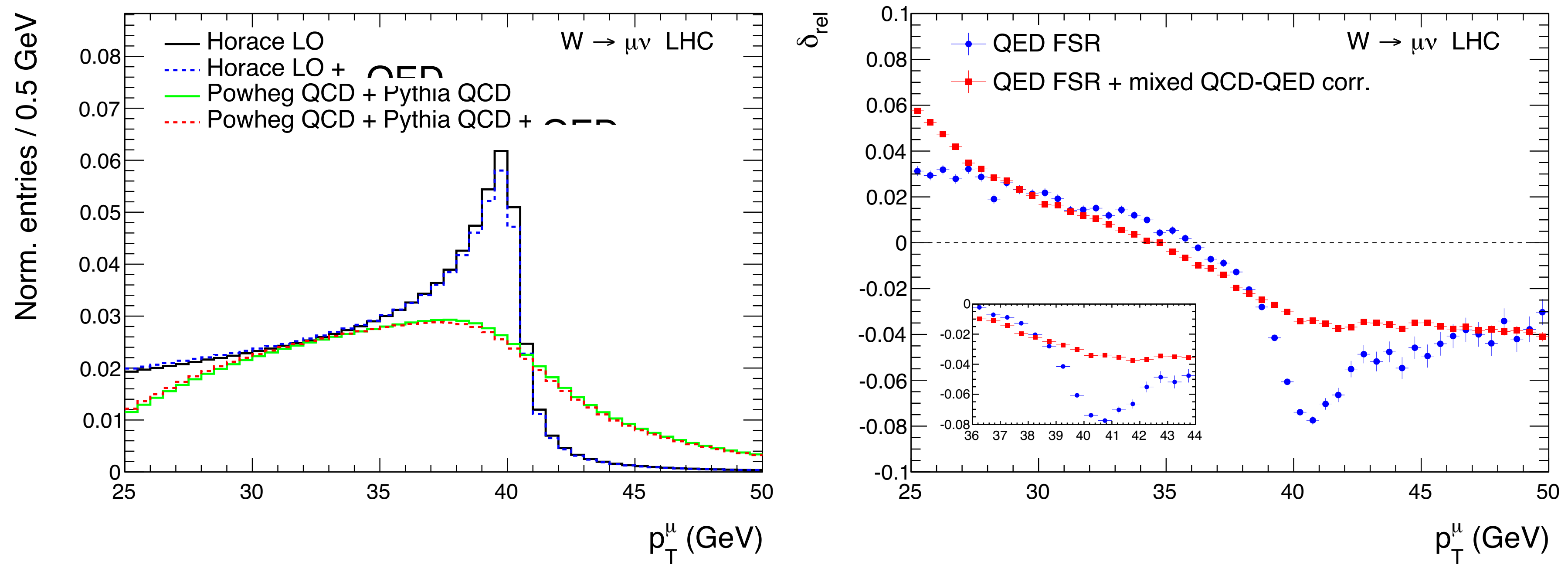

- QED FSR plays the major role
- subleading QED and weak induce further O(4 MeV) shifts

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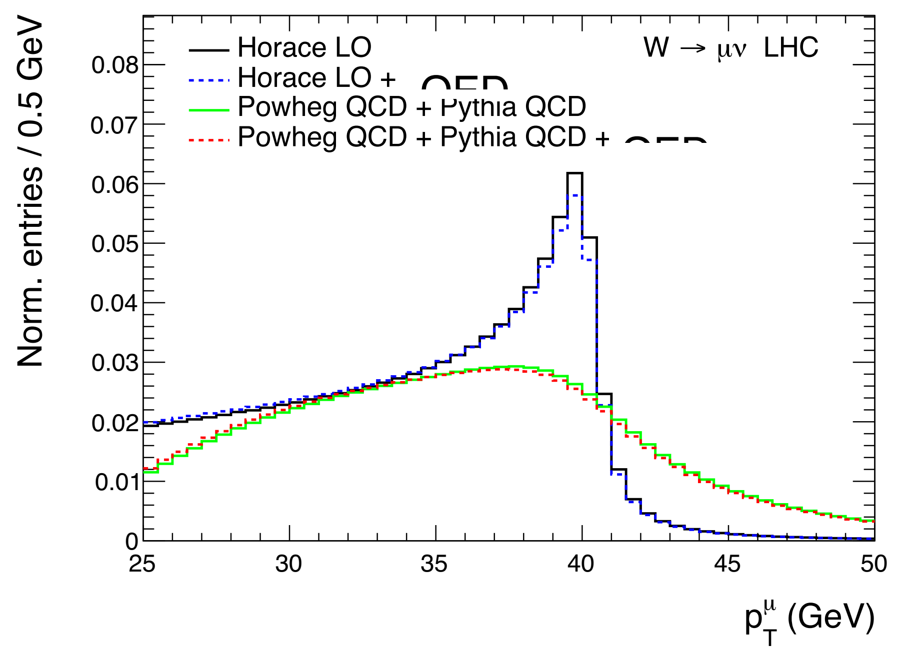

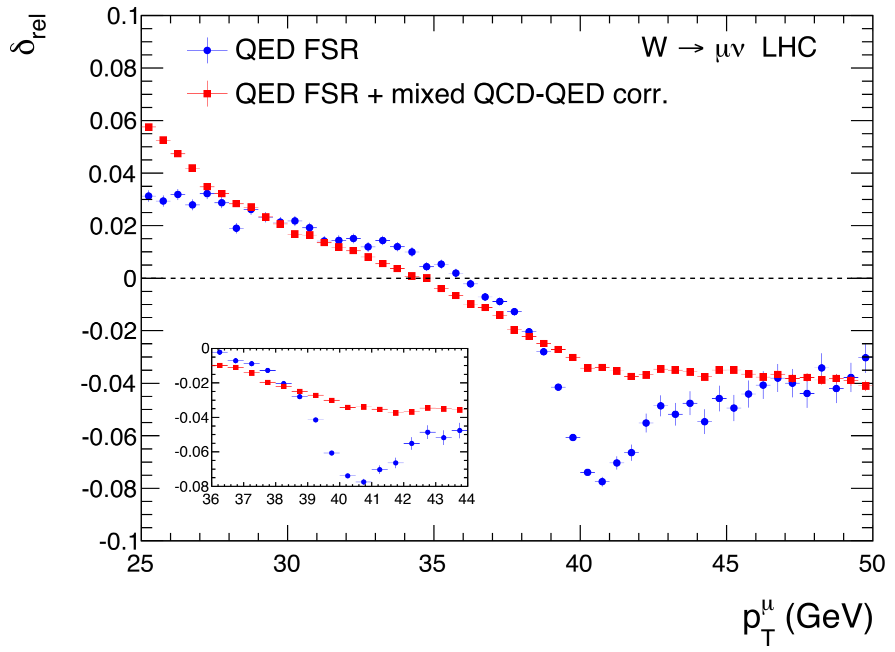

- QED FSR plays the major role
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the impact on MW of the mixed QCD QED-FSR corrections strongly depends on the underlying QCD shape/model

$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: NLO-QCD+QCD$_{PS}$ Pseudodata accuracy	 QED FSR	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	 p_T^ℓ	 $W^+ \to e^+\nu$(dres) M_T	 p_T^ℓ
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2 NLO-QCD+(QCD+QED)$_{PS}$	Photos	-88.0±0.6	-368±2	-38.4±0.6	-150±3
3 NLO-(QCD+EW)+(QCD+QED)$_{PS}$`two-rad`	Pythia	-89.0±0.6	-371±3	-38.8±0.6	-157±3
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the bulk of the corrections is included in the analyses
- what is the associated uncertainty ?
- what happens if we change the underlying QCD model ?

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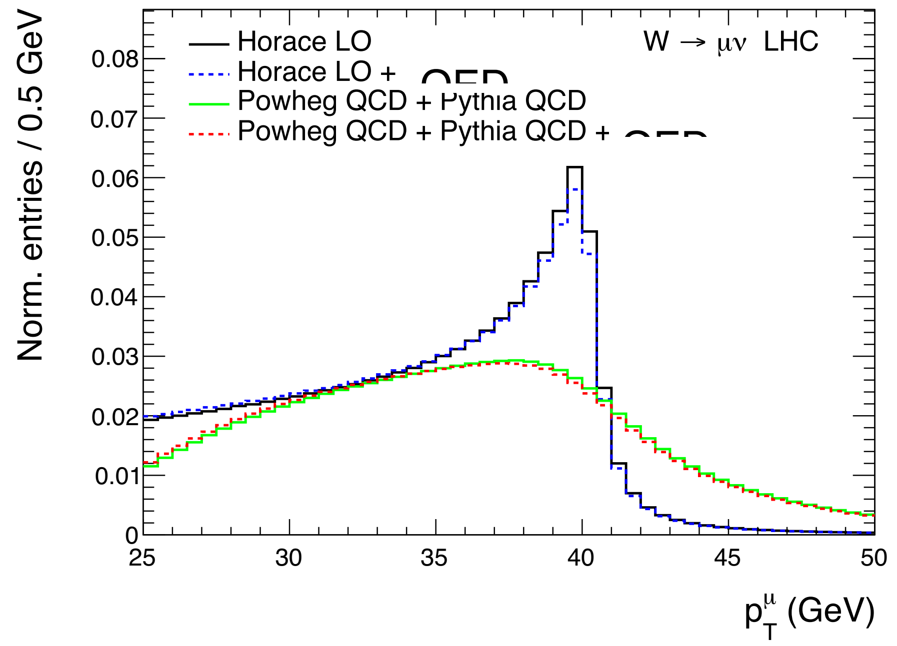

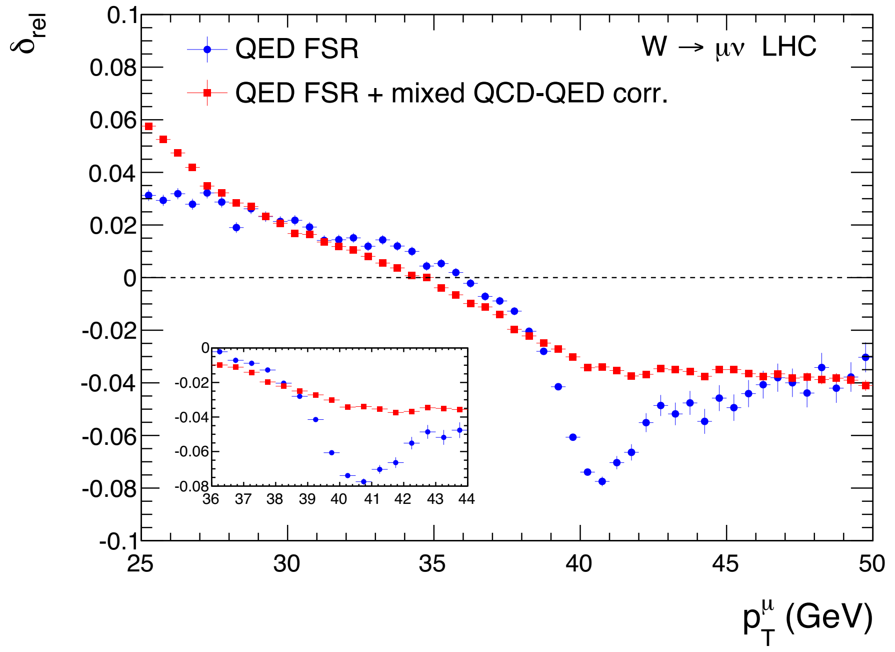

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the bulk of the corrections is included in the analyses

- what is the associated uncertainty ?
- what happens if
  we change the underlying QCD model ?

can we constrain the formulation, for the $\alpha\alpha_s$ contribution ?

very stable behaviour of the $M_\perp$ distribution in contrast to the $p_\perp^l$ case

Sensitivity to the W boson mass: covariance w.r.t. MW variations

The sensitivity to m_W can be quantified by means of a matrix of covariance w.r.t. m_W variations

$$\mathscr{C}_{ij} \equiv \langle \sigma_i \sigma_j \rangle - \langle \sigma_i \rangle \langle \sigma_j \rangle \quad \text{with} \quad \langle \sigma \rangle \equiv \frac{1}{N_W} \sum_{k=1}^{N_W} \sigma(m_W = m_W^{(k)})$$

and σ_i represents the i-th bin of the $p_\perp^\ell$ distribution

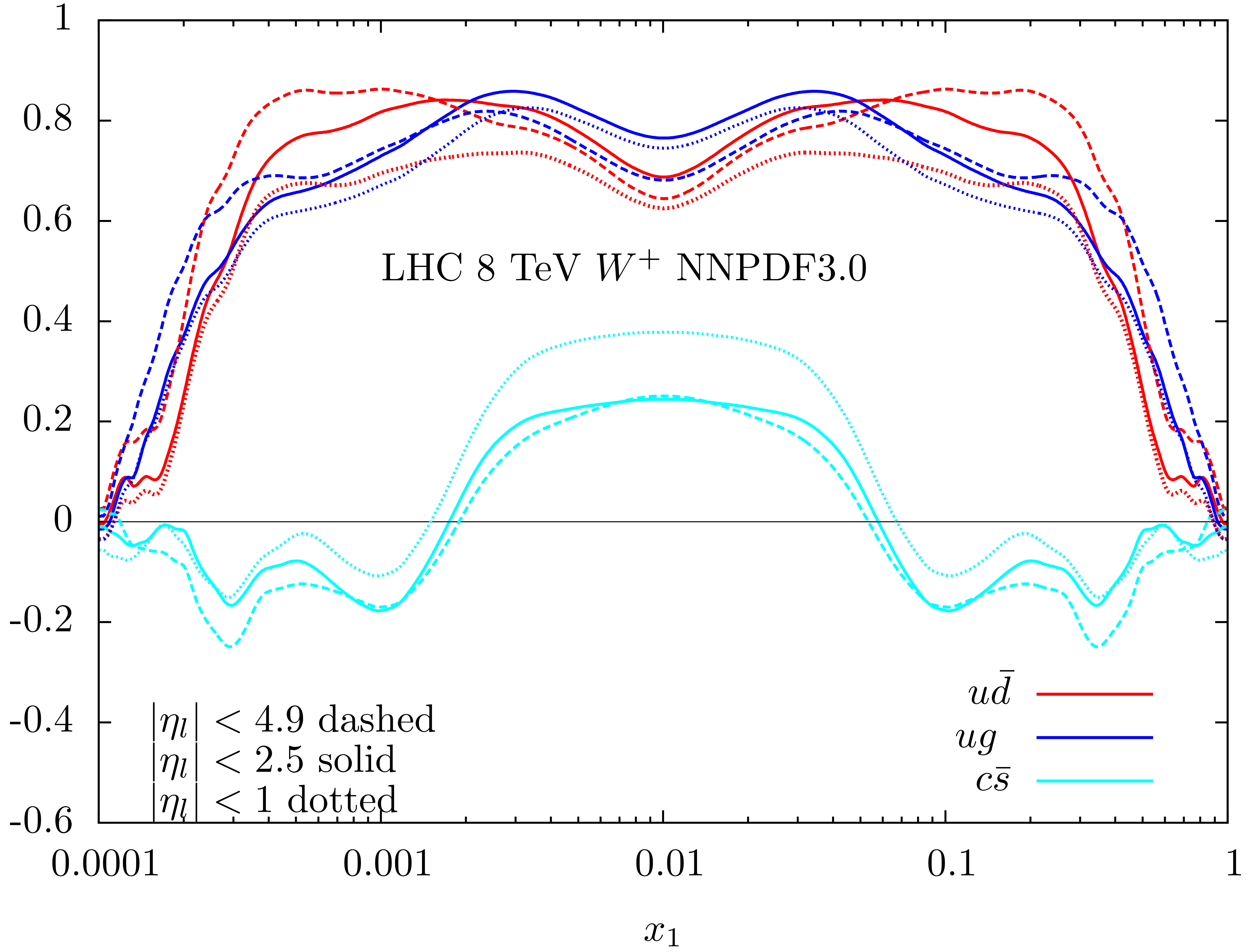
The diagonalization of the covariance matrix yields N_{bins} linear combinations of the σ_i transforming independently of each other under m_W variations

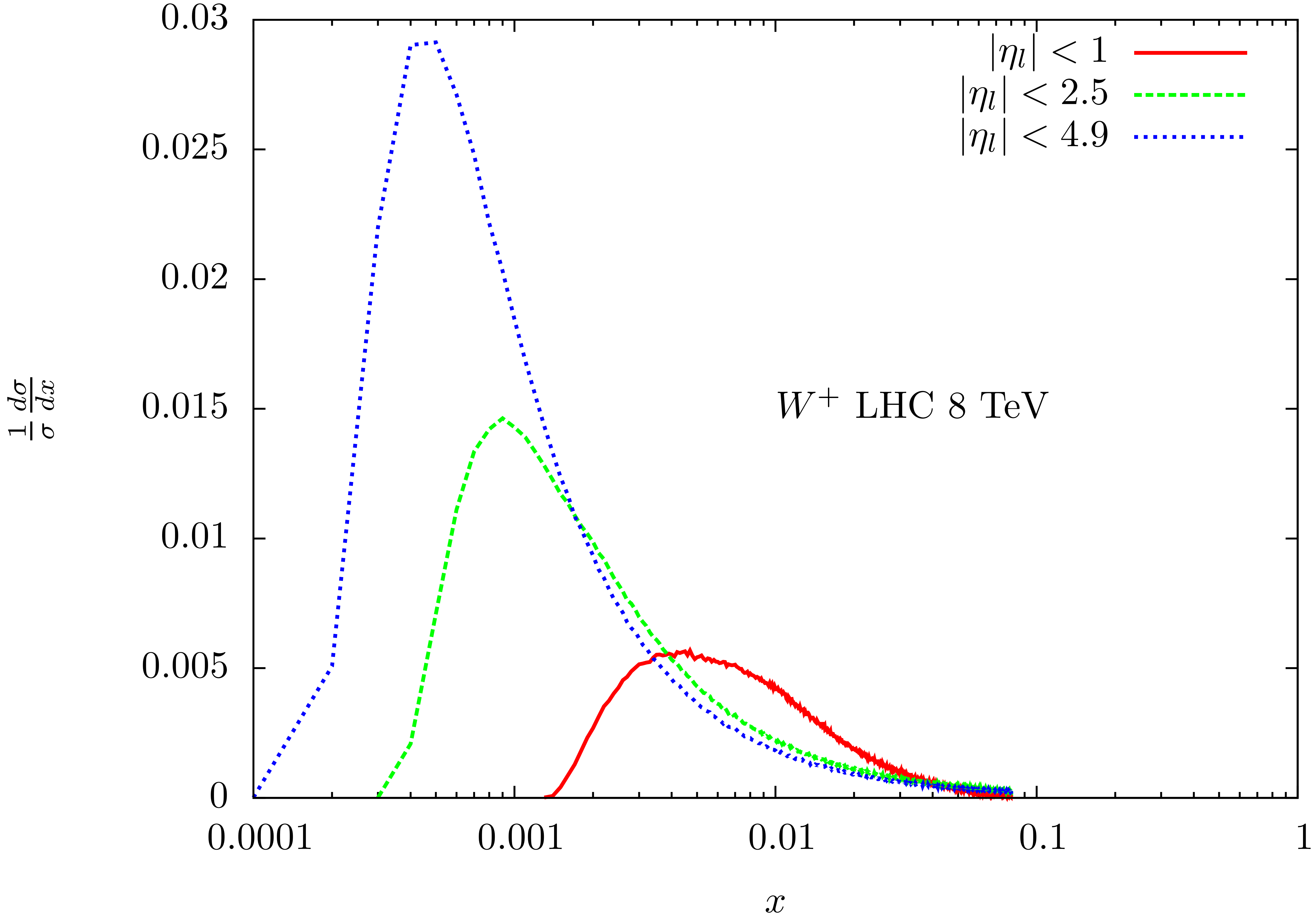
The eigenvalues express the sensitivity for a given Δm_W shift, and help classifying the different combinations

The first eigenvalue is 17 times the second one (in size)
The associated linear combination has a peculiar structure:
all coefficients are positive (negative) for $p_\perp^\ell < 37 \quad (p_\perp^\ell > 37)$ GeV
Explicit check that the value $p_\perp^\ell \sim 37$ is very stable changing QCD approximation or bin range

This value can be appreciated also in the plot of the ratio $\rightarrow$ indication for the definition of a new observable

Rapidity acceptance and the relevant partonic-x range





$$\rho(x,\tau) = \frac{\langle \mathcal{P}_{ij}(x,\tau)\frac{d\sigma}{dp_\perp^l}\rangle - \langle \mathcal{P}_{ij}(x,\tau)\rangle\langle\frac{d\sigma}{dp_\perp^l}\rangle}{\sigma^{PDF}_{\mathcal{P}_{ij}}\sigma^{PDF}_{d\sigma/dp_\perp^l}}$$

$$\frac{1}{\sigma}\frac{d\sigma}{dx}$$

PDF uncertainty on MW: exploiting the theoretical constraints

E.Bagnaschi, AV, Phys.Rev.Lett.126 (2021) 4, 041801

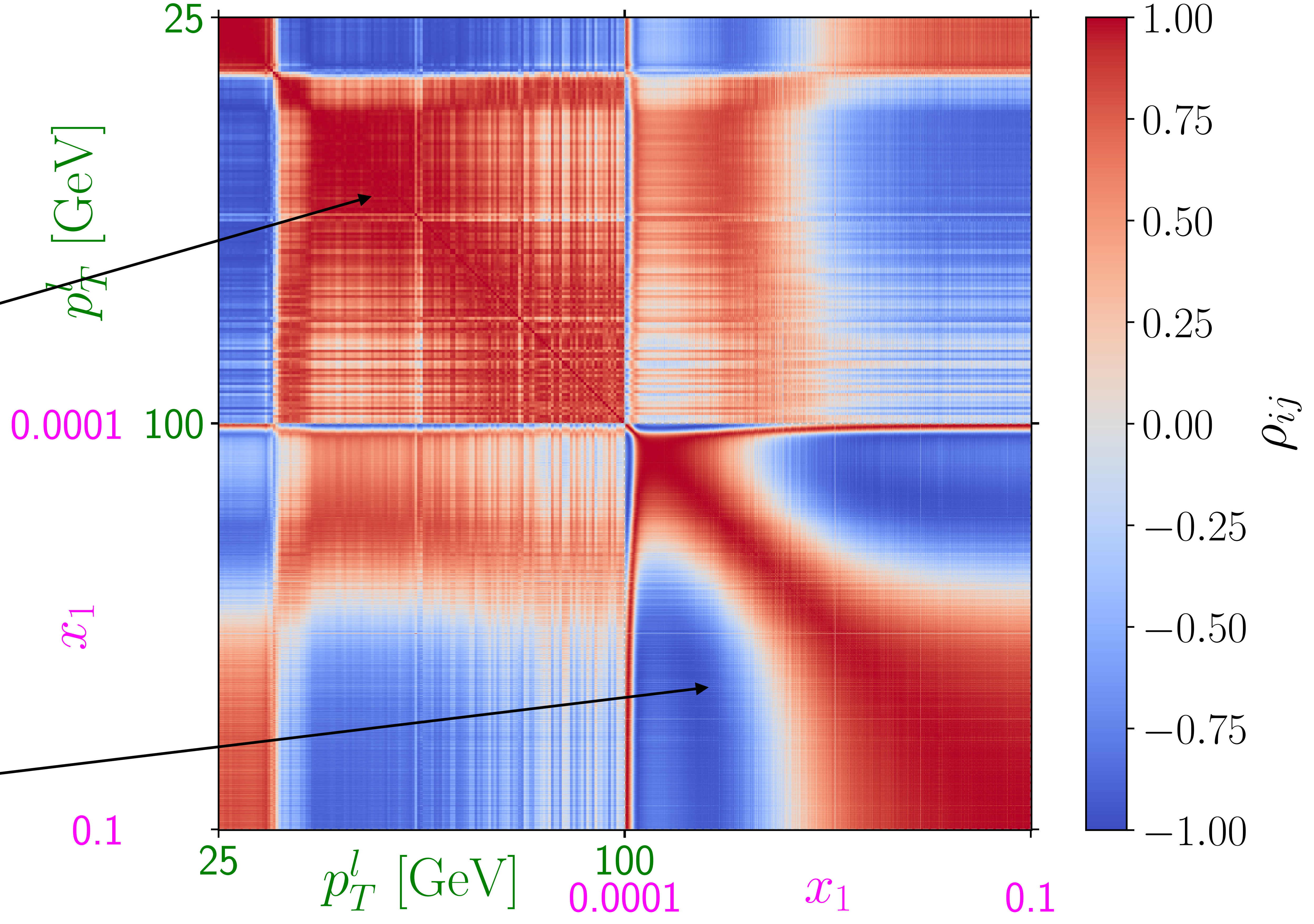
all PDF replicas are correlated because the parton densities are developed in the same QCD framework
1) obey sum rules, 2) satisfy DGLAP equations, 3) are based on the same data set

the "unitarity constraint" of each parton density affects the parton-parton luminosities, which, convoluted with the partonic xsec, in turn affect the hadron-level xsec

$$\rho_{ij} = \frac{\langle (\mathcal{O}_i - \langle \mathcal{O}_i \rangle_{PDF}) \left(\mathcal{O}_j - \langle \mathcal{O}_j \rangle_{PDF} \right) \rangle_{PDF}}{\sigma_i \sigma_j}$$

the tails of the $\frac{d\sigma}{dp_\perp^\ell}$ distribution
are strongly (anti)-correlated w.r.t. PDF variations

the tails of the $\frac{d\sigma}{dx}$ distribution
are strongly (anti)-correlated w.r.t. PDF variations



The uncertainty of PDF origin can be reduced to the few MeV level

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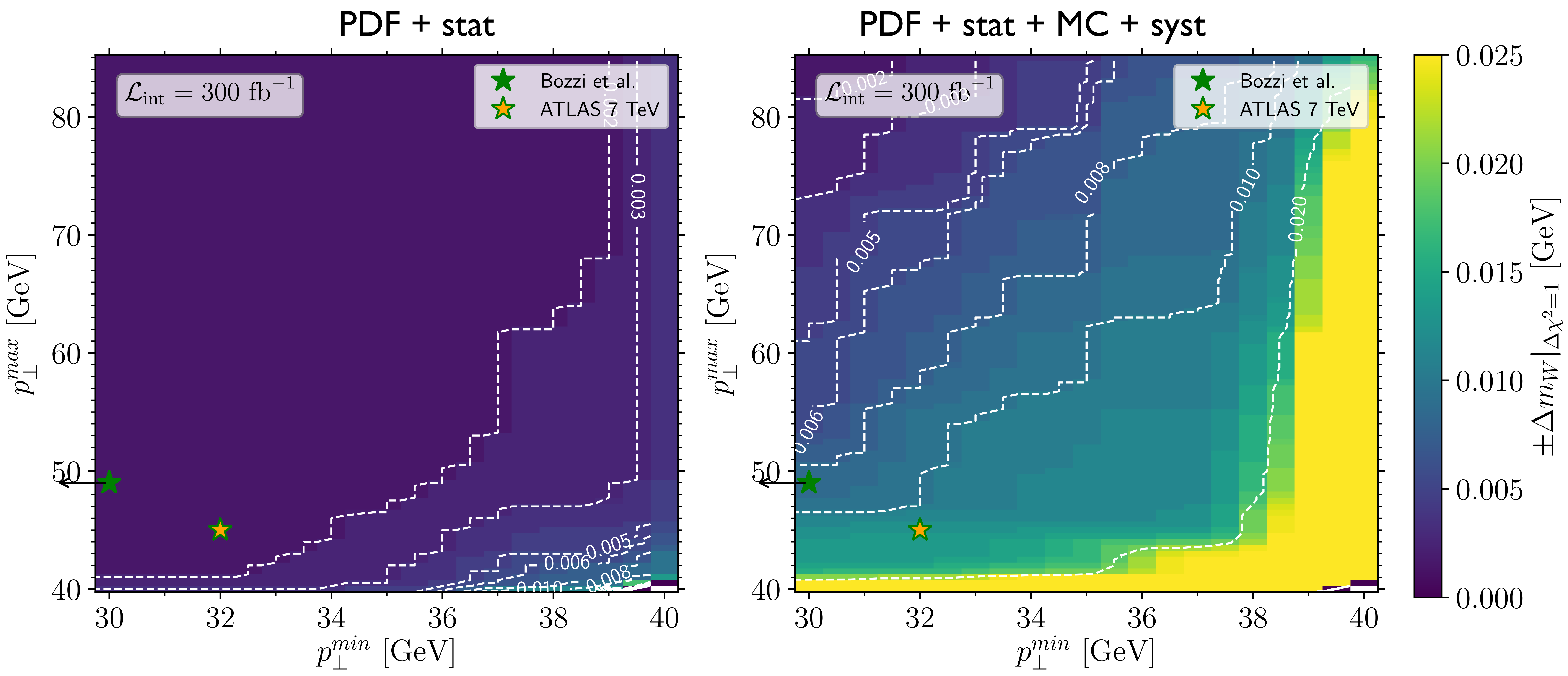
scan over fitting windows for normalised distributions



$$\chi^2_{k,min} = \sum_{r,s \in bins} \left(\mathcal{T}_{0,k} - \mathcal{D}^{exp}\right)_r C^{-1}_{rs} \left(\mathcal{T}_{0,k} - \mathcal{D}^{exp}\right)_s$$

$C = \Sigma_{PDF} + \Sigma_{stat} + \Sigma_{MC} + \Sigma_{exp\,syst}$ total covariance

total uncertainty determined with $\Delta\chi^2 = 1$ rule

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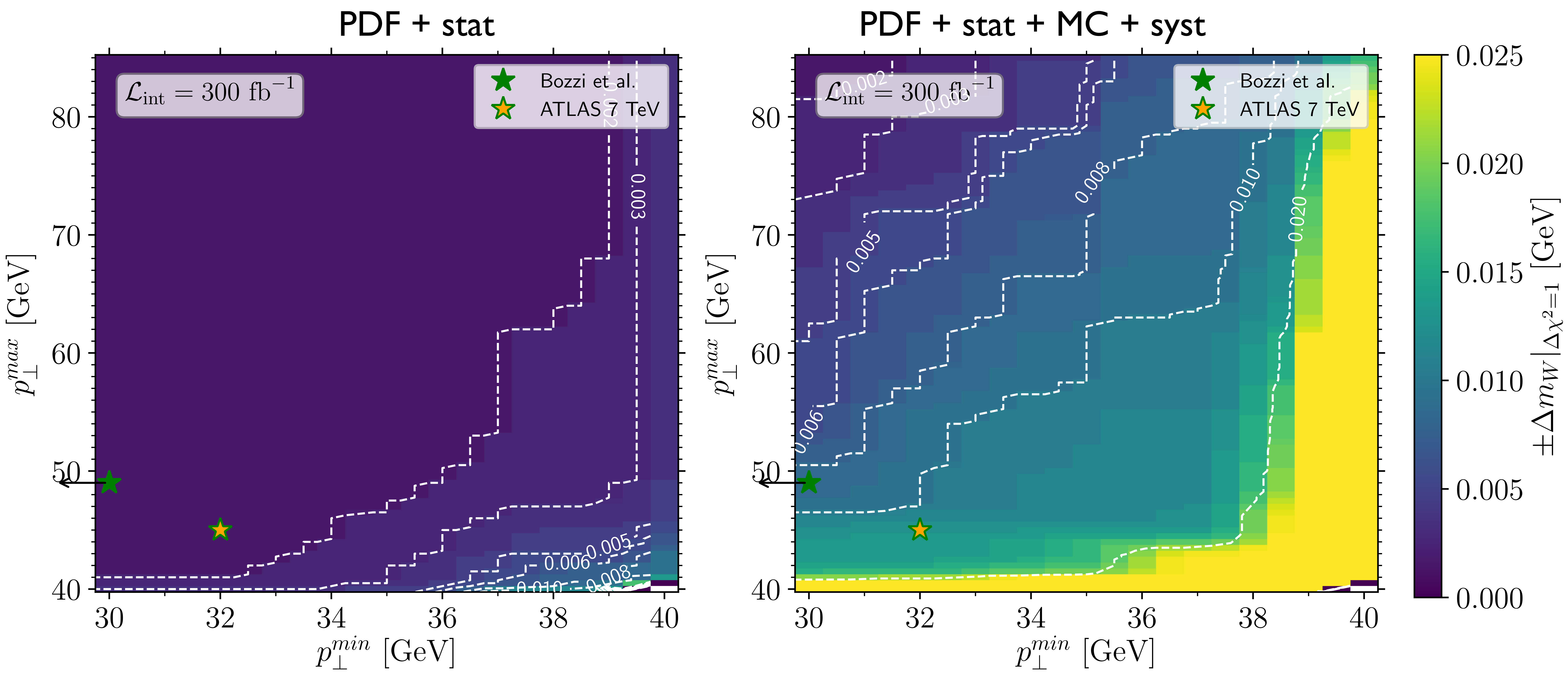

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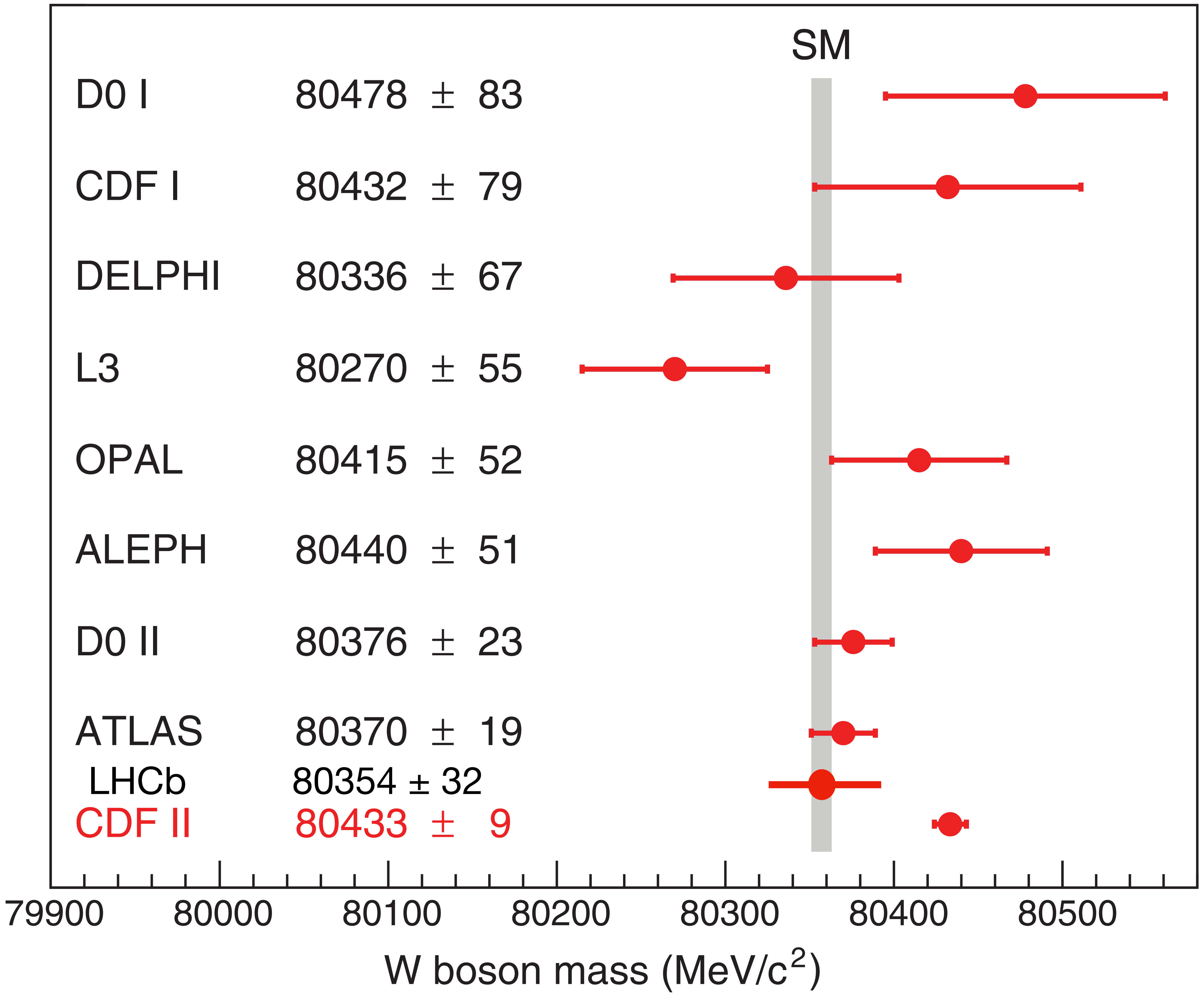
$C = \Sigma_{PDF} + \Sigma_{stat} + \Sigma_{MC} + \Sigma_{exp\,syst}$ total covariance

total uncertainty determined with $\Delta\chi^2 = 1$ rule

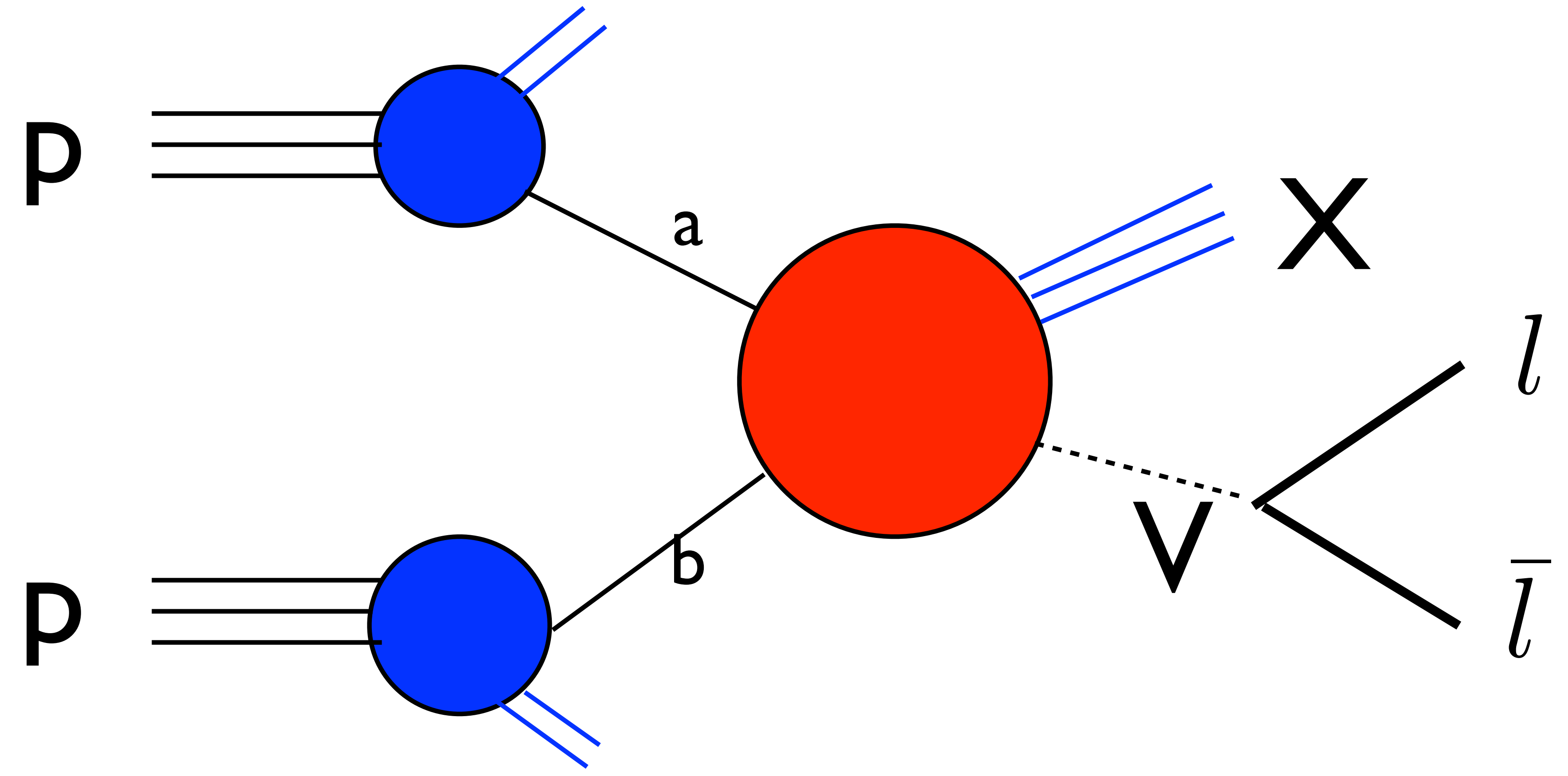
- The PDF uncertainty is not a limiting factor for MW with high luminosity and a "perfect" detector
- The MC statistics needed is of at least O(100B) of simulated events (several weeks on 1000 cores cluster)

Outline of the talk

- The Drell-Yan kinematical distributions and the m_W determination
- The modelling of the QCD effects and the difficult estimate of the associated uncertainties
- Proposal of a new observable, suitable for a transparent discussion of the uncertainties on m_W



MW determination at hadron colliders



- In charged-current DY, it is NOT possible to reconstruct the lepton-neutrino invariant mass
  Full reconstruction is possible (but not easy) only in the transverse plane

- A generic observable has a linear response to an m_W variation
  With a goal for the relative error of 10^{-4}, the problem seems to be unsolvable

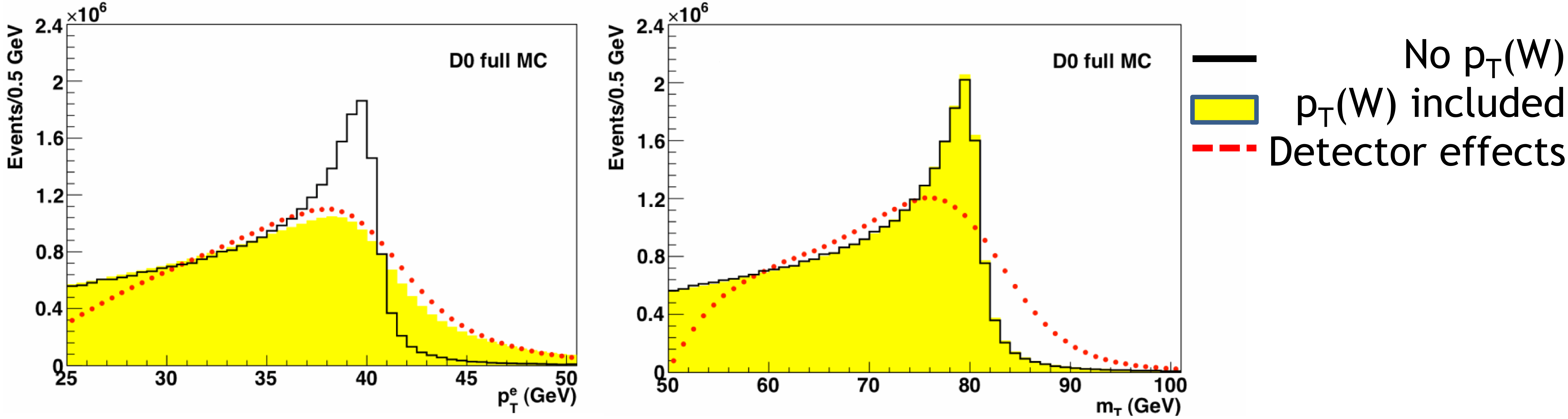
- m_W extracted from the study of the shape of the $p_\perp^l, M_\perp$ and $E_\perp^{miss}$ distributions in CC-DY
  thanks to the jacobian peak that enhances the sensitivity to m_W

$$\frac{d}{dp_\perp^2} \to \frac{2}{s}\frac{1}{\sqrt{1-4p_\perp^2/s}}\frac{d}{d\cos\theta} \sim \frac{d}{dp_\perp^2} \to \frac{2}{s}\frac{1}{\sqrt{1-4p_\perp^2/m_W^2}}\frac{d}{d\cos\theta}$$

$\rightarrow$ enhanced sensitivity at the 10^{-3} level ($p_\perp^l$ distribution) or even at the 10^{-2} level ($M_\perp$ distribution)

MW determination at hadron colliders

problems are due to
- the smearing of the distributions due to difficult neutrino reconstruction
- sensitivity to the modelling of initial state QCD effects



MW determination at hadron colliders: template fitting

Given one experimental kinematical distribution

- we compute the corresponding theoretical distribution for several hypotheses of one Lagrangian input parameters (e.g. m_W)
- we compute, for each $m_W^{(k)}$ hypothesis, a χ^2_k defined in a certain interval around the jacobian peak (fitting window)
- we look for the minimum of the χ^2 distribution

The m_W value associated to the position of the minimum is the experimental result

A determination at the 10^{-4} level requires
a control over the shape of the distributions at the per mille level

The theoretical uncertainties of the templates
contribute to the theoretical systematic error on m_W