Università degli Studi di Milano

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Ultimate precision in the determination of electroweak parameters at hadron colliders

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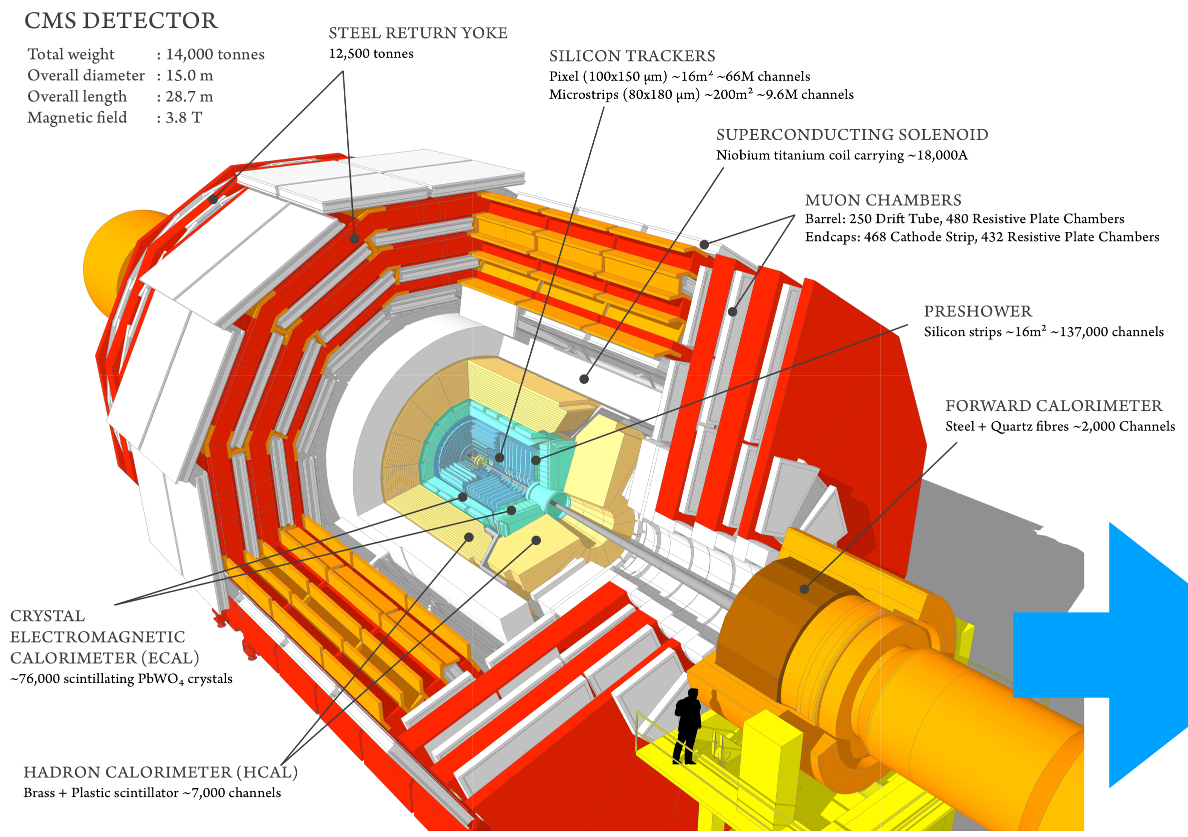
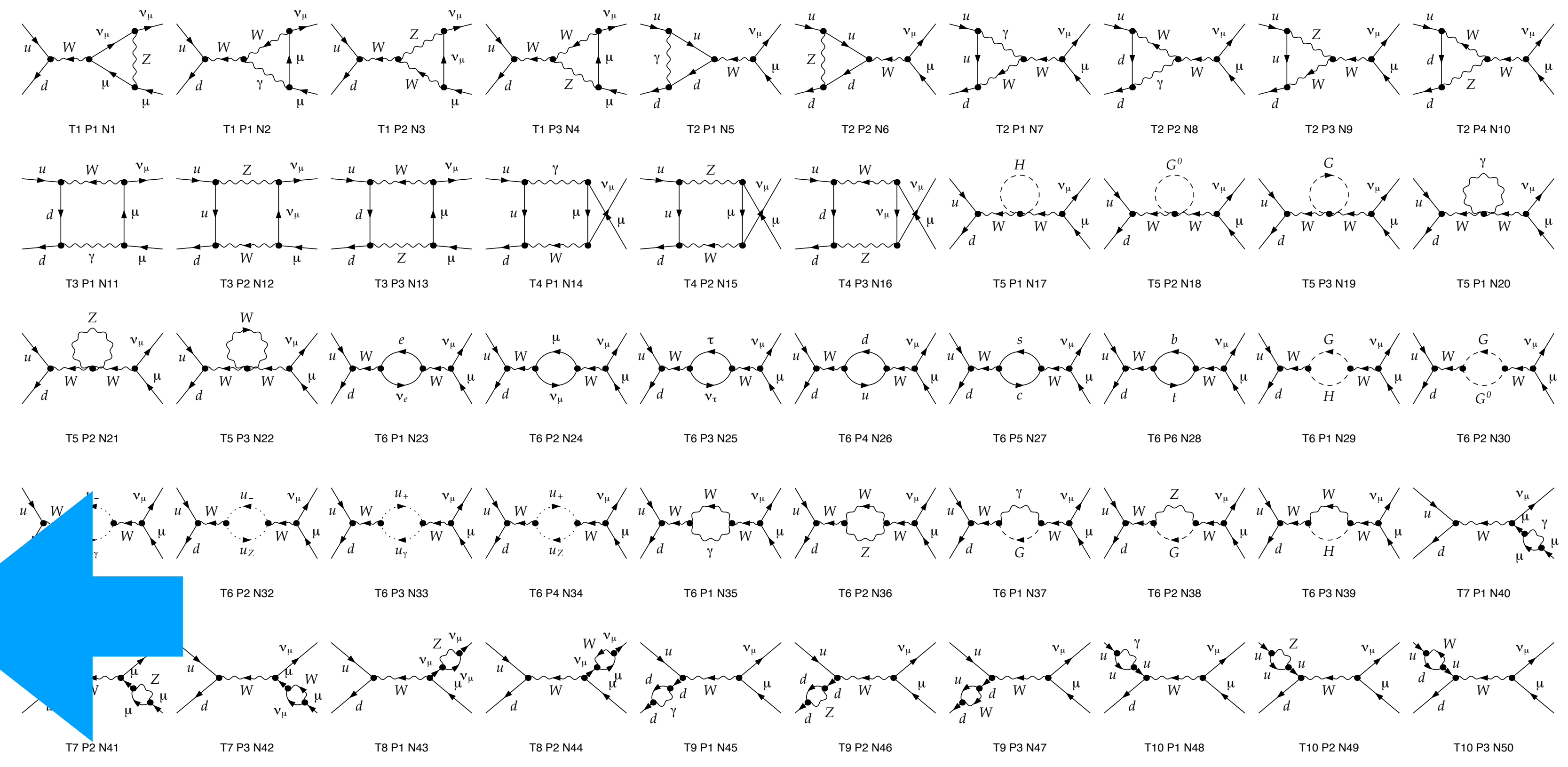
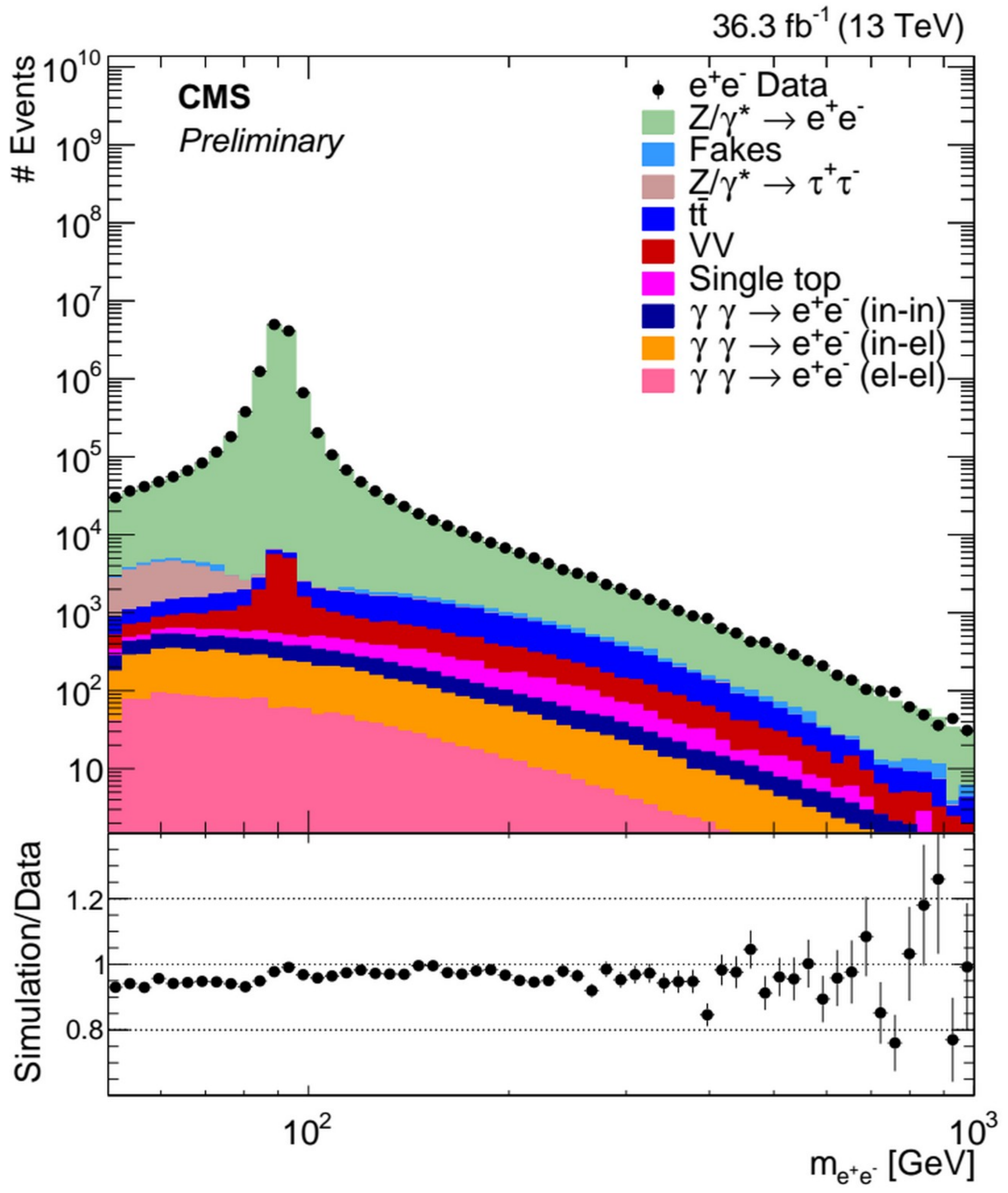
Schematic description of the tests of the SM at hadron colliders



1) comparison of the experimental distributions against the theoretical predictions

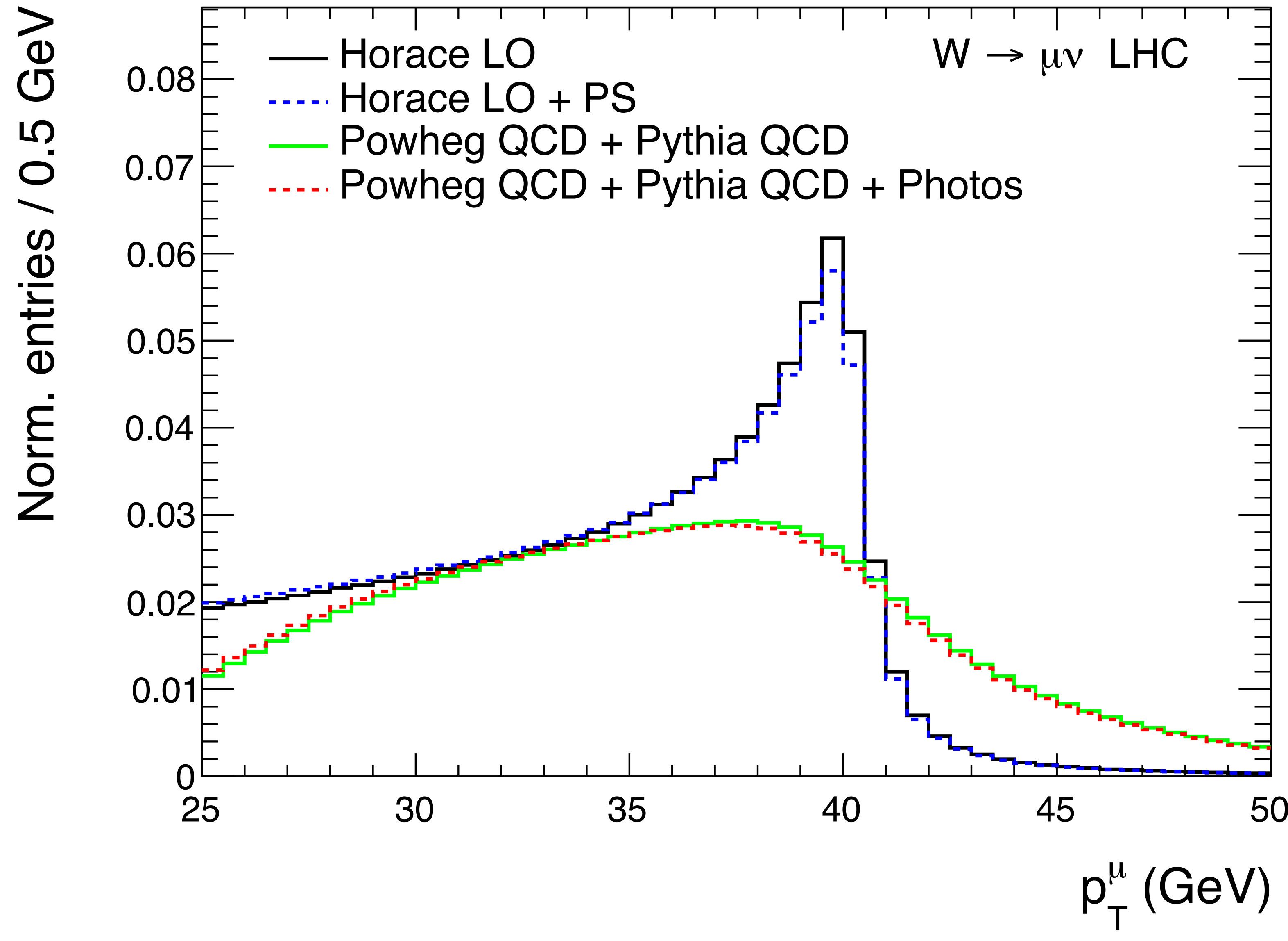
2) fit of the SM Lagrangian parameters using the theoretical histograms as templates





Different sources of systematic uncertainty are present on both sides and affect the fit results:

- imprecise data
- imprecise predictions
- inaccurate templates
  (perturbative and non-perturbative uncertainties)



Can we quantify our current uncertainties ?
If yes, can we attempt a long-term estimate of the ultimate precision ?

Basic questions

- how much does non-perturbative physics affect the determination of the EW parameters ?

  can the progress in perturbative calculations help to reduce the impact of these uncertainties ?

  can we optimise the choice of the observables ?

- how does the precision physics program link to the BSM searches ?

Perturbative calculations: QCD

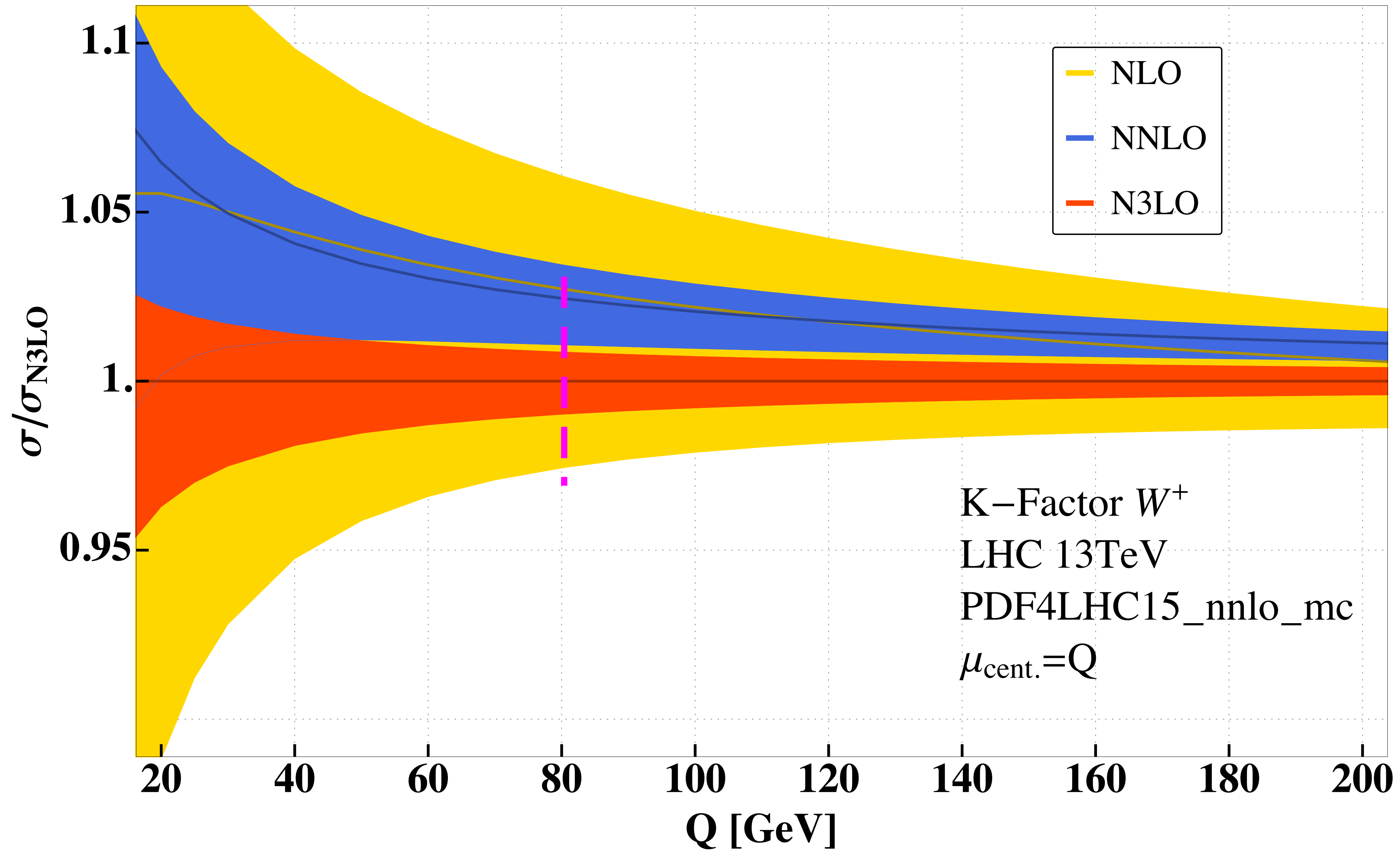
focus on the recent perturbative progress

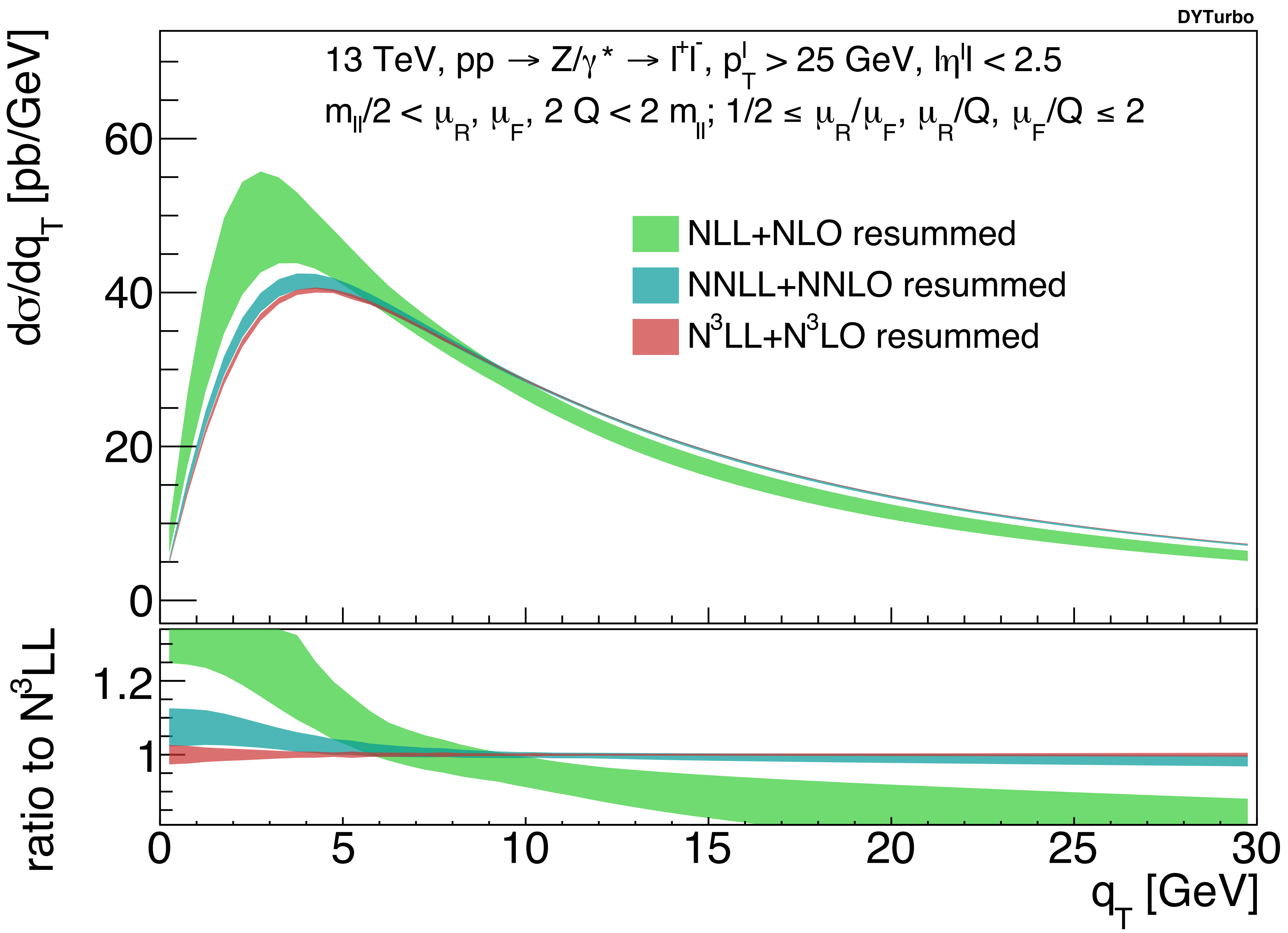
- N3LO-QCD results available for the total cross section (full phase-space) (Duhr et al., arXiv: 2001.07717, 2007.13313)
- N3LO+N3LL QCD available in DYTurbo (including fiducial cuts) (Camarda et al., arXiv:2103.04974)
- NNLO-QCD at large ptV +N3LL-QCD at small ptV available in RadISH (Bizon et al., arXiv:1805.05916)

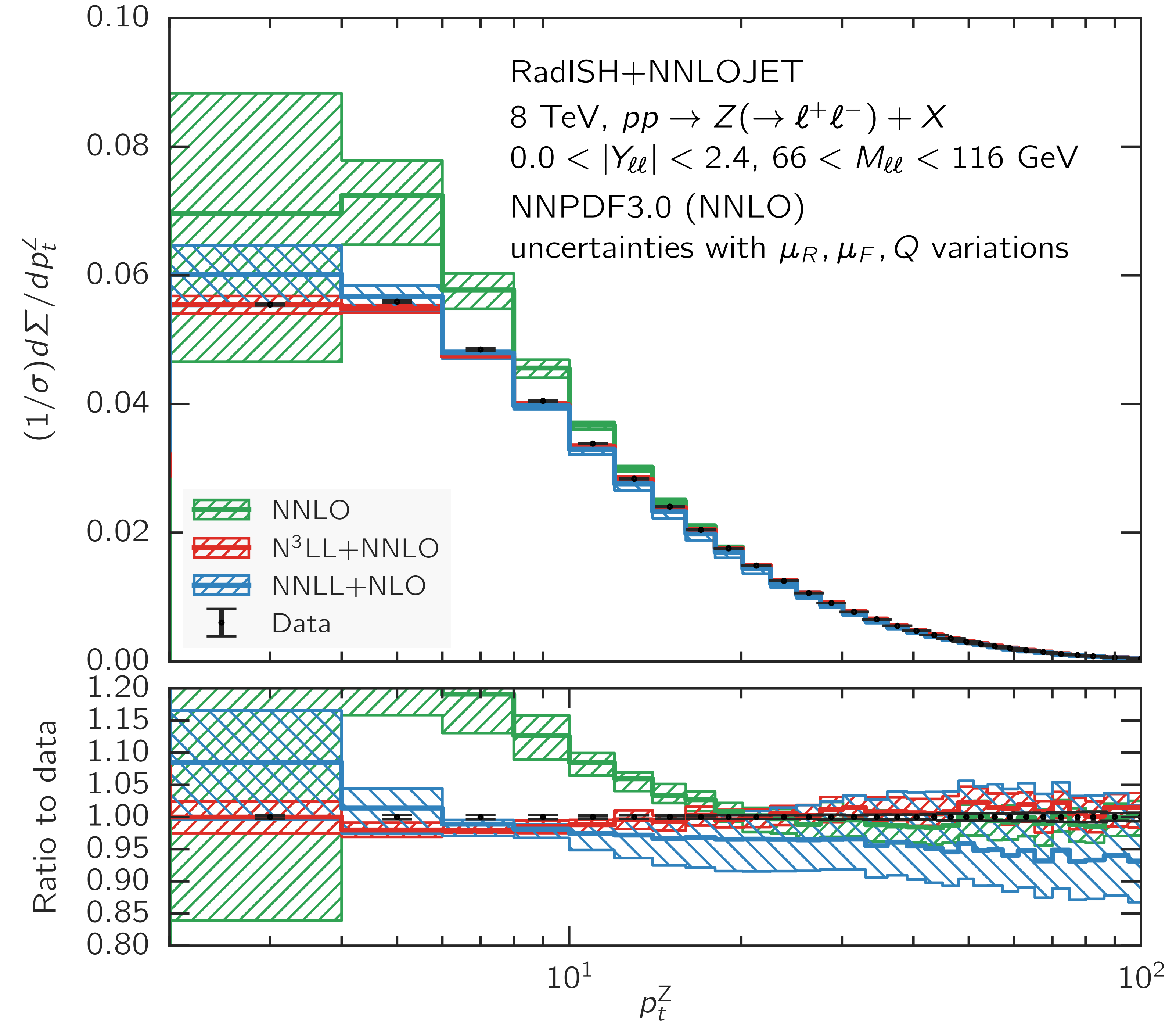
→ canonical scale variations show a significant reduction of the uncertainty bands

→ work in progress in the EW WG to have a systematic assessment of resummation ambiguities (ask Bozzi)

Perturbative calculations: QCD







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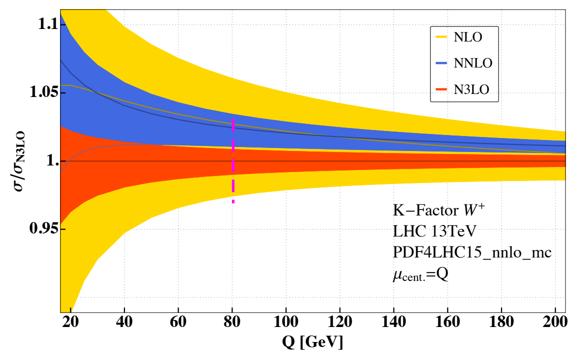

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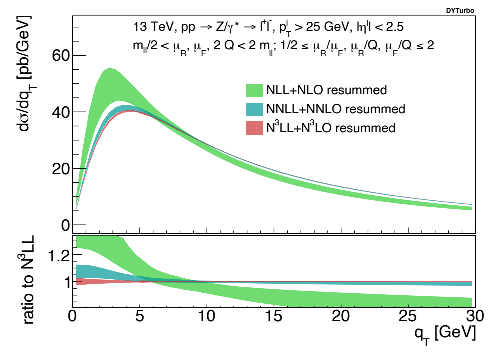

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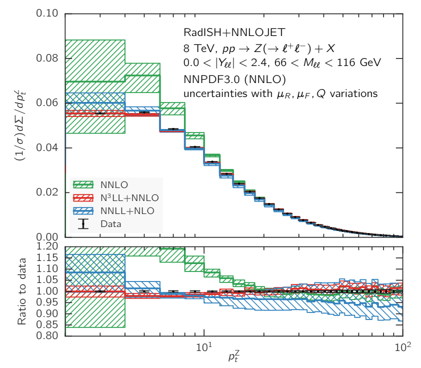

The improved predictions of the kinematical distributions allow a more significant test of the SM

How can we translate/apply these improvements to the determination of EW parameters ?
Is a purely perturbative description sufficient to describe the data?
If not, where is a non-perturbative component needed ?
How does such a non-perturbative component affect the EW parameters determination ?

Perturbative calculations: EW

- NLO-EW matched with QED Parton Shower
  HORACE, POWHEG, (MC@NLO??)
  → relevance of the matching to reduce the QED-PS ambiguities (e.g. Photos vs PYTHIA-QED)

important differences between NC-DY and CC-DY for the size of QED and weak effects (understood)
the size of multiple photon radiation is relevant for the precise determination of EW parameters (understood)

different matching recipes still unexplored
the size of the corrections depends on the observable
important interplay with QCD radiation
(size of the residual uncertainties is relevant for the precise determination of EW parameters,   in progress)

Perturbative calculations: EW

	$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: LO Pseudo–data accuracy	M_W shifts (MeV)			
		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$	
		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
5	PHOTOS FSR-LL	-92±1	-100±2	-182±1	-199±2

	$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: NLO-QCD+QCD$_{\text{PS}}$ Pseudodata accuracy	QED FSR	M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
			M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{\text{PS}}$	PYTHIA	-95.2±0.6	-400±3	-38.0±0.6	-149±2
2	NLO-QCD+(QCD+QED)$_{\text{PS}}$	PHOTOS	-88.0±0.6	-368±2	-38.4±0.6	-150±3
3	NLO-(QCD+EW)+(QCD+QED)$_{\text{PS}}$two-rad	PYTHIA	-89.0±0.6	-371±3	-38.8±0.6	-157±3
4	NLO-(QCD+EW)+(QCD+QED)$_{\text{PS}}$two-rad	PHOTOS	-88.6±0.6	-370±3	-39.2±0.6	-159±2

Perturbative calculations: QCD-EW

	$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: LO Pseudo–data accuracy	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	 p_T^ℓ	 $W^+ \to e^+\nu$ M_T	 p_T^ℓ
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- in the past, various combinations of NLO-QCD and NLO-EW results (additive or multiplicative in different implementations)
- the ambiguities are terms of $\mathcal{O}(\alpha\alpha_s)$, possibly subleading in a logarithmic counting;

  are they numerically small ? the answer is observable dependent

  the ambiguity can be fixed and pushed to the next perturbative order by means of a fixed-order calculation

  → Wednesday morning

- mixed QCD-EW effects depend also on the underlying non-perturbative QCD model (and its parameters)

  can we quantify also the uncertainties on these contributions ? (they can not be pushed to the next order)

Perturbative calculations and their interplay with non-perturbative effects

so far we discussed the partonic cross section, its perturbative content and the missing non-perturbative complements
now let's start from the incoming protons

the structure of the proton - has an intrinsic non-perturbative component, which we measure from the data
- satisfies a perturbative evolution ruled by DGLAP equations (for standard DY observables)

the longitudinal component is expressed via collinear PDFs → it affects all the observables that involve
the longitudinal component of the final-state 4-momenta
the transverse component can be - expressed via TMDs
- moved to the QCD Parton Shower parameters + Underlying Event models

Each formulation has a specific matching of its perturbative and non-perturbative components
The success of a formulation depends on its universality, so that it can be used to predict new observables,
but also to estimate the associated uncertainties → collinear PDFs are a striking example

To what extent do modelling effects bring us outside the SM ?
Are we determining the SM Lagrangian parameters, or those of a SM-based model ?

the non-perturbative (NP) component is physics which we can not describe in a perturbative approach (obviously!!!)

if BSM physics is expected to be at a very large scale, and absent in the proton, then NP effects are simply "difficult" SM physics

if the proton has a BSM component, we need a different discussion (later, not now)

remaining in the SM realm,

MW is determined fitting a kinematical distribution; the result is affected by intrinsic-kt / PDF choice

if we were able to compute in the SM non-perturbative effects, then we would have complete SM templates to fit MW;

since we are not able, we then build models, which are SM-inspired, but possibly different than the "SM solution"

I see two elements: the accuracy of the model (how close is it to the non-perturbative SM solution)

the error on the modelling (how precisely are its parameters tuned)

can we "deconvolute" such effects and get closer to the Lagrangian parameter, by means of different observables ?

Example: the charged-lepton pt distribution

- improved understanding of the PDF uncertainties on the distribution and on MW
- what is the dependence on the intrinsic kt? how much does it depend on the ptZ calibration?

Which test are we performing ?

- excellent measurement of the DY kinematical distributions:
  - which is the precise definition of a DY event ? (e.g. is it true that photon-induced processes are distinguishable ?)
  - to what extent DY observables rely on low-energy calibration?
  - how many independent d.o.f. can we consider, combining charged- and neutral current DY ?

- how do we test the SM ?
  - how many parameters are we "allowed" to tune to maximise the agreement between the data and the Monte Carlo ?
  - if a modelling component is necessary to describe the data, can we say that we are still testing the SM ?
  - do we use a P-value to express the likelihood of the SM ?
    is a good P-value a necessary condition to start the precision fit of MW or $\sin^2\theta_{eff}^{lep}$?

Precision measurements, SM tests and the link to BSM searches

- a bad χ^2 or a low P-value can signal the existence of a tension between the SM and the data

  such a tension could emerge if we try to simultaneously describe, in the SM, the W/Z resonances and the TeV tails
  (→ the most precise SM predictions are needed simultaneously at both energy scales)

  we might expect that such a tension translates, in a fit based on the SMEFT,
  into a significant non-vanishing value of the Wilson coefficients of some higher-dimension operators

- are the parameters of the d=4 operators on the same footing of the Wilson coefficients of the d=6,8,… operators ?
  are $M_W, \sin^2\theta_{eff}^{lep}, \ldots$ going to change their best-fit value, to accomodate a better high-energy description ?