Università degli Studi di Milano

Istituto Nazionale di Fisica Nucleare

Few aspects of electroweak phenomenology at hadron colliders

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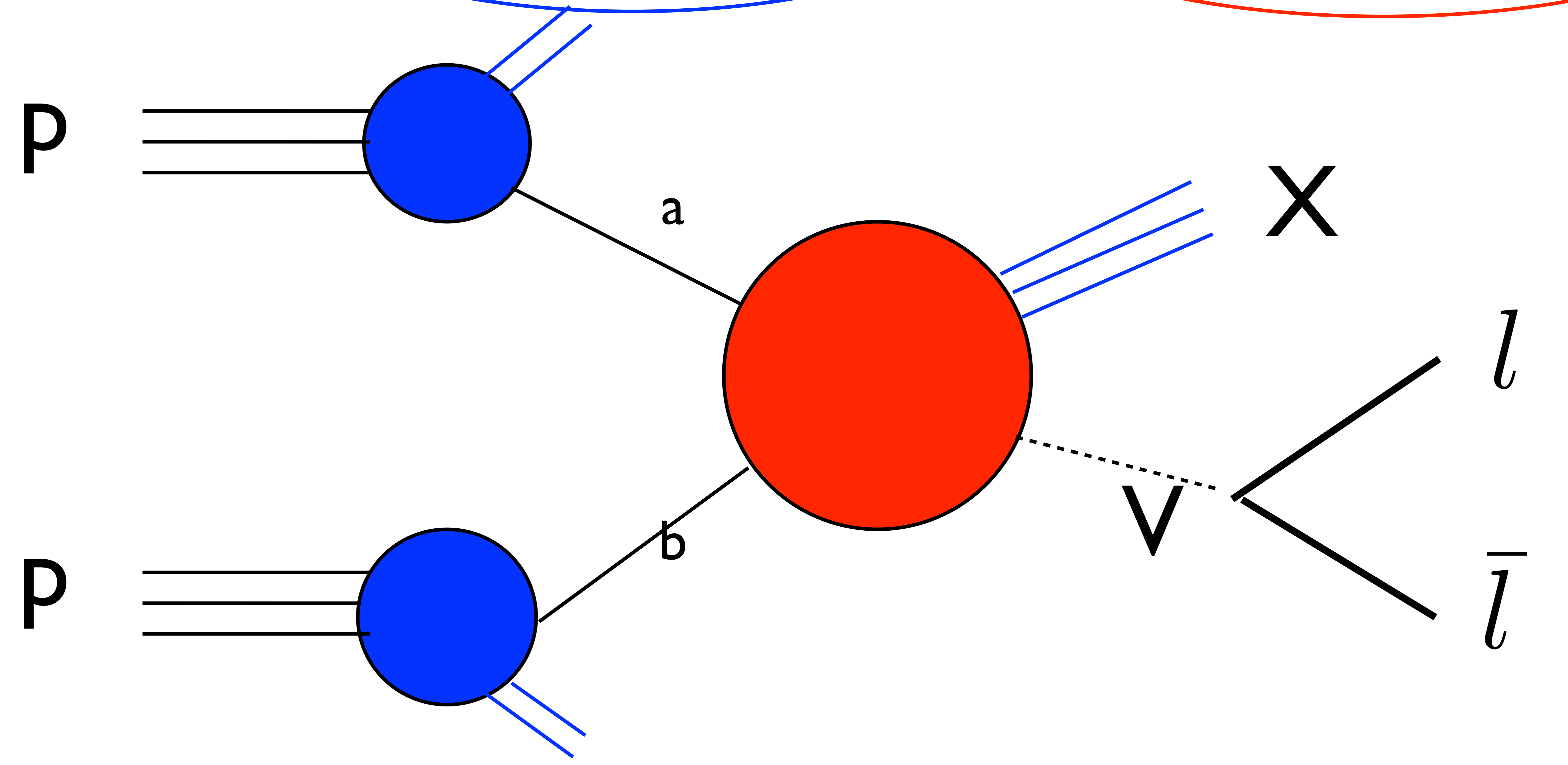
Outline of the lecture

- Phenomenology of the EW quantum corrections. QED effects, weak effects, interplay in higher orders.
- Scattering processes at a hadron collider: QCD, EW and mixed QCD-EW corrections
- Resonance-aware matching: algorithmic issues with two competing interactions
- Exact calculations with full off-shell description vs on-shell expansions.
- photon and leptons

Hard scattering at hadron colliders

$$\sigma(P_1, P_2; m_V) = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_{h_1,a}(x_1, M_F) f_{h_2,b}(x_2, M_F) \, \hat{\sigma}_{ab}(x_1 P_1, x_2 P_2, \alpha_s(\mu), M_F)$$



e.g. the Drell-Yan process

The factorisation theorems guarantee the validity of the above picture up to power correction effects

The interplay of QCD and EW interactions appears both in the partonic cross section and in the proton PDFs

- the partonic cross section receives both QCD and EW perturbative corrections
- the DGLAP evolution of the proton PDFs is achieved with a QCD+QED kernel

Electroweak corrections

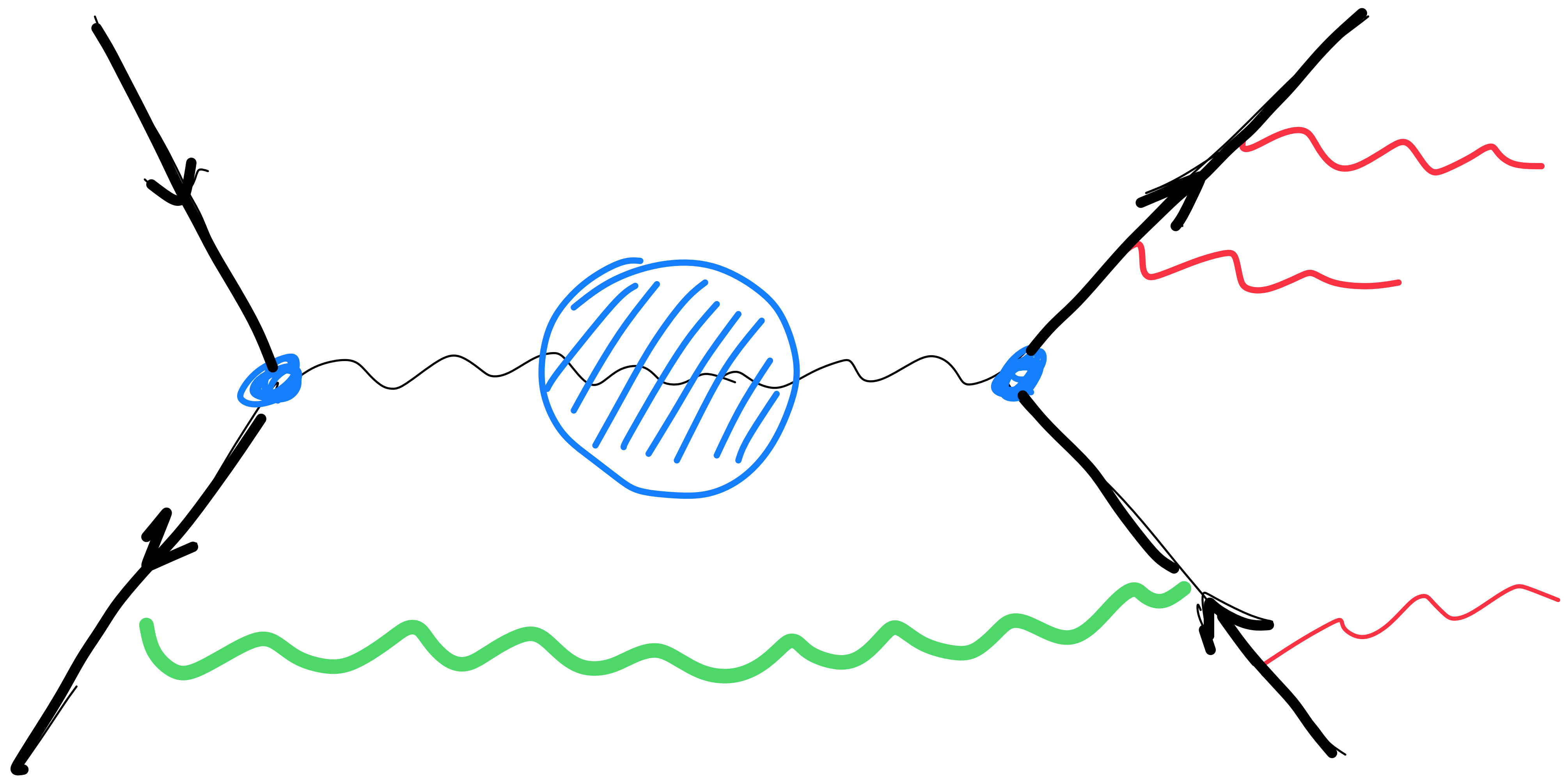
EW corrections: QED and weak effects

- Three main sources of large EW corrections:

  - coupling redefinition

  - QED real radiation

  - EW virtual Sudakov logarithms



Breakdown of the NLO-EW corrections to $q\bar{q} \to \mu^+\mu^-$

$$\sigma(q\bar{q} \to \mu^+\mu^- + X) \;=\; \sigma_0 + \frac{\alpha}{2\pi}\sigma_\alpha + \cdots \qquad \sigma_\alpha \;=\; \sigma_\alpha^{QED} \;+\; \sigma_\alpha^{weak}$$

$$\sigma_\alpha^{QED} \;=\; \sigma_\alpha^{QED,real} \;+\; \sigma_\alpha^{QED,virt} \;=\; \sigma_\alpha^{QED,LL} \;+\; \sigma_\alpha^{QED,remainder}$$

$$\sigma_\alpha^{weak} \;=\; \sigma_\alpha^{weak,virt} \;=\; \sigma_\alpha^{weak,renormalization} \;+\; \sigma_\alpha^{weak,Sudakov} \;+\; \sigma_\alpha^{weak,remainder}$$

The separation of QED and weak effects is not possible in general, in presence of a charged-current interaction

EW corrections: coupling constants and higher-order universal effects

- Given a scheme with $(\alpha(0), G_\mu, m_Z, m_H)$ as input parameters (renormalisation completed) can we improve our predictions, with the systematic inclusion of higher-order corrections ?

- at (N)NLO , the LO couplings receive radiative corrections, stemming from self-energy and vertex corrections

  we identify in these corrections some universal contributions, independent of the process details (scales, external particles)

  we can include up to 2-loop and possibly higher-loop contributions

$$\alpha(0) \to \alpha(m_Z) = \frac{\alpha(0)}{1 - \Delta\alpha(m_Z)} \qquad \Delta\alpha(m_Z) \sim 0.07$$

$$\sin^2\theta_W \to \sin^2\bar{\theta}_W \equiv \sin^2\theta_W + \Delta\rho\cos^2\theta_W$$

$$\Delta\rho = 3x_t\left[1 + \rho^{(2)}(m_H^2/m_t^2)x_t\right]\left[1 - \frac{2\alpha_s}{9\pi}(\pi^2+3)\right]$$

with $3x_t = \dfrac{3\sqrt{2}G_\mu m_t^2}{16\pi^2} \sim 0.01$

EW corrections: coupling constants and higher-order universal effects

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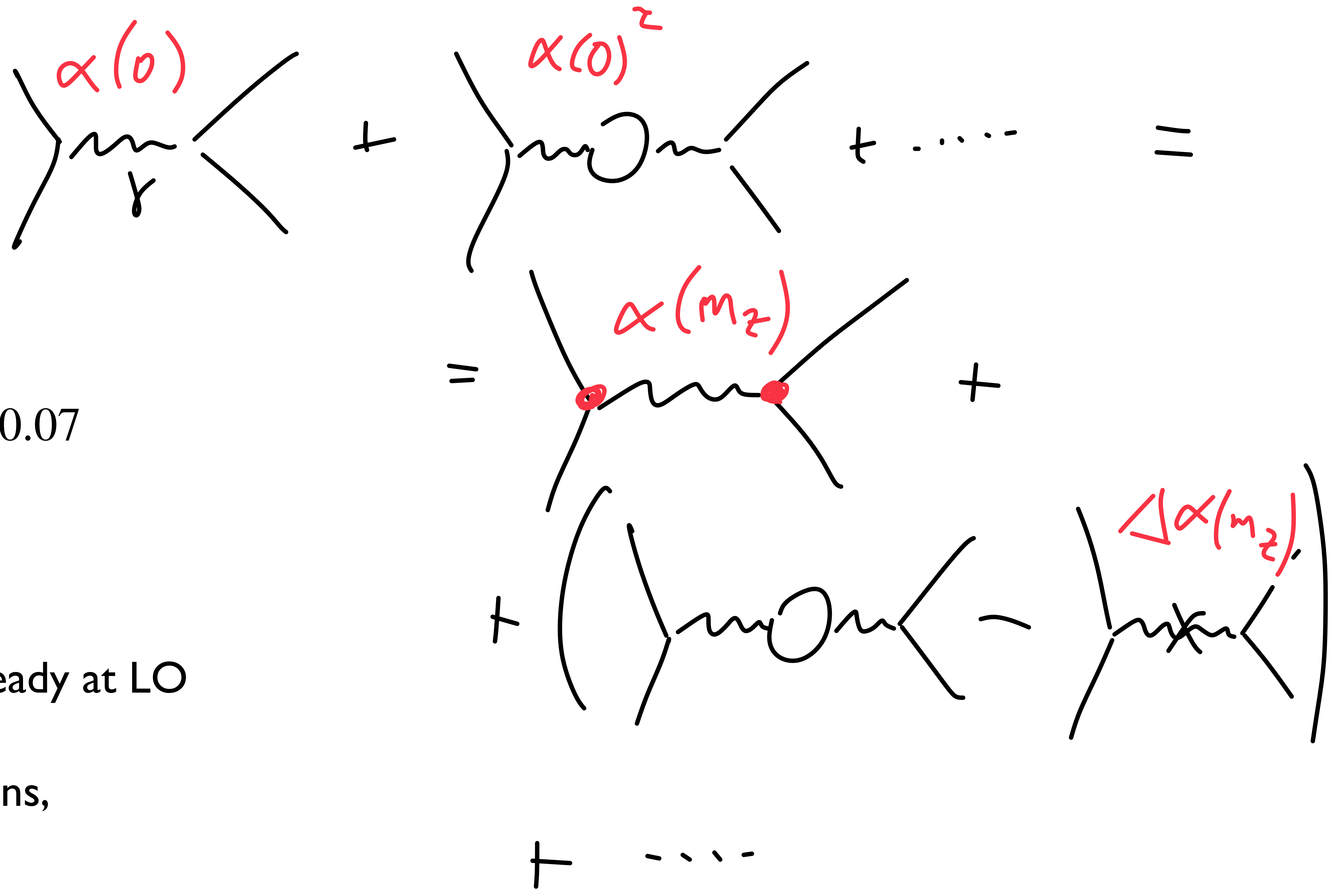
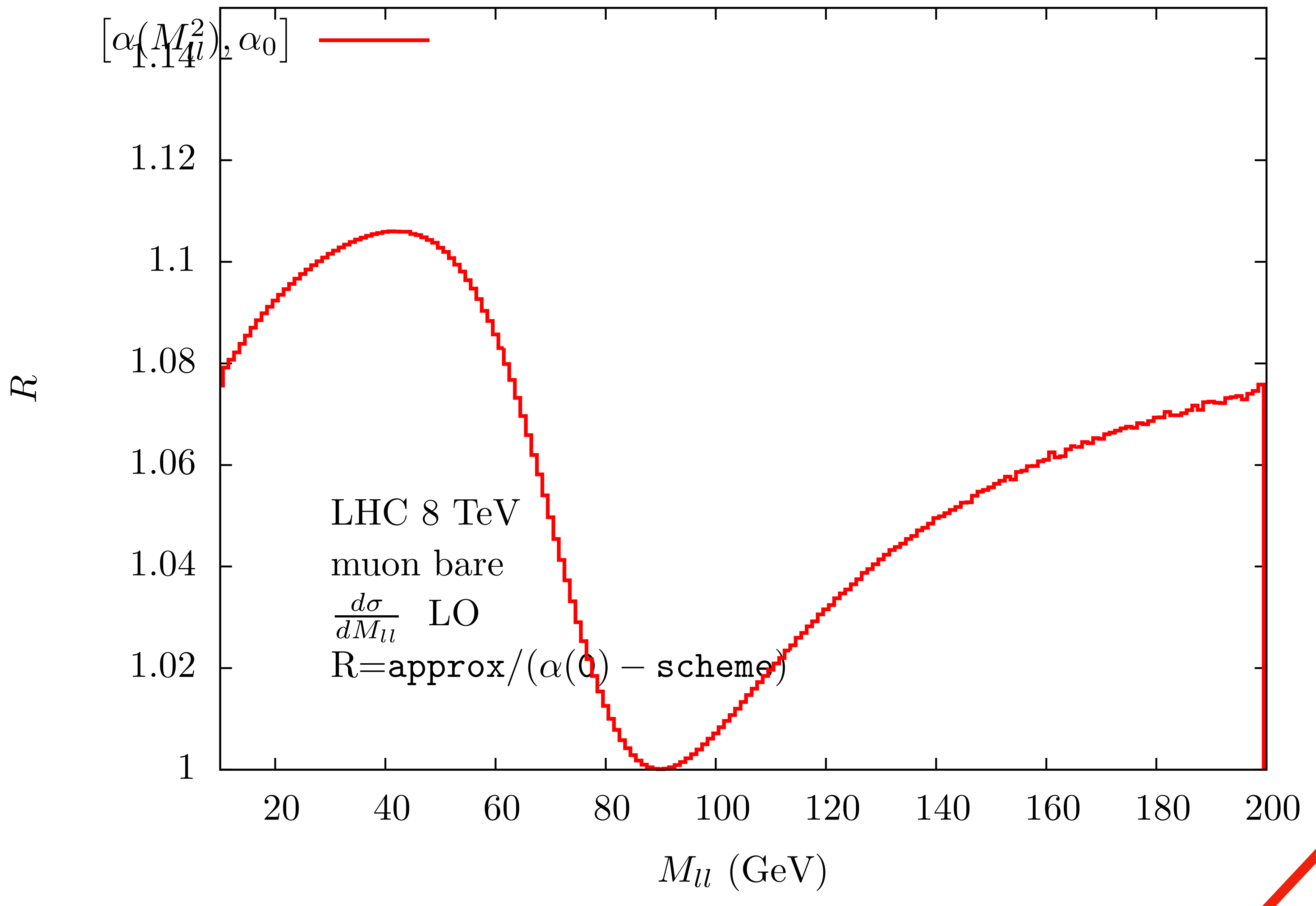


$$\alpha(0) \to \alpha(m_Z) = \frac{\alpha(0)}{1-\Delta\alpha(m_Z)} \qquad \Delta\alpha(m_Z) \sim 0.07$$

A proper choice of the couplings can yield
a more accurate description of the data already at LO

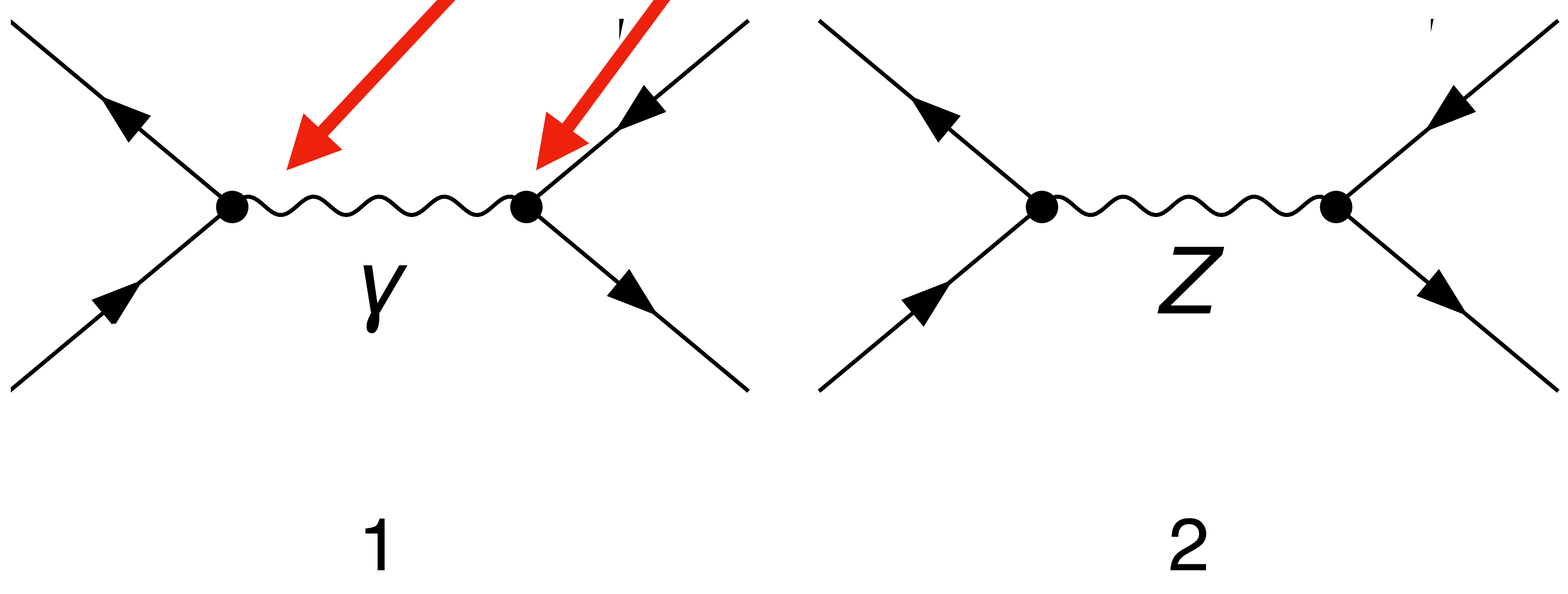
caveat: upon inclusion of (N)NLO corrections,
double counting must be removed !

Beyond LO approximation in neutral current Drell Yan

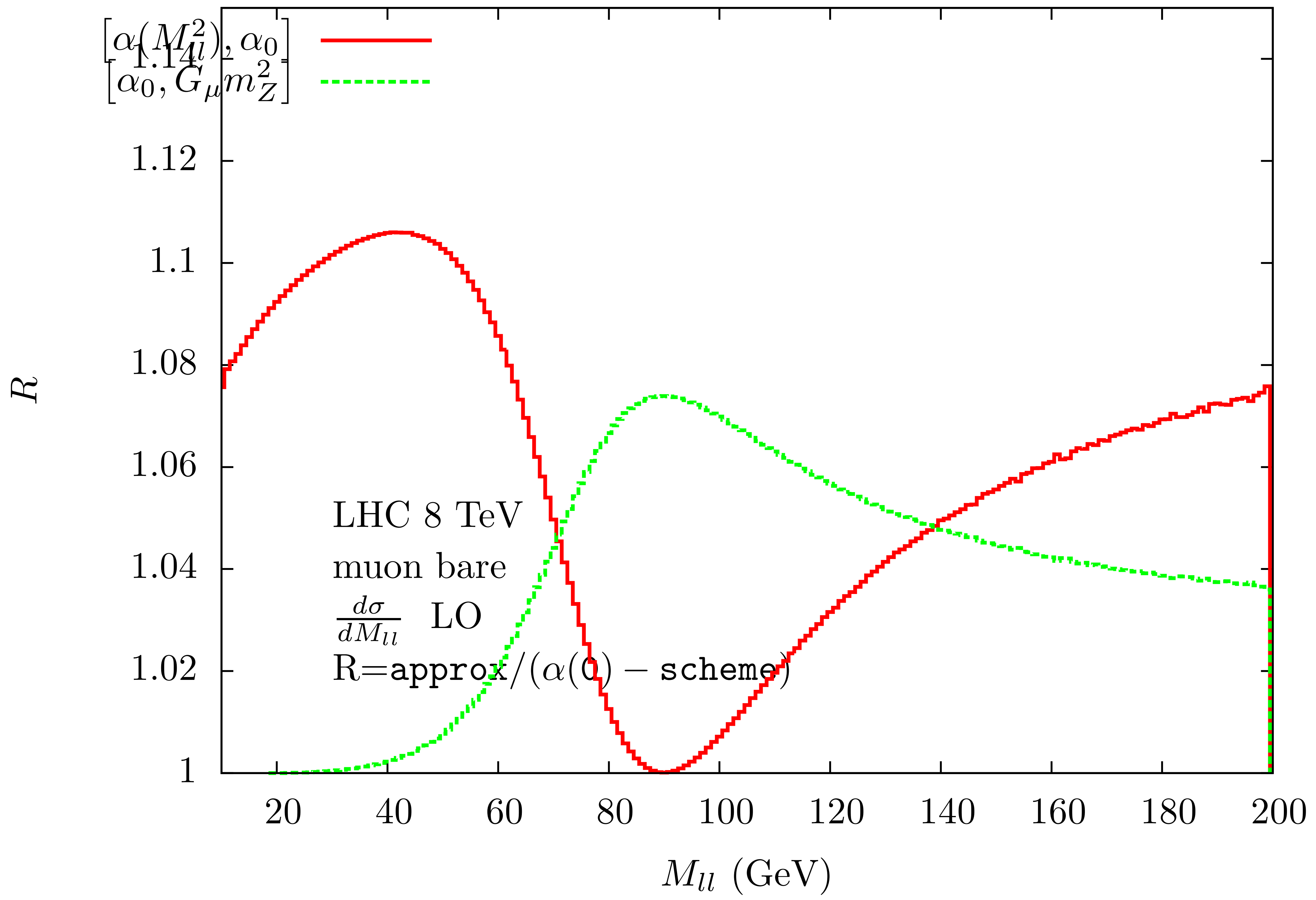


Running of α only in the photon diagram
enhances the photon exchange contribution
which grows with the invariant mass

$$\alpha(0) \to \alpha(M_{\ell\ell}^2)$$

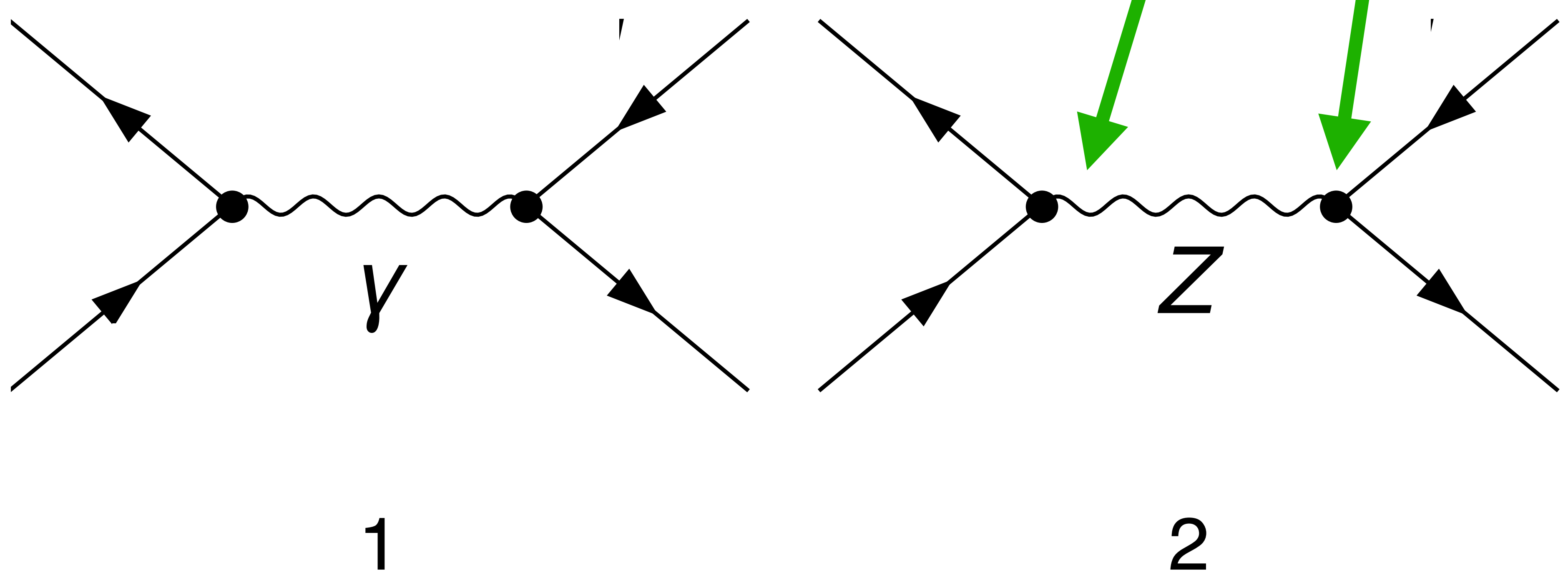


Beyond LO approximation in neutral current Drell Yan



Use of G_μ only in the Z diagram enhances the peak of the Z resonance

$\alpha(0) \to G_\mu$



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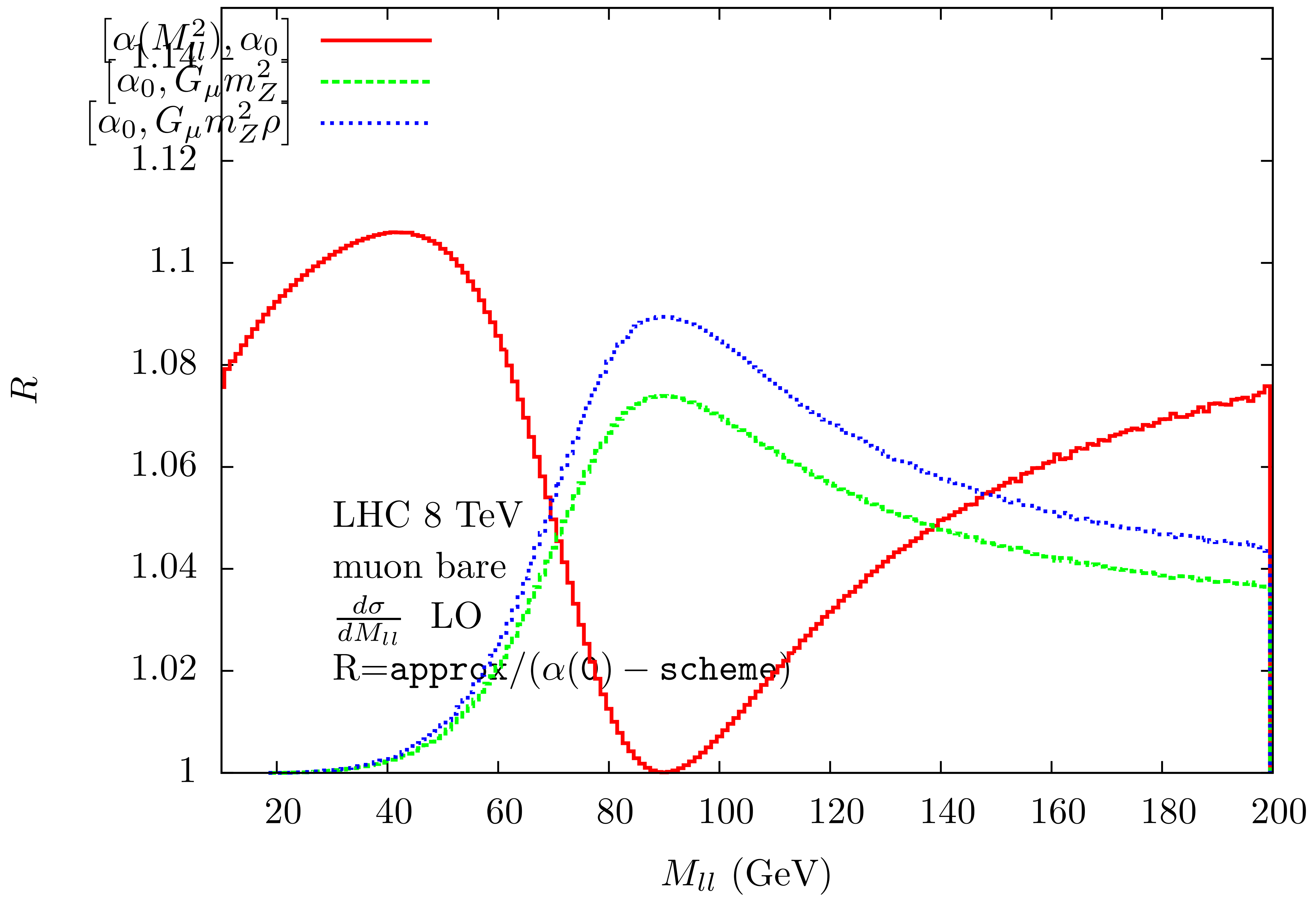
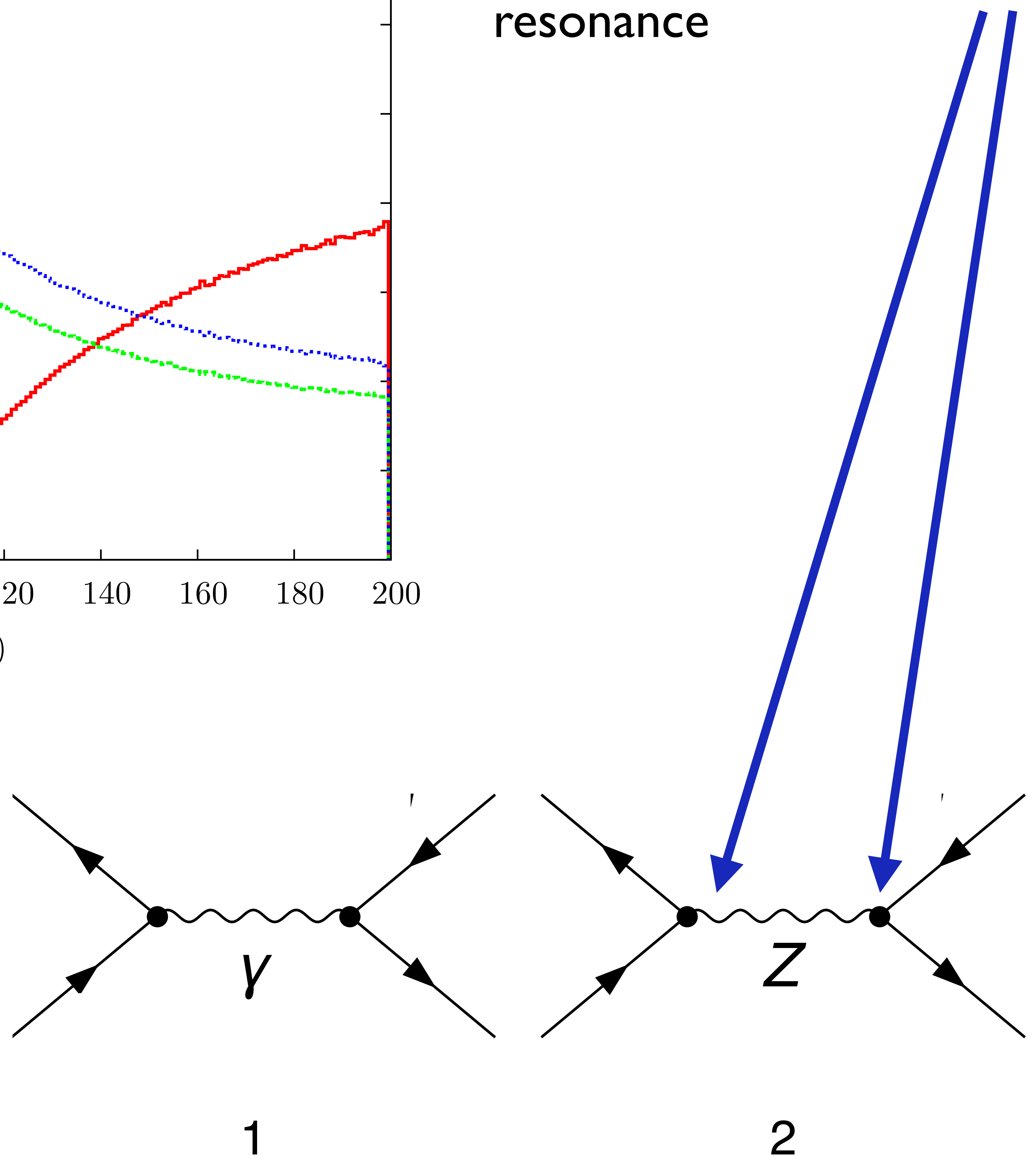
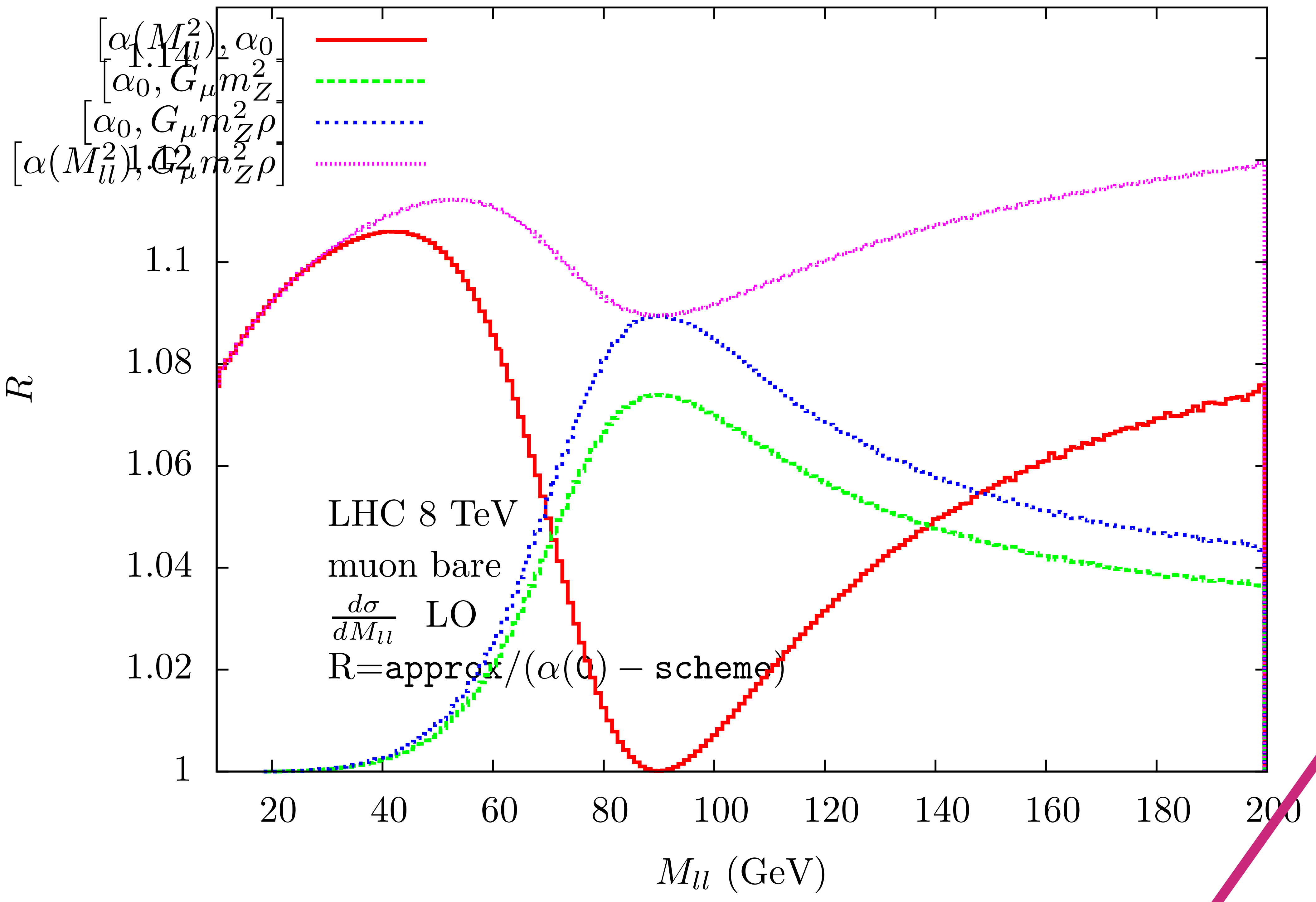


Use of G_μ and ρ only in the Z diagram enhances the peak of the Z resonance

$$\alpha(0) \to G_\mu \ \rho$$



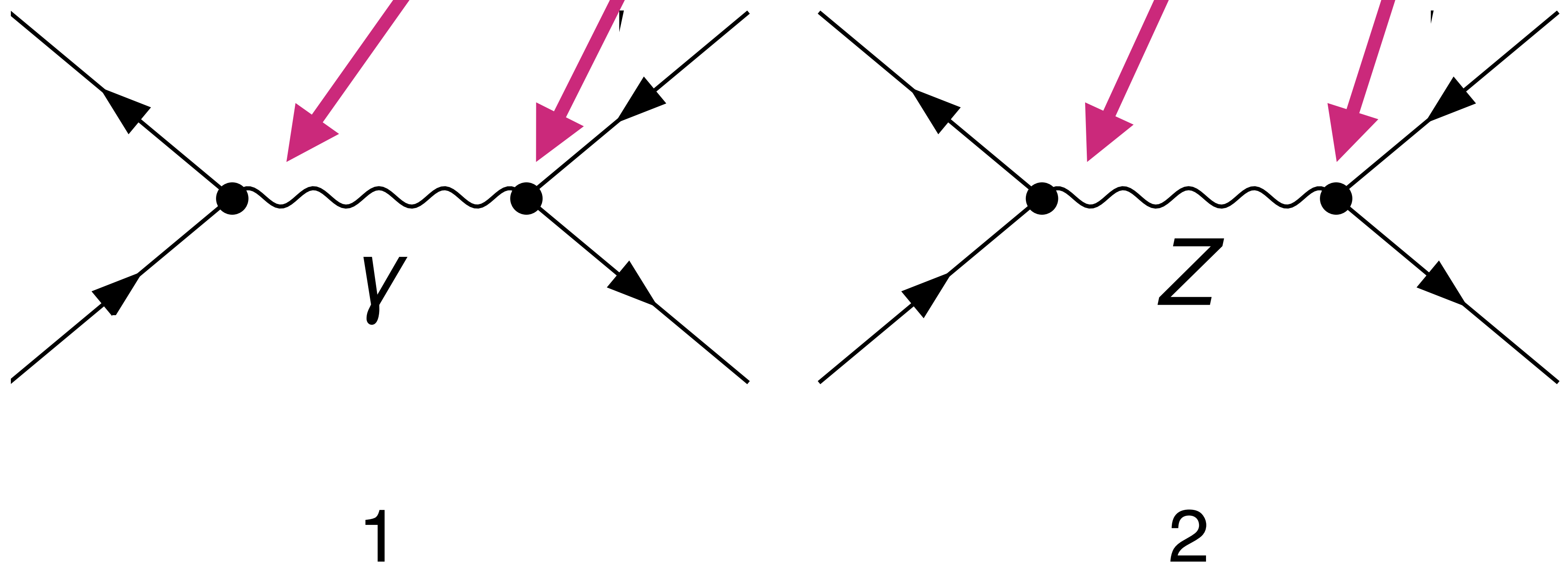
Beyond LO approximation in neutral current Drell Yan



- running of α only in the photon diagram
- use of G_μ and ρ only in the Z diagram:

$\alpha(0) \to G_\mu\ \rho$

$\alpha(0) \to \alpha(M^2_{\ell\ell})$



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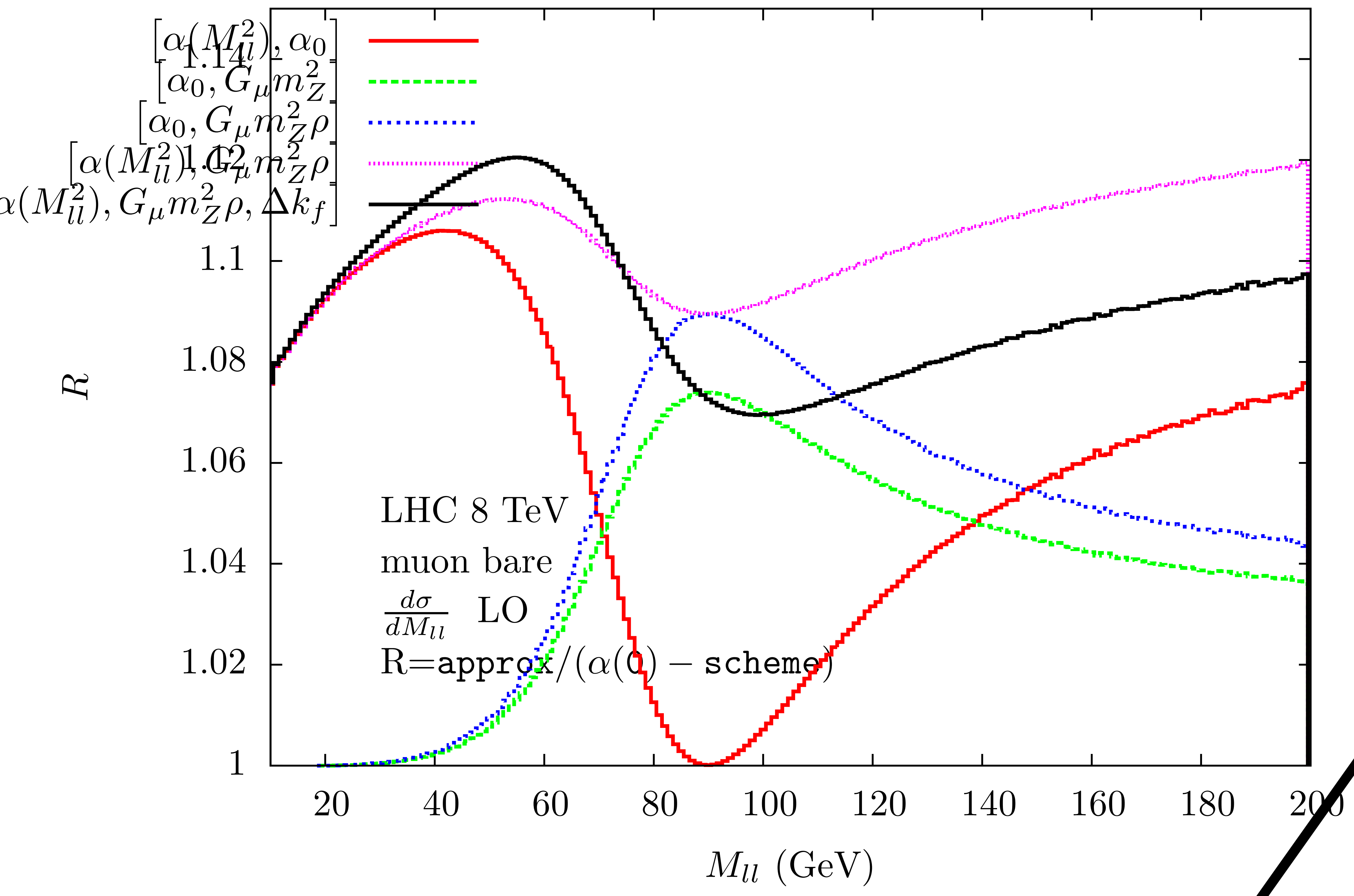


- running of α only in the photon diagram
- use of G_μ and ρ only in the Z diagram:
- rescaling of $\sin^2\theta_W$ in the Z vector coupling by $1 + \Delta\kappa_f$

$$\alpha(0) \to \alpha(M_{\ell\ell}^2)$$

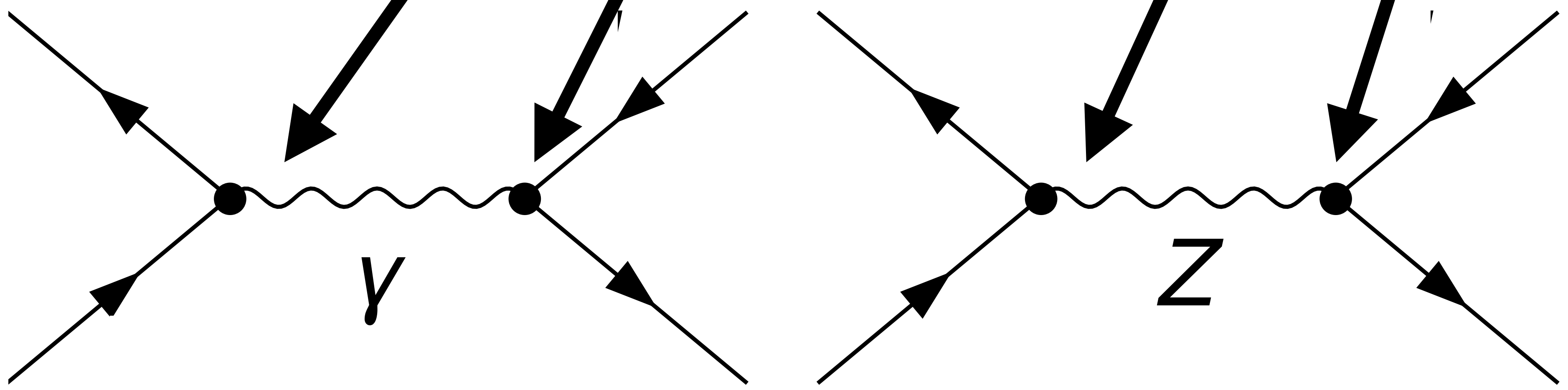
rescaling $\alpha(0) \to G_\mu\ \rho$

$$\sin^2\theta_W \to \left(1 + \Delta\kappa_f\right)\ \sin^2\theta_W$$

Several effects enter in the coupling redefinition

NLO-EW contains at first order all these effects but not the higher-order corrections

$\Delta\kappa_f$ is the only correction which modifies the precise $\sin^2\theta_W$ value



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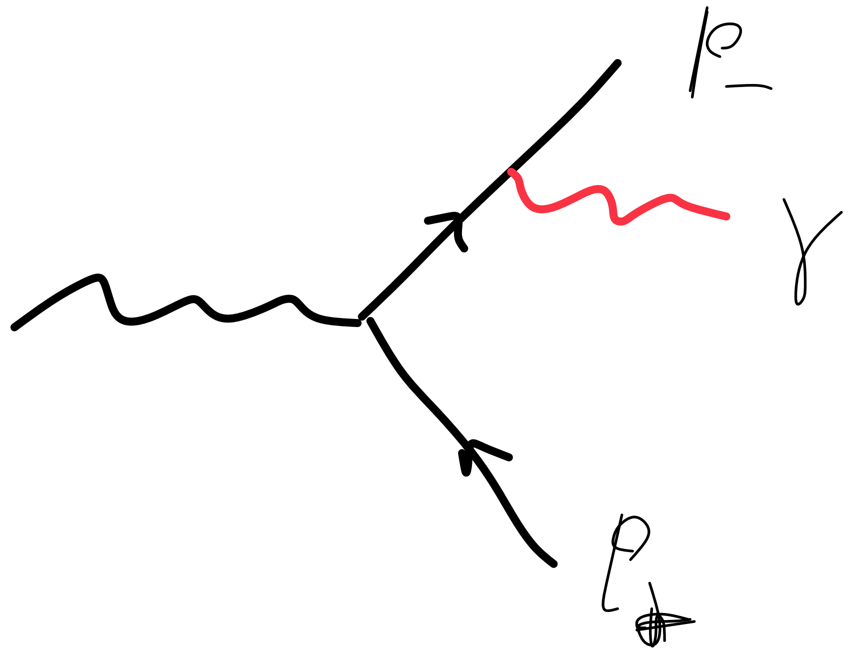
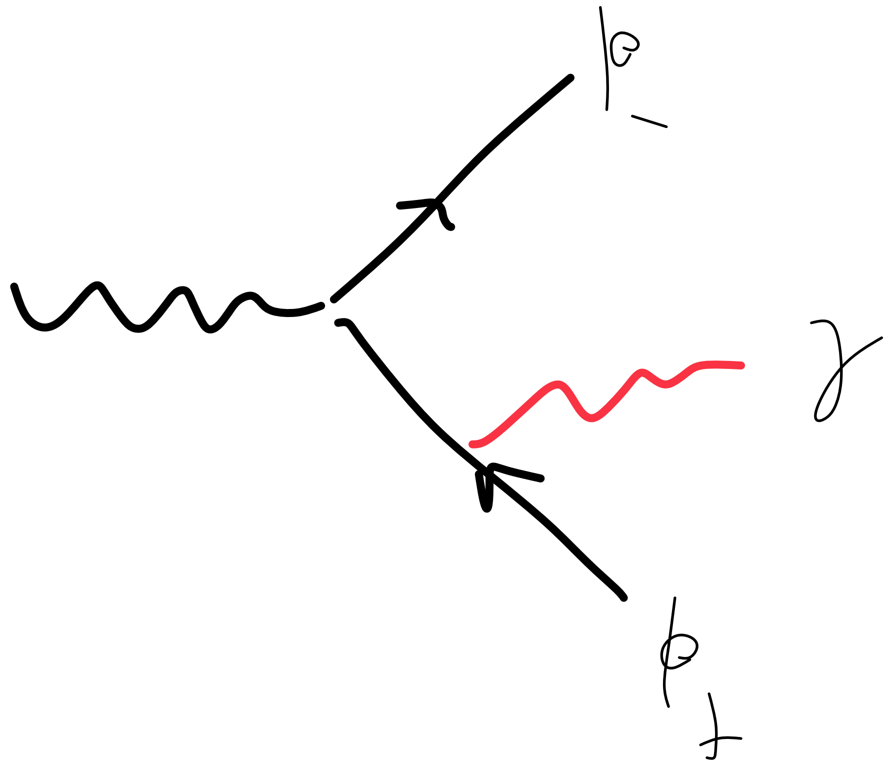
EW corrections: QED effects

- in soft approximation, the amplitude for the emission of a photon is described by an eikonal current

$$j^\mu_{eik} = -ie\left[\frac{p^\mu_-}{k\cdot p_-} - \frac{p^\mu_+}{k\cdot p_+}\right]$$





- leading QED radiation corrections, simulated via Parton Shower

$$d\sigma^\infty = \Pi(Q^2,\varepsilon)\sum_{n=0}^{\infty}\frac{1}{n!}|\mathscr{M}_{n,LL}|^2\, d\Phi_n$$

$$|M_{1,LL}|^2 = \frac{\alpha}{2\pi}\,P(z)\,I(k)\,\frac{8\pi^2}{E^2 z(1-z)}\,|\mathscr{M}_0|^2$$ and $|\mathscr{M}_{n,LL}|^2$ is obtained iterating

$$\Pi(Q^2,\varepsilon) = \exp\left(-\frac{\alpha}{2\pi}\,I_+\int d\Omega_\gamma\, I(k)\right)$$ with $I_+ = \int_0^{1-\varepsilon} dz\,\frac{1+z^2}{1-z}$ and $I(k) = \sum_{i,j} Q_i Q_j\,\eta_i\eta_j\,\frac{p_i\cdot p_j}{(p_i\cdot k)(p_j\cdot k)}E_\gamma^2$

EW corrections: matching NLO-EW with QED-PS

- leading soft and collinear enhancement factor is universal → can be easily applied to the final state of a hard scattering (see PHOTOS, or the PHOTONS module in Sherpa, or the QED-FSR showers in Pythia/Herwig)

  the inclusion of subleading EW effects requires a matching procedure with exact matrix elements (see Marek's lectures)

- Matching an exact NLO-EW calculation with a full QED Parton Shower can be achieved e.g. like in HORACE

$$d\sigma^\infty = \Pi(Q^2,\varepsilon)\, F_{SV} \sum_{n=0}^{\infty} \frac{1}{n!} \left(\Pi_{k=1}^{n} F_{H,k}\right) |\mathcal{M}_{n,LL}|^2 \, d\Phi_n$$

The expansion in α of this formula coincides with the exact fixed order calculation
Hard exact matrix element corrections are applied "democratically" to all the emitted photons
The correction factors F are by construction IR regular

$$d\sigma_\alpha = [1 + C_\alpha]\, |\mathcal{M}_0|^2 d\Phi_0 + |\mathcal{M}_1|^2 d\Phi_1$$

$$F_{SV} = 1 + (C_\alpha - C_{\alpha,LL})$$

$$F_H = 1 + \frac{|\mathcal{M}_1|^2 - |\mathcal{M}_{1,LL}|^2}{|\mathcal{M}_{1,LL}|^2}$$

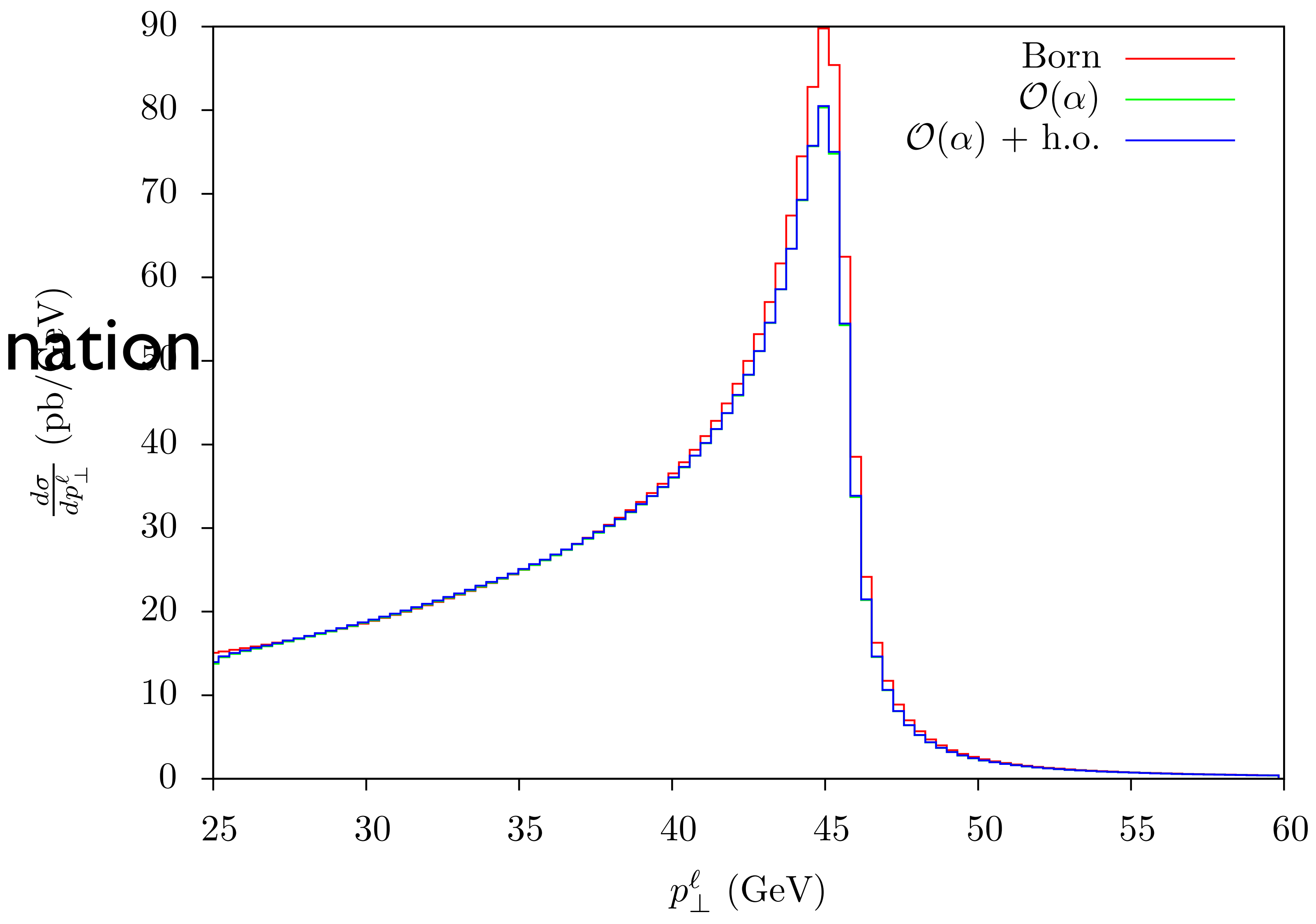
EW corrections: QED effects

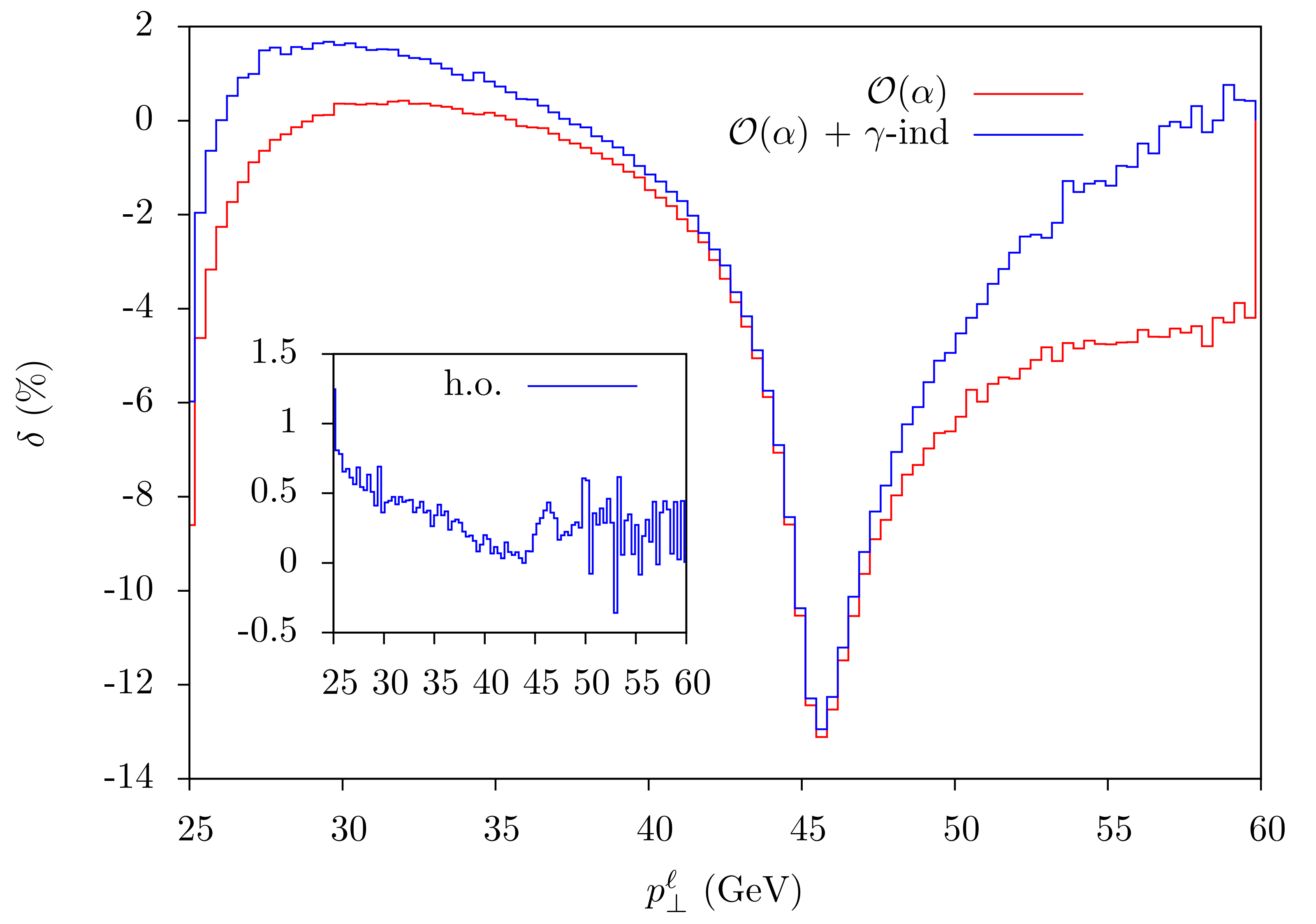
- distortion of the (leptonic) spectra

massive "bare" leptons, without any recombination

receive an enhancement factor $\propto \log \frac{s}{m^2}$

leading to O(10%) corrections





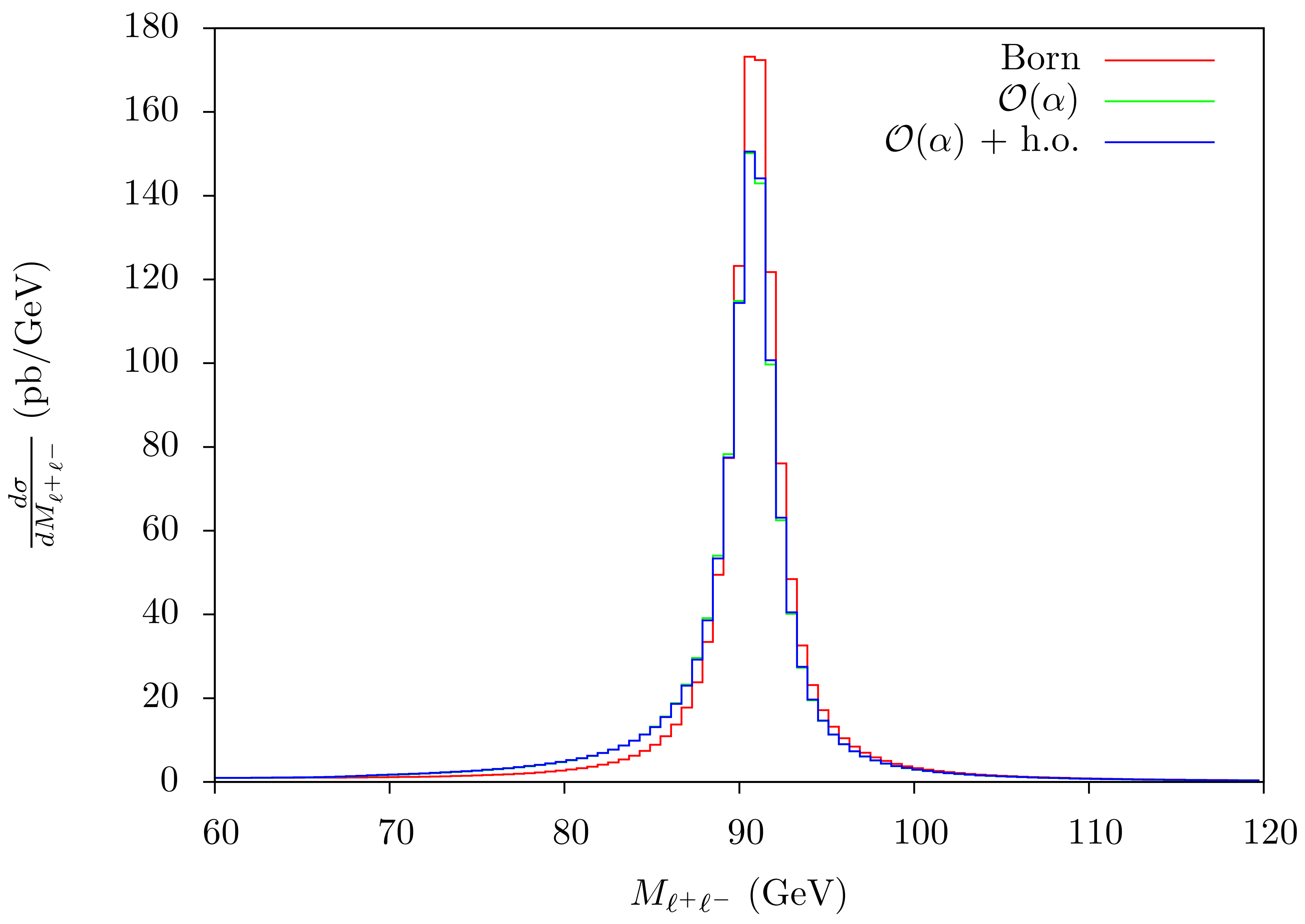
- radiative return mechanism

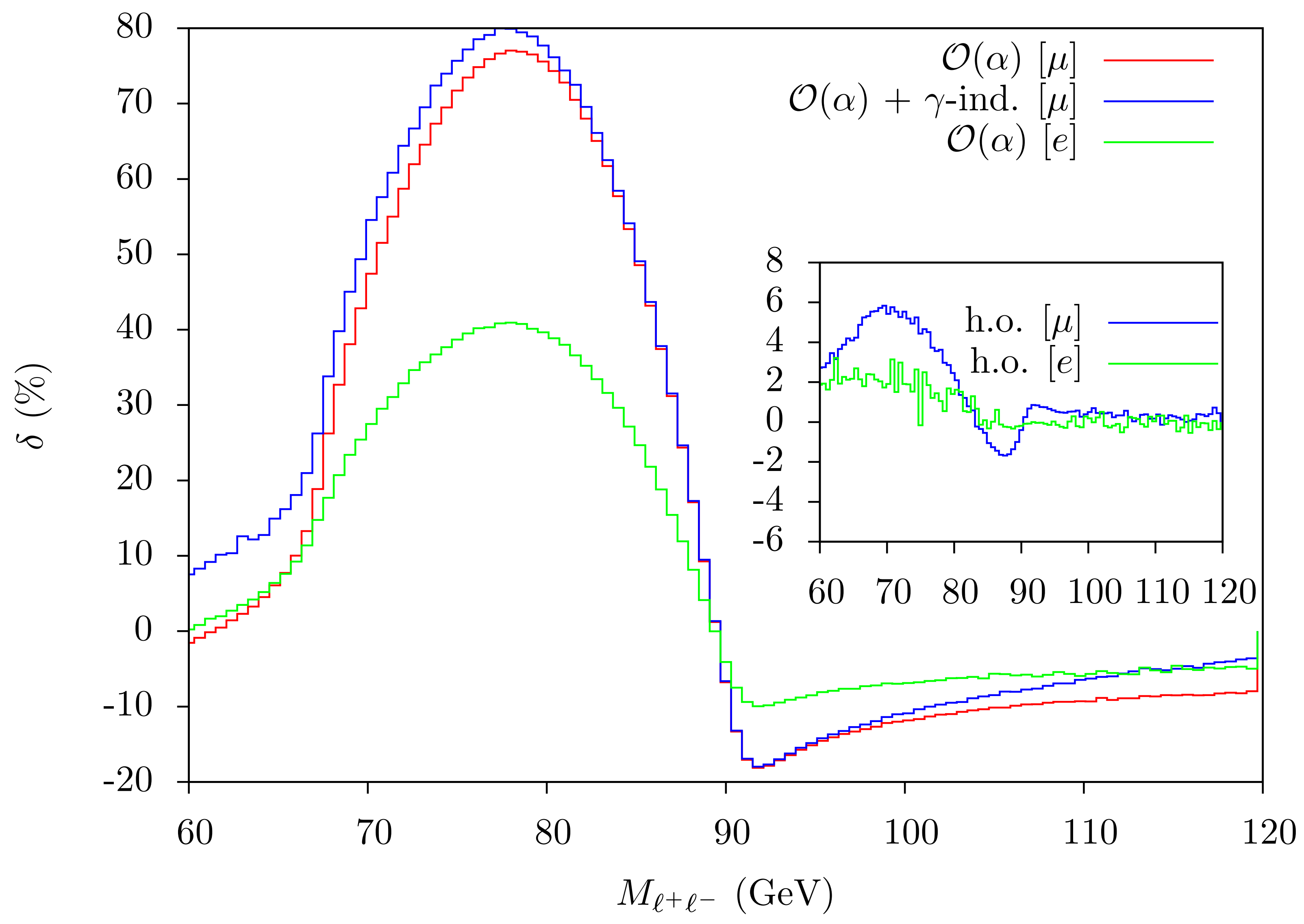
events generated at $\sqrt{s} \sim m_Z$ FSR radiate

so that $m_{\ell\ell} < m_Z$

filling the distribution below the resonance

O(1) effects in those bins !





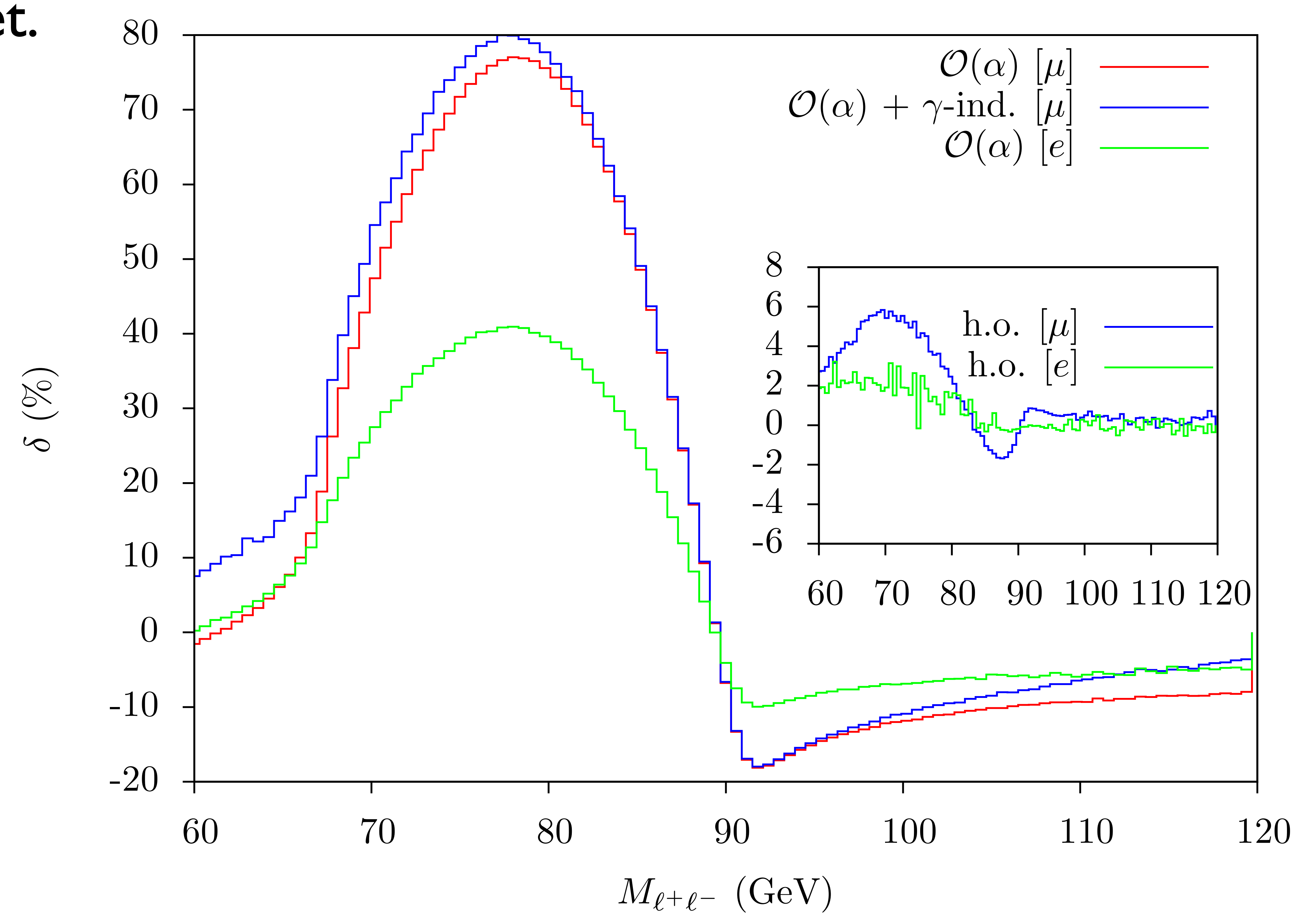
Leptons and photons

the radiation emitted by a massive (final state) lepton develops large mass (collinear) logarithms $\alpha \log \frac{s}{m_\ell^2}$

The Kinoshita-Lee-Nauenberg (KLN) theorem guarantees that when considering sufficiently inclusive observables,
i.e. integrating over the whole radiation emitted by the lepton, such divergent terms cancel

A "bare" lepton is described in an exclusive way by its 4-momentum components, after radiation has been emitted
A muon momentum reconstructed in a muon chamber is close to this description
The fully exclusive description of the radiation features the large logarithmic corrections

A recombined ("dressed") lepton can be seen as an electromagnetic jet.
The momentum of the dressed lepton is obtained by summing the lepton and surrounding photons momenta in a given phase-space region. Relevant for electrons.
Including the radiation effectively implements the KLN theorem, leading to smaller radiative effects

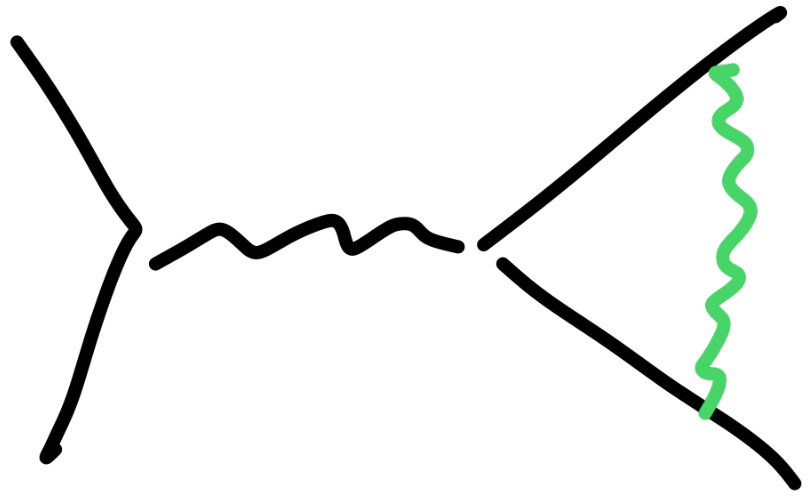


The "dressed lepton" definition is applicable at any order in perturbation theory (cfr. the discussion about QCD jet definitions)

Unfolding QED-FSR corrections is a dangerous procedure threatening the possibility of a detailed comparison with theory at high-precision level (beyond QED-LL)

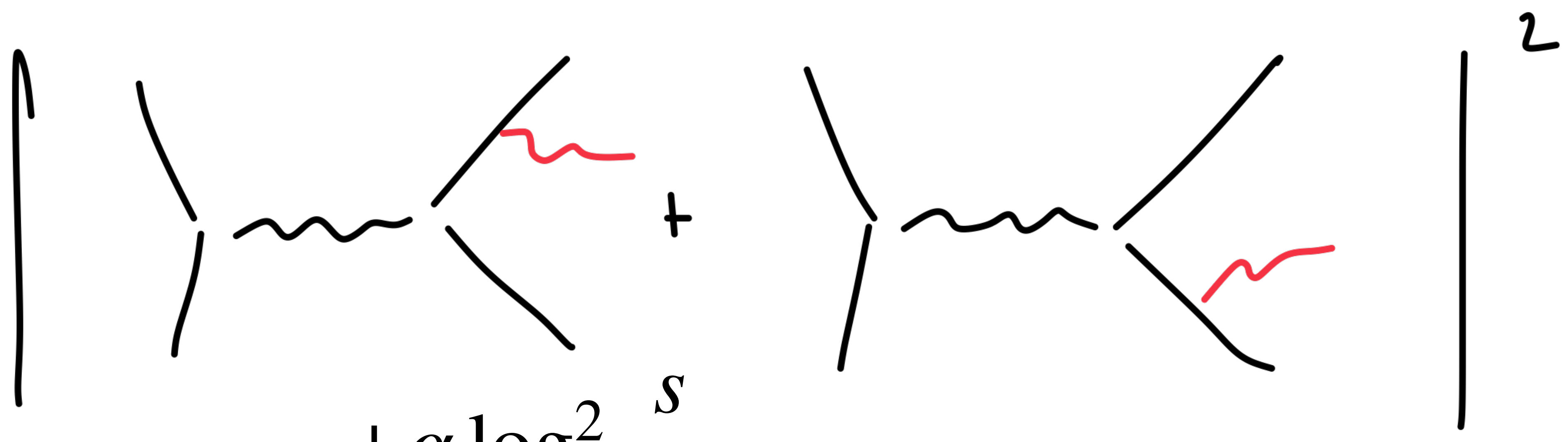
EW corrections: weak Sudakov logarithms

- for large values of the kinematical invariants, the gauge boson masses are "soft"
  → the virtual corrections feature, for each loop a term $\alpha \log^2 \frac{s}{m_W^2} \equiv \alpha L^2 \sim 0.18$ when $s = (1\ \mathrm{TeV})^2$

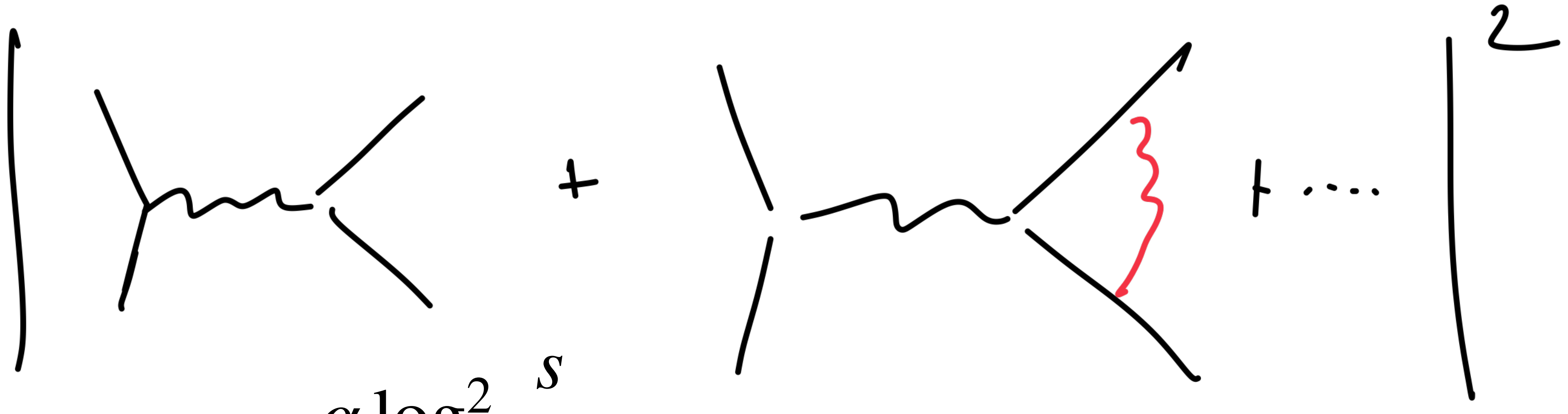


$$-\alpha \log^2 \frac{s}{m_W^2}$$

- contrary to the massless photon case,
  where corresponding terms stem from the real corrections and cancel the virtual ones



$$+\alpha \log^2 \frac{s}{\mu^2}$$



$$-\alpha \log^2 \frac{s}{\mu^2}$$

in the weak case
there is an unbalance between virtual and real weak exchanges, leaving the large negative virtual correction

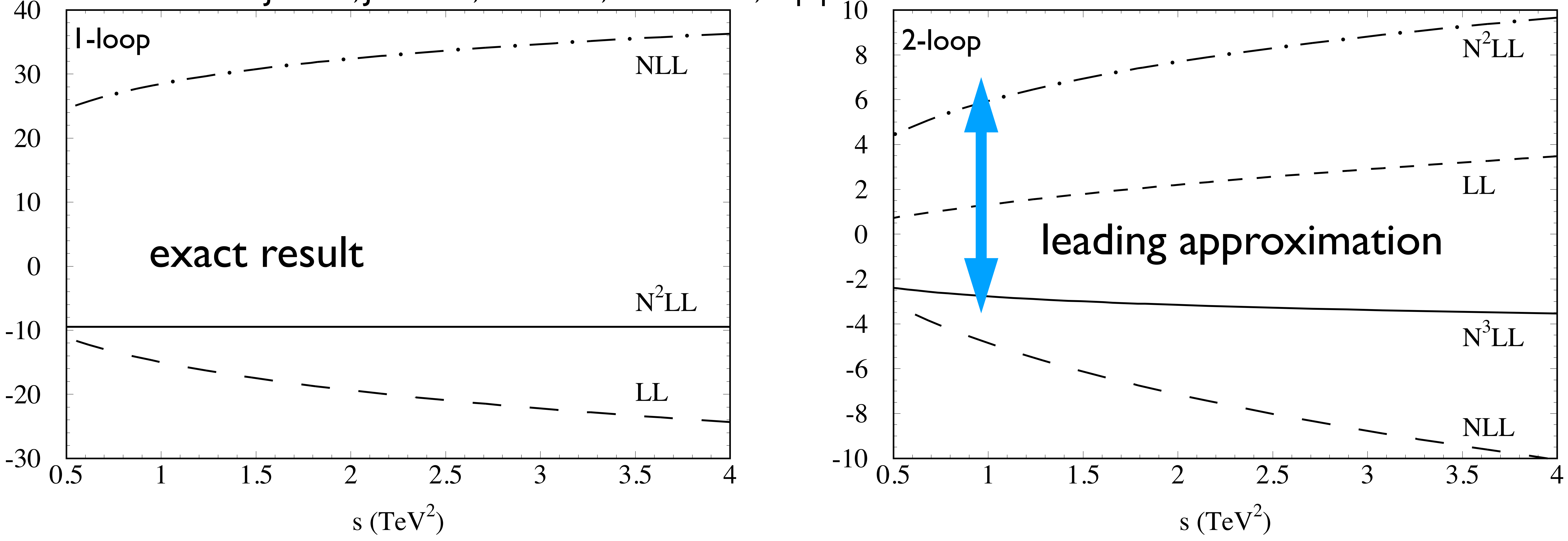
EW corrections: weak Sudakov logarithms

- for large values of the kinematical invariants, the gauge boson masses are soft
  → the virtual corrections feature, for each loop a term $-\frac{\alpha}{\sin^2\theta_W \pi}\log^2\frac{s}{m_W^2} \equiv -\frac{\alpha}{\sin^2\theta_W \pi} L^2 \sim -0.25$ when $s = (1\ \mathrm{TeV})^2$
- $\sigma = \sigma_0 + \frac{\alpha}{\pi}\sigma_\alpha + \left(\frac{\alpha}{\pi}\right)^2 \sigma_{\alpha^2} + \cdots$

  in the high-energy limit, we can isolate the EW Sudakov logarithms

$$\sigma_\alpha^{virt,Sudakov} \sim c_{12}L^2 + c_{11}L + c_{10}, \qquad \sigma_{\alpha^2}^{virt,Sudakov} \sim c_{24}L^4 + c_{23}L^3 + c_{22}L^2 + c_{21}L + c_{20}, \quad \ldots.$$

B.Jantzen, J.H.Kühn, A.A.Penin, V.A.Smirnov, hep-ph/0509157



corrections to $e^+e^- \to q\bar{q}$ due to EW Sudakov logs

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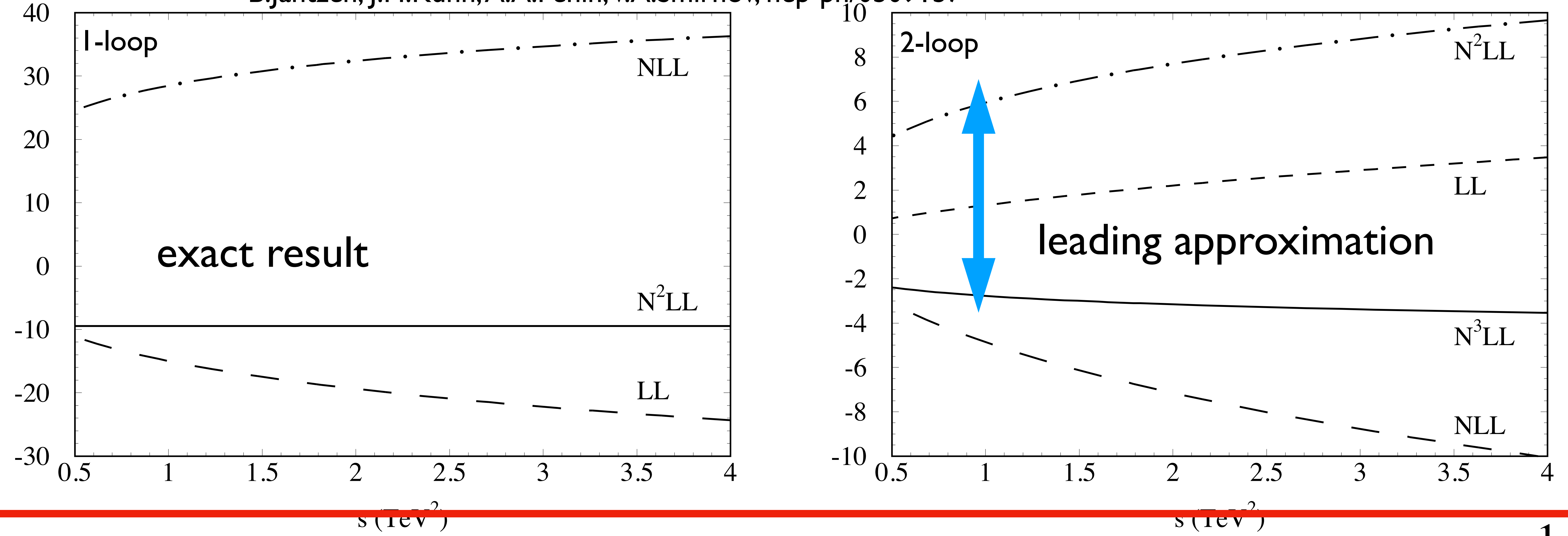


corrections to $e^+e^- \to q\bar{q}$ due to EW Sudakov logs

Estimate of missing higher-order logs: $\delta_\alpha^{Sudakov} \to \exp(\delta_\alpha^{Sudakov}) \to$ at 2-loop estimate $\sim \frac{1}{2}(\delta_\alpha^{Sudakov})^2$

caveat: the subleading logs are large and with alternating signs

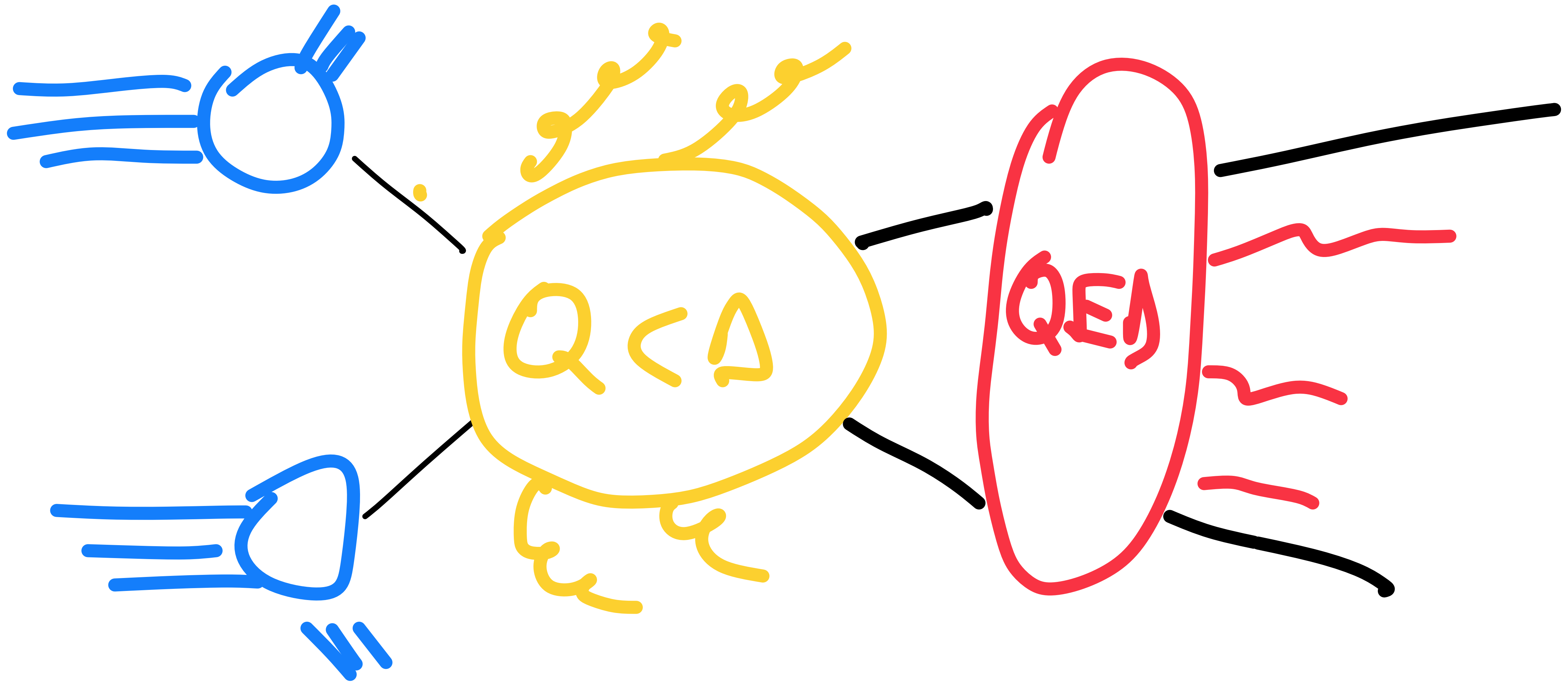
Mixed QCD-EW corrections

Mixed QCD and EW effects at hadron colliders

A reference approximated combination: QCD x QED-FSR

- the rate and distributions of the scattering processes are computed at (N)NLO-QCD, possibly matched with QCD-PS
  then the final state particles are further corrected by QED-FSR emissions (universality of LL QED corrections)

→ quite accurate description of all the phase-space regions with soft and/or collinear QCD/QED radiation



Mixed QCD and EW effects at hadron colliders

Matching NLO-QCD and NLO-EW with QCD-PS and QED-PS

POWHEG NLO-(QCD+EW)

no-emission probability

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \Bigg\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\mathbf{\Phi}_n, k_T)\, R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \Bigg\}$$

first hard emission probability

The exact NLO QCD+EW normalisation is guaranteed by the $\overline{B}$ function

QCD and QED radiation are described by { }

The first emission is by construction the hardest. The following emissions are handled by QCD and QED Parton Showers

The factorised formulation $\left[\overline{B}(QCD) + \overline{B}(EW)\right] \left\{R(QCD) + R(QED)\right\}$ (QCDPS + QEDPS) introduces mixed QCD-EW corrections

Good approximation of the exact results in the soft/collinear phase-space regions + improvement in the description of hard/large angle radiation

Mixed QCD and EW effects at hadron colliders

Matching NLO-QCD and NLO-EW with QCD-PS and QED-PS

POWHEG NLO-(QCD+EW)

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\mathbf{\Phi}_n, k_T)\, R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$

the difference between QCDxQED and QCDxEW approximations starts at O(αα$_s$)

POWHEG NLO-QCD x (QCD+QED)-PS $\qquad \alpha_s\alpha \left(c_2 L_{\rm QCD}^2 + c_1 L_{\rm QCD} + c_0\right)\left(c_{11} L_{\rm QED} l_{\rm QED} + c_{10} L_{\rm QED} + c_{01} l_{\rm QED}\right)$

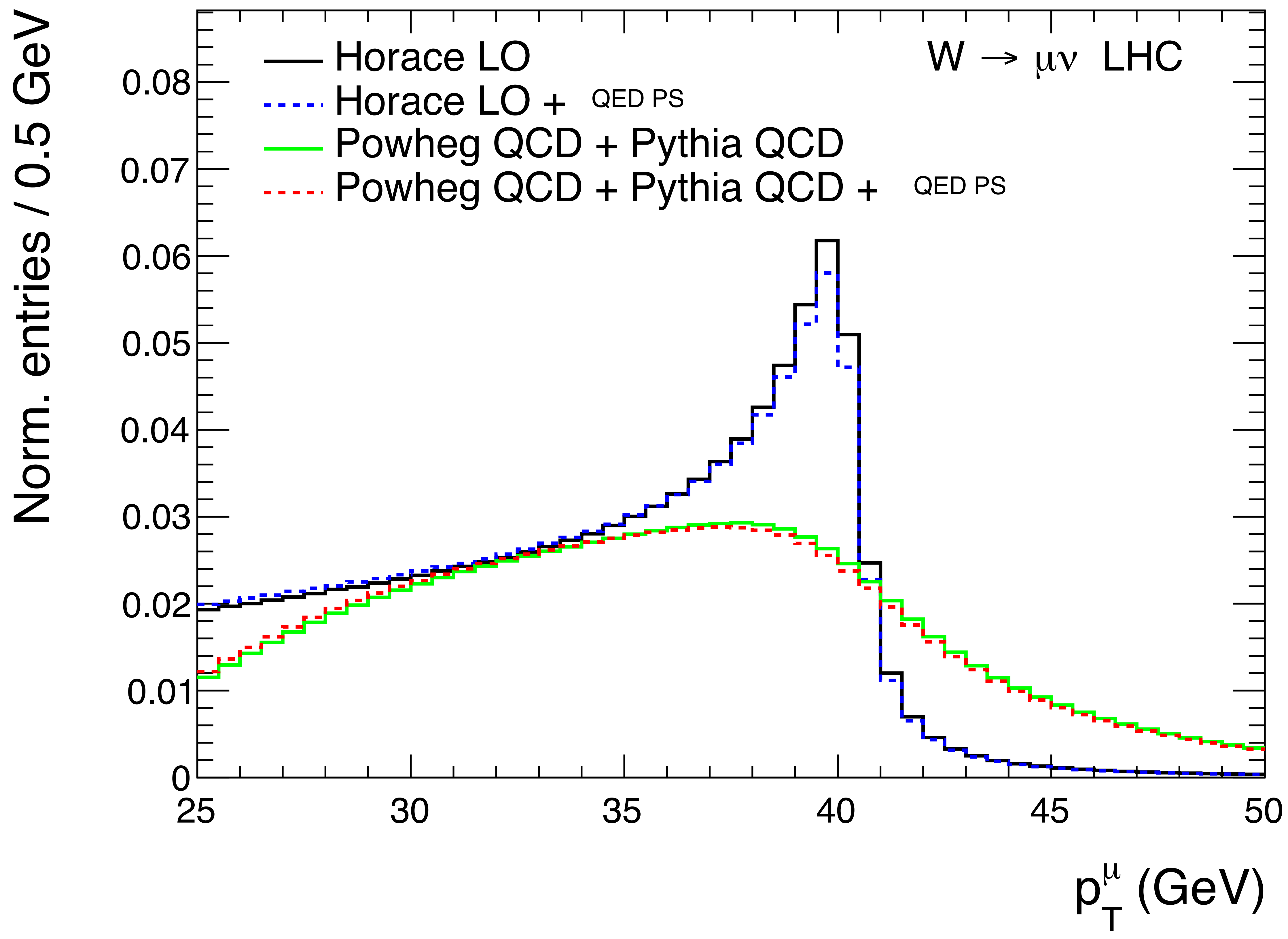
POWHEG NLO-(QCD+EW) x (QCD+QED)-PS $\qquad \alpha_s\alpha \left(c_2 L_{\rm QCD}^2 + c_1 L_{\rm QCD} + c_0\right)\left(c_{11} L_{\rm QED} l_{\rm QED} + c_{10} L_{\rm QED} + c_{01} l_{\rm QED} + c_{00}\right)$

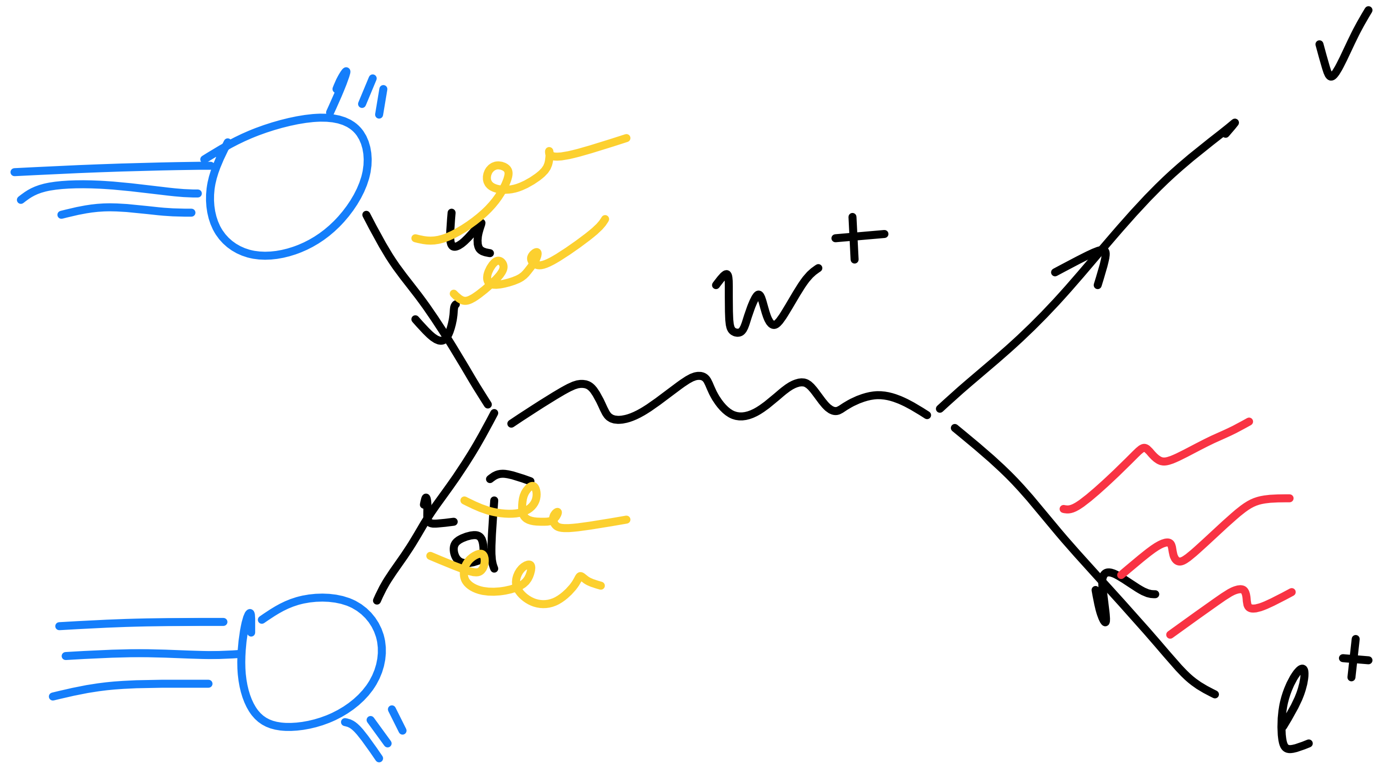
the difference $\alpha_s\alpha\, c_{00} \left(c_2 L_{\rm QCD}^2 + c_1 L_{\rm QCD} + c_0\right)$ important when c_{00} is large

c_{00} does not contain QED logs, but Sudakov EW logs $\qquad c_{00} \propto -\frac{\alpha}{4\pi \sin^2\theta_W} \log^2 \frac{s}{m_W^2}$

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

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- 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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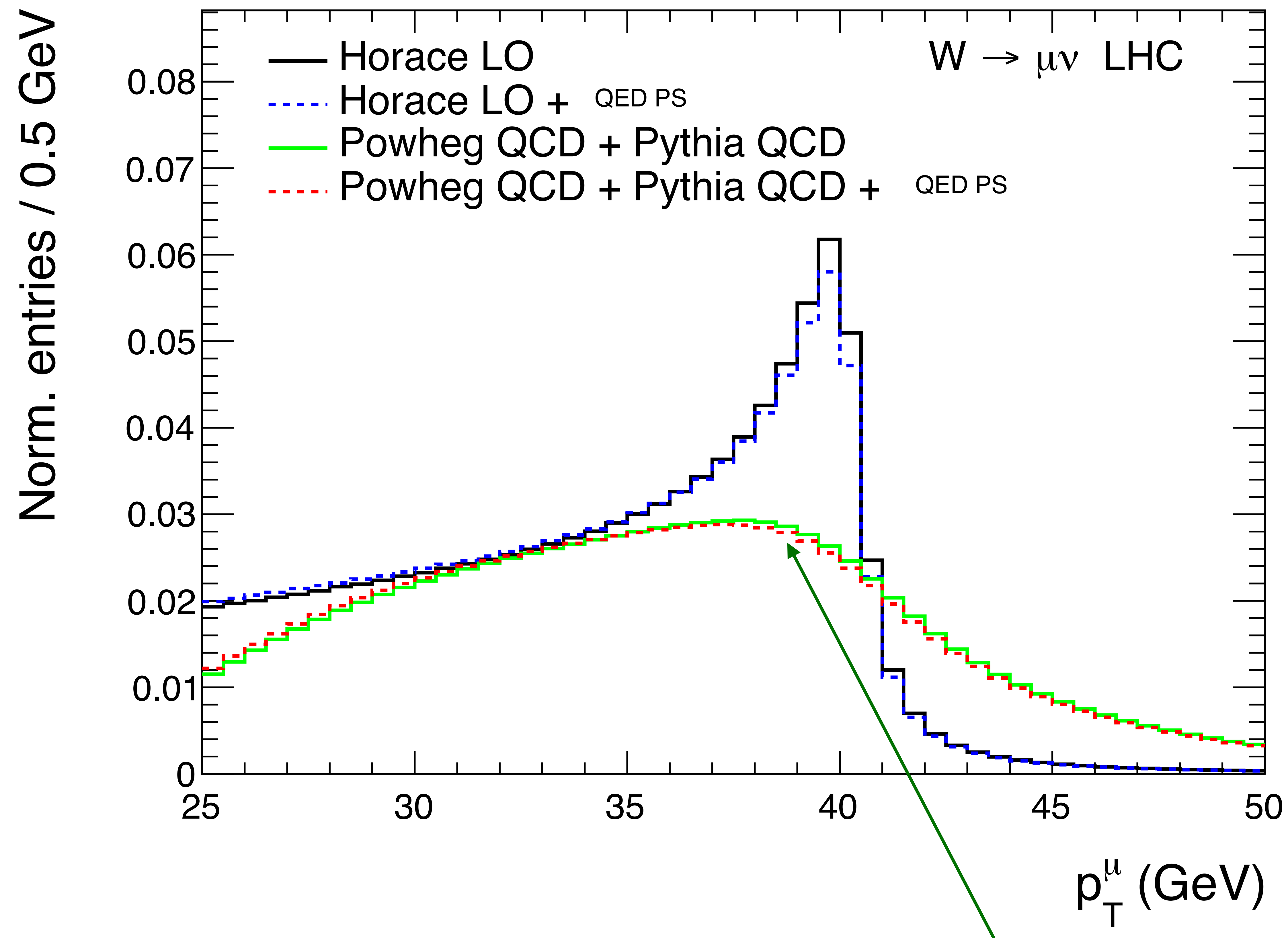
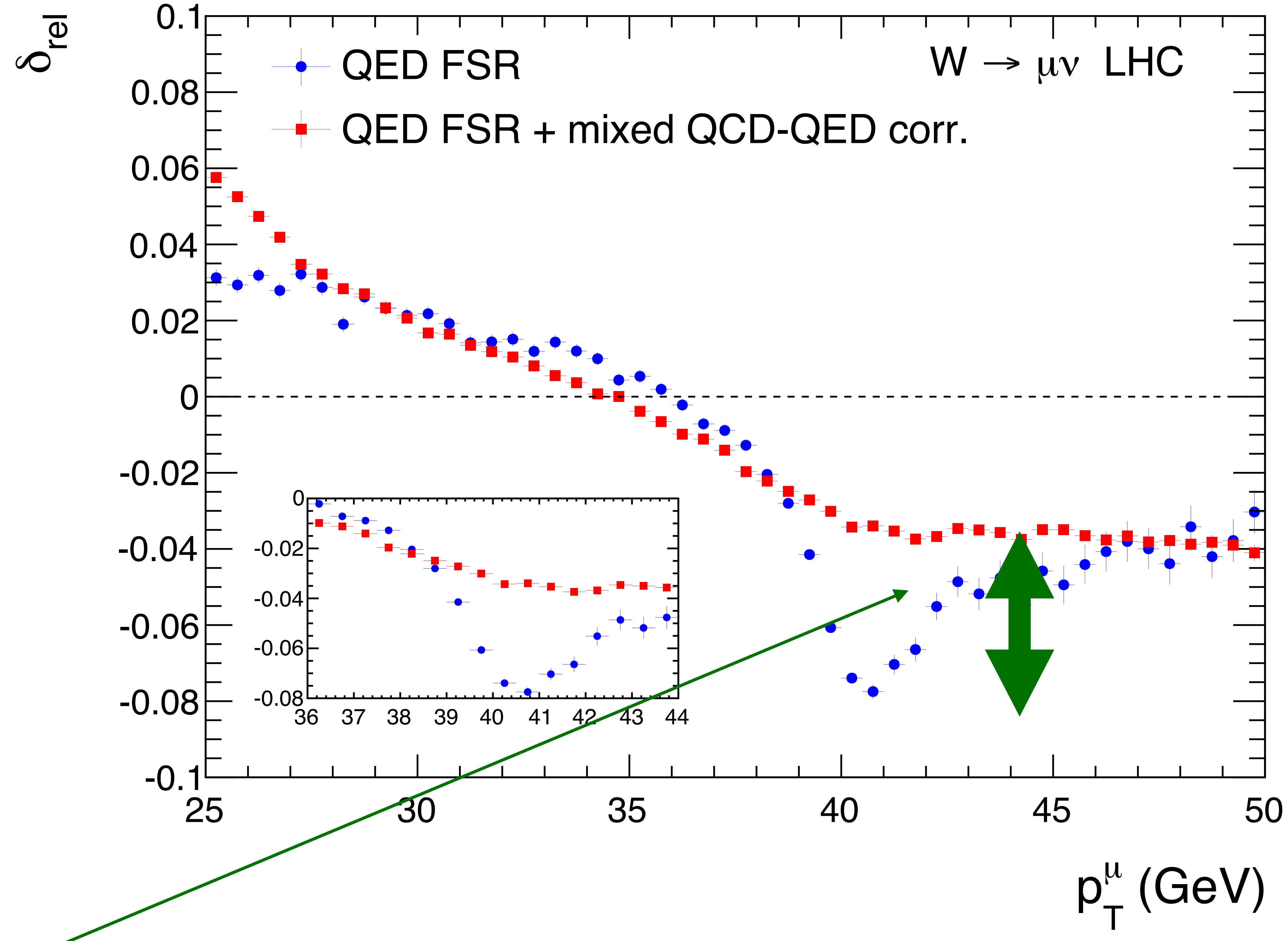




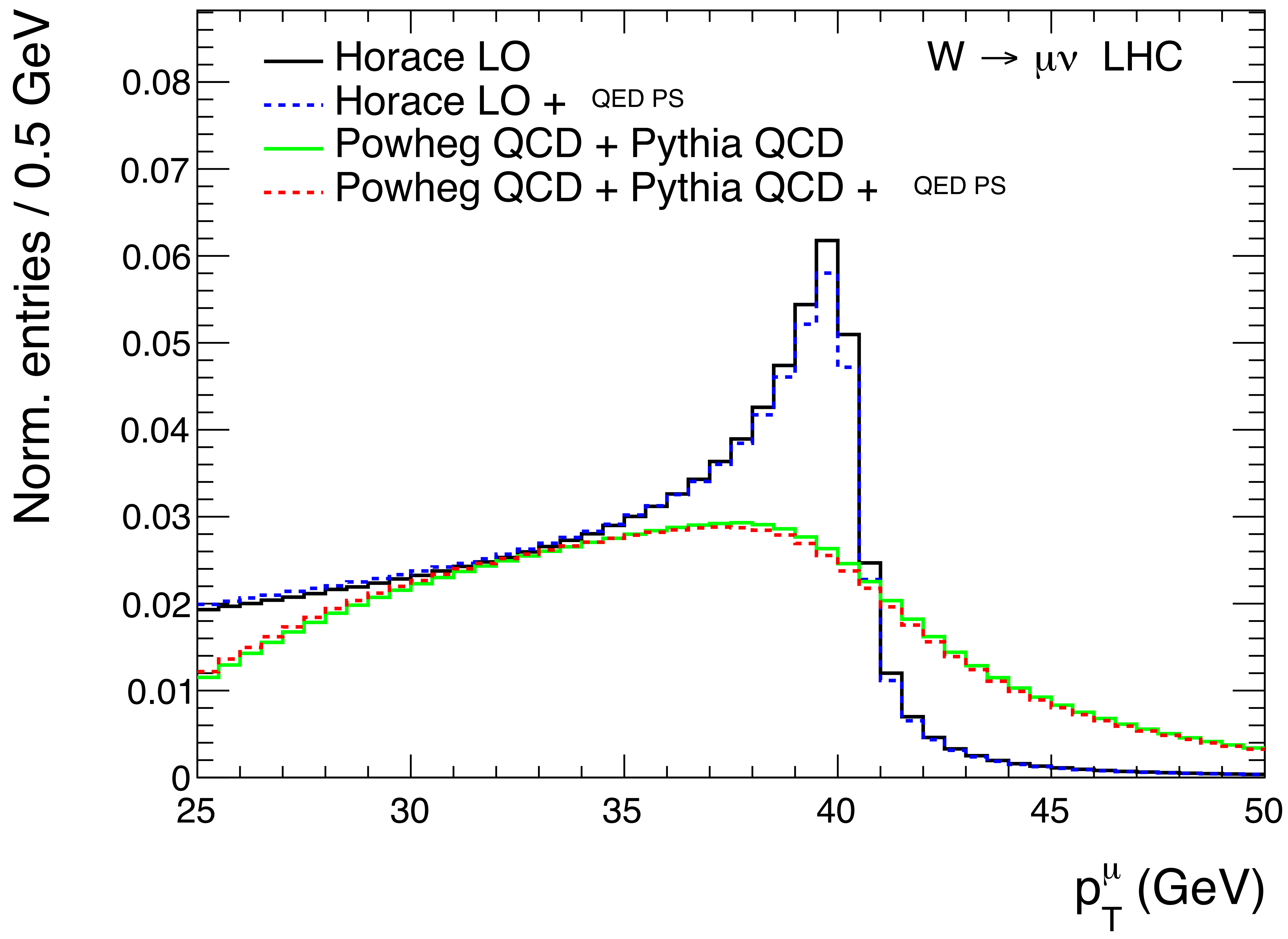
- very large impact of initial-state QCD radiation on the ptlep distribution
- large radiative corrections due to QED final state radiation at the jacobian peak
- very large interplay of QCD and QED corrections redefining the precise shape of the jacobian peak

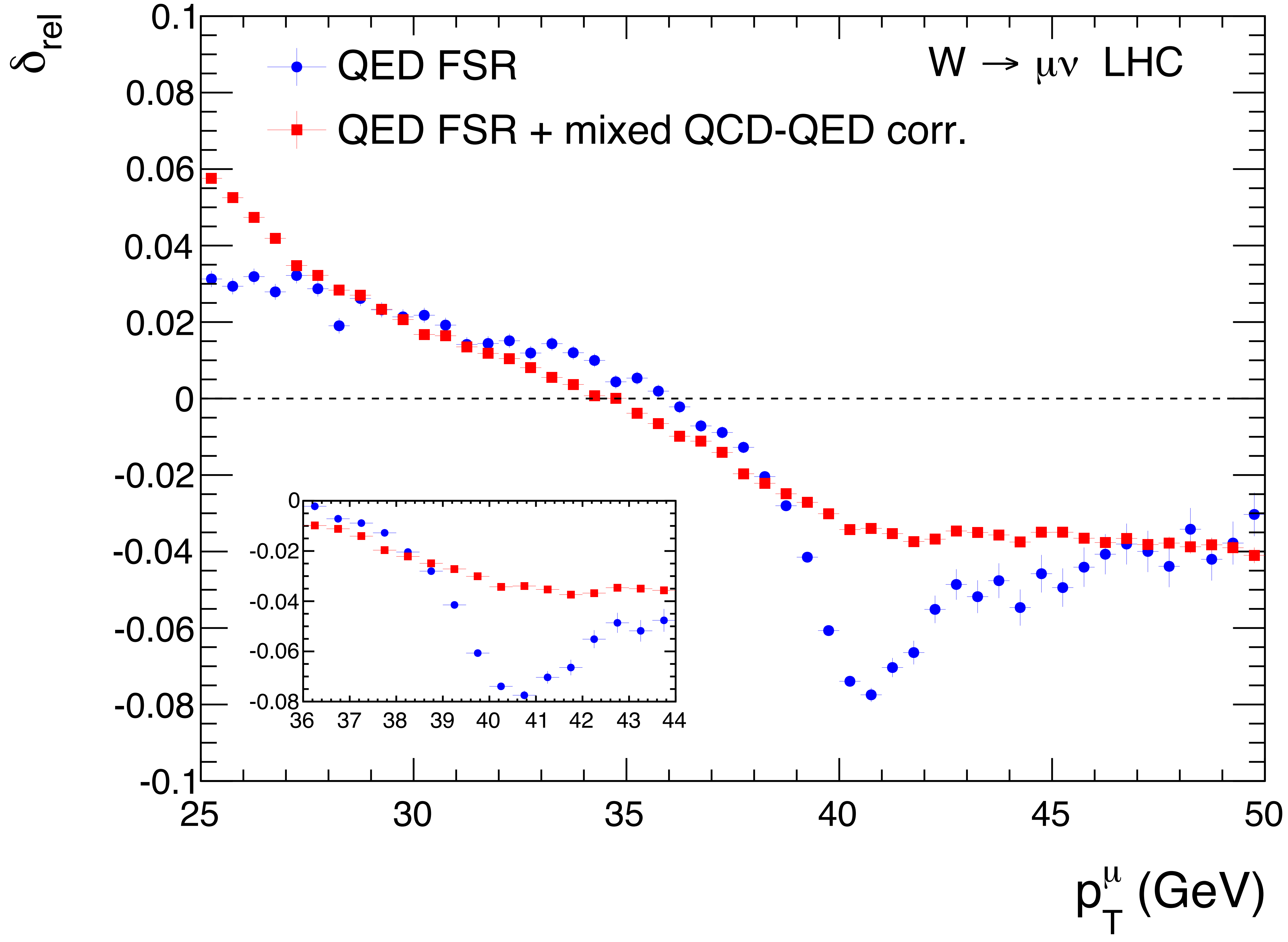
NLO-QCD + QCDPS + QEDPS is the lowest order meaningful approximation of this observable

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

Interplay of QCD and QED corrections

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





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in m_W determination we need a control over the shape of the distributions at 0.1% level
here we have effects of O(few %)

how can we assess a reliable estimate of 1) the size of the mixed QCD-EW effects
2) the residual error on these effects ?

QED and QCD competing in the algorithmic simulation of real radiation

How can we appreciate the differences between a PS with or without matching with fixed-order?

POWHEG NLO-(QCD+EW)

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\mathbf{\Phi}_n, k_T)\, R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$

the original version of the POWHEG describes radiation in two steps:

- the hardest emission (in p_T) is emitted according to the above probability distribution {}
- all subsequent emissions are emitted via Parton Shower in the remaining available phase space

the decision about emitting a parton is taken using the Sudakov form factor as emission probability density
the probability that a (hard) photon successfully passes the Sudakov test is suppressed compared to the gluon $Q_f \alpha \ll C_F \alpha_s$

if we generate with POWHEG only the hardest parton, only one parton, it will be in 99.5% of the cases a gluon
→ the photon radiation never benefits of the exact matrix element corrections !!! the photon spectrum is pure QED PS

→ Solution: use a resonance-aware approach to describe the gauge-boson production and decay

QED and QCD competing in the algorithmic simulation of real radiation

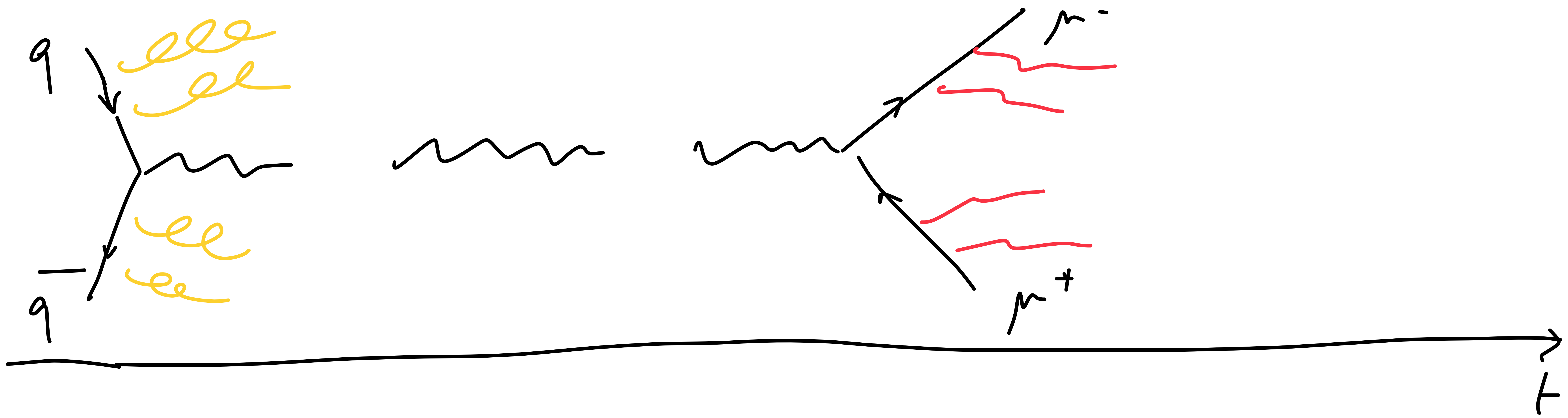
`Two-rad` approach to describe the gauge-boson production and decay simplified "resonance-aware" treatment

1) QCD emissions take place in the production process of the gauge boson
   → we apply the POWHEG algorithm to decide the hardest parton ;   it is ok if we get almost only gluons

2) The typical interaction time for QCD emissions is smaller than the lifetime of the intermediate gauge boson
   The subsequent gauge-boson decay has thus a distinct Monte Carlo history

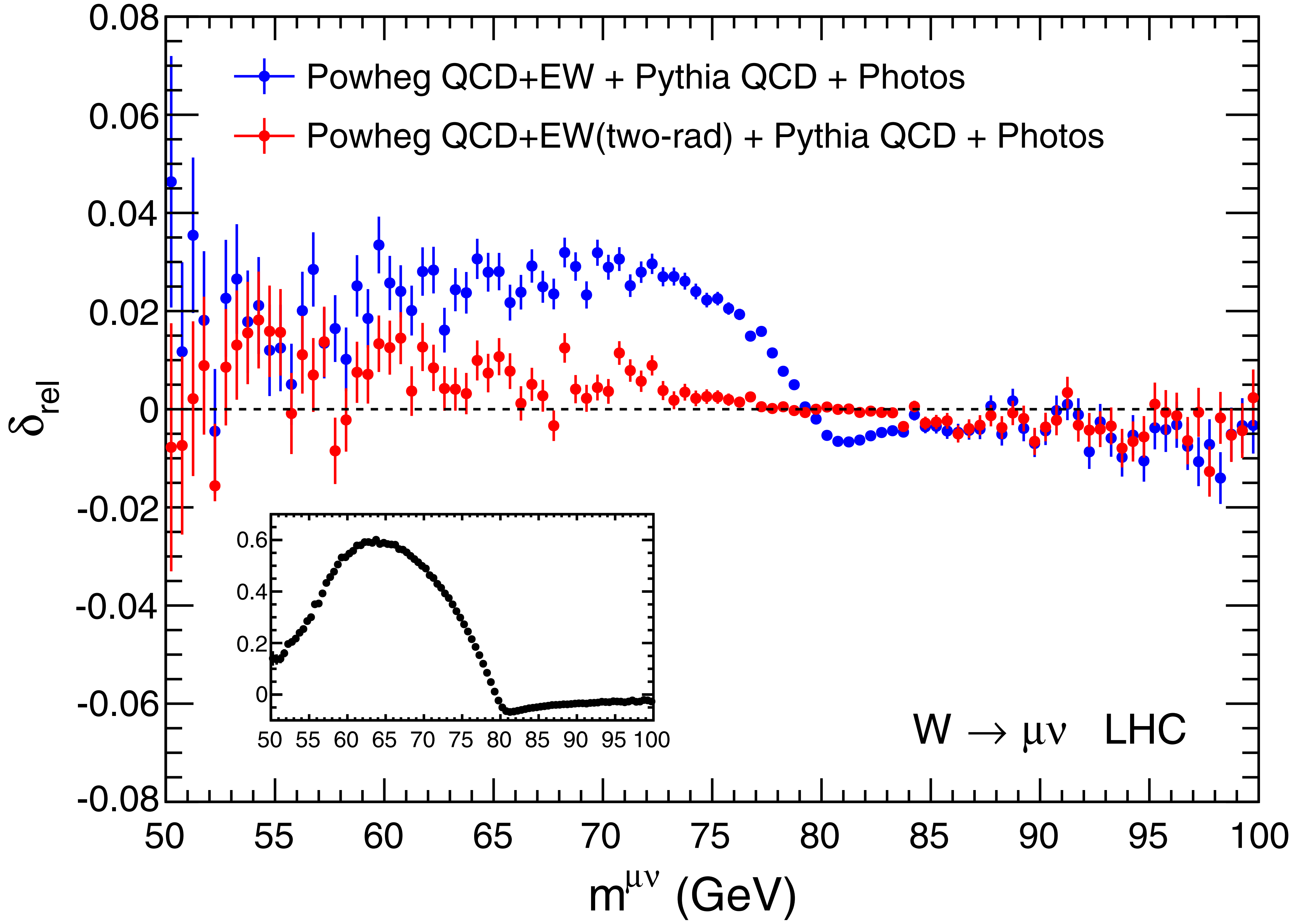
3) We can apply, in a separate independent way, the algorithm to emit the hardest photon, without competing with gluons
   → we always get a hardest photon; the algorithm only chooses its p_T

4) We always use the exact matrix elements, including photon radiation from all charged legs (no approximations)
   The resonance aware sampling improves the phase-space sampling, filling regions which would remain empty



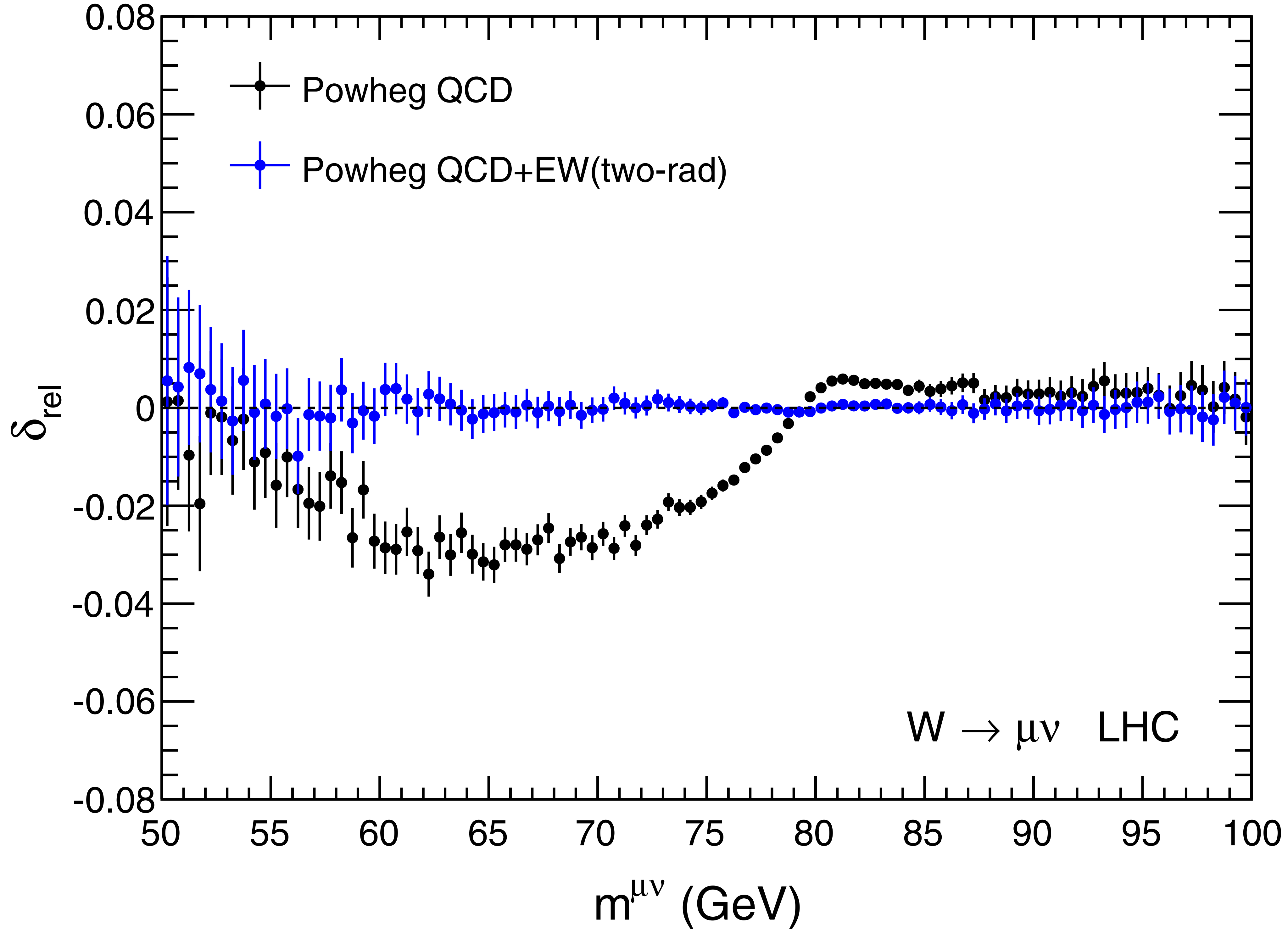
Impact of a resonance-aware treatment

Impact of neglecting vs including the matrix-element corrections



2 versions of POWHEG NLO-(QCD+EW)+(QCD+QED)-PS
in units POWHEG NLO-QCD +(QCD+QED)-PS

Impact of the QED showering model:
PHOTOS vs Pythia-QED



(POWHEG NLOPS-QCD +PHOTOS) /
(POWHEG NLOPS-QCD +Pythia-QED)

(POWHEG NLO-(QCD+EW)+QCDPS +PHOTOS) /
(POWHEG NLO-(QCD+EW)+QCDPS +Pythia-QED)

An excursus on resonance-aware simulations

Problems in POWHEG of algorithmic nature in the simulation of processes with resonance or several different scales

Radiation can bring the a configuration of momenta above a resonance to another one below,
with drastic changes in the weight associated to the event

1) IR subtraction terms (FKS, CS) do not preserve the virtuality of the resonance spoiling the efficiency of IR cancellations
→ severe convergence problem

2) The Sudakov form factor $\Delta(\Phi_B, p_T) = \exp\left\{ -\sum_\alpha \int_{k_T > p_T} R(\Phi_\alpha)/B(\Phi_B)\, d\Phi^\alpha_{rad} \right\}$
may feature very different ratios R/B, because of the interplay of the radiation with the resonance
leading to large distortions of the kinematical distributions

A solution is achieved by exploiting the idea of Monte Carlo history
forcing all the emissions stemming from one resonance to be generated at fixed virtuality of the resonance

→ optimisation of the IR cancellations
→ sensible way of filling the phase-space in a physically motivated way

W-boson mass determination

m_W determination at hadron colliders: template fitting

Given one experimental kinematical distribution

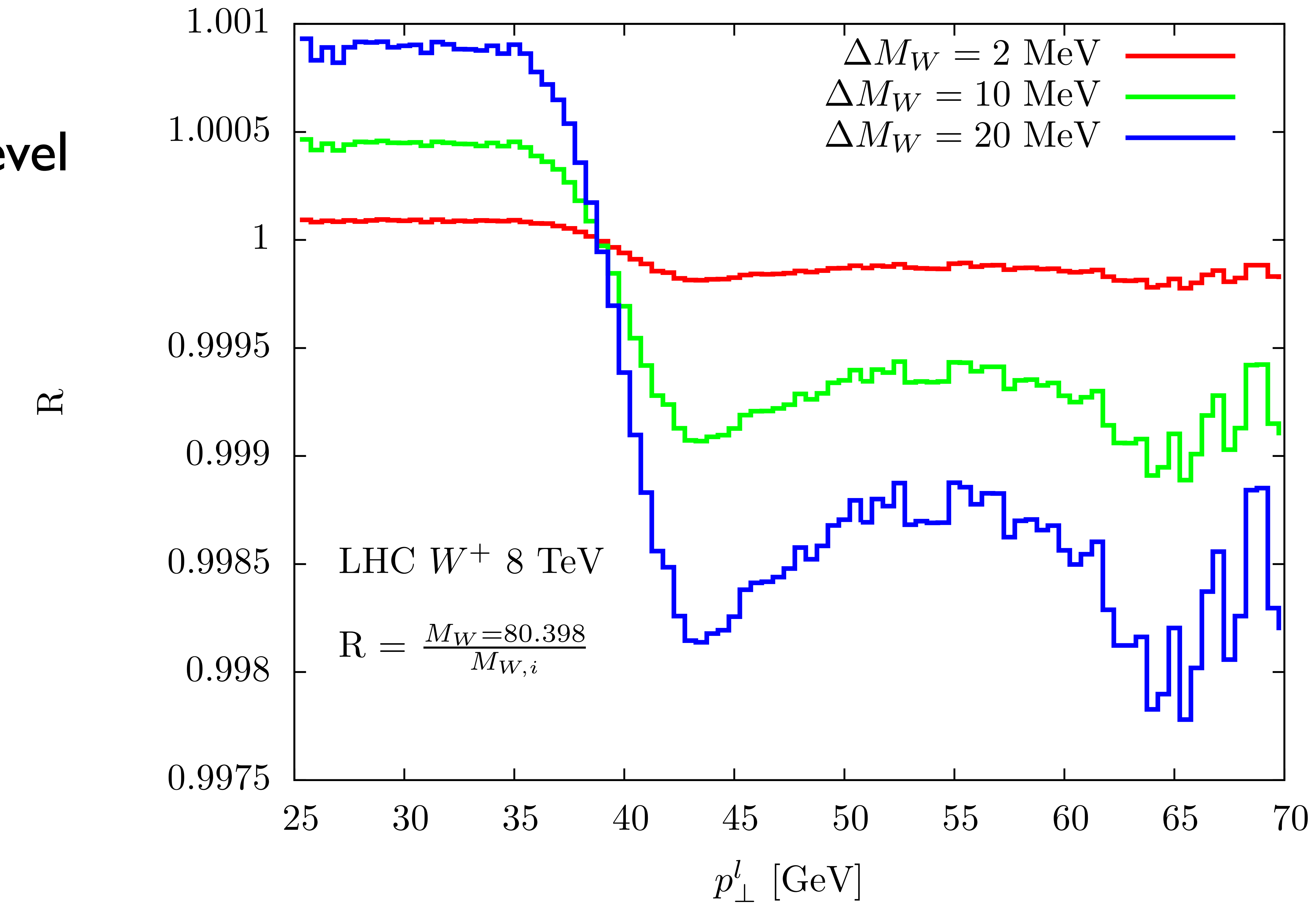
- we compute the corresponding theoretical distribution for several hypotheses of one Lagrangian input parameters (e.g. m_W)
- we compute, for each $m_W^{(k)}$ hypothesis, a χ^2_k defined in a certain interval around the jacobian peak (fitting window)
- we look for the minimum of the χ^2 distribution

The m_W value associated to the position of the minimum of the χ^2 distribution 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

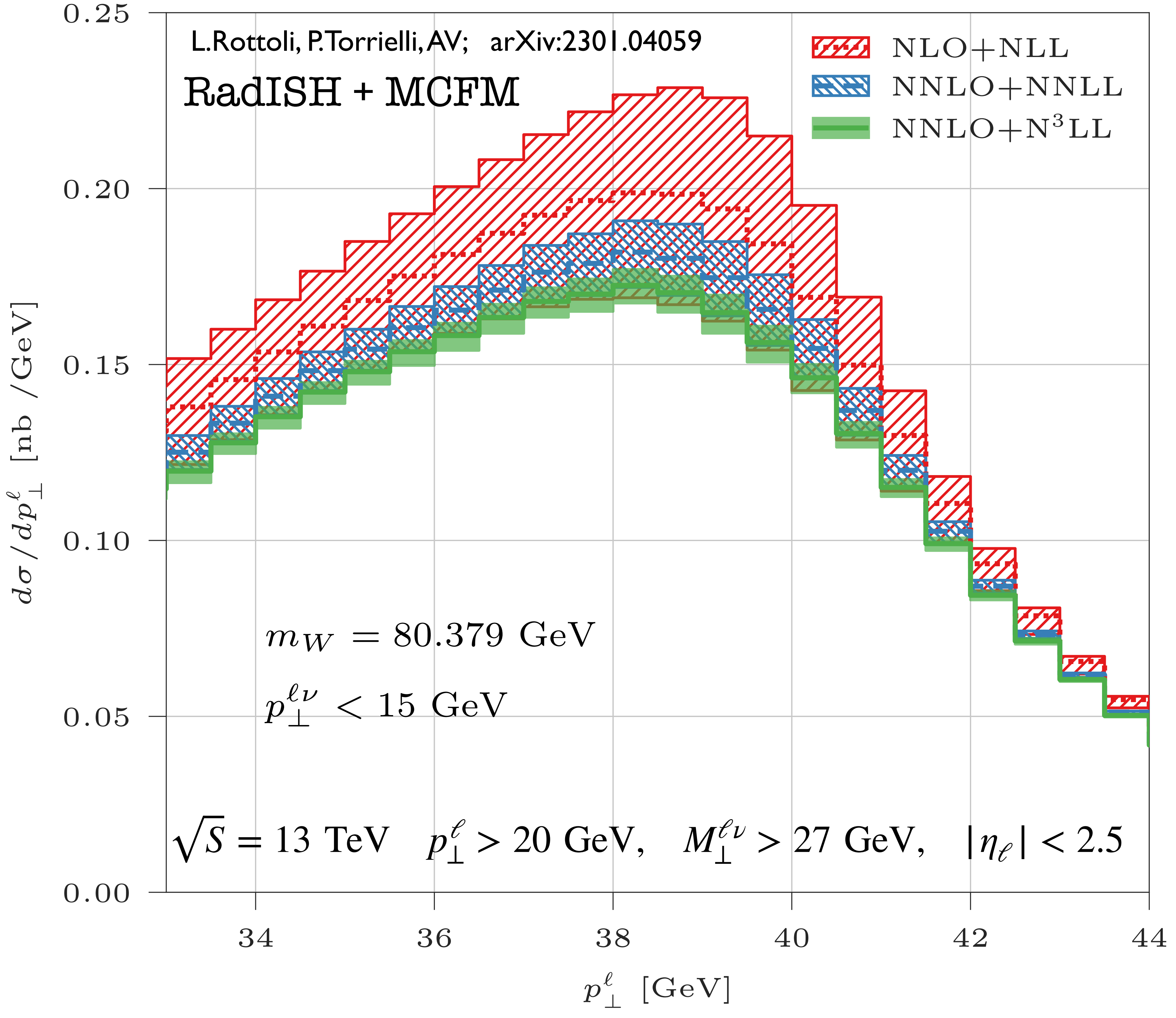
The theoretical uncertainties of the templates
contribute to the theoretical systematic error on m_W

- higher-order QCD
- non-perturbative QCD
- PDF uncertainties
- heavy quarks corrections
- EW corrections



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



Scale variation of the NNLO+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 !

→ data driven approach
a Monte Carlo event generator is tuned to the data in NCDY ($p_\perp^Z$)
for one QCD scale choice
↓
the same parameters are then used to prepare the CCDY templates

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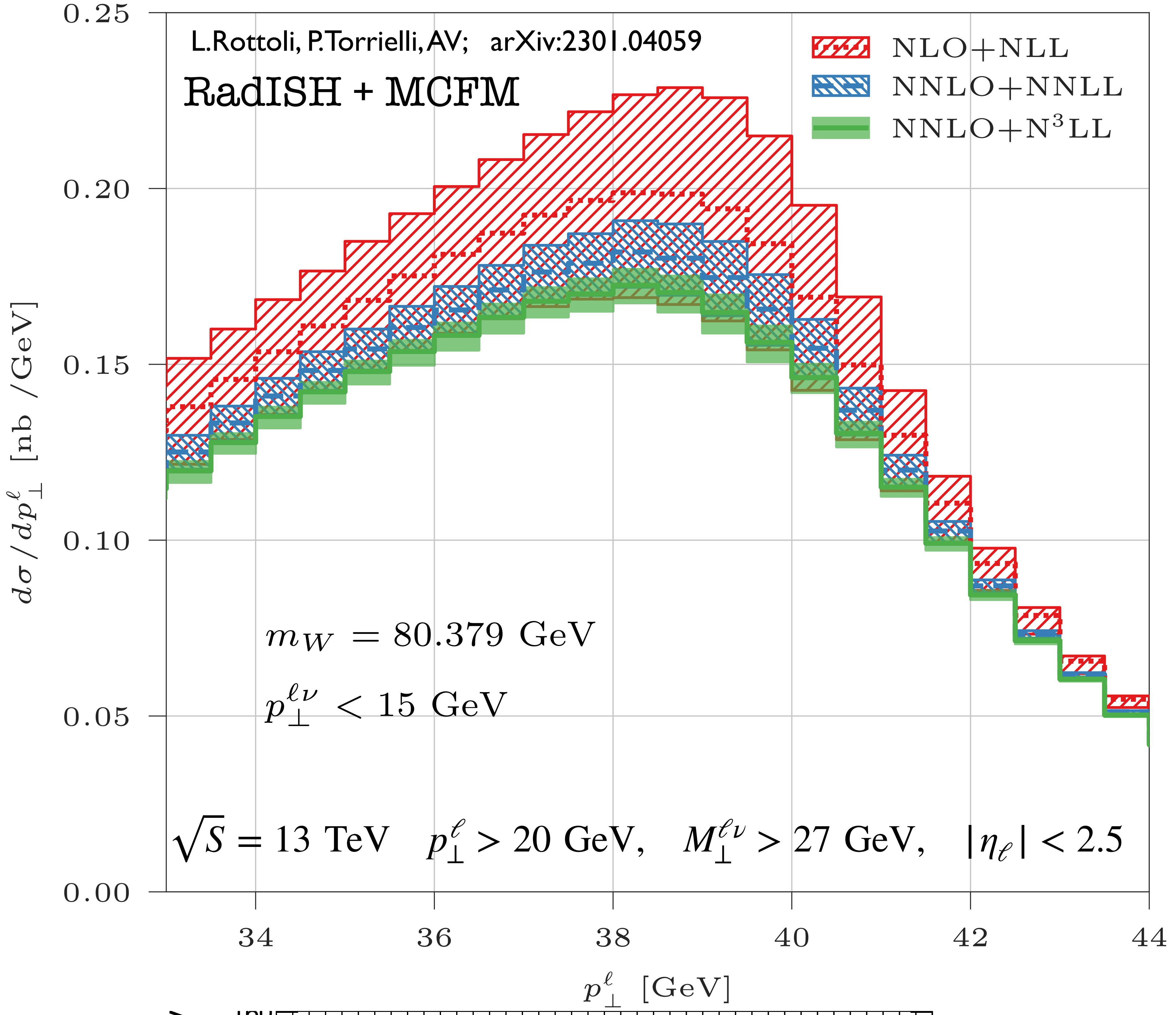

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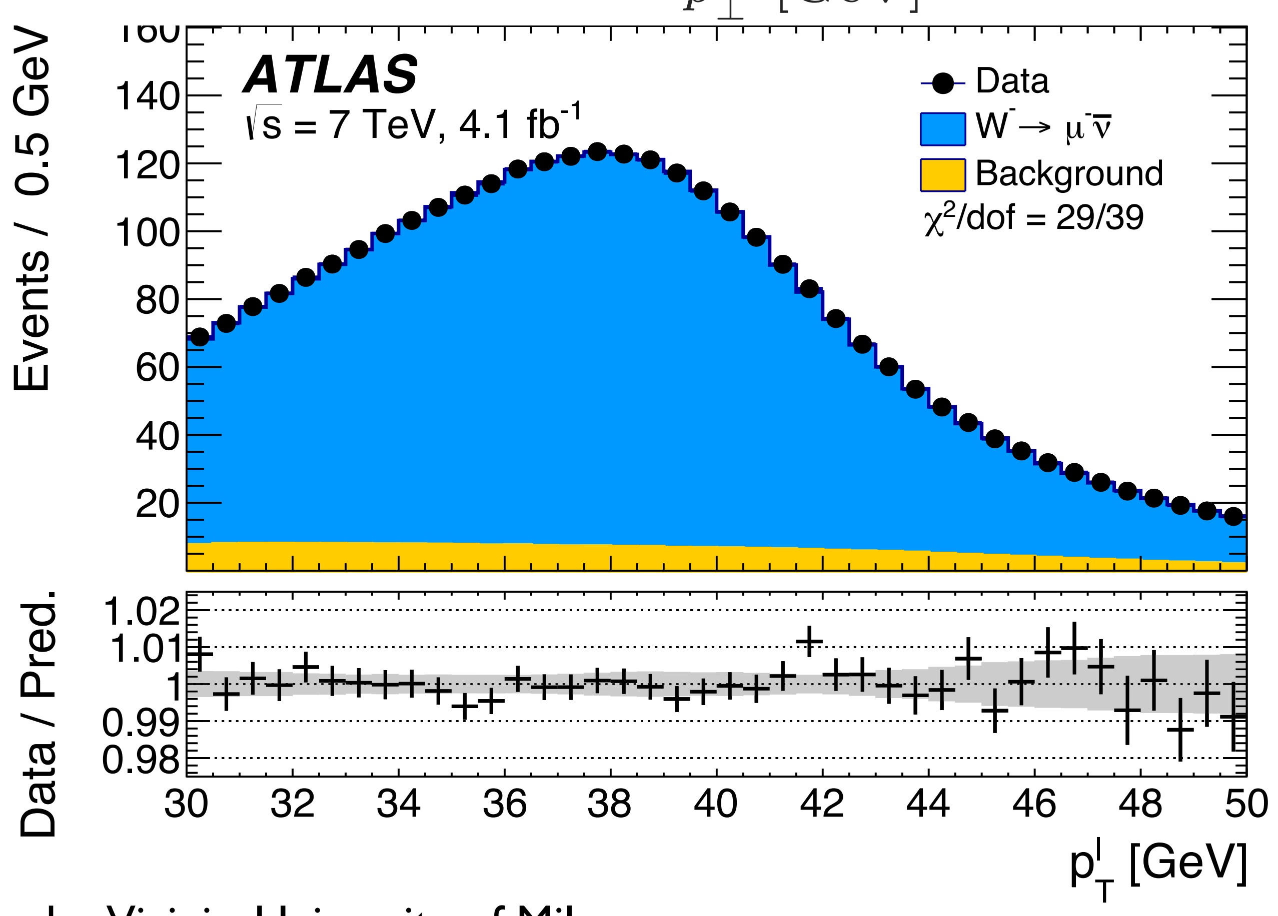
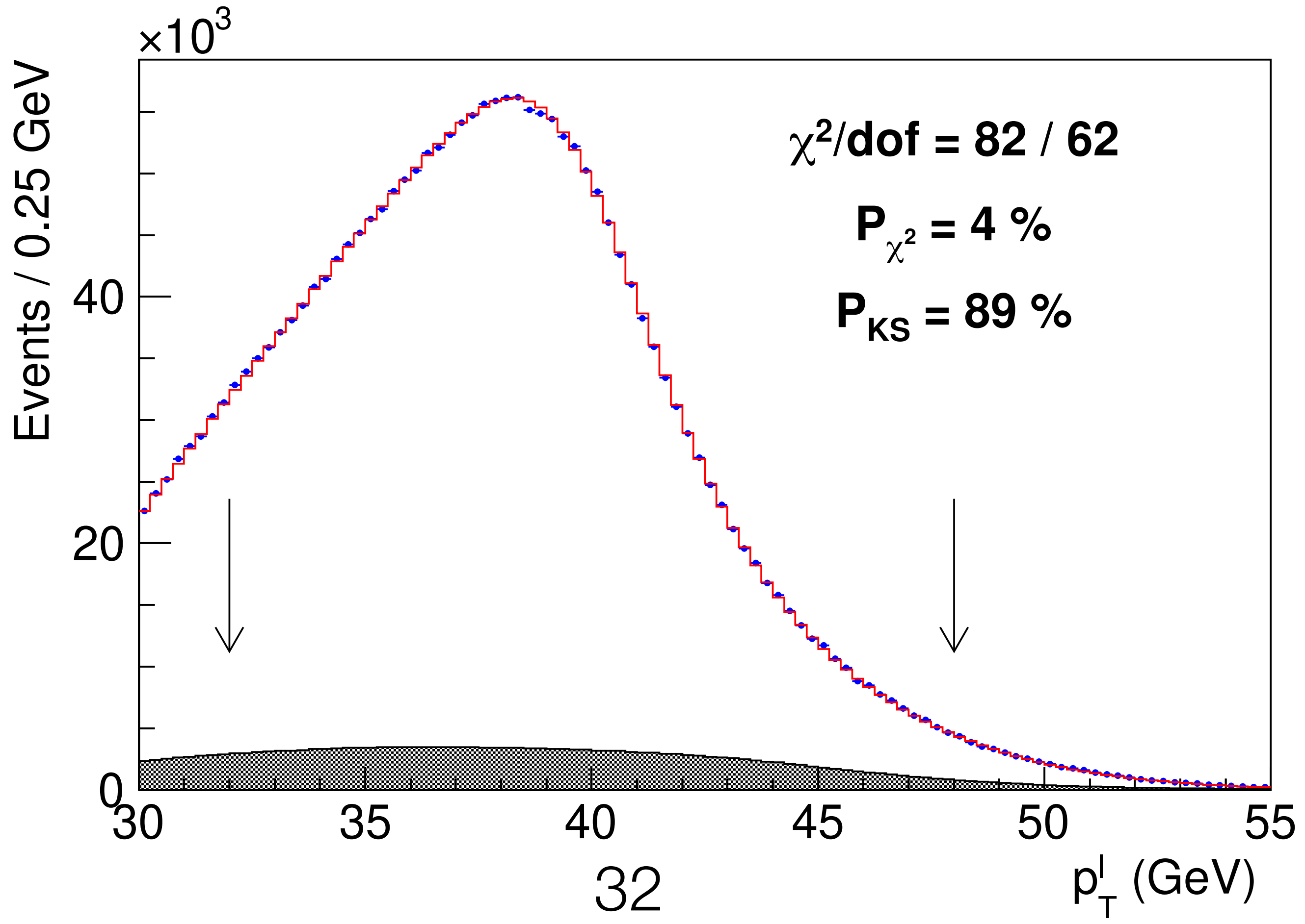
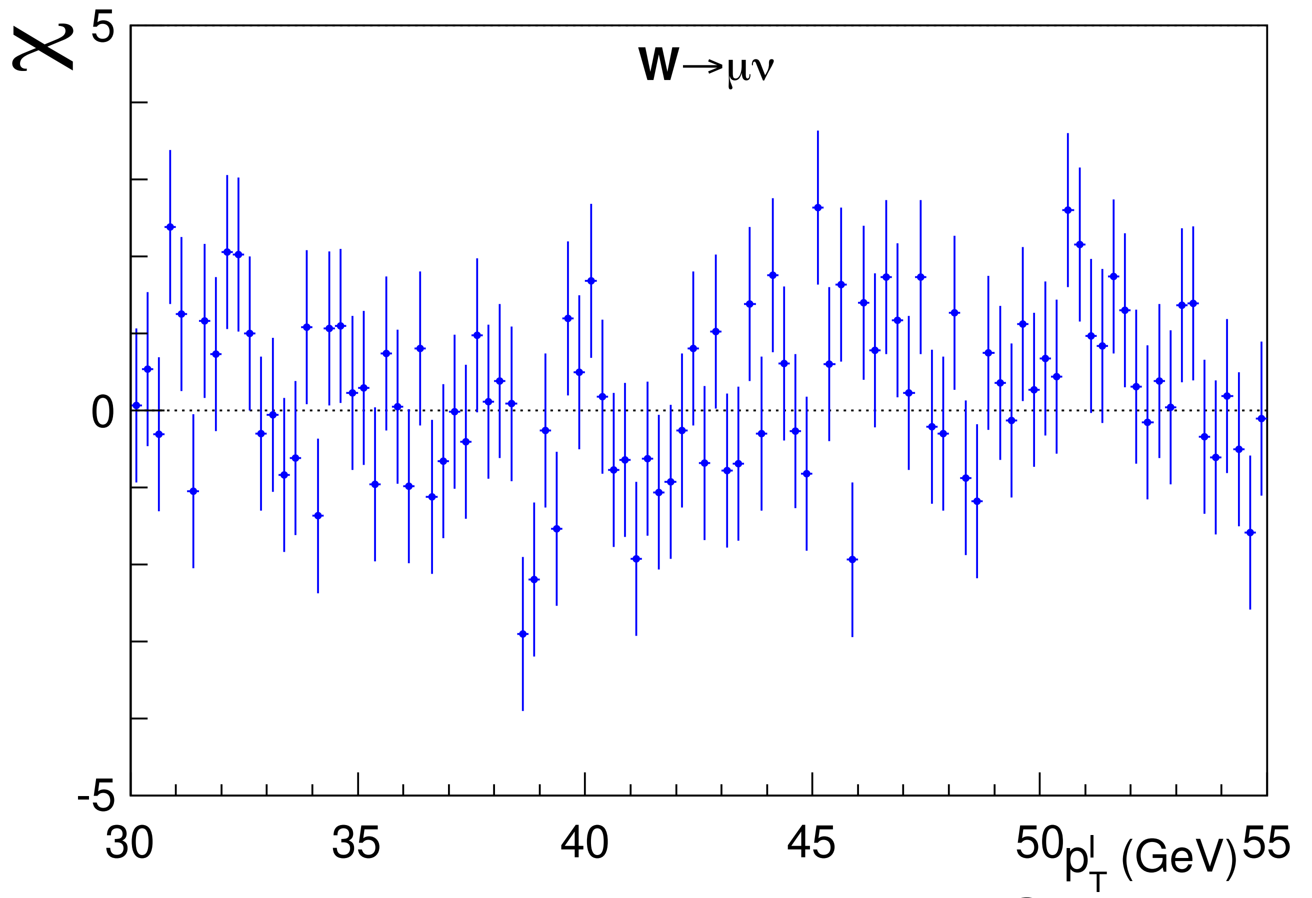


CDF collaboration, Scince 376, 170-176 (2022)





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Template fitting: description of the single lepton transverse momentum distribution

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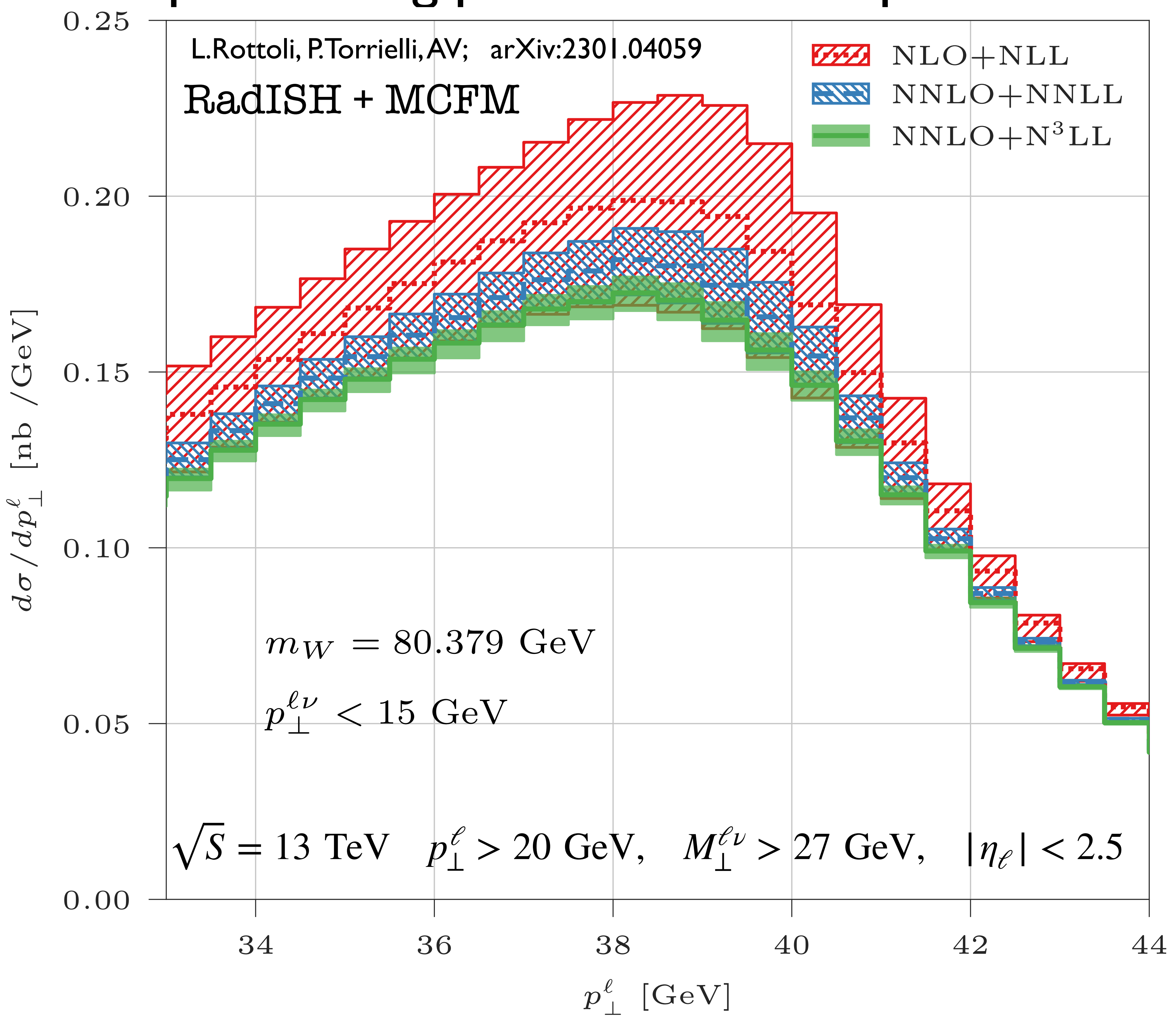

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→ data driven approach

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

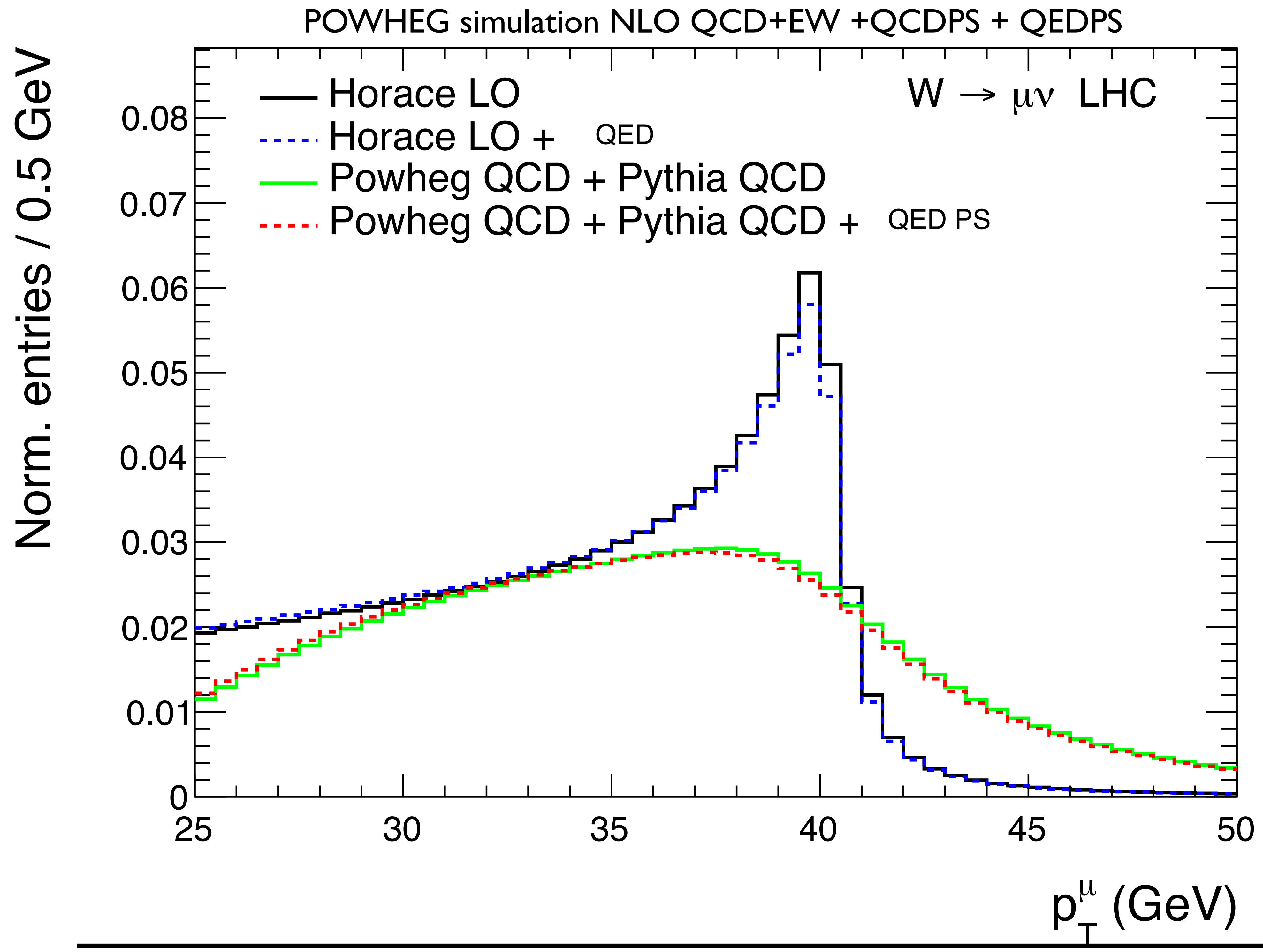
↓

the same parameters are then used to prepare the CCDY templates

A data driven approach improves	the accuracy of the model	(i.e. its ability to describe the data)
does not improve	the precision of the model	(the intrinsic ambiguities in the model formulation)

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

Impact of mixed QCD-QED corrections in the m_W determination



Huge impact of QED and mixed QCD-QED corrections in the m_W determination

What is the theoretical uncertainty on this estimated shift ?

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

How can we improve the estimate of mixed QCD-EW effects ?

Improve the calculations of fixed-order perturbative corrections

$$\sigma(h_1 h_2 \to \ell\bar{\ell} + X) = \sigma^{(0,0)} + \alpha_s\,\sigma^{(1,0)} + \alpha\,\sigma^{(0,1)} + \alpha_s^2\,\sigma^{(2,0)} + \alpha\,\alpha_s\,\sigma^{(1,1)} + \alpha^2\,\sigma^{(0,2)} + \alpha_s^3\,\sigma^{(3,0)} + \ldots$$

$\sigma^{(1,1)}$: NC-DY R.Bonciani, L.Buonocore, M.Grazzini, S.Kallweit, N.Rana, F.Tramontano, AV, (2021) T.Armadillo, R.Bonciani, S.Devoto, N.Rana, AV, (2022)
F.Buccioni, F.Caola, H.Chawdhry, F.Devoto, M.Heller, A.von Manteuffel, K.Melnikov, R.Röntsch, C.Signorile-Signorile, (2022)

CC-DY T.Armadillo, R.Bonciani, S.Devoto, N.Rana, AV, (2024)

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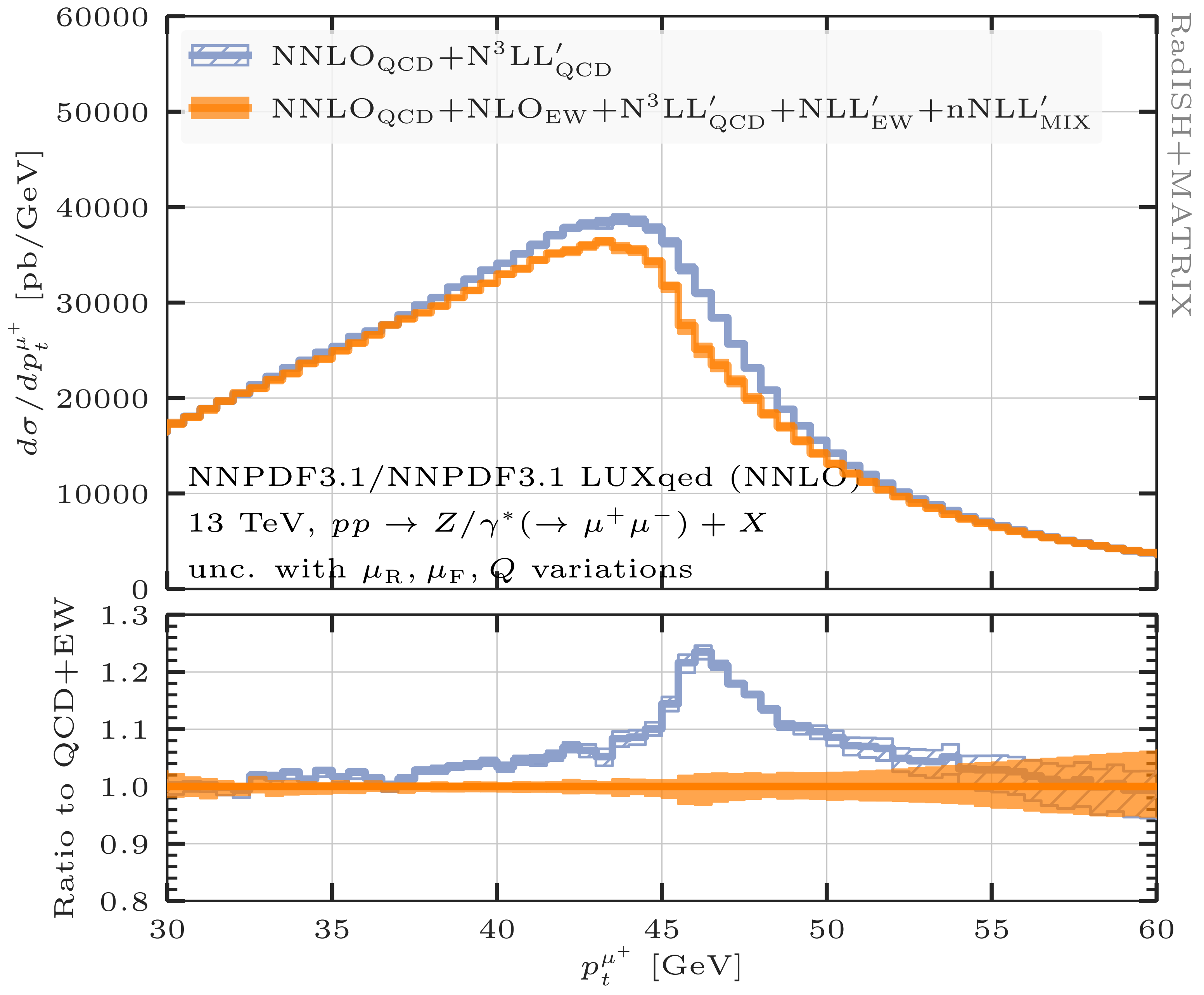
CC-DY T.Armadillo, R.Bonciani, S.Devoto, N.Rana, AV, (2024)

Match the fixed-order perturbative corrections with all-orders results in a joint QCD-QED resummation



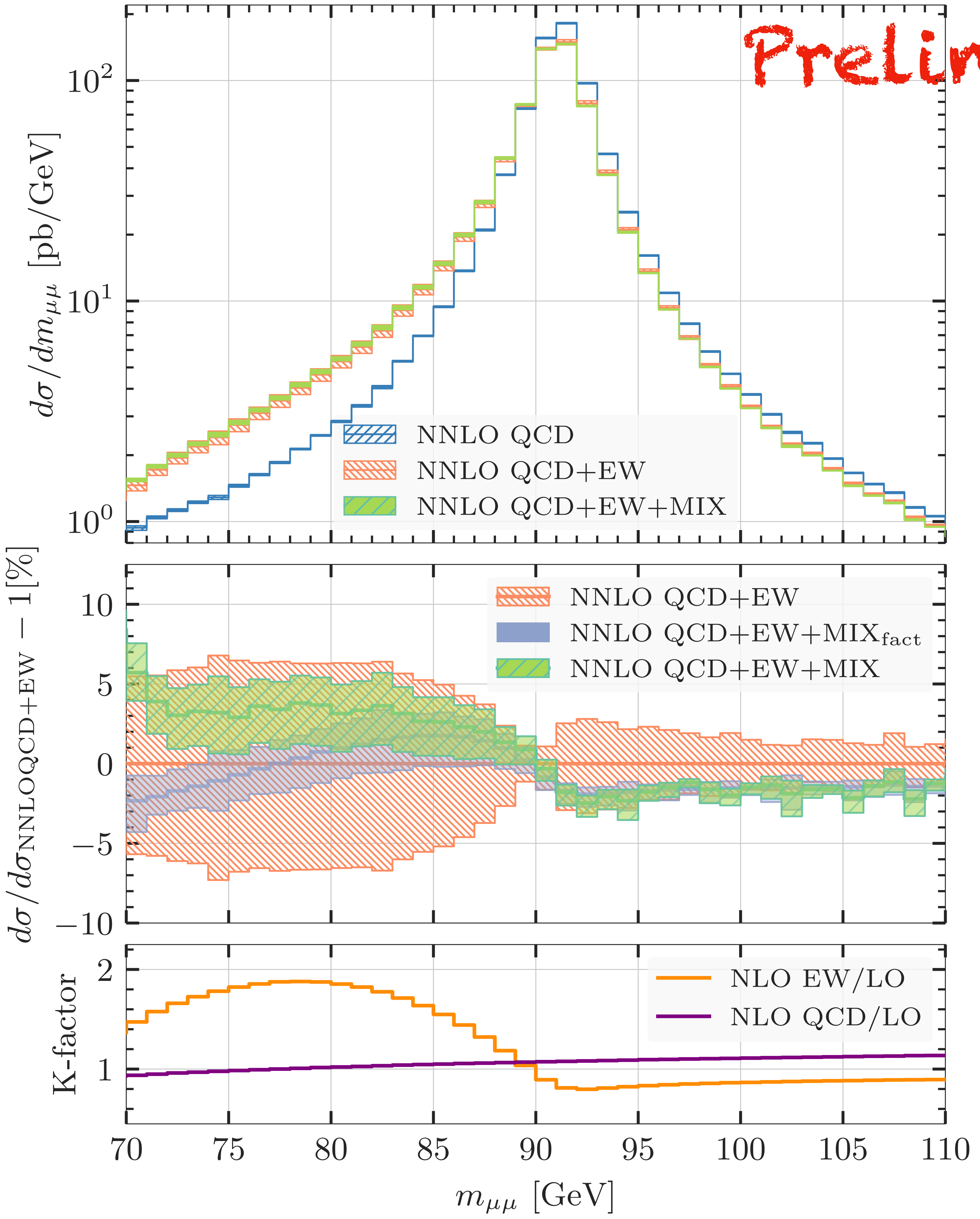
L.Buonocore, L.Rottoli, P.Torrielli, arXiv:2404.15112

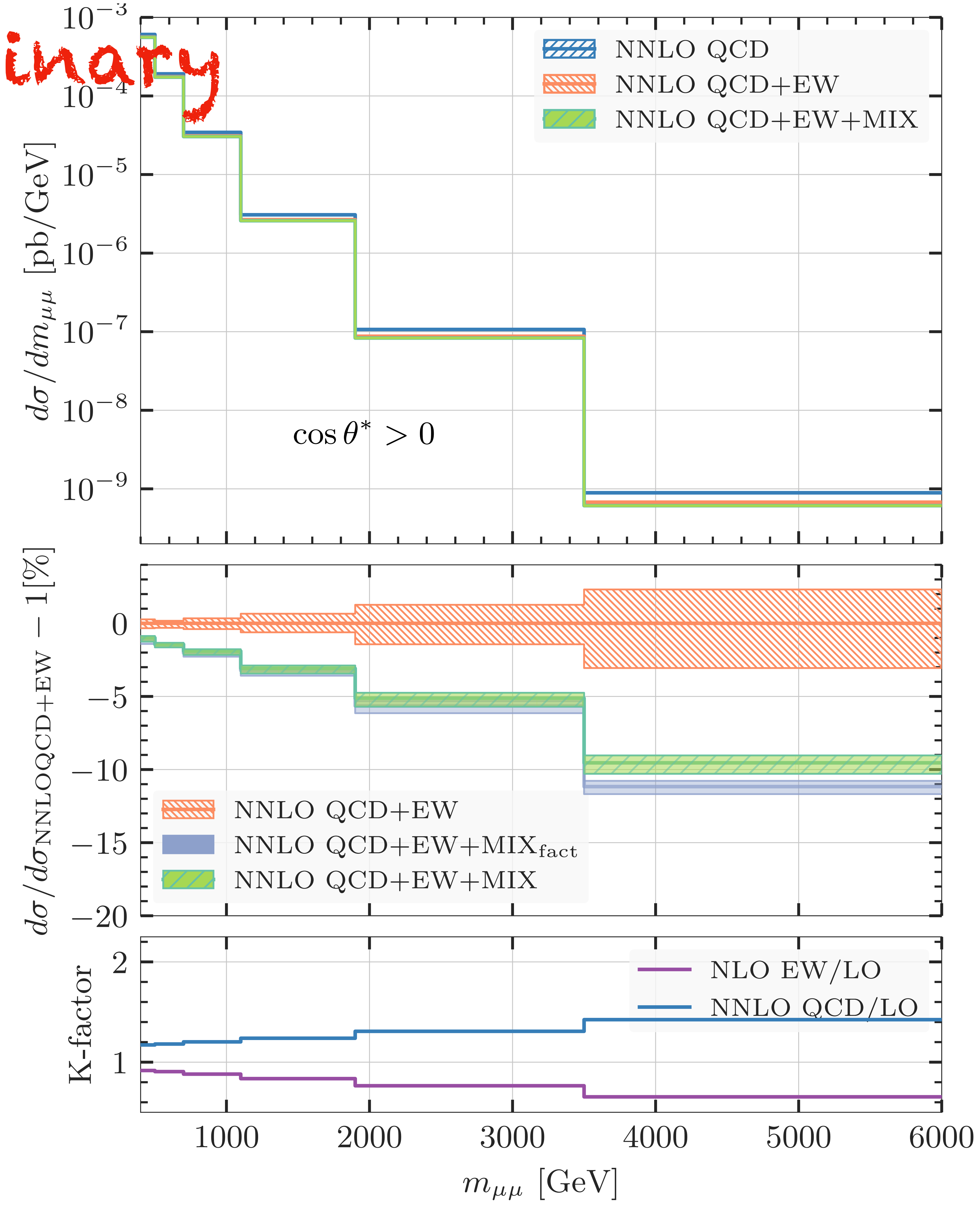
Matching in full QCD-EW SM at N3LL'-QCD + NLL'-EW + nNLL'-mixed accuracy including QED effects from all charged legs

Matching with the exact NNLO QCD-EW will be needed to reach full NNLL-mixed
→ Reliable estimate of the reduced residual theoretical uncertainties

Phenomenology of Neutral Current Drell-Yan including exact NNLO QCD-EW corrections

R.Bonciani, L.Buonocore, S.Devoto, M.Grazzini, S.Kallweit, N.Rana, F.Tramontano, AV, arXiv:2106.11953 , Phys.Rev.Lett. 128 (2022) 1, 012002 and work in preparation





First example of an exact calculation at this perturbative order

Large effects below the Z resonance (the factorised approximation fails) → impact on the $\sin^2\theta_{eff}$ determination

Large effects O(several %) above 1 TeV, with O(1%) non-factorizable contributions → impact on SMEFT studies

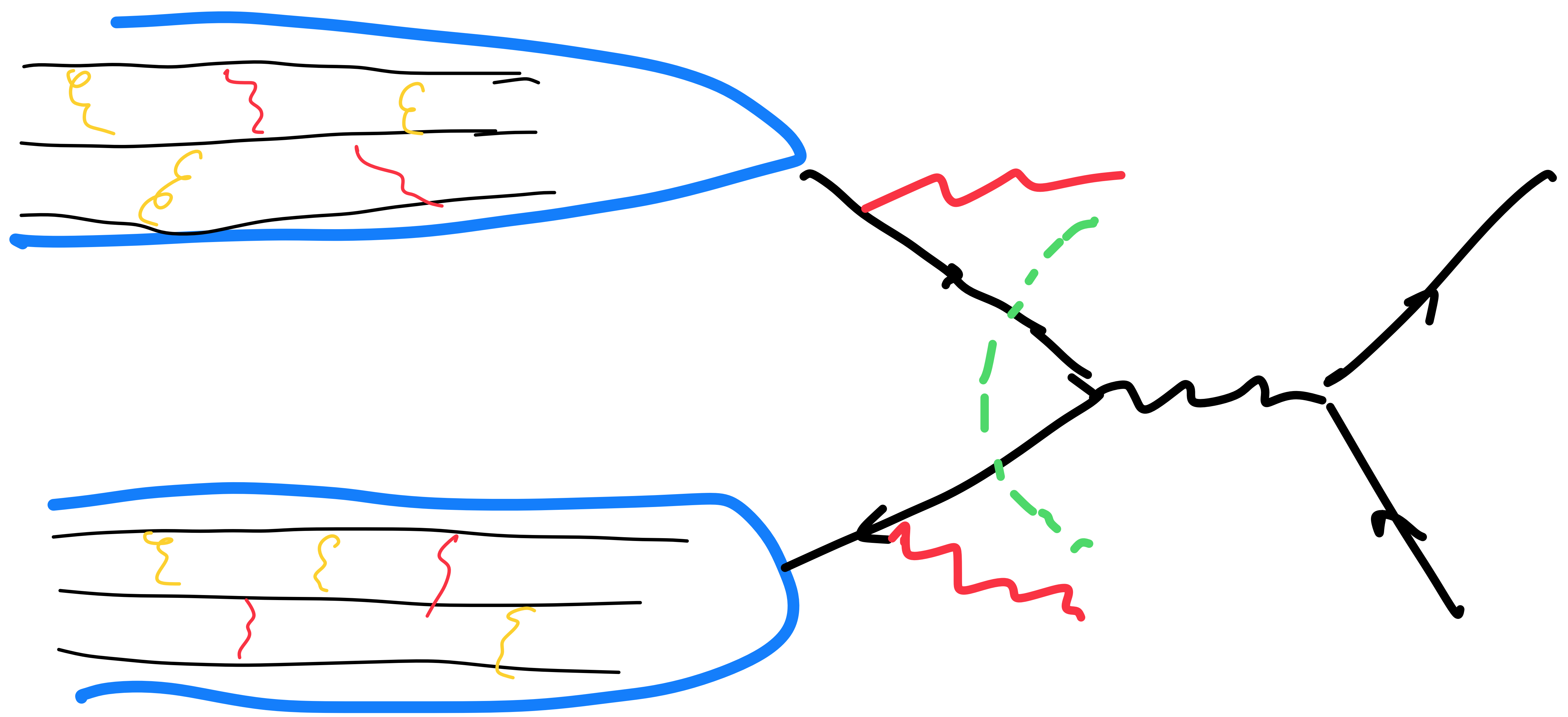
Photons in the proton

Quarks are electrically charged → they interact inside the proton → photon is a parton inside the proton (with its density)

Any hard scattering process with electrically charged initial state partons implies QED ISR → collinear divergences

The initial state collinear divergences are factorized and reabsorbed in the physical proton PDFs

Every time we include QED ISR effects, we must use proton PDFs with QCD+QED evolution kernels



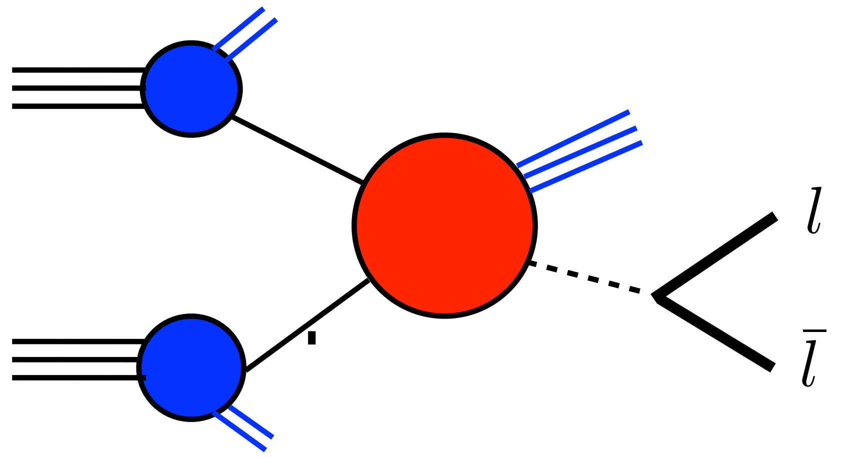
e.g. $\sigma(pp \to \mu^+\mu^- + X)$

at LO contributions from $q\bar{q} \to \mu^+\mu^-$
$\gamma\gamma \to \mu^+\mu^-$

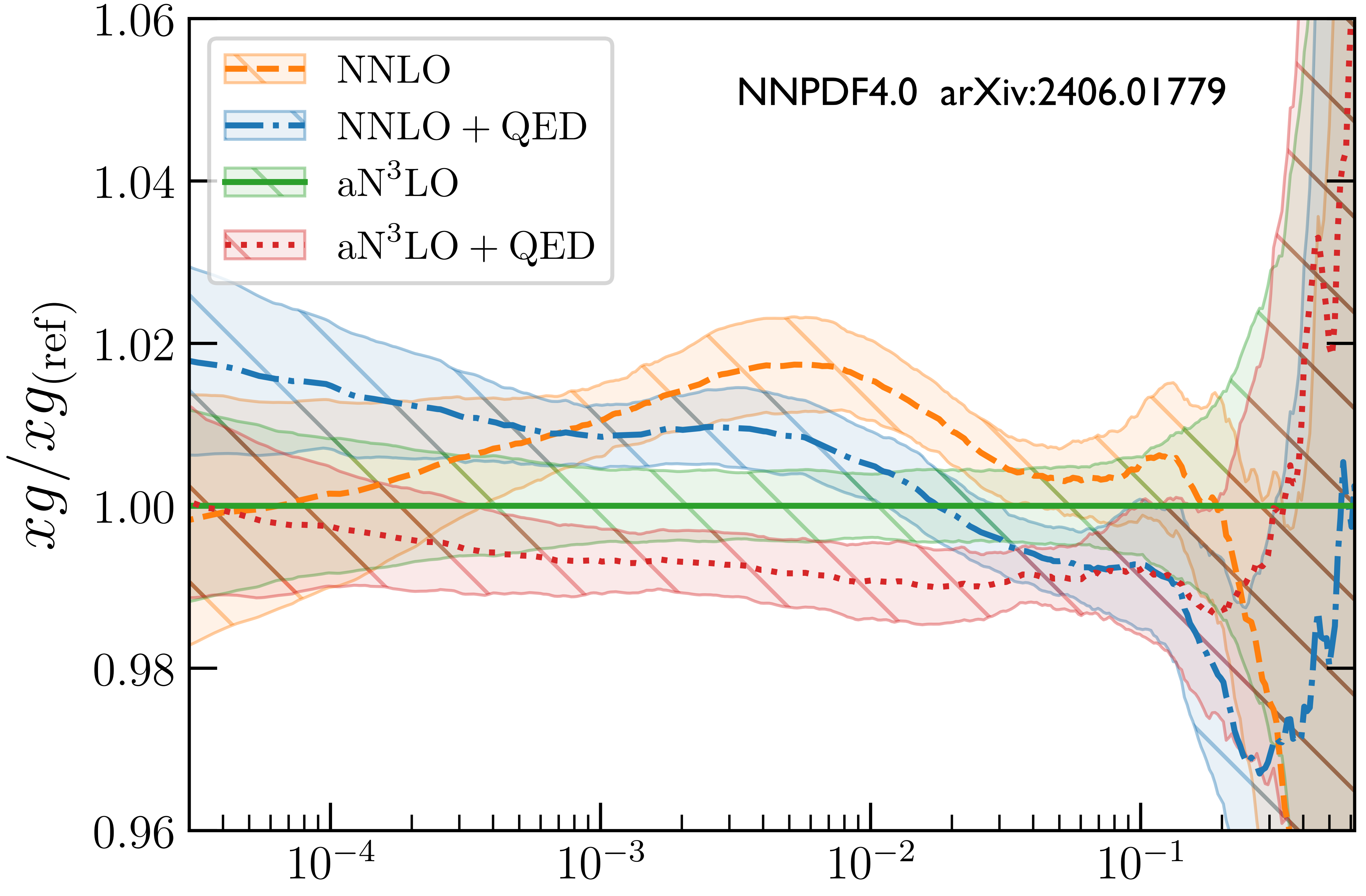
both partonic cross sections are of $\mathcal{O}(\alpha^2)$
the $\gamma\gamma$ process is suppressed by the small PDF luminosity

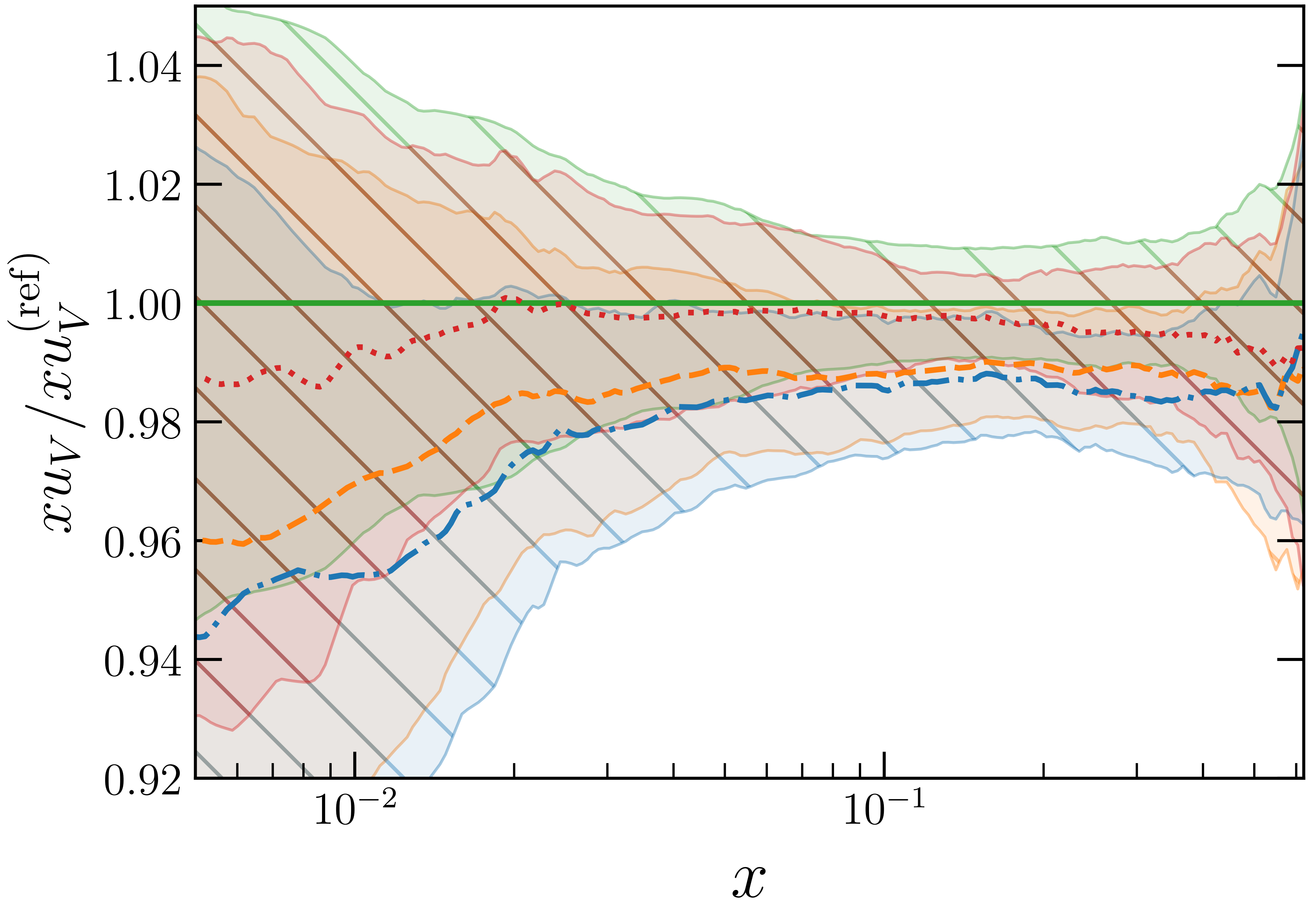
Mixed QCD and EW effects in proton PDFs

- two possible DGLAP evolutions of proton PDFs: - pure QCD
  - including QED and mixed QCD-QED kernels



- the inclusion of a photon density in the proton "subtracts" momentum to quarks and gluons
  → reduced xsecs → compensated by new photon-induced partonic channels





When
NLO QCD and EW corrections
are both large

Diboson production: NNLO-QCD + NLO-EW corrections

M.Grazzini, S.Kallweit, J.Lindert, S.Pozzorini, M.Wiesemann, arXiv:1912.00068

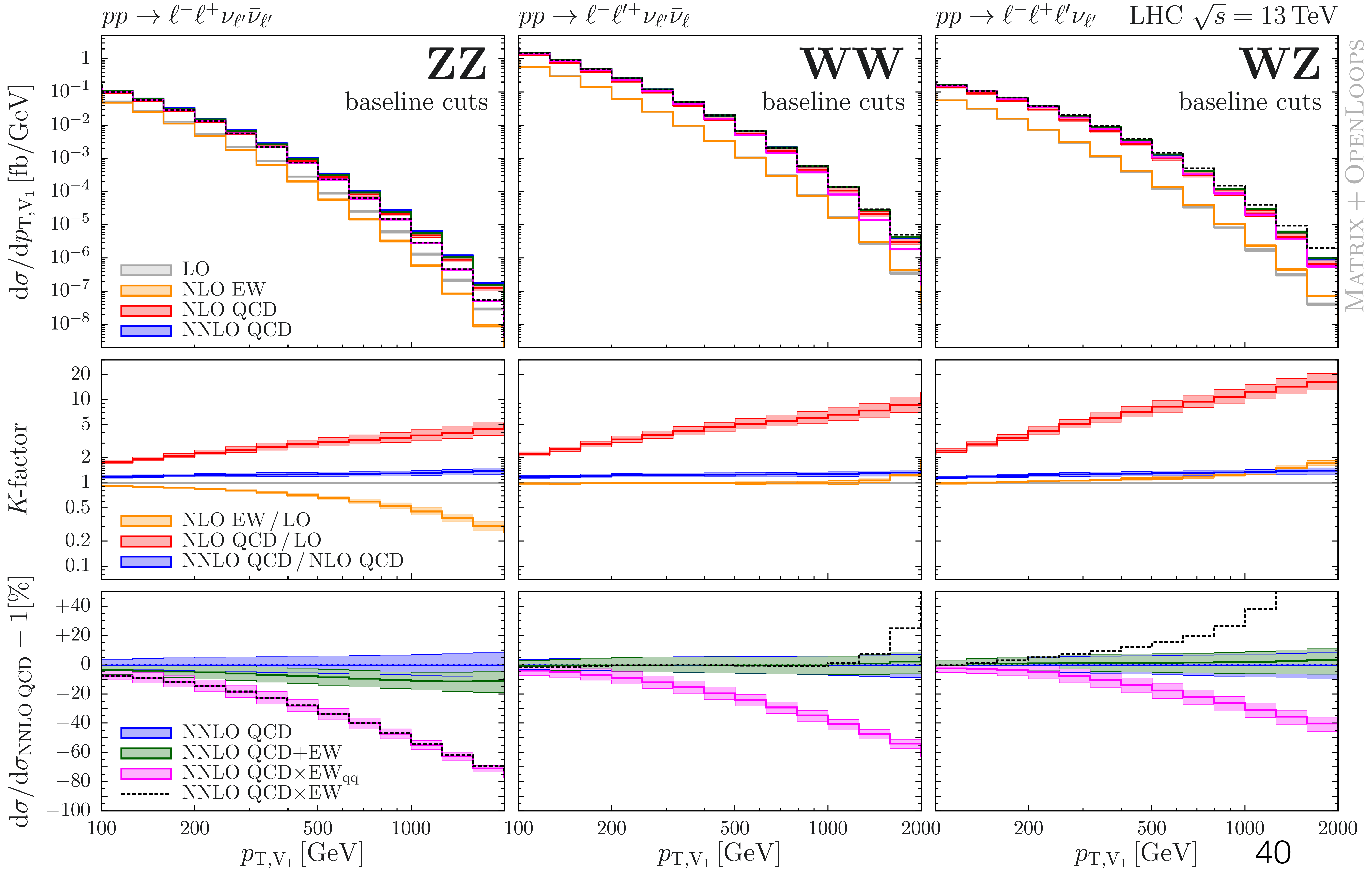
- large QCD and EW corrections need a consistent combination to achieve O(1%) precision → Matrix+OpenLoops
- comparison of additive vs multiplicative combinations of QCD and EW effects, to estimate mixed QCD-EW missing corrections
- differences between 1) hard-hard boson regions and 2) (hard boson, hard jet, soft boson) regions

  in 1) good convergence of the QCD expansion and factorisation of the EW Sudakov logs

  in 2) "giant" K-factors, large EW Sudakov logs, large photon-induced contributions compete to the final result

  → non-trivial estimate of the remaining uncertainties

  jet-vetoes milden the "giant" K-factor and enhance the sensitivity to tri- and quadri-linear couplings



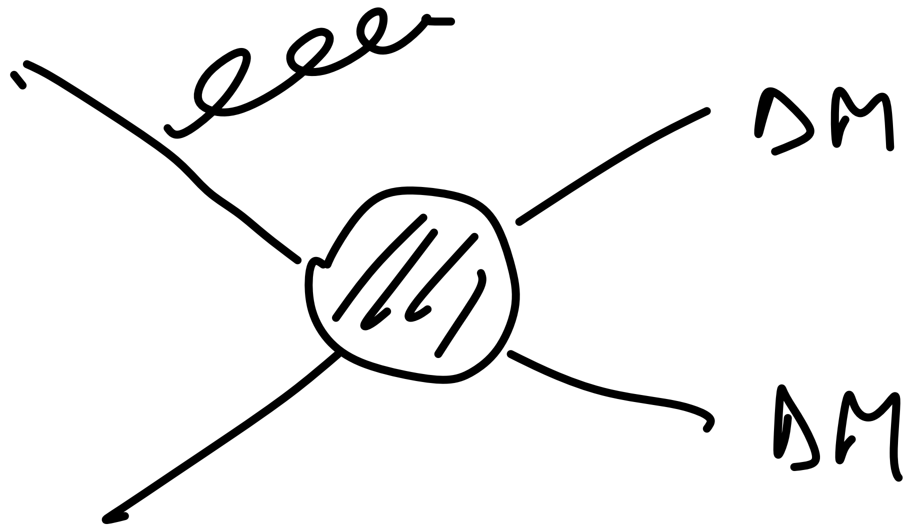
pt_V1 is a "worst-case" observable stressing all potential issues

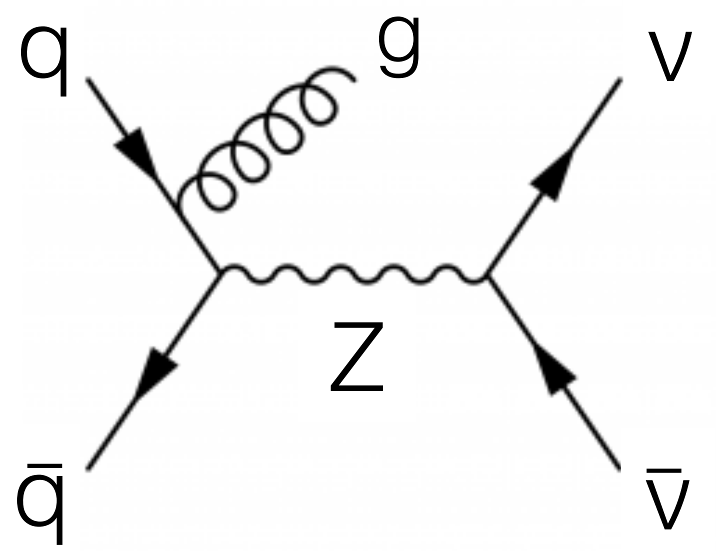
$$d\sigma_{\mathrm{NNLO\,QCD+EW}} = d\sigma_{\mathrm{LO}}\left(1+\delta_{\mathrm{QCD}}+\delta_{\mathrm{EW}}\right) + d\sigma_{\mathrm{LO}}^{gg}$$

$$d\sigma_{\mathrm{NNLO\,QCD\times EW}} = d\sigma_{\mathrm{NNLO\,QCD+EW}} + d\sigma_{\mathrm{LO}}\delta_{\mathrm{QCD}}\,\delta_{\mathrm{EW}}$$

$$d\sigma_{\mathrm{NNLO\,QCD\times EW_{qq}}} = d\sigma_{\mathrm{LO}}^{q\bar q}\left(1+\delta_{\mathrm{QCD}}^{q\bar q}\right)\left(1+\delta_{\mathrm{EW}}^{q\bar q}\right) + d\sigma_{\mathrm{LO}}^{\gamma\gamma}\left(1+\delta_{\mathrm{EW}}^{\gamma\gamma/q\gamma}\right) + d\sigma_{\mathrm{LO}}^{gg}$$

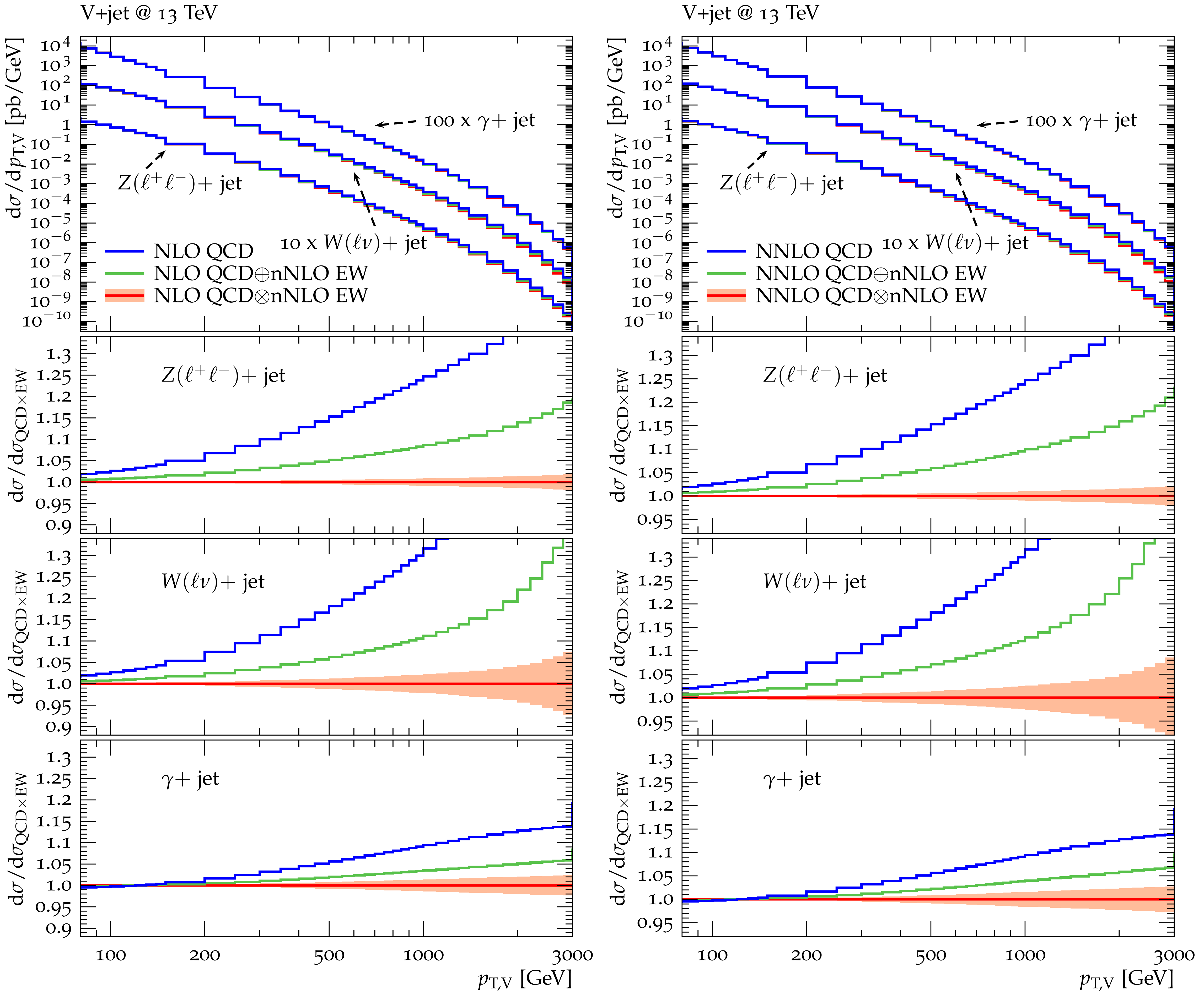
A background to dark matter searches

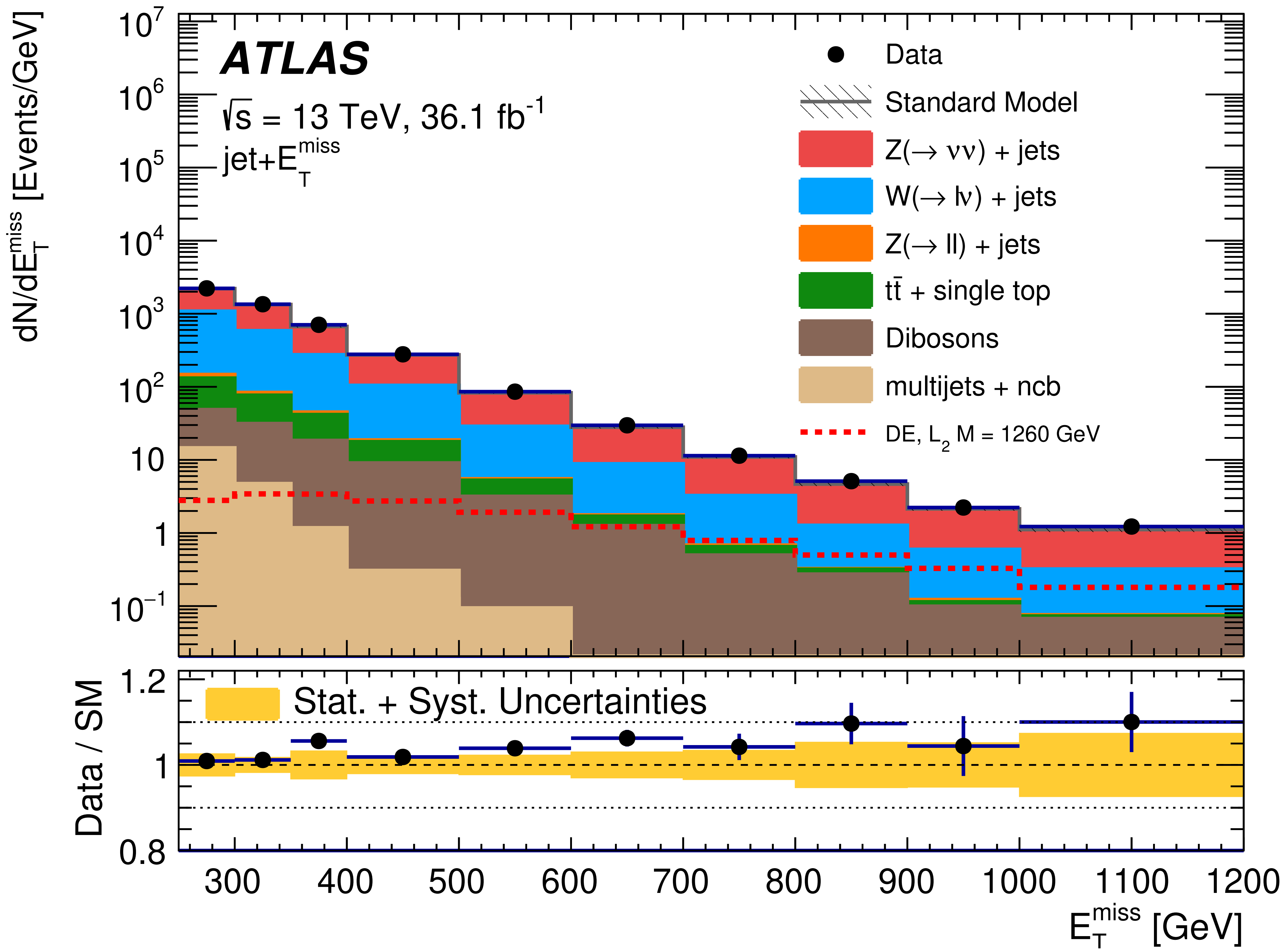




All possible channels of V+jet are studied as proxies to $pp \to \nu\bar{\nu} + j$ at large $p_\perp^V$

The uncertainties in the SM predictions are due to missing exact $\mathcal{O}(\alpha\alpha_s)$results

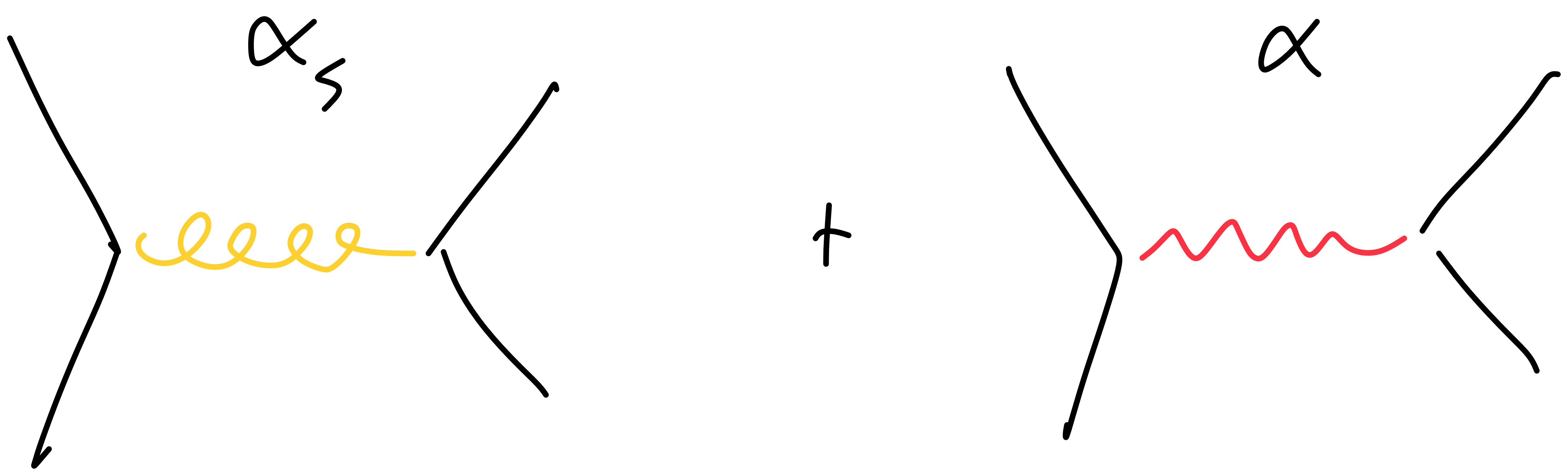




When both QCD and EW are present at LO

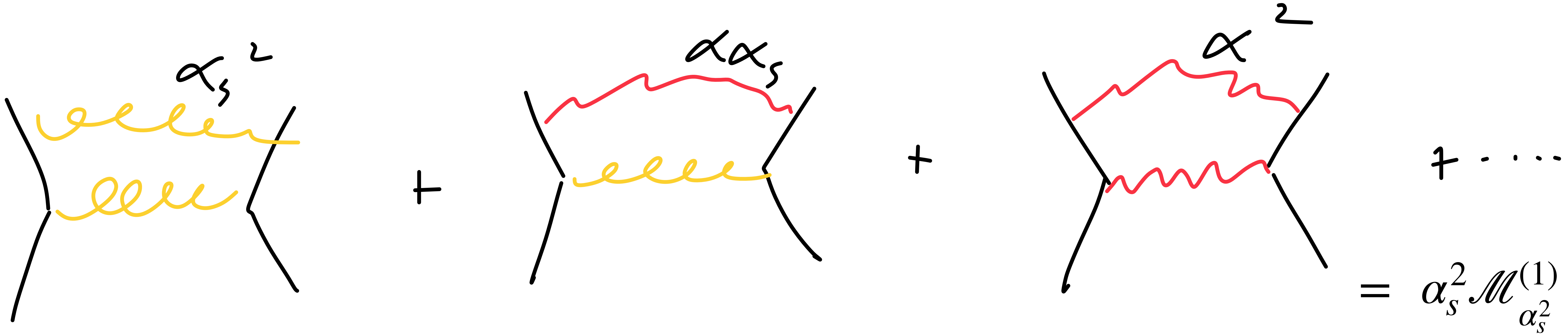
QCD and EW interfering at LO

$\mathcal{M}_0 =$



$= \alpha_s \mathcal{M}^{(0)}_{\alpha_s} + \alpha \mathcal{M}^{(0)}_{\alpha}$

$\mathcal{M}_1 =$



$= \alpha_s^2 \mathcal{M}^{(1)}_{\alpha_s^2} + \alpha\alpha_s \mathcal{M}^{(1)}_{\alpha_s\alpha} + \alpha^2 \mathcal{M}^{(1)}_{\alpha^2}$

$$|\mathcal{M}_0|^2 = \alpha_s^2 |\mathcal{M}^{(0)}_{\alpha_s}|^2 + \alpha\alpha_s 2\mathrm{Re}(\mathcal{M}^{(0)}_{\alpha}\, \mathcal{M}^{(0),\dagger}_{\alpha_s}) + \alpha^2 |\mathcal{M}^{(0)}_{\alpha}|^2 \equiv \mathrm{LO}_1 + \mathrm{LO}_2 + \mathrm{LO}_3$$

$$2\mathrm{Re}(\mathcal{M}_1 \mathcal{M}_0^\dagger) = 2\mathrm{Re}\left[\alpha_s^3 \mathcal{M}^{(1)}_{\alpha_s^2}\mathcal{M}^{(0),\dagger}_{\alpha_s} + \alpha_s^2\alpha\left(\mathcal{M}^{(1)}_{\alpha_s^2}\mathcal{M}^{(0),\dagger}_{\alpha} + \mathcal{M}^{(1)}_{\alpha_s\alpha}\mathcal{M}^{(0),\dagger}_{\alpha_s}\right) + \alpha_s\alpha^2\left(\mathcal{M}^{(1)}_{\alpha^2}\mathcal{M}^{(0),\dagger}_{\alpha_s} + \mathcal{M}^{(1)}_{\alpha_s\alpha}\mathcal{M}^{(0),\dagger}_{\alpha}\right) + \alpha^3 \mathcal{M}^{(1)}_{\alpha^2}\mathcal{M}^{(0),\dagger}_{\alpha}\right]$$

$$\equiv \mathrm{NLO}_1 + \mathrm{NLO}_2 + \mathrm{NLO}_3 + \mathrm{NLO}_4$$

When both interactions interfere at LO, then the splitting into NLO-QCD and NLO-EW loses meaning

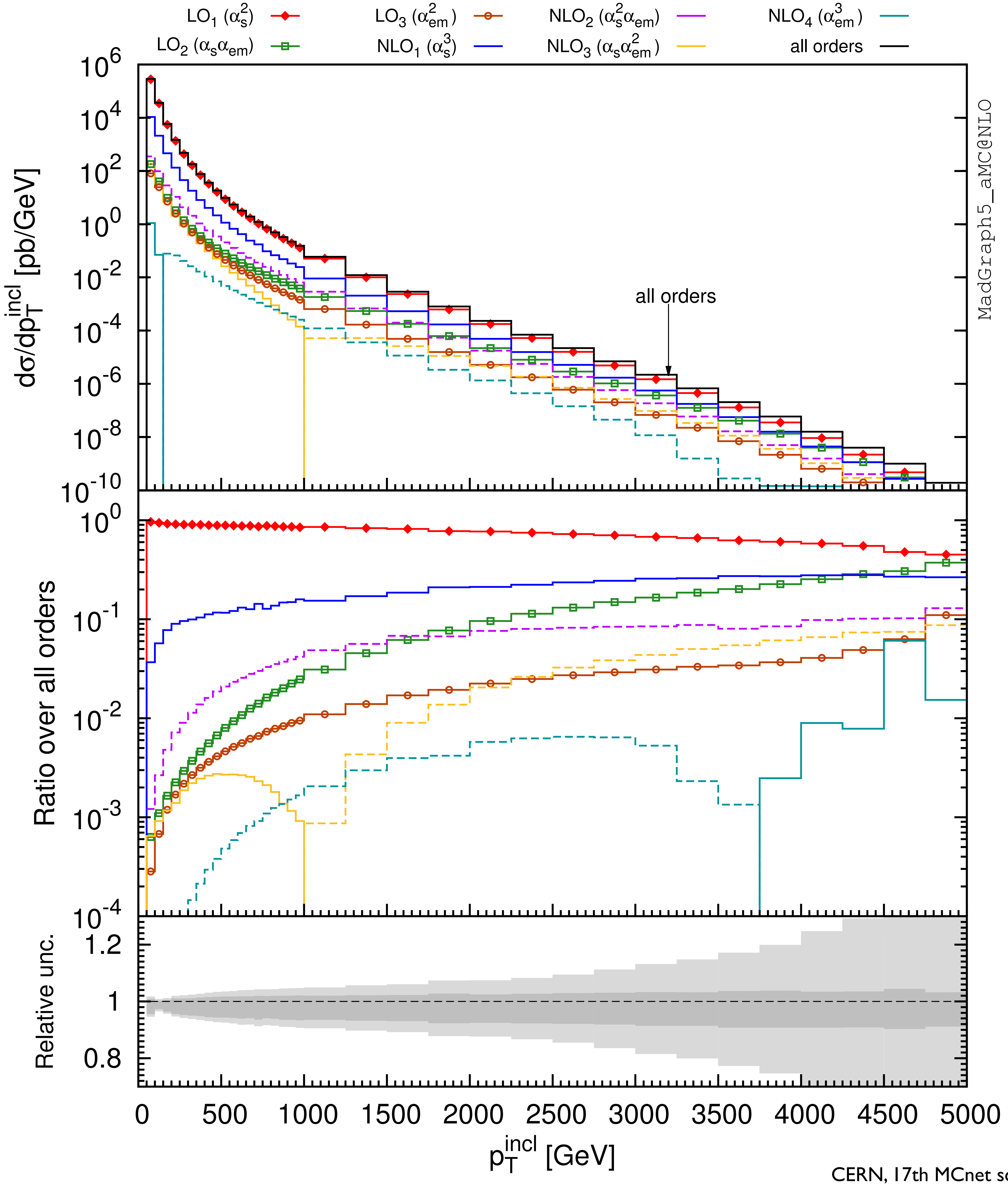
orders → loop counting

at a given order, → $\alpha_s^i \alpha^j$ power counting

QCD and EW interfering at LO

dijet hadroproduction

Frederix, Frixione, Hirschi, Pagani, Shah, Zaro, arXiv:1612.06548



Pole expansion
vs
full off-shell production

Gauge boson production and pole expansion

The presence of a resonance may help to organise the full amplitude in a hierarchical way

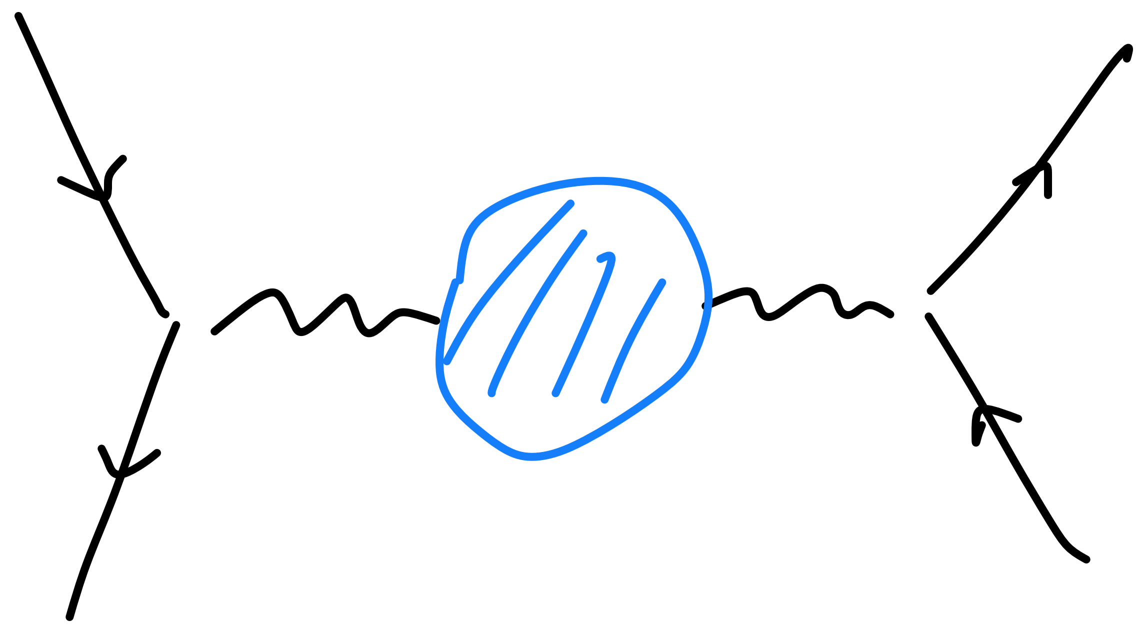
$$\mathcal{M}(q^2) \;=\; \frac{R^{(-1)}(\mu^2)}{q^2-\mu^2} \;+\; R^{(0)}(\mu^2) \;+\; (q^2-\mu^2)R^{(1)}(\mu^2) \;+\; \cdots$$

At the complex mass pole, the residue $R^{(-1)}(\mu^2)$ and all the other coefficients R are gauge invariant

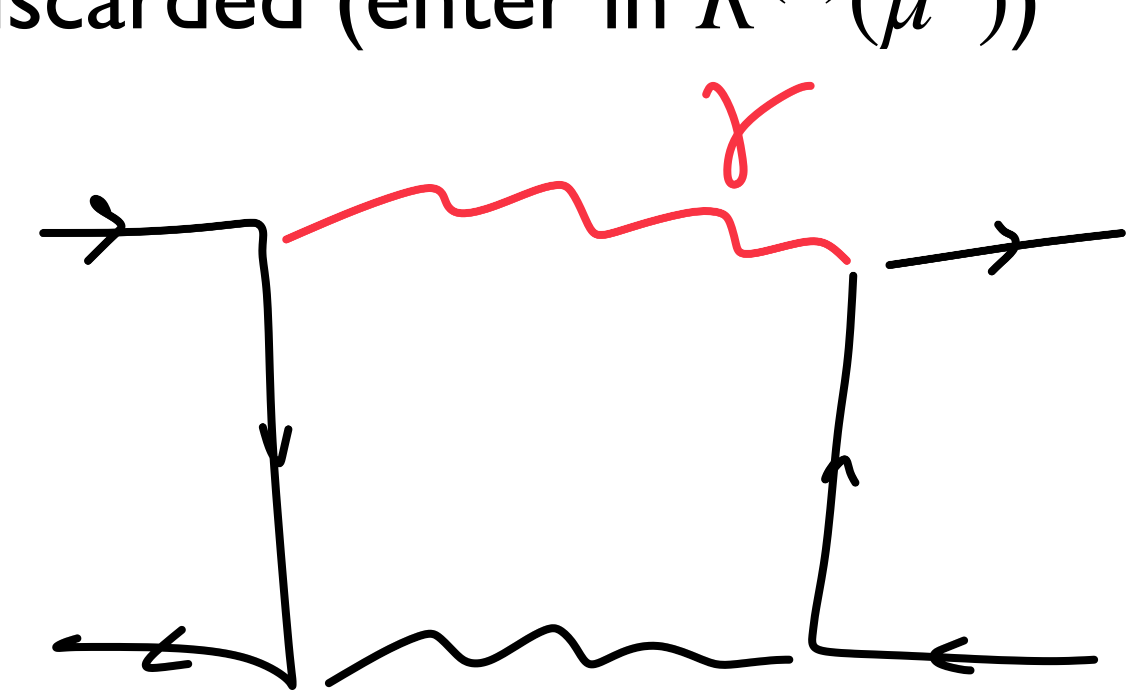
The expansion is expected to be accurate when $q^2-\mu^2 \sim \# \, m\Gamma$

The expansion helps to simplify loop calculations:

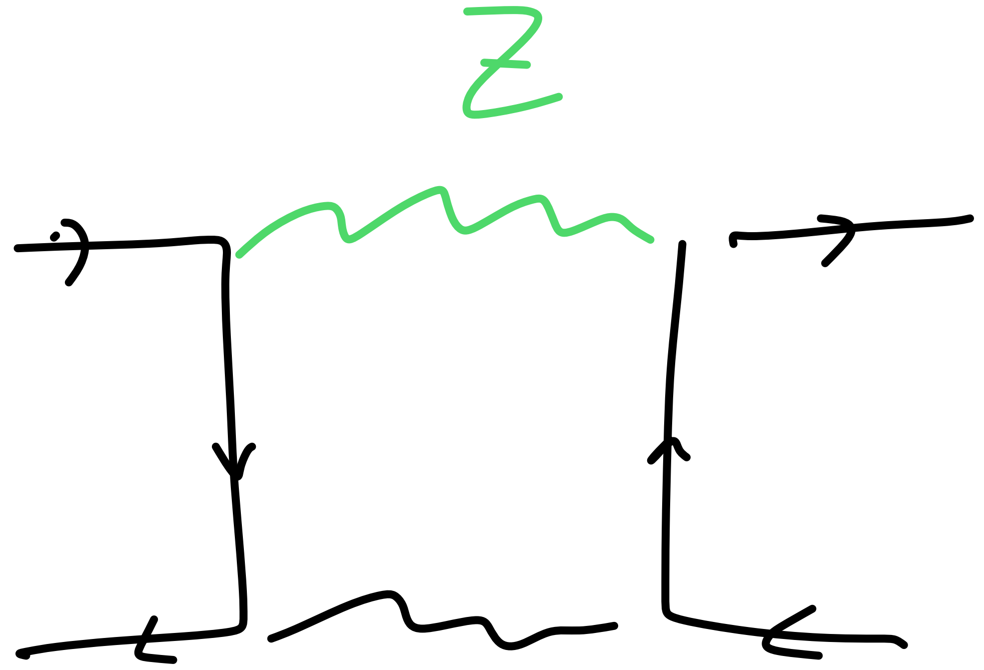
- the exchange of soft particles can be exactly computed
- difficult massive diagrams can be discarded (enter in $R^{(0)}(\mu^2)$)



resonant $\rightarrow R^{(-1)}(\mu^2)$



soft part resonant. $\rightarrow R^{(-1)}(\mu^2)$
hard part non-resonant $\rightarrow R^{(0)}(\mu^2)$

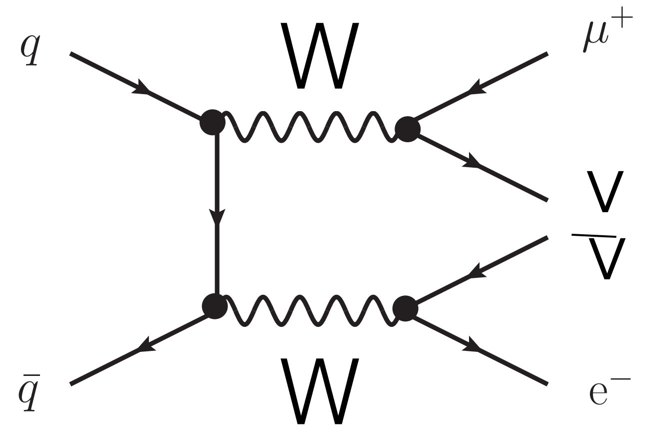


non-resonant $\rightarrow R^{(0)}(\mu^2)$

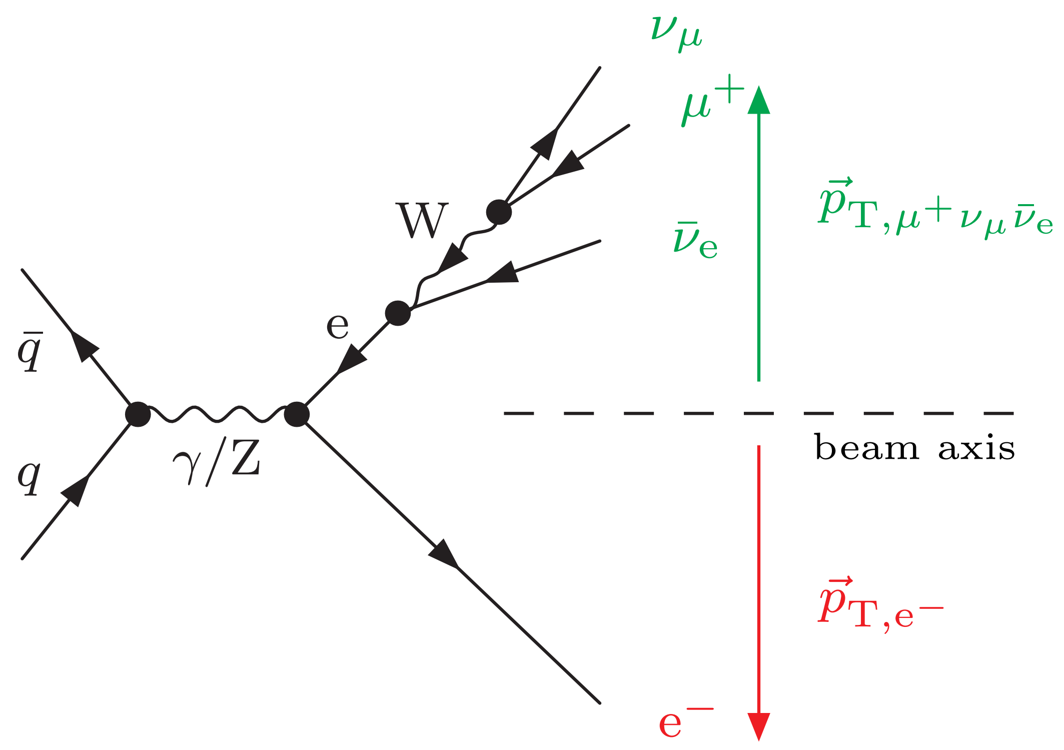
Charged current 4-fermion production and pole expansion

The pole expansion allows to separate

- a double pole term describing 2 quasi-on shell Ws

e.g. 

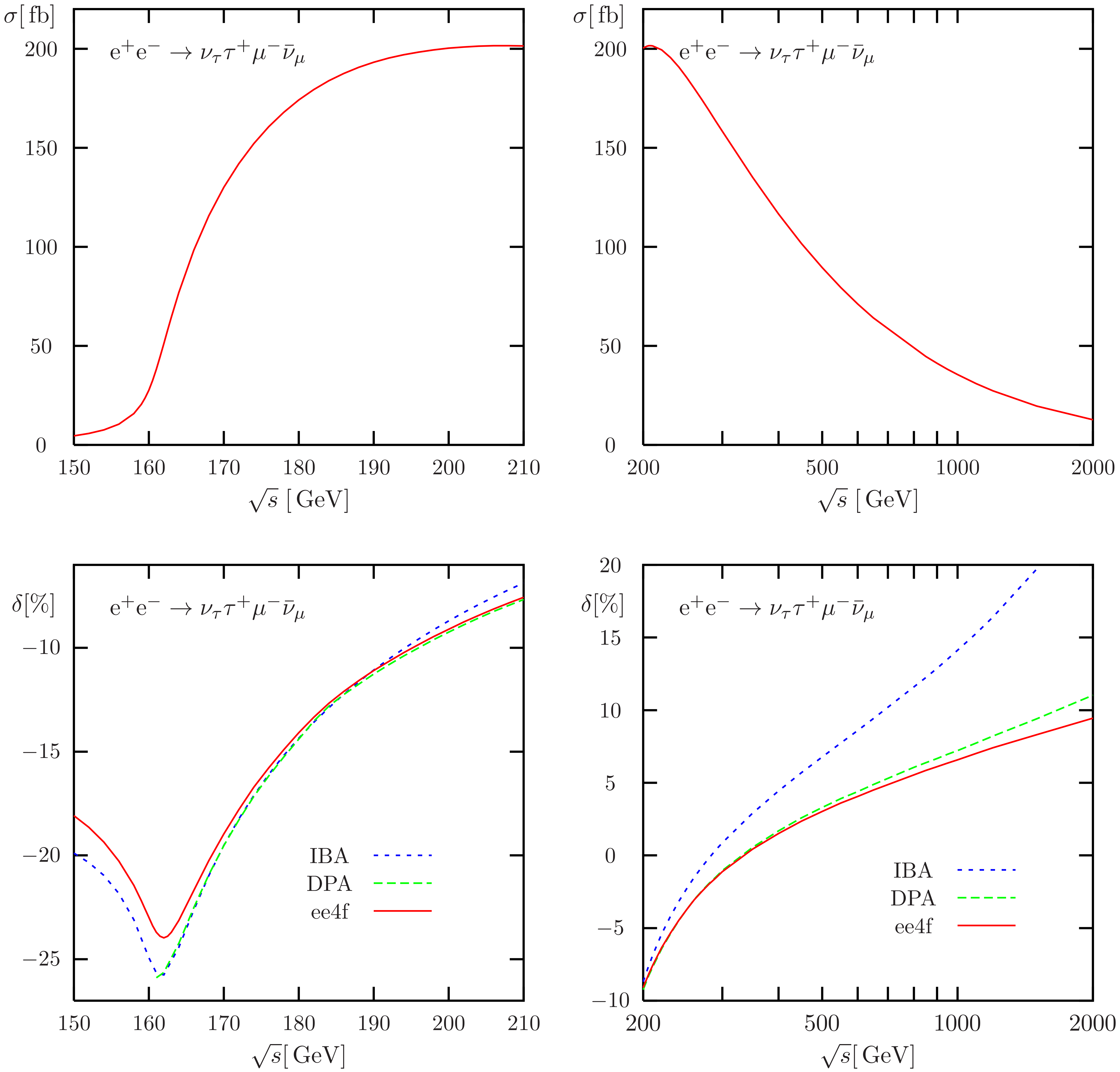
- a single pole term with one resonant W

e.g. 

- a regular remainder

- Motivated in some phase-space regions

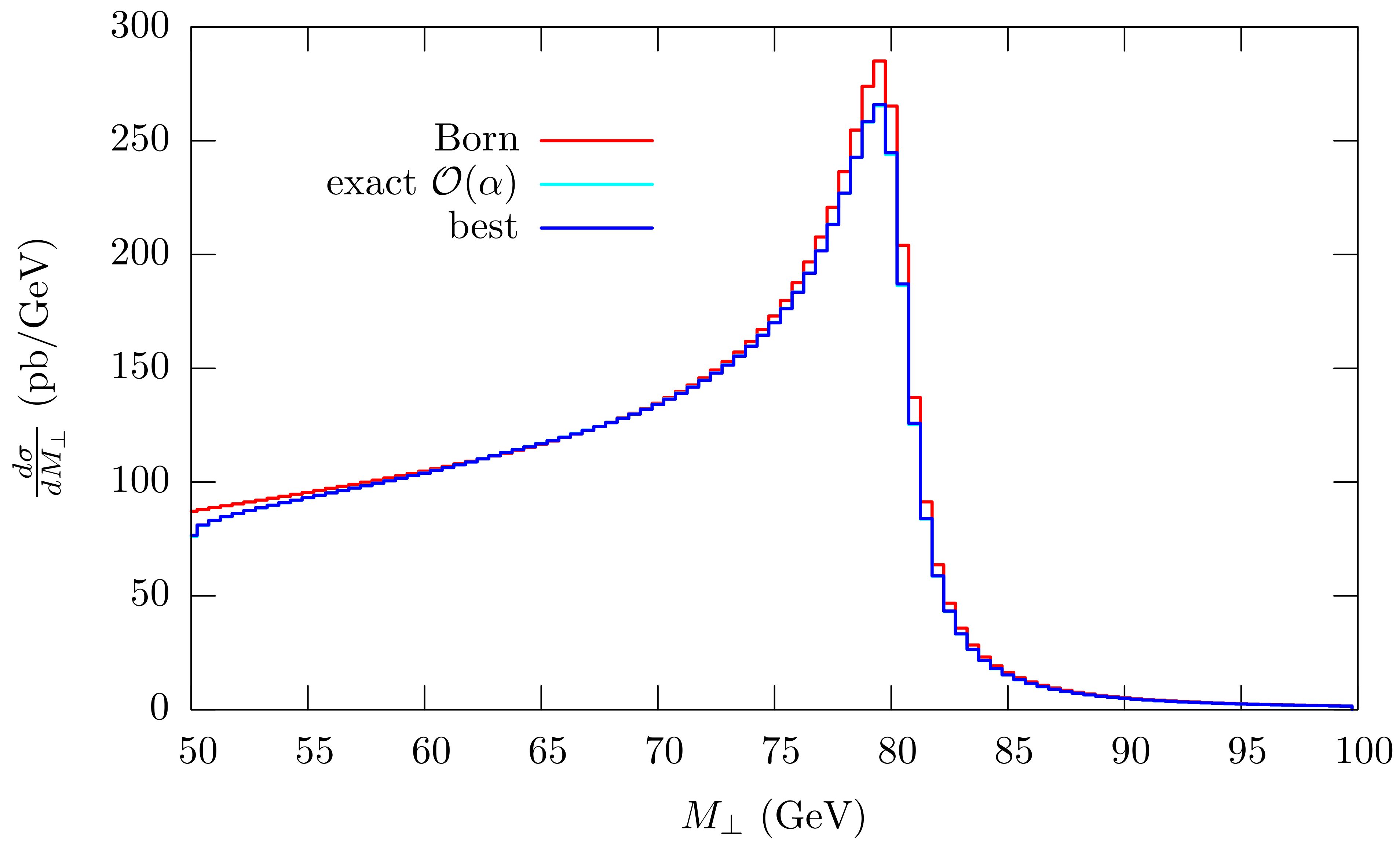
- Insufficient accuracy at the WW threshold, where m_W can be extracted with high precision

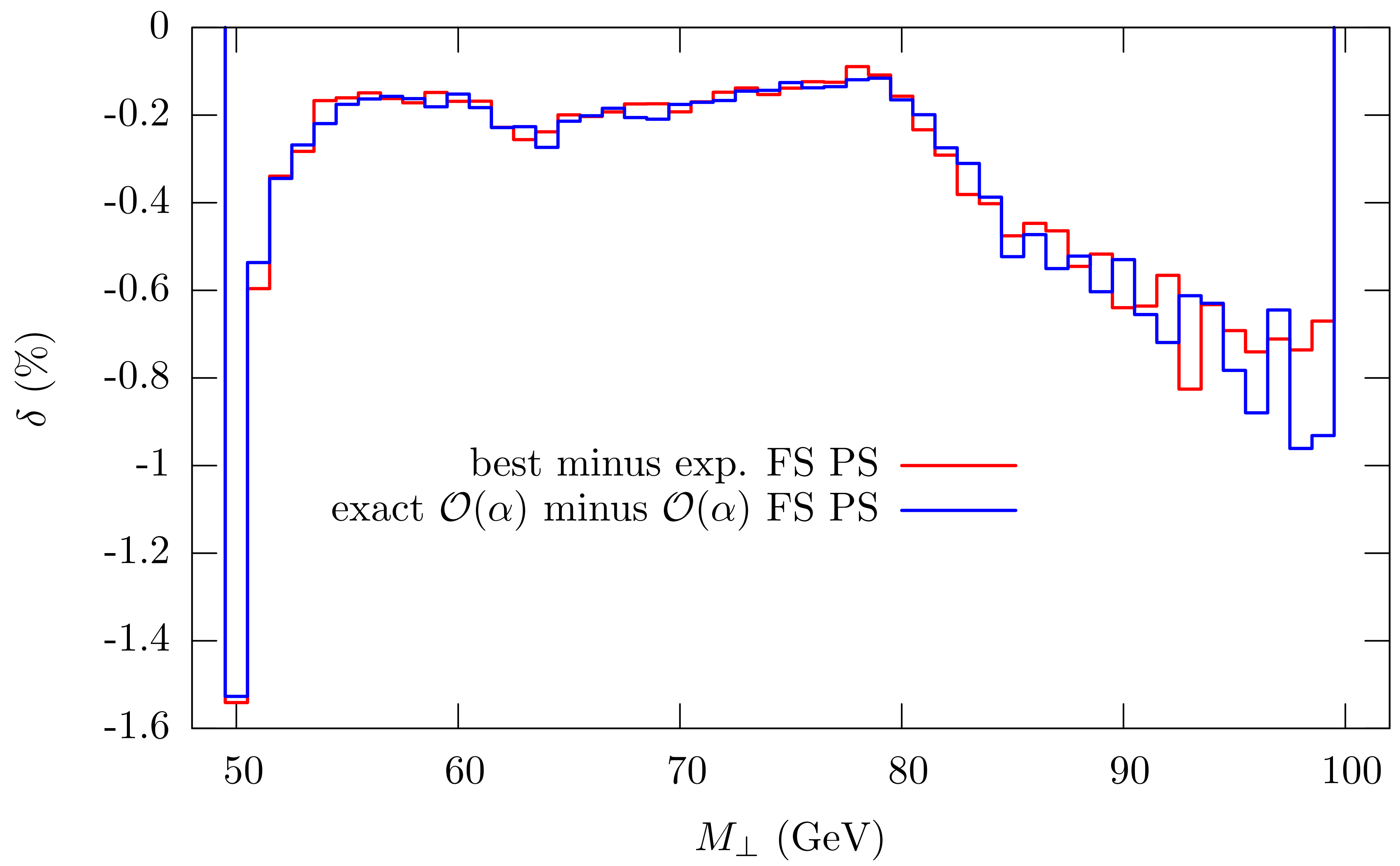


Off-shell corrections at (N)NLO

The complete inclusion of off-shell effects (i.e. the usage of exact amplitudes, without approximations) is needed, also for the radiative corrections:

- in the precision determination of the mass and width of intermediate particles because the line shape affects the outcome of the fit (performed in a not vanishing mass window)





e.g. single W production
Γ_W determination from the tail of $M_\perp^{\ell\nu}$

Off-shell corrections at (N)NLO

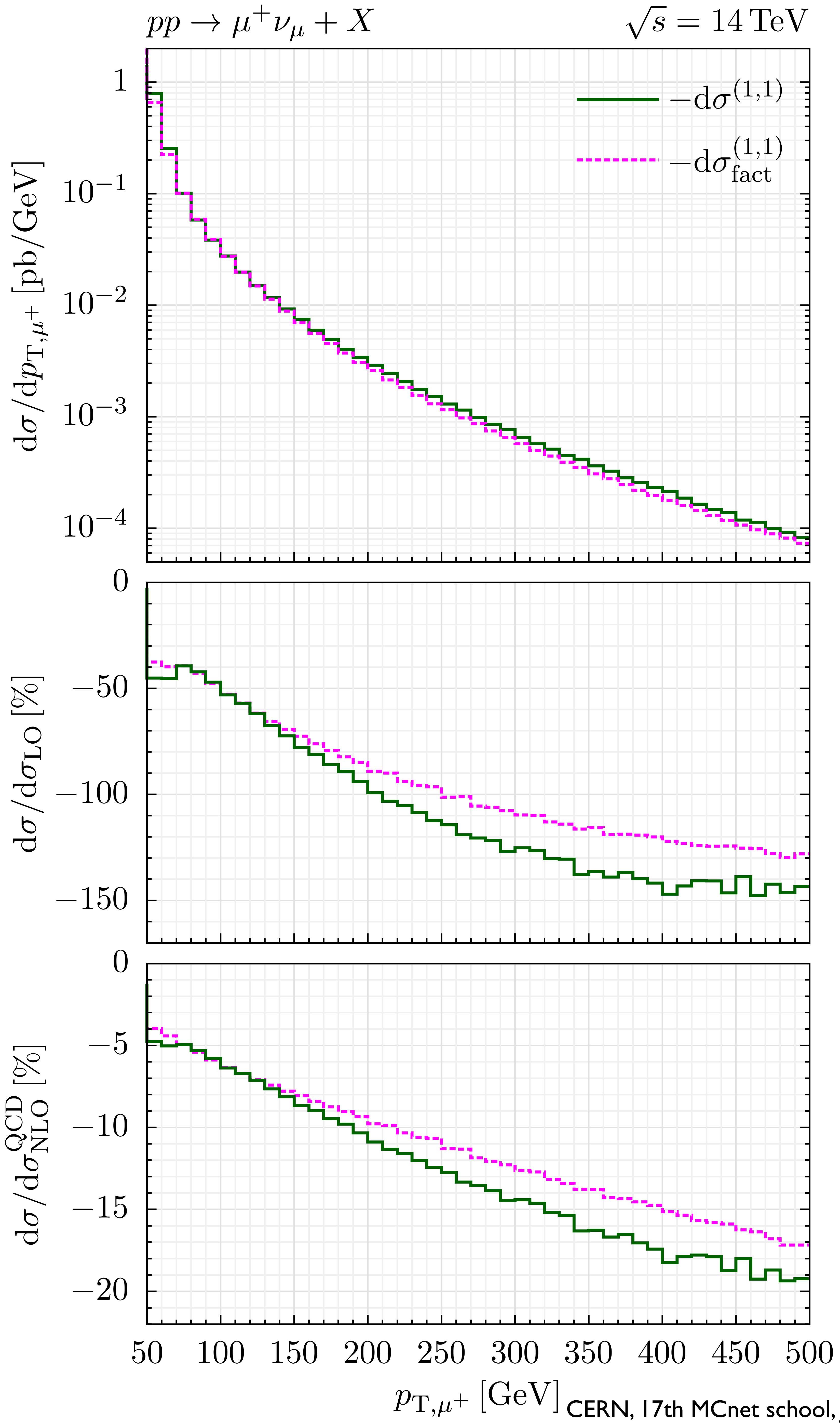
The complete inclusion of off-shell effects
(i.e. the usage of exact amplitudes, without approximations) is needed,
also for the radiative corrections:

- in the study of observables characterised by
  the presence of large differences between the energy scales of the process
  where large EW Sudakov logarithms develop and play a central role

$\mathcal{O}(\alpha\alpha_s)$ corrections to $\frac{d\sigma}{dp_\perp^\ell}$ in $pp \to \ell\nu + X$

overall, large effect induced by the recoil against the QCD emission

on top of the QCD effects, large negative EW Sudakov logs
including a truly non-factorizable component



Summary

- QED and EW corrections have a sizeable impact in the prediction of differential kinematical distributions

- the interplay of QCD and EW corrections is not trivial
  - combination of kinematical effects
  - presence of several partonic channels
  - large opposite sign effects

- the combined simulation of QCD and EW corrections is not trivial from algorithmic side
  (general problem of resonant intermediate systems)

- approximation of exact EW calculations can be devised for specific phase-space regions, with limited validity

Thank you