Electroweak Physics at the LHC

— Lecture 2 —

Single-W/Z Production

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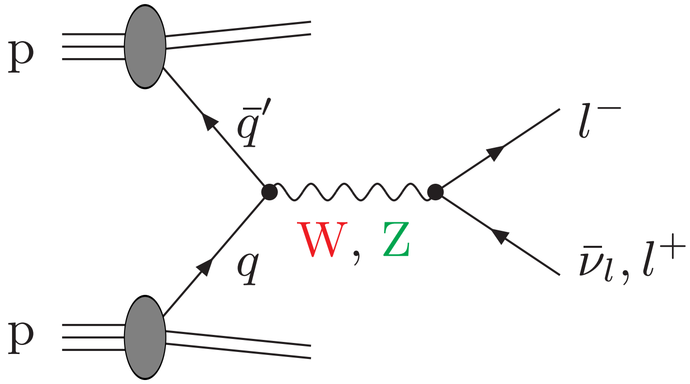


Physics goals:

- M_Z $\rightarrow$ detector calibration by comparing with LEP1 result
- $\sin^2\theta_{\text{eff}}^{\text{lept}}$ $\rightarrow$ comparison with results of LEP1 and SLC
- M_W $\rightarrow$ improvement to $\Delta M_W \sim 15\,\text{MeV}$, strengthen EW precision tests
  (W/Z shape comparisons even sensitive to $\Delta M_W \sim 7\,\text{MeV}$ at LHC)
  Besson et al. '08
- σ, $d\sigma$ $\rightarrow$ precision SM studies
- decay widths Γ_Z and Γ_W from M_{ll} or $M_{T,l\nu_l}$ tails
- search for Z' and W' at high M_{ll} or $M_{T,l\nu_l}$
- information on PDFs

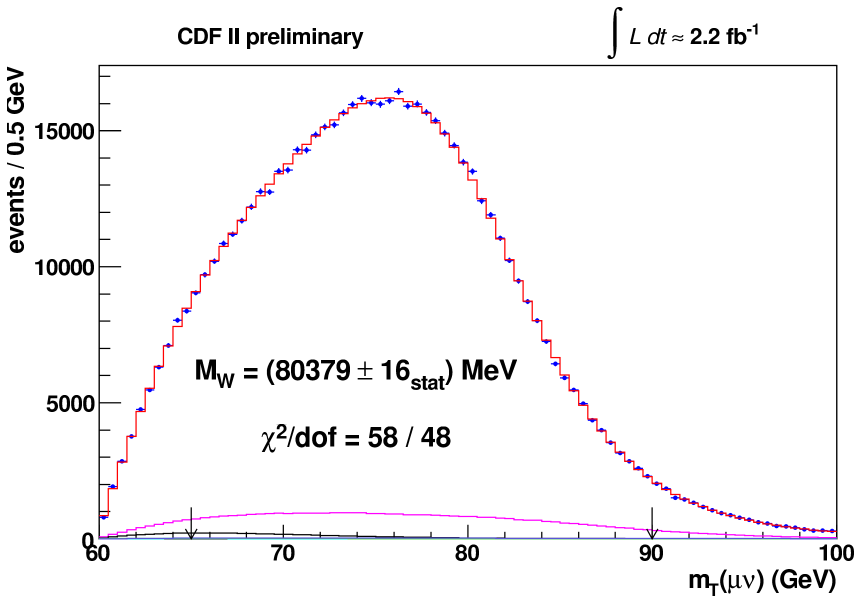
Tevatron example: M_{W} determination @ CDF (2012)

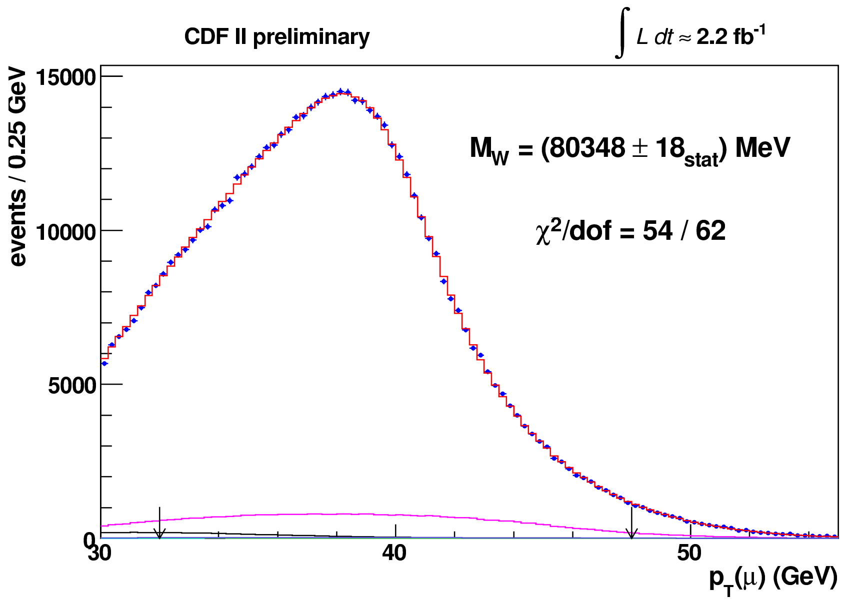
$M_{\mathrm{W}}^{\mathrm{CDF}} = 80.387\,\mathrm{GeV} \pm 19\,\mathrm{MeV}$ from fits to distributions in

a) transverse W-boson mass

$$M_{\mathrm{T},l\nu} = \sqrt{2(E_{\mathrm{T},l}\not{E}_{\mathrm{T}} - \mathbf{p}_{\mathrm{T},l}\cdot\not{\mathbf{p}}_{\mathrm{T}})}$$

b) transverse lepton momentum $p_{\mathrm{T},l}$





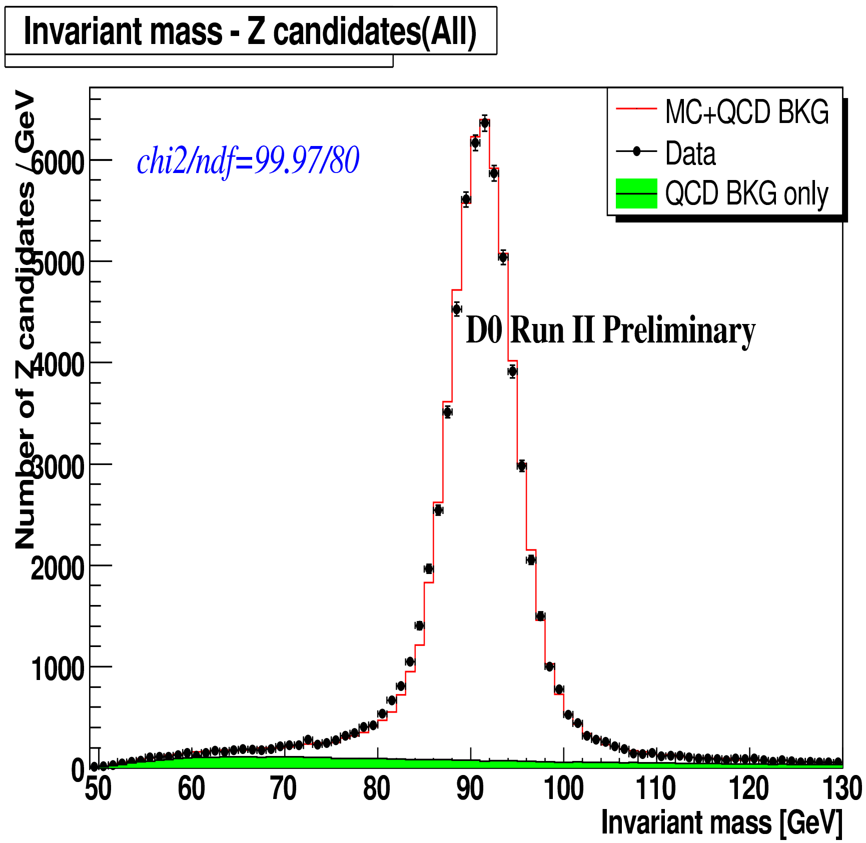
Sensitivity to M_{W} via Jacobian peaks from W resonance at

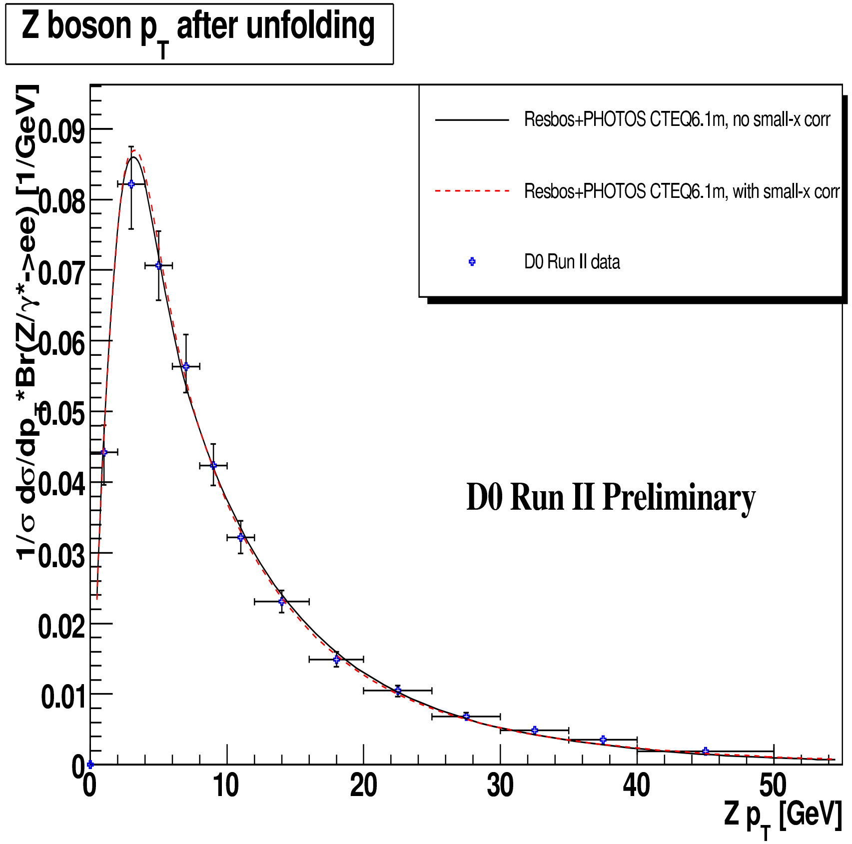
$$M_{\mathrm{T},l\nu} \sim M_{\mathrm{W}} \qquad\qquad p_{\mathrm{T},l} \sim M_{\mathrm{W}}/2$$

$\Rightarrow$ Reduction of ΔM_{W} requires higher theoretical precision in W resonance region !

(for Z resonance as well for reference)

Z-boson invariant-mass and transverse-momentum distributions

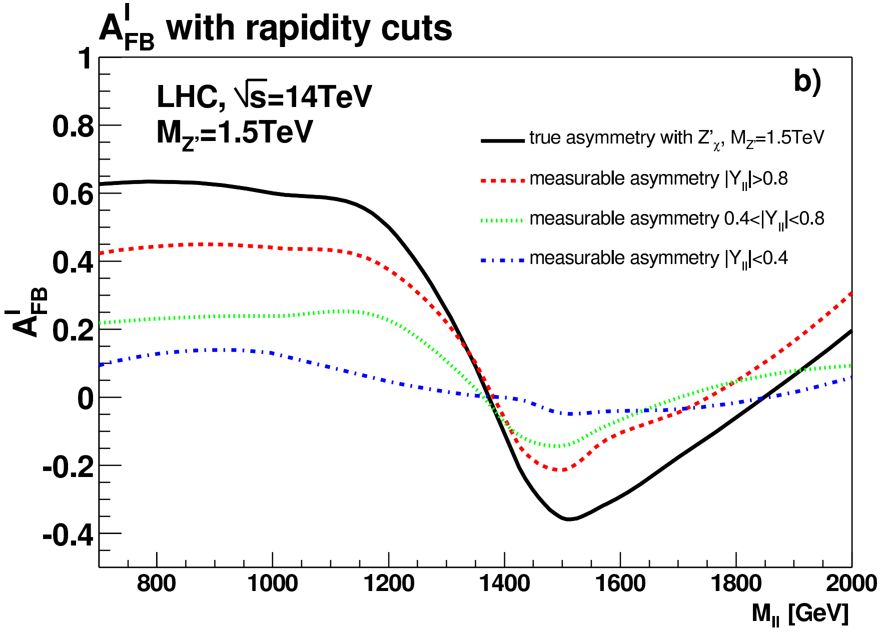


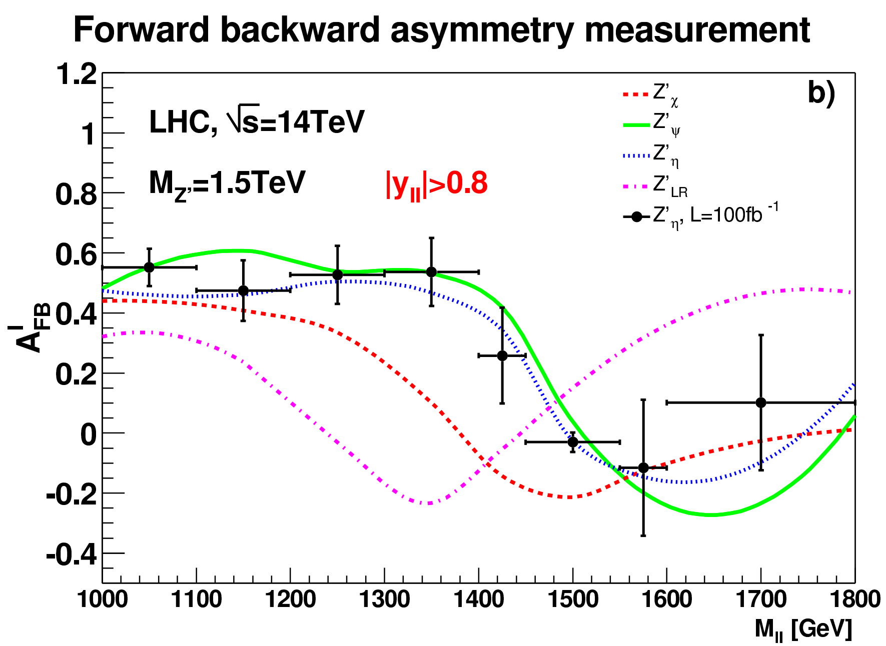


$p_{\mathrm{T,Z}}$ distribution:

- probes jet recoil, i.e. QCD jet dynamics
- at low $p_{\mathrm{T,Z}}$ not describable with fixed-order predictions
  $\hookrightarrow$ QCD resummations required

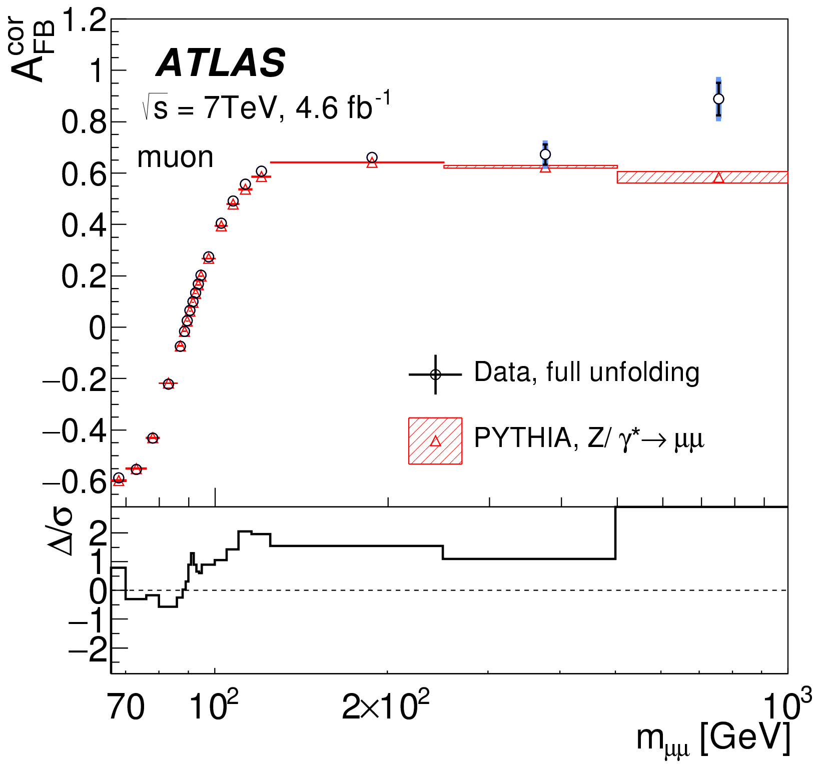
FB asymmetry at the LHC (plots taken from Dittmar, Djouadi, Nicollerat '03)

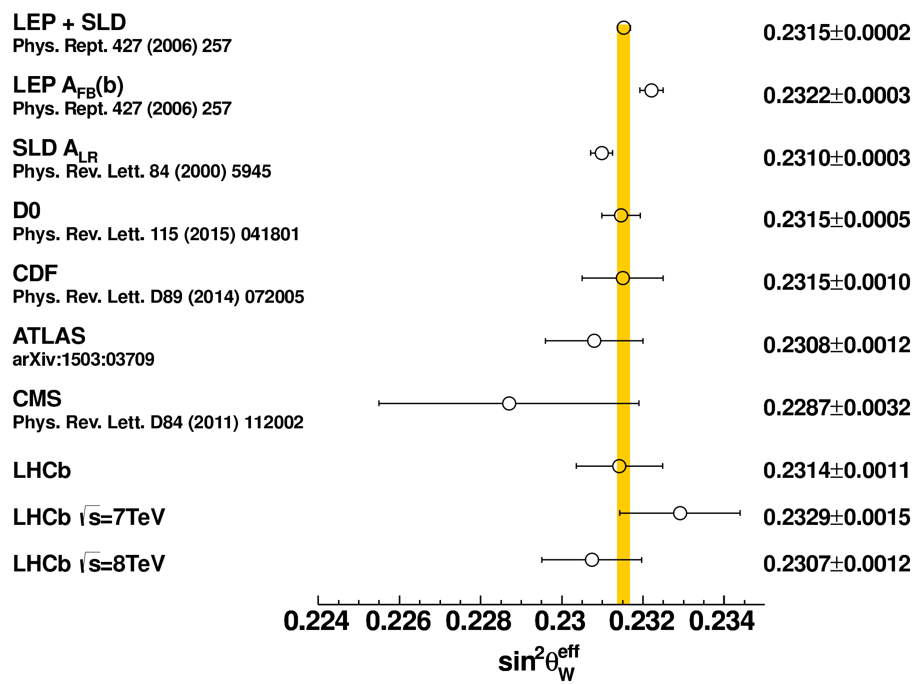




- Naive definition: $A_{\mathrm{FB}} = 0$ in pp collisions (no preferred direction!)
  "Good" definition: identify boost direction of l^+l^- pair with quark direction
  (x spectra of q / $\bar{\mathrm{q}}$ on average lead to boost in q direction)
- Measureable A_{FB} can be enhanced upon excluding small Z rapidity Y_{ll}
  $\hookrightarrow$ require e.g. $|Y_{ll}| > 0.8$
- A_{FB} can discriminate between different Z' models at the LHC

LHC measurements of A_{FB}





Status after LHC run 1:

- high $M_{\mu\mu}$: no evidence for Z' bosons up to TeV scale
- $M_{\mu\mu} \sim M_{\mathrm{Z}}$: first measurements of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$

  optimistic prospect: $\sim$ LEP/SLC accuracy

  But: improved theory predictions necessary !

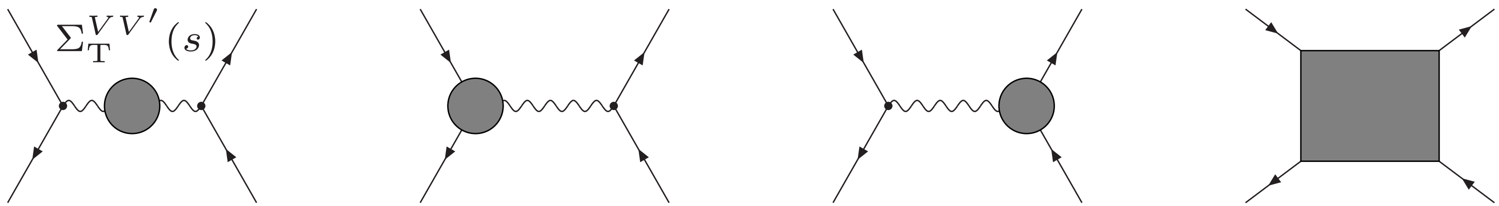
QCD and electroweak corrections to inclusive W/Z production

SM predictions for W/Z production:

- NNLO QCD (differential) — Melnikov, Petriello '06; Catani et al. '09; Gavin et al. '10,'12
- QCD resummations / parton showers — Arnold, Kauffman '91; Balazs et al. '95; ...
- NLO EW (+ h.o. improvements) — Baur et al. '97; Brein et al. '99; S.D., Krämer '01; Baur, Wackeroth '04; Arbuzov et al. '05; Carloni Calame et al. '06; ...
- NLO QCD/EW POWHEG matching — Bernaciak, Wackeroth '12; Barze et al. '13
- NNLO QCD + parton shower — Hoeche et al. '14; Karlberg et al. '14
- $\mathcal{O}(\alpha\alpha_s)$ corrs. near resonances — S.D., Huss, Schwinn '14,'15

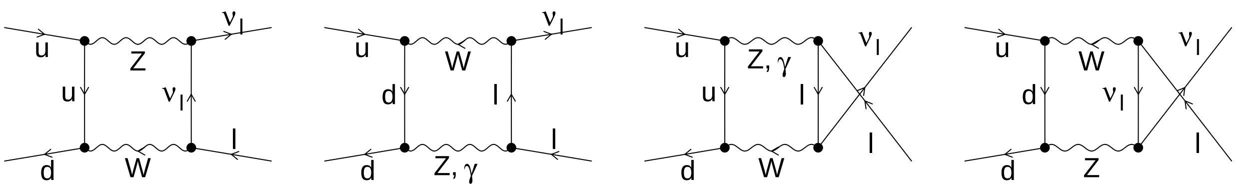
Some details on the NLO calculation

Loop corrections:



VV' self-energies　　$Vq\bar{q}'$ and Vll' vertex corrections　　box diagrams

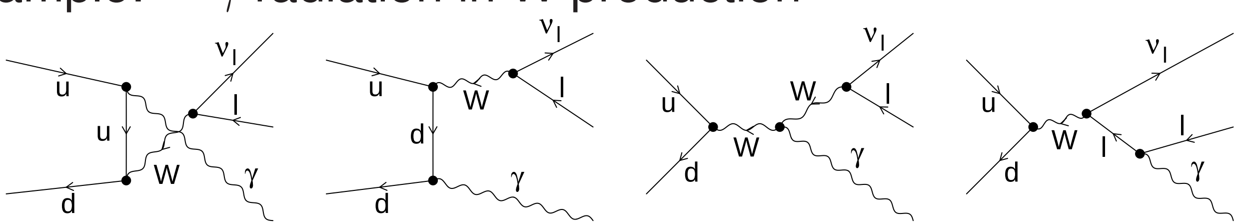
Example:　box corrections to W production



Real-emission corrections:

QCD: g emission, $q\mathrm{g}$ channels;　　EW: γ emission, $q\gamma/\gamma\gamma$ channels

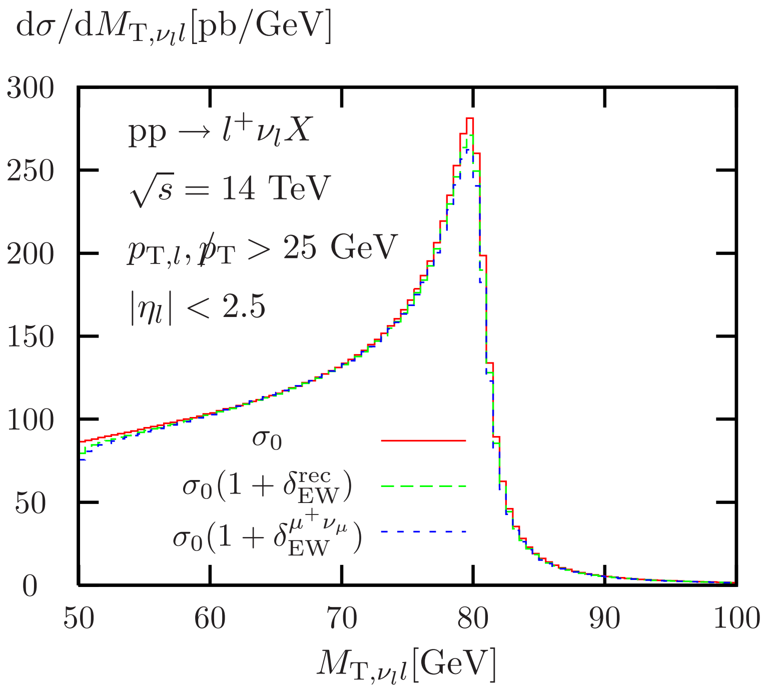
Example:　γ radiation in W production



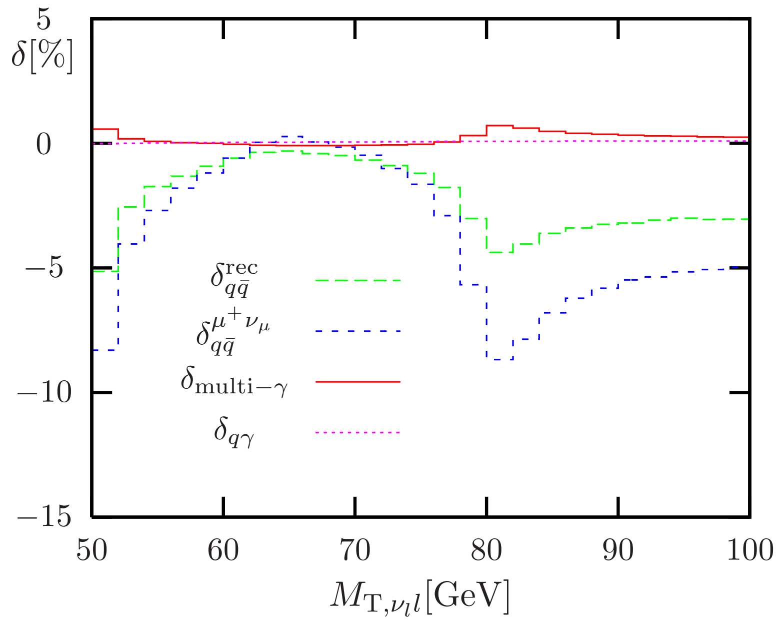
Field-theoretical subtlety:

gauge-invariant description of resonance with higher-order corrections

Corrections to $M_{\mathrm{T},l\nu}$ distribution in W production:

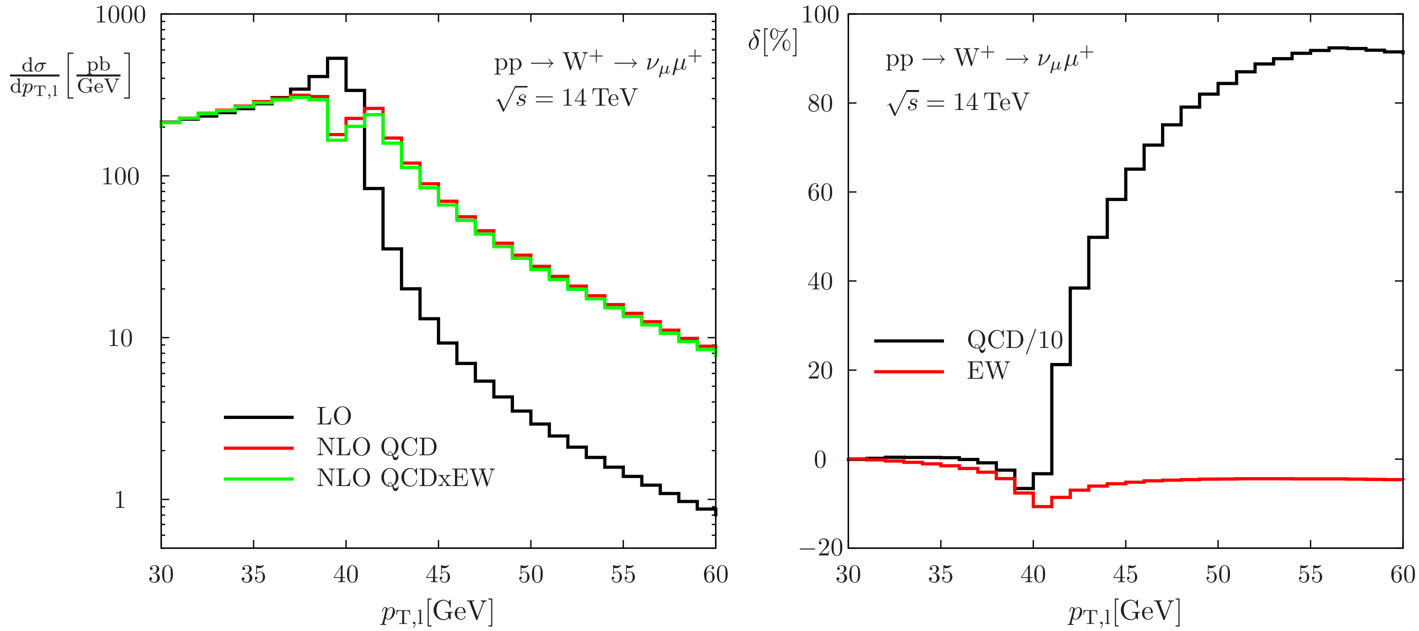


Brensing et al. '07



- QCD corrections (not shown) sizeable, but quite flat ($\sim 20-30\%$)
- EW corrections
  - ◇ no unambiguous separation into photonic and weak corrections for W
  - ◇ significant shape distortion near Jacobian peak
    $\hookrightarrow$ shift in M_{W} determination by $\sim 100(50)\,\mathrm{MeV}$ for bare (dressed) leptons
  - ◇ multi-photon final-state radiation relevant

Corrections to $p_{\mathrm{T},l}$ distribution in W production:

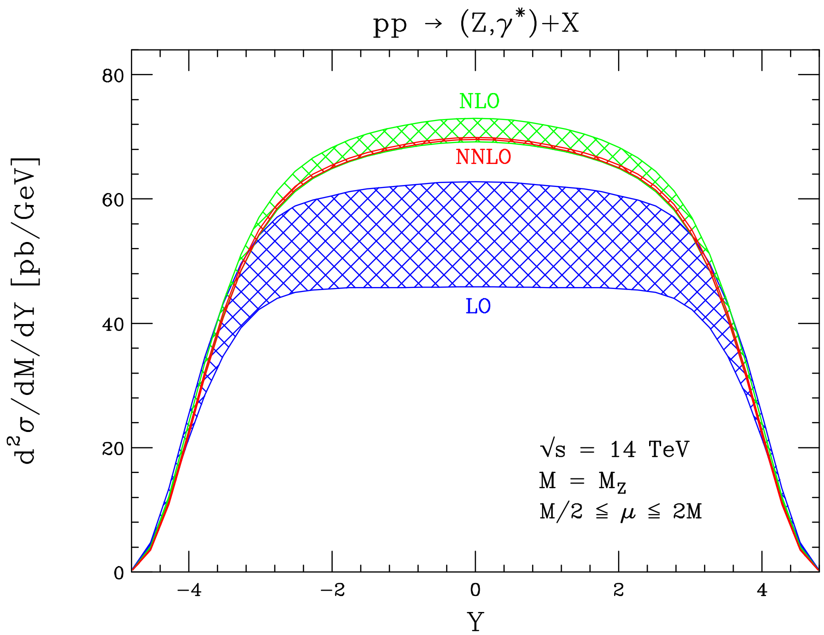


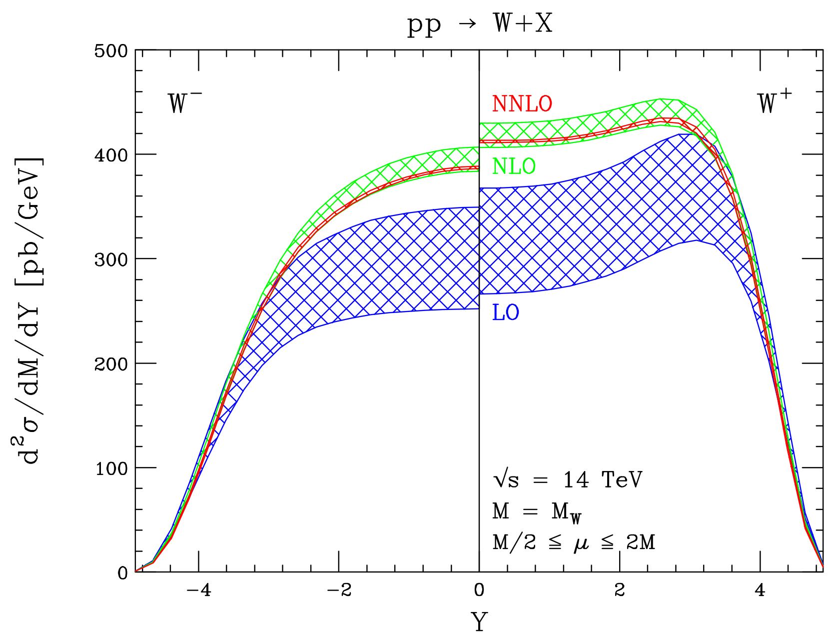
- QCD corrections huge ($> 100\%$) for $p_{\mathrm{T},l} \gtrsim M_\mathrm{W}/2$ due to jet recoil
  $\hookrightarrow$ importance of multi-jet merging / QCD parton-shower matching
- EW corrections
  - ◇ shape distortion, etc., similar to $M_{\mathrm{T},l\nu}$ distribution
- observable cleaner experimentally, but more delicate theoretically than $M_{\mathrm{T},l\nu}$

Corrections to W/Z rapidity distribution

QCD predictions at LO / NLO / NNLO:

Anastasiou et al. '03

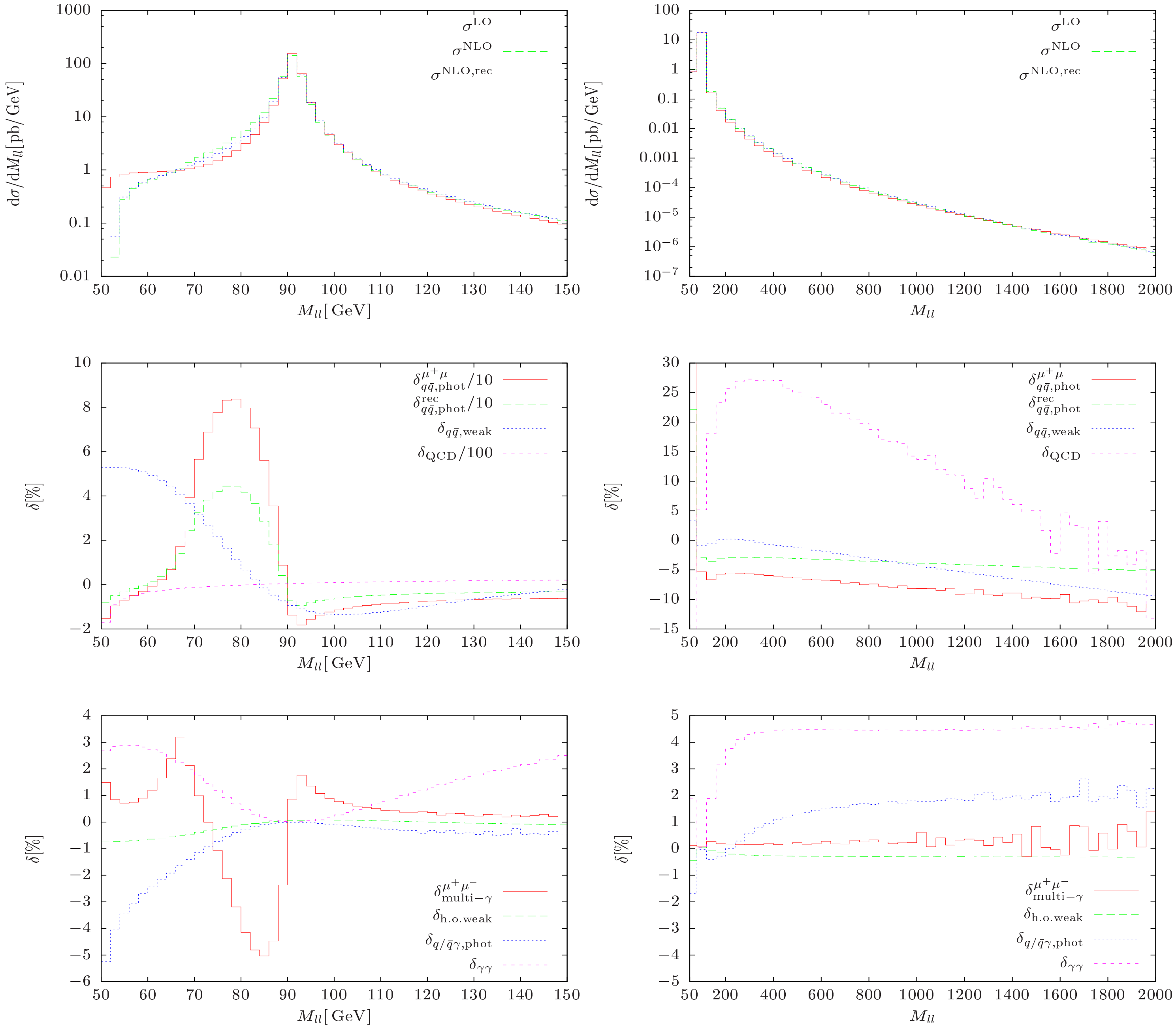




- particularly relevant in PDF fits
- QCD corrections show nice perturbative convergence
- EW corrections at the level of few % (mostly photonic)

Corrections to M_{ll} distribution in Z production – overview

S.D., Huber '09



Corrections to M_{ll} distribution in Z production – features

- QCD corrections significant, but quite flat in resonance region
- Photonic corrections
  - ◇ large radiative tail for $M_{ll} \lesssim M_{\mathrm{Z}}$ from photonic final-state radiation
  - ◇ multi-photon emission significant in resonance region
  - ◇ photon recombination reduces large corrections drastically
    (cancellation of large mass-singular corrections $\propto (\alpha \ln m_\ell)^n$ a la KLN)
- weak corrections significant for large $M_{ll} \gg M_{ll}$
- $q\gamma$ channel seemingly significant, but swamped by QCD corrections
  (same signature, similar shape!)
- $\gamma\gamma$ channel significant off resonance with kinematical signature different from $q\bar{q}$
  $\hookrightarrow$ sensitivity to photon PDF in PDF fits !

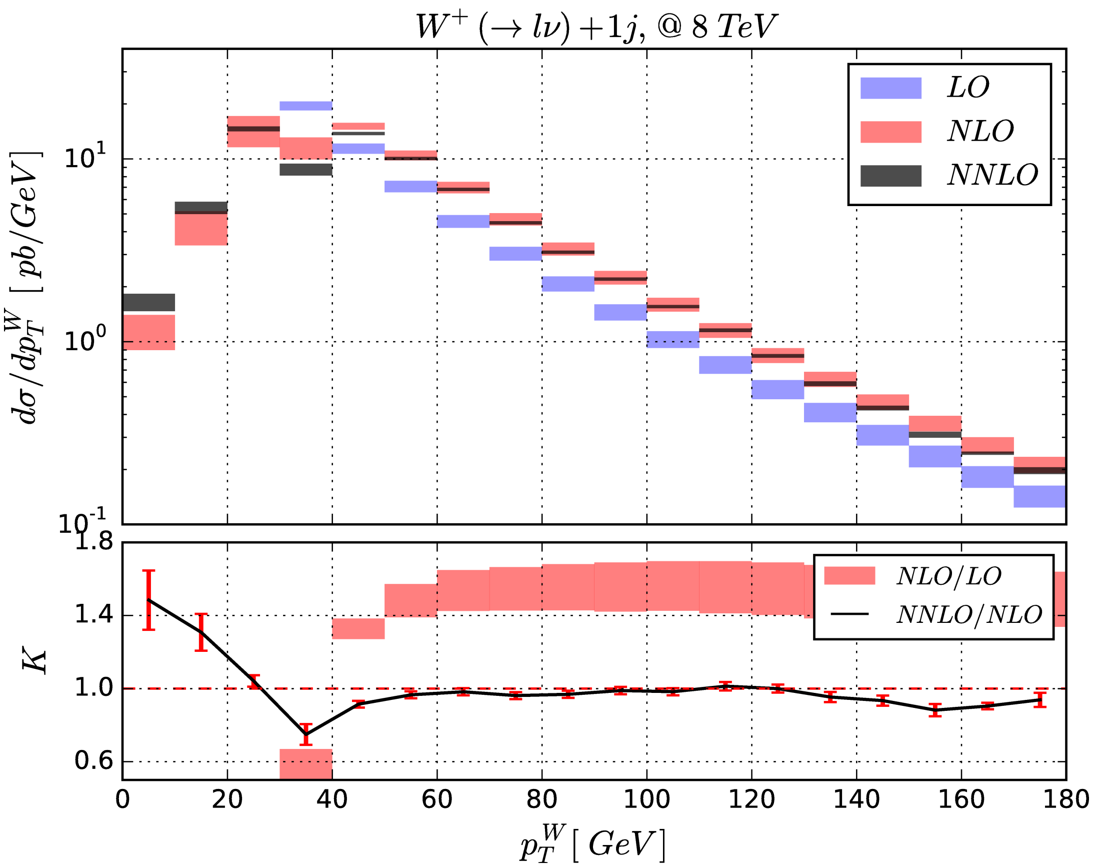
W/Z production with hard jets

SM predictions for W/Z ($\rightarrow$ leptons) + hard jets:

- NLO QCD to $\mathrm{W/Z} + \leq 5\,\mathrm{jets}$ — ... Berger et al. ’09,’10; Ellis et al. ’09; Bern et al. ’11–’13; Goetz et al. ’14
- NLO EW to $\mathrm{W/Z} + 1\,\mathrm{jet}$ — Denner et al. ’09–’12
- NLO EW to $\mathrm{Z} + 2\,\mathrm{jets}$ — Denner et al. ’14
- NLO EW to $\mathrm{W}_{\mathrm{(stable)}} + \leq 3\,\mathrm{jets}$ — Kallweit et al. ’14
- NNLO QCD to $\mathrm{W/Z} + 1\,\mathrm{jet}$ — Boughezal et al. ’15; Gehrmann et al. ’15

NNLO QCD corrections to W+jet production

Boughezal et al. '15



$\sqrt{s} = 8\,\mathrm{TeV}$

$p_{\mathrm{T,jet}} > 30\,\mathrm{GeV}$

- corrections $(\mu = M_\mathrm{W})$:
  LO $\xrightarrow{+\sim 40\%}$ NLO $\xrightarrow{+\mathrm{few}\%}$ NNLO
- scale uncertainty:
  $\sim 20\%$ NLO, $\quad 2{-}3\%$ NNLO

Technical breakthrough in treatment of IR divergences !

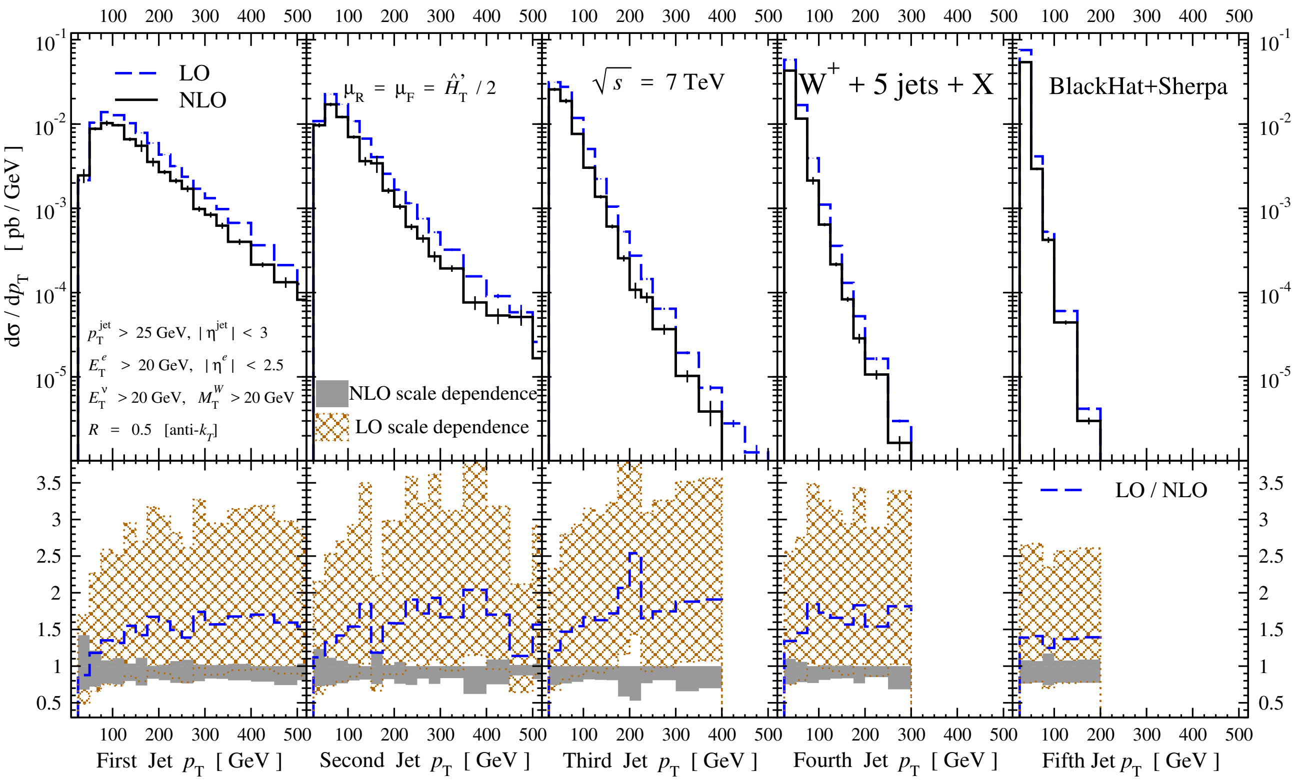
$\hookrightarrow$ "jettiness subtraction"

W/Z + higher jet multiplicities @ NLO QCD

$\hookrightarrow$ NLO QCD corrections known for $\mathrm{W/Z} + n\mathrm{jets}$ with $n \leq 5$

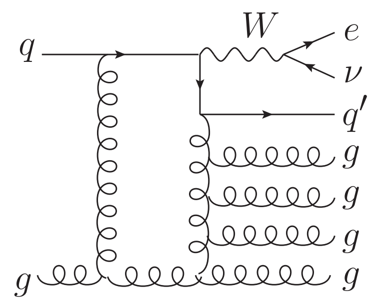
Bern et al. ’11–’13; Goetz et al. ’14

Example: $\mathrm{W} + \mathrm{jets}$



BlackHat+Sherpa

Example diagram:

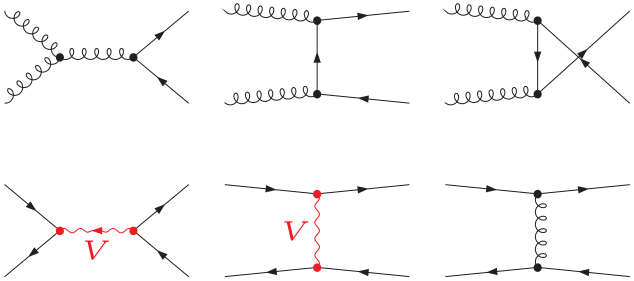


- theoretical uncertainty reduced from $\sim 100\%$ (LO) to $\sim 30\%$ (NLO)
- good agreement between theory and LHC Run 1 data

W/Z + higher jet multiplicities @ NLO QCD+EW

Note: QCD and EW orders mix for $\mathrm{W/Z} + \geq 2\,\mathrm{jets}$

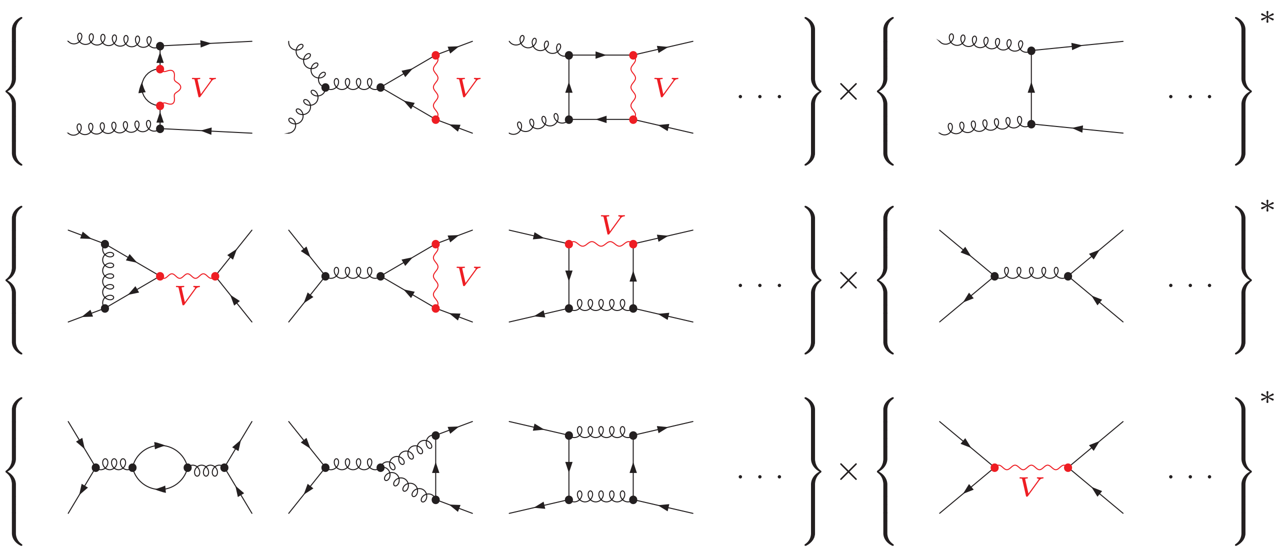
Tree contributions: $\mathcal{O}(\alpha_s\alpha)$, $\mathcal{O}(\alpha^2)$



(W/Z emission suppressed in graphs)

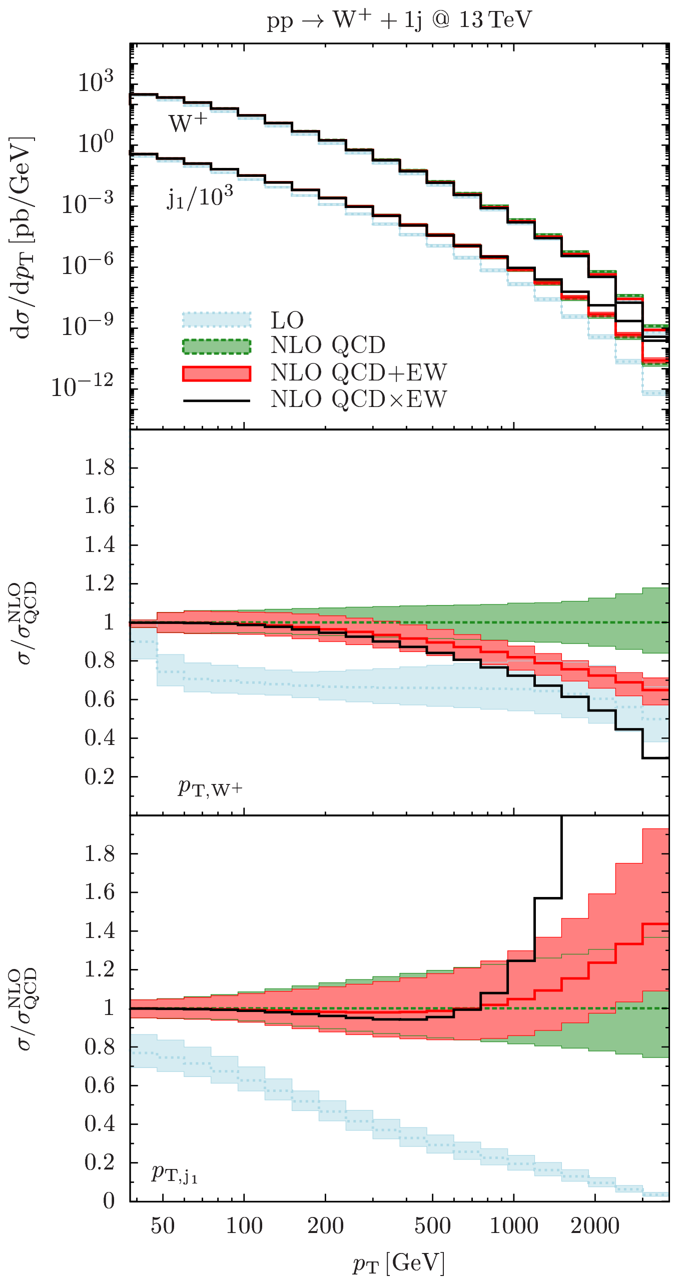
$V = \gamma, \mathrm{Z}, \mathrm{W}$

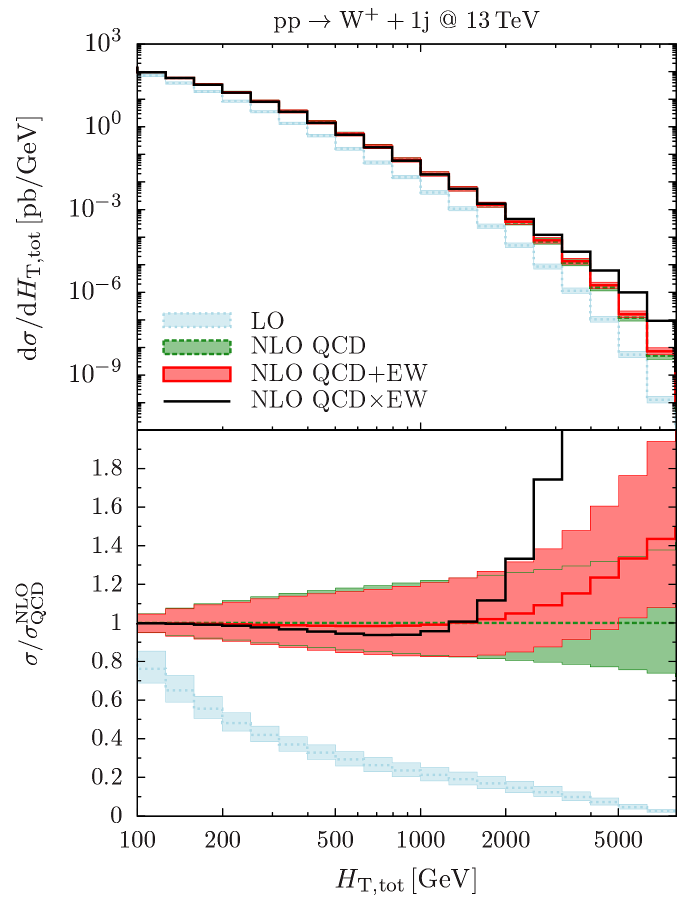
Loop contributions: $\mathcal{O}(\alpha_s^2\alpha)$



W/Z + higher jet multiplicities @ NLO – results

Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '14

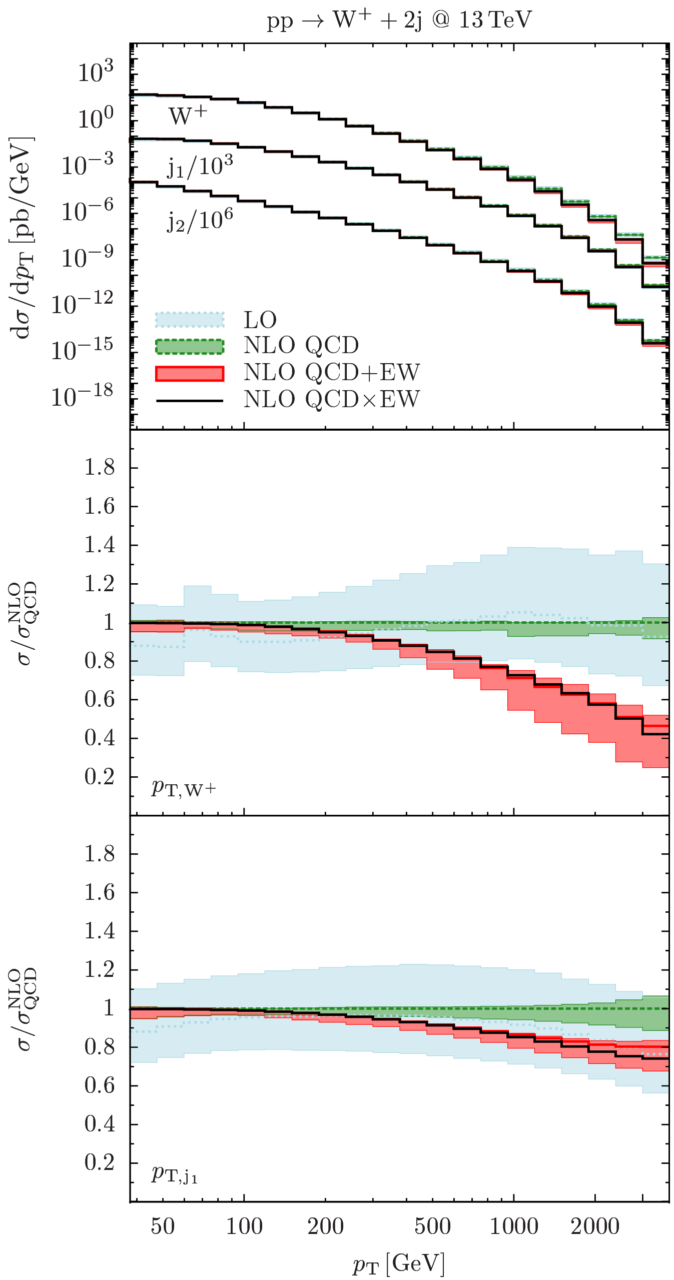


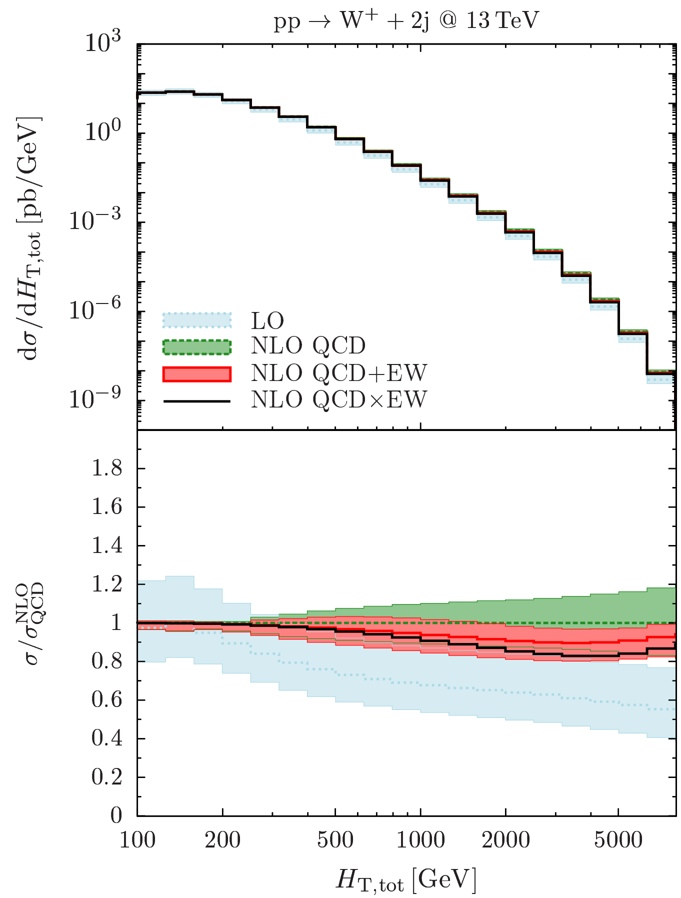


- normalization to $\sigma^{\rm NLO}_{\rm QCD}$
- $\mu_{\rm ren} = \mu_{\rm fact} = \hat{H}_{\rm T} = \sum E_{\rm T}$
- $H_{\rm T}^{\rm tot} = p_{\rm T,W} + \sum p_{{\rm T},j_k}$

W/Z + higher jet multiplicities @ NLO – results

Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '14

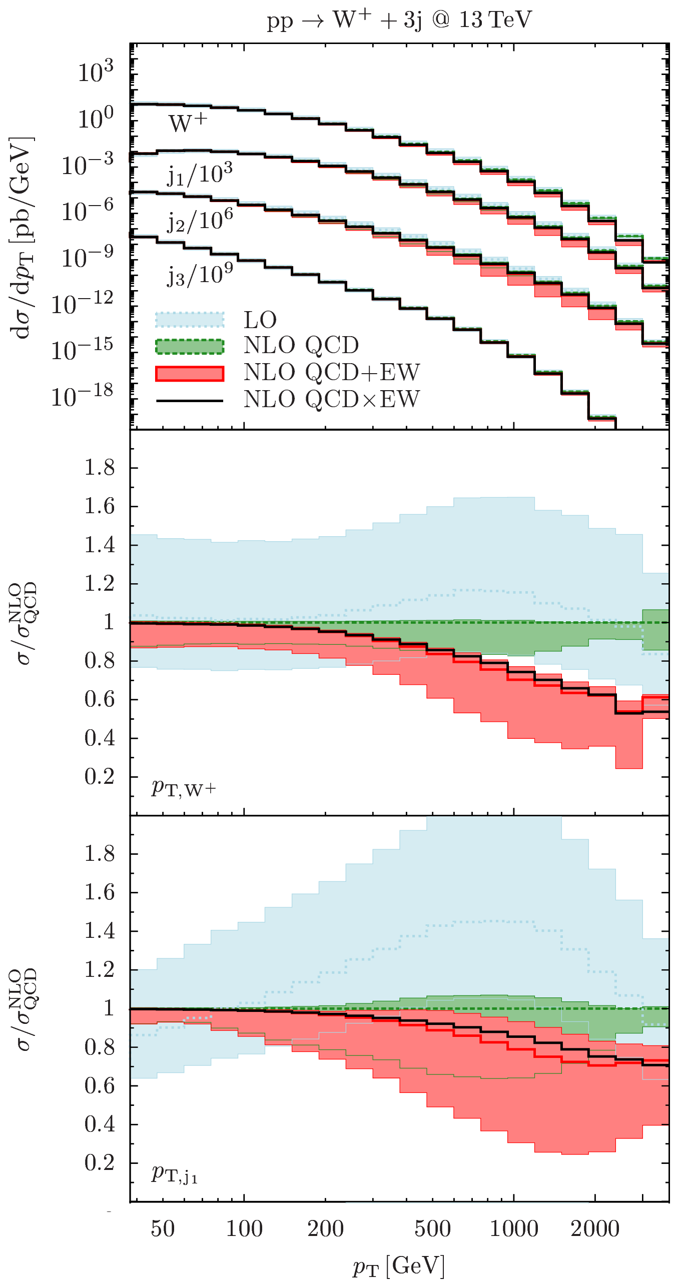


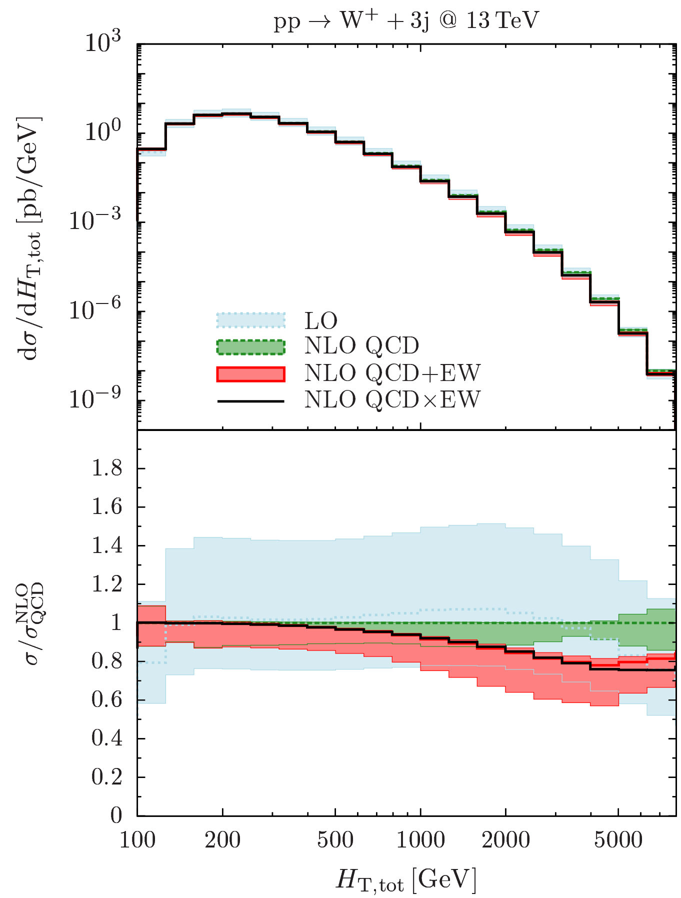


- normalization to $\sigma_{\mathrm{QCD}}^{\mathrm{NLO}}$
- $\mu_{\mathrm{ren}} = \mu_{\mathrm{fact}} = \hat{H}_{\mathrm{T}} = \sum E_{\mathrm{T}}$
- $H_{\mathrm{T}}^{\mathrm{tot}} = p_{\mathrm{T,W}} + \sum p_{\mathrm{T},j_k}$

W/Z + higher jet multiplicities @ NLO – results

Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '14





- normalization to $\sigma^{\rm NLO}_{\rm QCD}$
- $\mu_{\rm ren} = \mu_{\rm fact} = \hat{H}_{\rm T} = \sum E_{\rm T}$
- $H_{\rm T}^{\rm tot} = p_{\rm T,W} + \sum p_{{\rm T},j_k}$

W/Z + higher jet multiplicities @ NLO – results

Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr ’14

Observations:

- QCD corrections:

  “giant K factors” in $\mathrm{W}+1\,\mathrm{jet}$ due to real jet emission

  (soft W’s, hard jets recoiling against each other) Rubin, Salam, Sapeta ’10

  $\hookrightarrow$ multi-jet merging important (or apply jet veto)

- EW corrections: 2 competing effects in at high scales
  - ◇ negative EW Sudakov corrections $\propto \frac{\alpha}{s_\mathrm{W}^2} \ln^2(M_\mathrm{W}^2/\hat{s})$, etc.
  - ◇ positive tree-like contributions σ_tree of $\mathcal{O}(\alpha_\mathrm{s}\alpha^2)$

- combination of QCD and EW corrections:
  - ◇ QCD × EW versus QCD + EW

    $\hookrightarrow$ large difference if QCD and EW are huge !
  - ◇ factorization of some universal effects known, but use with care:

    $$\sigma_\mathrm{best} = \sum_{ij} \sigma_{\mathrm{QCD},ij} \times (1+\delta_{\mathrm{EW},ij}) + \sigma_\mathrm{tree} + \sigma_{\gamma-\mathrm{induced}}$$
  - ◇ issue ultimately resolved only by NNLO QCD–EW calculations

Combination of QCD and EW corrections

Combination of QCD and EW corrections to inclusive W/Z production

Issue unambiguously fixed only by calculating the 2-loop $\mathcal{O}(\alpha\alpha_s)$ corrections, until then rely on approximations and estimate the uncertainties:

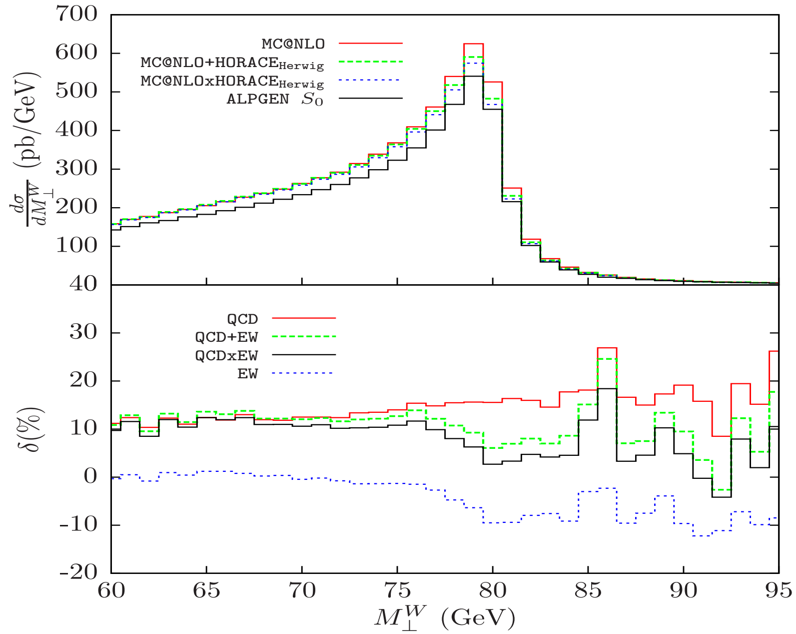
Comparison of two extreme alternatives:

$$(1+\delta_{QCD}^{NLO}+\delta_{EW}^{NLO})$$

versus

$$(1+\delta_{QCD}^{NLO})\times(1+\delta_{EW}^{NLO})$$

Balossini et al. '09 (HORACE)



Difference at %-level
with shape distortion
$\hookrightarrow$ limits precision in M_W measurement

$\Rightarrow$ Dominant $\mathcal{O}(\alpha\alpha_s)$ corrections calculated for resonance region

S.D., Huss, Schwinn '14,'15

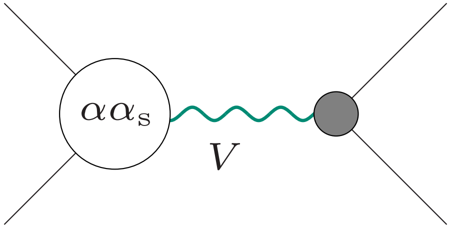
Note: $\Delta M_W^{\mathcal{O}(\alpha\alpha_s)} \sim 14\,\mathrm{MeV}\ (4\,\mathrm{MeV})$ for bare muons (dressed leptons)

$\mathcal{O}(\alpha\alpha_s)$ corrections in pole approximation S.D., Huss, Schwinn '14,'15

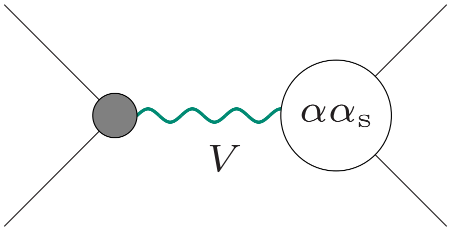
$\hookrightarrow$ take only leading (=resonant) contributions in expansion about resonance poles

Factorizable contributions:

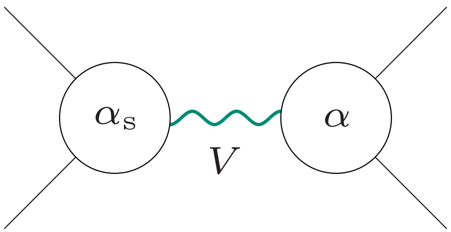
(only virtual contributions indicated)



- not yet known,
  but no significant resonance distortion expected
- no PDFs with $\mathcal{O}(\alpha\alpha_s)$ corrections



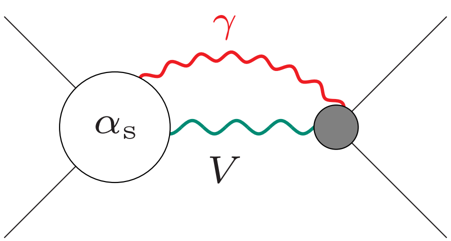
- only $Vl\bar{l}'$ counterterm contributions
- calculated $\rightarrow$ very small, uniform correction



- significant resonance distortions from FSR
- calculated and
  compared to leading-log parton shower approach

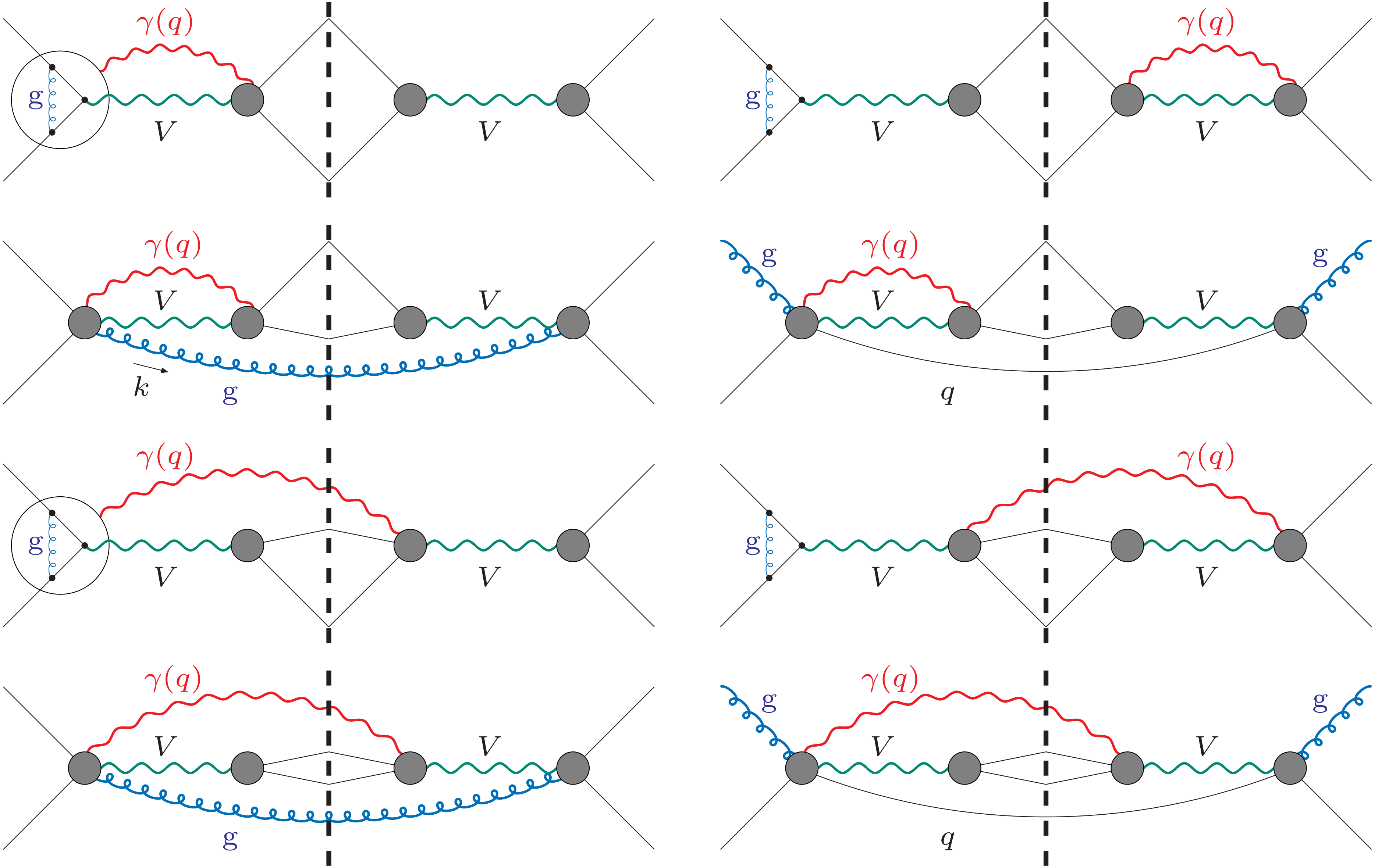
Non-factorizable contributions:

(only virtual contributions indicated)



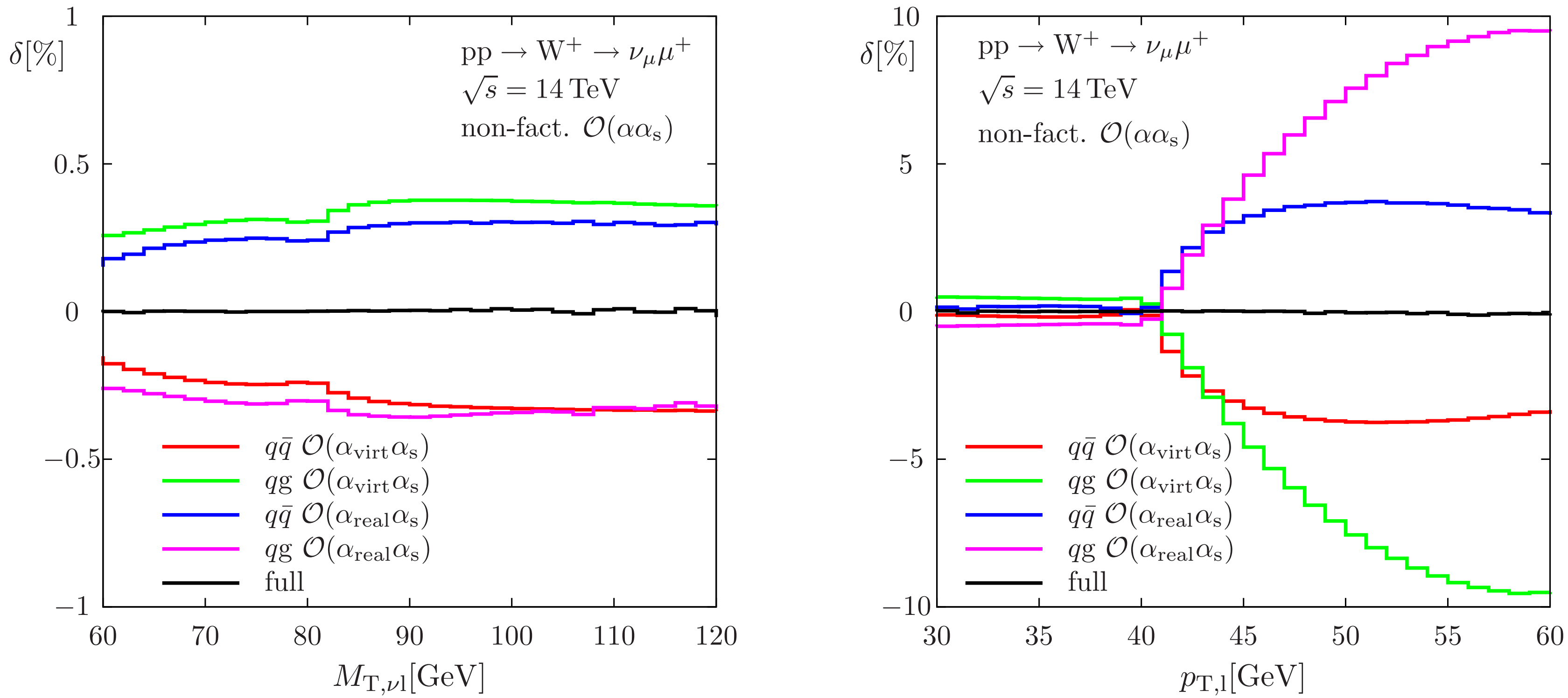
- could induce shape distortions
- calculated $\rightarrow$ phenomenologically negligible

Non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



Non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections S.D., Huss, Schwinn '14

W production:

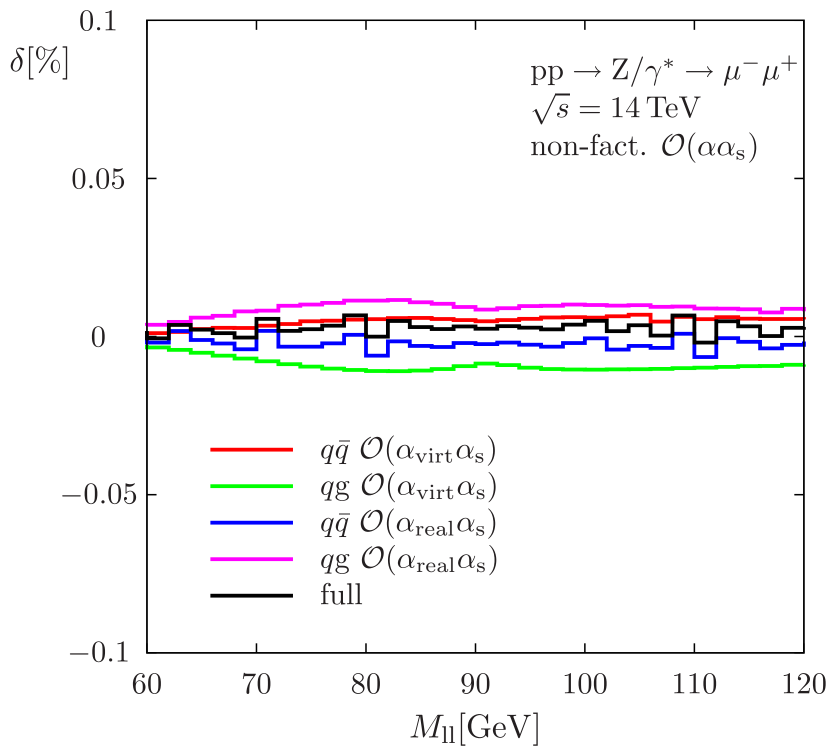


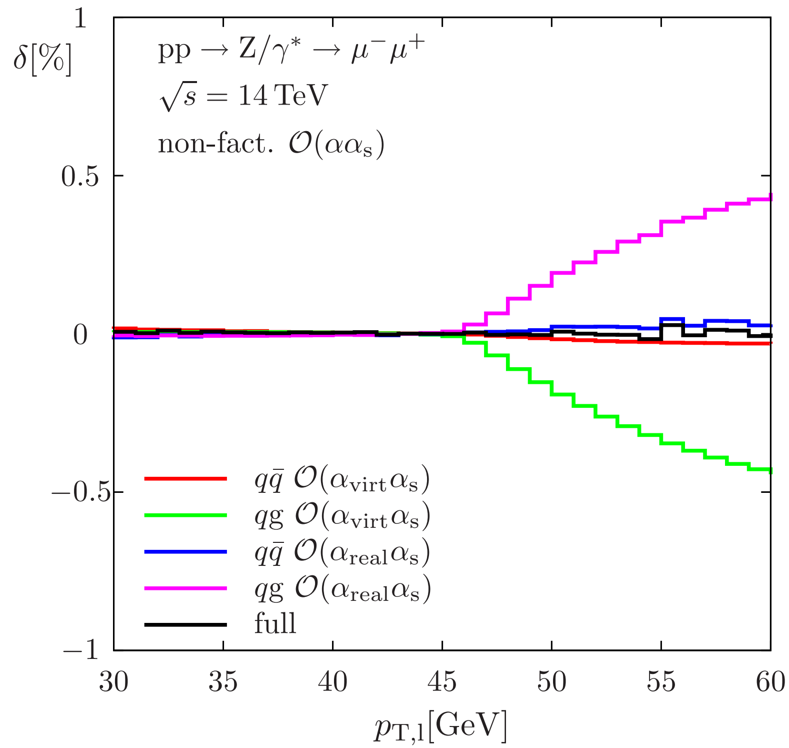
Full non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections tiny

due to complete cancellation between virtual and real corrections

Non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections S.D., Huss, Schwinn ’14

Z production:

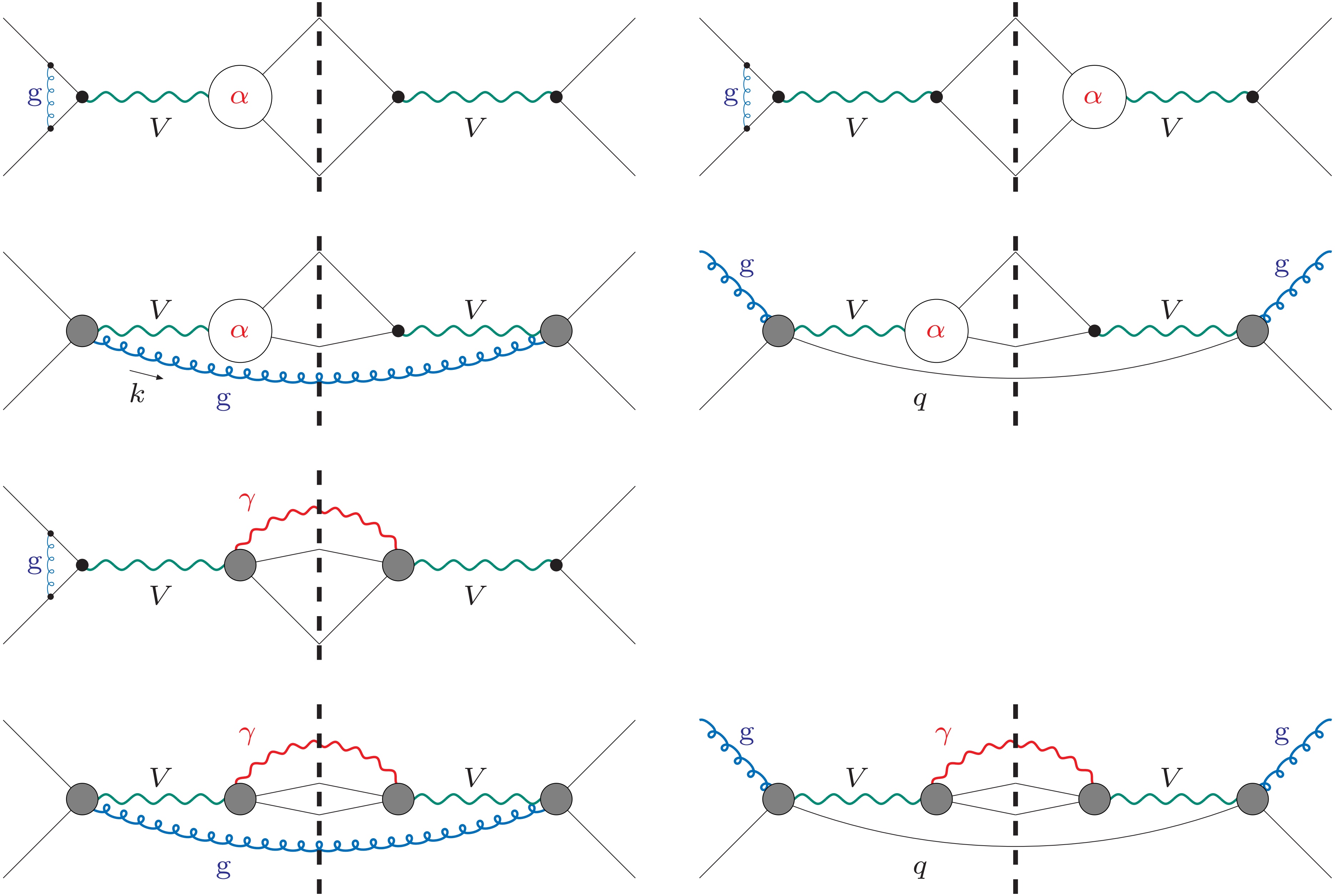




Full non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections tiny

due to complete cancellation between virtual and real corrections

Initial–final factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



Full $\mathcal{O}(\alpha\alpha_s)$ corrections versus naive factorization

NLO QCD and EW corrections:

$$\sigma^{\mathrm{NLO_s}} \equiv \sigma^{\mathrm{LO}} \underbrace{(1+\delta_{\alpha_s})}_{=K^{\mathrm{NLO}}_{\mathrm{QCD}}} = \sigma^0 + \sigma^{\mathrm{LO}} \underbrace{\left(\frac{\sigma^{\mathrm{LO}}-\sigma^0}{\sigma^{\mathrm{LO}}} + \delta_{\alpha_s}\right)}_{\equiv \delta'_{\alpha_s}},$$

$$\Delta\sigma^{\mathrm{NLO_{ew}}} = \sigma^0\, \delta_\alpha, \qquad \sigma^0 = \text{LO contribution with NLO PDFs}$$

$\mathcal{O}(\alpha\alpha_s)$-corrected cross section:

$$\sigma^{\mathrm{NNLO_{s\otimes ew}}} = \sigma^{\mathrm{NLO_s}} + \Delta\sigma^{\mathrm{NLO_{ew}}} + \underbrace{\Delta\sigma^{\mathrm{NNLO_{s\otimes ew}}}_{\mathrm{ini-fin}}}_{=\sigma^{\mathrm{LO}}\,\delta^{\mathrm{ini-fin}}_{\alpha_s\alpha}}$$

Naive factorization @ $\mathcal{O}(\alpha\alpha_s)$:

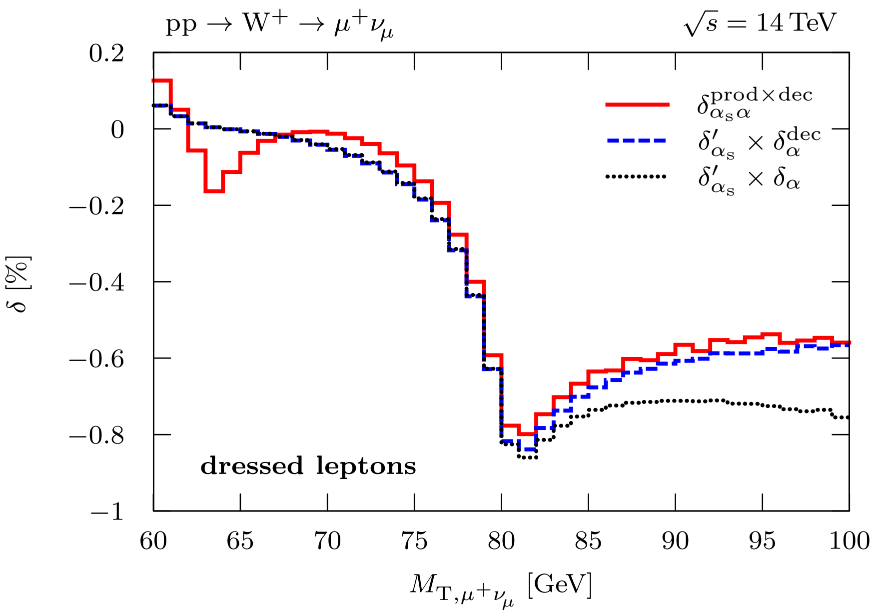
$$\sigma^{\mathrm{NNLO_{s\otimes ew}}}_{\mathrm{naive\,fact}} = \sigma^{\mathrm{NLO_s}}(1+\delta_\alpha) = \sigma^{\mathrm{LO}}(1+\delta_{\alpha_s})(1+\delta_\alpha)$$

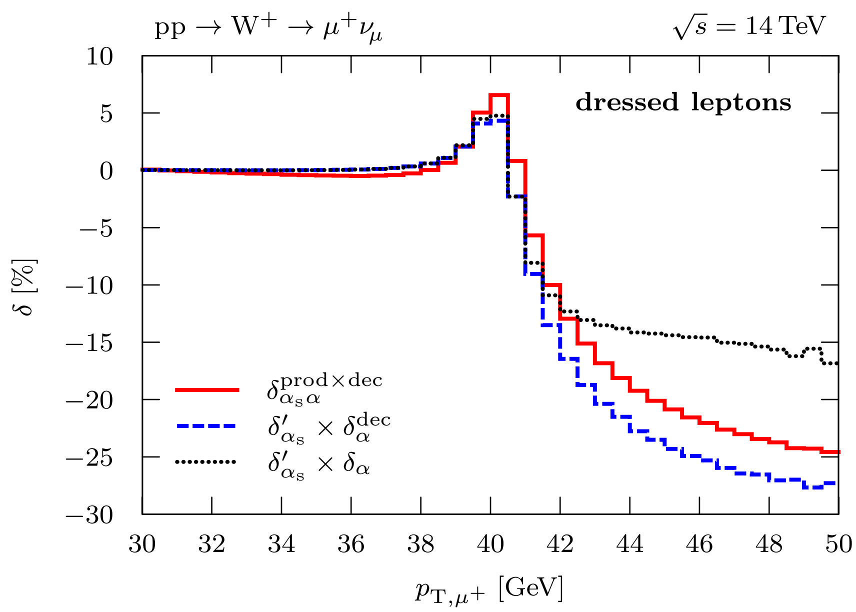
$\Rightarrow$ Comparison of relative corrections:

$$\frac{\sigma^{\mathrm{NNLO_{s\otimes ew}}} - \sigma^{\mathrm{NNLO_{s\otimes ew}}}_{\mathrm{naive\,fact}}}{\sigma^{\mathrm{LO}}} = \delta^{\mathrm{ini-fin}}_{\alpha_s\alpha} - \delta'_{\alpha_s}\delta_\alpha$$

Initial–final factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections
S.D., Huss, Schwinn '15

W production: (γ recombination applied, "dressed leptons")





Naive factorization works!

Naive factorization deteriorates for $p_{\mathrm{T},\mu^+} \gtrsim M_\mathrm{W}/2$

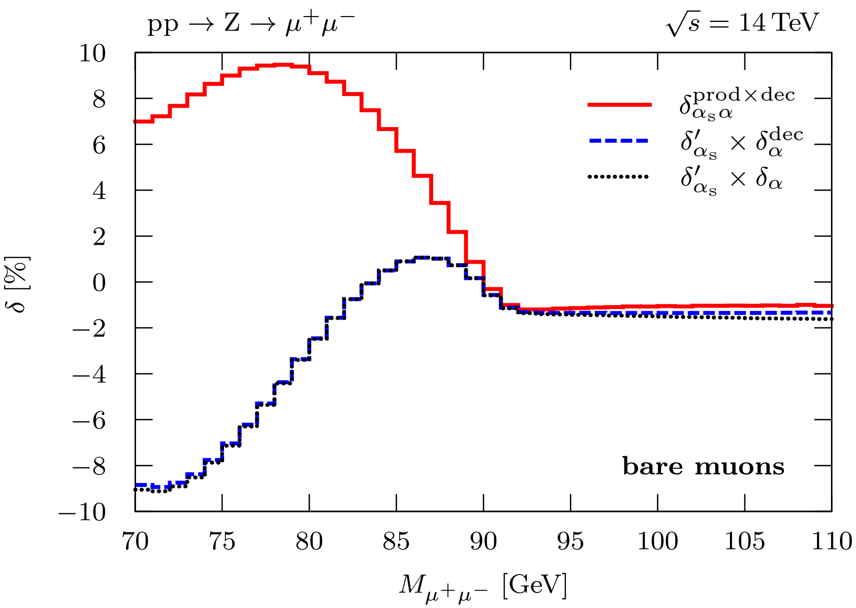
Important issues:

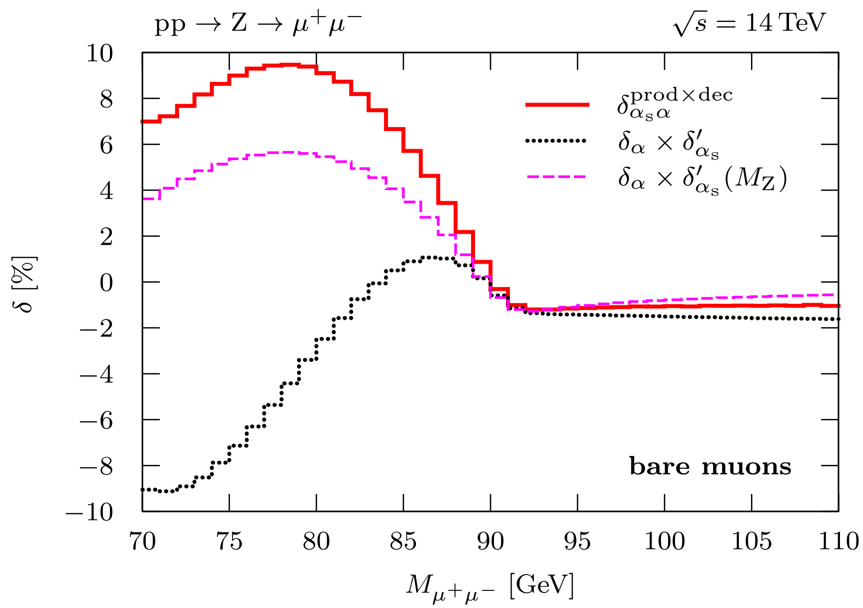
- comparison of $\delta^{\mathrm{ini-fin}}_{\alpha_s\alpha}$ with MC approach $\mathrm{d}\sigma_{\alpha_s} \otimes (\gamma \text{ shower})$
- estimate shifts in M_W by $\delta^{\mathrm{ini-fin}}_{\alpha_s\alpha}$

Initial–final factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections

S.D., Huss, Schwinn '15

Z production: (no γ recombination applied, "bare leptons")





Naive factorization fails !

Naive factorization takes "wrong QCD K factor"

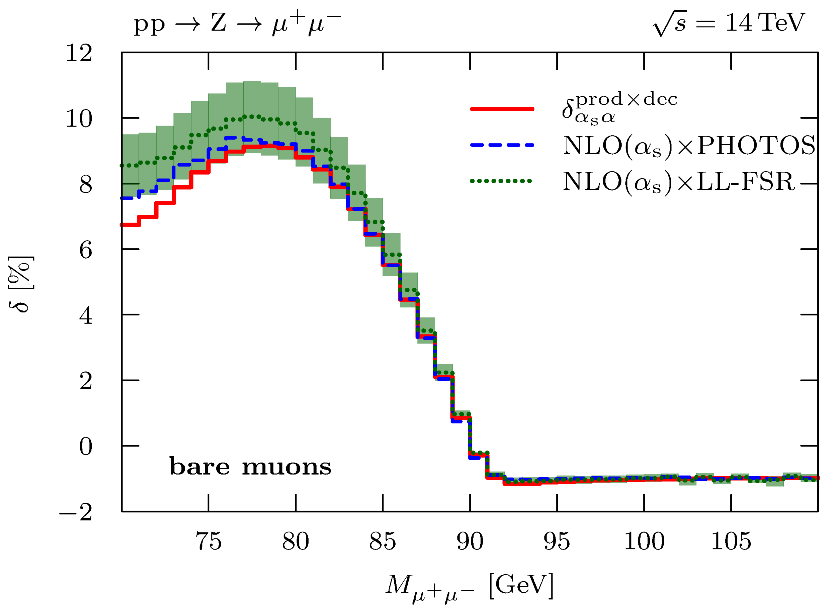
Important issues:

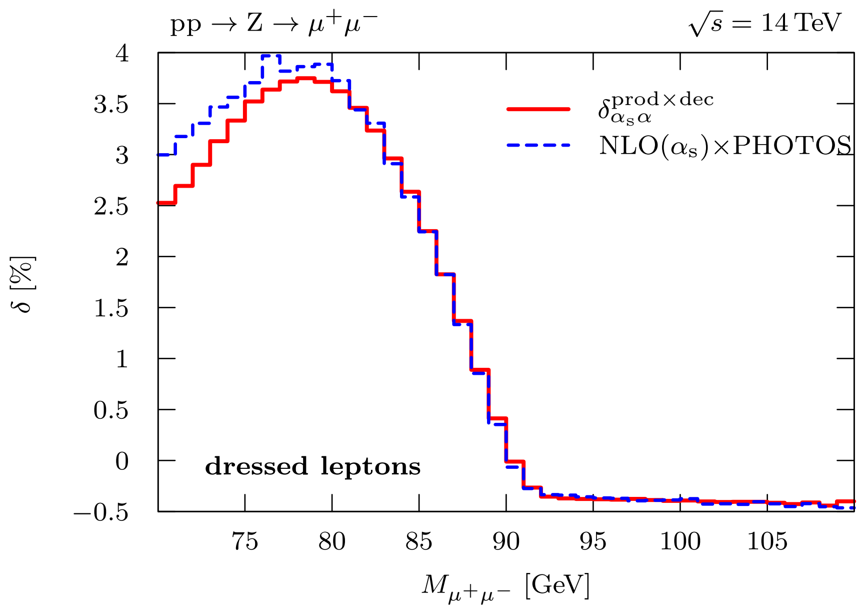
- comparison of $\delta^{\mathrm{ini-fin}}_{\alpha_s\alpha}$ with MC approach $\mathrm{d}\sigma_{\alpha_s} \otimes (\gamma$ shower$)$
- estimate shift in M_Z by $\delta^{\mathrm{ini-fin}}_{\alpha_s\alpha}$

Initial–final factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections

S.D., Huss, Schwinn '15

Z production: Leading-log QED $\otimes$ NLO QCD





Two QED FSR leading-log approaches: "Differential factorization" works!

- QED structure-function:

$$\sigma_{\alpha\alpha_s,\mathrm{LL\,FSR}} = \int_0^1 \mathrm{d}z_1 \underbrace{\Gamma_{\ell\ell}^{\mathrm{LL}}(z_1,Q^2)} \int_0^1 \mathrm{d}z_2\, \Gamma_{\ell\ell}^{\mathrm{LL}}(z_2,Q^2) \int \mathrm{d}\sigma_{\mathrm{NLO\,QCD}}(z_1 k_{\ell+}, z_2 k_{\ell-})$$

leading-log structure function, Q = typ. scale $\in (M_Z/2, 2M_Z)$

$\mathcal{O}(\alpha)$ approximation: $$\Gamma_{\ell\ell}^{\mathrm{LL},1}(z,Q^2) = \frac{\alpha(0)}{2\pi}\left[\ln\left(\frac{Q^2}{m_\ell^2}\right)-1\right]\left(\frac{1+z^2}{1-z}\right)_+$$

- QED parton-shower PHOTOS

Barberio, van Eijk, Was