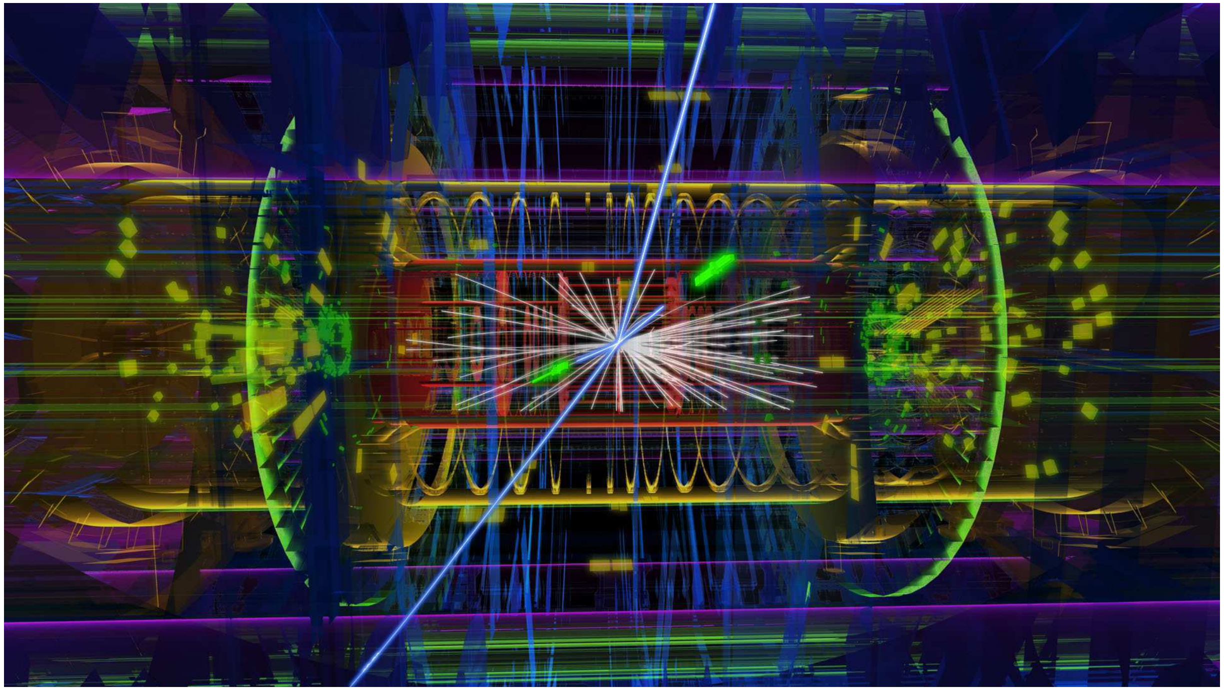
Electroweak Physics at the LHC

— Lecture 2 —

Single-W/Z Production



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Masse und Symmetrien nach der Higgs-Boson-Entdeckung am LHC

GRK 2044

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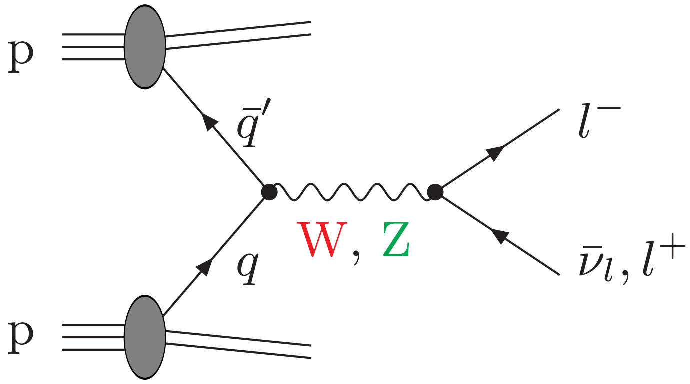
Drell–Yan-like W/Z production

—

physics goals

W- and Z-boson production at hadron colliders



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, $\text{d}\sigma$ $\rightarrow$ 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

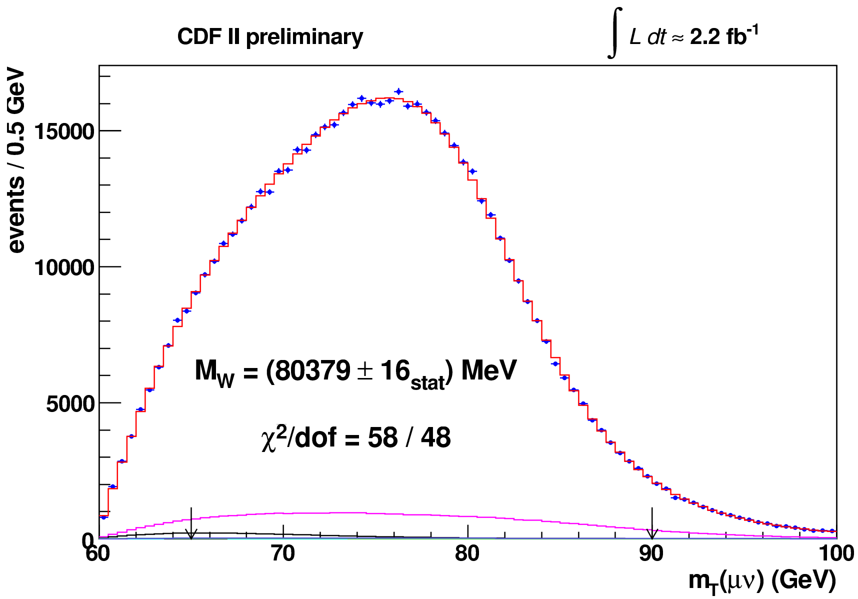
Tevatron example: M_{W} determination @ CDF (2012)

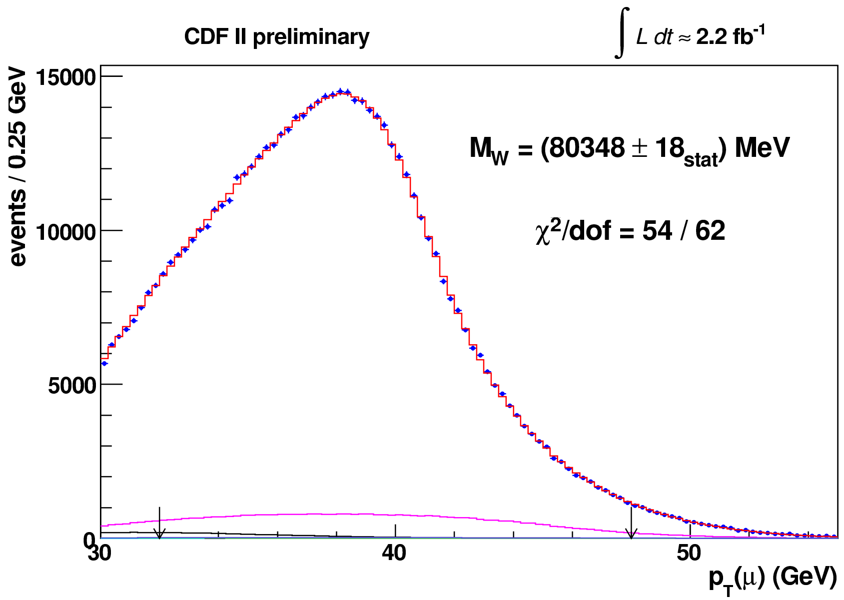
$M_{\mathrm{W}}^{\mathrm{CDF}} = 80.387\,\mathrm{GeV} \pm 19\,\mathrm{MeV}$ from fits to distributions in

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 $p_{\mathrm{T},l}$





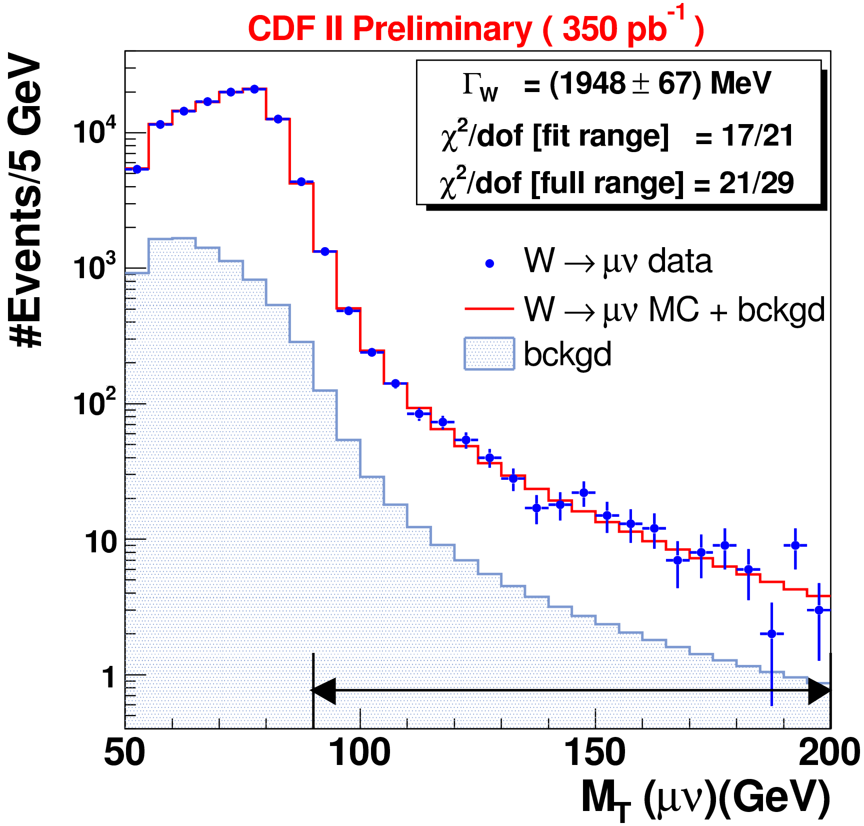
Sensitivity to M_{W} via Jacobian peaks from W resonance at

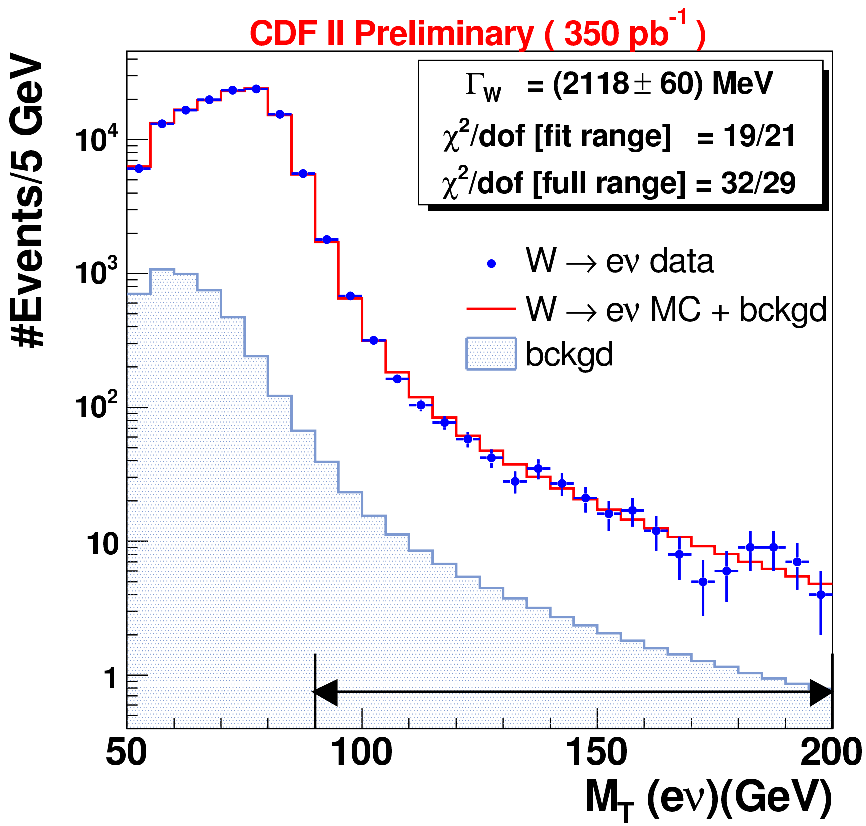
$$M_{\mathrm{T},l\nu} \sim M_{\mathrm{W}} \qquad\qquad p_{\mathrm{T},l} \sim M_{\mathrm{W}}/2$$

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

(for Z resonance as well for reference)

Fits of Γ_W to W transverse mass

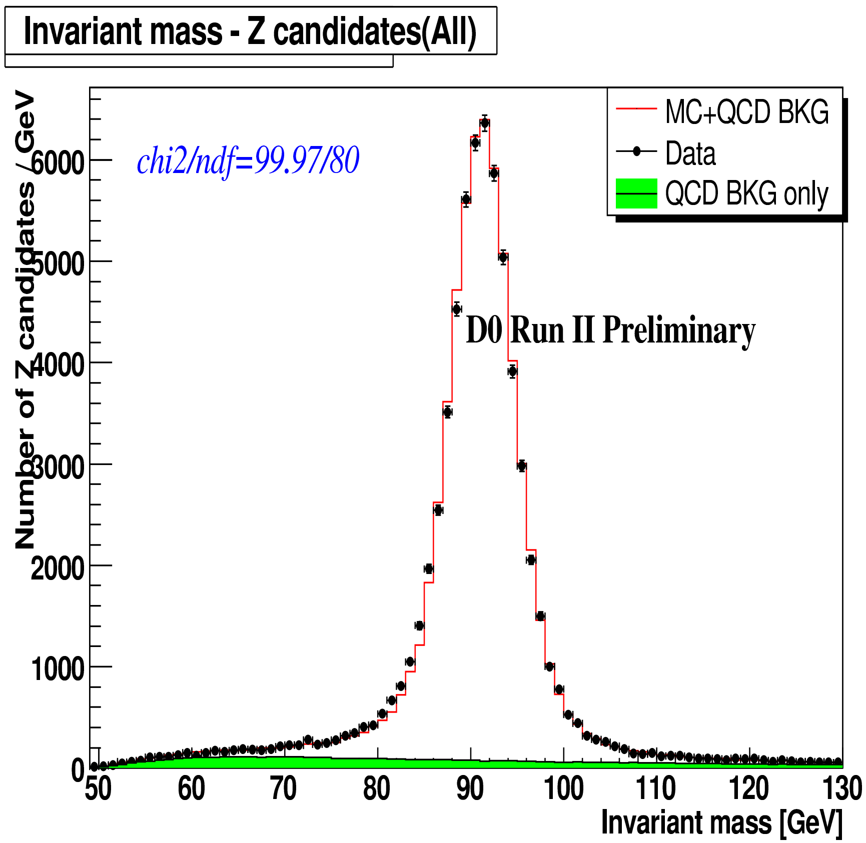


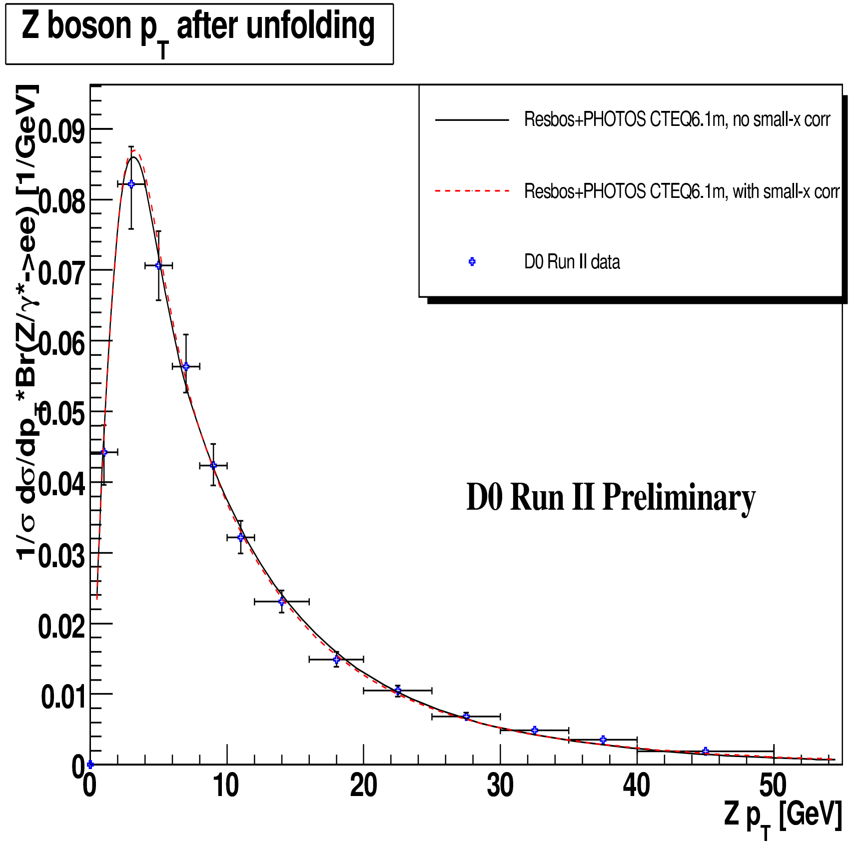


Result from CDF: $\Gamma_W = 2.032 \pm 0.071\,\mathrm{GeV}$ (=most precise single measurement)

Result from LEP: $\Gamma_W = 2.196 \pm 0.083\,\mathrm{GeV}$

Z-boson invariant-mass and transverse-momentum distributions



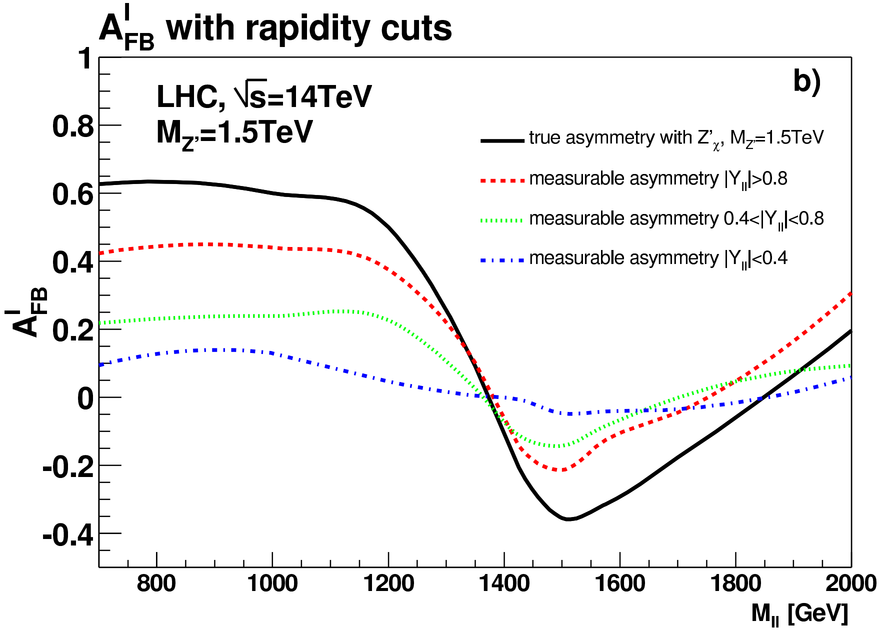


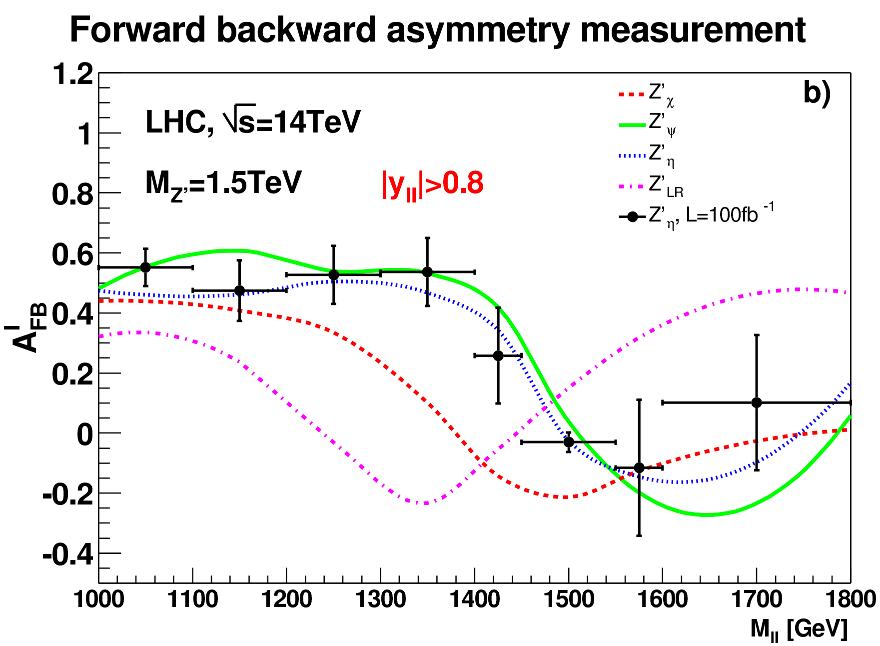
$p_{\mathrm{T,Z}}$ distribution:

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

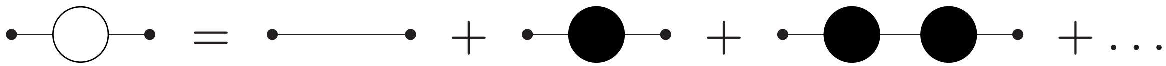
Unstable particles in QFT

Problem of unstable particles:

description of resonances requires resummation of propagator corrections

$\hookrightarrow$ mixing of perturbative orders potentially violates gauge invariance

Dyson series and propagator poles (scalar example)



$$G^{\phi\phi}(p) = \frac{\mathrm{i}}{p^2 - m^2} + \frac{\mathrm{i}}{p^2 - m^2}\,\mathrm{i}\Sigma(p^2)\,\frac{\mathrm{i}}{p^2 - m^2} + \ldots = \frac{\mathrm{i}}{p^2 - m^2 + \Sigma(p^2)}$$

$\Sigma(p^2)$ = renormalized self-energy, m = ren. mass

stable particle: $\mathrm{Im}\{\Sigma(p^2)\} = 0$ at $p^2 \sim m^2$

$\hookrightarrow$ propagator pole for real value of p^2,
renormalization condition for physical mass m: $\Sigma(m^2) = 0$

unstable particle: $\mathrm{Im}\{\Sigma(p^2)\} \neq 0$ at $p^2 \sim m^2$

$\hookrightarrow$ location μ^2 of propagator pole is complex,
possible definition of mass M and width Γ: $\mu^2 = M^2 - \mathrm{i}M\Gamma$

Different proposals:

- Naive fixed-width schemes:

$$\frac{1}{p^2 - M^2} \to \frac{1}{p^2 - M^2 + \mathrm{i}M\Gamma}$$ in all or at least in resonant propagators

$\hookrightarrow$ breaks gauge invariance only mildly (?),
but partial inclusion of widths in loops screws up singularity structure

- Pole scheme   Stuart '91; Aeppli et al. '93, '94; etc.

Isolate resonance pole and introduce width Γ only there.

$\hookrightarrow$ consistent, gauge invariant, but involves subtleties

Pole approximation: isolate and keep only leading (=resonant) terms

$\hookrightarrow$ consistent, gauge invariant,
but not reliable at threshold or in off-shell tails of resonances

- Effective field theory approach   Beneke et al. '04; Hoang, Reisser '04

$\hookrightarrow$ gauge invariant, involves pole expansions,
but can be combined with threshold expansions

- Complex-mass scheme   Denner, S.D., Roth, Wackeroth '99; Denner, S.D., Roth, Wieders '05

$\hookrightarrow$ gauge invariant, valid everywhere in phase space

The complex-mass scheme at NLO

Basic idea: mass^2 = location of propagator pole in complex p^2 plane

$\hookrightarrow$ consistent use of complex masses everywhere !

Application to gauge-boson resonances:

- replace $M_\mathrm{W}^2 \to \mu_\mathrm{W}^2 = M_\mathrm{W}^2 - \mathrm{i} M_\mathrm{W}\Gamma_\mathrm{W}, \qquad M_\mathrm{Z}^2 \to \mu_\mathrm{Z}^2 = M_\mathrm{Z}^2 - \mathrm{i} M_\mathrm{Z}\Gamma_\mathrm{Z}$

  and define (complex) weak mixing angle via $c_\mathrm{W}^2 = 1 - s_\mathrm{W}^2 = \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}$

- virtues:
  - ◇ gauge-invariant result (Slavnov–Taylor identities, gauge-parameter independence)

    $\hookrightarrow$ unitarity cancellations respected !
  - ◇ perturbative calculations as usual (loops and counterterms)
  - ◇ no double counting of contributions (bare Lagrangian unchanged !)

- drawbacks:
  - ◇ unitarity-violating spurious terms of $\mathcal{O}(\alpha^2)$ $\to$ but beyond NLO accuracy !

    (from t-channel/off-shell propagators and complex mixing angle)
  - ◇ complex gauge-boson masses also in loop integrals

Commonly used mass/width definitions:

- "on-shell mass/width" $M_{\rm OS}/\Gamma_{\rm OS}$: $\quad M_{\rm OS}^2 - m^2 + {\rm Re}\{\Sigma(M_{\rm OS}^2)\} \stackrel{!}{=} 0$

$$\hookrightarrow \quad G^{\phi\phi}(p) \underset{p^2\to M_{\rm OS}^2}{\widetilde{}} \frac{1}{(p^2 - M_{\rm OS}^2)(1 + {\rm Re}\{\Sigma'(M_{\rm OS}^2)\}) + {\rm i\,Im}\{\Sigma(p^2)\}}$$

comparison with form of Breit–Wigner resonance $\dfrac{R_{\rm OS}}{p^2 - m^2 + {\rm i}m\Gamma}$

yields: $\quad M_{\rm OS}\Gamma_{\rm OS} \equiv {\rm Im}\{\Sigma(M_{\rm OS}^2)\} \,/\, (1 + {\rm Re}\{\Sigma'(M_{\rm OS}^2)\}), \qquad \Sigma'(p^2) \equiv \frac{\partial\Sigma(p^2)}{\partial p^2}$

- "pole mass/width" M/Γ: $\quad \mu^2 - m^2 + \Sigma(\mu^2) \stackrel{!}{=} 0$

complex pole position: $\quad \mu^2 \equiv M^2 - {\rm i}M\Gamma$

$$\hookrightarrow \quad G^{\phi\phi}(p) \underset{p^2\to \mu^2}{\widetilde{}} \frac{1}{(p^2 - \mu^2)[1 + \Sigma'(\mu^2)]} = \frac{R}{p^2 - M^2 + {\rm i}M\Gamma}$$

Note: $\quad \mu =$ gauge independent for any particle (pole location is property of S-matrix)

$M_{\rm OS} =$ gauge dependent at 2-loop order $\quad$ Sirlin '91; Stuart '91; Gambino, Grassi '99; Grassi, Kniehl, Sirlin '01

Relation between "on-shell" and "pole" definitions:

Subtraction of defining equations yields:

$$M_{\rm OS}^2 + {\rm Re}\{\Sigma(M_{\rm OS}^2)\} \;=\; M^2 - {\rm i}M\Gamma + \Sigma(M^2 - {\rm i}M\Gamma)$$

Equation can be uniquely solved via recursion in powers of coupling α:

ansatz: $$M_{\rm OS}^2 = M^2 + c_1\alpha^1 + c_2\alpha^2 + \dots$$
$$M_{\rm OS}\Gamma_{\rm OS} = M\Gamma + d_2\alpha^2 + d_3\alpha^3 + \dots, \qquad c_i, d_i = \text{real}$$

counting in α: $$M_{\rm OS}, M = \mathcal{O}(\alpha^0), \quad \Gamma_{\rm OS}, \Gamma, \Sigma(p^2) = \mathcal{O}(\alpha^1)$$

Result:

$$M_{\rm OS}^2 \;=\; M^2 + {\rm Im}\{\Sigma(M^2)\}\,{\rm Im}\{\Sigma'(M^2)\} \;+\; \mathcal{O}(\alpha^3)$$

$$M_{\rm OS}\Gamma_{\rm OS} \;=\; M\Gamma + {\rm Im}\{\Sigma(M^2)\}\,{\rm Im}\{\Sigma'(M^2)\}^2 + \tfrac{1}{2}\,{\rm Im}\{\Sigma(M^2)\}^2\,{\rm Im}\{\Sigma''(M^2)\} \;+\; \mathcal{O}(\alpha^4)$$

i.e. $\{M_{\rm OS}, \Gamma_{\rm OS}\} \;=\; \{M, \Gamma\} \;+$ gauge-dependent 2-loop corrections

Important examples: W and Z bosons

In good approximation: $\mathrm{W} \to f\bar{f}', \quad \mathrm{Z} \to f\bar{f}$ with masses fermions f, f'

so that: $$\mathrm{Im}\{\Sigma_{\mathrm{T}}^{\mathrm{V}}(p^2)\} = p^2 \times \frac{\Gamma_{\mathrm{V}}}{M_{\mathrm{V}}}\,\theta(p^2), \qquad \mathrm{V} = \mathrm{W}, \mathrm{Z}$$

$$\hookrightarrow \; M_{\mathrm{OS}}^2 = M^2 + \Gamma^2 + \mathcal{O}(\alpha^3) \qquad M_{\mathrm{OS}}\Gamma_{\mathrm{OS}} = M\Gamma + \frac{\Gamma^3}{M} + \mathcal{O}(\alpha^4)$$

In terms of measured numbers:

W boson: $M_{\mathrm{W}} \approx 80\,\mathrm{GeV}, \qquad \Gamma_{\mathrm{W}} \approx 2.1\,\mathrm{GeV}$

$\hookrightarrow \; M_{\mathrm{W,OS}} - M_{\mathrm{W,pole}} \approx 28\,\mathrm{MeV}$

Z boson: $M_{\mathrm{Z}} \approx 91\,\mathrm{GeV}, \qquad \Gamma_{\mathrm{Z}} \approx 2.5\,\mathrm{GeV}$

$\hookrightarrow \; M_{\mathrm{Z,OS}} - M_{\mathrm{Z,pole}} \approx 34\,\mathrm{MeV}$

Exp. accuracy: $\Delta M_{\mathrm{W,exp}} = 29\,\mathrm{MeV}, \quad \Delta M_{\mathrm{Z,exp}} = 2.1\,\mathrm{MeV}$

$\hookrightarrow$ Difference in definitions phenomenologically important !

Example of W and Z bosons continued:

Approximation of massless decay fermions:

$$\Gamma_{\mathrm{V,OS}}(p^2) \;=\; \Gamma_{\mathrm{V,OS}} \times \frac{p^2}{M^2_{\mathrm{V,OS}}}\,\theta(p^2), \qquad \mathrm{V} = \mathrm{W}, \mathrm{Z}$$

Fit of W/Z resonance shapes to experimental data:

- ansatz $\left|\frac{R'}{p^2 - m'^2 + \mathrm{i}\gamma' p^2/m'}\right|^2$ yields: $m' = M_{\mathrm{V,OS}}, \quad \gamma' = \Gamma_{\mathrm{V,OS}}$
- ansatz $\left|\frac{R}{p^2 - m^2 + \mathrm{i}\gamma m}\right|^2$ yields: $m = M_{\mathrm{V,pole}}, \quad \gamma = \Gamma_{\mathrm{V,pole}}$

Note: the two forms are equivalent:

$$R = \frac{R'}{1 + \mathrm{i}\gamma'/m'}, \quad m^2 = \frac{m'^2}{1 + \gamma'^2/m'^2}, \quad m\gamma = \frac{m'\gamma'}{1 + \gamma'^2/m'^2}$$

$\hookrightarrow$ consistent with relation between “on-shell” and “pole” definitions !

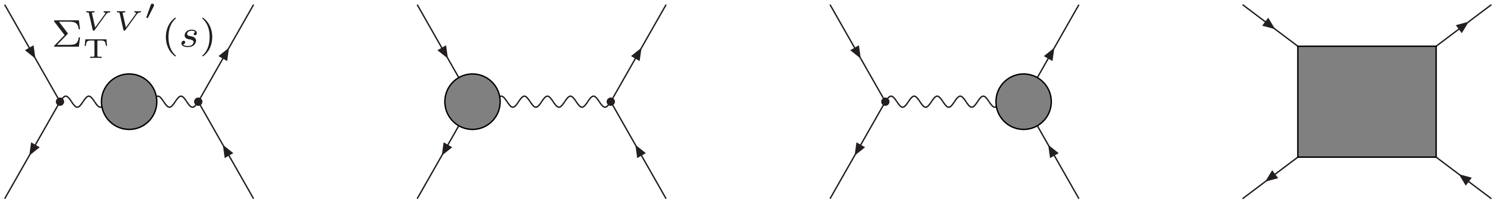
QCD and electroweak corrections to inclusive W/Z production

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
- $\mathcal{O}(\alpha\alpha_{\rm s})$ corrs. near resonances — S.D., Huss, Schwinn ’14,’15 (soon)

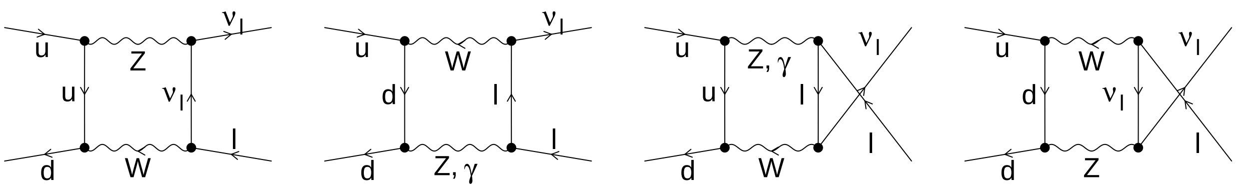
Some details on the NLO calculation

Loop corrections:



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

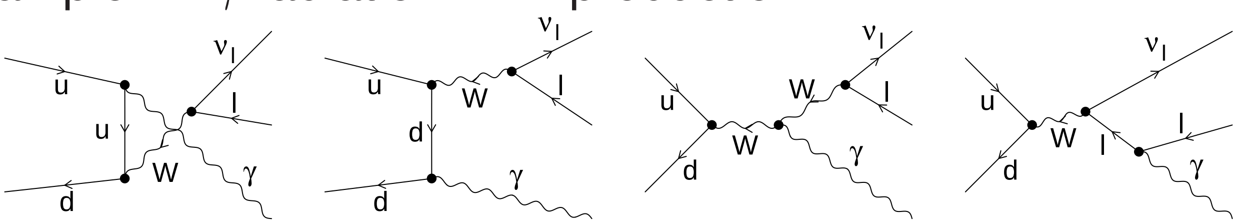
Example: box corrections to W production



Real-emission corrections:

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

Example: γ radiation in W production

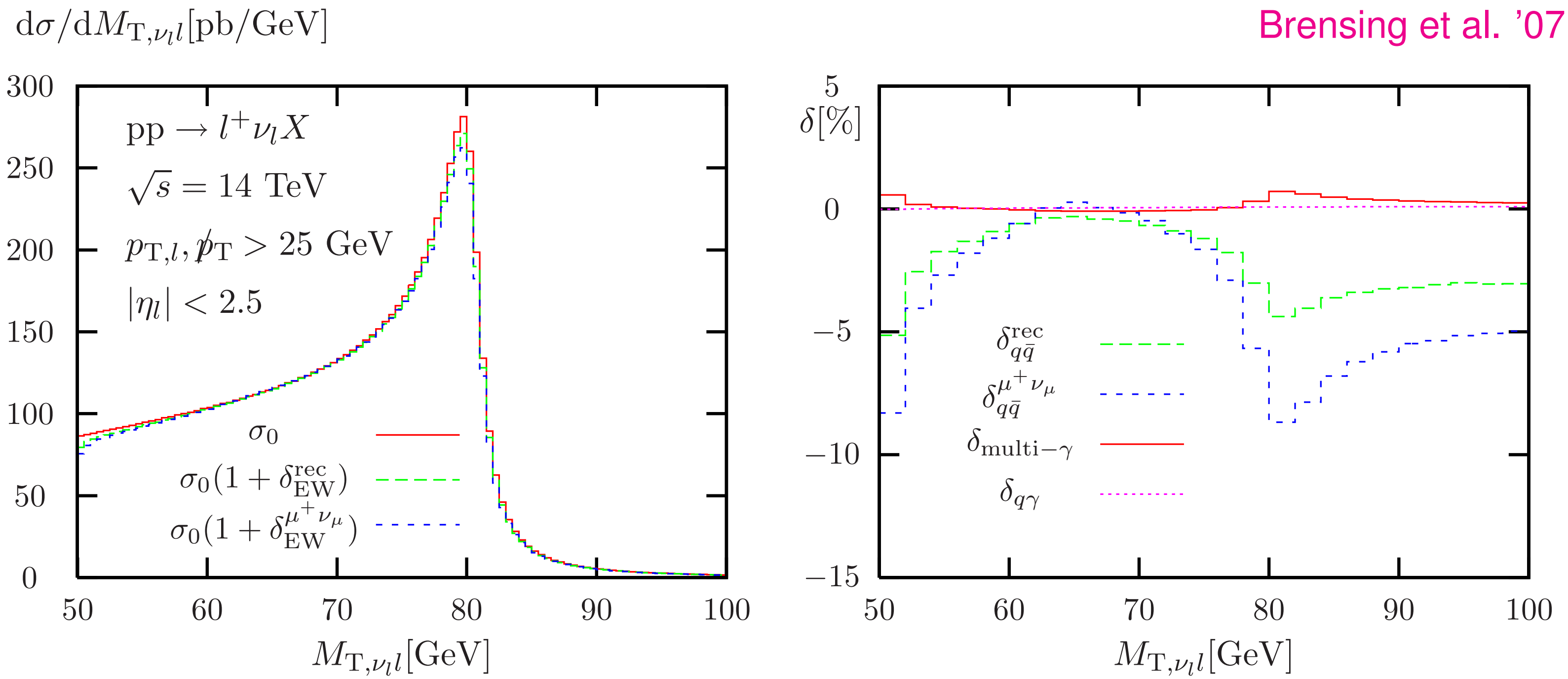


Field-theoretical subtlety:

gauge-invariant description of resonance with higher-order corrections

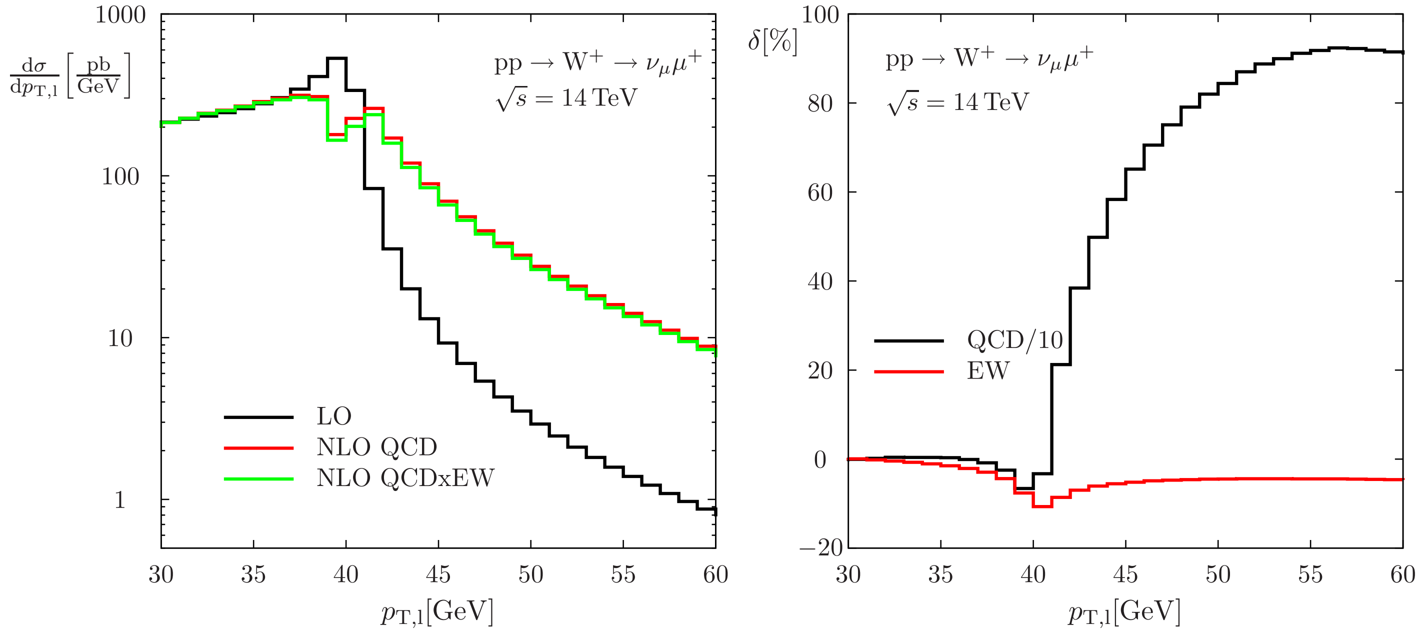
Corrections to $M_{\mathrm{T},l\nu}$ distribution in W production:

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:

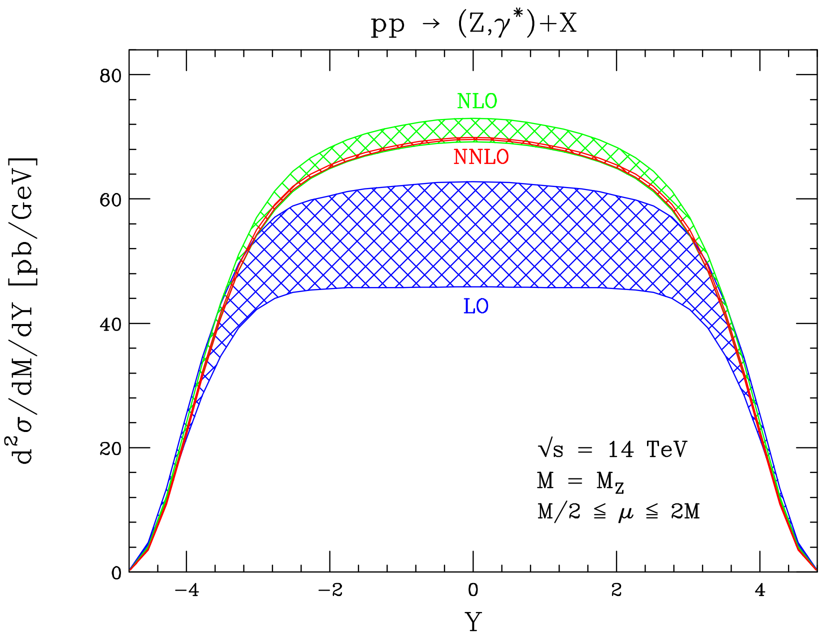


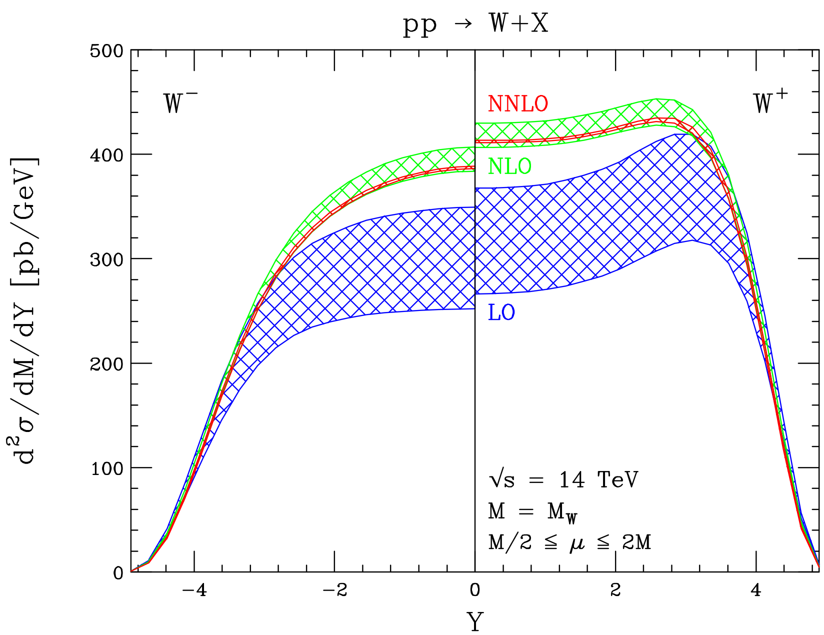
- QCD corrections huge ($> 100\%$) for $p_{\mathrm{T},l} \gtrsim M_\mathrm{W}/2$ due to jet recoil
  $\hookrightarrow$ importance of multi-jet merging / QCD parton-shower matching
- EW corrections
  - ◇ shape distortion, etc., similar to $M_{\mathrm{T},l\nu}$ distribution
- observable cleaner experimentally,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

Corrections to W/Z rapidity distribution

QCD predictions at LO / NLO / NNLO:

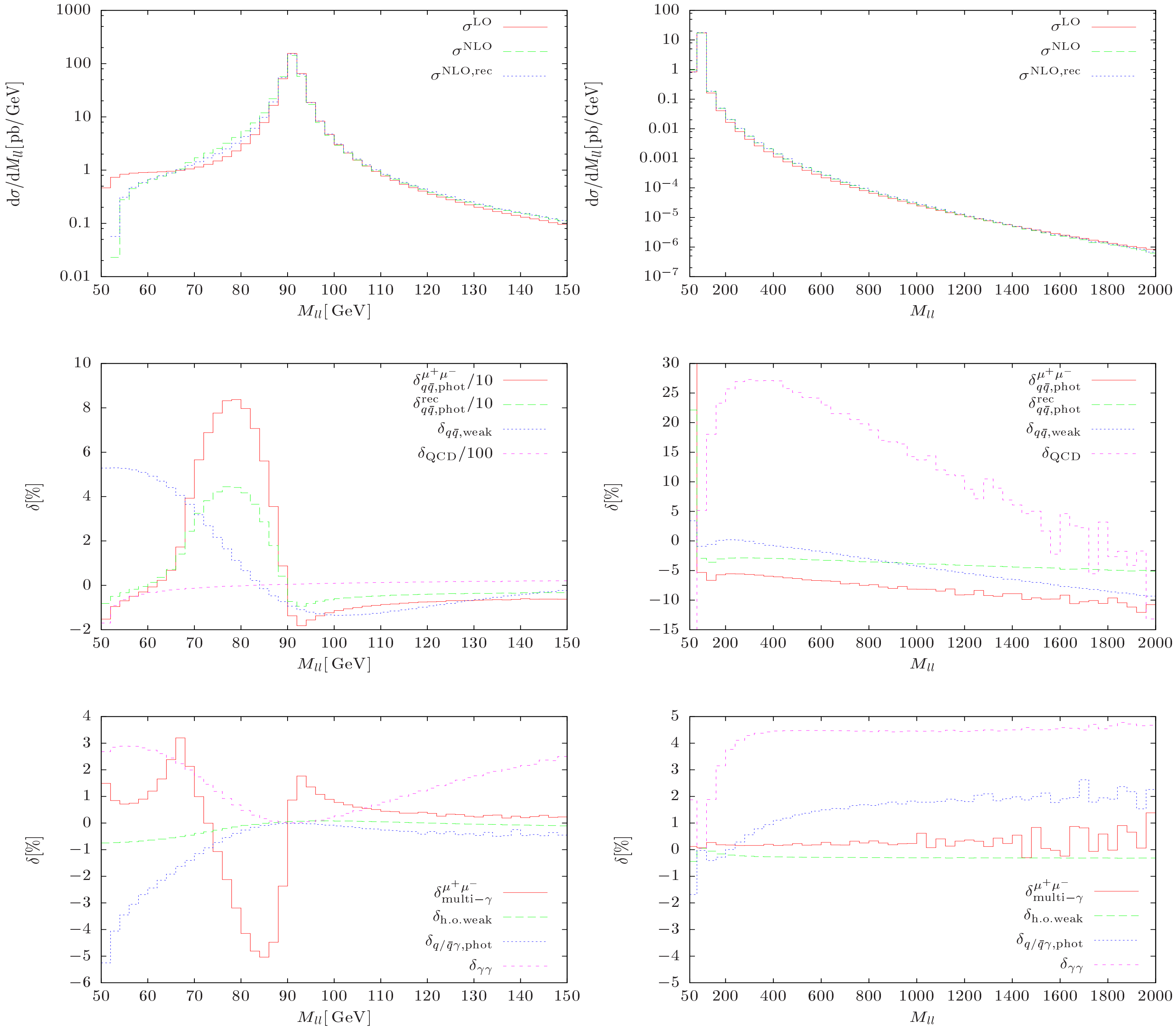
Anastasiou et al. ’03





- 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

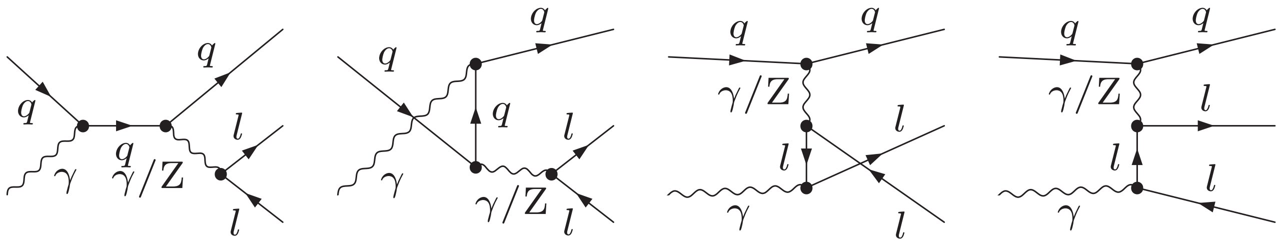
- QCD corrections significant, but quite flat in resonance region
- Photonic corrections
  - ◇ large radiative tail for $M_{ll} \lesssim M_Z$ from photonic final-state radiation
  - ◇ multi-photon emission significant in resonance region
  - ◇ photon recombination reduces large corrections drastically
    (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 !

Photon-induced processes

and photon PDF

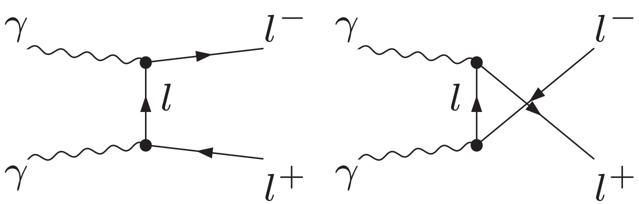
Photon-induced channels

γq collisions



- contributions to both W and Z production
- same signature as QCD corrections ($V + \text{jet}$)
  $\hookrightarrow$ contributions swamped by QCD radiation effects

$\gamma\gamma \to l^+l^-$



- contribution only to neutral-current process
- significant impact for high invariant mass M_{ll}

$\gamma\gamma \to l^+l^-$ – a handle on the photon PDF ?

Impact of $\gamma\gamma$ and $q\gamma$ channels enhanced above Z pole !

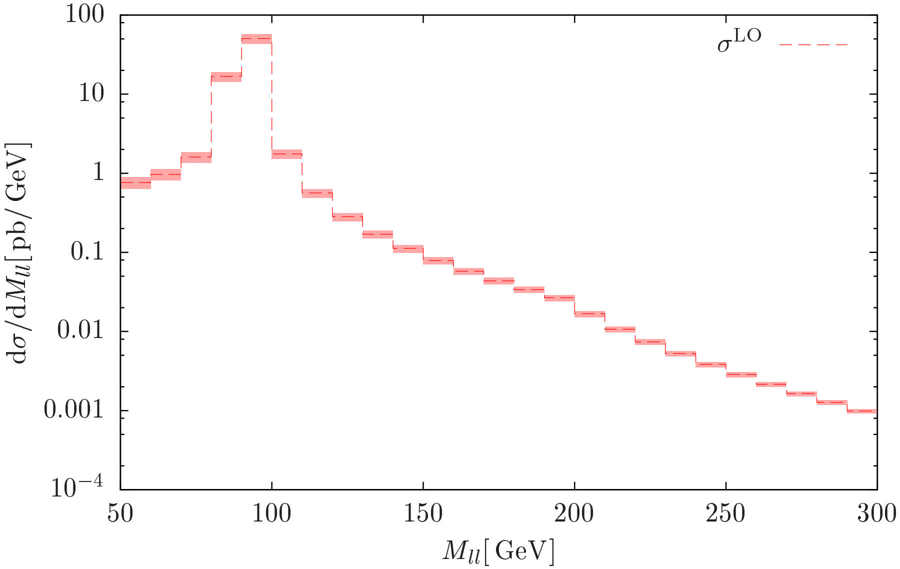
Note: $\gamma\gamma$ channel prefers scattering angles $\theta^* \to 0, \pi$!

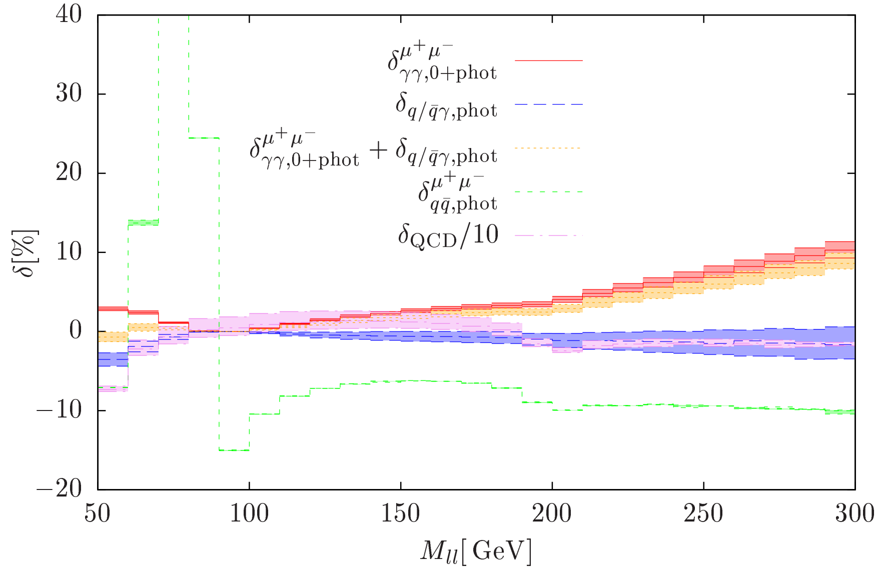
LO kinematics: $M_{ll} = \sqrt{\hat{s}}, \quad p_{\mathrm{T},l} = \frac{1}{2}\sqrt{\hat{s}}\sin\theta^* = \frac{1}{2}M_{ll}\sin\theta^*$

$\hookrightarrow$ Enhance $\gamma\gamma$ channel by cuts on $p_{\mathrm{T},l}$?!

Scenario (c): $p_{\mathrm{T},l^\pm} < 100\,\mathrm{GeV}$

S.D., Huber '09





$\gamma\gamma \to l^+l^-$ – a handle on the photon PDF ?

Impact of $\gamma\gamma$ and $q\gamma$ channels enhanced above Z pole !

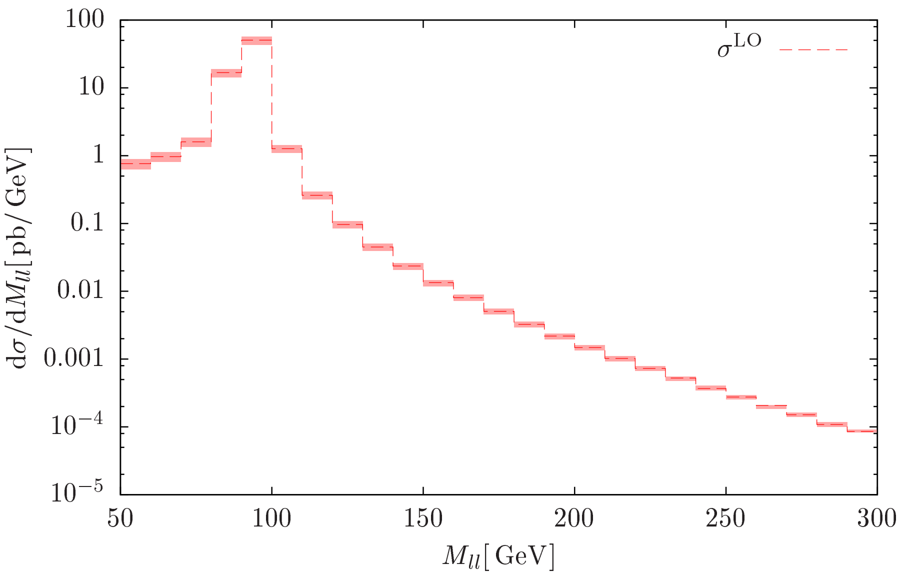
Note: $\gamma\gamma$ channel prefers scattering angles $\theta^* \to 0, \pi$!

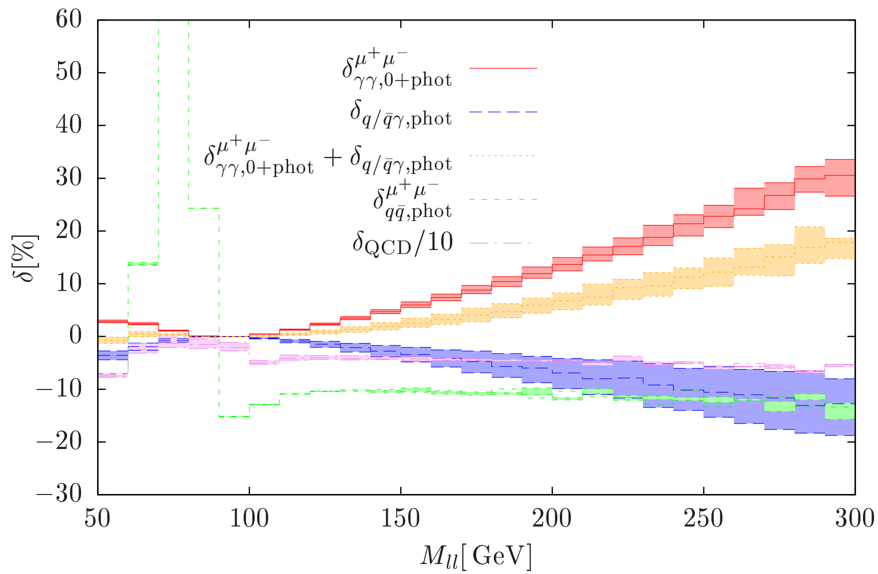
LO kinematics: $M_{ll} = \sqrt{\hat{s}}, \quad p_{\mathrm{T},l} = \frac{1}{2}\sqrt{\hat{s}}\sin\theta^* = \frac{1}{2}M_{ll}\sin\theta^*$

$\hookrightarrow$ Enhance $\gamma\gamma$ channel by cuts on $p_{\mathrm{T},l}$?!

Scenario (b): $p_{\mathrm{T},l^\pm} < 50\,\mathrm{GeV}$

S.D., Huber '09





$\gamma\gamma \to l^+l^-$ – a handle on the photon PDF ?

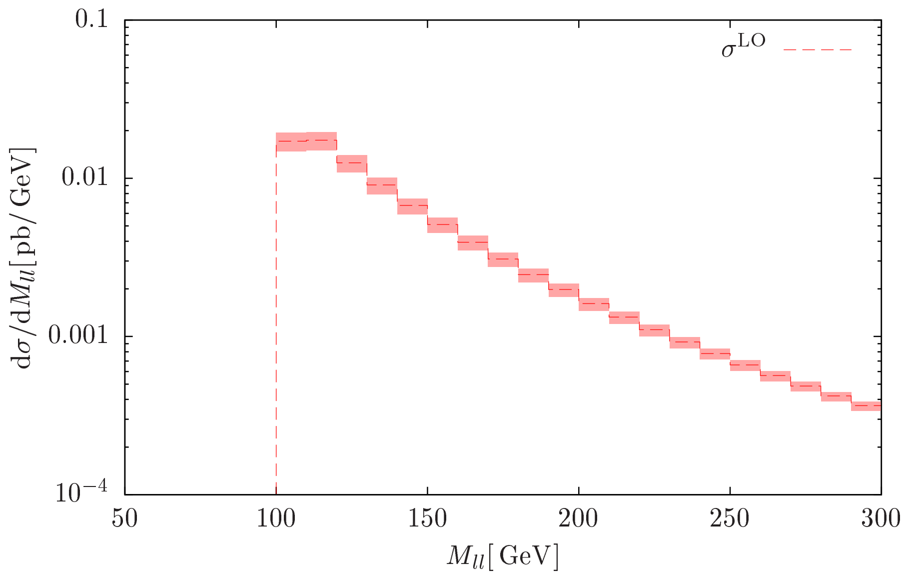
Impact of $\gamma\gamma$ and $q\gamma$ channels enhanced above Z pole !

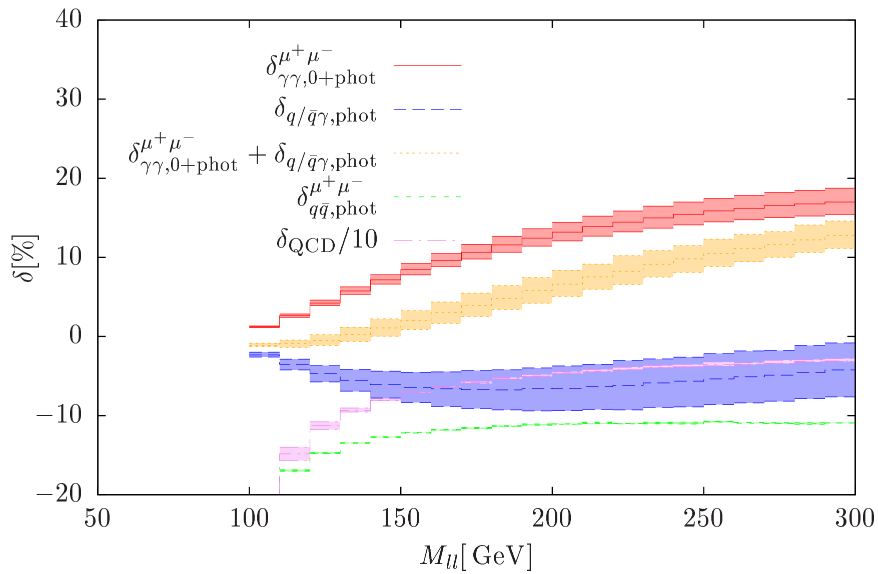
Note: $\gamma\gamma$ channel prefers scattering angles $\theta^* \to 0, \pi$!

LO kinematics: $M_{ll} = \sqrt{\hat{s}}, \quad p_{\mathrm{T},l} = \frac{1}{2}\sqrt{\hat{s}}\sin\theta^* = \frac{1}{2}M_{ll}\sin\theta^*$

$\hookrightarrow$ Enhance $\gamma\gamma$ channel by cuts on $p_{\mathrm{T},l}$?!

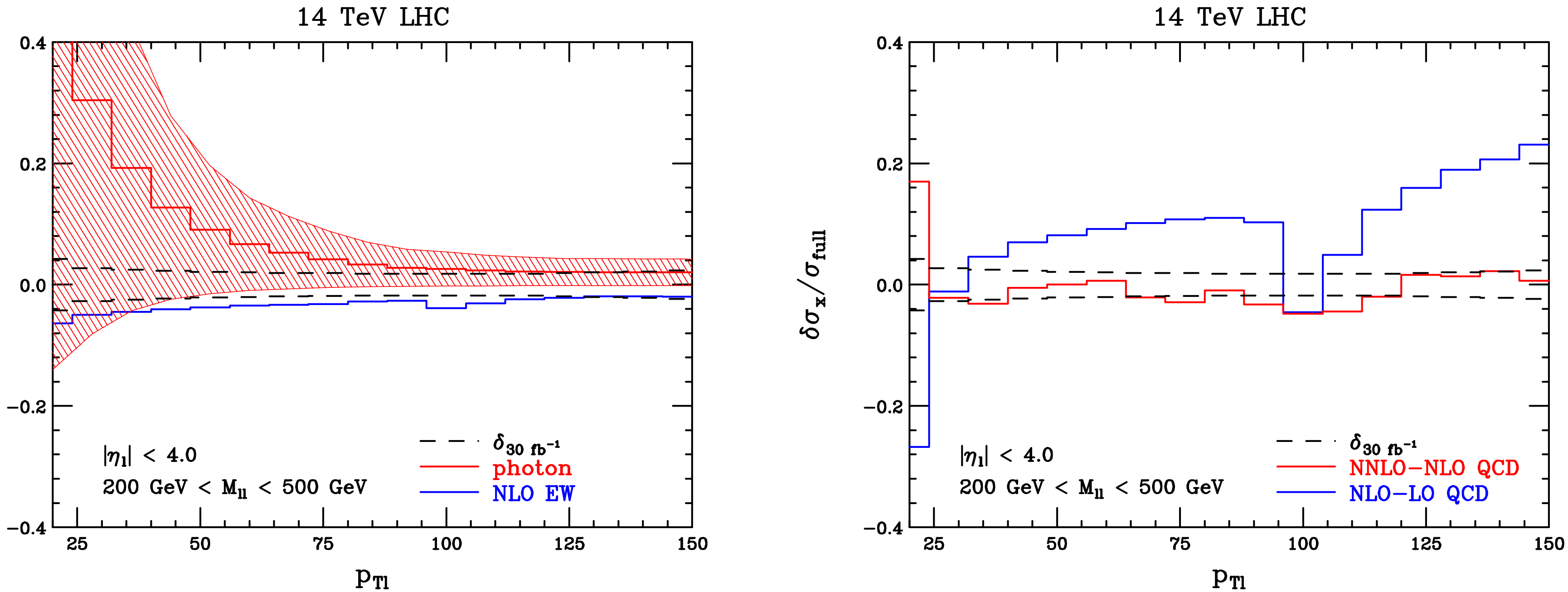
Scenario (a): $p_{\mathrm{T},l^\pm} < M_{ll}/4 \quad (\sin\theta^* < \frac{1}{2}$ in LO) S.D., Huber '09





New sensitivity study on NC Drell-Yan production

Boughezal, Petriello '14



High invariant dilepton masses $M_{\ell\ell}$

- $\gamma\gamma$ and NLO EW contributions can be separated by cuts
- γ PDF can be further constrained
- inclusion of EW corrections required
- QCD corrections are under control @ NNLO QCD

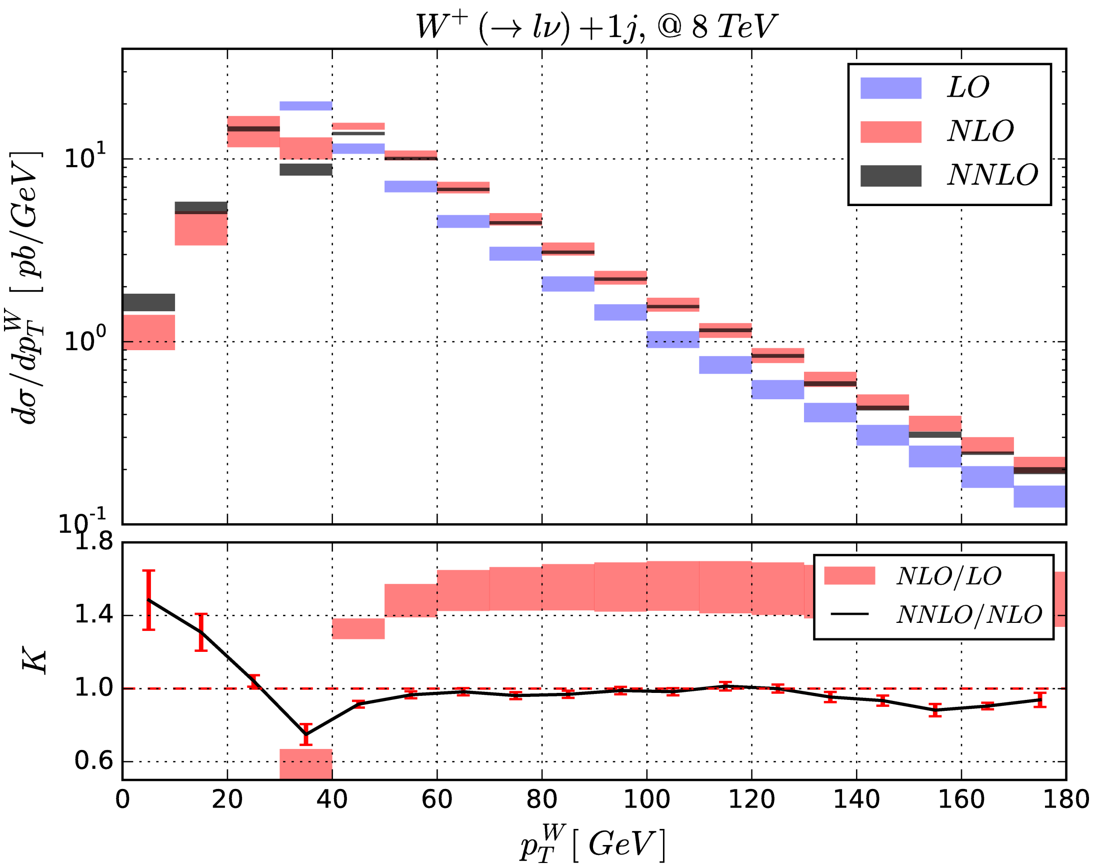
W/Z production with hard jets

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 $\mathrm{W} + 1\,\mathrm{jet}$ — Boughezal 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"

Jettiness subtraction – the idea

Boughezal et al. '15; Gaunt et al. '15

Definition: "jettiness" $\mathcal{T}_N \equiv \sum_k \min_i \left\{ \frac{2p_i \cdot q_k}{Q_i} \right\}$ Stewart, Tackmann, Waalewijn '10

Procedure for calculating $\mathcal{T}_N$:

1. Determine N jets with any jet algorithm
   $\hookrightarrow$ N light-like reference momenta p_i (+ 2 beam momenta for pp)
2. Calculate $\mathcal{T}_N$ from sum over all parton momenta q_k.
   (The scales Q_i characterize the hardness of the jets.)

$\Rightarrow$ $\mathcal{T}_N \to 0$ corresponds to exactly N resolved jets (independent of jet algorithm).

Phase-space partitioning by cutting on $\mathcal{T}_N$ with small $\mathcal{T}_N^{\mathrm{cut}}$:

$$\begin{aligned} \sigma^{(N)}_{\mathrm{NNLO}} &= \sigma^{(N)}_{\mathrm{NNLO}}\Big|_{\mathcal{T}_N<\mathcal{T}_N^{\mathrm{cut}}} + \sigma^{(N)}_{\mathrm{NNLO}}\Big|_{\mathcal{T}_N>\mathcal{T}_N^{\mathrm{cut}}} \\ &= \underbrace{\sigma^{(N)}_{\mathrm{LO}} \otimes V \otimes C \otimes S\Big|_{\mathcal{T}_N<\mathcal{T}_N^{\mathrm{cut}}}}_{\text{virtual corrections}} + \underbrace{\sigma^{(N)}_{\mathrm{NLO}}\Big|_{\mathcal{T}_N>\mathcal{T}_N^{\mathrm{cut}}}}_{\text{at least 1 hard jet}} \end{aligned}$$

virtual corrections
+ SCET-factorized double-unresolved emission

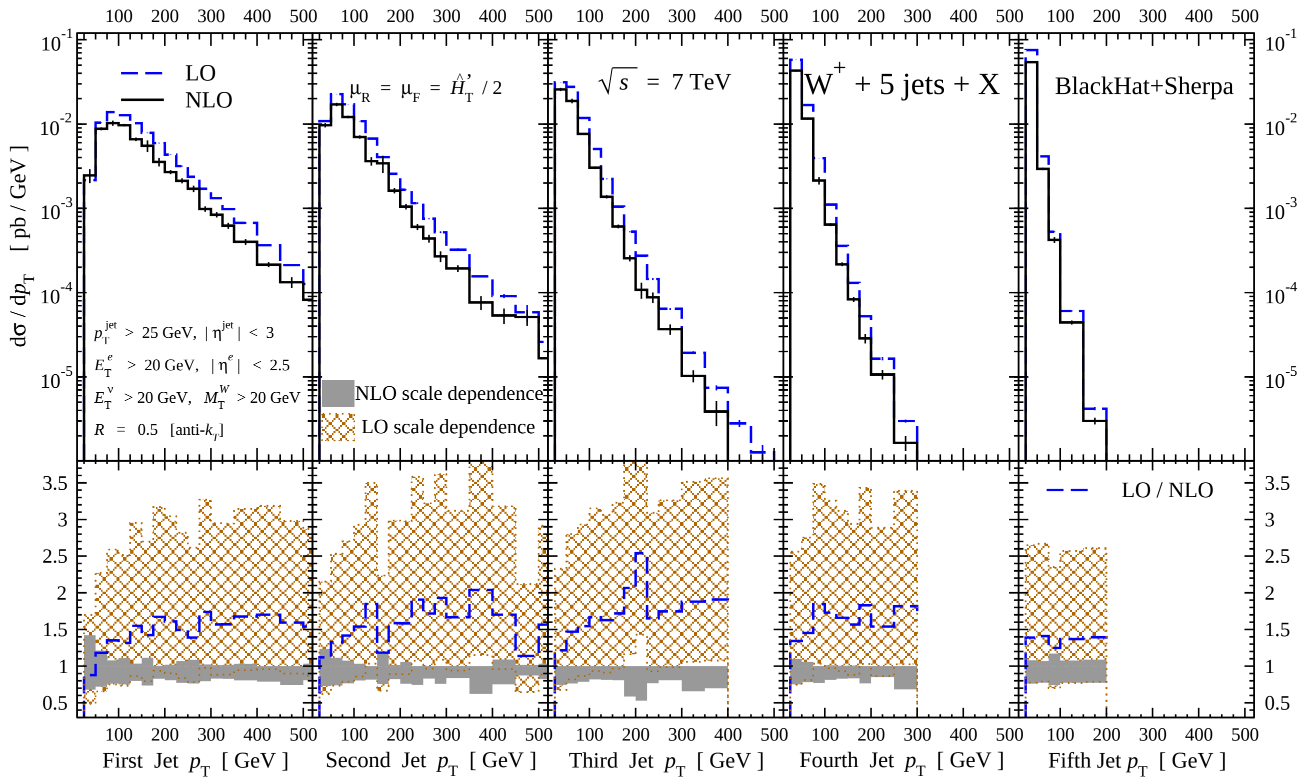
Becher, Neubert '06; Becher, Bell '10; Jouttenus et al. '11; Gaunt et al. '14; Boughezal '15

W/Z + higher jet multiplicities @ NLO QCD

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

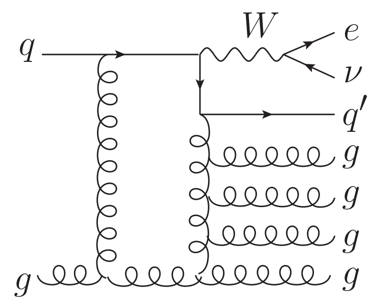
Bern et al. '11–'13; Goetz et al. '14

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



BlackHat+Sherpa

Example diagram:

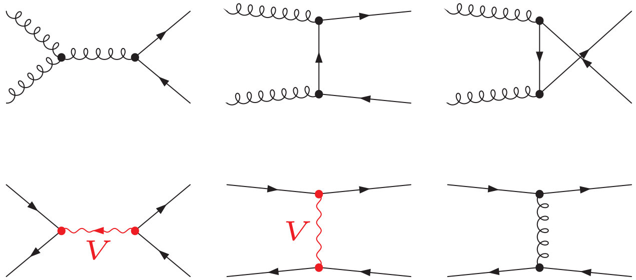


- theoretical uncertainty reduced from $\sim 100\%$ (LO) to $\sim 30\%$ (NLO)
- good agreement between theory and LHC Run 1 data

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

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

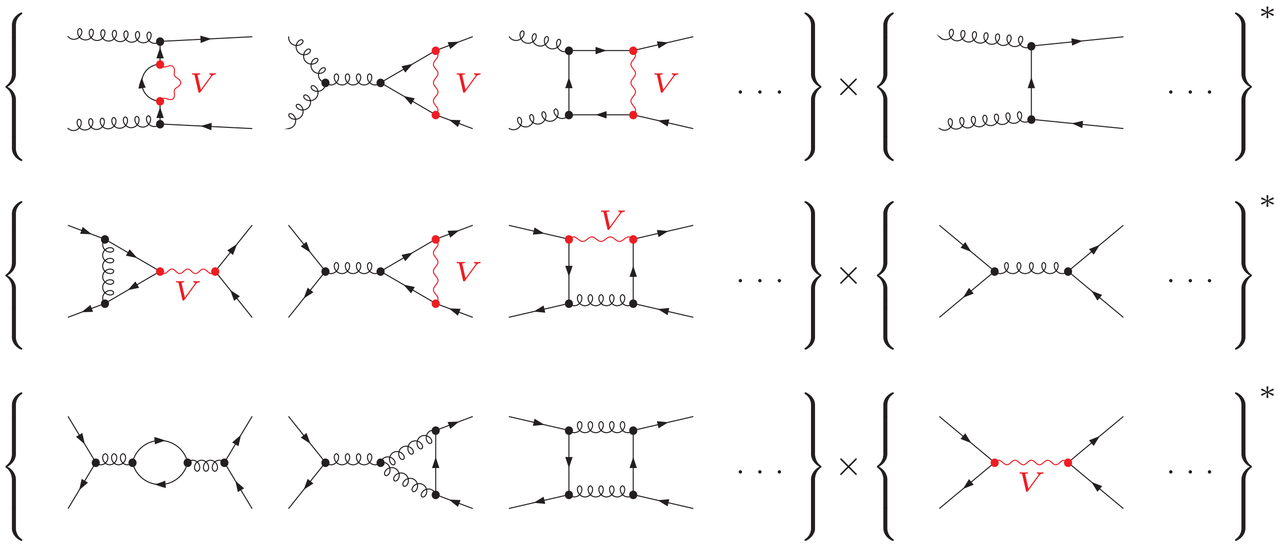
Tree contributions: $\mathcal{O}(\alpha_{\mathrm{s}}\alpha)$, $\mathcal{O}(\alpha^2)$



(W/Z emission suppressed in graphs)

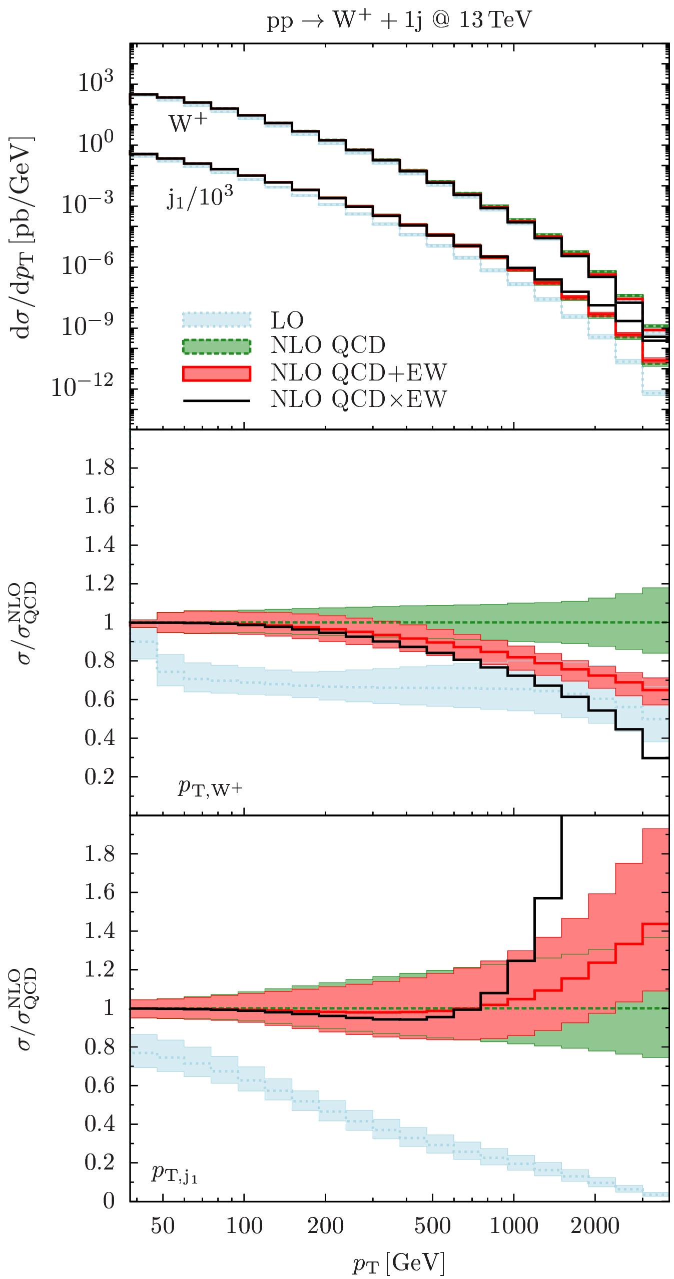
$V = \gamma, \mathrm{Z}, \mathrm{W}$

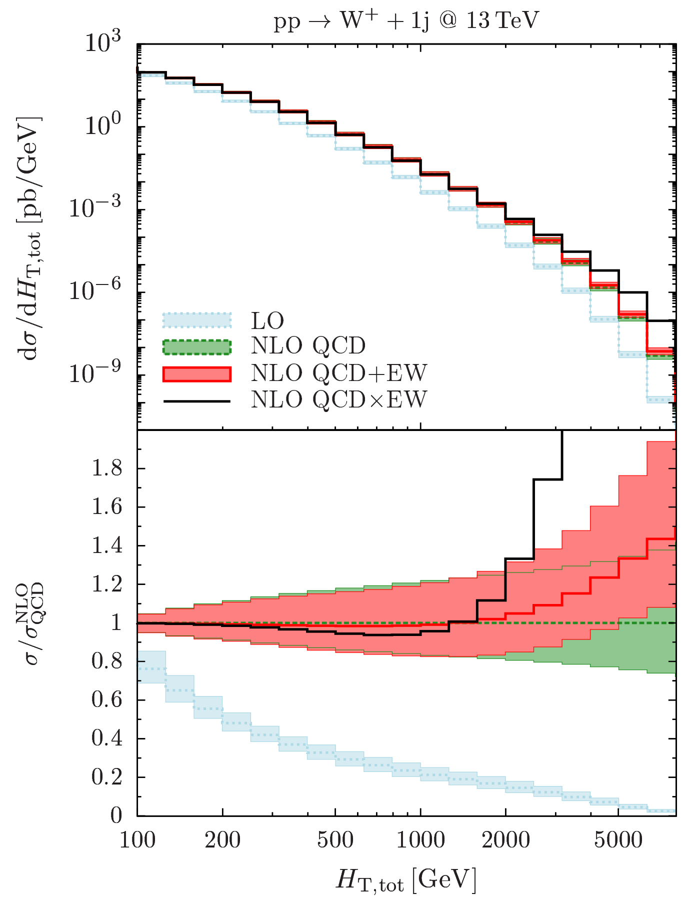
Loop contributions: $\mathcal{O}(\alpha_{\mathrm{s}}^2\alpha)$



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

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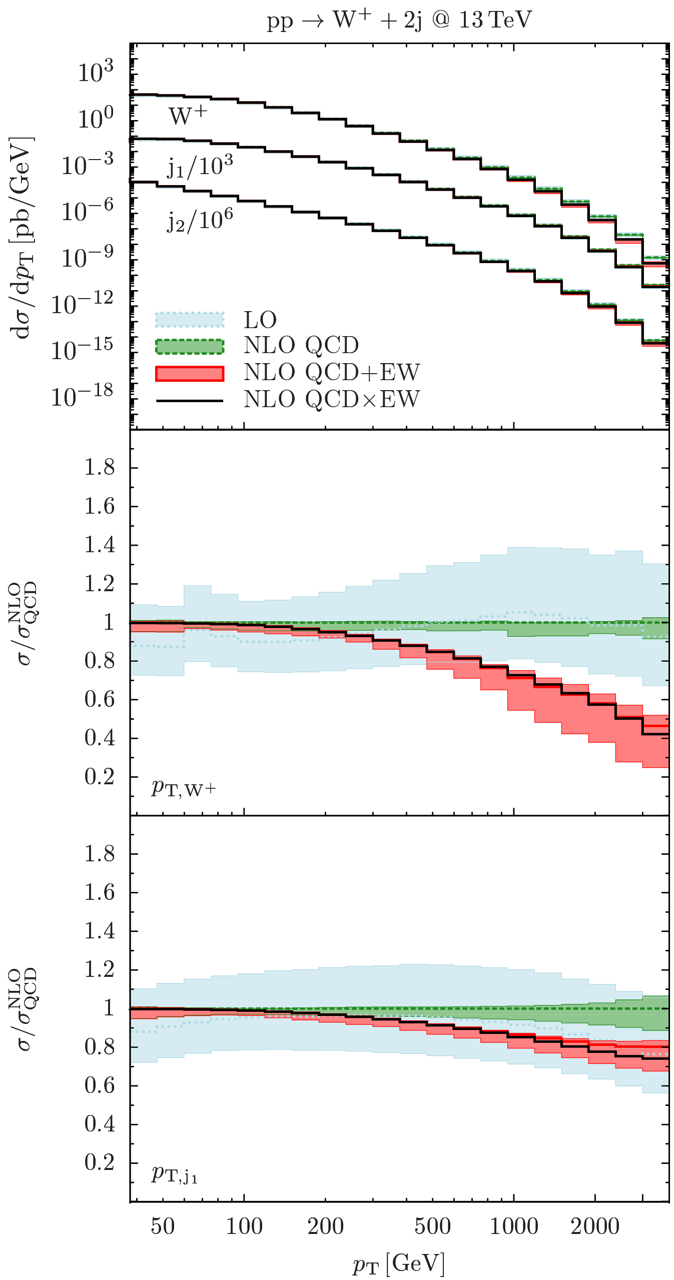
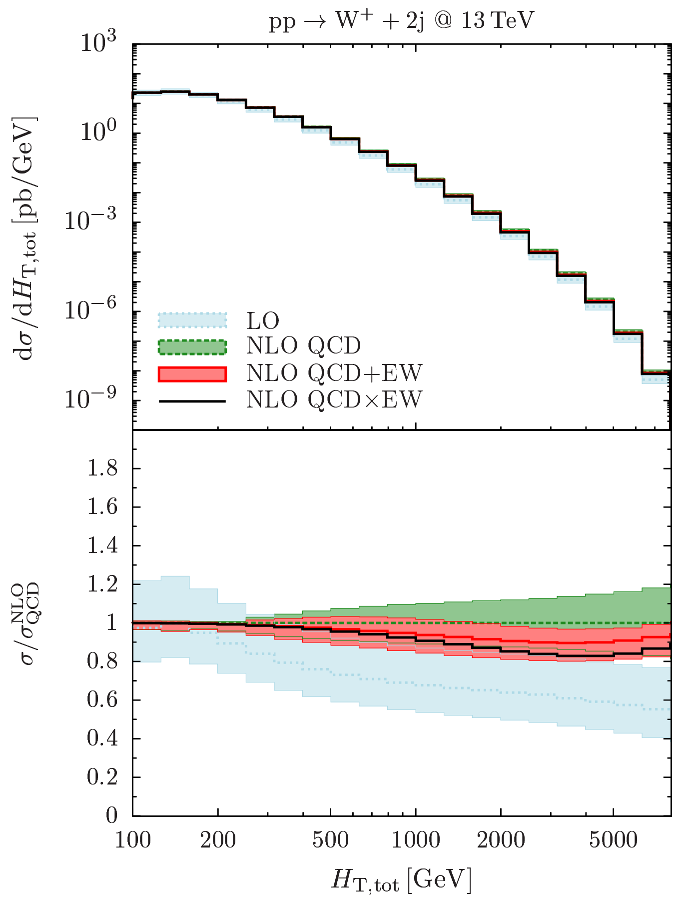
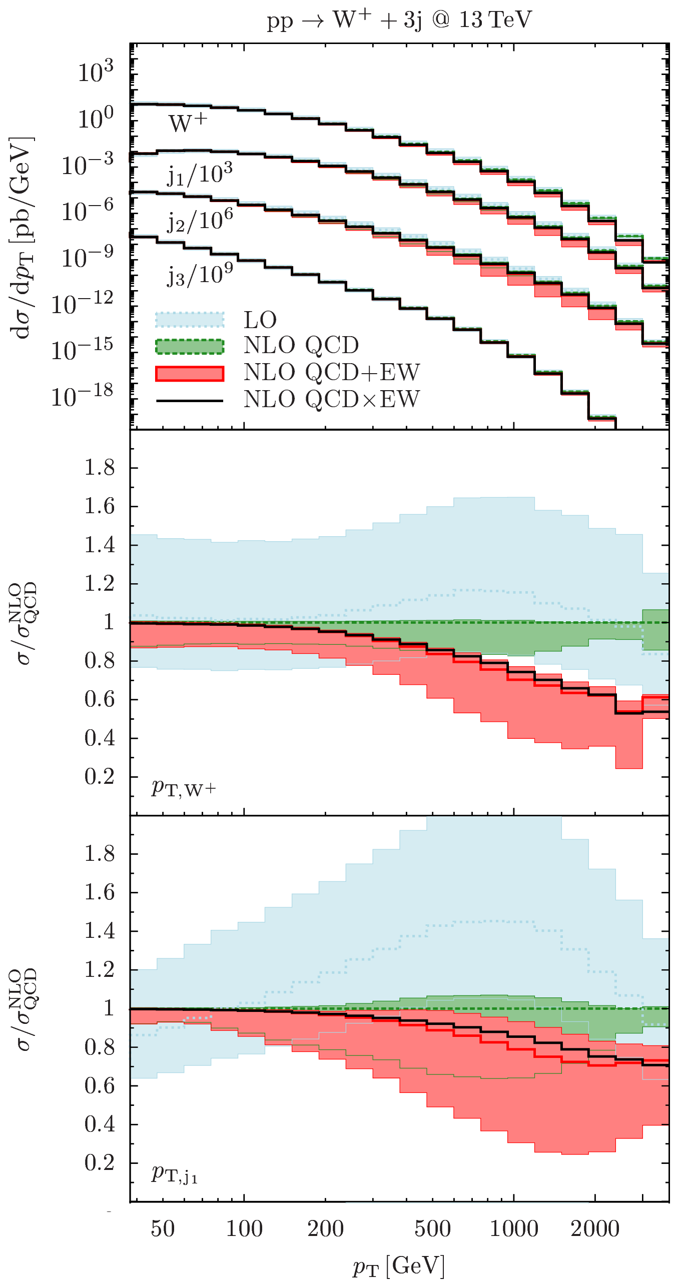


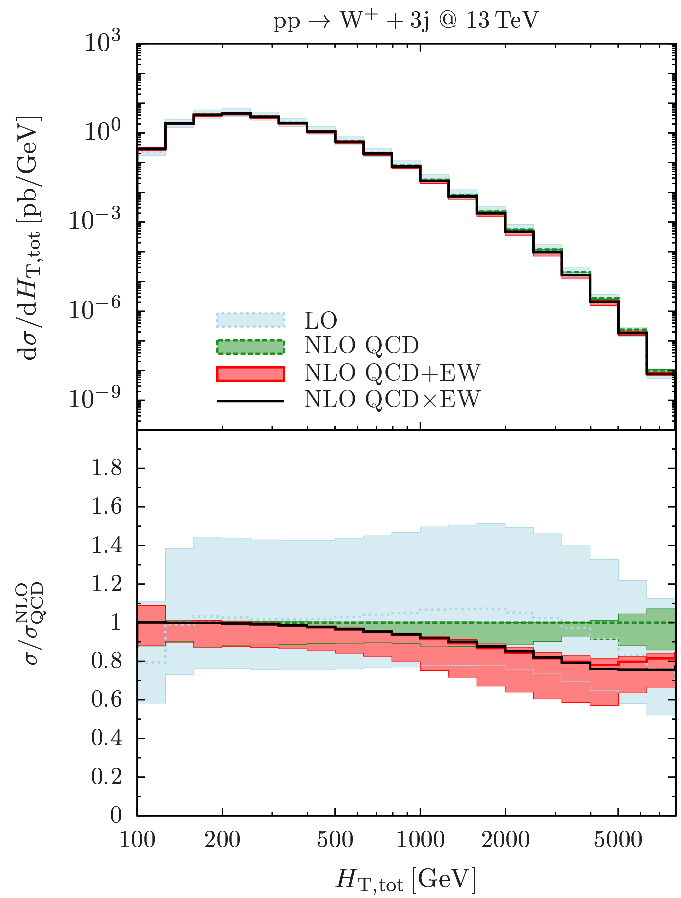


- normalization to σ^{NLO}_{QCD}
- $\mu_{ren} = \mu_{fact} = \hat{H}_T = \sum E_T$
- $H_T^{tot} = p_{T,W} + \sum p_{T,j_k}$

W/Z + higher jet multiplicities @ NLO – results

Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '14





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

W/Z + higher jet multiplicities @ NLO – results

Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '14

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 $\times$ 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:

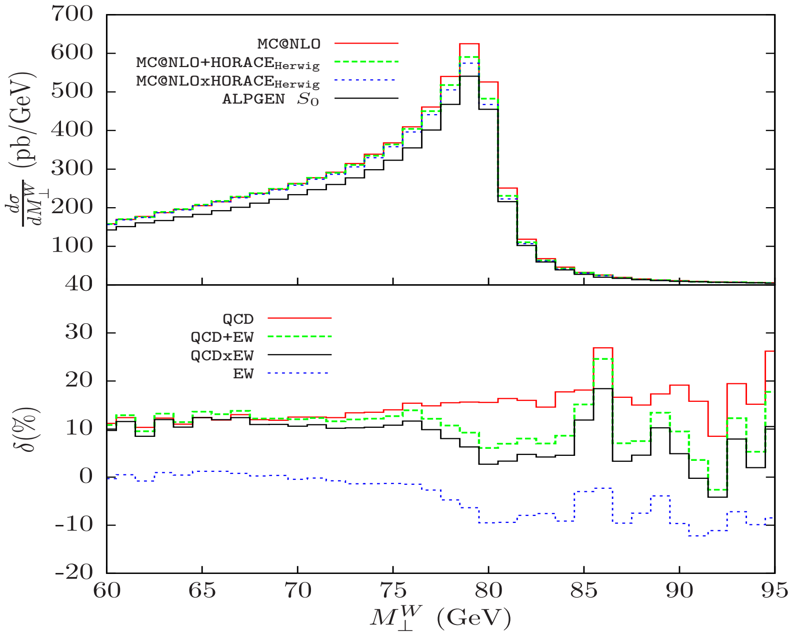
Comparison of two extreme alternatives:

$$(1 + \delta^{\text{NLO}}_{\text{QCD}} + \delta^{\text{NLO}}_{\text{EW}})$$

versus

$$(1 + \delta^{\text{NLO}}_{\text{QCD}}) \times (1 + \delta^{\text{NLO}}_{\text{EW}})$$

Balossini et al. '09 (HORACE)



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

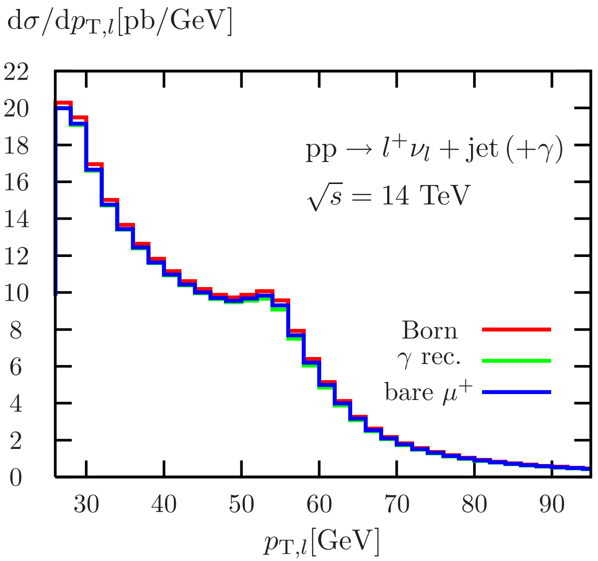
$\Rightarrow$ Calculation of $\mathcal{O}(\alpha\alpha_s)$ corrections in progress for resonance region

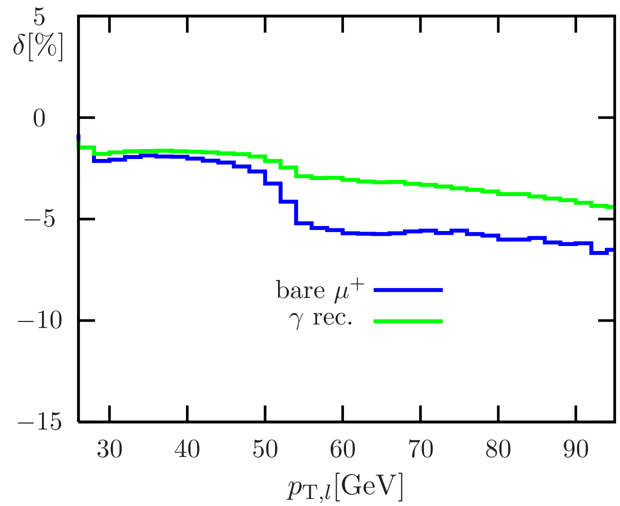
S.D., Huss, Schwinn '14,'15

Comparison of EW corrections to W+jet and single (jet-inclusive) W production

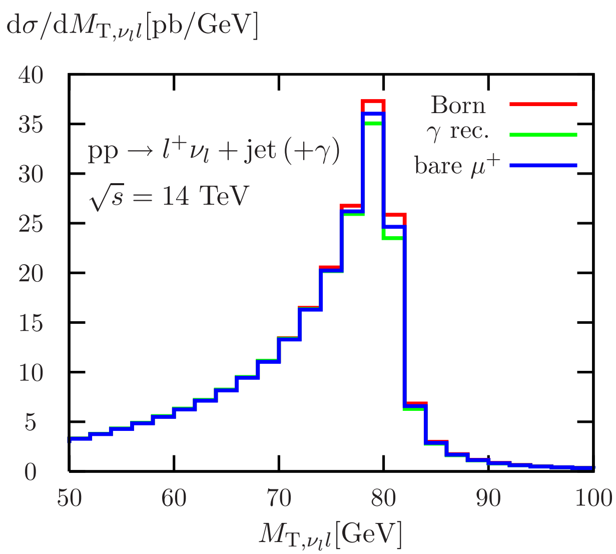
$\hookrightarrow$ argument for factorization QCD$\times$EW if EW corrections coincide

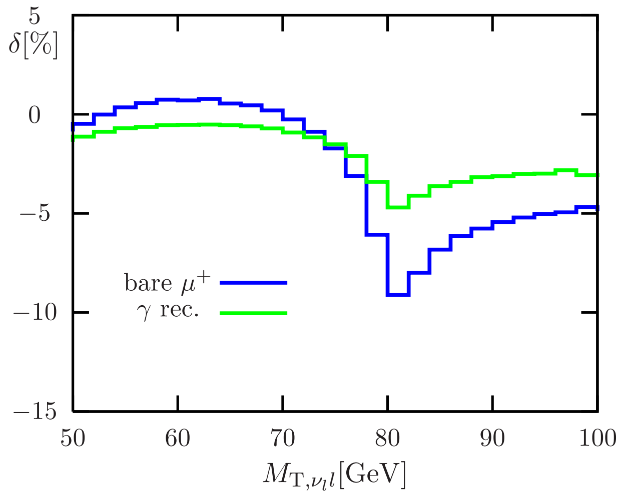
Denner et al. '09





Denner et al. '09





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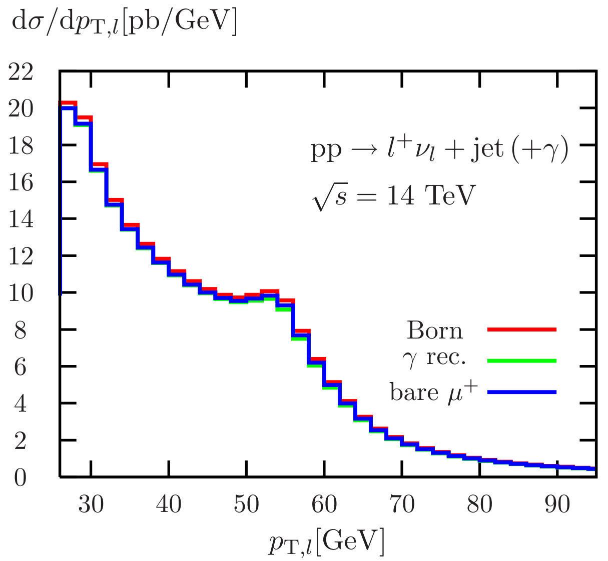
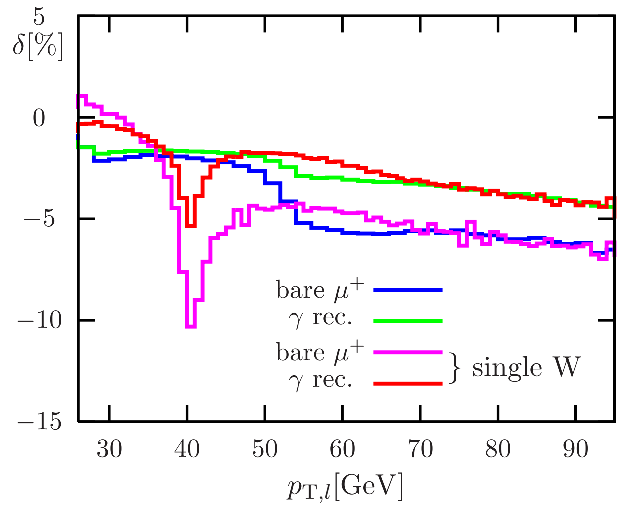
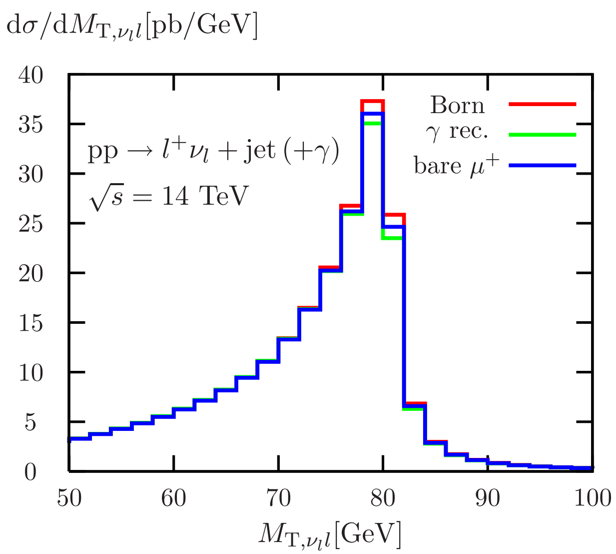


Denner et al. ’09

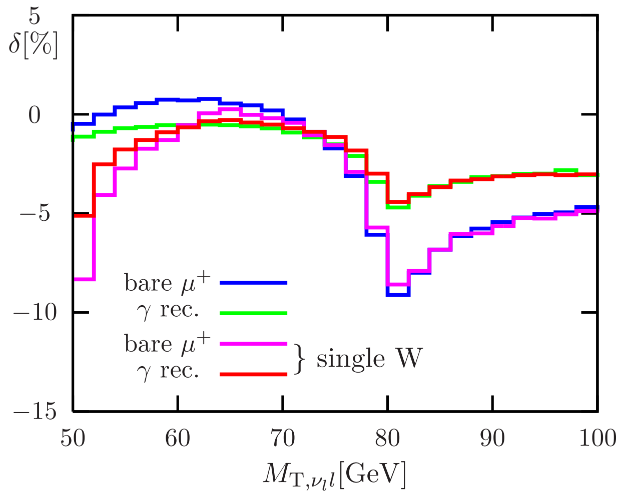


Jet recoil destroys simple factorization !

Single-W results from S.D./Krämer ’01; Brensing et al. ’07



Denner et al. ’09



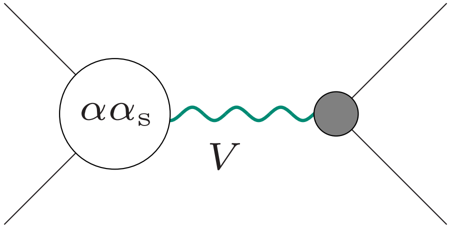
EW corrections factorize from hard gluon emission near Jacobian peak !

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

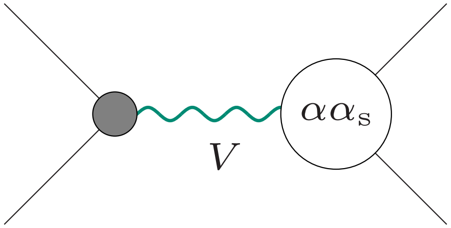
$\hookrightarrow$ take only leading (=resonant) contributions in expansion about resonance poles

Factorizable contributions:

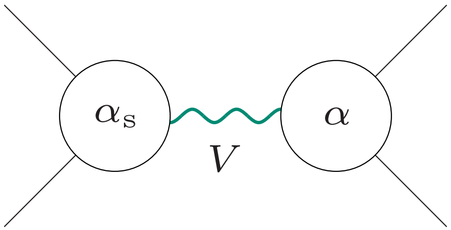
(only virtual contributions indicated)



- no significant resonance distortion expected
- no PDFs with $\mathcal{O}(\alpha\alpha_s)$ corrections



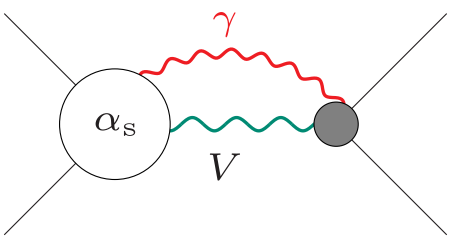
- only $Vl\bar{l}'$ counterterm contributions
  $\hookrightarrow$ uniform rescaling, no distortions



- significant resonance distortions from FSR
- calculated, preliminary results

Non-factorizable contributions:

(only virtual contributions indicated)

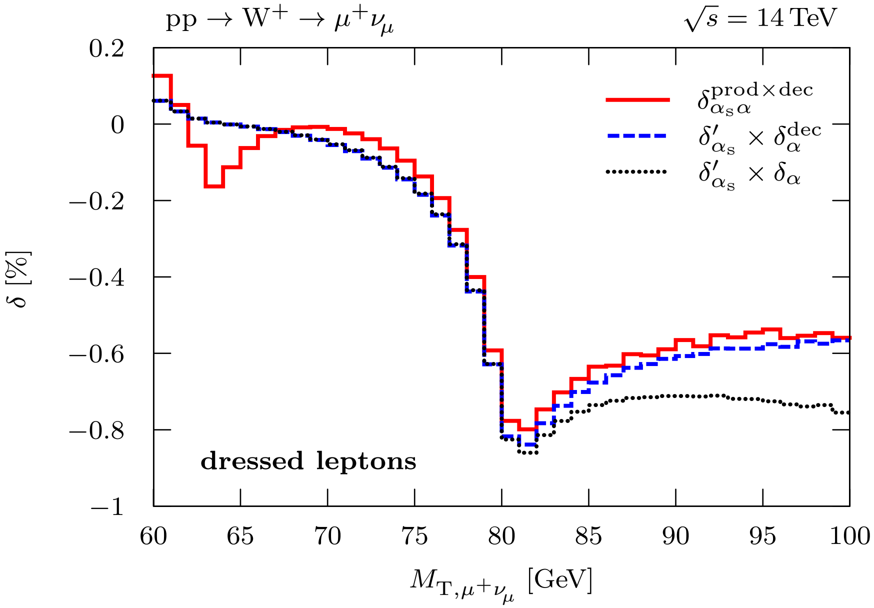


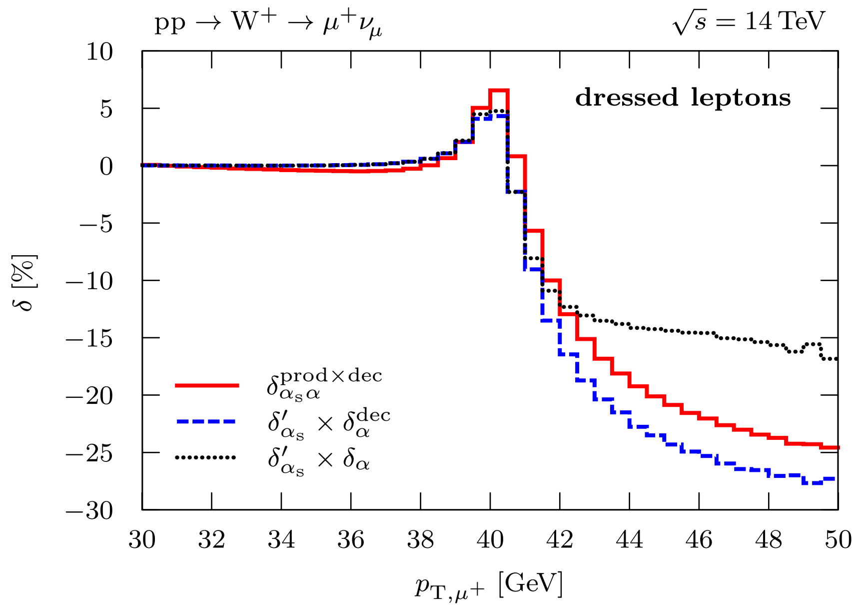
- could induce shape distortions
- calculated, turn out to be small

Numerical results on initial–final factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections

S.D., Huss, Schwinn '15 (preliminary)

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





Naive factorization $\delta'_{\alpha_s} \times \delta_\alpha$ works!

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

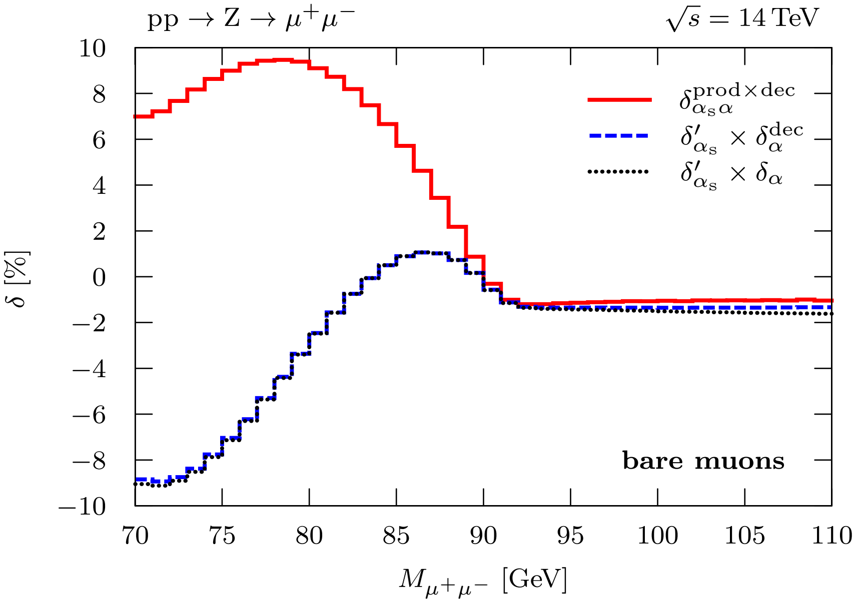
In progress:

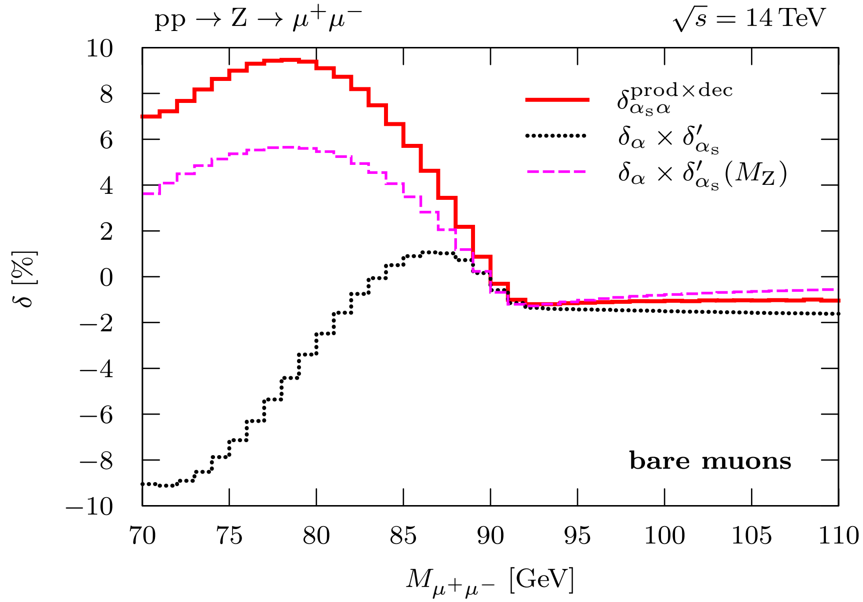
- comparison of $\mathcal{O}(\alpha_s\alpha)$ correction $\delta^{prod\times dec}_{\alpha_s\alpha}$ with MC approach $d\sigma_{\alpha_s} \otimes (\gamma$ shower)
- estimate shifts in M_W by $\delta^{prod\times dec}_{\alpha_s\alpha}$

Numerical results on initial–final factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections

S.D., Huss, Schwinn '15 (preliminary)

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





Naive factorization $\delta'_{\alpha_s} \times \delta_{\alpha}$ fails !

Naive factorization takes "wrong QCD K factor"

In progress:

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