



HEPKIT 2015

Shedding Light on our Understanding of Nature

KIT, Oct 5–8, 2015

Mixed QCD \times EW $\mathcal{O}(\alpha\alpha_s)$ corrections to Drell–Yan processes in the resonance region

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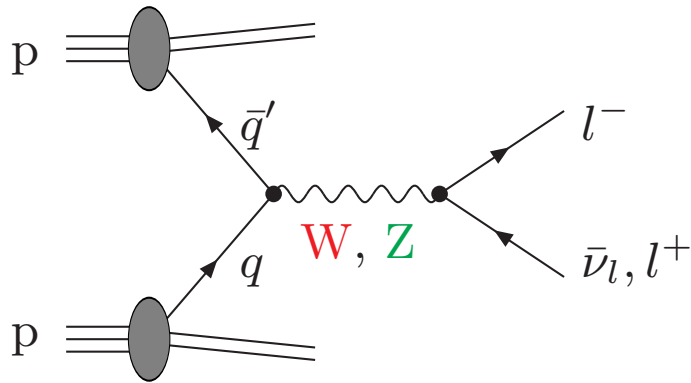
Introduction



corrections to Drell–Yan processes



W- and Z-boson production at hadron colliders



Physics issues:

- σ → standard candle
- M_Z → detector calibration by comparing with LEP1 result
- $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ → comparison with results of LEP1 and SLC
- M_W → improvement over $\Delta M_W \sim 15 \text{ MeV}$, strengthen EW precision tests
(W/Z shape comparisons even sensitive to $\Delta M_W \sim 7 \text{ MeV}$ at LHC)
Besson et al. '08
- 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

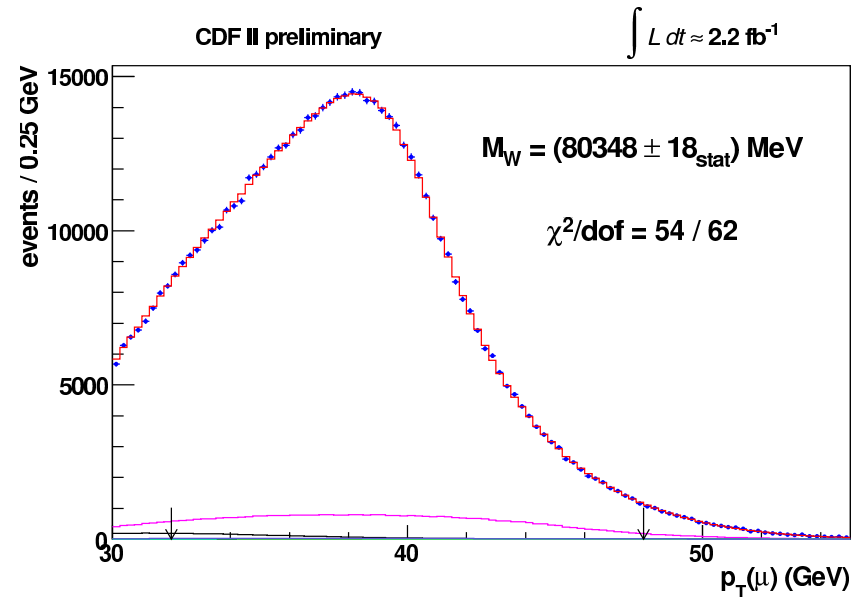
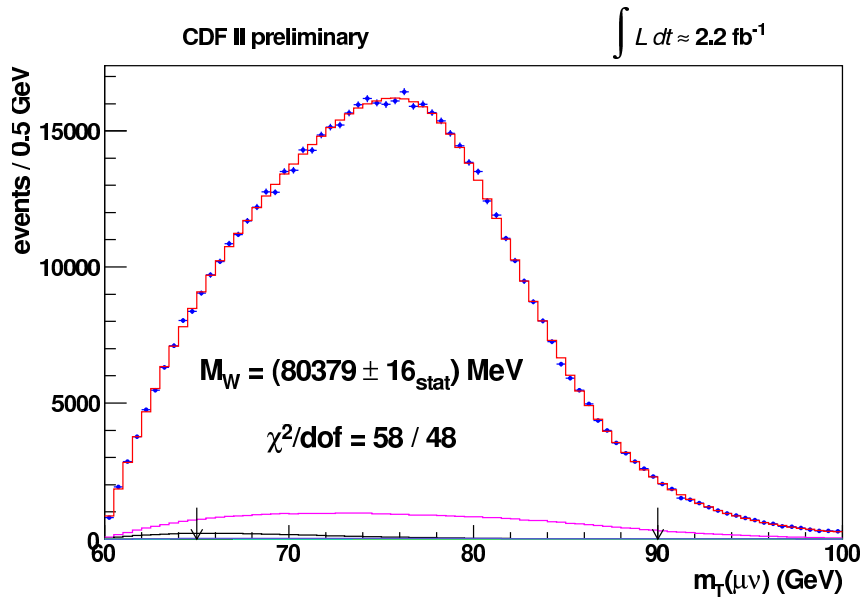
Tevatron example: M_W determination @ CDF (2012)

$M_W^{\text{CDF}} = 80.387 \text{ GeV} \pm 19 \text{ MeV}$ from fits to distributions in

a) transverse W-boson mass

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

$$M_{T,l\nu} = \sqrt{2(E_{T,l} \cancel{E}_T - \mathbf{p}_{T,l} \cdot \cancel{\mathbf{p}}_T)}$$



Sensitivity to M_W via Jacobian peaks from W resonance at

$$M_{T,l\nu} \sim M_W$$

$$p_{T,l} \sim M_W/2$$

⇒ Reduction of ΔM_W requires higher theoretical precision in W resonance region !

(for Z resonance as well for reference)

Combination of NLO QCD and EW corrections

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:

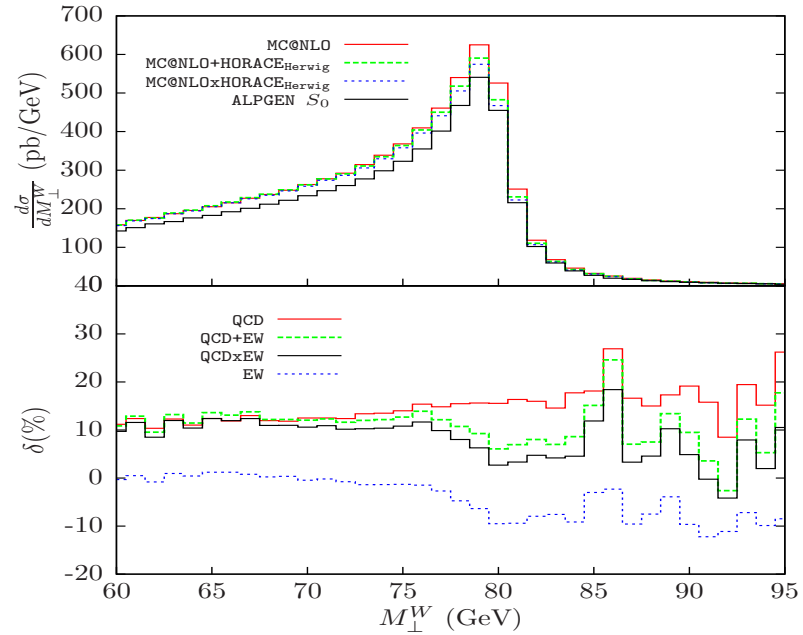
$$(1 + \delta_{\text{QCD}}^{\text{NLO}} + \delta_{\text{EW}}^{\text{NLO}})$$

versus

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

↪ difference at %-level
with shape distortion

Balossini et al. '09 (HORACE)



⇒ $\mathcal{O}(\alpha\alpha_s)$ corrections should be known at least in resonance region !

QCD and EW corrections to W/Z production:

NNLO QCD + NLO EW

- + QCD resummations / parton-shower matching
- + improvements known

Steps towards $\mathcal{O}(\alpha\alpha_s)$ corrections

- NLO EW for W/Z production with a hard jet

- ◊ W/Z/ γ + 1 jet, stable W/Z bosons

Maina, Moretti, Ross '04
Kühn, Kulesza, Pozzorini, Schulze '04–'07
Hollik, Kasprzik, Kniehl '07
Hollik, Kniehl, Shcherbakova, Veretin '15

- ◊ off-shell W/Z bosons with decays

Denner, S.D., Kasprzik, Mück '09–'12

$$W + 1 \text{ jet} \rightarrow l\nu_l + 1 \text{ jet}, \quad Z/\gamma^* + 1 \text{ jet} \rightarrow l^+l^-/\bar{\nu}_l\nu_l + 1 \text{ jet}$$

- further partial results

- ◊ on-shell $Zf\bar{f}$ vertex

Kotikov, Kühn, Veretin '07

- ◊ virtual corrections to $q\bar{q}' \rightarrow W/Z \rightarrow l\bar{l}'$

Bonciani '11; Kilgore, Sturm '11

- ◊ inclusive $\Gamma_{Z \rightarrow q\bar{q}}$ and $\Gamma_{W \rightarrow q\bar{q}'}$

Carnecki, Kühn '96; Kara '13

- resonance expansion for $q\bar{q}' \rightarrow W/Z \rightarrow l\bar{l}'$

S.D., Huss, Schwinn '13–'15



Pole expansion @ $\mathcal{O}(\alpha)$

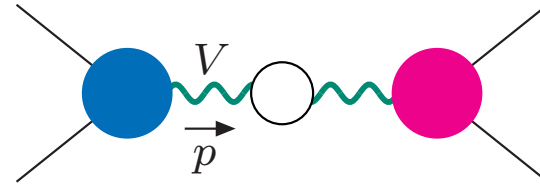


Pole expansion of loop amplitudes – general idea

Stuart '91; H.Veltman '92
Aeppli, v.Oldenborgh, Wyler '94

Starting point: Dyson-summed matrix element

$$\mathcal{M} = \underbrace{\frac{W(p^2)}{p^2 - M_V^2 + \Sigma(p^2)}}_{\text{resonant part with complex pole at } p^2 = \mu_V^2 = M_V^2 - iM_V\Gamma_V \text{ gauge invariant}} + N(p^2)$$



resonant part with complex pole at $p^2 = \mu_V^2 = M_V^2 - iM_V\Gamma_V$ gauge invariant

Sirlin '91; Stuart '91; Gambino, Grassi '99; Grassi, Kniehl, Sirlin '01

$$= \underbrace{\frac{W(\mu_V^2)}{p^2 - \mu_V^2} \frac{1}{1 + \Sigma'(\mu_V^2)}}_{\text{resonance pole = gauge invariant}} + \underbrace{\left[\frac{W(p^2)}{p^2 - M_V^2 + \Sigma(p^2)} - \frac{W(\mu_V^2)}{p^2 - \mu_V^2} \frac{1}{1 + \Sigma'(\mu_V^2)} \right]}_{\text{resonant "non-factorizable" corrections + non-resonant continuum}} + N(p^2)$$

resonance pole = gauge invariant

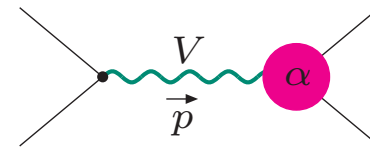
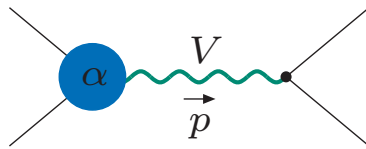
↪ “factorizable contributions”

resonant “non-factorizable” corrections

+ non-resonant continuum

Virtual factorizable corrections

$$\mathcal{M}_{\text{fact}}^{(1)} = \sum_{\lambda} \frac{\mathcal{M}_{\text{production}}^{(1)}(\lambda) \mathcal{M}_{\text{decay}}^{(0)}(\lambda) + \mathcal{M}_{\text{production}}^{(0)}(\lambda) \mathcal{M}_{\text{decay}}^{(1)}(\lambda)}{p^2 - \mu_V^2}$$



Comments:

respect V -spin correlations; $W(\mu_V^2) \rightarrow W(M_V^2)$ possible in $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s\alpha)$

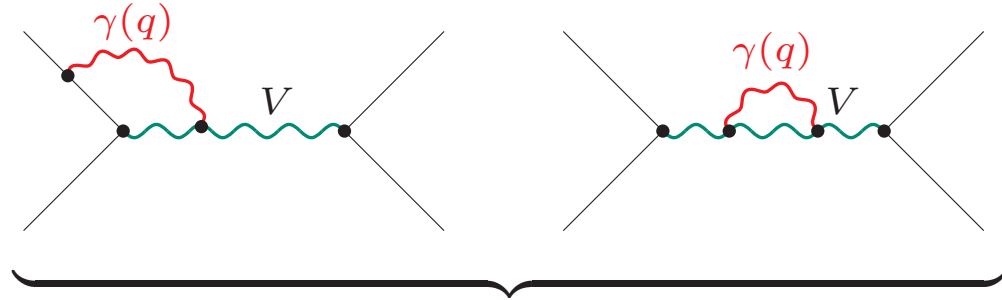
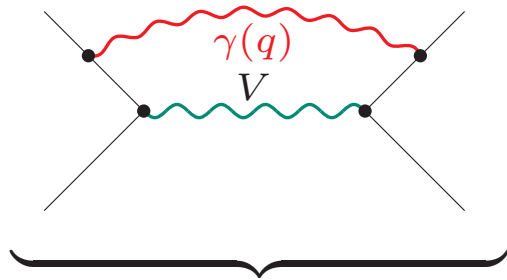
Virtual non-factorizable corrections

Fadin, Khoze, Martin '94; Melnikov, Yakovlev '96;
 Beenakker, Berends, Chapovsky '97;
 Denner, Dittmaier, Roth '97,'98

Origin:

on-shell limit ($p^2 \rightarrow M_V^2$) and IR regularization (e.g. $m_\gamma \rightarrow 0$) do not commute

for γ exchange between external and/or resonant lines:



“manifestly non-factorizable”

- resonant IR-divergent contribution

“not manifestly non-factorizable” diagrams

- fact. contribution: $W(M_V^2)$
- non-factorizable part:

$$W_{\text{non-fact}}(p^2) \equiv [W(p^2) - W(M_V^2)]_{p^2 \rightarrow M_V^2}$$

General features: Fadin, Khoze, Martin '94

- contributions only from **soft momenta** $|q^\mu| \sim \Gamma_V \ll M_V$
 \hookrightarrow calculation within “extended soft-photon approximation” (keep off-shell V propagators)
- result factorizes from Born amplitude: $\mathcal{M}_{\text{non-fact}}^{\text{virt}} = \delta_{\text{non-fact}}^{\text{virt}} \mathcal{M}^{(0)}$
- **virtual + real non-fact. corrections cancel in inclusive quantities** such as σ_{tot}

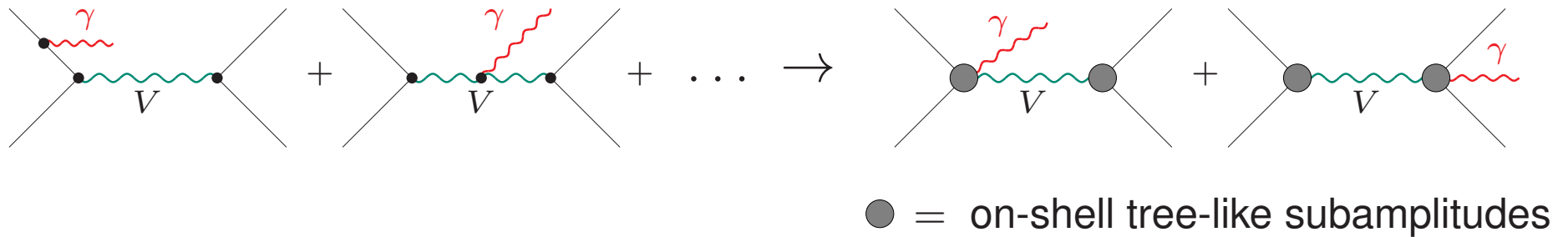
Pole expansion of real photonic corrections

Split diagrams with radiating resonances (2 resonant propagators) as follows:

$$\frac{1}{[(p+k)^2 - \mu_V^2](p^2 - \mu_V^2)} = \frac{1}{2pk} \left[\frac{1}{p^2 - \mu_V^2} - \frac{1}{(p+k)^2 - \mu_V^2} \right]$$

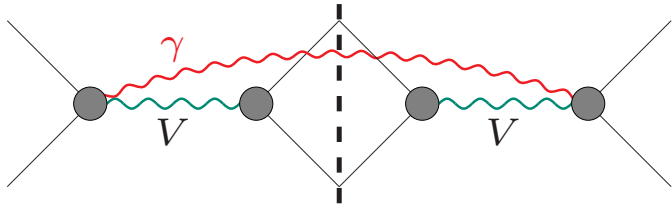


↪ decomposition of $\mathcal{M}_{i \rightarrow f + \gamma}$ into initial- and final-state radiation:

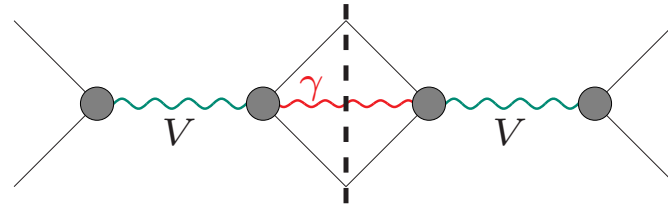


Classification of real photonic corrections in PA

Factorizable contributions to $|\mathcal{M}|^2$:

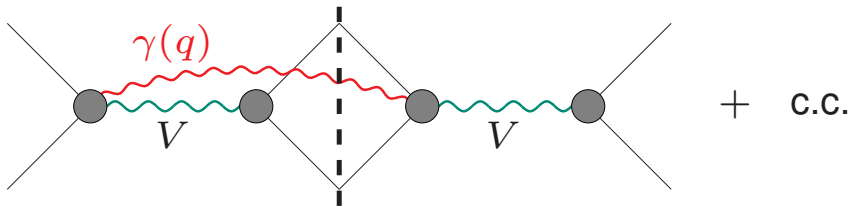


Initial-state radiation



Final-state radiation

Non-factorizable contributions to $|\mathcal{M}|^2$:



+ c.c.

Only $q = \mathcal{O}(\Gamma_V)$ relevant !

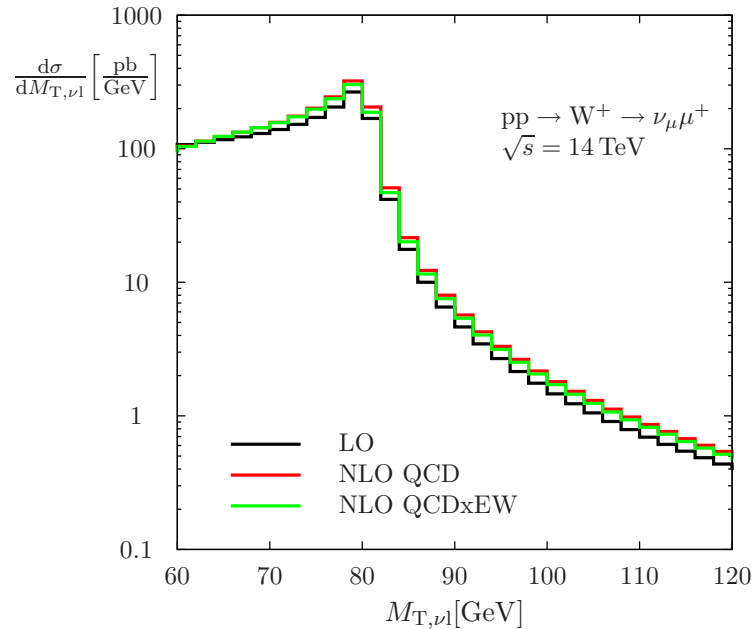
calculable from **modified eikonal currents**:

$$d\sigma_{\text{non-fact}} = d\sigma_0 \delta_{\text{non-fact}}^{\text{real}}, \quad \delta_{\text{non-fact}}^{\text{real}} = \frac{\alpha}{2\pi^2} \int \frac{d^3\mathbf{q}}{q^0} \text{Re}\{\mathcal{J}_{\text{prod}}^\mu \mathcal{J}_{\text{dec},\mu}^*\},$$

$$\mathcal{J}_{\text{prod}}^\mu = Q_1 \frac{p_1^\mu}{p_1 q} - Q_2 \frac{p_2^\mu}{p_2 q} - (Q_1 - Q_2) \frac{(p_1 + p_2)^\mu}{p_1 q + p_2 q},$$

$$\mathcal{J}_{\text{dec}}^\mu = \left[-Q'_1 \frac{k_1^\mu}{k_1 q} + Q'_2 \frac{k_2^\mu}{k_2 q} + (Q'_1 - Q'_2) \frac{(k_1 + k_2)^\mu}{k_1 q + k_2 q} \right] \frac{(k_1 + k_2)^2 - \mu_V^2}{(k_1 + k_2 + q)^2 - \mu_V^2}$$

Transverse-mass distribution for W production

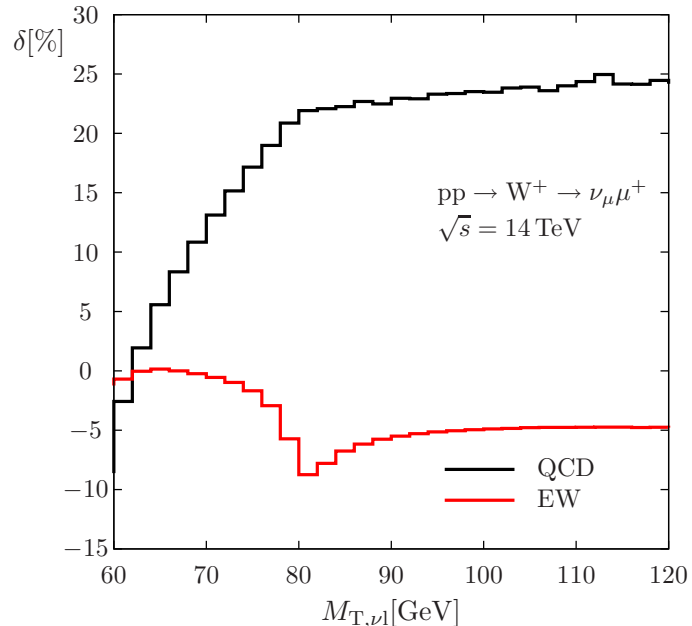


Features of $M_{T,\nu l}$:

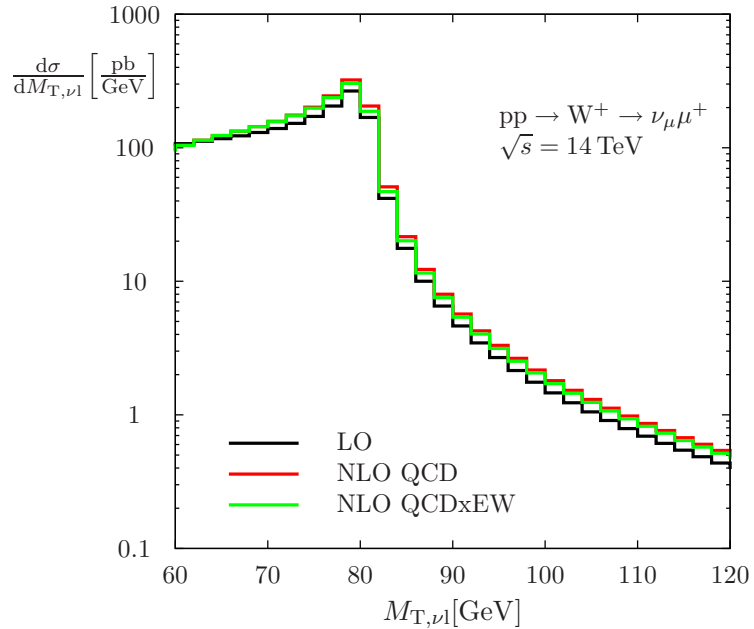
- most important observable for M_W det.
- stability wrt QCD corrs/uncertainties (insensitive to jet recoil)
- sensitive to detector effects via \cancel{E}_T

Corrections:

- QCD corrections quite flat near resonance
- **EW corrections** distort resonance shape



Transverse-mass distribution for W production

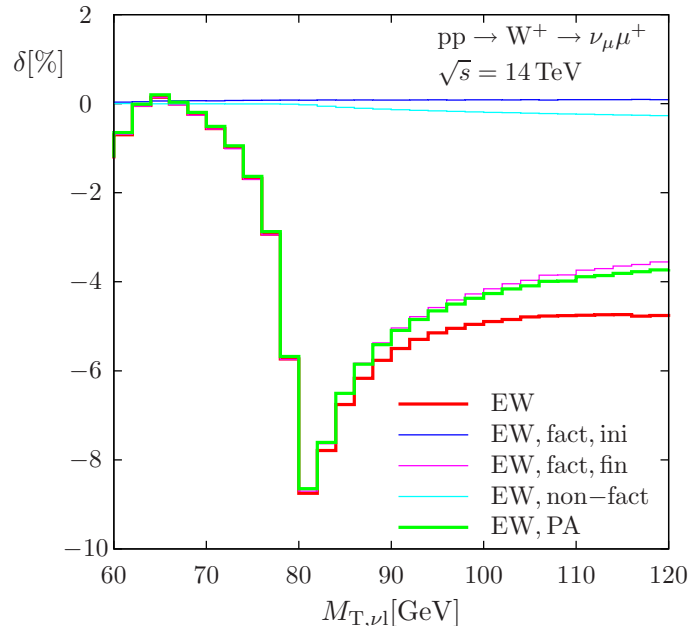


Features of $M_{T,\nu l}$:

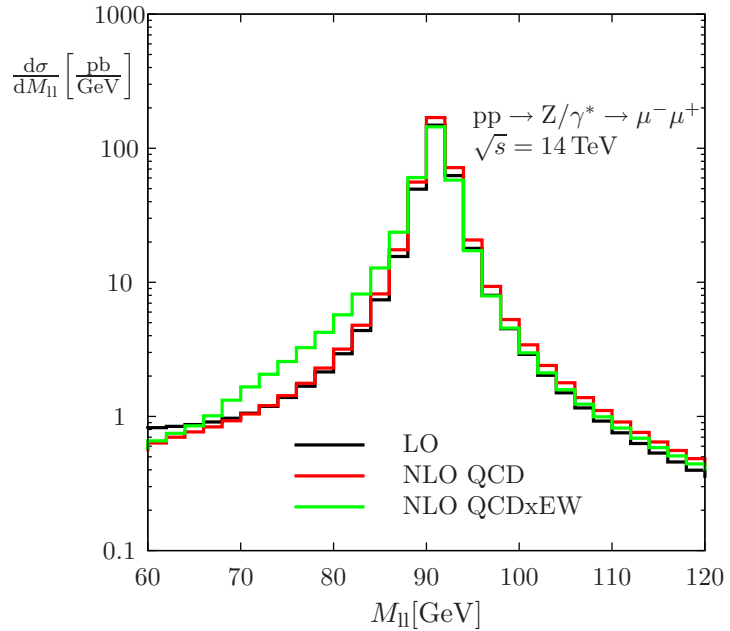
- most important observable for M_W det.
- stability wrt QCD corrs/uncertainties (insensitive to jet recoil)
- sensitive to detector effects via \cancel{E}_T

Pole approximation (PA):

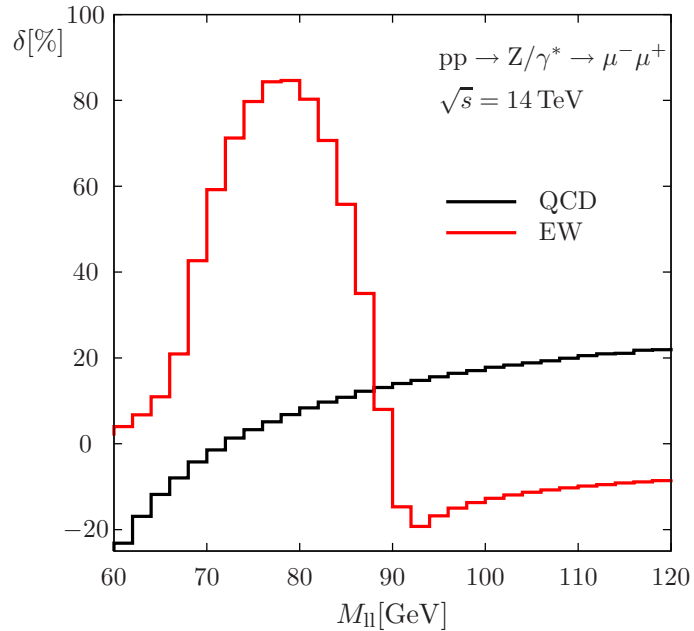
- PA reproduces EW corr near resonance
- resonance distortion merely due to factorizable FS correction
- factorizable IS and non-fact. corrections flat (and even negligible)



Invariant-mass distribution for Z production



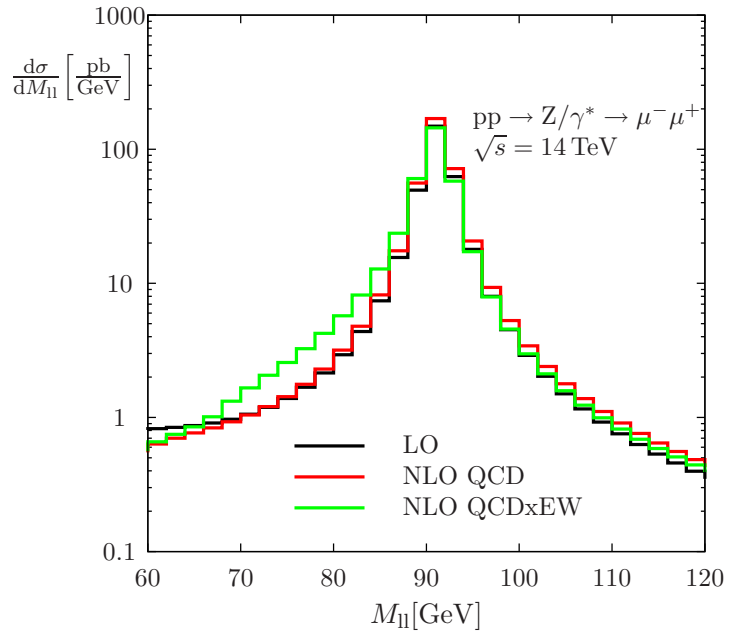
Reference process for M_W measurement



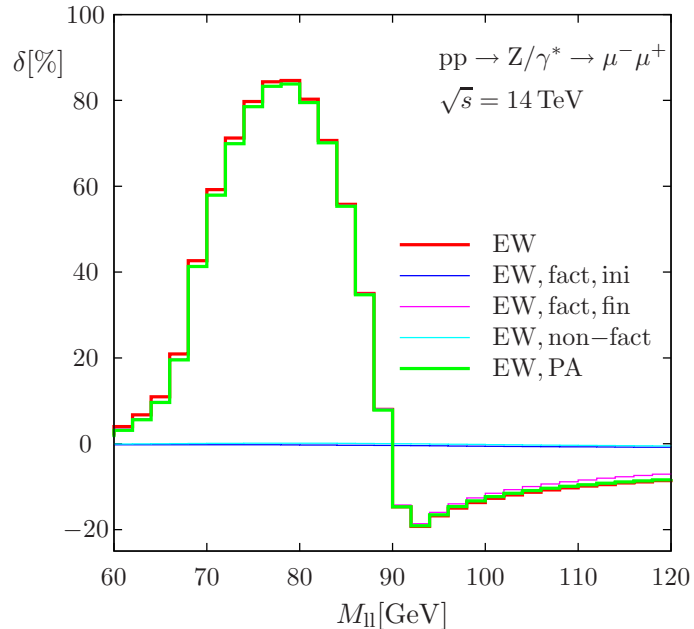
Corrections:

- QCD corrections quite flat near resonance
- **EW corrections** distort resonance shape

Invariant-mass distribution for Z production



Reference process for M_W measurement



Behaviour of PA analogous to $M_{T,\nu l}$:

- PA reproduces EW corr near resonance
- resonance distortion merely due to factorizable FS correction
- factorizable IS and non-fact. corrections flat (and even negligible)

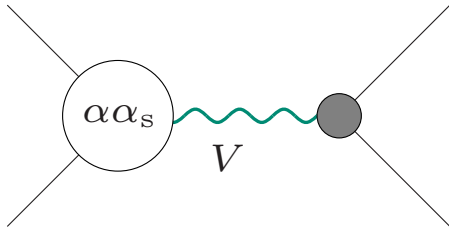
Pole expansion @ $\mathcal{O}(\alpha\alpha_s)$ and non-factorizable corrections



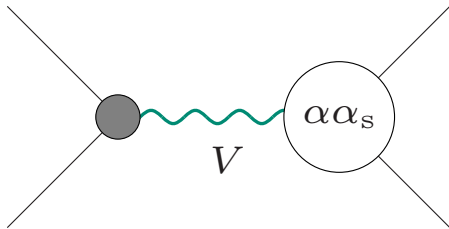
Classification of $\mathcal{O}(\alpha\alpha_s)$ corrections in PA

Factorizable contributions:

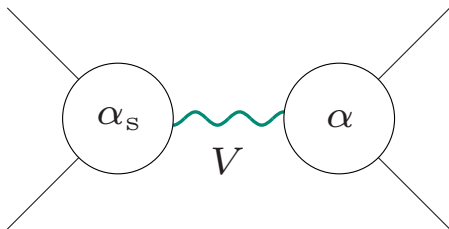
(only virtual contributions indicated)



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



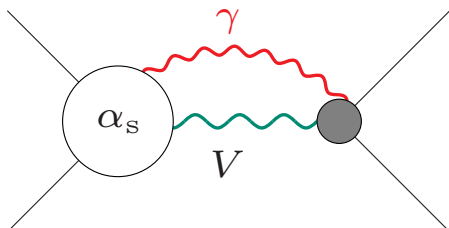
- only $Vl\bar{l}'$ counterterm contributions
 \hookrightarrow uniform rescaling, no distortions



- significant resonance distortions from FSR

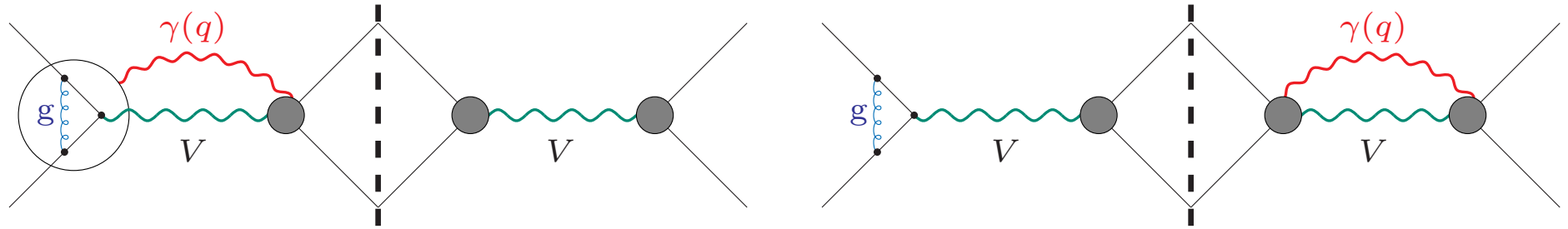
Non-factorizable contributions:

(only virtual contributions indicated)



- small @ $\mathcal{O}(\alpha)$, but could be enhanced by large $\mathcal{O}(\alpha_s)$ corrections (jet recoil)

Virtual–virtual contributions to non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections

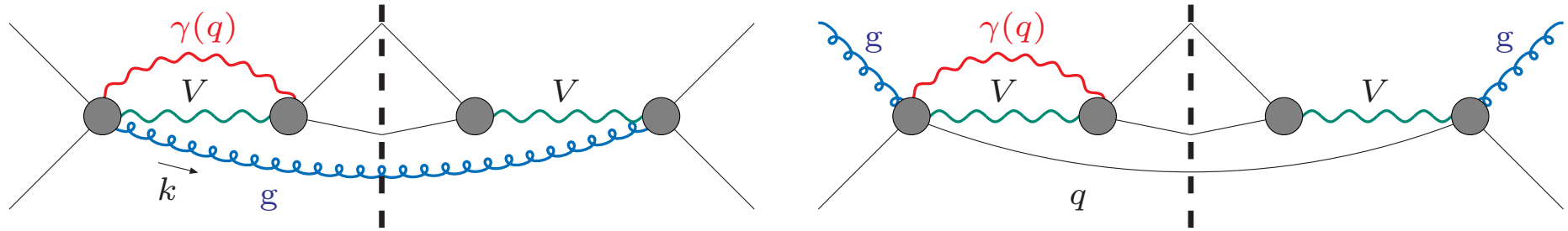


Result:

$$|\mathcal{M}|^2 \Big|_{\substack{\text{non-fact} \\ \text{virt-virt}}} = 4 \operatorname{Re}\{\delta_{q\bar{q}'V}^{(\alpha_s, \text{virt})}\} \operatorname{Re}\{\delta_{\text{non-fact}}^{(\alpha, \text{virt})}\} |\mathcal{M}_0|^2$$

- factorized structure (1-loop) \times (1-loop) after non-trivial cancellations
- expansion of all loops in $q^\mu \sim \Gamma_V \sim (p^2 - \mu_V^2)/M_V \rightarrow 0$
- issue of overlapping IR singularities
- different methods applied \rightarrow results agree
 - ◇ diagrammatic calculation (expansion via Mellin–Barnes technique)
 - ◇ gauge-invariance argument à la Yennie/Frauschi/Suura '61 (even holds to any order $\alpha\alpha_s^n$, $n = 1, 2, \dots$)
 - ◇ effective field theory for unstable particles Beneke et al. '03,'04

Virtual–real contributions to non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



Result:
$$|\mathcal{M}|^2 \Big|_{\substack{\text{non-fact} \\ \text{virt-real}}} = 2 \operatorname{Re} \left\{ \delta_{\text{non-fact}, q\bar{q}' \rightarrow l\bar{l}'g}^{(\alpha, \text{virt})} \right\} |\mathcal{M}_{0, q\bar{q} \rightarrow l\bar{l}'g}|^2, \quad \text{etc.}$$

- From explicit diagrammatic calculation analogous to NLO $\mathcal{O}(\alpha)$ calculation
- New feature in qg channels: γ exchange between final-state particles
Structure different from initial–final interferences \rightarrow enhancement ?

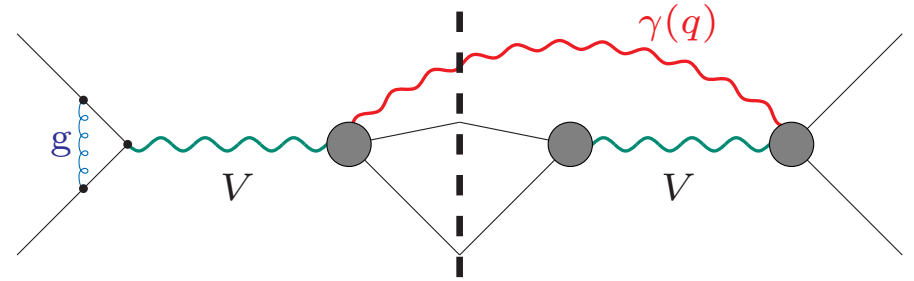
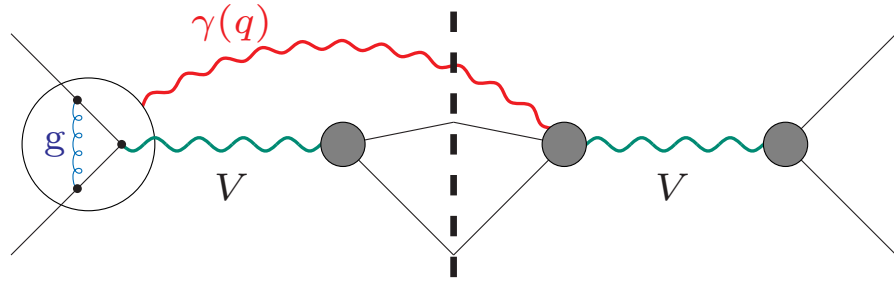
Example: W production $u\bar{d} \rightarrow W \rightarrow \nu_l l^+ g$

$$\delta_{\text{non-fact}, u\bar{d} \rightarrow \nu_l l^+ g}^{(\alpha, \text{virt})} = -\frac{\alpha}{2\pi} \left\{ -2 + Q_d \operatorname{Li} \left(1 + \frac{M_W^2 - \hat{t}_{ug}}{\hat{t}_{dl}} \right) - Q_u \operatorname{Li} \left(1 + \frac{M_W^2 - \hat{t}_{dg}}{\hat{t}_{ul}} \right) - \left[\frac{c_\epsilon}{\epsilon} - 2 \ln \left(\frac{\mu_W^2 - \hat{s}}{\mu M_W} \right) \right] \left[1 + Q_d \ln \left(\frac{M_W^2 - \hat{t}_{ug}}{-\hat{t}_{dl}} \right) - Q_u \ln \left(\frac{M_W^2 - \hat{t}_{dg}}{-\hat{t}_{ul}} \right) \right] \right\}$$

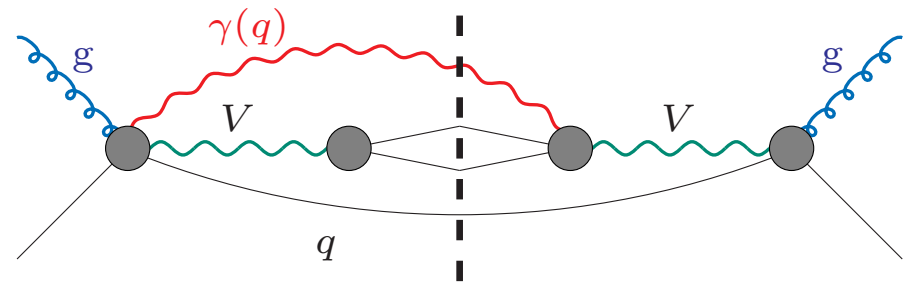
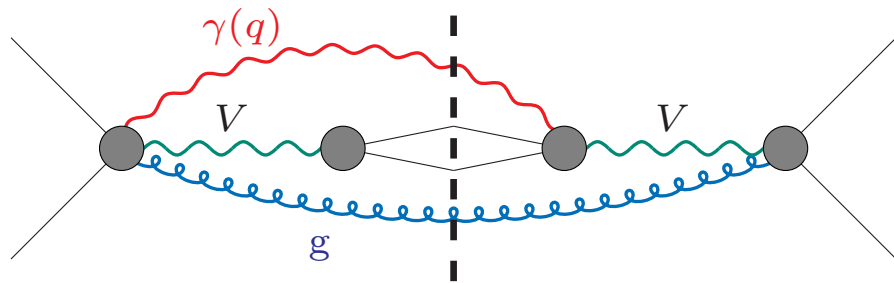
$(\hat{t}_{qj} = (p_q - k_j)^2, \text{ on-shell projection for W !})$

$$\xrightarrow{k \rightarrow 0} \delta_{\text{non-fact}, u\bar{d} \rightarrow \nu_l l^+}^{(\alpha, \text{virt})}$$

Real-virtual and real-real contributions to non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



Result:
$$|\mathcal{M}|^2 \Big|_{\substack{\text{non-fact} \\ \text{real-virt}}} = 2 \operatorname{Re}\{\delta_{q\bar{q}'V}^{(\alpha_s, \text{virt})}\} \delta_{\text{non-fact}}^{(\alpha, \text{real})} |\mathcal{M}_0|^2$$



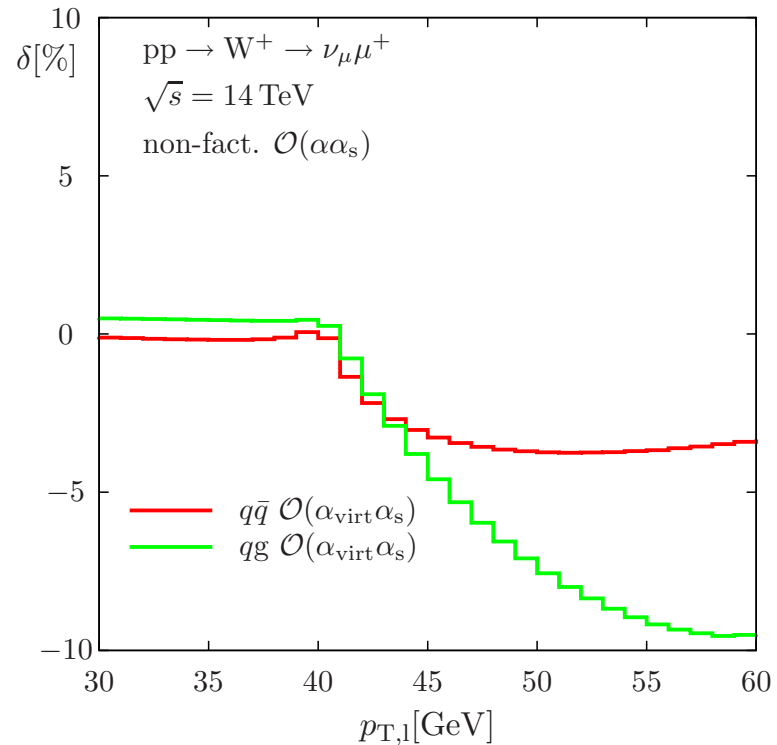
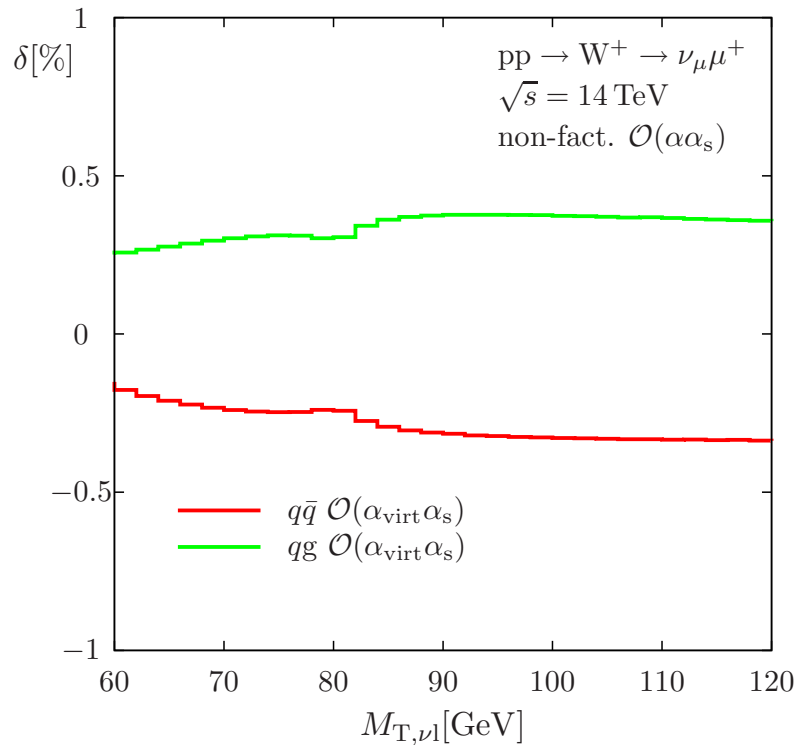
Result:
$$|\mathcal{M}|^2 \Big|_{\substack{\text{non-fact} \\ \text{real-real}}} = \delta_{\text{non-fact}}^{(\alpha, \text{real})} |\mathcal{M}_{0, q\bar{q} \rightarrow l\bar{l}'g}|^2, \quad \text{etc.}$$

$$\delta_{\text{non-fact}}^{(\alpha, \text{real})} = \frac{\alpha}{2\pi^2} \int \frac{d^3\mathbf{q}}{q^0} \operatorname{Re}\{\mathcal{J}_{\text{prod}}^\mu \mathcal{J}_{\text{dec}, \mu}^*\}$$

Note: factorization, e.g., justified by YFS argument as in virtual-virtual case

Virtual-photon + soft-photon non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections

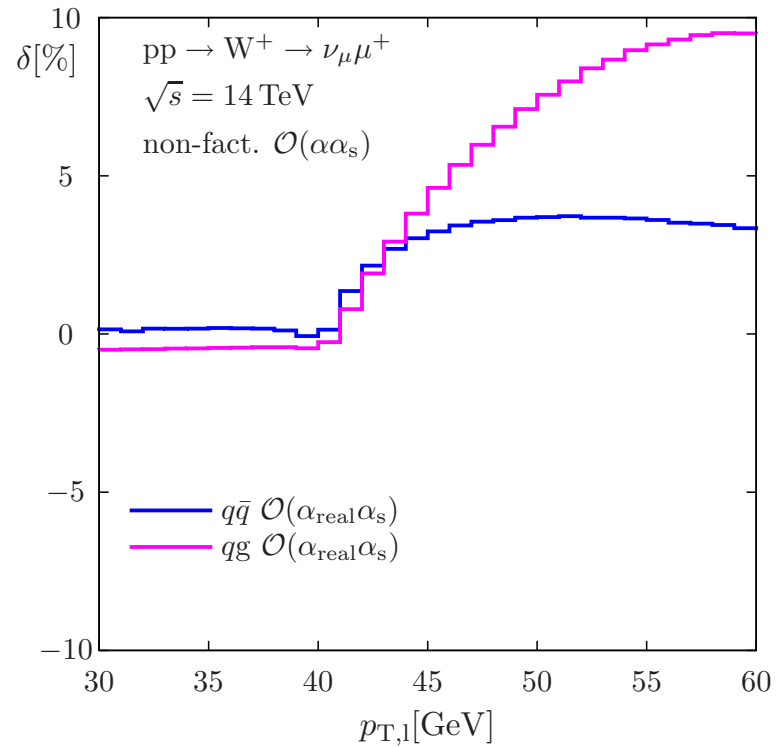
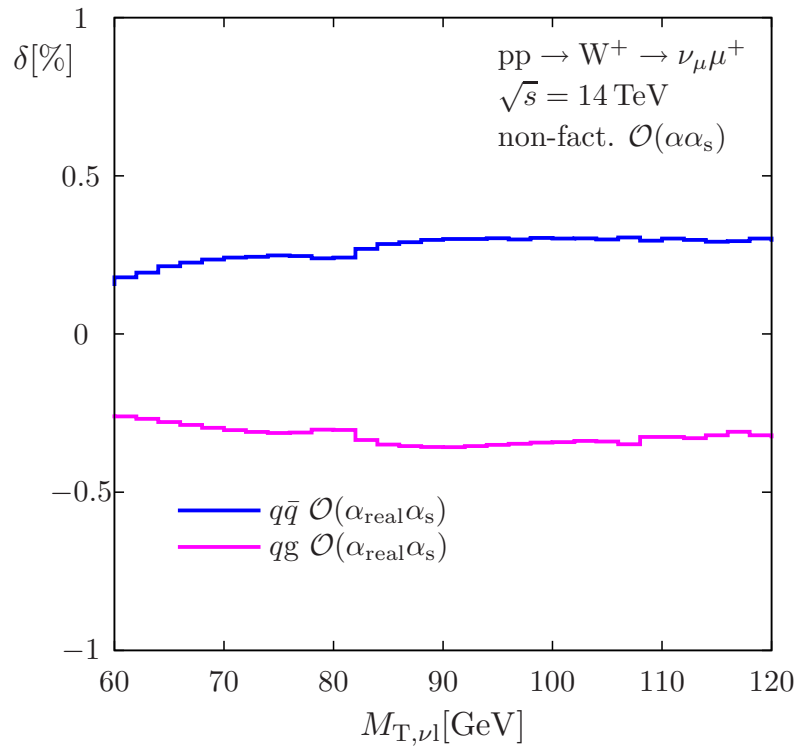
W production:



- $\delta = \delta_{\text{non-fact, virt}\gamma} + \delta_{\text{non-fact, soft}\gamma}(E_\gamma < \Delta E)$, $\Delta E = 10^{-4} \sqrt{\hat{s}}/2 \ll \Gamma_V$
- $M_{T,\nu l}$: corrections and distortion very small
- $p_{T,l}$: corrections several % with distortion
 \hookrightarrow cancellation against real photonic corrections ??

Real-photon and full non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections

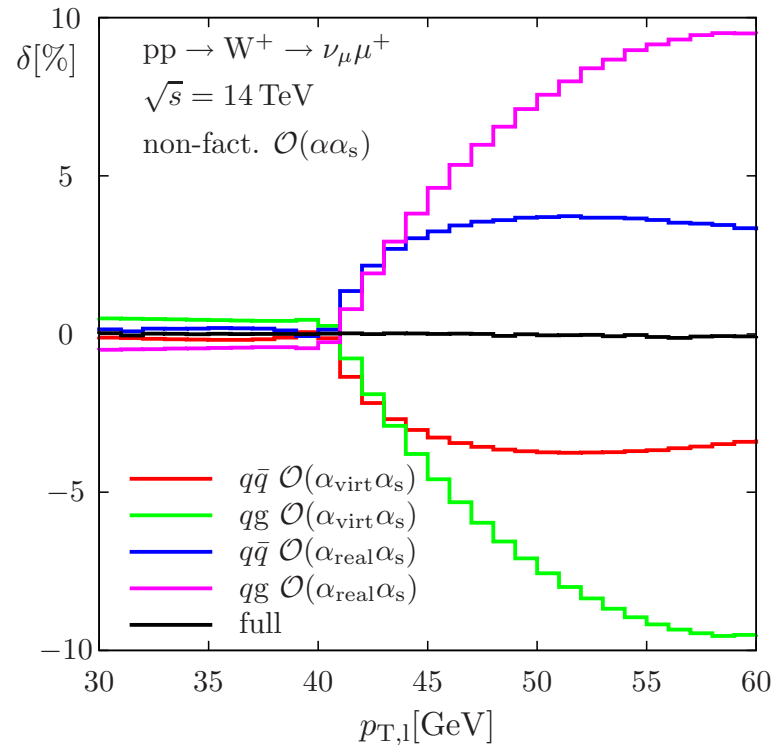
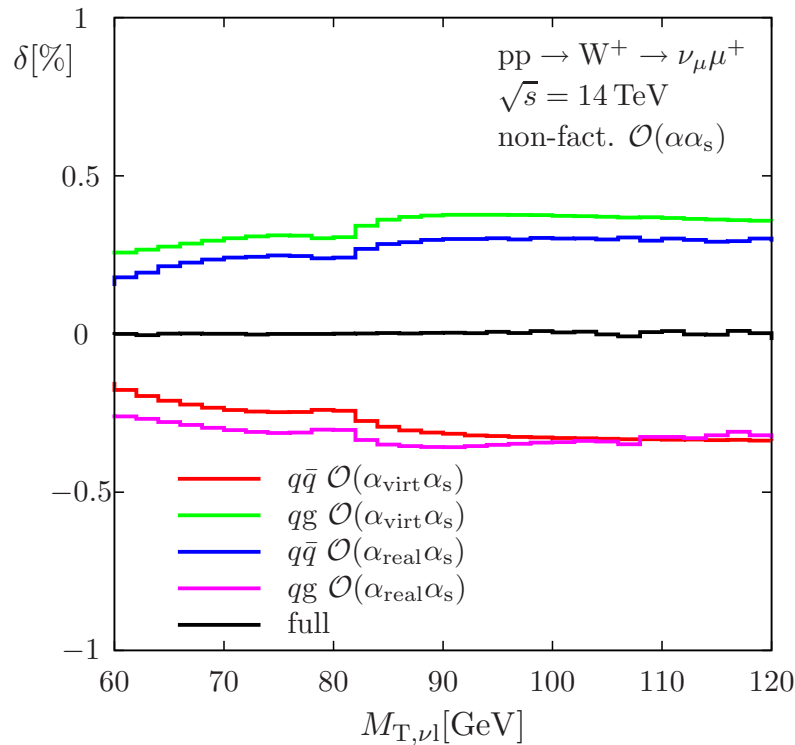
W production:



- $\delta = \delta_{\text{non-fact,real}\gamma}(E_\gamma > \Delta E), \quad \Delta E = 10^{-4} \sqrt{\hat{s}}/2 \ll \Gamma_V$

Real-photon and full non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections

W production:



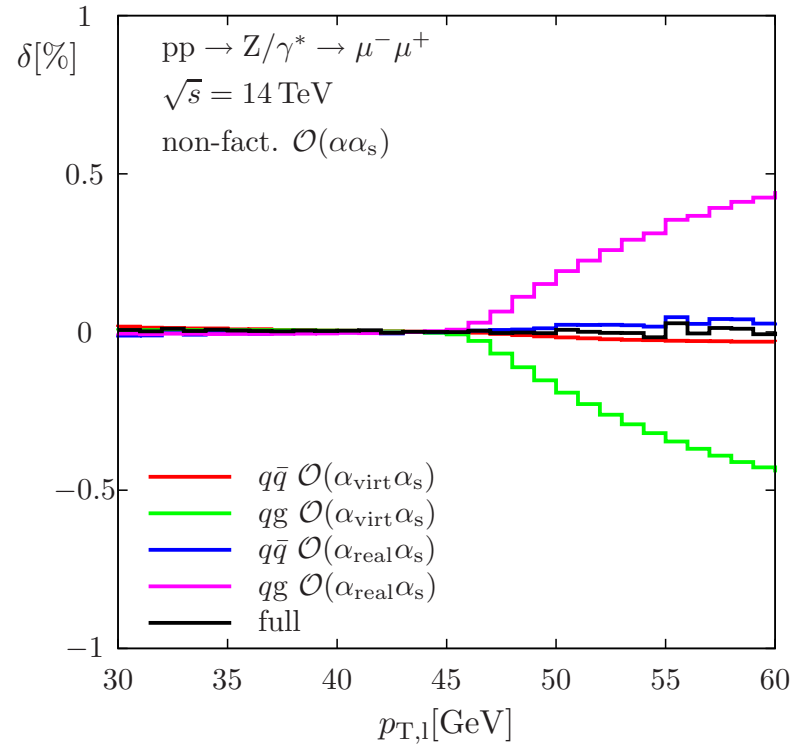
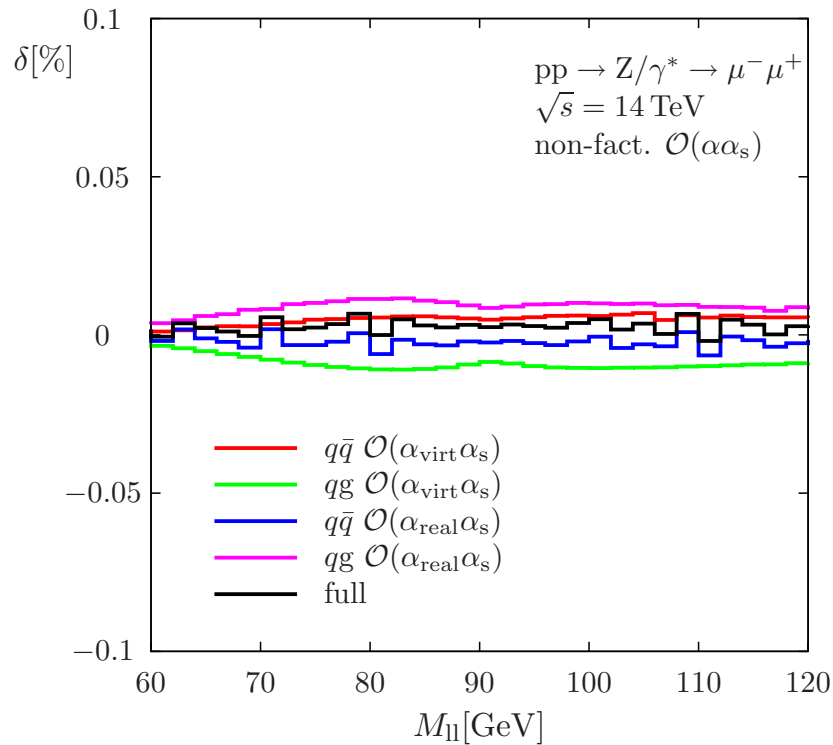
- $\delta = \delta_{\text{non-fact,real}\gamma}(E_\gamma > \Delta E), \quad \Delta E = 10^{-4} \sqrt{\hat{s}}/2 \ll \Gamma_V$

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

due to complete cancellation between virtual and real corrections

Real-photon and full non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections

Z production:



- $\delta = \delta_{\text{non-fact,real}\gamma}(E_\gamma > \Delta E), \quad \Delta E = 10^{-4} \sqrt{\hat{s}}/2 \ll \Gamma_V$

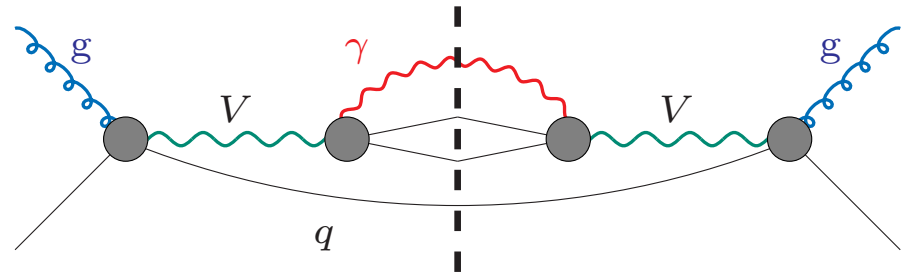
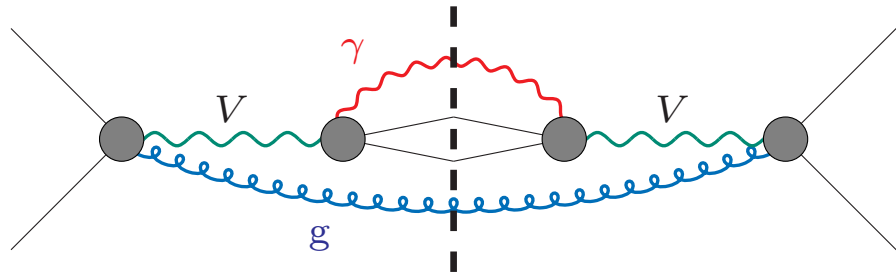
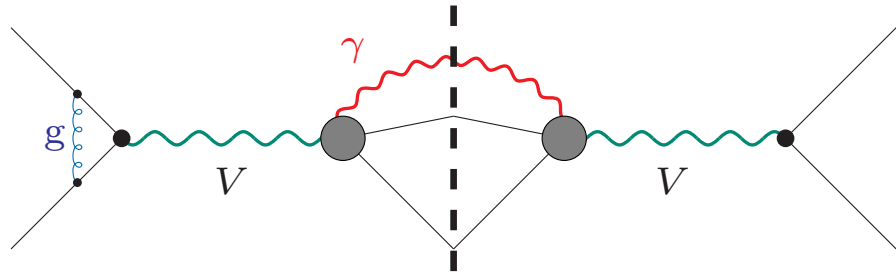
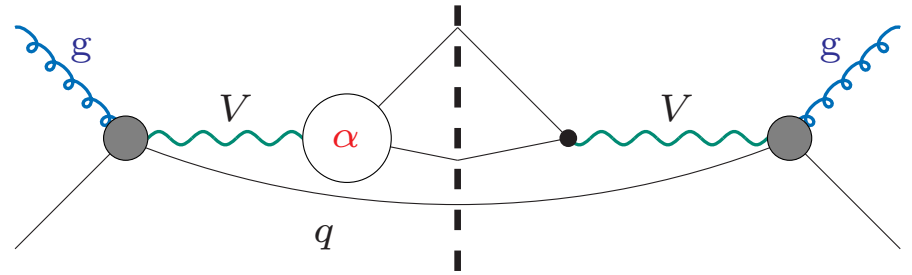
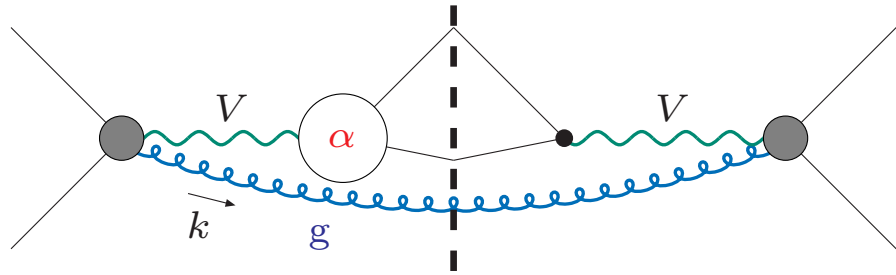
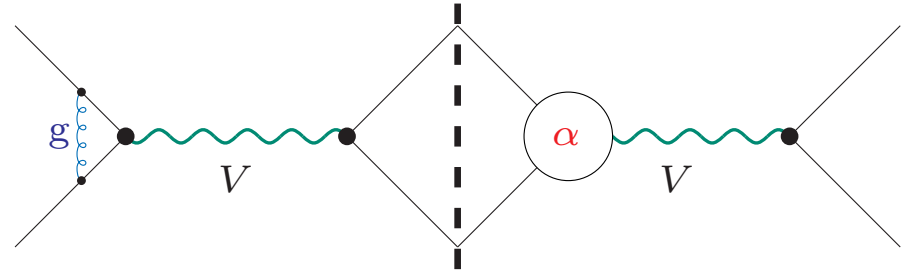
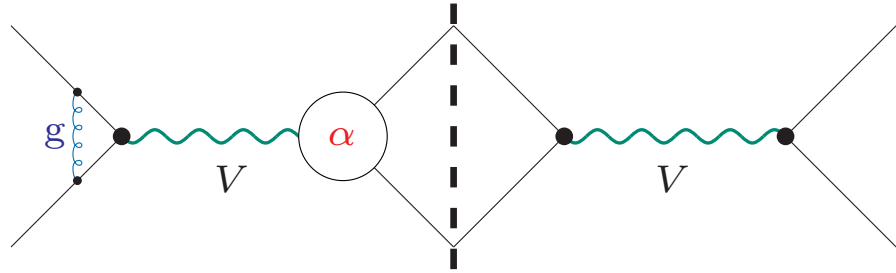
- Full non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections tiny

due to complete cancellation between virtual and real corrections

Dominant factorizable corrections



Contributions to initial-final factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



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

NLO QCD and EW corrections:

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

$$\Delta\sigma^{\text{NLO}_{\text{ew}}} = \sigma^0 \delta_{\alpha}, \quad \sigma^0 = \text{LO contribution with NLO PDFs}$$

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

$$\sigma^{\text{NNLO}_{s\otimes\text{ew}}} = \sigma^{\text{NLO}_s} + \Delta\sigma^{\text{NLO}_{\text{ew}}} + \underbrace{\Delta\sigma_{\text{ini-fin}}^{\text{NNLO}_{s\otimes\text{ew}}}}_{=\sigma^{\text{LO}} \delta_{\alpha_s}^{\text{ini-fin}} \alpha}$$

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

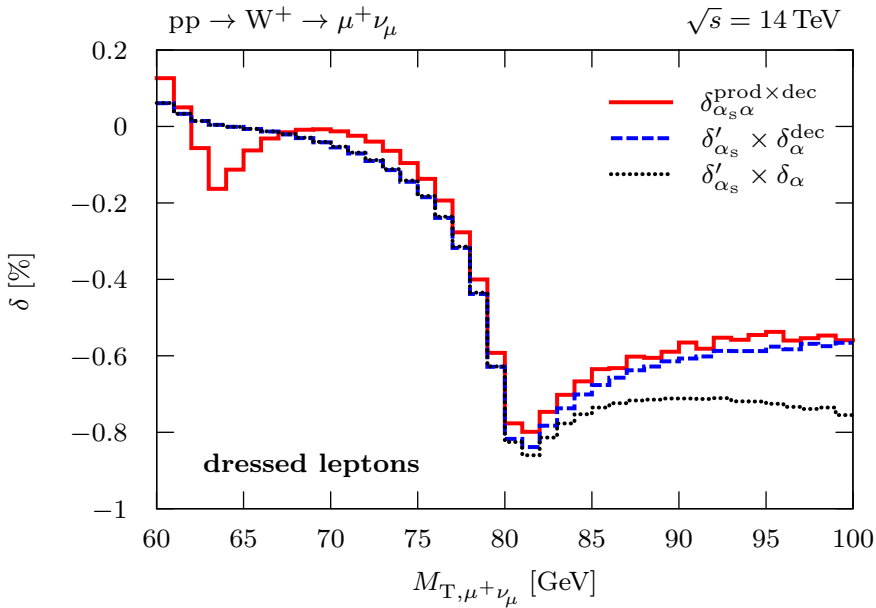
$$\sigma_{\text{naive fact}}^{\text{NNLO}_{s\otimes\text{ew}}} = \sigma^{\text{NLO}_s} (1 + \delta_{\alpha}) = \sigma^{\text{LO}} (1 + \delta_{\alpha_s}) (1 + \delta_{\alpha})$$

⇒ Comparison of relative corrections:

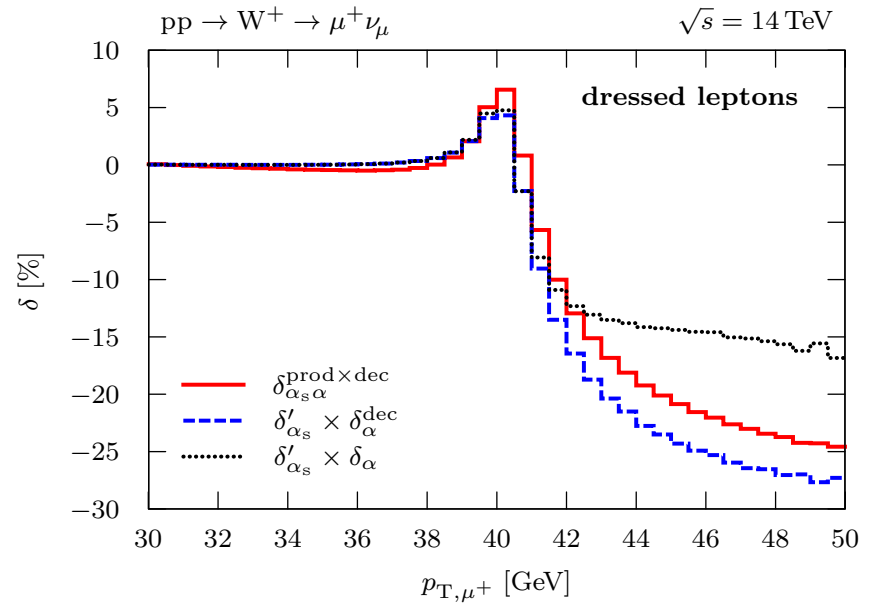
$$\frac{\sigma^{\text{NNLO}_{s\otimes\text{ew}}} - \sigma_{\text{naive fact}}^{\text{NNLO}_{s\otimes\text{ew}}}}{\sigma^{\text{LO}}} = \delta_{\alpha_s}^{\text{ini-fin}} - \delta'_{\alpha_s} \delta_{\alpha}$$

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

W production: (γ recombination applied, “dressed leptons”)



Naive factorization works!



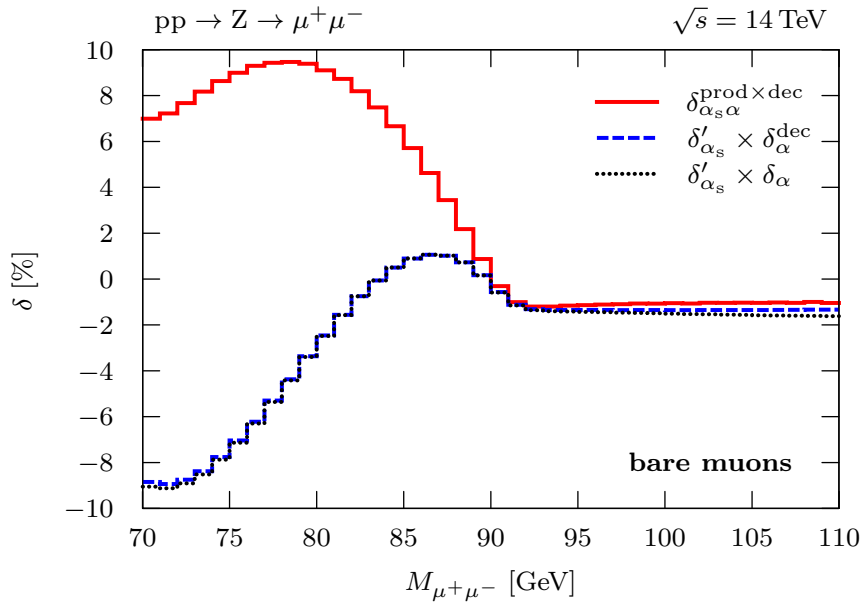
Naive factorization deteriorates
for $p_{T,\mu^+} \gtrsim M_W/2$

In progress:

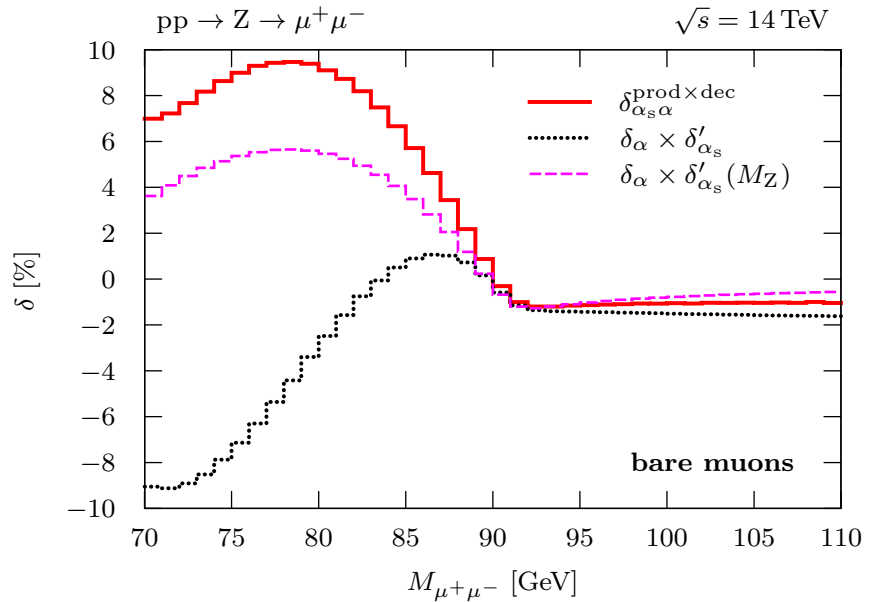
- comparison of $\delta_{\alpha_s\alpha}^{\text{ini-fin}}$ with MC approach $d\sigma_{\alpha_s} \otimes (\gamma \text{ shower})$
- estimate shifts in M_W by $\delta_{\alpha_s\alpha}^{\text{ini-fin}}$

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

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



Naive factorization fails !



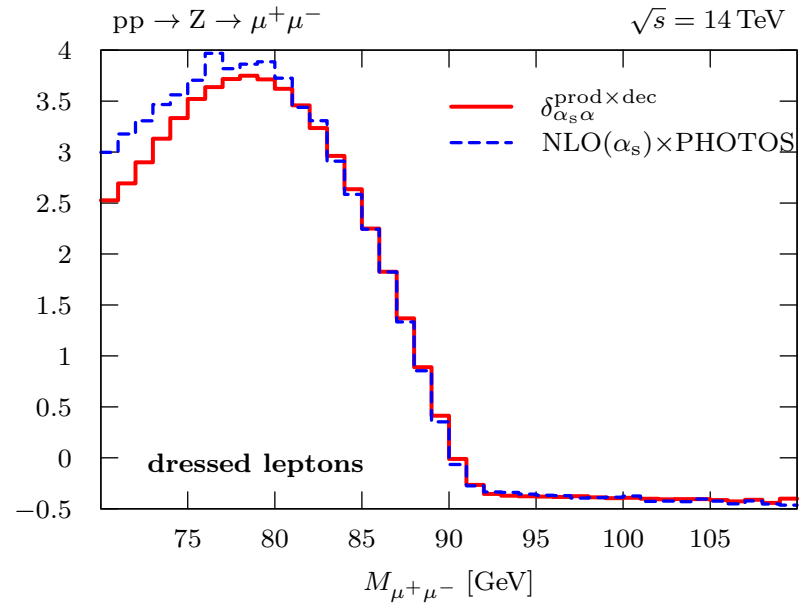
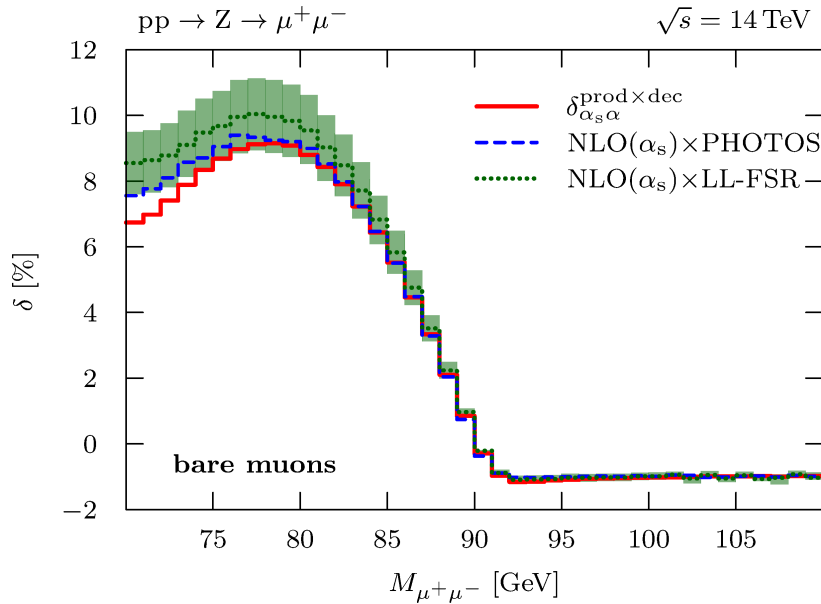
Naive factorization takes “wrong QCD K factor”

In progress:

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

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

Z production: Leading-log QED \otimes NLO QCD (preliminary)



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

- QED structure-function:

$$\sigma_{\alpha\alpha_s, LL FSR} = \int_0^1 dz_1 \underbrace{\Gamma_{II}^{LL}(z_1, Q^2)}_{\text{leading-log structure function, } Q = \text{typ. scale} \in (M_Z/2, 2M_Z)} \int_0^1 dz_2 \Gamma_{II}^{LL}(z_2, Q^2) \int d\sigma_{\text{NLO QCD}}(z_1 k_{\ell+}, z_2 k_{\ell-})$$

$$\mathcal{O}(\alpha) \text{ approximation: } \Gamma_{II}^{LL,1}(z, Q^2) = \frac{\alpha(0)}{2\pi} \left[\ln\left(\frac{Q^2}{m_1^2}\right) - 1 \right] \left(\frac{1+z^2}{1-z} \right)_+$$

- QED parton-shower PHOTOS

Barberio, van Eijk, Was



Summary & outlook



High-precision Drell–Yan physics @ LHC

- promises M_W with accuracy $\Delta M_W \lesssim 10 \text{ MeV}$ and $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ with $\mathcal{O}(\text{LEP precision})$
- requires highest possible theoretical precision near resonances
NNLO QCD + NLO EW + QCD resummations etc. known
 $\mathcal{O}(\alpha\alpha_s)$ is biggest unknown correction

$\mathcal{O}(\alpha\alpha_s)$ in pole approximation

- non-factorizable corrections calculated \rightarrow negligible
 \hookrightarrow only factorizable corrections to $2 \rightarrow 1$ and/or $1 \rightarrow 2$ processes relevant
- $\mathcal{O}(\alpha\alpha_s)$ corrections to $q\bar{q}' \rightarrow V$ production
 \hookrightarrow no significant resonance distortion expected
- $\mathcal{O}(\alpha\alpha_s)$ corrections to $V' \rightarrow l\bar{l}'$ decay
 \hookrightarrow only irrelevant rescaling of distributions (only from counterterms)
- $\left[\mathcal{O}(\alpha_s) \text{ to } q\bar{q}' \rightarrow V \right] \otimes \left[\mathcal{O}(\alpha) \text{ to } V' \rightarrow l\bar{l}' \right]$
 \hookrightarrow significant resonance distortions expected, but straightforward to calculate
... paper in preparation

Thanks,



for cooking up this nice workshop !

Backup slides



QCD and EW corrections to W/Z production:

- NNLO QCD corrections
- soft + virtual N³LO QCD
- QCD resummations
- MC@NLO matching
- NNLO PS matching
- NLO EW correction to W production
- NLO EW correction to Z production
- multi-photon radiation via leading logs
- photon-induced processes
- POWHEG matching of QCD/EW corrs.
- NLO SUSY corrections in the MSSM

Hamberg et al. '91; Harlander, Kilgore '02;
Anastasiou et al. '03; Melnikov, Petriello '06; Catani et al. '09;
Moch, Vogt '05; Laenen, Magnea '05; Idilbi et al. '05;
Ravindran, Smith '07

Arnold, Kauffman '91; Balazs et al. '95,'97;
R.K.Ellis et al. '97; Qiu, Zhang '00; Kulesza et al. '01,'02;
Landry et al. '02; Berge et al. '05; Bozzi et al. '08

Frixione, Webber '06

Hoeche et al. '14; Karlberg et al. '14

S.D., Krämer '01; Zykunov '01;
Baur, Wackerroth '04; Arbuzov et al. '05;
Carloni Calame et al. '06; Breusing et al. '07
Baur, Keller, Sakumoto '97; Baur, Wackerroth '99;
Brein, Hollik, Schappacher '99; Zykunov '05;
Arbuzov et al. '06; Carloni Calame et al. '07; S.D., Huber '09

Baur, Stelzer '99; Carloni Calame et al. '03;
Placzek, Jadach '04; Breusing et al. '07; S.D., Huber '09

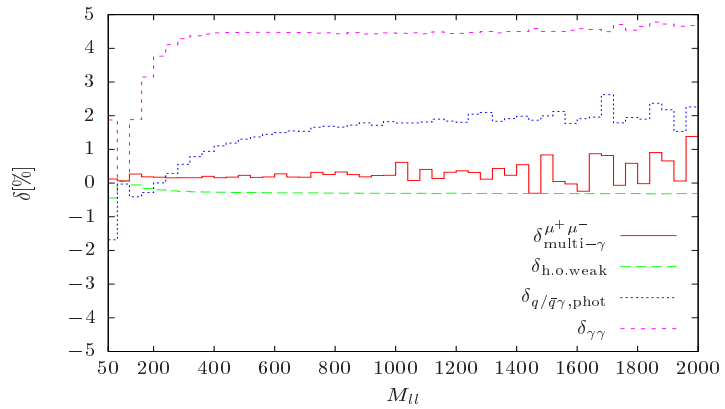
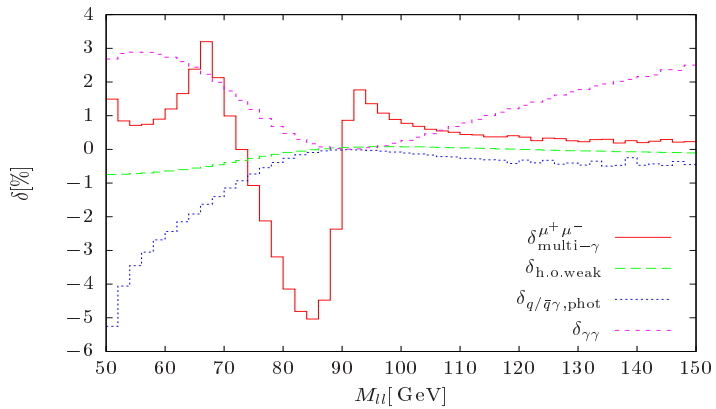
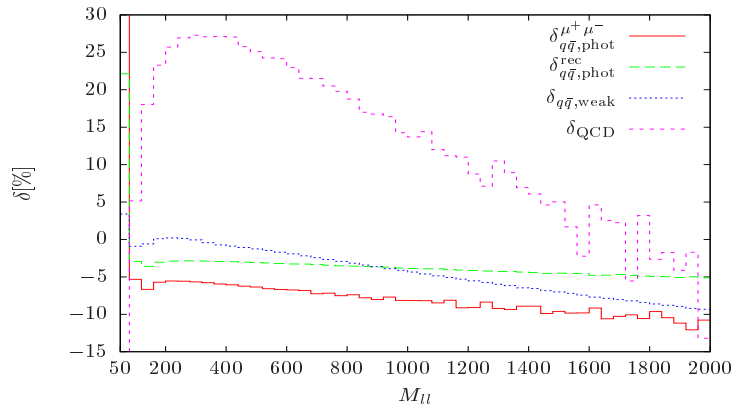
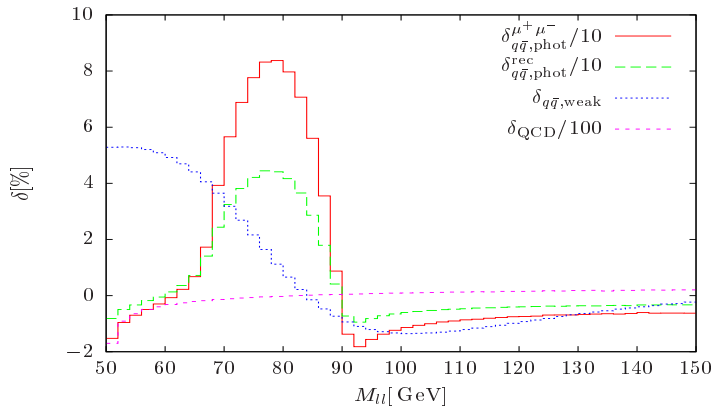
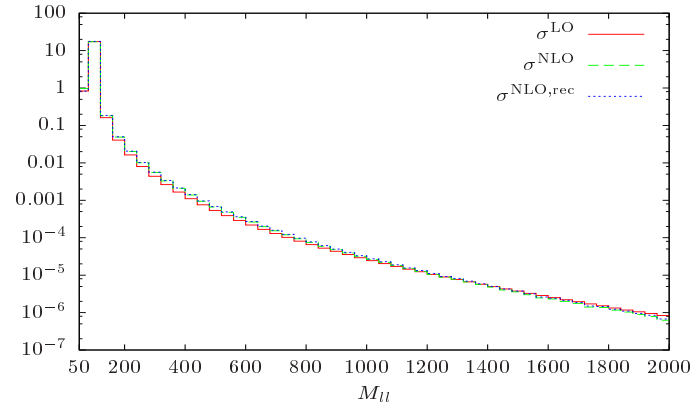
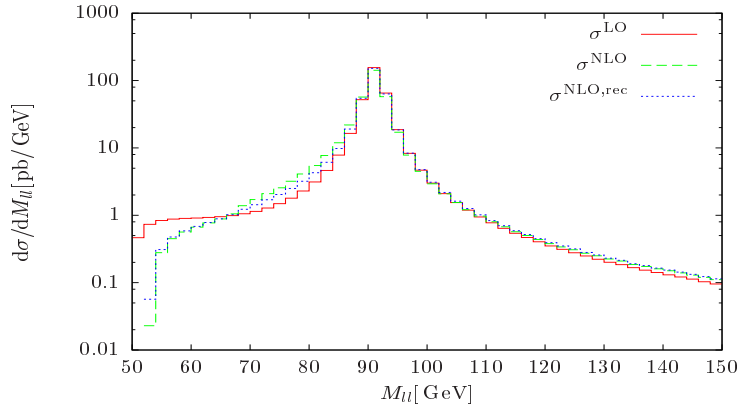
Arbuzov, Sadykov '07; Breusing et al. '07;
Carloni Calame et al. '07; S.D., Huber '09

Bernaciak, Wackerroth '12; Barze et al. '13

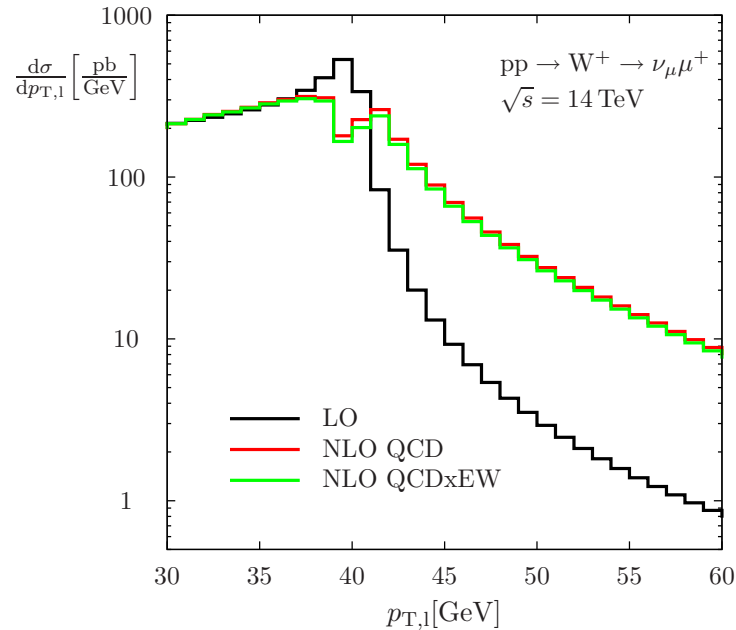
Breusing et al. '07; S.D., Huber '09

Corrections to Z production – overview

S.D., Huber '09

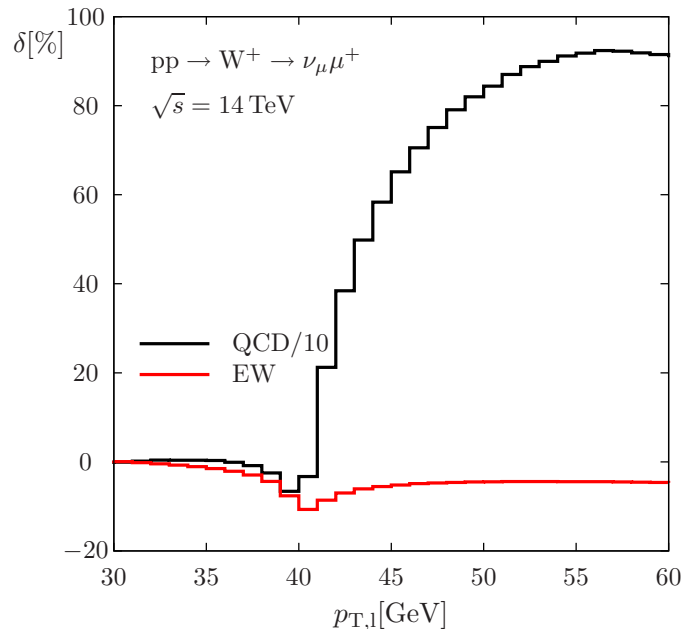


Transverse-momentum distribution for W production at NLO



Features of $p_{T,l}$:

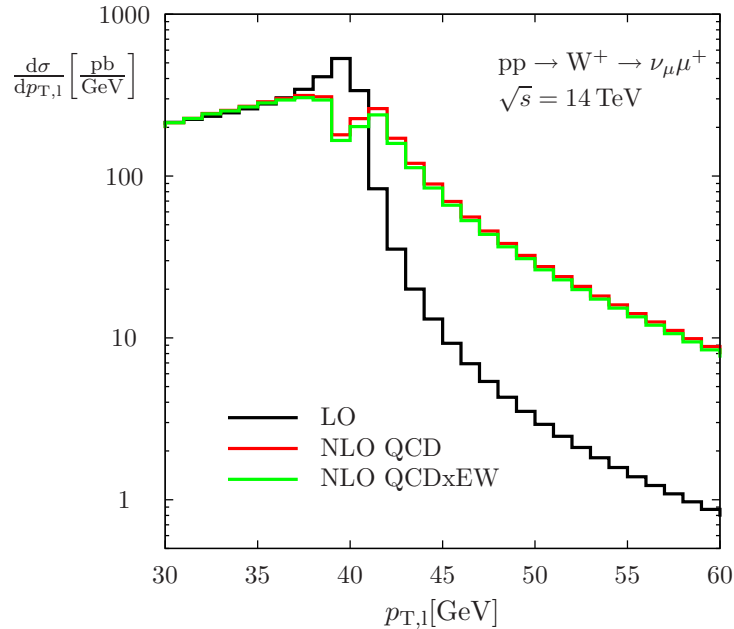
- also relevant for M_W measurement
- stability wrt detector effects
- sensitive to QCD effects/modelling/uncertainties



Corrections:

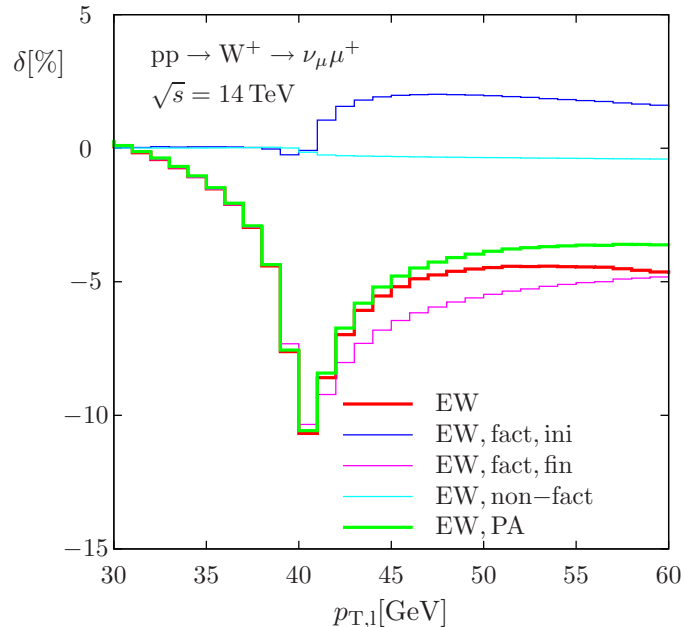
- QCD corrections huge above resonance (jet recoil)
- **EW corrections** distort resonance shape as well

Transverse-momentum distribution for W production at NLO



Features of $p_{T,l}$:

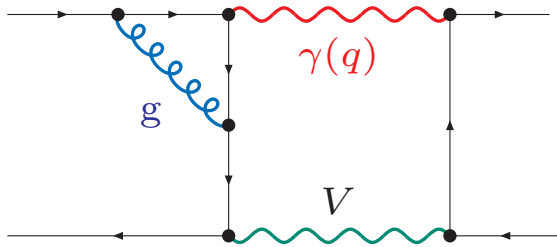
- also relevant for M_W measurement
- stability wrt detector effects
- sensitive to QCD effects/modelling/uncertainties



PA works well:

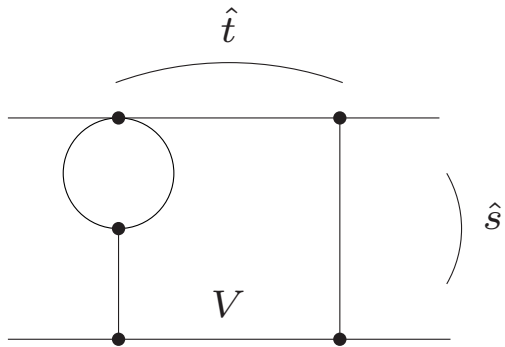
- **EW corr** reproduced near resonance
- **factorizable FS corrs** distort resonance shape
- **factorizable IS corrs** overwhelmed by QCD
- **non-fact. corrs** flat and negligible

Example: Two-loop box graph



$$\sim -\frac{C_F \alpha_s}{4\pi} \frac{Q_q Q_l \alpha}{2\pi} \mathcal{M}_0 (1 - \epsilon) (-\hat{t}) (\mu_V^2 - \hat{s}) I(\hat{s}, \hat{t})$$

Master integral:



$$= I(\hat{s}, \hat{t}) = \left(\frac{(2\pi\mu)^{2\epsilon}}{i\pi^2} \right)^2 \int d^D q \int d^D q' \frac{1}{q^2 \dots}$$

$$= \frac{c_\epsilon^2}{(-\hat{t})(\mu_V^2 - \hat{s})} \left(\frac{\mu_V^2 - \hat{s}}{M_V^2} \right)^{-3\epsilon} \left(\frac{-\hat{t}}{\mu^2} \right)^{-2\epsilon} \left\{ \frac{1}{2\epsilon^3} + \frac{1}{\epsilon^2} + \frac{1}{\epsilon} \left[\text{Li}_2 \left(1 + \frac{\hat{t}}{M_V^2} \right) + \frac{5\pi^2}{12} + 2 \right] \right. \\ \left. + 2 \text{Li}_3 \left(\frac{-\hat{t}}{M_V^2} \right) + \text{Li}_3 \left(1 + \frac{\hat{t}}{M_V^2} \right) - 6\zeta(3) + \ln^2 \left(\frac{-\hat{t}}{M_V^2} \right) \ln \left(1 + \frac{\hat{t}}{M_V^2} \right) \right. \\ \left. - 2 \ln \left(\frac{-\hat{t}}{M_V^2} \right) \left[\frac{\pi^2}{6} - \text{Li}_2 \left(1 + \frac{\hat{t}}{M_V^2} \right) \right] + \frac{5\pi^2}{6} + 2 \text{Li}_2 \left(1 + \frac{\hat{t}}{M_V^2} \right) + 4 + \mathcal{O}(\hat{s} - \mu_V^2) + \mathcal{O}(\epsilon) \right\}$$

Note: many cancellations in sum over all contributions ($1/\epsilon^4$, Li_3 , $\zeta(3)$, ...)