Electroweak corrections

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Electroweak corrections

LHC Run-II — entering the precision phase

- generic size of EW corrections $\mathcal{O}(\alpha) \sim \mathcal{O}\left({\alpha_s}^2\right)$
  $\hookrightarrow$ NLO EW $\sim$ NNLO QCD
- systematic enhancements possible:
  $\hookrightarrow$ Sudakov logarithms at high energies
  $\hookrightarrow$ final-state photon emission

This talk

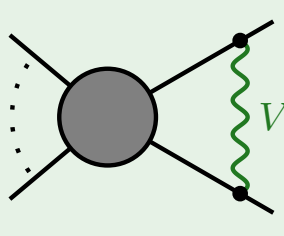
1. General features of EW corrections
2. Drell–Yan processes
3. $V + \text{jets}$
4. Di-boson production

General features of EW corrections

Electroweak corrections at high energies

Sudakov logarithms

- origin: virtual soft gauge-boson exchange



$$\sim \ln^2\left(\frac{s_{ij}}{M_{\mathrm{W}}^2}\right) + \text{sub-leading logs (collinear)}$$

- typical size for $\sqrt{\hat{s}} = 1\ \mathrm{TeV}$ $(2 \to 2)$

$$\delta_{\mathrm{LL}}^{\text{1-loop}} = -\frac{\alpha}{\pi s_{\mathrm{w}}^2}\ln^2\left(\frac{\hat{s}}{M_{\mathrm{W}}^2}\right) \approx -26\%, \quad \delta_{\mathrm{NLL}}^{\text{1-loop}} = +\frac{3\alpha}{\pi s_{\mathrm{w}}^2}\ln\left(\frac{\hat{s}}{M_{\mathrm{W}}^2}\right) \approx +16\%$$

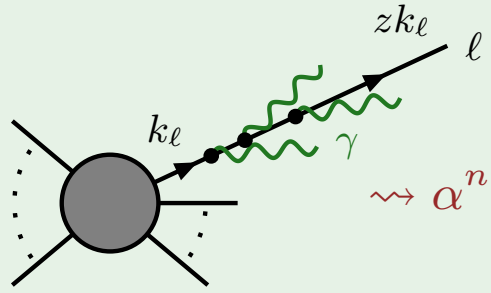
- most pronounced in the "Sudakov regime" ($s_{ij} \gg M_{\mathrm{W}}^2$)

* Real W/Z emission can partially compensate virtual Sudakov logs

Final-state photon radiation

Large corrections in distributions where the cross section varies strongly

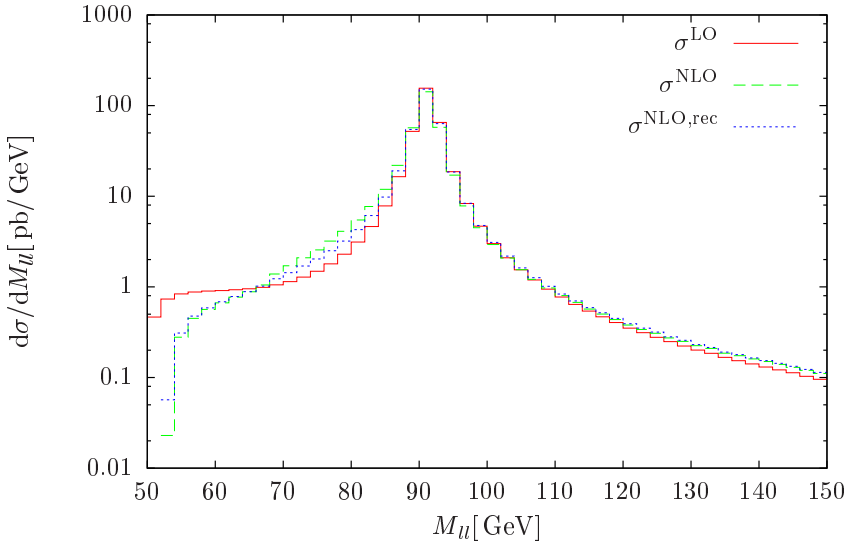
↪ resonances, shoulders,. . .

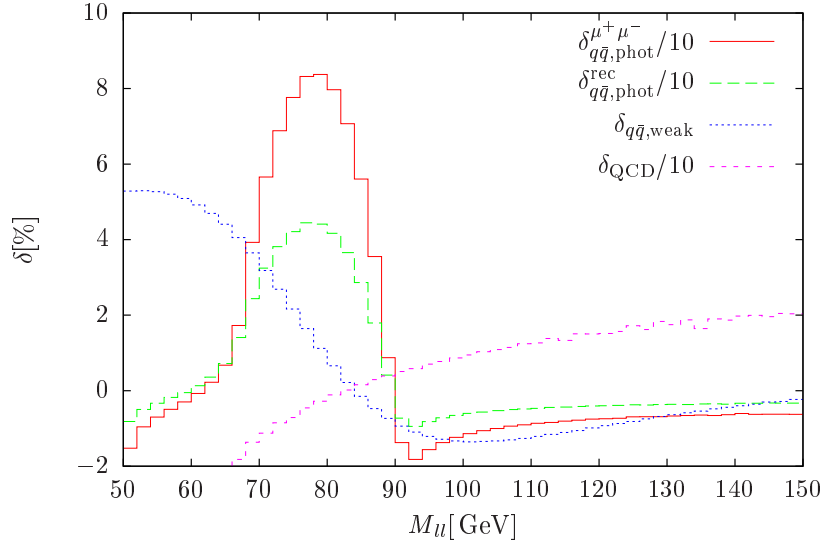


$$\rightsquigarrow \alpha^n \ln^n \left(Q^2/m_\ell^2\right)$$

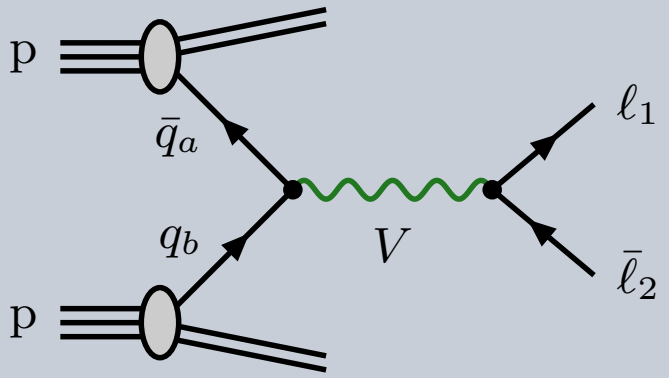
- "non-collinear safe" . . . . . bare leptons
  ↪ enhanced corrections
  ——— $\sim 90\%$
- "collinear safe" . . . . . dressed leptons
  ↪ mass-singular logarithms cancel
  - - - $\sim 40\%$

Inclusive-Z . . . . . [Dittmaier, Huber '09]





Drell–Yan processes



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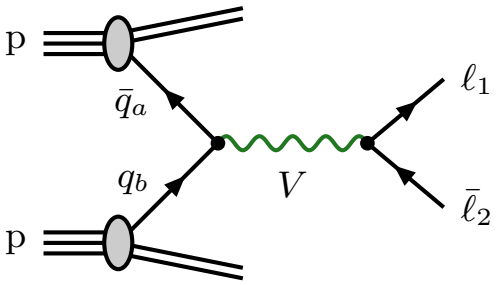


- important "standard candle" at LHC
  $\hookrightarrow$ test SM prediction, PDFs, ...
- precision measurements
  $\hookrightarrow$ $\sin^2\theta^{\text{lept}}_{\text{eff.}}$, M_{W} (LHC: $\Delta M_{\text{W}} \lesssim 10$ MeV)

QCD NNLO $\mathcal{O}(\alpha_{\text{s}}^2)$ (differential) ..... [Anastasiou et al. '04] [Melnikov, Petriello '06] [Catani et al. '09]

\+ resummation, PS matching (NNLO),...

EW NLO $\mathcal{O}(\alpha)$

W ..... [Dittmaier, Krämer '02] [Baur, Wackeroth '04] [Carloni Calame et al. '06] [Arbuzov et al. '06]

Z ..... [Baur et al. '02] [Carloni Calame, Montagna, Nicrosini, Vicini '07] [Dittmaier, Huber '10]

\+ multi-photon radiation,...

Approaches to combination

- NLO (EW+QCD) + PS matching ..... [Bernaciak, Wackeroth '12] [Barzè et al. '12, '13]

Steps towards NNLO QCD$\times$EW $\mathcal{O}(\alpha_{\text{s}}\alpha)$

- Pole expansion around the resonance ..... [Dittmaier, AH, Schwinn '14 '15]

Ambiguity in combination of QCD & EW corrections

additive: $(1+\delta^{\text{NLO}}_{\alpha_{\text{s}}}+\delta^{\text{NLO}}_{\alpha})$

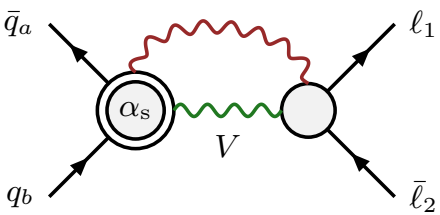
multiplicative: $(1+\delta^{\text{NLO}}_{\alpha_{\text{s}}})\cdot(1+\delta^{\text{NLO}}_{\alpha})$

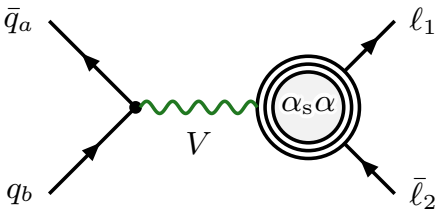
} difference $\sim$ %-level $\mathcal{O}(\alpha_{\text{s}}\alpha)$

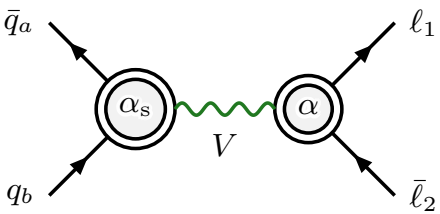
Pole Approximation @ NNLO $\mathcal{O}(\alpha_s\alpha)$—Contributions

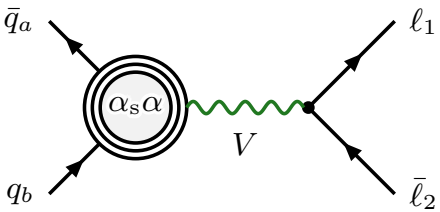
Systematic expansion about the resonance

[Dittmaier, AH, Schwinn '14,'15]









Non-factorizable corrections* ✓

- QCD corrections to production
  × soft-photon exchange: production & decay

Factorizable final–final corrections ✓

- only a constant $\mathcal{O}(\alpha_s\alpha)$ counterterm

Factorizable initial–final corrections* ✓

- QCD corrections to production
  × EW corrections to decay
- large corrections & shape distortion expected

Factorizable initial–initial corrections*

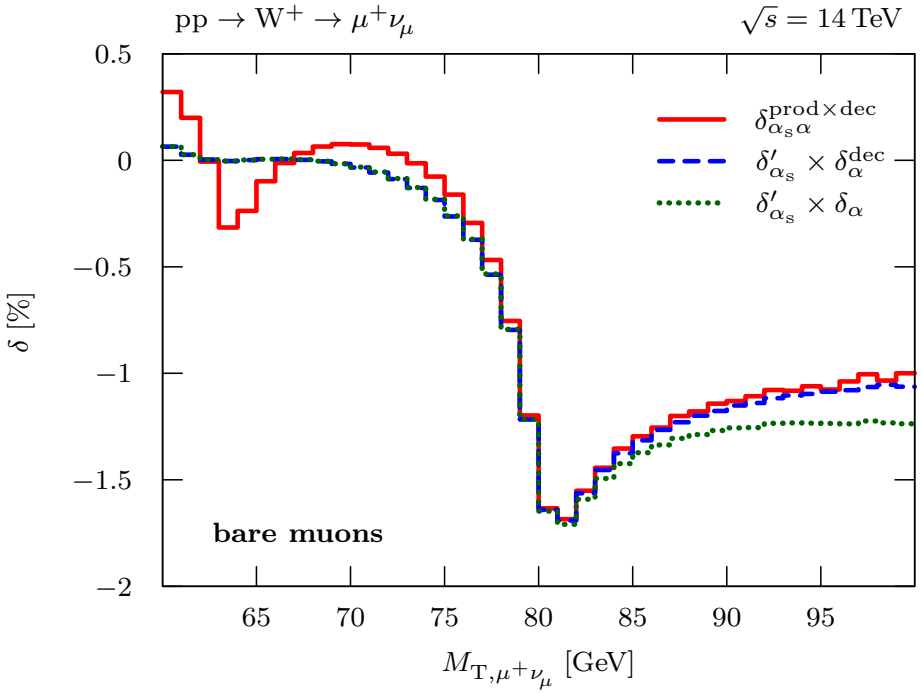
- $\mathcal{O}(\alpha_s\alpha)$ corrections to on-shell V production
- no significant shape distortion expected
- no $\mathcal{O}(\alpha_s\alpha)$ PDFs

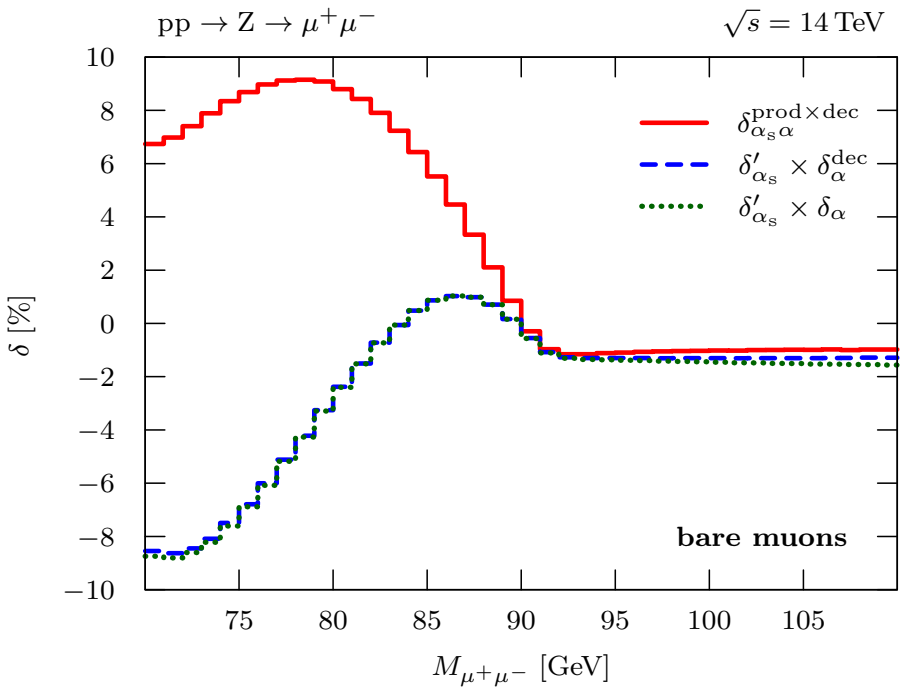
*only virtual contributions indicated ⇝ also real-, double-real emission, interferences,...

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

[Dittmaier, AH, Schwinn '15]

$\delta^{\mathrm{NNLO}}_{\alpha_s\alpha}$ (full) $\quad$ } $\delta^{\mathrm{NLO}}_{\alpha_s} \times \delta^{\mathrm{NLO}}_{\alpha}$ (naive products) $\quad$ (naive sum $\rightsquigarrow 0$)





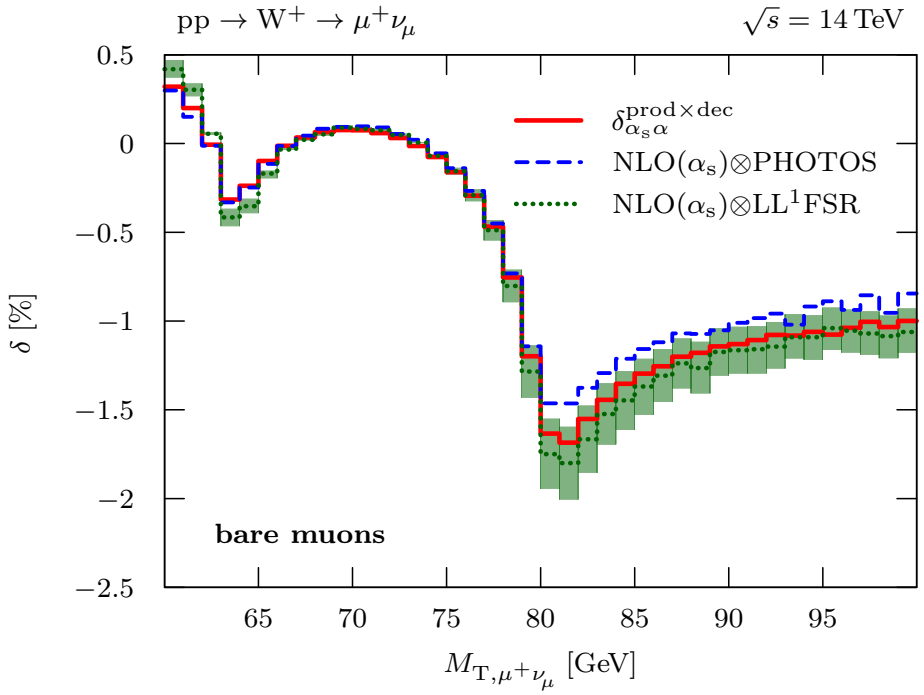
- moderate corrections $\sim -1.7\%$
- $\delta^{\mathrm{NNLO}}_{\alpha_s\alpha}$ well approximated by naive products
- $M_{\mathrm{T},\ell\nu}$ insensitive to ISR effects

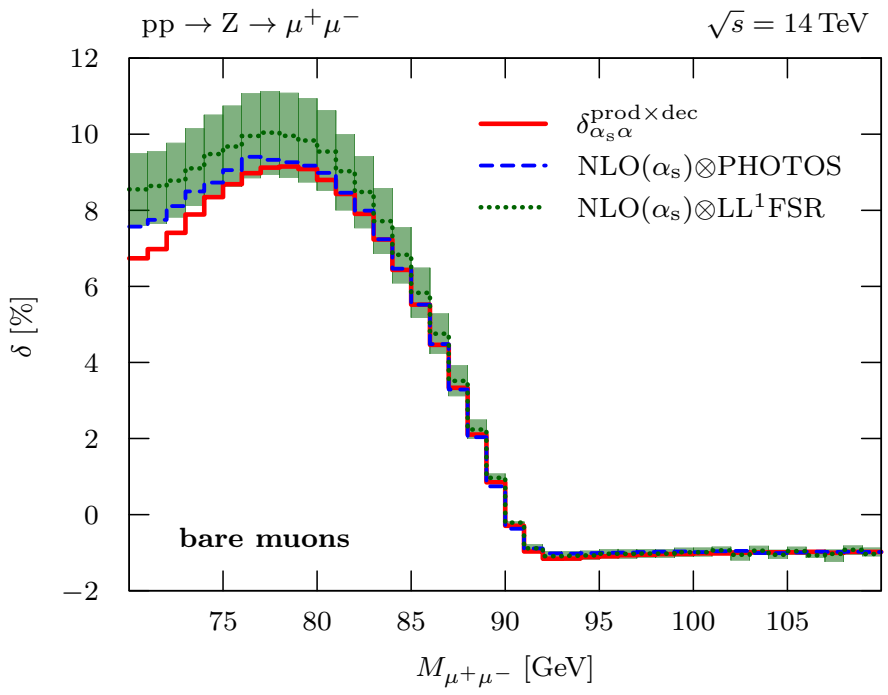
- corrections up to $\sim 10\%$
- naive product completely fail already a litte away from resonance
- large corrections below resonance
  $\hookrightarrow$ radiative tail from FSR

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

[Dittmaier, AH, Schwinn '15]

$\delta^{\text{NNLO}}_{\alpha_s\alpha}$ (full) — NLO(α_s) ⊗ PHOTOS — NLO(α_s) ⊗ LL^{1}FSR





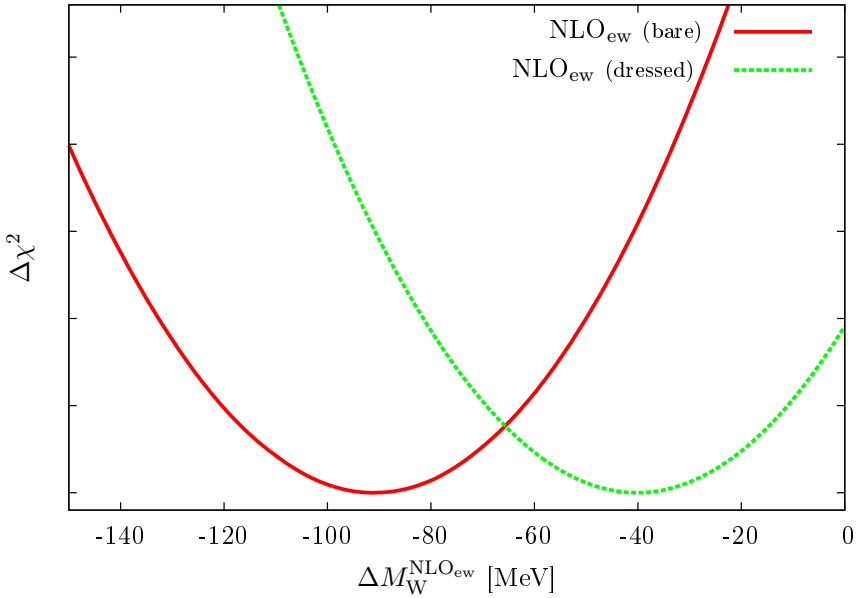
- leading-logarithmic (LL) approximation for FSR
  ↪ proper modelling of recoil effects
- clear improvement to naive products
- intrinsic uncertainty in LL approx $M_V/2 < Q < 2M_V$

Impact on M_{W} extraction

- bin-by-bin χ^2 fit

$$\chi^2 = \sum_{i \in \text{bins}} \frac{\left[\sigma_i^{\text{data}}(M) - \sigma_i^{\text{template}}(M + \Delta M)\right]^2}{2\Delta\sigma_i^2}$$

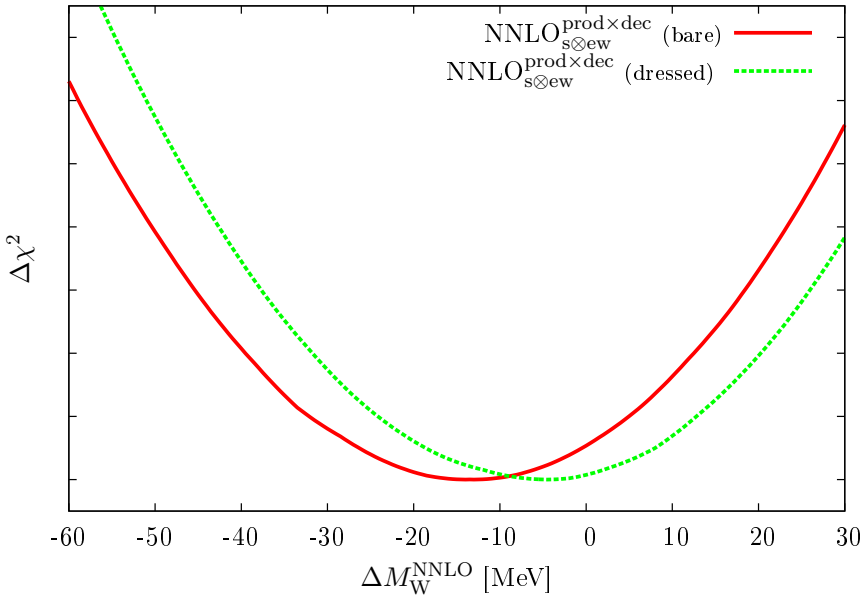
- "templates": LO
- "pseudo-data": HO
- distributions normalized in fit interval $M_{\mathrm{T},\ell\nu} \in [65, 90]$ GeV



LO $\rightarrow$ NLO(EW)

$\Delta M_{\mathrm{W}}(\text{bare}) \approx -90$ MeV

$\Delta M_{\mathrm{W}}(\text{dressed}) \approx -40$ MeV

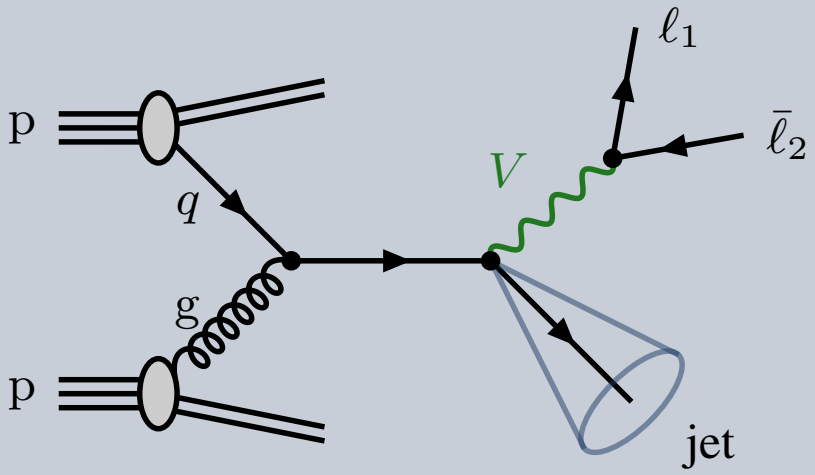


NLO(EW+QCD) $\rightarrow$ NNLO(EW$\times$QCD)

$\Delta M_{\mathrm{W}}(\text{bare}) \approx -14$ MeV

$\Delta M_{\mathrm{W}}(\text{dressed}) \approx -4$ MeV

V + jet(s)



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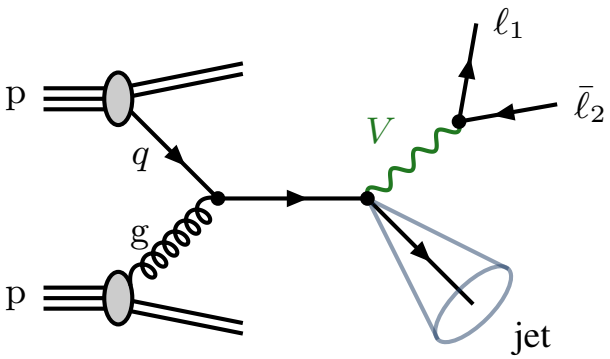


- large cross section, clean signature
  $\hookrightarrow$ test pQCD, PDFs, $p_{\mathrm{T}}^{\mathrm{Z}}$, ...
- important background to BSM searches

QCD NNLO $V + \text{jet}$ ..... [Gehrmann-De Ridder et al. '15] [Boughezal et al.'15]

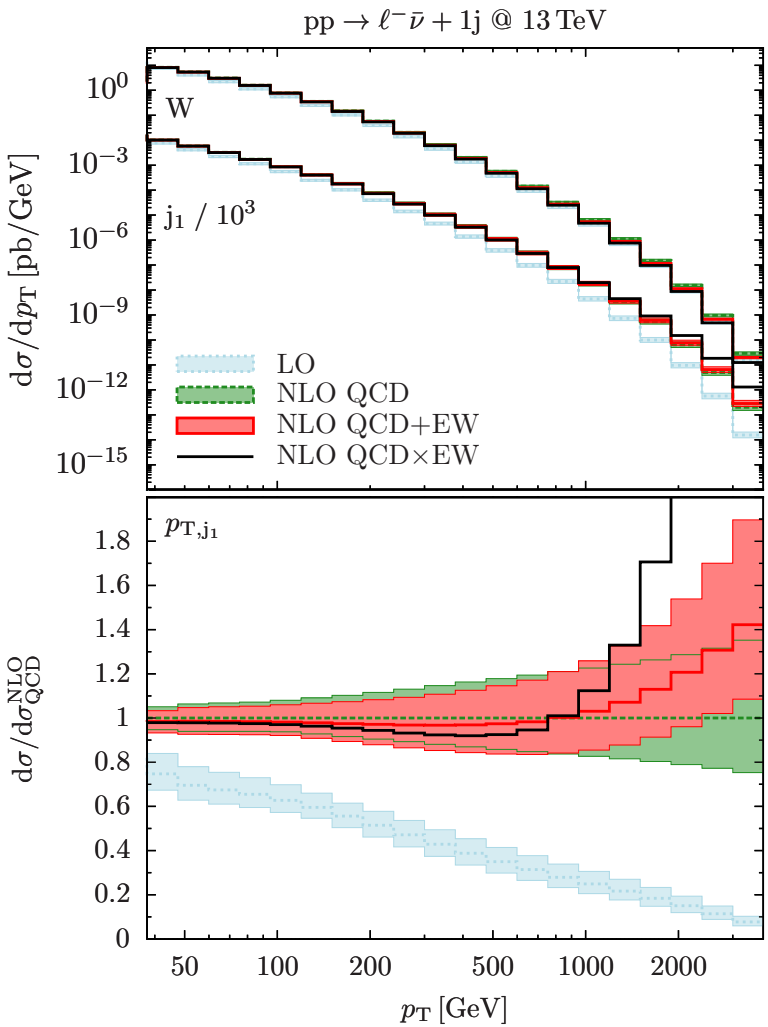
QCD NLO $V+ \leq 5\,\text{jets}$ ..... [Berger et al. '09,'10] [Ellis et al. '09] [Bern et al. '11–'13] [Goetz et al. '14]

EW NLO $V+ \leq 3\,\text{jets}$ ..... [Denner, Dittmaier, Kasprzik, Mück '09 '11]
[Denner, Hofer, Scharf, Uccirati '14] [Kallweit, et al. '15]
[Chiesa, Greiner, Tramontano '15]

NLO (QCD+EW) multi-jet merging

- $V + 0, 1, 2\,\text{jets}$ (MEPS@NLO) ..... [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '16]

W + 1 jet (inclusive)



[Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '16]

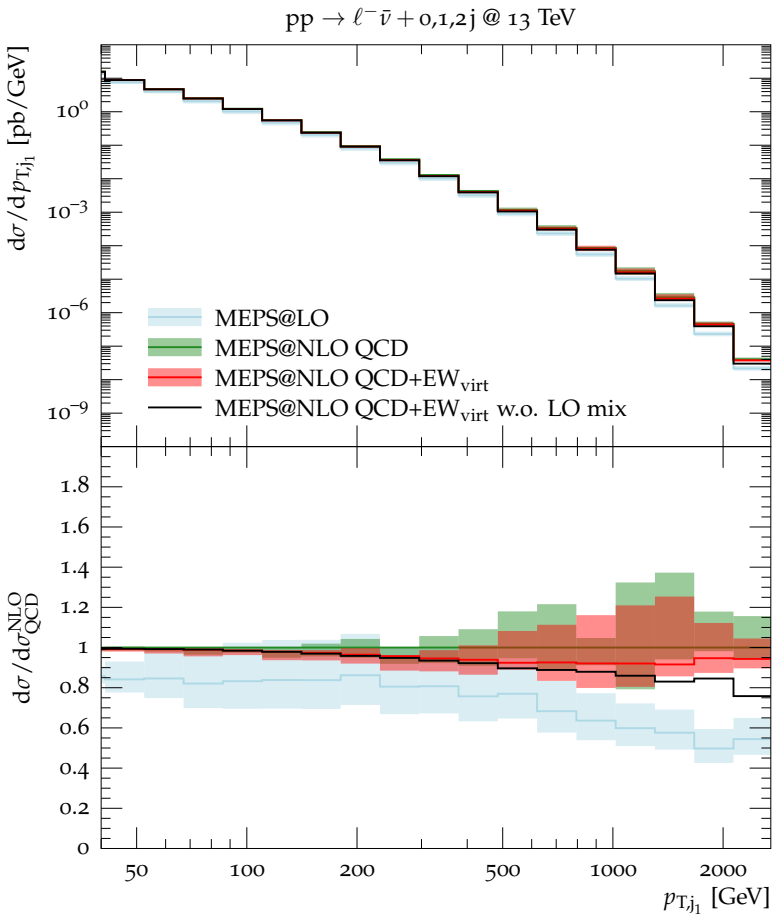
Inclusive cross section

- $\sim 1\%$ EW corrections

Leading jet p_{T,j_1}

- "giant K-factors"
  [Rubin, Salam, Sapeta '10]
- dominated by dijet configuration
  (suppress in excl. setup: $\Delta\phi_{j_1 j_2} < \frac{3\pi}{4}$)
- large scale uncertainty (LO)
- EW corrections meaningless

MEPS@NLO for NLO QCD+EW



[Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '16]

Approximation: infrared-subtracted virtual

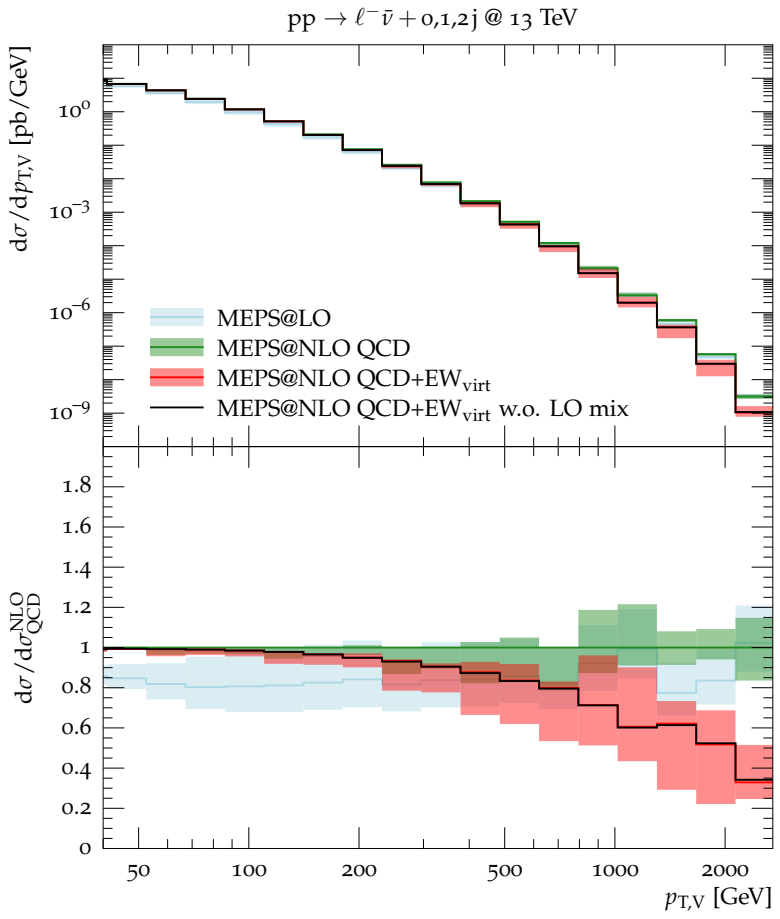
$\mathrm{EW}_{\mathrm{virt}} = V_{n,\mathrm{EW}} + I_{n,\mathrm{EW}}$ (n =#jets)

- $\oplus$ Sudakov logs in virtual corr.
- $\ominus$ photon emission: fully inclusive
  $\hookrightarrow$ ~~large FSR corr.~~ ($m_{\ell\ell}$)

Leading jet p_{T,j_1}

- no enhanced QCD behaviour @ high $p_{\mathrm{T},j1}$
- Sudakov logs compensated by sub-leading Born contribution

MEPS@NLO for NLO QCD+EW



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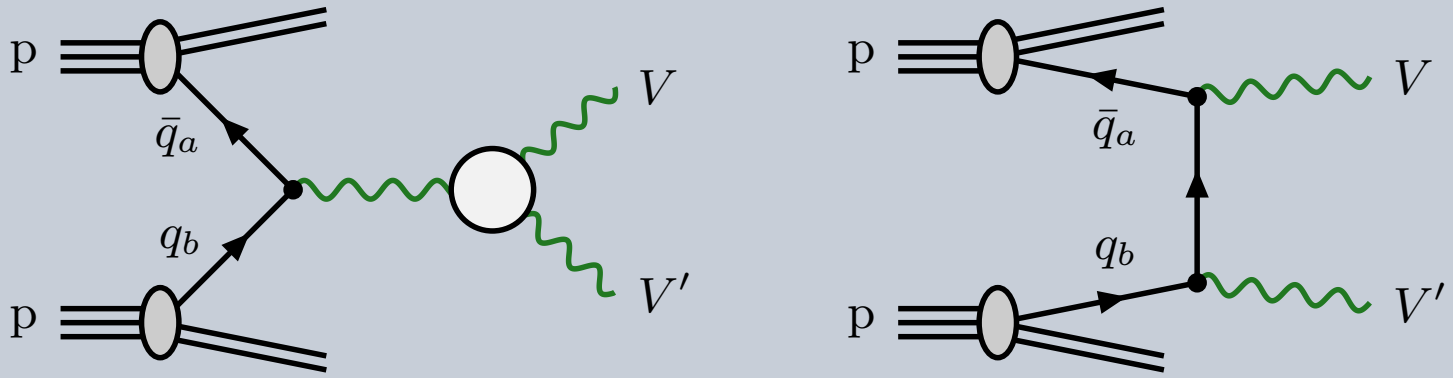
W-boson p_{T}

- stabilisation of QCD corrections
- larger Sudakov effects

Di-boson production



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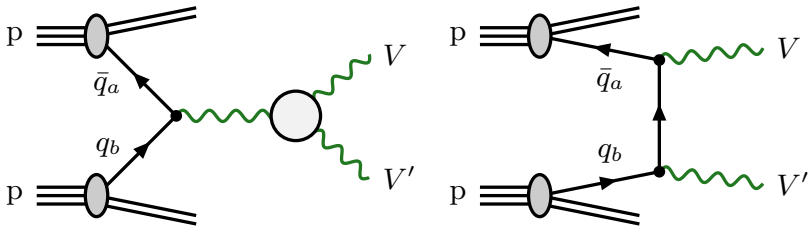


- probe triple-gauge-couplings
  ↪ test gauge structure of the SM
- important background
  ↪ $\mathrm{H} \to VV'$
  ↪ BSM searches

QCD NNLO ..... [Cascioli et al. '14] [Gehrmann et al. '14] [Grazzini et al. '14 '15 '16]

\+ resummation, gg-induced,...

EW NLO

stable W/Z bosons ..... [Bierweiler, Kasprzik, Kühn '12 '13] [Baglio, Le, Weber '13]

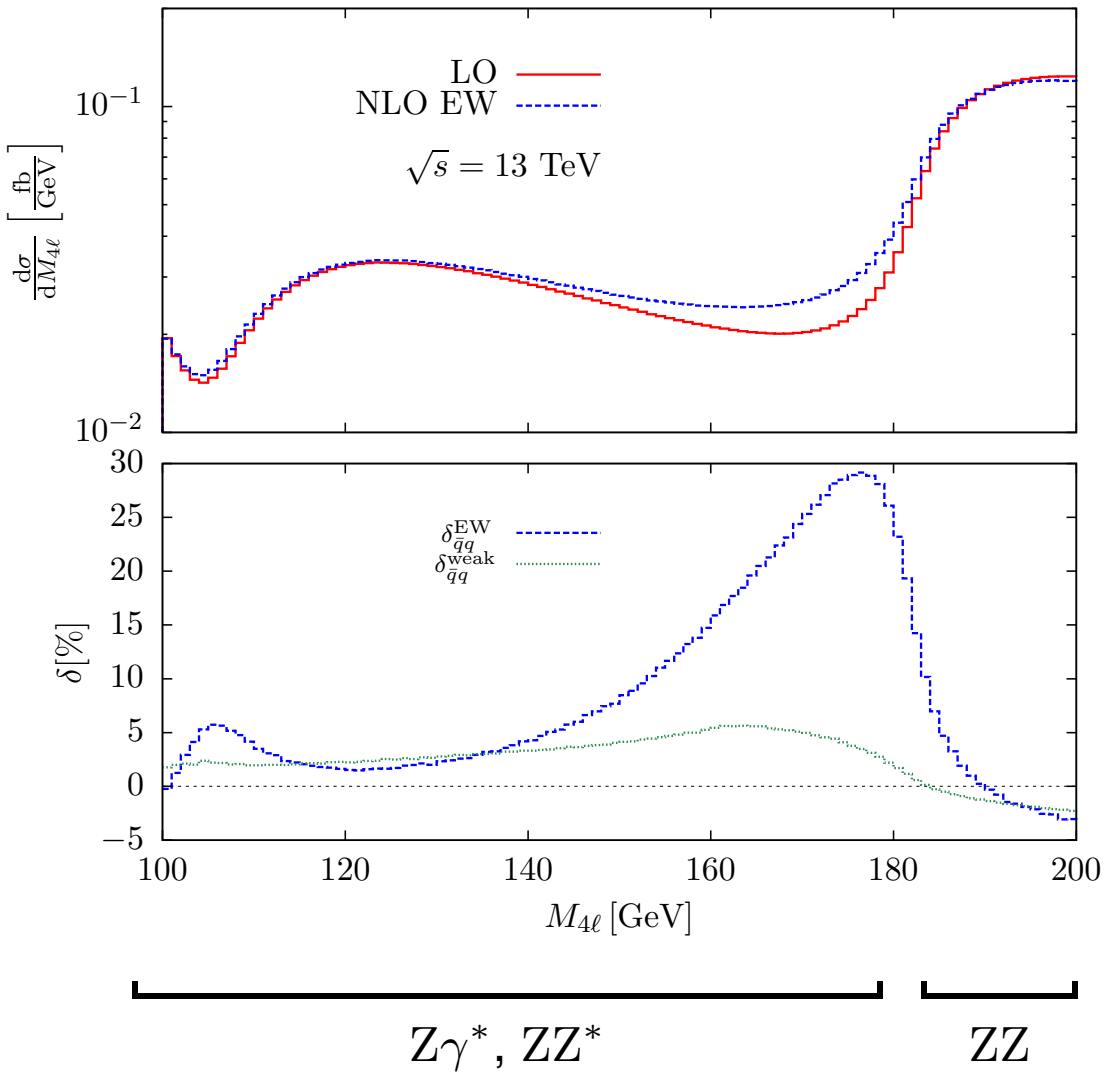
$\mathrm{W\,W} \to 4\ell$ (DPA) ..... [Billoni, Dittmaier, Jäger, Speckner '13]

Full off-shell calculations

- $\mathrm{pp} \to \ell\bar{\ell}\gamma$ ($\mathrm{W}\gamma$, $\mathrm{Z}\gamma$) ..... [Denner, Dittmaier, Hecht, Pasold '14 '15]
- $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-$ (ZZ) ..... [Biedermann, Denner, Dittmaier, Hofer, Jäger '16]
- $\mathrm{pp} \to \nu_\mu\mu^+\bar{\nu}_\mathrm{e}\mathrm{e}^-$ ($\mathrm{W}^+\mathrm{W}^-$) ... [Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder '16]

ZZ production ($pp \to \mu^+\mu^-e^+e^-$) — a Higgs background study

[Biedermann, Denner, Dittmaier, Hofer, Jäger '16]



$M_{4\ell} \gtrsim 2M_Z$: resonant ZZ production

$M_{4\ell} \lesssim 2M_Z$: off-shell 4ℓ production

$\delta_{q\bar{q}}^{EW}$ $\delta_{q\bar{q}}^{weak}$

- large radiative tail (FSR)
- sign flip in EW corrections
  (from genuine weak corrections)

$\delta_{q\bar{q}}^{EW}(\mathrm{tot}) \sim -3.5\%$

$\delta_{q\bar{q}}^{EW}(M_{4\ell} \approx M_H) \sim +2.5\%$

ZZ production $(\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-)$ — a Higgs background study

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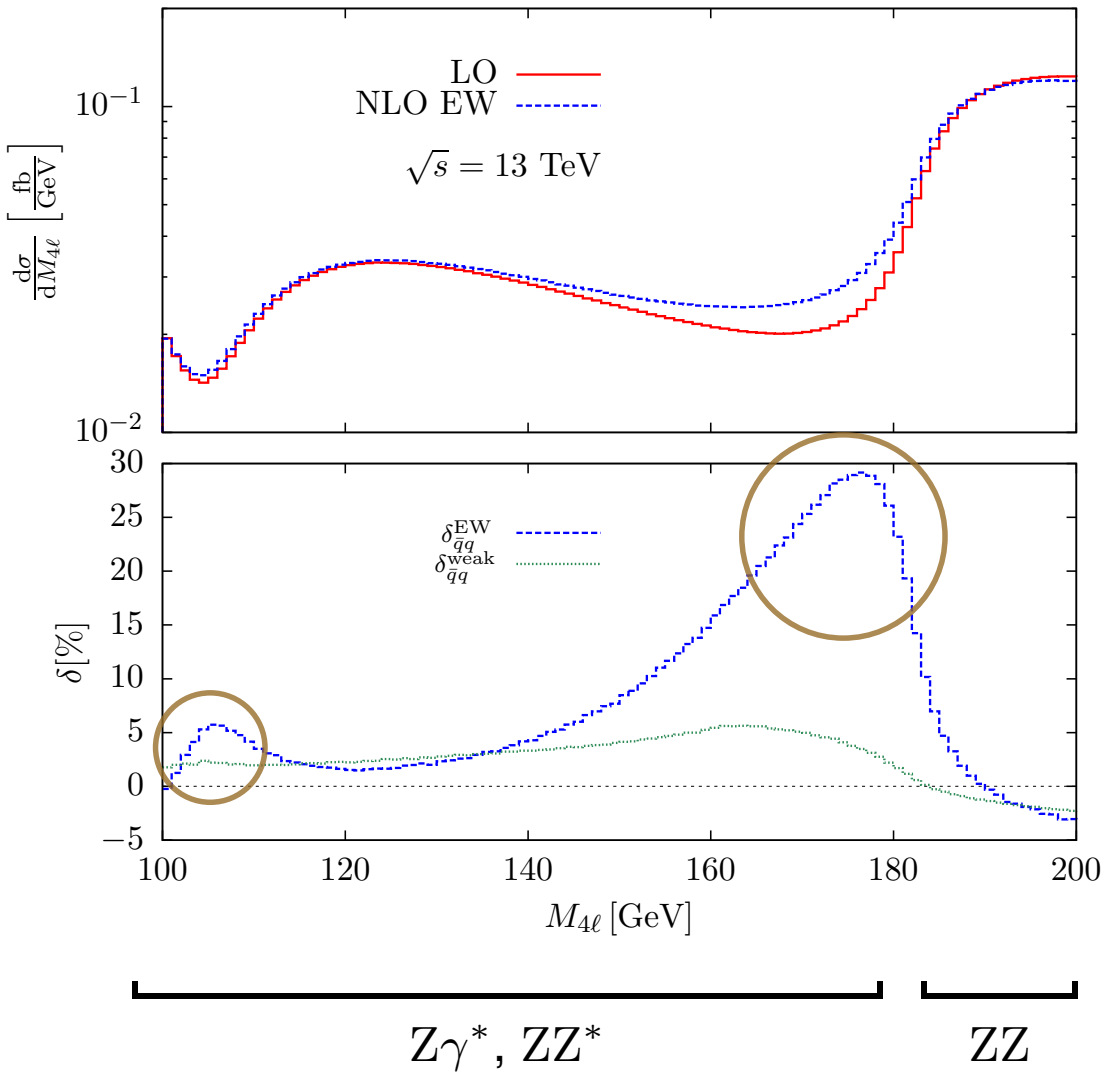

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- - - $\delta_{q\bar{q}}^{\mathrm{EW}}$ ..... $\delta_{q\bar{q}}^{\mathrm{weak}}$

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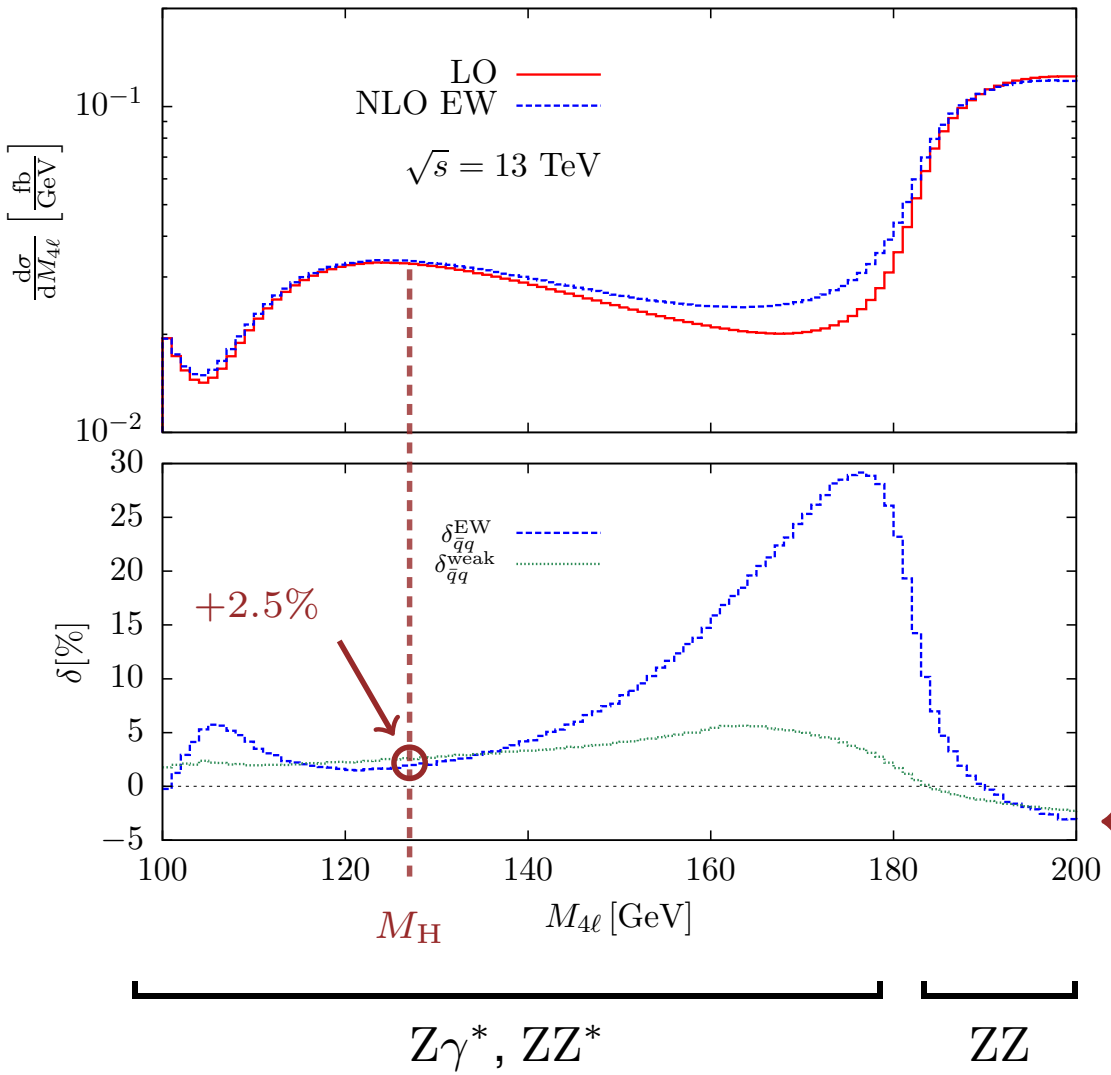

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- - - $\delta_{q\bar{q}}^{\mathrm{EW}}$ ..... $\delta_{q\bar{q}}^{\mathrm{weak}}$

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Summary & Outlook

Summary

The inclusion of electroweak corrections important for precision predictions

- very high-precision measurements ..... Drell–Yan
  - ↪ mixed QCD–EW corrections become relevant
  - ↪ study combination of QCD & EW corrections
- first multi-jet merging results including EW corrections ..... $V + \mathrm{jet(s)}$
  - ↪ stabilises QCD corrections where “giant K-factors” appear
  - ↪ correctly reproduces Sudakov logarithms
- more refinements: decay & off-shell effects ..... Di-bosons
  - ↪ full NLO accuracy over entire phase space

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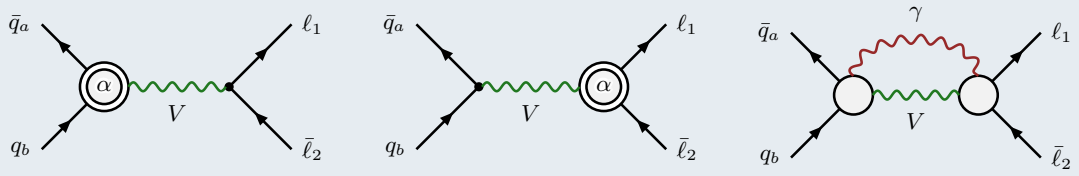
Thank you

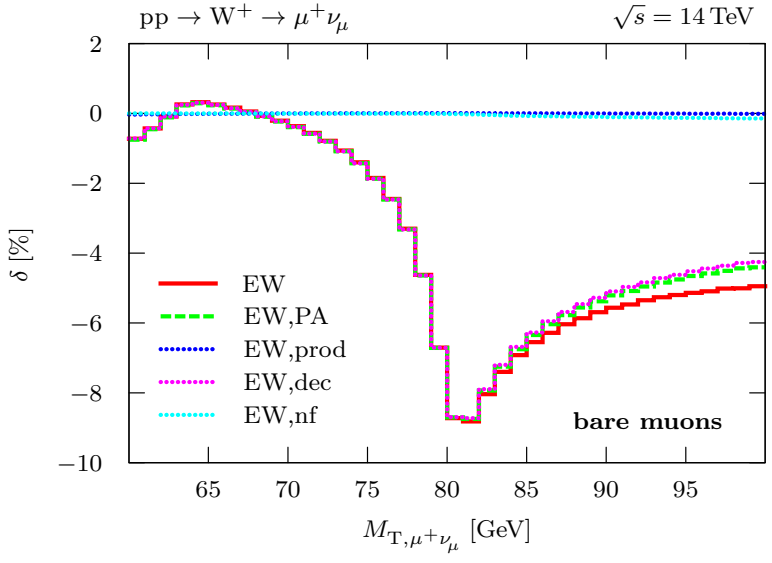
Backup Slides

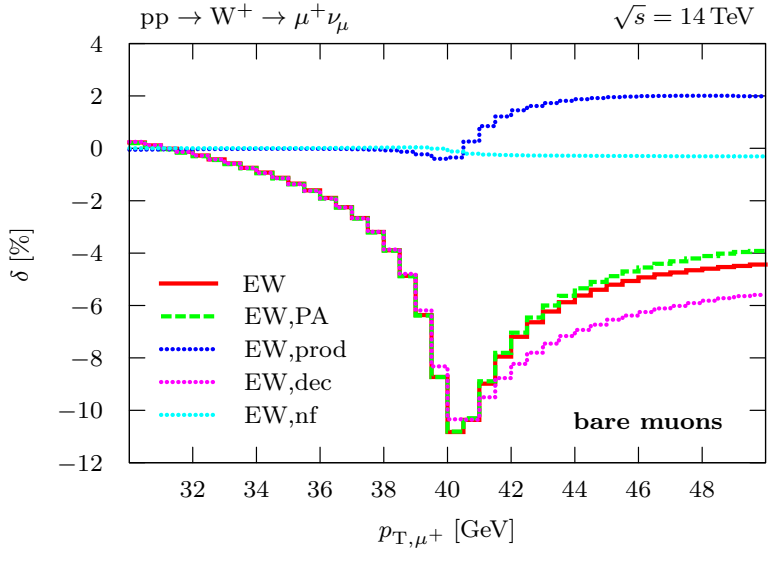
Pole Approximation @ NLO

full $\mathcal{O}(\alpha)$ corrections

PA
- fact. ini.
- fact. fin.
- non-fact



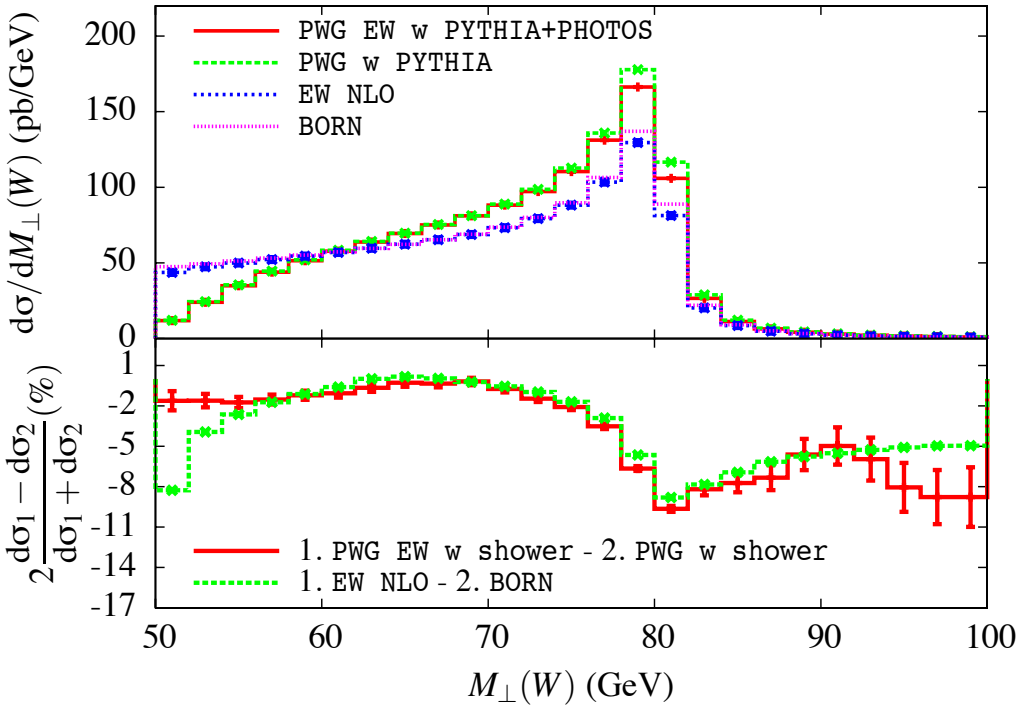




- full calculation vs. PA: agreement $\lesssim 1\%$ around resonance
- PA for $\mathcal{O}(\alpha_s\alpha)$ corrections expected to be sufficient
- dominant contribution: factorizable corrections to the decay

NLO (QCD+EW) ⊗ (PYTHIA+PHOTOS)

[Barzè, et al. '12]



W production (NLO matched)

- Exact first emission for QED and QCD
- $\mathcal{O}(\alpha_s\alpha)$ generated through
  - ↪ NLO QCD ⊗ PHOTOS
  - ↪ NLO EW ⊗ PYTHIA
- Double-real radiation

NLO (QCD + EW) ⊗ (QCD + QED) PS
v.s. NLO (QCD) ⊗ (QCD) PS

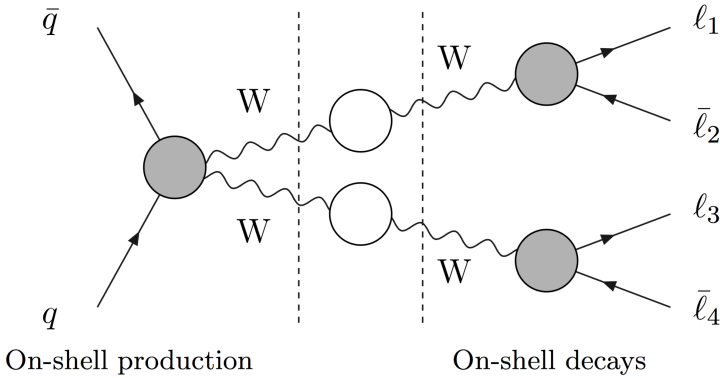
NLO (EW)
v.s. LO

estimate of $\mathcal{O}(\alpha_s\alpha)$ corrections

Difference ∼ %-level!

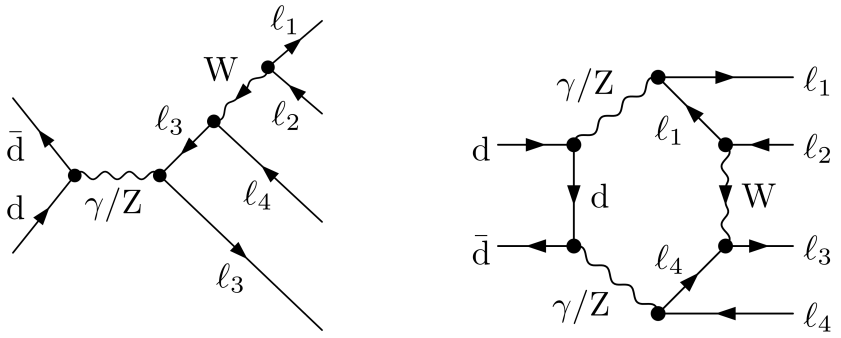
W^+W^- production

Double-pole approximation (DPA)



- expansion around the resonances
- – only applicable for $\sqrt{\hat{s}} \gtrsim 2M_V$

Off-shell calculation ($pp \to \ell_1\ell_2\ell_3\ell_4$)



- includes full off-shell contributions
- \+ Full NLO EW accuracy everywhere in phase space

LHC 13 TeV	$\sigma^{\text{LO}}_{\bar{q}q}$ [fb]	$\sigma^{\text{LO,DPA}}_{\bar{q}q}$ [fb]	$\delta_{\bar{q}q}$ [%]	$\delta^{\text{DPA}}_{\bar{q}q}$ [%]
inclusive	390.59(3)	384.96(9)	−3.41	−3.43
ATLAS WW	271.63(1)	265.31(3)	−3.71	−3.68
Higgs bkg	49.934(2)	48.88(2)	−2.54	−2.54

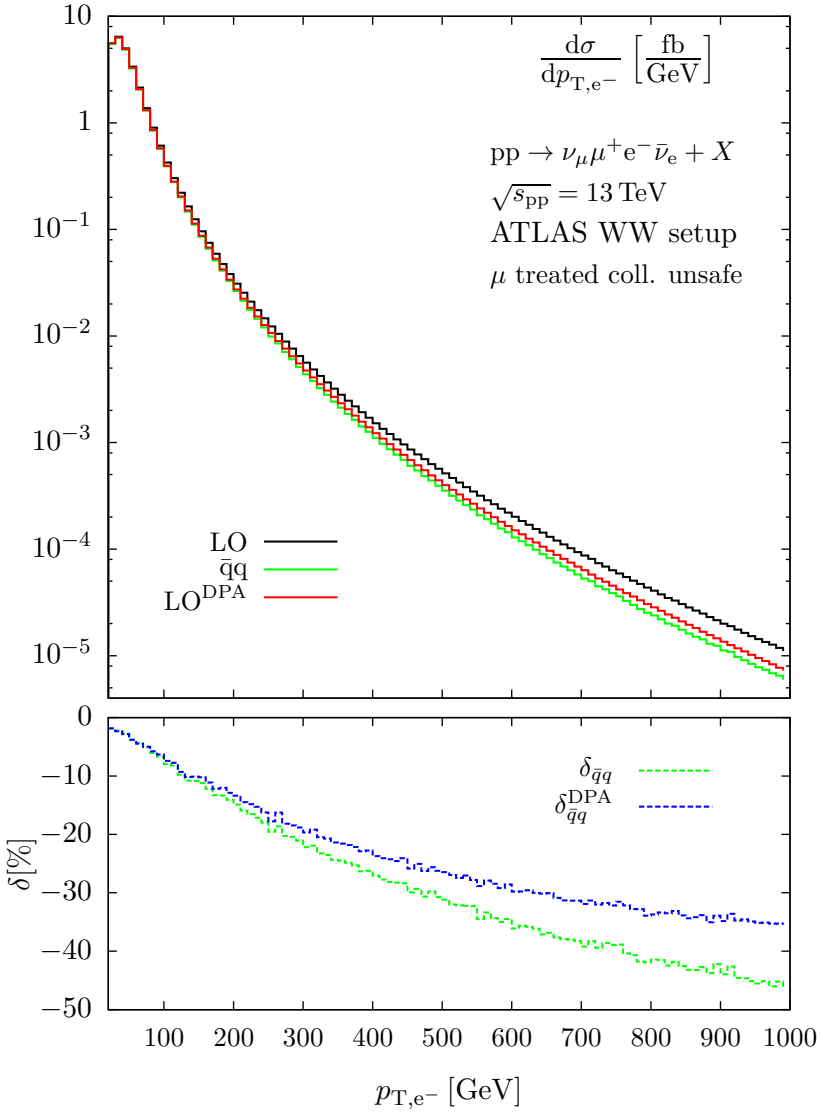
[Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder '16]

Very good agreement for total cross sections and observables dominated by the resonance region (y_ℓ)

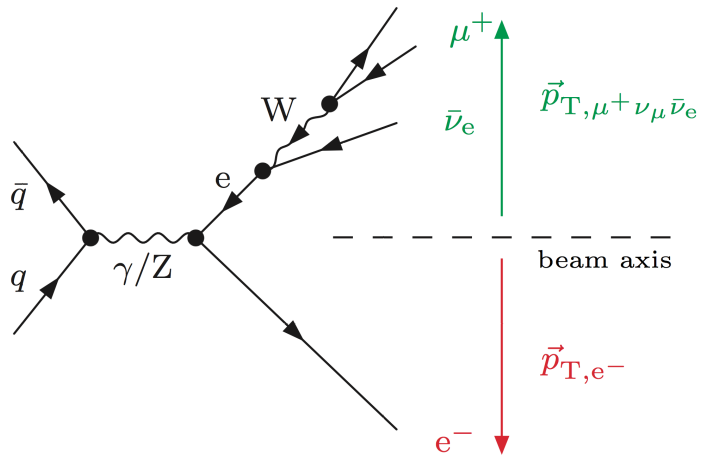
$\mathrm{W^+W^-}$ production $(\mathrm{pp} \to \nu_\mu \mu^+ \bar{\nu}_\mathrm{e} \mathrm{e}^-)$

[Biedermann et al. '16]

p_T of a charged lepton



enhancement of off-shell diagrams:

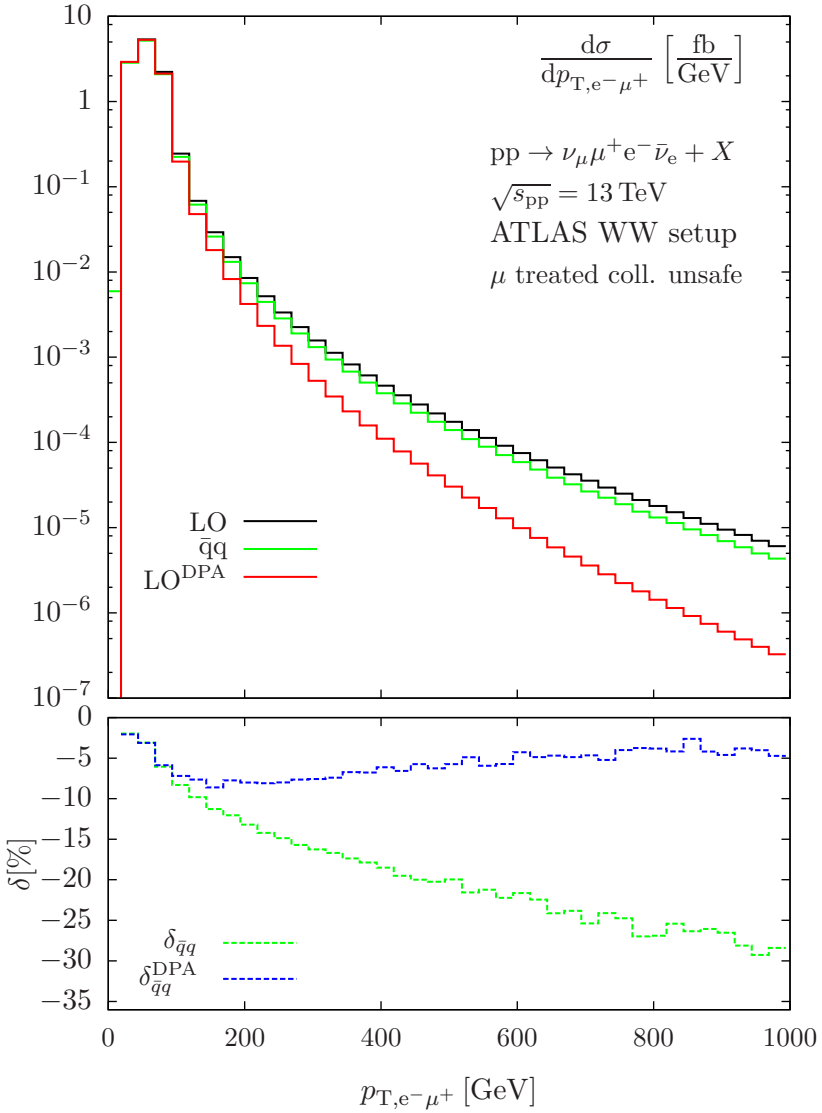


- DPA fails for $p_{\mathrm{T,e^-}} \gtrsim 500\ \mathrm{GeV}$
- can de identified already at LO
- less likely for double-resonant contributions

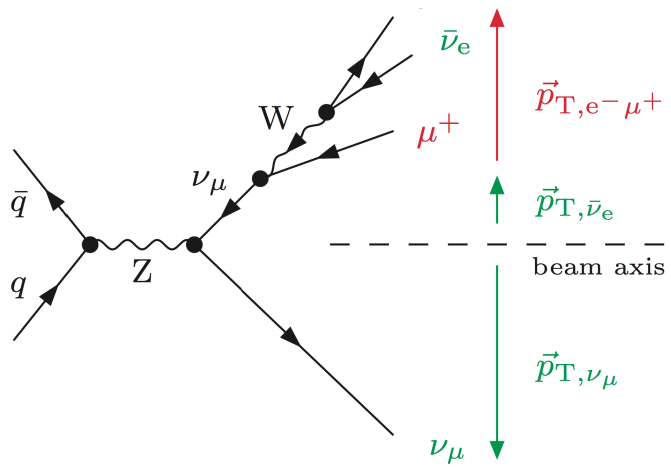
$\mathrm{W^+W^-}$ production $(\mathrm{pp} \to \nu_\mu \mu^+ \bar{\nu}_\mathrm{e} \mathrm{e}^-)$

[Biedermann et al. '16]

p_T of a charged lepton system



enhancement of off-shell diagrams:



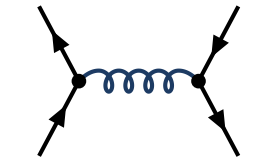
- DPA fails for $p_{\mathrm{T,e^-\mu^+}} \gtrsim 200\ \mathrm{GeV}$
- can de identified already at LO
- double-resonant contributions: e^- & μ^+ tend to recoil against each other

Perturbative power counting: In a “QCD world” ...

$$\mathrm{d}\sigma = \underbrace{\mathrm{d}\sigma(\alpha_s^{\,2})}_{\text{“LO”}} + \underbrace{\mathrm{d}\sigma(\alpha_s^{\,3})}_{\text{“NLO”}} + \underbrace{\mathrm{d}\sigma(\alpha_s^{\,4})}_{\text{“NNLO”}} + \vdots$$

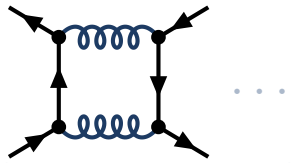
Example: $\mathrm{u}\bar{\mathrm{u}} \to \mathrm{d}\bar{\mathrm{d}}$

tree



$\mathcal{O}(\alpha_s)$

1-loop



$\mathcal{O}(\alpha_s^{\,2})$

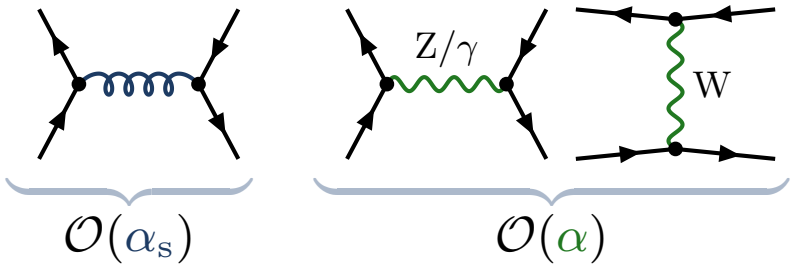
$\vdots$

Perturbative power counting: ... with EWK interactions

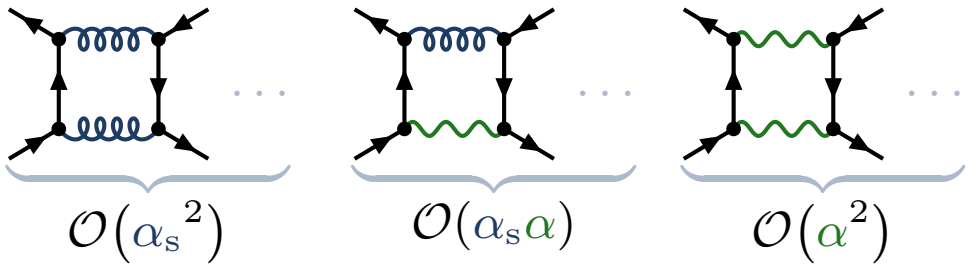
$$\mathrm{d}\sigma = \mathrm{d}\sigma(\alpha_s^2) + \mathrm{d}\sigma(\alpha_s^3) + \mathrm{d}\sigma(\alpha_s^4) + \vdots$$

Example: $\mathrm{u}\bar{\mathrm{u}} \to \mathrm{d}\bar{\mathrm{d}}$

tree

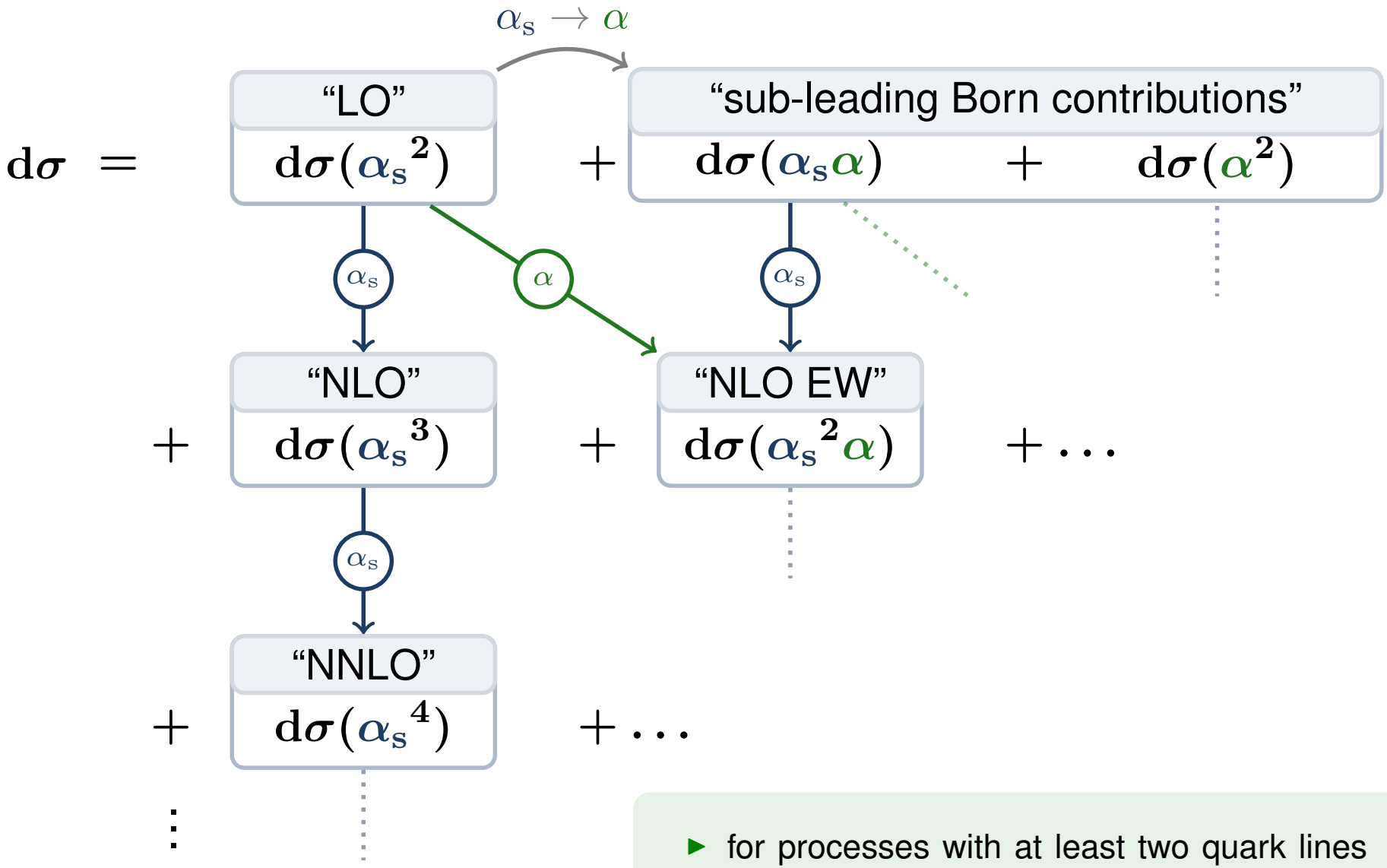


1-loop



$\vdots$

Perturbative power counting



- for processes with at least two quark lines
- no separation of QCD & EW corrections
- instead consider a fixed perturbative order