

NLO EW corrections to $pp \rightarrow W^+W^- \rightarrow 4$ leptons at the LHC

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in collaboration with

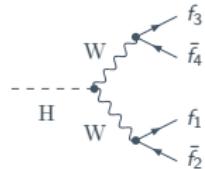
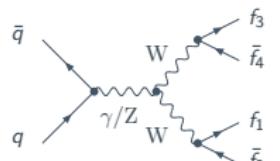
B. Biedermann, M. Billoni, A. Denner, S. Dittmaier, L. Hofer, and B. Jäger



based on **JHEP 06 (2016) 065**, [arXiv:1605.03419 [hep-ph]]

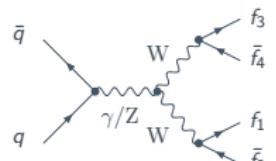
Why W^+W^- is interesting...

- Probe non-abelian structure of the Standard Model:
→ simplest process with trilinear gauge couplings
- Limits on anomalous gauge couplings
- Irreducible background to Higgs decay $H \rightarrow WW^*$



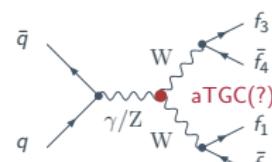
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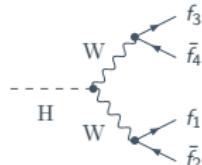
- Limits on anomalous gauge couplings

→ high energy region: $M_{4\ell} \gg 2M_W$



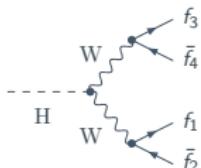
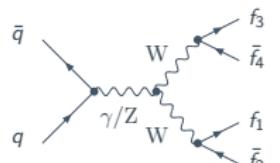
- Irreducible background to Higgs decay $H \rightarrow WW^*$

→ low energy region: $M_{4\ell} \leq 2M_W$



Why W^+W^- is interesting...

- Probe non-abelian structure of the Standard Model:
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- Limits on anomalous gauge couplings
→ high energy region: $M_{4\ell} \gg 2M_W$
- Irreducible background to Higgs decay $H \rightarrow WW^*$
→ low energy region: $M_{4\ell} \leq 2M_W$
- at leading order $\mathcal{O}(\alpha^4)$ → little "QCD-pollution"



Status of W^+W^- predictions at the LHC

QCD corrections

- NLO corrections

[Ohnemus et al. '91; Mele et al. '91; Frixione et al. '92 '93 - Baur et al. '96; Dixon et al. '98]

- NLO corrections + parton shower matching

[Frixione et al. '03; Nason et al. '06 - Hamilton '10; Höche et al. '10; Melia et al. '11; Frederix et al. '11]

- NNLO corrections

[T. Gehrmann et al. '14; Grazzini et al. '16]

EW corrections

- NLO corrections to on-shell W^+W^- production

[Bierweiler, Kasprzik, Kühn, Uccirati '12 '13]

- NLO corrections to on-shell W^+W^- including γq contributions

[Baglio, Ninh, Weber '13]

- NLO corrections to $pp \rightarrow W^+W^- \rightarrow 4l$ in DPA

[Billoni, Dittmaier, Jäger, Speckner '13]

- Full NLO corrections to $pp \rightarrow W^+W^- \rightarrow 4l$

[Biedermann et al. '16]

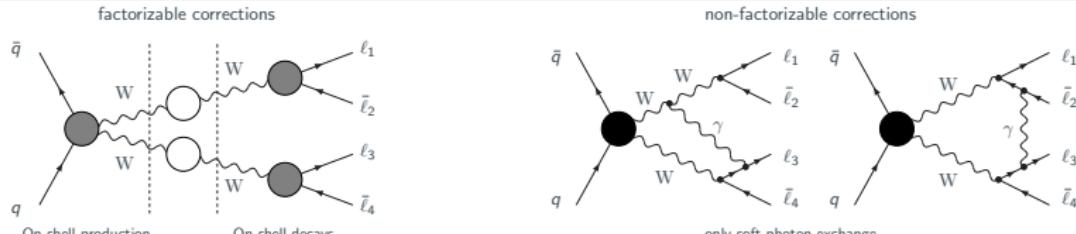
Outline

- ① EW corrections in double-pole approximation
- ② Full off-shell EW corrections to $p\bar{p} \rightarrow W^+W^- \rightarrow 4 \text{ leptons}$
- ③ Phenomenological results

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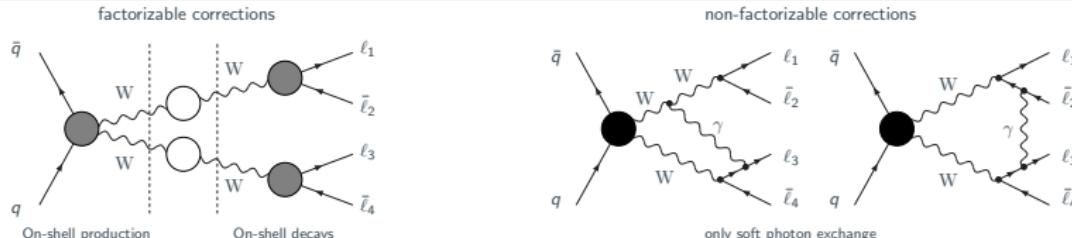
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EW corrections in DPA



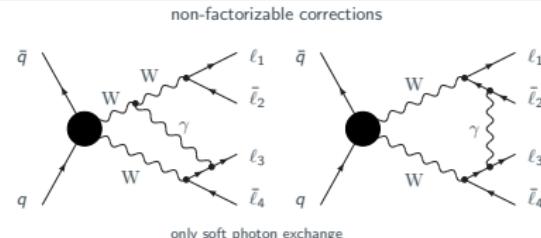
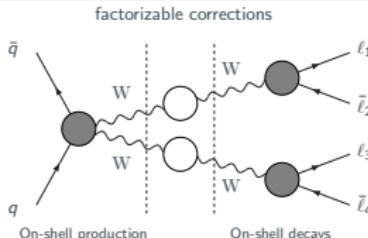
↔ RacooonWW [Denner, Dittmaier, Roth, Wackerloher '99-'02]

EW corrections in DPA



- X virtual corrections only to doubly resonant diagrams
- X only applicable in the high-energy region, $\sqrt{s} > 2M_W$, where xsec dominated by W-pairs

EW corrections in DPA

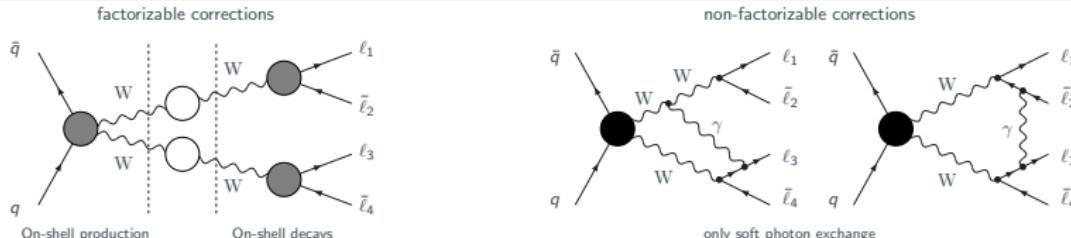


- ✗ virtual corrections only to doubly resonant diagrams
- ✗ only applicable in the high-energy region, $\sqrt{s} > 2M_W$, where xsec dominated by W-pairs

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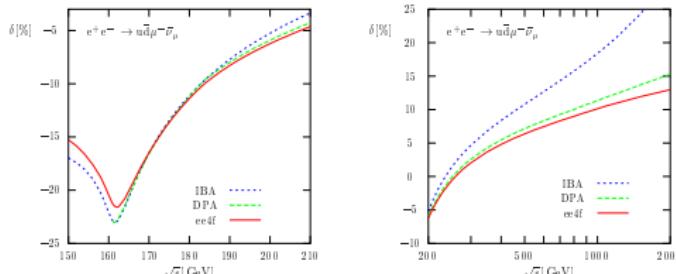
- ✓ less complex loop calculation
- ✓ less diagrams ($\sim \mathcal{O}(10^2)$)
- ✓ little CPU intensive
- ✓ numerically fast

EW corrections in DPA



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Full EW corrections to $e^+ e^- \rightarrow 4\ell$:



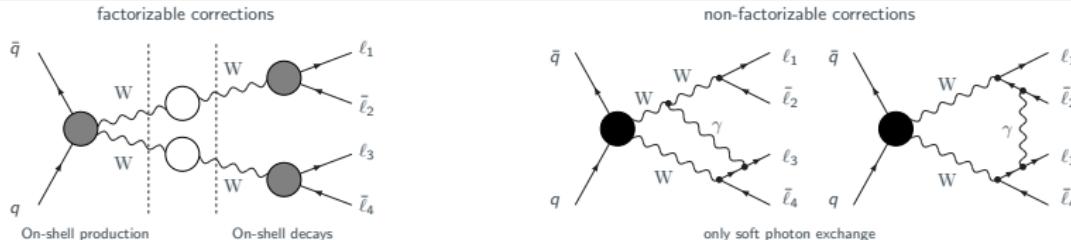
[Denner, Dittmaier, Roth, Wieders '05]

$$\Delta_{4\ell} \sim \delta_{\text{EW}}^2$$

$$\Delta_{\text{DPA}} \sim \frac{\alpha}{\pi} \frac{\Gamma_W}{M_W} \ln(\dots) \sim 0.5 \%$$

$$[170 \text{ GeV} \leq \sqrt{s} \lesssim 500 \text{ GeV}]$$

EW corrections in DPA



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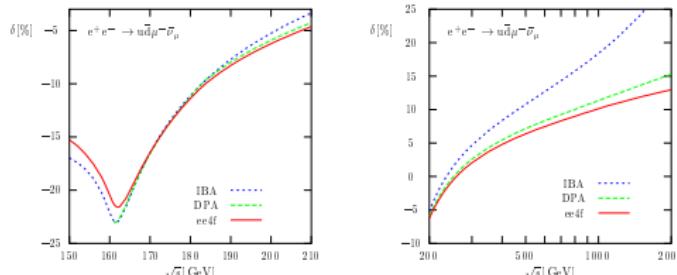
✓ less complex loop calculation
(10^2)

✗ only appear in distributions larger corrections in the TeV-range expected, especially for $p_T(\ell^\pm)$ or $p_T(\ell^+\ell^-)$

⇒ Accuracy in Higgs-signal region unclear

Full EW corrections to $e^+e^- \rightarrow 4\ell$:

[Denner, Dittmaier, Roth, Wieders '05]



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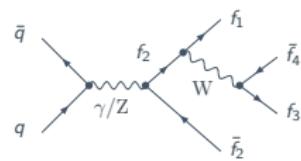
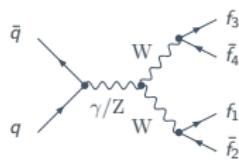
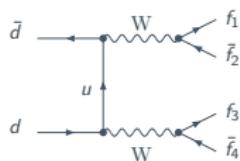
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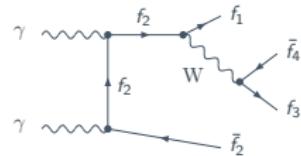
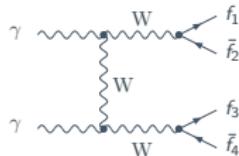
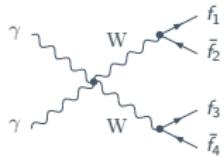
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Contributions to the cross-section

$$\sigma_{H_1 H_2}^{LO} = \sum_{q, \bar{q}} f_q^{H_1} f_{\bar{q}}^{H_2} \otimes \int_4 d\hat{\sigma}_{q\bar{q}}^{LO} \Big|_{+(q \leftrightarrow \bar{q})} + f_\gamma^{H_1} f_\gamma^{H_2} \otimes \int_4 d\hat{\sigma}_{\gamma\gamma}^{LO}$$



...



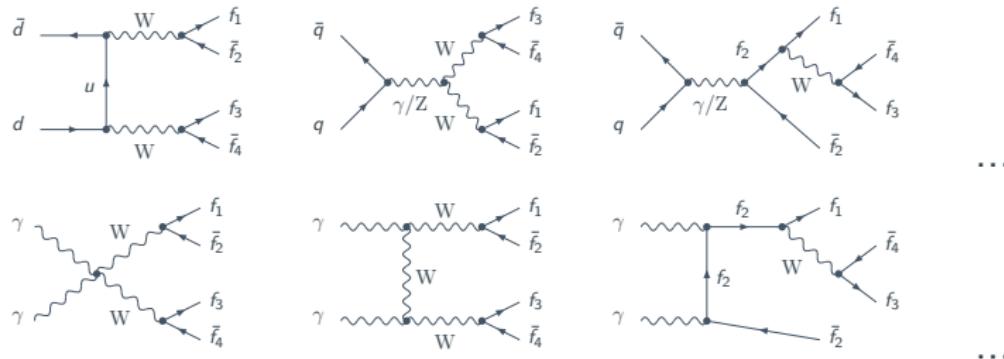
...

- $\sigma_{\bar{b}b}$: PDF-suppressed, contributes $\leq 2\%$ to $\sigma_{\bar{q}q}$
- $\sigma_{\gamma\gamma} : \leq 1\%$ of $\sigma_{\bar{q}q} \rightarrow$ treated as part of EW corrections

Contributions to the cross-section

$$\sigma_{H_1 H_2}^{NLO} = \sum_{q, \bar{q}} f_q^{H_1} f_{\bar{q}}^{H_2} \otimes \left(\int_4 d\hat{\sigma}_{q\bar{q}}^{LO} + \int_5 d\hat{\sigma}_{q\bar{q}}^{real} + \int_4 d\hat{\sigma}_{q\bar{q}}^{virt} + \int_0^1 dx \int_4 d\hat{\sigma}_{q\bar{q}}^{fact} \right) \Big|_{+(q \leftrightarrow \bar{q})}$$

$$+ f_\gamma^{H_1} f_\gamma^{H_2} \otimes \int_4 d\hat{\sigma}_{\gamma\gamma}^{LO}$$



- $\sigma_{\bar{b}b}$: PDF-suppressed, contributes $\leq 2\%$ to $\sigma_{\bar{q}q} \rightarrow m_t$ at NLO...
- $\sigma_{\gamma\gamma} : \leq 1\%$ of $\sigma_{\bar{q}q} \rightarrow$ treated as part of EW corrections

Contributions to the cross-section

$$\begin{aligned}\sigma_{H_1 H_2}^{NLO} = & \sum_{q,\bar{q}} f_q^{H_1} f_{\bar{q}}^{H_2} \otimes \left(\int_4 d\hat{\sigma}_{q\bar{q}}^{LO} + \int_5 d\hat{\sigma}_{q\bar{q}}^{\text{real}} + \int_4 d\hat{\sigma}_{q\bar{q}}^{\text{virt}} + \int_0^1 dx \int_4 d\hat{\sigma}_{q\bar{q}}^{\text{fact}} \right) \Big|_{+(q \leftrightarrow \bar{q})} \\ & + f_\gamma^{H_1} f_\gamma^{H_2} \otimes \int_4 d\hat{\sigma}_{\gamma\gamma}^{LO}\end{aligned}$$

Real corrections: $q\bar{q} \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e + \gamma$



Dipole subtraction for final-state photons

[Dittmaier, Kabelschacht, Kasprzik '99 '08]

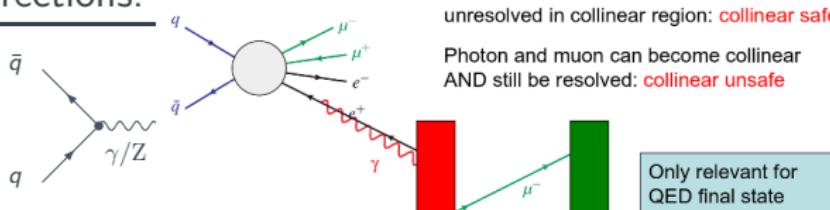
$$\underbrace{\int_5 d\hat{\sigma}_{q\bar{q}}^{\text{real,fin}}}_{\text{suitable for MC-Integration}} = \int_5 d\hat{\sigma}_{q\bar{q}}^{\text{real}} - \int_5 d\hat{\sigma}_{q\bar{q}}^{\text{subtr}}, \quad \int_5 d\hat{\sigma}_{q\bar{q}}^{\text{subtr}} = \underbrace{\int_0^1 dx \int_4 d\hat{\sigma}_{q\bar{q}}^{\text{conv}}}_{\rightarrow \hat{\sigma}^{\text{fact}}} + \underbrace{\int_4 d\hat{\sigma}_{q\bar{q}}^{\text{endp}}}_{\rightarrow \hat{\sigma}^{\text{virt}}}$$

- final-state leptons recombined if $\Delta_{\ell\gamma} < 0.1$ → collinear safe
- final-state muons may remain un-recombined
affects PS-cuts → additional contributions $\propto \frac{\alpha}{\pi} \ln(\frac{m_\mu}{Q})$ → collinear unsafe

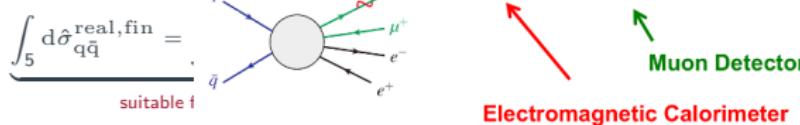
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Real corrections:



Dipole subtraction



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Singularities

belschacht, Kasprzik '99 '08]

$$nv + \underbrace{\int_4 d\hat{\sigma}_{q\bar{q}}^{endp}}_{\rightarrow \hat{\sigma}^{virt}}$$

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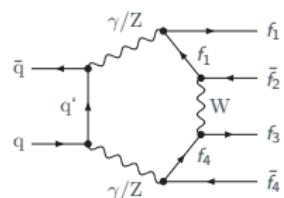
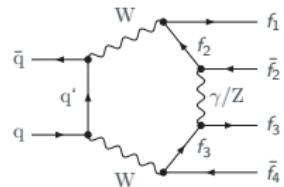
Virtual contributions: $q\bar{q} \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e$

- amplitude generation: inhouse Mathematica routines
→ up to 6-point one-loop tensor integrals
- evaluation of loop integrals with Collier

[Denner, Dittmaier, Hofer '14 '16]

- $\int_4 d\hat{\sigma}_{q\bar{q}}^{endp}$ from subtraction function cancels remaining IR singularities per construction:

$$\Rightarrow \int_4 d\hat{\sigma}_{q\bar{q}}^{virt,fin} = \int_4 d\hat{\sigma}_{q\bar{q}}^{virt} + \int_4 d\hat{\sigma}_{q\bar{q}}^{endp}$$

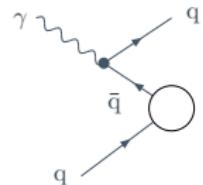


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Real corrections (II): Incoming photons

- $\gamma \rightarrow f\bar{f}^*$ splitting:
 - $f = l$: no singularities ($p_T(l^\pm)$ -cuts)
 - $f = q$: dipole-subtraction approach
- $q \rightarrow q\gamma^*$ splitting:
 - spin-correlated matrix elements for $\gamma\gamma \rightarrow 4\ell$ OR
 - effective collinear factor:
 - restores regulator mass dependence of amplitudes in collinear limit
 - no impact outside collinear regions



Further details on the calculation...

→ two independent implementations:

- **complex-mass scheme:** [Denner, Dittmaier, Roth, Wackerlo '99; Denner, Dittmaier, Roth, Wieders '05]
 $\mu_V^2 = M_V^2 - iM_V\Gamma_V$ for $V = W, Z \rightarrow$ all EW couplings $\propto c_W = \mu_W/\mu_Z \in \mathbb{C}$
- mass- or dimensional regularization
- *bare* and *dressed* leptons supported
- loop integration based on different branches of Collier

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- diagrammatic approach, following $e^+e^- \rightarrow 4\ell$ [Denner et al.'05]
- recursive method: Recola [Actis et al. '13 '16]
- DPA supported [Billoni et al. '13]
- full top-mass dependence
- $m_t = 0$ at NLO

Intensively checked all parts of the calculation.
Integrated results fully agree within stat. uncertainties.

Outline

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Phenomenological setup

LHC Setup:

- NNPDF2.3QED,NLO
- $\mu_F = M_W$
- $\alpha_{G_\mu} = \frac{\sqrt{2} G_\mu M_W^2 s_W^2}{\pi} \approx \frac{1}{132.36}$
- jet def.: $p_{T,i} > 25 \text{ GeV}$,
 $|y_i| < 5$

Minimal cuts:

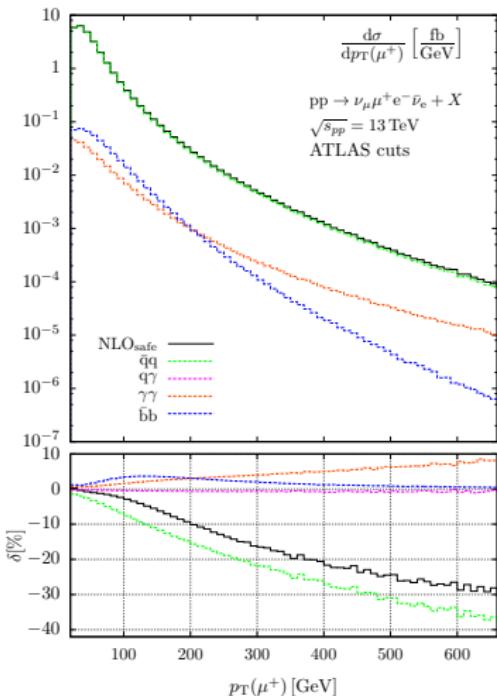
- $p_{T,\ell} > 20 \text{ GeV}$
- $|y_\ell| < 2.5$
- jet veto: $p_{T,\text{jet}} < 100 \text{ GeV}$,
 $R_{\text{jet}\ell} > 0.4$
⇒ avoid large QCD corrections

additional ATLAS cuts (WW search):

[arXiv:1210.2979[hep-ex]]

- $p_{T,\ell}^{\text{leading}} > 25 \text{ GeV}$
- $E_T^{\text{miss}} = |\vec{p}_T^{\text{miss}}| > 25 \text{ GeV}$
- $R_{e\mu} > 0.1$, $M_{e\mu} > 10 \text{ GeV}$
- jet veto: $p_{T,\text{jet}} < 25 \text{ GeV}$
⇒ No Jets!

collinear safe vs. collinear unsafe

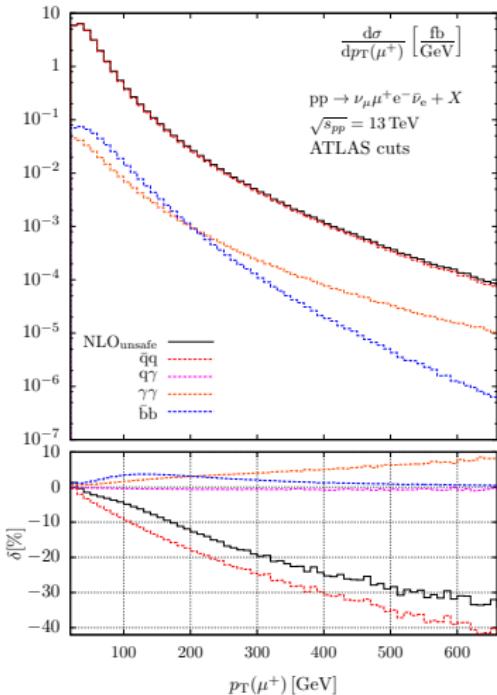


ATLAS-cuts @13 TeV

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$\sigma_{\bar{q}q}^{\text{LO}}$	267.28(5) [fb]	
$\delta_{\bar{q}q}$ safe	– 8.489(4) [fb]	($\approx -3.1\%$)
$\delta_{\bar{q}q}$ unsafe	– 9.913(5) [fb]	($\approx -3.7\%$)
$\delta_{q\gamma}$	– 0.744(2) [fb]	($\approx -0.3\%$)
$\delta_{\gamma\gamma}$	2.377(1) [fb]	($\approx +0.9\%$)
$\delta_{\bar{b}b}$	4.471(1) [fb]	($\approx +1.7\%$)

- $\delta_{q\gamma}$: very small contribution
[\rightarrow dedicated cuts!]
- $\delta_{\gamma\gamma}$: relevance increasing with energy
- $\delta_{\bar{b}b}$: $< 2\%$ (at $p_T \simeq 300 \text{ GeV}$)

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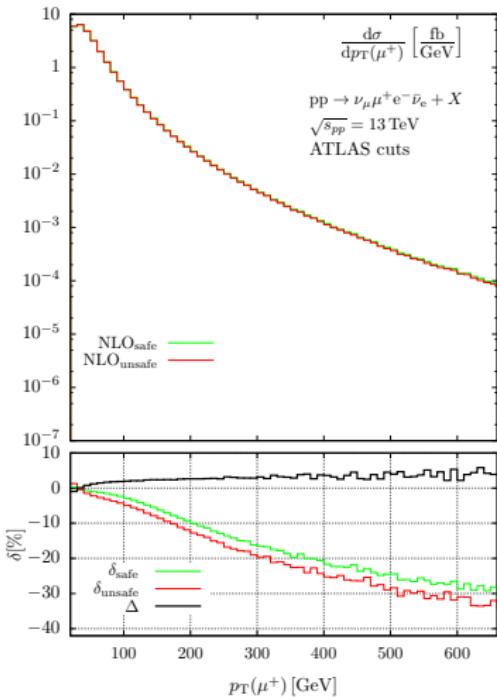


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- $\delta_{\bar{q}q}$: $\approx 35\% - 40\%$ (at $p_T \simeq 600 \text{ GeV}$)

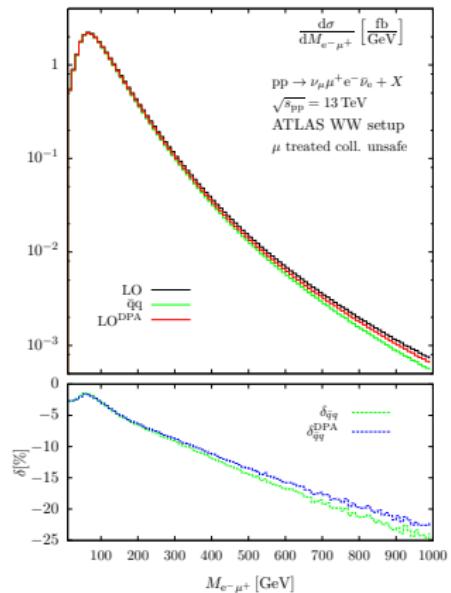
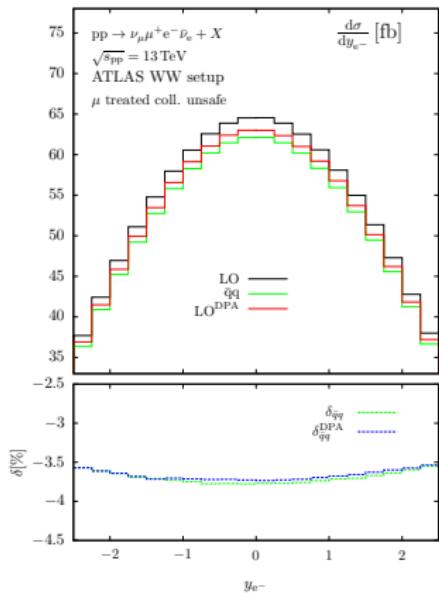
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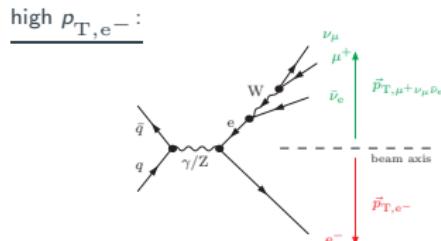
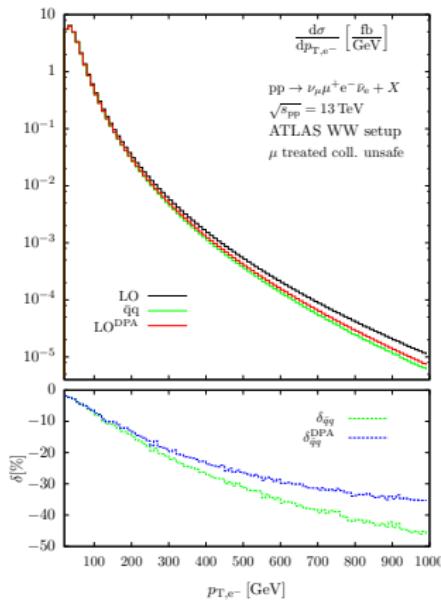
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- $\delta_{\bar{q}q}$: $\approx 35\% - 40\%$ (at $p_T \simeq 600 \text{ GeV}$)

Full corrections vs. DPA



- Rapidity and inv.-mass distributions: show expected agreement of δ^{DPA}
→ not sensitive to difference between DPA and full corrections

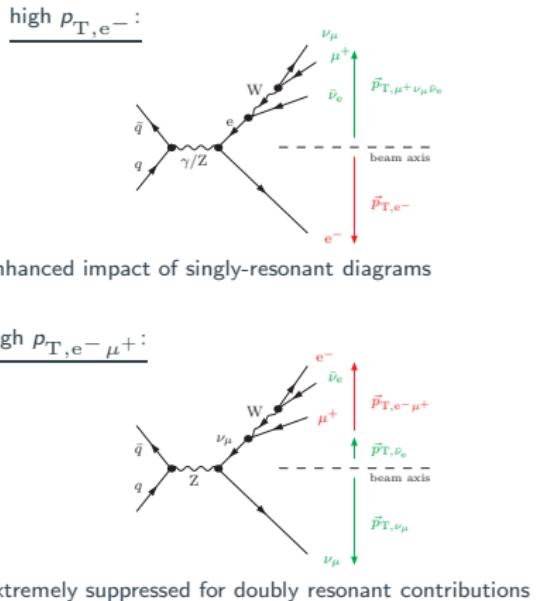
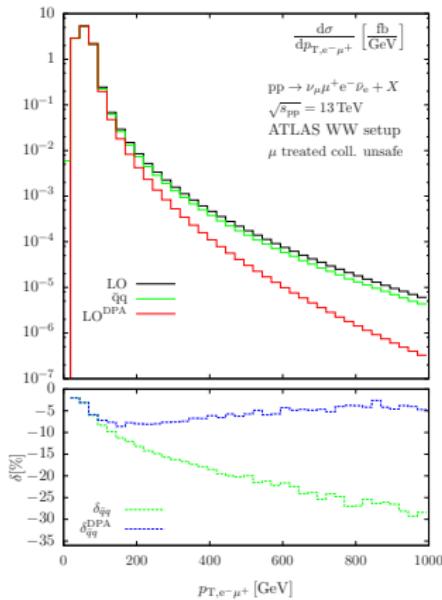
Full corrections vs. DPA



enhanced impact of singly-resonant diagrams

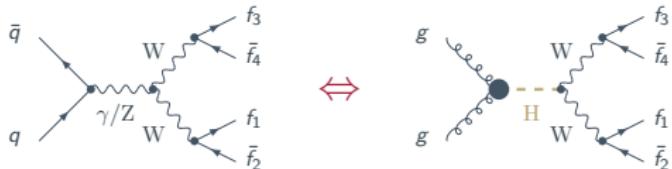
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- Predictions for p_{T} -distributions should be based on full 4-f calculation

Higgs-background setup

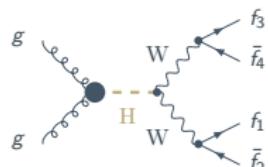
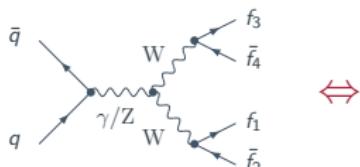


additional cuts:

[arXiv:1412.2641[hep-ex]]

- $10 \text{ GeV} < M_{e\mu} < 55 \text{ GeV}$
- $\Delta\phi_{e\mu} < 1.8$
- $E_T^{\text{miss}} = |\vec{p}_T^{\text{miss}}| > 25 \text{ GeV}$

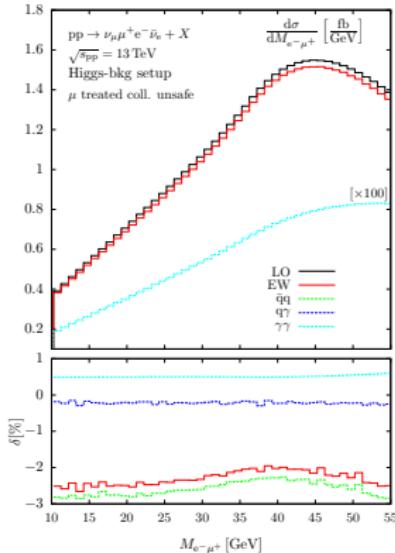
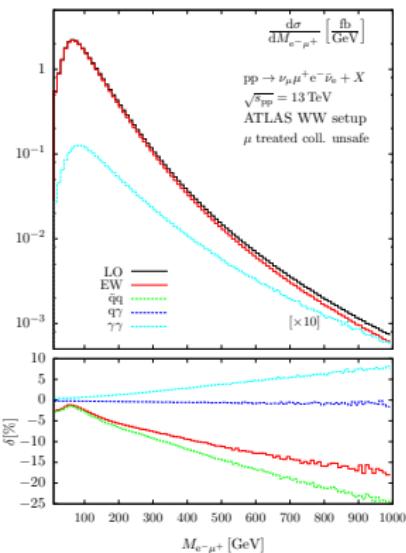
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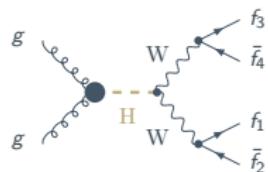
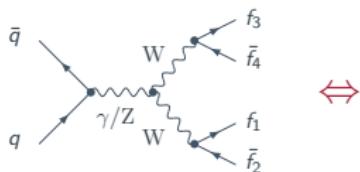
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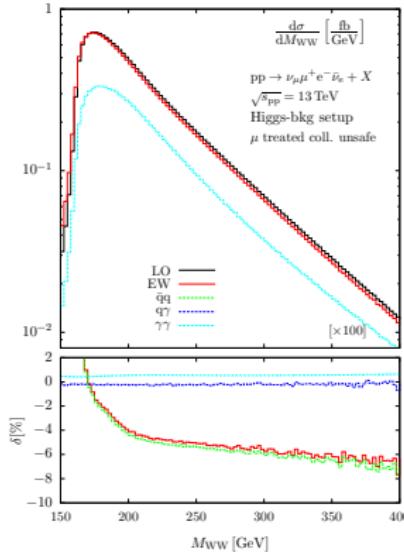
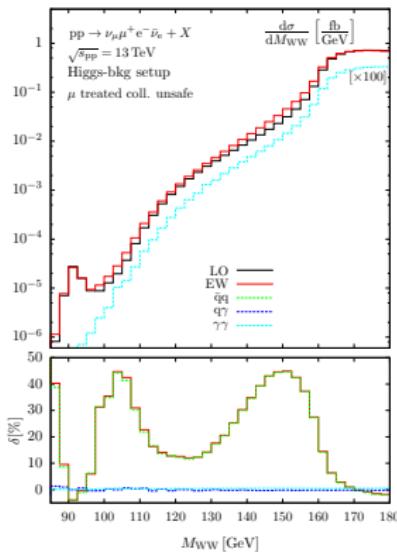
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- $\gamma\gamma$ and $q\gamma$ contributions almost cancel
- M_{WW} : (experimentally unobservable!)
 - XS still dominated by on-shell W-pairs
 - increasing neg. corr. above threshold
 - $\delta_{EW}(M_H) \sim +15 \%$!
 - radiative tail due to FSR below threshold

Summary

- W^+W^- production is very important for a detailed understanding of the EW gauge sector
- full EW corrections can reach up to $\mathcal{O}(-40\%)$ for certain observables
- collinear unsafe generalization enhances corrections ($\sim \mathcal{O}(0.5\%)$)
- below $2M_W$ and in certain phase-space regions: DPA not sufficient
- Higgs-background setup still dominated by on-shell W 's
- positive EW corrections at the physical Higgs-mass

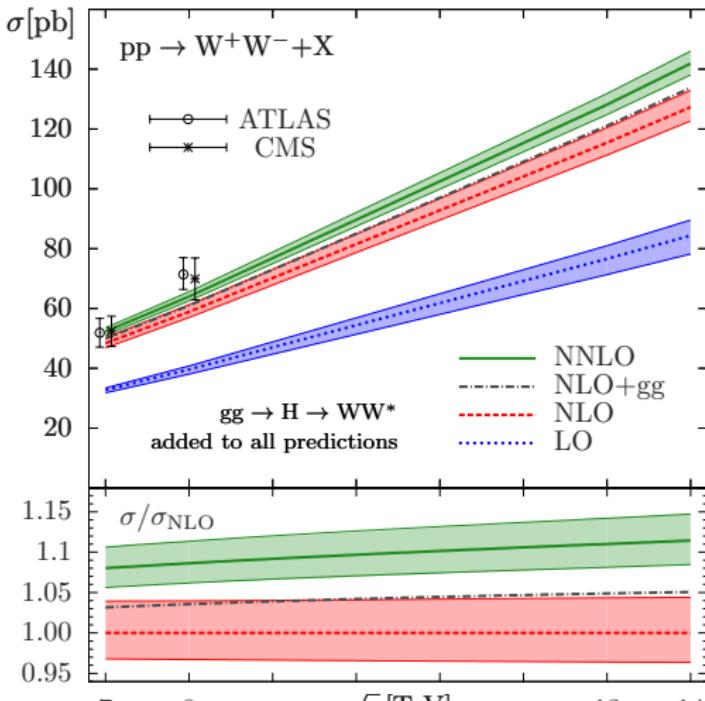
Summary

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Thank you

Backup...

QCD predictions and measurements



[T. Gehrmann et al. '14]

In NNLO-QCD:

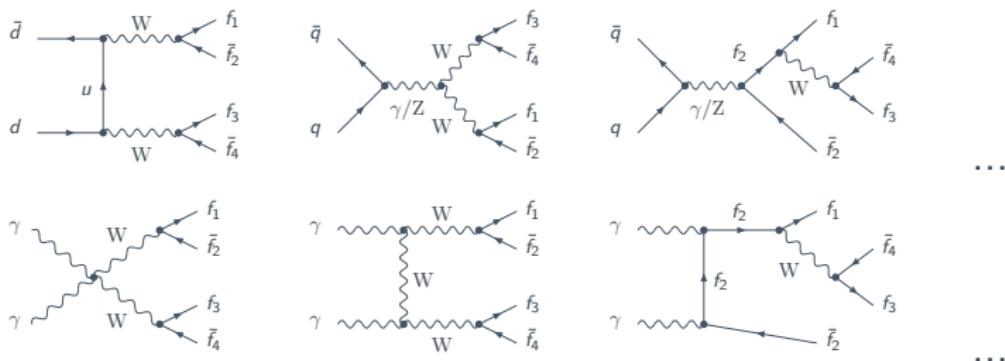
- gg-induced channel fully included
- realistic estimate of theoretical uncertainties
- tension almost disappeared

Measurements:

- for extrapolation from fiducial to inclusive cross section care needed...

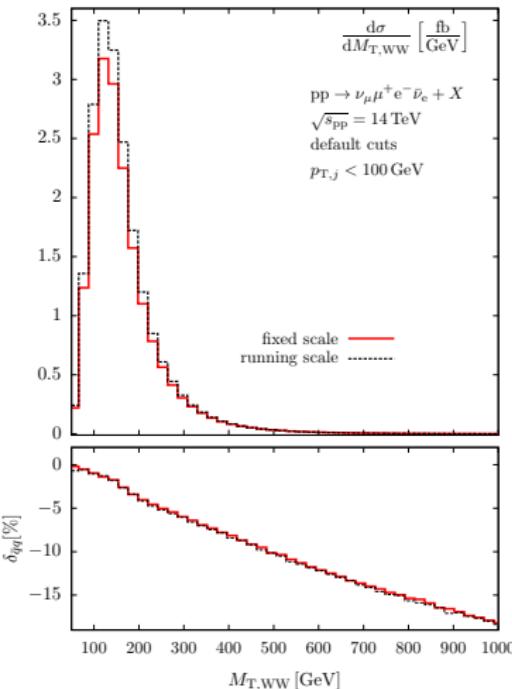
[Monni, Zanderighi '14]

Leading order contributions



- All external particles massless, CKM mixing negligible
⇒ Need partonic matrix elements for: $\bar{u}u/\bar{d}d/\bar{b}b/\gamma\gamma \rightarrow \nu_\mu\mu^+\bar{\nu}_e e^-$
- Only small contributions from $b\bar{b}$ (< 2 %) and $\gamma\gamma$ ($\lesssim 1\%$) on integrated cross-section
⇒ $\gamma\gamma$ -induced: important on differential level

Factorization ansatz

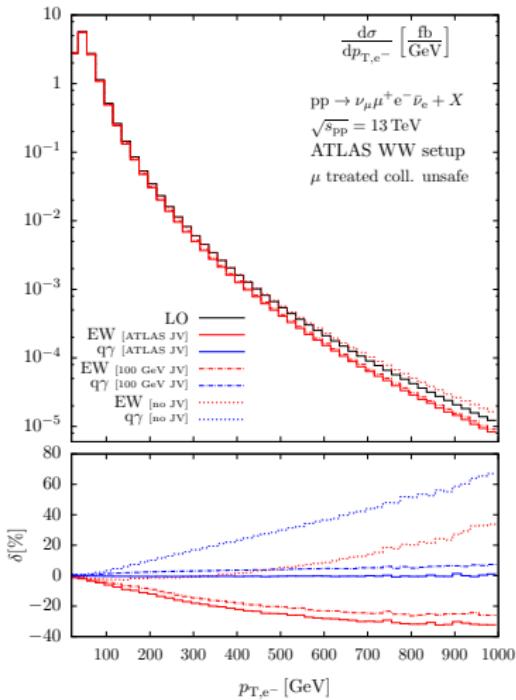


- Dependence on μ_F only via PDFs
- $\pm 8\%$ for $\mu_F = \xi M_W$, $0.5 < \xi < 2$
- shape of distributions affected, but relative corrections $\delta_{\bar{q}q}$ not!

$$d\sigma = d\sigma^{\text{QCD}_{qq}} \times (1 + \delta_{qq}^{\text{EW}}) \\ + d\sigma_{gg} + d\sigma_{\gamma\gamma} + d\sigma_{\gamma q}.$$

[Billoni, Dittmaier, Jäger, Speckner '13]

jet-veto dependence



- jet veto (default in ATLAS): -0.3%
- $p_{T,\text{jet}} < 100 \text{ GeV}$: +0.6%
- no jet-veto: +70%!!
 - giant k-factor
 - $q\gamma$ induced processes

[Baglio, Ninh, Weber '13]

Δ_{DPA} -definition

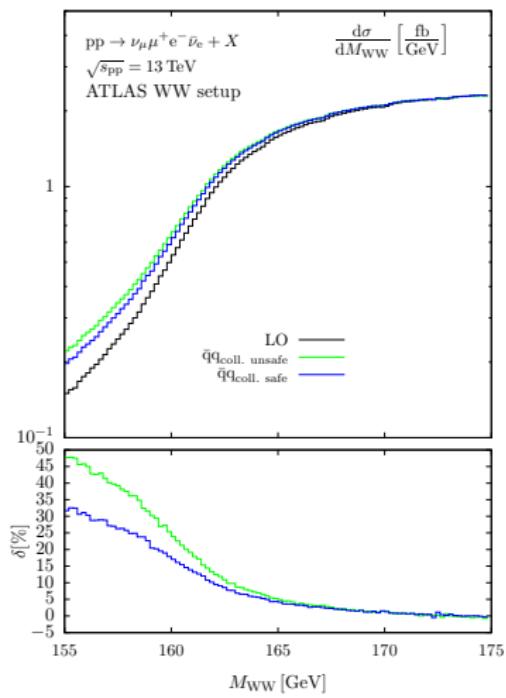
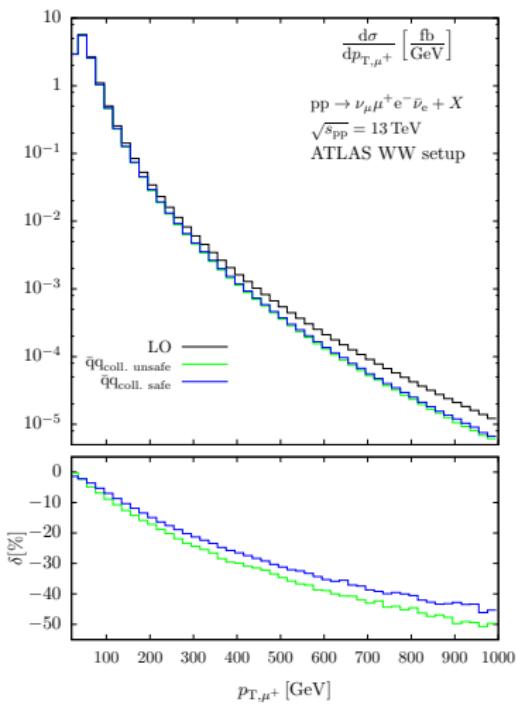
$$\sigma_{\text{NLO EW}}^{\text{DPA}} = \sigma_{\text{LO}} + \Delta\sigma_{\text{EW}}^{\text{DPA}} = \sigma_{\text{LO}} (1 + \delta_{\text{EW}}^{\text{DPA}}), \quad \delta_{\text{EW}}^{\text{DPA}} = \frac{\Delta\sigma_{\text{EW}}^{\text{DPA}}}{\sigma_{\text{LO}}}, \quad (1)$$

we estimate Δ_{DPA} to

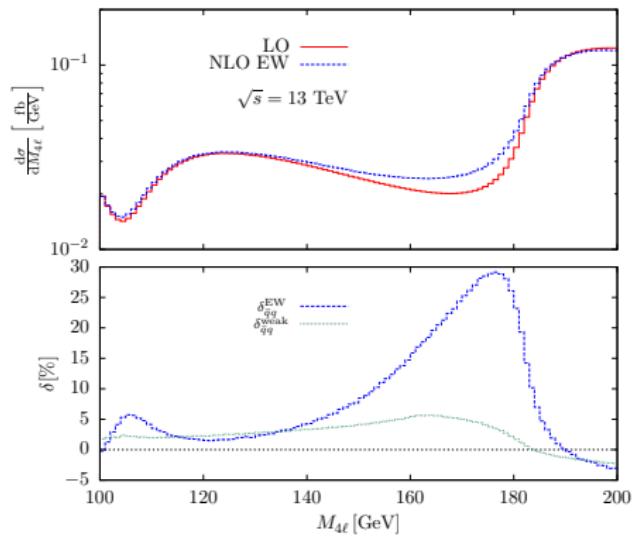
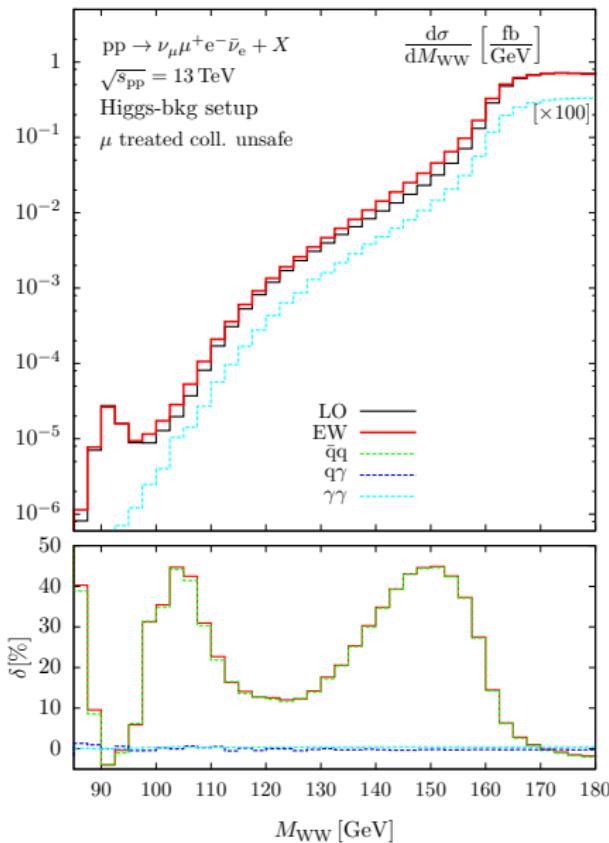
$$\Delta_{\text{DPA}} \sim \max \left\{ \left(\delta_{\text{EW}}^{\text{DPA}} \right)^2, \underbrace{\frac{\alpha}{\pi} \frac{\Gamma_W}{M_W} \ln(\dots), \left| \delta_{\text{EW}}^{\text{DPA}} \right| \times \frac{|\sigma_{\text{LO}} - \sigma_{\text{LO}}^{\text{DPA}}|}{\sigma_{\text{LO}}^{\text{DPA}}} }_{\lesssim 0.5\%} \right\}. \quad (2)$$

can also be written as $\Delta\sigma_{\text{EW}}^{\text{DPA}}/\sigma_{\text{LO}}^{\text{DPA}} \times |\sigma_{\text{LO}} - \sigma_{\text{LO}}^{\text{DPA}}|/\sigma_{\text{LO}}$, where $\Delta\sigma_{\text{EW}}^{\text{DPA}}/\sigma_{\text{LO}}^{\text{DPA}}$ would then be interpreted as the intrinsic relative EW correction of the DPA and $|\sigma_{\text{LO}} - \sigma_{\text{LO}}^{\text{DPA}}|/\sigma_{\text{LO}}$ is the relative deviation of the DPA LO from the full 4f LO cross section.

coll.-safe vs. coll. unsafe



radiative tail in ZZ



NLO-corrections to ZZ

Biedermann et al., [arXiv:1601.07787]

photon recombination

- only consider photons with $|y_\gamma| < 5$.
- determine separation R_{ij} in rapidity-azimuthal plane

$$R_{ij} = \sqrt{(y_i - y_j)^2 + (\Delta\phi_{ij})^2},$$

with y_k rapidity and $\Delta\phi_{ij}$ the azimuthal angle between i and j .

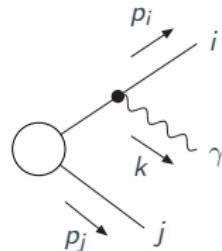
- recombine photons with the closest charged lepton ℓ whenever

$$R_{\gamma\ell} < 0.1.$$

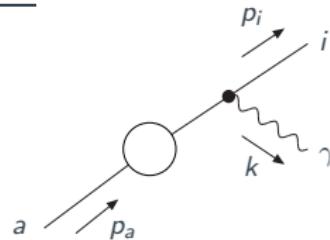
- We form dressed leptons by adding the momenta of the photon and the respective lepton. The momenta of the other particles in the event remain unaffected.

more on dipole subtraction... (i)

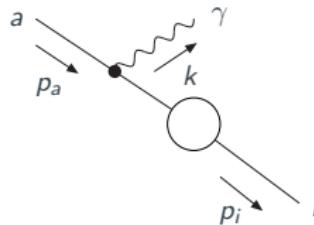
$g_{ij}^{(\text{sub})}$: Final-Final



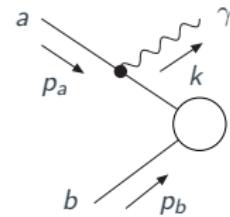
$g_{ia}^{(\text{sub})}$: Final-Initial



$g_{ai}^{(\text{sub})}$: Initial-Final



$g_{ab}^{(\text{sub})}$: Initial-Initial



$$\int_5 d\hat{\delta}_{\bar{q}q}^{\text{real,fin}} = F(x_1 x_2) \int_5 d\Phi_5 \left[\overline{\sum} \left| \mathcal{M}_{\text{real}}^{\bar{q}q \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e \gamma} \right|^2 \Theta(\Phi_5) - \sum_{i,j=1}^6 \sum_{i \neq j} |\mathcal{M}_{\text{sub},ij}|^2 \Theta(\tilde{\Phi}_{4,ij}) \right]$$

more on dipole subtraction... (ii)

$$\int_5 d\hat{\sigma}_{q\bar{q}}^{\text{subtr}} = \underbrace{\int_0^1 dx \int_4 d\hat{\sigma}_{q\bar{q}}^{\text{conv}}}_{\rightarrow \hat{\sigma}^{\text{fact}}} + \underbrace{\int_4 d\hat{\sigma}_{q\bar{q}}^{\text{endp}}}_{\rightarrow \hat{\sigma}^{\text{virt}}}, \quad \int_5 d\Phi_5 = \int_0^1 dx \int_4 d\tilde{\Phi}_{4,ij}(x) \int_1 d\Phi_{\gamma,ij}(x)$$

$$\begin{aligned} \int_5 d\hat{\sigma}_{q\bar{q}}^{\text{subtr}} &= -\frac{\alpha}{2\pi} \sum_{\substack{i,j=1 \\ i \neq j}}^6 (-1)^{i+j} Q_i Q_j \\ &\quad \times \int_0^1 dx \left[\int_4 d\tilde{\Phi}_{4,ij}(x) \mathcal{G}_{ij}(\tilde{s}_{ij}, x) F(x x_1 x_2) \overline{\sum} |\mathcal{M}_{\text{Born}}(\tilde{\Phi}_{4,ij}(x))|^2 \Theta(\tilde{\Phi}_{4,ij}(x)) \right. \\ &\quad \left. - \int_4 d\tilde{\Phi}_{4,ij}(1) \mathcal{G}_{ij}(\tilde{s}_{ij}, x) F(x_1 x_2) \overline{\sum} |\mathcal{M}_{\text{Born}}(\tilde{\Phi}_{4,ij}(1))|^2 \Theta(\tilde{\Phi}_{4,ij}(1)) \right] \\ &- \frac{\alpha}{2\pi} \sum_{\substack{i,j=1 \\ i \neq j}}^6 (-1)^{i+j} Q_i Q_j F(x_1 x_2) \int_4 d\Phi_4 \mathcal{G}_{ij}(s_{ij}) \overline{\sum} |\mathcal{M}_{\text{Born}}(\Phi_4)|^2 \Theta(\Phi_4) \end{aligned}$$

$$\mathcal{G}_{ij}(\tilde{s}_{ij}, x) = 8\pi^2 x \int_1 d\Phi_{\gamma,ij}(x) g_{ij}(q_i, q_j, k). \quad \mathcal{G}_{ij}(s_{ij}) = \int_0^1 dx \mathcal{G}_{ij}(s_{ij}, x) = \mathcal{L}(s_{ij}, m_i^2) + C_{ij},$$

$$\mathcal{L}(s, m^2) = \ln\left(\frac{m^2}{s}\right) \ln\left(\frac{\lambda^2}{s}\right) + \ln\left(\frac{\lambda^2}{s}\right) - \frac{1}{2} \ln^2\left(\frac{m^2}{s}\right) + \frac{1}{2} \ln\left(\frac{m^2}{s}\right)$$

Improved Born approximation

[Dittmaier, Böhm, Denner '92; Denner, Dittmaier, Roth, Wackerlo '01]

$$d\hat{\sigma}_{\bar{q}q}^{\text{IBA}} = F(x_1 x_2) d\Phi_4 \overline{\sum} \left| \mathcal{M}_{\text{IBA}}^{\bar{q}q \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e} \right|^2 [1 + \delta_{\text{Coul}}(\hat{s}, k_+^2, k_-^2)] g(\bar{\beta}).$$

- $\frac{e^2}{s_W^2} \rightarrow 4\sqrt{2} G_\mu M_W^2, \quad e^2 \rightarrow 4\pi\alpha(\hat{s})$
- for photon exchange:

$$\alpha(Q^2) = \frac{\alpha(M_Z^2)}{1 - \frac{\alpha(M_Z^2)}{3\pi} \ln\left(\frac{Q^2}{M_Z^2}\right) \sum_{f \neq t} N_f^c Q_f^2}$$

- universal correction factor δ_{Coul} to account for the contribution of the Coulomb singularity from photon exchange near W-pair production threshold. Has only an impact in the threshold region.