Electroweak corrections to $\mathrm{pp} \to \mathrm{W^+W^-} \to 4\,\mathrm{leptons}$ at the LHC

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in collaboration with

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DESY Theory Workshop
Sept. 29 - Oct. 02, 2015

Outline

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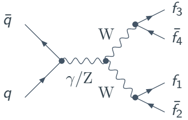
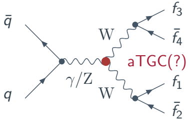
Motivation: Why W^+W^- is interesting...

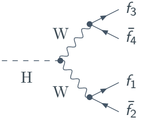
- Probe non-abelian structure of the Standard Model:
  $\rightarrow$ simplest process with trilinear gauge couplings



- Limits on anomalous gauge couplings



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



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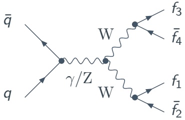
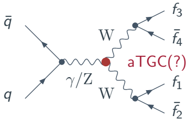


- Limits on anomalous gauge couplings

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



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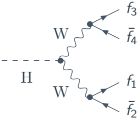
  $\rightarrow$ low energy region: $M_{4\ell} \leq 2M_W$



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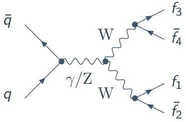

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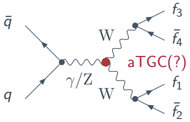

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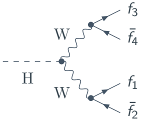


- at leading order $\mathcal{O}(\alpha^4) \rightarrow$ little "QCD-pollution"

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, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi '14]

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]

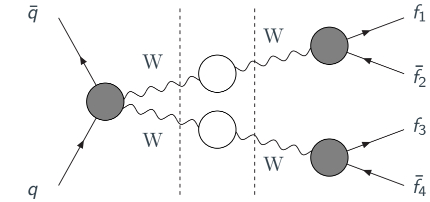
- NLO corrections to $pp \to W^+W^- \to 4\,l$ in DPA

[Billoni, Dittmaier, Jäger, Speckner '13]

Measurements

- Measurements of W^+W^- production cross sections at 7 and 8 TeV

[ATLAS, CMS '11 '13]

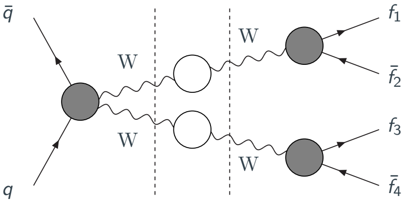


- Double-pole approximation (DPA):
  first applied in `RacoonWW`: $e^+e^- \to 4\,\ell$ [Denner, Dittmaier, Roth, Wackeroth '99 - '02]

- Full EW corrections to $e^+e^- \to 4\,\ell$ [Denner, Dittmaier, Roth, Wieders '06]

  $\Rightarrow \Delta_{\mathrm{DPA}} \sim \frac{\alpha}{2\pi}\frac{\Gamma_{\mathrm{W}}}{M_{\mathrm{W}}} \sim 0.5\,\%$ $\quad [170\,\mathrm{GeV} \leq \sqrt{s} \lesssim 500\,\mathrm{GeV}]$

NLO EW in double-pole approximation



$\Rightarrow$ virtual corrections only to doubly resonant diagrams!

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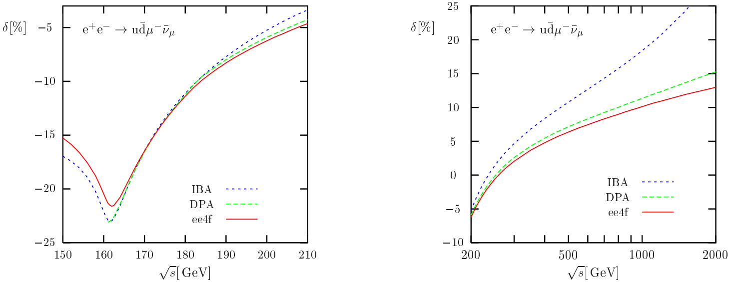


[Denner, Dittmaier, Roth, Wieders '06]

$\sqrt{s} \leq 2M_\mathrm{W}$:

- DPA not applicable!
- Improved Born approximation (IBA) used

$\sqrt{s} \gg 2M_\mathrm{W}$:

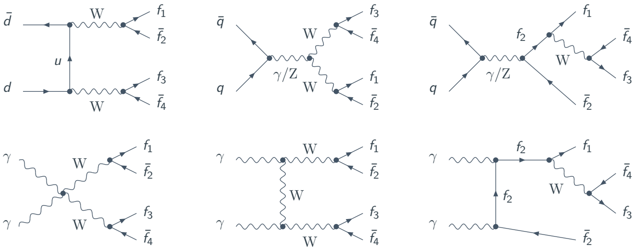
- Difference on integrated cross-section should stay $\lesssim 1\,\%$
- In distributions larger corrections in the TeV-range expected, especially for $p_\mathrm{T}(\ell^\pm)$ or $p_\mathrm{T}(\ell^+\ell^-)$

$\Rightarrow$ Full EW corrections needed

Outline

Contributions to the cross-section

$$
\begin{aligned}
\sigma_{\mathrm{H_1H_2}}^{\mathit{LO}} = &\left(\sum_{\mathrm{q},\bar{\mathrm{q}}} f_{\mathrm{q}}^{\mathrm{H}_1} f_{\bar{\mathrm{q}}}^{\mathrm{H}_2} \otimes \left[\int_4 \mathrm{d}\hat{\sigma}_{\mathrm{q}\bar{\mathrm{q}}}^{\mathit{LO}} \qquad\qquad\qquad \right] + (\mathrm{q} \leftrightarrow \bar{\mathrm{q}})\right) \\
&+ \left(\quad f_{\mathrm{b}}^{\mathrm{H}_1} f_{\bar{\mathrm{b}}}^{\mathrm{H}_2} \otimes \int_4 \mathrm{d}\hat{\sigma}_{\mathrm{b}\bar{\mathrm{b}}}^{\mathit{LO}} + (\mathrm{b} \leftrightarrow \bar{\mathrm{b}})\right) \\
&+ \left(\quad f_{\gamma}^{\mathrm{H}_1} f_{\gamma}^{\mathrm{H}_2} \otimes \int_4 \mathrm{d}\hat{\sigma}_{\gamma\gamma}^{\mathit{LO}} \quad \right)
\end{aligned}
$$



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Contributions to the cross-section

$$\sigma^{NLO}_{\mathrm{H_1H_2}} = \Bigg(\sum_{\mathrm{q},\bar{\mathrm{q}}} f^{\mathrm{H_1}}_{\mathrm{q}} f^{\mathrm{H_2}}_{\bar{\mathrm{q}}} \otimes \Bigg[\int_4 \mathrm{d}\hat{\sigma}^{LO}_{\mathrm{q}\bar{\mathrm{q}}} + \int_5 \mathrm{d}\hat{\sigma}^{real}_{\mathrm{q}\bar{\mathrm{q}}} + \int_4 \mathrm{d}\hat{\sigma}^{virt}_{\mathrm{q}\bar{\mathrm{q}}} + \int_0^1 \mathrm{d}x \int_4 \mathrm{d}\hat{\sigma}^{fact}_{\mathrm{q}\bar{\mathrm{q}}}\Bigg] + (\mathrm{q} \leftrightarrow \bar{\mathrm{q}})\Bigg)$$

$$+ \Bigg(f^{\mathrm{H_1}}_{\mathrm{b}} f^{\mathrm{H_2}}_{\bar{\mathrm{b}}} \otimes \int_4 \mathrm{d}\hat{\sigma}^{LO}_{\mathrm{b}\bar{\mathrm{b}}} + (\mathrm{b} \leftrightarrow \bar{\mathrm{b}})\Bigg)$$

$$+ \Bigg(f^{\mathrm{H_1}}_{\gamma} f^{\mathrm{H_2}}_{\gamma} \otimes \int_4 \mathrm{d}\hat{\sigma}^{LO}_{\gamma\gamma} \Bigg)$$

Contributions to the cross-section

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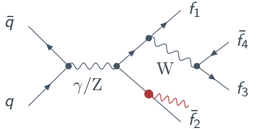
$$+ \left(f^{\mathrm{H_1}}_{b} f^{\mathrm{H_2}}_{\bar{b}} \otimes \int_4 d\hat{\sigma}^{LO}_{b\bar{b}} + (b \leftrightarrow \bar{b}) \right)$$
$$+ \left(f^{\mathrm{H_1}}_{\gamma} f^{\mathrm{H_2}}_{\gamma} \otimes \int_4 d\hat{\sigma}^{LO}_{\gamma\gamma} \right)$$

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



$\Rightarrow$ soft and/or collinear singularities!

Dipole subtraction formalism for final-state photons

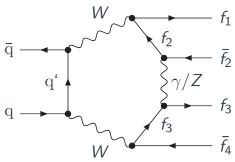
$\Rightarrow$ suitable for MC-Integration!

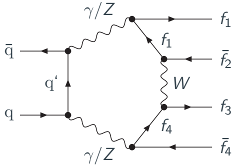
[Dittmaier, Kabelschacht, Kasprzik '99 '08]

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

- amplitude generation: inhouse `Mathematica` routines
  - $\to$ up to 6-point one-loop tensor integrals
  - $\to$ after renormalization: UV finite
- reduction of one-loop tensor integrals

[Denner,Dittmaier '05]





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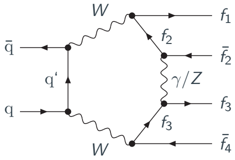
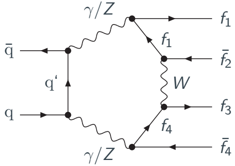
  [Denner,Dittmaier '05]
- $\int_4 d\hat{\sigma}^{\mathrm{endp}}_{q\bar{q}}$ from subtraction function cancels remaining IR singularities per construction:

$$\int_5 d\hat{\sigma}^{\mathrm{subtr}}_{q\bar{q}} = \underbrace{\int_0^1 dx \int_4 d\hat{\sigma}^{\mathrm{conv}}_{q\bar{q}}}_{\to\ \hat{\sigma}^{\mathrm{fact}}} + \underbrace{\int_4 d\hat{\sigma}^{\mathrm{endp}}_{q\bar{q}}}_{\to\ \hat{\sigma}^{\mathrm{virt}}}$$





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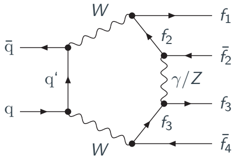

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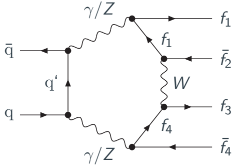

$$\Rightarrow \quad \int_4 \mathrm{d}\hat{\sigma}^{\mathrm{virt,fin}}_{q\bar{q}} = \int_4 \mathrm{d}\hat{\sigma}^{\mathrm{virt}}_{q\bar{q}} + \int_4 \mathrm{d}\hat{\sigma}^{\mathrm{endp}}_{q\bar{q}}$$

Contributions to the cross-section

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$$+ \Bigg(f^{\mathrm{H_1}}_{\mathrm{b}} f^{\mathrm{H_2}}_{\bar{\mathrm{b}}} \otimes \int_4 \mathrm{d}\hat{\sigma}^{LO}_{\mathrm{b\bar{b}}} + (\mathrm{b} \leftrightarrow \bar{\mathrm{b}}) \Bigg)$$

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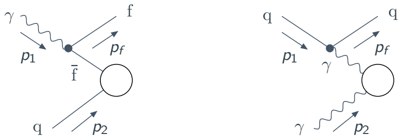
\end{aligned}
$$

Real corrections (II): Incoming photons



Further details on the calculation...

- Multi-channel integrator based on `Coffer`$\gamma\gamma$: $\gamma\gamma \to 4\,\ell$

[Bredenstein,Dittmaier,Roth '05]

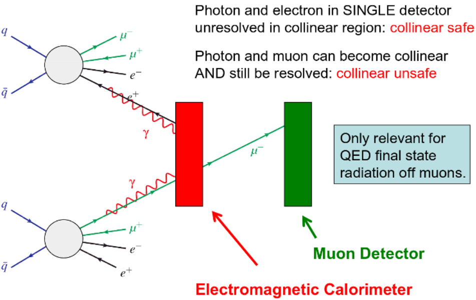
- Tree-level contributions:
  - Weyl-van-der-Waerder spinor formalism
  - complex-mass scheme:
    $\to \mu_V^2 = M_V^2 - \mathrm{i} M_V \Gamma_V$ for $V = \mathrm{W}, \mathrm{Z}$
    $\to$ all EW couplings $\propto c_\mathrm{w} = \mu_\mathrm{W} / \mu_\mathrm{Z}$

[Denner, Dittmaier, Roth, Wackeroth '99; Denner, Dittmaier, Roth, Wieders '05]

- generalized to non-collinear-safe observables

Collinear unsafe observables

[Dittmaier, Kabelschacht, Kasprzik '08]



muon mass enters as regulator only in the subtraction part

$\Rightarrow$ no complete cancellation against virtual corrections

no recombination for final-state muons

$\Rightarrow$ affects phase-space cuts and binning of certain observables

$\Rightarrow$impact on cross-section and differential distributions!

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[Denner, Dittmaier, Roth, Wackeroth '99; Denner, Dittmaier, Roth, Wieders '05]

- generalized to non-collinear-safe observables
  - final-state leptons recombined if $\Delta_{\ell\gamma} < 0.1$ $\to$ collinear safe
  - final-state muons may remain un-recombined $\to$ collinear unsafe

...extensively checked via second independent implementation by Benedikt Biedermann!

[Recola: Actis et al.; Collier: Denner, Dittmaier, Hofer '14]

Outline

Phenomenological setup

LHC Setup:

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

Minimal cuts:

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

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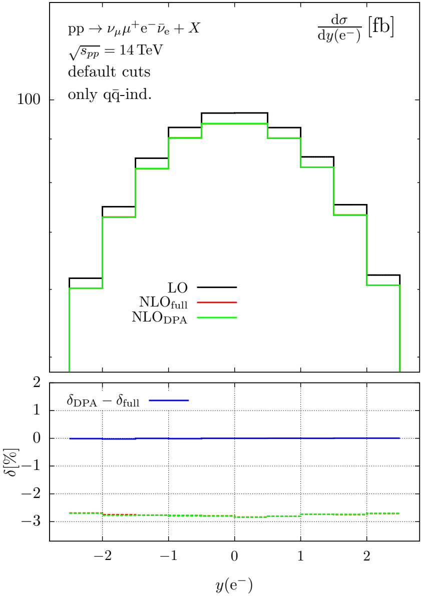
additional ATLAS cuts (WW search):

[arXiv:1210.2979[hep-ex]]

- $p_{\mathrm{T},\ell}^{\mathrm{leading}} > 25\,\mathrm{GeV}$
- $E_\mathrm{T}^{\mathrm{miss}} = |\vec{p}_\mathrm{T}^{\,\mathrm{miss}}| > 25\,\mathrm{GeV}$
- $R_{\mathrm{e}\mu} > 0.1\,,\;\; M_{\mathrm{e}\mu} > 10\,\mathrm{GeV}$
- jet veto: $p_{\mathrm{T,jet}} < 25\,\mathrm{GeV}$

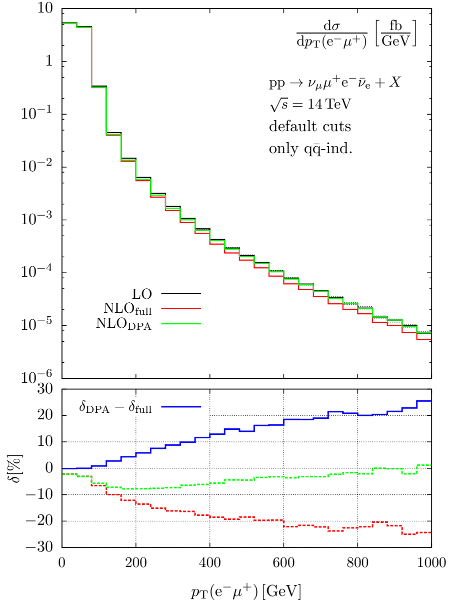
  $\Rightarrow$ No Jets!



- Rapidity: not sensitive to difference between DPA and full corrections

$$\delta_X(\mathcal{O}) = \frac{\frac{d\sigma_X^{\mathrm{NLO}}}{d\mathcal{O}} - \frac{d\sigma^{\mathrm{LO}}}{d\mathcal{O}}}{\frac{d\sigma^{\mathrm{LO}}}{d\mathcal{O}}}$$

Preliminary results(I): Full corrections vs. DPA



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- $p_T(\ell^+\ell^-)$:
  - $\rightarrow$ large difference in TeV-region
  - $\rightarrow$ high $p_T(l^+l^-) \leftrightarrow$ non-doubly resonant contributions

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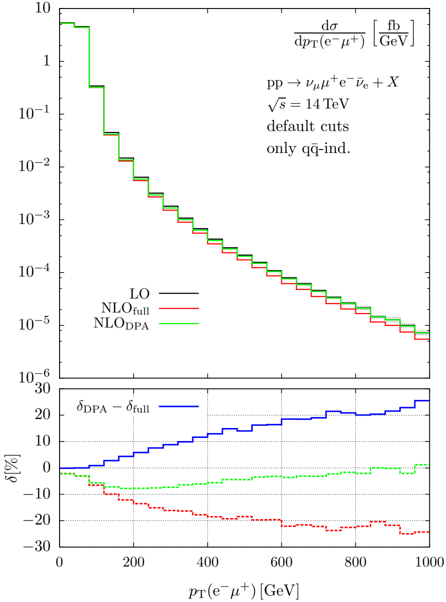

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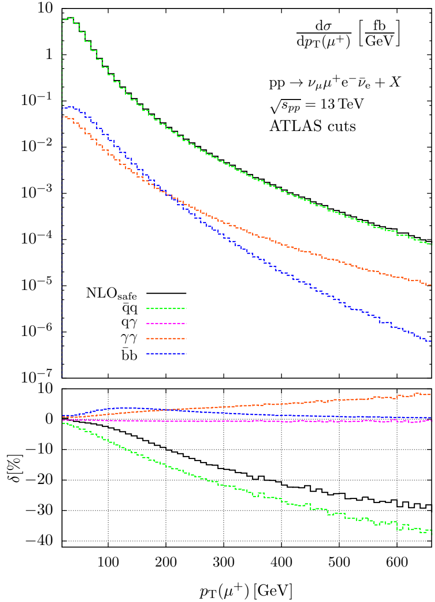
- $p_T(\ell^+\ell^-)$:
  - $\to$ large difference in TeV-region
  - $\to$ high $p_T(l^+l^-)$ $\leftrightarrow$ non-doubly resonant contributions
  - $\to$ large effect of virtual corrections to non-doubly resonant contributions

Only contained in full calculation!

Preliminary results(II): collinear safe vs. collinear unsafe



ATLAS-cuts @13 TeV

$\sigma^{LO}_{\bar{q}q}$			267.28(5) [fb]	
$\delta_{\bar{q}q}$	safe	$-$	8.489(4) [fb]	($\approx -3.1\,\%$)
	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]	($\approx +1.7\,\%$)

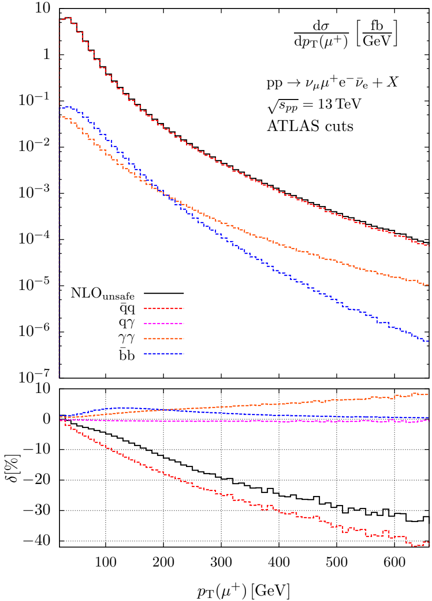
- $\delta_{q\gamma}$: very small contribution

  [→dedicated cuts!]

- $\delta_{\gamma\gamma}$: relevance increasing with energy

- $\delta_{\bar{b}b}$: $< 2\,\%$ (at $p_T \simeq 300$ GeV)

Preliminary results(II): collinear safe vs. collinear unsafe



ATLAS-cuts @13 TeV

$\sigma^{LO}_{\bar{q}q}$			267.28(5) [fb]	
$\delta_{\bar{q}q}$	safe	–	8.489(4) [fb]	($\approx -3.1\,\%$)
	unsafe	–	9.913(5) [fb]	($\approx -3.7\,\%$)
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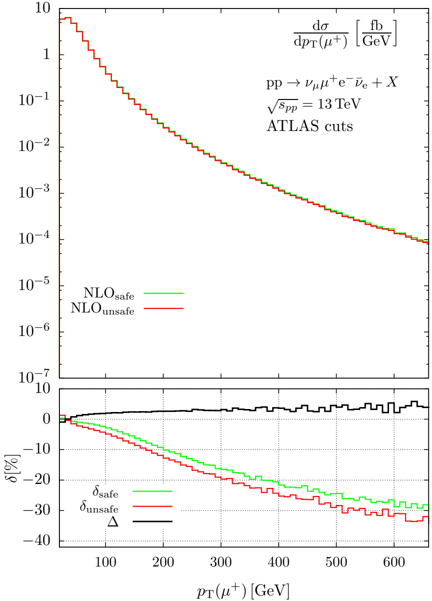

ATLAS-cuts @13 TeV

$\sigma^{LO}_{\bar{q}q}$			267.28(5) [fb]	
$\delta_{\bar{q}q}$	safe	−	8.489(4) [fb]	(≈ −3.1 %)
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$\delta_{\gamma\gamma}$			2.377(1) [fb]	(≈ +0.9 %)
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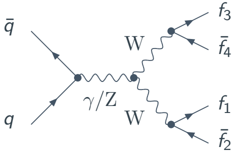
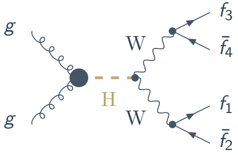
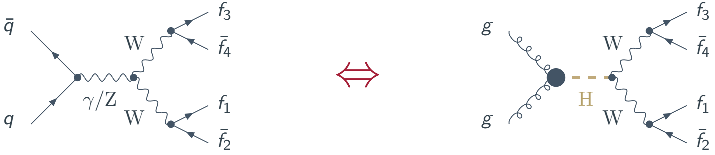
Preliminary results(III): Higgs-background setup



$\Leftrightarrow$



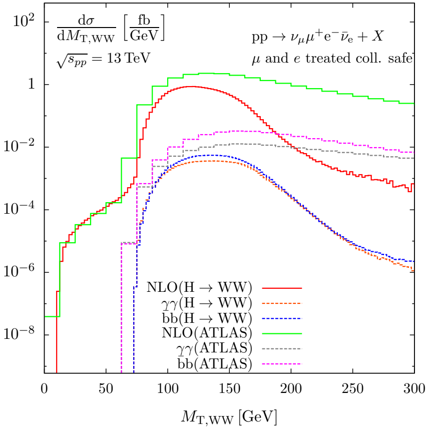


additional cuts: [arXiv:1412.2641[hep-ex]]

- $10\,\mathrm{GeV} < M_{e\mu} < 55\,\mathrm{GeV}$
- $\Delta\phi_{e\mu} < 1.8$
- $E_{\mathrm{T}}^{\mathrm{miss}} = |\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}| > 25\,\mathrm{GeV}$

Higgs-background-cuts @13 TeV

$\sigma^{\mathrm{LO}}_{\bar{q}q}$			49.54(3) [fb]	
$\delta_{\bar{q}q}$	safe	$-$	0.978(4) [fb]	($\approx -2.0\,\%$)
$\delta_{q\gamma}$		$-$	0.112(2) [fb]	($\approx -0.2\,\%$)
$\delta_{\gamma\gamma}$			0.257(1) [fb]	($\approx +0.5\,\%$)
$\delta_{\bar{b}b}$			0.358(1) [fb]	($\approx +0.7\,\%$)



Outline

Summary

- $\mathrm{W^+W^-}$ production is very important for a detailed understanding of the EW gauge sector
- below $2M_\mathrm{W}$ and in certain phase-space regions: DPA not sufficient
- full EW corrections can reach up to $\mathcal{O}(-40\%)$ for certain observables
- collinear unsafe generalization enhances corrections ($\sim \mathcal{O}(1\%)$)
- Higgs-background setup still dominated by on-shell W's

Summary

- $\mathrm{W^+W^-}$ production is very important for a detailed understanding of the EW gauge sector
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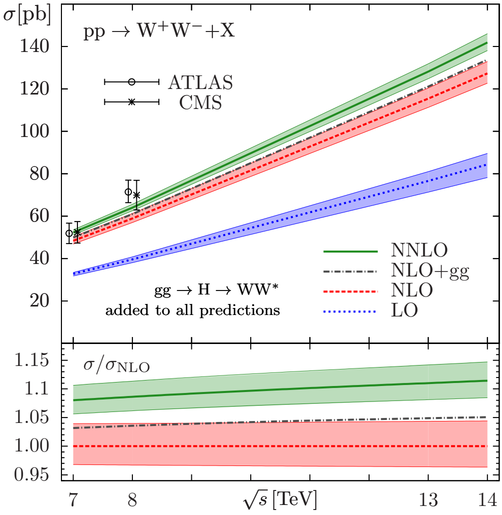
Thank you for your attention ☺

Backup...



[T. Gehrmann et al. '14]

In NNLO-QCD:

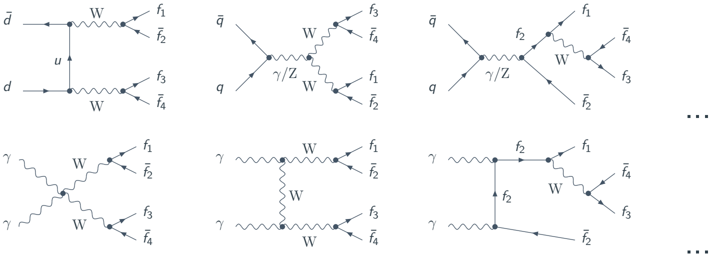
- → gg-induced channel fully included
- → realistic estimate of theoretical uncertainties
- → tension almost disappeared

Measurements:

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

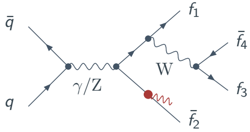
[Monni, Zanderighi '14]

Leading order contributions



- All external particles massless, CKM mixing negligible
  - $\Rightarrow$ Need partonic matrix elements for: $\bar{\mathrm{u}}\mathrm{u}/\bar{\mathrm{d}}\mathrm{d}/\bar{\mathrm{b}}\mathrm{b}/\gamma\gamma \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e}$
- Only small contributions from $\mathrm{b}\bar{\mathrm{b}}$ ($< 2\,\%$) and $\gamma\gamma$ ($\lesssim 1\,\%$) on integrated cross-section
  - $\Rightarrow$ No higher order corrections considered for these channels
  - $\Rightarrow$ $\gamma\gamma$-induced: important on differential level

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



$\Rightarrow$ soft and/or collinear singularities!

Dipole subtraction formalism for final-state photons:

[Dittmaier, Kabelschacht, Kasprzik '99 '08]

$$\int_5 d\hat{\sigma}_{q\bar{q}}^{\text{real,fin}} = \int_5 d\hat{\sigma}_{q\bar{q}}^{\text{real}} - \int_5 d\hat{\sigma}_{q\bar{q}}^{\text{subtr}}$$

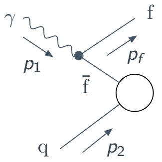
$\Rightarrow$ suitable for MC-Integration!

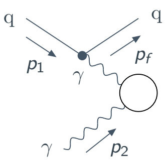
$$\int_5 d\hat{\sigma}_{q\bar{q}}^{\text{subtr}} = \underbrace{\int_0^1 dx \int_4 d\hat{\sigma}_{q\bar{q}}^{\text{conv}}}_{\to\ \hat{\sigma}^{\text{fact}}} + \underbrace{\int_4 d\hat{\sigma}_{q\bar{q}}^{\text{endp}}}_{\to\ \hat{\sigma}^{\text{virt}}}$$

$\Rightarrow$ both separately IR singular

- $\int_0^1 dx \int_4 \left(d\hat{\sigma}_{q\bar{q}}^{\text{fact}} + d\hat{\sigma}_{q\bar{q}}^{\text{conv}}\right)$ per construction IR finite
- $\int_4 d\hat{\sigma}_{q\bar{q}}^{\text{endp}}$: all real-emission IR singularities with LO kinematics

Real corrections (II): Incoming photons [Dittmaier, Kabelschacht, Kasprzik '08]



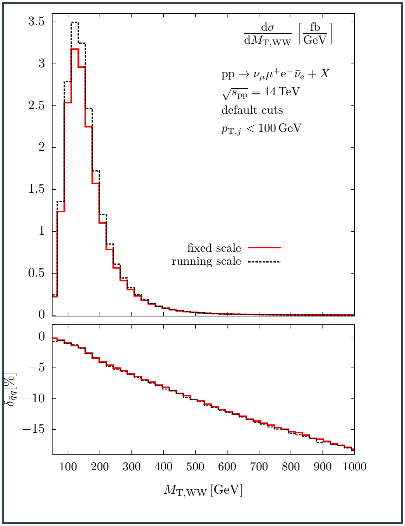


- $\gamma \to \mathrm{f}\bar{\mathrm{f}}^*$ splitting:
  - $\mathrm{f} = \mathrm{l}$: no singularities if $p_\mathrm{T}(\mathrm{l}^\pm)$-cuts applied
  - $\mathrm{f} = \mathrm{q}$: dipole-subtraction approach
- $\mathrm{q} \to \mathrm{q}\gamma^*$ splitting:
  - spin-correlated matrix elements for $\gamma\gamma \to 4\,\ell$ OR
  - effective collinear factor:

    $\to$ restores regulator mass dependence of amplitudes in collinear limit

    $\to$ no impact outside collinear regions

Factorization ansatz



[Billoni, Dittmaier, Jäger, Speckner '13]

- 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!

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

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

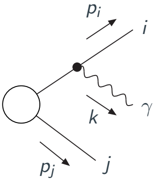
$$R_{ij} = \sqrt{(y_i - y_j)^2 + (\Delta\phi_{ij})^2}\,,$$

with y_k rapidity and $\Delta\phi_{ij}$ the azimuthal angle between i and j.
- recombine photons with the closest charged lepton ℓ whenever

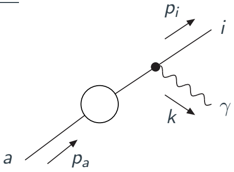
$$R_{\gamma\ell} < 0.1\,.$$

- 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.

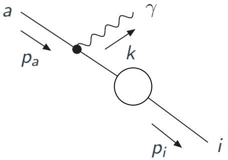
$g_{ij}^{(\mathrm{sub})}$: Final-Final



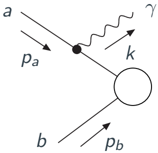
$g_{ia}^{(\mathrm{sub})}$: Final-Initial



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



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



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

more on dipole subtraction...(ii)

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

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

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

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

Improved Born approximation

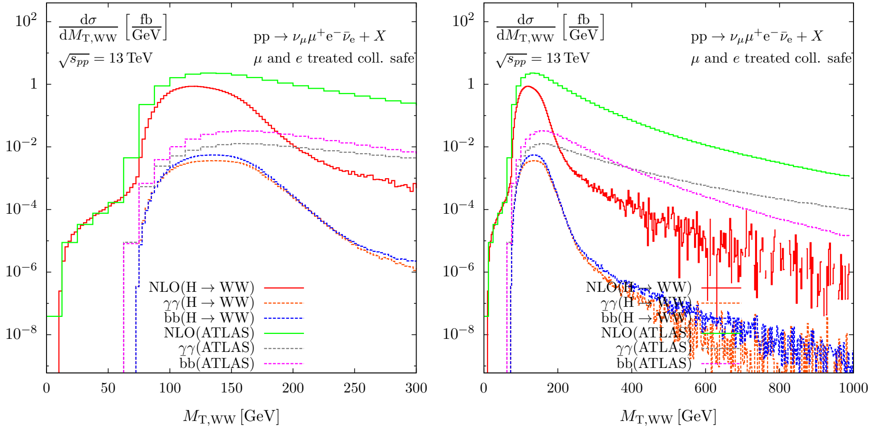
[Dittmaier, Böhm, Denner '92; Denner, Dittmaier, Roth, Wackeroth '01]

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

- $$\frac{e^2}{s_\mathrm{W}^2} \to 4\sqrt{2}G_\mu M_\mathrm{W}^2\,, \quad e^2 \to 4\pi\alpha(\hat{s})$$
- for photon exchange:

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

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



$\frac{d\sigma}{dM_{T,WW}}\left[\frac{fb}{GeV}\right]$
$\sqrt{s_{pp}} = 13\,TeV$
$pp \to \nu_\mu \mu^+ e^- \bar{\nu}_e + X$
μ and e treated coll. safe
NLO(H → WW)
$\gamma\gamma$(H → WW)
bb(H → WW)
NLO(ATLAS)
$\gamma\gamma$(ATLAS)
bb(ATLAS)
$M_{T,WW}$ [GeV]