NLO electroweak corrections to *WWW* production at proton–proton colliders

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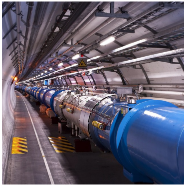
Motivation

LHC Run 2 with high luminosity and $\sqrt{s} = 13\,\text{TeV}$ started in mid 2015.

⇨ new all-time precision for BSM searches and some SM measurements

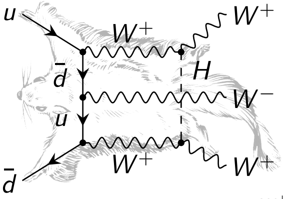
⇨ possibility to observe new class of processes, e.g. $pp \to VV'V''$



$pp \to VV'V''$

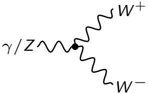
- sensitive to triple and quartic gauge couplings
  ⇨ search for anomalous gauge couplings
- access to EWSB
- NLO QCD well known for all final states
  [Lazopoulos et al.,Binoth et al.,Nhung et al.,Hankele&Zeppenfeld,Campanario et al.,Bozzi et al.,Baur et al.,2007-2011]
- first results known for NLO EW [Nhung et al.,2013][Shen et al.,2015-16]

$pp \to WWW$

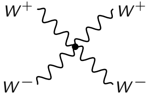


This talk

Preliminary results on NLO EW calculation in for on-shell W bosons



- $\mathcal{O}(\alpha^3)$ ⇨ small cross section, has not been observed yet
- distinct final state in detector: same-sign leptons
- quartic $4W$ coupling contributes already at LO
- $pp \to H^* W \to WWW$ (associated production)



$q\bar{q} \to WWW$ at NLO EW completed.

(Calculation for photon-induced process ($q\gamma$) in progress.)

↰ Enormous error on photon-induced cross section due to highly unconstrained photon pdf. Recently published ansatzes for γ pdf [Manohar et al.,2016][Schmidt et al.,2015] might yield better results than commonly used NNPDF set.

NLO cross section & dipole subtraction formalism

Full NLO cross section:

$$\sigma^{\text{NLO}} = \sigma^{\text{LO}} + \Delta\sigma^{\text{NLO}}.$$

Two contributions to $\Delta\sigma^{\text{NLO}}$:

$$\Delta\sigma^{\text{NLO}} = \int \mathrm{d}\Phi_{m+1} |\mathcal{M}_{\text{real}}|^2 + \int \mathrm{d}\Phi_m |\mathcal{M}_{\text{virt}}|^2 .$$

Problem: Both divergent in 4 space-time dimensions!

Ansatz: Subtract & readd local counterterm $|\mathcal{M}_{\text{sub}}|^2$, which mimics the pointwise singular behavior of $|\mathcal{M}_{\text{real}}|^2$. [Catani&Seymour,1997][Dittmaier,2000]

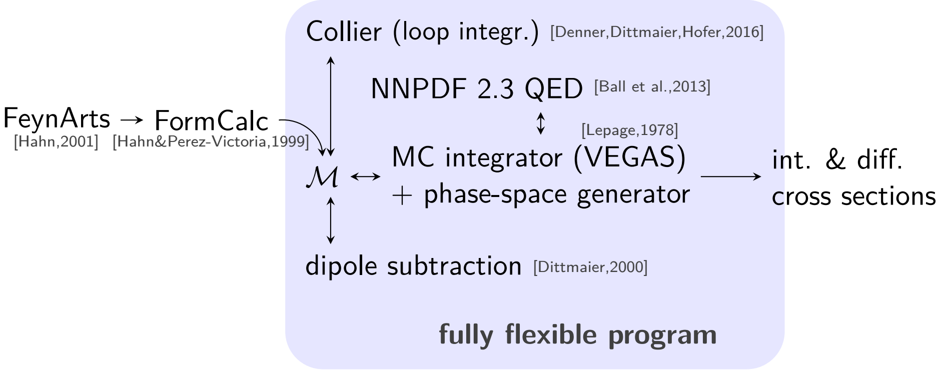
$$\Delta\sigma^{\text{NLO}} = \int \mathrm{d}\Phi_{m+1} \left(|\mathcal{M}_{\text{real}}|^2 - |\mathcal{M}_{\text{sub}}|^2 \right) + \int \mathrm{d}\Phi_m \left(|\mathcal{M}_{\text{virt}}|^2 + \int \mathrm{d}\Phi_1 \, |\mathcal{M}_{\text{sub}}|^2 \right) .$$

⇨ Both integrals finite by construction! (except for collin. IS singularities)

Obtaining NLO cross sections

Huge number of Feynman diagrams (~ 3000) needs to be evaluated.

⇨ Use automated tools to generate amplitudes.



$$\sigma^{\mathrm{NLO}} = \sigma^{\mathrm{LO}} + \Delta\sigma^{\mathrm{NLO}} = (1+\delta)\sigma^{\mathrm{LO}}$$

Input parameter scheme

- M_W,M_Z,M_H and G_μ as given by Particle Data Group. [Olive et al.,2014]
- Mixing with 3rd generation quarks negligible. ($\theta_c = 0.227$)
- All fermions massless except for b & t.
  ⇨ No light-fermion–Higgs coupling.
  ⇨ CKM matrix factorizes from the matrix elements:

$$\sigma = \int \mathrm{d}x_a \int \mathrm{d}x_b \int \mathrm{d}\Phi \left(\sum_{i,j=1}^{2} f_{u_i}(x_a) f_{d_j}(x_b) |V_{ij}|^2 \right) |\mathcal{M}|^2$$

- α_{G_μ}-scheme with $\alpha_{G_\mu} = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)$.
- Fixed factorization scale $\mu_F = M_W$.

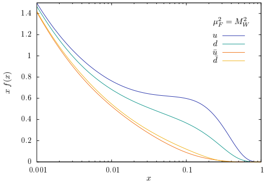
Total cross section – $W^-W^+W^+$ vs. $W^+W^-W^-$

REMINDER:
PRELIMINARY RESULTS

Two possible charge configurations:

process (@$\sqrt{s}$ = 13 TeV)	σ^{LO} / pb	σ^{NLO}_{EW} / pb	δ / %
$pp \to W^-W^+W^+$	0.081652(6)	0.078098(6)	−4.35
$pp \to W^+W^-W^-$	0.045216(3)	0.043429(4)	−3.79

⇨ sizable corrections for WWW production



At LO:
$u_i\bar{d}_j \to W^-W^+W^+$ and $\bar{u}_i d_j \to W^+W^-W^-$

high PDF value for valence quarks, esp. for $x \sim 0.1$

⇨ $\sigma_{W^-W^+W^+} > \sigma_{W^+W^-W^-}$

⇨ deeper partonic energy reach for $pp \to W^-W^+W^+$

⇨ $\delta_{W^-W^+W^+} > \delta_{W^+W^-W^-}$ (←high energy logs, e.g. Sudakov logs)

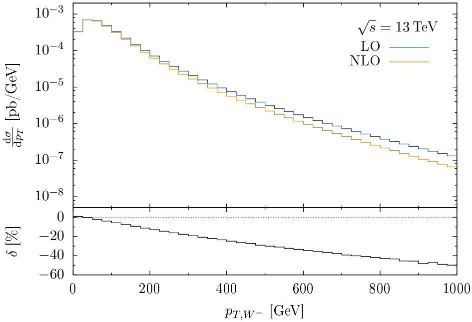
Total cross section – CM energy dependence

$\sqrt{s}$ / TeV	σ^{LO} / pb	$\sigma_{\text{EW}}^{\text{NLO}}$ / pb	δ / %
7	0.030897(2)	0.029775(2)	−3.63
8	0.038786(3)	0.037314(3)	−3.79
13	0.081652(6)	0.078098(6)	−4.35
14	0.090617(7)	0.086598(9)	−4.44
100	0.88810(9)	0.83707(12)	−5.75

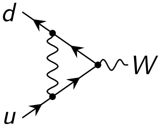
Increase in CM energy $\sqrt{s}$ leads to

- growing probability to find partons with sufficient energy to surpass production threshold ⇨ increase in σ,
- deeper partonic energy reach ⇨ increase in δ.

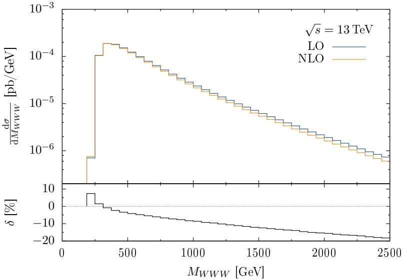
Transversal-momentum distribution

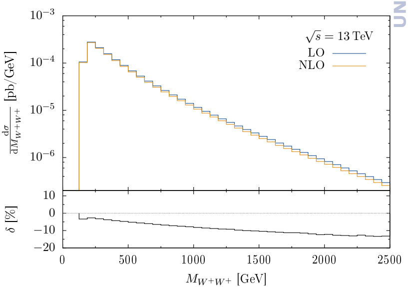


large negative corrections for high p_T (several 10 %)
↰ Sudakov logarithms, $-\frac{\alpha}{\pi s_w} \ln^2 (p_T^2/M_W^2)$, induced by soft gauge-boson exchange.



Invariant-mass distributions

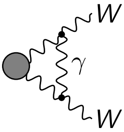




- large negative corrections from Sudakov logarithms (smaller than for p_T)
- production threshold at $M_{WWW} = 3M_W$, $M_{W^+W^+} = 2M_W$
- effect of Coulomb singularity at small invariant masses

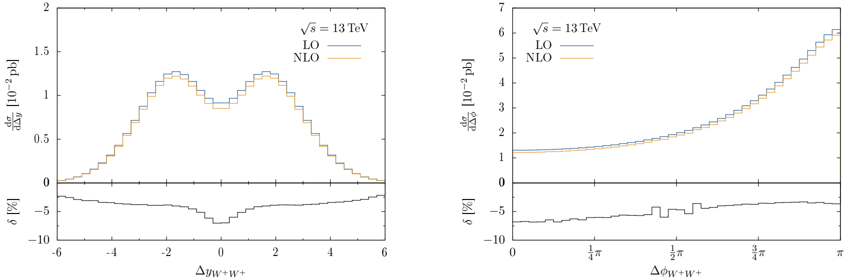
Coulomb singularity: $\alpha\frac{\pi}{2}\frac{1}{\beta}$, from virt. photon exchange between two W bosons

QED effect, either neg. (same charge) or pos. (opposite charge)



Angular distributions

essential when checking for anomalous couplings
(non-including might fake anom. coupl.)



- separated W^+ bosons favored
- corrections much smaller than p_T and M_X ($\sim$ overall correction)

Conclusion

Summary

- NLO EW calculation of $pp \to WWW$
- sizable negative corrections ($\sim 5\,\%$) for total cross sections
- large negative correction in high-energy regions due to Sudakov logarithms
- Coulomb singularities visible at small invariant masses

Outlook

- include photon-induced processes
  (might reduce impact of large negative virtual corrections)
- take into account decays of W bosons

Thank you for your attention!

BACKUP

Basic requirements on $|\mathcal{M}_{\text{sub}}|^2$

Requirement on analytic form of $|\mathcal{M}_{\text{sub}}|^2$

$|\mathcal{M}_{\text{sub}}|^2$ should have a **simple form**, so that the analytic integration over the 1-particle sub space $\int \mathrm{d}\Phi_1 \, |\mathcal{M}_{\text{sub}}|^2$ can be easily performed.

Singularities to be mimicked by $|\mathcal{M}_{\text{sub}}|^2$

- **soft singularities**
  arising from soft photon emission
- **collinear singularities**
  arising from collinear photon emission off a massless fermion

Universality of $|\mathcal{M}_{\text{sub}}|^2$

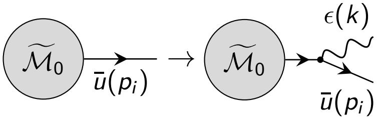
Singularities are universal!

⇨ Structure of $|\mathcal{M}_{\text{sub}}|^2$ is **process independent**!

Singularity structure – soft photon

Modification to LO matrix element by real emission:

$$\mathcal{M}_0(p_i) = \bar{u}(p_i)\widetilde{\mathcal{M}}_0(p_i)$$

$=$ 

$$= eQ_i \bar{u}(p_i) \not{\epsilon}^*(k) \frac{\not{p}_i + \not{k} + m}{(p_i + k)^2 - m^2} \widetilde{\mathcal{M}}_0(p_i + k).$$

In the soft-limit $k \to 0$: $\quad \mathcal{M}_0(p_i) \to eQ_i \frac{p_i \epsilon}{p_i k} \mathcal{M}_0(p_i)$

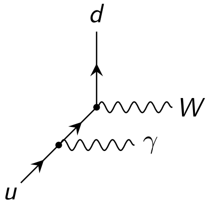
⇨ soft-photon (eikonal) approximation
(similarly for collin. photon approx.)

In the full NLO calculation, soft singularities and FSR collinear singularities are canceled by the virtual correction. (Bloch–Nordsieck & KLN theorem)

⇨ Construct $|\mathcal{M}_{\text{sub}}|^2$ such that it yields approx. in singular regions.

Higher order corrections to the parton model

IS photon emission:



Redefine PDF:

factorization-scheme dependent

$$f_q(x) \to f_q(x, \mu_F^2) - \frac{\alpha}{2\pi} Q_q^2 \int_x^1 \frac{dz}{z} f_q(\frac{x}{z}, \mu_F^2)\; g(z, \mu_F^2)$$

Factorization scale μ_F discriminates between hard scattering process and soft process.

⇨ Collinear photon singularities are absorbed into the PDF!

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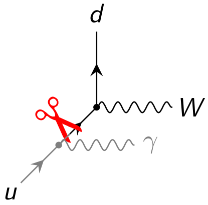

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