QCD and EW corrections for DM searches

Jonas M. Lindert

work in collaboration with: R. Boughezal, A. Denner, S. Dittmaier, A. Huss,T. Gehrmann, N. Glover, S. Kallweit, M. L. Mangano, A. Mück, M. Schönherr, F. Petriello, S. Pozzorini, G. Salam

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V+jets backgrounds in monojet/MET + jets searches

irreducible background:

 $pp\rightarrow Z(\rightarrow v\overline{v})+jets \implies MET + jets$

 $pp \rightarrow W(\rightarrow V)+jets \implies MET + jets$ (lepton lost)

- can be determined from $Z(\rightarrow \overline{I})$ +jets, W($\rightarrow \overline{I}$)+jets or γ +jets measurements (combination!)
- hardly any systematics (just QED dressing)
- but: limited statistics at large pT
- fairly large data samples at large pT
- ‣ need theory input, i.e. predictions at (N)NLO QCD+NLO EW:

 $R_{Z\gamma}(\mathrm{d}p_{\mathrm{T}}) = \frac{\mathrm{d}\sigma(Z \to \nu\bar{\nu} + \mathrm{jets})/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma(z + \mathrm{jets})/\mathrm{d}p_{\mathrm{T}}}$ $\mathrm{d}\sigma(\gamma + \mathrm{jets})/\mathrm{d}p_\mathrm{T}$ $R_{ZZ}(\mathrm{d}p_{\mathrm{T}}) = \frac{\mathrm{d}\sigma(Z \to \nu\bar{\nu} + \mathrm{jets})/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma(Z \to \ell\bar{\ell} + \mathrm{jets})/\mathrm{d}\mu}$ $d\sigma(Z \to \ell \overline{\ell} + \text{jets})/dp_T$ $R_{ZW}(\mathrm{d}p_{\mathrm{T}}) = \frac{\mathrm{d}\sigma(Z \to \nu\bar{\nu} + \mathrm{jets})/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma(W \to \ell\bar{\nu} + \mathrm{jets})/\mathrm{d}p_{\mathrm{T}}}$ $d\sigma(W \to \ell \bar{\nu} + \text{jets})/dp_T$

QCD corrections

- mostly moderate and stable QCD corrections
- ‣ (almost) identical QCD corrections in the tail, sizeable differences for small pT (mass effects)

EW corrections

- \triangleright correction in $pT(Z)$ > correction in $pT(Y)$
- \rightarrow -20/-8% EW for Z/ γ at I TeV
- \triangleright EW corrections > QCD uncertainties for $p_{T,Z}$ > 350 GeV

Goal of the ongoing study

- Combination of state-of-the-art predictions including QCD and EW corrections in order to match future experimental sensitivities (1-10% accuracy in the multi-TeV range)
- Robust uncertainty estimates including
	- ▶ Pure QCD uncertainties
	- ‣ Pure EW uncertainties
	- ‣ Mixed QCD-EW uncertainties
- Study of correlation of these uncertainties
	- ‣ within a process (between low-pT and high-pT)
	- ‣ across processes
- First draft of a prescription to incorporate NNLO QCD + (N)NLO EW corrections and uncertainties in the MCs has already been circulated within ATLAS and CMS and will be made publicly available within the DM WG in the next few weeks.

Pure QCD uncertainties ²⁰² with nuisance parameters ~"TH = (~"QCD*,* "ˆ*,* ~"EW*,* ") defined in the following. 4.1 Pure QCD uncertainties of relative *O*(↵² S 203) and the second state of the second state of the second state of the second state of the second state o
Second state of the second sta Fure QCD uncertainties *µ*R*,*^F = ⇠R*,*F*µ*0*,* with *µ*⁰ = *H*ˆ ⁰ where *H*ˆ ⁰

Best handle we have for pure QCD uncertainties: muR / muF scale variations and standard 7-point factors and standard 7-point factors are *muR* / muF ²⁰⁷ The first two parameters describe PDF variations (quite relevant in the TeV $\frac{1}{2}$ and, consistently we have for part \leq $\frac{1}{2}$ at the top threshold we switch from five to six active to six active to six active to six and the renormalisation of \mathbb{R} . \rightarrow *p*₂ + *p*₂ \rightarrow *p*₂ \rightarrow *p*₂ \rightarrow *for pure* \cap Also QCD partons and photons that are radiated at NLO are included in *H*ˆ ⁰ ^T, and the vector-boson rnurs / mur scale vanations

$$
\mu_0 = \frac{H_{\rm T}}{2} = \frac{1}{2} \left(\sqrt{M_V^2 + p_{\rm T,V}^2} + \sum_{i \in \rm partons} |p_{\rm T,i}| \right) \qquad \begin{array}{c} \stackrel{\text{st.}}{\sim} & 10^{-1} \\ \stackrel{\text{N}}{\sim} & 10^{-1} \\ \stackrel{\text{N}}{\sim} & 10^{-2} \end{array} \right)
$$

 $\mu_{\rm R,F} = \xi_{\rm R,F} \mu_0,$ 212.2 312.2 60

 $(2, 5)$ (0.0) $(0, 1)$ $(1, 0)$ $(1, 1)$ $(1, 0, 5)$ $(0, 5, 1)$ $(0, 5, 0, 5)$ $(\xi_R, \xi_F) = (2, 2), (2, 1), (1, 2), (1, 1), (1, 0.5), (0.5, 1), (0.5, 0.5)$

n → *H*_T 0 yields variations (⇠R*,* ⇠F) = (2*,* 2), (1*,* 1), (0*.*5*,* 0*.*5). As shown in [14–19] the scale choice (2.11) guarantees

 $O(20%)$ *uncertaintie* $O(20%)$ uncertainties at LO $O(10%)$ uncertainties at NLO $O(5\%)$ uncertainties at NNLO (see later) ²¹⁷ *H^T* ("shape) ! *H*T*/*"shape at large *p^T* . The values "shape = 0*.*5 and 2 would be $O(1076)$ uncertainties at INLO are radiated in the N O(20%) uncertainties at LO $\frac{3}{2}$ $\frac{3}{2}$ $\frac{3}{2}$ $\frac{3}{2}$ $\frac{3}{2}$ $\frac{3}{2}$ $\frac{3}{2}$ $\frac{3}{2}$ $\frac{3}{2}$ (Muniches) $\frac{3}{2}$ (Munich) $\frac{3}{2}$ (Muniches) $\frac{3}{2}$ O(5%) uncertainties at NNLO (see later)

> different V+jets processes?

> and leptons of this end, all terms in (250 are computed in this end, all terms in (250 and 250 are computed i What about correlations between

What about correlations between different V+jets processes?

consider $Z+jet / W+jet p_{T,V}\text{-ratio} \textcircled{a}$ LO

uncorrelated treatment yields O(40%) uncertainties

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correlated treatment yields tiny $O(\leq \sim 1\%)$ uncertainties

check against NLO QCD!

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NLO QCD corrections remarkably flat in Z+jet / W+jet ratio! → NLO predictions support correlated treatment of uncertainties!

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Also holds for higher jet-multiplicities \rightarrow indication of correlation also in higher-order corrections beyond NLO!

NNLO for W/Z+jet

- unprecedented reduction of scale uncertainties at NNLO: $O(\sim 5\%)$
- we can now check the correlation of the uncertainties going from NLO to NNLO
- . both groups joined our collaborative effort and will provide dedicated NNLO samples for Z+jet and W+jet including conservative factor-4 scale variations

NNLO for ɣ+jet

Figure 4: A comparison of the MCFM predictions for

¹ & 0*.*2 GeV,

EW corrections become sizeable at large p_{T,V}

Origin: EW Sudakov logarithms $r =$ $r =$ $r = 0$ result. Livial suddition in ratio in ratios

How to estimate corresponding pure \Box EW uncertainties of relative $\mathcal{O}(\alpha^2)$?

 235 ± 235 to describe uncertainties of order 100 ± 200 times the NLO EW correction, which are correction, which are 100 ± 200

Virtual EW Sudakov logarithms

Originate from soft/collinear *virtual* EW bosons coupling to on-shell legs Originate from soft/collinear virtual EW bosons coupling to on-shell legs

Universality and factorisation similar as in QCD *[Denner, Pozzorini; '01]*

$$
\delta_{\text{LL+NLL}}^{1-\text{loop}} = \frac{\alpha}{4\pi} \sum_{k=1}^{n} \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma, Z, W^{\pm}} I^{a}(k) I^{\bar{a}}(l) \ln^{2} \frac{s_{kl}}{M^{2}} + \gamma^{\text{ew}}(k) \ln \frac{s}{M^{2}} \right\}
$$

- process-independent, simple structure
- 2-loop extension and resummation partially available
- typical size at $\sqrt{\hat s} = 1, 5$, 10 TeV: $\frac{1}{2}$ $\hat{s} =$

$$
\delta_{\rm LL} \sim -\frac{\alpha}{\pi s_W^2} \log^2 \frac{\hat{s}}{M_W^2} \simeq -28, -76, -104\%,
$$

\n
$$
\delta_{\rm NLL} \sim +\frac{3\alpha}{\pi s_W^4} \log \frac{\hat{s}}{M_W^2} \simeq +16, +28, +32\%
$$

Large EW corrections dominated by Sudakov logs

Include (positive) two-loop Sudakov logs *[Kühn, Kulesza, Pozzorini, Schulze; 05-07]*

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Estimate missing higher-order log-enhanced corrections via factor-2 variation in the $\alpha^2(L^4 + L^3)$ $\begin{bmatrix} \equiv \ \end{bmatrix}$ two-loop NLL: $\log(s/(\xi M_W)^2)$, $\xi = (0.5, 2)$

> Can be considered as correlated between V+jets processes

Add additional uncorrelated 10% x NLO EW uncertainty to account for non-log enhanced higher-order corrections: $\delta^{\rm (2)}_{\rm har}$ $\overrightarrow{\text{hard}}$ 0.1π α $\delta^{\rm (1)}_{\rm hard} \approx 40 \times \delta^{\rm (1)}_{\rm har}$ hard

Under discussion!

Photon-induced production

• ~1% uncertainties in photon PDFs due to LUXqed

1

5

QED corrections to quark PDFs

QED effects on (qq) luminosity

- small percent-level QED effects on qg/qq luminosities (included via LUXqed)
- 1.5-5% PDF uncertainties

Mixed QCD-EW uncertainties $\frac{1}{2}$ a QUD-LYY and tann *p*T*,j^k ,* (6.3)

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EW $\frac{\sigma^\mathrm{NLO}_\mathrm{EW}}{\sigma^\mathrm{LO}}\bigg)$

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Include theory predictions via MC reweighting respectively predictions via rich coverging 12 under the some productions μ NC μ $\frac{1}{2}$ include the respective productions via the following formula $\frac{1}{2}$ the ratio (d) α 110000 druw y predictions via rich revolgituitie

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\frac{d}{dx} \frac{d}{dy} \sigma^{(V)}(\vec{\varepsilon}_{\text{MC}}, \vec{\varepsilon}_{\text{TH}}) := \frac{d}{dx} \frac{d}{dy} \sigma^{(V)}_{\text{MC}}(\vec{\varepsilon}_{\text{MC}}) \left[\frac{\frac{d}{dx} \sigma^{(V)}_{\text{TH}}(\vec{\varepsilon}_{\text{TH}})}{\frac{d}{dx} \sigma^{(V)}_{\text{MC}}(\vec{\varepsilon}_{\text{MC}})} \right]
$$
\none-dimensional reweighting of MC samples in $x = p_{\text{T}}^{(V)}$
\n
$$
\frac{d}{dx} \sigma^{(V)}_{\text{TH}}(\vec{\varepsilon}_{\text{TH}}) = \frac{d}{dx} \sigma^{(V)}_{\text{QCD}}(\vec{\varepsilon}_{\text{QCD}}) \left[1 + \frac{\frac{d}{dx} \sigma^{(V)}_{\text{EW}}(\vec{\varepsilon}_{\text{EW}}, \vec{\varepsilon}_{\text{QCD}})}{\frac{d}{dx} \sigma^{(V)}_{\text{QCD}}(\vec{\varepsilon}, \vec{\varepsilon}_{\text{QCD}})} \right] + \frac{d}{dx} \sigma^{(V)}_{\gamma-\text{ind.}}(\varepsilon_{\gamma}, \vec{\varepsilon}_{\text{QCD}})
$$
\nFactorization!
\n
$$
\frac{d}{dx} \sigma^{(V)}_{\text{QCD}} = \frac{d}{dx} \sigma^{(V)}_{\text{LO QCD}} + \frac{d}{dx} \sigma^{(V)}_{\text{NLO QCD}} + \frac{d}{dx} \sigma^{(V)}_{\text{NNLO QCD}}
$$
\n
$$
\frac{d}{dx} \sigma^{(V)}_{\text{EW}} = \frac{d}{dx} \sigma^{(V)}_{\text{NLO EW}} + \frac{d}{dx} \sigma^{(V)}_{\text{Sudakov NNLO EW}}
$$

 \mathcal{L} disc (JL+SP): 1 or 2 \mathcal{L} or 2 Gaussian uncertainties? e parameters $\varepsilon_{\rm TH}=(\varepsilon_{\rm QCD},\varepsilon,\varepsilon_{\rm EW},\varepsilon_\gamma)$ ⁵⁹ which should be understood as 1 Gaussian uncertainties. $\frac{1}{2}$ in we do not include the extra factor $\frac{1}{2}$ with nuisance parameters $\vec{\varepsilon}_{\text{TH}} = (\vec{\varepsilon}_{\text{QCD}}, \hat{\varepsilon}, \vec{\varepsilon}_{\text{FW}} , \varepsilon_{\text{R}})$ *NIOR HURGHI*C parameters \circ 1H (\circ QUE with nuisance parameters $\vec{\varepsilon}_{\rm TH} = (\vec{\varepsilon}_{\rm QCD}, \hat{\varepsilon}, \vec{\varepsilon}_{\rm EW}, \varepsilon_{\gamma})$

4.1 Pure QCD uncertainties of relative *O*(↵²

² ⁼ ¹

2

Conclusions & Outlook

‣ monojet / MET+jets searches *soon* limited by V+jets background systematics

- \triangleright MC reweighting allows to promote V + jet to NNLO QCD+(N)NLO EW:
	- inclusion of EW corrections *crucial* due to large Sudakov logs
	- NNLO QCD *crucial* due to remarkable reduction of scale variations
- ▶ High statistics MC runs are under way
- ▶ Ongoing technical studies:
	- refine treatment of uncertainties (incl. correlations and shape uncertainties)
	- impact of isolation in χ +jet
	- \bullet ...
- ‣ Public document available very soon

NNLO to the rescue

[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]

Z/γ + 1 jet: pT-ratio

Overall

mild dependence on the boson pT

QCD corrections

- ‣ 10-15% below 250 GeV
- \blacktriangleright \leq 5% above 350 GeV

EW corrections

- ‣ sizeable difference in EW corrections results in 10-15% corrections at several hundred GeV
- ▶ ~5% difference between NLO QCD+EW and NLO QCDxEW

Compare against data

 \triangleright remarkable agreement with data at $@$ NLO QCD+EW!

Combination of NLO QCD and EW & Setup Combination of NLO OCD and EW, & Sotun COMBITATION OF INLY QUD and LYY & JEMP \sim corrections also consider the following factorised consider the following factorised combination of \sim would combination of NLO $O(1)$ and \vdash approach introducing a finite width reg in all potentially reg in all potentially resonant propagators while ke integrable pseudo singularity emerges that has to be regularized for numerical convergence. To this t $\overline{\mathcal{Q}}$ and EVV \propto setup consistently apply the constant mass mass $\overline{\mathcal{Q}}$

Two alternatives: with a standard additional additional τ Two alternatives: Two alternatives:
NLO IW mixing and the on-shell scheme. In the on-shell scheme. In the virtual contributions the virtual contributions the virtual contributions that \mathcal{L} regulators the virtual contributions that \mathcal{L} regulators the vi

Two alternatives:
\n
$$
\sigma_{\text{QCD+EW}}^{\text{NLO}} = \sigma^{\text{LO}} + \delta \sigma_{\text{QCD}}^{\text{NLO}} + \delta \sigma_{\text{EW}}^{\text{NLO}}
$$
\n
$$
\sigma_{\text{QCD} \times \text{EW}}^{\text{NLO}} = \sigma_{\text{QCD}}^{\text{NLO}} \left(1 + \frac{\delta \sigma_{\text{EW}}^{\text{NLO}}}{\sigma^{\text{LO}}} \right) = \sigma_{\text{EW}}^{\text{NLO}} \left(1 + \frac{\delta \sigma_{\text{QCD}}^{\text{NLO}}}{\sigma^{\text{LO}}} \right)
$$

Difference between the two approaches indicates uncertainties due to missing two-loop EW-QCD corrections of ${\cal O}(\alpha\alpha_s)$ Difference between the two approaches indicates uncertainties due to missing two-loop
EW OCD corrections of $\mathcal{O}(\alpha\alpha$ corrections are dominated by soft interactions well below the EW scale—the factorised formula EW-QCD corrections of $\mathcal{O}(\alpha\alpha_s)$ Difference between the two approaches indicates uncertaint E V V – Q C es due to missing two-loop and contributions due to a regulate propagator of \sim

 $relative corrections wrt$ NLO, OCD Relative corrections w.r.t. NLO QCD:
Relative corrections w.r.t. NLO QCD: Relative corrections w.r.t. NLO QCD: In the following we present a series of NLO QCD+EW simulations for *W*+ productions for *W*+ production in a series of *M*+ *production in a series of the series* of *w*+ *production in a series of the series* of *w*+ *pro*

$$
\frac{\sigma_{\text{QCD}+\text{EW}}^{\text{NLO}}}{\sigma_{\text{QCD}}^{\text{NLO}}} = \left(1 + \frac{\delta \sigma_{\text{EW}}^{\text{NLO}}}{\sigma_{\text{QCD}}^{\text{NLO}}} \right) \qquad \text{suppressed by large NLO QCD corrections}
$$
\n
$$
\frac{\sigma_{\text{QCD} \times \text{EW}}^{\text{NLO}}}{\sigma_{\text{QCD}}^{\text{NLO}}} = \left(1 + \frac{\delta \sigma_{\text{EW}}^{\text{NLO}}}{\sigma^{\text{LO}}} \right) \qquad \text{``usual'' NLO EW w.r.t. LO}}
$$

NLO

$$
\blacktriangleright \alpha = \frac{\sqrt{2}}{\pi} G_{\mu} M_{\rm W}^2 \left(1 - \frac{M_{\rm W}^2}{M_{\rm Z}^2} \right) \text{ in } \mathsf{G}_{\mu} \text{-scheme with } G_{\mu} = 1.16637 \times 10^{-5} \text{ GeV}^{-2}
$$

corrections are dominated by soft interactions well below the EW scale—the factorised formula

 $\overline{}$. That the $\overline{}$ ratio (6.8) correction relative to the usual NLO EW correction relative to $\overline{}$

 $\overline{}$. Note that the $\overline{}$ ratio (6.8) corresponds to the usual NLO EW correction relative to $\overline{}$

NLO QCD

^G^µ = 1*.*16637⇥10⁵ GeV², in the so-called *^Gµ*-scheme, where the fine structure constant is given

⇡

LUXqed

PDF uncertainties (Q = 100 GeV)

[Manohar, Nason, Salam, Zanderighi, '16]