Precise predictions for V+jets dark matter backgrounds

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based on work with:

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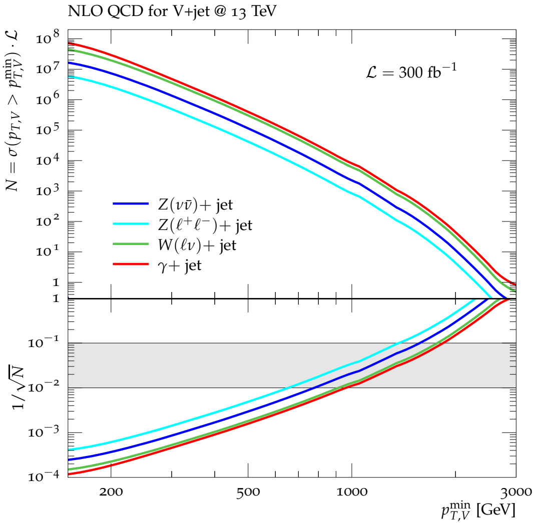
Motivation for precise V+jets predictions in dark-matter searches

Leading SM background to MET+jets searches:

- **$Z(\nu\bar{\nu})$ + jets**
- $W(\ell\nu)$ + jets (τ-channel or unidentified lepton)

Experimental constraints on $Z(\nu\bar{\nu})$ + jets from visible V + jets channels:

- **$Z(\ell\ell)$ + jets**
  - ideal at low $p_{\mathrm{T,V}}$
  - statistics limited at high $p_{\mathrm{T,V}}$
- **$W(\ell\nu)$ + jets** & **γ + jets**
  - better statistics at high $p_{\mathrm{T,V}}$
  - no **Z** + jets processes



↪ **Theoretical prediction required**

- for extrapolating the **shape of the Z spectrum** to the high-$p_{\mathrm{T,V}}$ region,
- for modelling the relation between spectra of **different V+jets processes**.

One-dimensional reweighting of Monte Carlo samples

Master formula:

$$\frac{d}{dx}\frac{d}{d\vec{y}}\sigma^{(V)}(\vec{\varepsilon}_{MC},\vec{\varepsilon}_{TH}) = \frac{d}{dx}\frac{d}{d\vec{y}}\sigma^{(V)}_{MC}(\vec{\varepsilon}_{MC})\left[\frac{\frac{d}{dx}\sigma^{(V)}_{TH}(\vec{\varepsilon}_{TH})}{\frac{d}{dx}\sigma^{(V)}_{MC}(\vec{\varepsilon}_{MC})}\right]$$

- $x = p_{T,V}$,
- $\vec{y}$: remaining phase-space variables (integrated out in $\frac{d}{dx}\sigma^{(V)}$ terms),
- $\vec{\varepsilon}_{TH}, \vec{\varepsilon}_{MC}$: **nuisance parameters** with $-1 < \varepsilon_{TH,k} < 1$, understood as **Gaussian**.

- Same **scale choices, inputs and PDFs** in numerator and denominator of

$$R_{MC}(x,\vec{y}) = \frac{\frac{d}{dx}\frac{d}{d\vec{y}}\sigma^{(V)}_{MC}}{\frac{d}{dx}\sigma^{(V)}_{MC}}$$

All such parameters and inputs can be chosen differently from the ones used in the calculation of $\frac{d}{dx}\sigma^{(V)}_{TH}(\vec{\varepsilon}_{TH})$.

- Same **phase-space cuts** to be applied only in numerator and denominator of

$$R_{TH/MC}(x) = \frac{\frac{d}{dx}\sigma^{(V)}_{TH}}{\frac{d}{dx}\sigma^{(V)}_{MC}}$$

More exclusive or inclusive cuts can be applied in the experimental analysis and thus in $\frac{d}{dx}\frac{d}{d\vec{y}}\sigma^{(V)}_{MC}(\vec{\varepsilon}_{MC})$.

- Only the **definition of x** and its **binning** must be the same everywhere.

Limitations of Monte Carlo reweighting approach

Conditions to be fulfilled for optimal TH – MC combination:

- **TH** prediction should describe the **distribution in reweighting variable** x better than MC sample.

$$\boldsymbol{\Delta}\left[\frac{\mathrm{d}}{\mathrm{dx}}\boldsymbol{\sigma}^{(\mathbf{V})}_{\mathbf{TH}}\right] \leq \boldsymbol{\Delta}\left[\frac{\mathrm{d}}{\mathrm{dx}}\boldsymbol{\sigma}^{(\mathbf{V})}_{\mathbf{MC}}\right]$$

- **MC** sample should be more accurate than TH prediction in describing the **correlation between** x **and** $\vec{y}$.

$$\boldsymbol{\Delta}\left[\frac{\frac{\mathrm{d}}{\mathrm{dx}}\frac{\mathrm{d}}{\mathrm{d}\vec{\mathbf{y}}}\boldsymbol{\sigma}^{(\mathbf{V})}_{\mathbf{MC}}}{\frac{\mathrm{d}}{\mathrm{dx}}\boldsymbol{\sigma}^{(\mathbf{V})}_{\mathbf{MC}}}\right] \leq \boldsymbol{\Delta}\left[\frac{\frac{\mathrm{d}}{\mathrm{dx}}\frac{\mathrm{d}}{\mathrm{d}\vec{\mathbf{y}}}\boldsymbol{\sigma}^{(\mathbf{V})}_{\mathbf{TH}}}{\frac{\mathrm{d}}{\mathrm{dx}}\boldsymbol{\sigma}^{(\mathbf{V})}_{\mathbf{TH}}}\right]$$

- $\mathbf{x = p_{T,V}}$ has low sensitivity to aspects that would spoil the above conditions:
  - multiple jet emissions hardly affect the $p_{\mathrm{T,V}}$ distribution,
  - resummation effects suppressed by excluding $p_{\mathrm{T,V}} \ll M_V$ from reweighting.

- Aspects of $\mathbf{x = p_{T,V}}$ that are better described at MC level should be excluded from the definition of x and included in $\vec{y}$:
  - multiple photon emissions off leptons,
  - isolation prescriptions for soft QCD radiation that surrounds leptons or photons,
  - non-perturbative aspects like MPI, UE, hadronisation and hadron decays.

Above considerations are focussed on analysis of inclusive MET distribution!
$\hookrightarrow$ Other cases might require multi-jet merging with QCD+EW corrections on MC level.

Setup for V+jet calculations

Dressed leptons (charged leptons recombined with nearly collinear photons within cone)

$$\Delta R_{\ell\gamma} = \sqrt{\Delta\phi^2_{\ell\gamma} + \Delta\eta^2_{\ell\gamma}} < R_{\mathrm{rec}}, \qquad R_{\mathrm{rec}} = 0.1$$

Observable: transverse momentum of (recombined) vector boson

$$p_{\mathrm{T,V}} \in [30, 40, \ldots, 150, 200, \ldots, 1000, 1100, \ldots, 1400, 1600 \ldots, 3000, 6500]\,\mathrm{GeV}$$

Event-selection criteria

process	extra cuts	observable	comments
$pp \to W^+(\ell^+\nu_\ell)+$jet	none	$p_{\mathrm{T},\ell^+\nu_\ell}$	$\ell = e$ or μ
$pp \to W^-(\ell^-\bar\nu_\ell)+$jet	none	$p_{\mathrm{T},\ell^-\bar\nu_\ell}$	$\ell = e$ or μ
$pp \to Z(\nu_\ell\bar\nu_\ell)+$jet	none	$p_{\mathrm{T},\nu_\ell\bar\nu_\ell}$	$\ell = e+\mu+\tau$
$pp \to Z(\ell^+\ell^-)+$jet	$m_{\ell\ell} > 30\,\mathrm{GeV}$	$p_{\mathrm{T},\ell^+\ell^-}$	$\ell = e$ or μ
$pp \to \gamma+$jet	dynamic isolation	$p_{\mathrm{T},\gamma}$	

EW scheme

Z/W+jet: $\alpha = \left|\frac{\sqrt{2}\sin^2\theta_{\mathrm{w}}\mu^2_{\mathrm{W}}G_\mu}{\pi}\right|$ γ+jet: $\alpha = \alpha(0)$

$$\mu_i^2 = M_i^2 - \mathrm{i}\Gamma_i M_i,\ i = \mathrm{W,Z,t}, \quad \sin^2\theta_{\mathrm{w}} = 1 - \mu^2_{\mathrm{W}}/\mu^2_{\mathrm{Z}}.$$

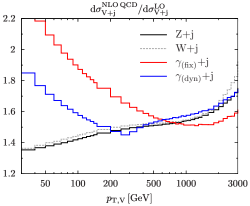
Photon isolation with a dynamic cone

QED collinear singularities from $q \to q\gamma$ splittings due to QCD radiation in direction of the photon $\Rightarrow$ isolation prescription needed $\Rightarrow$ **Frixione isolation**

$$\sum_{i=\text{partons/hadrons}} p_{\mathrm{T,i}}\, \Theta(R - \Delta R_{i\gamma}) \leq \epsilon_0\, p_{\mathrm{T},\gamma} \left(\frac{1-\cos R}{1-\cos R_0} \right)^n \quad \forall\, R \leq R_0,$$

As a consequence, **W/Z+jet** and **γ+jet** behave differently.

At the TeV scale ($p_{\mathrm{T},V} \gg M_{W,Z}$), they exhibit logarithmic sensitivity to $\mathbf{\ln(p_{T,V}/M_V)}$ and $\mathbf{\ln(R_0)}$ terms, respectively.

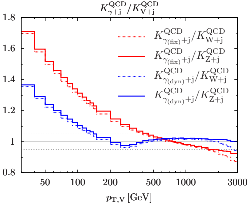


Modified prescription based on dynamic cone radius:

$$\mathbf{R_{dyn}(p_{T,\gamma}, \varepsilon_0) = \min\left\{ \frac{M_Z}{p_{T,\gamma}\sqrt{\varepsilon_0}},\ 1.0 \right\}}$$

$$\left(\text{based on } M^2_{\gamma j} \simeq p_{\mathrm{T},\gamma}\, p_{\mathrm{T},j} R^2_{\gamma j} = \varepsilon_0\, p^2_{\mathrm{T},\gamma} R^2_{\mathrm{dyn}} = M^2_Z\right)$$

$$\mathbf{\varepsilon_{0,dyn} = 0.1,\ n_{dyn} = 1,\ R_{0,dyn} = R_{dyn}(p_{T,\gamma}, \varepsilon_{0,dyn})}$$



Additional uncertainty from comparison to standard isolation needs to be taken into account on the MC side.

$$\mathbf{\varepsilon_{0,fix} = 0.025,\ n_{fix} = 2,\ R_{0,fix} = 0.4}$$

Higher-order QCD and EW predictions

Constitution of higher-order theory prediction for each V+jet process:

$$\frac{d}{dx}\sigma^{(V)}_{TH} = \frac{d}{dx}\sigma^{(V)}_{QCD} + \frac{d}{dx}\Delta\sigma^{(V)}_{EW} + \frac{d}{dx}\Delta\sigma^{(V)}_{mix} + \frac{d}{dx}\sigma^{(V)}_{\gamma-ind.}$$

Involved higher-order calculations:

- QCD corrections: NNLO QCD (NLO QCD from MUNICH/SHERPA+OPENLOOPS*)
  [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '15]
  - $Z(\ell\ell) + \text{jet}$ antenna subtraction: NNLOJET [Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan '15]
  - $W(\ell\nu) + \text{jet}$ N-jettiness subtraction: $\tau < \tau_{cut}$: [Boughezal, Focke, Liu, Petriello '15] ,
    $\tau > \tau_{cut}$: MUNICH+OPENLOOPS* [Kallweit]; [Lindert, Maierhöfer, Pozzorini]
  - $\gamma + \text{jet}$ N-jettiness subtraction: MCFM [Campbell, Ellis, Williams '17]
- EW corrections: NLO EW and NNLO EW Sudakov approximation (nNLO EW)
  - $V + \text{jet}$ MUNICH/SHERPA+OPENLOOPS* [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '15]
- Mixed corrections: approximation based on NLO QCDxEW, QCD+EW, V+2jets EW
  - $V + 2\text{jets}$ MUNICH/SHERPA+OPENLOOPS* [Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '15]
- Photon-induced corrections: LO

* COLLIER [Denner, Dittmaier, Hofer] is used in all OPENLOOPS calculations.

Higher-order QCD corrections

Notation for QCD predictions at LO, NLO, NNLO ($k = 0, 1, 2$):

$$\frac{d}{dx}\sigma^{(V)}_{\mathrm{QCD}} = \frac{d}{dx}\sigma^{(V)}_{\mathrm{N^kLO\,QCD}}$$

Results expressed in terms of LO prediction ($\vec{\mu}_0$) and relative correction factors ($\vec{\mu}$):

$$\frac{d}{dx}\sigma^{(V)}_{\mathrm{N^kLO\,QCD}}(\vec{\mu}) = K^{(V)}_{\mathrm{N^kLO}}(x,\vec{\mu})\frac{d}{dx}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0), \qquad \vec{\mu} = (\mu_R, \mu_F),\ \vec{\mu}_0 = (\mu_{R,0}, \mu_{F,0})$$

Central scale μ_0: half of the total transverse energy $\hat{H}'_{\mathrm{T}}$:

$$\mu_{R,0} = \mu_{F,0} = \mu_0 = \hat{H}'_{\mathrm{T}}/2, \qquad \hat{H}'_{\mathrm{T}} = E_{\mathrm{T,V}} + \sum_{i\in\{q,g,\gamma\}} |p_{\mathrm{T},i}|$$

Scale-variation band from standard 7-point variation by a factor of 2:

$$K^{(V,\mathrm{min/max})}_{\mathrm{N^kLO}}(x) = \mathrm{min/max}\left\{ K^{(V)}_{\mathrm{N^kLO}}(x,\vec{\mu}_i) \middle| 0 \le i \le 6 \right\},$$

$$\vec{\mu}_i/\mu_0 = (1,1),(2,2),(0.5,0.5),(2,1),(1,2),(1,0.5),(0.5,1)$$

Nominal prediction (defined as the centre of the scale band):

$$K^{(V)}_{\mathrm{N^kLO}}(x) = \frac{1}{2}\left[K^{(V,\mathrm{max})}_{\mathrm{N^kLO}}(x) + K^{(V,\mathrm{min})}_{\mathrm{N^kLO}}(x)\right]$$

QCD scale, shape and process-correlation uncertainties

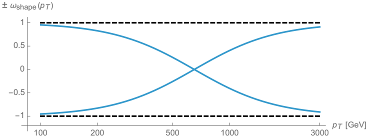
Scale uncertainty (defined as half the width of 7-point factor-2 variation band):

$$\delta^{(1)}\mathbf{K}^{(\mathbf{V})}_{\mathrm{N^kLO}}(\mathbf{x}) = \frac{1}{2}\left[\mathbf{K}^{(\mathbf{V},\max)}_{\mathrm{N^kLO}}(\mathbf{x}) - \mathbf{K}^{(\mathbf{V},\min)}_{\mathrm{N^kLO}}(\mathbf{x})\right]$$

Shape uncertainty (reference $p_{\mathrm{T},0} = 650\ GeV$):

$$\delta^{(2)}\mathbf{K}^{(\mathbf{V})}_{\mathrm{N^kLO}}(\mathbf{x}) = \omega_{\mathrm{shape}}(\mathbf{x})\,\delta^{(1)}\mathbf{K}^{(\mathbf{V})}_{\mathrm{N^kLO}}(\mathbf{x}),$$

$$\omega_{\mathrm{shape}}(p_{\mathrm{T}}) = \tanh\left[\ln\left(\frac{p_{\mathrm{T}}}{p_{\mathrm{T},0}}\right)\right]$$



Process-correlation uncertainty (defined wrt. $Z+$jet as reference):

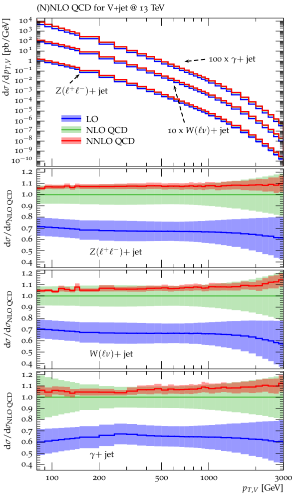
$$\delta^{(3)}\mathbf{K}^{(\mathbf{V})}_{\mathrm{N^kLO}}(\mathbf{x}) = \Delta\mathbf{K}^{(\mathbf{V})}_{\mathrm{N^kLO}}(\mathbf{x}) - \Delta\mathbf{K}^{(\mathbf{Z})}_{\mathrm{N^kLO}}(\mathbf{x}), \qquad \Delta K^{(V)}_{\mathrm{N^kLO}} = K^{(V)}_{\mathrm{N^kLO}}/K^{(V)}_{\mathrm{N^{k-1}LO}} - 1$$

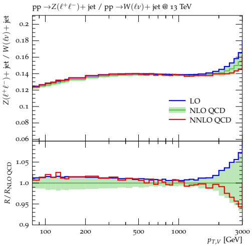
QCD uncertainties parametrized through a set of independent nuisance parameters:

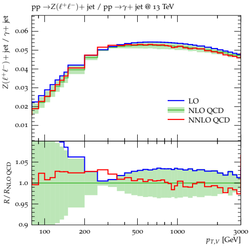
$$\frac{\mathrm{d}}{\mathrm{d}\mathbf{x}}\sigma^{(\mathbf{V})}_{\mathrm{N^kLO\,QCD}}(\vec{\varepsilon}_{\mathrm{QCD}}) = \left[\mathbf{K}^{(\mathbf{V})}_{\mathrm{N^kLO}}(\mathbf{x}) + \sum_{\mathbf{i}=1}^{3}\varepsilon_{\mathrm{QCD},\mathbf{i}}\,\delta^{(\mathbf{i})}\mathbf{K}^{(\mathbf{V})}_{\mathrm{N^kLO}}(\mathbf{x})\right] \times \frac{\mathrm{d}}{\mathrm{d}\mathbf{x}}\sigma^{(\mathbf{V})}_{\mathrm{LO\,QCD}}(\vec{\mu}_0)$$

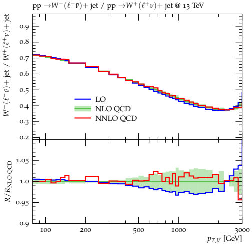
- uncorrelated $\varepsilon_{\mathrm{QCD},\mathbf{i}}$ ($i = 1, 2, 3$) Gaussian distributed, $1\,\sigma \sim \varepsilon_{\mathrm{QCD},i} \in [-1, +1]$,
- each $\varepsilon_{\mathrm{QCD},\mathbf{i}}$ applied in correlated way across p_{T} bins and processes.

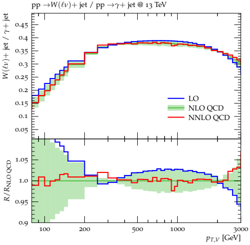
QCD uncertainties of V+jet $p_{\mathrm{T,V}}$ distributions and ratios thereof











- combined uncertainty $\delta^{(1-3)}K^{(V)}_{\mathrm{LO,NLO}}$
- only scale uncertainty $\delta^{(1)}K^{(V)}_{\mathrm{NNLO}}$
- combined uncertainty bands at NLO
- only nominal predictions at LO and NNLO

Higher-order EW corrections

Notation for EW predictions at NLO EW, and Sudakov NLL approximation:

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{EW}}(\vec{\mu}) = \left[1 + \kappa^{(V)}_{\mathrm{EW}}(x)\right] \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\ QCD}}(\vec{\mu})$$

- $\kappa^{(V)}_{\mathrm{EW}}(x)$ can be evaluated at μ_0 throughout, since $\kappa^{(V)}_{\mathrm{EW}}(x, \vec{\mu}_0) \approx \kappa^{(V)}_{\mathrm{EW}}(x, \vec{\mu})$.

Schematic decomposition of higher-order EW corrections:

$$\mathrm{d}\sigma_{\mathrm{EW}} = \underbrace{\left[1 + \frac{\alpha}{\pi}\delta^{(1)}_{\mathrm{Sud}} + \left(\frac{\alpha}{\pi}\right)^2 \delta^{(2)}_{\mathrm{Sud}} + \dots\right]}_{\text{EW (Sudakov and subleading high-energy) logarithms of type } \alpha^m \ln^n\left(Q^2/M_W^2\right)} \underbrace{\left[1 + \frac{\alpha}{\pi}\delta^{(1)}_{\mathrm{hard}} + \left(\frac{\alpha}{\pi}\right)^2 \delta^{(2)}_{\mathrm{hard}} + \dots\right]}_{\delta^{(k)}_{\mathrm{hard}} \text{ finite in the limit } Q^2/M_W^2 \to \infty} \mathrm{d}\sigma_{\mathrm{Born}}$$

$$= \left[1 + \underbrace{\frac{\alpha}{\pi}\left(\delta^{(1)}_{\mathrm{hard}} + \delta^{(1)}_{\mathrm{Sud}}\right)}_{=\kappa^{(V)}_{\mathrm{NLO\ EW}}(x)} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2\left(\delta^{(2)}_{\mathrm{Sud}}\right.}_{=\kappa^{(V)}_{\mathrm{NNLO\ Sud}}(x)} + \underbrace{\left.\delta^{(1)}_{\mathrm{Sud}}\delta^{(1)}_{\mathrm{hard}} + \delta^{(2)}_{\mathrm{hard}}\right)}_{\to \delta^{(2)}\kappa^{(V)}_{\mathrm{nNLO\ EW}}(x)} + \underbrace{\left(\frac{\alpha}{\pi}\right)^3\left(\delta^{(3)}_{\mathrm{Sud}} \dots\right.}_{\to \delta^{(1)}\kappa^{(V)}_{\mathrm{nNLO\ EW}}(x)}\right] \mathrm{d}\sigma_{\mathrm{Born}}$$

- **NLO EW:** $\kappa^{(V)}_{\mathrm{EW}}(x) = \kappa^{(V)}_{\mathrm{NLO\ EW}}(x)$
- **nNLO EW:** $\kappa^{(V)}_{\mathrm{EW}}(x) = \kappa^{(V)}_{\mathrm{nNLO\ EW}}(x) = \kappa^{(V)}_{\mathrm{NLO\ EW}}(x) + \kappa^{(V)}_{\mathrm{NNLO\ Sud}}(x)$

EW scale, shape and process-correlation uncertainties

Uncertainty from $\mathcal{O}(\alpha^3)$ Sudakov terms (naive exponentiation):

$$\delta^{(1)}\kappa^{(V)}_{\mathrm{nNLO\,EW}}(x) = \frac{2}{3}\kappa^{(V)}_{\mathrm{NLO\,EW}}(x)\,\kappa^{(V)}_{\mathrm{NNLO\,Sud}}(x)$$

- based on $\delta^{(2)}_{\mathrm{Sud}} \simeq \frac{1}{2}[\delta^{(1)}_{\mathrm{Sud}}]^2$, $\delta^{(3)}_{\mathrm{Sud}} \simeq \frac{1}{3!}[\delta^{(1)}_{\mathrm{Sud}}]^3 \simeq \frac{1}{3}\delta^{(1)}_{\mathrm{Sud}}\,\delta^{(2)}_{\mathrm{Sud}}$, conservative factor 2.

Uncertainty from missing $\mathcal{O}(\alpha^2)$ corrections (beyond Sudakov approximation):

$$\delta^{(2)}\kappa^{(V)}_{\mathrm{nNLO\,EW}}(x) = 0.05\,|\kappa^{(V)}_{\mathrm{NLO\,EW}}(x)|$$

- to cover both $\left(\frac{\alpha}{\pi}\right)^2\delta^{(1)}_{\mathrm{Sud}}\delta^{(1)}_{\mathrm{hard}}$ up to $\kappa_{\mathrm{NLO\,hard}} = 5\%$ and $\delta^{(2)}_{\mathrm{hard}} \lesssim 20\,\delta^{(1)}_{\mathrm{hard}}$.

Uncertainty from limitations of Sudakov approximation:

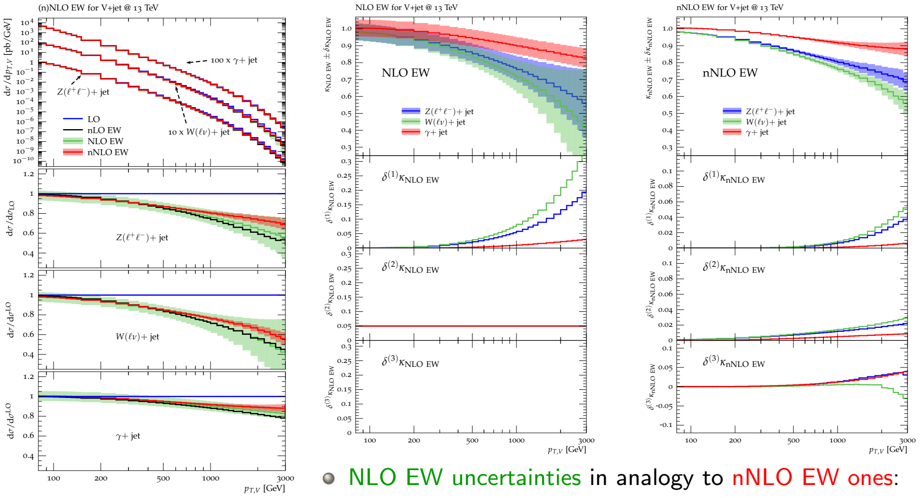
$$\delta^{(3)}\kappa^{(V)}_{\mathrm{nNLO\,EW}}(x) = \kappa^{(V)}_{\mathrm{NNLO\,Sud}}(x) - \frac{1}{2}[\kappa^{(V)}_{\mathrm{NLO\,EW}}(x)]^2$$

EW uncertainties parametrized through a set of independent nuisance parameters:

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{EW}}(\vec{\varepsilon}_{\mathrm{EW}},\vec{\varepsilon}_{\mathrm{QCD}}) = \left[\kappa^{(V)}_{\mathrm{EW}}(x) + \sum_{i=1}^{3}\varepsilon^{(V)}_{\mathrm{EW},i}\,\delta^{(i)}\kappa^{(V)}_{\mathrm{EW}}(x)\right] \times \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\varepsilon}_{\mathrm{QCD}}),$$

- uncorrelated $\varepsilon_{\mathrm{EW},i}$ ($i = 1,2,3$) Gaussian distributed, $1\,\sigma \sim \varepsilon_{\mathrm{EW},i} \in [-1,+1]$,
- each $\varepsilon_{\mathrm{EW},i}$ applied in correlated way across p_{T} bins,
- $\varepsilon_{\mathrm{EW},1}$ fully correlated, $\varepsilon_{\mathrm{EW},2}$ and $\varepsilon_{\mathrm{EW},3}$ uncorrelated across processes.

EW uncertainties of V+jet $p_{\mathrm{T,V}}$ distributions



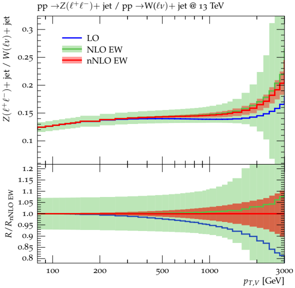
- $d\sigma_{\mathrm{nLO\ EW}} \approx d\sigma_{\mathrm{NLO\ EW}}$!
- $d\sigma_{\mathrm{nNLO\ EW}}$ well covered by NLO EW uncertainty.

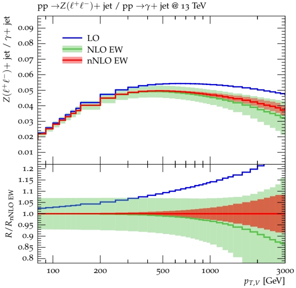
- NLO EW uncertainties in analogy to nNLO EW ones:

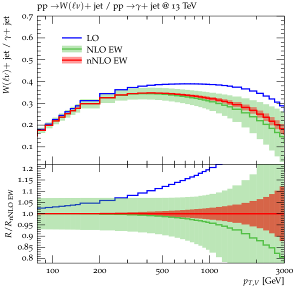
$$\delta^{(1)}\kappa^{(V)}_{\mathrm{NLO\,EW}}(x) = \frac{2}{2}\left[\kappa^{(V)}_{\mathrm{NLO\,EW}}(x)\right]^2,$$

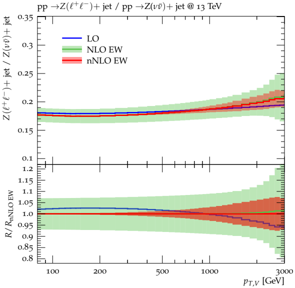
$$\delta^{(2)}\kappa^{(V)}_{\mathrm{NLO\,EW}}(x) = 0.05, \qquad \delta^{(3)}\kappa^{(V)}_{\mathrm{NLO\,EW}}(x) = 0.$$

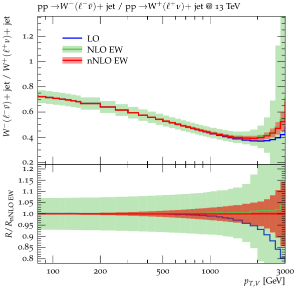
EW uncertainties of ratios of V+jet $p_{\mathrm{T,V}}$ distributions











- significant shape effects on different $p_{\mathrm{T,V}}$ ratios due to EW corrections (largest in Z/γ & W/γ)
- combined uncertainties at the level of few percent in the TeV range ($\approx 5\%$ at $p_{\mathrm{T,V}} = 2\,\mathrm{TeV}$)

Combination of QCD and EW corrections

Notation for combination of higher-order QCD and EW predictions:

$$\frac{d}{dx}\sigma^{(V)}_{\rm TH}(\vec{\mu}) = K^{(V)}_{\rm TH}(x,\vec{\mu})\,\frac{d}{dx}\sigma^{(V)}_{\rm LO\ QCD}(\vec{\mu}_0) + \frac{d}{dx}\sigma^{(V)}_{\gamma-\rm ind.}(x,\vec{\mu})$$

Additive or multiplicative combination are the standard approaches:

$$\begin{aligned} K^{(V)}_{\rm TH,\oplus}(x,\vec{\mu}) &= K^{(V)}_{\rm N^kLO}(x,\vec{\mu}) + \kappa^{(V)}_{\rm EW}(x)\,K^{(V)}_{\rm LO}(x,\vec{\mu}) \\ K^{(V)}_{\rm TH,\otimes}(x,\vec{\mu}) &= K^{(V)}_{\rm N^kLO}(x,\vec{\mu})\left[1+\kappa^{(V)}_{\rm EW}(x)\right]. \end{aligned}$$

Multiplicative approach motivated by known factorization of QCD corrections from large Sudakov-enhanced EW corrections at high energies:

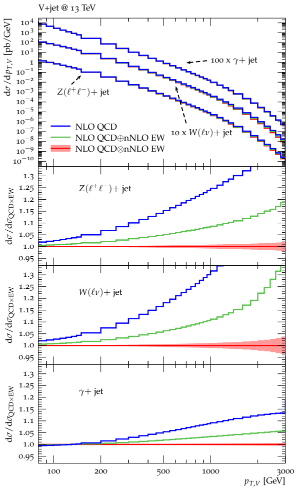
$$K^{(V)}_{\rm TH}(x,\vec{\varepsilon}_{\rm QCD},\vec{\varepsilon}_{\rm EW},\varepsilon_{\rm mix}) = K^{(V)}_{\rm TH,\otimes}(x,\vec{\varepsilon}_{\rm QCD},\vec{\varepsilon}_{\rm EW}) + \varepsilon_{\rm mix}\,\delta K^{(V)}_{\rm mix}(x)$$

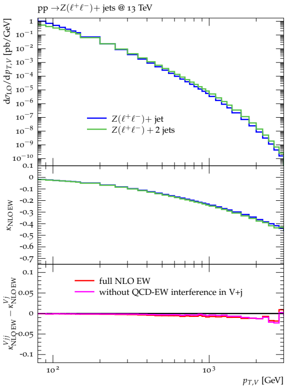
Mixed EW–QCD uncertainty parametrized via nuisance parameter $\varepsilon_{\rm mix}$:

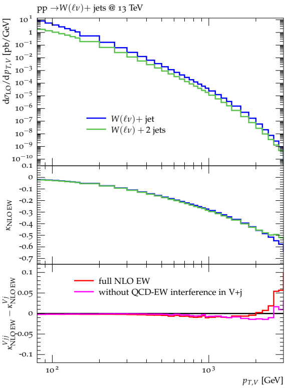
$$\delta K^{(V)}_{\rm mix}(x) = 0.1\left[K^{(V)}_{\rm TH,\oplus}(x,\vec{\mu}_0) - K^{(V)}_{\rm TH,\otimes}(x,\vec{\mu}_0)\right]$$

- small factor 0.1 motivated by comparison to V+2jets at NLO EW,
- $\varepsilon_{\rm mix}$ Gaussian distributed, $1\,\sigma \sim \varepsilon_{\rm mix} \in [-1,+1]$,
- $\varepsilon_{\rm mix}$ applied in correlated way across different processes.

Combined $p_{T,V}$ distributions and NLO EW comparison of V+1,2jets







- large difference between multiplicative and additive combination

- For V+2jets predictions, at least two anti-k_T jets with $R = 0.4$ and $p_T > 30\,\mathrm{GeV}$ (no η cuts) are required.
- Agreement of V+jet and V+2jets EW K-factors is better than 2% almost in full $p_{T,V}$ range.
- Factorization slightly disturbed by finite mixed QCD–EW bremsstrahlung interference contributions.

Real-boson emission, γ-induced production and PDF uncertainties

Real-boson emission:

- real-emission counterpart to virtual EW corrections, but separately finite,
- inclusion via separate diboson MC samples recommended (avoid double-counting).

Photon-induced processes:

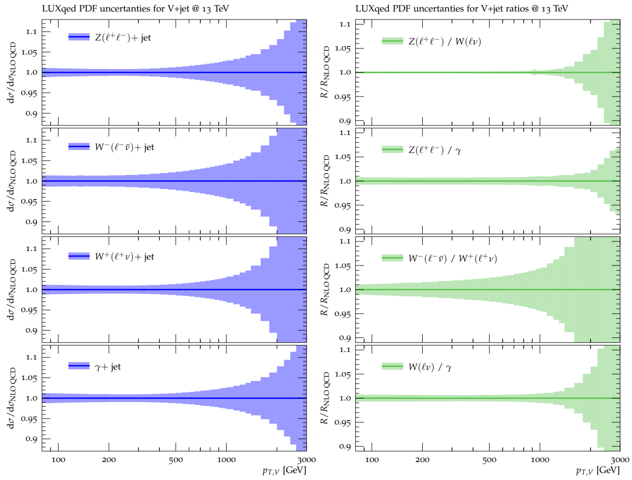
- might become relevant in TeV range
  (in particular for W+jet due to IS photon coupling to a t-channel W boson)
- suppressed by relative factor $\alpha/\alpha_{\mathrm{s}}$, thus LO (maybe NLO QCD) should be sufficient,
- inclusion of photon-induced production via separate MC samples possible.

PDF uncertainties treated via additional nuisance parameters $\vec{\varepsilon}_{\mathrm{PDF}}$,
on same footing as the QCD scale, shape and process-dependence uncertainties:

$$\vec{\varepsilon}_{\mathrm{QCD}} = (\varepsilon_{\mathrm{QCD},1}, \varepsilon_{\mathrm{QCD},2}, \varepsilon_{\mathrm{QCD},3}, \varepsilon_{\mathrm{PDF},1}, \varepsilon_{\mathrm{PDF},2}, \dots)$$

- $\vec{\varepsilon}_{\mathrm{PDF}}$ applied in correlated way across p_{T} bins and processes,
- details of implementation follow PDF4LHC recommendation [Butterworth et al. '15] .

PDF uncertainties of $p_{\mathrm{T,V}}$ distributions and ratios thereof

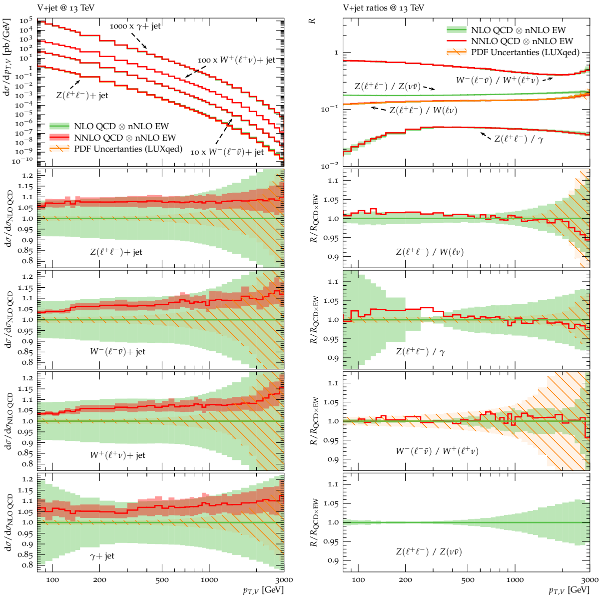


Uncertainties:

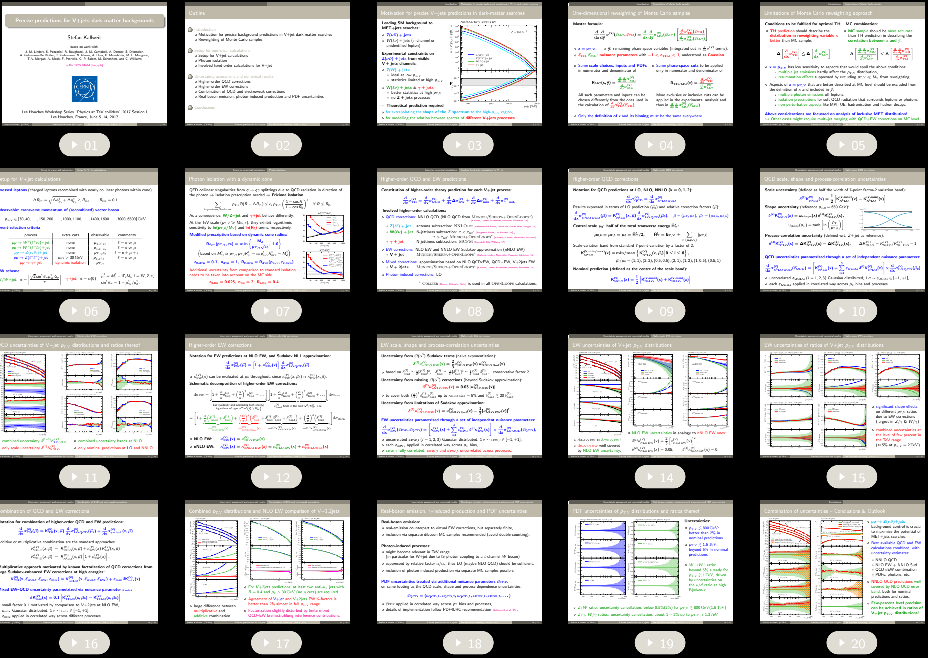
- $p_{\mathrm{T,V}} \lesssim 800\,\mathrm{GeV}$: better than 2% in nominal predictions
- $p_{\mathrm{T,V}} \gtrsim 1.5\,\mathrm{TeV}$: beyond 5% in nominal predictions
- W^-/W^+ ratio: beyond 5% already for $p_{\mathrm{T,V}} \gtrsim 1\,\mathrm{TeV}$, driven by uncertainties on the u/d ratio at high Bjorken-x

- Z/W ratio: uncertainty cancellation, below 0.5%(2%) for $p_{\mathrm{T,V}} \lesssim 800\,\mathrm{GeV}(1.5\,\mathrm{TeV})$
- Z/γ, W/γ ratios: uncertainty cancellation, about $1-2\%$ up to $p_{\mathrm{T,V}} \approx 1.3\,TeV$

Combination of uncertainties – Conclusions & Outlook



- **$pp \to Z(\nu\bar{\nu})$+jets** background control is crucial to maximise the potential of MET+jets searches.
- Best available QCD and EW calculations combined, with uncertainty estimates:
  - NNLO QCD
  - NLO EW + NNLO Sud
  - QCD×EW combination
  - PDFs, photons, etc.
- NNLO QCD predictions well covered by NLO QCD error band, both for nominal predictions and ratios.
- **Few-percent level precision can be achieved in ratios of V+jet $p_{T,V}$ distributions!**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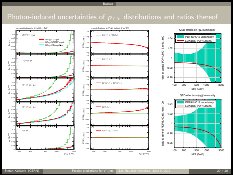

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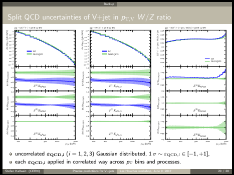

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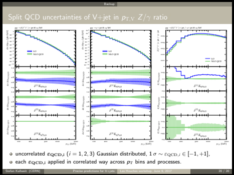

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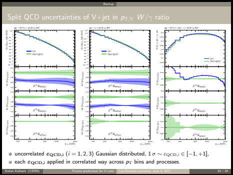

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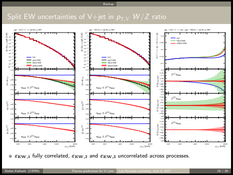

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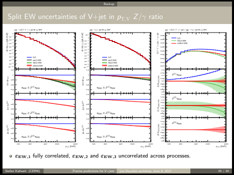

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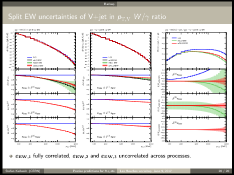

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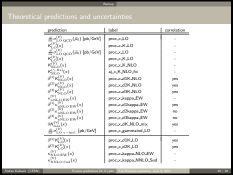
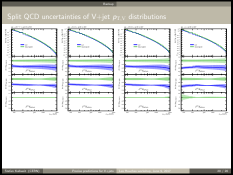


Theoretical predictions and uncertainties

prediction	label	correlation
$\frac{d}{dx}\sigma^{(V)}_{LO\,QCD}(\vec{\mu}_0)$ [pb/GeV]	proc_x_LO	-
$K^{(V)}_{LO}(x)$	proc_x_K_LO	-
$\frac{d}{dx}\sigma^{(V)}_{LO\,QCD}(\vec{\mu}_0)$ [pb/GeV]	proc_x_LO	-
$K^{(V)}_{LO}(x)$	proc_x_K_LO	-
$K^{(V)}_{NLO}(x)$	proc_x_K_NLO	-
$K^{(\gamma,\text{fix})}_{NLO}(x)$	aj_x_K_NLO_fix	-
$\delta^{(1)}K^{(V)}_{NLO}(x)$	proc_x_d1K_NLO	yes
$\delta^{(2)}K^{(V)}_{NLO}(x)$	proc_x_d2K_NLO	yes
$\delta^{(3)}K^{(V)}_{NLO}(x)$	proc_x_d3K_NLO	yes
$\kappa^{(V)}_{nNLO\,EW}(x)$	proc_x_kappa_EW	-
$\delta^{(1)}\kappa^{(V)}_{nNLO\,EW}(x)$	proc_x_d1kappa_EW	yes
$\delta^{(2)}\kappa^{(V)}_{nNLO\,EW}(x)$	proc_x_d2kappa_EW	no
$\delta^{(3)}\kappa^{(V)}_{nNLO\,EW}(x)$	proc_x_d3kappa_EW	no
$\delta K^{(V)}_{mix}(x)$	proc_x_dK_NLO_mix	yes
$\frac{d}{dx}\sigma^{(V)}_{LO\,\gamma-\text{ind.}}$ [pb/GeV]	proc_x_gammaind_LO	-
$\delta^{(1)}K^{(V)}_{LO}(x)$	proc_x_d1K_LO	yes
$\delta^{(2)}K^{(V)}_{LO}(x)$	proc_x_d2K_LO	yes
$\kappa^{(V)}_{NLO\,EW}(x)$	proc_x_kappa_NLO_EW	-
$\kappa^{(V)}_{NNLO\,Sud}(x)$	proc_x_kappa_NNLO_Sud	-

B08



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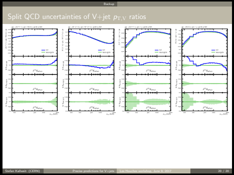

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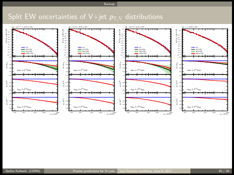

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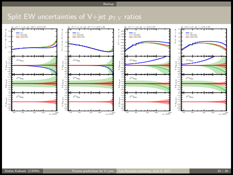
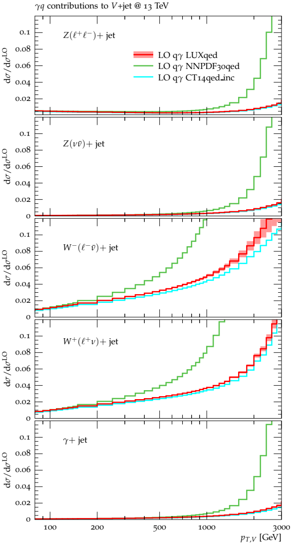
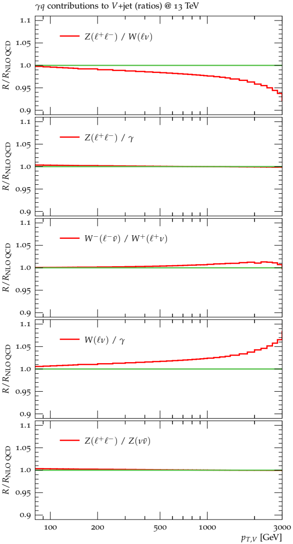
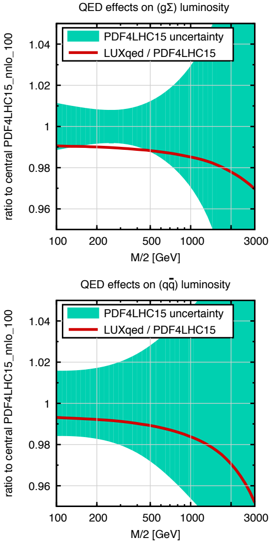


B12

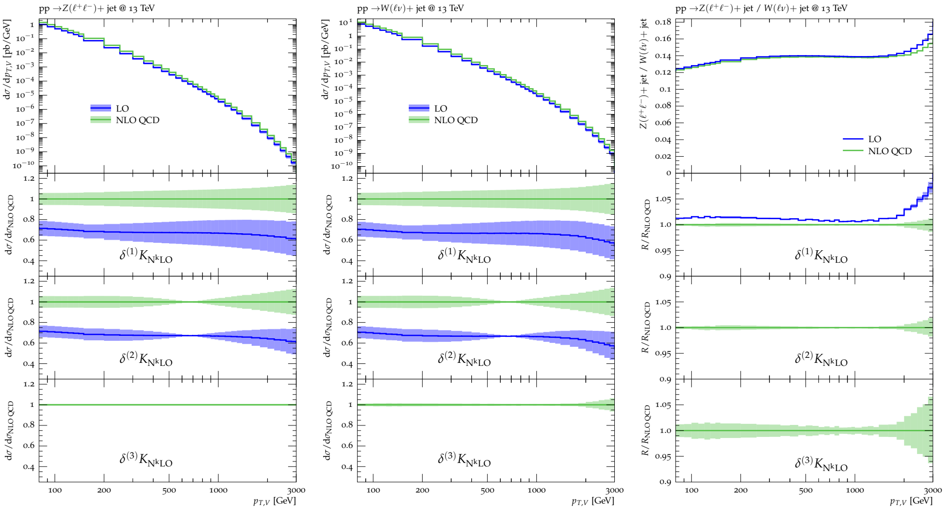
Photon-induced uncertainties of $p_{\mathrm{T,V}}$ distributions and ratios thereof





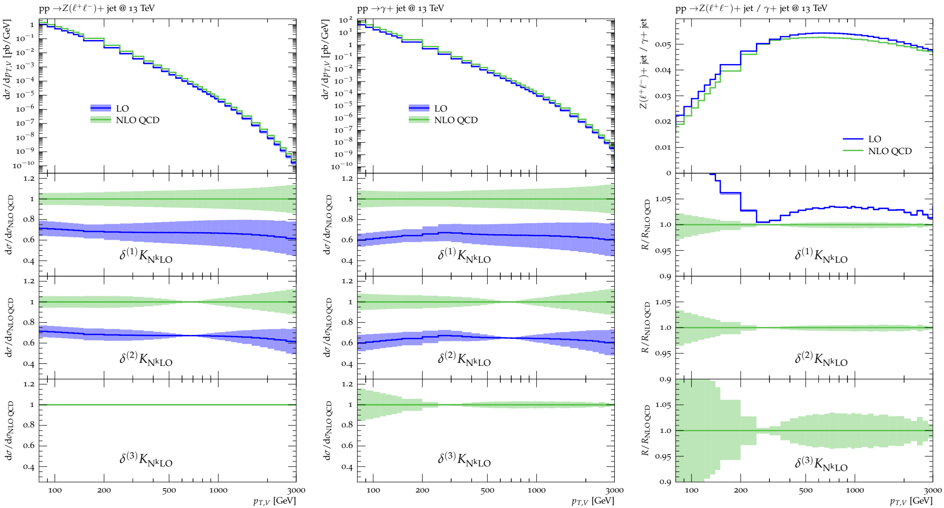


Split QCD uncertainties of V+jet in $p_{\mathrm{T,V}}$ W/Z ratio



- uncorrelated $\boldsymbol{\varepsilon_{\mathrm{QCD},i}}$ $(i = 1, 2, 3)$ Gaussian distributed, $1\,\sigma \sim \varepsilon_{\mathrm{QCD},i} \in [-1, +1]$,
- each $\boldsymbol{\varepsilon_{\mathrm{QCD},i}}$ applied in correlated way across p_{T} bins and processes.

Split QCD uncertainties of V+jet in $p_{\mathrm{T,V}}$ Z/γ ratio



- uncorrelated $\varepsilon_{\mathbf{QCD,i}}$ $(i = 1, 2, 3)$ Gaussian distributed, $1\,\sigma \sim \varepsilon_{\mathrm{QCD},i} \in [-1, +1]$,
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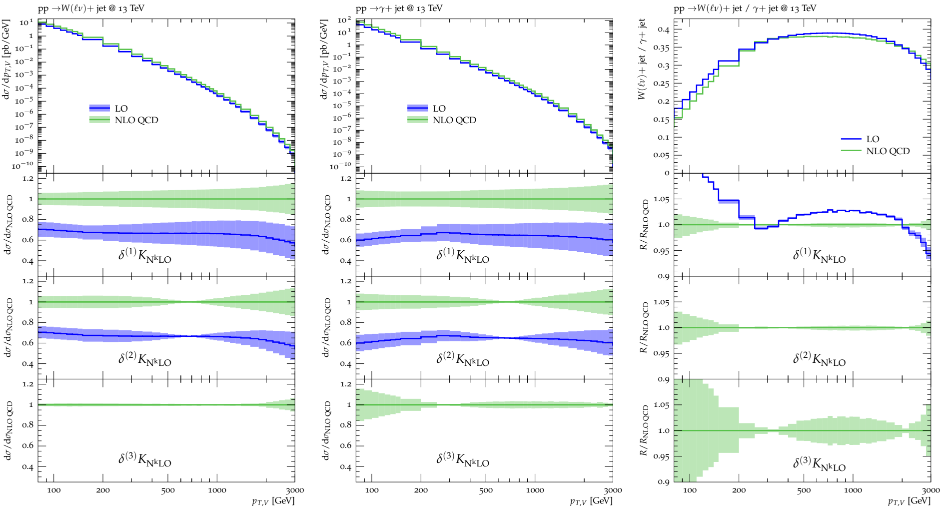
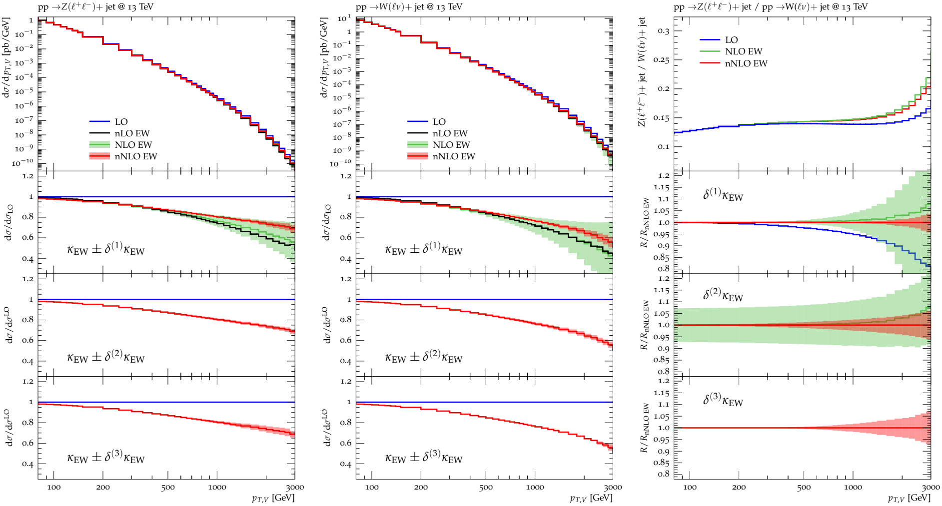
Split QCD uncertainties of V+jet in $p_{\mathrm{T,V}}$ W/γ ratio



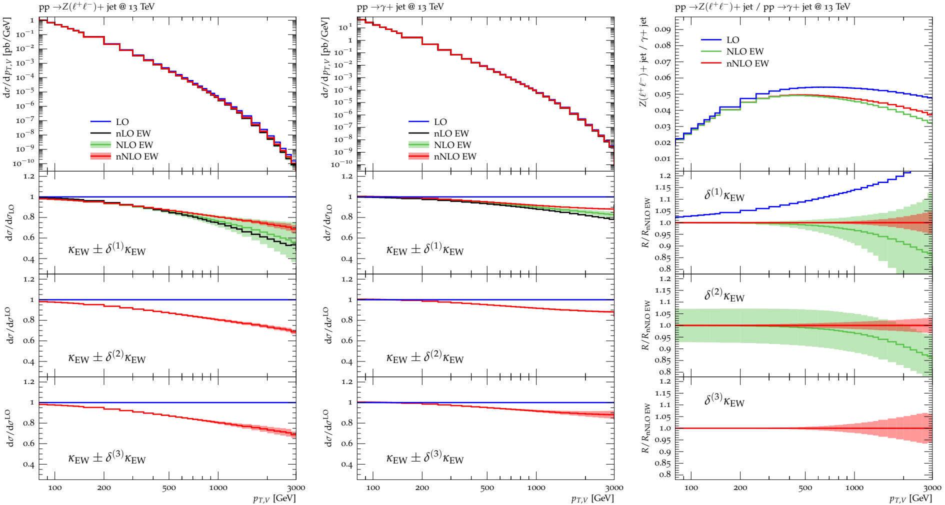
- uncorrelated $\boldsymbol{\varepsilon_{\mathrm{QCD},i}}$ $(i = 1, 2, 3)$ Gaussian distributed, $1\,\sigma \sim \varepsilon_{\mathrm{QCD},i} \in [-1, +1]$,
- each $\boldsymbol{\varepsilon_{\mathrm{QCD},i}}$ applied in correlated way across p_{T} bins and processes.

Split EW uncertainties of V+jet in $p_{\mathrm{T,V}}$ W/Z ratio



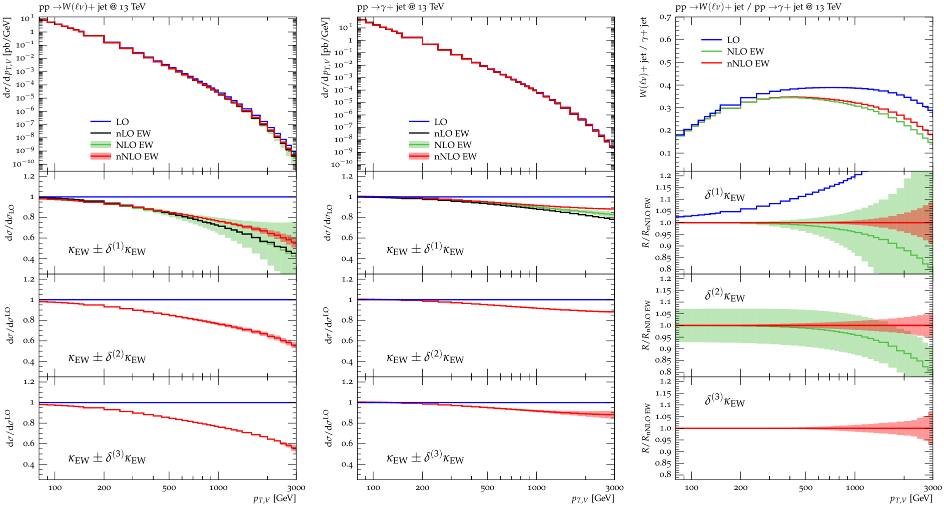
- $\varepsilon_{\mathrm{EW},1}$ fully correlated, $\varepsilon_{\mathrm{EW},2}$ and $\varepsilon_{\mathrm{EW},3}$ uncorrelated across processes.

Split EW uncertainties of V+jet in $p_{\mathrm{T,V}}$ Z/γ ratio



- $\varepsilon_{\mathbf{EW,1}}$ fully correlated, $\varepsilon_{\mathbf{EW,2}}$ and $\varepsilon_{\mathbf{EW,3}}$ uncorrelated across processes.

Split EW uncertainties of V+jet in $p_{\mathrm{T,V}}$ W/γ ratio

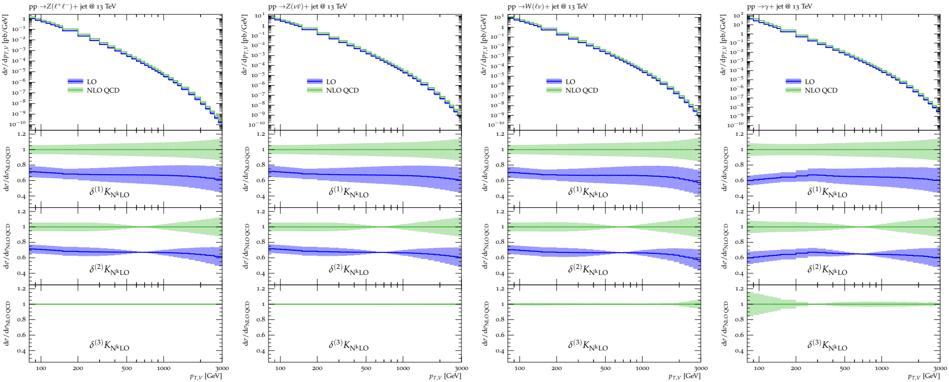


- $\varepsilon_{\mathbf{EW,1}}$ fully correlated, $\varepsilon_{\mathbf{EW,2}}$ and $\varepsilon_{\mathbf{EW,3}}$ uncorrelated across processes.

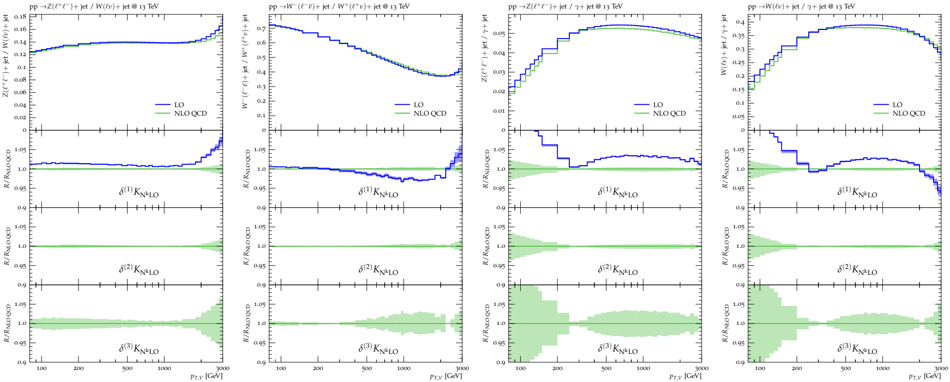
Theoretical predictions and uncertainties

prediction	label	correlation
$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0)$ [pb/GeV]	proc_x_LO	-
$K^{(V)}_{\mathrm{LO}}(x)$	proc_x_K_LO	-
$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0)$ [pb/GeV]	proc_x_LO	-
$K^{(V)}_{\mathrm{LO}}(x)$	proc_x_K_LO	-
$K^{(V)}_{\mathrm{NLO}}(x)$	proc_x_K_NLO	-
$K^{(\gamma,\mathrm{fix})}_{\mathrm{NLO}}(x)$	aj_x_K_NLO_fix	-
$\delta^{(1)}K^{(V)}_{\mathrm{NLO}}(x)$	proc_x_d1K_NLO	yes
$\delta^{(2)}K^{(V)}_{\mathrm{NLO}}(x)$	proc_x_d2K_NLO	yes
$\delta^{(3)}K^{(V)}_{\mathrm{NLO}}(x)$	proc_x_d3K_NLO	yes
$\kappa^{(V)}_{\mathrm{nNLO\,EW}}(x)$	proc_x_kappa_EW	-
$\delta^{(1)}\kappa^{(V)}_{\mathrm{nNLO\,EW}}(x)$	proc_x_d1kappa_EW	yes
$\delta^{(2)}\kappa^{(V)}_{\mathrm{nNLO\,EW}}(x)$	proc_x_d2kappa_EW	no
$\delta^{(3)}\kappa^{(V)}_{\mathrm{nNLO\,EW}}(x)$	proc_x_d3kappa_EW	no
$\delta K^{(V)}_{\mathrm{mix}}(x)$	proc_x_dK_NLO_mix	yes
$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO}\,\gamma-\mathrm{ind.}}$ [pb/GeV]	proc_x_gammaind_LO	-
$\delta^{(1)}K^{(V)}_{\mathrm{LO}}(x)$	proc_x_d1K_LO	yes
$\delta^{(2)}K^{(V)}_{\mathrm{LO}}(x)$	proc_x_d2K_LO	yes
$\kappa^{(V)}_{\mathrm{NLO\,EW}}(x)$	proc_x_kappa_NLO_EW	-
$\kappa^{(V)}_{\mathrm{NNLO\,Sud}}(x)$	proc_x_kappa_NNLO_Sud	-

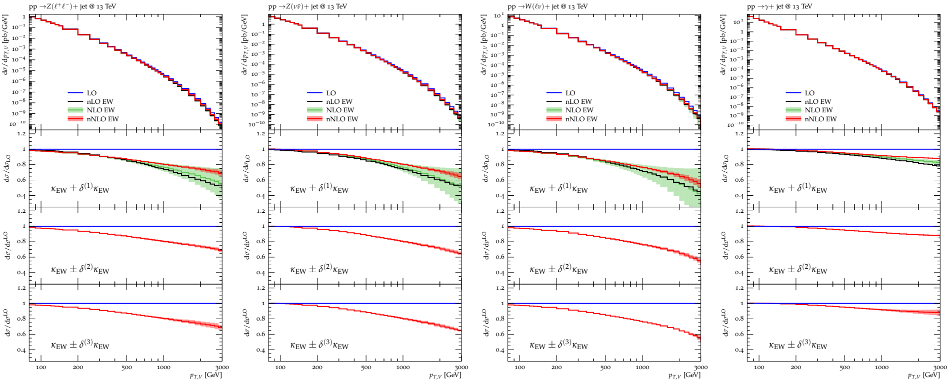
Split QCD uncertainties of V+jet $p_{\mathrm{T,V}}$ distributions



Split QCD uncertainties of V+jet $p_{\mathrm{T,V}}$ ratios



Split EW uncertainties of V+jet $p_{\mathrm{T,V}}$ distributions



Split EW uncertainties of V+jet $p_{\mathrm{T,V}}$ ratios