Standard Model theory (EW & top)

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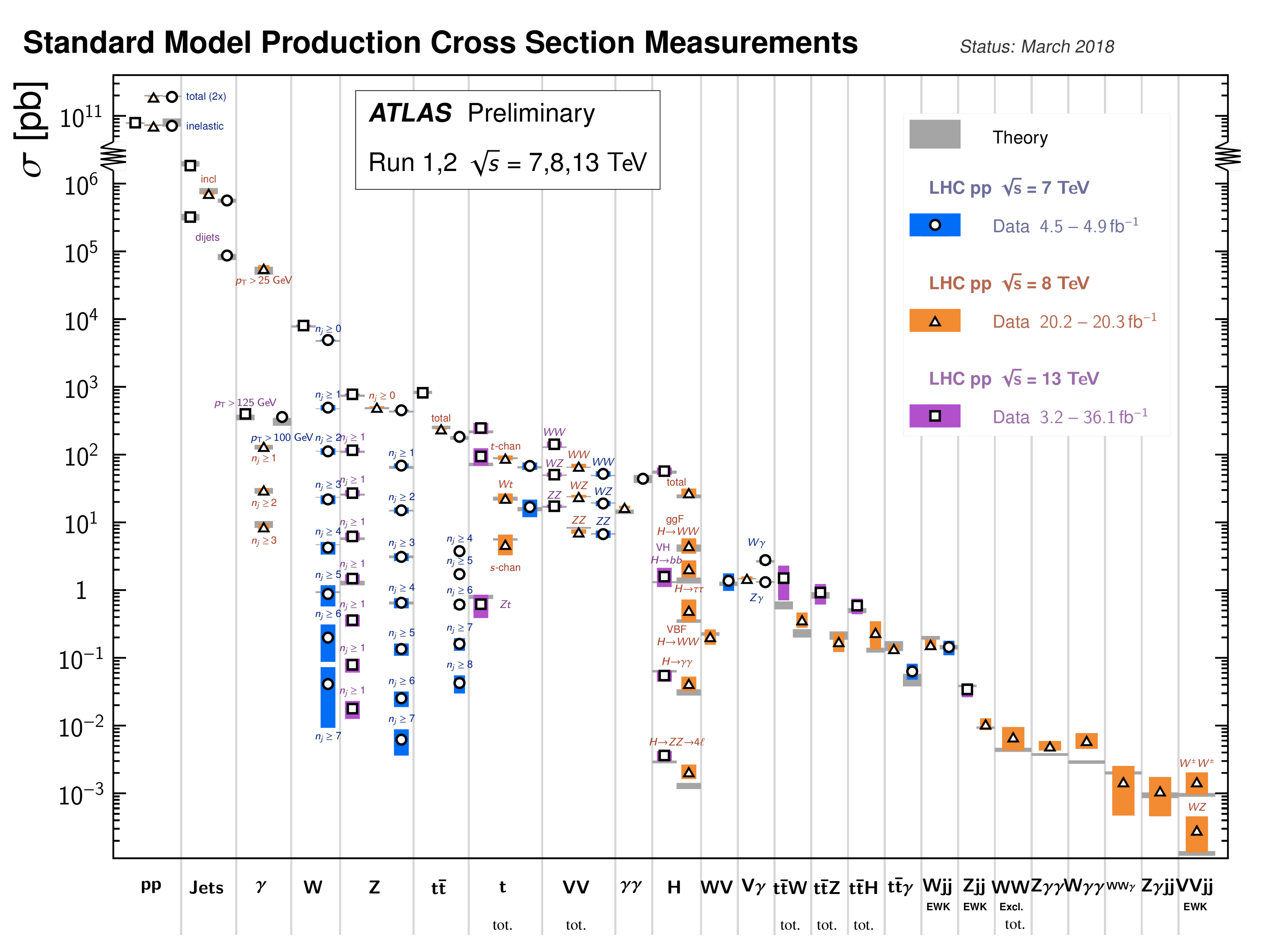
IP3

Pushing the Boundaries of the Energy and Intensity Frontiers
-- the HL-LHC and Beyond
IPPP, 4.7.18

The success of the SM

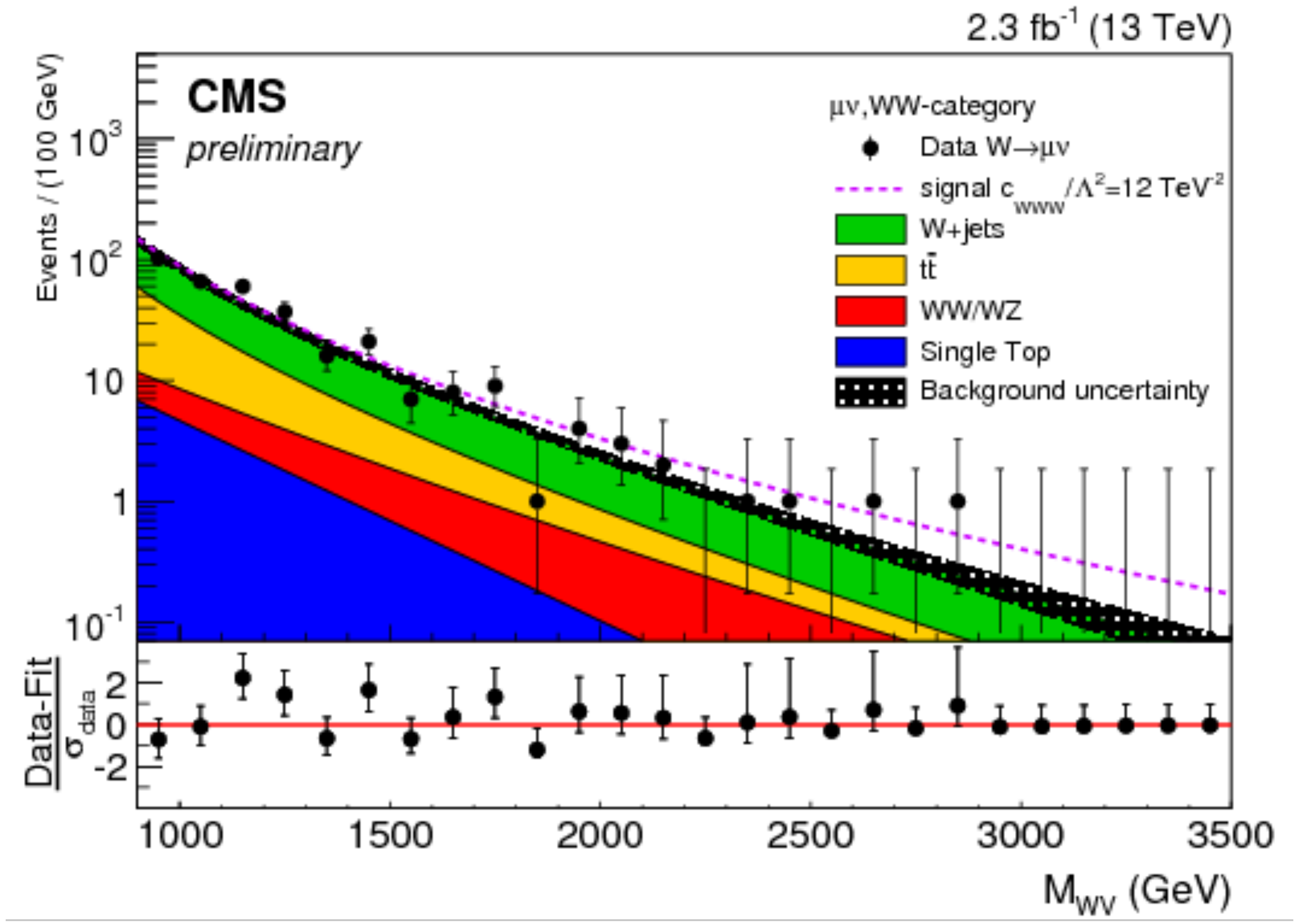


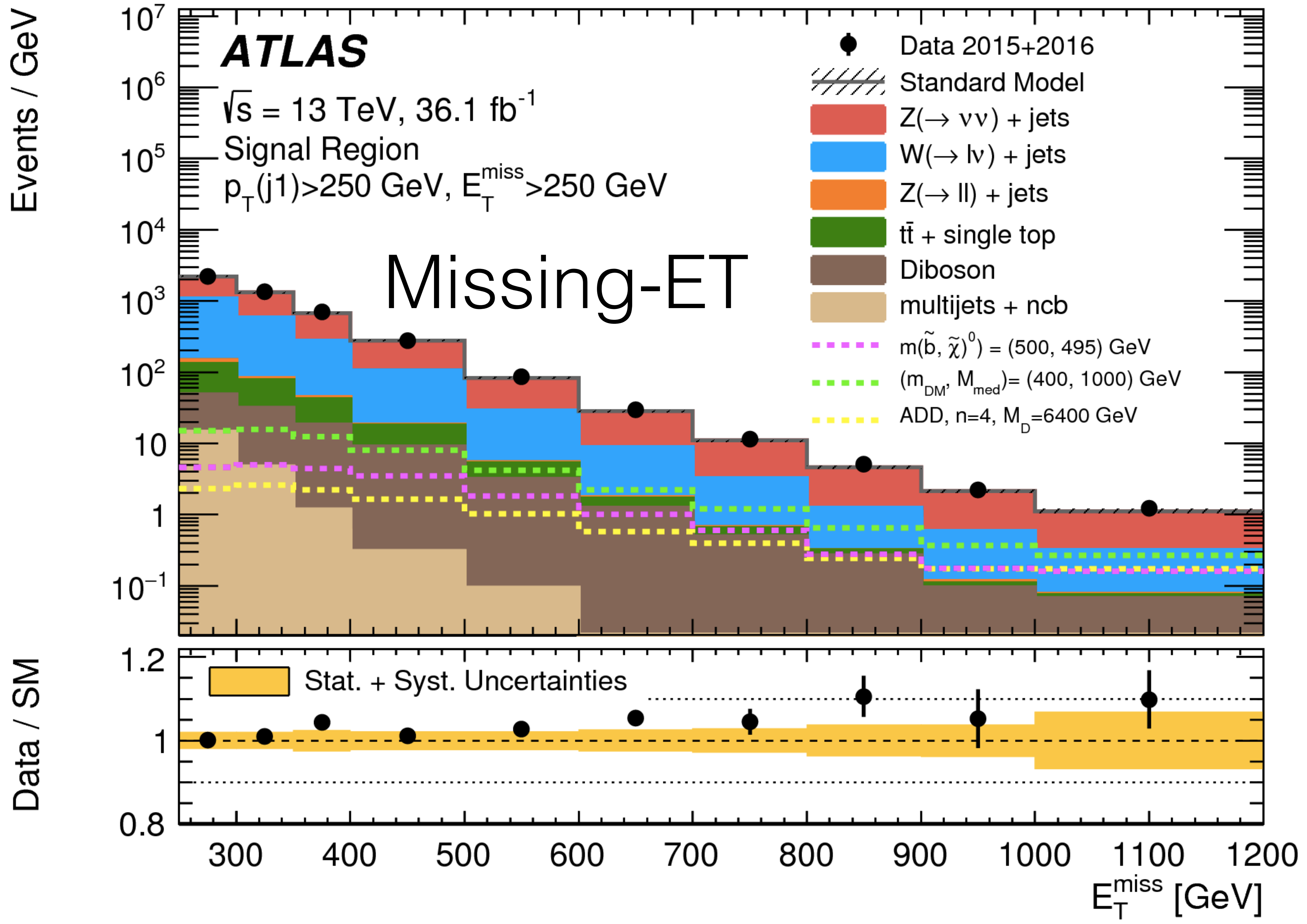
Overall extremely good experiment-theory agreement

Differential SM measurements

The need for precision in tails

Diboson Dark Matter





- In case new physics is heavy: expect small deviations in tails of distributions

→ **good control on theory necessary!**

- Dark Matter particles produced at the LHC leave the detectors unobserved: signature missing transverse energy
- large irreducible SM backgrounds

→ **good control on theory necessary!**

SM physics at Run-III/HL/HE-LHC

Precision EW

- VV
- V+jets
- MW

Precision top

- (multi)differential top-pair
- MT

Rare processes

- VBS
- 4-top
- ….

Higgs *[see Talk by Andrea Banfi]*

- precision couplings
- high-pT
- HH

Precision at the LHC

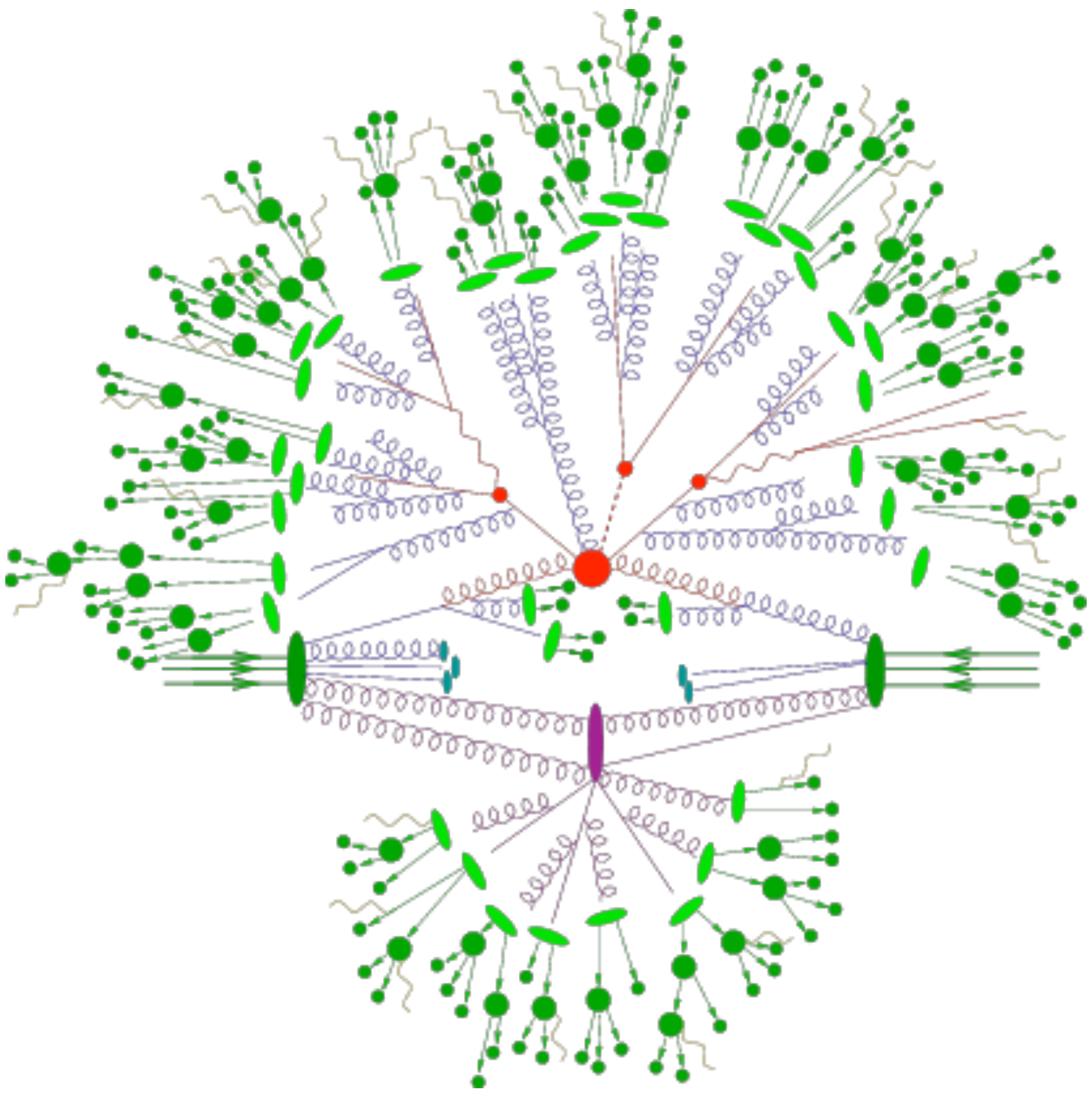
$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\overline{\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{gathered}
$$

$$|\mathcal{M}|^2 \longrightarrow \sigma$$

Precision at the LHC

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda\,M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\overline{\bar{\nu}_\lambda\,M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{gathered}
$$

$$\hookrightarrow |\mathcal{M}|^2 \curvearrowright \sigma$$

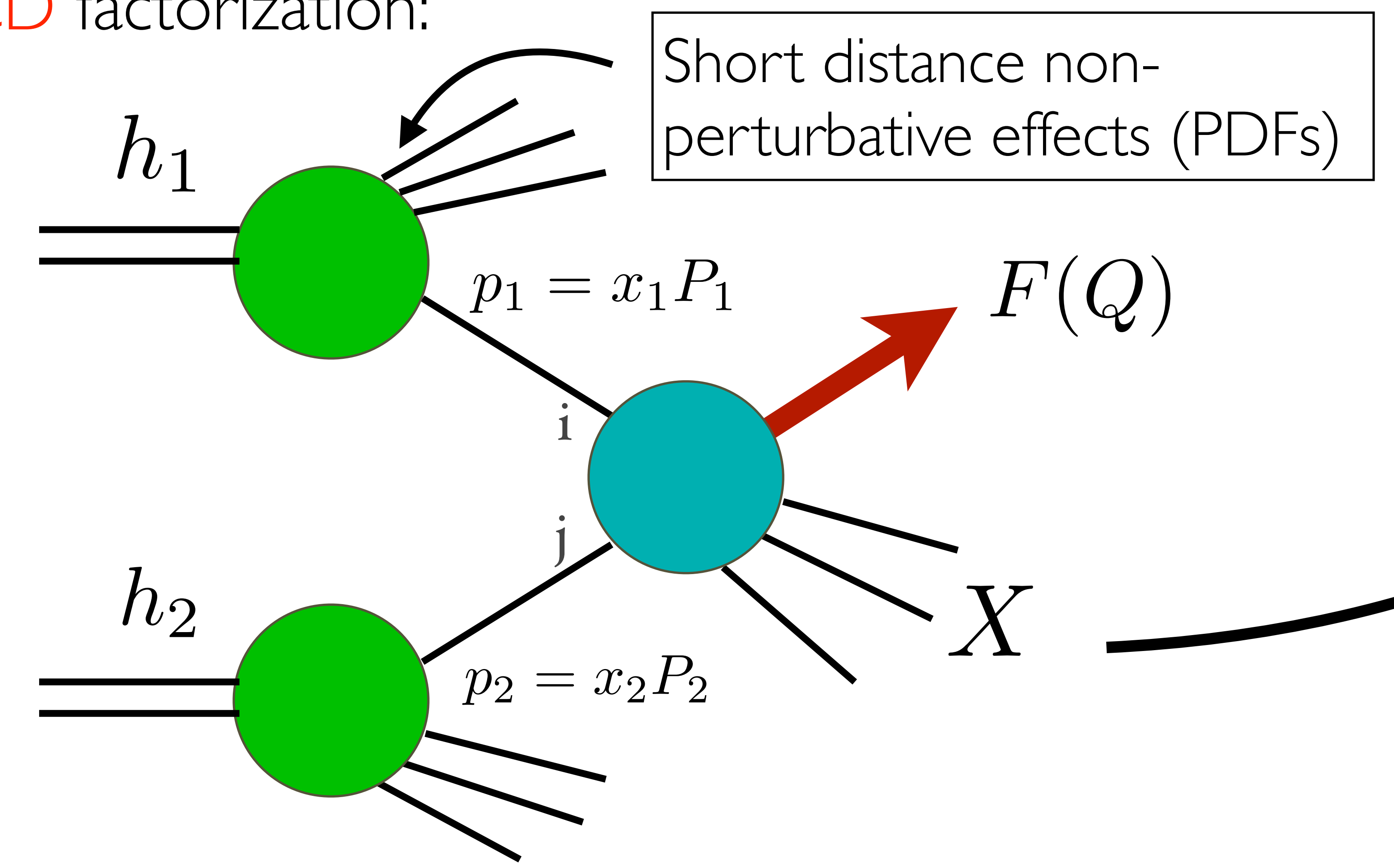


Precision at the LHC

Hard (perturbative) scattering process

- **N(N)LO QCD + EW**

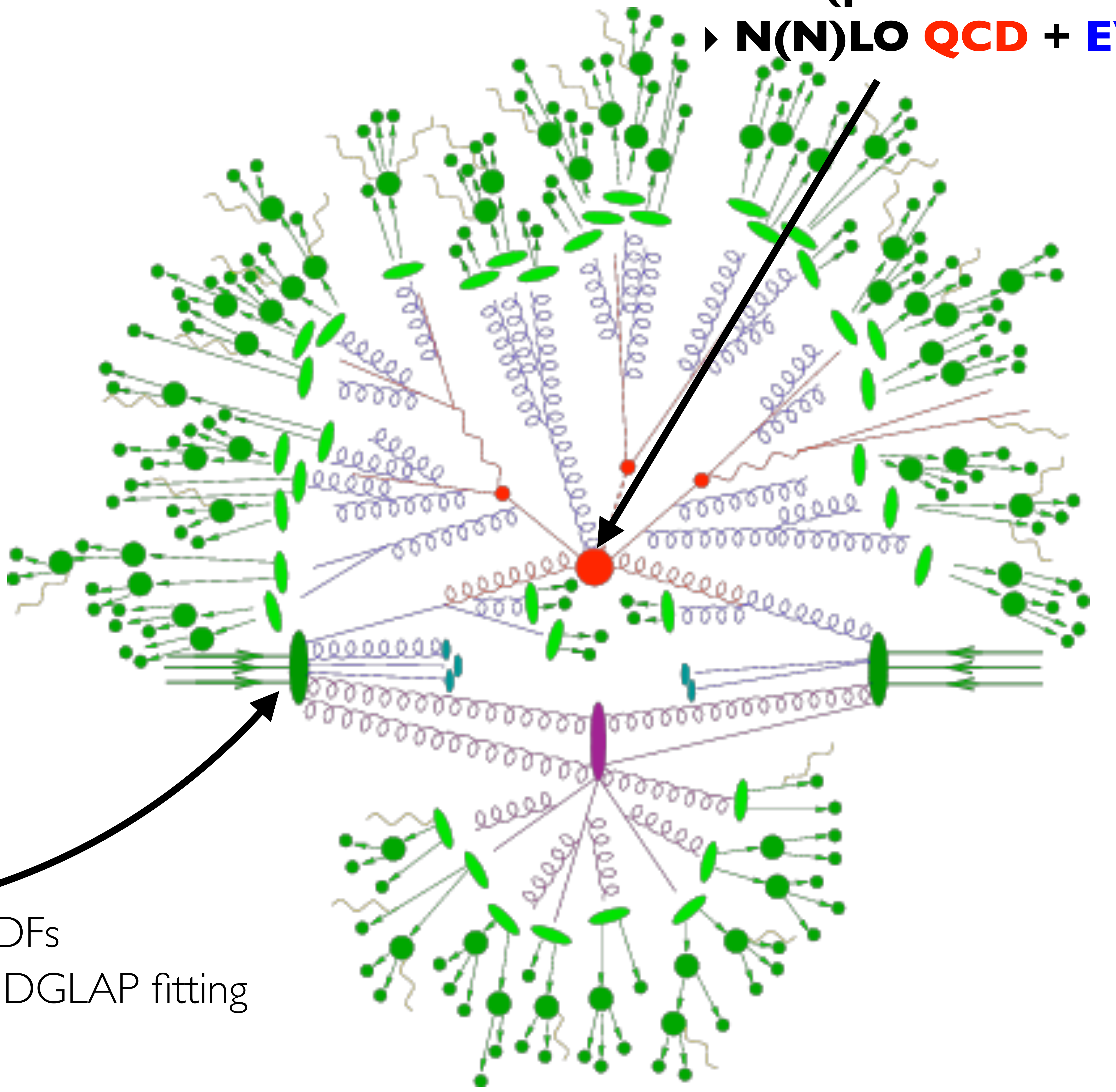
Key: QCD factorization:



$$d\sigma = \sum_{ij} \int dx_1 dx_2 f_1^{(P_1)}(x_1) f_2^{(P_2)}(x_2) d\hat{\sigma}_{ij}(x_1 x_2 s)$$

PDFs

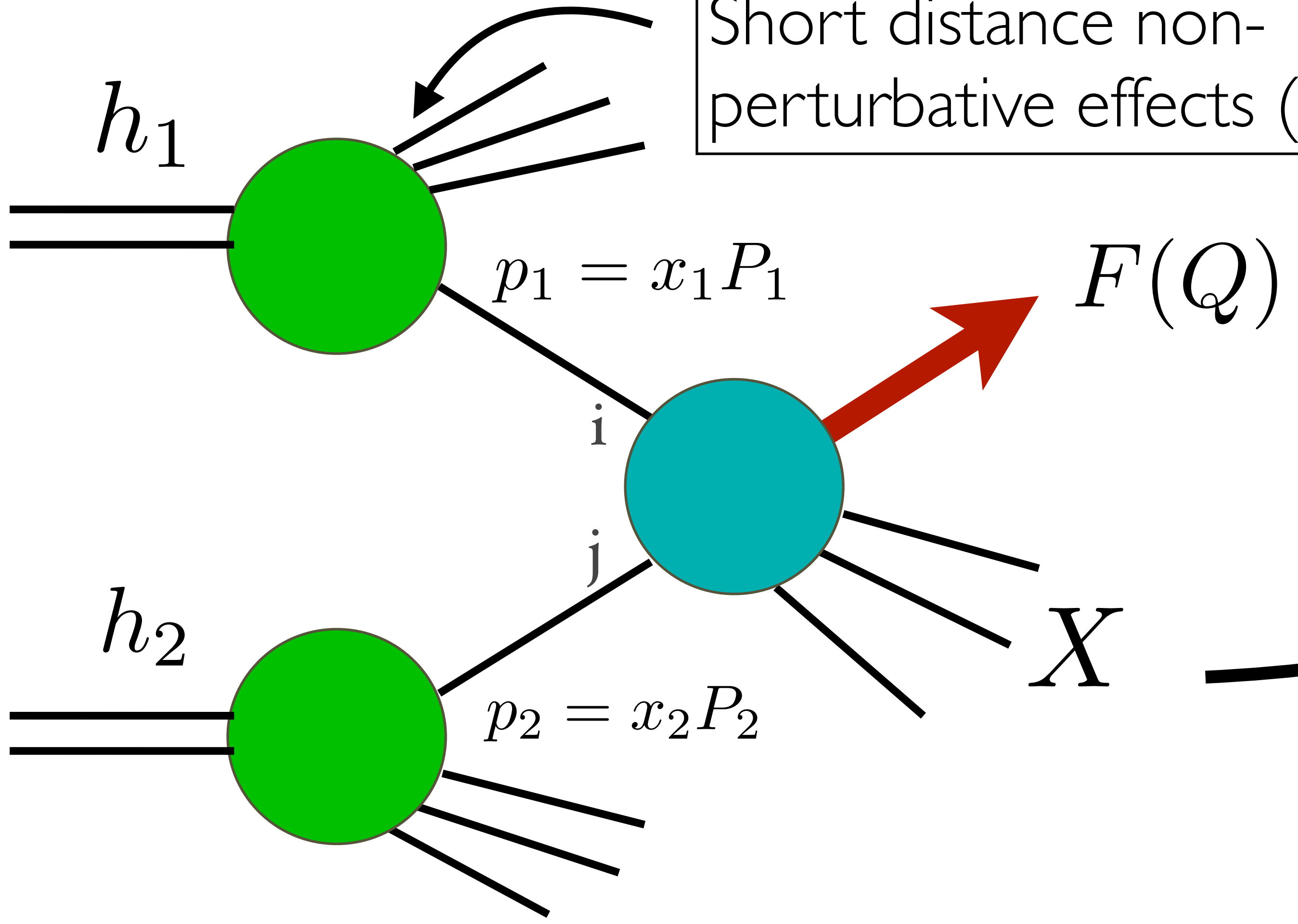
- DGLAP fitting



Precision at the LHC

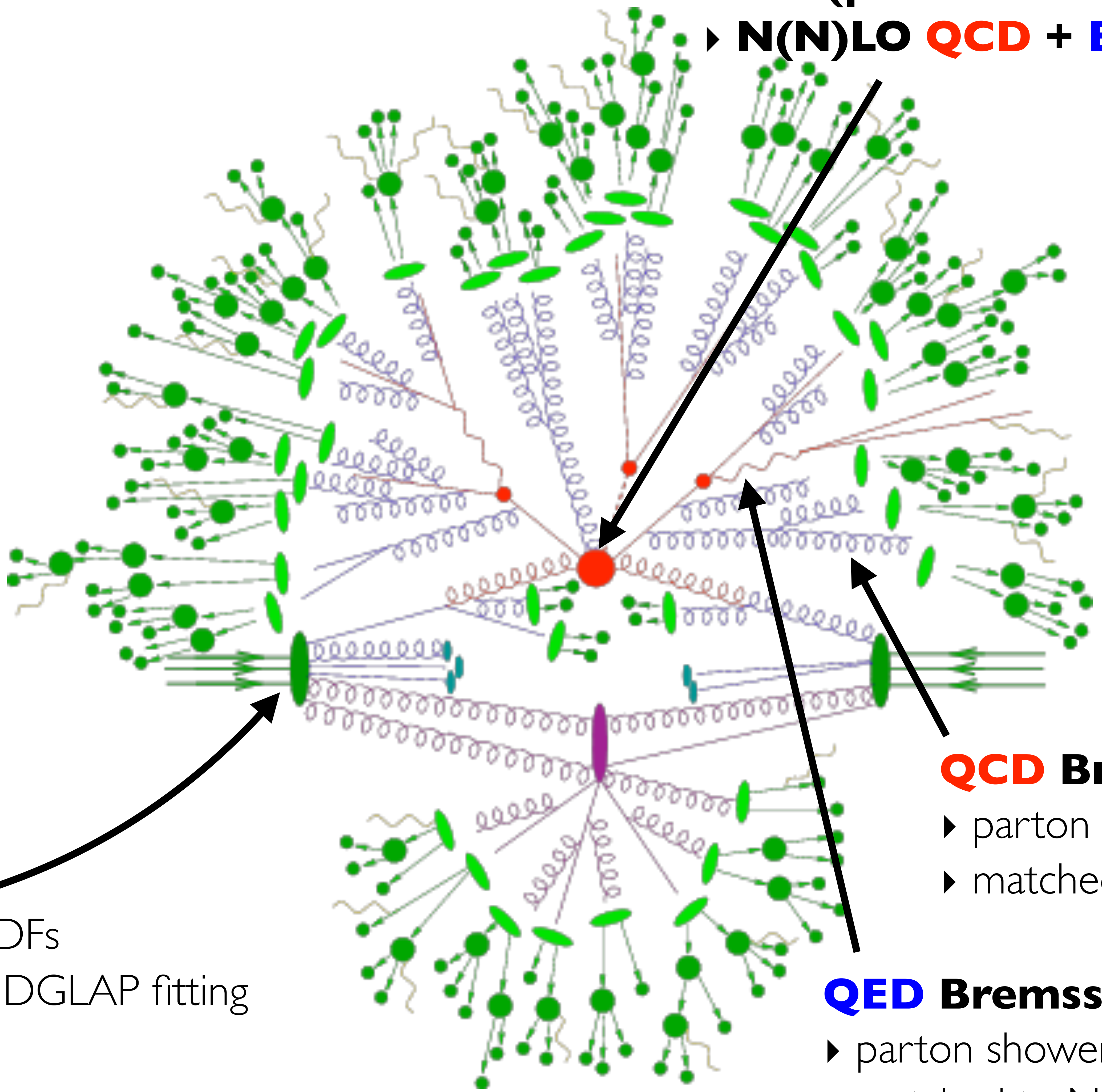
Key: QCD factorization:

Short distance non-perturbative effects (PDFs)



$$d\sigma = \sum_{ij} \int dx_1 dx_2 f_1^{(P_1)}(x_1) f_2^{(P_2)}(x_2) d\hat{\sigma}_{ij}(x_1 x_2 s)$$

PDFs
- DGLAP fitting



Hard (perturbative) scattering process
- **N(N)LO QCD + EW**

QCD Bremsstrahlung
- parton shower
- matched to NLO matrix elements

QED Bremsstrahlung
- parton shower
- matched to NLO matrix elements

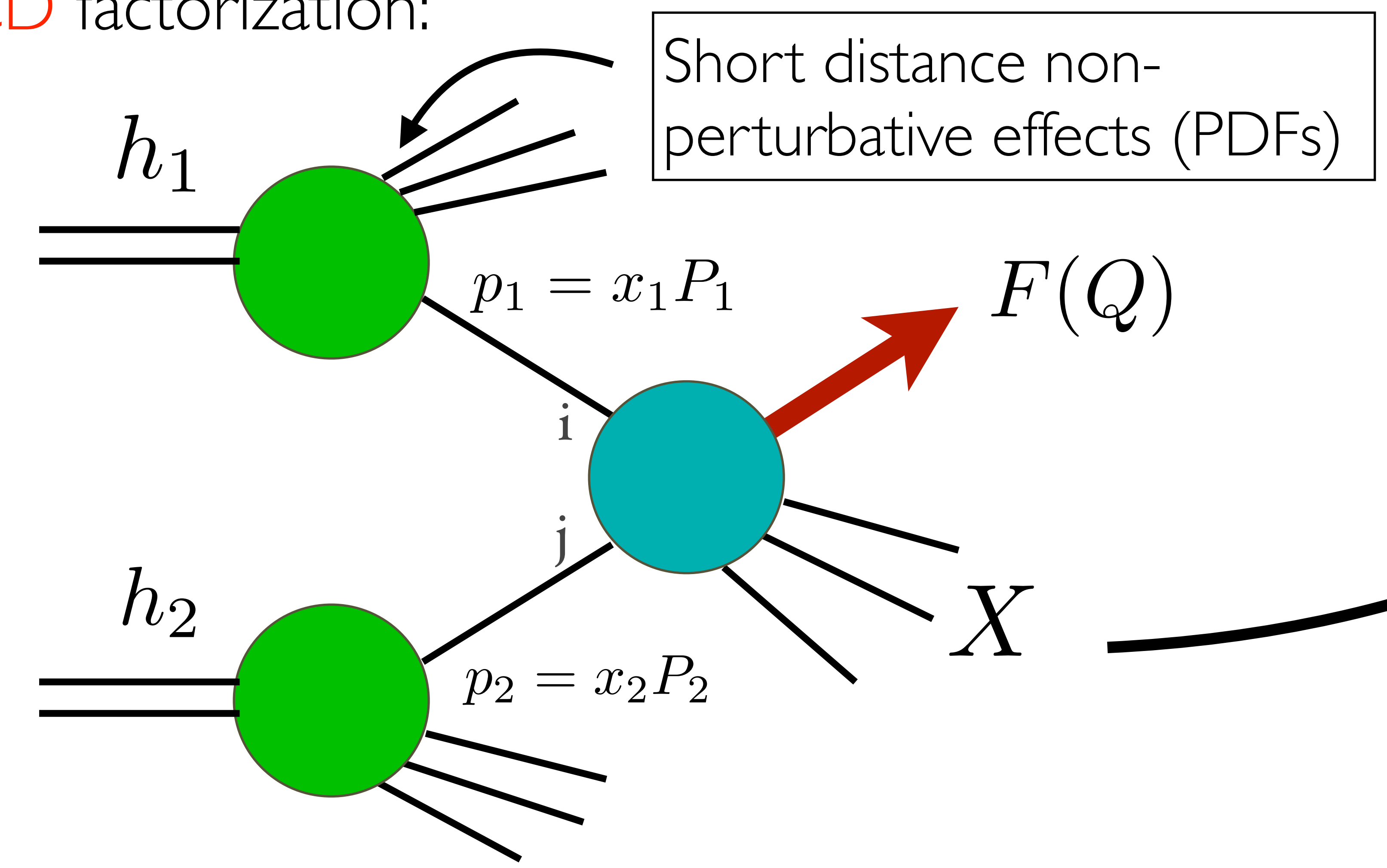
Precision at the LHC

Hard (perturbative) scattering process
- **N(N)LO QCD + EW**

Hadronization/fragmentation/decay
- pheno models

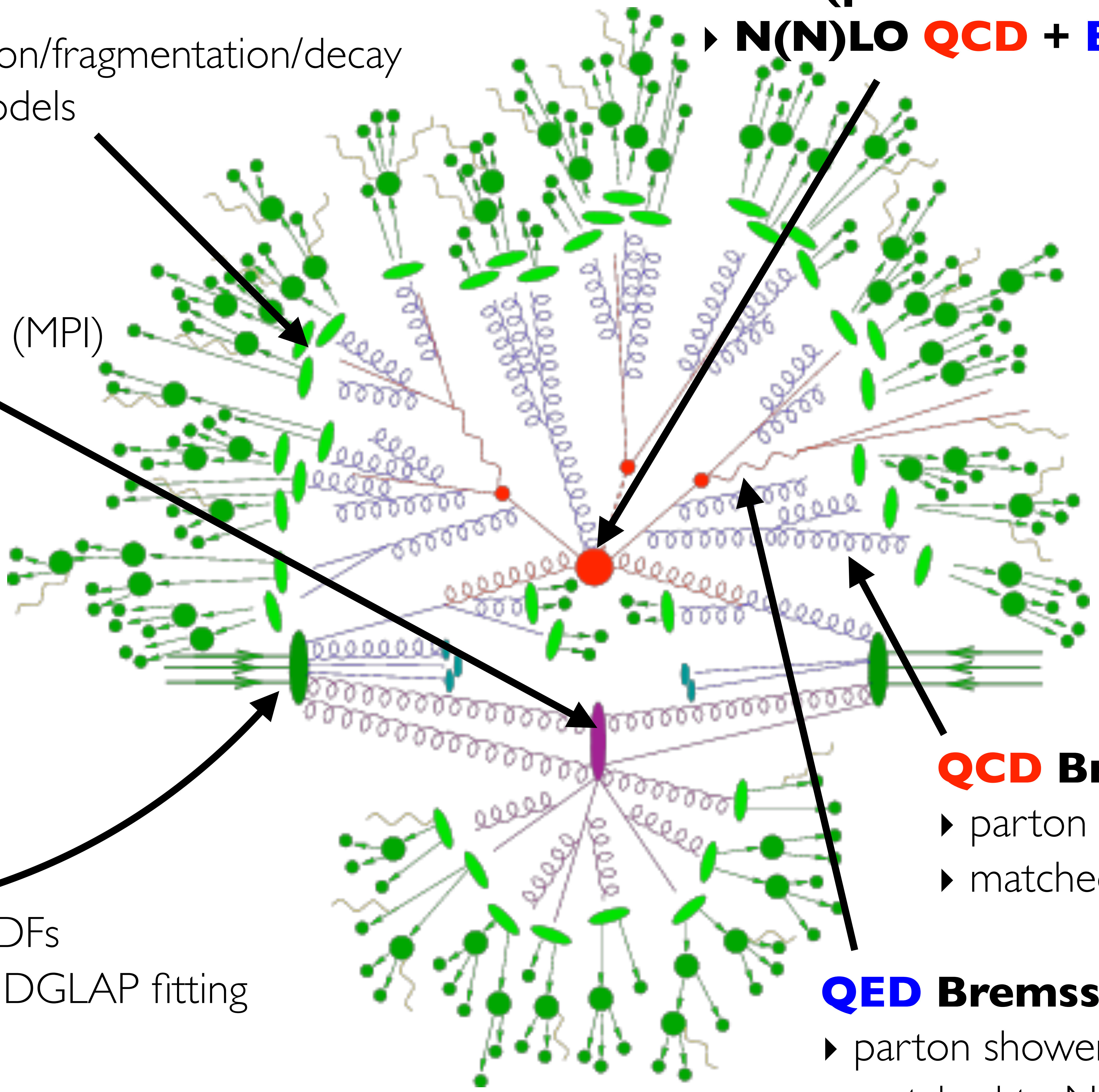
Multi Particle Interactions (MPI)
- pheno model

Key: QCD factorization:



$$d\sigma = \sum_{ij} \int dx_1 dx_2 f_1^{(P_1)}(x_1) f_2^{(P_2)}(x_2) d\hat{\sigma}_{ij}(x_1 x_2 s)$$

PDFs
- DGLAP fitting



QCD Bremsstrahlung
- parton shower
- matched to NLO matrix elements

QED Bremsstrahlung
- parton shower
- matched to NLO matrix elements

Theoretical Predictions for the LHC

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right) .
\end{gathered}
$$

$$|\mathcal{M}|^2 \longrightarrow \sigma$$

Hard (perturbative) scattering process:

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{LO}} + \alpha_S\,\mathrm{d}\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\,\mathrm{d}\sigma_{\mathrm{NLO\,EW}}$$

$$+\alpha_S^2\,\mathrm{d}\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\,\mathrm{d}\sigma_{\mathrm{NNLO\,EW}} + \alpha_S\alpha_{\mathrm{EW}}\,\mathrm{d}\sigma_{\mathrm{NNLO\,QCDxEW}}$$

Theoretical Predictions for the LHC

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right) .
\end{gathered}
$$

$$|\mathcal{M}|^2 \longrightarrow \sigma$$

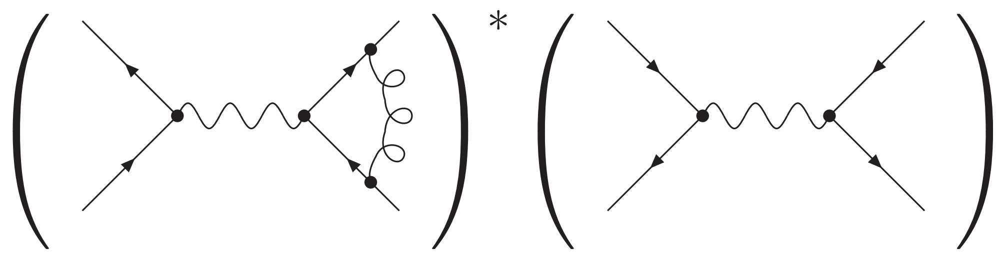
Hard (perturbative) scattering process:

$$
\begin{aligned}
d\sigma = d\sigma_{\mathrm{LO}} + \alpha_S\, d\sigma_{\mathrm{NLO}} + \alpha_{\mathrm{EW}}\, d\sigma_{\mathrm{NLO\,EW}} \\
+\alpha_S^2\, d\sigma_{\mathrm{NNLO}} + \alpha_{\mathrm{EW}}^2\, d\sigma_{\mathrm{NNLO\,EW}} + \alpha_S\alpha_{\mathrm{EW}}\, d\sigma_{\mathrm{NNLO\,QCDxEW}}
\end{aligned}
$$

$$
\boxed{d\sigma_{\mathrm{NLO}} = \frac{1}{2s}\int d\Phi_n \left[|\mathcal{M}_{\mathrm{LO}}|^2 + 2\mathrm{Re}\{\mathcal{M}_{\mathrm{LO}}\mathcal{M}^*_{\mathrm{NLO,V}}\}\right] + \frac{1}{2s}\int d\Phi_{n+1}|\mathcal{M}_{\mathrm{NLO,R}}|^2}
$$

NLO = B + V + R

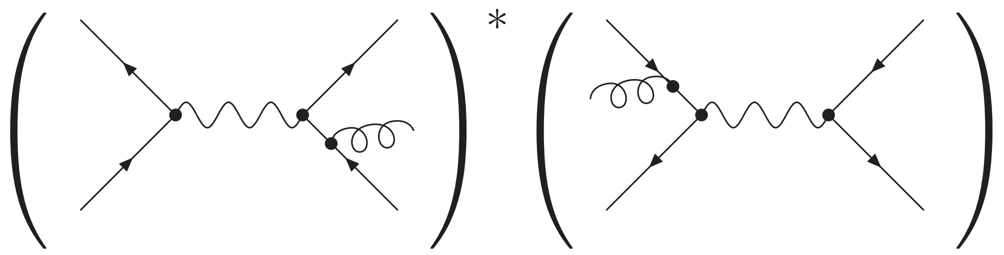
$\mathrm{Re}\{\mathcal{M}_{\mathrm{LO}}\mathcal{M}^*_{\mathrm{NLO,V}}\}$



$\mathcal{M}_{\mathrm{NLO,V}}$ **virtual** one-loop matrix element

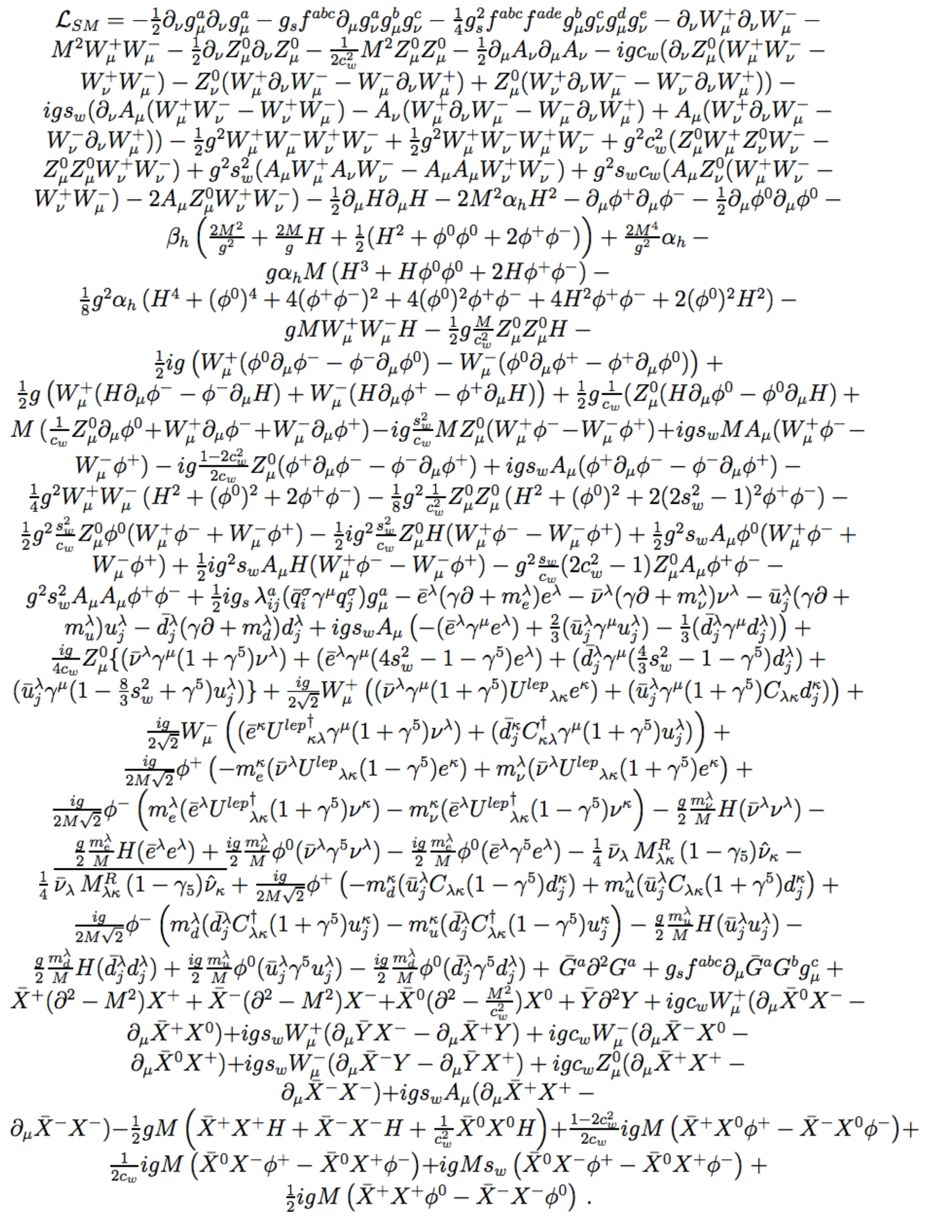
$\mathcal{M}_{\mathrm{NLO,R}}$ **real** tree-level matrix element

$|\mathcal{M}_{\mathrm{NLO,R}}|^2$



- UV renormalisation ⇒ reduction of **μ_R dependence**
- soft/collinear cancellations+PDF renormalisation ⇒ reduction of **μ_F dependence**

Theoretical Predictions for the LHC



$$\hookrightarrow |\mathcal{M}|^2 \longrightarrow \sigma$$

Hard (perturbative) scattering process:

$$d\sigma = d\sigma_{\rm LO} + \alpha_S\, d\sigma_{\rm NLO} + \alpha_{\rm EW}\, d\sigma_{\rm NLO\,EW}$$

$$+\alpha_S^2\, d\sigma_{\rm NNLO} + \alpha_{\rm EW}^2\, d\sigma_{\rm NNLO\,EW} + \alpha_S\alpha_{\rm EW}\, d\sigma_{\rm NNLO\,QCDxEW}$$

$$d\hat{\sigma}_{\rm NNLO} = \frac{1}{2s}\int d\Phi_n \left[|\mathcal{M}_{\rm LO}|^2 + 2{\rm Re}\{\mathcal{M}_{\rm LO}\mathcal{M}^*_{\rm NLO,V}\} + 2{\rm Re}\{\mathcal{M}_{\rm LO}\mathcal{M}^*_{\rm NNLO,V}\}\right]$$

NNLO = B + V + V2 + ...

$$+\frac{1}{2s}\int d\Phi_{n+1}\left[|\mathcal{M}_{\rm NLO,R}|^2 + 2{\rm Re}|\mathcal{M}_{\rm NLO,R}\mathcal{M}^*_{\rm NNLO,RV}|\right] + \frac{1}{2s}\int d\Phi_{n+2}|\mathcal{M}_{\rm NNLO,RR}|^2$$

+ R + RV + RR

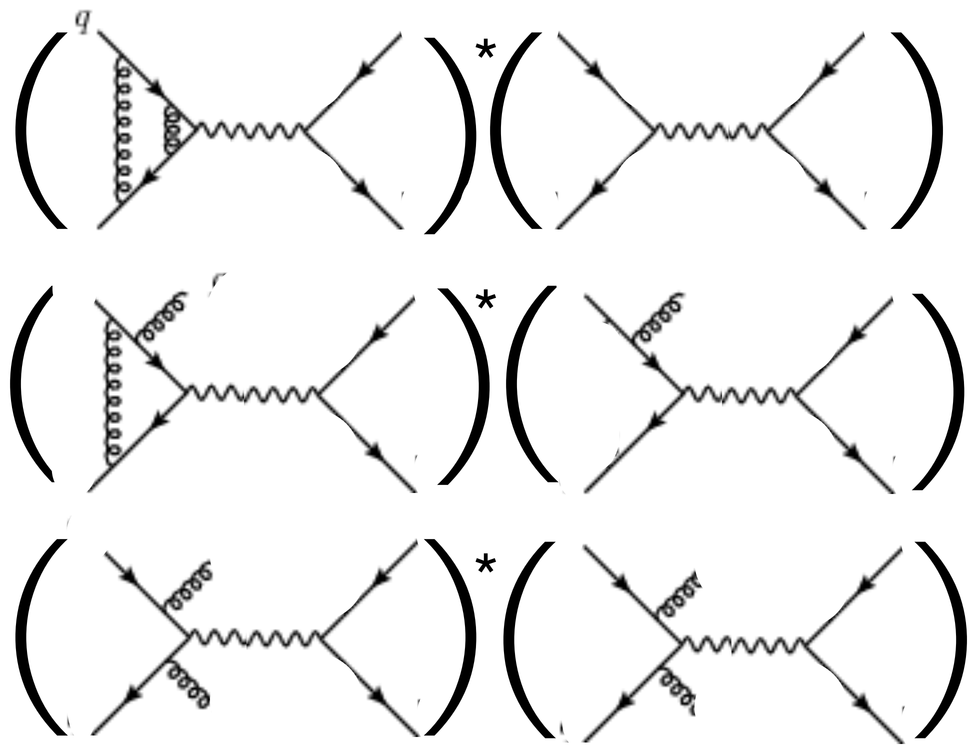
$\int d\Phi_{n(+1)}$ n, n+1, n+2 particle phase space

ΔNLO $\propto \alpha$

- $\mathcal{M}_{\rm NLO,V}$ **virtual** one-loop matrix element
- $\mathcal{M}_{\rm NLO,R}$ **real** tree-level matrix element

ΔNNLO $\propto \alpha^2$

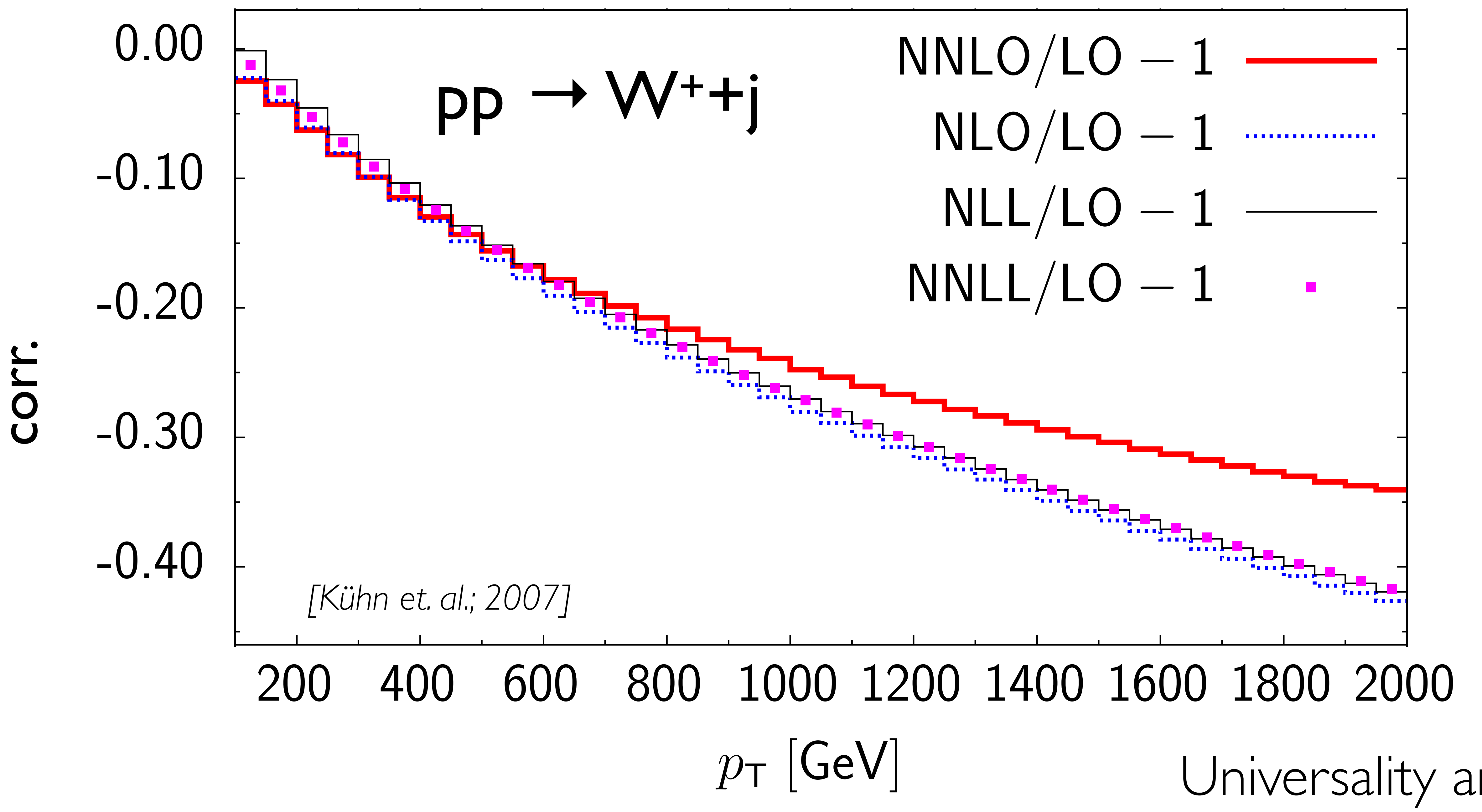
- $\mathcal{M}_{\rm NNLO,V}$ **double-virtual** two-loop matrix element
- $\mathcal{M}_{\rm NNLO,RV}$ **real-virtual** one-loop matrix element
- $\mathcal{M}_{\rm NNLO,RR}$ **double-real** tree-level matrix element

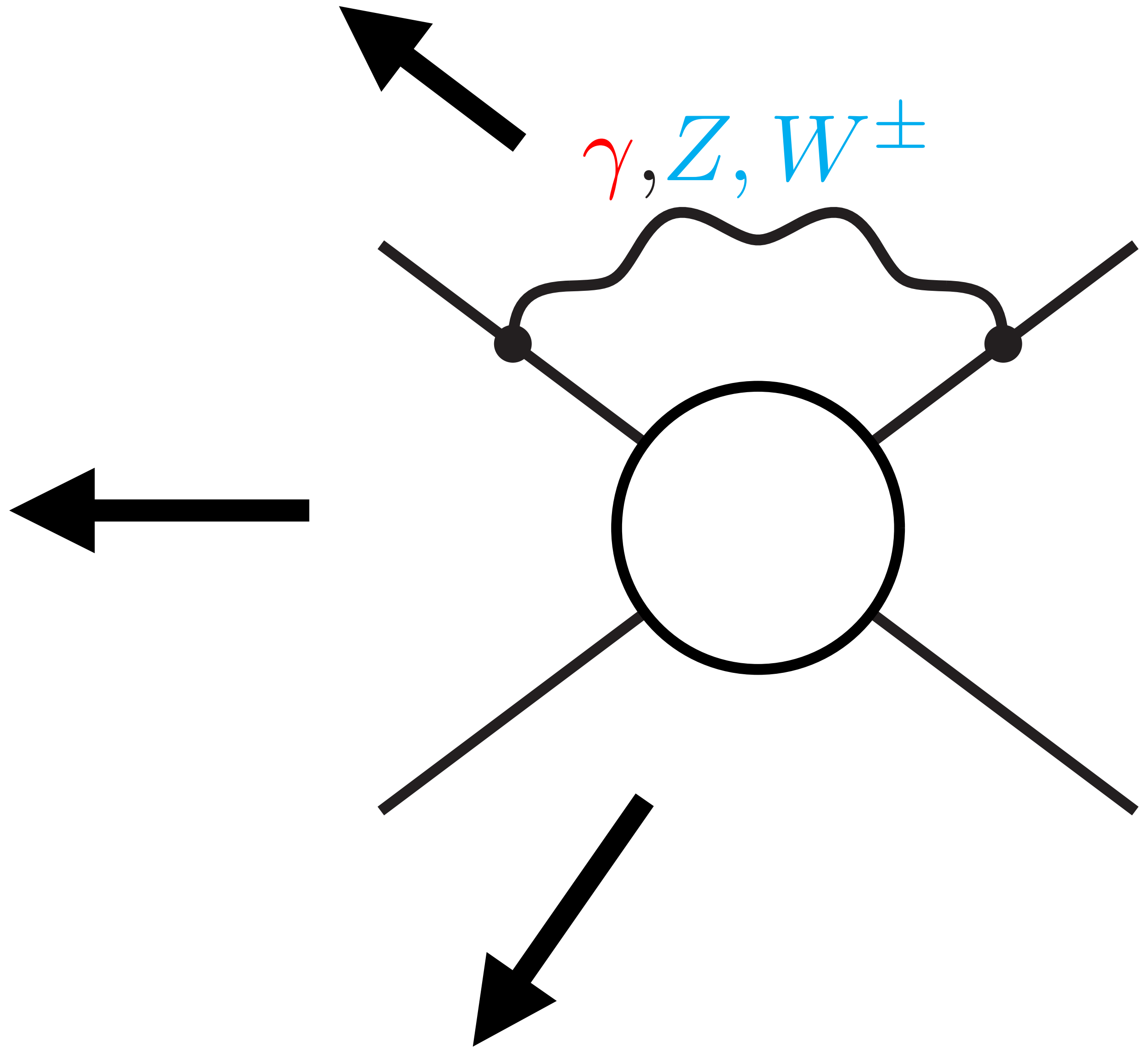


Relevance of EW higher-order corrections I

Numerically $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow$ $\boxed{\text{NLO EW} \sim \text{NNLO QCD}}$

1. Possible large (negative) enhancement due to soft/collinear **logs** from virtual EW gauge bosons:





[Ciafaloni, Comelli,'98; Lipatov, Fadin, Martin, Melles, '99; Kuehen, Penin, Smirnov, '99; Denner, Pozzorini, '00]

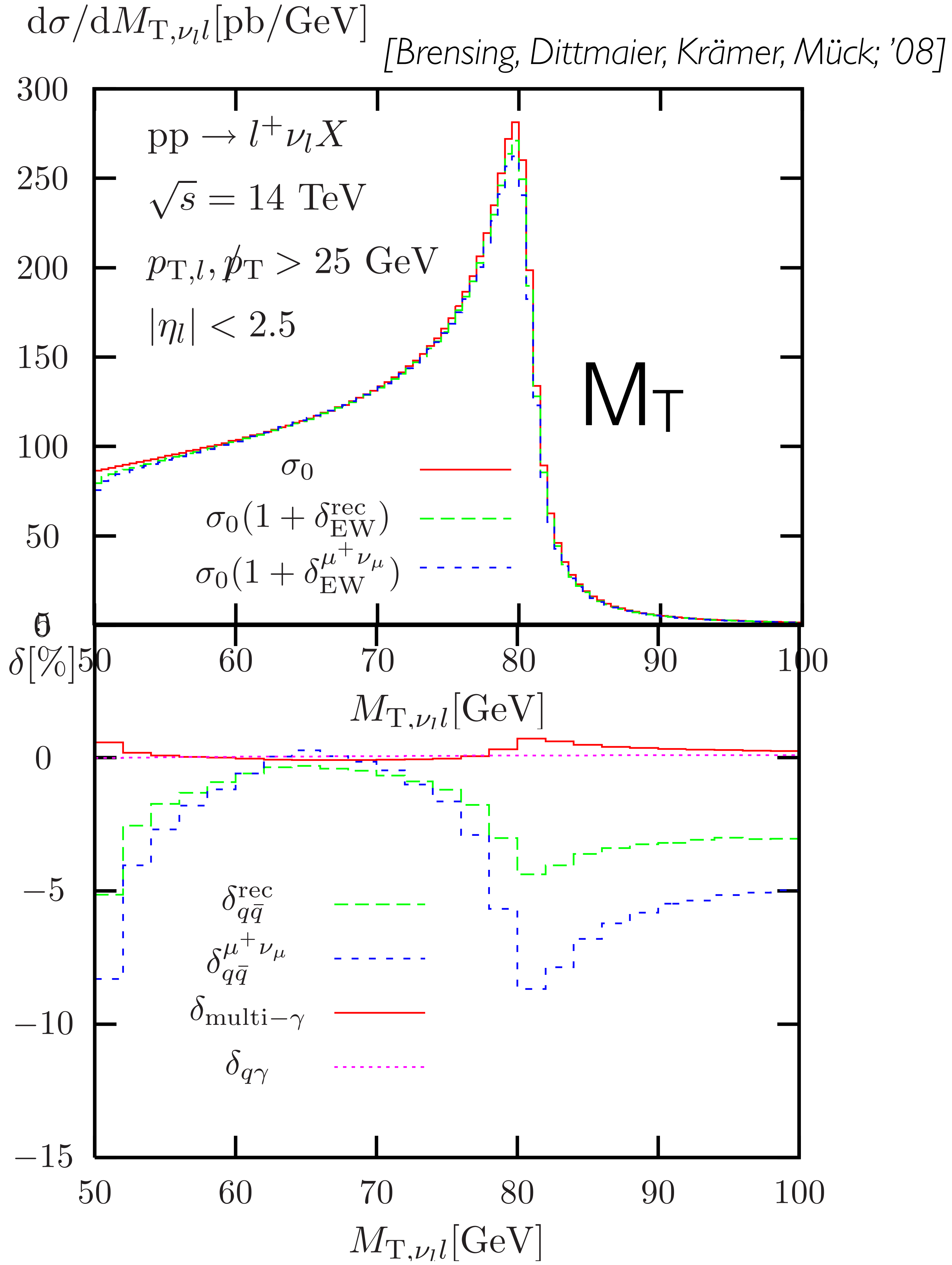
Universality and factorisation: *[Denner, Pozzorini; '01]*

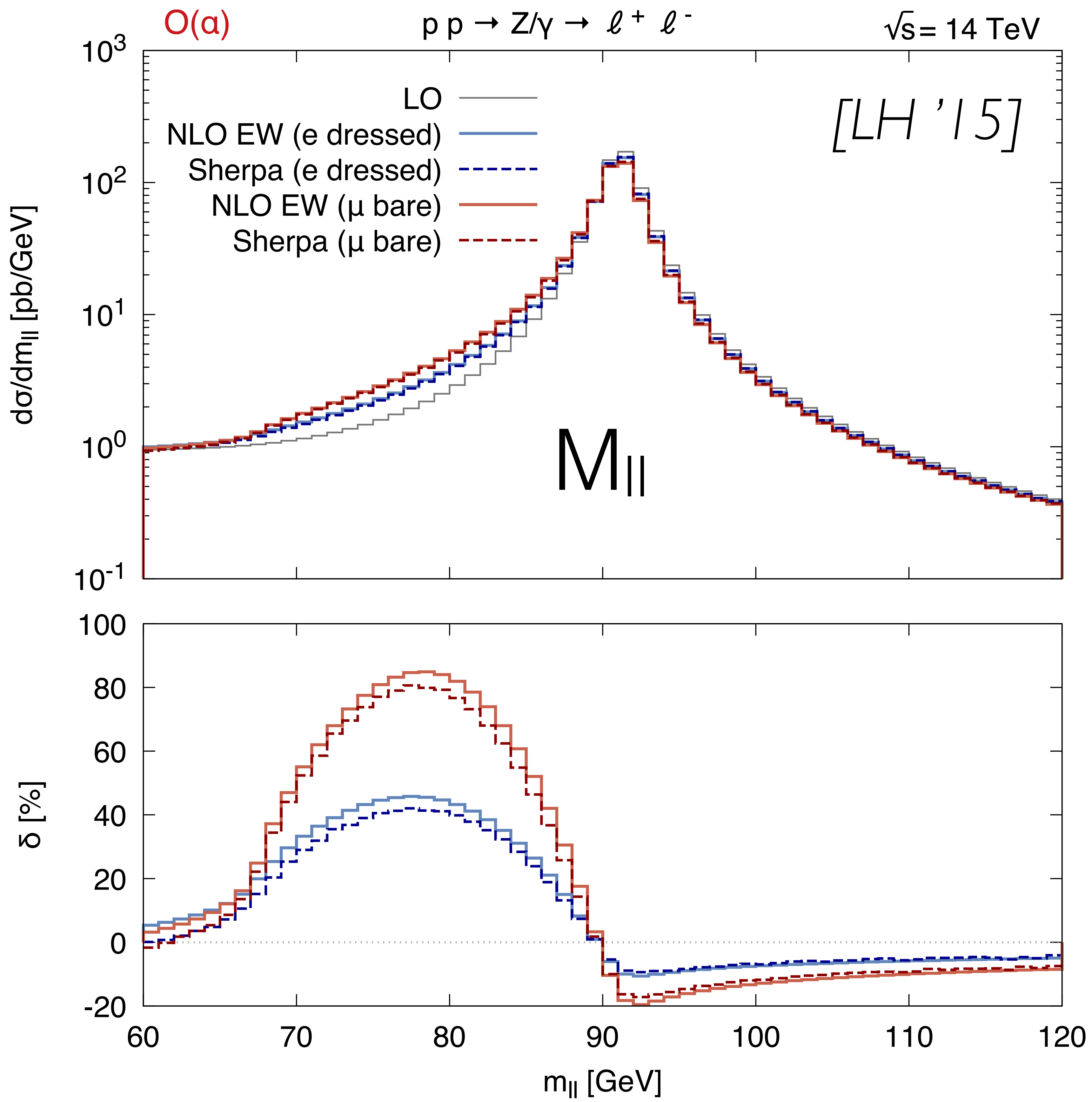
$$\delta\mathcal{M}^{1-\mathrm{loop}}_{\mathrm{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\mathrm{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

➜ **overall large effect in the tails of distributions: p_T, m_{inv}, H_T,… (relevant for BSM searches!)**

Relevance of EW higher-order corrections II

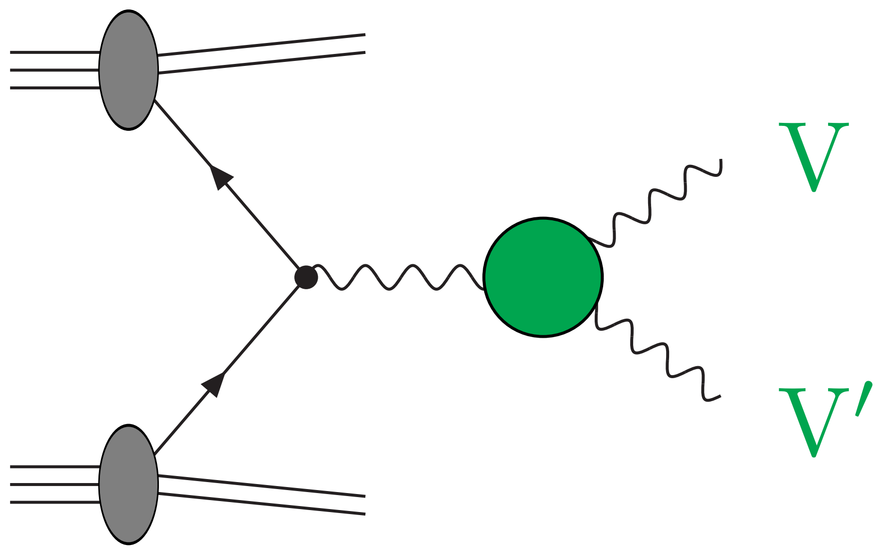
2. Possible large enhancement due to soft/collinear **logs** from photon radiation $\sim \alpha \log\left(\frac{m_f^2}{Q^2}\right)$ in sufficiently exclusive observables.

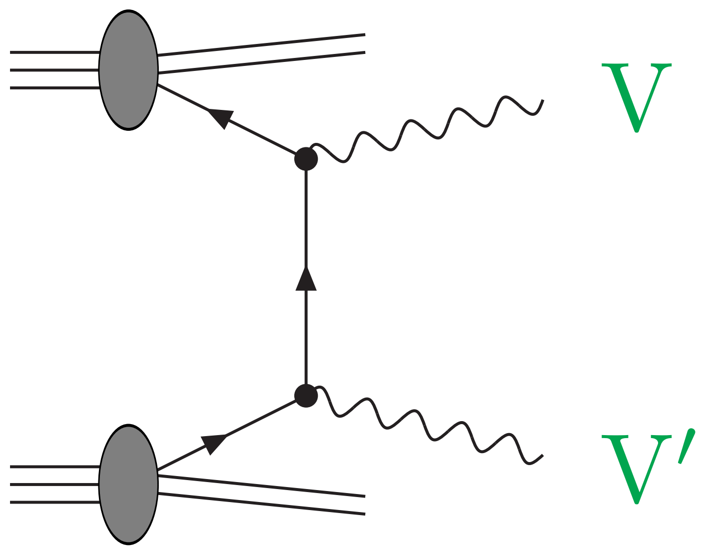




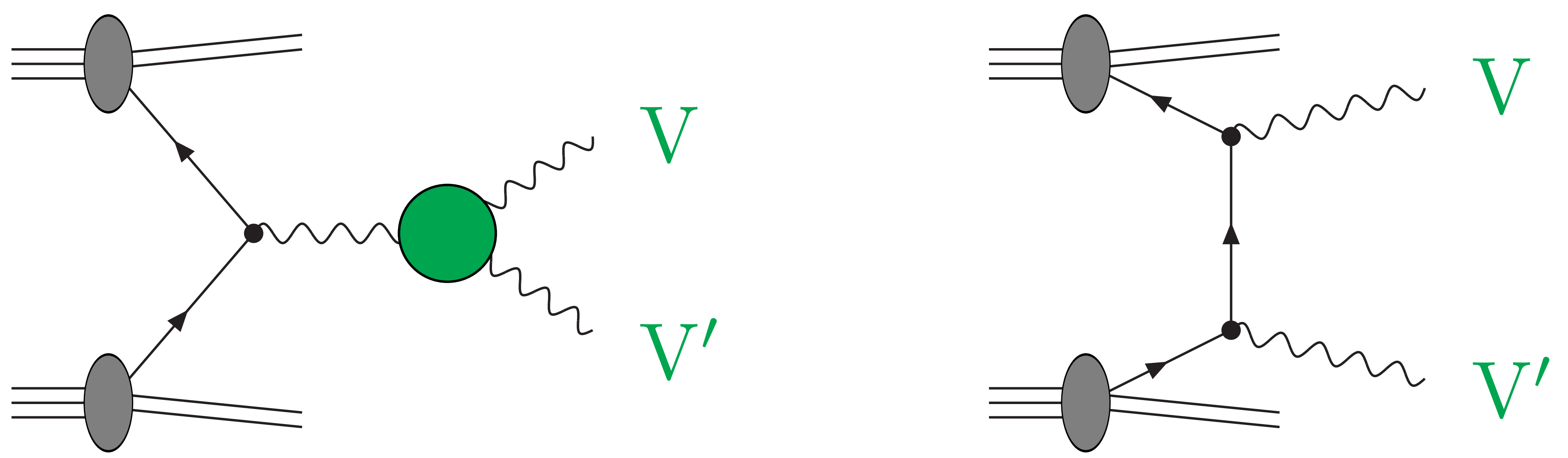
➜ **important for various precision observables, e.g. for determination of M_W in DY**

Diboson production

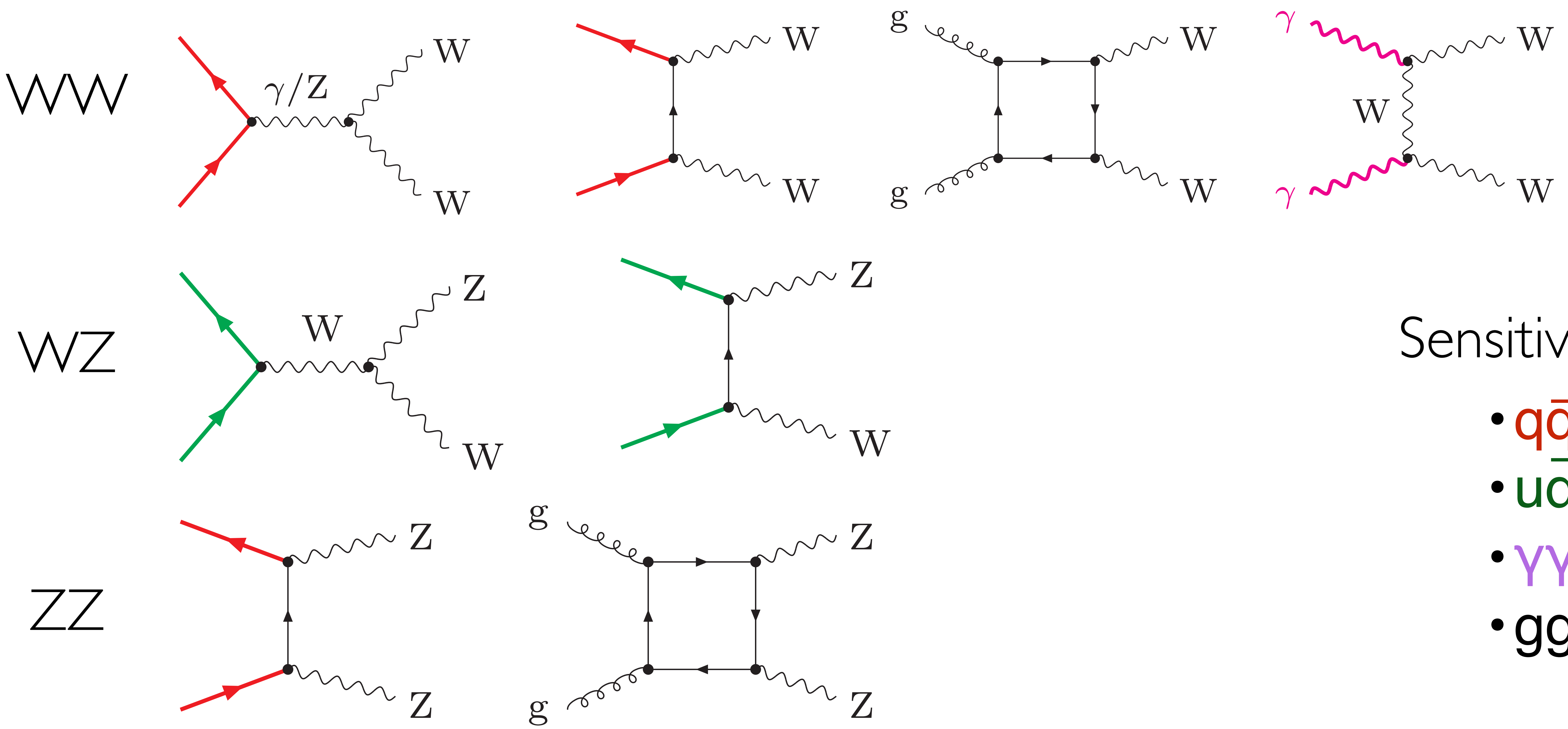




Diboson production



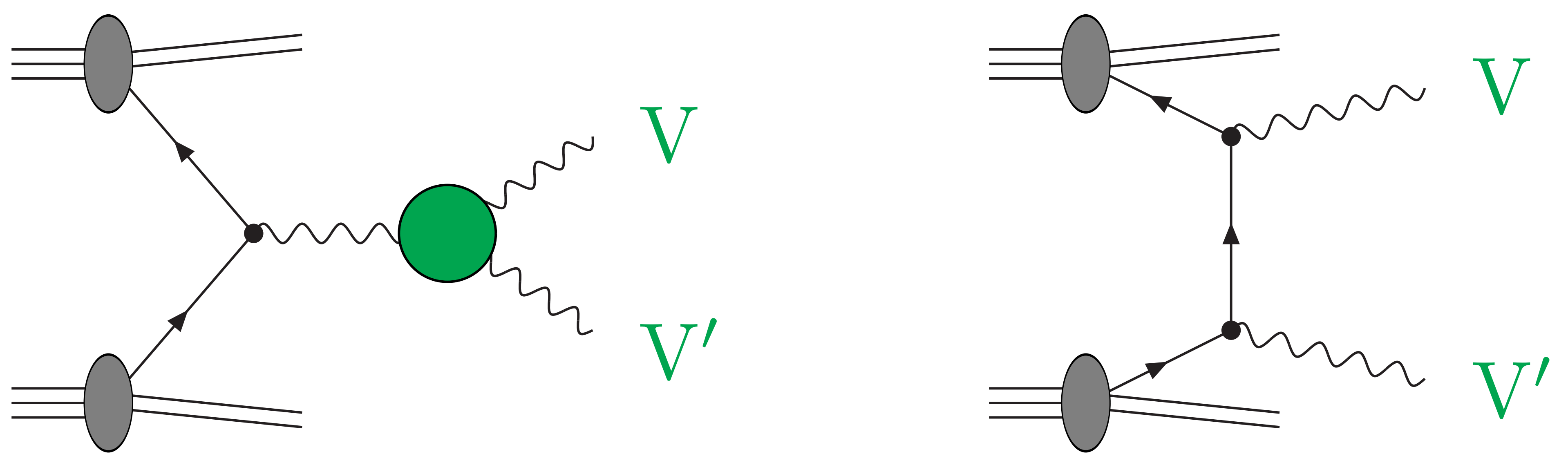
Complementarity in WW / WZ / ZZ production



Sensitivity to different PDF combinations:

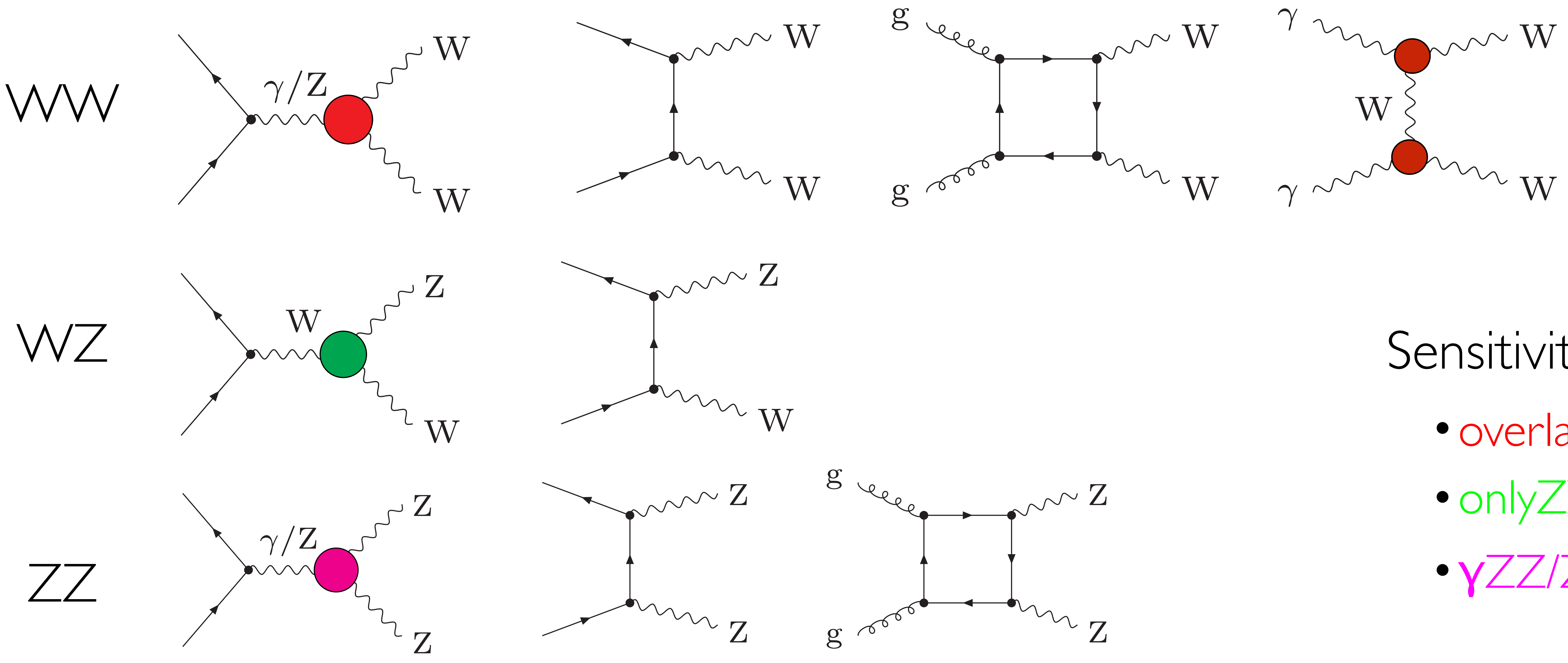
- $q\bar{q}$ in WW/ZZ
- $u\bar{d}/d\bar{u}$ in WZ
- $\gamma\gamma$ in WW
- gg in WW/ZZ

Diboson production



Complementarity in WW / WZ / ZZ production

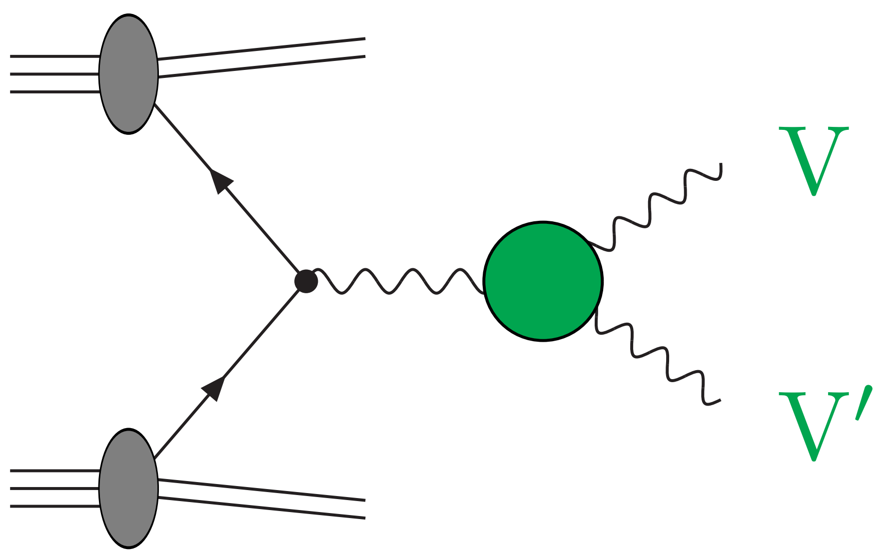
[see Talk by Francesco Riva]

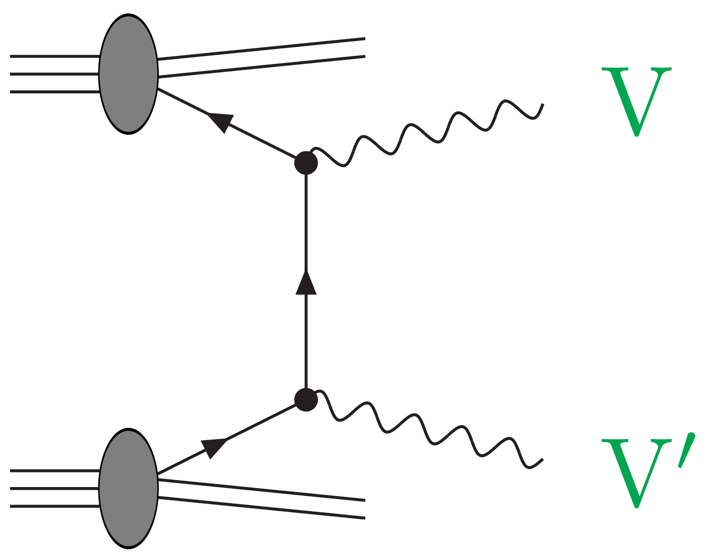


Sensitivity to different aTGCs:

- overlay of γWW/ZWW in WW
- onlyZWW inWZ
- γZZ/ZZZ in ZZ

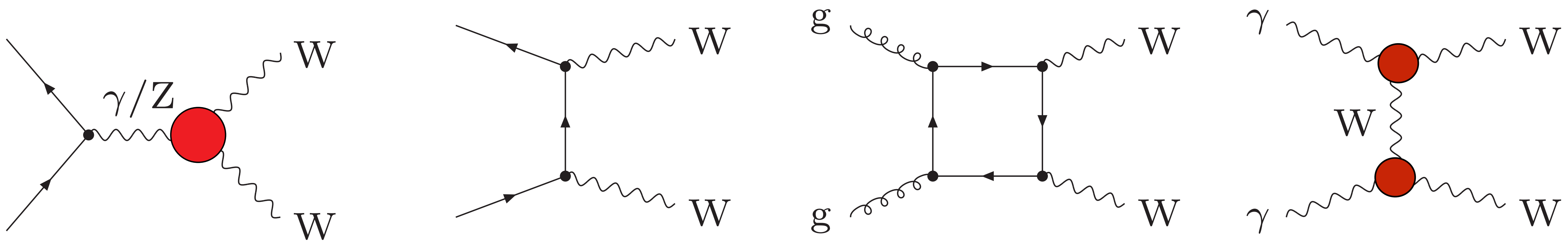
Diboson production



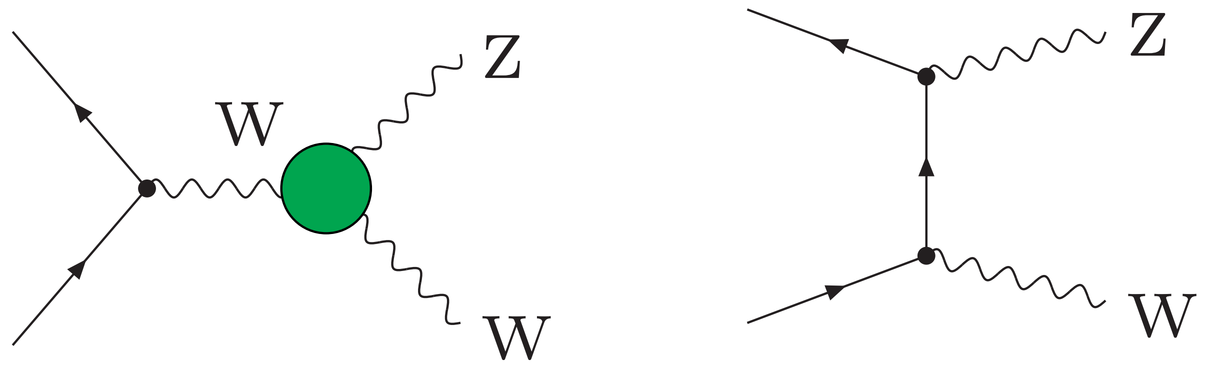


Complementarity in WW / WZ / ZZ production

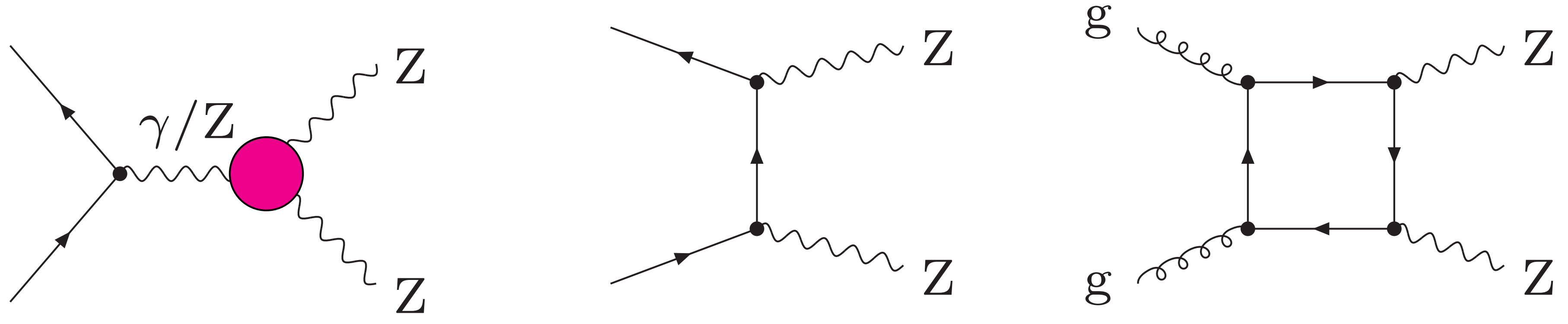
WW



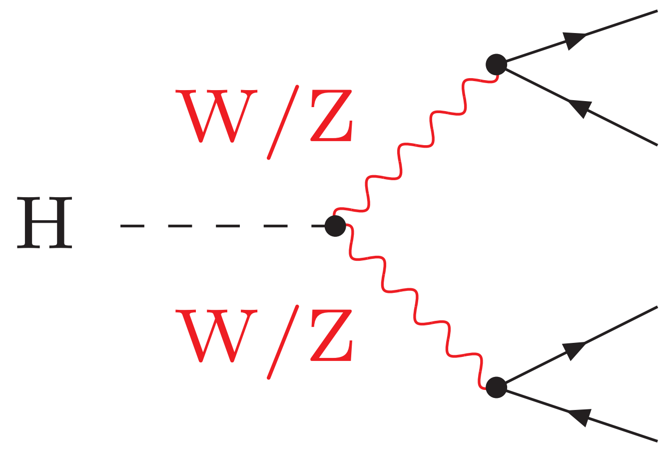
WZ



ZZ

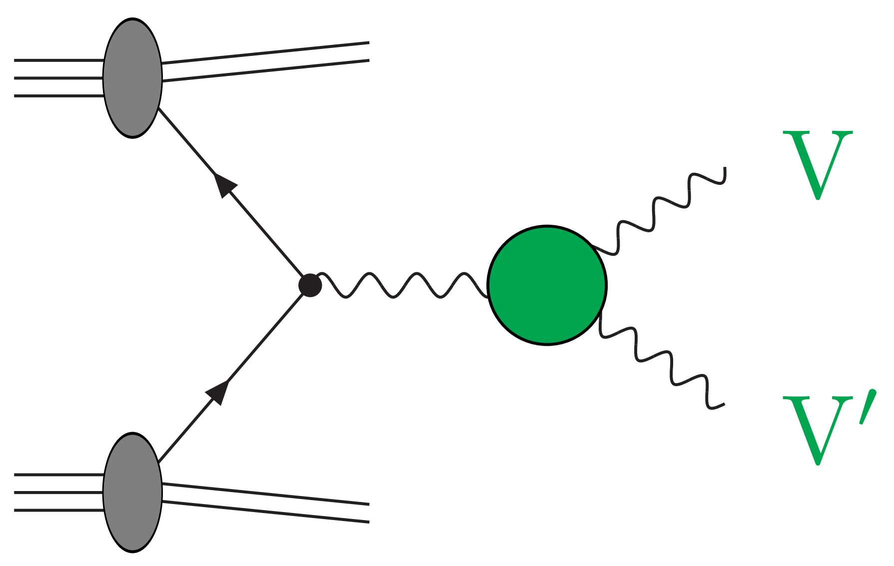


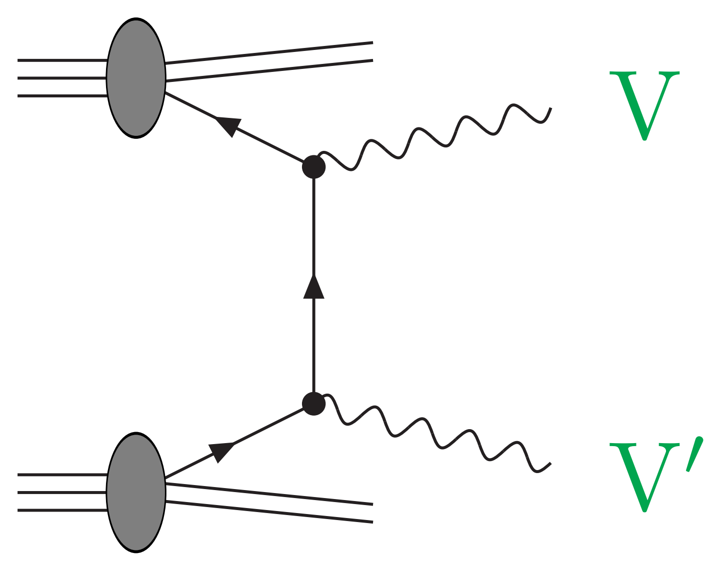
WW & ZZ are background in H→VV:



(off-shell calculations mandatory)

Diboson production





Theoretical status: NNLO QCD + NLO EW

- WW [Gehrmann et. al '14, Grazzini et. al. '16]
- WZ [Grazzini et. al. '16+'17]
- ZZ [Cascioli et.al. '14, Grazzini et. al. '15, Kallweit '18]
- Zγ/Wγ [Grazzini et. al. '15]

- gg→WW/ZZ [Caola et. al. '15+'16]
- NNLO+PS for WW [Re et. al. '18]

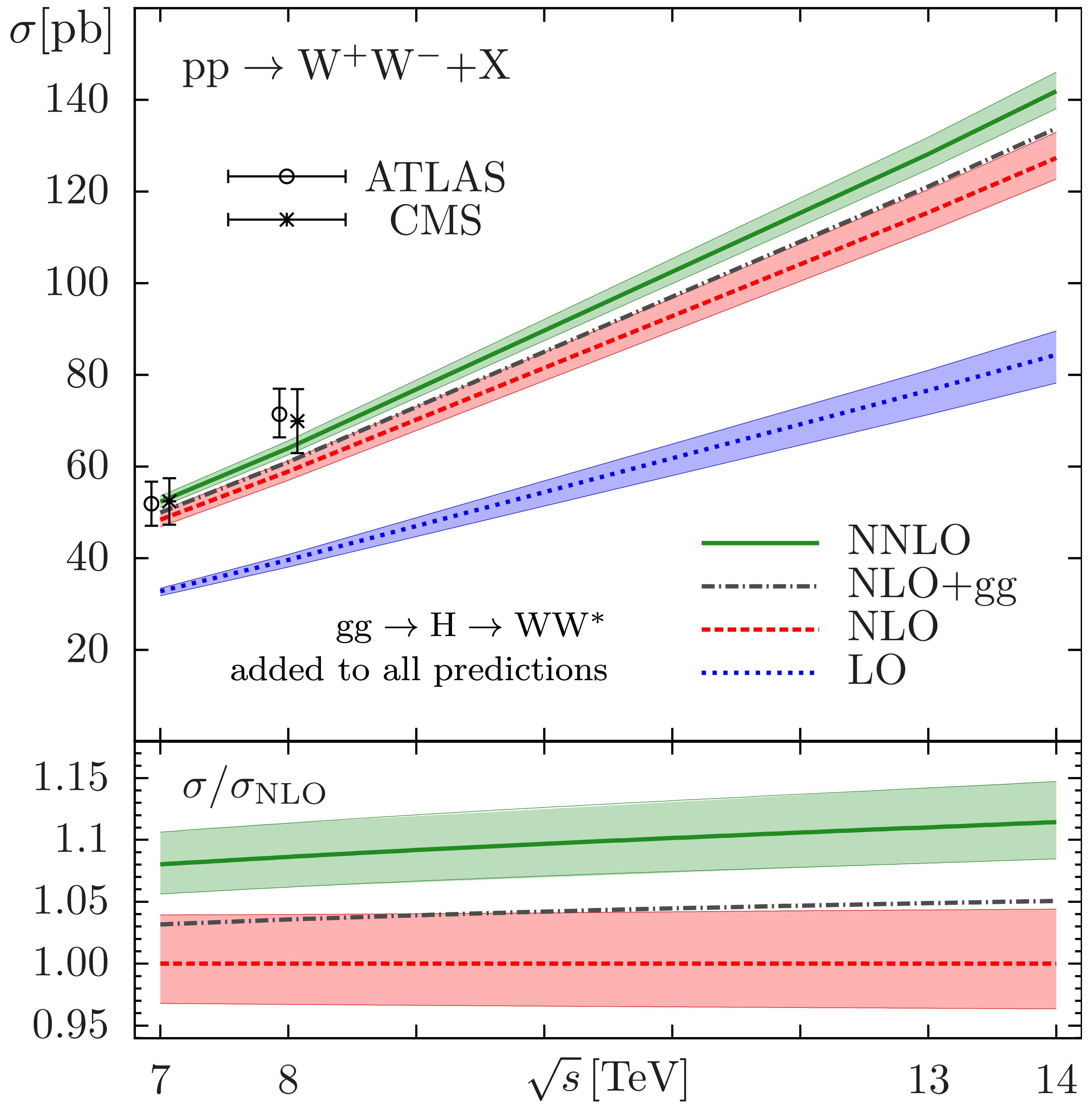
Tool: MATRIX [Grazzini et. al '17]

- stable VV [Bierweiler, Kasprzik, Kühn '13, Baglio, Ninh, Weber '13]
- DPA [Biloni et. al. '13]
- off-shell ZZ (4l) [Biedermann et. al. '16]
- off-shell WW (2l2v) [Biedermann et. al. '16, Kallweit et.al '17]
- off-shell WZ (3lv) [Biedermann et. al. '17]
- off-shell Zγ/Wγ [Denner et. al.'14+'15]

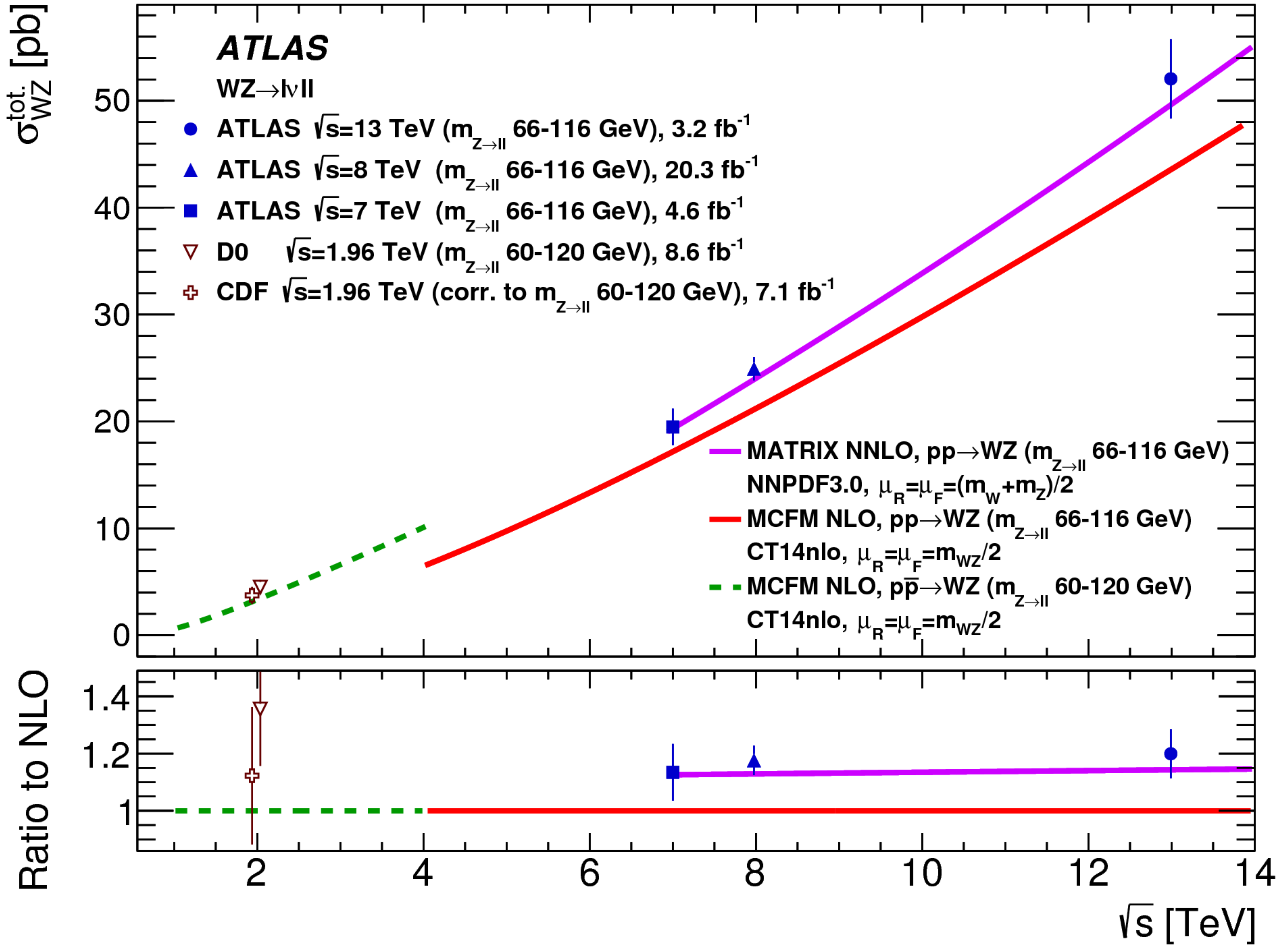
Tools: - Sherpa+OpenLoops/Recola/GoSam
- MadGraph_aMC@NLO

Diboson production at NNLO QCD

WW



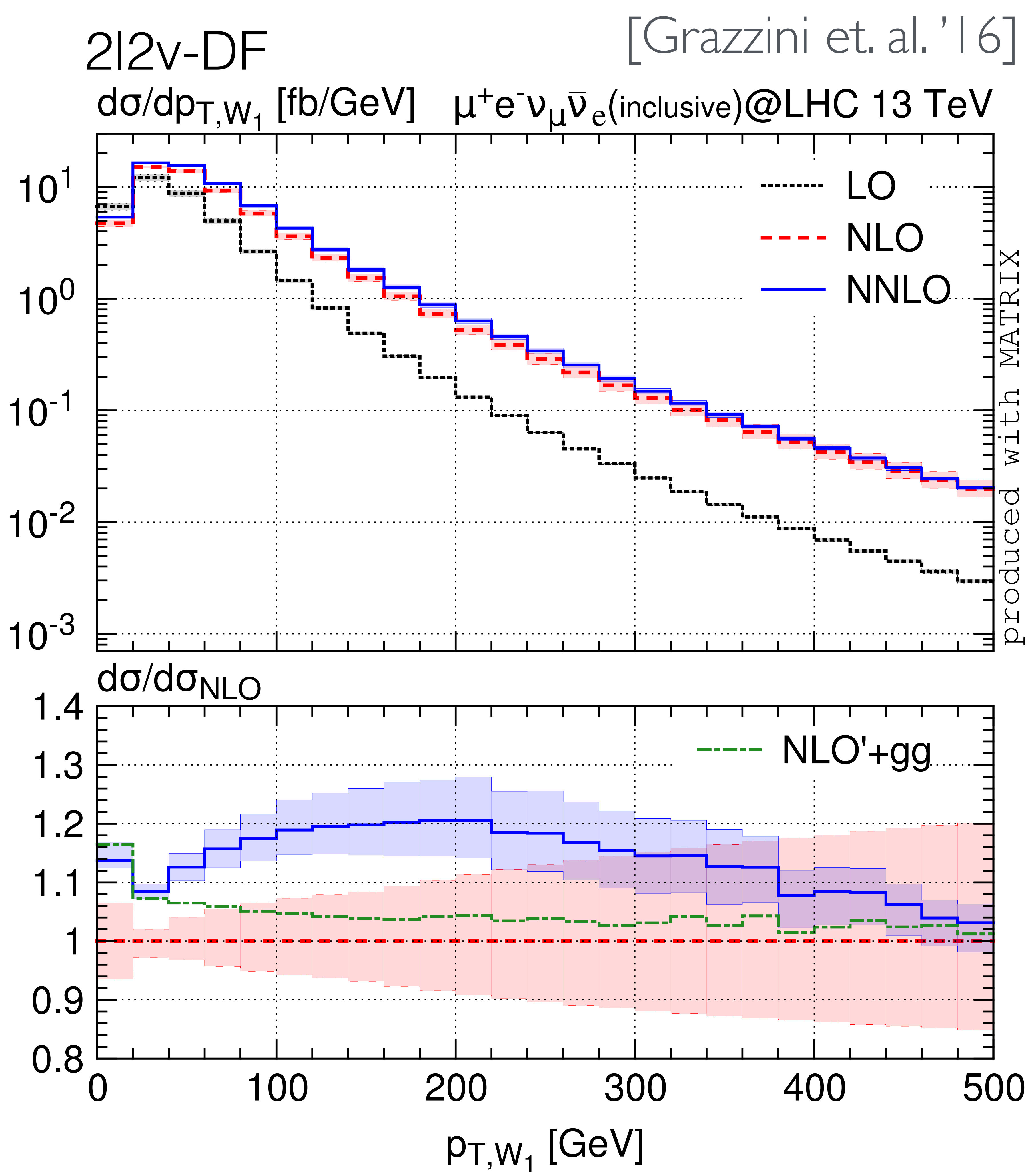
WZ

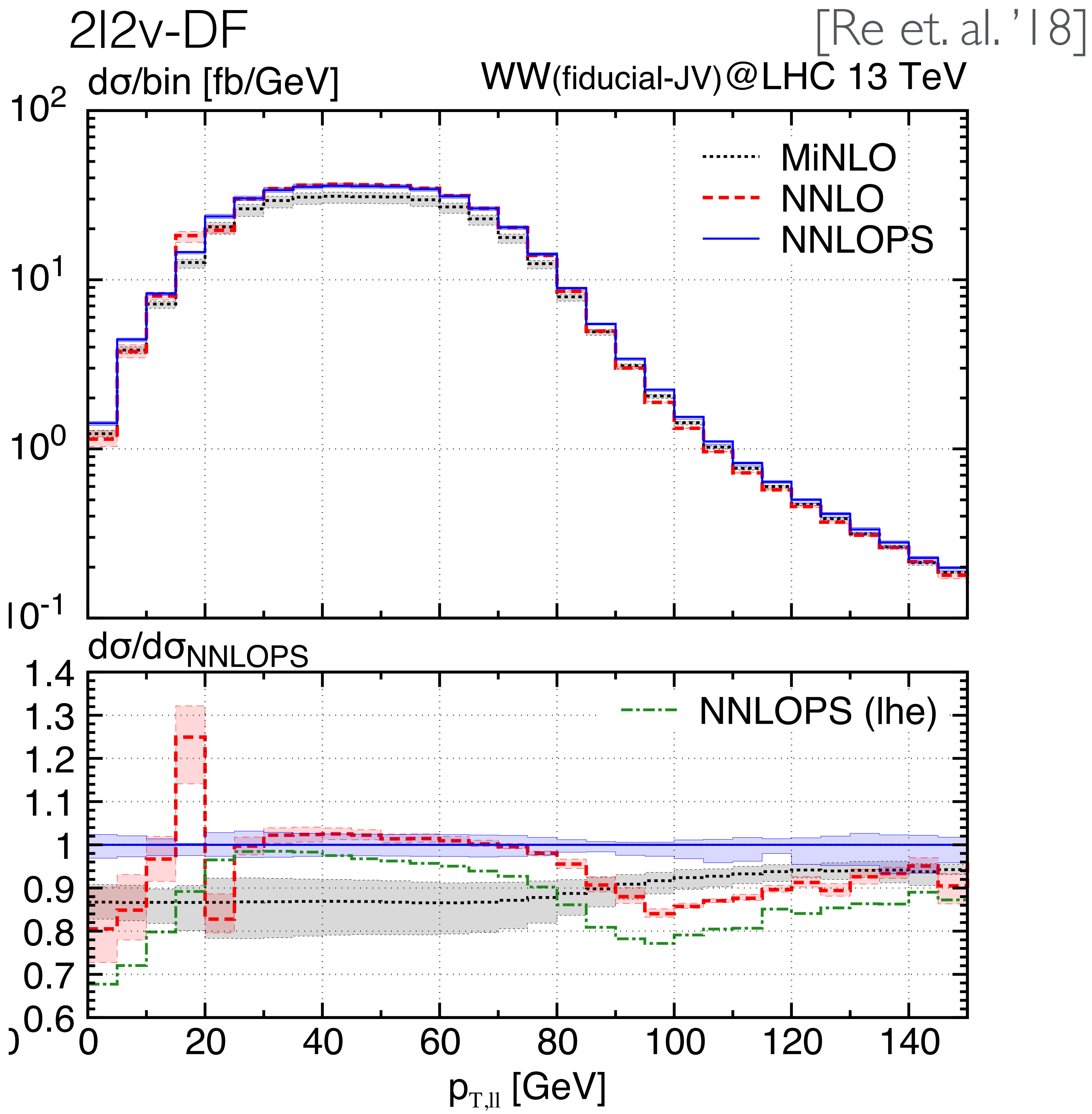


- Quite large QCD corrections well beyond expected size from scale uncertainties and $gg \to W^+W^-$ (+4%): +58% NLO & +12% NNLO at 14 TeV
- Residual scale uncertainty: 3% at NNLO

➡ NNLO mandatory to describe the data!

Diboson production at NNLO QCD (+ PS)





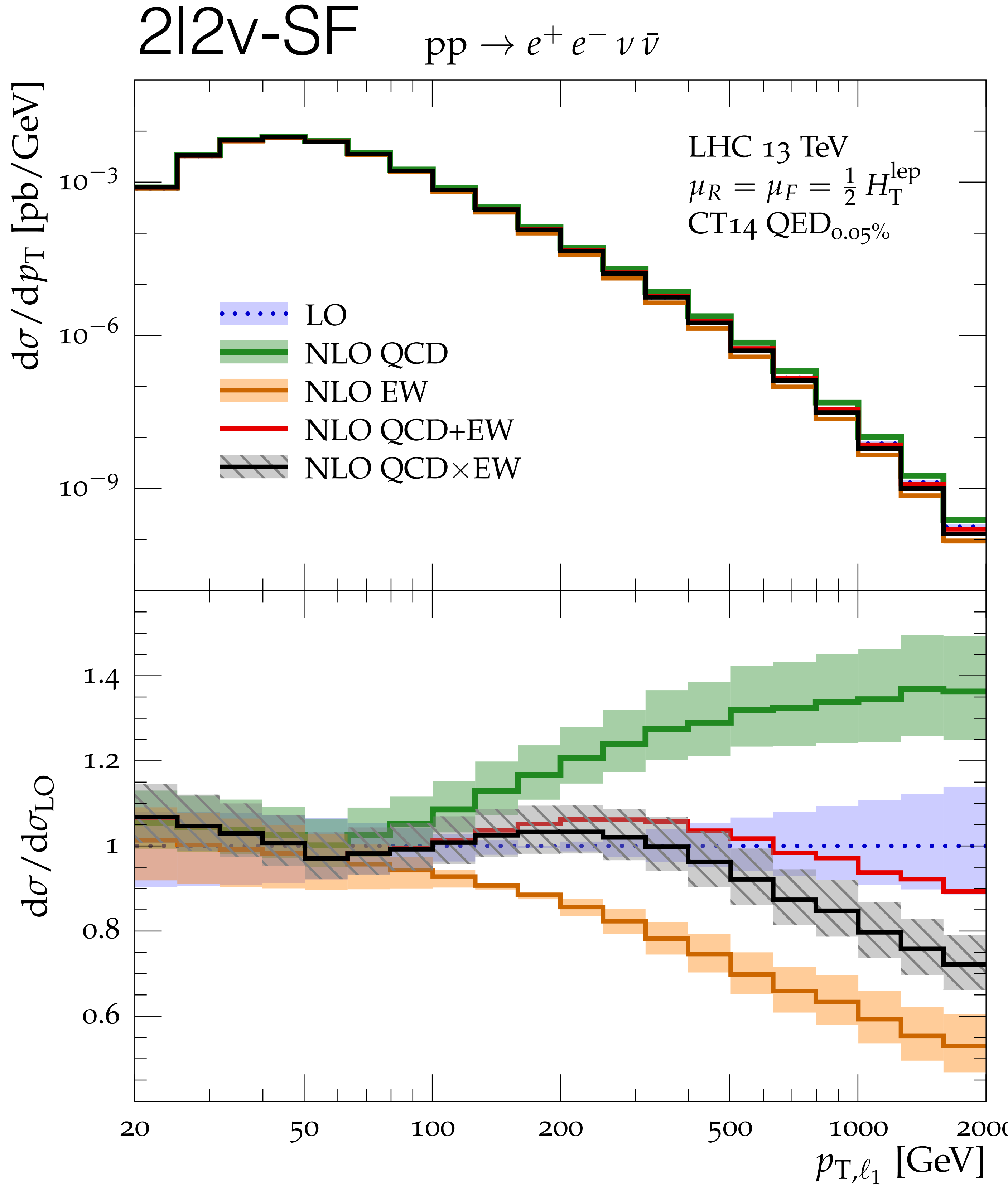
- NNLO corrections quite strongly observable dependent
- scale uncertainties reduced to few percent level

- NNLO+PS via reweighting of WW+1jet @ NLO-MiNLO
- NNLO+PS cures perturbative instabilities at phase-space boundaries

(off-shell) Diboson production at NLO QCD+EW

[Kallweit, JML, Pozzorini, Schönherr; '17]

2l2v-SF



pT of hardest lepton

- +40 % QCD corrections in the tail (Note: slight jet veto applied)
- LARGE negative EW corrections due to **Sudakov behaviour:** -40% @ 1 TeV
- Combination of QCD and EW corrections:

Additive combination

$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD+EW}} = \sigma^{\mathrm{LO}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{QCD}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$$

(no $\mathcal{O}(\alpha\alpha_s)$ contributions)

Multiplicative combination

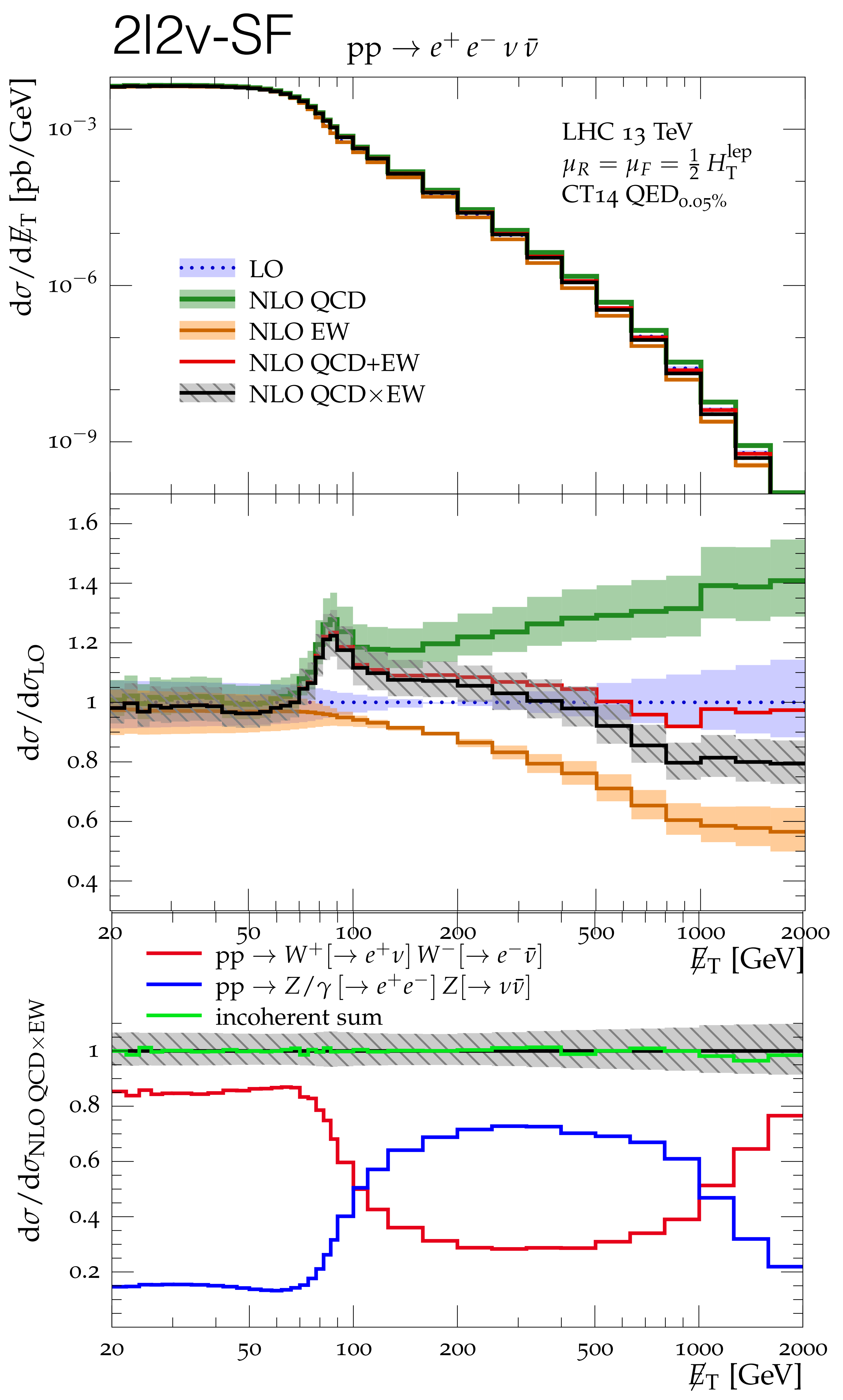
$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD\times EW}} = \sigma^{\mathrm{NLO}}_{\mathrm{QCD}} \left(1 + \frac{\delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}}\right)$$

|QCD+EW - QCDxEW | ~ $\delta_{\mathrm{QCD}} \times \delta_{\mathrm{EW}}$ ~ NNLO QCDxEW
~ 10-20% in the tail!

Note: exact NNLO QCDxEW extremely hard!

(off-shell) Diboson production at NLO QCD+EW

[Kallweit, JML, Pozzorini, Schönherr; '17]



MET

- at large MET>M_W: W's are forced off-shell

- jump in QCD corrections (extra jet unlocks back-to-back configuration)

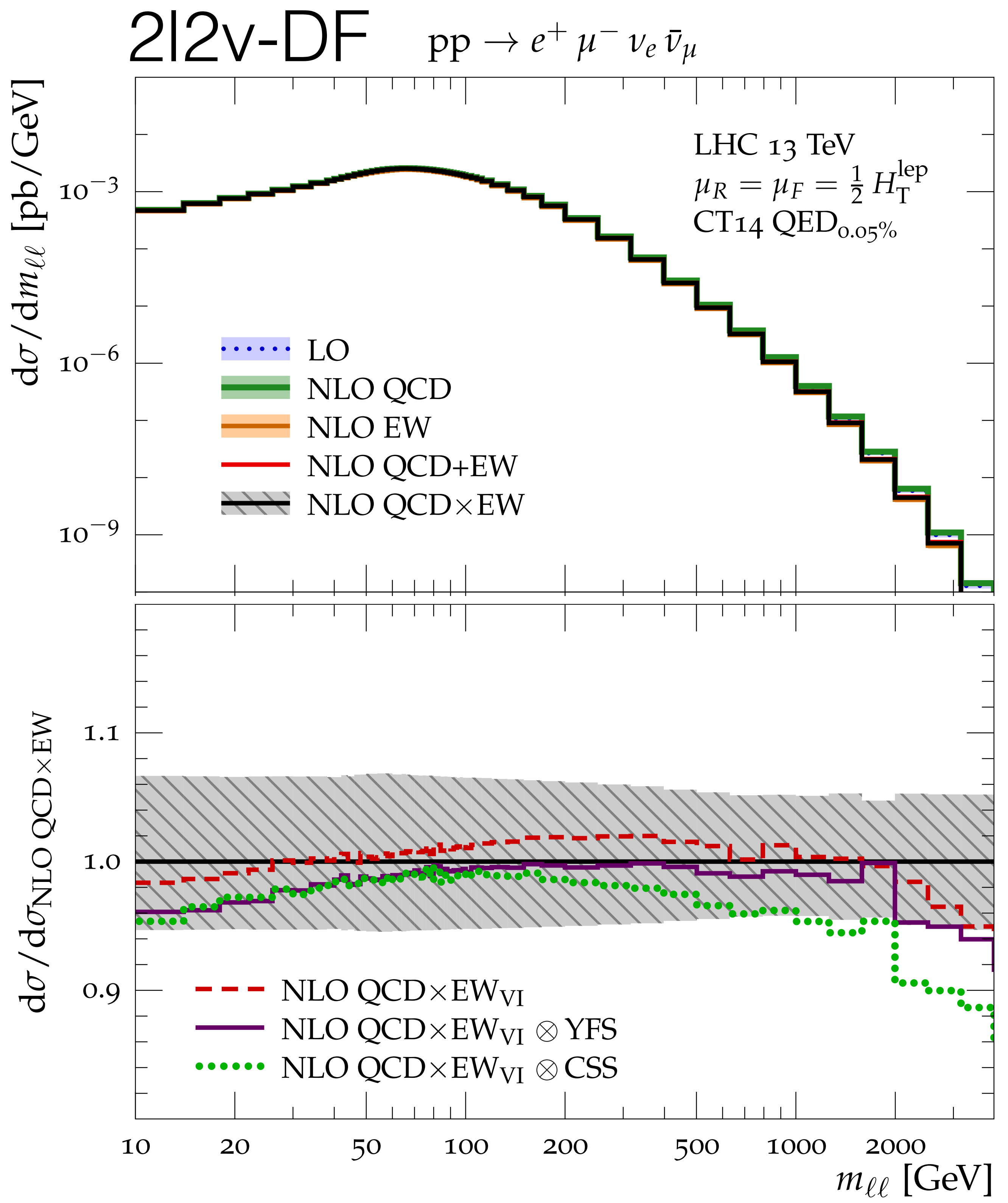
- very large EW corrections: up to 50% (WW/ZZ dependent!)

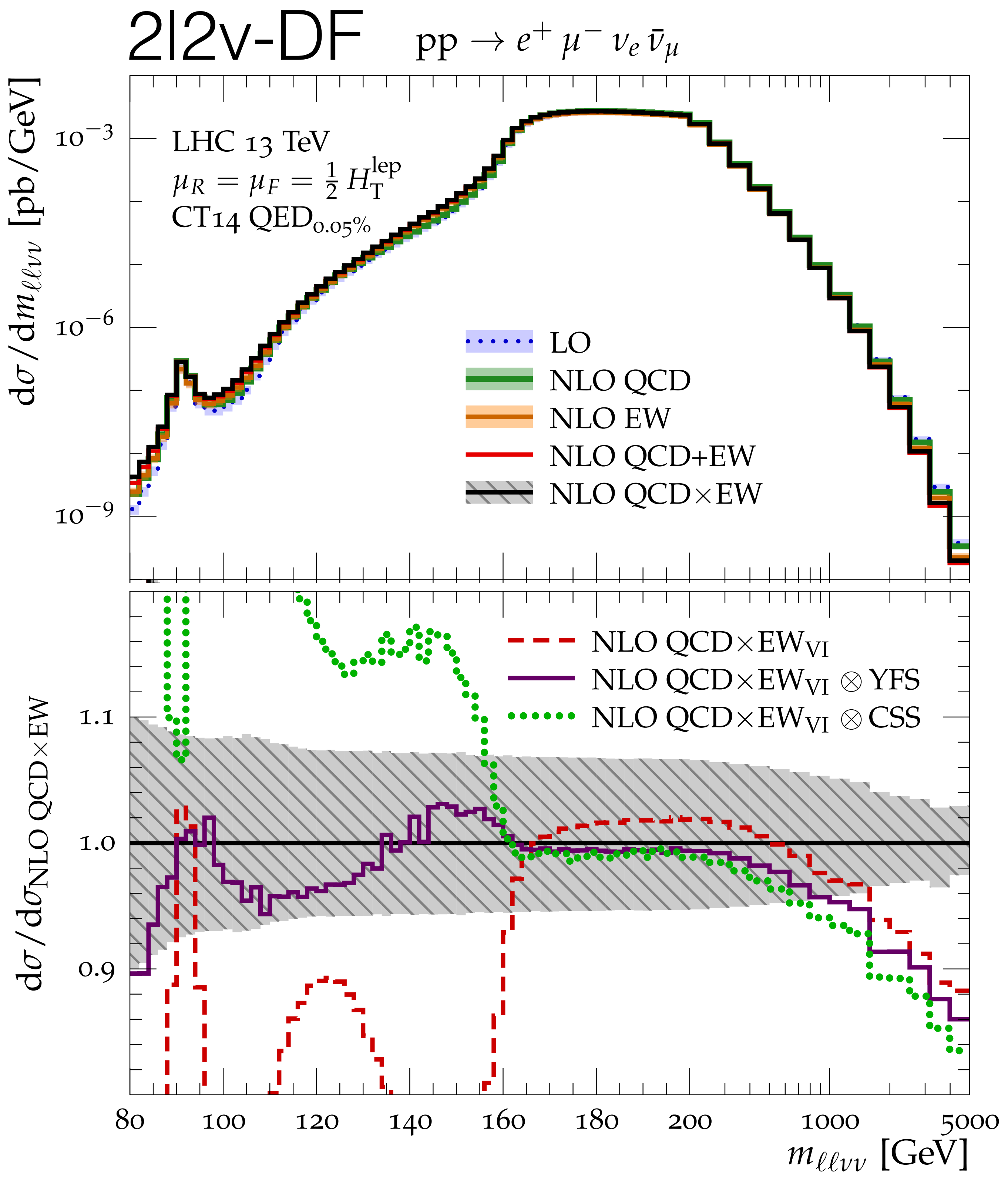
- WW-ZZ interference very suppressed (as expected from LO)

- Combination of QCD and EW corrections: |QCD+EW - QCDxEW | ~ $\delta_{QCD} \times \delta_{EW}$ ~ NNLO QCDxEW ~ 10-20% in the ETmiss tail

(off-shell) Diboson production at NLO QCD+EW

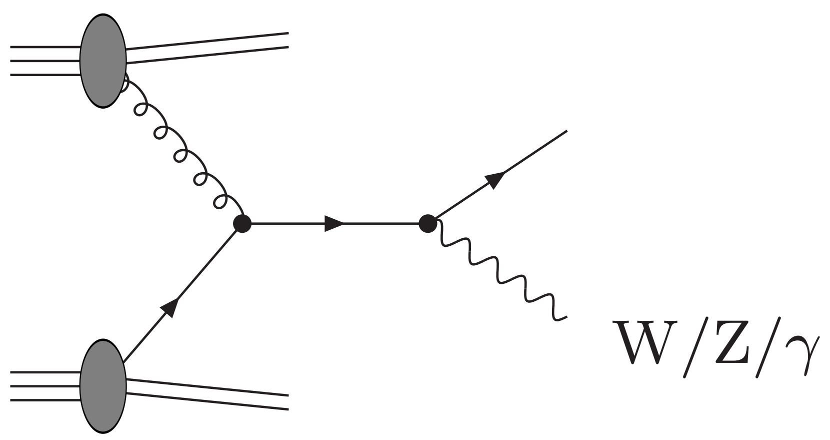
[Kallweit, JML, Pozzorini, Schönherr; '17]

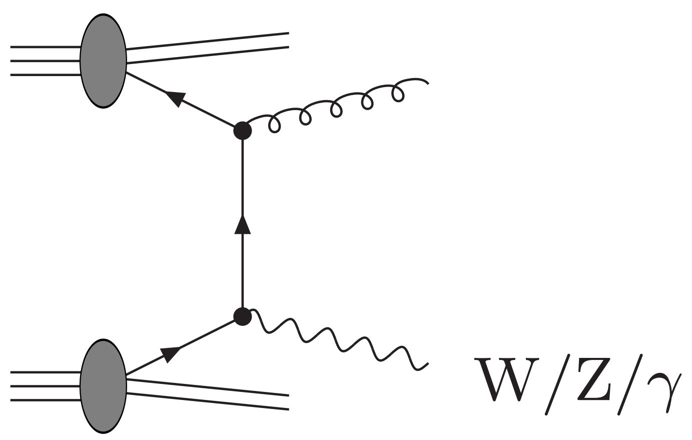




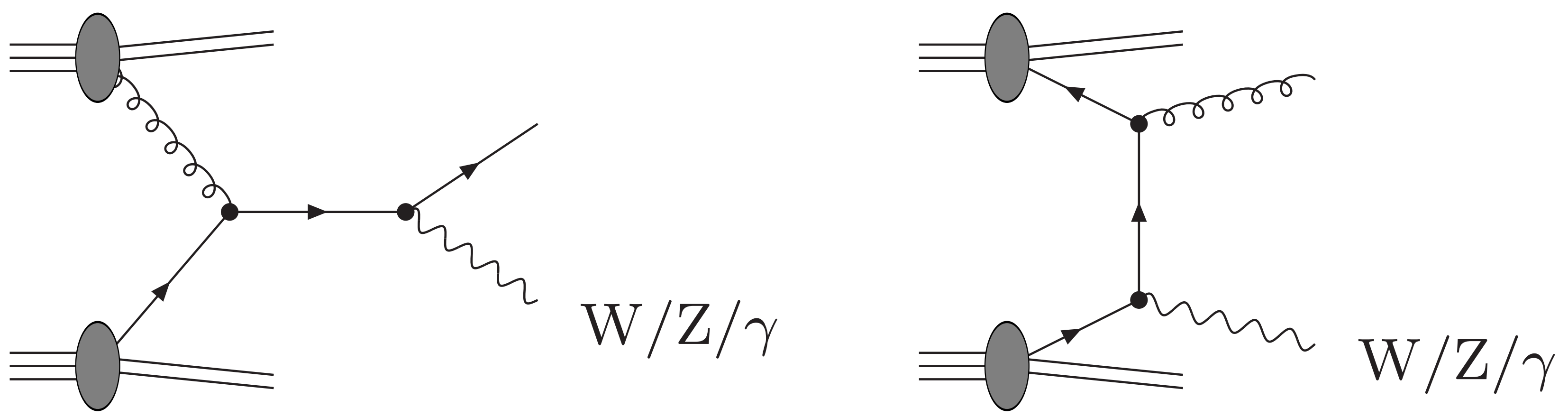
- Fully consistent PS matching at NLO EW under development
- Naive NLO EW+PS matching available in Sherpa+OpenLoops (applicable at particle level)
  - ➡CSS dipole shower (not resonaonce aware) ⇒ significant mismodelling
  - ➡YFS resummation **(resonaonce aware)** ⇒ valid approximation

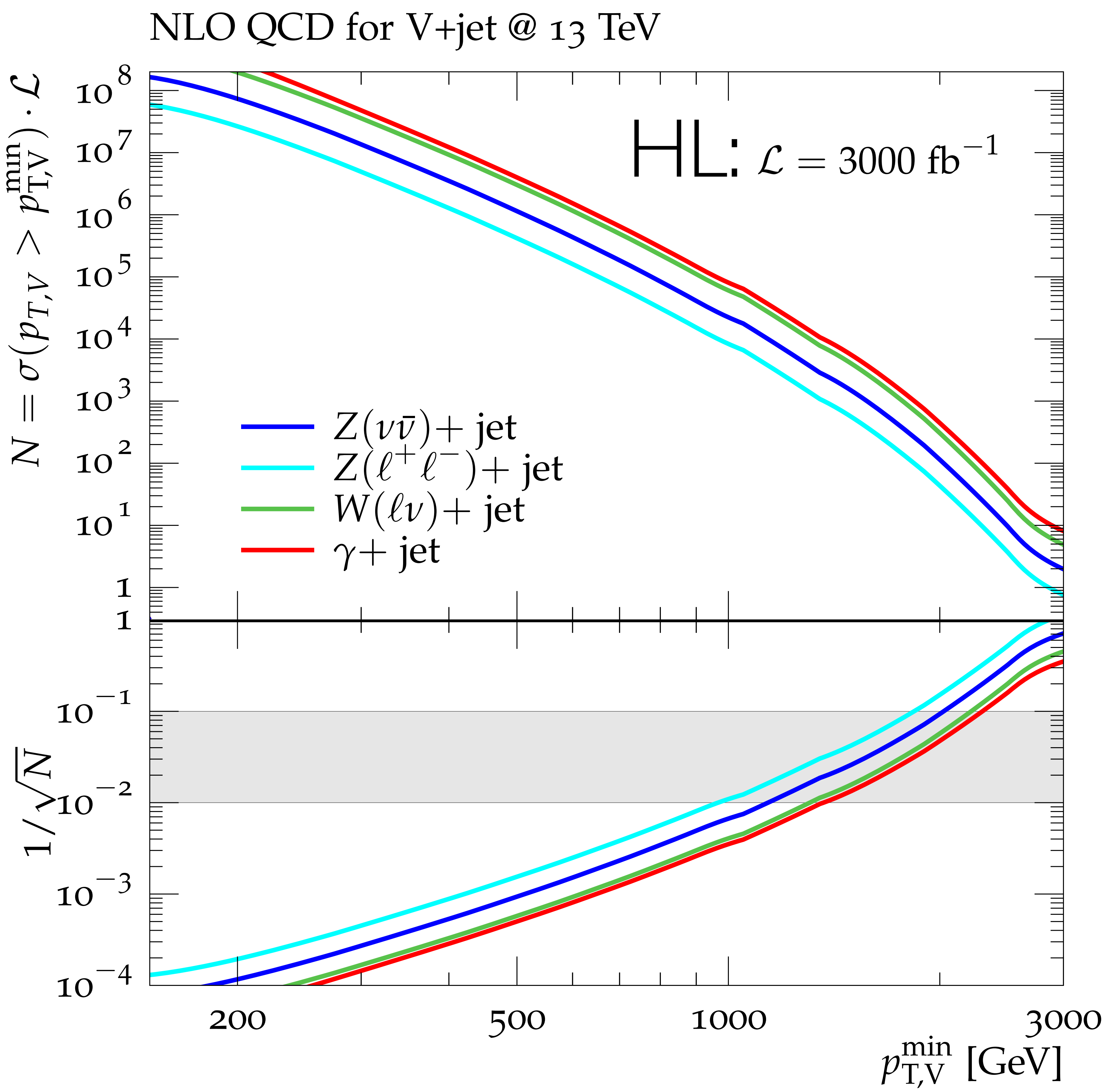
V+jets





V+jets





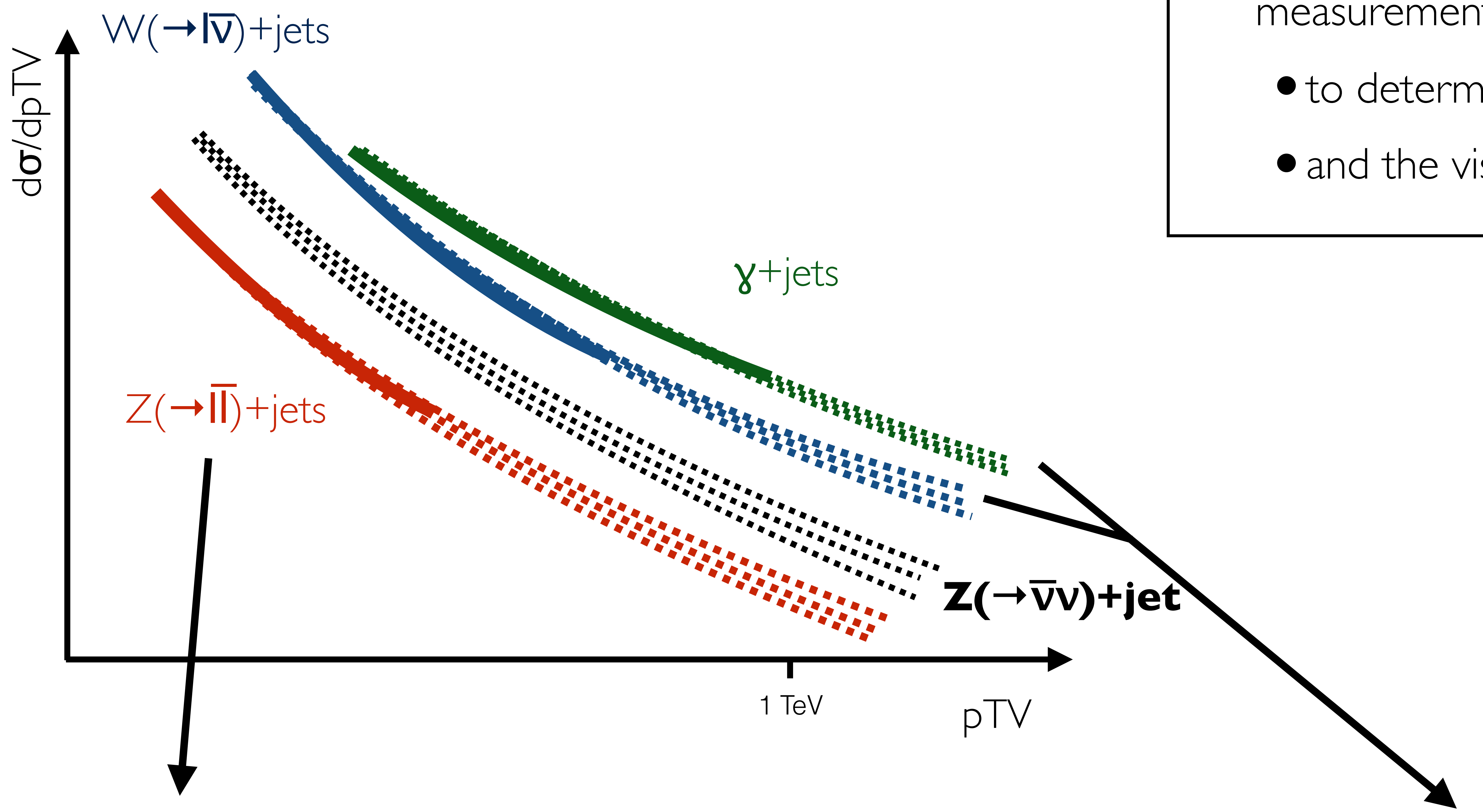
V+jets is crucial background

- Important/dominant background for various BSM searches
  (lepton(s) + jets + missing E_T)
- Dominant background in many DM searches: MET+X
- Dominant background for top physics (W+jets)
- Important background for Higgs physics, e.g.VH

- statistical uncertainty at the **1% level** for pT,V ≳ 1-1.5 TeV
- statistical uncertainty at the **10% level** for pT,V ≳ 2 TeV

➡ need to consider state of the art higher-order corrections:
NNLO QCD + NNLO EW

Determine V+jets backgrounds: the DM case



global fit of Z(→ll̄)+jets, W(→lν̄)+jets and γ+jets measurements

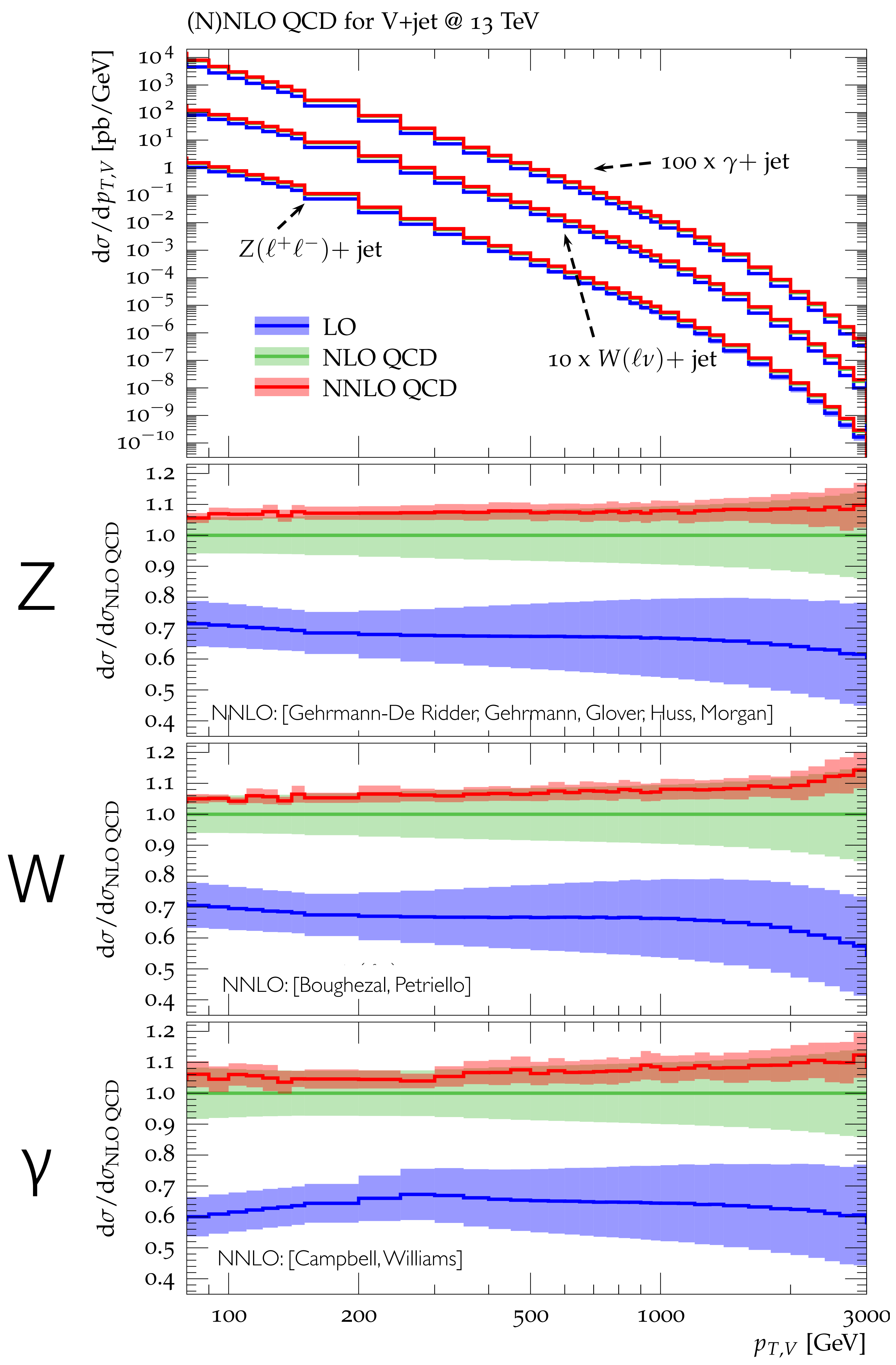
- to determine Z(→ν̄ν)+jet
- and the visible channels at high-pT

- hardly any systematics (just QED dressing)
- very precise at low pT
- but: limited statistics at large pT

- fairly large data samples at large pT
- systematics from transfer factors: ratios of V+jets processes

Pure QCD uncertainties

[JML et. al.: 1705.04664]



$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NLO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NNLO\,QCD}}$$

$$\boxed{\mu_0 = \frac{1}{2}\left(\sqrt{p^2_{\mathrm{T},\ell^+\ell^-} + m^2_{\ell^+\ell^-}} + \sum_{i\in\{q,g,\gamma\}} |p_{\mathrm{T,i}}|\right)}$$

this is a 'good' scale for V+jets

- at large pTV: HT'/2 ≈ pTV
- modest higher-order corrections
- sufficient convergence

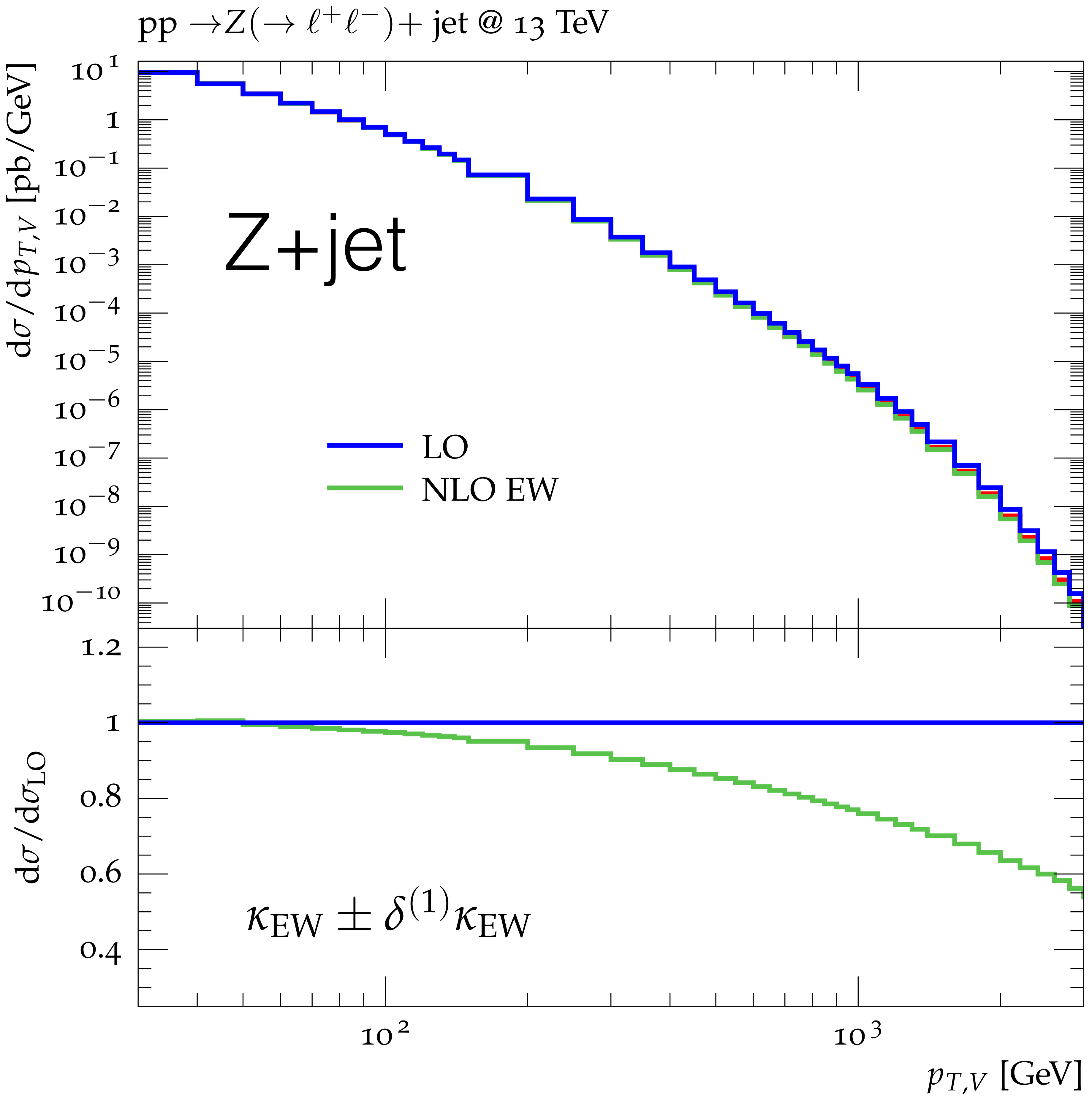
scale uncertainties due to 7-pt variations:

O(20%) uncertainties at LO
O(10%) uncertainties at NLO
O(5%) uncertainties at NNLO

with minor shape variations

How to correlate these uncertainties across processes?

Pure EW uncertainties



EW corrections become sizeable at large $p_{T,V}$: -30% @ 1 TeV

Origin: virtual EW Sudakov logarithms

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

Precise predictions for V+jet DM backgrounds

[1705.04664]

work in collaboration with:
R. Boughezal, J.M. Campell, A. Denner, S. Dittmaier, A. Huss, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, S. Kallweit, M. L. Mangano, P. Maierhöfer, T.A. Morgan, A. Mück, M. Schönherr, F. Petriello, S. Pozzorini, G. P. Salam, C.Williams

- Combination of state-of-the-art predictions: (N)NLO QCD+(N)NLO EW in order to match (future) experimental sensitivities (1-10% accuracy in the few hundred GeV-TeV range)

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

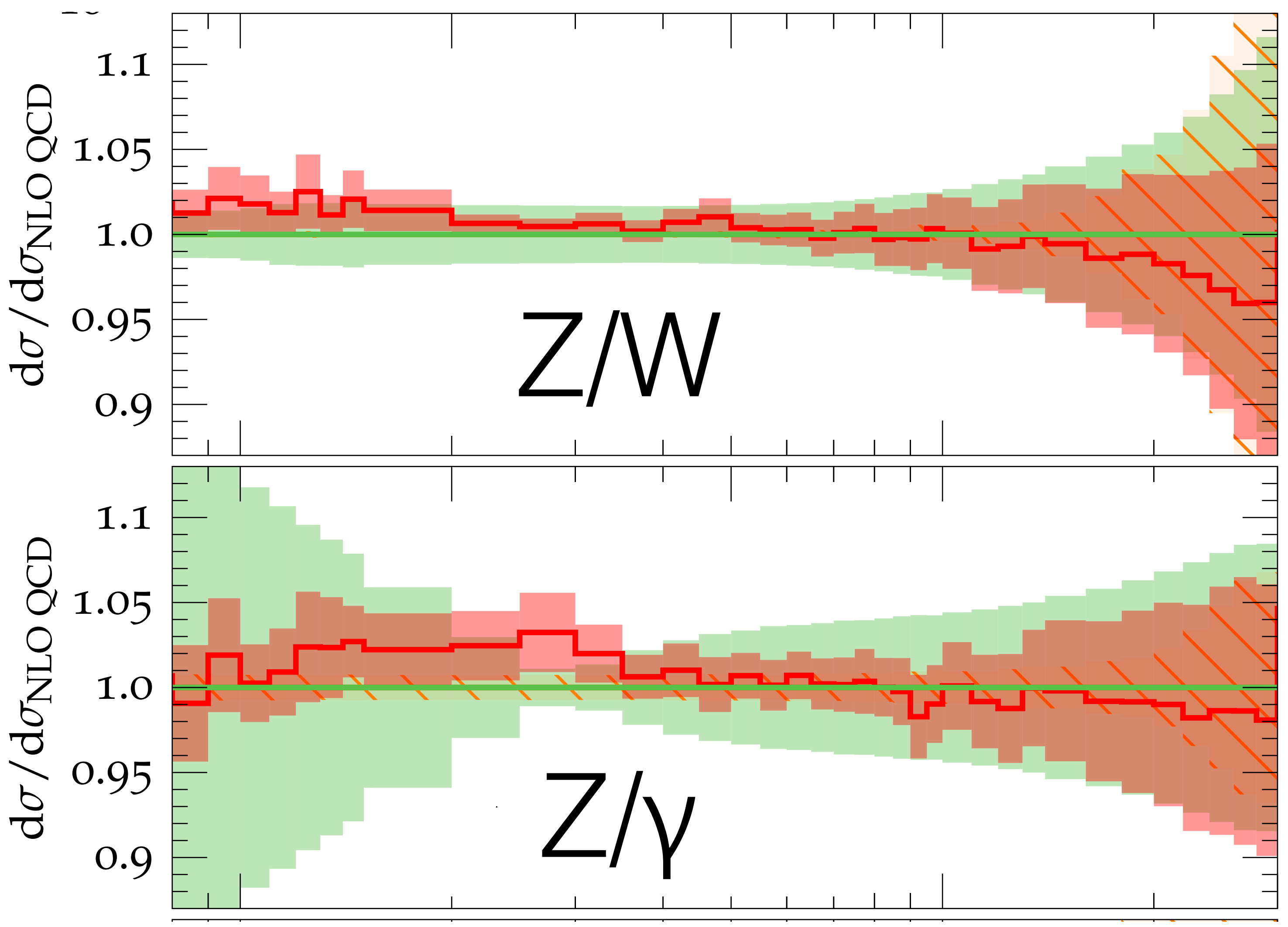
one-dimensional reweighting of MC samples in $x = p_{\mathrm{T}}^{(V)}$

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

- **Robust uncertainty estimates including**
  1. **Pure QCD uncertainties**
  2. **Pure EW uncertainties**
  3. **Mixed QCD-EW uncertainties**
  4. **PDF, γ-induced uncertainties ….**

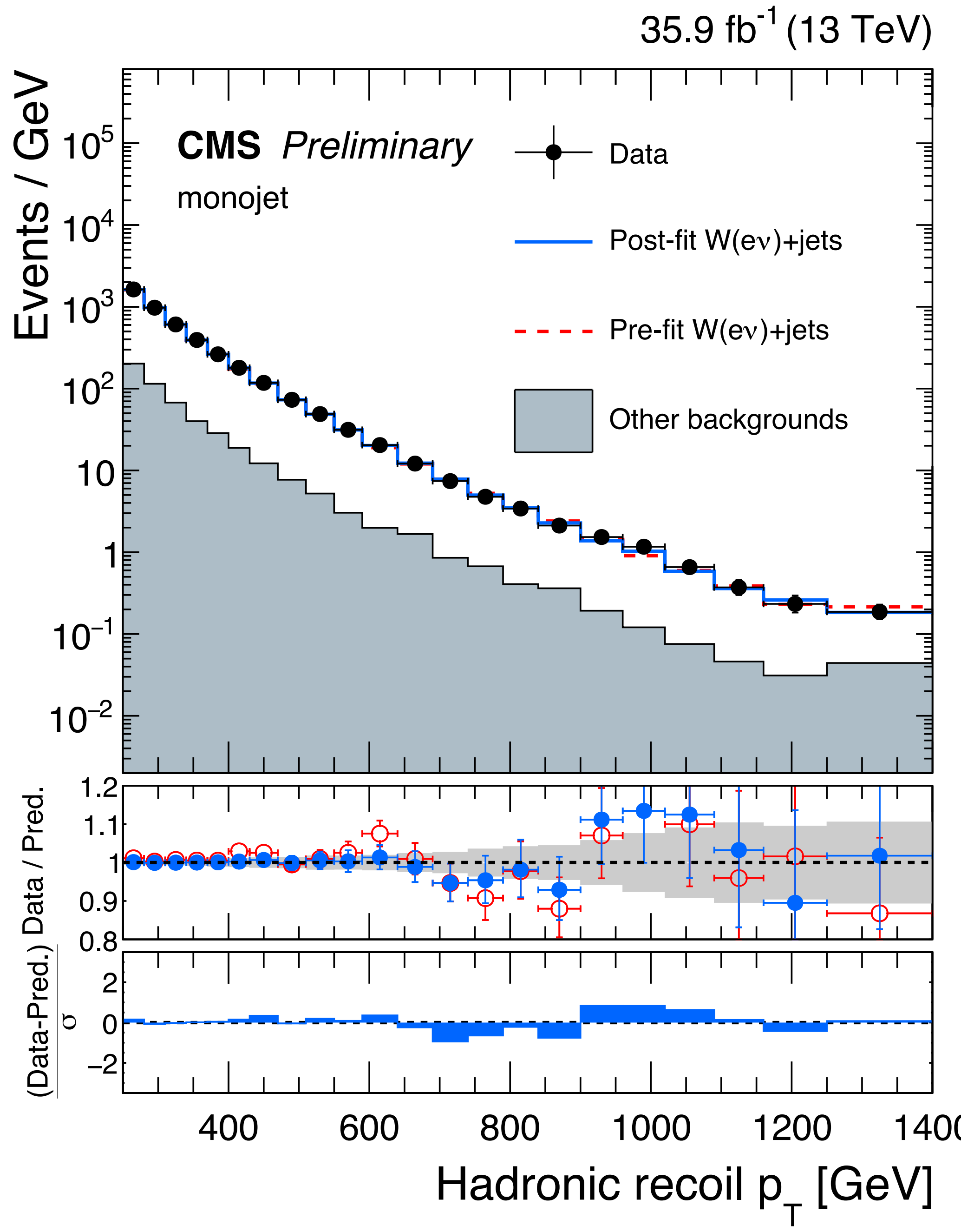
- Prescription for **correlation** of these uncertainties
  - within a process (between low-pT and high-pT)
  - across processes

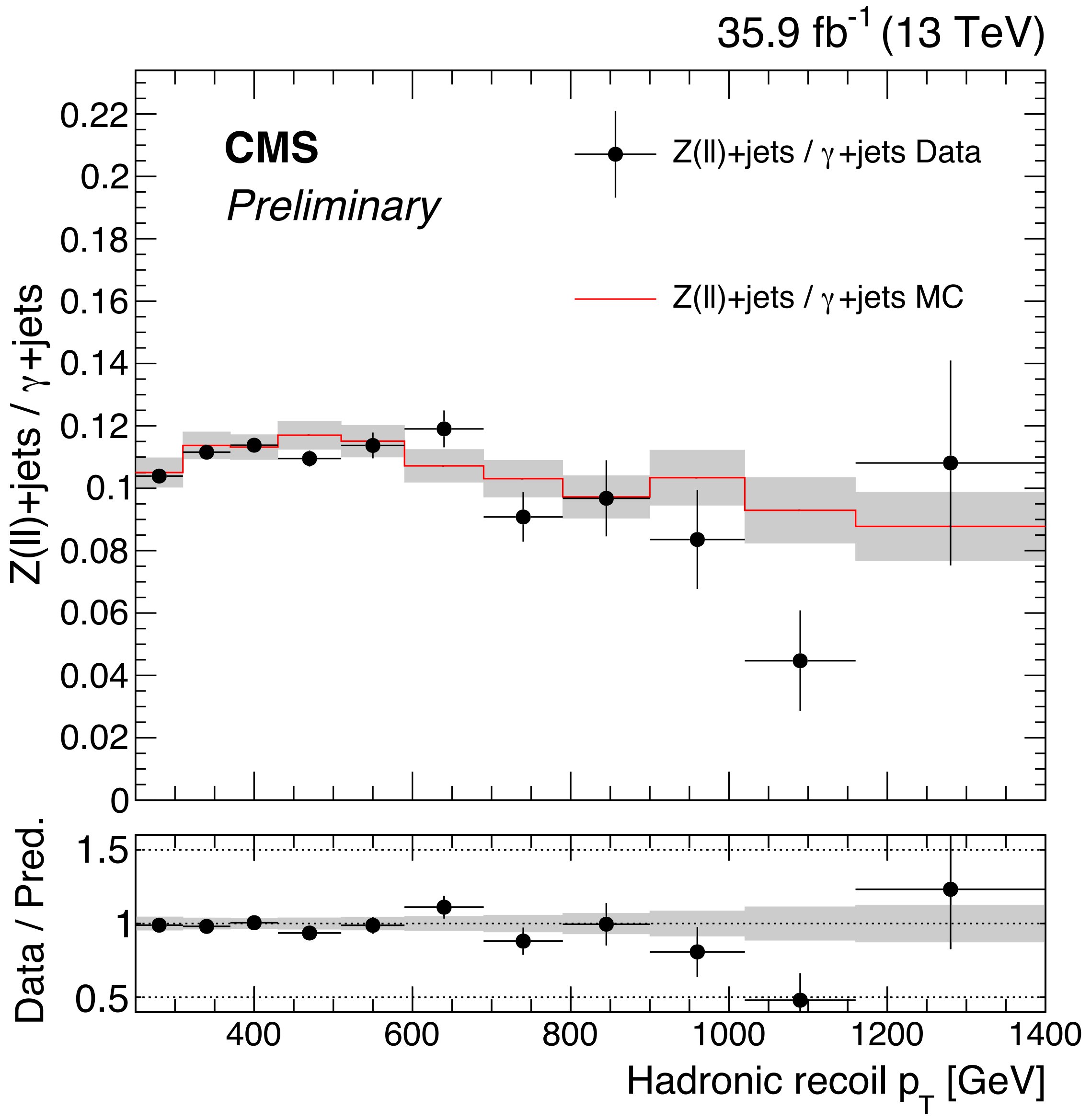
Combined uncertainties on V+jets ratios



- $\delta_{Z/W}$ =1-3% for pT < 1 TeV
- $\delta_{Z/\gamma}$ = 3-5% for pT < 1 TeV

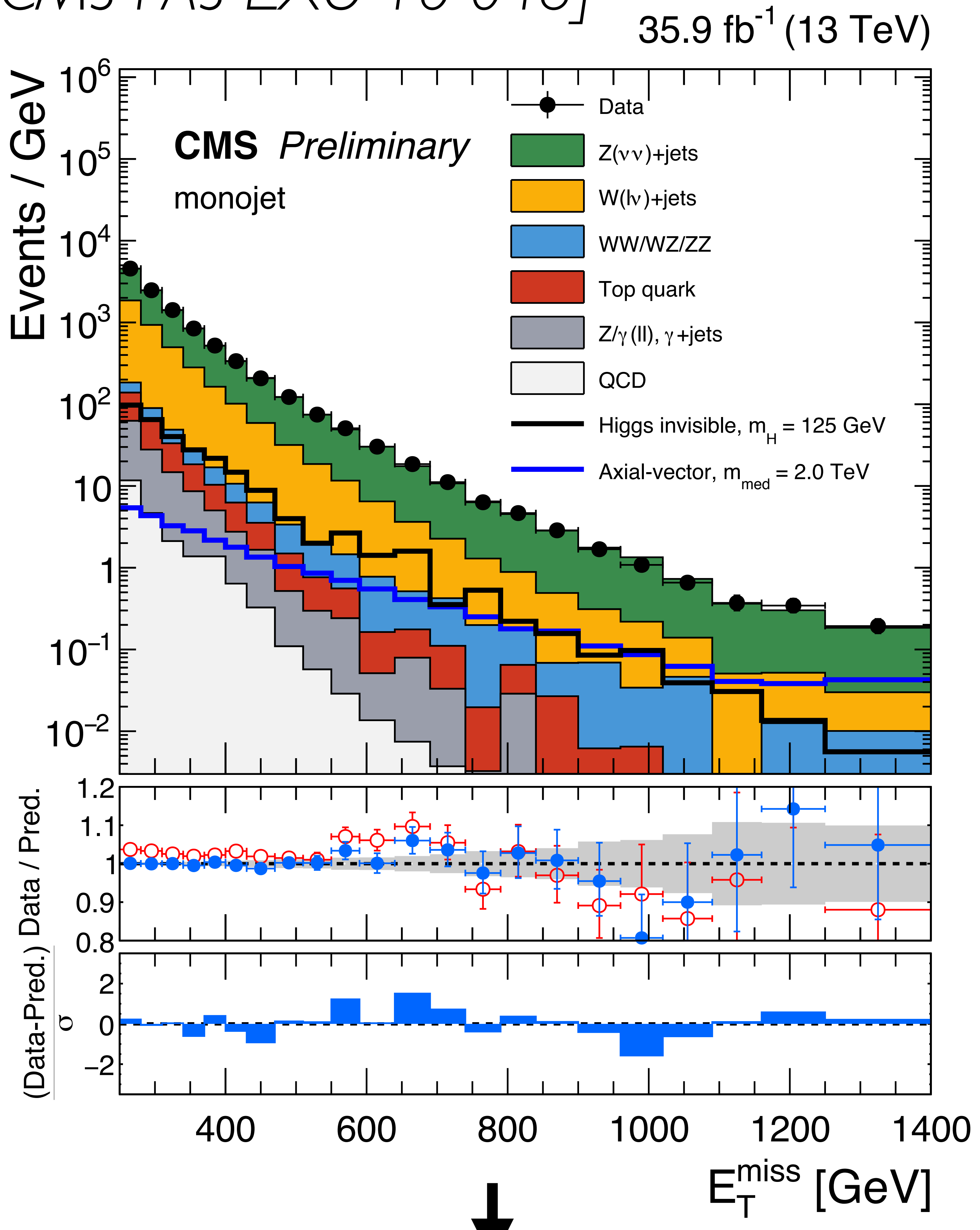
CR





SR

[CMS PAS EXO-16-048]

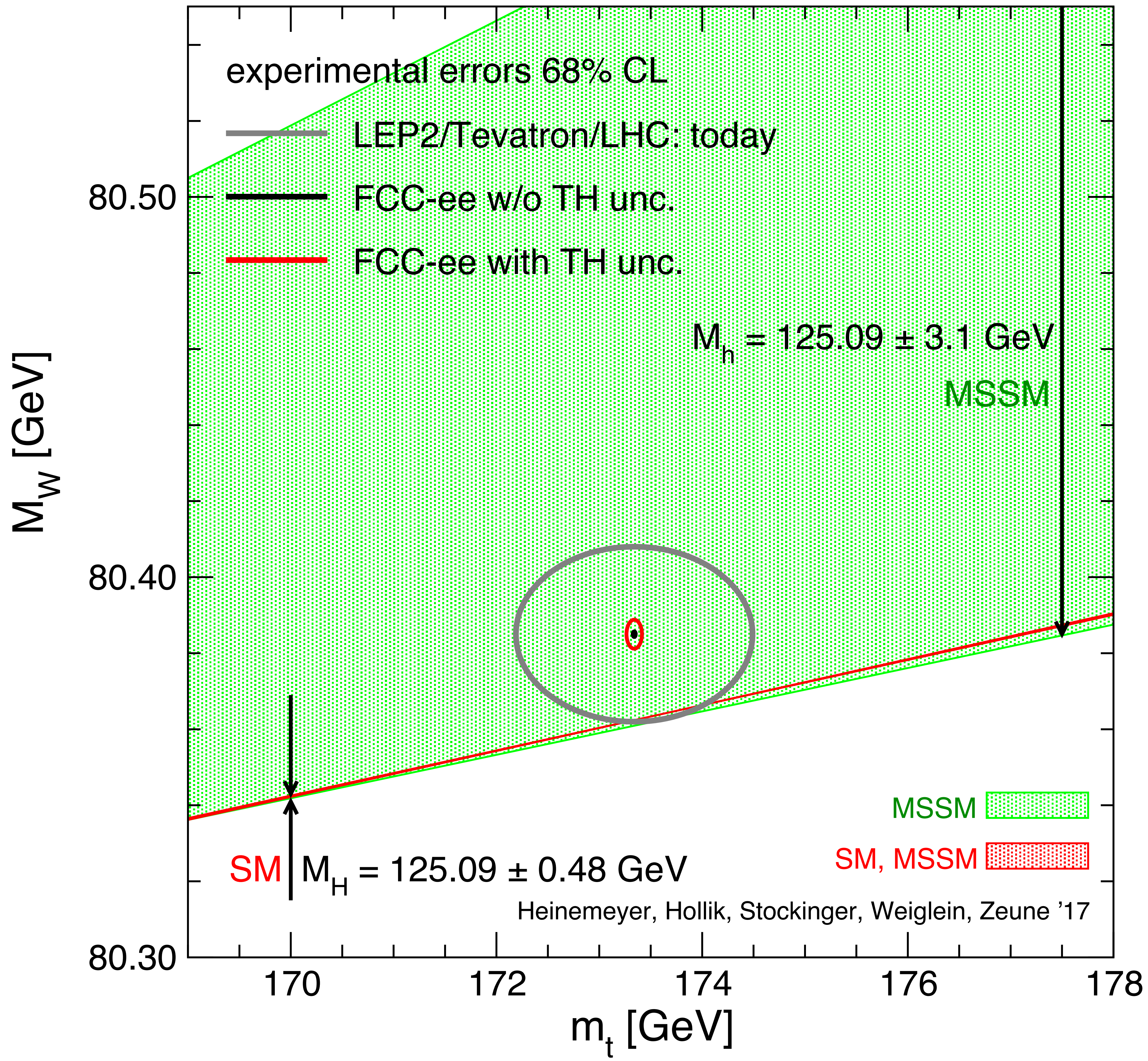


Unprecedented limits on monojet DM production!

M_W measurements (precision DY)

- Motivation: precise measurement of M_W → stringent test of SM!

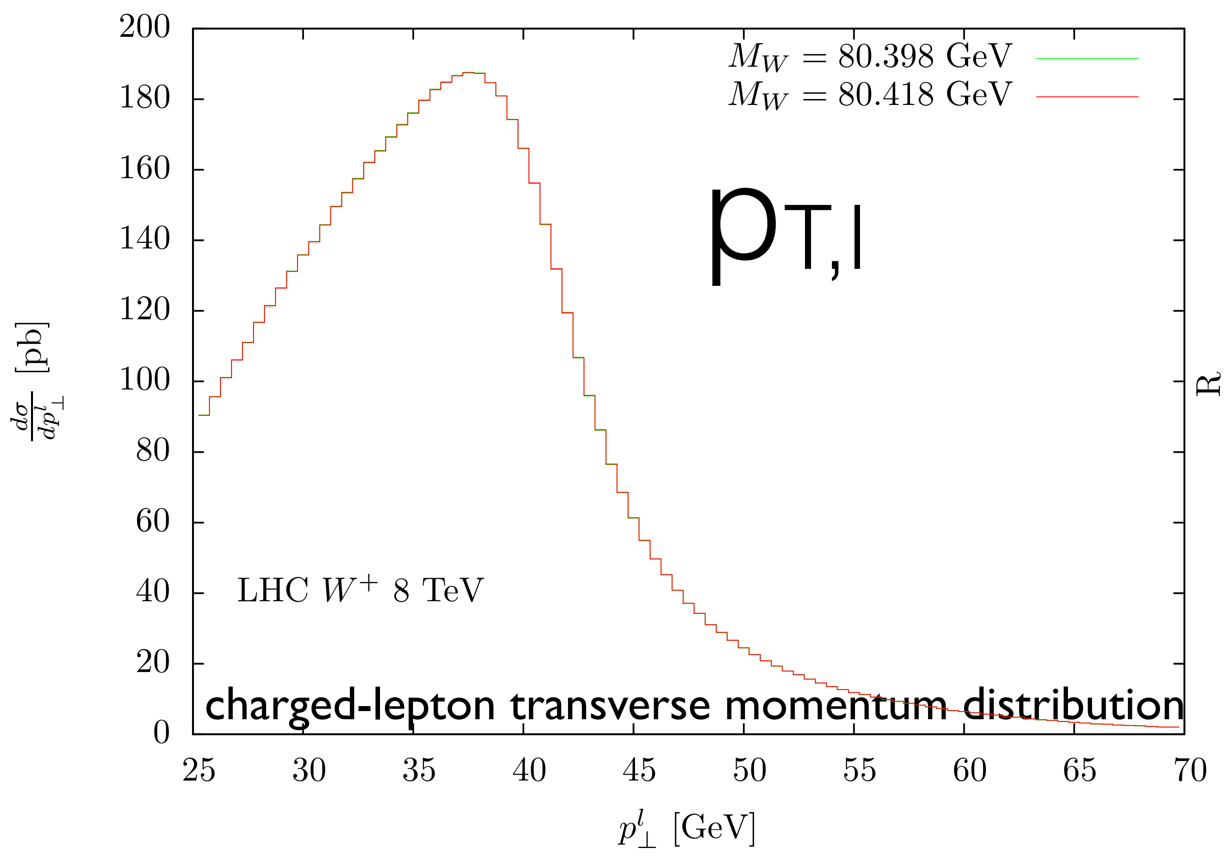
[S. Heinemeyer, FCC week 2017]

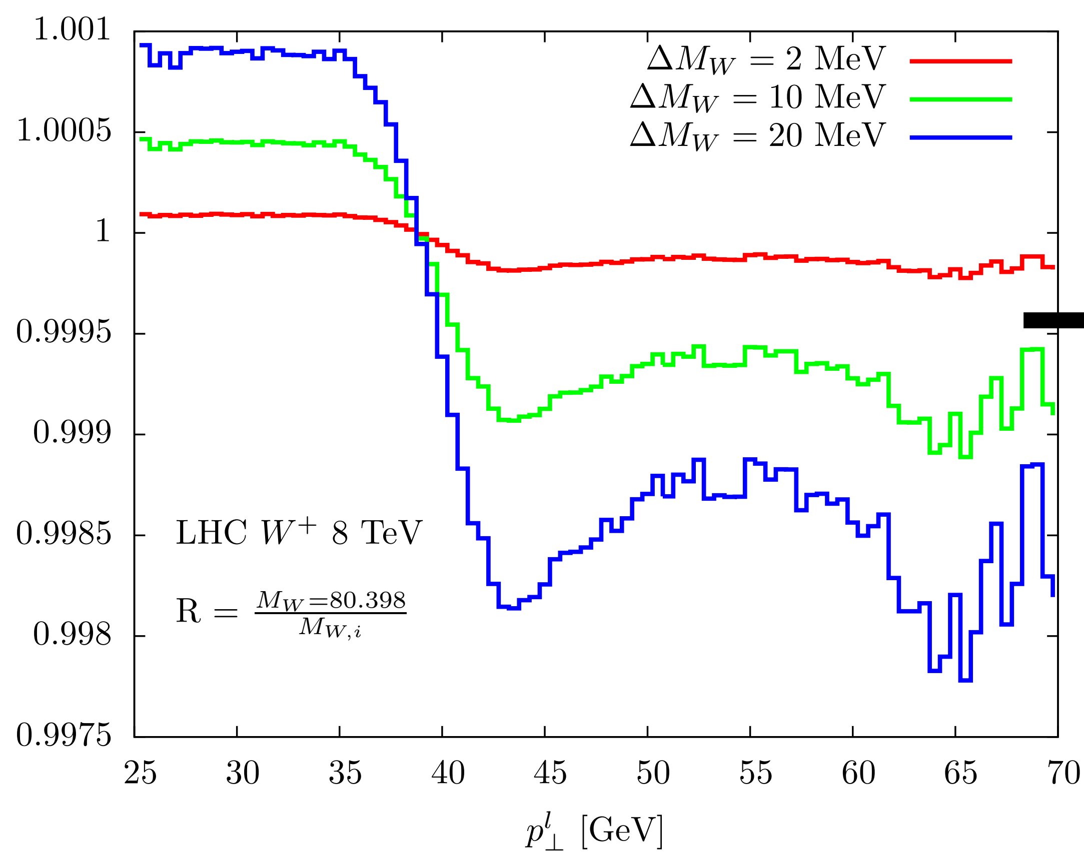


M_W measurements (precision DY)

- Motivation: precise measurement of M_W → stringent test of SM!
- Method: **template fits** of sensitive CC DY distributions ($p_{T,l},\ M_T,\ E_{\text{miss}}$)

$$\boxed{M_W = 80.385 \pm 0.015 \text{ GeV}}$$



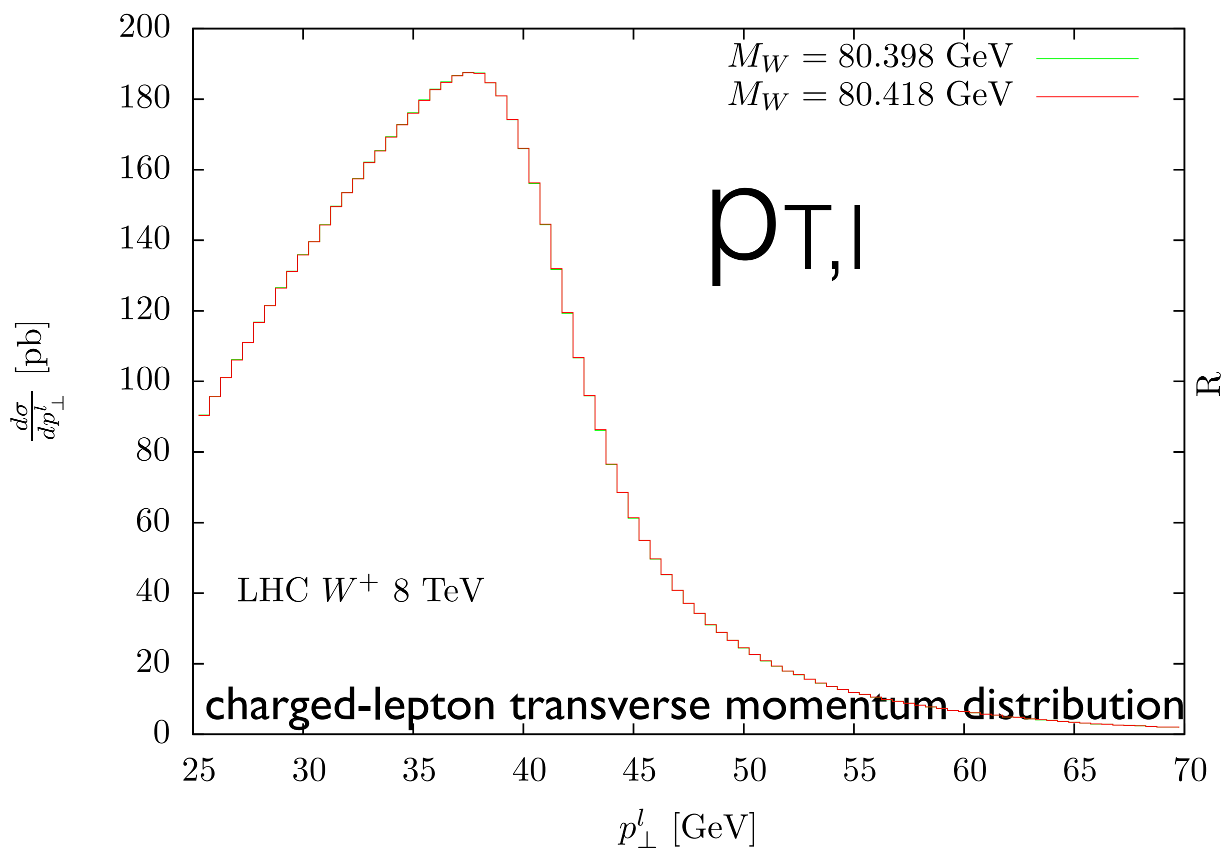


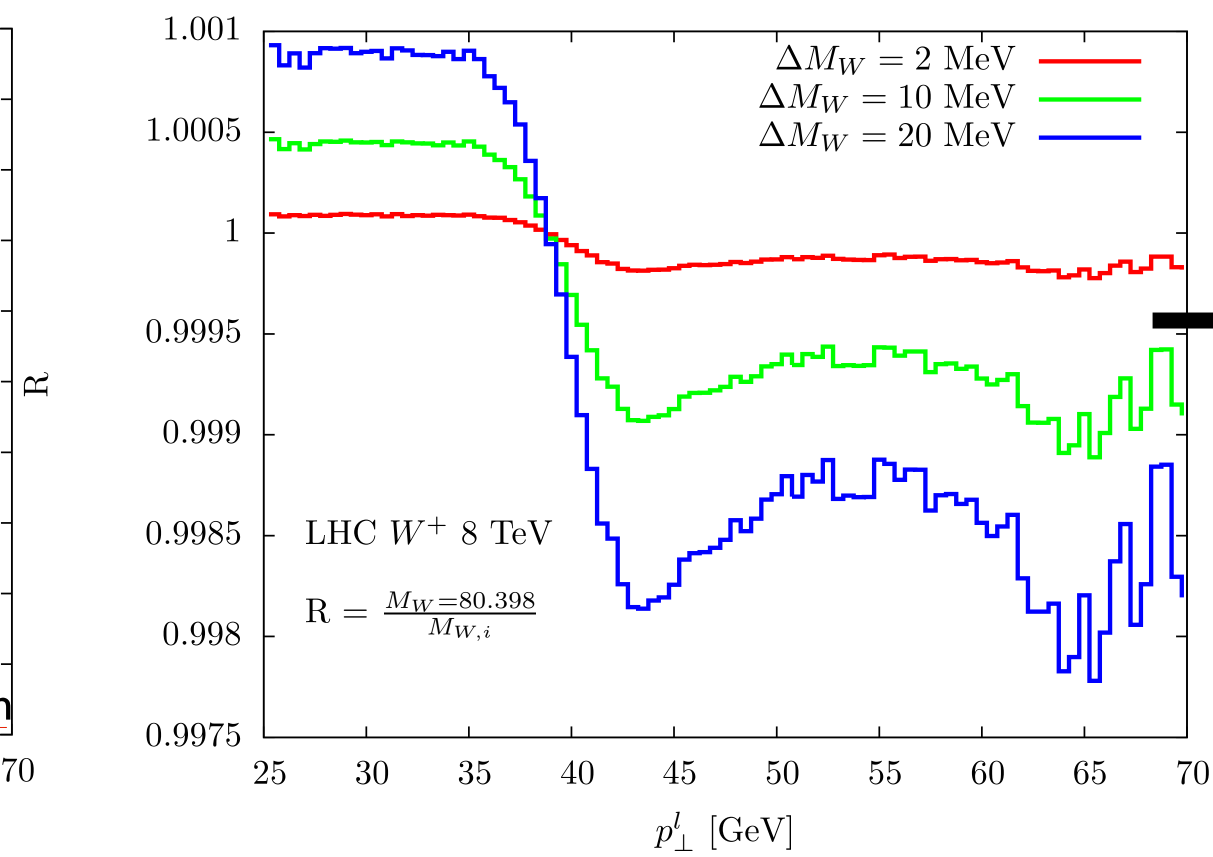
- Need to control shape effects at the sub-1% level!
- Normalization not relevant
- Dominant effects: QCD ISR and QED FSR

M_W measurements (precision DY)

- Motivation: precise measurement of M_W → stringent test of SM!
- Method: **template fits** of sensitive CC DY distributions ($p_{T,l},\ M_T,\ E_{\text{miss}}$)

$$\boxed{M_W = 80.385 \pm 0.015 \text{ GeV}}$$

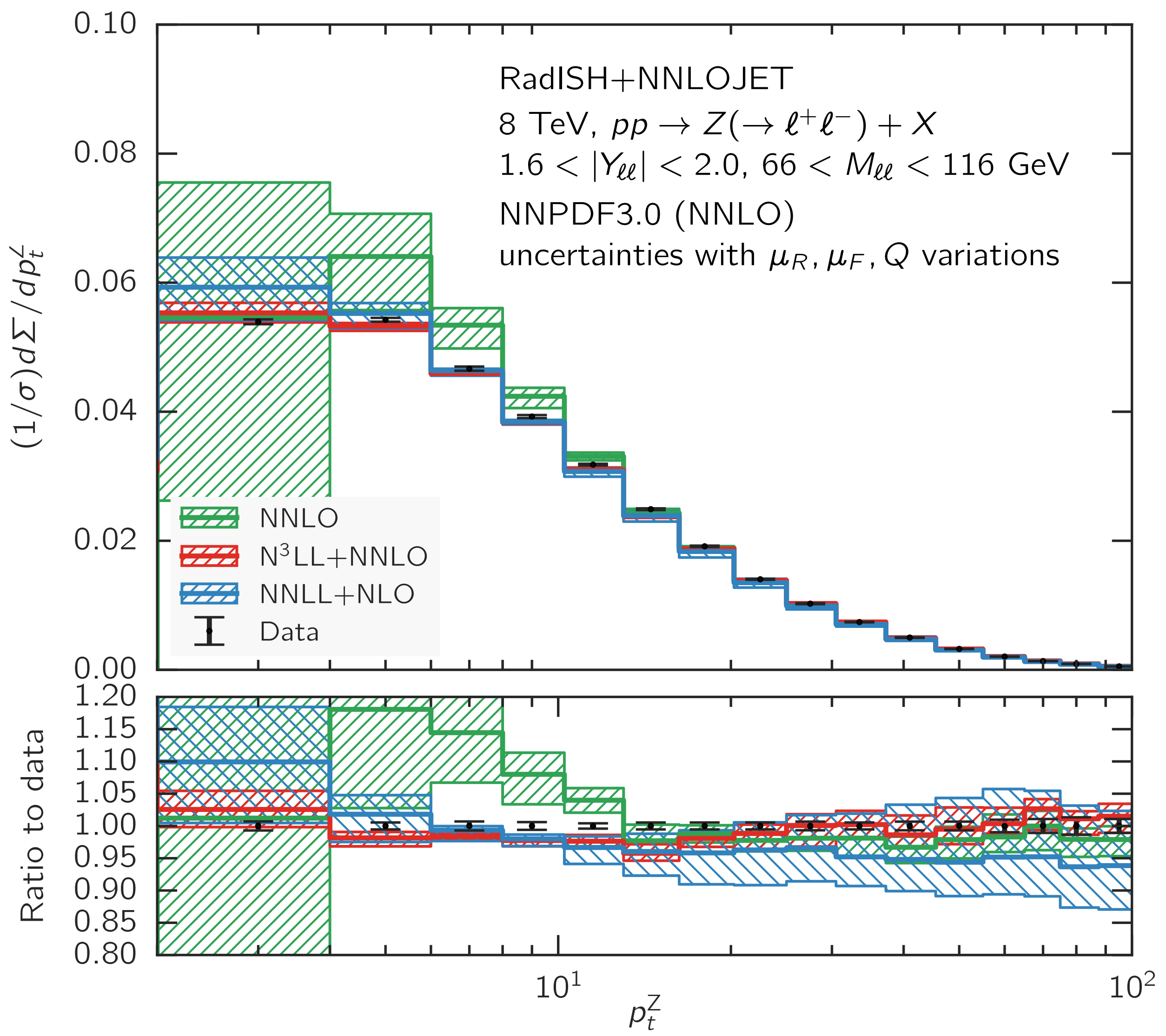




- Need to control shape effects at the sub-1% level!
- Normalization not relevant
- Dominant effects: QCD ISR and QED FSR

DY@NNLO+N3LL

[Bizon et. al. '18]

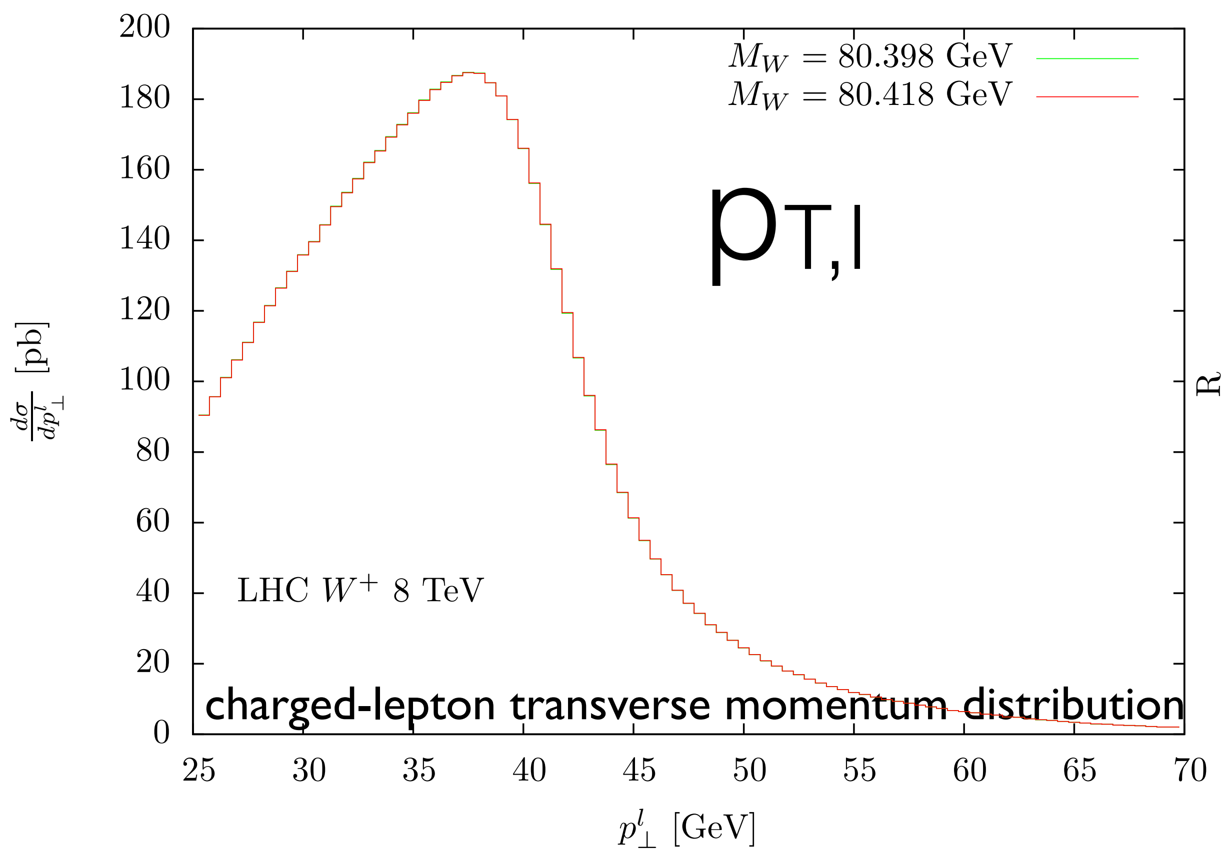


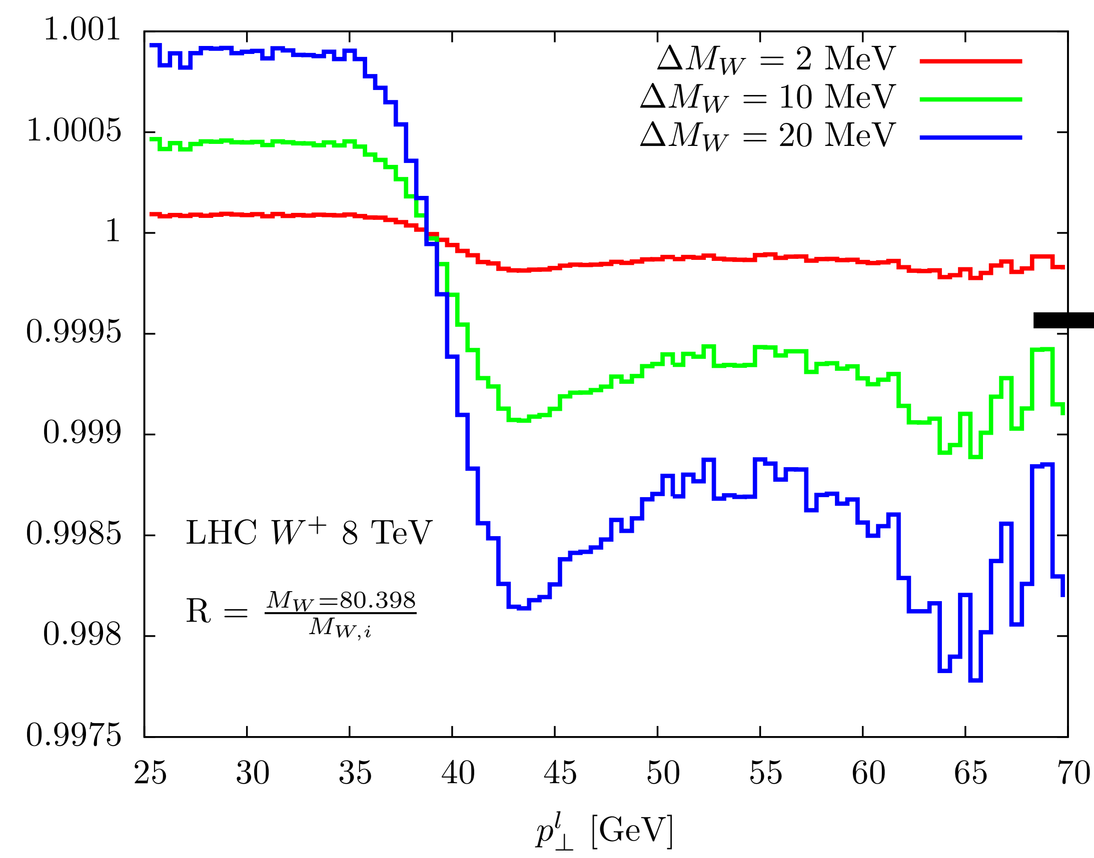
- Need to control W-pT spectrum at the sub-% level!
- Idea: use measurement of Z-pT to control W-pT
- Problem: precision in transfer-factor has to match experimental precision

M_W measurements (precision DY)

- Motivation: precise measurement of M_W → stringent test of SM!
- Method: **template fits** of sensitive CC DY distributions $(p_{T,l},\ M_T,\ E_{\text{miss}})$

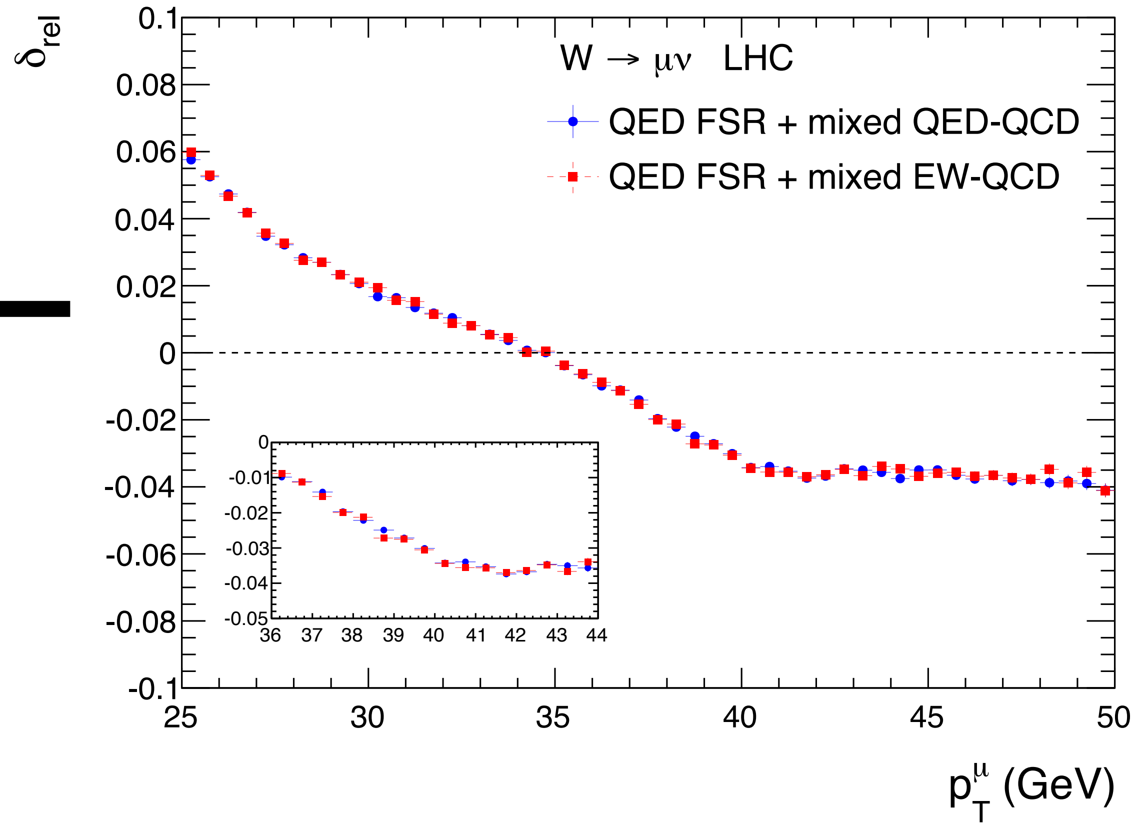
$$\boxed{M_W = 80.385 \pm 0.015\ \text{GeV}}$$





- Need to control shape effects at the sub-1% level!
- Normalization not relevant
- Dominant effects: QCD ISR and QED FSR

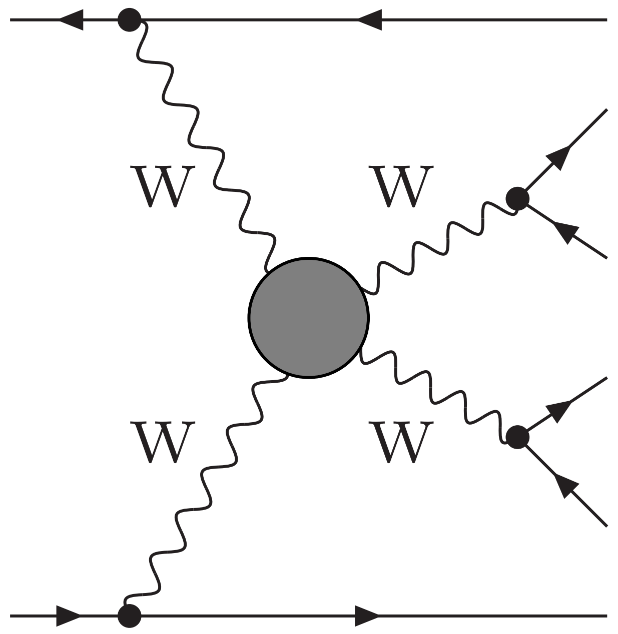
- new (resonance aware) POWHEG generators: **NLO+PS QCDxEW** for CC/NC DY
- simultaneously QED and QCD radiation thanks to multiplicative matching in POWHEG



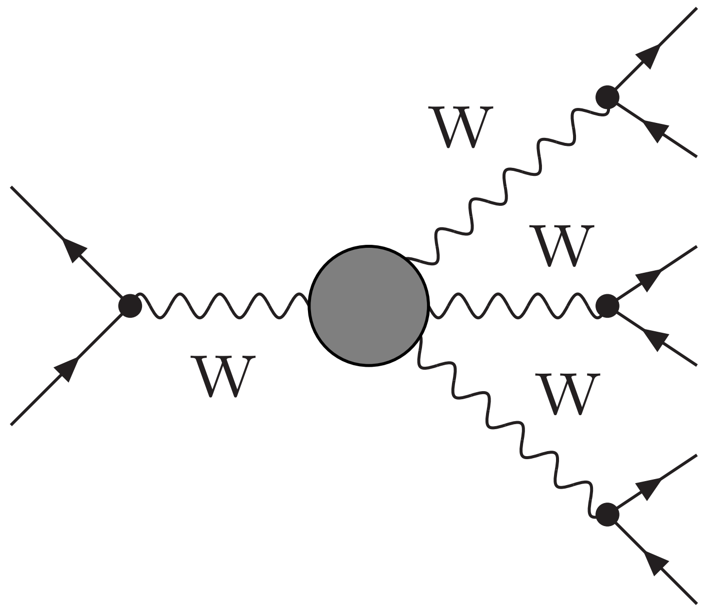
mixed QCDxEW seems to be under good control!

[Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, Vicini;'16]

Rare EW processes

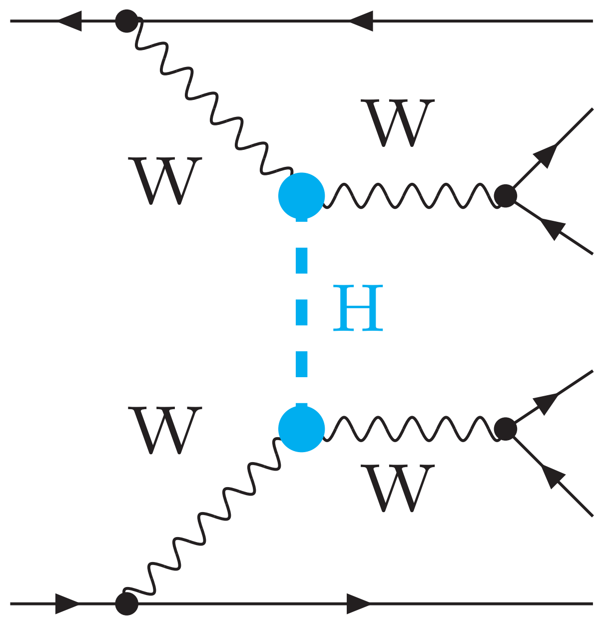


VBS



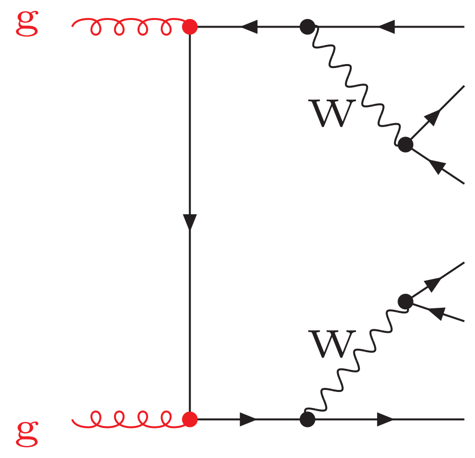
Triboson

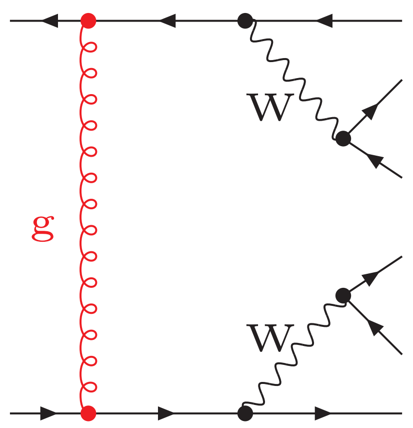
- direct access to quartic EW gauge couplings
- VBS: longitudinal gauge bosons at high energies
- window to electroweak symmetry breaking via off-shell Higgs exchange

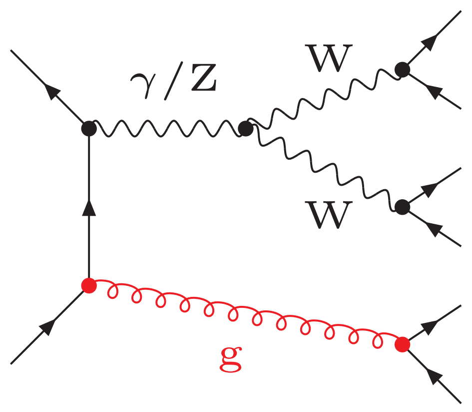


VBS

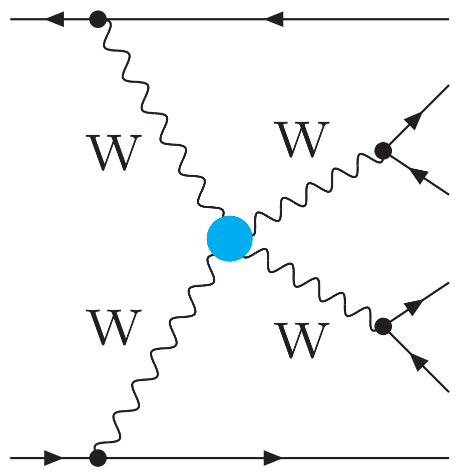
Note: severe QCD background to VBS signatures + interference:







vs.



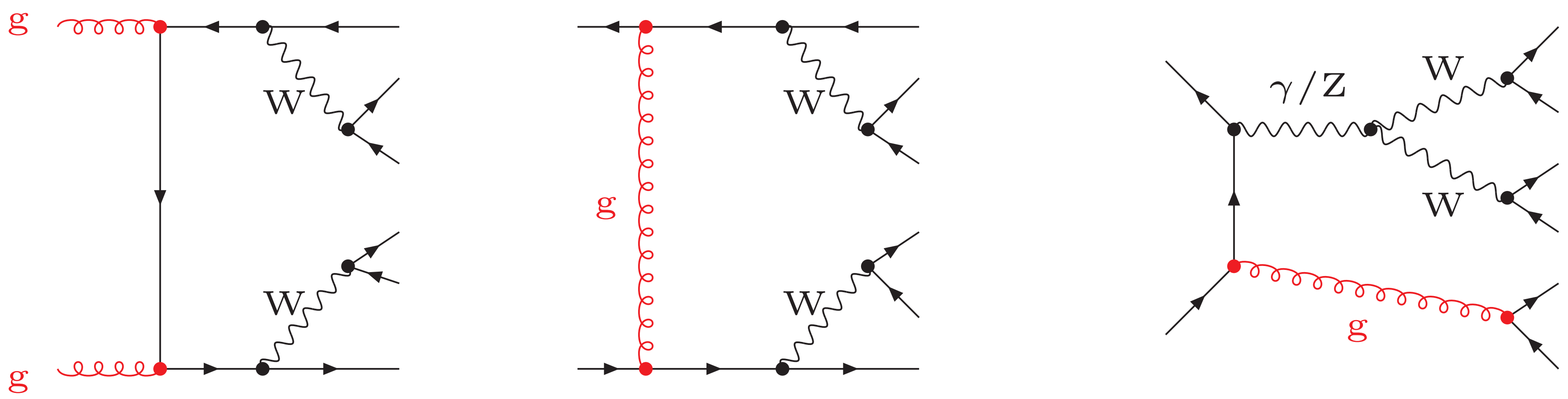
$$d\sigma = d\sigma(\alpha_S^2\alpha^4) + d\sigma(\alpha_S\alpha^5) + d\sigma(\alpha^6) + \ldots$$

LO

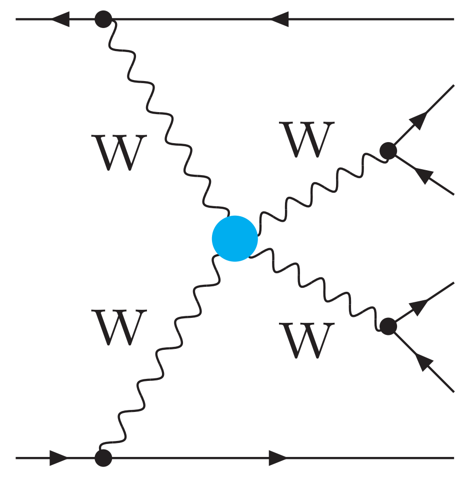
QCD-background interference VBS-signal

VBS

Note: severe QCD background to VBS signatures + interference:



vs.



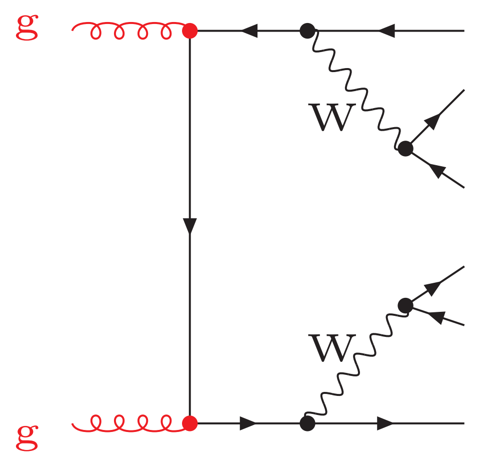
$$d\sigma = d\sigma(\alpha_S^2\alpha^4) + d\sigma(\alpha_S\alpha^5) + d\sigma(\alpha^6) + \dots$$ LO

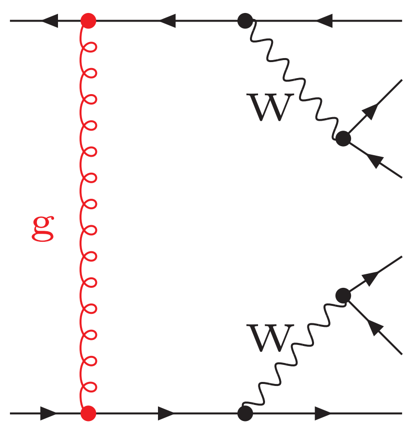
QCD-background interference VBS-signal

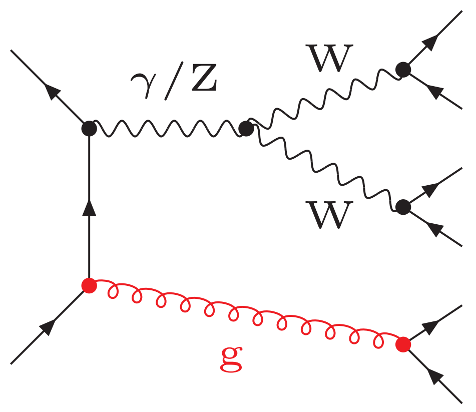
$$\dots + d\sigma(\alpha_S^3\alpha^4) + d\sigma(\alpha_S^2\alpha^5) + d\sigma(\alpha_S\alpha^6) + \sigma(\alpha^7)$$ NLO

VBS

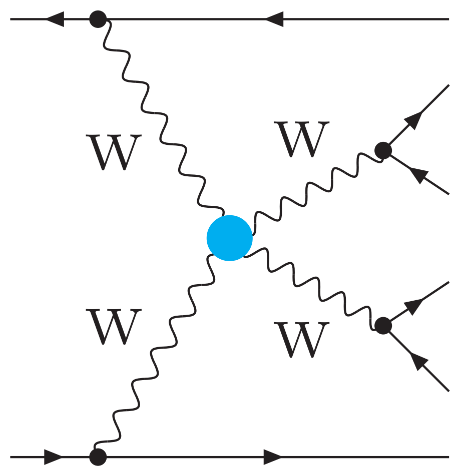
Note: severe QCD background to VBS signatures + interference:







vs.



$$d\sigma = d\sigma(\alpha_S^2\alpha^4) + d\sigma(\alpha_S\alpha^5) + d\sigma(\alpha^6) + \ldots$$ LO

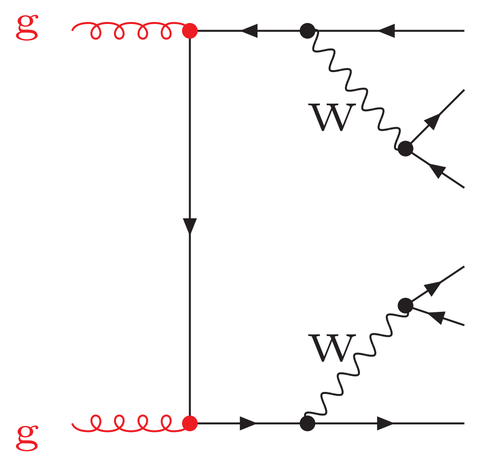
QCD-background $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$ interference $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$ VBS-signal

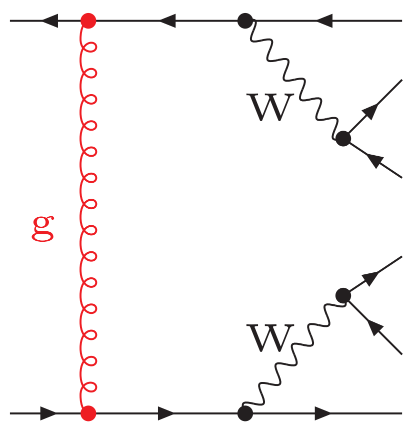
$$\cdots + d\sigma(\alpha_S^3\alpha^4) + d\sigma(\alpha_S^2\alpha^5) + d\sigma(\alpha_S\alpha^6) + \sigma(\alpha^7)$$ NLO

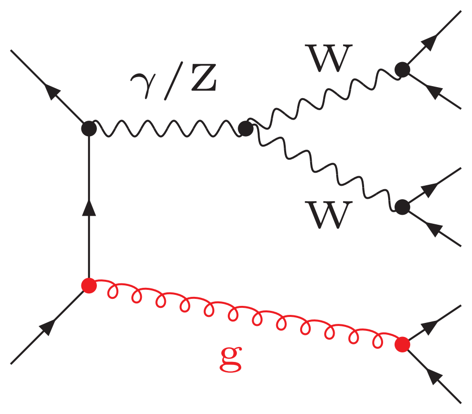
"NLO QCD" "NLO EW" "NLO QCD" "NLO EW"

VBS

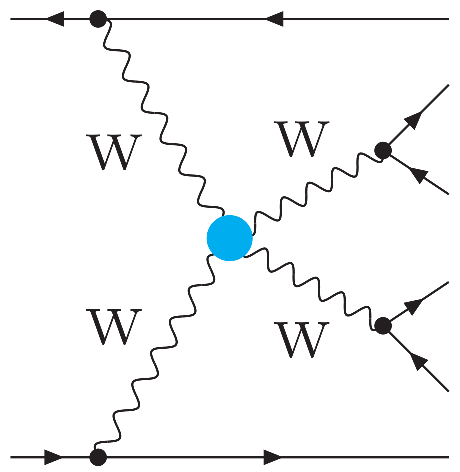
Note: severe QCD background to VBS signatures + interference:







vs.



$$d\sigma = d\sigma(\alpha_S^2\alpha^4) + d\sigma(\alpha_S\alpha^5) + d\sigma(\alpha^6) + \ldots$$ LO

QCD-background interference VBS-signal

$\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$

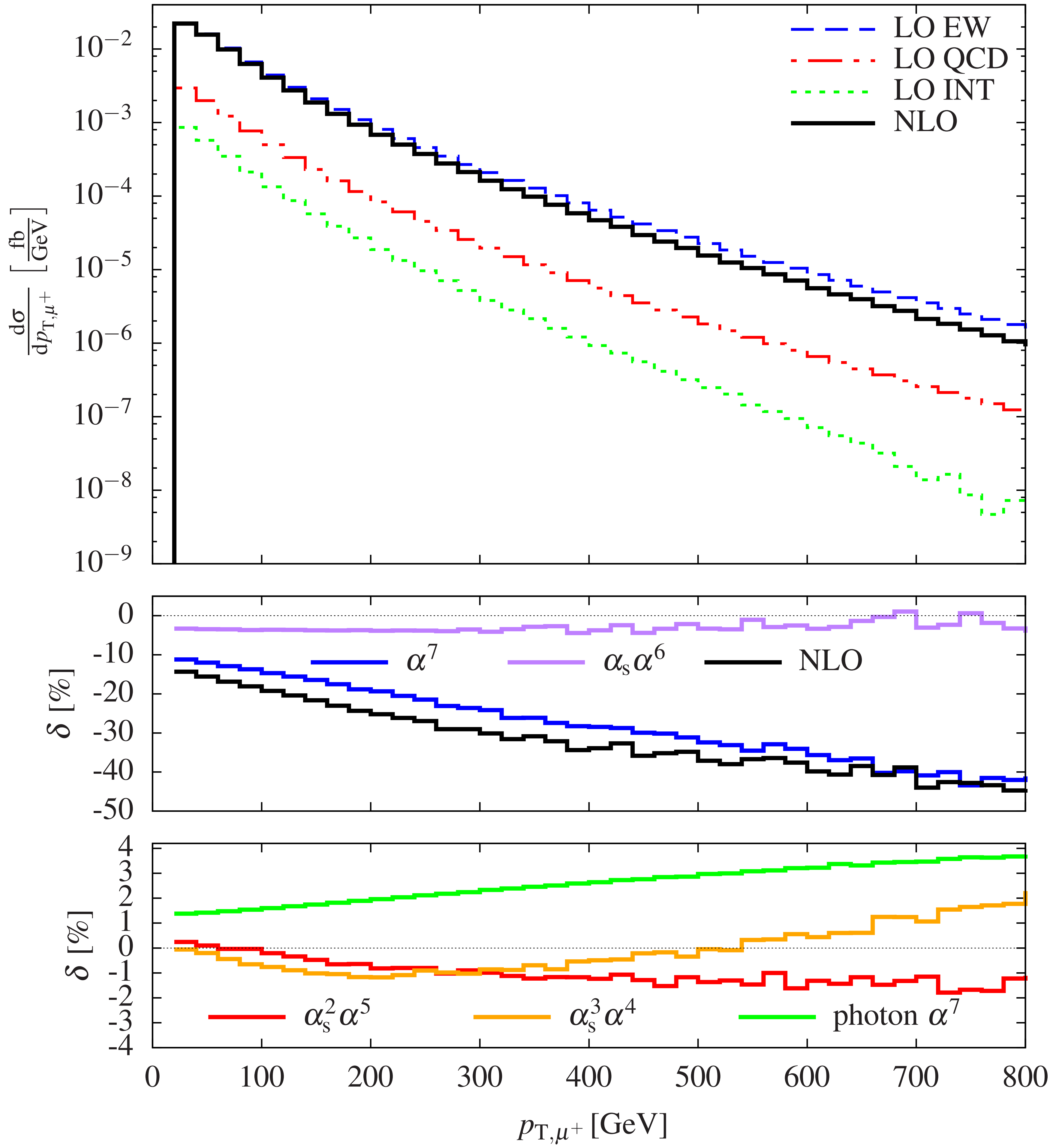
$$\cdots + d\sigma(\alpha_S^3\alpha^4) + d\sigma(\alpha_S^2\alpha^5) + d\sigma(\alpha_S\alpha^6) + \sigma(\alpha^7)$$ NLO

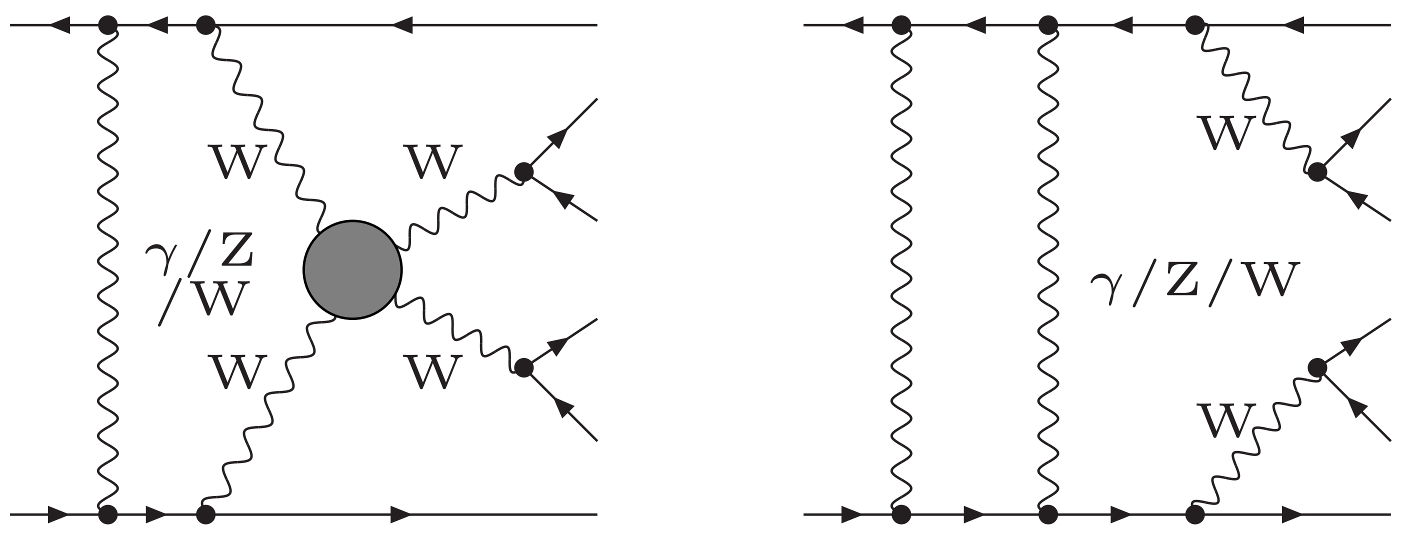
"NLO QCD" "NLO EW" "NLO QCD" "NLO EW"

➡separation meaningless at NLO

VBS: W^+W^++2jets @ full NLO

[Biedermann, Denner, Pellen '16+'17]





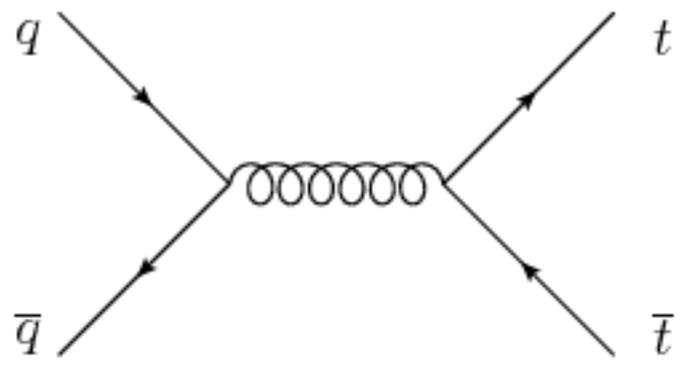
$2 \rightarrow 6$ particles at NLO EW !

- NLO corrections dominated by α^7 :

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{NLO}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

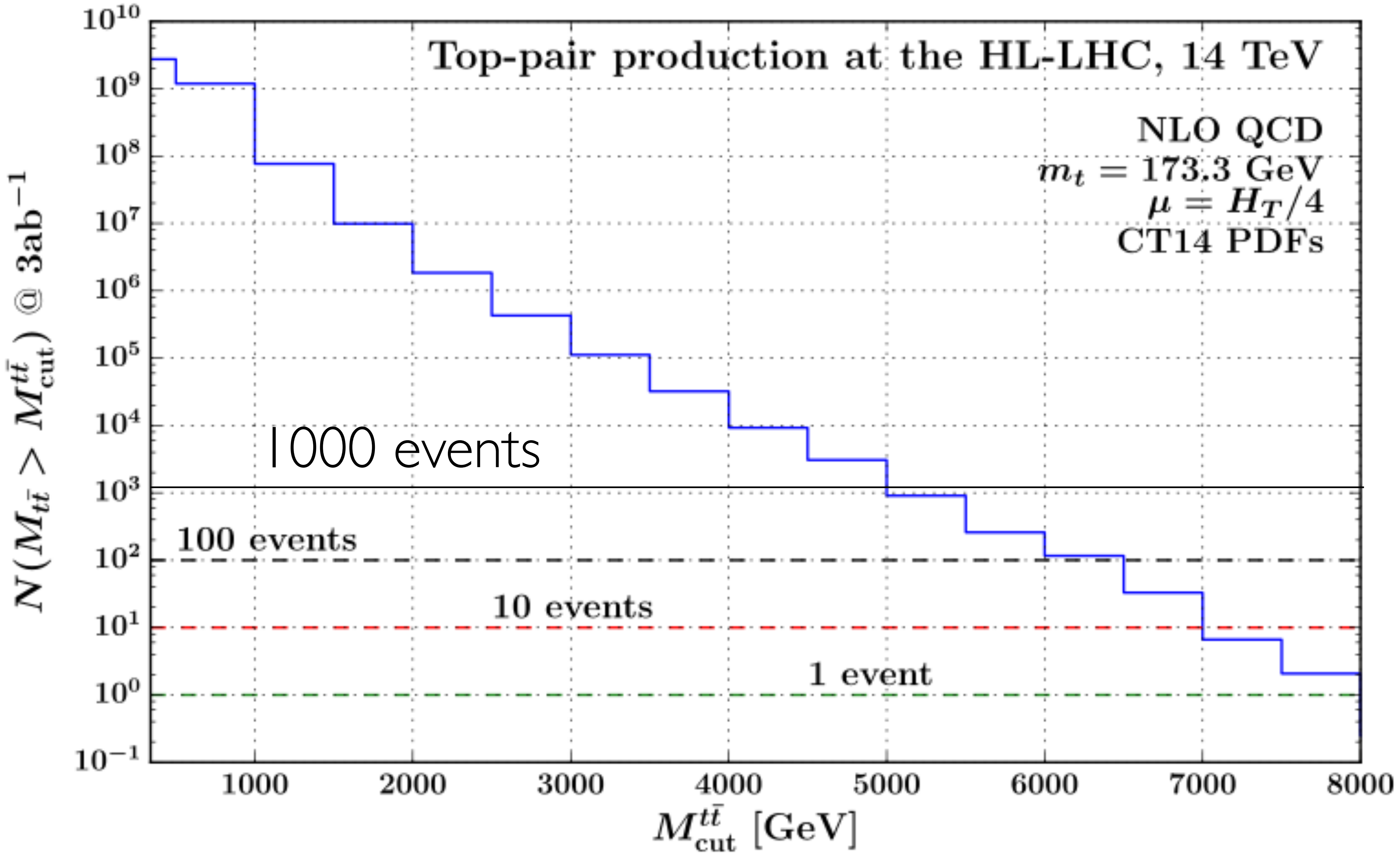
with $M_{jj} > 500\,\text{GeV},\ p_{T,j} > 30\,\text{GeV},\ p_{T,\ell} > 20\,\text{GeV},$

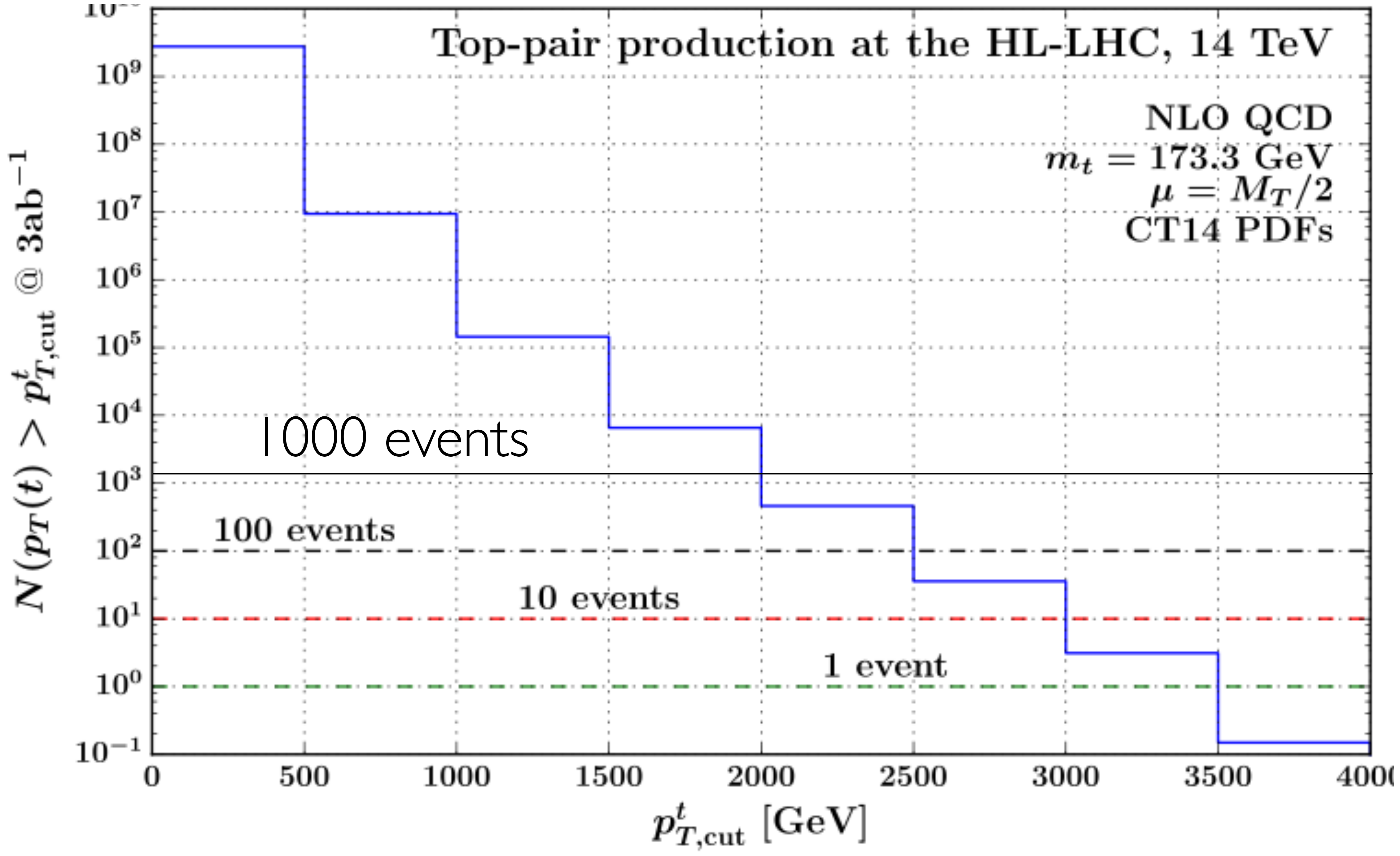
Precision Top physics



(b)

[M. Zaro, HL/HE LHC workshop, June 2018]



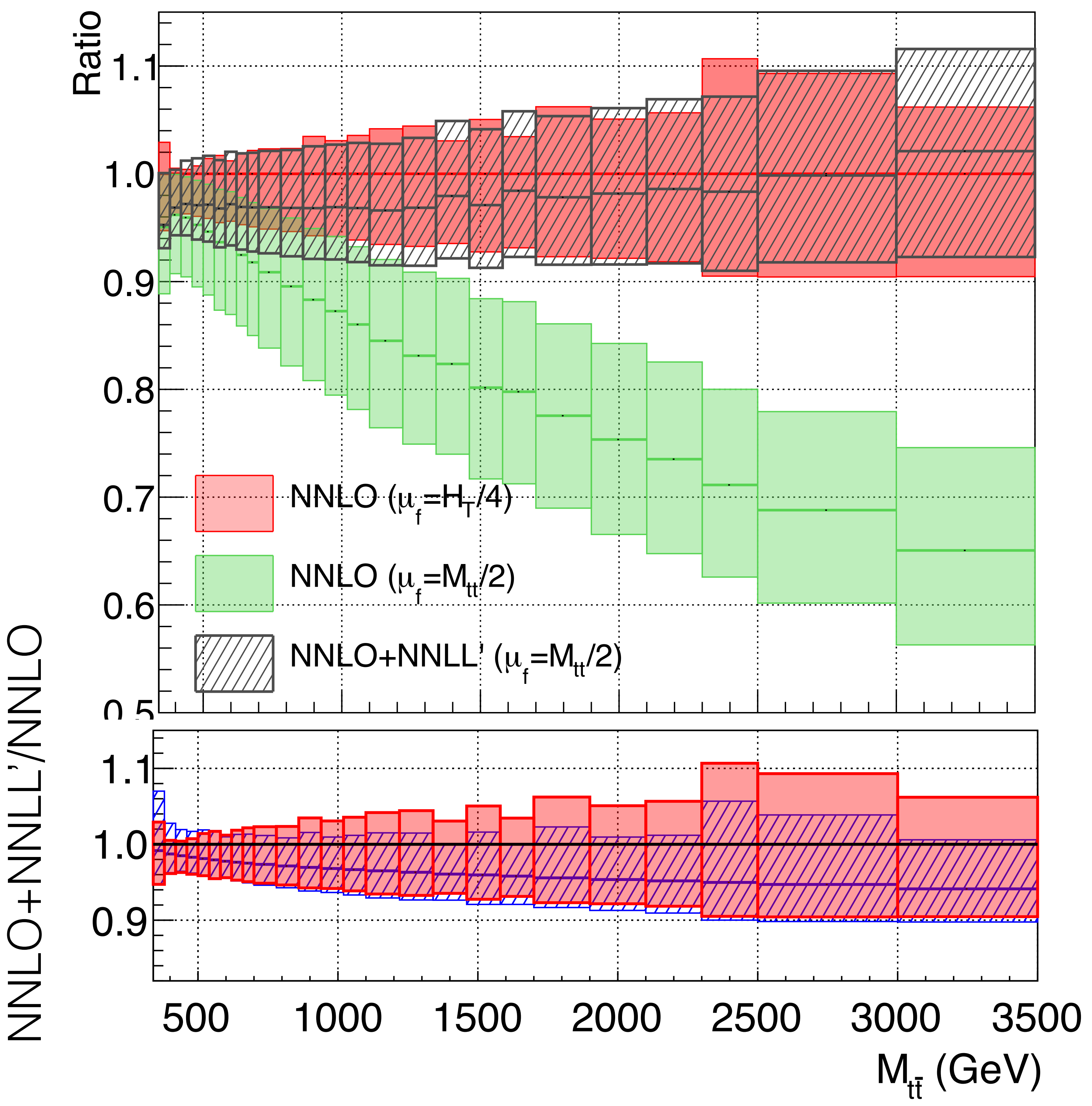


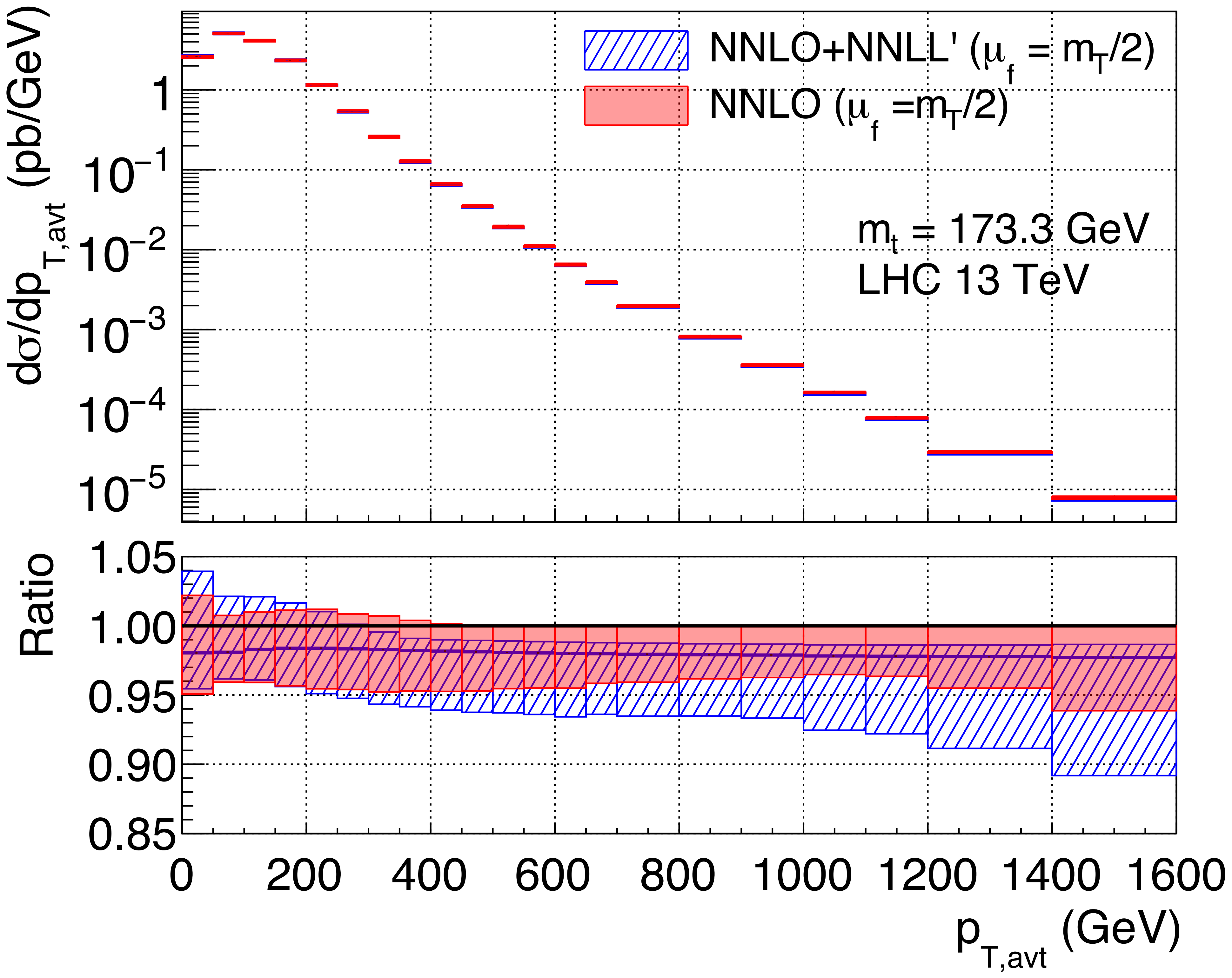
- 1-10% precision for M_{tt}=5000-6000 GeV
- 1-10% precision for pT_{top}=2000-2500 GeV

Precision Top physics

- 1-10% precision for M_{tt}=5000-6000 GeV
- 1-10% precision for pT_{top}=2000-2500 GeV

NNLO+NNLL′ for top-pair production [Czakon et. al.,'18]



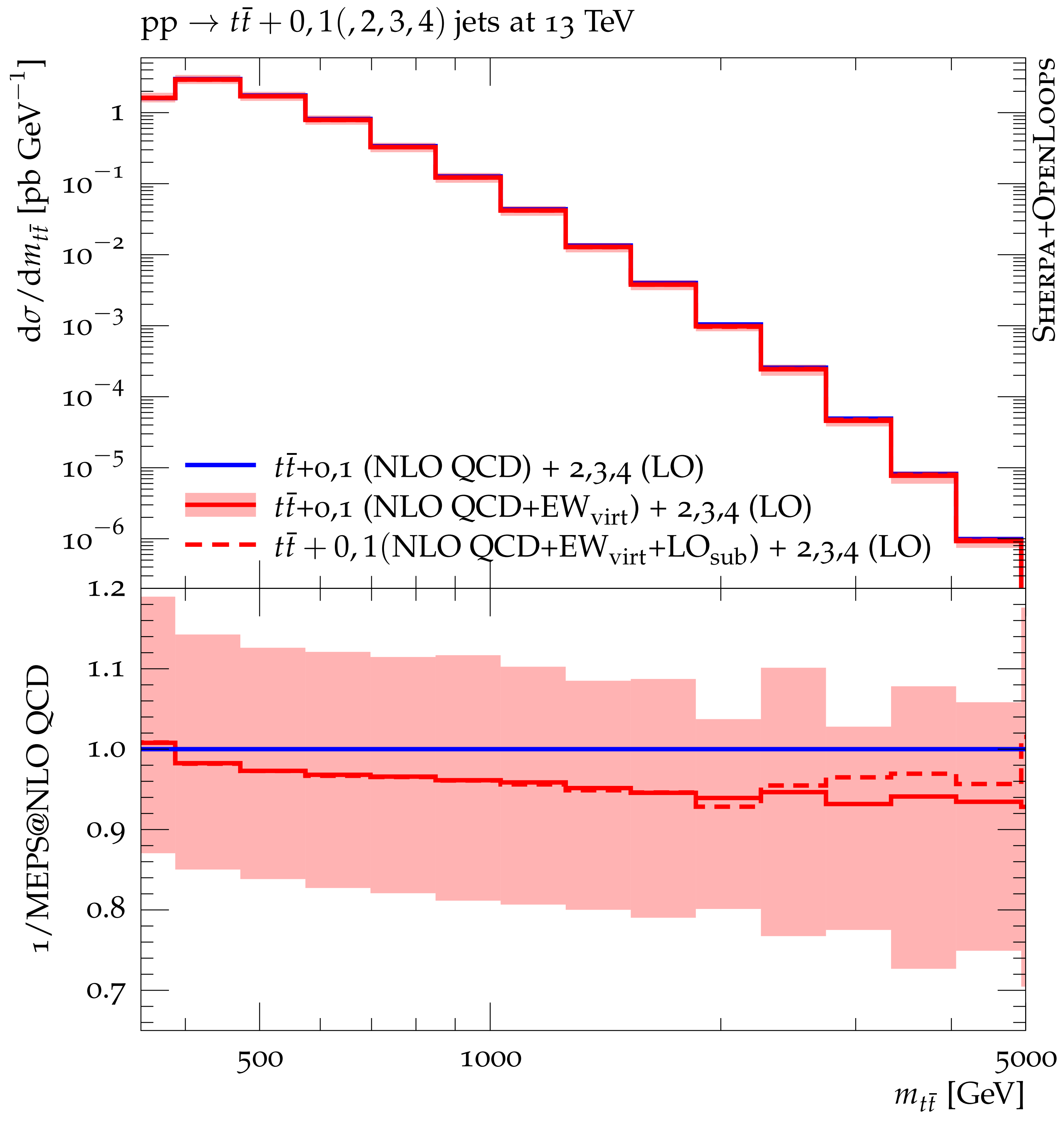


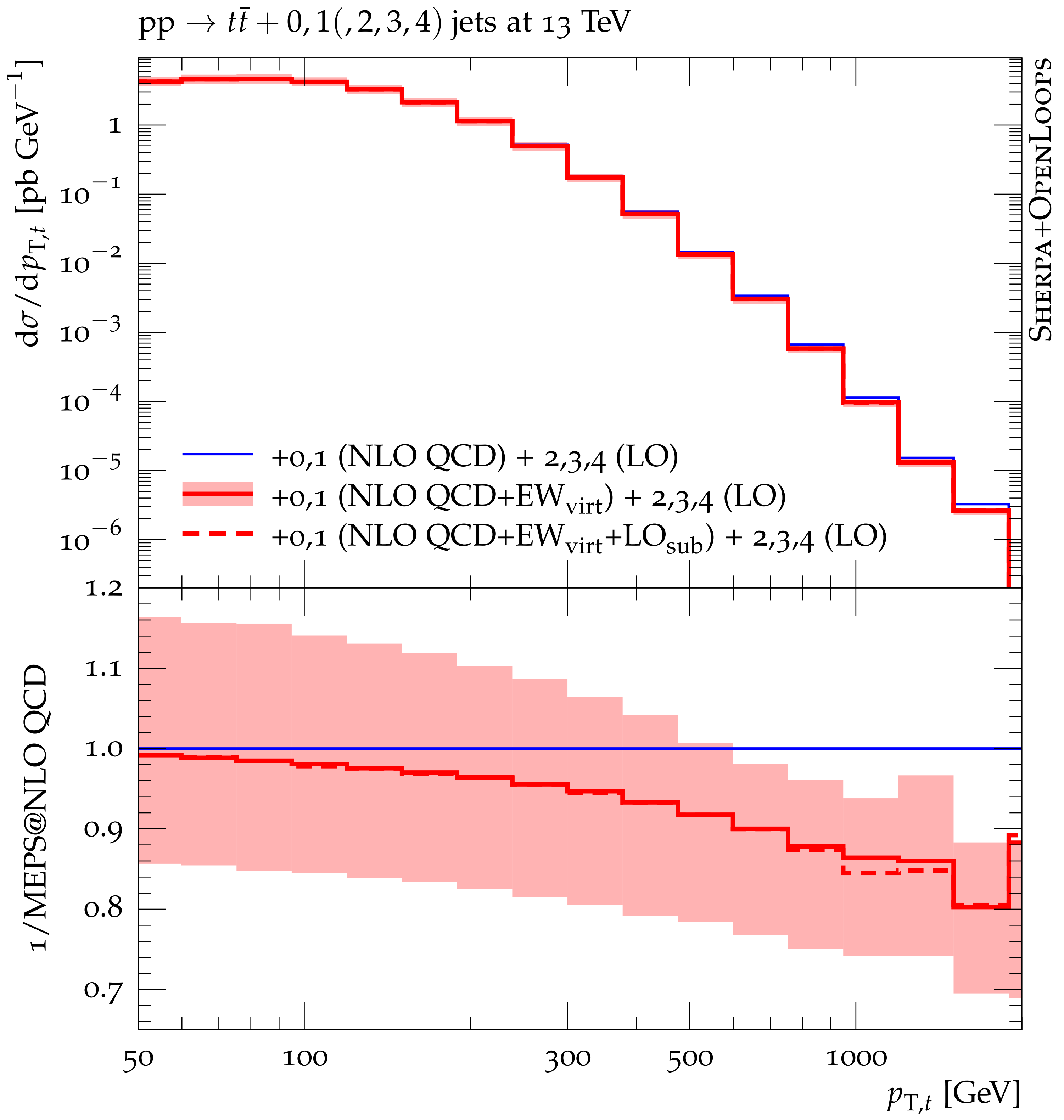
- most relevant hard scale is not M_{tt} itself but rather H_T
- remaining scale uncertainties at the level of 5%
- remaining scale uncertainties in the tail at the level of 5-10%

Precision Top physics

- 1-10% precision for M_{tt}=5000-6000 GeV
- 1-10% precision for pT_{top}=2000-2500 GeV

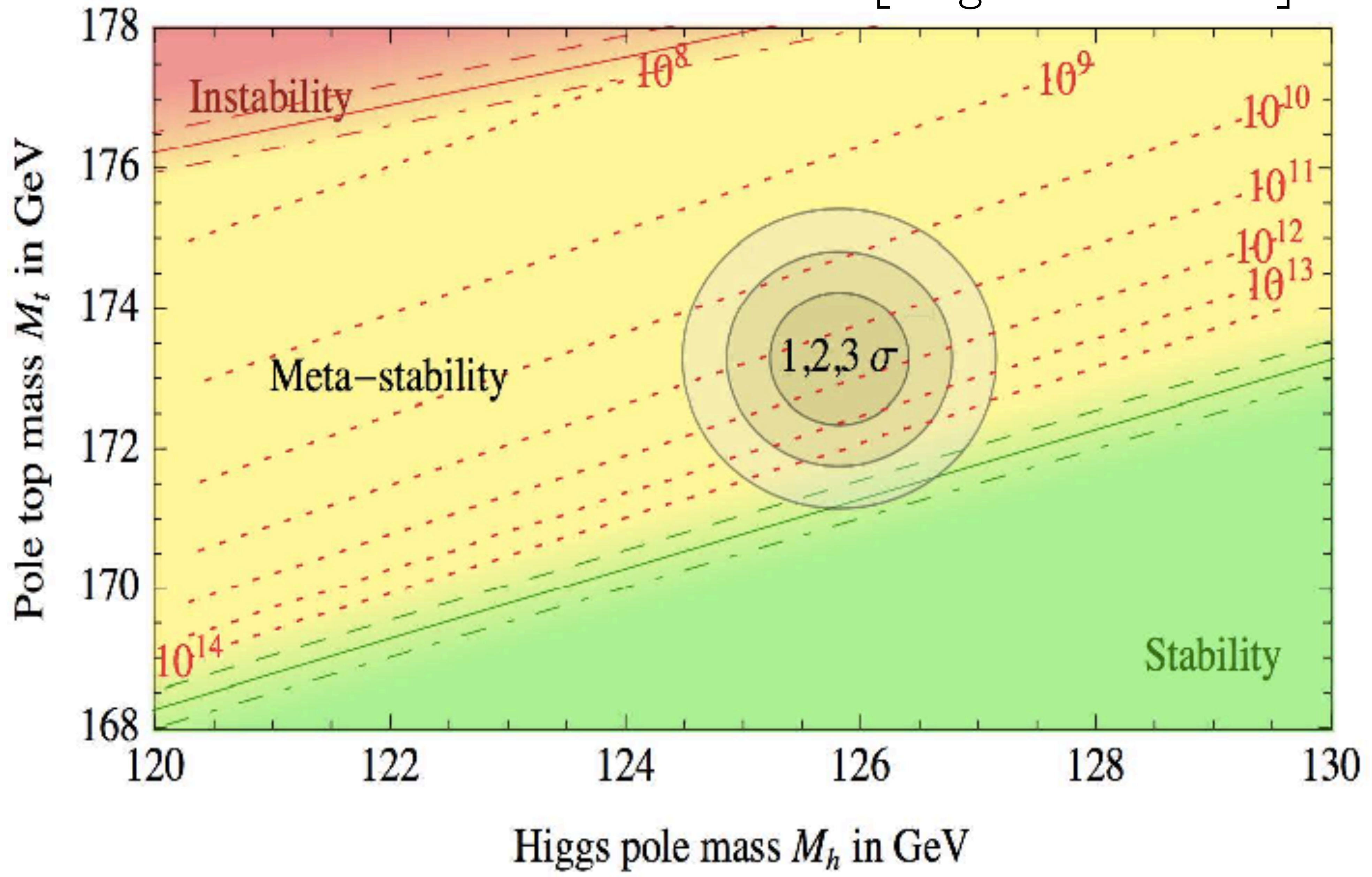
MEPS@NLO QCD+EW_{virt} 0,1jets merged [Gütschow, JML, Schönherr,'18]



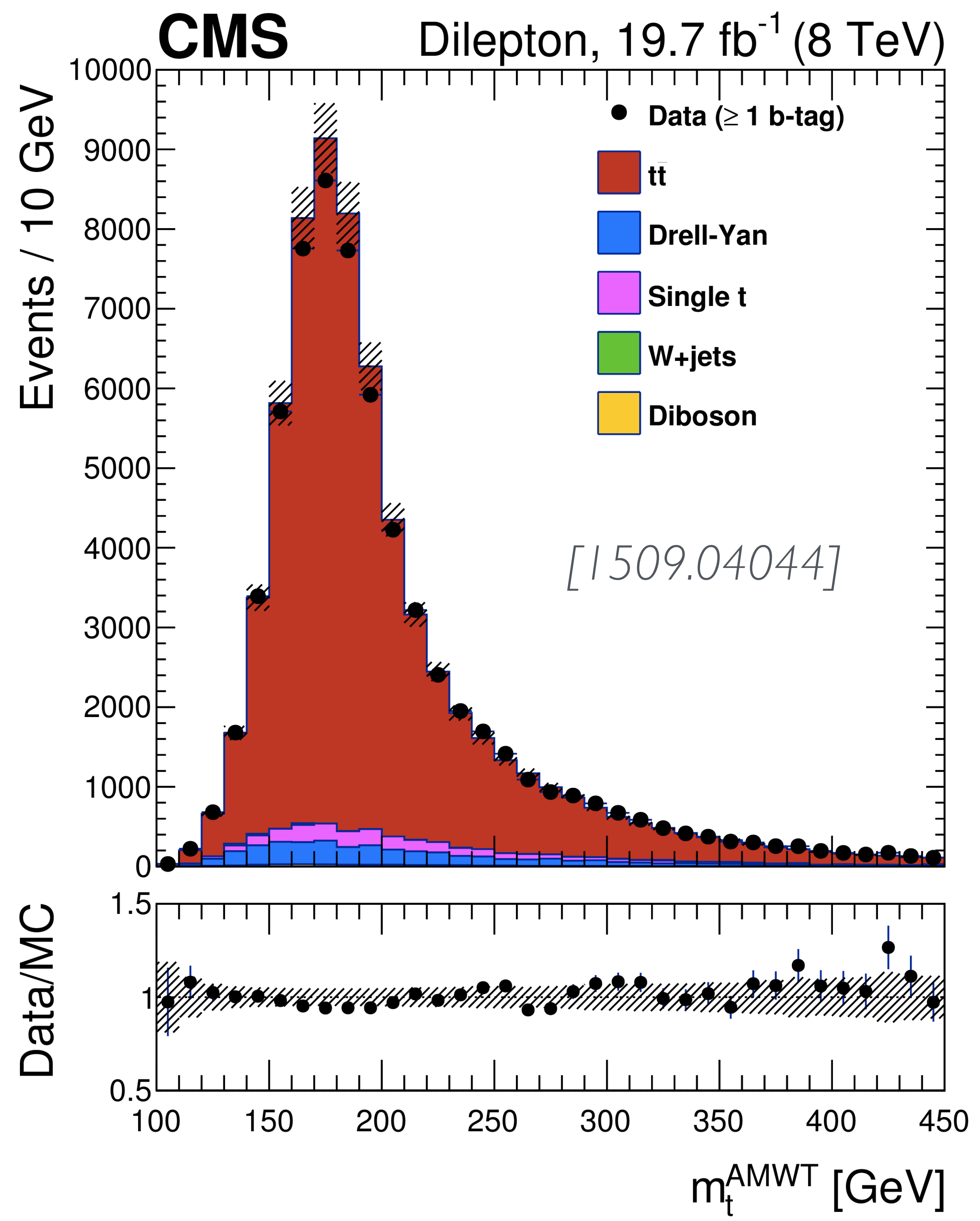


Top-mass

[Degrassi et. al. '12]



reconstruction using analytical distributions derived from simulated samples

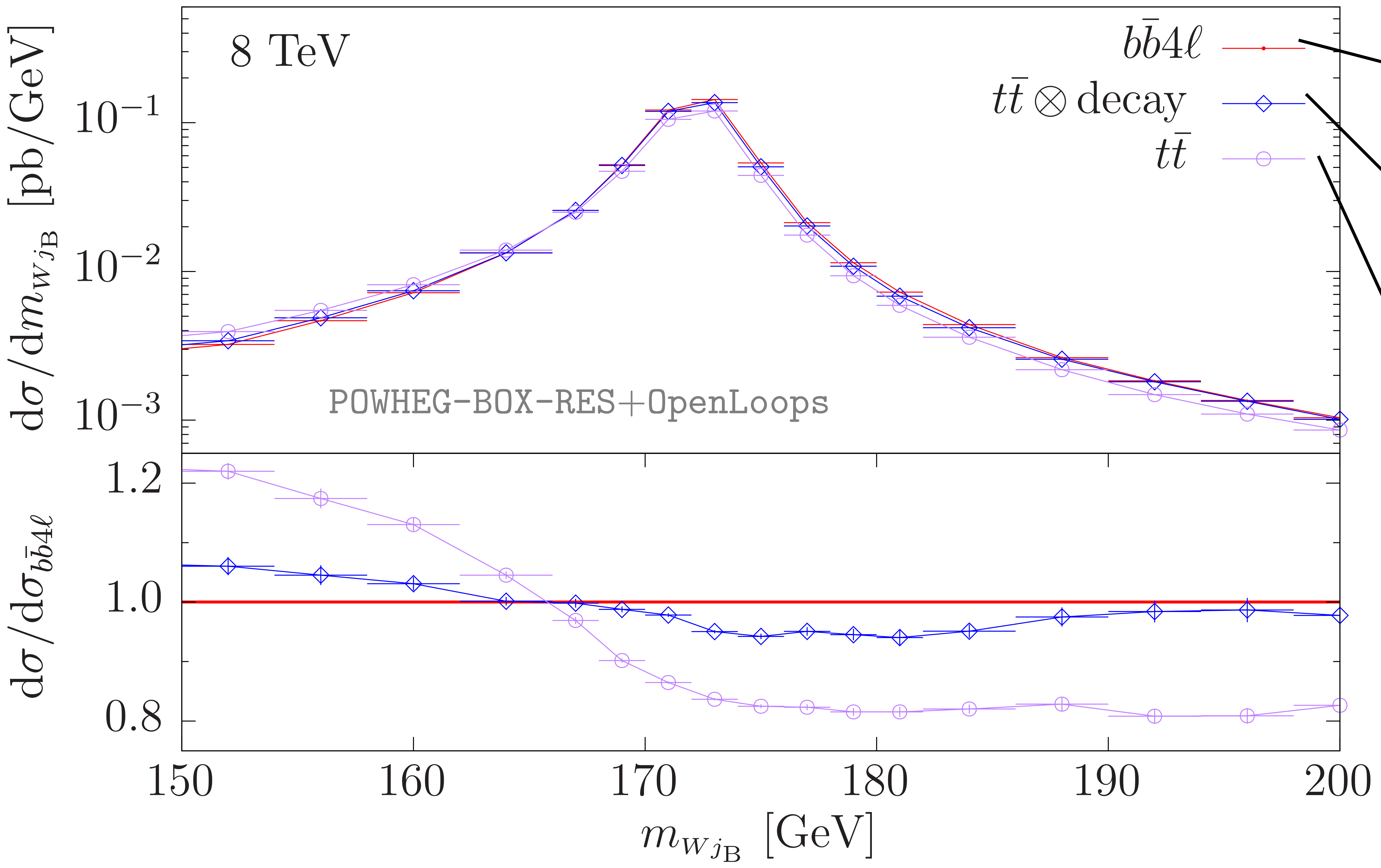


mtop = 172.82 ± 0.19 (stat) ± 1.22 (syst) GeV

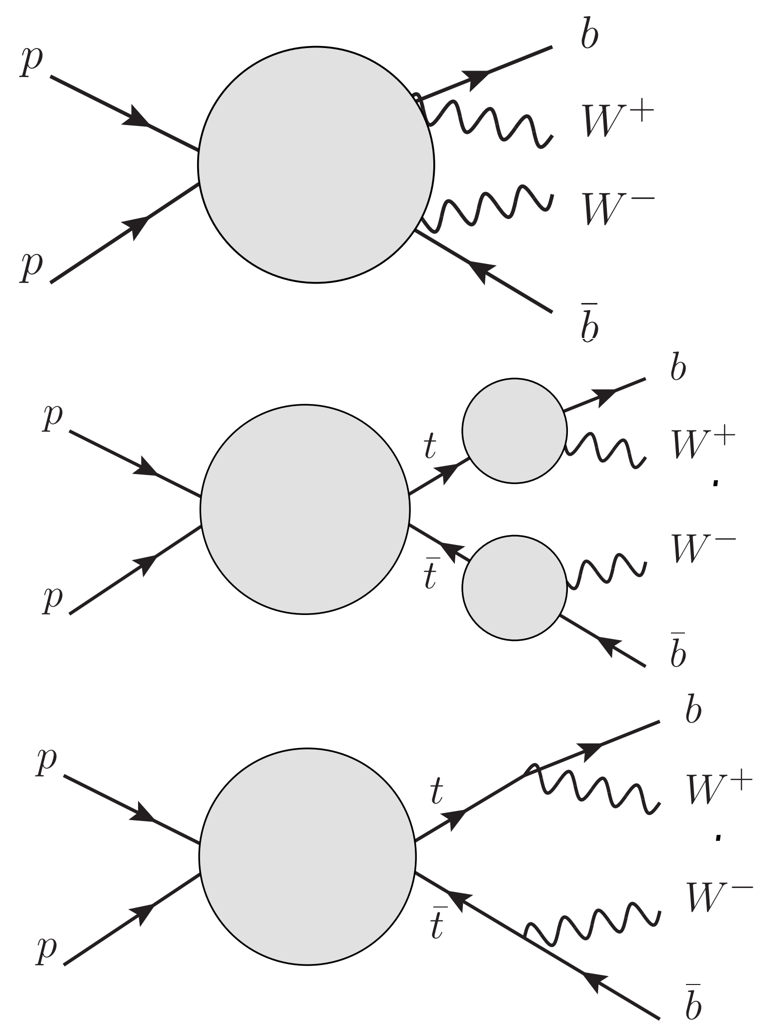
- precise value of top mass crucial for stability of EW vacuum

- kinematic measurements strongly rely on MC modelling!
- these are based on on-shell tt production @ NLO + LO decays
- what about **NLO in decay and off-shell effects**?

Reconstructed top-quark mass at NLO+PS



Different level of precision in top decays:



[Ježo, JML, Nason, Oleari, Pozzorini; '16]

[Campbell, Ellis, Nason, Re; '15]

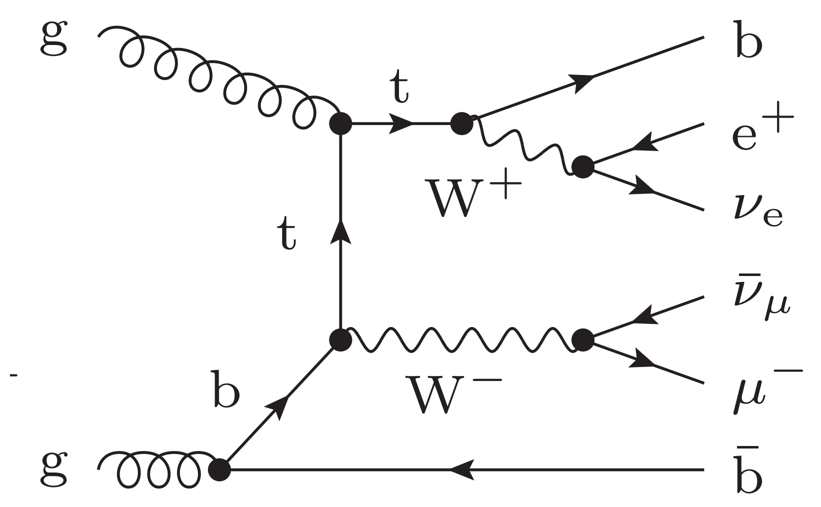
[Frixione, Nason, Ridolfi; '07]

- significant shape distortions around resonance with respect to on-shell $t\bar{t}$ calculation
- very relevant for top mass determination
  - ★ **average m_{Wj_B} roughly 500 MeV smaller in on-shell $t\bar{t}$ (in ±30 GeV around mtop)**
- very good agreement (mostly <5%) level between $b\bar{b}4\ell$ and $t\bar{t} \otimes \mathrm{decay}$
  - ✦ **average m_{Wj_B} roughly 100 MeV smaller in tt⊗decay (in ±30 GeV around mtop)**

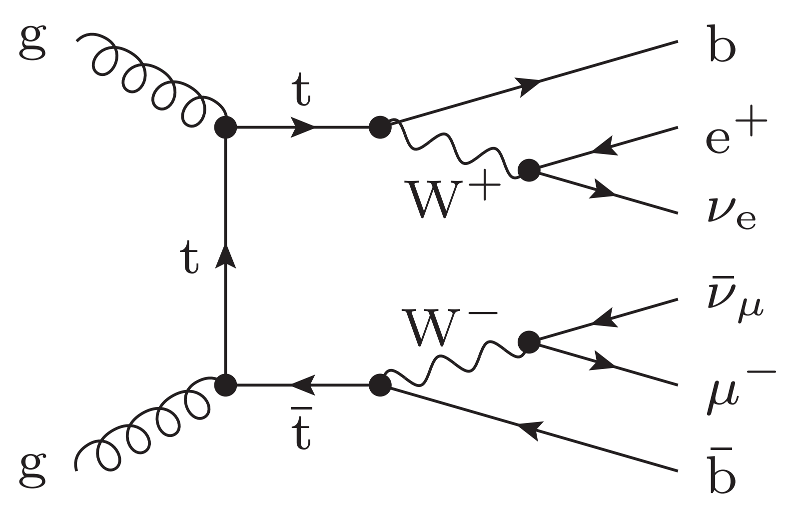
Interplay between top-pair and Wt single-top production

4FS

LO



Wt



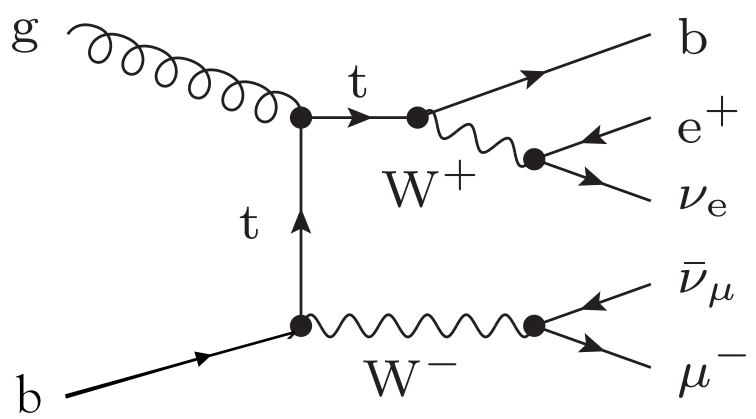
$t\bar{t}$

same finale state!

- **unified treatment of top-pair and Wt including *interference***
- Wt enhanced in phase-space regions where one b becomes unresolved/vetoed
- requires off-shell WWbb calculation (with massive b's)

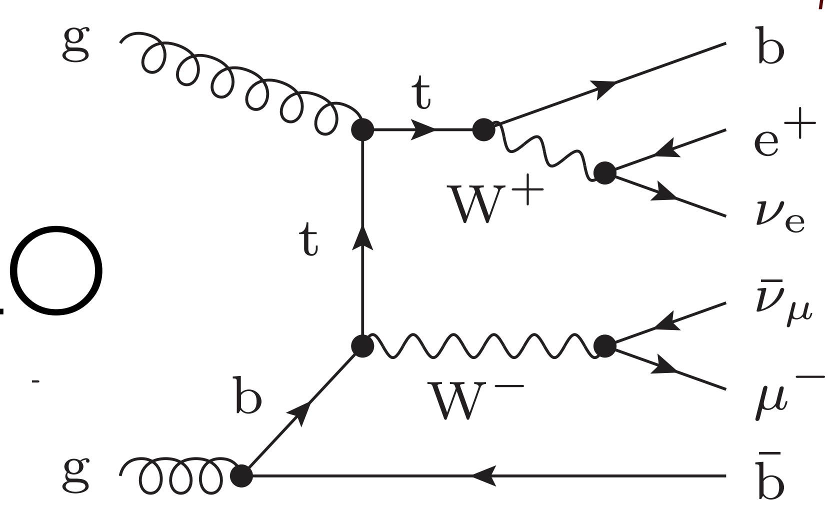
5FS

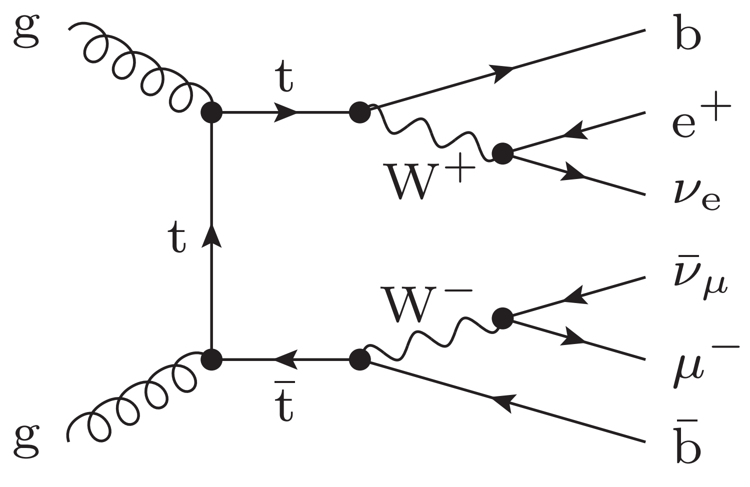
LO

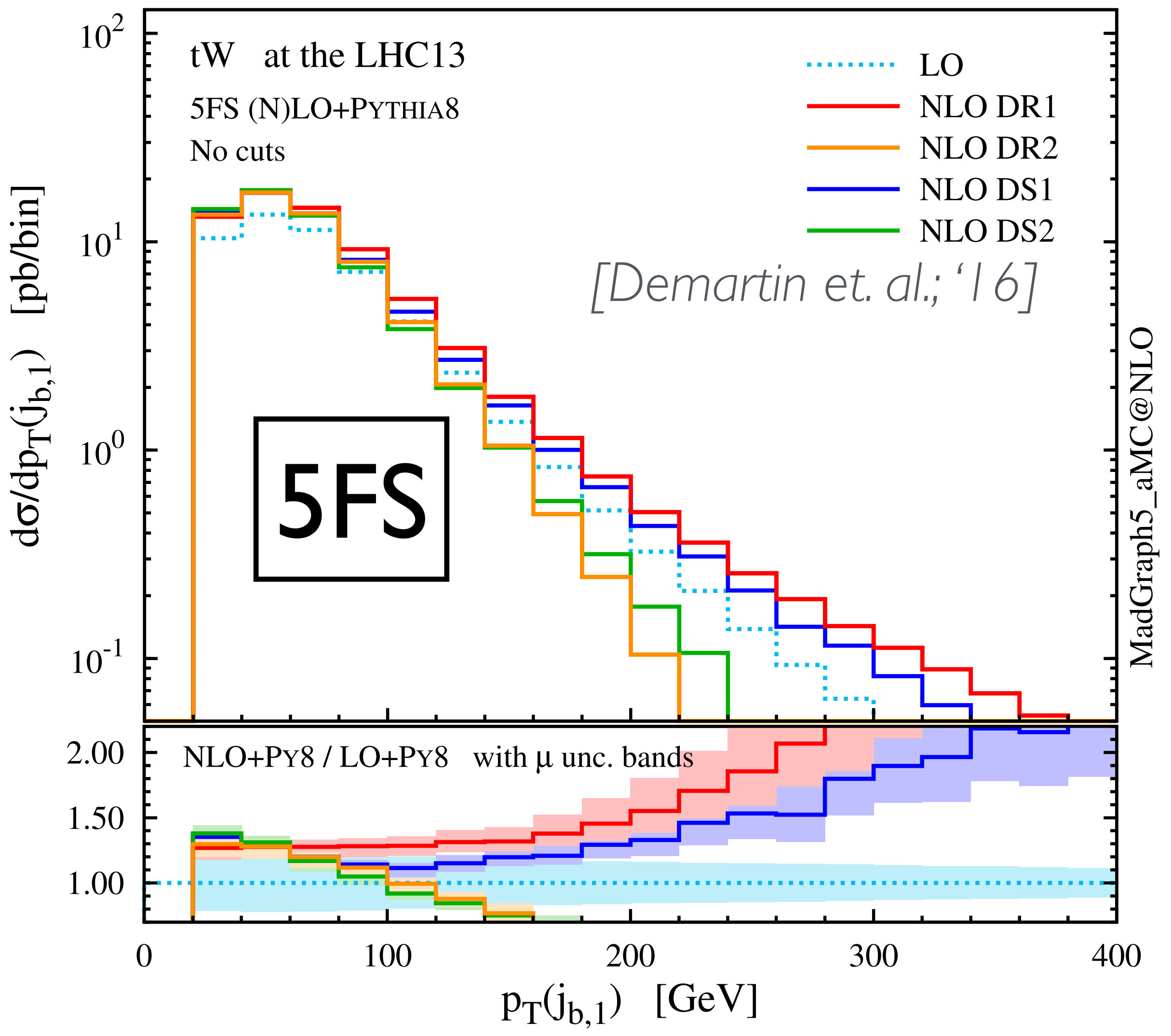


NLO

same finale state!



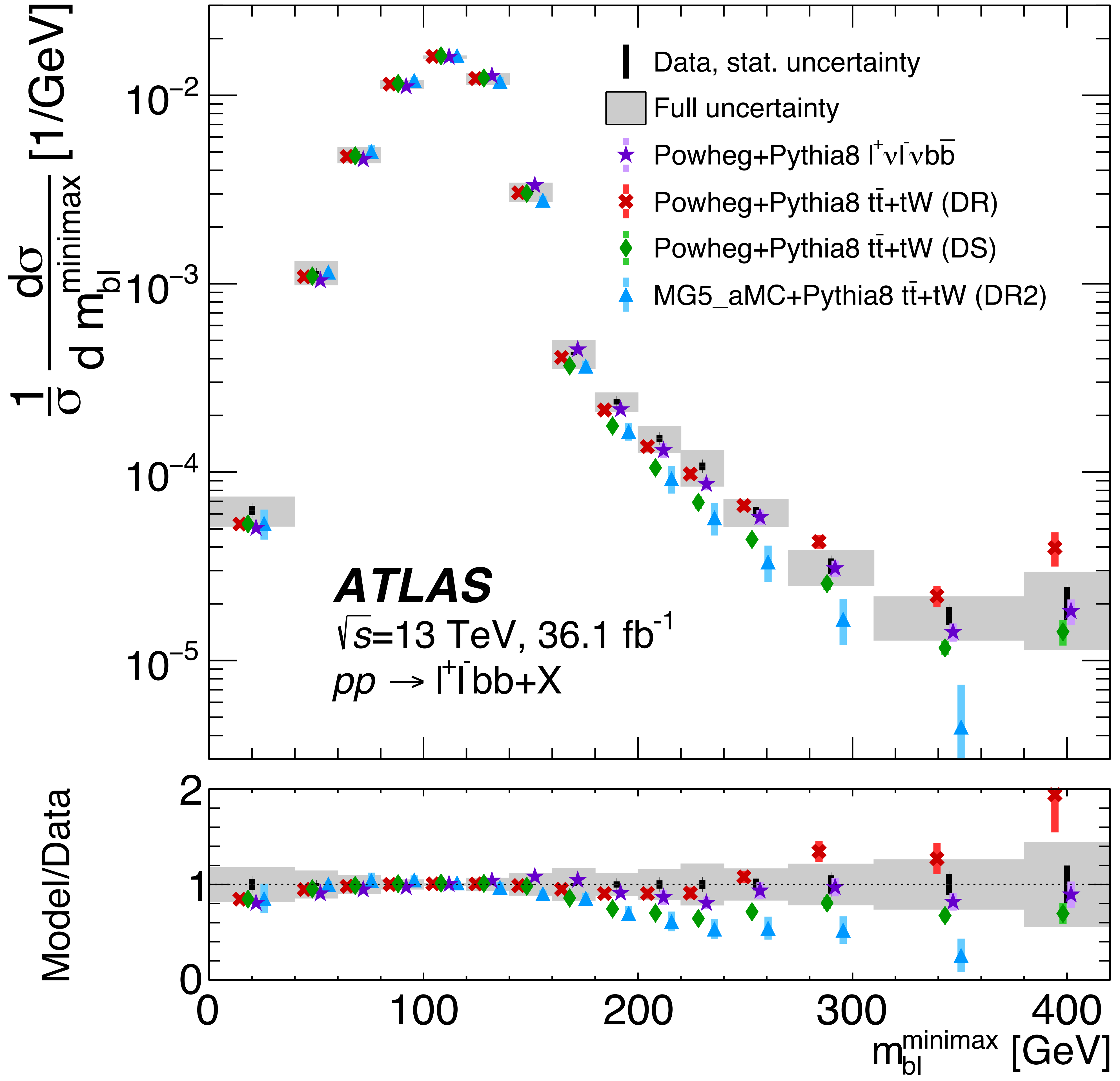




- NLO corrections to Wt swamped by LO $t\bar{t}$ decay
- requires ad-hoc subtraction prescription: DRI, DRII, DSI, DSII
- NLO+PS for Wt available in MC@NLO *[Frixione, et. al.; '08]*, POWHEG *[Re; '11]* and Madgraph_aMC@NLO *[Demartin et. al.; '16]*

Interplay between top-pair and Wt single-top production

[CERN-EP-2018-087]



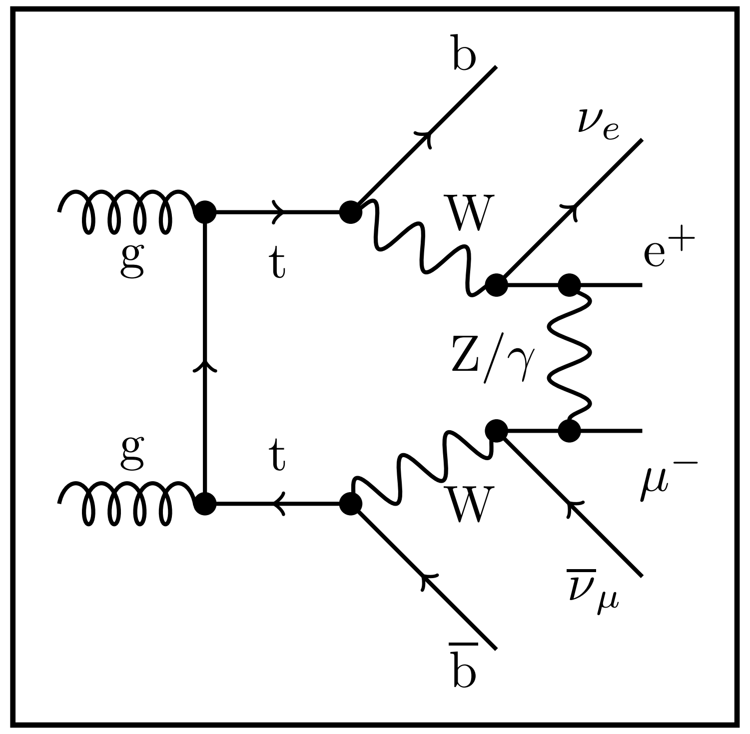
$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

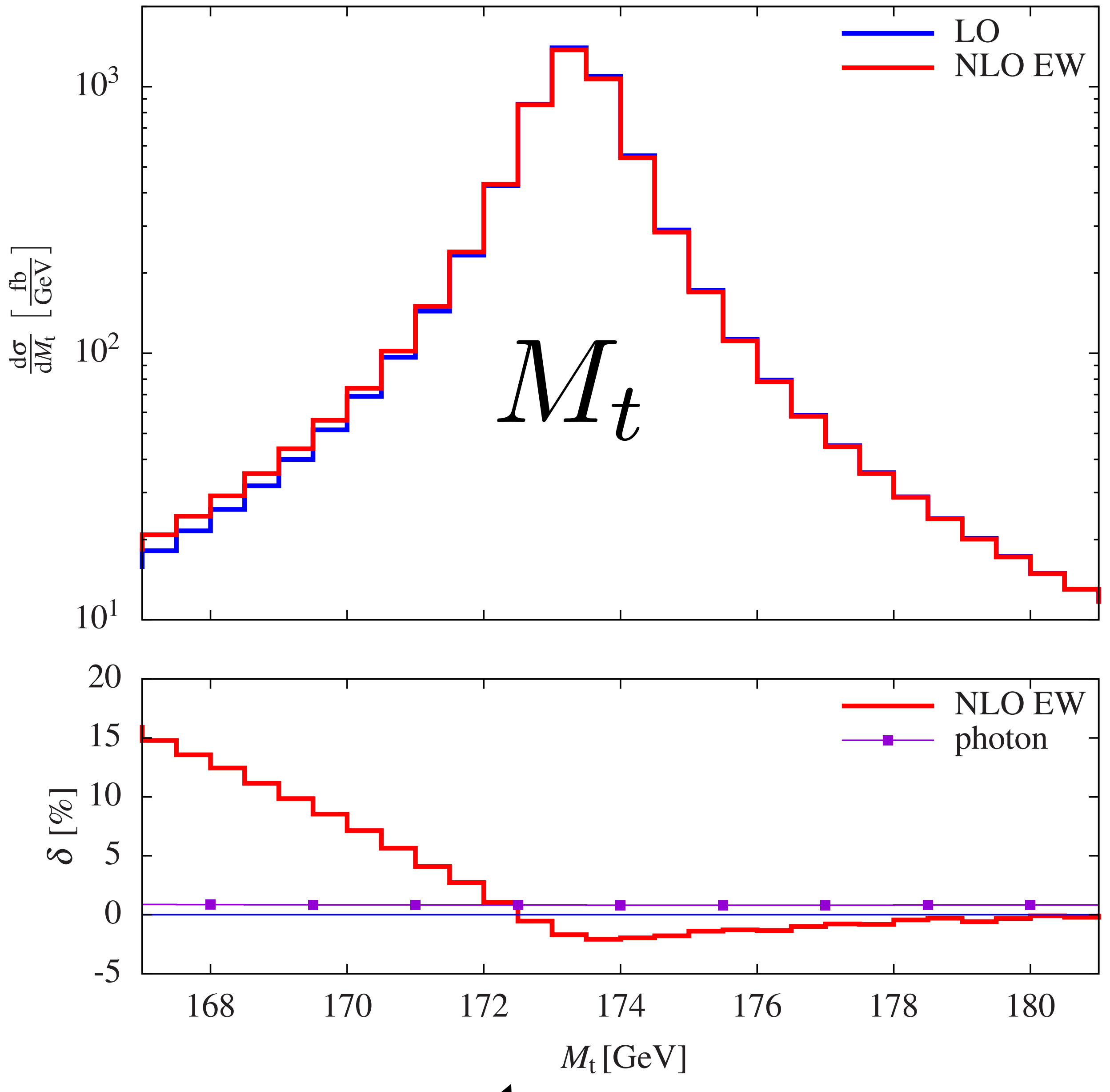
- sizeable tt-Wt interference expected for large $m_{bl}^{minimax}$
- very good data vs. off-shell 4FS agreement
- DR vs. DS yields conservative uncertainty estimate

Top-pair: off-shell NLO EW

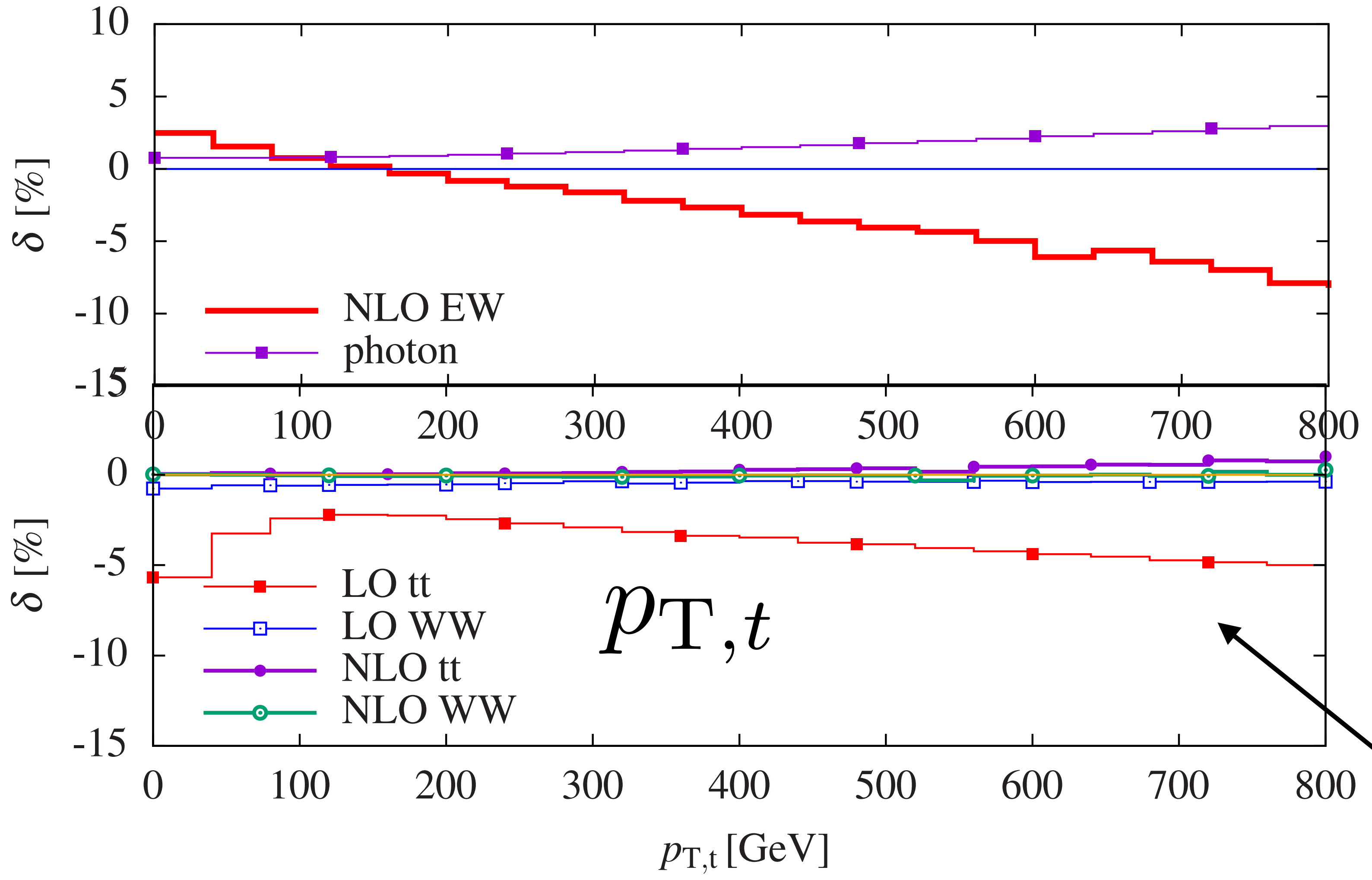
[Denner, Pellen; '16]

Technical challenge: full **2 →6 process**, i.e. pp → $\bar{b}$b e$^+$ν$_e$μ$^-$ν$_\mu$ @ NLO EW (*)



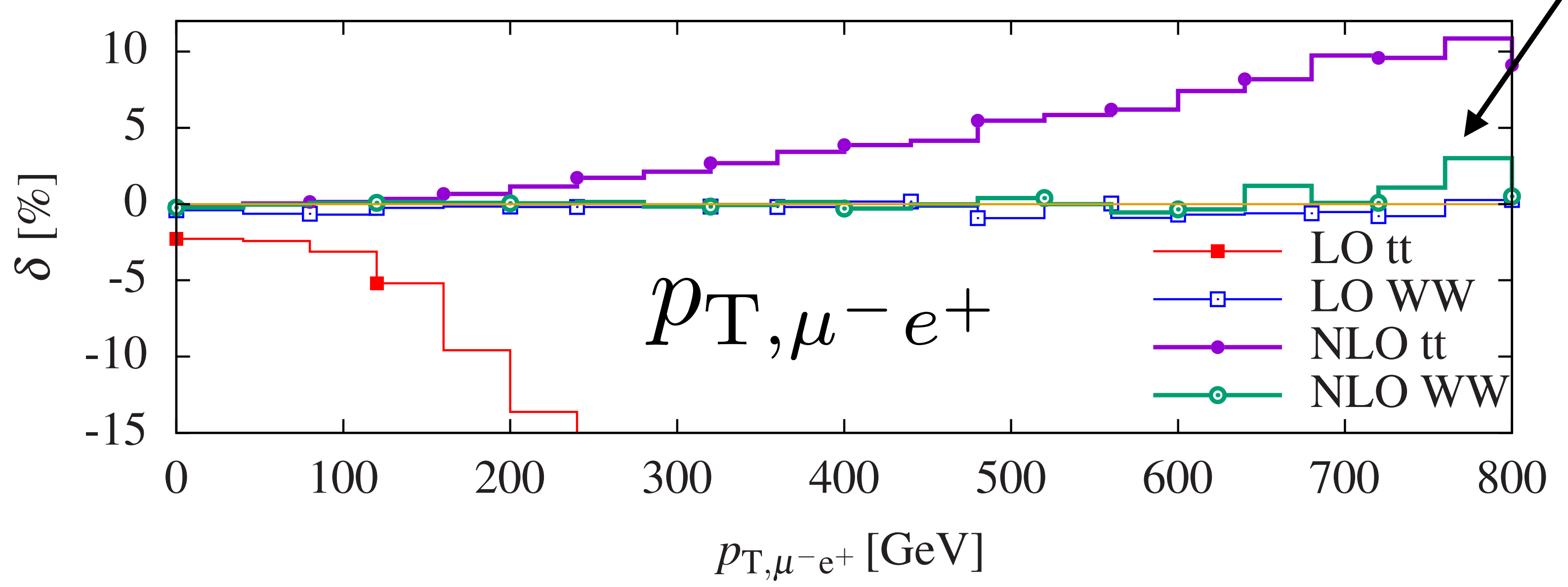


- O(2-5%) around top resonance
- possible relevance for top mass measurements



- typical Sudakov behaviour O(10%) for pT,t = 800 GeV
- LO non-resonant: 5% for pT,t = 800 GeV

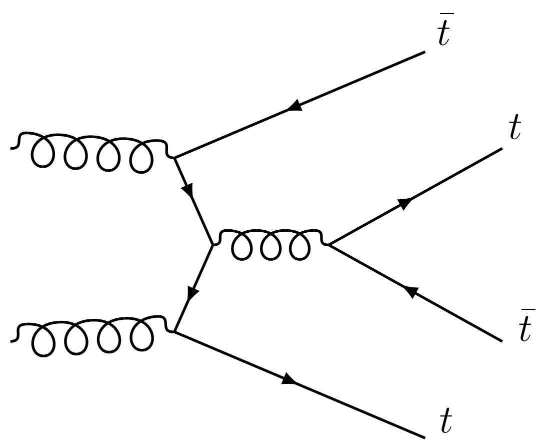
pole approximations/full

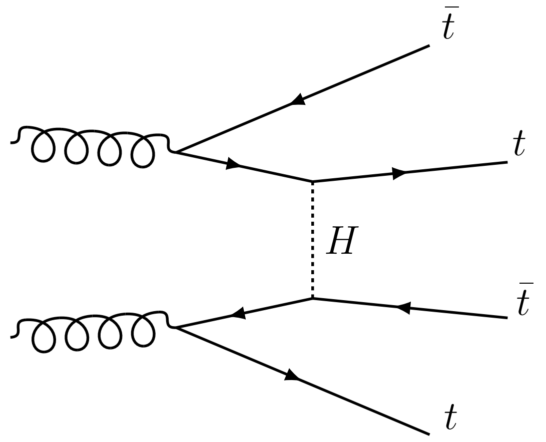


- non-resonant configurations important in various observables!
- well described by WWbb approximation

(*) also: pp → bb e$^+$ν$_e$μ$^-$ν$_\mu$H *[Denner, Lang, Pellen, Uccirati;'16]*

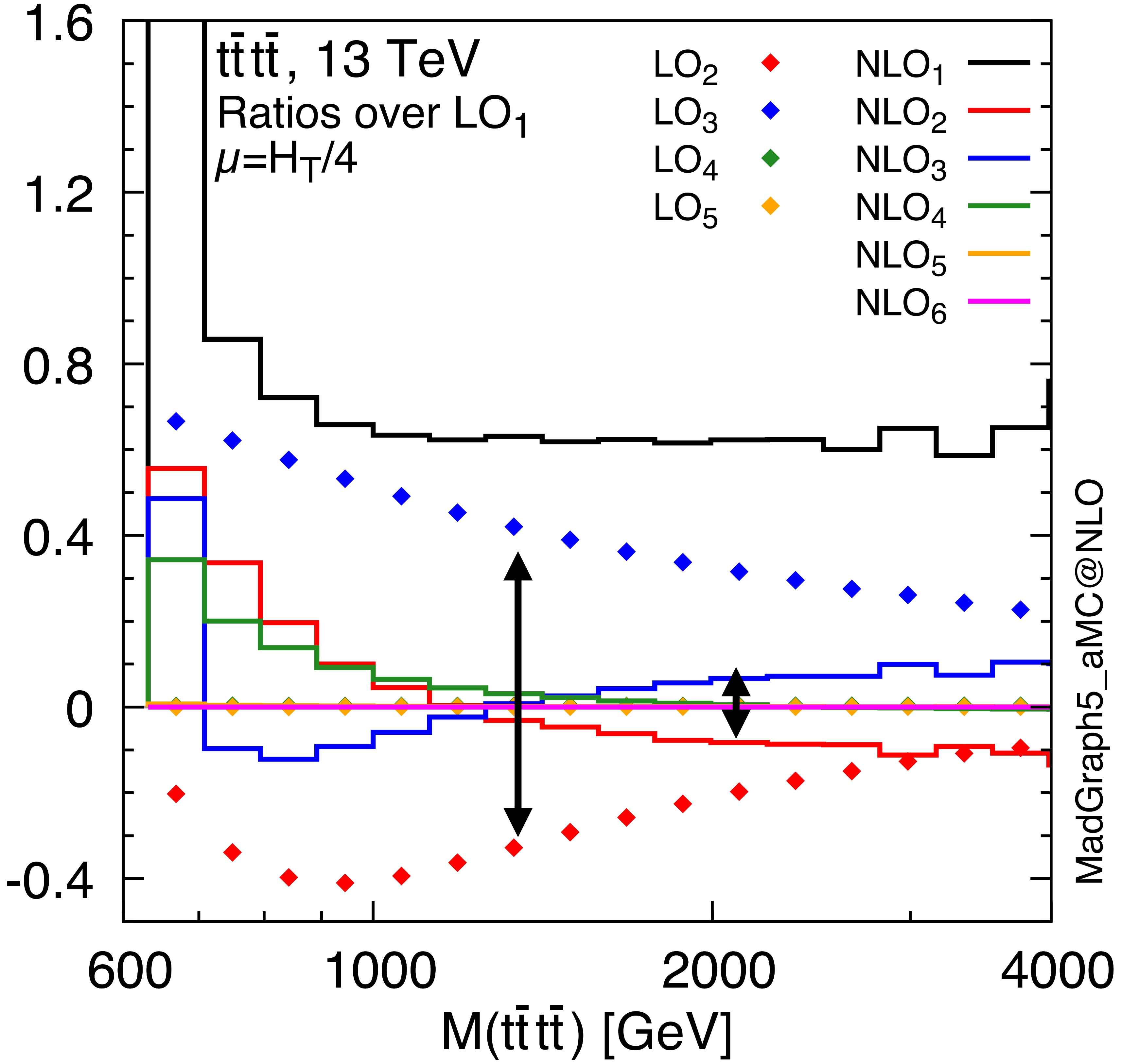
Rare top processes





Motivation:

- Constraining top-quark flavour violation [1804.05598]
- Constraining qqtt operators [1708.05928
- Higgs width and top quark Yukawa coupling [1602.01934]



[Frederix, Pagani, Zaro; '17]

$$\Sigma_{\rm LO}^{t\bar{t}t\bar{t}}(\alpha_s,\alpha) = \alpha_s^4\Sigma_{4,0}^{t\bar{t}t\bar{t}} + \alpha_s^3\alpha\Sigma_{4,1}^{t\bar{t}t\bar{t}} + \alpha_s^2\alpha^2\Sigma_{4,2}^{t\bar{t}t\bar{t}} + \alpha_s^3\alpha\Sigma_{4,3}^{t\bar{t}t\bar{t}} + \alpha^4\Sigma_{4,4}^{t\bar{t}t\bar{t}}$$
$$\equiv \Sigma_{\rm LO_1} + \Sigma_{\rm LO_2} + \Sigma_{\rm LO_3} + \Sigma_{\rm LO_4} + \Sigma_{\rm LO_5}\,.$$

$$\Sigma_{\rm NLO}^{t\bar{t}t\bar{t}}(\alpha_s,\alpha) = \alpha_s^5\Sigma_{5,0}^{t\bar{t}t\bar{t}} + \alpha_s^4\alpha^1\Sigma_{5,1}^{t\bar{t}t\bar{t}} + \alpha_s^3\alpha^2\Sigma_{5,2}^{t\bar{t}t\bar{t}} + \alpha_s^2\alpha^3\Sigma_{5,3}^{t\bar{t}t\bar{t}} + \alpha_s^1\alpha^4\Sigma_{5,4}^{t\bar{t}t\bar{t}} + \alpha^5\Sigma_{5,5}^{t\bar{t}t\bar{t}}$$
$$\equiv \Sigma_{\rm NLO_1} + \Sigma_{\rm NLO_2} + \Sigma_{\rm NLO_3} + \Sigma_{\rm NLO_4} + \Sigma_{\rm NLO_5} + \Sigma_{\rm NLO_6}\,.$$

- Sizeable (accidental) cancellation between different LO and NLO orders
- calculation of only part of the complete-NLO results would be misleading
- cancellation could be spiked by BSM effects

Conclusions

- SM is in excellent shape
- High-precision (Theo + Exp) allows to push limits to unprecedented levels (LHC completes LEP)
- NNLO QCD + NLO EW is the new standard: VV, V+jets, dijets, tt, HV, VBF
- Explore the unknown: **tail, tails, tails!!**

New theoretical, mathematical, and computational concepts ?

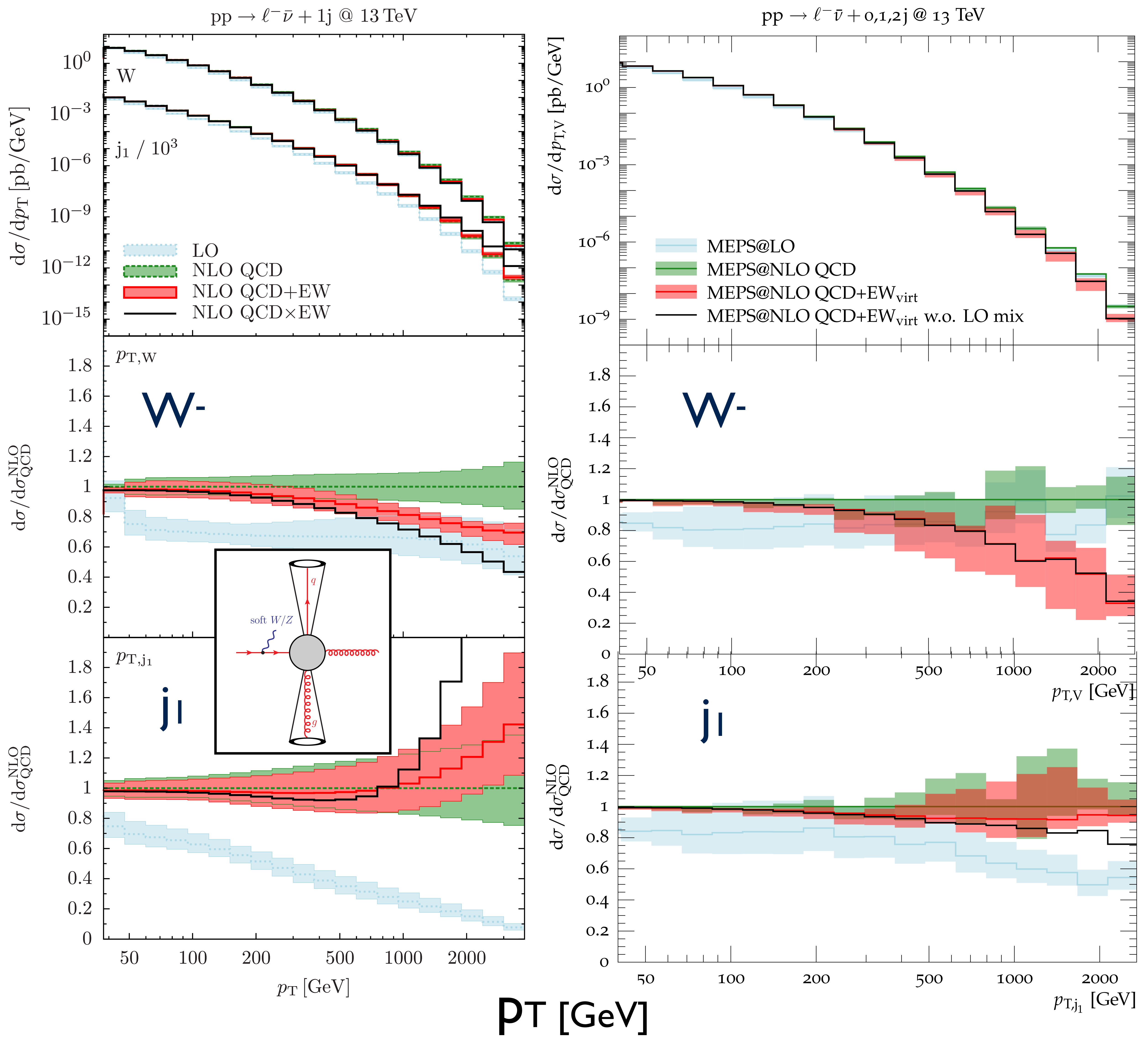
Possible technical developments towards HL/HE-LHC

- NNLO QCD + PS
- PS matching and multi-jet merging @ NLO QCD+EW
- NNLO QCD for 2→3(4)
- NNLO QCDxEW & NNLO EW
- N3LO QCD for 2→2

precision for HL/HE-LHC

Backup

inclusive V: MEPS@NLO QCD+EW$_{\text{virt}}$

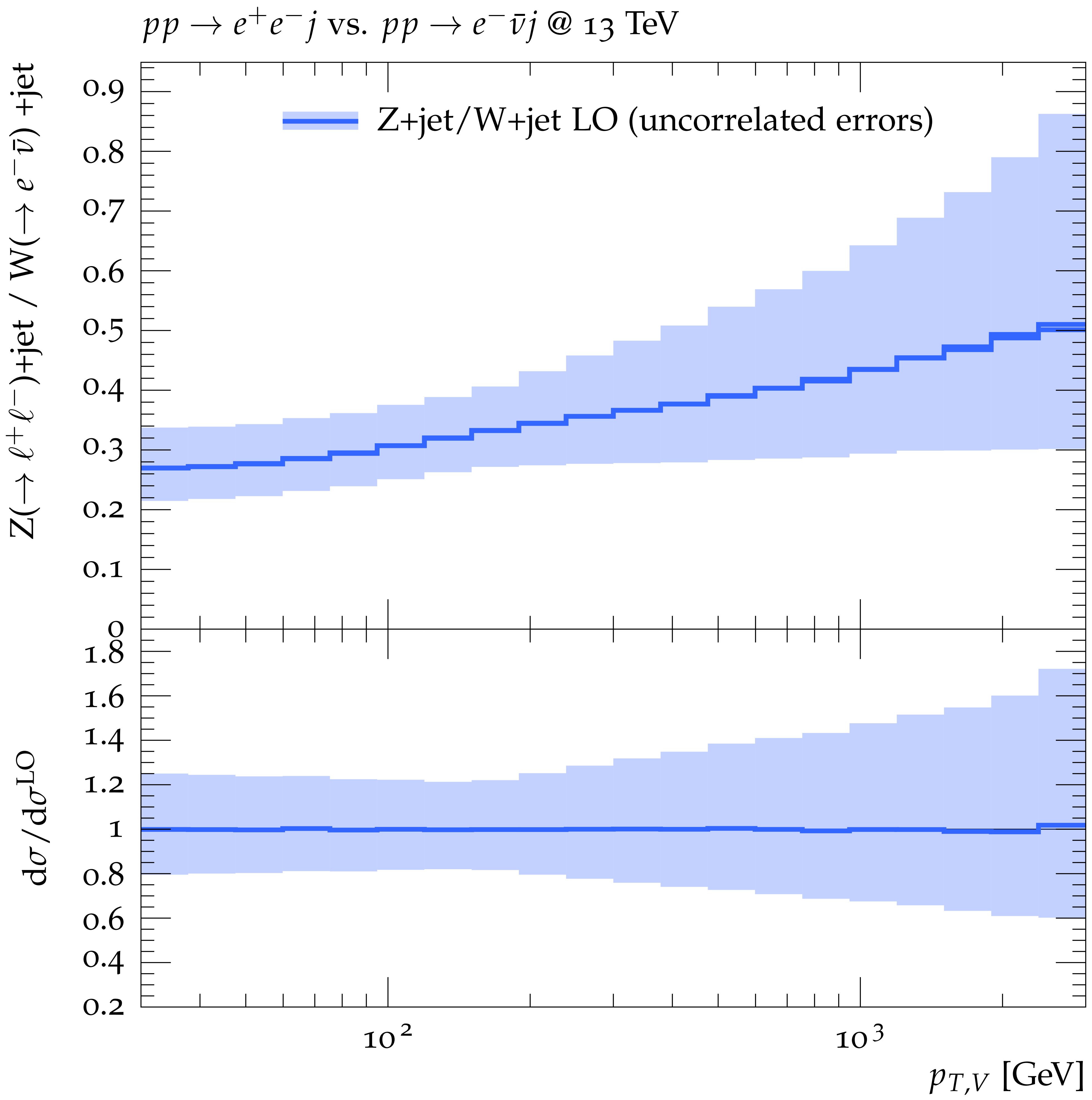


[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]

- Bases on Sherpa's standard MEPS@NLO
- Stable NLO QCD+EW predictions in all of the phase-space…
- …including Parton-Shower effects.
- Can directly be used by the experimental collaborations

- $p_{T,V}$: MEPS@NLO QCD+EW in agreement with QCDxEW (fixed-order)
- $p_{T,j1}$:
  - merging ensures stable results (dijet topology at LO)
  - compensation between negative Sudakov and LO mix

How to correlate QCD uncertainties across processes?

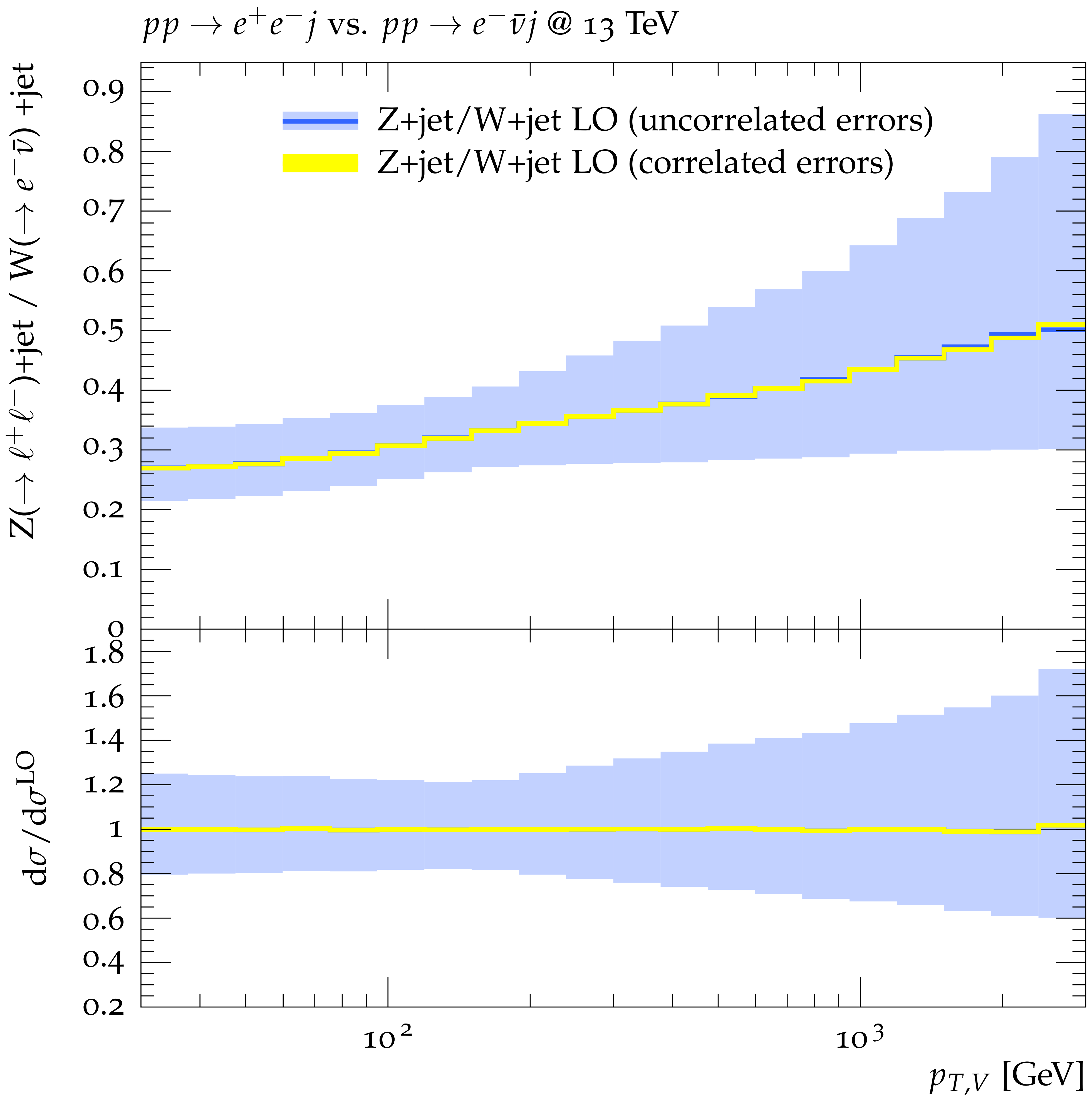


consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

How to correlate QCD uncertainties across processes?

[1705.04664]



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correlated treatment yields tiny O(<~ 1%) uncertainties

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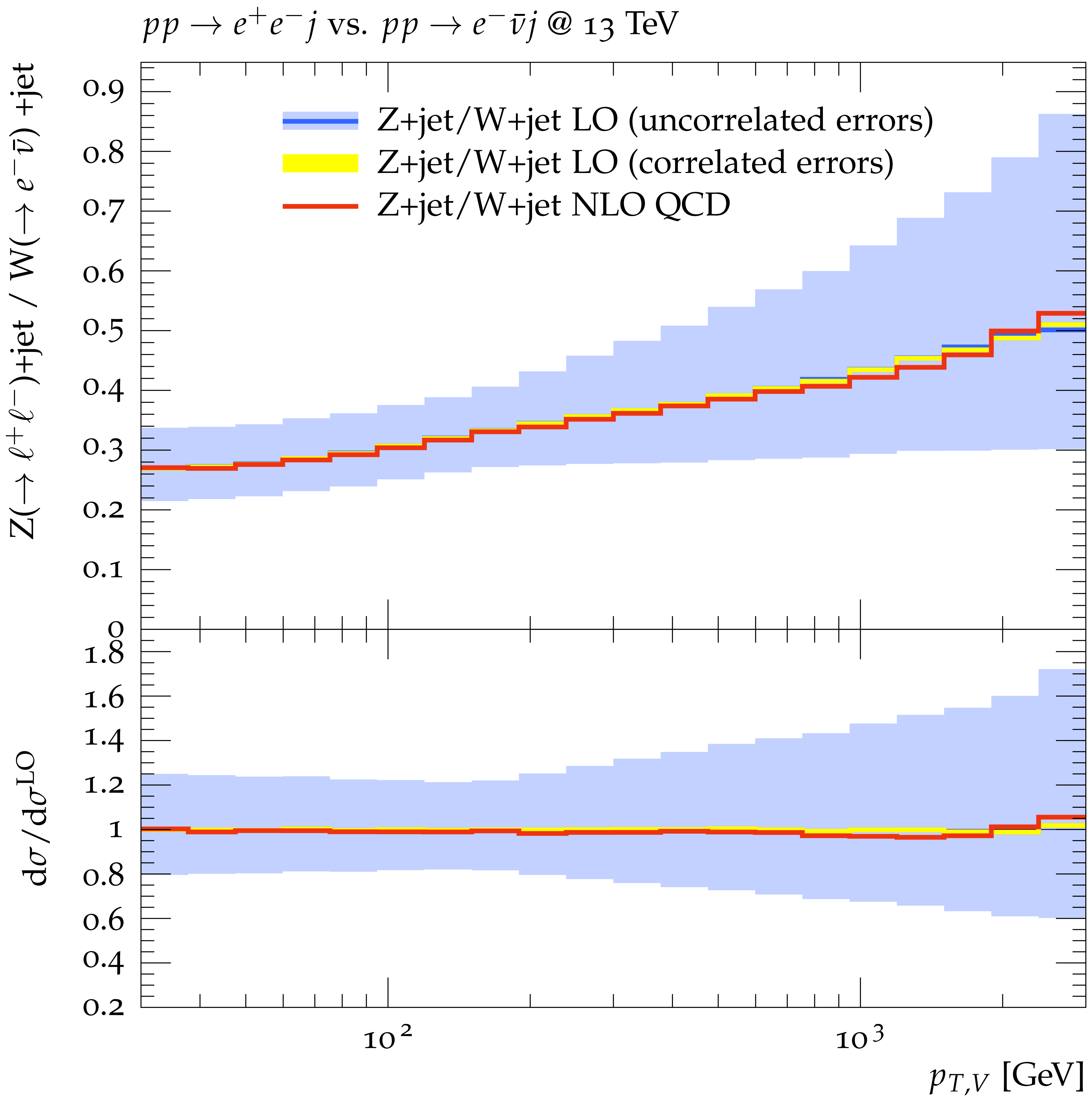

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check against NLO QCD!

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

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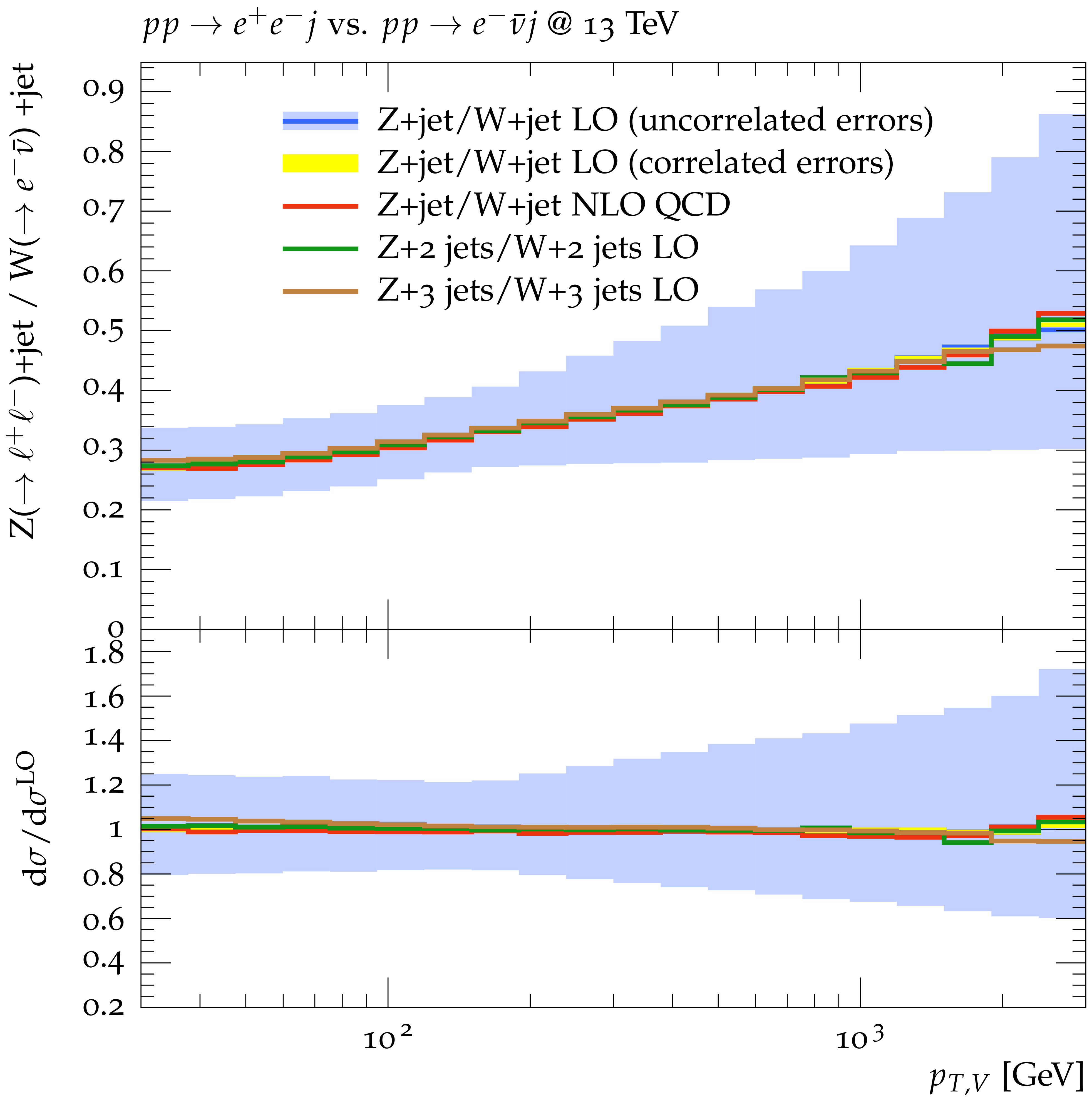
[1705.04664]



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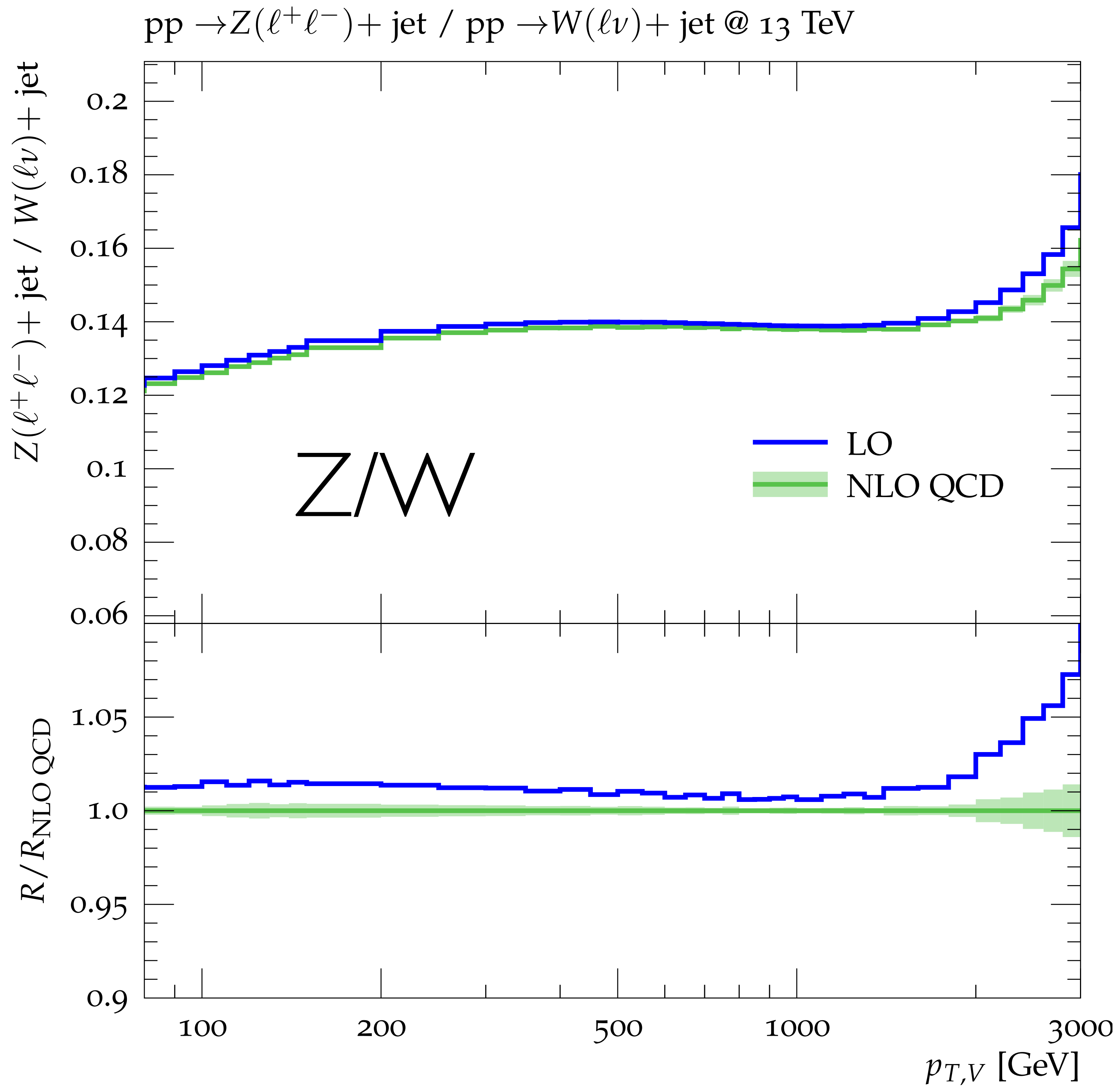
NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!
→ supports correlated treatment of uncertainties!

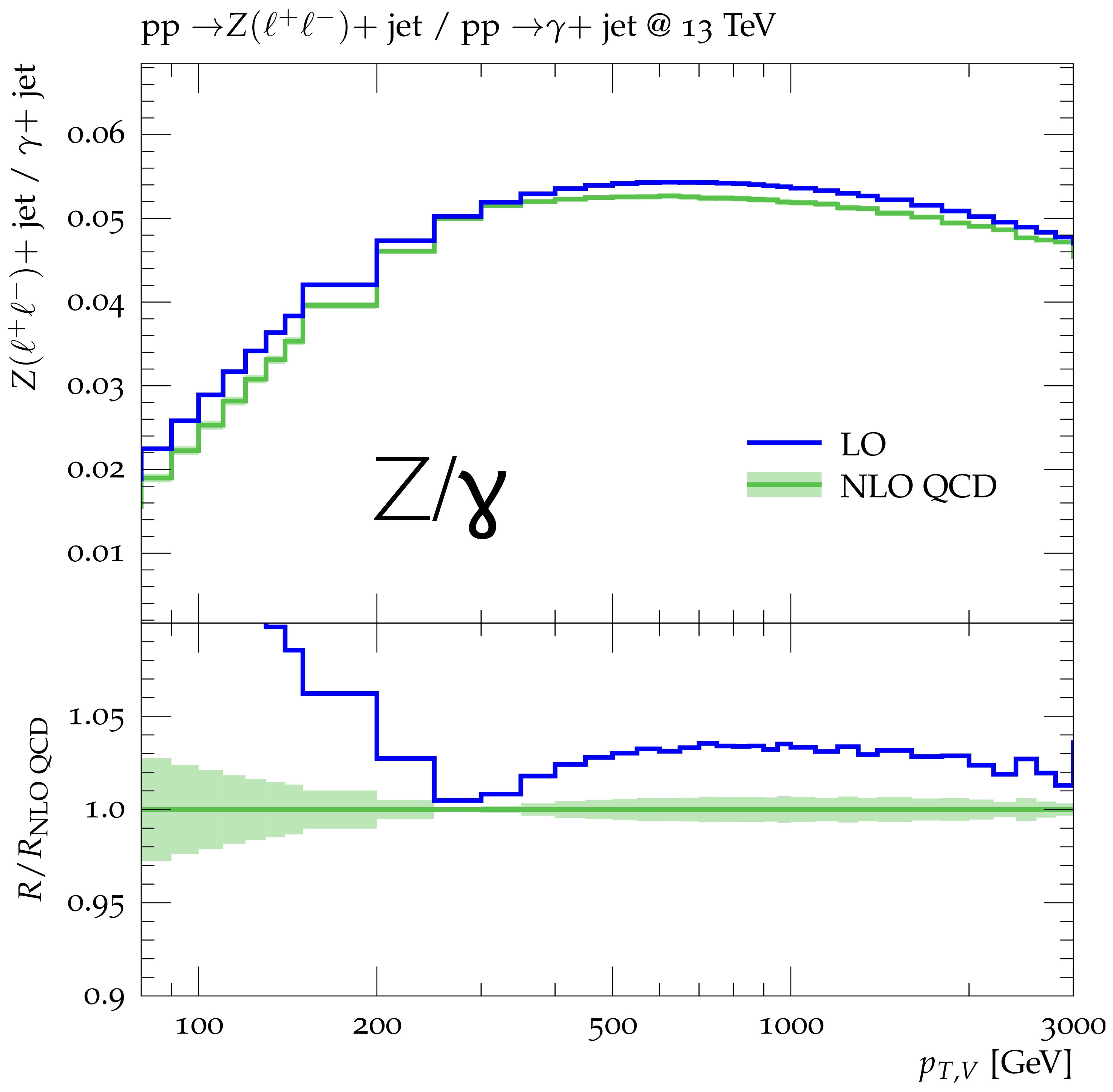
Also holds for higher jet-multiplicities
→ indication of correlation also in higher-order corrections beyond NLO!

QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level

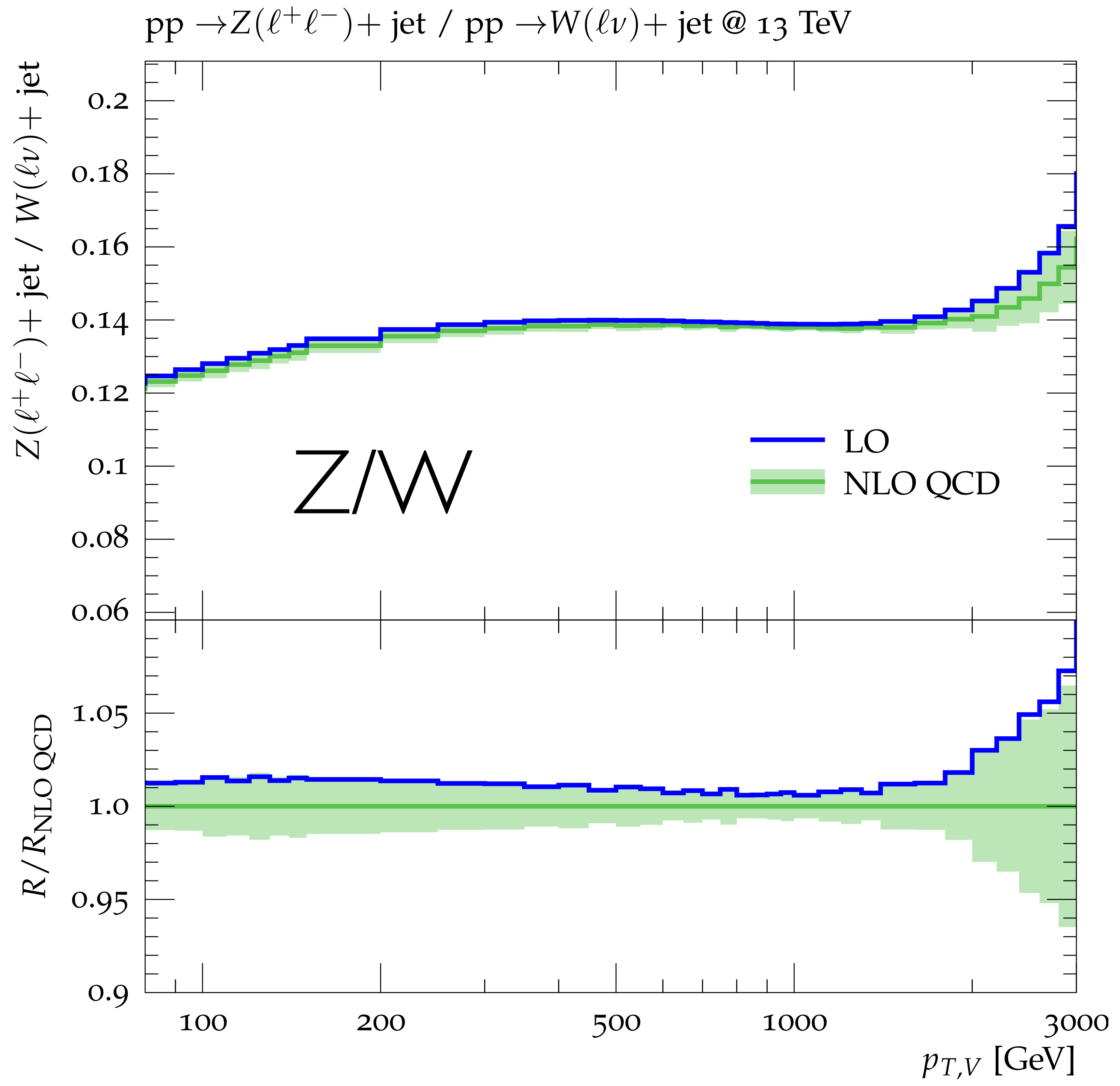


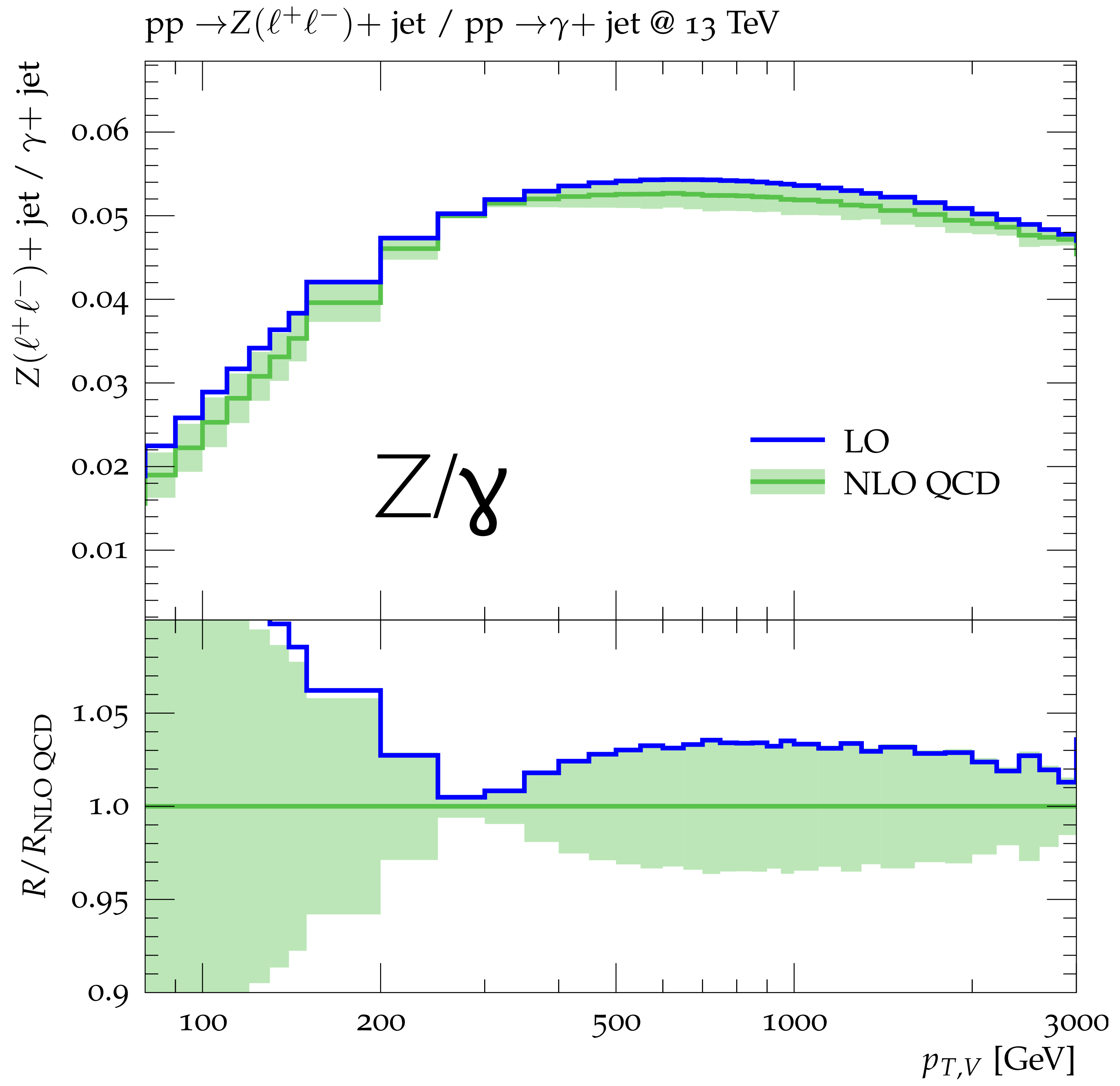


QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level
- introduce **process correlation uncertainty** based on K-factor difference: $\delta K_{\mathrm{NLO}} = K^{V}_{\mathrm{NLO}} - K^{Z}_{\mathrm{NLO}}$
  →effectively degrades precision of last calculated order





δ < 2 %

δ < 3-4 %

QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated: NLO QCD uncertainties cancel at the <~ 1 % level
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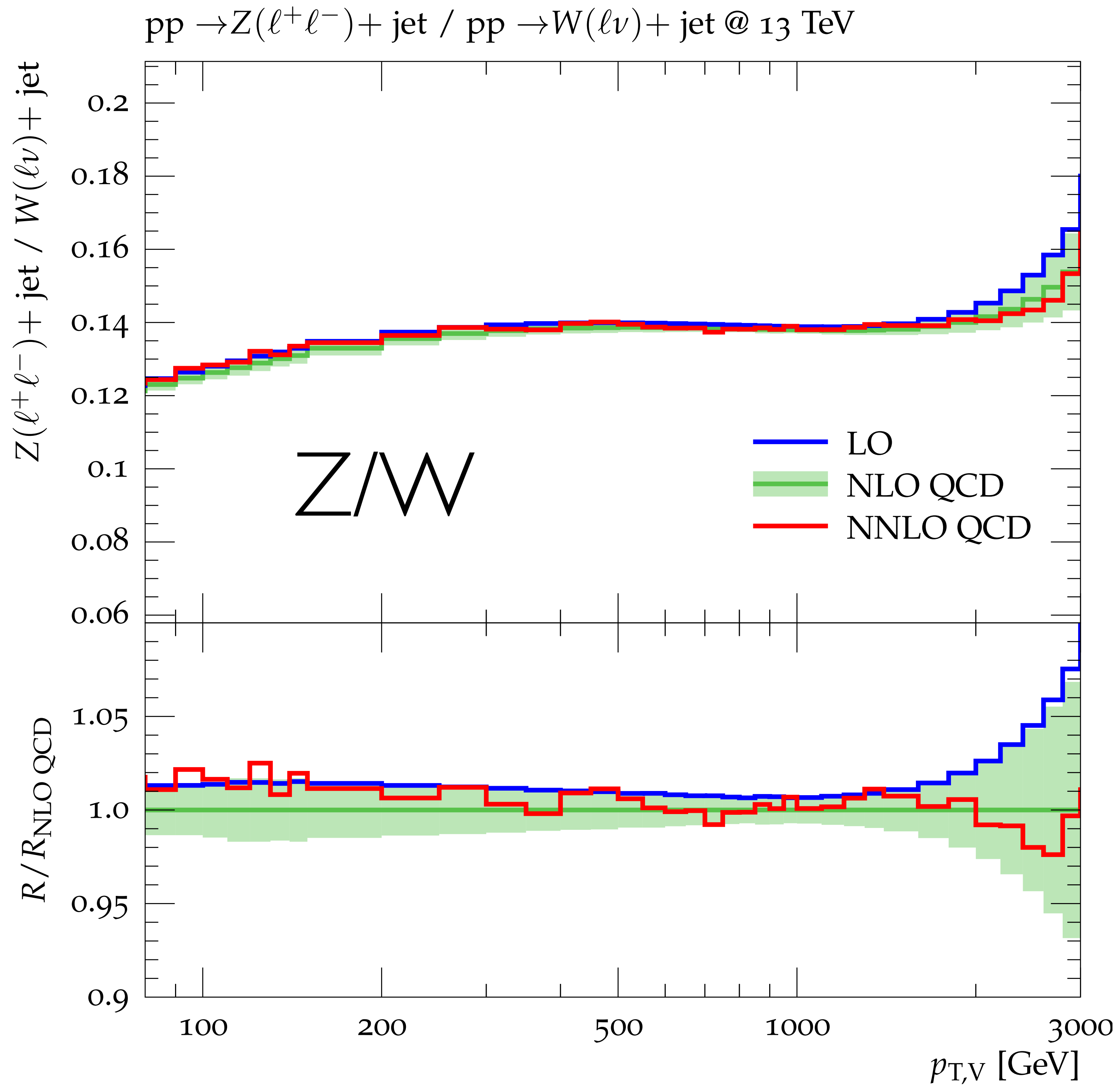
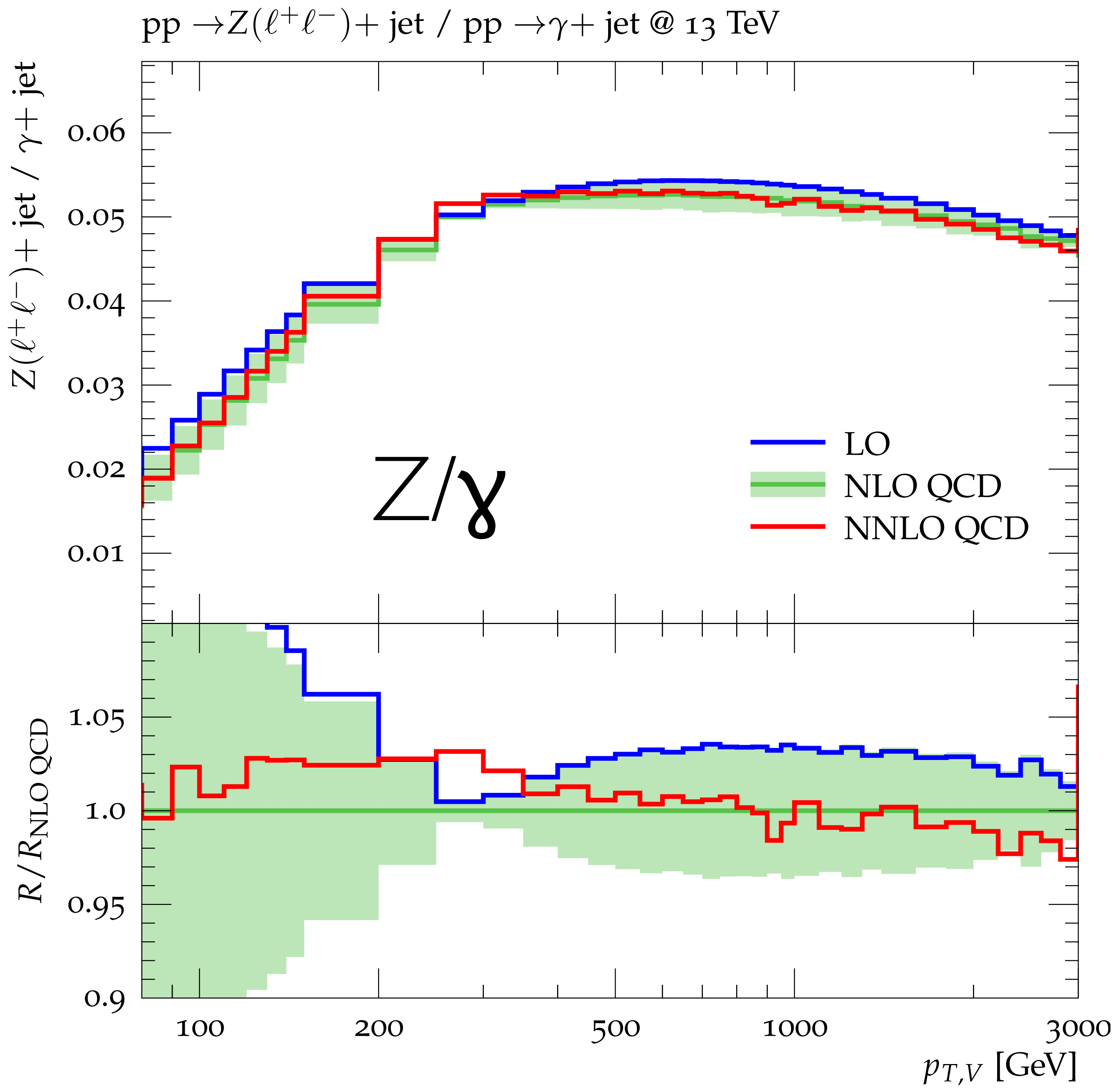


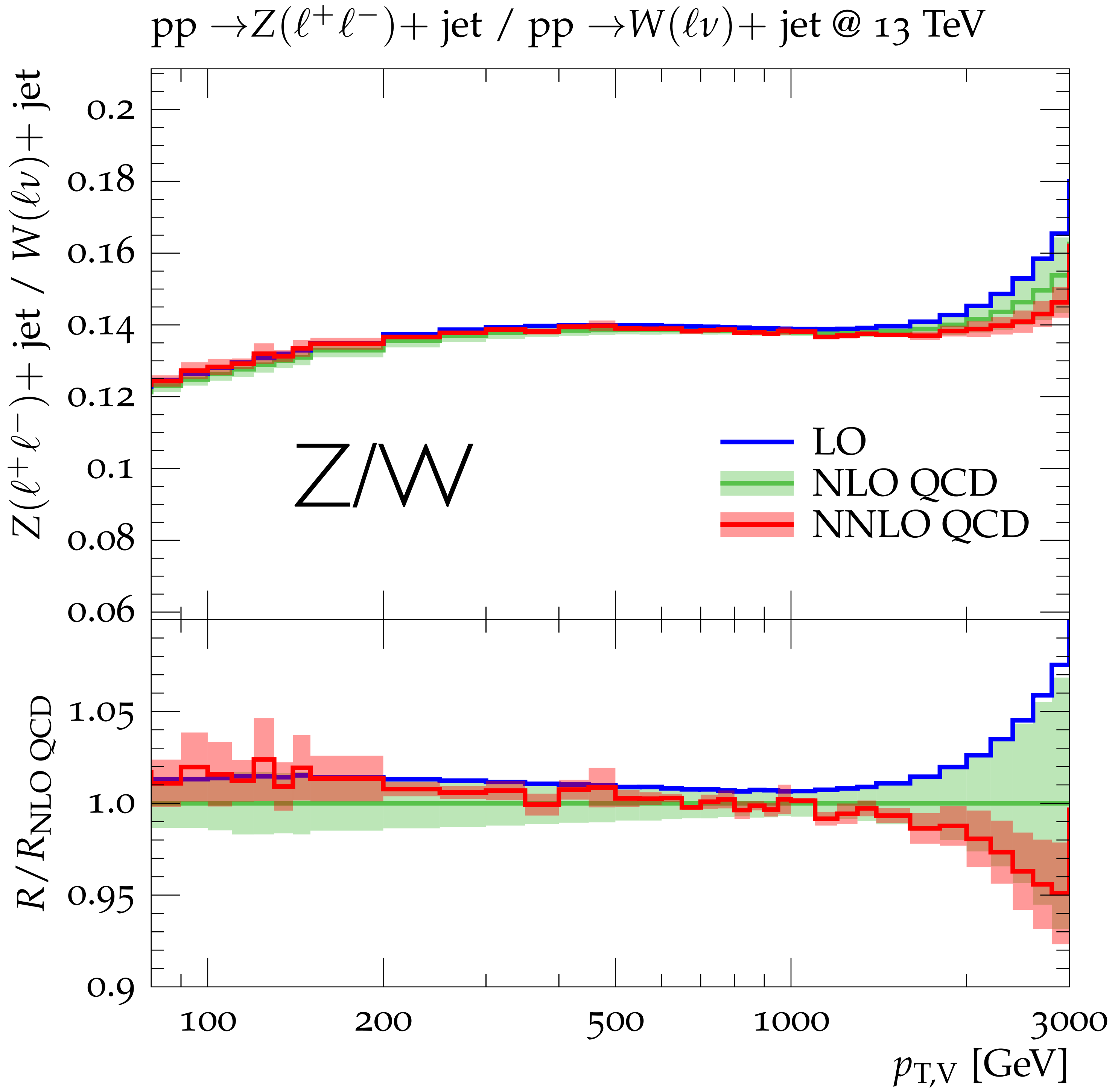


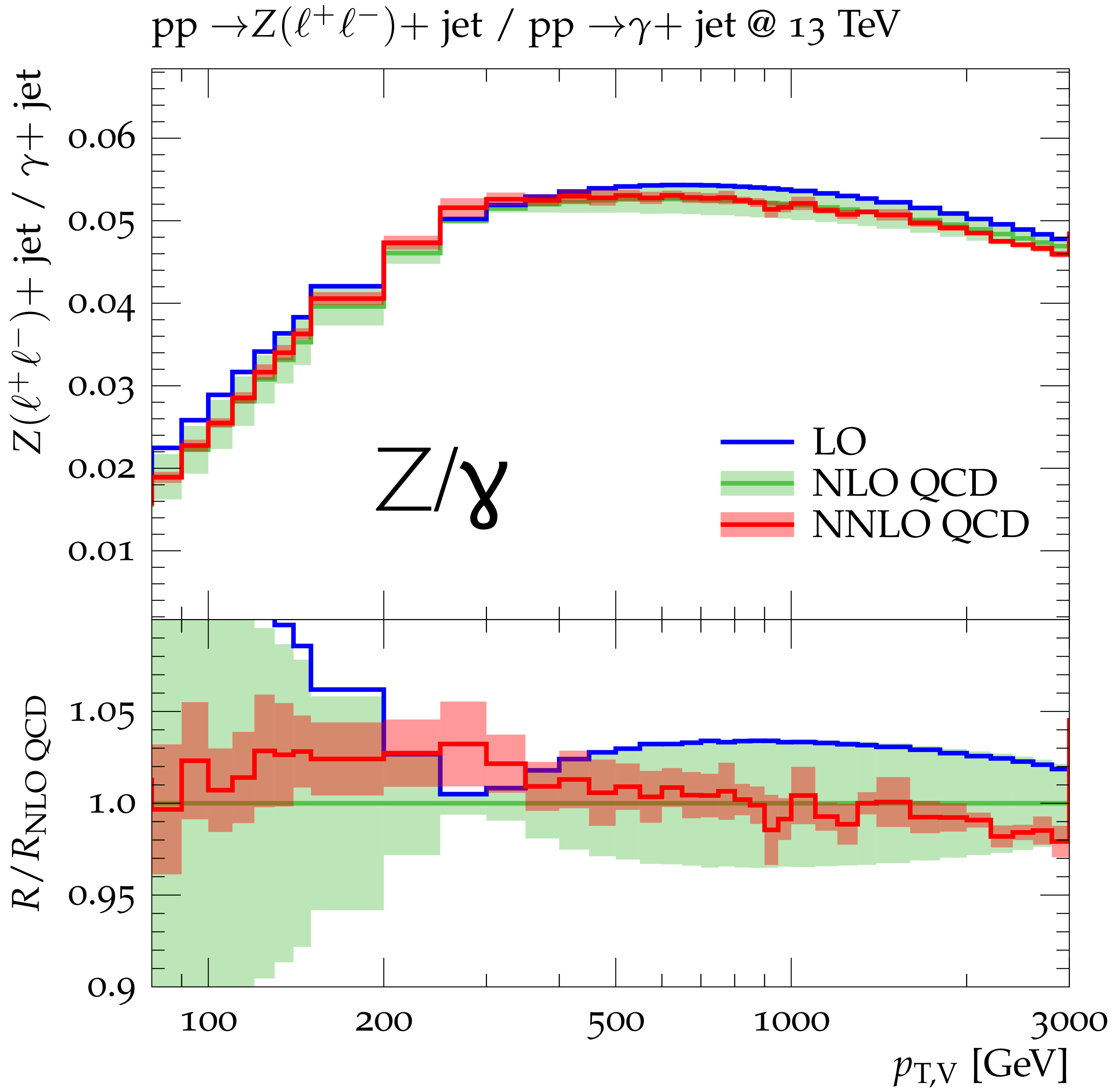
check against NNLO QCD!

QCD uncertainties: ratios

How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated:
  NLO QCD uncertainties cancel at the <~ 1 % level
- introduce **process correlation uncertainty** based on K-factor difference: $\delta K_{\mathrm{(N)NLO}} = K^{V}_{\mathrm{(N)NLO}} - K^{Z}_{\mathrm{(N)NLO}}$
  →effectively degrades precision of last calculated order

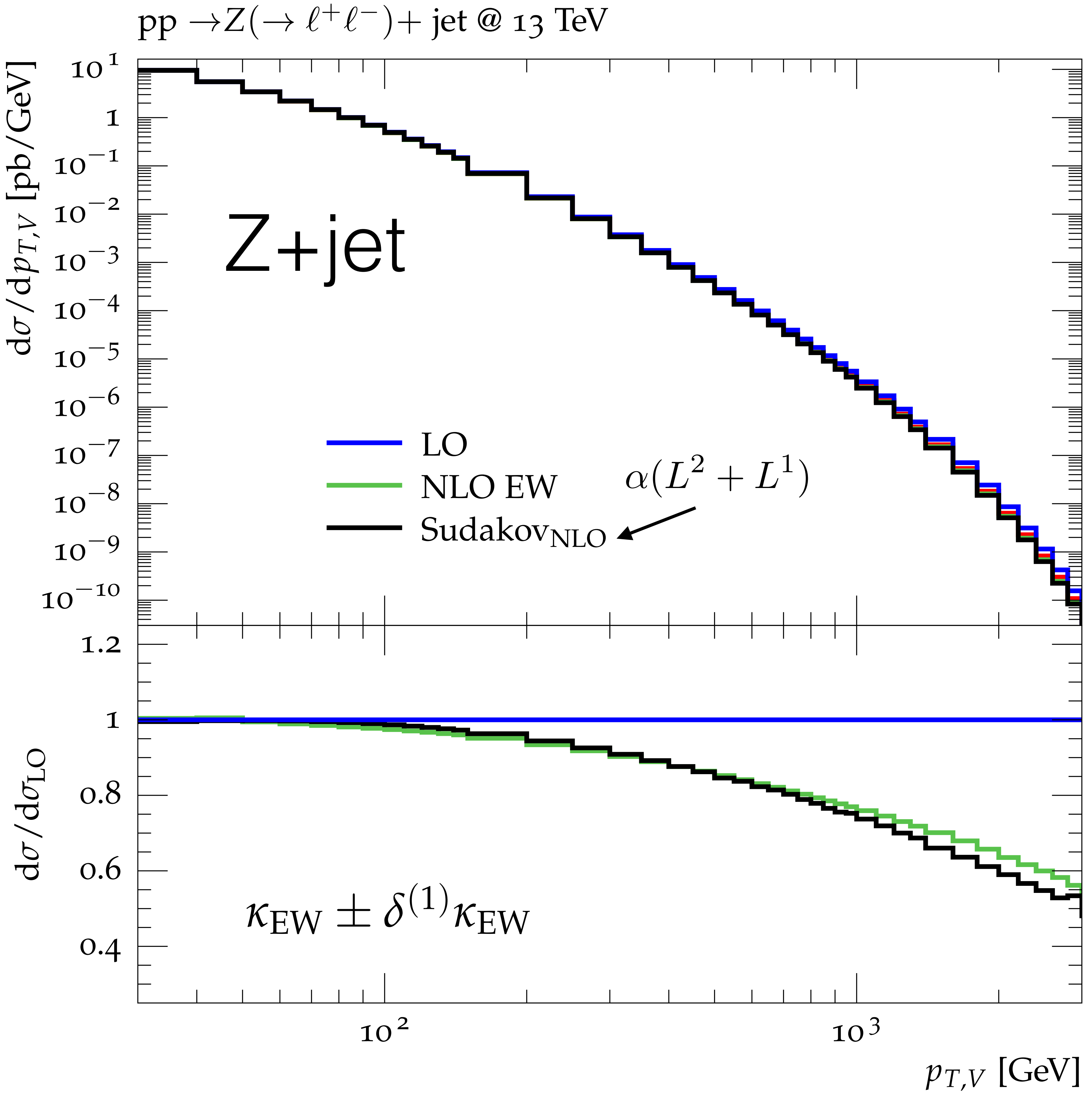




Uncertainty estimates at NNLO QCD

Pure EW uncertainties

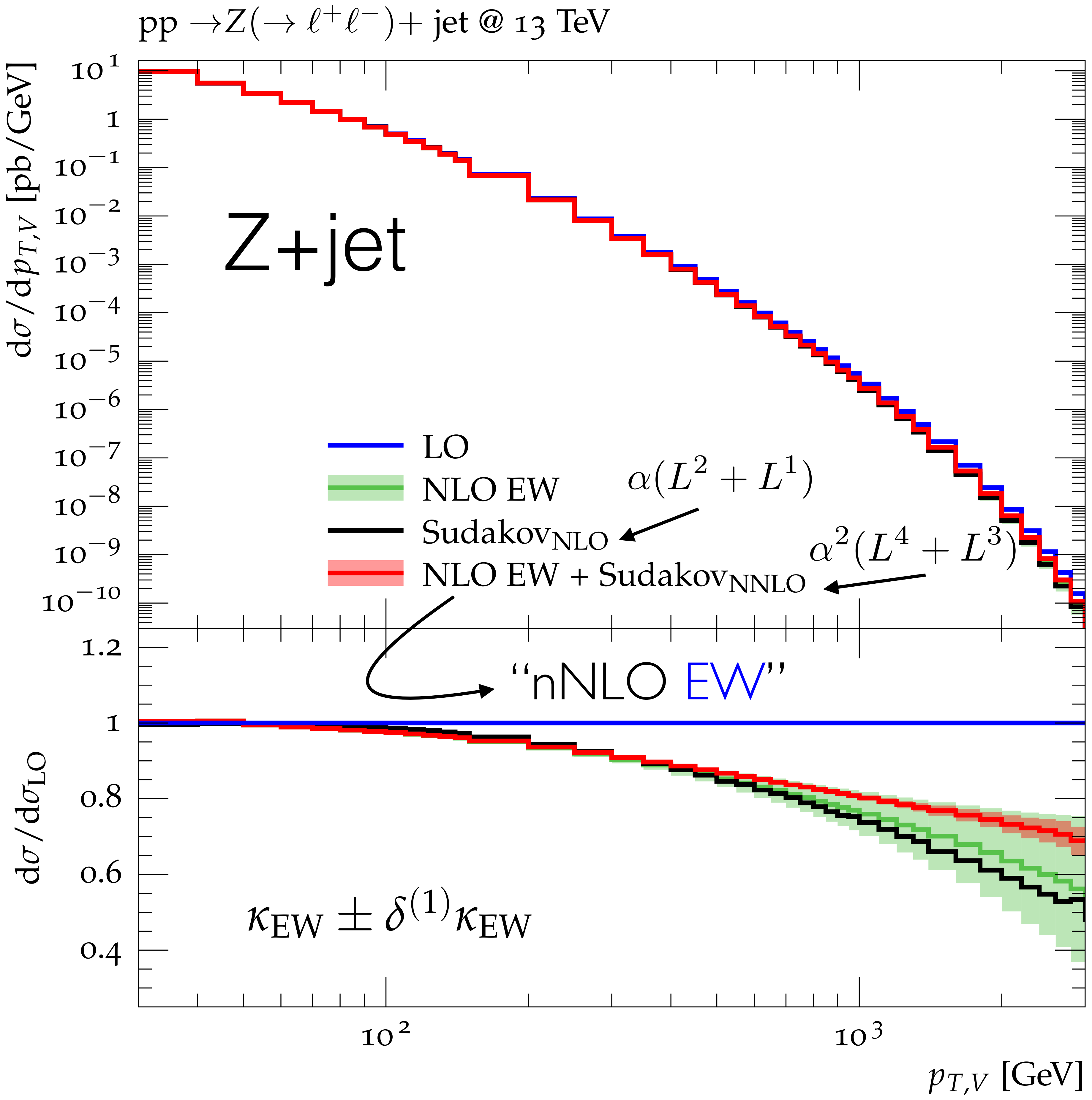
[JML et. al.: 1705.04664]



Large EW corrections dominated by Sudakov logs

Pure EW uncertainties

[JML et. al.: 1705.04664]



$$\kappa_{\mathrm{NLO\,EW}}(\hat{s},\hat{t}) = \frac{\alpha}{\pi}\left[\delta^{(1)}_{\mathrm{hard}} + \delta^{(1)}_{\mathrm{Sud}}\right]$$

$$\kappa_{\mathrm{NNLO\,Sud}}(\hat{s},\hat{t}) = \left(\frac{\alpha}{\pi}\right)^2 \delta^{(2)}_{\mathrm{Sud}}$$

Large EW corrections dominated by Sudakov logs

⬇

Uncertainty estimate of (N)NLO EW from naive exponentiation x 2:

$$\delta^{(1)}\kappa_{\mathrm{EW}} \simeq \frac{2}{k!}\left(\kappa_{\mathrm{NLO,EW}}\right)^k \qquad \textit{(correlated)}$$

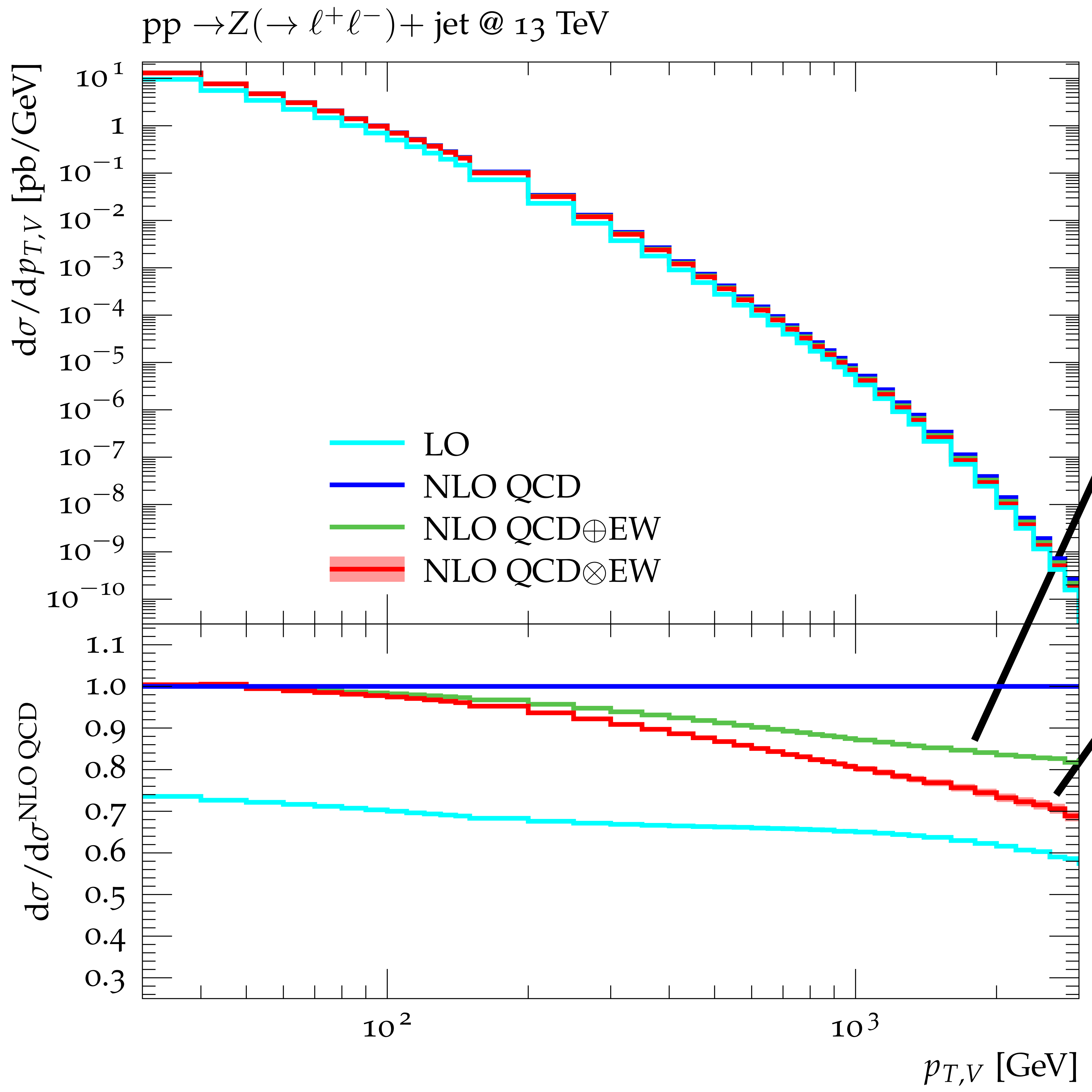
⬇

check against two-loop Sudakov logs

[Kühn, Kulesza, Pozzorini, Schulze; 05-07]

+ additional uncertainties for hard non-log NNLO EW effects *(uncorrelated)*

Mixed QCD-EW uncertainties



Given QCD and EW corrections are sizeable, also mixed QCD-EW uncertainties of relative $\mathcal{O}(\alpha\alpha_s)$ have to be considered.

Additive combination

$$\sigma^{\text{NLO}}_{\text{QCD+EW}} = \sigma^{\text{LO}} + \delta\sigma^{\text{NLO}}_{\text{QCD}} + \delta\sigma^{\text{NLO}}_{\text{EW}}$$

(no $\mathcal{O}(\alpha\alpha_s)$ contributions)

Multiplicative combination

$$\sigma^{\text{NLO}}_{\text{QCD}\times\text{EW}} = \sigma^{\text{NLO}}_{\text{QCD}}\left(1 + \frac{\delta\sigma^{\text{NLO}}_{\text{EW}}}{\sigma^{\text{LO}}}\right)$$

(try to capture some $\mathcal{O}(\alpha\alpha_s)$ contributions, e.g. EW Sudakov logs × soft QCD)

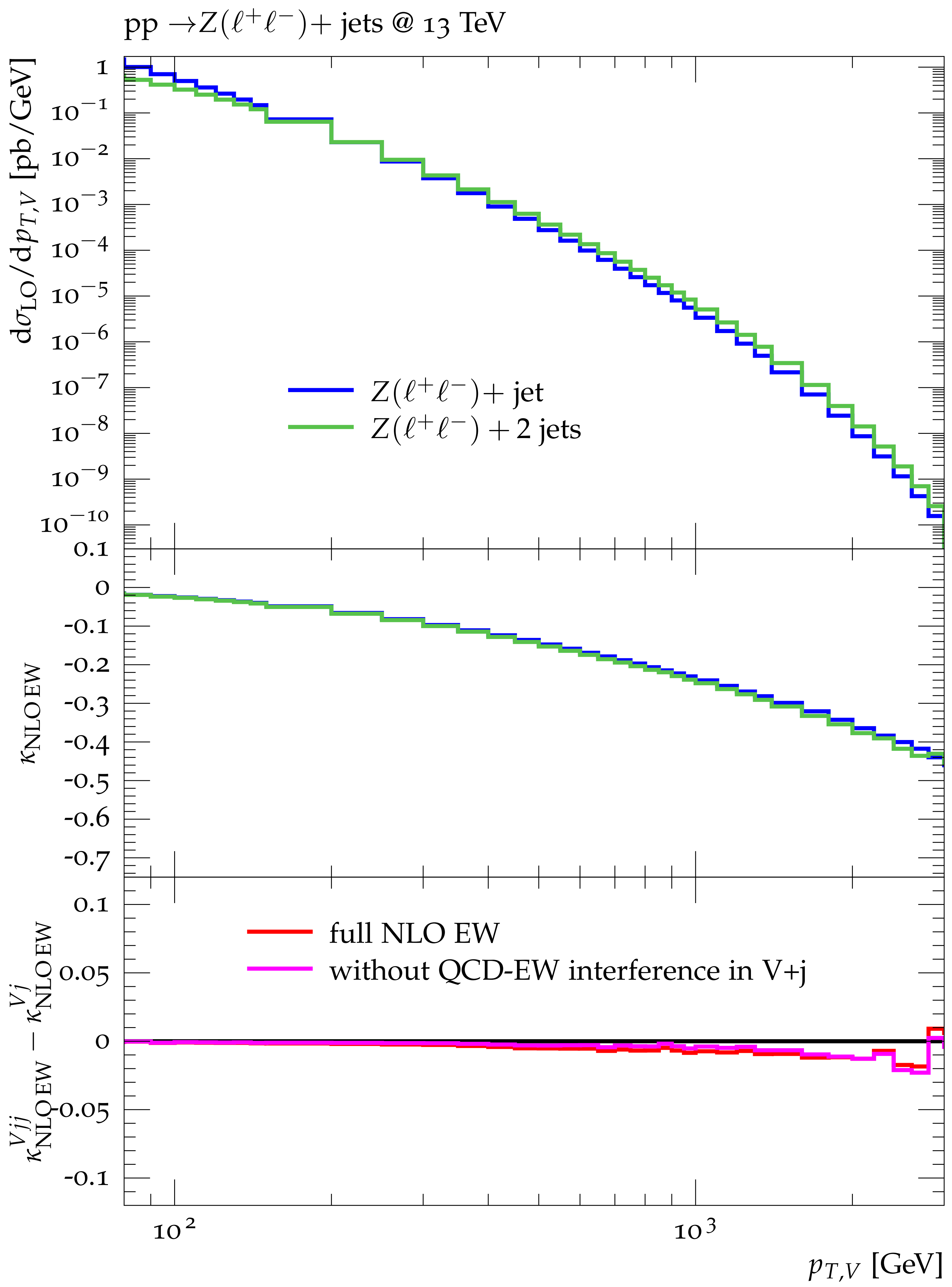
Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

$$K_{\text{QCD}\otimes\text{EW}} - K_{\text{QCD}\oplus\text{EW}} \sim 10\% \quad \text{at 1 TeV}$$

Too conservative!?

For dominant Sudakov EW logarithms factorization should be exact!

Mixed QCD-EW uncertainties



Bold estimate:

Consider real $\mathcal{O}(\alpha\alpha_s)$ correction to V+jet

$\simeq$ **NLO EW to V+2jets**

and we observe

$$\left.\frac{d\sigma_{\mathrm{NLO\,EW}}}{d\sigma_{\mathrm{LO}}}\right|_{V+2\mathrm{jet}} - \left.\frac{d\sigma_{\mathrm{NLO\,EW}}}{d\sigma_{\mathrm{LO}}}\right|_{V+1\mathrm{jet}} \lesssim 1\%$$

strong support for
- factorization
- multiplicative QCD x EW combination

Estimate of non-factorising contributions

(correlated)

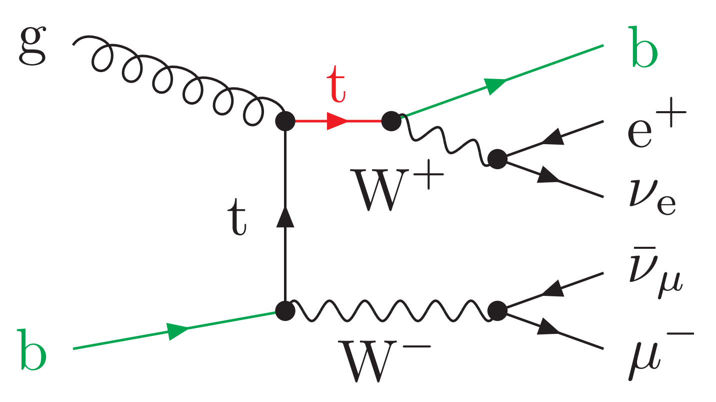
$$\delta K^{(V)}_{\mathrm{mix}}(x) \quad = \quad 0.1\left[K^{(V)}_{\mathrm{TH},\oplus}(x,\vec{\mu}_0) - K^{(V)}_{\mathrm{TH},\otimes}(x,\vec{\mu}_0)\right]$$

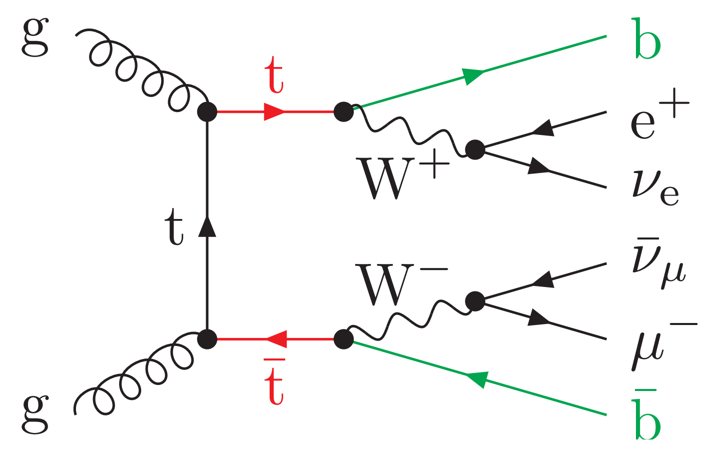
(tuned to cover above difference of EW K-factors)

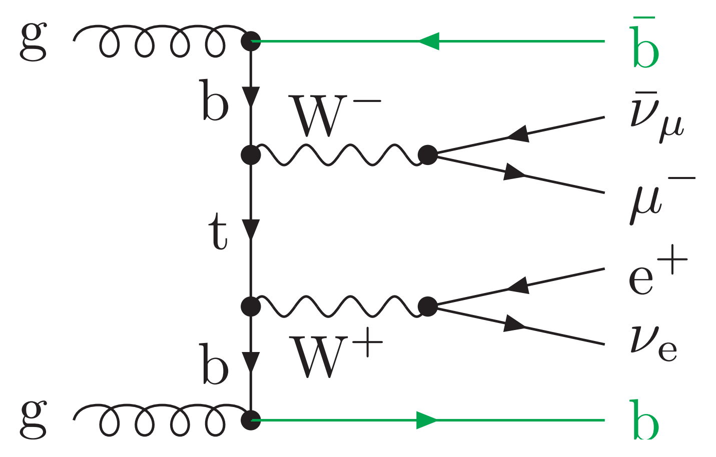
Top-free W⁺W⁻ definitions

Huge Wt and $t\bar{t}$ contamination from $\overbrace{W^+W^-b}^{+40\%\ \text{NLO}}$ and $\overbrace{W^+W^-b\bar{b}}^{+400\%\ \text{NNLO}}$

- intimately connected with W^+W^- through $g \to b\bar{b}$ singularities
- top subtraction tricky and not unique $\Rightarrow$ theoretical ambiguity in $\sigma_{WW}^{\text{(N)NLO}}$!

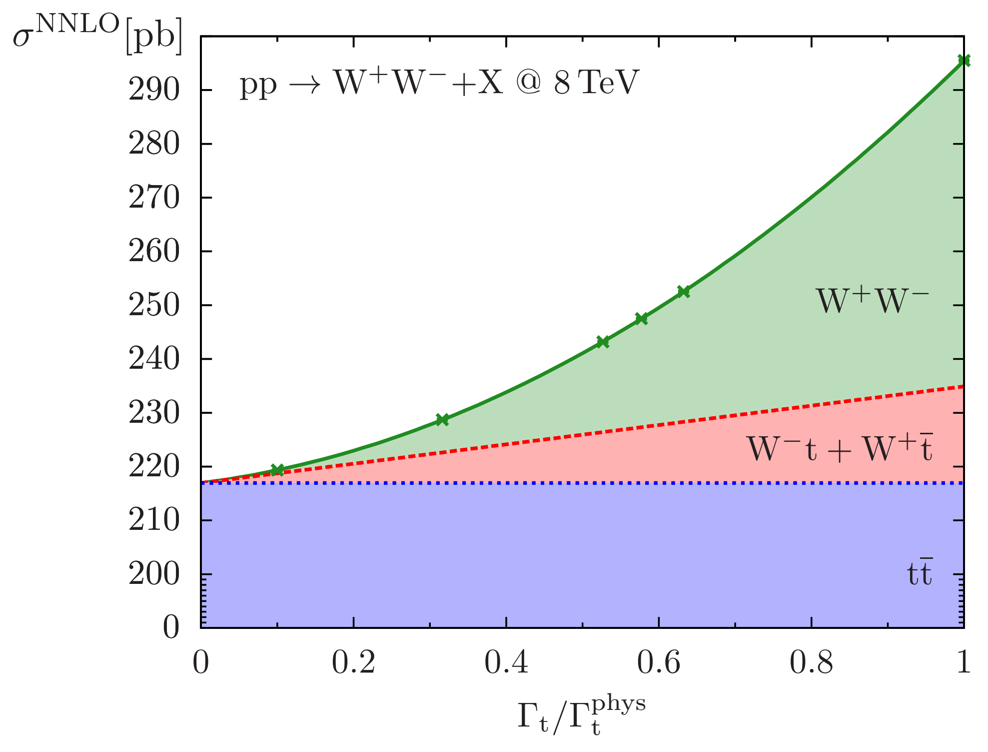






Definition A: **veto b-quark emissions in 4F scheme** $(m_b > 0)$

- $\Rightarrow \ln(m_b/M_W)$ terms might jeopardize NNLO accuracy!



Definition B: **top-resonance fit in 5F-scheme** $(m_b = 0)$

$$\lim_{\xi_t \to 0} \sigma_{\text{full}}^{\text{5F}}(\xi_t \Gamma_t) = \xi_t^{-2}\left[\sigma_{t\bar{t}}^{\text{5F}} + \xi_t\, \sigma_{Wt}^{\text{5F}} + \xi_t^2\, \sigma_{W^+W^-}^{\text{5F}}\right]$$

$\Rightarrow$ for inclusive $\sigma_{WW}^{\text{NNLO}}$ only 1–2% ambiguity (A vs B)

Relevant issue for percent-precision tests of W^+W^- physics! . . . Relation to σ_{WW}^{EXP}?