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COMETA

Polarised calculations with POWHEG-BOX-RES

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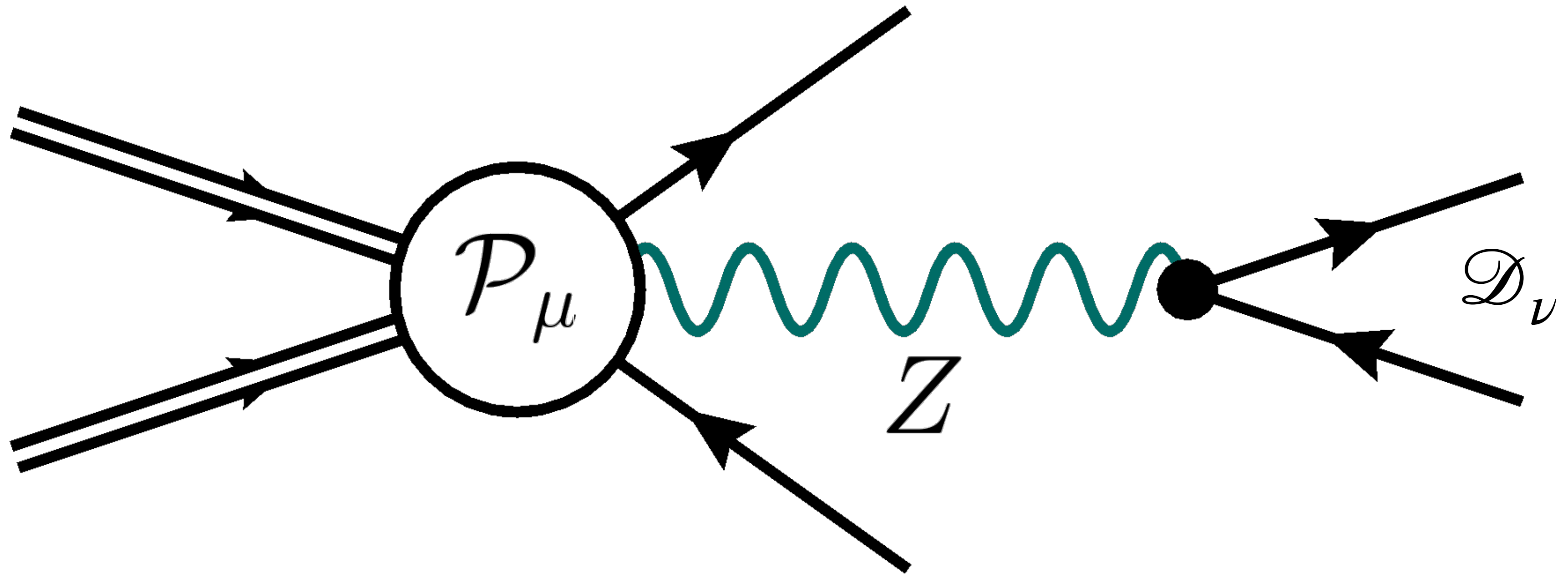
1. Polarisation splitting of amplitudes

Separating polarisations in amplitudes



$$\mathscr{A}^{\text{unpol}} = \mathscr{P}_\mu \frac{-g^{\mu\nu}}{k^2 - m_Z^2 + i\Gamma_Z m_Z} \mathscr{D}_\nu$$

$$= \mathscr{P}_\mu \frac{\sum_\lambda \epsilon_\lambda^\mu(k)\epsilon_\lambda^{*\nu}(k)}{k^2 - m_Z^2 + i\Gamma_Z m_Z} \mathscr{D}_\nu$$

$$\rightarrow \mathscr{P}_\mu \frac{\epsilon_\lambda^\mu(k)\epsilon_\lambda^{*\nu}(k)}{k^2 - m_Z^2 + i\Gamma_Z m_Z} \mathscr{D}_\nu \equiv \mathscr{A}_\lambda$$

Cross section level [Ballestrero et al. 1710.09339, Denner GP 2006.14867]:

$$|\mathscr{A}^{\text{unpol}}|^2 = \underbrace{\sum_\lambda \left|\mathscr{A}_\lambda\right|^2}_{\text{incoherent sum}} + \underbrace{\sum_{\lambda\neq\lambda'} \mathscr{A}_\lambda^* \mathscr{A}_{\lambda'}}_{\text{interference terms}}$$

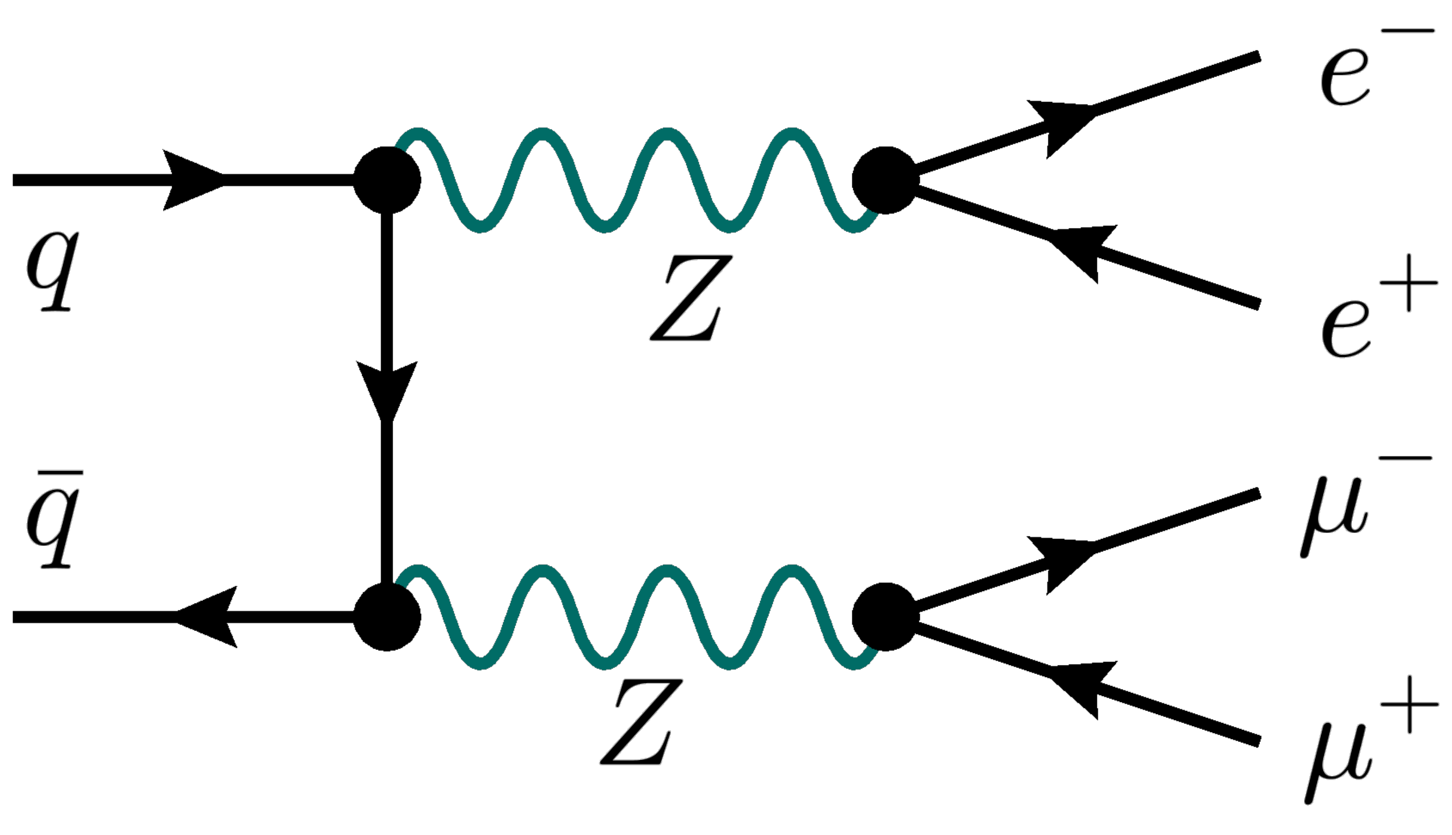
$\longrightarrow$ $|\mathscr{A}_\lambda|^2 \propto$ polarised cross section

Polarisation states are not **Lorentz invariant**:

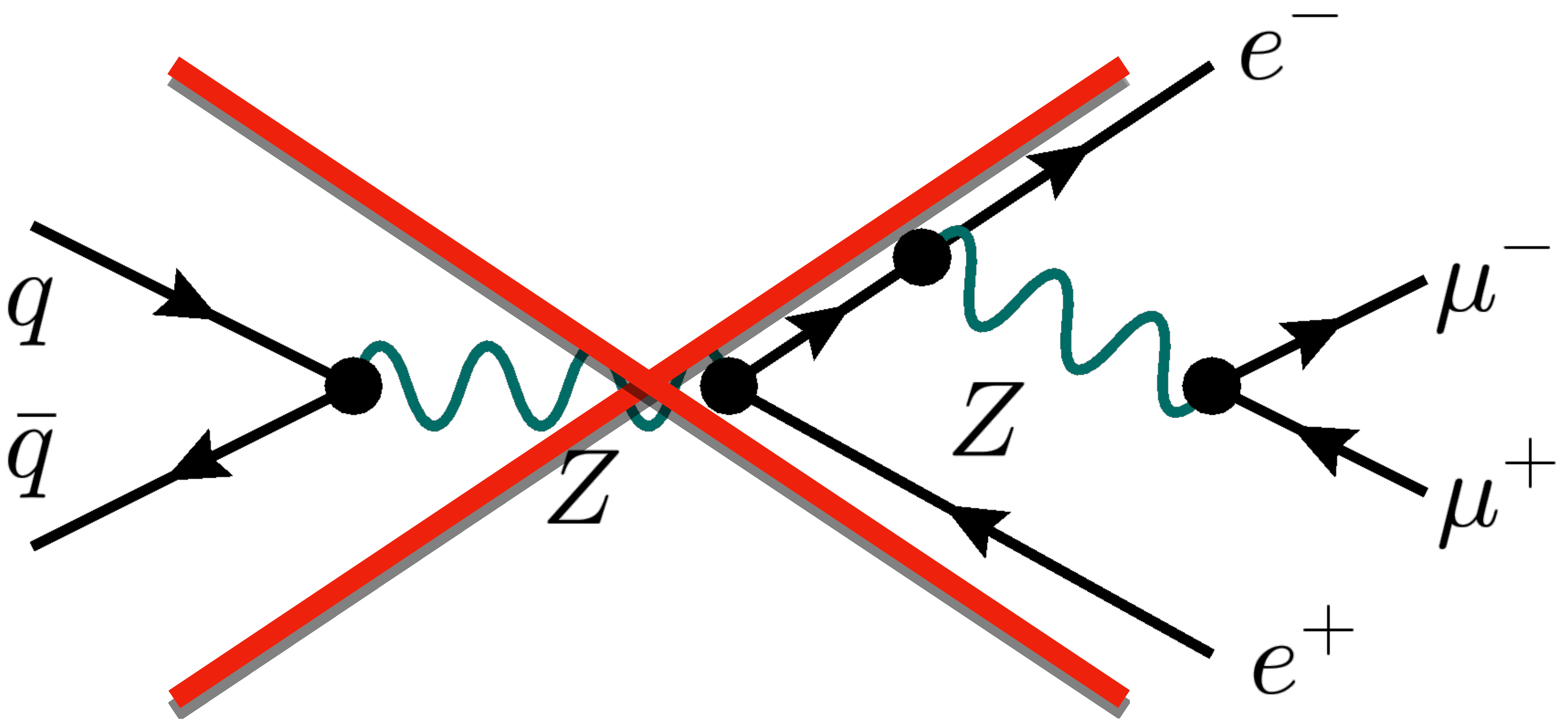
→ Defined in **VV-CM frame** for diboson production

2. Double Pole Approximation

Factorised amplitude: production × propagator × decay



(Double) Resonant



Non-resonant/ single resonant

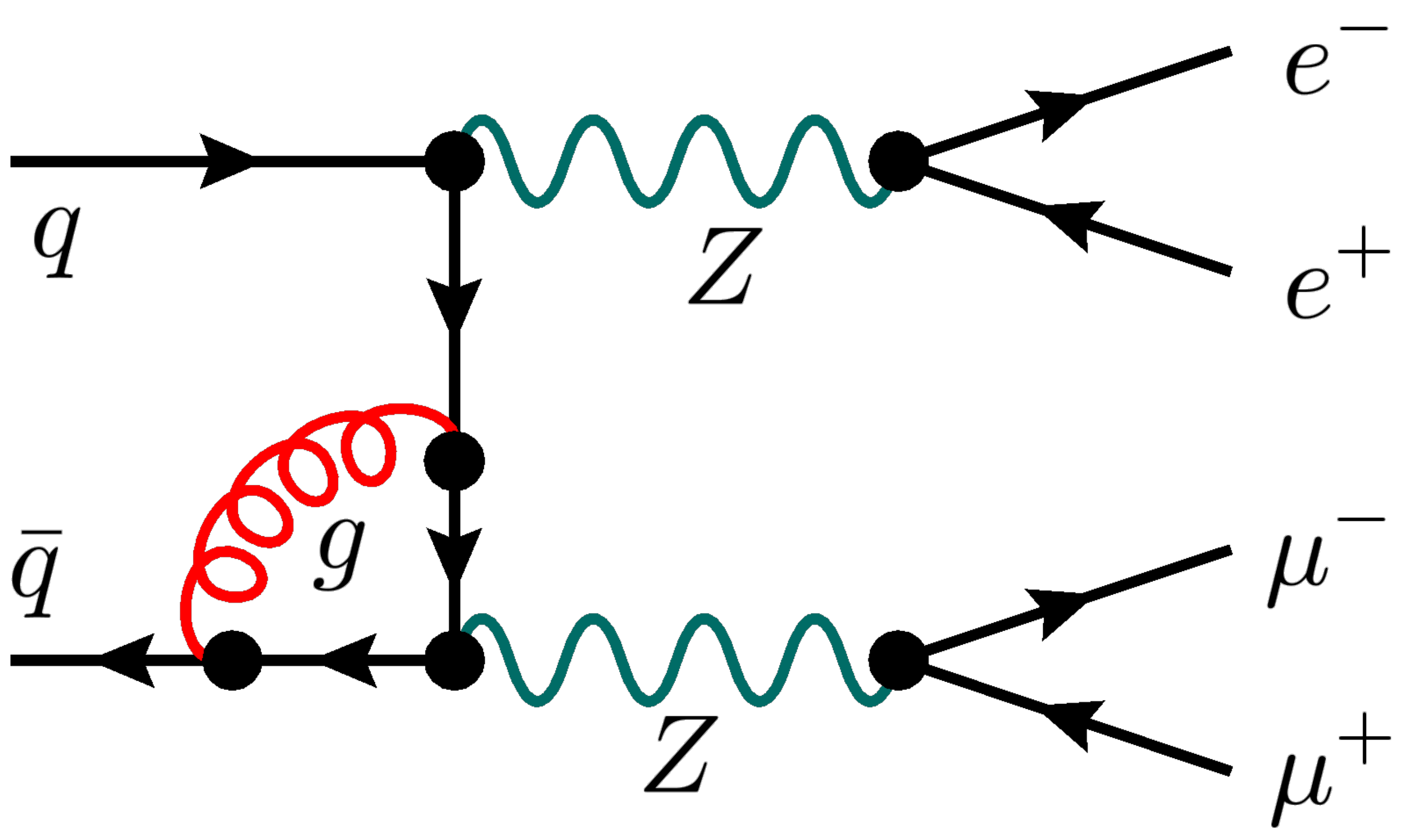
Gauge invariance? → **Double pole approximation** **[Denner et al. 0006307]**

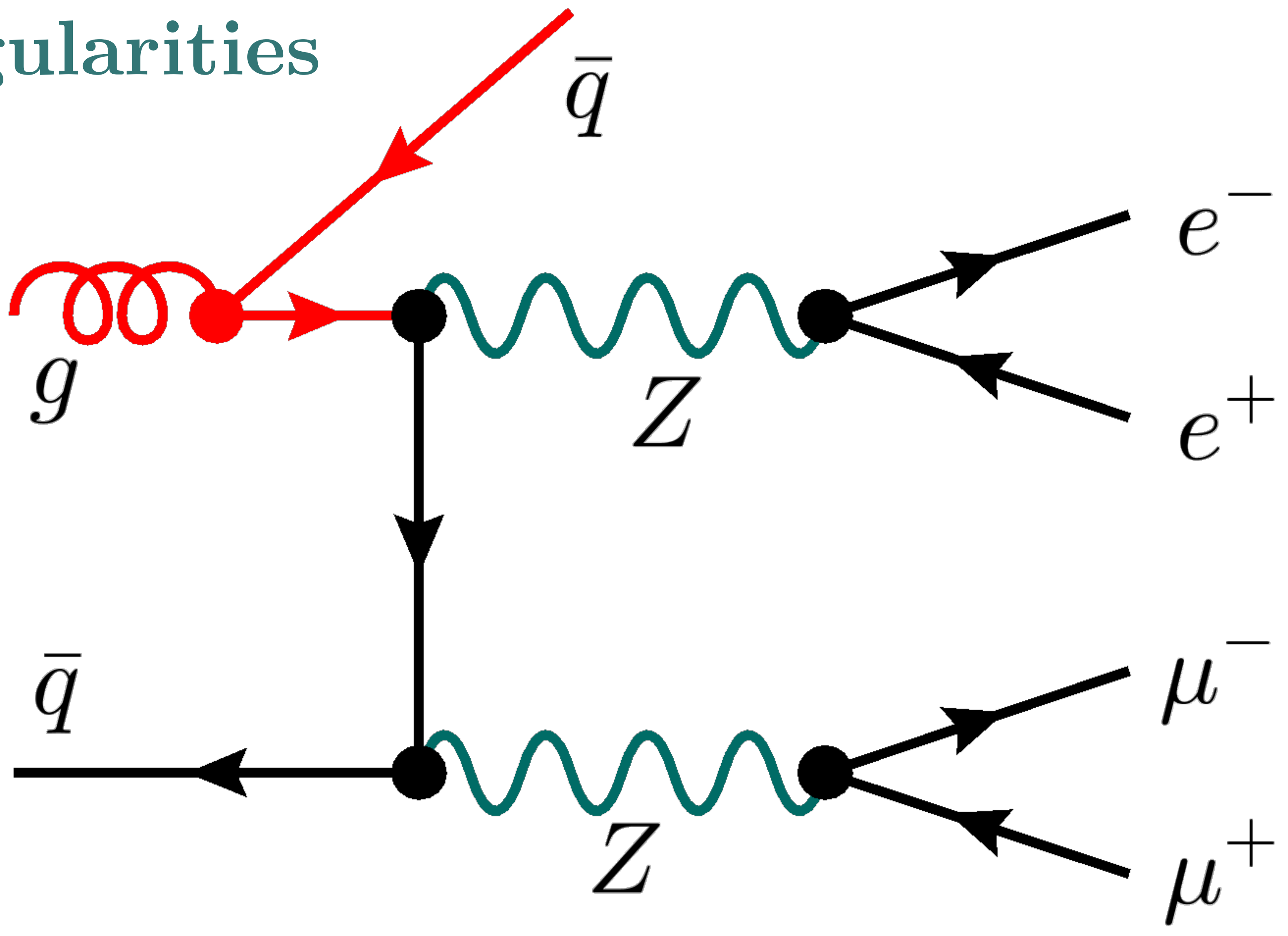
- Project momenta in numerator of Z-propagator to on-shell momenta (keep denominator):

$$(p_{e^-} + p_{e^+})^2 \to (\bar{p}_{e^-} + \bar{p}_{e^+})^2 = M_Z^2$$

3. NLO corrections (to the production)

Virtual (V) and real (R) corrections: $V + R$ free of IR singularities





- **Corrections** for **production of resonances**
- **Subtraction** to get separately finite integrals:

$$\frac{d\sigma^{\rm NLO}}{d\xi} = \int d\Phi_6 \left(B + V + \int d\Phi_{\rm rad}\, \mathscr{C} \right) \delta_\xi^{(6)} \quad + \int d\Phi_{6+1} \left(R\, \delta_\xi^{(6+1)} - \mathscr{C}\, \delta_\xi^{(6)} \right)$$

- `POWHEG-BOX-RES` uses **FKS** [Frixione et. al. hep-ph/9512328, hep-ph/9706545]
- **DPA** needs to be **applied to V, R and $\mathscr{C}$ too**.
- All contribution **specific to** a **polarisation**

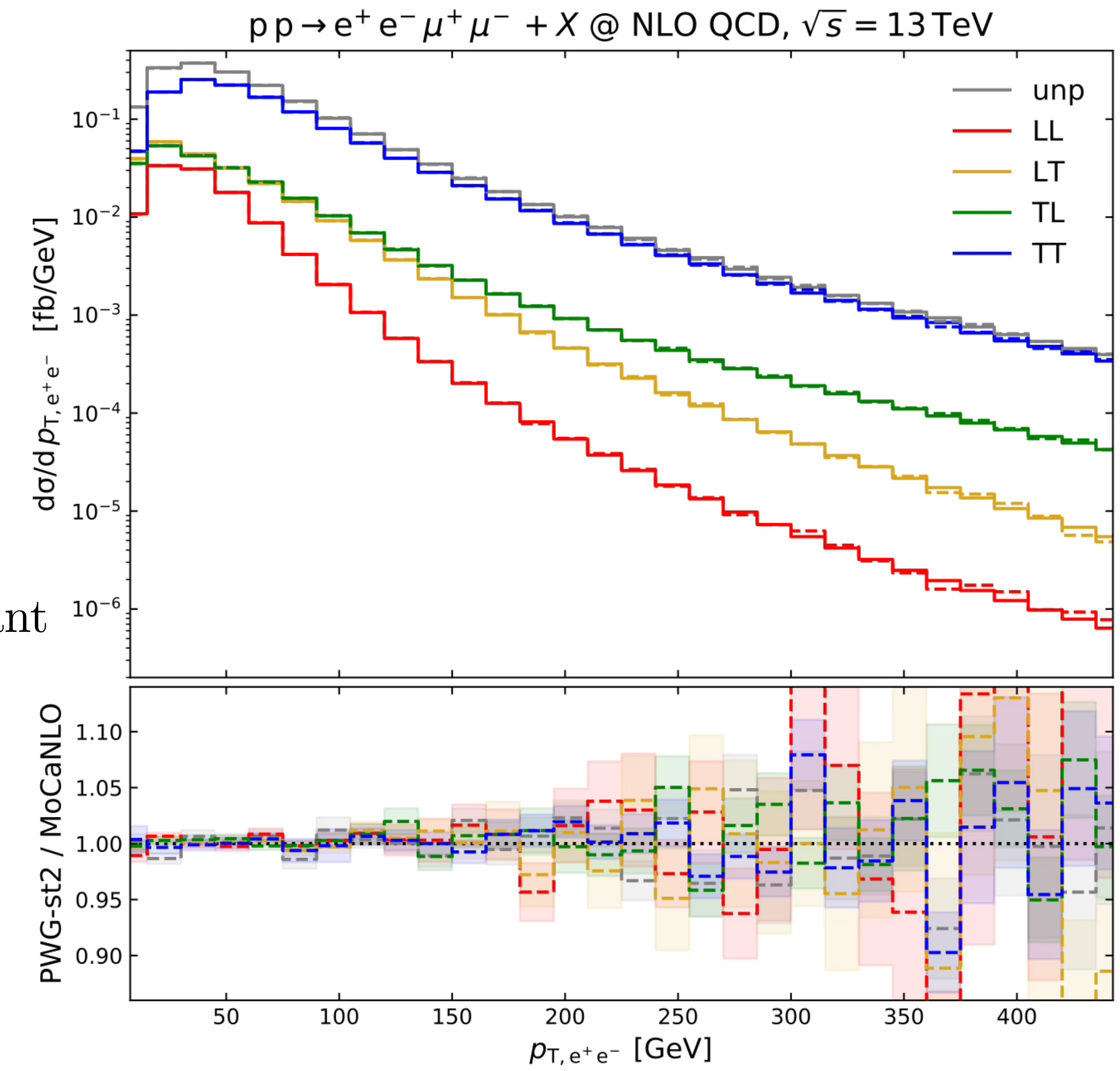
4. Fixed order results [Pellicciolli, Zanderighi 2311.05220]

Available processes

- $\mathrm{p\,p} \to \mathrm{W}^+_\lambda\left(\ell^+\nu_\ell\right)\,\mathrm{W}^-_{\lambda'}\left(\ell'^-\bar{\nu}_{\ell'}\right)$ [Denner, Pellicioli 2006.14867]
- $\mathrm{p\,p} \to \mathrm{W}^\pm_\lambda\left(\ell^\pm \overset{(-)}{\nu'}_\ell\right)\,\mathrm{Z}'_\lambda\left(\ell'^+\ell'^-\right)$ [Denner, Pellicioli 2010.07149]
- $\mathrm{p\,p} \to \mathrm{Z}_\lambda\left(\ell^+\ell^-\right)\,\mathrm{Z}_{\lambda'}\left(\ell'^+\ell'^-\right)$ [Denner, Pellicioli 2107.06579]

  - Compared to `MoCaNLO` with perfect agreement within the integration uncertainties
  - E.g.: Inclusive cross sections (in fb) for ZZ with only invariant mass cut: $81\,\mathrm{GeV} < M_{\ell^+\ell^-} < 101\,\mathrm{GeV}$

state	POWHEG-BOX-RES	MoCaNLO
$\mathrm{Z_U\ Z_U}$	$28.22(1)^{+2.9\%}_{-2.3\%}$	$28.21(2)^{+2.9\%}_{-2.4\%}$
$\mathrm{Z_L\ Z_L}$	$1.664(1)^{+3.0\%}_{-2.4\%}$	$1.664(2)^{+3.0\%}_{-2.5\%}$
$\mathrm{Z_L\ Z_T}$	$3.551(2)^{+3.7\%}_{-2.9\%}$	$3.548(1)^{+3.6\%}_{-3.0\%}$
$\mathrm{Z_T\ Z_L}$	$3.554(2)^{+3.7\%}_{-3.0\%}$	$3.548(2)^{+3.6\%}_{-3.0\%}$
$\mathrm{Z_T\ Z_T}$	$19.46(1)^{+2.6\%}_{-2.1\%}$	$19.45(1)^{+2.6\%}_{-2.1\%}$



5. Matching to Parton shower

POWHEG master formula [Nason 0409146]

$$\langle \mathcal{O} \rangle = \int \mathrm{d}\Phi_6 \, \overline{B}(\tilde{\Phi}_6) \left[\mathcal{O}(\tilde{\Phi}_6)\, \Delta(p_\perp^{\min}) + \int_{p_\perp > p_\perp^{\min}} \mathrm{d}\Phi_{\mathrm{rad}}\, \mathcal{O}(\tilde{\bar{\Phi}}_6, \Phi_{\mathrm{rad}}) \frac{R(\tilde{\bar{\Phi}}_6, \Phi_{\mathrm{rad}})}{B(\tilde{\Phi}_6)} \Delta(p_\perp) \right]$$

NLO-accurate $\overline{B}$ weight:

$$\overline{B}(\tilde{\Phi}_6) = B(\tilde{\Phi}_6) + V_{\mathrm{reg}}(\tilde{\Phi}_6) + \int \mathrm{d}\Phi_{6+\mathrm{rad}} \left[R(\tilde{\bar{\Phi}}_6, \Phi_{\mathrm{rad}}) - \mathcal{C}(\tilde{\bar{\Phi}}_6, \Phi_{\mathrm{rad}}) \right],$$

Sudakov form factor

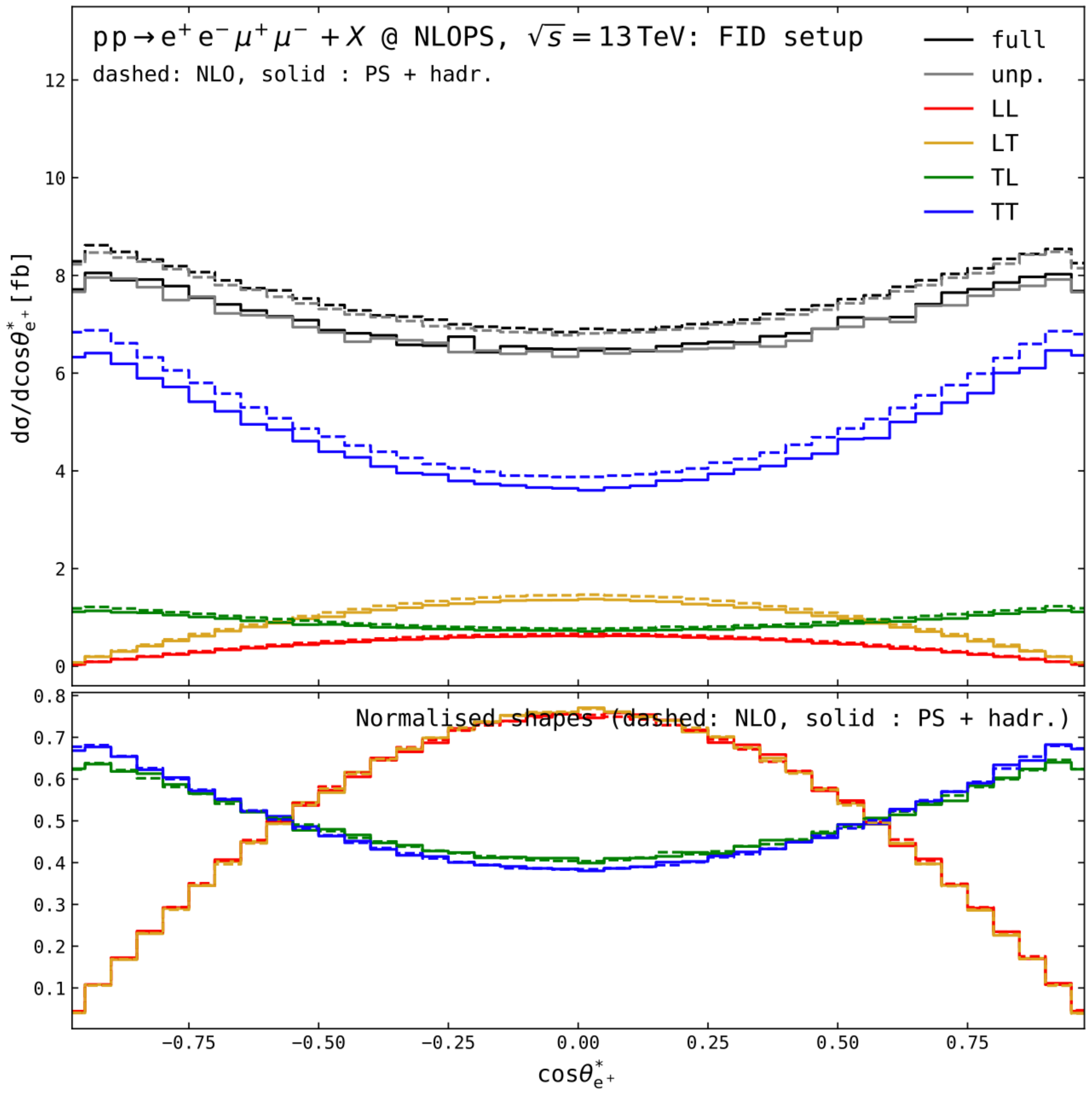
$$\Delta(p_\perp) = \exp\left(- \int_{k_\perp(\Phi_{6+\mathrm{rad}}) > p_\perp} \mathrm{d}\Phi_{\mathrm{rad}} \frac{R(\tilde{\bar{\Phi}}_6, \Phi_{\mathrm{rad}})}{B(\tilde{\Phi}_6)} \right)$$

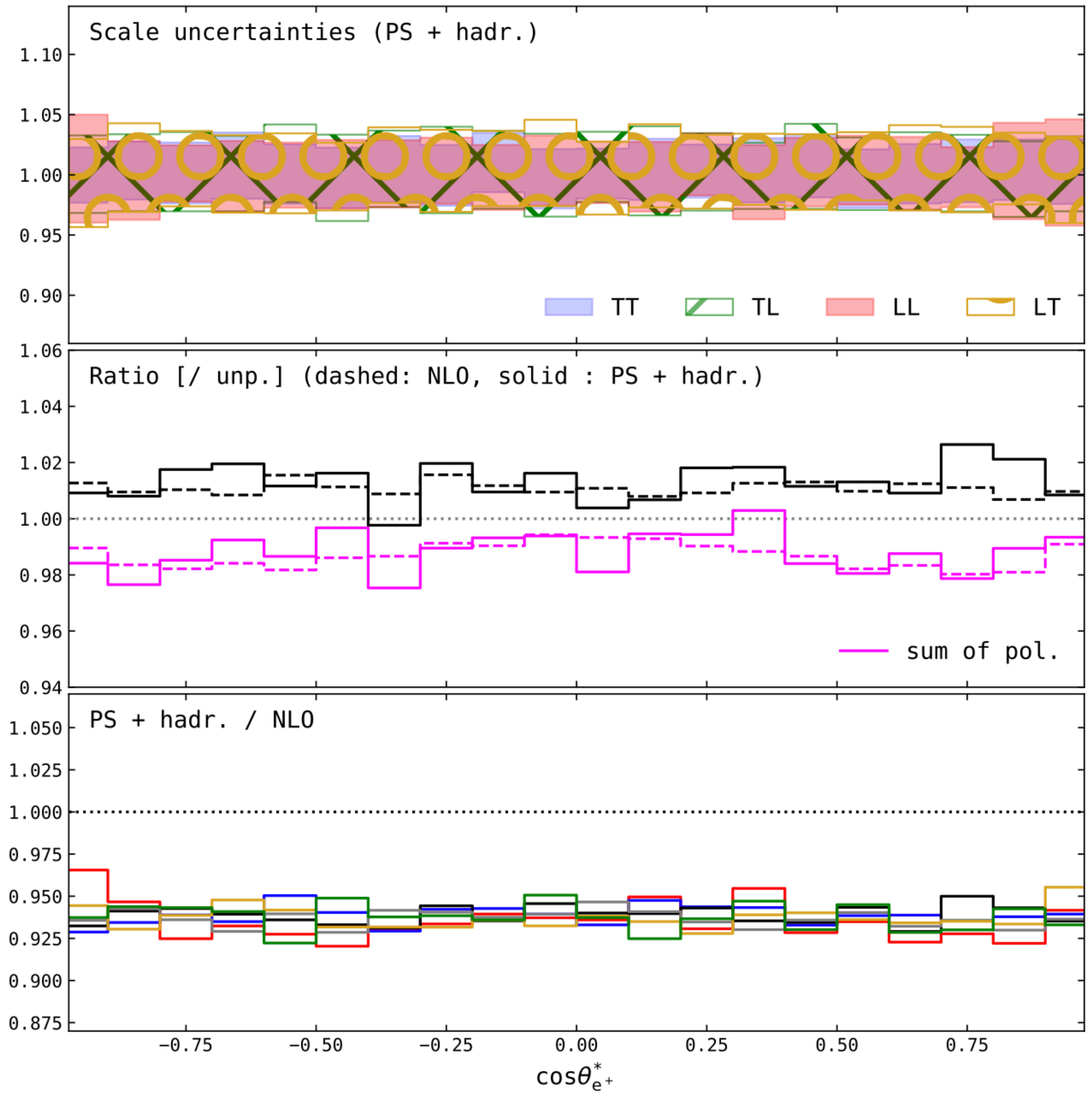
FKS mapping, followed by DPA on-shell mapping

$$\Phi_6 = \{x_1, x_2, p_{1\ldots4}\} \xrightarrow{\mathrm{FKS}^{-1}} \left(\overline{\Phi}_6, \Phi_{\mathrm{rad}}\right) = \{\bar{x}_1, \bar{x}_2, \bar{p}_{1\ldots4}, p_{\mathrm{rad}}\} \xrightarrow{\mathrm{DPA}} \left(\tilde{\bar{\Phi}}_6, \Phi_{\mathrm{rad}}\right) = \{\bar{x}_1, \bar{x}_2, \tilde{\bar{p}}_{1\ldots4}, p_{\mathrm{rad}}\}$$

5. Matching to Parton shower

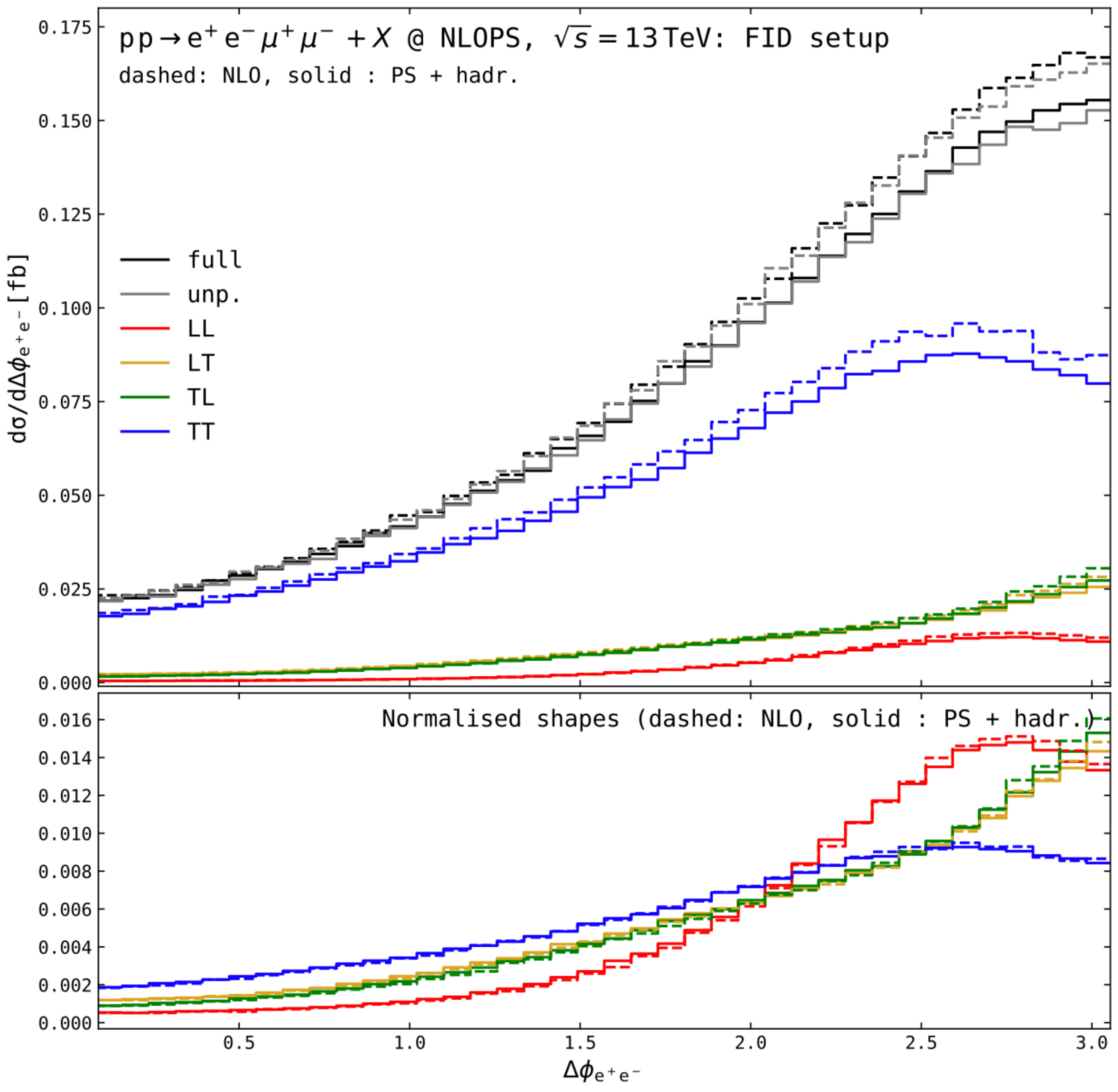
Decay angle of e^+ in the Z boson rest frame, w.r.t. the direction of the Z in the VV-CM

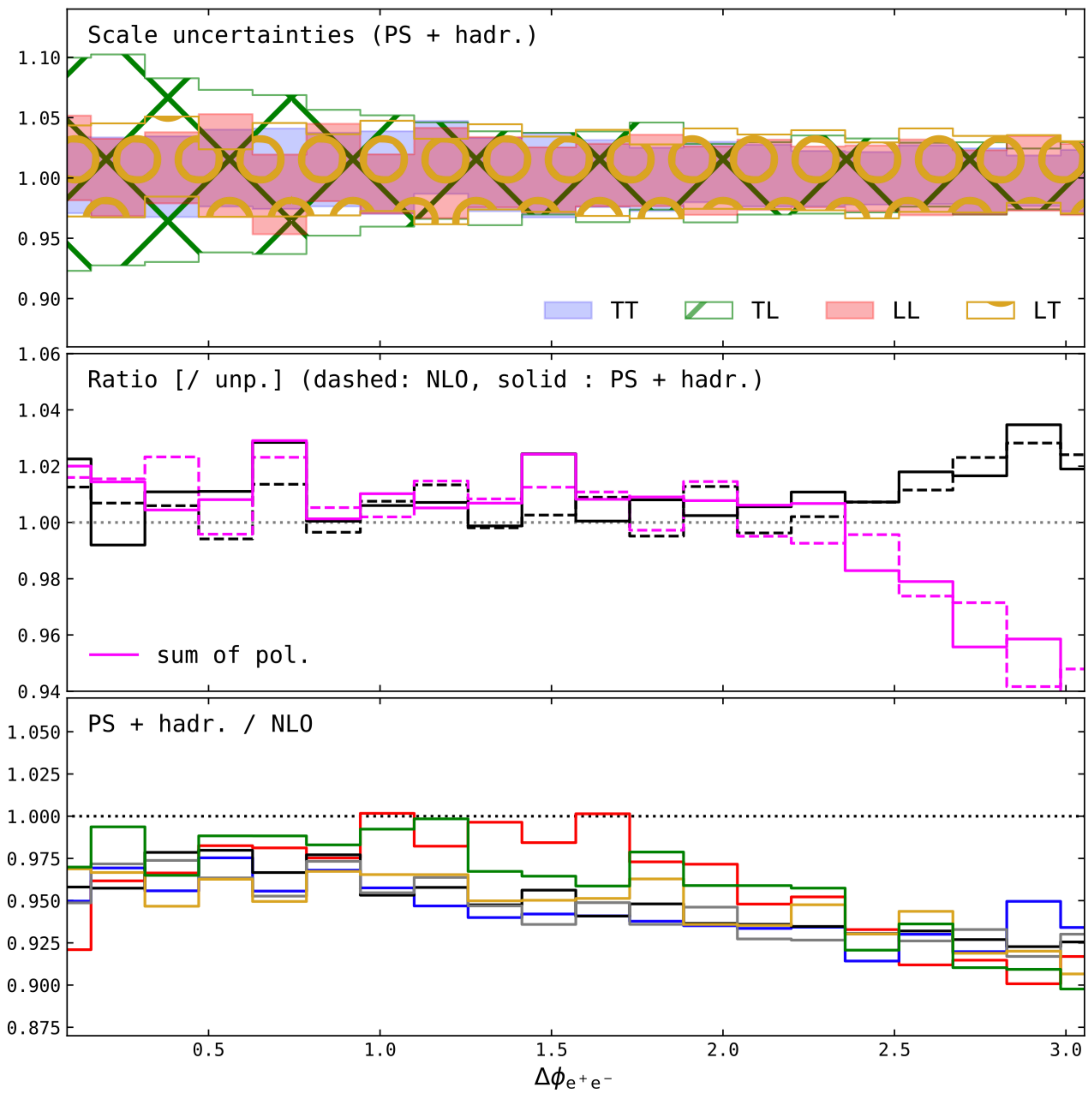




5. Matching to Parton shower

Azimuthal distance of e^+ and e^- in LAB frame





5. Matching to Parton shower

Comparison with ATLAS measurement [ATLAS 2310.04350]

fraction	POWHEG-BOX-RES **PS+hadr (our work)**	MoCaNLO TH (QCD)	MoCaNLO TH (QCD+EW+gg)	**measured**
L L	$5.84^{+0.03}_{-0.05}$	5.9	5.8	7.1 ± 1.7
L T + T L	$25.41^{+0.08}_{-0.07}$	25.3	23.2	22.8 ± 1.1
T T	$67.52^{+0.09}_{-0.13}$	67.4	69.8	69.0 ± 2.7
interference	1.28	1.3	1.2	1.1 ± 0.1

6. SMEFT extension

$$\mathscr{L}^{\text{eff.}} = \mathscr{L}^{\text{SM}} + \sum_i \frac{c_6^i}{\Lambda^2}\mathscr{O}_6^i + \cdots$$

Anomalous triple gauge couplings (ATGC) in W^+Z

$$\mathscr{O}_{WWW} = -\frac{g_{\text{w}}^3}{4}\epsilon_{ijk}W_{\mu\nu}^{i}W^{\nu\rho\,j}W_{\rho}^{\mu\,k},$$

$$\mathscr{O}_{W} = -ig_{\text{w}}(D_\mu\Phi)^\dagger\frac{\tau_k}{2}W^{\mu\nu\,k}(D_\nu\Phi),$$

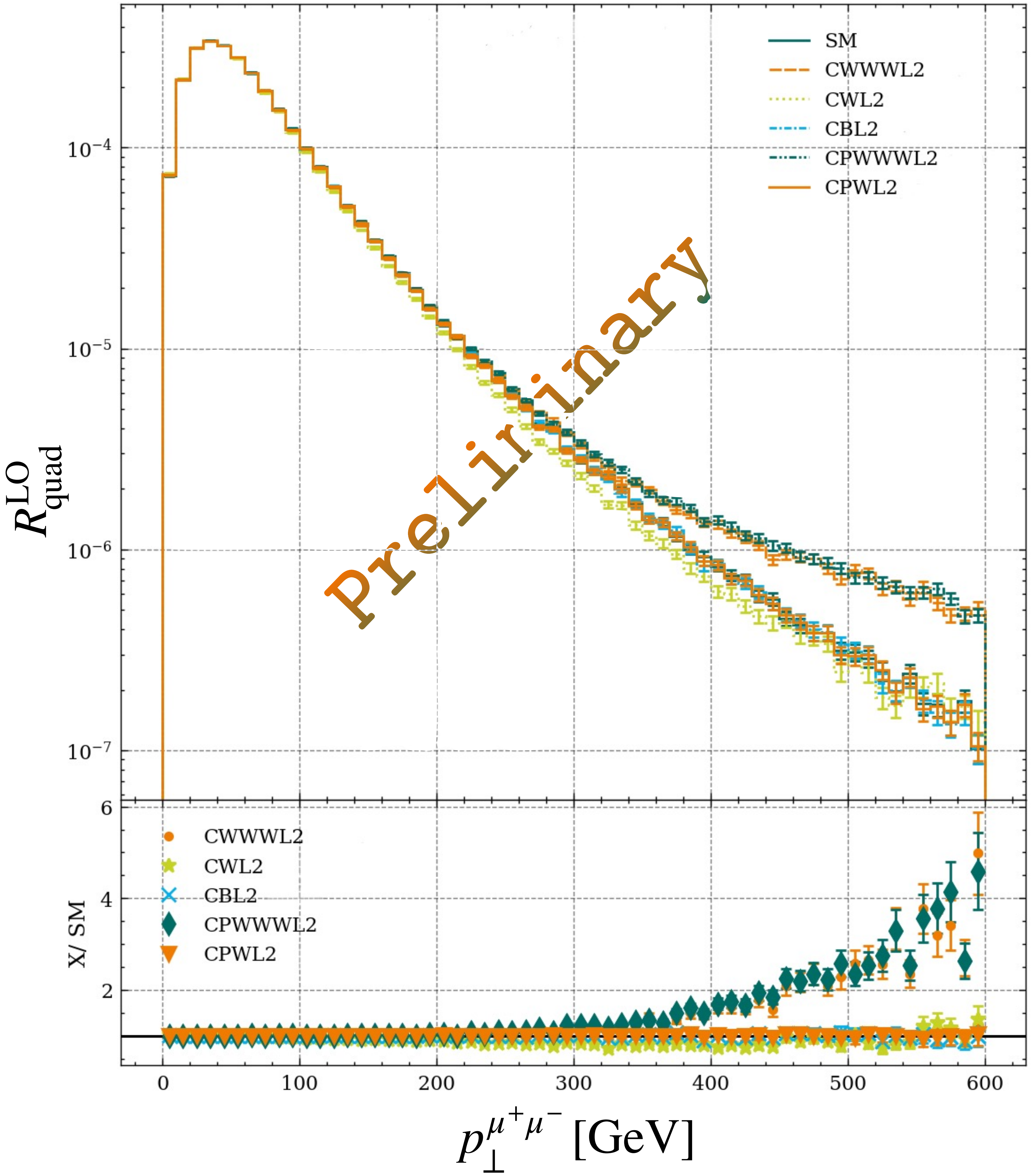
$$\mathscr{O}_{B} = +i\frac{g_1}{2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi),$$

$$\mathscr{O}_{\widetilde{W}WW} = +\frac{g_{\text{w}}^3}{4}\epsilon_{ijk}\widetilde{W}_{\mu\nu}^{i}W^{\nu\rho\,j}W_{\rho}^{\mu\,k},$$

$$\mathscr{O}_{\widetilde{W}} = +ig_{\text{w}}(D_\mu\Phi)^\dagger\frac{\tau_k}{2}\widetilde{W}^{\mu\nu\,k}(D_\nu\Phi),$$

- Test ATGC (without DPA) against `RECOLA2+ATGC` [Chiesa et al. 1804.01477]:

$$R_{\text{quad}}^{\text{LO}} = \frac{d\left(\sigma_{\text{SM}^2} + \sigma_{\text{SM}\times\text{EFT}} + \sigma_{\text{EFT}^2}\right)^{\text{LO QCD}}/dp_\perp^{\mu^+\mu^-}}{d\sigma_{\text{SM}^2}^{\text{LO QCD}}/dp_\perp^{\mu^+\mu^-}}$$



Conclusion

- `POWHEG-BOX-RES` capable of dealing with polarised states in diboson production.
- SM study already done, at exact NLO QCD accuracy matched to `PYTHIA` shower.
- SM package broadly validated [Pelliccioli, Zanderighi 2311.05220].
- Extension towards `POWHEG-BOX-RES + Recola 2` to examine BSM effects in polarisations.
- Not yet public (hopefully made public soon).

Thank you for your attention!