GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

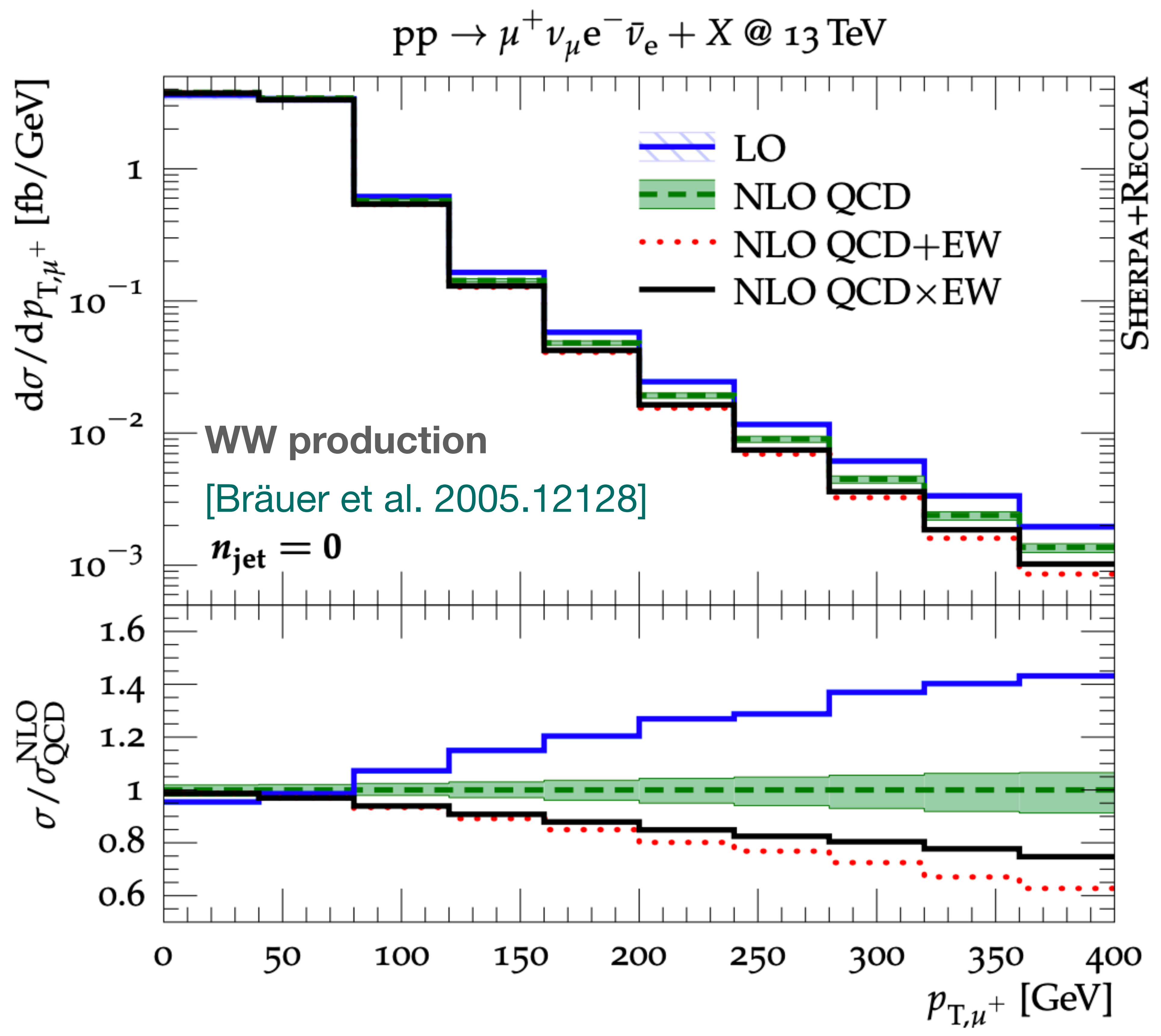
Institut für Theoretische Physik

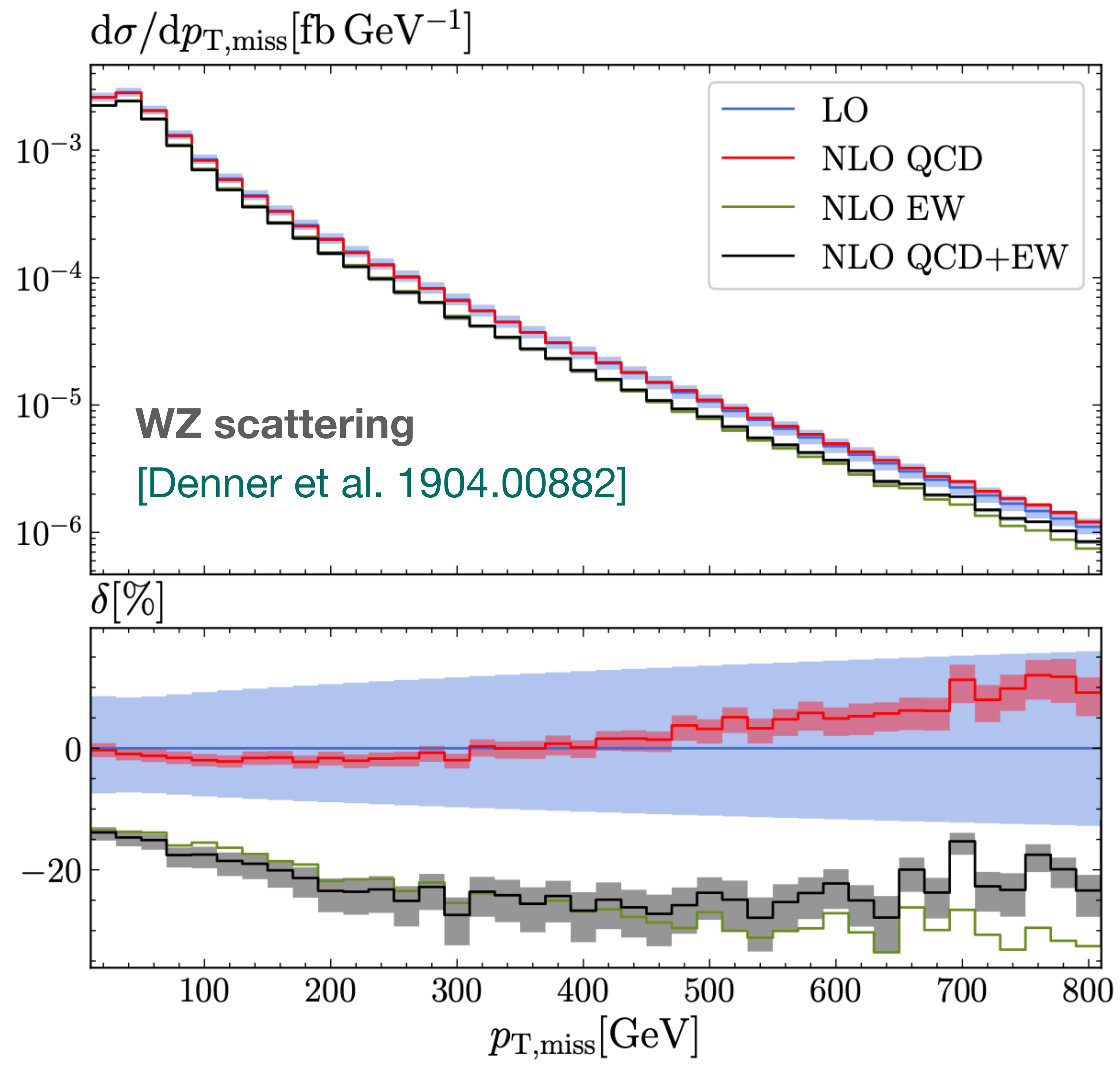
EW corrections in LHC simulations in the SHERPA framework

PSR 2021

Enrico Bothmann 2021-05-27

Invitation





$\mathcal{O}(\alpha_s^2) \sim \mathcal{O}(\alpha)$

→ EW effects can be enhanced, e.g. logarithmic Sudakov suppression towards high energy* that are of interest e.g. for BSM searches

* all invariants larger m_W

→ for Run II and beyond: EW corrections required for precision measurements with (sub)percent accuracy and for searches in tails of (invariant mass) distributions

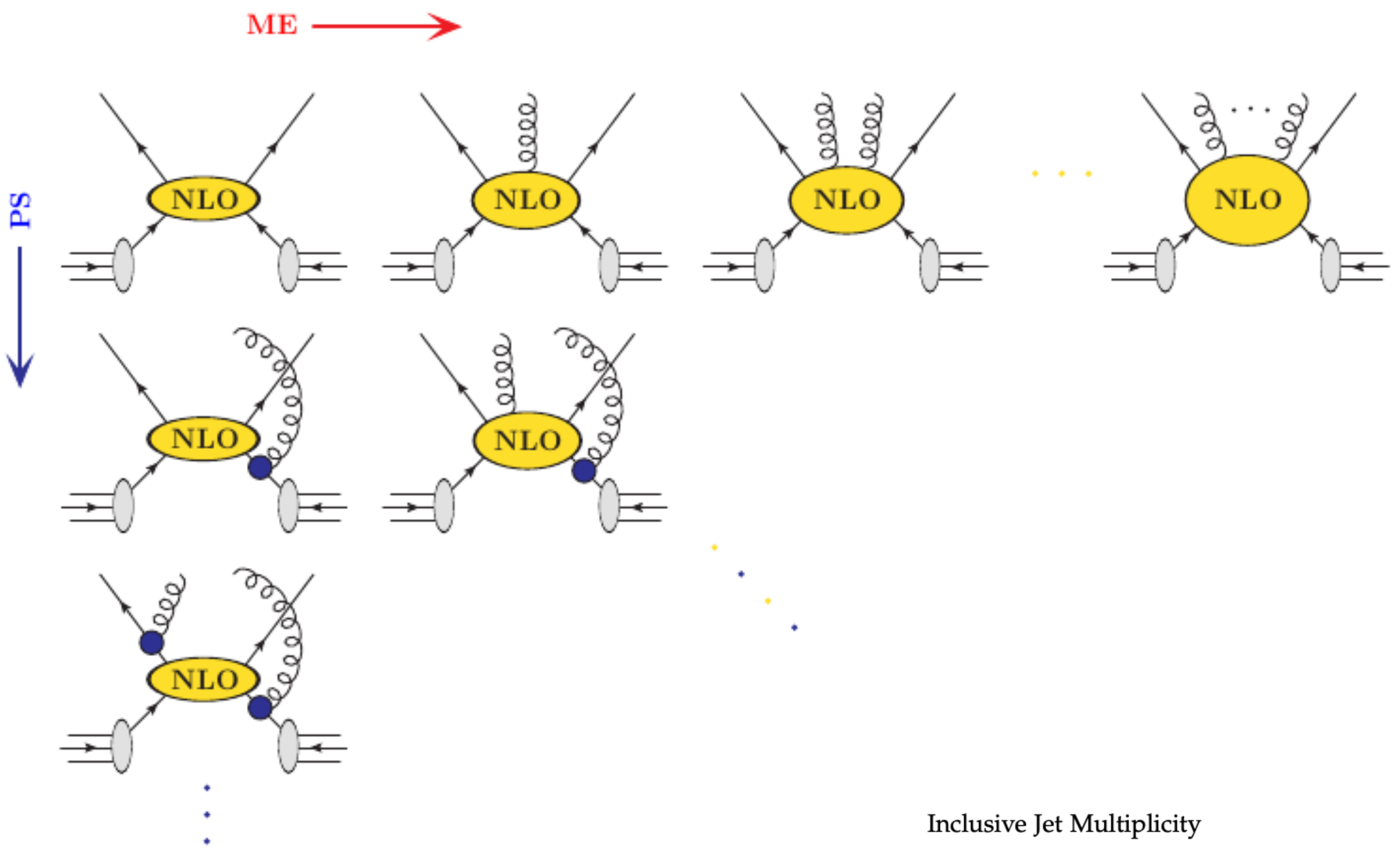
- This talk: (approx.) NLO QCD+EW in state-of-the-art (showered!) event generation for the LHC
- No fixed-order talk, instead interested in inclusion of higher-order EW corrections within matching+merging setups (in Sherpa) and their automation
- Will not discuss lower-scale QED like QED FSR/PDFs, EPA (established tools/methods available)

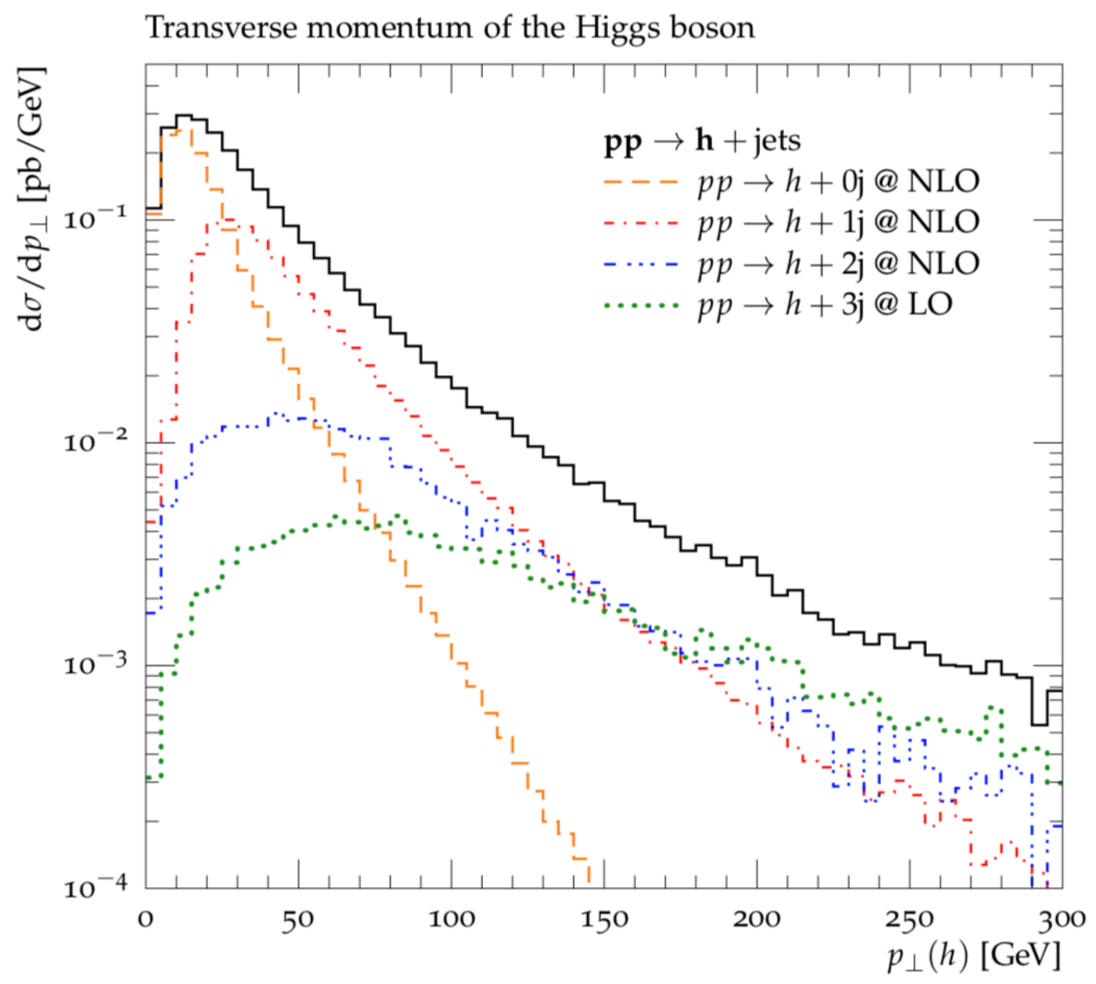
Multijet-merging

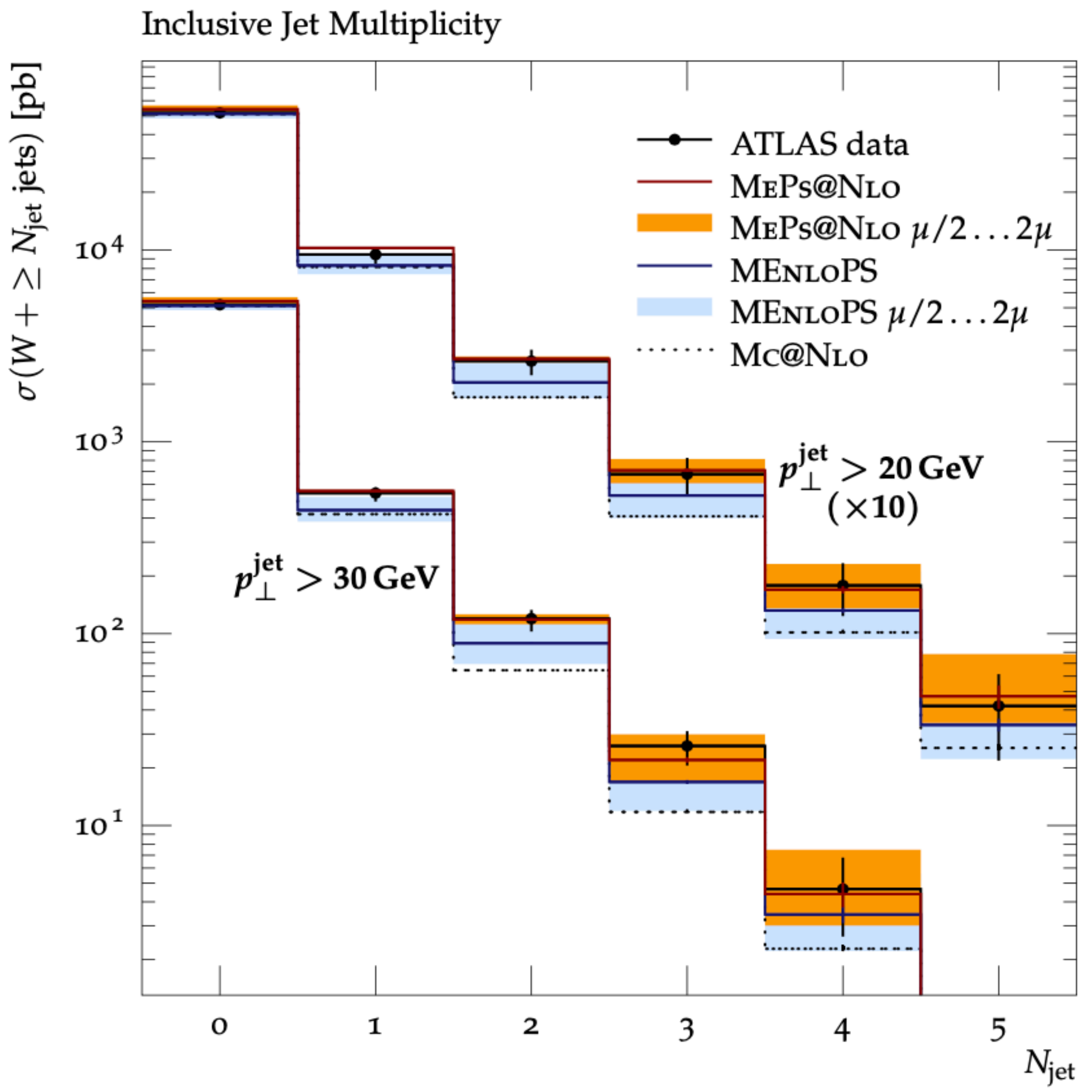
CKKW-L / “MEPS@(N)LO”

[Höche et al. 0903.1219, 1009.1127]

- (Other: MiNLO, FxFx, MLM, UMEPS, UNLOPS …)
- such merging schemes @ NLO are de-facto standard for LHC simulated samples
- combine parton-shower matched calculations for several jet multiplicities in a single inclusive sample
    - resolution criterion to separate ME and PS regions
    - QCD Shower Sudakov form factor to render multiplicities exclusive
- predictive for multi-jet observables (= wide region of phase space)
- can be hadronised for particle-level prediction
- support for QCD+EW NLO?
    - No fully automated implementation yet
    - matched to QCD+QED shower impl’d & studied for individual procs in POWHEG-BOX





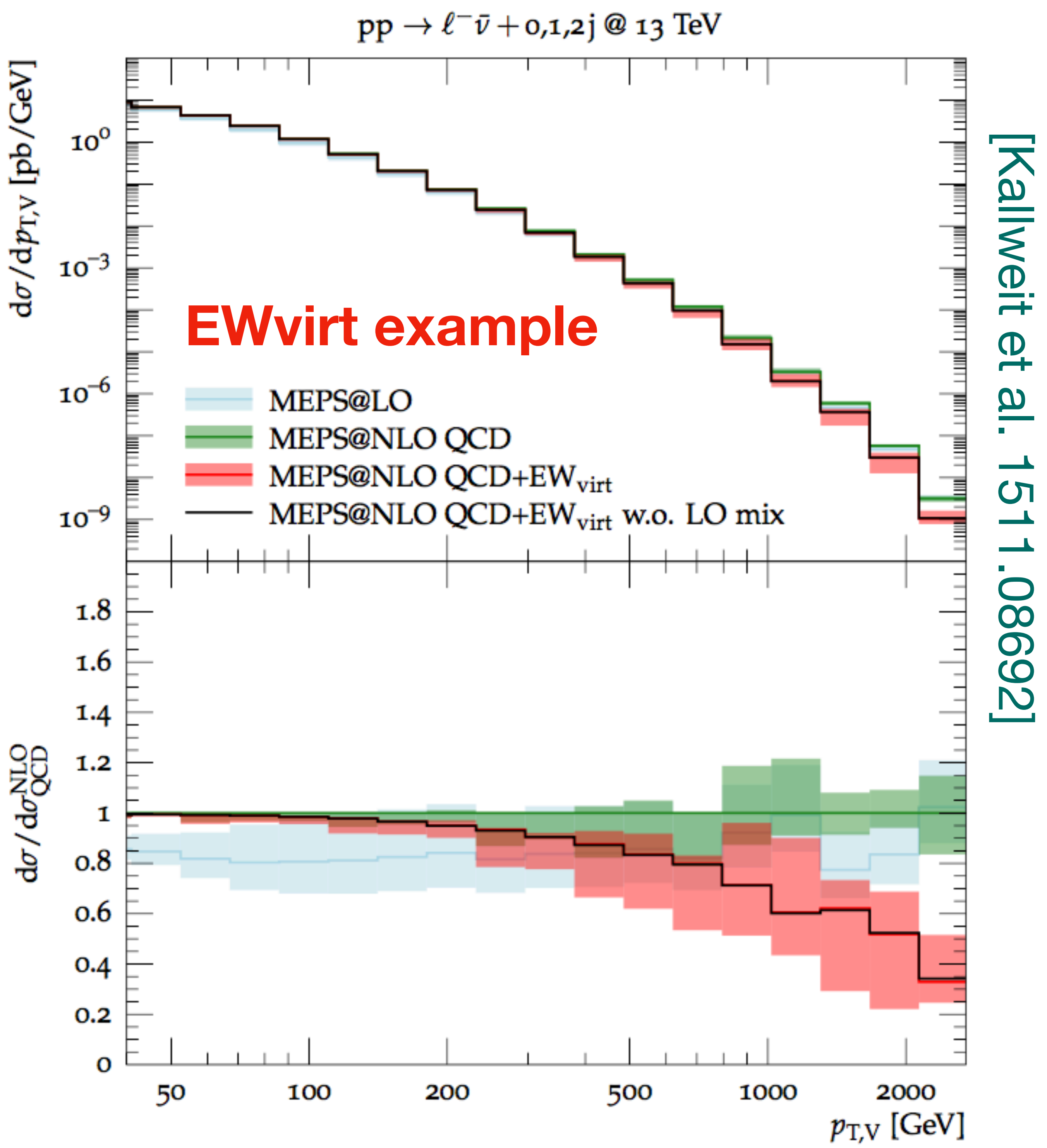


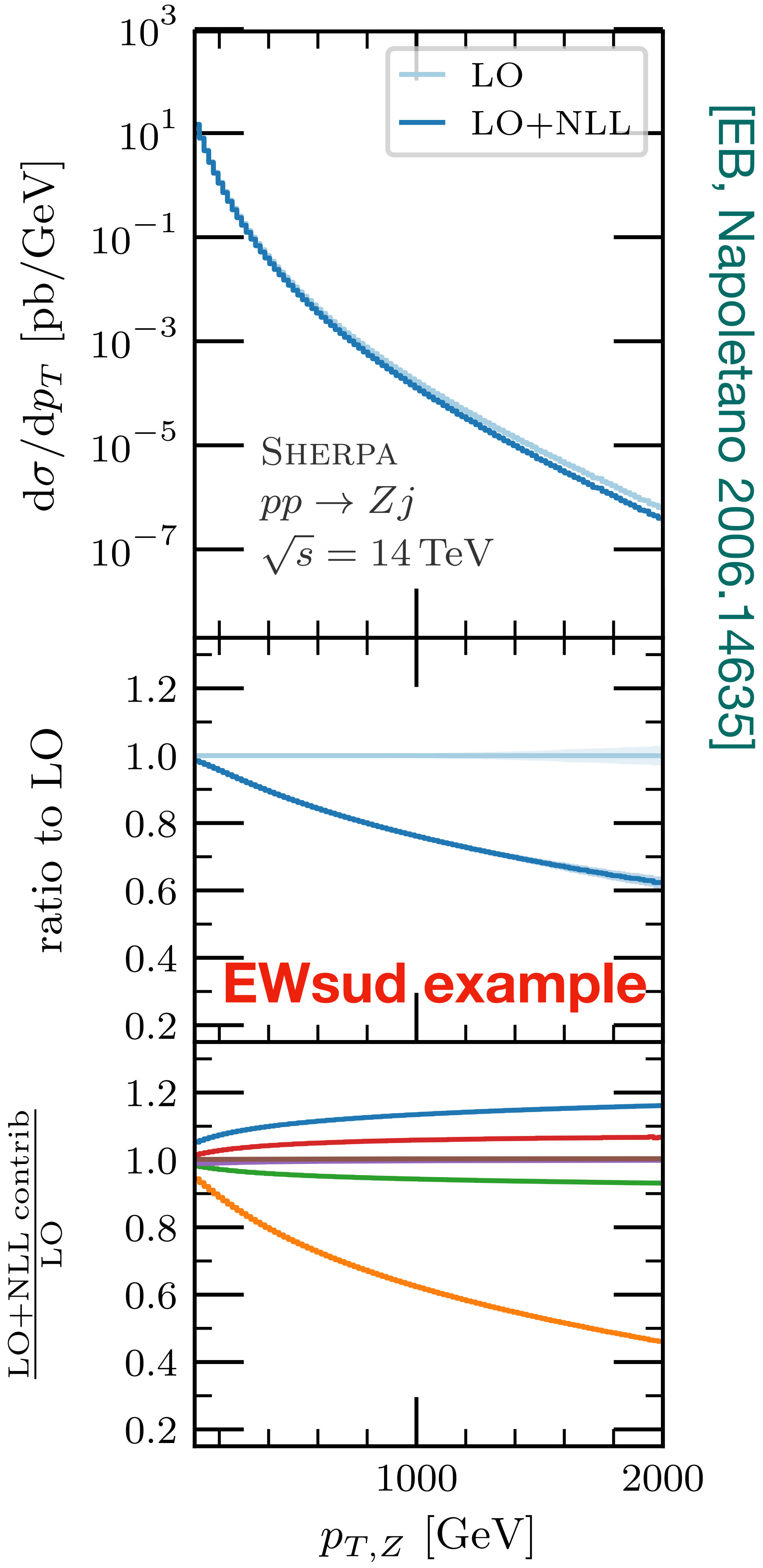
[Höche et al. 0903.1219, 1009.1127]

No full automation for NLO+PS EW …

To the rescue: approximate schemes

- can at least capture logarithmic suppression from virtual gauge boson exchanges and hence the Sudakov suppression in the high energy region → approximate NLO EW
    - implement as local K factor to QCD NLO → easy to include within existing schemes
- in Sherpa 2: **EWvirt**
  [Kallweit et al. 1511.08692]
    - calculate K factor via EW virtual loop ME (among other contribs)
- in Sherpa 3: supplemented by **EWsud**
  [EB, Napoletano 2006.14635]
    - calculate K factor using LL and NLL terms in high energy limit
- can be mixed: proposal of **EWhybrid**





EWvirt 1

EW virtual approximation

[Kallweit et al. 1511.08692]

- construct approximation that only reweights a Born configuration

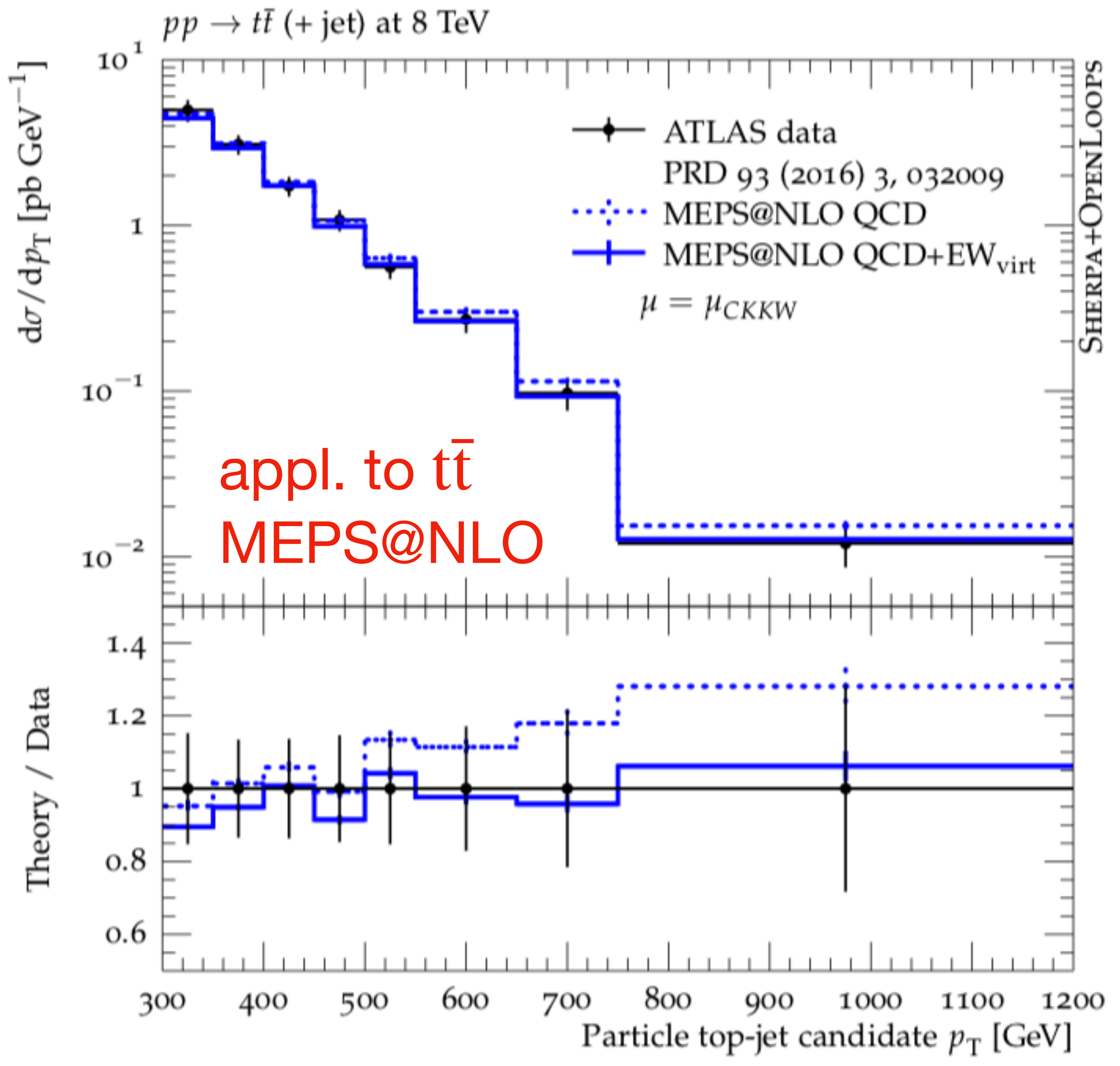
$$\delta_{\mathrm{EW}}^{\mathrm{approx}}\left(\Phi_n\right) = \frac{\mathrm{V}_n^{\mathrm{EW}}\left(\Phi_n\right) + \mathrm{I}_n^{\mathrm{EW}}\left(\Phi_n\right)}{B_n(\Phi_n)}$$

- exact virtual $\mathrm{V}_n^{\mathrm{EW}}$, approx. integrated real contribution $\mathrm{I}_n^{\mathrm{EW}}$
- just a local K factor → apply within MEPS@NLO, replacing QCD $\overline{\mathrm{B}}_{n,\mathrm{QCD}}$ with

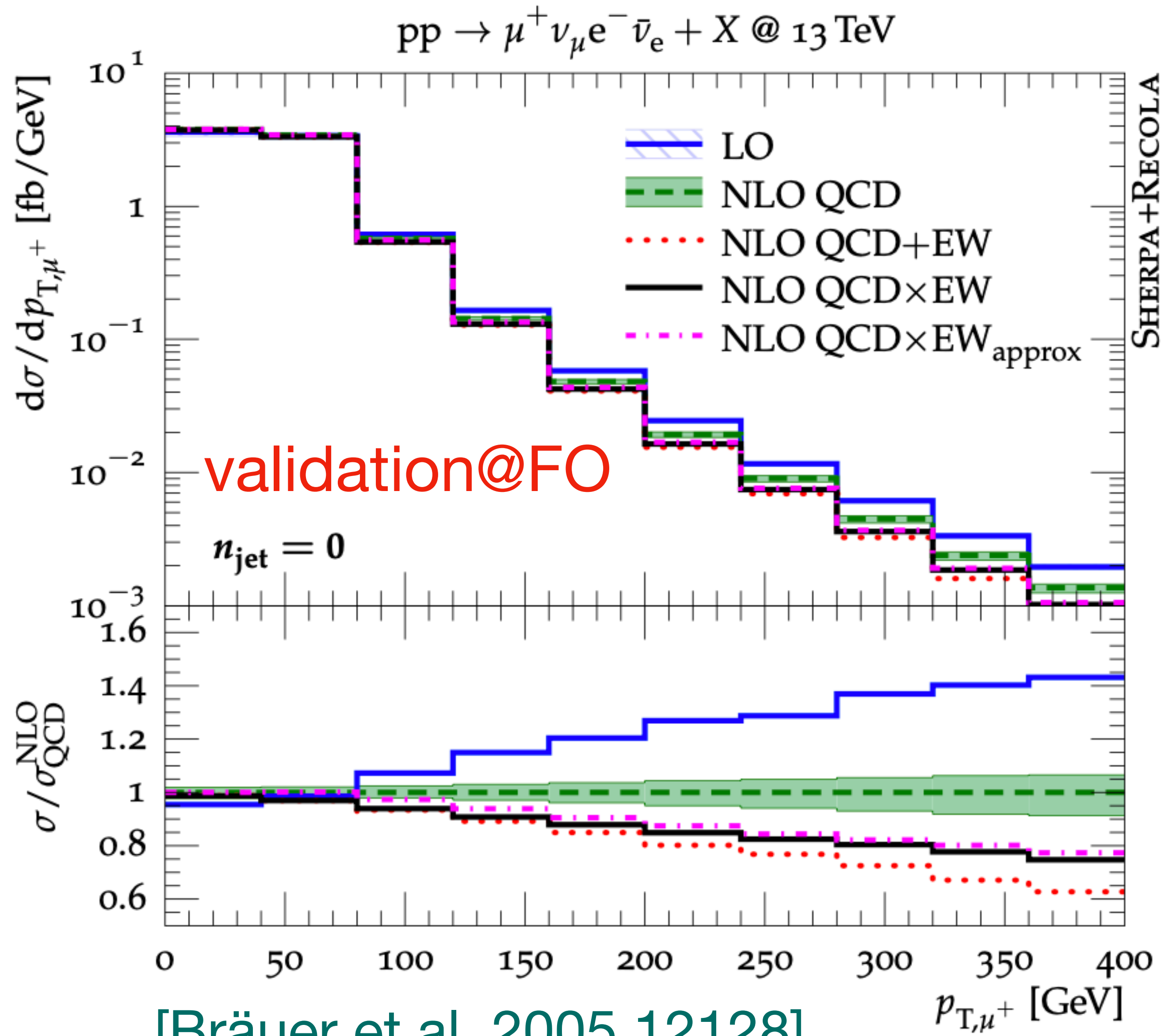
$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{approx}}}\left(\Phi_n\right) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}\left(\Phi_n\right) + \mathrm{B}_n\left(\Phi_n\right)\delta_{\mathrm{EW}}^{\mathrm{approx}} + \mathrm{B}_{n,\mathrm{mix}}\left(\Phi_n\right)$$

$$\overline{\mathrm{B}}_{n,\mathrm{QCD\times EW_{approx}}}\left(\Phi_n\right) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}\left(\Phi_n\right)\left(1 + \delta_{\mathrm{EW}}^{\mathrm{approx}}\right) + \mathrm{B}_{n,\mathrm{mix}}\left(\Phi_n\right)$$

- can also exponentiate $\left(1 + \delta_{\mathrm{EW}}^{\mathrm{approx}}\right) \to \exp\left(\delta_{\mathrm{EW}}^{\mathrm{approx}}\right)$, but consider that this will also exponentiate non-logarithmic terms in $\delta_{\mathrm{EW}}^{\mathrm{approx}}$
- real QED radiation can be added during event generation, using PS or soft-photon resummation à la YFS
- works well for large-pT regions where EW corrections dominated by virtual W/Z exchange, ≲ 5 % if observable not driven by real radiation



[Gütschow et a., Eur.Phys.J. C78 (2018) 317]

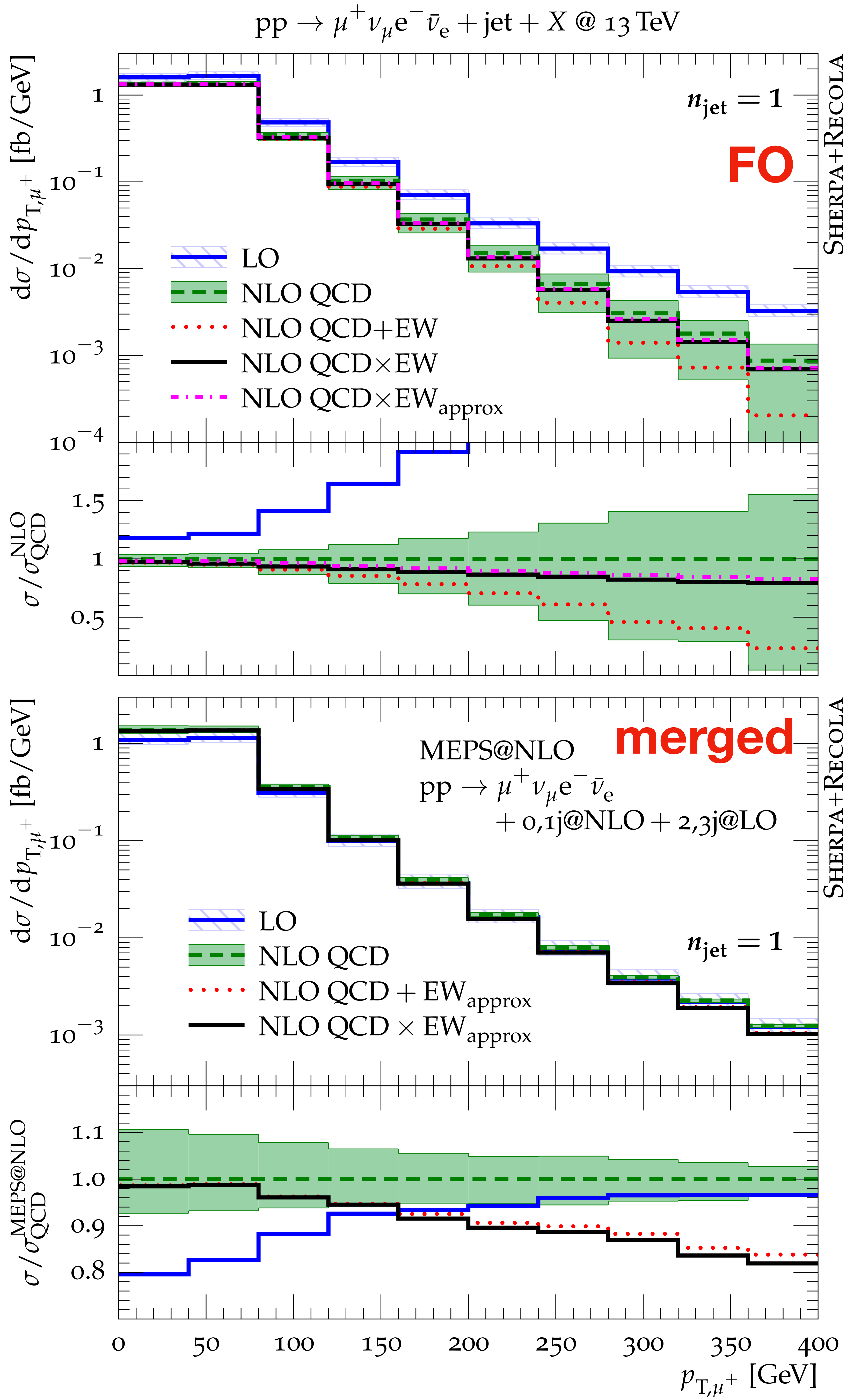


[Bräuer et al. 2005.12128]

EWvirt 2

Application to WW(j) production [Bräuer et al. 2005.12128]

- example: WWj selection, realistic experimental set-up
- NLO QCD×EW$_{approx}$ within few percent of NLO QCD×EW
- fixed-order results problematic due to jet veto logarithms
  - also induces large difference "+" vs. "×"
- parton shower in merged results stabilises QCD predictions → also "+" vs. "×" stable
- very similar EW corrections in merged sample



EWvirt 3

Some observations

- $\mathrm{EW}_{\mathrm{approx}}$ additive/multiplicative scheme (for $\overline{\mathrm{B}}_n$ K factor) ≠ schemes at FO (at histogram level):
  - additive scheme actually includes QCD×EW via higher multi procs and PS
  - No approx corrections for subtracted real emission events H_n (often quite small in merging context, because usually more LO multis follow that make up the tails, $\lesssim$ 10 % usually)
- Not expected to improve inclusive observables
- adding PS / soft-photon resummation can introduce double-counting of virtual QED corrections
  - with QED shower: dipoles that span high pT legs
  - with YFS (only applied to decays) → does not impact accuracy in targeted high-energy regime
  - both: unitarity of resummation ensures incl. xs not affected

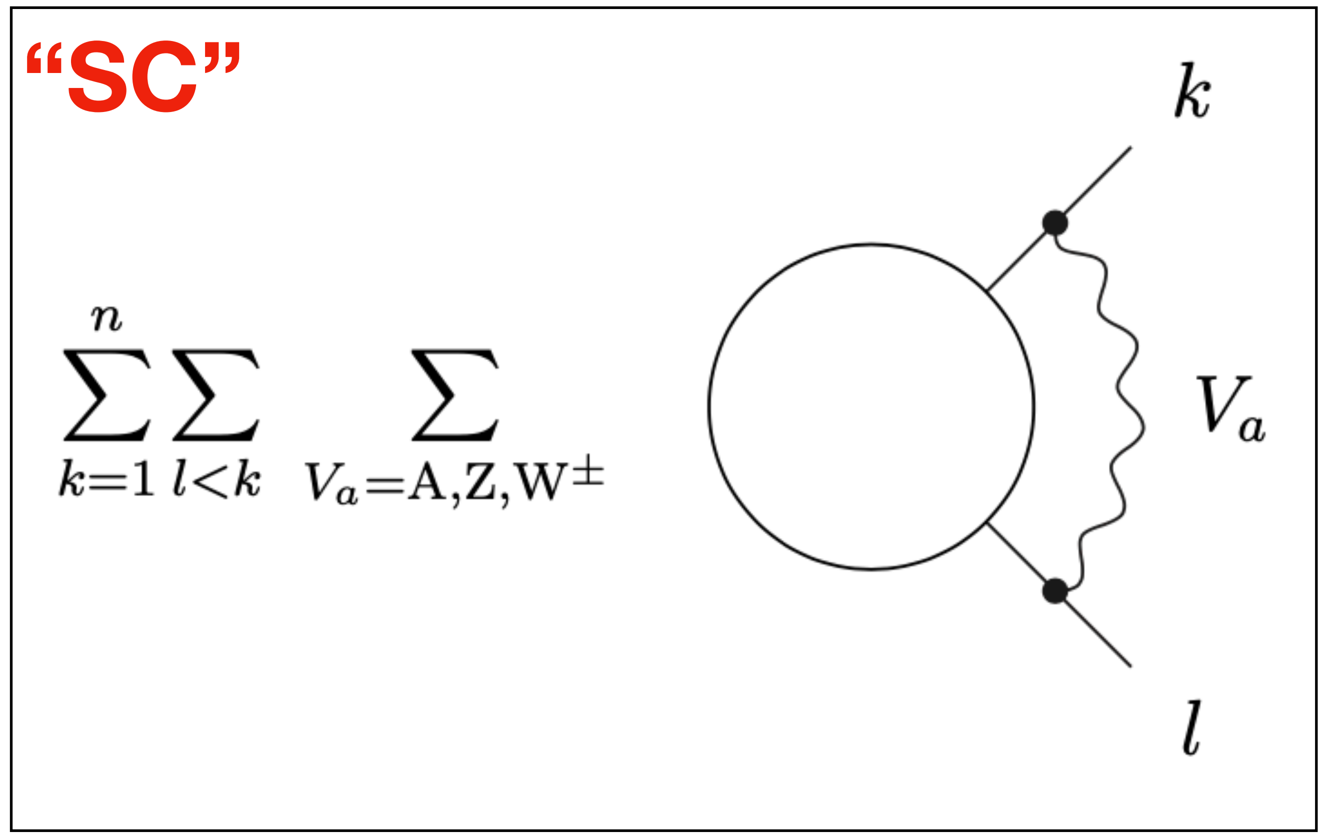
EWsud 1

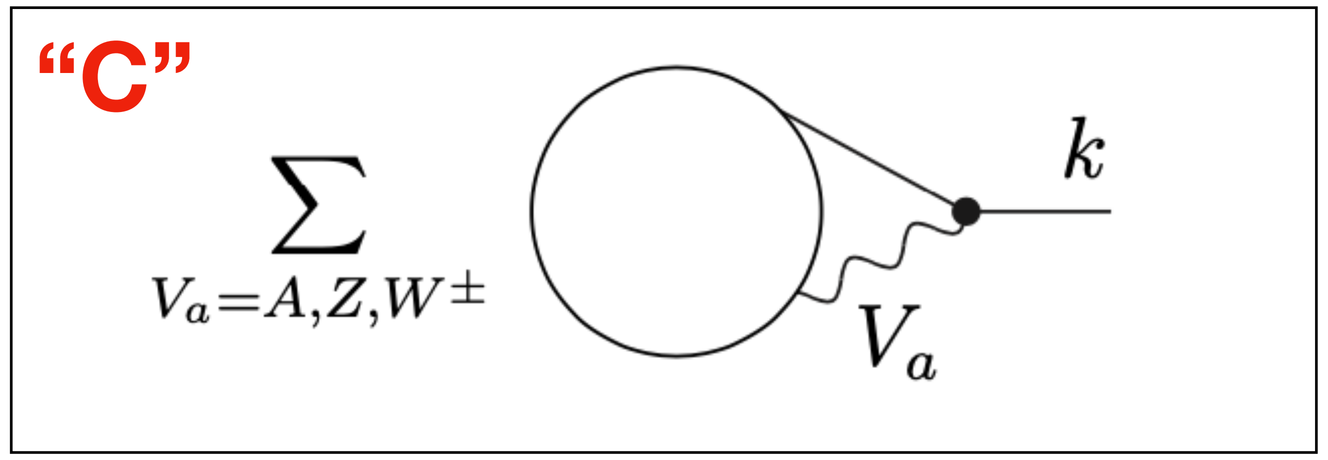
LL and NLL terms in Sudakov limit

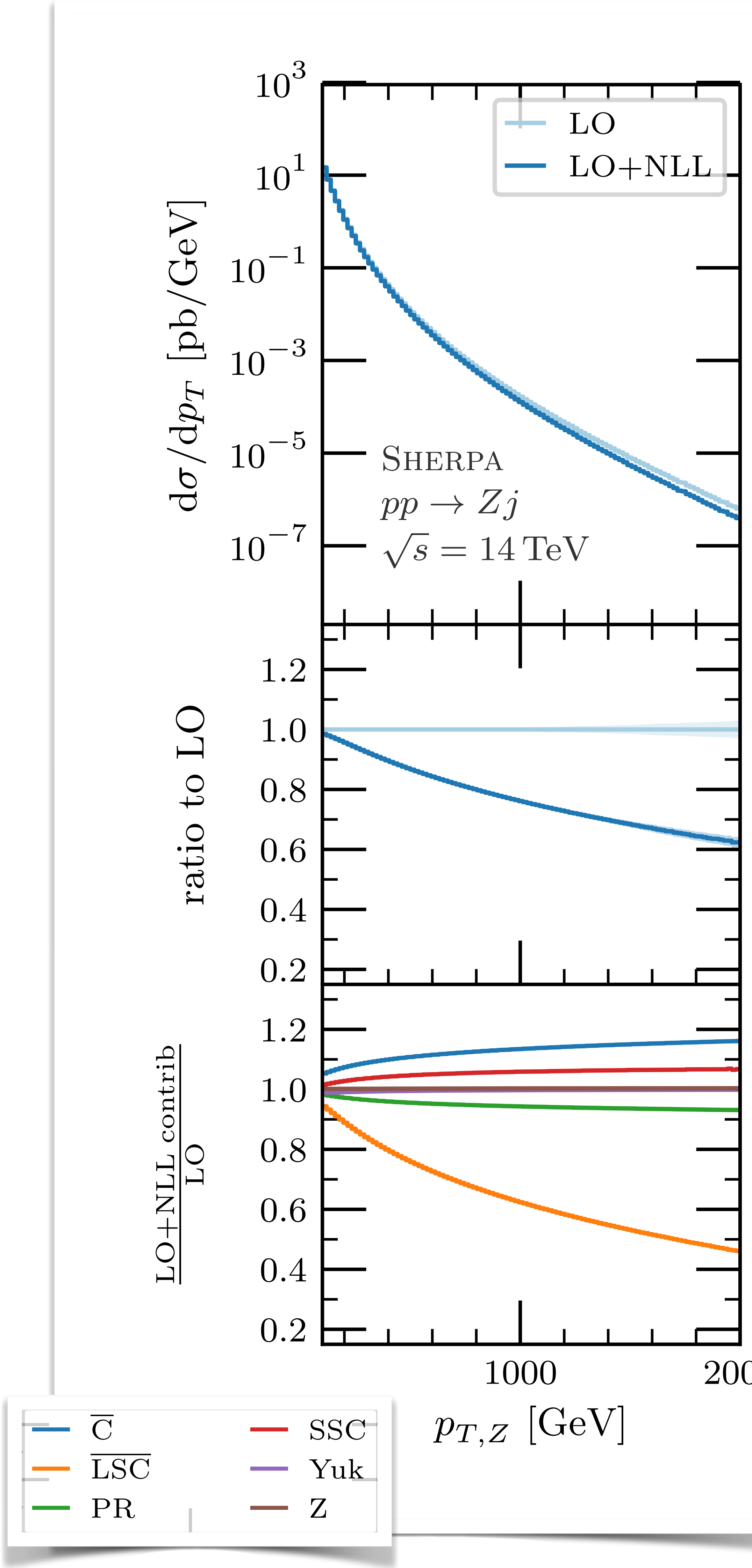
[Denner, Pozzorini (2001) hep-ph/0010201]

- calculation of all LL and NLL terms in Sudakov limit
  - "SC" soft+coll. double logs: W,Z,γ loops between pairs of ext. legs, split into …
    - LSC $\propto \frac{\alpha}{4\pi} \log^2 \frac{s}{M^2}$
    - SSC~ $\propto \frac{\alpha}{4\pi} \log \frac{s}{M^2} \log \frac{p_k \cdot p_l}{s}$
  - "C" soft/coll. single logs: ext. line splits into pair of int. lines with one W,Z,γ; and FRC $\delta Z_\varphi/2$
  - "PR" single logs from parameter renormalisation $e, c_{\mathrm{w}}, h_{\mathrm{t}}, h_{\mathrm{H}}$
- All shown to factorise for helicity amplitudes:

$$\delta \mathcal{M}^{i_1 \ldots i_n}(p_1, \ldots, p_n) = \delta^{\mathrm{Sud}}_{i'_1 i_1 \ldots i'_n i_n} \mathcal{M}^{i'_1 \ldots i'_n}(p_1, \ldots, p_n)$$







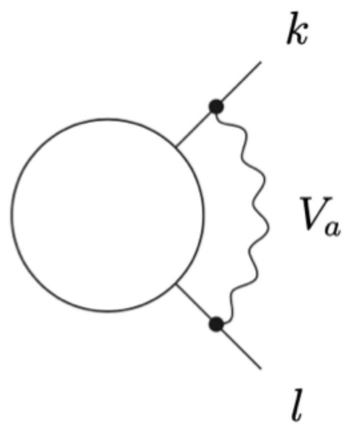
[EB, Napoletano 2006.14635]

EWsud 2

Implementation in Sherpa

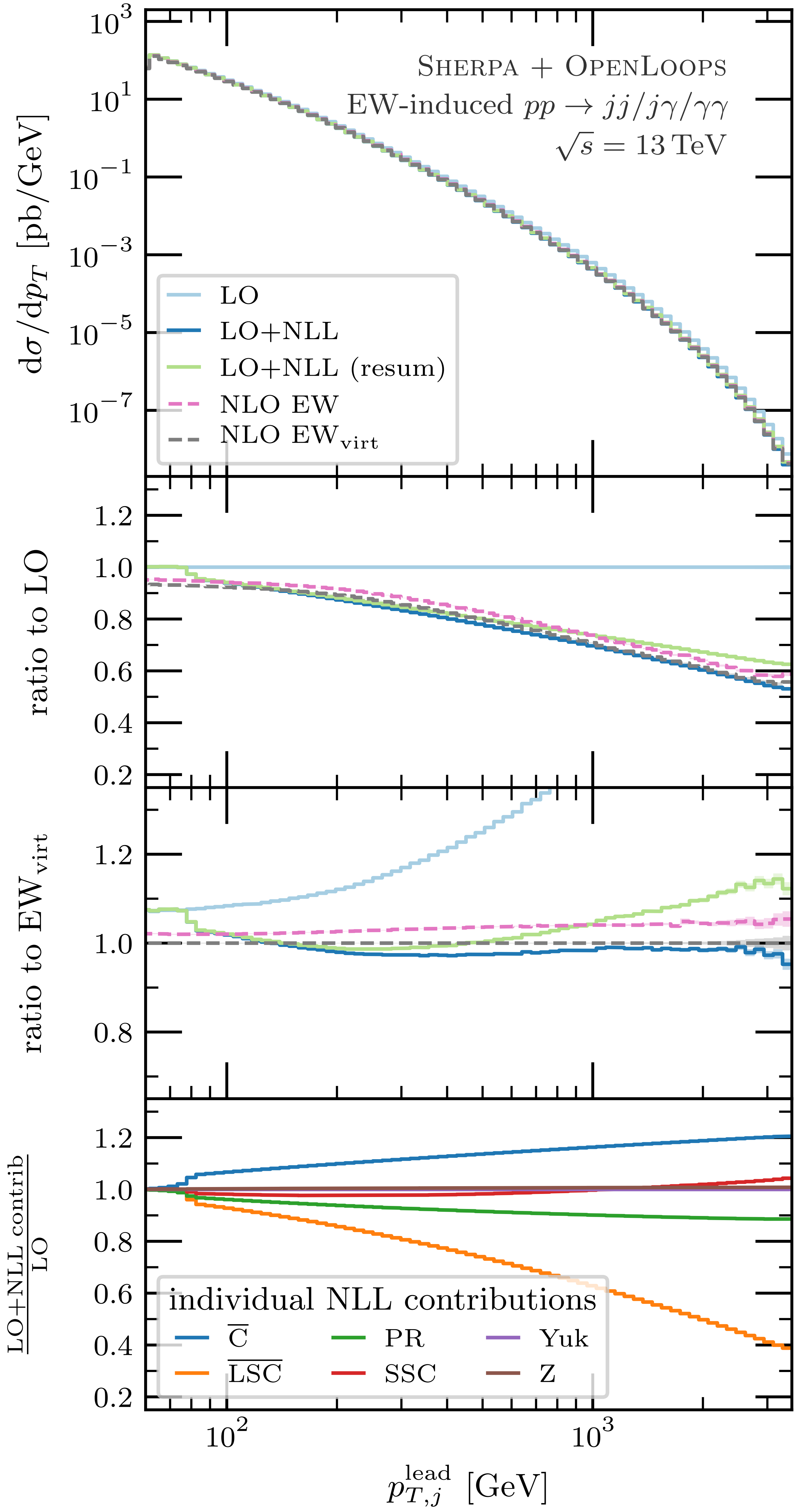
[EB, Napoletano 2006.14635]

- follows Denner/Pozzorini
- correction on amplitude level means we can implement as local K factor as with EWvirt and apply within merged/matched event generation
  - however, apply to all events, not only to $\overline{\mathrm{B}}$
- use internal COMIX ME generator to evaluate ME ratios $(\delta^{\mathrm{Sud}}\mathcal{M})/\mathcal{M} = \mathcal{M}'/\mathcal{M}$



  - allows us to be completely general and automated
- can exponentiate: $\mathrm{K} \rightarrow \exp(1 - K)$
- alternative implementation exists in AlpGen (no longitudinal W/Z modes) [Chiesa et al. (2013) 1305.6837]
  - we use the Goldstone boson equivalence theorem to overcome this limitation, as in Denner/Pozzorini

$$\epsilon_{\mathrm{L}}^{\mu}(p) = \frac{p^{\mu}}{M} + \mathcal{O}\left(\frac{M}{p^{0}}\right)$$



[EB, Napoletano 2006.14635]

EWsud 3

Processes with resonances

[EB Napoletano Schönherr Schumann Villani tbp]

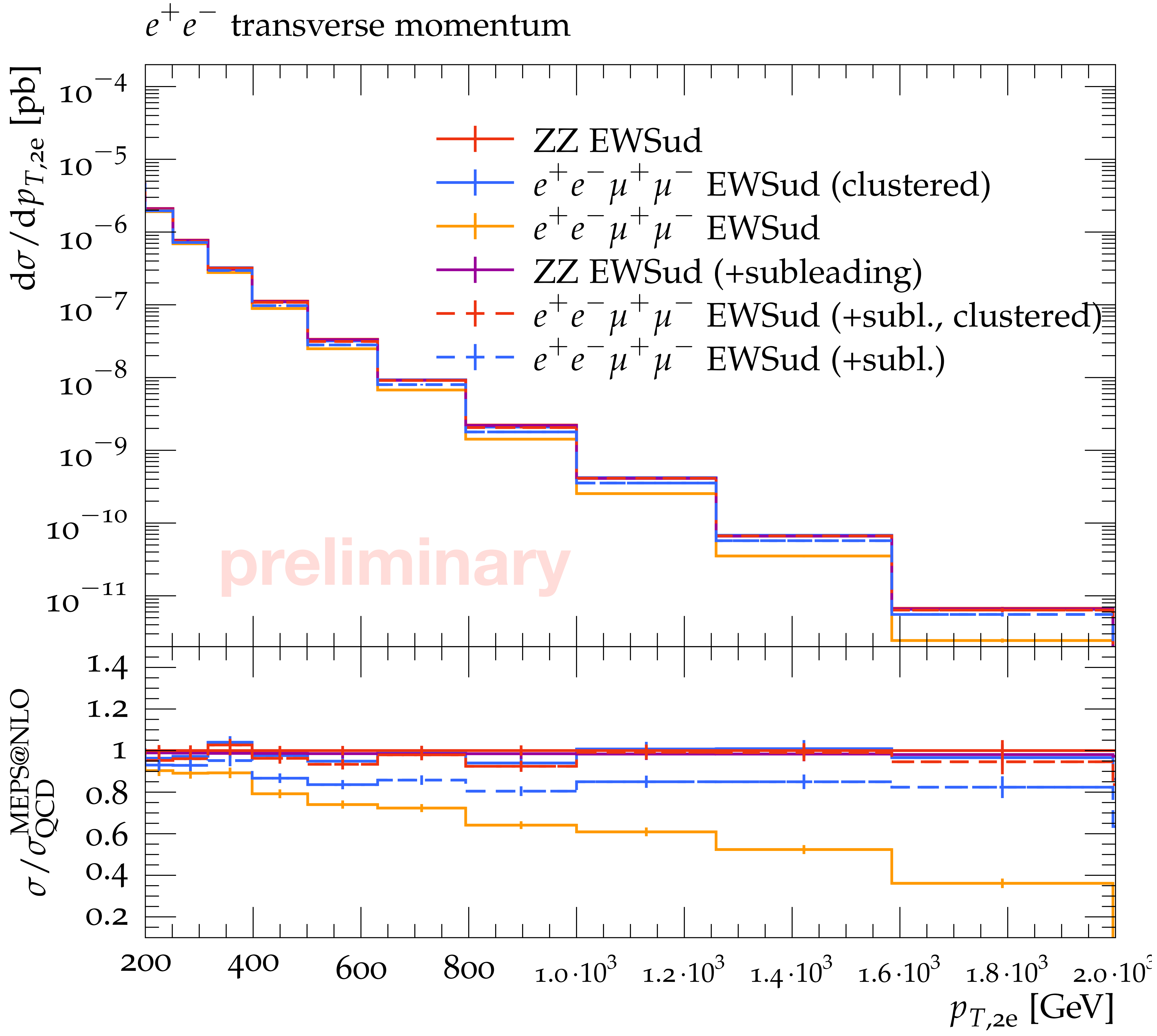
- all invariants should be
  $r_{kl} = (p_k + p_l)^2 \sim 2p_k p_l \gg M_W^2$
- $d\sigma$ better not have any resonances
- consider e.g. two leptons $f_{1,2}$ from a W/Z decay:

$$\text{SSC} \propto \frac{\alpha}{4\pi} \log \frac{s}{M^2} \log \frac{p_{f_1} \cdot p_{f_2}}{s}$$

- overcome by using resonance finder

$$\Delta = \left| m_{f_1 f_2} - m_{\text{res}} \right| / \Gamma_{\text{res}} < \Delta_{\text{thr}}$$

- cluster leptons into bosons, then calculate logarithms for clustered amplitude (NWA)



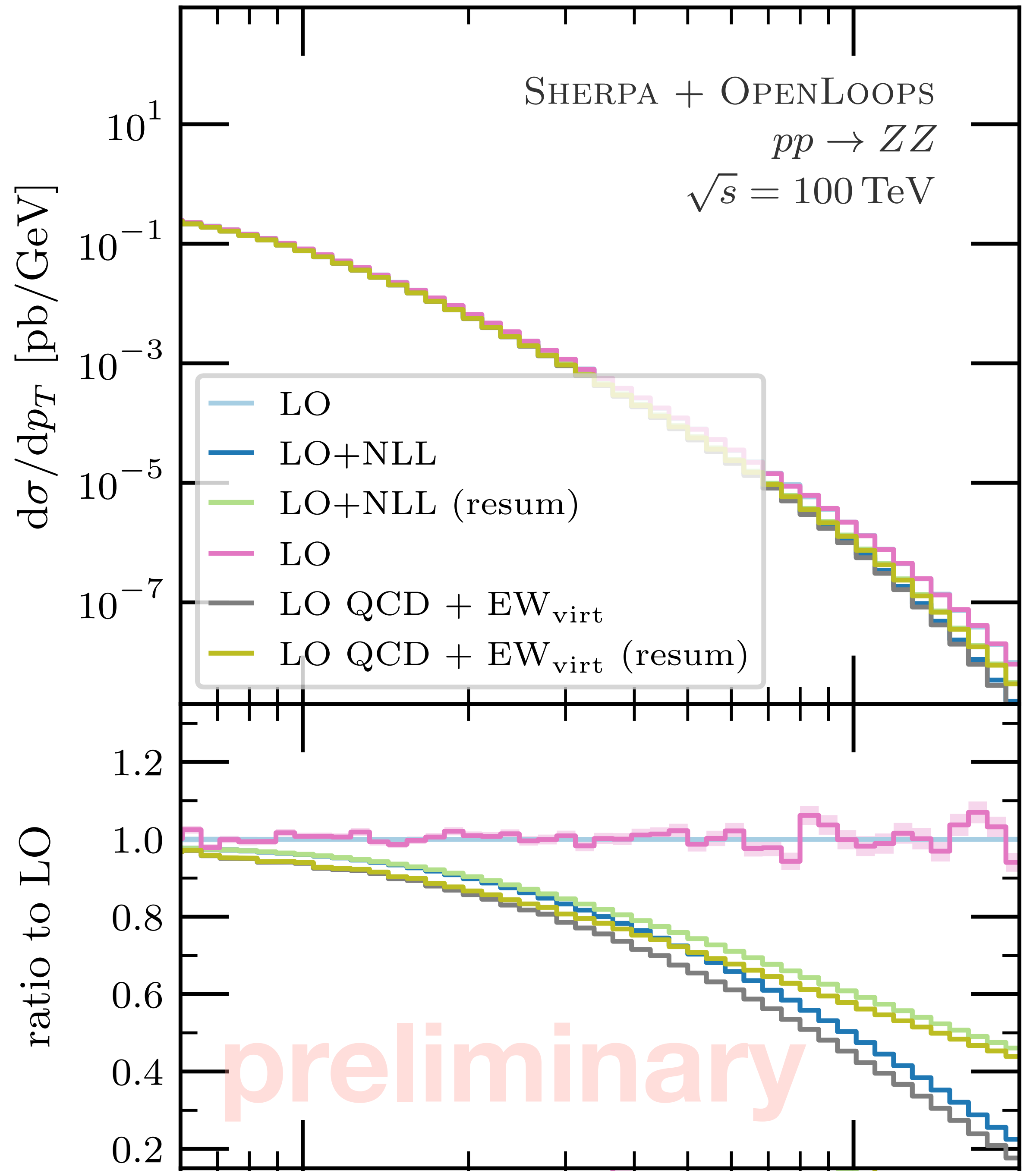
EWvirt & EWsud

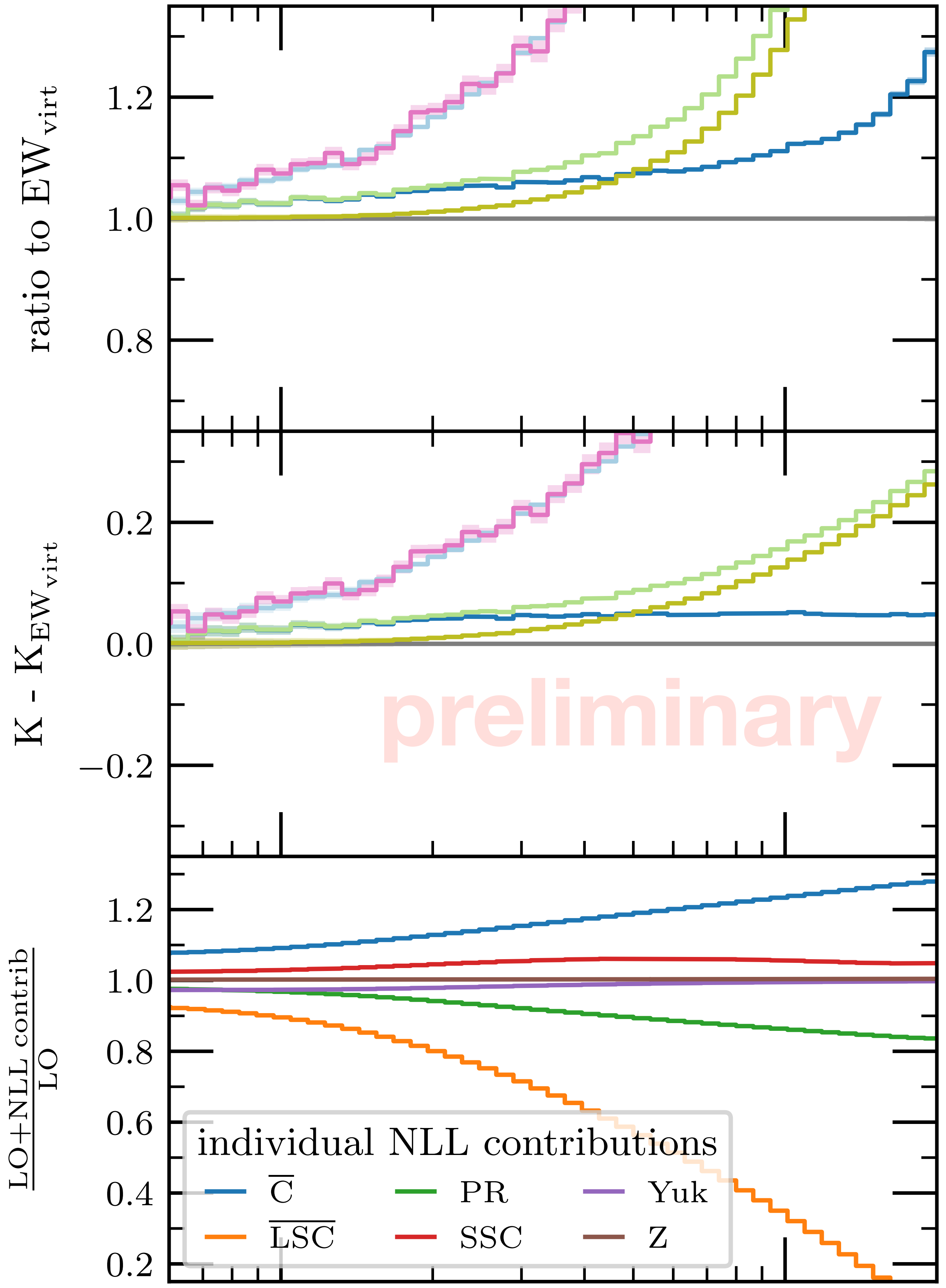
Comparative study in ZZ production

[EB Napoletano Schönherr Schumann Villani tbp]

- Both schemes capture dominant logs in Sudakov region → while no perfect agreement, usually see K factors consistent within couple percent
- EWvirt:
  - + subleading Born (can be sizable, e.g. in 3-jet production) [Reyer Schönherr Schumann 1902.01763]
  - + approx. integrated real emission
  - + finite terms in virtual loop
  - - not applied to real-emission events
  - - requires virtual loop ME, and if we have it, it's still expensive
- EWsud has no finite terms, but is cheap and can be applied everywhere
- **proposal**: apply EWvirt to lower multis and EWsud to real-emission terms and higher multis, in a single merged sample („Hybrid")
  - capture finite corrections (~incl. EW K factor) in low p_T region
  - smoothly transition to high p_T / large multi behaviour, where real-emission/higher multiplicity events take over

LO+PS ZZ production





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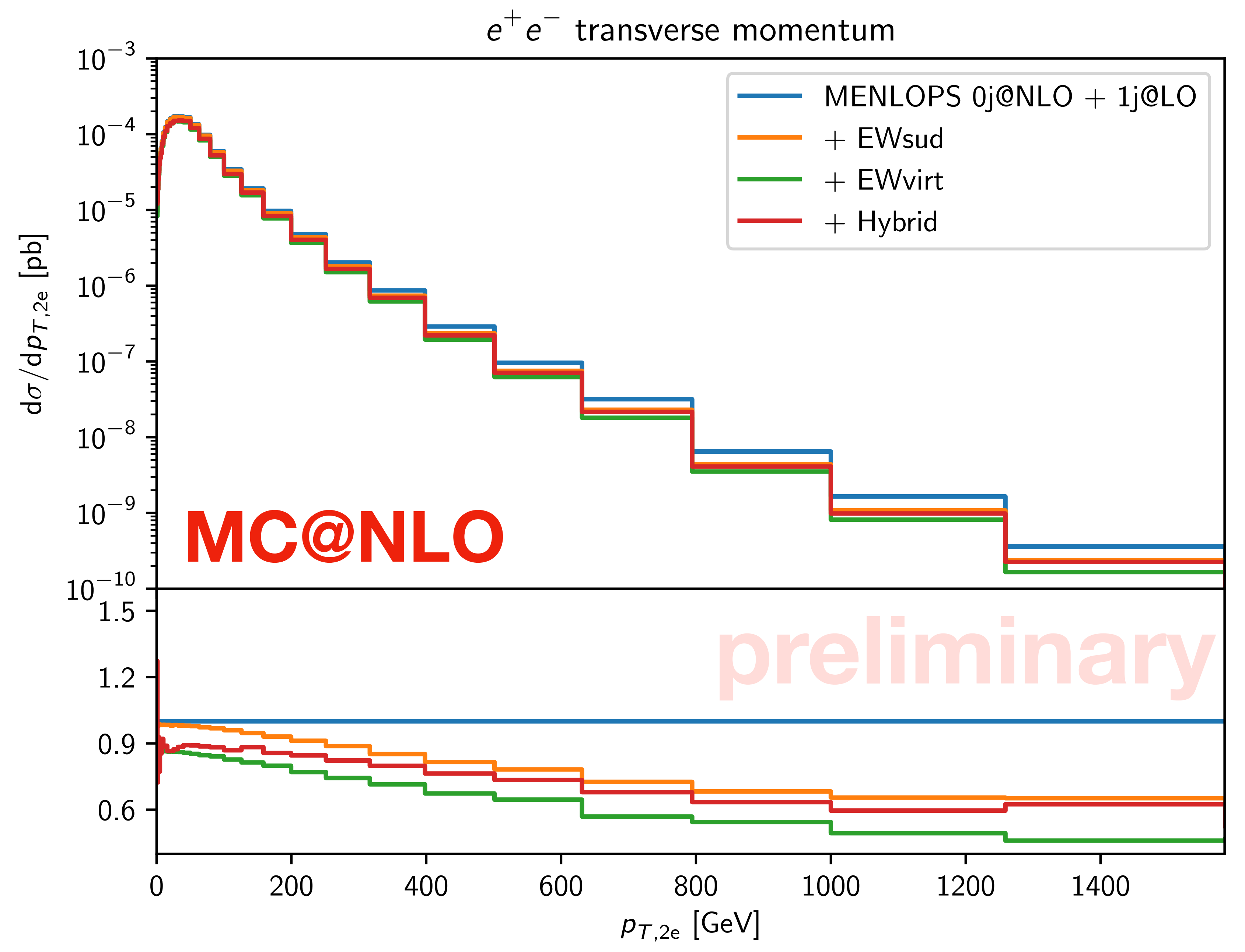
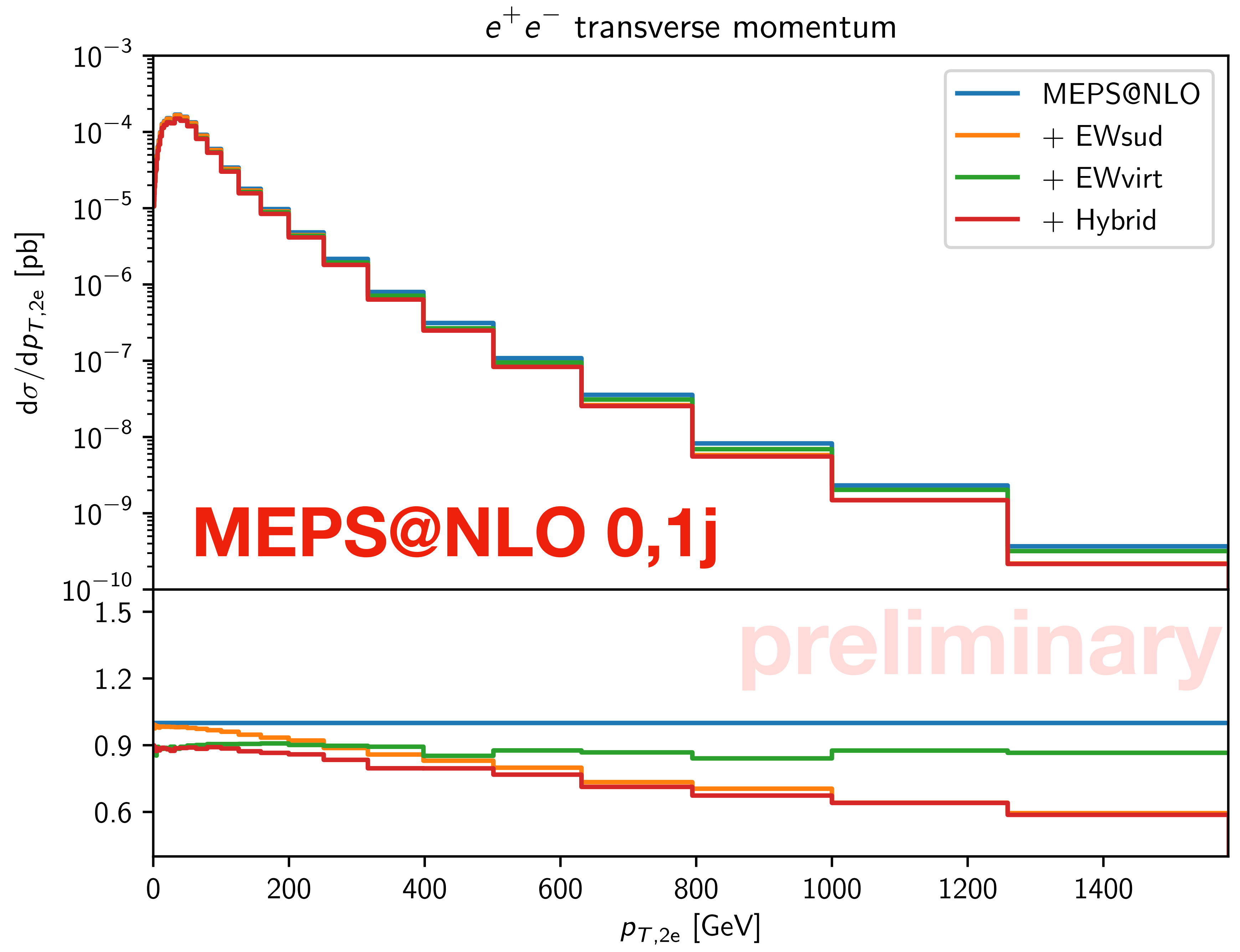




Conclusions

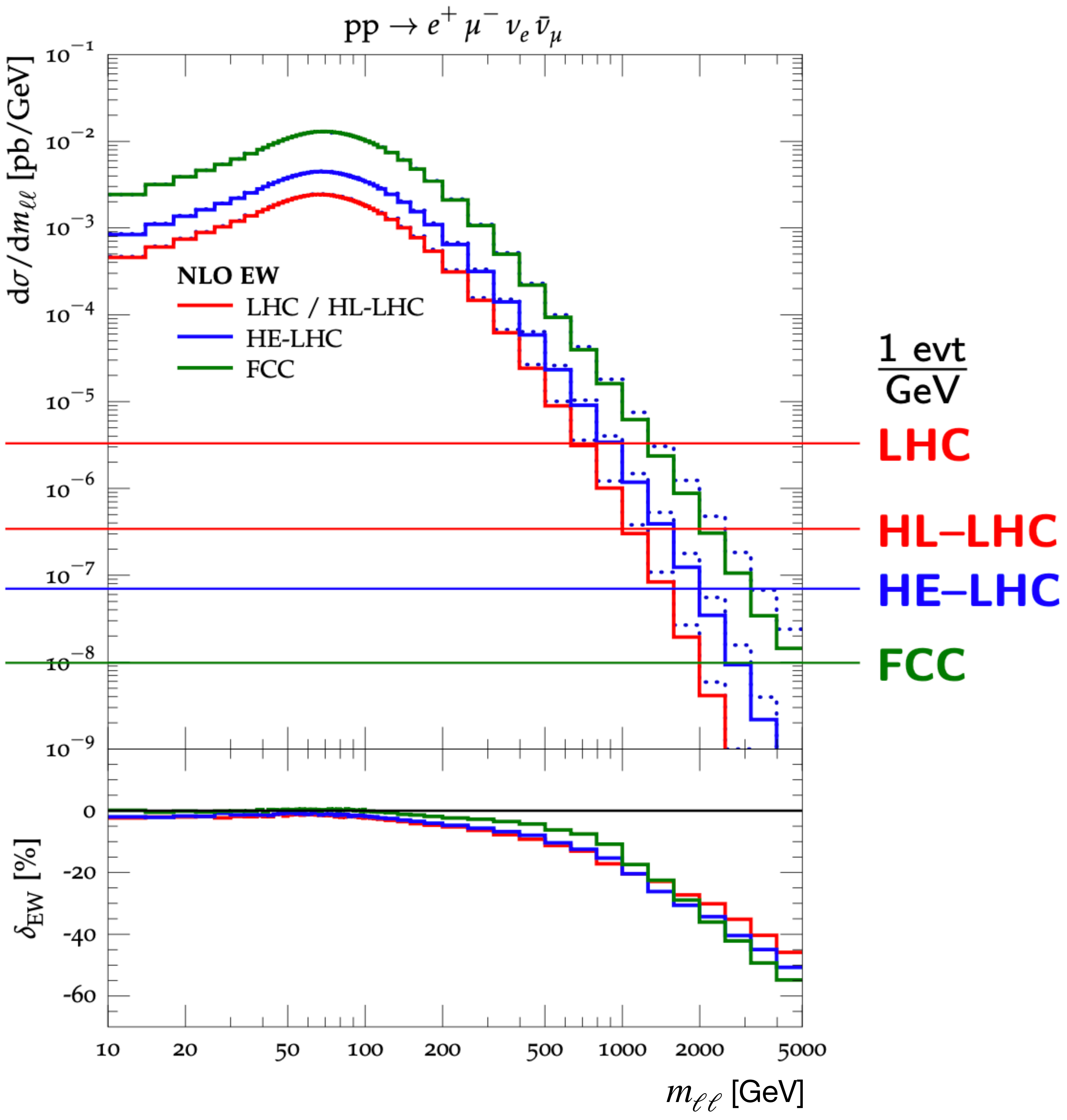
- electroweak effects are increasingly important at LHC (Run 2), HE–LHC, FCC, etc.
- become large whenever the process scale is large compared to EW scale
- can be incorporated as an approximation in multi-jet merged event generation to improve description in those regions
    - EWvirt included since Sherpa 2.2.1
    - EWsud will be added in Sherpa 3.x
    - comparative study in ZZ, exploration of Hybrid scheme

Thank you!

Back-up

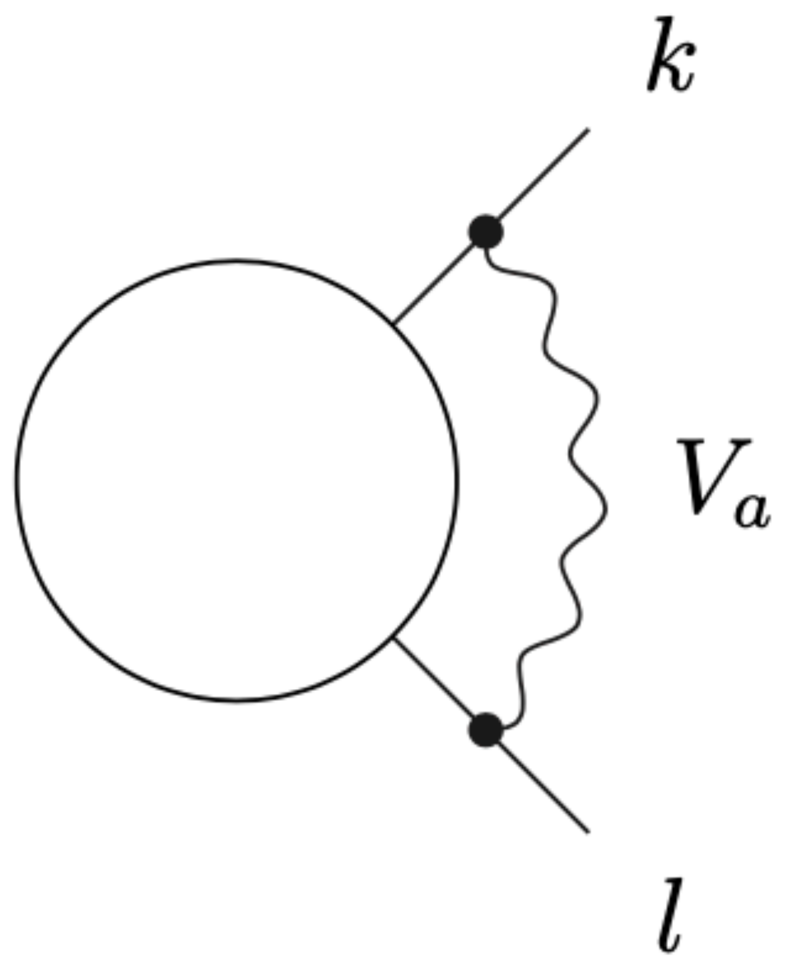
Collider reach

- Plot taken from a talk by Marek Schönherr
- How far the integrated luminosity takes us into the Sudakov region



Subleading SC term

$$\sum_{k=1}^{n} \sum_{l<k} \sum_{V_a = A, Z, W^{\pm}}$$



$$r_{kl} = \left(p_k + p_l\right)^2 \sim 2 p_k p_l \gg M_{\mathrm{W}}^2$$

$$L\left(\left|r_{kl}\right|, M^2\right) := \frac{\alpha}{4\pi} \log^2 \frac{r_{kl}}{M^2}$$

$$L\left(\left|r_{kl}\right|, M^2\right) = L\left(s, M^2\right) + 2l\left(s, M^2\right) \log \frac{\left|r_{kl}\right|}{s} + L\left(\left|r_{kl}\right|, s\right)$$

Support of NLO EW+QCD in POWHEG-BOX

- NLO EW+QCD matched to QCD+QED PS V* production
  Barzè et al 2012, 2013 https://arxiv.org/abs/1202.0465 https://arxiv.org/abs/1302.4606

- NLO EW+QCD matched to QCD+QED PS for HV*+0,1j merged with MiNLO using OpenLoops
  Granata et al 2017 https://arxiv.org/abs/1706.03522

- NLO EW matched to QED PS same-sign W*W* production using Recola2
  Chiesa et al 2020 https://arxiv.org/abs/1906.01863

- NLO EW+QCD matched to QCD+QED PS V*V* production using Recola2
  Chiesa Oleari Re 2020 https://arxiv.org/abs/2005.12146

- …

EWSudakov: GBET

Derivation of gauge invariance from high-energy unitarity bounds on the S matrix*

John M. Cornwall,[†] David N. Levin, and George Tiktopoulos
Department of Physics, University of California at Los Angeles, Los Angeles, California 90024
(Received 21 March 1974)

- Set masses to zero in loop integrand numerator
  - → Feynman rules should have no inverse powers of M_{V_a}

- BUUUT what about the HE limit of longitudinal polarisation vectors!?

$$\epsilon_{\mathrm{L}}^{\mu}(p) = \frac{p^{\mu}}{M} + \mathcal{O}\left(\frac{M}{p^0}\right)$$

→ derivation of Denner/Pozzorini not applicable!

- Use the Goldstone-Boson Equivalence Theorem (GBET)

$$\mathcal{M}_0^{\ldots \mathrm{W}_{\mathrm{L}}^{\pm}} = \mathcal{M}_0^{\ldots \phi^{\pm}}$$

$$\mathcal{M}_0^{\ldots Z_{\mathrm{L}} \ldots} = \mathrm{i}\mathcal{M}_0^{\ldots \chi \ldots}$$

→ ALPGEN does not support GB, hence no V_a^L corrections

one-loop corrections of the GBET:

→ do not contain DL

→ DL corrections can use Born approximation on the left

Tackling this w/o GB?:

→ [Cuomo, Vecchi, Wulzer (2019) 1911.12366]

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  - no subleading logs from RG
  - requires virtual loop ME
- don't expect perfect agreement, but so far we see K factors consistent within couple percent
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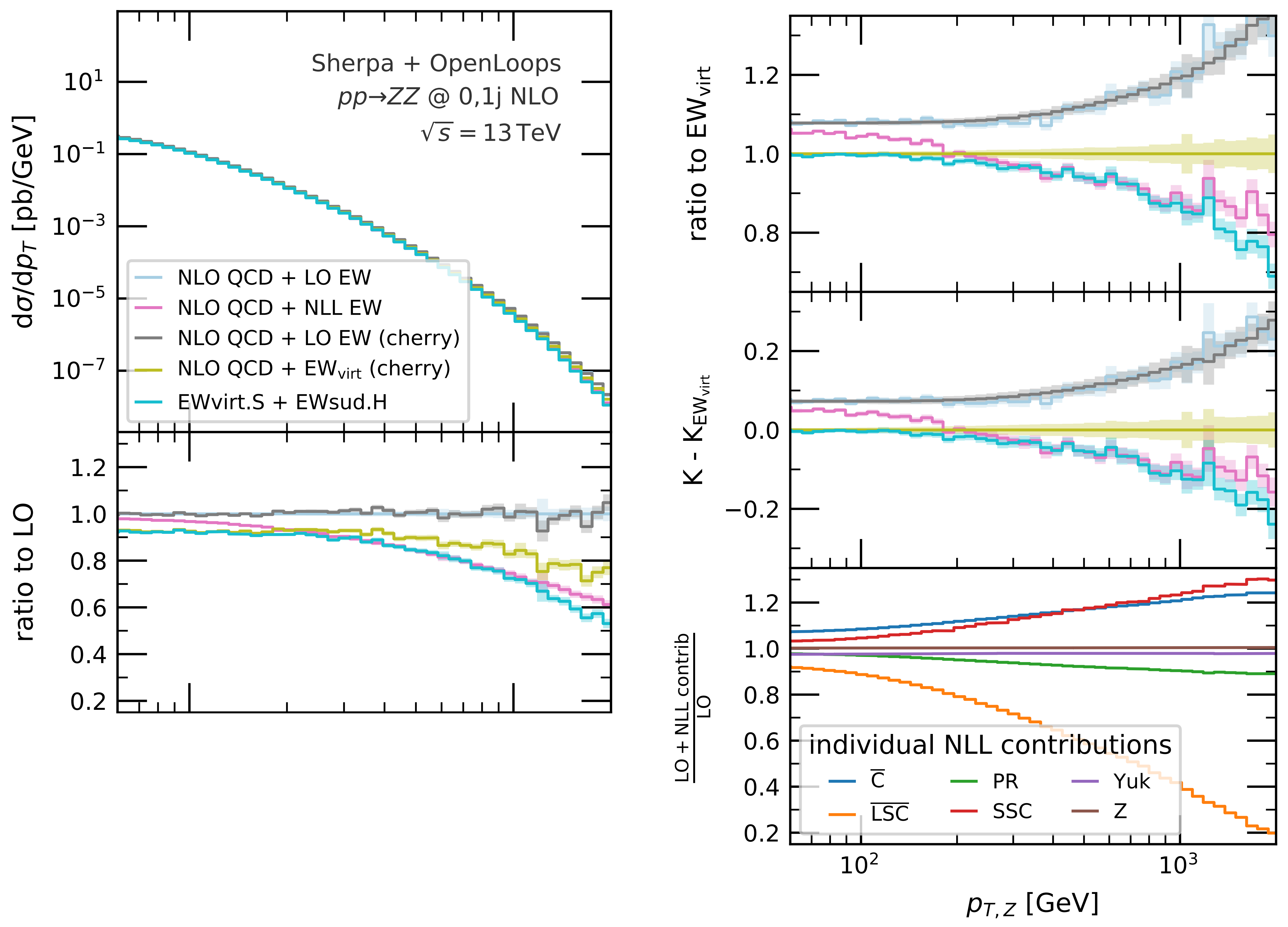
preliminary, MEPS@NLO ZZ production, 0,1j@NLO, 3,4j@LO

Hybrid: EWvirt.S + EWsud.H + EWsud.j4



ZZ LO validation

EWvirt/sud vs. EW NLO

- even more preliminary than the other plots
- EWvirt lacks KP terms, real emissions
- EWsud lacks finite terms, ~20%
- EW renormalisation scheme dependence as uncertainty?