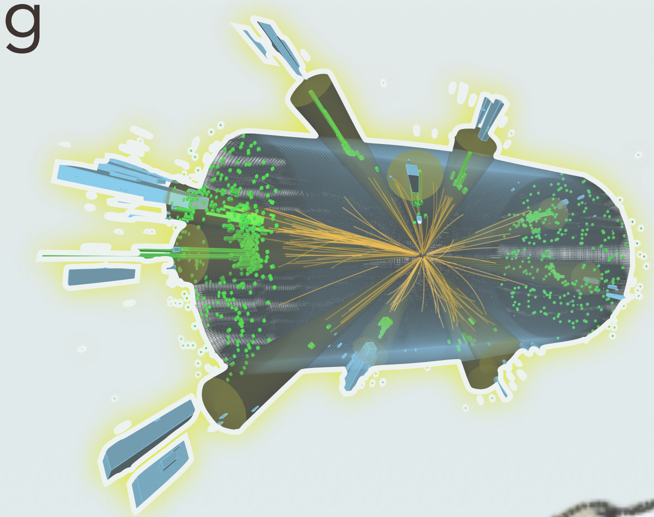
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Institut für Theoretische Physik

Z[$\ell\ell$]+jets benchmarks with Sherpa-2.2.7

LHC EW Jets and EW Bosons Subgroup Meeting

28 May 2019

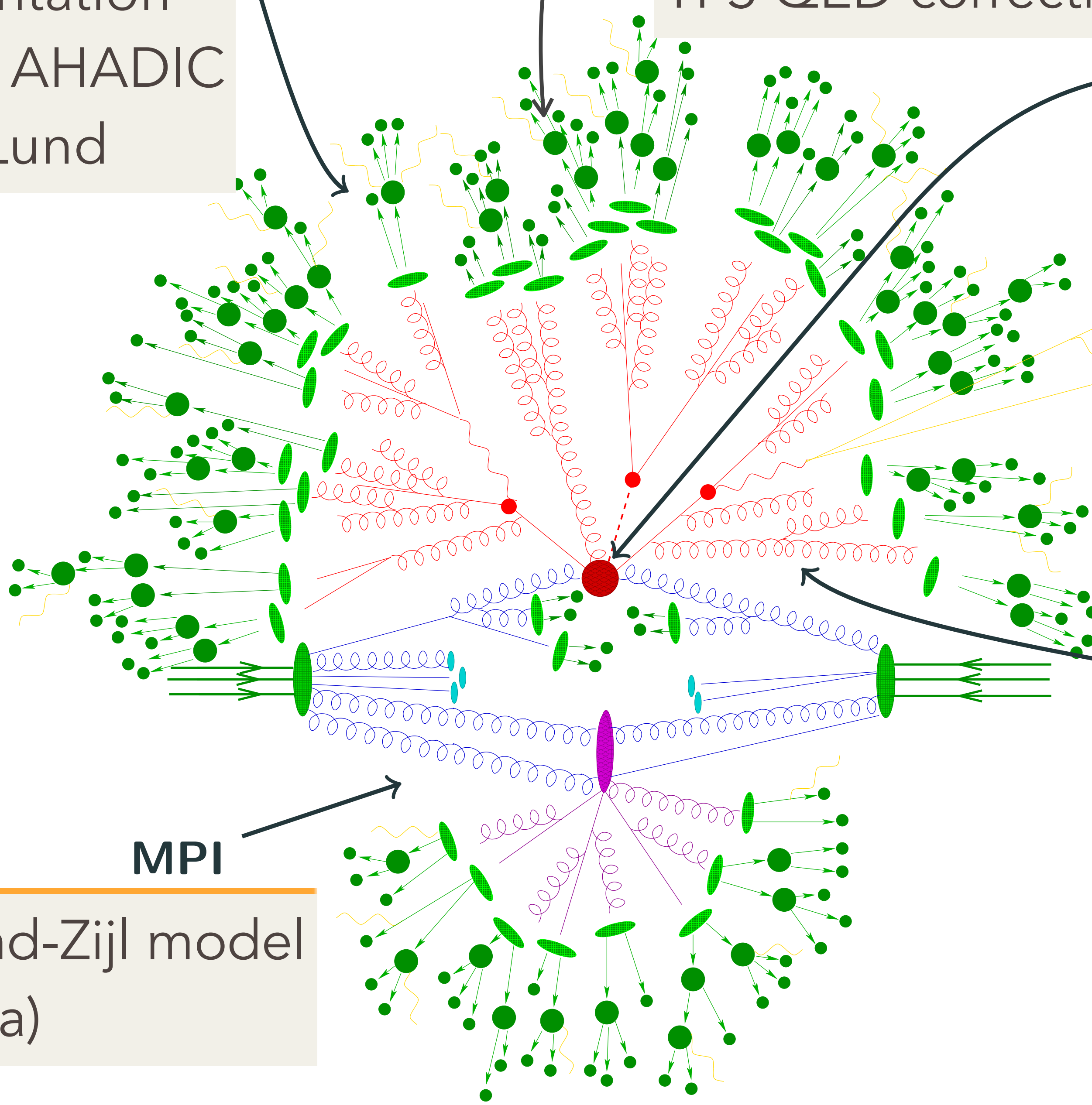


Enrico Bothmann

MCnet

Sherpa overview

[Gleisberg et al. 0811.4622]



Hadronization

Fragmentation
Cluster: AHADIC
String: Lund

Hadron Decays

Phase-space or EFTs
YFS QED corrections

Hard process

LO, NLO QCD/EW*, NNLO QCD**
ME generators (Amegic & Comix)
hard decays (W, Z, h, t, BSM)

Parton shower

parton showers (CS & Dire)
QED (YFS resummation & shower)

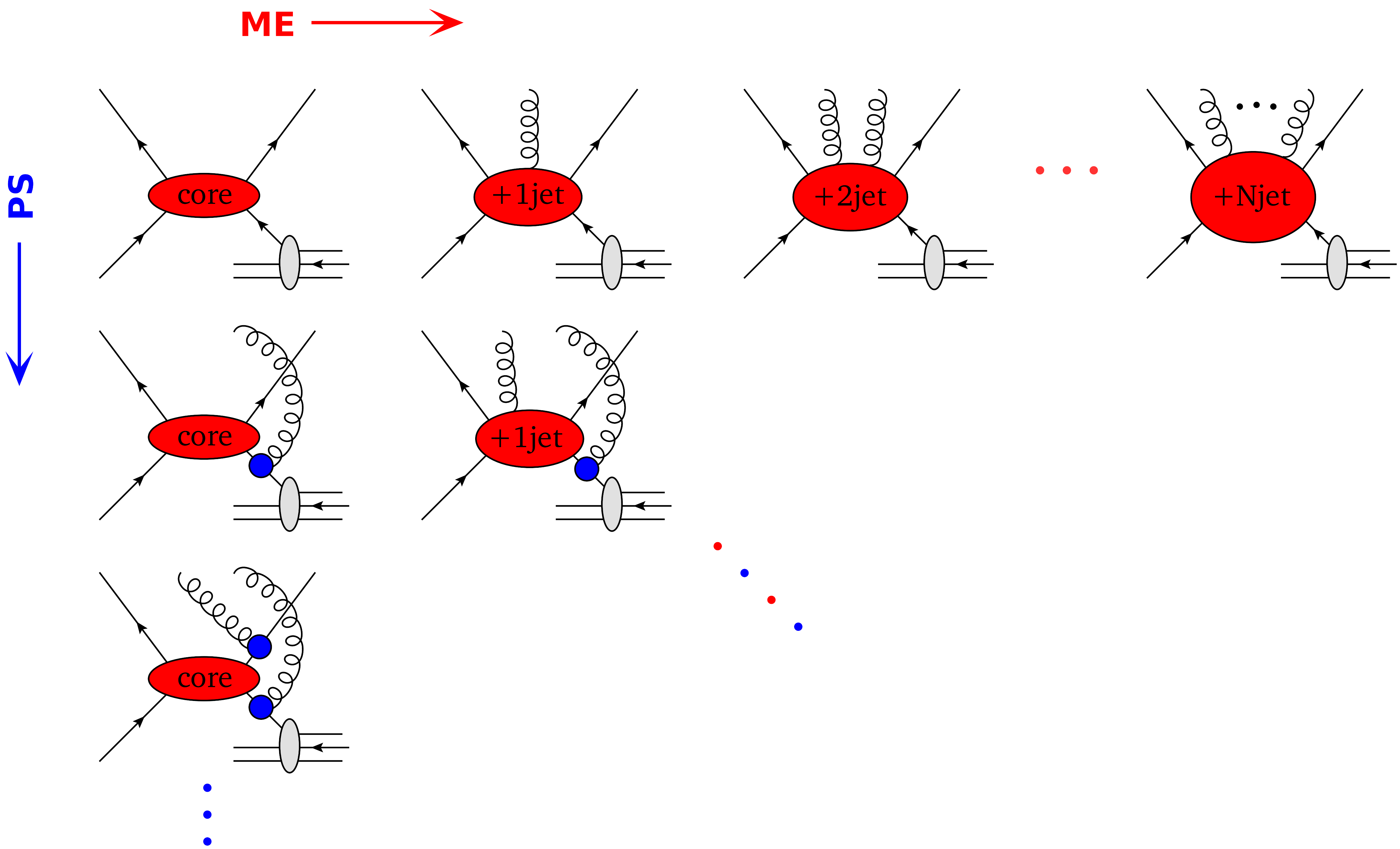
MPI

Sjöstrand-Zijl model
(~ Pythia)

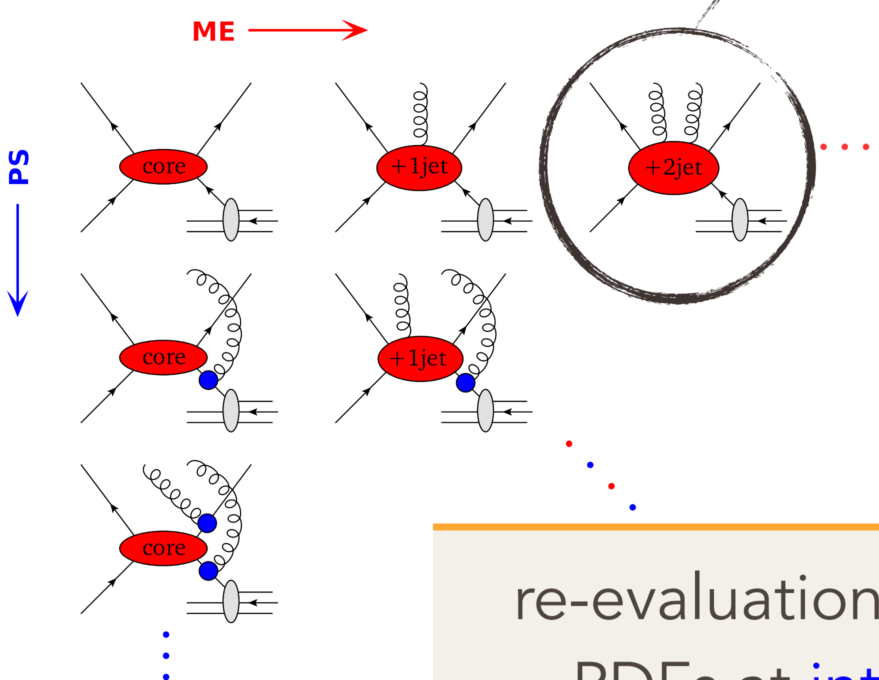
Sherpa pQCD calculations for $Z[\ell\ell]$(+jets)

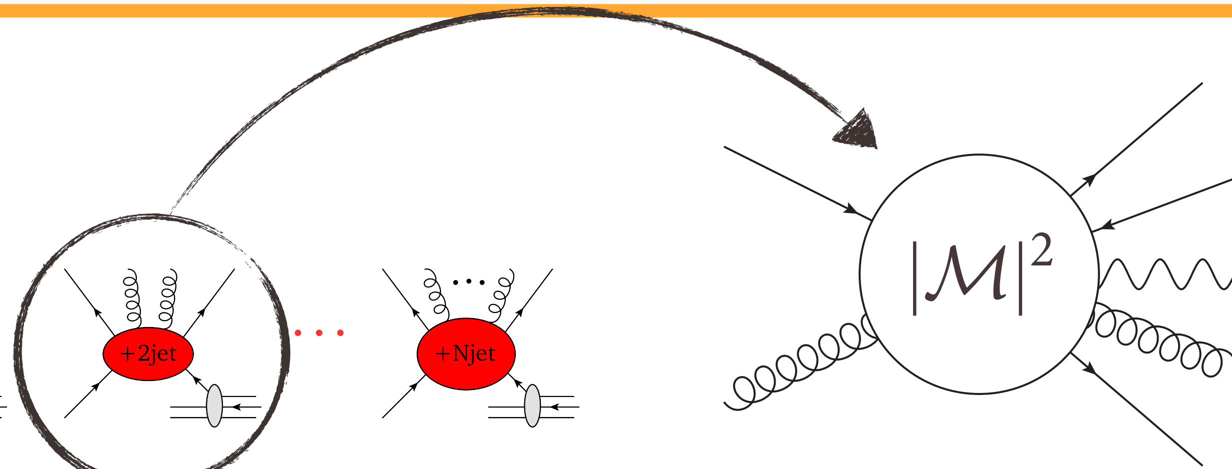
- methods available to generate $Z[\ell\ell]$(+jets) predictions include:
  - **Fixed-order** (LO, NLO, NNLO)
    - NNLO QCD and NLO EW for incl. Z
    - NLO QCD and NLO EW für $Z[\ell\ell]+j^n$ (for QCD, $n \leq 4$)
    - parton-level
  - **Parton-shower matched** (LOPS, NLOPS/MC@NLO, NNLOPS)
    - NNLOPS for incl. Z
    - NLOPS (S-MC@NLO) for $Z[\ell\ell]+j^n$ ($n \leq 4$)
    - particle-level, but not predictive for multi-jet observables
  - **Multi-jet merged** (MEPS@LO, MEPS@NLO, MENLOPS)
    [Höche et al. 0903.1219, 1009.1127]
    - NLOPS (S-MC@NLO) for $Z[\ell\ell]+j^n$ ($n \leq 4$), can add more multiplicities at LOPS
    - particle-level, predictive for multi-jet observables
- full pQCD reweighting for on-the-fly uncertainties in all modes
  [EB,Schönherr,Schumann 1606.08753]

Multi-jet merging



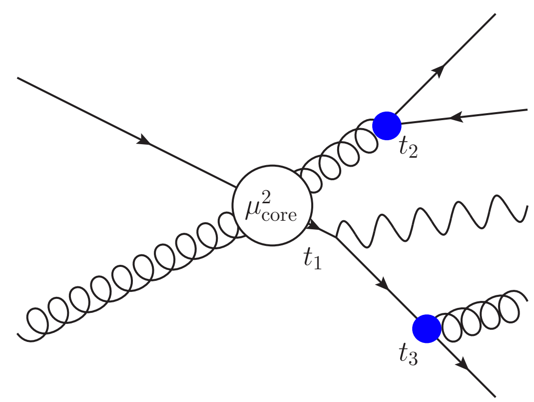
Multi-jet merging: algorithm





re-interpretation as
parton-shower history

re-evaluation of α_S and PDFs at intermediate splitting t_i scales

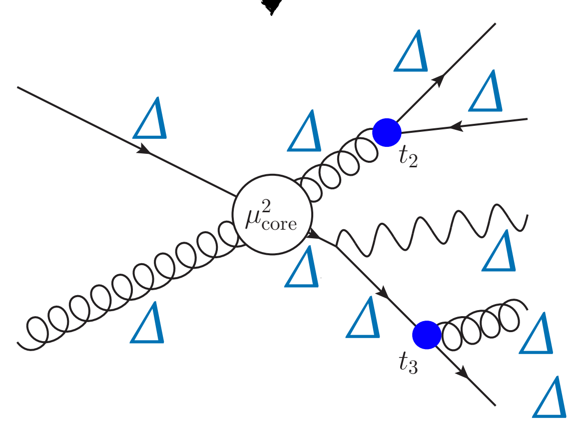


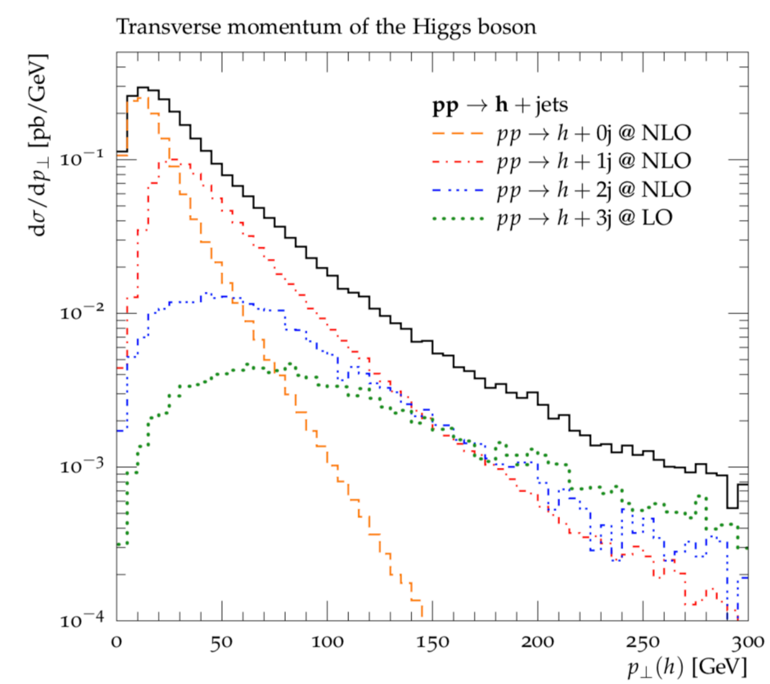
METS scale setter:

$$\alpha_s^{n+j}(\mu_R^2) = \alpha_s^{n+e}(\mu^2_{R,\rm core}) \prod_{i=1}^{j} \alpha_s^{1-\epsilon_i}(k_{\alpha_s} t_i)$$

introduce $Q_{\rm CUT}$

Sudakov rejection to make matrix elements exclusive down to $Q_{\rm CUT}$





finally add genuine parton-shower emissions below $Q_{\rm CUT}$

EW corrections in particle-level evtgen

slide adapted from Marek Schönherr

[Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr 1511.08692]

- already many QCD+EW NLO *fixed-order* results
  V*+1,2j, W+1,2,3j, γ+j, also $\gamma\gamma$+0,1,2j, $\gamma\gamma\gamma$, $\gamma\gamma$V*, Z*Z*, ttH, W*W*W*, tt+0,1j

- particle-level not automated yet, but approx. EW corrections in MEPS@NLO though K factor to Born configuration:

$$\bar{B}_{n,\mathrm{QCD+EW_{approx}}}(\Phi_n) = \bar{B}_{n,\mathrm{QCD}}(\Phi_n) + V_{n,\mathrm{EW}}(\Phi_n) + I_{n,\mathrm{EW}}(\Phi_n) + B_{n,\mathrm{mix}}(\Phi_n)$$

- real QED radiation through parton shower / YFS
- stand-in for proper matching & merging
- comparisons to fixed-order, found to be reliable:
  - $\lesssim$ 5 % if observable not driven by real radiation
    inaccurate e.g. for $m_{\ell\nu} < m_V$ due to large real photon radiation corrections

Roadmap / https://gitlab.com/sherpa-team/sherpa

- 2.2.6 (current)
  - EW_{approx} within merging as alternate event weights
  - include sub-leading terms in MEPS@NLO in on-the-fly reweighting
  - bugfixes
- 2.2.7 (~hours/days)
  - improvements+fixes for massive quark production
  - bugfix in shower reweighting
  - better support for recent Rivet and OPENLOOPS 2
  - bugfixes

- 3.0.0 (~few months)
  - partial NLO shower, sub-leading colour effects [Dulat, Hoeche, Krauss, Prestel 1705.00982, 1705.00742, 1805.03757]
  - complete NLO EW subtraction automation [Schönherr 1712.07975]
  - semi-automated MC@NLO for loop-induced processes [Jones, Kuttimalai 1711.03319]
  - improved HPC support [Benjamin, Childers, Höche, LeCompte, Uram J.Phys.Conf.Ser. 898 (2017) 072044]
  - physical colour flow in VBF-like configurations

☛ up-to-date infos: gitlab/tags & gitlab/milestones
☛ communicate with us via our gitlab/issue-tracker

Sherpa 2.2.7 Z[ee]+jets @ 13 TeV benchmarks

Sherpa 2.2.6 Z[ee]+jets @ 13 TeV benchmarks

event generation

- MEPS@NLO
  V + 0,1,2j@NLO + 3,4j@LO
  Q_{CUT} = 20 GeV
- NNPDF30_nnlo_as_0118 default
- $\alpha_S(m_Z) = 0.118$ default
- default core scale μ^2
  - $\ell\ell$-like → $m_{\ell\ell}{}^2$
  - Vj-like → $m_T{}^2 / 4$
  - jj-like → $-1/(1/s+1/t+1/u)/4$
- Virtuals from OpenLoops
- 7-point scale variations
  on-the-fly, with and w/o shower dependence
- extra variation includes EW_{approx}
- minimal cut ($66 \leq m_{\ell\ell}$)

event sample

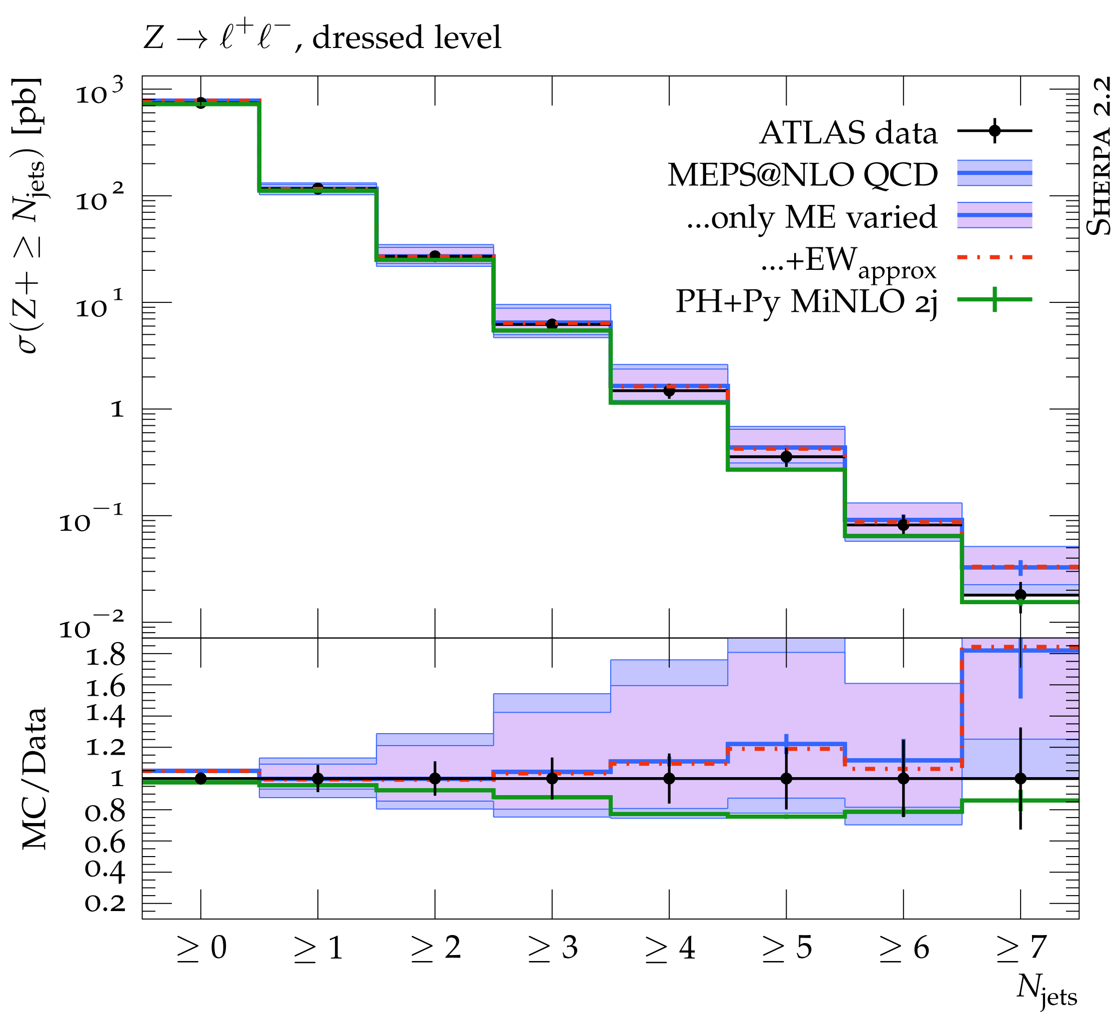
- 2k HepMC event files à 7.5k events (100MB)
  ➡ in total 15M events and 200 GB data
- ready to be pushed to common storage space

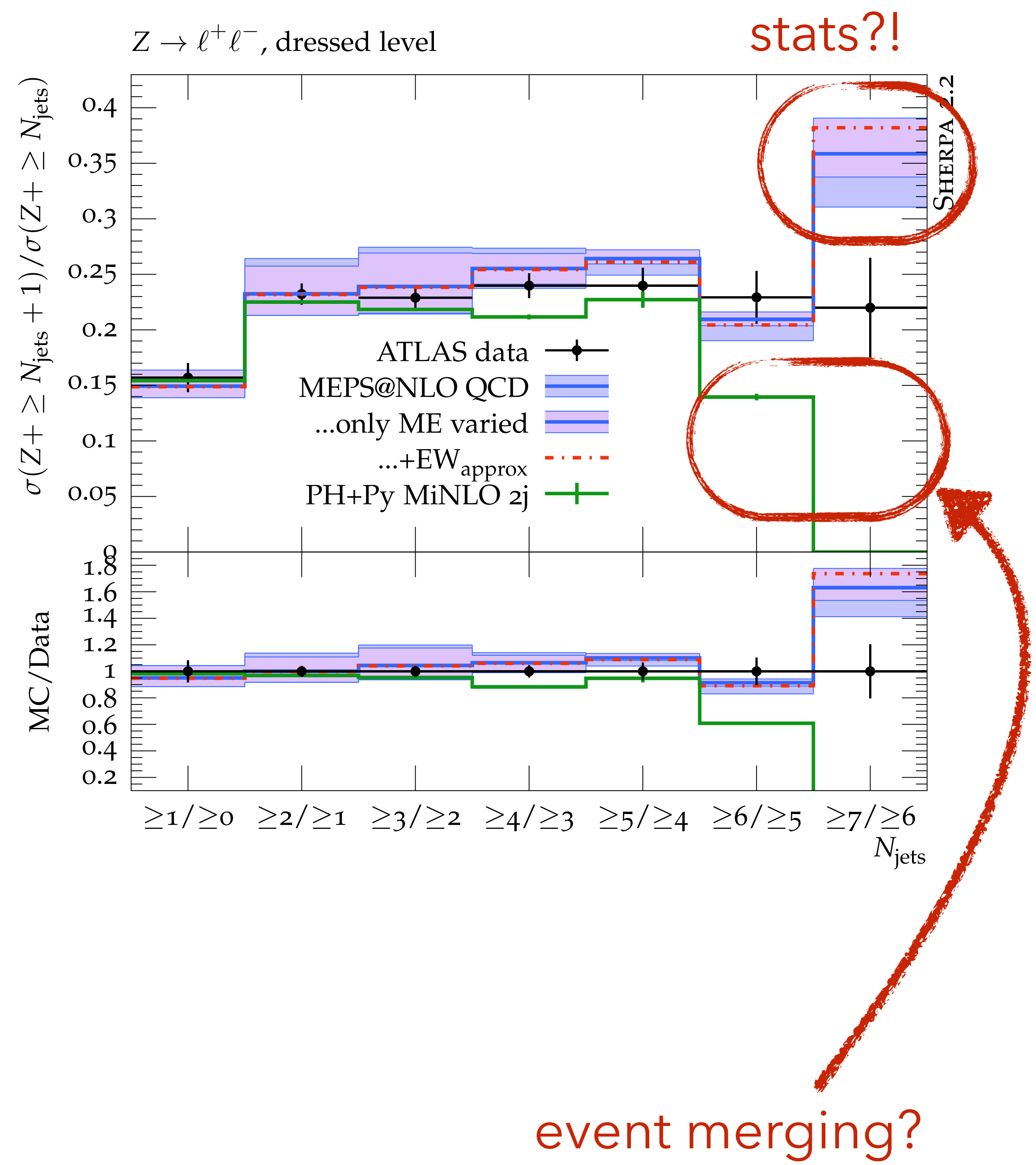
analysis

- ATLAS_2017_I1514251
  - 3.16 fb^{-1}
  - $p_{T,j} > 30$ and $|y_j| > 2.5$
- comparison to Hannes Jung's POWHEG V+2j MiNLO / Pythia (CUETP8M1) Z[ee] benchmarks linked at the WG TWiki page
  - also NLO accurate up to 2j
  - 4th+ jet from parton shower!
  - same PDF in hard process
  - sintw instead of sintweff
    ~5 % normalisation

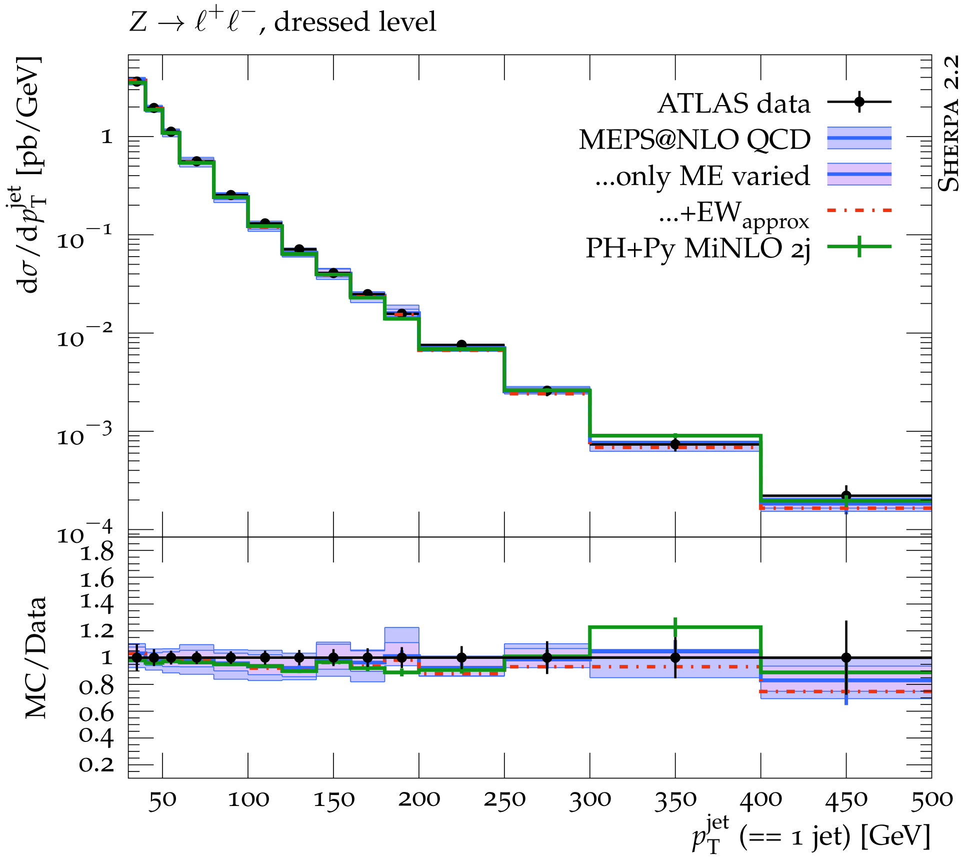
https://www.theorie.physik.uni-goettingen.de/~bothmann/LHCEW_Zjets_benchmarks/

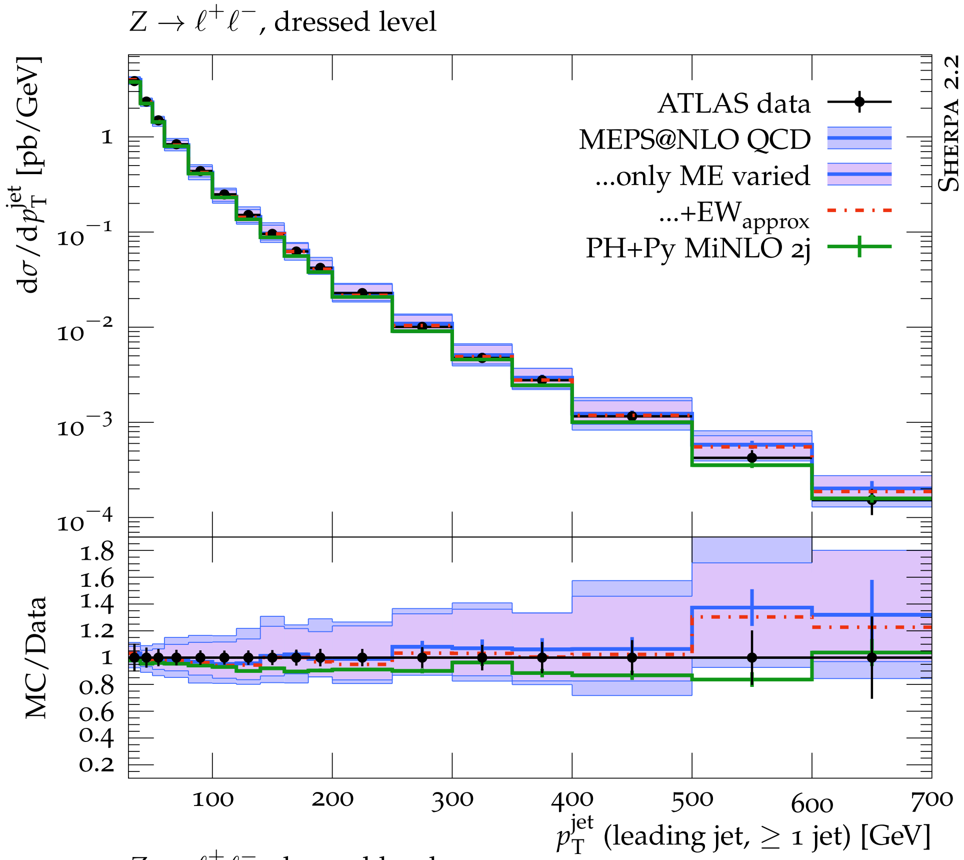
Z[ee]+jets benchmarks: N_{jets}

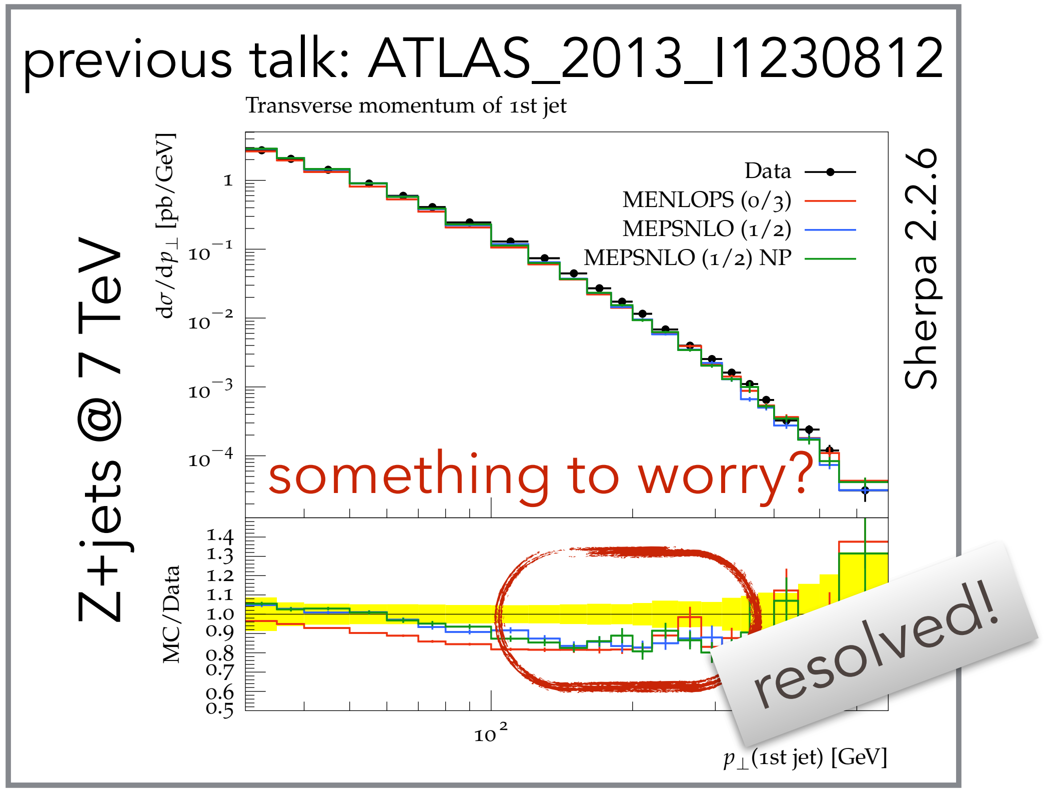


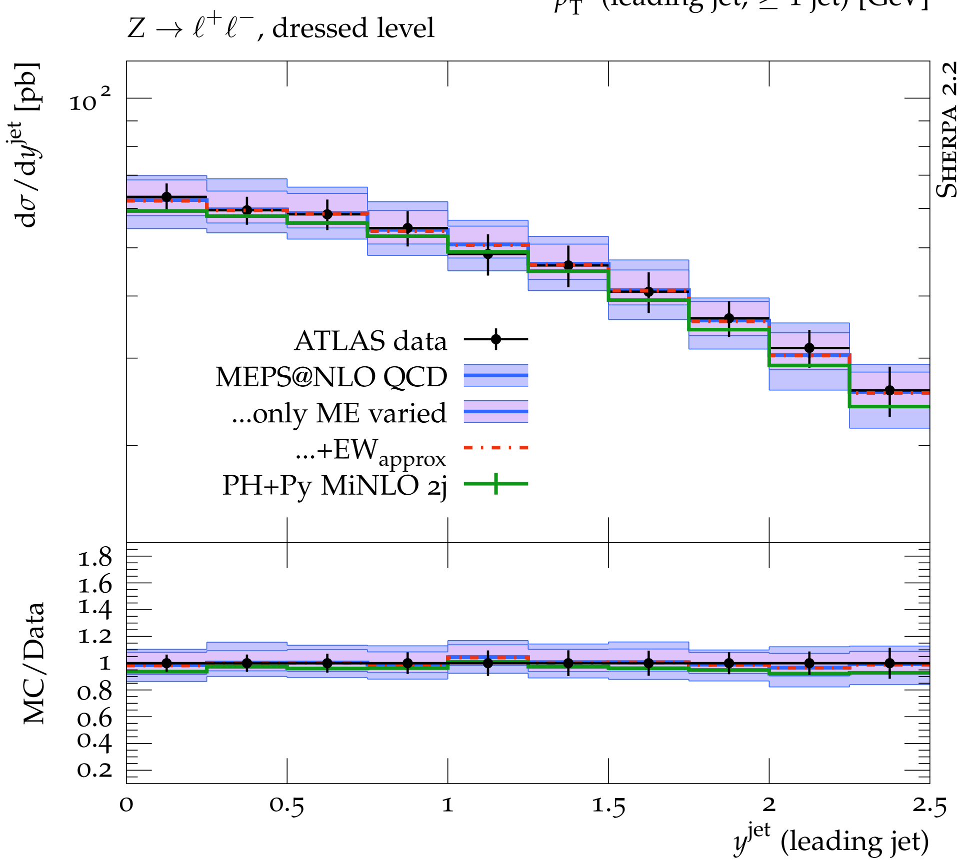


Z[ee]+jets benchmarks: leading jet

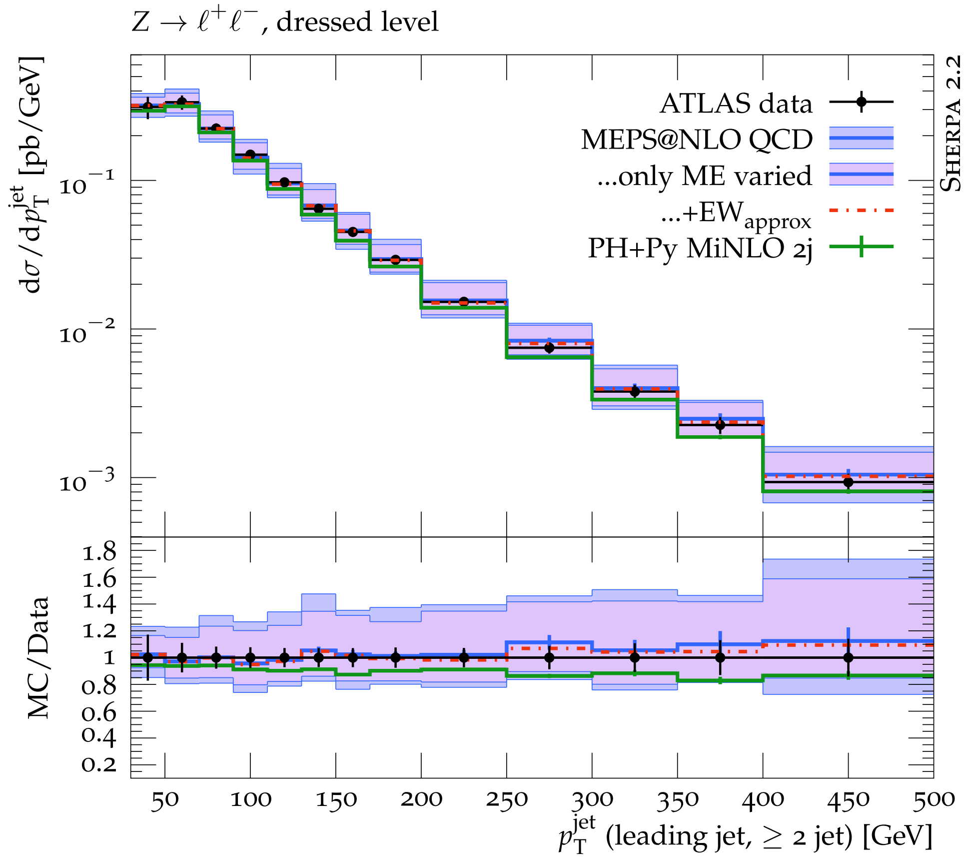


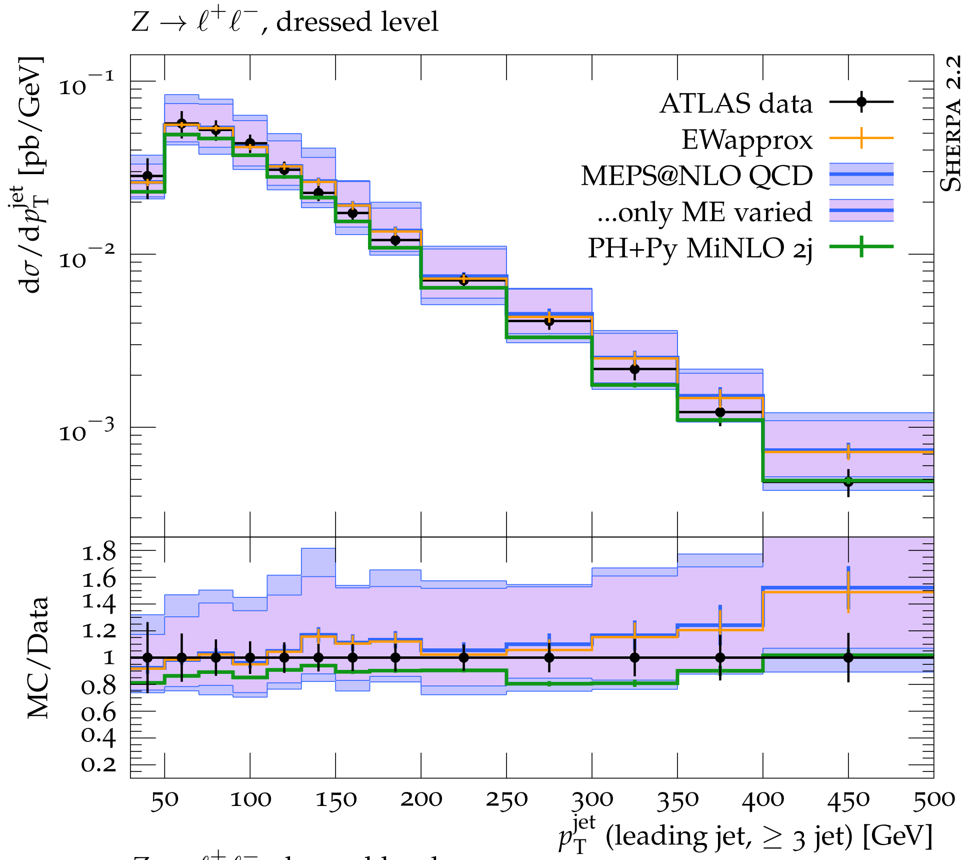


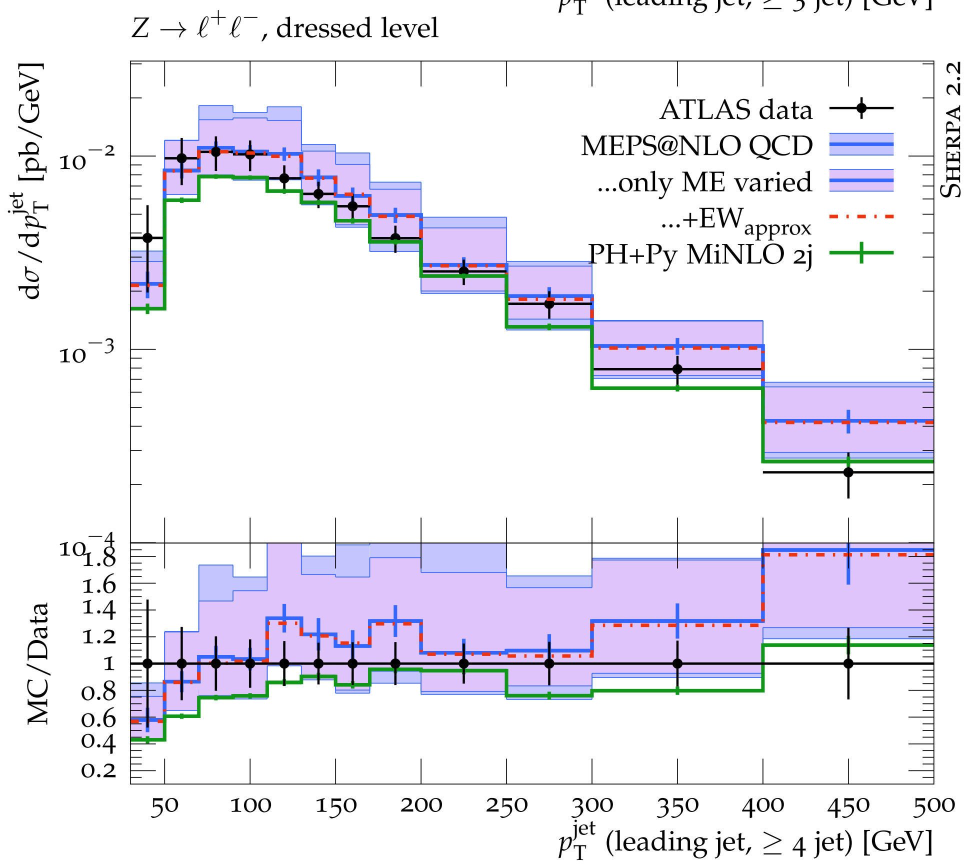




Z[ee]+jets benchmarks: 2–4th jet p_T





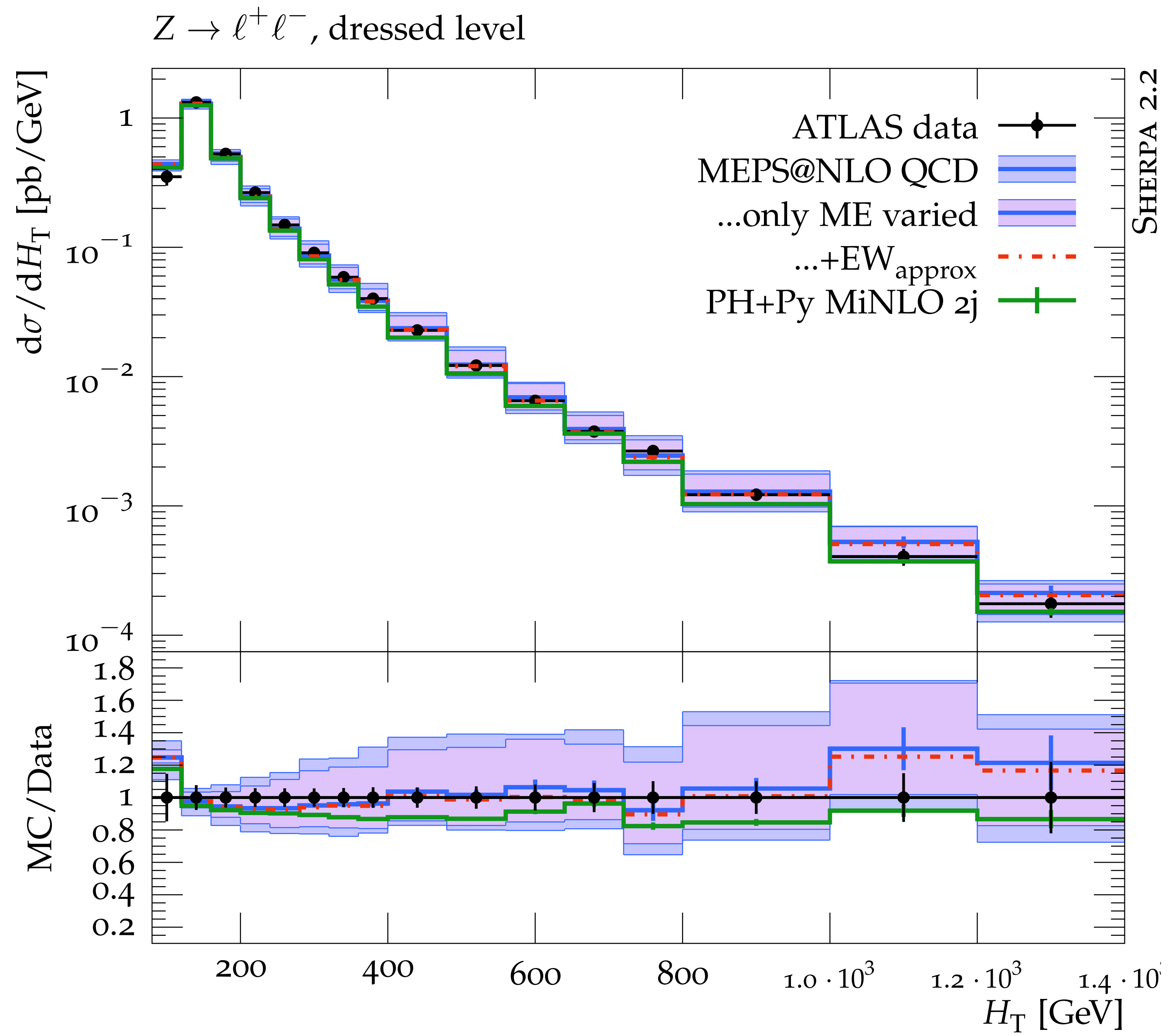


⤳ no shape differences even for the 4th jet, but normalisation difference increases to ~20%

Z[ee]+jets benchmarks: H_T

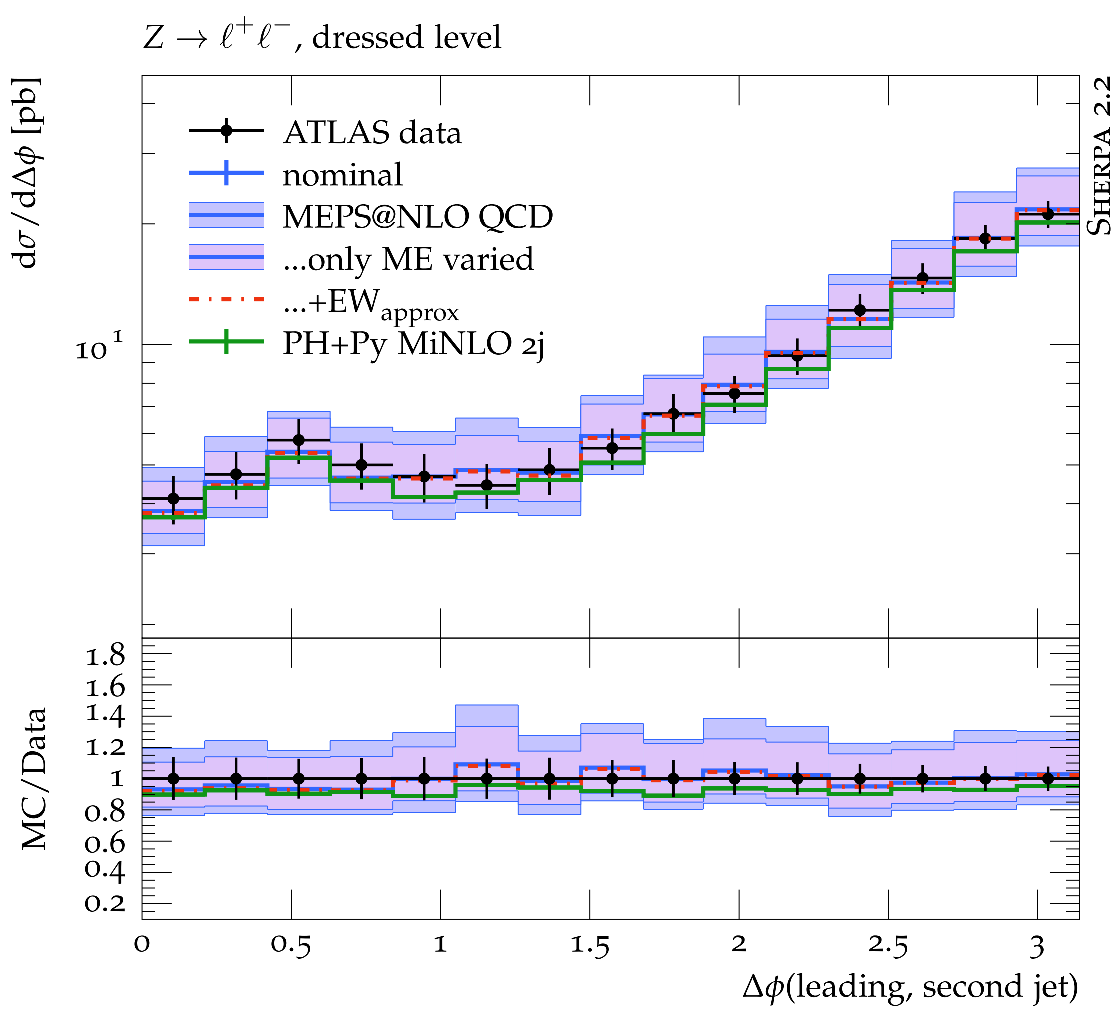
$$H_T = p_{T,\ell_1} + p_{T,\ell_1} + \sum_i p_{T,j_i}$$

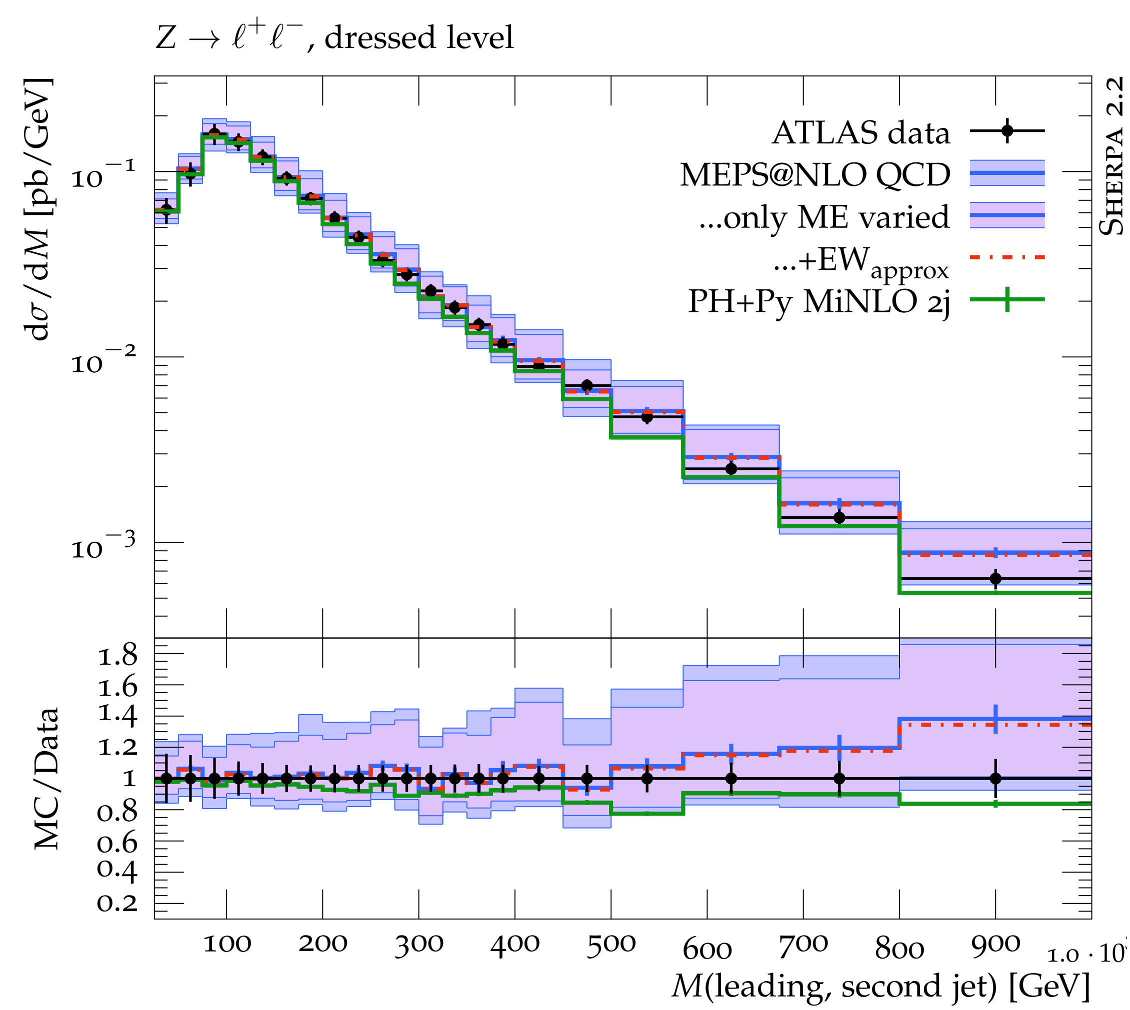
- here: only events with at least 1 jet!



⇝ Sherpa 2.2.7 tends to has slightly enhanced tails (also visible in previous observables)

Z[ee]+jets benchmarks: jet pairs





Conclusions

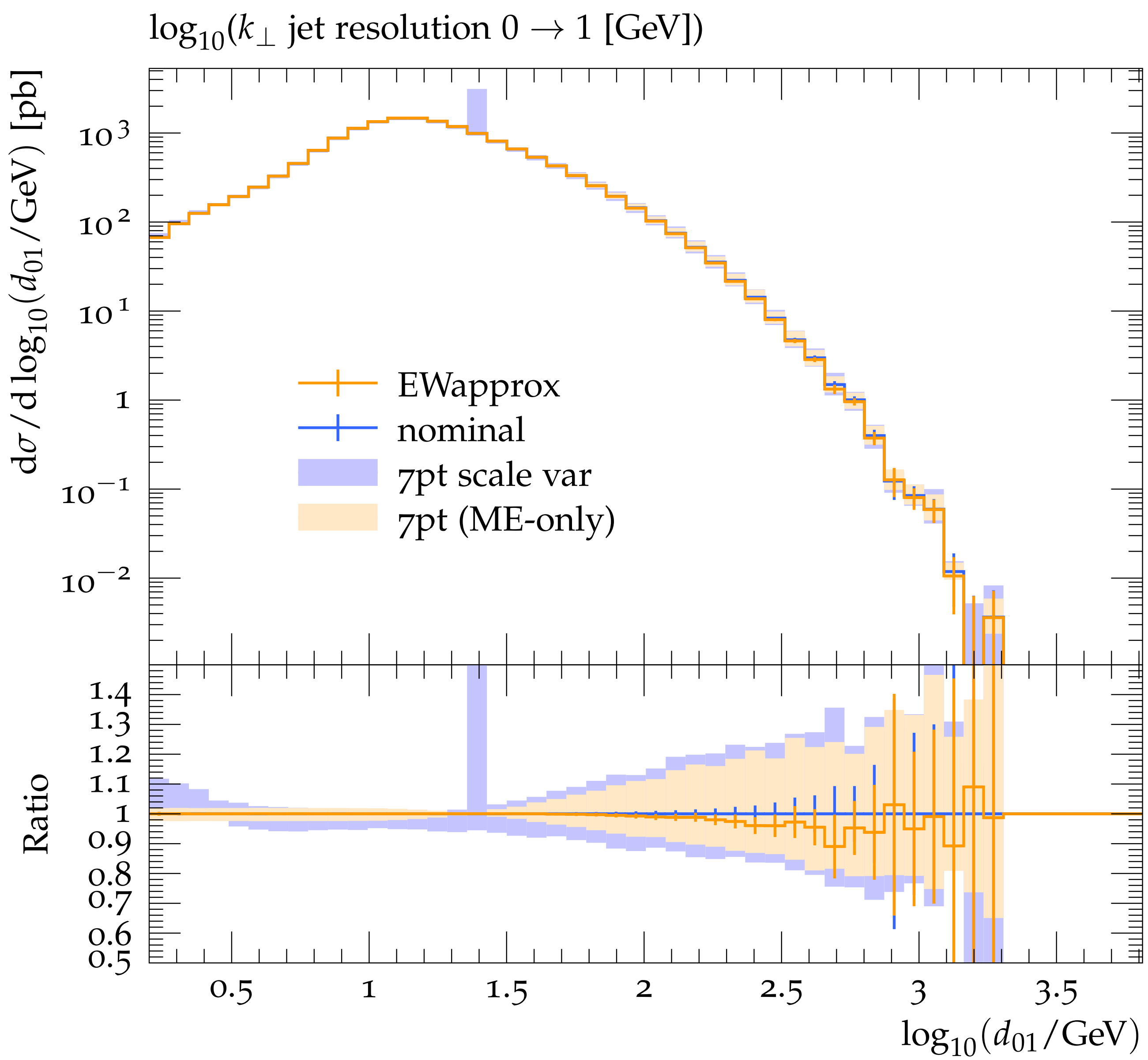
- Sherpa ❤️ V+jets
  - we provide a comprehensive list of example configs, only one tune & hopefully sensible defaults
    ⤳ easy to compare across experiments
  - MEPS@NLO (+EWvirt) state-of-the-art
    particle-level, multi-jet observables
- Z+jets @ 13 TeV benchmarks consistent with PH+Py and data
- generate W+Jets @ 13 TeV
  on the way, will include 5j @ LO
- **THANKS!**

BACK-UP

pQCD uncertainties with Sherpa

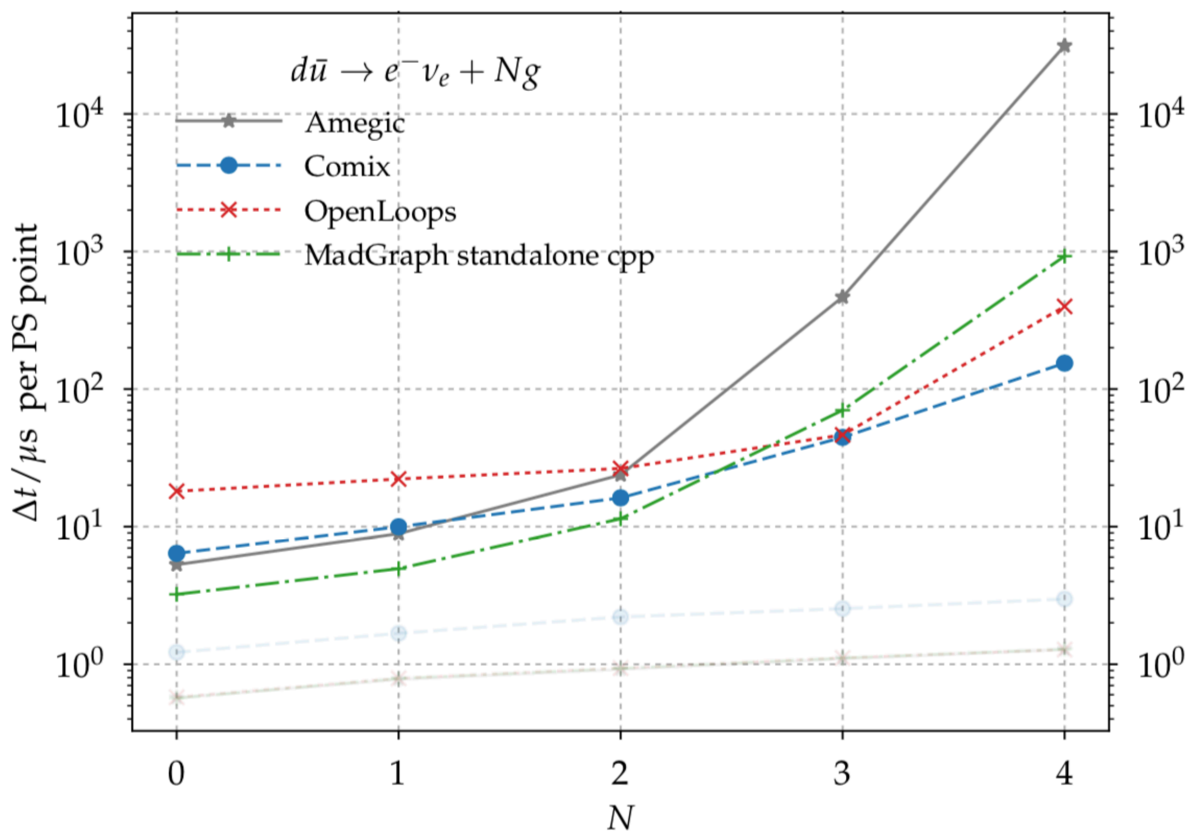
- see following talk(s) for more systematic discussion (?)
- here: QCD input parameters & scale choices:
  - ➡ $\alpha_S(M_Z)$, PDFs, μ_R, μ_F, μ_{CKKW}
  - ➡ appear both in ME & PS: traceable
- dedicated re-simulation often too expensive/time consuming
- solutions:
  - interpolations grids
    - APPLGRID, FASTNLO
      [Sutton et al.] PoS DIS2010 (2010) 051; [Wobisch et al.] hep-ph/0609285
    - automated using AMCFAST, MCGRID
      [Bertone et al.] JHEP 1408 (2014) 166; [DelDebbio,Hartland,Schumann] CPC 185 (2014) 2115
  - extended event files (BLACKHAT/SHERPA NTUPLE)
    [Bern et al.] CPC 185 (2014) 1443
  - on-the-fly reweighting of ME …
    - ➡ … and new since 2016 in SHERPA/HERWIG/PYTHIA: PS
      [EB,Schönherr,Schumann], [Bellm et al.] PRD 94 (2016) 034028, [Mrenna,Skands] PRD 94 (2016) 074005
  - a-posteriori PS variations using a neural net
    TODO: provide reference

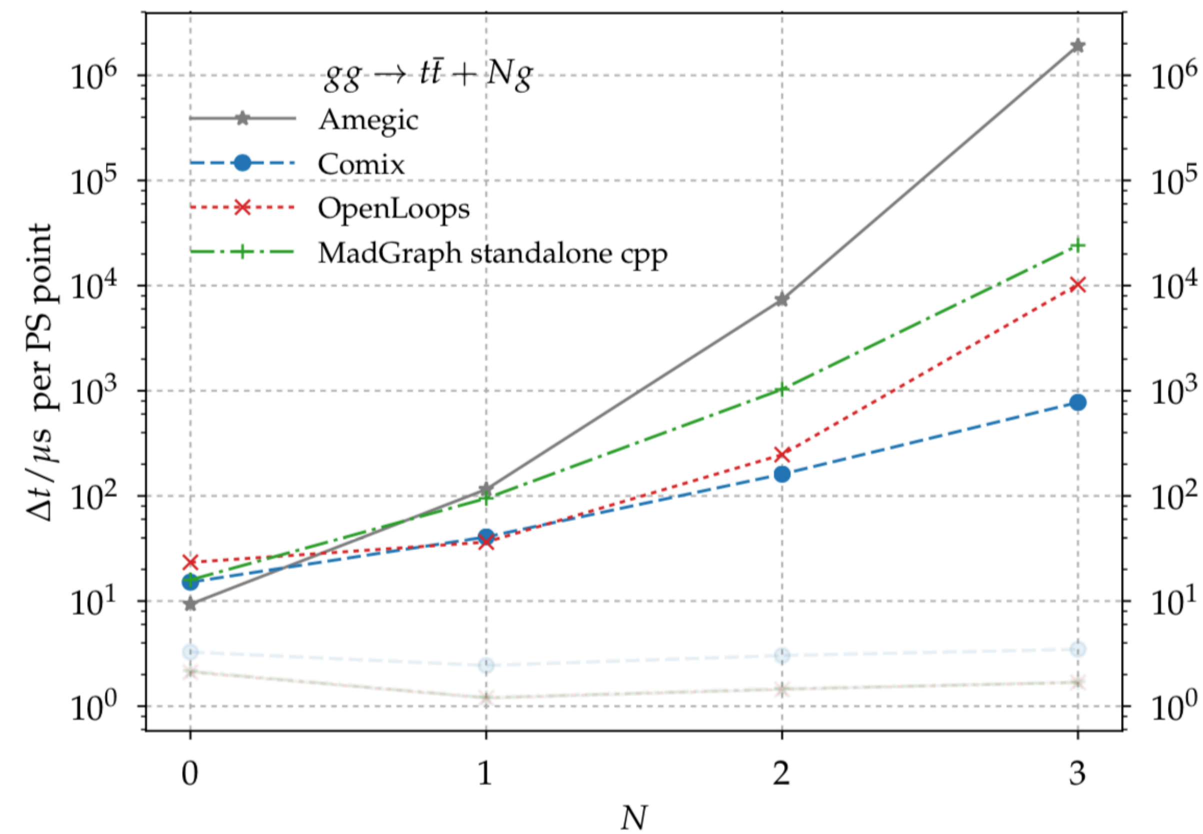
Issue with the 0-jet OTF uncertainty band



- ⤳ a freak event spoils the 7-point uncertainty band for 0-jet events
- ⤳ used ME-only variation for 0-jet bin on previous slides
- ⤳ will search+remove the event from the final sample

CPU cycles

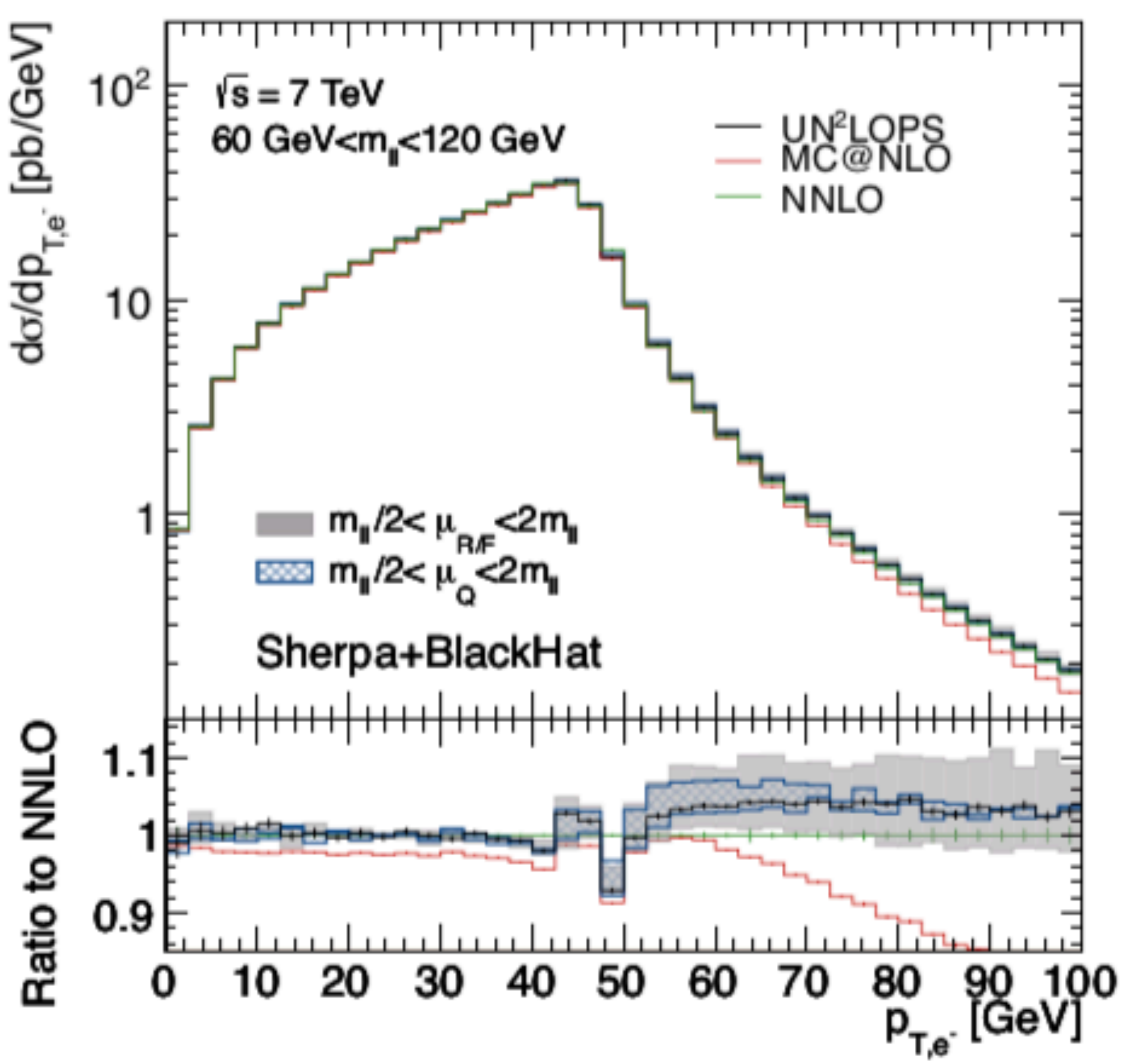




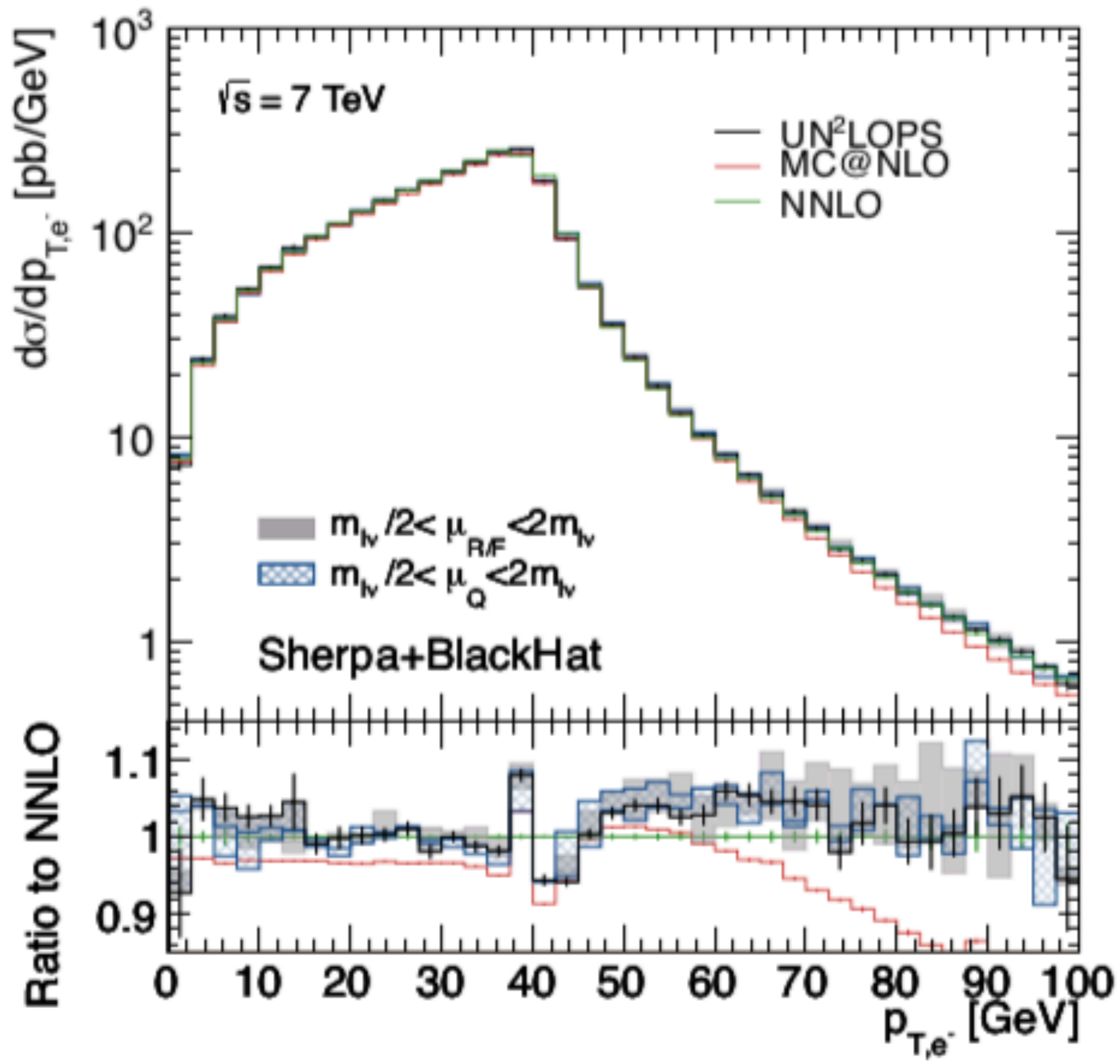
- Efficient tree-level generators for Born and real-emission corrections
  Amegic [Krauss,Kuhn,Soff] hep-ph/0109036, Comix [Gleisberg,SH] arXiv:0808.3674
- In Comix factorial scaling with multiplicity reduced to exponential by dynamic programming & sampling of color configurations
  [Berends,Giele] NPB306(1988)759, [Duhr,Maltoni,SH] hep-ph/0607057

NNLOPS for pp → V

[Hoeche et al.] arXiv:1405.3607,1407.3773



$pp \to \ell\ell$

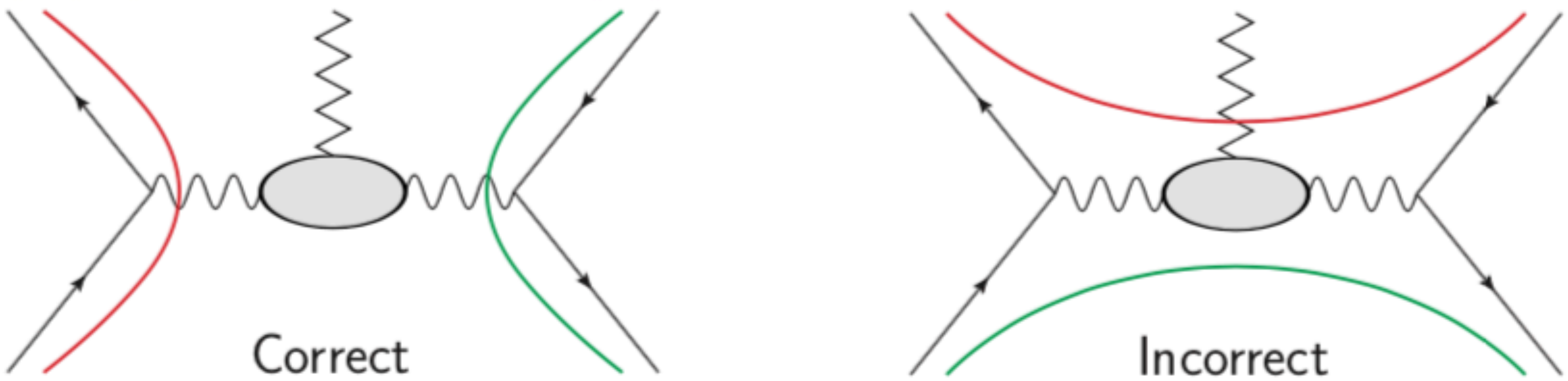


$pp \to \ell\nu$

Vector-boson scattering simulations with Sherpa

slide by Stefan Höche

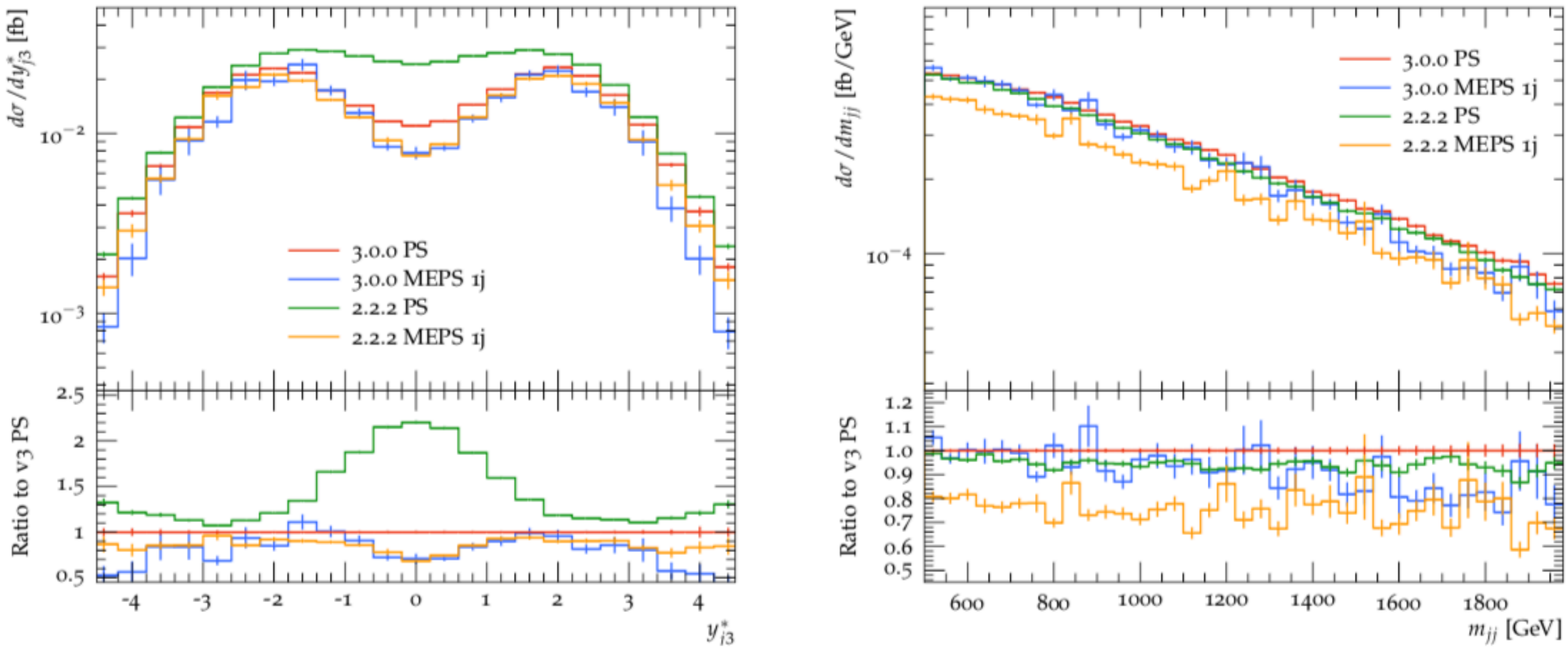
- VBF-like situations require judicious setting of color flow information in interface between fixed-order calculation and parton shower



- Current color selection in Sherpa based on hardcoded probabilities for the most relevant processes, VBF topologies are *not* included
- Alternative, generic option in future version 3.0.0
  - Idenitify all possible color flows in core interaction (after ME+PS clustering, e.g. $pp \to e^+e^-$ in $pp \to e^+e^-$+jets)
  - Compute corresonding partial amplitudes [Gleisberg,SH] arXiv:0808.3674
  - Select winner topology probabilistically
- Sherpa 3.0.0 also allows to specify different starting scales for parton-shower evolution of disconnected dipoles

Vector-boson scattering simulations with Sherpa

slide by Stefan Höche

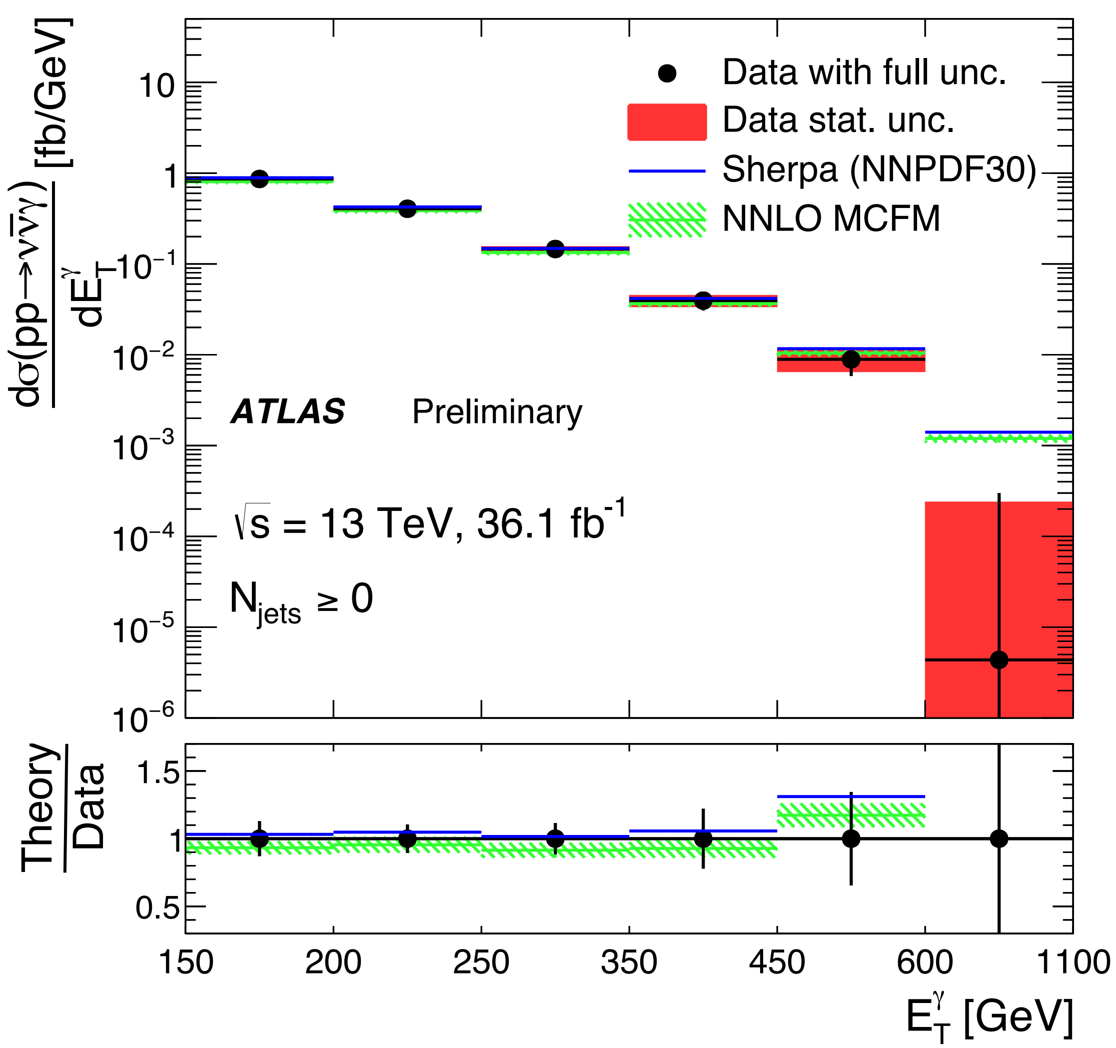


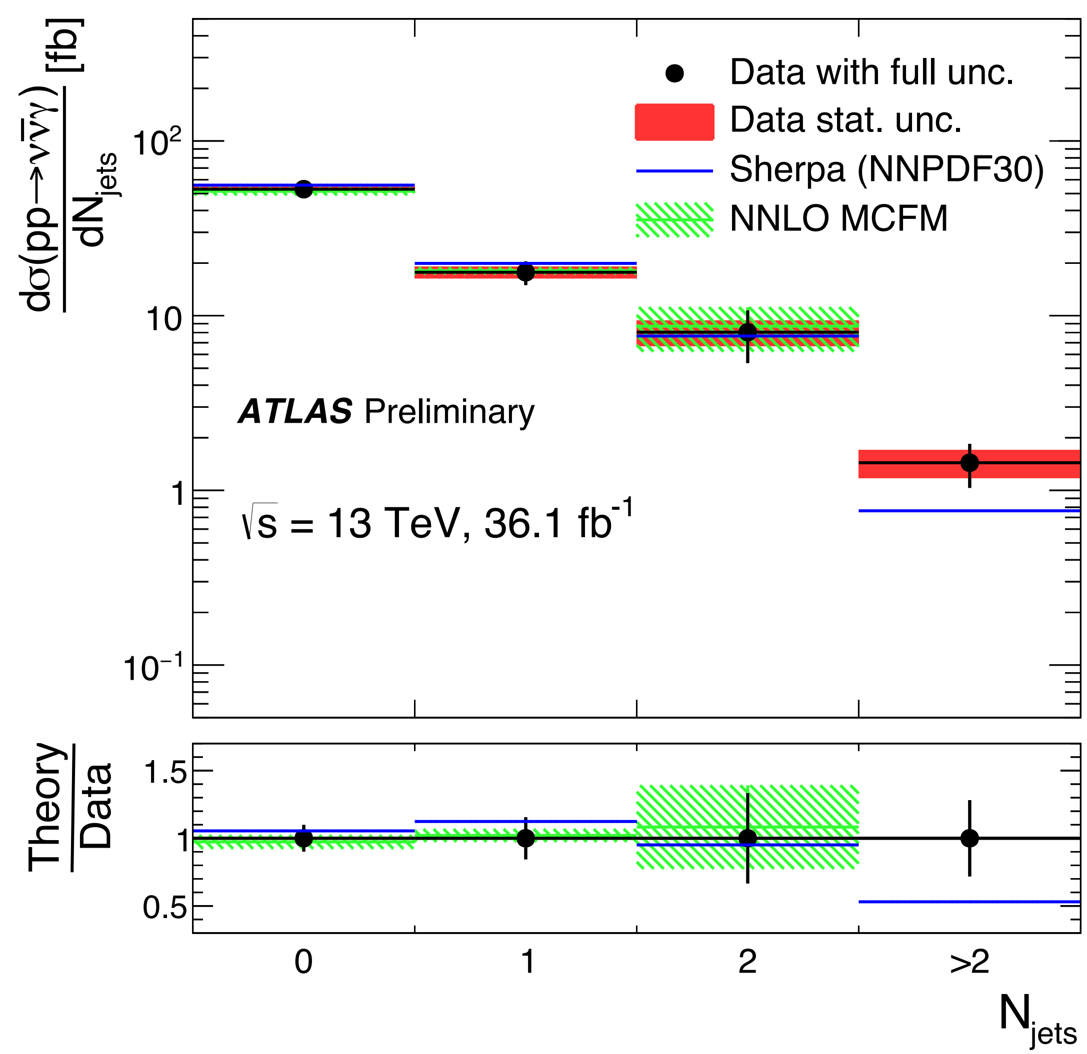
- Differential distributions confirm improvement:
  - Third jet produced more forward and at lower rate in Sherpa 3.0.0
  - PS radiation pattern in Sherpa 2.2.0 corrected by ME+PS merging, but breaking of PS unitarity in CKKW(L) decreases overall event rate
- Sherpa 3.0.0 predicts $\sim$20% larger cross section after cuts as a result of correct color flow and PS starting scales

WHAT WE GET OUT

[ATLAS-CONF-2018-035]

- Sherpa pp→Zγ→ννγ, NLO ≤ 1j, LO ≤ 3j (multi-jet merging)
- compares well to data & NNLO





also see recent Sherpa pheno study on Zγ→ννγ production [Krause, Siegert, Eur.Phys.J. C78 (2018) no.2, 161]

EW NLO

needed to regularise V and R ME pieces in MCEG based on universal behaviour in divergent limit

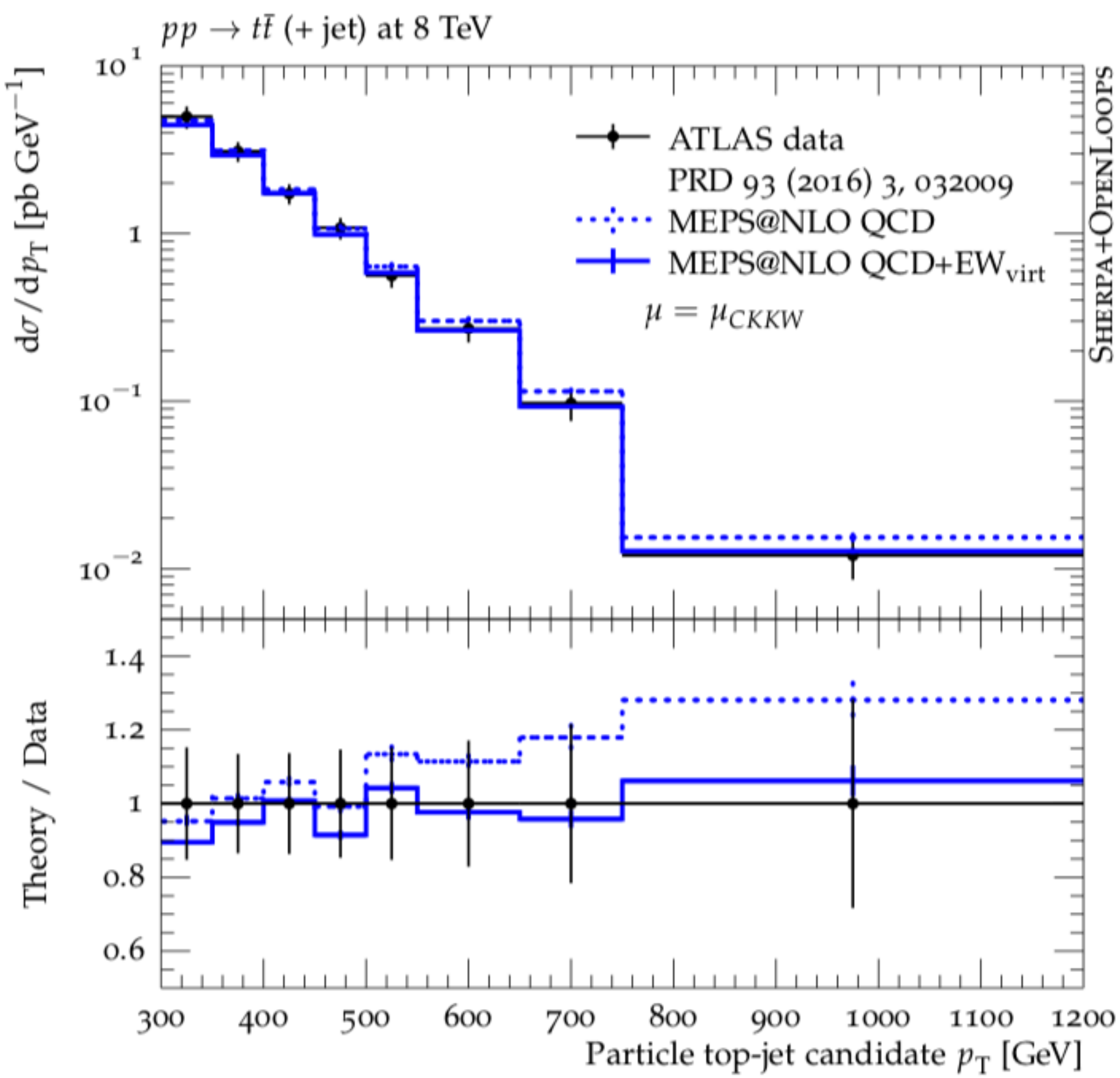
lists by S. Kuttimalai

- motivation: previous talk $\alpha_s^2 \approx \alpha$
- Sherpa: tree-level ME, IR subtraction, process management, PS integration
- one-loop MEs from external libraries
- SHERPA+GOSAM:
  - γγ+0,1,2 jets
    [Chiesa et al, JHEP 1710 (2017) 181]
  - γγγ/γγℓν/γγℓℓ
    [Greiner, Schönherr, JHEP 1801 (2018) 079]
- SHERPA+RECOLA
  - V/ℓν/ℓℓ+j, ℓℓ+2j, ℓℓℓℓ, ttH
    [Biedermann et al, Eur.Phys.J. C77 (2017) 492]
  - ℓℓℓννν [Schönherr, JHEP 1807 (2018) 076]
- SHERPA+OPENLOOPS
  - W+1,2,3 jets
    [Kallweit et al, JHEP 04 (2015) 012]
  - Z/γ+j
    [Kallweit et al, Moriond QCD2015 proceeding]
  - ℓℓ/ℓν/νν/γ+j
    [Lindert et al, Eur.Phys.J. C77 (2017)]
  - ℓℓνν [Kallweit et al., JHEP 1711 (2017) 120]
  - ℓℓ/ℓν+2j, ttH [LH 2015 SM WG report]
  - tt+0,1 jets [Gütschow, Lindert, Schönherr, Eur.Phys.J. C78 (2018) no.4, 317]

EW NLO: TOP PAIR PRODUCTION & APPROX MERGING

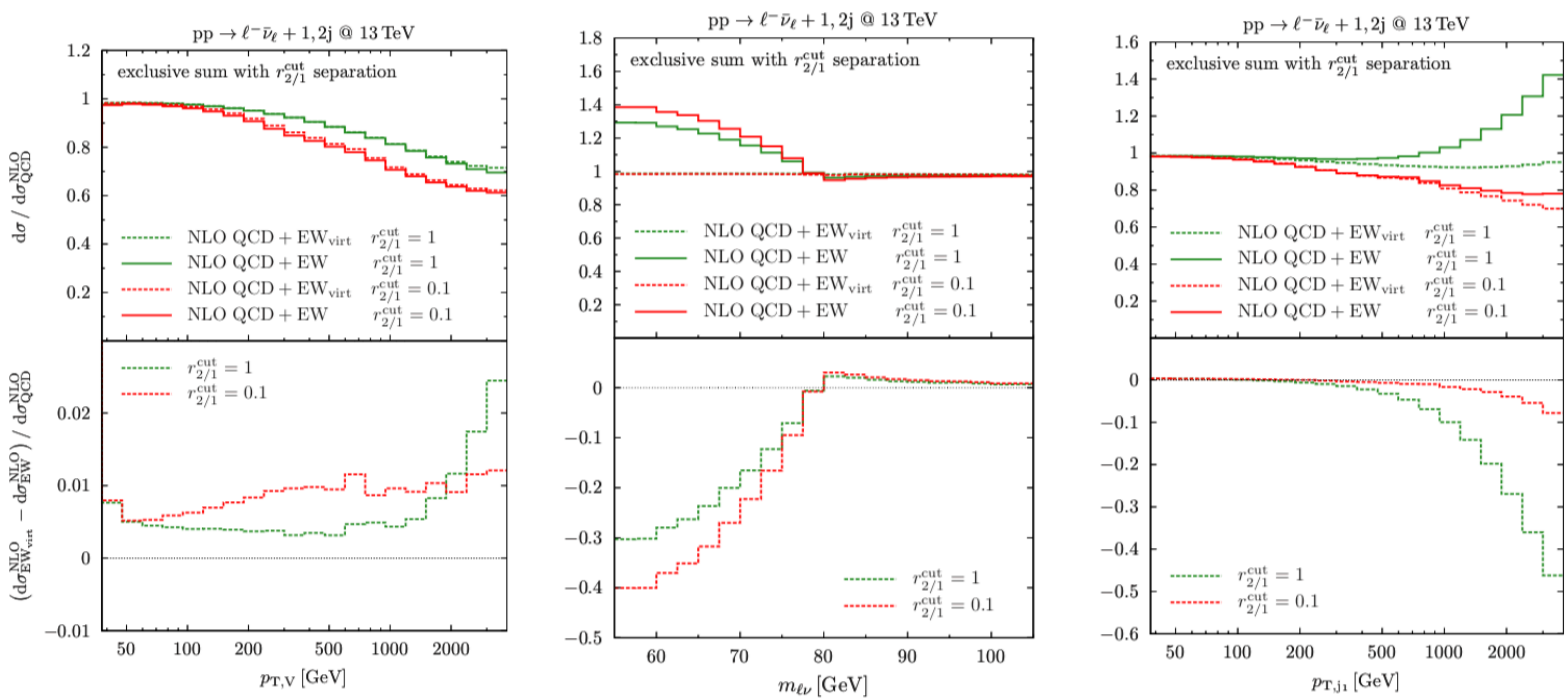
[Gütschow, Lindert, Schönherr, Eur.Phys.J. C78 (2018) no.4, 317]

$$d\sigma^{NLO\,EW}{}_{virt} = \left[B_{QCD} + V_{EW} + \int R^{approx} d\Phi_1 + B_{sub}\right] d\Phi_B$$



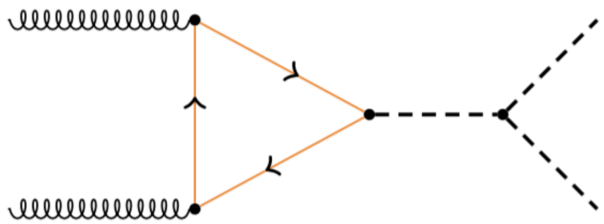
- MEPS@NLO QCD+EW$_{virt}$ *0,1 @ NLO, 2,3,4 @ LO*
- recover real QED bremsstrahlung: YFS
- boosted top quark, ID by substructure technique from fat jet

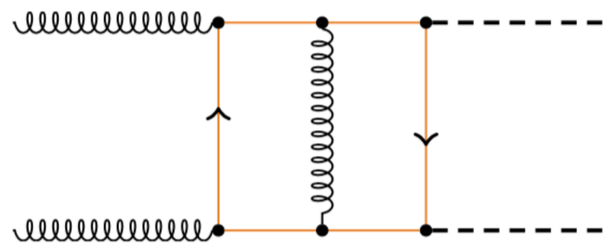
EW NLO VS. EW$_{\text{APPROX}}$

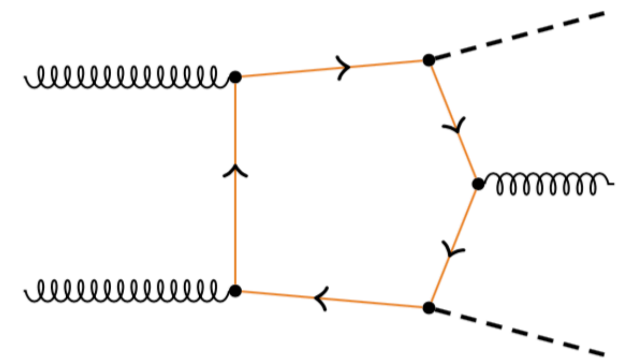


LOOP-INDUCED PROCESSES AT MC@NLO

slide adapted from S. Kuttimalai



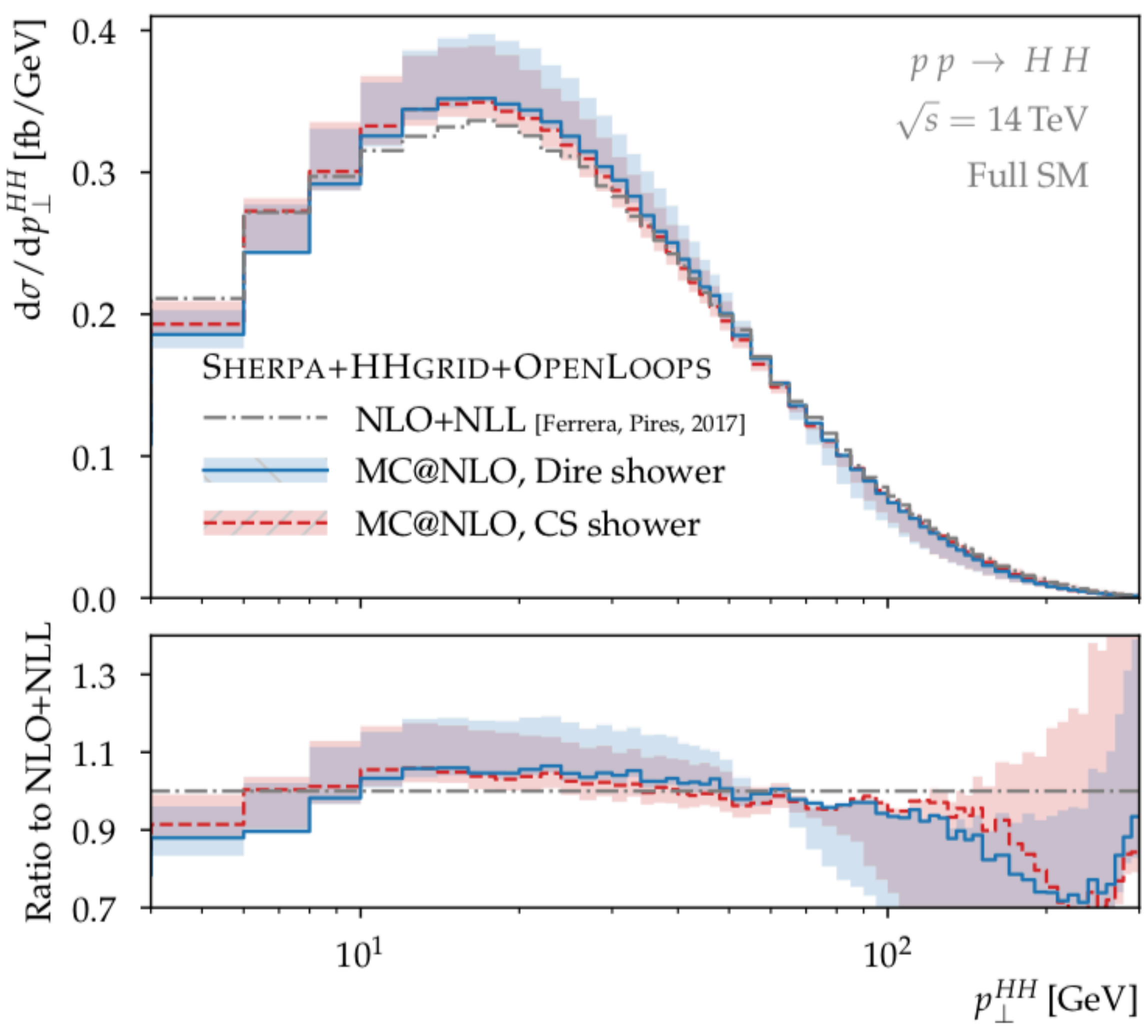


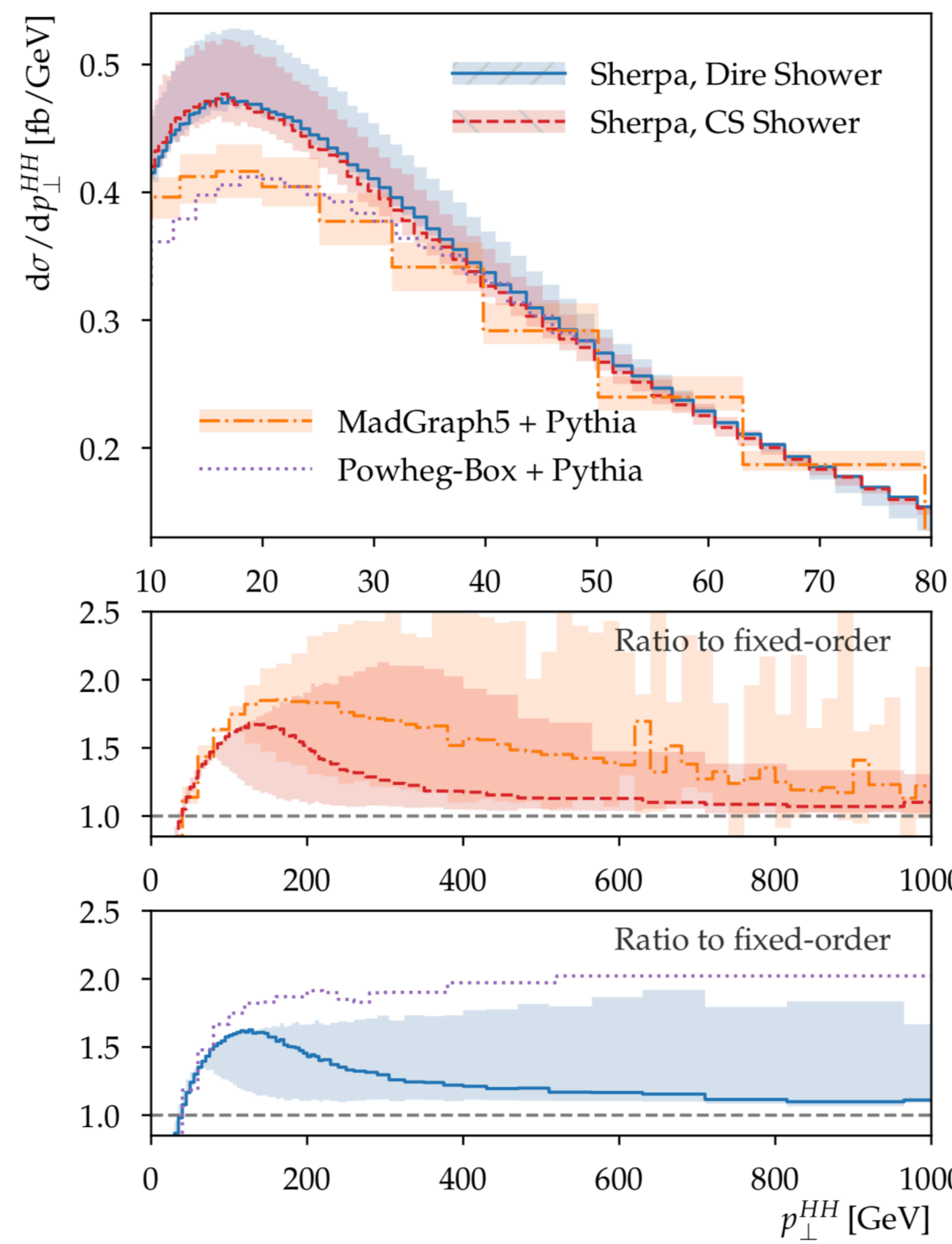


- Born & real-emission by automated one-loop tools
- SHERPA: IR subtraction, process management, PS integration, matching (MC@NLO), fully automated [Jones, Kuttimalai: JHEP 1802 (2018)]
- Available two-loop virtual amplitudes
  - $gg \to \gamma\gamma/HH/Hj$
    e.g. ggHH difficult due to massive propagators & externals
  - $gg \to VV \to \ell\ell\ell\ell$

LOOP-INDUCED PROCESSES AT MC@NLO

- gg → γγ/HH (full top-quark mass dependence) [Jones, Kuttimalai, JHEP 1802 (2018) 176]
- large K factor enhances matching uncertainties
- other impl PYTHIA via POWHEG/MC@NLO
  [Heinrich et al, JHEP 08 (2017), p. 088]





uncertainties on NLO+NLL in left plot: 3% near $p_\perp^{HH} = 20$ GeV, 10% near 100 GeV

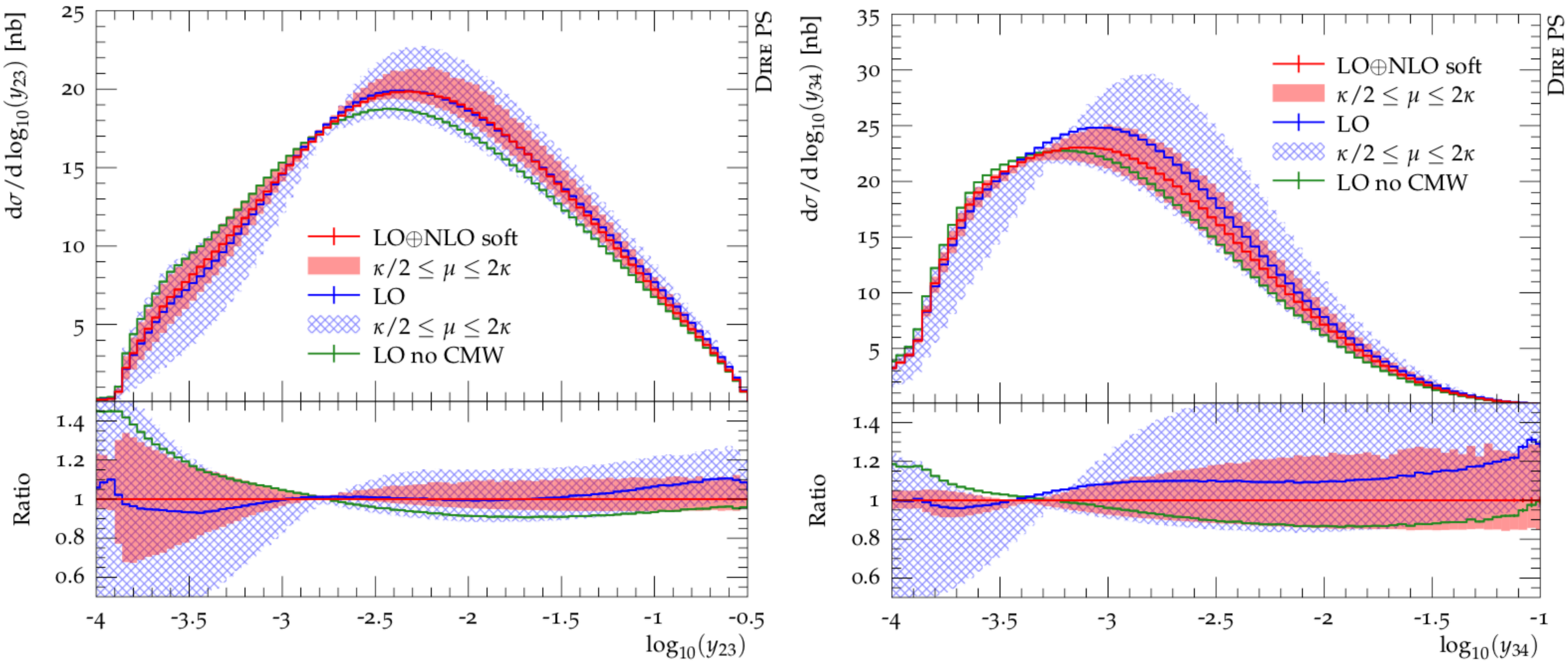
NLO DGLAP IN THE PARTON SHOWER

- goal: fully differential PS evolution with NLO kernels
  - last year: inclusion of NLO *collinear* splitting functions (NLO DGLAP) & flavour-changing 1→3 *collinear* splittings
    [Höche, Prestel, Phys.Rev. D96 (2017) no.7, 074017] [Höche, Krauss, Prestel, JHEP 1710 (2017) 093]
  - this year: higher-order *soft* terms
    [Dulat, Höche, Prestel, 1805.03757]
  - implemented in SHERPA and PYTHIA
    via two independent cross-checked DIRE shower implementations
- higher-order soft terms, fully differential in one-emission PS
  - check: sum of integrated terms = two-loop cusp anomalous dimension which is included in CMW method already for "LO" showers

NLO DGLAP IN THE PARTON SHOWER

[Dulat, Höche, Prestel, 1805.03757]

- fair agreement between fully diff NLO and approximate treatment using CMW in "LO" shower



SHERPA tunes

- SHERPA comes with exactly one tune

1) tune **hadronisation** parameters to **LEP data**
   → iterative between event shapes and hadron multiplicities
   → colour-reconnection found not to be needed to improve tune
2) tune **intrinsic transverse momentum** parameters to **LHC DY data**
   → no Tevatron data, as mostly corrected to unphysical Born leptons
3) tune **multiple interaction** and **beam remnant** parameters to **LHC** data
   → model rather basic, but key observables can be described
   → currently no Tevatron data used

- LEP data mostly ALEPH 2004 event shapes
  LHC data selection somewhat ATLAS biased for historical reasons