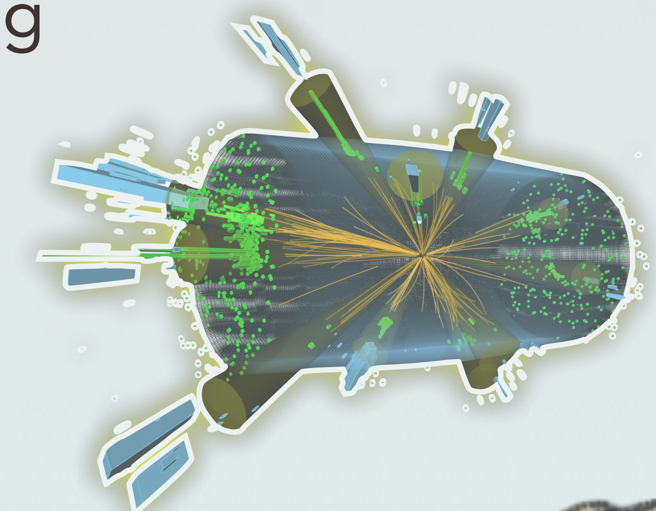
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Institut für Theoretische Physik

V+Jets with Sherpa

LHC EW Jets and EW Bosons Subgroup Meeting
30 October 2018

Enrico Bothmann



MCnet

Sherpa overview

[Gleisberg et al. 0811.4622]

Hadron Decays

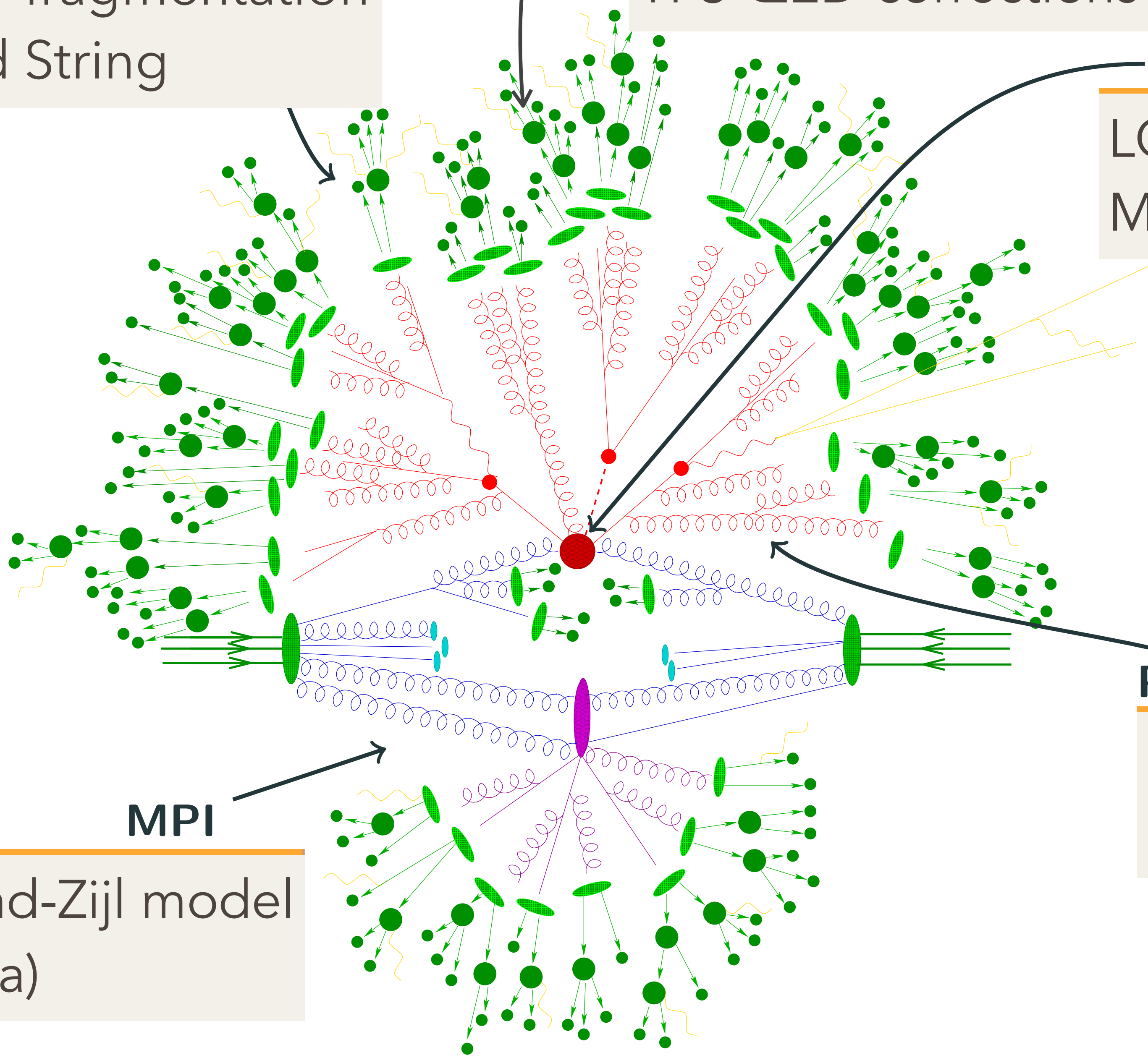
Phase-space or EFTs
YFS QED corrections

Hadronization

Cluster fragmentation
& Lund String

Hard process

LO, NLO QCD/EW*, NNLO QCD**
ME generators (Amegic & Comix)



Parton shower

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

MPI

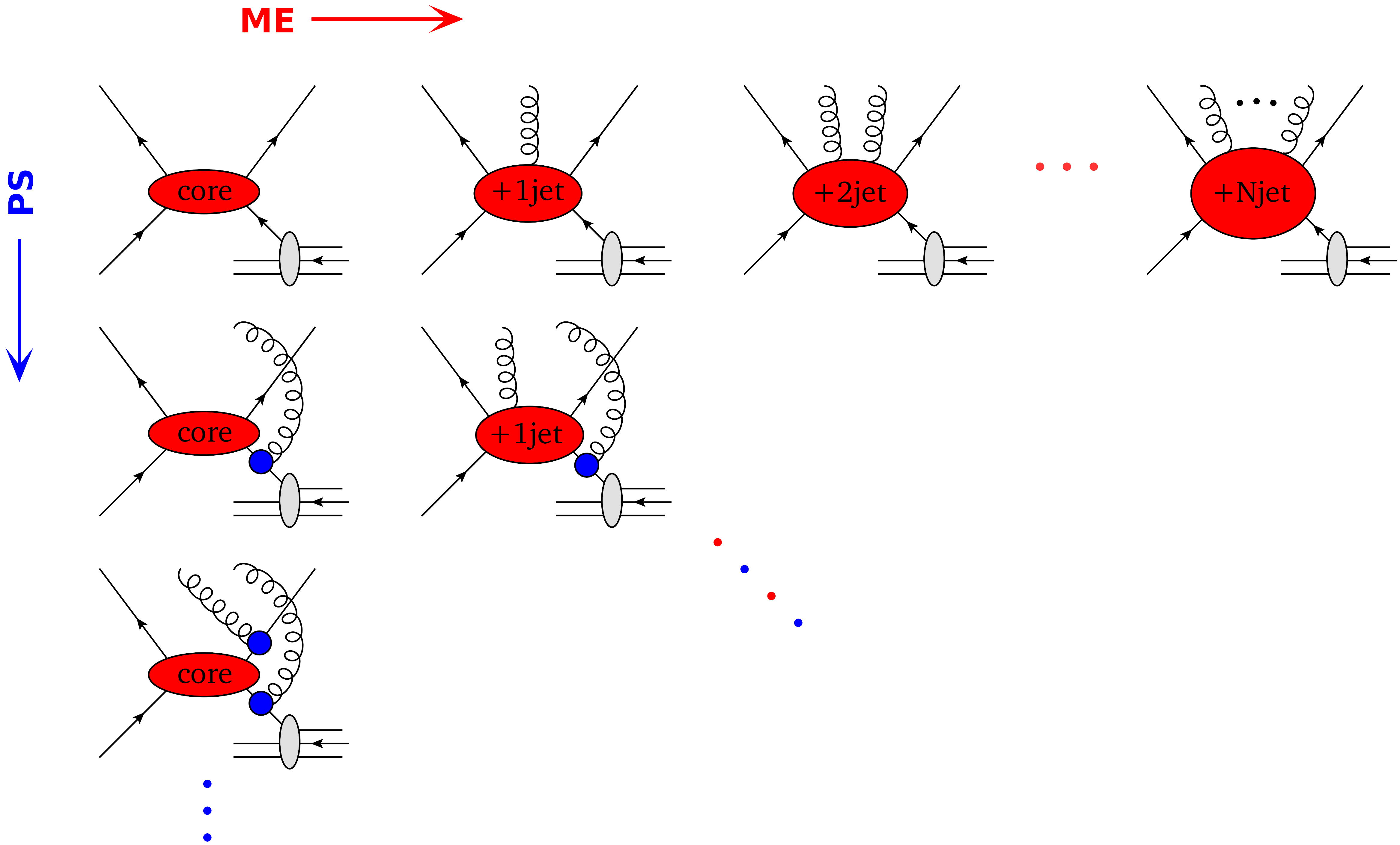
Sjöstrand-Zijl model
(~ Pythia)

Sherpa pQCD calculations*

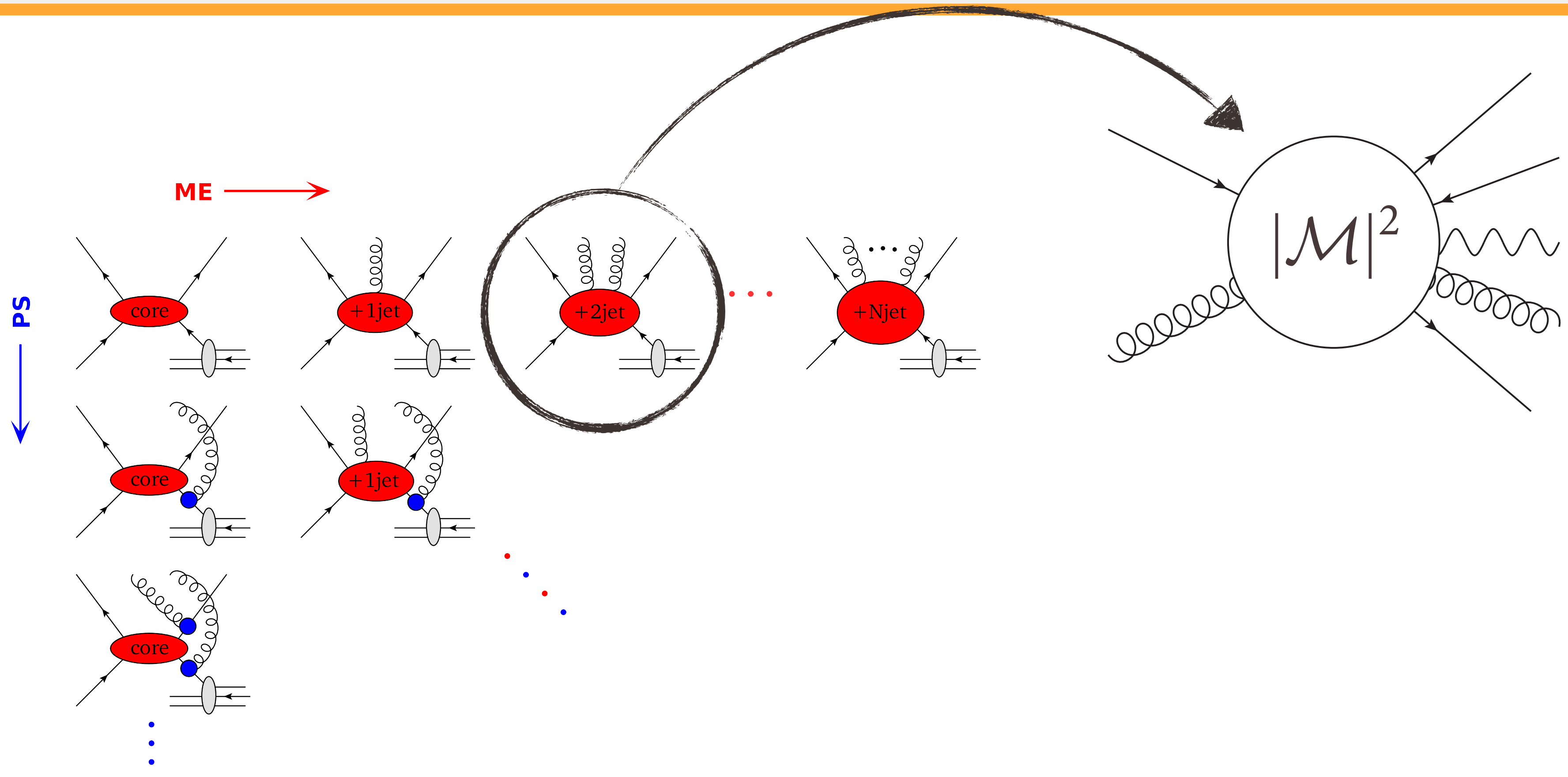
*a.k.a. Acronymology

- methods available to generate SM predictions include:
  - **Fixed-order** (LO, NLO, NNLO)
    - ME only $\rightsquigarrow$ fixed final-state multiplicity
    - no parton shower, no non-perturbative effects, no particle level
  - **Parton-shower matched** (LOPS, NLOPS/MC@NLO, NNLOPS)
    - combine fixed-order with parton shower for a single multiplicity
    - particle-level, but not predictive for multi-jet observables
  - **Multi-jet merged** (MEPS@LO, MEPS@NLO, MENLOPS)
    [Höche et al. 0903.1219, 1009.1127]
    - combine parton-shower matched calculations for several jet multiplicities in a single sample
    - particle-level, predictive for multi-jet observables
- NLO V + n jets limited by availability of external libs for virtuals
  n=5 for W[$\ell\nu$], n=4 for γ/Z[$\ell\ell/\nu\nu$]
- full pQCD reweighting for on-the-fly uncertainties in all modes
  [EB,Schönherr,Schumann 1606.08753]

Multi-jet merging



Multi-jet merging



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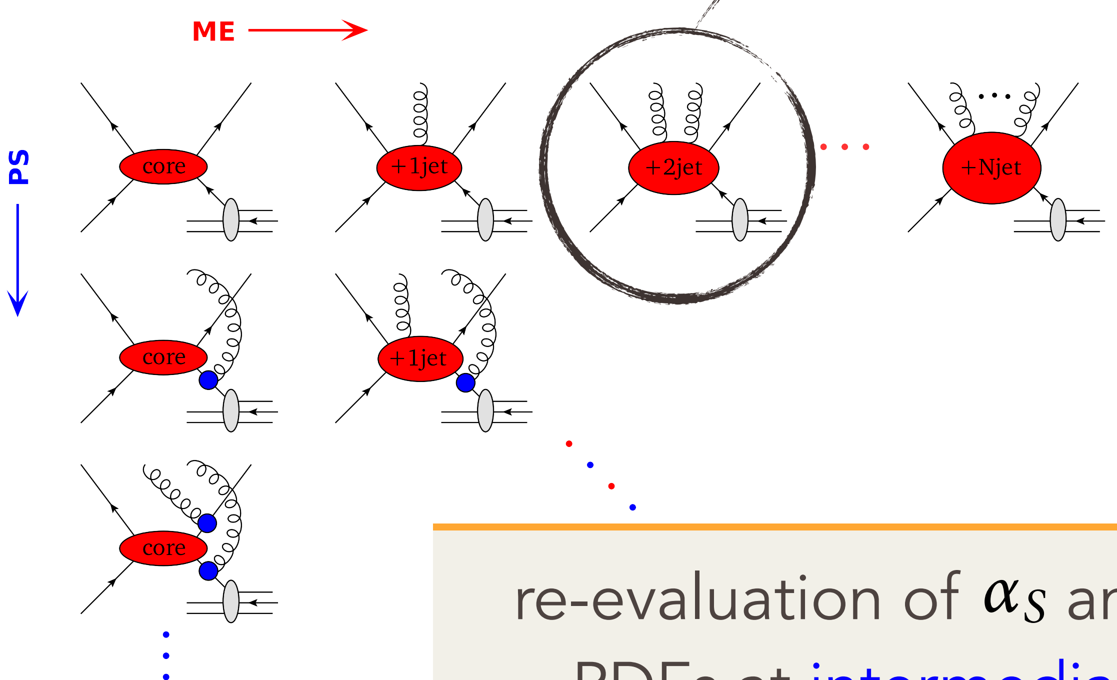
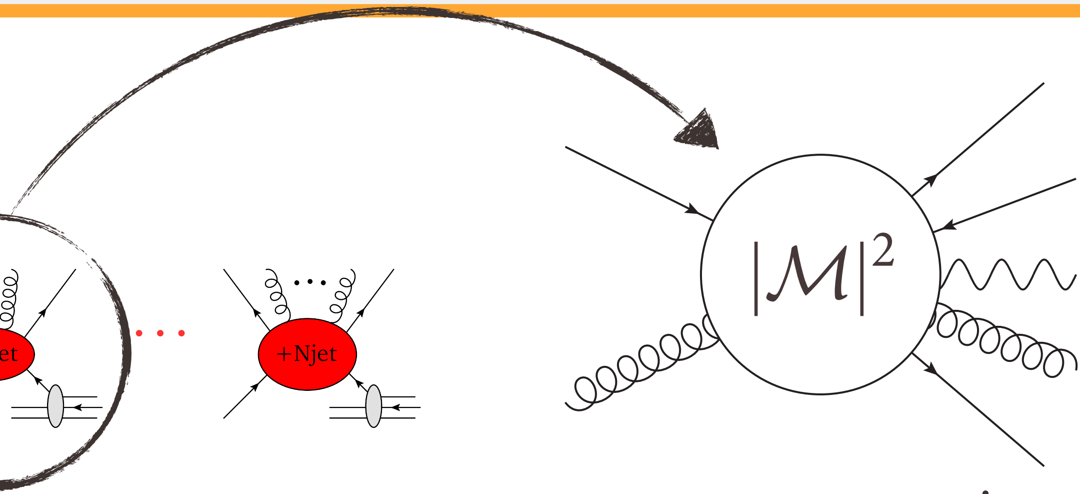
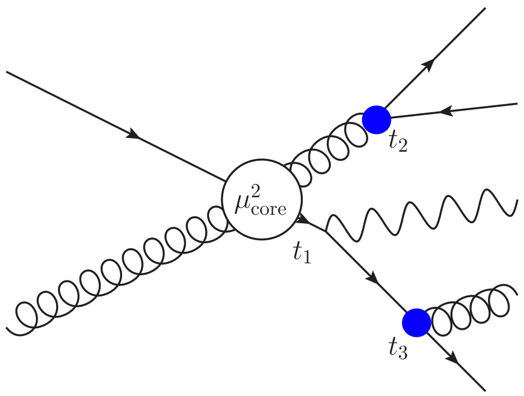




re-interpretation as parton-shower history

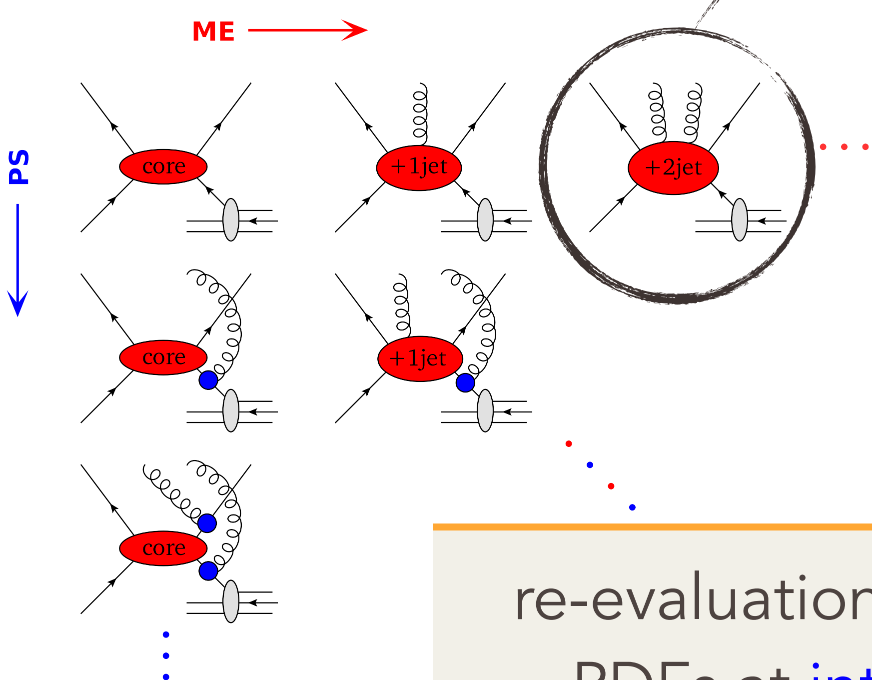


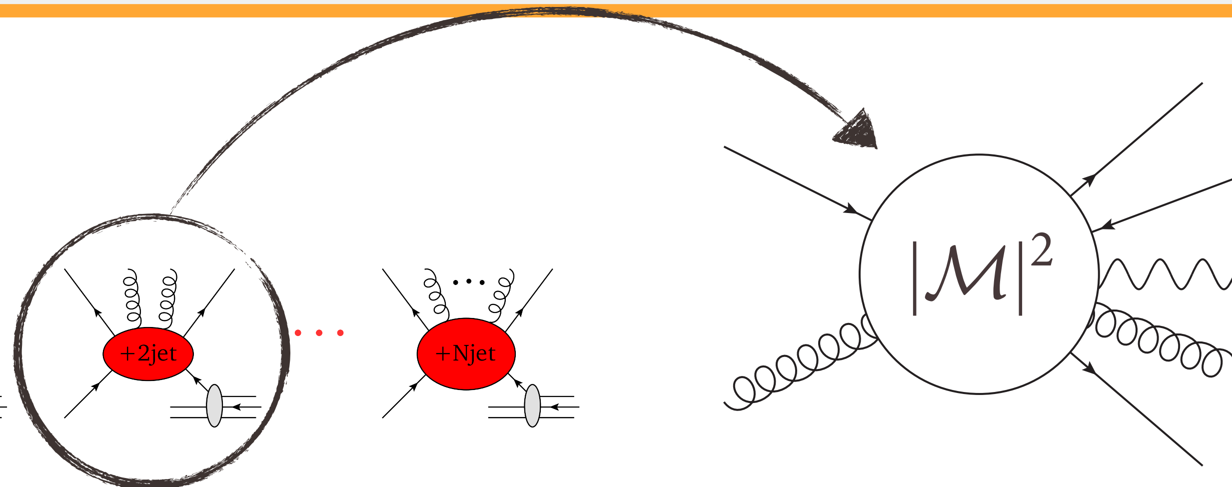
re-evaluation of α_S and PDFs at intermediate splitting t_i scales

METS scale setter:

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

Multi-jet merging





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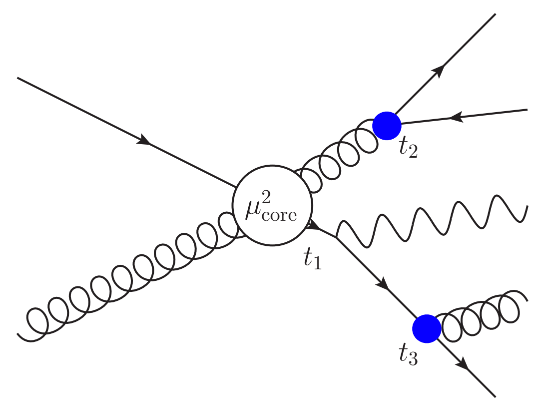

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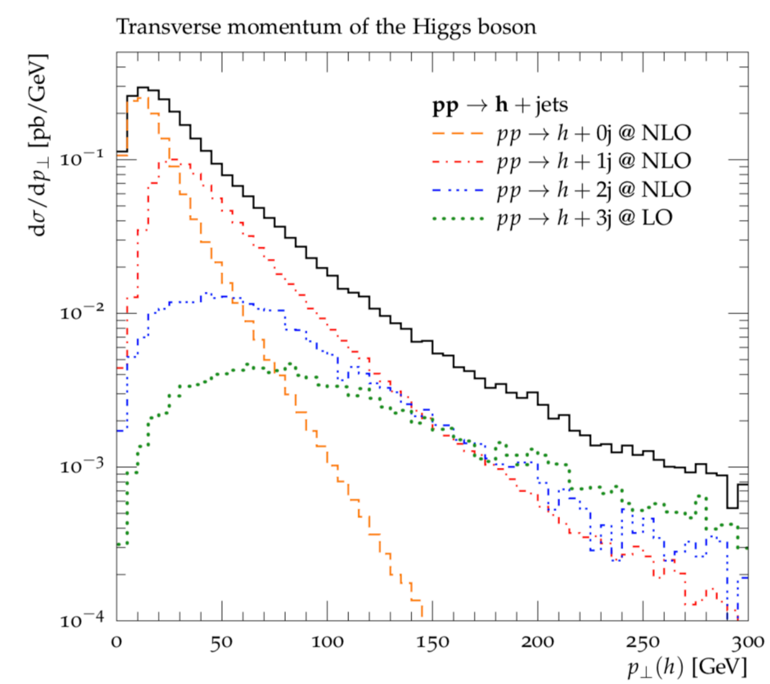
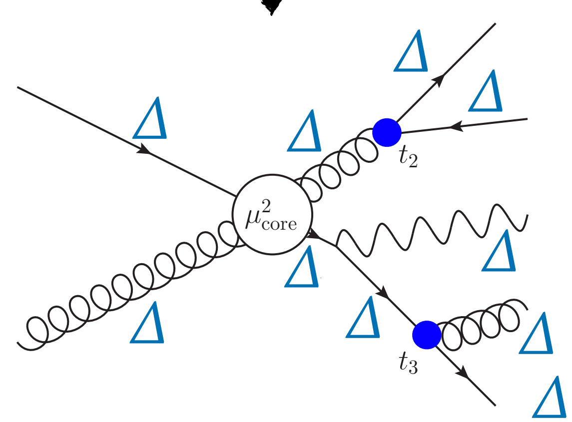


introduce Q_{CUT}

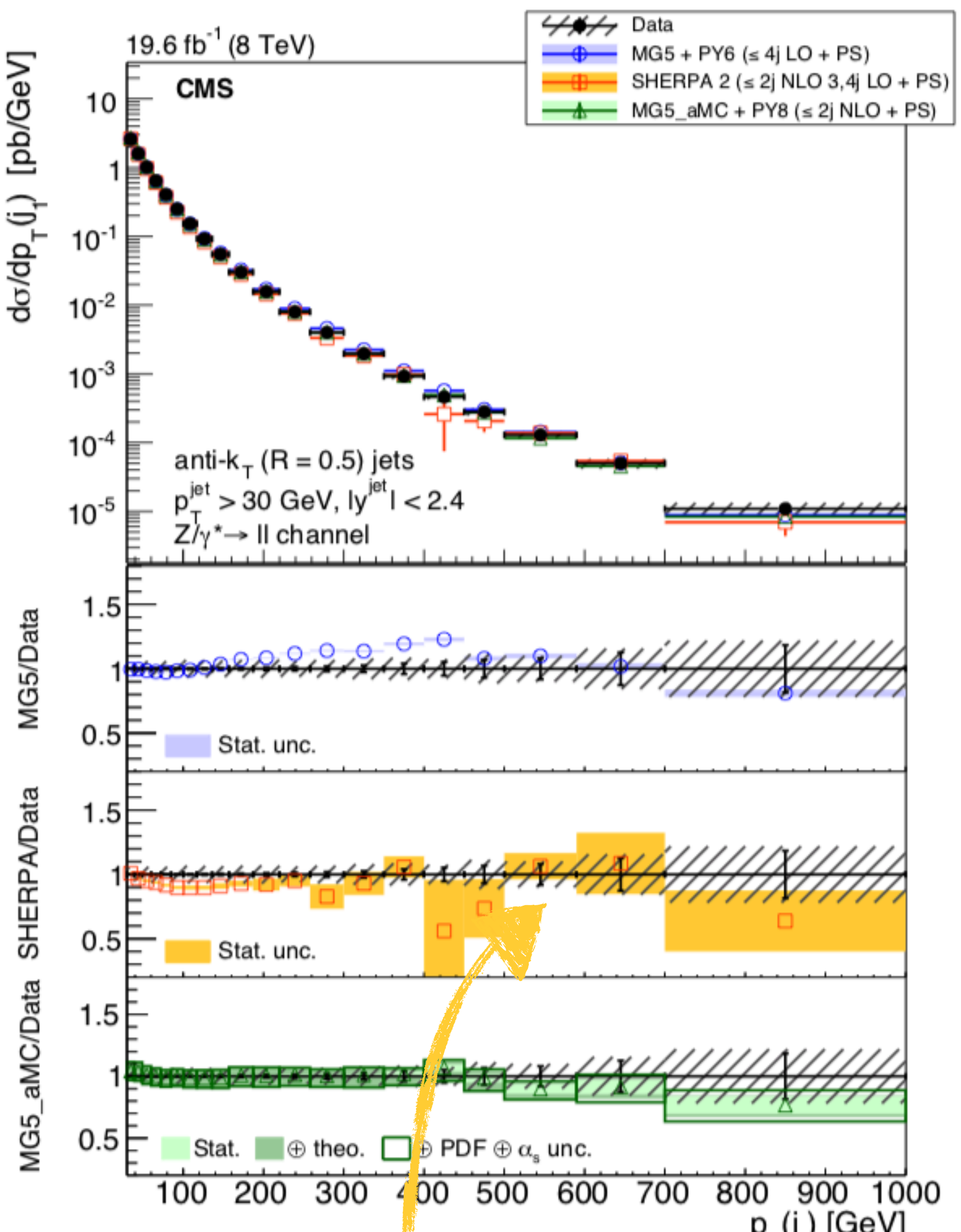
Sudakov rejection to make matrix elements exclusive down to Q_{CUT}



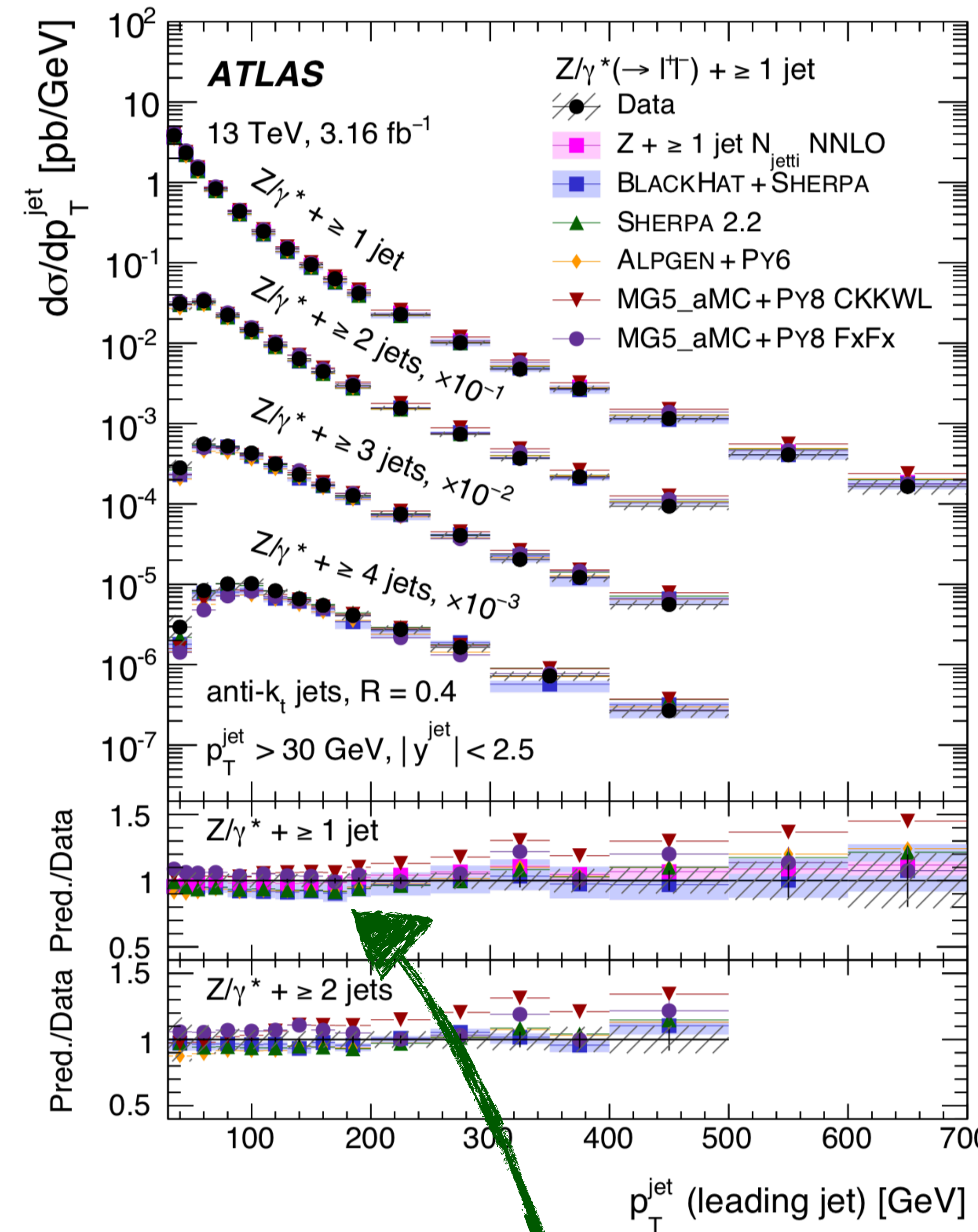
finally add genuine parton-shower emissions below Q_{CUT}

Z+jets CMS@8 vs. ATLAS@13 – $p_{T,\text{lead}}$

[CMS 1611.03844]



[ATLAS 1702.05725]



Sherpa 2.0.0
stat. unc.

Z + 0,1,2j@NLO + 3,4j@LO

Sherpa 2.2.1

- shapes similar accross versions & experiments (& beam energies)

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:

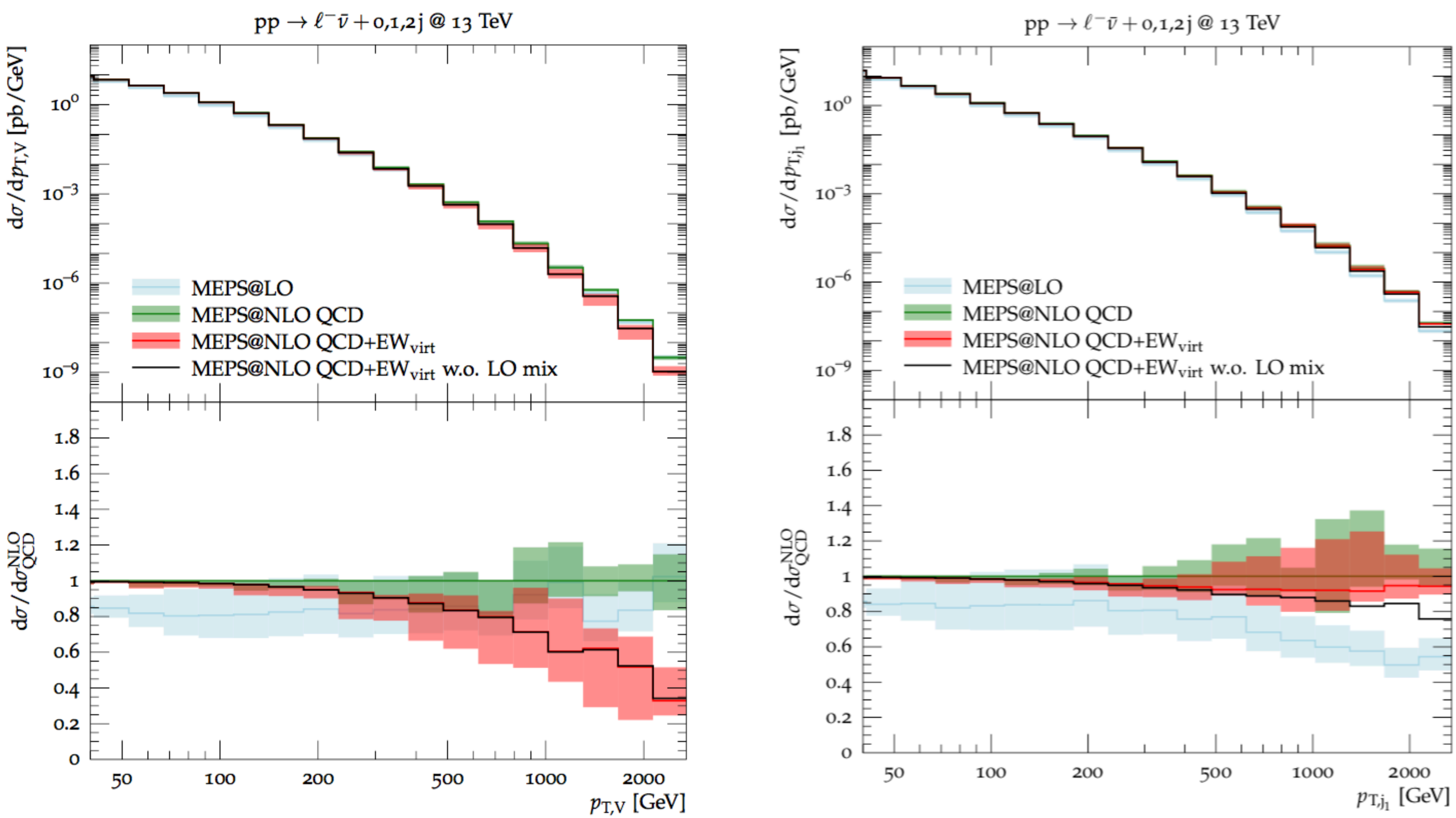
$$\bar{B}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \bar{B}_{n,\mathrm{QCD}}(\Phi_n) + V_{n,\mathrm{EW}}(\Phi_n) + I_{n,\mathrm{EW}}(\Phi_n) + B_{n,\mathrm{mix}}(\Phi_n)$$

- 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

EW corrections in particle-level evtgen

slide adapted from Marek Schönherr

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



similar validation+study for top-pair production:

[Gütschow, Lindert, Schönherr 1803.00950]

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

- 2.2.5 (current)
  - support for single-top production, examples for s/t/tW channels
    [EB, Krauss, Schönherr 1711.02568]
  - custom user hook phase after event generation
  - improved PS on-the-fly reweighting
  - bugfixes
- 2.2.6 (~days/few weeks)
  - approx EW merging as alternate event weights
    needs non-public version of OpenLoops
  - include sub-leading terms in MEPS@NLO in on-the-fly reweighting
  - bugfixes
- 3.0.0 (~few months)
  - NNLO+PS for V/H production & DIS
    [Hoeche, Kuttimalai, Li, Prestel 1405.3607, 1407.3773, 1809.04192]
  - 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]
  - 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

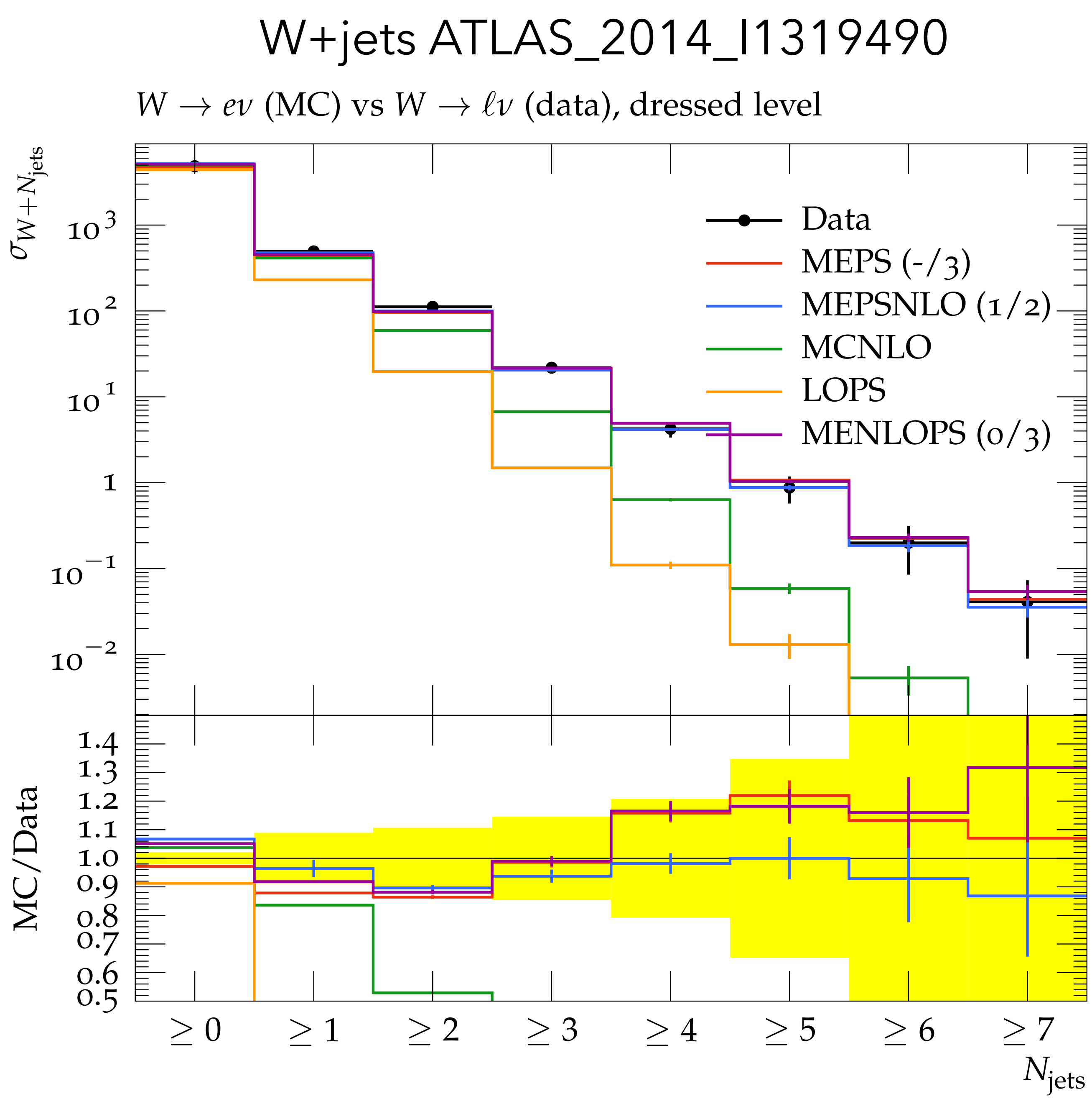
☛ up-to-date infos: gitlab/tags & gitlab/milestones
☛ communicate with us via our gitlab/issue-tracker

Sherpa 2.2.6 V+jets @ 7 TeV benchmarks

Sherpa 2.2.6 V+jets @ 7 TeV benchmarks

https://www2.ph.ed.ac.uk/~ebothman/LHCEW-benchmarks-7TeV

- MEPS@NLO
  V + 0,1j@NLO + 2j@LO
- MEPS (MENLOPS)
  V + 0j@(N)LO + 1,2,3j@LO
- NNPDF30NNLO (default)
- $\alpha_S(m_Z)$ = 0.118 (default)
- Q_{CUT} = 20 GeV
- default core scale μ^2
  - $\ell\ell/\ell\nu$-like → $m_{\ell\ell/\ell\nu}{}^2$
  - Vj-like → $m_T{}^2$ / 4
  - jj-like → $-1/(1/s+1/t+1/u)/4$
- V+1j virtuals from OPENLOOPS



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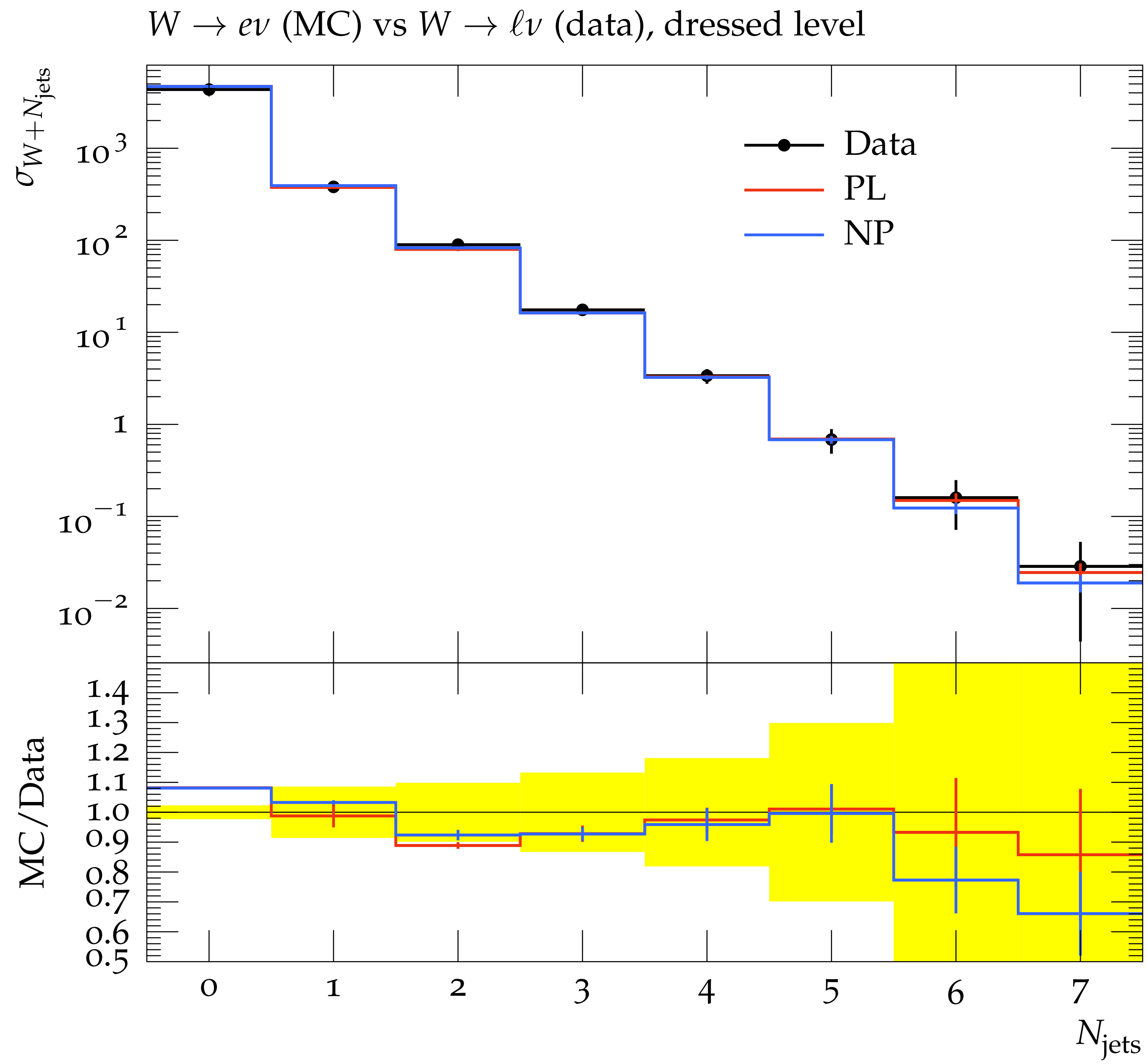
W+jets ATLAS_2014_I1319490



parton-level vs. hadron-level

Sherpa 2.2.6 V+jets @ 7 TeV benchmarks

https://www2.ph.ed.ac.uk/~ebothman/LHCEW-benchmarks-7TeV

- MEPS@NLO
  V + 0,1j@NLO + 2j@LO
- MEPS (MENLOPS)
  V + 0j@(N)LO + 1,2,3j@LO
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- default core scale μ^2
  - $\ell\ell/\ell\nu$-like → $m_{\ell\ell/\ell\nu}^2$
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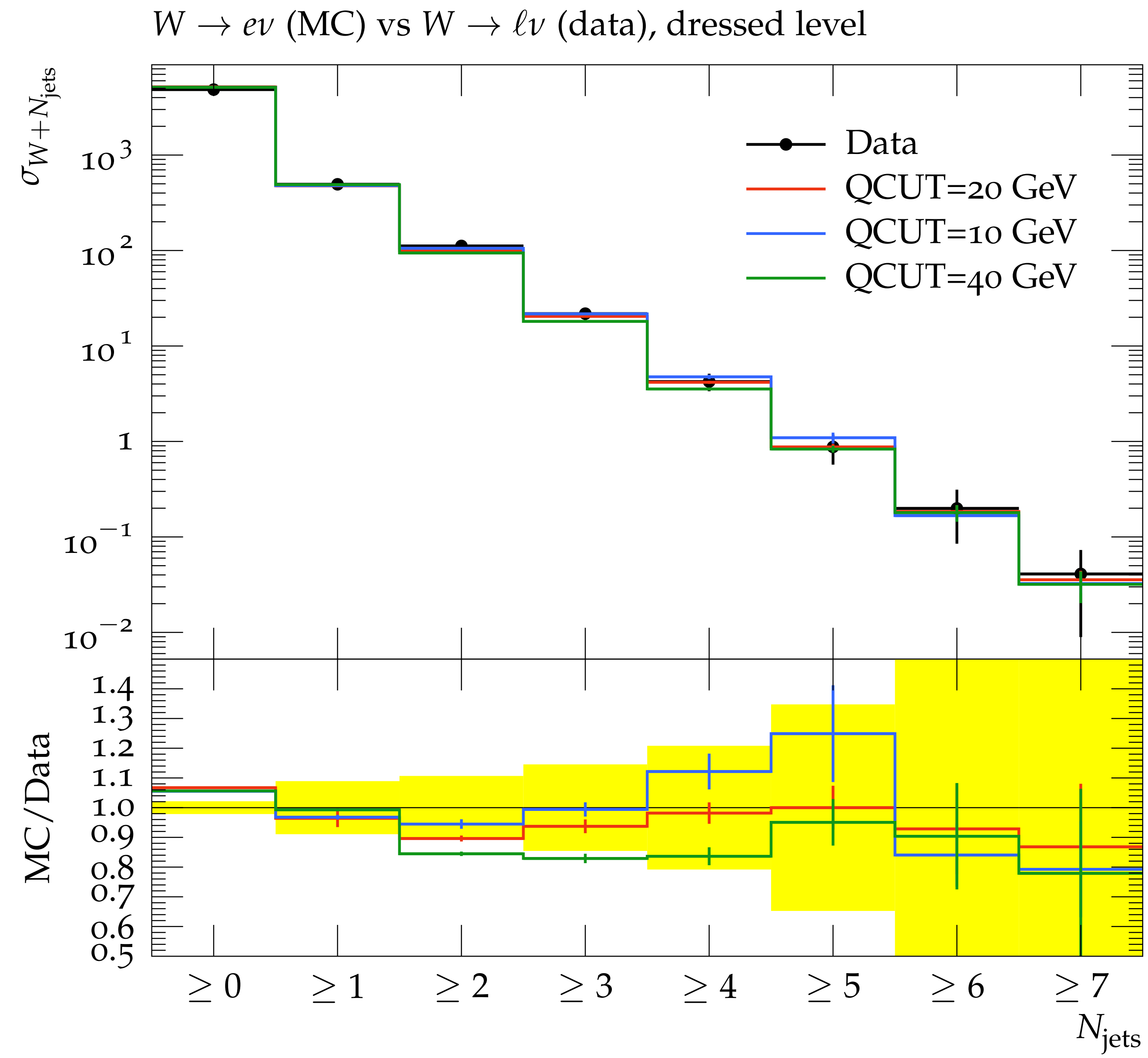
W+jets ATLAS_2014_I1319490

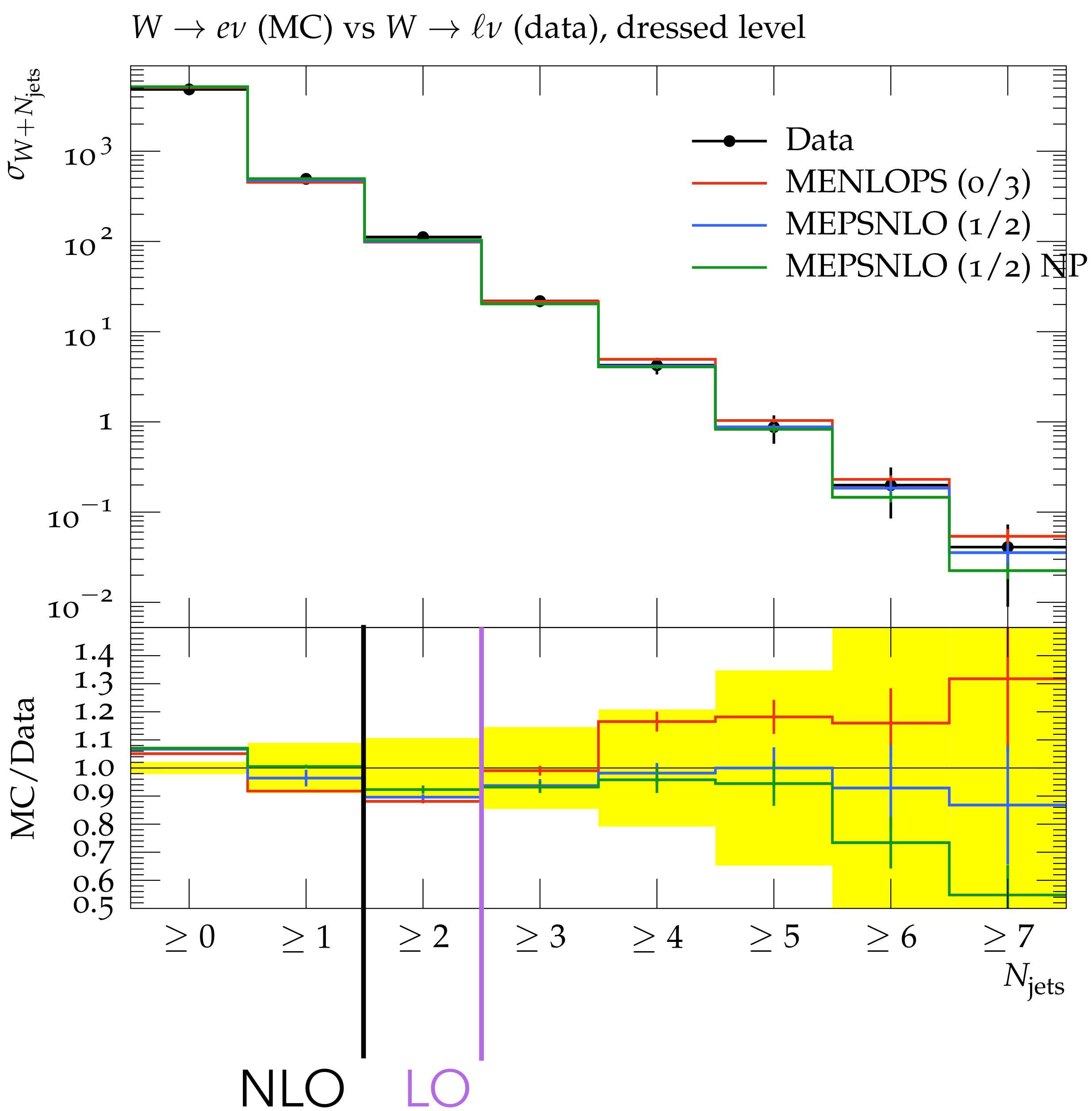


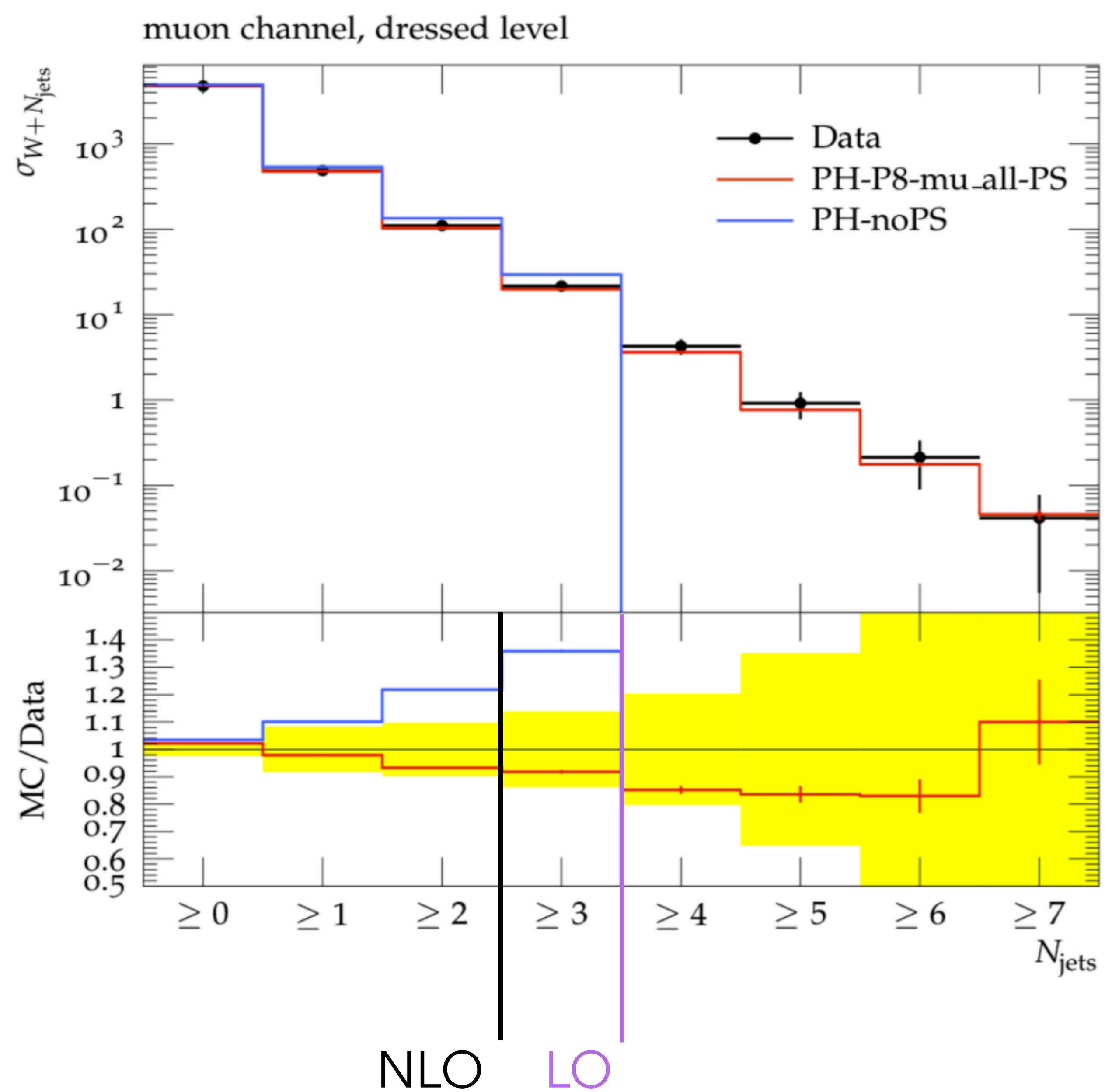
Q_{CUT} variation (10, 20, 40)

Sherpa 2.2.6 V+jets @ 7 TeV benchmarks

W+jets ATLAS_2014_I1319490

[Schönherr, Jung, POWHEG+PYTHIA benchmarks
http://jung.web.cern.ch/jung/LHCEW/Benchmark/7TeV/]

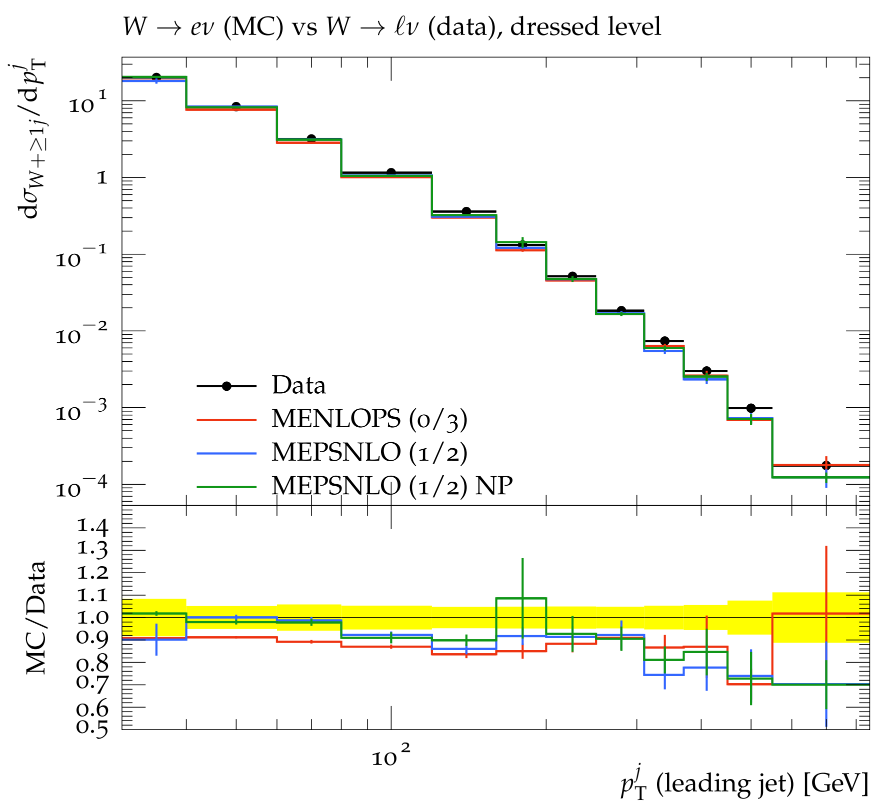




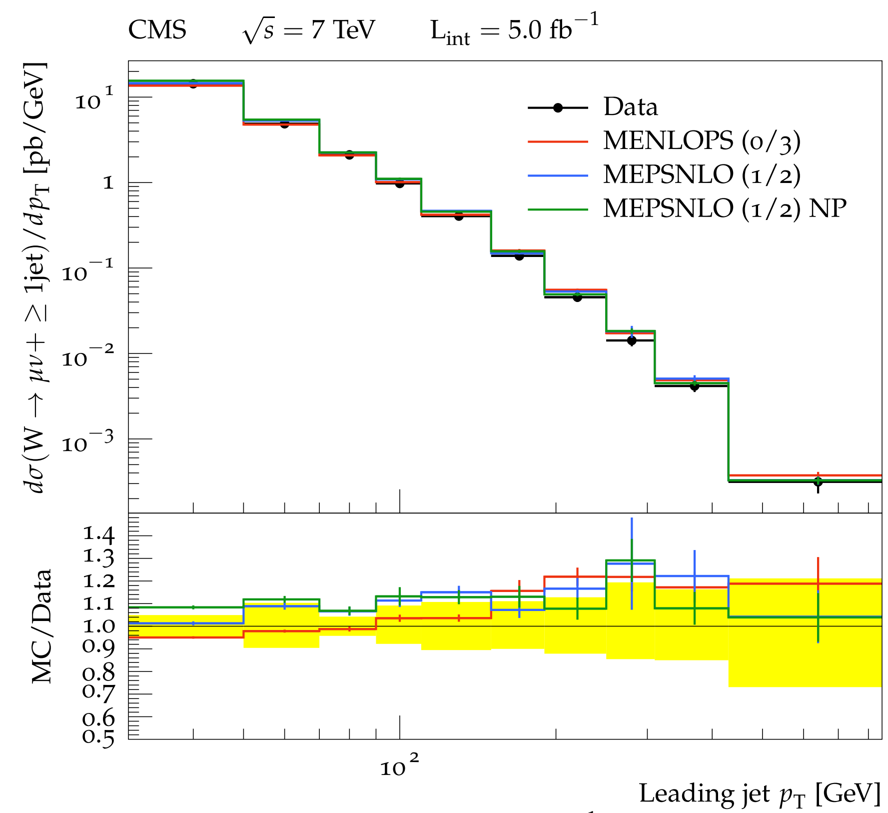
Sherpa 2.2.6 V+jets @ 7 TeV benchmarks

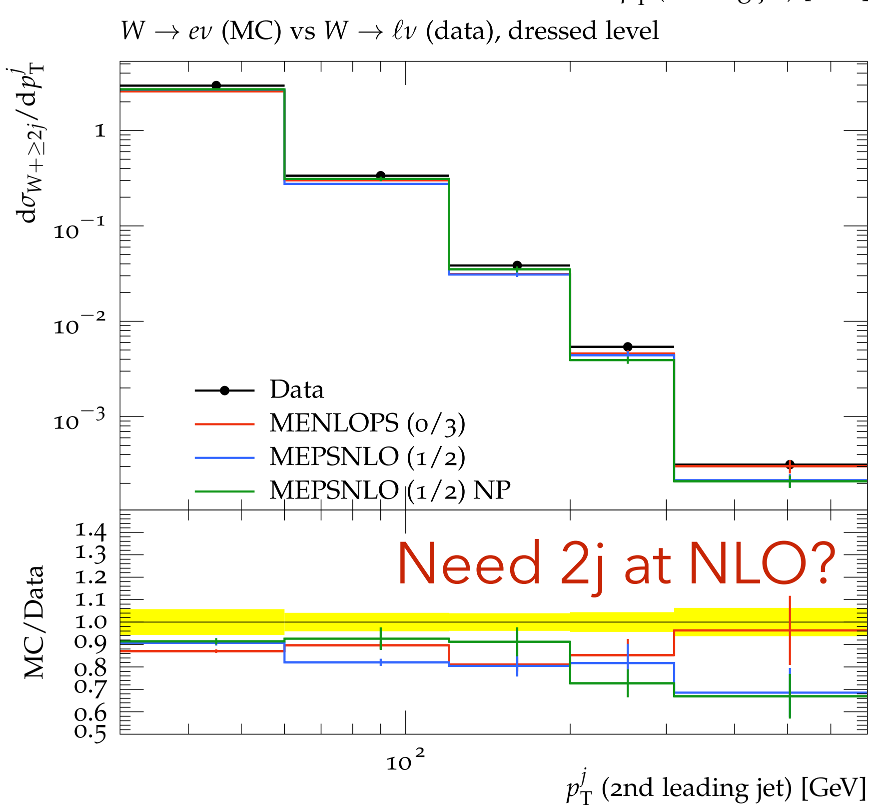
W+jets

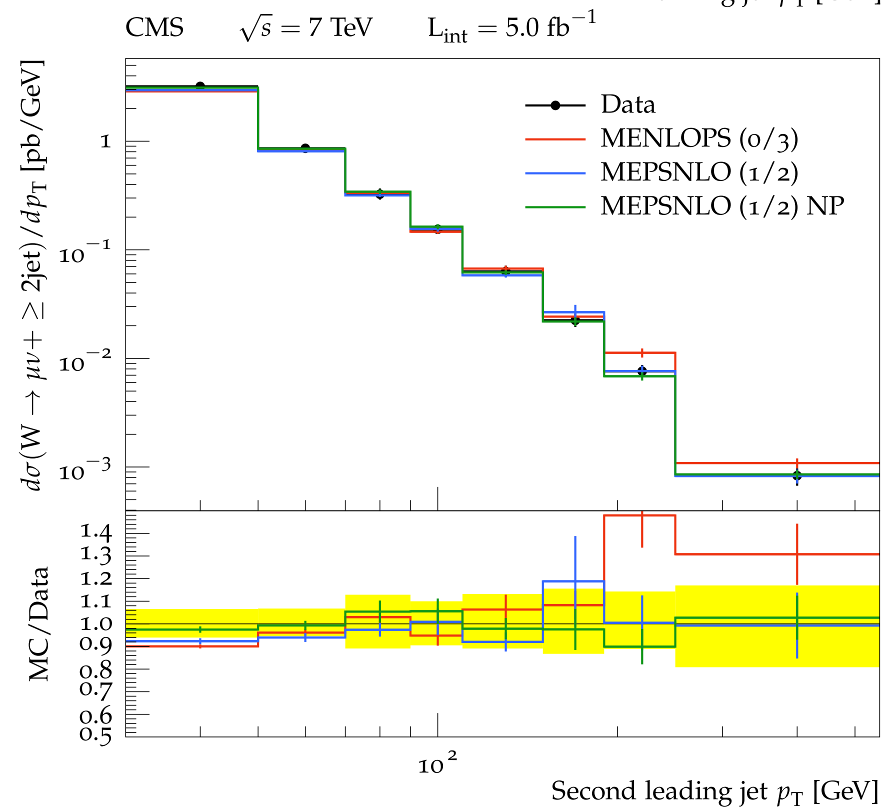
ATLAS_2014_I1319490



CMS_2014_I1303894



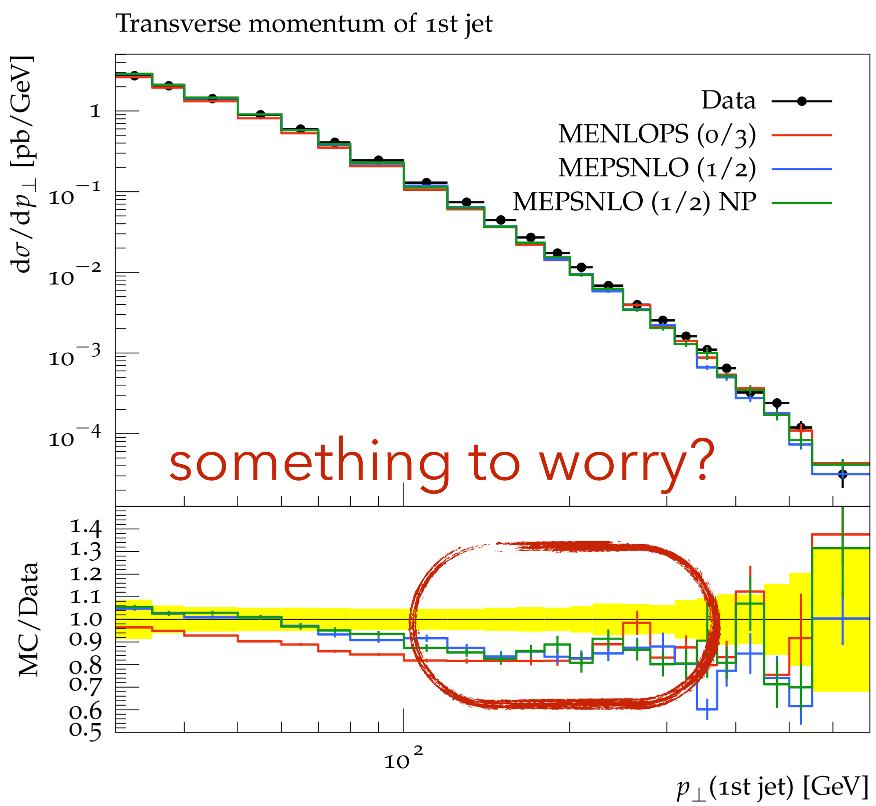


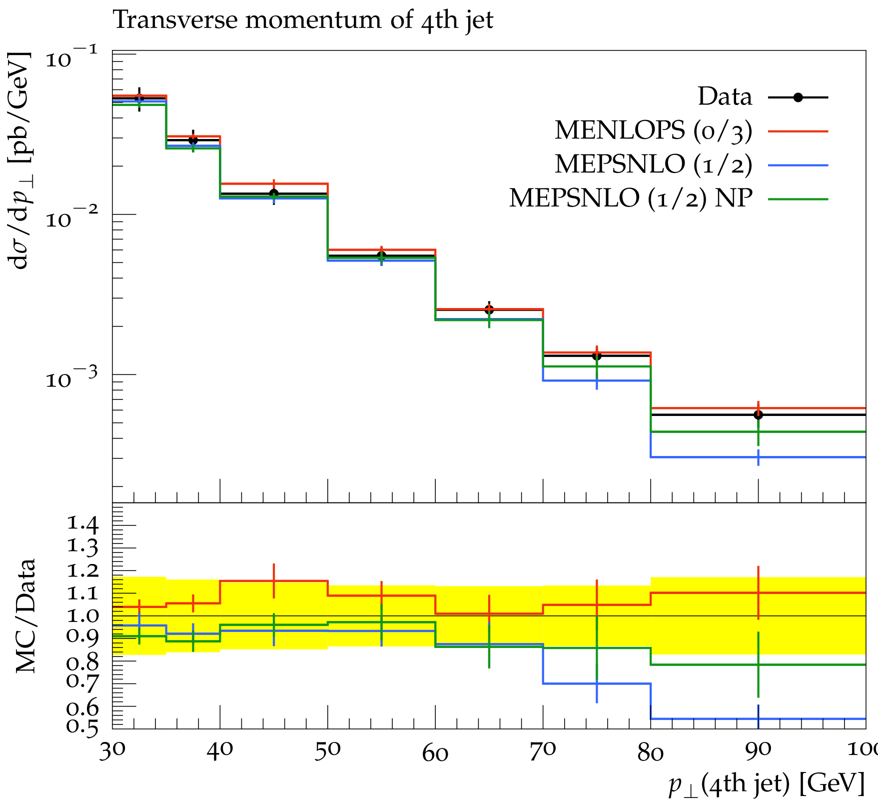


Sherpa 2.2.6 V+jets @ 7 TeV benchmarks

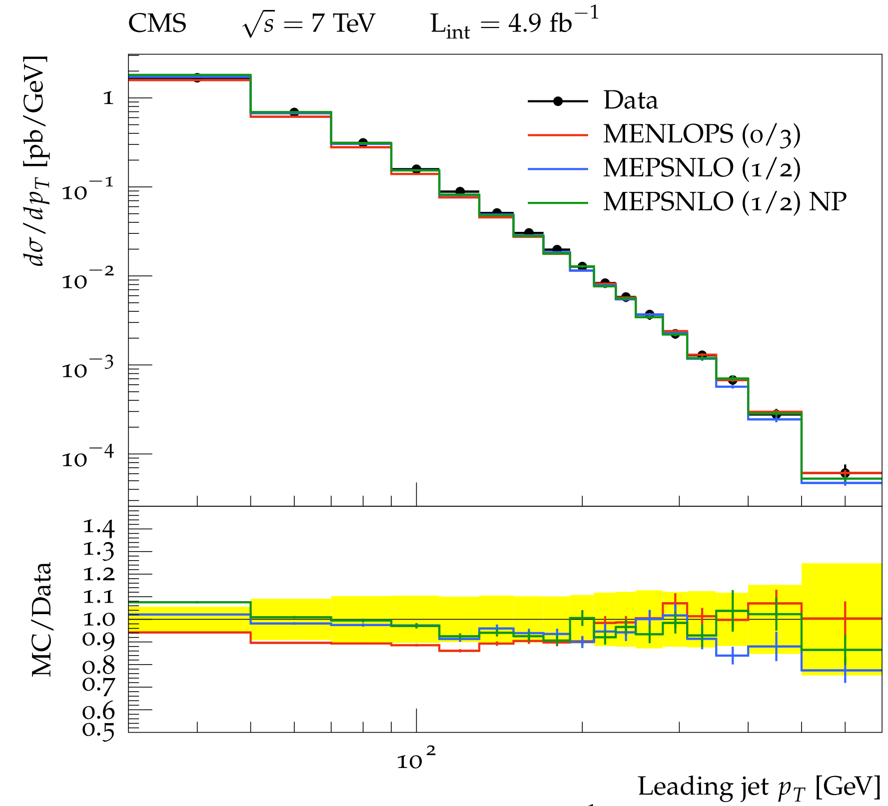
Z+jets

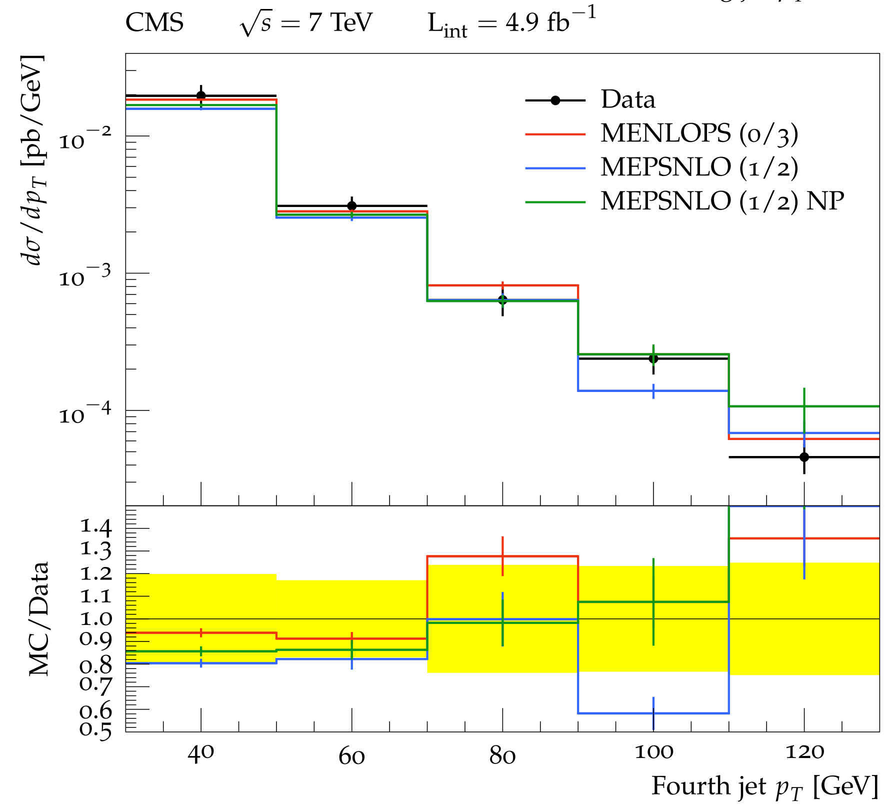
ATLAS_2013_I1230812





CMS_2015_I1310737

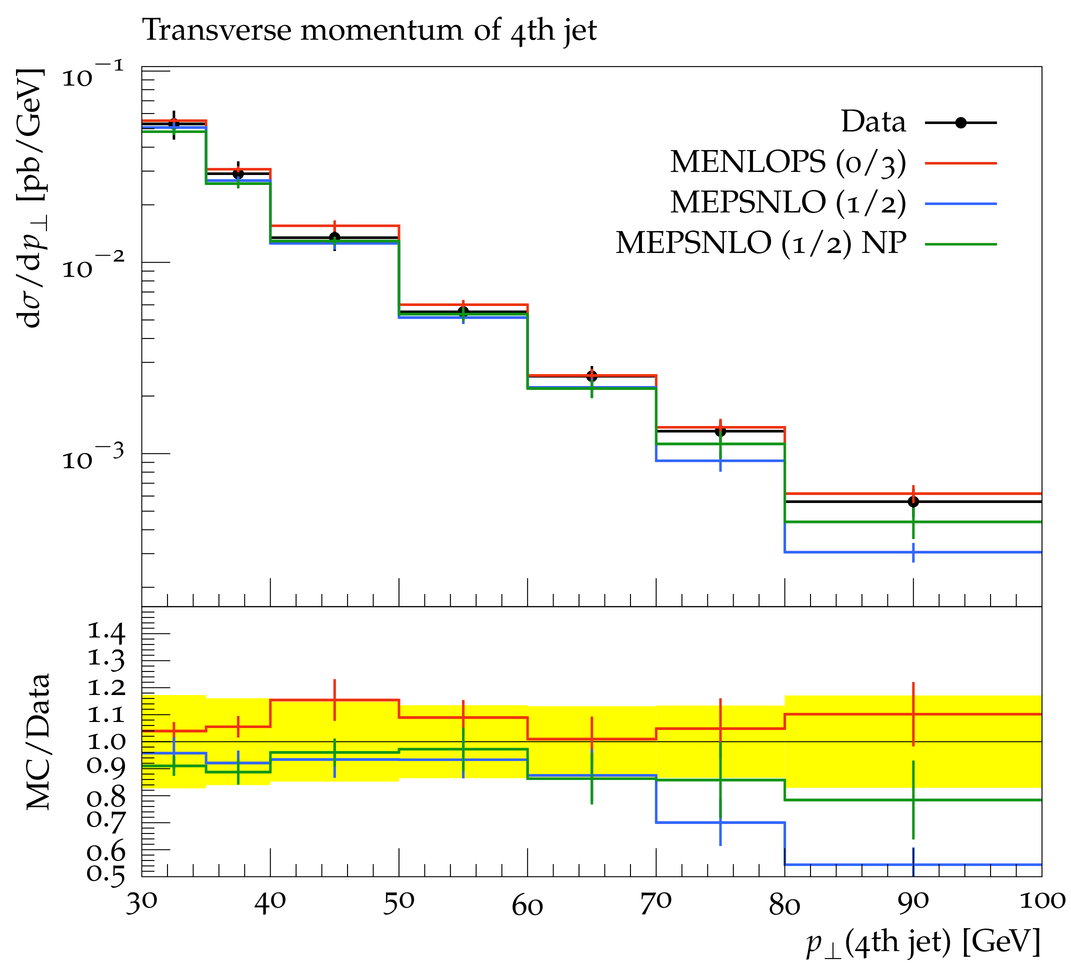


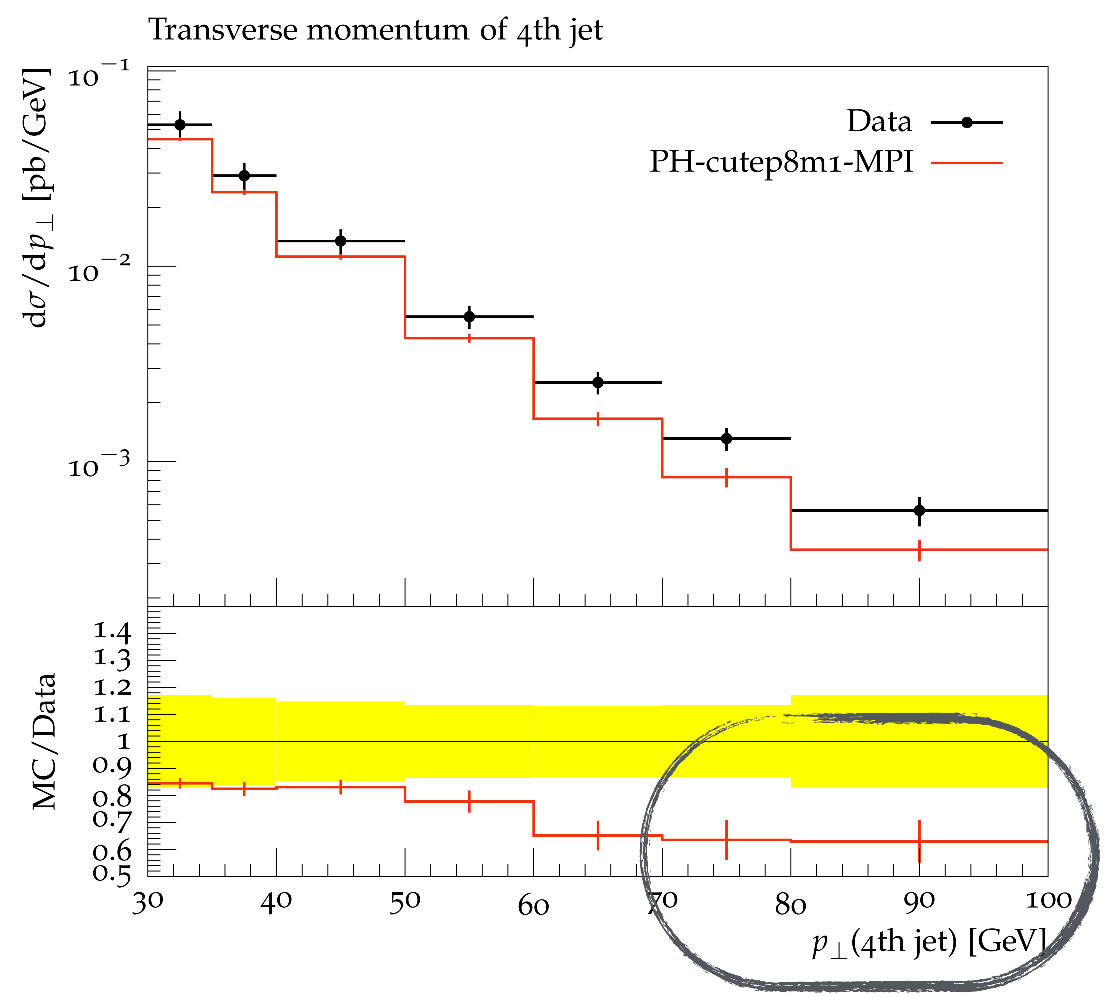


Sherpa 2.2.6 V+jets @ 7 TeV benchmarks

ATLAS_2013_I1230812

Z+jets





"Is this something to worry?"

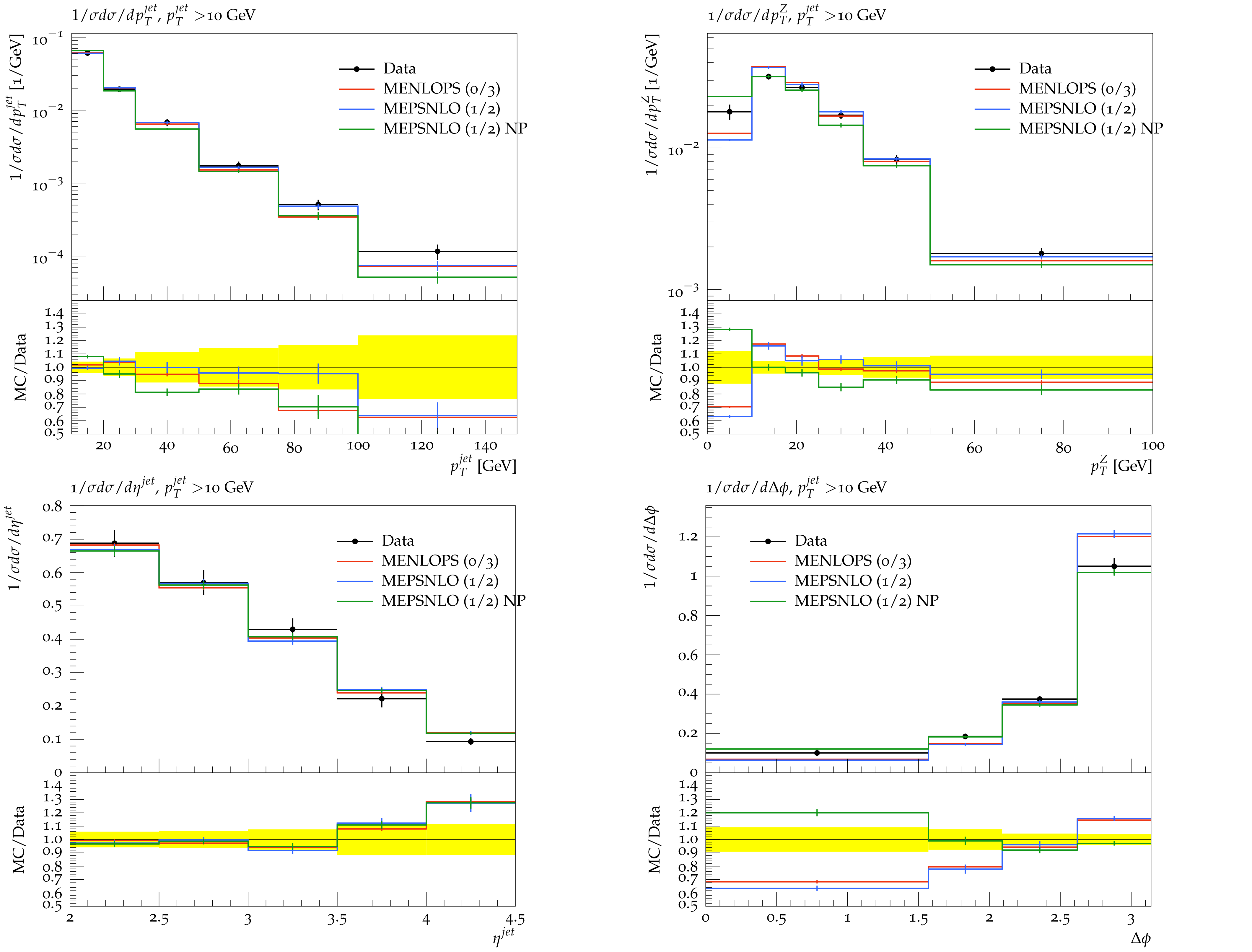
[Schönherr, Jung, POWHEG+PYTHIA benchmarks]

- possibly mitigated by adding LO jets?

Sherpa 2.2.6 V+jets @ 7 TeV benchmarks

LHCB_2014_I1262703

Z+jets



Conclusions

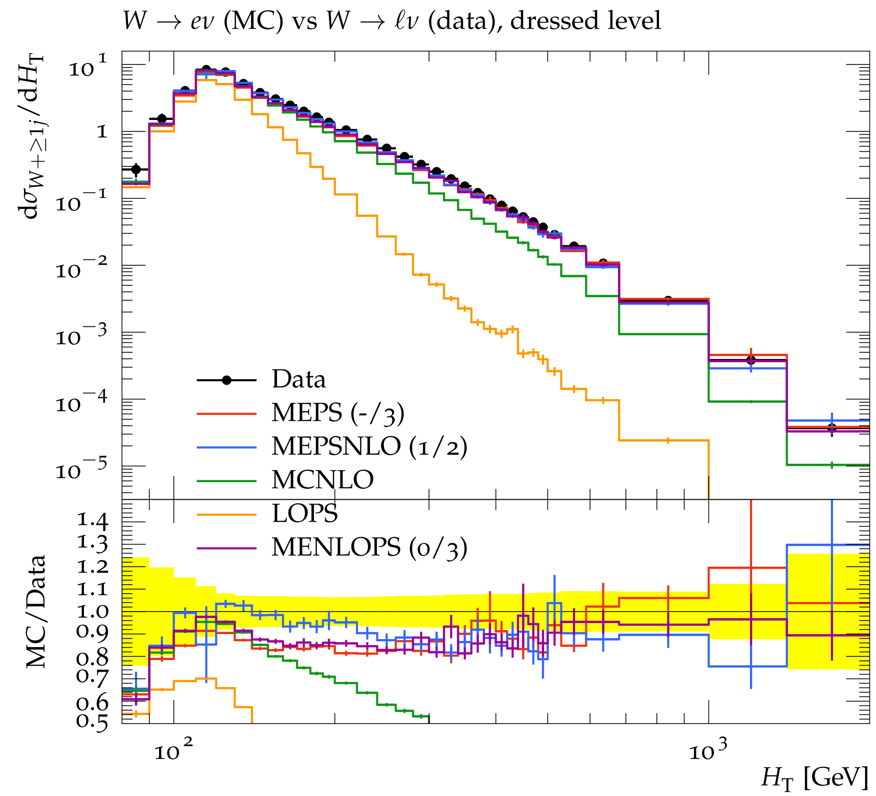
- Sherpa ❤️ V+jets
- we provide a comprehensive list of example configs, only one tune & hopefully sensible defaults
  ⤳ easy to compare across experiments
- MEPS@NLO (+EWvirt) state-of-the-art
  particle-level, multi-jet observables
- benchmarks promising (1st jet p_T for Z+jets?)
  - need V+2j @ NLO & more stats as in Hannes' and Marek's benchmarks to say more
    also: at least scale uncertainties
- **THANKS!**

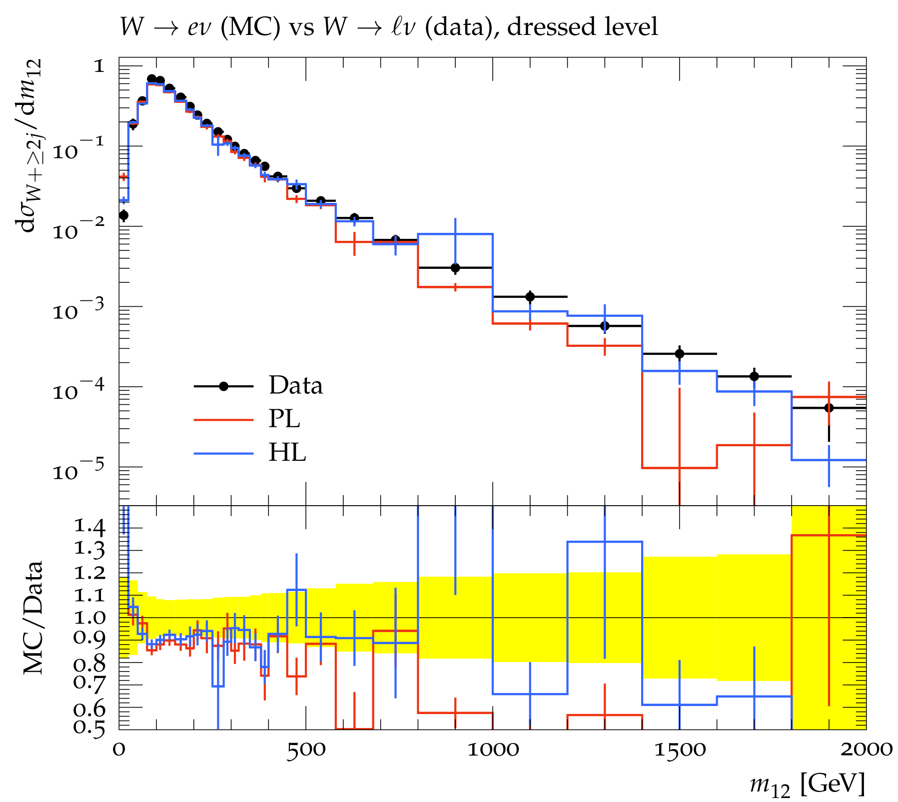
Back-up

Sherpa 2.2.6 V+jets @ 7 TeV benchmarks

W+jets

ATLAS_2014_I1319490





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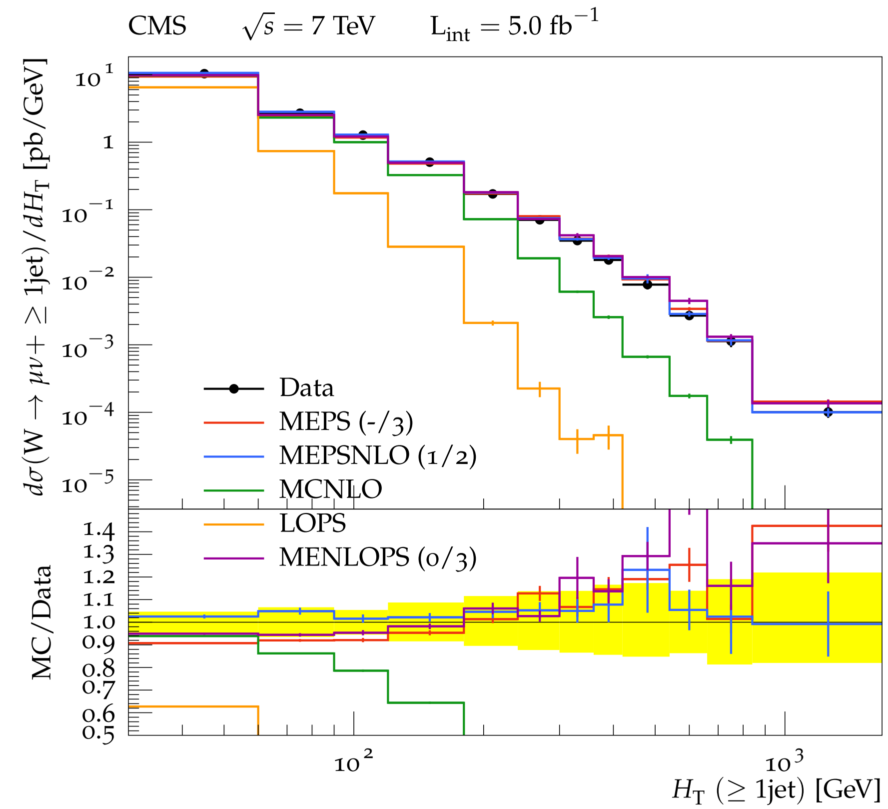


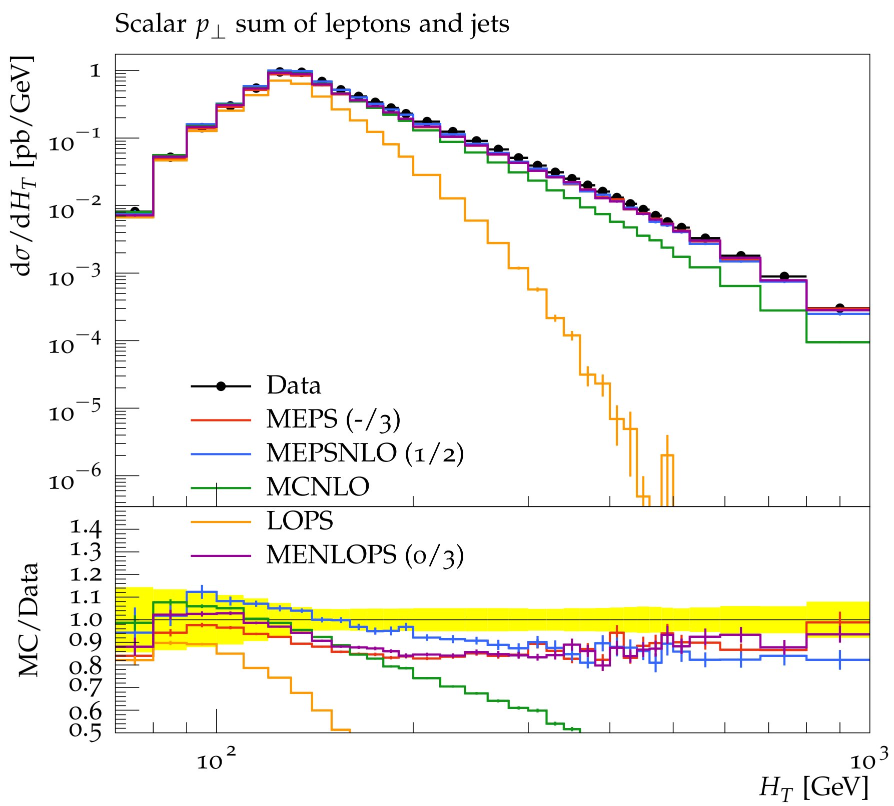
$$H_T^{\text{CMS}} = S_T = \sum_i p_{T,j_i}$$

$$H_T^{\text{ATLAS}} = S_T + \sum_i p_{T,\ell_i}$$

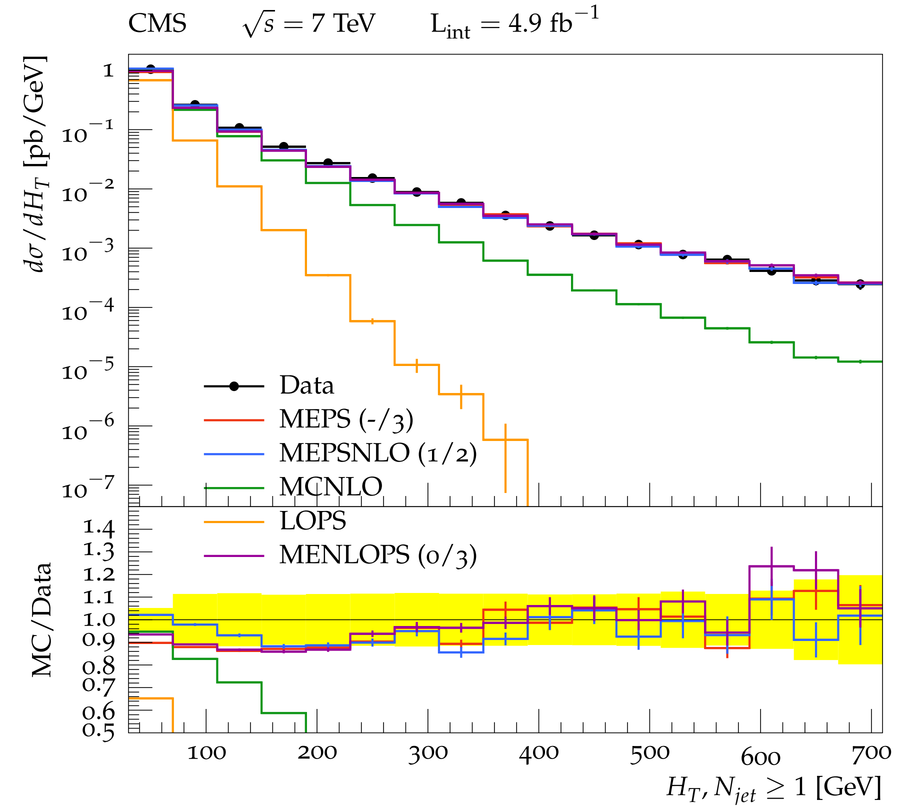
Sherpa 2.2.6 V+jets @ 7 TeV benchmarks

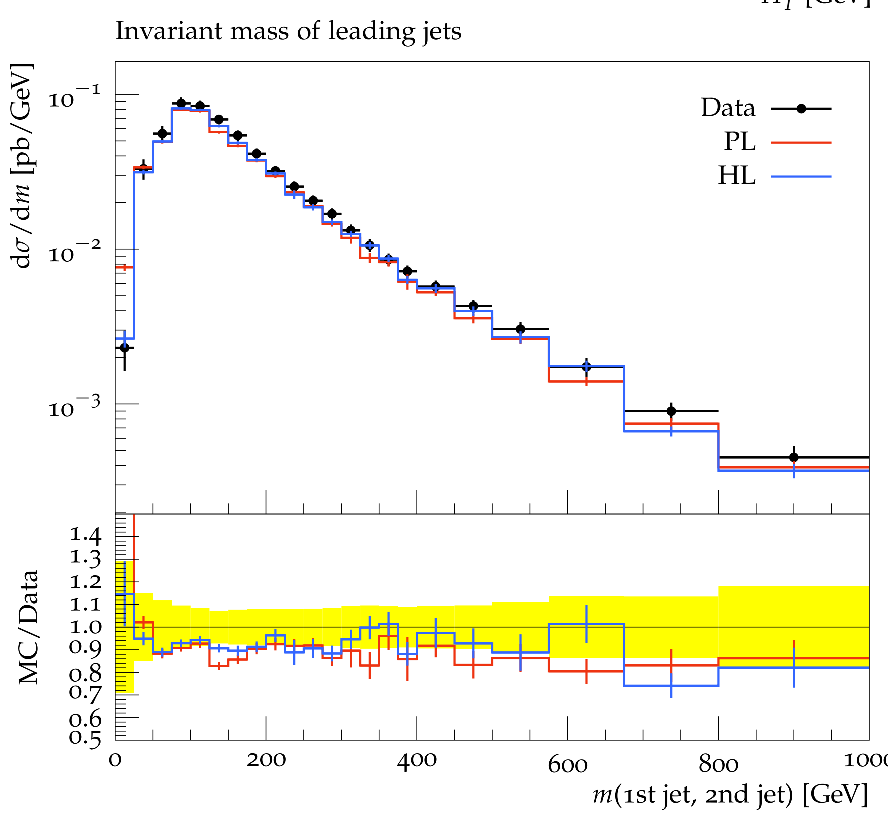
Z+jets

ATLAS_2013_I1230812



CMS_2015_I1310737





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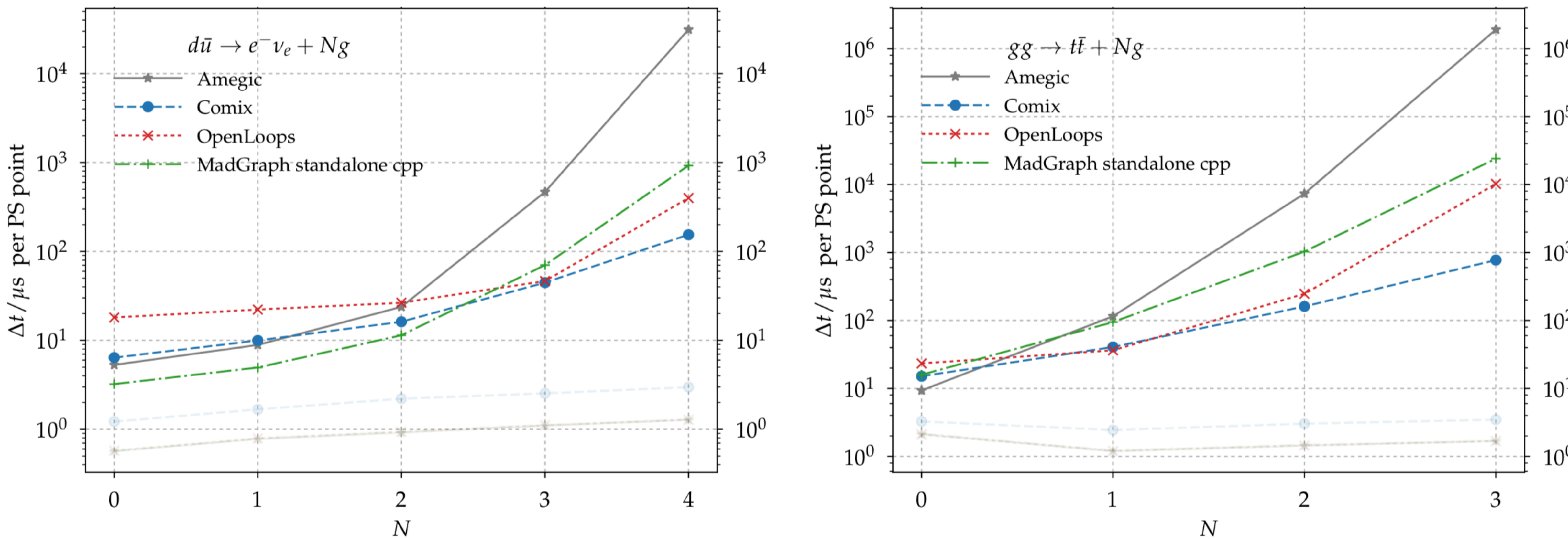
pQCD uncertainties with Sherpa

- 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

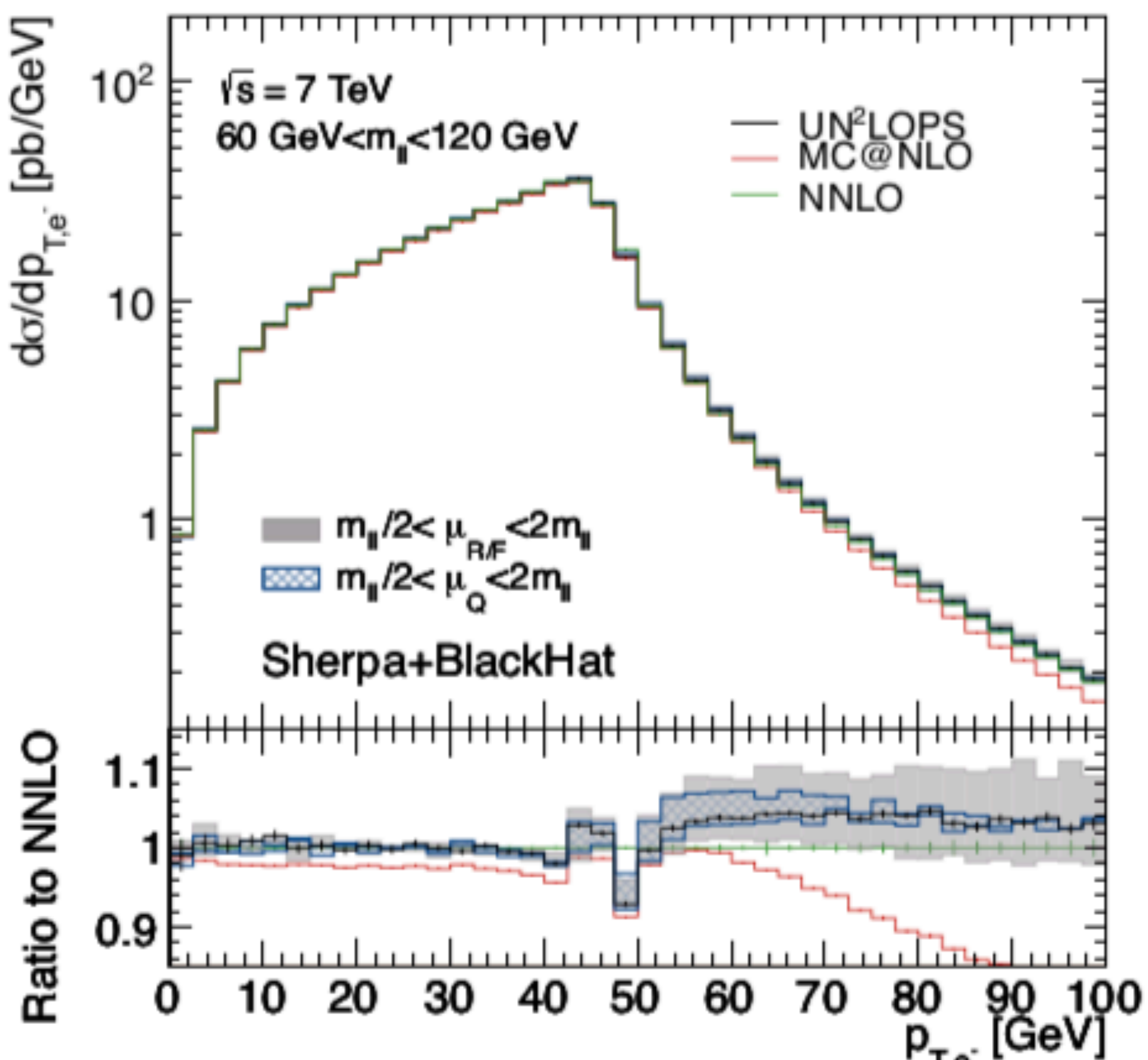
CPU cycles



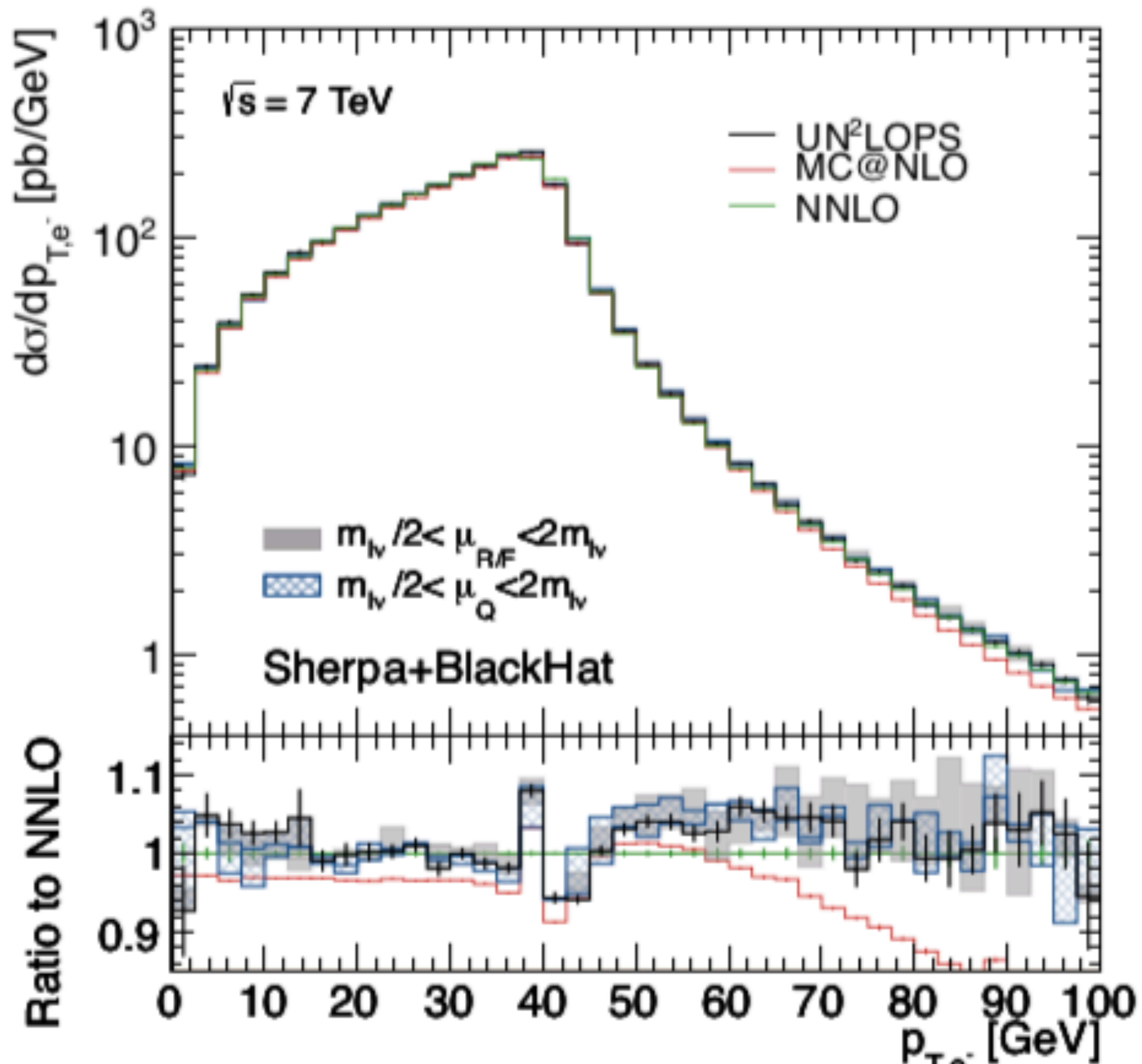
- Efficient tree-level generators for Born and real-emission corrections Amegic [Krauss,Kuhn,Soff] hep-ph/0109036, Comix [Gleisberg,SH] arXiv:0808.3674
- In Comix factorial scaling with multiplicity reduced to exponential by dynamic programming & sampling of color configurations [Berends,Giele] NPB306(1988)759,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

NNLOPS for pp → V

[Hoeche et al.] arXiv:1405.3607,1407.3773



$pp \to \ell\ell$

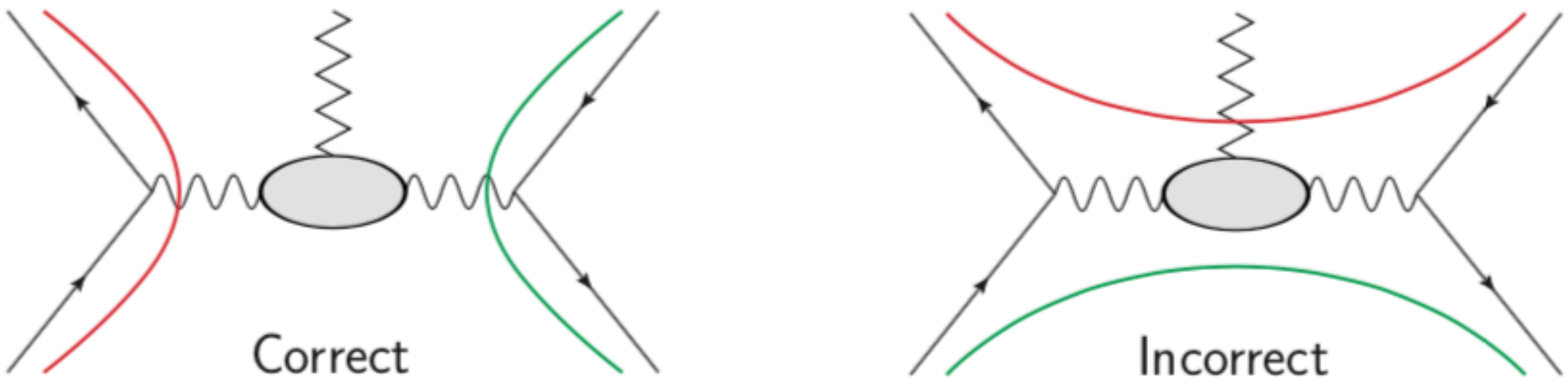


$pp \to \ell\nu$

Vector-boson scattering simulations with Sherpa

slide by Stefan Höche

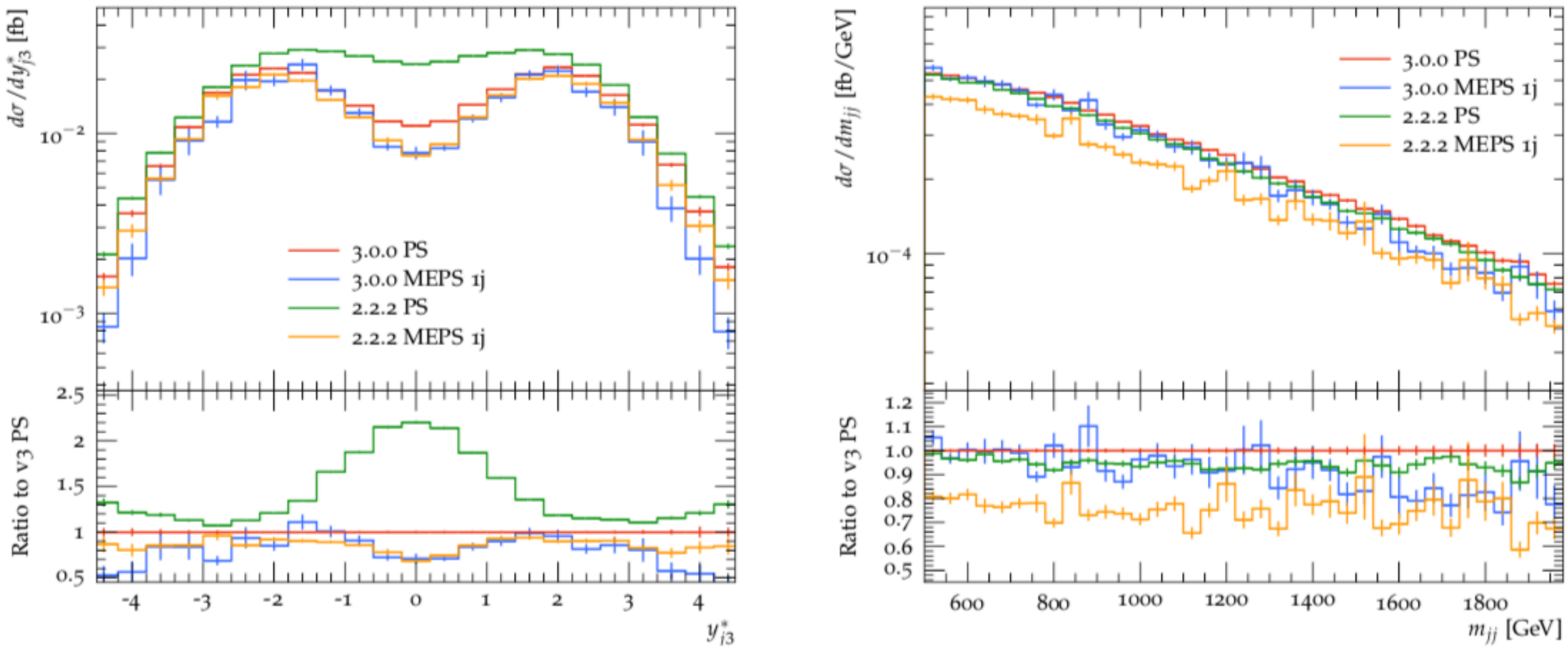
- VBF-like situations require judicious setting of color flow information in interface between fixed-order calculation and parton shower



- 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

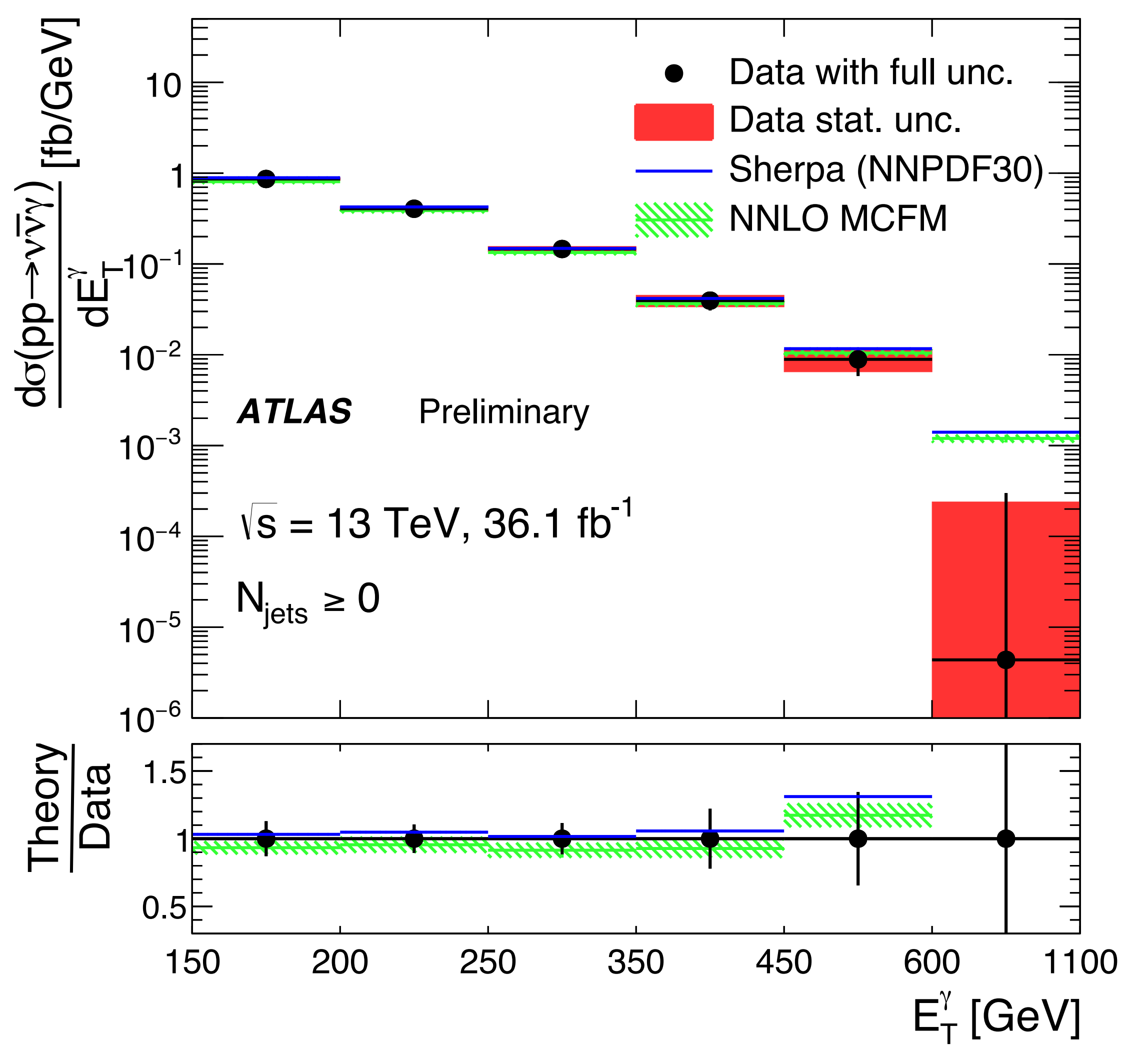


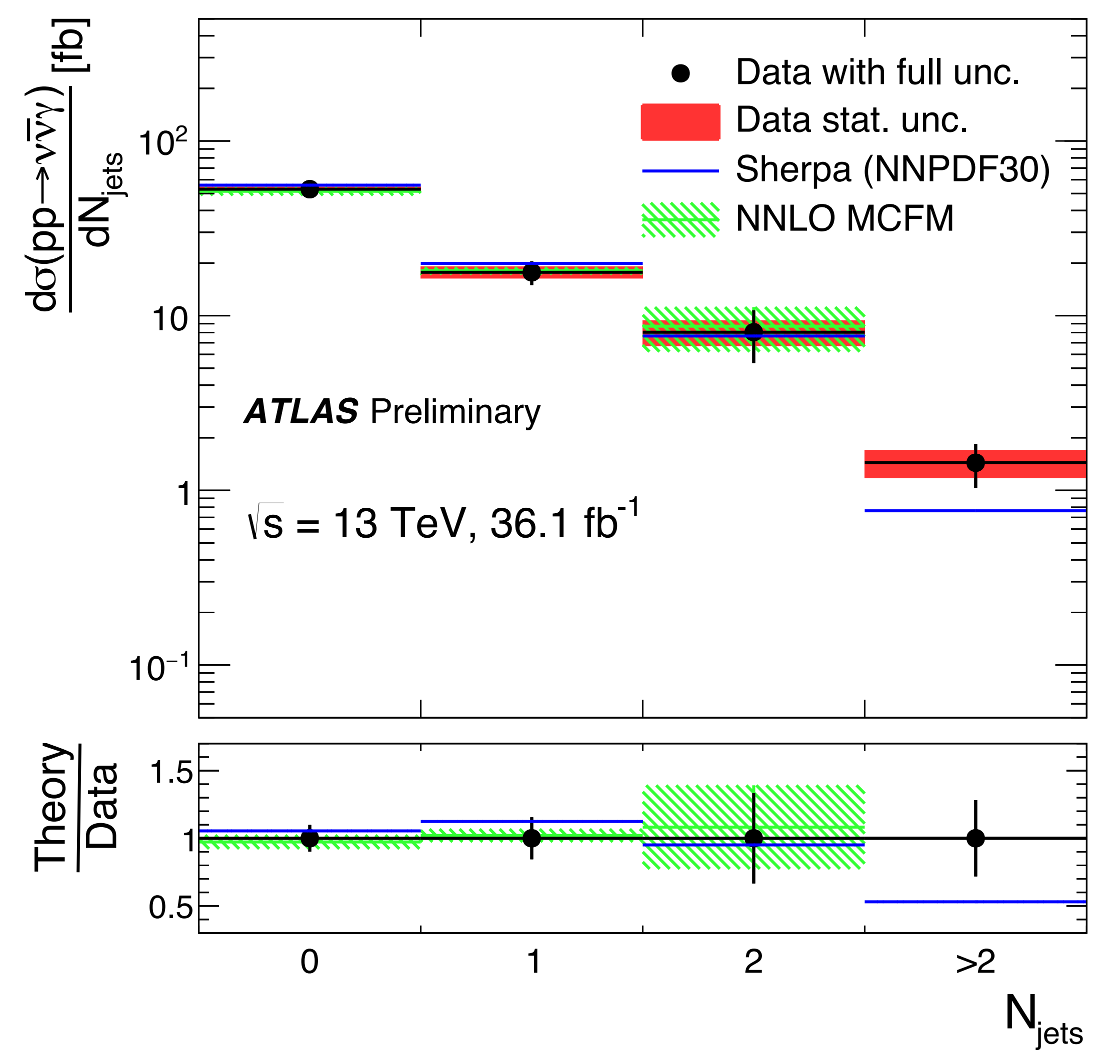
- Differential distributions confirm improvement:
  - Third jet produced more forward and at lower rate in Sherpa 3.0.0
  - PS radiation pattern in Sherpa 2.2.0 corrected by ME+PS merging, but breaking of PS unitarity in CKKW(L) decreases overall event rate
- Sherpa 3.0.0 predicts $\sim$20% larger cross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

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:
  - $\gamma\gamma$+0,1,2 jets
    [Chiesa et al, JHEP 1710 (2017) 181]
  - $\gamma\gamma\gamma/\gamma\gamma\ell\nu/\gamma\gamma\ell\ell$
    [Greiner, Schönherr, JHEP 1801 (2018) 079]
- SHERPA+RECOLA
  - $V/\ell\nu/\ell\ell$+j, $\ell\ell$+2j, $\ell\ell\ell\ell$, ttH
    [Biedermann et al, Eur.Phys.J. C77 (2017) 492]
  - $\ell\ell\ell\nu\nu\nu$ [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]
  - $\ell\ell/\ell\nu/\nu\nu/\gamma$+j
    [Lindert et al, Eur.Phys.J. C77 (2017)]
  - $\ell\ell\nu\nu$ [Kallweit et al., JHEP 1711 (2017) 120]
  - $\ell\ell/\ell\nu$+2j, ttH [LH 2015 SM WG report]
  - tt+0,1 jets [Gütschow, Lindert, Schönherr, Eur.Phys.J. C78 (2018) no.4, 317]

EW NLO

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

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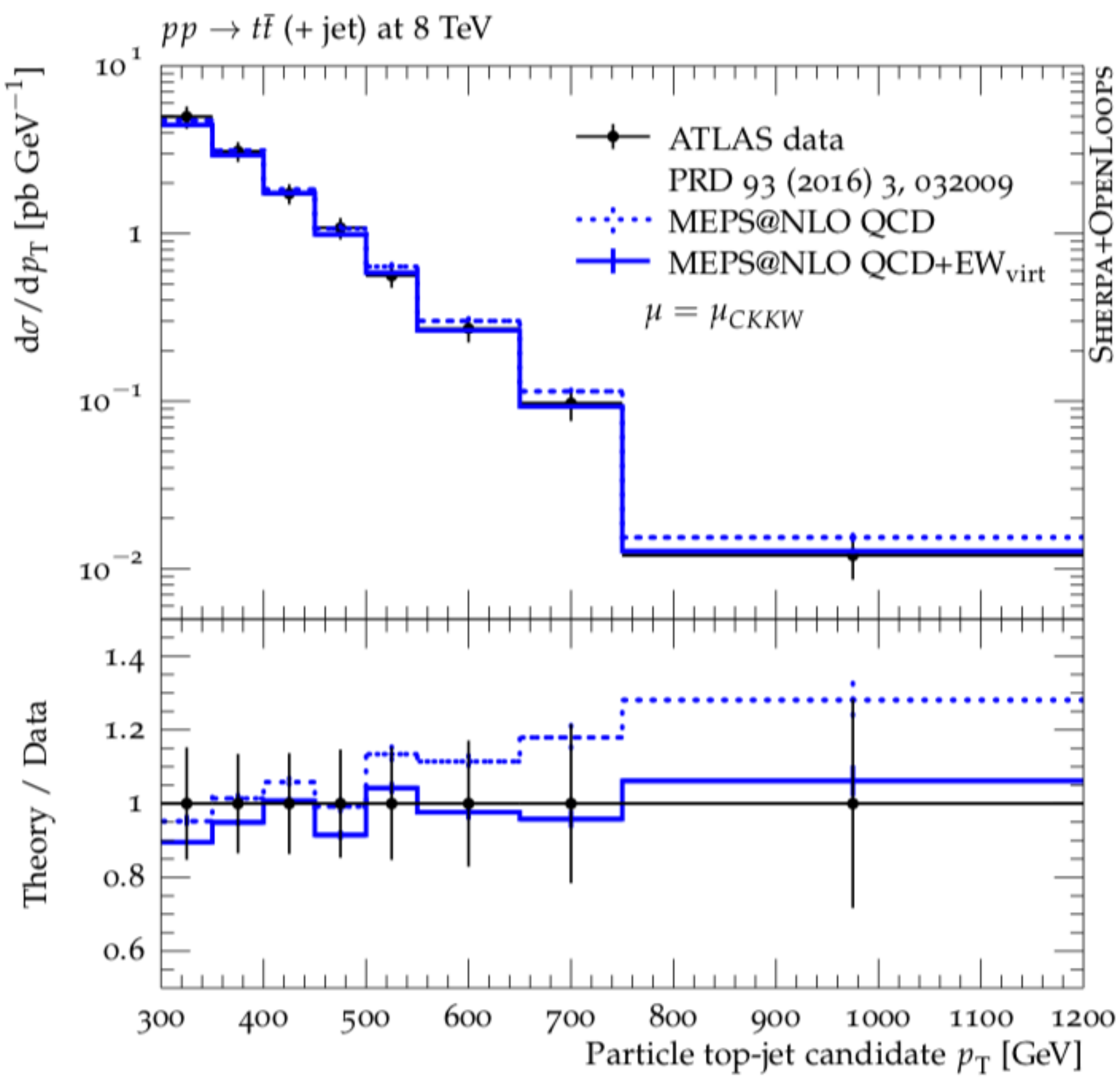
EW NLO: TOP PAIR PRODUCTION & APPROX MERGING

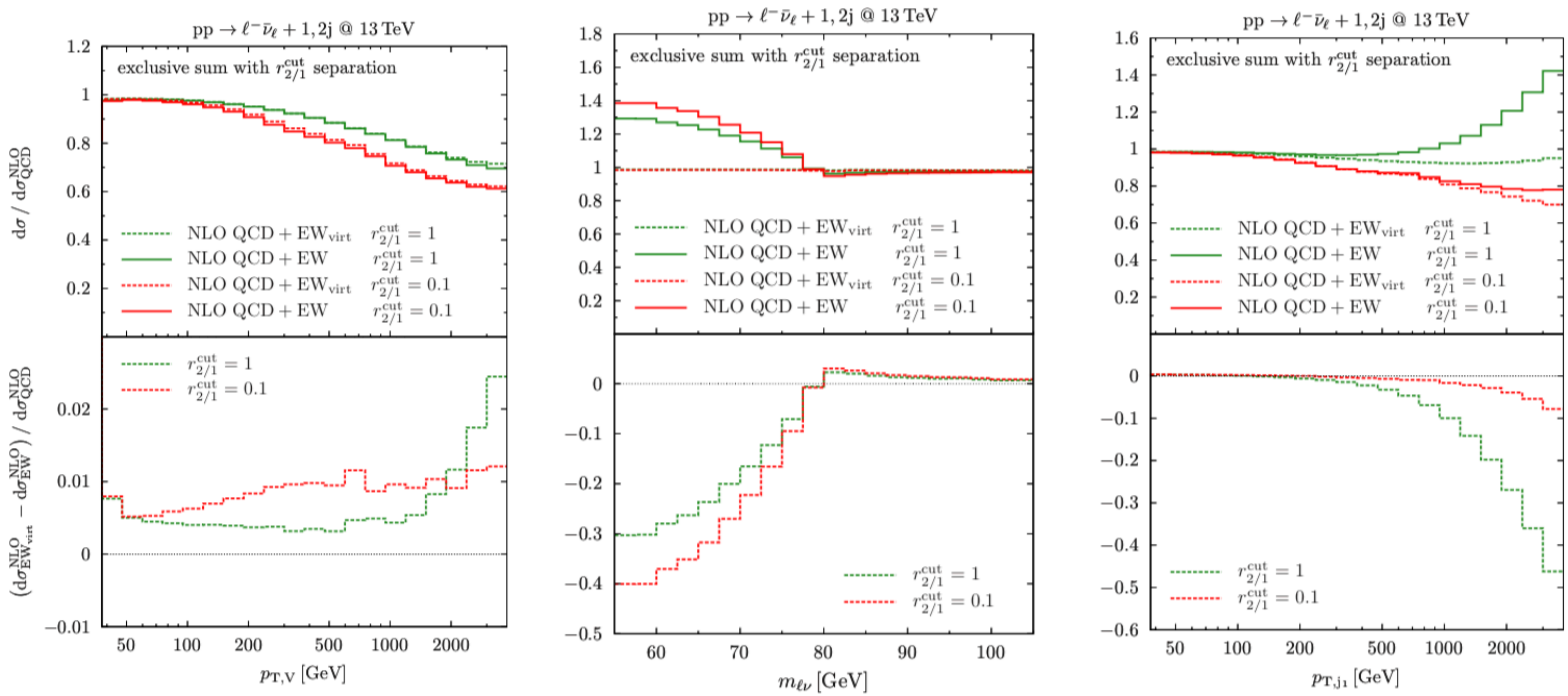
[Gütschow, Lindert, Schönherr, Eur.Phys.J. C78 (2018) no.4, 317]

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



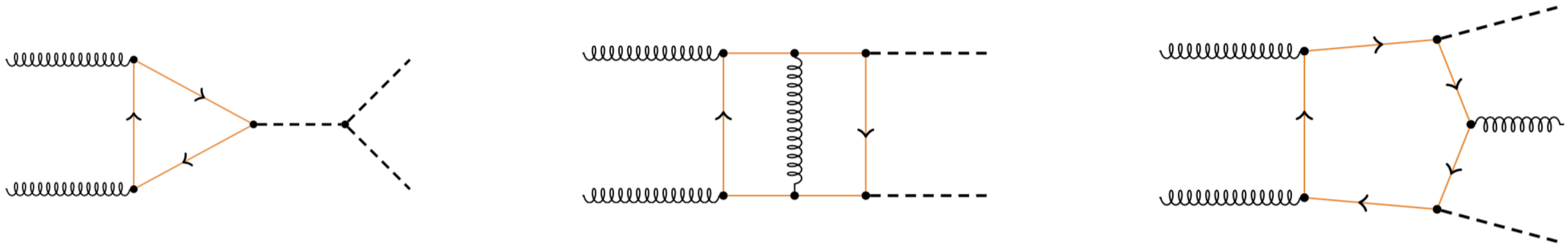
- MEPS@NLO QCD+EW$_{virt}$ *0,1 @ NLO, 2,3,4 @ LO*
- recover real QED bremsstrahlung: YFS
- boosted top quark, ID by substructure technique from fat jet

EW NLO VS. EW$_{VIRT}$



LOOP-INDUCED PROCESSES AT MC@NLO

slide adapted from S. Kuttimalai

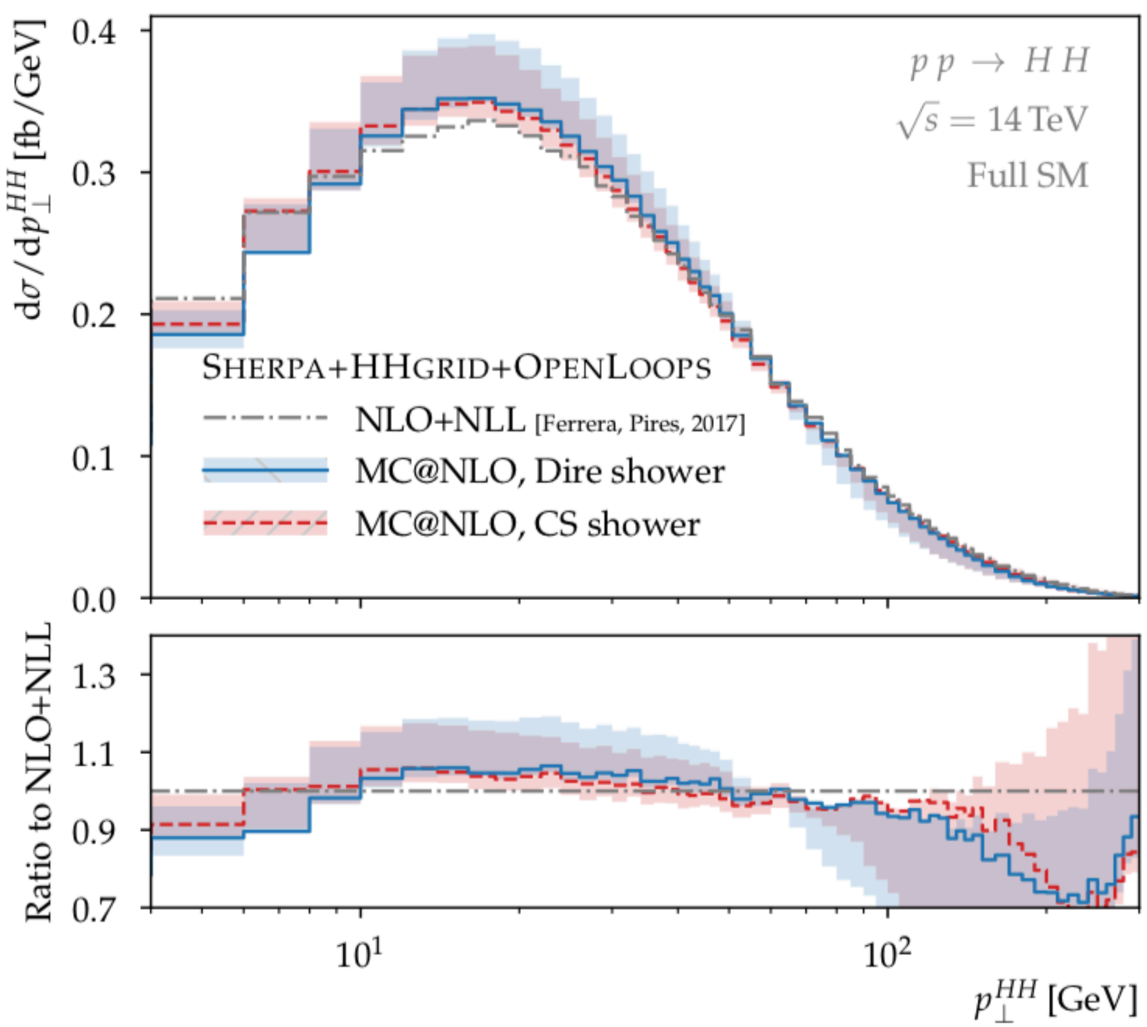


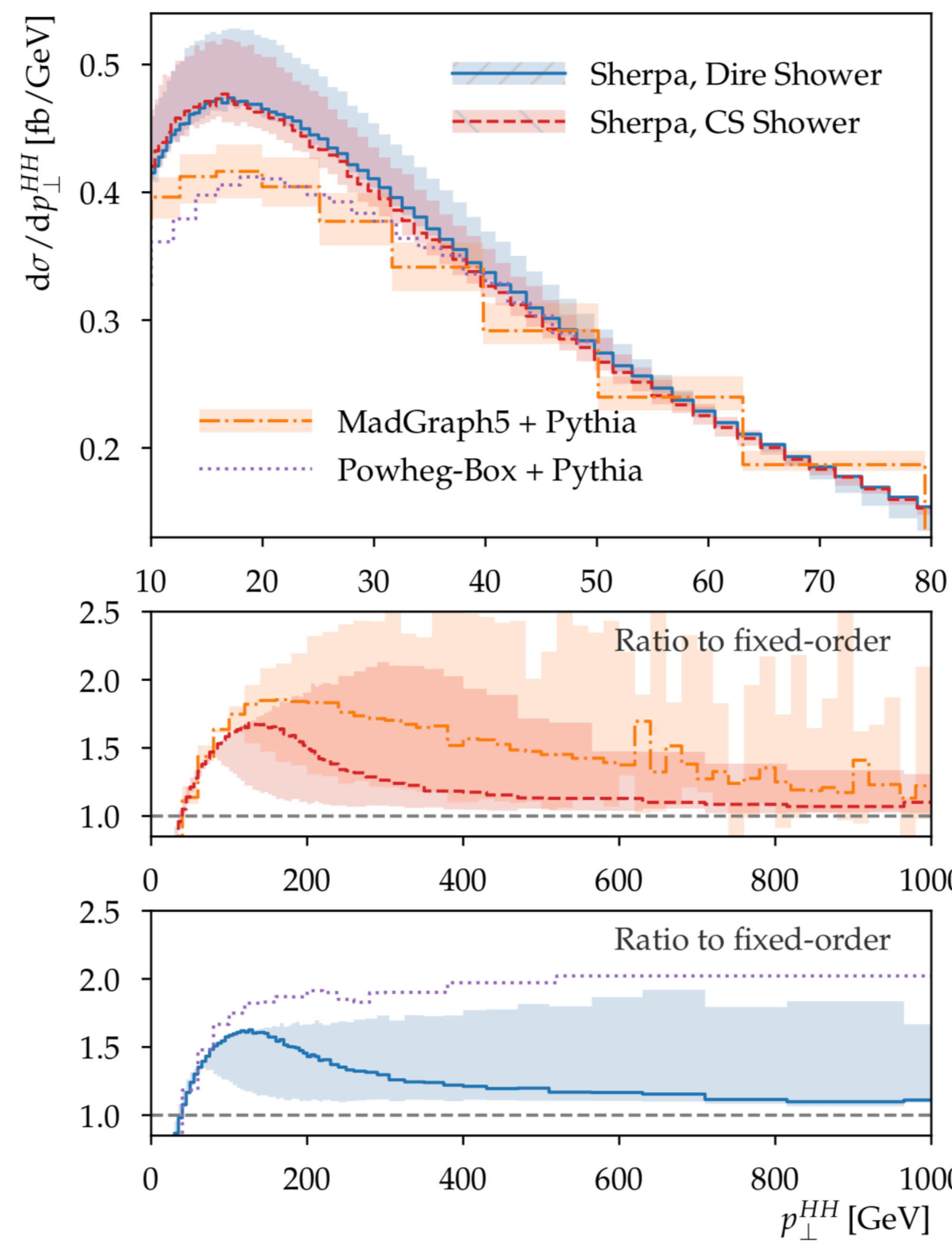
- Born & real-emission by automated one-loop tools
- SHERPA: IR subtraction, process management, PS integration, matching (MC@NLO), fully automated [Jones, Kuttimalai: JHEP 1802 (2018)]
- Available two-loop virtual amplitudes
  - $gg \to \gamma\gamma/HH/Hj$

    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

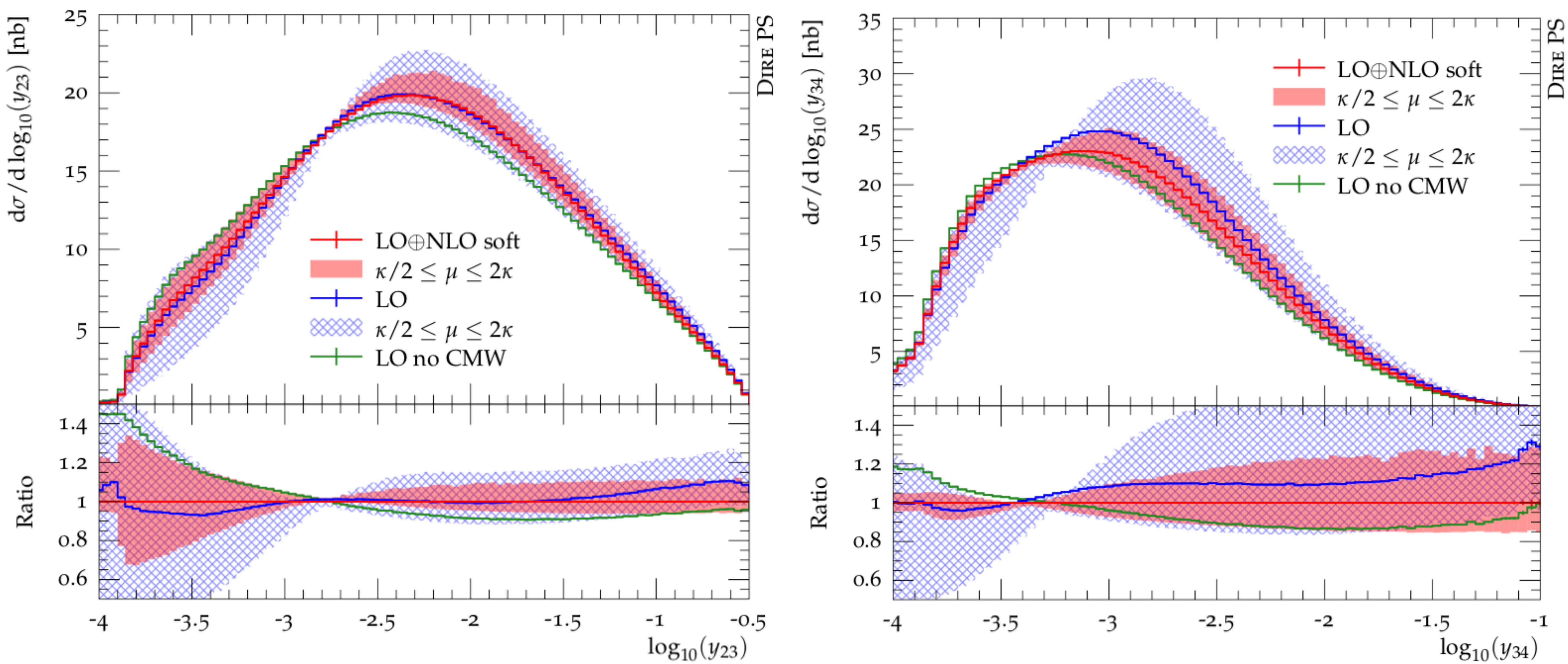
NLO DGLAP IN THE PARTON SHOWER

- 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



SYSTEMATIC VARIATIONS: NNPS

[EB, Del Debbio, 1808.07802]

- how to vary shower in PDF fits (complementing fixed-order interpolation grid technology)
- idea: train NN to predict parton shower dependence in observable bins
- first study for α_S variations (scale and $\alpha_S(m_Z)$) [EB, Del Debbio, 1808.07802]

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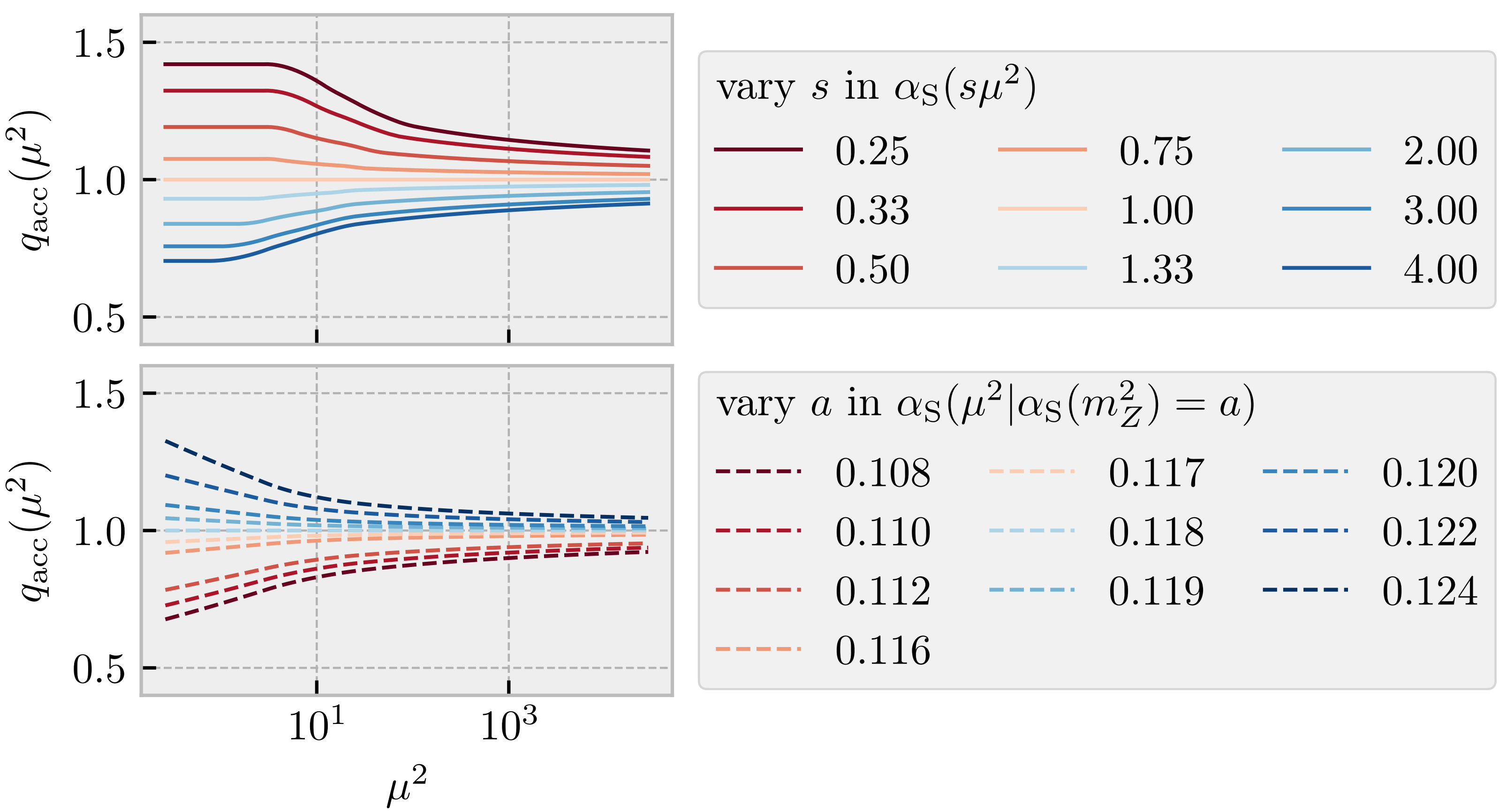

NN input:
$\alpha_S(\mu^2)$ ratio

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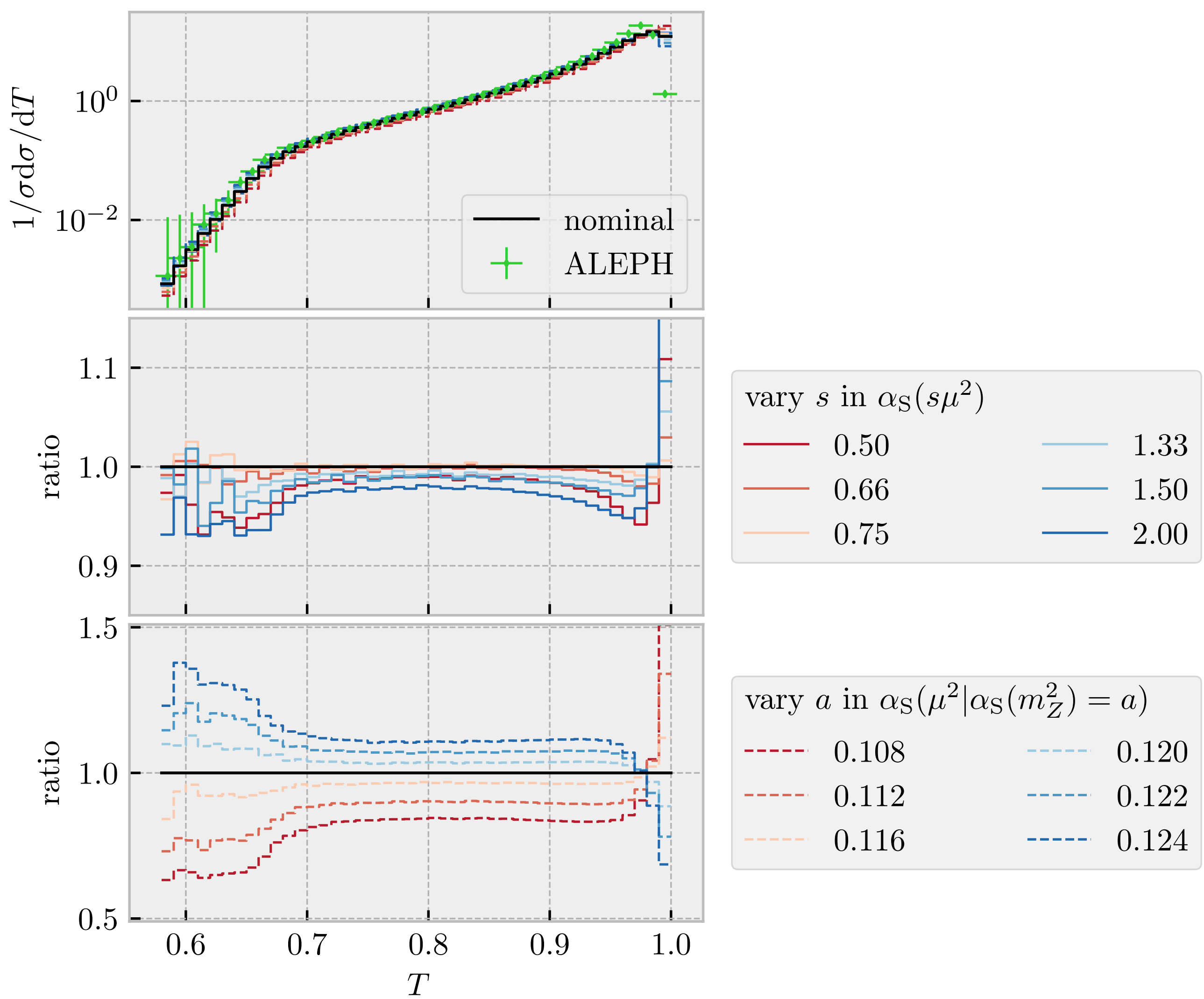

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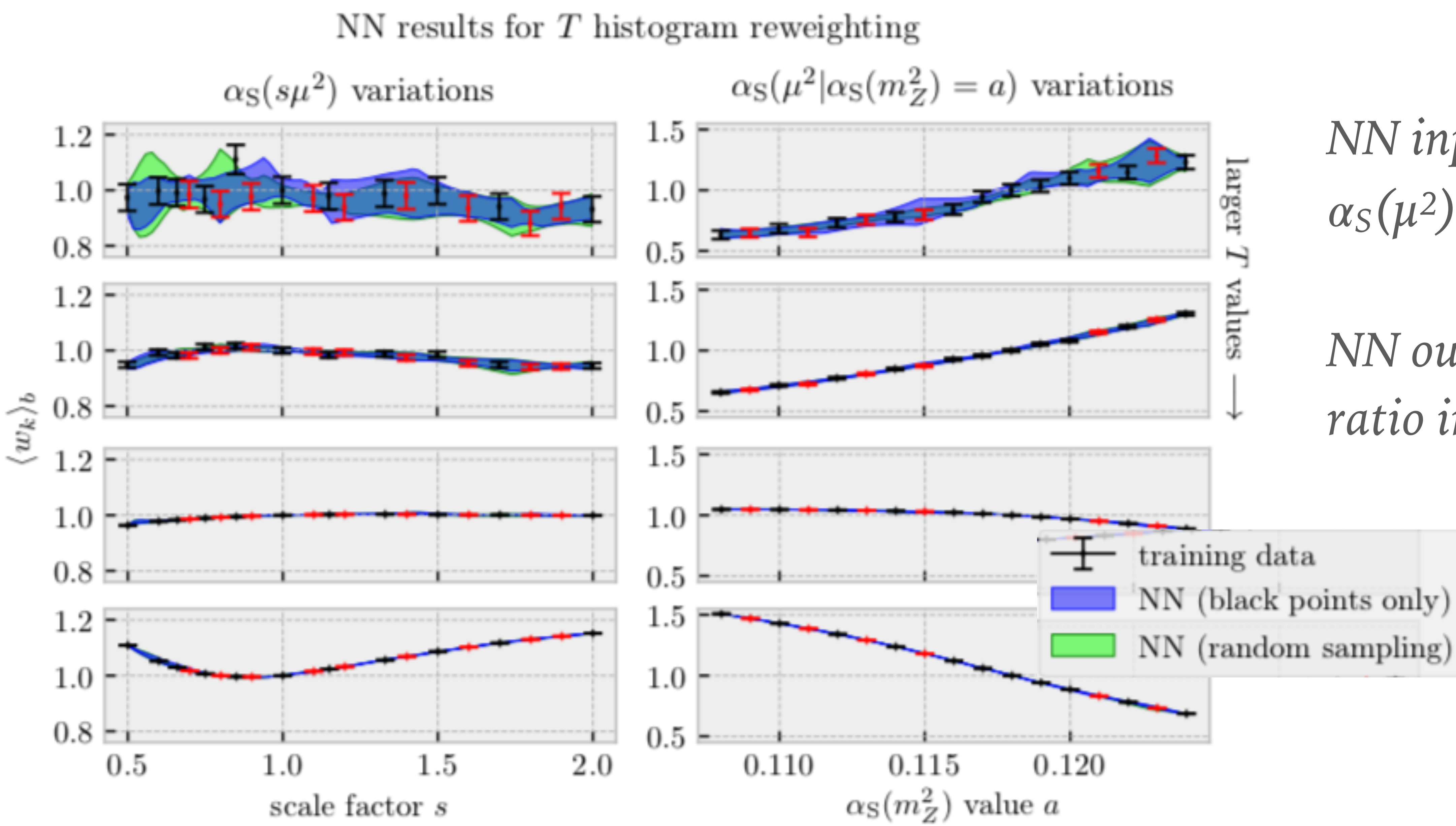
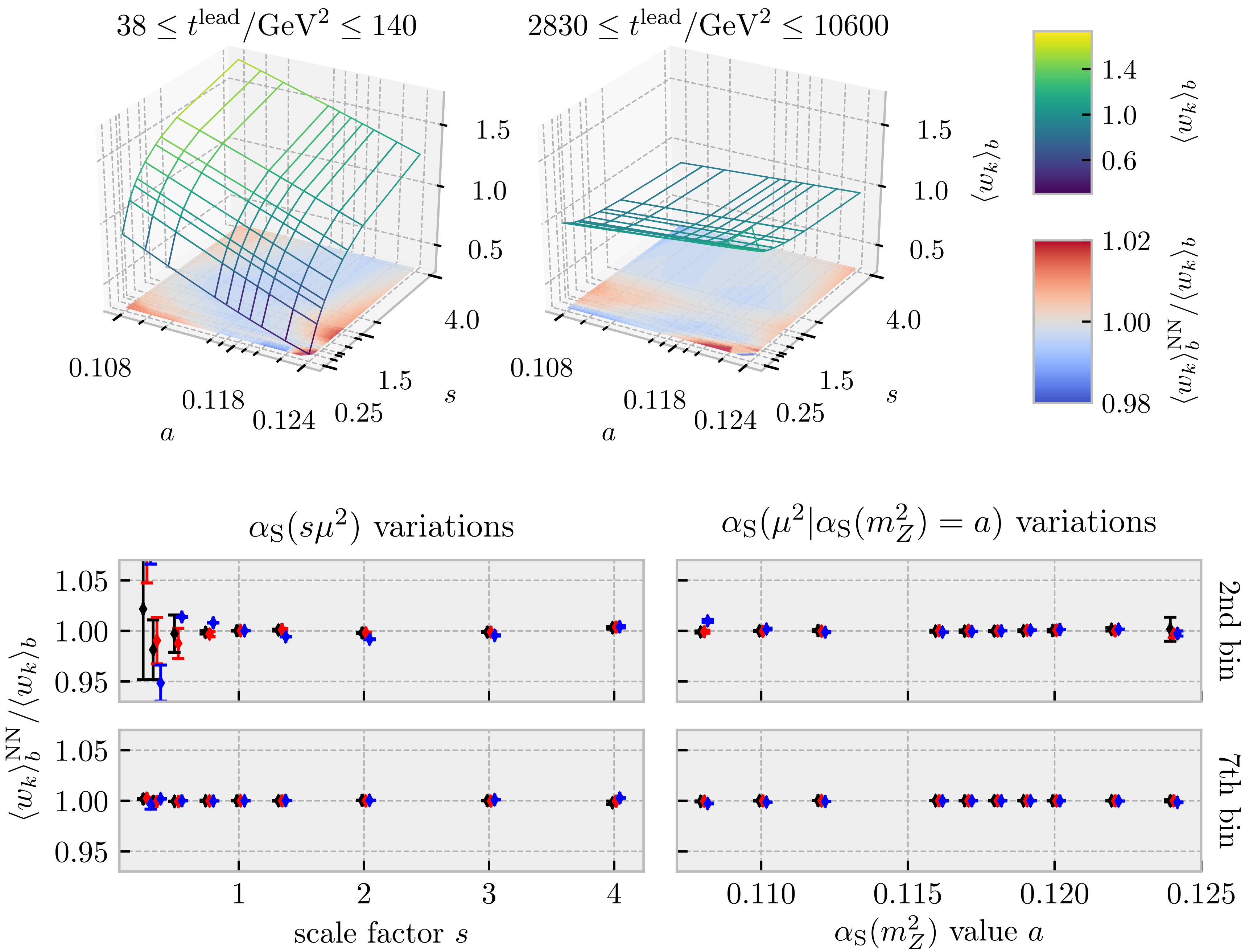


NN input: $\alpha_S(\mu^2)$ ratio

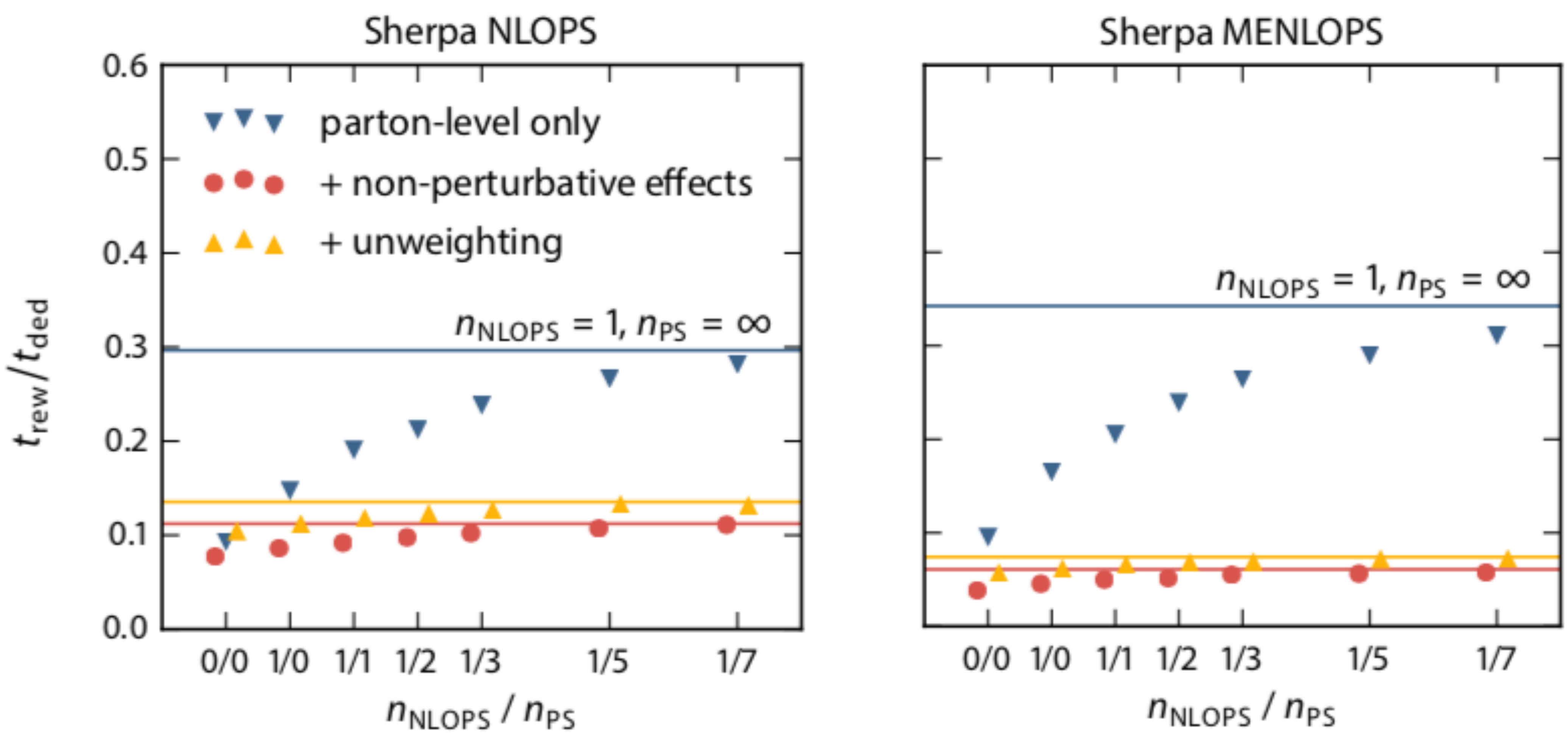
NN output: ratio in bin

NNPS: VALIDATION

- to-be-validated variation excluded from training



COMPUTATIONAL COST (REWEIGHTING)



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