The University of Edinburgh
School of Physics & Astronomy

SHERPA

where we are & what's next

Enrico Bothmann

27th August 2018

QCD@LHC 2018

MCnet

WHAT WE PUT IN

SHERPA: multi-purpose MC event generator [Gleisberg et al., JHEP 0902 (2009) 007]

Perturbative QCD (≲1fm)

hard interaction → (N)NLO

radiative corrections:
dipole PS→(N)LL

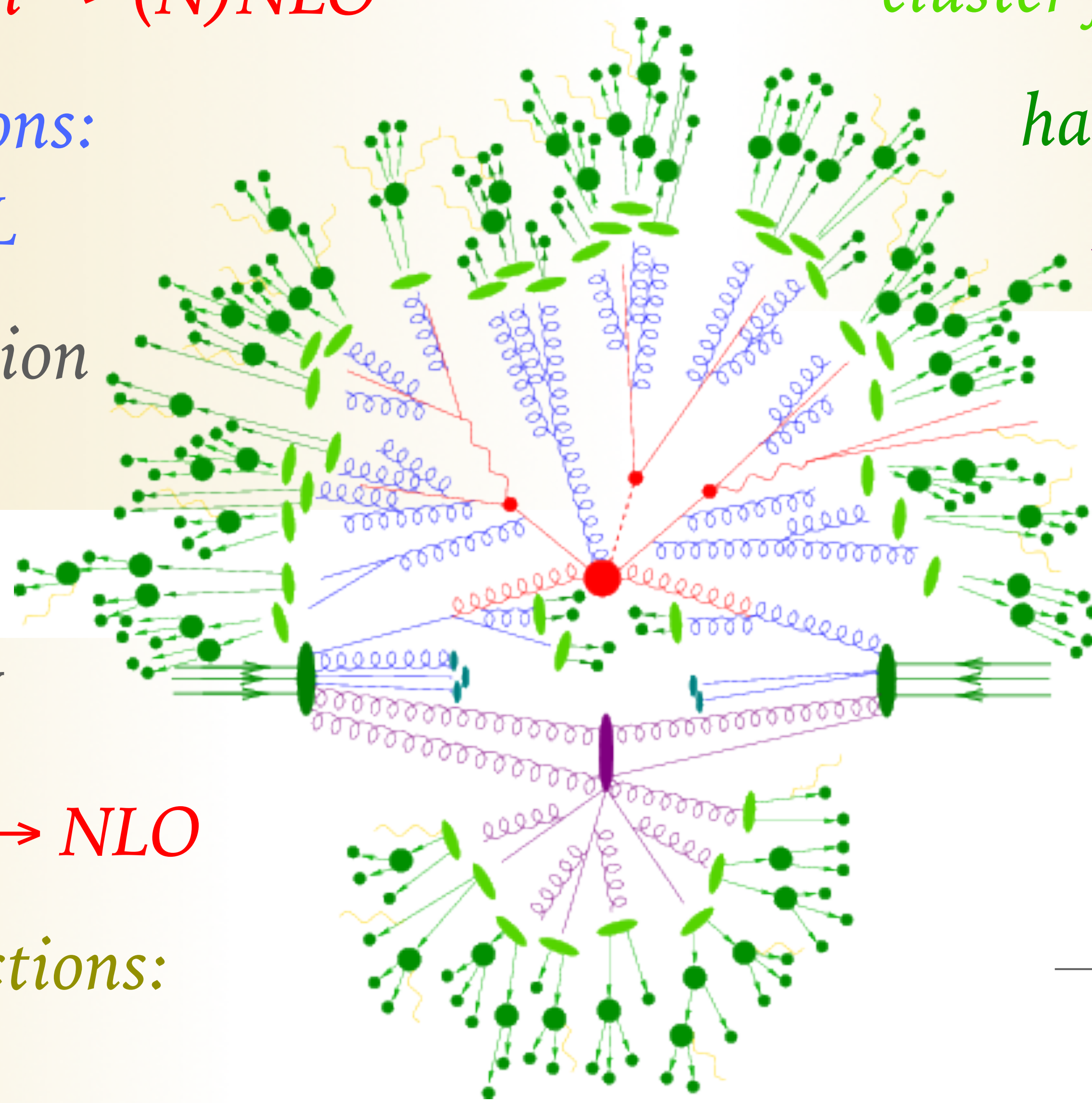
systematic combination
matching/merging

Non-perturbative QCD (≳1fm)

cluster fragmentation

hadron decays

multiple parton interactions



Perturbative BSM

via UFO → LO

Perturbative EW

hard interaction → NLO

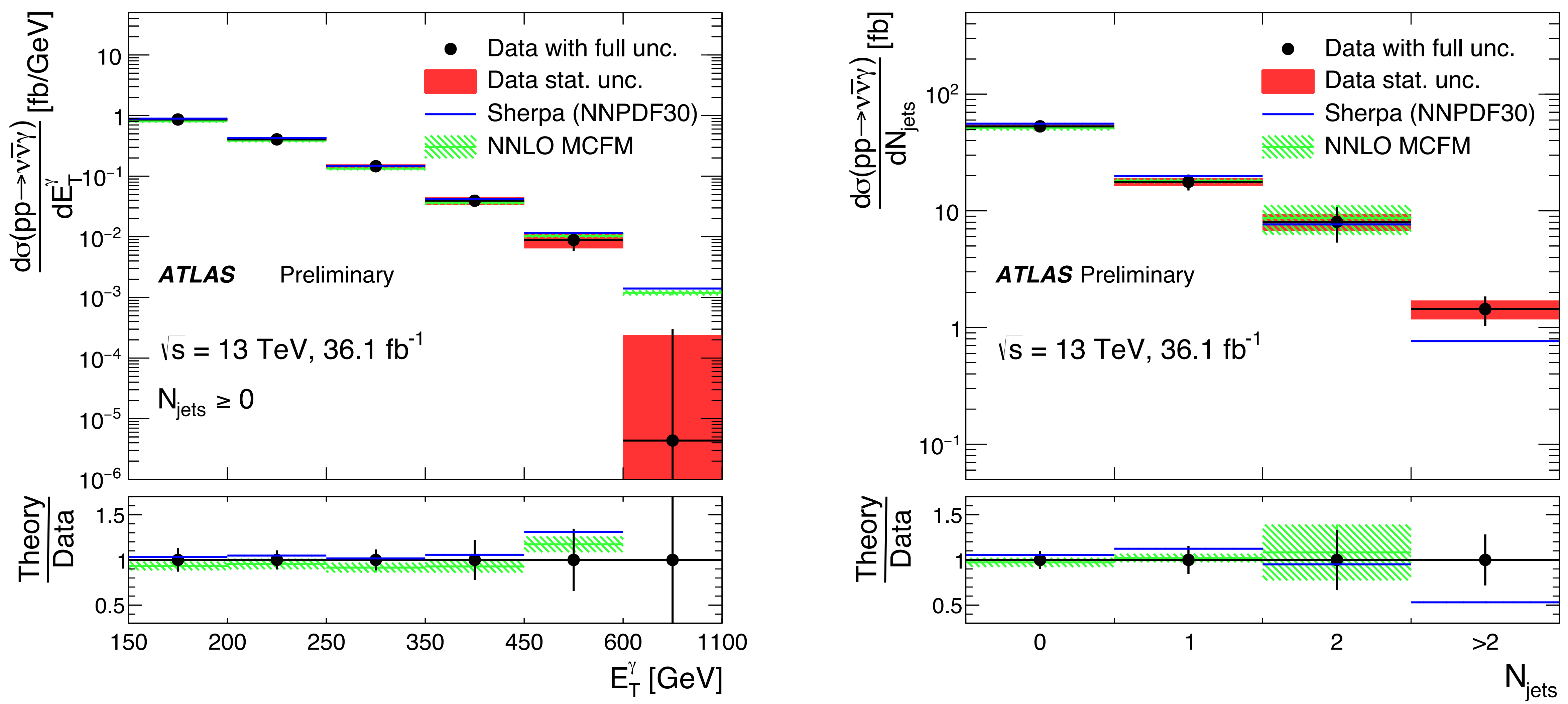
radiative corrections:
YFS → (N)LL

→ *fully differential*
particle-level events

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]

OUTLINE

- no non-perturbative (soft) stuff today!
  currently undergoing a rewrite process to prepare for improvements …
- perturbative EW
  - NLO (exact/approx) developments
- perturbative QCD
  - loop-induced processes
  - MC@NLO single-top production
  - NLO DGLAP in the parton shower
  - systematic variations
- (BSM)
- concluding remarks

EW

full NLO & approximations

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]
  - $\ell\ell\nu\nu\nu$ [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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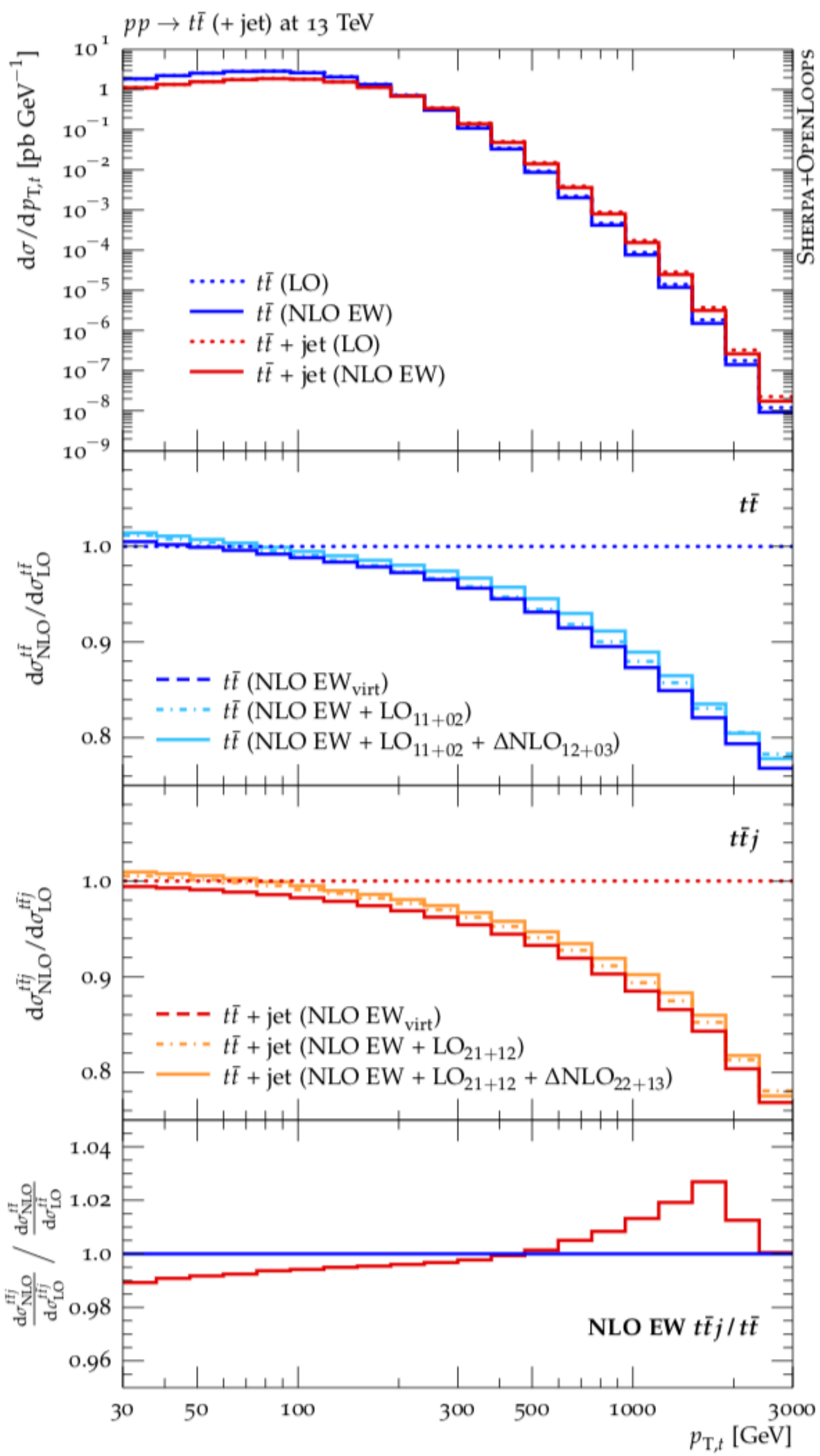
EW NLO

- complete automation in SHERPA/AMEGIC: adapt CS subtraction for EW
  [Schönherr, Eur.Phys.J. C78 (2018) no.2, 119]
  - massive/massless emitters/spectators
  - simultaneous subtraction of EW and QCD singularities

$$\mathcal{O}(\alpha_s^n \alpha^{N-n}),\, \mathcal{O}(\alpha_s^{n-1} n \alpha^{N-n+1}) \stackrel{EW,\,QCD}{\to} \mathcal{O}(\alpha_s^n \alpha^{N-n+1})$$

  - on-the-fly variations of μ_F and μ_R for all subtraction terms
  - IR-safe dressed-particle/isolation/jet selectors
  - interface to OPENLOOPS, GOSAM and RECOLA fully functional
  - other public EW dipole subtraction impl [Gehrmann, Greiner, JHEP 12 (2010), 050]
- next steps: COMIX, adapt matching and merging

EW NLO: TOP PAIR PRODUCTION & APPROX MERGING



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

- first prediction for ttj incl Born and EW corrections
- large top p_T $\rightsquigarrow$ new physics searches with tt as BG
- typical Sudakov suppression for large p_T
- sub-leading Born small
- universal EW corrections for tt and ttj
- NLO EW ~ NLO EW$_{virt}$

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

- motivates use of MEPS@NLO QCD+EW$_{virt}$
- stand-in for proper QCD+EW merging

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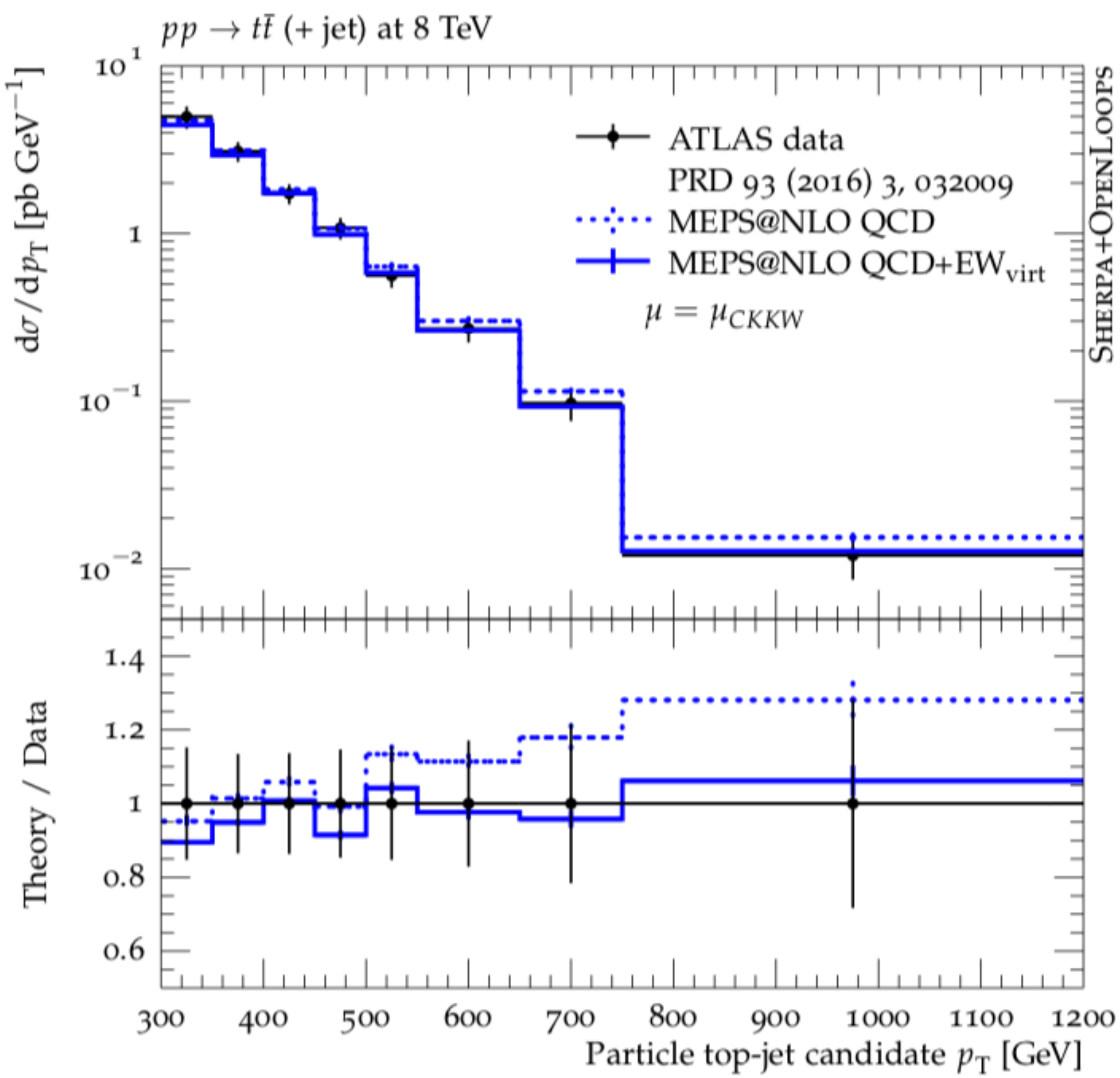
[Gütschow, Lindert, Schönherr, Eur.Phys.J. C78 (2018) no.4, 317]

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



- 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: SUDAKOV LOG APPROX

[EB, Davide Napoletano, WIP]

- LO+EW, all Sudakov one-loop log corrections (DL, SL)
  [Denner, Pozzorini, Eur.Phys.J.C18:461-480,2001]

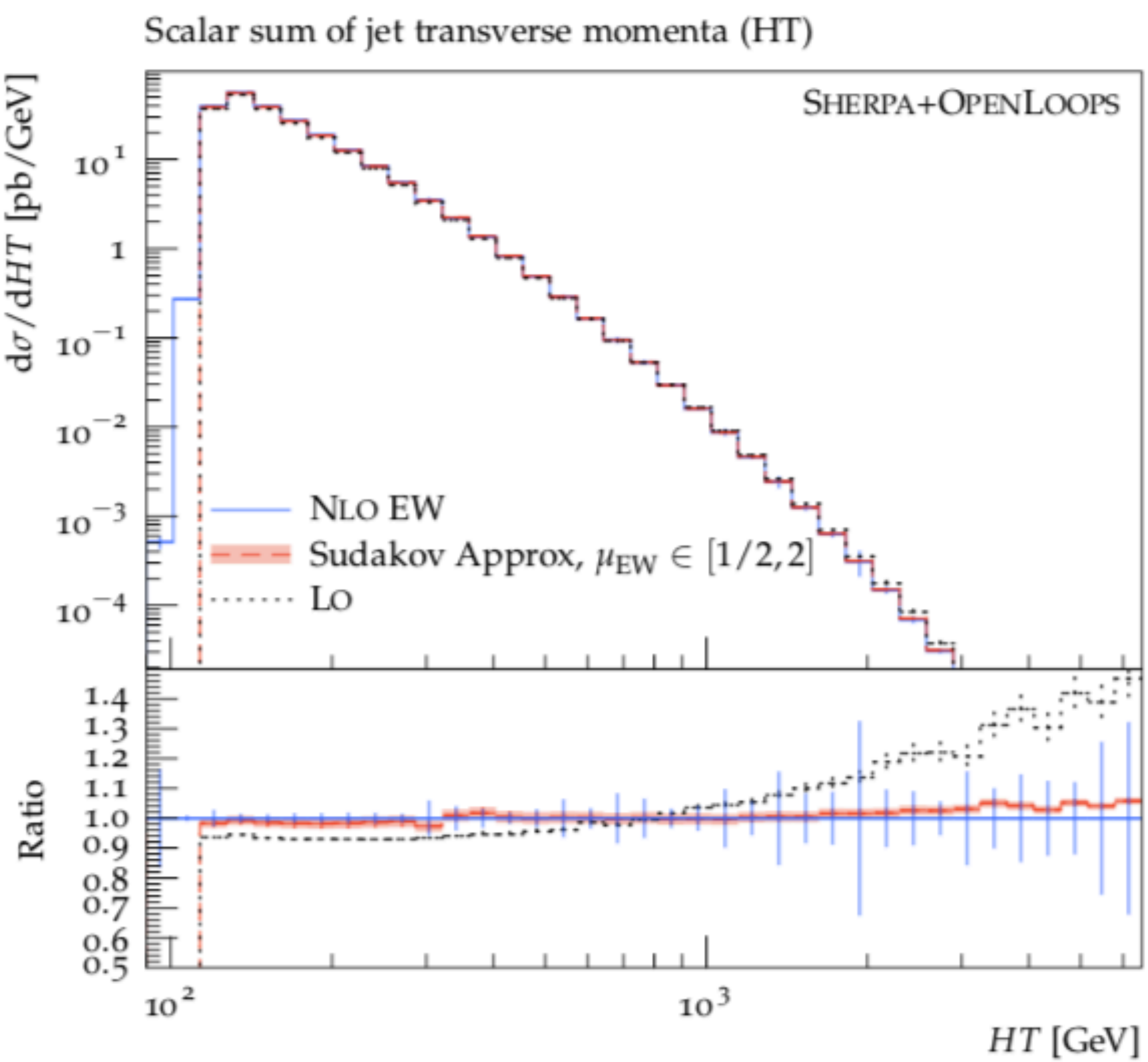
$$d\sigma^{NLO\ EW_{Sudakov}} = B_{QCD}\Delta_{EW}d\Phi_B$$

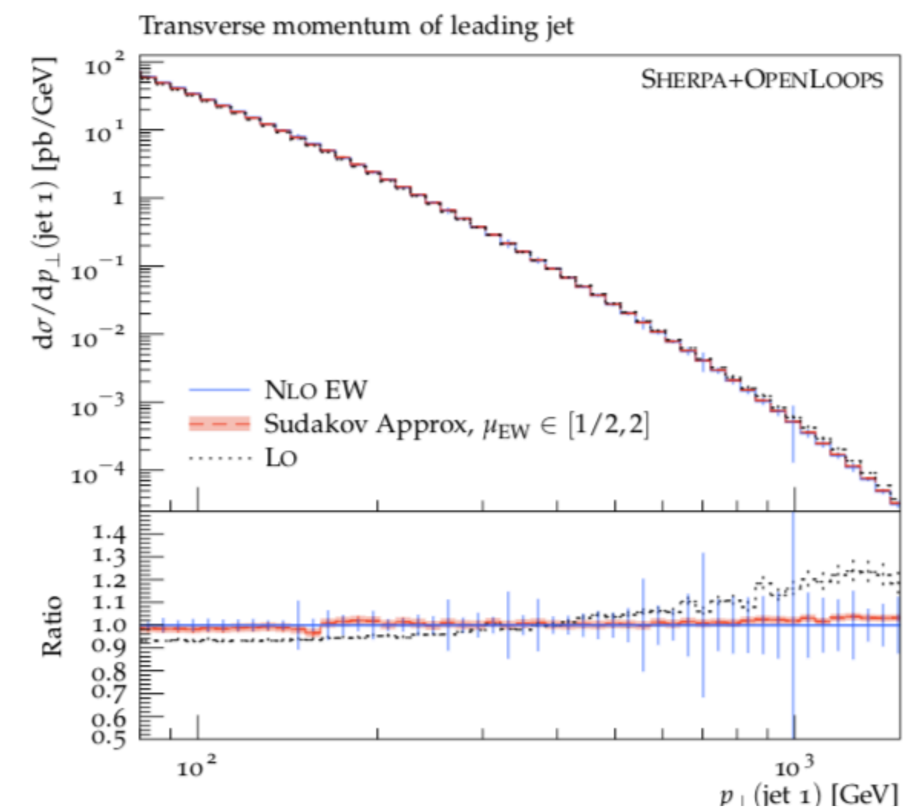
- expected to be faster than full NLO EW or MEPS@NLO QCD+EW_{virt}
- test-driven development towards exact reproduction of log coeffs in for example processes ee → tt/bb/μμ/VV
- implementation mostly finished
- finalise & test some FO calculations for relevant observables

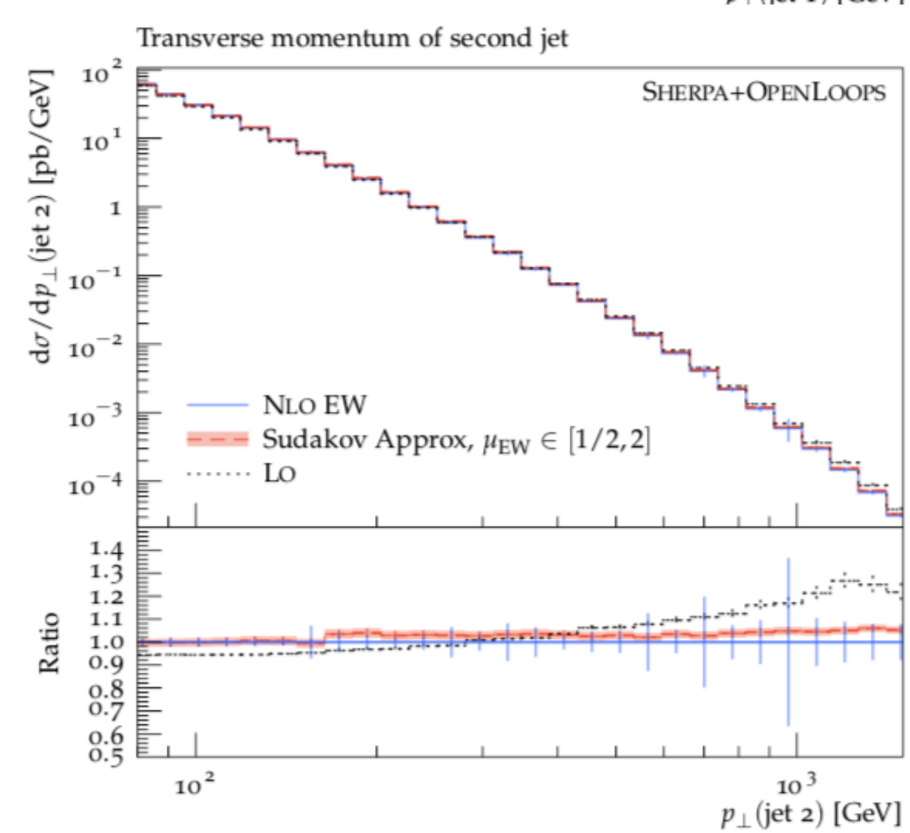
EW NLO: SUDAKOV LOG APPROX

[EB, Davide Napoletano, WIP]

- quick look: ee → jj





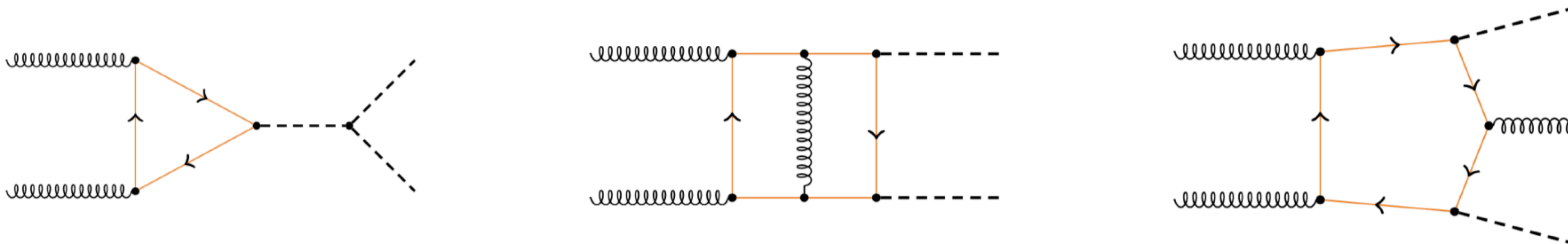


QCD

loop-induced, NLO DGLAP & more

LOOP-INDUCED PROCESSES AT MC@NLO

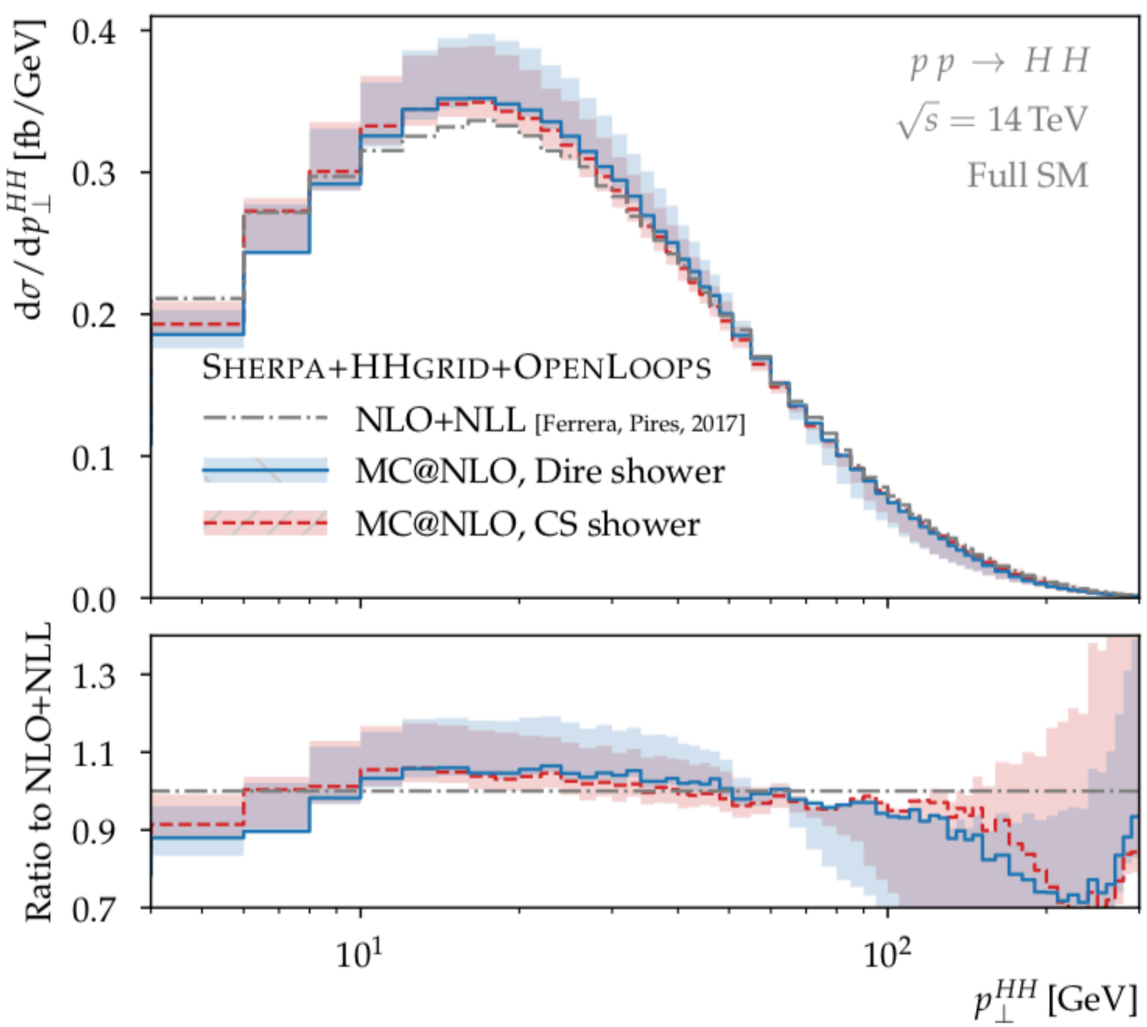
slide adapted from S. Kuttimalai

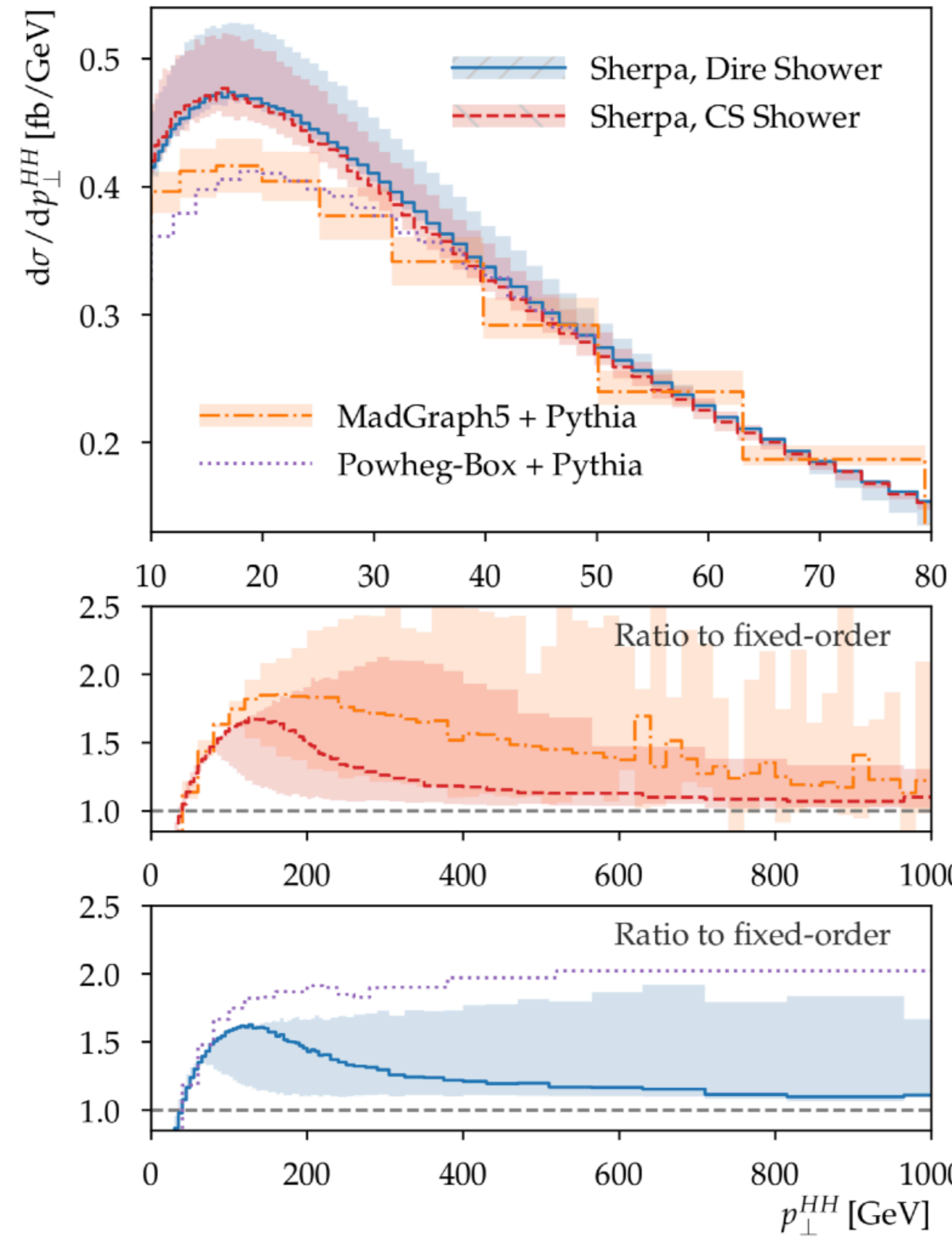


- Born & real-emission by automated one-loop tools
- SHERPA: IR subtraction, process management, PS integration, matching (MC@NLO), fully automated [Jones, Kuttimalai: JHEP 1802 (2018)]
- Available two-loop virtual amplitudes
  - $gg \to \gamma\gamma/HH/Hj$
    e.g. ggHH difficult due to massive propagators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



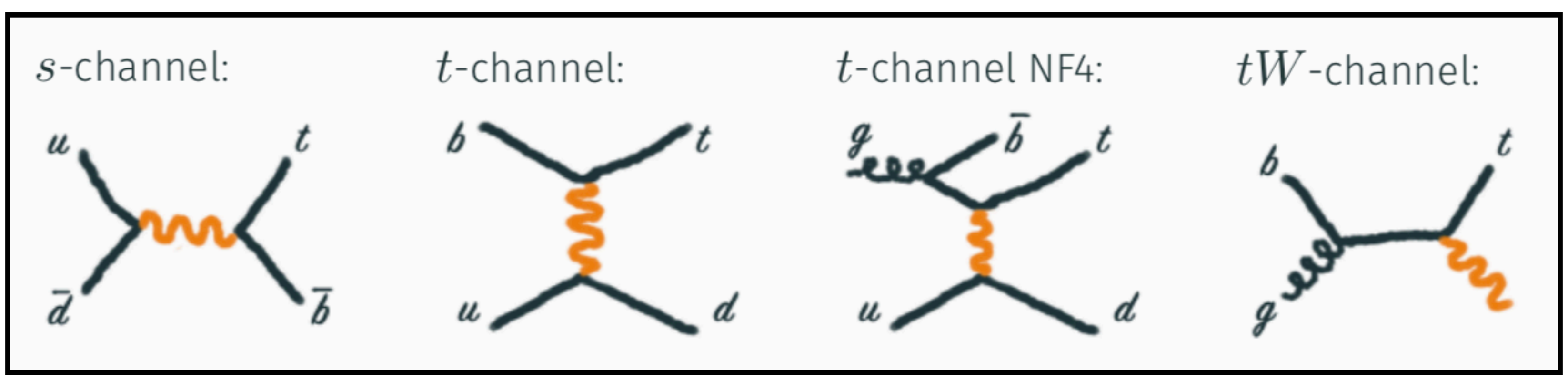


uncertainties on NLO+NLL in left plot: 3% near $p_\perp^{HH} = 20$ GeV, 10% near 100 GeV

MC@NLO SINGLE-TOP PRODUCTION

[Bothmann, Krauss, Schönherr, Eur.Phys.J. C78 (2018) no.3, 220]

- earlier calculations for MC@NLO/POWHEG
  [Frixione et al, hep-ph/0512250, Laenen et al, 0805.3067, Alioli et al, 0907.4076, Re, 1009.2450, Campbell et al, 0903.0005, Frederix et al, 1207.5391]
- $\mu^2 = t, s$ for t-/s-channel (clustering to $2 \to 2$)
- tW-channel: top $\mu^2 = m_T^2$, DR for tW definition (small gauge violation)
- comparison to ATLAS/CMS for all three channels



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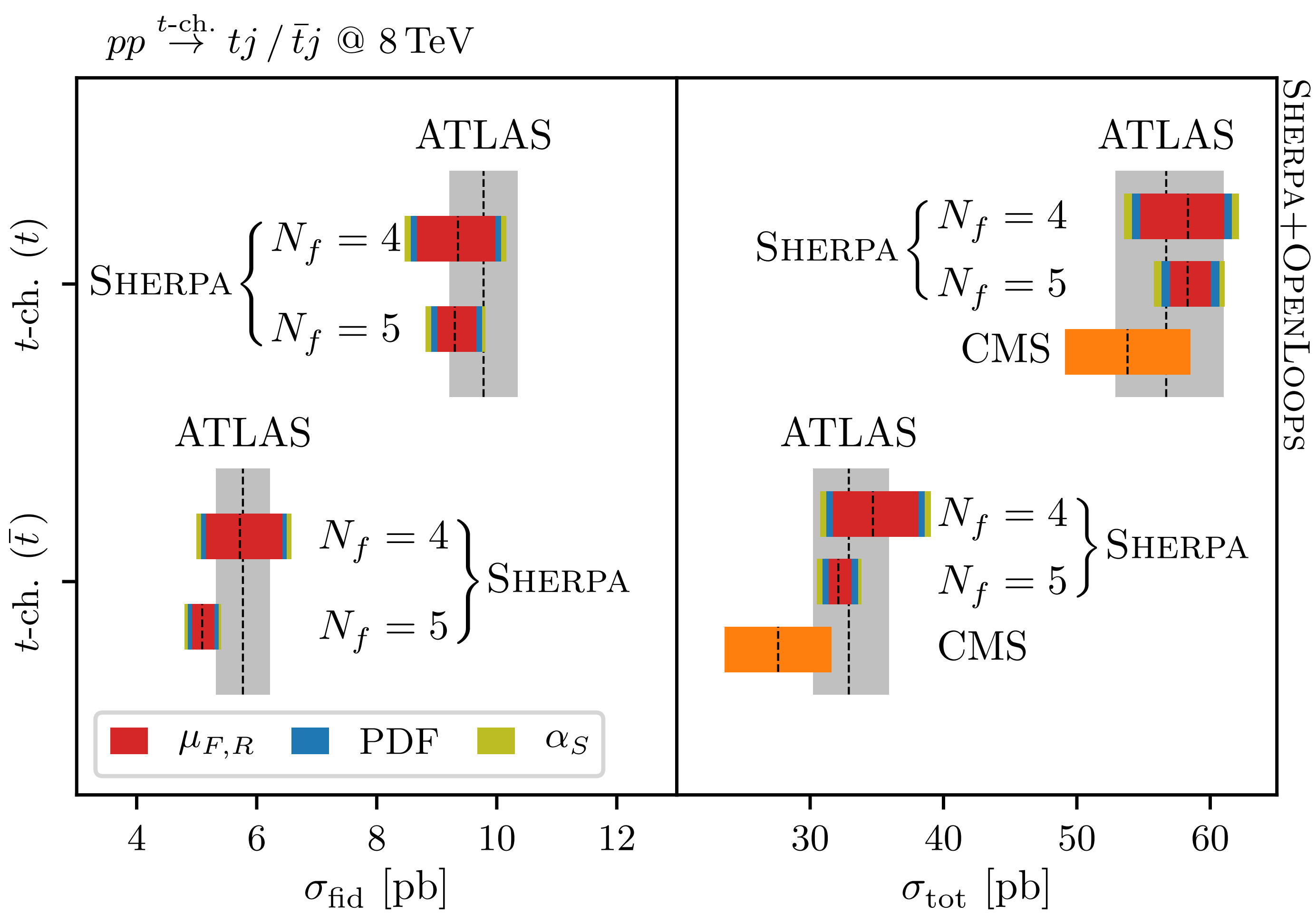
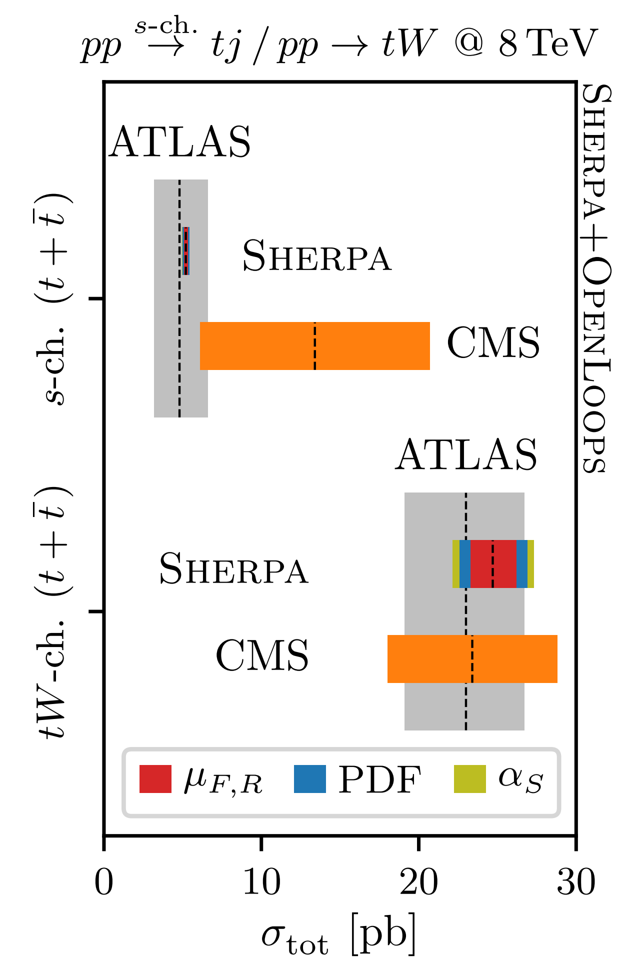
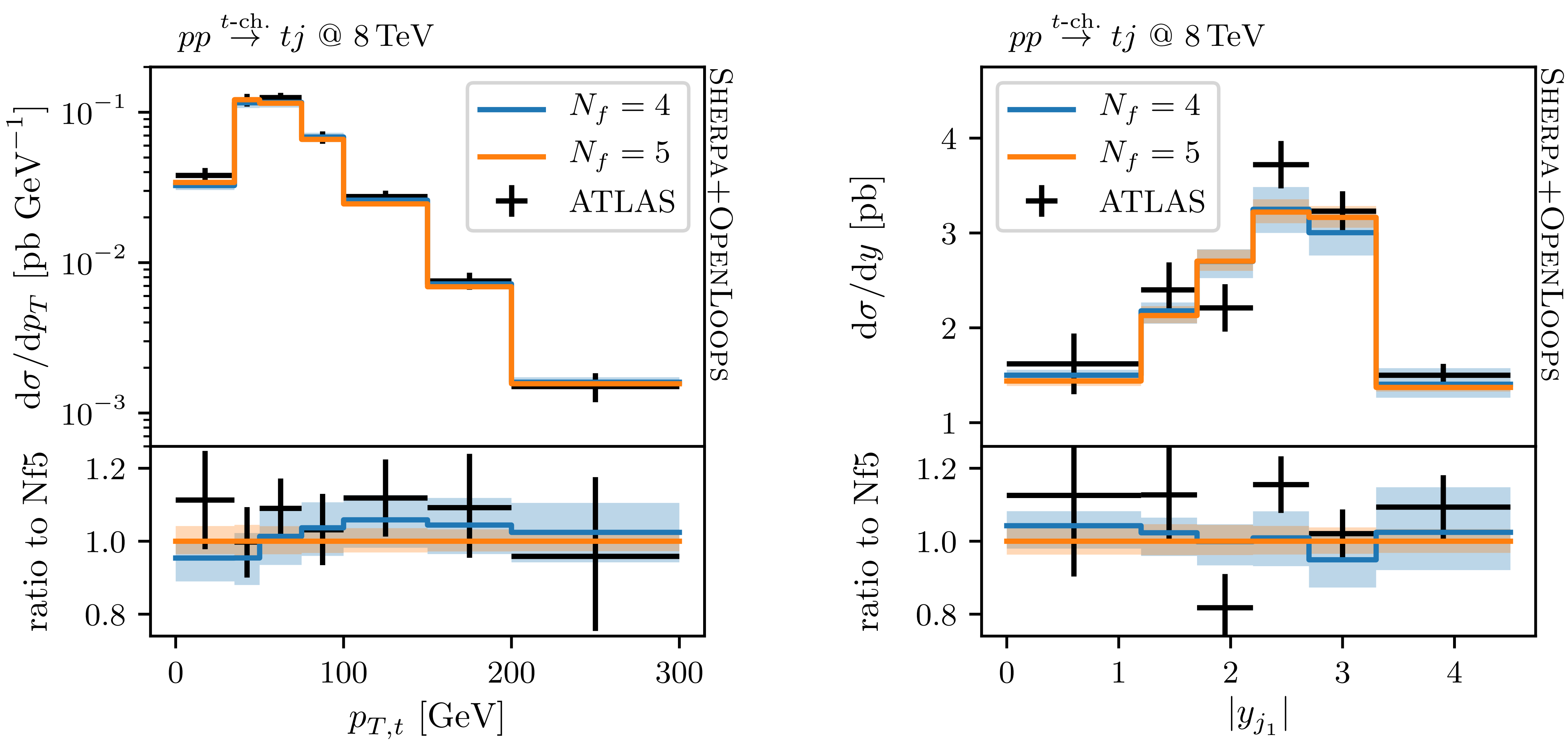




MC@NLO SINGLE-TOP PRODUCTION

[Bothmann, Krauss, Schönherr, Eur.Phys.J. C78 (2018) no.3, 220]

- no strong b-PDF constraint with current precision
- differential comparison for *t*-channel to ATLAS [Eur. Phys. J. C77 (2017)]



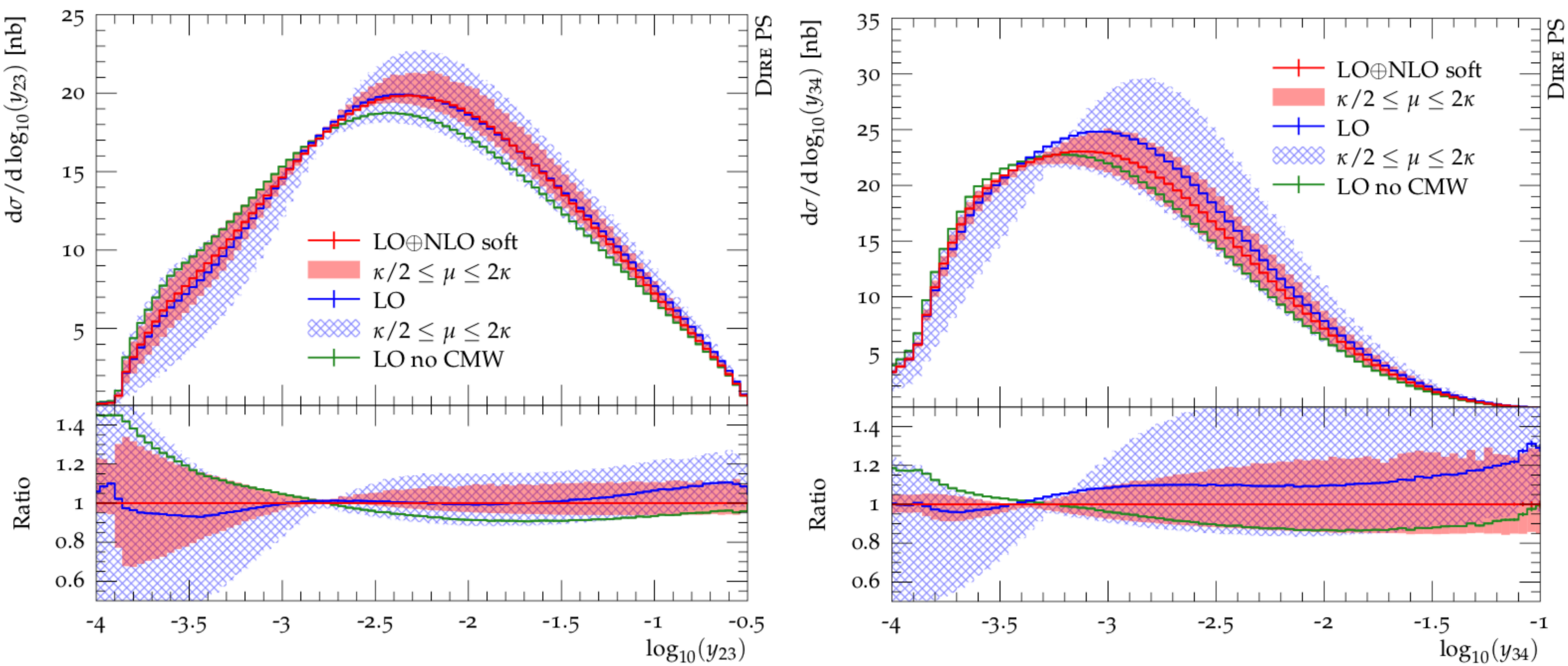
NLO DGLAP IN THE PARTON SHOWER

- 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



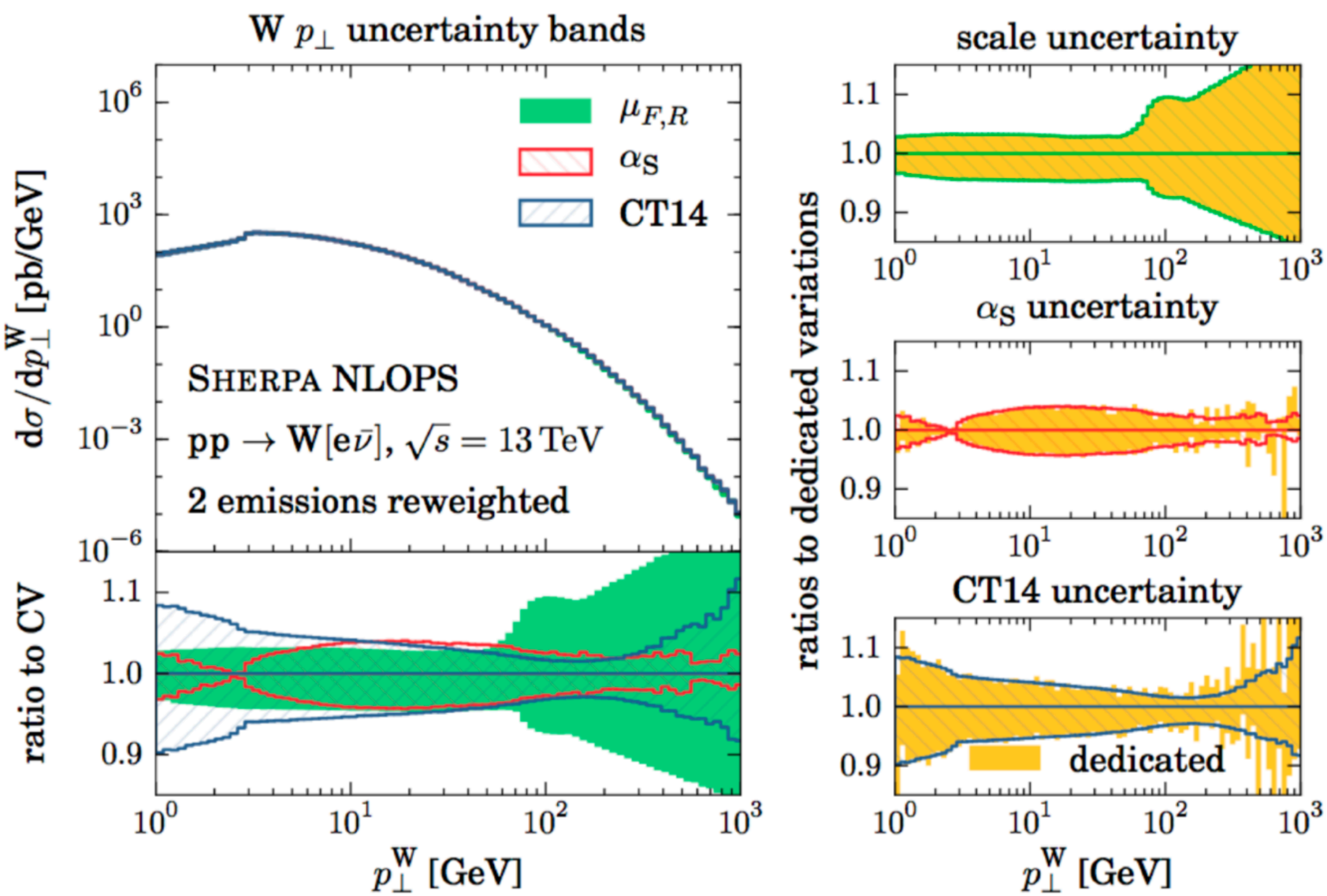
SYSTEMATIC VARIATIONS: ON-THE-FLY REWEIGHTING

[Bothmann, Schönherr, Schumann, Eur.Phys.J. C76 (2016) no.11, 590]

- 110 variations of μ, α_s and PDFs in one go

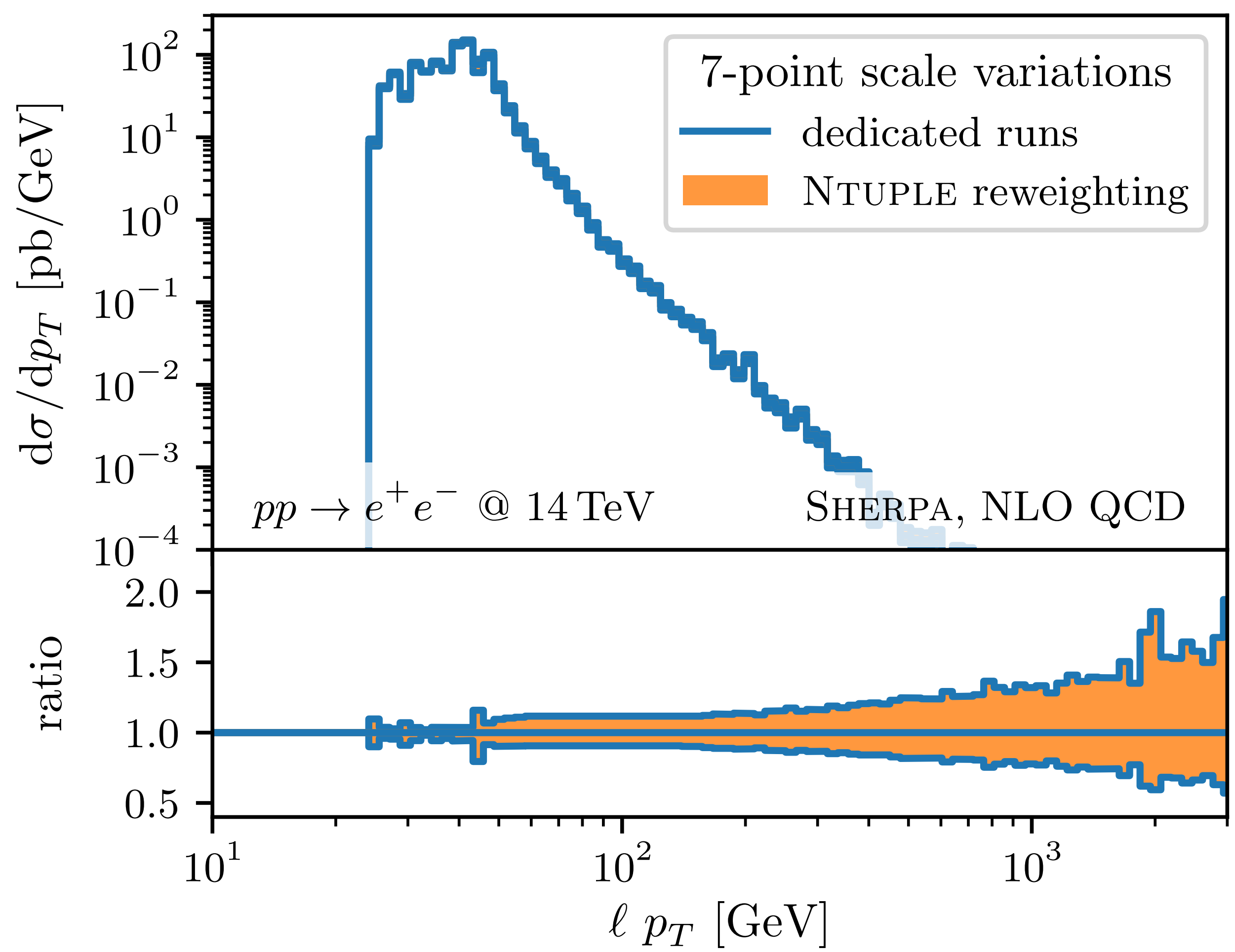
  include all pQCD dependences: ME, PS and matching/merging

- encoded as alternate event weights → save CPU time



SYSTEMATIC VARIATIONS: ON-THE-FLY REWEIGHTING

- continuous improvements
  - EW NLO subtraction terms
  - subleading dependence in $\bar{B}/B$ term for MENLOPS
  - more universal cut-off in shower (p_T instead of N_em)
  - NTUPLE variations
  - merging-cut variations
- ✓ on-the-fly reweighting ubiquitous & default way to generate uncertainty bands!



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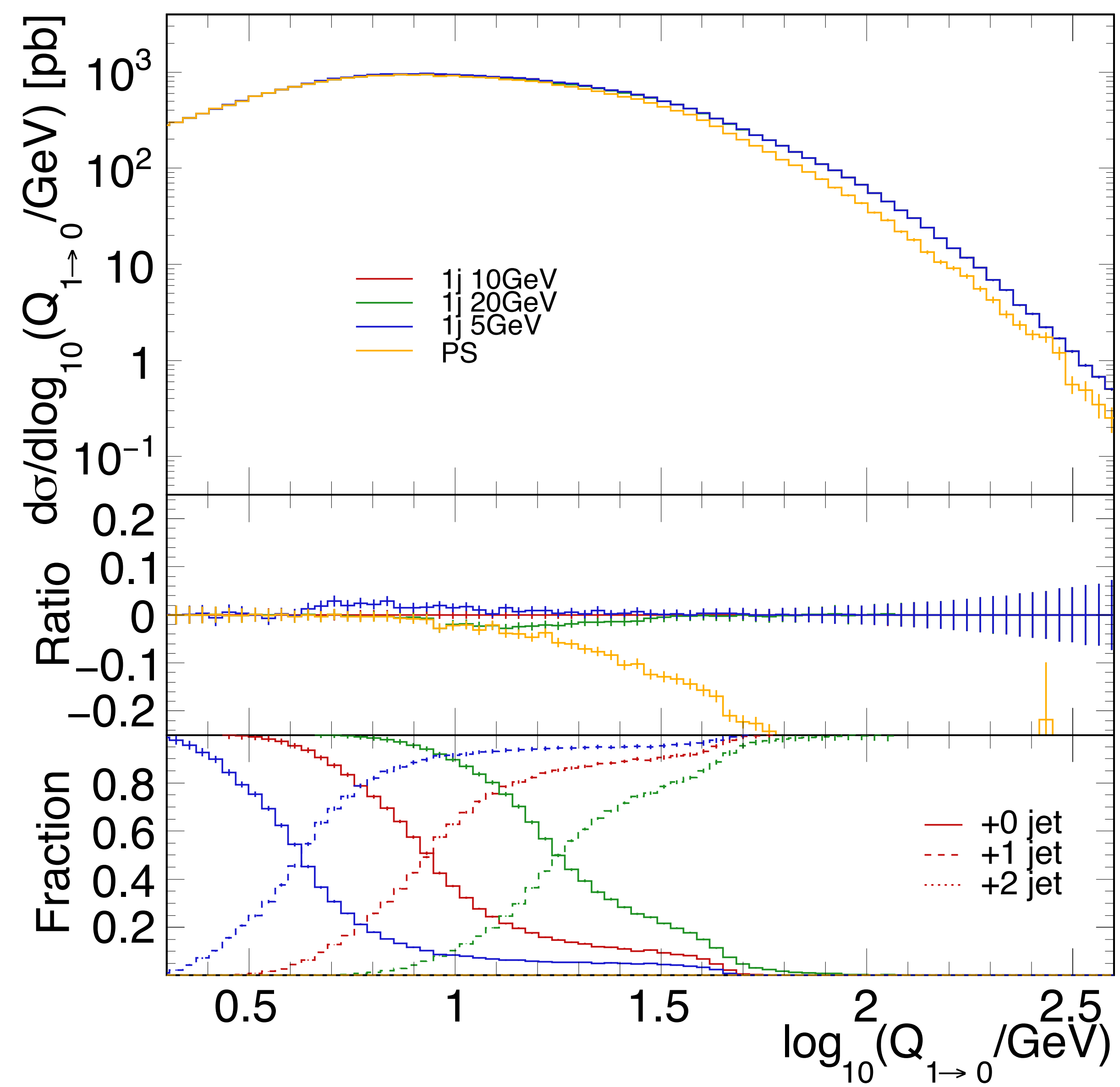

SYSTEMATIC VARIATIONS: NNPS

[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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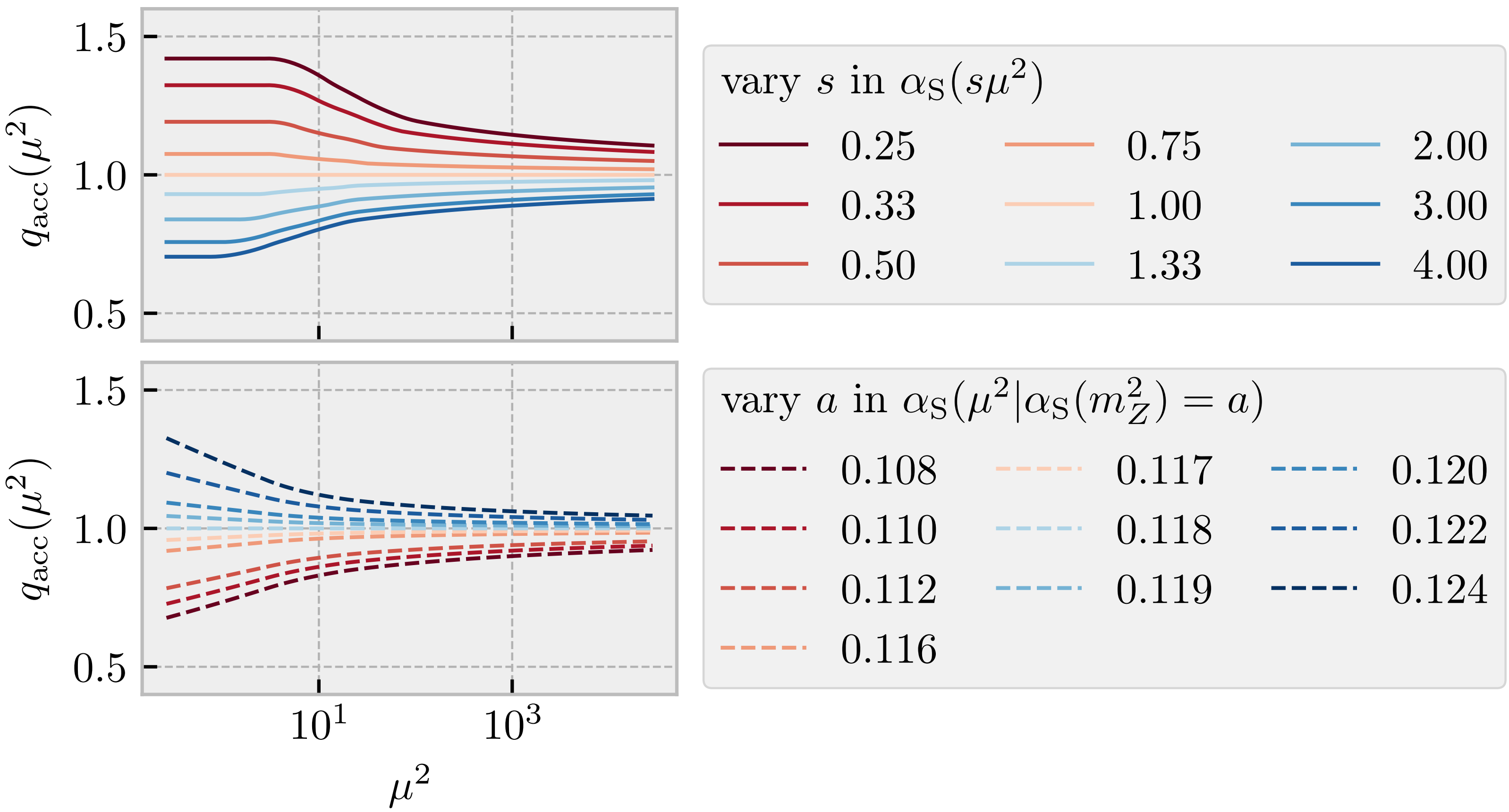

NN input:
$\alpha_S(\mu^2)$ ratio

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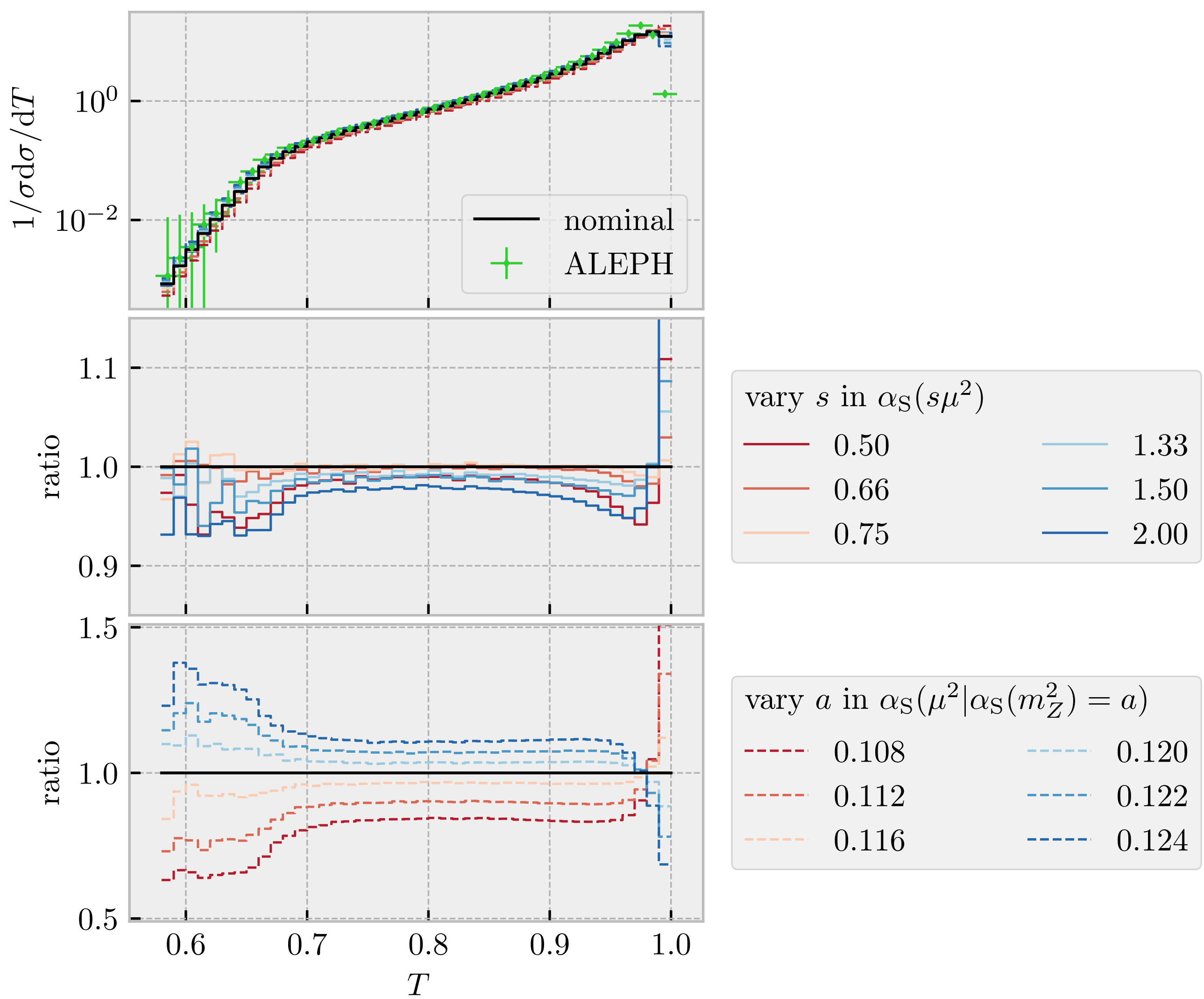

NN input: $\alpha_S(\mu^2)$ ratio

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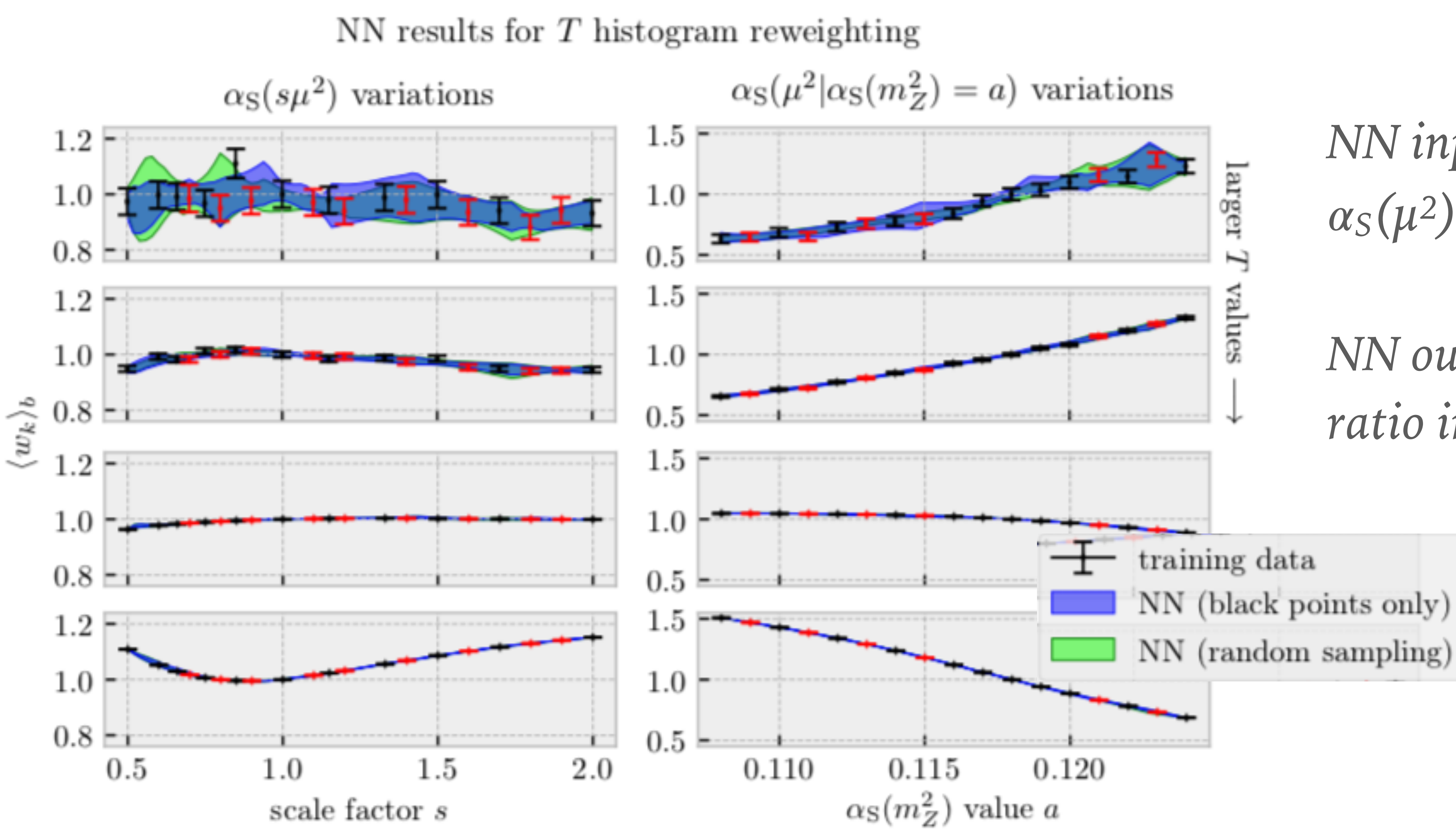
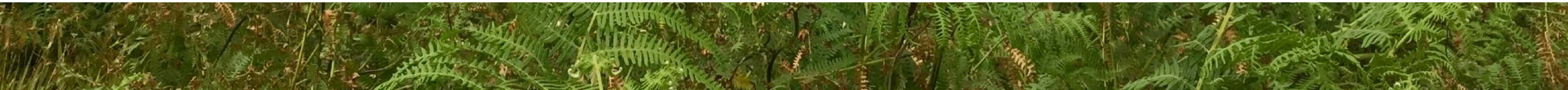


NN input: $\alpha_S(\mu^2)$ ratio

NN output: ratio in bin

BSM

example: dimension-six effective gluon interactions



BSM

BSM slides adapted from S. Kuttimalai

- BSM input via universal UFO format: $\mathscr{L}$ → FEYNRULES → UFO → SHERPA
  [Alloul et al., CPC 185 (2014)], [Degrande et al., CPC 183 (2012)], [Krauss, Kuttimalai, Plehn, Phys.Rev. D95 (2017)]
- support particles with spins 0, ½ or 1
- arbitrary Lorentz- and colour structures → EFT
- spin-correlated decay chains
  [Höche et al., Eur.Phys.J. C75 (2015)]
- many processes cross-validated against MADGRAPH5:

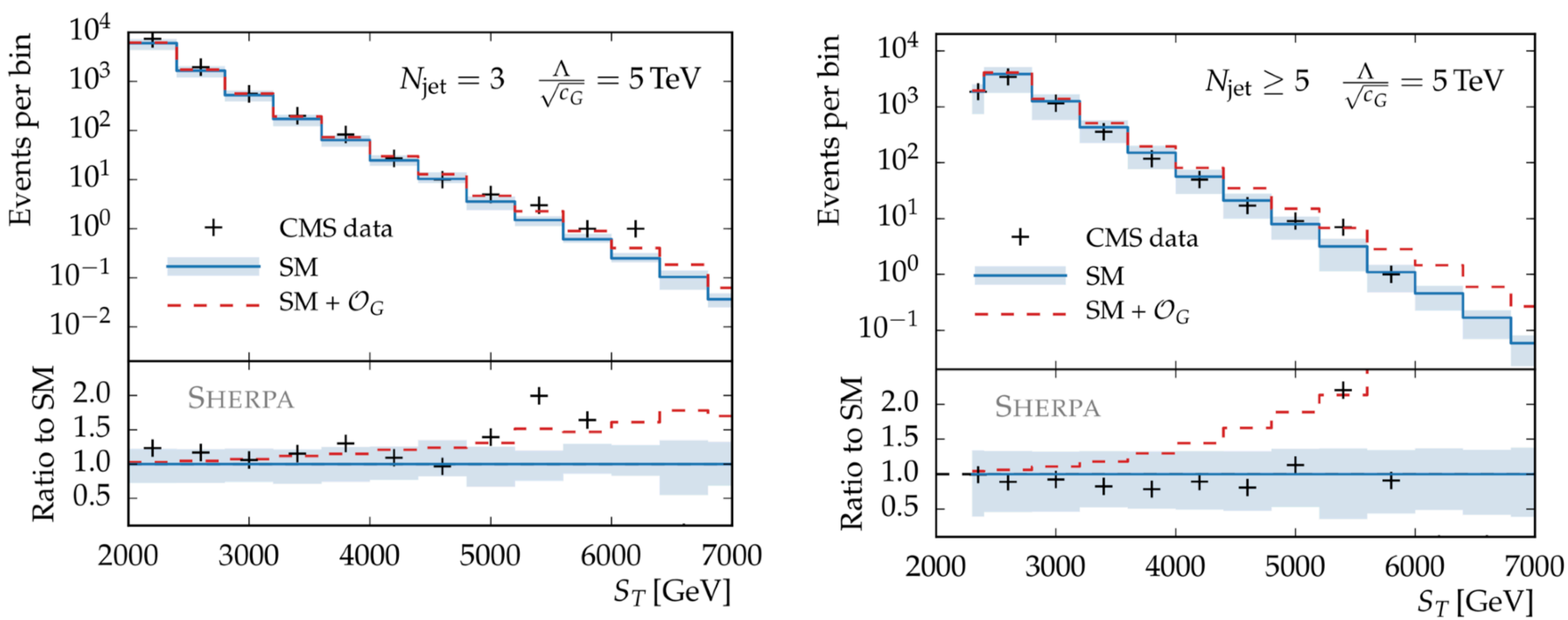
Model	number of processes tested	max. rel. deviation Comix ↔ MadGraph5
Standard Model	60	$2.3 \cdot 10^{-10}$
Higgs Effective Field Theory	13	$4.3 \cdot 10^{-13}$
MSSM	401	$1.0 \cdot 10^{-10}$
Minimal Universal Extra Dimensions	51	$2.8 \cdot 10^{-12}$
Anomalous Quartic Gauge Couplings	16	$5.9 \cdot 10^{-12}$
...		

BSM: DIMENSION-SIX EFFECTIVE GLUON INTERACTIONS

[Krauss, Kuttimalai, Plehn, Phys.Rev. D95 (2017)]

$$\mathcal{O}_G = \frac{c_G}{\Lambda^2} f_{abc} G^{\mu}_{a,\nu} G^{\nu}_{b,\kappa} G^{\kappa}_{c,\mu}$$

- from tt production → $\Lambda/\sqrt{c_G} > 850$ GeV
  [Buckley et al., JHEP 04 (2016)]
- idea: try multi-jets, $N_{\text{jets}} \geq 4$ not considered before



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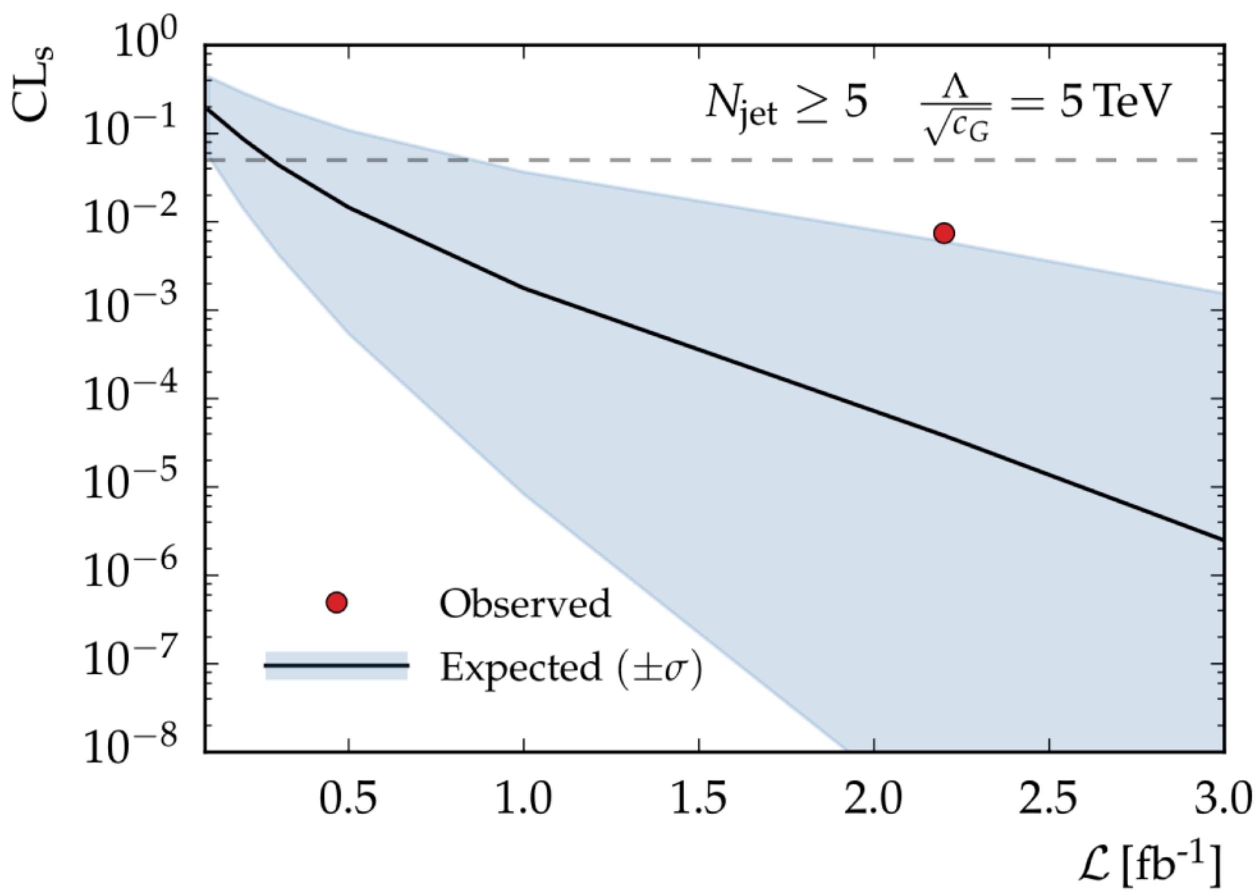

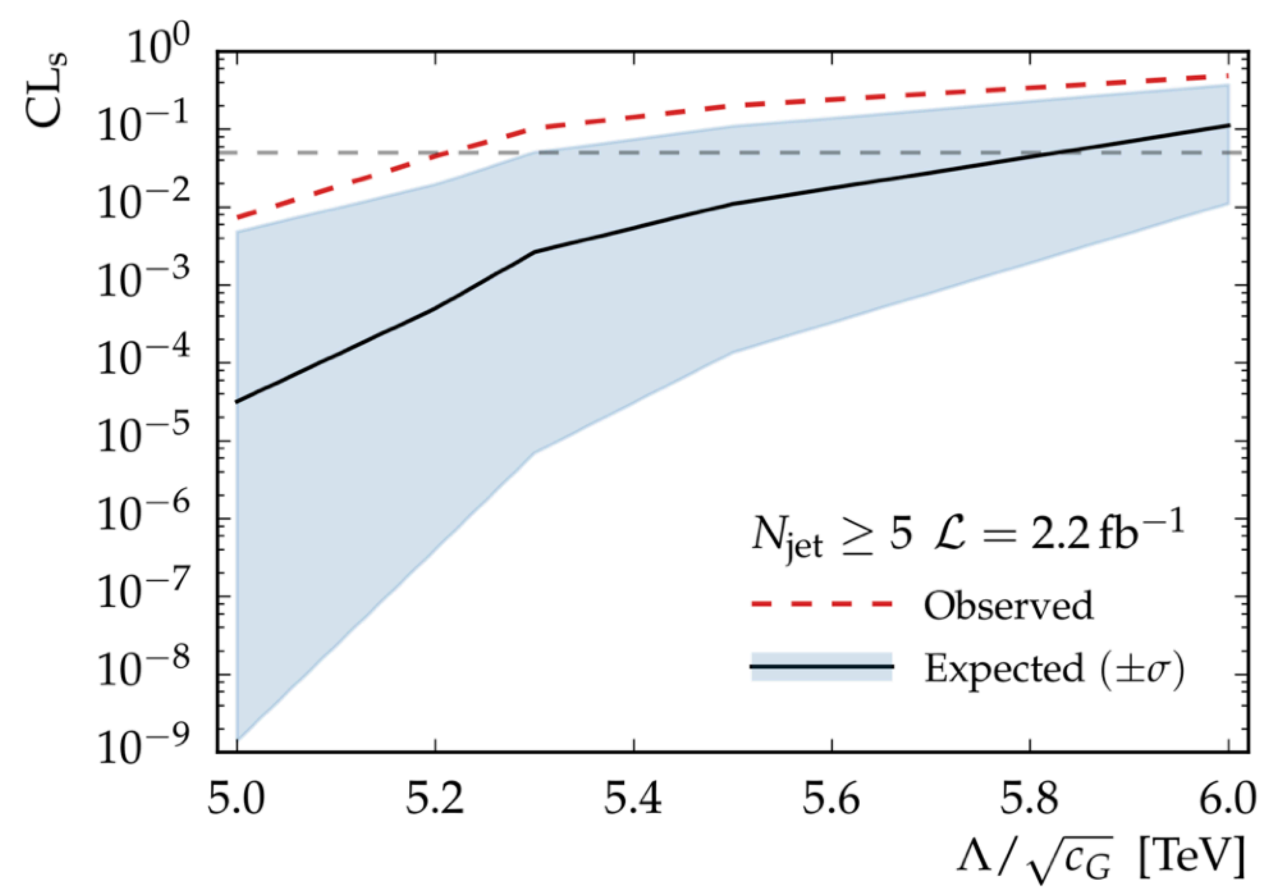

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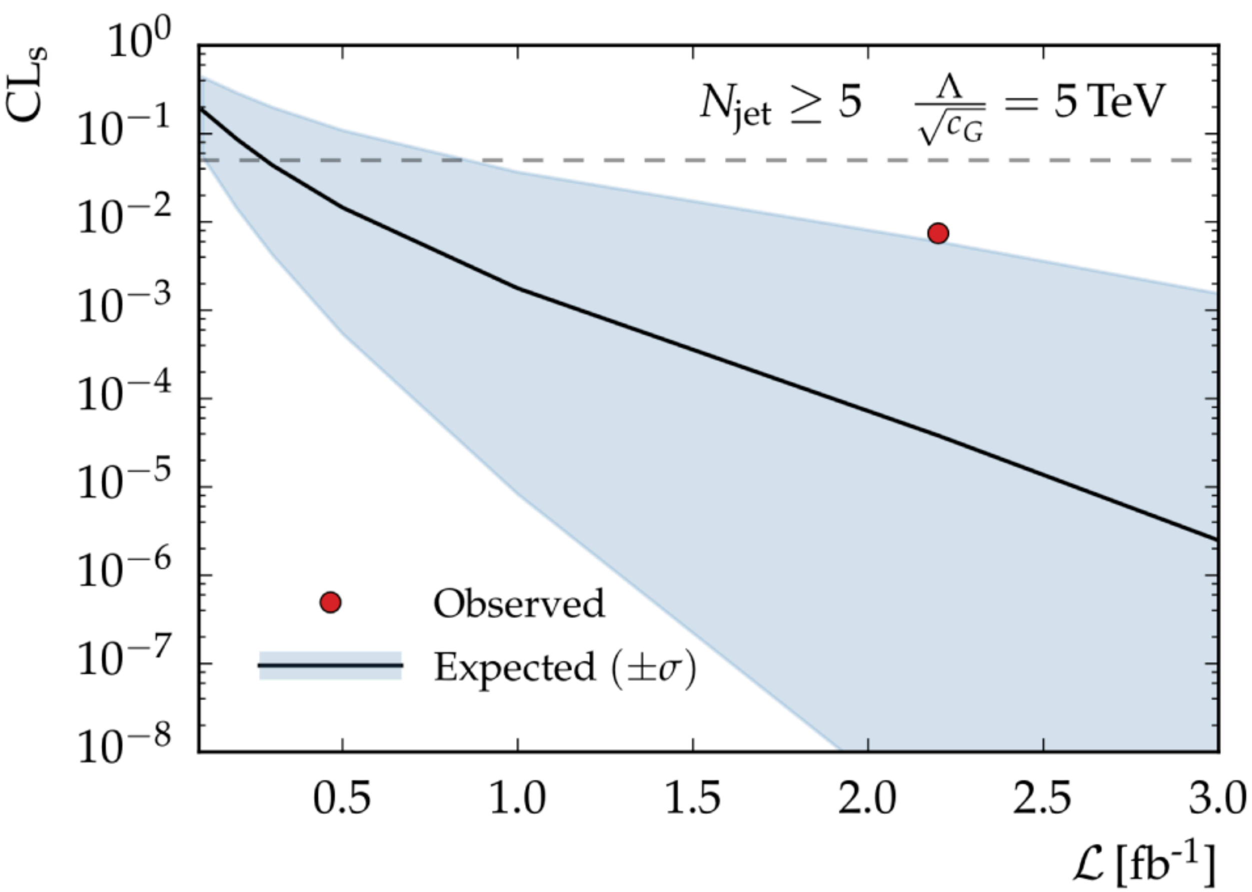
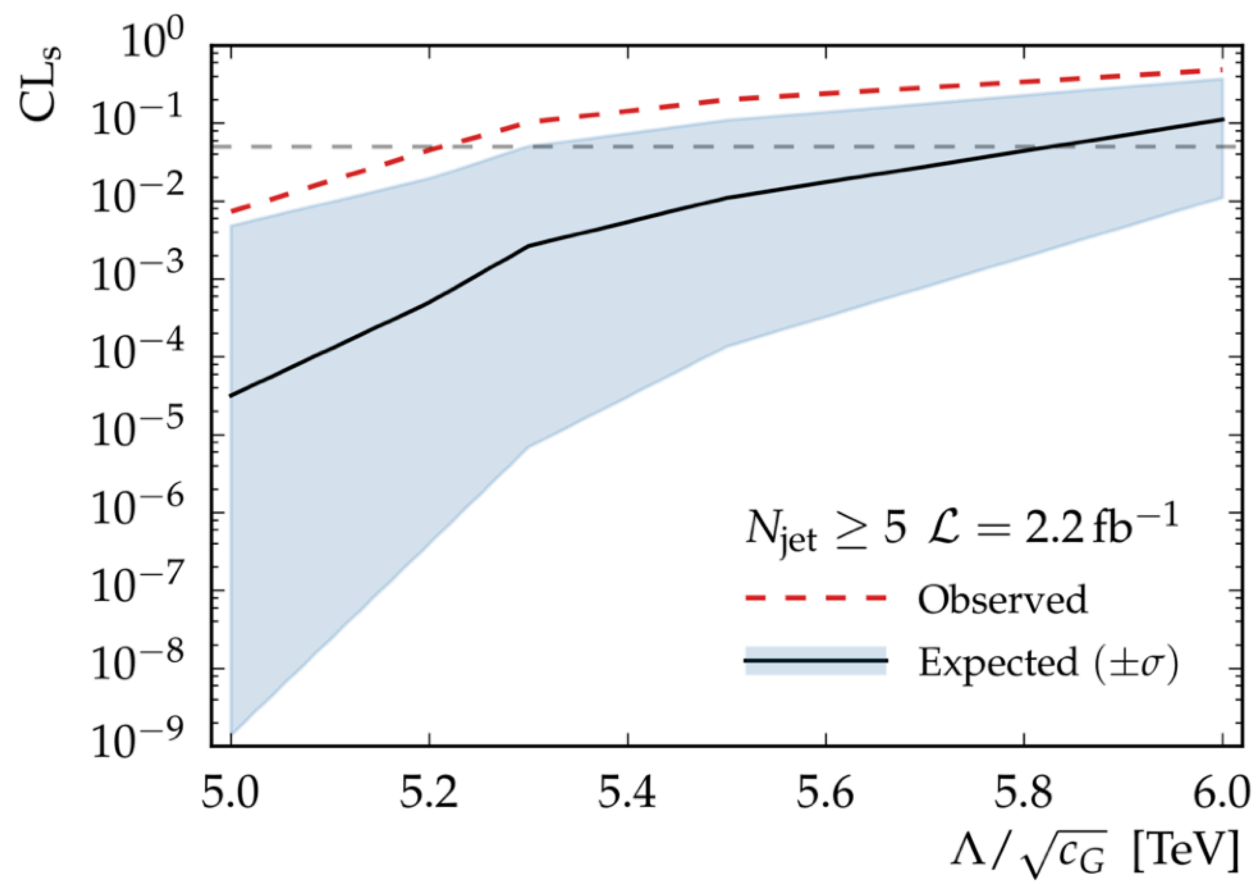
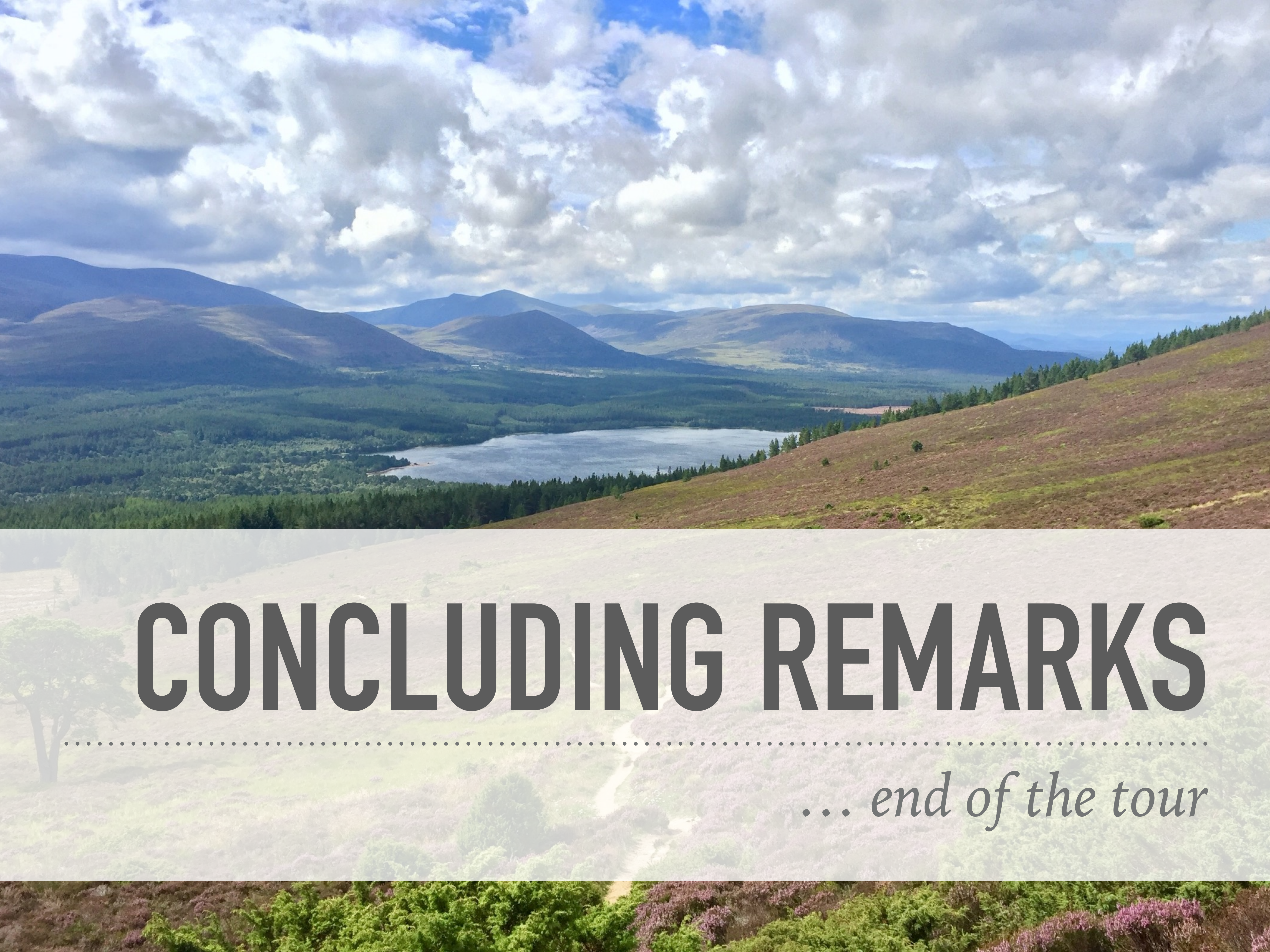
- from ~~tt production~~ *multi-jets* → $\Lambda/\sqrt{c_G} >$ ~~850 GeV~~ *5.2 TeV*
  [Buckley et al., JHEP 04 (2016)]
- idea: try multi-jets, $N_{\text{jets}} \geq 4$ not considered before



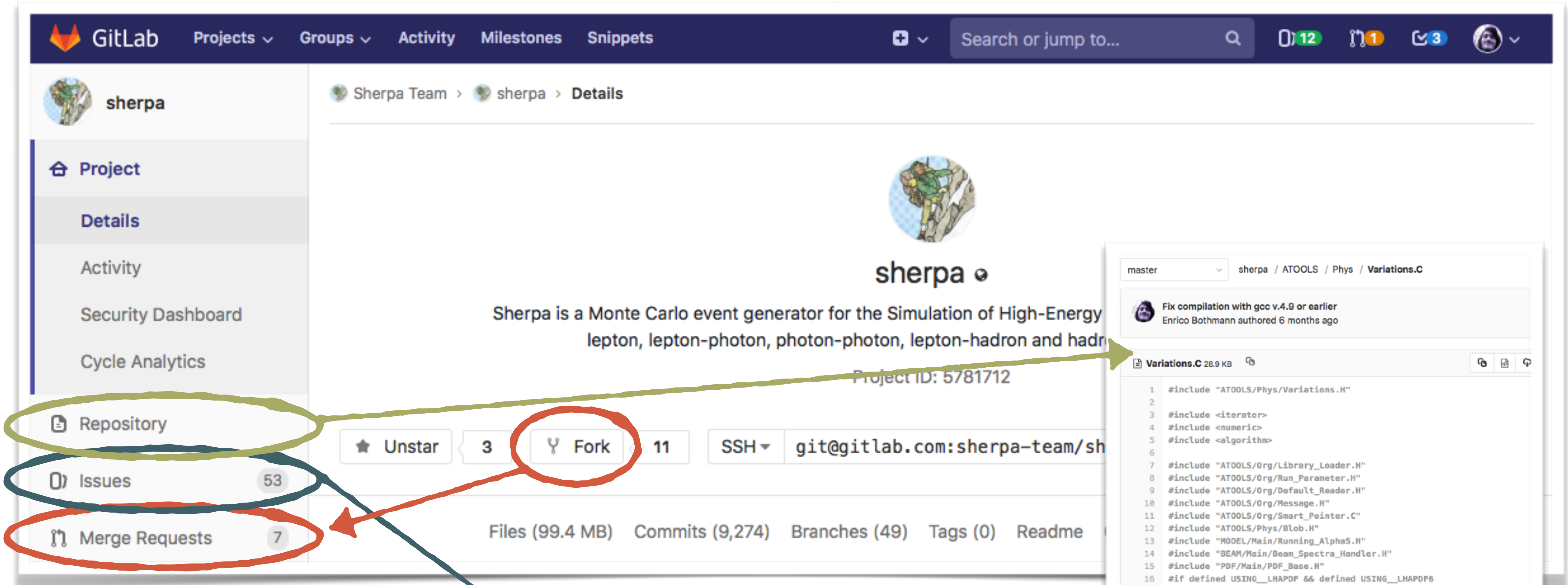


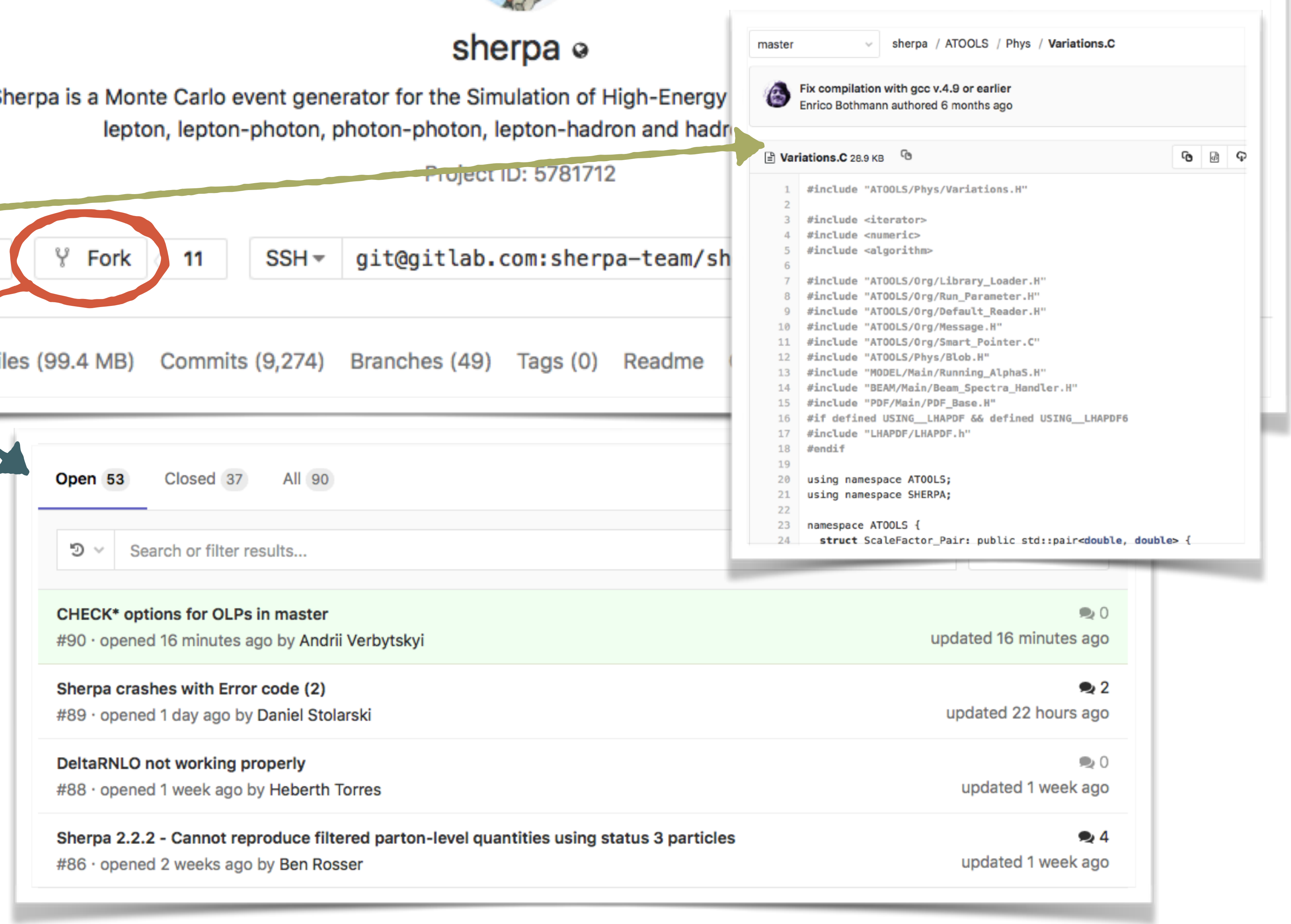


CONCLUDING REMARKS

… end of the tour

HTTPS://GITLAB.COM/SHERPA-TEAM/SHERPA





- open-source
- reporting
- contributing

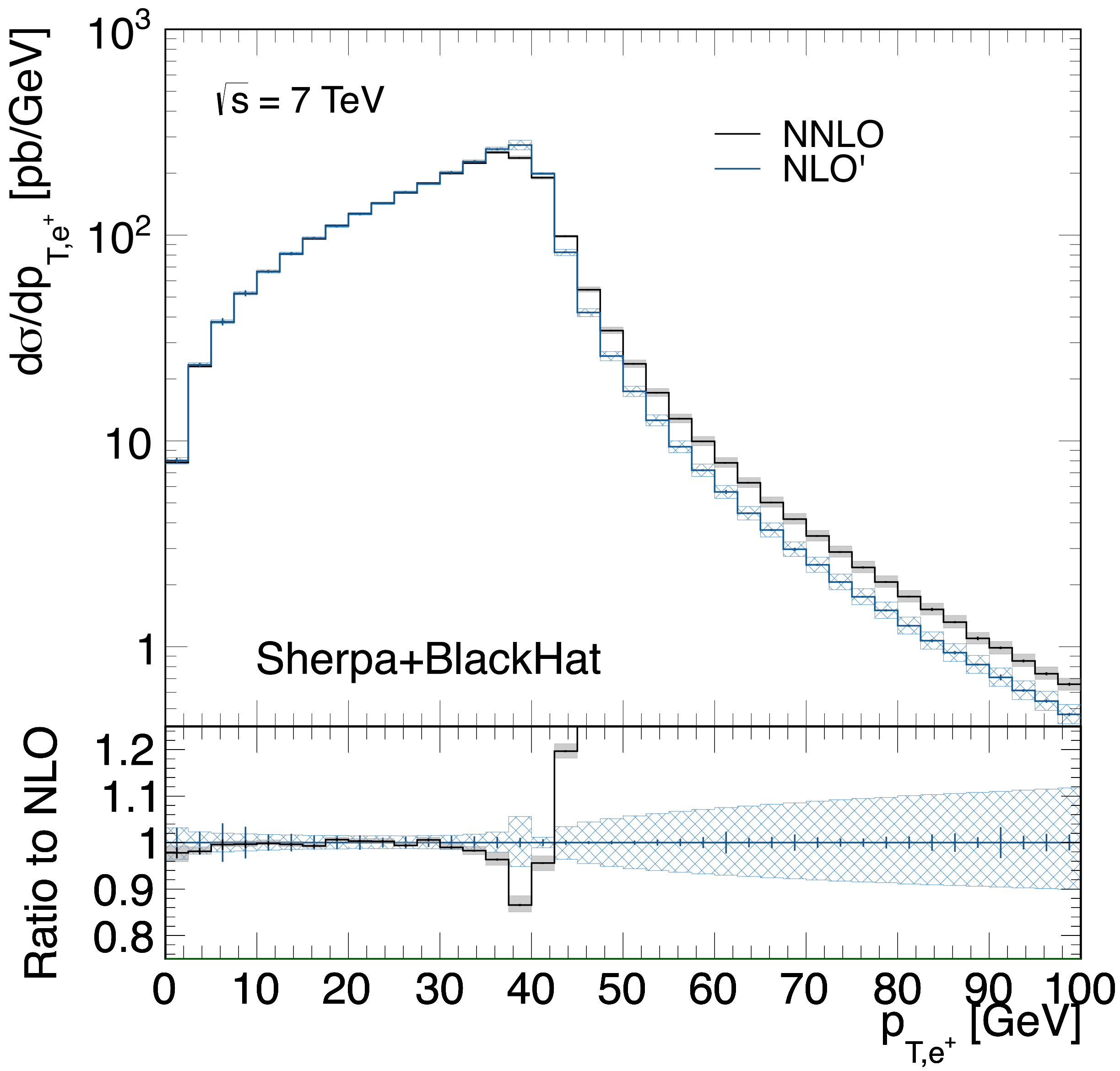
CONCLUSIONS

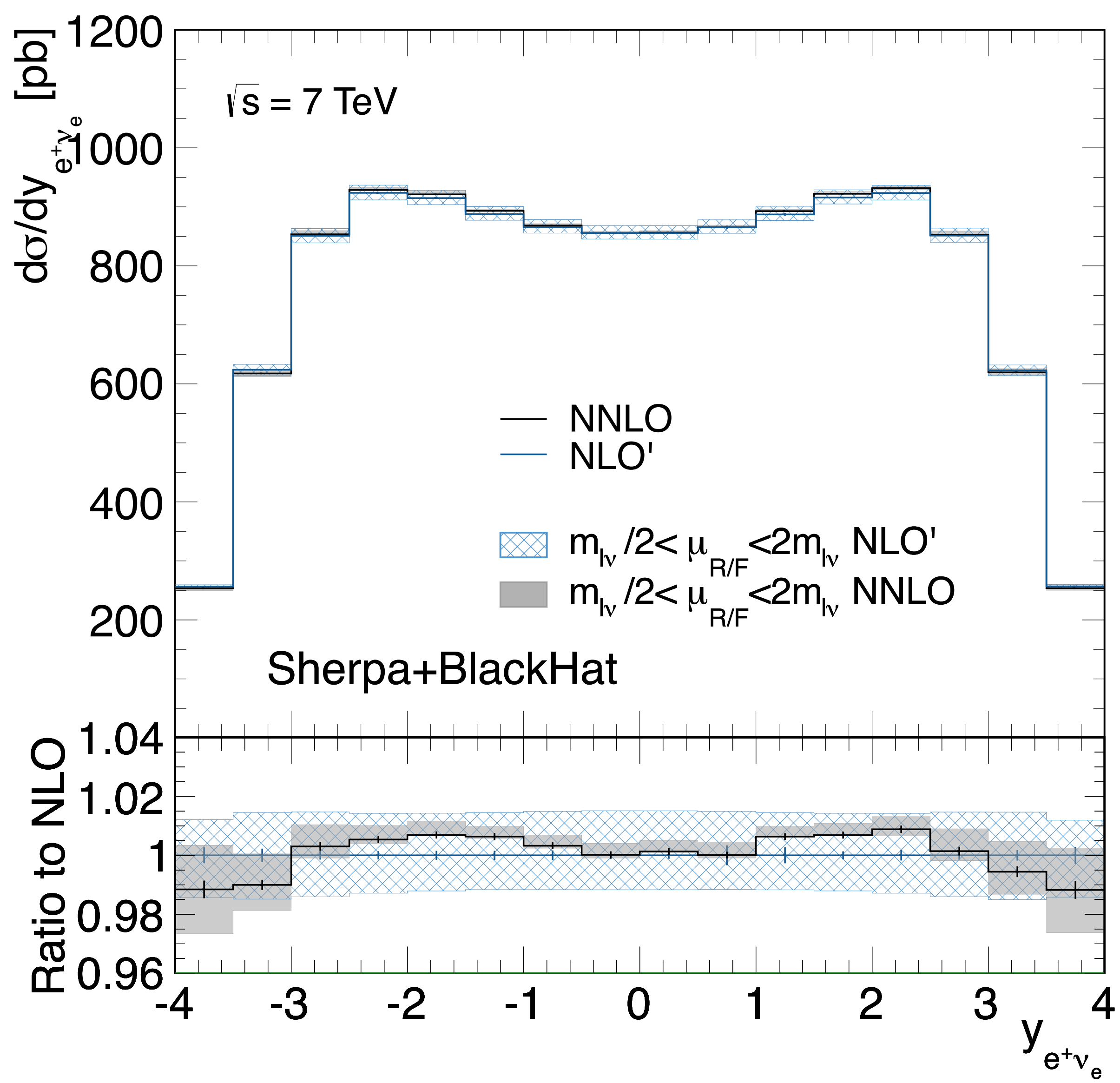
- automated exact EW NLO, approximation for merging runs
- support for loop-induced processes
- differential higher-order soft terms in shower
- MC@NLO single-top validated (2.2.5)
- on-the-fly variations improved (2.2.5)
- more SHERPA-related news in other talks!
  - S. Liebschner: resonance-aware subtraction (tomorrow afternoon) [Höche, Liebschner, Siegert 1807.04348]
  - J. Krause: matching/merging with massive b quarks in tt+jets/ttbb (Thu afternoon)
  - D. Reichelt: shower vs. resummation (Thu afternoon) [Höche, Reichelt, Siegert, JHEP 1801 (2018) 118]
  - plenaries M. Schönherr (EW, Wed), S. Kuttimalai (MCEG, Fri)


BACK-UP
… let’s keep going

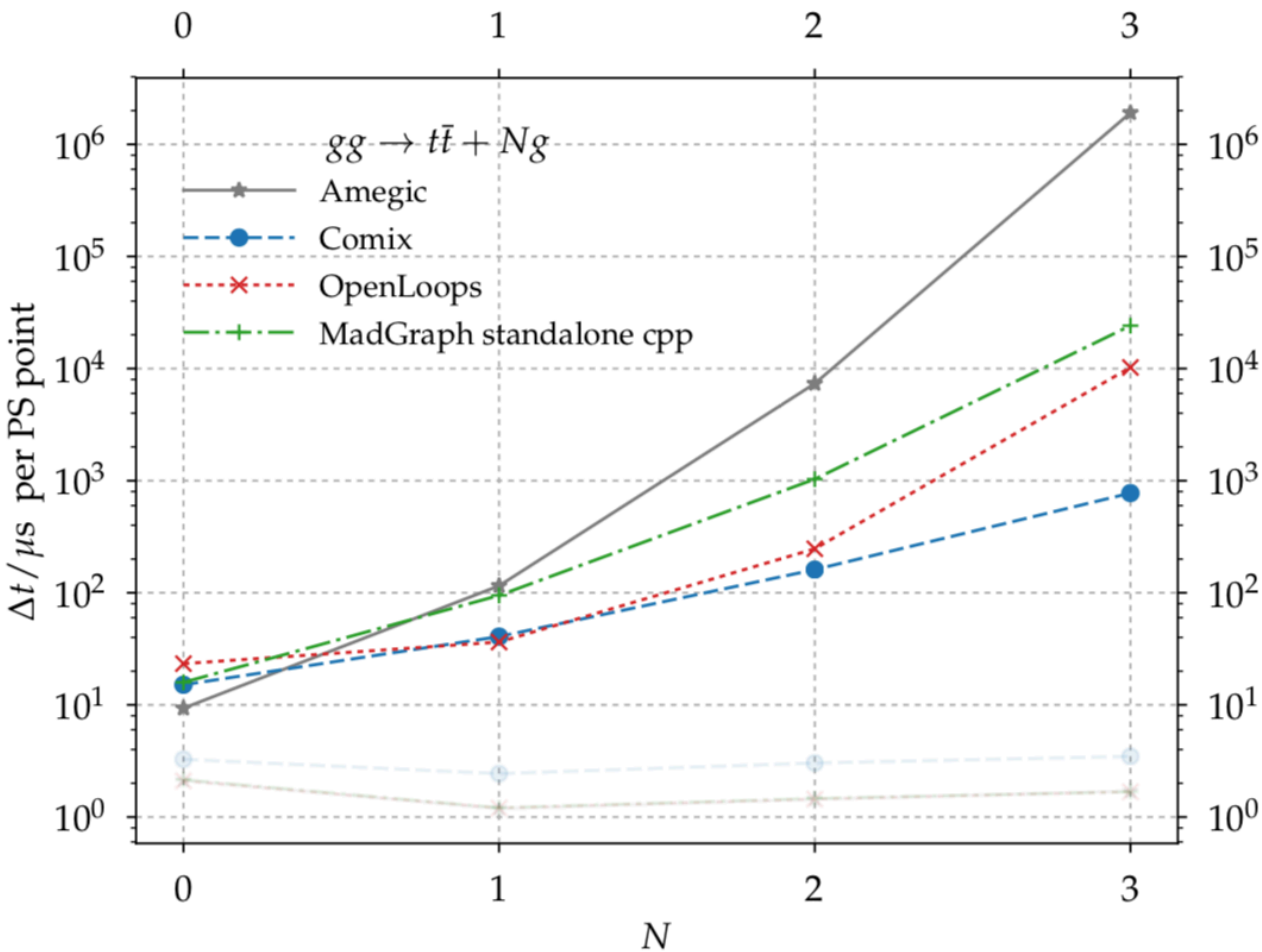
NNLO+PS IN SHERPA

[Höche et al. Phys. Rev. D 91 (2015) 074015]

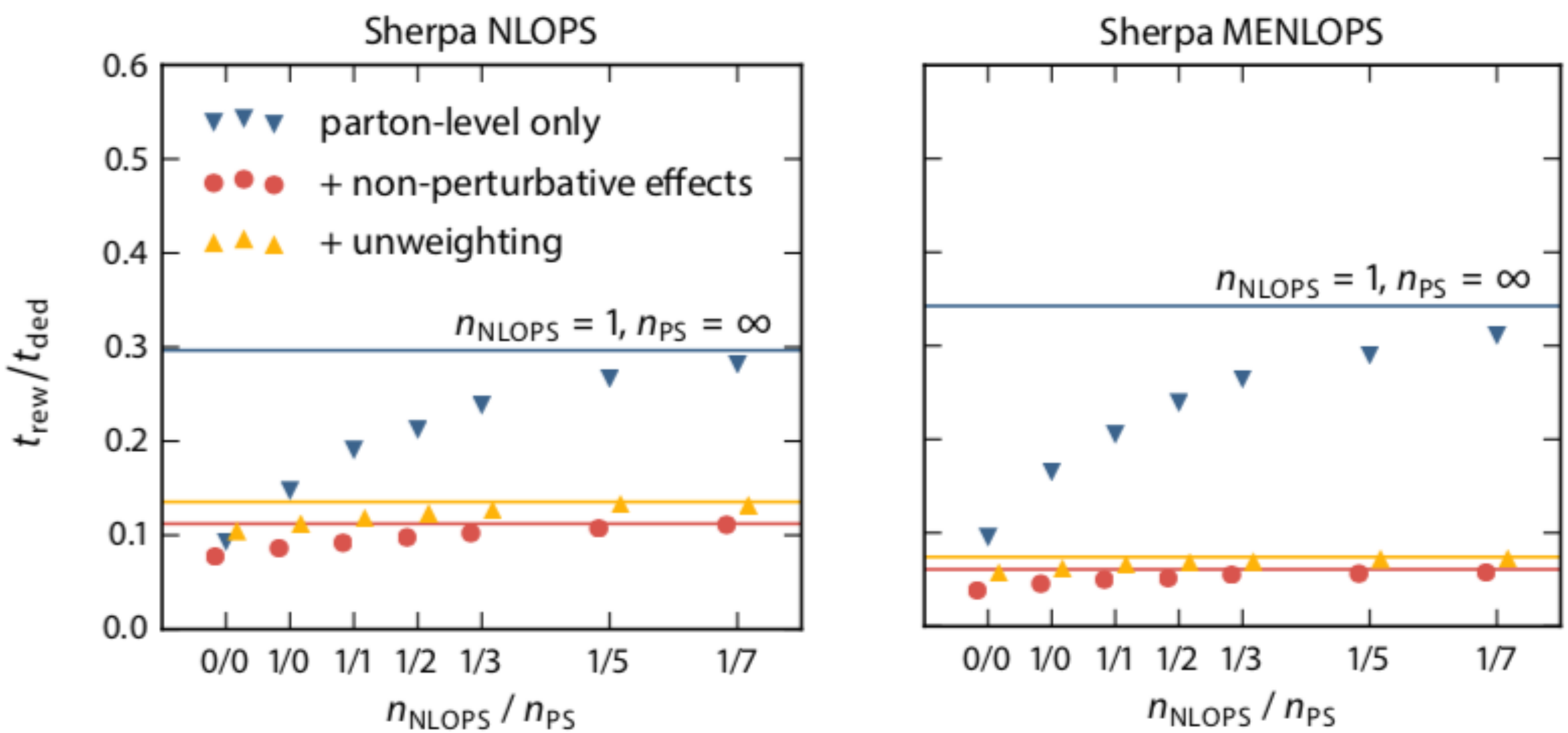




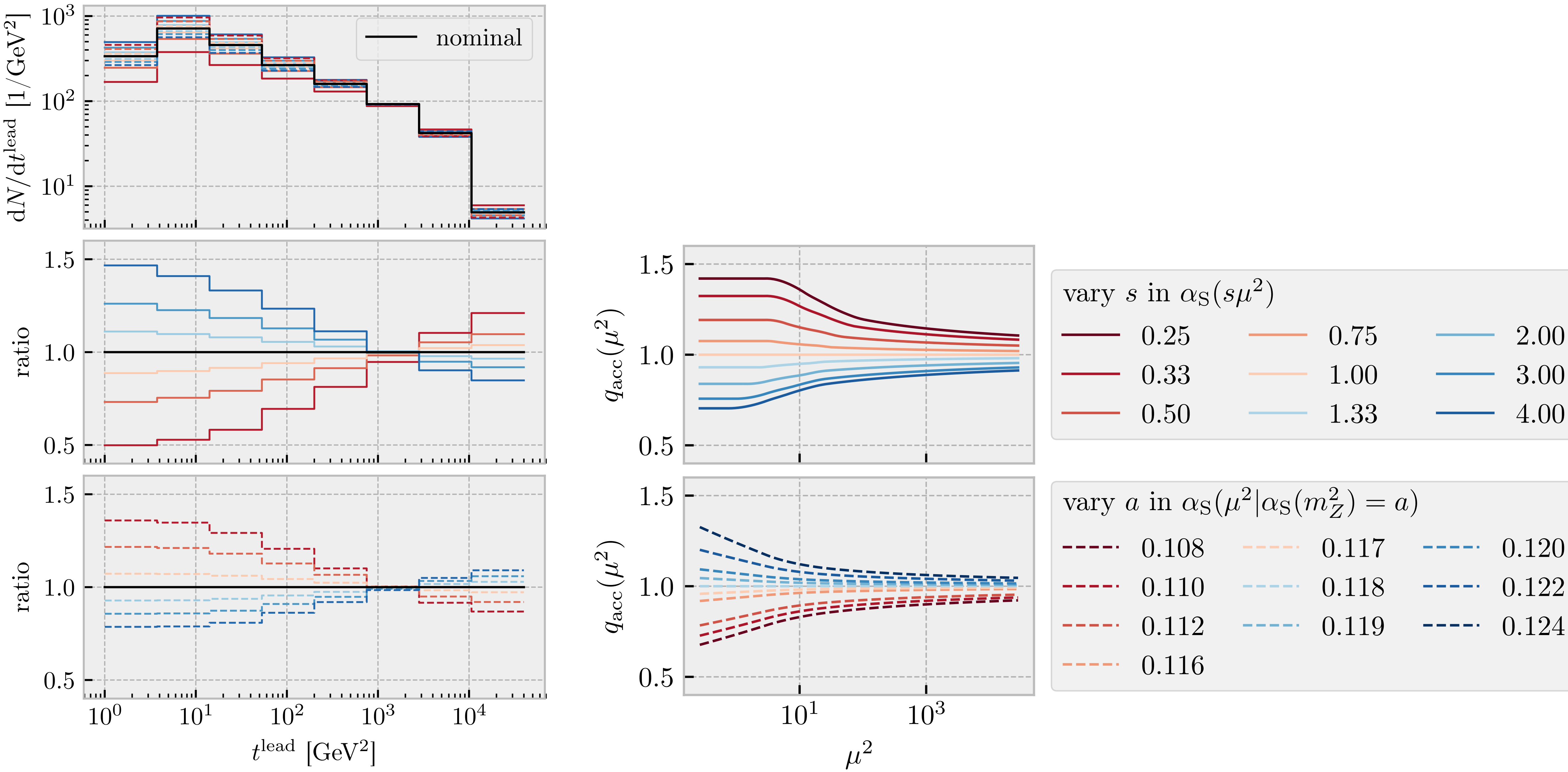
COMPUTATIONAL COST (GENERATORS)



COMPUTATIONAL COST (REWEIGHTING)



NNPS: HOW IT WORKS



NNPS: VALIDATION

- ➤ to-be-validated variation excluded from training