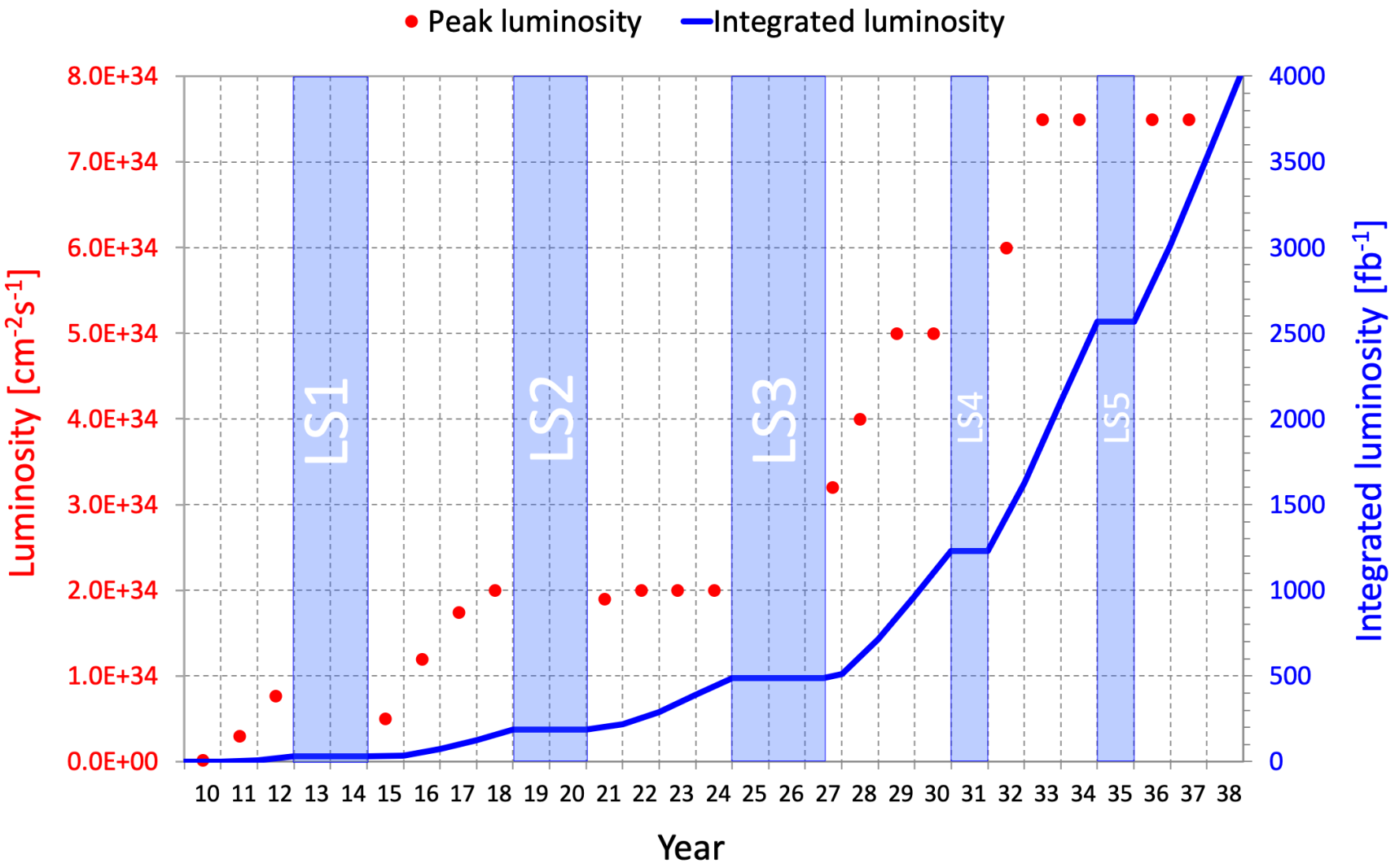
Future experimental needs in event simulation

Christian Gütschow

Taming the Accuracy of Event Generators

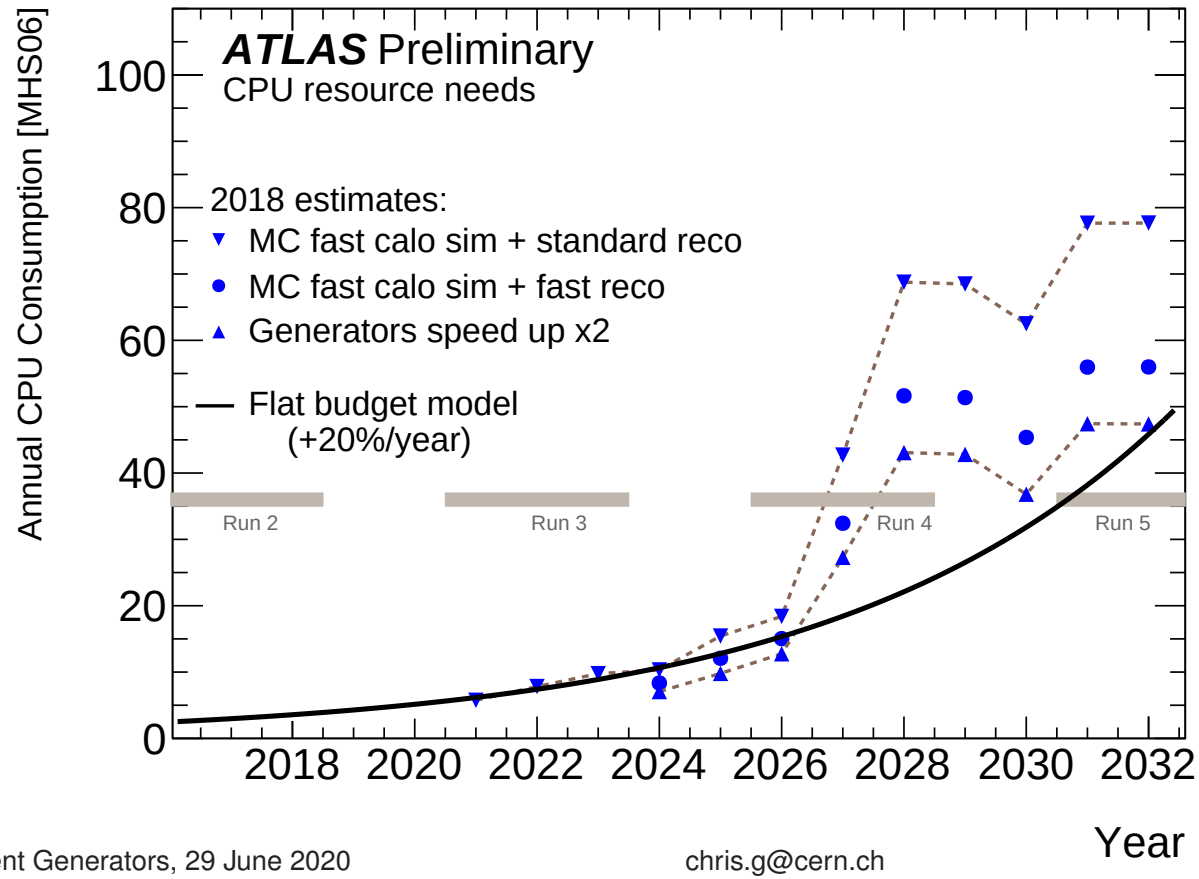
29 June 2020

Projected integrated luminosity



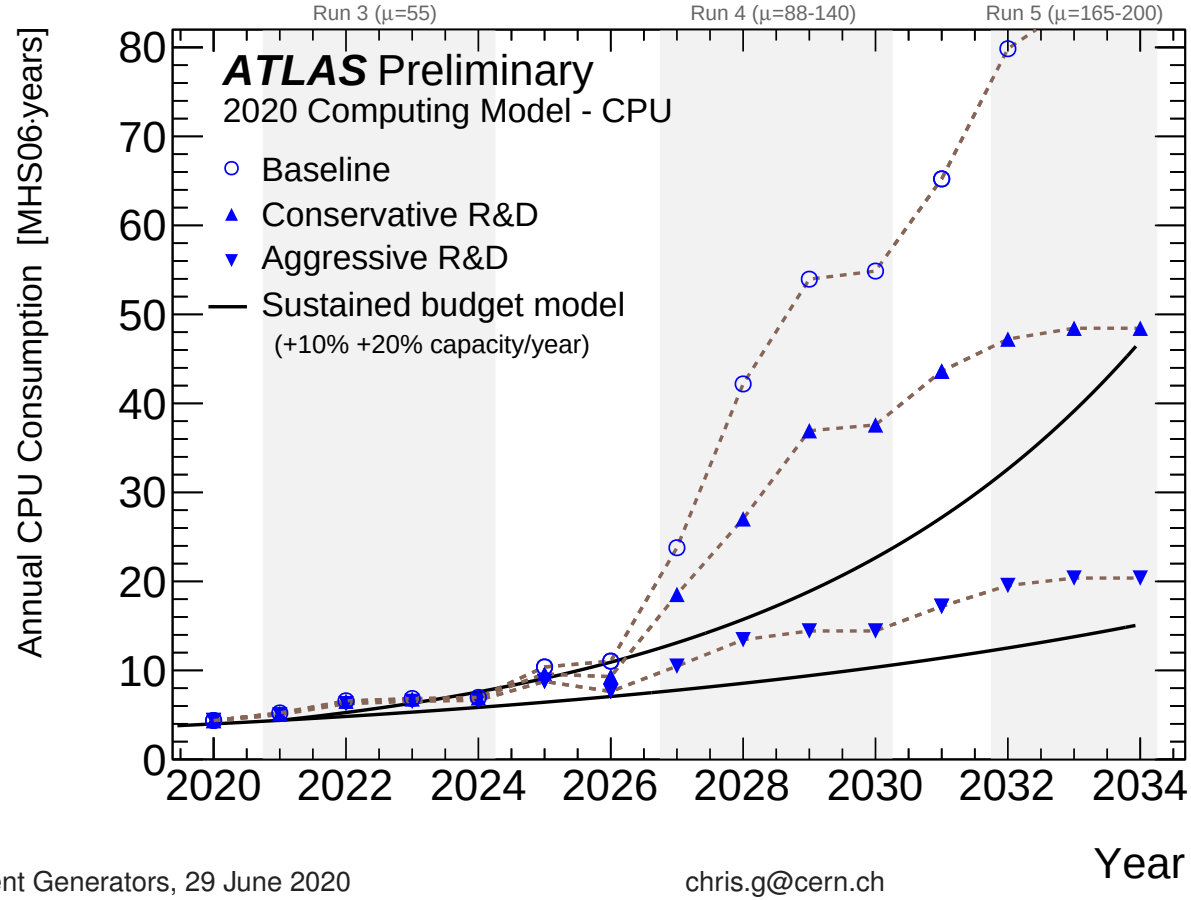
Wishful thinking (pre-corona)

- flat budget not going to get us annual 20% CPU increase as Moore's law no longer holds
- no magical factor-2 'speed up' of generators in sight, but some CPU reductions possible
- still LHC measurements in danger of being limited by Monte Carlo statistics



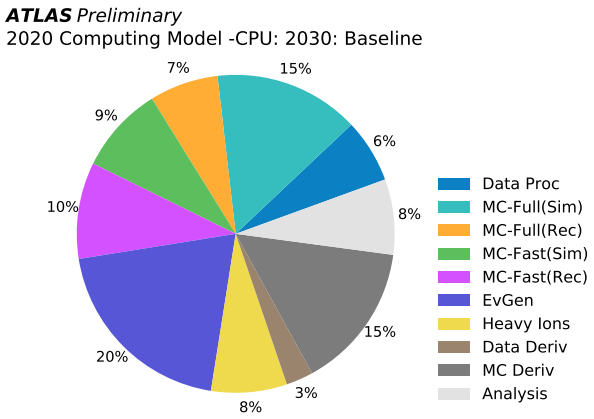
Revised computing model

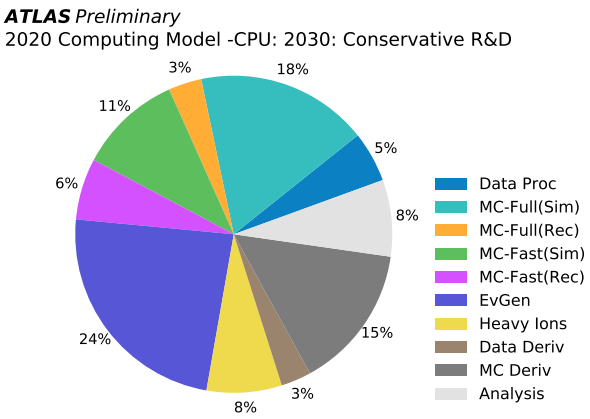
- baseline: assume Run-2 performance (compromise on physics quality)
- conservative: achieve better physics quality for same CPU time / event as in Run-2
- aggressive: CPU time / event halved, generate 30% (simulate 10%) fewer events

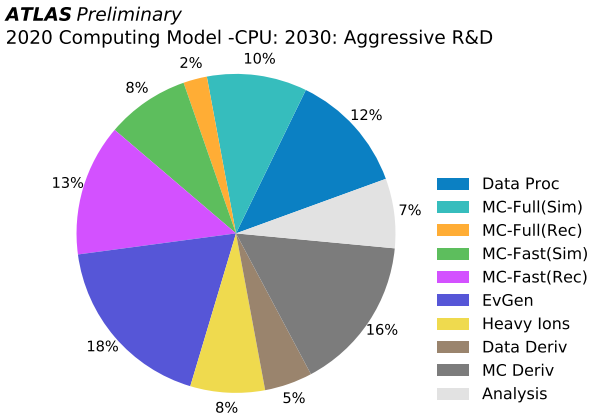


Projected CPU breakdown

- baseline: assume Run-2 performance (compromise on physics quality)
- conservative: achieve better physics quality for same CPU time / event as in Run-2
- aggressive: CPU time / event halved, generate 30% (simulate 10%) fewer events



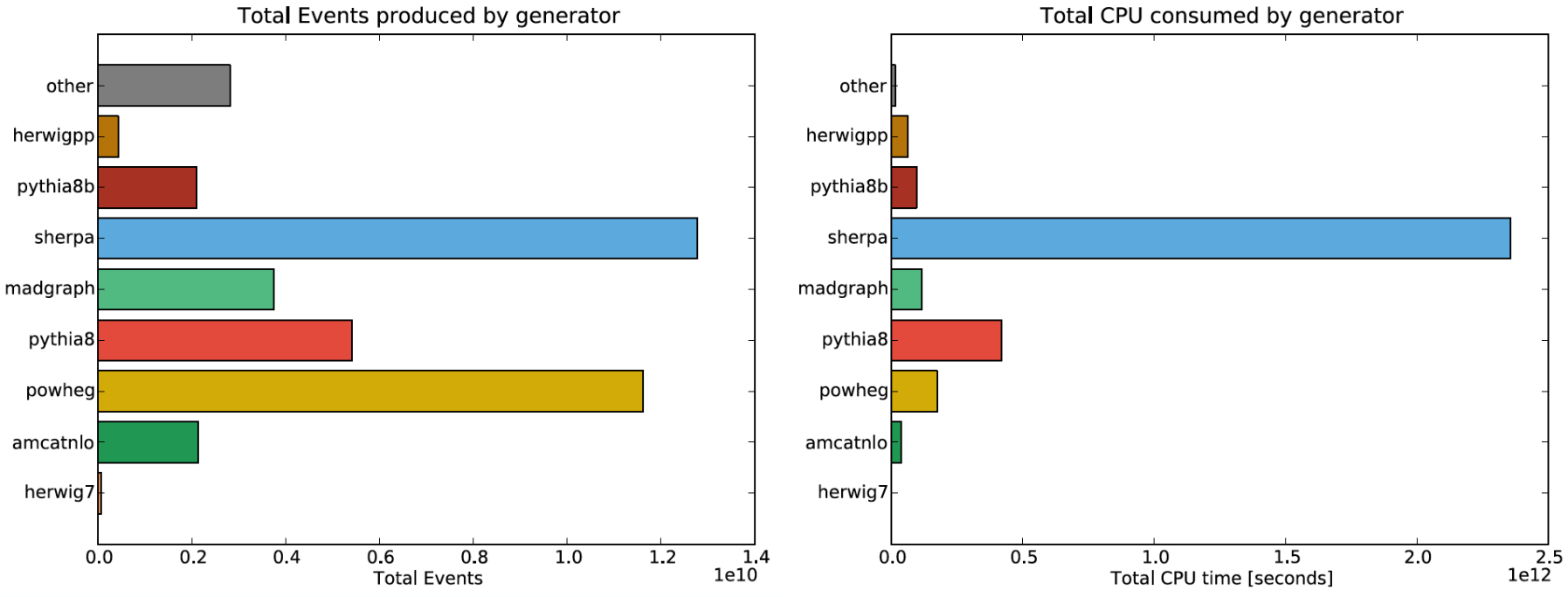




- event generation on par with detector simulation

Breakdown by generator (bit outdated, but not too bad)

- left plot: does not account for alternative multi-leg setups
- right plot: most CPU spent on high-precision multi-leg calculations (e.g. for ATLAS: $V + 0, 1, 2j$@NLO+$3, 4j$@LO and $t\bar{t} + 0, 1j$@NLO+$2, 3, 4j$@LO)



[courtesy of Josh McFayden]

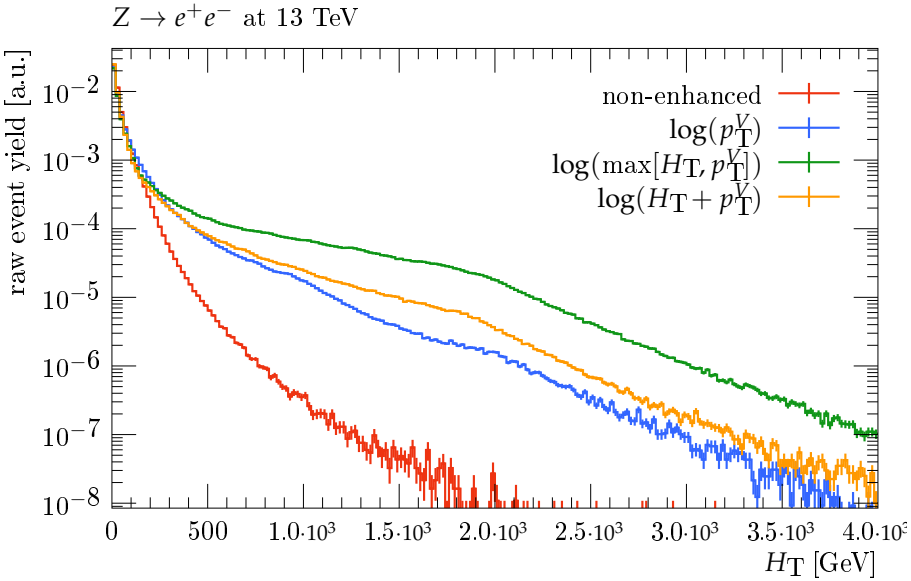
- outlook: CPU spent on expensive setups expected to increase faster than for fast setups

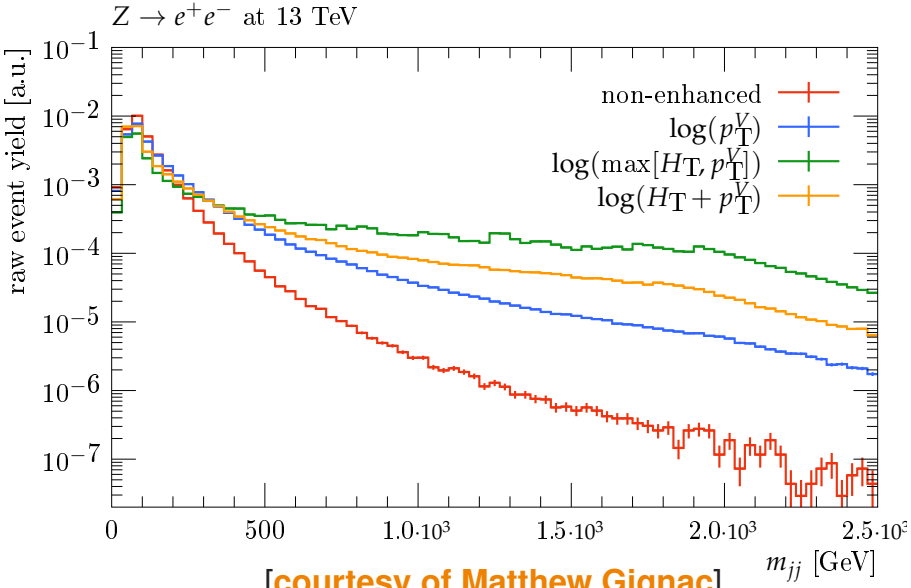
Negative weights are expensive

- relative uncertainty increased by factor $1/(1-2f_{\mathrm{nw}})$, so sample size needs to be factor $(1-2f_{\mathrm{nw}})^2$ larger
  - $f_{\mathrm{nw}} = 10\,\%$ implies statistical error becomes factor 1.25 larger
    - need factor 1.5 as many events
  - $f_{\mathrm{nw}} = 20\,\%$ implies statistical error becomes factor 1.7 larger
    - need factor 2.8 as many events
  - $f_{\mathrm{nw}} = 30\,\%$ implies statistical error becomes factor 2.5 larger
    - need factor 6.3 as many events
  - $f_{\mathrm{nw}} = 40\,\%$ implies statistical error becomes factor 5 larger
    - need factor 25 as many events
- setups notorious for large negative weight fraction are just not feasible for production

Populating extreme regions of phase space

- phase-space slicing: add a cut at the generator level, stitch together multiple slices
  - cross-section falls 'naturally' within each slice
- phase-space biasing: produce events flat as a function of some observable
  - events are assigned weights to produce physical distribution

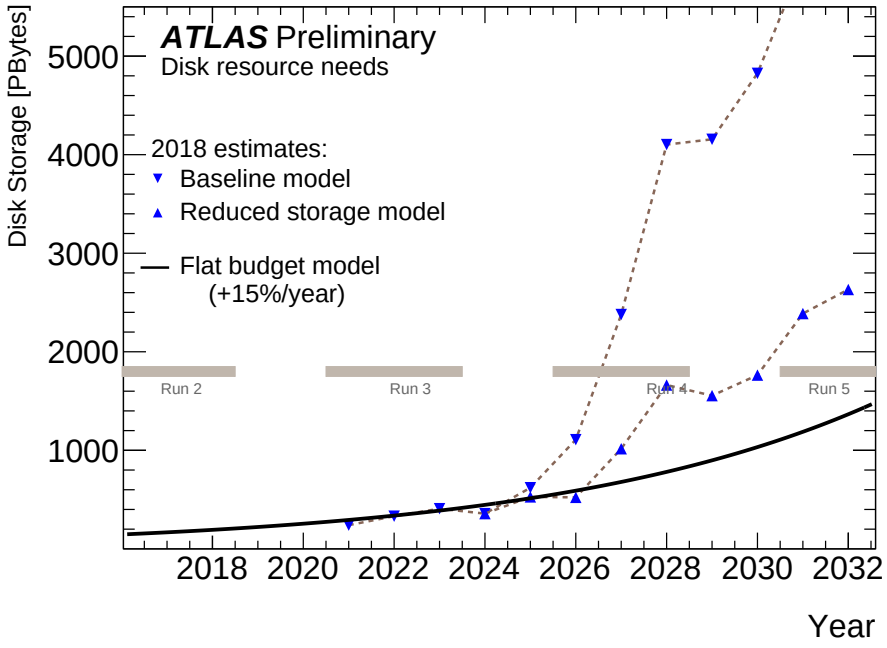


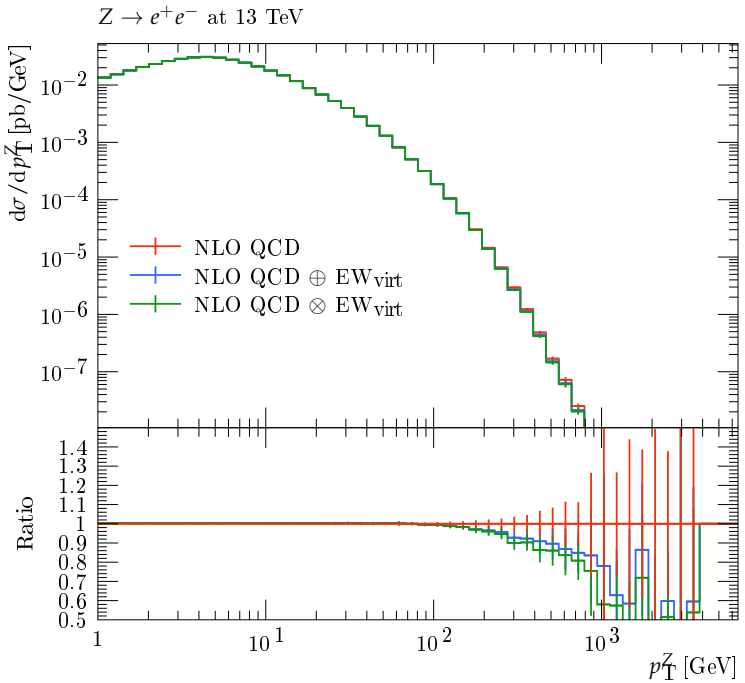


[courtesy of Matthew Gignac]

On-the-fly variations

- multiweights huge CPU saving compared to explicit variations for generator uncertainties
  - setup with ∼100 weights only ∼30% slower
- more variations to be included in the future
  - parton-shower scale variations, alternative scale choices, electroweak corrections, . . .
  - but some algorithmic variations cannot be achieved through reweighting

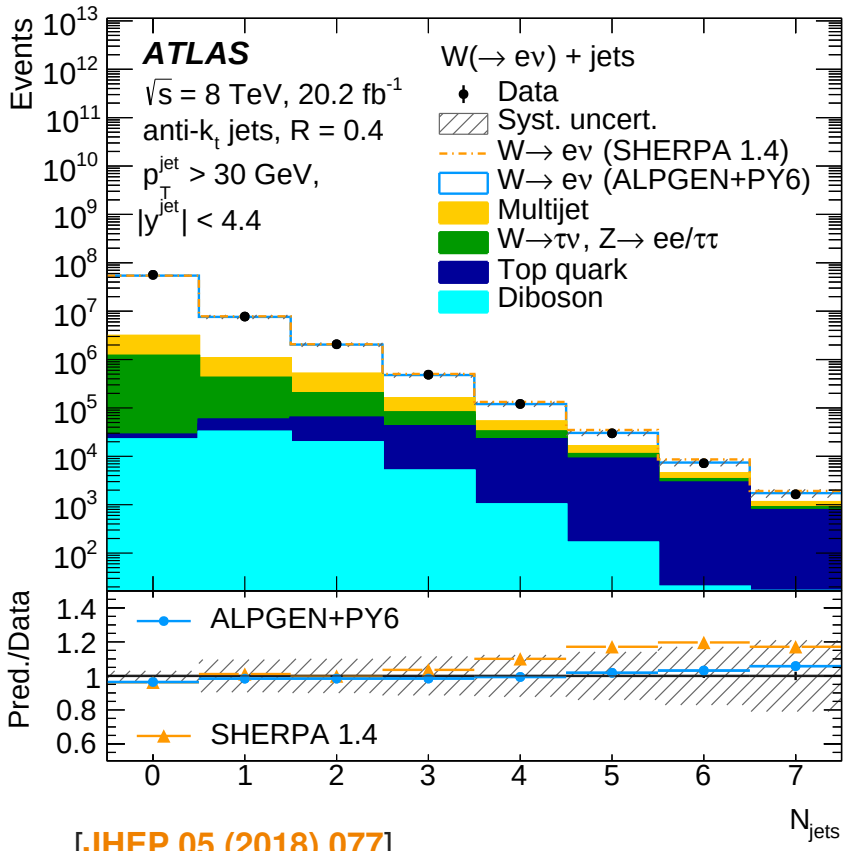




[courtesy of Matthew Gignac]

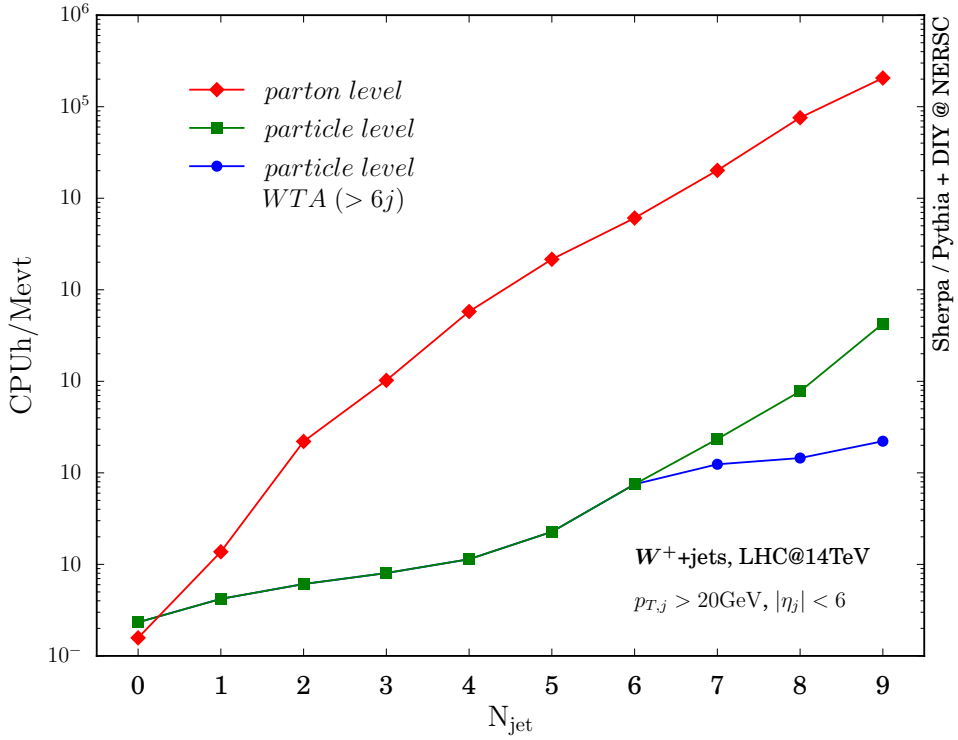
(HL-)LHC: a jet factory

- pretty much everything the detector sees is a jet to start with
  - excellent understanding of jet modelling and associated theoretical uncertainties is vital
  - 'sit back and relax' for data-statistical/experimental uncertainties to drop – except theory



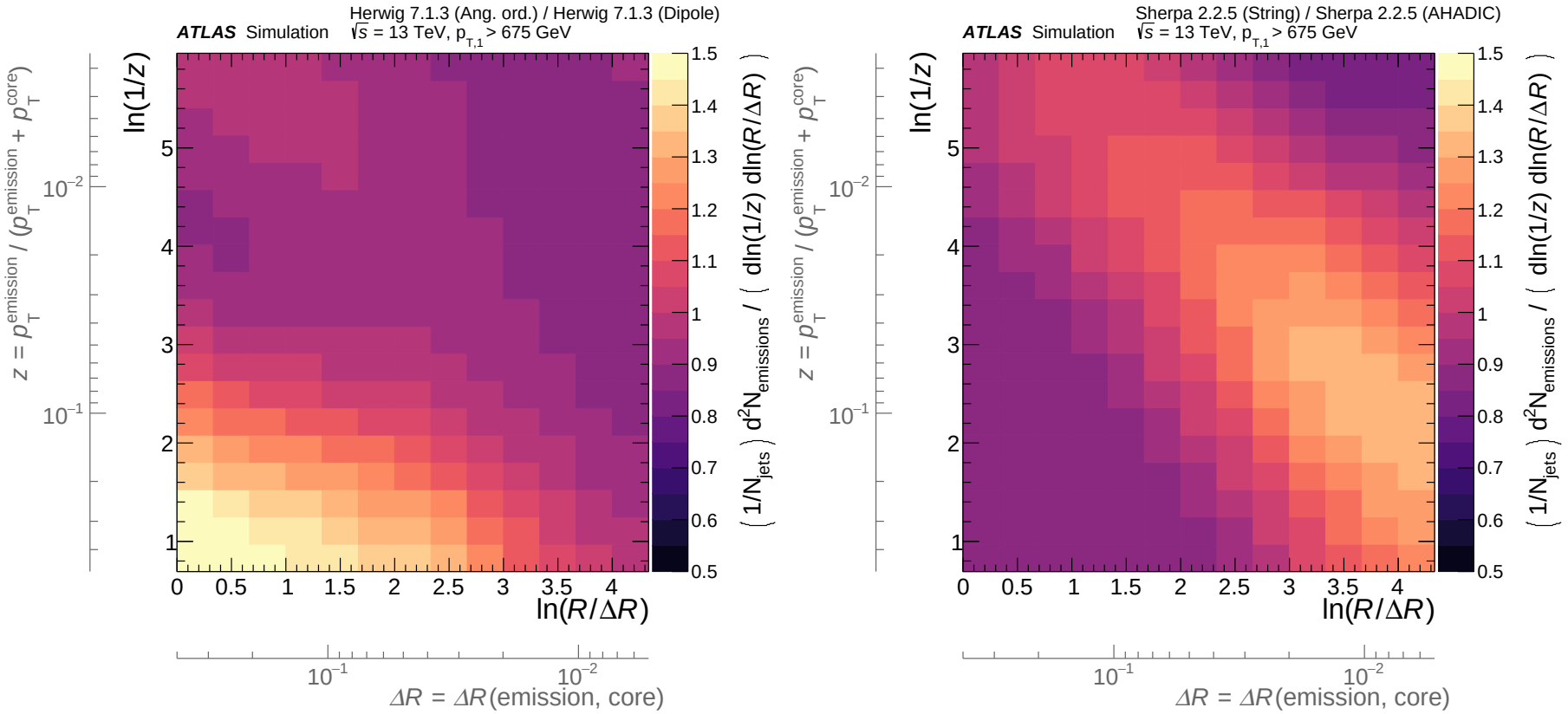
[JHEP 05 (2018) 077]

[Phys. Rev. D 100 (2019) 014024]



Parton shower modelling uncertainties

- analyses rely on reasonable modelling and a solid uncertainty estimate
- often a bottleneck: desire to have comprehensive survey of models but struggle to estimate associated uncertainty in CPU efficient way

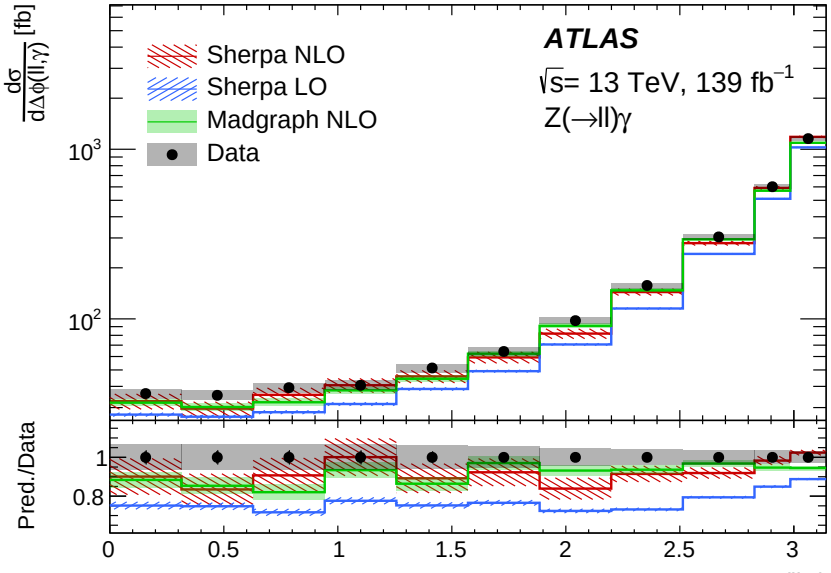


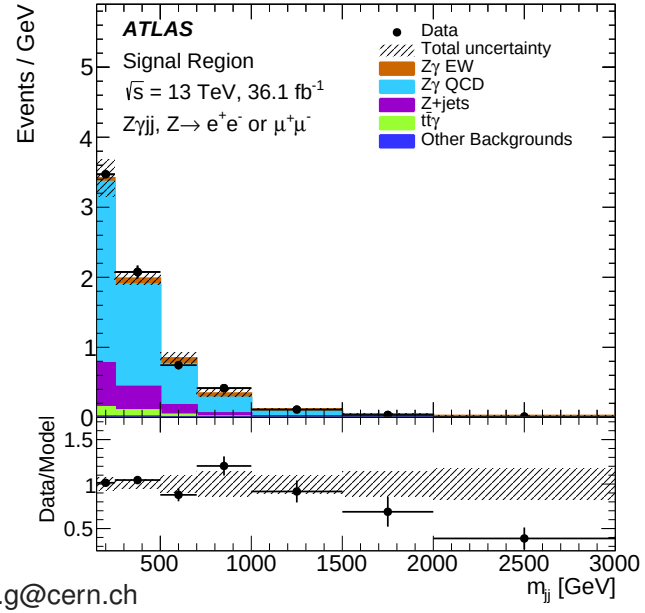
[Phys. Rev. Lett. 124 (2020) 222002]

Dawn of the multi-boson precision area

- differential analyses of multi-boson final states well underway
- challenging high-multiplicity final states with lots of combinations
  - full coverage of final states is important
  - (NLO multi-leg) setups not trivial to integrate
- as always: VV+jets can be signal but also background for other measurements/searches
  - needs good statistial coverage in different regions of phase space / jet multiplicities
  - need good description of third jet activity and matching to parton shower

[JHEP 03 (2020) 054]



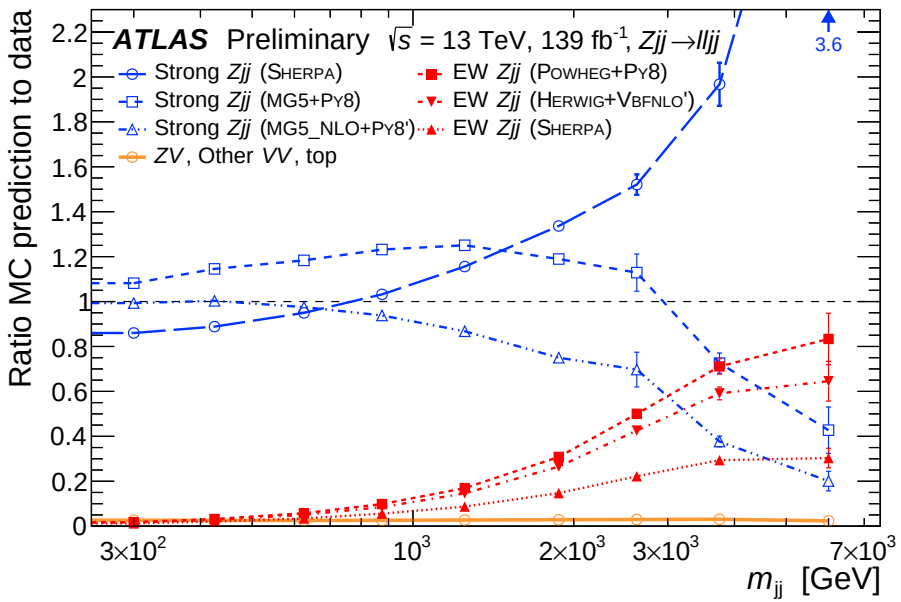


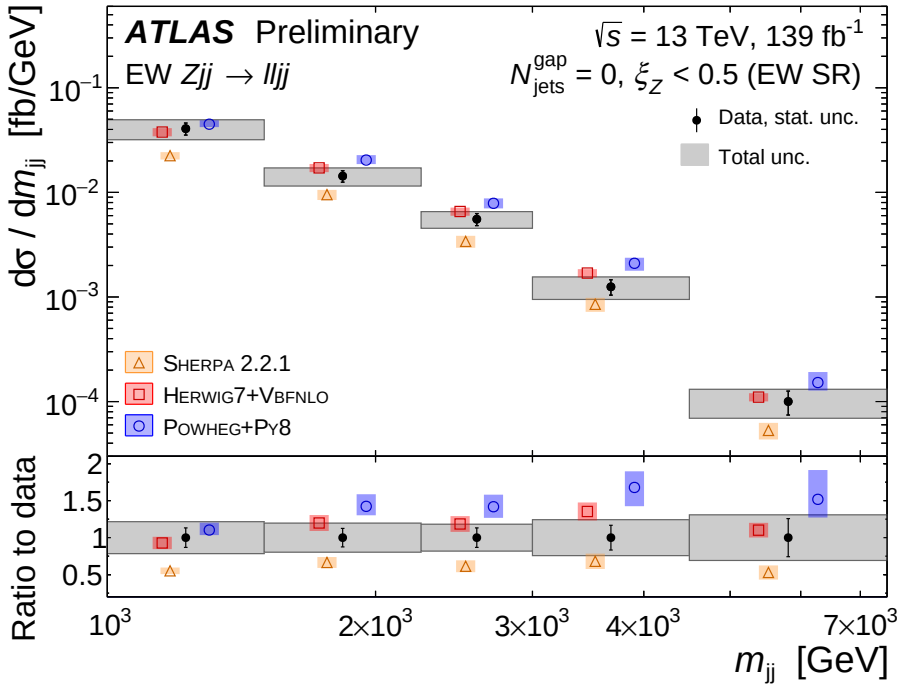
[Phys. Lett. B 803 (2020) 135341]

Topologies with suppressed colour flow

- pinning down weak boson fusion/scattering at the core of LHC physics programme
  - vital probe of the electroweak gauge structure of the Standard Model
  - stress test of perturbative QCD
- current models do not seem to live up to this challenge
  - poor modelling, not all final states available, lack of multi-weight support, . . .

[CERN-EP-2020-045]





Event generation in times of near-infinite data statistics

- ~~What do experiments need?~~ What can experiments afford?
  - expensive high-precision calculations can only be supported, if they benefit a wide range of clients
  - need to bear in mind that processes are typically both signal and background
- ~~What processes are they trying to measure?~~ What final states do they probe?
  - $V + 0, 1j$ are also part of the $V+ \geq 2j$ phase space
  - $t\bar{t}$+light jets also part of the $t\bar{t}$+heavy flavour jets final state
  - need precise SM predictions both for the bulk as well as extreme kinematic regions
- precision through higher-order corrections
  - tends to simplify analysis, but difficult to sustain given CPU constraints
- precision through correlation models
  - ratios of different processes increasingly popular to constrain systematics
  - not always clear how to correlate parton shower knobs across processes/regions of phase space (needs solid uncertainty estimate for the parton shower in the first place . . .)

Summary