MC Modelling and Production at CMS

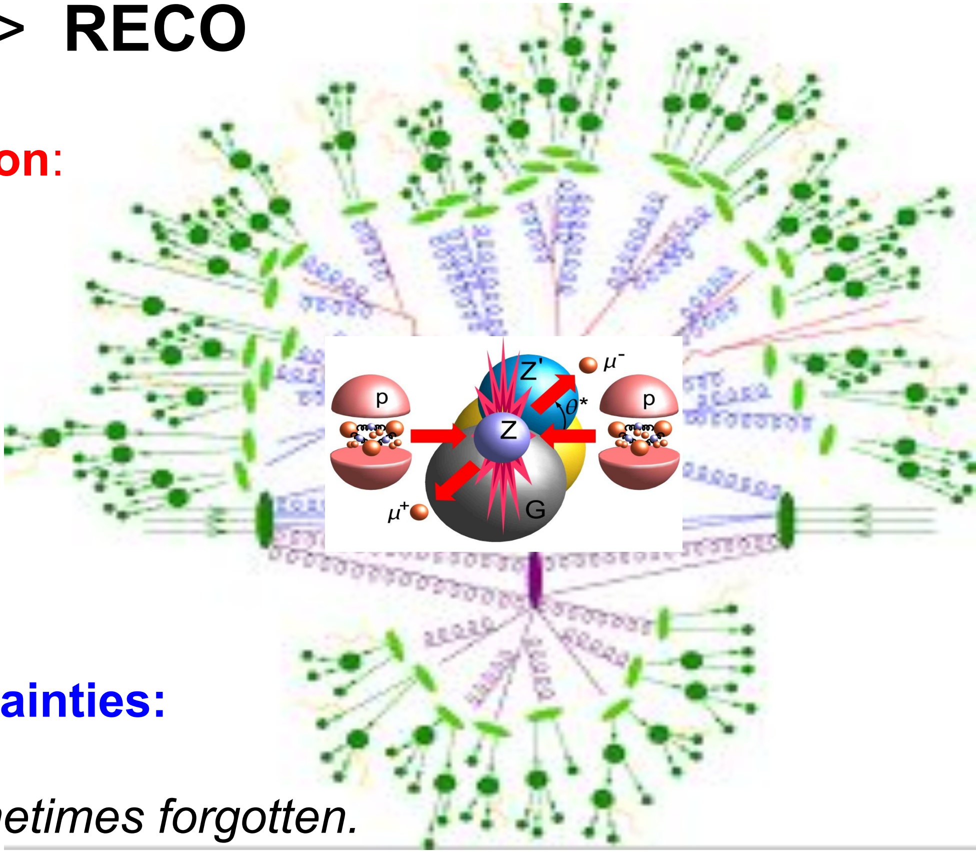
April 20th, 2019

14th workshop on TeV Physics, Nanjing

Qiang Li (Peking University)

CMS MC Simulation

(LHE –>) GEN–> SIM–> DIGI–> RECO



– **Hard process/Matrix Element generation**:
parton level, perturbative QCD

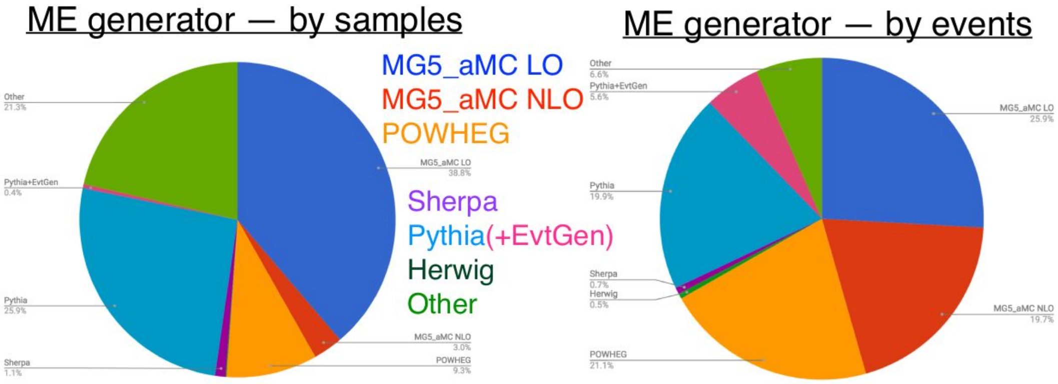
– **Parton Shower/Hadronization**:
QCD/QED emissions to a low scale,
Produces hadrons from QCD partons

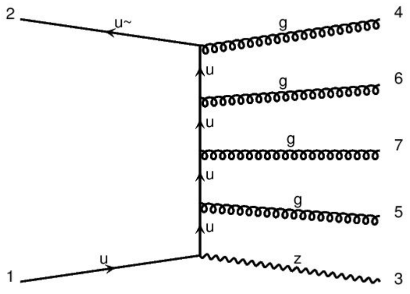
– *Multiple Parton Interaction*
– *Detector Simulation and Digitization*:
– *Reconstruction*:

Factorised approach may lead to uncertainties:
PDF, ME, "Tune" and PS, …
→ *In most cases they are relevant but sometimes forgotten.*

Generator usage in CMS

based on 2016 MC campaign





- **Multi-leg LO and NLO consistently matched to the parton shower**
  - **LO: Z+0/1/2/3/4 Jets**

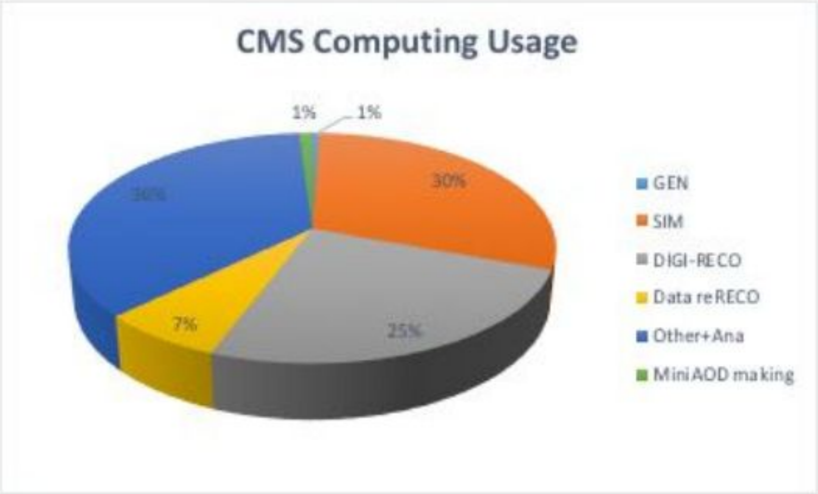
    Most commonly used in CMS: MG5_aMC@NLO+Pythia8 with MLM matching
    Most complex process up to 4 additional jets
  - **NLO TTbar+0/1/2 Jets** **O(10-100)s/event**

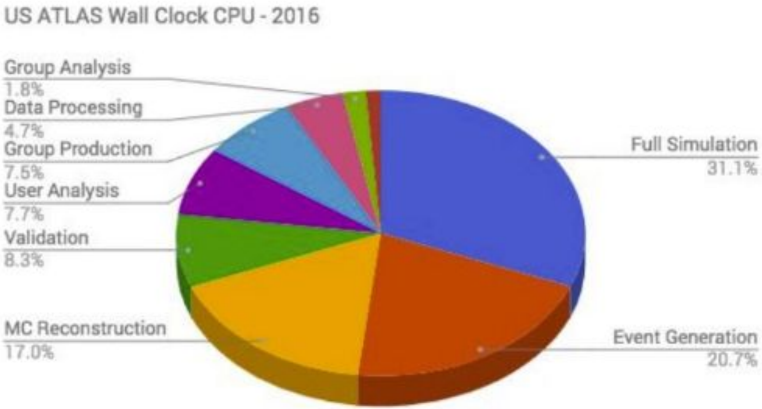
    Most commonly used in CMS: MG5_aMC+Pythia8 with FxFx merging
    Most complex process up to 2 additional jets at NLO.
- **For signal, NNLO+PS**

  POWHEG: MINLO_NNLOPS

  CMS HWW reweight the nominal signal to this one

Generators Can be Computationally Intensive





CMS usage from 2017, ATLAS went down to 14.3% in 2017

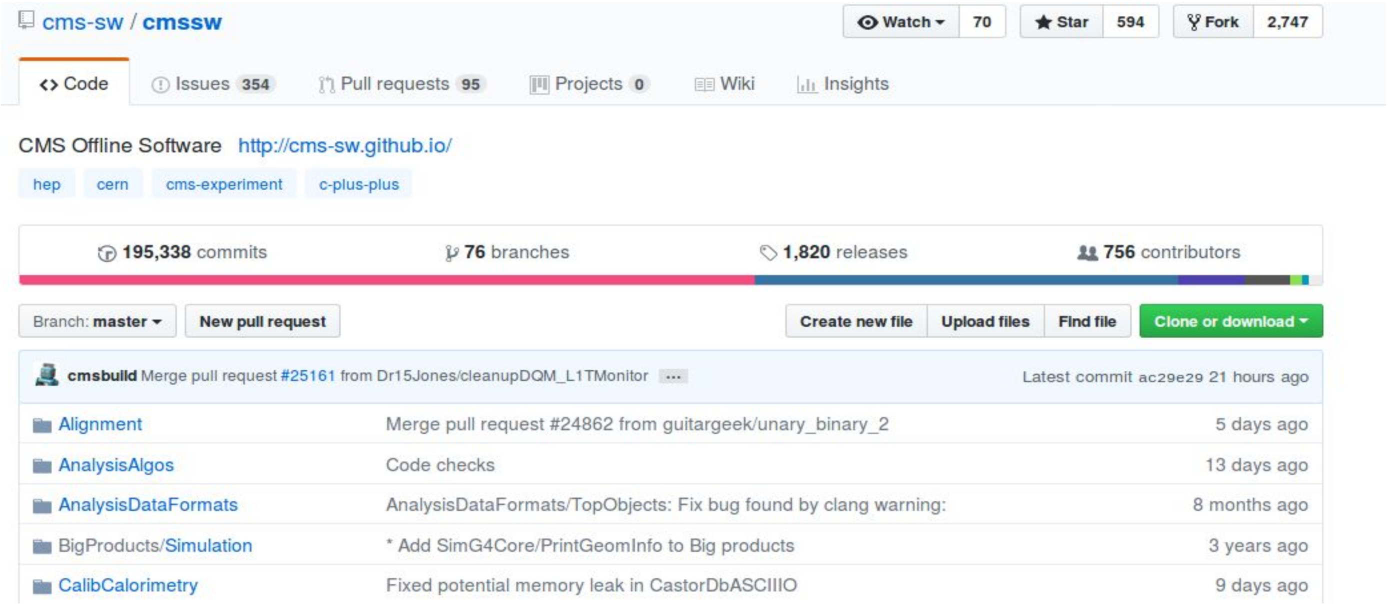
Elizabeth Sexton-Kennedy

- These values vary from year to year as analysis needs vary
- CMS uses more LO samples in this year and grid-pack configurations

Most HEP tools Typically executes 1 instruction at a time (per thread)
Much room for improvement.

CMS Software

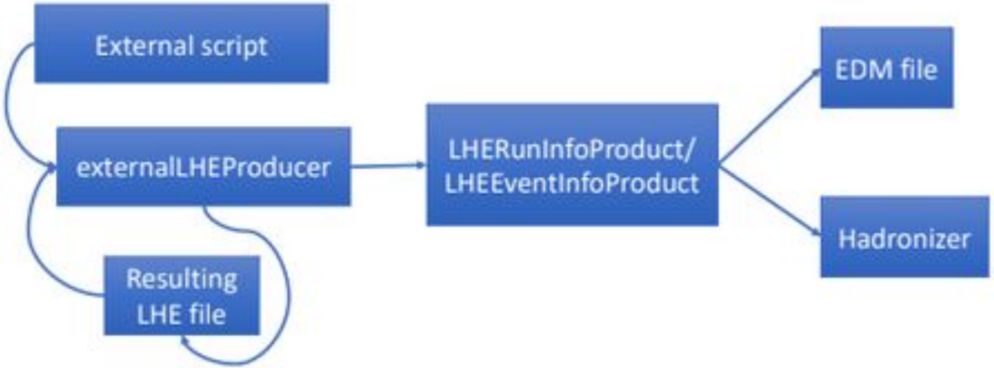
- **Main CMS software application: CMSSW**
  – Modular C++ application used for event generation, detector simulation, reconstruction, and analysis
- **Configuration of CMSSW runs steered with python configuration files**
- **Input and output with ROOT-based Event Data Model (EDM) files**
- **CMSSW links directly to many externals: Pythia, Sherpa**



ExternalLHEProducer and Gridpack

- **Compiling code on batch workers discouraged, long init time discouraged**
- **Pre-generated and compiled code** with initial phase space integration results stored in a tarball (with fixed model/run parameters) -> **Gridpack**

- Gridpack **placed in CVMFS** and accessed by remote jobs
- Gridpack location – a parameter of the **externalLHEProducer** module
- Input arguments: number of events, random number seed and **possibly nCPU**



Gridpack Production

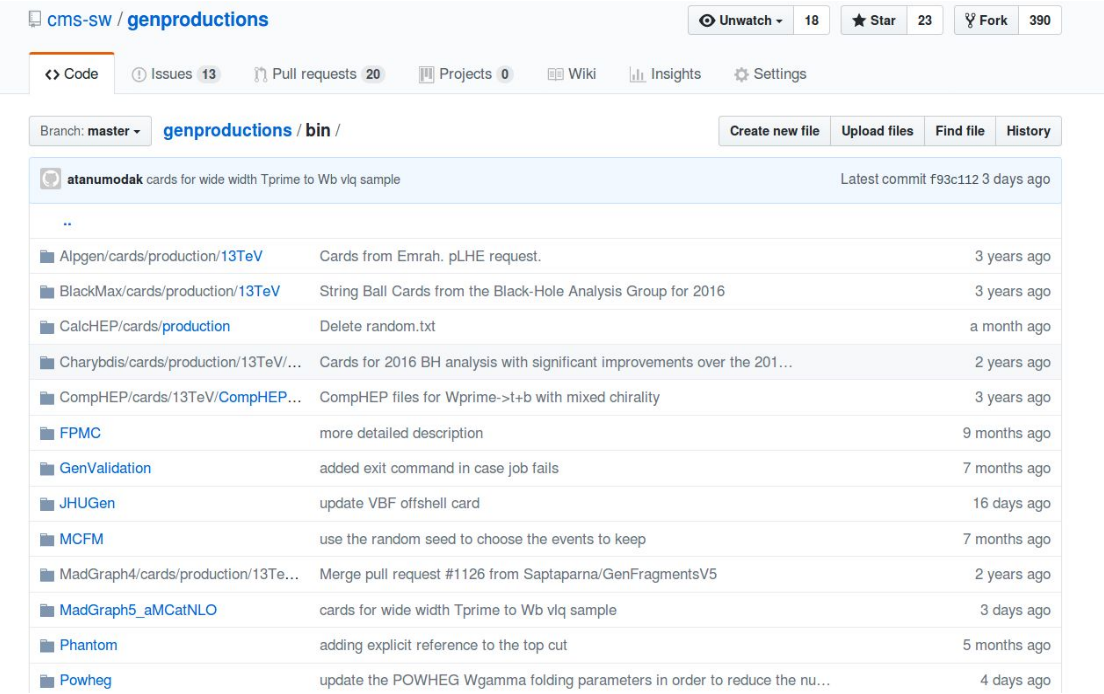
Gridpack (LHE) –> GEN–> SIM–> DIGI–> RECO

LSF / Condor / CMS-Connect (grid-like condor jobs using CMS Global Pool)

Gridpack size can be an issue (>500MB for the tarball and 5GB decompressed)

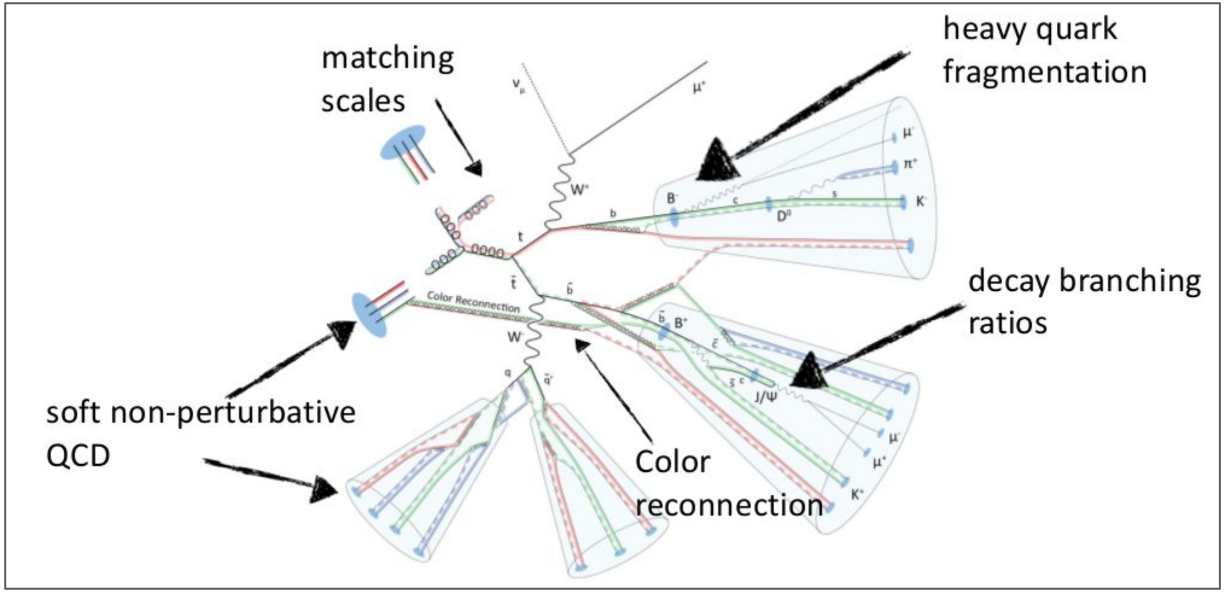
We maintain scripts
for all major generators
to produce gridpack tarballs

- **Madgraph** aMC@NLO
  - tt012FxFx ~72h@lxplus batch
  - DY01234MLM ~15h@cms-connect
- **POWHEG**
- **Sherpa, Herwig7** and others
  - tt01234 MEPS Sherpa
    - ~70h@cms-connect
    - ~O(100s)/event



Showering and Hadronization

- Pythia 8.226 default; Herwig++ replaced by Herwig7.
- Fragment settings different depend on Matrix Element
  - LO, NLO; MLM, FxFx matching/merging; POWHEG emission vetoing
- Pythia 8.240 integrated in CMS recently:
  - NLO shower DIRE, VINCIA;   Dipolerecoil option for better description on VBS



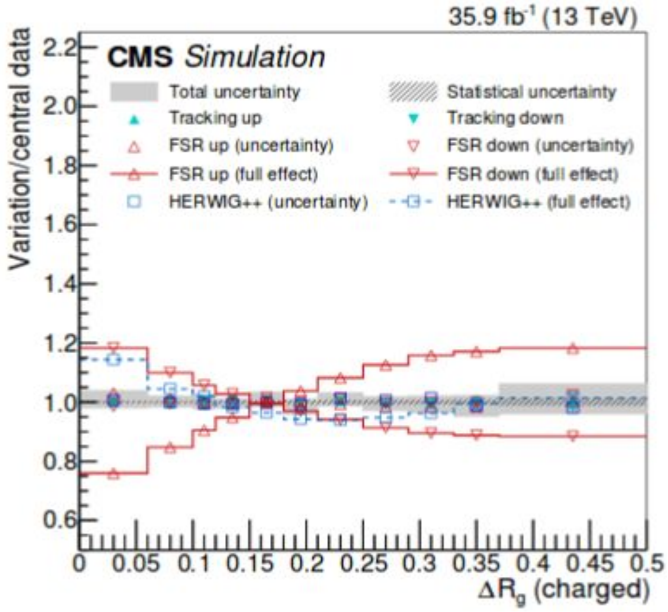
Showering and Hadronization

- Parton Shower Weights, Tune Variations etc included

$$(\text{ISR, FSR}) \otimes (\mu_R, \text{cNS}) \otimes (g \to gg,\ g \to q\bar{q},\ q \to qg,\ b/t \to b/t + g) \otimes (\text{up, down})$$

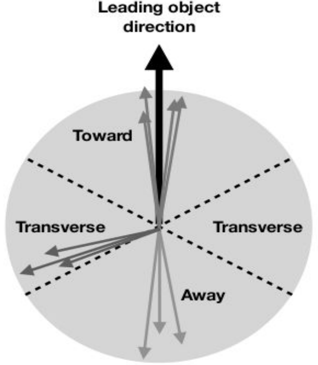
Source	Handle	Weights	Variation	Note/Reference	Dedicated studies
Shower scales	ISR scale (SpaceShower:renormMultFac) FSR scale (TimeShower:renormMultFac)	YES	0.5-2.0 0.5-2.0	FSR variations can be scaled down by √2 from LEP	TOP-15-011, TOP-16-021 TOP-17-13, TOP-17-015, ...
ME-PS Matching	hdamp	No	hdamp=1.58m_t +0.66-0.59 m_t	see TOP-16-021	Starting scale variations for MG5_aMC@NLO
Soft QCD	UE parameters	YES	UE tune up/down	See TOP-16-021 MPI & CR strength doesn't affect resonance decays	TOP-17-015 GEN-17-001
Color reconnection (odd clusters)	MPI based, QCD-inspired, gluon move	No	different models	CR affecting resonance decays	TOP-17-13, TOP-17-015
Fragmentation	momentum transfer from the b-quark to the B hadron: x_b=p_T(B)/p_T(b-jet)	YES	Vary Bower-Lund parameter within uncertainties from LEP/SLD fits	see TOP-16-022 (re-weight x_b)	
Flavor response/ hadronization	Pythia vs Herwig	No	Vary the JES independently per flavour for light, g, c, b.		
Decay tables	B semi-leptonic BR	YES	vary semileptonic BR +0.77%/-0.45%	re-weight the fraction of semi-leptonic b jets by the PDG values (scale Λ_b to match PDG)	

CMS: Jet substructure in ttbar events at 13 TeV (2016)

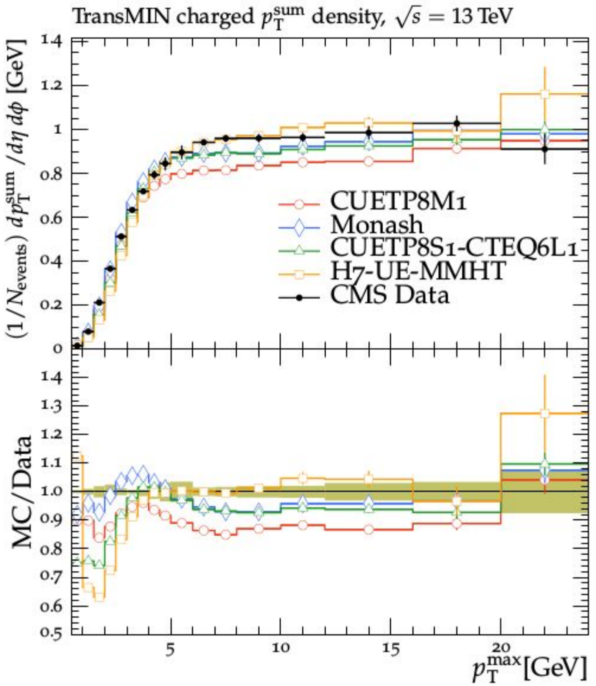


angle between the groomed subjets

MC Tuning: CUETP8M1 Tune



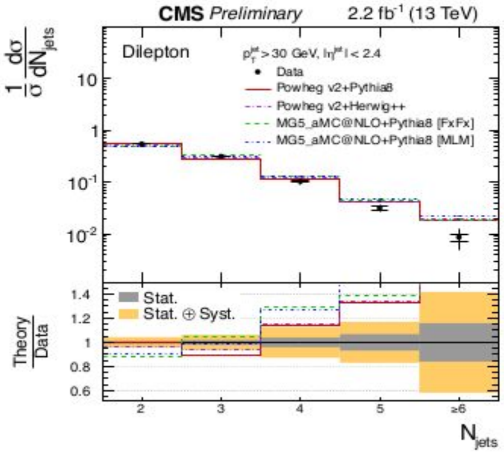
Until 2017 analyses (except 2016 ttbar), **Pythia8 CUETP8M1 tune** [EPJC 76 (2016) 155] based on the **Monash** tune was used. Fitting MPI energy dependence parameters to UE data @sqrt(s) = 0.9, 1.96 & 7 TeV



- α_s and shower parameters kept as in Monash → $\alpha_s^{ISR/FSR}$=0.1365 despite the prefered values of 0.130 in LO and 0.118 in NLO matrix elements/ PDF sets.
  - α_s^{FSR} in Monash → by fitting Pythia8 predictions to LEP event shape measurements and α_s^{ISR} is just assumed to be the same as α_s^{FSR}.
  - α_s^{MPI} = 0.130 set to the value prefered in the LO PDF set.
- Revisited the shower parameters
  - Starting from parton shower in ttbar events → CUETP8M2T4 tune.
  - Using a NNLO PDF set in PS → CP5 (and CP0-4 tunes).

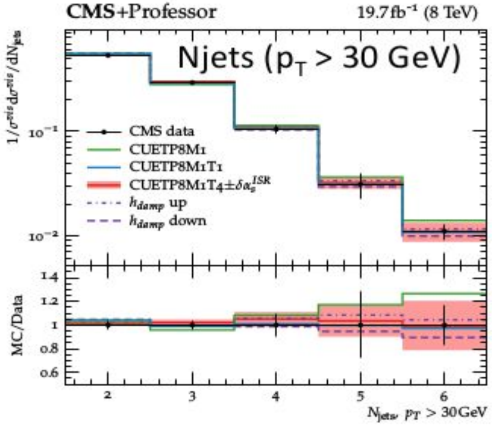
CUETP8M1 does not describe well the central values of 13TeV data

MC Tuning: CUETP8M2T4 Tune [TOP-16-021]



- Predictions overshoot the data for large jet multiplicities when out of the box parameters are used (in Monash-based tunes: α_s^{ISR}=0.1365)
- Effect also observed with 8 TeV data.

CMS-PAS-TOP-12-041 (dilepton 8 TeV),
CMS-PAS-TOP-16-011 (dilepton 13 TeV),
CMS-PAS-TOP-16-008 (l+jets 13 TeV)



CMS-PAS-TOP-16-021

Tune α_s^{ISR} using 8 TeV ttbar Njets and jet pT data —>

$$\alpha_s^{ISR} = 0.1108^{+0.0145}_{-0.0142}$$
$$h_{damp} = 1.581^{+0.658}_{-0.585} \times m_t$$

with **SpaceShowerRapidityOrdering=on** *(special care of options needed for the emissions produced by the PS)*

==> Significantly lower shower α_s cures the overshoot of CUETP8M1 at high jet multiplicities.
==> UE and min-bias are described better
==> POWHEG+PYTHIA8: generally consistent with data, with residual differences covered by theory uncertainties. arXiv:1803.0399

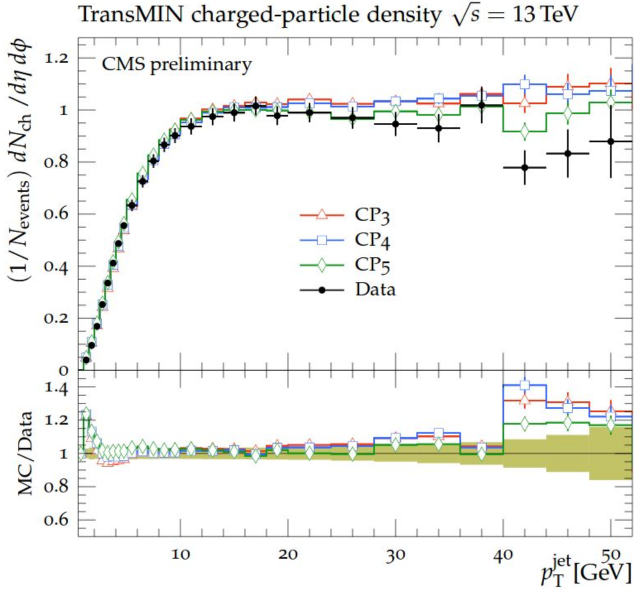
MC Tuning: CPX Tune

arXiv:1903.12179

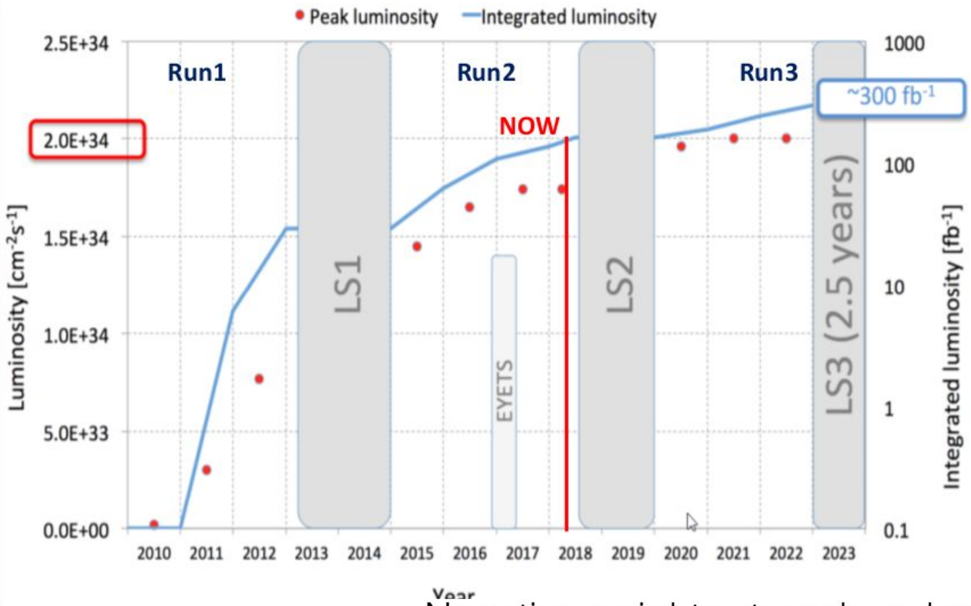
- **First CMS tune with 13 TeV LHC data**
- **Match PDF and αs in the PS and in the ME.**
  - PYTHIA tunes are mostly based on LO PDFs.
  - Sherpa tunes are based on NNLO PDFs.
  - HERWIG7 provide tunes based on NLO PDFs (MPI still based on LO).
- **Test the effect of using different PDF orders of NNPDF sets in PYTHIA8**
- CP5 with NNPDF3.1NNLO is the default for 2017 and 2018 MC productions

- CP1: NNPDF3.1 LO (α s =0.130)
- CP2: NNPDF3.1 LO (α s =0.130)
- CP3: NNPDF3.1 NLO (α s =0.118)
- CP4: NNPDF3.1 NLO (α s =0.118)
- CP5: NNPDF3.1 NNLO (α s =0.118)

PYTHIA8 parameter	CP1	CP2	
PDF Set	NNPDF3.1 LO	NNPDF3.1 LO	Fixed inputs
$\alpha_S(m_Z)$	0.130	0.130	
SpaceShower:rapidityOrder	off	off	
MultipartonInteractions:EcmRef [GeV]	7000	7000	
$\alpha_S^{ISR}(m_Z)$ value/order	0.1365/LO	0.130/LO	
$\alpha_S^{FSR}(m_Z)$ value/order	0.1365/LO	0.130/LO	
$\alpha_S^{MPI}(m_Z)$ value/order	0.130/LO	0.130/LO	
$\alpha_S^{ME}(m_Z)$ value/order	0.130/LO	0.130/LO	
MultipartonInteractions:pT0Ref [GeV]	2.4	2.3	Fitted parameters
MultipartonInteractions:ecmPow	0.15	0.14	
MultipartonInteractions:coreRadius	0.54	0.38	
MultipartonInteractions:coreFraction	0.68	0.33	
ColorReconnection:range	2.63	2.32	
χ^2/dof	0.89	0.54	



Beyond Run2/3 and Future



Need to "fight" against conflicting requirements:

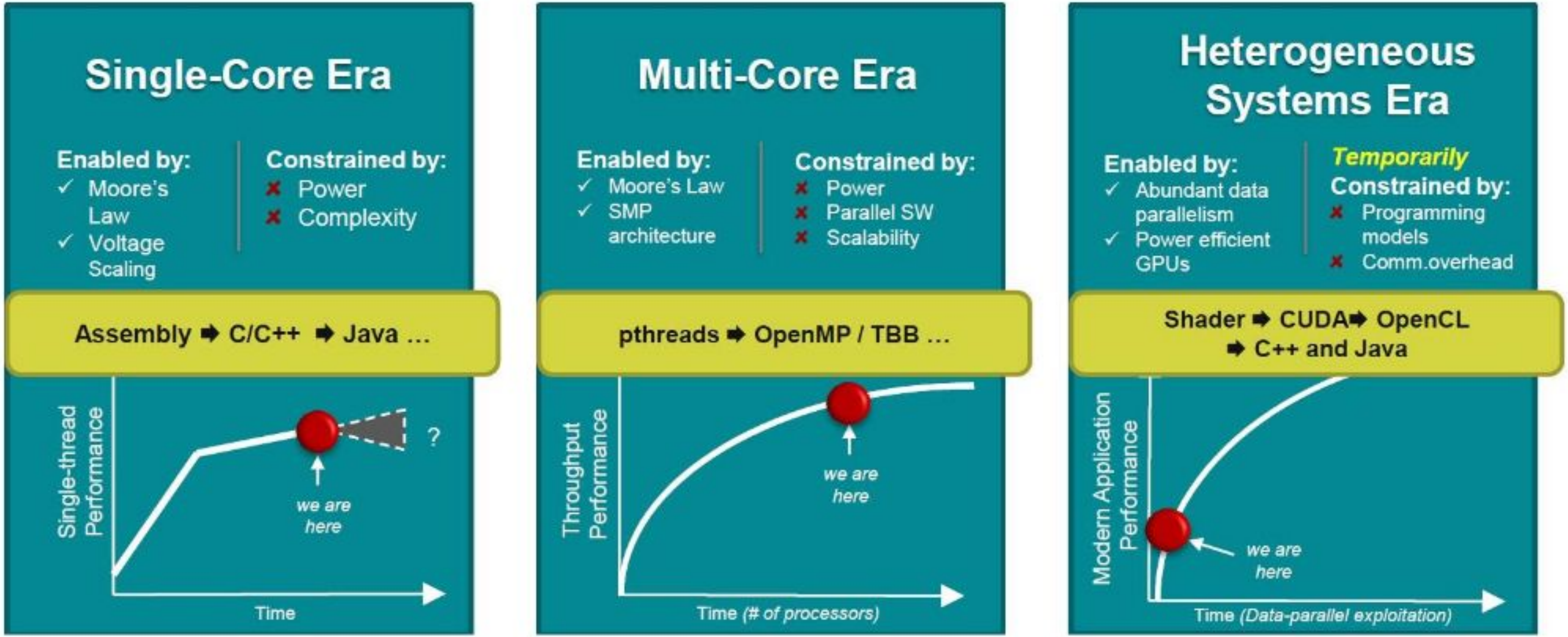
– (Much) larger datasets
– Increased measurement precision
– Need for alternative samples for systematics
– Flattening of computing resources (both cpu and disk space)

- Negative weights strongly reduce statistical power
- For weighted events w_i, effective events N_{eff} for fraction of negative weights f:

$$N_{eff} = \frac{(\sum_i w_i)^2}{\sum w_i^2} = N(1-2f)^2$$

- for 35% negative weights (common at for high jet-mulitplicity/ high pt)
  $\Longrightarrow$ 9% effective events compared to $w_i = 1$

The Future : Heterogeneous Architecture



https://opensourceforu.com/2016/12/how-heterogeneous-systems-evolved-and-the-challenges-going-forward/

The computing available in 2026 will be heterogeneous and highly concurrent.

different types of compute units and interconnects

HSF and Generator Workshop

The HEP Software Foundation facilitates cooperation and common efforts in High Energy Physics software and computing internationally.
Community White Paper: summarising R&D in a variety of technical areas for HEP Software and Computing

HEP Software Foundation

Physics Event Generator Computing Workshop

26 Nov 2018, 09:00 → 28 Nov 2018, 18:00 Europe/Zurich

4-3-006 - TH Conference Room (CERN)

Goals of this workshop:

○ Identify the most crucial areas for technical improvements to the generators used by the experiments.

○ Define a programme of work that can be used to attract investment in these technical areas, aiming to have software engineers who can work together with the generator authors.

○ Identify ways of making new theoretical advances easier to implement in a computationally efficient way.

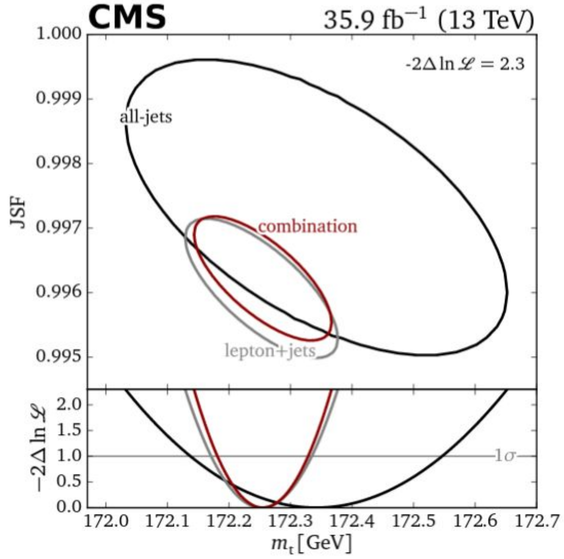
Thanks

MC Modelling: b jet and Color-Connection ...

- The Bowler–Lund fragmentation function varied within uncertainties determined by the ALEPH and DELPHI
- Alternatively, the Peterson fragmentation function is used to derive additional uncertainty.
- Semileptonic b hadron branching fraction, varied by −0.45% and+0.77%, motivated by measurements of B0/B+decays and their corresponding uncertainties

	2D		1D	hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
b jet modeling (quad. sum)	0.09	0.0	0.09	0.09	0.0
– b frag. Bowler–Lund	−0.07	0.0	−0.07	−0.07	0.0
– b frag. Peterson	−0.05	0.0	−0.04	−0.05	0.0
– semileptonic b hadron decays	−0.03	0.0	−0.03	−0.03	0.0
PDF	0.01	0.0	0.01	0.01	0.0
Ren. and fact. scales	0.05	0.0	0.04	0.04	0.0
ME/PS matching	$+0.32 \pm 0.20$	−0.3	-0.05 ± 0.14	$+0.24 \pm 0.18$	−0.2
ISR PS scale	$+0.17 \pm 0.17$	−0.2	$+0.13 \pm 0.12$	$+0.12 \pm 0.14$	−0.1
FSR PS scale	$+0.22 \pm 0.12$	−0.2	$+0.11 \pm 0.08$	$+0.18 \pm 0.11$	−0.1
Top quark p_T	+0.03	0.0	+0.02	+0.03	0.0
Underlying event	$+0.16 \pm 0.19$	−0.3	-0.07 ± 0.14	$+0.10 \pm 0.17$	−0.2
Early resonance decays	$+0.02 \pm 0.28$	+0.4	$+0.38 \pm 0.19$	$+0.13 \pm 0.24$	+0.3
CR modeling (max. shift)	$+0.41 \pm 0.29$	−0.4	-0.43 ± 0.20	-0.36 ± 0.25	−0.3
– "gluon move" (ERD on)	$+0.41 \pm 0.29$	−0.4	$+0.10 \pm 0.20$	$+0.32 \pm 0.25$	−0.3
– "QCD inspired" (ERD on)	-0.32 ± 0.29	−0.1	-0.43 ± 0.20	-0.36 ± 0.25	−0.1
Total systematic	0.81	0.9	1.03	0.70	0.7
Statistical (expected)	0.21	0.2	0.16	0.20	0.1
Total (expected)	0.83	0.9	1.04	0.72	0.7

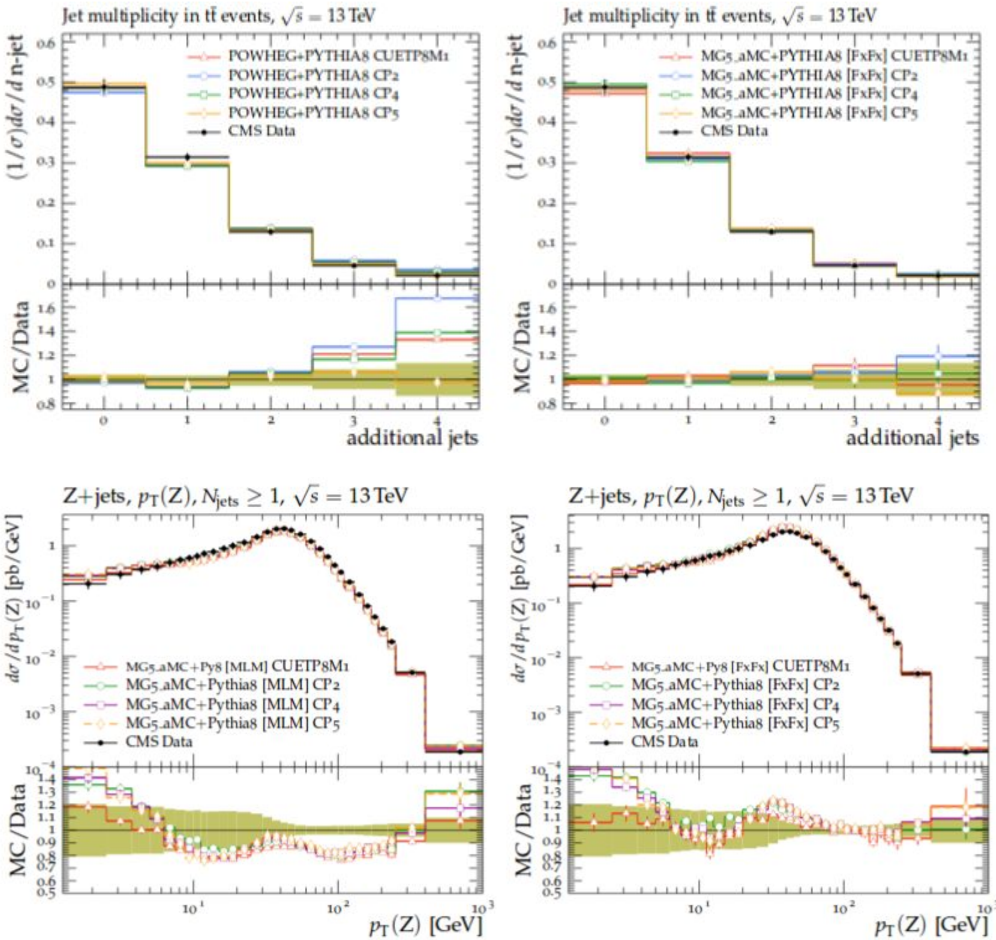
[Top quark mass from ttbar fully hadronic (2016)]



$$m_t^{hyb} = 172.26 \pm 0.07\,(\text{stat+JSF}) \pm 0.61\,(\text{syst})\,\text{GeV}$$

MC Tuning: CPX Tune

arXiv:1903.12179



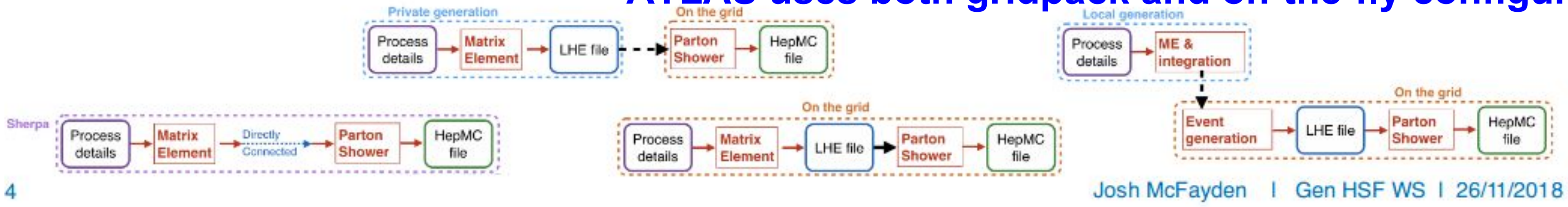
Predictions from the new Tunes based on higher-order PDF sets, interfacing with higher-order and multileg matrix element generators, such as POWHEG and MG5_aMC, are shown to give a reliable description of observables measured in multijet final states, Drell–Yan, and top quark production processes

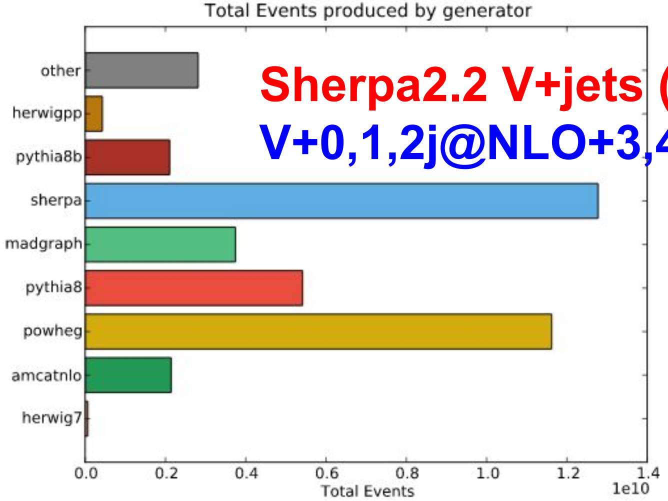
ATLAS Generator Usage

Josh McFayden

- Various possible configurations result in many different running modes
  - Also requires flexibility in the software integration and production system configuration.

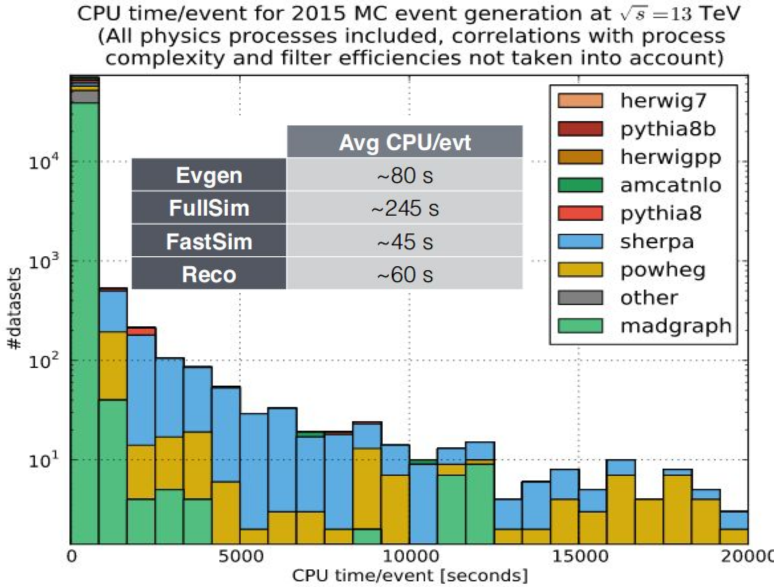
ATLAS uses both gridpack and on-the-fly configurations





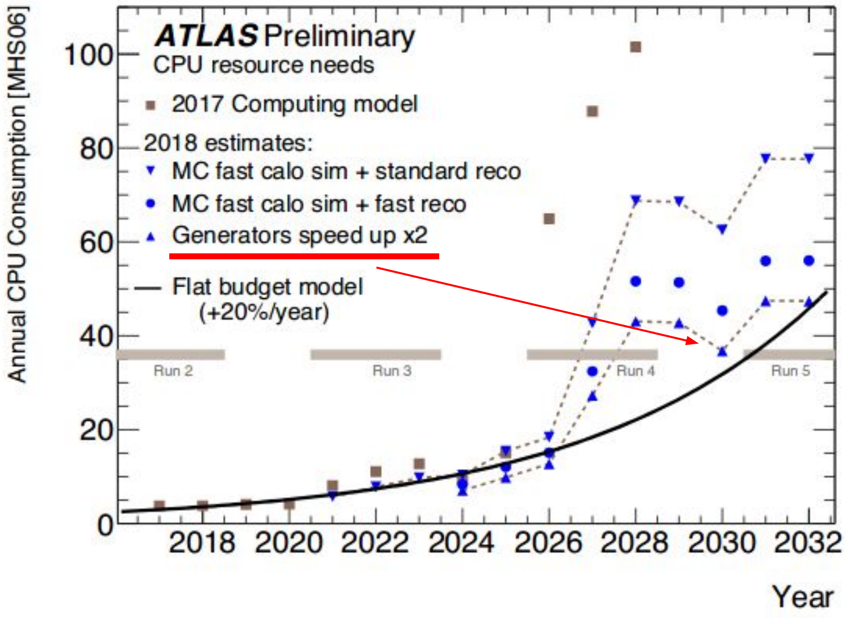
Sherpa2.2 V+jets (3.2B)

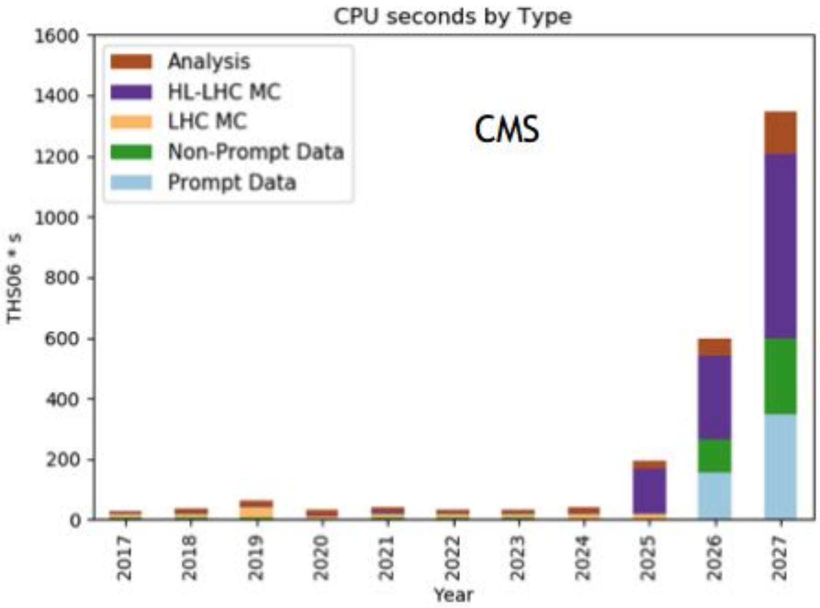
V+0,1,2j@NLO+3,4j@LO



	Avg CPU/evt
Evgen	~80 s
FullSim	~245 s
FastSim	~45 s
Reco	~60 s

Motivation for Generator upgrade





- We are OFF by ~5x on CPU power when considering Moore's law
- HL-LHC salvation will come from software improvements, not from hardware

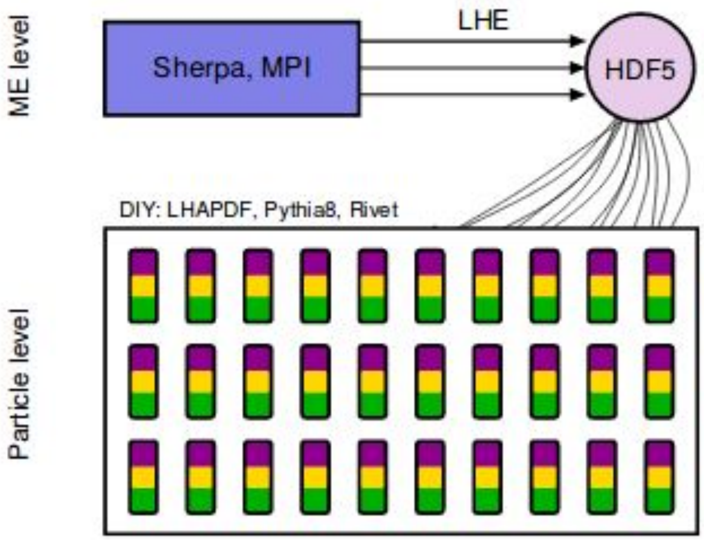
Elizabeth Sexton-Kennedy

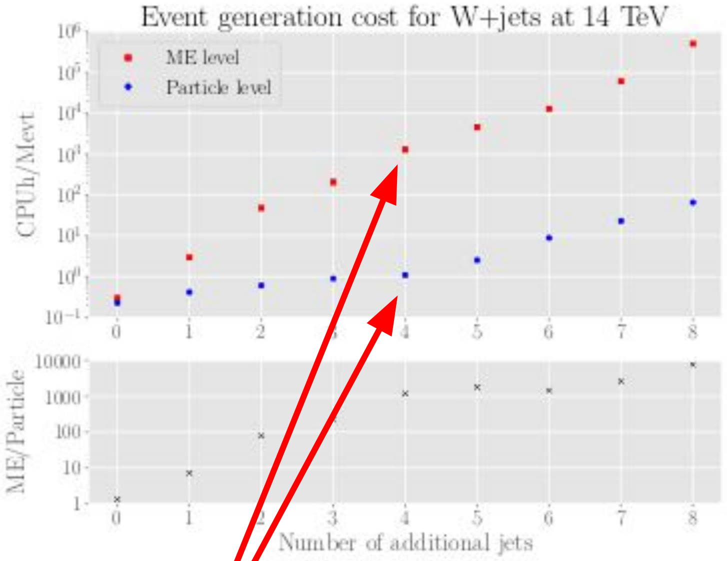
Highlight of recent effort towards HPC

Holger Schulz

High-multiplicity multi-jet merging with HPC technology   W+up to 8 Jets

1. HDF5 (Hierarchical Data Format) storage for ME events: The CPU expensive part of the simulation is stored in a parton-shower independent format.
2. Particle level and merging with Pythia with ASCR's (Advanced Scientific Computing Research) DIY, which does all the low-level MPI communication. Particle level run-time up to 4 orders of magnitude faster than ME.





For comparison, CMS WJetsToLNu_TuneCUETP8M1_13TeV-madgraphMLM-pythia8 (W+0/1/2/3/4Jets) time/evnet~16s, then 1M events->4000hr (ME+PS)