Event Generators in CMS

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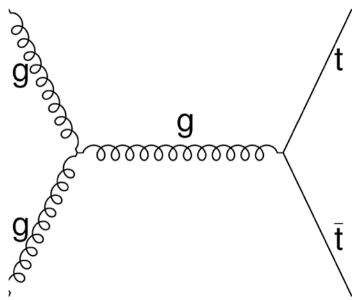
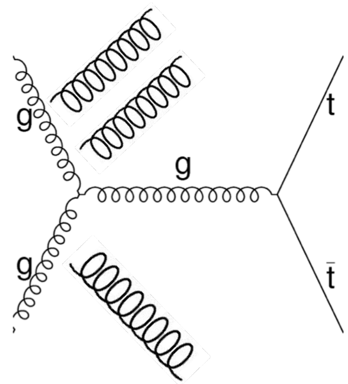
Event Modeling in CMS

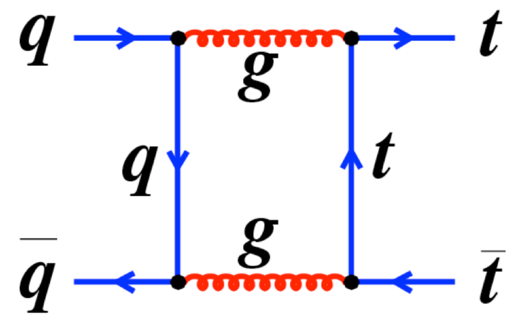
- Most measurements at hadron colliders rely on large scale Monte Carlo production.
  - Understanding and interpretation of data – test SM with more precise and complex calculations.
  - Many cases in which irreducible backgrounds extrapolated to signal phase-space regions for new physics searches through predictions using MC simulations.
- At the LHC, most events are accompanied by additional hard jets from initial or final state QCD radiation.
  - SM measurements
  - Many searches select or veto these extra jets.

→ NLO/multi-leg/merged MC generators needed for high accuracy predictions for the LHC

Matrix Element Generation



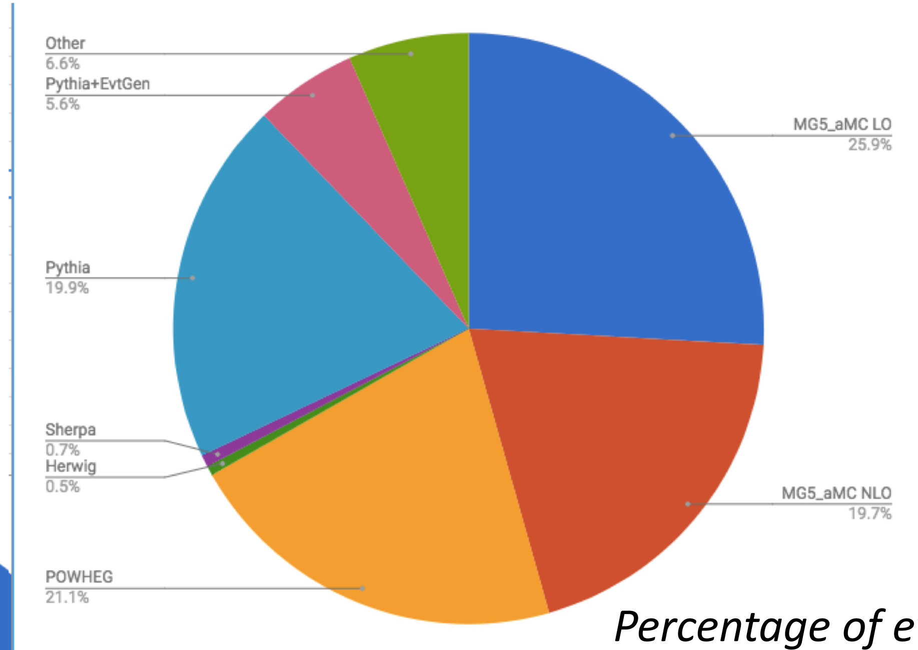




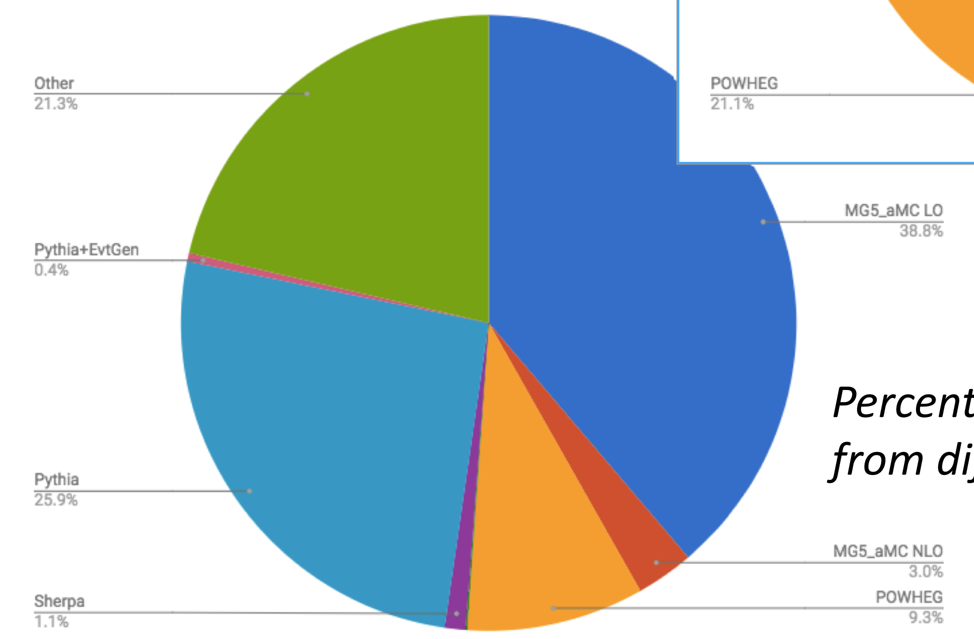
- Multi-leg LO and NLO consistently matched to the parton shower
- LO: Most commonly used in CMS: MG5_aMC@NLO+Pythia8 with MLM matching
  - Most complex process up to 4 additional jets
- NLO:
  - Most commonly used in CMS: MG5_aMC+Pythia8 with FxFx merging
    - Most complex process up to 2 additional jets at NLO.
- And POWHEG

Standard Setups for CMS Monte Carlo at Run II

→ *Approximate and based on 2016 MC campaign*

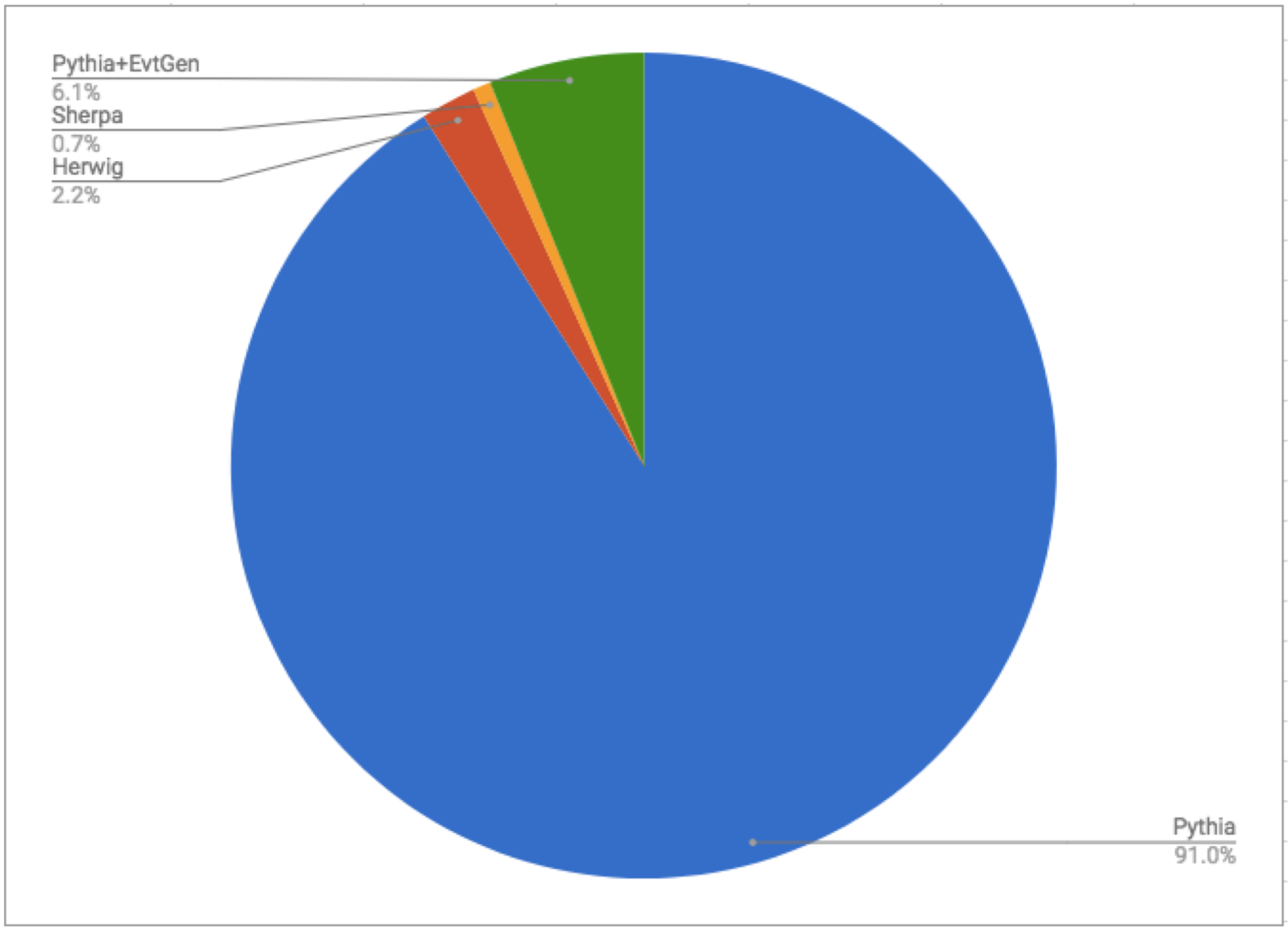


Percentage of events from different generators



Percentage of samples from different generators

Standard Setups for CMS Monte Carlo at Run II – parton shower



→ *Percentage of events from different generators*

→ *Approximate and based on 2016 MC campaign*

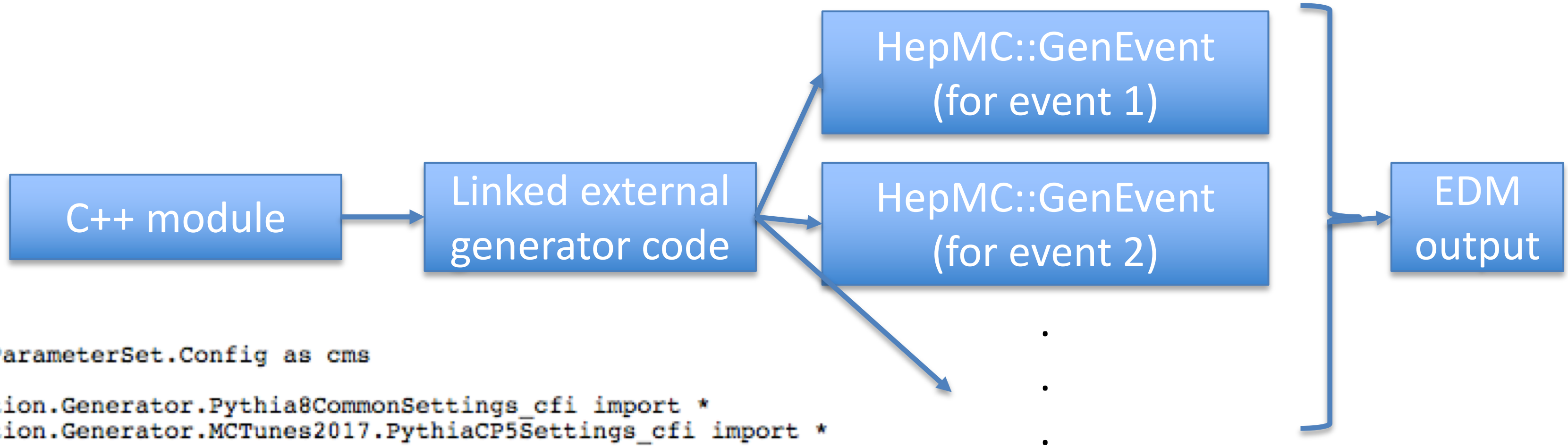
CMS Software

- Modular C++ application used for event generation, detector simulation, reconstruction and analysis
- Steered with python-based configuration files
- Input/output: root-based EDM files
  - Store run-,lumi-section-, and event-level data
- Links directly to « externals »
  - Externally maintained fortran, python, C, C++, … codes (e.g. parton shower codes Pythia, Herwig, …)
  - External code versions locked to CMSSW release

CMS Central Monte Carlo Sample Production

- Python-based tools for submission of CMSSW jobs to grid resources
- Similar mechanism available for users to submit analysis jobs
- CMSSW + externals available on worker nodes through CVMFS (CERN Virtual Machine File System)
    - distributed disk system for providing code and libraries to interactive nodes and grid worldwide.

CMS Event Generation



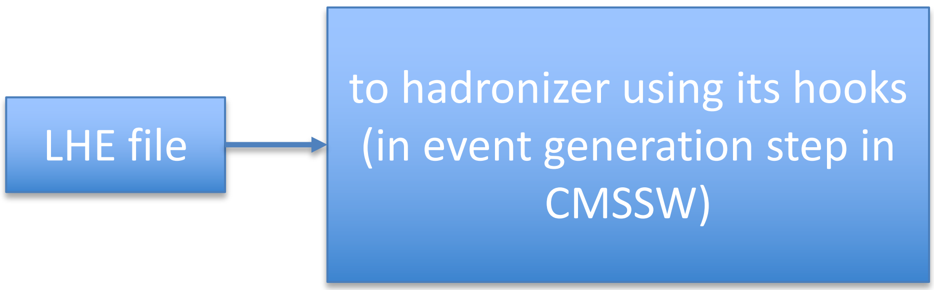

```
import FWCore.ParameterSet.Config as cms

from Configuration.Generator.Pythia8CommonSettings_cfi import *
from Configuration.Generator.MCTunes2017.PythiaCP5Settings_cfi import *

generator = cms.EDFilter("Pythia8GeneratorFilter",
        maxEventsToPrint = cms.untracked.int32(1),
        pythiaPylistVerbosity = cms.untracked.int32(1),
        filterEfficiency = cms.untracked.double(1.0),
        pythiaHepMCVerbosity = cms.untracked.bool(False),
        comEnergy = cms.double(13000.0),

        crossSection = cms.untracked.double(1.83741e+09),

        PythiaParameters = cms.PSet(
            pythia8CommonSettingsBlock,
            pythia8CP5SettingsBlock,
            processParameters = cms.vstring(
                        'HardQCD:all = on',
                        'PhaseSpace:pTHatMin = 15  ',
                        'PhaseSpace:pTHatMax = 30  ',
            ),
            parameterSets = cms.vstring('pythia8CommonSettings',
                                        'pythia8CP5Settings',
                                        'processParameters',
                                        )
        )
)

configurationMetadata = cms.untracked.PSet(
    version = cms.untracked.string('\$Revision$'),
    name = cms.untracked.string('\$Source$'),
    annotation = cms.untracked.string('QCD pthat 15to30 GeV, 13 TeV, TuneCP5')
)
```

Generator configuration controlled by CMSSW python configuration.

🡸 Example fragment

CMSSW: LHE Input

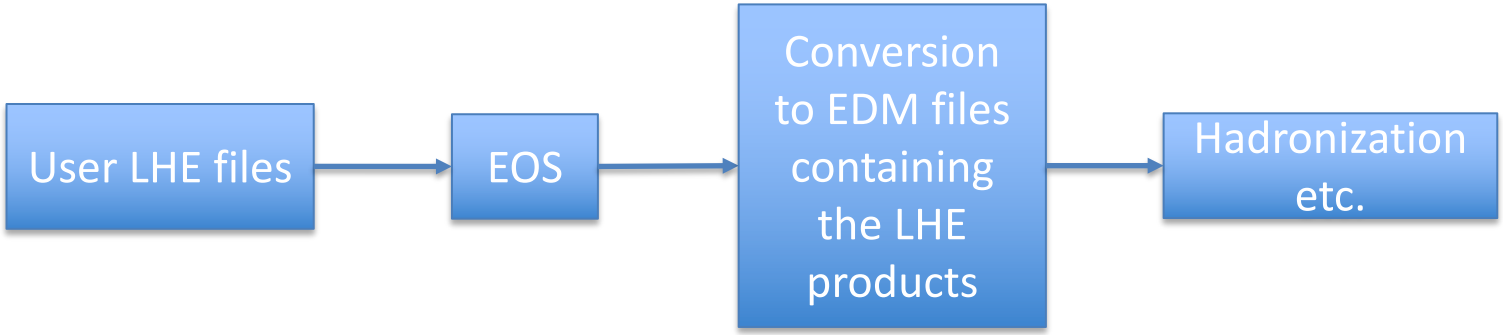
- CMS maintains a custom LHE parser to have uniform hadronizer-independent storage and access to LHE info.



e.g. Pythia8::LHAup, the base class for initialization and event information from an external parton-level generator.

LHE Input for Central Production

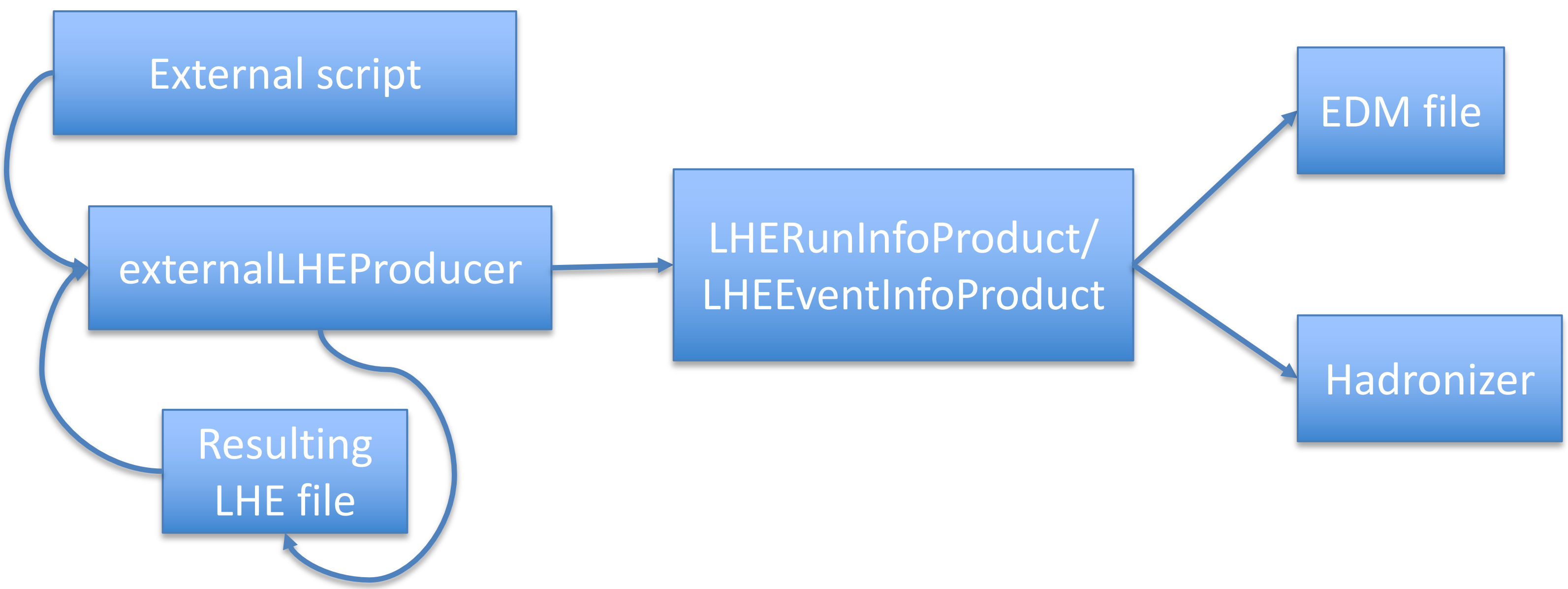
- ascii LHE input not ideal for central production
  - Metadata not automatically available in data management system, skipping of events inefficient, …
- Can use privately produced LHE files for central production
  - but pLHE is STRONGLY DISCOURAGED unless no other solution is possible



Major issues with large sets of LHE files: disk space, file corruption, …

Central Production of LHE Events

- MG5_aMC, Powheg, … not compatible with our computing model, i.e. they can't be called from CMSSW.
  - Solution: C++ CMSSW externalLHEProducer module



Central Production of LHE Events

- LHE generator code difficult to include as an external, since each process requires dedicated and sometimes dynamically generated libraries.
  - Solution: gridpacks

```
externalLHEProducer = cms.EDProducer("ExternalLHEProducer",
    args = cms.vstring('/cvmfs/cms.cern.ch/phys_generator/gridpacks/2017/13TeV/madgraph/V5_2.4.2/ttGamma_Dilept
/ttGamma_Dilept_5f_ckm_LO_slc6_amd64_gcc481_CMSSW_7_1_30_tarball.tar.xz'),
    nEvents = cms.untracked.uint32(5000),
    numberOfParameters = cms.uint32(1),
    outputFile = cms.string('cmsgrid_final.lhe'),
    scriptName = cms.FileInPath('GeneratorInterface/LHEInterface/data/run_generic_tarball_cvmfs.sh')
)
```

Gridpacks

- Pre-generated and compiled code with initial phase space integration results stored in a tarball (with fixed model/run parameters).
- Contribution from each subprocess is calculated with high precision in the creation of the gridpack. Then the gridpack jobs *randomly include subprocesses based on their relative contributions* to the total cross section.
- Once the gridpack has been generated the number of events and the random number seed are the only input variables.
- Placed in CVMFS and accessed by remote jobs
- Gridpack location – a parameter of the externalLHEProducer module

```
process.externalLHEProducer = cms.EDProducer("ExternalLHEProducer",
    args = cms.vstring('/cvmfs/cms.cern.ch/phys_generator/gridpacks/slc6_amd64_gcc481/14TeV/madgraph/V5_2.4
.2/ttGamma_Dilept_5f_ckm_LO/v1/ttGamma_Dilept_5f_ckm_LO_tarball.tar.xz','false', 'slc6_amd64_gcc481','CMSSW
_7_1_28'),
    nEvents = cms.untracked.uint32(10),
    numberOfParameters = cms.uint32(4),
    outputFile = cms.string('cmsgrid_final.lhe'),
    scriptName = cms.FileInPath('GeneratorInterface/LHEInterface/data/run_generic_tarball_cvmfs.sh')
)
```

Gridpacks

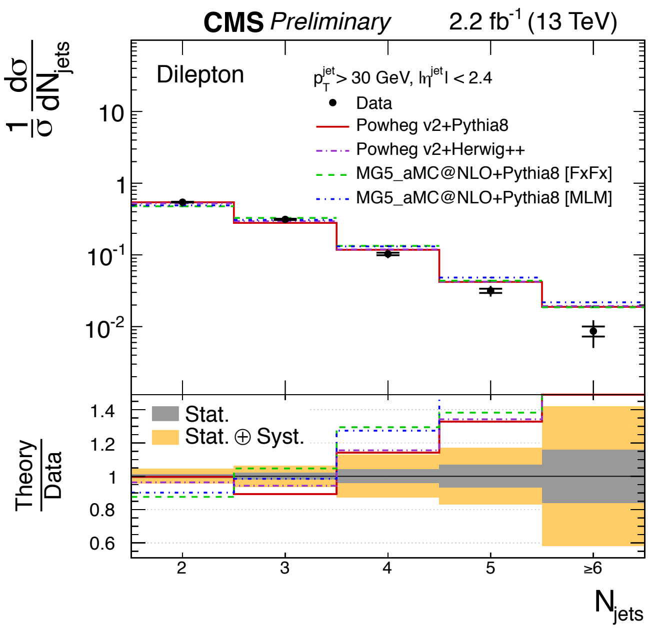
- CMSSW version used to produce the gridpacks from the one used to produce the GEN-SIM can be decoupled → Newly produced gridpacks can be used for previous campaigns (provided, e.g., PDFs match)
- CMS maintains scripts for MG5_aMC@NLO (for LO and NLO), Powheg, Sherpa, JHUGen to produce gridpacks.
- Gridpack generation rely heavily on LSF or HTCondor at specific sites, i.e., full CMS computing resources not accessible.
- To allow users to CMS Global Pool → CMS Connect, a service to provide local-like CMS analysis cluster capability to institutions for non-CRAB workflow jobs.

Standard Setups for CMS Monte Carlo at Run II – Pythia8 Tunes

- Until 2017 analyses (except 2016 ttbar), CUETP8M1 tune [*] based on the Monash tune was used.
  - 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).

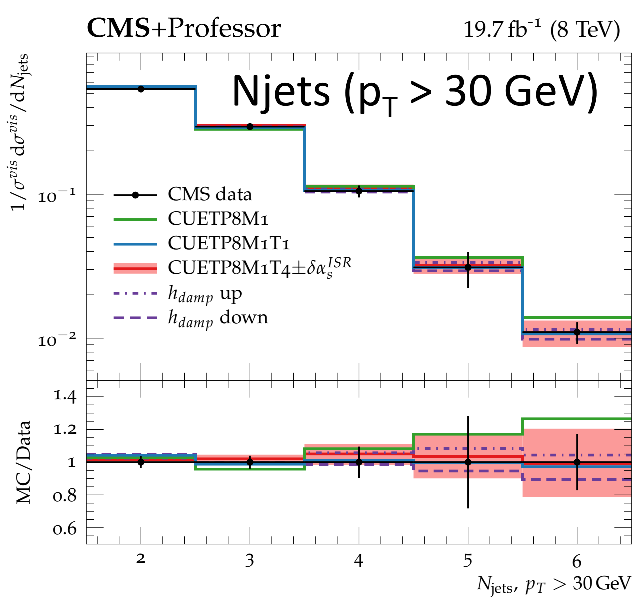
[*] CMS Collaboration, Eur. Phys. J. C 76 (2016) 155

CUETP8M2T4 Event 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 —>

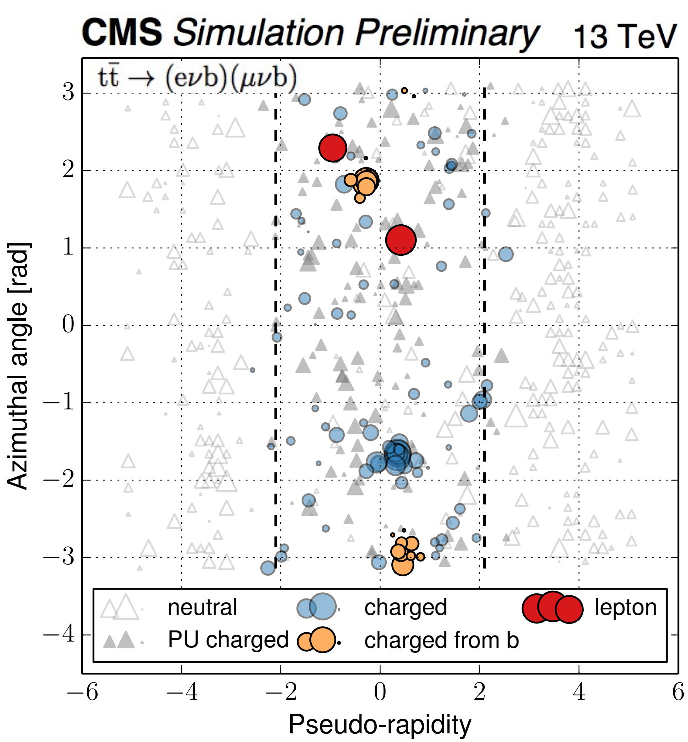
$$\alpha_s^{ISR} = 0.1108^{+0.0145}_{-0.0142}$$
$$h_{damp} = 1.581^{+0.658}_{-0.585} \times m_t$$

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

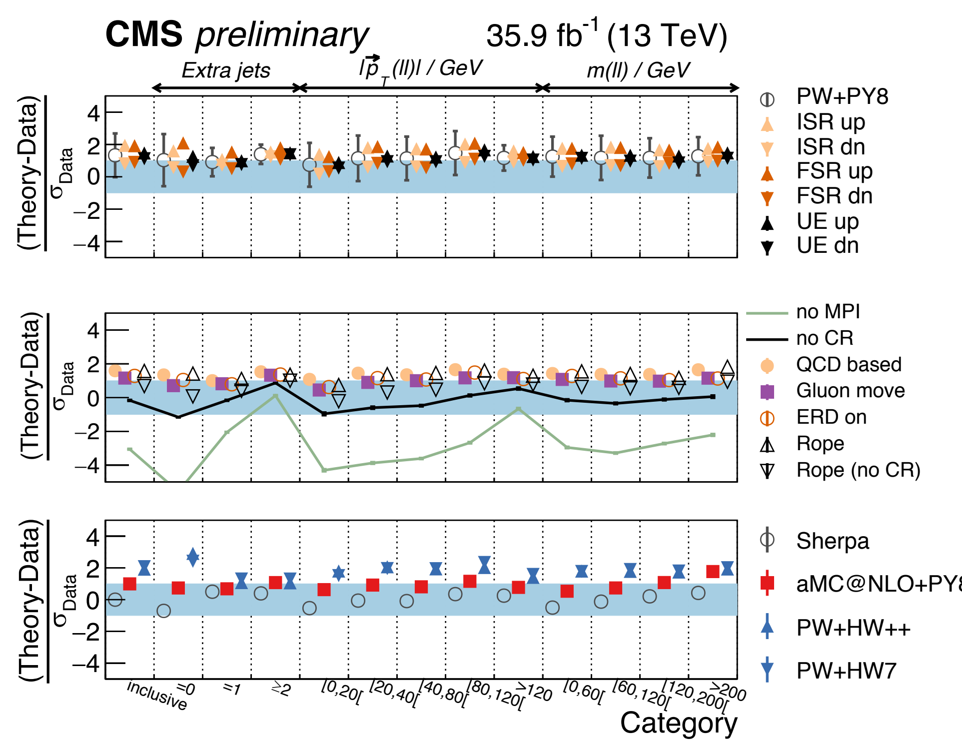
==> Significantly lower shower α_s cures the overshoot of CUETP8M1 at high jet multiplicities.
==> UE and min-bias are described better
==> POWHEG+PYTHIA8: generally consistent with data, with residual differences covered by theory uncertainties. arXiv:1803.0399

Underlying Event in ttbar Events [TOP-17-015]

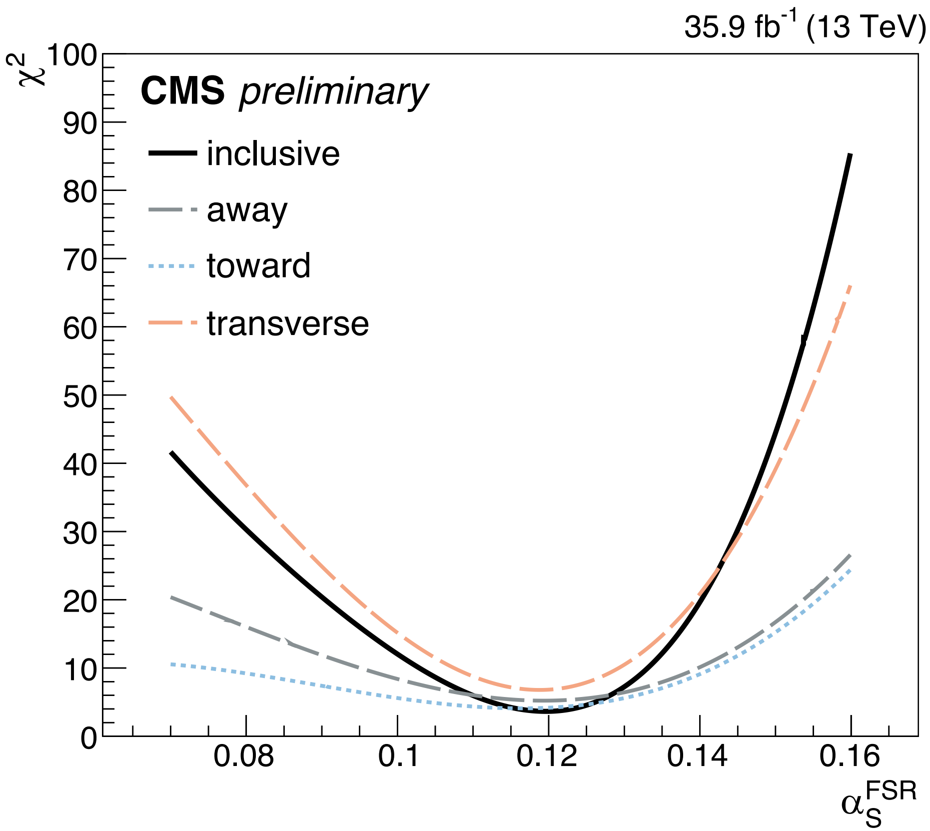
- Observables/categories enhance sensitivity to the modeling of MPI, color reconnection, and $\alpha_s^{FSR}(M_Z)$ in Pythia8.
  - Among the parameters with the largest impact on the ttbar modeling.
  - Data disfavor default settings in HERWIG++, HERWIG7, and SHERPA → Need tuning.
  - Choice of NLO ME generator (Powheg or MG5_aMC@NLO[FxFx] + Pythia8) does not impact the UE in ttbar.



$$< \Sigma p_T > \quad [GeV]$$



Underlying Event in ttbar Events [TOP-17-015]



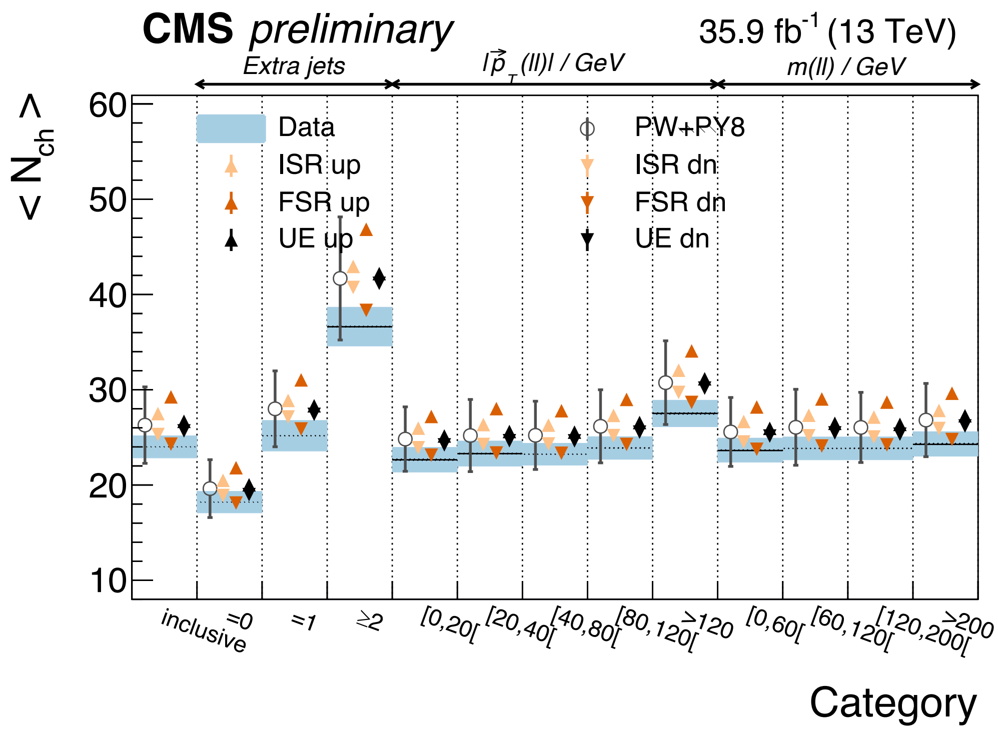
- Data prefers lower $\alpha_s^{FSR}(M_Z)$ than *assumed* in Monash.

$\lvert\vec{p}_T(\ell\ell)\rvert$ region	Inclusive	Away	Toward	Transverse
Best fit α_S^{FSR}	0.120	0.119	0.116	0.119
68% CI	[-0.006,+0.006]	[-0.011,+0.010]	[-0.013,+0.011]	[-0.006,+0.006]
95.45% CI	[-0.013,+0.011]	[-0.022,+0.019]	[-0.030,+0.021]	[-0.013,+0.012]

Uncertainties ~√2 variation of μ_R.

Underlying Event in ttbar Events [TOP-17-015]

- Test the universality of the UE hypothesis to scales up to $2m_t$ than the ones UE models are usually tuned.
  - Measurements in categories of m(ll) indicate that it should be valid at even higher scales.



- The measurements can be used to improve the assessment of systematic uncertainties in future measurements.
- *We have the data (not only from SM measurements) to make similar dedicated studies to control modeling in many different processes and in different phase-space regions.*

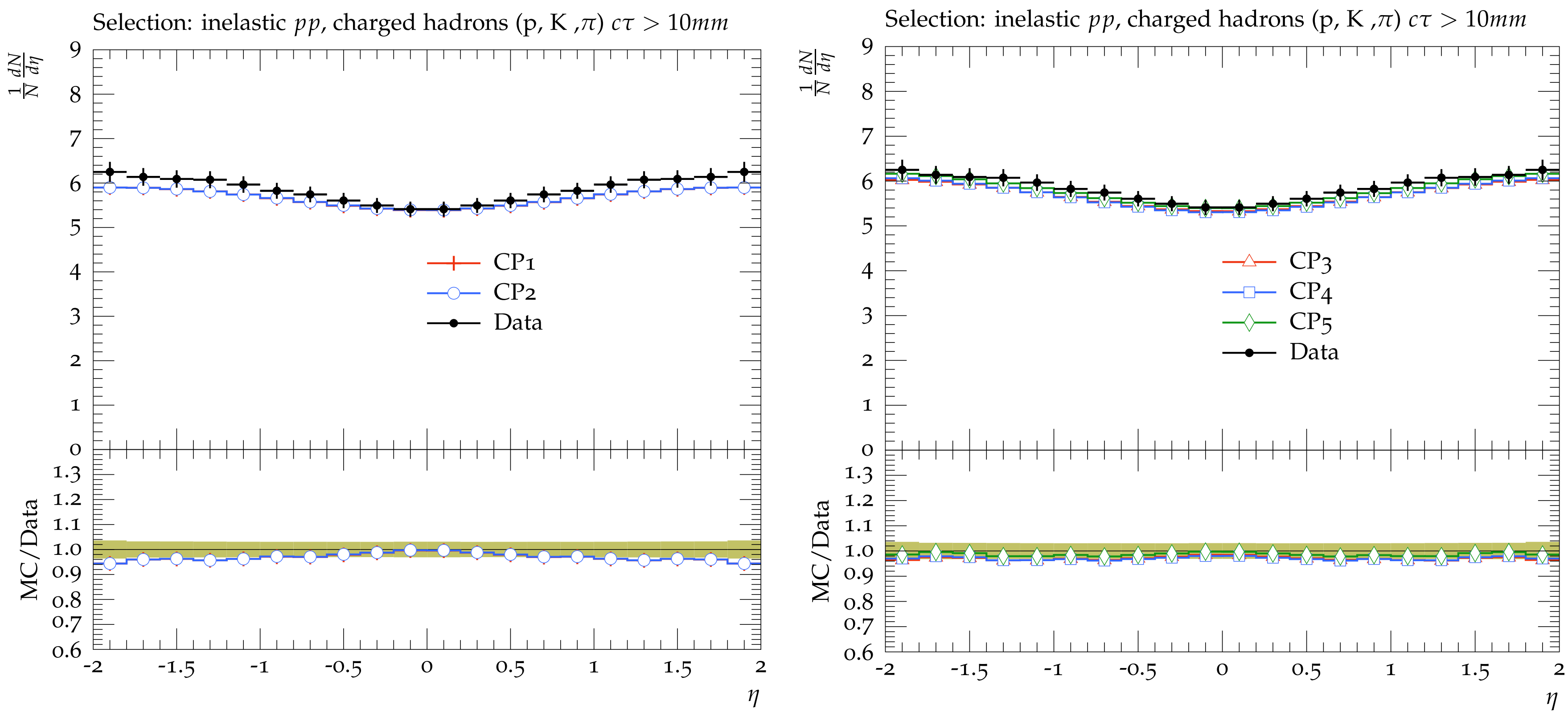
Another dedicated measurement, Jet Shapes in ttbar [TOP-17-013] –> See Markus Seidel's presentation.

α_s Consistency in ME and PS and PDF Choices

- Pythia (LO PDF), Herwig (NLO PDF), and Sherpa (NNLO PDF) have different PDF choices for parton showers.
- PDF used for the hard process is constrained by the accuracy of the ME calculation.
- Even though it may not be numerically significant for some processes/configurations, it may be beneficial to match the PDF in the ME and the PS, especially for matched/merged configurations.
- Match PDF and α_s in parton showers but have LO PDF for MPI to make sure small x-gluon is physical.
  - Not possible to set different PDFs in MPI and PS in Pythia.
- We test the effect using different PDF orders of NNPDF3.1 sets in Pythia8 among other parameter variations.
  - CP1,2: LO (α_s =0.130)
  - CP3 : NLO (α_s =0.118)
  - CP4,5: NNLO (α_s =0.118)

α_s Consistency in ME and PS and PDF Choices – MinBias and Underlying Event

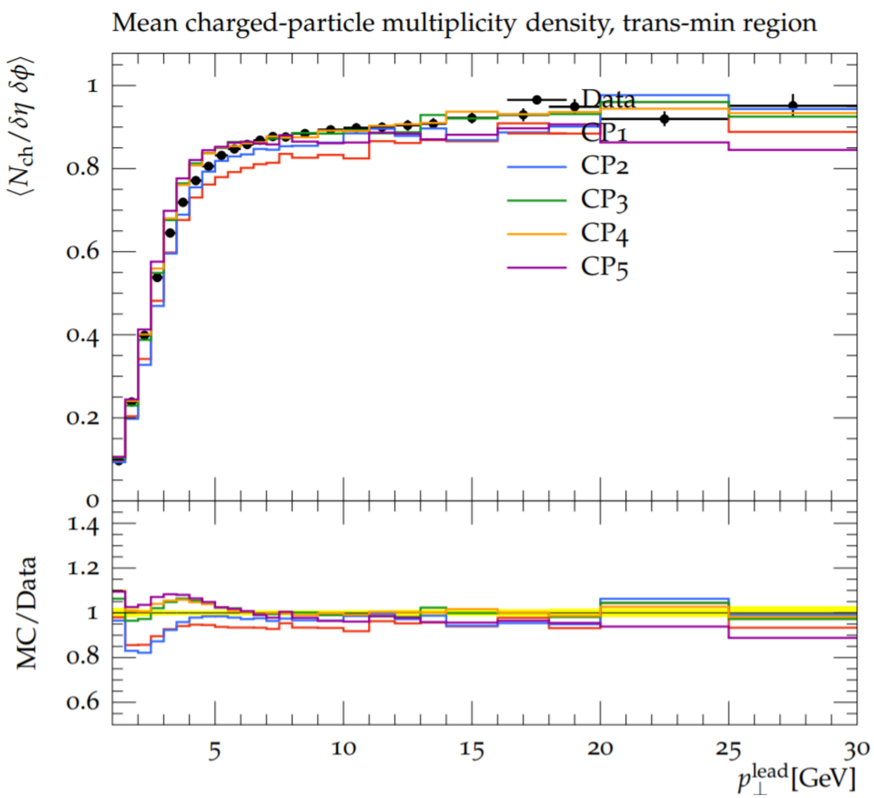
LO (N)NLO

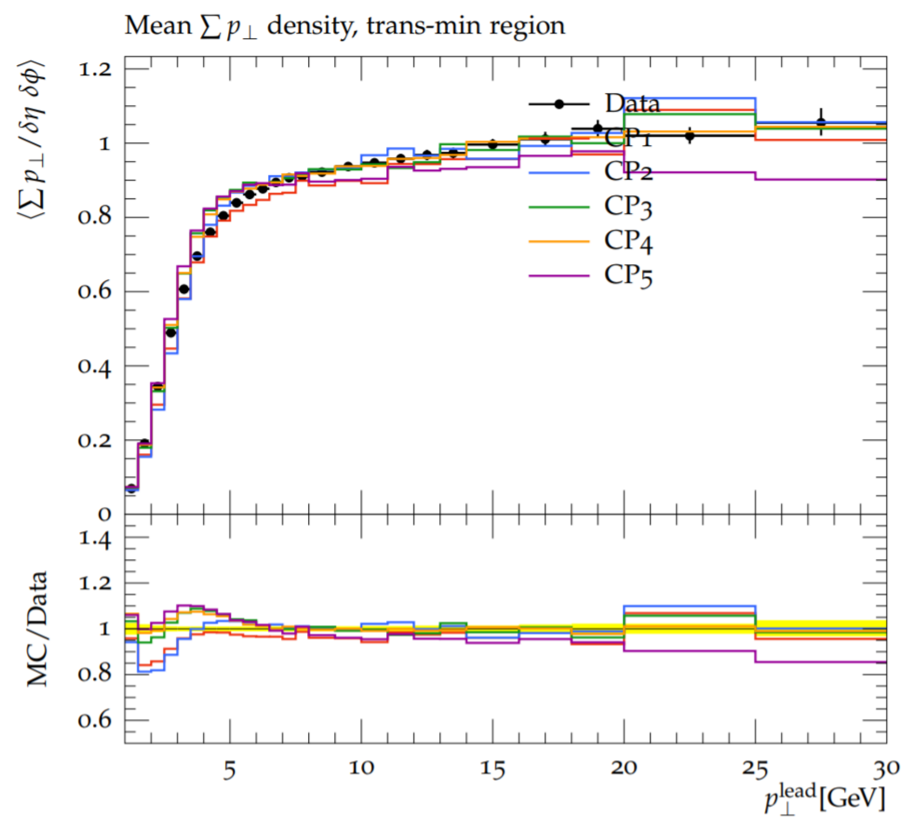


Rivet:CMS_2015_I1384119, 0 Tesla, $|\eta|<2$, $\sqrt{s}$=13 TeV

- Min-bias data are described at the same level by tunes with LO, NLO, and NNLO PDF NNPDF3.1 sets.

α_s Consistency in ME and PS and PDF Choices – MinBias and Underlying Event





Rivet: ATLAS_2017_I1509919, |η|<2.5, p_T>0.5 GeV with at least 1 of the charged particle p_T > 1 GeV, √s=13 TeV

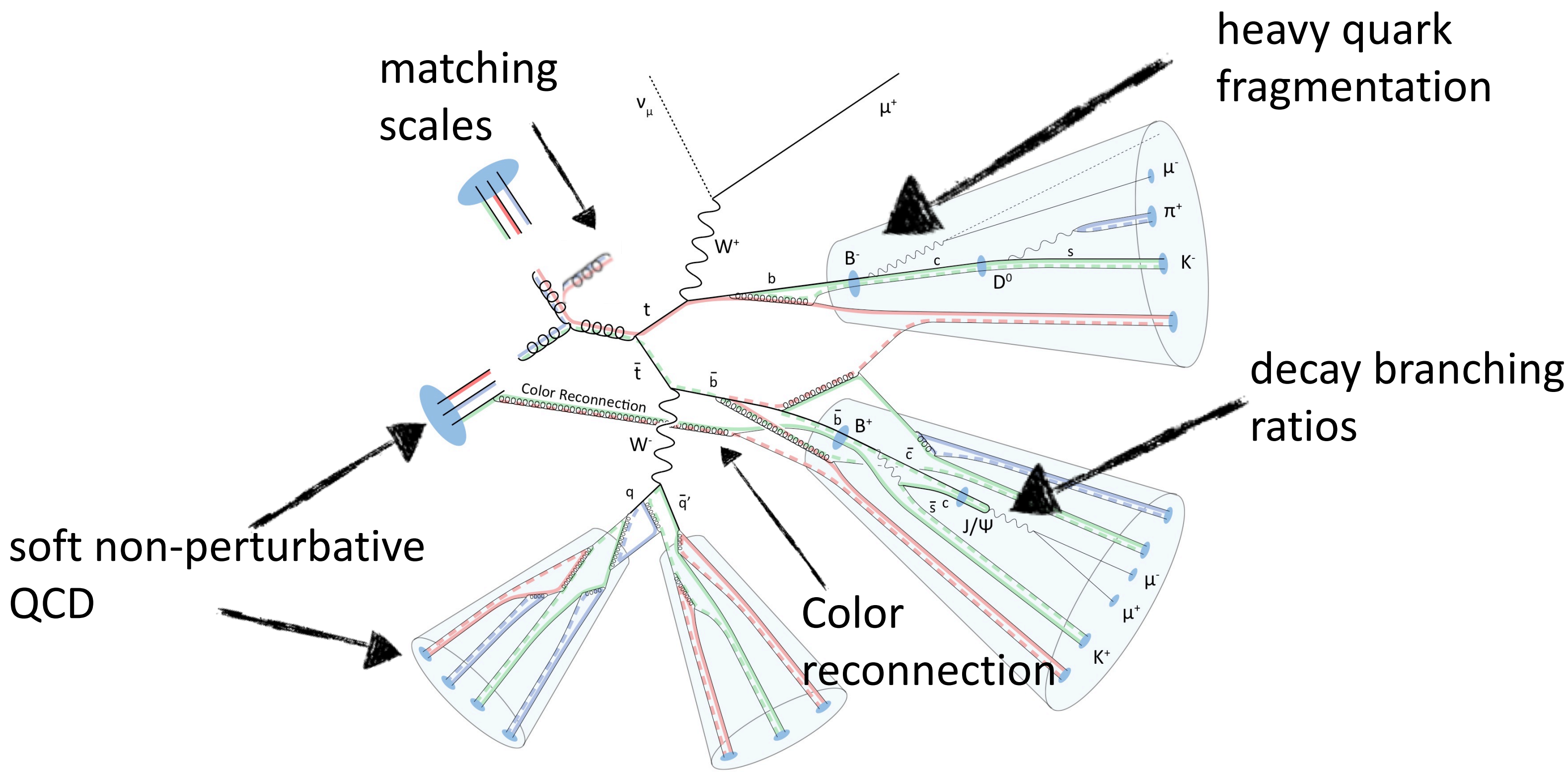
- UE data are described at the same level by tunes with LO, NLO, and NNLO PDF NNPDF3.1 sets.

PDFs

- 2016:
  - NNPDF30LO or NLO depending on the ME + uncertainties using appropriate LO, NLO, 4FS and 5FS variations.
  - NNPDF30LO for all parton shower.
- 2017:
  - NNPDF31NNLO set for all ME and Pythia8.
  - Also allowed for a much wider set of alternative PDF weights in the samples homogeneously for all the samples except the Pythia8-only ones.

Improving Theory Uncertainties

- Test ME+PS configurations and tunes using well-defined differential measurements.
  - ttbar, V+jets, Higgs boson, ….
- Dedicated stuies of each source of modeling uncertainty.
  - UE in ttbar, Z+Jets, …
- Measurements in different phase-space regions
  - Top mass, control regions in BSM searches, …

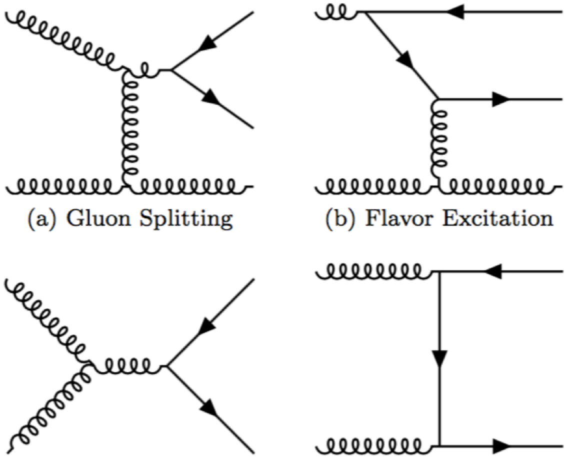


Factorized Parton Shower/Hadronization Uncertainties

Source	Handle	Weights	Variation	Note/Reference	Dedicated studies
Shower scales	ISR scale (SpaceShower:renormMultFac) FSR scale (TimeShower:renormMultFac)	~~No~~ ***YES*** ~~No~~	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 still to be studied
Soft QCD	UE parameters	No	***CP5 (2017)*** CUETP8M2T4(2016) up/down	See TOP-16-021 MPI & CR strength doesn't affect resonance decays	TOP-17-015
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: $x_b=p_T(B)/p_T(b\text{-jet})$	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)	

Heavy Flavor Production

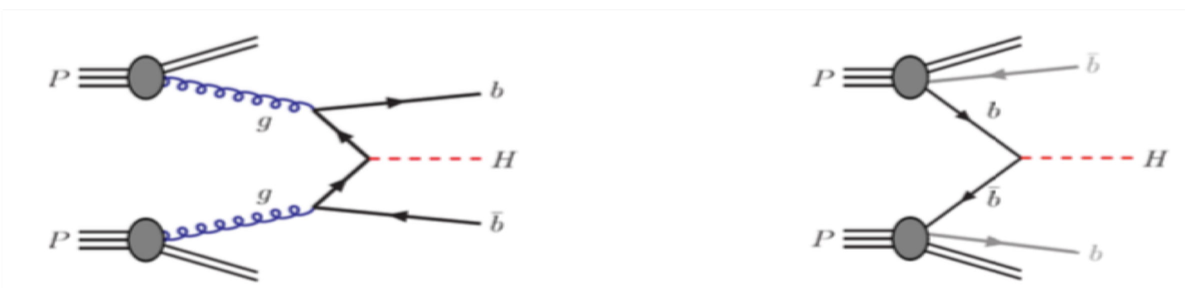
arXiv:1702.02947



(a) Gluon Splitting (b) Flavor Excitation (c) *s*-channel Flavor Creation (d) *t*-channel Flavor Creation

$$m_{W,Z,H,t} >> m_{b,c} >> \Lambda_{QCD}$$

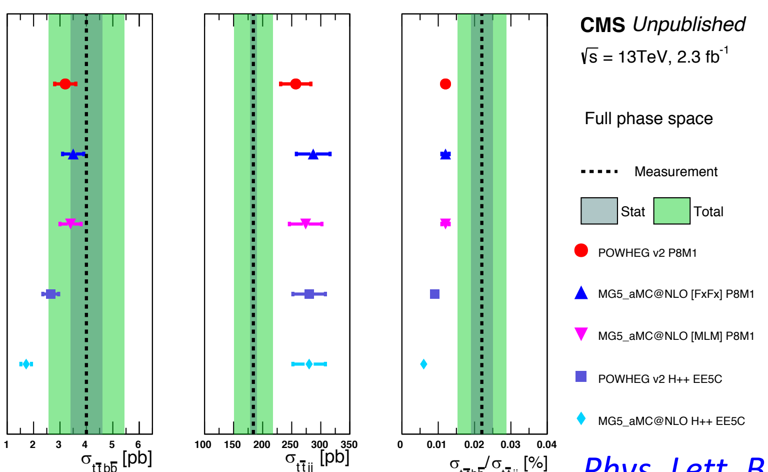
- Top quarks simulated with NLO MEs but other heavy quarks are mainly produced through g→QQbar splitting.
- Mass treatment:
  - Massive b: 4 flavor scheme
  - Massless b: 5 flavor scheme (treated as light quarks in the initial and final state)
  - Matched calculations to combine both schemes: e.g. FONLL scheme (see e.g. application of FONLL procedure to bbZ: arXiv:1803.10248)



CMS uses mostly 5FS but for single top: 4FS (except tW channel, tγ and tZq, ….)

Heavy Flavor Production – Main Issues

- Large theory uncertainties
  - Scale choices,
  - 4FS vs 5FS (e.g. for V/Hbb) → *See the talks by S. Cooperstein, L. Mastrolorenzo, V. Sotnikov*
  - g→bb splitting (especially at small opening angles) → *L. Perrozzi*
  - ME-PS matching
  - Different implementations in different MC simulation codes, … → *P. Nason, G.S. Chahal*
  - e.g. tt+b-jet: tt+bb, tt+b (1b not in acceptance), tt+2b (overlapping b's), tt+cc → normalization has 35% uncertainty.
    - But tt+bb/b/2b 4 FS Sherpa+OpenLoops at NLO precision vs 5FS tt+jets Powheg+Pythia8 → OK [e.g. HIG-17-026]
- Heavy flavor decay → T. E. Latham
- b fragmentation → B. Yates
- …



→ Cross section in data ~1.3x Powheg+Pythia8
→ New lower α_s CMS tune may fix this (for Powheg+Pythia8 and MG5_aMC+Pythia8)?

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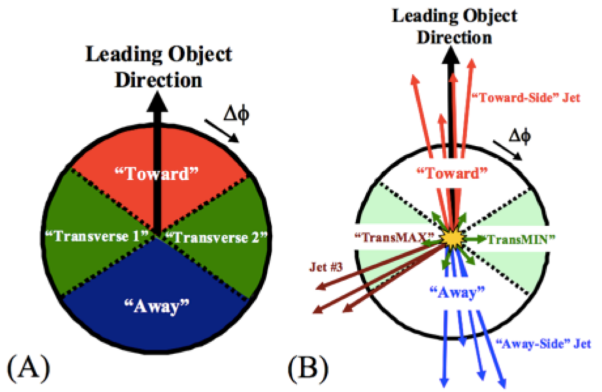
Additional slides

(Approximate) CPU Time

- Multi-leg LO
  - up to ~10s/gen-evt
  - ~10% matching efficiency → 100s/full-sim-evt
- Multi-leg NLO
  - up to ~30s/gen-evt
  - ~30% matching efficiency → 100s/full-sim-evt
  - Large fraction of negative weights of up to ~40% → larger samples!

CUETP8M2T4 Event Tune [TOP-16-021]

- Fixing the amount of ISR, a new UE tune is derived optimizing MPI parameters → fit to 5 measurements
  - UE data (pT > 0.5 GeV, |eta| < 2): Charged-particle and energy densities in TransMin and TransMax regions vs leading charged particle pT.
  - MinBias data (pT > 0): Charged-particle eta distribution.

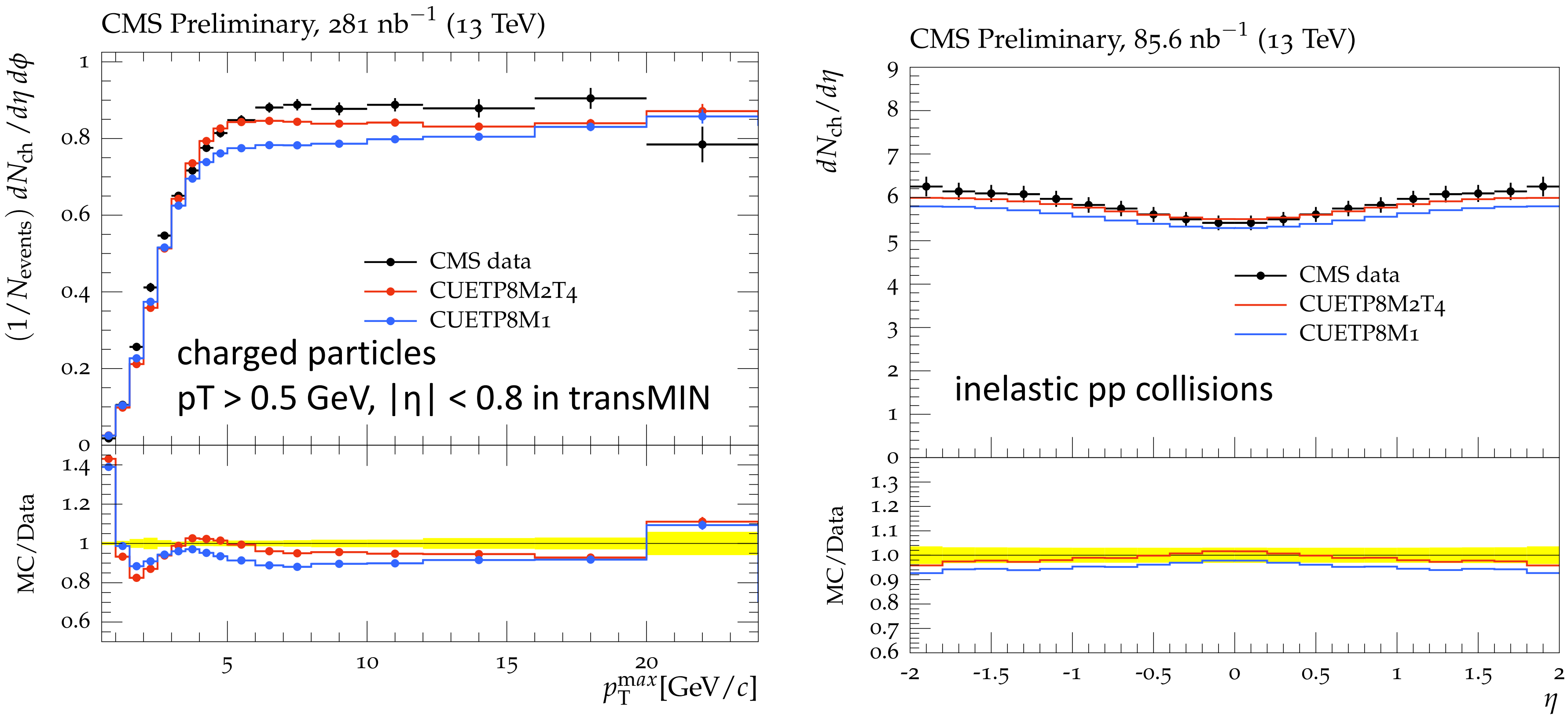


Transverse:

* TransMax: maximum activity <== MPI/BR & ISR/FSR
* TransMin: minimum activity <== MPI/BR
* TransAve = (TransMax + TransMIN)/2
* TransDIF = TransMax - TransMIN <== ISR/FSR

	CUETP8M1	CUETP8M2T4
Tune	pp 14	pp 14
Tune	ee 7	ee 7
MultipartonInteractions ecmPow	0.2521	0.2521
SpaceShower:alphaSvalue	0.1365	0.1108
PDF pSet LHAPDF6	NNPDF23_lo_qed_as_0130	NNPDF30_lo_as_0130
MultipartonInteractions:pT0Ref	2.40	2.20
MultipartonInteractions:expPow	1.6	1.6
ColourReconnection:range	1.8	6.6

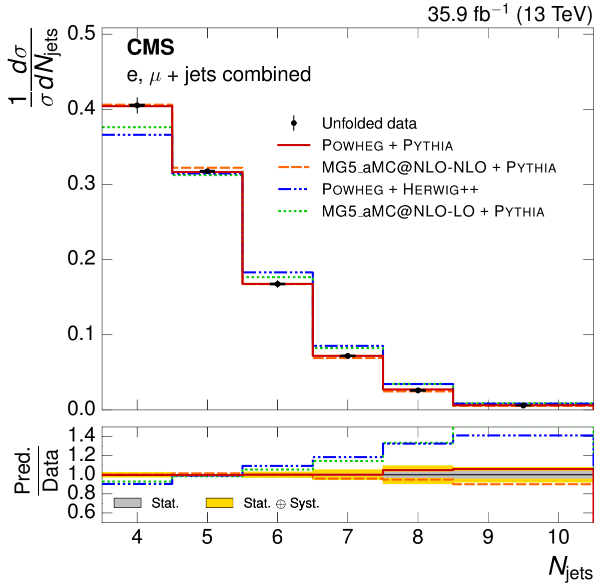
CUETP8M2T4 Event Tune [TOP-16-021]

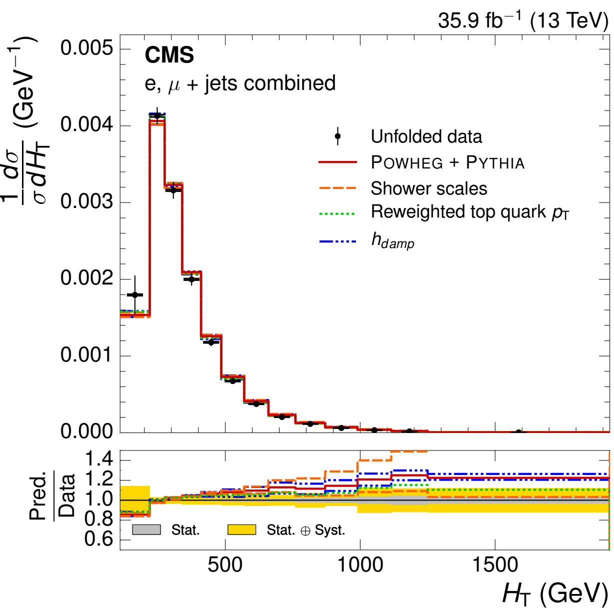


- CUETP8M2T4 tune describes UE and MinBias data at √s=13 TeV simultaneously.
- Performs well at √s= 7 TeV.
- Provides a better description of the plateau.
- Single-diffractive enchanced observables and inelastic cross sections not well described.

Performance of CUETP8M2T4 with Top Quark Data at 13 TeV

arXiv:1803.0399





	POWHEG+PYTHIA		With MC theoretical uncertainties	
	χ^2/ndf	p-value	χ^2/ndf	p-value
N_{jets}	2.3 / 6	0.90	1.7 / 6	0.95
H_T	23 / 13	0.05	4.3 / 13	0.99
S_T	19 / 13	0.11	4.7 / 13	0.98
p_T^{miss}	13 / 6	0.05	3.1 / 6	0.80
p_T^W	17 / 7	0.02	2.7 / 7	0.91
p_T^ℓ	20 / 17	0.28	14 / 17	0.68
$\lvert\eta^\ell\rvert$	16 / 8	0.04	15 / 8	0.06

	POWHEG+HERWIG++		MG5_aMC@NLO-NLO+PYTHIA		MG5_aMC@NLO-LO+PYTHIA	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
N_{jets}	39 / 6	<0.01	12 / 6	0.07	94 / 6	<0.01
H_T	21 / 13	0.07	10 / 13	0.66	150 / 13	<0.01
S_T	18 / 13	0.17	9.3 / 13	0.75	110 / 13	<0.01
p_T^{miss}	1.5 / 6	0.96	6.6 / 6	0.36	26 / 6	<0.01
p_T^W	0.9 / 7	1	9.2 / 7	0.24	33 / 7	<0.01
p_T^ℓ	11 / 17	0.87	15 / 17	0.58	36 / 17	<0.01
$\lvert\eta^\ell\rvert$	17 / 8	0.04	23 / 8	<0.01	31 / 8	<0.01

- POWHEG+PYTHIA8: generally consistent with data, with residual differences covered by theory uncertainties.
- Other considered configurations in general OK but MG5_aMC@NLO [LO] does not provide an accurate description of any variable in data.
- Impact of shower starting scale in MG5_aMC@NLO not studied in detail yet.

Standard Setups for CMS Monte Carlo at Run II

- Parton Shower codes
  - Pythia8
    - EvtGen
    - Dire shower plugin being integrated
    - Vincia being integrated
  - Herwig7
  - Sherpa

Standard Setups for CMS Monte Carlo at Run II

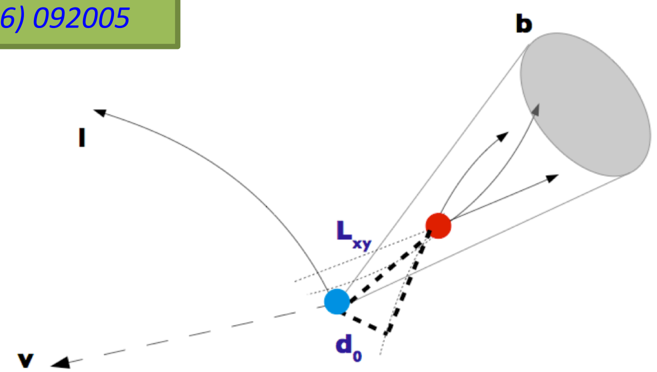
- MG5_aMC@NLO+Pythia8
  - LO w/o matching for many BSM signal production
  - LO w/ MLM matching for boosted/multijet phase space for search backgrounds with W/Z/γ+jets, QCD multijets, ttbar+jets, and for SUSY signal samples.
  - NLO w/o merging for a few complex processes with extra jets (ttW/Z/ γ, ttbb, …), or not possible with FxFx (γ+jets, dijets, VBF, ..)
  - NLO w/ FxFx merging for Z/W+jets, dibosons, ttbar, some Higgs boson signals.
  - CKKW/UMEPs/UNLOPS technical problems with combining samples and weights (solved??)
- Powheg+Pythia8
  - Mostly for Higgs boson, ttH, diboson production, and ttbar production
  - MINLO and NNLOPS starting to be used
- Pythia8 standalone
  - Mainly for QCD, w/ additional generator level filters and ’’multiple hadronization’’ feature had been added to CMSSW to make this more feasible.
- Sherpa 2X
- Some others for special samples

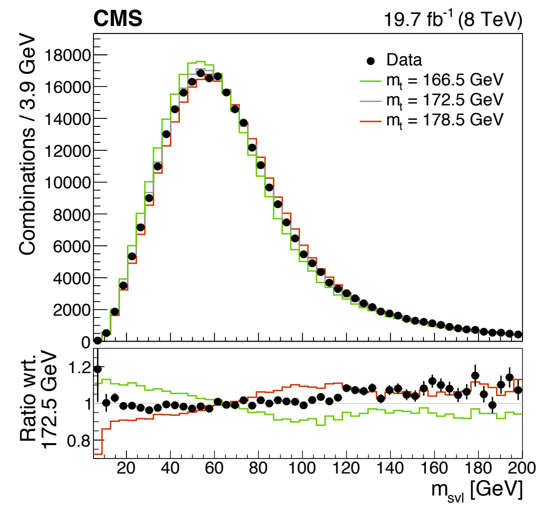
Standard Setups for CMS Monte Carlo at Run II

- Sherpa2.X
- Powheg+Herwig++
- Powheg+Herwig7
- MG5_aMC@NLO+Herwig++ (no merging)
- Herwig++ standalone for QCD and MinBias
- Herwig7
- JHUGen for anomalous Higgs boson spin/parity studies and H→VV decays
- Photos and some other special samples

Top Quark Mass using Charged Particles

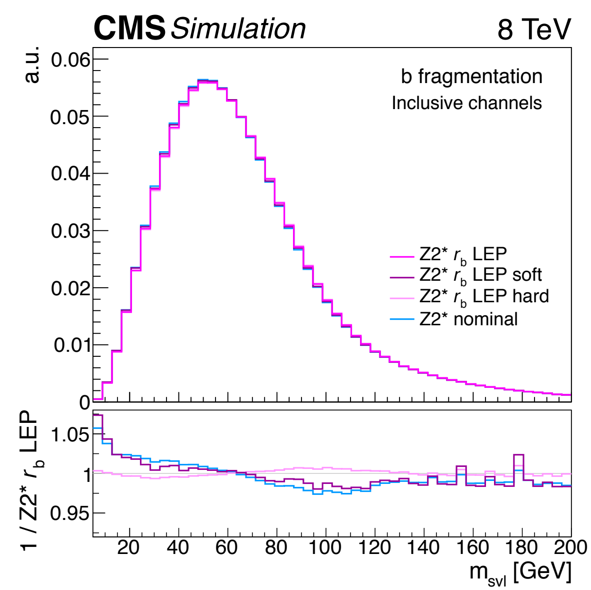
PRD 93 (2016) 092005





Use only charged decay products of the top quark:
Invariant mass of the secondary vertex w/ >= 3 tracks + lepton.

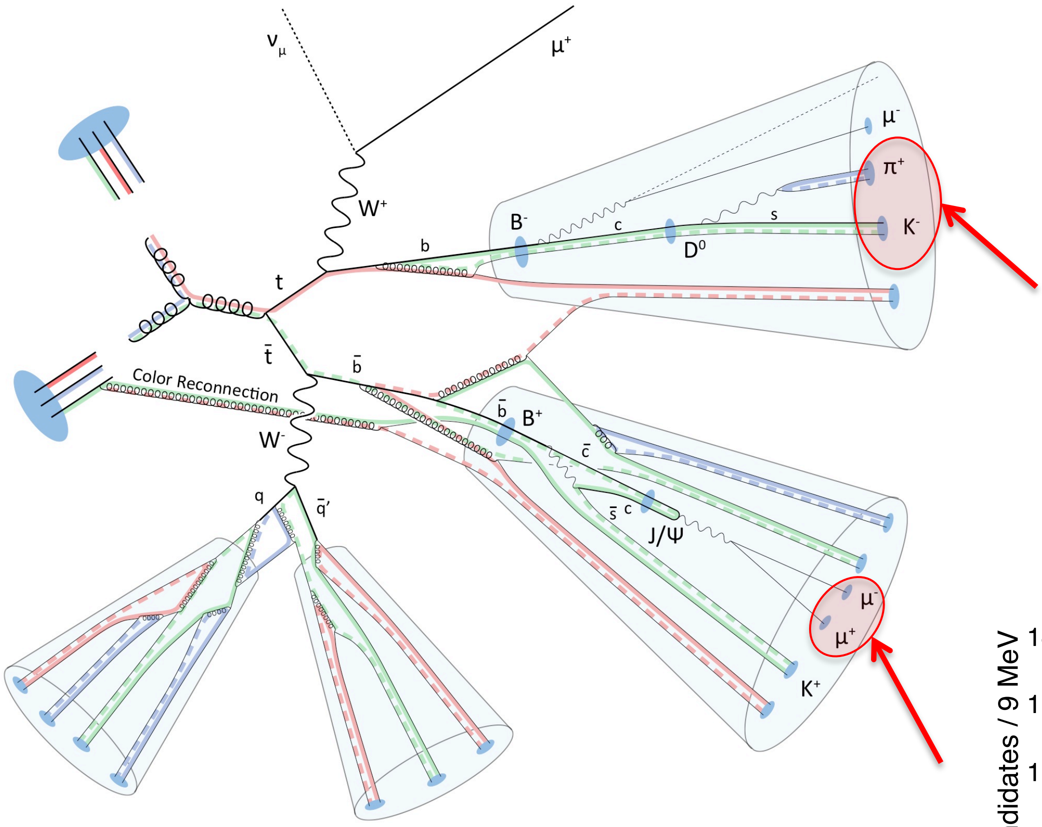
$$m_t = 173.68 \pm 0.20 (stat)^{+1.58}_{-0.97} (syst)\ GeV$$

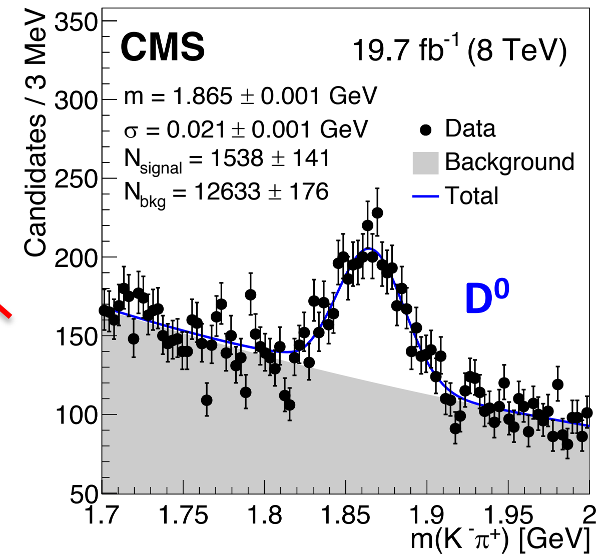


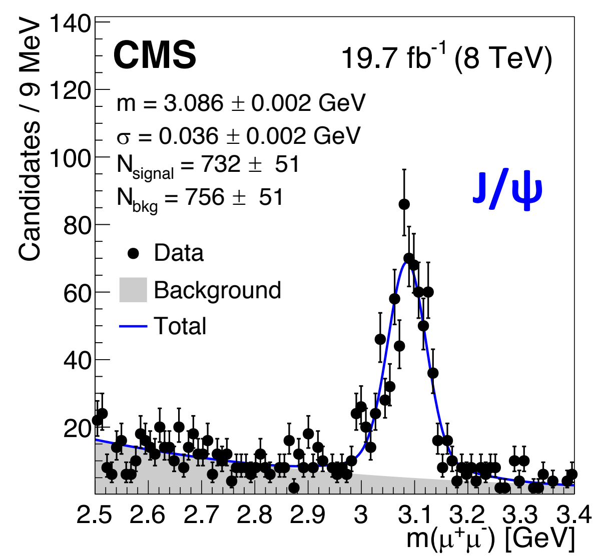
- Minimal experimental uncertainties.
- Large dependence on quark fragmentation modeling (~ 1 GeV)
- Top pT modeling ~ 0.8 GeV
- Standard measurements affected by hadronization effects on jet energy scale.

Inclusive charm mesons in ttbar events.

PRD 93 (2016) 092005



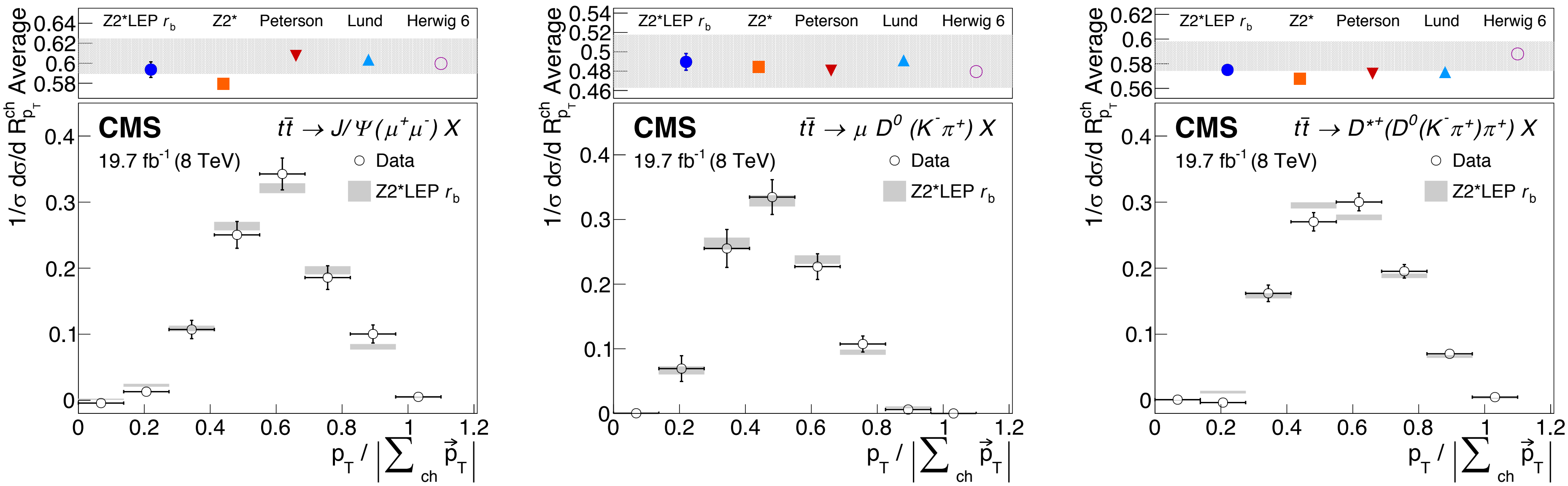




- Uncertainties in hadronization modeling of the colored decay products of the top affect
  - Kinematics of the tracks
  - Flavor composition and charged multiplicity

Inclusive charm mesons in ttbar events and b quark fragmentation

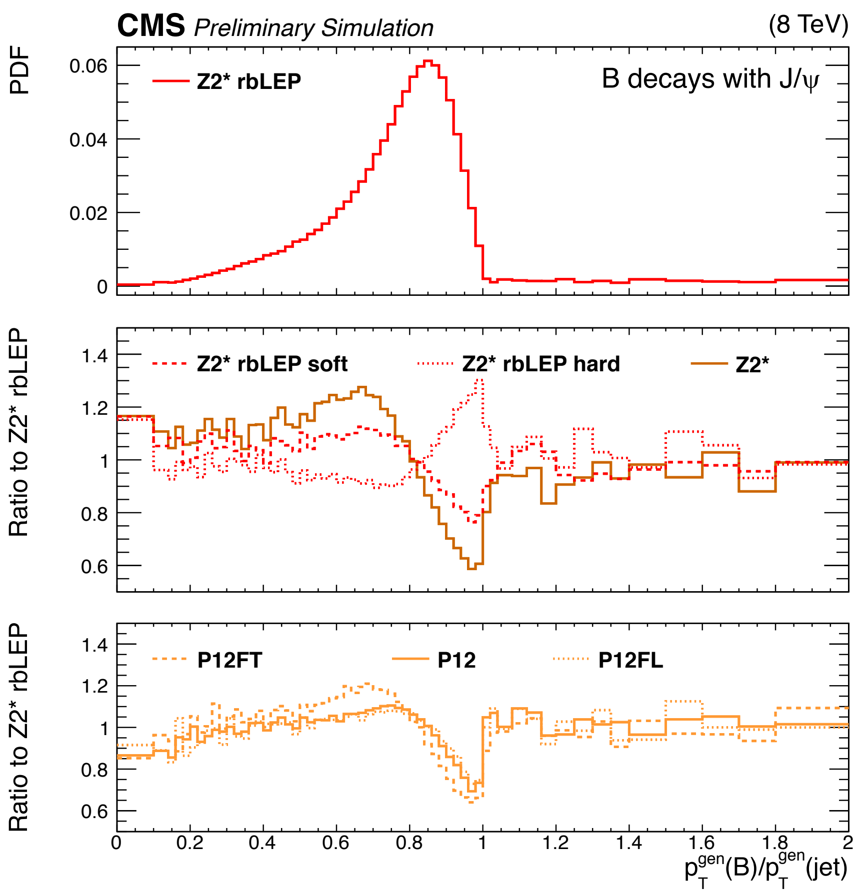
PRD 93 (2016) 092005

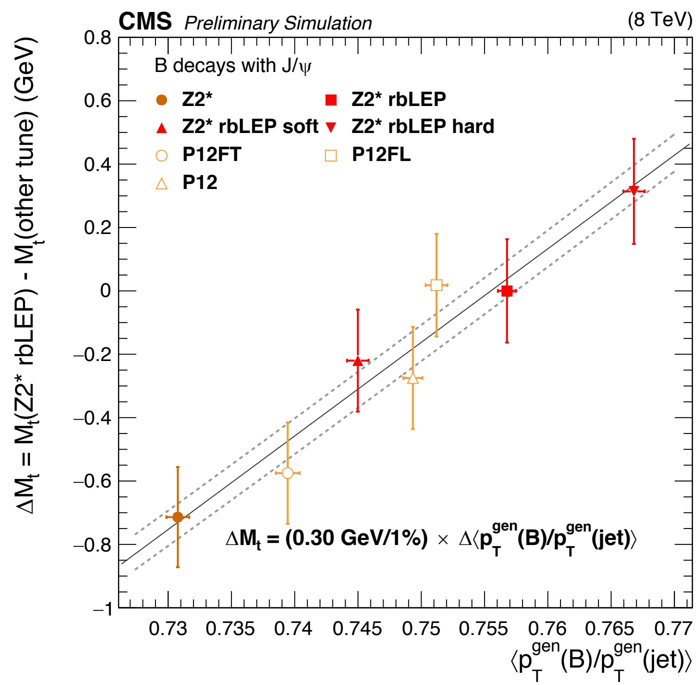


- Reconstructed mesons carry ~ 50-60% of the overall charged jet momentum.
- Z2* LEP r_b fragmentation displays better agreement with data than Z2* (with large statistical uncertainties).
  - Confirmed by secondary vertex properties in Z+jets and ttbar events.
  - *Select Z2* LEP rb as the central b quark fragmentation shape.*
- Larger data sets of LHC Run II → secondary vertices or charmed mesons & top mass to constrain b quark fragmentation

Top Quark Mass in ttbar Events with a J/Ψ

- Parton-to-hadron p_T transfer (b quark fragmentation)





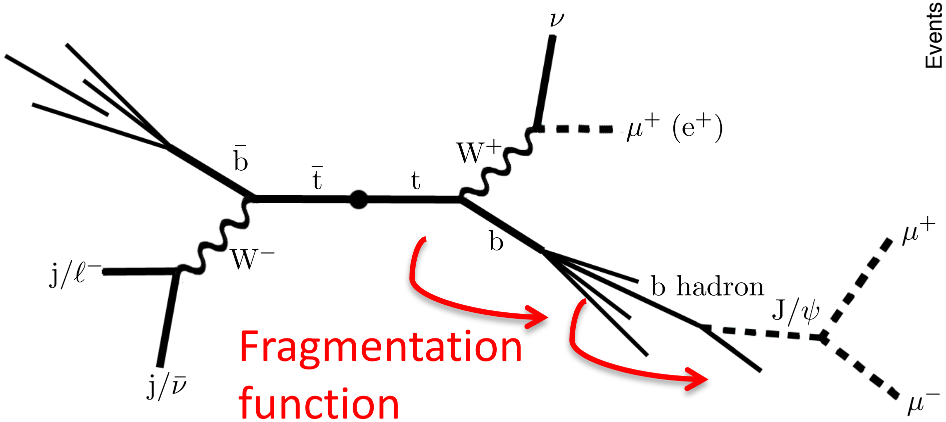
Average fragmentation

$$M_t(Z2^*rbLEP) - M_t(Z2^*) = -0.71$$

CMS-PAS-TOP-15-014

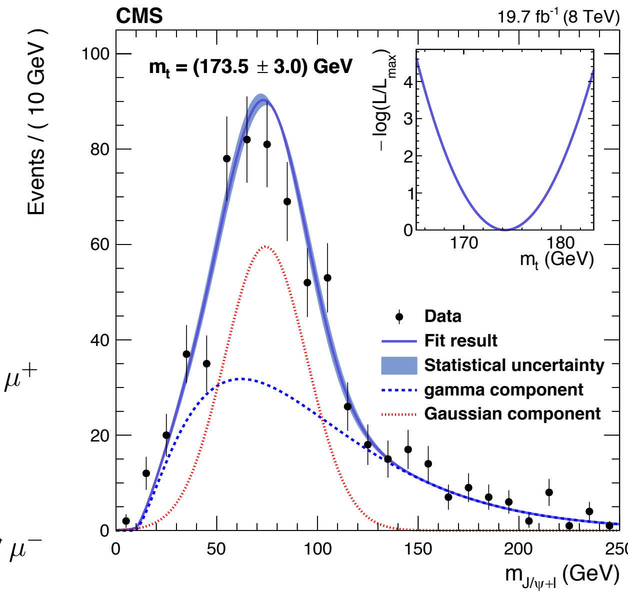
Top Quark Mass in ttbar Events with a J/ψ

- Use the correlation between the 3-prong leptonic mass and the top quark mass. CMS, CERN-LHCC 92-003, 1992



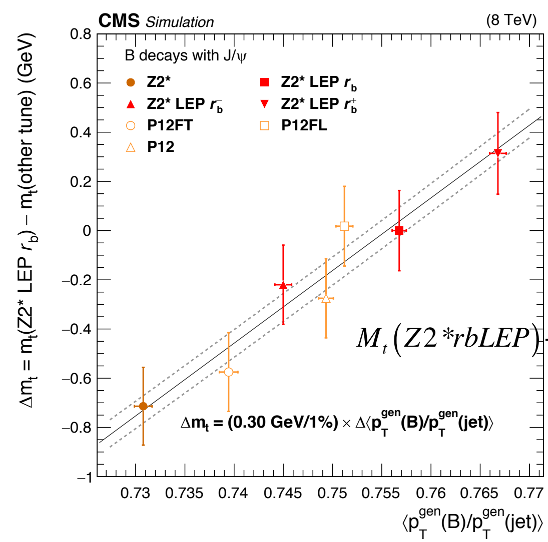
Fragmentation function

Precisely known from B factories



arXiv:1608.03560

	δ [GeV]
Small number of events; BR=3.2x10^{-4}	3
Minimal experimental uncertainties	0.10
b quark fragmentation modeling	0.30 →
Top pT	0.64
ME/PS matching	+0.12/-0.58
QCD scales	+0.12/-0.46



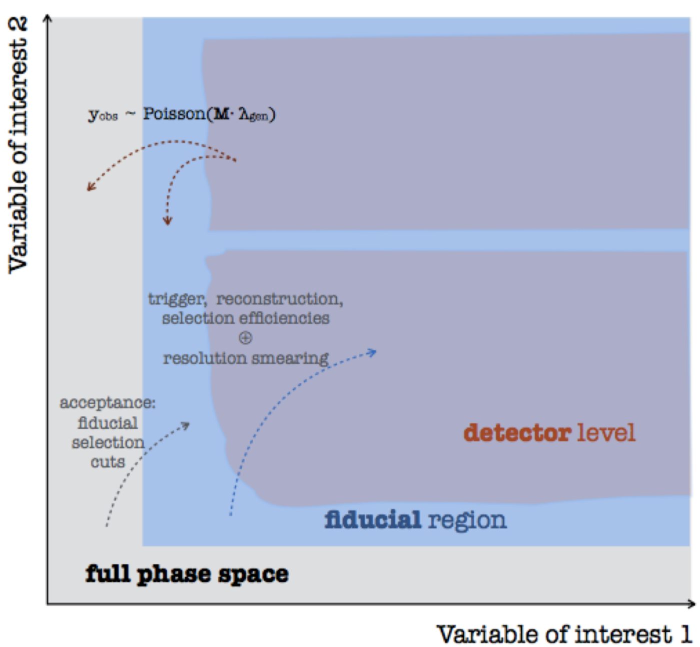
$M_t(Z2*rbLEP) - M_t(Z2*) = -0.71$

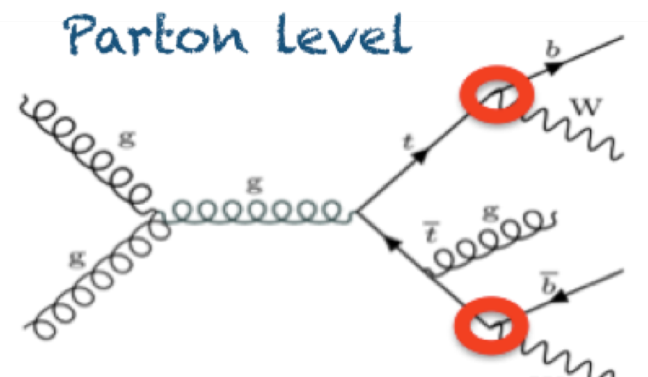
Average fragmentation

Improving uncertainties: Object Definitions for Top Particle

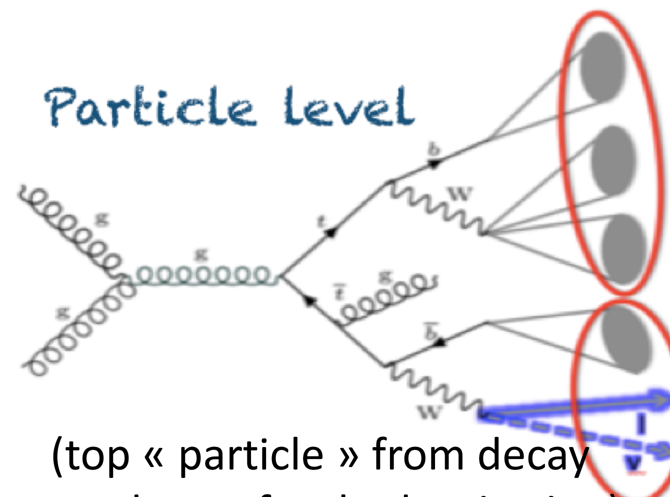
CMS-NOTE-2017-004

- Top quark simulations
  - at NLO+PS
  - finite width of the top quark for off-shell production and interference with the backgrounds.
  - Parton level top ill-defined.
  - Construct tops only from observed final-state = particle level top.
    - *fundamental aspect of performing current and future measurements of top quark differential production cross sections*





(before decay after radiation)



(top « particle » from decay products after hadronization)

The Top Quark p_T

- LHC Run I « discovery »: harder spectrum in LO/NLO + PS predictions than in data (also observed in run II)
  - NNLO+NNLL: significantly better description.

CMS-PAS-TOP-16-011