Model uncertainties in top-quark physics

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Introduction

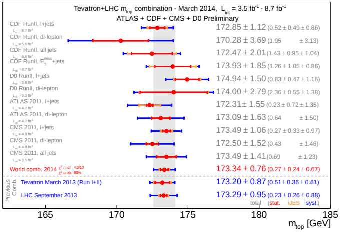
- Many top-quark measurements limited by systematic uncertainties
  - Top-quark mass world combination (arXiv:1403.4427)

$$m_t = 173.34 \pm 0.27\ (\text{stat.}) \pm 0.24\ (\text{iJES}) \pm 0.67\ (\text{syst.})\ \text{GeV}$$

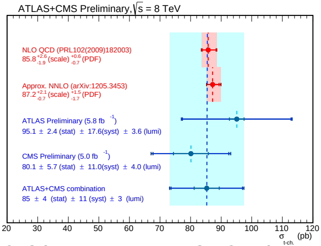
  - LHC t-channel combination (ATLAS-CONF-2013-098, CMS TOP-12-002)

$$\sigma_{\text{t-ch.}} = 85 \pm 4\ (\text{stat.}) \pm 11\ (\text{syst.}) \pm 3\ (\text{lumi.})\ \text{pb}$$

- Large impact of signal modeling uncertainties
- Get reasonable estimates, using input from theory and experiments

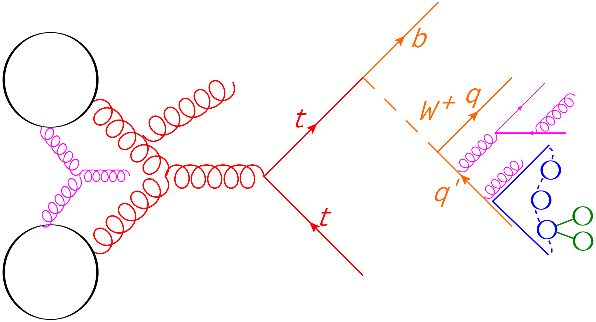


arXiv:1403.4427



ATLAS-CONF-2013-098, CMS TOP-12-002

Event anatomy / outline



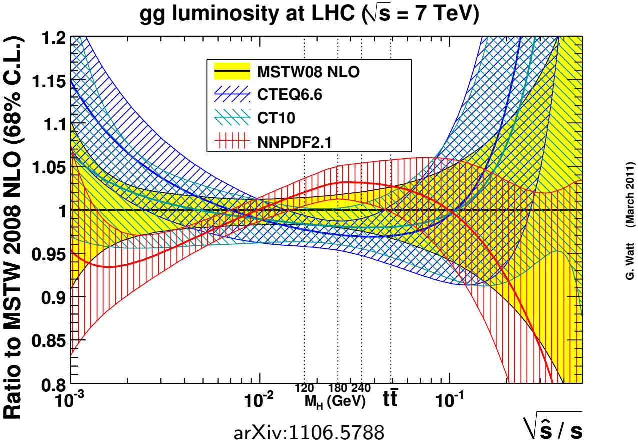
- Proton PDF
- Hard process
- Resonance decays
- Parton shower, MPI
- Hadronization
- Hadron decays

MCnet standard tuning strategy (arXiv:1101.2599)

1. Tune FSR and hadronization to e^+e^- data (LEP, SLD, b-factories)
2. Tune ISR (and FSR off ISR) to proton data (Tevatron, LHC)
3. Tune MPI to proton data (Tevatron, LHC)

Perturbative QCD

PDF



arXiv:1106.5788

- PDF4LHC prescription: envelope of CT10, MSTW2008, NNPDF2.3, including α_s variations (± 0.0012)
- Occasionally used in insensitive analyses: CT6/CT10 variations (+MSTW2008/NNPDF2.3 central values)
- Point for discussion: one PDF set with all relevant uncertainties?

$t\bar{t}$ MC generator uncertainty

TOP LHC WG guidelines

(https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TheorySystematics)

- Comparison of central predictions from different generators
- Use at least 1 multileg and 1 NLO generator setup
- In general: difficult to disentangle underlying effects

ATLAS Default setup: Powheg+Pythia6

(until ~TOP2013: MC@NLO+Herwig6)

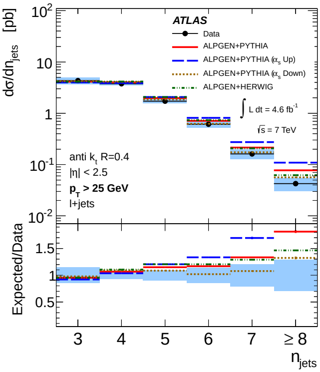
- Quoted as MC generator:
  Powheg+Pythia6 vs. MC@NLO+Herwig6 (vs. Alpgen+Herwig6)

CMS Default setup: MadGraph+Pythia6

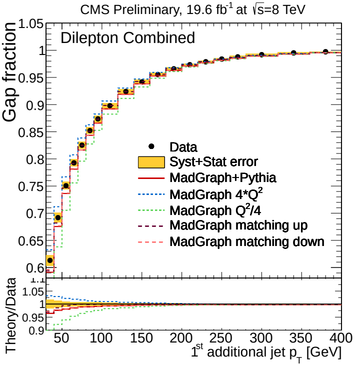
- Quoted as MC generator: MadGraph+Pythia6 vs. Powheg+Pythia6
  (became larger for m_t when spin correlations were included in MadGraph)

Initial state radiation uncertainties

- ATLAS Vary ren. scale in Alpgen+Pythia by factors 1/2 and 2
- CMS Vary ren. and fact. scales in MadGraph+Pythia by 1/2 and 2
  Vary ME-PS matching threshold



arXiv:1407.0891



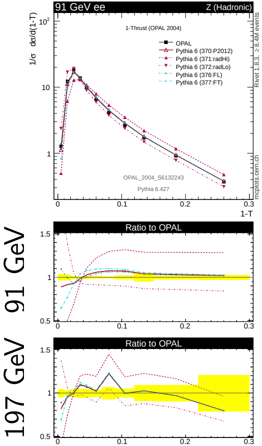
CMS TOP-12-041

- High-precision tests of QCD in $t\bar{t}$ production!

Radiation in resonance decays

- Precision better than LL due to ME corrections in Z/W/t decay

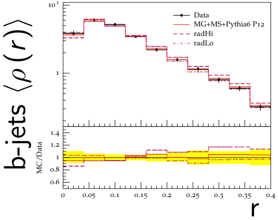
OPAL Thrust
arXiv:hep-ex/0503051

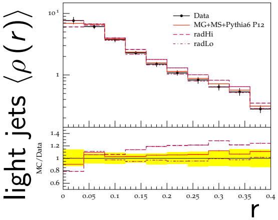


- FSR in resonance decays constrained by LEP
  - Thrust (left)
    $T = 1$ back-to-back
    $T = 1/2$ isotropic
  - Very precise data at $\sqrt{s} = 91$ GeV

- Jet shapes in $t\bar{t}$ events
  - Relative momentum distribution inside jets
  - FSR scale drives jet broadening

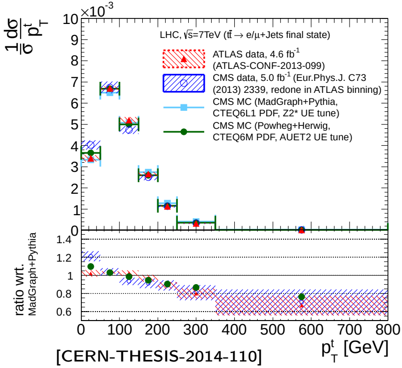
ATLAS jet shapes
data from arXiv:1307.5749



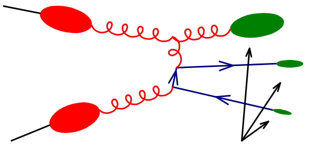


$t\bar{t}$ top-quark p_T (mis)modeling

- CMS sees softer top p_T in data, agreement with ATLAS at high p_T
- Powheg+Herwig6 seems to agree with data, rescaling of $t, \bar{t}, j$ momenta to give virtuality to extra jet
  [P. Nason, https://indico.cern.ch/event/301787]
- Different reshuffling schemes implemented in Herwig++ 2.7.1
- Pythia8: dipole-recoil vs. global recoil
- NNLO might be able to resolve
- CMS short-term solution: uncertainty from top p_T reweighting (similar approach at D0 for $t\bar{t}$ p_T)

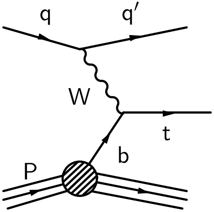


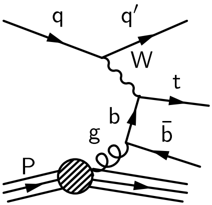
[CERN-THESIS-2014-110]



[P. Nason]

Single-top *t*-channel





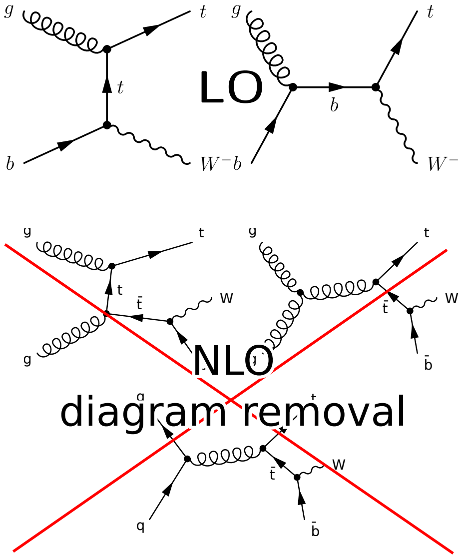
5FS:	LO	(part of) NLO
4FS:	x	(part of) LO

- 5FS: massless b in proton, b-jet from parton shower
- 4FS: ME description of additional b-quark
- Matched scheme adds $2 \to 2$ and $2 \to 3$ LO diagrams
- NLO generators provide automatic matching

- Comparison of all three schemes in new measurements (CMS TOP-14-004)
- Run1 defaults: ATLAS AcerMC+Pythia6 (4FS+5FS LO)
  Powheg+Pythia6 (4FS NLO) NEW
  CMS Powheg+Pythia6 (5FS NLO)
- Plan for Run2: 4FS at NLO (Powheg and aMCatNLO)

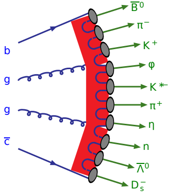
Single-top tW-channel

- Default setup: Powheg+Pythia6
- tW at NLO similar to $t\bar{t}$
- Diagram removal:
  remove double-resonant
  diagrams from signal definition
- Diagram subtraction:
  implement a subtraction term to
  cancel the $t\bar{t}$ contribution locally
- DR/DS comparison, impact on
  cross-section measurement small
- Future: treat as WbWb final
  state? ($\rightarrow$ Jan's talk)

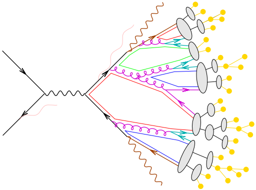


Soft QCD

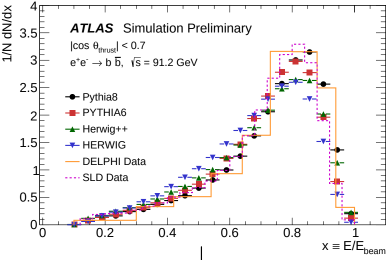
Hadronization model: String vs. cluster



Lund string



Cluster



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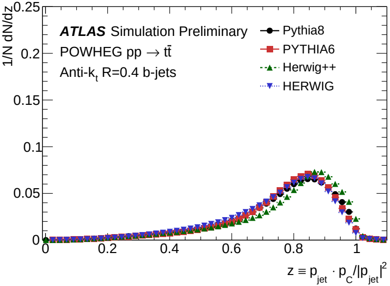


ATL-PHYS-PUB-2014-008

- Detector response may vary with momenta and types of hadrons
- Similar e^+e^- tunings $\rightarrow$ different predictions for LHC
- Explore different models and sensible parameter variations

Hadronization model: Pythia vs. Herwig

- Comparison non-trivial due to different shower, matching, UE/MPI
- Possibility to spot previously unnoticed effects (top p_T)

ATLAS

- Powheg+Pythia6 vs. Powheg+Herwig6 in $t\bar{t}$ and single top (complete analysis)
- Pythia6 vs. Herwig++ in JES and b-JES

CMS

↕ particle→reco

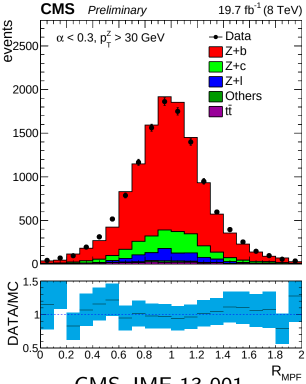
- Pythia6 vs. Herwig++ in JES (flavour-dep.)
- Cross-checks: b-JES from Z+b events NEW

Powheg+Pythia6 vs. MC@NLO/Powheg+Herwig6 in $t\bar{t}$

CDF Pythia vs. Herwig in $t\bar{t}$ and in JES

D0 Alpgen+Pythia vs. Alpgen+Herwig in $t\bar{t}$

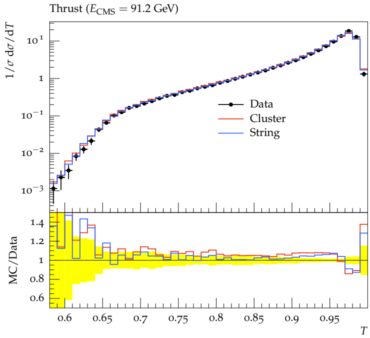
Analysis on particle-level jets, after reco selection



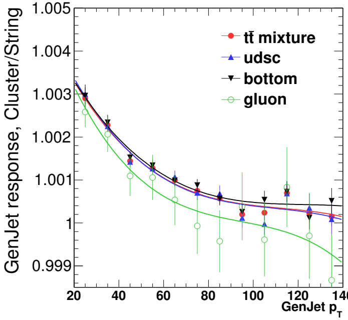
CMS JME-13-001

Hadronization model: Cluster vs. string in Sherpa

- Comparison of cluster and string in Sherpa 2.1.0, same parton shower
- Left: Tuning validated in e^+e^- at $\sqrt{s} = 91$ GeV (Thrust)
- Right: Parton$\rightarrow$particle response in 8 TeV $t\bar{t}$ events



ALEPH data: Eur.Phys.J. C35 (2004) 457-486



[MS]

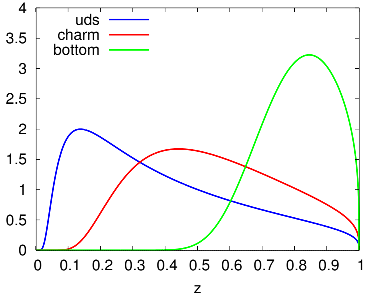
- 0.3% difference at low jet p_T, flavors agree within 0.05%
- Particle-level top-quark and W mass changed by ~ 10 MeV

Fragmentation functions

- In string model, on string break:
  - $z =$ fraction of $(E + p_z)$ taken by new hadron

$$f_{light}(z) \propto \frac{1}{z}(1-z)^{a} \exp\left(\frac{-bm_\perp^2}{z}\right)$$

  - $p_{x,y}$: Distributed according to gauss, width $\sigma = 0.30 - 0.36$ GeV



- 2→3-jet transition: jet parameter y_{23}, where jet multiplicity changes between 2 and 3
- P12 FL/FT cover LEP uncertainty
- Larger difference between Pythia and Herwig++

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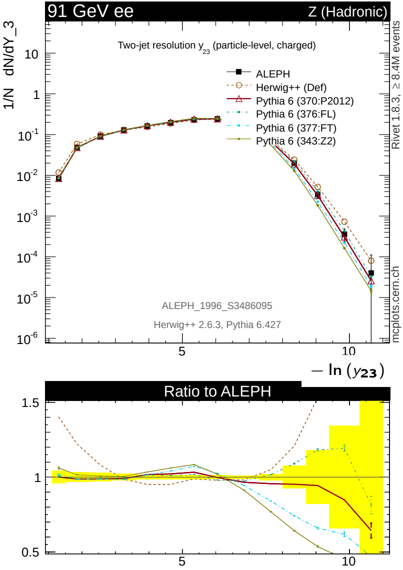


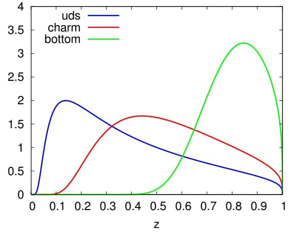
Fragmentation functions for b quarks

- Light flavour: $f(z) \propto \frac{1}{z}(1-z)^a \exp\left(\frac{-bm_\perp^2}{z}\right)$
- Heavy flavour (Bowler extension)

$$f(z) \propto \frac{1}{z^{1+r \cdot bm_\perp^2}}(1-z)^a \exp\left(\frac{-bm_\perp^2}{z}\right)$$

- Tunable parameters: a, b, r

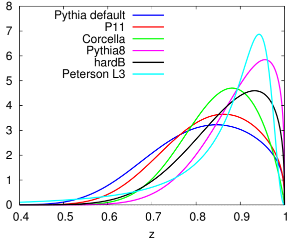
  a, b same for all flavours in Pythia6,
  r can be separated to r_c, r_b



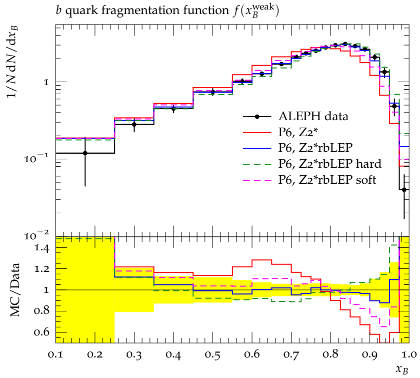
- Different parameter sets and functional forms (Bowler-Lund, Peterson,...)

Expect impact on

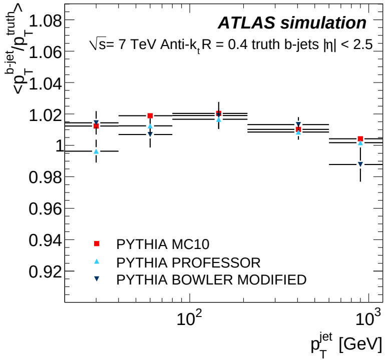
- b-tagging for jets, b jet energy scale
- Measurements using B hadrons or their decay products (J/Ψ)



Fragmentation functions for b quarks: tuning to LEP



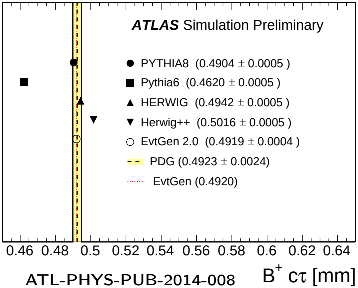
ALEPH data: arXiv:hep-ex/0106051



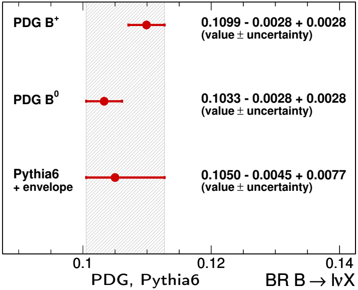
arXiv:1112.6426

- $x_B = E_B/E_{beam}$, B = weakly decaying B hadron
- CMS Retuned Pythia6 Z2* to LEP data, evaluated in $t\bar{t}$
- ATLAS Pythia tunes covering the LEP data → b-JES uncertainty

B-hadron decays



ATL-PHYS-PUB-2014-008



PDG, Pythia6

Lifetime of B hadrons

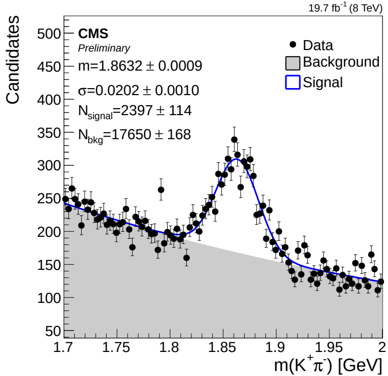
- b-tag efficiencies (constrained from data)
- CMS m_t from B decay length

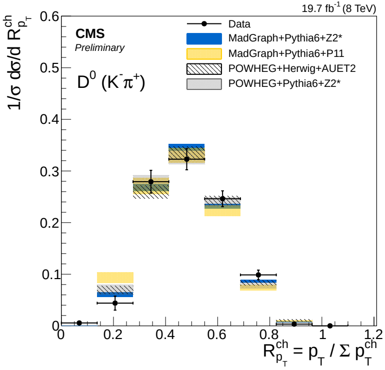
BR $B \to \ell\nu X$

- Determines neutrino fraction in b jets, direct impact on response
- Pythia: same value for B^+, B^0
- CMS Envelope as uncertainty

- Best parameter set in EvtGen? Used for $t\bar{t}$ mass difference ATLAS

CMS Charmed mesons in b jets NEW



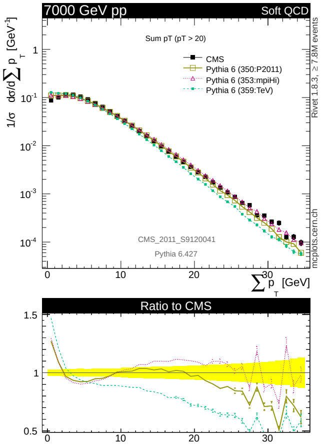


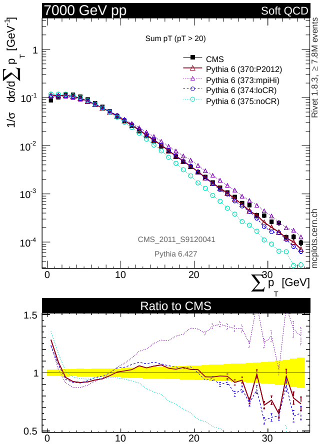
CMS TOP-13-007 additional plots

- Identified $D^{0/\pm}$ and J/Ψ mesons in $t\bar{t}$ events
- Momentum fraction wrt (charged particles clustered in) b jet
  $\rightarrow$ constrain b fragmentation
- Combine with ATLAS jet shapes (constraints on radiation)
- Goal: Measure m_t from $J/\Psi + \ell$

Underlying event

CMS data, arXiv:1107.0330

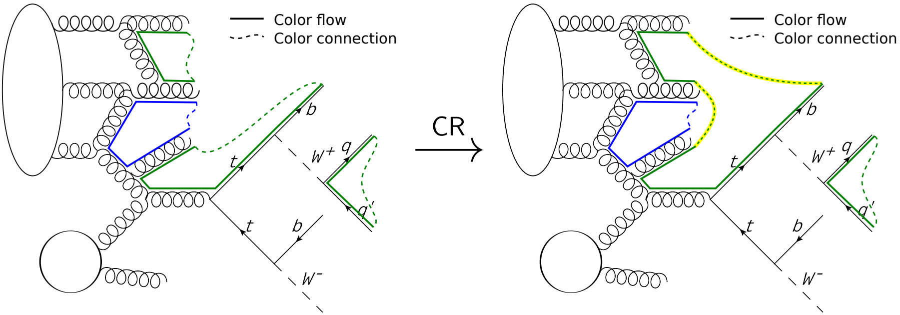




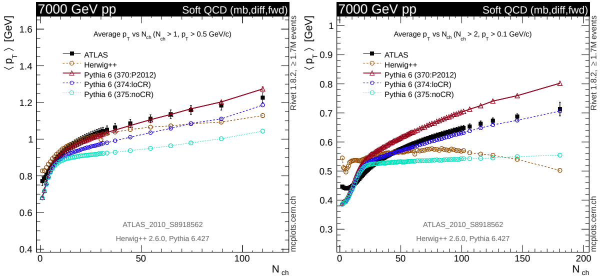
- CMS Pythia6 Tune P11 vs. P11mpiHi P11TeV (left)
- ATLAS Pythia6 Tune P11 vs. P11mpiHi (left)
- ATLAS Pythia6 Tune P12 vs. P12mpiHi (right) NEW

Colour reconnection

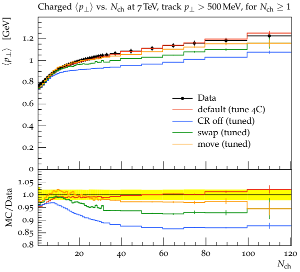
- Different empiric models possible, most common:
  find colour configurations with less potential energy / string length
- Connection probability steered via parameters



Colour reconnection



arXiv:1012.5104



arXiv:1407.6653

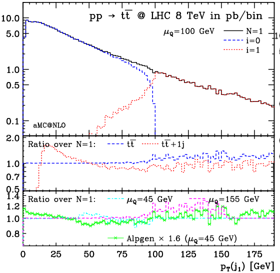
- Improved description of $\langle p_T \rangle$ vs. N_{ch} in minimum-bias events
- Disagreement for different cuts on particle p_T
  $\rightarrow$ still ambiguous and models are "crude"
- CMS ATLAS Pythia6 Tune P11 vs. P11noCR
  ATLAS Pythia6 Tune P12 vs. P12loCR NEW
- New range of CR models implemented in Pythia8 (arXiv:1407.6653)
  $\rightarrow$ possibly larger effects than on/off?

Outlook

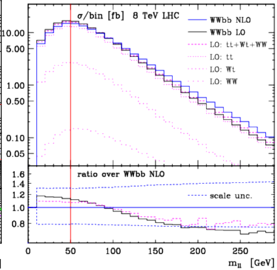
(and ongoing things)

NLO+multileg

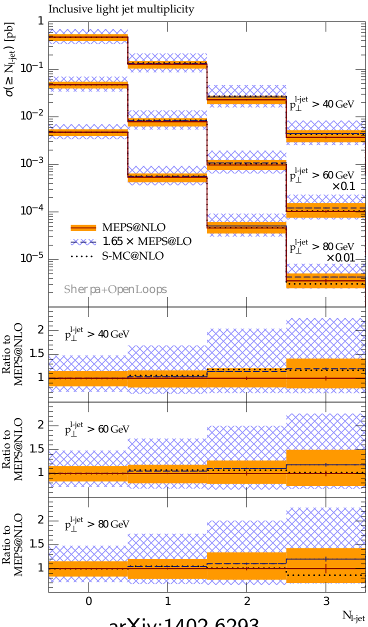
- Accurate description of processes with additional jets
- Reduced/meaningful scale uncertainties
- 2 user-friendly frameworks with multiplicity merging for $t\bar{t}$: aMCatNLO, SherpaNLO
- Simulate decays at NLO



arXiv:1209.6215



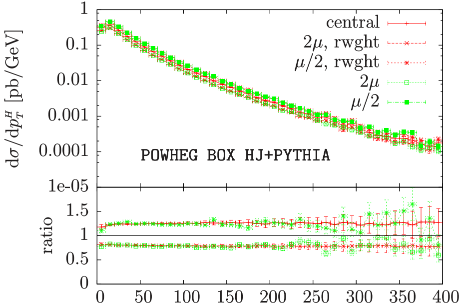
arXiv:1311.4893



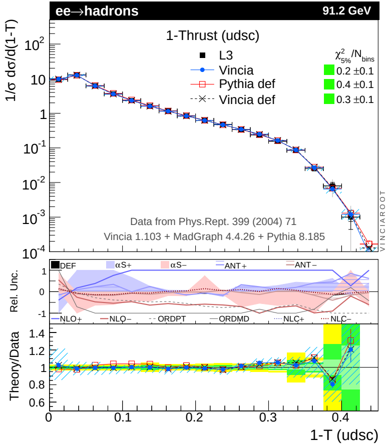
arXiv:1402.6293

Automated generator weights

- Generate one sample, including weights for scale variations
- ME weights implemented in aMCatNLO and Powheg
- PS weights implemented in Vincia shower (FSR in resonances)



[Carlo Oleari]



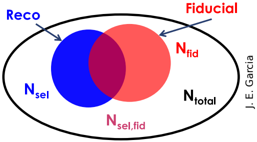
- Potential for efficient and precise estimation of uncertainties
  (restricted to perturbative QCD?)

Reduce generator dependency of measurements

Core capability of experiments: Measure leptons and jets in $|\eta| \lesssim 2.5/5$

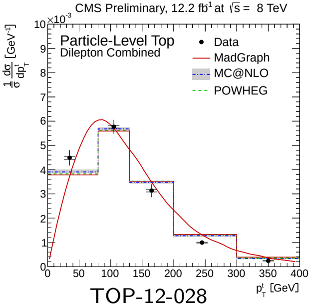
Fiducial cross sections

- Additional measurement in detector-friendly phase space
- Smaller acceptance uncertainties compared to inclusive cross section
- Final states incl. interference effects



Top reconstruction at particle-level

- Close to detector level
- Reduced theory uncertainties
- MC comparison and parameter constraints in Rivet+Professor



TOP-12-028

→ Complementary to inclusive/parton-level measurements

→ Data preserved for all practical purposes

Summary

Summary

- Estimation of systematic uncertainties frequently debated
  - Useful exchange of information/opinions in TOP LHC WG
  - Agreement on radiation uncertainties, will benefit from new NLO+multileg generators
  - Similar Pythia variations for (b-)fragmentation, UE, CR
  - Hadronization debate: string vs. cluster (aka Pythia vs. Herwig)
- Started to constrain $t\bar{t}$ modeling directly from LHC top-quark data
- New experimental results include fiducial cross sections and particle-level measurements as complementary information

predictions

$\longrightarrow$

measurements