Top-quark mass measurement at CMS

in the ℓ+jets and all-hadronic channels

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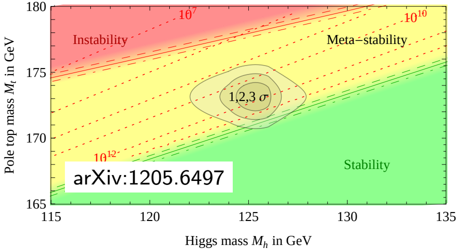
Measurement of the top-quark mass

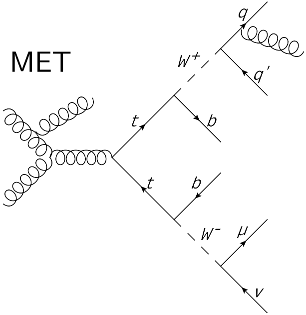
Theory motivation

- m_t important parameter of Standard Model
- Input to calculations of EW vacuum stability



Experimental motivation

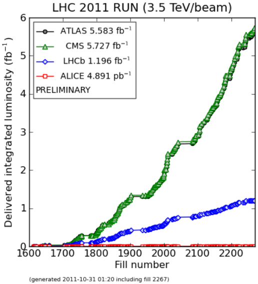
- Challenging event topologies
- $t\bar{t}$ "ℓ+jets" events contain (b-)jets, leptons, MET
- Benchmark for detector performance (improve Tevatron precision: 0.5%)

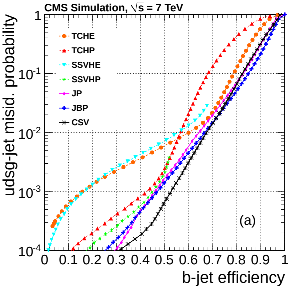


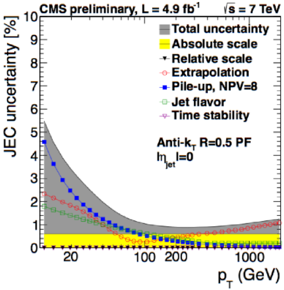
Covered in this talk

- Measurements at 7 TeV
- Studies and improvements of systematic uncertainties for 8 TeV

Preconditions for measurements of m_t at CMS







- Great machine performance in 2011, delivered $> 5\ \mathrm{fb}^{-1}$ $\rightarrow$ nearly 1 million top-quark pairs produced at $\sqrt{s} = 7$ TeV
- Efficient algorithms for identifying b-jets
- Using particle-flow algorithm, good understanding of jet energy scale gained using 2011 data

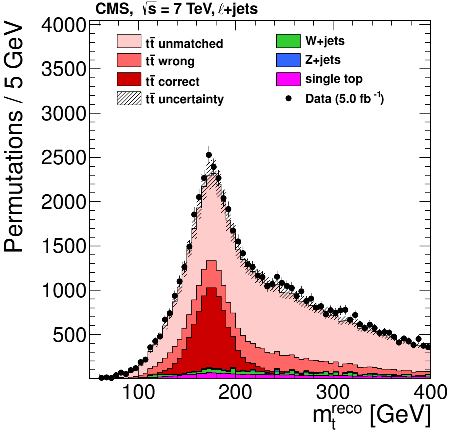
Lepton+jets: Selection & reconstruction (JHEP 12 (2012) 105)

- Exactly 1 isolated muon/electron with $p_T > 30$ GeV, $|\eta| < 2.1$
- ≥ 4 jets with $p_T > 30$ GeV, $|\eta| < 2.4$, ≥ 2 with b-tag
- Assign b-tagged jets $\rightarrow$ b-quarks, untagged jets $\rightarrow$ light quarks

Kinematic fit & final selection

- Use 4 leading jets, constraints: $m_W = 80.4$ GeV, $m_t = m_{\bar{t}}$
- Weight each permutation by $P_{\text{gof}}(\chi^2) = \exp\left(-\frac{1}{2}\chi^2\right)$, $P_{\text{gof}}(\chi^2) > 0.2$ required

before kinematic fit: 13% of $t\bar{t}$ correct



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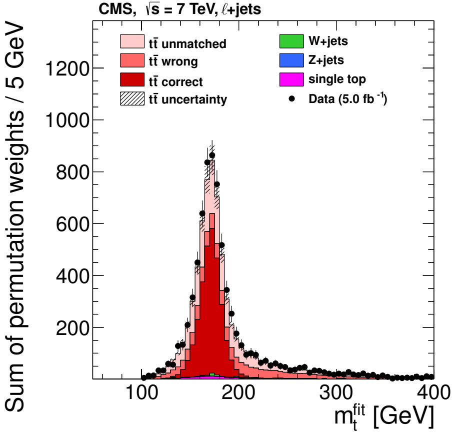
- Selected sample contains 5194 events in 5 fb^{-1} data
- Estimated purity: 96% $t\bar{t}$ events

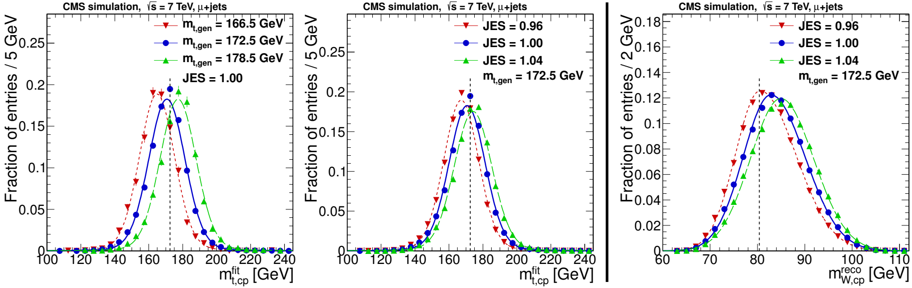
after kinematic fit: 44% of $t\bar{t}$ correct



Ideogram method: probability densities

- Simulated samples with
  - 9 different top masses: 161.5–184.5 GeV
  - 3 different JES: 0.96, 1.00, 1.04
- Fit $m_t^{\mathrm{fit}}, m_W^{\mathrm{reco}}$ distributions with analytical expressions
- Parametrize linearly in m_t, JES, $m_t \times$ JES

Example: *correct permutations*



$P_{cp}\left(m_t^{\mathrm{fit}} | m_t, \mathrm{JES}\right)$ $P_{cp}\left(m_W^{\mathrm{reco}} | \mathrm{JES}\right)$

Ideogram method

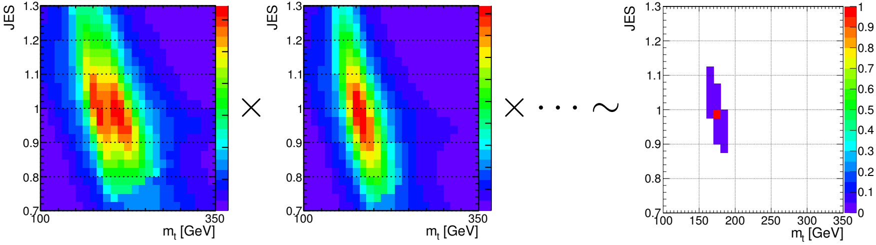
- Calculate likelihood for event with n permutations, j denotes *correct*, *wrong* and *unmatched* permutations

$$\mathcal{L}\left(\text{event}|m_t, \text{JES}\right) = \sum_{i=0}^{n} P_{gof}\left(i\right) P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t, \text{JES}\right),$$

$$P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t, \text{JES}\right) = \sum_{j} f_j P_j\left(m_{t,i}^{fit}|m_t, \text{JES}\right) \cdot P_j\left(m_{W,i}^{reco}|m_t, \text{JES}\right)$$

- Most likely m_t and JES by maximizing

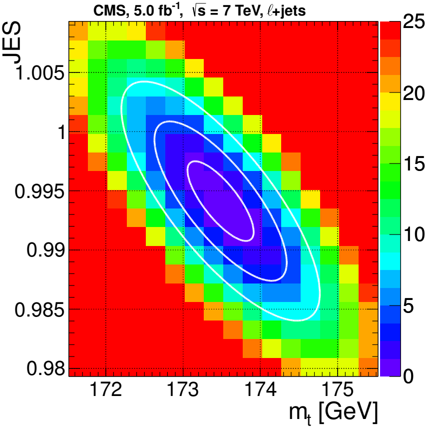
$$\mathcal{L}\left(m_t, \text{JES}|\text{sample}\right) \sim \prod_{\text{events}} \mathcal{L}\left(\text{event}|m_t, \text{JES}\right)^{w_{\text{event}}}$$



Lepton+jets: Result (JHEP 12 (2012) 105)

- Calibration with pseudo-experiments, small corrections for m_t and JES

Systematic uncertainty	$\Delta m_{\rm top}$ [GeV]
Calibration	0.06
b-JES	0.61
p_T- and η-dependent JES	0.28
Lepton energy scale	0.02
Missing transverse energy	0.06
Jet energy resolution	0.23
b-tagging	0.12
Pile-up	0.07
Non-$t\bar{t}$ background	0.13
PDF	0.07
μ_R, μ_F	0.24
ME-PS matching threshold	0.18
Underlying event	0.15
Color reconnections	0.54
Total	**0.98**



Result: $m_t = 173.49 \pm 0.43$ (stat+JES) $\pm\, 0.98$ (syst) GeV

All-hadronic: 1D/2D ideogram method (CMS PAS TOP-11-017)

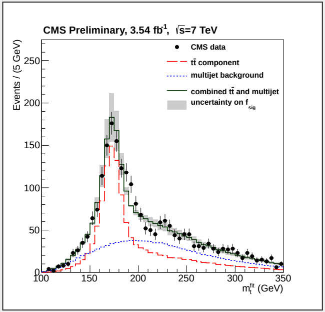
Eike Schlieckau

- ≥ 6 high-p_T jets, ≥ 2 b-tags, cut on ΔR_{bb}
- Event mixing for background estimation
- Kinematic fit, use permutation with minimum χ^2, weighted by $P_{\text{gof}}(\chi^2) > 0.09$
- 1D ideogram more stable against statistical fluctuations in MC samples

Main systematic uncertainties	Δm_{top} [GeV]
Jet energy scale	0.97
b-jet energy scale	0.49
Trigger	0.24
Non-$t\bar{t}$ background	0.20
μ_R, μ_F	0.22
Underlying event	0.32
Color reconnections	0.15
+ others → Total	**1.21**

Selected events

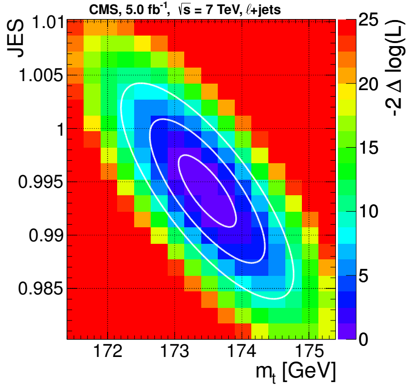
- 2418 events in 5 fb^{-1}
- 51% $t\bar{t}$ events, 49% multijet



Result: $m_t = 173.49 \pm 0.69\ (\text{stat}) \pm 1.21\ (\text{syst})$ GeV

Differential mass measurement (CMS PAS TOP-12-029)

- Start with mass measurement in lepton+jets channel
- Apply to subsets depending on value of kinematic observable $X \in \{p_{T,t}, \eta_b, \dots\}$ (Mangano, TOPLHCWG, July 2012)



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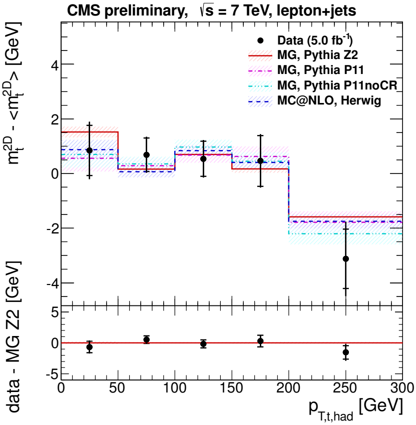

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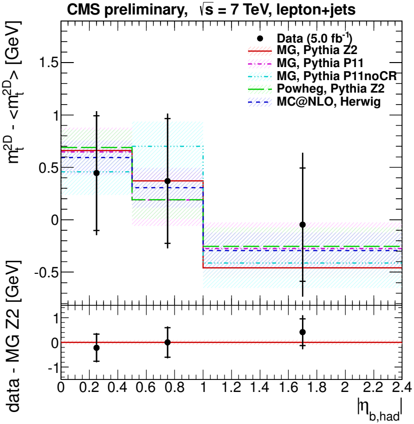
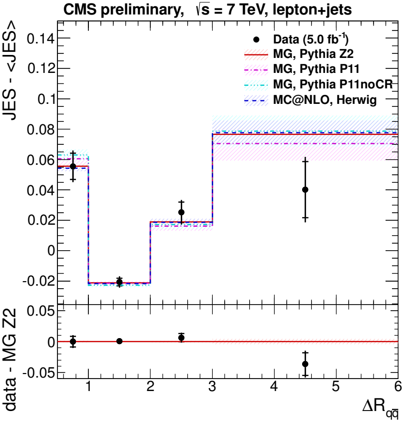
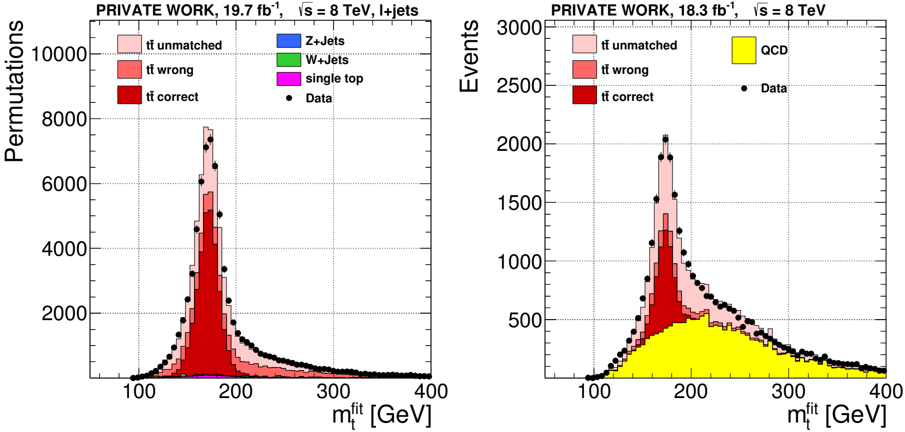




- First mass measurement binned in kinematic variables
- Provides additional validation for inclusive measurement
- Good description of data, no significant differences between models
- Tested 12 observables, global $\chi^2/\text{ndf} = 68.58/78 \rightarrow P = 0.77$

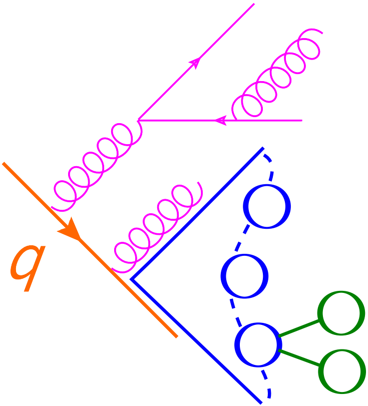
Preview 8 TeV



- Identical setup for both lepton+jets (left) and all-hadronic (right)
- Ability to perform direct Likelihood combination as cross-check to BLUE method (used for official combinations)

Modelling of jets: From (b) quarks to detectable hadrons

1. Parton (from hard process)
2. Parton shower (Pythia, Herwig)
   - Gluon emission: $q \rightarrow qg$,
   - Gluon splitting: $g \rightarrow q\bar{q}, gg$,
   - Good constraints from Z decays
3. Hadronization (Pythia, Herwig)
   - Non-perturbative formation of hadrons along colour strings
   - Steered by fragmentation functions and flavour parameters
4. Hadron decays (Pythia, Herwig, EvtGen)
   - Steered by decay tables

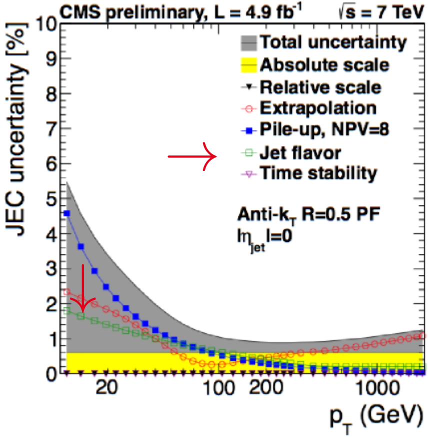


- Direct impact of b-JES uncertainty on reconstructed top-quark mass
- Try to disentangle different effects to avoid 3x "Pythia vs. Herwig"

Pythia vs. Herwig: Jet energy response

JEC "Flavor" uncertainty (7 TeV):
Pythia6 vs. Herwig++ for QCD

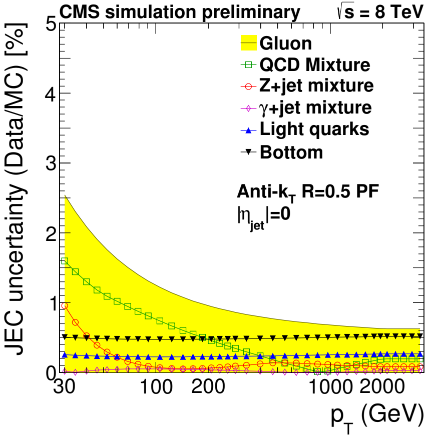
CMS-DP-2012-006



- 0.61 GeV shift in m_t

JEC "FlavorPureBottom" (8 TeV):
Pythia6 vs. Herwig++ for bottom

CMS-DP-2013-033



- 0.32 GeV shift in m_t

Lund string fragmentation

- $q_0\bar{q}_0$ pair spans string with tension $\kappa \approx 1$ GeV/fm
- On string break
  - Production of new $q_1\bar{q}_1$ pair
  - $f(z)$ = fraction of $(E + p_z)$ taken by hadron $q_0\bar{q}_1$
  - $p_{x,y}$: Gauss with $\sigma = 0.3$ GeV
- Light flavour

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

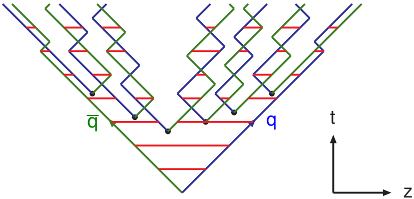
- Heavy flavour (Bowler extension)

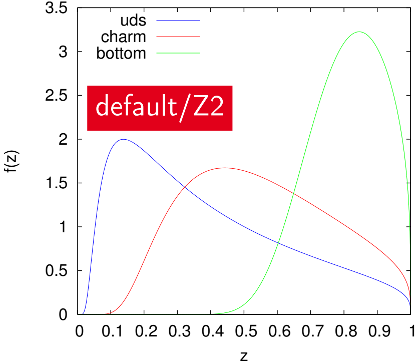
$$f(z) \propto \frac{1}{z^{1+r\cdot bm_\perp^2}}(1-z)^a \exp\left(\frac{-bm_\perp^2}{z}\right)$$

- Tunable parameters: a, b, r

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

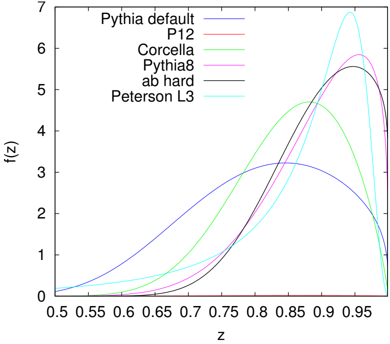
Motion of quarks and antiquarks in a $q\bar{q}$ system:





Fragmentation function for b-jets

Many functions on the market

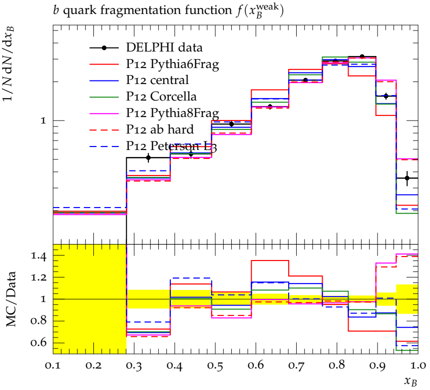


Expect impact on...

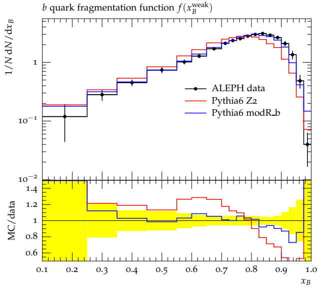
- measurements of B hadrons or their decay products
- b-tagging for jets
- b jet energy scale

Experimental observable

- Most useful: $x_B = E_B / E_{beam}$
- Measured in e^+e^- collisions at $\sqrt{s} = 91$ GeV



Assigning an uncertainty on b-fragmentation

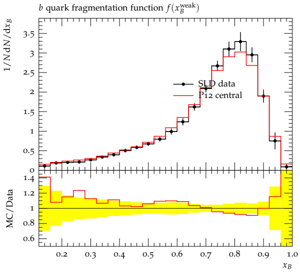


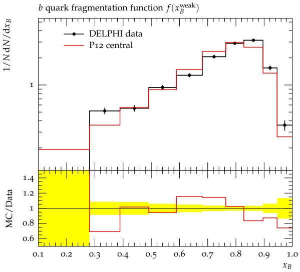
Variation based on Z2 $\rightarrow \delta m_t = 0.2$ GeV

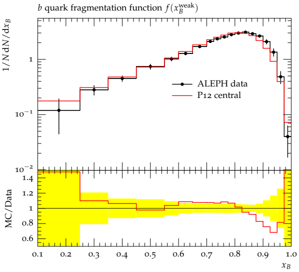
- r_b is relevant parameter for x_B hardness, leave others (a, b) untouched
- Tuned for improved agreement with x_B

Possible recipe for b-fragmentation uncertainty

- Retune r_b to minimal χ^2
- Compare SLD (left) vs. LEP (right)

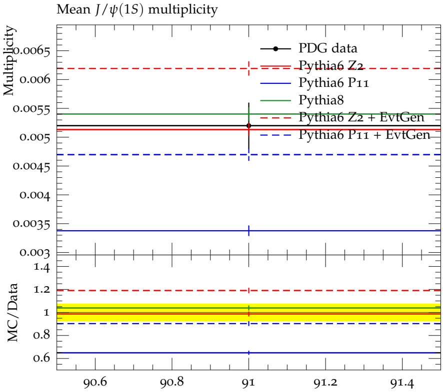






Improving B hadron decays with EvtGen?

- EvtGen from B physics for better modelling of hadron decays
- J/Ψ production
  - explicit: $B \to J/\Psi + X$
  - implicit: $B \to c\bar{c}\bar{s}\,(u/d)$ + subsequent flavour combination (probability for heavy spin-1 meson in hadronization)



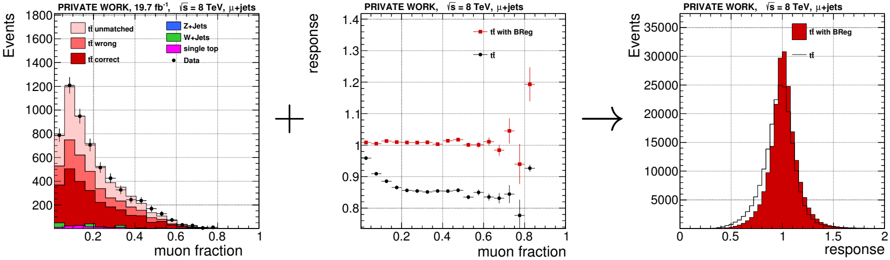
- EvtGen provides higher explicit branching ratios
  - Z2+EvtGen: J/Ψ rate too high
  - P11+EvtGen: J/Ψ rate ok; but too few B^*

- Some hadronization retuning needed for using EvtGen correctly

Improve on the analysis side: b-jet energy regression

Henning Kirschenmann

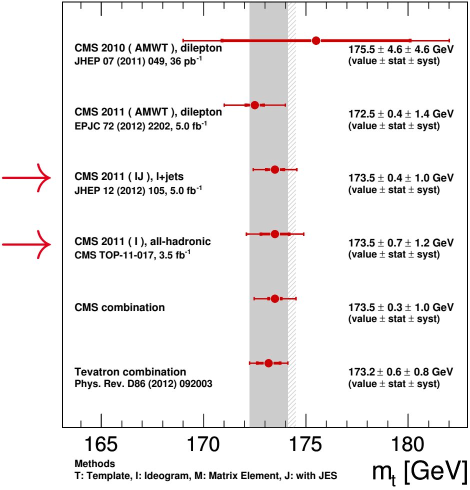
- Use jet properties to correct energies and get better resolution
- Example: lepton fraction inside jet $= p_T^{\ell}/p_T^{b}$
  - Indicates missing momentum from neutrino



- Improved statistical uncertainty of m_t
- Improved stability against some modelling uncertainties, e.g. semileptonic branching ratios

Summary

- Very precise measurements of m_t in lepton+jets and all-hadronic channels
- Perfect agreement with TevatronSummary, close in precision



Outlook

- Analyzing new 8 TeV data
- Working on improved understanding of systematic uncertainties