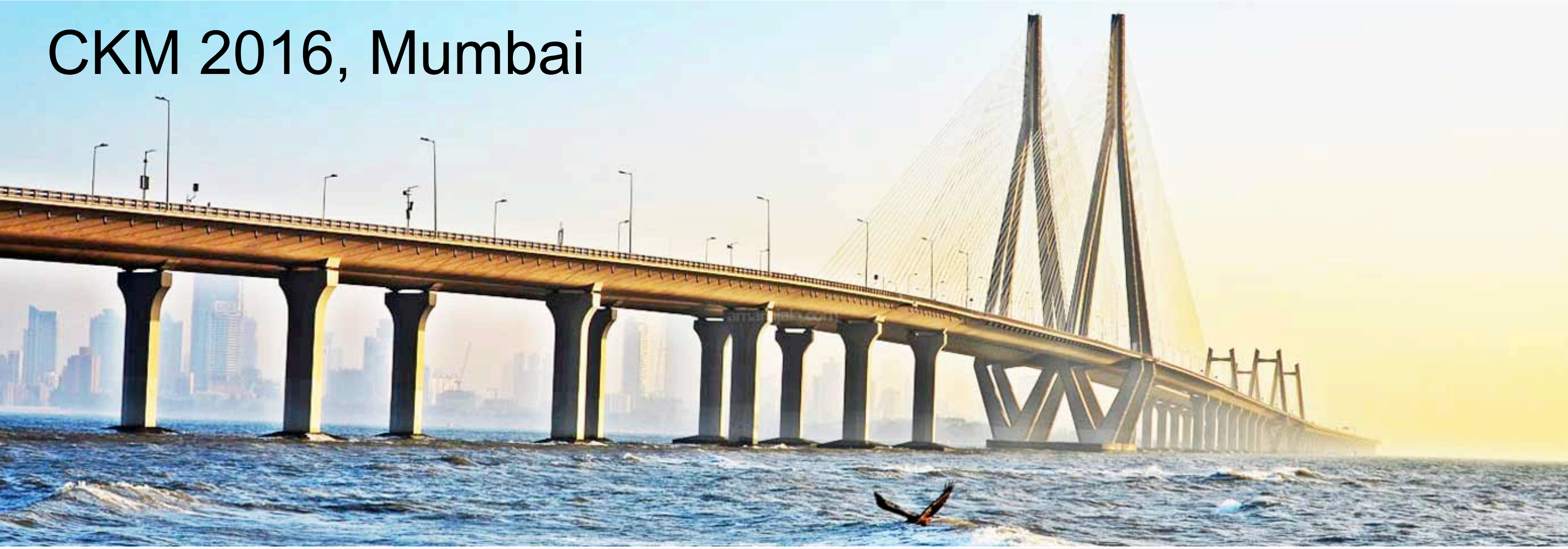
TOP QUARK MASS MEASUREMENTS FROM LHC + TEVATRON

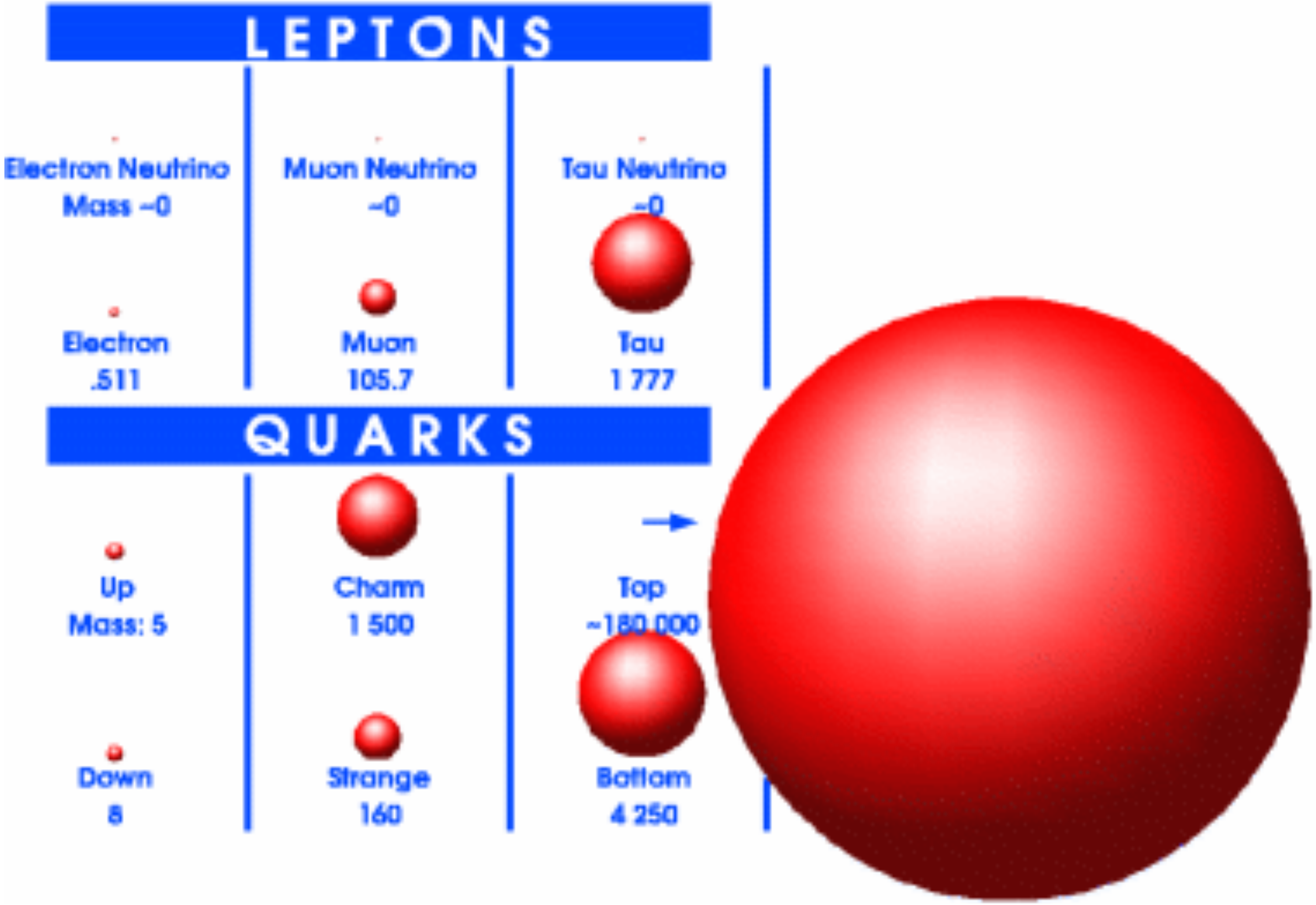
Oleg Brandt
30.11.2016

CKM 2016, Mumbai

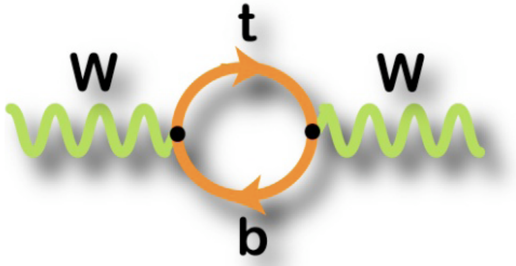


MOTIVATION & EXPERIMENTAL ASPECTS

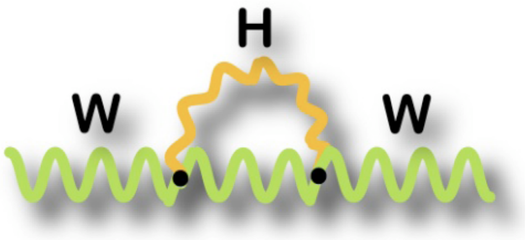
- The top quark mass (m_t) is a fundamental parameter of the SM
- The top quark is special:
  - heaviest quark of the SM!
  - heaviest fundamental particle known



- Special role in EW symmetry breaking?
  - M_W related to m_t & M_{Higgs}:

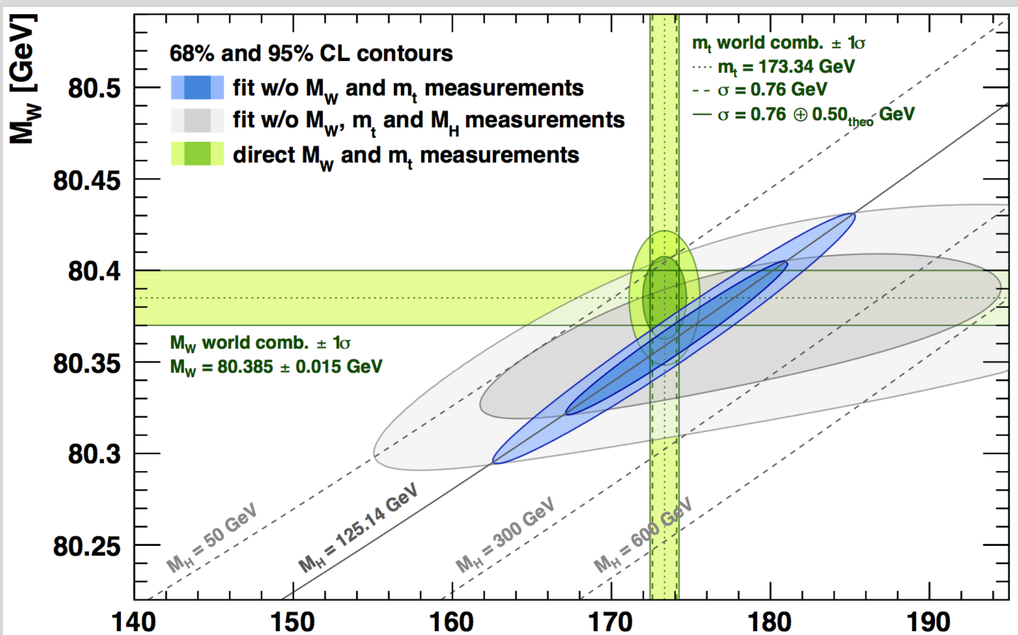


$\Delta M_W \propto M_{top}^2$



$\Delta M_W \propto \ln M_H$

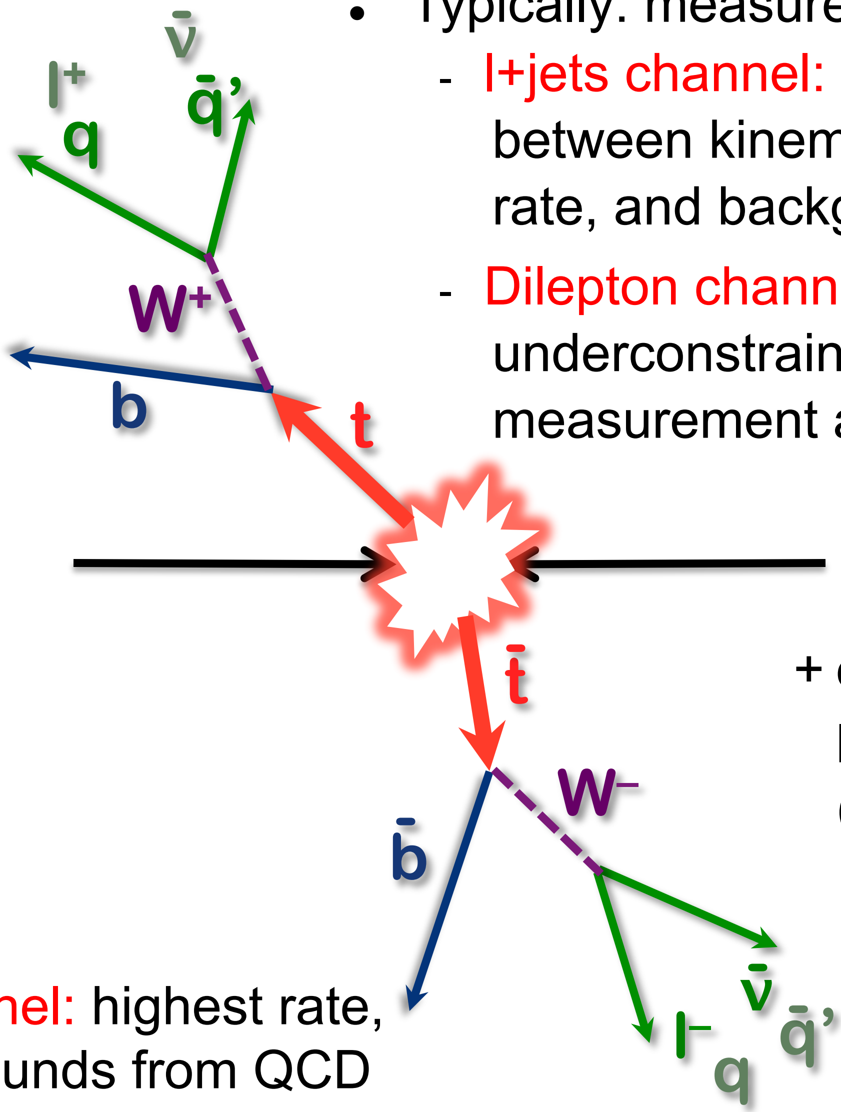
  - Overconstrain M_W, m_t, M_{higgs} Consistency check of the SM! →



Gfitter Coll., EPJC, **74** 3046 (2014)

Definition of decay channels

- Typically: measure m_t in tt events [1]:
  - l+jets channel: good compromise between kinematic reconstruction, high rate, and backgrounds
  - Dilepton channel: low backgrounds, but underconstrained kinematics for m_t measurement and low rate



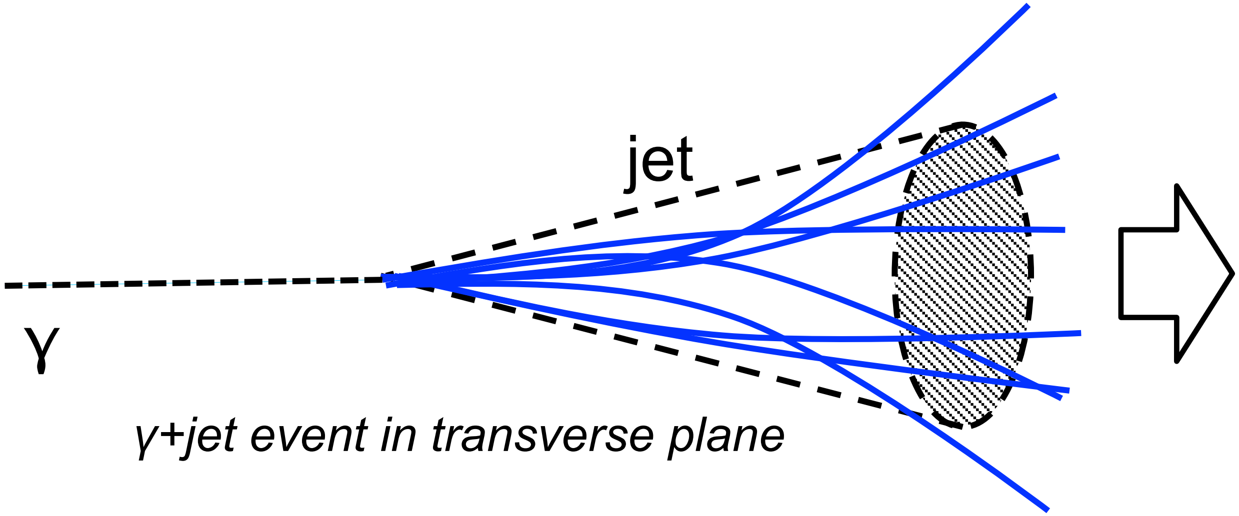
\+ electroweak single top production

(not shown in diagram)

- All-hadronic channel: highest rate, very high backgrounds from QCD multijet production

[1] *"bar" notation implicit throughout this talk*

- Generic procedure to calibrate jet energies:
  - 1) Calibrate EM energy scale with SM candles, i.e. $Z \to e^+e^-$
    - Central (well instrumented) region for absolute calibration
  - 2) Correct EM energy scale for e to that of γ
  - 3) γ+jet events to calibrate major JES components
    - Basic idea: momentum balance in transverse plane



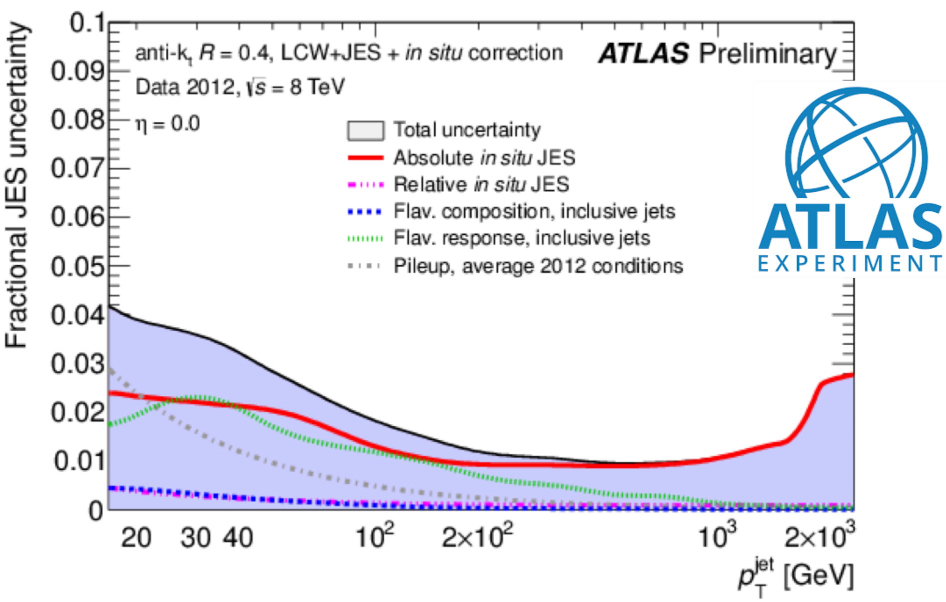
γ+jet event in transverse plane

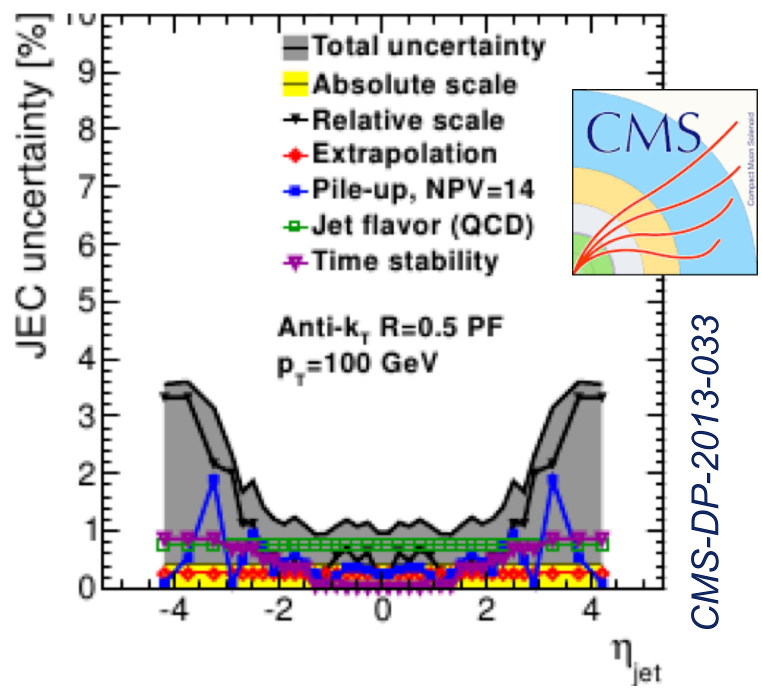
$$E^{\text{ptcl}} = \frac{E^{\text{meas}} - E_{\text{O}}}{R \cdot S}$$

- Alternatively use Z+jet events to calibrate JES
  - Use γ+jet, Z+jet, and dijets to extend calibration in p_T,η

JES CALIBRATION (II)

- Typically, JES uncertainty is dominant or next-to-dominant [1]
  - Pronounced dependence on η:
    - Better instrumentation for central η, $\Delta_{JES} \approx 1.5\%$
    - Upstream material & pile up for forward η, $\Delta_{JES} \approx 3\%$
  - Pronounced dependence on p_T:
    - Noise and pile up relevant for small p_T, $\Delta_{JES} \approx 5\%$
    - Extrapolation to p_T > 0.5 TeV (1.5 TeV) for Tevatron (LHC), $\Delta_{JES} \approx 3\%$



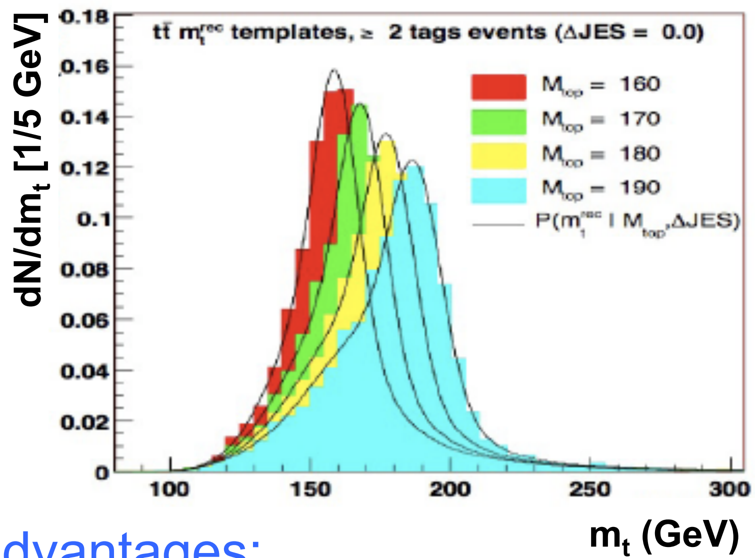


[1] *Δm_t is almost directly proportional to Δ_{JES}*

Direct measurements and methods

Template method:

- Exploit dependence of m_t on kinematic observables
  - Form templates using MC
  - Maximise consistency of templates with data given m_t



- Advantages:
  - Robust and straight-forward
- Drawback:
  - Sub-optimal sensitivity

Matrix element (ME) method:

- Directly calculate the event probability as:

$$P_{\rm evt}(m_{\rm top}) \propto f P_{\rm sig}(m_{\rm top}) + (1-f) P_{\rm bgr}$$

$$P_{\rm sig}(m_{\rm top}) \propto \int ... \mathrm{d}\sigma_{t\bar{t}}(m_{\rm top})$$

$$\mathrm{d}\sigma_{t\bar{t}} \propto |\mathcal{M}_{t\bar{t}}|^2(m_{\rm top})$$

- Advantages:
  - Use full 4-vectors → maximal use of information
  - Theory assumptions
- Drawback:
  - Computationally intensive
  - Theory assumptions

Ideogram method

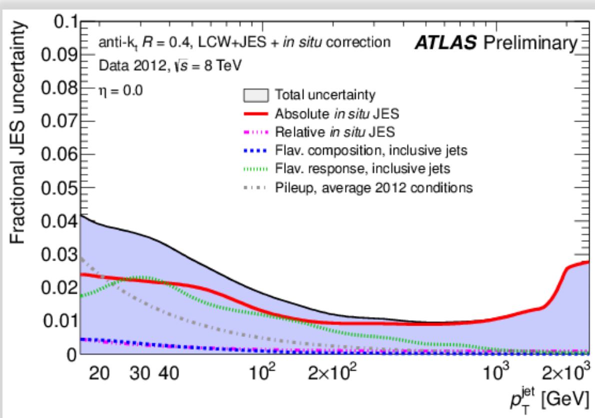
- in-between the two

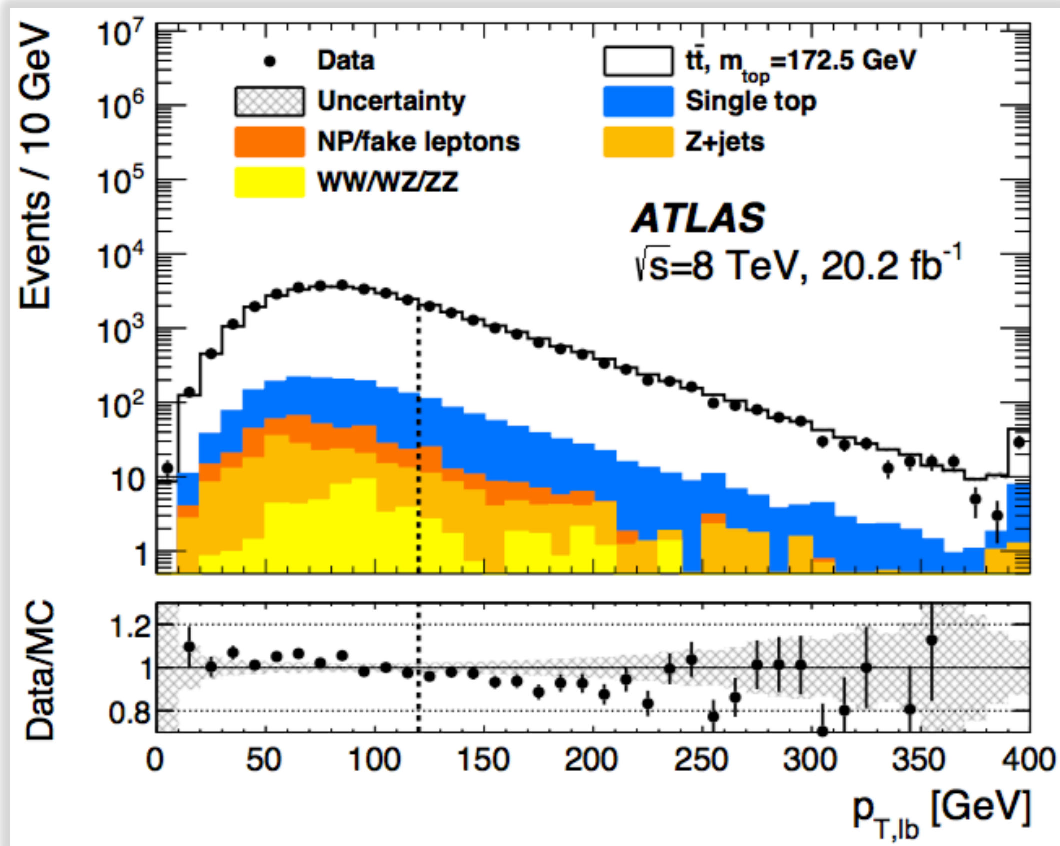
DILEPTON CHANNEL

DILEPTON CHANNEL (ATLAS) [1]

- **ATLAS dilepton channel, 20.2 fb^{-1} @ 8 TeV [1]**
- Selection (typical for such analyses):
  - 2 opposite-sign *e* or μ, high p_T, $M_{ee,\mu\mu}$ away from Z, γ
  - ≥2 jets, ≥1 *b*-tag
  - Lots of energy $\Sigma_{e,\mu,jets}\, p_T$
  - Neutrinos: E_T^{miss}
  - average $p_{T,\ell b} > 120$ GeV.
    - Better JES precision!

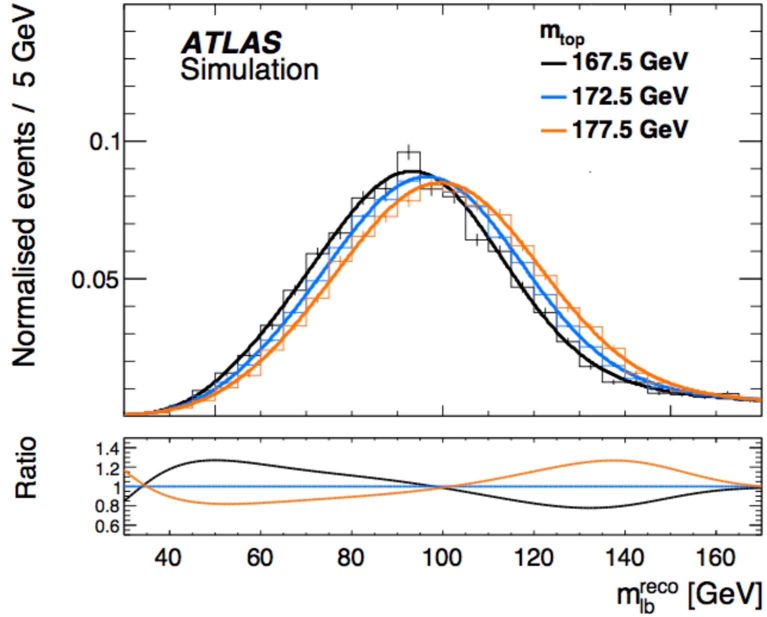
[1] *PLB* ***761*** *(2016) 350*

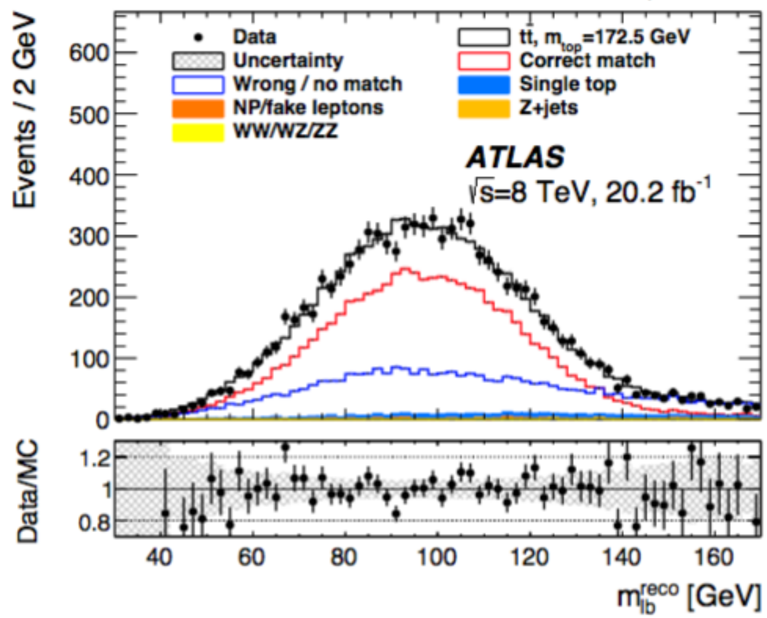




- → Reduce systematics

- **Extraction of m_t:**
  - Template method using $m_{\ell b}$:
    - Average invariant mass of charged lepton ℓ=e,μ and *b* jet system
    - Reduced sensitivity to systematic uncertainties
  - Signal template (tt and single-top)
    - Gaussian+Landau
  - Background template
    - Landau

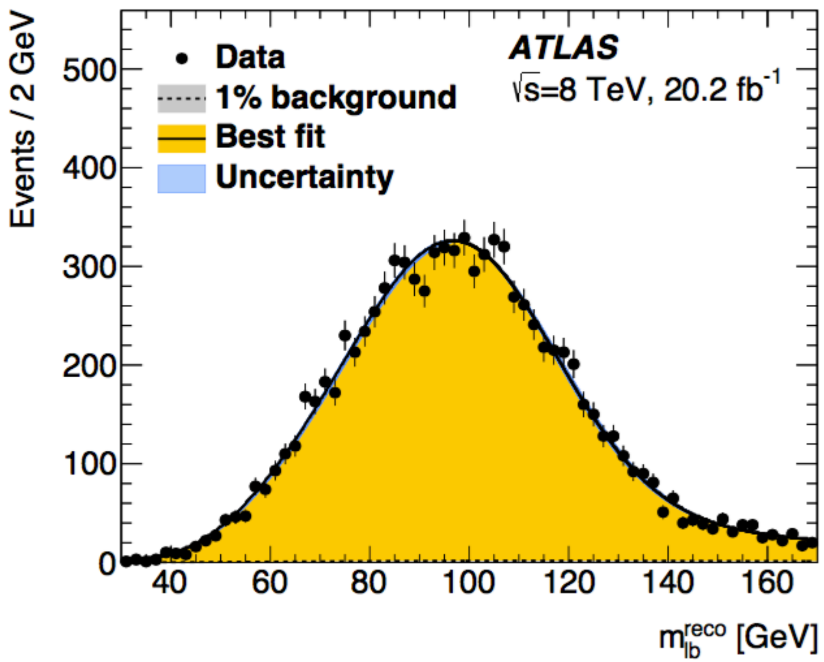




[1] *PLB* ***761*** *(2016) 350*

- **Result:** $\Delta m_t/m_t = 0.49\%!$

$$m_t = 172.99 \pm 0.41\ (\text{stat}) \pm 0.74\ (\text{syst})\ \text{GeV}$$



- **Dominant uncertainties:**
  - JES (0.54 GeV)
  - b-quark JES (0.30 GeV)
  - ISR/FSR (0.23)

Results	172.99
Statistics	0.41
Method	0.05 ± 0.07
Signal Monte Carlo generator	0.09 ± 0.15
Hadronisation	0.22 ± 0.09
Initial- and final-state QCD radiation *"ISR/FSR"*	0.23 ± 0.07
Underlying event	0.10 ± 0.14
Colour reconnection	0.03 ± 0.14
Parton distribution function	0.05 ± 0.00
Background normalisation	0.03 ± 0.00
W/*Z*+jets shape	0
Fake leptons shape	0.08 ± 0.00
Jet energy scale	0.54 ± 0.04
Relative *b*-to-light-jet energy scale	0.30 ± 0.01
Jet energy resolution	0.09 ± 0.05
Jet reconstruction efficiency	0.01 ± 0.00
Jet vertex fraction	0.02 ± 0.00
b-tagging	0.03 ± 0.02
Leptons	0.14 ± 0.01
E_T^{miss}	0.01 ± 0.01
Pile-up	0.05 ± 0.01
Total systematic uncertainty	0.74 ± 0.29
Total	0.84 ± 0.29

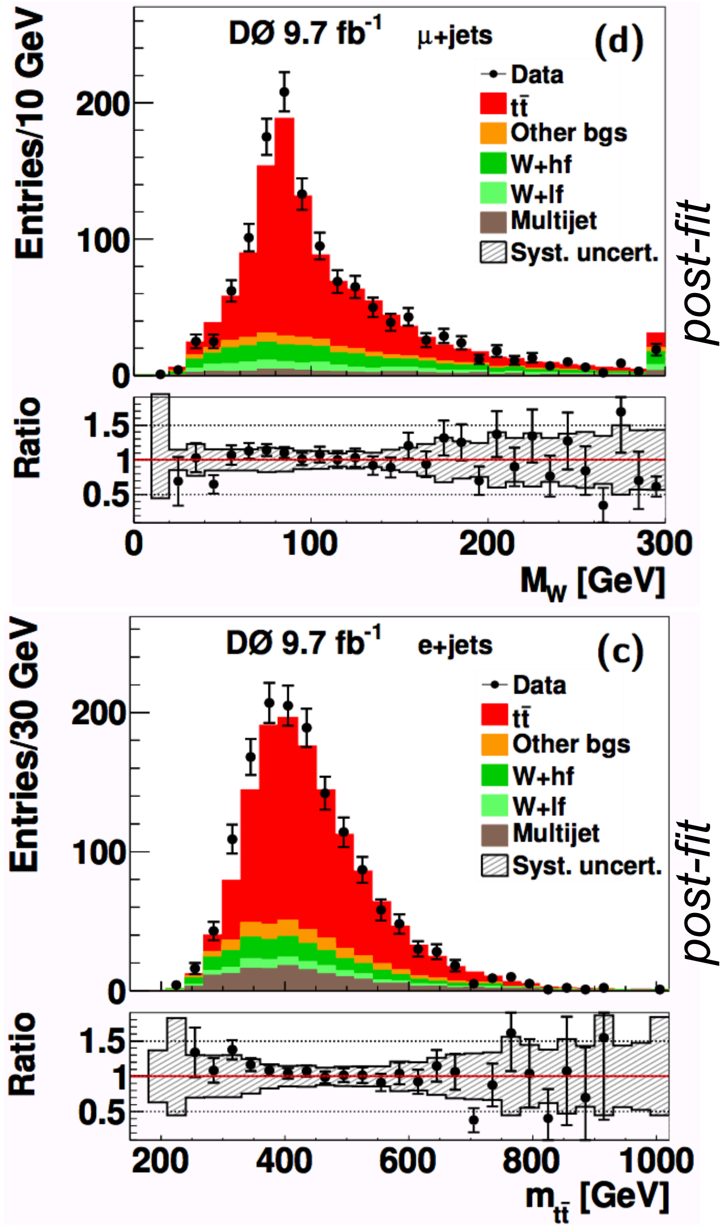
[1] *PLB **761** (2016) 350*

LEPTON+JETS CHANNEL

- **DØ l+jets channel, 9.7 fb^{-1} @ 1.96 TeV [1]**
- Selection:
  - 1 high-p_T e or μ
  - ==4 jets, at least one b-tag
    - Matches the LO picture
    - Reduced ISR/FSR systematics!
  - Topological cuts on $\not\!\!E_T$, scalar sum p_T, …
- **Extraction of m_t:**
  - Matrix Element method:

$$P_{\rm evt}(m_{\rm top}) \propto f P_{\rm sig}(m_{\rm top}) + (1-f) P_{\rm bgr}$$

    - (details next slide)



[1] *PRL* ***113****, 032002 (2014), PRD* ***91****, 112003 (2015)*

- **Matrix element method in a nutshell:**

Sum over 24 possible jet-parton assignments

b tag-based weight: identify relevant jet-parton assignments

Integration over phase space (10 dim)

$$P_{\text{sig}} = \frac{1}{\sigma_{\text{obs}}^{t\bar{t}}} \sum_{i=1}^{24} w_i \int d\rho\, dm_1^2\, dM_1^2\, dm_2^2\, dM_2^2\, d\rho_\ell\, dq_1^x\, dq_1^y\, dq_2^x\, dq_2^y$$

$$\sum_{\text{flavors},\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f'(q_1) f'(q_2)}{\sqrt{(\eta_{\alpha\beta} q_1^\alpha q_2^\beta)^2 - m_{q_1}^2 m_{q_2}^2}} \Phi_6 W(x, y; k_{\text{JES}})$$

LO matrix element
PRD **53**, 4886 (1996)
PLB **411**, 173 (1997)

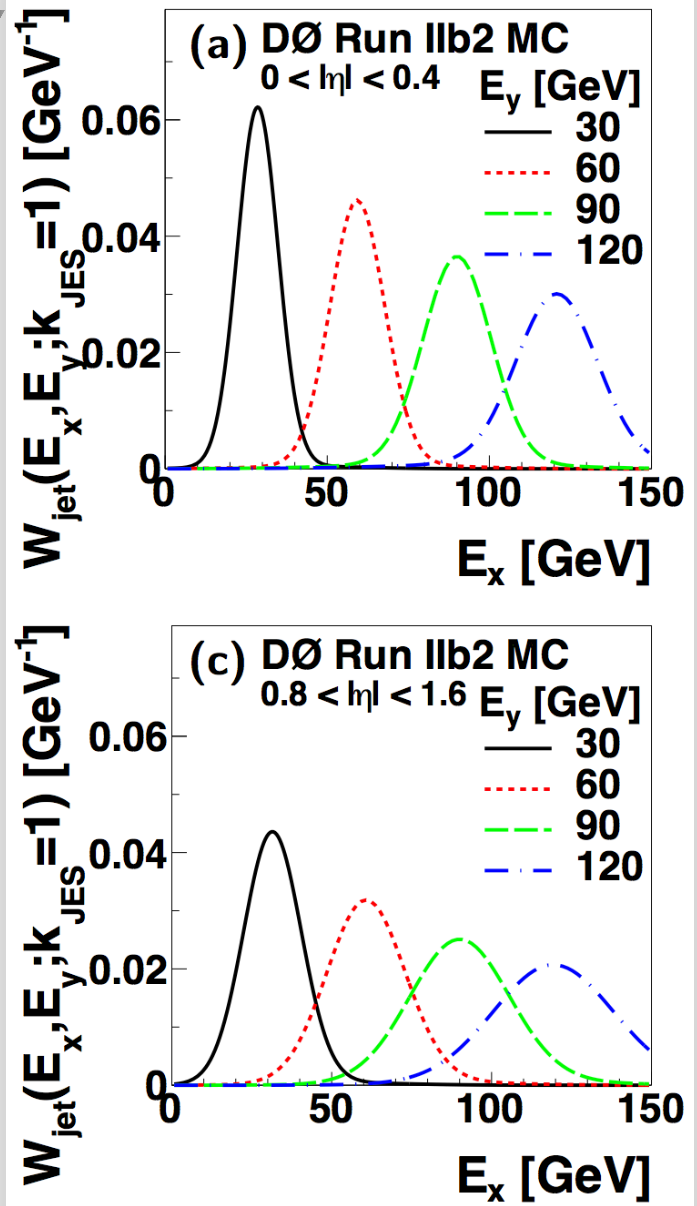
Phase space factor

Transfer functions to map
parton level quantities *y* to reco level quantities *x*

[1] *PRL **113**, 032002 (2014), PRD **91**, 112003 (2015)*

KIRCHHOFF-INSTITUT FÜR PHYSIK

- **Map parton-level** variables *x* to detector-level *y*
  - Transfer function for lepton and jet energies
  - Directions well-measured

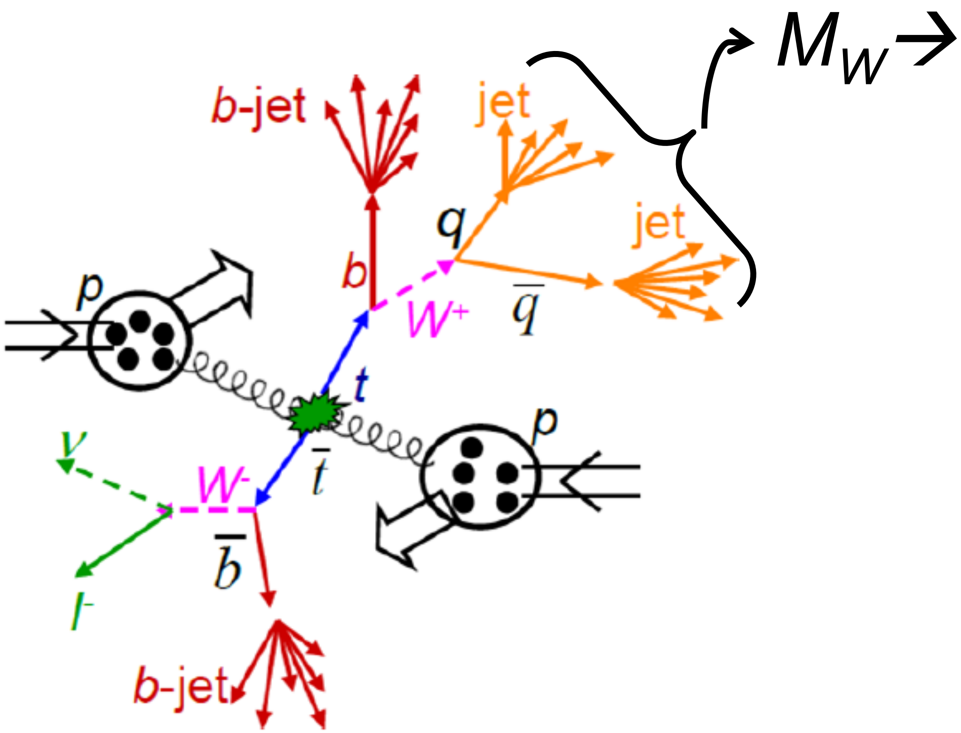


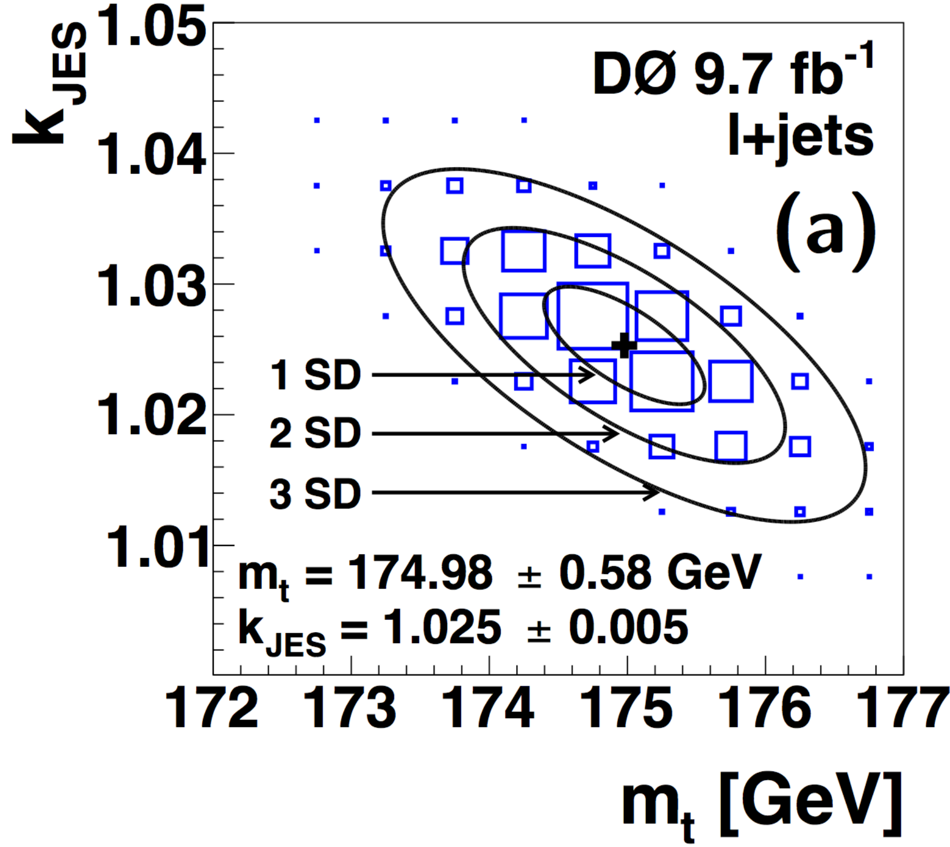
- **Address computational challenge** (10-dim integral):
  - importance sampling [1]
  - low-discrepancy sequences [1]
  - etc.
- → Computation time reduced by 90x
  - → can employ at LHC!
- → Eliminate systematics from MC statistics:
  - ≈ 0.25 GeV → 0.01–0.05 GeV

[1] *PRL **113**, 032002 (2014), PRD **91**, 112003 (2015)*
[2] *OB, G. Gutierrez, MHLS Wang, Z. Ye, NIM A **775** 27 (2015)*

LETPON+JETS CHANNEL (DØ) [1]

- **In-situ calibration of JES:**





- **Result:**

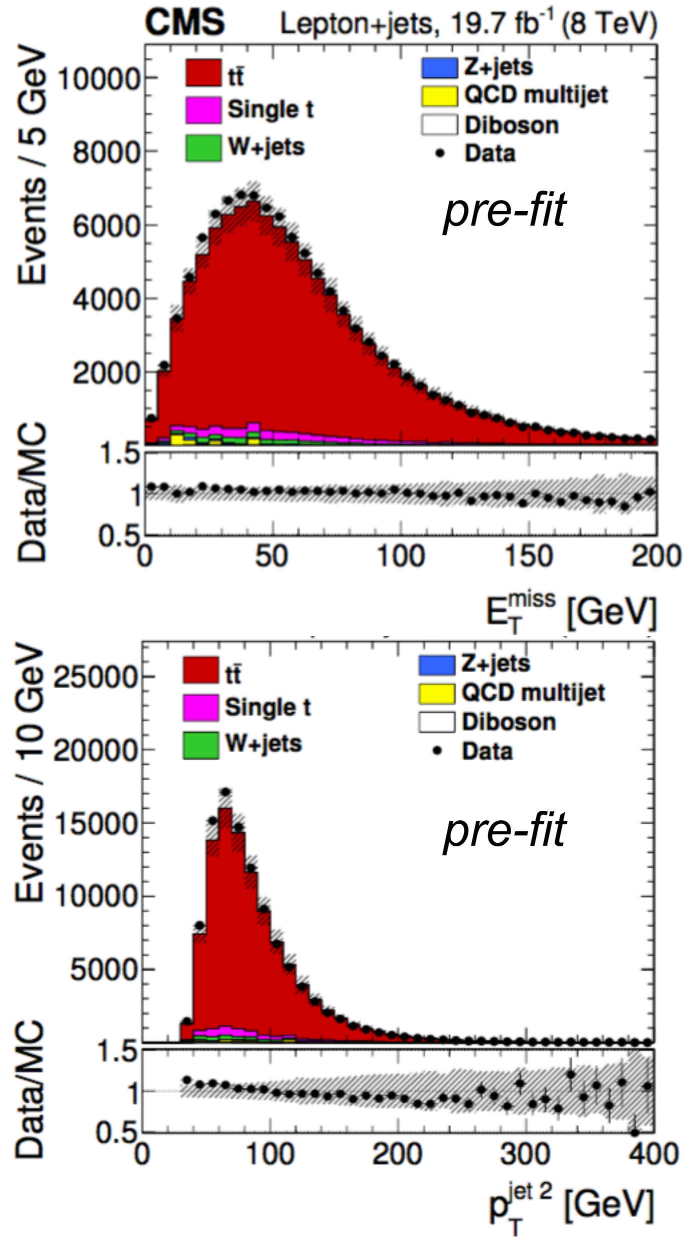
$$m_t = 174.98 \pm 0.58\ (\mathrm{stat} + \mathrm{JES}) \pm 0.49\ (\mathrm{syst})\ \mathrm{GeV}$$

- **Dominant uncertainties:**
  - Hadronisation and underlying event (0.26 GeV)
  - Residual JES (0.21 GeV)
  - b-quark JES (0.16 GeV)

$$\Delta m_t / m_t = 0.43\%!$$

Most precise Tevatron result

- **CMS l+jets channel, 19.7 fb^{-1} @ 8 TeV [1]**
- Selection:
  - Similar to DØ, main difference:
    - 2 b-tags
      - High signal purity: 97%



- **Extraction of m_t:**
  - Ideogram method

$$\mathcal{L}\left(\text{event}|m_t,\text{JSF}\right) = \sum_{i=1}^{n} P_{\text{gof}}\left(i\right) P_{\text{sig}}\left(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}}|m_t,\text{JSF}\right)$$

"ideogramm"

- P_{sig} from MC (like template method)
  - Maximise likelihood in m_t and JES ("JSF")

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

- Higher weight to well-measured events

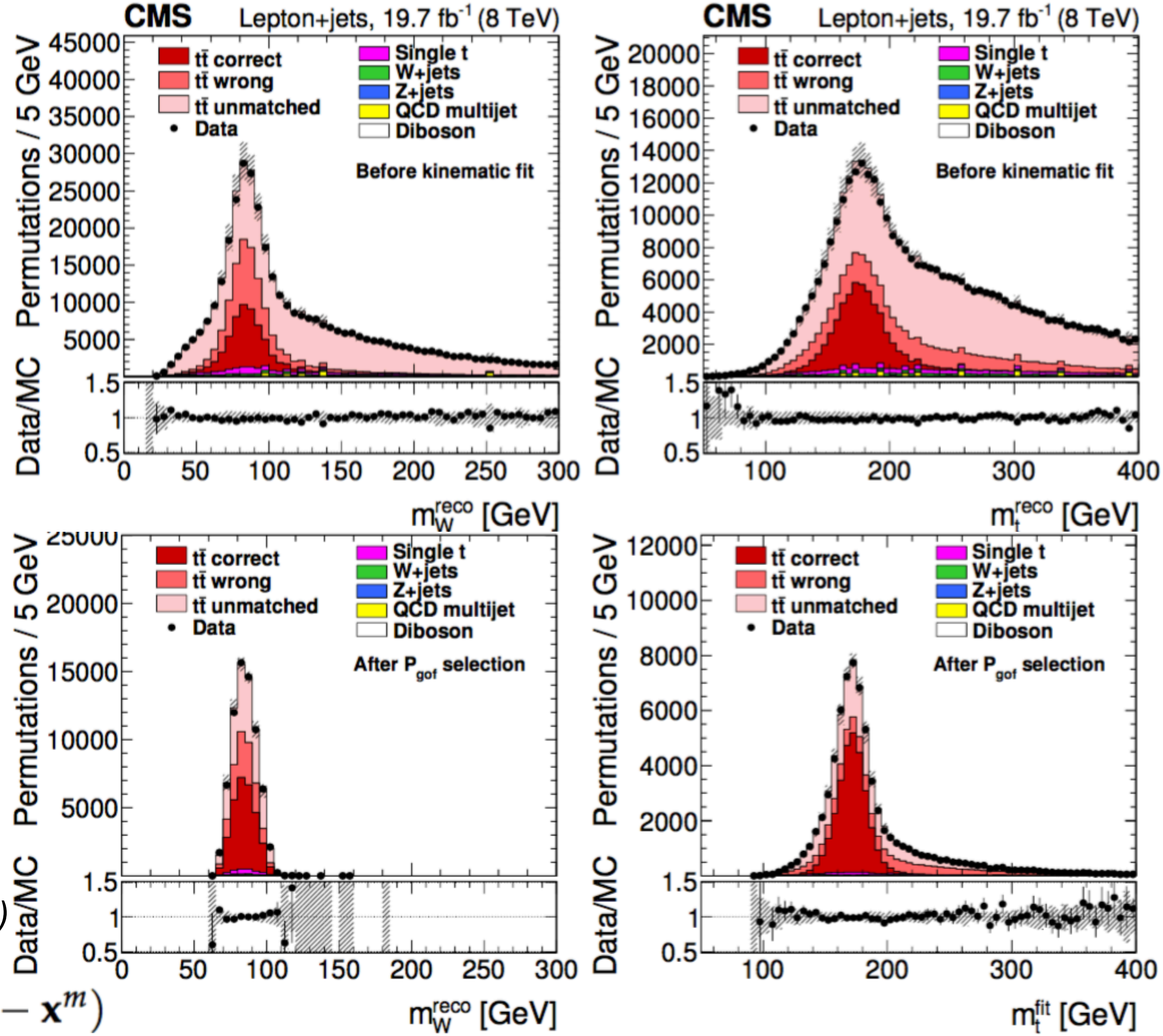
[1] *PRD **93**, 072004 (2016)*

LEPTON+JETS CHANNEL (CMS) [1]

Select only events with high goodness-of-fit probability

$$P_{\text{gof}} = e^{-\frac{1}{2}\chi^2} > 0.2$$

(probability for correct reconstruction + matching + in-situ JES calibration)

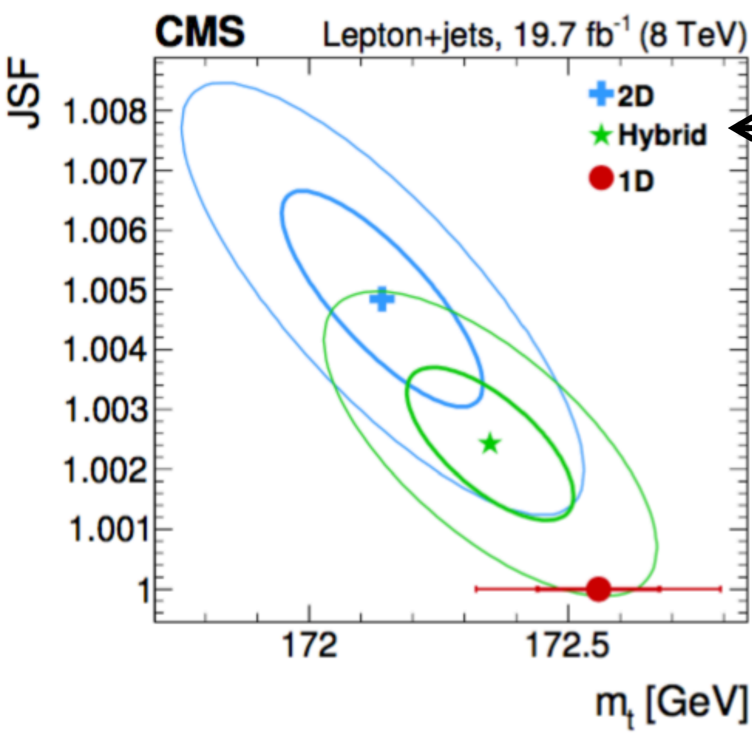


[1] *PRD* ***93****, 072004 (2016)*
[2] P_{gof} calculated from

$$\chi^2 = (\mathbf{x} - \mathbf{x}^m)^T E^{-1} (\mathbf{x} - \mathbf{x}^m)$$

LEPTON+JETS CHANNEL (CMS) [1]

- **Result:** $m_t^{\text{hyb}} = 172.35 \pm 0.16\,(\text{stat+JSF}) \pm 0.48\,(\text{syst})\ \text{GeV}$



Most precise LHC result:
$\Delta m_t / m_t = 0.30\%!$

"Hybrid":
in-situ JES and standard JES constraints

Experimental uncertainties	
Method calibration	0.04
Jet energy corrections	
– JEC: Intercalibration	+0.01
– JEC: In situ calibration	+0.12
– JEC: Uncorrelated non-pileup	−0.10
– JEC: Uncorrelated pileup	−0.04
Lepton energy scale	+0.01
E_T^{miss} scale	+0.04
Jet energy resolution	−0.03
b tagging	+0.06
Pileup	−0.04
Backgrounds	+0.03
Modeling of hadronization	
JEC: Flavor-dependent	
– light quarks (u d s)	+0.05
– charm	+0.01
– bottom	−0.32
– gluon	−0.08
b jet modeling	
– b fragmentation	<0.01
– Semileptonic b hadron decays	−0.16
Modeling of perturbative QCD	
PDF	0.04
Ren. and fact. scales	-0.09 ± 0.07
ME-PS matching threshold	$+0.03 \pm 0.07$
ME generator	-0.12 ± 0.08
Top quark p_T	+0.02
Modeling of soft QCD	
Underlying event	$+0.08 \pm 0.11$
Color reconnection modeling	$+0.01 \pm 0.09$
Total systematic	0.48
Statistical	0.16
Total	0.51

- **Dominant uncertainties:**
  - *b*-quark JES (0.32 GeV)
  - JES (0.16 GeV)
  - tt event generator (0.12)

[1] *PRD* ***93****, 072004 (2016)*

Lepton+jets channel (CMS) [1]

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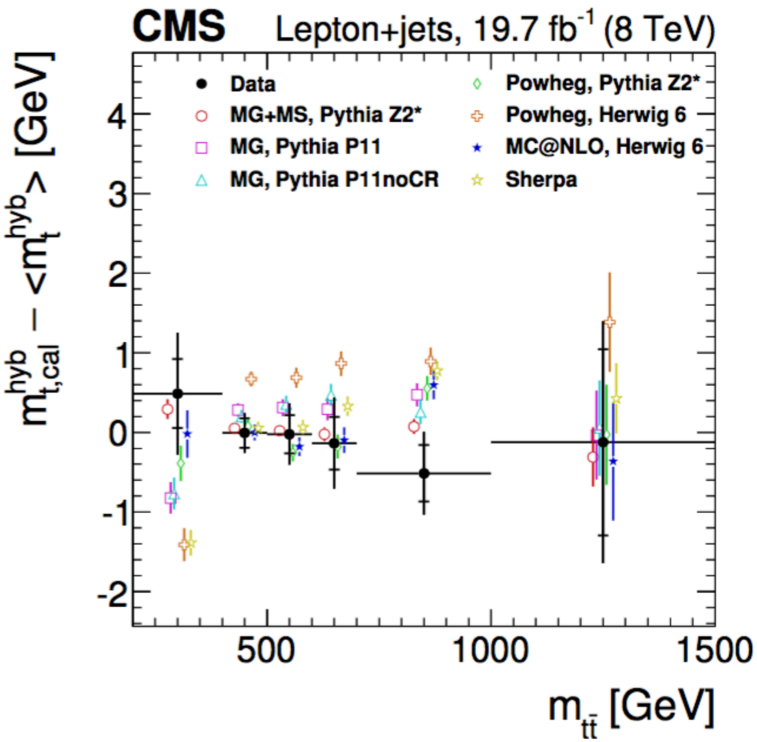

Most precise LHC result: $\Delta m_t / m_t = 0.30\%$!

Cross-check:
extract m_t in different phase space regions + using different tt MC generators
→ all consistent *(slides 63-64)*

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[1] *PRD* ***93****, 072004 (2016)*

ALL-HADRONIC CHANNEL

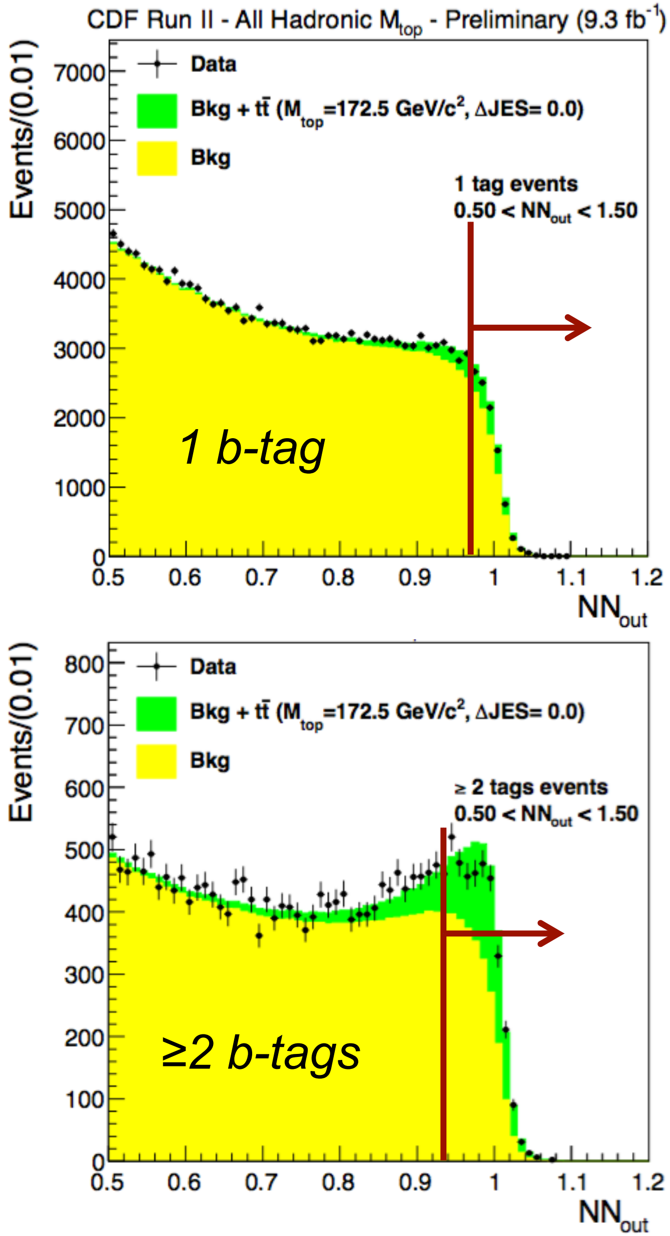
ALL-HADRONIC CHANNEL (CDF) [1]

- **CDF all-hadronic, 9.3 fb^{-1} @ 1.96 TeV [1]**
- Pre-selection (purity ≈1/700):
  - No *e* or ***μ*** candidate
  - No neutrinos:

$$\not{E}_T/\sqrt{\sum E_T} < 3\ \mathrm{GeV}^{\frac{1}{2}}$$

  - $6 \le N_{jet} \le 8$

- **Selection** (purity ≈1/3 for 2 b-tags)**:**
  - Neural network based on:
    - Jet shapes (width, depth)
    - Kinematics (max m_{jj}, max m_{jjj}, …)
    - Topology (centrality, aplanarity, …)
  - ≥1 *b*-tags



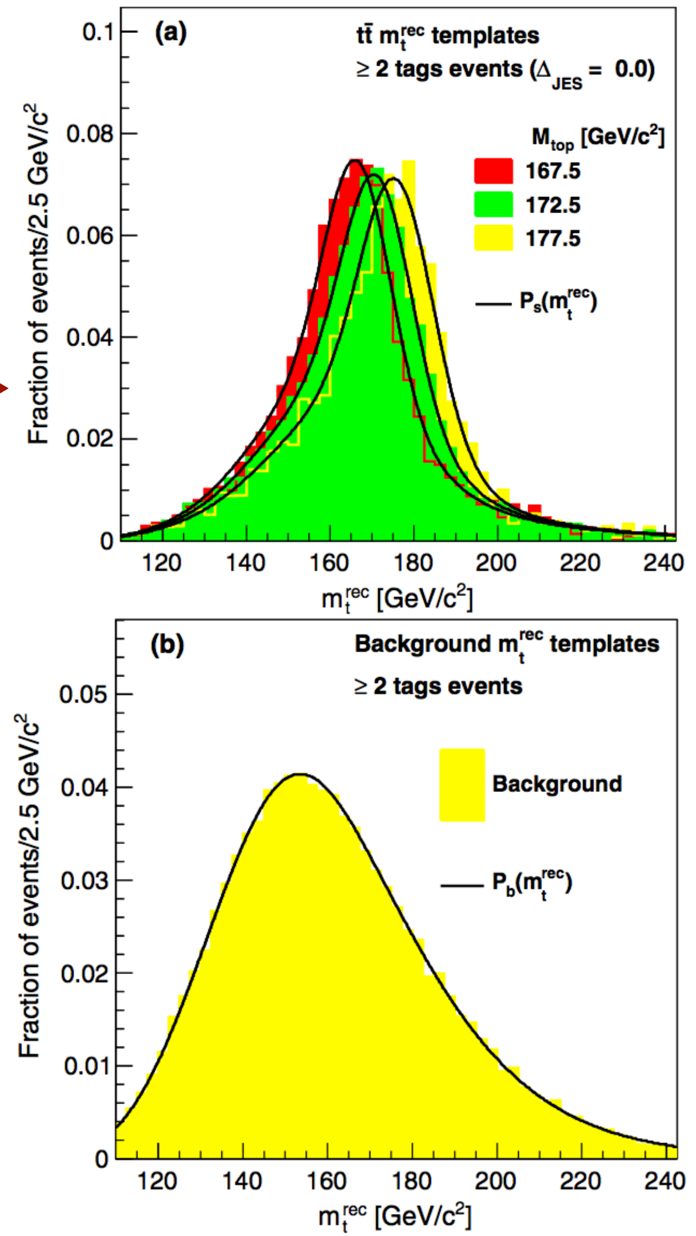
[1] *PRD* ***90****, 091101(R) (2014)*

- **Extraction of m_t:**
  - Reconstruction through kinematic fit:

$$\chi_t^2 = \frac{(m_{jj}^{(1)} - M_W)^2 c^4}{\Gamma_W^2} + \frac{(m_{jj}^{(2)} - M_W)^2 c^4}{\Gamma_W^2} + \frac{(m_{jjb}^{(1)} - m_t^{\text{rec}})^2 c^4}{\Gamma_t^2} + \frac{(m_{jjb}^{(2)} - m_t^{\text{rec}})^2 c^4}{\Gamma_t^2} + \sum_{i=1}^{6} \frac{(p_{T,i}^{\text{fit}} - p_{T,i}^{\text{meas}})^2}{\sigma_i^2},$$

Input to the fit

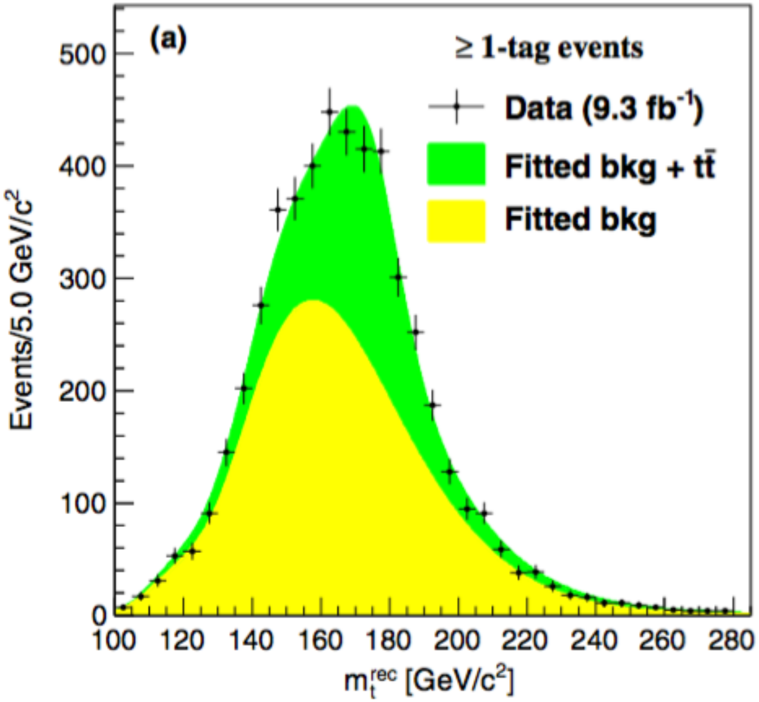
  - Template method using m_t^{rec}
  - Background template from data
    - Signal-depleted multijet events
      - Promote jets to be "*b*-tagged"
        - Account for correlations



[1] *PRD* **90**, *091101(R) (2014)*

- **Result:**

$$M_{\rm top} = 175.07 \pm 1.19({\rm stat})\,^{+1.55}_{-1.58}({\rm syst})\ {\rm GeV}$$



- **Dominant uncertainties:**
  - Trigger (0.61 GeV)
  - Residual JES (0.57 GeV)
  - Colour reconnection (0.32)

$$\Delta m_t/m_t = 1.1\%$$

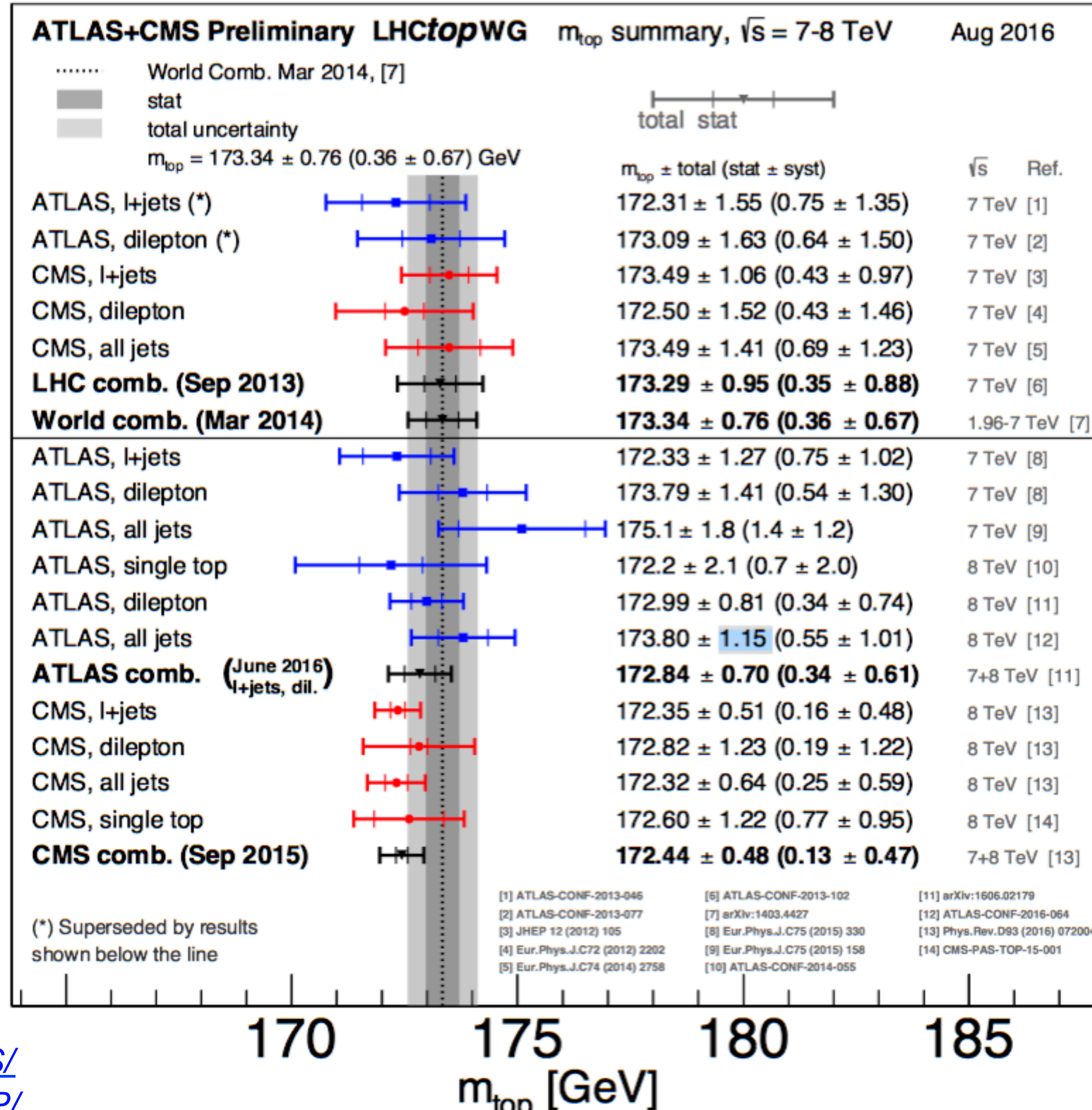
Source	$\sigma_{M_{\rm top}}$ (GeV/c^2)
Generator (hadronization)	0.29
Parton distribution functions	$^{+0.18}_{-0.36}$
Initial/Final state radiation	0.13
Color reconnection	0.32
$\Delta_{\rm JES}$ fit	0.97
$M_{\rm top}$ fit	...
Other free parameters of the fit	0.41
Templates sample size	0.34
$t\bar{t}$ cross section	0.15
Integrated luminosity	0.15
Trigger	0.61
Background shape	0.15
b tagging	0.04
b-jets energy scale	0.20
Pileup	0.22
Residual JES	0.57
Residual bias/Calibration	$^{+0.27}_{-0.24}$
Total	$^{+1.55}_{-1.58}$

[1] *PRD* ***90**, 091101(R) (2014)*

OVERVIEW:

DIRECT TOP MASS MEASUREMENTS

Representative results shown today are only a small fraction from a wealth of m_t measurements!



***References to individual analyses** given at the bottom of the plot and*
[*https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/*](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/)

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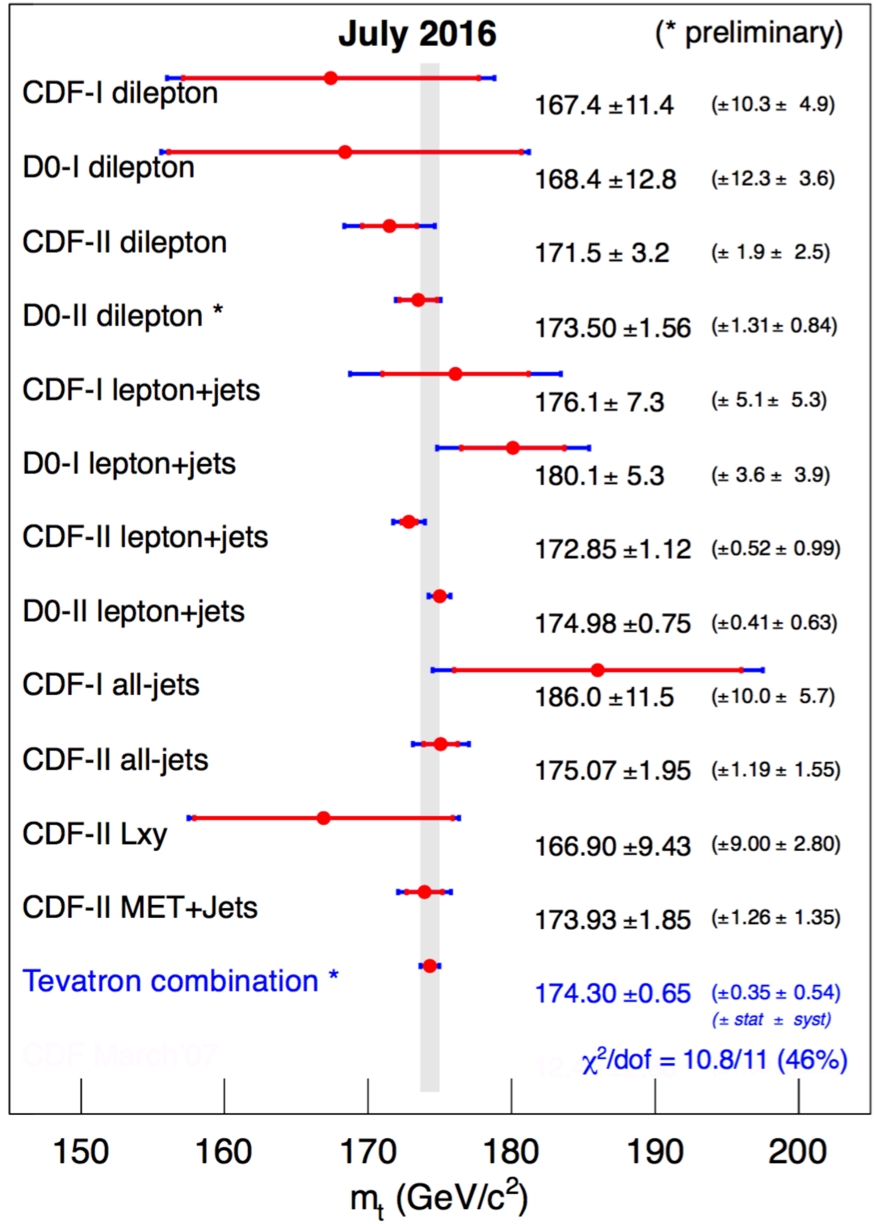
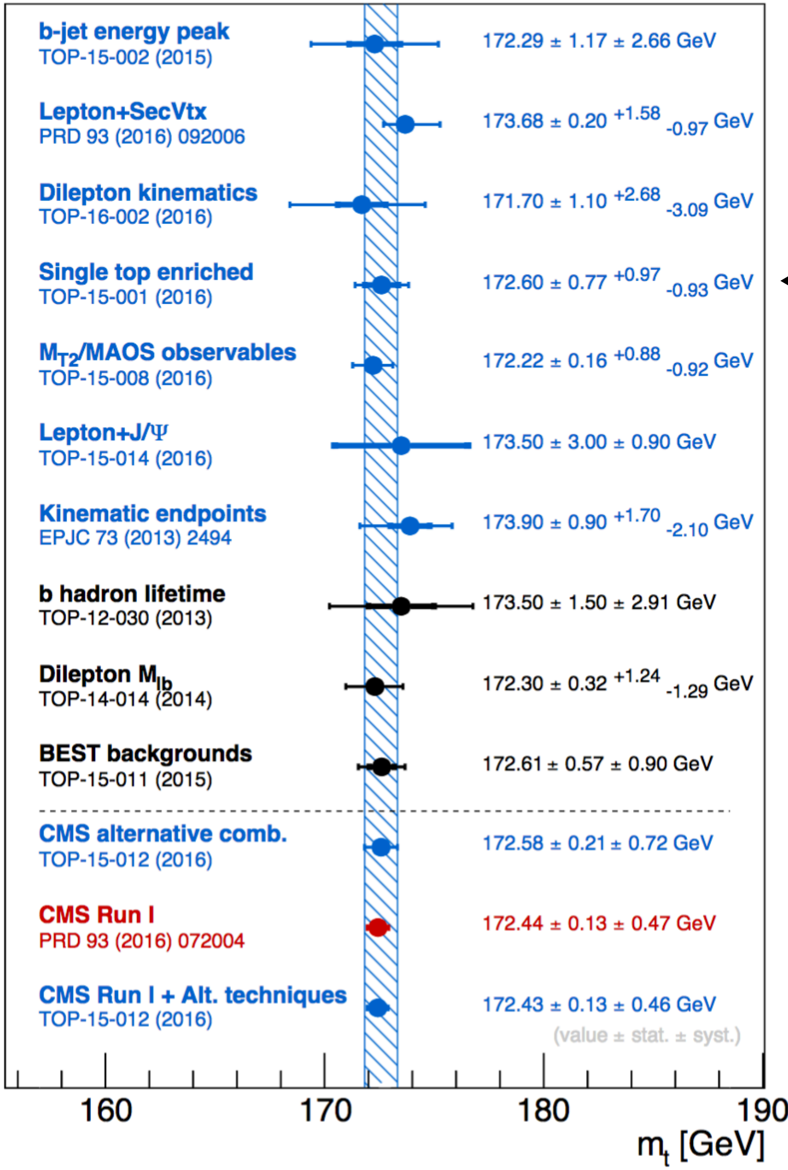


References to individual analyses
from the Tevatron m_t combination note arXiv:1608.01881, or CDF Note 11204, or DØ Note 6486

Alternative measurements (CMS)



← *Same idea as ATLAS-CONF-2014-055*

$$m_t = 172.2 \pm 0.7\ (\text{stat}) \pm 2.0\ (\text{syst})\ \text{GeV}$$

Tevatron alternative results not listed explicitly (no recent updates)

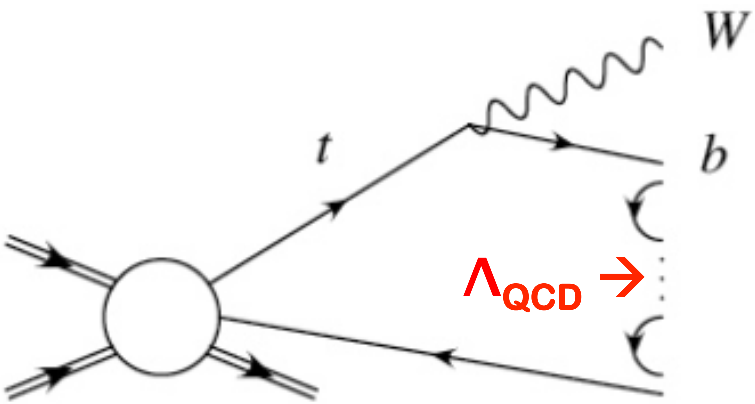
TOP QUARK MASS MEASUREMENTS IN THE POLE MASS SCHEME

- m_t is not an observable but a SM parameter
  - → inferred from its effect on kinematic observables
  - → not well-defined concept at LO
- **Pole mass concept:**

$$\frac{i\left(\not{p}_t + m_t\right)}{p_t^2 - m_t^2} = \frac{i}{\not{p}_t - m_t}$$

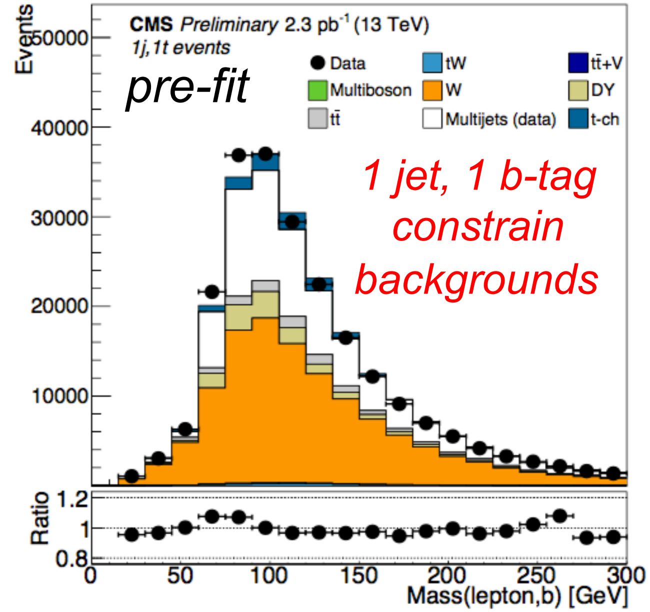
← *"Pole" in the top quark propagator*

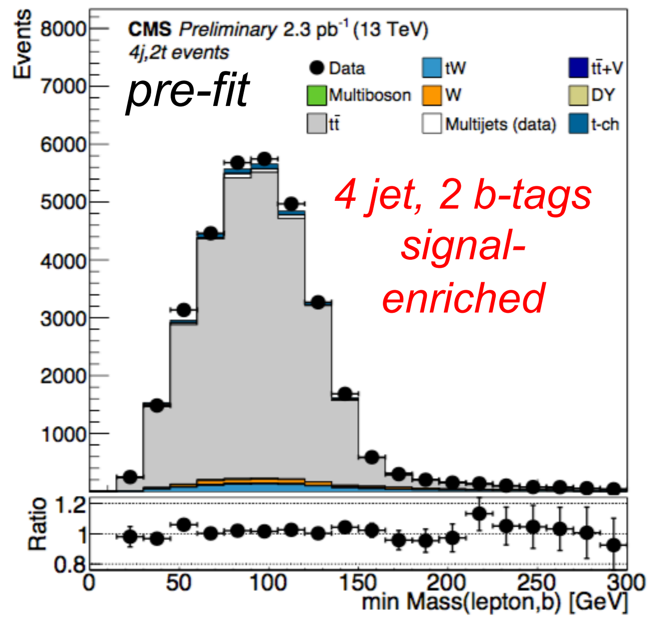
  - Not exact (but hadronisation effects small, o(Λ_{QCD}))
  - Direct measurements (shown so far):
    - m^{MC} (neither MS, nor pole mass)
    - "Close" to pole mass (≈0.5 GeV)
    - True also for "NLO generators", e.g. Powheg
      - Top decay not simulated at NLO



- **Next slides:**
  - Measurements of m_t in the pole mass scheme

- **Experiment** (CMS):
  - Measurement of σ_{tt} as a function of m_t [1], $\Delta\sigma_{tt}^{exper}$: ≈4%!
- **Theory**:
  - NNLO+NNLL calculation [2], $\Delta\sigma_{tt}^{theory}$: ≈3%!
- **Selection:**
  - Similar to m_t result in l+jets @ 8 TeV
  - Main difference:
    - Include low jet multiplicity & *b*-tag bins
      - → constrain *W*+jets, single top, etc. from sidebands in data
- **Observable for σ_{tt} extraction:**
  - $m_{\ell b}$ or min($m_{\ell b}$)





[1] *CMS-PAS-TOP-16-006*

[2] *PRL **110**, 252004 (2013)*

KIRCHHOFF-INSTITUT FÜR PHYSIK

*Similar ATLAS analysis EPJC **74**, 3109 (2014)*
[1] *CMS-PAS-TOP-16-006*

- **Ansatz** for m_t extraction:

$$\mu(m_t) = \frac{\sigma(m_t)}{\sigma_{th}} \cdot \frac{A}{A(m_t)} \quad \text{with} \quad \mu = \sigma/\sigma_{th}$$

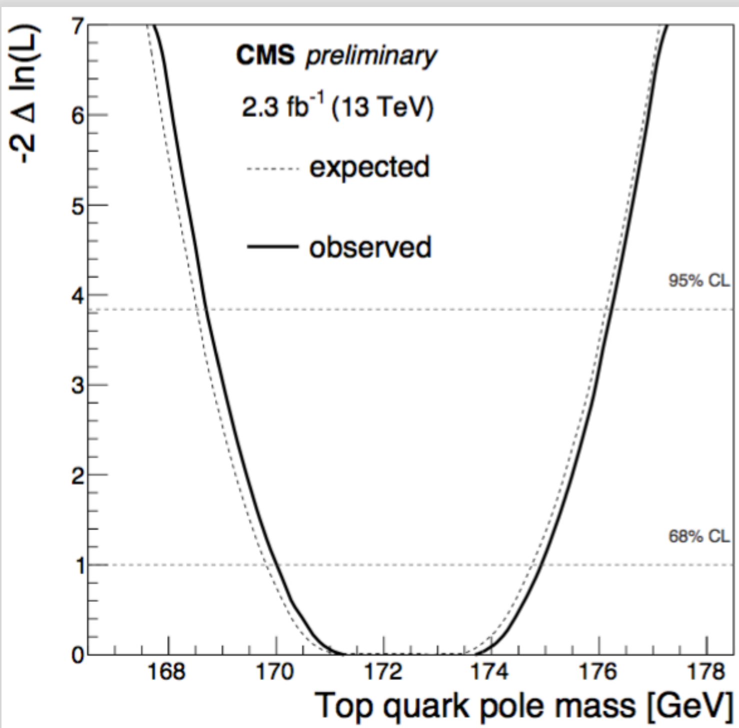
from theory — *experimental acceptance A depends on m_t:*

$$dA/dm_t(m_t) \approx 0.08\% \text{ GeV}^{-1}$$

- **Result:**

$$m_t = 172.3^{+2.7}_{-2.3}\ \text{GeV}$$

$\Delta m_t/m_t \approx 1.5\%$ *first LHC m_t result @ 13 TeV!*



Systematic uncertainties:

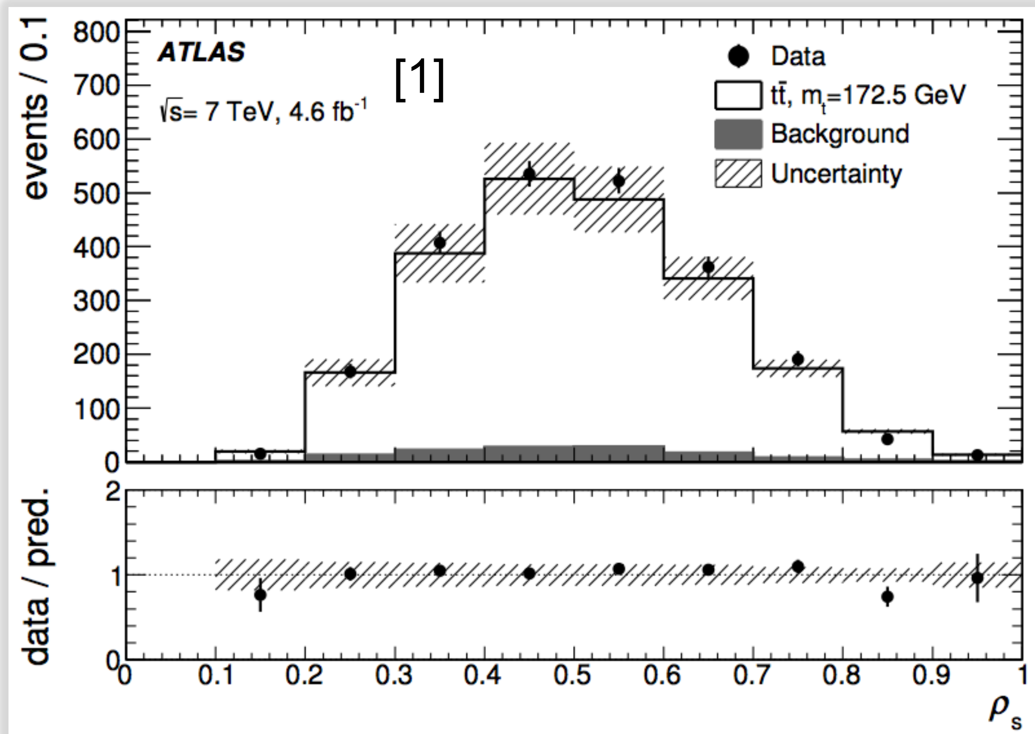
- Detector+signal modelling ($^{+2.1}_{-2.0}$ GeV)
- Full phase space result ($^{+1.1}_{-0.7}$ GeV)
- Beam energy ($^{+0.8}_{-0.5}$ GeV)
- Theory ($^{+1.1}_{-0.9}$ GeV)

- **Ansatz:** Hard gluon radiation off the top quark $\sigma_{tt+1jet}$ depends on m_t:

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s) \qquad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

  - Unfold $\mathcal{R}(m_t^{\text{pole}}, \rho_s)$ + extract m_t^{pole} using NLO calculation [2,3]

- **Reconstruct *tt* system** using kinematic χ^2-fit
  - Define extra jet:
    - not matched to *tt* system
    - high p_T > 50 GeV
    - →Enhanced sensitivity



- **Selection:**
  - similar to CMS l+jets

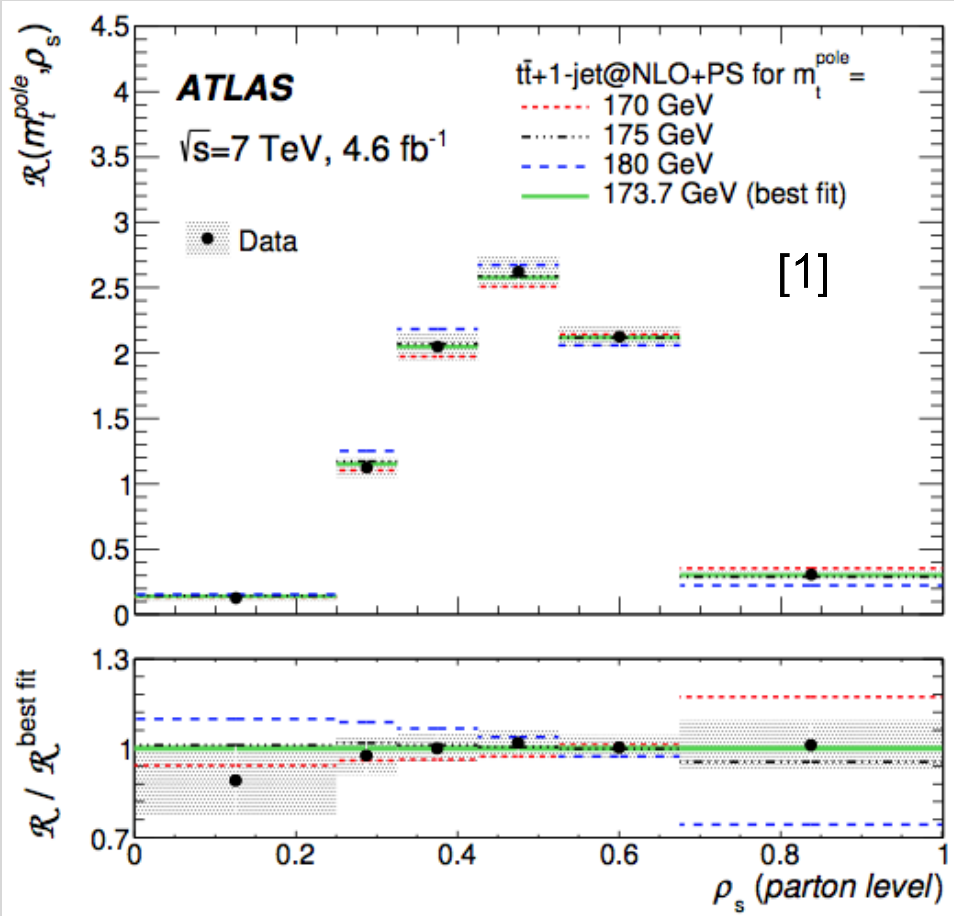
[1] *JHEP* ***10*** *(2015) 121*
[2] *PRL* ***98*** *262002 (2007)*
[3] *EPJC* ***59*** *(2009) 625*

- **Result:**

$$m_t^{\text{pole}} = 173.7 \pm 1.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})^{+1.0}_{-0.5}\,(\text{theory})\ \text{GeV},$$

$$\Delta m_t / m_t = 1.3\%!$$

- World's most precise m_t^{pole} result
- Precision approaching the ball park of direct measurements!

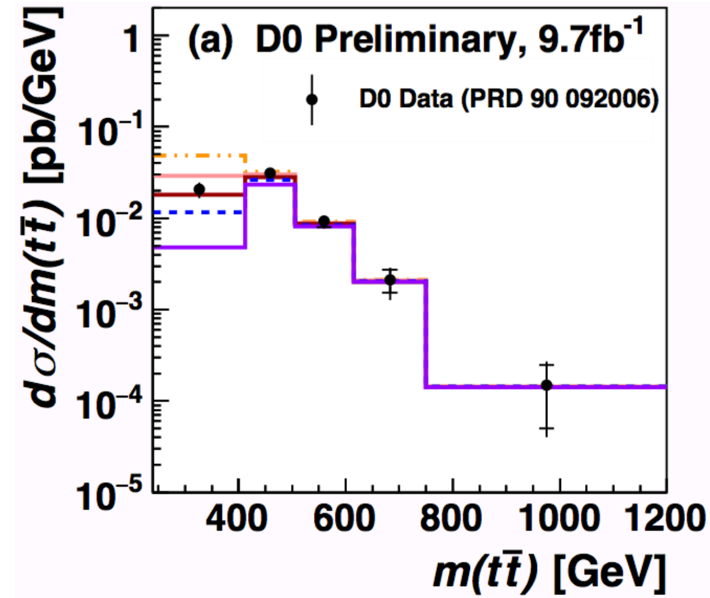


Dominant systematics:

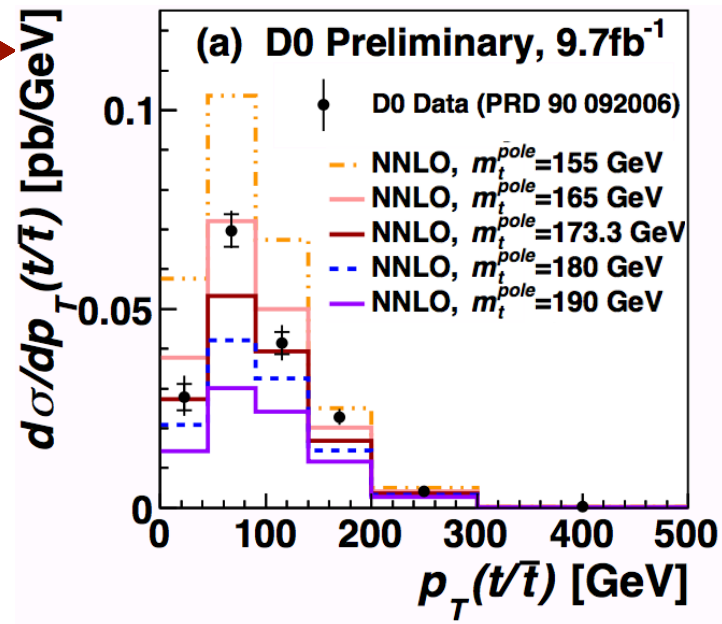
- JES + *b*-quark JES (0.9 GeV)
- Initial/final state radiation (0.7 GeV)
- PDF in experiment (0.5 GeV)
- Theory ($^{+1.0}_{-0.5}$ GeV)

[1] *JHEP* ***10*** *(2015) 121*
Similar CMS analysis: TOP-13-006

- **Ansatz:**
  - Invariant mass of tt system depends on m_t:
    - $d\sigma/dm_{t\bar{t}}(m_t)$
  - Top transverse momentum depends on m_t:
    - $d\sigma/dp_{T,t/\bar{t}}(m_t)$
  - Unfold + extract m_t^{pole} using pNNLO and NLO calculations [2]



- **Reconstruct *tt* system**:
  - Infer neutrino p_z using M_W constraint
  - Identify jet-parton assignment using χ^2-fit



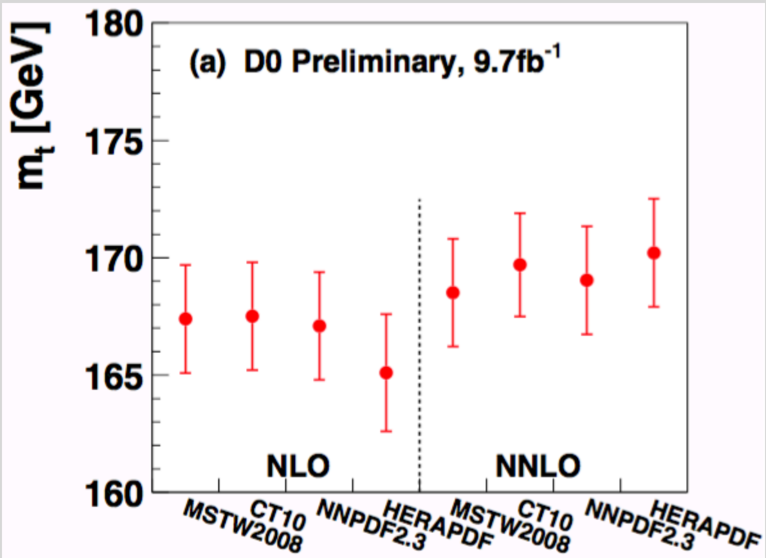
- **Selection:**
  - Similar to DØ direct m_t analysis in l+jets

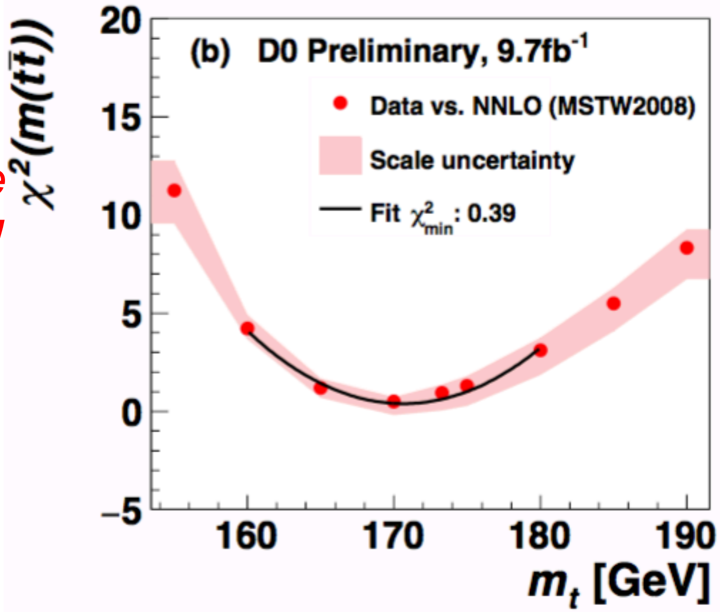
[1] *DØ note 6473 (2016)*
[2] *JHEP 1605, 034 (2016)*

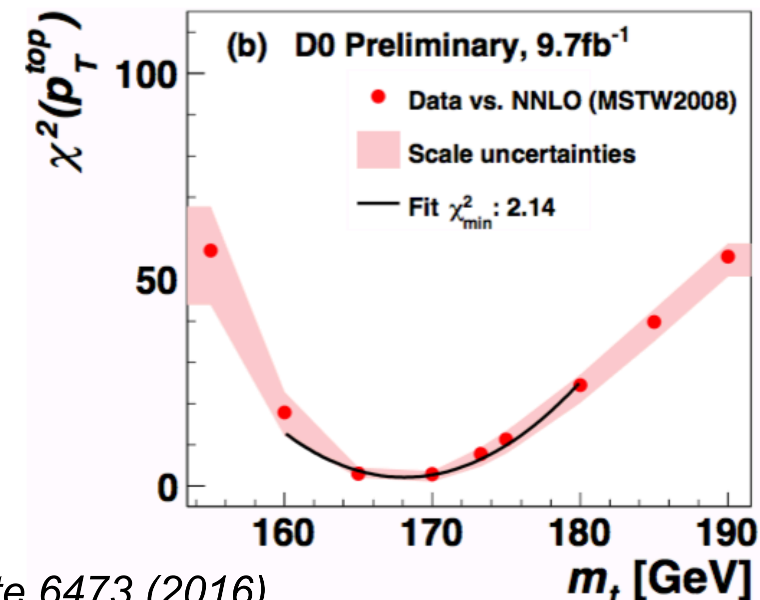
- **Result:**

$$m_t^{\text{pole,NNLO}} = 169.1 \pm 2.5 \text{ GeV}$$

$$\Delta m_t / m_t = 1.5\%!$$ *Tevatron's most precise m_t^{pole} result!*



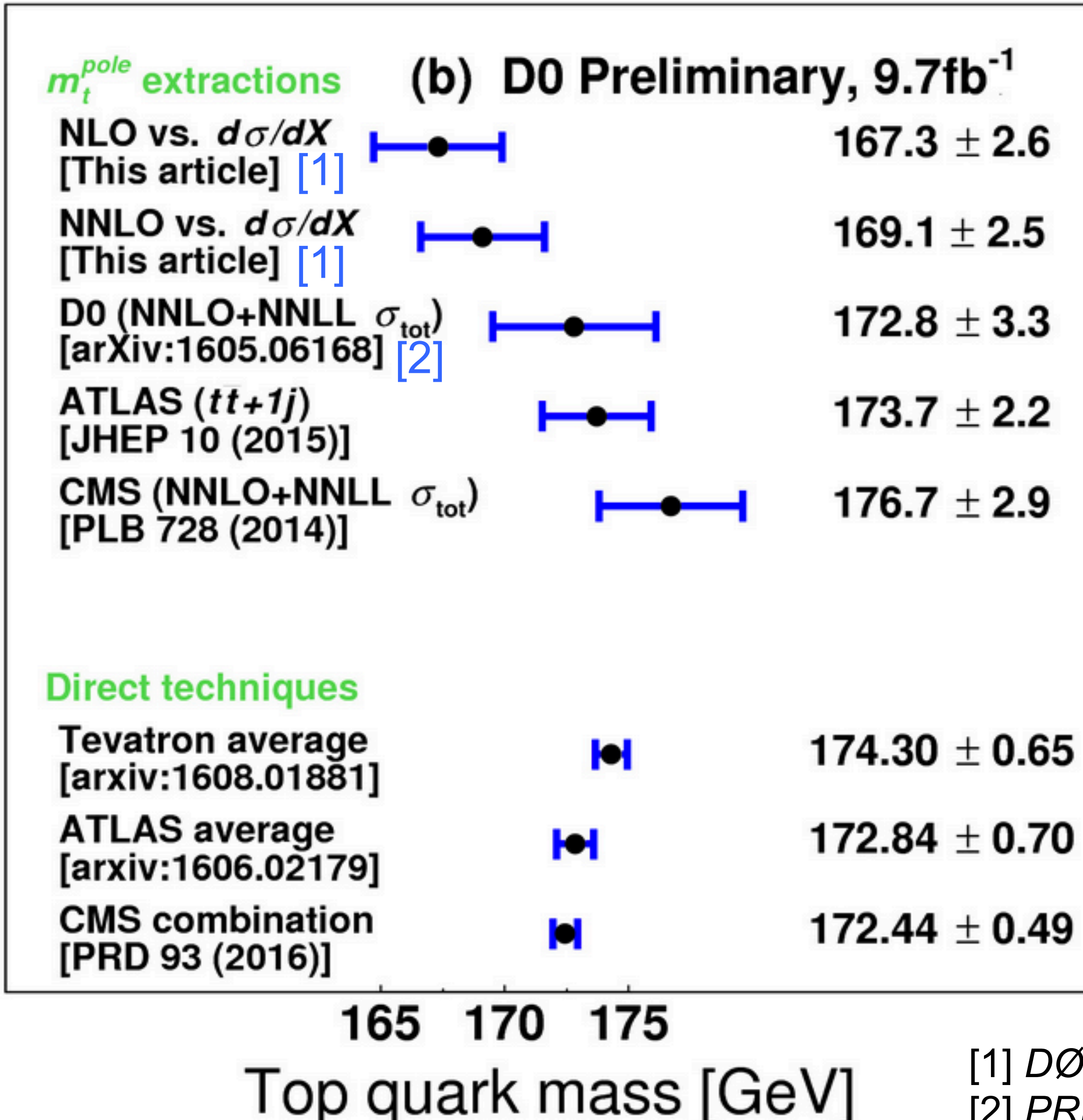




- **Systematic uncertainties:**
  - Experiment:
    - Detector+signal modelling (2.2 GeV)
  - Theory:
    - PDF (1.2 GeV)
    - Scale choice + α_s (0.8 GeV)

[1] *DØ note 6473 (2016)*

OVERVIEW OF POLE MASS SCHEME MEASUREMENTS



Only most precise m_t^{pole} measurements up to ICHEP 2016 shown

[1] *DØ note 6473 (2016)*
[2] *PRD 94 092004 (2016)*

Summary & Outlook

- **Summary:**
  - A wealth of m_t results in the last 5 years:
    - Improved overall precision below sub-GeV level
    - LHC achieves similar precision as the Tevatron
  - Novel techniques put in place:
    - Complementary approaches:
      - *E.g. m_t from single top, J/Ψ, etc.*
    - *In situ* calibration of *b* quark JES
    - Extraction of m_t^{pole} from $\sigma_{tt+1jet}$
    - Extraction of m_t^{pole} from differential σ_{tt}
  - First m_t results from the LHC @ √s=13 TeV
- **Outlook:**
  - New studies with large datasets @ √s=13 TeV
    - Better constrain systematic uncertainties from data

Thank you!


GAME OVER
BONUS MATERIAL

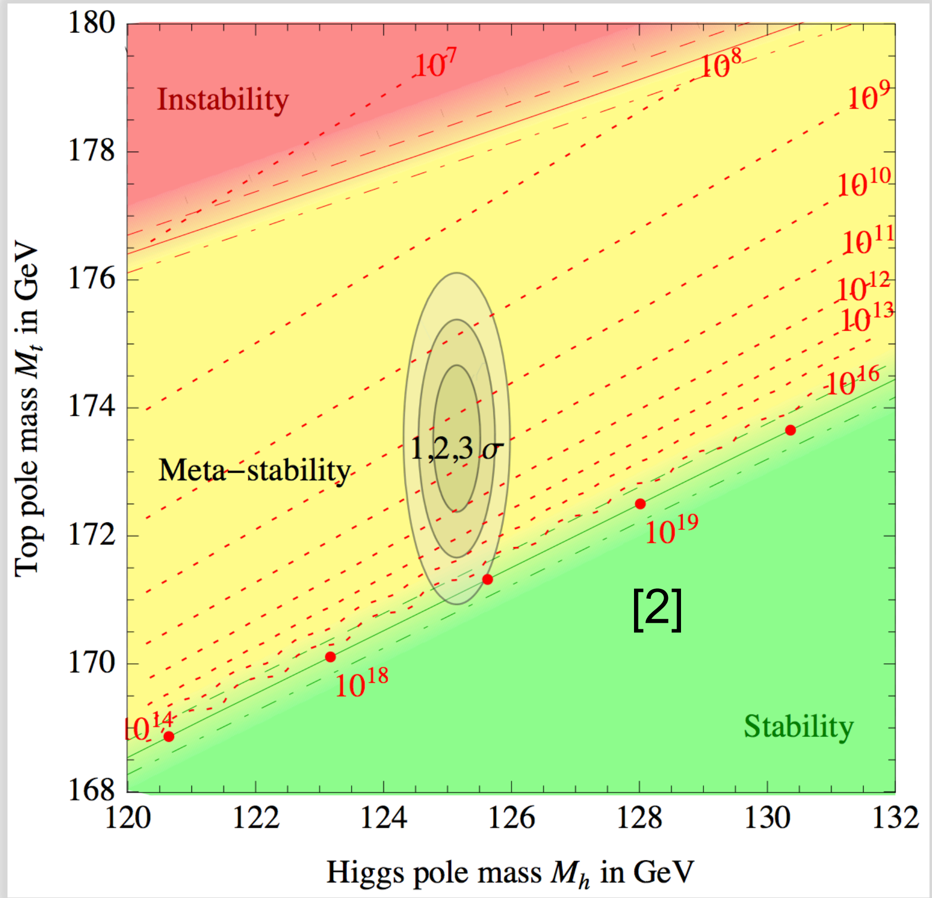
- The fate of our Universe depends on m_t!

$$\mathcal{L}_H = \left| \left(\partial_\mu - igW^a_\mu \tau^a - i\frac{g'}{2}B_\mu \right) \phi \right|^2 + \mu^2 \phi^\dagger \phi - \underline{\lambda(\phi^\dagger\phi)^2},$$

Mexican hat only if λ > 0!

(Bavarian hat otherwise)

- λ receives radiative corrections from all SM particles
  → the top quark dominates due to large m_t!
  - Evolve corrections to Planck scale:
    - λ should remain positive!
- Our universe is metastable [1] using world average m_t [2]
  - → New Physics?!



The calculation includes NNLO effects, RG equation at NNNLO

[1] *Degrassi et al., arXiv:1205.6497v4 [hep-ph]*
[2] *ATLAS, CDF, CMS, DØ, arXiv:1403.4427 [hep-ex]*

[1] *EPJC **74**, 3109 (2014)*, [2] PRL ***110**, 252004 (2013)*

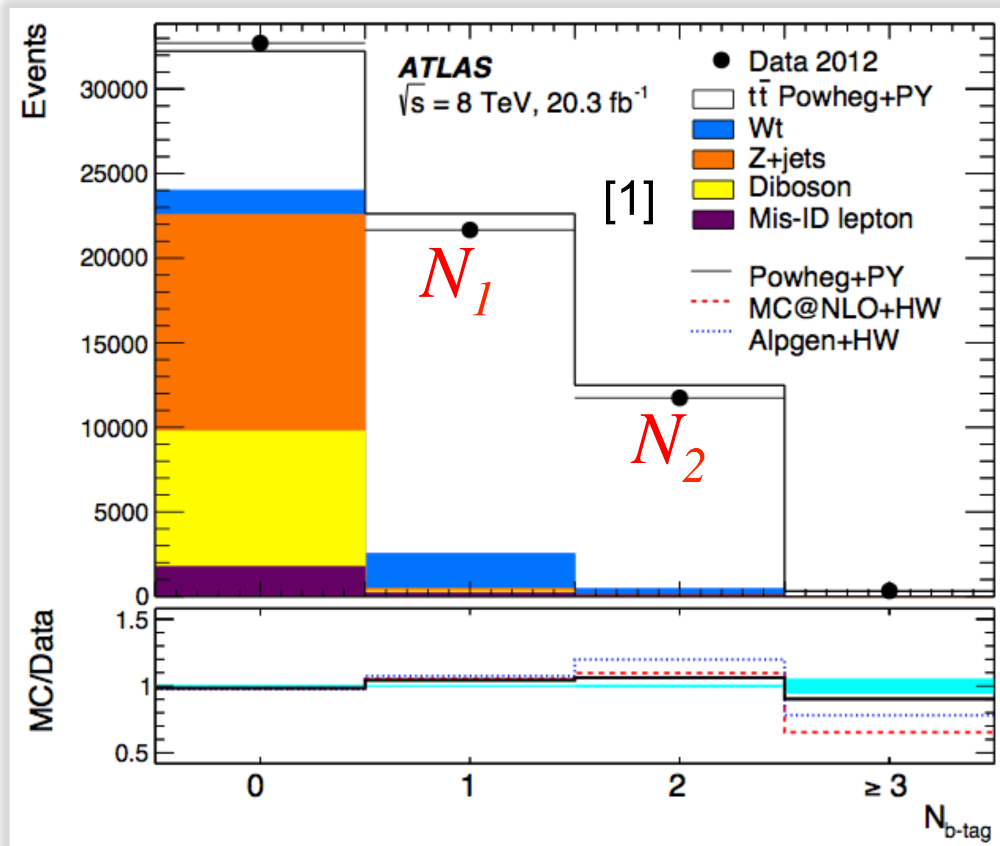
- **Experiment** (ATLAS):
  - World's most precise measurement of m_t from σ_{tT} [1], $\Delta\sigma_{tT}$: ≈4%!
- **Theory**:
  - Recent NNLO+NNLL calculation [2], $\Delta\sigma_{tT}$: ≈3%!
- Selection:
  - Similar to l+jets m_t
  - $e^{\pm}\mu^{\mp}$, no topological cuts
- Fit *b*-tagging efficiency x acceptance x reco eff. ε_b together with σ_{tt}:

$$N_1 = \int dt\,\mathscr{L} \times \sigma_{t\bar{t}}\,\varepsilon_{e\mu} \times 2\varepsilon_b(1 - C_b\varepsilon_b) + N_1^{\rm bgr}$$

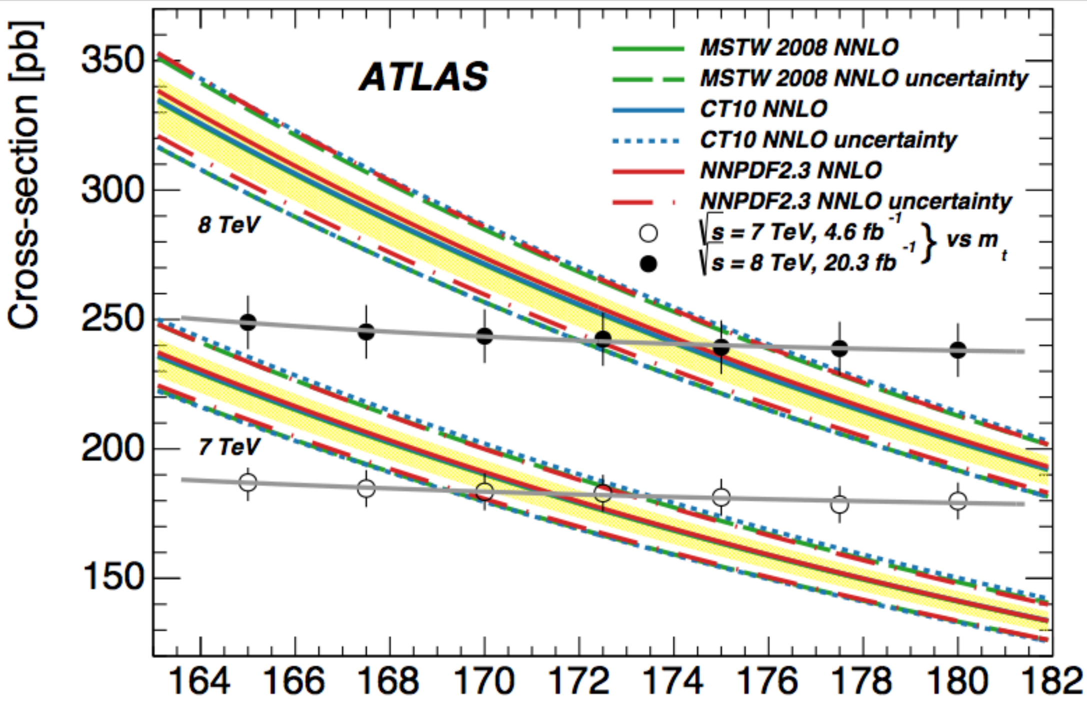
$$N_2 = \int dt\,\mathscr{L} \times \sigma_{t\bar{t}}\,\varepsilon_{e\mu} \times C_b\varepsilon_b^2 + N_2^{\rm bgr},$$

$$C_b = \varepsilon_{bb}/\varepsilon_b$$

- Minimal use of MC simulations



POLE MASS FROM σ_{tt} (ATLAS) [1]



[1] *EPJC* ***74****, 3109 (2014)*

$$m_t^{\rm pole} = 171.4 \pm 2.6\ {\rm GeV} \quad (\sqrt{s} = 7\ {\rm TeV})$$
$$m_t^{\rm pole} = 174.1 \pm 2.6\ {\rm GeV} \quad (\sqrt{s} = 8\ {\rm TeV}).$$

- Very small dependence of σ_{tt} on m_t
  - Higher precision on m_t!
  - due to minimal MC use

Dominant uncertainties:

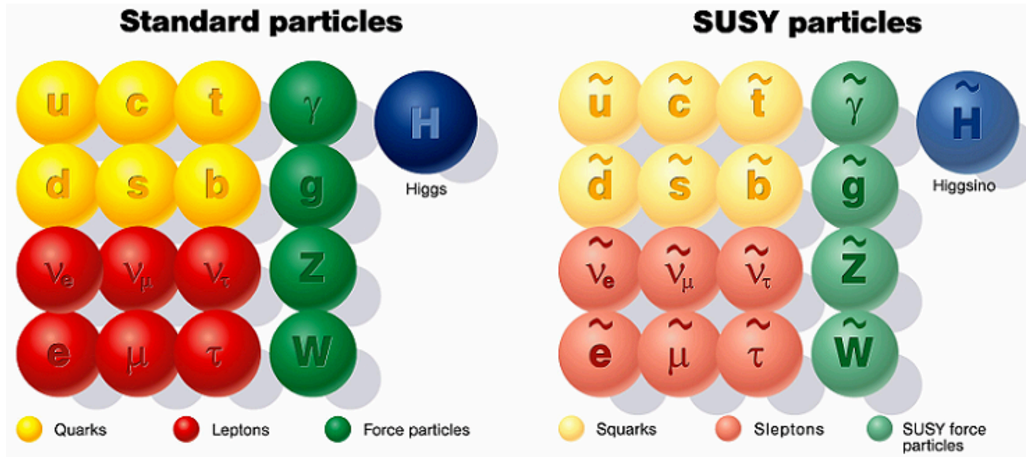
- Experimental:
  - Luminosity (0.9 GeV)
  - Beam energy (0.6 GeV)
- Theory:
  - PDF + α_s (1.7 GeV)
  - Scale choice (1.2 GeV)

- World's most precise m_t^{pole} from σ_{tt}
  - Precision in the same ballpark as direct methods: ≈1.5%!

Motivation

24 Feb. 1995

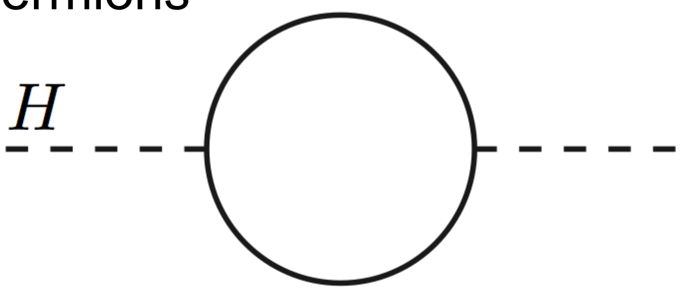
- Special role in many new physics scenarios
  - E.g. supersymmetry →



- Radiative corrections to M_{Higgs}:

spin-½ fermions

f ← *t dominates*



spin-0 bosons

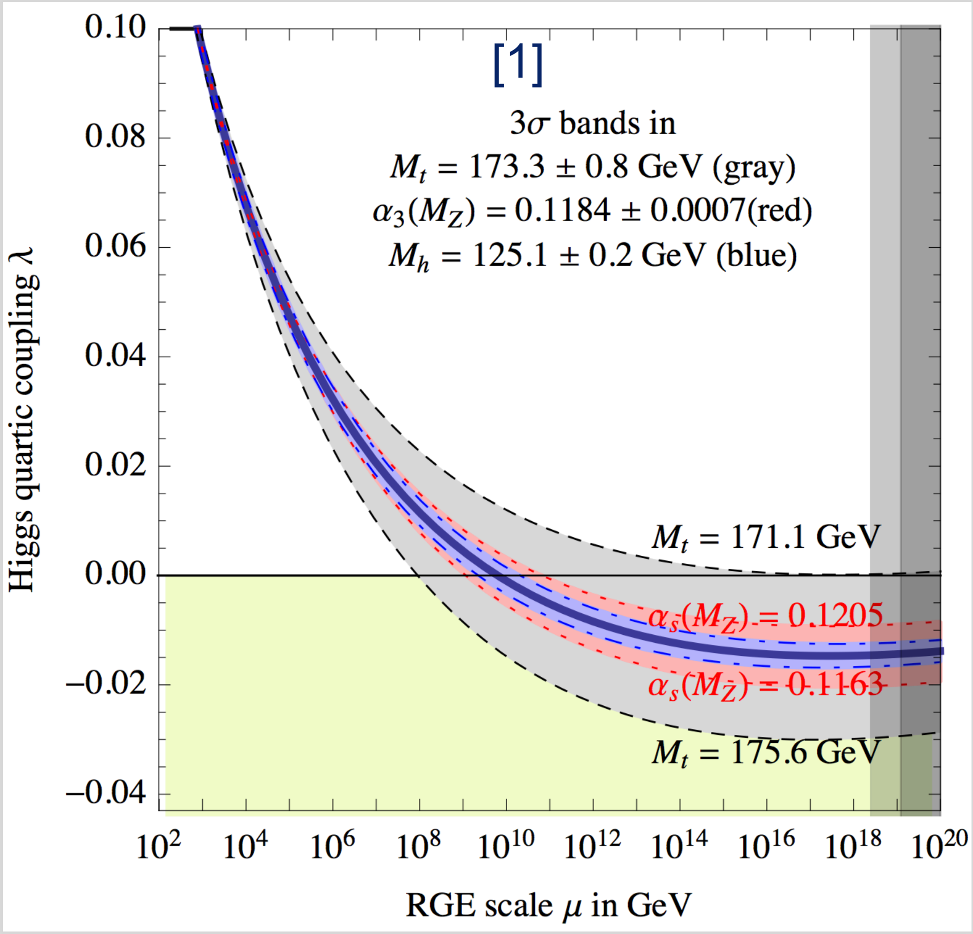
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\Lambda_{\rm UV}^2 + \ldots$$

- UV divergencies cancel if $|\lambda_f|^2 \approx \lambda_S$ or $m_t \approx M_{\tilde{t}}$

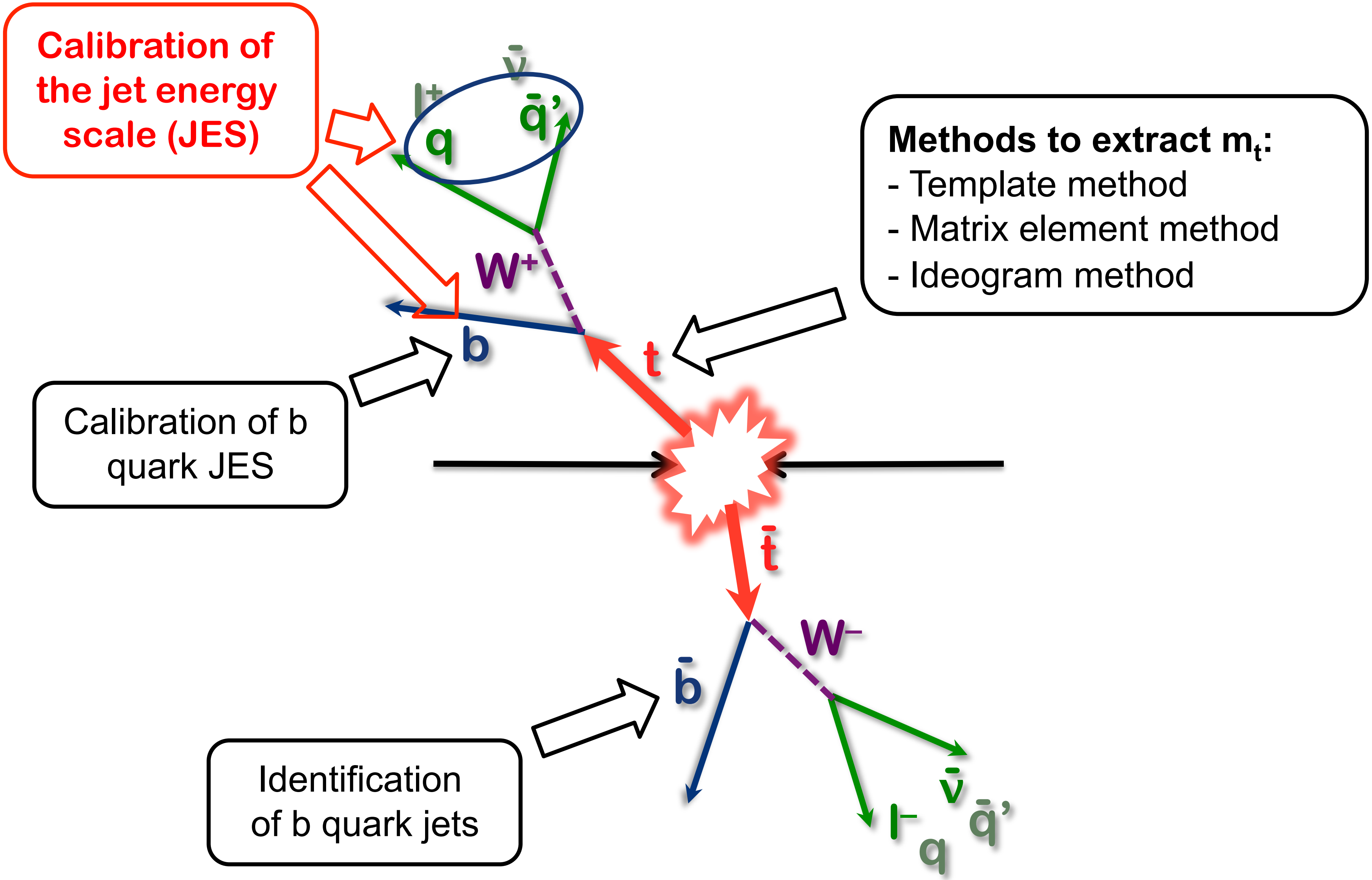
MOTIVATION

- λ receives radiative corrections from all SM particles
  → mostly from the top quark!
  - Evolve corrections to Planck scale:
    - λ should remain positive!

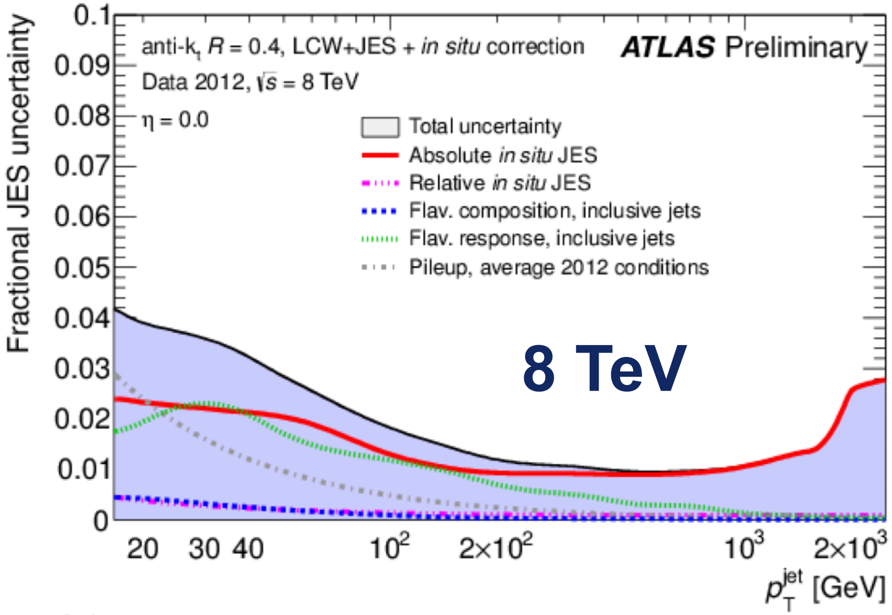


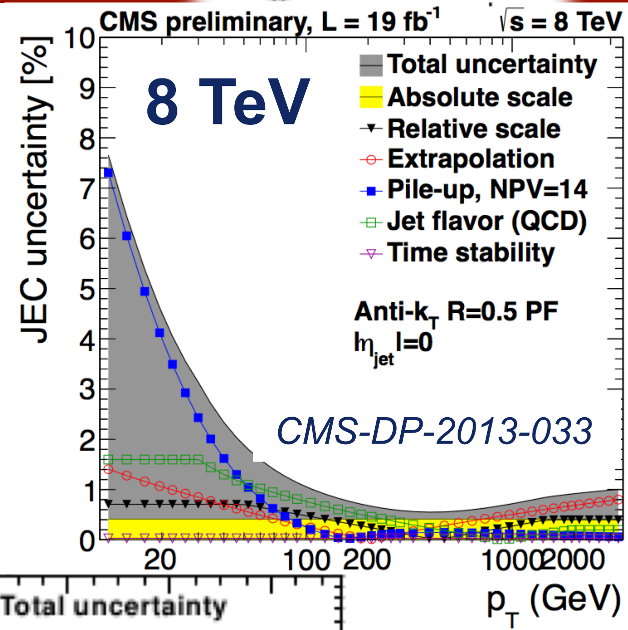
The calculation includes NNLO effects, RG equation at NNNLO

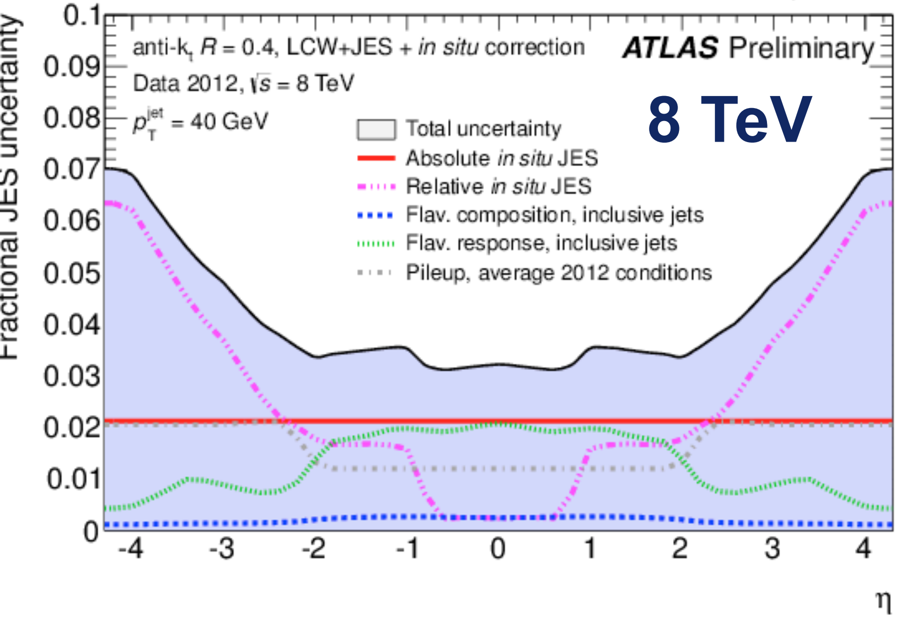
[2] *Degrassi et al., arXiv:1205.6497v4 [hep-ph]*

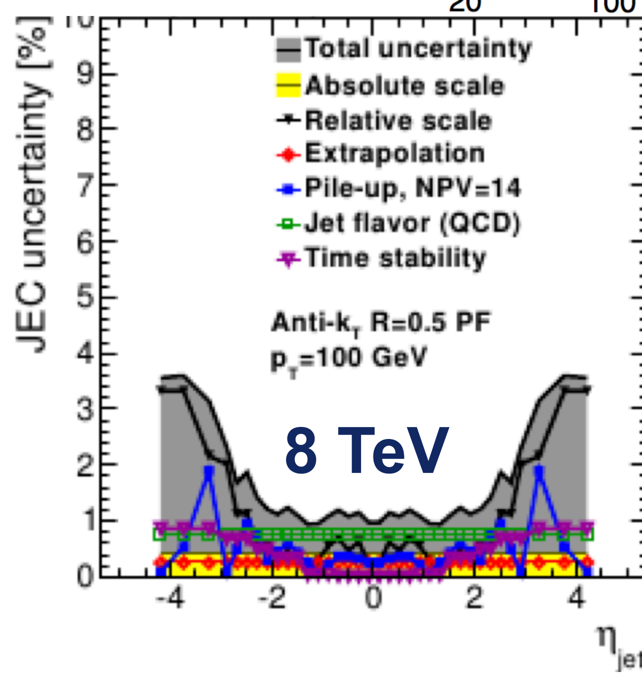

Calibration of the jet energy scale (JES)
$\bar{\nu}$
l^+
q
$\bar{q}'$
W^+
b
t
$\bar{t}$
$\bar{b}$
W^-
l^-
q
$\bar{\nu}$
$\bar{q}'$
Methods to extract m_t:
- Template method
- Matrix element method
- Ideogram method
Calibration of b quark JES
Identification of b quark jets

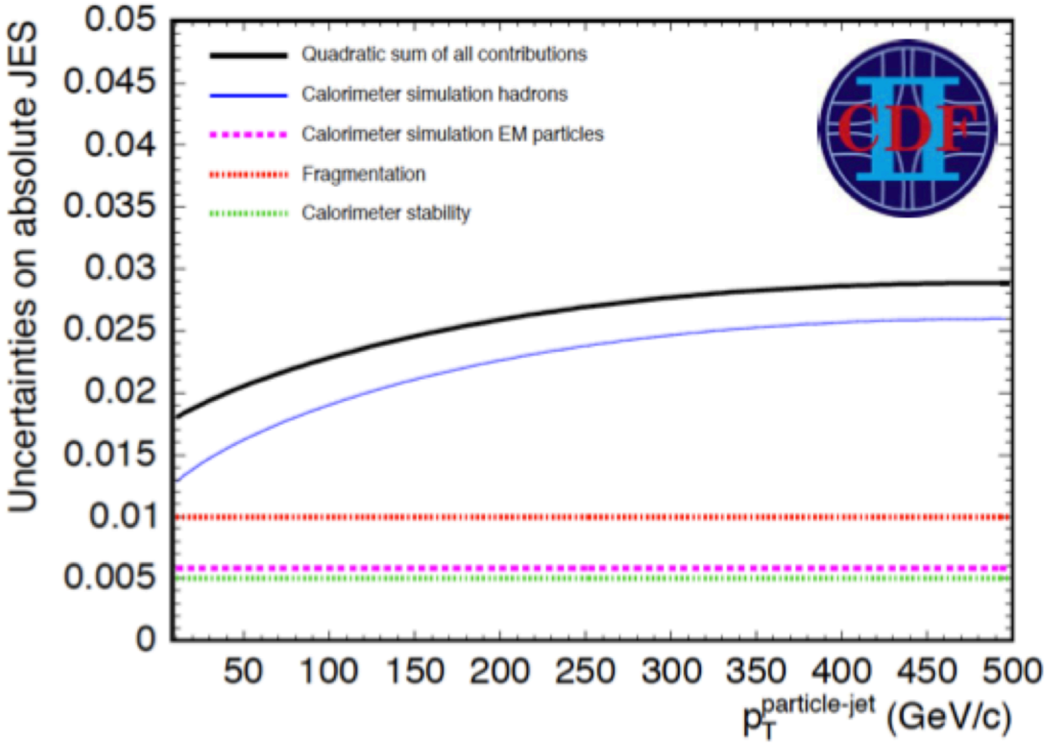
JES UNCERTAINTIES

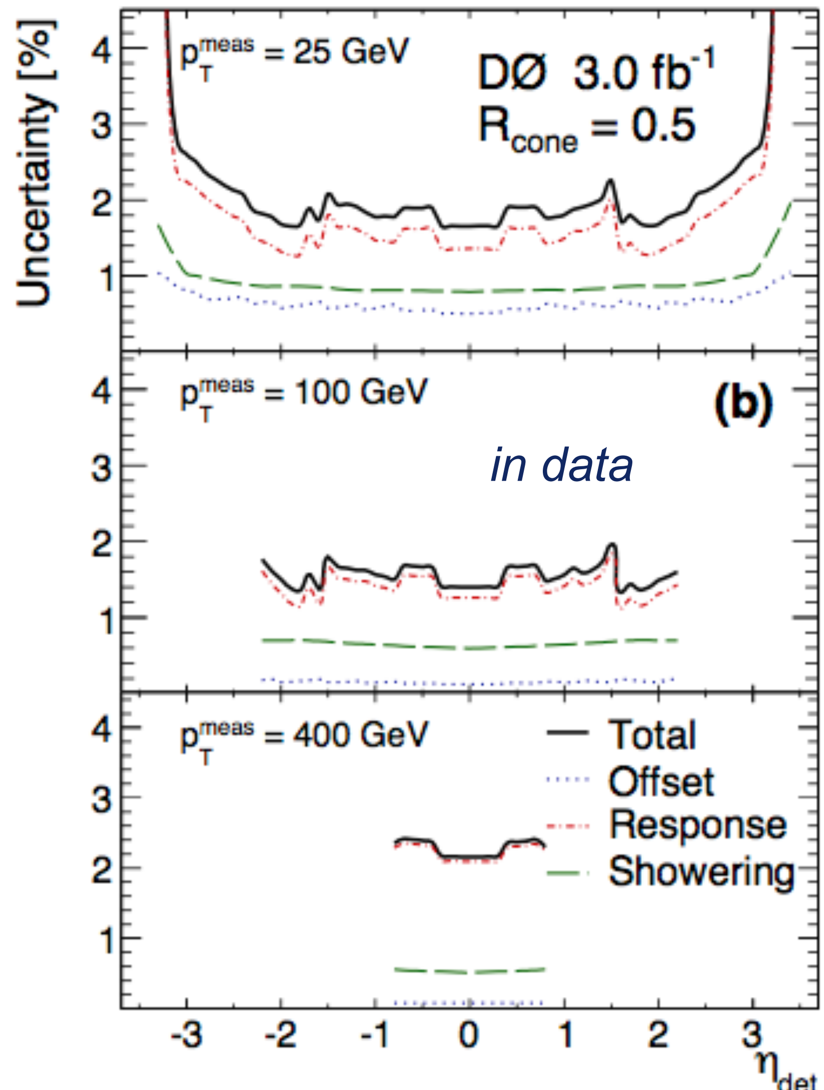












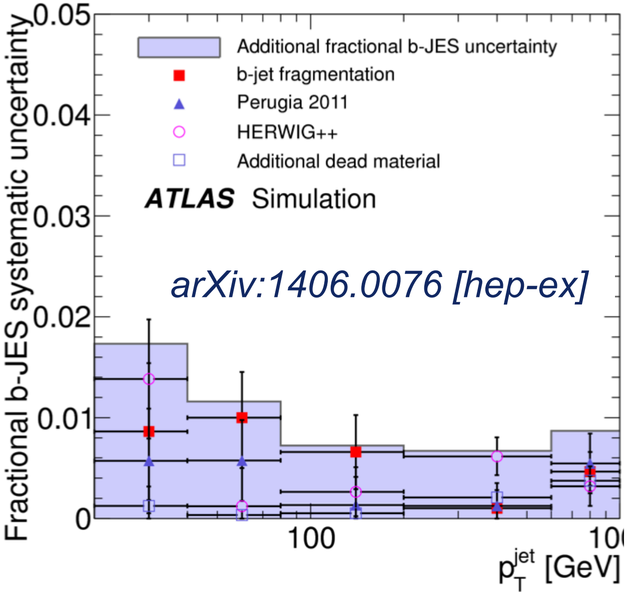
*DØ, NIM A **763**, 290 (2014)*

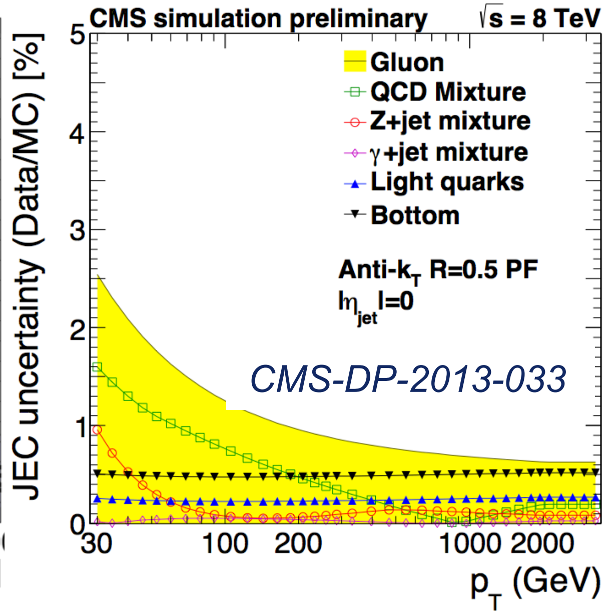
FLAVOUR-DEPENDENCE OF JES CALIBRATION

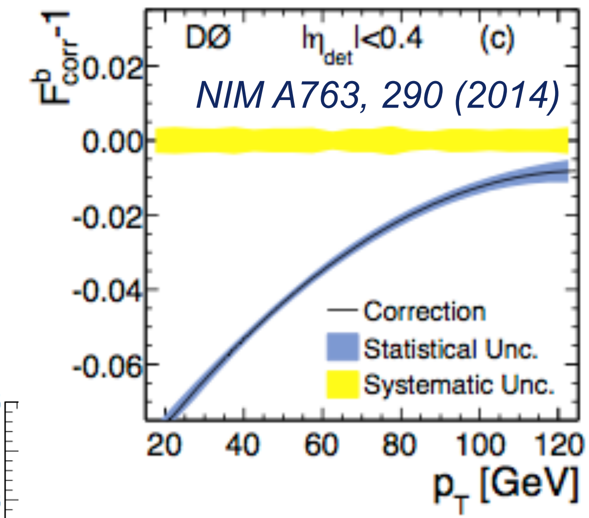
- JES calibration is determined in samples dominated by:
  - gluon jets (LHC)
  - quark jets at low p_T, gluon jets at high p_T (Tevatron)
- JES differences between the flavours expected due to:
  - Size in (η,φ): g > b > q jets
  - Mass: b > q > g jets
  - Particle composition of the jet
  - Specifically for b quark jets:
    - Decay tables of b quark jets
    - b quark fragmentation
- Difference between quark-gluon jets not so important at Tevatron since initial state 85% dominated by qq
- Difference between b and q jets important both at LHC and Tevatron

FLAVOUR-DEPENDENCE OF JES CALIBRATION

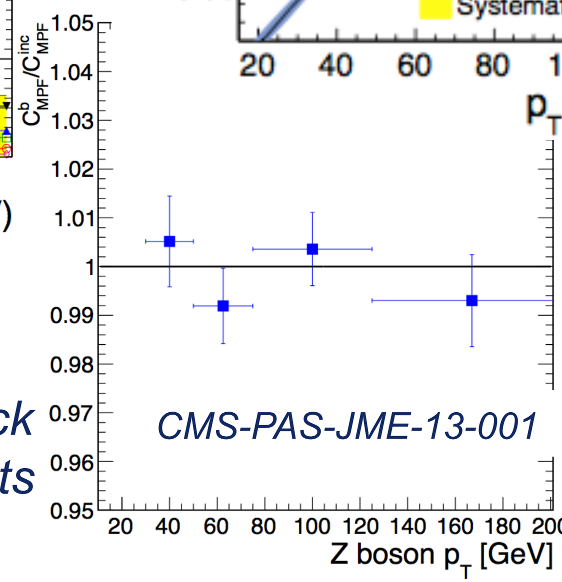
- Typically, estimate the uncertainty on the difference between b quark JES and standard JES by comparing fragmentation and parton shower models



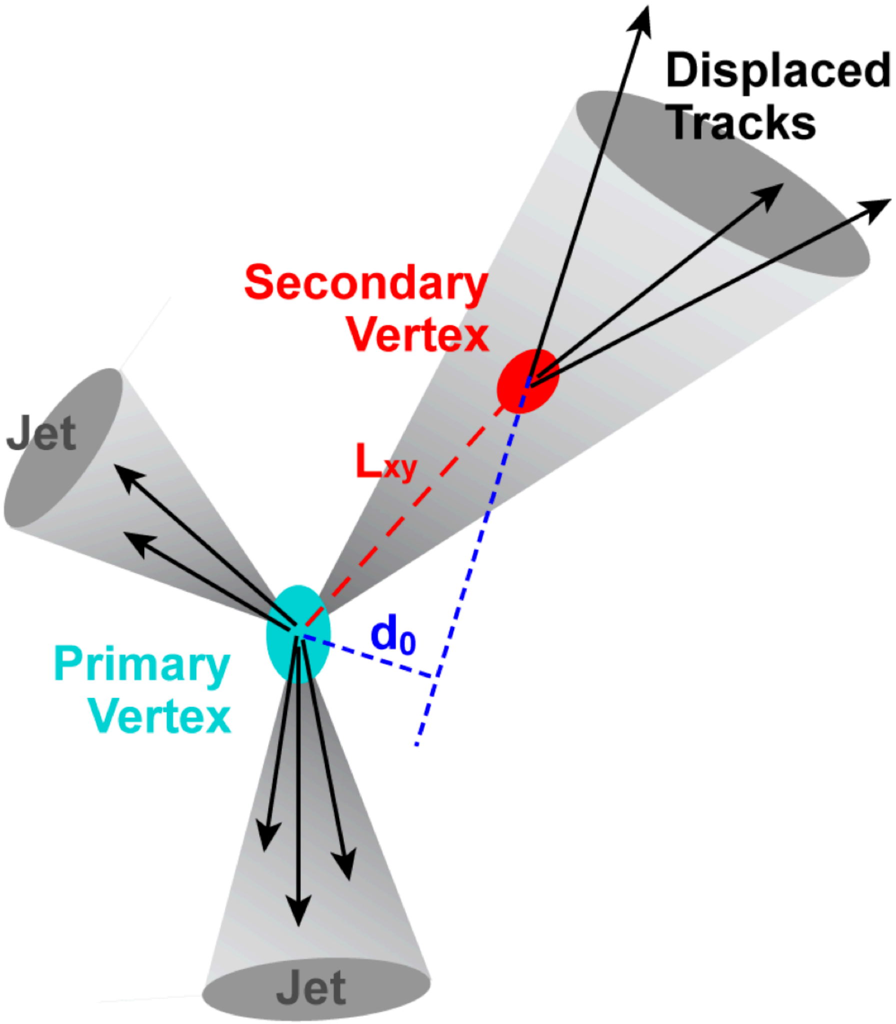




Cross-check using Z+b events



- 2 b quark jets in each tT event at Born level
  - → Separate signal from background
- Identify b quark jets:
  - Existence of a displaced secondary vertex
  - Impact parameters d_0 of tracks associated with the secondary vertex
  - Mass of the secondary vertex
  - Etc.

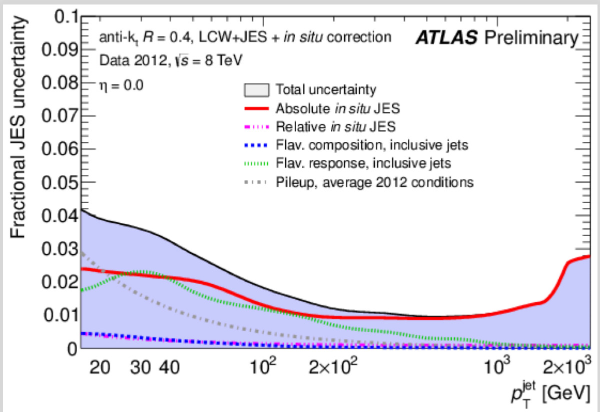


- Typical operation points chosen in top analyses:

	ATLAS	CDF	CMS	DØ
$\varepsilon_{\text{b quark}}$	70%	60%	≈ 70%	65%
$\varepsilon_{\text{light quark}}$	≈ 1%	≈ 3%	1%	≈ 3%

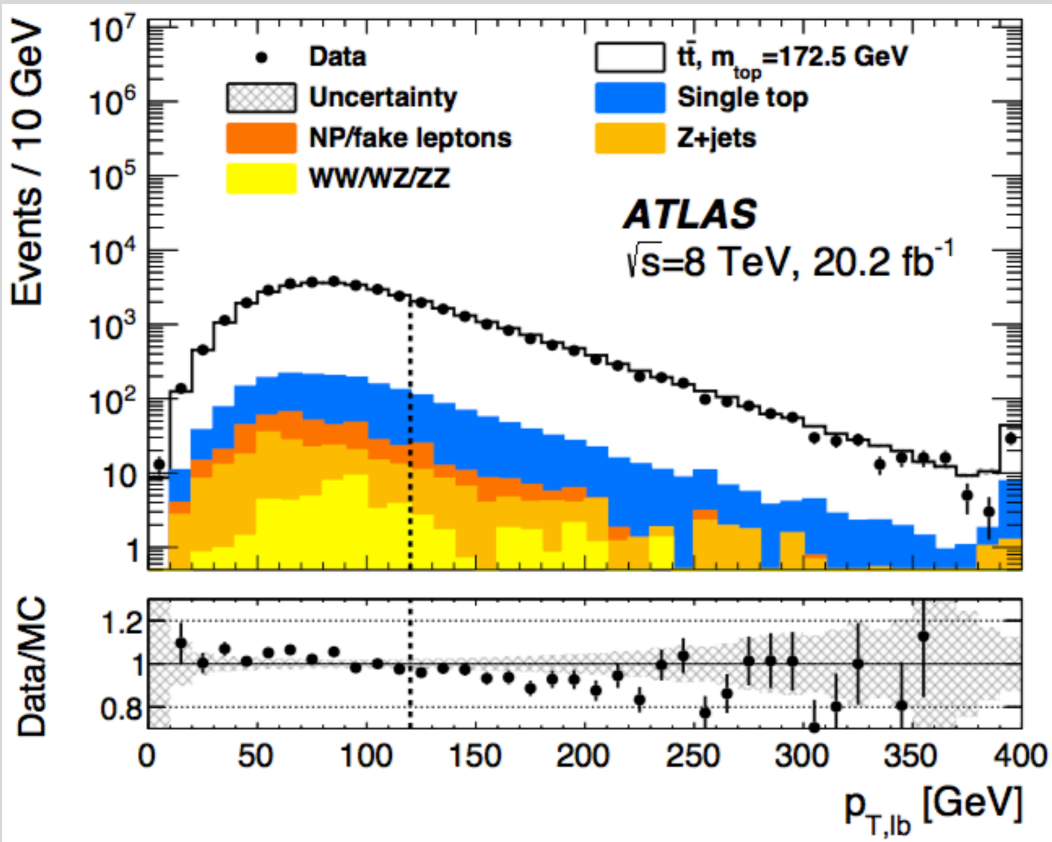
- Uncertainties dependent on p_T and η
  - Pronounced impact on shape-sensitive analyses

- **ATLAS dilepton channel, 20.2 fb^{-1} @ 8 TeV [1]**
- Selection (typical for such analyses):
  - 2 opposite-sign *e* or μ with p_T > 25 GeV, $M_{ee,\mu\mu}$ away from Z, γ
  - 2 jets with p_T > 25 GeV
    - At least one *b*-tag
  - ee,$\mu\mu$: $E_T^{miss} > 60$ GeV
  - eμ: $\Sigma_{e,\mu,jets}\, p_T$ > 130 GeV
  - average $p_{T,\ell b} > 120$ GeV.
    - Better JES precision:



    - → Reduce systematics

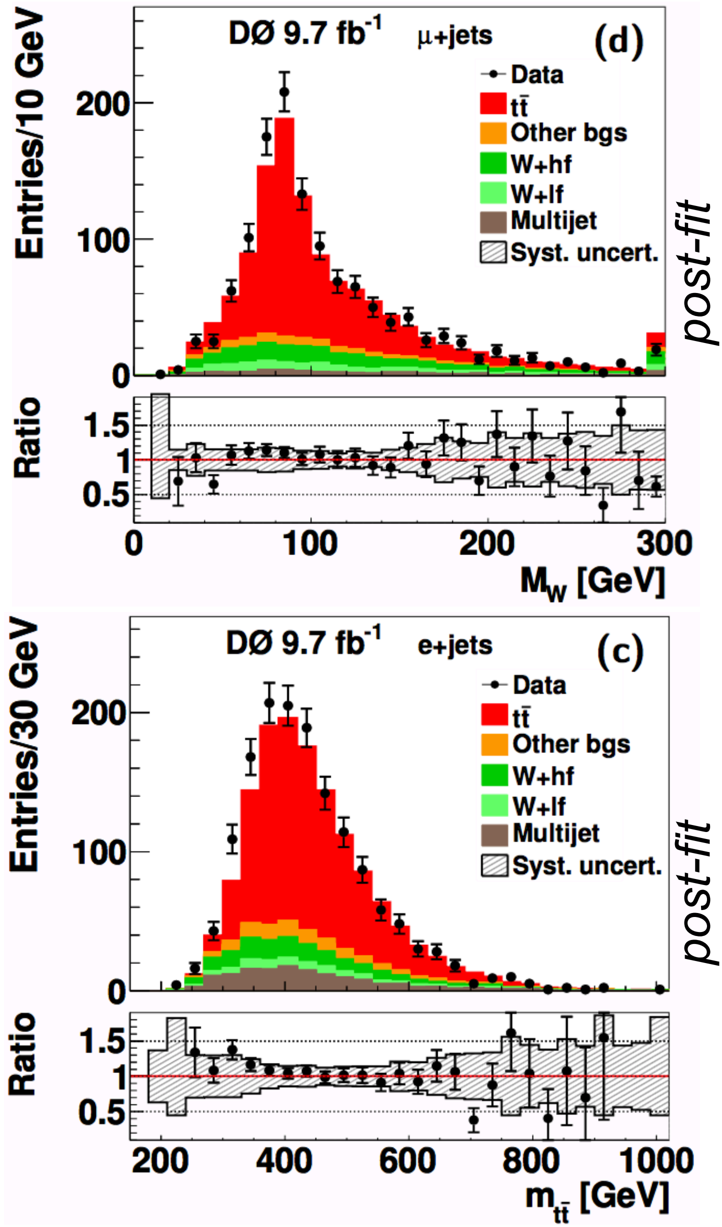
[1] *PLB* ***761*** *(2016) 350*



- **DØ l+jets channel, 9.7 fb^{-1} @ 1.96 TeV [1]**
- Selection:
  - 1 e or μ with p_T > 20 GeV
  - 4 jets with p_T > 20 GeV, at least one b-tag
    - Matches the LO picture
    - Reduced ISR/FSR systematic uncert.
  - Topological cuts on $\not{E}_T$, scalar sum p_T, …
  - (generally lower p_T requirements due to lower pile-up contamination at Tevatron)
- **Extraction of m_t:**
  - Matrix Element method:

$$P_{\text{evt}}(m_{\text{top}}) \propto f P_{\text{sig}}(m_{\text{top}}) + (1-f) P_{\text{bgr}}$$

    - (details next slide)
  - Maximise likelihood in m_t and in in-situ JES calibration factor k_{JES} (details in 3 slides)



[1] *PRL **113**, 032002 (2014), PRD **91**, 112003 (2015)*

- **CMS l+jets channel, 19.7 fb^{-1} @ 8 TeV [1]**
- Selection:
  - 1 e or μ with p_T > 33 GeV
  - 4+ jets with p_T > 30 GeV
    - 2 b-tags
  - No further topological cuts
    - High signal purity: 97% (tt+single top)
- **Extraction of m_t:**
  - Ideogram method

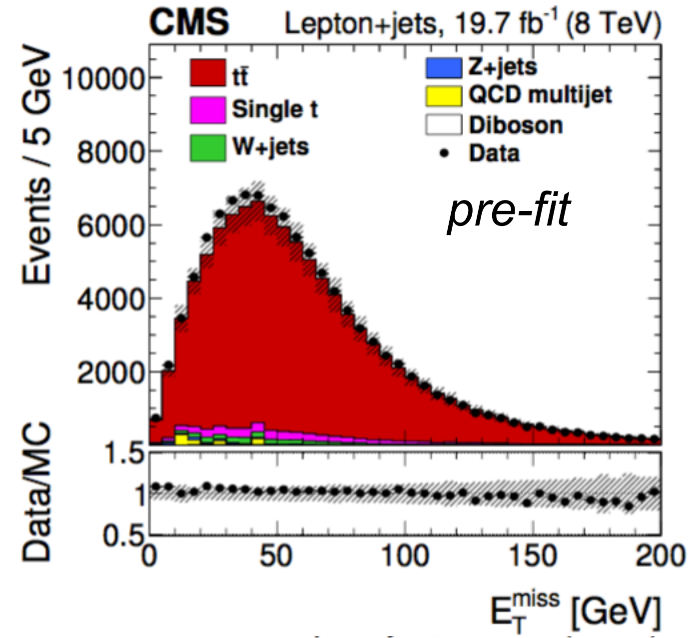
$$\mathcal{L}\left(\text{event}|m_t,\text{JSF}\right) = \sum_{i=1}^{n} P_{\text{gof}}(i)\, \underline{P_{\text{sig}}\left(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}}|m_t,\text{JSF}\right)}$$

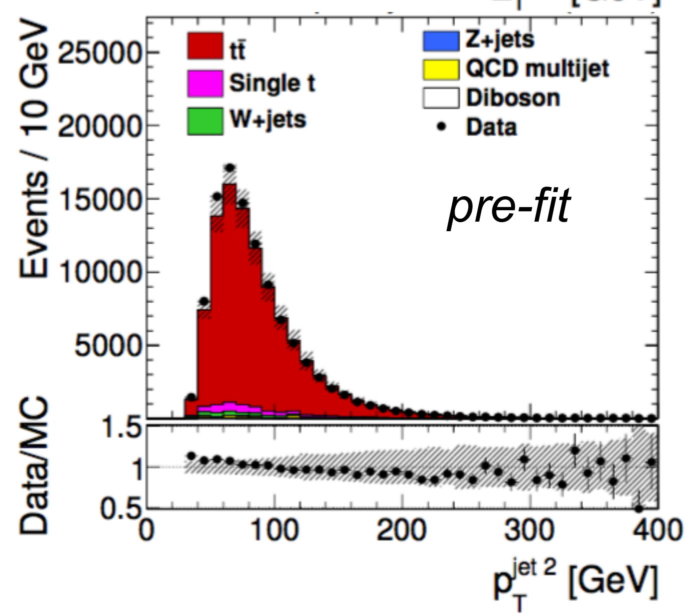
"ideogramm"

    - P_{sig} from MC (like template method)
  - Maximise likelihood in m_t and JES (≈JSF)

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

    - Higher weight to correctly reconstructed + parton/detector level-matched events





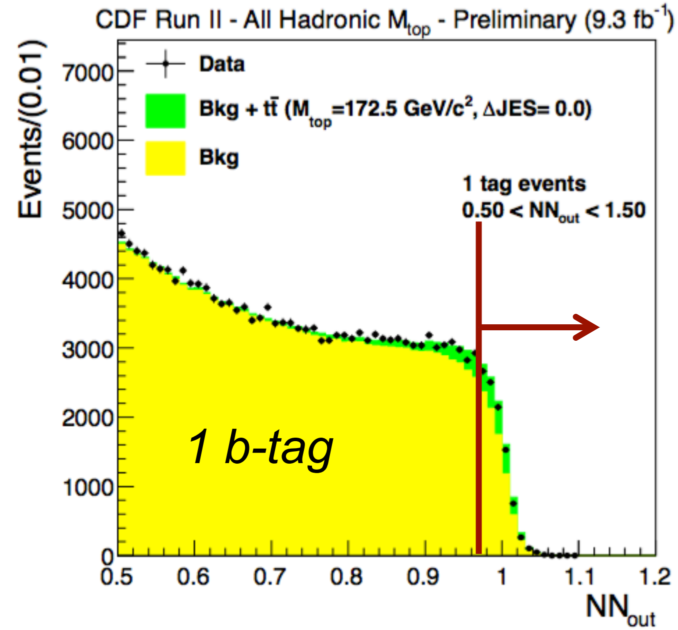
[1] *PRD **93**, 072004 (2016)*

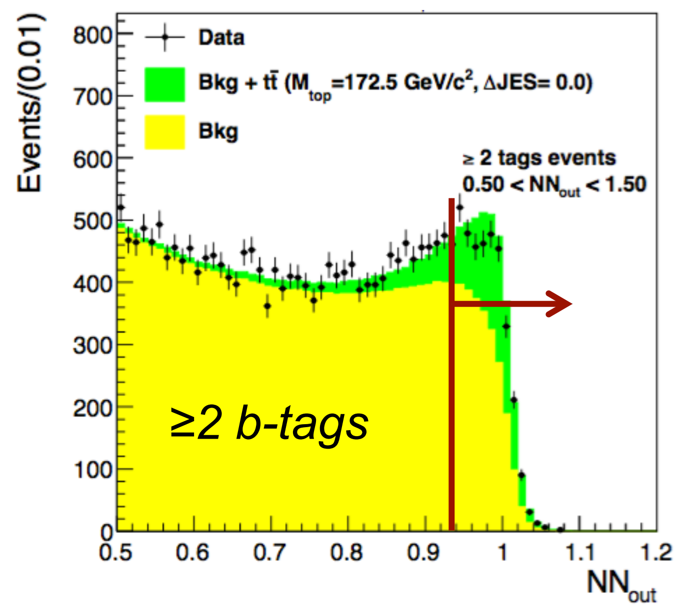
ALL-HADRONIC CHANNEL (CDF) [1]

- **CDF all-hadronic, 9.3 fb^{-1} @ 1.96 TeV [1]**
- Pre-selection:
  - No *e* or $\boldsymbol{\mu}$ candidate
  - No neutrinos:

$$\not{E}_T/\sqrt{\sum E_T} < 3\ \text{GeV}^{\frac{1}{2}}$$

  - ≥ 6 jets with p_T > 15 GeV
    - Maximum 6 jets to reduce combinatorics
  - tt purity ≈ 1/700
- **Selection:**
  - Neural network based on:
    - Jet shapes (width, depth)
    - Kinematics (max m_{jj}, max m_{jjj}, …)
    - Topology (centrality, aplanarity, …)
  - ≥1 *b*-tags
  - tt purity: 1/3 (2 *b*-tags)





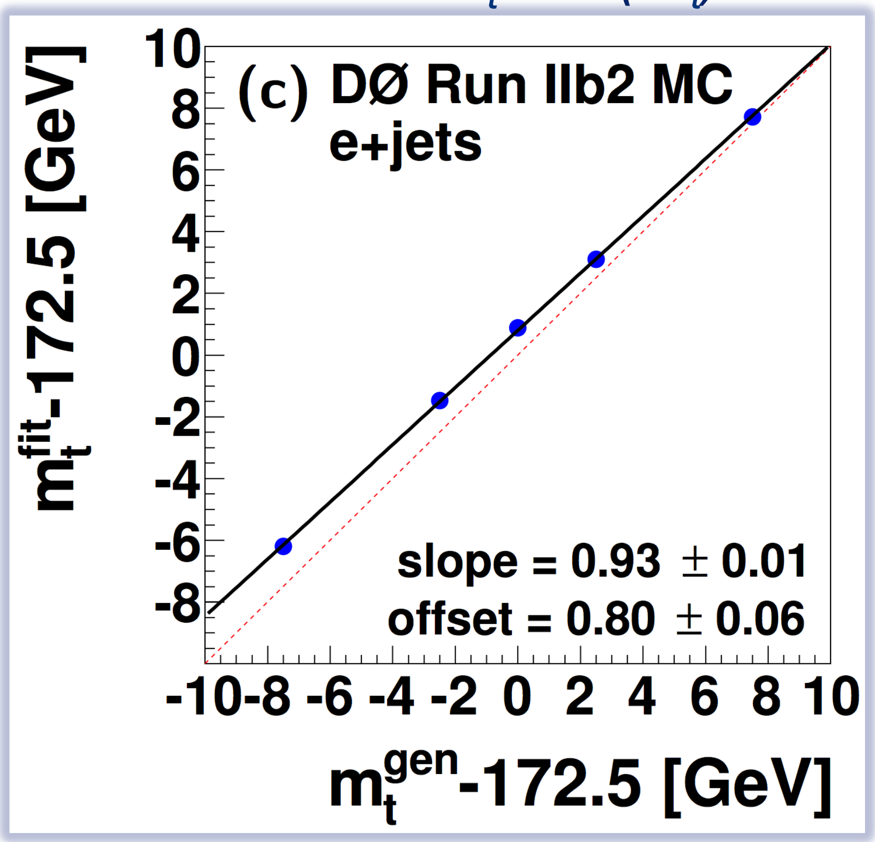
[1] *PRD* ***90****, 091101(R) (2014)*

ME METHOD (V)

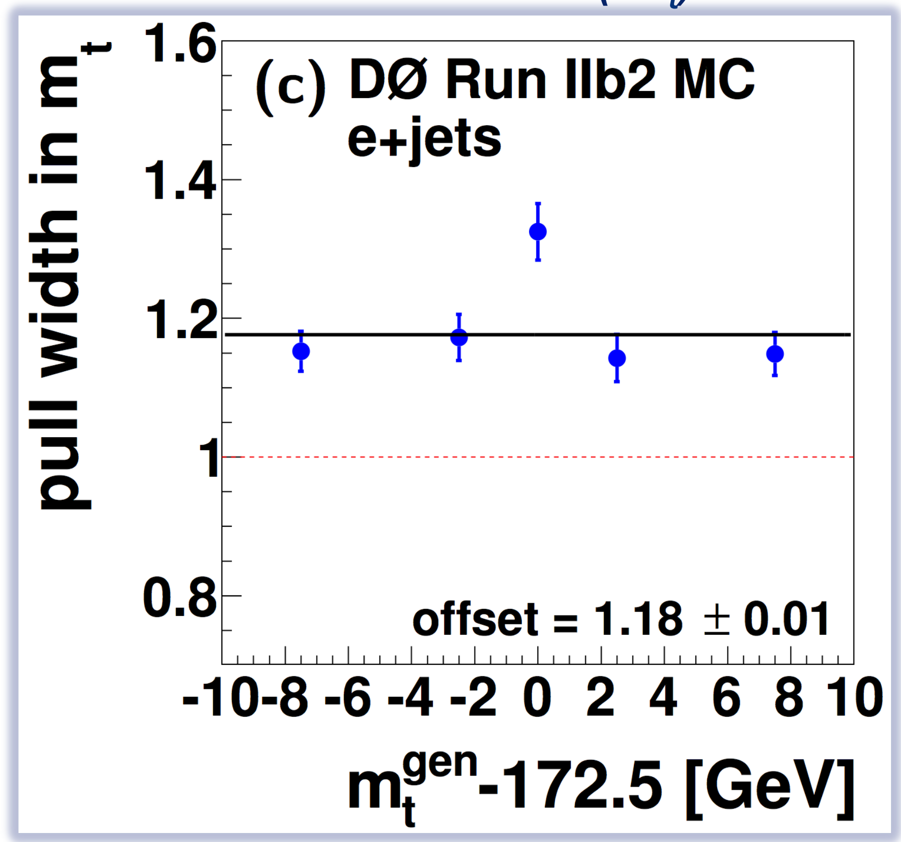
- Calibrate the method with pseudo-experiments (PE)
  - P_{evt} obtained *ab initio* with LO ME + transfer function

    → calibration imperative:

Calibrate m_t & $\sigma(m_t)$

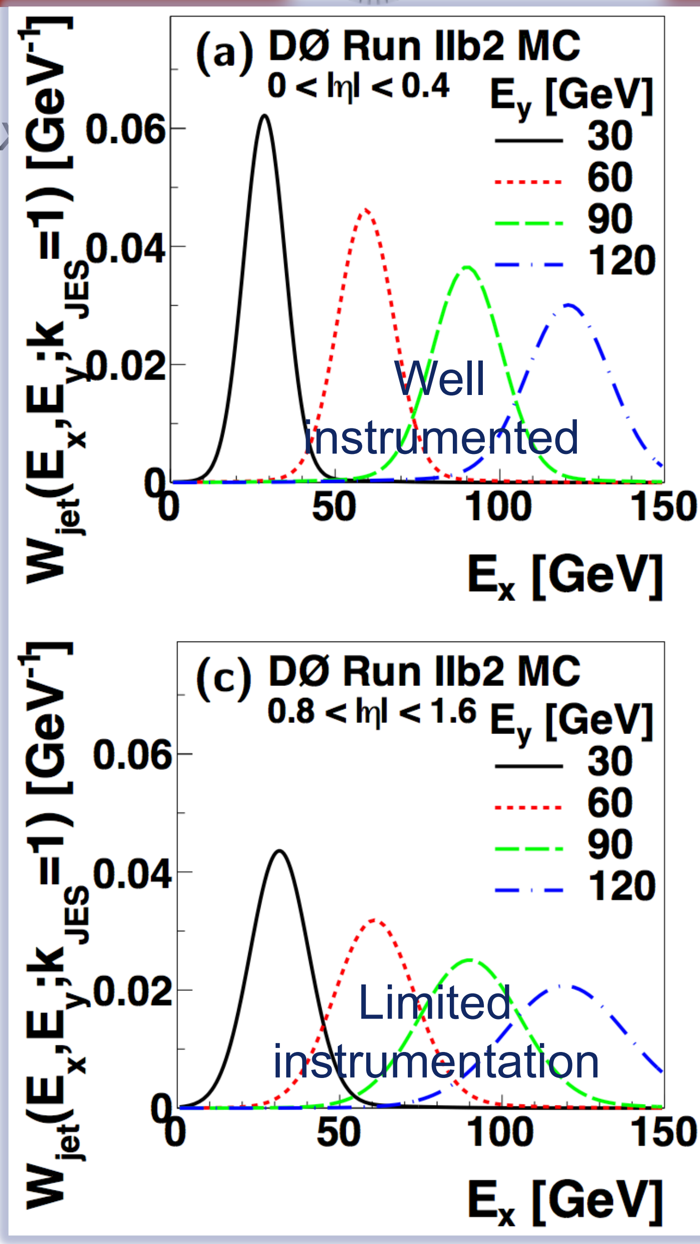


Calibrate $\sigma(m_t)$



KIRCHHOFF-INSTITUT FÜR PHYSIK

- The Transfer Functions $W(x, y; k_{\mathrm{JES}})$ e parton-level quantities *y* to detector-level ones
  - Two Gaussians:
    - One for the core of the distribution
    - One for the tails
  - Direction of jets and leptons in (η,ϕ) well-measured



LETPON+JETS CHANNEL (DØ) [1]

This measurement

Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections*	0.15
Initial/final state radiation*	0.09
Hadronization & UE*	0.26
Color reconnection*	0.10
Multiple $p\bar{p}$ interactions	0.06
Heavy flavor scale factor	0.06
b-jet modeling	0.09
PDF uncertainty	0.11
Detector modeling:	
Residual jet energy scale	0.21
Data-MC jet response difference	0.16
b-tagging	0.10
Trigger	0.01
Lepton momentum scale	0.01
Jet energy resolution	0.07
Jet ID efficiency	0.01
Method:	
Modeling of multijet events	0.04
Signal fraction	0.08
MC calibration	0.07
Total systematic uncertainty	0.49
Total statistical uncertainty	0.58
Total uncertainty	0.76

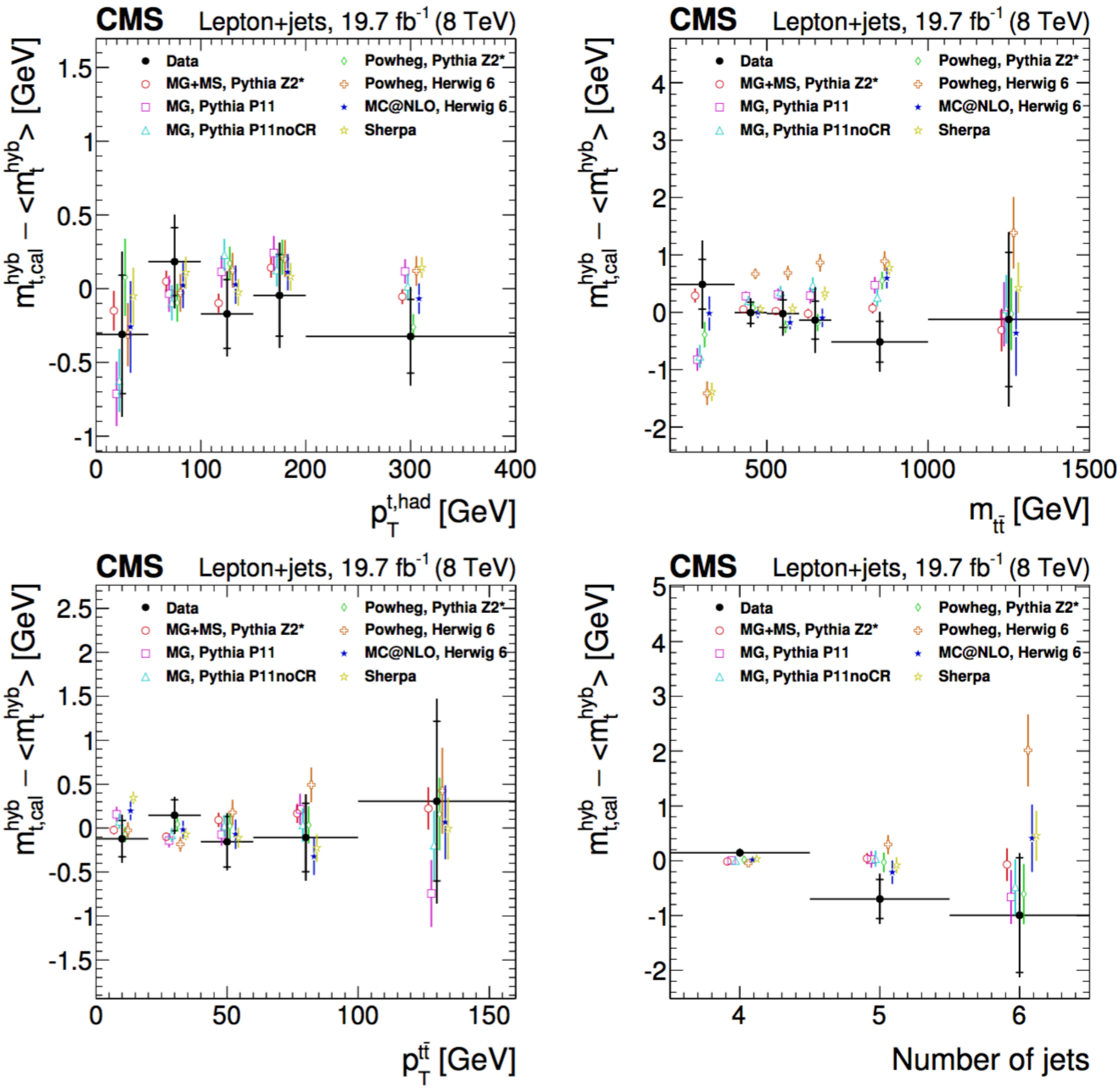
1.02 GeV

0.49 GeV

*Previous DØ result: PRD **84**, 032004 (2011)*

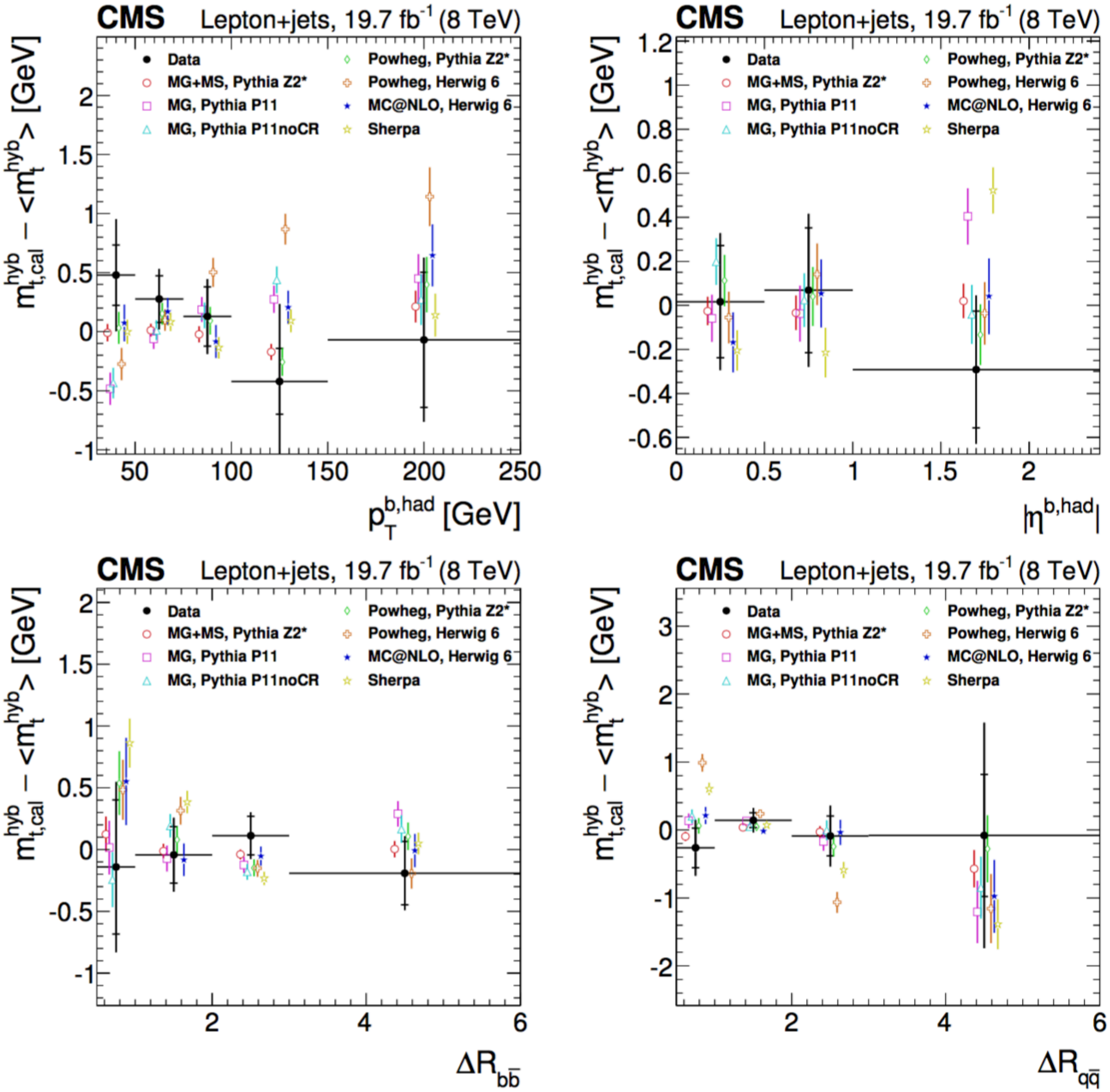
Source	Uncertainty (GeV)
Modeling of production:	
Modeling of signal:	
Higher-order effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
Color reconnection	±0.28
Multiple $p\bar{p}$ interactions	±0.07
Modeling of background	±0.16
W+jets heavy-flavor scale factor	±0.07
Modeling of b jets	±0.09
Choice of PDF	±0.24
Modeling of detector:	
Residual jet energy scale	±0.21
Data-MC jet response difference	±0.28
b-tagging efficiency	±0.08
Trigger efficiency	±0.01
Lepton momentum scale	±0.17
Jet energy resolution	±0.32
Jet ID efficiency	±0.26
Method:	
Multijet contamination	±0.14
Signal fraction	±0.10
MC calibration	±0.20
Total	±1.02

LEPTON+JETS CHANNEL (CMS) [1]



[1] *PRD* ***93****, 072004 (2016)*

LEPTON+JETS CHANNEL (CMS) [1]



[1] *PRD **93**, 072004 (2016)*

Overview of alternative measurements

- Single top events:
  - ATLAS, *ATLAS-CONF-2014-055*
    - $m_t = 172.2 \pm 0.7\ (\text{stat}) \pm 2.0\ (\text{syst})\ \text{GeV}$
  - CMS, *CMS-PAS-TOP-15-001*
    - $m_t = 172.60 \pm 0.77\ (\text{stat})\ ^{+0.97}_{-0.93}\ (\text{syst})\ \text{GeV}$
- Charged particles (CMS, *PRD **93** (2016) 092006*):
    - $m_t = 173.68 \pm 0.20\ (\text{stat})\ ^{+1.58}_{-0.97}\ (\text{syst})\ \text{GeV}$
- Invariant mass of ℓ,J/Ψ (CMS, *subm. to JHEP, arXiv:1608.03560*):
    - $m_t = 173.5 \pm 3.0\ (\text{stat}) \pm 0.9\ (\text{syst})\ \text{GeV}$
- Leptonic observables (CMS, CMS-PAS-TOP-16-002):
    - $m_t = 171.1 \pm 1.1\ (\text{stat})\ ^{+2.7}_{-3.1}\ (\text{syst})\ \text{GeV}$

- **Outlook promising!**

- *Tevatron alternative measurements not listed explicitly*
  - *(no recent updates)*