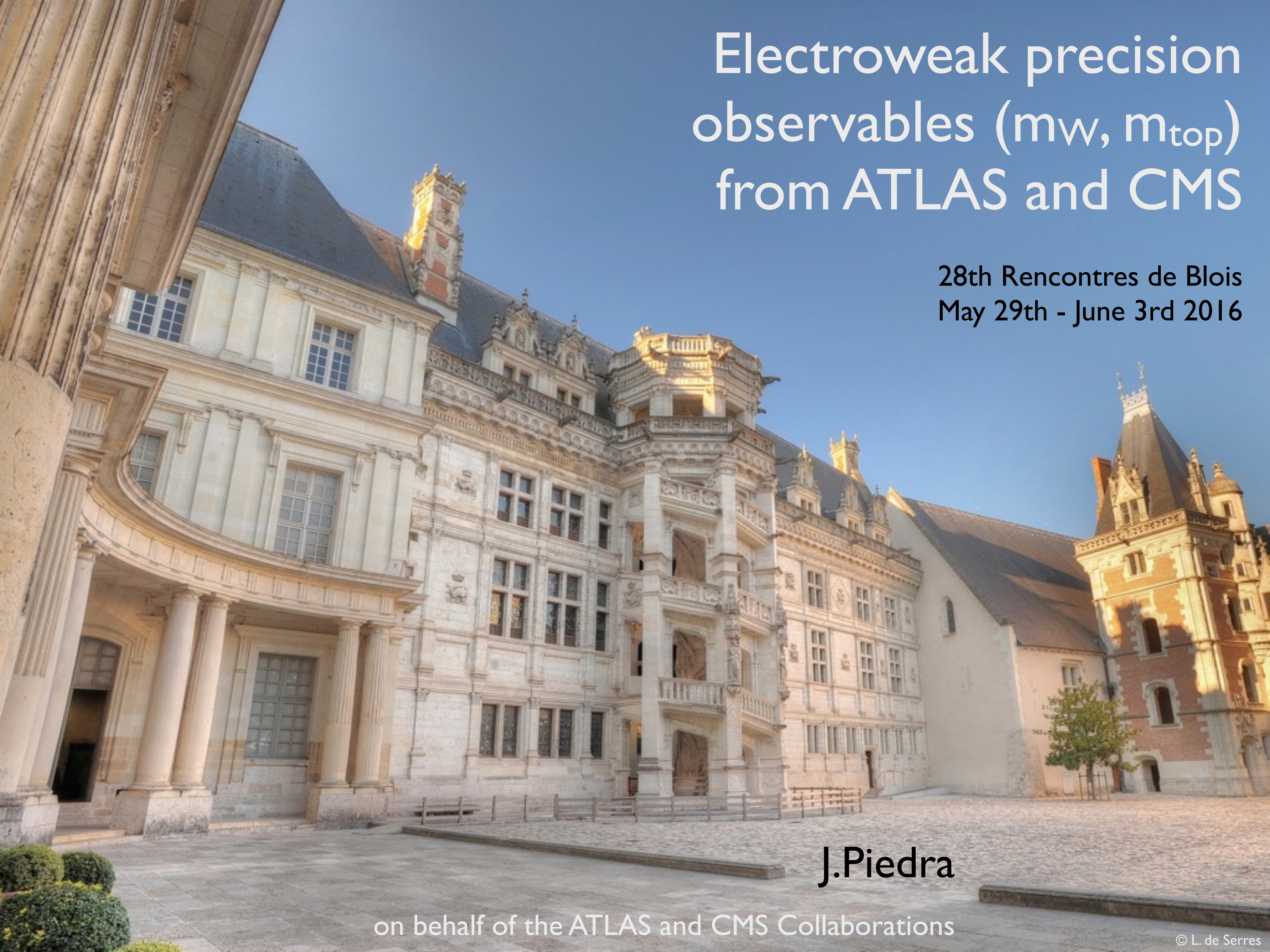

Electroweak precision observables (m_W, m_{top}) from ATLAS and CMS

28th Rencontres de Blois
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on behalf of the ATLAS and CMS Collaborations

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outline

the content of this talk is devoted to the latest ATLAS and CMS efforts in reducing the W mass and top mass uncertainties

- using 7 and 8 TeV LHC data
- we will also highlight the latest LHCb, CDF and ATLAS efforts in determining $\sin\theta_{eff}$
- the experiments aim at a 6 MeV resolution for m_W
- a huge effort has been made at ATLAS and CMS to improve the top mass determination, both in direct and indirect measurements

these high precision measurements will provide a crucial test of the SM

forward-backward asymmetry

- ATLAS CERN-PH-EP-2014-259 (4.8 fb-1 at 7 TeV)

vector and axial-vector couplings in the neutral current annihilation process qq ➛ Z ➛ ll lead to a forward-backward asymmetry A_{FB} in the polar angle θ^*_{CS} (Collins-Soper frame) distribution of the final state leptons wrt. the quark direction in the rest frame of the dilepton system

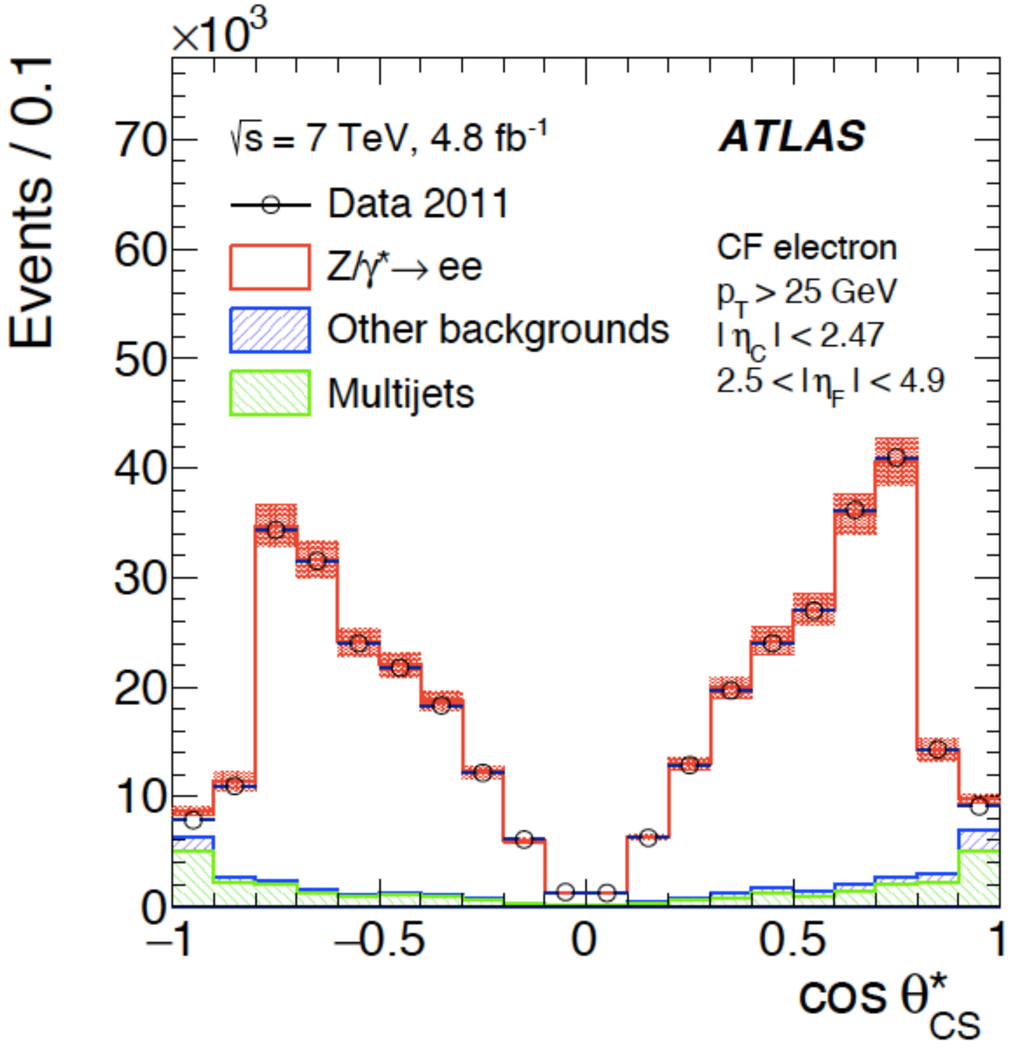
forward for $\cos\theta^* \geq 0$ and backward for $\cos\theta^* < 0$

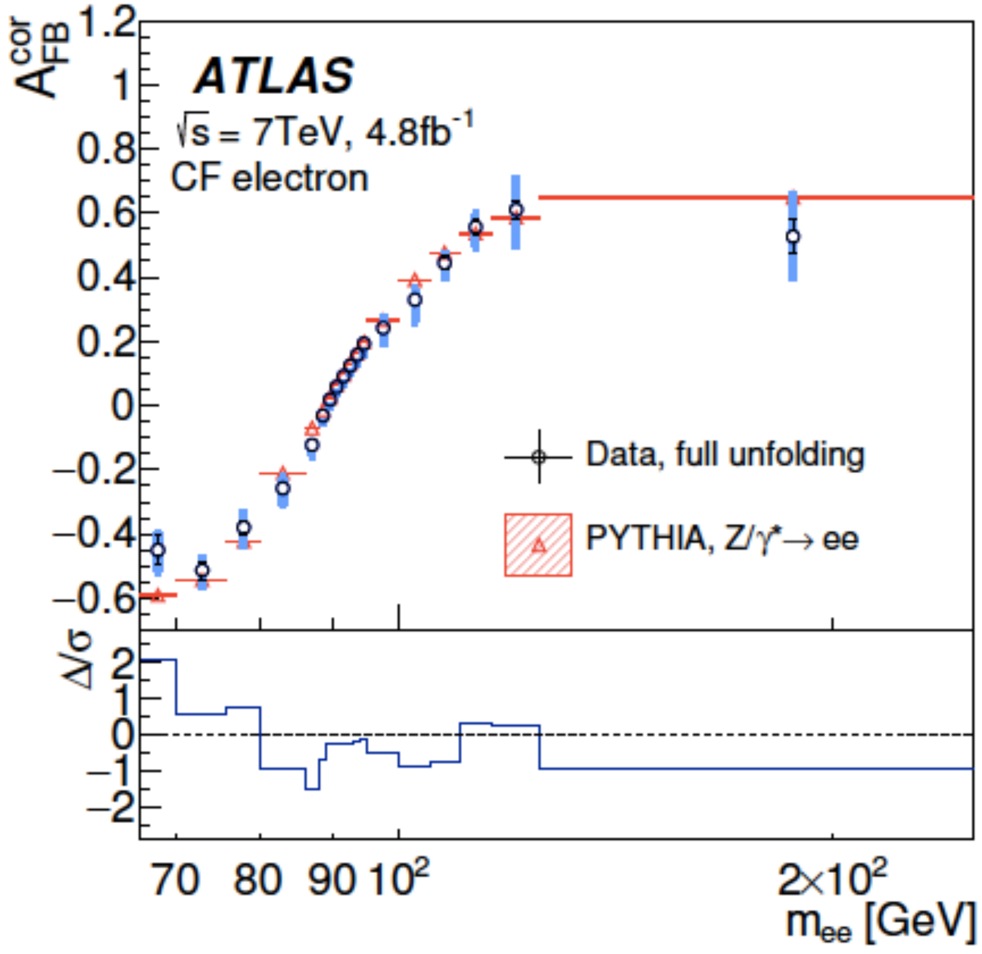
- we extract the EWK mixing angle $\sin^2\theta_W$ from the measurement of $A_{FB} = (N_F - N_B) / (N_F + N_B)$ as a function of the dilepton invariant mass

indeed we measure the effective leptonic weak mixing angle $\sin^2\theta_{eff}^{lept} = k_f \cdot \sin^2\theta_W$ with k_f fermion-dependent

most precise $\sin^2\theta_{eff}^{lept} = 0.23153 \pm 0.0016$ (LEP + SLD)

- electron (muon) energy > 25 (20) GeV
- use central muons and central+forward electrons
  - forward leptons reduce the asymmetry dilution
- ttbar, ZZ, WZ, WW and Z from simulation; multijets is data-driven
- the A_{FB} is estimated in m_{ll} bins for both muons and electrons
  - we perform an unfolding that corrects for detector effects and radiative corrections (mass bin migration)
  - with another unfolding we also correct for dilution effects, which occur when the wrong choice is made for the incoming quark direction
  - **the unfolded asymmetry agrees with SM predictions**
- $\sin^2\theta_{eff}^{lept}$ is extracted from the measured A_{FB}
  - MC samples have been reweighed for different $\sin^2\theta_{eff}^{lept}$ values
  - a χ^2 minimisation method is performed





$\sin^2\theta_{\text{eff}}^{\text{lept}}$ results

- ATLAS

CERN-PH-EP-2014-259 and JHEP09 (2015) 049

0.2308 ± 0.0005 (stat) ± 0.0006 (syst) ± 0.0009 (PDF)

the dominant uncertainty comes from knowledge of the PDFs

expected to be reduced with improved extraction methods.
Besides, more data is coming! *(We're still far from hitting the wall :)*

- latest from LHCb

CERN-PH-EP-2015-250 and JHEP 1511 (2015) 190

0.23142 ± 0.00073 (stat) ± 0.00052 (syst) ± 0.00056 (theory)

most precise LHC measurement

- latest from CDF

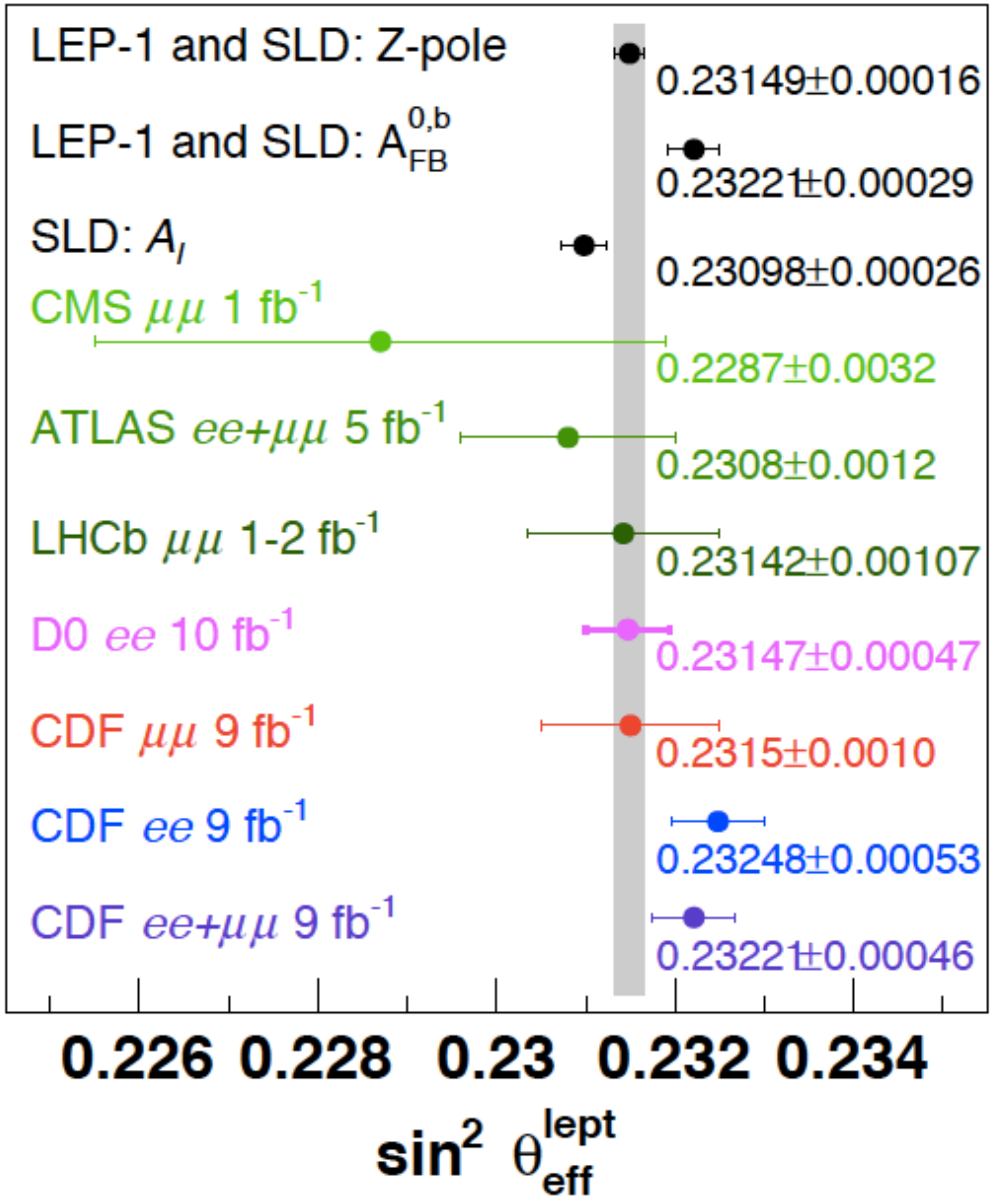
FERMILAB-PUB-16-165-E

0.23248 ± 0.00049 (stat) ± 0.00019 (syst) from Z → ee

this is a benchmark for future LHC measurements

includes a new strategy for PDF uncertainty reduction

0.23221 ± 0.00043 (stat) ± 0.00018 (syst) when combined with previous CDF μμ



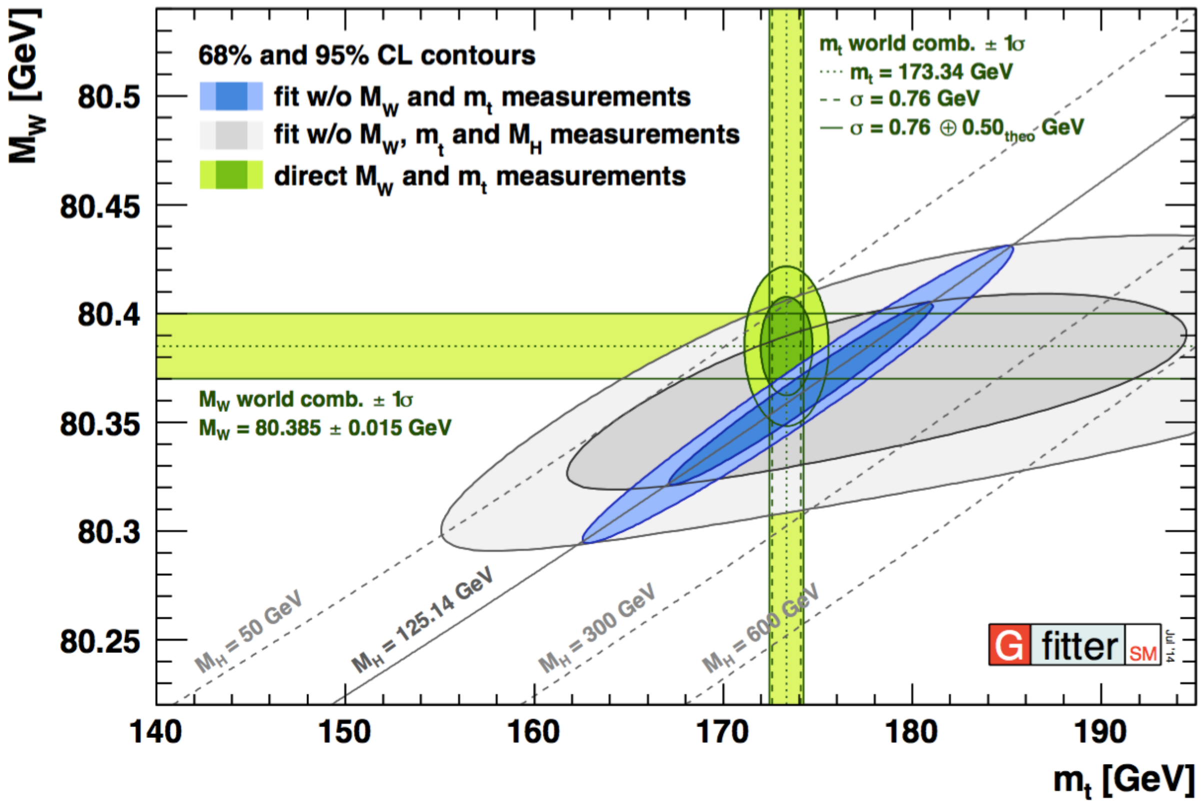
W-like measurement of the Z mass

CMS-SMP-14-007 @ 7 TeV

the W boson mass is at the moment the key observable in the EWK precision fit to test the overall consistency of the SM

given the current m_{top} and m_H accuracies, the W mass should be measured with a 6 MeV precision (the world average has a 15 MeV precision)

- LHC experiments ATLAS and CMS will have O(7 MeV) statistical accuracy on m_W
  - **detector performance and physics modelling are key to realise this potential**
- we will report on recent detector performance studies by CMS
- physics modelling studies can be found at ATL-PHYS-PUB-2014-015
  - quantitative study on theoretical uncertainties due to incomplete knowledge of quark PDF and uncertainty in the modelling of the low-*pt* regime of W/Z bosons
  - confirmed importance of uncertainties on the W-polarisation



muon scale and track-based recoil

- improved muon momentum scale calibration

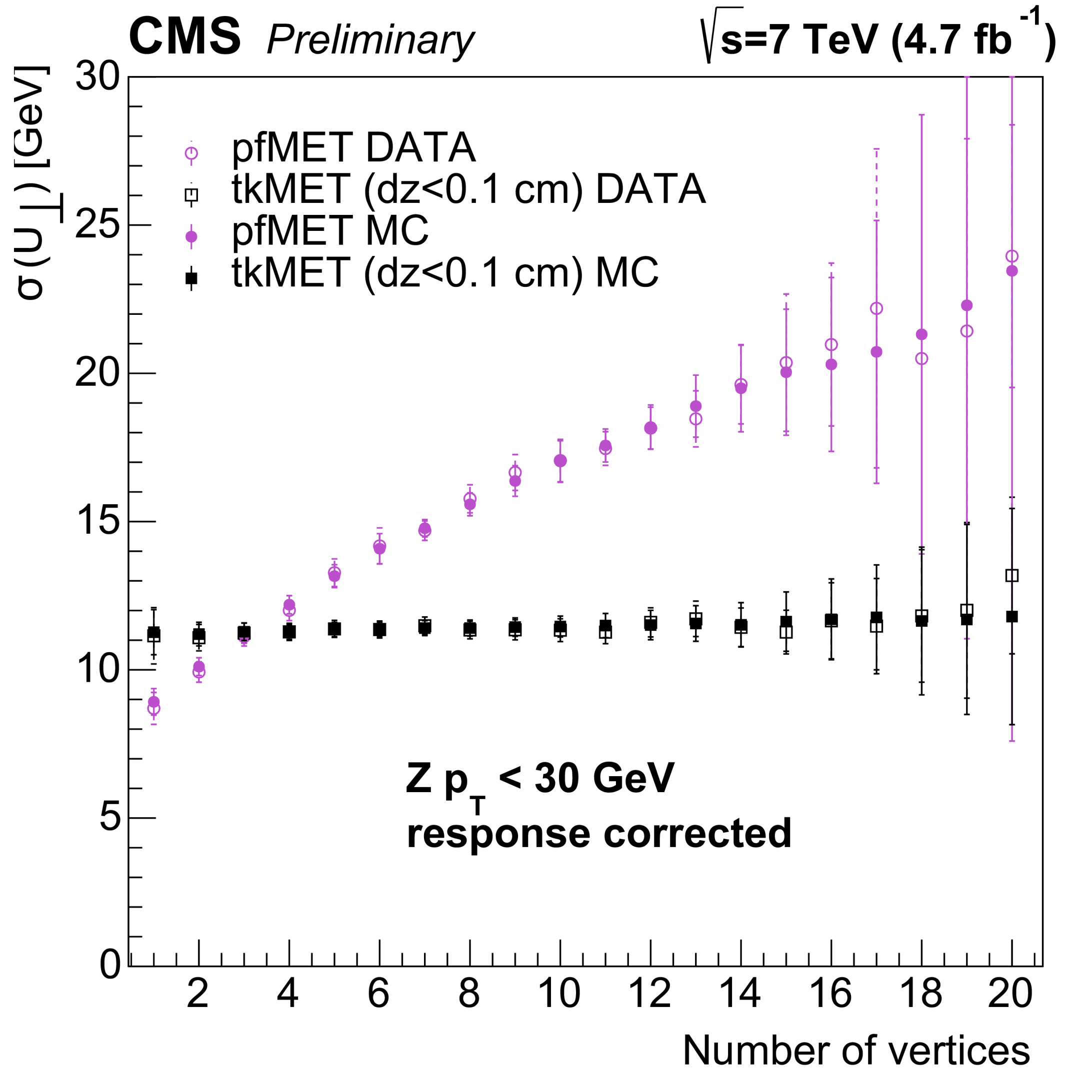
  correct curvature for small variations of the magnetic field, residual misalignment effects, and imperfect modelling of the material resulting in different energy loss

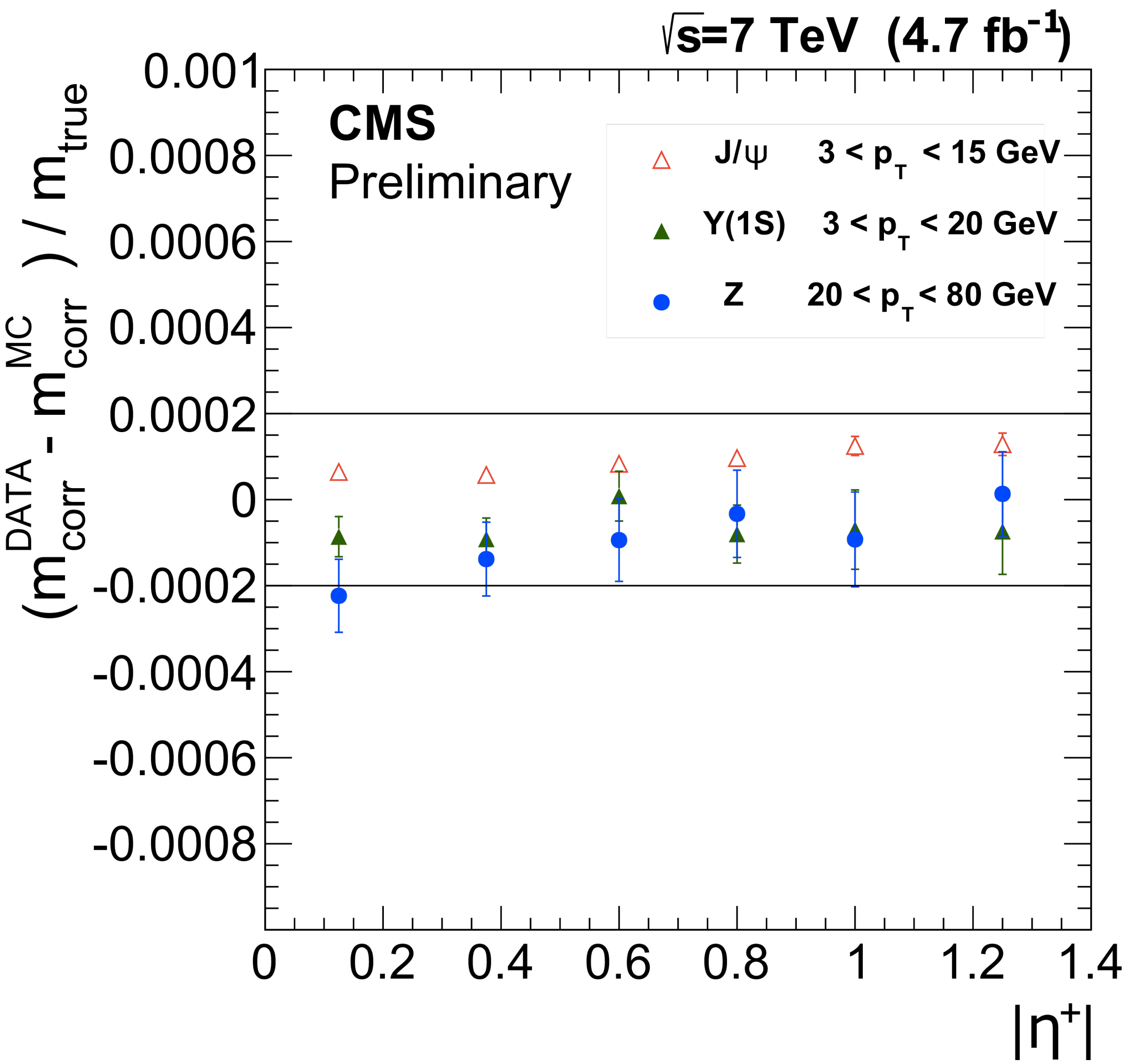
  calibrated with J/ψ and Υ(1S) resonances, closure test done on Z+jets ➠ 0.2 per-mil level achieved or < 8 MeV

- track-based recoil

  using track-based MET we get flat recoil response wrt. the number of vertices

  the track-based MET also provides the best discriminating power for the transverse mass peak





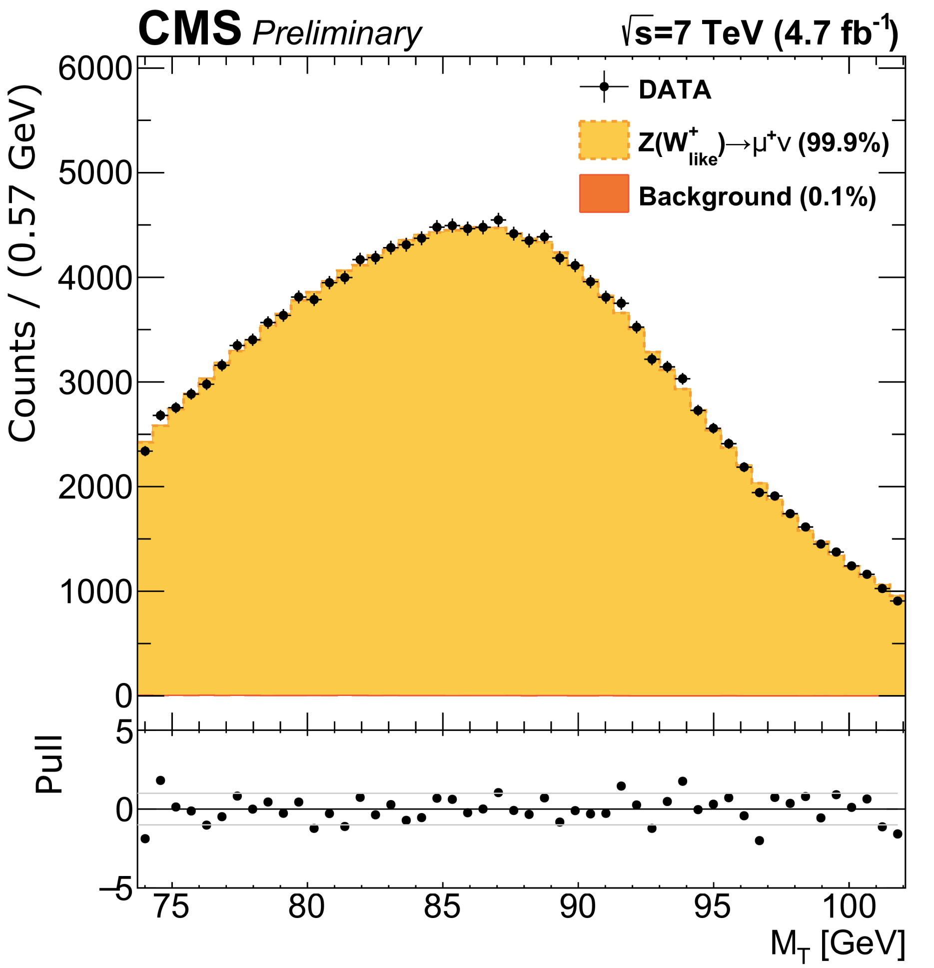
results

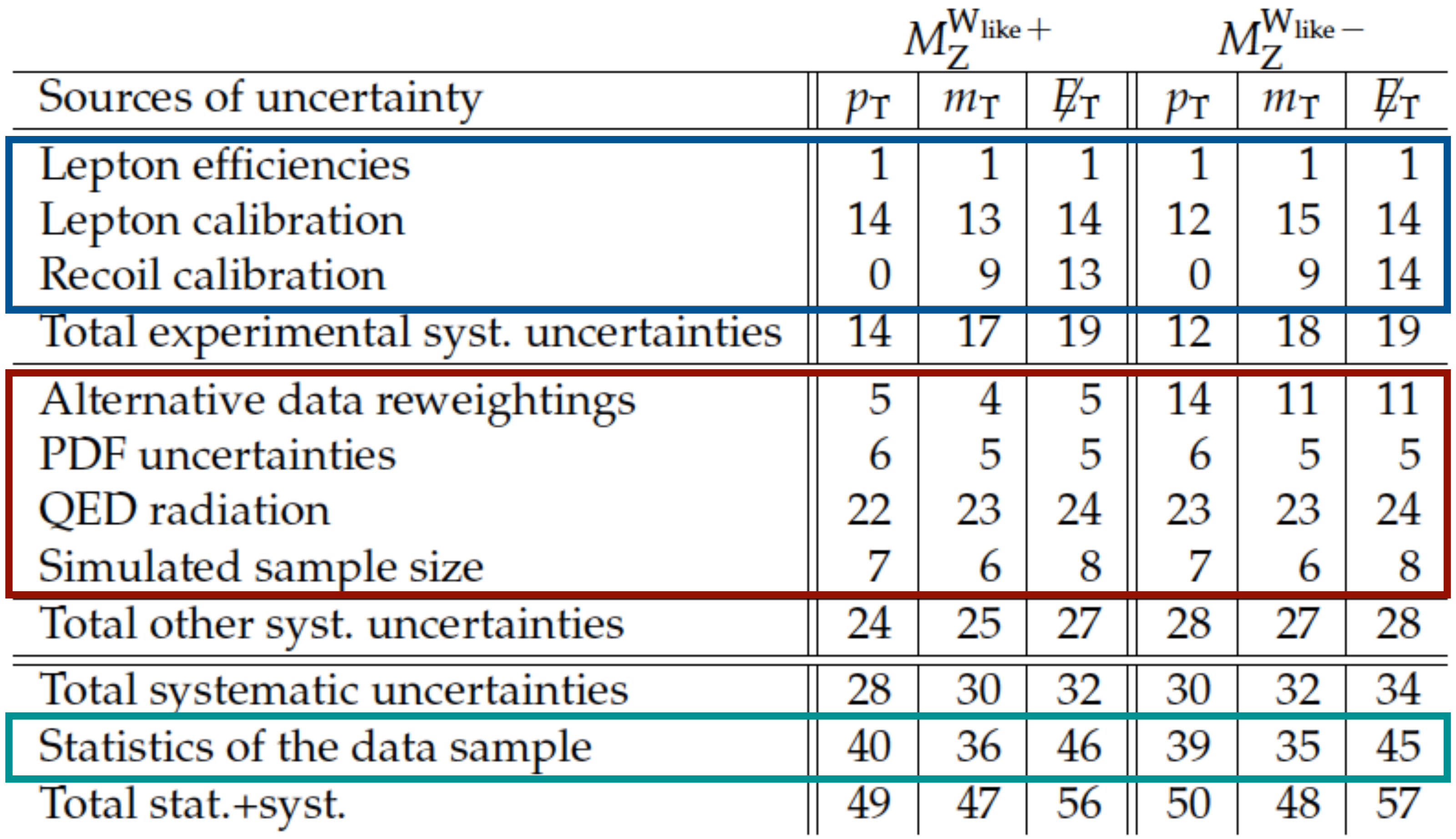
- take a Z ➛ μμ sample, remove one lepton… and compute the Z mass as one would do for W ➛ μν events
- mimic the W mass phase space
- the lowest uncertainty is obtained when using the $W_{\text{like+}}$ transverse mass

M_Z = 91206 ± 36 (stat.) ± 30 (syst.) MeV

M_Z(PDG) = 91187.6 ± 2.1 MeV

- several uncertainties related to the real W mass measurement are missing here (like the boson *pt*) or likely to be smaller (PDFs)





	$M_Z^{W_{\text{like}+}}$			$M_Z^{W_{\text{like}-}}$		
Sources of uncertainty	p_T	m_T	$\not\!E_T$	p_T	m_T	$\not\!E_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

include statistical and systematic component of the calibration

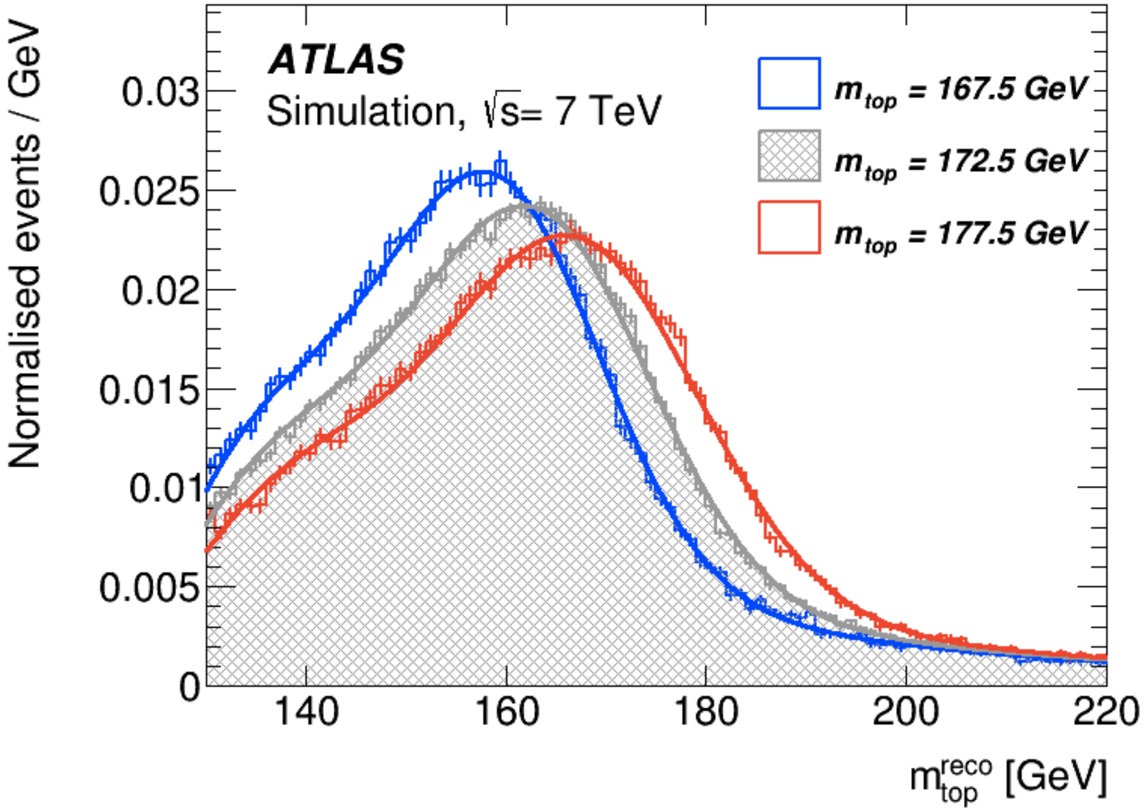
do not directly translate to W

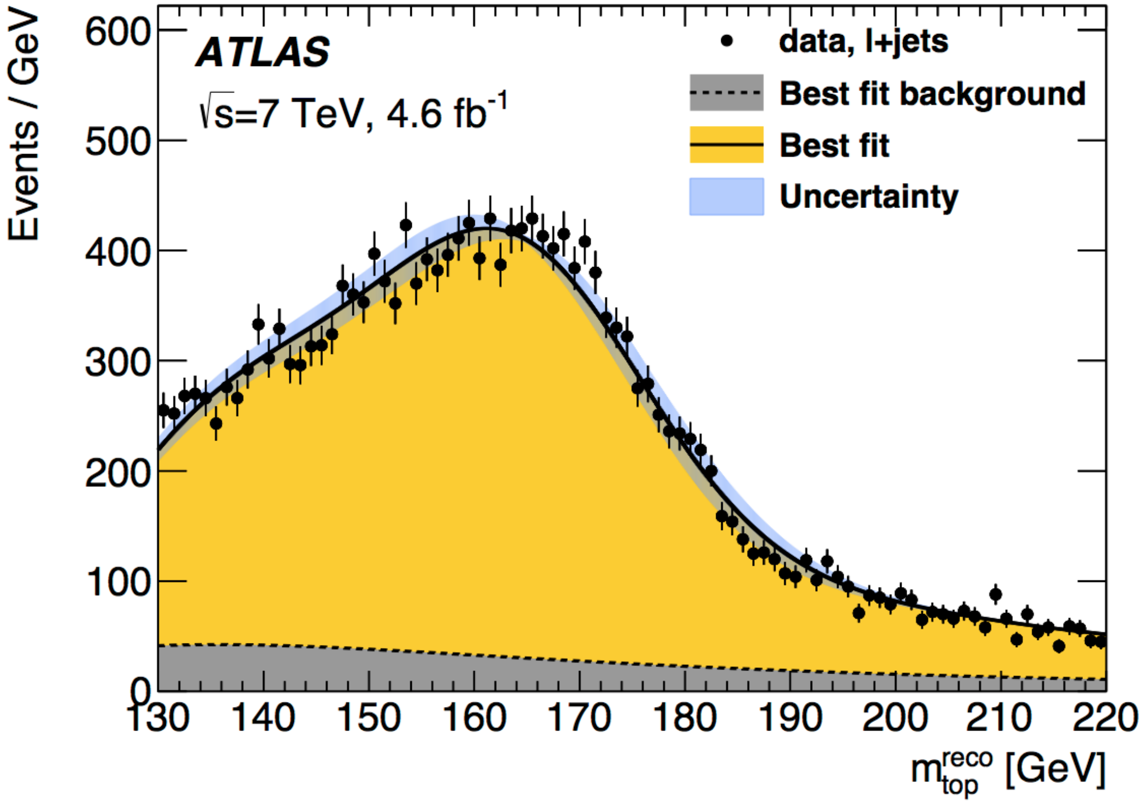
expected to decrease to few MeV for the W

top mass
direct measurements

lepton+jets @ 7 TeV

ATLAS Eur. Phys. J. C (2015) 75:330





targets three different observables, each sensitive to a particular key parameter

background also sensitive to the light-jet energy scale factor (JSF) and b-to-light-jet energy scale factor (bJSF)

build template parameterisation and perform a global 3D fit to extract all parameters simultaneously

Observable $m_{\mathrm{top}}^{\mathrm{reco}}$

$P_{\mathrm{top}}(m_{\mathrm{top}}^{\mathrm{reco},i} \mid m_{\mathrm{top}}, \mathrm{JSF}, \mathrm{bJSF}, f_{\mathrm{bkg}})$

Target sensitivity

Observable m_{W}^{reco}

$P_{W}(m_{W}^{\mathrm{reco},i} \mid \mathrm{JSF}, f_{\mathrm{bkg}})$

Target sensitivity

Observable R_{bq}^{reco}

$P_{bq}(R_{bq}^{\mathrm{reco},i} \mid m_{\mathrm{top}}, \mathrm{bJSF}, f_{\mathrm{bkg}})$

Target sensitivity

Where R_{bq}^{reco} is defined differently for events with **1** or **≥ 2** b-tagged jets

$$R_{bq}^{\mathrm{reco,2b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{had}}} + p_{\mathrm{T}}^{b_{\mathrm{lep}}}}{p_{\mathrm{T}}^{W_{\mathrm{jet}_1}} + p_{\mathrm{T}}^{W_{\mathrm{jet}_2}}},$$

$$R_{bq}^{\mathrm{reco,1b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{tag}}}}{(p_{\mathrm{T}}^{W_{\mathrm{jet}_1}} + p_{\mathrm{T}}^{W_{\mathrm{jet}_2}})/2}$$

lepton+jets and dilepton @ 7 TeV

ATLAS Eur. Phys. J. C (2015) 75:330

- lepton+jets

  background from ~25% in 1 b-tag events (mostly W+jets) to 3% in 2 b-tag events (mostly single top)

  use of 3D template method improves JES and systematic uncertainties

- dominant uncertainty sources

  0.4% from statistics (which includes JSF / bJSF) ➠ Δm_{top} = 0.75 GeV

  0.3% from Jet Energy Scale, 0.3% from b-tagging efficiency / mistag

- top mass from lepton + jets

  172.33 ± 0.75 (stat. + JSF + bJSF) ± 1.02 (syst.) GeV

- top mass from dilepton

  1D template method uses m(lb) = average invariant mass of the two lepton+b pairs in the event

  173.79 ± 0.54 (stat.) ± 1.30 (syst.) GeV

top mass from combination with a total uncertainty of 0.91 GeV

172.99 ± 0.48 (stat.) ± 0.78 (syst.) GeV

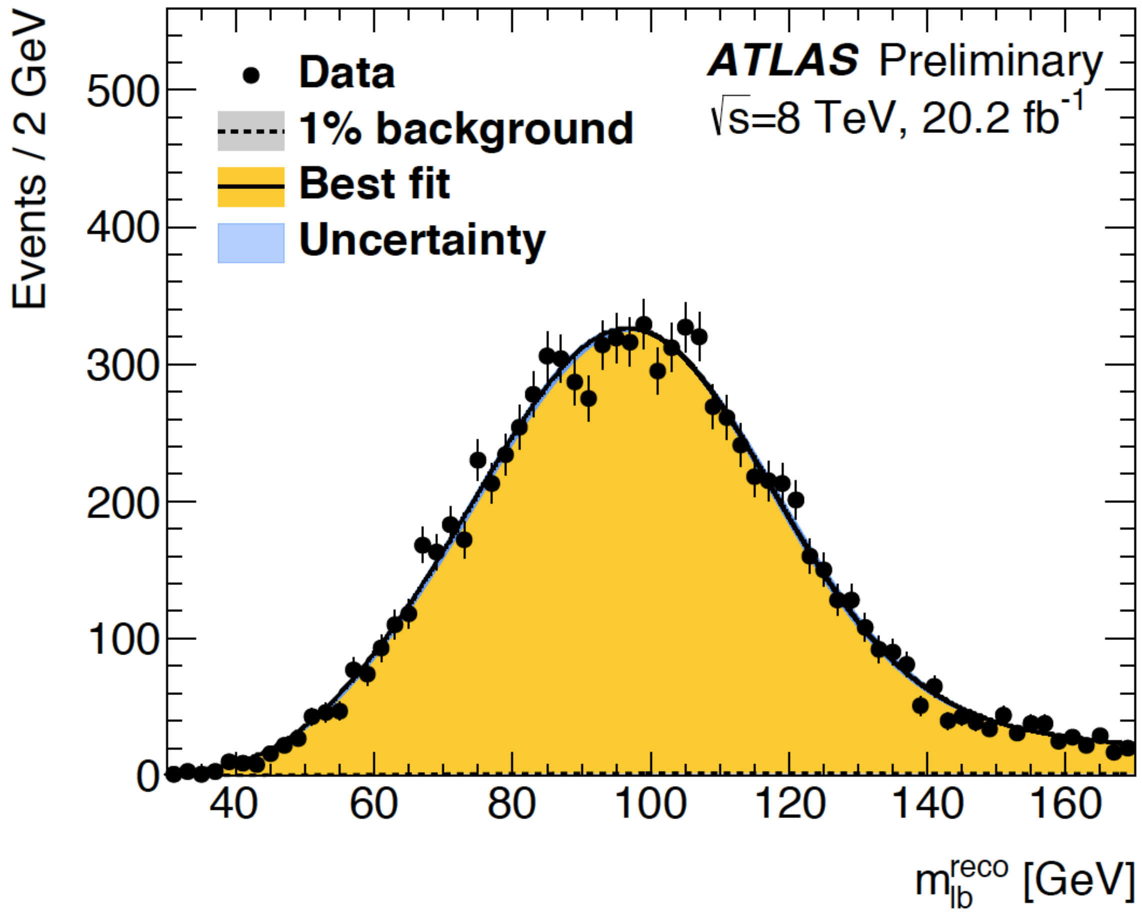
dilepton @ 8 TeV

ATLAS paper in preparation

- released in May
- *channel with underconstrained event kinematics*

  use the minimum average mass of the lepton-bjet system

  optimise the 7 TeV selection



- results

  m_t = 172.99 ± 0.41 (stat) ± 0.74 (syst) = 172.99 ± 0.84 GeV

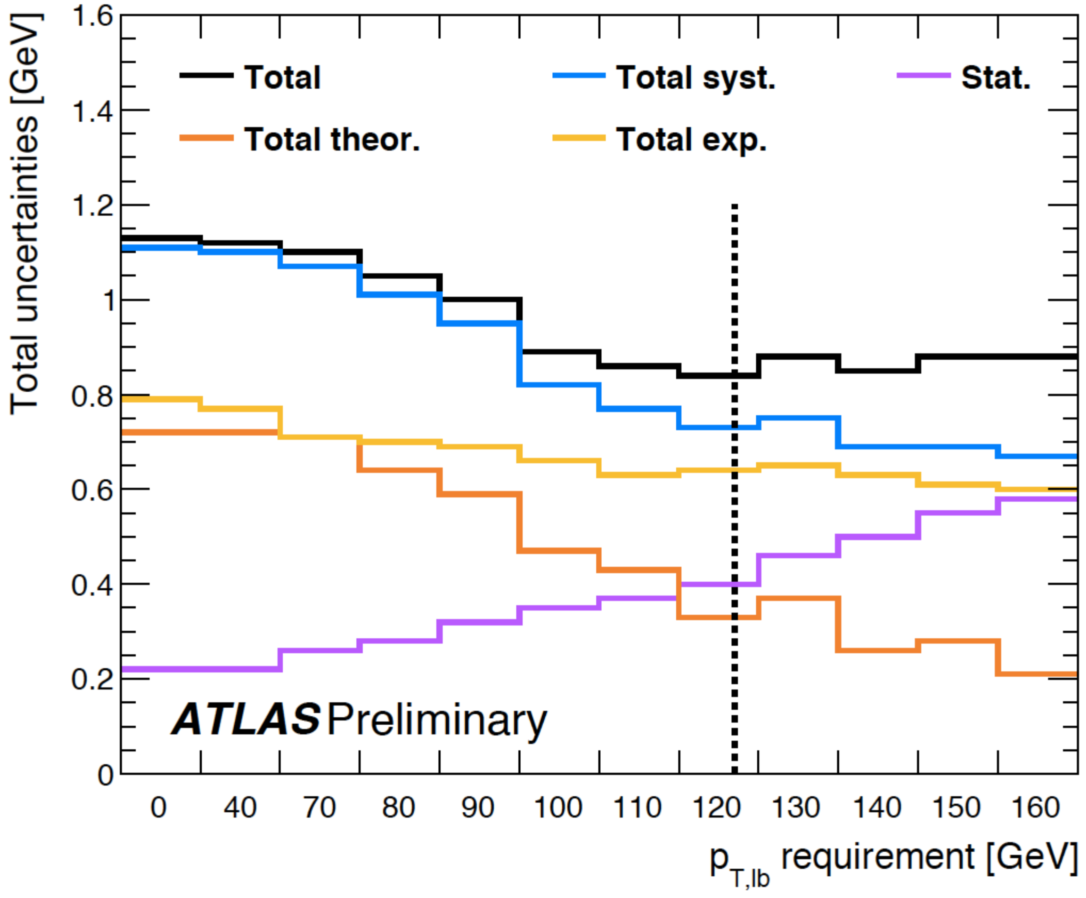
  40% improvement wrt. 7 TeV measurement

  most precise m_t in the dilepton channel to date

- combining with dilepton and lepton+jets at 7 TeV (using BLUE)

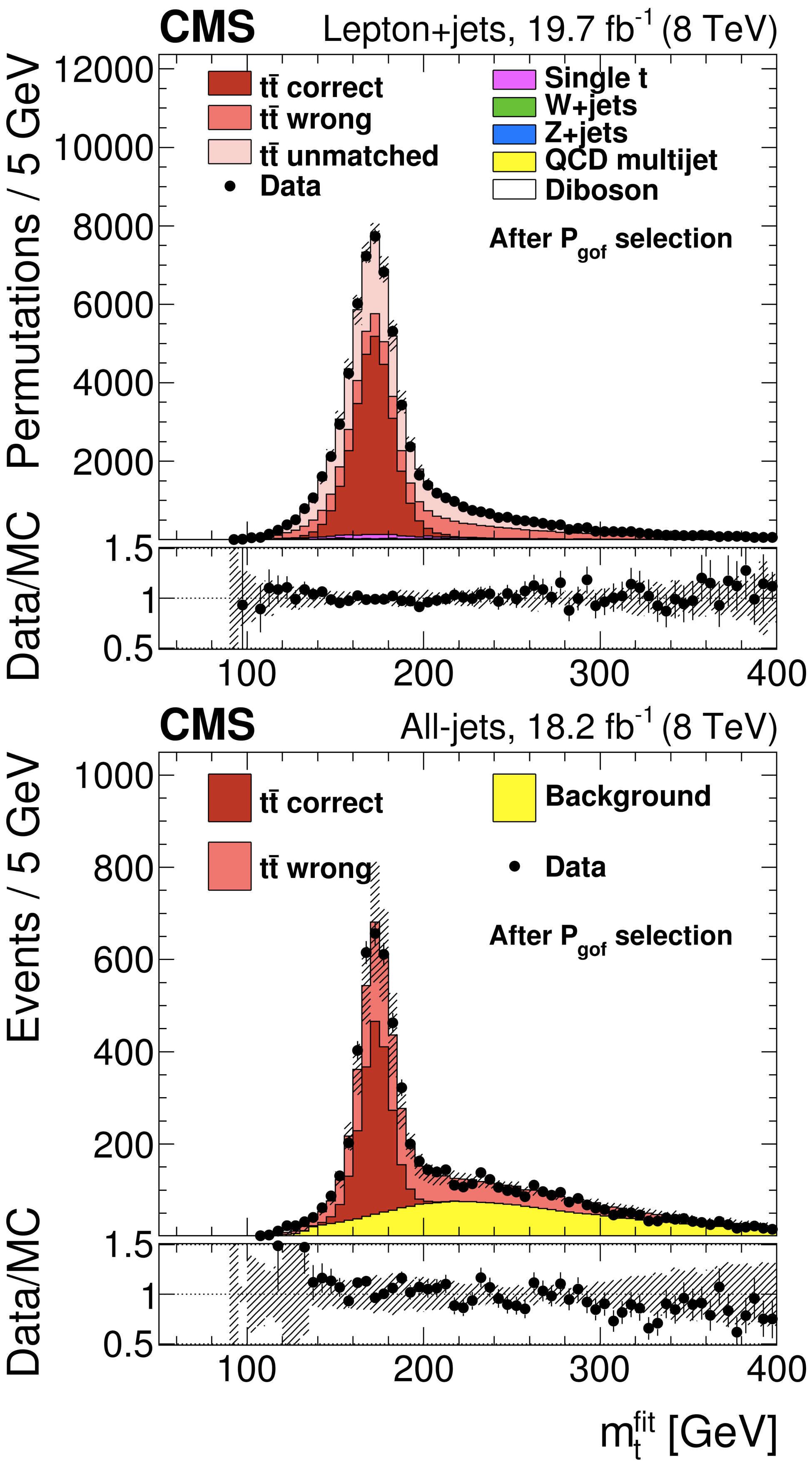
  m_t = 172.84 ± 0.70 GeV

  23% improvement wrt. old ATLAS combination



top mass at 8 TeV

CMS, Phys. Rev. D 93, 072004 (2016)



lepton+jets and all-jets channels

extract simultaneously m_{top} and the overall jet energy scale factor JSF

the observable m_t^{fit} is estimated by a kinematic fit with m_W constraint to 80.4 GeV

lepton+jets: per-permutation weights applied to heighten contribution from correct jet-quark match

figures: event permutations after goodness-of-fit probability from kinematic fit (P_{gof}) selection

2D ➠ hybrid approach

incorporates prior knowledge about the JES using a Gaussian constraint

top mass at 8 TeV

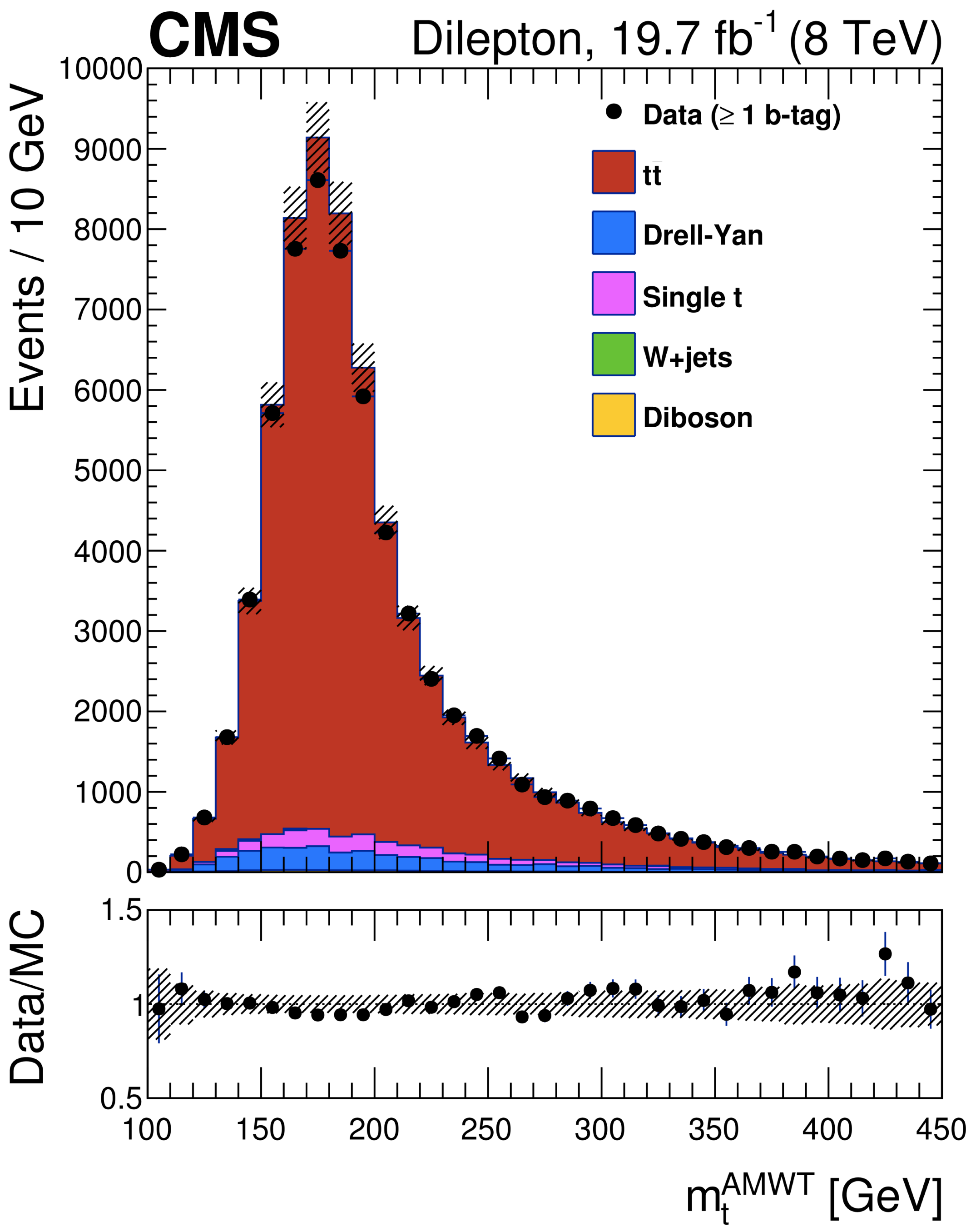
CMS, Phys. Rev. D 93, 072004 (2016)

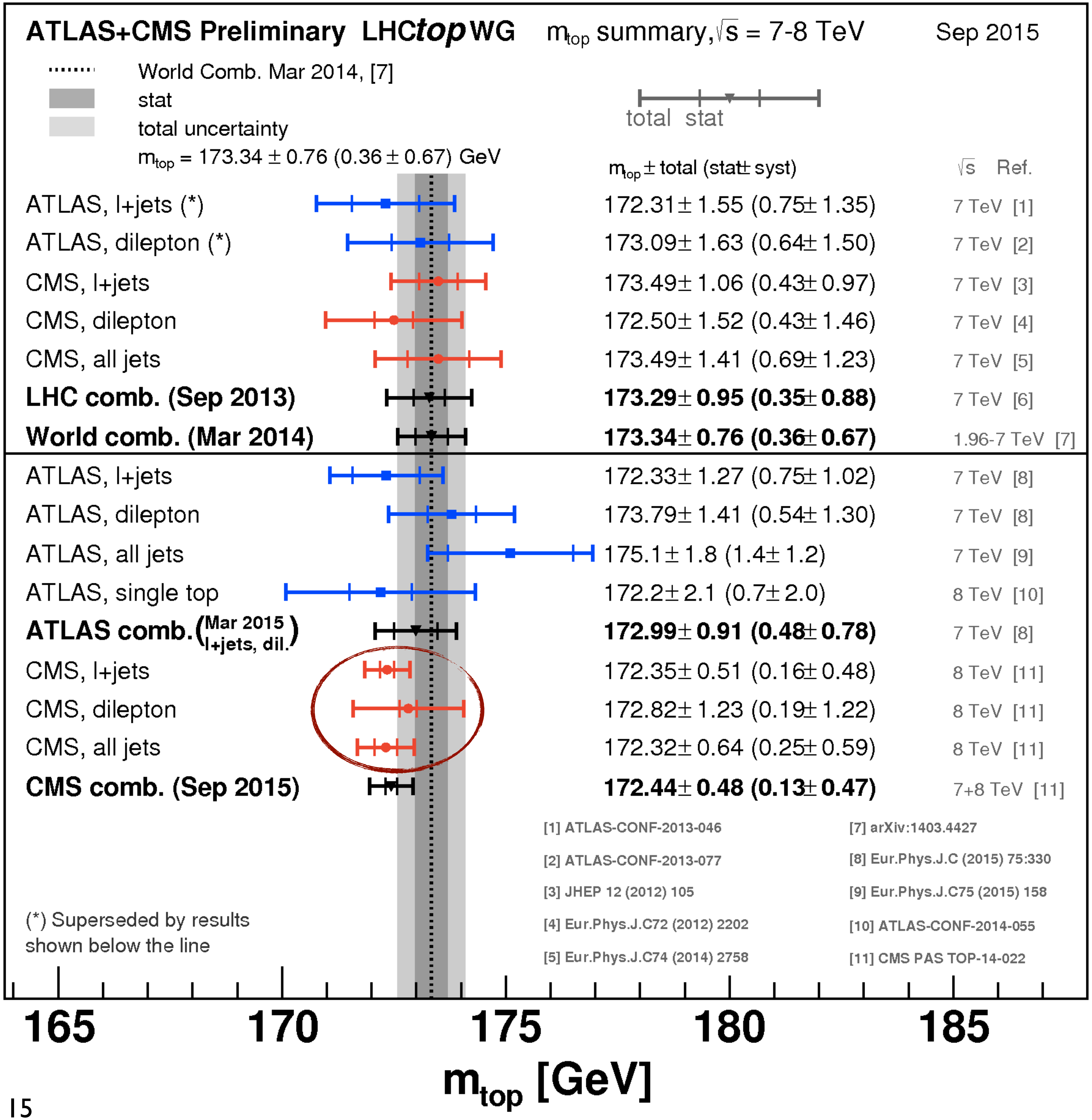
dilepton channel = ee/μμ/eμ

- require at least one b-tagged jet
- clean analysis, largest background is DY

employ an Analytic Matrix Weighing Technique (AMWT)

- it allows the determination of m_{top} with the assumption of JSF = 1
- *the results are comparable to the 1D fits performed in lepton+jets and all-jets*
- a large number of possible neutrino momenta is considered
- m_{top} is extracted from a likelihood fit based on templates from simulation

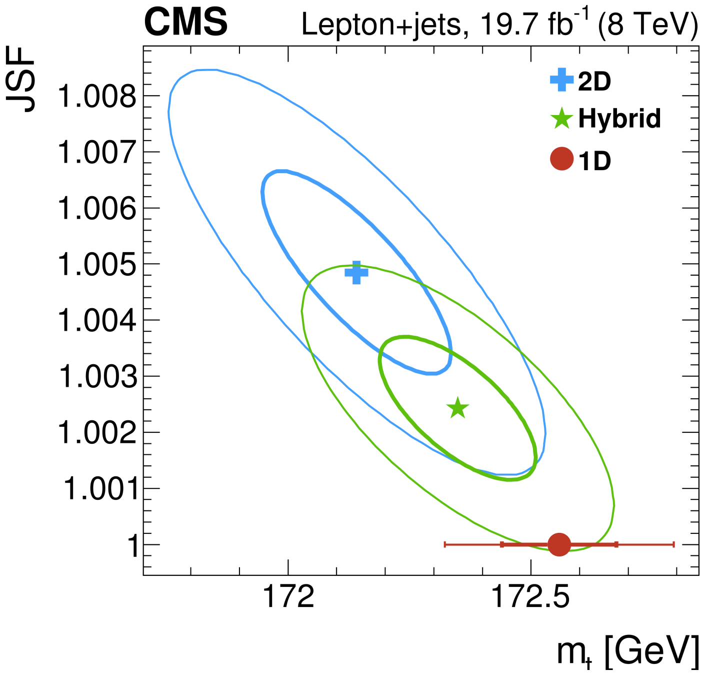


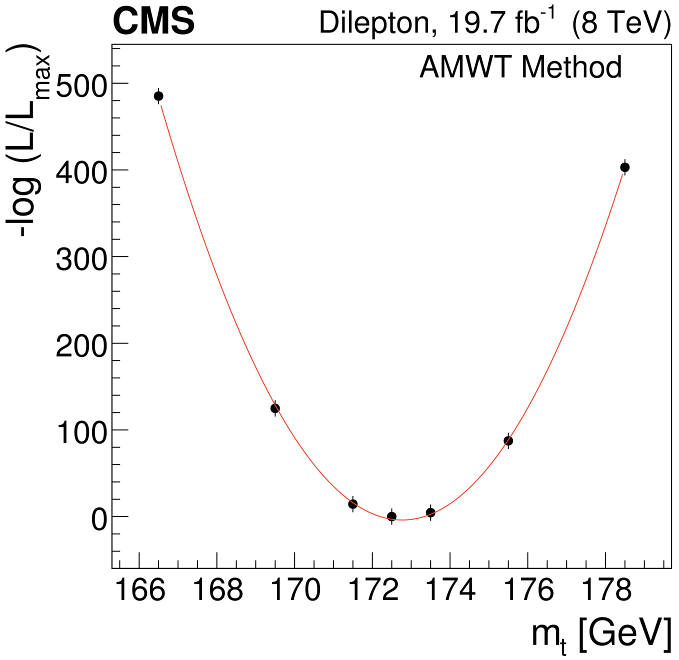


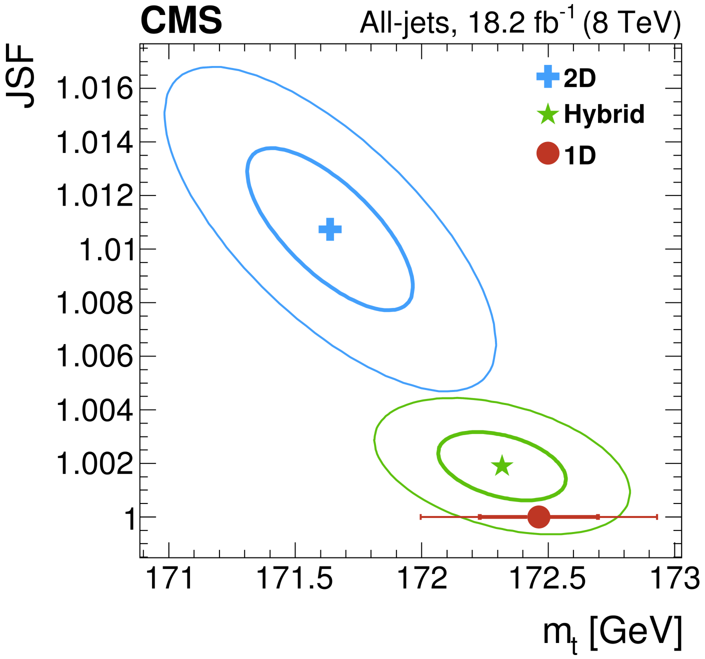
	m_{top} ± total (stat ± syst)	$\sqrt{s}$	Ref.
ATLAS, l+jets (*)	172.31 ± 1.55 (0.75 ± 1.35)	7 TeV	[1]
ATLAS, dilepton (*)	173.09 ± 1.63 (0.64 ± 1.50)	7 TeV	[2]
CMS, l+jets	173.49 ± 1.06 (0.43 ± 0.97)	7 TeV	[3]
CMS, dilepton	172.50 ± 1.52 (0.43 ± 1.46)	7 TeV	[4]
CMS, all jets	173.49 ± 1.41 (0.69 ± 1.23)	7 TeV	[5]
LHC comb. (Sep 2013)	**173.29 ± 0.95 (0.35 ± 0.88)**	7 TeV	[6]
World comb. (Mar 2014)	**173.34 ± 0.76 (0.36 ± 0.67)**	1.96-7 TeV	[7]
ATLAS, l+jets	172.33 ± 1.27 (0.75 ± 1.02)	7 TeV	[8]
ATLAS, dilepton	173.79 ± 1.41 (0.54 ± 1.30)	7 TeV	[8]
ATLAS, all jets	175.1 ± 1.8 (1.4 ± 1.2)	7 TeV	[9]
ATLAS, single top	172.2 ± 2.1 (0.7 ± 2.0)	8 TeV	[10]
ATLAS comb. (Mar 2015 l+jets, dil.)	**172.99 ± 0.91 (0.48 ± 0.78)**	7 TeV	[8]
CMS, l+jets	172.35 ± 0.51 (0.16 ± 0.48)	8 TeV	[11]
CMS, dilepton	172.82 ± 1.23 (0.19 ± 1.22)	8 TeV	[11]
CMS, all jets	172.32 ± 0.64 (0.25 ± 0.59)	8 TeV	[11]
CMS comb. (Sep 2015)	**172.44 ± 0.48 (0.13 ± 0.47)**	7+8 TeV	[11]

(*) Superseded by results
shown below the line

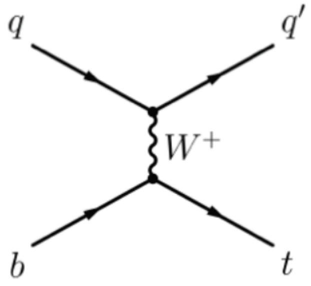
[1] ATLAS-CONF-2013-046
[2] ATLAS-CONF-2013-077
[3] JHEP 12 (2012) 105
[4] Eur.Phys.J.C72 (2012) 2202
[5] Eur.Phys.J.C74 (2014) 2758
[7] arXiv:1403.4427
[8] Eur.Phys.J.C (2015) 75:330
[9] Eur.Phys.J.C75 (2015) 158
[10] ATLAS-CONF-2014-055
[11] CMS PAS TOP-14-022







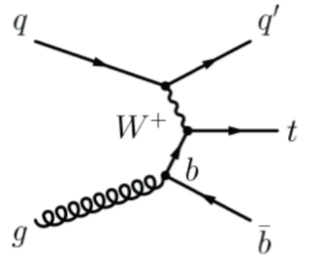
top mass
alternative measurements



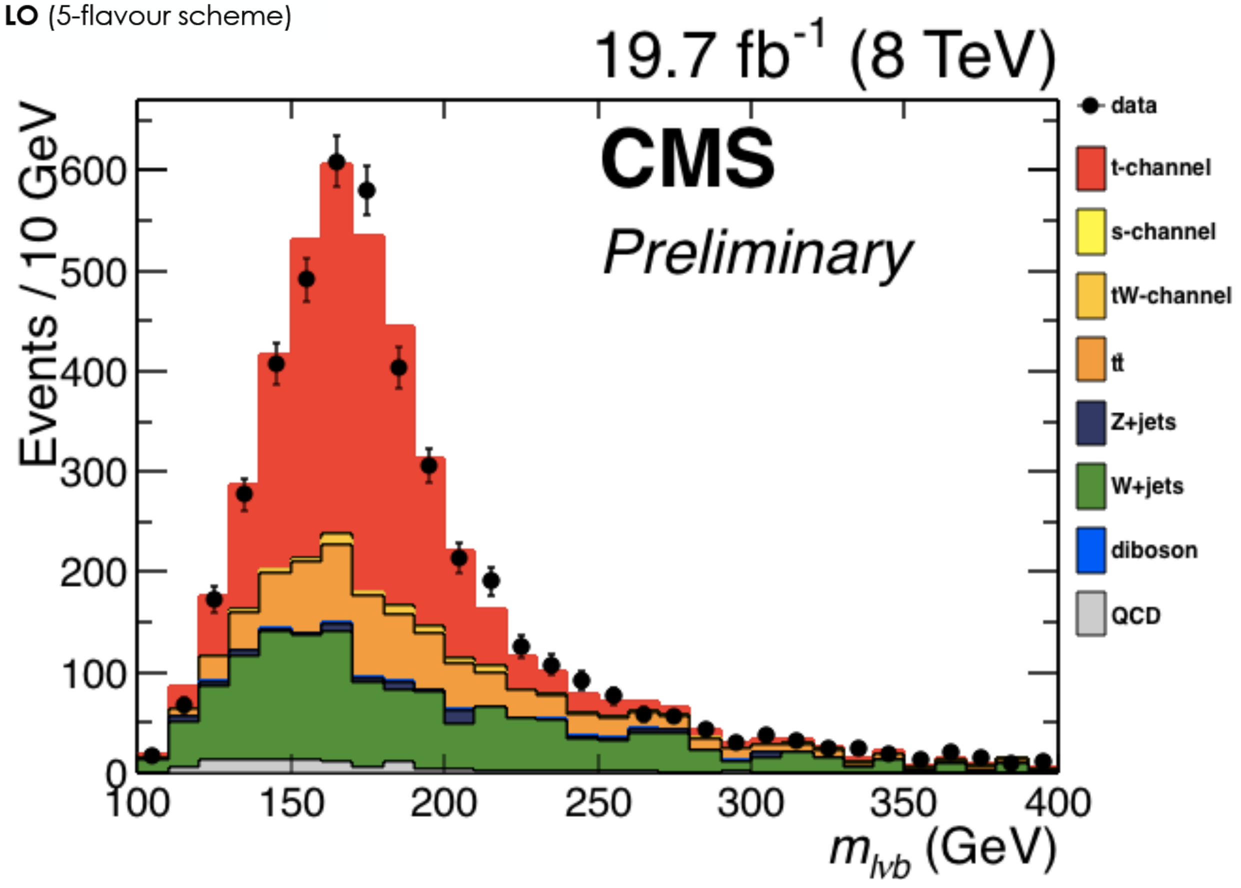
LO (5-flavour scheme)

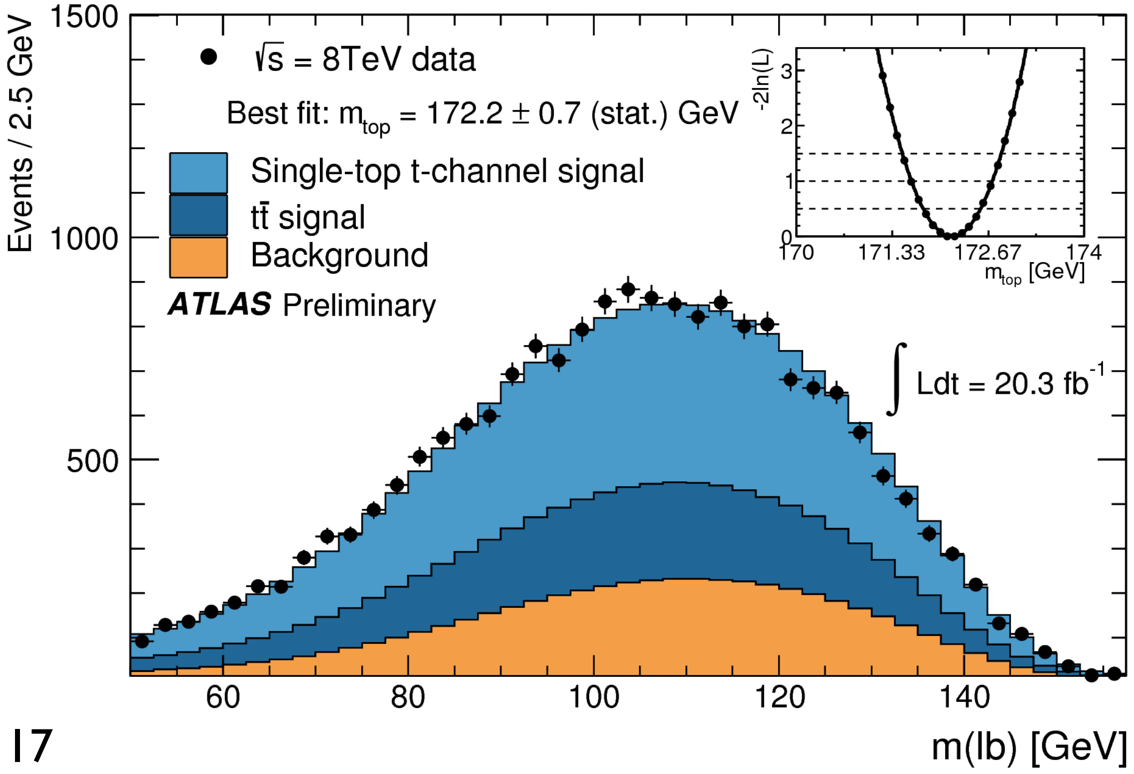
single top enhanced (t-channel) at 8 TeV

ATLAS-CONF-2014-055, CMS-TOP-15-001



NLO (4-flavour scheme)





access m_{top} through EWK production

- unfortunately it has smaller xs and higher backgrounds

muon channel for CMS

- high-*pt* isolated muon + 2 jets + 1 btag (signal region)
- 0 btag (W+jets region)
- observable is m(lνb) and m_{top} is extracted from extended unbinned likelihood fit

m_{top} = 172.60 ± 0.77 (stat.) $^{+0.93}_{-0.97}$ (syst.) GeV

largest systematic uncertainty (0.4%) comes from JES

e/μ in the case of ATLAS

- using the 1D template method with the m(lb) observable
- W+jets region defined by loosening the btag requirement

m_{top} = 172.2 ± 0.7 (stat.) ± 2.0 (syst.) GeV

largest systematic uncertainty (0.9%) comes from JES

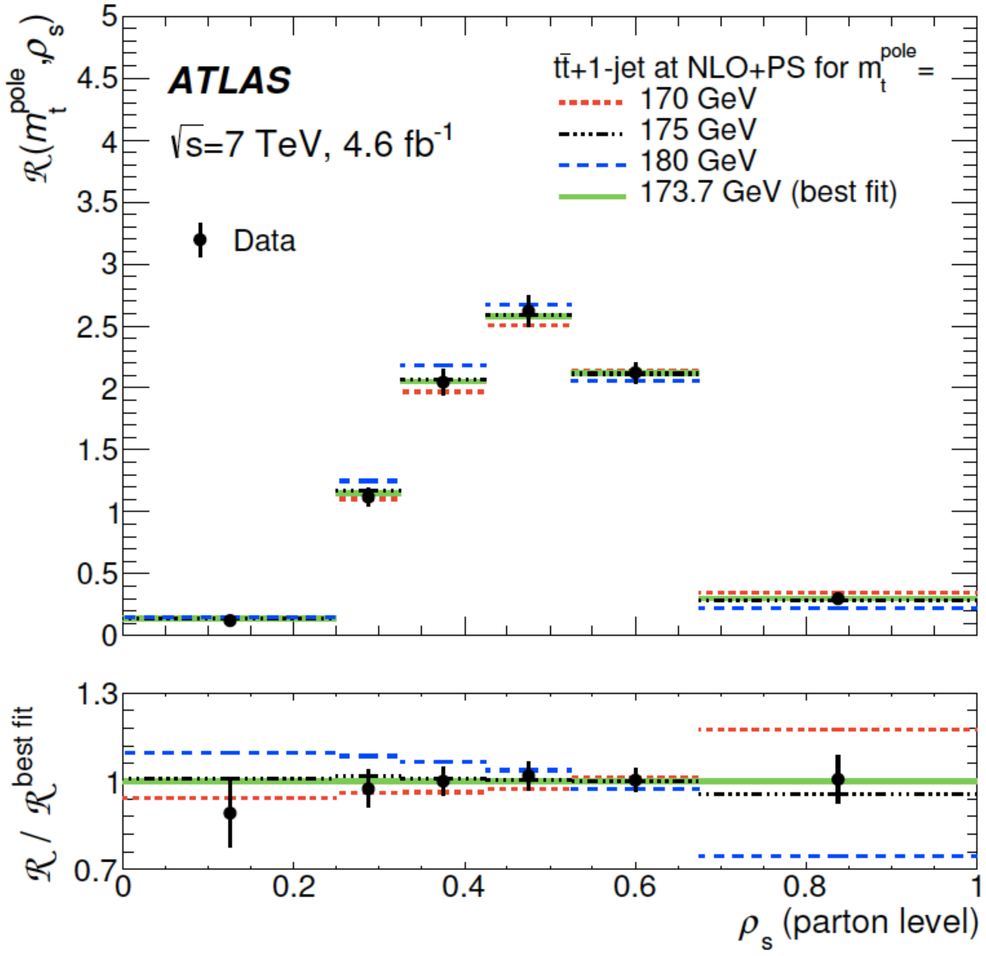
top pole mass from tt+jet

method originally proposed in arXiv:1303.6415

use the normalised differential cross section as a function of the inverse of the invariant mass of the tt + leading jet system

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

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}},$$

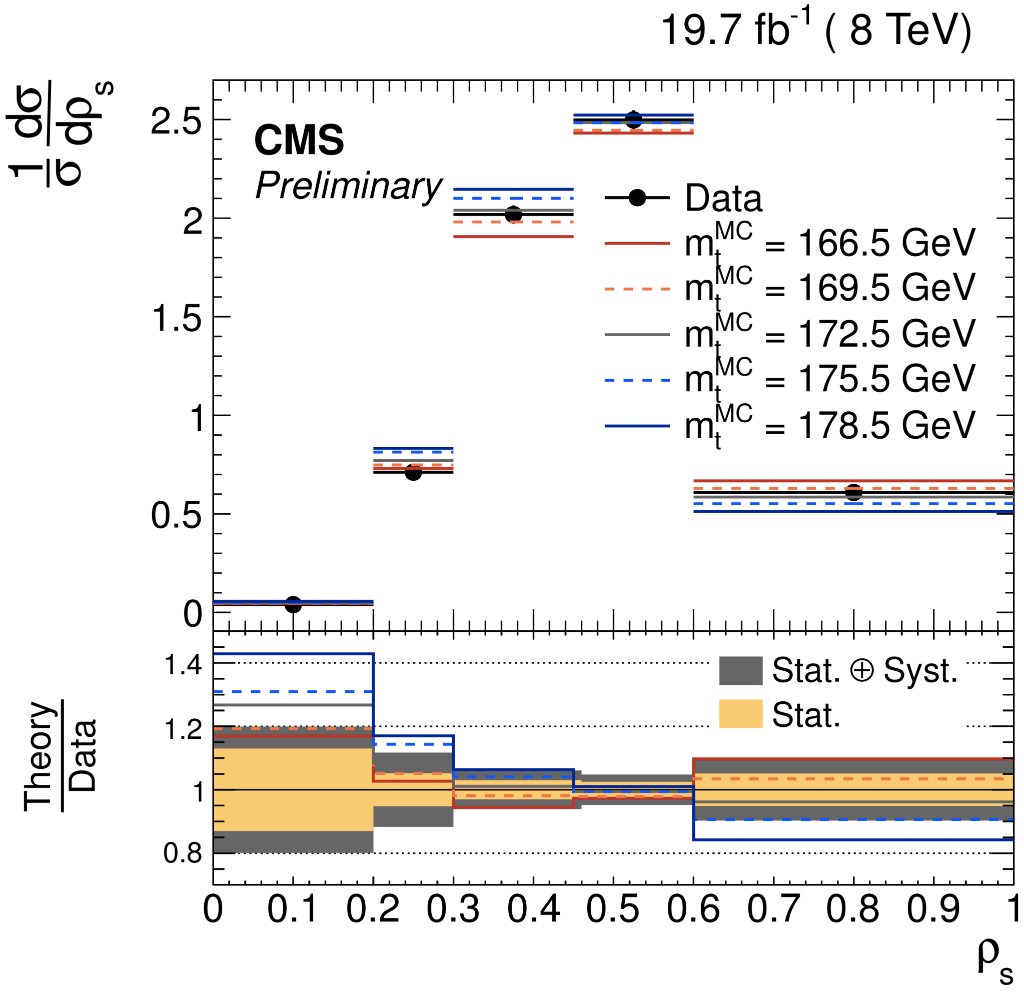


ATLAS, JHEP 10 (2015) 121

lepton+jets channel with two b-tags

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

0.9% from data statistics, 0.5% from JES and bJES



CMS-TOP-13-006

dilepton channel with one b-tag

m_t = 169.9 ± 1.1 (stat.) $^{+2.5}_{-3.1}$ (syst.) $^{+3.6}_{-1.6}$ (theo) GeV

precision mostly limited by the systematic uncertainties arising from modelling sources and the theory uncertainties in POWHEG

top pole mass from cross sections

using eμ events with b-tagged jets

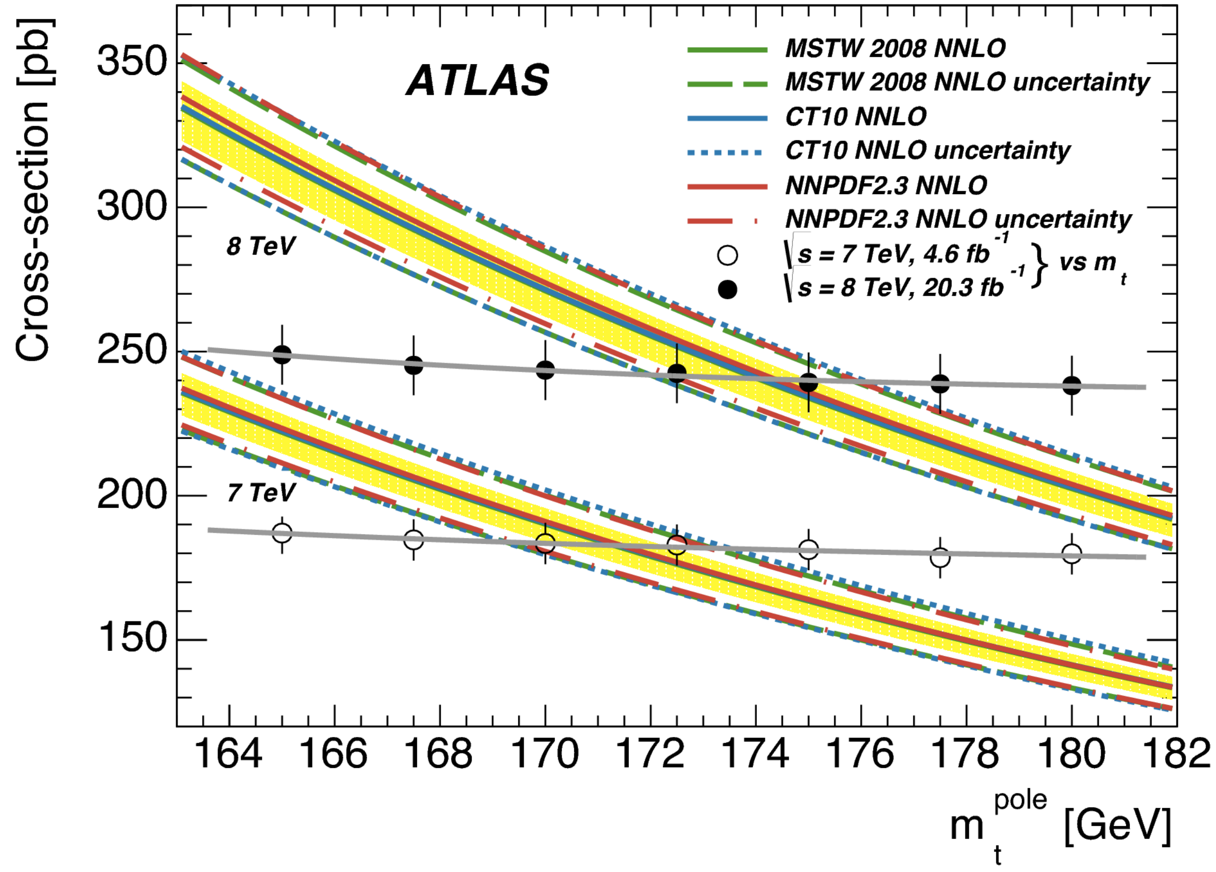
figures contain the 7 and 8 TeV measured and predicted cross-section vs. m_t

ATLAS, Eur.Phys.J. C74 (2014) 3109

- measurement of the tt cross section together with NNLO theoretical prediction allows for extraction of the pole mass
- several PDF sets considered: MSTW2008, CT10 and NNPDF2.3
- final value from maximizing a product of likelihoods at 7 and 8 TeV

main uncertainties come from PDFs and α_s

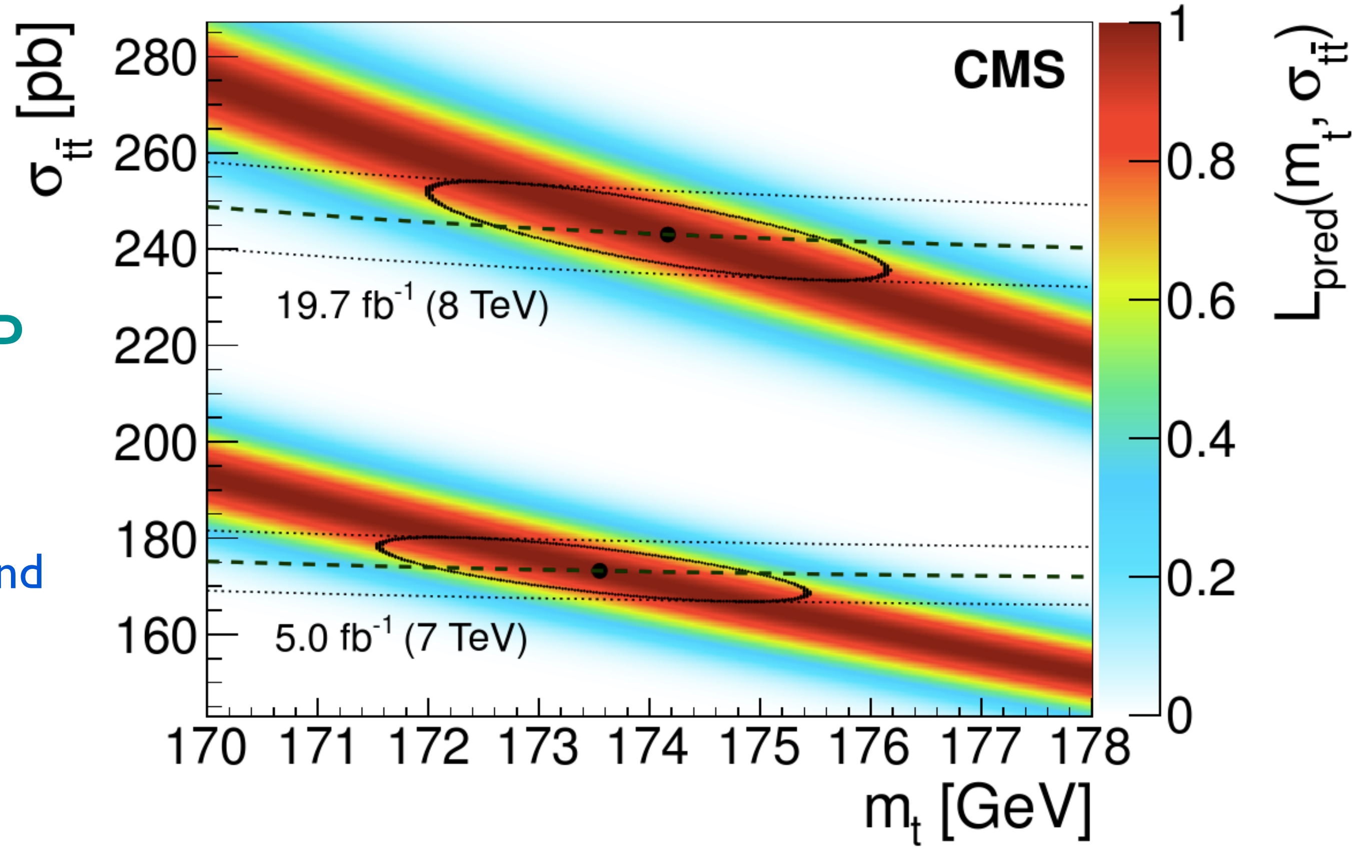
$m_t^{pole} = 172.9\,^{+2.5}_{-2.6}$ GeV



CMS, arXiv:1603.02303 submitted to JHEP

- these results use NNPDF3.0 and $\alpha_s = 0.118 \pm 0.001$
- compared (and found consistent results) with CT14 and MMHT2014, even with the 7 and 8 TeV datasets considered separately

$m_t^{pole} = 173.8\,^{+1.7}_{-1.8}$ GeV



top quark mass from events with a J/ψ

CMS-PAS-TOP-15-014

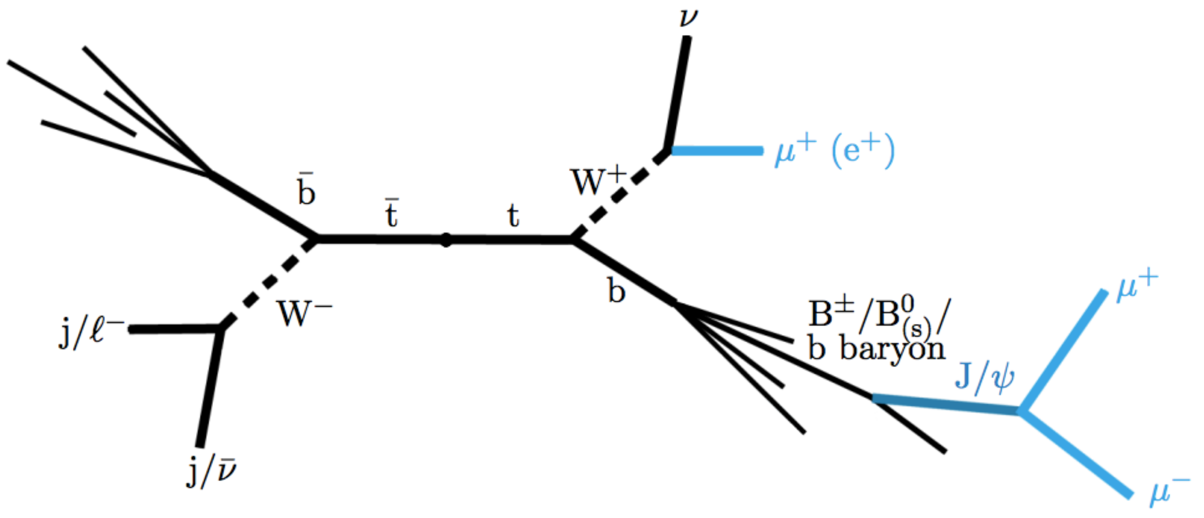
- using full 8 TeV luminosity
- start from a "nominal" semileptonic / dileptonic analysis
  - in addition we require one of the b-quarks to have a J/psi at the end of the chain
  - b → J/ψ + X → μμ + X
  - it has a small BR (0.032%) thus it's still statistically limited
  - on the other hand, m_{top} is extracted from m(J/ψ + W lepton). This way we avoid jets (and therefore systematics from JES)
- dominant uncertainties and result

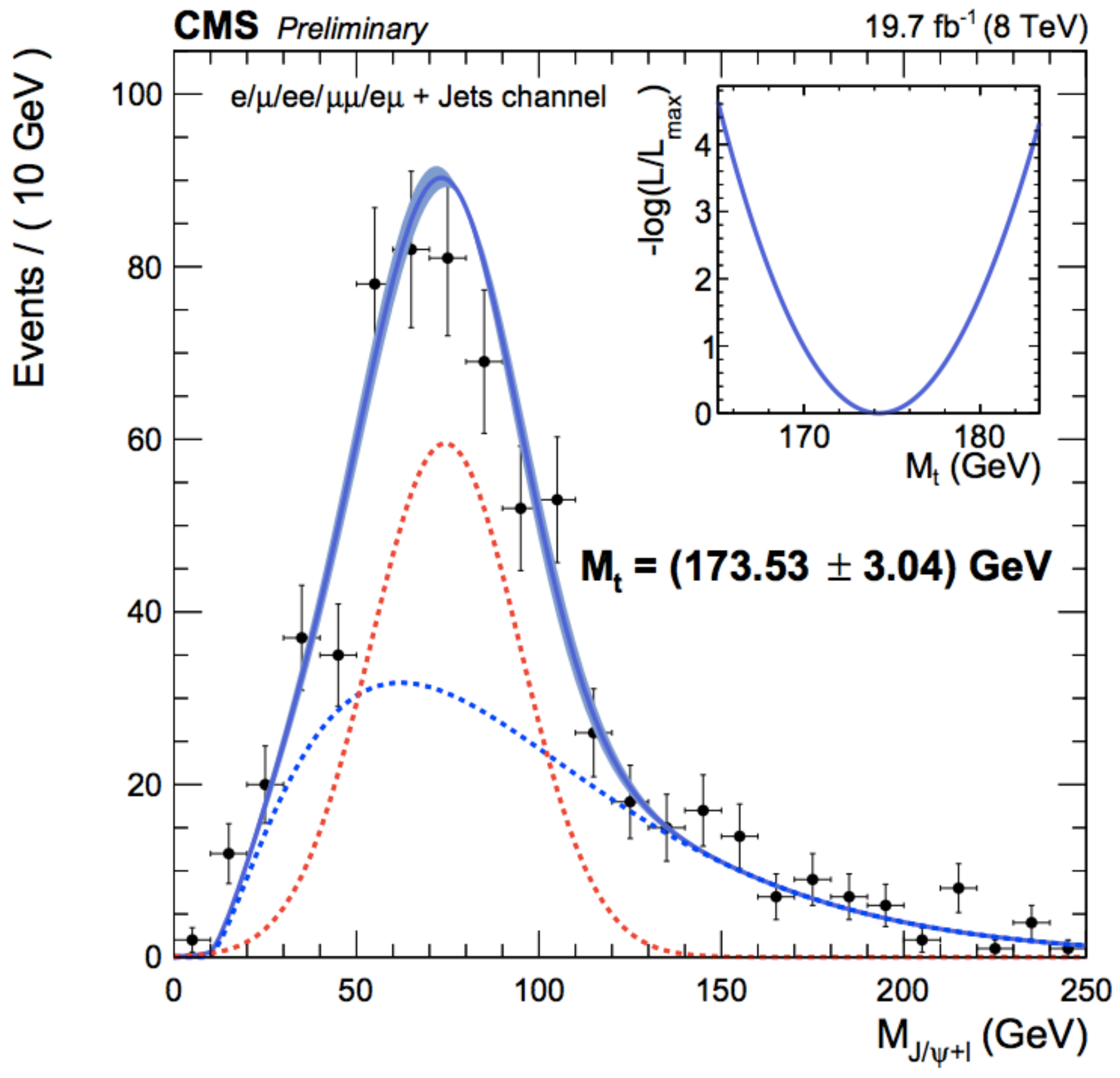
  0.4% from the top quark *pt*

  0.3% from MatrixElements-PartonShower matching threshold

  0.3% from renormalization scale

  m_{top} = 173.5 ± 3.0 (stat.) ± 0.9 (syst.) GeV





top quark mass using charged particles

CMS, CERN-EP-2016-062 (accepted in PRD)

- semileptonic and dileptonic channels

  a key ingredient is the decay length of charged hadrons

  like in the J/ψ analysis, the dominant uncertainty comes from the top quark *pt* (and also from the b-quark fragmentation, studied in detail)

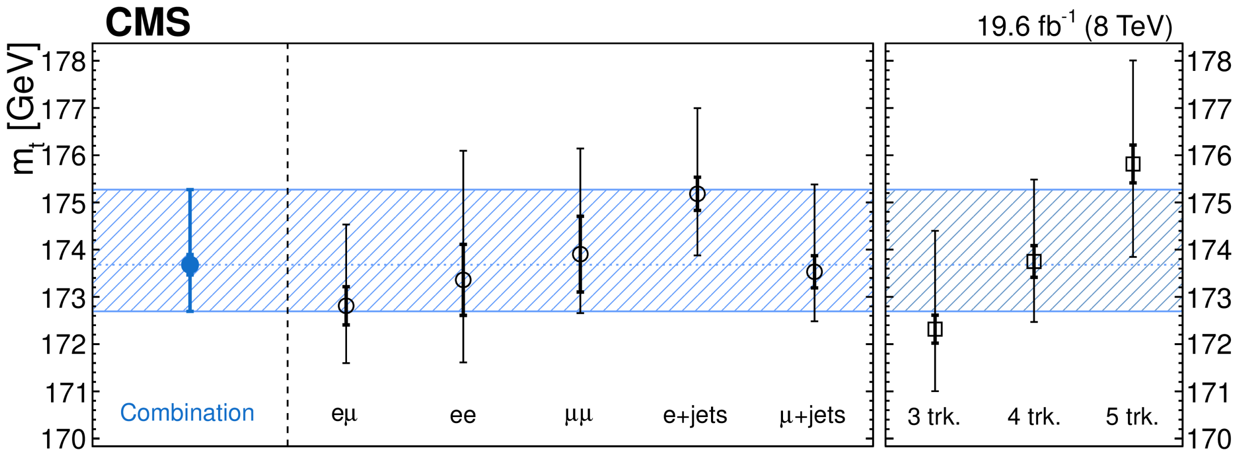
- reconstruct several types of charged hadrons

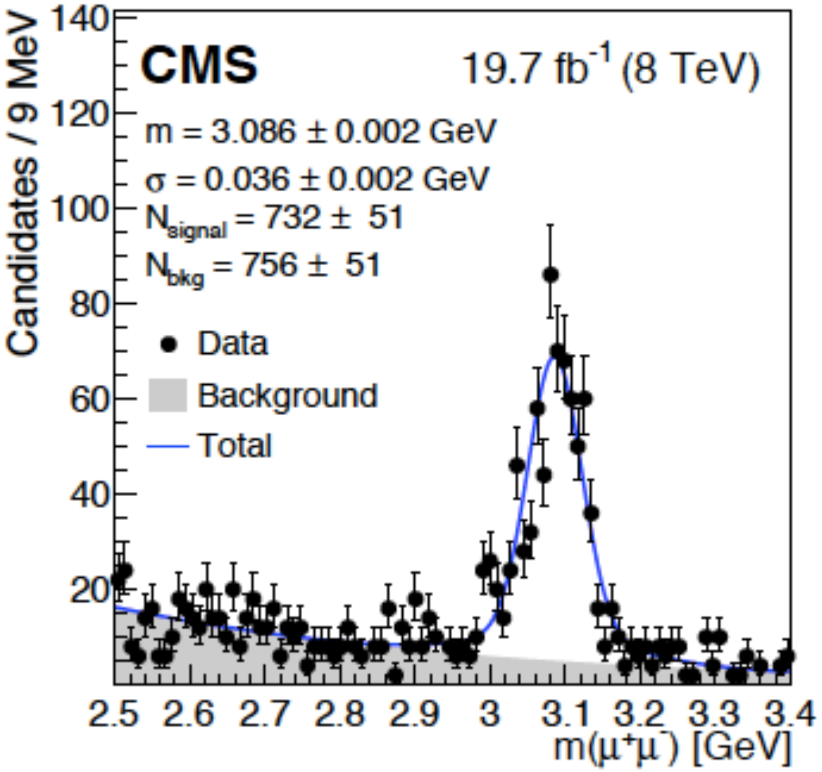
  J/ψ → μμ, D0 → Kπ and D*(2010) → D0π → Kππ

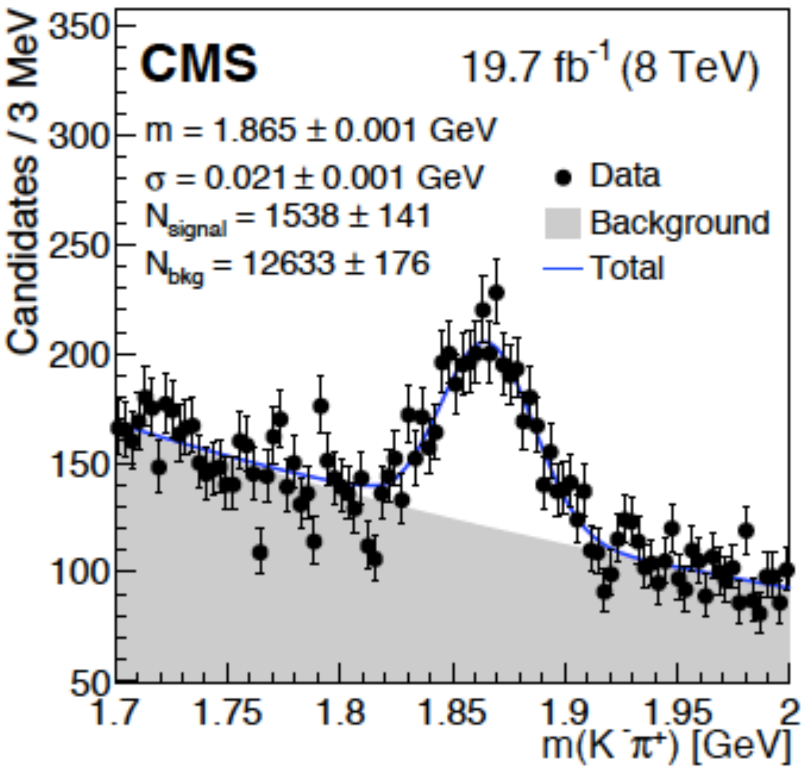
- perform template fit of m(secondary vertex + W lepton)

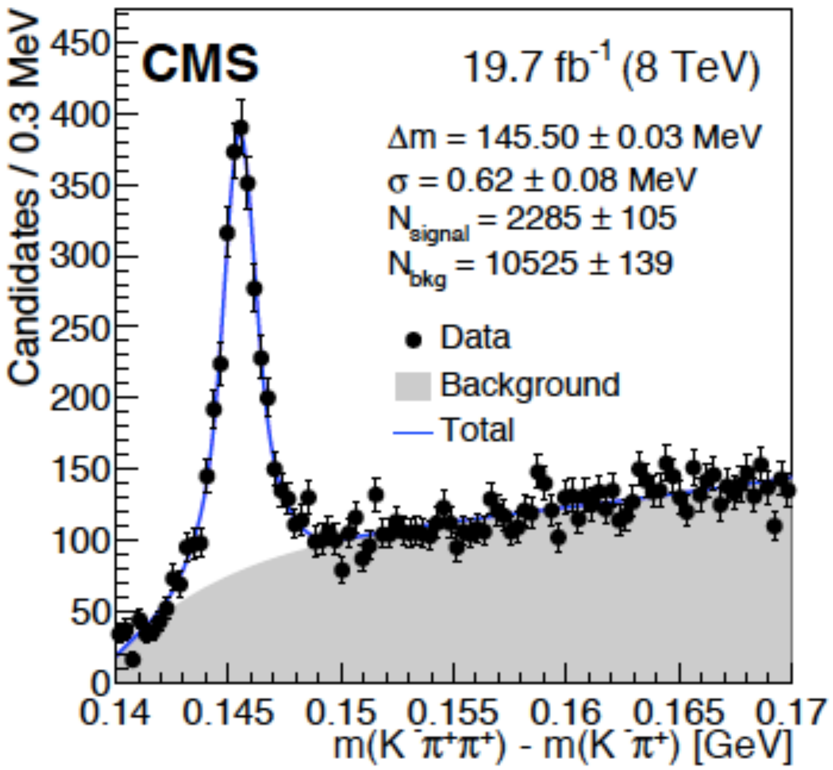
  $m_{top} = 173.68 \pm 0.20\ (\text{stat.})\ ^{+1.58}_{-0.97}\ (\text{syst.})\ \text{GeV}$

  with top *pt* and b quark fragmentation as the main systematic uncertainties









top quark mass from leptonic observables

CMS-TOP-16-002

- following proposal from JHEP 1409 (2014) 012
- consider ttbar dileptonic decays (in the eμ channel) with at least one jet

  using full 8 TeV luminosity

most precise direct m_t measurements reconstruct the top quark decay products

  affected by jet and b-jet uncertainties

  solid against production kinematics modelling

  using only leptons avoids jet uncertainties… but introduces modelling dependence

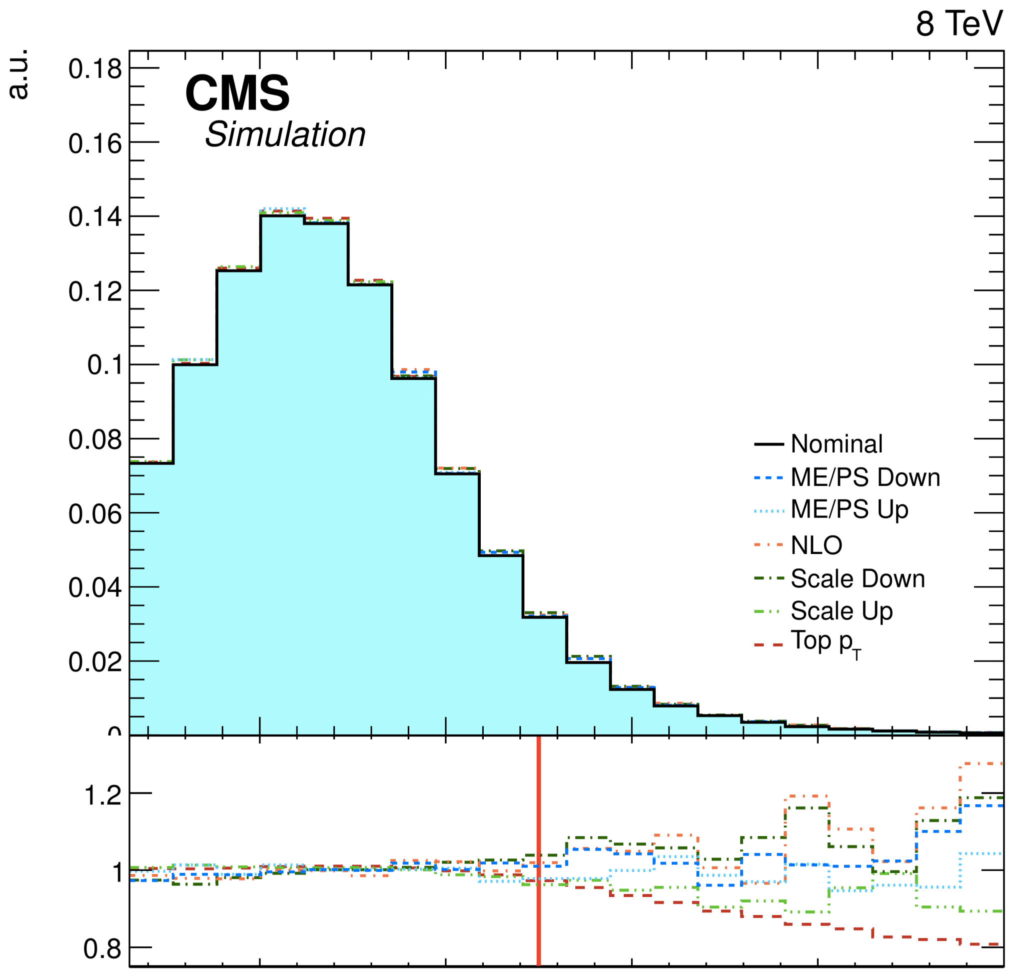
- we have studied several leptonic observables

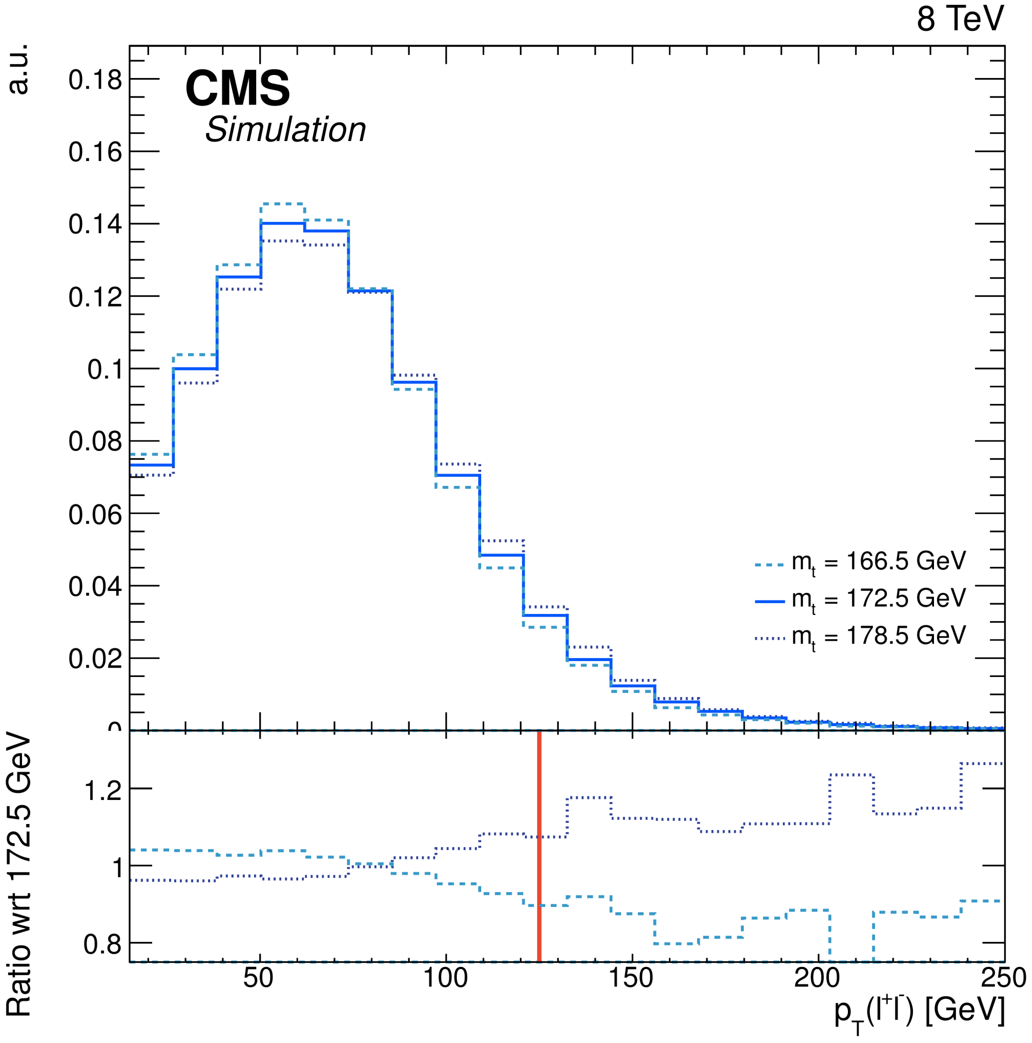
  pt(eμ) is chosen, as it is the most robust against theory uncertainties and most sensitive to m_t

  m_t extracted from first moment, second moment and shape of pt(eμ)

  $\mathbf{m_t = 171.7 \pm 1.1\ (stat) \pm 0.5\ (exp)\ ^{+2.5}_{-3.1}\ (theo)\ ^{+0.8}_{-0.0}\ (pt(t))\ GeV}$

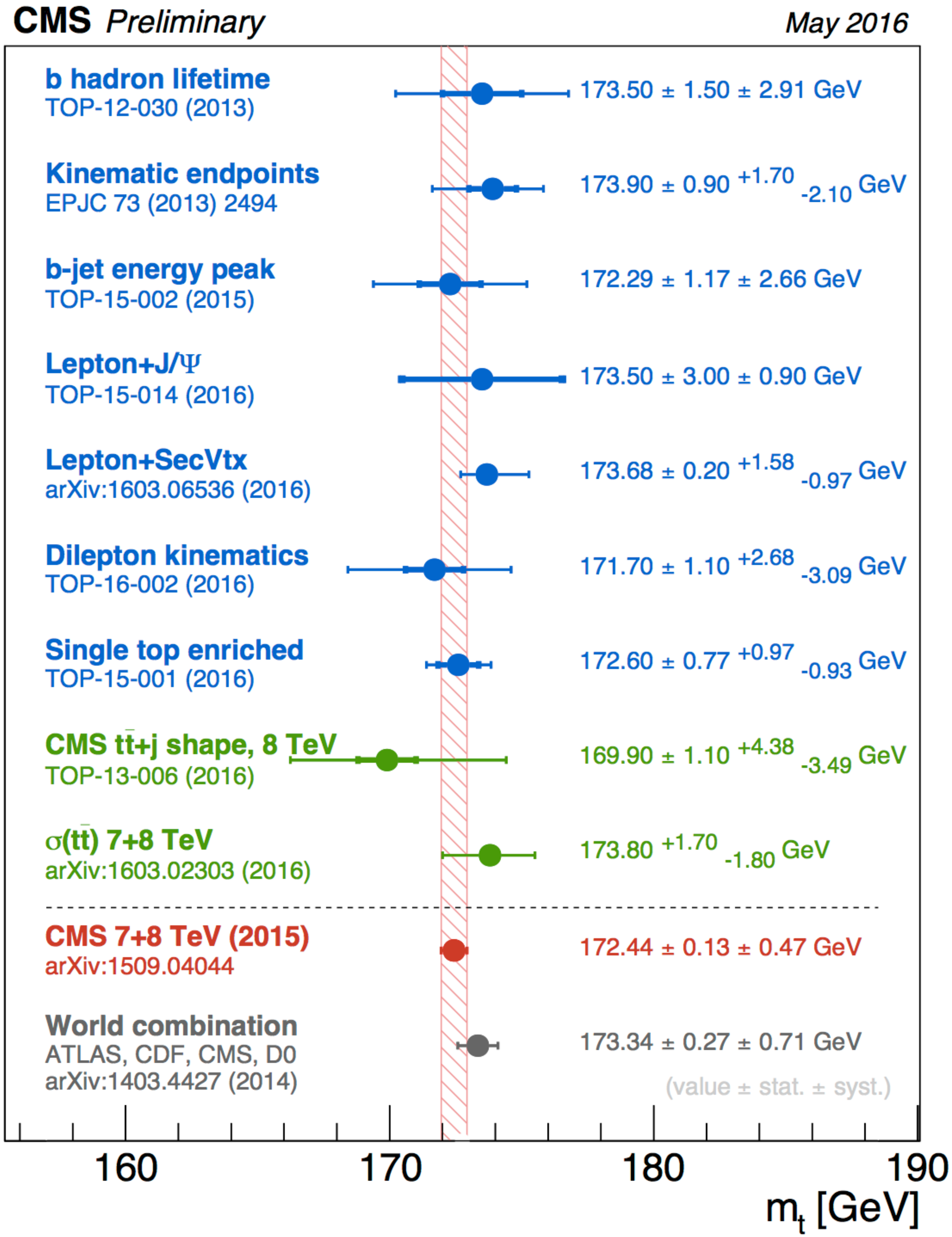
  dominant systematic uncertainty from signal modelling





CMS 7 and 8 TeV top mass alternative measurements

still far from the precision reached by standard measurements, but good to see agreement among them!



- outstanding m_{top} measurements by ATLAS and CMS
  - for both 7 and 8 TeV ➠ ready for 13 TeV
  - introduced several novel approaches
  - performed analyses with and without jets
- presented new $\sin\theta_{eff}$ results
  - performed studies to improve direct m_W precision

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backup

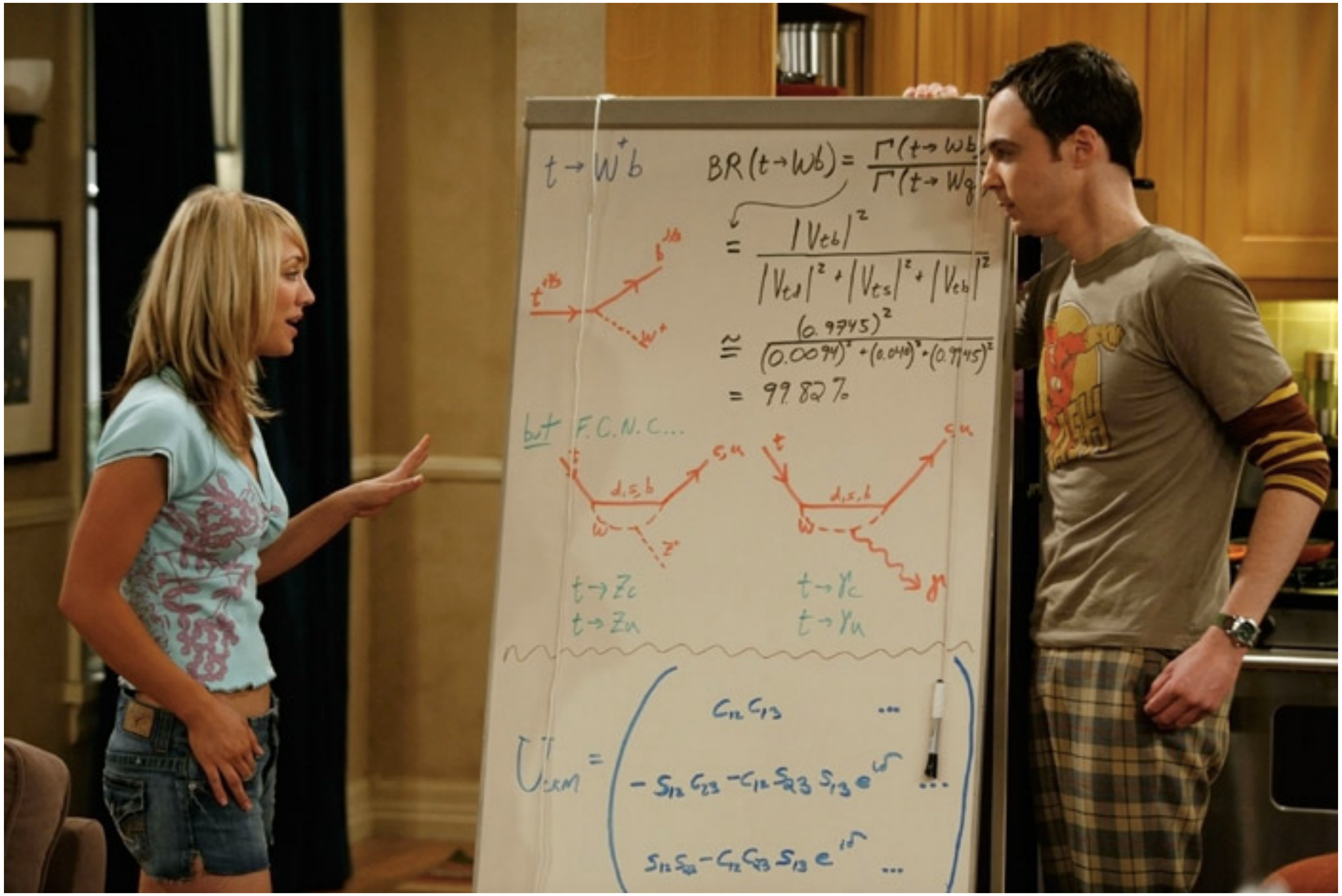
precise m_{top} measurements provide critical inputs to fits of global electroweak parameters that help assess the internal consistency of the SM

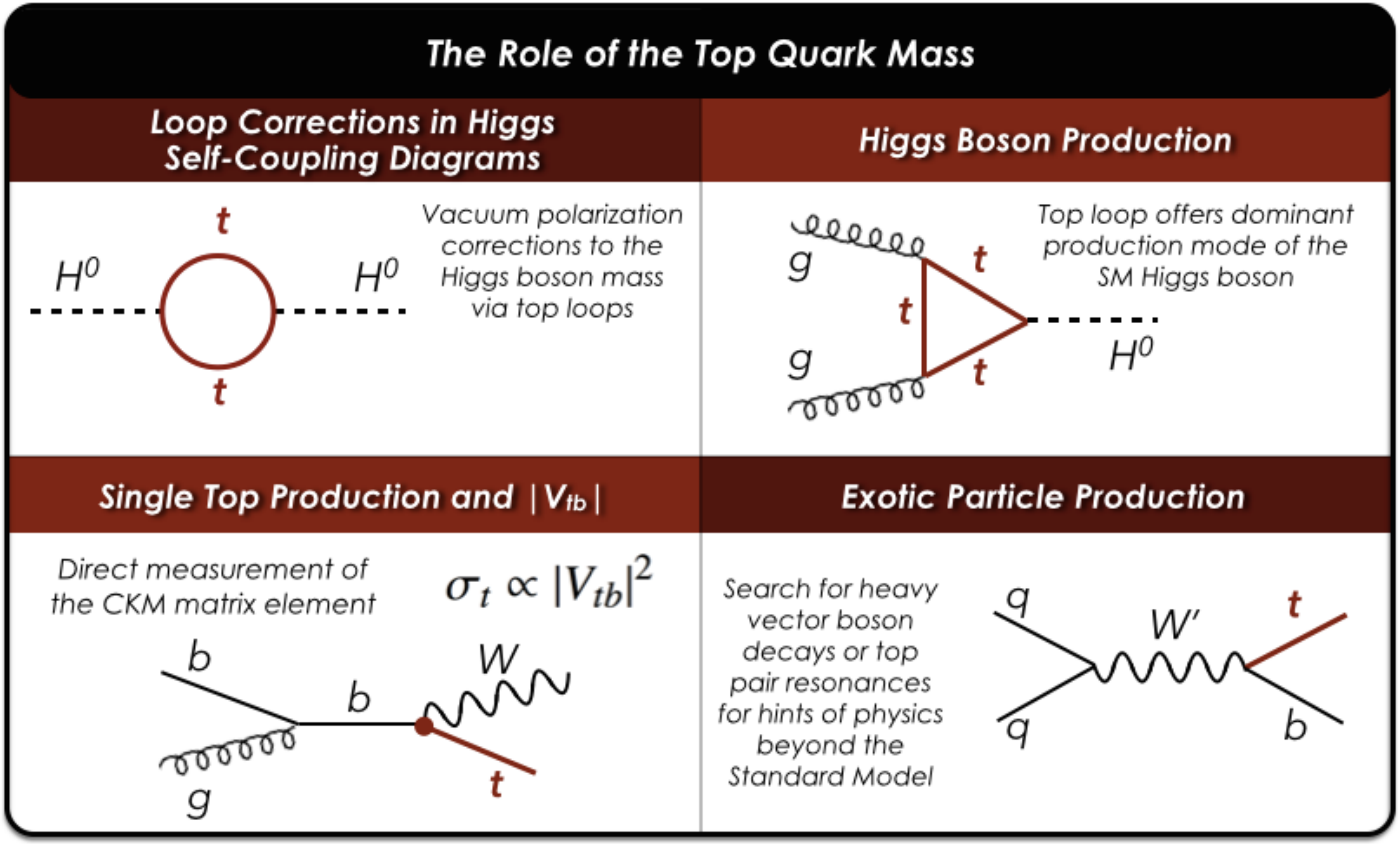
Tevatron (proton-antiproton collisions at 1.96 TeV) m_{top} combination

174.34 ± 0.37 (stat.) ± 0.52 (syst.) GeV = 174.34 ± 0.64 GeV

first Tevatron + LHC

173.34 ± 0.27 (stat.) ± 0.71 (syst.) GeV = 173.34 ± 0.76 GeV





The Role of the Top Quark Mass

Loop Corrections in Higgs Self-Coupling Diagrams

Vacuum polarization corrections to the Higgs boson mass via top loops

Higgs Boson Production

Top loop offers dominant production mode of the SM Higgs boson

Single Top Production and $|V_{tb}|$

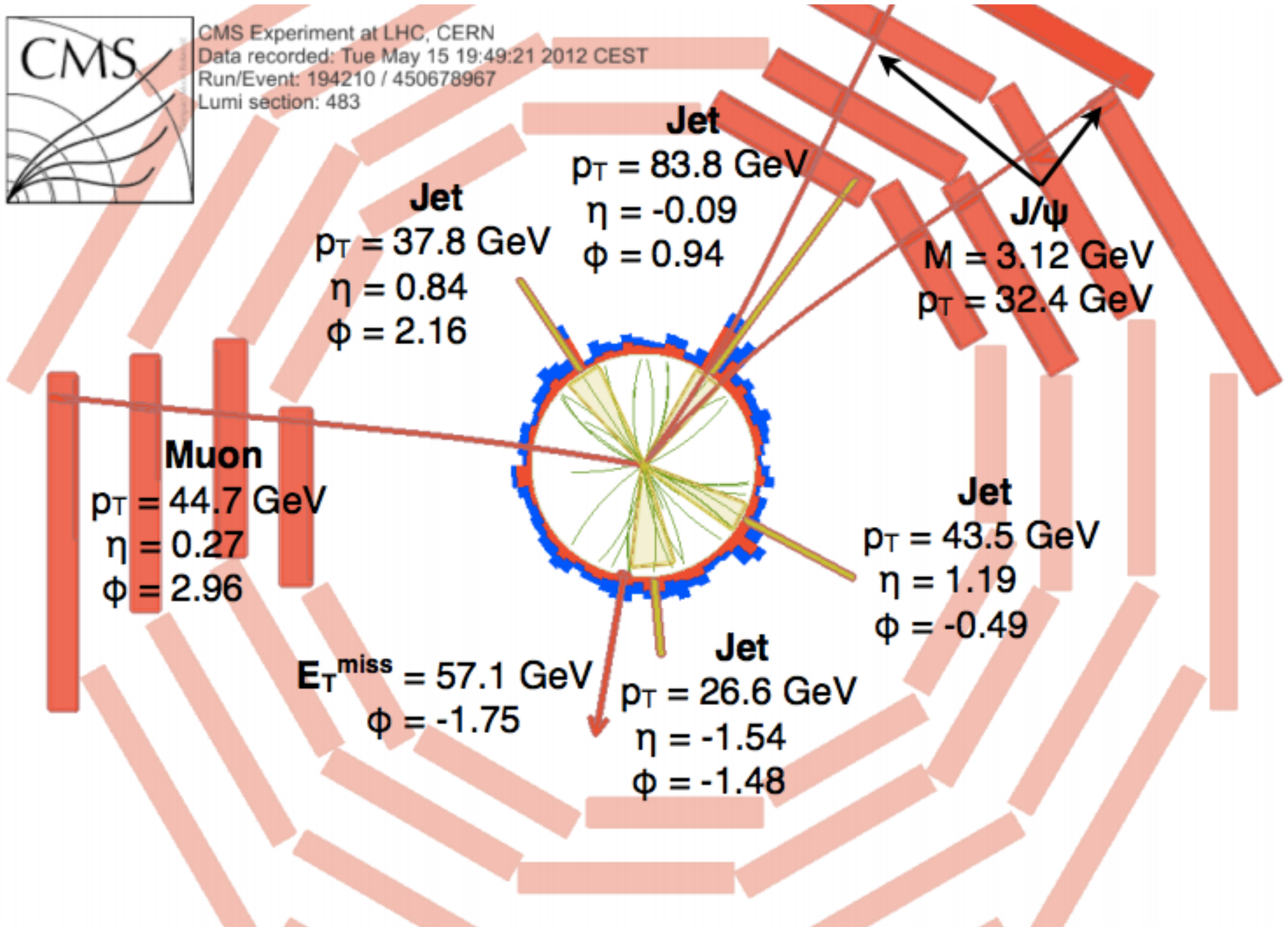
Direct measurement of the CKM matrix element

$\sigma_t \propto |V_{tb}|^2$

Exotic Particle Production

Search for heavy vector boson decays or top pair resonances for hints of physics beyond the Standard Model

Taken from http://www.thomasgmccarthy.com/topquark/


CMS
CMS Experiment at LHC, CERN
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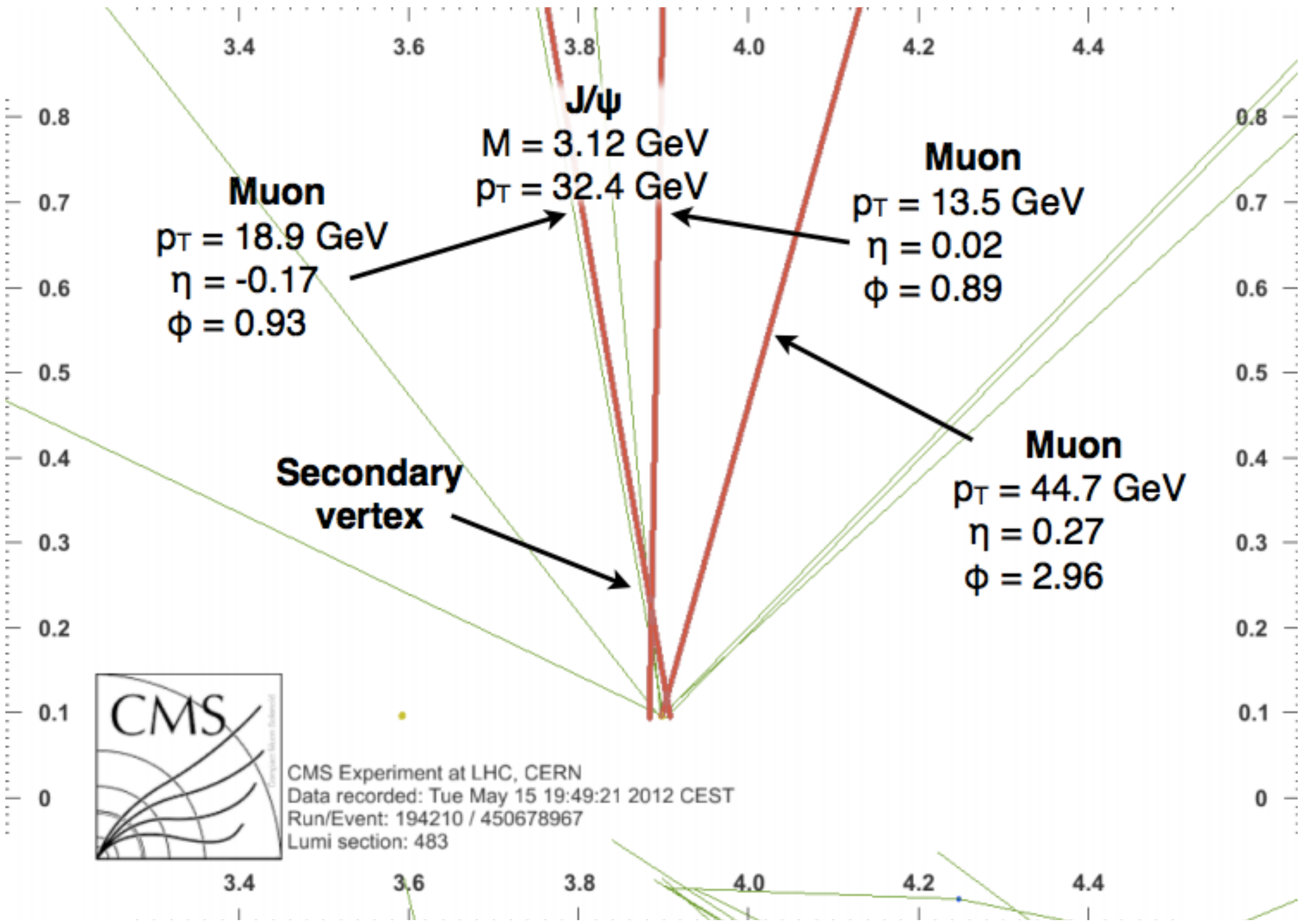
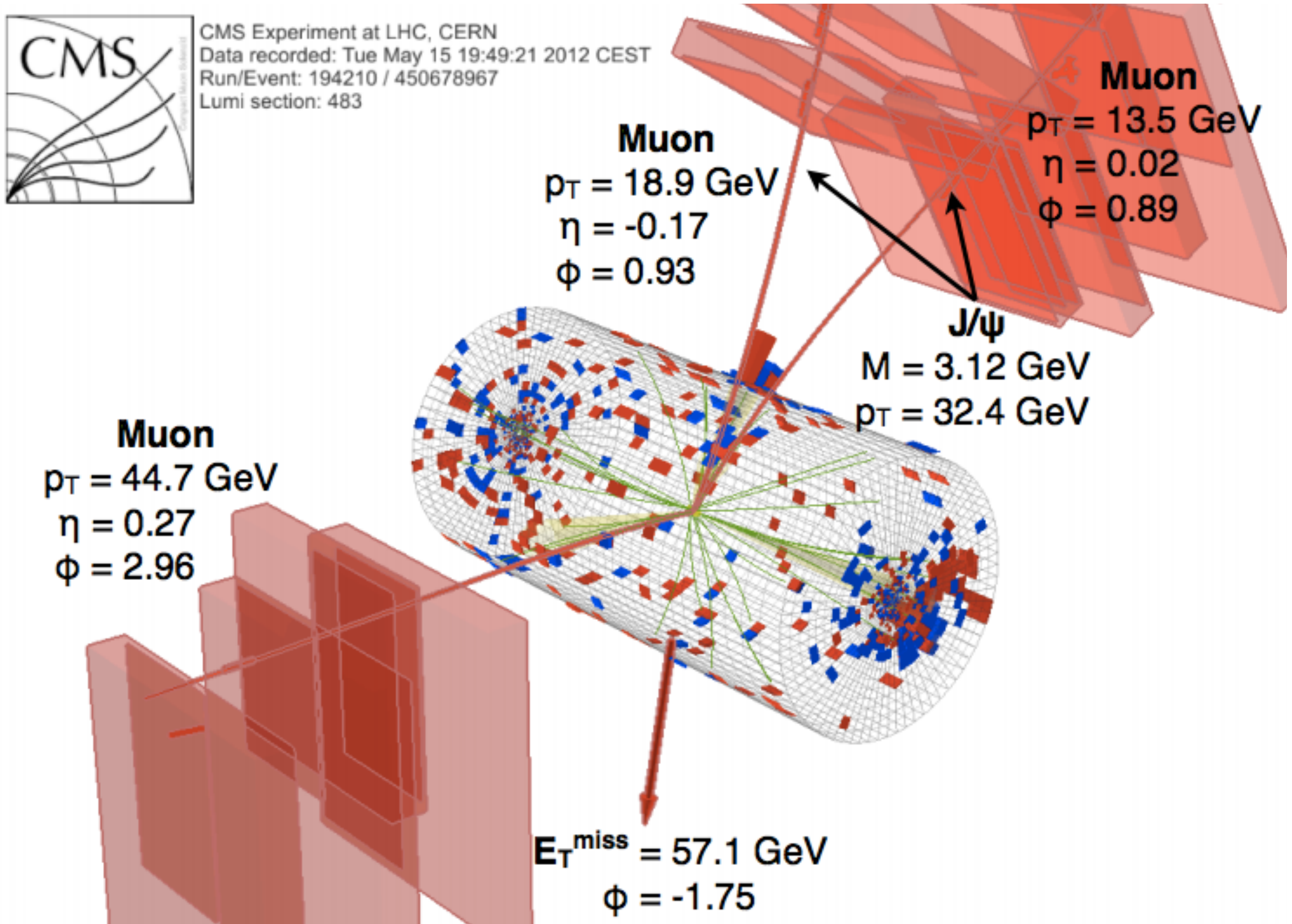
Run/Event: 194210 / 450678967
Lumi section: 483
Jet
p_T = 83.8 GeV
η = -0.09
ϕ = 0.94
Jet
p_T = 37.8 GeV
η = 0.84
ϕ = 2.16
J/ψ
M = 3.12 GeV
p_T = 32.4 GeV
Muon
p_T = 44.7 GeV
η = 0.27
ϕ = 2.96
Jet
p_T = 43.5 GeV
η = 1.19
ϕ = -0.49
Jet
p_T = 26.6 GeV
η = -1.54
ϕ = -1.48
E_T^{miss} = 57.1 GeV
ϕ = -1.75


3.4
3.6
3.8
4.0
4.2
4.4
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
J/ψ
M = 3.12 GeV
p_T = 32.4 GeV
Muon
p_T = 18.9 GeV
η = -0.17
ϕ = 0.93
Muon
p_T = 13.5 GeV
η = 0.02
ϕ = 0.89
Secondary vertex
Muon
p_T = 44.7 GeV
η = 0.27
ϕ = 2.96
CMS
CMS Experiment at LHC, CERN
Data recorded: Tue May 15 19:49:21 2012 CEST
Run/Event: 194210 / 450678967
Lumi section: 483


CMS
CMS Experiment at LHC, CERN
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Lumi section: 483
Muon
p_T = 13.5 GeV
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J/ψ
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p_T = 32.4 GeV
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p_T = 44.7 GeV
η = 0.27
ϕ = 2.96
E_T^{miss} = 57.1 GeV
ϕ = -1.75