LHC top mass

Alternative methods and prospects for the future

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for the ATLAS and CMS collaborations

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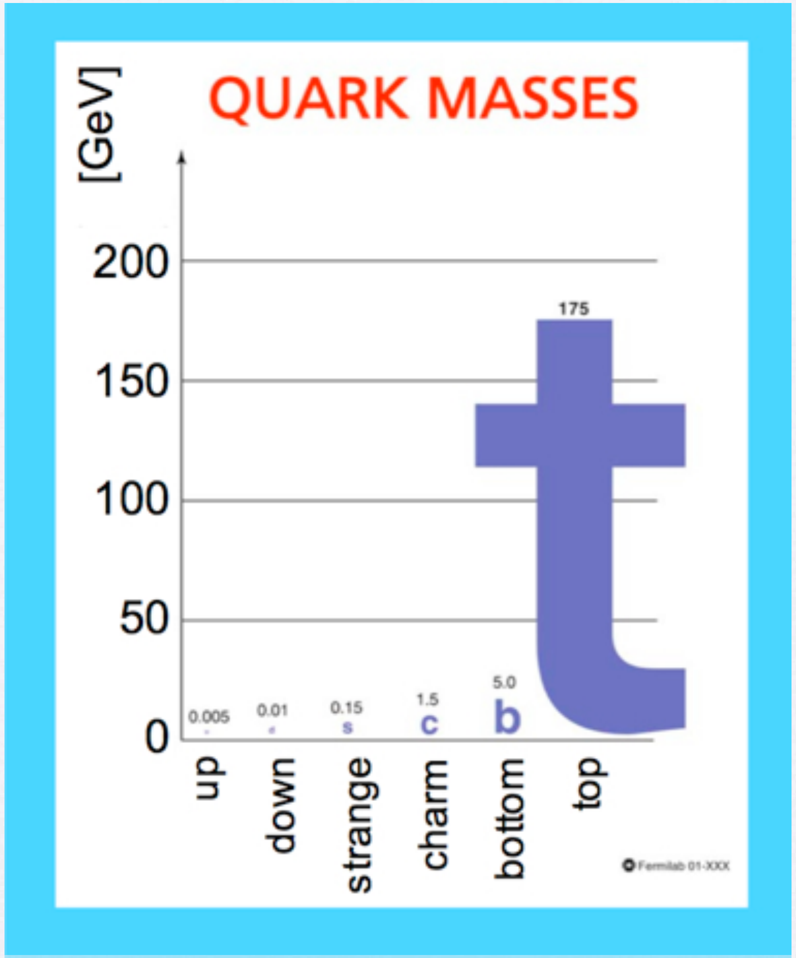
Outline

- Motivation
- Current Status
- Current Prospects
- More Luminosity
- Alternative Methods
- Summary

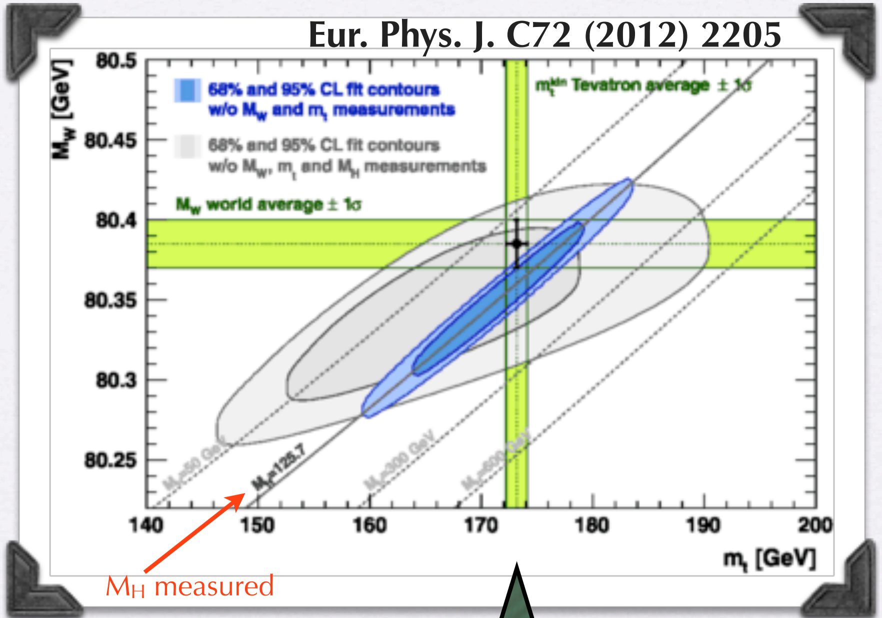


Motivation

- Fundamental, heaviest known particle in the SM

		m_{top} (GeV)
Tevatron	Run I	175 ± 6
	Run I + II	173.20 ± 0.87
LHC	7 TeV	173.29 ± 0.95

arXiv:1305.3929
CMS-PAS-TOP-13-005, ATLAS-CONF-2013-102



measured mass agrees with the fits

- Precision measurement of SM

✓ Critical inputs to global electroweak fits

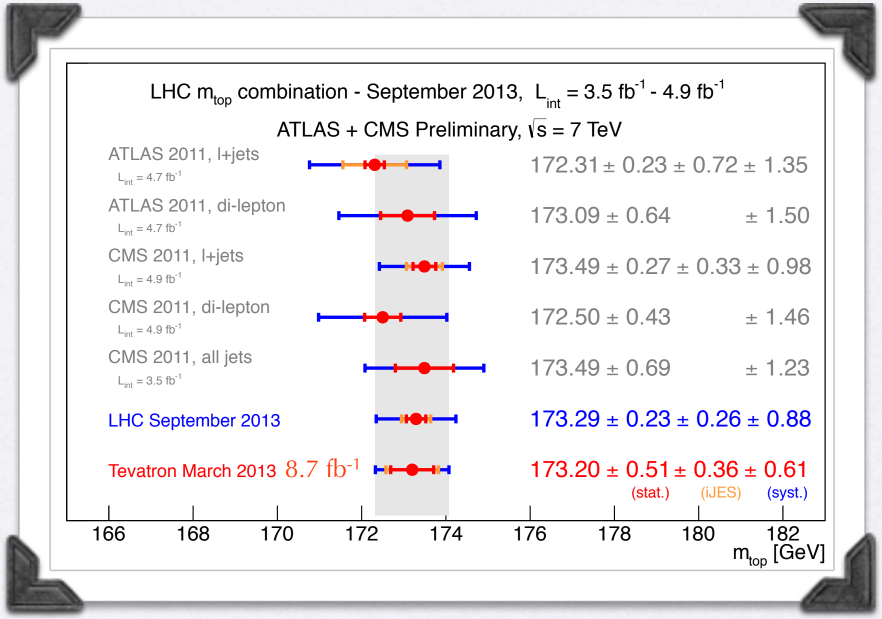
✓ Providing constraints on the Higgs boson properties

✓ Shown in CL fit contours from scans of fixed M_W & m_{top} using all data except M_W, m_{top}, and M_H measurements

Current Status

- LHC m_{top} combination **CMS-PAS-TOP-13-005, ATLAS-CONF-2013-102**

	ATLAS	CMS
Channels	• di-lepton • l + jets	• di-lepton • l + jets • all jets
Luminosity	4.7 fb^{-1}	4.9 fb^{-1}



- Precisely measured, but systematically limited
  - ✓ So far, 0.95 GeV at LHC (0.87 at Tevatron)
  - ✓ Mostly from invariant mass-based method

Where can we improve?

→ Need more luminosity?

→ Consider several alternatives, providing consistency check

Current Prospects

- LHC projection at Snowmass top mass study arXiv:1311.2028
  - ultimate precision at LHC ~ 0.6 GeV for conventional methods

    totally dominated by systematic uncertainties

    note: extra 300 MeV included to account for extrapolation errors & mass definition
- e^+e^- : ILC/CLIC and TLEP benchmarks arXiv:1303.3758, 1308.6176
  - measured from threshold scan in well-defined mass scheme
  - key: statistics-dominated, challenge: theory interpretation

	M_W [MeV]	m_{top} [MeV]
Present	80385 ± 15	173200 ± **870**
Snowmass	± 5-10	± **600**
ILC & CLIC	± 10	± **100**
TLEP	± 0.5	± **10-20**

m_{top} still hot topic as a motivation for future colliders

Experimental sensitivity of sub-GeV range → Theoretical interpretation important

➤ This talk going to present a New projection, based on the latest insights from current CMS studies using a cautiously optimistic approach (CMS-FTR-13-017)

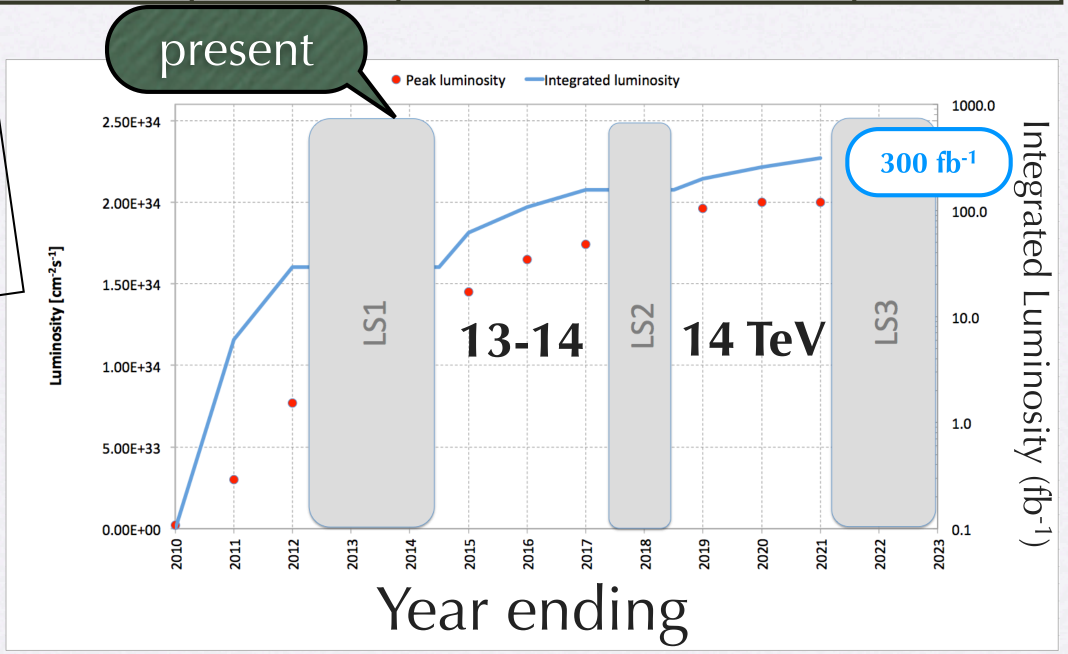
More Luminosity

- Cross-section and pileup evolution

	Present		2015	nominal	HL-LHC
CM energy (TeV)	7	8	13	14	
Cross section (pb)	167	246	806	951	
Luminosity (fb^{-1})	5	20	30	300	3000
<Pileup>	9.3	19	~30	~30	~95

Scenarios considered! x10 or x100

Go to design energy → what can be achieved based on projection studies



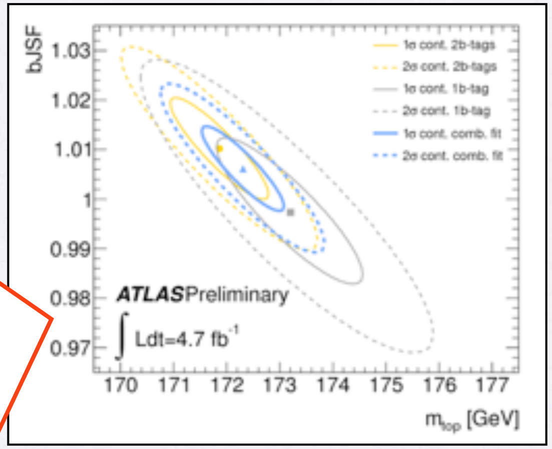
Extrapolating standard methods (I)

Increased pileup

Use of 3D fitting methods (pioneered by ATLAS)

ATLAS-CONF-2013-046

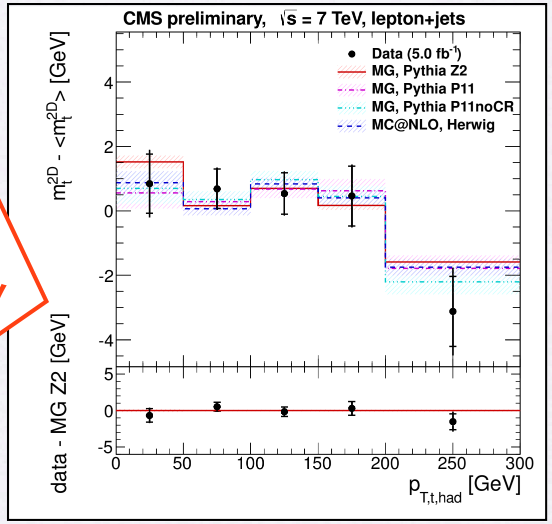
constrain b-JES in-situ



Differential studies (pioneered by CMS)

constrain signal model in-situ

CMS-PAS-TOP-12-029



Full NLO+PS MC tools & data-driven constraints

	New	Results
ATLAS	3d template fit	b-JES significantly reduced
CMS	detailed study of top mass dependence on event kinematics (CR, ISR/FSR, b-quark kin.)	excellent stability observed

(ATLAS: measurements of differential σ and jet shapes: Eur. Phys. J. C73 (2013) 2261 & PHYS-PUB-2013-005)

Extrapolating standard methods (II)

Increased pileup → Loss in trigger efficiency → *Compensation and help:*

- increased σ_{tt}
- new techniques
- improved methods
- Phase-2 (HL-LHC) upgrades

Extrapolating standard methods (III)

Increased pileup	Loss in trigger efficiency	*Compensation and help:* • increased σ_{tt} • new techniques • improved methods • Phase-2 (HL-LHC) upgrades
Use of 3D fitting methods (pioneered by ATLAS)	Constrain b-JES uncertainty	*Appearance:* • b-JES stat. comp. (~0.7 GeV) • b-tagging uncertainty
Differential studies (pioneered by CMS)	Handle JES dependence & non-perturbative QCD	Search for possible mis-modeling to QCD & JES; treat such effects

➤ ***Differential analysis approaches to improve JES uncertainty, and further constrain and tune theory (fully effective with 3000 fb^{-1})***

Extrapolating standard methods (IV)

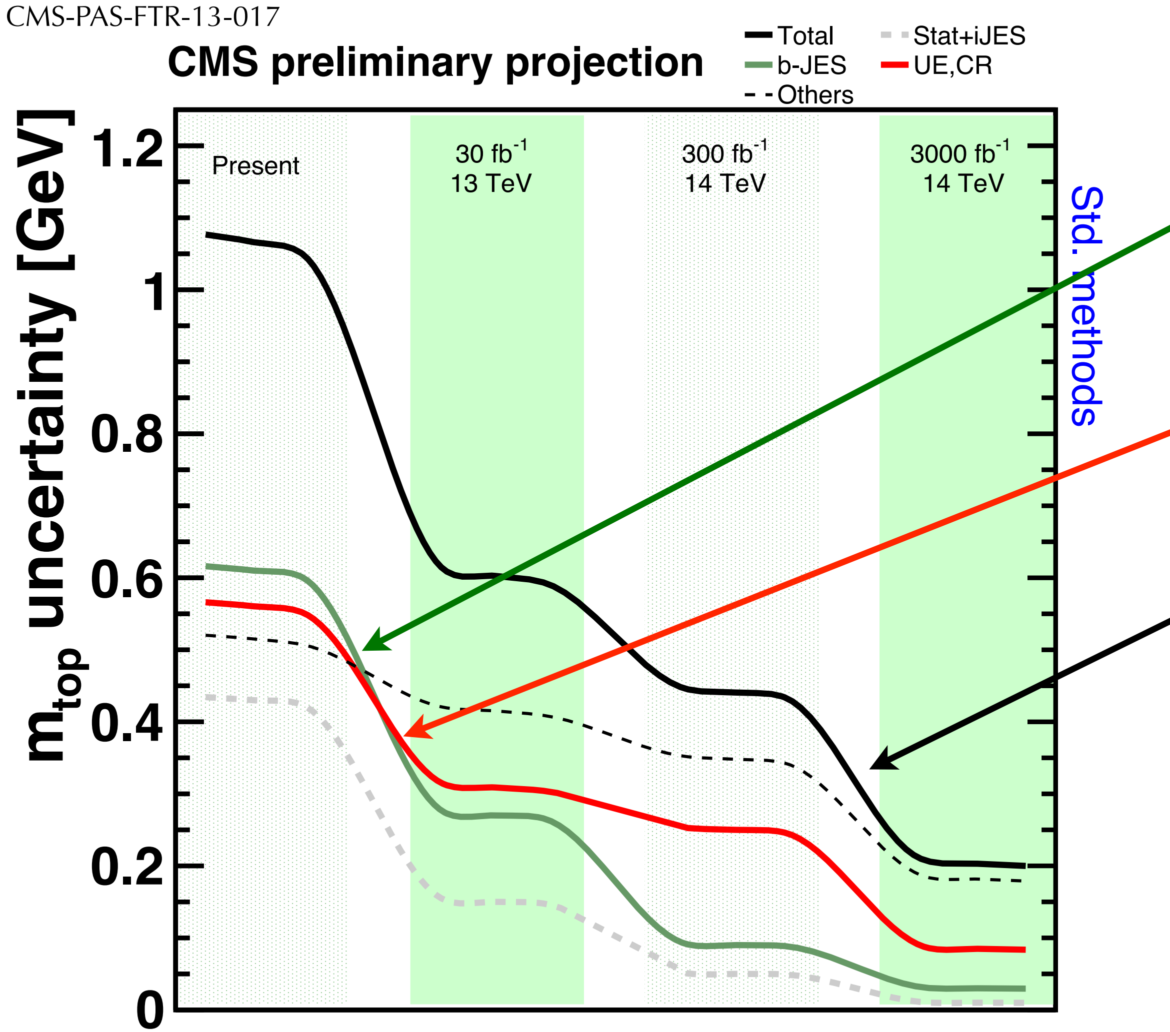
Increased pileup	Loss in trigger efficiency	*Compensation and help:* • increased σ_{tt} • new techniques • improved methods • Phase-2 (HL-LHC) upgrades
Use of 3D fitting methods (pioneered by ATLAS)	Constrain the relative b-JES uncertainty	*Appearance:* • b-JES stat. comp. (~0.7 GeV) • b-tagging uncertainty
Differential studies (pioneered by CMS)	Handle JES dependence & non-perturbative QCD	Search for possible mis-modeling to QCD & JES; treat such effects
Full NLO+PS MC tools & data-driven constraints →	Allow a well-defined MC mass scheme and reduced scale uncertainties & improved MC validation with data and UE tunes →	*Opportunity:* • reduce as well double counting of uncertainties (PU, ISR/FSR evaluated separately, but also included in JES) • assume factor-2 reduction: b-tagging, background shape, PDFs, QCD effects

Extrapolating standard methods (V)

Increased pileup	→ Loss in trigger efficiency	→ *Compensation and help:* • increased σ_{tt} • new techniques • improved methods • Phase-2 (HL-LHC) upgrades
Use of 3D fitting methods (pioneered by ATLAS)	→ Constrain the relative b-JES uncertainty	→ *Appearance:* • b-JES stat. comp. (~0.7 GeV) • b-tagging uncertainty
Differential studies (pioneered by CMS)	Handle JES dependence & non-perturbative QCD	Search for possible mis-modeling to QCD & JES; treat such effects
Full NLO+PS MC tools & data-driven constraints	→ Allow a well-defined MC mass scheme and reduced scale uncertainties & improved MC validation with data and UE tunes	→ *Opportunity:* • reduce as well double counting of uncertainties (PU, ISR/FSR evaluated separately, but also included in JES) • assume factor-2 reduction: b-tagging, background shape, PDFs, QCD effects

Can be reduced in the future! (benefits from increased statistics)

Projection for standard methods (I)



move to 3D fit

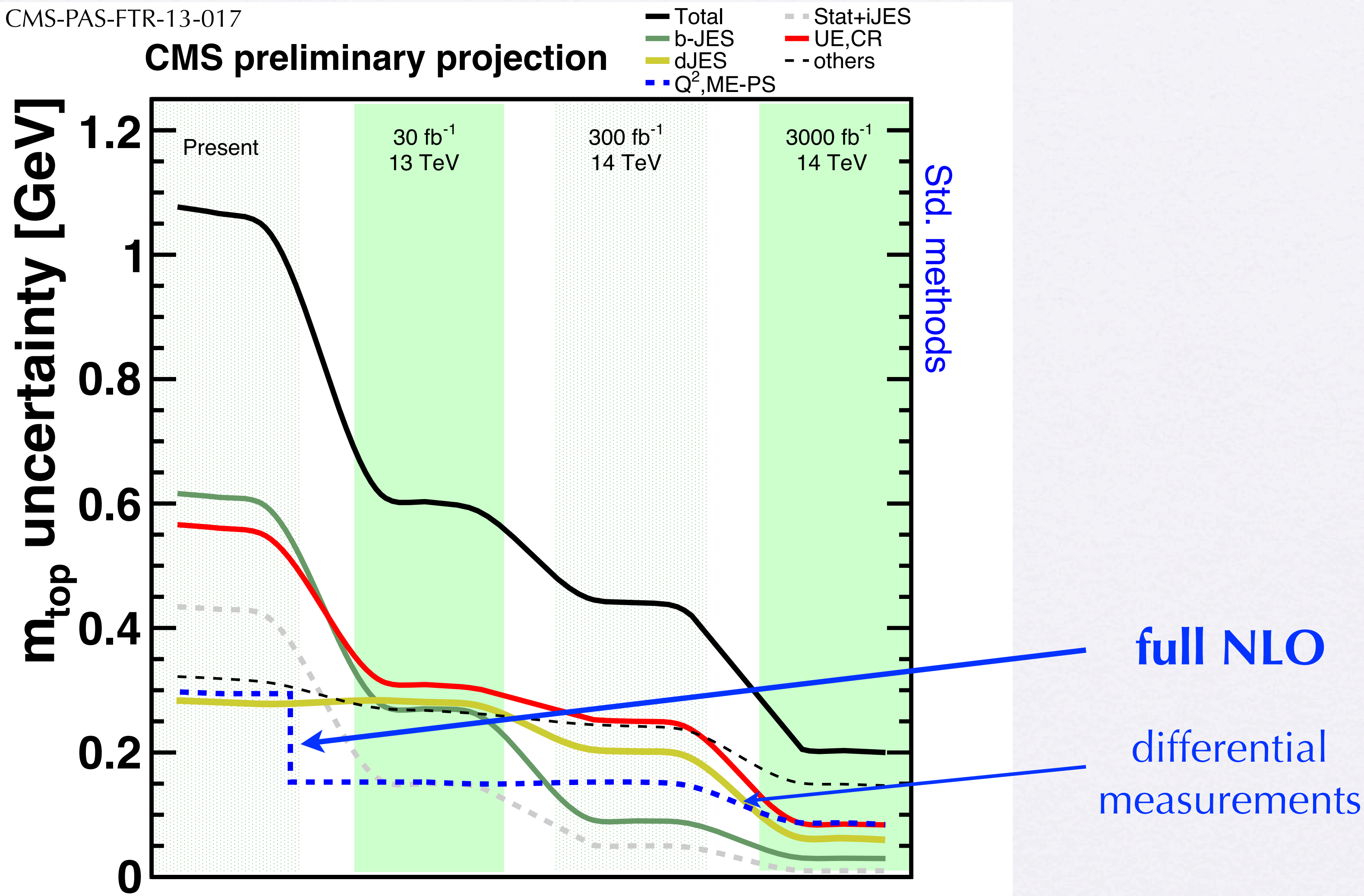
dedicated UE studies

differential measurements

For the projections, used the baseline l+jets measurement at 7 TeV

JHEP 12 (2012) 105

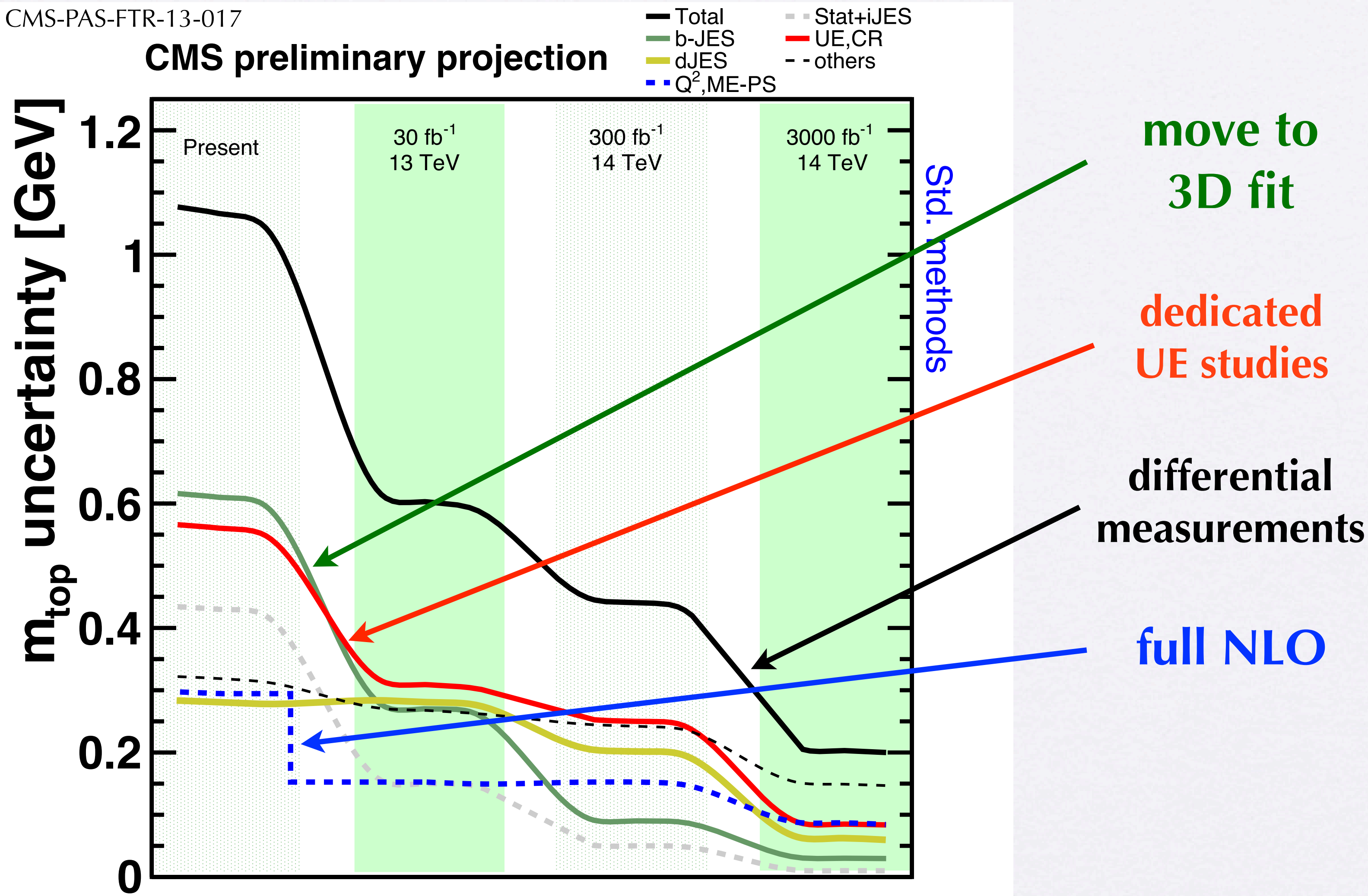
Projection for standard methods (II)



For the projections, used the baseline l+jets measurement at 7 TeV

JHEP 12 (2012) 105

Projection for standard methods (III)



For the projections, used the baseline l+jets measurement at 7 TeV

JHEP 12 (2012) 105

Table of projection in l+jets (GeV)

CMS-PAS-FTR-13-017

Center-of-mass energy / Integrated luminosity	Current 7 TeV l+jets 5 fb^{-1}	Future 13 TeV 30 fb^{-1}	14 TeV 300 fb^{-1}	14 TeV 3000 fb^{-1}	Comment
Fit calibration	0.06	0.03	0.03	0.03	MC statistics
b-JES	0.61	0.27	0.09	0.03	3D fit
Residual JES (p_T- and η-dependent JES)	0.28	0.28	*0.2*	*0.06*	*differential*
Lepton energy scale	0.02	0.02	0.02	0.02	unchanged
Missing transverse momentum	0.06	0.06	0.06	0.06	unchanged
Jet energy resolution	0.23	0.23	*0.2*	*0.06*	*differential*
b tagging	0.12	0.06	0.06	0.06	factor 2 (data)
Pileup	0.07	0.07	0.07	0.07	unchanged
Non-$t\bar{t}$ background	0.13	0.06	0.06	0.06	factor 2 (S/B)
Parton distribution functions	0.07	0.04	0.04	0.04	factor 2 (PDF fits)
Renormalization and factorization scales	0.24	0.12	0.12	*0.06*	full NLO + *differential*
ME-PS matching threshold	0.18	0.09	0.09	*0.06*	full NLO + *differential*
Underlying event	0.15	0.15	0.15	*0.06*	*differential*
Color reconnection effects	0.54	0.27	*0.2*	*0.06*	factor 2 + *differential*
Systematic	0.98	0.60	0.44	0.20	
Statistical	0.43	0.15	0.05	0.01	
Total	1.07	0.62	0.44	0.20	

Optimistic Scenarios

	Present		2015	nominal	HL-LHC
CM energy (TeV)	7	8	13	14	
Cross section (pb)	167	246	806	951	
Luminosity (fb^{-1})	5	20	30	300	3000
<Pileup>	9.3	19	~30	~30	~95
Syst. (GeV)	0.98		0.60	0.44	0.20
Stat. (GeV)	0.43		**0.15**	**0.05**	**0.01**
Total	**1.07**		**0.62**	**0.44**	**0.20**

x1 ***x10*** ***x100***

l+jets as a baseline

Alternative Methods

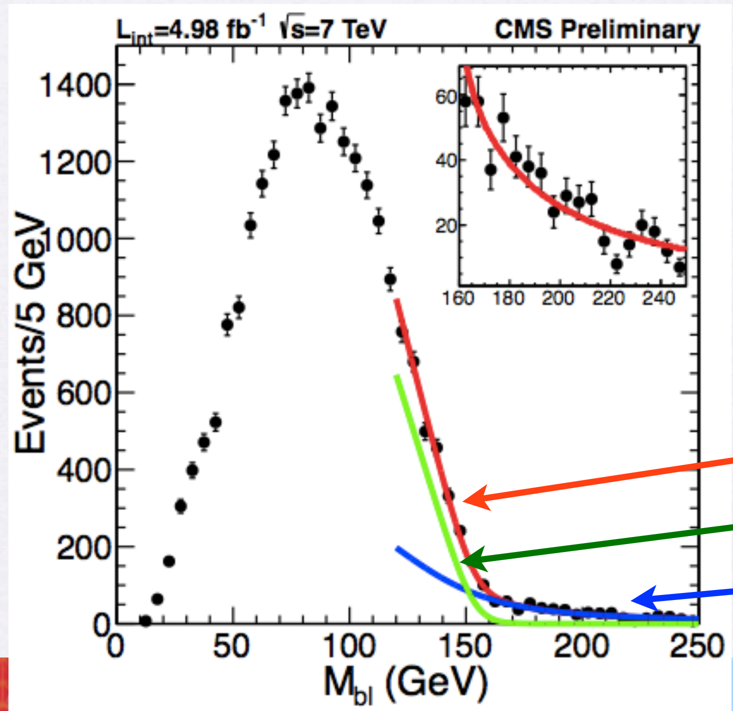
- Alternative approaches to m_{top} are considered
  - provide consistency checks
  - factorize specific systematic uncertainties
  - impact final combination or backup if the standard methods do not evolve as initially projected

To get a better understanding of measured m_{top} and its relation to theory, a considerable reduction of the total uncertainty is needed

→ *application of alternative methods to improve the experimental precision!*

Kinematic endpoints

- m_{top} from lepton-jet spectra + other related variables
  - endpoint has a relation to the parent particle's mass
  - independent of assumptions on shapes (no templates or transfer functions)
  - M_{T2}: minimum parent mass consistent with observed final state
  - three $M_{T2\perp}$ subsystem variables: measure top, W and ν simultaneously



→ *not rely on MC calibration!*

Fit result in di-lepton channel

constraints: $m_\nu = 0$ and $M_W = 80.4$
$m_{top} = 173.9 \pm 0.9 \text{ (stat.) } ^{+1.7}_{-2.1} \text{ (syst.)}$

Eur. Phys. J. C73 (2013) 2494

total
signal
bkg (tau decays, single top,...)

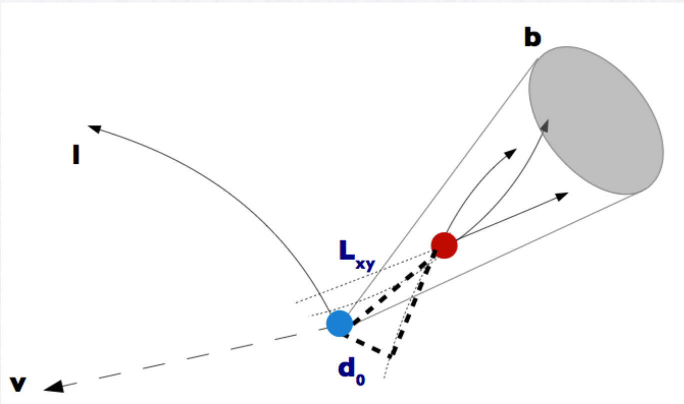
B-hadron lifetime (L_{xy})

- m_{top} from displacement of secondary vertices reconstructed in jets (formed from hadronization of b quark)
  - consider B hadron decay length to be analogously correlated to m_{top}

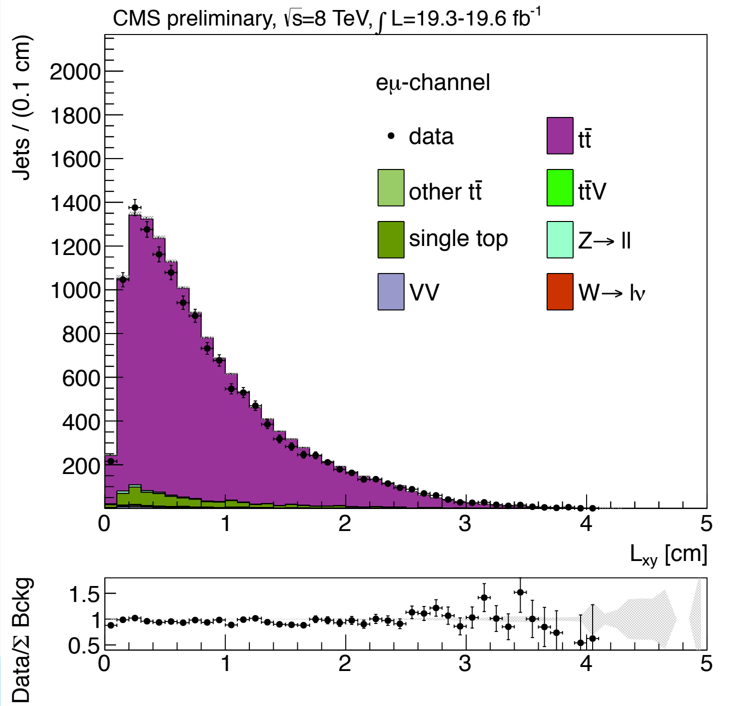
◉ not sensitive to Jet Energy Scale
◉ relies on proper understanding of top kinematics modeling

→ ***Statistics already enough at 8 TeV!***

Channel	m_t [GeV]
muon+jets	$173.2 \pm 1.0_{stat} \pm 1.6_{syst} \pm 3.3_{p_T(t)}$
electron+jets	$172.8 \pm 1.0_{stat} \pm 1.7_{syst} \pm 3.1_{p_T(t)}$
electron-muon	$173.7 \pm 2.0_{stat} \pm 1.4_{syst} \pm 2.4_{p_T(t)}$



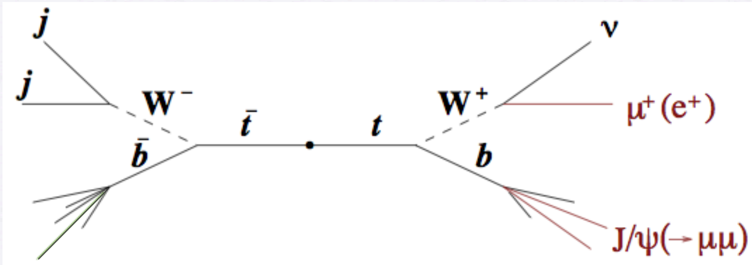
Final state product of t→Wb with W→lν
Blue & red : primary and secondary vertices
L_{xy} : transverse decay length
d_0 : transverse impact parameter distance



CMS-PAS-TOP-12-030

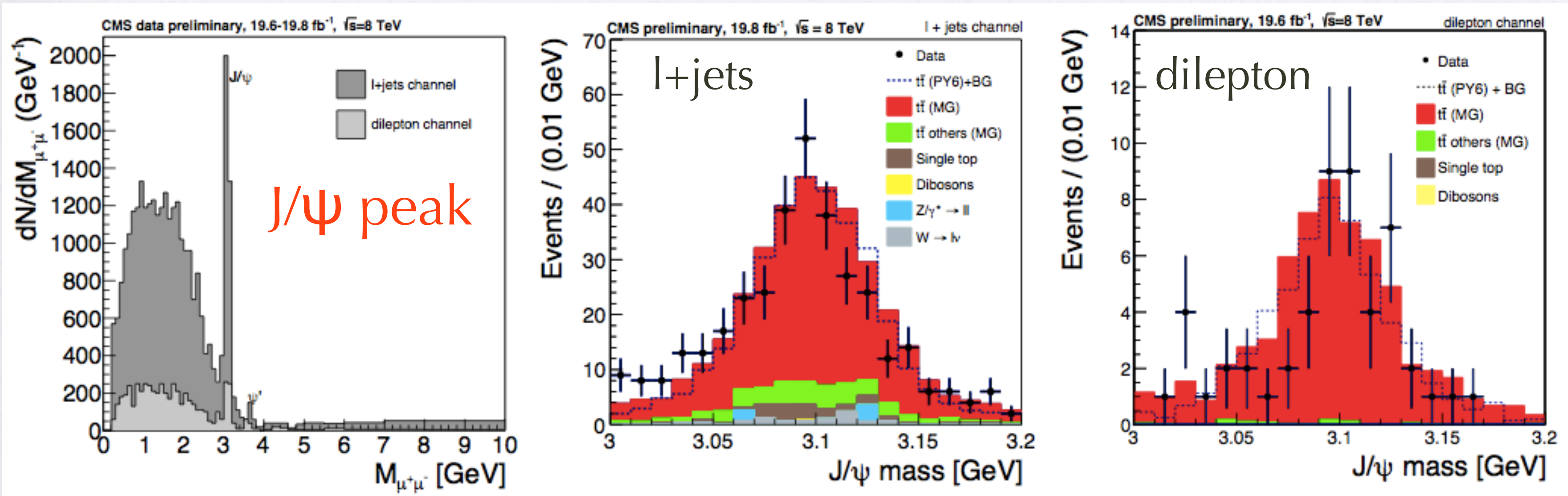
J/ψ method

- J/ψ method: m_{top} from tri-lepton invariant mass
  - no use of jets, thus minimize effects on jet energy calibration



- J/ψ plots

CMS-TOP-13-007



➔ *For future projections, adopted the uncertainties from the TDR study*

CMS Physics TDR: Physics Performance", J. Phys. G: Nucl. Part. Phys. 34, 995 (2007)

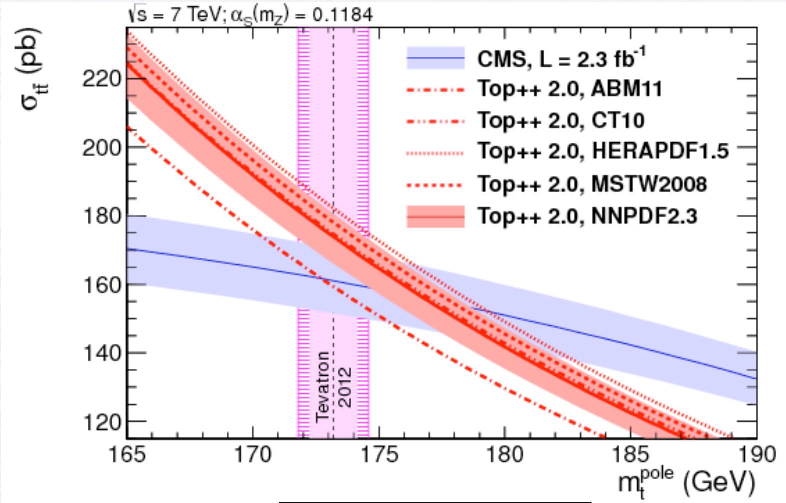
Extraction from $\sigma_{pp\to t\bar{t}}$

- Comparing measured σ_{tt} to the QCD prediction
  - under the assumption that $m_{top} = m_t^{pole}$

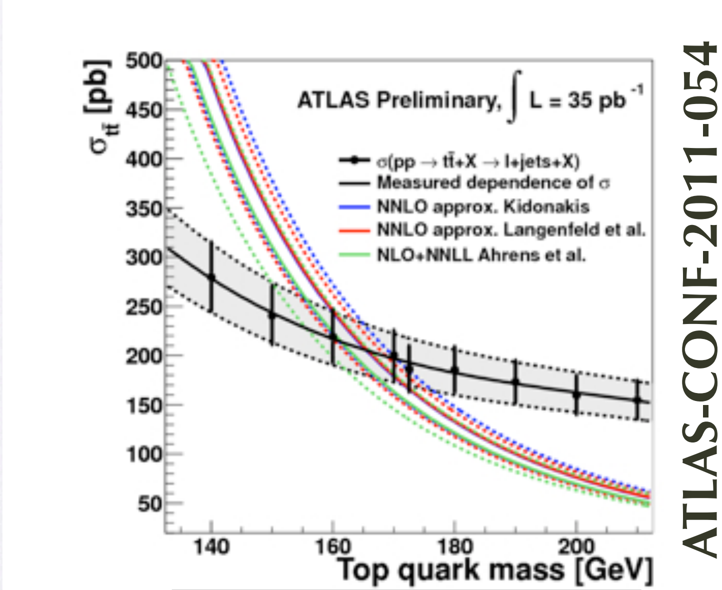
    m_{top} obtained in a well-defined theoretical mass scheme
    → expected to be limited by the relatively poor sensitivity of σ_{tt} to m_{top}
- Predicted σ_{tt} using different NNLO PDF sets vs. m_t

◉ mass for fixed α_s

arXiv:1307.1907



$176.7^{+3.8}_{-3.4}$ GeV



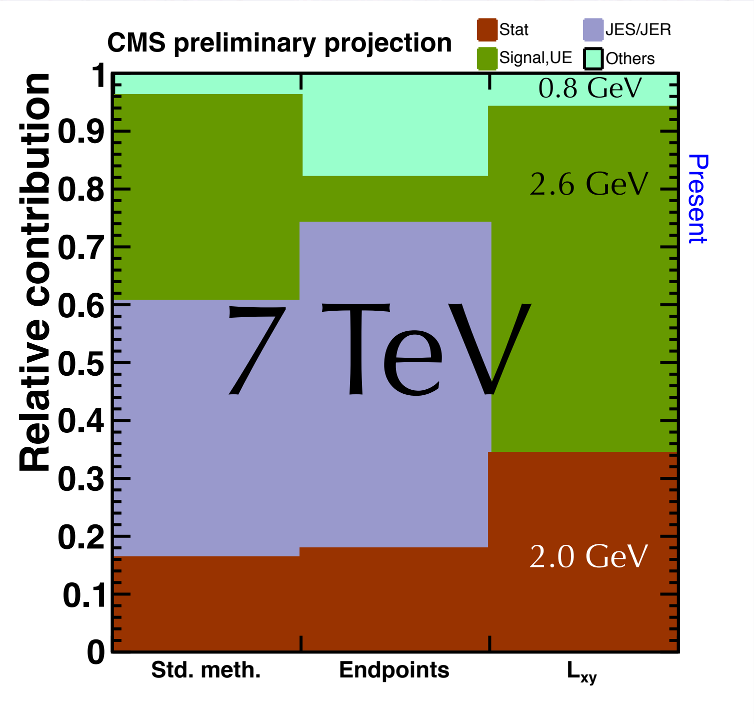
ATLAS-CONF-2011-054

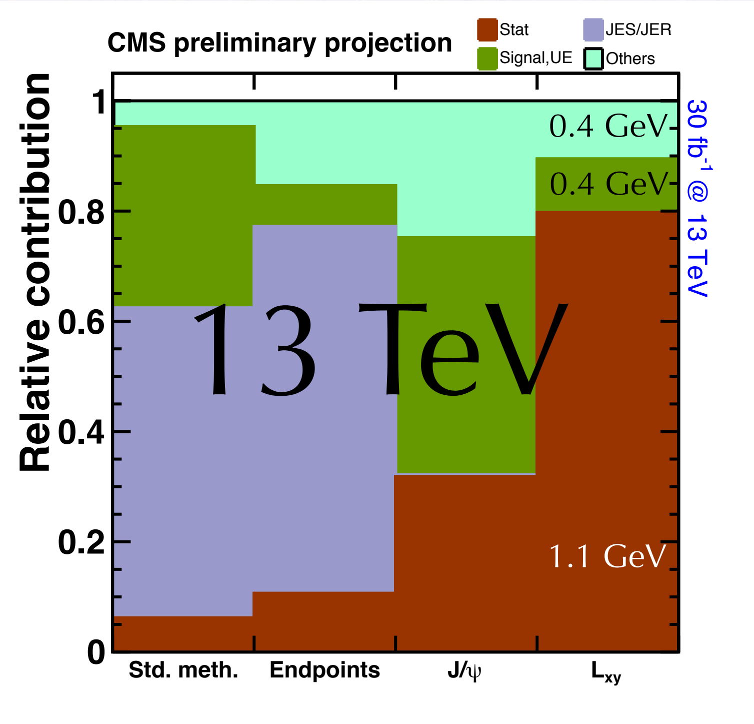
$m_{top}^{pole} = (166.4^{+7.8}_{-7.3})$ GeV

- not possible to determine m_t and α_s simultaneously from σ_{tt} alone
- optimistic: a few GeV if mass dependence of measured σ_{tt} can be reduced

Projection overview (I): higher E

No J/ψ result at present





increase in σ

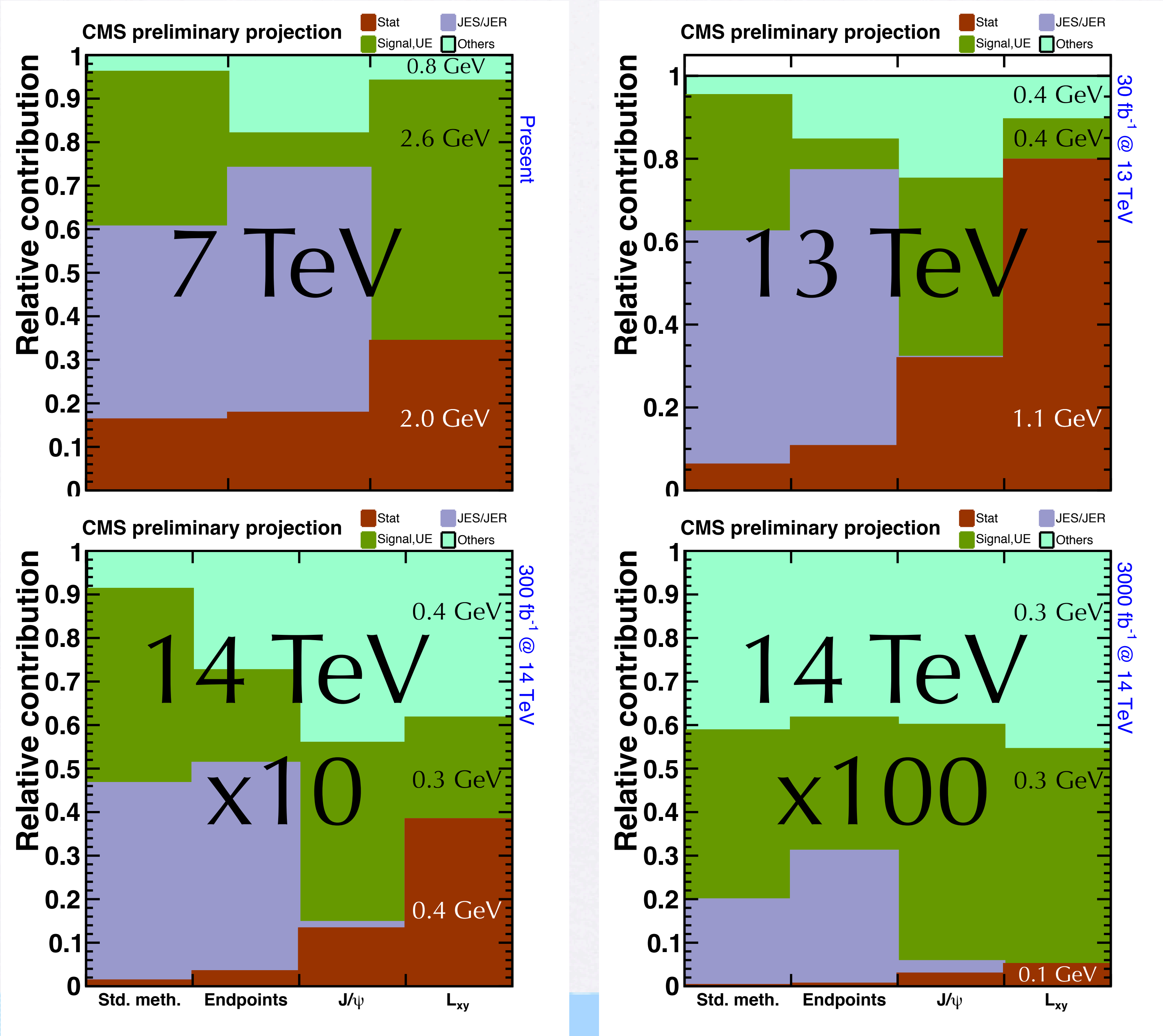
CMS-PAS-FTR-13-017

Additional L_{int} and statistics in 2015!

- *Standard method in l+jets at 7 TeV, JHEP 12 (2012) 105*
- *L_{xy} method in e-mu channel only for extrapolation*

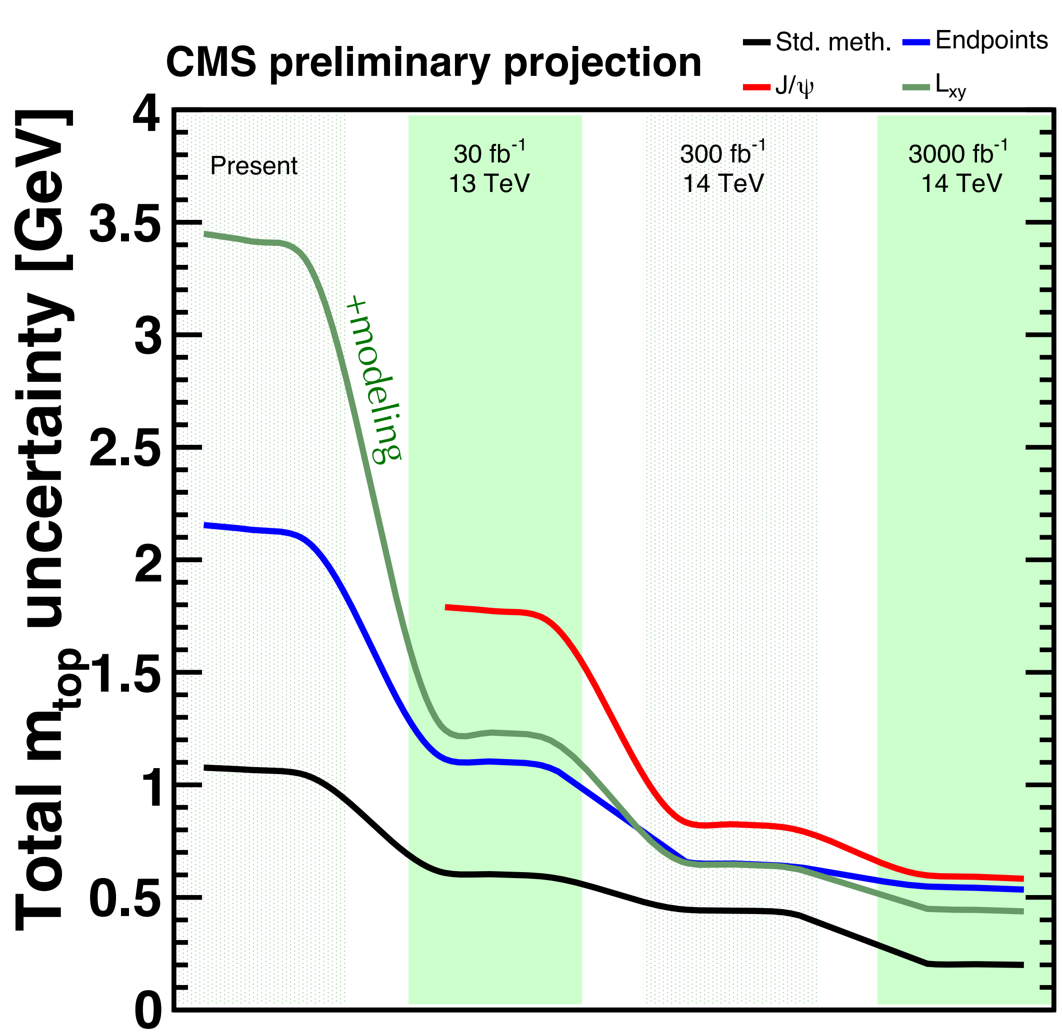
Projection overview (II): +higher L

No J/ψ result at present



CMS-PAS-FTR-13-017

Projection overview: total



Uncertainty drops mainly by the increase in L_{int} !!

CMS-PAS-FTR-13-017

CM (TeV)	7	13	14
L_{int} (fb^{-1})	*5*	*30*	*300*
J/ψ		*1.8*	***0.8***
Lxy (8 TeV)	*3.4*	*1.3*	***0.6***
Endpoints	*2.1*	*1.1*	***0.6***
Standard	1.1	0.6	**0.4**

Summary

- Overview of LHC top mass measurements projections
  - Higher statistics is crucial → great benefits in the standard methods
  - New considerations: 3D fits, differential measurements, full NLO

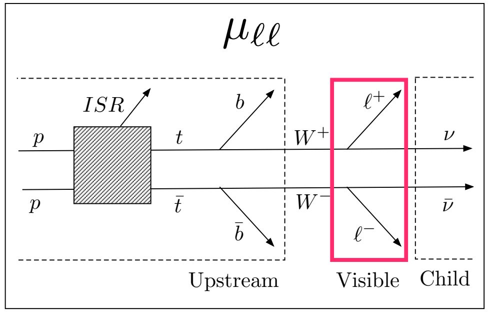
  → very good prospects for reduction of JES calibration & QCD effects
  - Purely experimental point of view → theoretical interest for ILC
- Overview of alternative methods with projections
  - Can't compete with the standard methods, but can provide cross-checks and better understanding of systematic uncertainties
  - May be more easily interpreted from the theoretical point of view
  - Did not yet consider combinations (different channels & techniques)

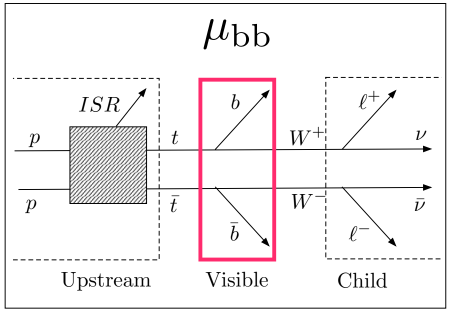
Backup

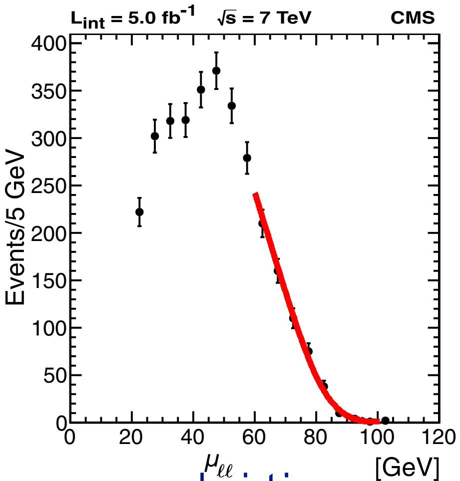
Mass from Endpoint Analysis

arXiv:1304.5783

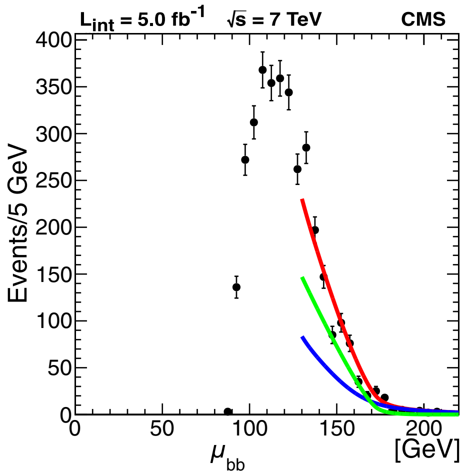
- Endpoint analysis: independent of assumptions on shapes (no templates or transfer functions)
- M_{T2}: minimum parent mass consistent with observed final state
- $M_{T2\perp}$: remove production dynamics, keep only momentum components perpendicular to 2-parent p_T
- Three $M_{T2\perp}$ subsystem variables: measure top, W- and neutrino masses simultaneously



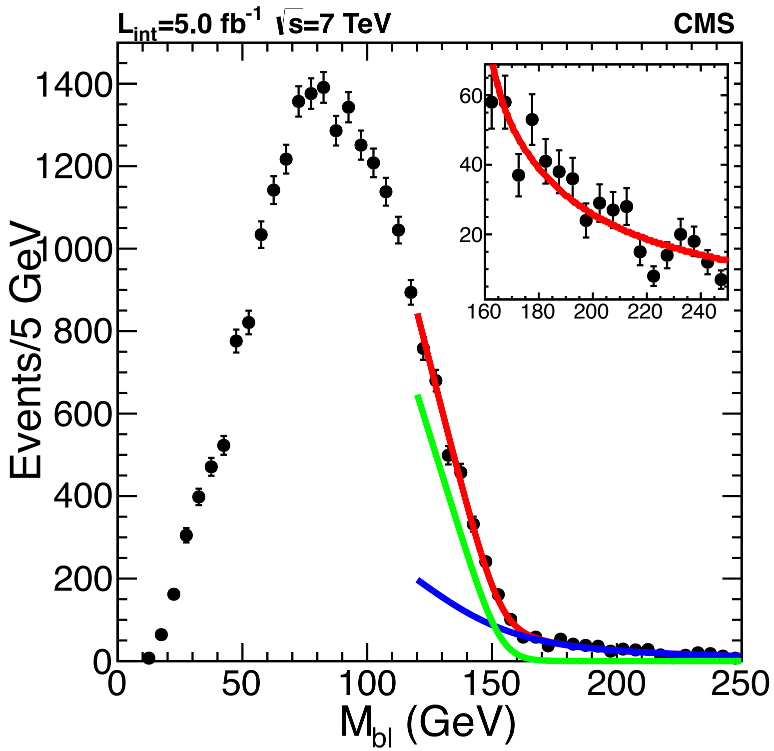




endpoint is m_W



lower bound of m_{top} for known m_W



$m_{top} = 173.9 \pm 0.9_{stat} + 1.6\text{-}2.0_{syst}$ GeV

Extrapolating the endpoint method

CMS-PAS-FTR-13-017

Table 2: Projection of the top-quark mass precision (in GeV) obtained with the endpoint method, for various integrated luminosities using the assumptions explained in the text.

	Current	Future			Comment
Center-of-mass energy	7 TeV	13 TeV	14 TeV	14 TeV	
Integrated luminosity	5 fb^{-1}	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}	
Jet energy scale and resolution	1.6	0.9	0.5	0.3	improve with data
Lepton energy scale	0.4	0.2	0.2	0.2	factor 2
Jet and lepton efficiencies	0.2	0.2	0.2	0.2	unchanged
Fit range	0.6	0.2	0.2	0.2	statistics (factor 4)
Background shape	0.5	0.2	0.1	0.02	statistics
QCD effects	0.6	0.3	0.3	0.3	factor 2
Pileup	0.1	0.1	0.1	0.1	unchanged
Systematic	1.9	1.0	0.6	0.5	
Statistical	0.9	0.4	0.1	0.04	
Total	2.1	1.1	0.6	0.5	

Extrapolating the J/ψ method

note: no result at 7 or 8 TeV, so starting at 30 fb^{-1}

CMS-PAS-FTR-13-017

Table 3: Expected top-quark mass precision (in GeV) achieved with the J/ψ method, for various integrated luminosities using the assumptions explained in the text.

	Future			Comment
Center-of-mass energy	13 TeV	14 TeV	14 TeV	
Integrated luminosity	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}	
Parton distribution functions	0.3	0.2	0.1	improve with theory and data
Renormalisation and factorization scales	0.9	0.4	0.4	improve with NNLO for $m_{\ell B}$
Initial- and final-state radiation	0.3	0.2	0.1	full NLO gen. + diff. data
b and light fragmentation	0.7	0.5	0.3	improve with data
Underlying event	0.6	0.2	0.1	improve with data
Lepton energy scale and resolution	0.5	0.2	0.2	improve with data
Jet energy scale and resolution	0.1	0.1	0.1	
Background knowledge	0.2	0.1	0.1	
Systematic	1.5	0.8	0.6	
Statistical	1.0	0.3	0.1	
Total	1.8	0.8	0.6	

➤ *CMS PAS TOP-13-007 confirmed J/ψ selection efficiencies from the TDR*

Extrapolating the L_{xy} method

note: use e-mu channel only (96% pure sample)

CMS-PAS-FTR-13-017

Table 4: Projection of the top-quark mass precision (in GeV) obtained with the L_{xy} method, for various integrated luminosities using the assumptions explained in the text.

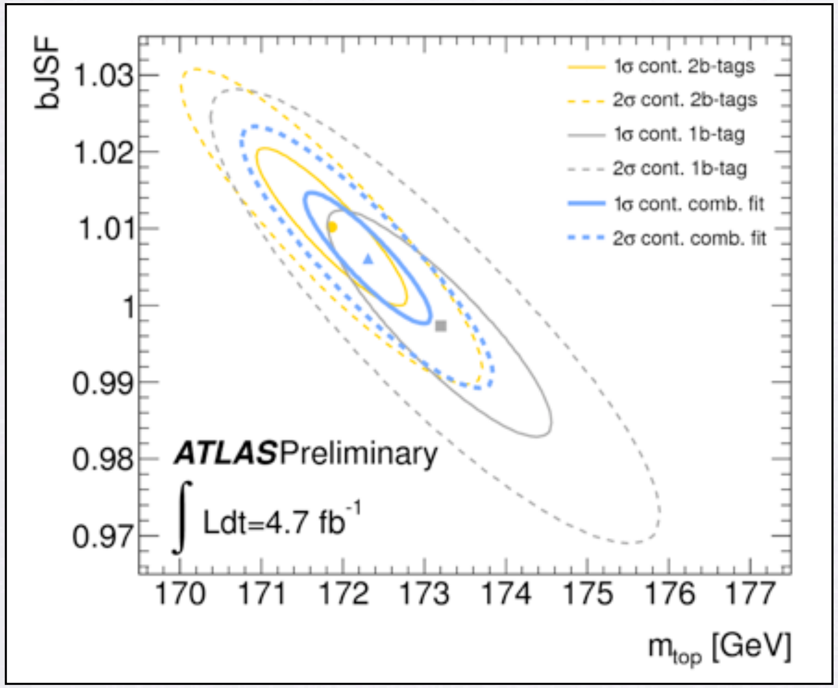
	Current	Future			Comment
Center-of-mass energy	8 TeV $e\mu$	13 TeV	14 TeV	14 TeV	
Integrated luminosity	20 fb^{-1}	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}	
b fragmentation/hadronization	0.8	0.4	0.4	0.3	improve with data
Top p_T modeling	2.4	0.2	0.2	0.2	improve at NNLO
Other systematic uncertainties	1.1	0.3	0.2	0.2	improve with data
Systematic	2.8	0.6	0.5	0.4	
Statistical	2.0	1.1	0.4	0.1	
Total	3.4	1.3	0.6	0.4	

Investigating possible evolution of m_{top} precision

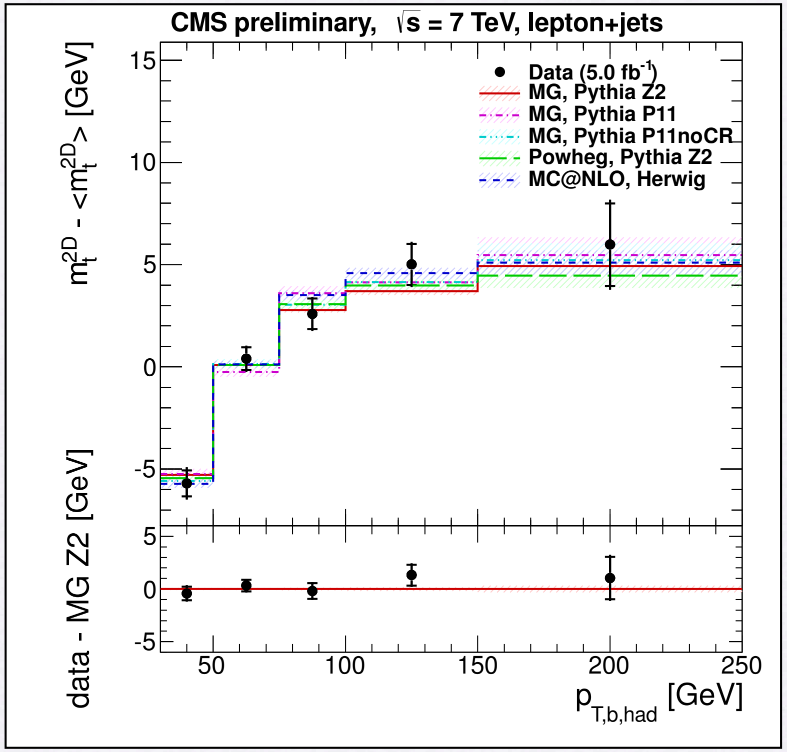
Use of 3D fits
→ *constrain b-JES in-situ*

Use of differential distributions
→ *constrain signal model in-situ*

ATLAS-CONF-2013-046



CMS-PAS-TOP-12-029



Currently limited by statistical uncertainties

➤ ***Will offer the possibility to constrain the dominant systematics***

but fully effective with 3000 fb^{-1}