Top quark mass at LHC

Alexander Mitov

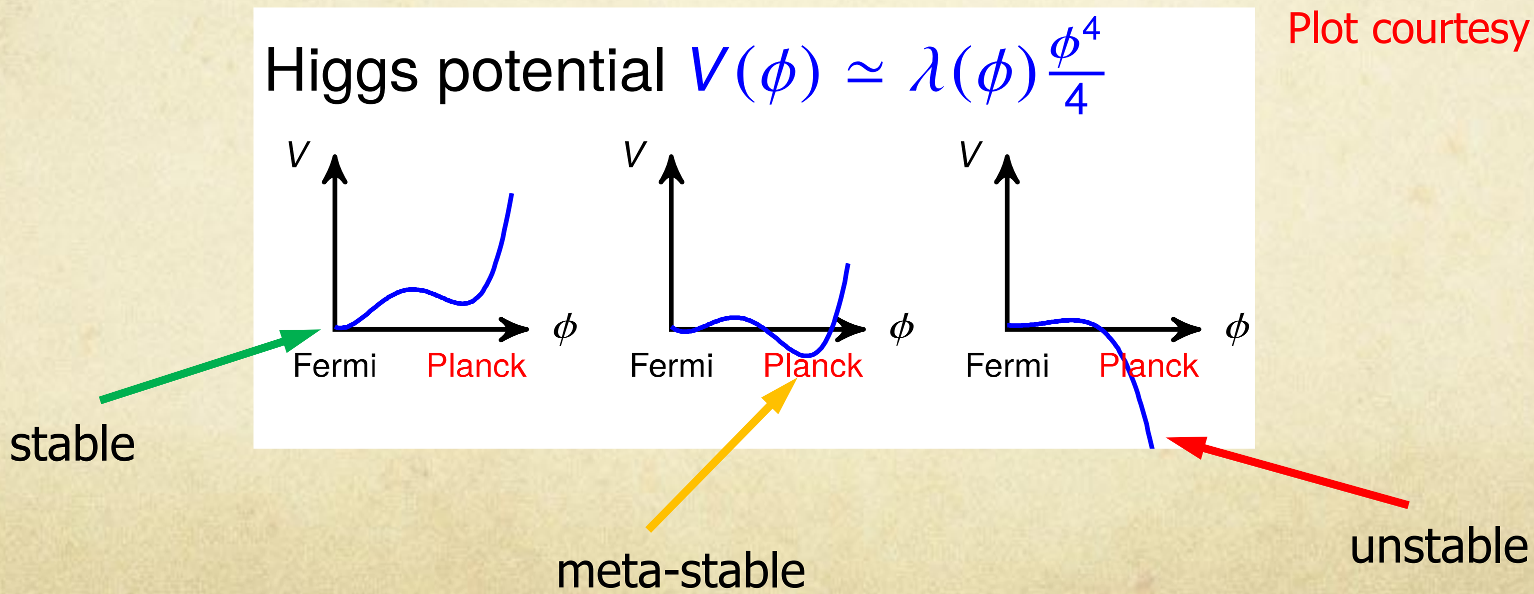
Cavendish Laboratory

UNIVERSITY OF CAMBRIDGE

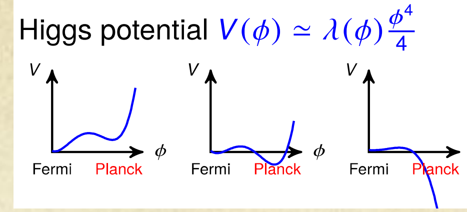
Intro: why the top mass?

- It is a fundamental parameter of the SM
- Its precision affects many precision observables in the SM.
- Its precision affects the searches for new physics.
- However, the most relevant case is: extrapolation of the SM to very high energies.
  - Once the Higgs boson was found (and the mass measured quite precisely) m_{top} is the SM parameter that mostly parametrically affects SM predictions
  - Prime example: stability of EW vacuum

Plot courtesy of F. Bezrukov



Intro: why the top mass?



✓ Here is how m_{top} enters the game:

✓ Take the pole-masses m_{top} and m_h as input parameters. Then:

$$\lambda(\mu) = \frac{G_\mu}{\sqrt{2}} m_h^2 + \text{loop corrections}$$

$$y_t(\mu) = \frac{\sqrt{2}}{v} m_t + \text{loop corrections}$$

$\overline{MS}$ - running parameters

Defs: $$\mathcal{L} = \frac{y_t}{\sqrt{2}} h\bar{t}t$$
$$G_\mu = \frac{1}{\sqrt{2}v^2} + \text{loop corrections}$$

Size of loop effects:

$\bar{\mu} = M_t$	λ	y_t
LO	0.12917	0.99561
NLO	0.12774	0.95113
NNLO	0.12604	0.94018

All numbers on this slide adapted from Buttazzo et al arXiv:1307.3536v4

✓ In other words in SM both λ and y_t are derived parameters. Their values are:

$$\lambda(\mu = m_t) \approx 0.126 - 0.00004 \left(\frac{\Delta m_t}{1\text{GeV}}\right) + 0.000412 \left(\frac{\Delta m_h}{0.2\text{GeV}}\right) \pm \ldots$$

Where: $\boxed{\Delta x \equiv x - x^{\text{ref}}}$

$$\lambda(\mu = m_{\text{PL}}) \approx -0.0143 - 0.0066 \left(\frac{\Delta m_t}{1\text{GeV}}\right) + 0.0026 \left(\frac{\Delta \alpha_s}{0.001}\right) + 0.0006 \left(\frac{\Delta m_h}{0.2\text{GeV}}\right) \pm \ldots$$

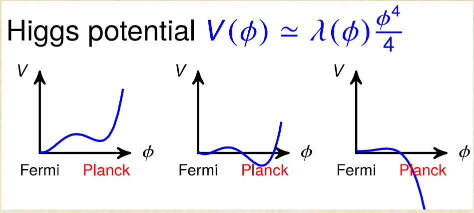
$$y_t(\mu = m_t) \approx 0.9369 + 0.0056 \left(\frac{\Delta m_t}{1\text{GeV}}\right) - 0.0006 \left(\frac{\Delta \alpha_s}{0.001}\right) \pm \ldots$$

$$y_t(\mu = m_{\text{PL}}) \approx 0.3825 + 0.0051 \left(\frac{\Delta m_t}{1\text{GeV}}\right) - 0.003 \left(\frac{\Delta \alpha_s}{0.001}\right) \pm \ldots$$

Driven by m_{top} , not m_h!

Intro: why the top mass?

$$\lambda(\mu = m_{\rm PL}) \approx -0.0143 - 0.0066\left(\frac{\Delta m_t}{1\mathrm{GeV}}\right) + 0.0026\left(\frac{\Delta\alpha_s}{0.001}\right) + 0.0006\left(\frac{\Delta m_h}{0.2\mathrm{GeV}}\right) \pm \ldots$$

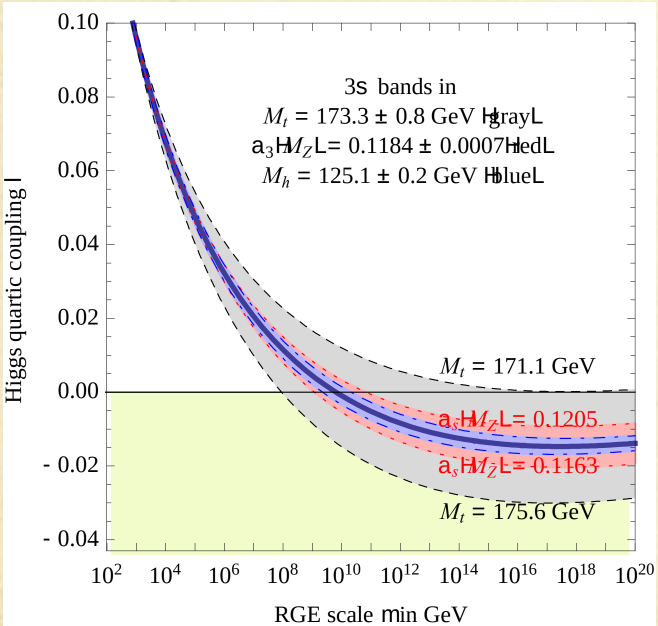


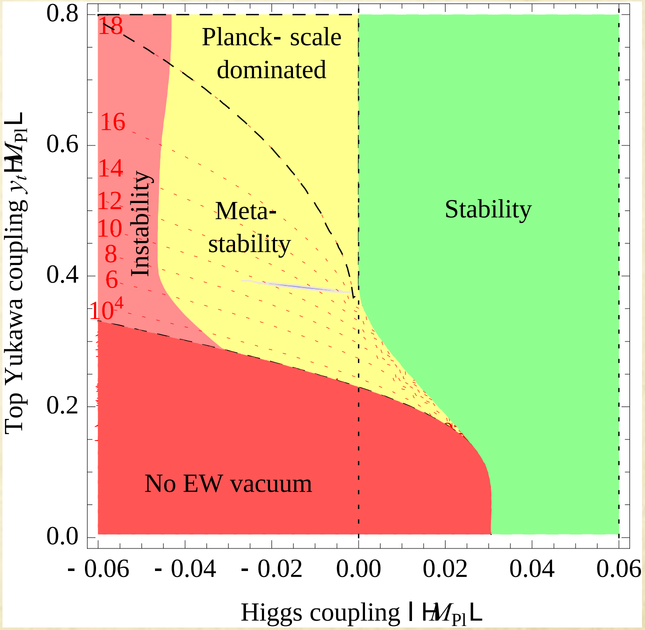
✓ The effective potential can be non-negative all the way to m_{PL} if the top mass were **lower** than the current world average by about 2 GeV.

✓ Stated differently, stability requires:

Buttazzo et al arXiv:1307.3536v4

$$M_t < (171.53 \pm 0.15 \pm 0.23_{\alpha_3} \pm 0.15_{M_h})\,\mathrm{GeV} = (171.53 \pm 0.42)\,\mathrm{GeV}.$$





So, what is the value of m_{top} and how well do we know it?

So how well do we (think) we know the top mass?

$$M_t < (171.53 \pm 0.15 \pm 0.23_{\alpha_3} \pm 0.15_{M_h})\,\mathrm{GeV} = (171.53 \pm 0.42)\,\mathrm{GeV}.$$

- ✓ Here is the latest PDG review (2017)

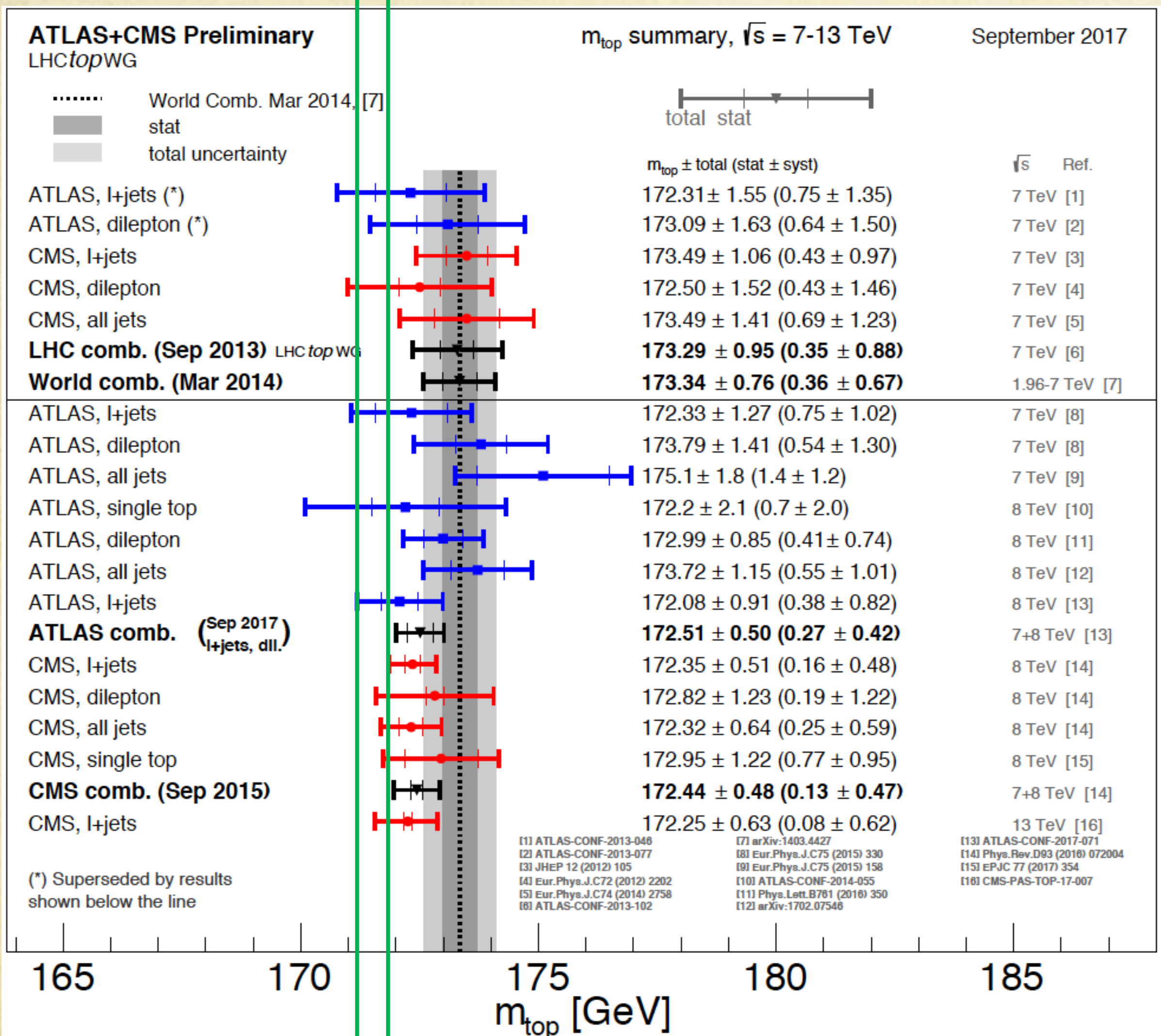
m_t (GeV/c^2)	Source	$\int L\,dt$	Ref.	Channel
$172.99 \pm 0.48 \pm 0.78$	ATLAS	4.6	[145]	ℓ+jets+$\ell\ell$
$172.44 \pm 0.13 \pm 0.47$	CMS	19.7	[146]	ℓ+jets+$\ell\ell$+All jets
$172.35 \pm 0.16 \pm 0.48$	CMS	19.7	[146]	ℓ+jets
$172.22 \pm 0.18^{+0.89}_{-0.93}$	CMS	19.7	[152]	$\ell\ell$
$173.72 \pm 0.55 \pm 1.01$	ATLAS	20.2	[158]	All jets
$172.25 \pm 0.08 \pm 0.62$	CMS	35.9	[159]	ℓ+jets
$174.30 \pm 0.35 \pm 0.54$	CDF,DØ (I+II)	≤ 9.7	[174]	publ. or prelim.
$173.34 \pm 0.27 \pm 0.71$	Tevatron+LHC	$\leq 8.7 + \leq 4.9$	[2]	publ. or prelim.

- ✓ Few takes:
  - ✓ LHC is lower than Tevatron
  - ✓ Separately LHC is lower than the World Average
  - ✓ CMS tends to be lower than ATLAS
  - ✓ Notable spread among measurements

So how well do we (think) we know the top mass?

✓ And the latest LHCtopWG combination:

$$M_t < (171.53 \pm 0.15 \pm 0.23_{\alpha_3} \pm 0.15_{M_h})\,\mathrm{GeV} = (171.53 \pm 0.42)\,\mathrm{GeV}.$$



✓ At face value, the World Average is more than 3σ away from stability.

✓ In practice, the most-precise LHC measurements are almost consistent with stability!

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So how well do we (think) we know the top mass?

- ✓ The relevant questions is: how well do we really know the top mass?

- ✓ Few general comments:

  - ✓ m_{top} is not an observable so it cannot me measured directly. This becomes important once we want to probe the top quark with precision below its width ~ 1.4 GeV

  - ✓ Implication: theory must enter in any top mass extraction, along with all experimental errors. The problem is how to quantify this implied theory error.

  - ✓ Two experimental approaches:

    1. Try to "reconstruct" the top mass from the top decay products

    2. Extract m_{top} from observables that are sensitive to it

- ✓ In practice, 1. is not really different from 2. since the top decay product cannot be reconstructed (this are not exclusive decays!). In other words:

  - 1. is a version of 2.

  - 1. and 2. use different classes of theoretical tools: MC's for 1. or more inclusive observables and MC's for 2.

Top mass: precision and scheme dependence

See talk by Yuichiro Kiyo on Tue

- ✓ Computing in terms of the pole mass is easy and natural.

- ✓ However, that particular mass has non-perturbative corrections that restrict its ultimate precision
- ✓ Recent estimate based on the 4-loop relation: pole mass <--> Msbar mass

Marquard, Smirnov, Smirnov, Steinhauser '15

$$m_P = 163.643 + 7.557 + 1.617 + 0.501 + (0.195 \pm 0.005)\ \mathrm{GeV}$$

Assuming: $\overline{m}_t = m_t(\overline{m}_t) = 163.643\ \mathrm{GeV}$ and $\alpha_s^{(6)}(m_t) = 0.1088$

- ✓ Exploring the leading asymptotic behavior of the above relation Beneke '94

- ✓ One can derive an improved relation which predicts (approximately) higher terms in the above expansion. Beneke, Marquard, Nason, Steinhauser '16

- ✓ The ultimate precision is taken for the term where the term-to-term difference is smallest

  - ✓ Error from the terms beyond 4 loops: ~ 250 MeV
  - ✓ Ultimate intrinsic error in the above relation: ~ 70 MeV

However see new work by A. Hoang et al. '17

- ✓ All this is very important at e^+e^- colliders See talk by Yuichiro Kiyo on Tue

Ongoing/future developments: POWHEG

- ✓ Many (most) m_{top} extractions rely on event generators. Newest POWHEG developments:

  Ferrario-Ravasio, Jezo, Oleari, Nason, arXiv:1801.03944

- ✓ Complete treatment at NLO (off shell effects etc)
- ✓ 3 different versions (of the generator) used in order to estimate perturbative effects
- ✓ Different showers used to estimate shower/hadronization effects
- ✓ Study both:
  - ✓ ”direct observables” (i.e. 1.): W-b_{jet} mass, assuming W is fully reconstructed
  - ✓ Inclusive ones (i.e. 2.): b_{jet} energy peak; leptonic distributions

Ongoing/future developments: POWHEG

✓ Peak position of the "direct" measurement (plus: strong correlation with m_{top})

Ferrario-Ravasio, Jezo, Oleari, Nason, arXiv:1801.03944

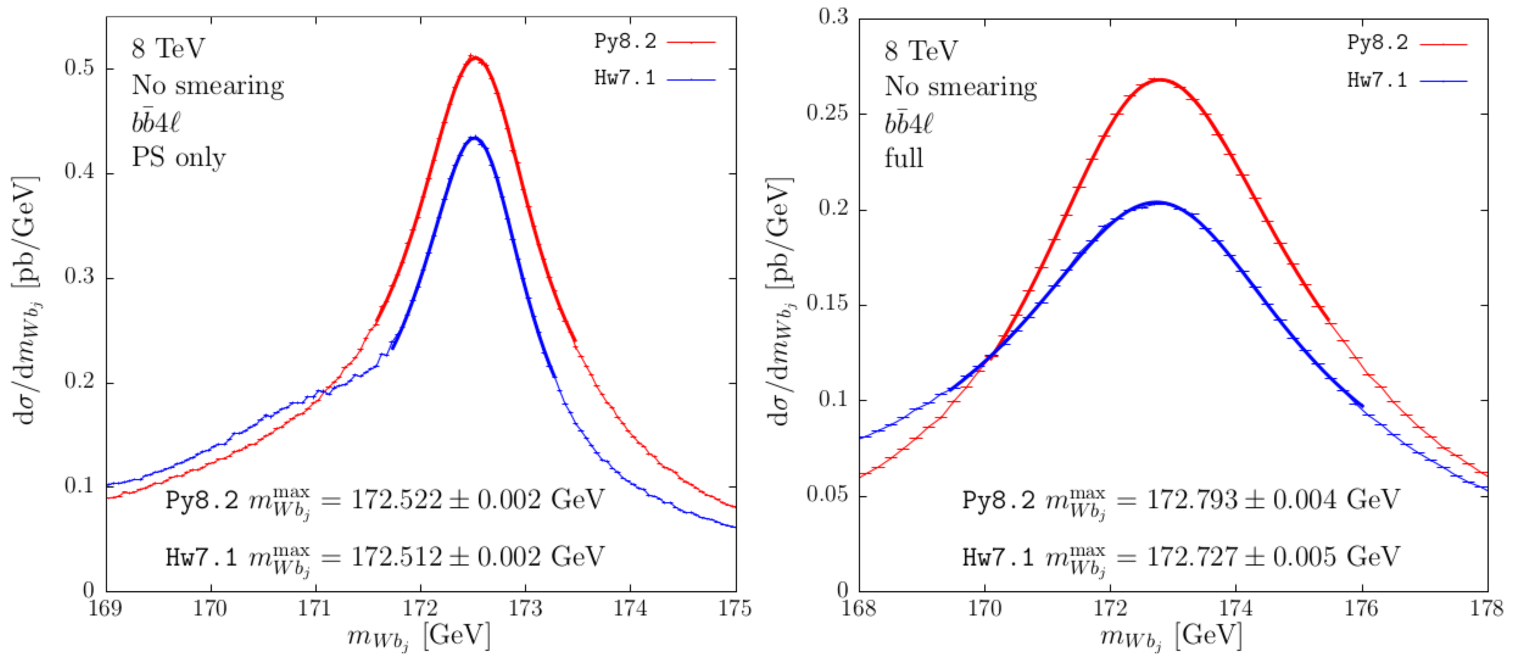


Figure 12. $d\sigma/dm_{Wb_j}$ distribution obtained by showering the $b\bar{b}4\ell$ results with Pythia8.2 and Herwig7.1, at parton-shower level (left) and with hadronization and underlying events (right).

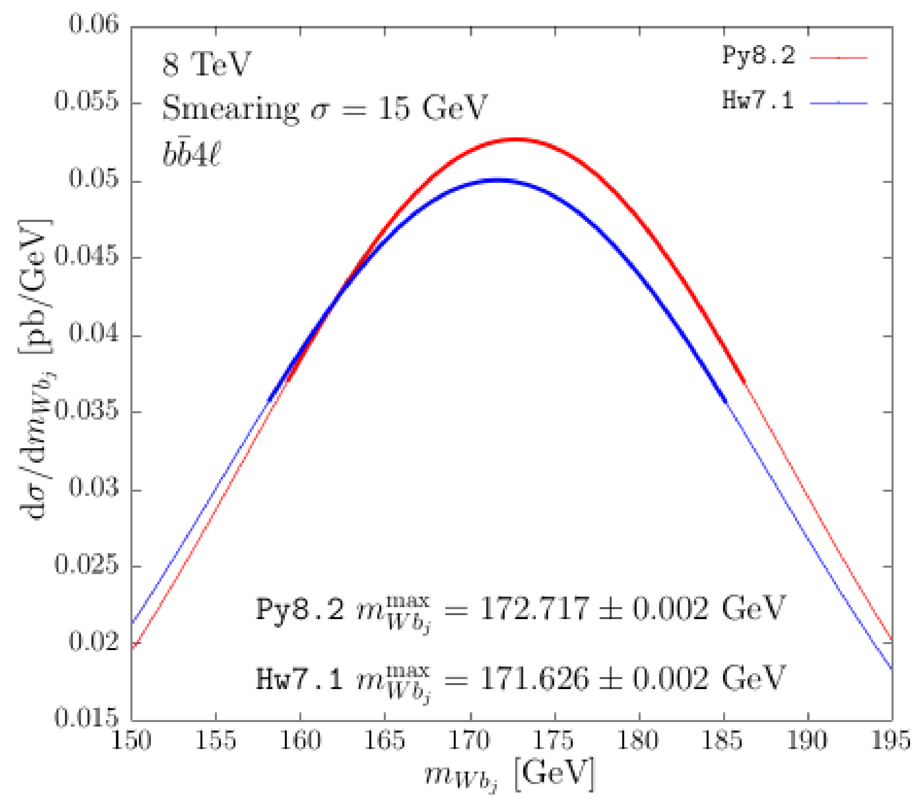
No large difference in the peak position (i.e. no indication here of large NP effects that displace the peak.). However, the marked difference in shape is bound to lead to problems when the experimental resolution is taken into account.

Ongoing/future developments: POWHEG

✓ Peak position of the "direct" measurement (plus: strong correlation with m_{top})

Ferrario-Ravasio, Jezo, Oleari, Nason, arXiv:1801.03944

✓ After smearing (i.e. experimental resolution)



When the resolution is accounted for, we find a 1.1 GeV difference between Herwig7 and Pythia8.

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Ongoing/future developments: POWHEG

- ✓ Peak position of the "direct" measurement (plus: strong correlation with m_{top})

  Ferrario-Ravasio, Jezo, Oleari, Nason, arXiv:1801.03944

- ✓ Very significant difference found between Pythia8 and Herwig7. Is it the shower?
  - ✓ To check this, Herwig 6 also included in the comparison
  - ✓ Interestingly, Herig6 is closer to Pythia8 than to Herwig7

M_{Wj} (GeV)						
	Py8		Hw6		Hw7	
	bare	smeared	bare	smeared	bare	smeared
$b\bar{b}4l$	172.793	172.717	172.59	172.384	172.727	171.626
$t\bar{t}$_dec	172.814	172.857	172.602	172.484	172.775	171.678
hvq	172.803	172.570	172.803	172.95	173.038	172.552

as a fortuitous consequence of compensation due to hadronization and MPI in Herwig6.
This findings also suggest that shower and hadronization uncertainties may be dominant in direct measurements.

Clearly, shower and non-perturbative effects represent a significant systematics!

Ongoing/future developments: POWHEG

Ferrario-Ravasio, Jezo, Oleari, Nason, arXiv:1801.03944

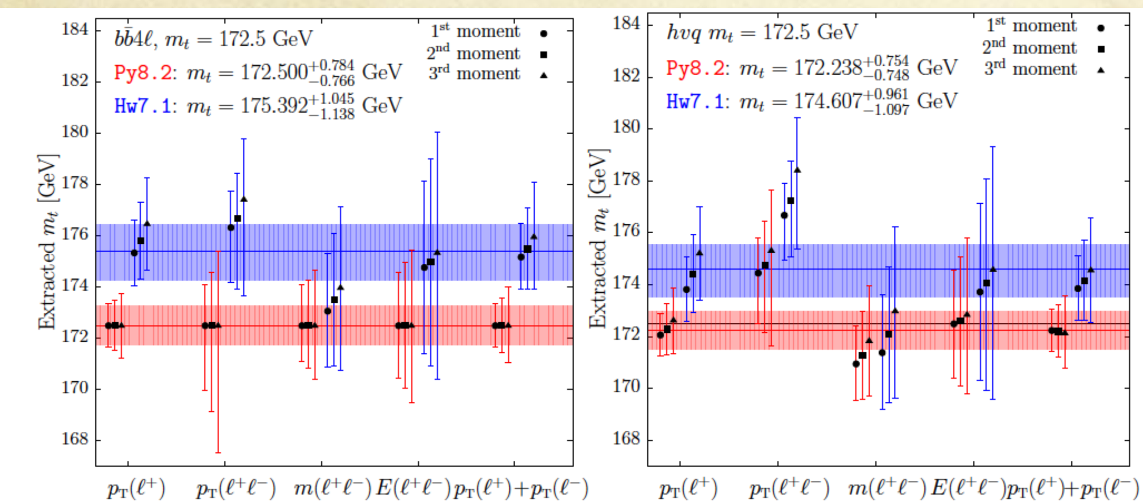
- ✓ Application to inclusive observables

- ✓ Study of the b_{jet} energy peak. Agashe, Franceschini, Kim, Schulze, 2016

  - ✓ Very sensitive radiation from top decay. Pure perturbative corrections seem O(500 MeV). However:

    Switching from Pythia8 to Herwig7 leads to large differences, that would impact the mass measurement by more than 4 GeV.

- ✓ Lepton-only observables (minimize effect due to modeling of hadronic radiation)



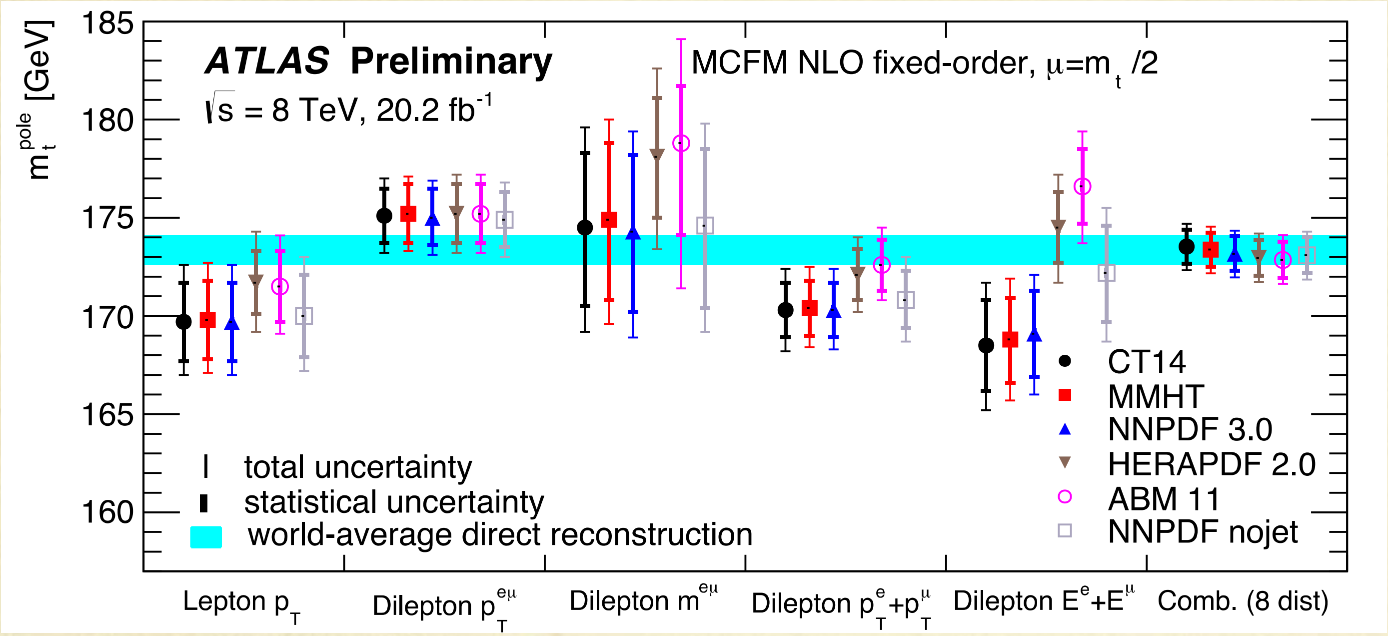
Looking only at Pythia8: only $p_T(\ell^+\ell^-)$ and $m(\ell^+\ell^-)$ differ, presumably because of their sensitivity to spin correlations. Nearly 3 GeV difference between Pythia8 and Herwig7.

Kawabata, Shimizu, Sumino, Yokoya '11-`14
Frixione, A.M. '14

Ongoing/future developments: ATLAS

✓ Recent ATLAS study of the same observable within MCFM (fixed order NLO)

ATLAS-CONF-2017-044



IMPORTANT:

Combine observables in order to avoid theoretical biases!

✓ Appears rather promising.

✓ This should be, perhaps, the first application for a full NNLO calculation with NNLO decay!

✓ Note: the POWHEG study finds non-negligible hadronic radiation modeling effect.

Ongoing/future developments: theorists

✓ Recent update on measurements sensitive to B-fragmentation (J/Psi method, etc)

Corcella, Franceschini, Kim 2017

3.1 m_t-determination observables

We first list up the observables that we consider for the top-quark mass measurement.

- E_B: energy of each tagged B-hadron;
- $p_{T,B}$: B-hadron transverse momentum;
- $E_B + E_{\bar{B}}$ and $p_{T,B} + p_{T,\bar{B}}$: sum of the energies and transverse momenta of B and $\bar{B}$ (in events where both B hadrons are tagged);
- $m_{B\ell}$: invariant mass of the B-hadron and one lepton from W decay (the prescription for combinatorial ambiguity arising in forming $m_{B\ell}$ will be discussed shortly);
- m_{T2} [59] and $m_{T2,\perp}$ [60] of the B and the $B\ell$ subsystems defined below;
- $m_{BB\ell\ell}$, the total mass of the system constructed by the two leptons and the two tagged B-hadrons in the event.

✓ Basically, observables where b_{jets} are replaced with identified B-hadrons.

✓ Can be studied either within the fragmentation models of, say, Pythia or using analytically extracted fragmentation functions (all known to NNLO).

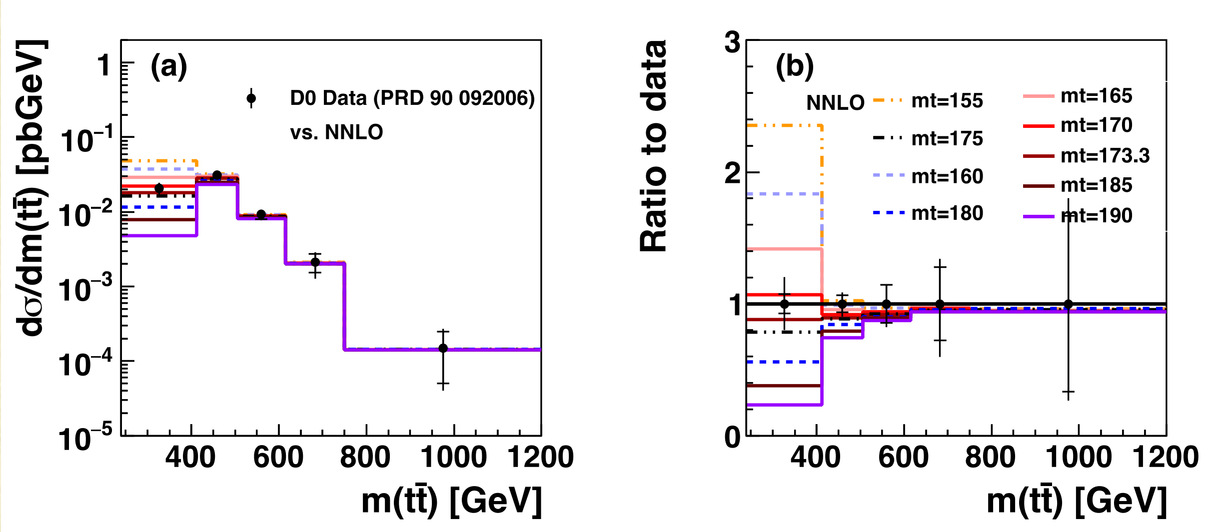
✓ The ultimate constrain may be B-hadron data from LEP and SLD

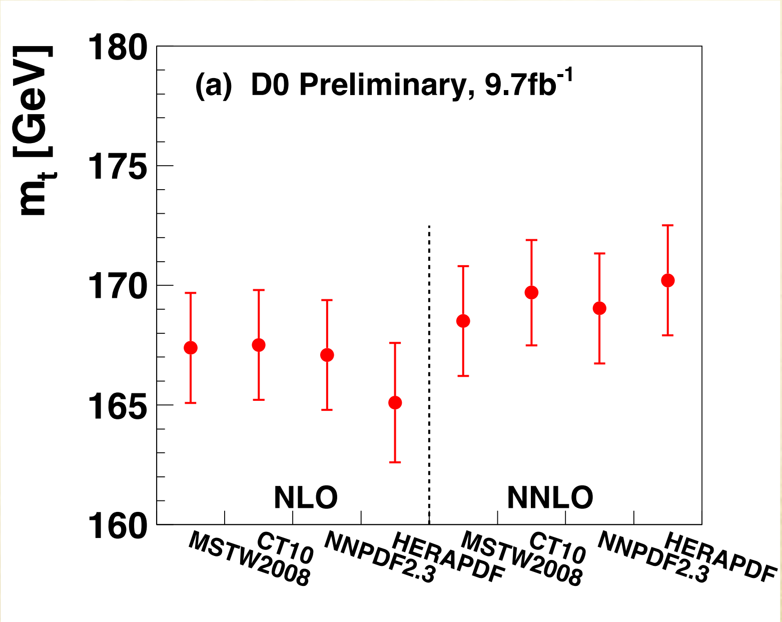
Ongoing/future developments: D0

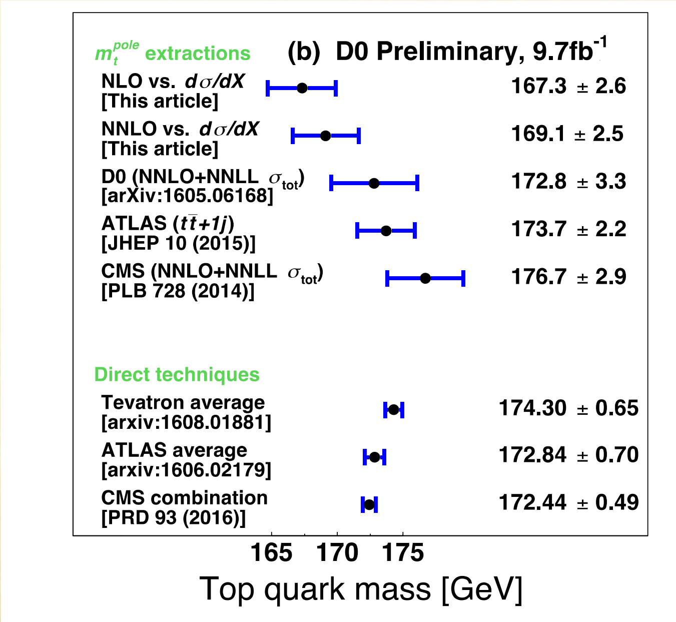
✓ Extraction of m_{top} from NNLO differential distributions at the Tevatron

D0 Note 6473-CONF

Ideal for the LHC!







Ongoing/future developments: theorists

✓ Simultaneous extraction of m_{top} and α_s from NNLO differential distributions at the LHC 8 TeV

A. Cooper-Sarkar, Czakon, Lim, Mitov, Papanastasiou, to appear

✓ Never done before! Allows access to the correlation between these two parameters

✓ Technically possible because the NNLO calculations are now available as fastNLO tables for all measured single differential distributions for m_{top}={169,171,172.5,173.3,175} GeV

Czakon, Heymes, Mitov 2017
Kluge, Rabbertz, Wobisch, 2006
D. Britzger et al., arXiv:1208.3641

Least squares extraction for normalised and absolute distributions

$$\zeta_i = \zeta_i^{\text{data}} - \zeta_i^{\text{theory}}$$

$$\chi^2_{\text{norm}} = \frac{1}{(N_{\text{data}}-1)} \sum_{i,j=1}^{N_{\text{data}}-1} \zeta_i C_{ij}^{-1} \zeta_j \quad + \frac{(\sigma_{\text{NNLO}} - \sigma_{\text{data}})^2}{\delta\sigma^2_{\text{data}}}$$

$$\chi^2_{\text{abs}} = \frac{1}{N_{\text{data}}} \sum_{i,j=1}^{N_{\text{data}}} \zeta_i C_{ij}^{-1} \zeta_j$$

- Measured values of $\sigma_{t\bar{t}}$ taken from separate 8 TeV ATLAS/CMS measurements [1]

✓ The chi^2 needs each bin as a function of m_{top} and α_s .

✓ We derive this by a 2-dim interpolation of a grid of precomputed m_{top} and α_s points.

Ongoing/future developments: theorists

✓ Simultaneous extraction of m_{top} and α_s from NNLO differential distributions at the LHC 8 TeV

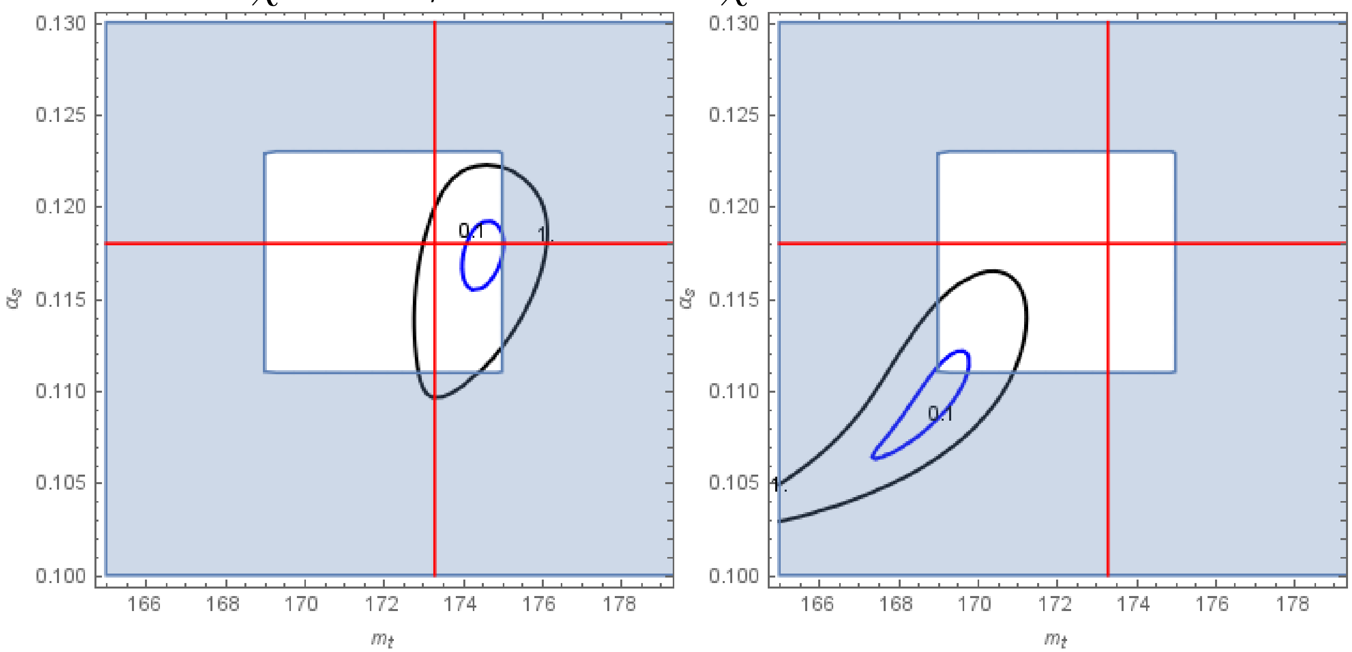
A. Cooper-Sarkar, Czakon, Lim, Mitov, Papanastasiou, to appear

Results: p_t^T

CT14, normalised results

White region: interpolated, blue region: extrapolated

Blue line: $\Delta\chi^2 = 0.1$, black line: $\Delta\chi^2 = 1.0$



	ATLAS			CMS		
	α_s	m_t	$\chi^2_{\rm min}$	α_s	m_t	$\chi^2_{\rm min}$
p_T^t	0.1175	174.5	0.50	0.1096	168.9	0.71

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Ongoing/future developments: theorists

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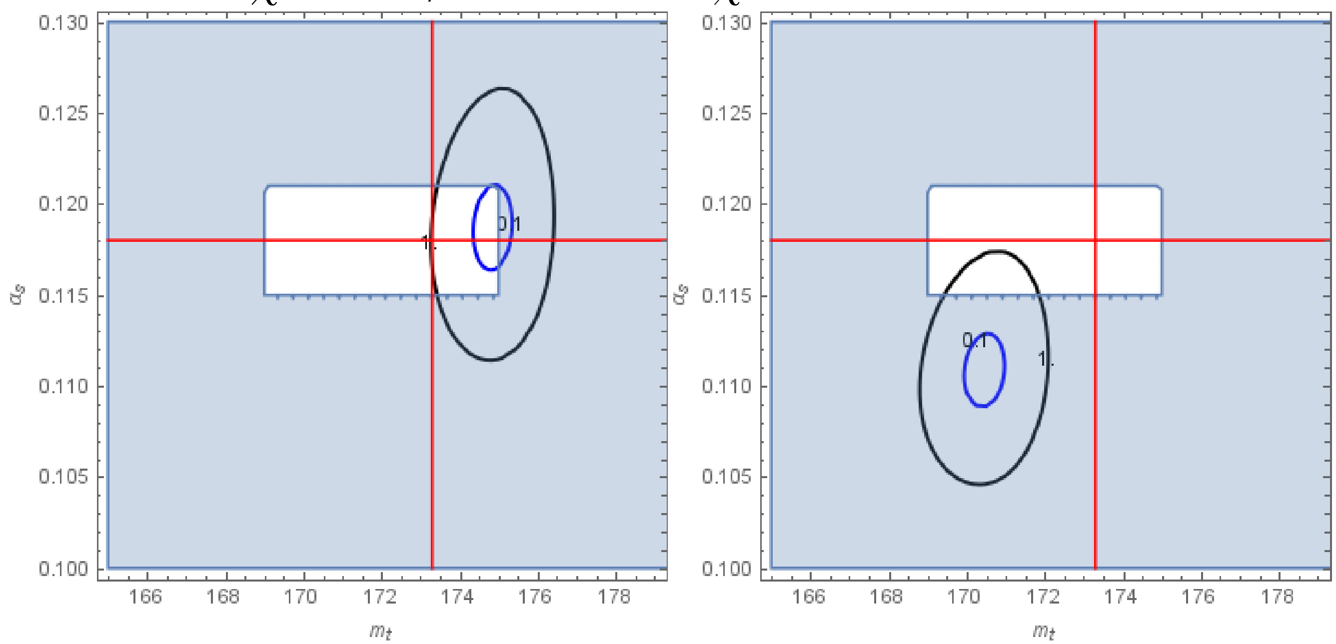
A. Cooper-Sarkar, Czakon, Lim, Mitov, Papanastasiou, to appear

Results: p_t^T

NNPDF3.0, normalised results

White region: interpolated, blue region: extrapolated

Blue line: $\Delta\chi^2 = 0.1$, black line: $\Delta\chi^2 = 1.0$



	ATLAS			CMS		
	α_s	m_t	χ^2_{min}	α_s	m_t	χ^2_{min}
p_T^t	0.1187	174.9	0.46	0.1108	170.5	0.68

Ongoing/future developments: theorists

✓ Simultaneous extraction of m_{top} and α_s from NNLO differential distributions at the LHC 8 TeV

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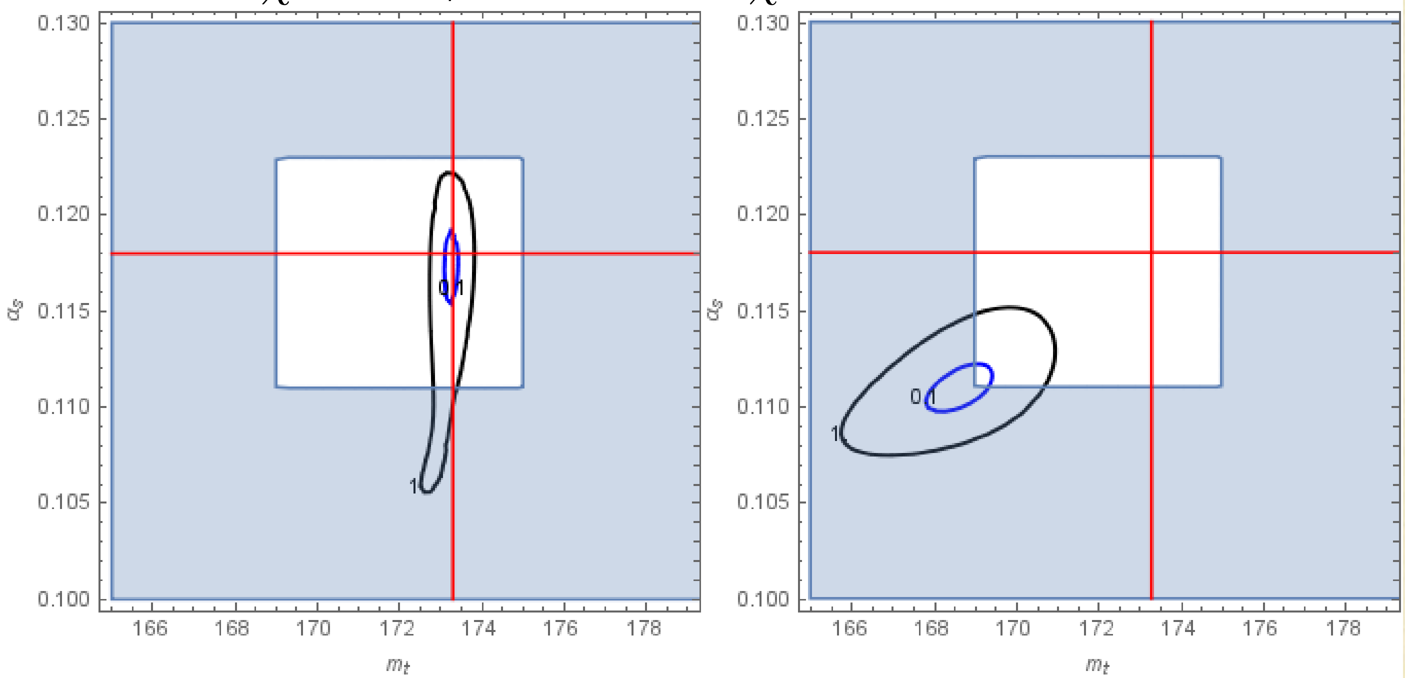
Results: $M_{t\bar{t}}$

CT14, normalised results

White region: interpolated, blue region: extrapolated

Blue line: $\Delta\chi^2 = 0.1$, black line: $\Delta\chi^2 = 1.0$



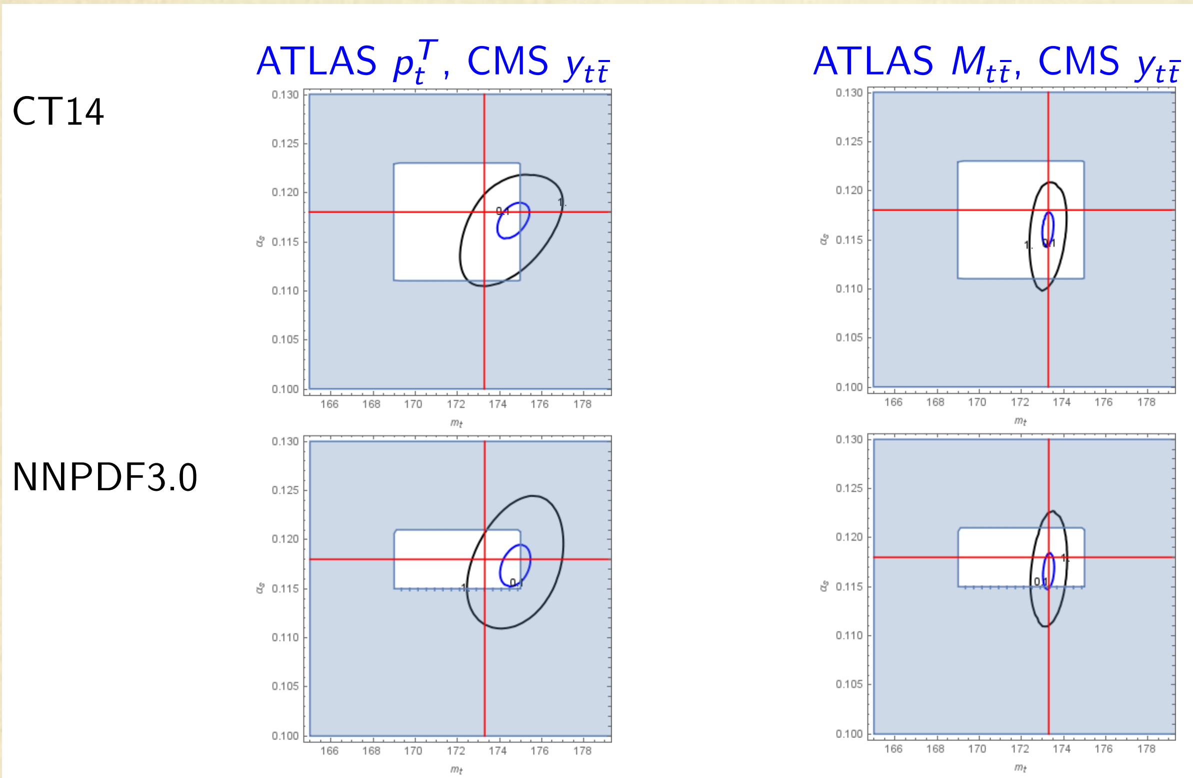
	ATLAS			CMS		
	α_s	m_t	χ^2_{min}	α_s	m_t	χ^2_{min}
$M_{t\bar{t}}$	0.1174	173.2	1.23	0.1109	168.7	4.77

Ongoing/future developments: theorists

- ✓ Simultaneous extraction of m_{top} and α_s from NNLO differential distributions at the LHC 8 TeV

A. Cooper-Sarkar, Czakon, Lim, Mitov, Papanastasiou, to appear

- ✓ Would be great to combine observables. However no correlations available. Try the next best thing: one CMS and one ATLAS distribution assuming no correlation between them



We observe greatly improved stability of the extracted values!

		CT14			NNPDF3.0		
ATLAS	CMS	α_s	m_t	χ^2_{min}	α_s	m_t	χ^2_{min}
p_T^t	$y_{t\bar{t}}$	$0.1172^{+0.0044}_{-0.0058}$	$174.7^{+2.2}_{-2.2}$	1.33	$0.1173^{+0.0066}_{-0.0061}$	$174.7^{+2.2}_{-2.1}$	0.78
$M_{t\bar{t}}$	$y_{t\bar{t}}$	$0.1161^{+0.0048}_{-0.0060}$	$173.3^{+0.9}_{-0.8}$	1.80	$0.1166^{+0.0060}_{-0.0056}$	$173.3^{+0.9}_{-0.8}$	1.36

Conclusions

- Top mass extraction at the LHC: as dynamic as ever!
- Emphasis on improving MC generators and quantifying their precision.
- Inclusion of higher order corrections also in progress.
- NNLO top production with decay (NWA at NNLO but exact through NLO) should offer great opportunities.
- Questions regarding mass definitions abound but are they relevant at the LHC?
  - NO at present,
  - MAYBE in the future
  - DEFINITELY YES for e^+e^- colliders
- Do we know the top mass at present with O(500 MeV)?
  - Depends on who you ask. I suspect not.
- Is 300-500MeV error possible in the future (at the LHC): probably, but with a lot of work!