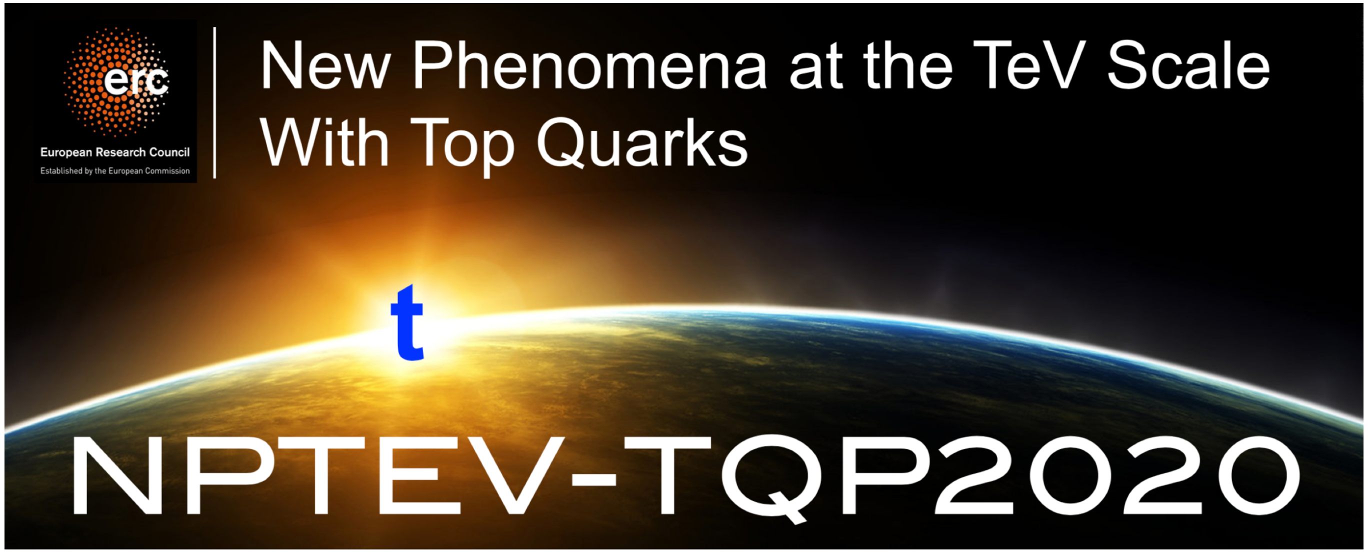
Precision Measurements of the Top Quark Mass



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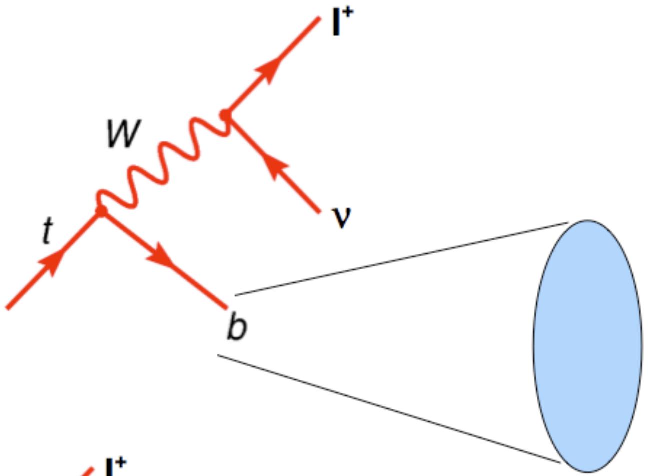
13.06.2018 — VRIJE UNIVERSITEIT BRUSSEL

Outline

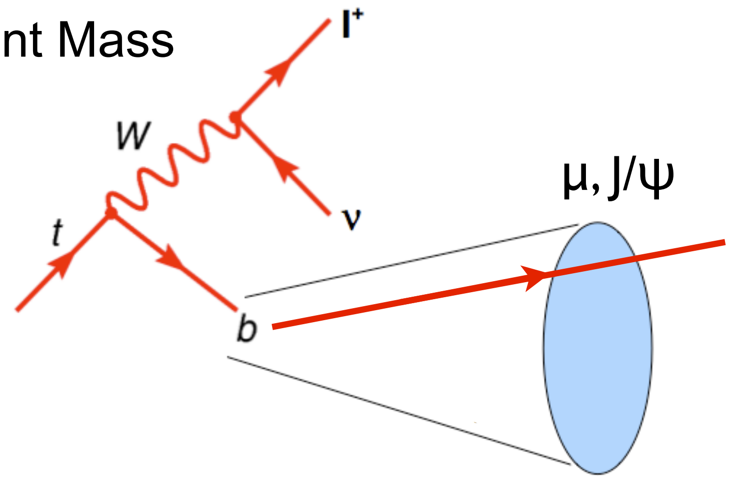
- The top quark and its mass
- The ATLAS Programme

Direct

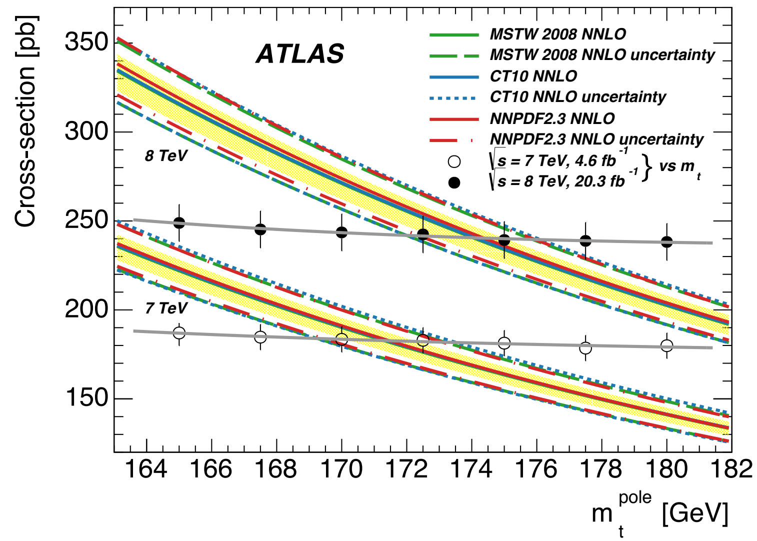
Full Invariant Mass



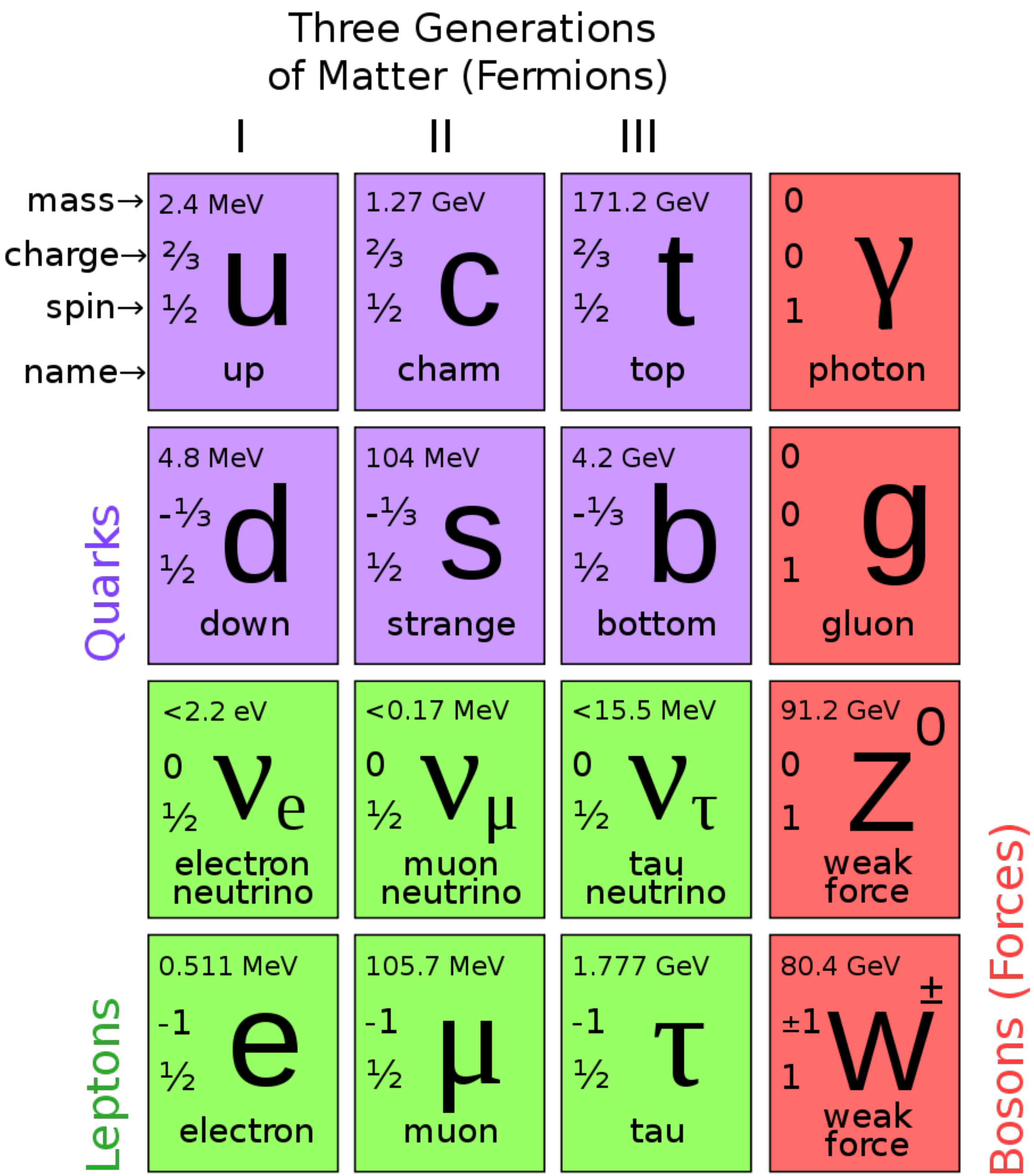
Partial Invariant Mass



Indirect



Brief introduction to top quarks



Top Quark:

- Particle type: weak isospin partner of the bottom quark
- Spin: +1/2
- Mass: approximately 173 GeV/c^2
- Width: ~1.5 GeV/c^2 or ~10^{-24} s
- Couplings: Strong (color triplet), EM (Q=+2e/3), Weak ($I_{3,L}$=+1/2)
- Decay: almost exclusively to W+b

Top quark discovery: 1995

The search for top lasted almost two decades. Its heavy mass delayed discovery. The reason(s) for such mass remains… a mystery.

VOLUME 74, NUMBER 14 PHYSICAL RE

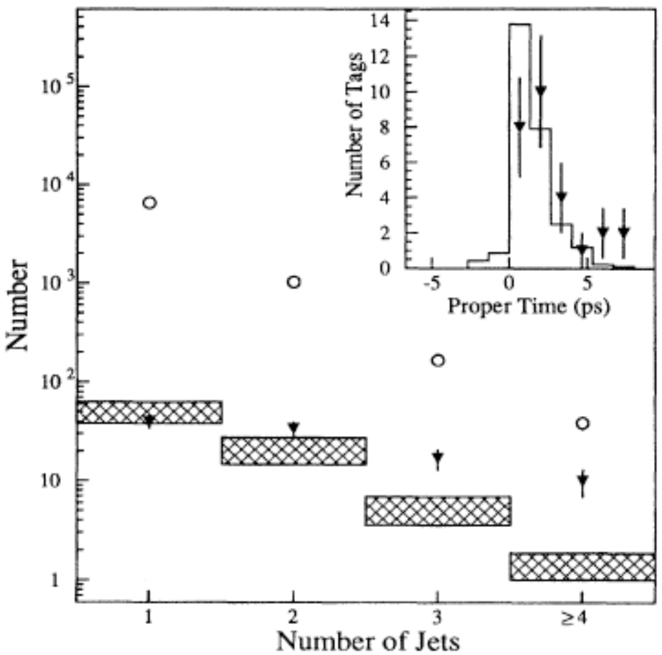


FIG. 1. Number of events before SVX tagging (circles), number of tags observed (triangles), and expected number of background tags (hatched) versus jet multiplicity. Based on the excess number of tags in events with ≥3 jets, we expect an additional 0.5 and 5 tags from $t\bar{t}$ decay in the 1- and 2-jet bins, respectively. The inset shows the secondary vertex proper time distribution for the 27 tagged jets in the $W+\geq 3$-jet data (triangles) compared to the expectation for b quark jets from $t\bar{t}$ decay.

<u>April 1994</u>: "Evidence for top production at the Tevatron" <u>CDF</u>

PRD 50, 2966 (1994).... lum = 19 pb^{-1}

150 pages ..... 2.8 σ excess

Mtop = 174 (16) GeV & σ(tt) = 14 (6) pb

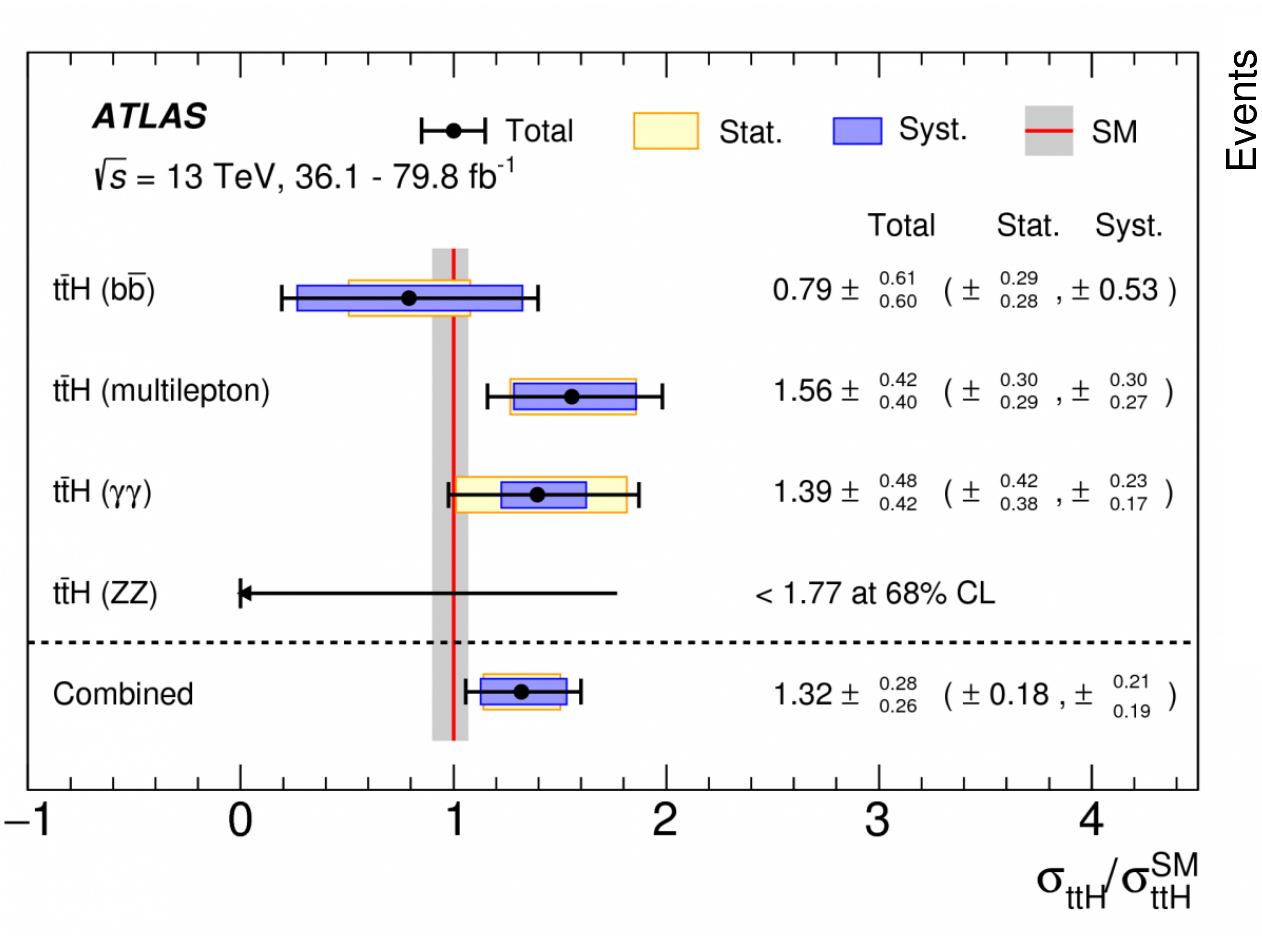
<u>March 1995</u>: CDF and D0 announce simultaneously the discovery of the Top Quark

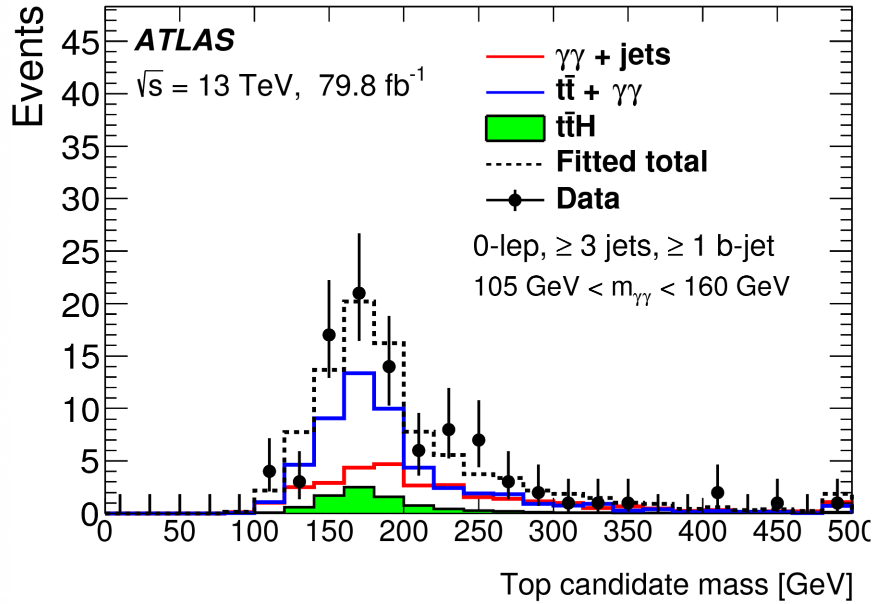
CDF: PRL 74, 2626 (1995) .... 67 pb^{-1}

D0: PRL 74, 2632 (1995).... 50 pb^{-1}

Experimental top physics begins

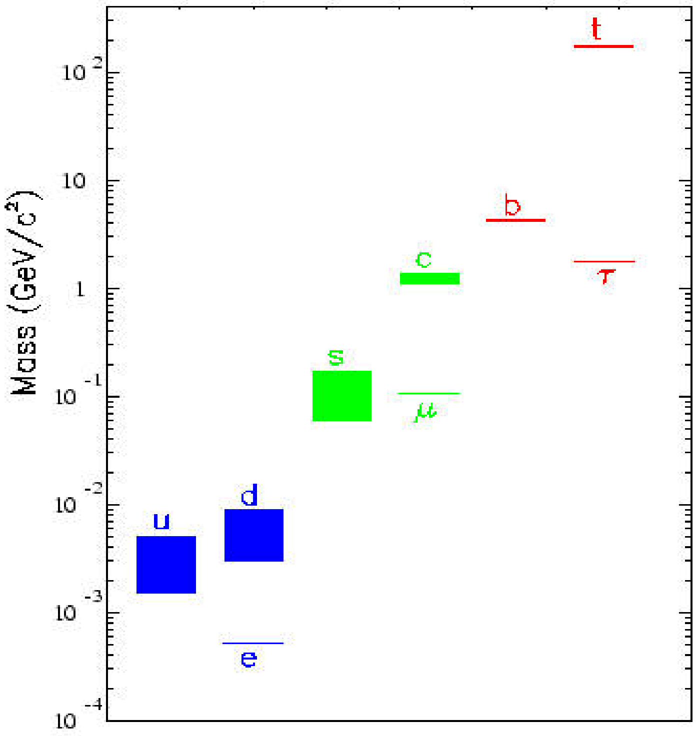
Origin of the top quark mass



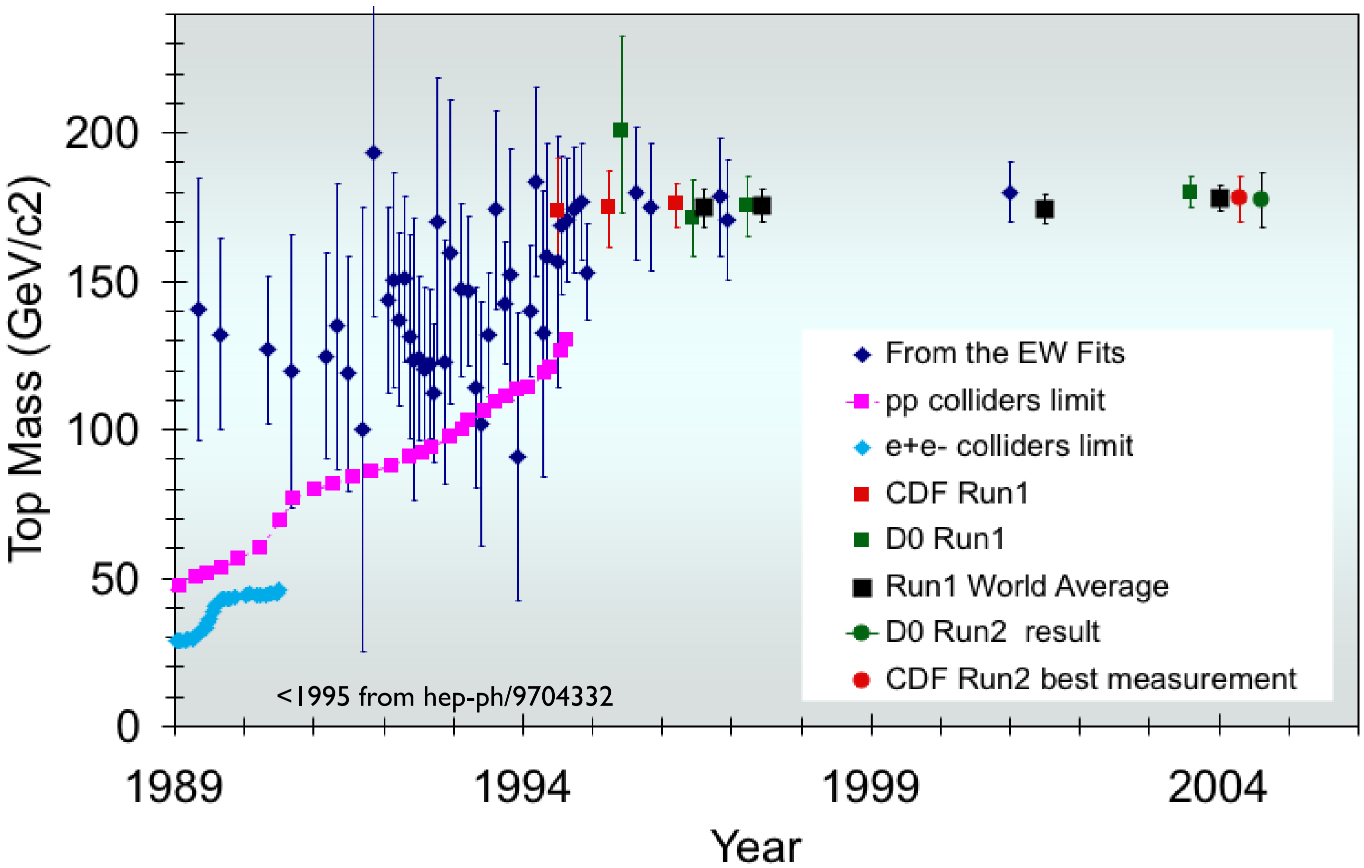


ATLAS Collaboration, arXiv:1806.00425

Top in the standard model: mass



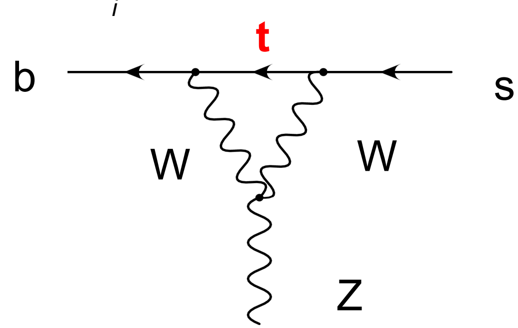
The mass spectrum of elementary particles



-The SM needs 3 generations (→ CP violation)

$$trQ = \sum_i Q = -1 + \left(\tfrac{2}{3} - \tfrac{1}{3}\right) \cdot 3 = 0$$

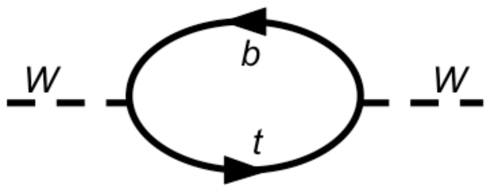
-Only *b*-quark not enough (renormalisation of SM)



-m_{top} is a free parameter… but experimental evidence suggested a large-ish top mass before its discovery because of e.g. FCNC in K and B

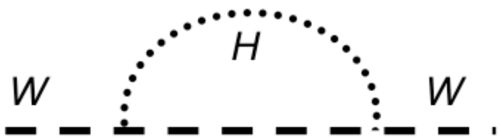
Top in the standard model: mass

Radiative corrections to the W mass calculation:



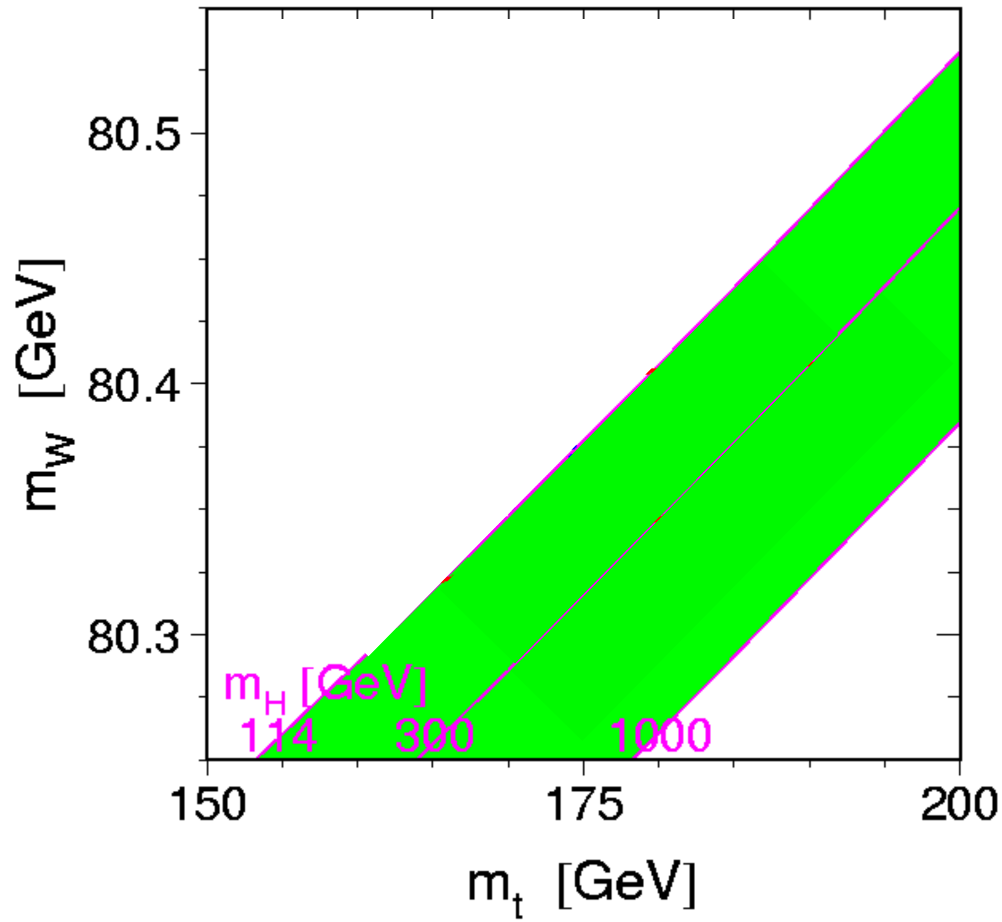
Quadratic in the top mass:

$$\Delta M_W \propto M_t^2$$



Logarithmic in the Higgs mass:

$$\Delta M_W \propto \ln(M_H)$$

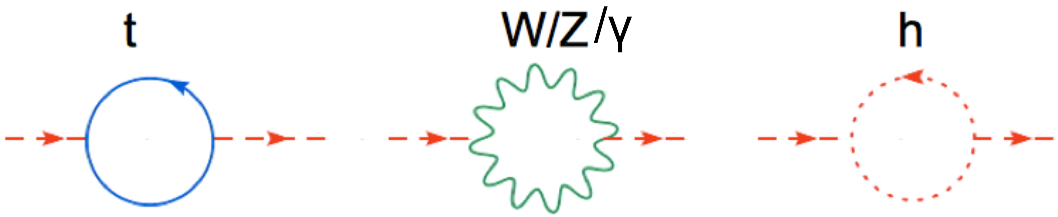


The top mass enters many EW parameters, with sizeable corrections.

The Higgs "Naturalness" Problem

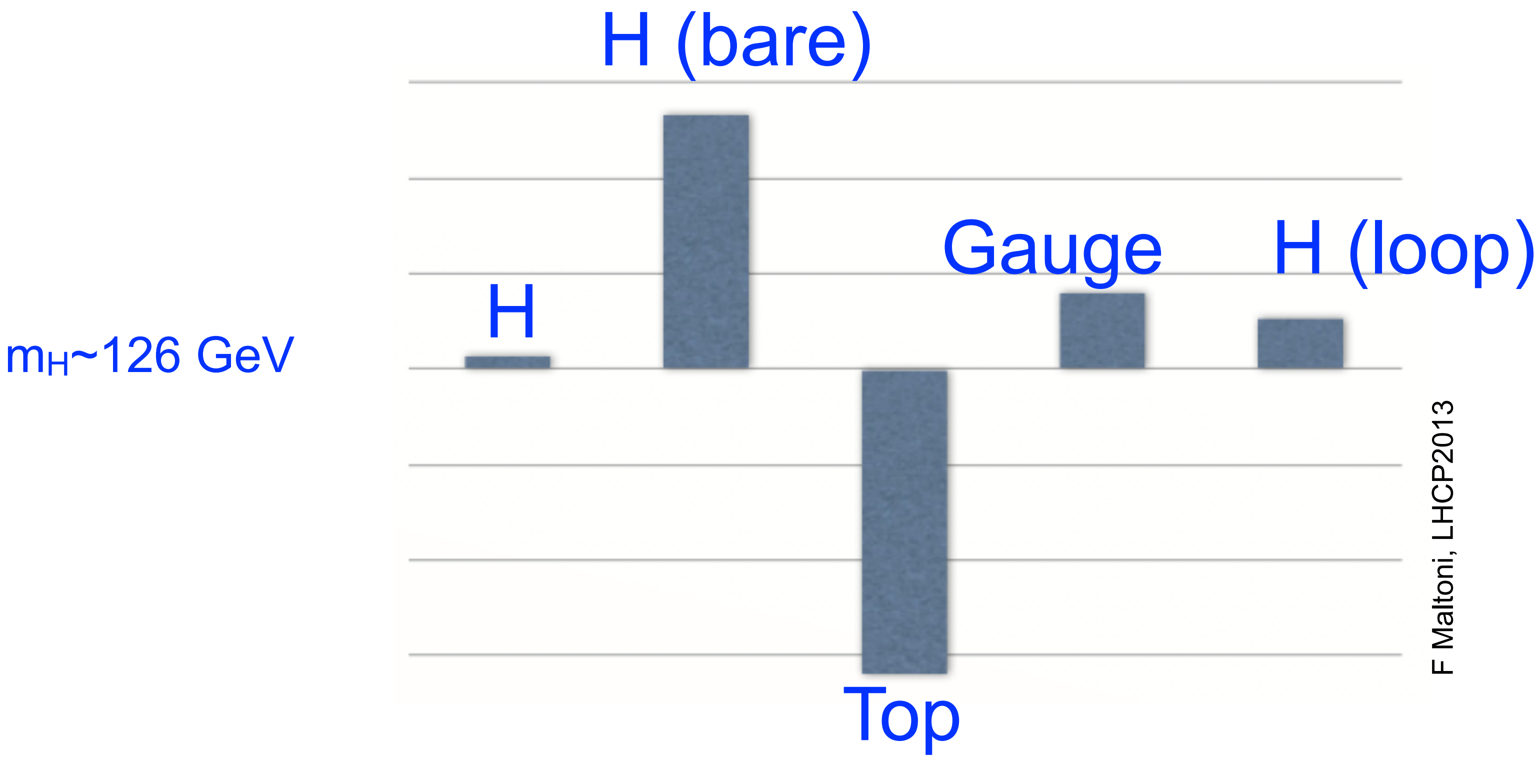
Radiative corrections to the Higgs boson mass diverge with the SM cut-off energy (Λ)

$\delta m_H^2 =$



$\propto \Lambda^2$

$\Lambda \simeq 10^{19}$ GeV ?



The large top quark mass (173 GeV/c^2) gives "un-naturally" large corrections.

Top in the standard model: lifetime

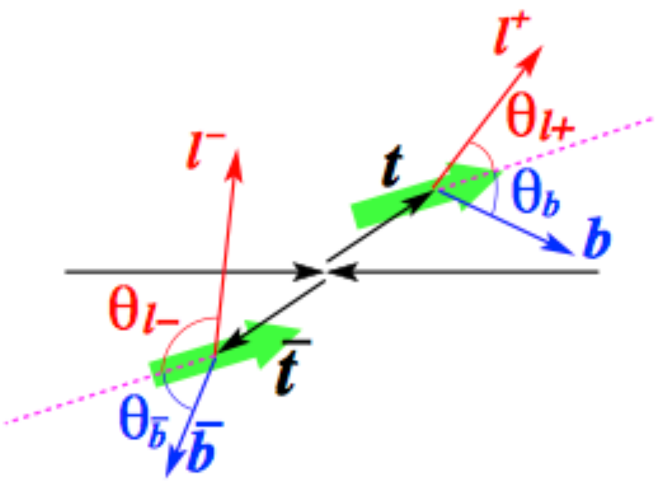
The large width of the top quark implies a very short decay time:

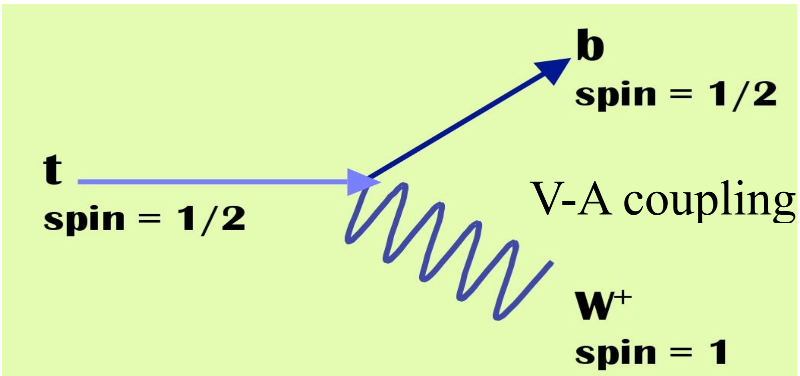
$\Gamma_t \approx 1.5\ \mathrm{GeV}$ corresponding to $\tau \approx 5 \cdot 10^{-25}\ \mathrm{s}$

This is one order of magnitude larger than the hadronisation scale:

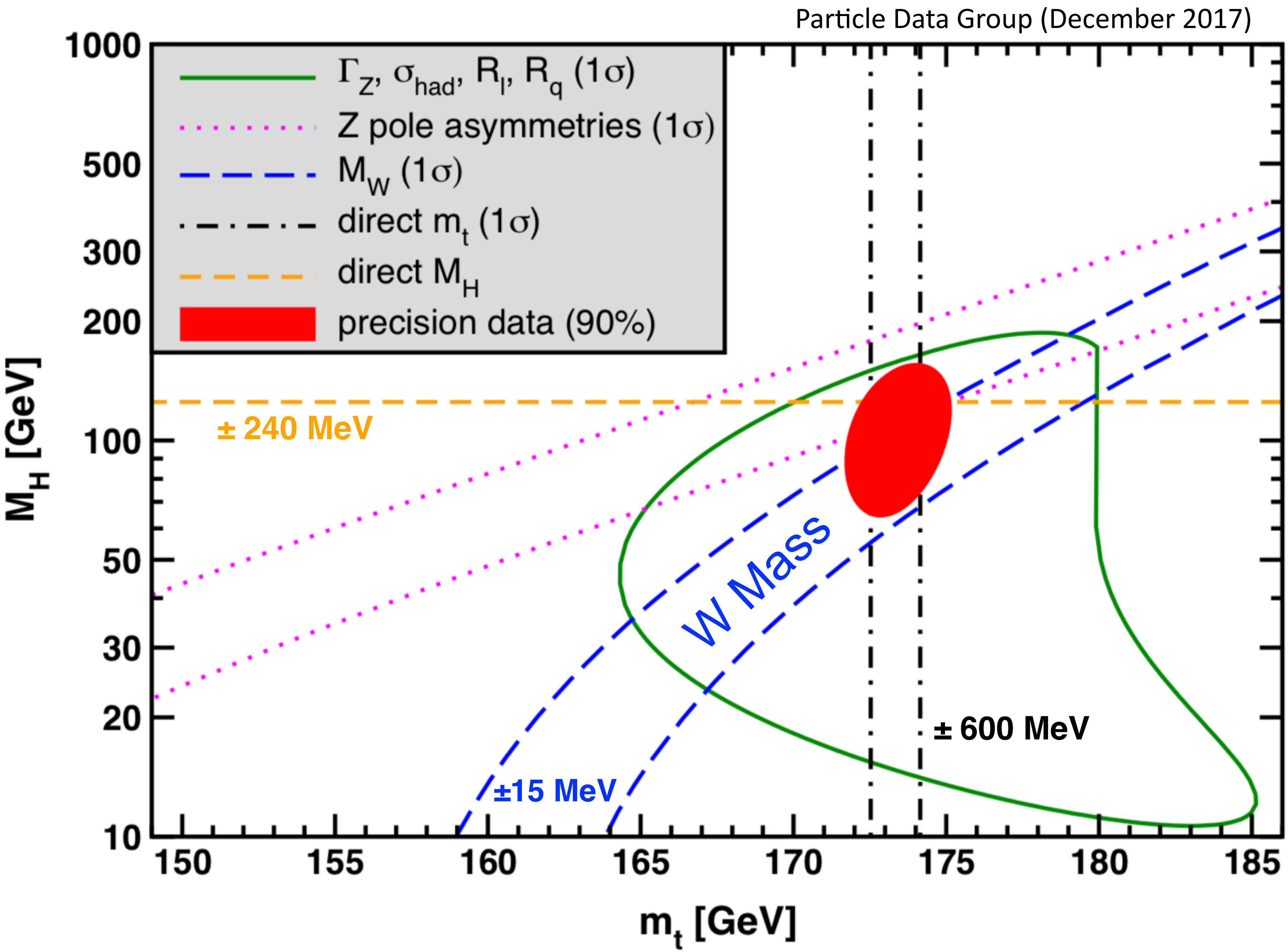
$\Lambda \approx 0.2\ \mathrm{GeV}$ or $\tau \approx 10^{-24}\ \mathrm{s}$

top is the only quark which is created and decays as a free quark

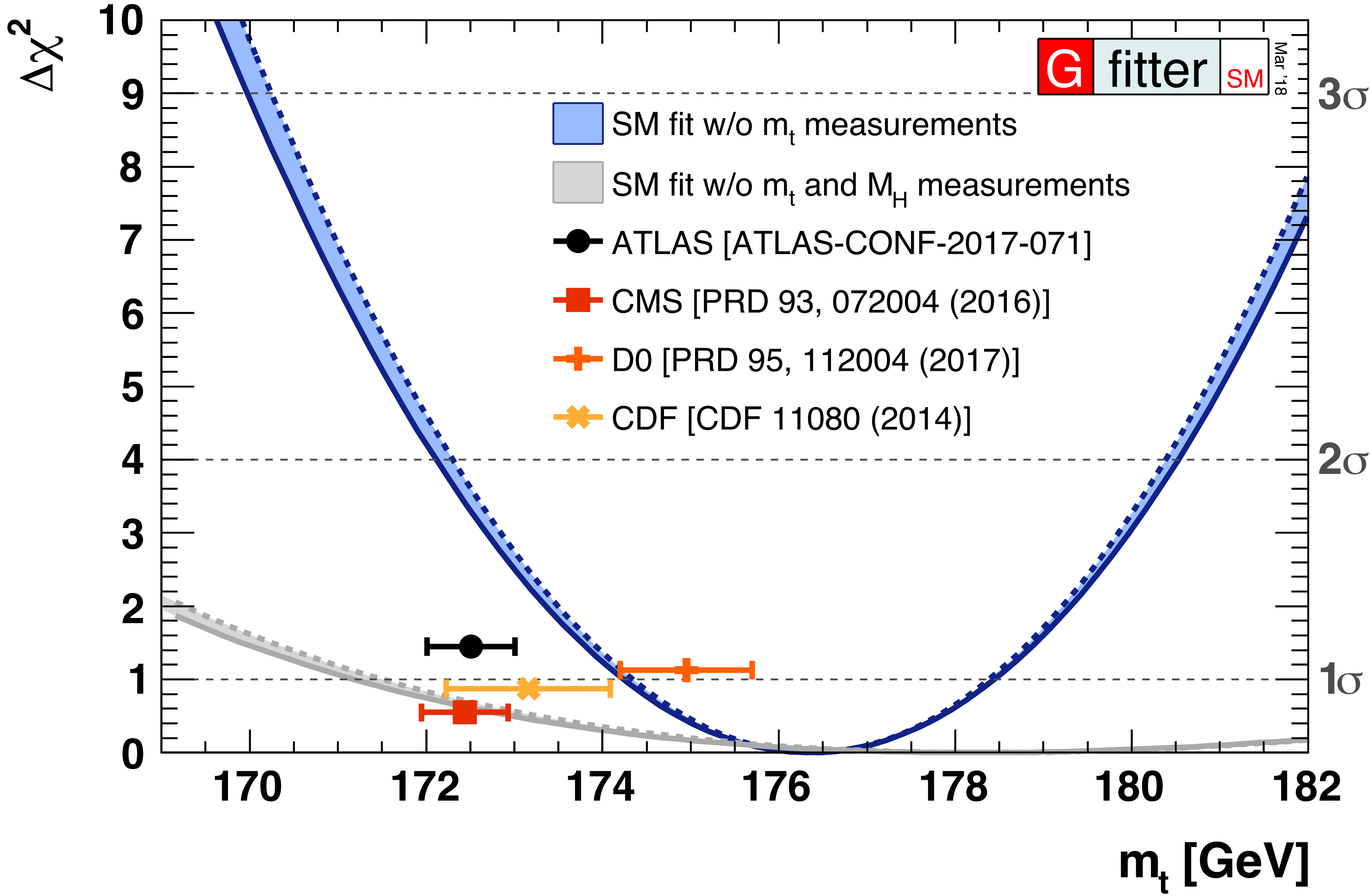




The role of m_{top} in the SM



The role of m_{top} in the SM



GFItter, arXiv:1803.01853 [hep-ph] (Mar 2018)

Top Mass and SM Vacuum Stability

=3

$$V_{RG}(\phi) \simeq -\frac{1}{2}m^2(\Lambda)\phi^2(\Lambda) + \frac{1}{4}\lambda^4(\Lambda)\phi^4(\Lambda), \qquad \phi \sim \Lambda >> v$$

Quartic may turn negative in UV—> Vacuum Instability

Test m_t with 250 MeV precision

Degrassi et al, arXiv:1205.6497 [hep-ph] (2012)
Andreassen, Frost, Schwartz, 2017

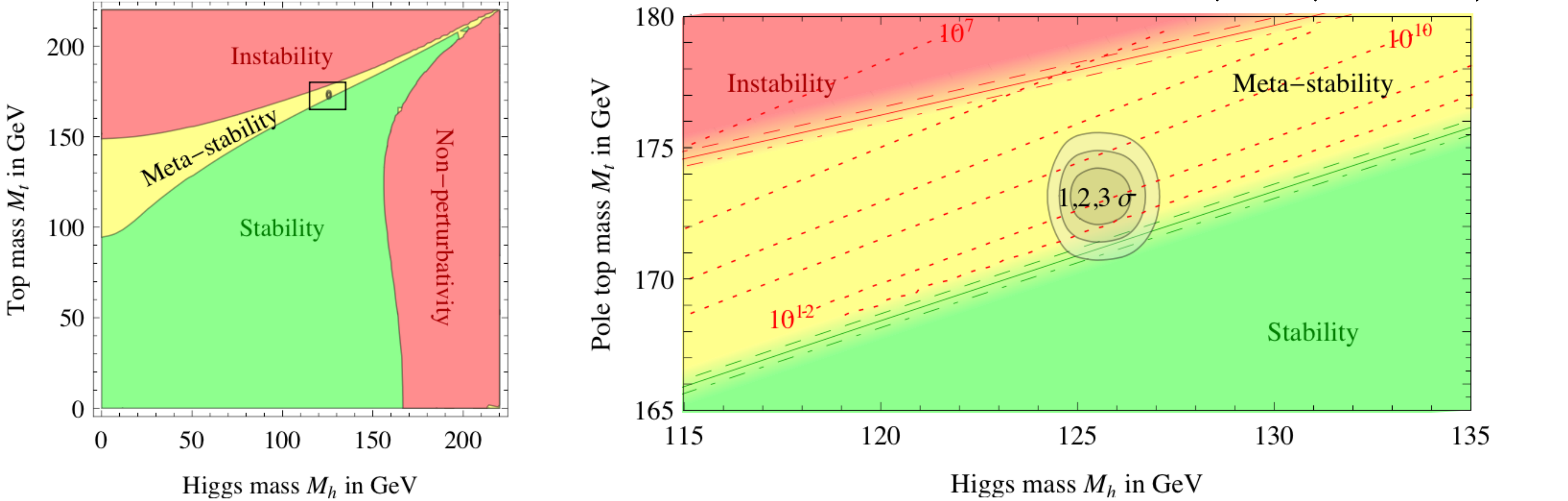


Figure 5: *Regions of absolute stability, meta-stability and instability of the SM vacuum in the* M_t–M_h *plane (upper left) and in the* λ–y_t *plane, in terms of parameter renormalized at the Planck scale (upper right).* **Bottom**: *Zoom in the region of the preferred experimental range of* M_h *and* M_t *(the gray areas denote the allowed region at 1, 2, and 3σ). The three boundary lines correspond to* $\alpha_s(M_Z) = 0.1184 \pm 0.0007$*, and the grading of the colors indicates the size of the theoretical error. The dotted contour-lines show the instability scale* Λ *in* GeV *assuming* $\alpha_s(M_Z) = 0.1184$.

The Mass of the Top Quark ?

For an interesting read, check: P. Nason in arXiv:1712.02796v1 [hep-ph] (2017)

Mass-Energy of a particle

$m^2 = E^2 - p^2$

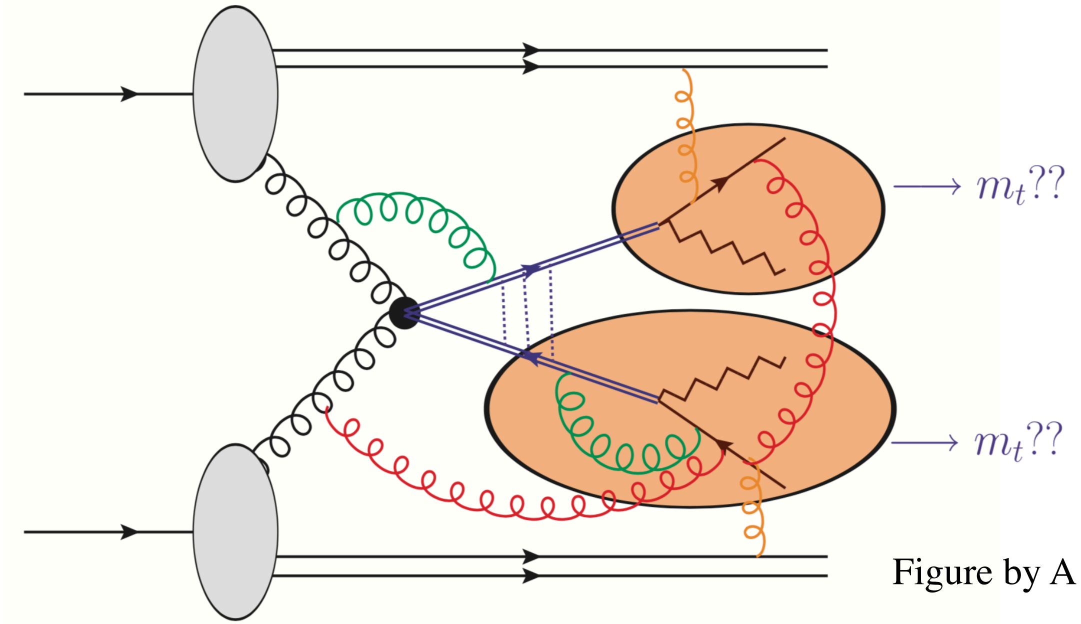
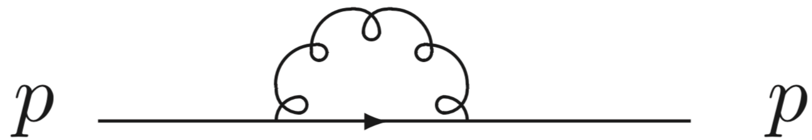


Figure by A. Signer

We would want the mass parameter in the SM Lagrangian → The top mass parameter in a theoretical calculation of the SM must be defined within a given renormalisation scheme

One such scheme is the Pole Mass scheme:

Need to subtract the UV divergences in the self energy



The Mass of the Top Quark ?

Divergent perturbative corrections arise order by order in perturbation theory. In the pole mass scheme the divergent mass corrections are subtracted in such a way that the pole in the quark propagator remains fixed, order by order in perturbation theory.

Pole mass = pole of the propagator

$$S^R_{\mathrm{o.s.}}(p) \sim \frac{i}{\not{p} - m_{\mathrm{pole}}}$$

On-shell renormalisation

In the $\overline{\mathrm{MS}}$ scheme the position of the pole in the top propagator receives corrections at all orders in perturbation theory.

$$m_p = m + \underbrace{7.557}_{\mathrm{NLO}} + \underbrace{1.617}_{\mathrm{NNLO}} + \underbrace{0.501}_{\mathrm{N^3LO}} + \underbrace{0.195 \pm 0.005}_{\mathrm{N^4LO}}\,\mathrm{GeV}.$$

P. Nason

Relation pole/$\overline{\mathrm{MS}}$ mass at 4 loops: (Marquard et al, PRL'15) $\Delta m_{\mathrm{pole,MS}} \simeq$ 195 MeV

HOWEVER: Pole mass is a physical mass for free particles like electrons, but for heavy quarks it exhibits an ambiguity $O(\Lambda_{QCD})$ (Braun,Beneke'94)

MSR masses in terms of an infrared scale R

Difference between Pole mass and MSR mass ("renormalon" ambiguity) of order 110-250 MeV

(Beneke et al., Phys. Lett. B775 (2017) 63–70, [1605.03609]; Hoang et al JHEP 09 (2017) 099, [1706.08526])

Possible Strategies

There is **NO consensus** on how to interpret top mass at O(300 MeV).
See also: Corcella et al., 1712.05801, Butenschoen et al. PRL 117 232001

"Direct" measurement

Measurement from mass of the system of the decay products

Problem:

m_{top} cannot be defined in terms of the mass of the system of its decay products

Since top is a coloured object, no final-state hadronic system can unambiguously be associated with it

"Indirect" measurement

Measurement from a property which **depends** on top mass

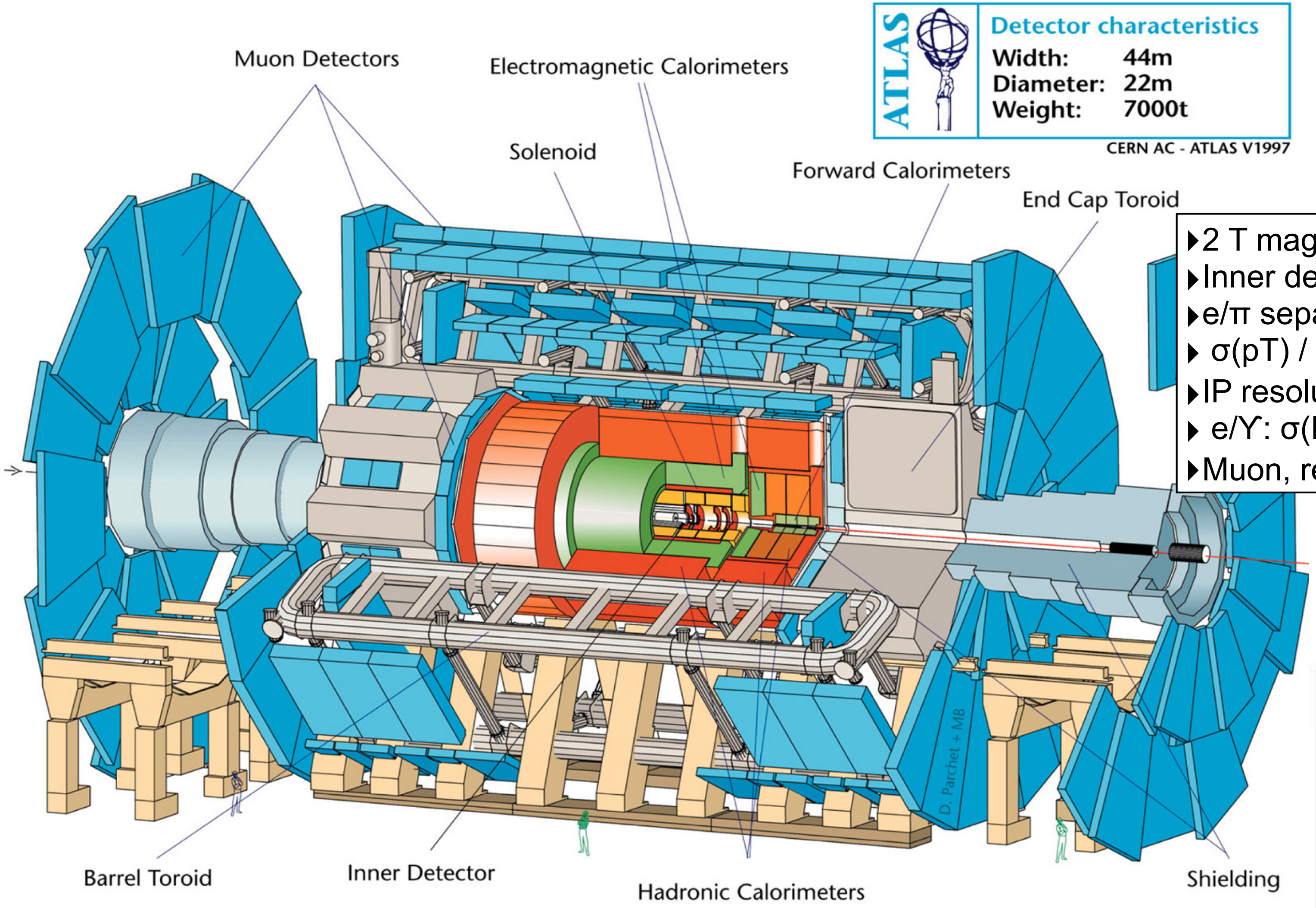
e.g.: production cross section + a theory that relates top mass and production rate

Problem:

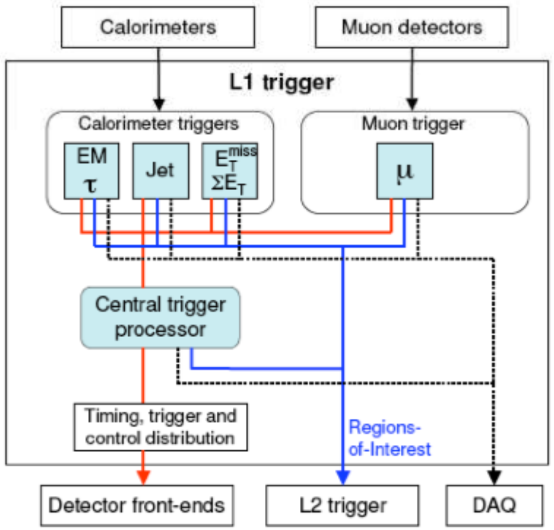
"Fixed order calculations of kinematical distributions involving top quarks are also subject to soft radiation and non-perturbative effects, and thus cannot be considered as privileged pole mass determinations, to be presented in isolation from those obtained with direct measurements. If the former can be considered pole mass determinations, the same holds for the latter. Notice that this also holds for total cross section."

P. Nason

The ATLAS detector at the LHC

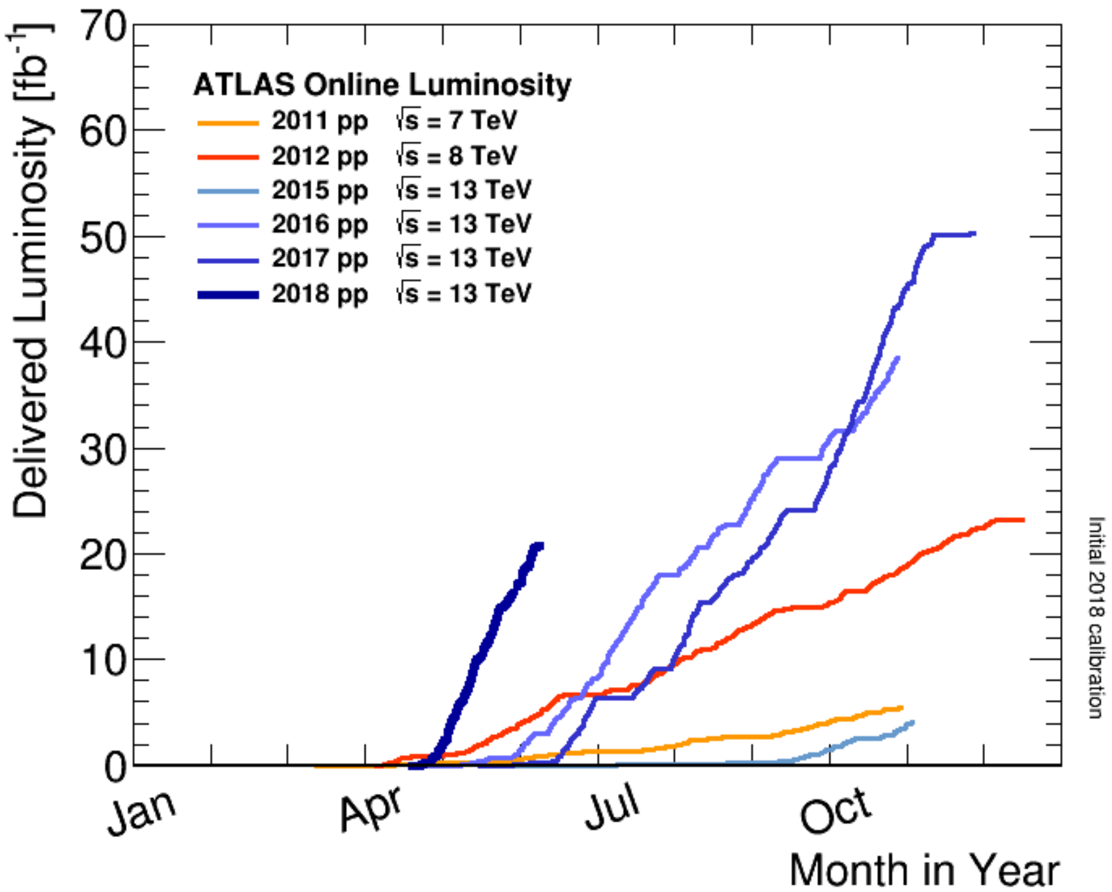


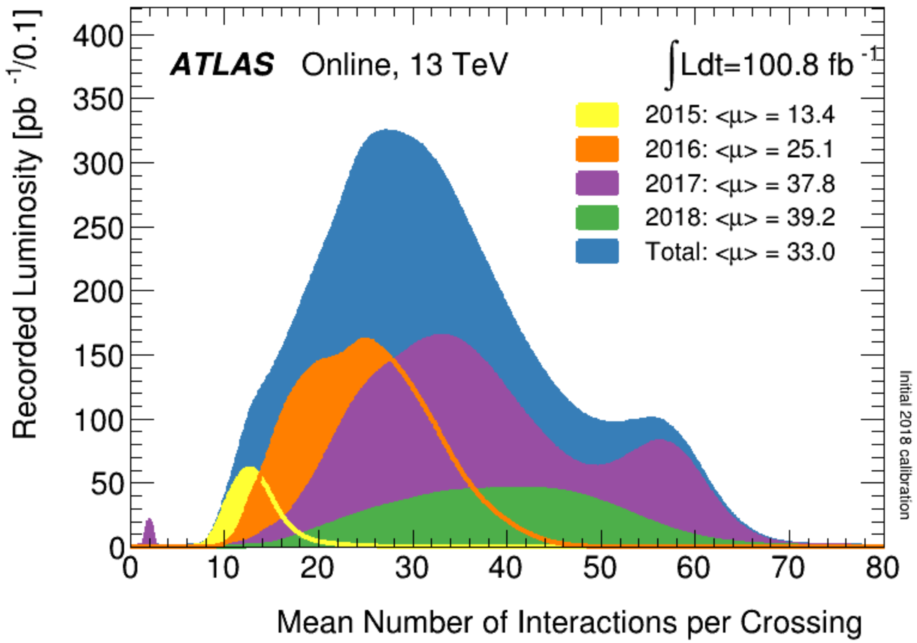
- 2 T magnetic field for ID
- Inner detectors $|\eta|<2.5$
- e/π separation
- $\sigma(pT) / pT = 0.038\%\ pT \oplus 1.5\%\ [GeV/c]^{-1}$
- IP resolution: ~22μm
- e/ϒ: $\sigma(E)/E = 10\% / \sqrt{E} \oplus 1\%$
- Muon, resolution <10% up to ~1 TeV

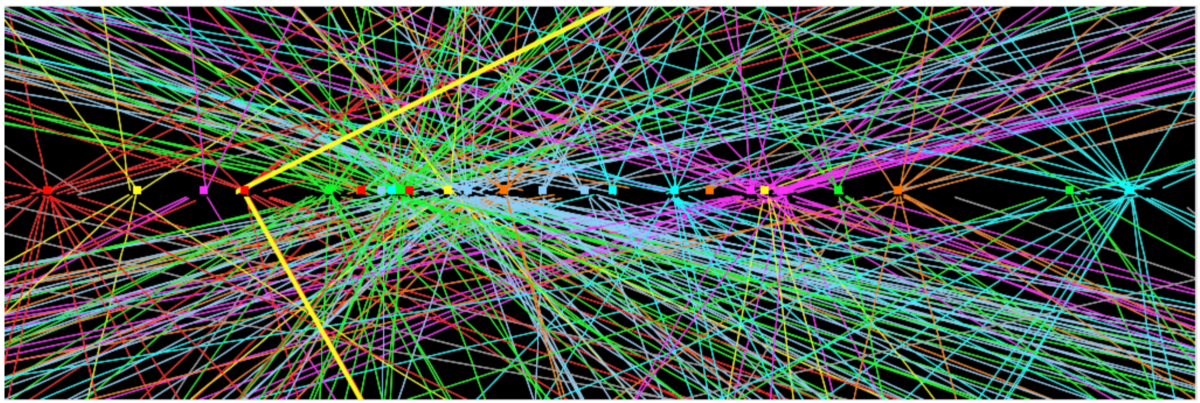


R Achenbach *et al* 2008 *JINST* **3** P03001

ATLAS Data taking

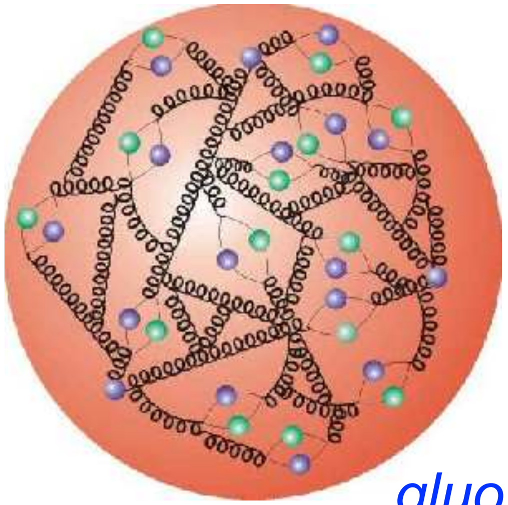




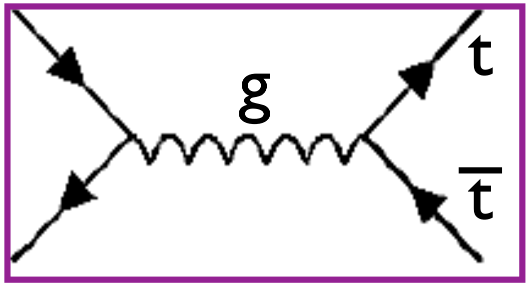


Z→μμ with 25 pileups)

Pair production in hadronic collisions

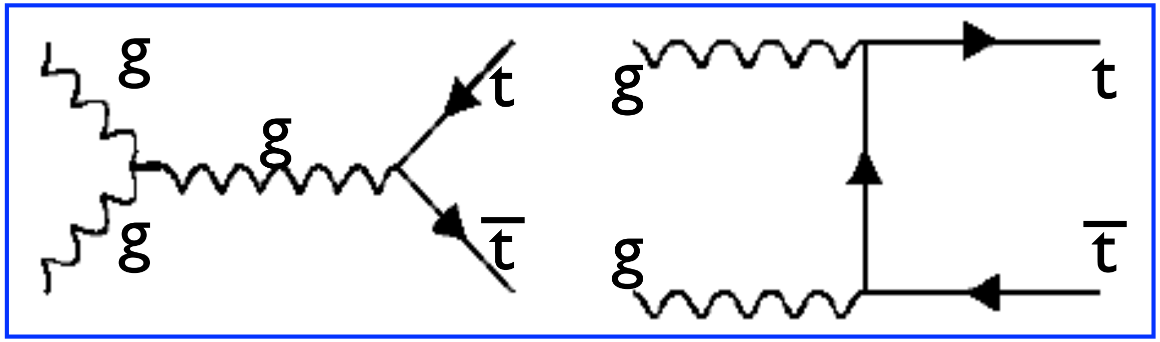


quark annihilation
(~85% at the Tevatron)



NOTE: Production through virtual Z and γ are much smaller

gluon fusion
(~90% at the LHC)



Expected production rates

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

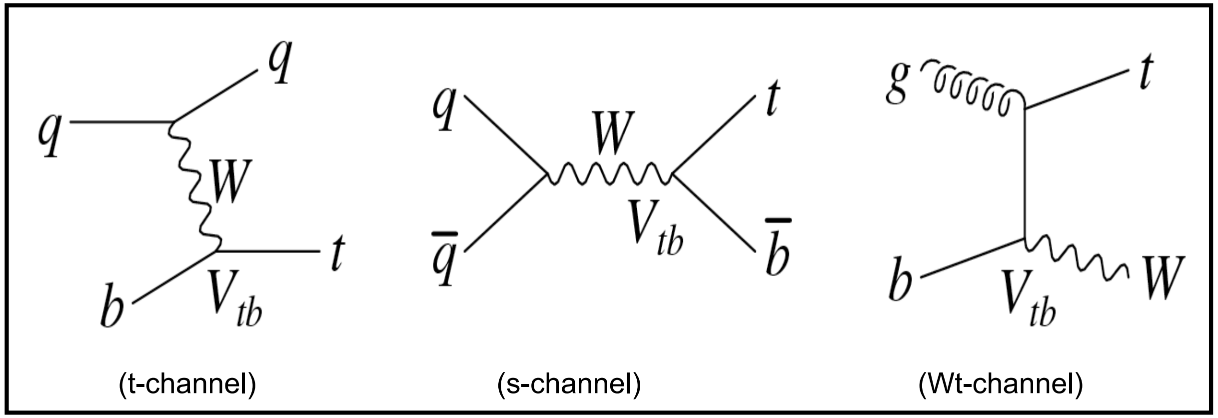
- ~70k/y *tt* @ Tevatron
- ~6M/y *tt* @ LHC8
- ~100M/y @ LHC14

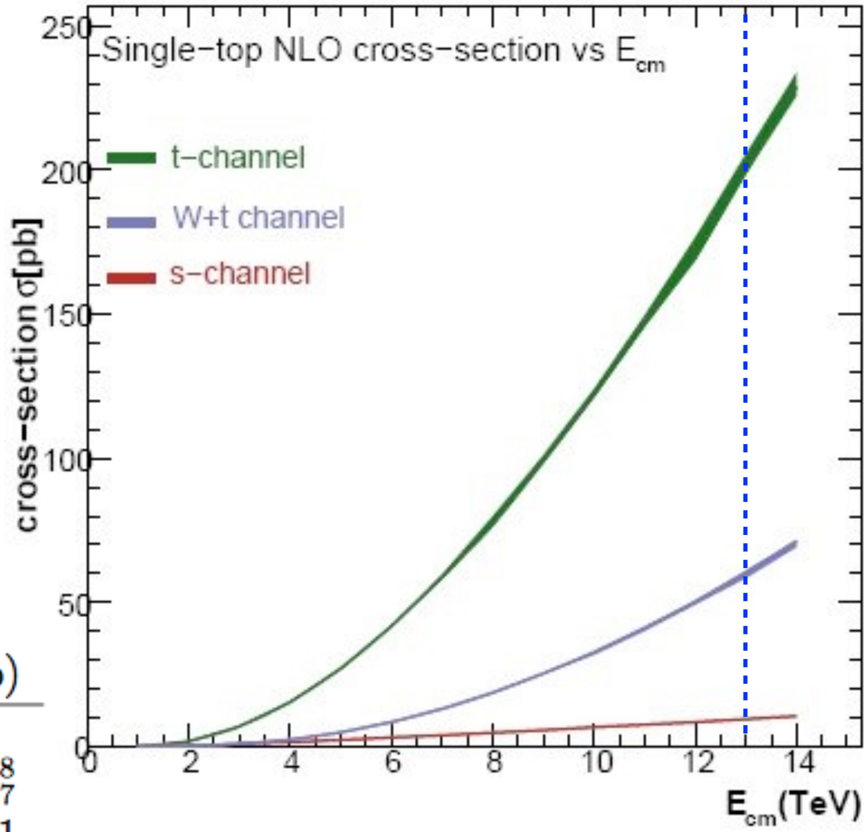
- theory precision: ~3–4%⊕3%(Δm_t)

Computed with: Top++ NNLO+NNLL, mt=173.3 GeV, arXiv:1303:6254 (2013)

Single production in hadronic collisions

Single (EWK production):





Expected production rates

LHC 7 TeV	$\sigma(t)$ (pb)	$\sigma(\bar{t})$ (pb)	$\sigma(t)+\sigma(\bar{t})$ (pb)
t-channel	$43.0^{+1.6}_{-0.2} \pm 0.8$	$22.9 \pm 0.5^{+0.7}_{-0.9}$	$65.9^{+2.1+1.5}_{-0.7-1.7}$
s-channel	$3.14 \pm 0.06^{+0.12}_{-0.10}$	$1.42 \pm 0.01^{+0.06}_{-0.07}$	$4.56 \pm 0.07^{+0.18}_{-0.17}$
tW	$7.8 \pm 0.2^{+0.5}_{-0.6}$	$7.8 \pm 0.2^{+0.5}_{-0.6}$	$15.6 \pm 0.4 \pm 1.1$

Kidonakis, arXiv:1210.7813 [hep-ph] (2012), m_t=173 GeV/c^2 (2)

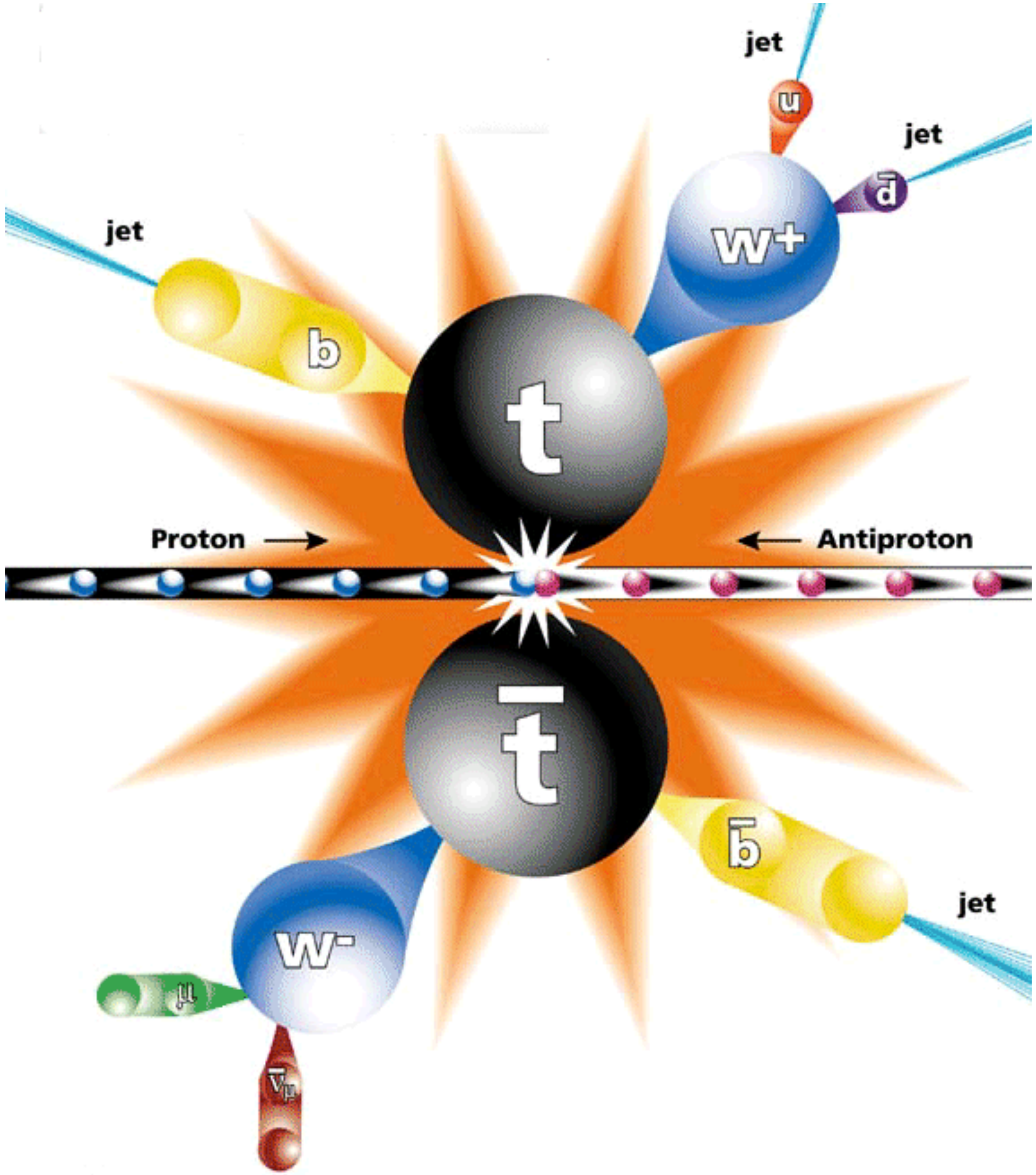
Tevatron	σ(pb)
s-ch	1.05 ± 0.05 [a]
t-ch	2.08 ± 0.08 [b]
Wt-ch	0.25 ± 0.03 [c]

Kidonakis, arXiv:1001.5034, 1103.2792, 1005,4451 [hep-ph], m_t=173 GeV/c^2

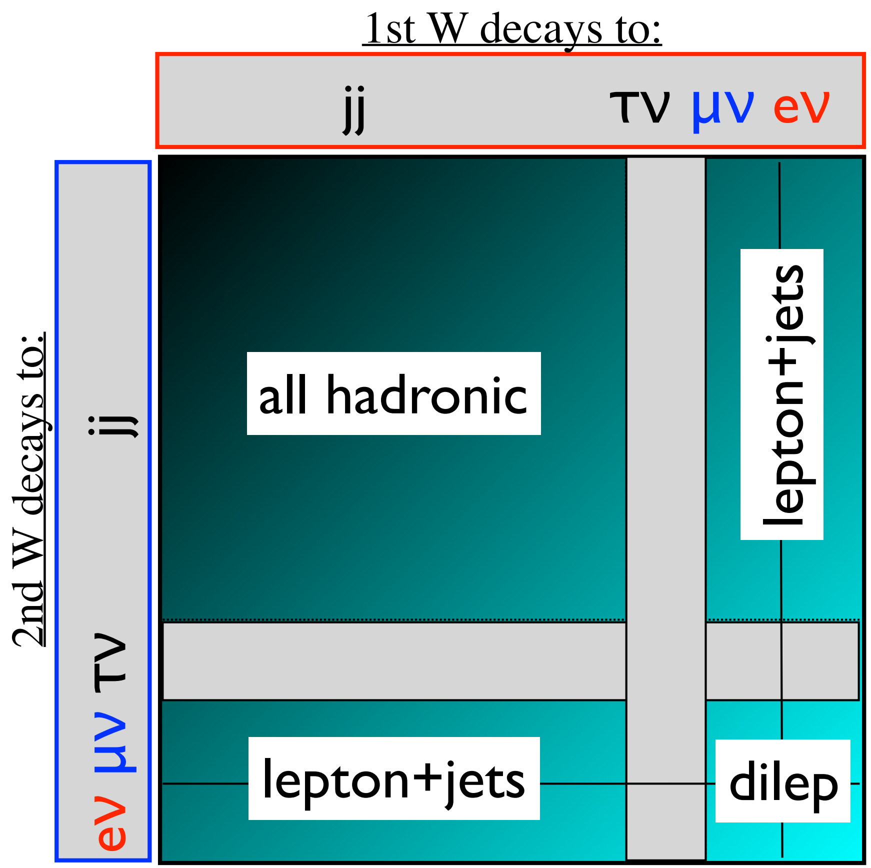
Rates ≲75% than pair production

Top decay and event classification

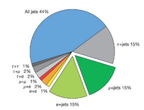
$|V_{tb}| \sim 1$, and $M_t > M_W + M_b \Rightarrow t \to Wb$ almost exclusively.



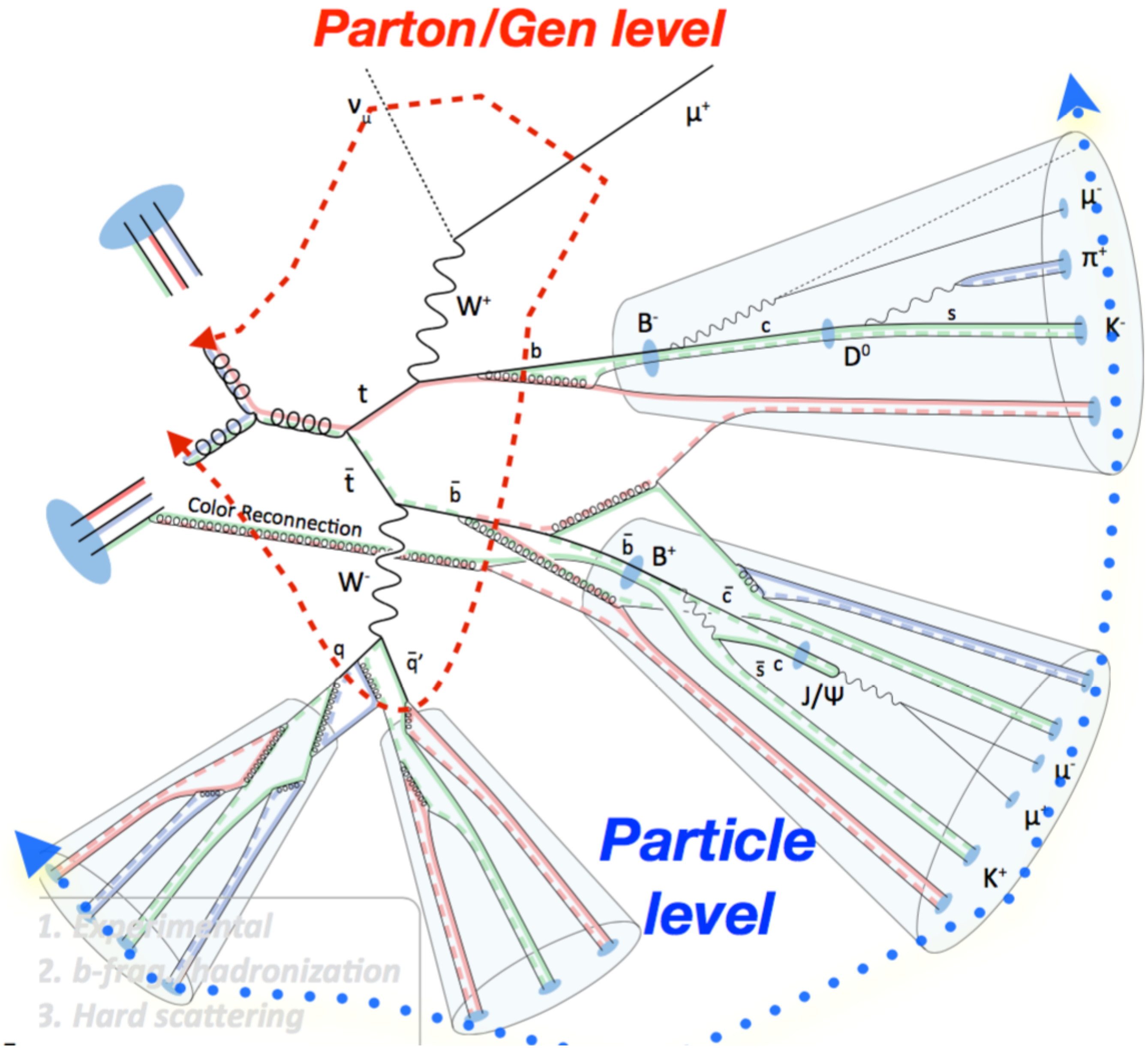
tt event classification:



Br(W→leptons) = 1/3
Br(W→quarks) = 2/3



Top decay and event classification



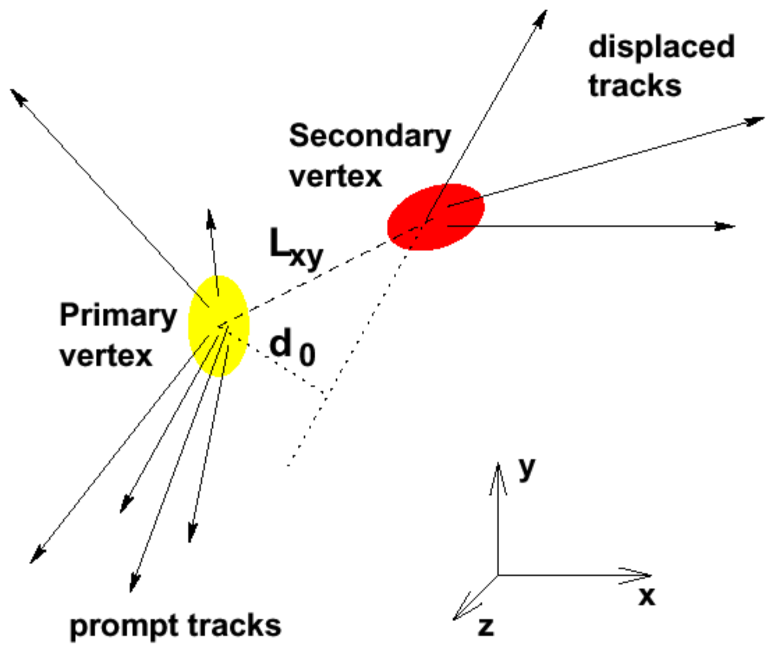
[Figure by B Stieger (CERN)]

b-quark identification

B hadrons in top events..

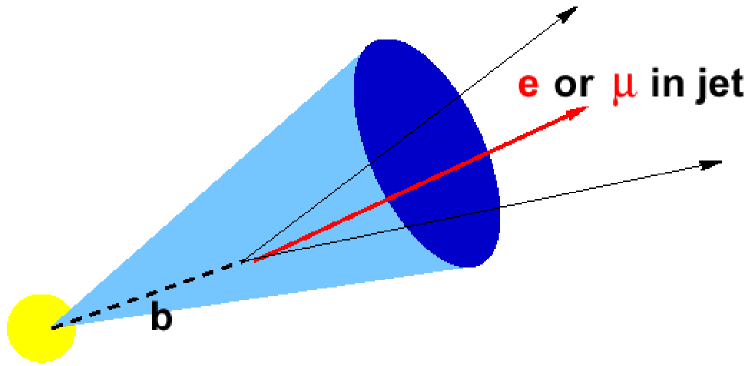
are long-lived and massive

Detect secondary vertices



may decay semileptonically

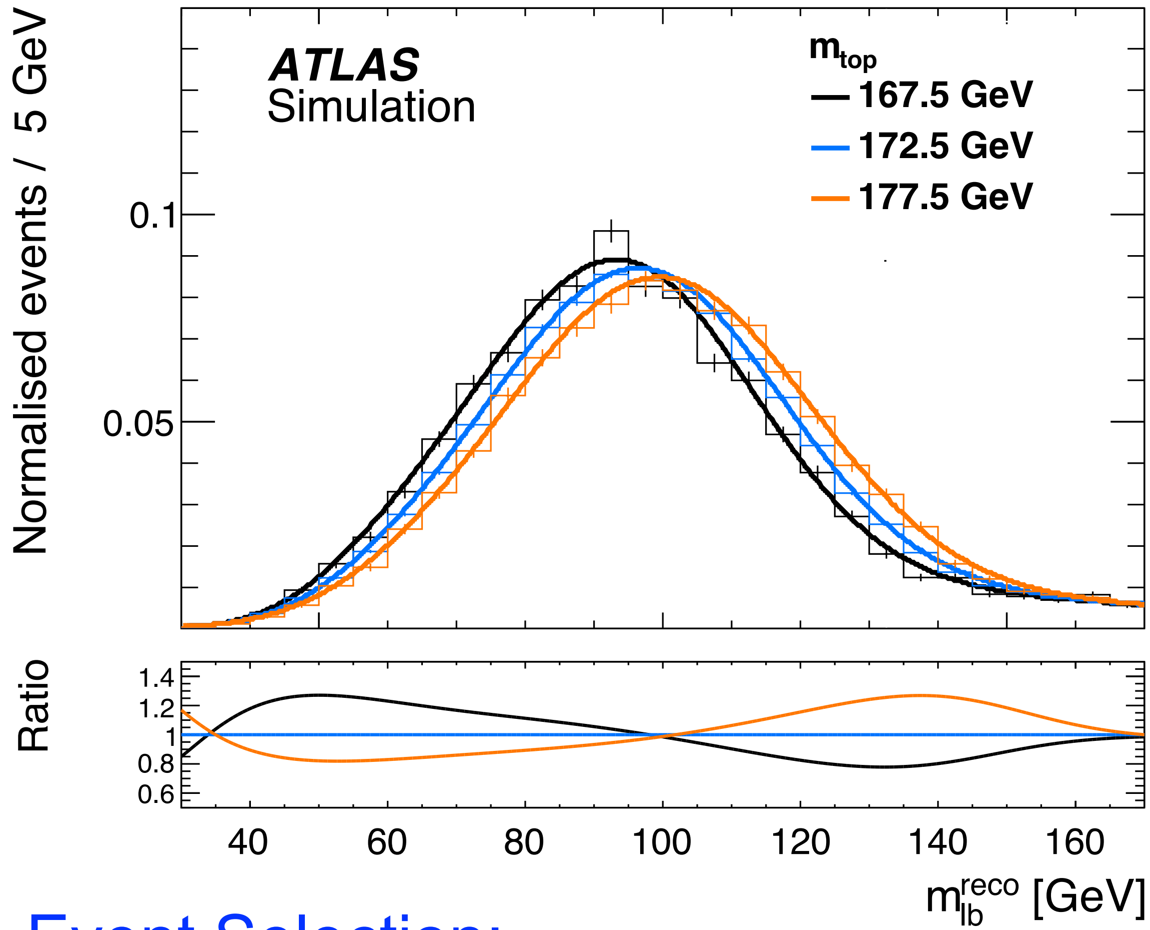
Identify muons in jets



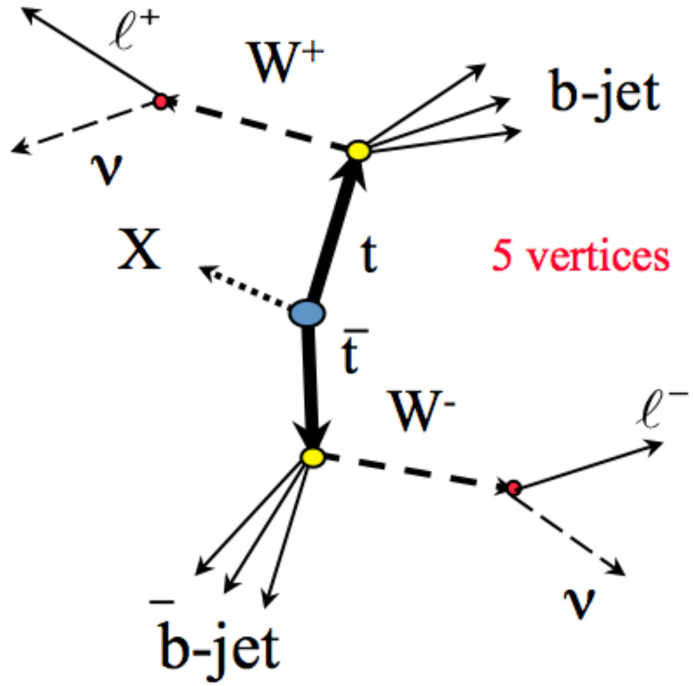
- $b \to \ell \nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell \nu s$ (BR $\sim$ 20%)

The “Direct” Measurements

Dilepton top mass at 8 TeV

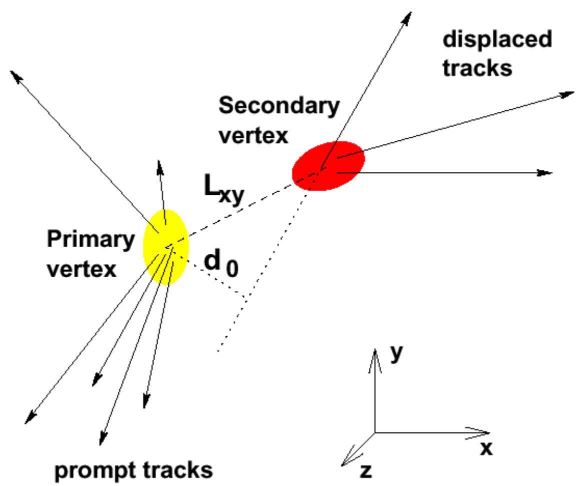


Physics Letters B 761 (2016) 350



Event Selection:

- Two oppositely charged central leptons
- Two *b*-tagged jets



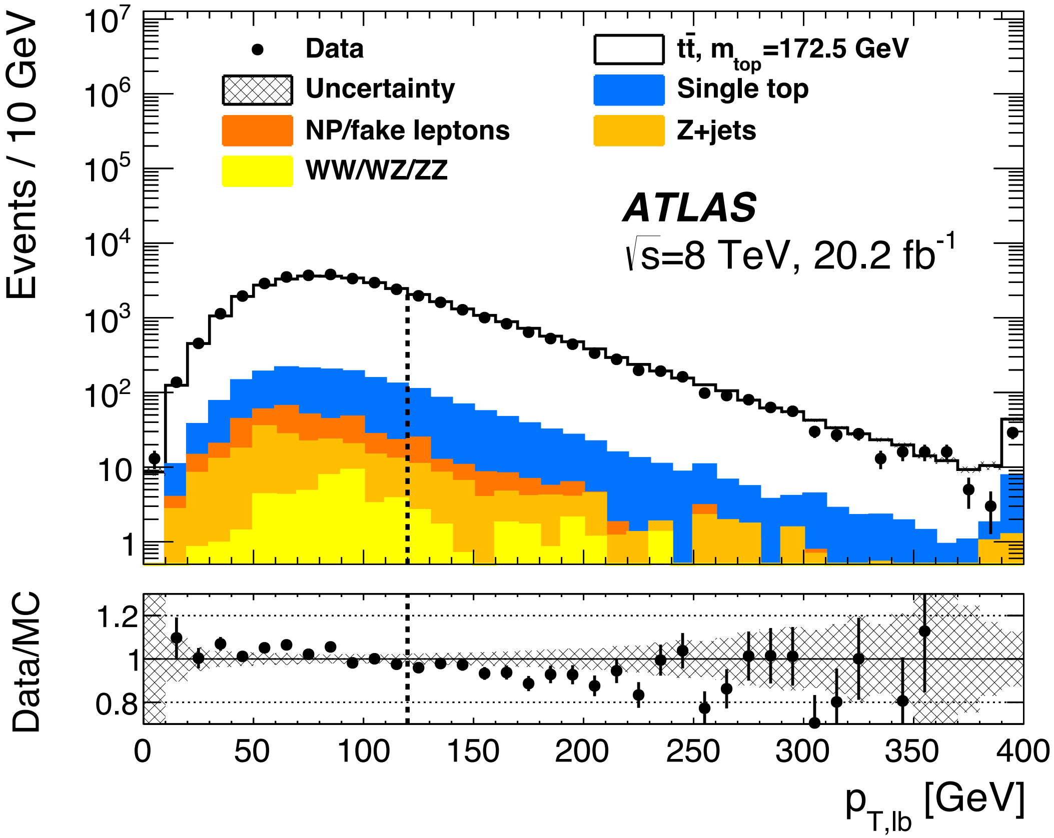
Observable:

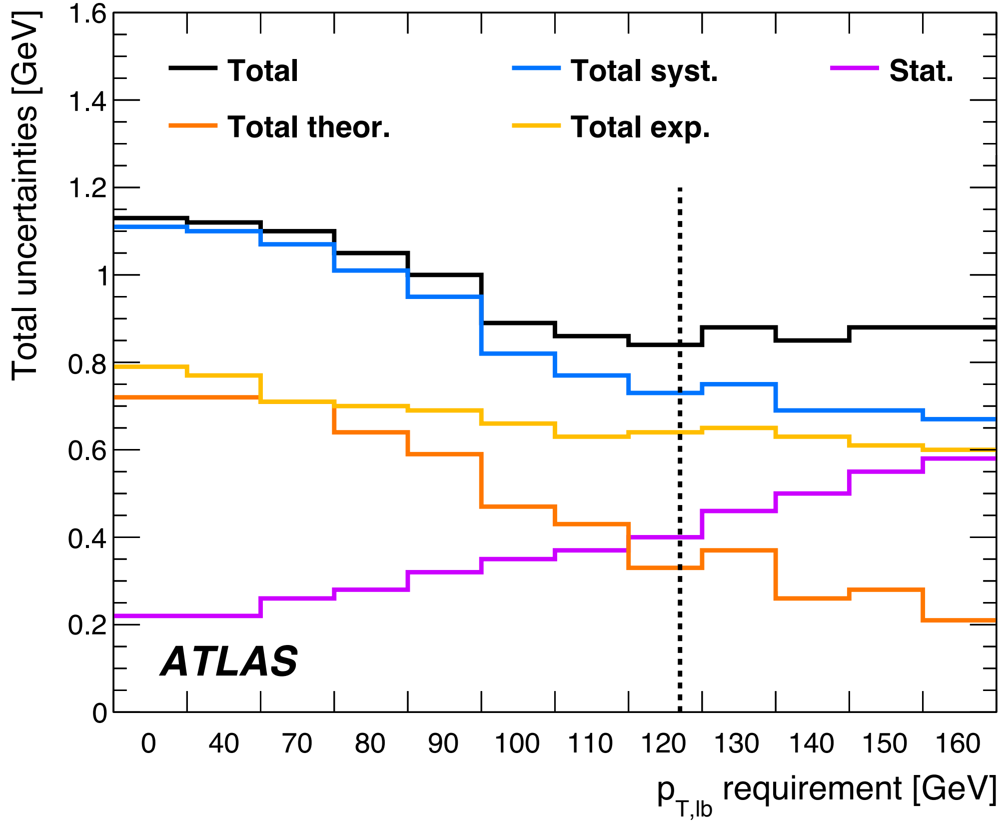
- Invariant mass of lepton and *b*-jet

Dilepton top mass at 8 TeV

Optimisation: Large <p_T> of the two lepton–*b*-jet pairs: → high Q^2 /more boosted tops

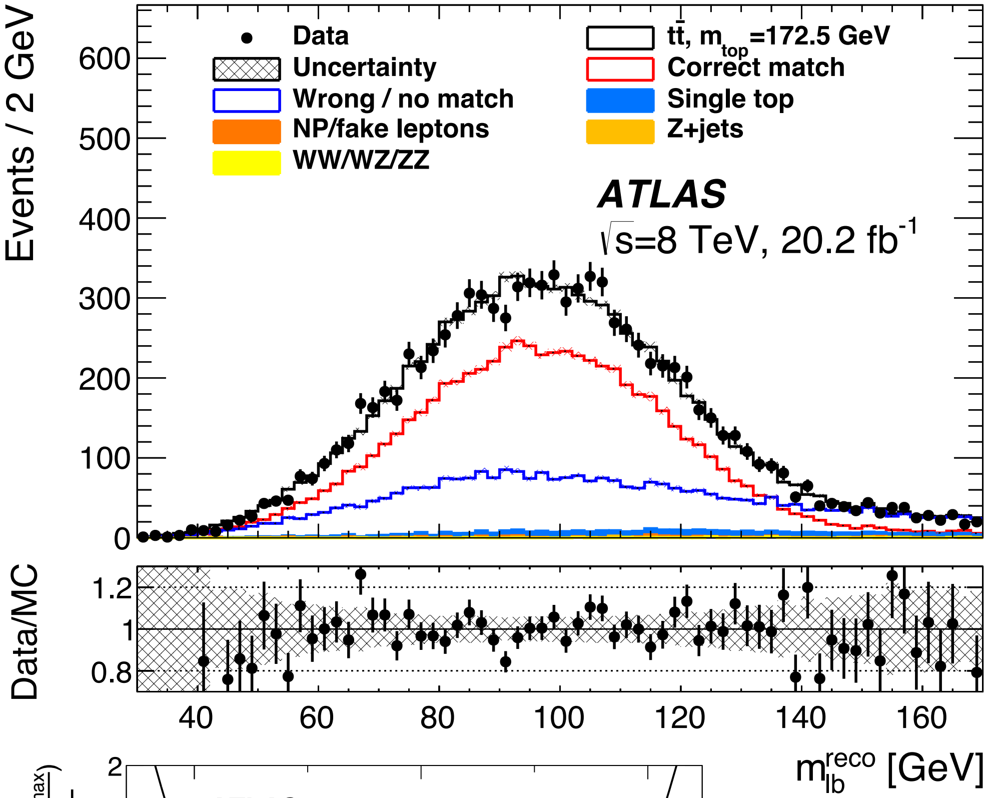
Why ?: (1) increases correctly matched events (2) Reduction in (*b*)JES (3) Significant reduction in I/FSR and hadronisation uncertainties

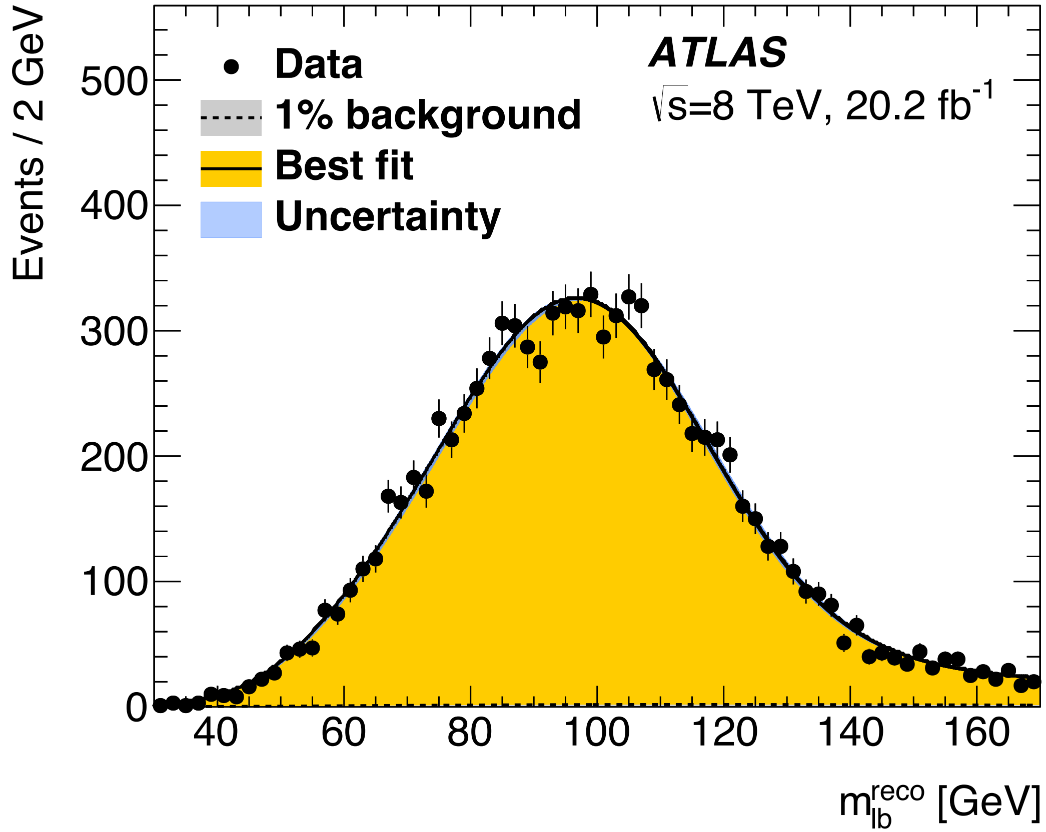


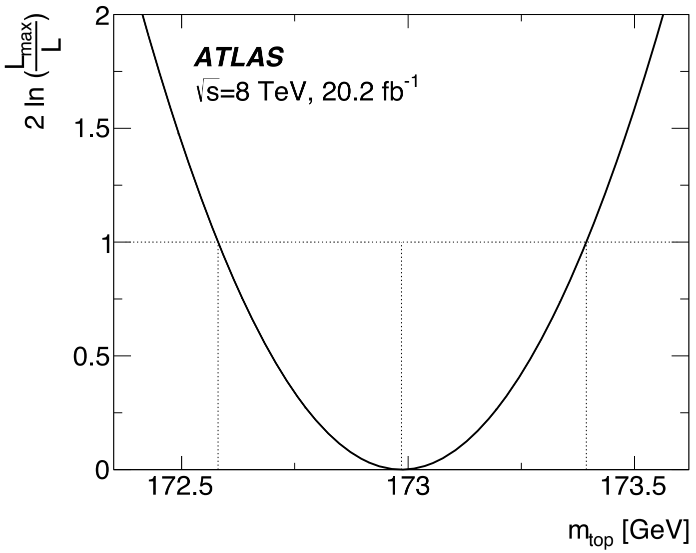


retains only 26% of events !

Dilepton top mass at 8 TeV







- Unbinned maximum likelihood fit to data

Dilepton top mass at 8 TeV

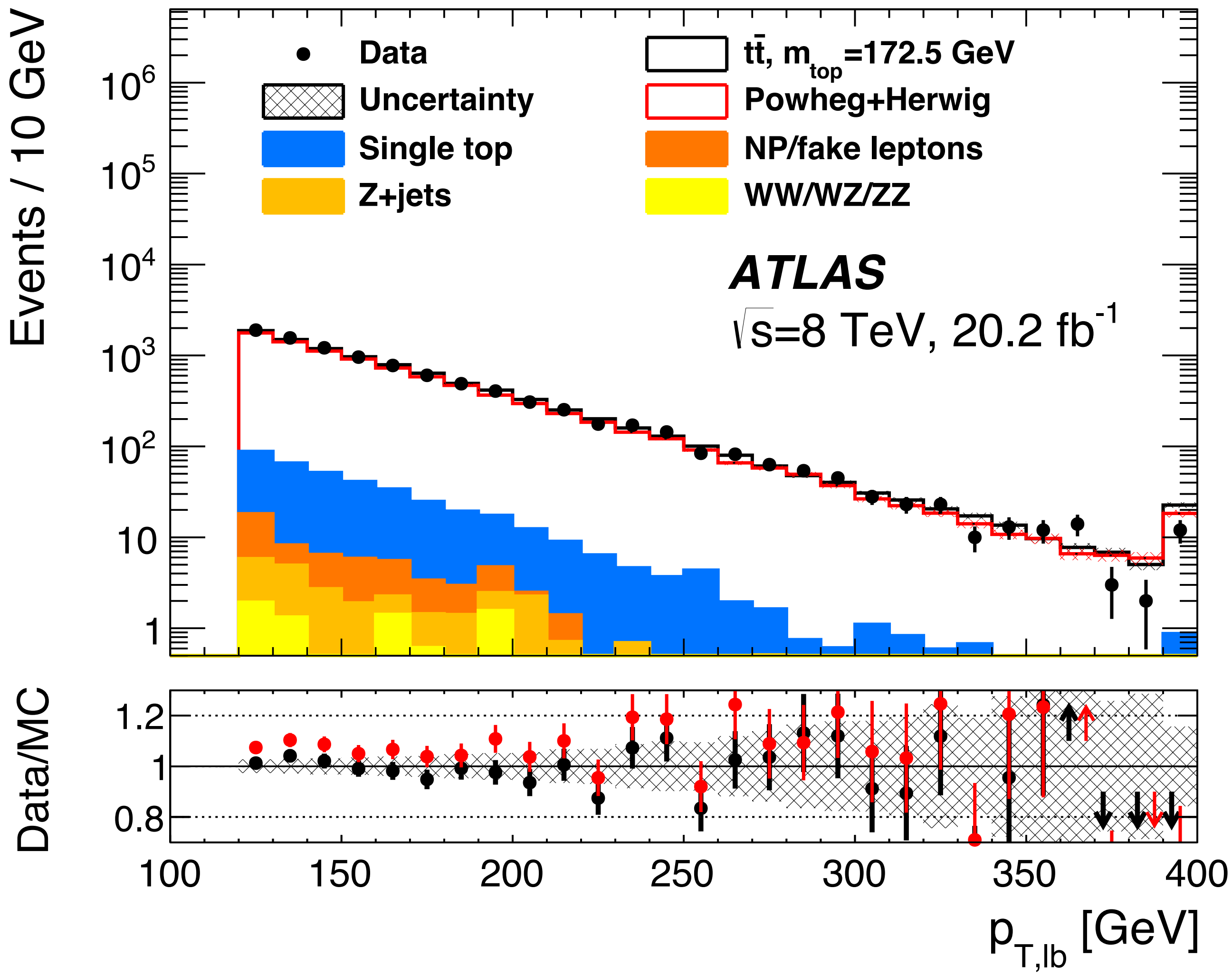
	$\sqrt{s} = 7$ TeV		$\sqrt{s} = 8$ TeV
	$m_{\rm top}^{\ell+\rm jets}$ [GeV]	$m_{\rm top}^{\rm dil}$ [GeV]	$m_{\rm top}^{\rm dil}$ [GeV]
Results	172.33	173.79	172.99
Statistics	0.75	0.54	0.41
Method	0.11 ± 0.10	0.09 ± 0.07	0.05 ± 0.07
Signal Monte Carlo generator	0.22 ± 0.21	0.26 ± 0.16	0.09 ± 0.15
Hadronisation	0.18 ± 0.12	0.53 ± 0.09	0.22 ± 0.09
Initial- and final-state QCD radiation	0.32 ± 0.06	0.47 ± 0.05	0.23 ± 0.07
Underlying event	0.15 ± 0.07	0.05 ± 0.05	0.10 ± 0.14
Colour reconnection	0.11 ± 0.07	0.14 ± 0.05	0.03 ± 0.14
Parton distribution function	0.25 ± 0.00	0.11 ± 0.00	0.05 ± 0.00
Background normalisation	0.10 ± 0.00	0.04 ± 0.00	0.03 ± 0.00
W/Z+jets shape	0.29 ± 0.00	0.00 ± 0.00	0
Fake leptons shape	0.05 ± 0.00	0.01 ± 0.00	0.08 ± 0.00
Jet energy scale	0.58 ± 0.11	0.75 ± 0.08	0.54 ± 0.04
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.68 ± 0.02	0.30 ± 0.01
Jet energy resolution	0.22 ± 0.11	0.19 ± 0.04	0.09 ± 0.05
Jet reconstruction efficiency	0.12 ± 0.00	0.07 ± 0.00	0.01 ± 0.00
Jet vertex fraction	0.01 ± 0.00	0.00 ± 0.00	0.02 ± 0.00
b-tagging	0.50 ± 0.00	0.07 ± 0.00	0.03 ± 0.02
Leptons	0.04 ± 0.00	0.13 ± 0.00	0.14 ± 0.01
$E_{\rm T}^{\rm miss}$	0.15 ± 0.04	0.04 ± 0.03	0.01 ± 0.01
Pile-up	0.02 ± 0.01	0.01 ± 0.00	0.05 ± 0.01
Total systematic uncertainty	1.03 ± 0.31	1.31 ± 0.23	0.74 ± 0.29
Total	1.27 ± 0.33	1.41 ± 0.24	0.84 ± 0.29

Dilepton top mass at 8 TeV

Example: I/FSR with Powheg-Box and Pythia6 programs that differ in several parameters: the QCD scale Λ_{QCD}, the transverse momentum scale for space-like parton-shower evolution Q^2 max and the h_{damp} parameter.

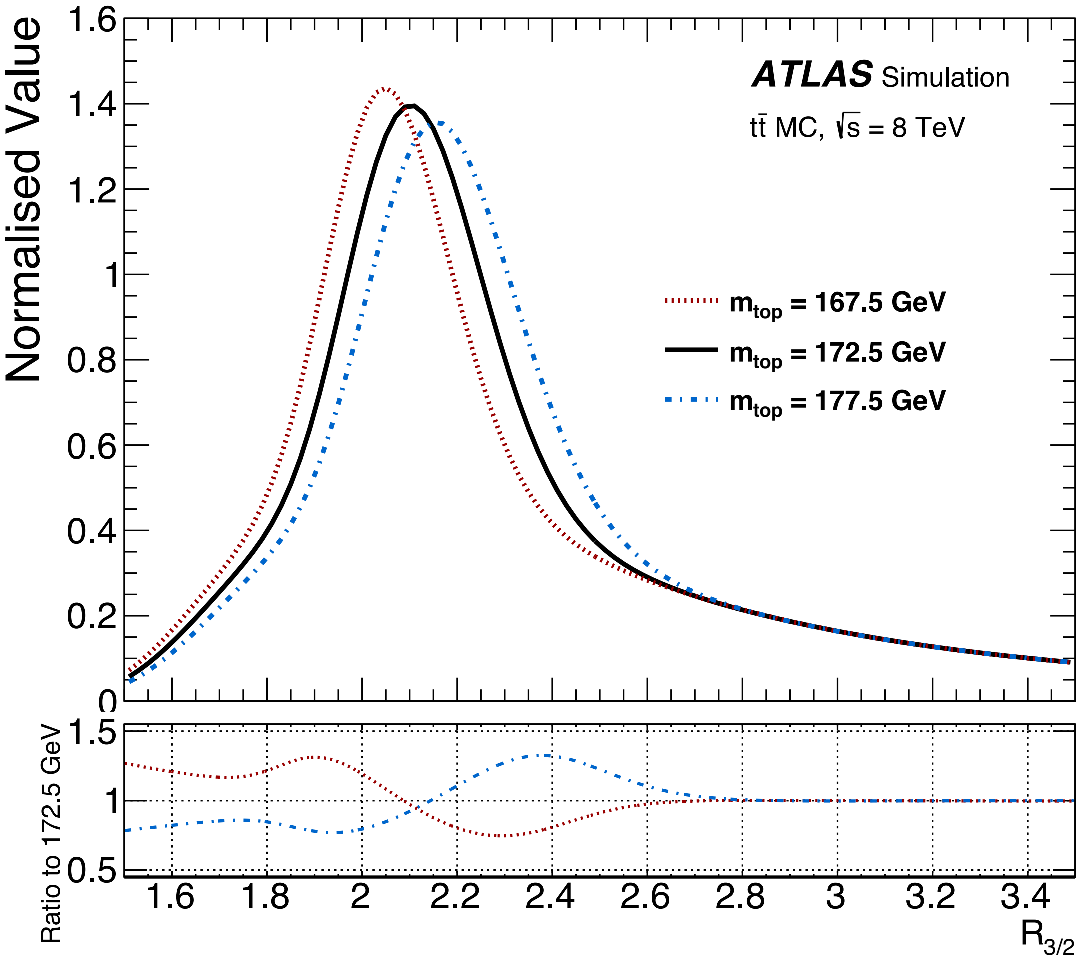
Half the observed difference between the up variation and the down variation is quoted as a systematic uncertainty

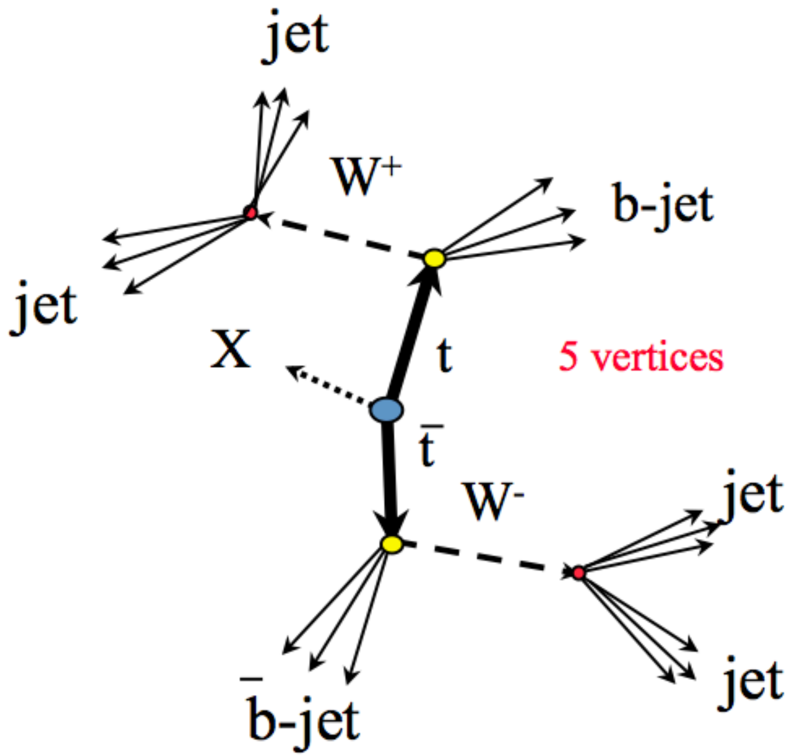
Example: Powheg program with either the PYTHIA or the HERWIG program

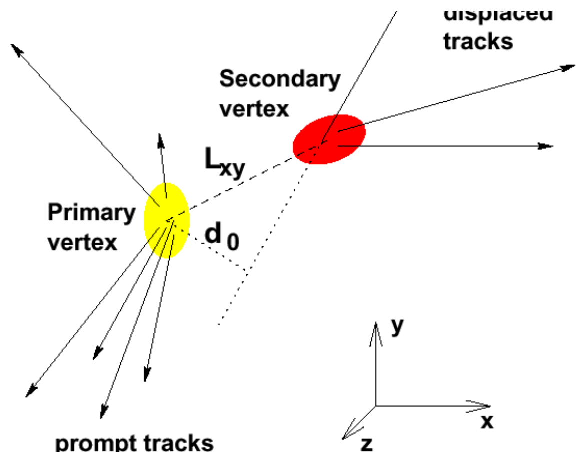


All-jets top mass at 8 TeV

J. High E. Phys. 09 (2017) 118





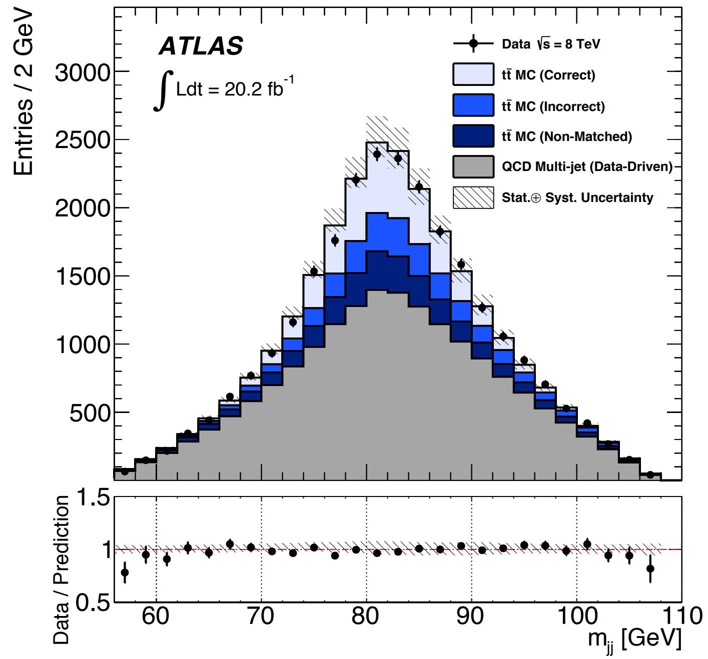


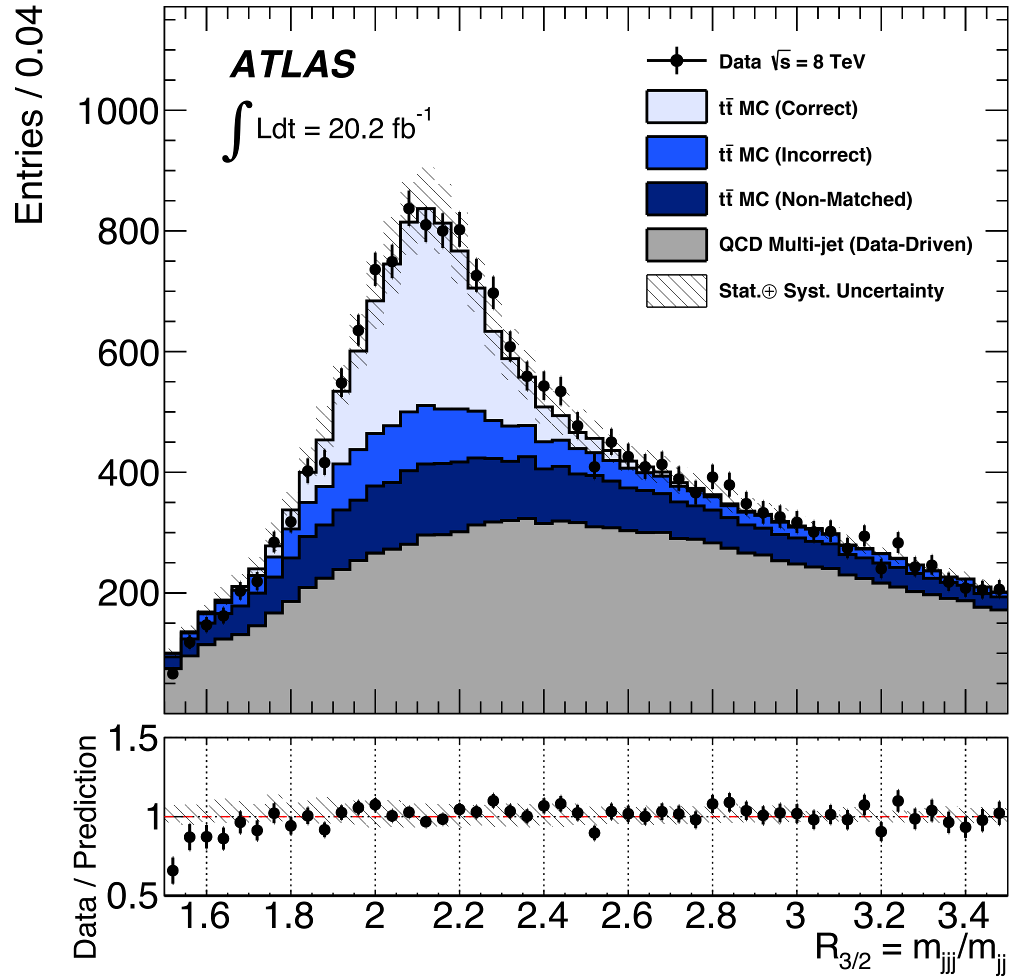
Observable: $R_{3/2}$ ratio of 3-jet to 2-jet invariant mass

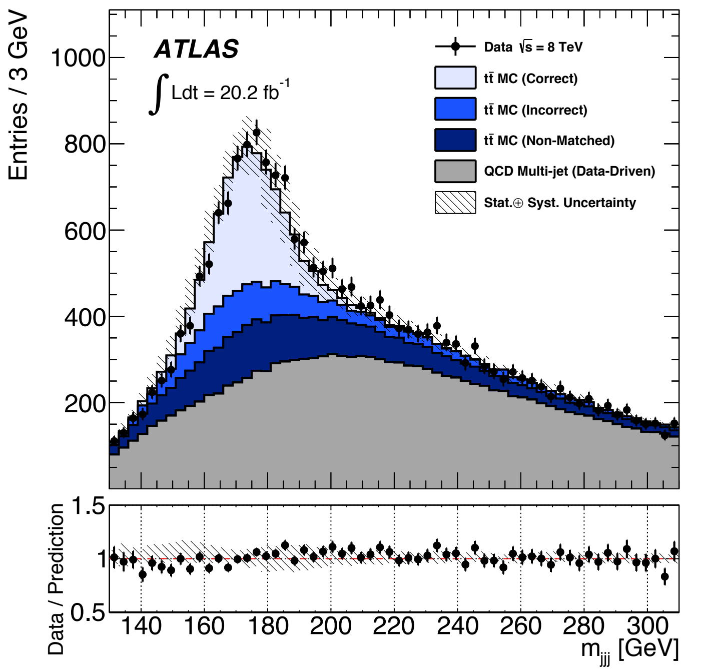
Event Selection:

- at least 5 central jets with p_T> 60 GeV
- Jet separation ΔR > 0.6
- At least 2 *b*-jets ($\Delta\phi_{bb}$>1.5, $\Delta\phi_{bW}$<2) , with *c*-jet rejection

All-jets top mass at 8 TeV



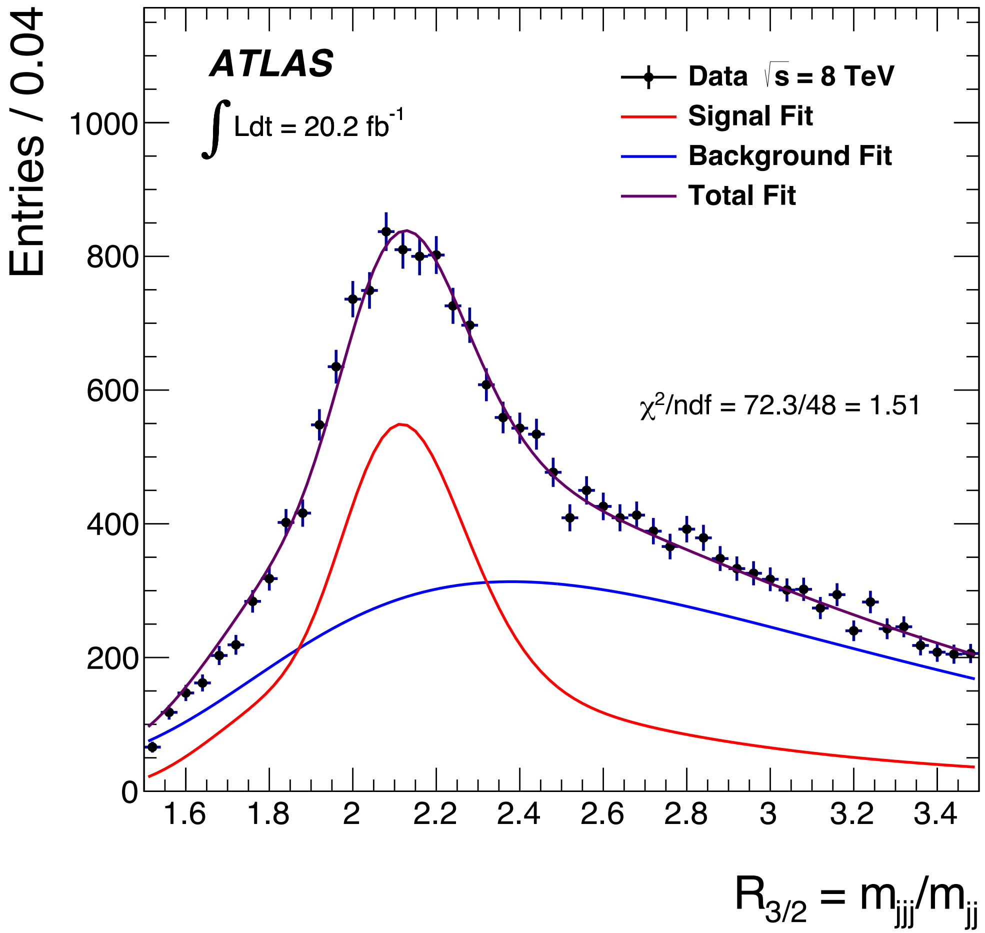


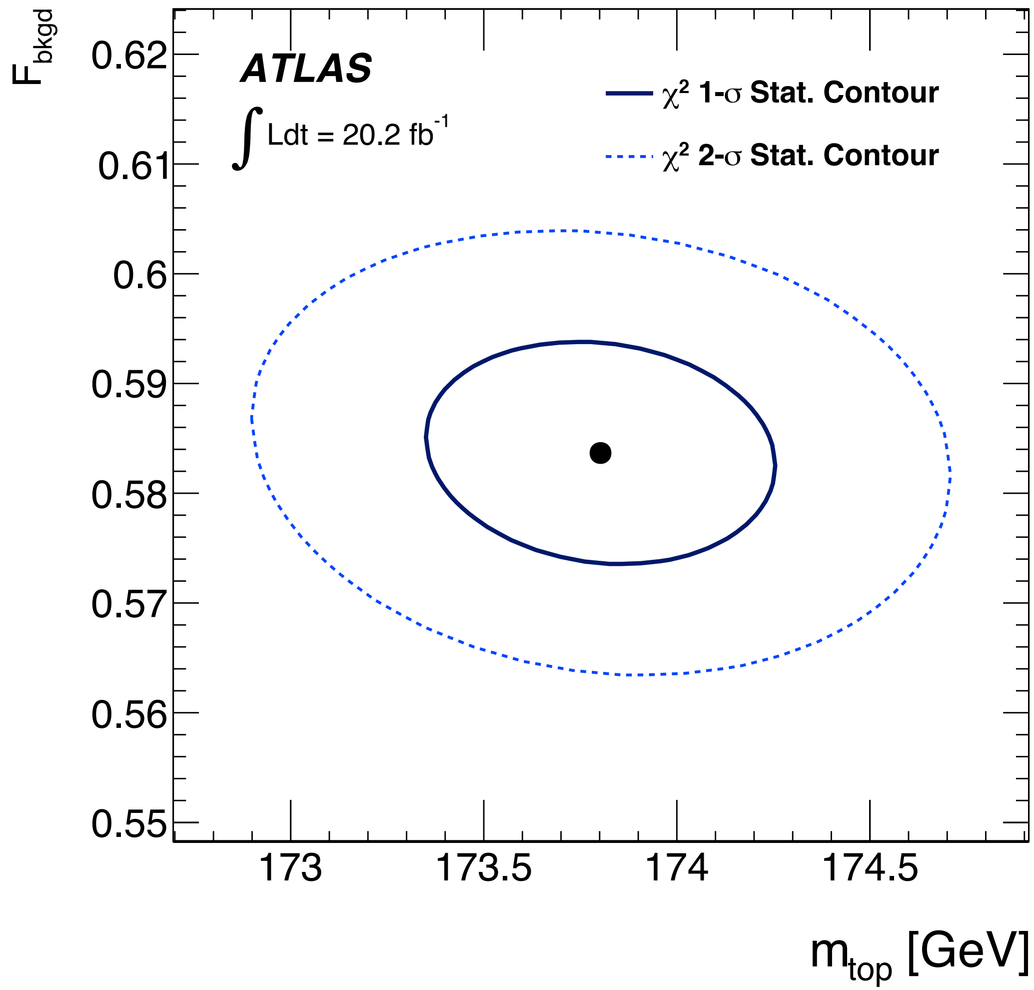


$$\chi^2 = \frac{(m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4})^2}{\sigma^2_{\Delta m_{bjj}}} + \frac{(m_{j_1 j_2} - m_W^{\mathrm{MC}})^2}{\sigma^2_{m_W^{\mathrm{MC}}}} + \frac{(m_{j_3 j_4} - m_W^{\mathrm{MC}})^2}{\sigma^2_{m_W^{\mathrm{MC}}}}.$$

$R_{3/2}$ ensures self-calibration of the jet energy

All-jets top mass at 8 TeV





Data-driven estimation of the large multi-jet background (using N_b, $\Delta\varphi_{bW}$)

Binned minimum χ^2 on functional templates (Novosibirsk+Landau)

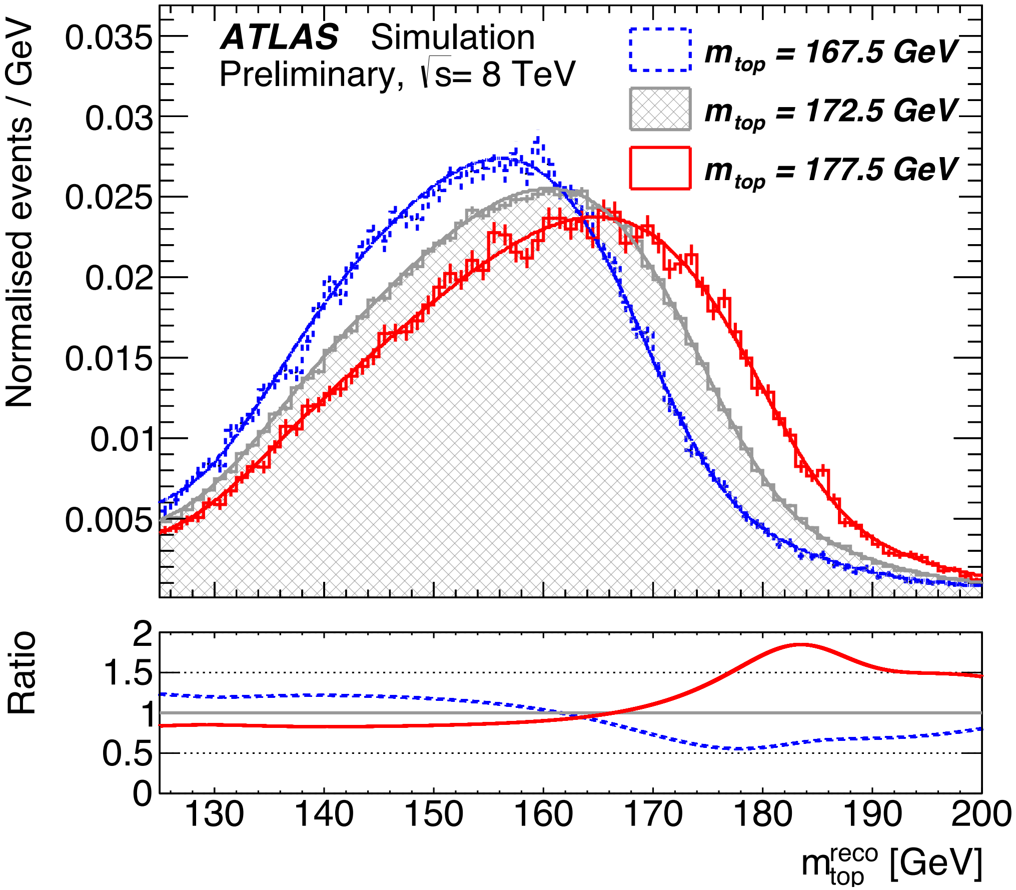
All-jets top mass at 8 TeV

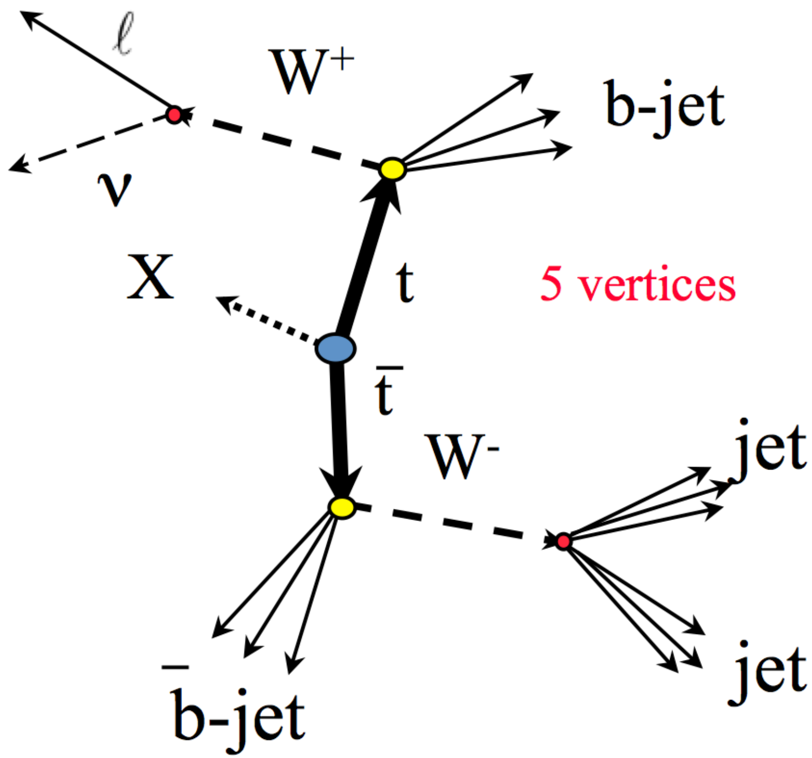
Source of uncertainty	Δm_{top} [GeV]
Monte Carlo generator	0.18 ± 0.21
Hadronisation modelling	0.64 ± 0.15
Parton distribution functions	0.04 ± 0.00
Initial/final-state radiation	0.10 ± 0.28
Underlying event	0.13 ± 0.16
Colour reconnection	0.12 ± 0.16
Bias in template method	0.06
Signal and bkgd parameterisation	0.09
Non all-hadronic $t\bar{t}$ contribution	0.06
ABCD method *vs.* ABCDEF method	0.16
Trigger efficiency	0.08 ± 0.01
Lepton/$E_{\mathrm{T}}^{\mathrm{miss}}$ calibration	0.02 ± 0.01
Overall flavour-tagging	0.10 ± 0.00
Jet energy scale (JES)	0.60 ± 0.05
b-jet energy scale (bJES)	0.34 ± 0.02
Jet energy resolution	0.10 ± 0.04
Jet vertex fraction	0.03 ± 0.01
Total systematic uncertainty	1.01
Total statistical uncertainty	0.55
Total uncertainty	1.15

Example: Comparison of Pythia 6.427 used to model the parton shower, hadronisation and underlying event with the Perugia 2012 tunes, against Herwig 6.520.2 with the AUET2 tune

Lepton+jets top mass at 8 TeV

ATLAS-CONF-2017-071 (2017)



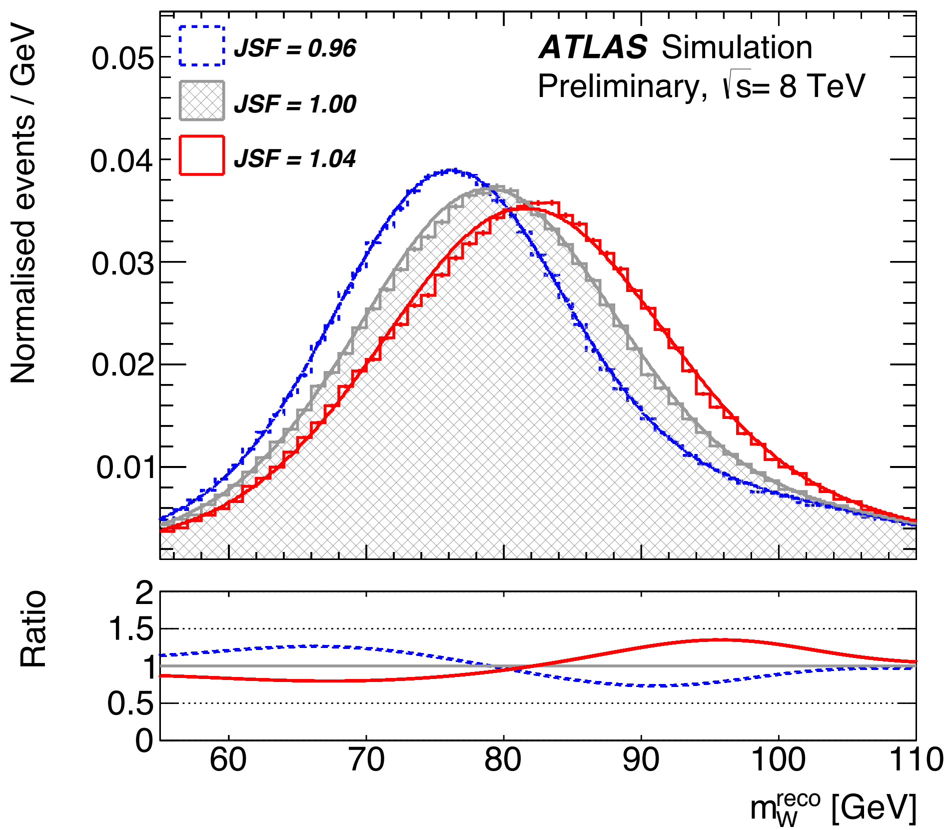


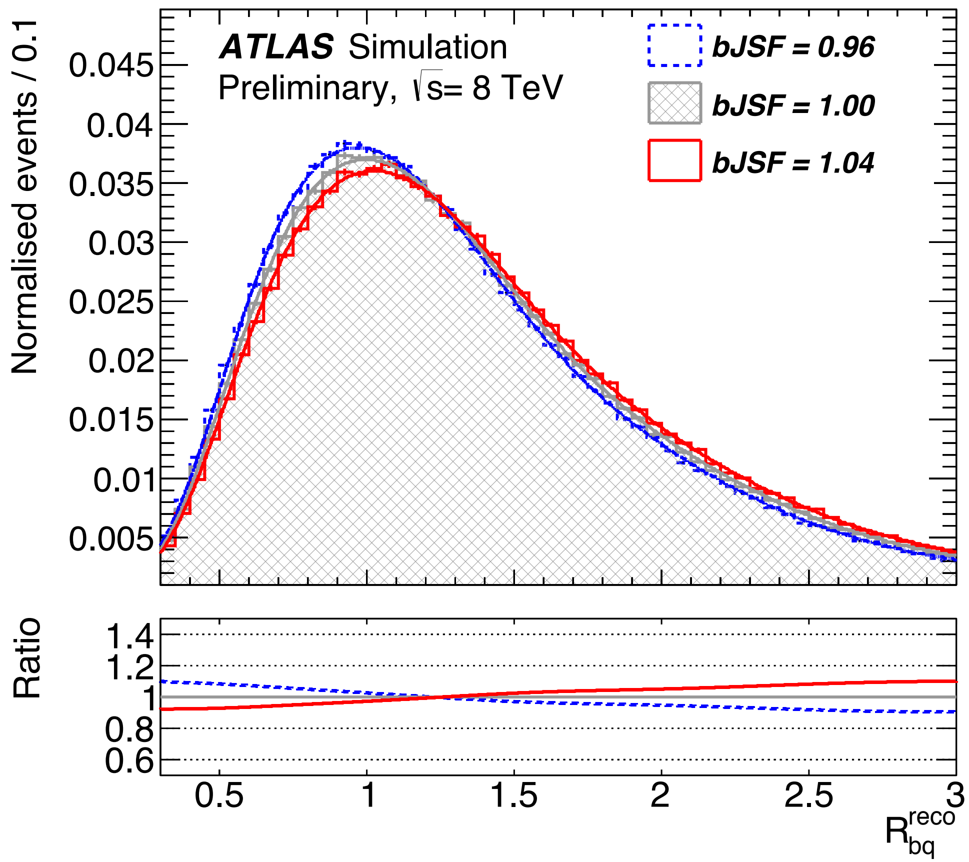
Observable: Breight-Wigner of leptonic and had. decaying tops

Event Selection:

- One electron(muon) with p_T>25 GeV, large missing E_T
- At least 4 jets with p_T>25 GeV. At least 2 b-jets

Lepton+jets top mass at 8 TeV

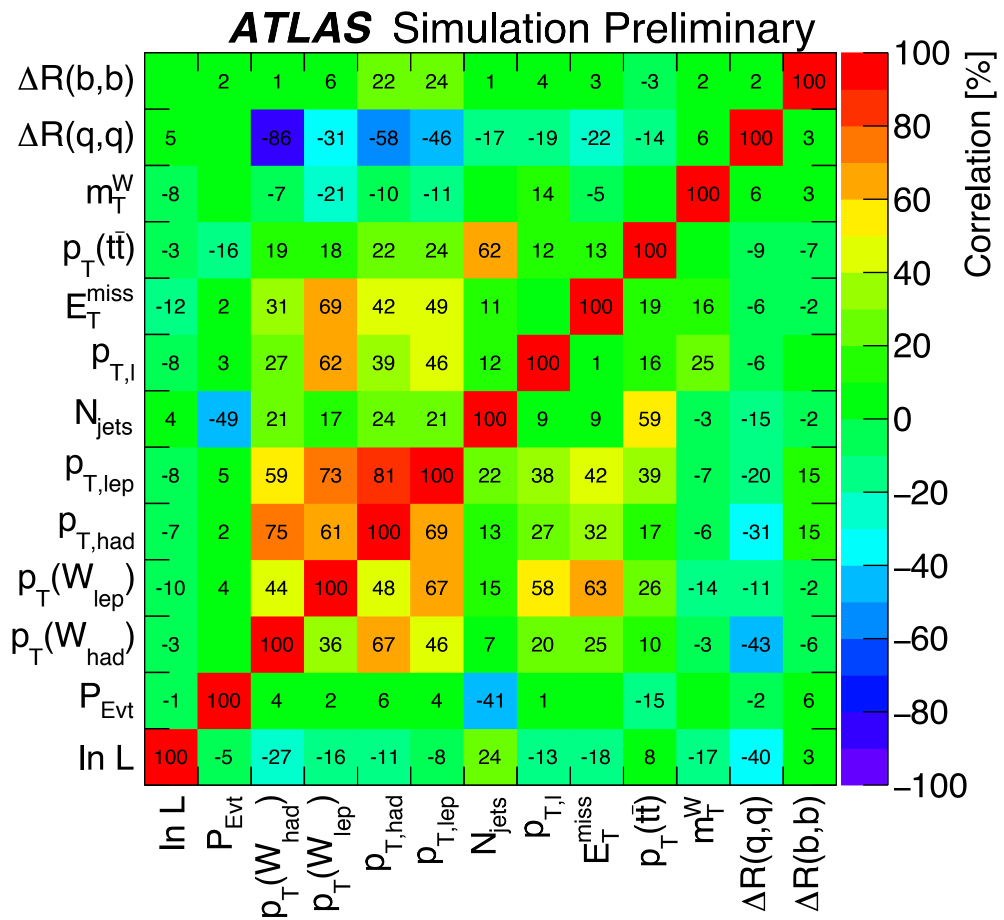


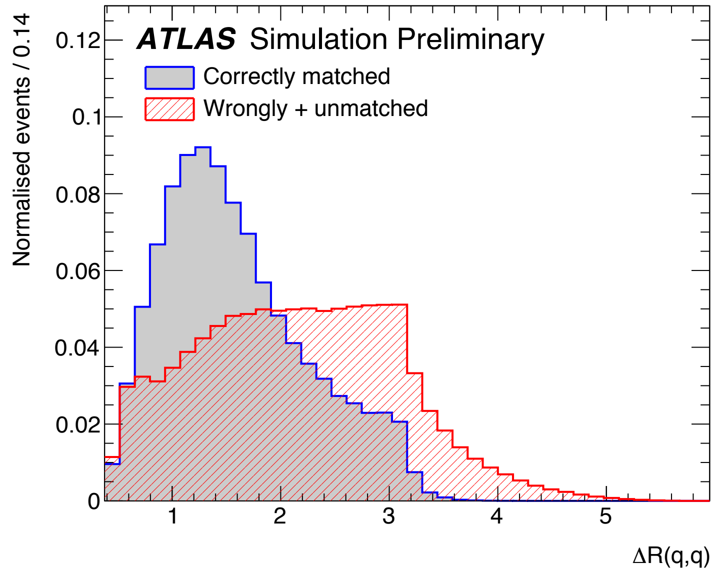


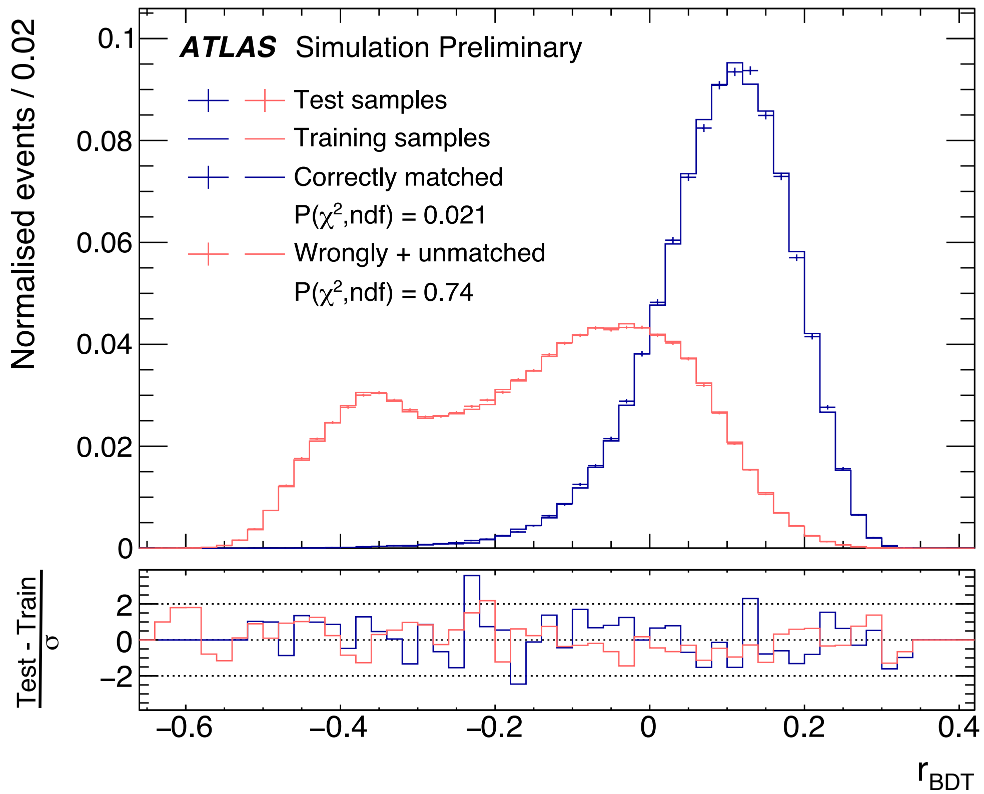
Two more observables are identified for their sensitivity to Jet Scale Factor (JSF) and *b*JSF: m_W and R_{bq}

$$R_{bq}^{\mathrm{reco}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{had}}} + p_{\mathrm{T}}^{b_{\mathrm{lep}}}}{p_{\mathrm{T}}^{q_1} + p_{\mathrm{T}}^{q_2}} \, .$$

Lepton+jets top mass at 8 TeV

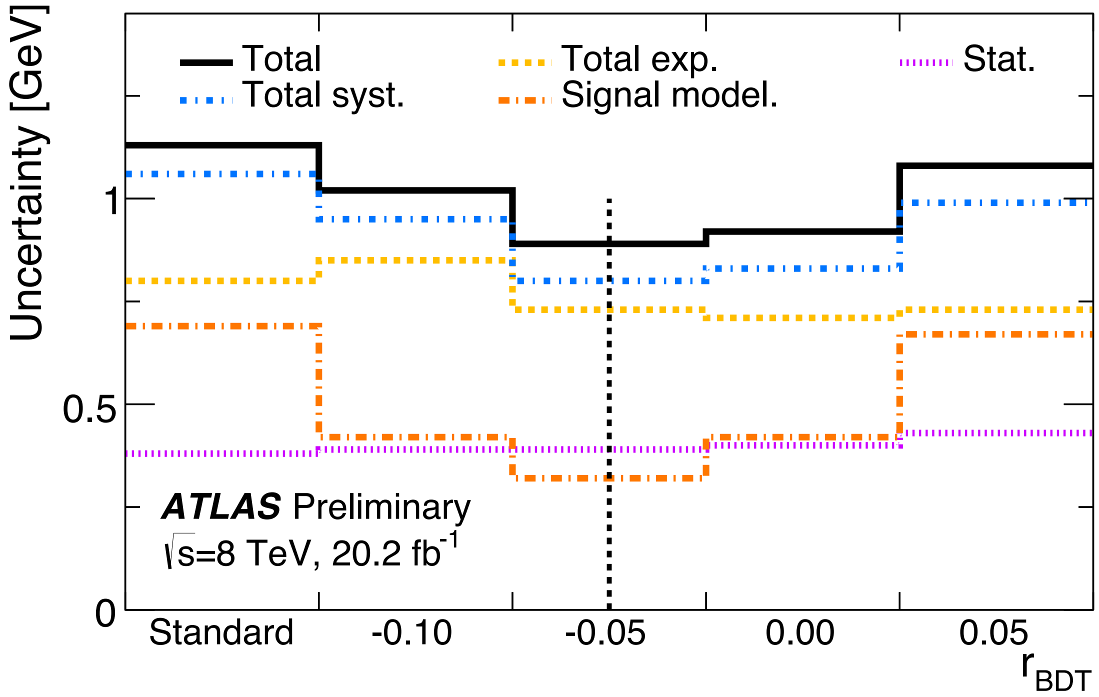


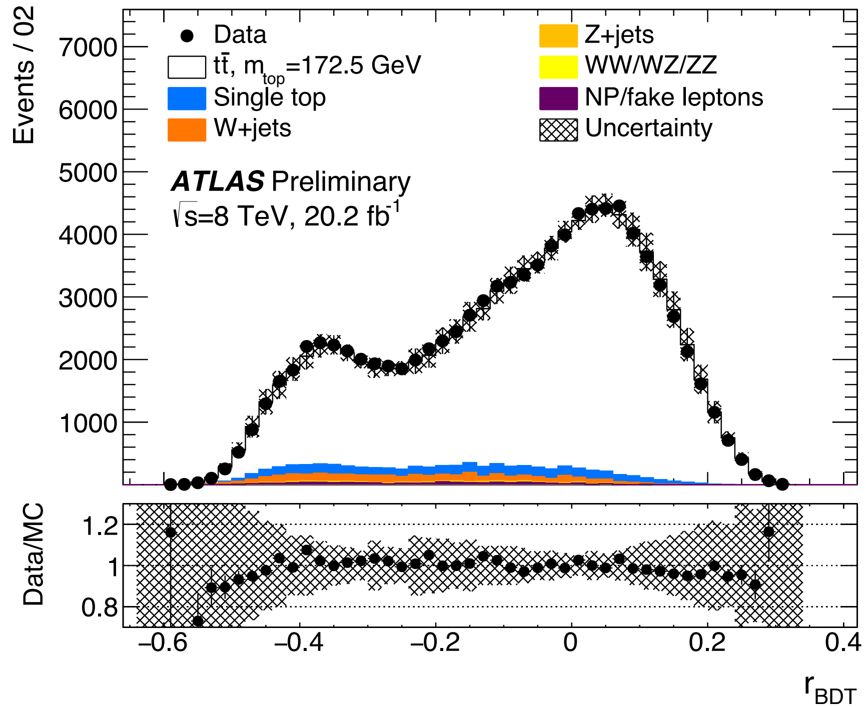


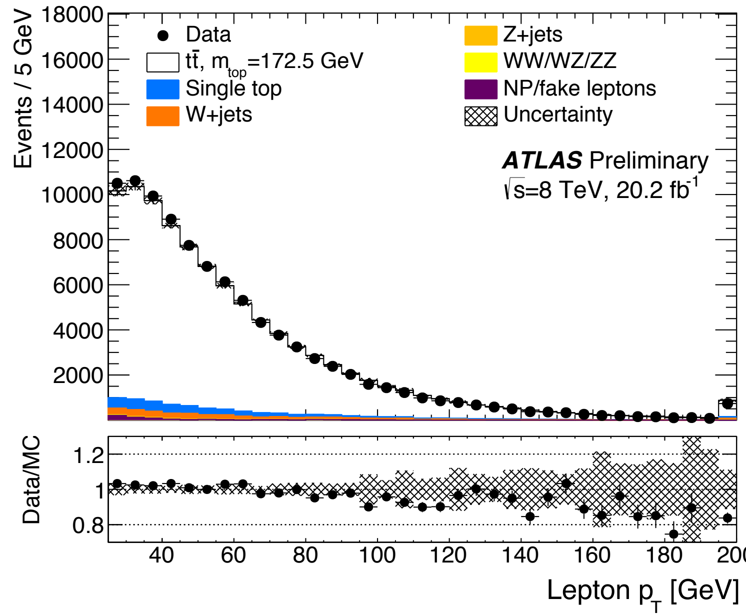


Kinematically reconstructed top events. 13 observables fed to a BDT to decide correctly matched events

Lepton+jets top mass at 8 TeV

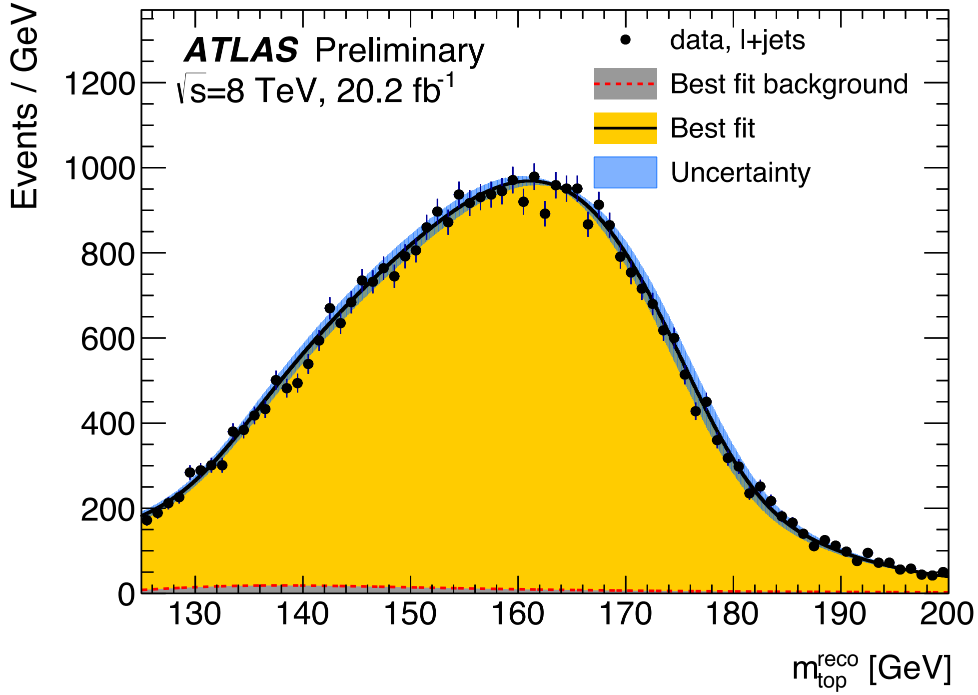


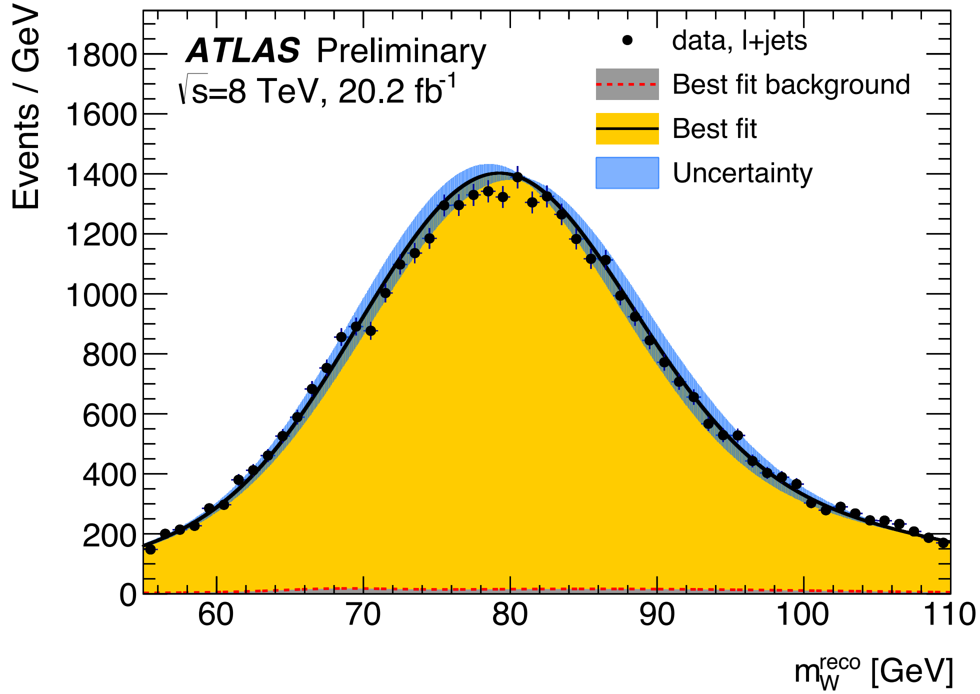


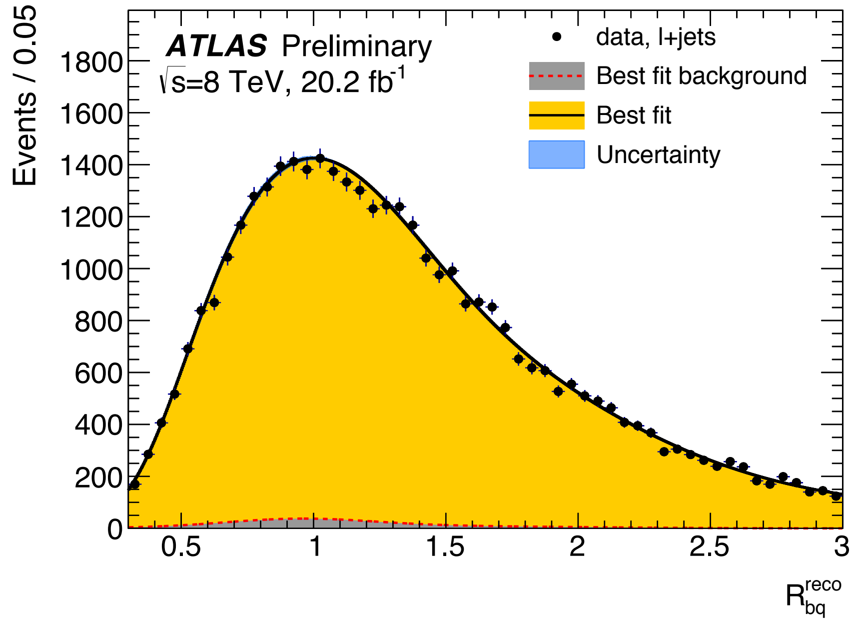


BTD-optimised selection based on total m_{top} uncertainty

Lepton+jets top mass at 8 TeV







Simultaneous un-binned likelihood fits on functional templates (Gaussians/Landau) for m_{top}, JSF, *b*JSF

Lepton+jets top mass at 8 TeV

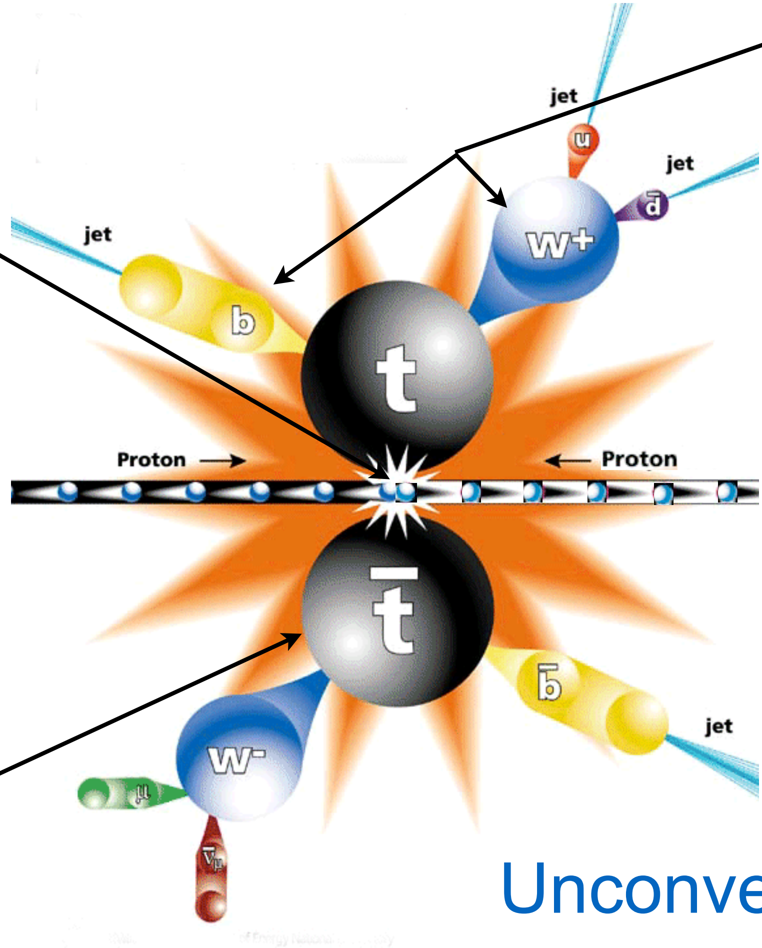
	m_{top} [GeV]		
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	
Event selection	Standard	Standard	BDT
Result	172.33	171.90	172.08
Statistics	0.75	0.38	0.39
– *Stat. comp.* (m_{top})	0.23	0.12	0.11
– *Stat. comp.* (JSF)	0.25	0.11	0.11
– *Stat. comp.* (bJSF)	0.67	0.34	0.35
Method	0.11 ± 0.10	0.04 ± 0.11	0.13 ± 0.11
Signal Monte Carlo generator	0.22 ± 0.21	0.50 ± 0.17	0.16 ± 0.17
Hadronisation	0.18 ± 0.12	0.05 ± 0.10	0.15 ± 0.10
Initial- and final-state QCD radiation	0.32 ± 0.06	0.28 ± 0.11	0.08 ± 0.11
Underlying event	0.15 ± 0.07	0.08 ± 0.15	0.08 ± 0.15
Colour reconnection	0.11 ± 0.07	0.37 ± 0.15	0.19 ± 0.15
Parton distribution function	0.25 ± 0.00	0.08 ± 0.00	0.09 ± 0.01
Background normalisation	0.10 ± 0.00	0.04 ± 0.00	0.08 ± 0.00
W+jets shape	0.29 ± 0.00	0.05 ± 0.00	0.11 ± 0.00
Fake leptons shape	0.05 ± 0.00	0	0
Jet energy scale	0.58 ± 0.11	0.63 ± 0.02	0.54 ± 0.02
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.05 ± 0.01	0.03 ± 0.01
Jet energy resolution	0.22 ± 0.11	0.23 ± 0.03	0.20 ± 0.04
Jet reconstruction efficiency	0.12 ± 0.00	0.04 ± 0.01	0.02 ± 0.01
Jet vertex fraction	0.01 ± 0.00	0.13 ± 0.01	0.09 ± 0.01
b-tagging	0.50 ± 0.00	0.37 ± 0.00	0.38 ± 0.00
Leptons	0.04 ± 0.00	0.16 ± 0.01	0.16 ± 0.01
$E_{\text{T}}^{\text{miss}}$	0.15 ± 0.04	0.08 ± 0.01	0.05 ± 0.01
Pile-up	0.02 ± 0.01	0.14 ± 0.01	0.15 ± 0.01
Total systematic uncertainty	1.03 ± 0.08	1.07 ± 0.10	0.82 ± 0.06
Total	1.27 ± 0.08	1.13 ± 0.10	0.91 ± 0.06

The ERC NPTEV-TQP2020 Programme

$t\bar{t}Z$: vs p_T^Z, vs $\Delta\varphi(l^+l^-)$
First couplings measurement

Resonances in top pairs with di-lepton events
Sensitivity up to 3-3.5 TeV

Exclusive Flavour Changing Neutral Current decay $t \rightarrow Zc$
BR sensitivity improved by x6 and first exclusive measurement



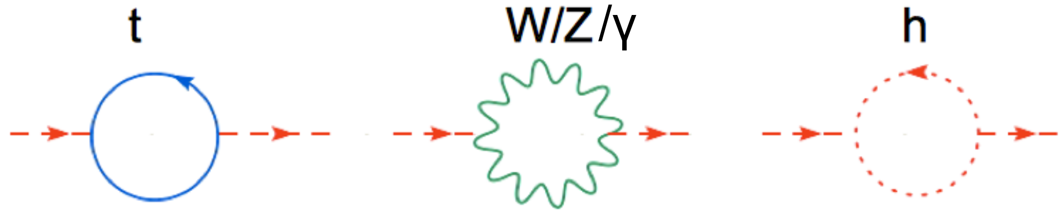
CP violation in B from top quarks
First measurement

Mass of top quark with leptonic endpoints
Improvement of 40%

Unconventional Techniques
New Channels
New Observables

Possible Discoveries: a Revolution

$\delta m_H^2 =$



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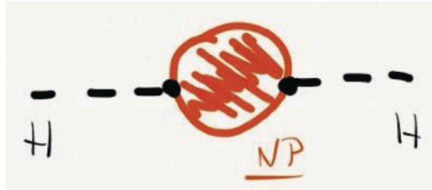


$= \log\Lambda$ or finite Λ=O(TeV)

Most Natural theories of physics Beyond the Standard Model (BSM) foresee modifications of the top dynamics at O(TeV)

Models with partners of the top:

new scalars/vectors, possibly strongly coupled with the top. e.g. SUSY.
Cancel the divergence

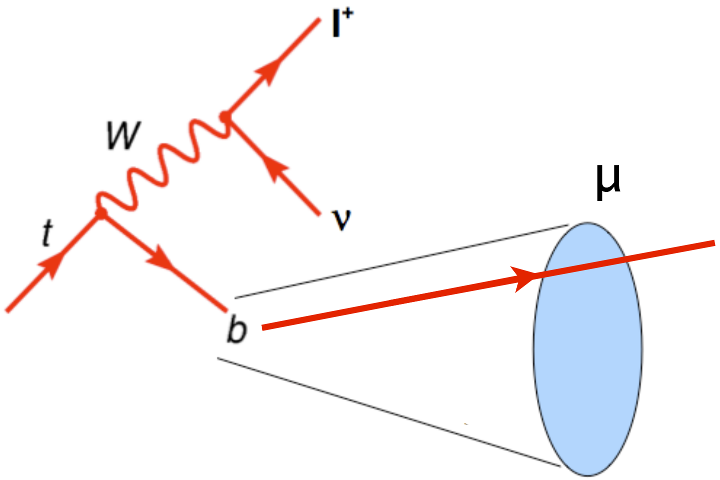
Models with compositeness and strong dynamics:

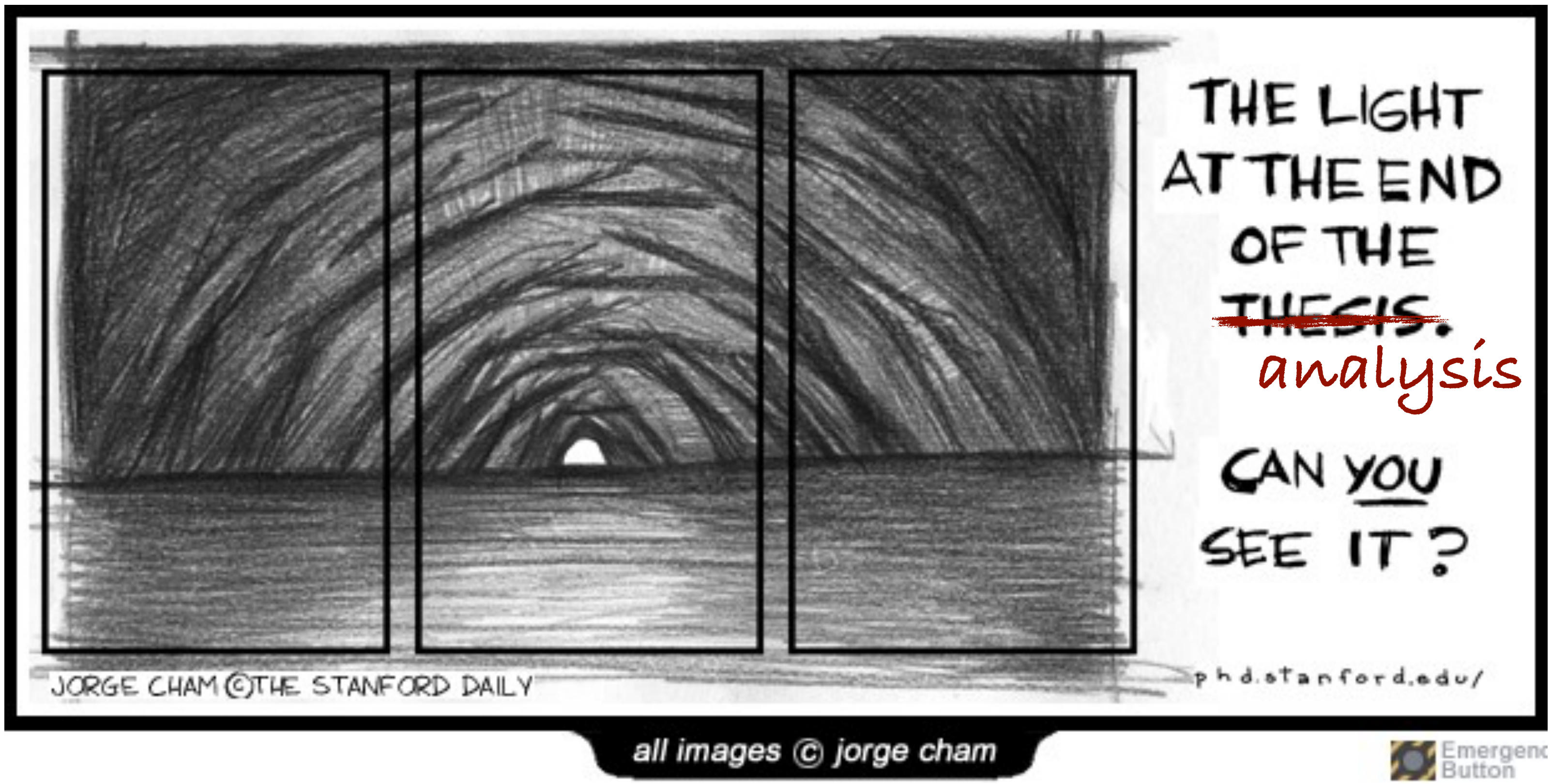
top bound states, top is not elementary, e.g. Technicolour.
New dynamics at ~TeV

New space-time structure:

Extra dimensions. e.g. Kaluza-Klein theories.
Lower the cut-off Λ

WP1: Partial IM Reconstruction



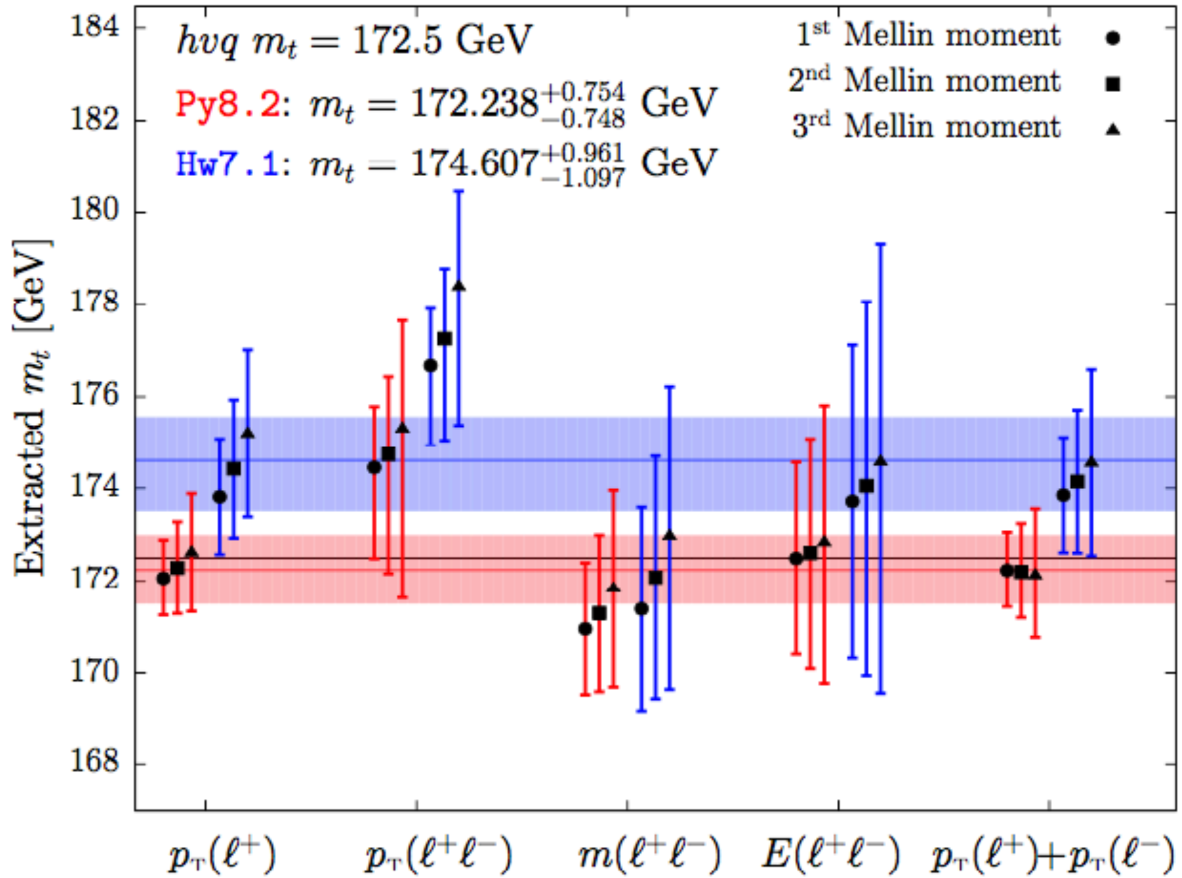


WP1: Top Quark Mass

Addressing precision estimate of the impact on the reconstructed top mass and improved modelling of the:

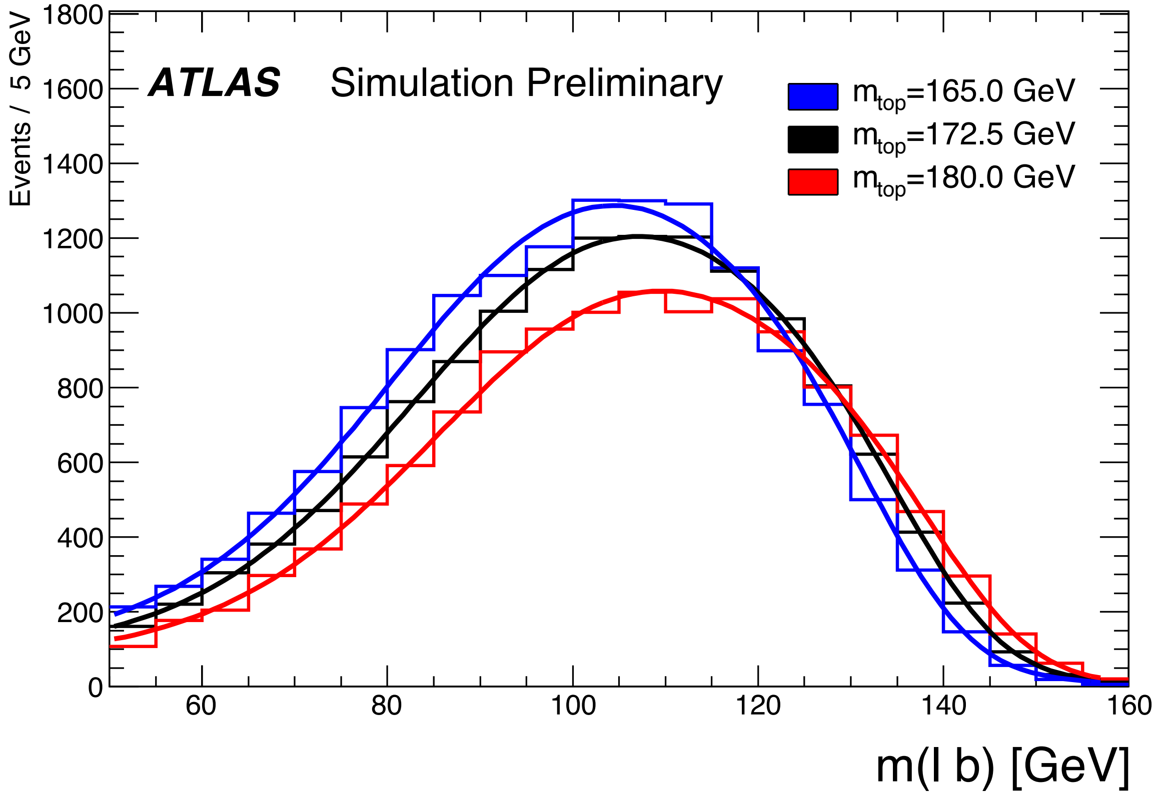
- Fragmentation of *b*-quark into hadrons
- Hadronisation modelling
- Production fractions
- Decay rates

Very recent theoretical work comparing Pythia8.2 and Herwig7.1 (with same POWHEG BOX generators) seem to point to the shower modelling leading to large uncertainties. More work needed on this front

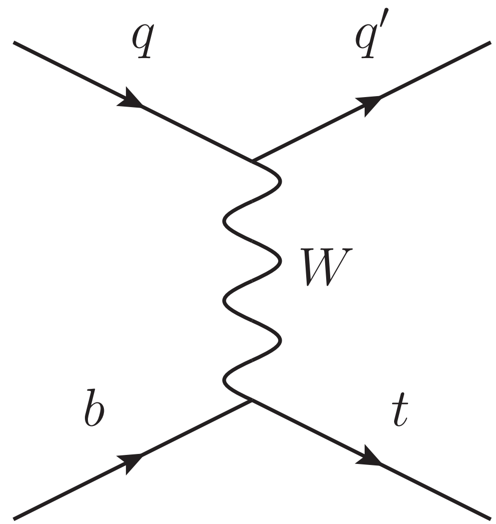


Ravasio et al., arXiv:1801.03944v1 [hep-ph] (11 Jan 2018)

Top mass with single top events



ATLAS-CONF-2014-055

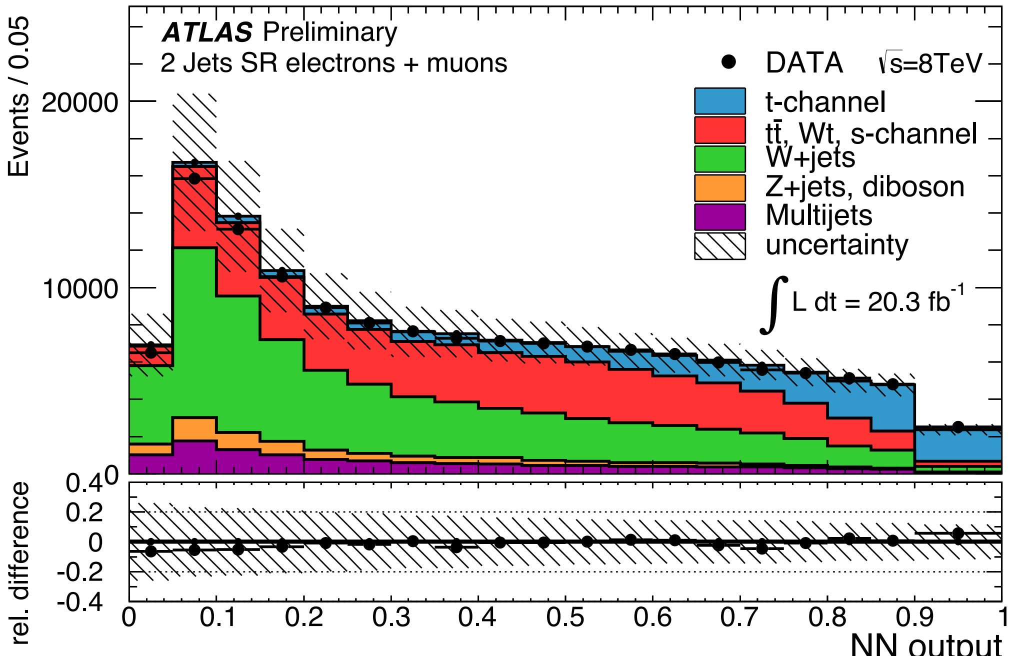


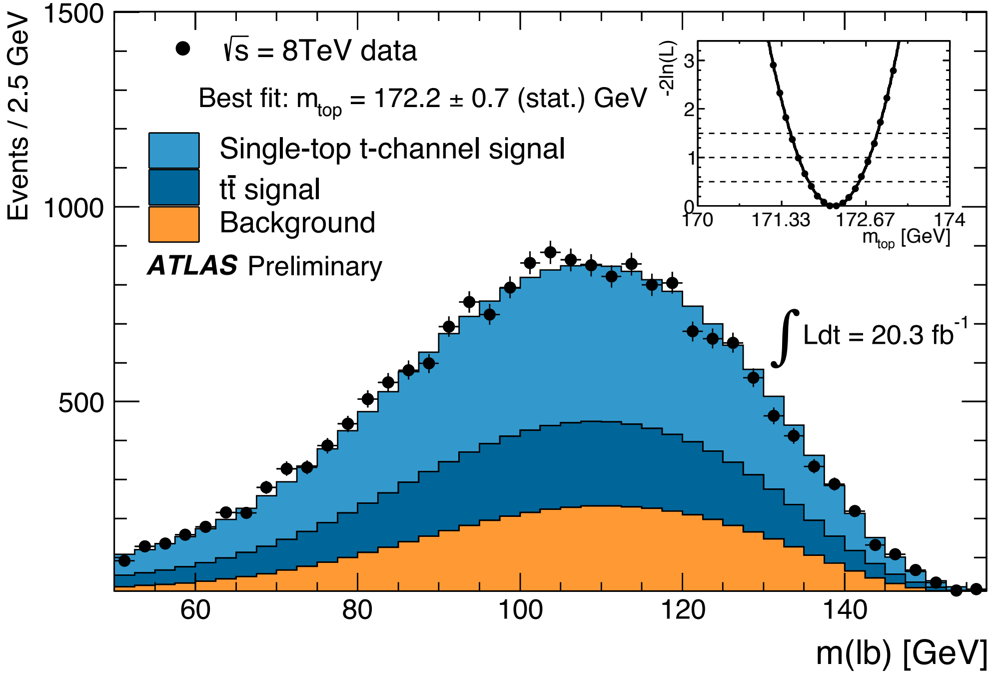
Weak interaction process with different colour flow

Event Selection:

- One electron(muon) with p_T>25 GeV, large missing E_T
- At least 2 jets with p_T>30 GeV. Exactly 1 *b*-jet
- Additional NN to distinguish signal from background
- Lack of JES self-constraint

Top mass with single top events

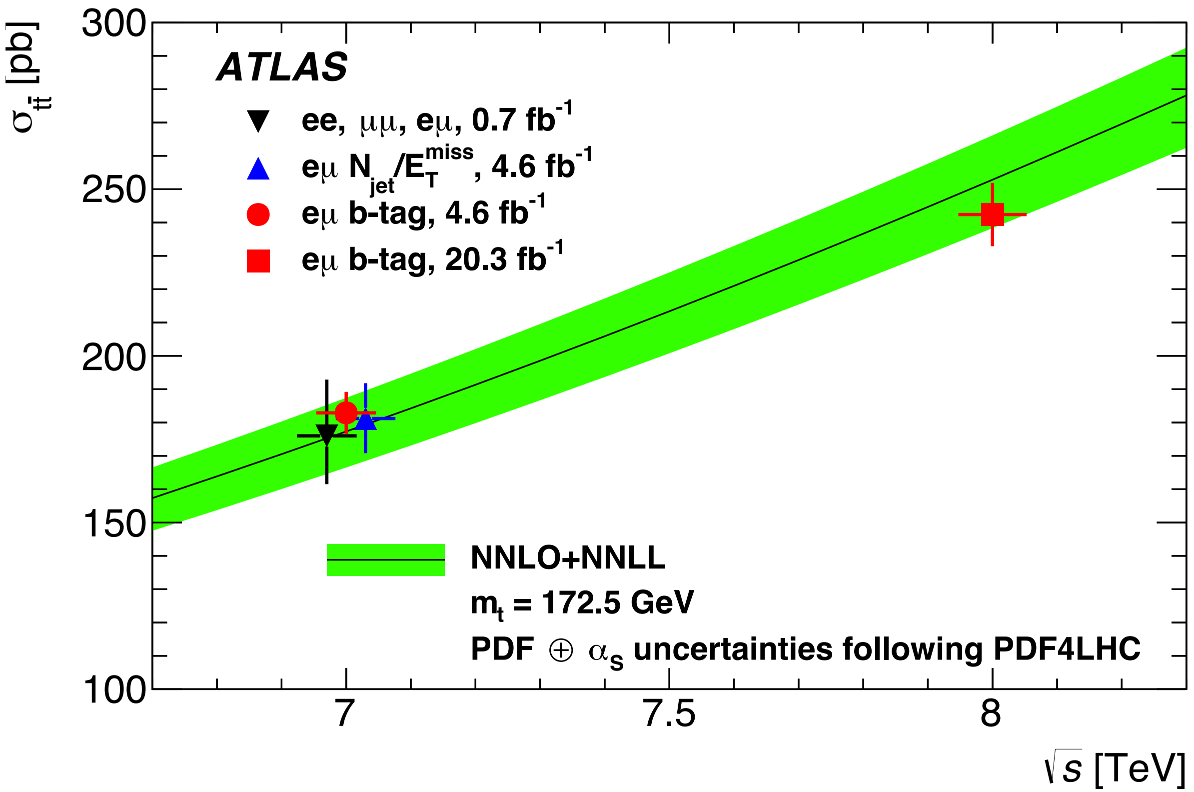




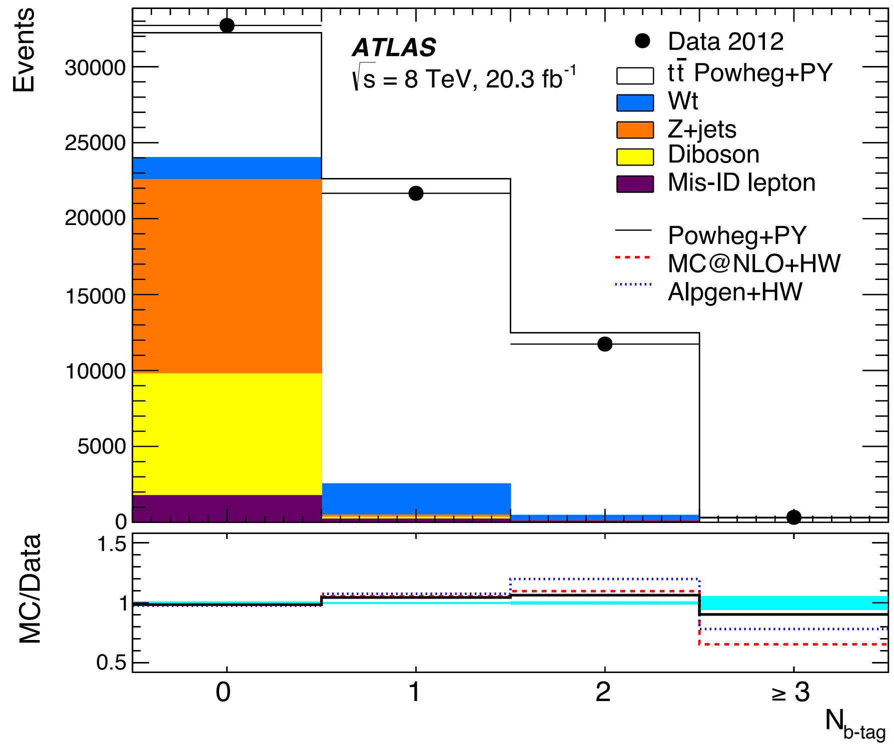
	Value [GeV]
Measured value	172.2
Statistical uncertainty	0.7
Jet energy scale	1.5
Jet energy resolution	< 0.1
Jet vertex fraction	< 0.1
Flavour tagging efficiency	0.3
Electron uncertainties	0.3
Muon uncertainties	0.1
Missing transverse momentum	0.2
W+jets normalisation	0.4
W+jets shape	0.3
Z+jets/diboson normalisation	0.2
Multijet normalisation	0.2
Multijet shape	0.3
Top normalisation	0.2
t-channel generator	< 0.1
t-channel hadronisation	0.7
t-channel colour reconnection	0.3
t-channel underlying event	< 0.1
$t\bar{t}$,Wt, and s-channel generator	0.2
$t\bar{t}$ hadronisation	< 0.1
$t\bar{t}$ colour reconnection	0.2
$t\bar{t}$ underlying event	0.1
$t\bar{t}$ ISR/FSR	0.2
Proton PDF	< 0.1
Simulation sample statistics	0.3
Total systematic uncertainty	2.0
Total uncertainty	2.1

The “Indirect” Measurements

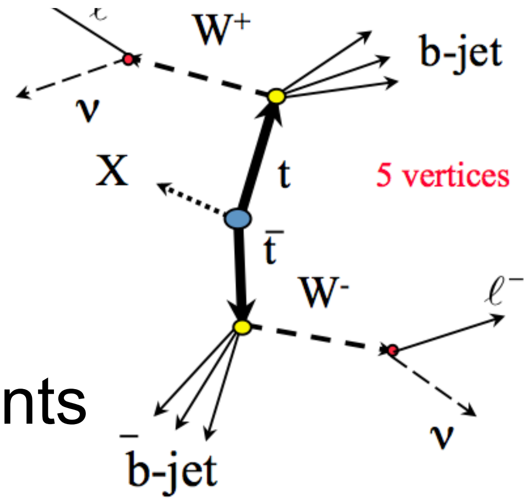
Top mass (indirect): from cross section



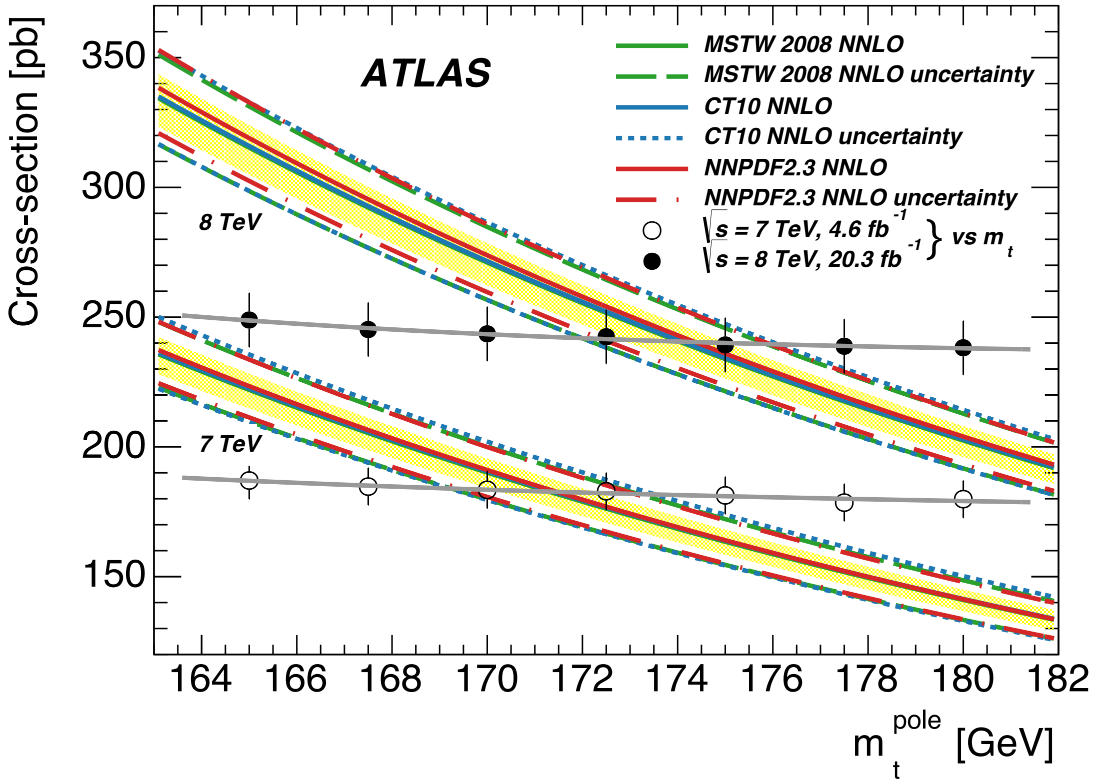
Eur. Phys. J. C74 (2014) 3109



- Measure a property that is a function of the top quark mass, $\sigma_{tt}(m_t)$
- Use a theoretical calculation to relate the two
- Two dilepton-based σ_{tt} ($\sqrt{s}$=7,8 TeV) measurements



Top mass (indirect): from cross section

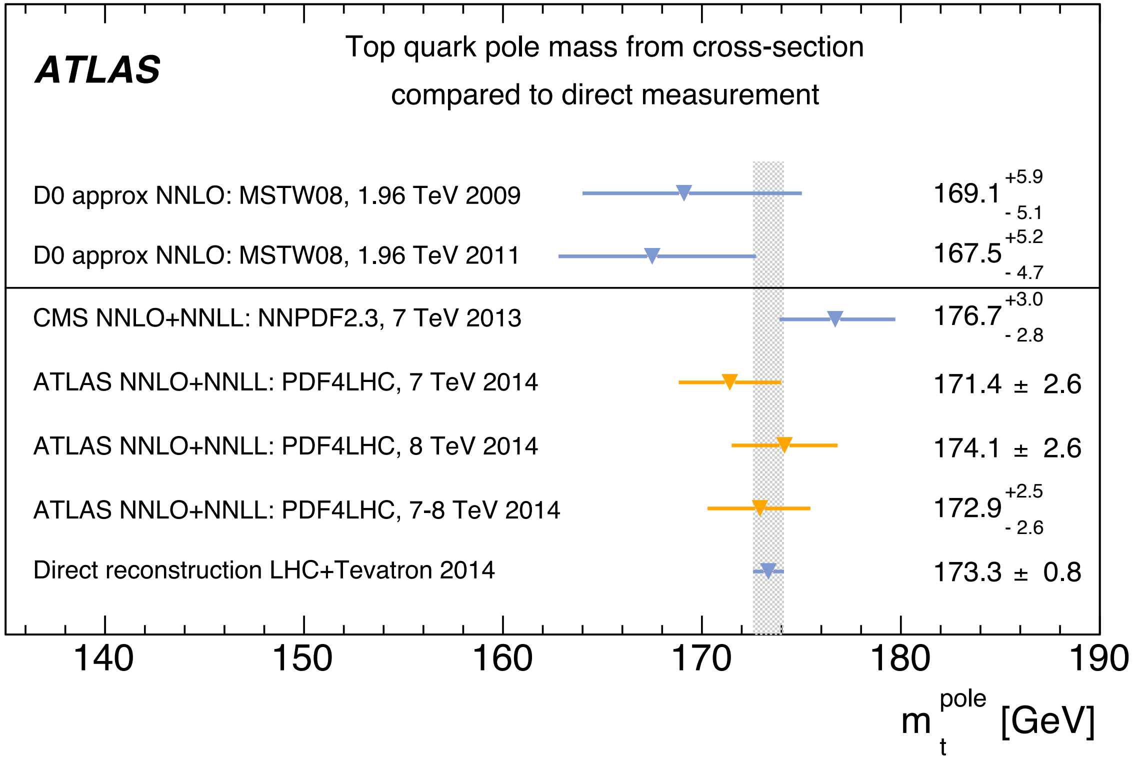


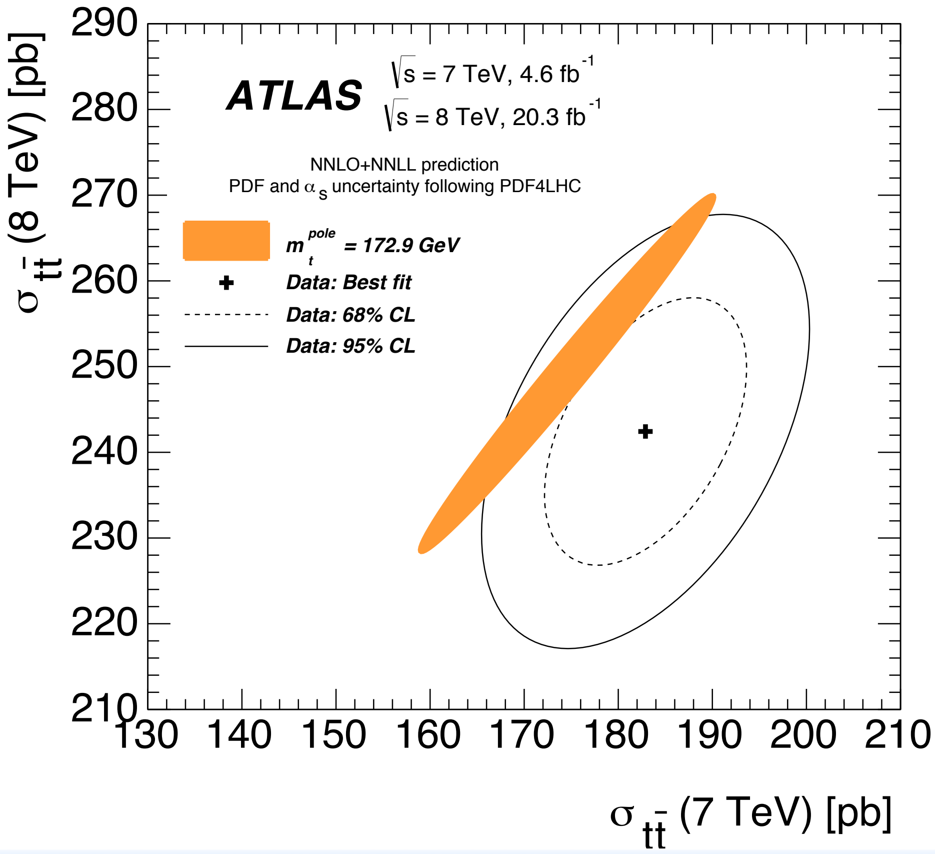
Uncertainty $\sqrt{s}$	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%) 7 TeV	8 TeV
Data statistics	1.69	0.71
$t\bar{t}$ modelling and QCD scale	1.46	1.26
Parton distribution functions	1.04	1.13
Background modelling	0.83	0.83
Lepton efficiencies	0.87	0.88
Jets and b-tagging	0.58	0.82
Misidentified leptons	0.41	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	2.27	2.26
Integrated luminosity	1.98	3.10
LHC beam energy	1.79	1.72
Total uncertainty	3.89	4.27

$\Delta m_t^{\mathrm{pole}}$ (GeV)	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
Data statistics	0.6	0.3
Analysis systematics	0.8	0.9
Integrated luminosity	0.7	1.2
LHC beam energy	0.7	0.6
PDF+α_s	1.8	1.7
QCD scale choice	$^{+0.9}_{-1.2}$	$^{+0.9}_{-1.3}$

- Sensitive to gluon PDF
- Limited by theoretical uncertainties to $\mathcal{O}$(2 GeV)

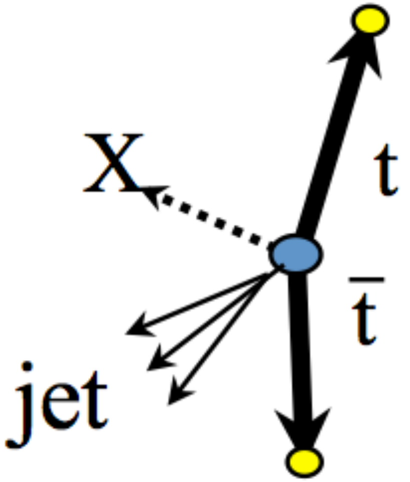
Top mass (indirect): from cross section

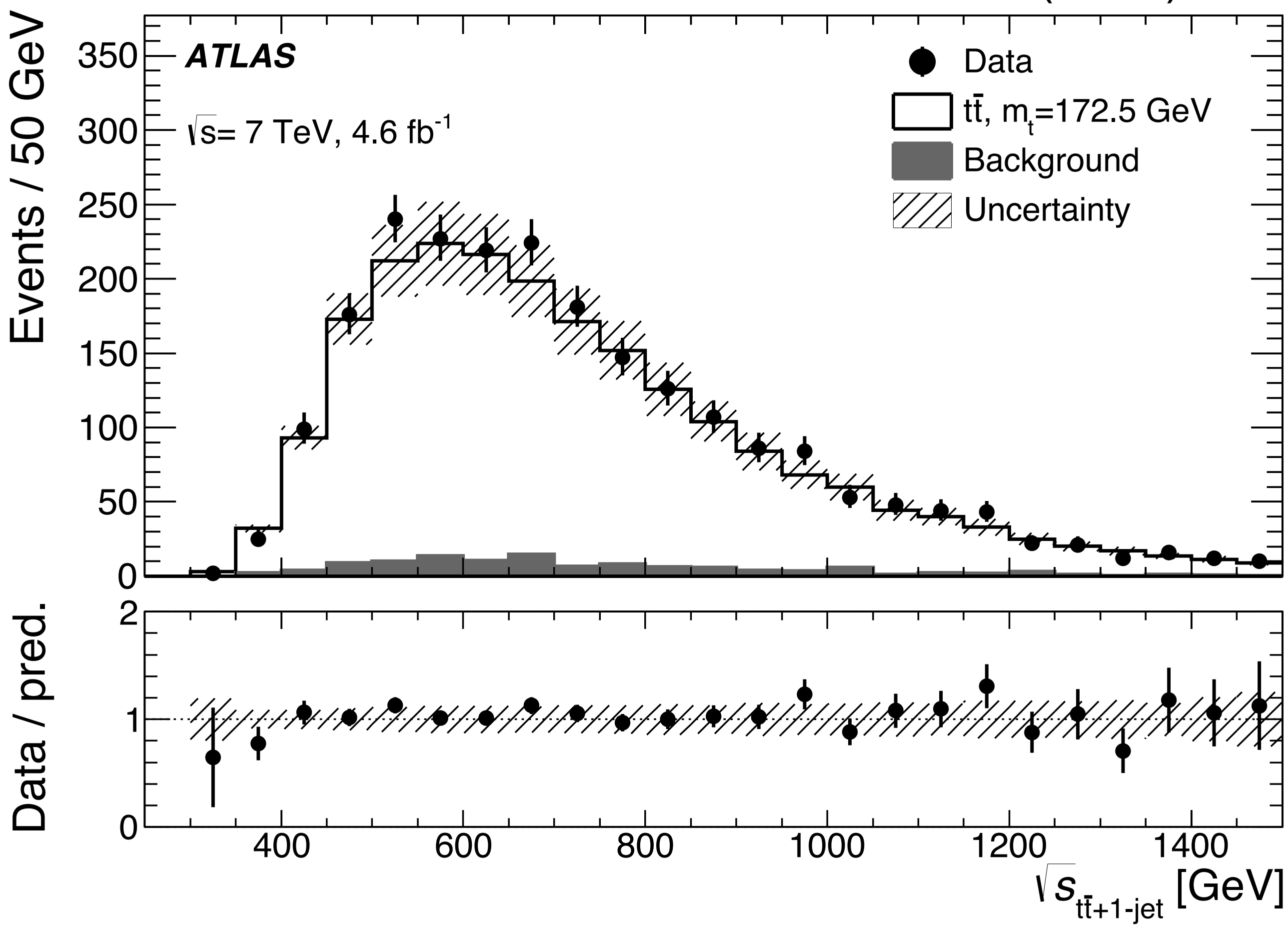




Top mass (indirect): tt+1 jet differential

JHEP 10 (2015) 121





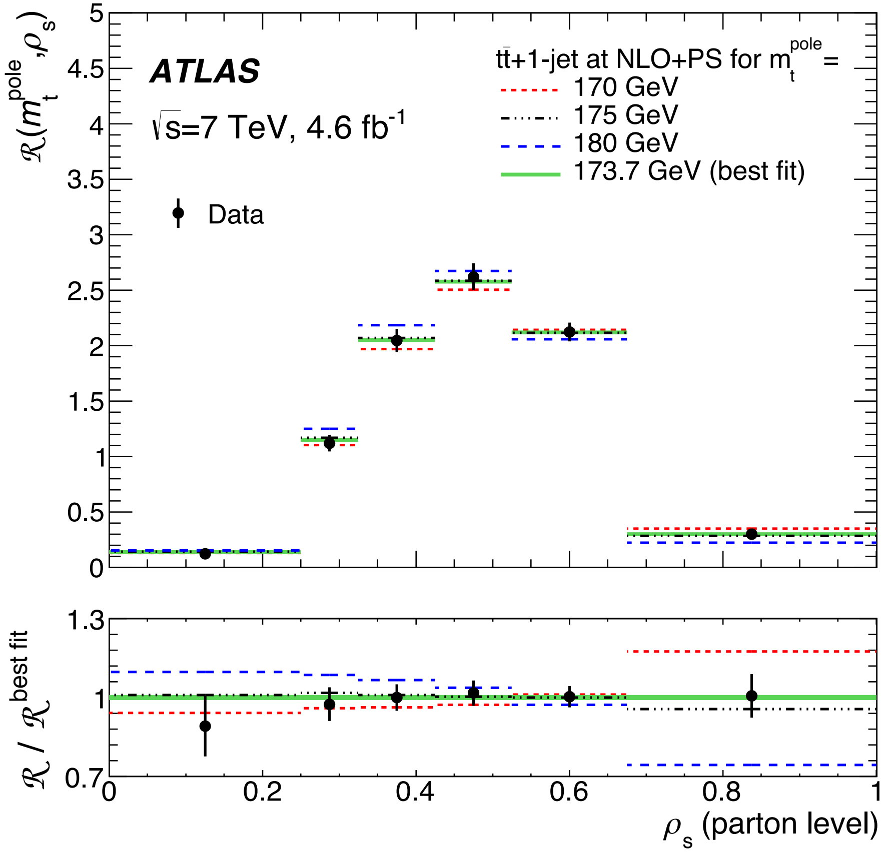
Observable:

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

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

Lepton+jets event selection with 1 additional jet

Top mass (indirect): tt+1 jet differential

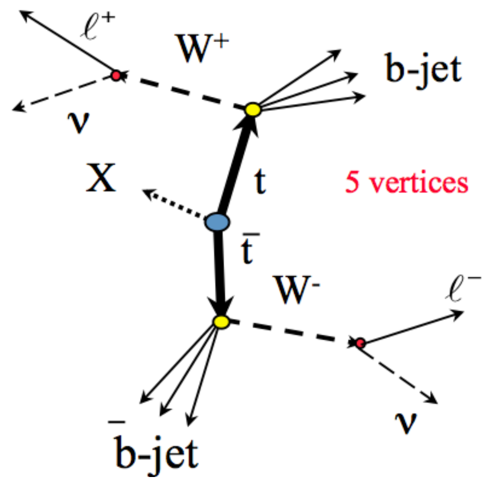


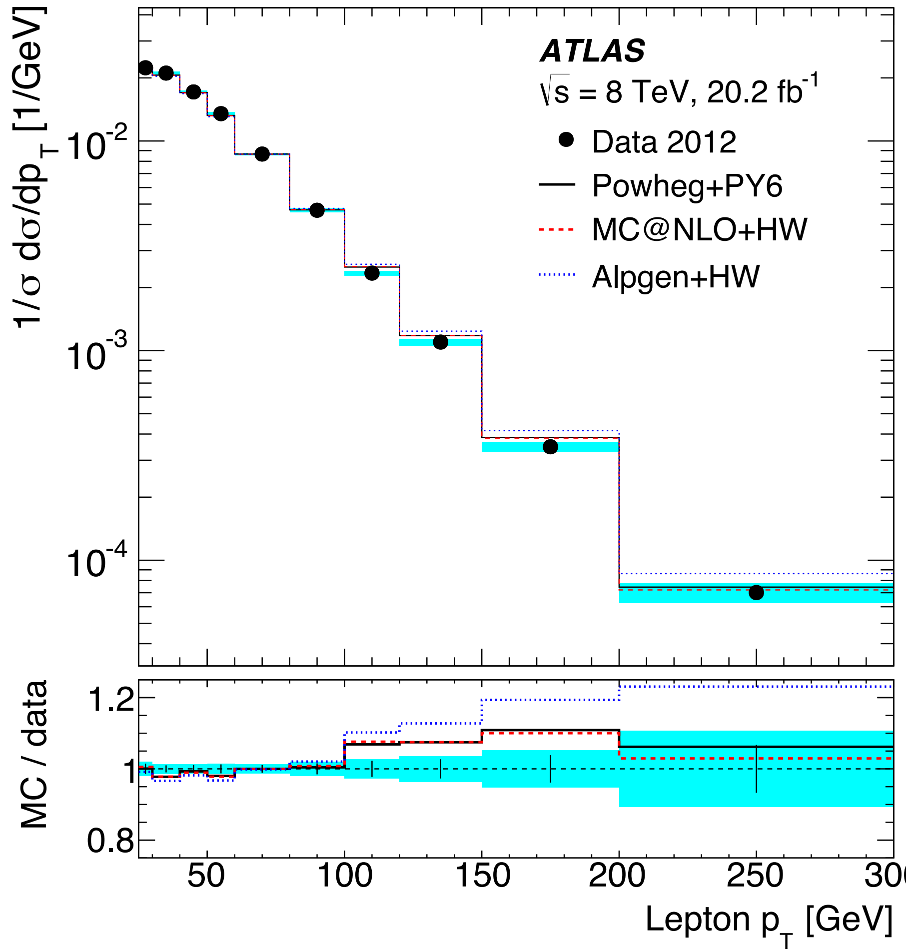
Description	Value [GeV]
$m_t^{\mathbf{pole}}$	**173.71**
Statistical uncertainty	**1.50**
Scale variations	(+0.93, −0.44)
Proton PDF (theory) and α_s	0.21
Total theory systematic uncertainty	**(+0.95, −0.49)**
Jet energy scale (including b-jet energy scale)	0.94
Jet energy resolution	0.02
Jet reconstruction efficiency	0.05
b-tagging efficiency and mistag rate	0.17
Lepton uncertainties	0.07
Missing transverse momentum	0.02
MC statistics	0.13
Signal MC generator	0.28
Hadronization	0.33
ISR/FSR	0.72
Colour reconnection	0.14
Underlying event	0.25
Proton PDF (experimental)	0.54
Background	0.20
Total experimental systematic uncertainty	**1.44**
Total uncertainty	**(+2.29, −2.14)**

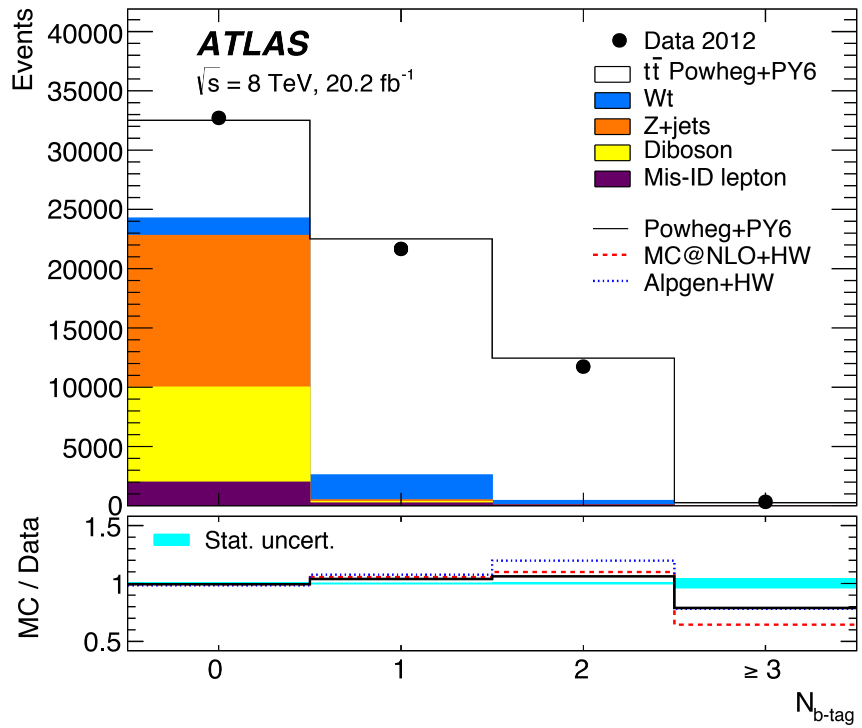
Mass (indirect): differential cross sections

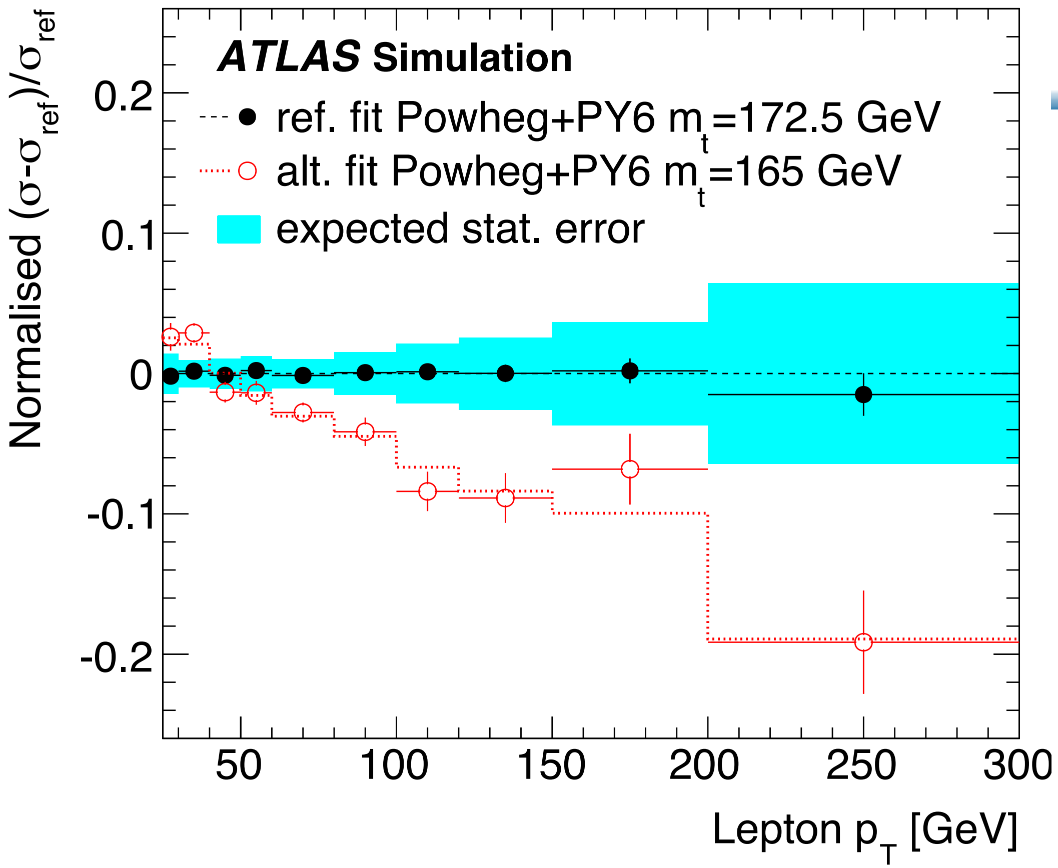
- Dileptonic events
- Single and double-lepton variables
- Absolute and normalised distributions
- Sensitivity to gluon PDF and m_t
- Fixed-order NLO predictions

Eur. Phys. J. C 77 (2017) 804



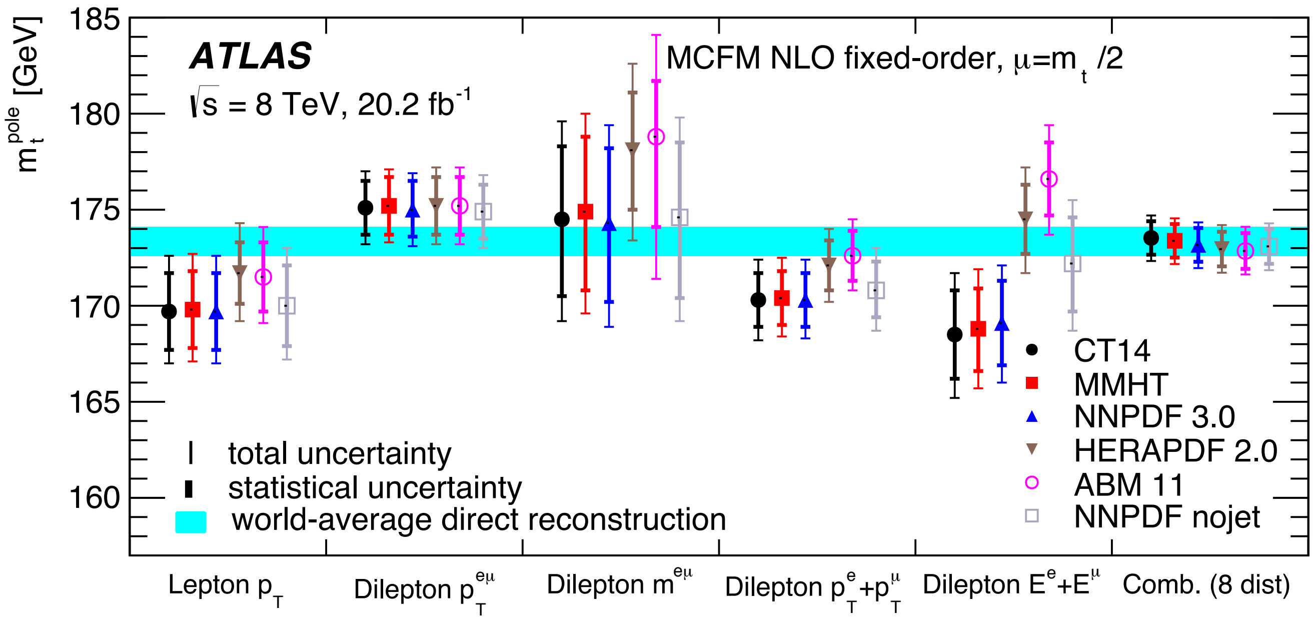






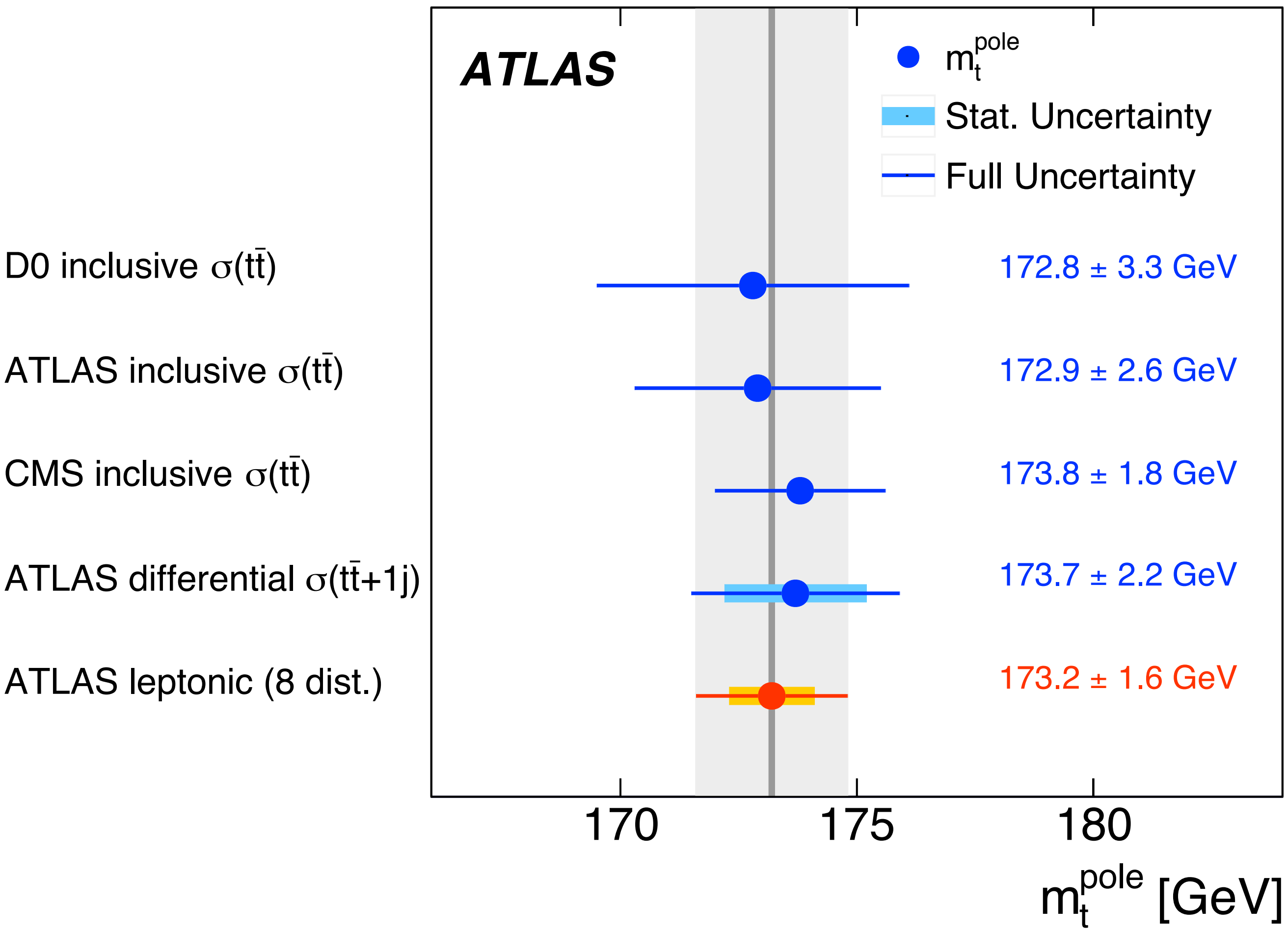
- Up to 8 differential cross section measurements:

p^{ℓ}_T, $|\eta^{\ell}|$, $p_T^{e\mu}$, $m^{e\mu}$, $|y^{e\mu}|$, $\Delta\varphi^{e\mu}$, $p^e_T + p^{\mu}_T$, $E^e + E^{\mu}$



Mass (indirect): differential cross sections

	p_T^ℓ	$p_T^{e\mu}$	$m^{e\mu}$	$p_T^e + p_T^\mu$	$E^e + E^\mu$
χ^2/N_{dof}	9/8	5/7	11/10	11/6	8/8
m_t^{pole} [GeV]	$169.7^{+2.9}_{-2.7}$	175.1 ± 1.9	$174.5^{+5.1}_{-5.3}$	170.3 ± 2.1	$168.5^{+3.2}_{-3.3}$
Data statistics	± 2.0	± 1.4	$^{+3.8}_{-4.0}$	± 1.4	± 2.3
Expt. systematic	$^{+2.5}_{-2.3}$	± 0.9	$^{+2.9}_{-3.3}$	$^{+1.5}_{-1.6}$	± 2.0
PDF uncertainty	± 0.5	± 0.1	± 1.1	± 0.5	± 1.4
QCD scales	± 1.1	$^{+0.7}_{-0.8}$	± 2.6	$^{+0.4}_{-0.5}$	± 0.7

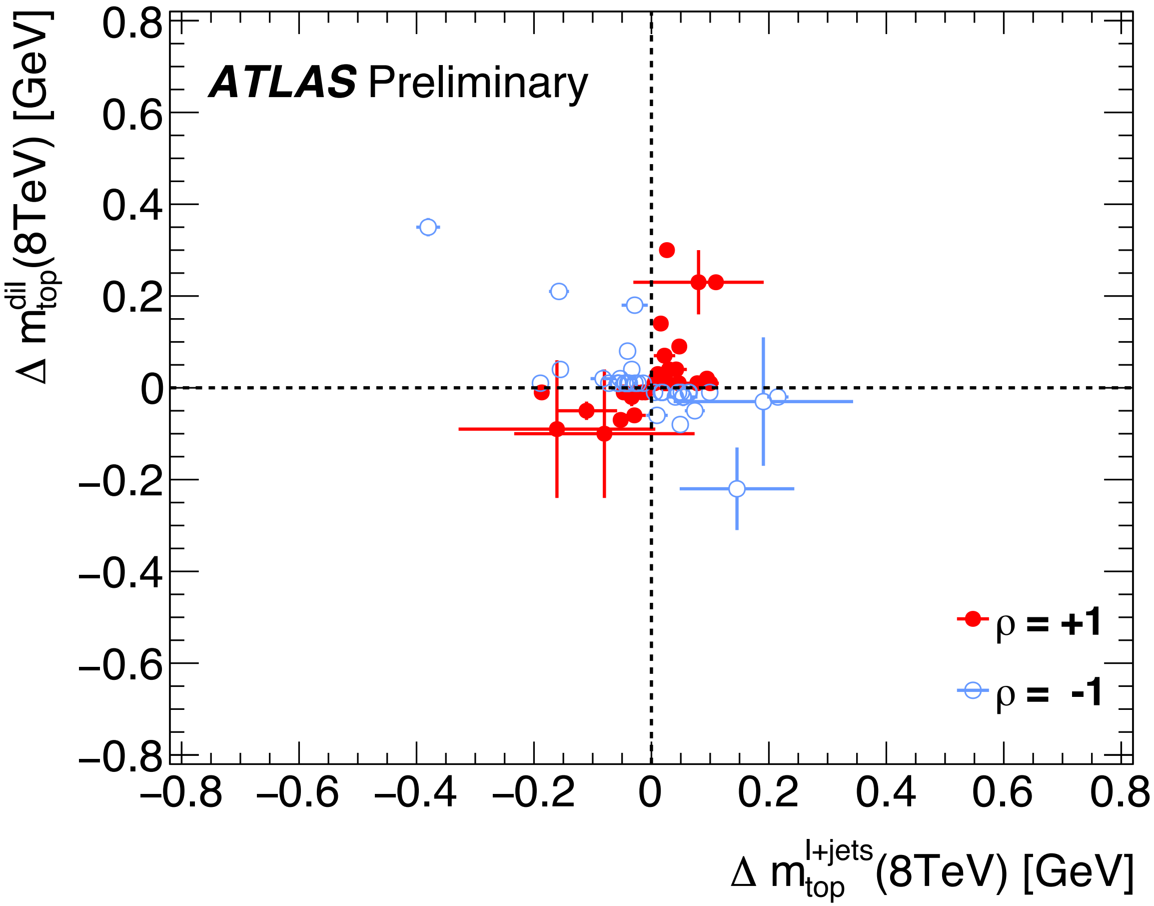


Summary Table of Uncertainties

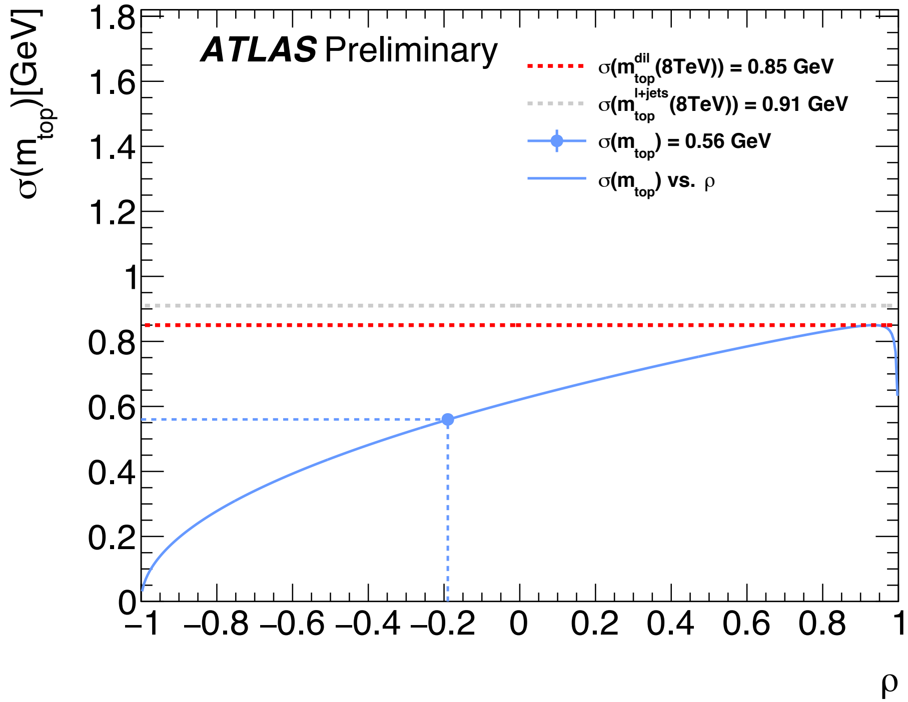
Analysis [GeV]	Direct M_{lb}-8TeV	Direct M_{jjj}/M_{jj}-8TeV	Direct m^{top}_{reco}-8TeV	Indirect σ_{tt} -7,8TeV	Indirect $1/\sigma\, d\sigma_{tt}/dp^{e\mu}_{T}$-8TeV (example)	Indirect $1/\sigma\, d\sigma_{tt}/d\rho_{S}$-7 TeV
Lead Syst.	JES: 0.5 bJES: 0.3 Hadr.: 0.2 I/FSR: 0.2	Hadr.: 0.6 JES: 0.6 bJES: 0.3	JES: 0.5 bTag: 0.4 JER: 0.2	*PDF+α_S: 1.7* Int Lumin.: 1.2 *QCD scale:1.1*	*Analysis*: 0.9 QCD scale:0.8	*JES,bJES*:0.9 *I/FSR:* 0.7 *PDF*:0.7 QCD scale:0.7
Total Syst.	0.7	1.0	0.8	2.5	1.2	1.6
Total Stat.	0.4	0.5	0.4	0.3	1.4	1.5
Total Unc.	**0.8**	1.1	**0.9**	2.5	1.9*	2.2

* if 8-distributions combined: 1.6

Combining Measurements

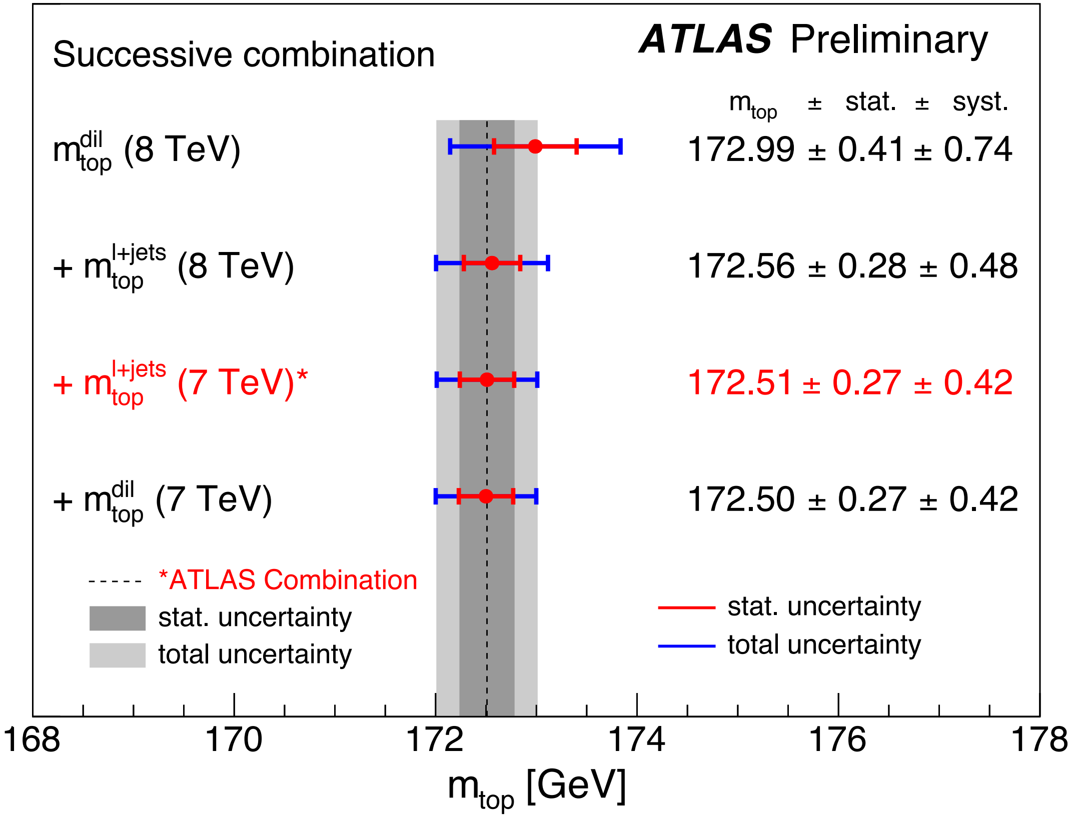


- Combination uses BLUE
- Un-correlated and Anti-correlated sources may bring valuable improvements (in this case JES, *b*JES)

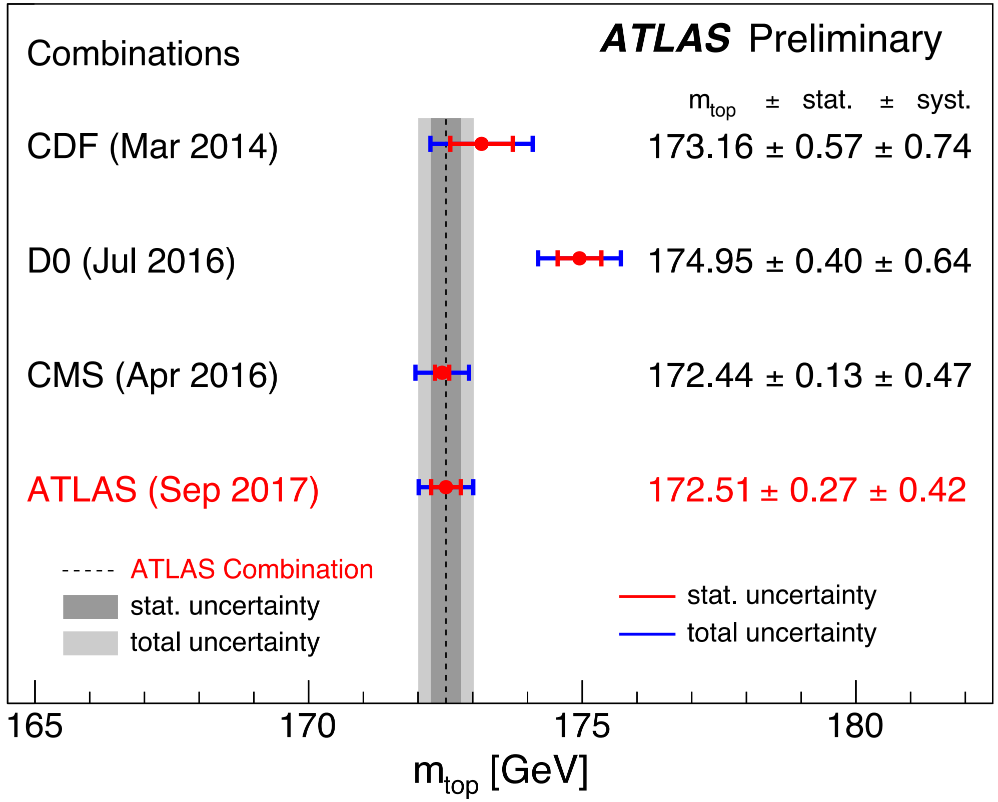


Combining Measurements

Successive combination

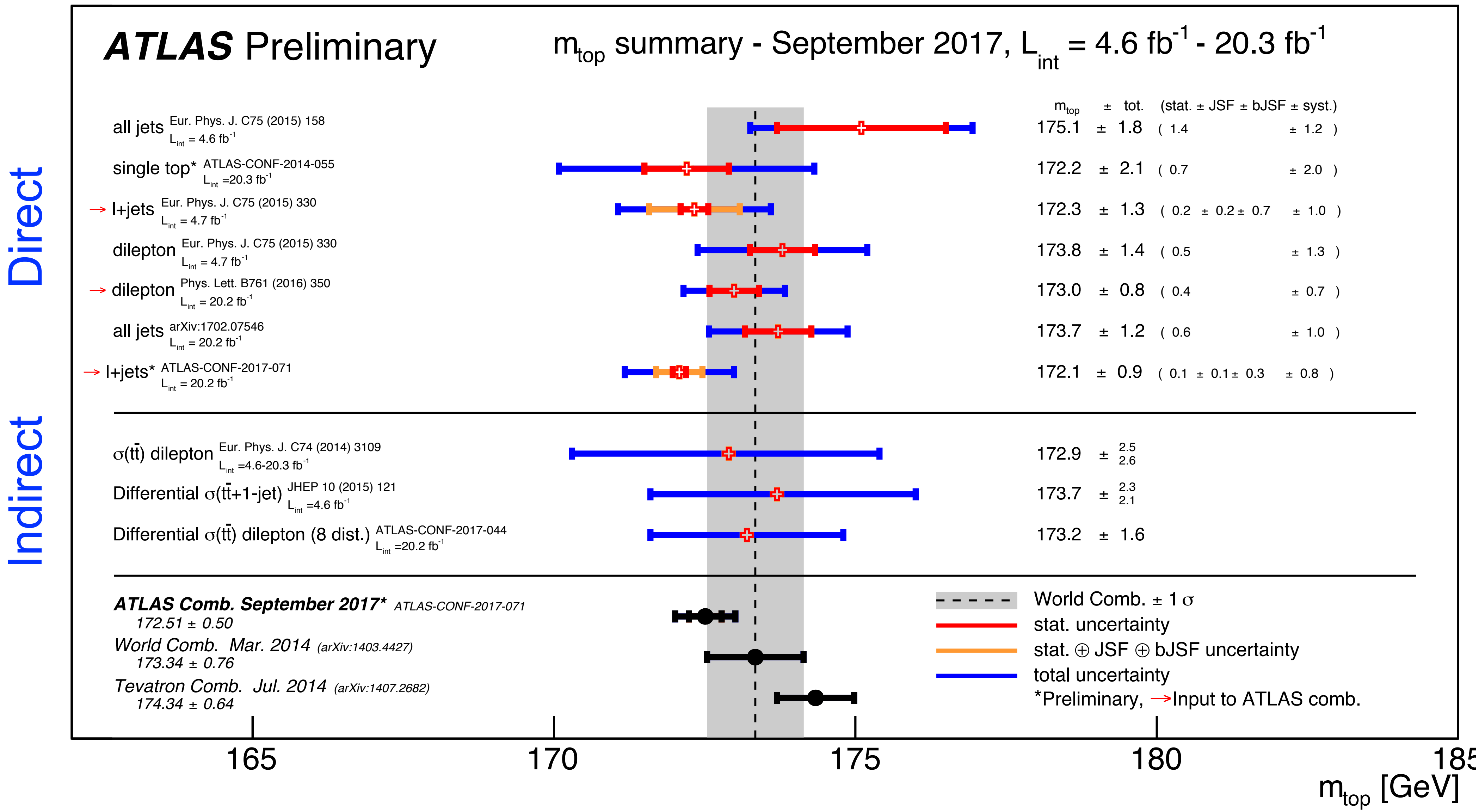


ATLAS vs Others



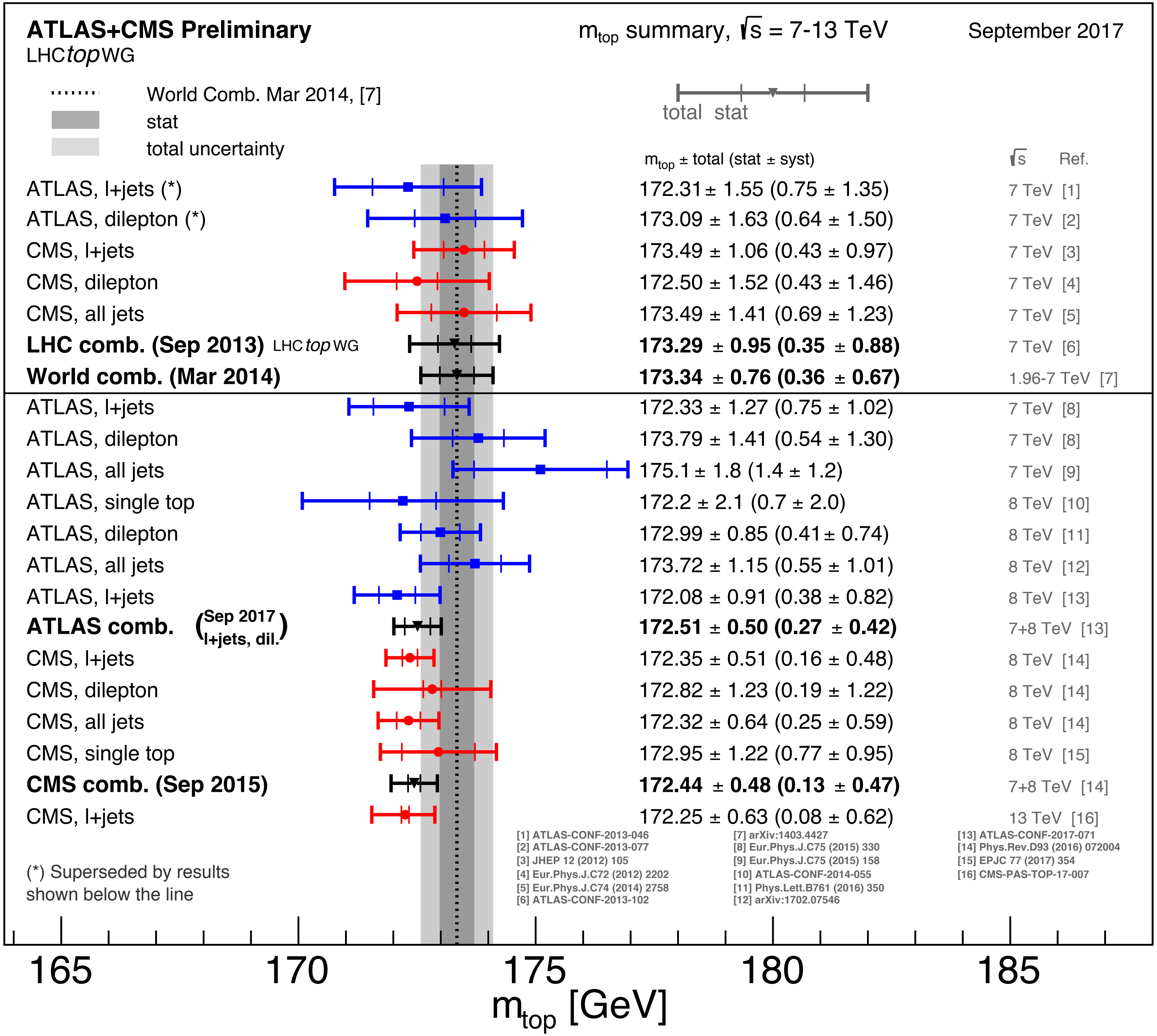
Reached the ~500 MeV barrier !

ATLAS Overview



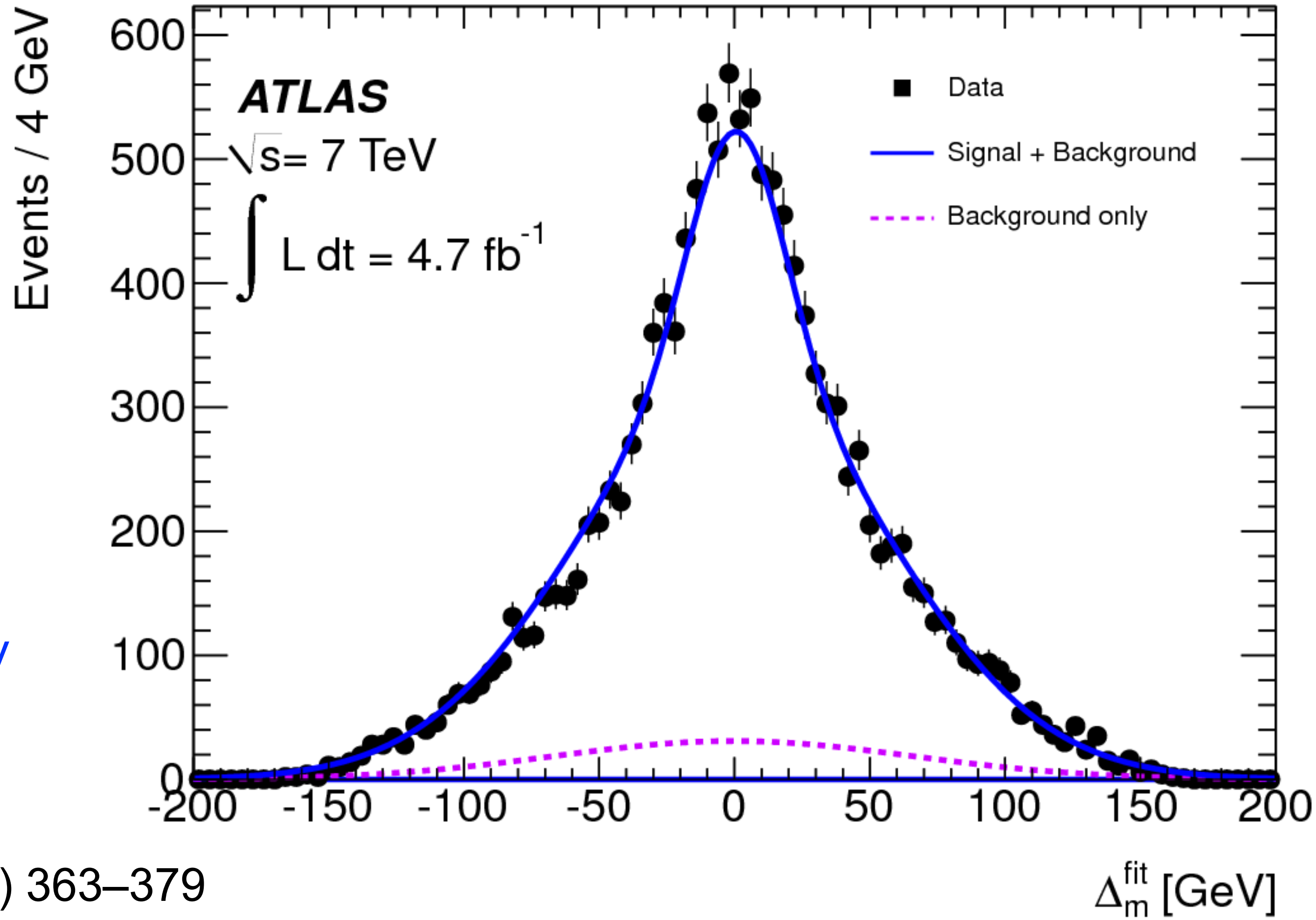
World Measurements Overview

Not yet updated with the latest measurements



Top and Anti-top masses

In case you are wondering if top and anti-top might have a different mass… it doesn't seem the case



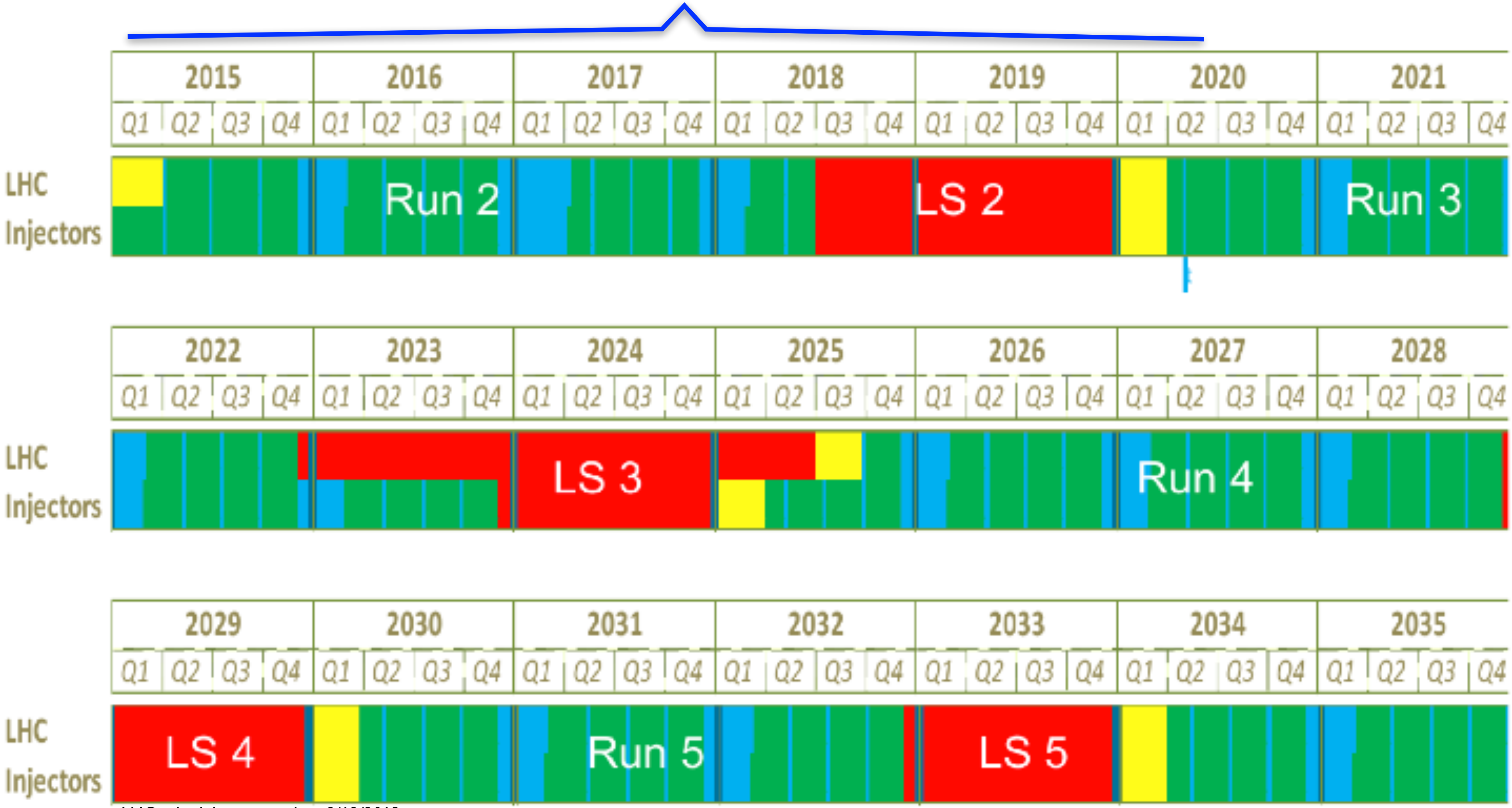
Δm = mt − mtbar = 0.67 ± 0.61 (stat) ± 0.41 (syst) GeV

Physics Letters B 728 (2014) 363–379

LHC schedule

LHC Run 2

- Collision energy: $\sqrt{s}$=13–14 TeV
- Accumulated Data: ~100 fb^{-1}
- Top Quarks: x15-20 Run I sample



LHC schedule approved on 2/12/2013

Conclusive Remarks

As always with precision measurements, it takes **meticulous** work and a **long time** to measure the top quark mass. But it's important ! and … fun !

Further improvements will likely come from:

—Anti-correlations,

—Different systematics

—Lepton-based measurements

These will lead to significant uncertainty reduction

$\rightarrow \Delta m_t < 500$ MeV

But need to clarify the theoretical aspects

Job Openings

For this programme, we are looking for:

- One 3-year Postdoctoral RA
- One 2-year Postdoctoral Grantee (junior)

At the University of Rome Tor Vergata

Info and to Apply (deadlines mid July):
http://nptev-tqp2020.roma2.infn.it/vacancies/