ATLAS SMT top mass and uncertainties at 13 TeV with focus on b-fragmentation (ATLAS) and Color Reconnection (CMS)

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on behalf of the ATLAS and CMS collaborations

LHC TOP WG Meeting, 15/11/2019

Outline

- Analysis of two top mass measurements:
  - Measurement of the top quark mass using a dileptonic invariant mass in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector ATLAS-CONF-2019-046
  - Measurement of the mass of the top quark in decays with a J/ψ meson in pp collisions at $\sqrt{s} = 8$ TeV with the CMS detector JHEP12(2016)123

- Focus on the common/different aspects in the treatment of some of the main systematic uncertainties
  - b-quark fragmentation
  - Color Reconnection
  - Other tt modelling uncertainties

Top mass: what are we measuring (and why)?

- m_t fundamental parameter of SM
  - EW precision test, Higgs interplay, vacuum stability, cosmological consequences (e.g. Higgs inflation model PRL 108 (2012) 191302) ...

- Measurement from direct reconstruction:
  - decay products → m_t
  - problem: measurement of "m_t^{MC}" due to color

Scheme not well defined, e.g. due to Parton Shower

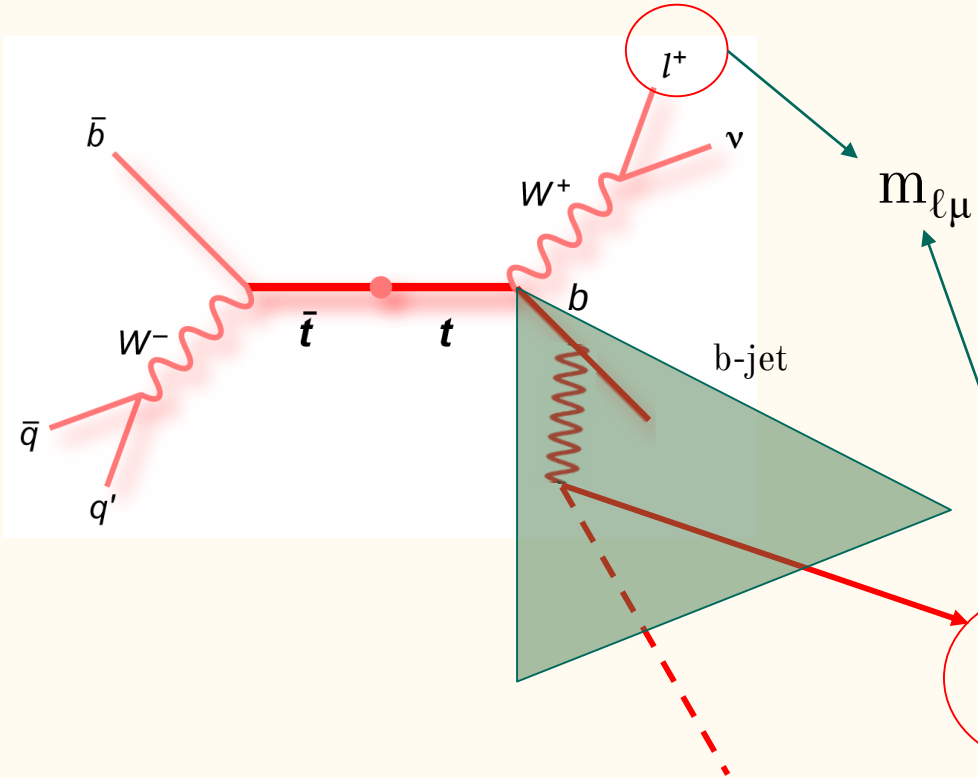
recent review on top mass definitions

- Measurement from production properties:
  - property $f(m_t^{pole})$ (e.g. cross section) + theory → m_t(scheme)
  - but: uncertainties in fixed-order calculations due to soft radiation, NP effects, ...

No full consensus on uncertainties on $m_t^{MC} \leftrightarrow m_t^{pole}$, ~few hundreds MeV

Top mass is not a physical mass, but a scheme dependent parameter

Top mass: the idea



- "Standard": e.g. $m_{\ell b} \rightarrow m_t$
- Here: semi-lept. decay of B-hadrons
  - BR = 20% for B→...→μ+X
  - BR = 0.016% for B→J/ψ + X
- Invariant mass $m_{\ell\mu} \rightarrow m_t$
  - purely leptonic,

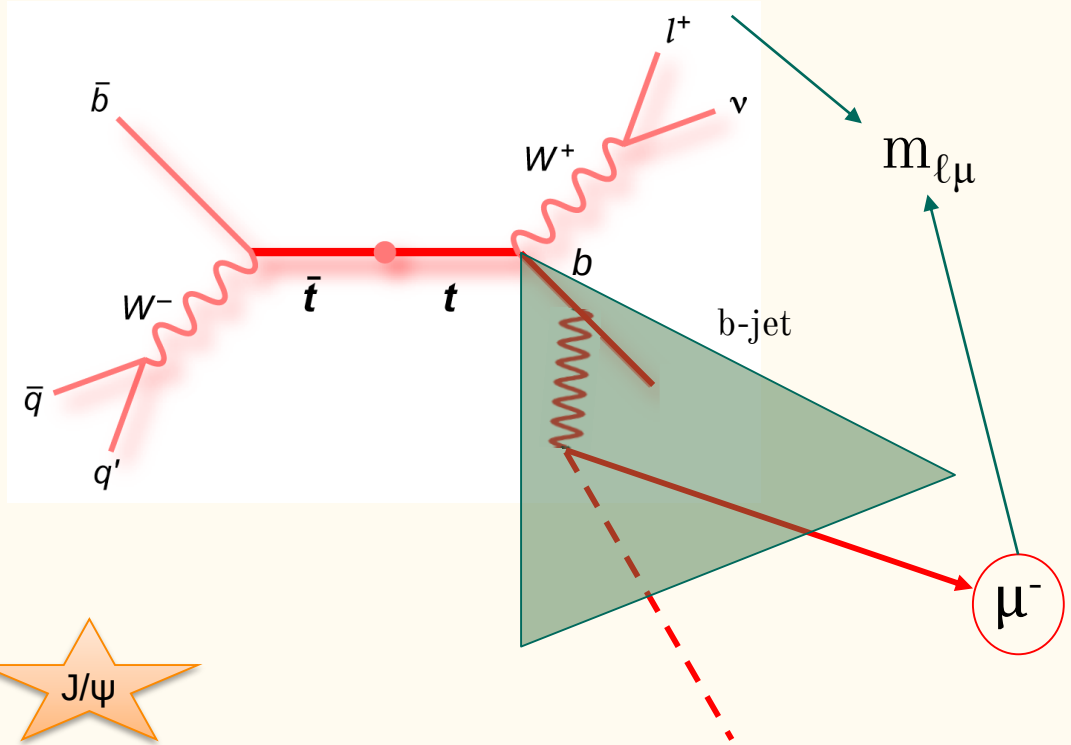
    less sensitive to jets unc.
  - more direct impact from b→B

    fragmentation modelling

    "Soft" Muon Tagging (SMT)

1st proof of principle: CDF Phys. Rev. D80 (2009) 051104, m_t=180.5 ± 12.5 GeV

Top mass: baseline selection



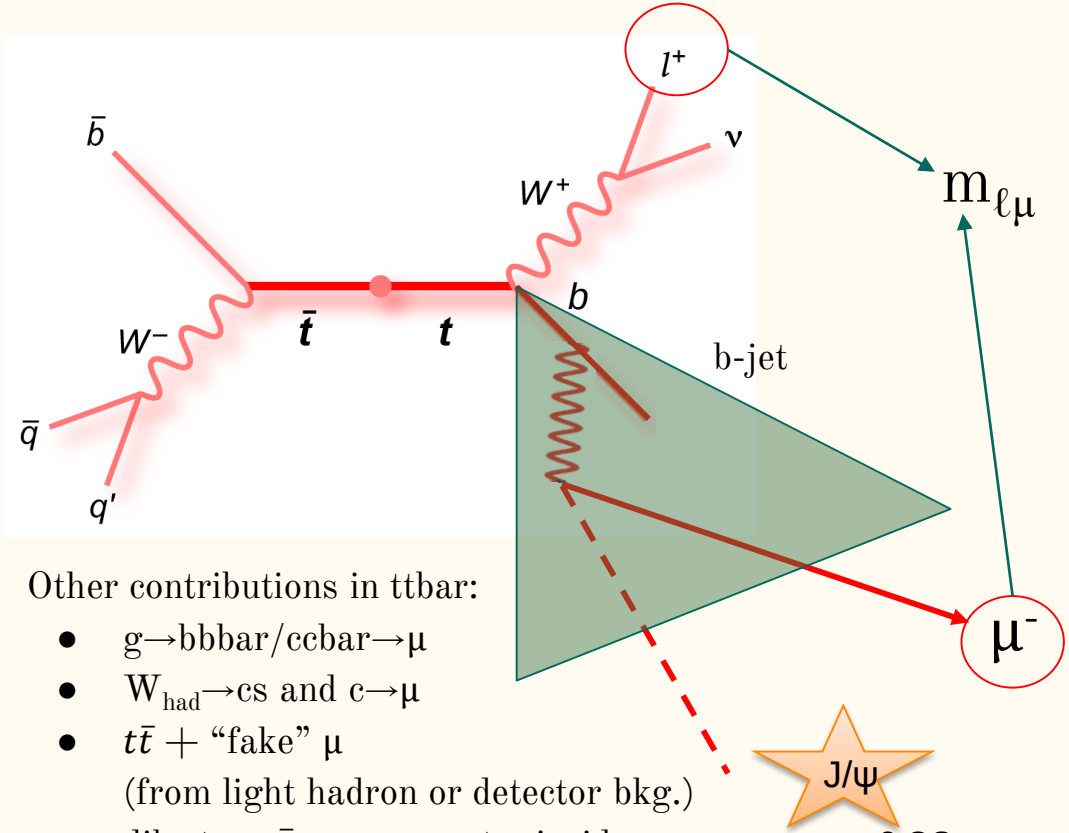
In the J/ψ analysis: 3 or 4 leptons final state where dileptonic ttbar events and single top events are part of the signal

- $=1$ isolated e/μ
- Cuts on E_T^{miss} and M_T^W
- ≥ 4 jets
- ≥ 1 jet 'b-tagged' (i.e. SV tagging)
- ≥ 1 SMT jet
  - i.e. μ with $p_T > 8$ GeV found within $\Delta R < 0.4$ of a jet

SMT calibrated in data:

- efficiency from $J/\Psi \rightarrow \mu\mu$
- fake rate from W+1 jet

Top mass: signal composition



Soft-μ in jets have different origins in $t\bar{t}$:

- direct b-hadron decay: most sensitive to m_t!
- B→D→μ and B→DDbar→μ (rarer)

More sensitivity to m_t if leptons from

SAME Top→ ΔR(W-lep, soft-μ)<2

OS

($q_{lep}q_{soft\ \mu}<0$ → more direct b→μ, more same top)

SS

($q_{lep}q_{soft\ \mu}>0$ → more b→c→μ, more different top)

Other contributions in ttbar:

- g→bbbar/ccbar→μ
- W_{had}→cs and c→μ
- $t\bar{t}$ + "fake" μ (from light hadron or detector bkg.)
- dilepton $t\bar{t}$, one prompt μ inside real/pile-up jet

- 2 OS muons to reconstruct the J/ψ. Charge of the 3rd lepton irrelevant
- Both same-top and different-top contributions considered

Top mass: backgrounds and yields

- Multi-jet from data-driven matrix method
- W+jets from MC, normalized in data using W^+/W^- asymmetry; flavor composition also data-driven
- Z+jets from MC, validated in data
- SMT fake from MC, validated in data
- Other from MC

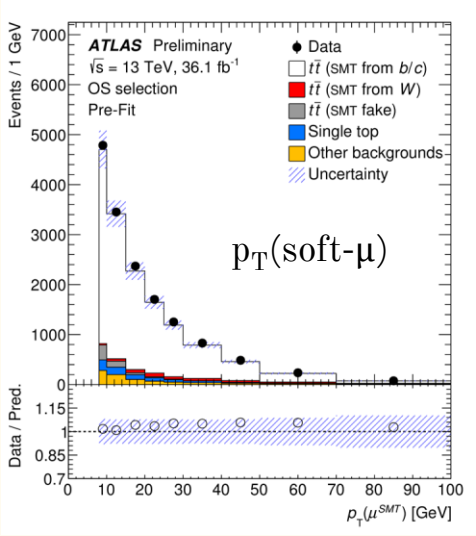
Process	Yield (OS)	Yield (SS)
$t\bar{t}$ (SMT from b- or c-hadron)	56 000 ± 4000	34 800 ± 2800
$t\bar{t}$ (SMT from $W \to \mu\nu$)	2190 ± 320	4.9 ± 3.6
$t\bar{t}$ (SMT fake)	1490 ± 210	1240 ± 170
Single top t-chan	770 ± 70	490 ± 40
Single top s-chan	63 ± 6	49 ± 4
Single top Wt	1840 ± 140	1260 ± 100
W+jets	1600 ± 400	1080 ± 240
Z+light jets	210 ± 80	15 ± 6
Z+HF jets	550 ± 170	310 ± 100
Diboson	17.2 ± 2.9	6.3 ± 1.4
Multi-jet	530 ± 140	480 ± 130
Total Expected	65 000 ± 5000	39 800 ± 3000
Data	66 891	42 087

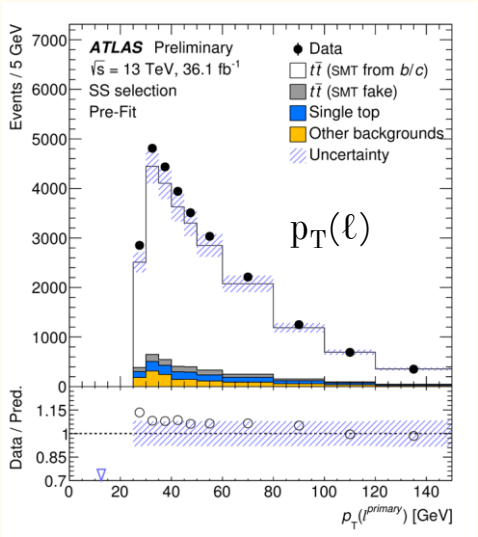
Break-up of ttbar (SMT from b- or c-hadron)

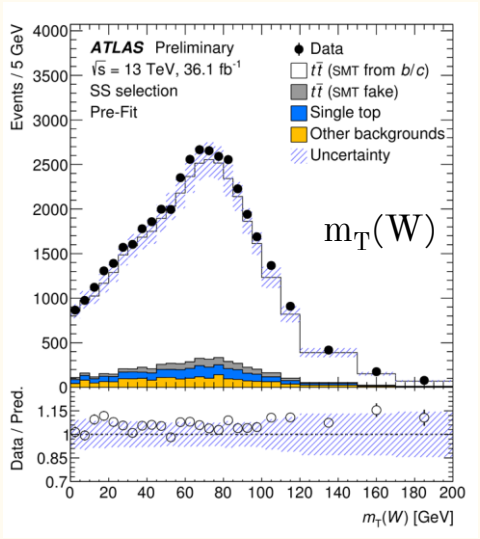
	OS [%]	SS [%]
Processes involving a μ from a t or $\bar{t}$		
$t \to B \to \mu$	73.6	51.2
$t \to B \to D \to \mu$	16.7	44.2
$t \to B \to \tau \to \mu$	2.0	1.3
$t \to B \to D \to \tau \to \mu$	0.8	0.8
Processes involving a μ not from a t or $\bar{t}$		
$B \to \mu$	0.6	0.9
$D \to \mu$	5.8	1.4
$\tau \to \mu$	0.5	0.1

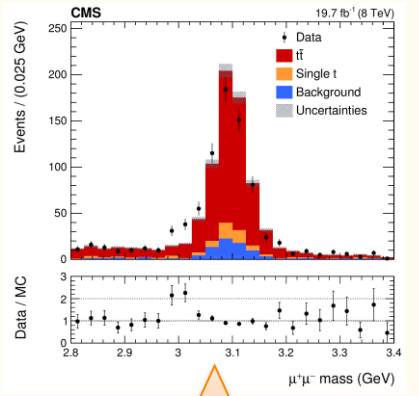
Process	Number of events	
	Leading μ	Leading e
$t\bar{t} \to b\ell^-\bar{\nu}\bar{b}q\bar{q}'$	228.1 ± 4.0	195.6 ± 3.7
$t\bar{t} \to b\ell^-\bar{\nu}\bar{b}\ell^+\nu$	66.3 ± 1.7	56.9 ± 1.6
$t\bar{t} \to bq\bar{q}'\bar{b}q\bar{q}'$	negligible	negligible
Single top quark	39.4 ± 3.8	30.6 ± 3.3
$W \to \ell\nu$ + jets	18.3 ± 3.2	12.1 ± 2.7
$Z/\gamma^* \to \ell^+\ell^-$ + jets	4.5 ± 0.9	6.3 ± 1.0
WW, WZ, ZZ	1.1 ± 0.3	1.2 ± 0.3
Predicted yield	357.7 ± 6.6	302.7 ± 5.9
Data	355	311

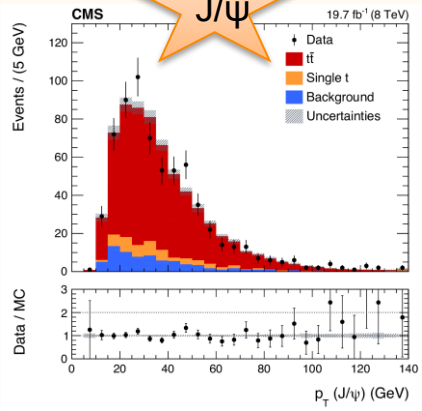
Top mass: backgrounds and yields











Control plots for few kinematic variables

- in the final analysis ttbar normalization fitted from data
- W-lepton p_T data/MC slope well known from many other analyses, no significant impact on m_t measurement

Top mass: signal modelling

Reweighted MC → PDG for:

- Production Fractions
  - For b- and c-hadrons (change muon kinematics)

Hadron	PDG (%)	Powheg+Pythia8	Scale Factor
B^0	0.404±0.006	0.429	0.941
B^+	0.404±0.006	0.429	0.942
B_s^0	0.103±0.005	0.095	1.088
b-baryon	0.088±0.012	0.047	1.874
D^+	0.226±0.008	0.290	0.780
D^0	0.564±0.015	0.553	1.020
D_s^0	0.080±0.005	0.093	0.857
c-baryon	0.109±0.009	0.038	2.898

- inclusive BRs to μ
  - For b- and c-hadrons (change signal composition)

Hadron	PDG	Powheg+Pythia8	Scale Factor
$b \to \mu$	$0.1095^{+0.0029}_{-0.0025}$	0.106	1.032
$b \to \tau$	0.0042 ± 0.0004	0.0064	0.661
$b \to c \to \mu$	0.0802 ± 0.0019	0.085	0.946
$b \to c\bar{c} \to \mu$	$0.016^{+0.003}_{-0.003}$	0.018	0.888
$c \to \mu$	0.082 ± 0.005	0.084	0.976

J/ψ

- Not done for the J/ψ analysis
  - It affects only the total yield and not the m(lep, J/ψ)

Top mass: signal modelling

Crucial to control fragmentation, i.e. b-quark→B-hadron momentum transfer

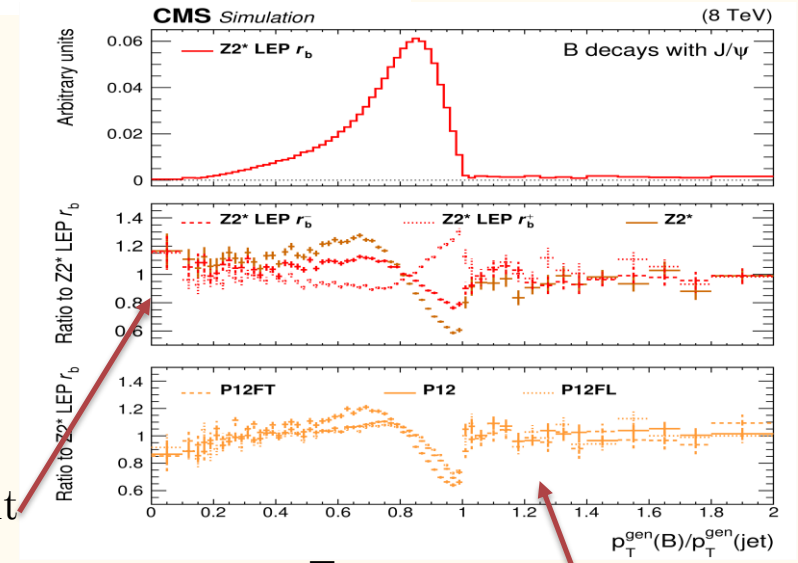
$z \sim E_{B\text{-had}}/E_{b\text{-quark}}$

- used Lund-Bowler model in Pythia8 → $f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp(-bm_T^2/z)$

a,b parameters not fitted: sensitive to light quark fragm.

- used LEP + SLD $e^+e^- \rightarrow Z \rightarrow b\bar{b}$ data to tune r_b parameter for the standard ATLAS A14 tune

$r_b = 0.855$ (Monash) → $r_b = 1.05 \pm 0.02$



J/ψ

- Two "retunings":

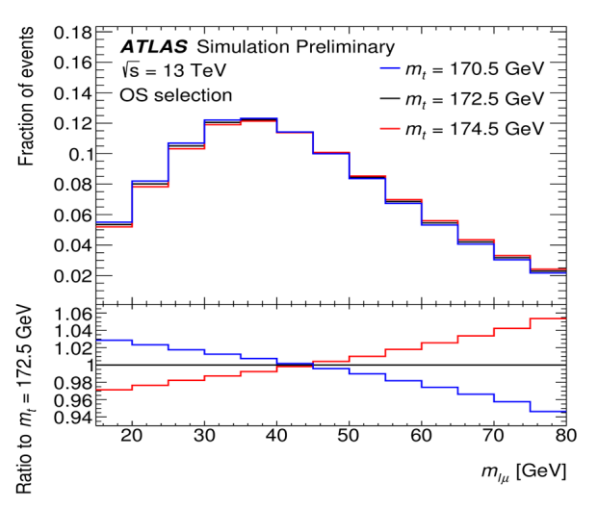
a) same Lund-Bowler implementation in Pythia6

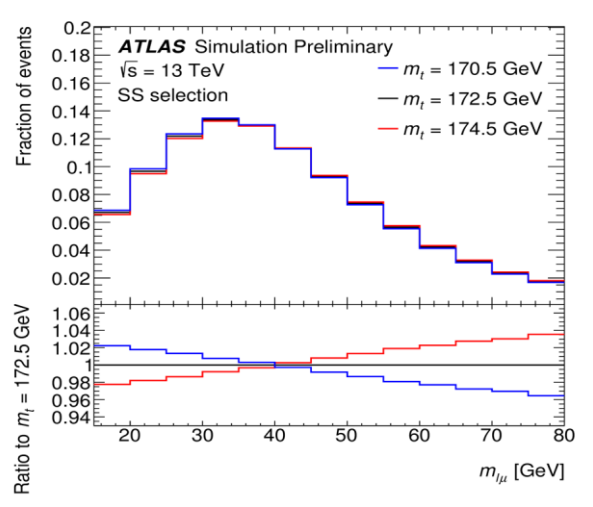
- rb=1 → rb = $0.591^{+0.216}_{-0.274}$ (rb value is different due to a different original "tune" Z2*) refitted to LEP $e^+e^- \rightarrow Z \rightarrow b\bar{b}$ data

b) Perugia12 tune with two variants in the Lund fragmentation function (called "FL" and "FT")

- Reweight of $PT(B)_{gen}/PT(jet)_{gen}$ distribution of the Z2* tuned $t\bar{t}$ sample to option a)

Top mass: extraction

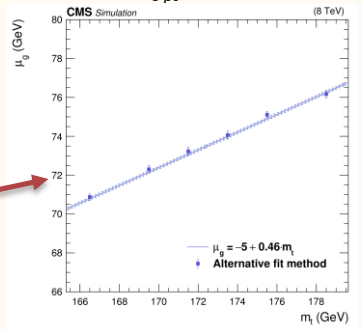




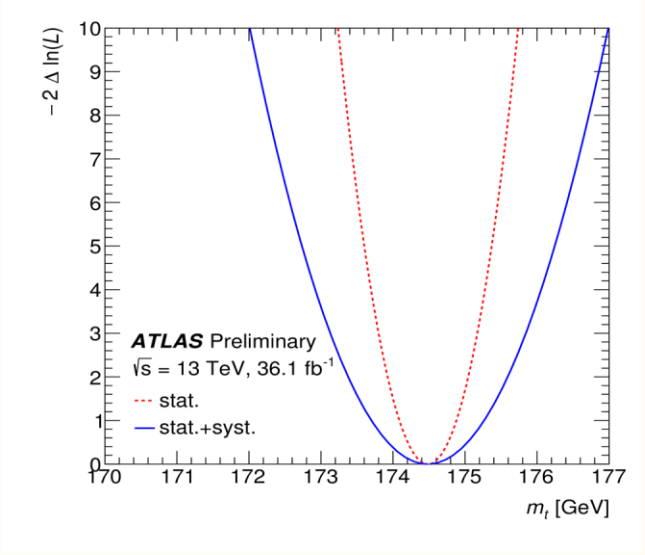
OS more sensitive to mt!

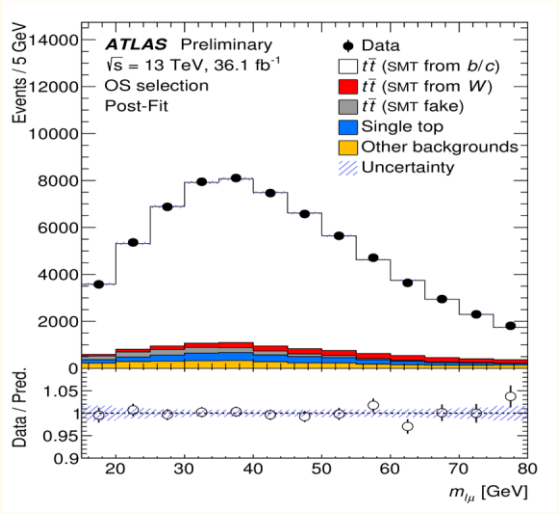
- Profiled Binned likelihood template fit in the 15-80 GeV region of $m_{\ell\mu}$
  - systematic uncertainties used as nuisance parameters
- Fit in the 0-250 GeV region of $m_{J/\psi\ell}$ with analytic function where mt depends linearly on the fitted parameters

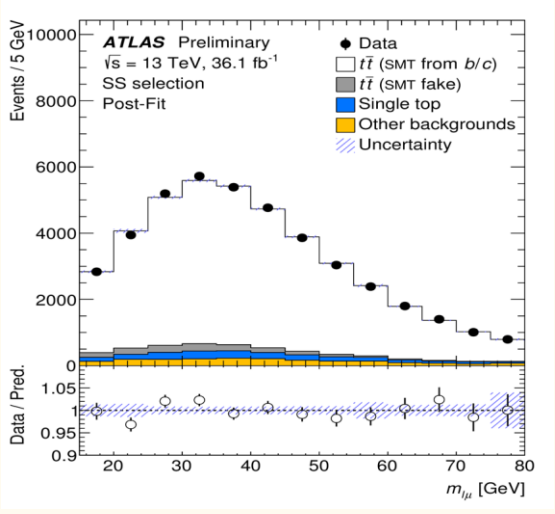
J/ψ



Top mass: results



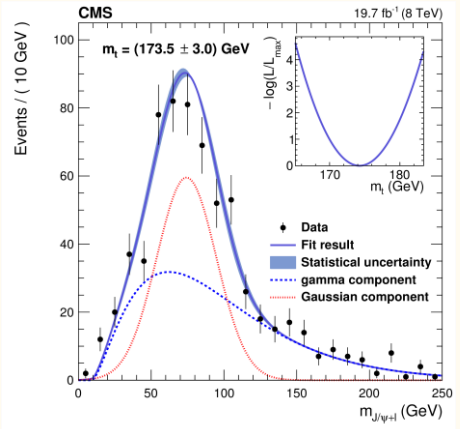




$$m_t = 174.48 \pm 0.40\,(\text{stat}) \pm 0.67\,(\text{syst})\ \text{GeV} = 174.48 \pm 0.78\ \text{GeV}$$

J/ψ

$$m_t = 173.5\ \pm 3.0\,(stat.)\ \pm 0.9\,(\text{syst.}) = 173.5\ \pm 3.1\ \text{GeV}$$



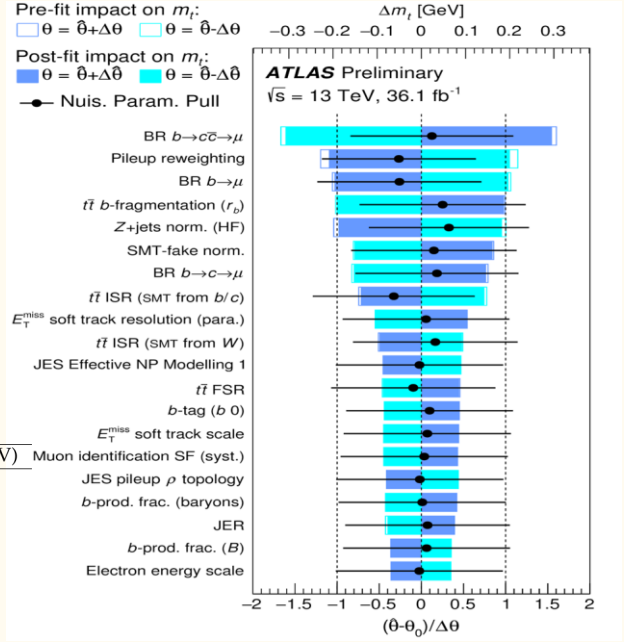
- ATLAS result limited by systematics
- CMS result limited by statistics at 8 TeV

Top mass: systematic uncertainties comparison

- BR b→ccbar→μ
  - ~ 30% uncertainty from direct meas.
- Pile-up
- BR b→μ: affects composition
- r_b: impacts fragmentation

- Top PT reweighting
- b-quark fragmentation
- Ren. and fact. scales
- ME/PS matching

Source	Value (GeV)
Experimental uncertainties	
Limited size of the simulation samples	±0.22
Muon momentum scale	±0.09
Electron momentum scale	±0.11
Modeling of the J/ψ meson candidate mass distribution	+0.09
Jet energy scale	<0.01
Jet energy resolution	<0.01
Trigger efficiencies	±0.02
Pileup	±0.07
Theoretical uncertainties	
Background normalization	±0.01
Matrix-element generator	−0.37
Factorization and renormalization scales	+0.12, −0.46
Matching of matrix element and parton shower	+0.12, −0.58
Top quark transverse momentum	+0.64
b quark fragmentation	±0.30
Underlying event	±0.13
Modeling of color reconnection	+0.12
Parton distribution functions	+0.39, −0.11
Total (in quadrature)	+0.89, −0.94



1) b-quark fragmentation systematics

ATLAS

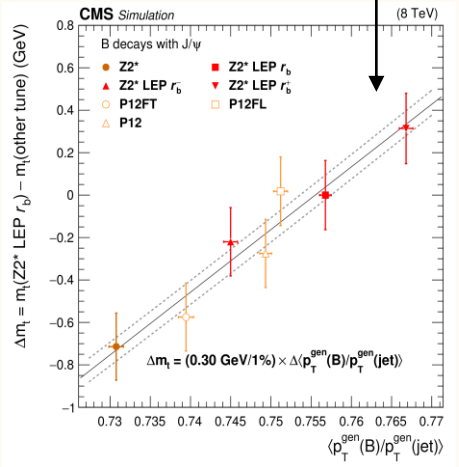
- Key variable: X_B (i.e. E(B)/E(b) at LEP)
- 3 sources affecting X_B distribution at LEP :
  - Uncertainty on LEP fit of $r_b = 1.05 \pm \mathbf{0.021}$
  - Parton Shower (a.k.a Pythia8 vs Herwig7.1.3)
  - $\alpha_{S,FSR}$ explicit variation by $\sqrt{2}$ and $1/\sqrt{2}$ after keeping X_B distribution at LEP constant
  - Uses only Lund-Bowler parameterisation
- Passage from LEP to LHC:
  - Color reconnection (see next slide)
- B-hadrons decay modelling
  - Change masses of D* mesons decays (covered by BRs uncertainties)
- Impact on top mass:
- rb fragmentation : 0.19 GeV
- Parton Shower: 0.07 GeV
- $\alpha_{S,FSR}$: 0.08 GeV

} 0.22 GeV

- Others negligible < 0.02 GeV

CMS

- Key variable: X_B (i.e. E(B)/E(b) at LEP)
- 1 source affecting X_B distribution at LEP :
  - Uncertainty on LEP fit of $r_b = 0.591^{+\mathbf{0.216}}_{-\mathbf{0.274}}$
  - Uses Lund-Bowler with Z2* tune and Lund param. for Perugia12 tune (also Peterson in previous papers)
  - Take the biggest impact on $PT(B)_{gen}/PT(jet)_{gen}$
- With Pythia8: CUETP8M2T4 tune including LEP+SLD data
  - $r_b = 0.95^{+\mathbf{0.14}}_{-\mathbf{0.197}}$ from eigentunes
- Passage from LEP to LHC:
  - Color reconnection
- Parton Shower
  - Variations of Pythia parameters
- Hadronisation:
  - Cluster vs string model with Sherpa as ME
- J/ψ decay modelling



- Impact on top mass:
- rb fragmentation : 0.30 GeV
- Hadronisation and J/ψ modelling: negligible

2) Color Reconnection and Underlying event

ATLAS

- Color Reconnection and underlying event
- 4 variations w.r.t. the nominal Pythia8 model:
  - Pythia8 eigentunes for UE
  - CR parameters in UE from jet measurements
  - CR Pythia8 strength set to maximum value
  - CR Pythia8 strength set to zero
  - ERD model used (to “connect” b-quarks in the top decay with the rest of the event)

- Impact on top mass: negligible < 0.02 GeV

CMS

- In J/ψ analysis using Pythia6:
  - 2 variations of UE tune based on P12 (Phys. Rev. D 82, 074018)
  - 1 variation of CR parameters (decrease the amount of CR)

- In more recent mass analysis Pythia8 is used:
  - CR parameters in UE tuned to CMS tt 13 TeV data (arXiv:1807.02810). Variations of UE/CR parameters within their uncertainties used as systematic.
  - CR systematics: 2 alternatives to the standard CR calculations in Pythia 8 with ERD’s turned on (+1 with ERD off):
    - QCD-Inspired (JHEP 08 (2015) 003)
    - Gluon Move (JHEP 11 (2014) 043)
  - Take the largest difference of the three alternatives (it’s the gluon move model) as systematic.

- Impact on top mass:
  - 0.33 ± 0.07 GeV (hadronic channel) – EPJC 79 (2019) 313
  - 0.31 ± 0.08 GeV (l+jets channel) – EPJC 78 (2018) 891

Second largest systematic uncertainty in CMS Run 2 mass measurements.

3) Other modelling systematics

ATLAS

- B-hadrons production fractions/b→μ BRs and decay modelling
  - b → $c\bar{c}$ → μ dominant! (Still LEP measurement)
- Scale variations (a.k.a ISR):
  - Var3cUP/Var3cDOWN variations including coherent renormalisation and factorization x0.5 or x2 and hdamp variations
- PDF: Standard PDF4LHC15 prescription
- NLO generator choice:
  - Powheg+Pythia8 vs amc@nlo+Pythia8 with the same shower settings (global recoil and ME corrections)
- Top-PT reweighting to NNLO calc.
  - Not applied. Help curing Lepton-PT non-ideal modelling?
- Impact on top mass:
- B-hadron prod. fractions: 0.11 GeV
- b→μ BRs and decay modelling: 0.39 GeV
- ISR : 0.17 GeV
- PDF: 0.06 GeV
- NLO: 0.04 GeV

CMS (most recent analyses)

- b-jet modelling. Quadrature sum of:
  - b-fragmentation modeling (includes Lund-bowler vs Peterson)
  - b→μ BR uncertainties → 0.09 (0.12) GeV on m_{top} for hadronic (l+jets) channel
- Scale variations (ren. and fact.): same as ATLAS –> Negligible impact
- PDF: same as ATLAS
- ME/PS matching: Powheg+Pythia with variation of hdamp within its uncert.
- NLO generator choice: same as ATLAS but different matching scheme.
- ISR/FSR scales (Pythia8):
  - ISR scales variations: x 2, x 0.5;
  - FSR variations: x $\sqrt{2}$, x 1/ $\sqrt{2}$
- Top-pT reweighted to data
  - Difference between the NLO and re-weighted NLO results taken as systematics
  - Main systematic in J/ψ analysis (0.64 GeV); negligible in hadronic and l+jets
- Hadronization modeling: Flavor dependent JEC by comparing string vs cluster model.
  - Linear sum of the signed uncertainties
  - b-quark component dominant → Impact on m_{top} : 0.34 GeV (hadronic) 0.39 GeV (l+jets)

Conclusions

- New ATLAS m_t measurement using soft-muons from b-quark decays has a 0.78 GeV (0.45%) uncertainty
  - “alternative” methods now competitive with “standard” methods
  - “independent” cross-check, sensitive to different modelling effects, useful for combinations
- Comparison with CMS measurement using J/ψ (limited by statistics in Run1 data)
  - Modelling uncertainties dominates
  - b-fragmentation treated roughly in the same way. Impact of 220-300 MeV (despite very different uncertainty on r_b and difference in the usage if the LEP+SLD data)
  - Color Reconnection systematics estimated by using other models (not simply on/off)
    - Crucial aspect in the b-fragmentation description from LEP to LHC (measurement of the b-fragmentation in $t\bar{t}$ events at LHC needed…)
  - ATLAS main systematic is the uncert. on b → $c\bar{c}$ → μ BR measurement
  - CMS has almost no impact from CR in the J/ψ analysis, but a big one in the all-hadronic one
  - Top-PT reweighting: CMS does it (take full difference as syst.), ATLAS doesn’t
    - Smaller for Powheg than for Madgraph. To be applied or not for future combinations ?

BACKUP

CMS J/ψ

Source	Value (GeV)
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Top quark transverse momentum	+0.64
b quark fragmentation	±0.30
Underlying event	±0.13
Modeling of color reconnection	+0.12
Parton distribution functions	+0.39, −0.11
Total (in quadrature)	+0.89, −0.94

ATLAS SMT

Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Data statistics	0.40	
Signal and background model statistics	0.16	
Monte Carlo generator	0.04	±0.07
Parton shower and hadronisation	0.07	±0.07
Initial-state QCD radiation	0.17	±0.07
Parton shower α_S^{FSR}	0.09	±0.04
b-quark fragmentation	0.19	±0.02
HF-hadron production fractions	0.11	±0.01
HF-hadron decay modelling	0.39	±0.01
Underlying event	< 0.01	±0.02
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.06	±0.01
W/Z+jets modelling	0.17	±0.01
Single top modelling	0.01	±0.01
Fake lepton modelling ($t \to W \to \ell$)	0.06	±0.02
Soft muon fake modelling	0.15	±0.03
Jet energy scale	0.12	±0.02
Soft muon jet p_T calibration	< 0.01	±0.01
Jet energy resolution	0.07	±0.05
Jet vertex tagger	< 0.01	±0.01
b-tagging	0.10	±0.01
Leptons	0.12	±0.00
Missing transverse momentum modelling	0.15	±0.01
Pile-up	0.20	±0.05
Luminosity	< 0.01	±0.01
Total systematic uncertainty	0.67	±0.04
Total uncertainty	0.78	±0.03

CMS all-had

Table 1 List of systematic uncertainties for the all-jets channel. The signs of the shifts ($\delta x = x_{\text{variation}} - x_{\text{nominal}}$) correspond to the +1 standard deviation variation of the systematic uncertainty source. For linear sums of the uncertainty groups, the relative signs have been considered. Shifts determined using dedicated samples for the systematic variation are displayed with the corresponding statistical uncertainty

	2D		1D	Hybrid	
	δm_t^{2D} [GeV]	$\delta \text{JSF}^{\text{2D}}$ [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	$\delta \text{JSF}^{\text{hyb}}$ [%]
Experimental uncertainties					
Method calibration	0.06	0.2	0.06	0.06	0.2
JEC (quad. sum)	0.18	0.3	0.73	0.15	0.2
Intercalibration	−0.04	−0.1	+0.12	−0.04	−0.1
MPFInSitu	−0.03	0.0	+0.22	+0.08	+0.1
Uncorrelated	−0.17	−0.3	+0.69	+0.12	+0.2
Jet energy resolution	−0.09	+0.2	+0.09	−0.04	+0.1
b tagging	0.02	0.0	0.01	0.02	0.0
Pileup	−0.06	+0.1	0.00	−0.04	+0.1
Background	0.10	0.1	0.03	0.07	0.1
Trigger	+0.04	−0.1	−0.04	+0.02	−0.1
Modeling uncertainties					
JEC flavor (linear sum)	−0.35	+0.1	−0.31	−0.34	0.0
Light quarks (uds)	+0.10	−0.1	−0.01	+0.07	−0.1
Charm	+0.03	0.0	−0.01	+0.02	0.0
Bottom	−0.29	0.0	−0.29	−0.29	0.0
Gluon	−0.19	+0.2	+0.03	−0.13	+0.2
b jet modeling (quad. sum)	0.09	0.0	0.09	0.09	0.0
b frag. Bowler–Lund	−0.07	0.0	−0.07	−0.07	0.0
b frag. Peterson	−0.05	0.0	−0.04	−0.05	0.0
Semileptonic b hadron decays	−0.03	0.0	−0.03	−0.03	0.0
PDF	0.01	0.0	0.01	0.01	0.0
Ren. and fact. scales	0.05	0.0	0.04	0.04	0.0
ME/PS matching	+0.32 ± 0.20	−0.3	−0.05 ± 0.14	+0.24 ± 0.18	−0.2
ISR PS scale	+0.17 ± 0.17	−0.2	+0.13 ± 0.12	+0.12 ± 0.14	−0.1
FSR PS scale	+0.22 ± 0.12	−0.2	+0.11 ± 0.08	+0.18 ± 0.11	−0.1
Top quark p_T	+0.03	0.0	+0.02	+0.03	0.0
Underlying event	+0.16 ± 0.19	−0.3	−0.07 ± 0.14	+0.10 ± 0.17	−0.2
Early resonance decays	+0.02 ± 0.28	+0.4	+0.38 ± 0.19	+0.13 ± 0.24	+0.3
CR modeling (max. shift)	+0.41 ± 0.29	−0.4	−0.43 ± 0.20	−0.36 ± 0.25	−0.3
"gluon move" (ERD on)	+0.41 ± 0.29	−0.4	+0.10 ± 0.20	+0.32 ± 0.25	−0.3
"QCD inspired" (ERD on)	−0.32 ± 0.29	−0.1	−0.43 ± 0.20	−0.36 ± 0.25	−0.1
Total systematic	0.81	0.9	1.03	0.70	0.7
Statistical (expected)	0.21	0.2	0.16	0.20	0.1
Total (expected)	0.83	0.9	1.04	0.72	0.7

ATLAS SMT

Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Data statistics	0.40	
Signal and background model statistics	0.16	
Monte Carlo generator	0.04	±0.07
Parton shower and hadronisation	0.07	±0.07
Initial-state QCD radiation	0.17	±0.07
Parton shower α_S^{FSR}	0.09	±0.04
b-quark fragmentation	0.19	±0.02
HF-hadron production fractions	0.11	±0.01
HF-hadron decay modelling	0.39	±0.01
Underlying event	< 0.01	±0.02
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.06	±0.01
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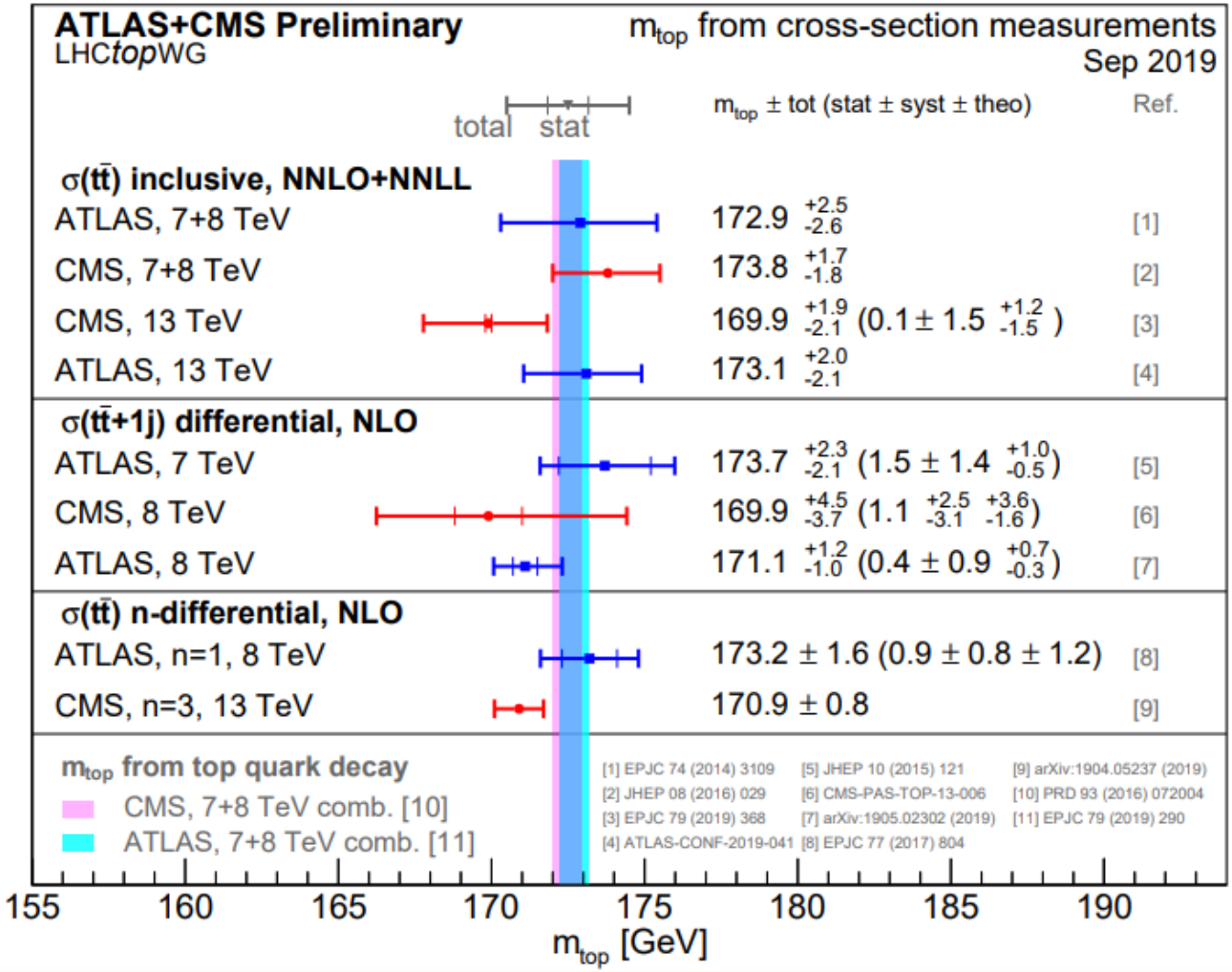
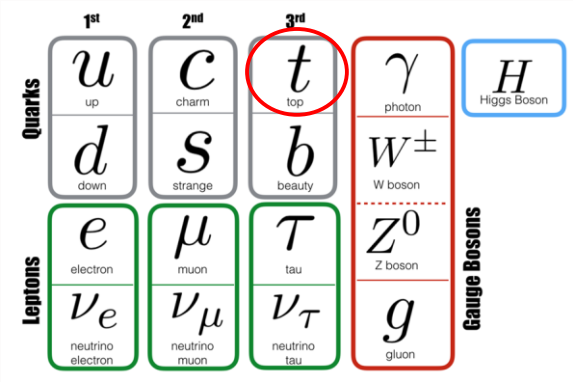
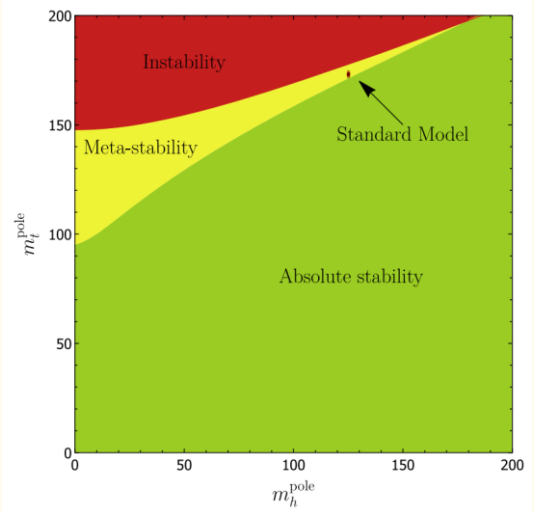


Summary of “indirect” top mass measurements

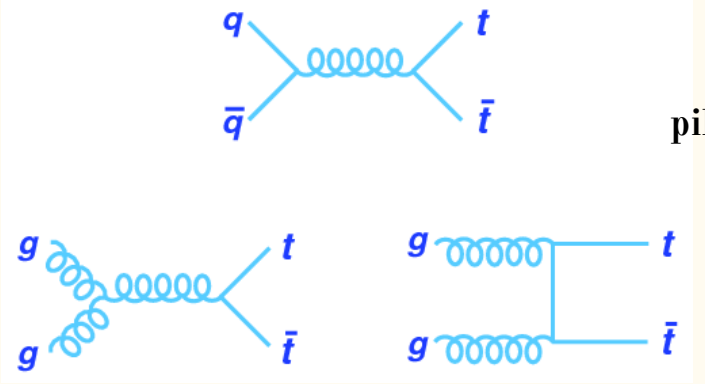
Physics of the top quark



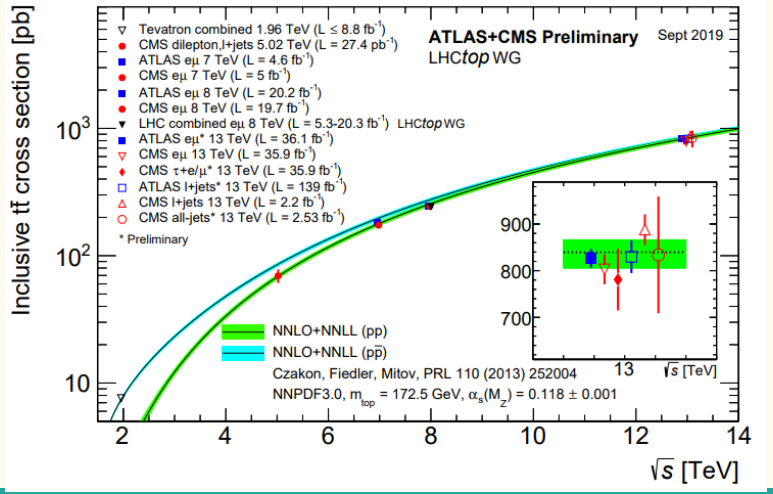


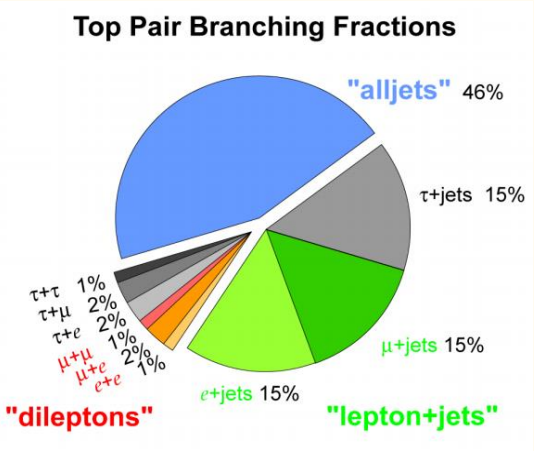
- Heaviest elementary particle in the SM
  - $m_t \sim 173$ GeV
- High mass → special properties
  - only quark decaying before hadronization
  - m_t crucial input for EW precision tests
- Special interplay with the Higgs boson
  - Yukawa coupling O(1)
  - naturalness, vacuum stability, quartic coupling...
- Cosmological consequences
  - e.g. Universe lifetime, see PhysRevD.97.056006
- Challenging for experiments AND theory
- Top physics → new physics?

Top pairs production at hadron colliders



- Production at LHC
  - 90% gg, σ(pp→ttbar @ 13 TeV)~830 pb
  - pile-up
  - $O(10^{34}cm^{-2}s^{-1}) \rightarrow O(10\ ttbar/s)$
- Decay: t→Wb





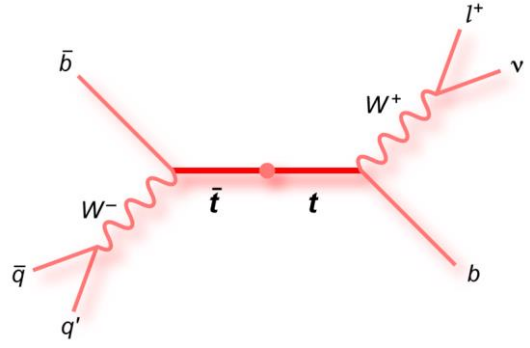
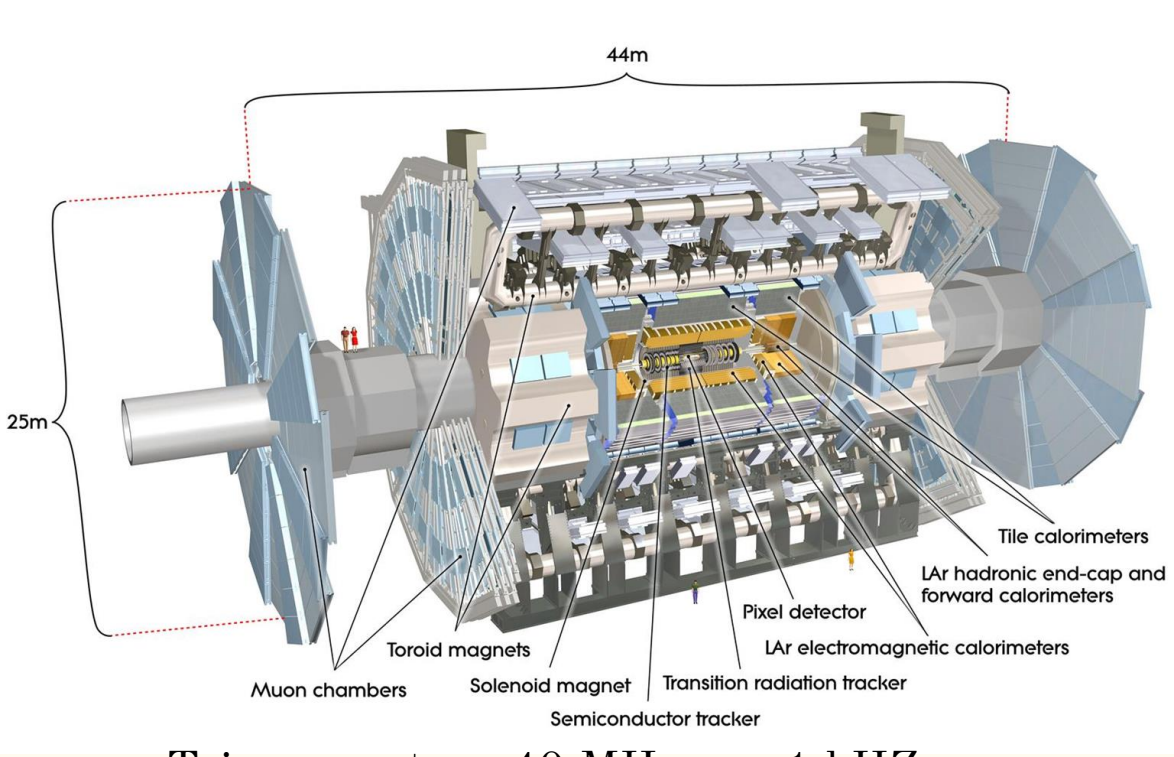
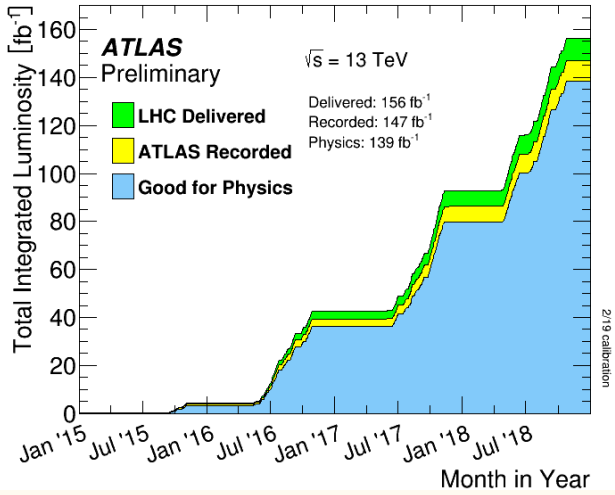
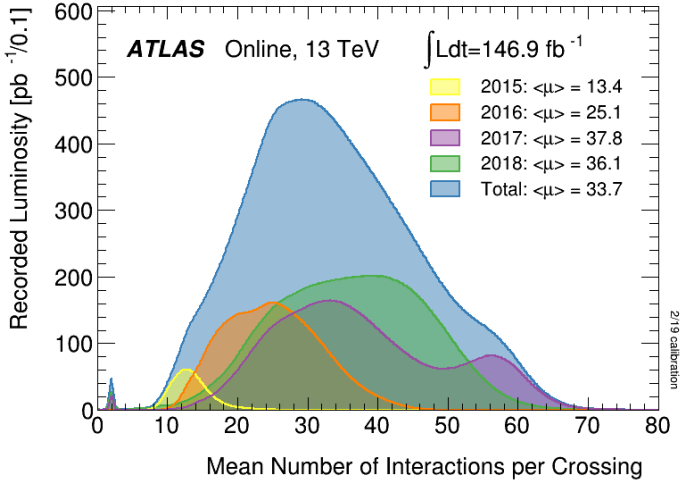


Diagram of a l+jets decay

The ATLAS detector





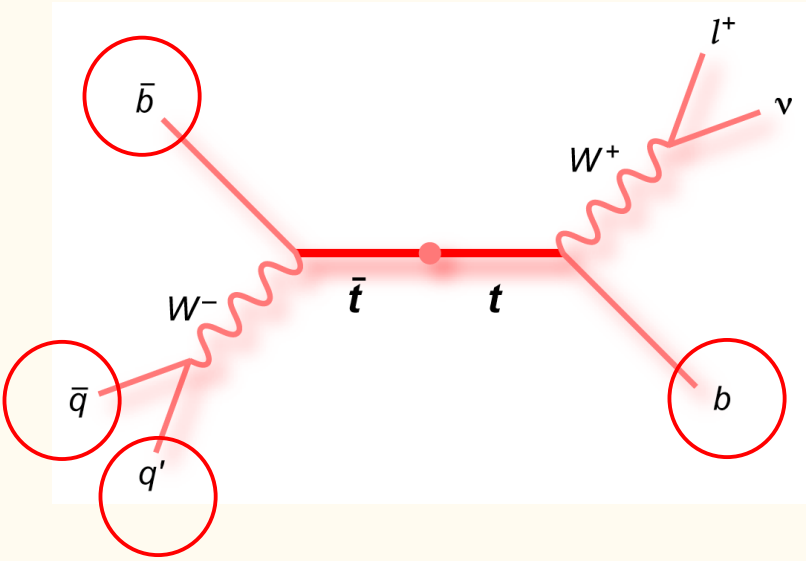


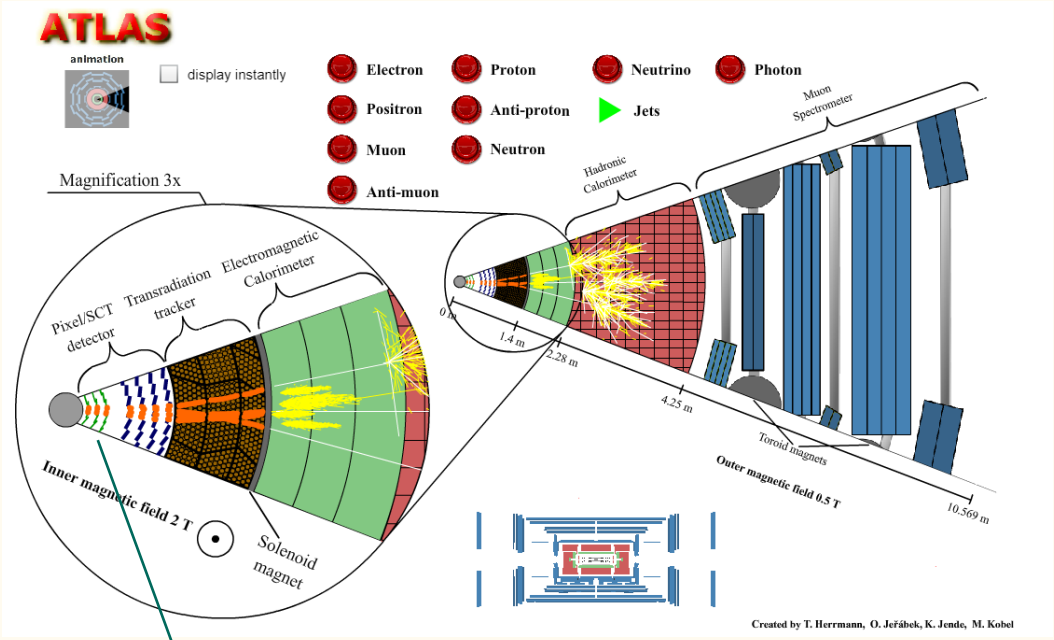
Trigger system: 40 MHz → ~1 kHZ

~139/fb of 13 TeV data available for analyses,

~1.7% uncertainty on luminosity ATLAS-CONF-2019-021

ttbar events in the ATLAS detector: jets



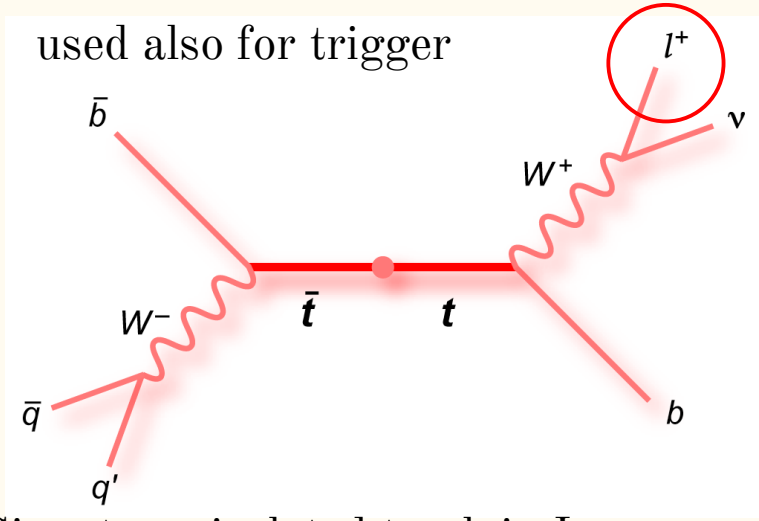


Signature: shower of hadrons in Inner Detector + Calorimeters
(+ Muon Spectrometer punch-through...)

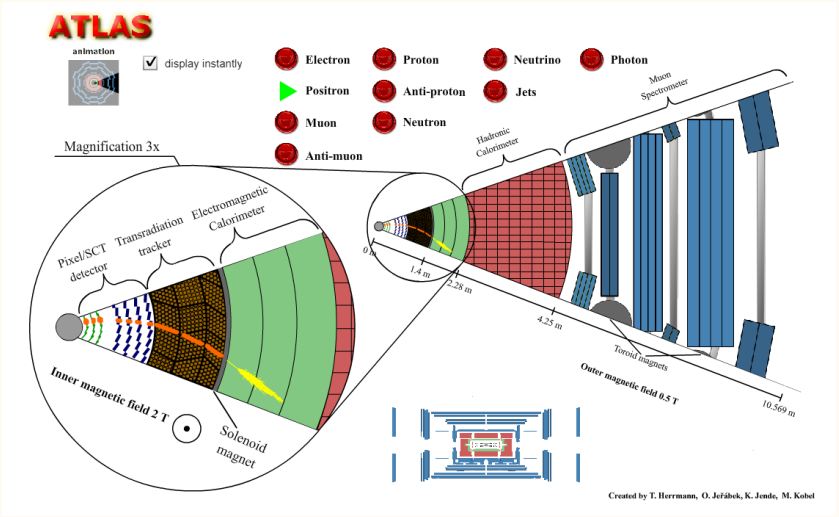
b-jet tagging: secondary vertices, impact parameter of tracks associated to jets...

ID is crucial, in run-2 added Inner B-layer @ 3.3 cm from beams

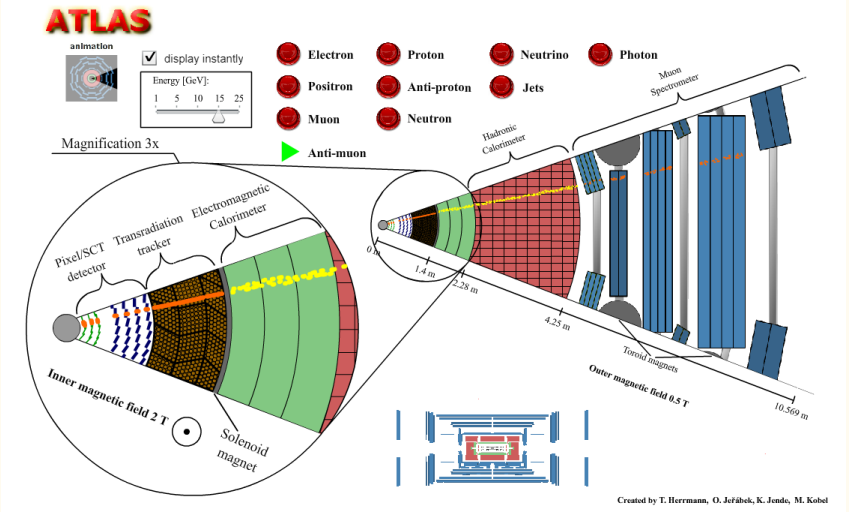
ttbar events in the ATLAS detector: e/μ



e



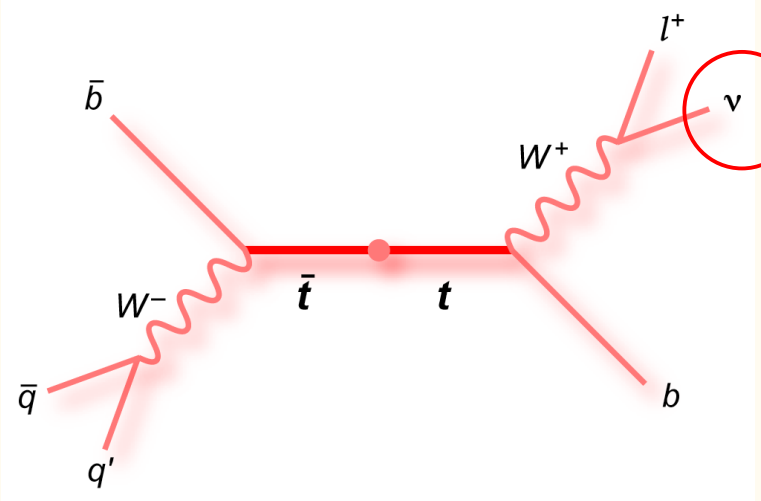
μ

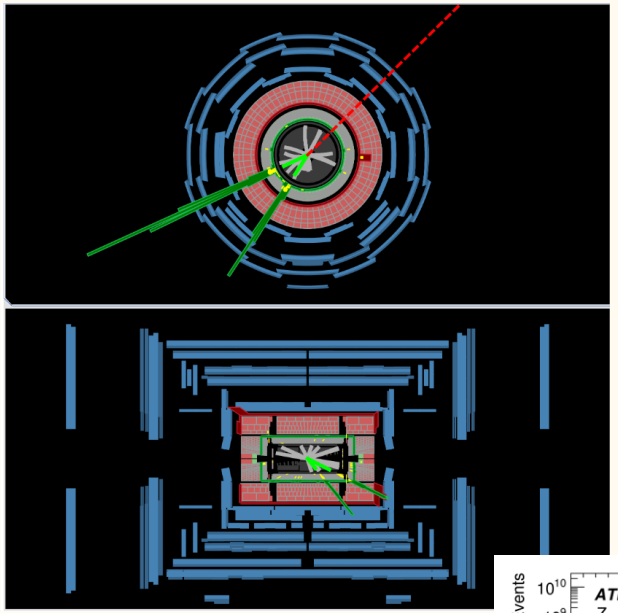


Signature: isolated track in Inner Detector + deposits in Calorimeters (e) or track in Muon Spectrometer (μ)

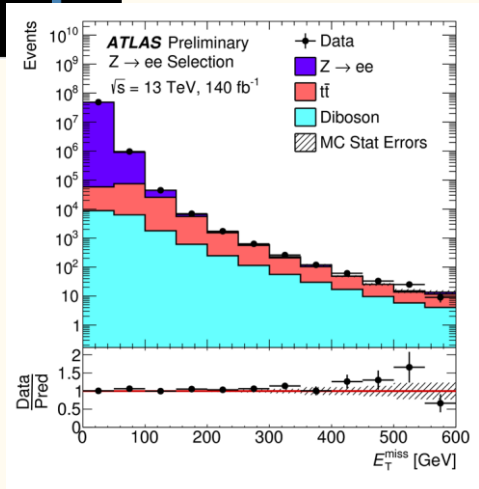
Reconstructed with high efficiency and O(1%)-level resolution

ttbar events in the ATLAS detector: ν





[Eur. Phys. J. C (2018) 78: 903]

Signature: transverse momentum imbalance → pp collisions

$$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} = -\sum \mathbf{p}_{\mathrm{T}}^{e} - \sum \mathbf{p}_{\mathrm{T}}^{\gamma} - \sum \mathbf{p}_{\mathrm{T}}^{\tau_{\mathrm{had}}} - \sum \mathbf{p}_{\mathrm{T}}^{\mu} - \sum \mathbf{p}_{\mathrm{T}}^{\mathrm{jet}} - \sum \mathbf{p}_{\mathrm{T}}^{\mathrm{track}}$$