ATLAS results on top quark mass

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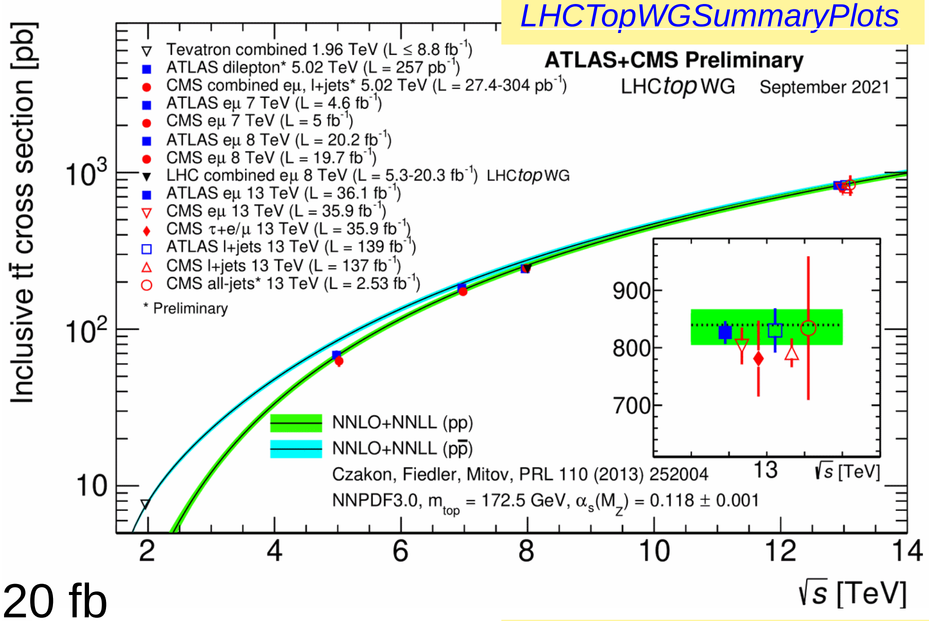
- ○ introduction
- ○ motivations & measurements
- ○ using $t\bar{t}$ pairs for tuning
- ○ Run 3 and HL-LHC prospects

Top quark as a probe for the SM

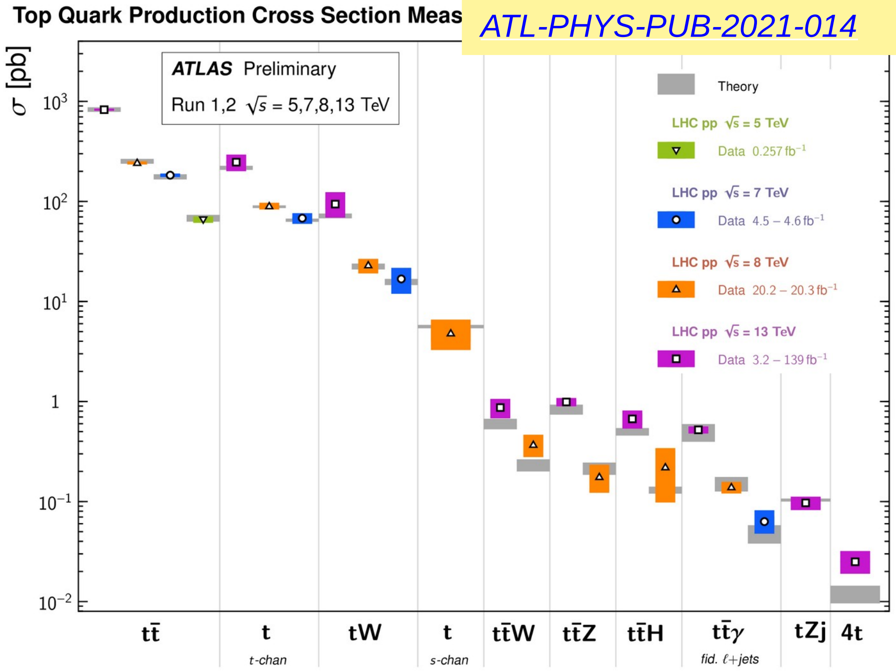
- **Most striking properties**
  - very short lifetime $\tau \sim 5 \times 10^{-25}$ ps
    - inhibits to form bound states
    - unique way to study quasi free quark
  - heaviest fundamental particle known
    - Yukawa coupling to Higgs boson ~1
    - high relevance to EWK Symmetry Breaking mechanism

- **High production rate at LHC**
  - probed cross sections from ~800 pb to ~20 fb
    - ~100 M $t\bar{t}$ (~15 pairs/s at 13 TeV)
  - allowing for deep understanding of the production mechanisms
  - increasing number of differential measurements with high precision, exploiting new datasets, high-p_T regime,

- **Multiple of interesting SM/top properties measurements**



LHCTopWGSummaryPlots

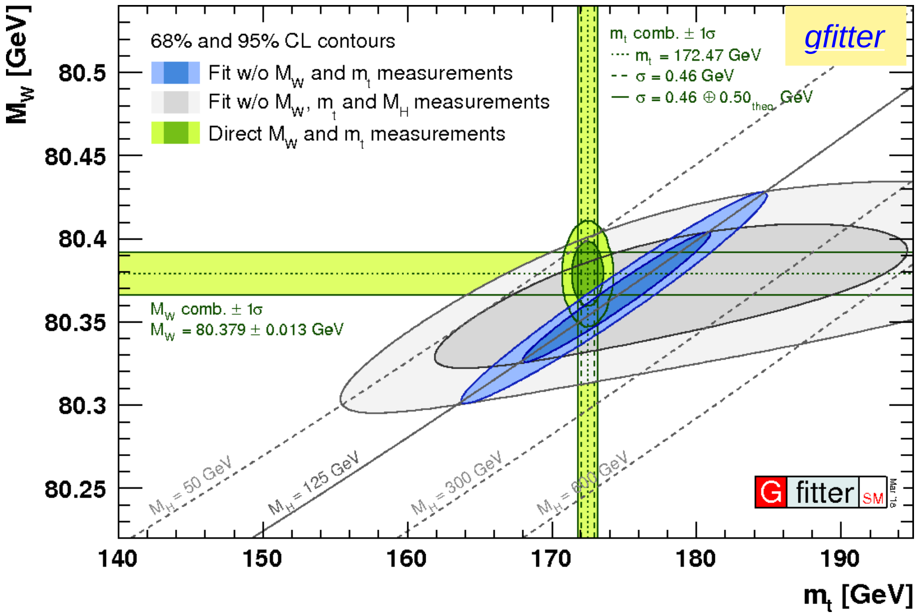


ATL-PHYS-PUB-2021-014

Motivations for m_t measurement

Top quark mass plays a crucial role in the SM

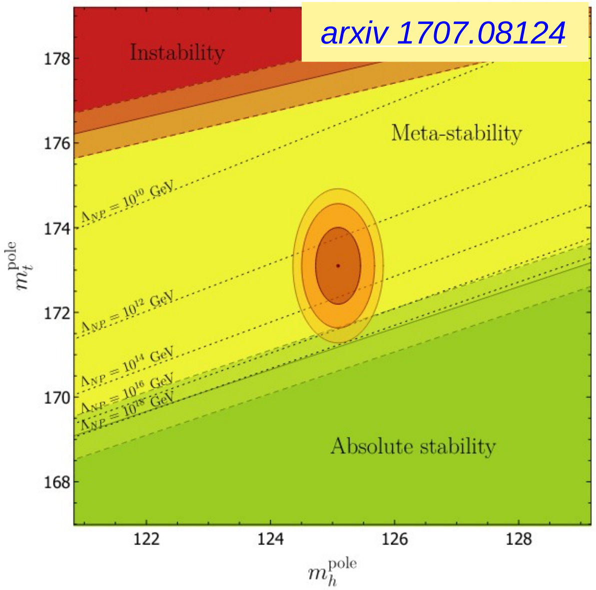
Electroweak fit



gfitter

- relation between m_t, m_W and m_H
- internal consistency of the SM
- test of high energy scales via radiative corrections

Stability of EW vacuum



arxiv 1707.08124

- relation between m_t and m_H
  - predict the evolution of the Higgs quartic coupling at high scales, which affects the shape of the Higgs potential
- measured values lead to a vacuum between stability and meta-stability
- search for New Physics

Its definition depends on the renormalization scheme used

m_t definition

The top quark is colour charged and does not exist as an asymptotic state: the value of m_t, extracted from the experiments, depends on the theoretical definition of the mass, which varies according to the renormalisation scheme adopted: pole mass or running mass.

CERN Yellow Report
arXiv:1902.04070

measured m_t can be connected to the pole mass by means of a relation like

$$m_t = (m_t^{\text{pole}} + \delta m_t) \pm \Delta m_t$$

δm_t : shift between measured and pole mass
Δm_t : uncertainty

$\delta m_t \sim 0$: the extracted mass through top-decay final-state reconstruction mimics the pole mass, up to some computable uncertainty.
$\Delta m_t \sim$ hadronisation scale
Nason et al.: arXiv:1712.02796
arXiv:1602.00443

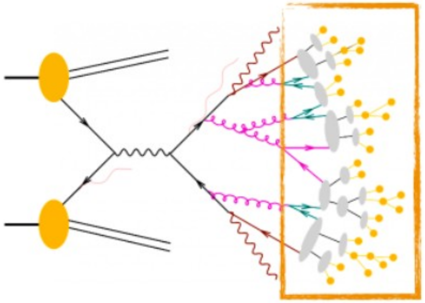
$\delta m_t \sim 200\text{-}900$ MeV
Δm_t is 250 MeV, 280-380 MeV
Hoang et al. : NPPS (2008) 185:220–6
arXiv:1708.02586
JHEP (2018) 10:200
Butenschoen et al.: PRL (2016) 117:232001

m_t is determined experimentally by performing direct and indirect measurements

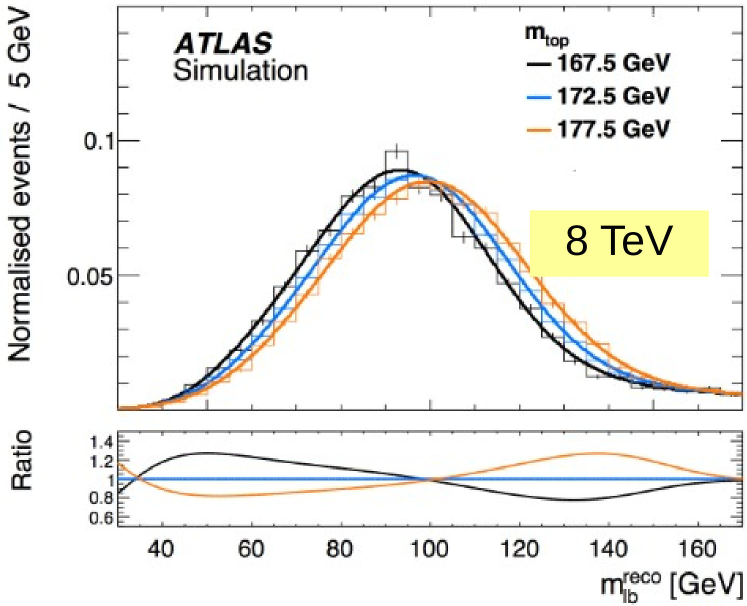
m_t direct measurements

Direct measurements m_t^{MC}

- ○ relies on details of MC simulation
  - often named « Monte Carlo mass »
- ○ using reconstructed decay products
  - tt and single top; fully hadronic, lepton+jet, dileptonic ...
  - template methods using « invariant masses »



$t\bar{t}$ dileptonic channel

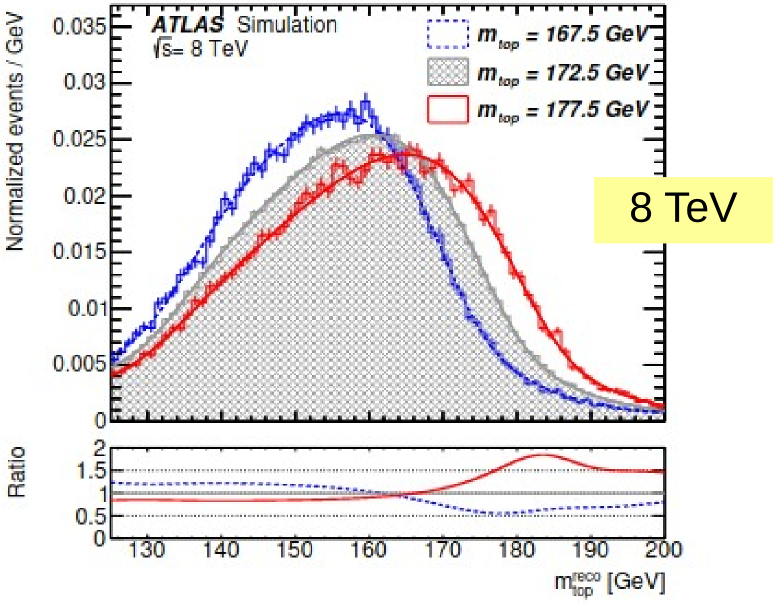


8 TeV

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

PLB 761 (2016) 350 - 371

$t\bar{t}$ lepton+jet channel



8 TeV

m_t = 172.08 ± 0.39 (stat+JES+bJES) ± 0.82 (syst) GeV

EPJC 79 (2019) 290

ATLAS Comb. m_t = 172.69 ± 0.25 (stat) ± 0.41 (syst) GeV EPJC 79 (2019) 290

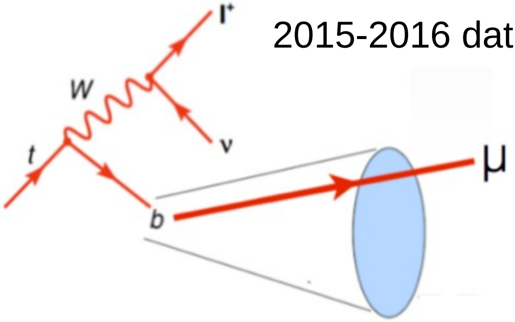
Systematic uncertainties in Run 1 & 2 are dominated by JES/bJES

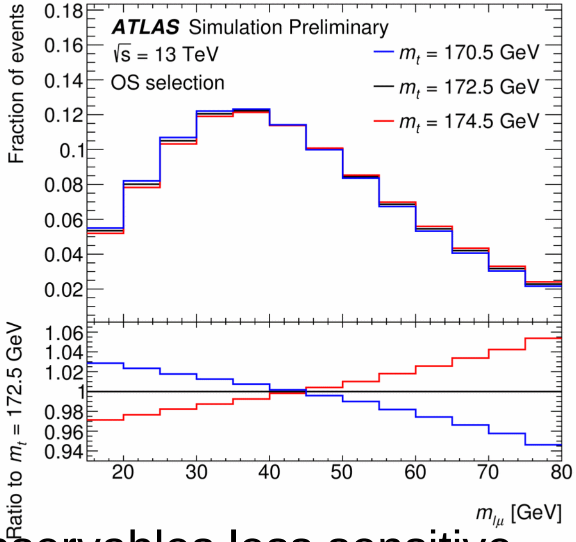
m_t measurement using leptonic invariant mass

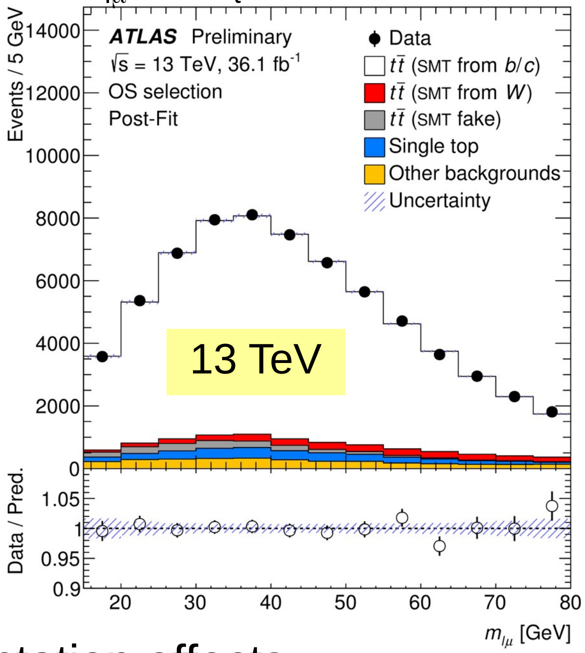
Study of $t\bar{t}$ pairs with in final state a B-hadron decaying in b → $\mu\nu$ offers alternative channel to measure m_t using the sensitivity of $m_{l\mu}$ to m_t

ATLAS-CONF-2019-046

2015-2016 data







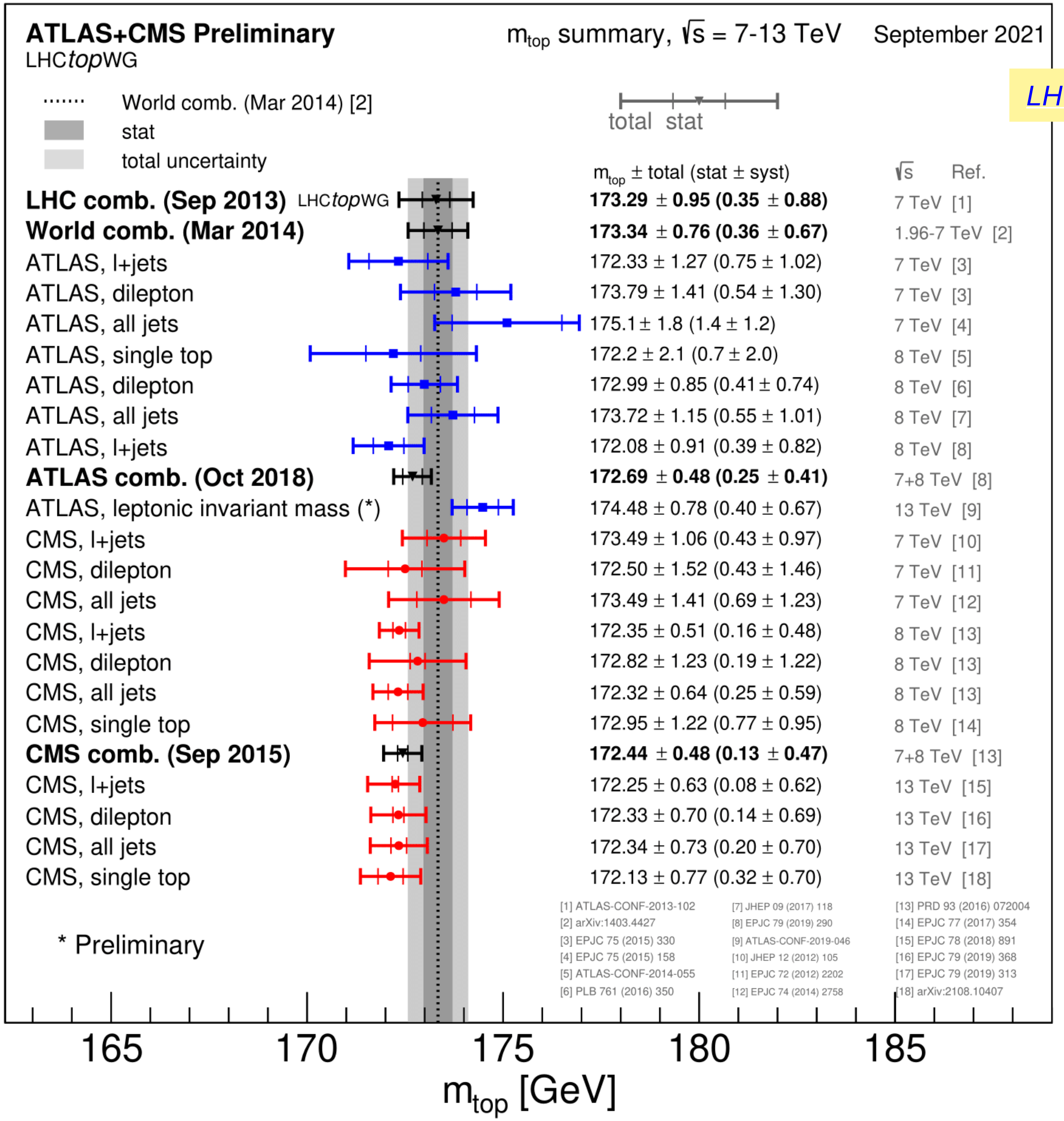
- **Motivations**
  - ○ purely leptonic/tracking observables less sensitive to JES than the ones from jet reconstruction
  - ○ still sensitive to parton shower, hadronization, b-fragmentation effects…
  - ○ help to reduce the uncertainties in combination of all measurements
- **Retuned simulation using**
  - ○ recalibrated b-quark fragmentation Bowler-Lund parameter r_b~1.05
  - ○ recent measurements of hadron production and decay fractions
  - ○ likelihood template fit to $m_{l\mu}$ spectrum in OS and SS channels

m_t=174.48 ± 0.40 (stat) ± 0.67 (syst) GeV

dominant syst. uncertainty : hadron decay branching fractions (~0.4 GeV) and b-fragmentation (0.19 GeV); JES uncertainty reduced to 0.12 GeV

m_t direct measurements

LHCTopWGSummaryPlots



	m_{top} ± total (stat ± syst)	$\sqrt{s}$	Ref.
LHC comb. (Sep 2013)	**173.29 ± 0.95 (0.35 ± 0.88)**	7 TeV	[1]
World comb. (Mar 2014)	**173.34 ± 0.76 (0.36 ± 0.67)**	1.96-7 TeV	[2]
ATLAS, l+jets	172.33 ± 1.27 (0.75 ± 1.02)	7 TeV	[3]
ATLAS, dilepton	173.79 ± 1.41 (0.54 ± 1.30)	7 TeV	[3]
ATLAS, all jets	175.1 ± 1.8 (1.4 ± 1.2)	7 TeV	[4]
ATLAS, single top	172.2 ± 2.1 (0.7 ± 2.0)	8 TeV	[5]
ATLAS, dilepton	172.99 ± 0.85 (0.41 ± 0.74)	8 TeV	[6]
ATLAS, all jets	173.72 ± 1.15 (0.55 ± 1.01)	8 TeV	[7]
ATLAS, l+jets	172.08 ± 0.91 (0.39 ± 0.82)	8 TeV	[8]
ATLAS comb. (Oct 2018)	**172.69 ± 0.48 (0.25 ± 0.41)**	7+8 TeV	[8]
ATLAS, leptonic invariant mass (*)	174.48 ± 0.78 (0.40 ± 0.67)	13 TeV	[9]
CMS, l+jets	173.49 ± 1.06 (0.43 ± 0.97)	7 TeV	[10]
CMS, dilepton	172.50 ± 1.52 (0.43 ± 1.46)	7 TeV	[11]
CMS, all jets	173.49 ± 1.41 (0.69 ± 1.23)	7 TeV	[12]
CMS, l+jets	172.35 ± 0.51 (0.16 ± 0.48)	8 TeV	[13]
CMS, dilepton	172.82 ± 1.23 (0.19 ± 1.22)	8 TeV	[13]
CMS, all jets	172.32 ± 0.64 (0.25 ± 0.59)	8 TeV	[13]
CMS, single top	172.95 ± 1.22 (0.77 ± 0.95)	8 TeV	[14]
CMS comb. (Sep 2015)	**172.44 ± 0.48 (0.13 ± 0.47)**	7+8 TeV	[13]
CMS, l+jets	172.25 ± 0.63 (0.08 ± 0.62)	13 TeV	[15]
CMS, dilepton	172.33 ± 0.70 (0.14 ± 0.69)	13 TeV	[16]
CMS, all jets	172.34 ± 0.73 (0.20 ± 0.70)	13 TeV	[17]
CMS, single top	172.13 ± 0.77 (0.32 ± 0.70)	13 TeV	[18]

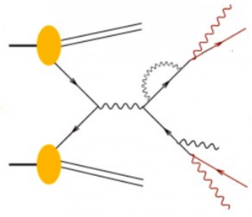
* Preliminary

[1] ATLAS-CONF-2013-102
[2] arXiv:1403.4427
[3] EPJC 75 (2015) 330
[4] EPJC 75 (2015) 158
[5] ATLAS-CONF-2014-055
[6] PLB 761 (2016) 350
[7] JHEP 09 (2017) 118
[8] EPJC 79 (2019) 290
[9] ATLAS-CONF-2019-046
[10] JHEP 12 (2012) 105
[11] EPJC 72 (2012) 2202
[12] EPJC 74 (2014) 2758
[13] PRD 93 (2016) 072004
[14] EPJC 77 (2017) 354
[15] EPJC 78 (2018) 891
[16] EPJC 79 (2019) 368
[17] EPJC 79 (2019) 313
[18] arXiv:2108.10407

m_t indirect measurements

Indirect measurements m_t

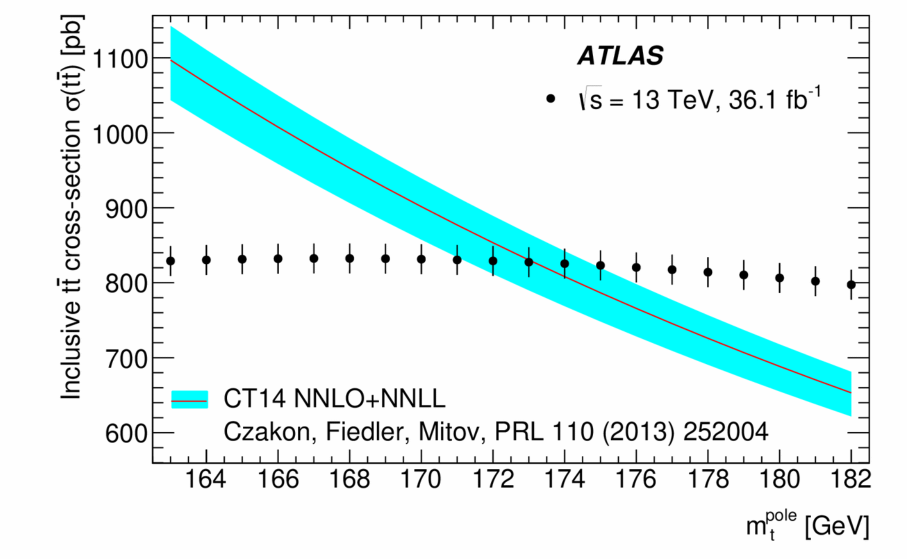
- ○ measuring cross section
  - unfolded at at parton-level and compared to the prediction
- ○ well defined renormalization scheme ⇒ m_t^{pole}



$t\bar{t}$ dileptonic eμ channel (inclusive cross section)

EPJC 80 (2020) 528

13 TeV



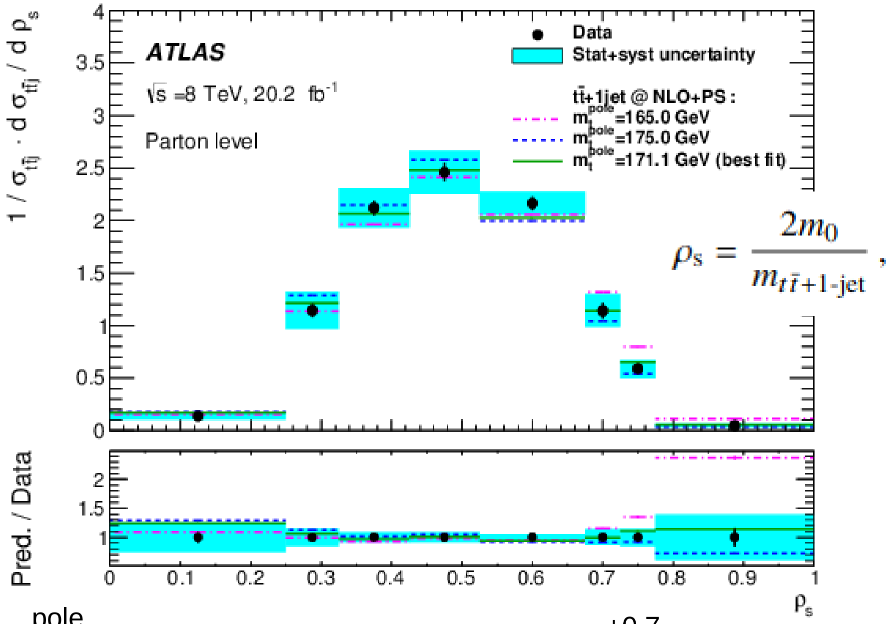
$$m_t^{pole} = 173.1^{+2.0}_{-2.1}\,\text{GeV}$$

Statistical uncertainty ~0.2 GeV
Systematic uncertainties dominated by uncertainties on PDF+α_s (1.5 GeV)

$t\bar{t}$+1j channel (differential cross section)

JHEP 11 (2019) 150

8 TeV

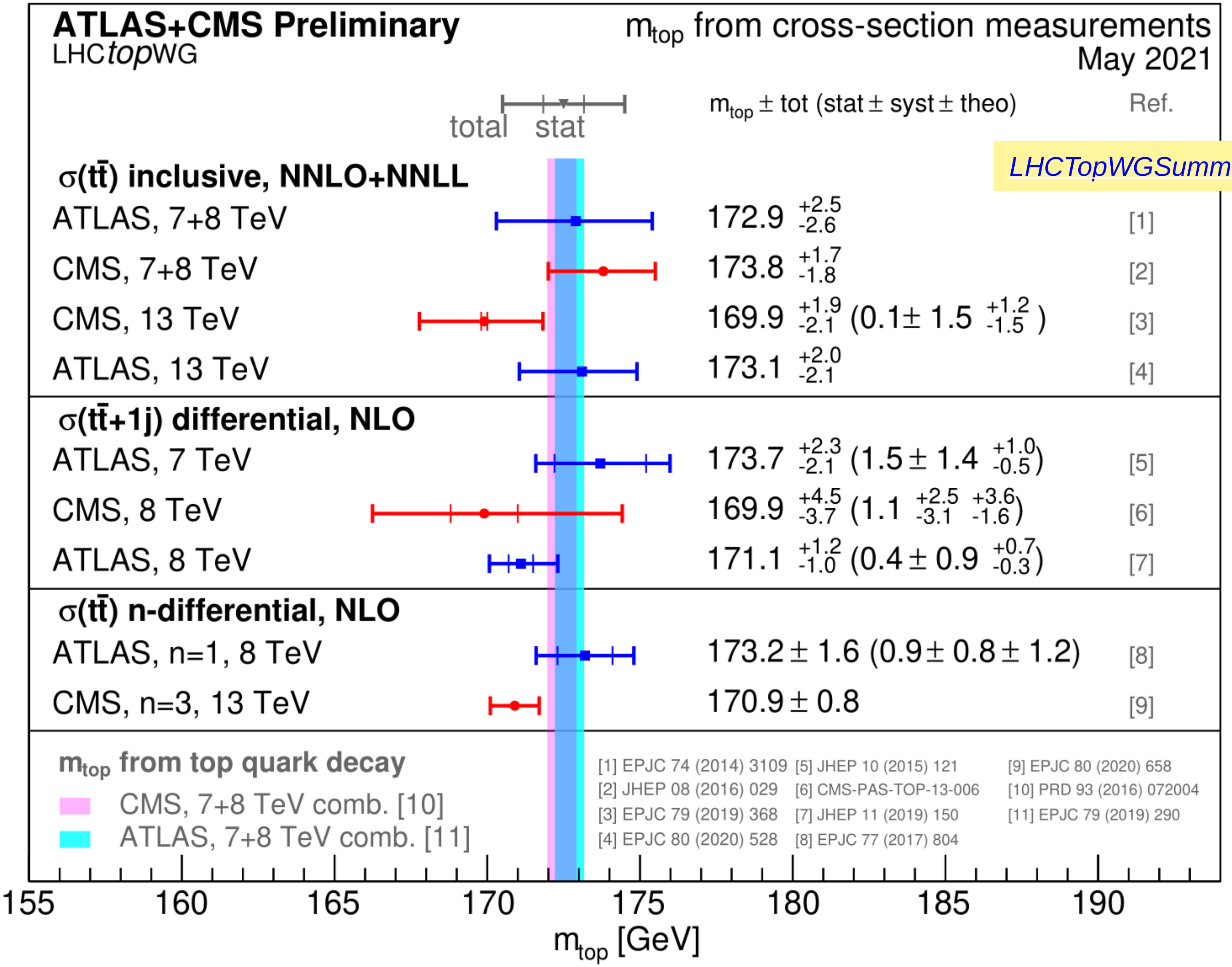


$$\rho_s = \frac{2m_0}{m_{t\bar{t}+1\text{-jet}}},$$

$$m_t^{pole} = 171.1 \pm 0.4\,(\text{stat}) \pm 0.9\,(\text{syst})^{+0.7}_{-0.3}\,(\text{theo})\,\text{GeV}$$

Systematic uncertainties dominated by JES , PS-hadronisation, colour reconnection ~0.4 GeV each
Theo uncertainties scale variations ~0.6 GeV

m_t indirect measurements



LHCTopWGSummaryPlots

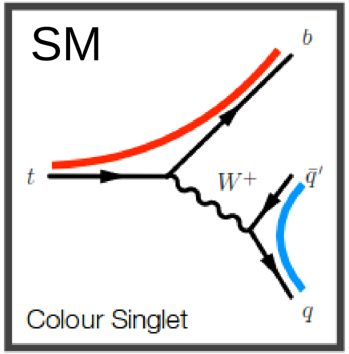
Using $t\bar{t}$ pairs for tuning

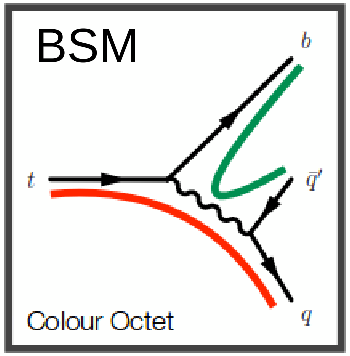
Monte Carlo simulation is a crucial ingredient in top analysis and LHC analysis
where top quark is an important background
It is a limiting factor in many precision measurements

- **Covered in this talk**
  - colour reconnection tuning
  - measurement of observables sensitive to b-quark fragmentation parameters
  - interpretation of MC top mass parameter in the generators
  - towards common ATLAS/CMS MC samples

Colour reconnection in $t\bar{t}$ events

- **Motivation**
  - interactions and interference between the top decay products during hadronization
  - sub-dominant contribution of the quoted top quark mass uncertainties, to be reduced
  - colour reconnection between hadrons in jets affect the jet energy distributions inside and between jets
  - techniques to exploit colour reconnections can be tested using jets with an expected colour structure, e.g jets from a W boson in top quark decays, and compared to jets without colour flow, e.g between the two b-jets of the $t\bar{t}$ system.



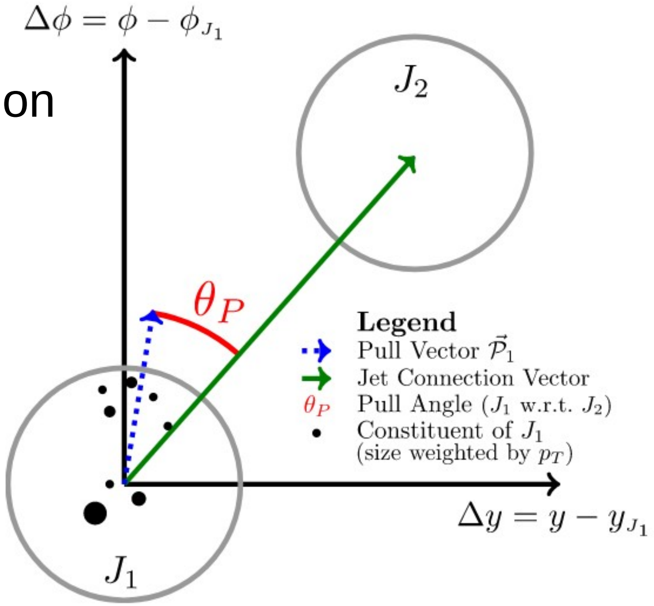


- **Method**
  - the jet pull vector $\vec{\mathcal{P}}(J)$ predicted to contain information about the colour representation of a dijet system
  - measure quantities derived from the jet pull vector
    - p_T-weighted radial jet moment

$$\vec{\mathcal{P}}(J_1) = \sum_{i \in J_1} \frac{p_T^i \cdot |\vec{r}_i|}{p_T^J} \vec{r}_i$$ magnitude $|\vec{\mathcal{P}}|$

$$\vec{\mathcal{C}}(J_1, J_2) = \vec{J}_2 - \vec{J}_1$$

$$\theta_{\mathcal{P}}(J_1, J_2) = \sphericalangle\left(\vec{\mathcal{P}}(J_1), \vec{\mathcal{C}}(J_1, J_2)\right)$$ angle $\theta_{\mathcal{P}}$

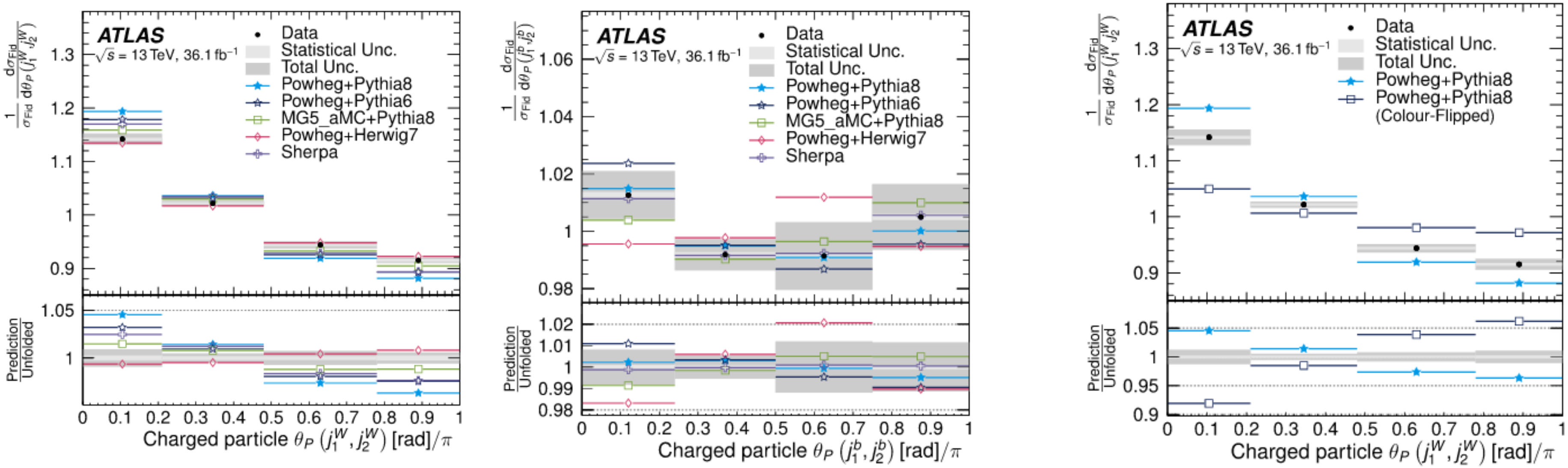


For two colour-connected jets, J1 and J2, it is expected that P(J1) and P(J2) are aligned with the jet connection vector, i.e. $\theta_P \sim 0$

Colour reconnection in $t\bar{t}$ events

EPJC 78 (2018) 847

- ○ 'signal' color flow (left) is best modeled by Powheg+Herwig7
- ○ data prefers less strong effect (smaller angle) and wider jets (larger magnitude)
- ○ 'spurious' color flow (middle) is generally well-modeled, except by Powheg+Herwig7



- ○ data agree more (right plot) with the SM description than with the colour-flipped (BSM) model

b-quark fragmentation in $t\bar{t}$ events

- **Motivation**
  - check/quantify our knowledge of hadronization of b-quarks in hadron collider
  - today's partonic shower generators tuned to LEP results
    - LEP results were done based on ee → Z → bb
    - events in a clean environment with back-to-back events : production of bb colour singlets, no colour reconnection to the beam or underlying events
- **Use of LHC events**
  - measurements of b-jet moments sensitive to b-quark fragmentation $t\bar{t}$ events (eμ channel, 2015-2016 data)
  - observables used at LHC are relative to the jet, and use information from associated charged tracks
  - unfolded to particle level

$$z^{\mathrm{ch}}_{\mathrm{T},b} = \frac{p^{\mathrm{ch}}_{\mathrm{T},b}}{p^{\mathrm{ch}}_{\mathrm{T,jet}}}$$

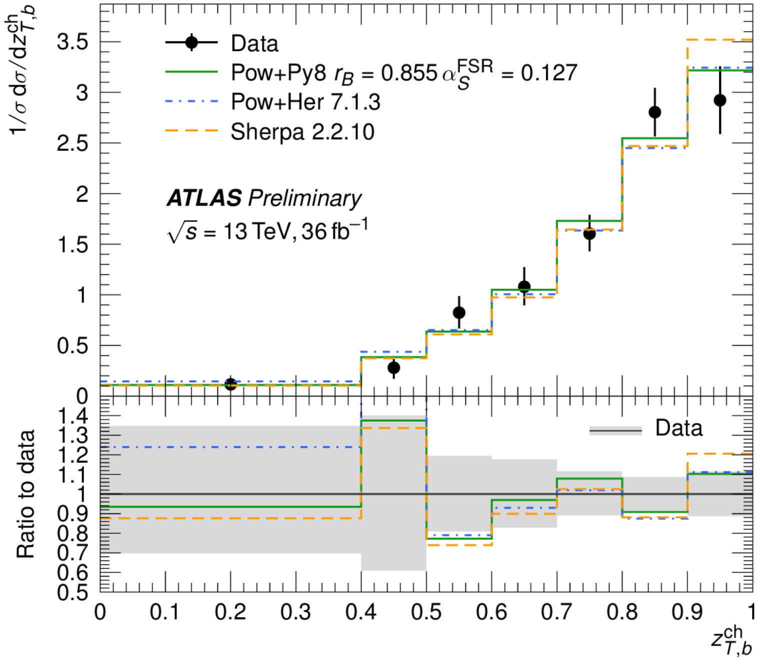
$$z^{\mathrm{ch}}_{\mathrm{L},b} = \frac{\vec{p}_b^{\,\mathrm{ch}} \cdot \vec{p}^{\,\mathrm{ch}}_{\mathrm{jet}}}{|p^{\mathrm{ch}}_{\mathrm{jet}}|^2}$$

$$\rho = \frac{2p^{\mathrm{ch}}_{\mathrm{T},b}}{p^{e}_{\mathrm{T}} + p^{\mu}_{\mathrm{T}}}$$

$$n^{\mathrm{ch}}_{b} = \text{number of fiducial } b\text{-hadron children.}$$

  - Powheg+Pythia8 / Powheg+Herwig 7 / Sherpa successfully predict shape of observables

ATLAS-CONF-2020-050



Interpretation of m_t parameter in generators

- **Motivation**
  - compare the boosted jet mass distribution from hadronic tops in MC to analytical calculation with npQCD effects at particle level
  - relation $m_t^{MC} = m_t^{MSR}(1\ \text{GeV}) + \Delta m_t^{MSR}$
  - nominal MC : Powheg+Pythia8, m_t=172.5 GeV
    - consider also Powheg+Herwig7,
- **Analysis**

arXiv 1708.02586

  - Soft-Collinear Effective Theory: prediction of $d\sigma_{t\bar{t}}$ as a function of the jet mass at NLL precision at particle level
  - inclusive treatment of hadronic top quark decays
    - events with at least 1 large R-jet with p_T>750 GeV (to capture decay products in a single jet)
    - large R-jet to hadronically decaying top parton matching applied
    - build mass distributions in 3 bins of p_T at particle level
    - light soft-drop grooming to remove soft-wide radiation
  - 3 free parameters: m_t(pole~MSR), Ω (np-QCD parameter, first moment of hadronic shape function) and x_2 (ratio of second moment to Ω)
  - does not account for UE effects

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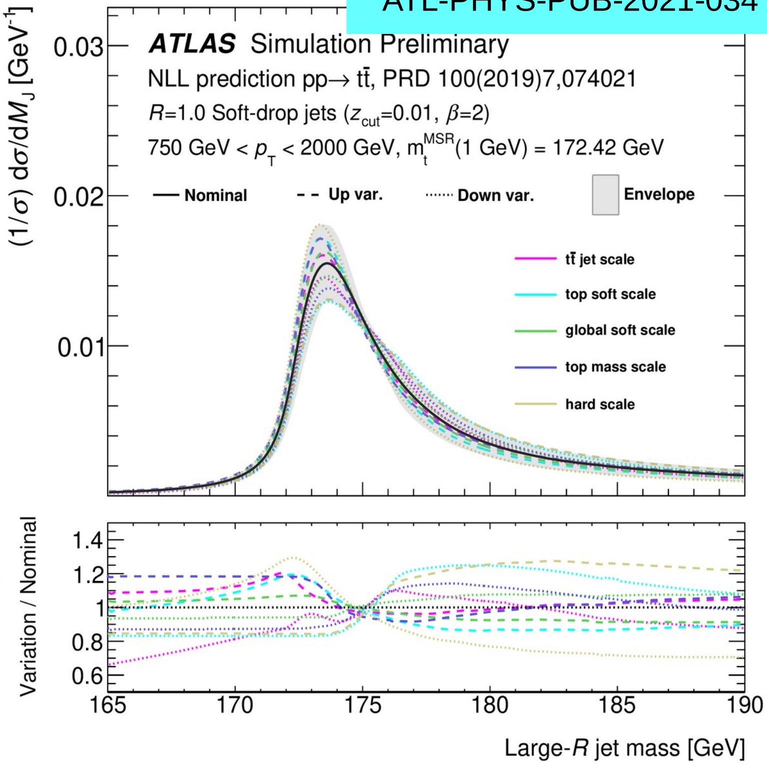


Interpretation of m_t parameter in generators

- **Results**
  - χ^2 fit to find the theory prediction that best describes MC (Powheg+Pythia8)

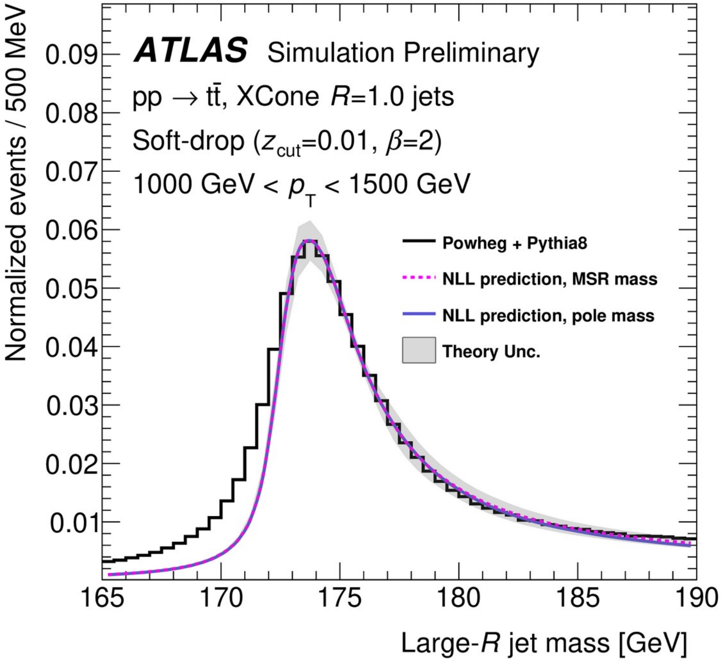
$$m_t^{MSR}(1\ \text{GeV}) = 172.42 \pm 0.10\ (\text{stat})\ \text{GeV}$$

$$\Omega_{1q} = 1.49 \pm 0.03\ \text{GeV},\ x_2 = 0.52 \pm 0.09$$

$$m_t^{MC} = m_t^{MSR}(1\ \text{GeV}) + 80^{+350}_{-480}\ \text{MeV}$$

$$m_t^{MC} = m_t^{pole} + 350\ ^{+300}_{-360}\ \text{MeV}$$

ATL-PHYS-PUB-2021-034



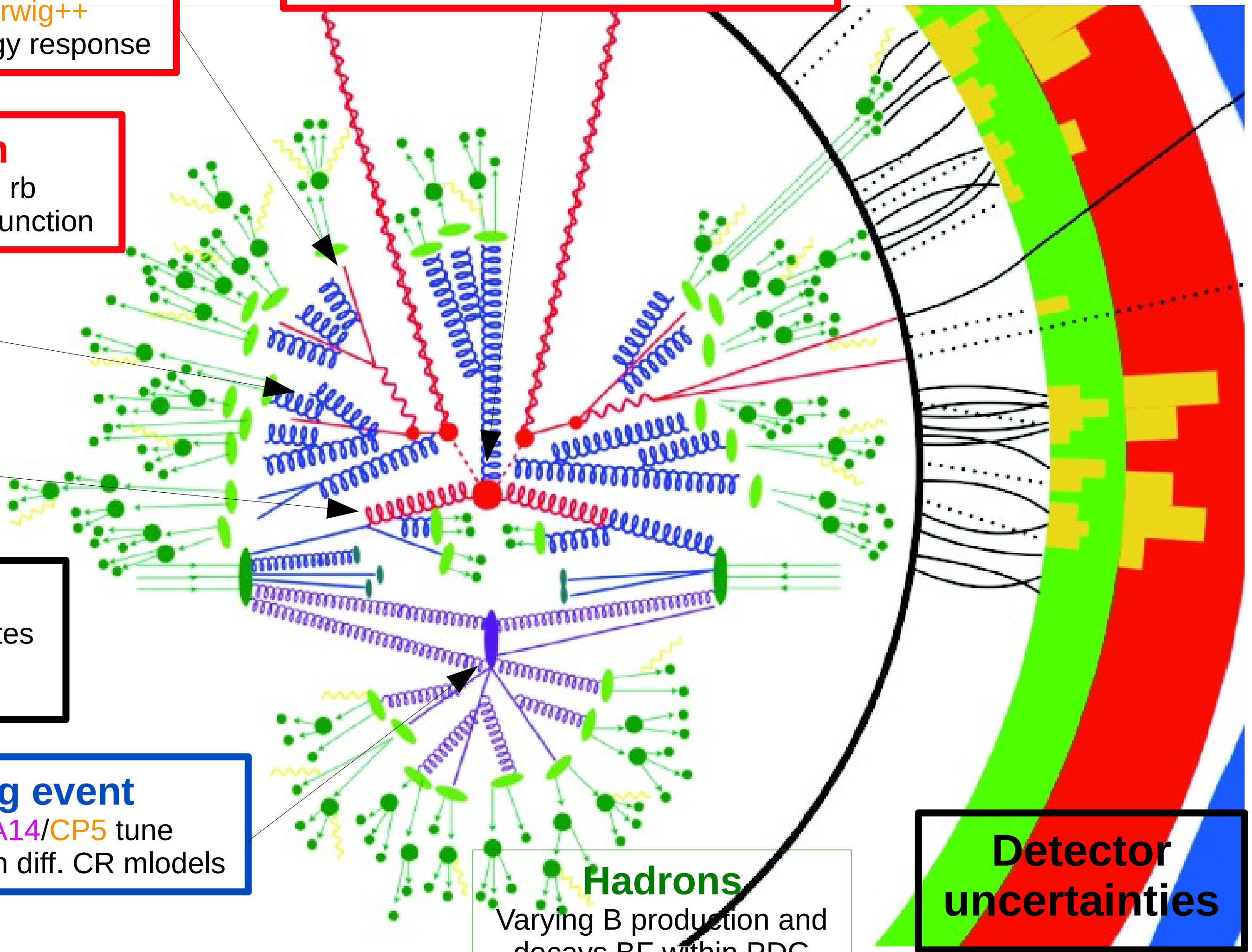
  - similar results found for Powheg+Herwig 7: 172±0.09 (stat) GeV (in spite of the harder jet mass spectrum)
  - main uncertainty from missing higher orders in theory

The result is compatible with that obtained in e^+e^- collisions and future advances in the formal accuracy of the theory calculations may lead to reduction of systematic uncertainties [PRL 117, 232001 (2016)]

To take advantage of this relation in an optimal way, a direct top mass measurement in boosted top quark production is needed

Modelling uncertainty recommendations

ATLAS and CMS use same generators but have different settings and procedures to assess uncertainties associated



Hadronisation
Pythia 8 vs Herwig 7
Pythia 6 vs Herwig++
impact on jet energy response

Hard interaction
Powheg vs MC@NLO as uncertainty
Powheg vs MC@NLO as cross check

b-fragmentation
variation of Bowler-Lund rb
parameter of fragmentation function

FSR
μ_F (from 0.5 to 2)

ISR
α_s, μ_R, μ_F (from 0.5 to 2)

ME-PS matching
variation of $\mathbf{h}_{damp}$ that regulates
first high-p_T emission

Underlying event
UE : variation of A14/CP5 tune
CR : retuning UE with diff. CR mlodels

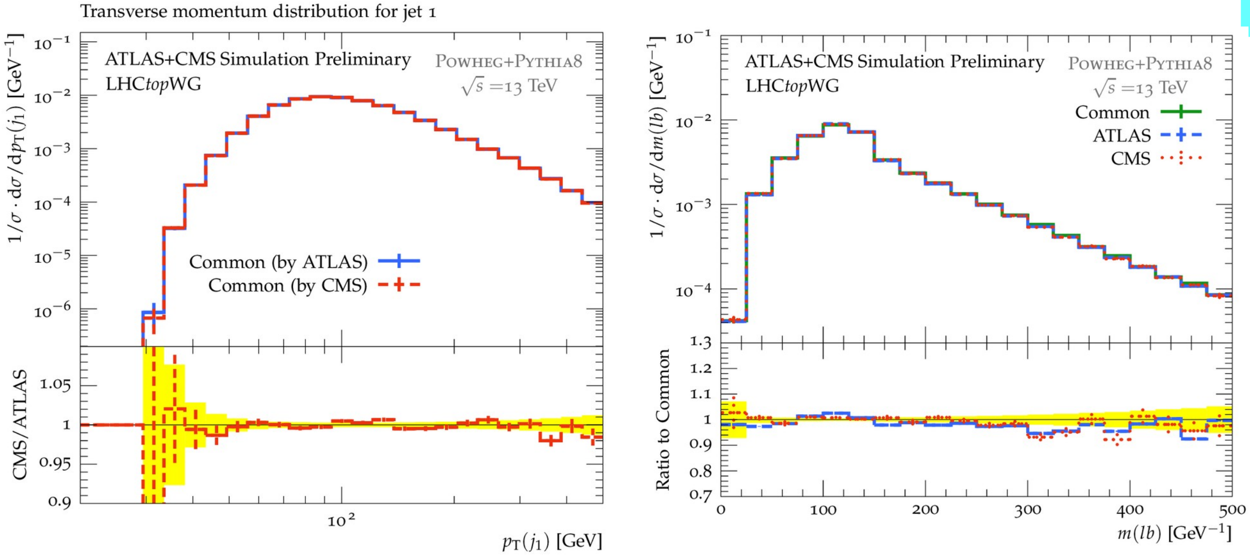
Hadrons
Varying B production and
decays BF within PDG
value uncertainties

Detector uncertainties

An ATLAS/CMS Top quark common sample

- **Motivation**
  - a $t\bar{t}$ sample with common settings would facilitate ATLAS-CMS combinations and comparisons and could :
    - help to understand correlations of systematic uncertainties due to MC modelling
    - remove differences in high-precision measurements
    - be used as baseline prediction
  - first step towards sharing resources, for current and future generators
- **Production of a first sample (Powheg+Pythia 8 $t\bar{t}$) with common settings**
  - approximate average settings for all physical parameters (not optimised to data)
  - produced independently in the respective frameworks
  - comparison performed at particle level for validation

ATL-PHYS-PUB-2021-016
CMS NOTE-2021/005



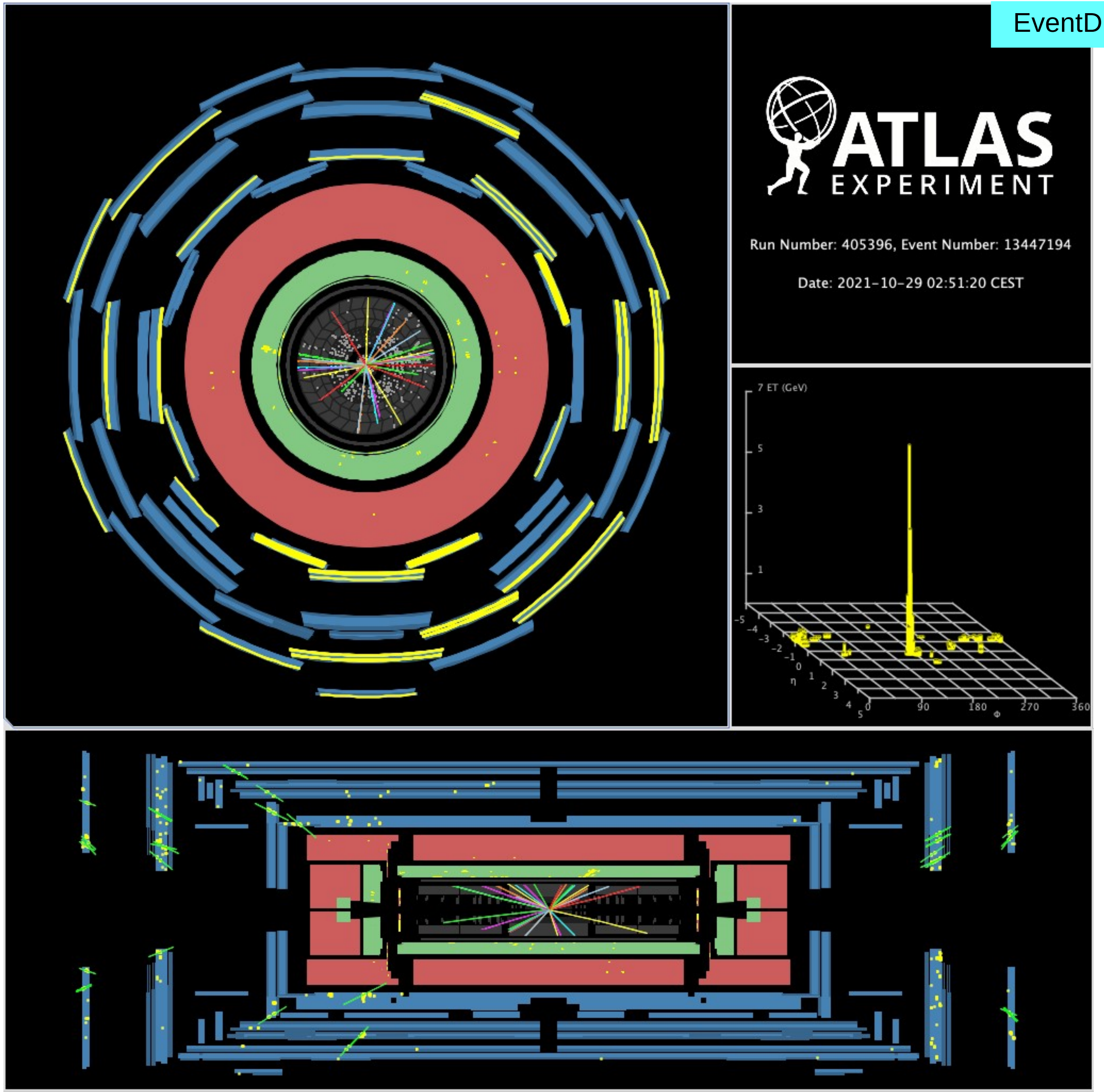
- good agreement within statistical uncertainties
- differences observed in many distributions (e.g jet kinematics and resonance masses)
- next step: obtain a set of tuned parameter settings

Prospectives for Run 3 and HL-LHC

LHC / HL-LHC plan

Recent test collision event at 450 GeV

EventDisplayRun3Collisions



Run Number: 405396, Event Number: 13447194

Date: 2021-10-29 02:51:20 CEST

Plan and ideas for m_t at Run 3

- **Top quark @ Run 3 and top quark physics**
  - slight increase in instantaneous and integrated luminosity x2 to collect up to 300 fb^{-1}
  - yield increase : 300M $t\bar{t}$ events, 30 M tW, 3 M s-channel, 3k 4-top
    - many analyses will benefit from this increase : FCNC, ttX, 4-top

- **Ideas for top quark mass studies**
  - new measurements
    - pole mass scan $\sigma(m_t)/m_t \sim 1.2\ \sigma(m_{t\bar{t}})/m_{t\bar{t}}$ (JHEP 0901:047,2009)
    - top mass running (e.g CMS PLB 803 (2020) 135263)
  - using differential measurements
    - shed light on nature of MC mass
    - does MC mass depend on event kinematics?
    - how is dependence described by different generators?
    - differential mass measurements should be possible
  - direct measurements
    - for standard measurements (l+jet, dilepton …)
      - → can trade statistical precision to better systematic uncertainties
      - → 3D fit: mt, JSF, bJSF → ND fits
      - → in-situ constraints on non-pert. QCD and from ancillary measurements
    - top quark mass measurements using alternative extraction methods,
      - → soft muons
      - → $J/\psi \rightarrow \mu\mu$ cf. CMS mt=173.50±3.00(stat)±0.90(syst) GeV JHEP 12 (2016) 123
      - → complement systematics → gain in combination

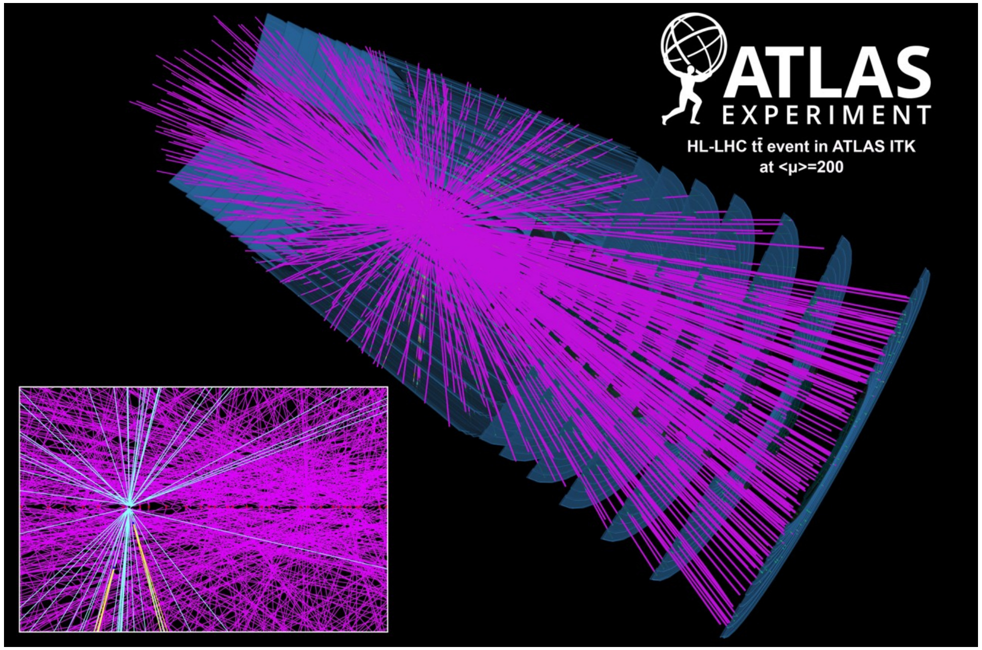
All (MC) mass analysis potentially gain a lot of precision in Run 3

HL-LHC key parameters

- **HL-LHC**
  - the HL-LHC represents the ultimate evolution of LHC machine performance
  - operation at 14 TeV
  - instantaneous nominal luminosity x5-7.5 up to $L=7.5\times10^{34}$ cm^{-2} s^{-1}
    - increased particle densities
  - integrated luminosity x10 to collect up to 3-4 ab^{-1}
    - increased radiation damage
  - challenging experimental conditions
    - up to 140-200 p-p collisions per bunch crossing
    - mitigated by extensive upgrades of experiment during LS3

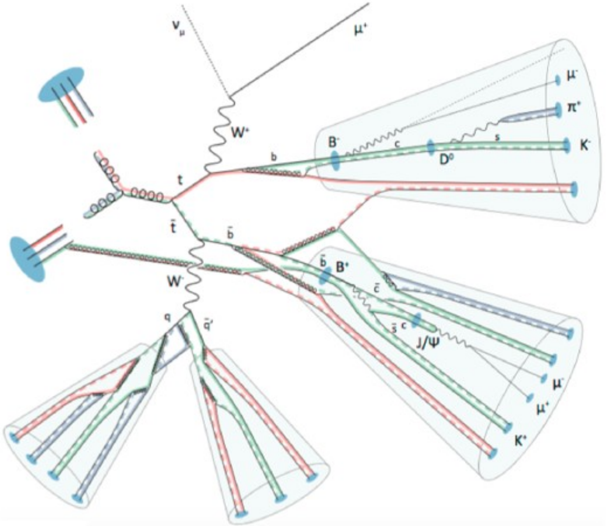
- **Top @ HL-LHC**
  - huge yield increase : 3B tt̄ events, 300 M tW, 30 M s-channel, 30k 4-top

a simulated tt̄ event at average pile-up of 200 collisions per bunch crossing [*Upgraded Event displays*]



m_t measurements using $b \rightarrow J/\psi \rightarrow \mu^+\mu^-$

Study of $t\bar{t}$ pairs with in final state a B-hadron decaying in J/ψ ($b \rightarrow J/\psi \rightarrow \mu\mu$) offers alternative channel to measure m_t using the sensitivity of $m_{l\mu\mu}$ to m_t



- **Motivations**
  - purely leptonic/tracking observables less sensitive to JES than the ones from jet reconstruction
  - still sensitive to parton shower, hadronization, b-fragmentation effects…
  - help to reduce the uncertainties in combination of all measurements
- **Low BR final states**
  - $BR(b \rightarrow J/\psi \rightarrow \mu\mu) \sim 6.8 \times 10^{-4}$

"Standard Model Physics at the HL-LHC and HE-LHC"

CERN Yellow Report
arXiv:1902.04070

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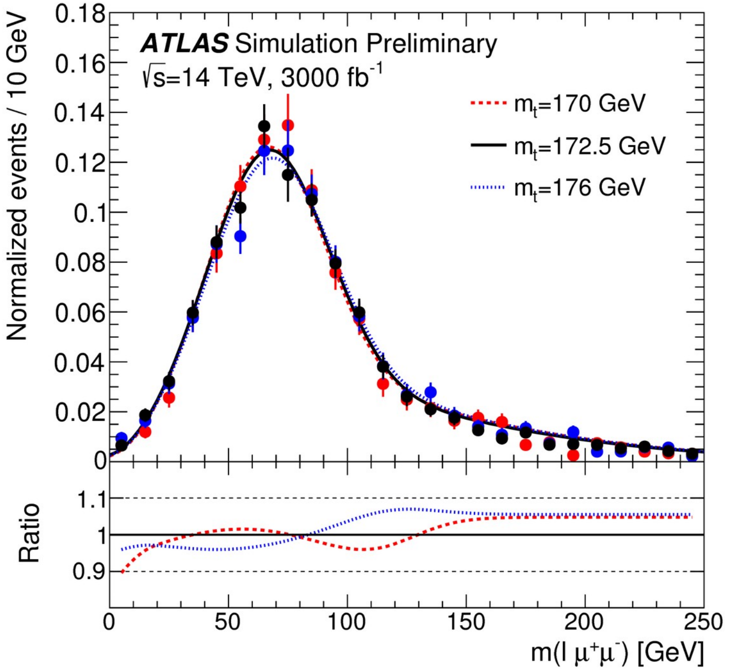


Number of expected events: 2×10^5 candidates

- 18% additionnal events thanks to higher cross section
- 10% additionnal events thanks to larger coverage in $|\eta|<4$

$\sigma(m_t)$ = 0.14 (stat) ± 0.48 (syst) GeV ~ 0.50 GeV

Conclusion

- **Run 2 legacy**
  - top quark mass measured with a precision already around 0.5 GeV relative precision of ~0.3%
  - direct measurements done in a wide variety of channels
    - most of measurements are already systematically limited
    - largest experiment uncertainy stem from the calibration of the jet and b-jet energy scales
    - largest modelling uncertainties originate from the parton shower and hadronisation models
  - indirect measurements limited by theory uncertainties

- **Run 3 and HL-LHC prospects**
  - for Run 3 statistics will be about twice the one of Run 2 with rather similar data taking conditions
  - dramatic change for HL-LHC data taking with gain of factor 10 in statistics

need to improve $t\bar{t}$ modelling to avoid systematic uncertainties wall
⇒ work already ongoing with Run 2 data

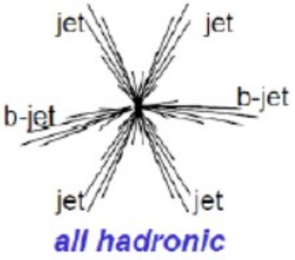
All ATLAS results on top quark physics can be found in:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

Backup slides

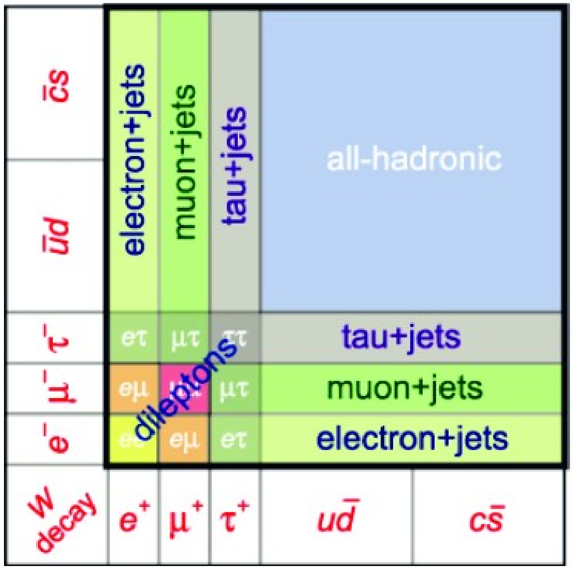
$t\bar{t}$ decay modes

General distinction according to the $W^\pm$ pairs decay modes

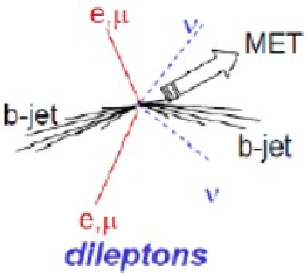
"All hadronic"	45.7%	high background
$e^\pm \nu_e$ + jets	14.53 %	"lepton+jets"
$\mu^\pm \nu_\mu$+ jets	14.29 %	
$\tau^\pm \nu_\tau$ + jets	15.21 %	leptonic or hadronic τ decay modes
$e^\pm \tau^\pm \nu_\tau \nu_e$	2.42 %	
$\mu^\pm \tau^\pm \nu_\tau \nu_\mu$	2.23 %	
$\tau^+ \tau^- \nu_\tau \nu_\tau$	1.26 %	
$e^+ e^- \nu_\tau \nu_\mu$	1.15 %	Clean in terms of trigger and selection Presence of two ν's. Transverse mass. "dilepton"
$\mu^+ \mu^- \nu_\tau \nu_\mu$	1.12 %	
$e^\pm \mu^\pm \nu_\tau \nu_\mu$	2.27 %	



Top pair decay channels



Plot from Angela Barbaro Galtieri et al.
2012 Rep. Prog. Phys. 75 056201



Colour reconnection in $t\bar{t}$ events

- **Definition of three Colour reconnection models**
  - new models / MC samples now used for analyses
  - minimise the colour string length across different parton-parton interactions
    - CR0 - default model. Merges complete MPI systems, starting with the hardest
    - CR1 - new model. Considers all dipole pairs and joins them if a) allowed and b) doing so reduces the colour string length
    - CR2 - new model. Considers all “final” gluons and moves them between a parton pair if doing so reduces the total string length

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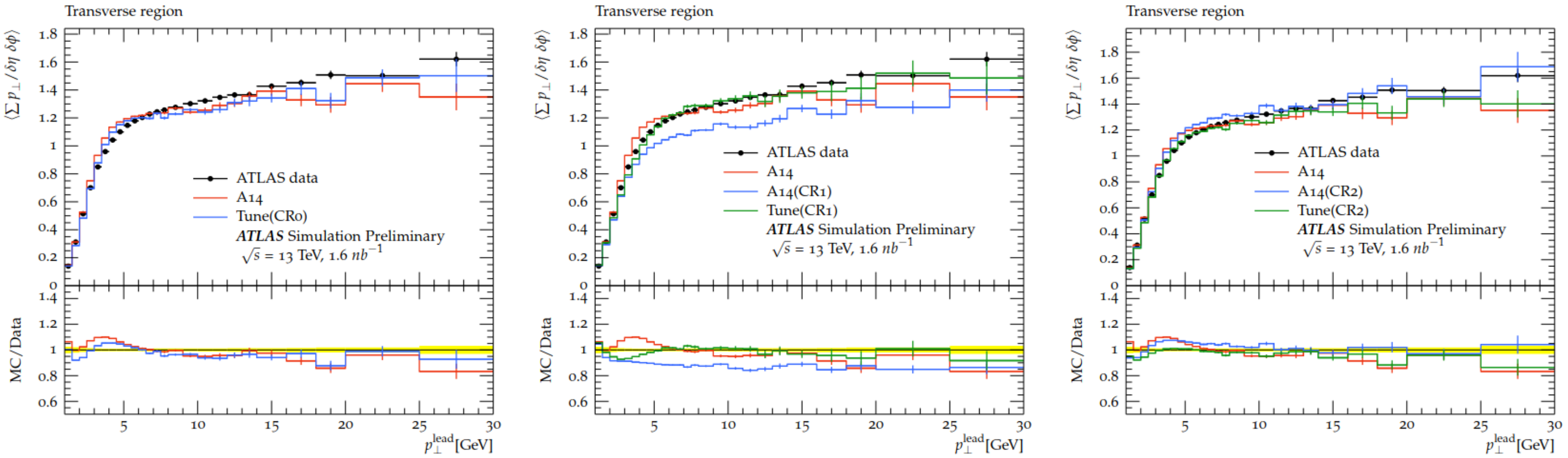
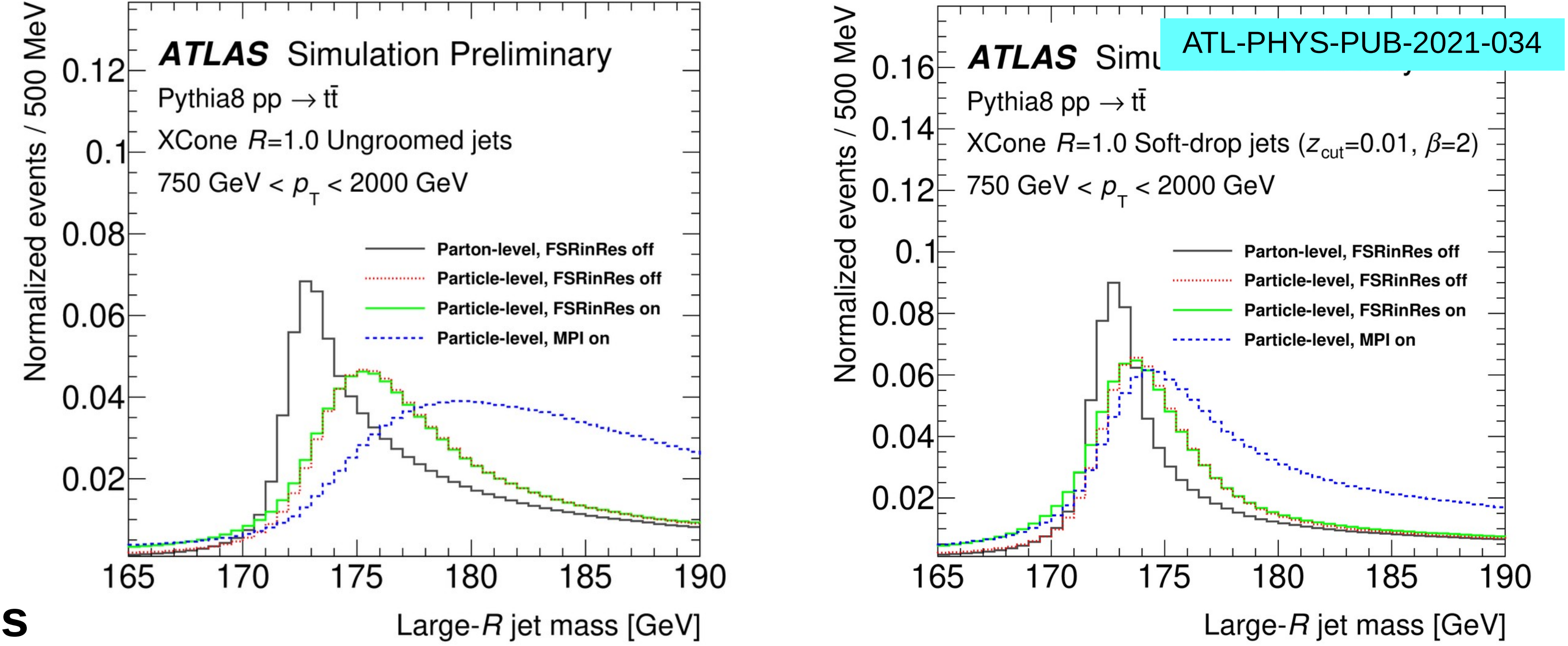


Interpretation of m_t parameter in generators

- **Generator setup and reconstruction**
  - nominal MC : Powheg+Pythia8, m_t^{MC} = 172.5 GeV
    - consider also Powheg+Herwig7, aMC@NLO+Pythia 8, and various MC settings
  - Reconstruction
    - events with at least 1 large R-jet with p_T>750 GeV (to capture decay products in a single jet)
    - large R-jet to hadronically decaying top parton matching applied
    - build mass distributions in 3 bins of p_T at particle level



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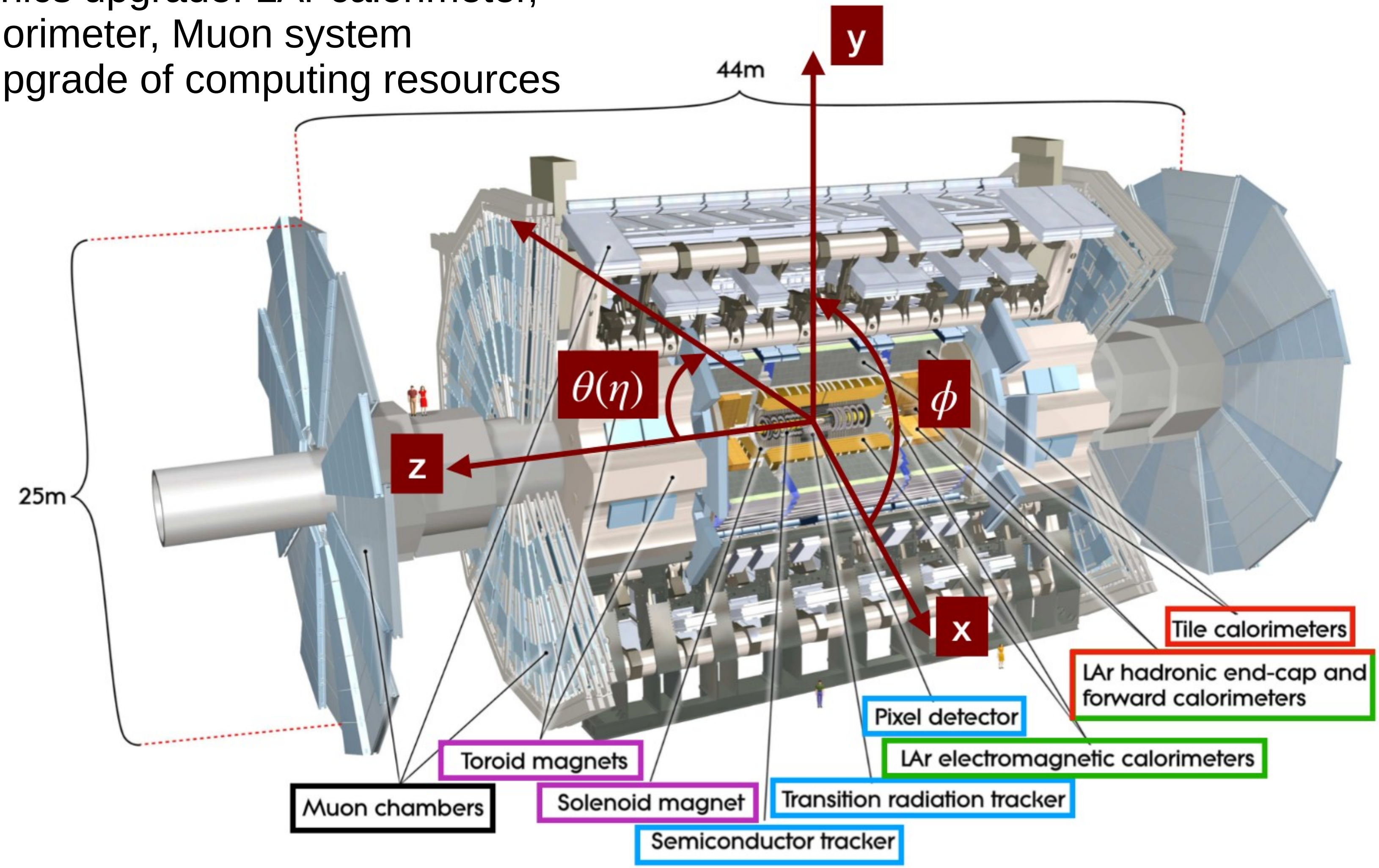
- **Results**
  - hadronization shifts and smears the peak (particle level)
  - radiation from decay products enhances low mass tail (FSR)
  - MPI broadens the distribution and lifts the high mass tail
  - grooming reduces sensitivity to hadronization and UE effects

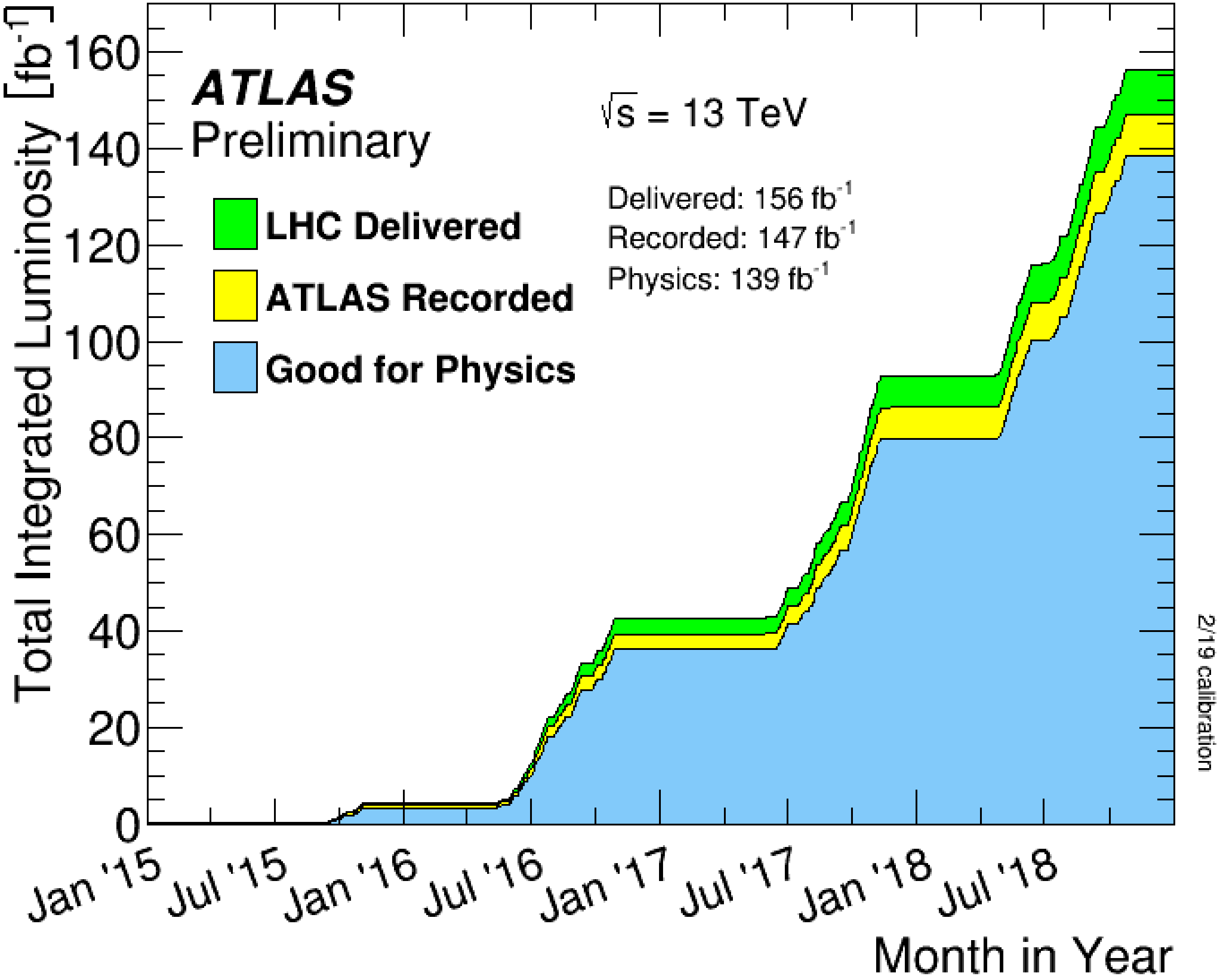
ATLAS Phase II upgrade

- Upgraded Trigger and Data Acquisition System : L1 @ 1 MHz, HLT : 10 kHz
- new all silicon tracker |η|<4
- new dedicated endcap timing detector 2.4<|η|<4
- improved muon coverage (new muon chambers in the inner barrel region) and trigger
- electronics upgrade: LAr calorimeter, Tile calorimeter, Muon system
- large upgrade of computing resources



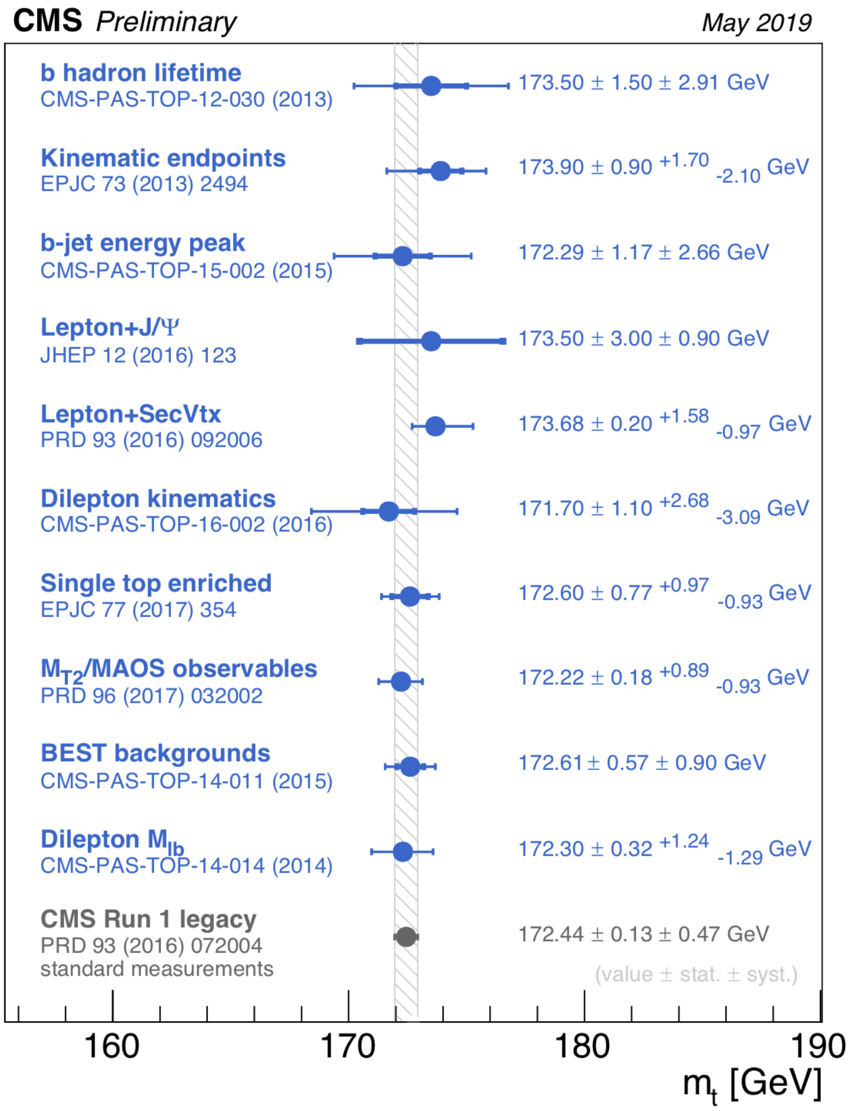
Run 2 luminosity

LuminosityPublicResultsRun2



CMS alternative m_t measurements

CMS TopSummary



CMS m_t precision projections

CMS-PAS-FTR-16-006