The top quark mass: towards a more precise measurement at the LHC

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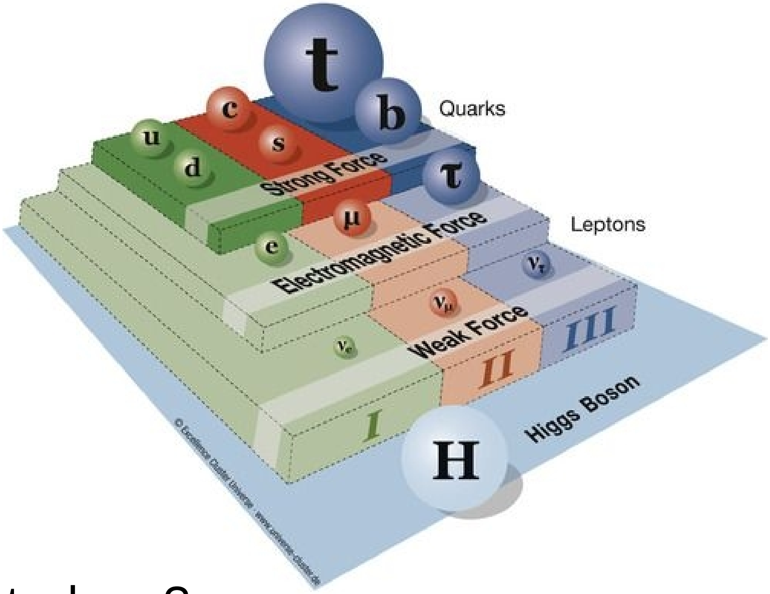
To be able to calculate with the Standard Model, its free parameters need to be determined precisely

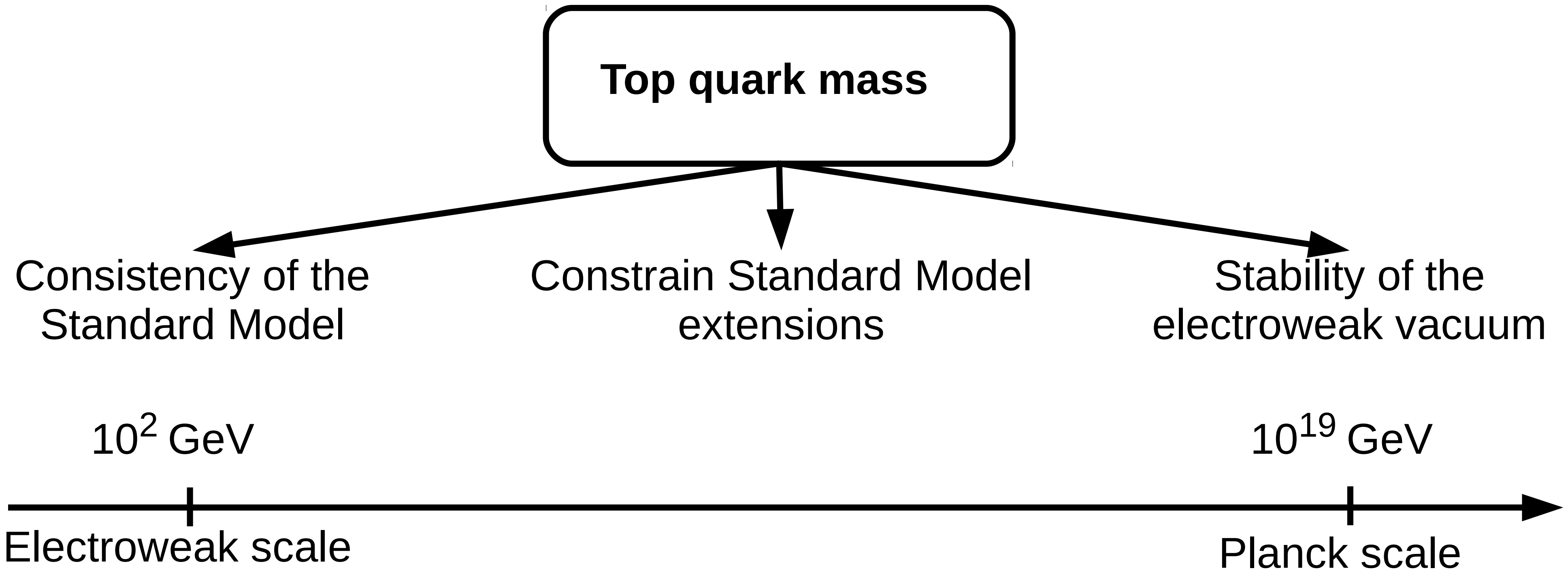
- The Standard Model describes the elementary particles and their interactions



- New physics exists, but where?
- Use the Standard Model and its extensions to make accurate predictions that can be compared with direct measurements/searches and basic principles

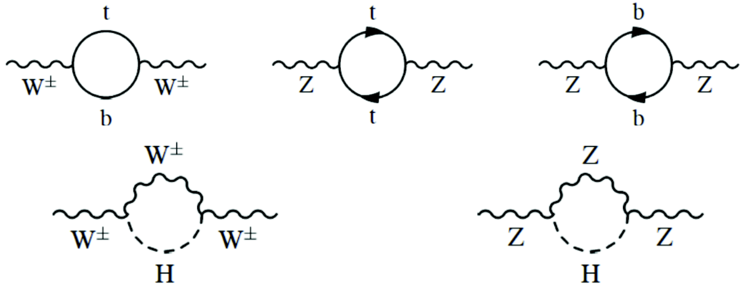
The precise value of the top quark mass is crucial in these calculations

The top quark mass is a key parameter for making precise predictions at all energy scales

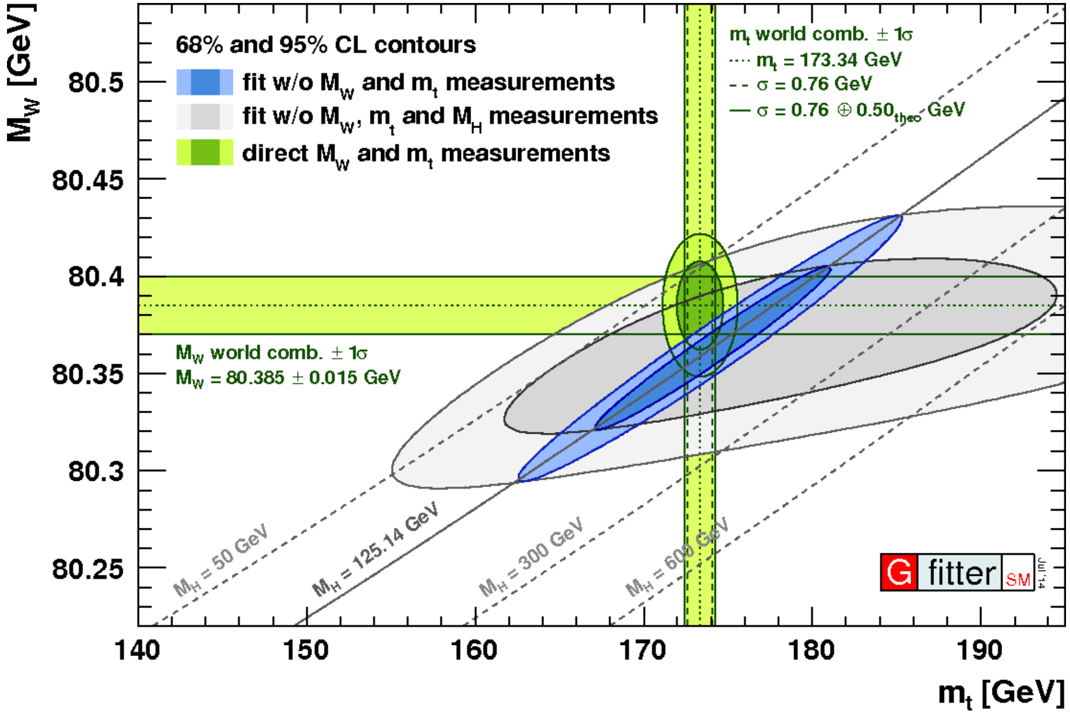


Top quark mass: consistency of the Standard Model

- The mass of the Higgs boson is constrained by the masses of the W boson and the top quark through radiative corrections



arXiv:1407.3792 [hep-ph]

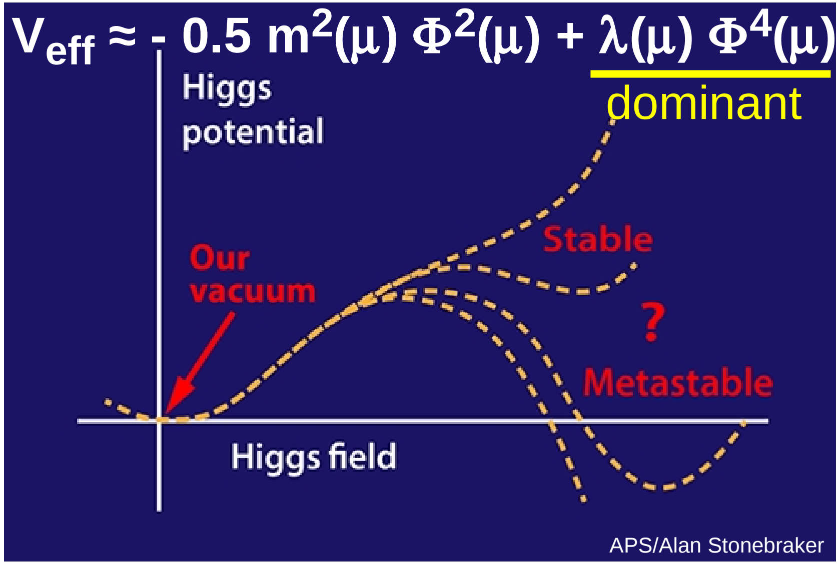


- Compare precisely measured observables with predictions through a global fit of the electroweak observables

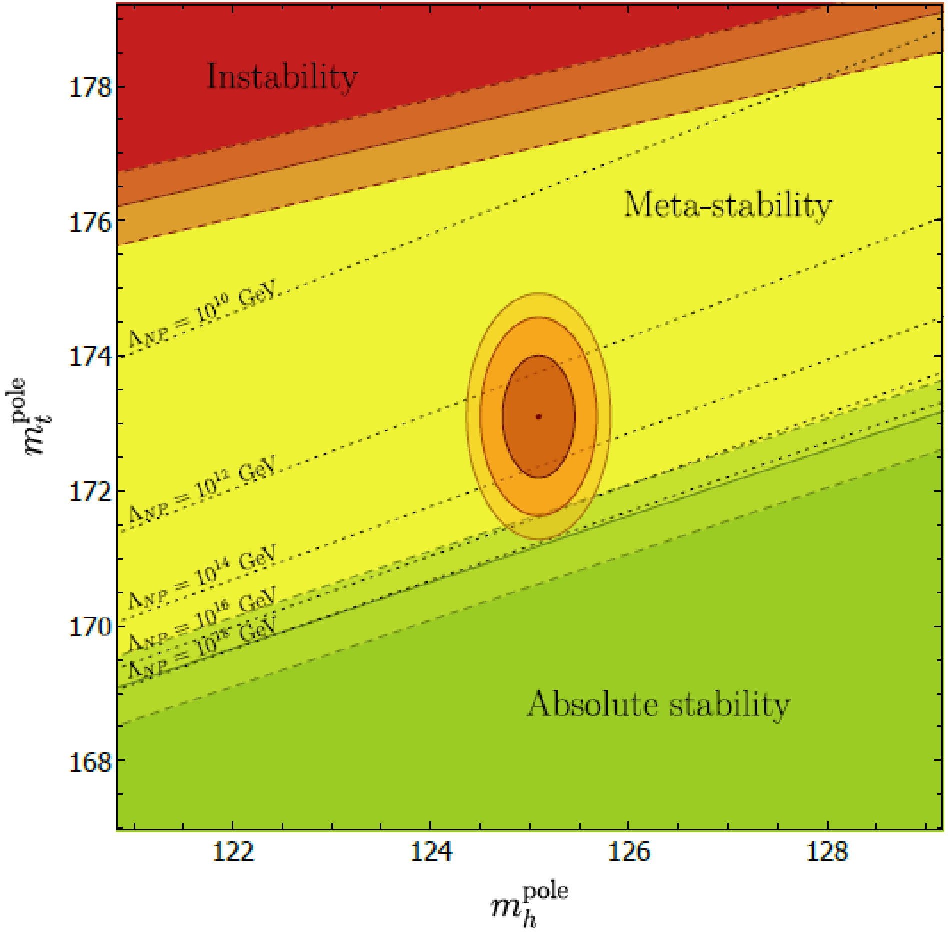
- $\delta m_W < 0.02\%$ and $\delta m_H < 0.2\%$
→ top quark mass is the dominant uncertainty in the fit

Top quark mass: stability of the electroweak vacuum

- Higgs field effective potential:



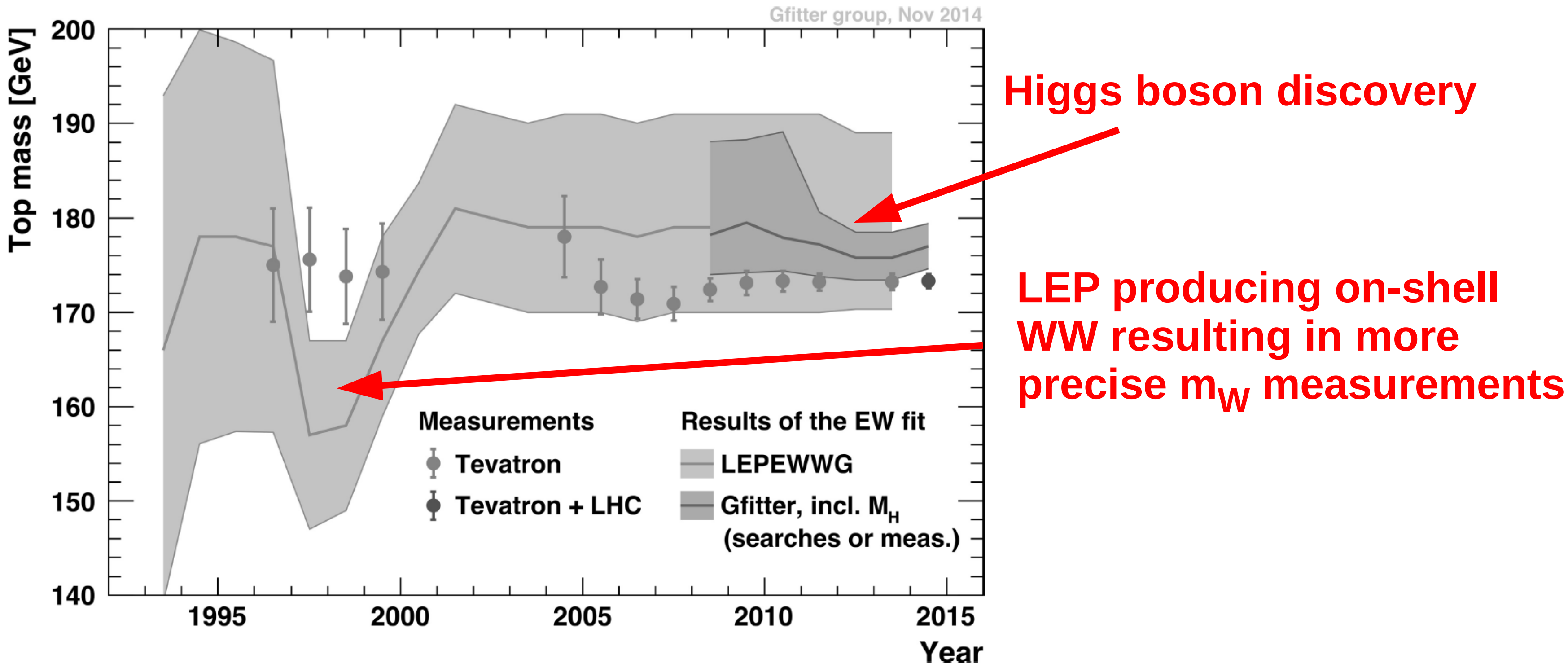
arXiv:1707.08124 [hep-ph]



- Quartic coupling λ runs with scale μ
  → dependence on m_t (and α_S and m_H)
  → decreasing due to top loop corrections
  → if $\lambda < 0$ → unstable (or meta-stable)

Historical evolution of the predicted and measured top quark mass

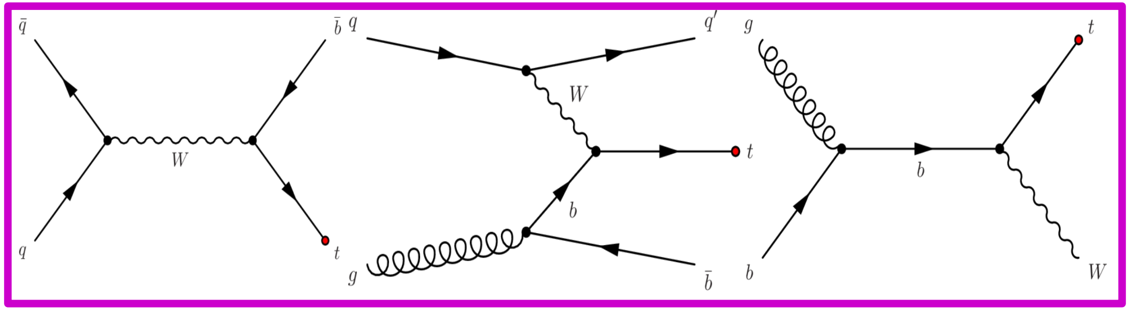
- Only the most precise measurements (or combinations) are shown



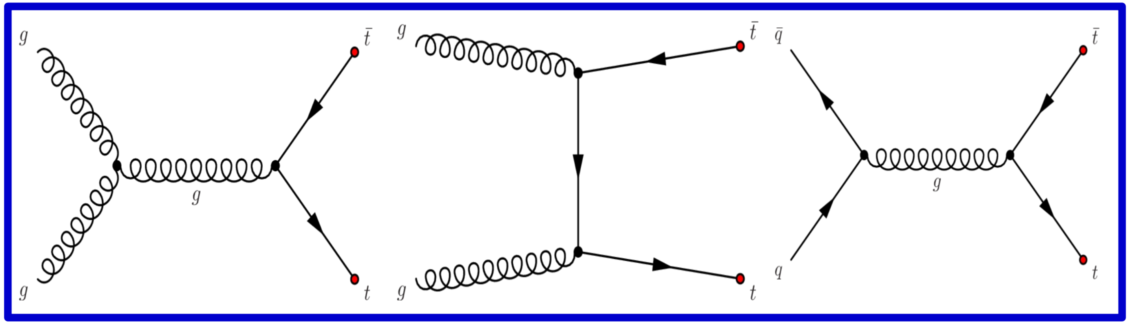
- In the early days techniques were used that optimize the statistical uncertainty (e.g. matrix element method)

Top quark production at the LHC and top quark decay

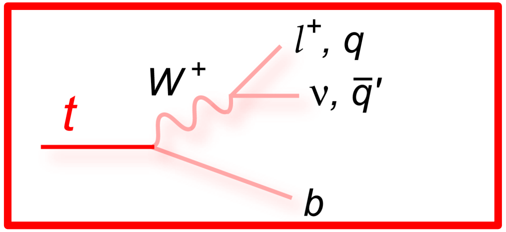
Electroweak "single" production

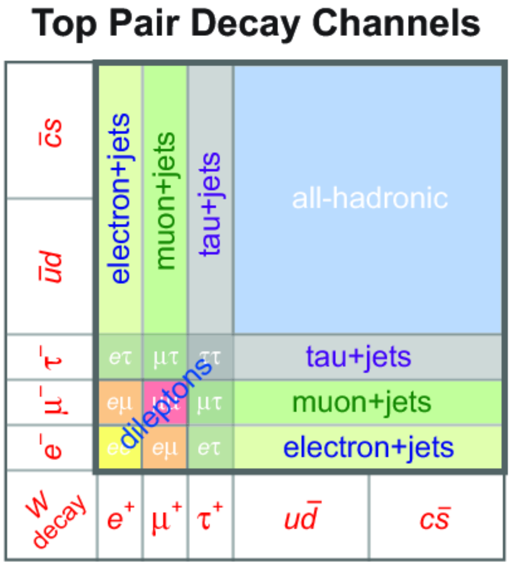


Strong "pair" production



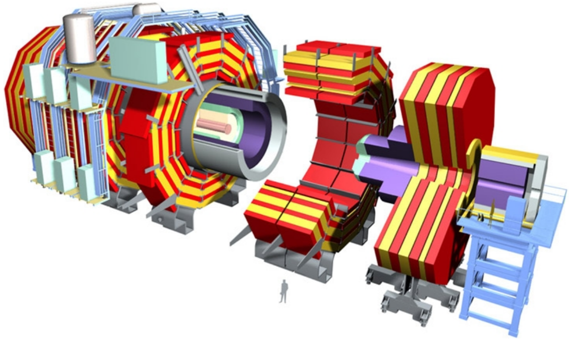
Top quark decay



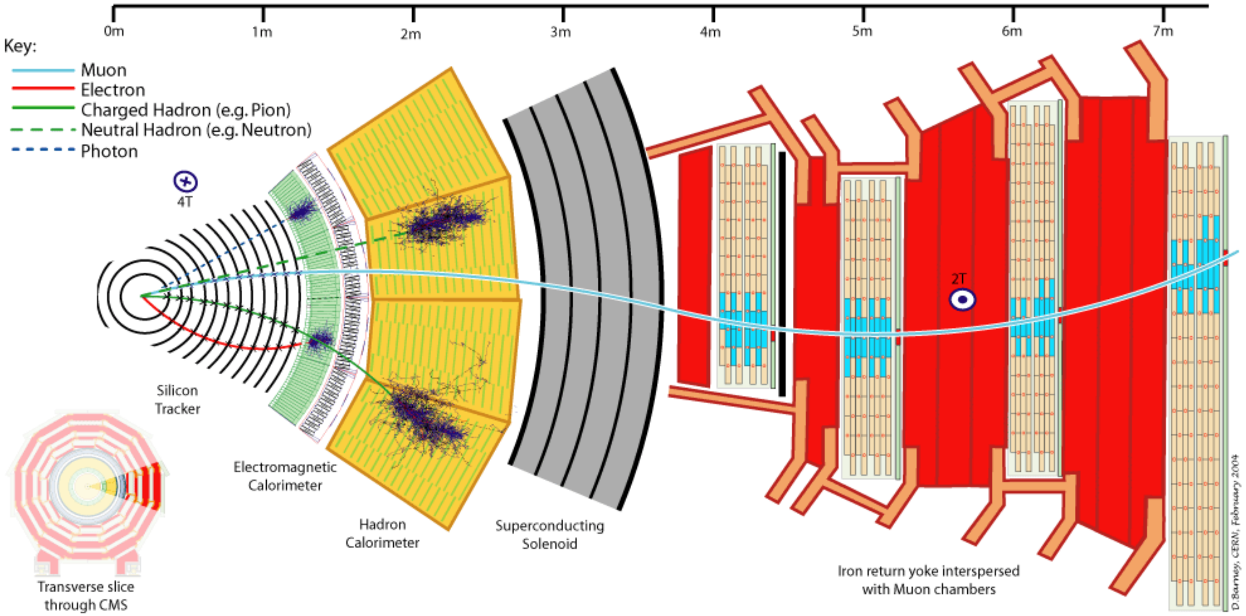


- The top quark mass can be measured:
  - **Indirectly:** via the cross section dependence
  - **Directly:** via a (partial) kinematic reconstruction using the decay products

Reconstruction of top quark events with a general-purpose detector



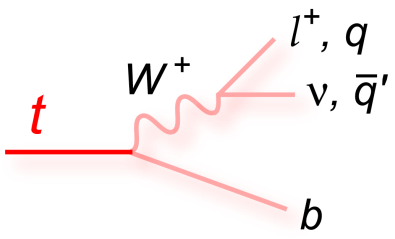
- The full detector is exploited to study $t\bar{t}$ events
- Quarks hadronize → jets of stable neutral and charged particles detected in the inner tracker and calorimeters
- Electrons detected in the inner tracker and EM calorimeter



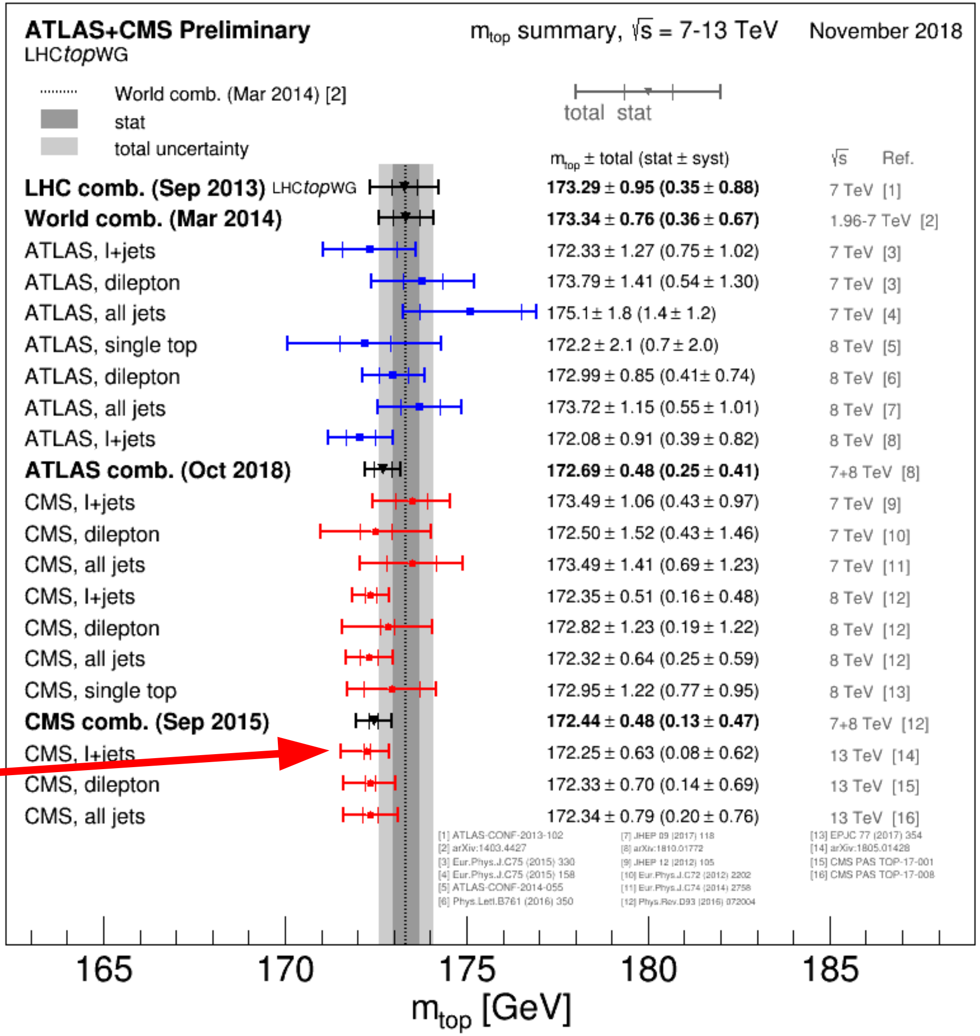
- Muons detected in the inner tracker and muon chambers
- The inner tracker is exploited to improve the energy resolution of charged particles and to identify displaced decays (e.g. for b-jet identification)
- Detector is hermetic
→ infer presence of neutrinos

Overview of the “traditional” direct measurements

- Reconstruct the top quark (partially) using its decay products: e.g. 3-jet combination or lepton + b jet



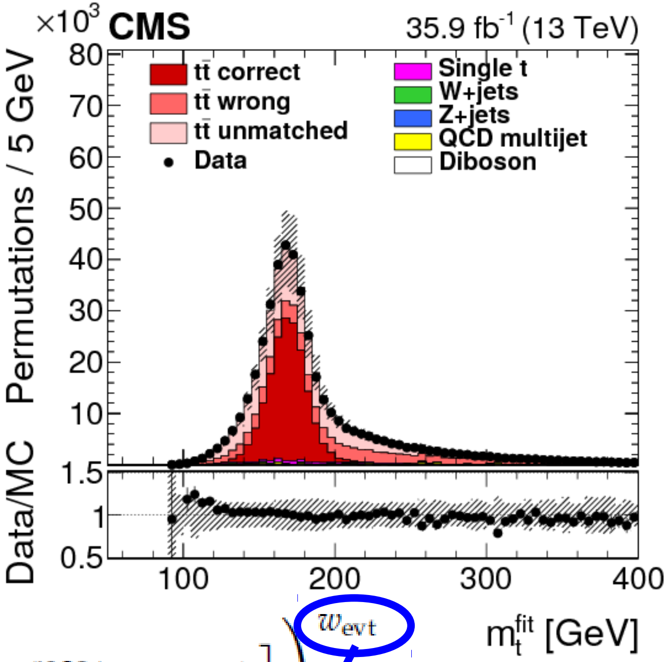
- Direct measurements are more precise than indirect
- The most precise direct measurement is obtained in the l+jets channel (see next slide)



The most precise direct measurement is obtained with the ideogram method in the l+jet channel

Eur. Phys. J. C (2018) 78

- Lepton+jets channel: 1 isolated e or μ and ≥ 4 jets
- Kinematic fit is applied to each three-jet combination with m_W as a constraint → m_t^{fit}
- m_W^{reco} (before kinematic fit) allows to measure jet energy scale factor "JSF"
- All jet-quark permutations are used with $P_{gof} > 0.2$
- Measure simultaneously m_t and JSF by maximizing:



$$\mathcal{L}\left(\text{sample}|m_t,\text{JSF}\right) = P(\text{JSF}) \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\text{gof}}(i) \left[\sum_j f_j\, P_j(m_{t,i}^{\text{fit}}|m_t,\text{JSF})\, P_j(m_{W,i}^{\text{reco}}|m_t,\text{JSF}) \right] \right)^{w_{\text{evt}}}$$

$$w_{\text{evt}} = c \sum_{i=1}^{n} P_{\text{gof}}(i)$$

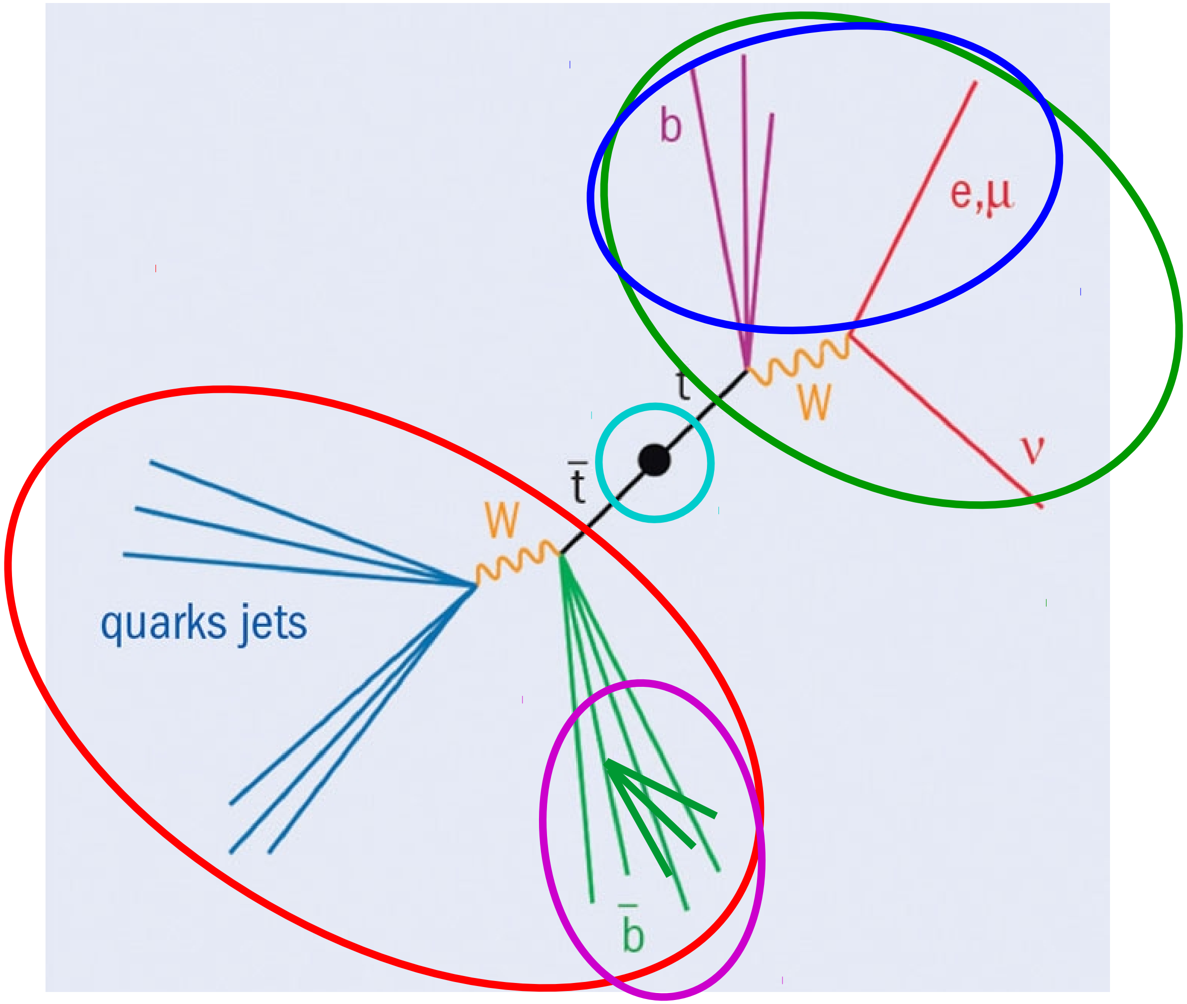
$$m_t^{\text{hyb}} = 172.25 \pm 0.08\,(\text{stat+JSF}) \pm 0.62\,(\text{syst})\,\text{GeV},$$
$$\text{JSF}^{\text{hyb}} = 0.996 \pm 0.001\,(\text{stat}) \pm 0.008\,(\text{syst}).$$

Dominant systematic uncertainties for direct measurements

- Systematic uncertainties are the limiting factor for direct measurements
- Experimental uncertainties:
  - Jet energy corrections
  - Pile up
- Modelling uncertainties:
  - Hadronization (flavour-dependent jet energy corrections)
  - b jet modelling (fragmentation and decays)
  - Renormalization and factorization scales
  - Matrix element generator
  - Underlying event

→ To reduce those, a wide variety of alternative measurements were considered

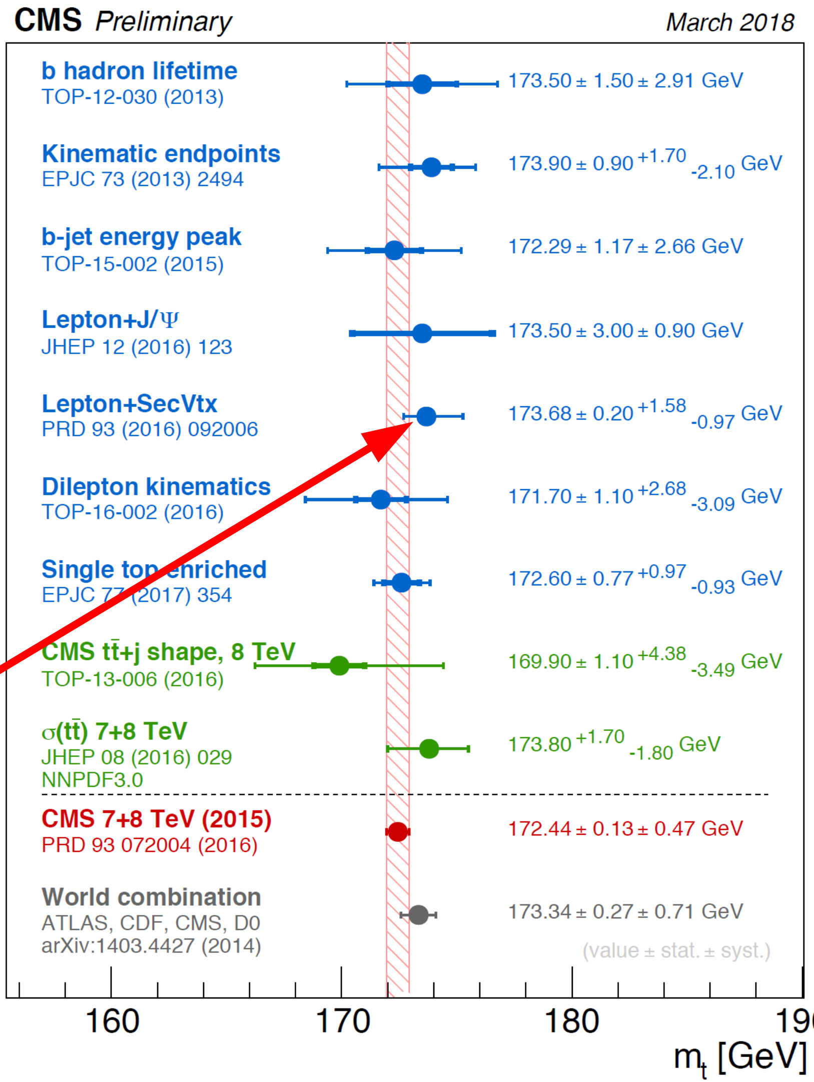
Many observables are sensitive to the top quark mass



- Full reconstruction (3 jets or blν)
- Partial reconstruction (lepton+b)
- Partial reconstruction (lifetime or decay properties of B hadron)
- Production cross section dependence
- …

The alternative direct measurements are typically less precise

- Alternative topologies (e.g. single top)
  - Fit $m_{l\nu b}$
  - Dominant systematics: jet energy scale and hadronization model
- Alternative kinematic variables (e.g. b jet energy spectrum)
  - Less sensitive and large systematics
- Alternative approach to reduce systematic uncertainties: (e.g. lepton+secondary vertex) → reduced jet energy scale uncertainty



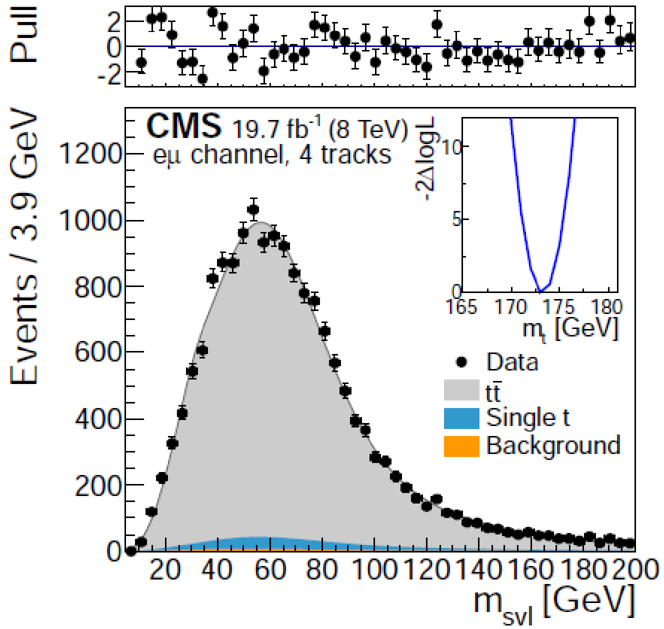
The invariant mass formed by the lepton and the vertex from the b hadron decay is sensitive to m_t

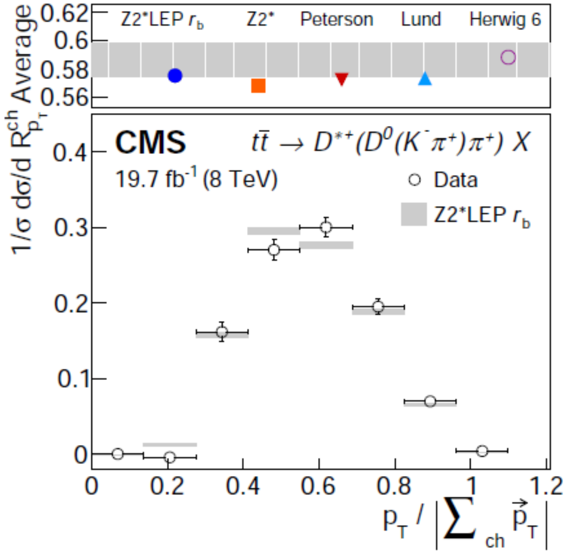
- Fit m_t dependence of the mass formed by the lepton and the charged tracks from the displaced vertex from the b hadron decay in different categories

$$m_t = 173.68 \pm 0.20(\text{stat})\ ^{+1.58}_{-0.97}(\text{syst})\ \text{GeV}$$

- Dominant uncertainties: b quark fragmentation and mismodelling of the top quark p_T distribution

Phys. Rev. D 93 (2016) 092006

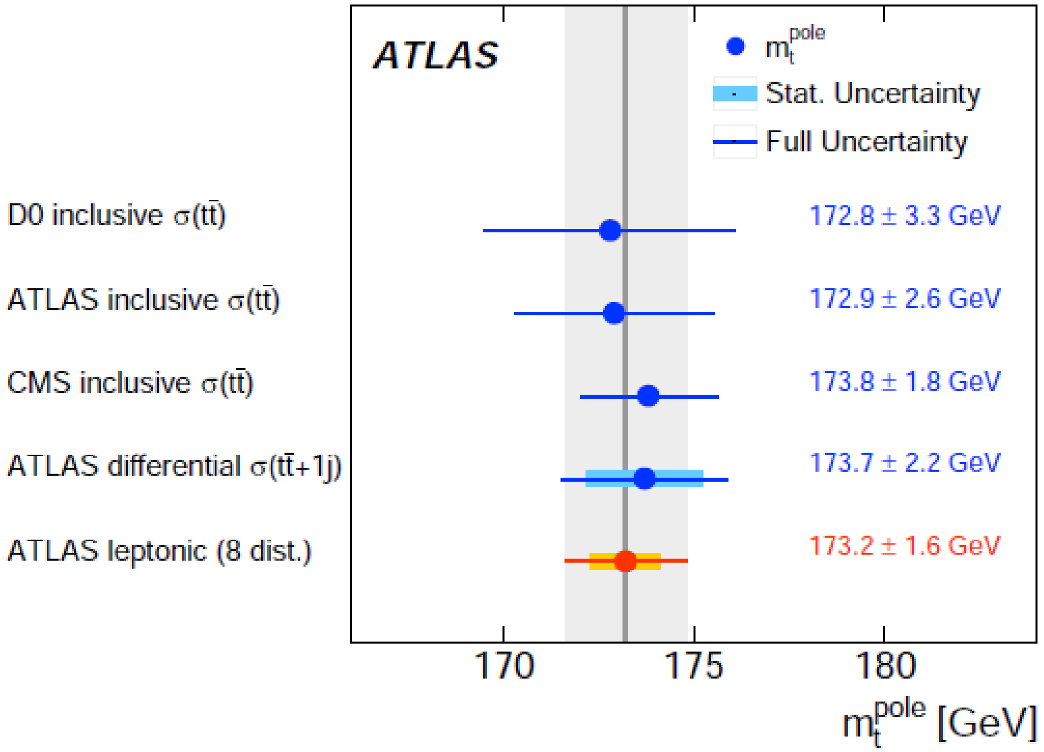




Sensitivity to b quark fragmentation using J/ψ, D^0 and $D^{*\pm}$ → could be used to measure the b quark fragmentation parameters at the LHC!

Overview of the “indirect” measurements

- The top quark production cross section depends on the top quark mass
- Use this theoretical dependence to measure the top quark mass
  → precision depends on accuracy for cross section prediction
- Assumes that no new physics is interfering with the production cross section
- Most precise measurements reach < 2 GeV precision
  → see next slides

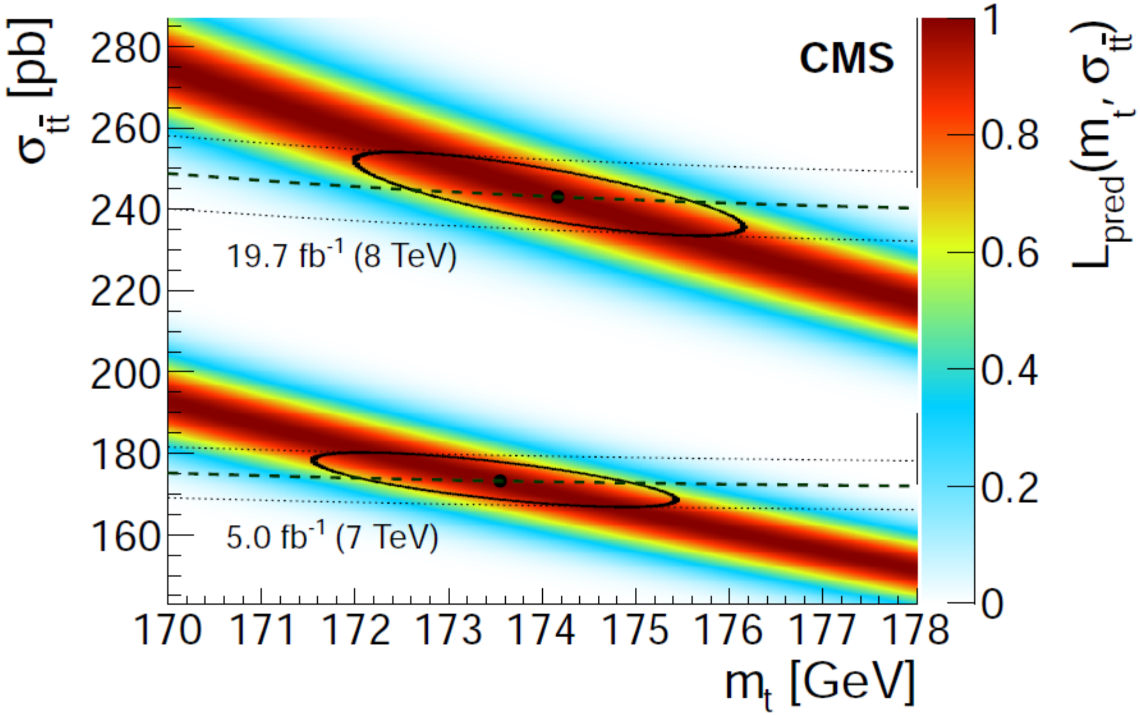


Example of a top quark mass measurement using the inclusive measured production cross section

- Use mass dependence of measured production cross section and NNLO+NNLL prediction to determine the top quark mass

JHEP 08 (2016) 029

- Dilepton (eμ) decay channel, using data collected at 7 and 8 TeV



	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$

Dominant systematic uncertainties:

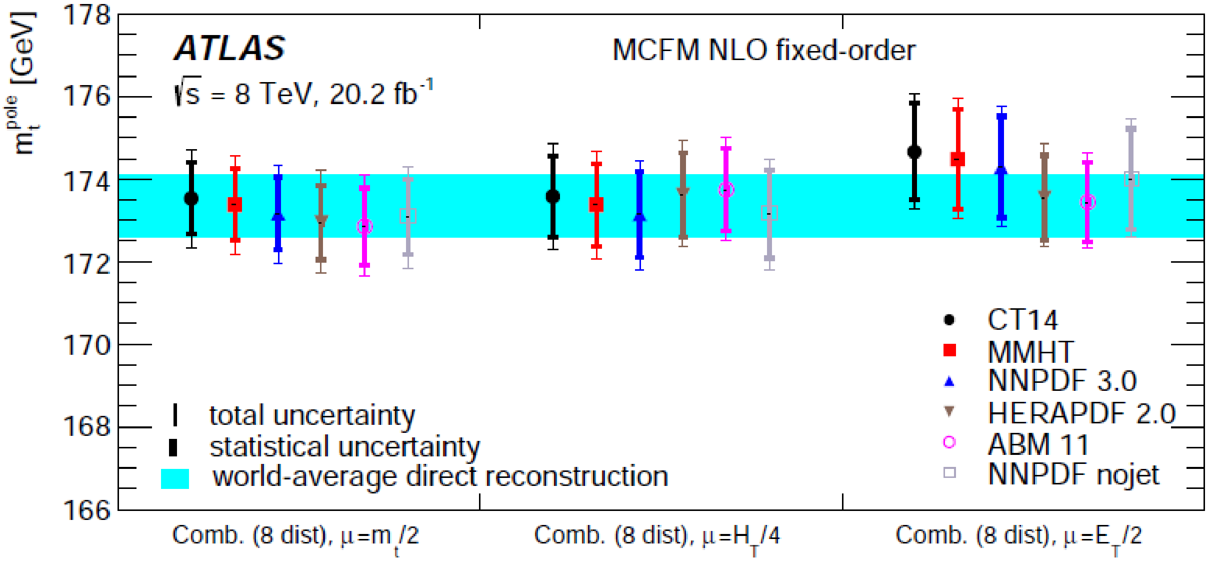
- LHC beam energy and luminosity
- Parton density functions
- α_S

Example of a top quark mass measurement via the differentially measured production cross section

- Dilepton (eμ) channel, using 8 TeV data

Eur. Phys. J C 77 (2017) 804

- Differential cross section for 8 observable distributions related to the leptons



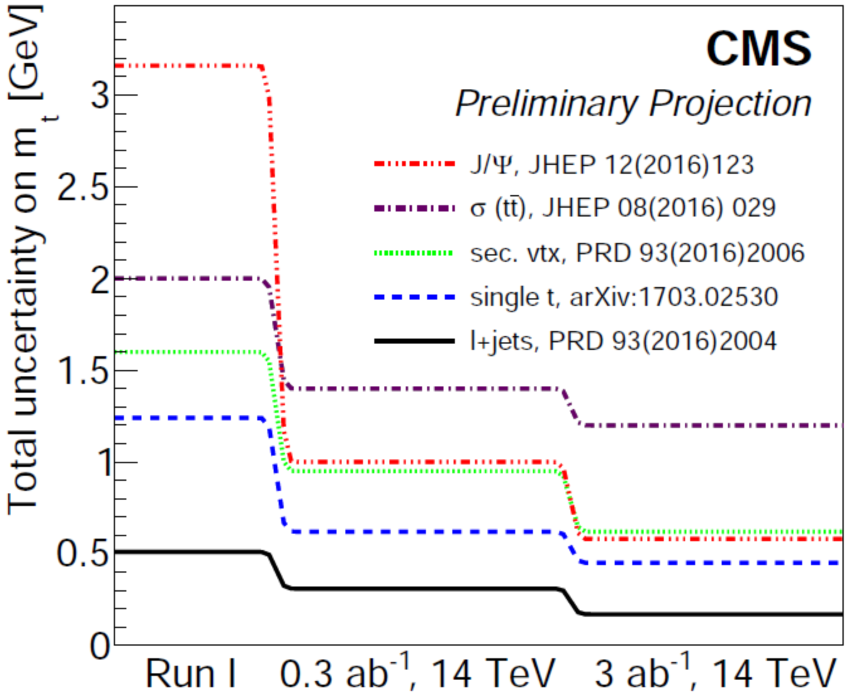
- Mass is extracted from a fit to NLO fixed-order predictions with MCFM
- Missing NNLO corrections are absorbed into the variations of the factorization and renormalization scales, which are constrained by the fit to the complete set of distributions
- Higher accuracy in MC useful!

$$m_t^{\text{pole}} = 173.2 \pm 0.9 \pm 0.8 \pm 1.2\,\text{GeV}$$

Prospects at the (HL-)LHC

- The systematic uncertainties will be further reduced with more statistics

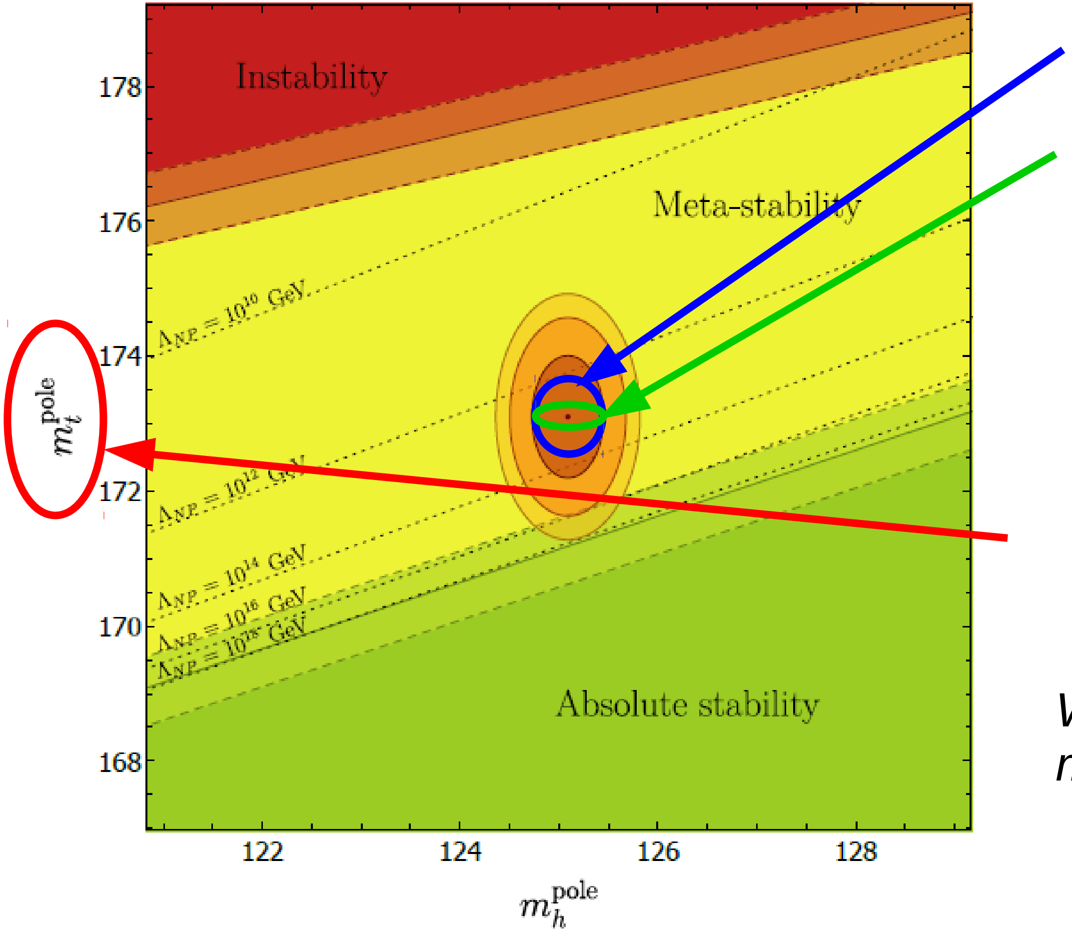
CMS-PAS-FTR-16-006



- Most of the experimental uncertainties (e.g. jet energy scale will be measured more precisely)
- Some modelling parameters (hadronization) are assumed to be constrained by the data
- The precision will be limited by theoretical modelling uncertainties
- <300 MeV precision by the end of Run 3
- Ultimately < 150 MeV precision

How useful is the precisely measured top quark mass?

arXiv:1707.08124 [hep-ph]



- Today ~500 MeV precision
- Ultimately < 150 MeV precision

“top quark pole mass”

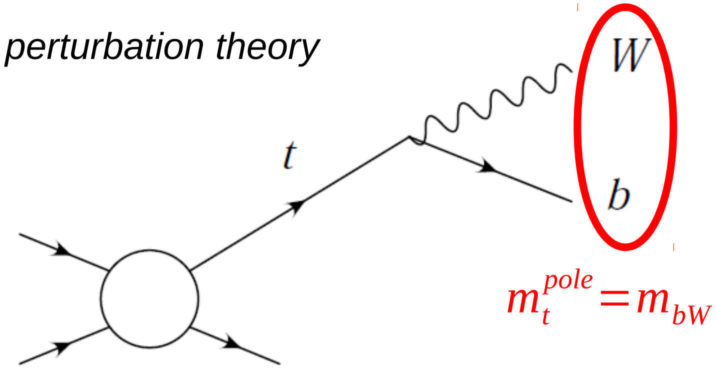
What is the connection between the measured mass and the top quark pole mass?

The pole mass has an irreducible ambiguity of O(200 MeV)

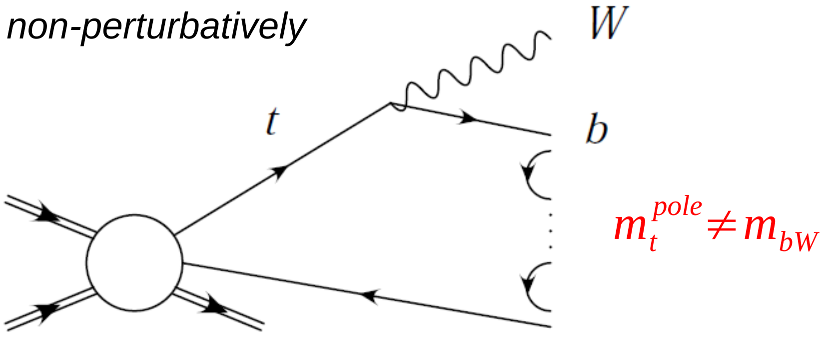
- The pole mass = the position of the pole in the top quark propagator:

$$\frac{i}{\not{p} - m_t^{pole}}$$

perturbation theory



non-perturbatively



- Quarks are confined → ambiguous definition of pole mass
- The renormalization constant for the pole mass includes contributions from all momentum scales (both UV and IR)
- The IR contributions give rise to a non-perturbative effect in the summation: “the IR renormalon ambiguity of the pole mass”:
  ~110 MeV **arXiv:1605.03609 [hep-ph]** ~250 MeV **arXiv:1706.08526 [hep-ph]**

Short-distance mass avoids the ambiguity in definition

- Minimal Subtraction ($\overline{MS}$) scheme:
  → include only UV divergences, i.e. short-distance effects
- $\overline{MS}$ mass is a short-distance mass → no IR renormalon ambiguity
- Relation with the pole mass:

$$m_t^{pole} = m_t^{\overline{MS}}(m_t^{\overline{MS}})\left(1 + c_1 \frac{\alpha_S}{\pi} + c_2\left(\frac{\alpha_S}{\pi}\right)^2 + c_3\left(\frac{\alpha_S}{\pi}\right)^3 + c_4\left(\frac{\alpha_S}{\pi}\right)^4 + \ldots\right)$$

→ coefficients c_1 to c_4 have been determined, i.e. N^{4}LO accuracy **arXiv:1502.01030 [hep-ph]**

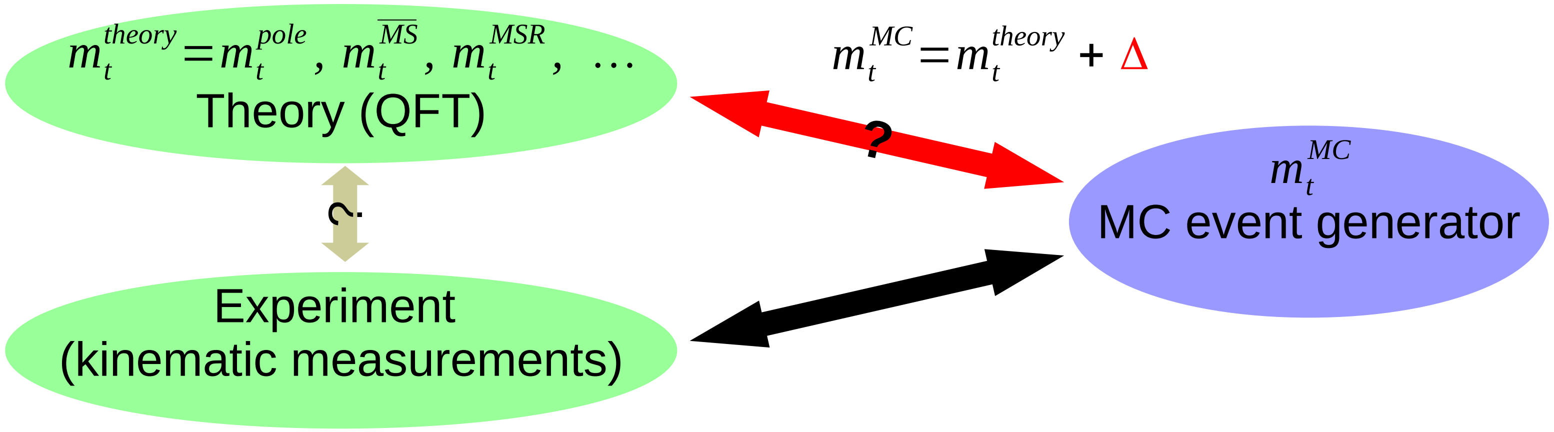
→ contributions from higher orders are estimated to be around 300 MeV

arXiv:1605.03609 [hep-ph]

- Both the $\overline{MS}$ mass and the pole mass can be measured via the pp→$t\bar{t}$ cross section dependence!

Direct measurements are useful
if we are able to relate the MC mass to a theory mass

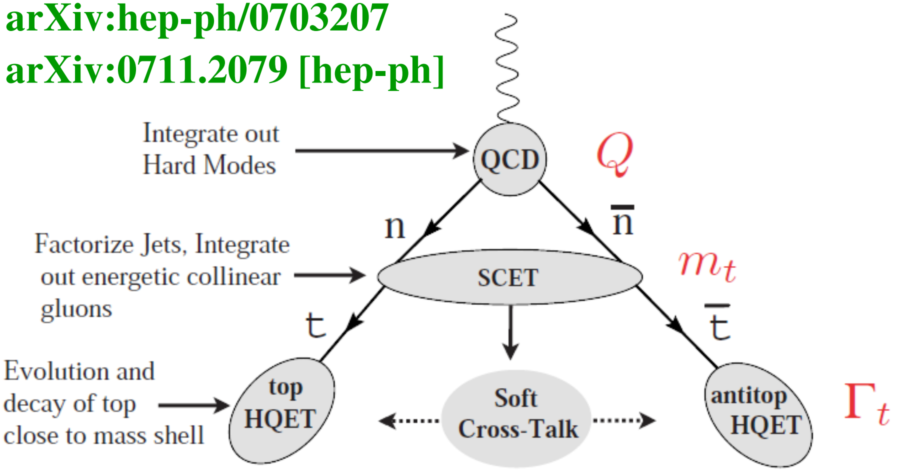
- Are the most precise (i.e. direct) measurements useless?
- Direct measurements rely on the MC event generator to extract the mass
  → “MC mass”

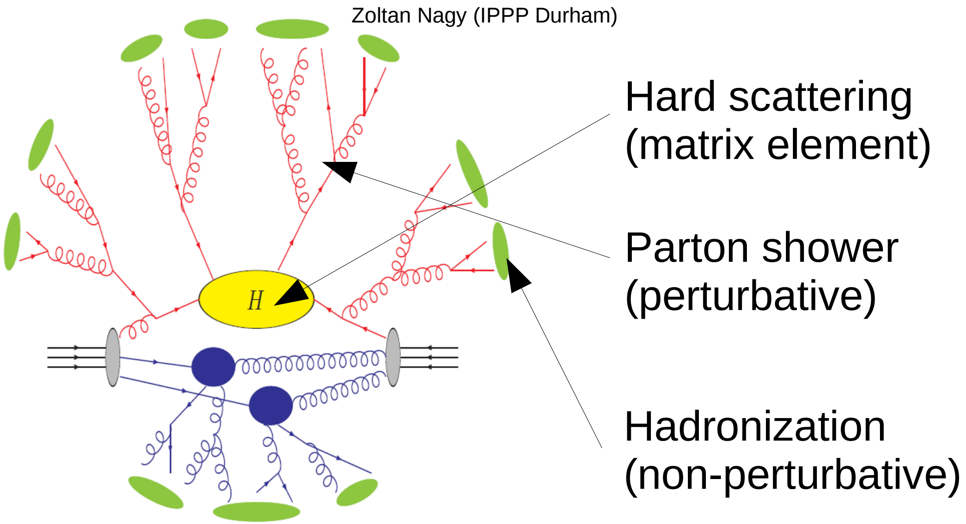


- What is the size of Δ?
- Exploit analogy between factorization in effective field theory and factorization in MC event generators

Factorization in effective field theory and MC generators

arXiv:hep-ph/0703207
arXiv:0711.2079 [hep-ph]





- Three separate scales are governing the dynamics of the system:
  $Q >> m_t >> \Gamma_t > \Lambda_{QCD}$
- By numerical coincidence Γ_t is close to the parton shower cut off (~1 GeV)
- Define a low-energy $\overline{\text{MS}}$ mass such that $m_t^{MSR}(R=0)=m_t^{pole}$ and $m_t^{MSR}(R=m_t^{MS})=m_t^{MS}$
  → relate m_t^{MC} with $m_t^{MSR}(R=\Gamma_t)$

Calibration of the MC mass to a field theory mass (e^+e^-)

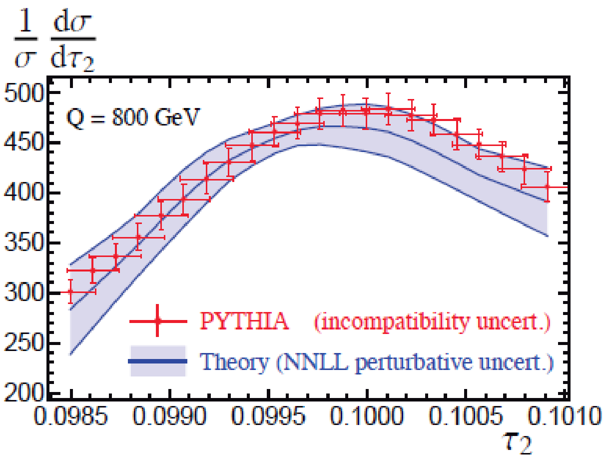
arXiv:1608.01318 [hep-ph]

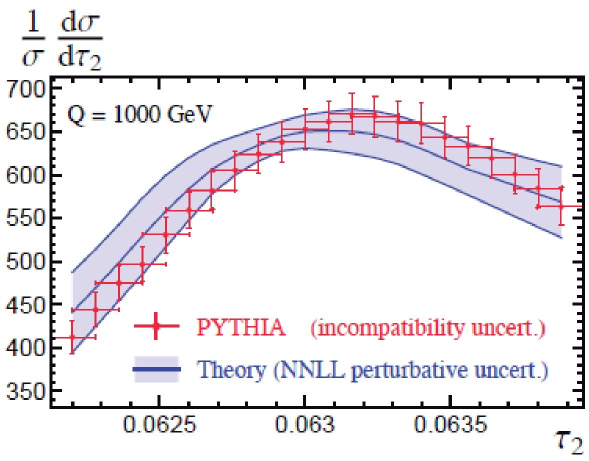
- Numerical relation between Pythia MC top quark mass and MSR mass using 2-jettiness (τ_2) in e^+e^- in resonance region (i.e. for boosted top quarks) from calibration fits

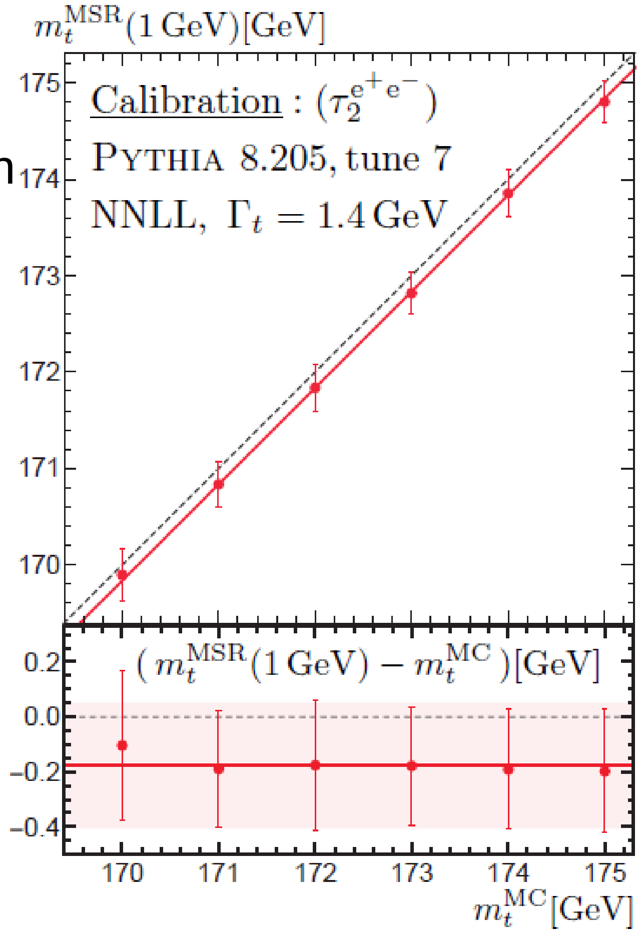
$$m_t^{MC} = m_t^{MSR} + (0.18 \pm 0.22)\ GeV$$

$$m_t^{MC} = m_t^{pole} + (0.57 \pm 0.28)\ GeV$$

- Agreement between Pythia and analytical calculation



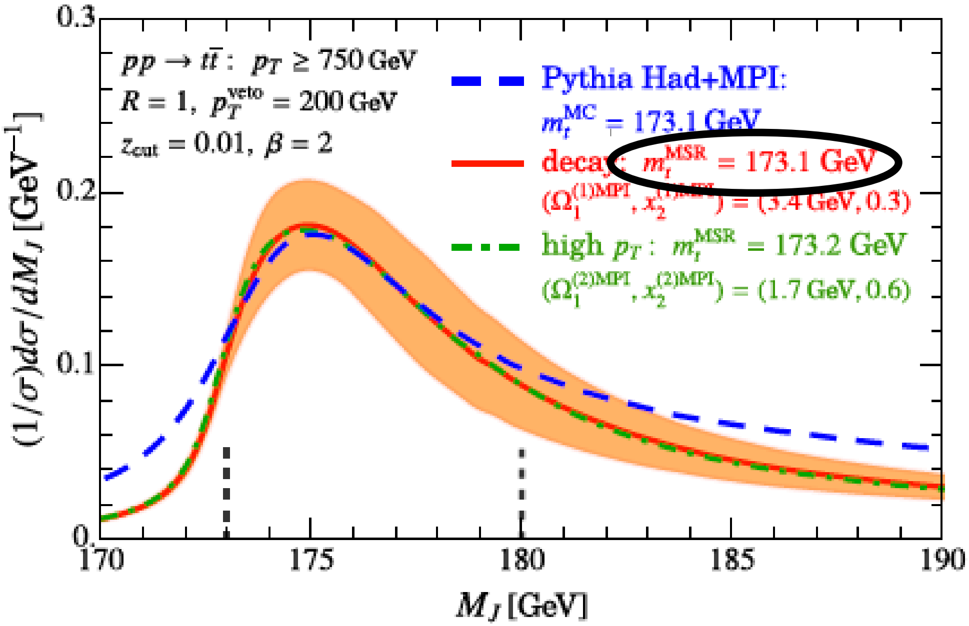


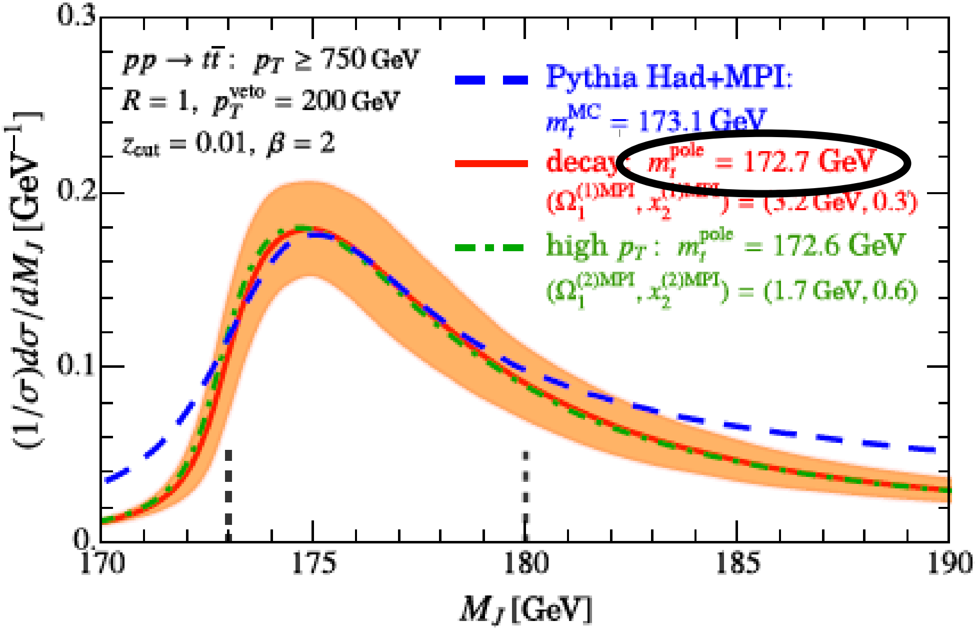


Calibration of the MC mass to a field theory mass (LHC)

arXiv:1708.02586 [hep-ph]

- Framework extended to LHC using groomed jet mass for boosted top quarks
- Hadronization and multi-parton interactions included





- Full calibration has to be done but the results are consistent with e^+e^- calibration

Calibration of the MC mass to a field theory mass is a hot topic these days

- The 'inclusive' calibration solves the interpretation issue, but does not provide more insight

- Improve understanding:

$$m_t^{MC} = m_t^{pole} + \Delta m^{pert} + \Delta m^{non-pert} + \Delta m^{MC}$$

Scheme definition (parton shower)

hadronization model parameters

Modelling uncertainties: color reconnection, b-jet fragmentation, finite width,...

- Quantify Δm^{pert} **arXiv:1807.06617 [hep-ph]**

$$m_t^{pole} = m_t^{Herwig} + (0.540 \pm 0.260)\ GeV$$

→ uncertainty on shift dominated by ambiguity of 250 MeV on m_t^{pole}
→ shift itself is as large as current experimental uncertainty

- Work ongoing to determine $\Delta m^{non-pert}$ using dedicated MC simulations

What else is happening?

- Recently a lot of progress was made to calibrate the MC top quark mass to a field theory interpretable mass
- Better MC event generators for $t\bar{t}$ production and decay:
  - NLO QCD + PS for $t\bar{t}$ + tW with decay (dilepton) **arXiv:1607.04538 [hep-ph]**
  - NLO QCD + NLO EW for $t\bar{t}$ with decay **arXiv:1711.08910 [hep-ph]**
  - NNLO QCD + NLO EW for $t\bar{t}$ **arXiv:1712.04842 [hep-ph]**
  - NNLO approximations in $t\bar{t}$ production and decay **arXiv:1705.08903 [hep-ph]**
  - NNLO + NNLL' QCD for (boosted) $t\bar{t}$ **arXiv:1803.07623 [hep-ph]**
  - ...
- Differential measurements will allow to better understand the nature of the MC mass (the top mass should be the same in every corner of the phase space)
- Even if some of the systematic uncertainties will be reduced with more data, we would need techniques to reduce the others → example in the next slides

Techniques are needed to reduce the systematic uncertainty

- For many precision measurements the systematic uncertainty is (much) larger than the statistical

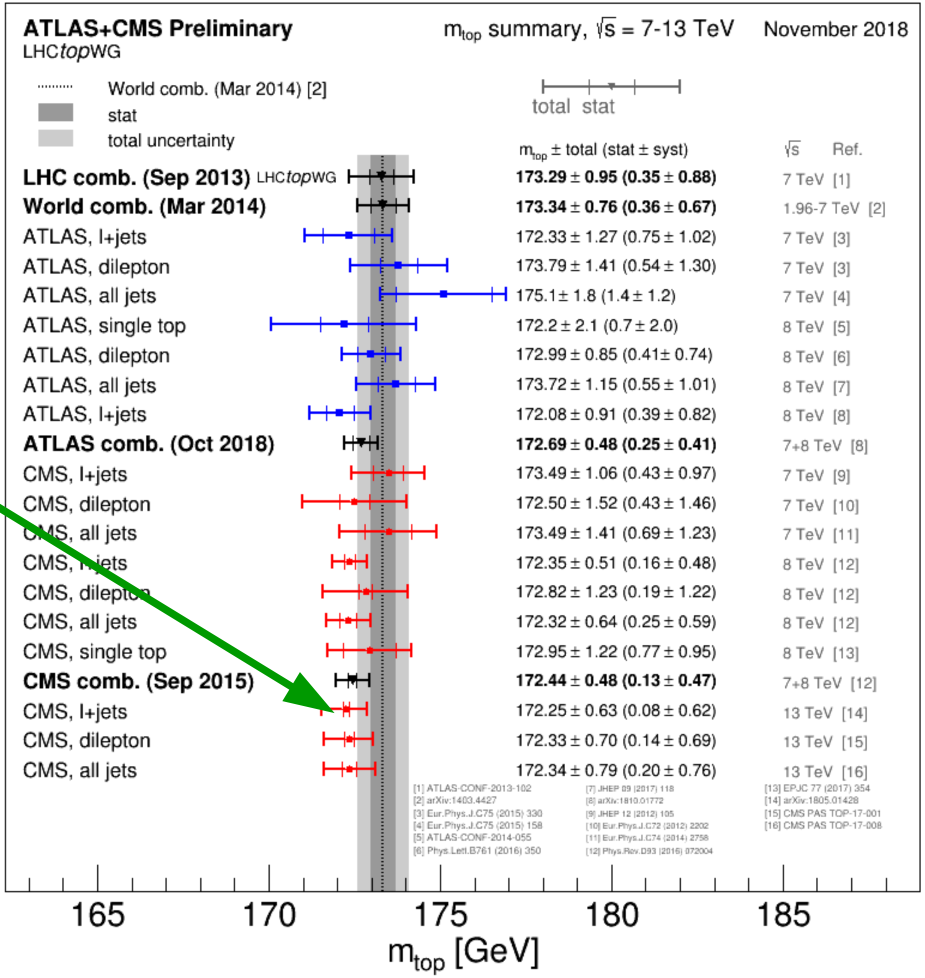
- E.g. the top quark mass:

Eur. Phys. J. C (2018) 78

172.25 ± 0.08 (stat+JSF) ± 0.62 (syst) GeV

the statistical uncertainty is 8 times smaller than the systematic uncertainty

- In an effort to reduce the total uncertainty, we can afford to cut some data



Concept of the ReSyst technique

- ***"ReSyst:*** *a novel technique to Reduce the Systematic uncertainty for precision measurements"* documented in **arXiv:1809.07700**

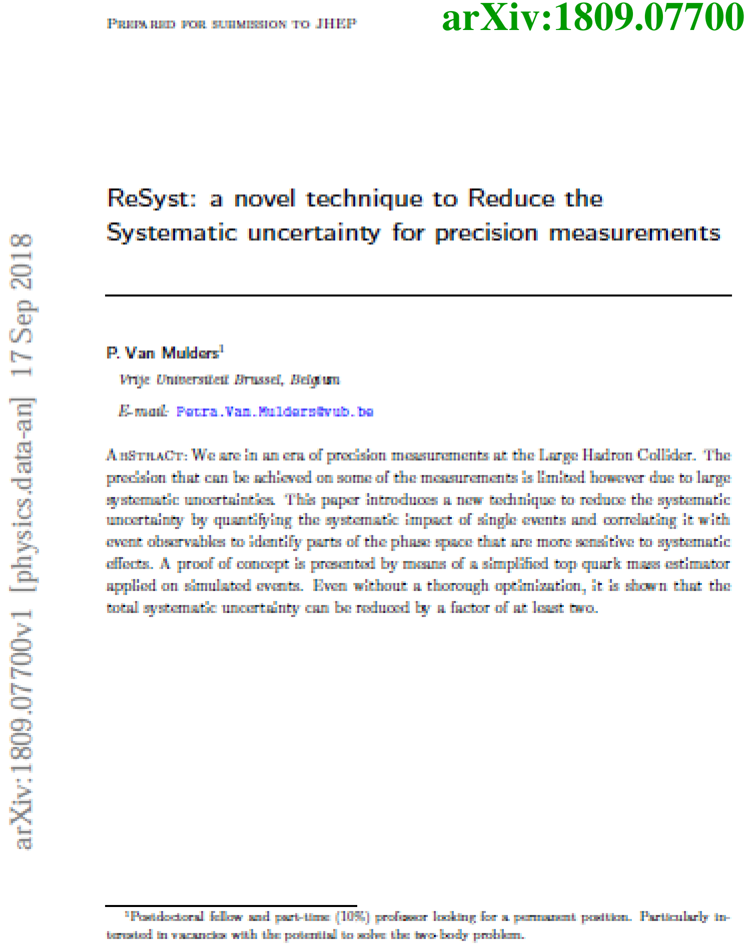
- **Goal**: reject those events that make the systematic uncertainty large

- **How?**
  - Systematic uncertainties are typically assessed by varying experimental or theoretical parameters in the MC simulation (their size is determined inclusively)
  - Define for each event a quantifier related to its impact on the total systematic uncertainty → inspired by the "delete one event" Jackknife resampling method
  - Correlate this non-observable quantifier (determined on simulation) with observable event properties to identify regions of the phase space (classes of events) which result in a large systematic uncertainty

Conceptual demonstration of the ReSyst technique

- Event generation and selection
- Simplified top quark mass estimator
- Proof-of-concept
- Cross-checks
- Food for thought

arXiv:1809.07700



PREPARED FOR SUBMISSION TO JHEP

arXiv:1809.07700v1 [physics.data-an] 17 Sep 2018

ReSyst: a novel technique to Reduce the Systematic uncertainty for precision measurements

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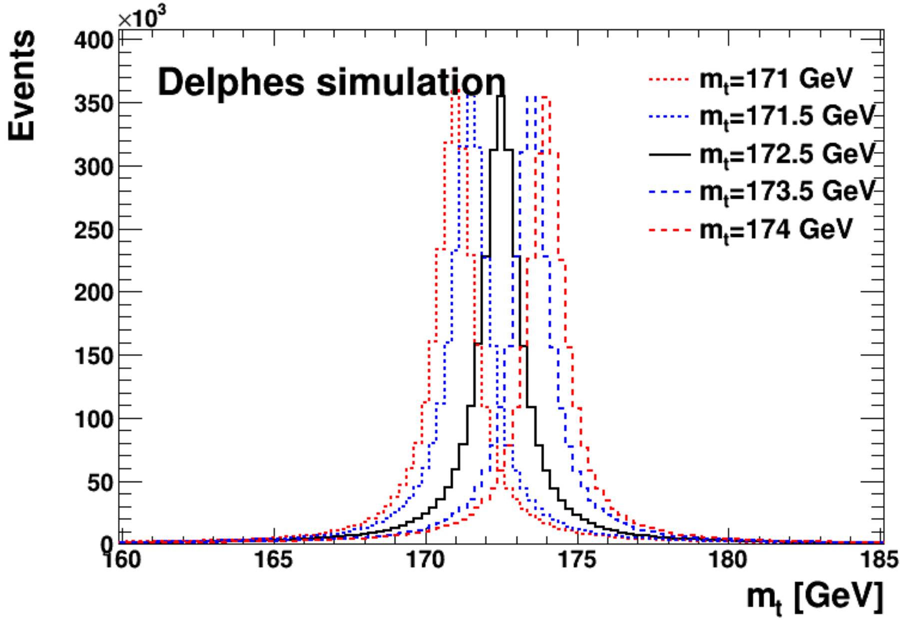
ABSTRACT: We are in an era of precision measurements at the Large Hadron Collider. The precision that can be achieved on some of the measurements is limited however due to large systematic uncertainties. This paper introduces a new technique to reduce the systematic uncertainty by quantifying the systematic impact of single events and correlating it with event observables to identify parts of the phase space that are more sensitive to systematic effects. A proof of concept is presented by means of a simplified top quark mass estimator applied on simulated events. Even without a thorough optimization, it is shown that the total systematic uncertainty can be reduced by a factor of at least two.

[1]Postdoctoral fellow and part-time (10%) professor looking for a permanent position. Particularly interested in vacancies with the potential to solve the two-body problem.

Event generation, selection and reweighting

- 10M POWHEG v2 $pp \to t\bar{t} \to b\mu\nu\bar{b}qq$ events at 13 TeV with m_t = 172.5 GeV
- PYTHIA 8.2 + CUETP8ME2T4 for parton shower, hadronization and decay
- Parameterized default CMS detector simulation using DELPHES v3.4.2pre03 ("DeepCSV M" b-tagging efficiencies from appendix JINST 13 (2018) P05011)
- Event selection:
  - Muon: p_T > 25 GeV, $|\eta|<2.4$
  - ≥ 4 jets: p_T> 30 GeV, $|\eta|<2.4$ of which ≥ 2 b-tagged jets

  → selection efficiency of ~15%
- No other $t\bar{t}$ decays or background
- Events reweighted → other m_t masses (reweight both top and antitop)



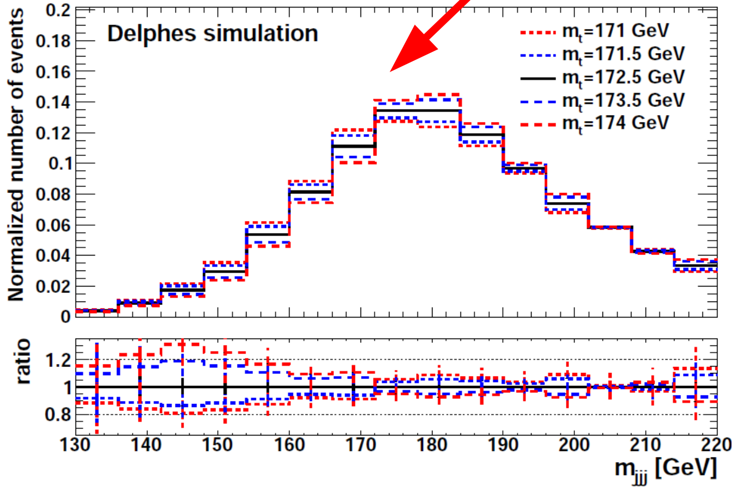
Simplified event-by-event top quark mass estimator: probability density functions and likelihood

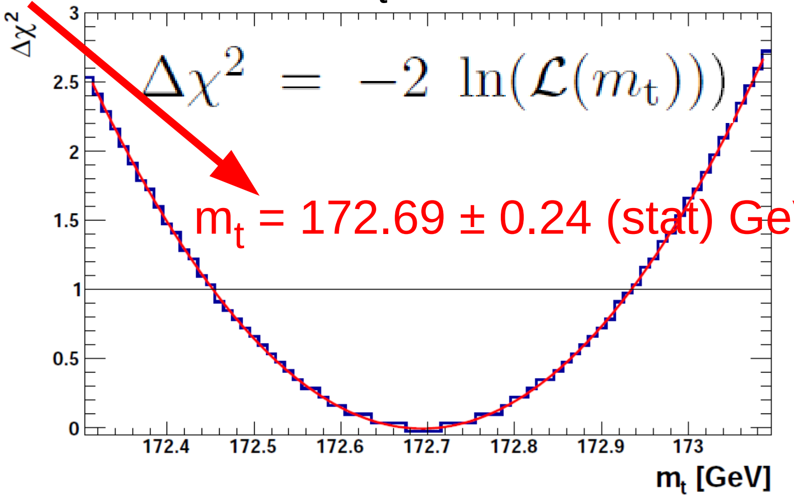
- The three leading p_T jets are used to reconstruct the “hadronic top”
  $\rightarrow$ distribution of the mass m_{jjj} *(in range 130 to 220 GeV)* is sensitive to m_t
  (selection efficiency ~1.6%)
- Construct a likelihood (based on pdf's for correctly & wrongly matched events)

$$\mathcal{L}(m_t) = \prod_{i=1}^{n} f_{CM}(m_t) P_{CM}(m_{\mathrm{jjj},i}|m_t) + (1 - f_{CM}(m_t)) P_{NM}(m_{\mathrm{jjj},i})$$

with f_{CM}~16%

- Minimize negative logarithm of likelihood to obtain estimation of m_t





Simplified top quark mass estimator: systematic uncertainties

Systematic source	$+1\sigma$ effect [GeV]	-1σ effect [GeV]	CMS 1D
b tagging efficiency and mistagging probability	0.01	-0.01	0.01
Jet energy scale	1.07	-1.47	0.83
Factorization and renormalization scales	0.03	-0.04	0.02
Matrix element and parton shower matching (h_{damp})	0.01	< 0.01	+0.03
Top quark p_{T}	n.a.	-0.04	-0.06
b quark fragmentation	0.67	-0.71	0.09
Total systematic uncertainty	1.26	-1.63	1.10

- **m_t = 172.69 ± 0.24 (stat.) +1.26 –1.63 (syst.) GeV**
- **Size of systematic uncertainties is in the same ball-park as for the “1D approach”** in lepton+jets ideogram method documented in Eur. Phys. J. C (2018) 78
- b quark fragmentation is larger here but different approaches to assess
  Note that for the CMS “1D approach” the “b JEC flavor” has an additional systematic effect of -0.31 GeV on top of JEC uncertainty in table

Identifying classes of events with a large systematic impact

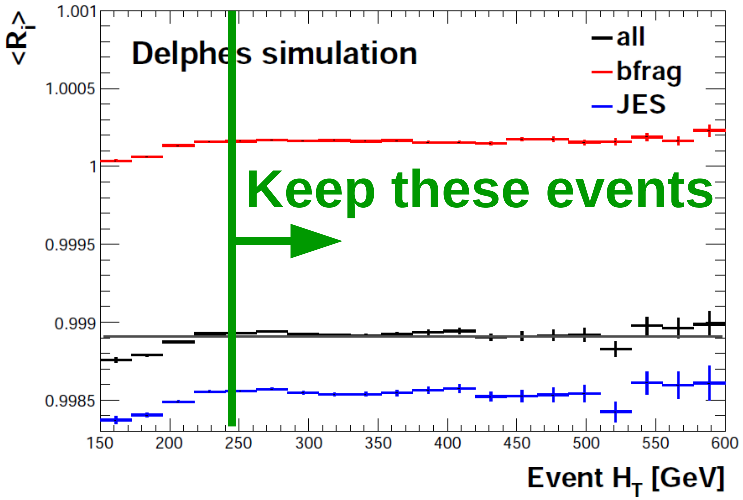
- For each event quantifier R_i:

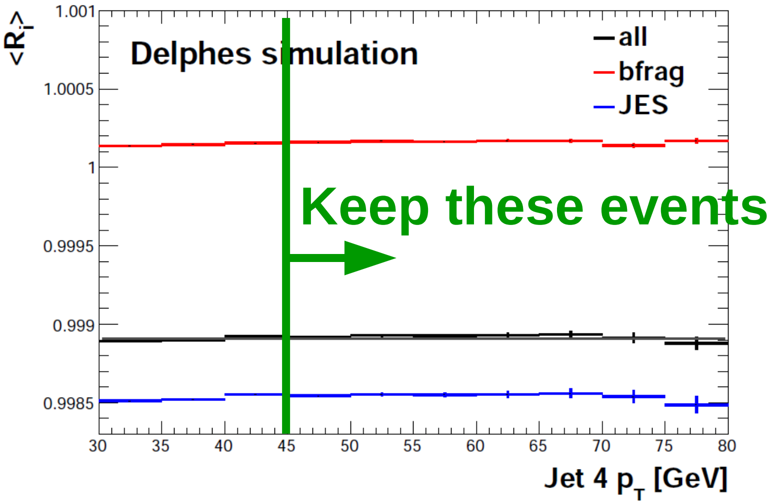
$$R_i = \frac{\sqrt{\sum_j (m_{t(i)}^{+1\sigma_j} - m_{t(i)}^{-1\sigma_j})^2}}{\sqrt{\sum_j (m_t^{+1\sigma_j} - m_t^{-1\sigma_j})^2}}$$

Total systematic impact without event "i" (numerator)

Total systematic impact = fixed for all events (denominator)

- Smaller value of R_i → systematic uncertainty reduced by removing event "i"
- Correlate R_i with event observables and keep events with higher $\langle R_i \rangle$ values:





Impact of the additional selection requirements

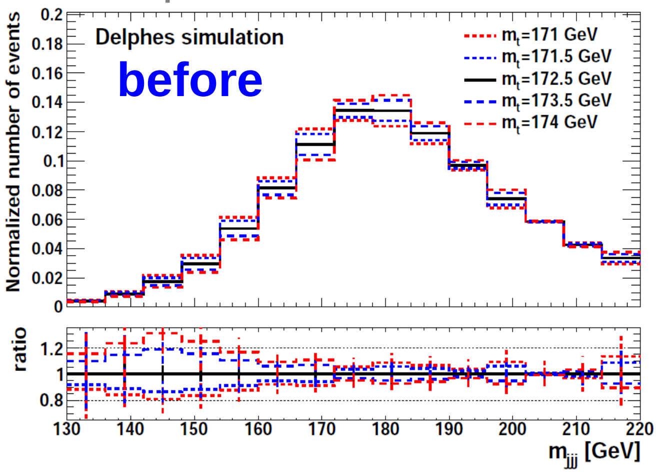
Systematic source	before: $+1\sigma$ effect [GeV]	before: -1σ effect [GeV]	after: $+1\sigma$ effect [GeV]	after: -1σ effect [GeV]
b tagging efficiency and mistagging probability	0.01	-0.01	0.01	-0.01
Jet energy scale	1.07	-1.47	0.59	-0.48
Factorization and renormalization scales	0.03	-0.04	0.03	-0.03
Matrix element and parton shower matching (h_{damp})	0.01	< 0.01	0.01	-0.01
Top quark p_{T}	n.a.	-0.04	0.07	n.a.
b quark fragmentation	0.67	-0.71	0.18	-0.18
Total systematic uncertainty	1.26	-1.63	0.64	-0.55

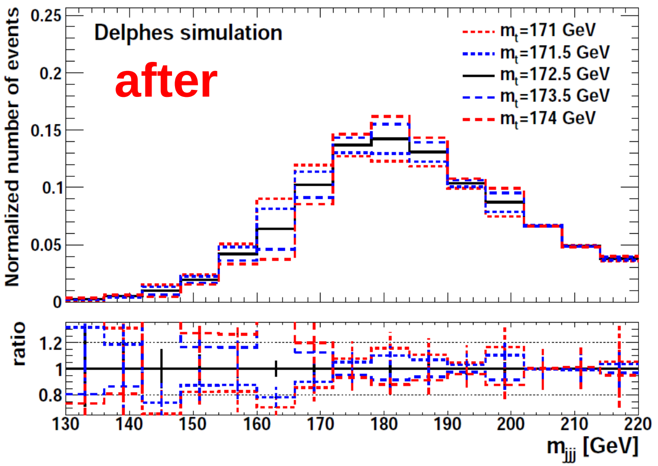
- After the additional selection requirements, the uncertainties are reduced:
  before: m_t = 172.69 ± 0.24 (stat.) + 1.26 – 1.63 (syst.) GeV
  after: m_t = 172.60 ± 0.19 (stat.) + 0.67 – 0.58 (syst.) GeV
  → *technique seems to work conceptually*
- **Note 1:** statistical uncertainty also reduced → see next slide
- **Note 2:** the effect of these requirements will not be the same in a real analysis because the estimator is too simple in this study (statistical uncertainty is 4 times larger compared to the CMS ideogram method)

Why is the statistical uncertainty smaller after the cuts?

- **before: m_t = 172.69 ± 0.24 (stat.) + 1.26 – 1.63 (syst.) GeV**
  after: m_t = 172.60 ± 0.19 (stat.) + 0.67 – 0.58 (syst.) GeV

- Only 1 out of 4 events is kept, so we expect a doubling of the statistical uncertainty, yet the statistical uncertainty is reduced from 0.24 GeV to 0.19 GeV
  - More wrongly matched events are rejected:
    → fraction of correctly matched events raises from ~16% to ~22%
  - The pdf's are remade after the selection requirements
    → new pdf's more sensitive





Cross-checks show technique behaves as expected

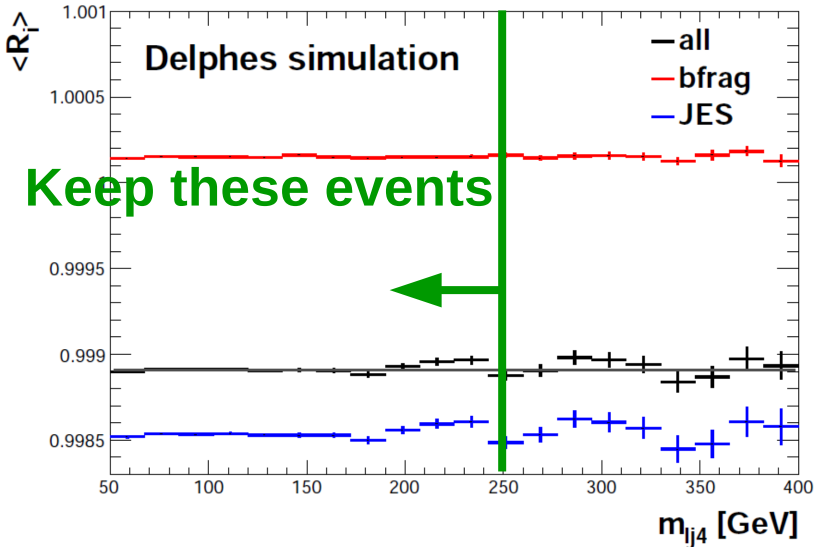
- **First cross-check:** reverse additional selection requirements
  - **Expected:** similar systematic uncertainties
  - **Observed:** systematic uncertainties fall outside the considered top quark mass window (171 < m_t < 174 GeV)

- **Second cross-check:** apply a requirement on an observable for which <R_i> shows no trend,
  e.g. $m_{l,jet\ 4}$ < 250 GeV
  - **Expected:** no effect on systematic uncertainty
  - **Observed:** 36% of the events rejected and no effect on systematic uncertainty:

m_t = 172.74 ± 0.30 (stat.) + 1.23 – 1.64 (syst.) GeV

to be compared with:

m_t = 172.69 ± 0.24 (stat.) + 1.26 – 1.63 (syst.) GeV



- ***The method behaves as expected***

Summary and prospects concerning ReSyst

- ReSyst allows to quantify the systematic impact for each event: quantifier “R_i”
- The quantifier “R_i” can be correlated to observables to identify classes of events inducing a large effect, which could then be used to:
  → reject certain classes of events;
  → identify observables to be used to profile uncertainties in a likelihood fit.
- **Limitation: R_i is only defined when using weight-based systematics, i.e. when the “nominal” and “systematic” event have a one-to-one connection**

$$R_i = \frac{\sqrt{\sum_j (m_{t(i)}^{+1\sigma_j} - m_{t(i)}^{-1\sigma_j})^2}}{\sqrt{\sum_j (m_t^{+1\sigma_j} - m_t^{-1\sigma_j})^2}}$$

The same event “i”

- The paper is under review by JHEP
- The next step is to test the ReSyst technique in a real physics analysis
  → CMS lepton+jets ideogram top quark mass measurement
  → Optimize the additional selection requirements (using machine learning)

Summary and prospects for top quark mass measurements

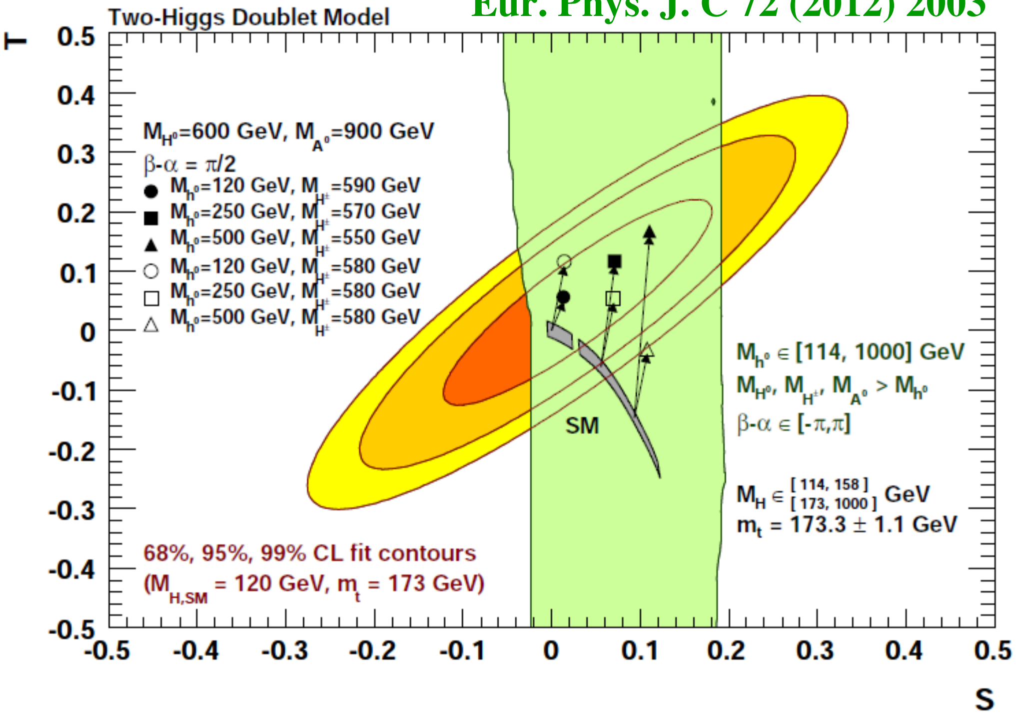
- Experiments are measuring the (MC) top quark mass with ~500 MeV precision
- The community is divided about the usefulness of these measurements
  → progress is being made on both experimental and theoretical fronts
- We can potentially increase the precision on top quark mass measurements with a factor of 2 at the LHC
  - **Worst case:** newly developed techniques and profound understanding of MC generators result in better MC generators for top quark physics
  - **Best case:** resolve the debate on the interpretation of the measured top quark mass and use the precisely measured top quark mass for theory predictions
- Nothing to lose!

Additional material aka backup

Top quark mass: validity of Standard Model extensions

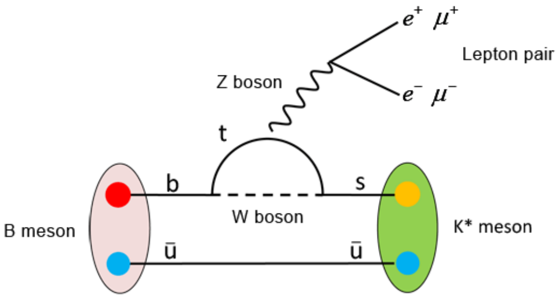
- New physics (NP) models can be constrained from the electroweak precision observables
- Most NP effects can be parameterised by 3 parameters: S,T,U introduced by Peskin and Takeuchi **Phys. Rev. D 46, 381-409 (1992)**
- Tools available like Gfitter: **project-gfitter.web.cern.ch/project-gfitter**
- In this plot the constraints from direct searches are not applied

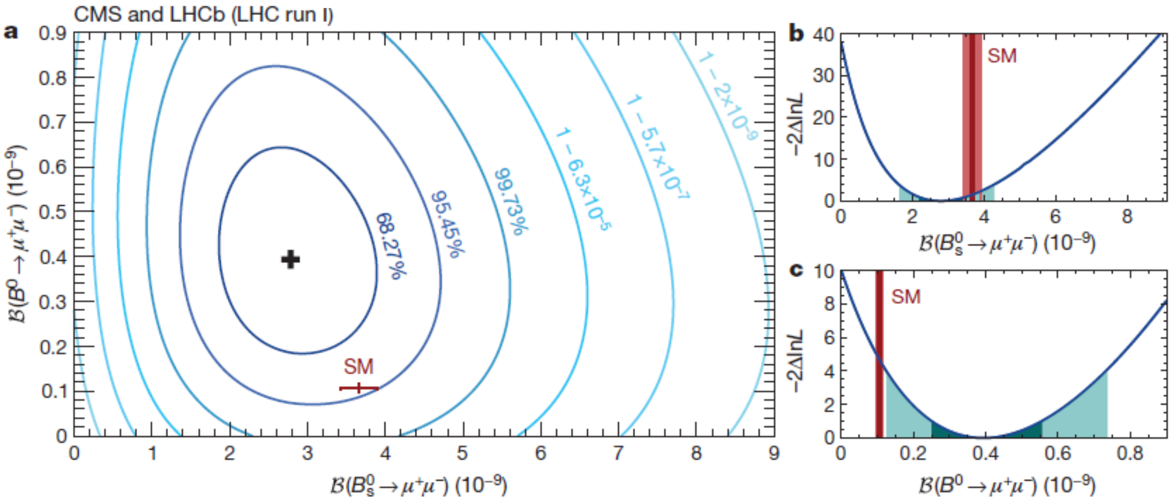
Eur. Phys. J. C 72 (2012) 2003



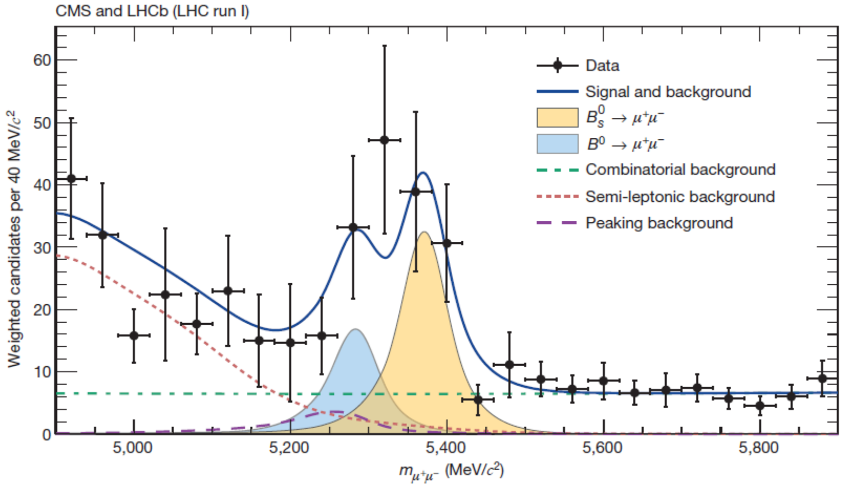
Top quark mass in flavour physics, e.g.: rare B decays

- The top quark is present in the loops for rare decays
  → its mass impacts the decay rate





Nature 522 (2015) 68

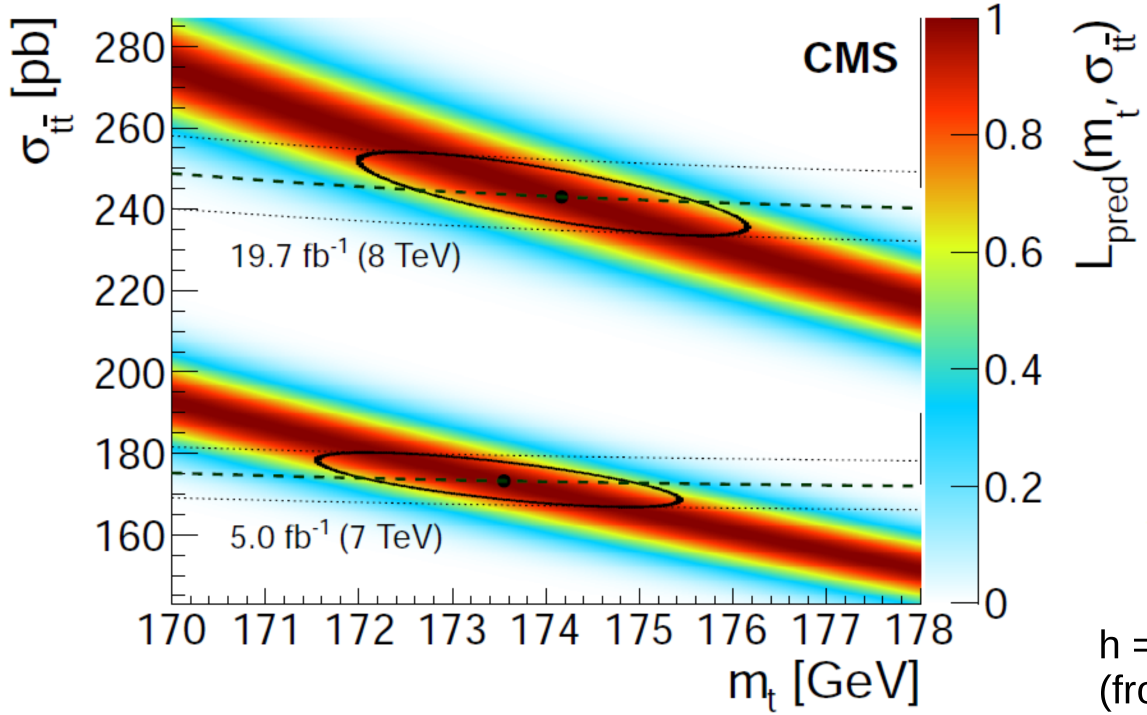


- 7.4σ observation of $B_s \rightarrow \mu^+\mu^-$
- 0.8σ for $B \rightarrow \mu^+\mu^-$
- Branching ratios consistent with SM and minimal flavour violating new physics models

Example of a top quark mass measurement using the inclusive measured production cross section

JHEP 08 (2016) 029

- Use mass dependence of measured production cross section and NNLO+NNLL prediction to determine the top quark mass
- Dilepton (eμ) decay channel, using data collected at 7 and 8 TeV



$$\sigma_{t\bar{t}}(7\,\mathrm{TeV}, m_t^{MC}) = \exp\left[-0.1718\,(m_t^{MC}/\mathrm{GeV} - 178.5)\right] + 170.9\,\mathrm{pb},$$

$$\sigma_{t\bar{t}}(8\,\mathrm{TeV}, m_t^{MC}) = \exp\left[-0.1603\,(m_t^{MC}/\mathrm{GeV} - 185.4)\right] + 237.0\,\mathrm{pb}.$$

$m_t = m_t^{MC} \pm 1$ GeV

→ ~ negligible effect

$$L_{exp}(m_t, \sigma_{t\bar{t}}) = \exp\left[\frac{\left(\sigma_{t\bar{t}}(m_t) - \sigma_{t\bar{t}}\right)^2}{-2(\Delta^2 + \Delta^2_{m_t\pm})}\right]$$

$$L_{pred}(m_t, \sigma_{t\bar{t}}) = \frac{1}{C(m_t)}\left(\mathrm{erf}\left[\frac{\sigma_{t\bar{t}}^{(h)}(m_t) - \sigma_{t\bar{t}}}{\sqrt{2}\Delta_{p,+}}\right] - \mathrm{erf}\left[\frac{\sigma_{t\bar{t}}^{(l)}(m_t) - \sigma_{t\bar{t}}}{\sqrt{2}\Delta_{p,-}}\right]\right)$$

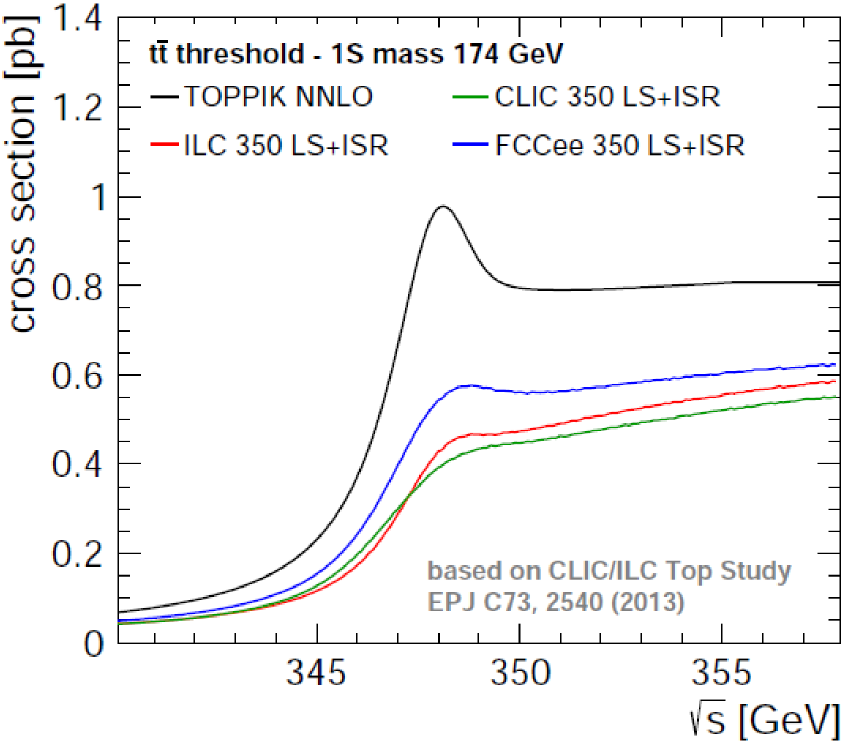
h = upper XS value; l = lower XS value
(from variation of fact./renorm. scales)

Wait for a linear collider?

- At a linear electron-positron collider with a centre-of-mass energy of 350 GeV, a theoretically well-defined top quark mass can be precisely measured
- Top quark mass from threshold scan
  → precision of ~100 MeV possible
- Theoretically well-defined
- 'Cleaner environment' compared to LHC

- **BUT:**
  - Far future (beyond LHC/HL-LHC)
  - Not certain an e+e- collider reaching 350 GeV will be build any time soon

arXiv:1364.08122 [hep-ph]



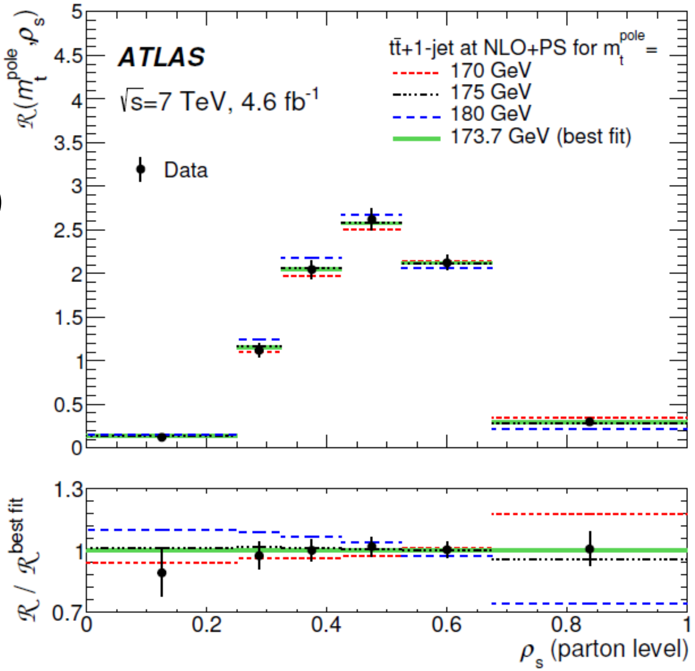
Top quark mass from tt+1jet production cross section

- The normalized differential $t\bar{t}$+1jet cross section is sensitive to m_t
- It is 5 times more sensitive compared to the inclusive cross section
- ATLAS performed a measurement using lepton+jets decay channel, requiring at least 5 jets are required **JHEP 10 (2015) 121**

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

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

m_0 = 170 GeV (arbitrary)

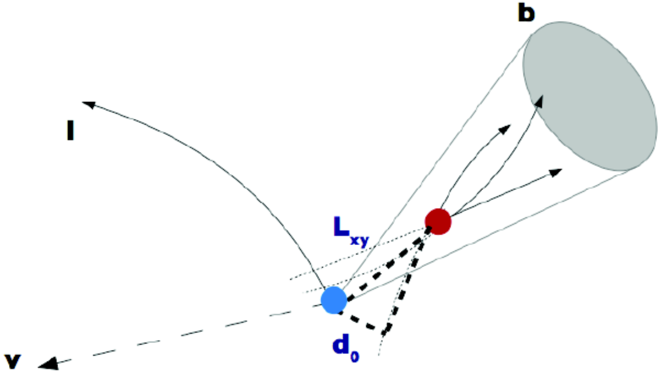


$$m_t^{\text{pole}} = 173.7 \pm 1.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})^{+1.0}_{-0.5}\,(\text{theory})\ \text{GeV}$$

- Systematic uncertainties dominated by:
  - Scale variations
  - Jet energy scale (including b)
  - Initial and final state radiation

Top quark mass from b-hadron lifetime

- Reduce systematic uncertainty from jet energy scale and resolution
- Exploit kinematics of b hadron, in particular the transverse decay length, L_{xy}



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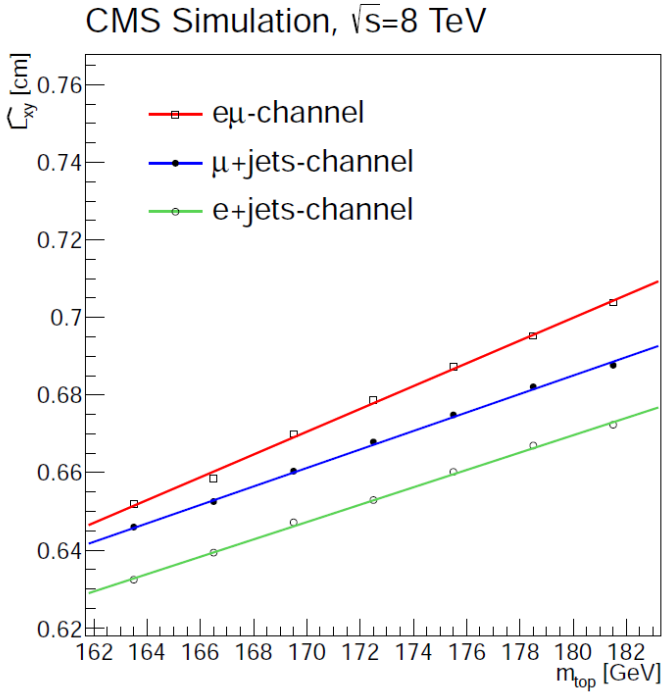
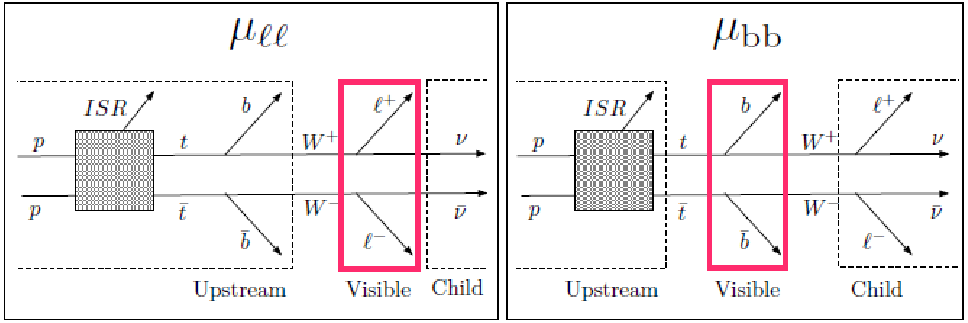


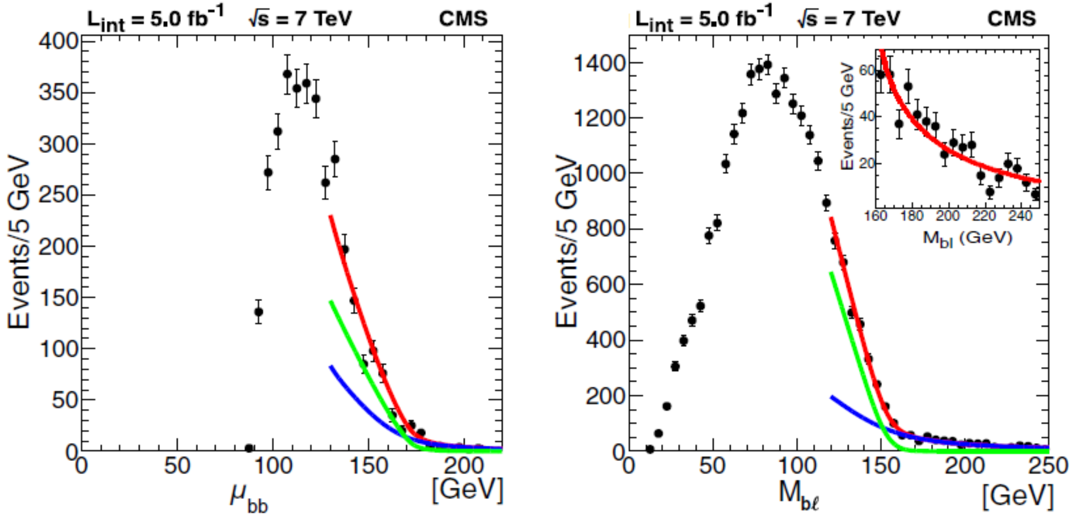
- In each event use secondary vertex with largest L_{xy}
- Use median of L_{xy} distribution to extract m_t

$$m_t = 173.5 \pm 1.5_{stat} \pm 1.3_{syst} \pm 2.6_{p_T(t)}\ \text{GeV}$$

Top quark mass from kinematic endpoints

- Doubly-constrained (using m_W and m_ν) fit of M_{T2} or variants





Eur. Phys. J. C 73 (2013) 2494

$$M_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.7}_{-2.1}\,(\text{syst.})\,\text{GeV}$$

- Similar distributions used for 8 TeV analysis, but using full distribution for fit **CMS-PAS-TOP-15-008**

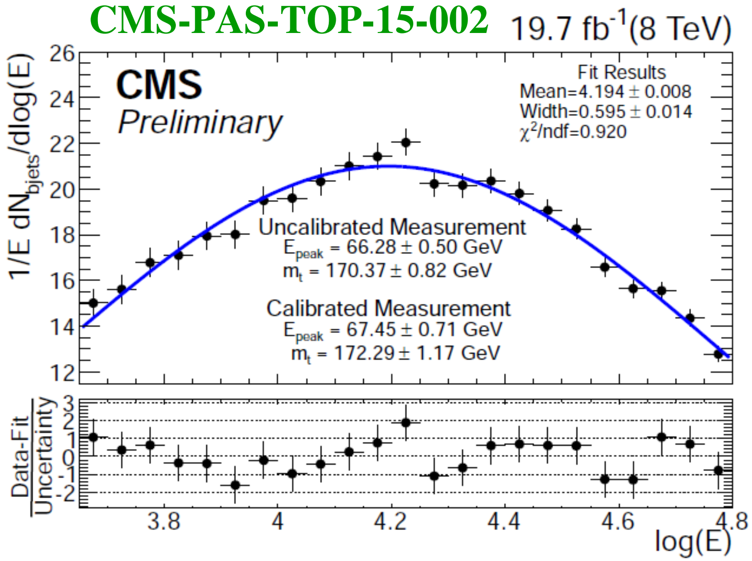
$$M_t^{hyb} = 172.22 \pm 0.18\,(\text{stat})\,^{+0.89}_{-0.93}\,(\text{syst})\,\text{GeV}$$

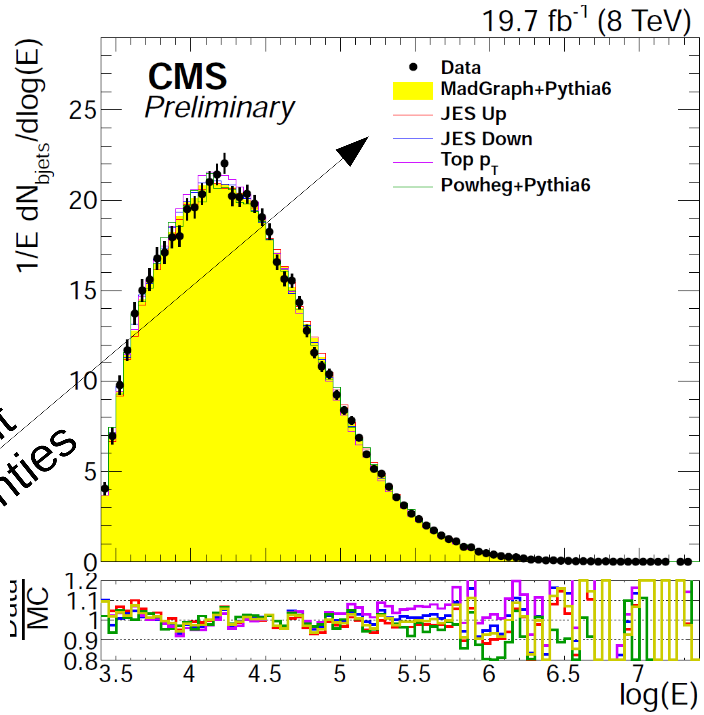
- Dominant systematics:
  - Top quark p_T
  - Jet energy corrections
  - b quark fragmentation
  - Scale uncertainties

Top quark mass from b-jet energy peak

- Use the peak position of the b-jet energy spectrum in the laboratory frame
- Top quarks are unpolarized → independent from the boost of top quarks → the b-jet energy can be related to the energy of the b quark in the top quark rest frame → related to the top quark mass

CMS-PAS-TOP-15-002





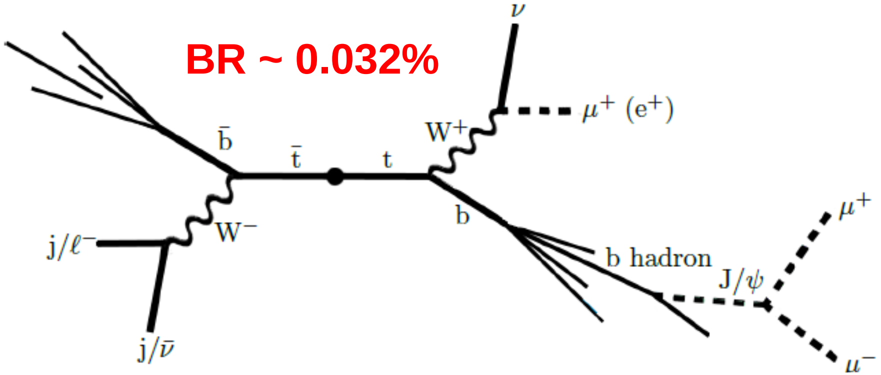
dominant uncertainties

$$m_t = 172.29 \pm 1.17\,(\text{stat.}) \pm 2.66\,(\text{syst.})\ \text{GeV}$$

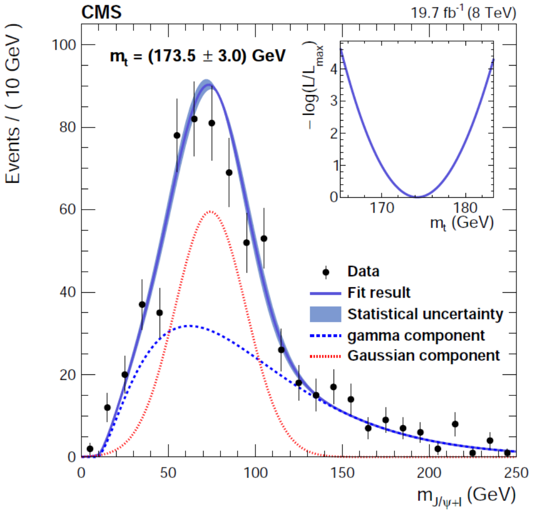
Top quark mass from J/ψ

- Use the invariant mass formed by the charged lepton and the J/ψ to extract m_t

BR ~ 0.032%



JHEP 12 (2016) 123



- Limited by statistics due to small branching ratio:

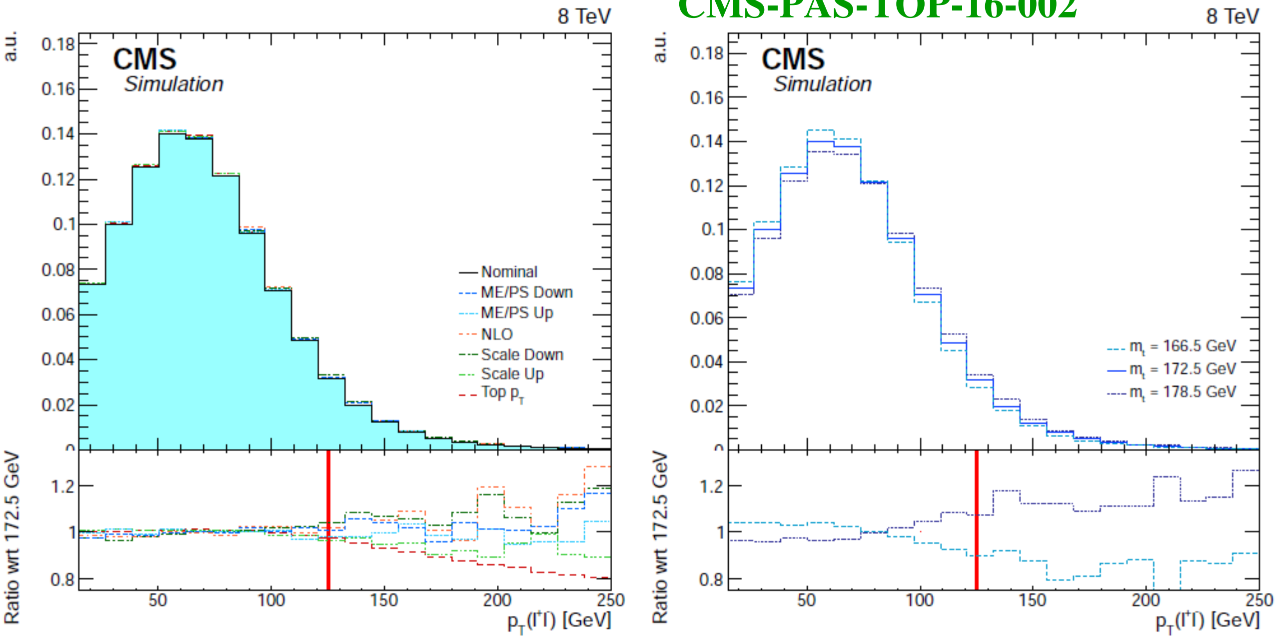
$$173.5 \pm 3.0\,(\text{stat}) \pm 0.9\,(\text{syst})\,\text{GeV}$$

- Dominant systematics are related to modelling:
  - Top quark p_T
  - Matching scale
  - Factorization and renormalization scales
  - ME generator
  - b quark fragmentation

Top quark mass from dilepton kinematics

- Kinematic observables reconstructed from the two leptons in dilepton (eμ) events are used to extract m_t

CMS-PAS-TOP-16-002



- Used LO MC
  → large uncertainties!

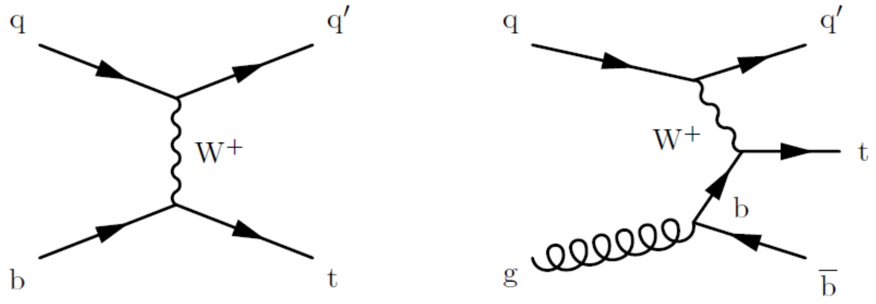
- Dominant systematics:
  - Scale uncertainties
  - Matching scale
  - Top quark p_T

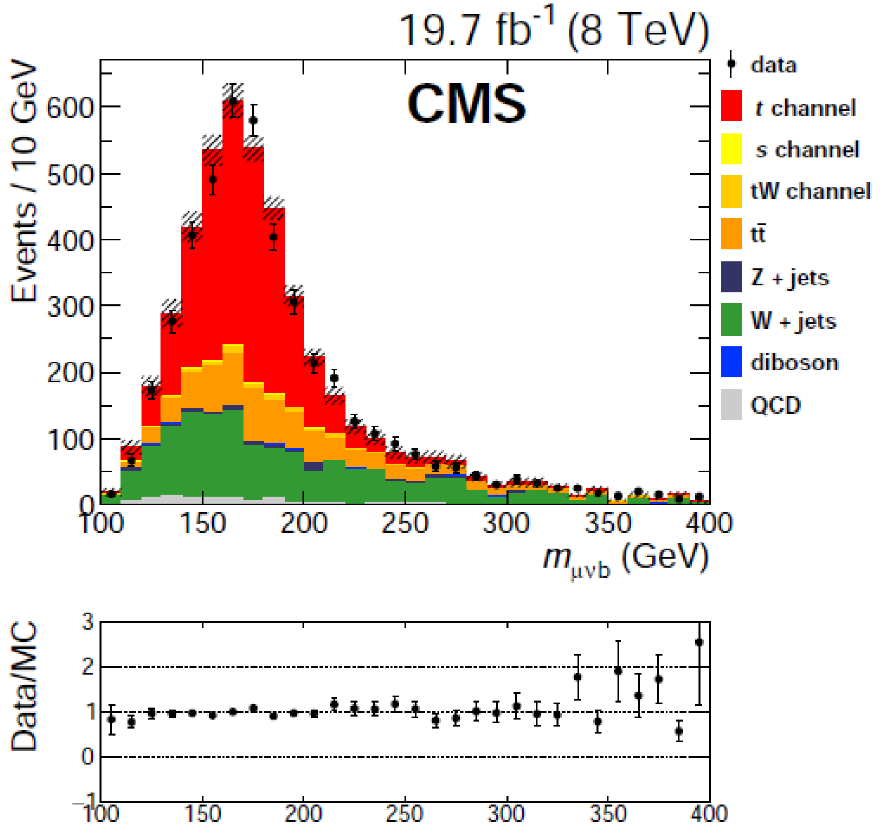
$$m_t = 171.7 \pm 1.1\,(\text{stat.}) \pm 0.5\,(\text{exp.})^{+2.5}_{-3.1}\,(\text{th.})^{+0.8}_{-0.0}\,(p_T(\text{t}))\ \text{GeV}$$

Top quark mass from single top events

Eur. Phys. J. C 77 (2017) 354

- Extract the top quark mass from the reconstructed t→ blν decay in t-channel single top events





$$m_{\mathrm{t}} = 172.95 \pm 0.77\,(\mathrm{stat})^{+0.97}_{-0.93}\,(\mathrm{syst})\ \mathrm{GeV}$$

- Dominant systematics:
  - Jet energy scale
  - Matching scale for tt̄ background
  - Calibration procedure

2-jettiness and top mass sensitivity

- 2-jettiness:

$$\tau_2 = 1 - \max_{\vec{n}_t} \frac{\sum_i |\vec{n}_t \cdot \vec{p}_i|}{Q}$$

- Q is c.o.m energy, the sum runs over all particle 3-momenta p_i, and the maximum defines the thrust axis n_t → defines the two hemispheres

- τ_2 distribution has a peak which is sensitive to the top mass

  → peak region is dominated by dijet events with the two top quarks produced back to back and decaying in narrow cones (boosted)

  $(\tau_2)_{\rm peak} \approx (M_a^2 + M_b^2)/Q^2$

Systematic effects considered for the proof-of-concept of the ReSyst technique

- **b-tagging efficiency and mistagging probability:** The (mis)tagging efficiencies are varied by ± 2% for b jets, ± 5% c jets and ± 15% for light-quark jets, independently.
- **Jet energy scale:** The jet four-momenta are varied by ± 1% before the event selection.
- **Factorization and renormalization scales:** The Q^2 scales at the matrix element level are independently varied by a factor 2 and 0.5 → envelope for the 6 physical variations.
- **Matching between the matrix element and parton shower (h_{damp}):** Radiated quarks and gluons are damped by a certain factor that includes h_{damp}, which was tuned to $(1.581^{+0.658}_{-0.585})\, m_t$, and is varied by an amount corresponding to the uncertainties.
- **Top quark p_T:** The top quark p_T in data is softer than in MC → (anti)top quark p_T spectra are reweighted.
- **B quark fragmentation:** p_T(B hadron) / p_T (b jet) is varied by ± 2.5%.

The estimation is repeated and the shift in estimated top quark mass is taken as the size of the systematic effect.