ReSyst:
proof-of-concept for
a technique to Reduce the Systematic uncertainty

arXiv:1809.07700

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Techniques are needed to reduce the systematic uncertainty

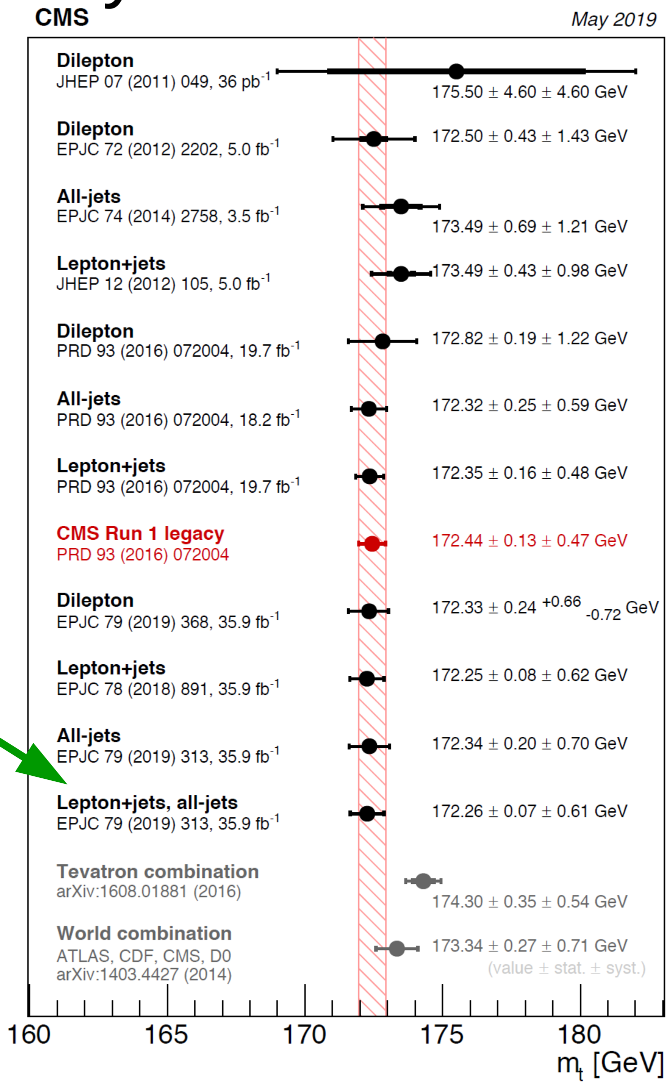
- For many precision measurements the systematic uncertainty is (much) larger than the statistical

- E.g. the top quark mass:

  172.26 ± 0.07 (stat+JSF) ± 0.61 (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 behind the ReSyst technique

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

- **How?**
  - Systematic uncertainties are typically assessed by varying experimental or theoretical (modelling) parameters in the MC simulation
  - 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
- Extensions/other ideas

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

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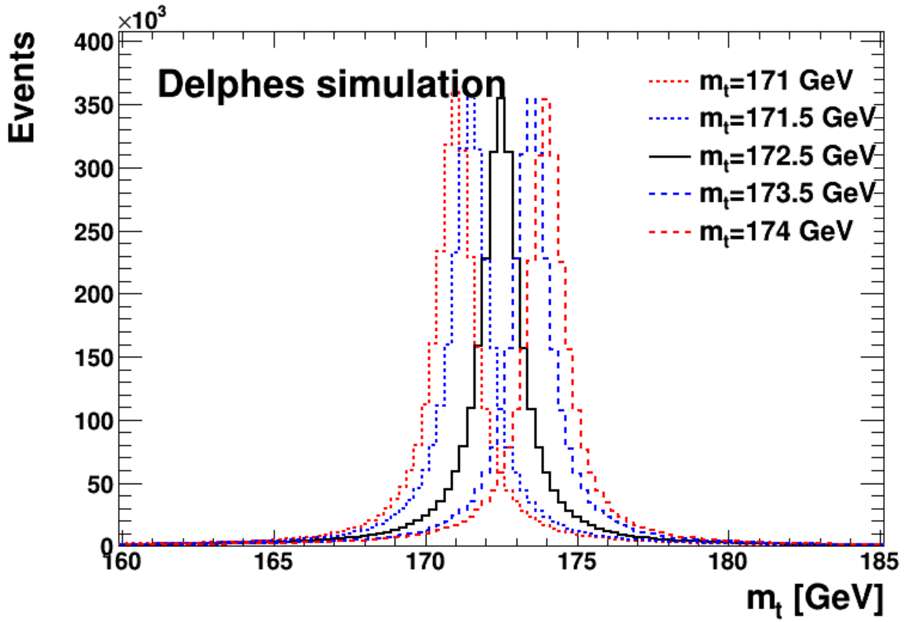
ABSTRACT: We are in an era of precision measurements at the Large Hadron Collider. The precision that can be achieved on some of the measurements is limited however due to large systematic uncertainties. This paper introduces a new technique to reduce the systematic uncertainty by quantifying the systematic 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 → $t\bar{t}$ → $b\mu\nu\bar{b}qq$ 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)

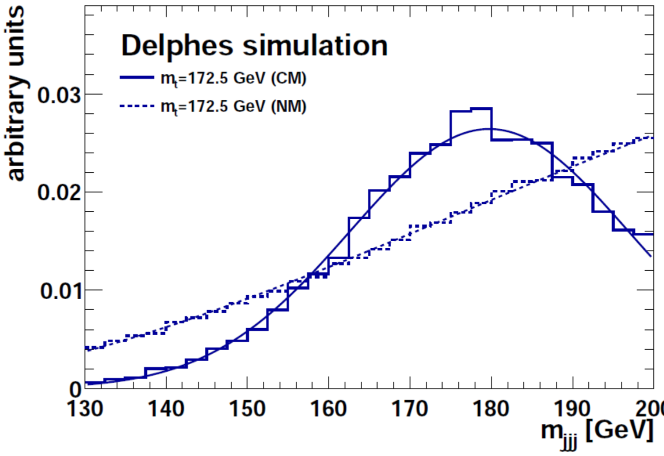


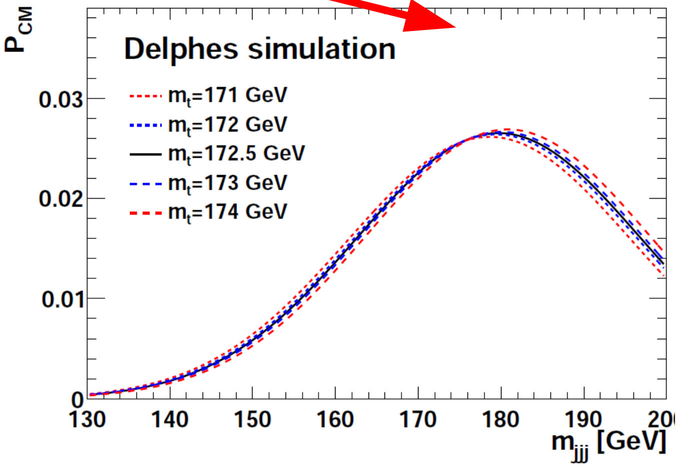
Simplified event-by-event top quark mass estimator: probability density functions and likelihood

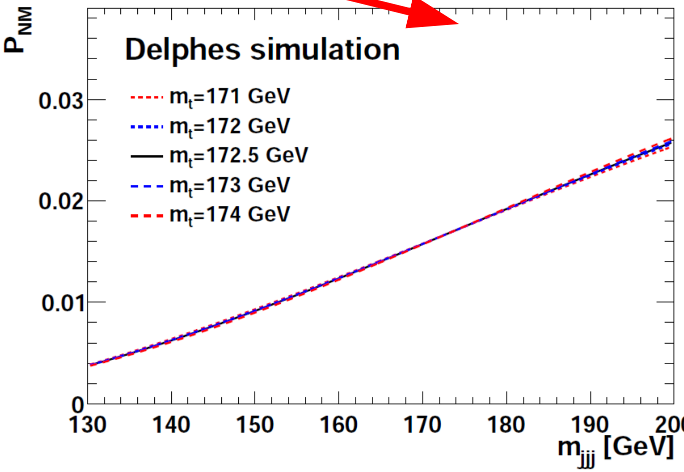
- The three leading p_T jets are used to reconstruct the “hadronic top”
  $\rightarrow$ distribution of the mass m_{jjj} *(in range 130 to 200 GeV)* is sensitive to m_t
  (selection efficiency ~1.2%)
- Construct a likelihood (based on pdf's for correctly & wrongly matched events)

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

with f_{CM}~20%







- Pdf's are constructed by fitting Gaussian (3rd order polynomial function) for CM (NM)

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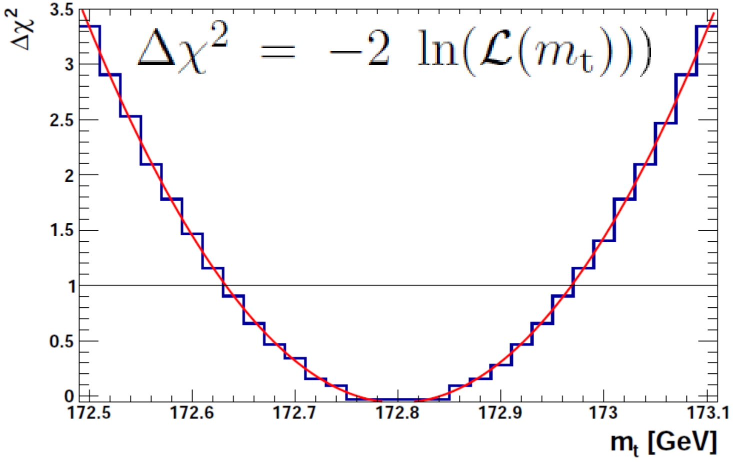
- Minimize negative of logarithm of likelihood to obtain estimation of m_t



m_t = 172.80 ± 0.16 (stat.) GeV

Systematic effects considered for the proof-of-concept

- **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.

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	0.88	-0.87	0.83
Factorization and renormalization scales	0.01	-0.02	0.02
Matrix element and parton shower matching (h_{damp})	0.04	-0.01	+0.03
Top quark p_{T}	n.a.	-0.01	-0.06
b quark fragmentation	0.39	-0.41	0.09
Total systematic uncertainty	0.96	-0.97	1.10

- **m_t = 172.80 ± 0.16 (stat.) +0.96 –0.97 (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:

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

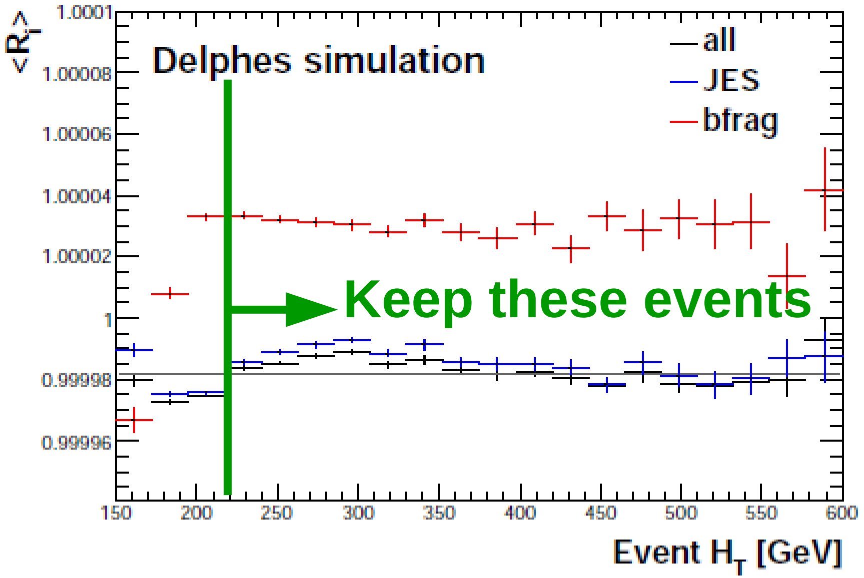
Total systematic impact without event "i"

Total systematic impact = fixed for all events

- 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

- Here: H_T > 220 GeV
  → 31% of the formerly selected events are now rejected
  → f_{CM} goes from 20% to 23%



Impact of the additional selection requirements

- Remake pdf's and repeat the estimation

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	0.88	-0.87	0.62	-0.54
Factorization and renormalization scales	0.01	-0.02	0.04	-0.04
Matrix element and parton shower matching (h_{damp})	0.04	-0.01	$<$0.01	$>$-0.01
Top quark p_{T}	n.a.	-0.01	0.10	n.a.
b quark fragmentation	0.39	-0.41	0.23	-0.23
Total systematic uncertainty	0.96	-0.97	0.67	-0.59

- After the additional selection requirements, the uncertainties are reduced:
  before: m_t = 172.80 ± 0.16 (stat.) +0.96 –0.97 (syst.) GeV
  after: m_t = 172.53 ± 0.18 (stat.) + 0.67 – 0.59 (syst.) GeV
  → *technique seems to work conceptually (traded stat. precision for 30% lower syst. unc.)*
- **Note:** 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 2 times larger compared to the CMS ideogram method)

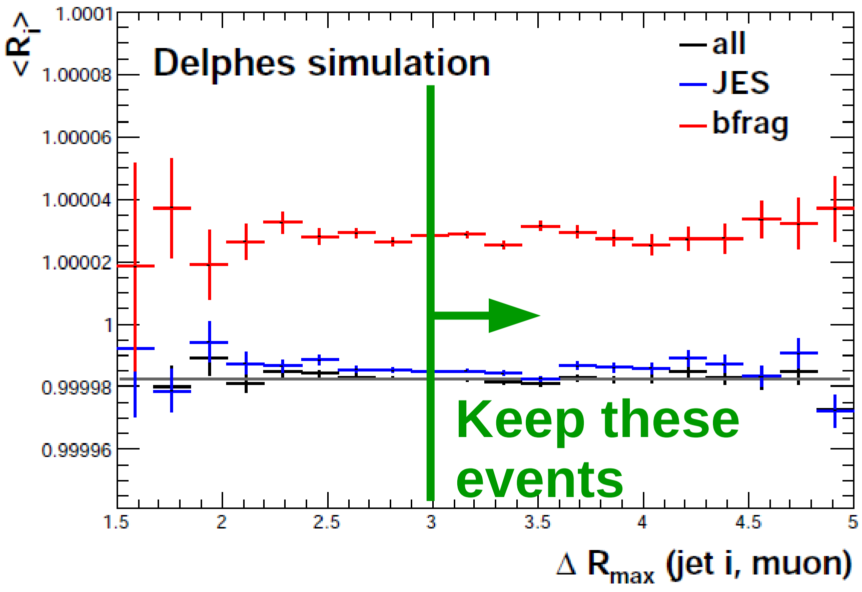
Cross-check: apply cut on observable not correlated with R_i

- **Cross-check:** apply a requirement on an observable for which $\langle R_i \rangle$ shows no trend
- ΔR_{max}(jet, muon) >3
  - **Expected:** no effect on systematic uncertainty
  - **Observed:** 36% of the events rejected and no effect on systematic uncertainty:

    M_t = 173.04 ± 0.28 (stat.) +0.81 –0.94 (syst.) GeV

    to be compared with:

    m_t = 172.80 ± 0.16 (stat.) +0.96 –0.97 (syst.) GeV



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

Summary

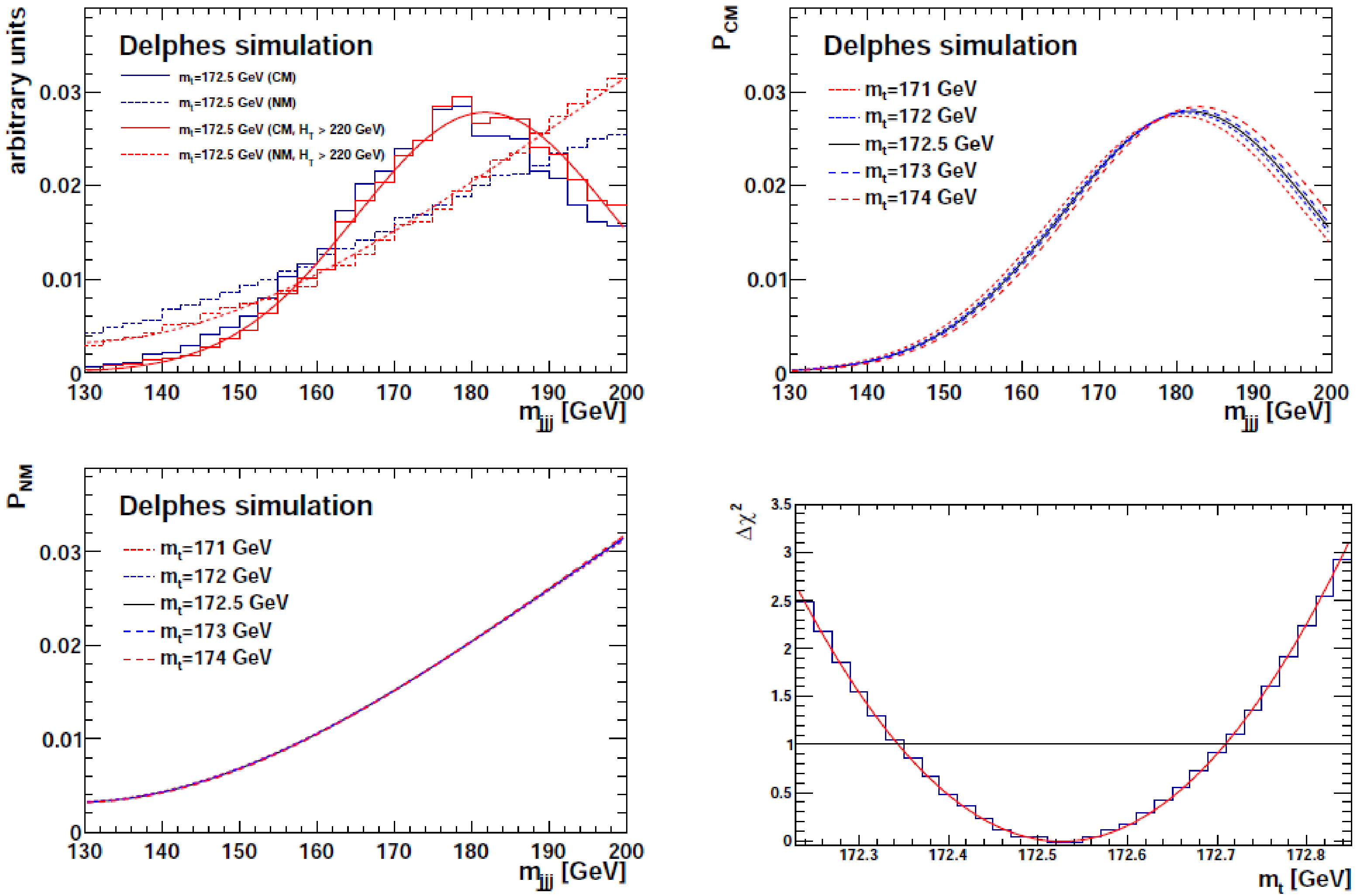
- ReSyst allows to quantify the systematic impact for each event: quantifier "R_i"
- The quantifier "R_i" can be correlated to observables to identify classes of events inducing a large effect, which could then be used to:
  → reject certain classes of events;
  → identify observables to be used to profile uncertainties in a likelihood fit:
  relevant for precision measurements and searches (constrain syst. in situ)!
- **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"

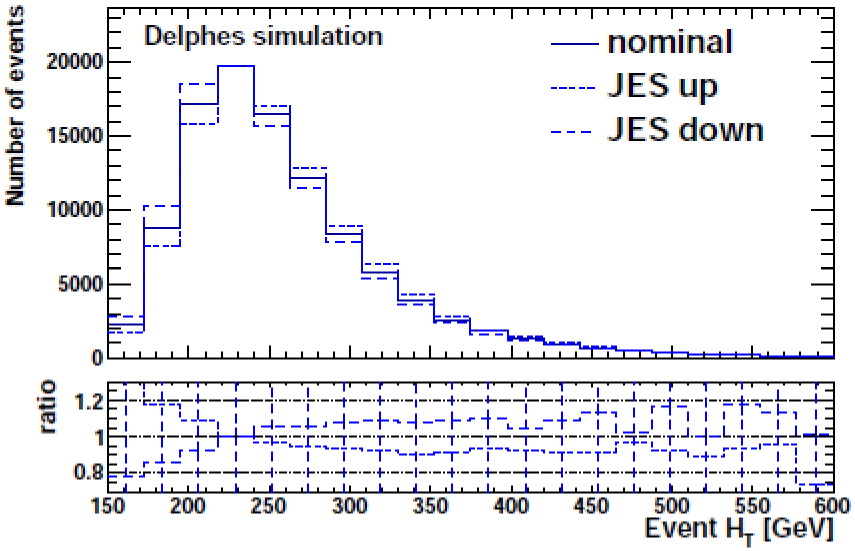
- The technique could be extended to also include the statistical impact of 1 event
- Paper is under review by JHEP
- Test technique for a realistic case (e.g. top quark mass measurement at LHC)

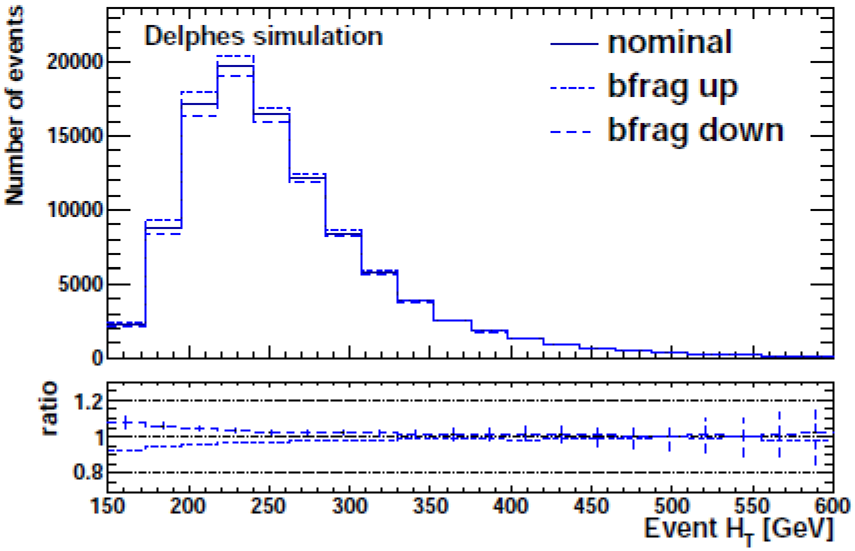
Pdf's after H_T requirement



Why the H_T cut works

- The effect of varying the JES and b quark fragmentation is largest at small H_T values:





Food for thought:
Should we remove events to reduce the total uncertainty?

- Are we biasing the (top quark mass) measurement by removing events?

  → in principle the top quark mass should be the same in the entire sample,
  i.e. there should be no 'extrapolation' uncertainties

  → check the correlation between the reconstructed observables and the generated top quark mass distribution

  → check the generated top quark mass distribution before/after the selection requirements

  → avoid to remove events blindly, but try to understand why certain classes of events have a large impact (is it a feature of the modelling in the MC simulation or is it real physics?)

- Potentially we introduce new systematic uncertainties due to additional selection criteria