Using Jets to Measure Top Properties

(And the other way around?)

Ryan Roberts 10/11/2023

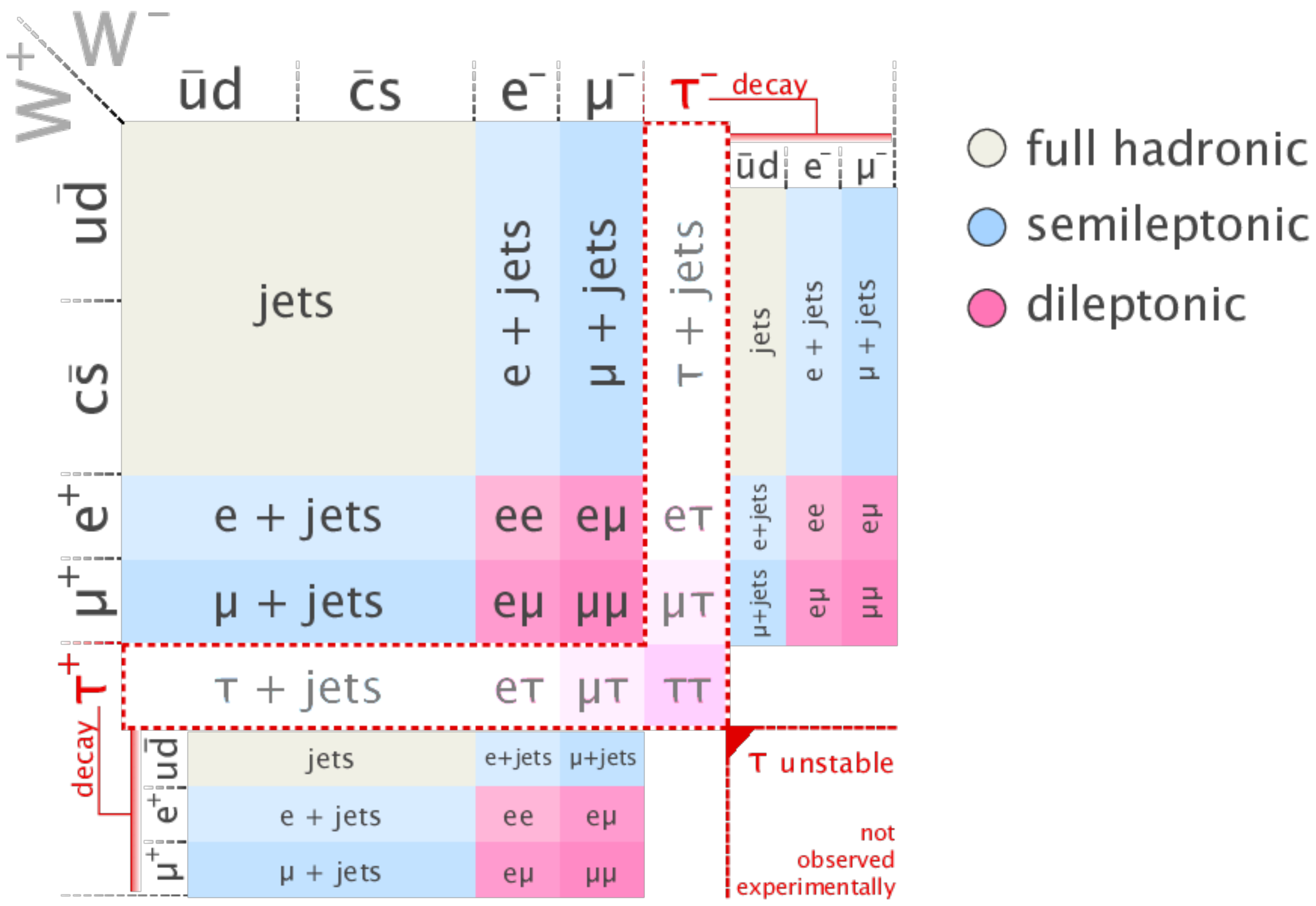
Overview

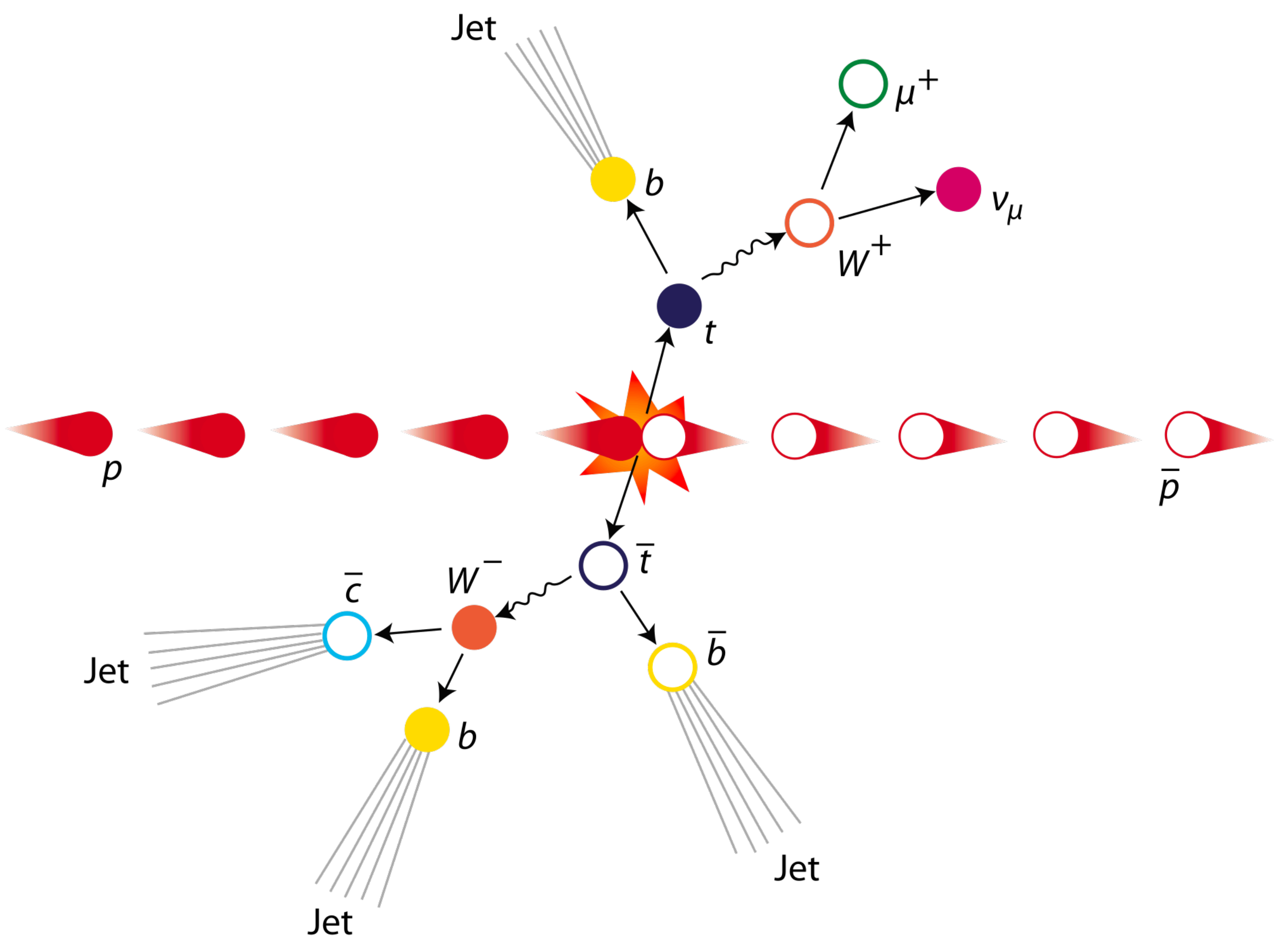
- Basics of Top Physics
- Cross-section Measurements
- Jet Substructure in $t\bar{t}$ Events
- Jet Pull and Color Flow in $t\bar{t}$ Events
- Top Mass Measurements
- Tops in Heavy Ion Collisions

Top Physics Basics

Overview

- Heaviest fundamental particle in the SM: $m_t = 172$ GeV. c.f. $m_H = 125$ GeV and $m_b = 4.2$ GeV. (Large coupling to Higgs!)
- Weak decay (like other heavy quarks).
  - CKM mixing with 3rd generation suppressed ($|V_{td}| < |V_{ts}| = 42 \times 10^{-3}$).
  - On-shell decay $t \to W^+ b$ is kinematically allowed, much larger width (1.42 GeV $> \Lambda_{QCD}$), top quarks decay before hadronization.
  - W decays to $u\bar{d}$, $c\bar{s}$ (33% each), $e^+\nu_e$, $\mu^+\nu_\mu$, $\tau^+\nu_\tau$ (11% each).
- Only produced at hadron colliders - $t\bar{t}$ dominant at LHC, single top production at Tevatron?
- Critical for EW, Higgs measurements, many BSM models…
- ≈ Impossible to measure tops without jets!





Top Physics Basics

Discovery Techniques

- Observed by CDF and D0 in $t\bar{t}$ production in the single and double lepton channels.
- B-tagging done with secondary vertexing or low momentum muons.
- Aplanarity used by D0 in untagged l+jets events.

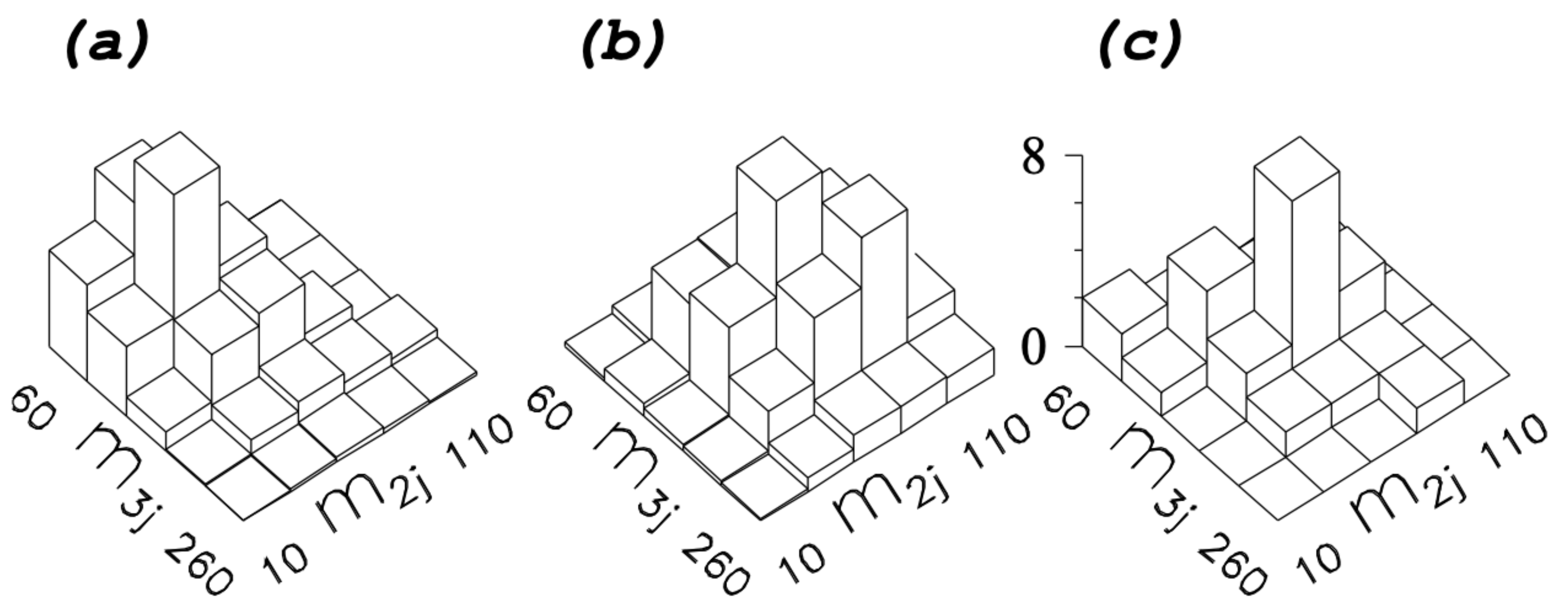
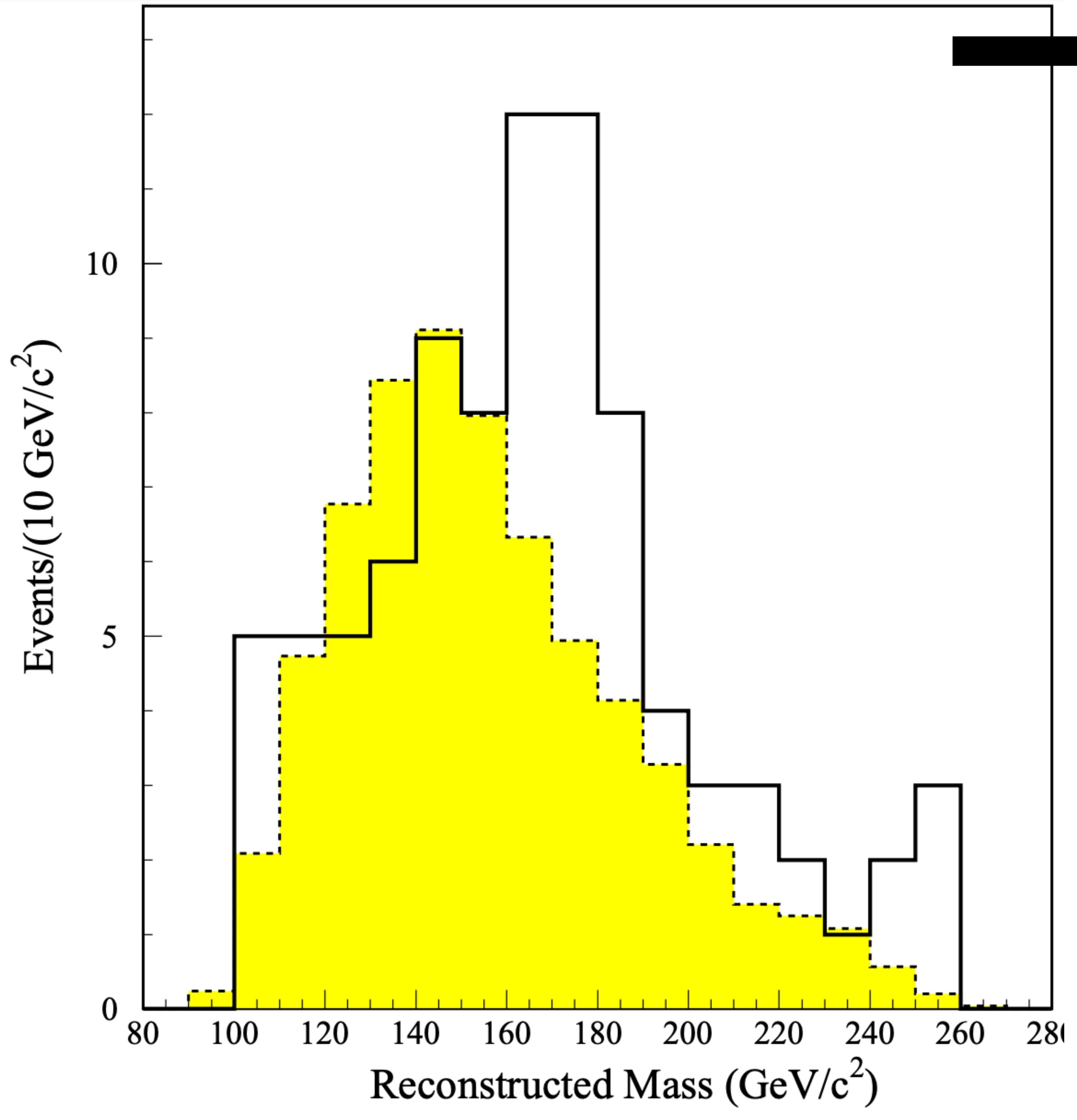
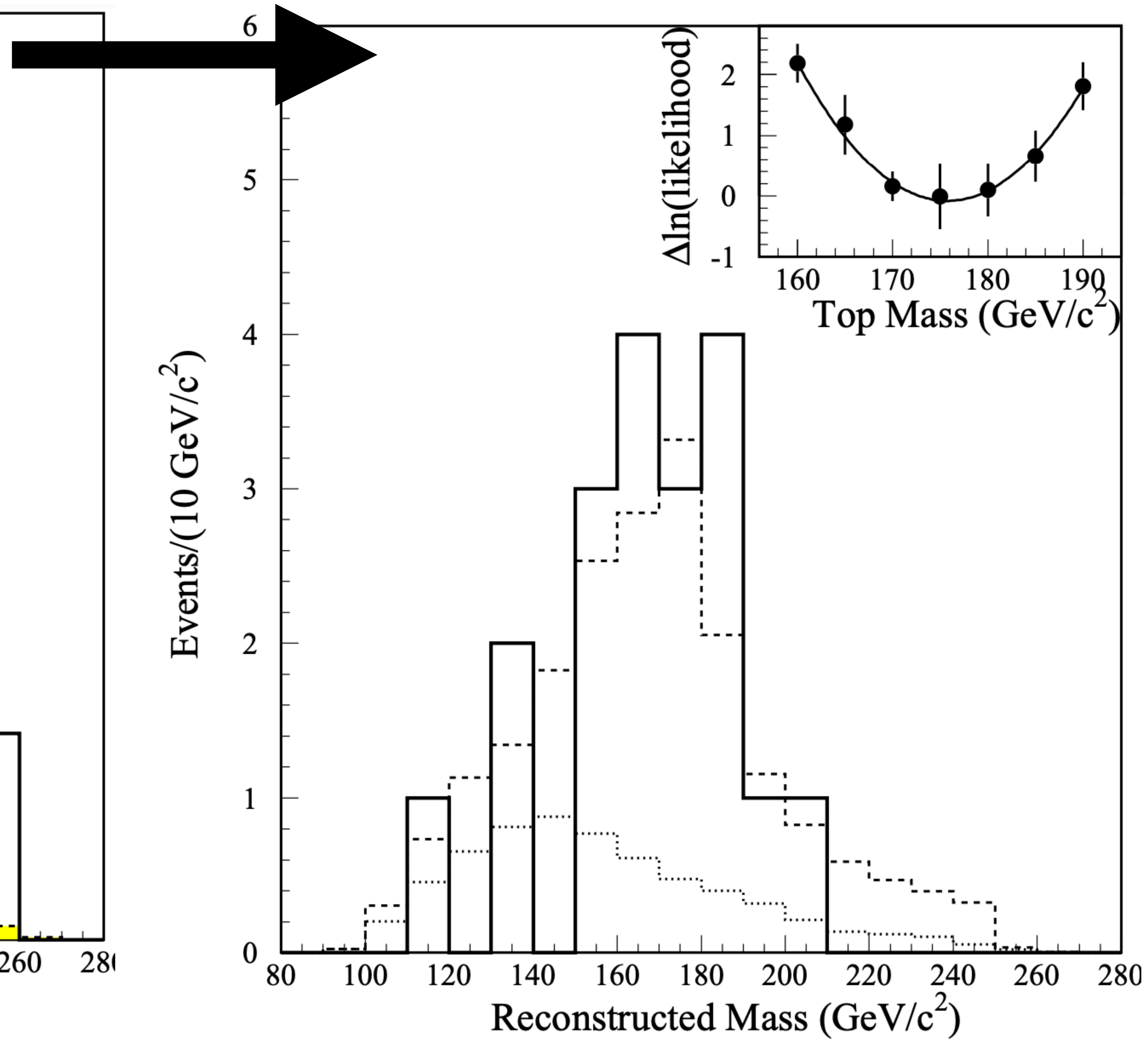


FIG. 4. Single-lepton + jets two-jet *vs.* three-jet invariant mass distribution for (a) background, (b) 200 GeV/c^2 top Monte Carlo (ISAJET), and (c) data.

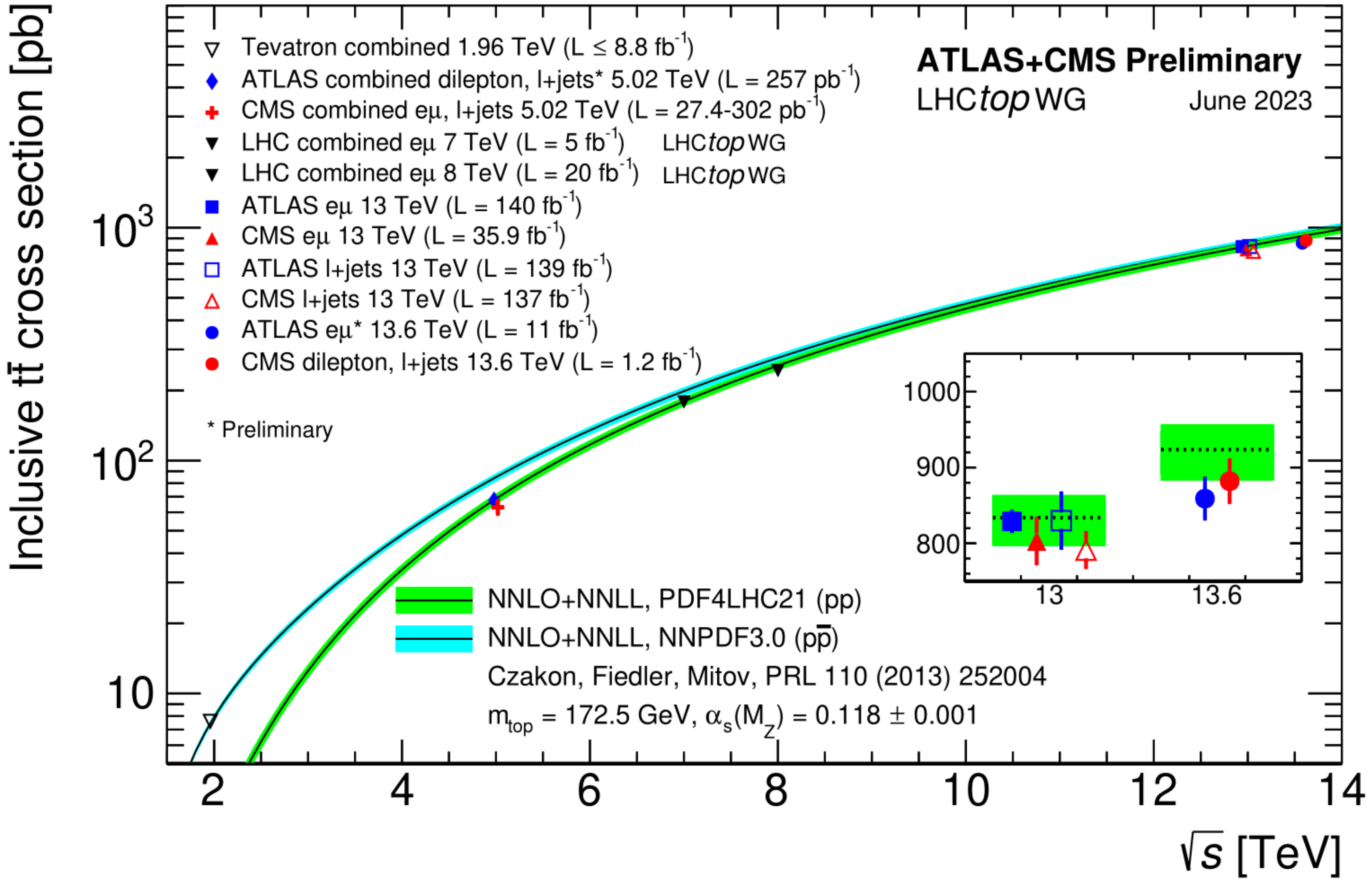




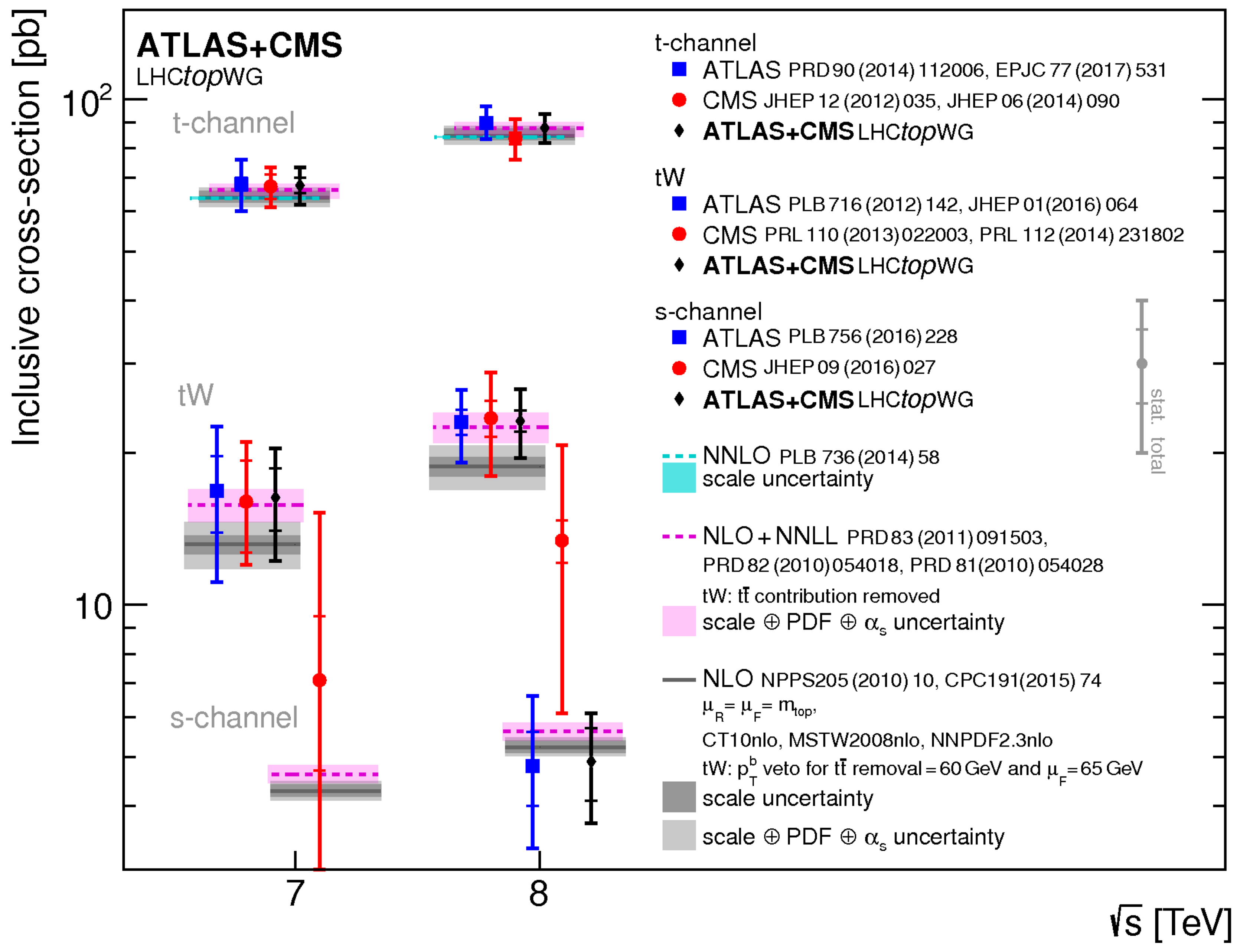
Top Cross-Sections

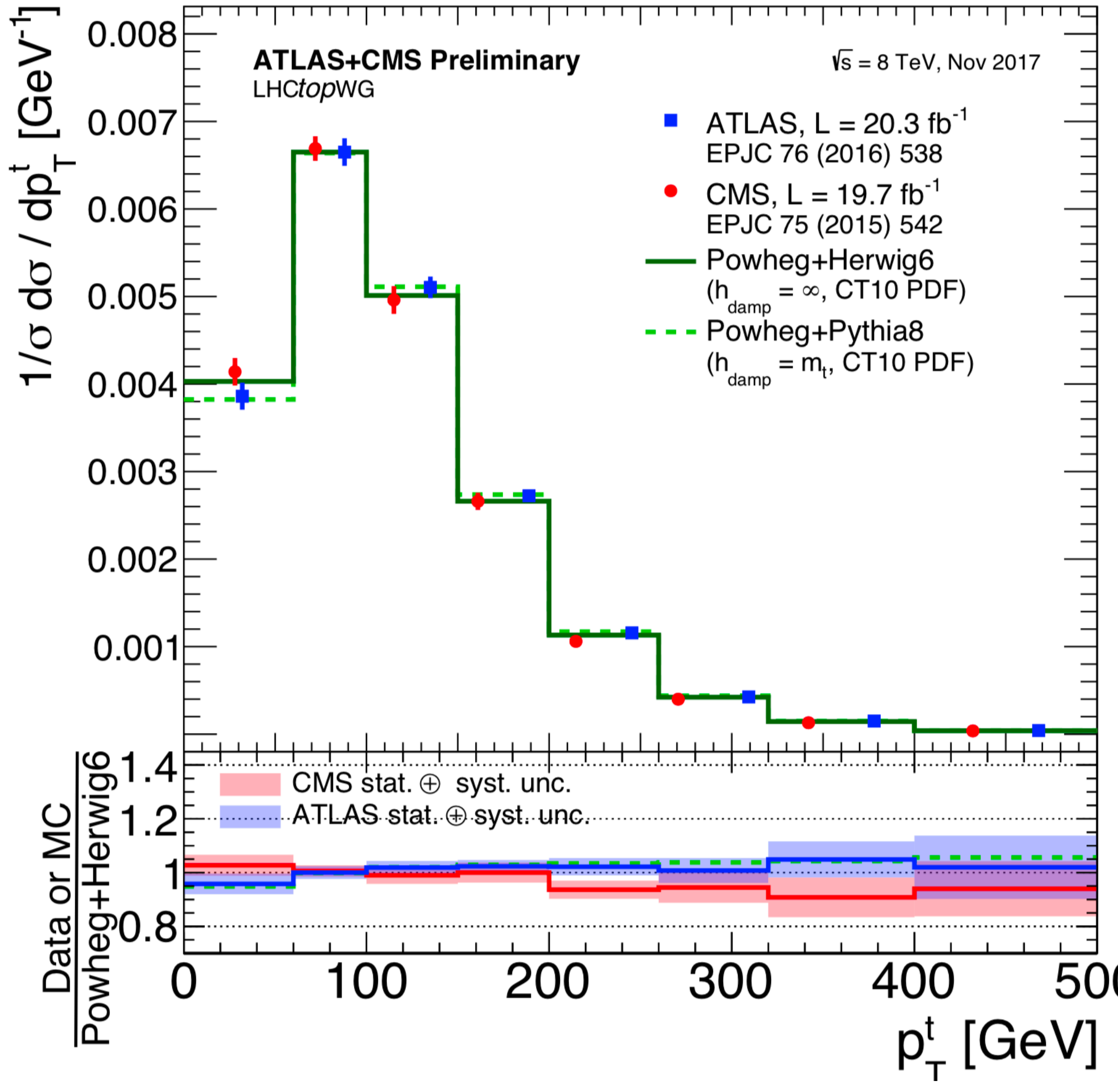
Overview

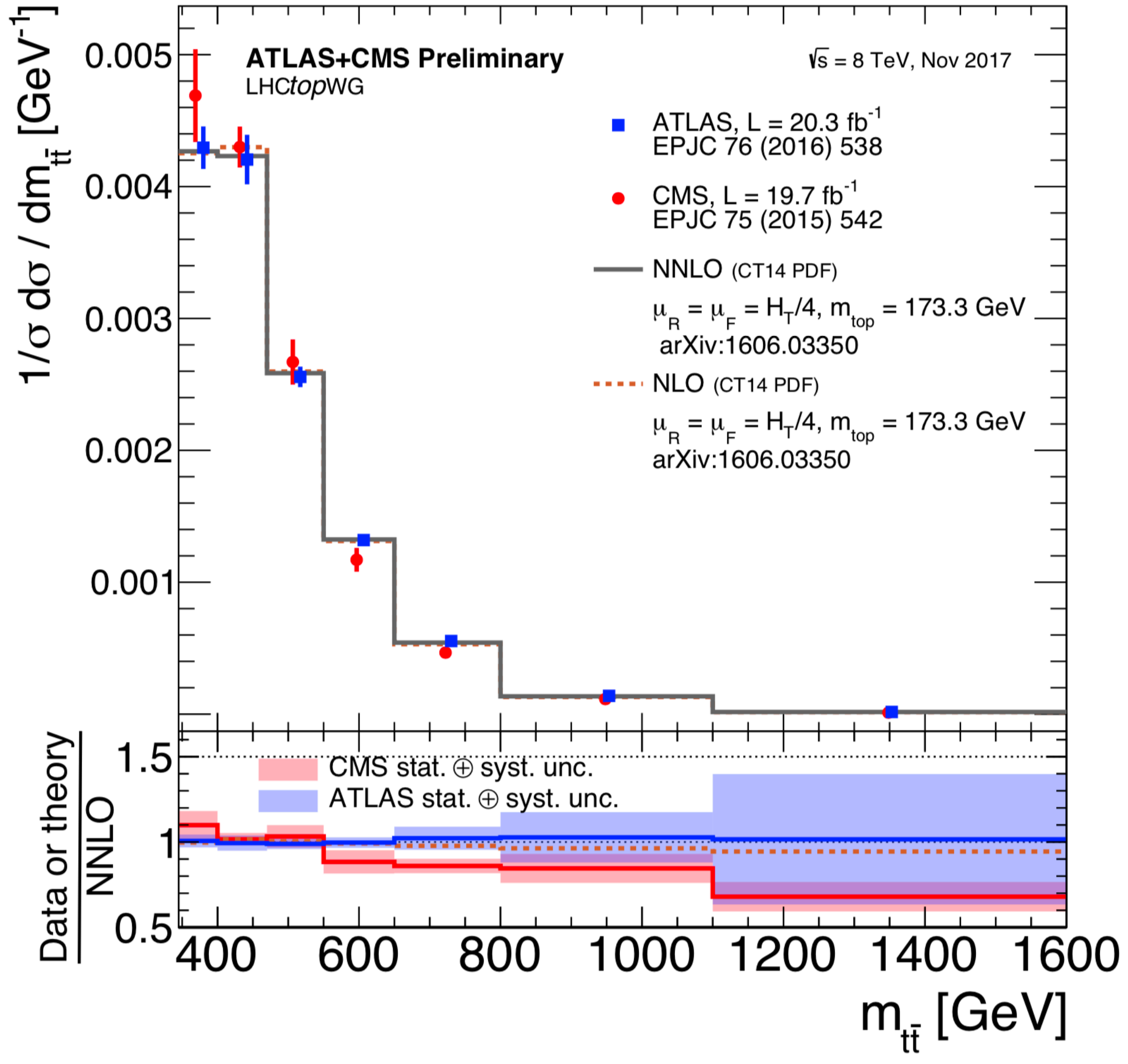
- Cross-section measurements of $t\bar{t}$, single-top, and associated top production $(t\bar{t} + X)$ constrain EW couplings of the top, including possible contact interactions introduced by EFT operators.



LHC Top Working Group
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots#Top_Quark_Mass



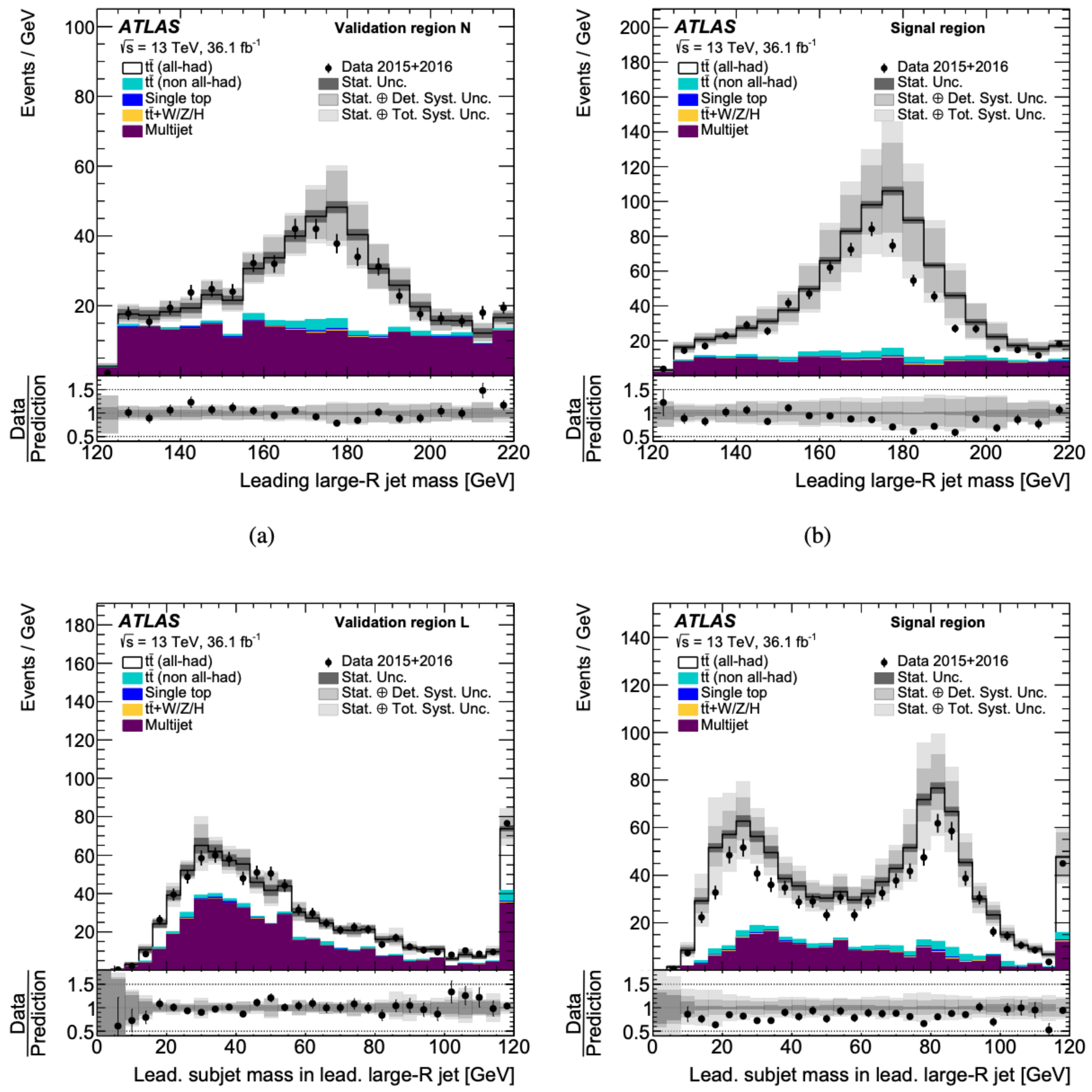




Top Cross-Sections

Boosted top quarks

https://browse.arxiv.org/pdf/1801.02052.pdf



- Several measurements of top cross-sections and properties using highly boosted tops reconstruct top quark decays as single jets.
- Typical features of these analyses:
  - Small radius anti-kt jets used for b-tagging, lepton isolation, etc.
  - Large radius jets used as to candidates with various jet algorithms and grooming techniques used.
  - May require matching between b-jets and large-R jets.
  - Jet substructure techniques used to select jets containing three-body decays.
- These techniques for boosted top quarks are also used in searches for heavy resonances decaying to tops.

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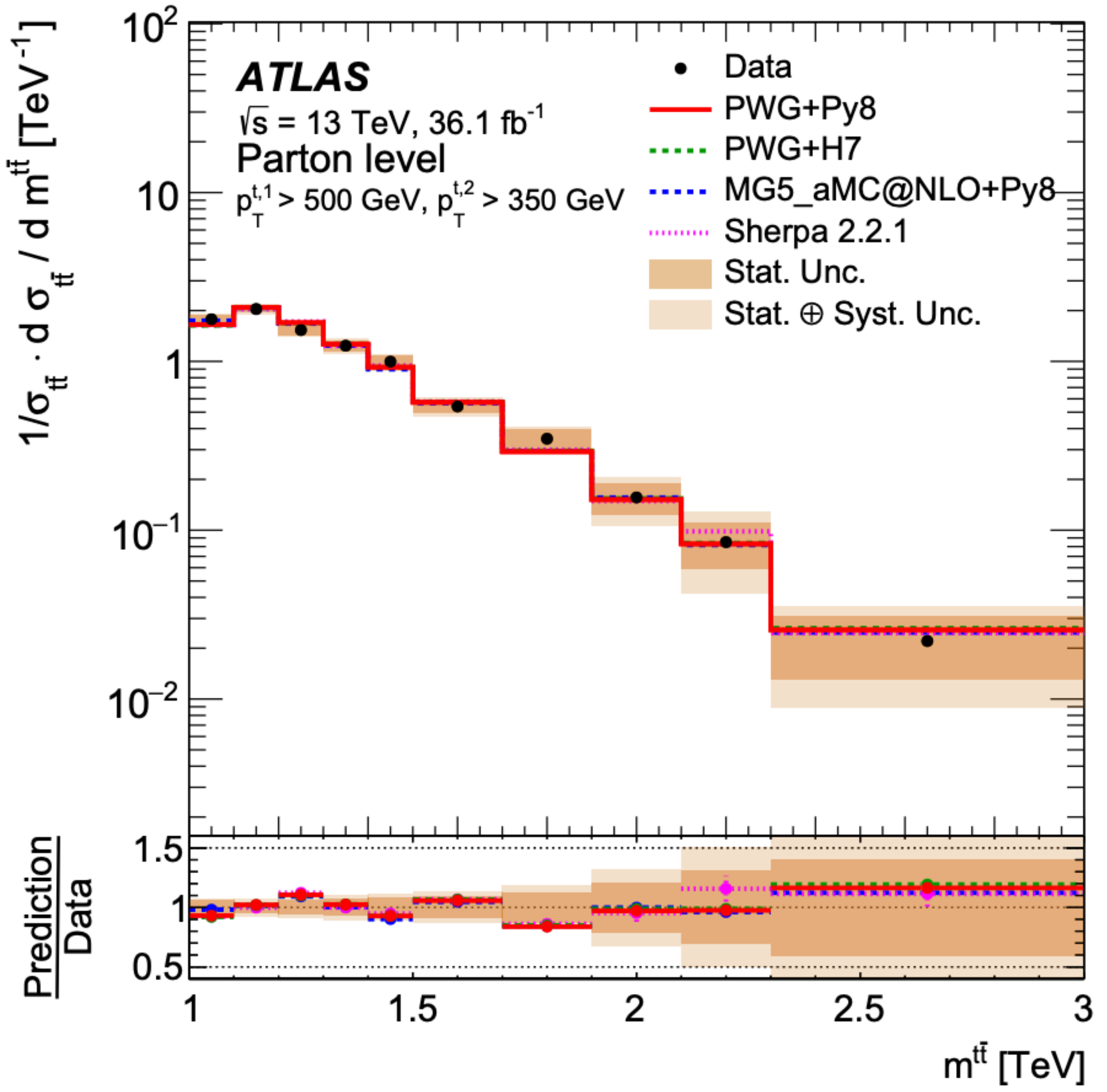
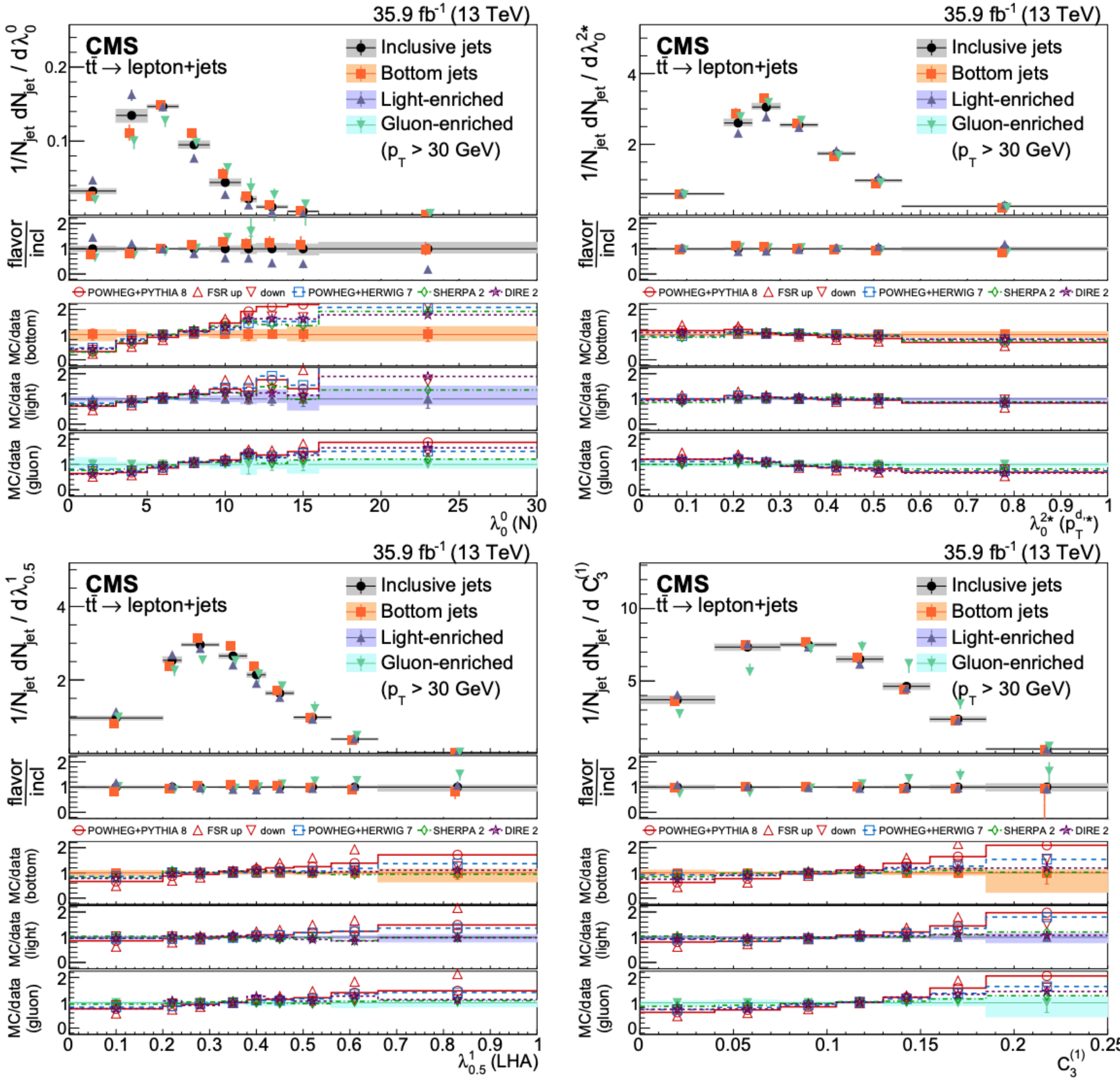


https://arxiv.org/pdf/1808.07340.pdf

Jet Substructure

- Fully resolved $t\bar{t}$ events give jets with a range of flavors and momenta at relatively high purity.
- CMS has used the l+jets channel to measure jet substructure observables.
    - Reconstruction uses lepton, b-tagging, and W mass constraint.
    - Separate categories enriched with b-jets (flavor tagging), light quark jets (W mass constraint), and gluon jets (ISR).

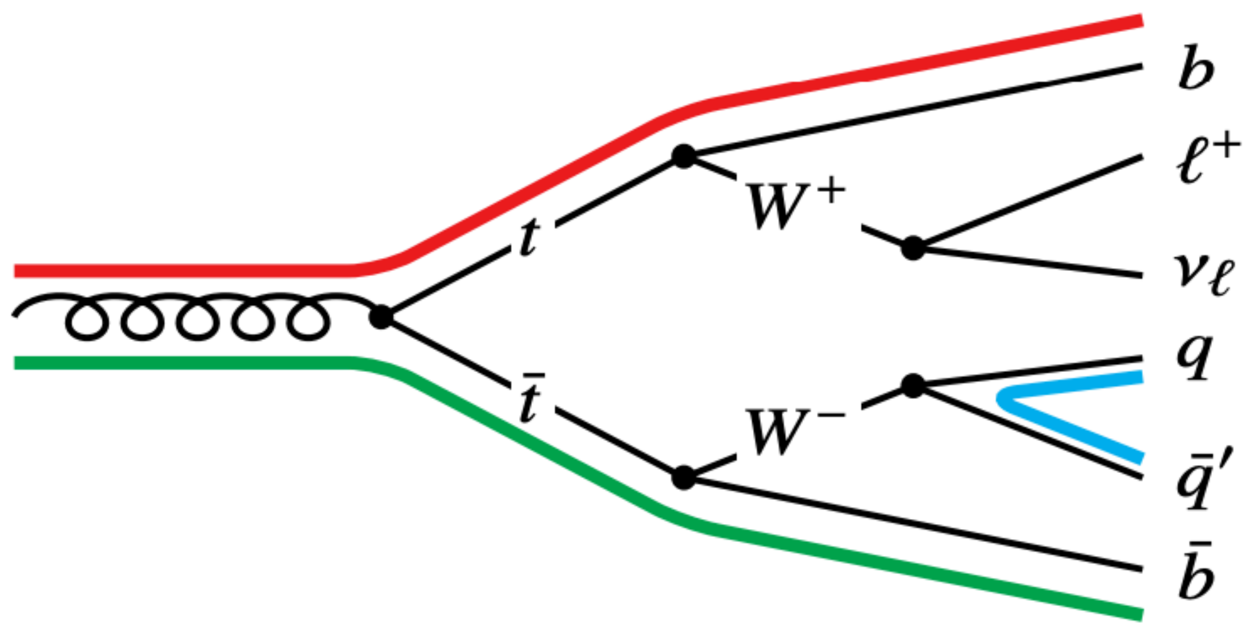


https://arxiv.org/pdf/1805.02935.pdf

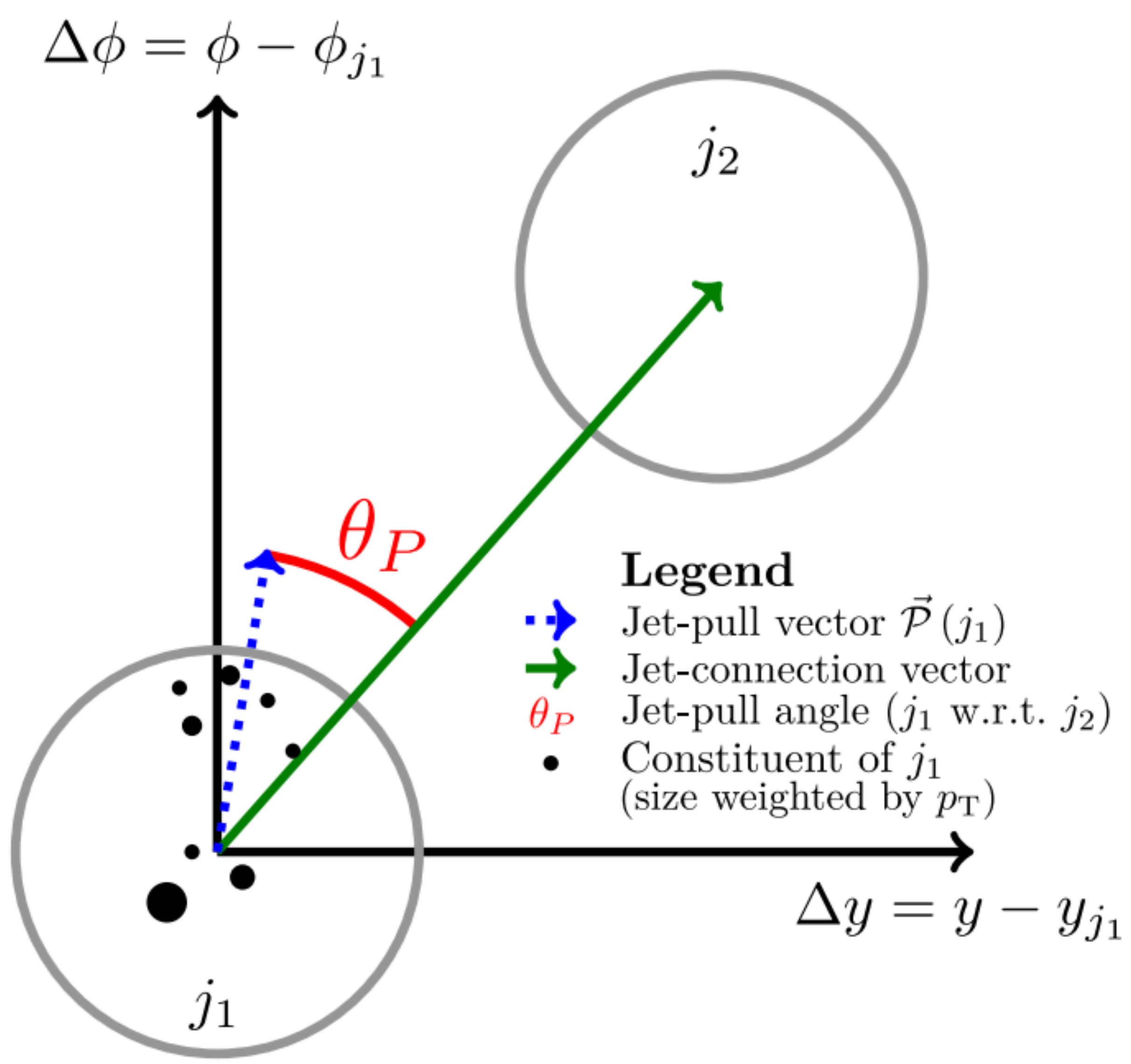
Color Flow in $t\bar{t}$ Events

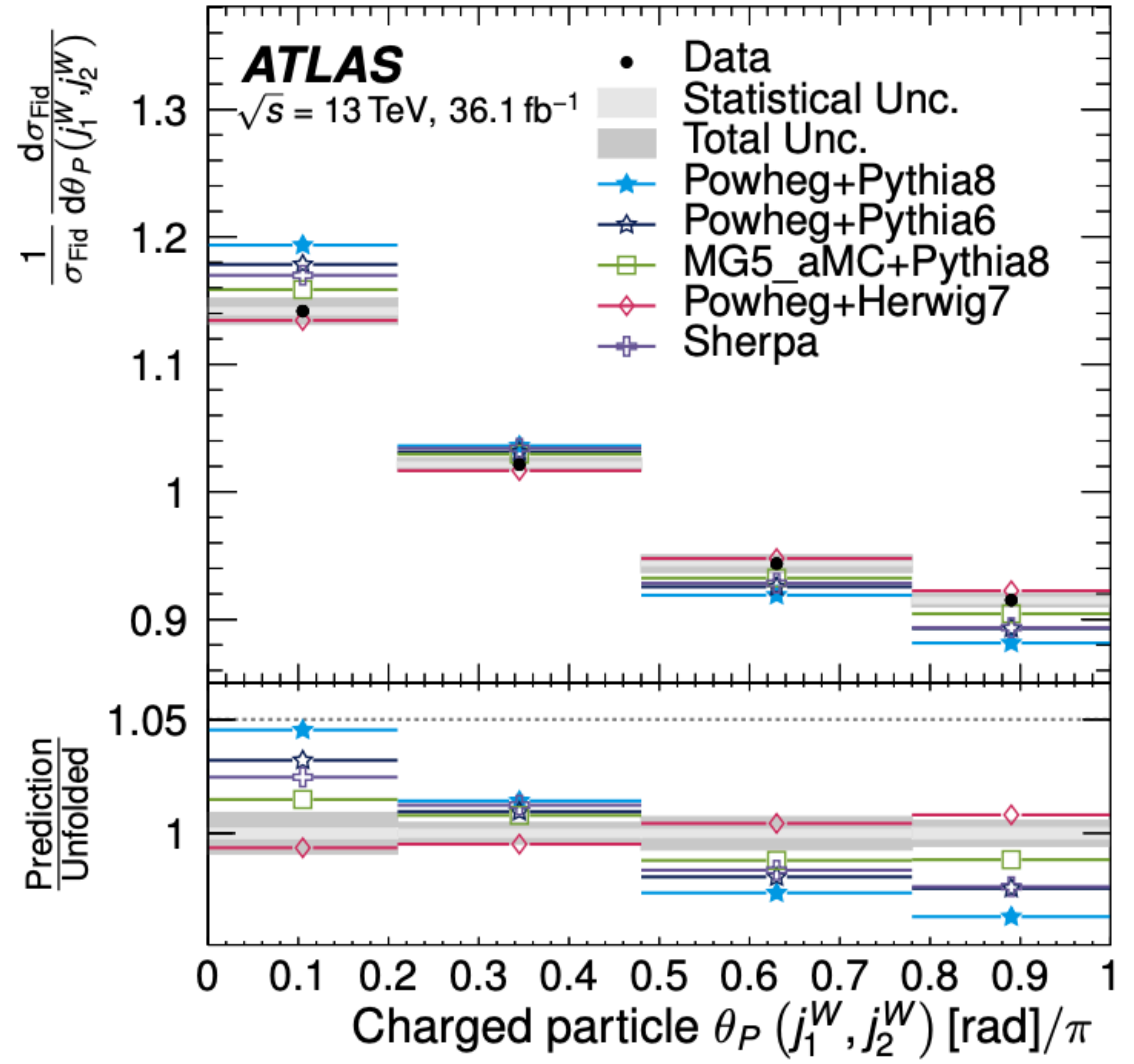
Jet Pull

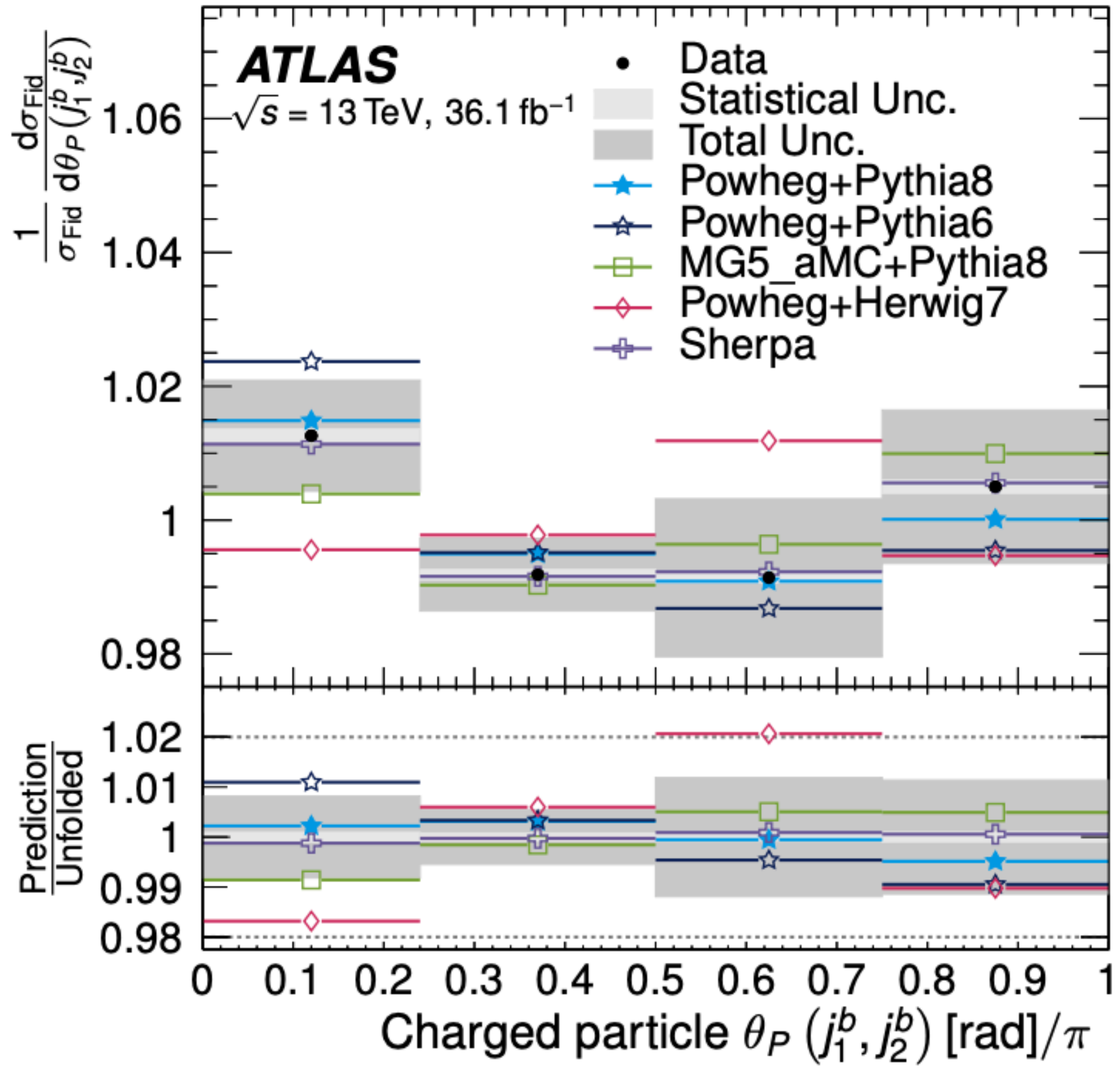
- Jet pull vector describes the preferred direction of soft radiation within a jet.
- Color connected jets are expected to have correlated jet pull, so use the angle between jet pull vectors as an observable.
- Tried to show that color structure of the top decays is as expected. Instead concluded that none of the available models describe the data well across all observables.



$$\vec{\mathcal{P}}(j) = \sum_{i \in j} \frac{\left|\Delta \vec{r}_i\right| \cdot p_{\mathrm{T}}^i}{p_{\mathrm{T}}^j} \Delta \vec{r}_i \,,$$







Top Quark Mass

Basic Methods

“Direct” measurements - reconstruct the top decay and use the invariant mass of the decay products.

- ‘Template Method’ is the original and most sensitive approach.
  - Used in l+jets and all-had channels.
  - Compare reconstructed 3j mass distribution to MC templates generated at different masses.
  - Mass in each event may be determined from kinematic fit rather than simply m_{bjj}.
- ‘Matrix Element’ calculates a per-event probability for the top quark mass based on the LO matrix element.
- Dilepton channel either attempts reconstruction of the neutrinos or uses sensitive observables like m_{lb}.
- $t\bar{t}$ and $t\bar{t}+j$ (differential) cross-section measurements recently used to extract both pole and bare masses. Indirect measurements have different considerations.

Top Quark Mass

Digression on the Mass Measurement

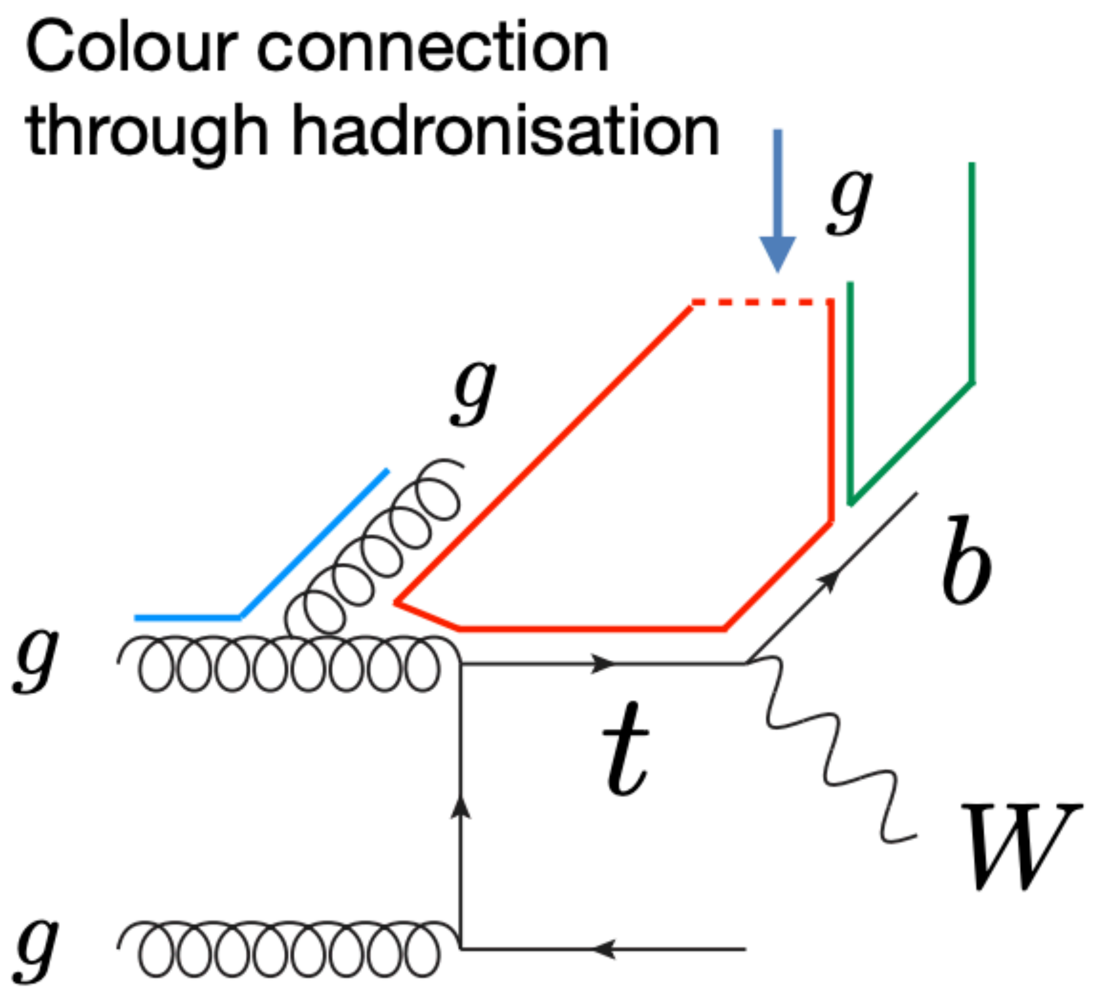
The relation between the Monte Carlo template used to fit the mass spectrum and the Field Theoretical parameter of the pole mass is not straightforward.

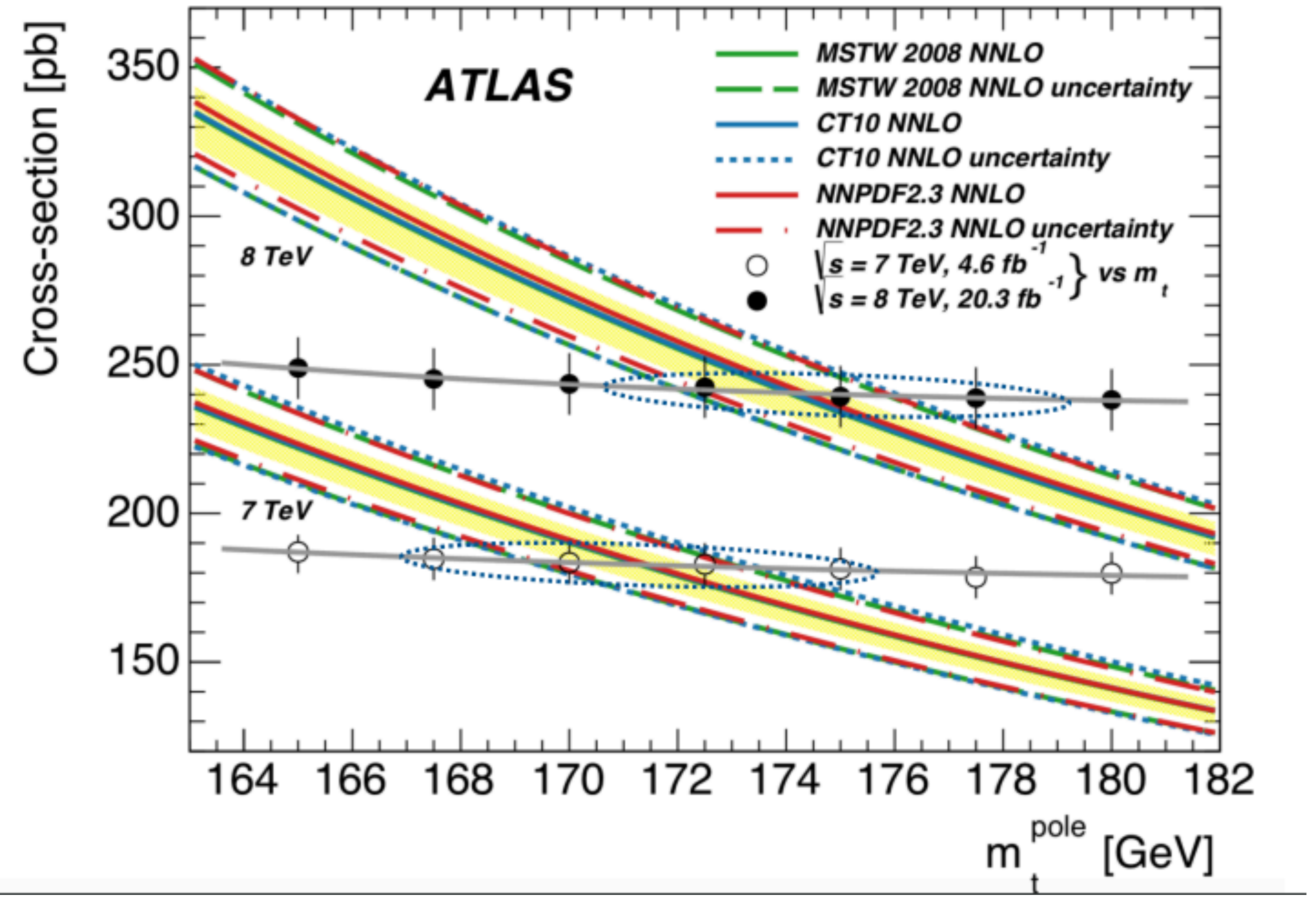
The top is coloured, so it is impossible to unambiguously associate every object in the final state to it!

These ambiguities lead to an uncertainty on the top mass measurement varying between 1 GeV and 200 MeV.

The pole mass can be measured using observables that are not dependent on the detailed reconstruction of the top system.

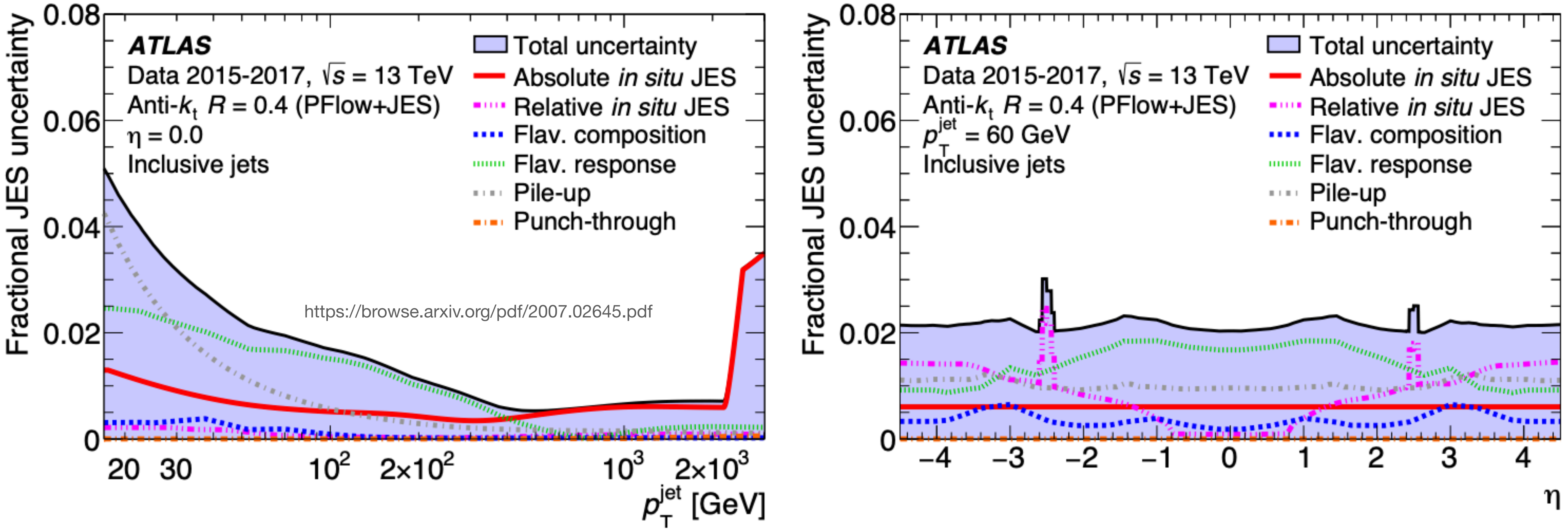
e.g. the pole mass can be measured using the top production cross section (at the cost of introducing a dependence on the production prediction).



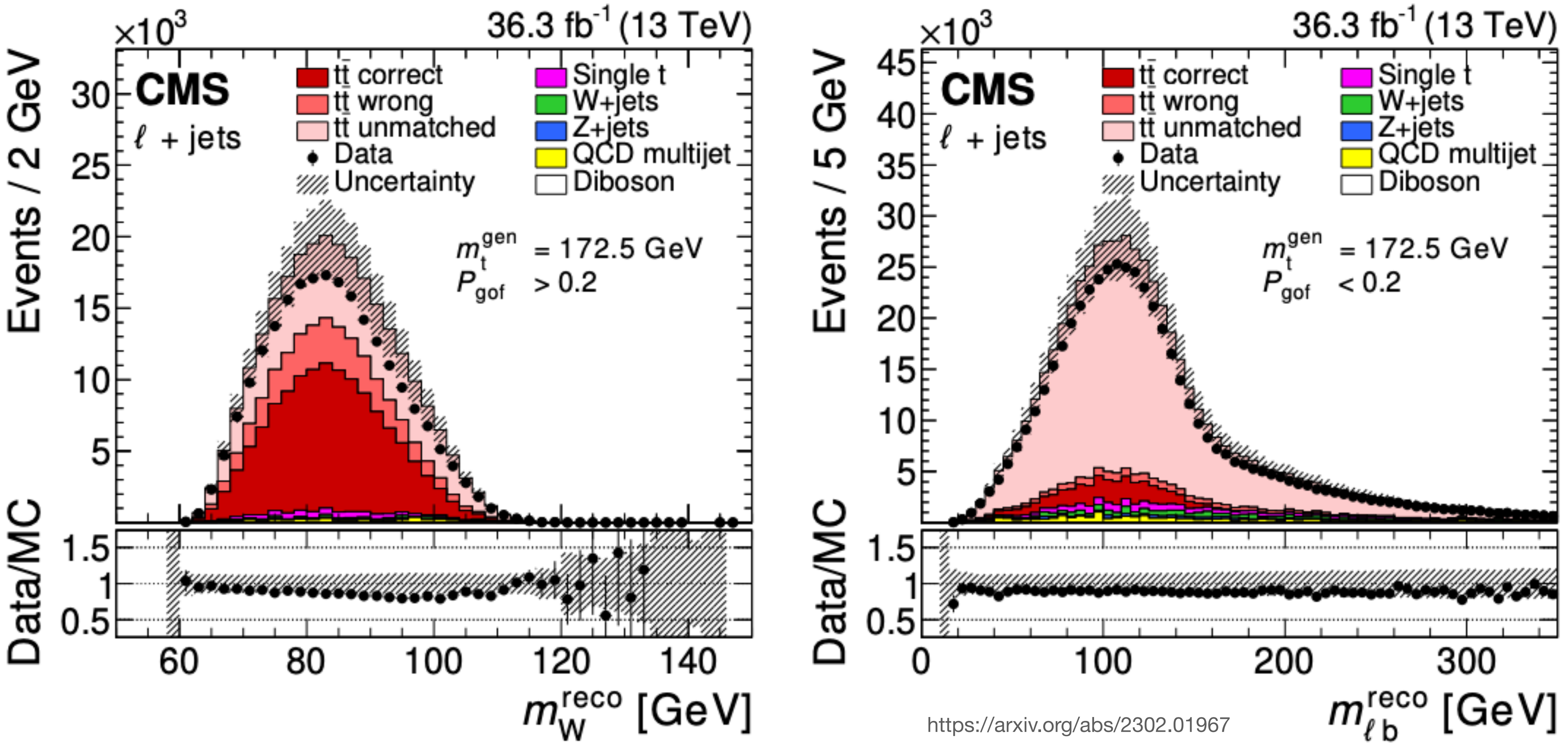


Top Quark Mass

JES Uncertainty



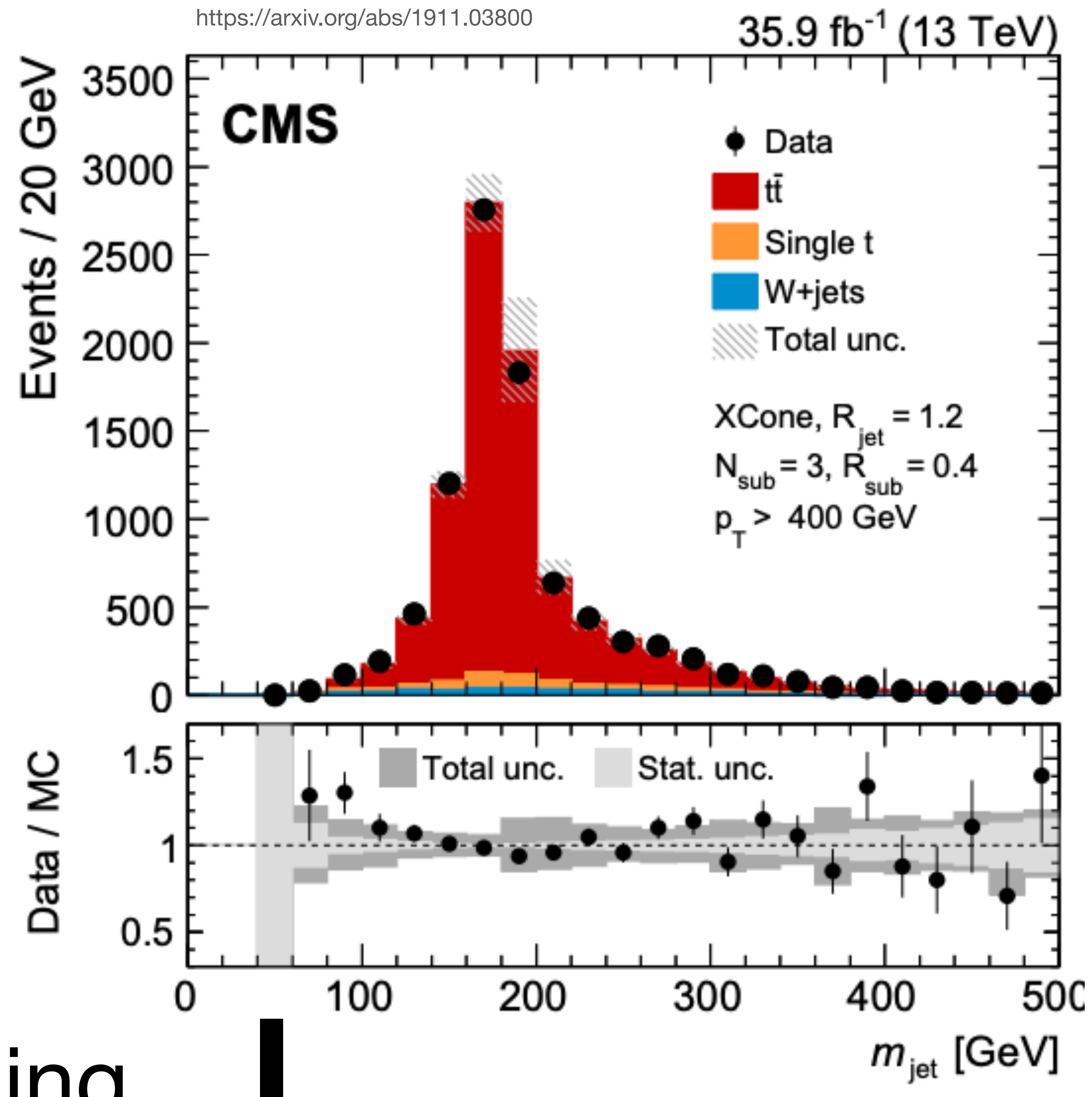
- Jet Energy Scale systematics dominate top mass uncertainties.
- Corrections to the measured 4-momentum of a jet to account for pileup, data/MC differences.
- Corrections depend on pileup conditions, number of primary vertices, jet area, η, and fraction of a jet's energy observed in tracks vs. calorimeters.
- Effect in top mass measurement somewhat reduced by including reconstructed W mass in fit.
    - Flavor dependent component can't be controlled this way. Newer analyses use additional variables
- Some attempts to make JES-independent measurements including using soft μ from B decays as proxy for b quark.



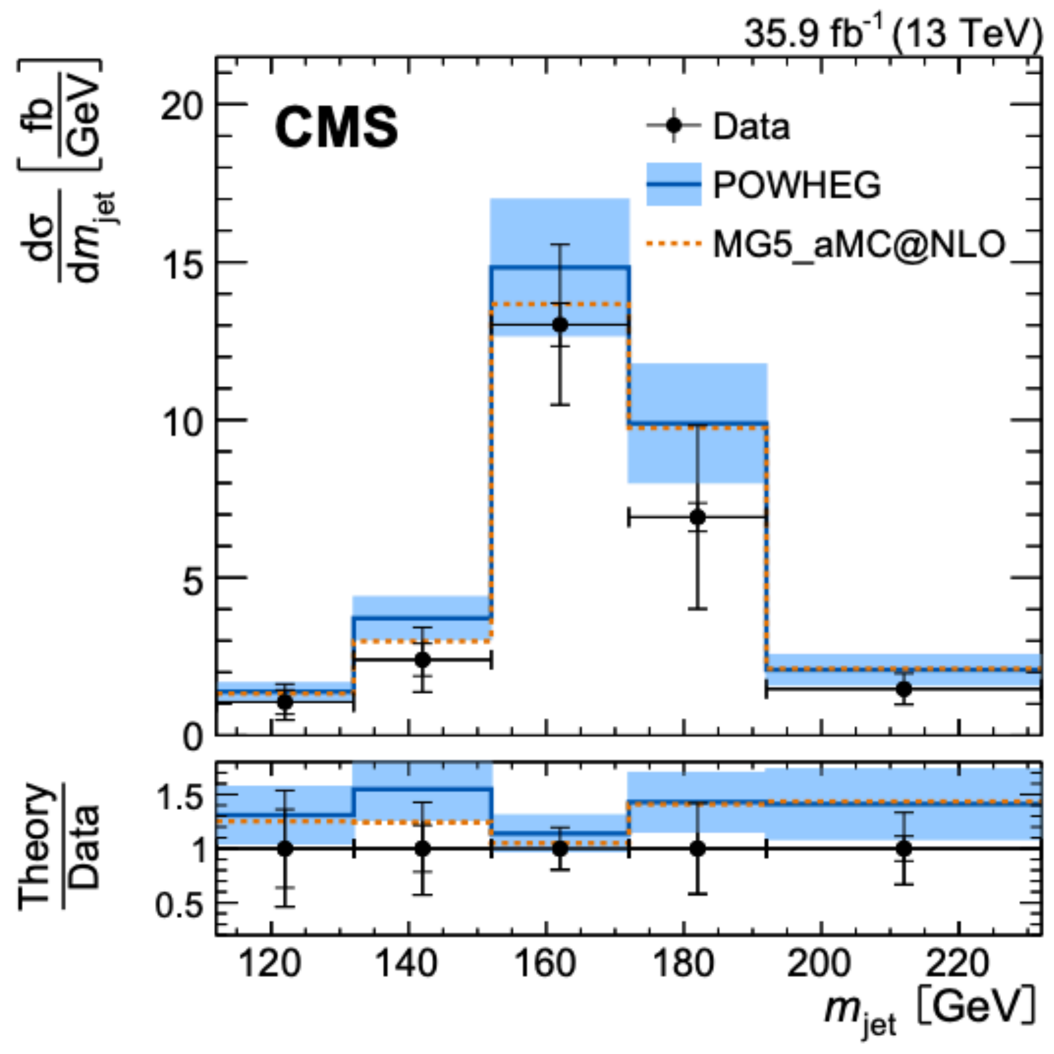
Top Quark Mass

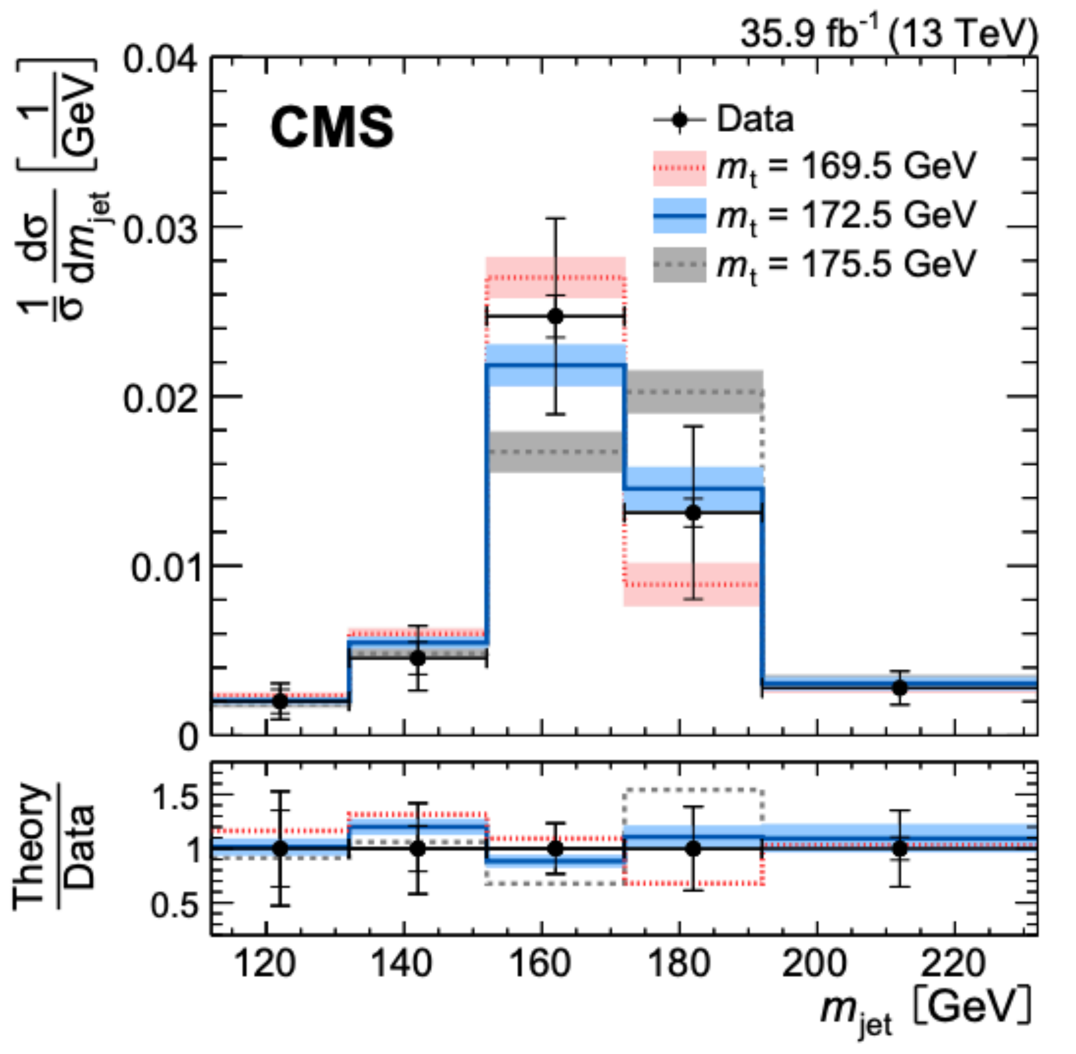
Boosted Tops

- CMS top mass measurement performed on boosted tops with large radius jets in single lepton + jets + MET events.
- Reconstruct 2 R = 1.2 XCone jets.
- Reconstruct 3 R = 0.4 sub-jets from the constituents of each large R jet.
- B-tagging requirements on anti-kt jets, pT requirements on large and small XCone jets.
- Measure mass using jet with largest ΔR to lepton.
- Jet mass resolution 2x that of R=1.2 Cambridge-Aachen jets.

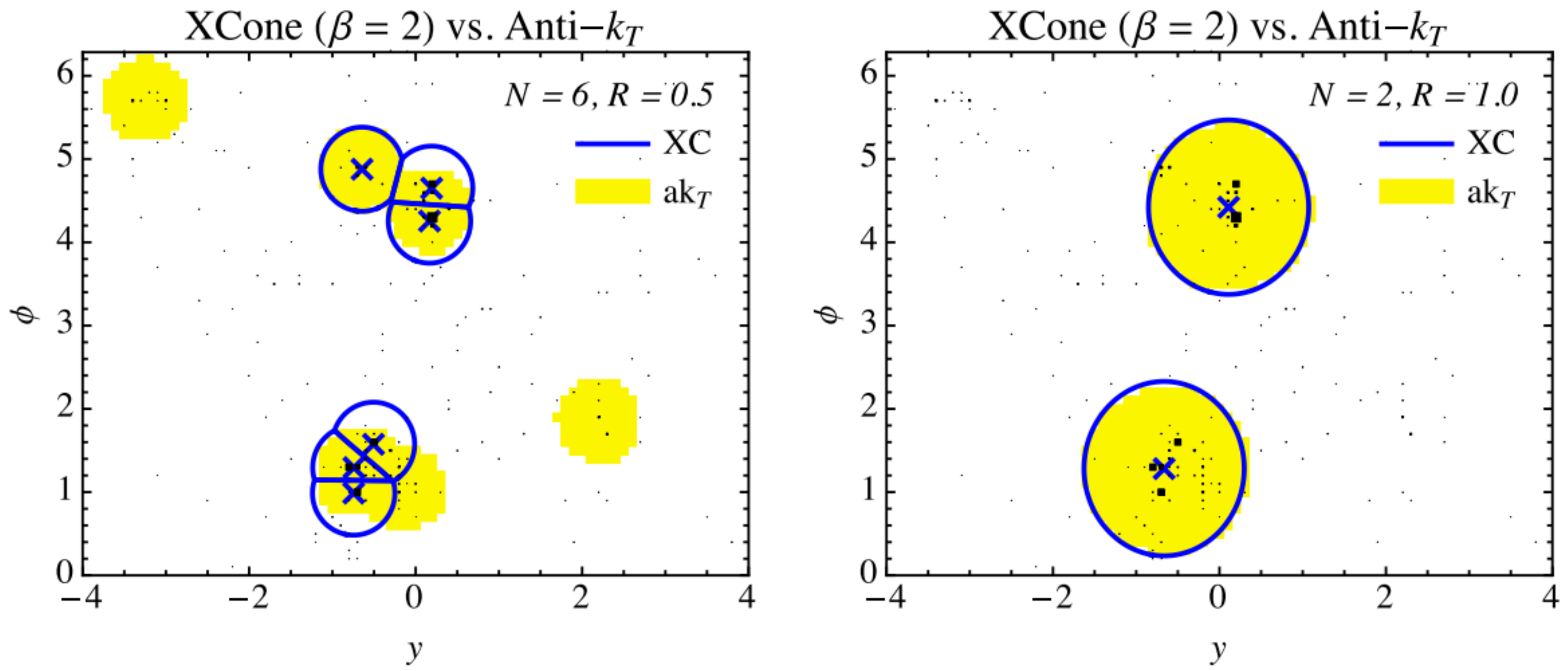


Unfolding





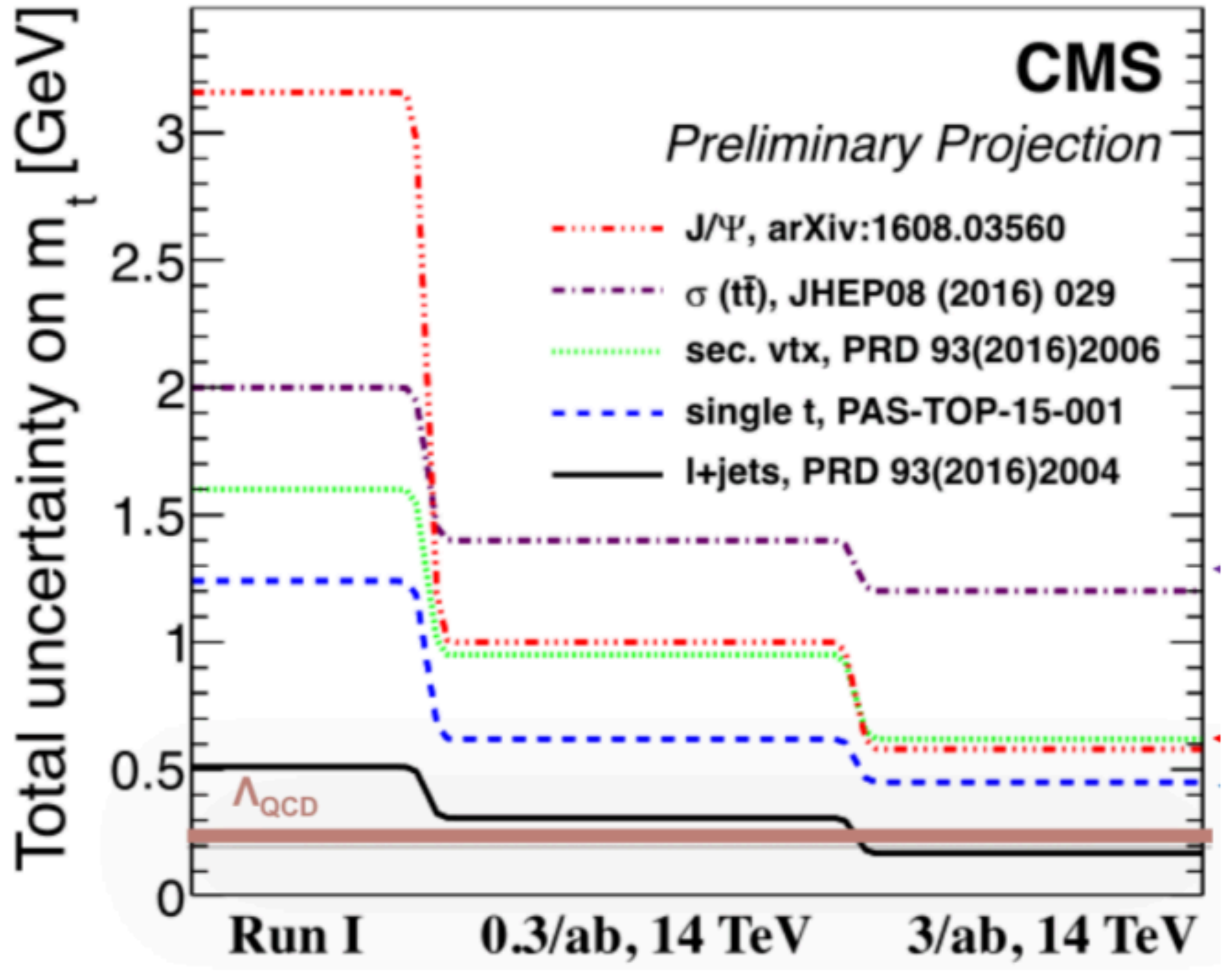
XCone Algorithm

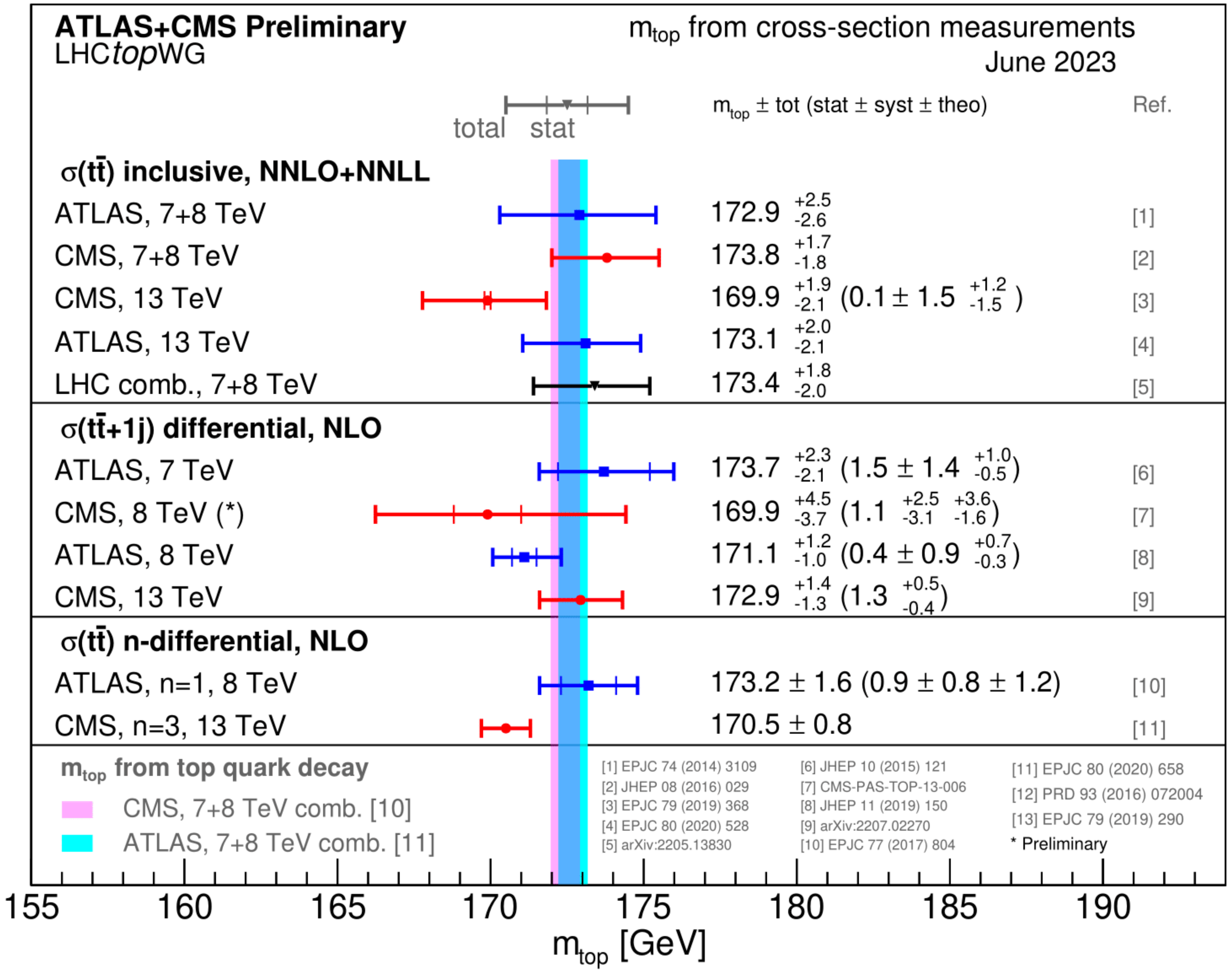


https://arxiv.org/pdf/1508.01516.pdf

- Cone algorithm that reconstructs a fixed number of jets per event.
- Chooses a set of N jet axes that optimize N-jettiness. $\widetilde{\mathcal{T}}_N = \sum_i \min\{\rho_{\text{jet}}(p_i, n_1), \ldots, \rho_{\text{jet}}(p_i, n_N), \rho_{\text{beam}}(p_i)\}$.
- Assigns jet constituents to one of N jets or to a beam region using a distance metric.
- Re-clustering a jet into N sub-jets removes soft radiation (grooming).
- N-(sub)jettiness provides a quality metric for how well the event is described by N jets.
- IRC safe and calculable in Soft-Collinear Effective Theory.

Top Quark Mass





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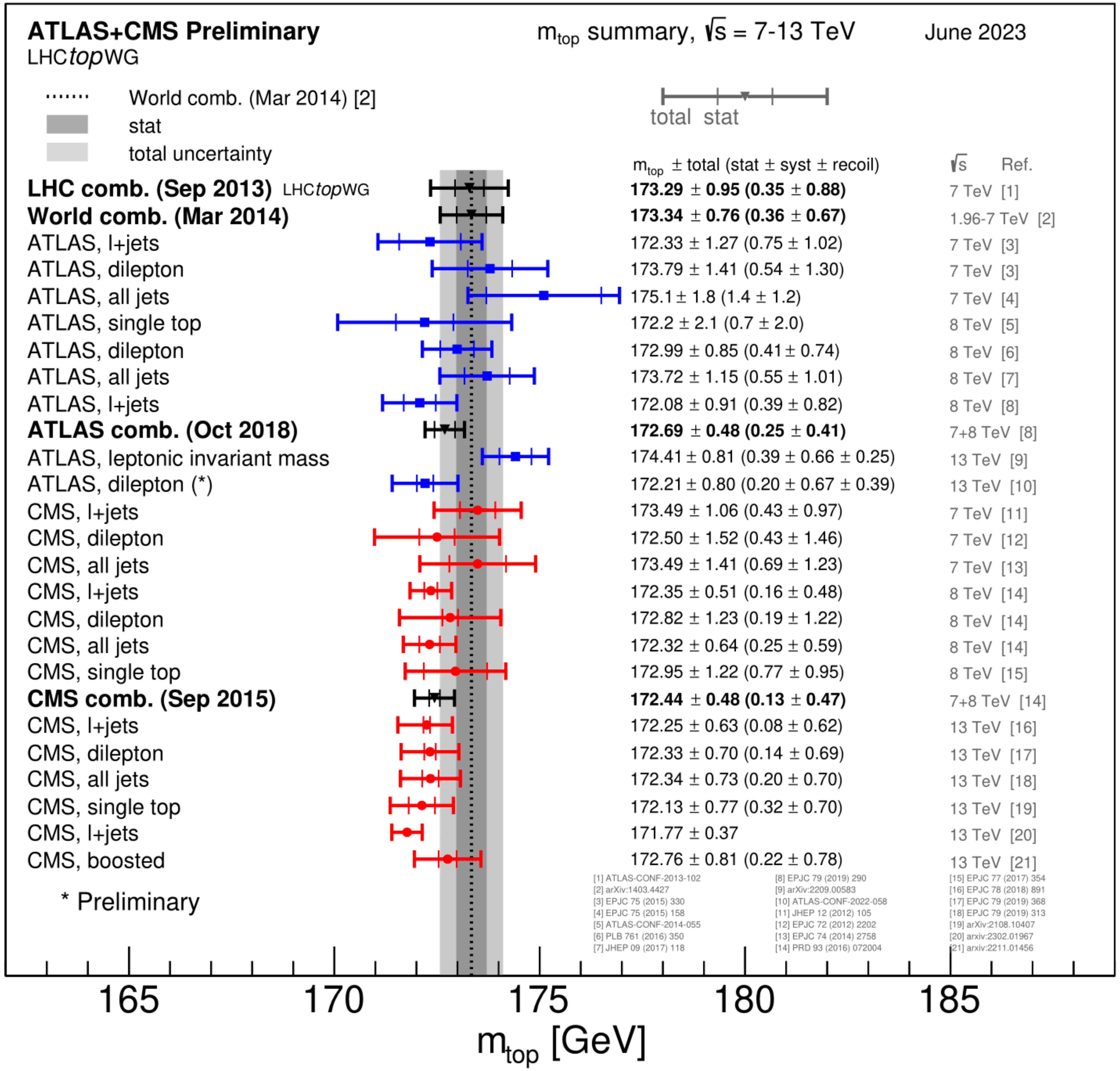
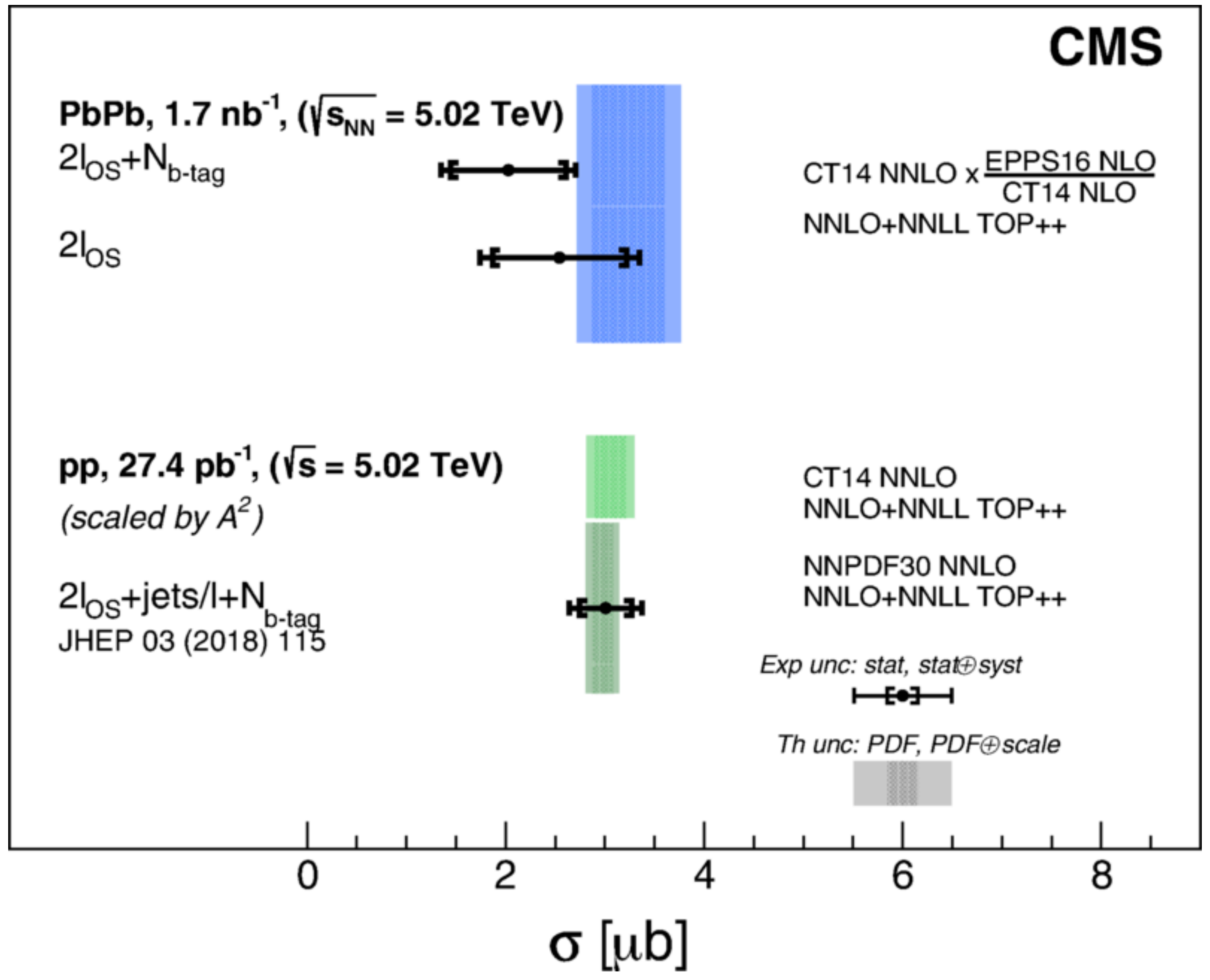


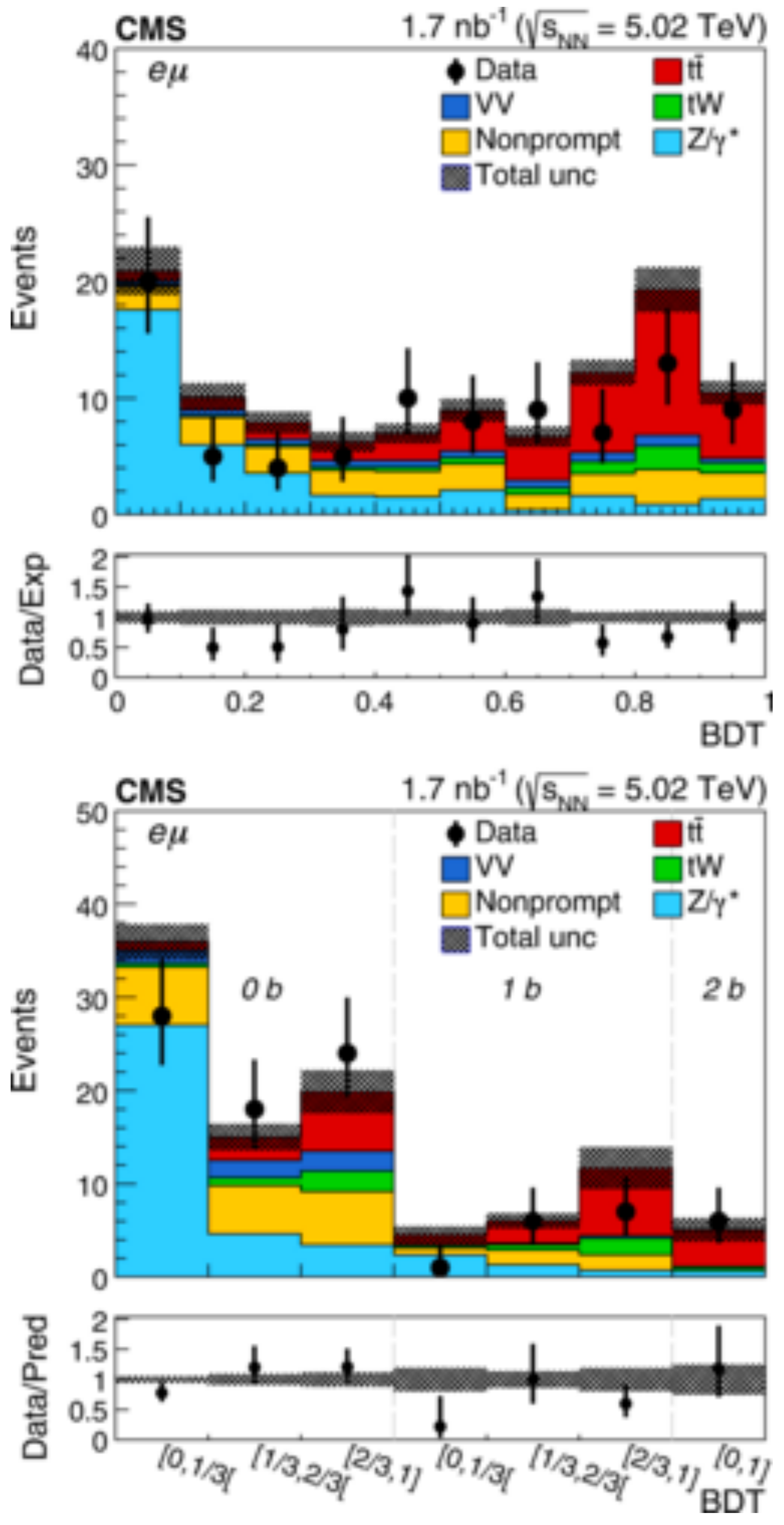
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.125.222001#fulltext

Top Quarks in Heavy Ion Collisions

Evidence from CMS

- Top production in PbPb collisions requires nucleon-nucleon collision with high-x partons.
    - Sensitive to hard gluons in the nucleon PDF.
- Significant challenge flavor tagging in HI environment.
- Evidence found in dilepton channel.





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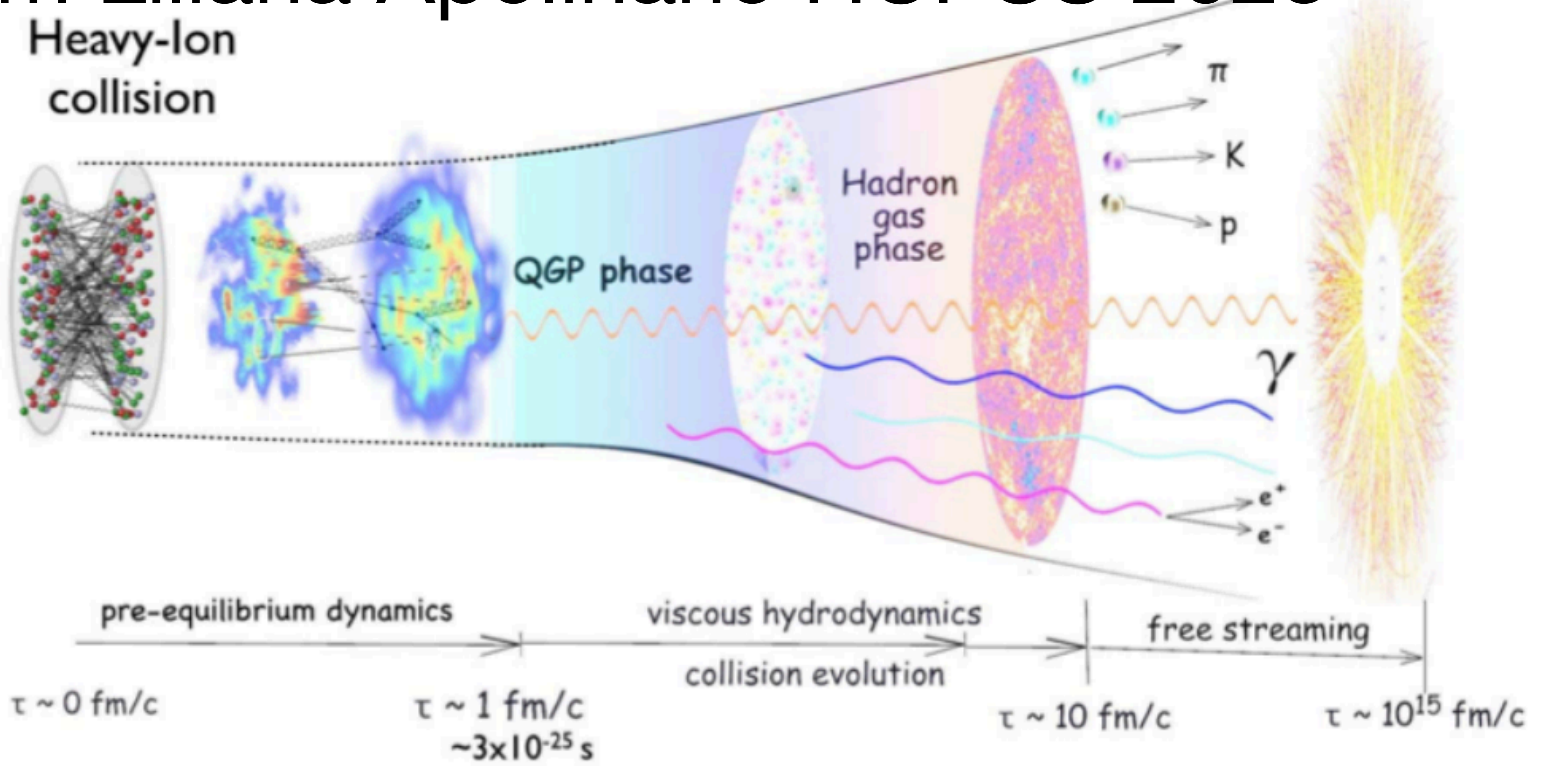
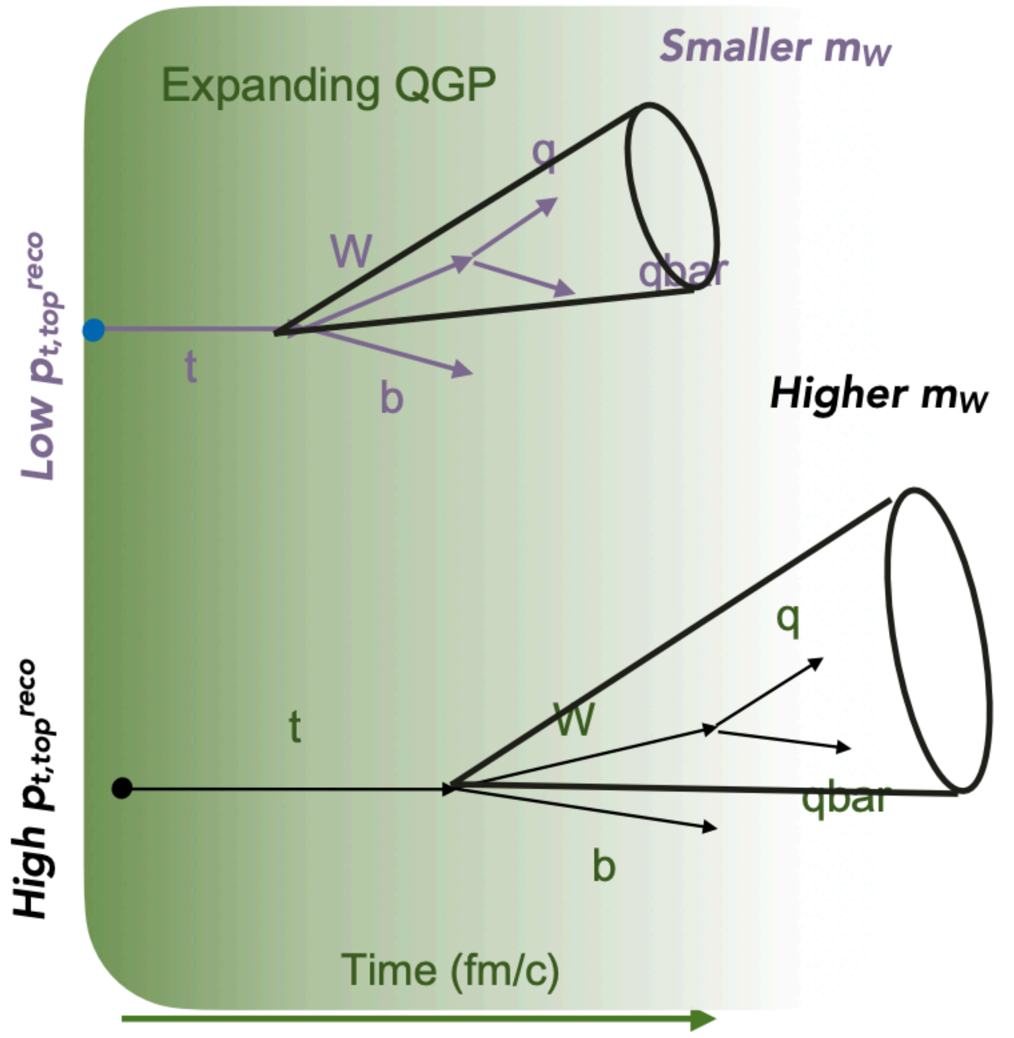
Top Quarks in Heavy Ion Collisions

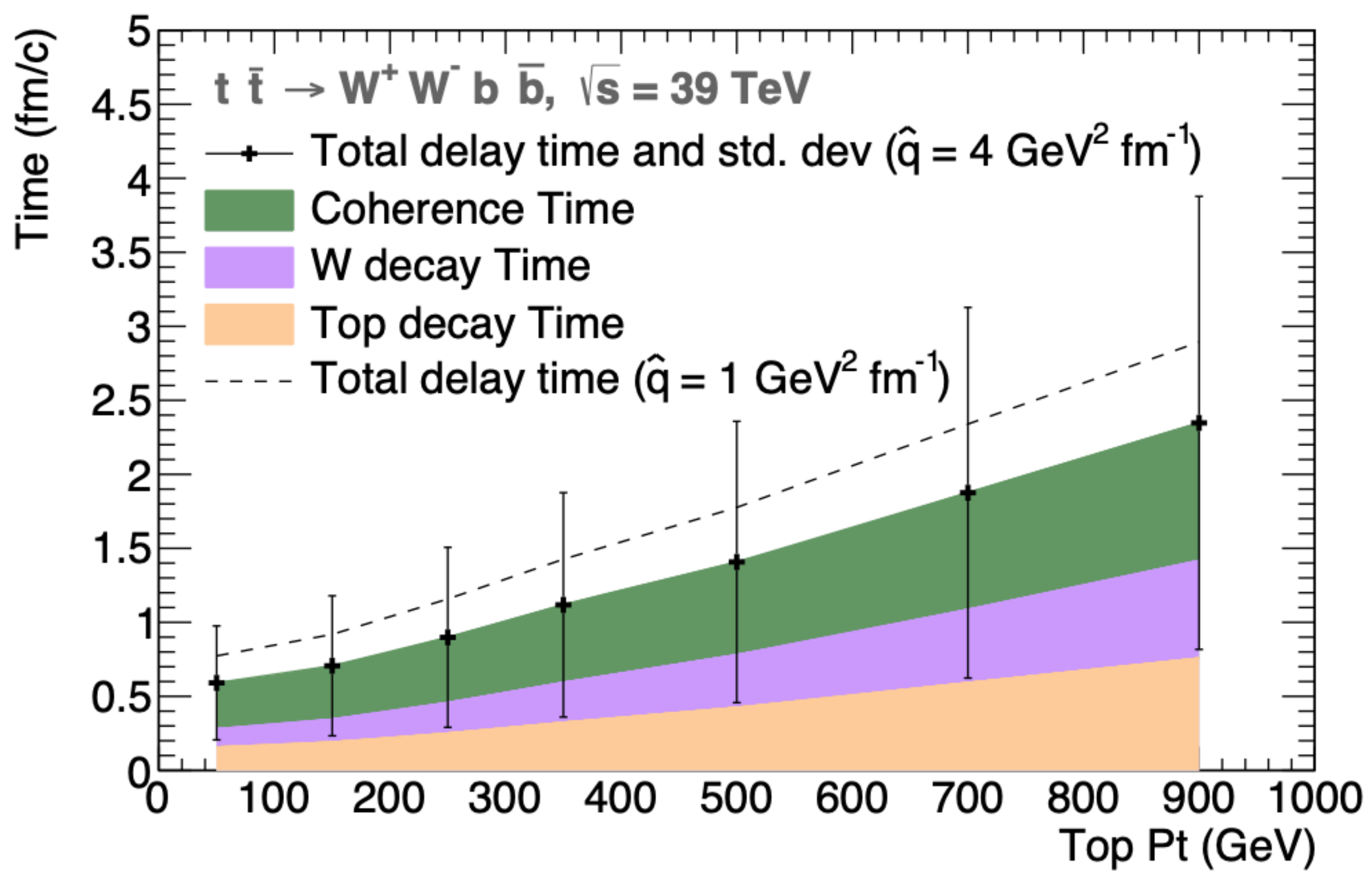
Future Prospects



- Top lifetime 0.5×10^{-24} s $= 0.15$ fm/c. Boosted tops could have total lifetimes similar to the timescale of QGP.
- W decays to color singlet state. QGP causes color singlet state to decohere.
- Decoherent state is quenched by the medium - reconstructed m_W decreases.



[Apolinario et al (1711.03105)]



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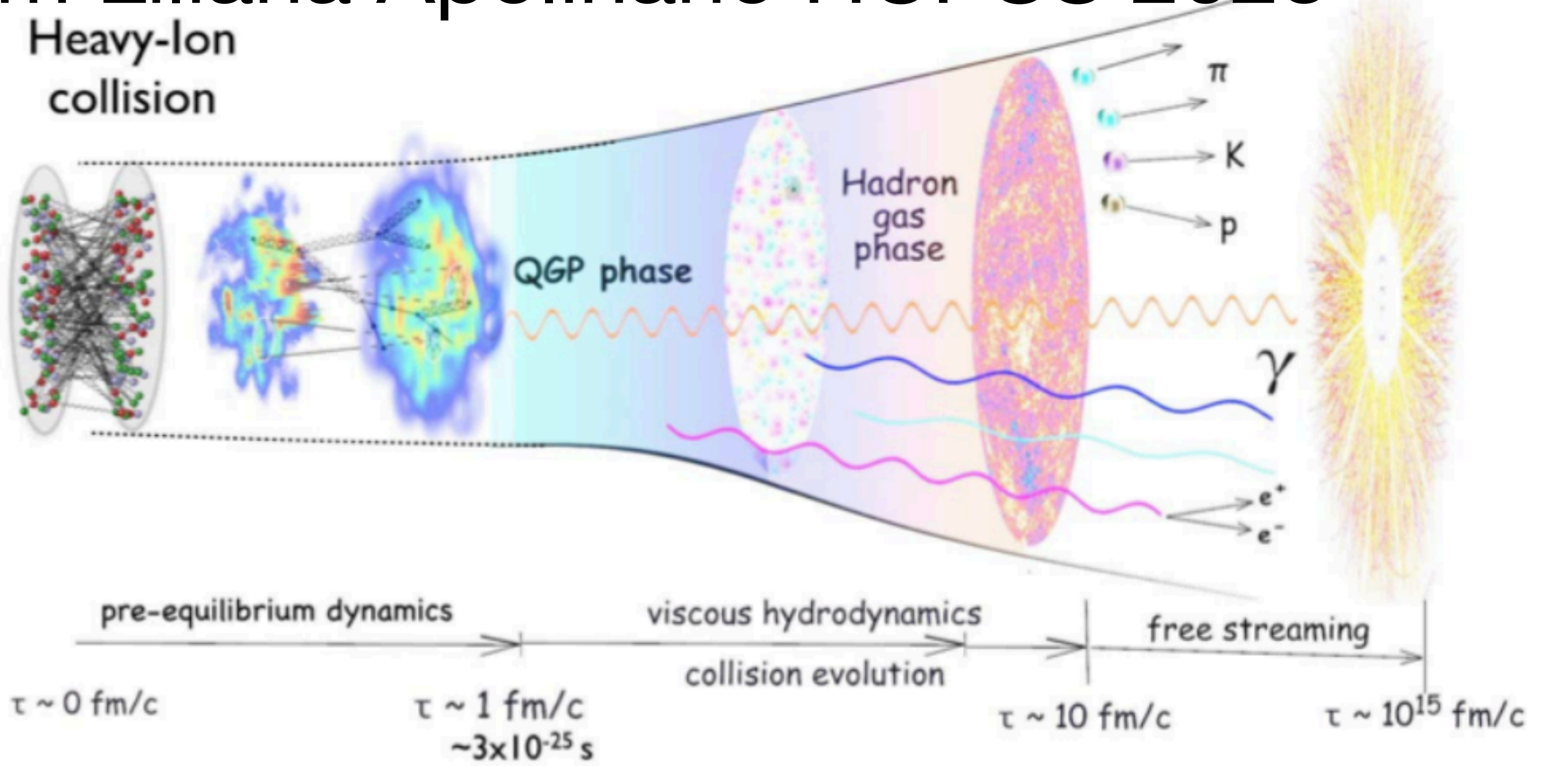
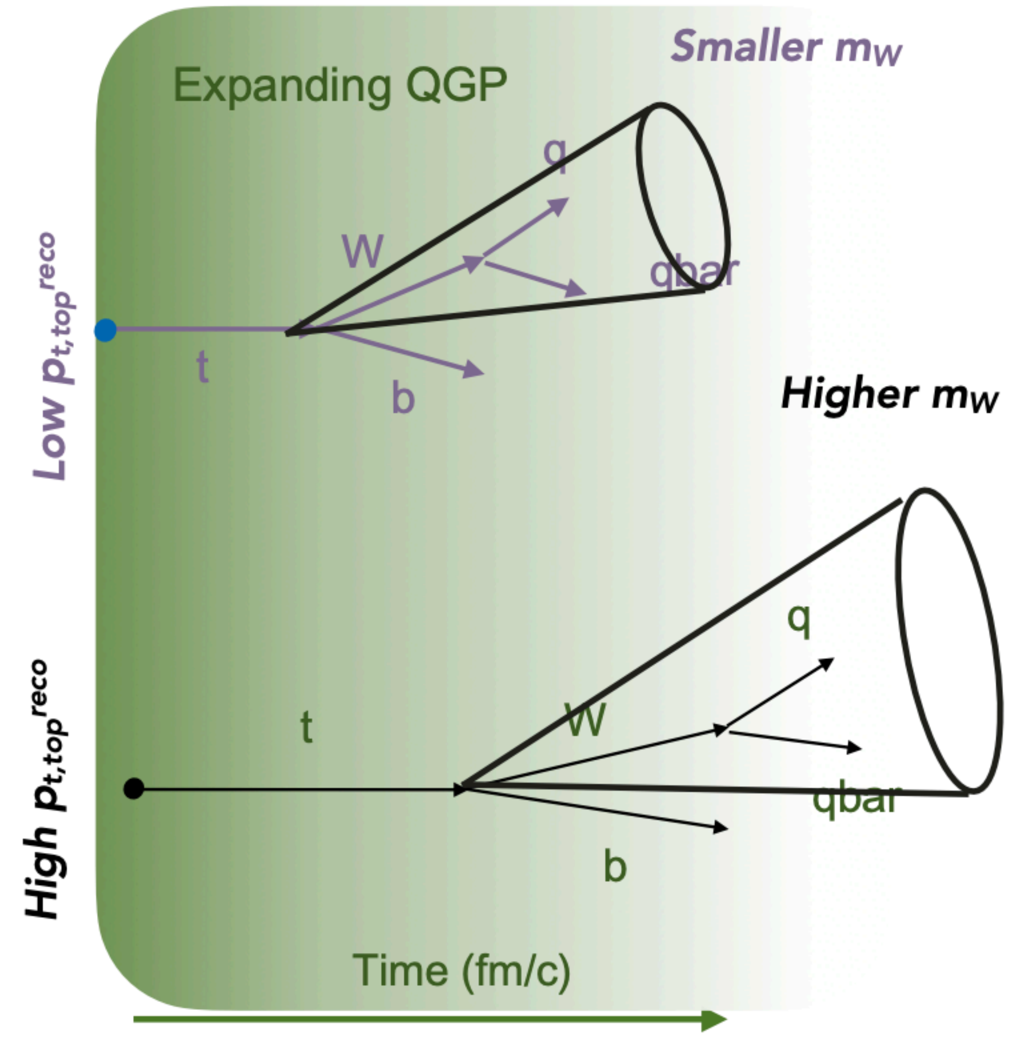
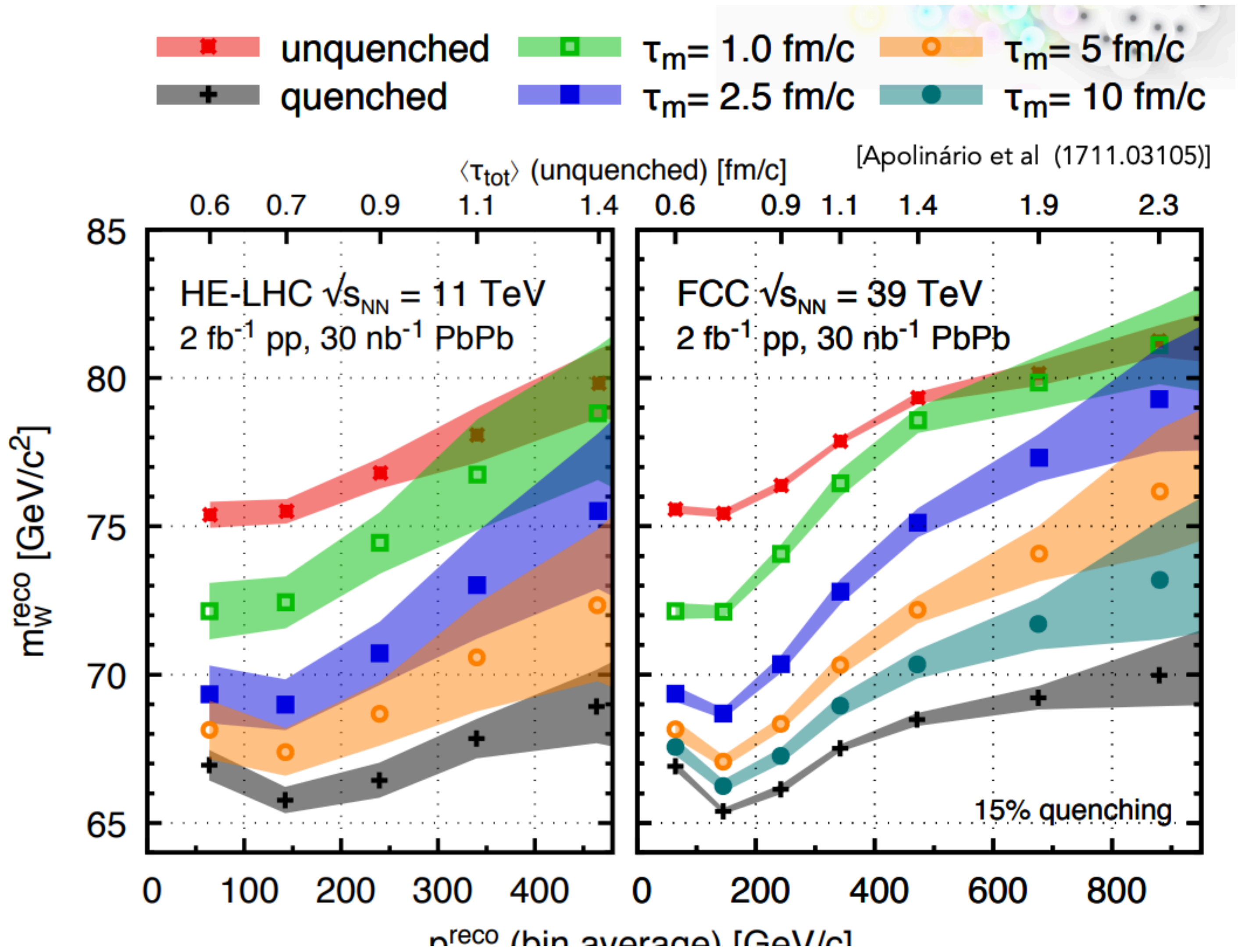
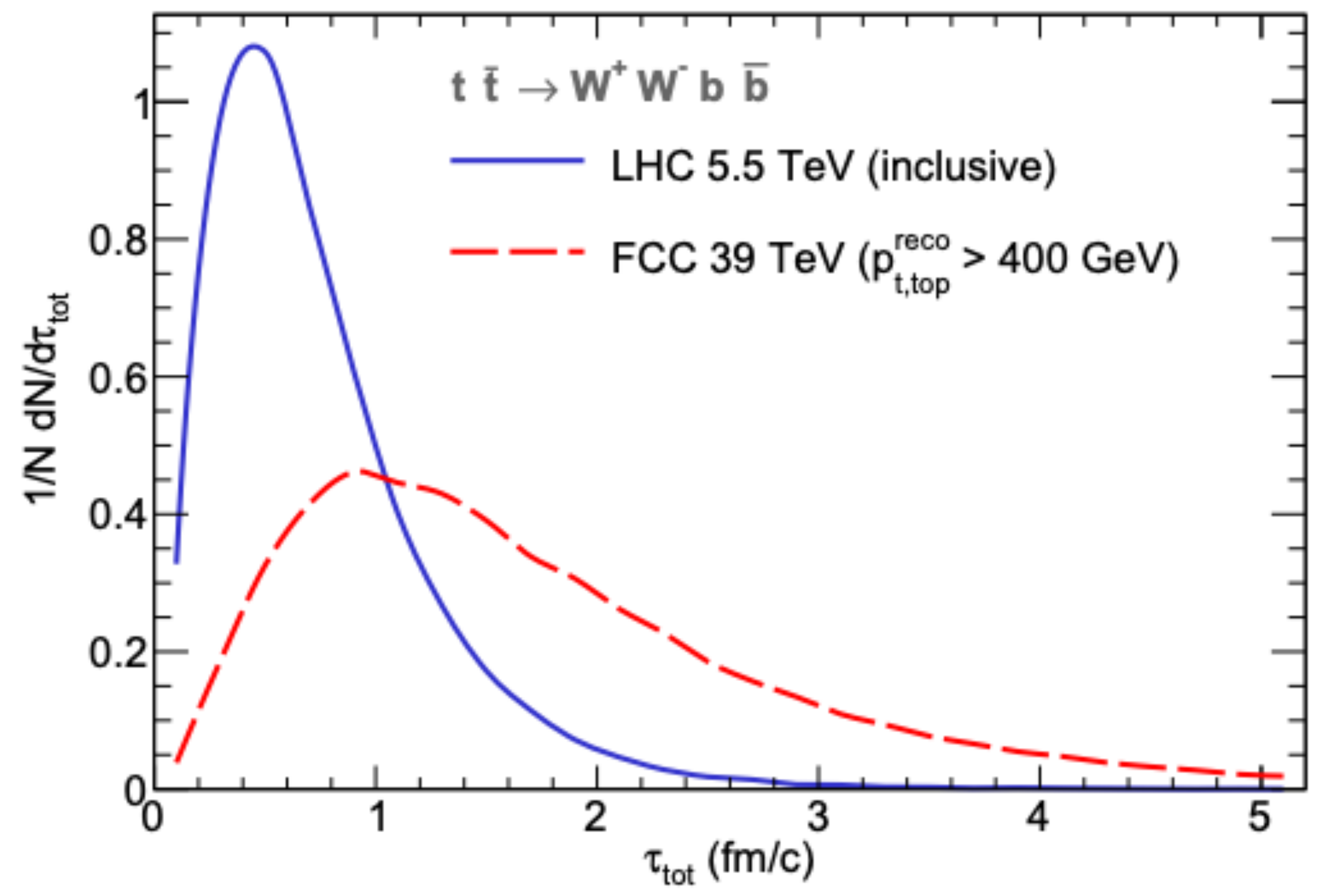


- Measuring m_{jj} for the W boson as a function of top momentum gives a handle on the QGP state at different times. (QGP tomography).
- …needs higher momentum tops than we have at LHC to probe the most important region.







Summary

- Top physics cannot be separated from jets. There are always jets and often a lot of them.
- Precision top measurements require excellent experimental handles on jet energy and flavor.
- Advances in jet substructure allow measurements of tops as single jets at higher momenta. This boosted regime is useful for the SM measurement program and is especially sensitive to many potential sources of new physics.
- $t\bar{t}$ events at the LHC also provide a rich playground for improving our understanding of jets themselves. Common events with an known decay chain and flavor ratios are important for measuring jet substructure.
- Top quarks as a tool may extend even to measurements of the QGP in the future.

References

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