Measurements of jet substructure observables and jet fragmentation at the LHC

SUSY 2019

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on behalf of the ATLAS and CMS Collaborations

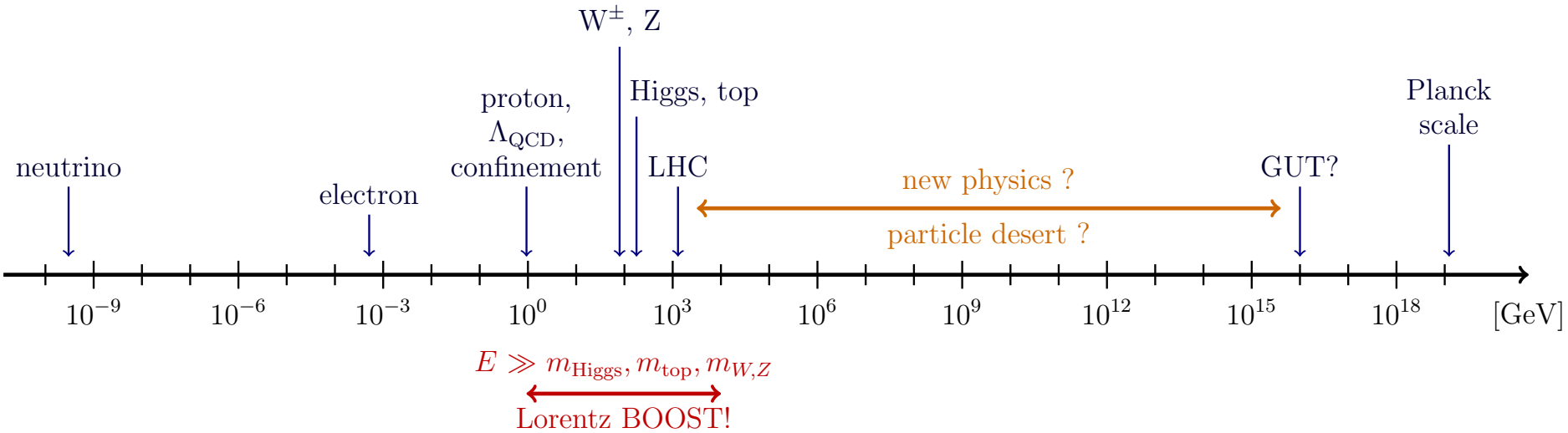
Enrico Fermi Institute

THE UNIVERSITY OF CHICAGO

May 21, 2019

The current era of particle physics

For the first time in the history of particle physics, the collision energy is well above the scale of electroweak symmetry breaking and Λ_{QCD}.



Lorentz-boosted objects are an *inevitability* for SM processes & new physics!

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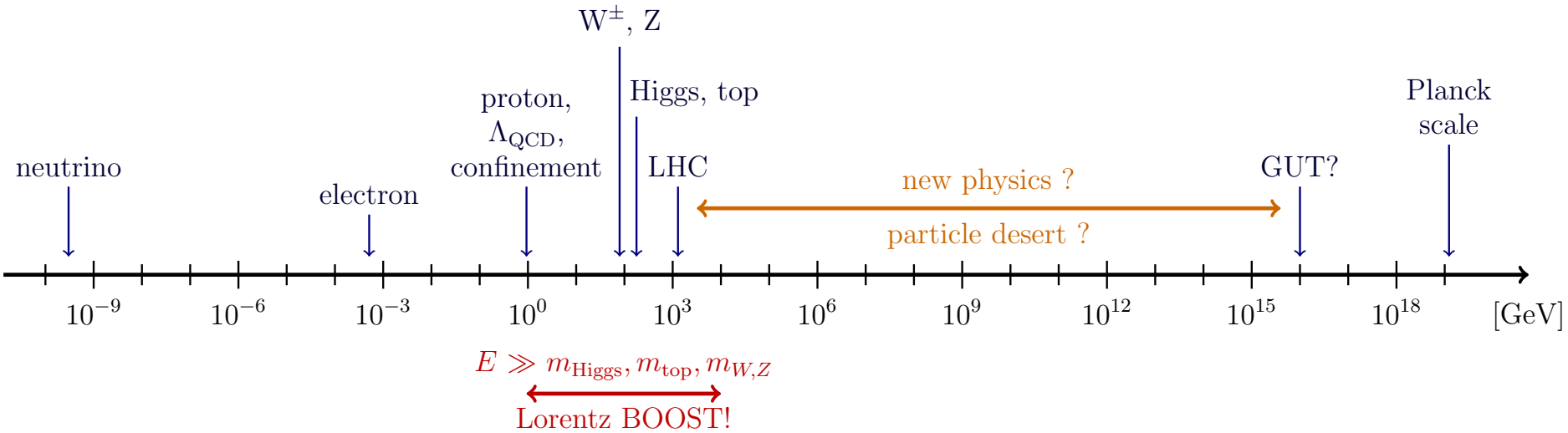

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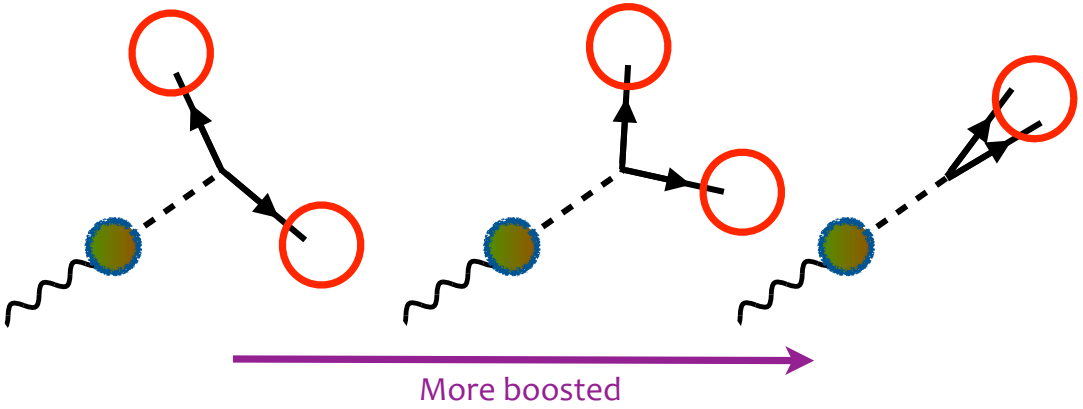
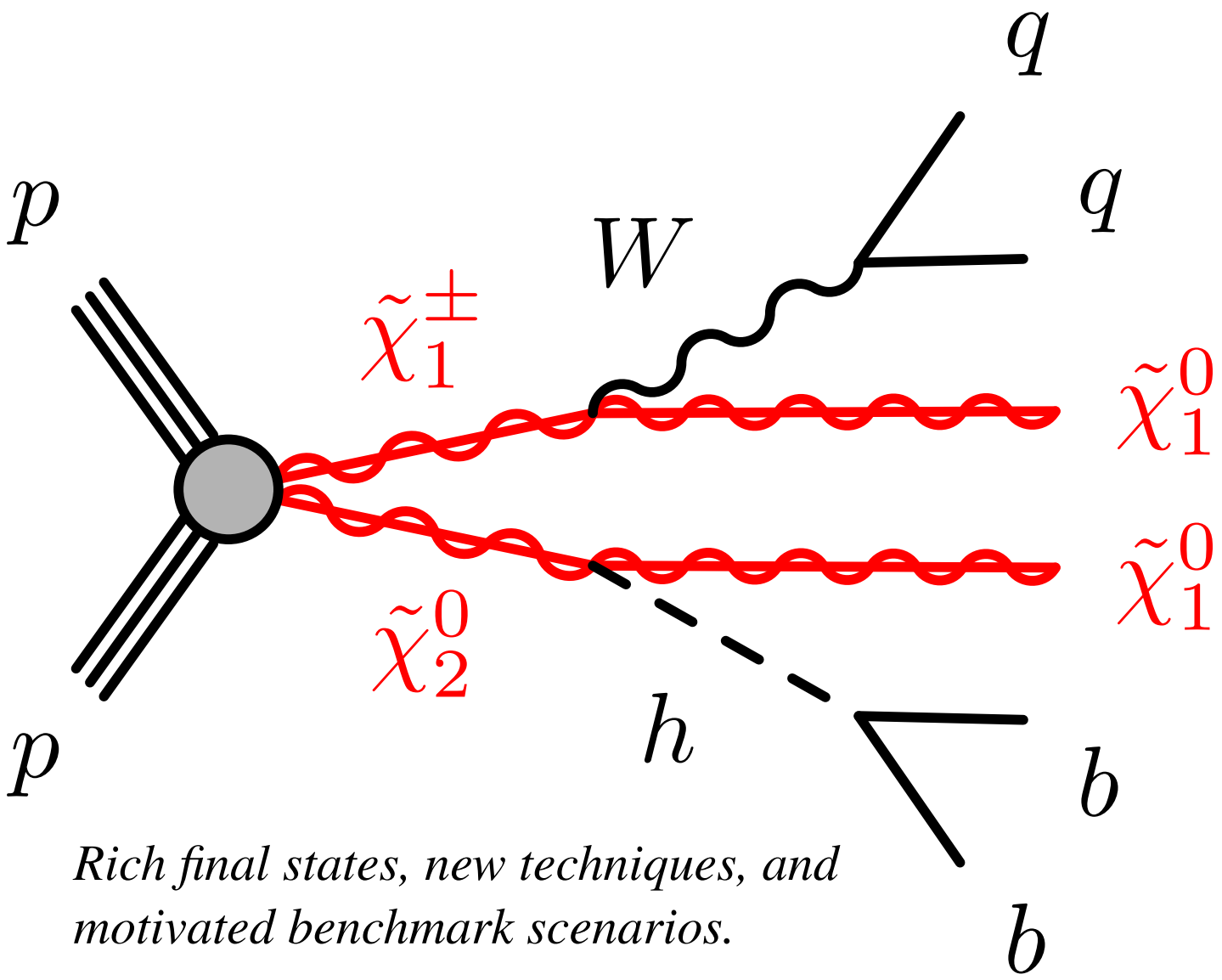
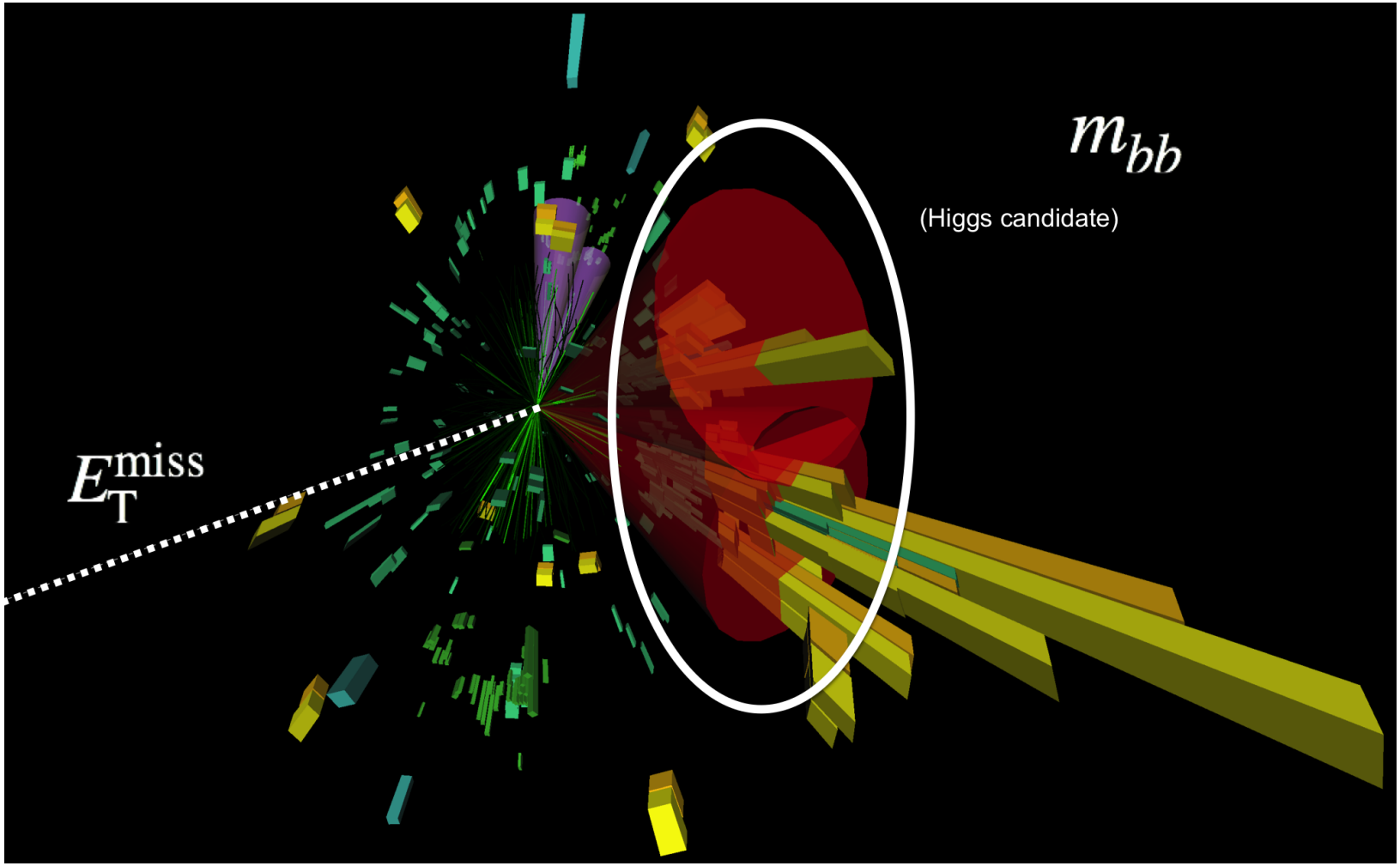


Searches are pushing the boundaries of hadronic final states

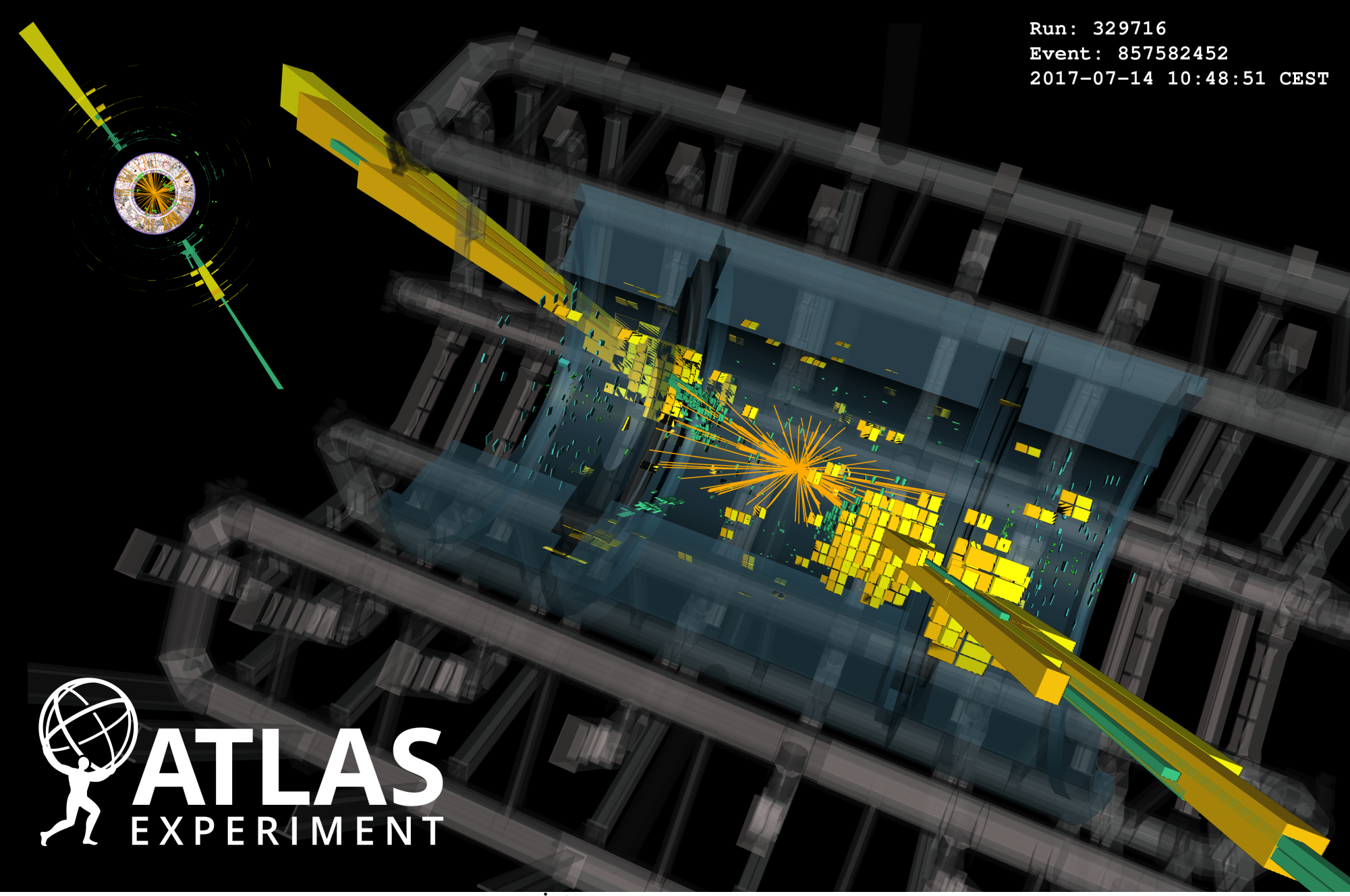


Rich final states, new techniques, and motivated benchmark scenarios.

Hadronic final states: major part of LHC physics program



- Major background to new physics, even in the case of EWK-oriented searches
- Wealth of interesting physics & precision tests in QCD(+EWK) processes
- **Boosted hadronic object tagging critical for high-mass SUSY sensitivity**

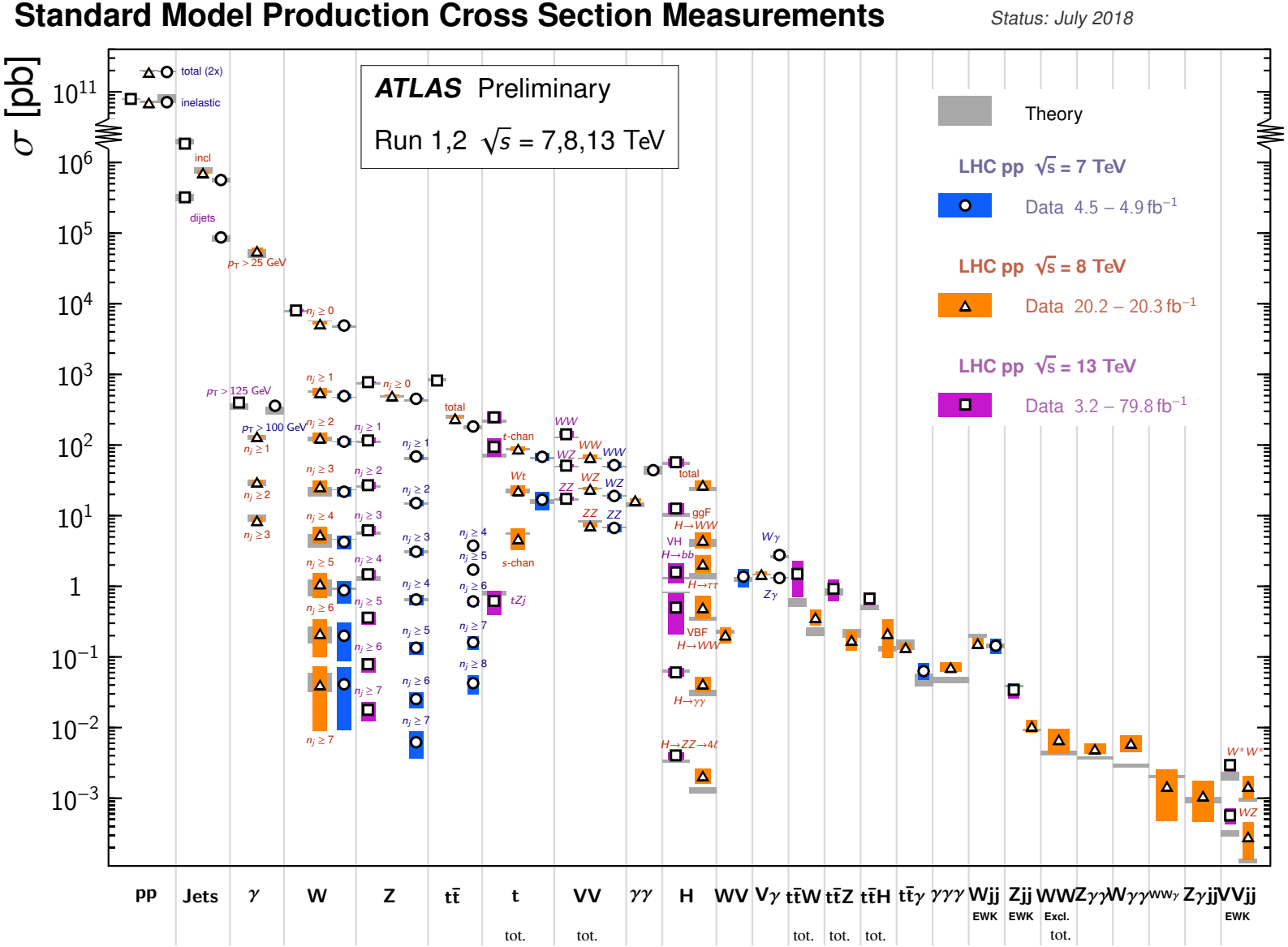


$m_{jj} = 9.3$ TeV, with $p_{\mathrm{T}}^{\mathrm{jet}} = 2.9$ TeV $\rightarrow$**more than** $35 \times m_W$**!**

$(p_{\mathrm{T}}^{\mathrm{jet}} >> m_{W/Z/\mathrm{Higgs/top}})$

Essential to measure and understand jet substructure

Run 2 LHC: $\mathcal{L}_{inst} = 2 \times 10^{34} cm^{-2} s^{-1} = 0.02\ \mathrm{pb}^{-1}\ s^{-1} = 6\ kHz$ *of dijet events*



Highlights in this talk

1. **Precision mass and fragmentation measurements using light QCD processes**

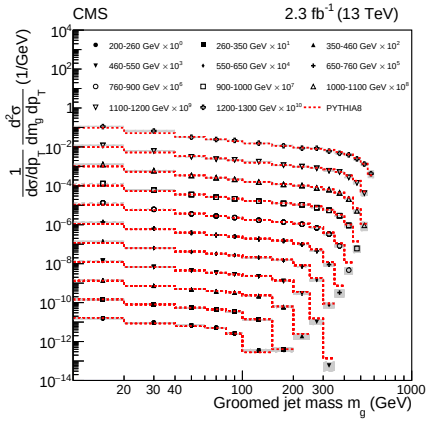
   → ▸ STDM-2017-16 (ATLAS) ▸ arXiv:1807.05974 (CMS) ▸ arXiv:1711.08341 (ATLAS)

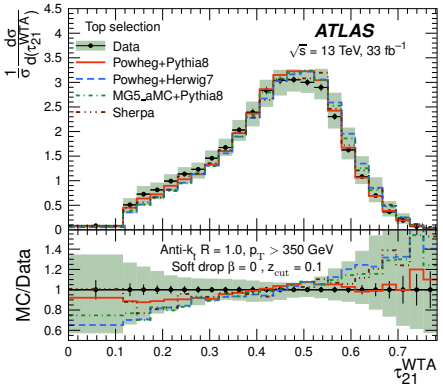
2. **Jet substructure measurements in $t\bar{t}$ events**

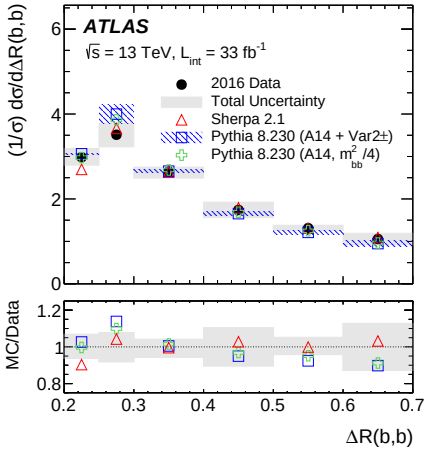
   → ▸ 1903.02942 (ATLAS) ▸ arXiv:1808.07340 (CMS) ▸ 1805.02935 (ATLAS)

3. **Properties of $b\bar{b}$ resonances**

   → ▸ arXiv:1812.09283 (ATLAS) ▸ arXiv:1709.05543 (CMS)

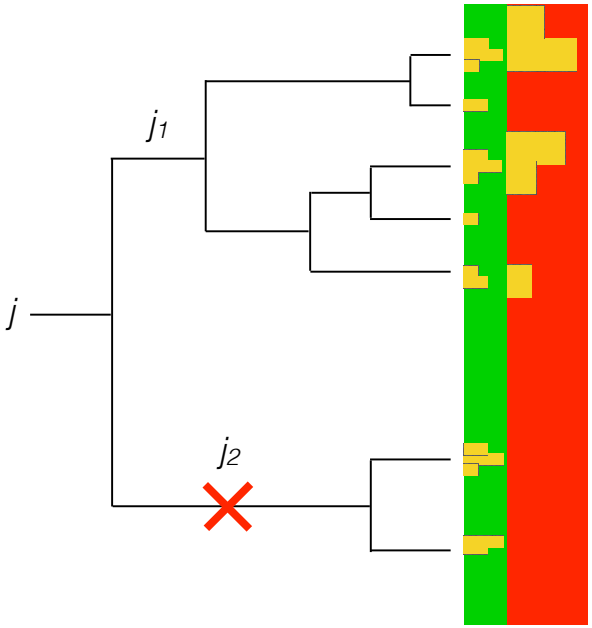


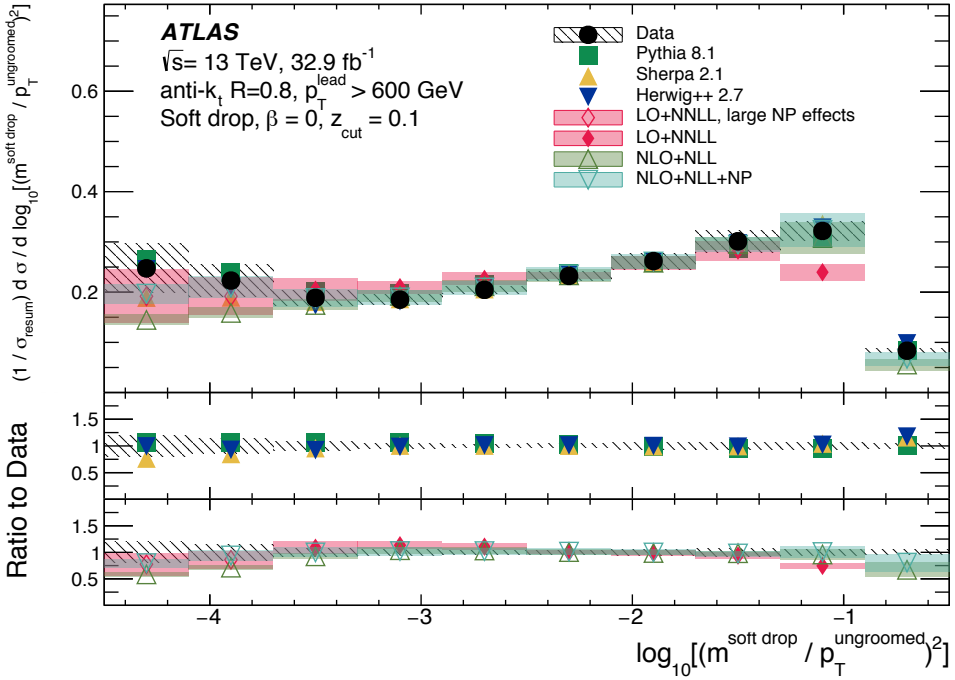




ATLAS soft drop jet mass measurement

▸ *Phys. Rev. Lett. 121 (2018) 092001* ▸ *(arXiv:1711.08341)*





Soft drop grooming

$$\frac{\min(p_{\mathrm{T},j_1}, p_{\mathrm{T},j_2})}{p_{\mathrm{T},j_1} + p_{\mathrm{T},j_2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

Soft drop $R = 0.8$ jet mass: $\beta = 0, 1, 2$

- Higher β implies softer grooming
- Non-perturbative effects less well-modeled

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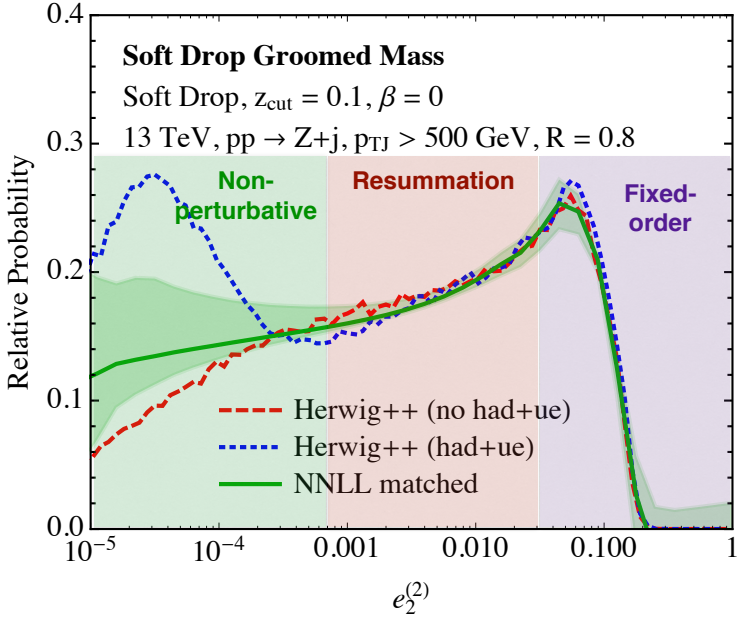

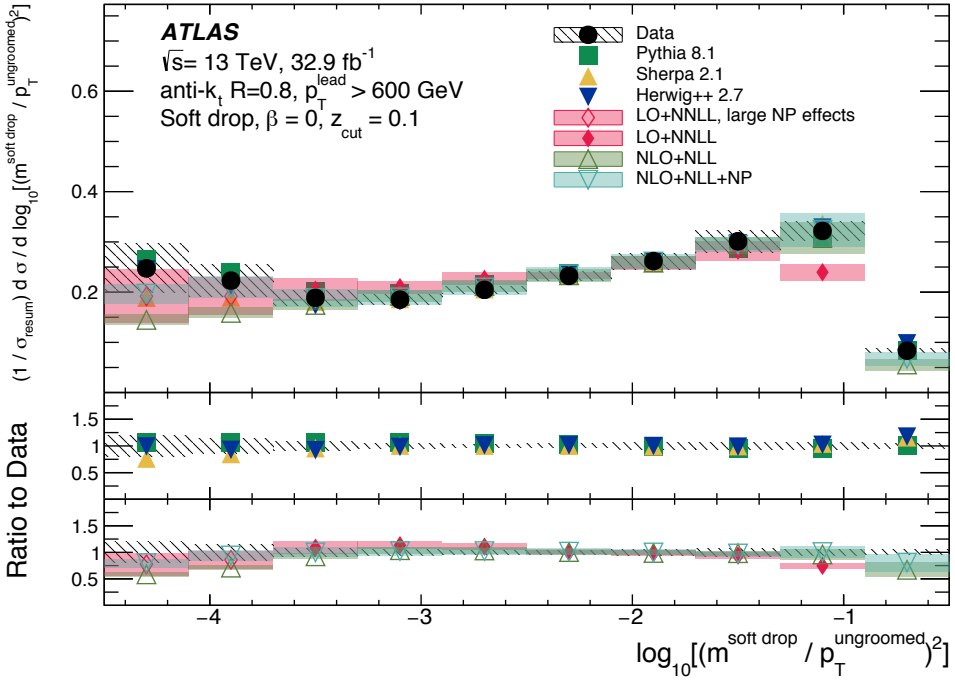

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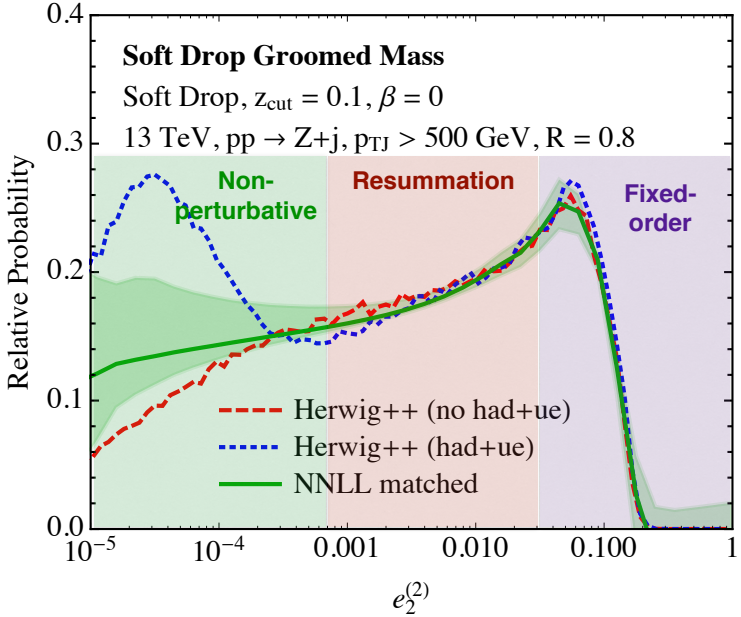

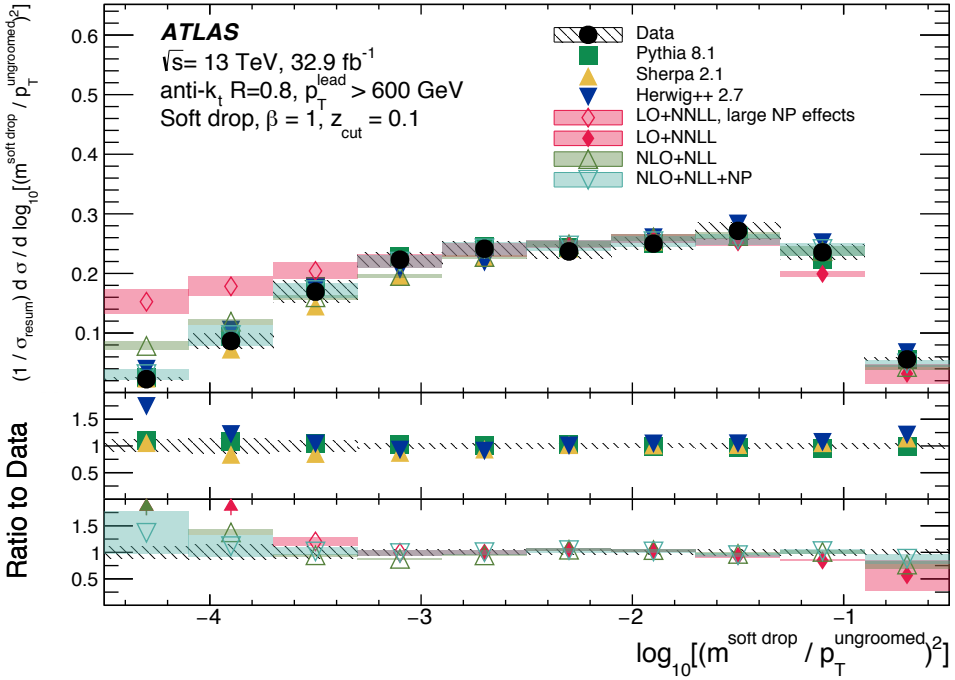

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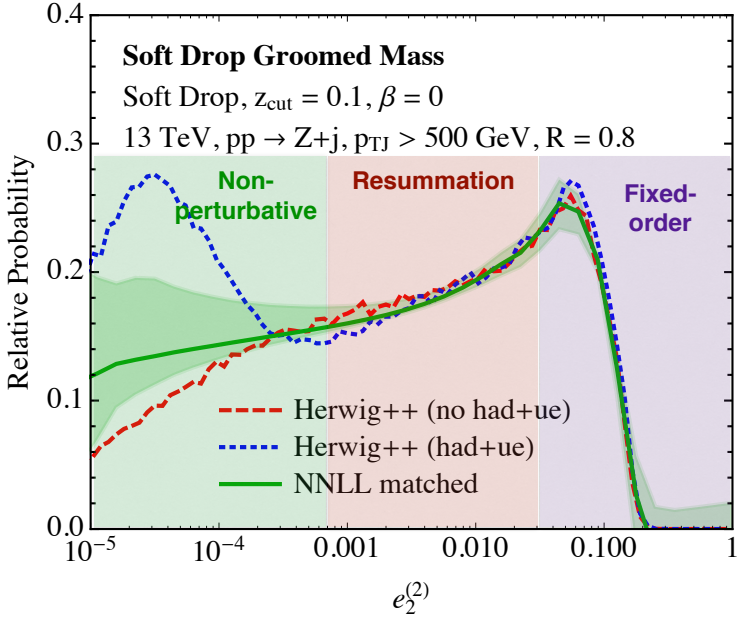

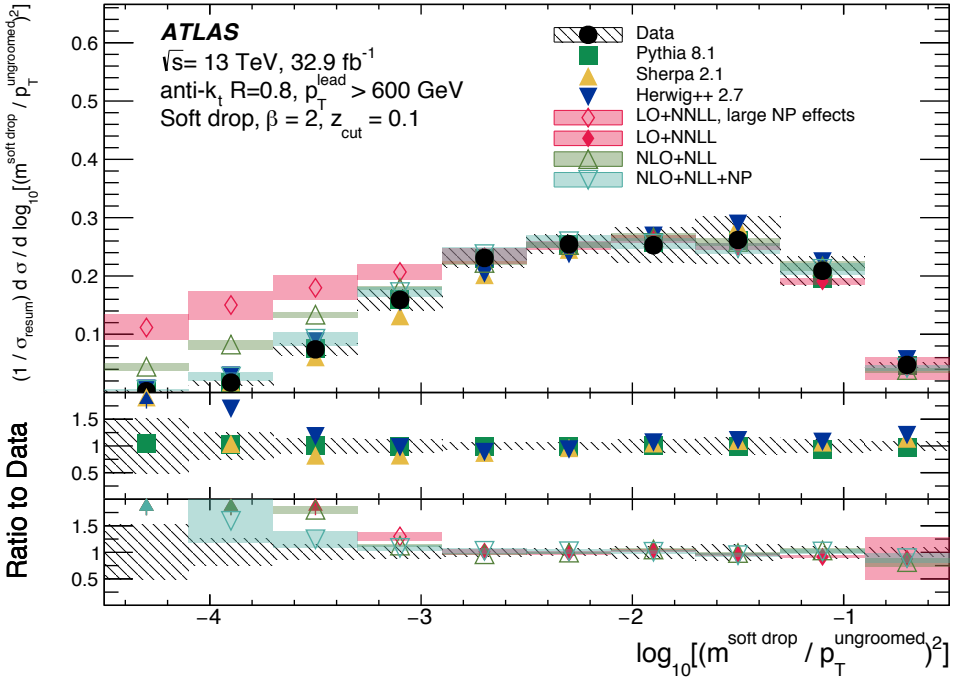

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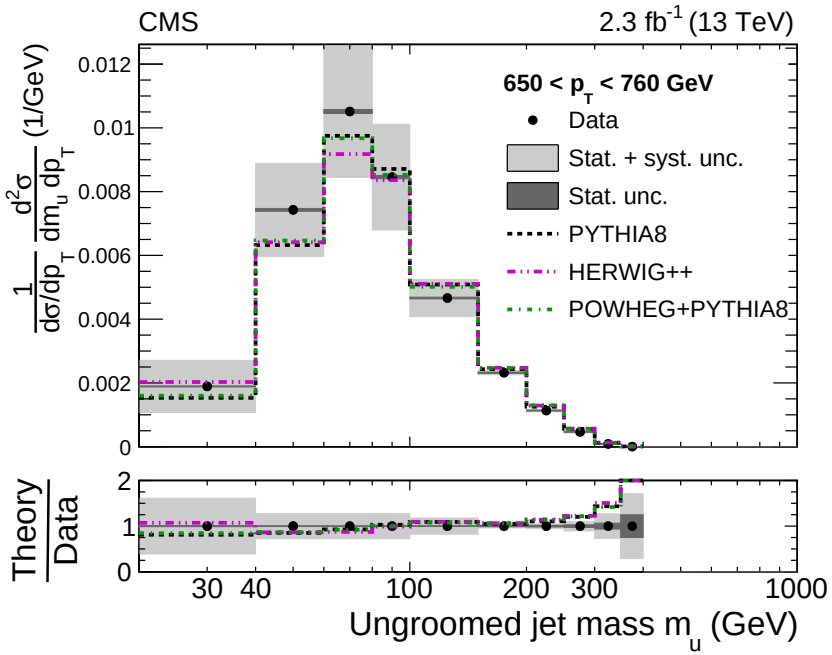
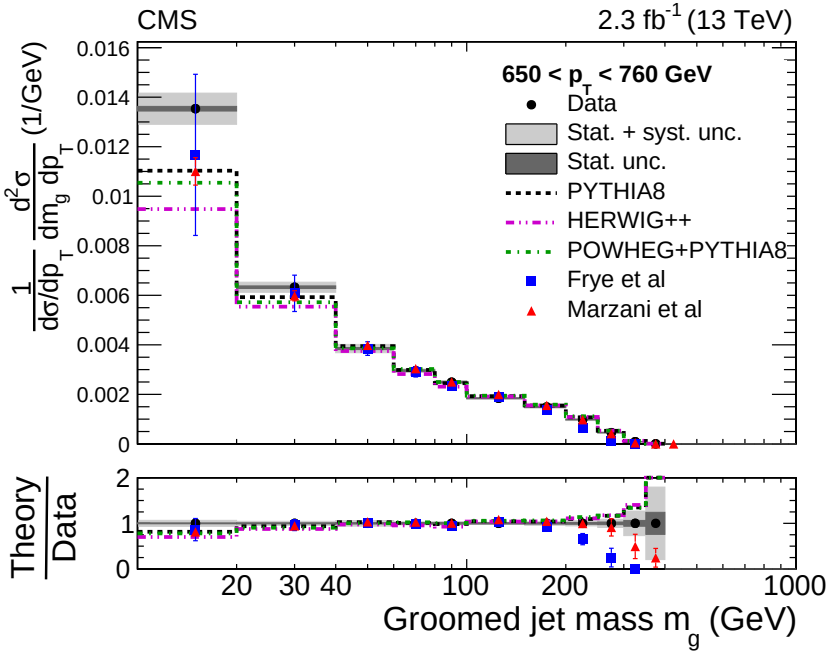
CMS soft drop jet mass measurement

▸ *JHEP 11 (2018) 113* ▸ *(arXiv:1807.05974)*





Ungroomed $R = 0.8$ jet mass

- Higher syst. uncertainty: $\sim$10% vs. $\sim$3%
- Significant Sudakov peak

Soft drop $R = 0.8$ jet mass: $\beta = 0$

- Sudakov peak suppressed
- Similar agreement with MC models

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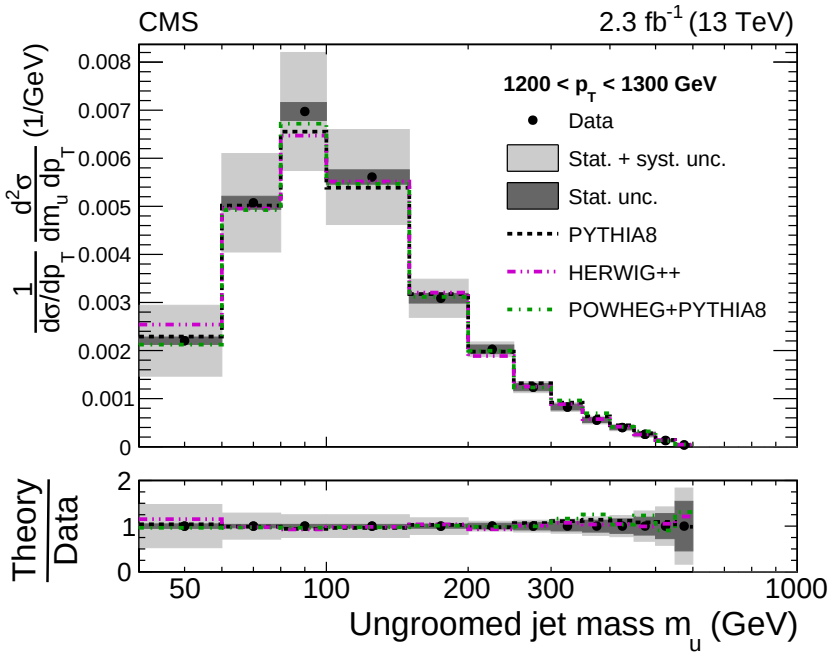

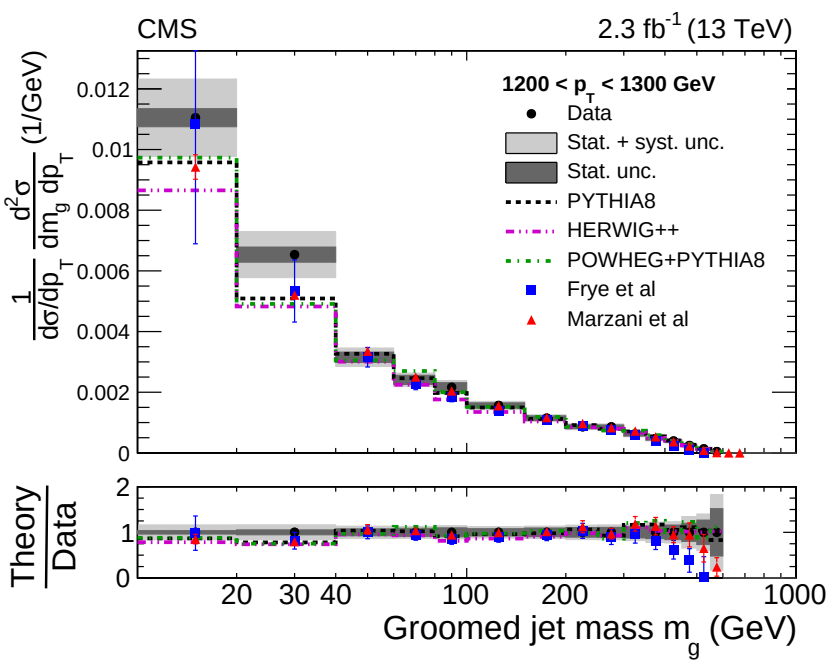

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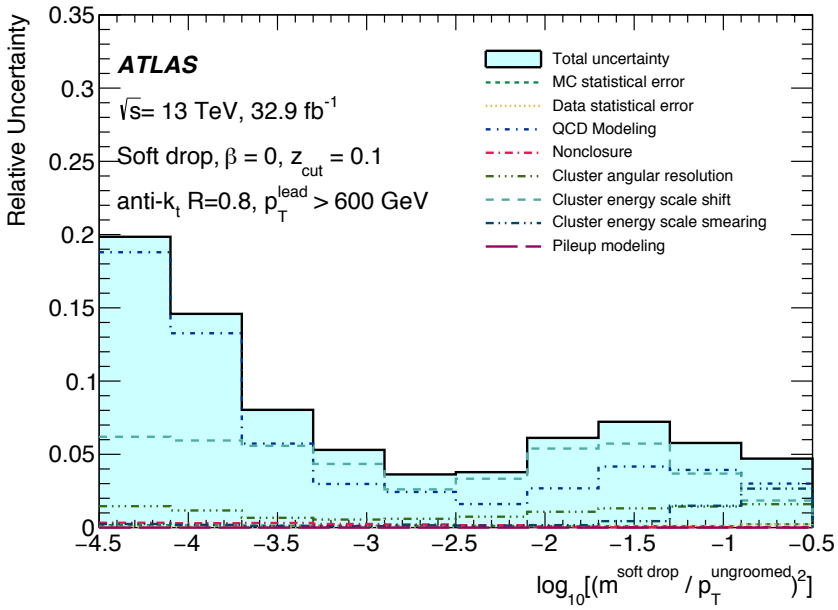
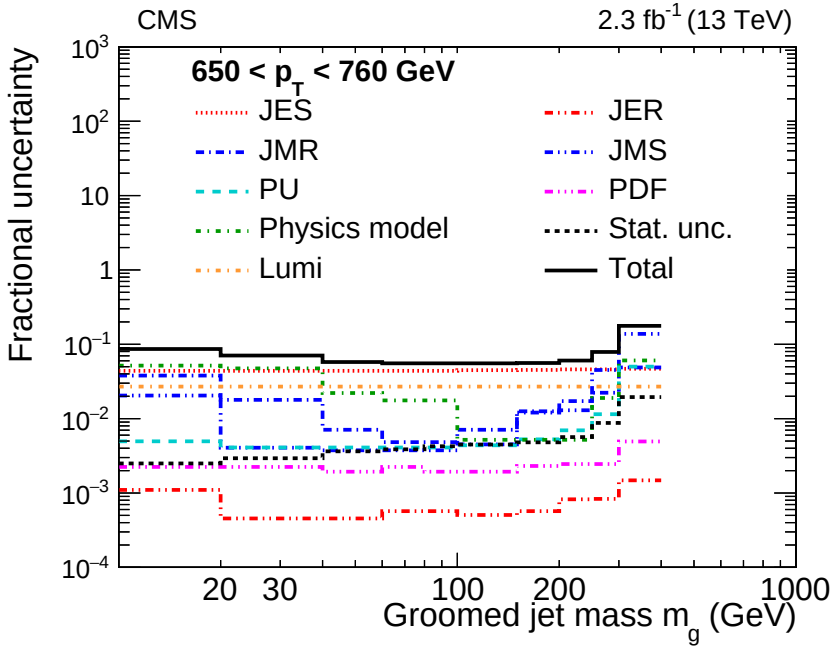
Soft drop jet mass measurement undertainty comparisons





ATLAS uncertainty

- "Bottom-up" uncertainties based on calorimeter clusters and E/p
- Determined in QCD dijet samples

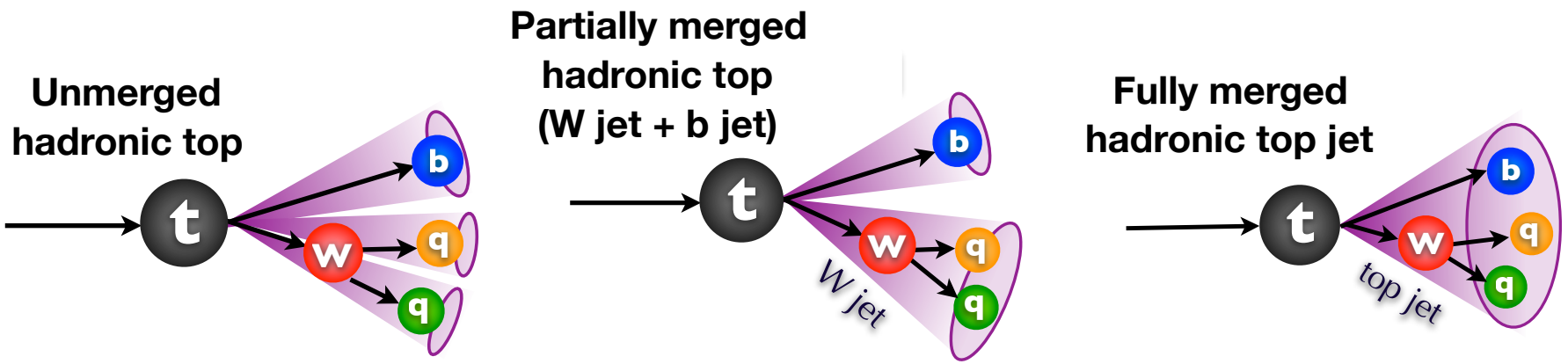
CMS uncertainty

- "Top down" uncertainties based on comparison of W mass peak
- Determined in $t\bar{t}$ samples

ATLAS & CMS jet substructures in $t\bar{t}$ events

▸ *1903.02942 (ATLAS)* ▸ *arXiv:1808.07340 (CMS)* ▸ *1805.02935 (ATLAS)*

Image credit: James Dolen

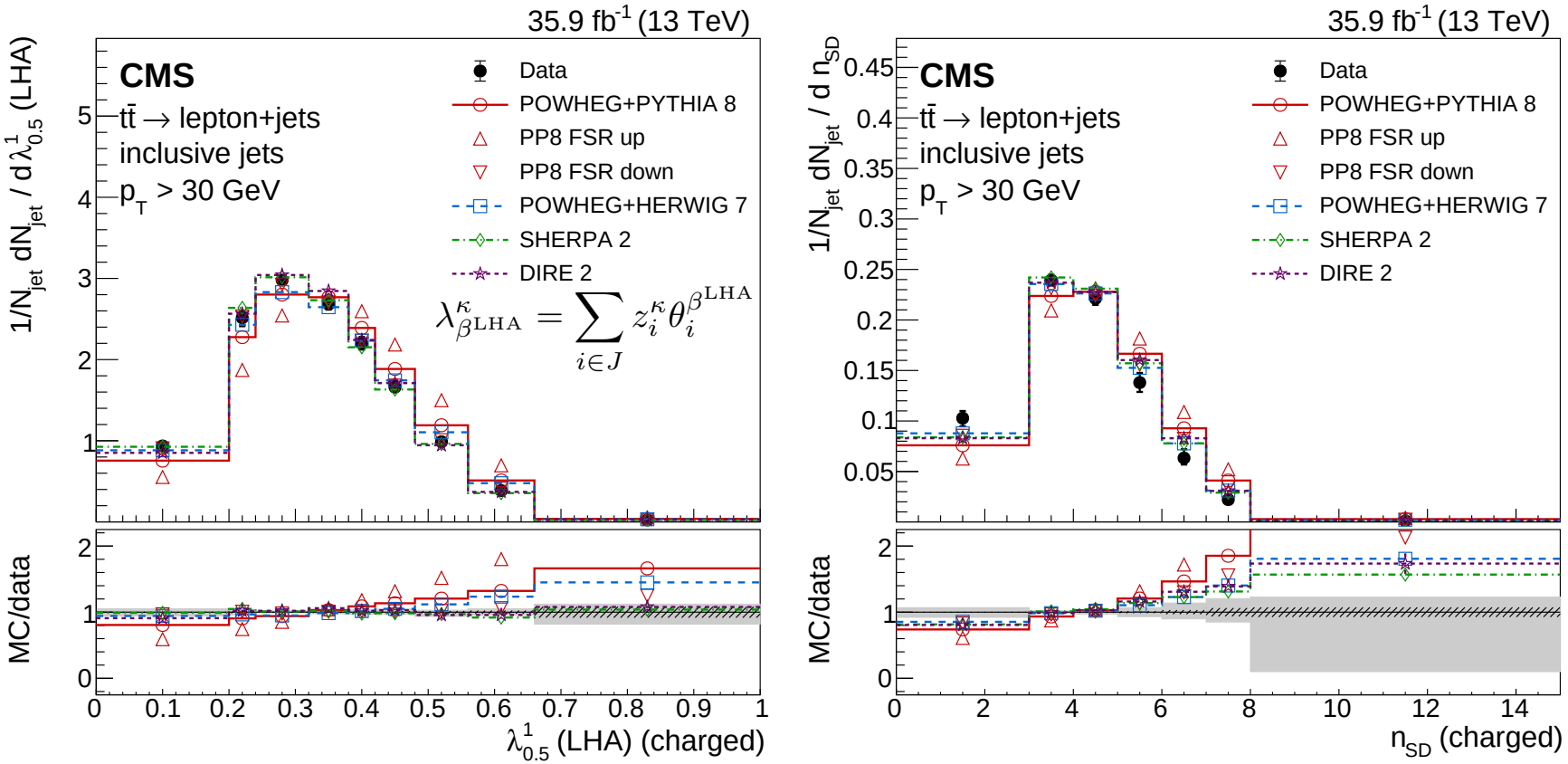


Top quark pair events are an ideal proving ground for measurements of jet substructure

- Plentiful process, and key background for many new physics searches
- High purity, and relatively orthogonal event selection criteria (for lepton+jets samples)
- Multiple jet flavors involved: b, q, g
- Two resonances, W & t, including colorless object

CMS jet substructure measurements in resolved $t\bar{t}$ events

▸ *Phys. Rev. D 98 (2018) 092014* ▸ *arXiv:1808.07340*



Structures of small-radius $R = 0.4$ jets

- IRC safe **angular** and **counting** observables that are sensitive to multi-prong vs. single prong decays
- **Wide-angle** & **high-multiplicity** structures least well-described by MC

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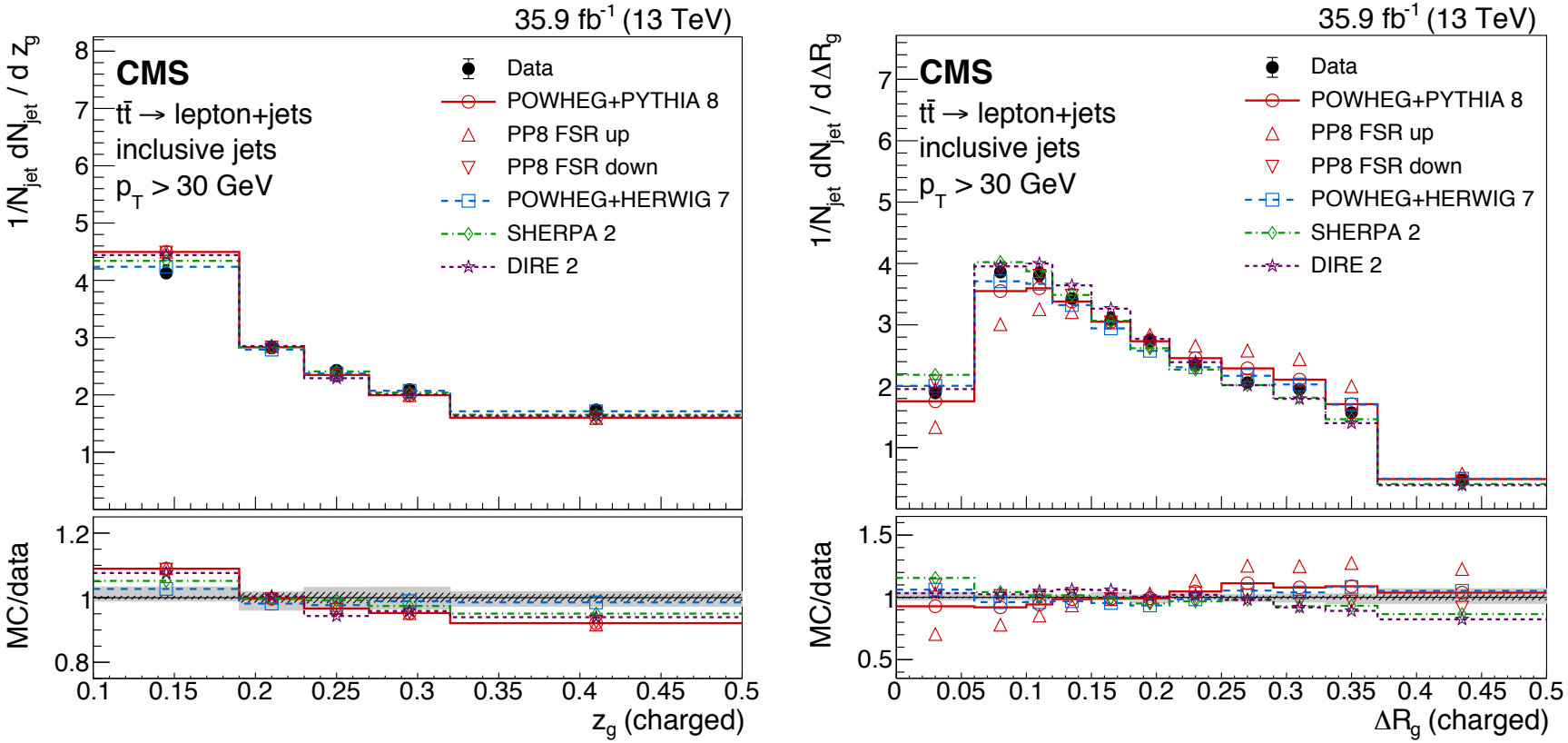

Structures of small-radius $R = 0.4$ jets

- Soft-drop observables delated to **energy partitioning** and **angular structures** are very well-described
- Sensitive to very different physics: **ΔR_g is particularly sensitive to α_S**

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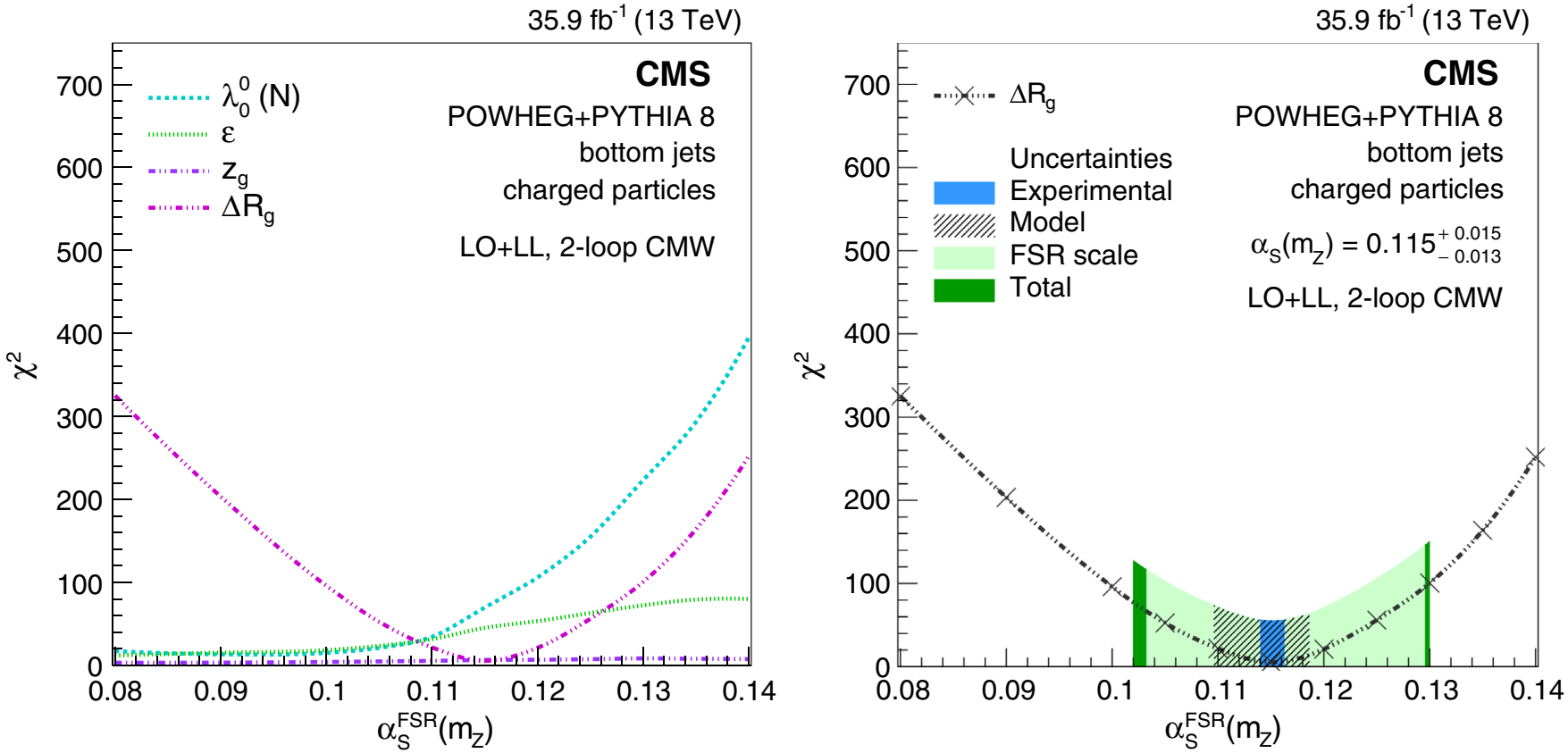


Measurement of α_S from bottom-quarks in $t\bar{t}$ sample

- α_S scan allows for best-fit value $\alpha_S(m_Z) = 0.115^{+0.015}_{-0.013}$
- Dominated by FSR scale uncertainties

ATLAS jet substructure measurements in resolved $t\bar{t}$ events

arXiv:1903.02942

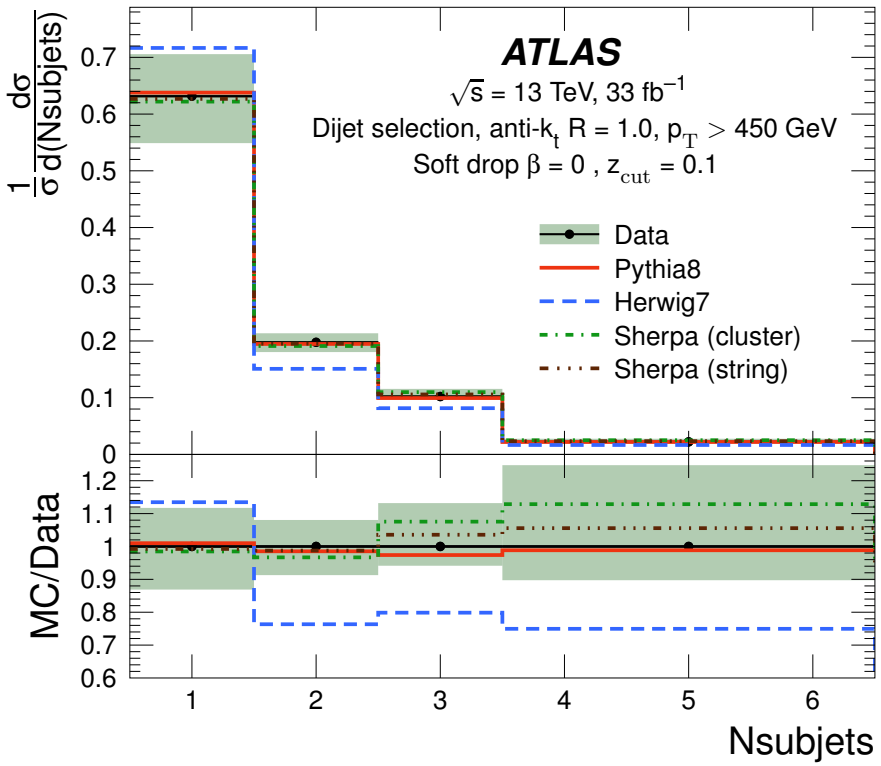
- **Large-radius jet substructure for: W, top, and light quark jets!**:
  - Semi-leptonic selections for W and top jets in $t\bar{t}$ events
  - Dijet selection for light quark jets in QCD events

8 observables for W, top, QCD jets

- **Modeling can differ significantly**
- **Complex angular structures modeled well**
- **N-body structure modeling harder**

Validation regions (VR) are used to confirm the predictions from the CRs.

[Subjet multiplicity]



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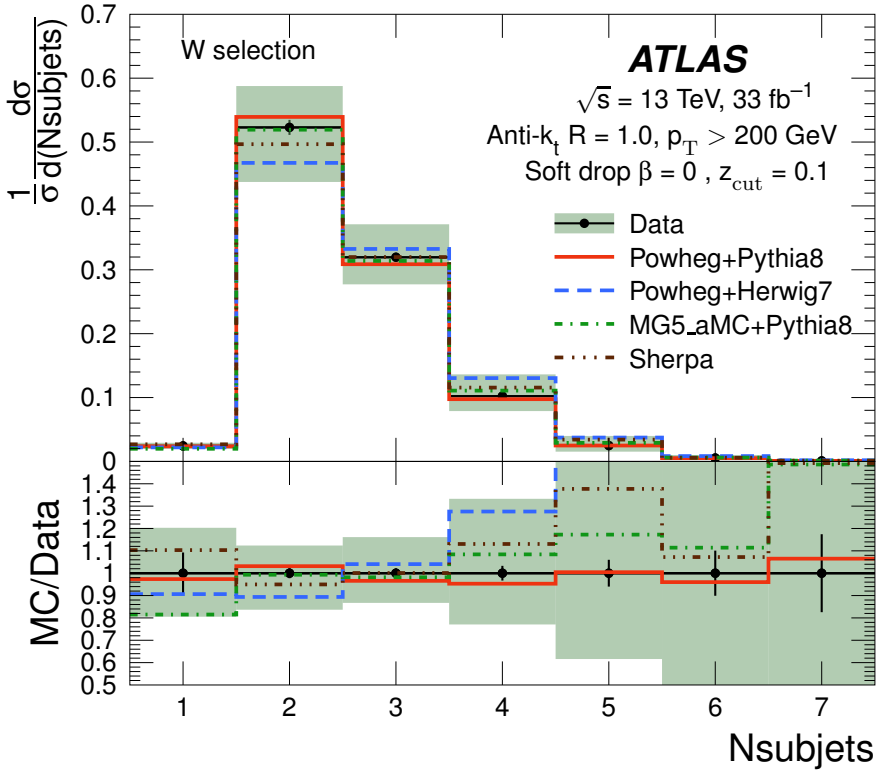

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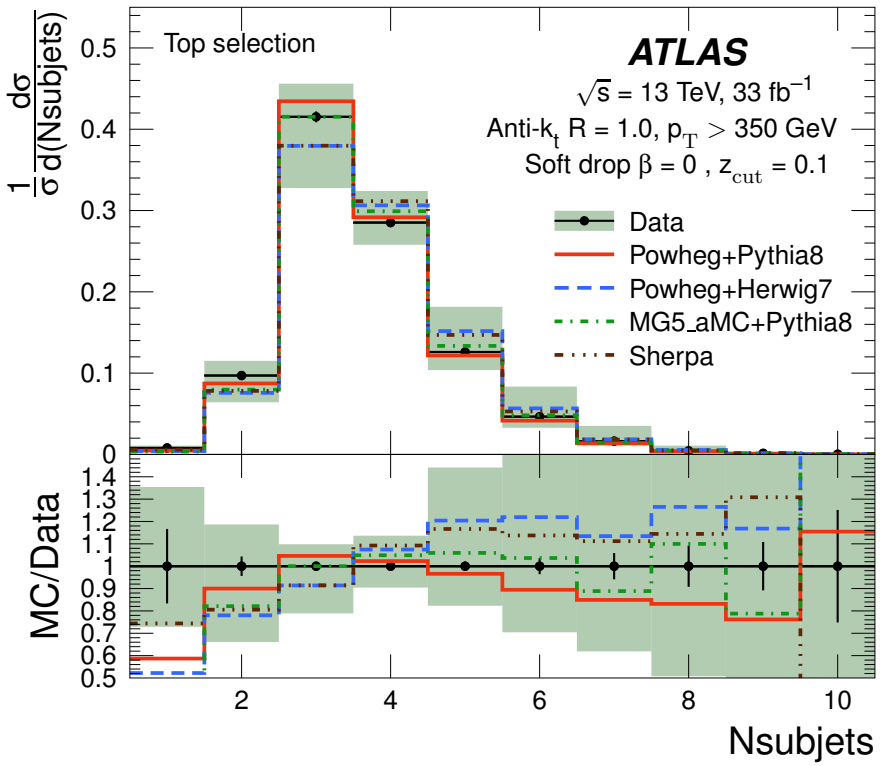

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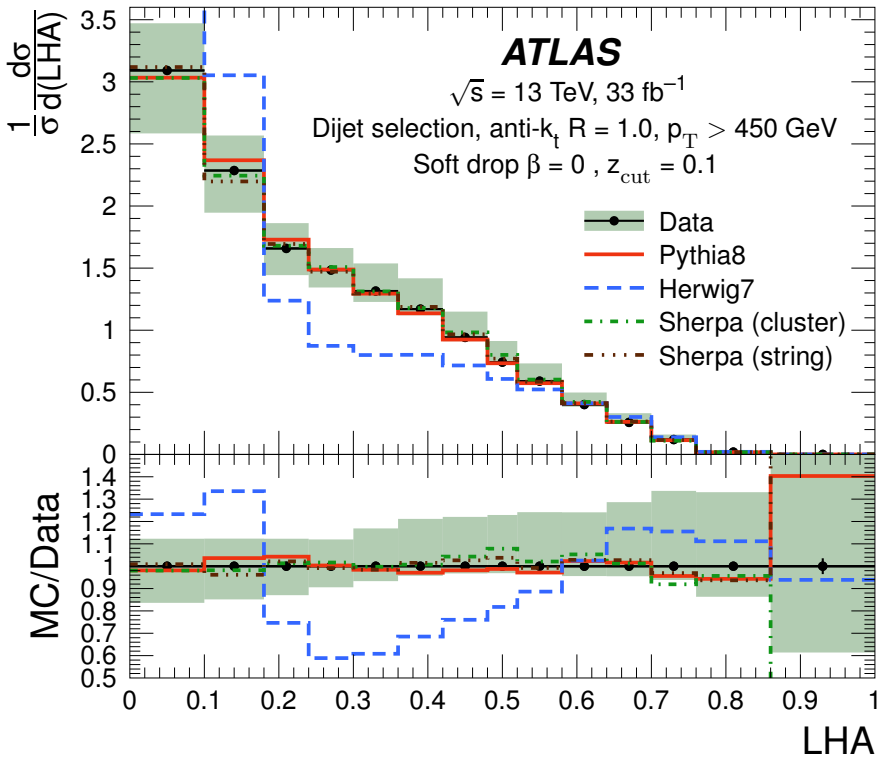

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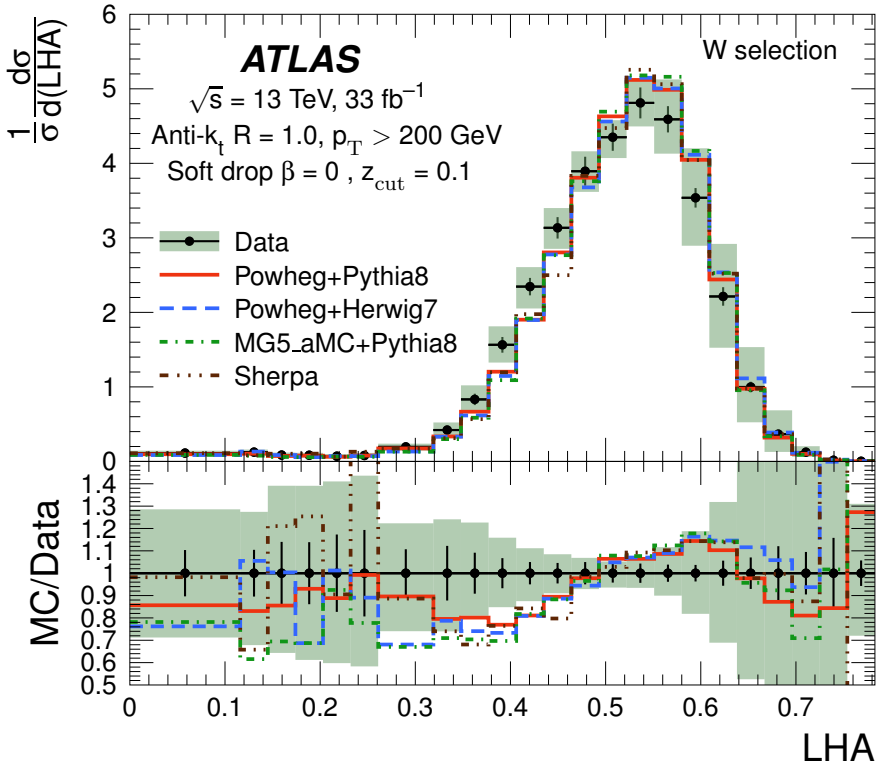

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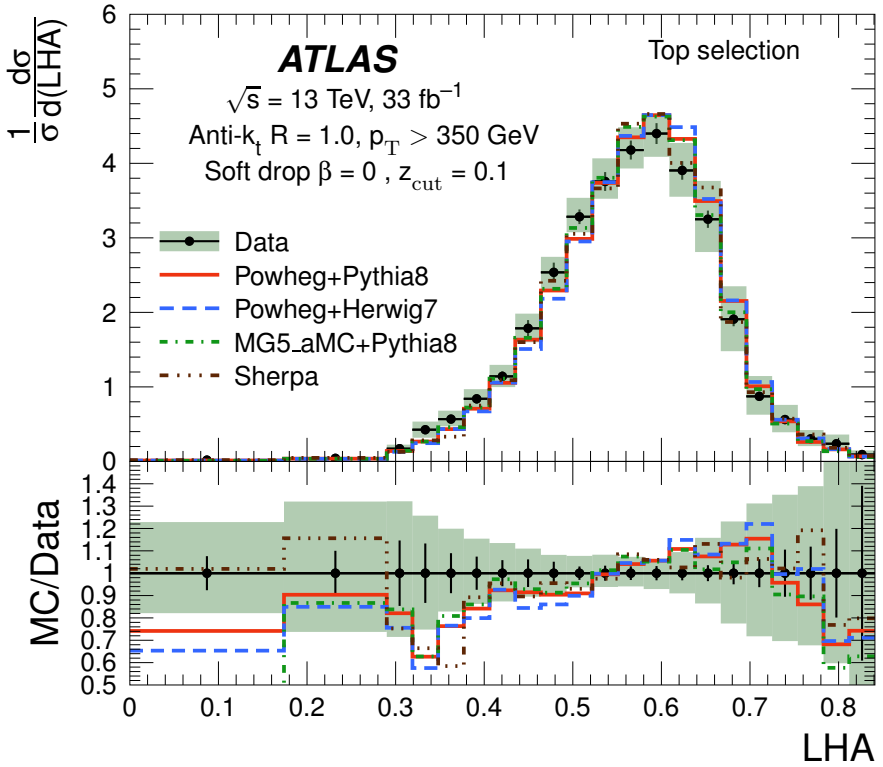

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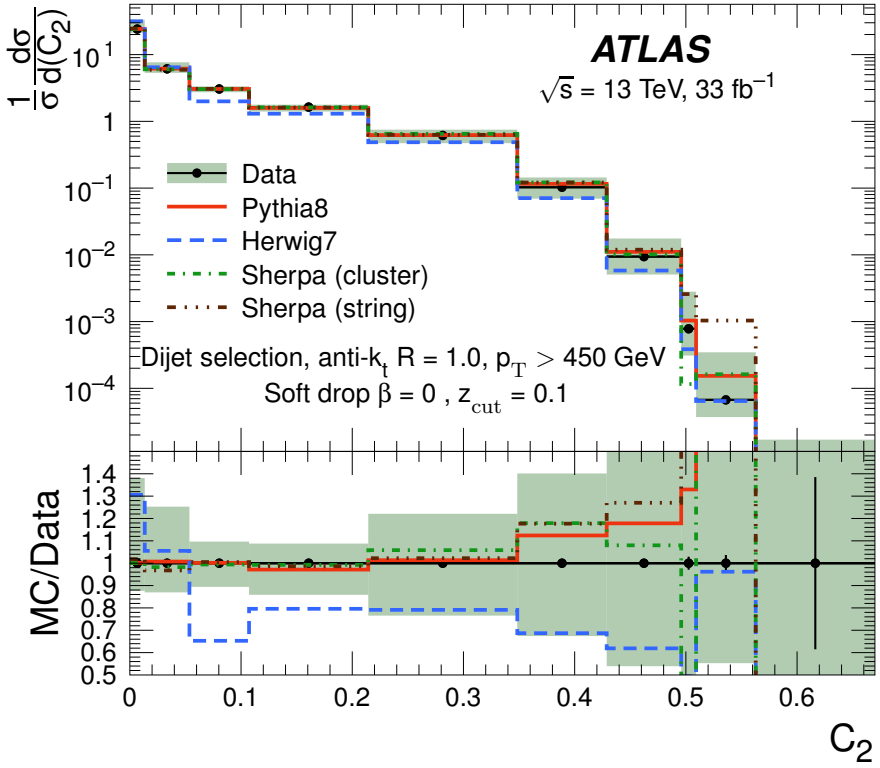

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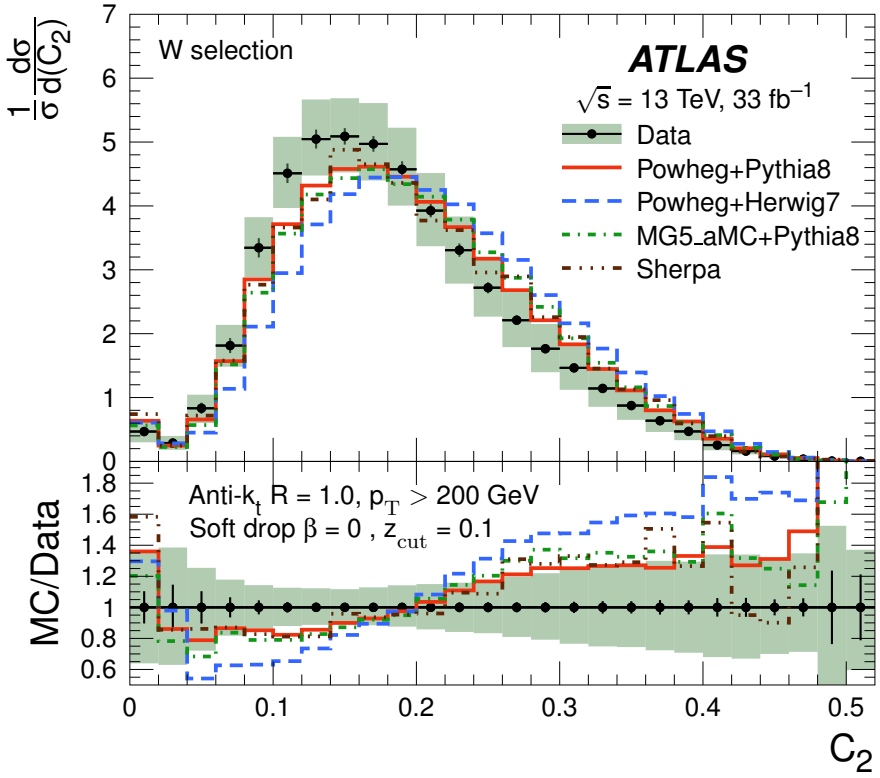

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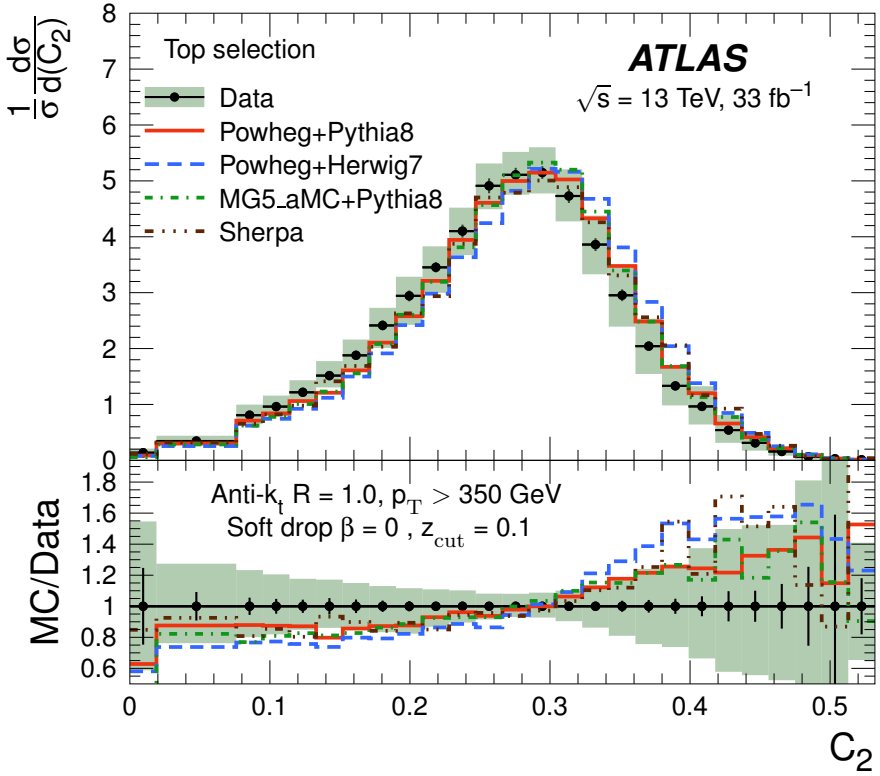

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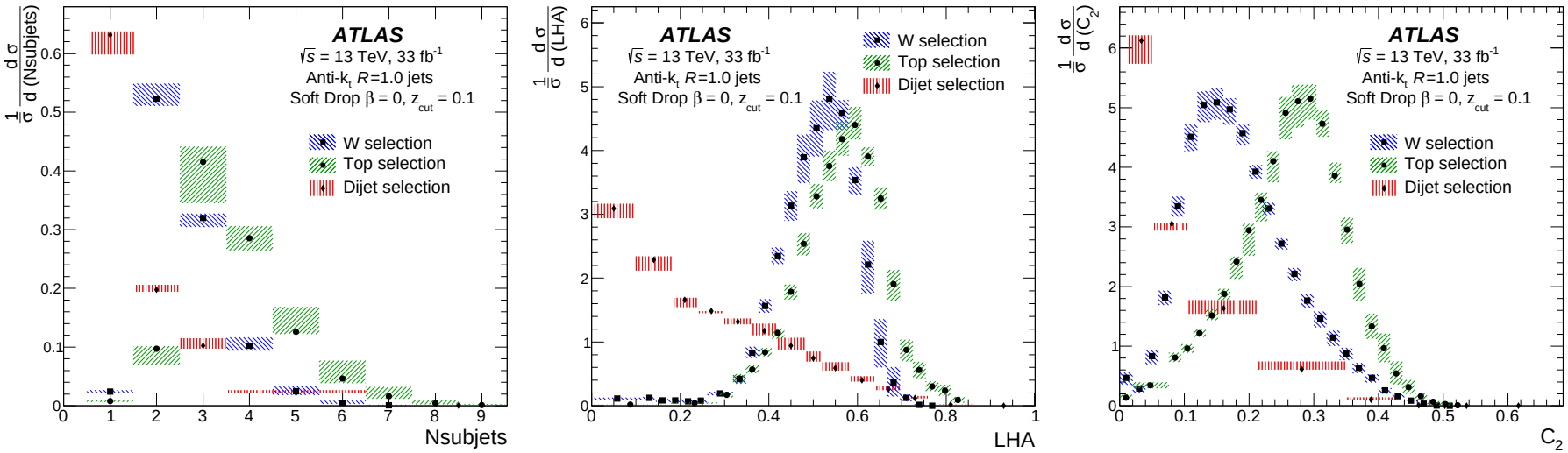
arXiv:1903.02942

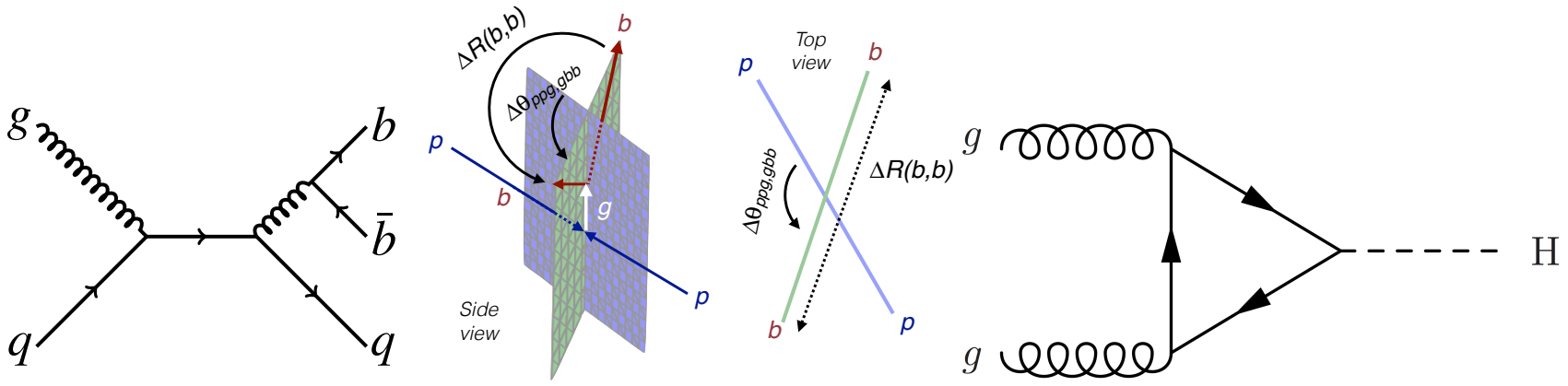


Important discrimination for BSM physics tagging!

- Clear differences in **boosted jet shapes and substructures**
- Many of these are already **used or soon to be used in searches for SUSY** at large masses (and thus with significant Lorentz boosts!)
- Detailed measurements and MC tuning essential for **optimizing physics performance of both measurements and searches**

ATLAS & CMS jet measurements of boosted $b\bar{b}$ final states

arXiv:1812.09283 (ATLAS), *arXiv:1709.05543 (CMS)*



Critical process for deep understanding of Standard Model

- Gluon splitting is a fundamental component of QCD
- Careful measurement required for understanding Higgs couplings
- Backgrounds, calibration, b-tagging, jet substructure all come together

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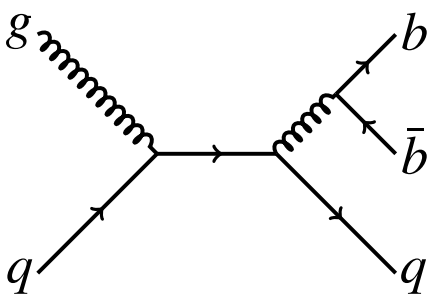
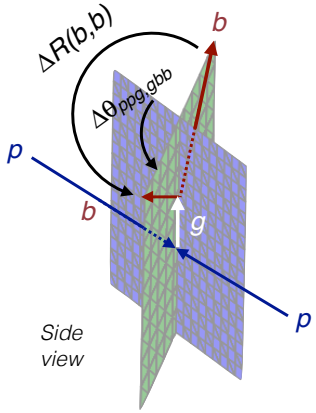
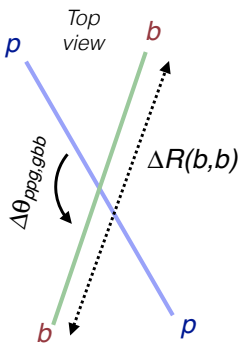
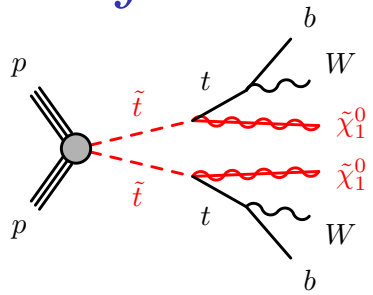
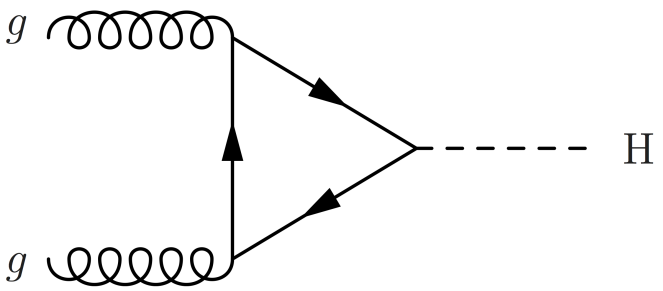








▸ Boosted stops (arXiv:1709.04183)

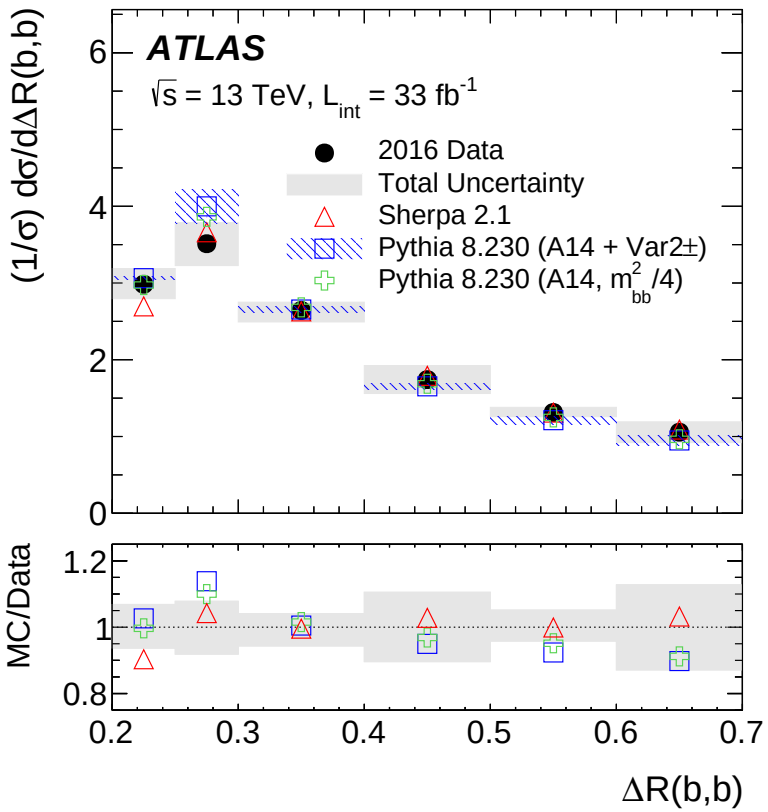


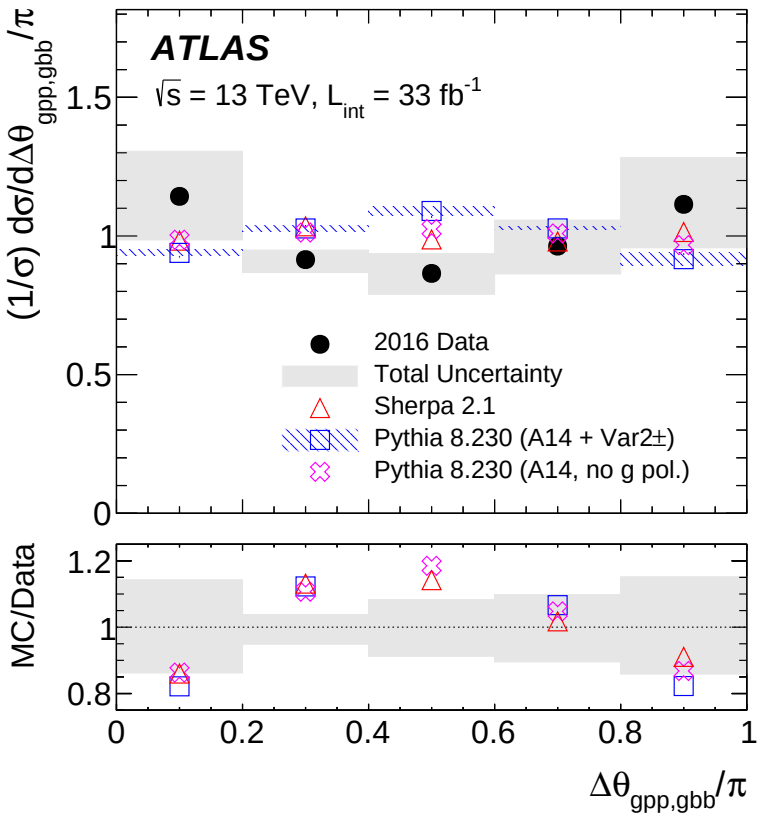
Critical process for deep understanding of Standard Model

- Gluon splitting is a fundamental component of QCD
- Careful measurement required for understanding Higgs couplings
- Backgrounds, calibration, b-tagging, jet substructure all come together
- **Important to constrain difficult bckgs to sophisticated searches!**

ATLAS measurements of $g \to b\bar{b}$

▸ *Phys. Rev. D 99 (2019) 052004* ▸ *(arXiv:1812.09283)*



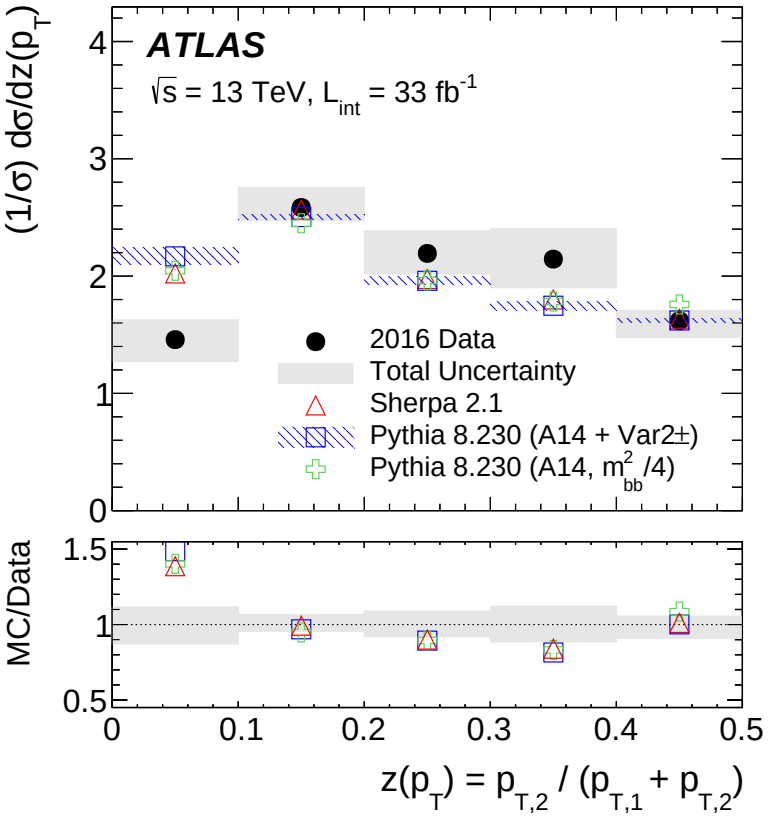


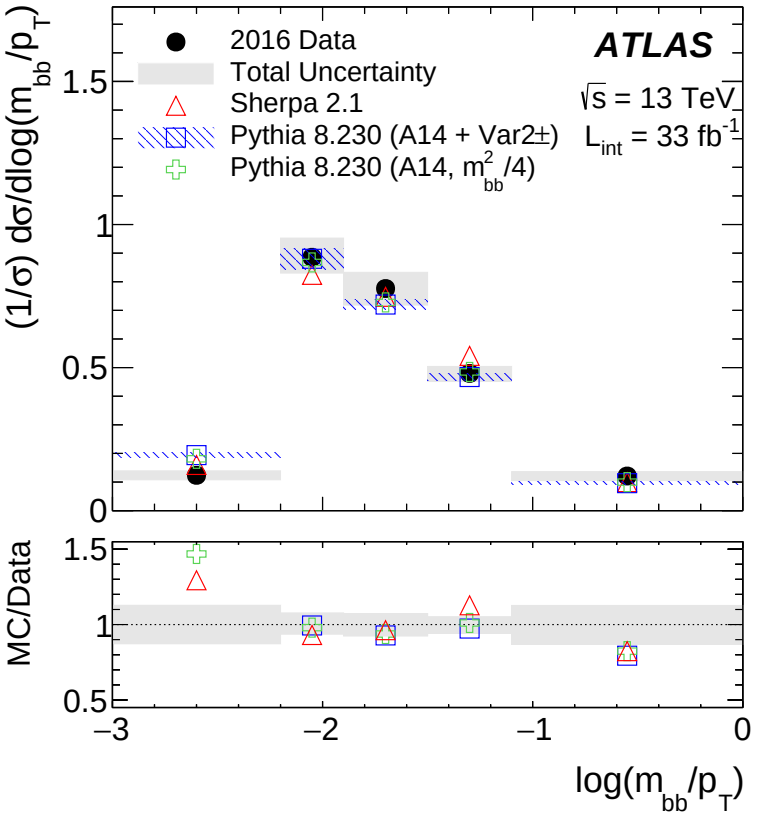
Gluon splitting to $b\bar{b}$ is present in almost any search with $N_{b-\text{jet}} \geq 2$

- Angular properties measured in dedicated sample
- Basic modeling of ΔR is good, but decay plane more difficult

ATLAS measurements of $g \to b\bar{b}$

▸ *Phys. Rev. D 99 (2019) 052004* ▸ *(arXiv:1812.09283)*



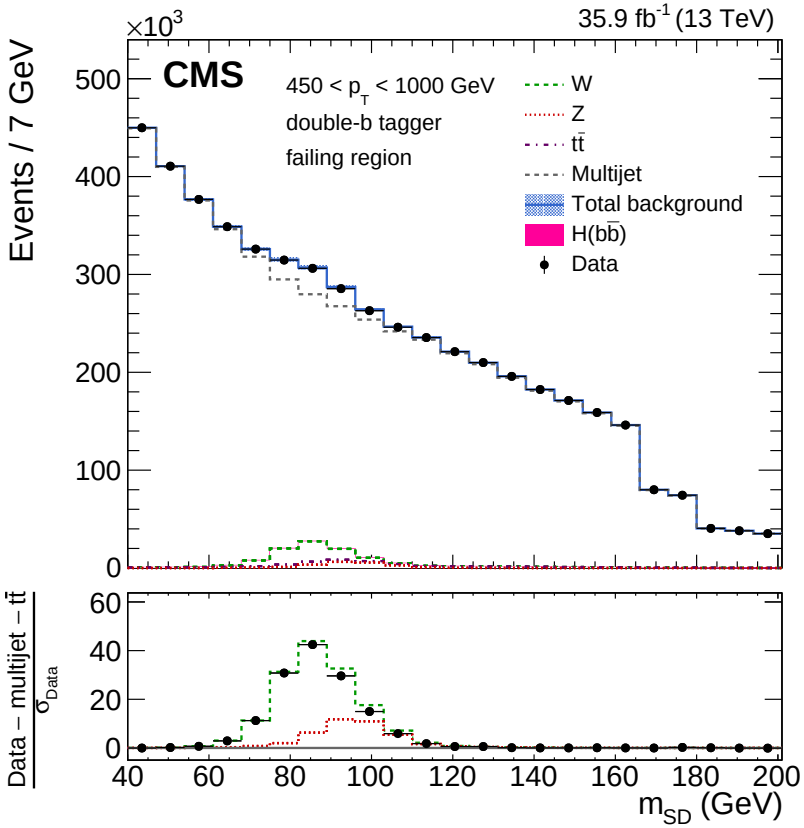


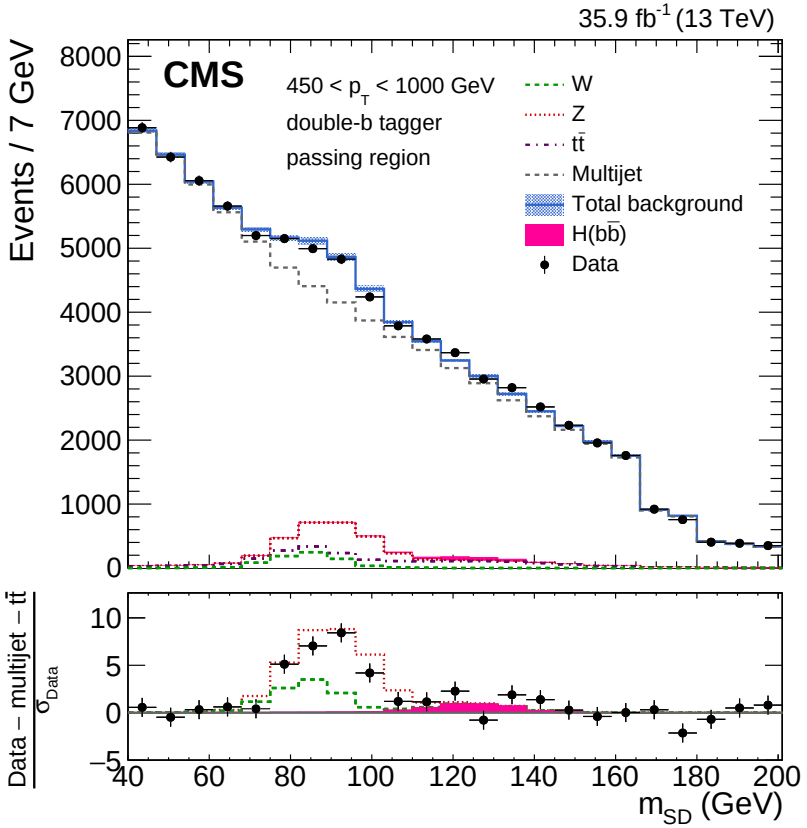
Momentum sharing and invariant mass

- Kinematic measurements extend to the study of the **fragmentation** of the gluon using $z = p_{T,2}/p_{\mathrm{T}}$ and the **invariant mass** of the $b\bar{b}$ system
- Low z and $m_{b\bar{b}}$ exhibit some mismodeling, otherwise good

CMS studies of $Z \to b\bar{b}$

▸ *Phys. Rev. Lett. 120 (2018) 071802* ▸ *(arXiv:1709.05543)*



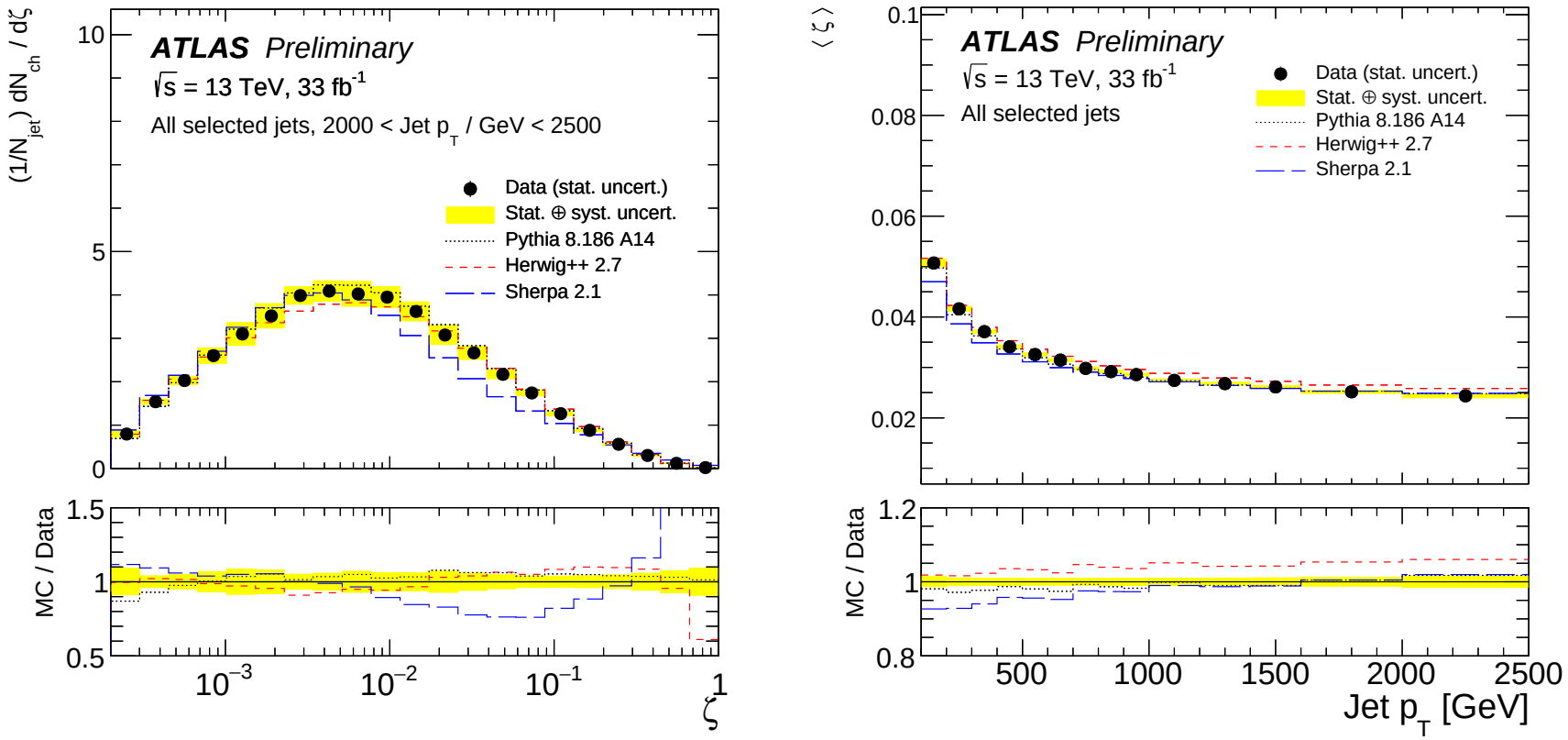


Observation of $Z \to b\bar{b}$

- Impressive & successful $Z \to b\bar{b}$ **observation**
- **Soft-drop grooming** and **energy-energy correlations** critical to mitigating multijet background

ATLAS jet fragmentation measurements: 33 fb^{-1}

STDM-2017-16 *(paper released soon!)*

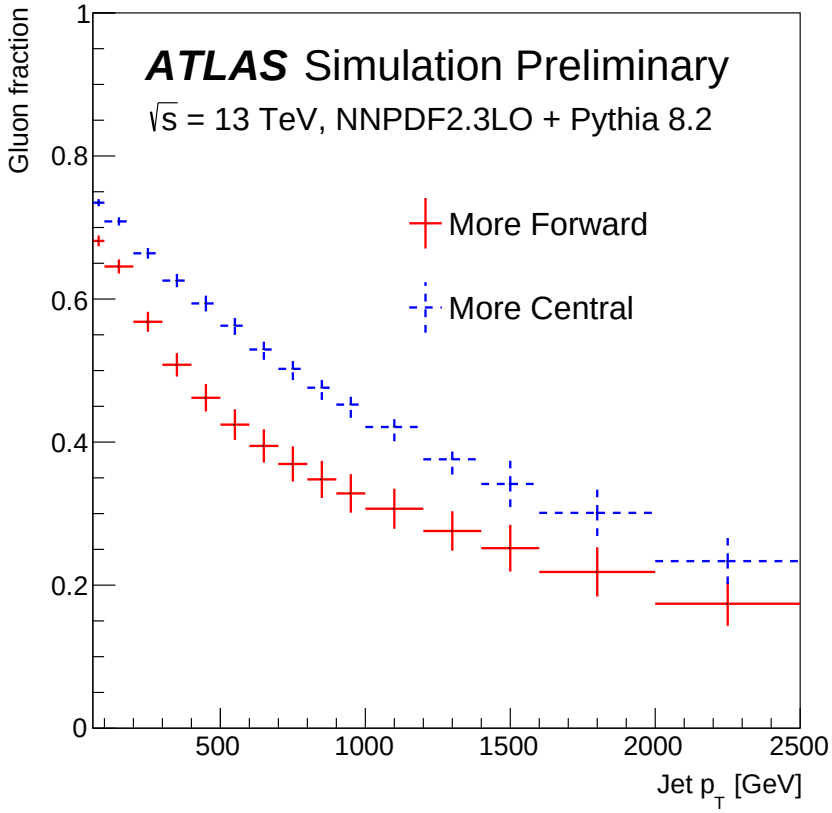


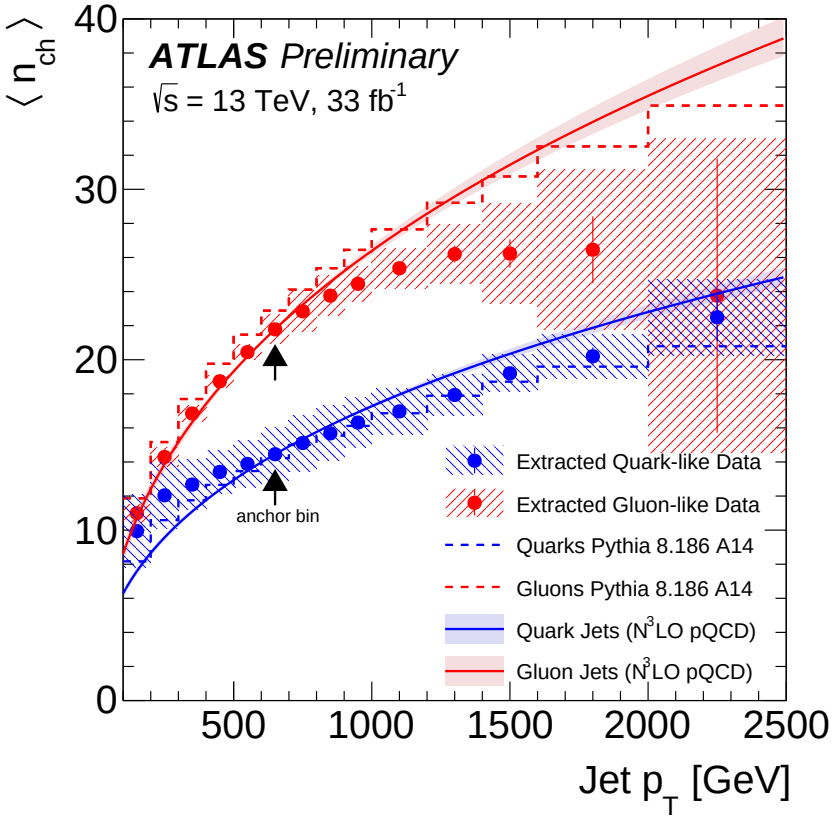
Jet fragmentation function $\zeta = p_{\mathrm{T}}^{\mathrm{particle}} / p_{\mathrm{T}}^{\mathrm{jet}}$

- Measurements up to very high $p_{\mathrm{T}}^{\mathrm{jet}}$: 2–2.5 TeV
- Tuned `PYTHIA` and `Herwig++` model data well, `Sherpa` less so

ATLAS jet fragmentation measurements

▸ *STDM-2017-16* *(paper released soon!)*





Charged particle multiplicity in forward vs. central dijets

- Rapidity used to isolate **quark-like vs. gluon-like "topics"**.

Summary and conclusions

- **New physics searches with sensitive hadronic final state observables based on jet substructure are pushing sensitivities well above 2 TeV**
- **Detailed measurements of both QCD and EWK processes of the SM needed**
  - Interesting in their own right to shed light on the SM in extreme regions of phase space
  - Improve search sensitivity by demonstrating robustness, systematics, and MC modeling issues
- **Extensive jet substructure and properties measurement campaign to expand with Run 2 data and Run 3**
  - Rarer QCD and QCD+EWK processes now accessible
  - Needed for Higgs physics program as well as search program

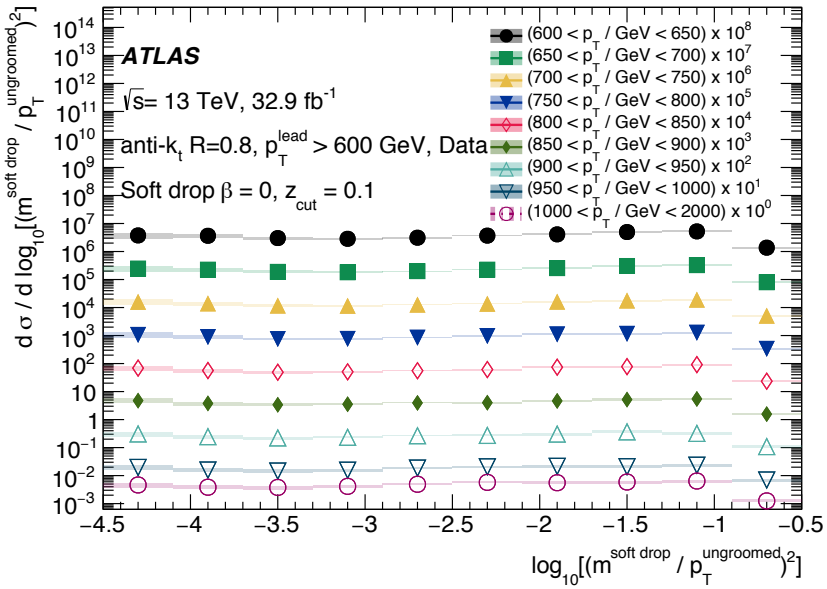
Additional Material

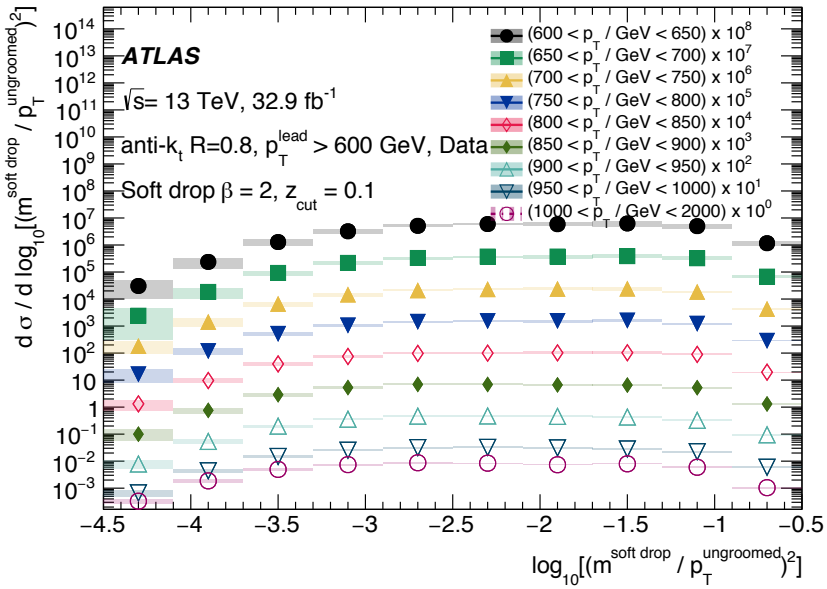
Outline

4. *Backup slides and additional information*
   - ATLAS soft drop jet mass measurement
   - CMS soft drop jet mass measurement
   - ATLAS jet substructure measurements in $t\bar{t}$ events
   - CMS jet substructure measurements in $t\bar{t}$ events
   - ATLAS measurements of jet fragmentation

ATLAS soft drop jet mass measurement

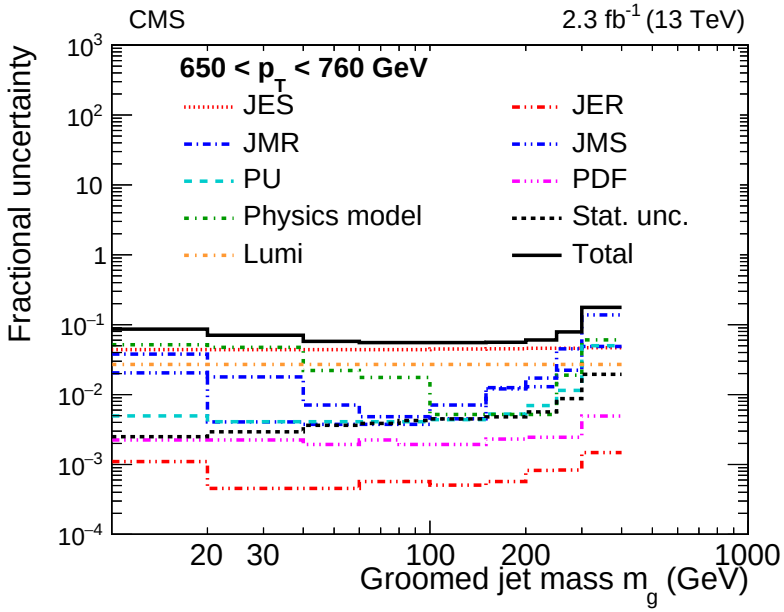
- *Phys. Rev. Lett. 121 (2018) 092001*
- *(arXiv:1711.08341)*

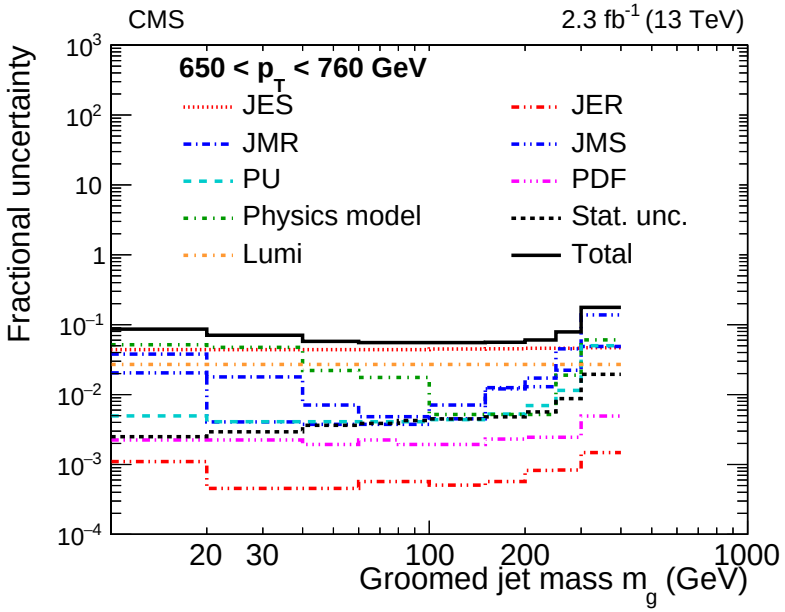




CMS soft drop jet mass measurement

▸ *JHEP 11 (2018) 113* ▸ *(arXiv:1807.05974)*





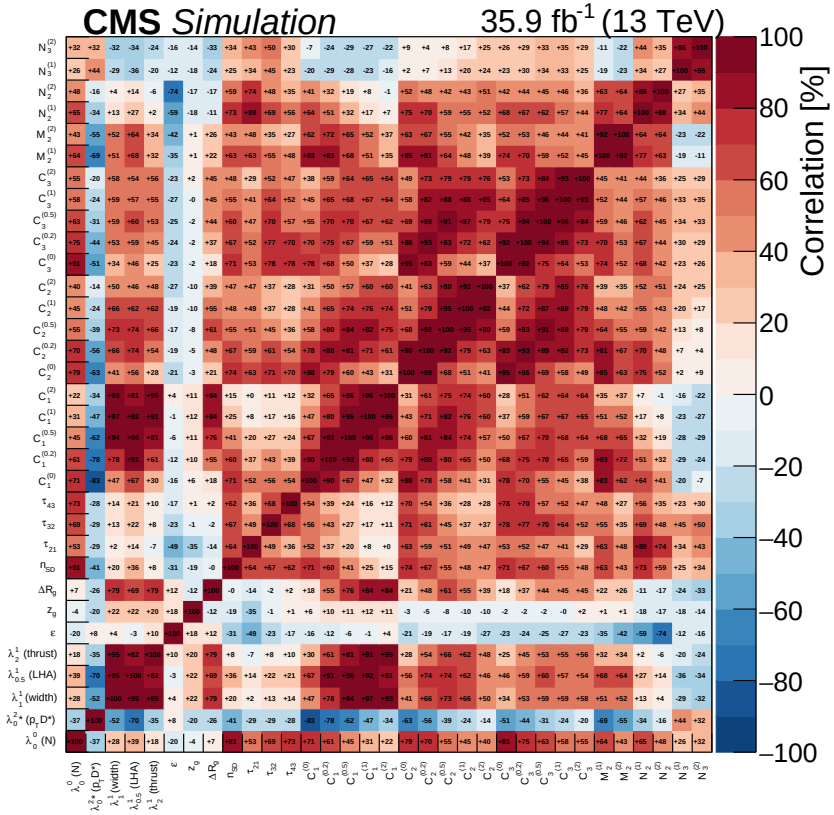
ATLAS jet substructure measurements in resolved $t\bar{t}$ events

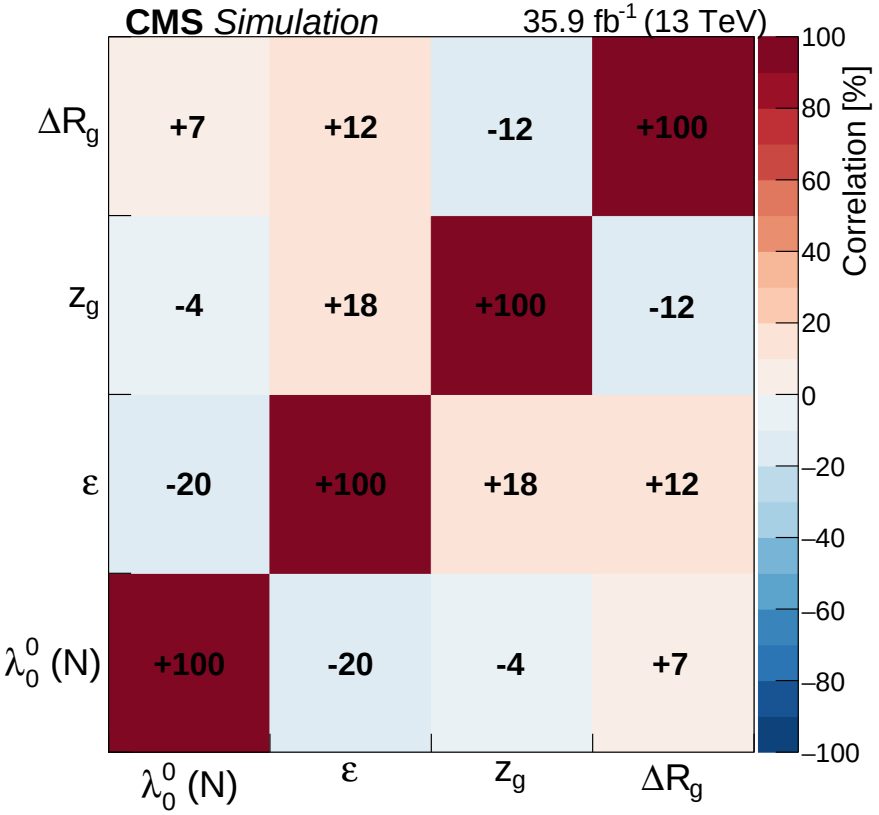
▸ *arXiv:1903.02942*

	Detector level	Particle level
Dijet selection:		
Two trimmed anti-k_t $R = 1.0$ jets	$p_{\mathrm{T}} > 200$ GeV $\lvert\eta\rvert < 2.5$	$p_{\mathrm{T}} > 200$ GeV $\lvert\eta\rvert < 2.5$
Leading-p_{T}trimmed anti-k_t $R = 1.0$ jet	$p_{\mathrm{T}} > 450$ GeV	
Top and W selections:		
Exactly one muon	$p_{\mathrm{T}} > 30$ GeV $\lvert\eta\rvert < 2.5$ $\lvert z_0 \sin(\theta)\rvert < 0.5$ mm and $\lvert d_0/\sigma(d_0)\rvert < 3$	$p_{\mathrm{T}} > 30$ GeV $\lvert\eta\rvert < 2.5$
Anti-k_t $R = 0.4$ jets	$p_{\mathrm{T}} > 25$ GeV $\lvert\eta\rvert < 4.4$ JVT output > 0.5 (if $p_{\mathrm{T}} < 60$ GeV)	$p_{\mathrm{T}} > 25$ GeV $\lvert\eta\rvert < 4.4$
Muon isolation criteria	If $\Delta R(\mu, \mathrm{jet}) < 0.04 + 10$ GeV $/p_{\mathrm{T},\mu}$: muon is removed, so the event is discarded	None
$E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{T}}^{\mathrm{W}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV , $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{\mathrm{W}} > 60$ GeV	
Leptonic top	At least one small-radius jet with $0.4 < \Delta R(\mu, \mathrm{jet}) < 1.5$	
Top selection:		
Leading-p_{T}trimmed anti-k_t $R = 1.0$ jet	$\lvert\eta\rvert < 1.5$, $p_{\mathrm{T}} > 350$ GeV , mass > 140 GeV $\Delta R(\mathrm{large-radius\ jet}, b\text{-tagged jet}) < 1$ $\Delta\phi(\mu, \mathrm{large-radius\ jet}) > 2.3$	
W selection:		
Leading-p_{T}trimmed anti-k_t $R = 1.0$ jet	$\lvert\eta\rvert < 1.5$, $p_{\mathrm{T}} > 200$ GeV , mass > 60 GeV and mass < 100 GeV $1 < \Delta R(\mathrm{large-radius\ jet}, b\text{-tagged jet}) < 1.8$ $\Delta\phi(\mu, \mathrm{large-radius\ jet}) > 2.3$	

CMS jet substructure measurements in resolved $t\bar{t}$ events

▸ *Phys. Rev. D 98 (2018) 092014* ▸ *(arXiv:1808.07340)*



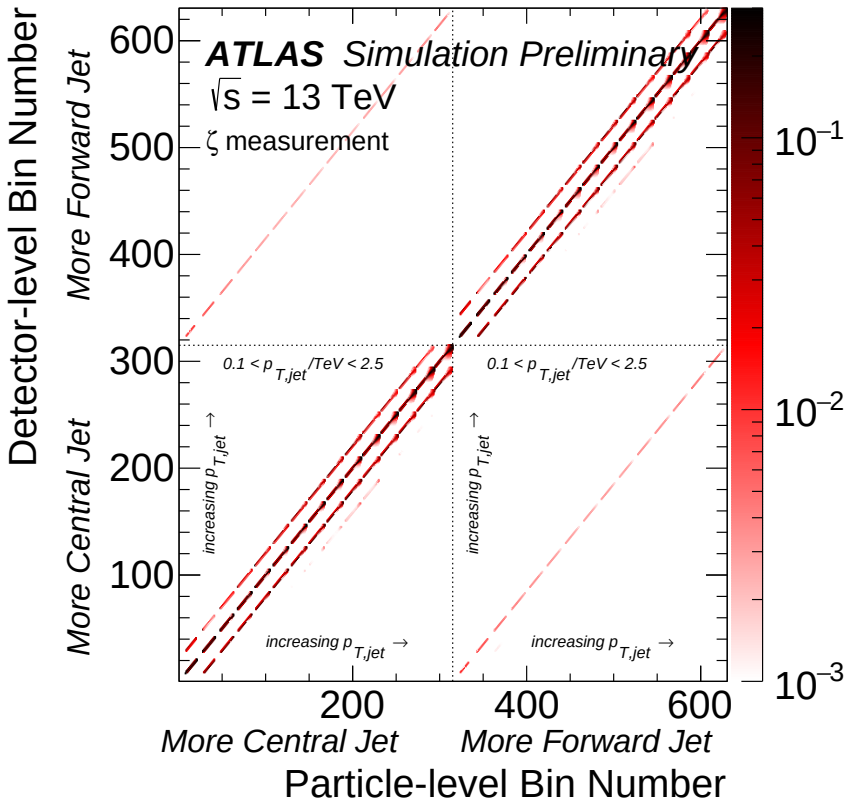


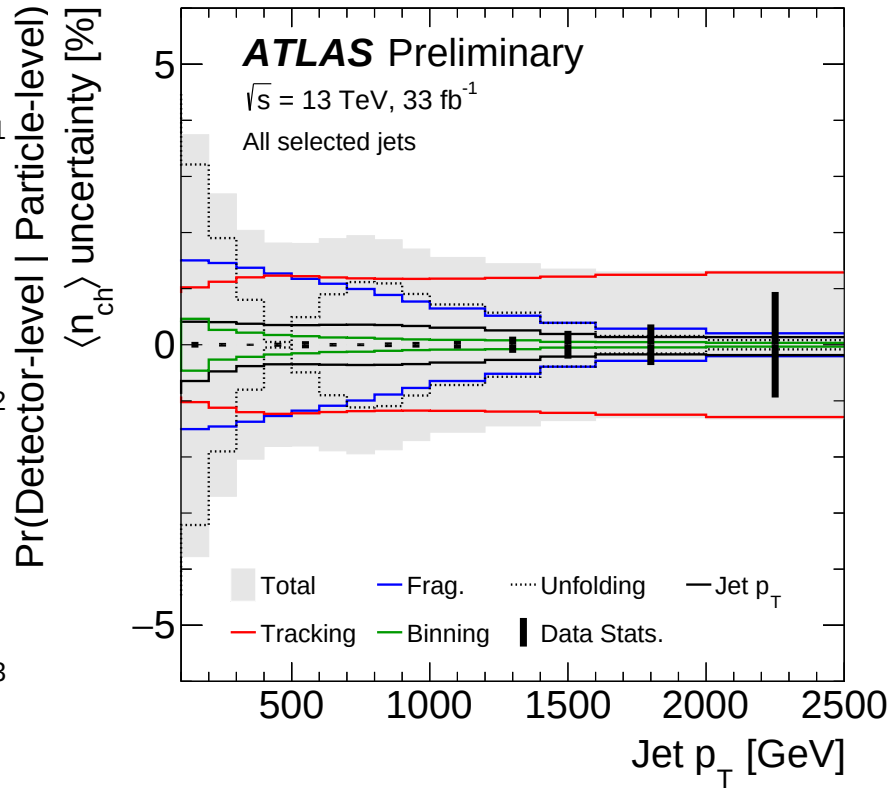
Correlations of jet substructure observables

- Deciding on observables to use in search is complex, understanding the correlations among them can be an important consideration
- Systematic uncertainties & complexity of results also important

ATLAS jet fragmentation measurements

STDM-2017-16 *(paper released soon!)*





- Excellent experimental control of charged particle measurements
- Systematic uncertainties at the level of 1–2%

ATLAS jet fragmentation measurements

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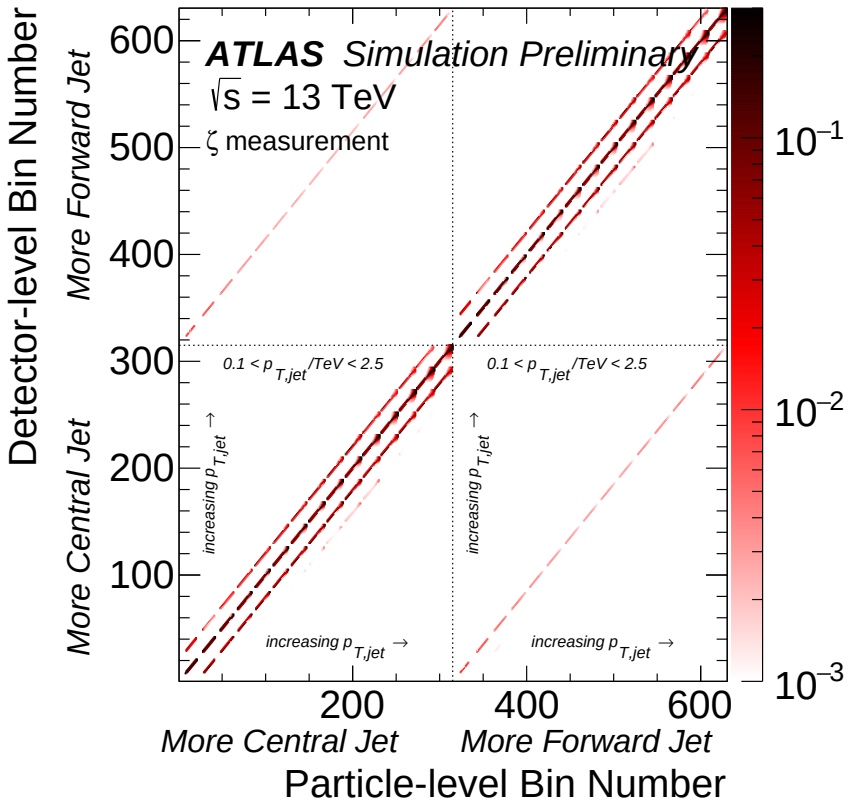

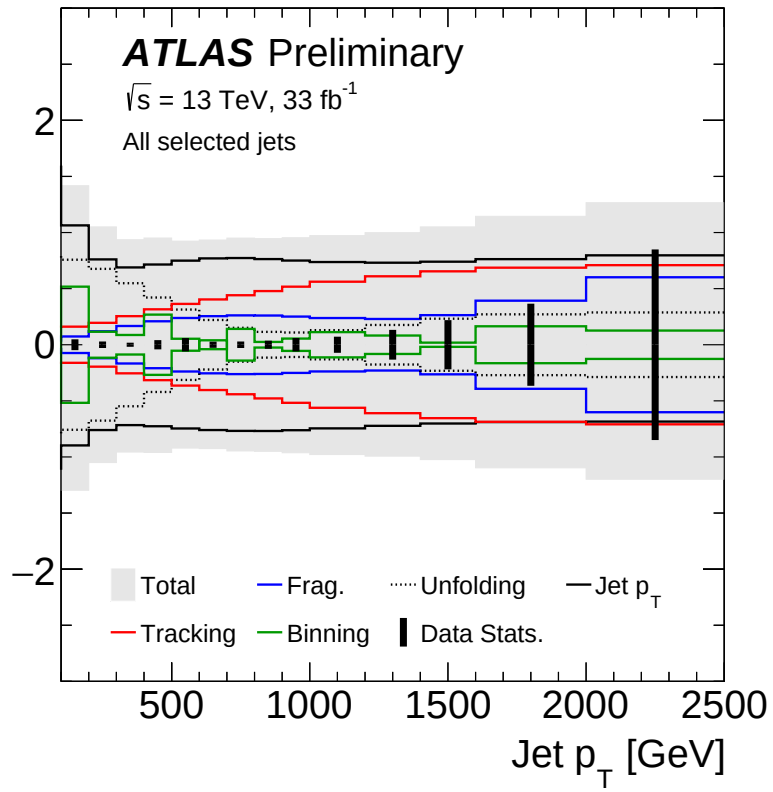

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