BOOST Experimental Summary

Genova 2024

Jennifer Roloff

DISCLAIMERS

The future is here

We've come so far, and BOOST is everywhere

Zooming in

It's all about the details

Making the most of it

Using everything we have

Understanding the space

There's so much more to explore

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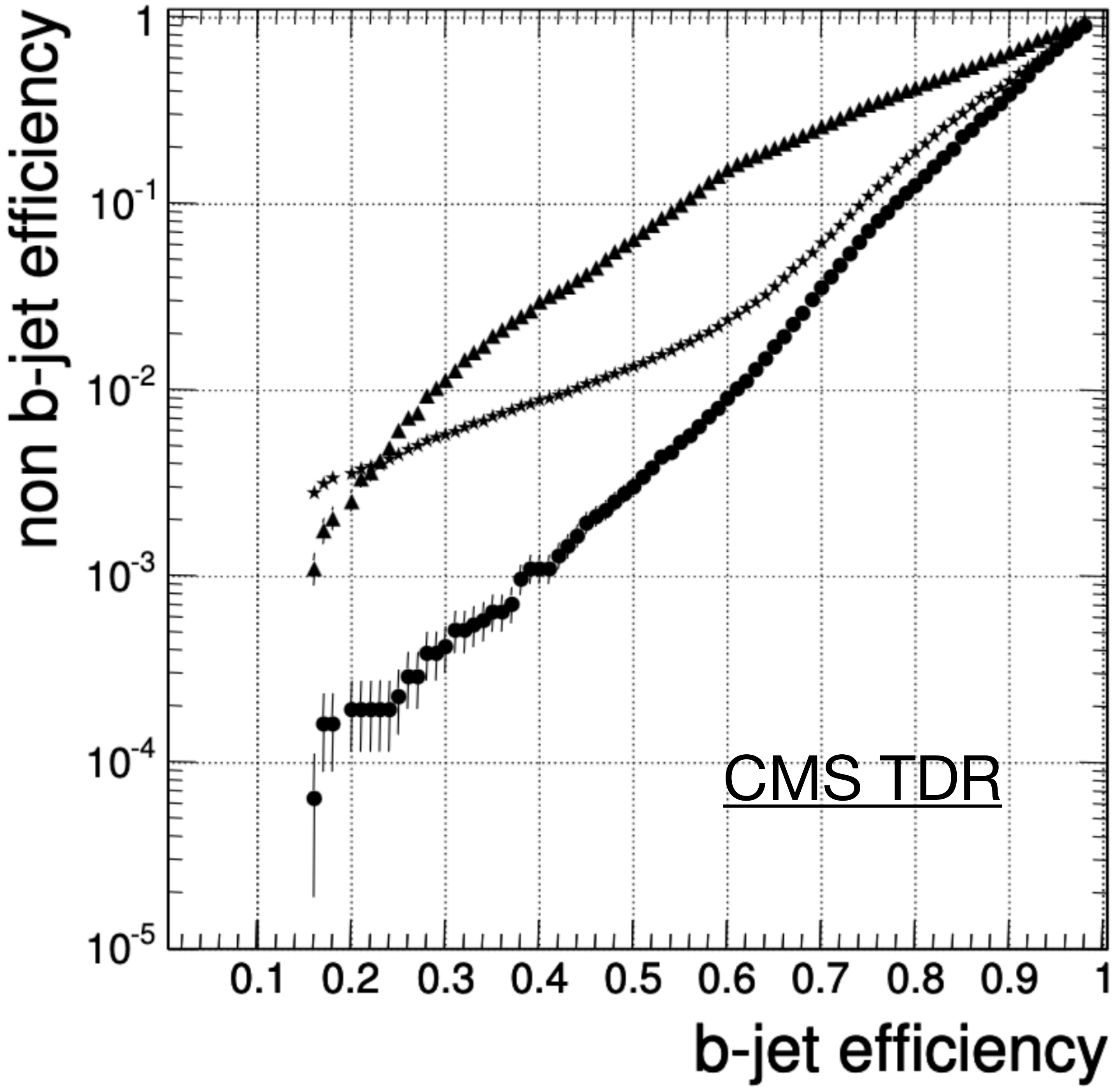
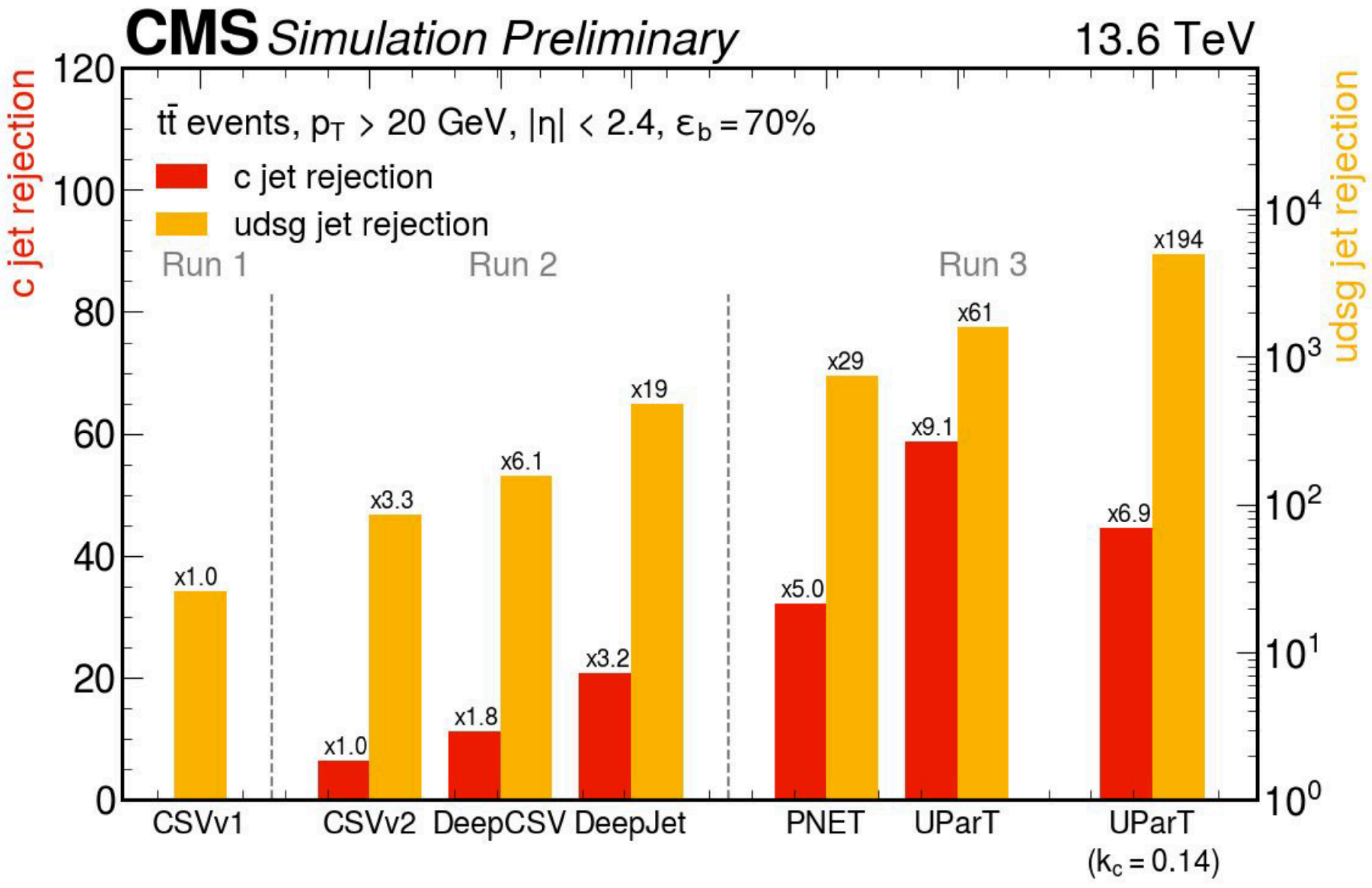
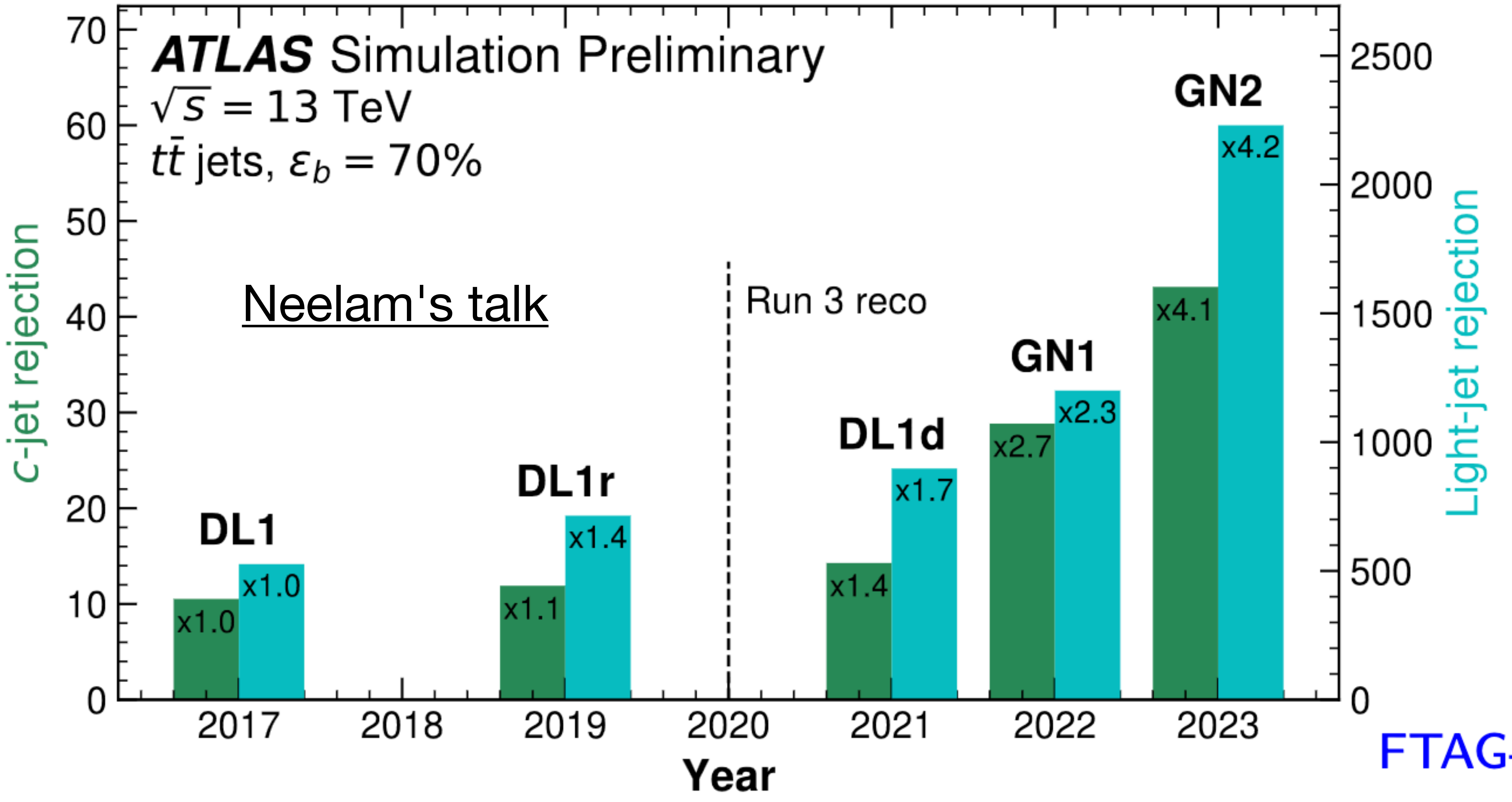
Machine learning is integrated into our conversations

The future is here

- ATLAS and CMS have made huge gains in their b-jet and c-jet tagging since the start of the LHC
  - *… and even more since the TDR!*
- Neural networks are the default, and we are trying to optimize their architectures





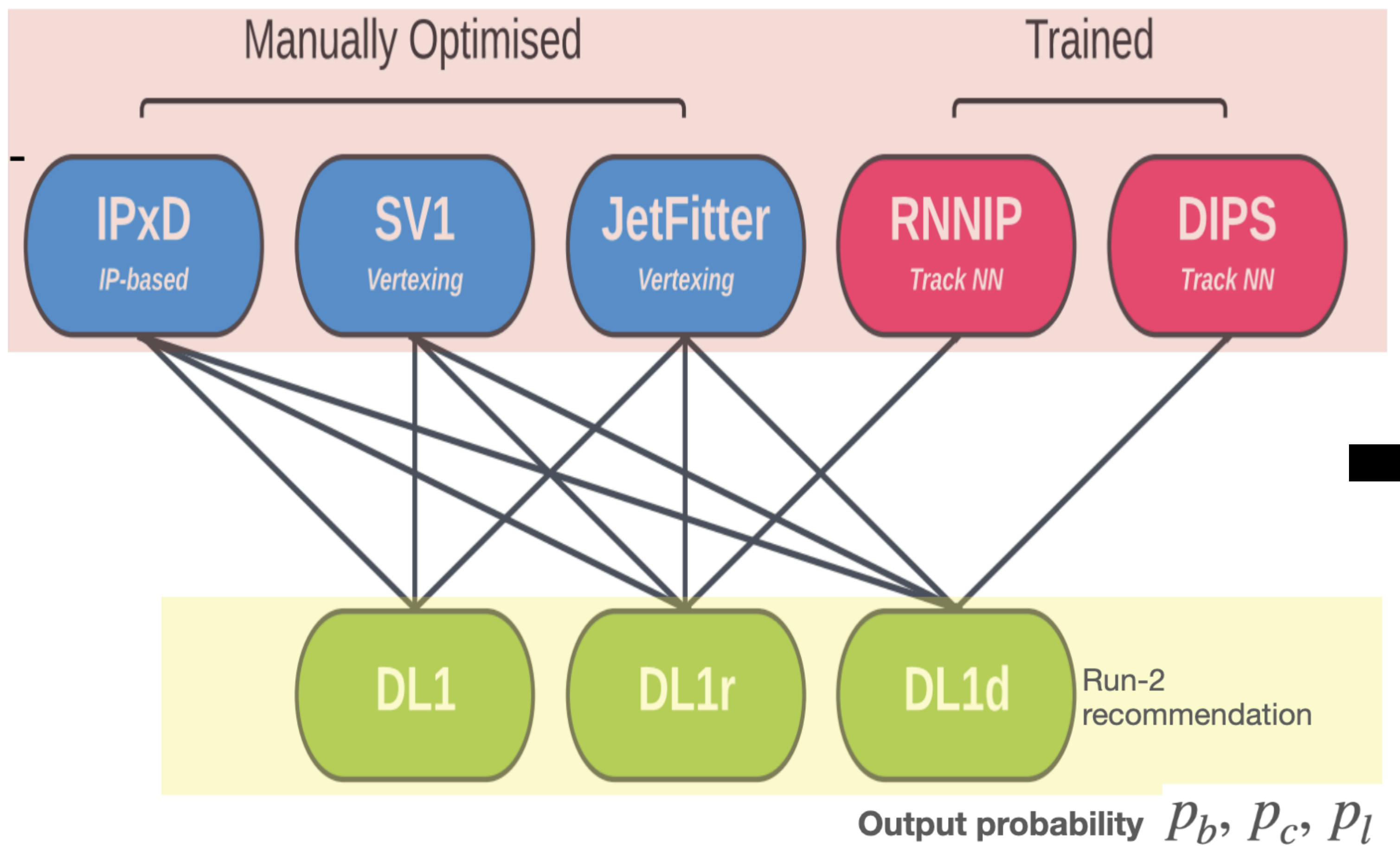


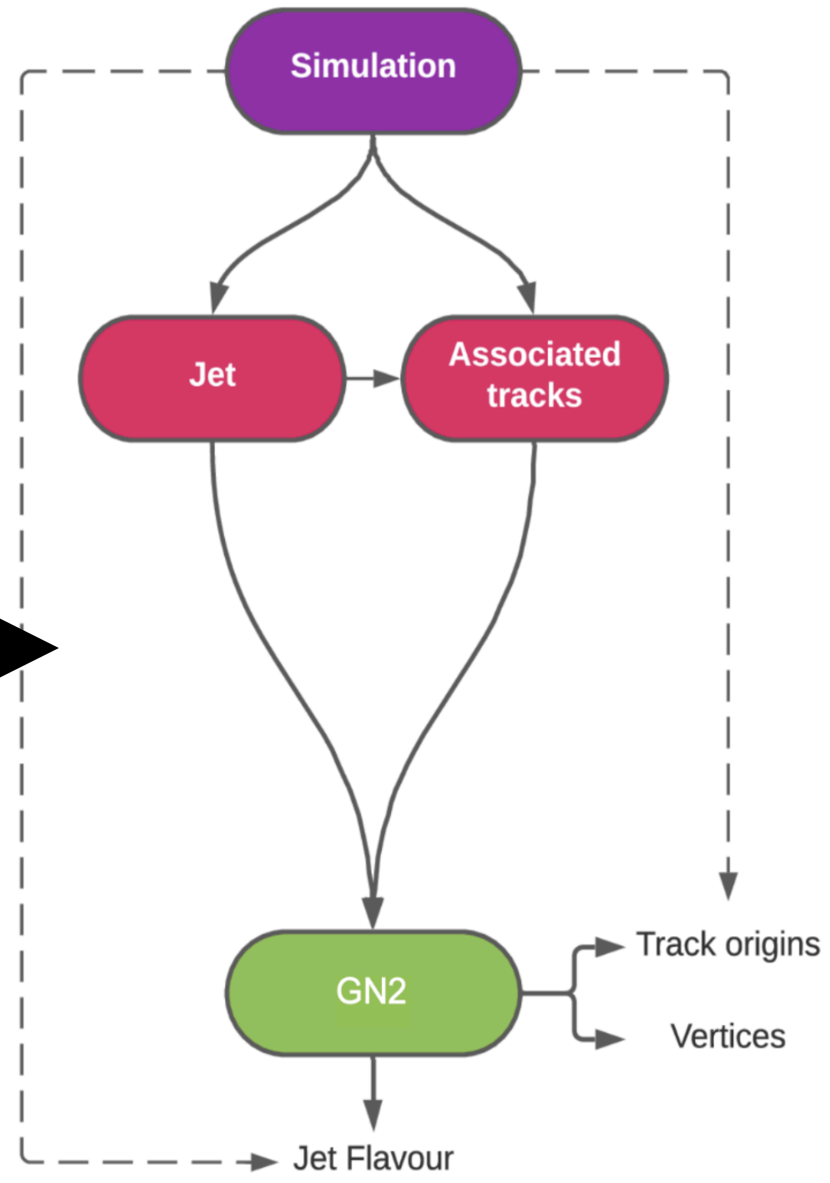
FTAG-2023-01

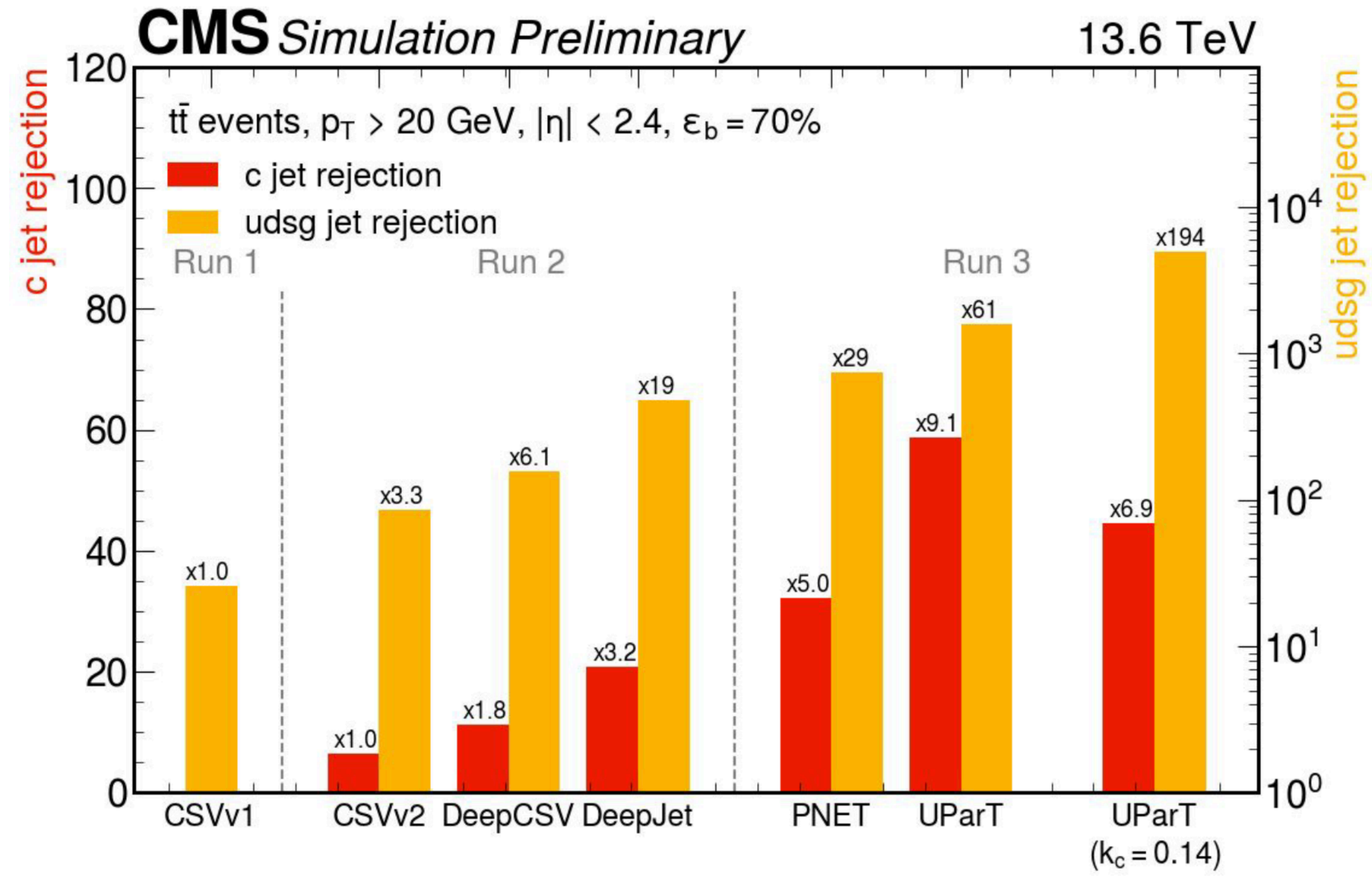
The future is here

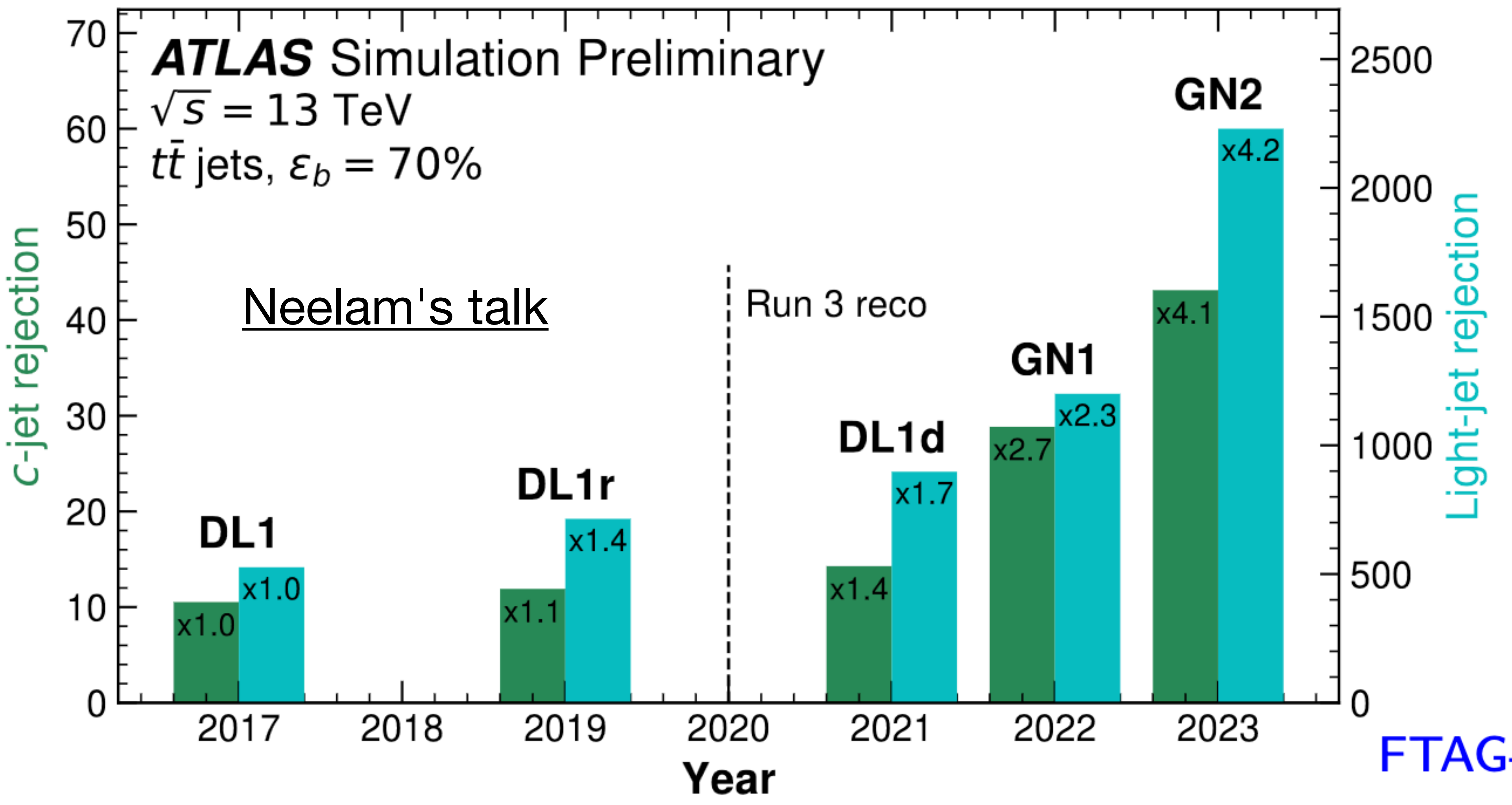
- ATLAS and CMS have made huge gains in their b-jet and c-jet tagging since the start of the LHC
  - *… and even more since the TDR!*
- Neural networks are the default, and we are trying to optimize their architectures

Using much simpler inputs and also getting much better performance!







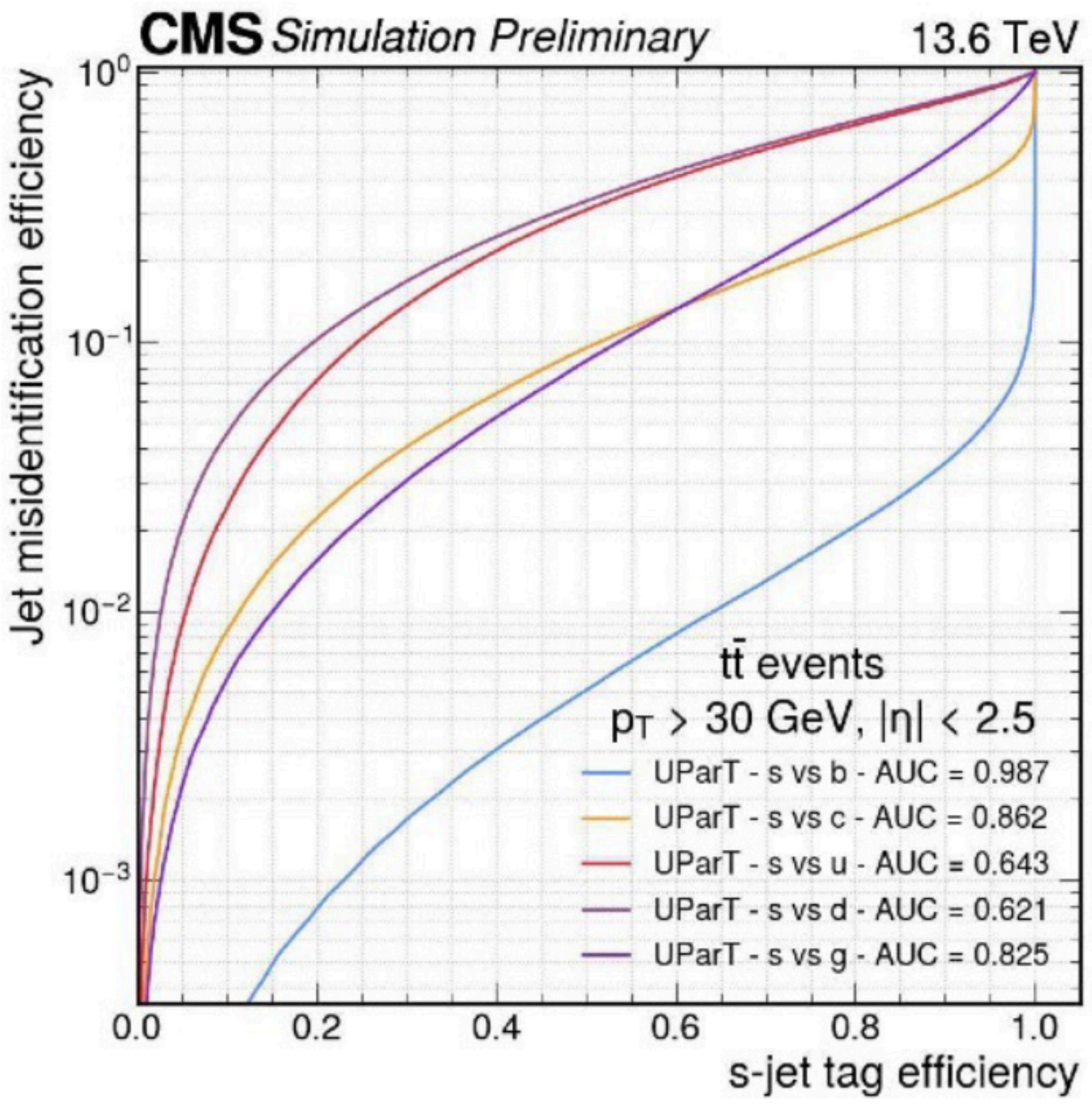


FTAG-2023-01

The future is here

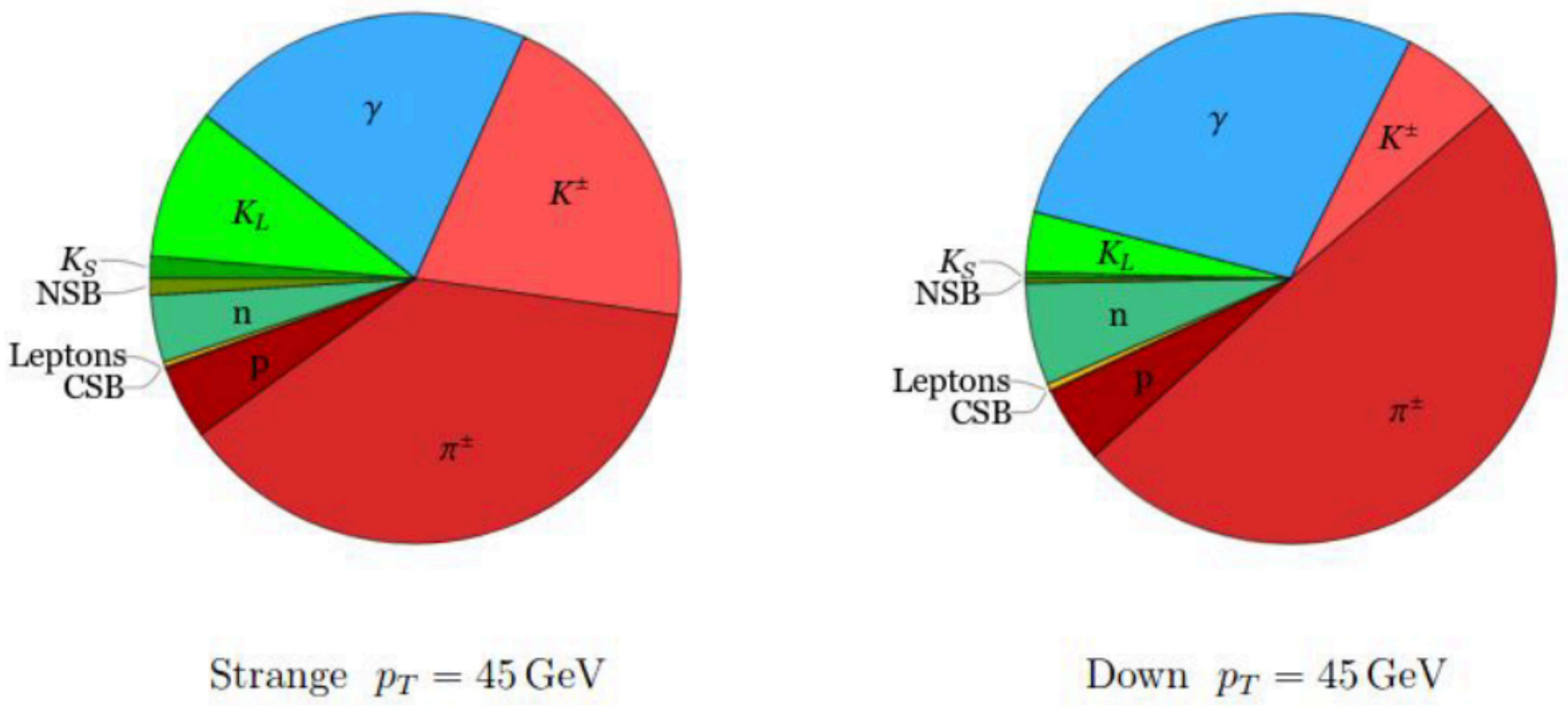
s-jet

Fikri's talk

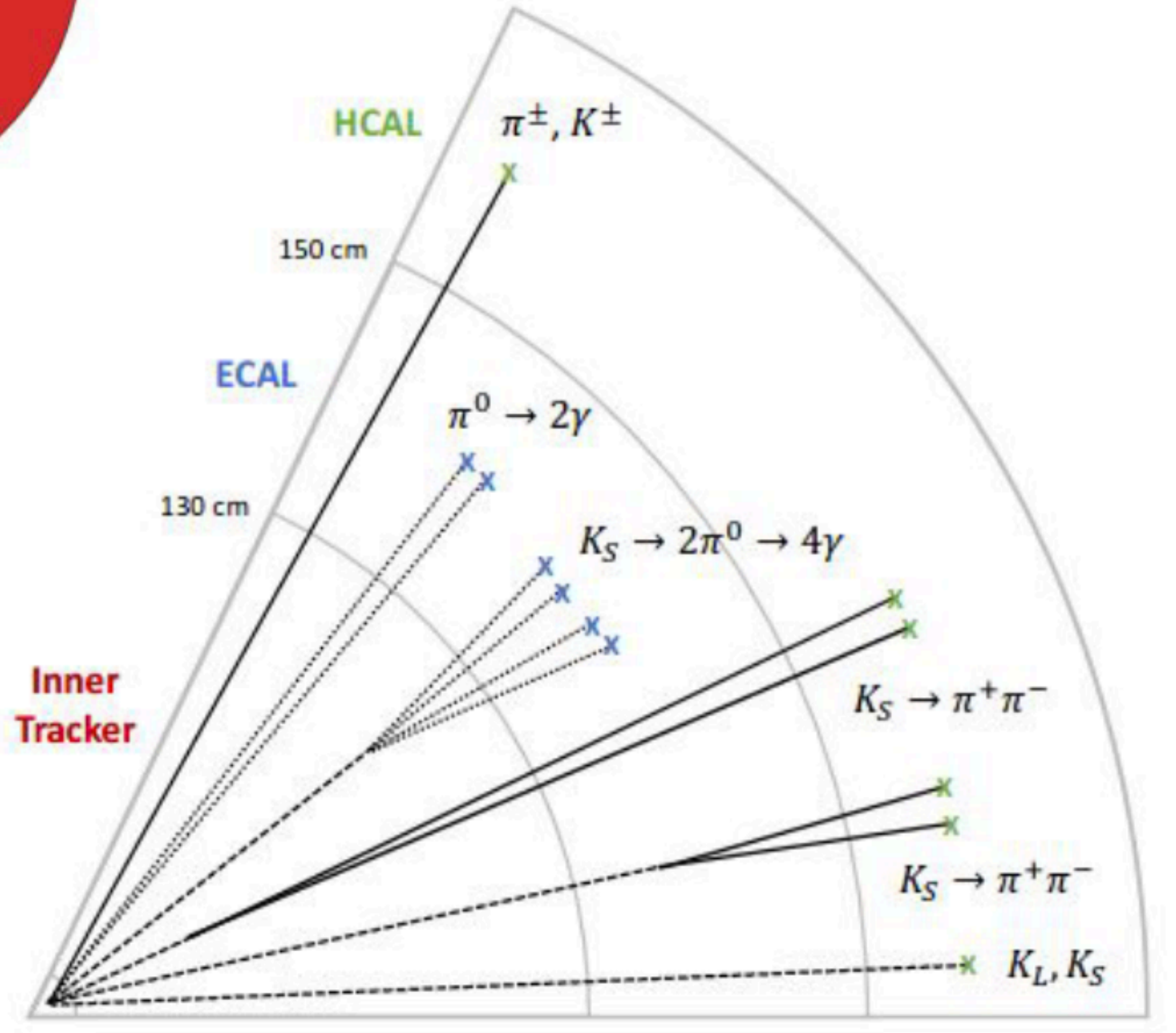


First attempt at strange-jet tagging in CMS!

Michele's talk



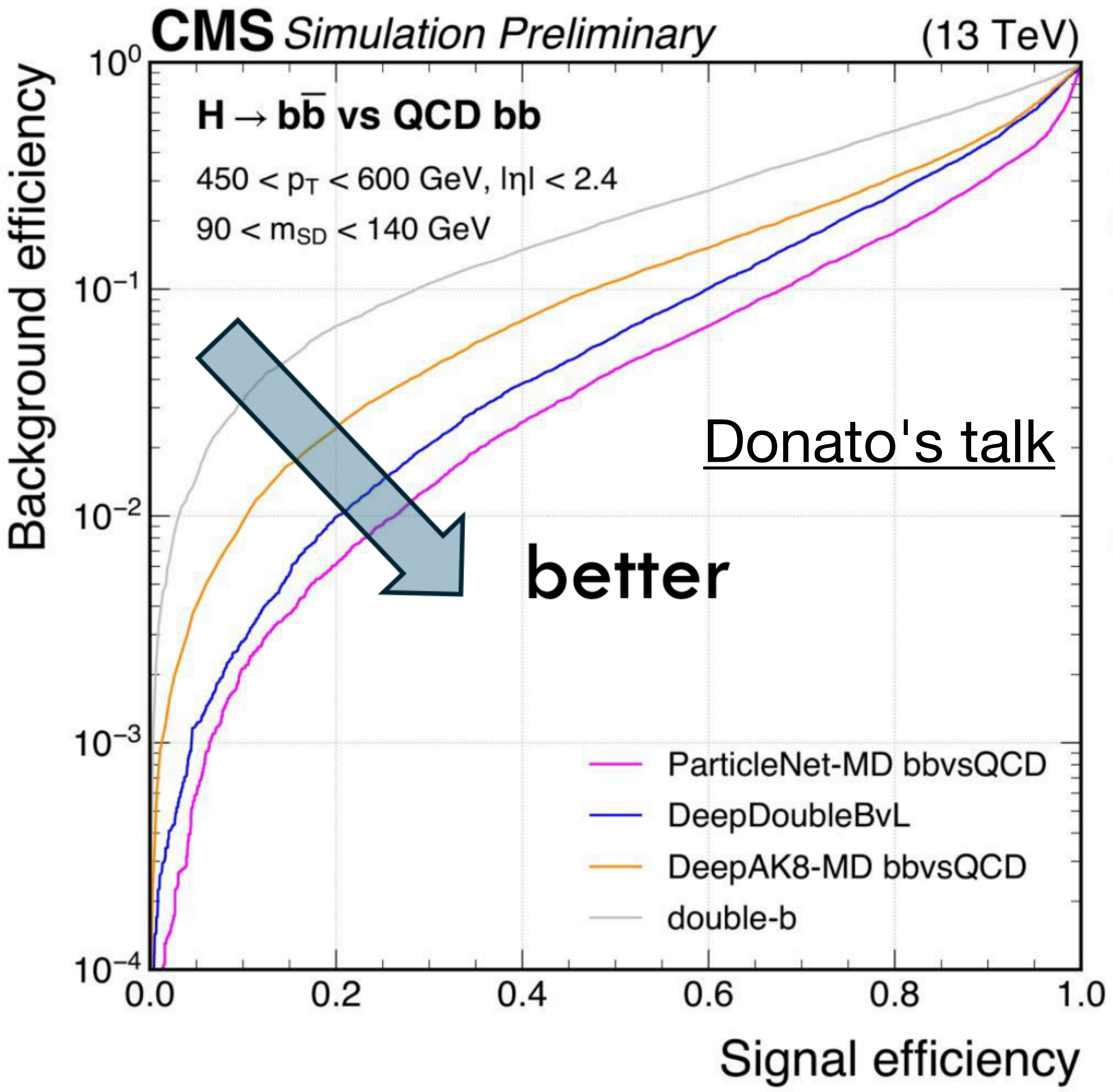
[Nakhai, Shih, Thomas]

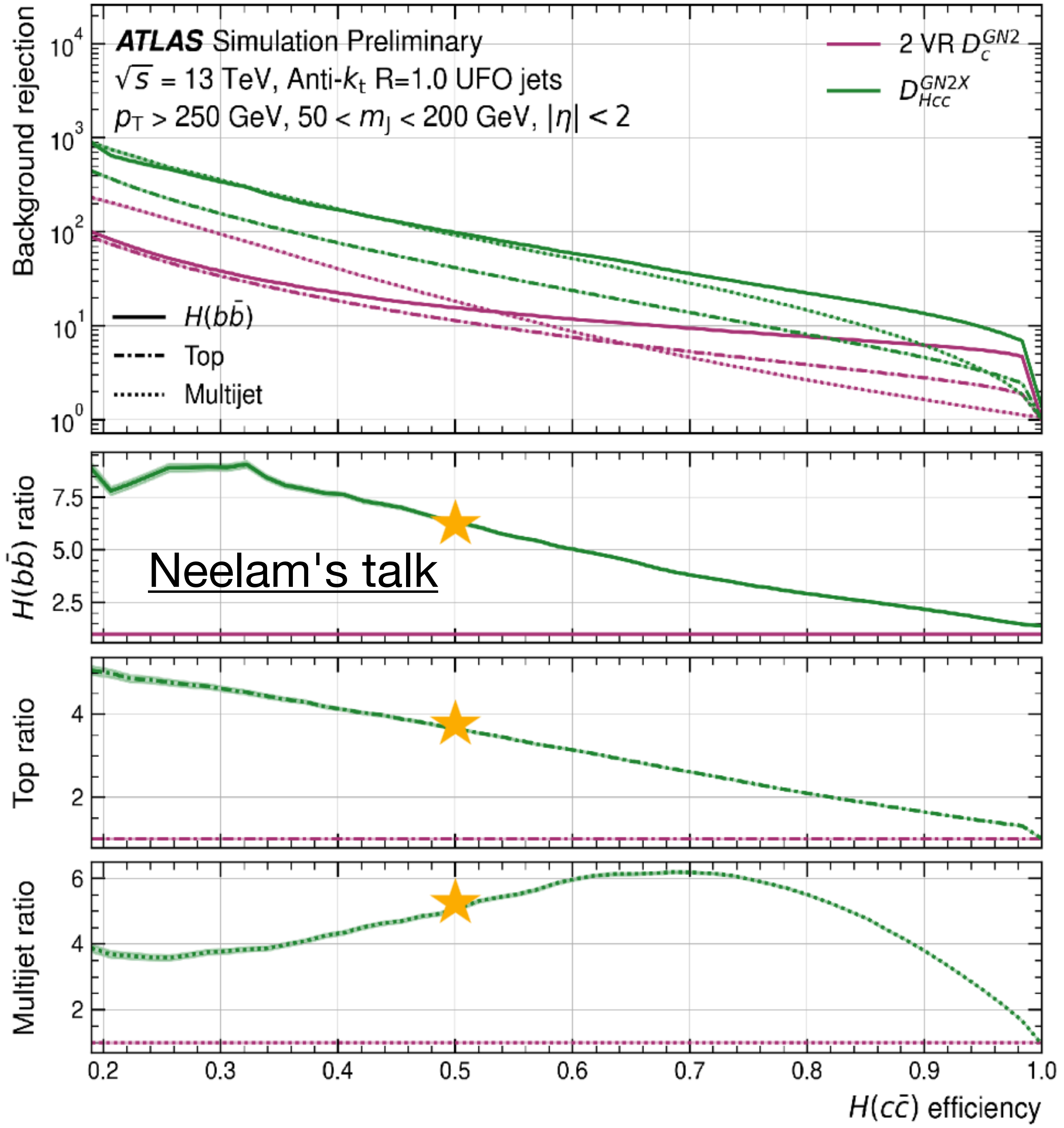


- Heard about potential applications of strange-tagging at future colliders
    - … and this is already being attempted at the LHC!
- *Some handles on the differences in hadron composition, but much harder problem than b- or c-tagging*

The future is here

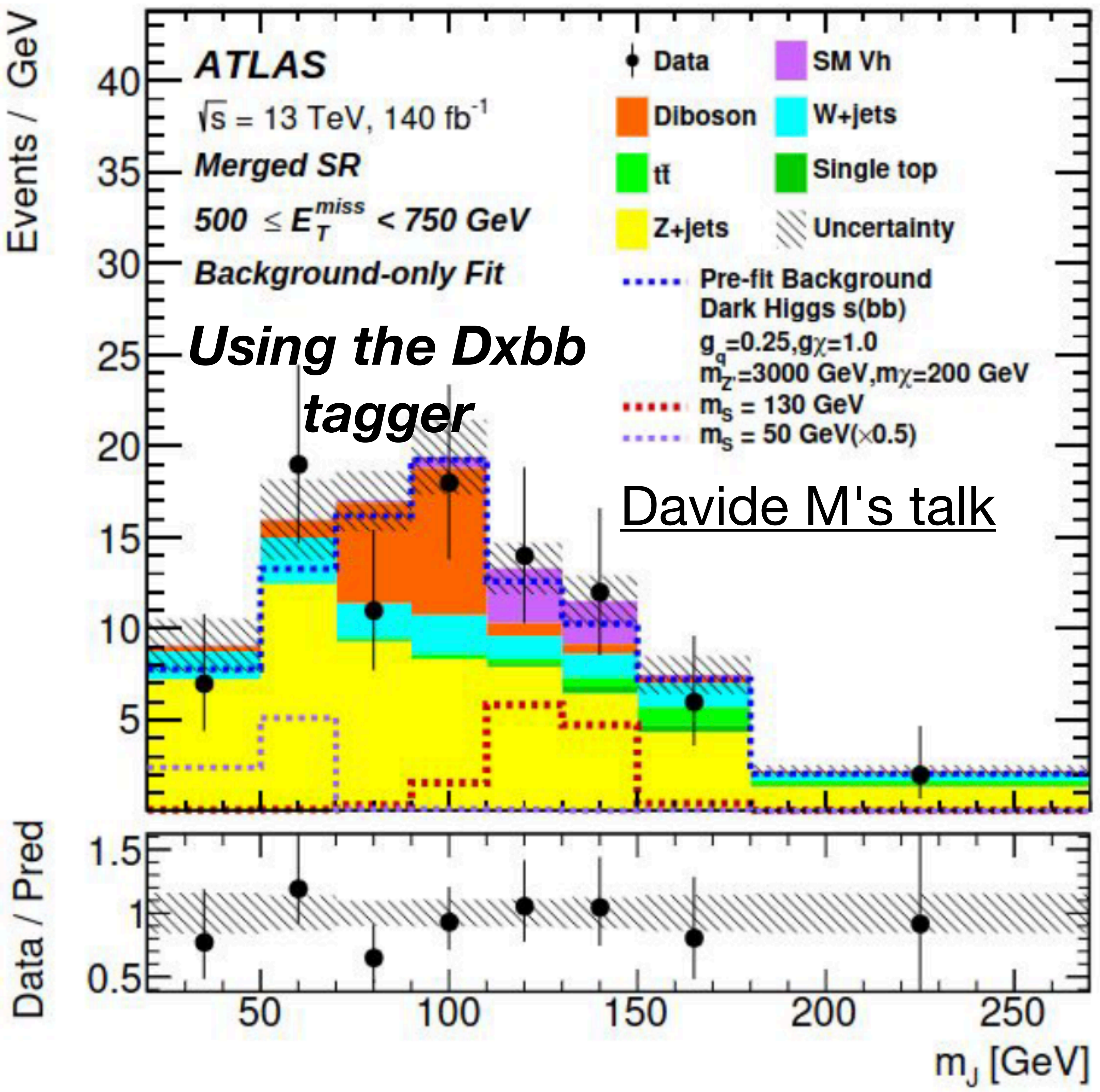
- Double-b and double-c tagging are part of the standard toolkit
  - *Still making big gains in the tagging performance, so expect more improvements to come*

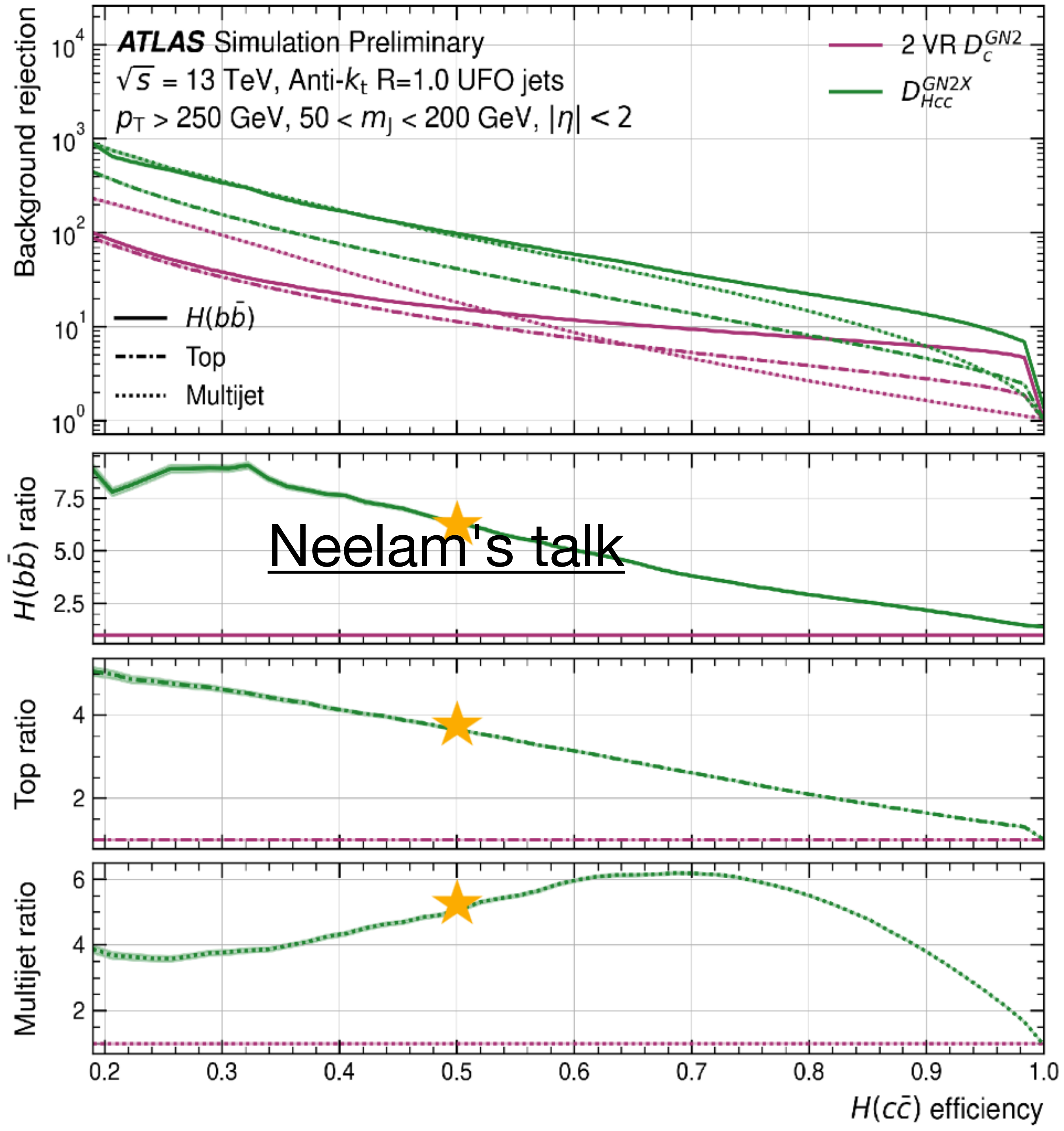


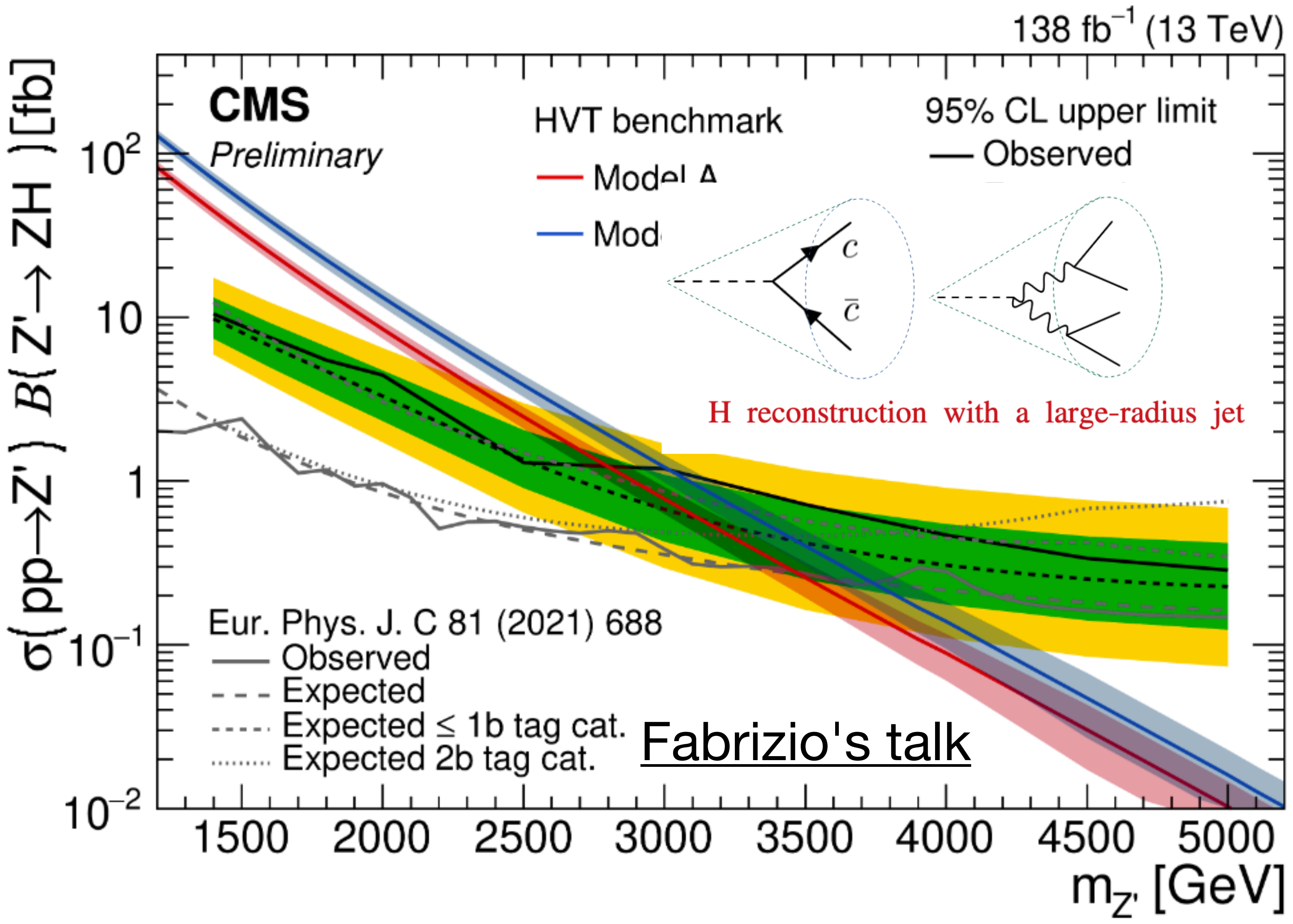


The future is here

- X→bb/cc taggers are used for a wide range of searches



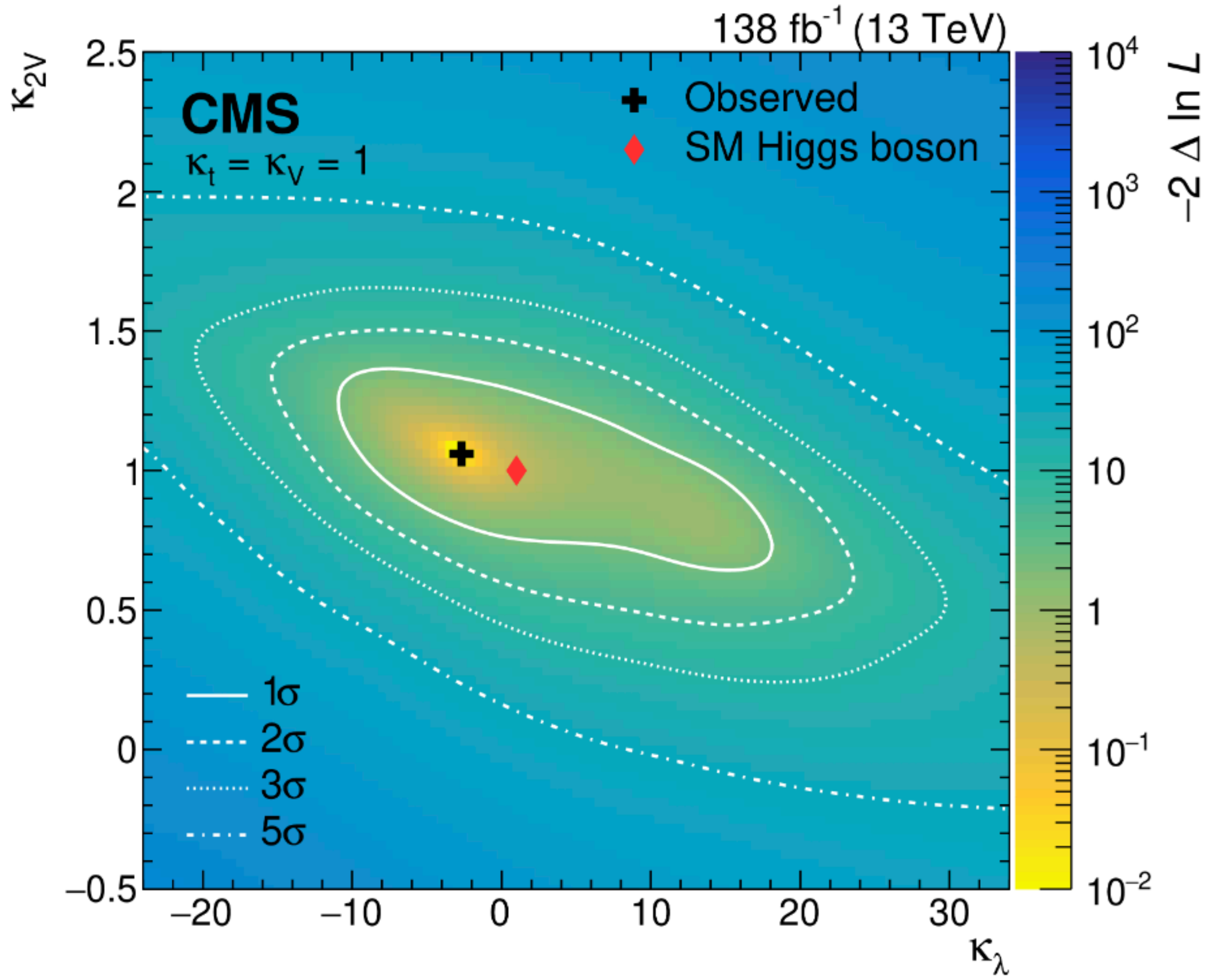




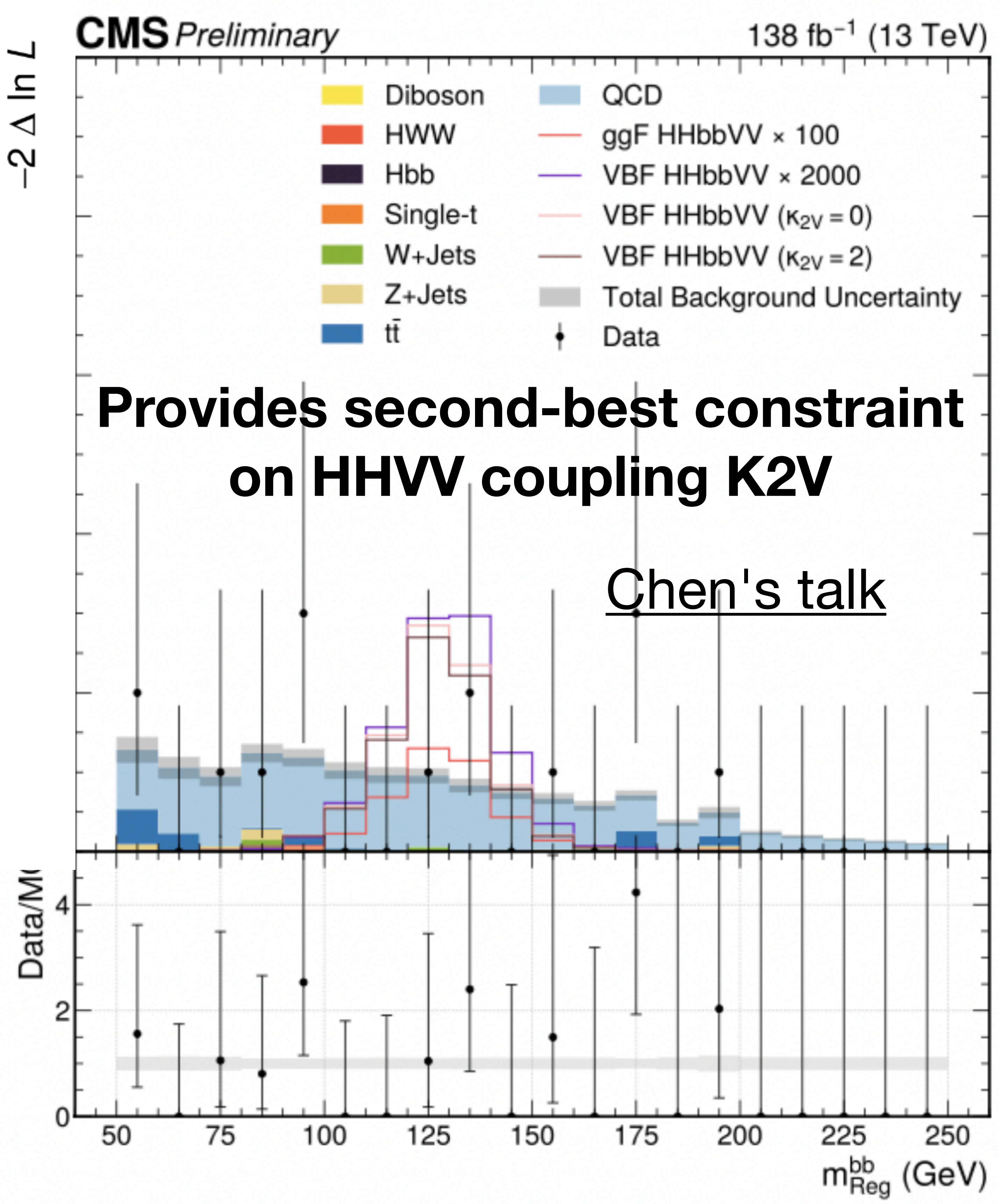
- New taggers take time to optimize and calibrate → can take a few years to go from proof of concept to being used in analysis
  - *Can expect more sensitivity in many searches without more data!*

The future is here

- Boosted channels are now a staple of the Higgs and di-Higgs physics programs



Excluding κ_{2V}=0 for the first time

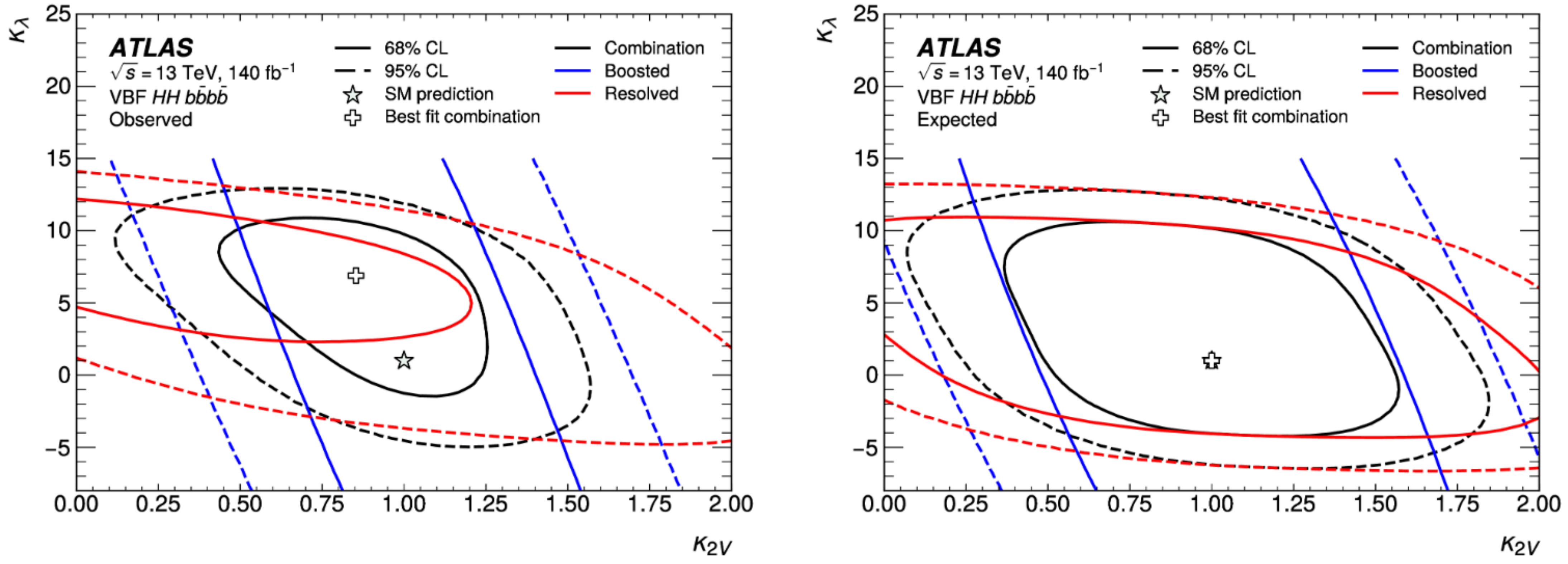


Provides second-best constraint on HHVV coupling K2V

Chen's talk

Fabrizio's talk

- Boosted analysis is dominant for κ_{2V} sensitivity while κ_λ sensitivity is driven by the resolved analysis

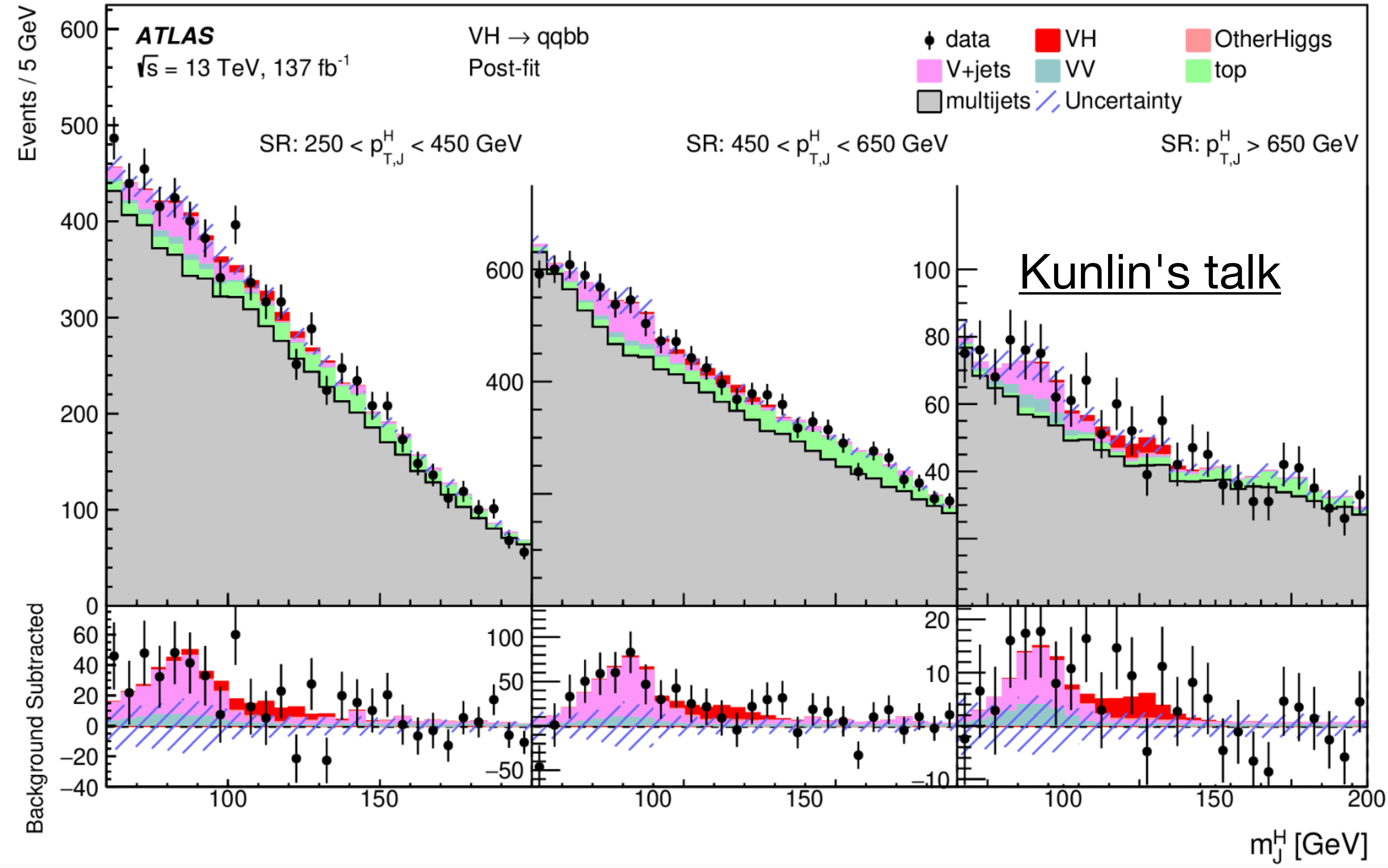


- Results on κ_{2V} analysis are as good as the HL-LHC projections of the previous-best VBF HH analysis (the full Run 2 resolved VBF hh4b).

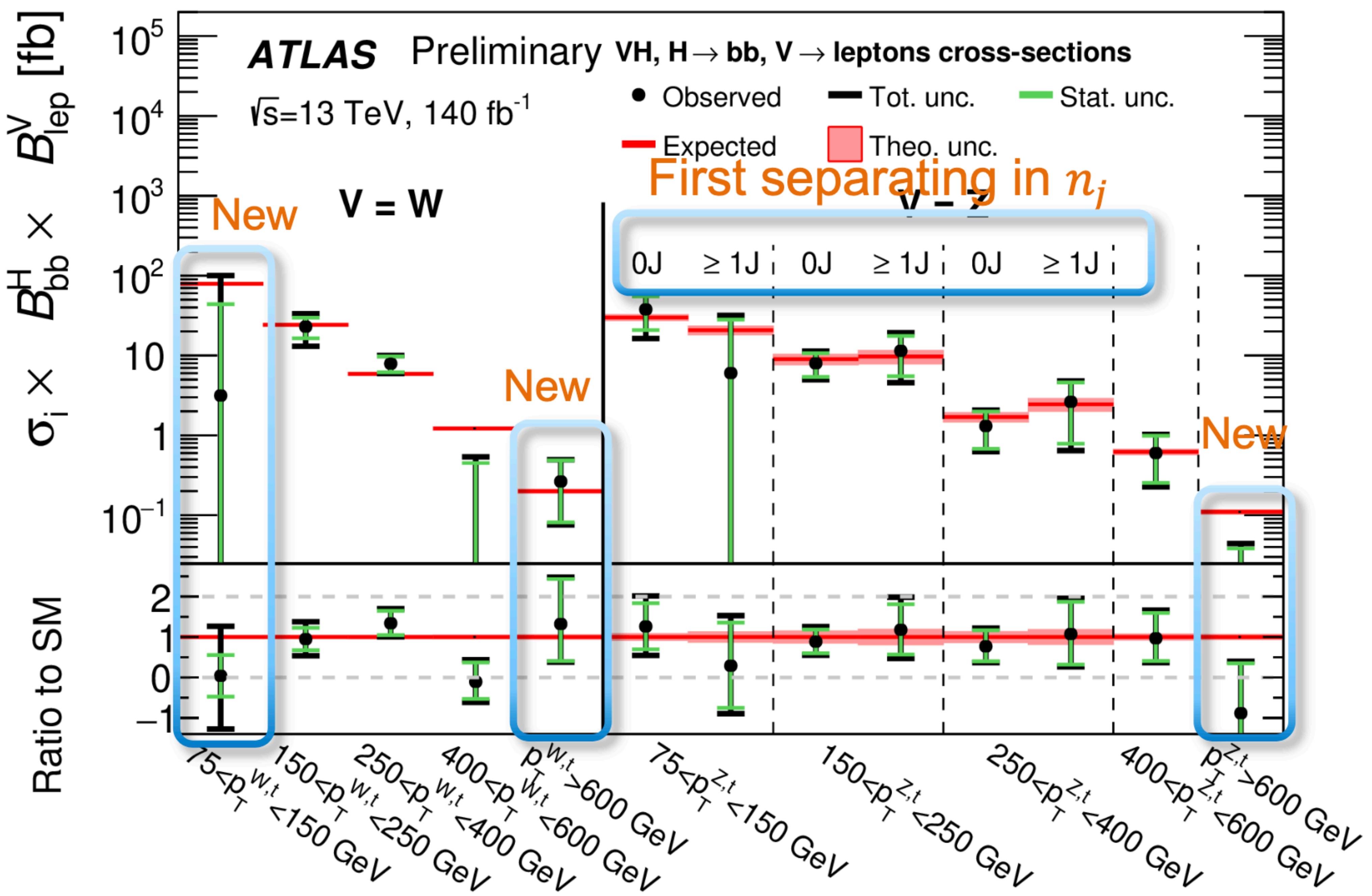
- Rapid tagger improvements mean we are already reaching expectations for the HL-LHC with Run-2 data
  - *Expect more improvements to come*

The future is here

- Starting to use all-hadronic channels to gain access to higher p_T, and with higher statistics (at the cost of higher backgrounds…)
    - Relevant for EFT interpretations, and will benefit from better background modeling and more background reduction

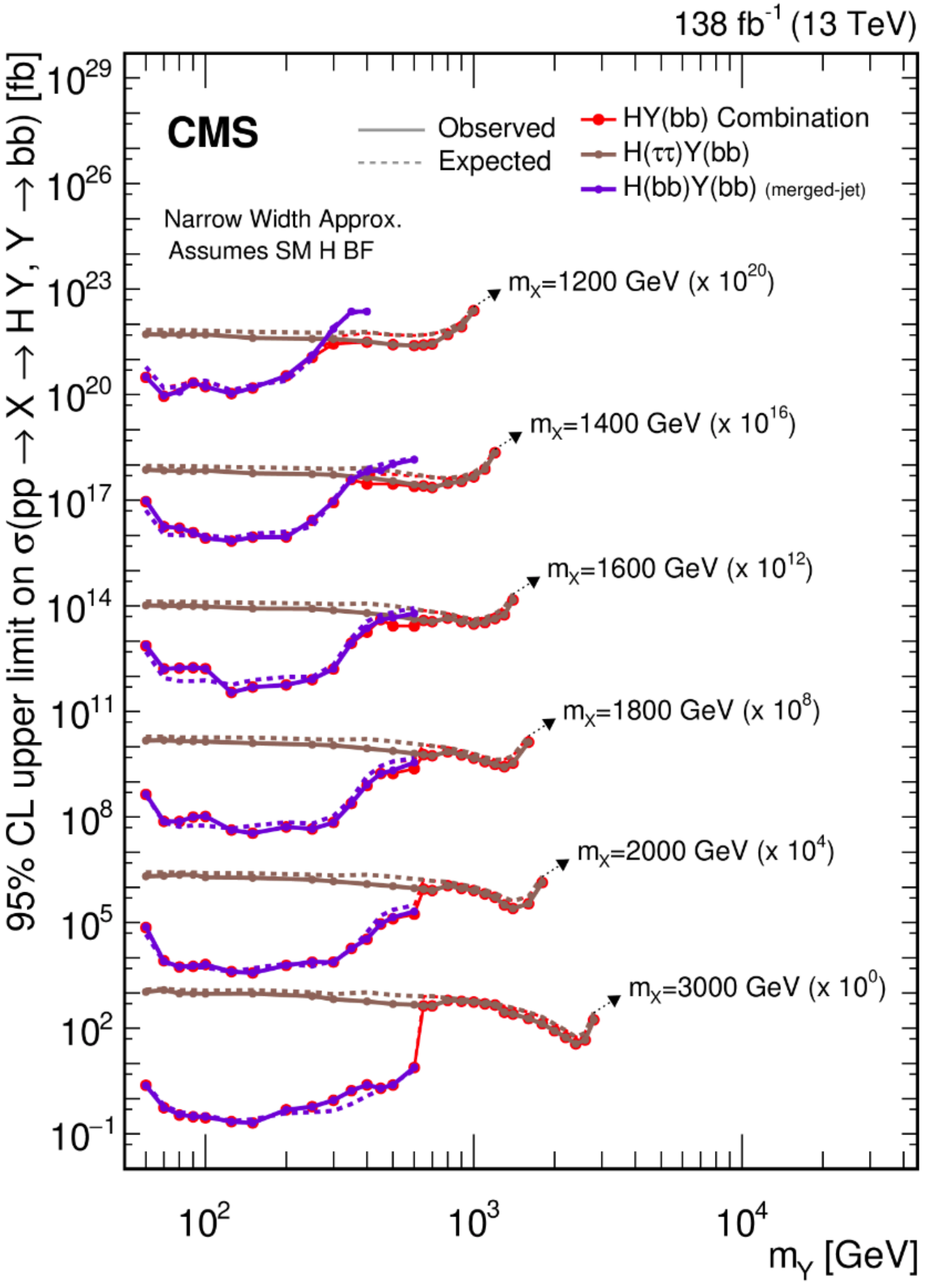


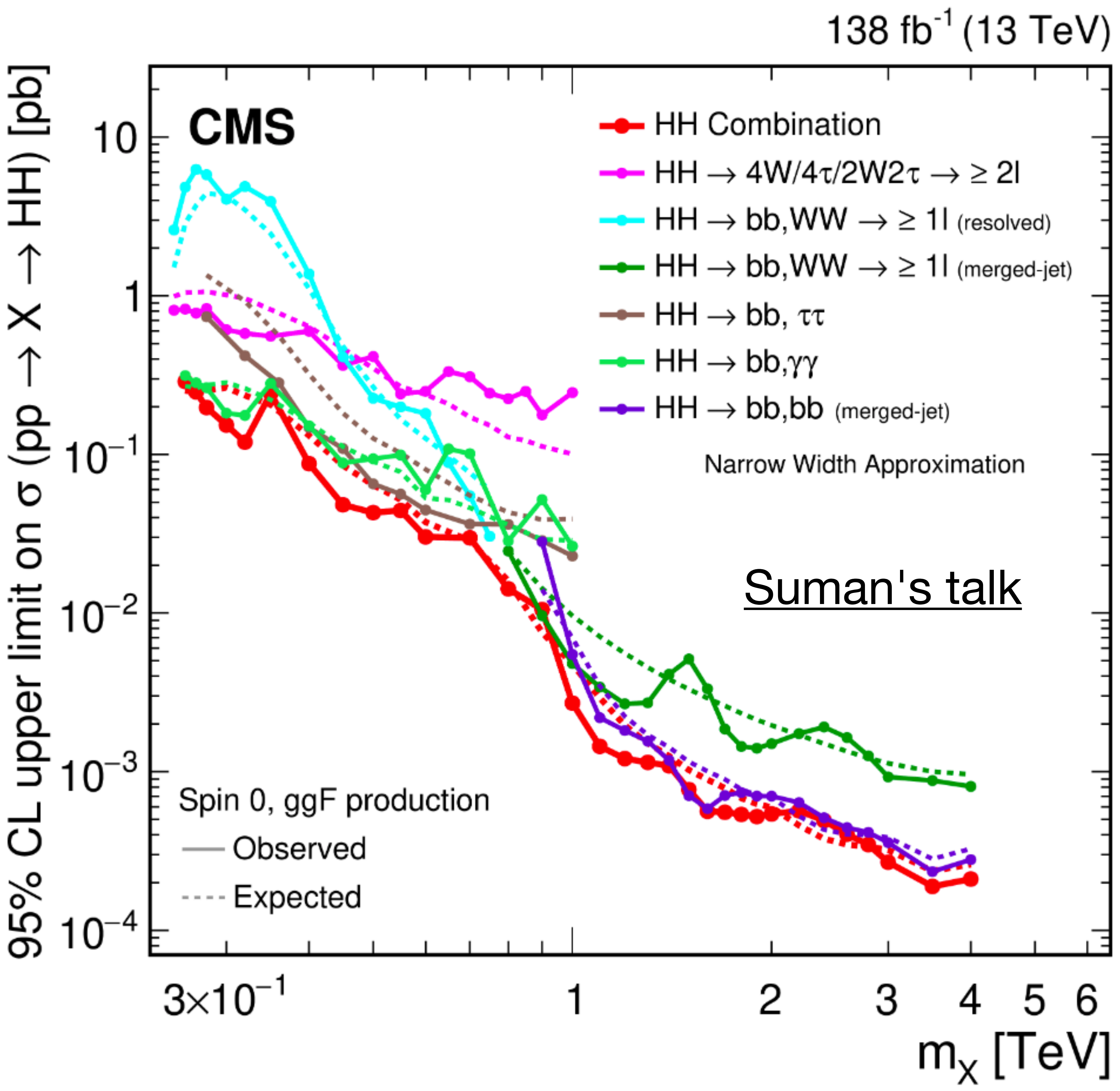
Kunlin's talk



- These analyses benefit a lot from the performance work done to optimize these taggers and calibrations!

The future is here

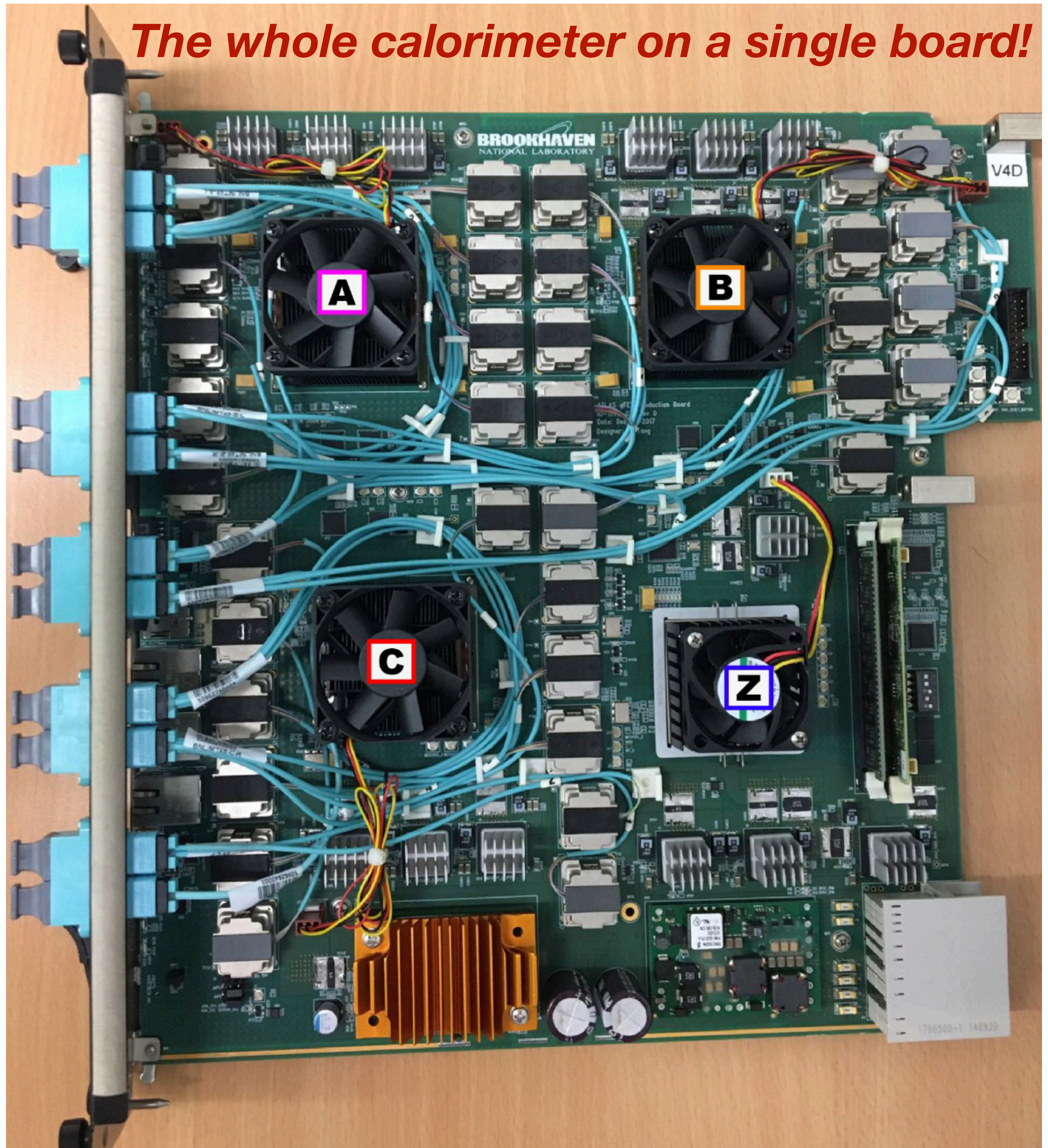


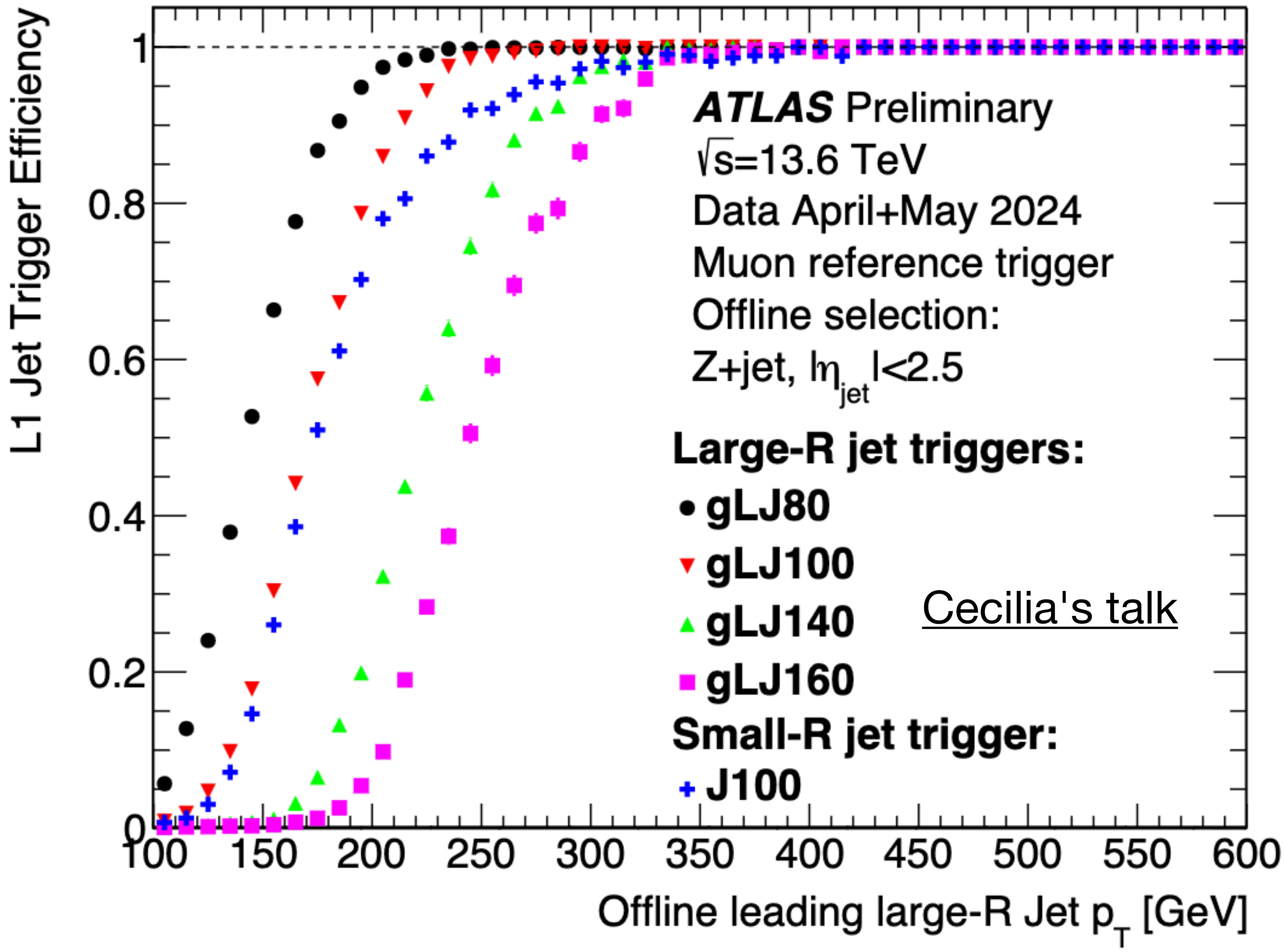


- Boosted jets are used to probe a wide range of models, often bringing more sensitivity than any other channel
    - *We are no longer surprised to see searches that use boosted jets as one of the main channels*

The future is here

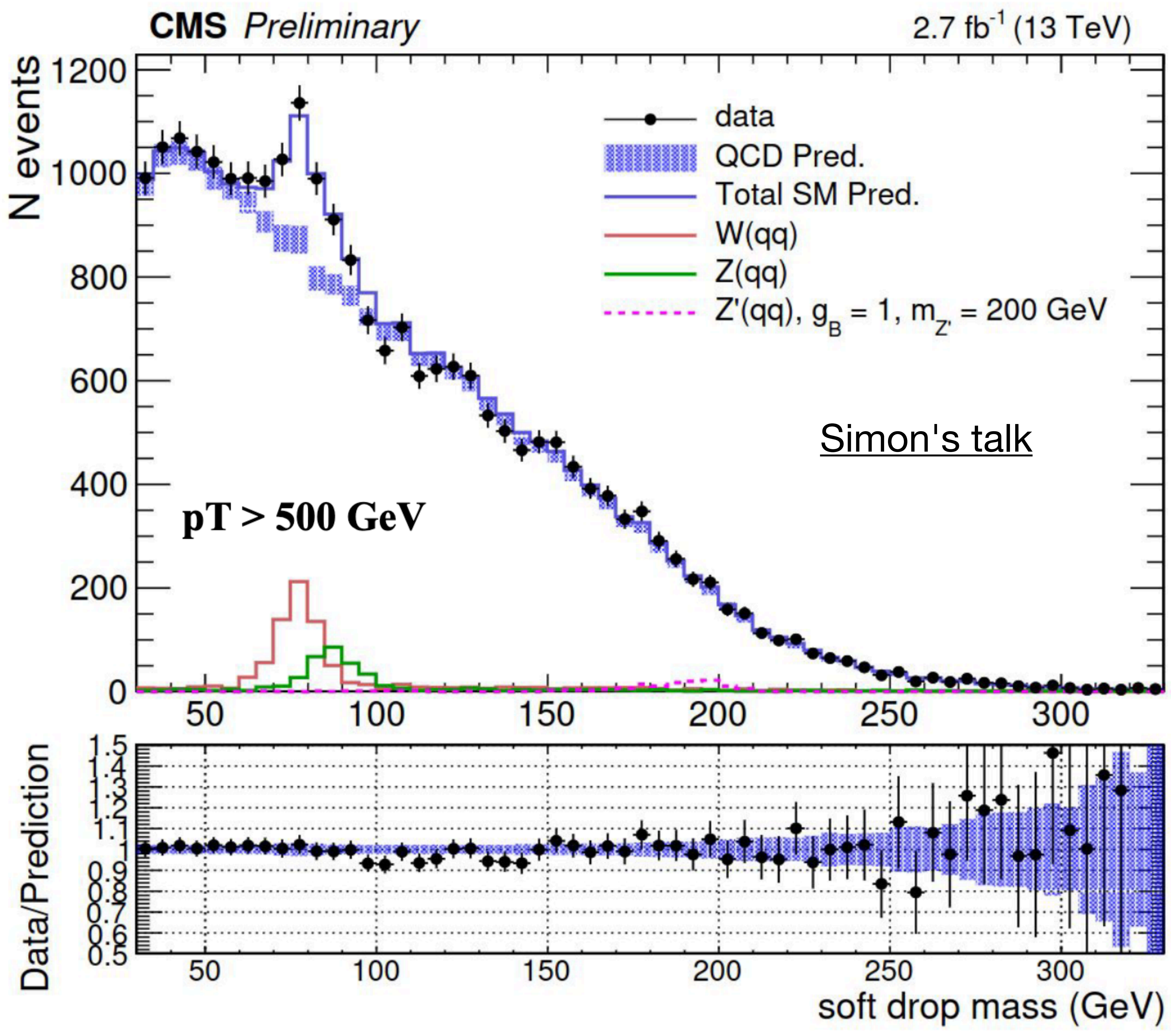
- Trigger strategies for single-prong jets do not always apply for multi-prong jets





- ATLAS is commissioning a new system that can trigger on multi-prong jets more efficiently
  - *Lots of potential for development with new ideas!*

The future is here

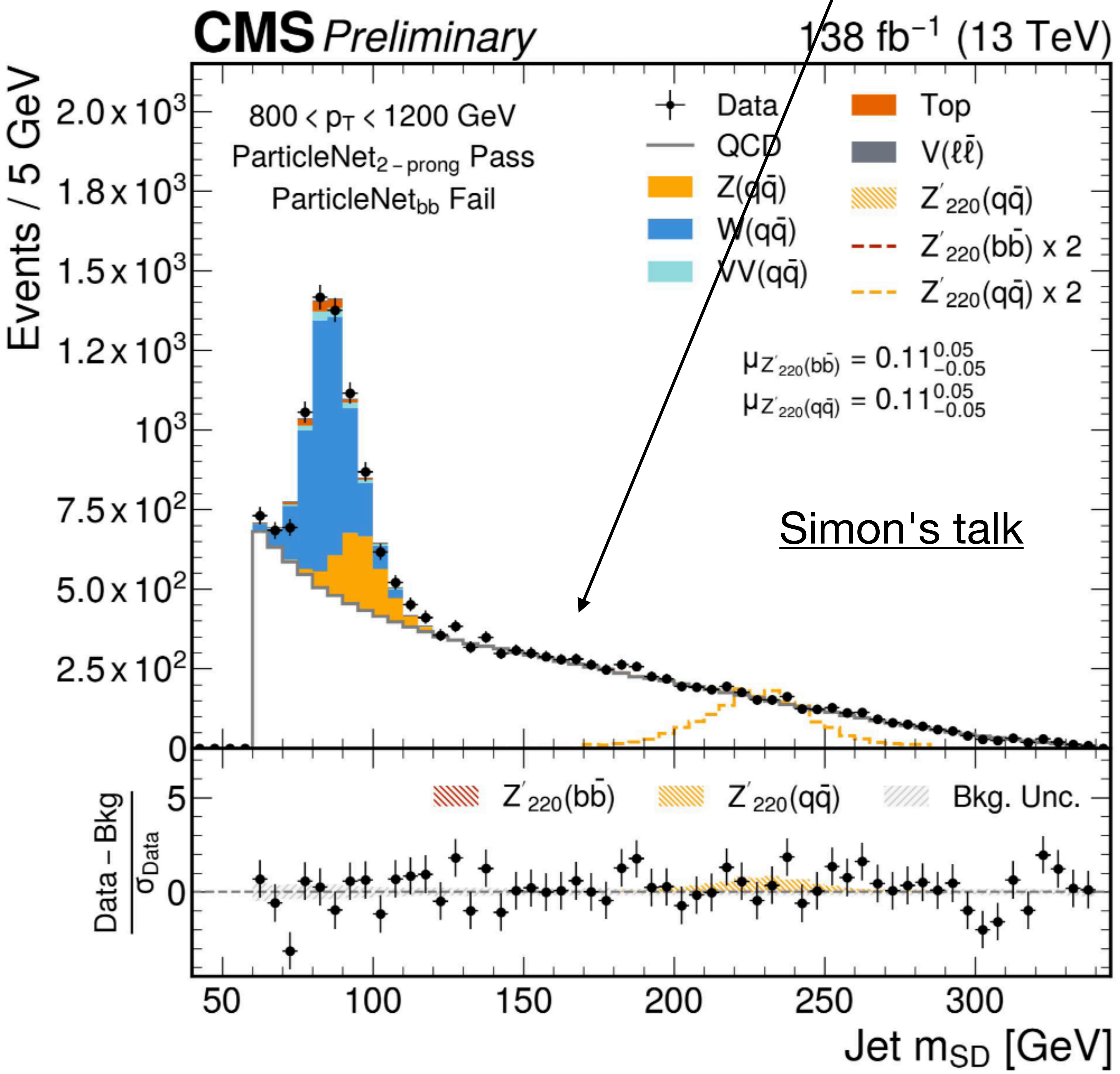


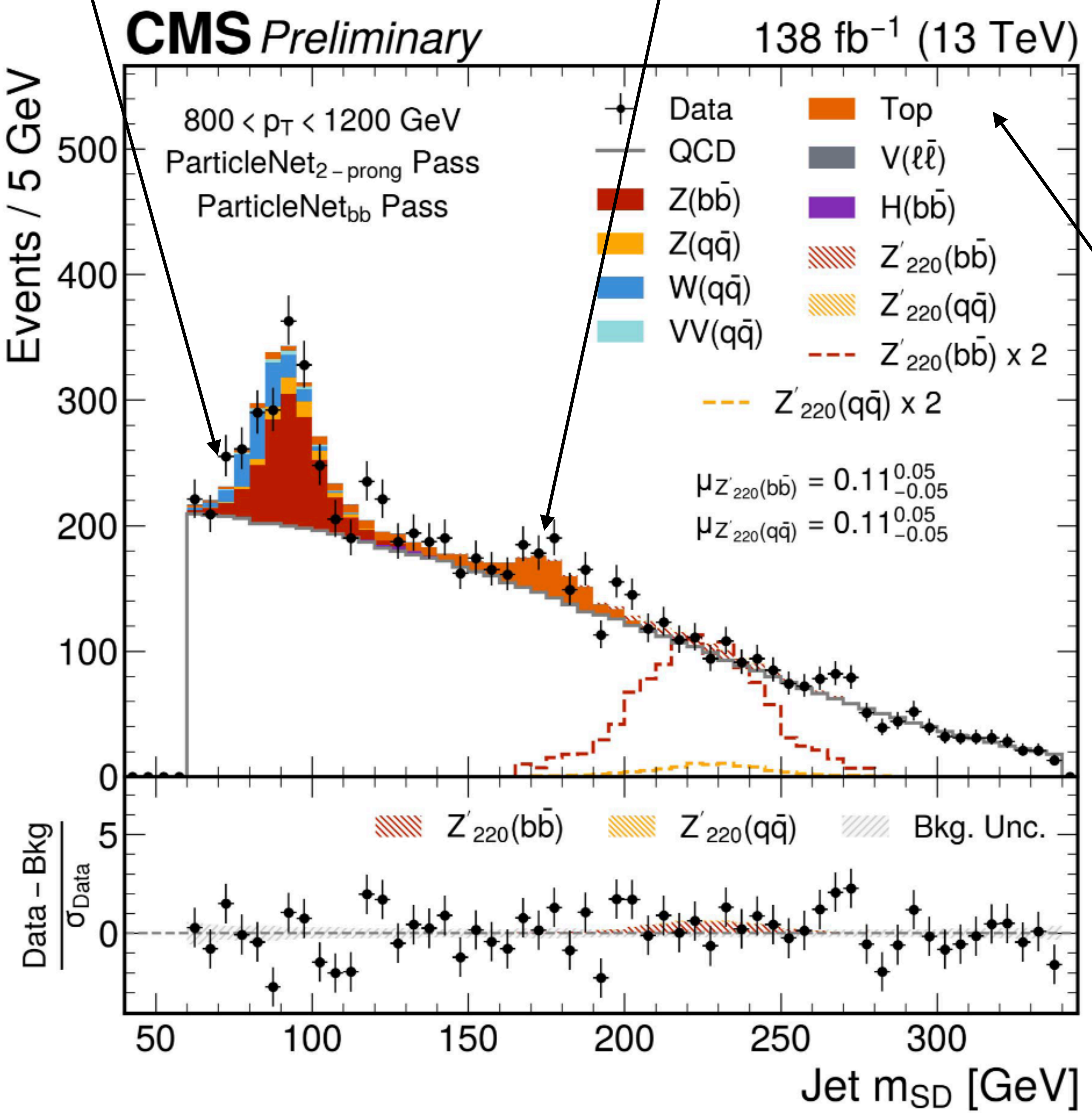
The future is here

50x the data, not 50x the background

Dedicated channel for bb decays

Need to also fit the top peak

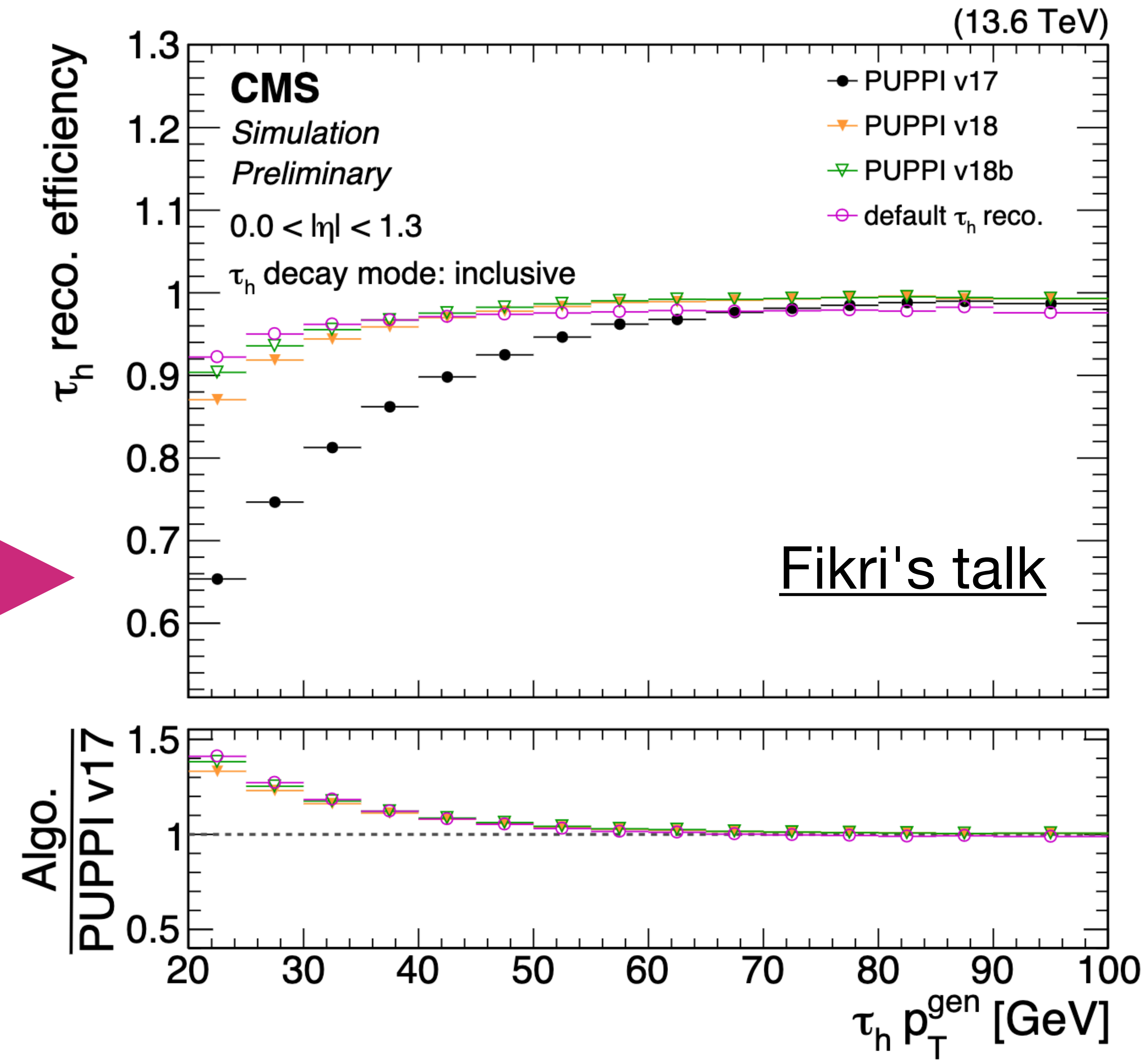




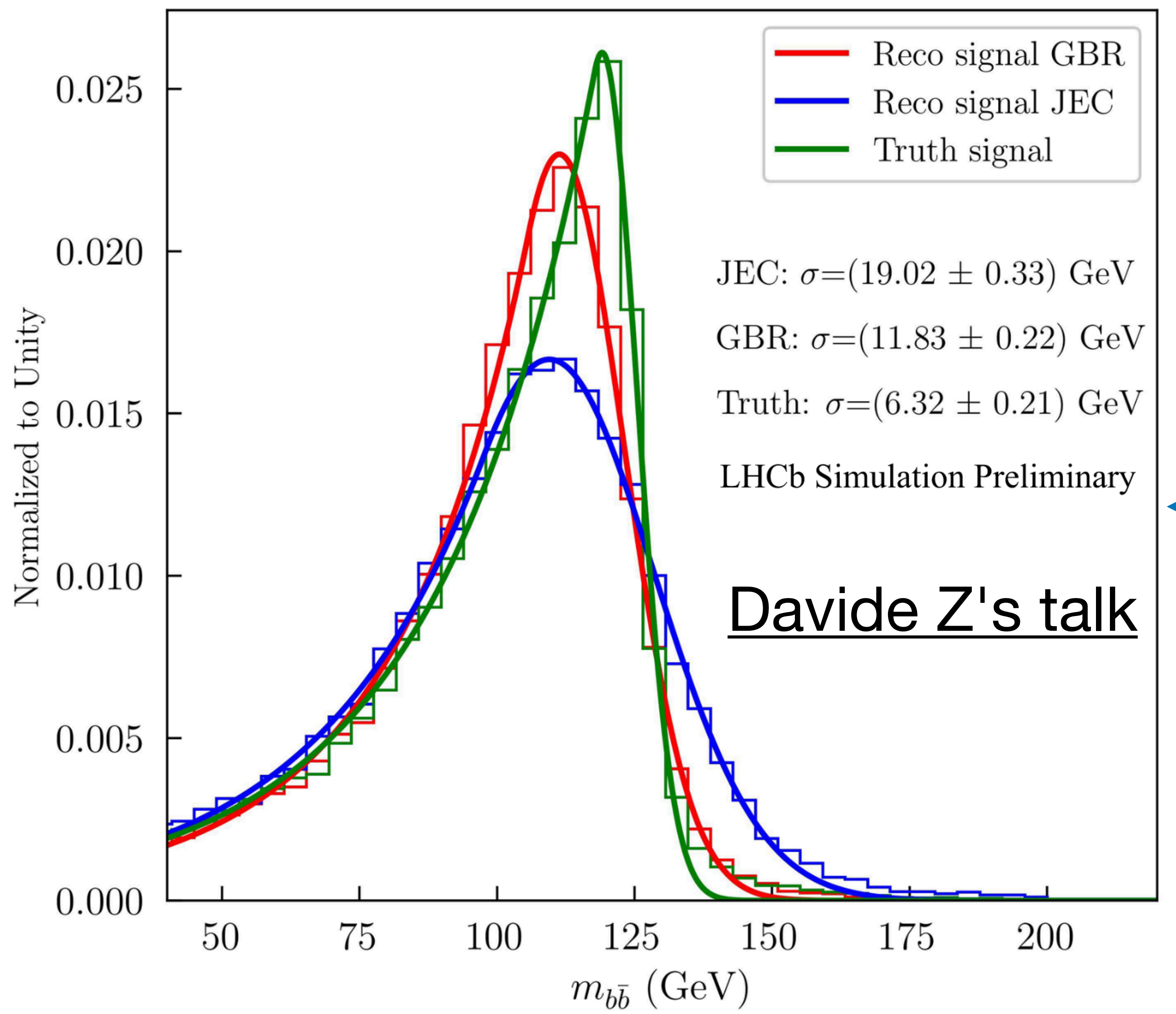
Controlling for many more backgrounds

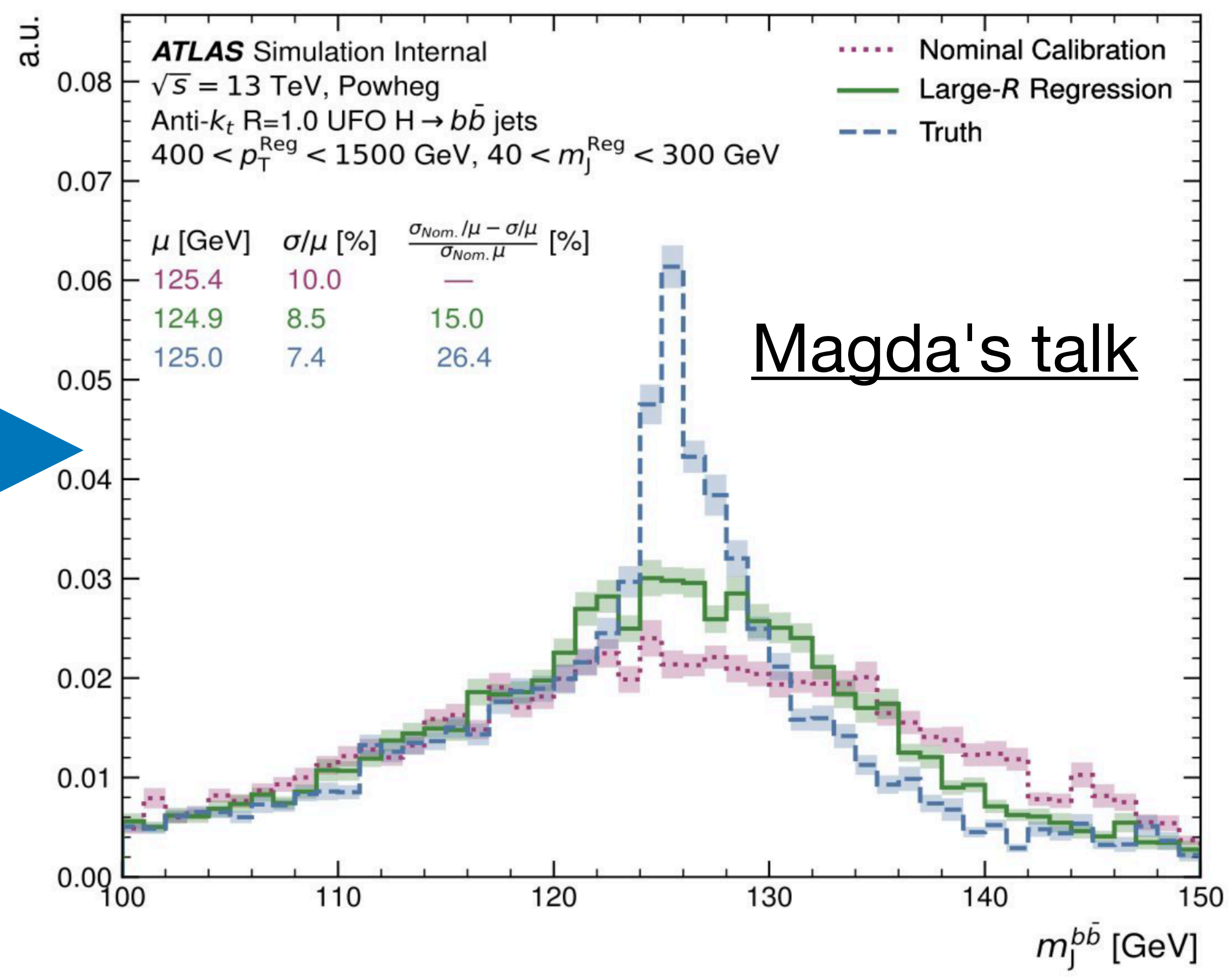
Zooming in

- Low efficiency for τ's due to the interaction between PUPPI and the association of (displaced) tracks to primary vertices
  - Improved the algorithm to handle these cases, achieving similar or better τ efficiency than the standard reconstruction method



- Can use additional information from b-jets to provide better calibrations
  - *LHCb is also getting in on the fun!*

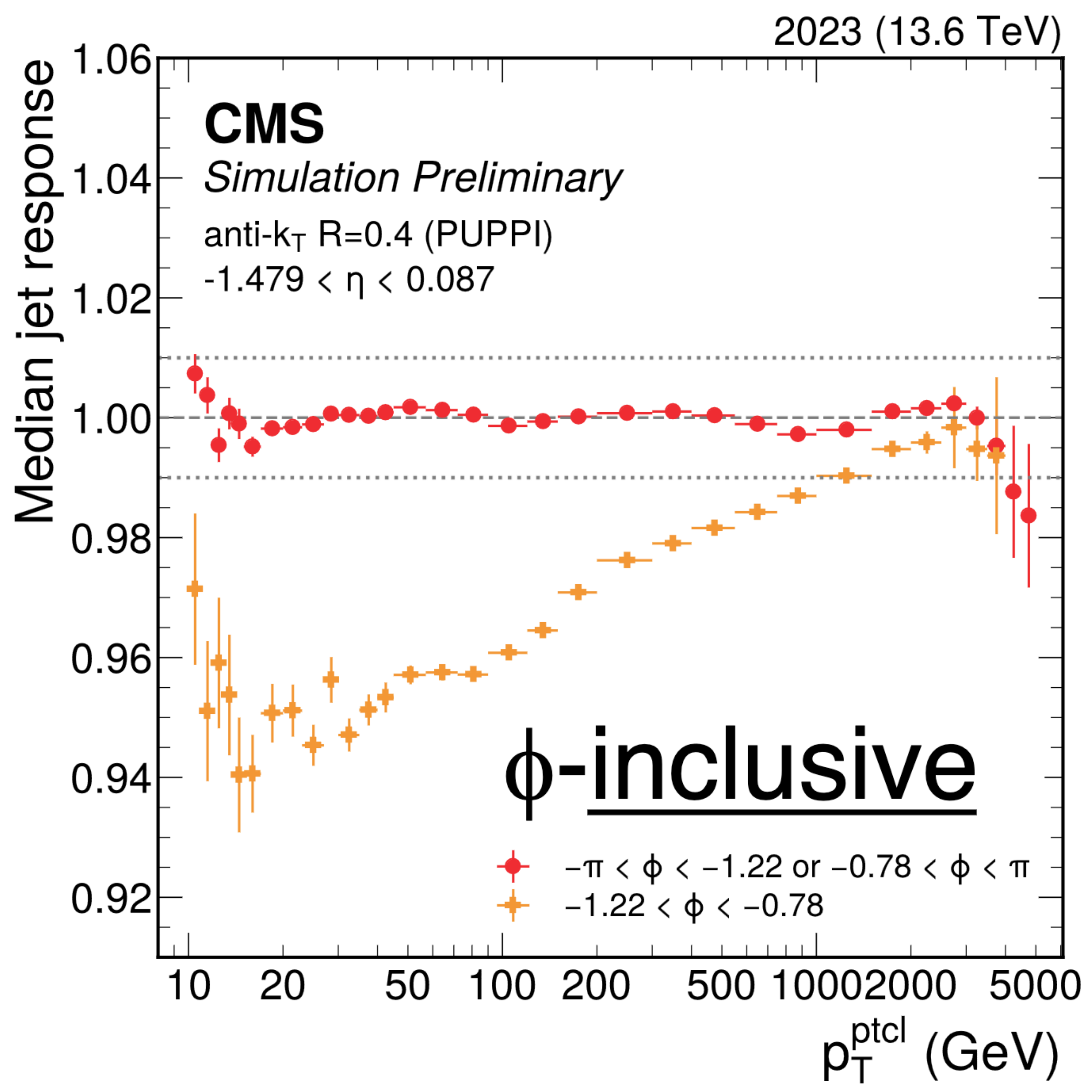




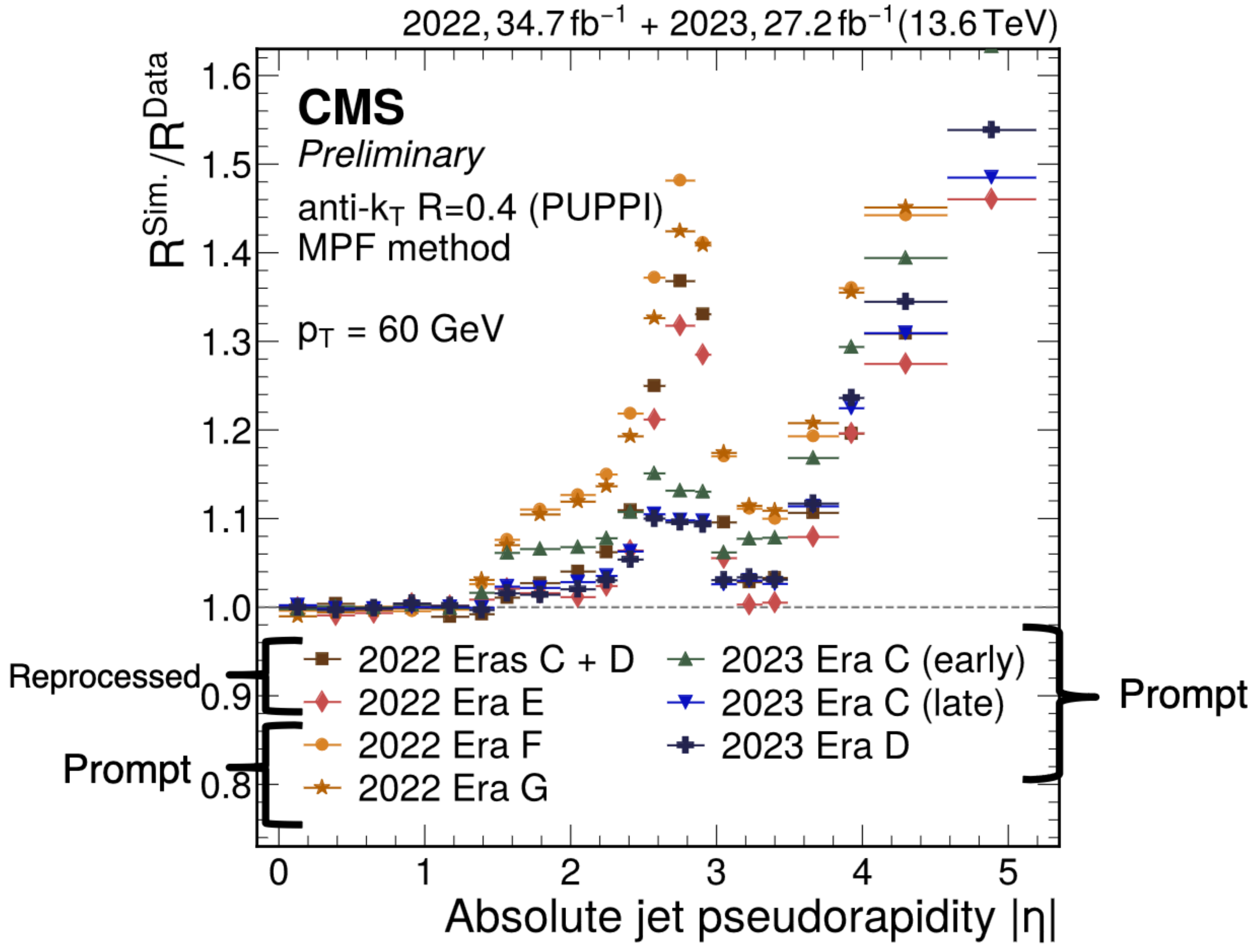
Fikri's talk

Zooming in

- Detector aging adds challenges to our reconstruction and calibration
  - This will become even more relevant at the HL-LHC



JES residual corrections



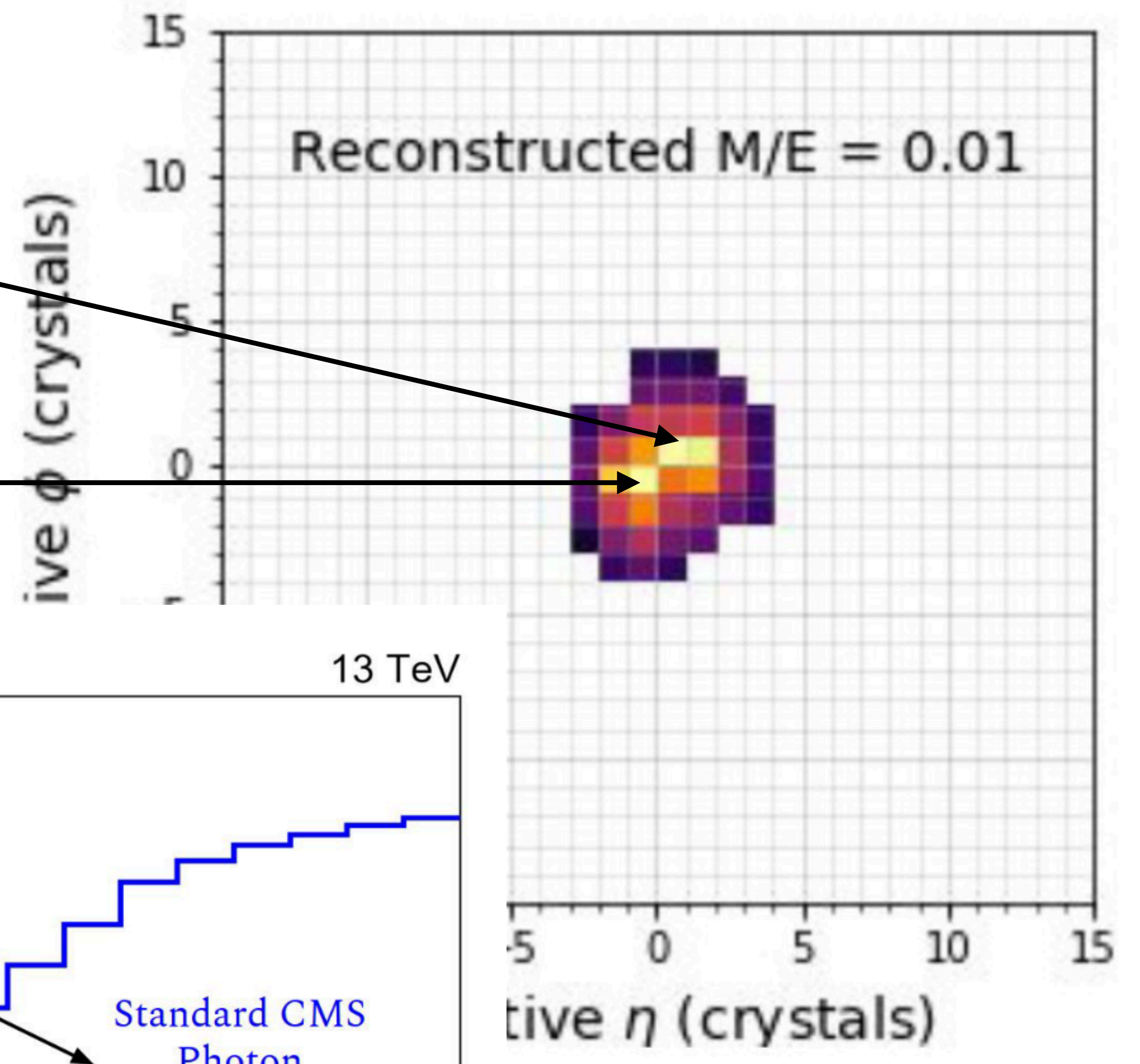
- Many effects can be mitigated or improved by dedicated solutions
  - Need good understanding of detector conditions, and strategies so we can handle these sorts of changes with relative simplicity

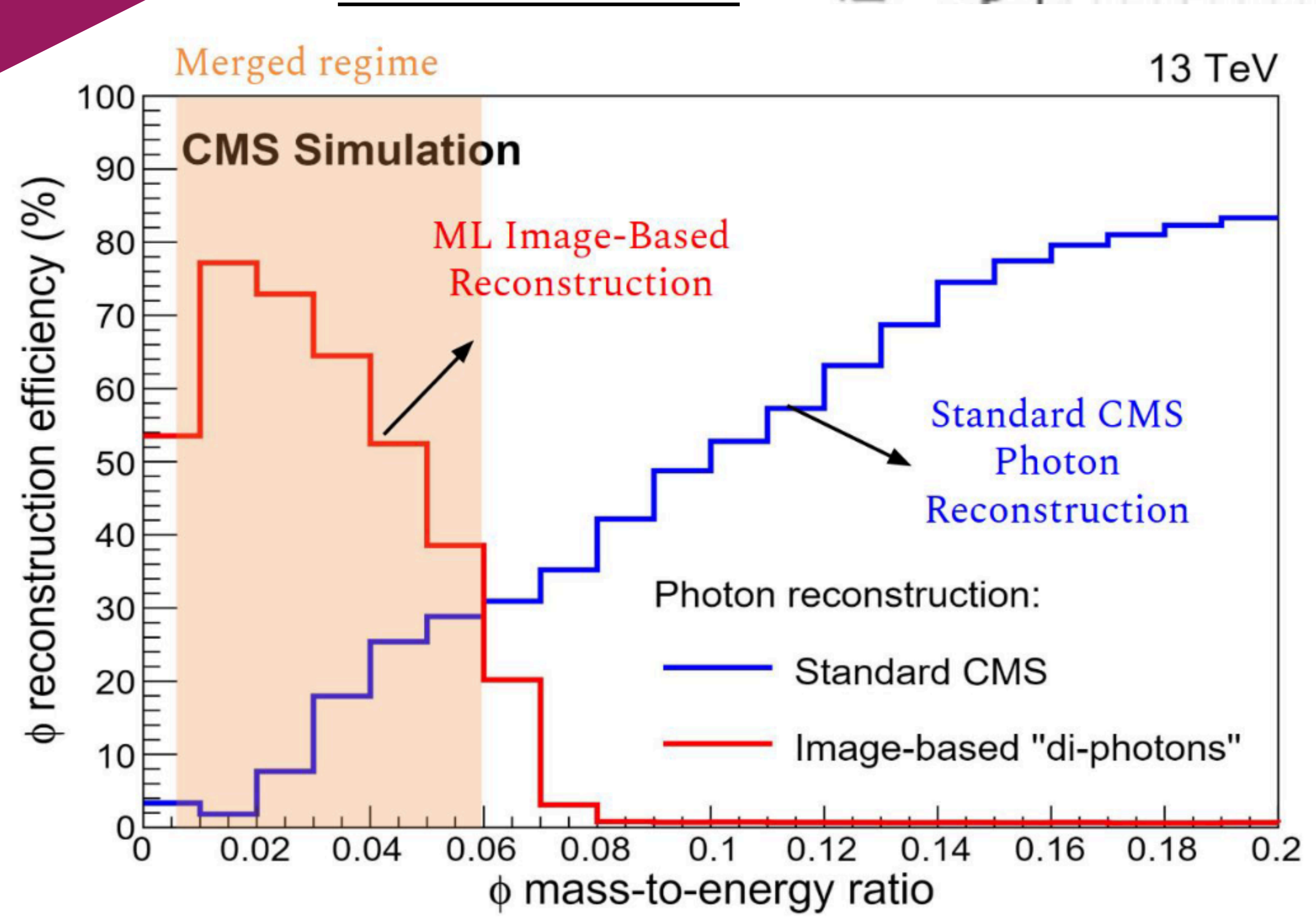
Zooming in

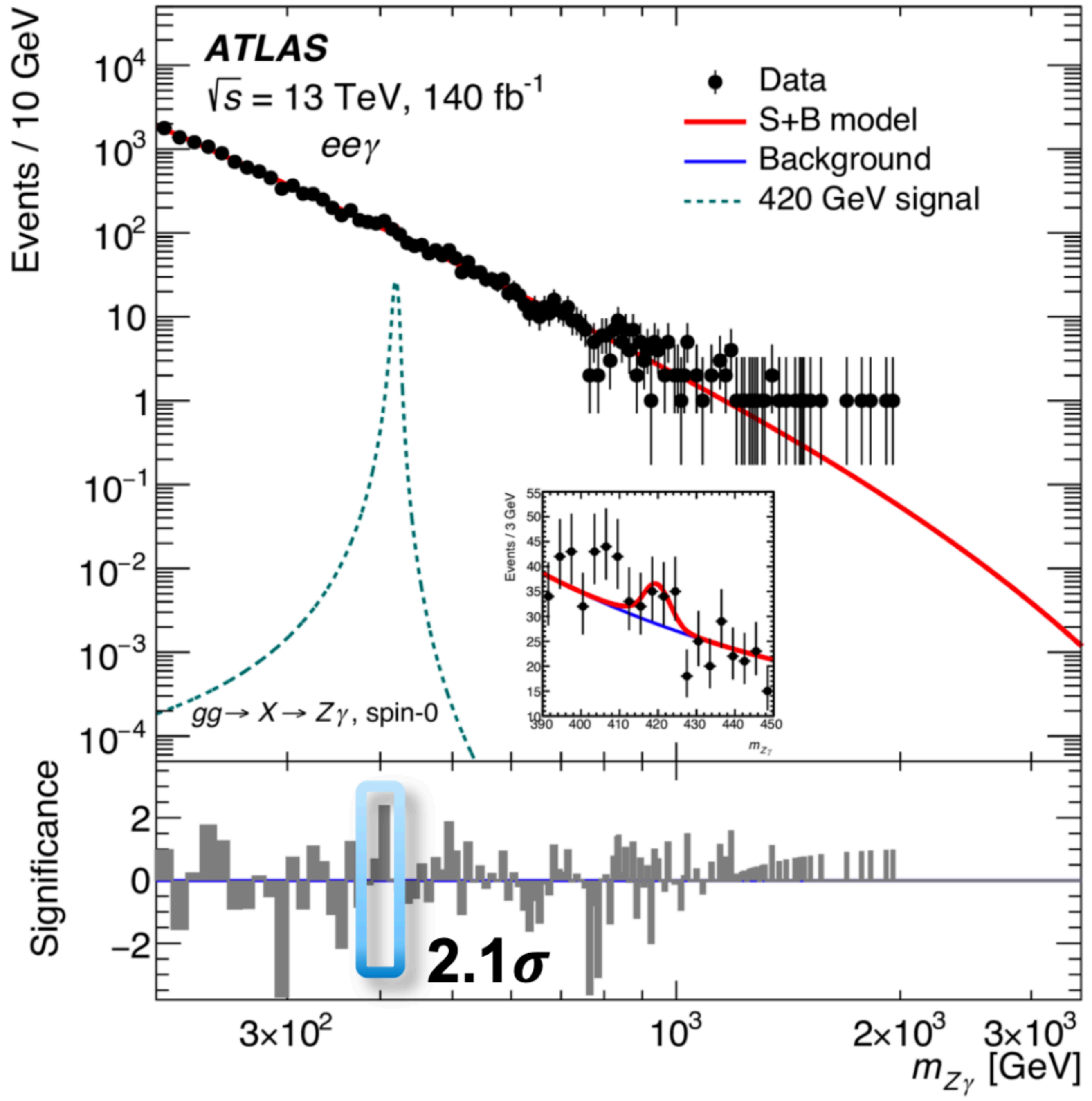
- Jets are not the only thing that can be boosted!
- CMS created a dedicated algorithm to separate showers from boosted di-photons for a BSM search
  - Using hadronic decays within jets to validate the analysis strategy (reconstructing η's)

Overlapping EM showers from two photons

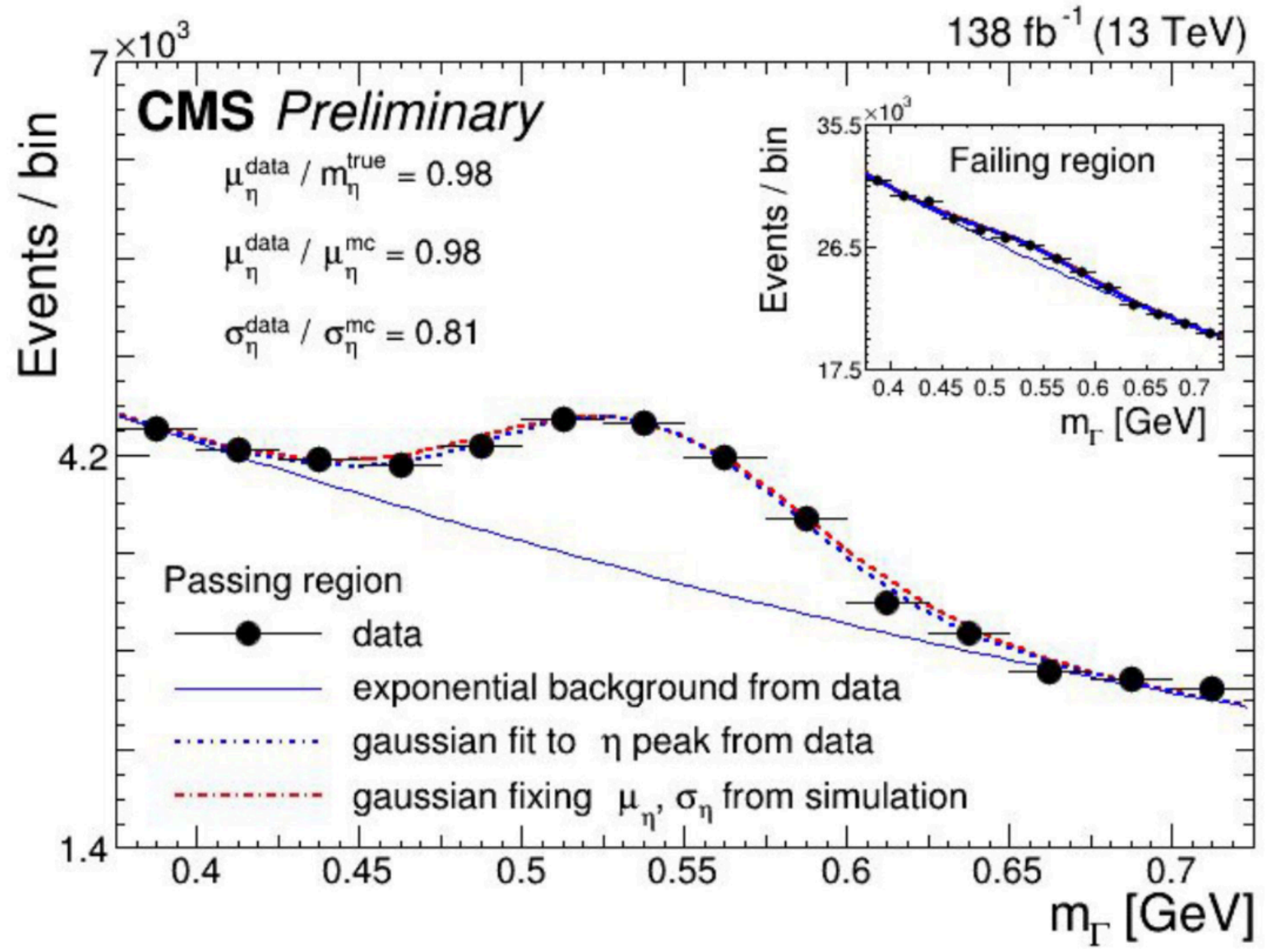
Simon's talk







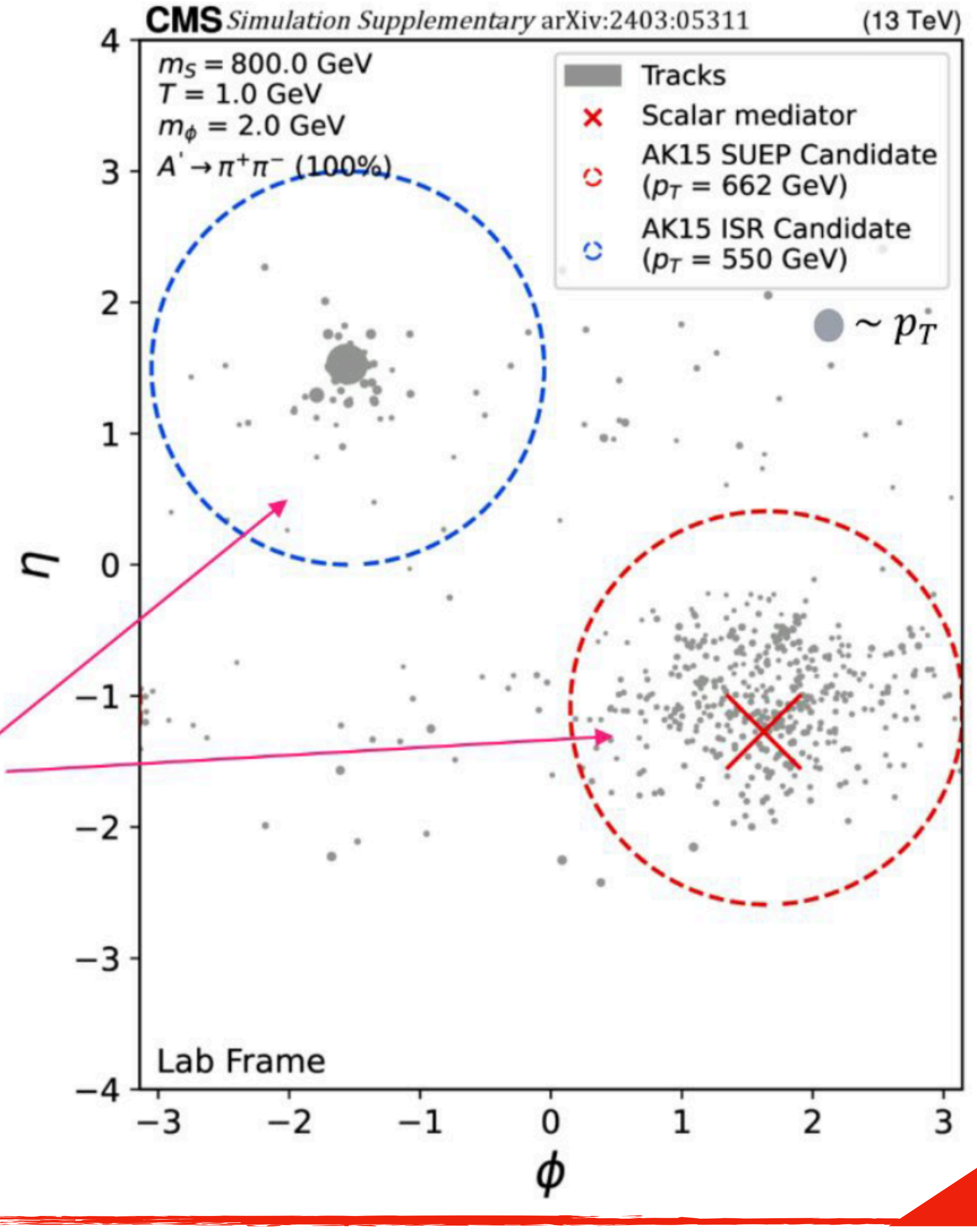
- ATLAS has a dedicated algorithm for boosted di-electrons



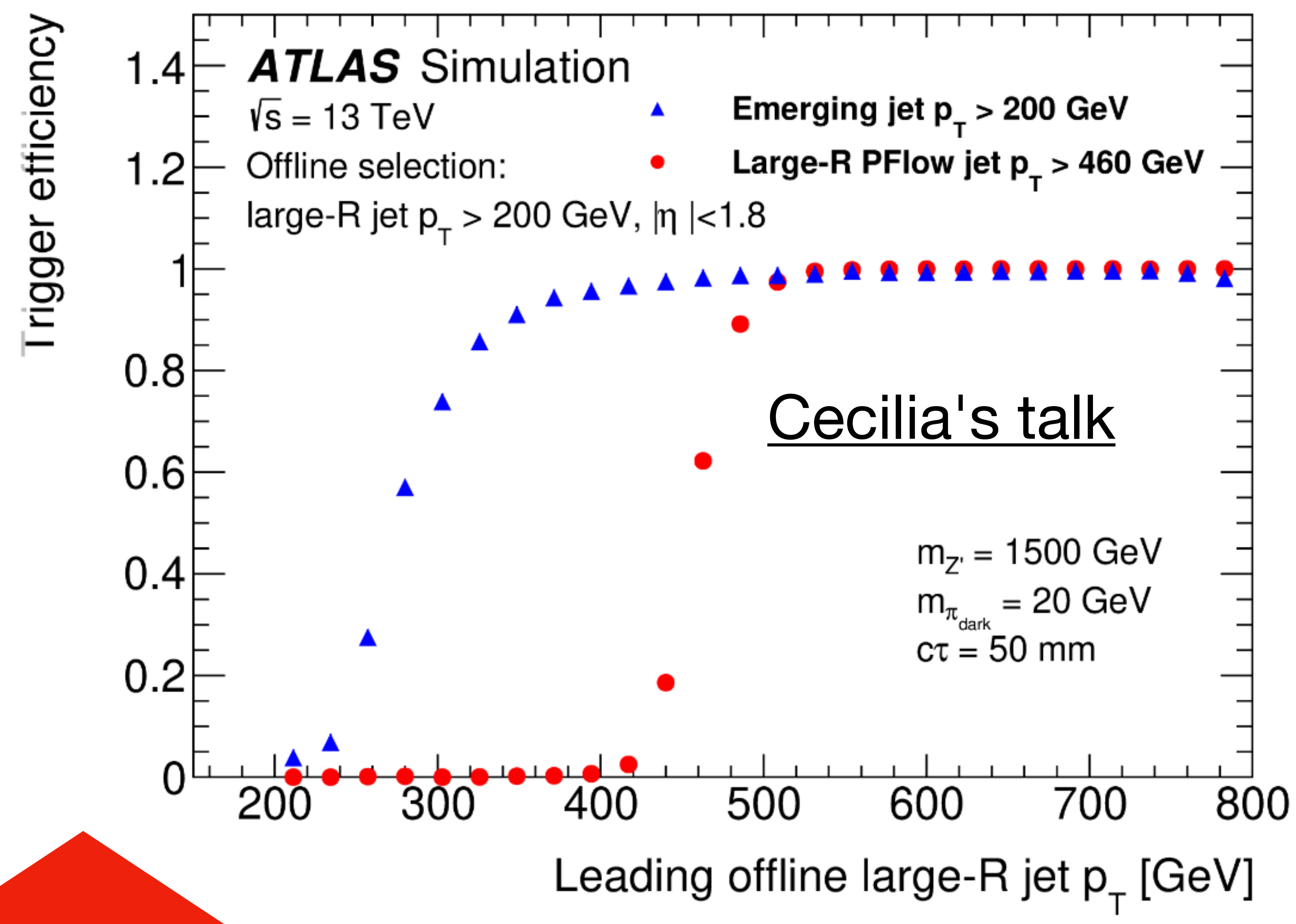
Zooming in

- Many searches need dedicated reconstruction and observables to target challenging signatures

Simon's talk

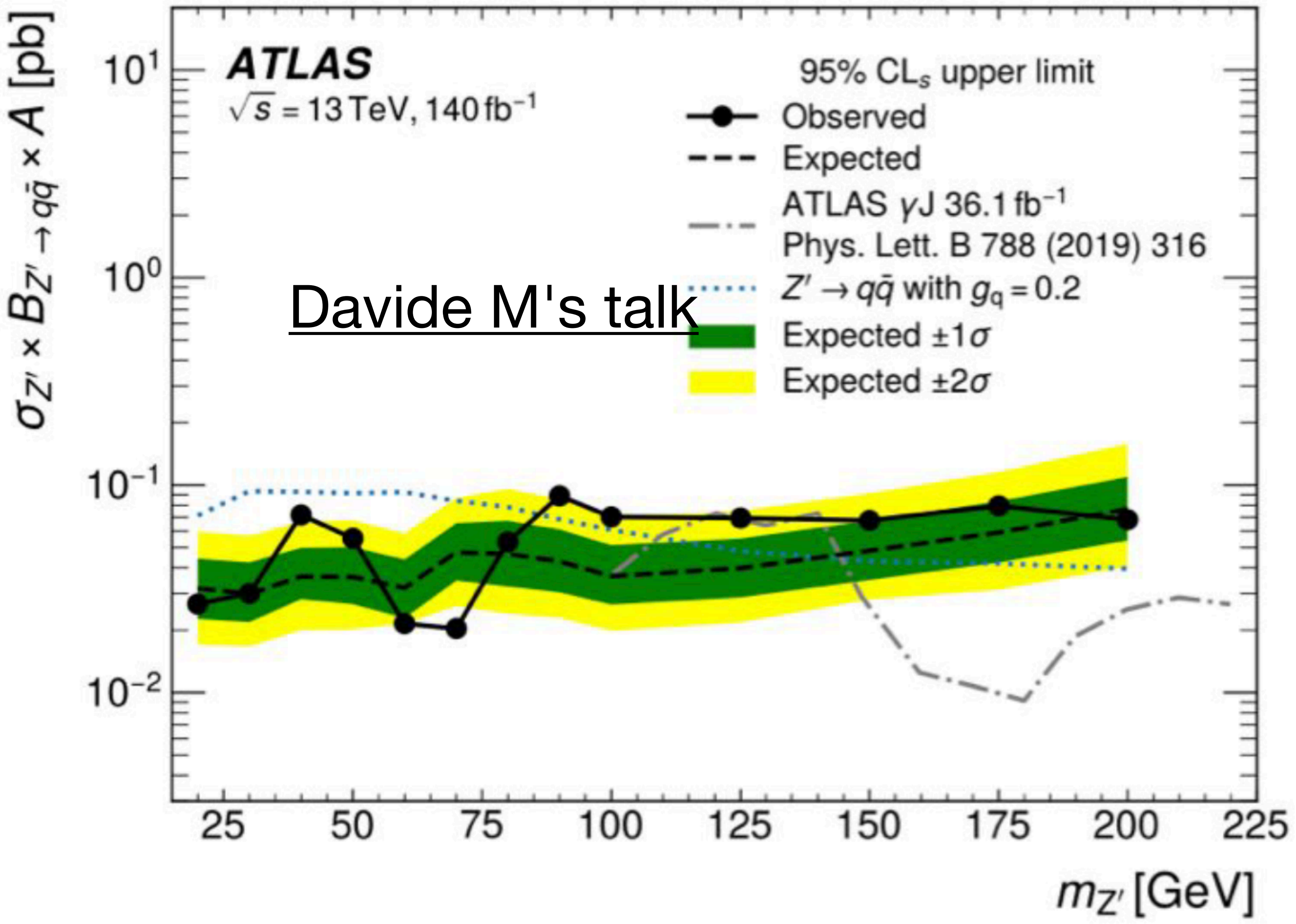


Recoiling SUEP and ISR systems

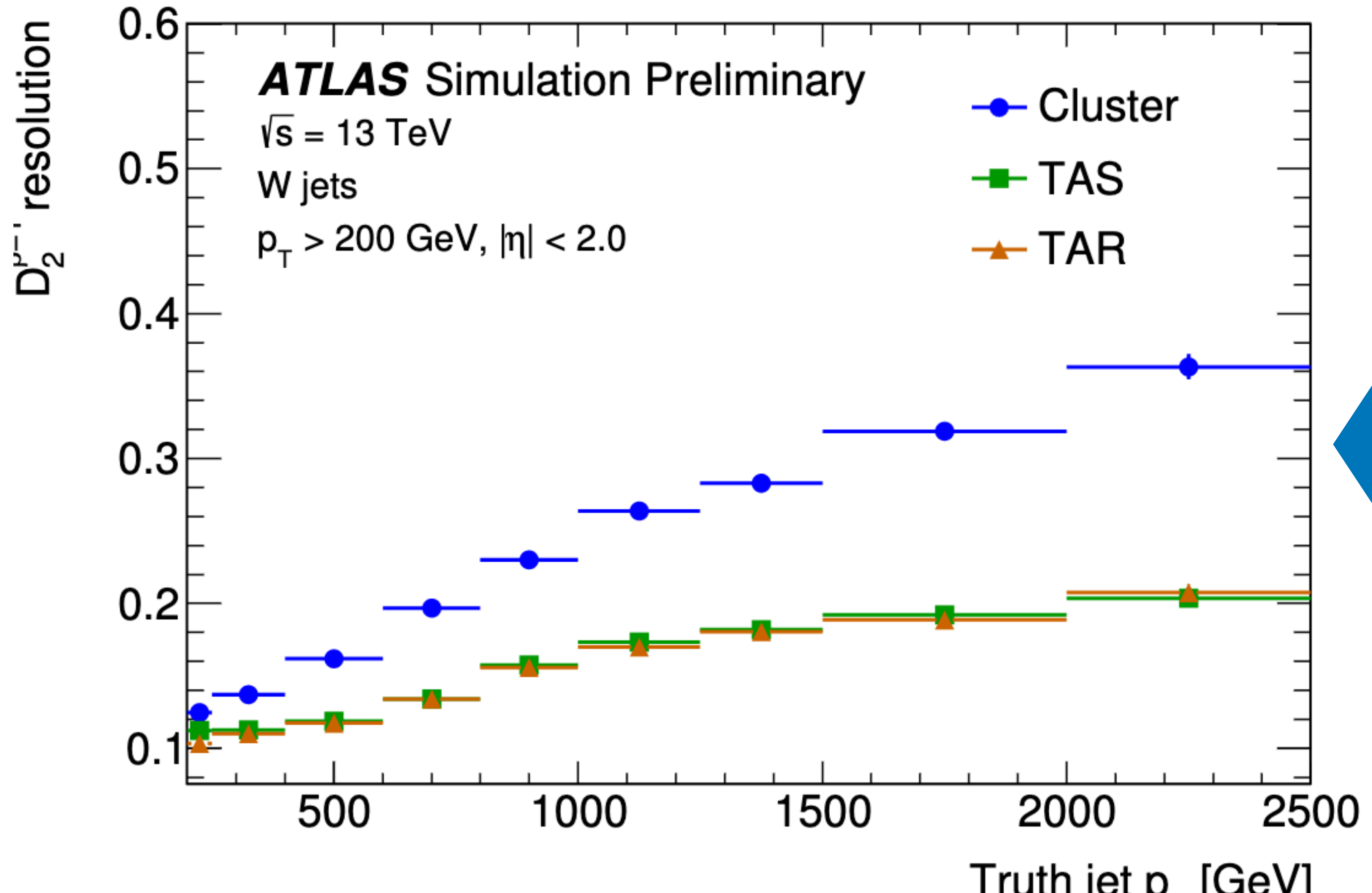


Cecilia's talk

- Unusual structure that does not get captured by the standard algorithms

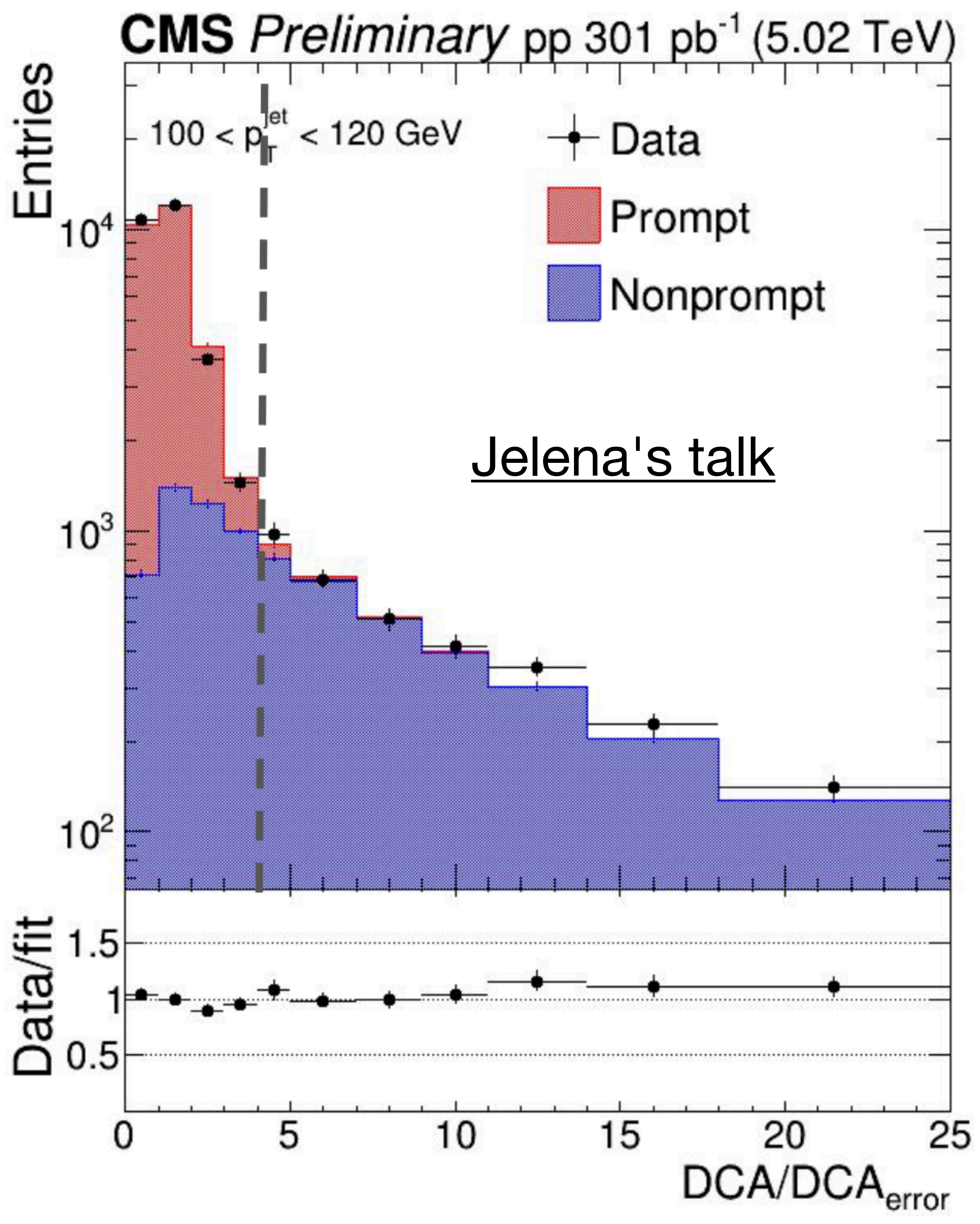


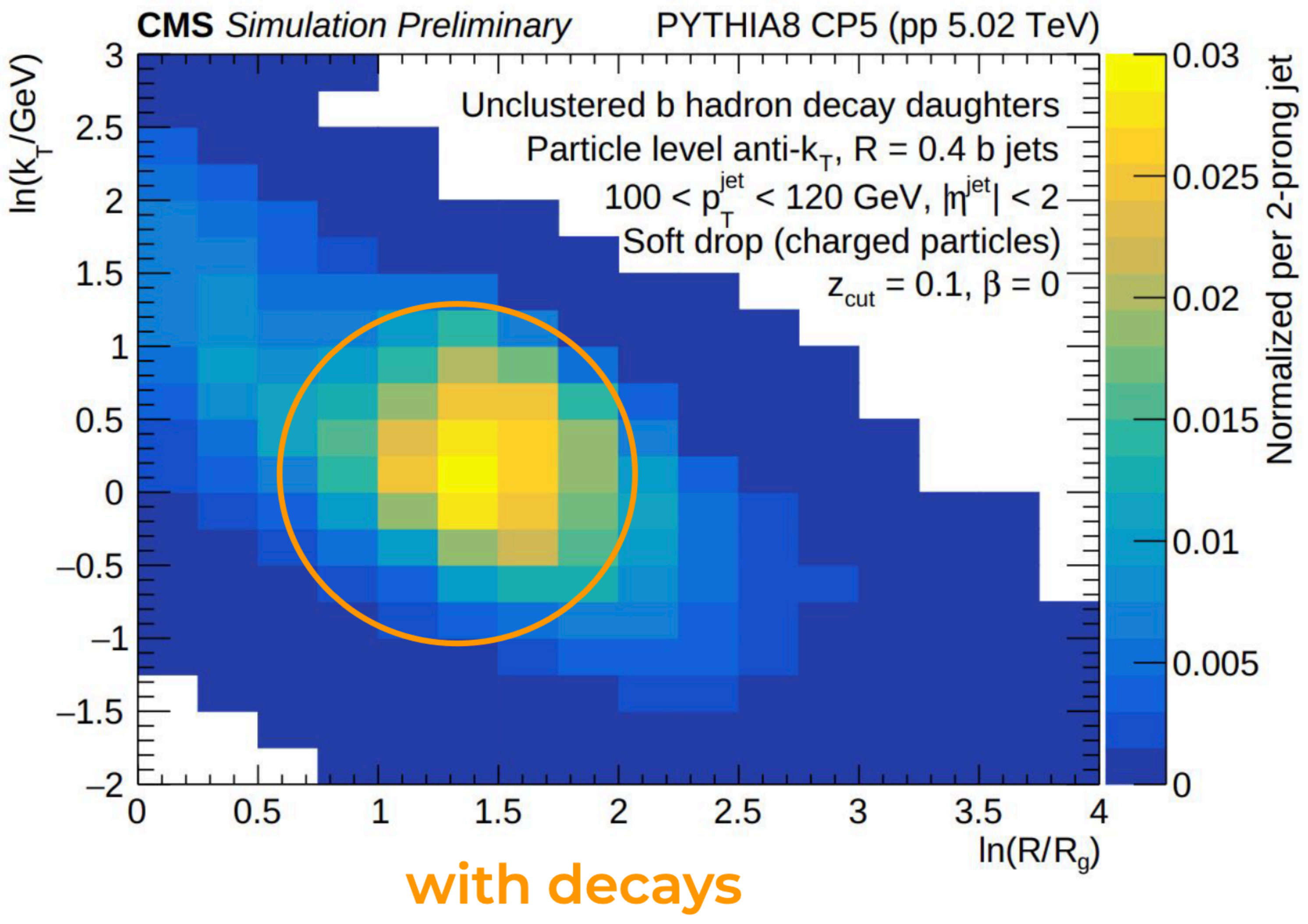
Davide M's talk

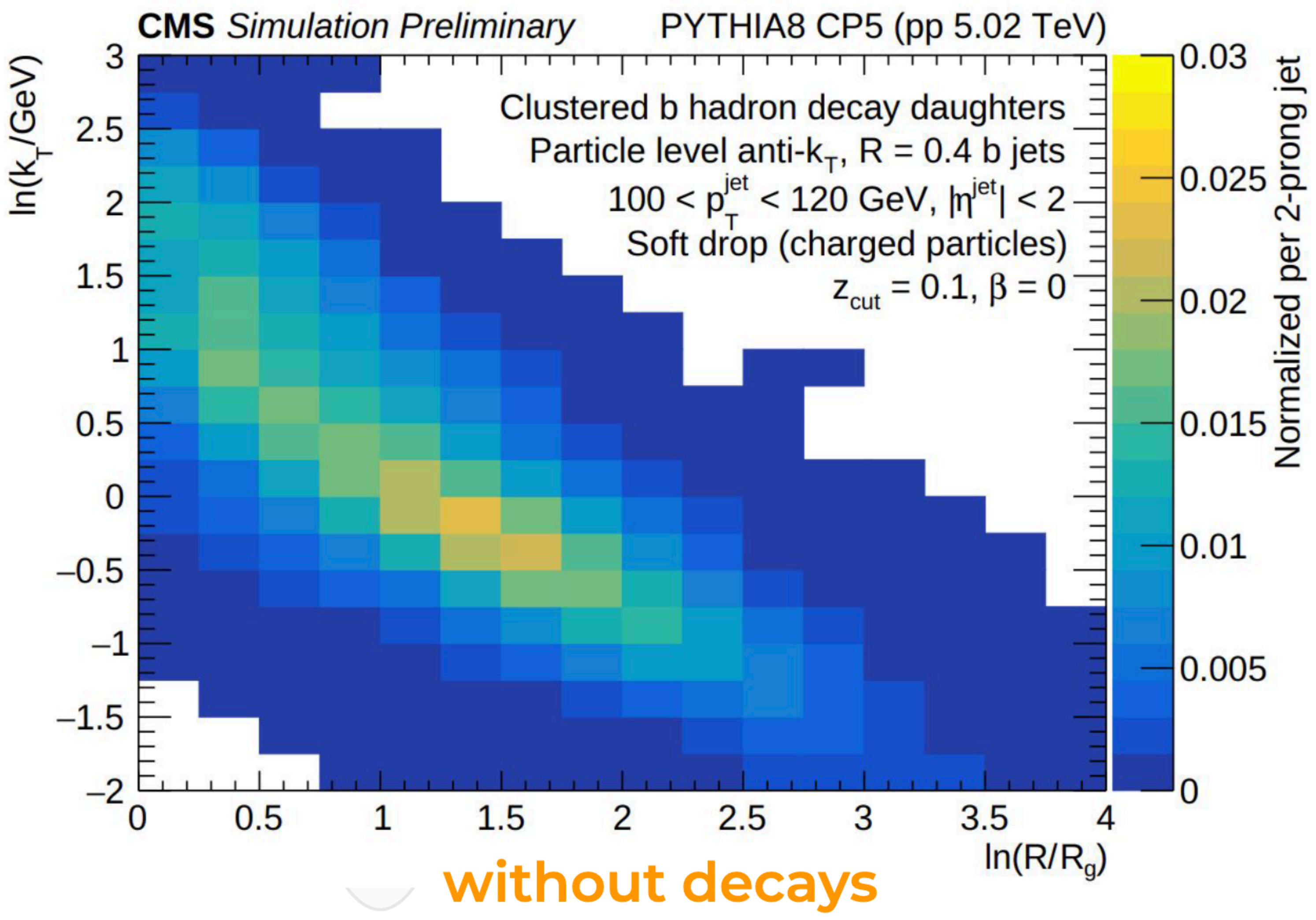


- Difficult phase space where standard calibrations do not apply

Zooming in

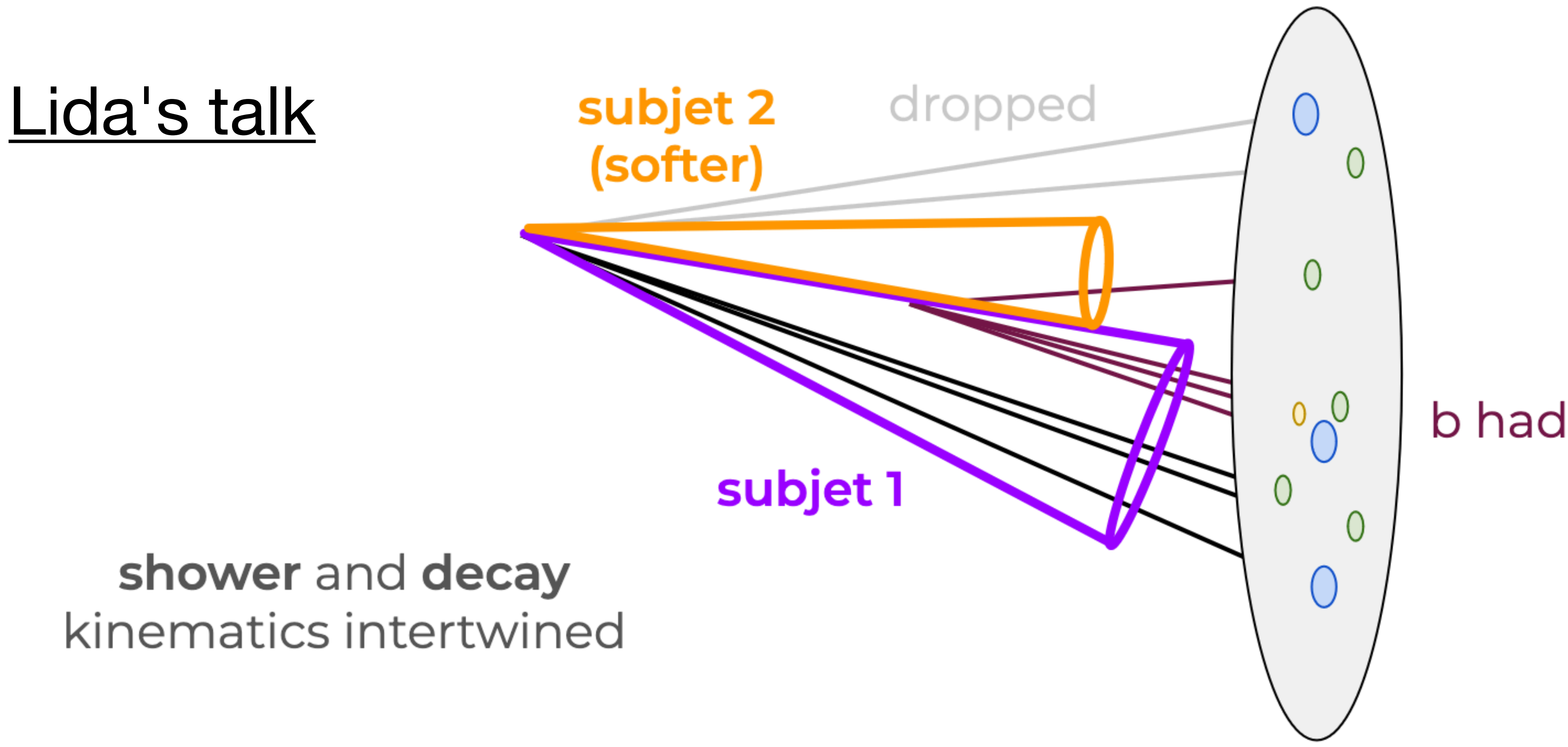






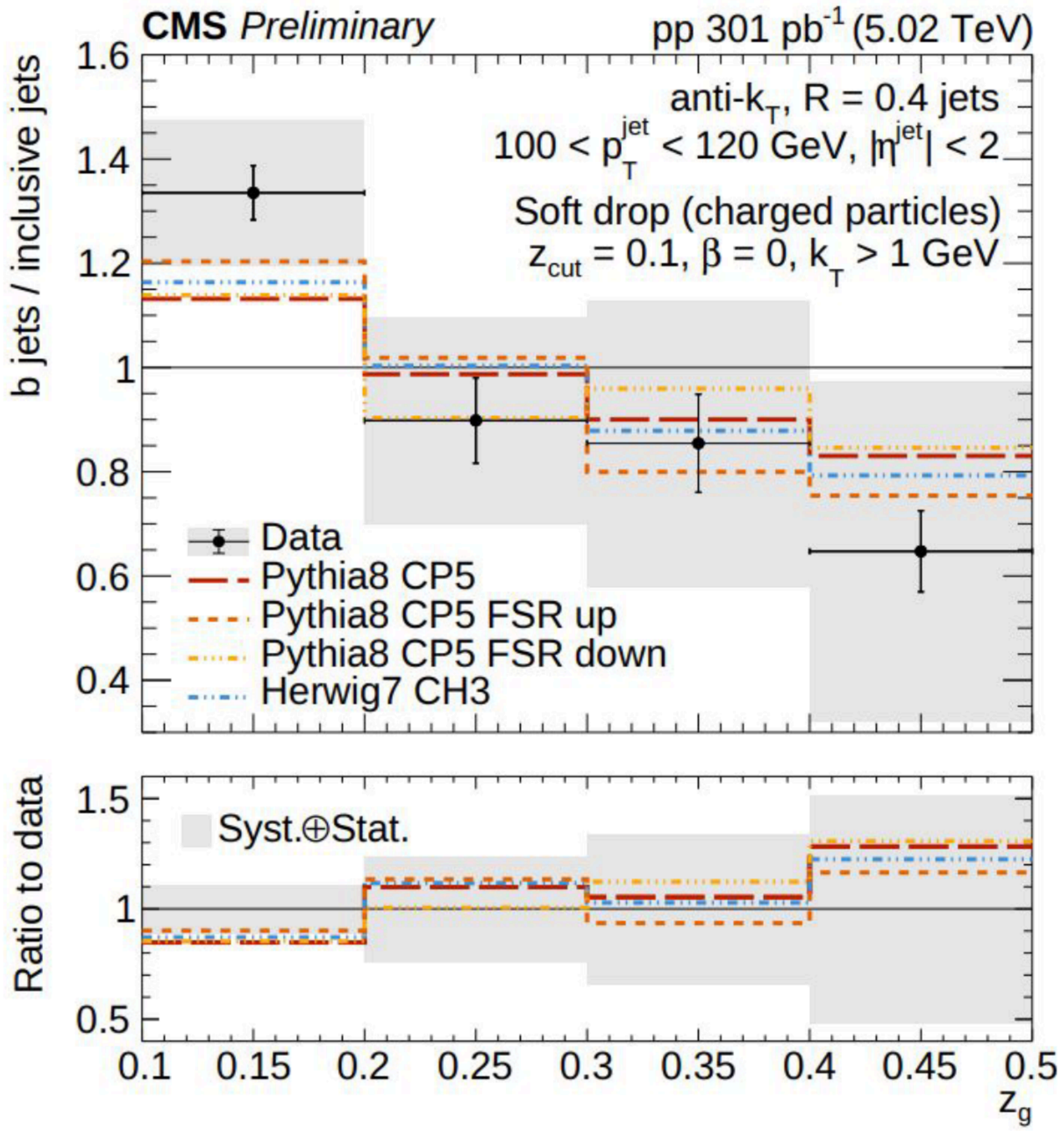
- Starting to see more measurements of substructure of heavy flavor jets Lida's talk
- Lots of interesting physics to explore, but also specific experimental challenges
  - Jet substructure can be spoiled by the B/D meson decays → need to reconstruct these!

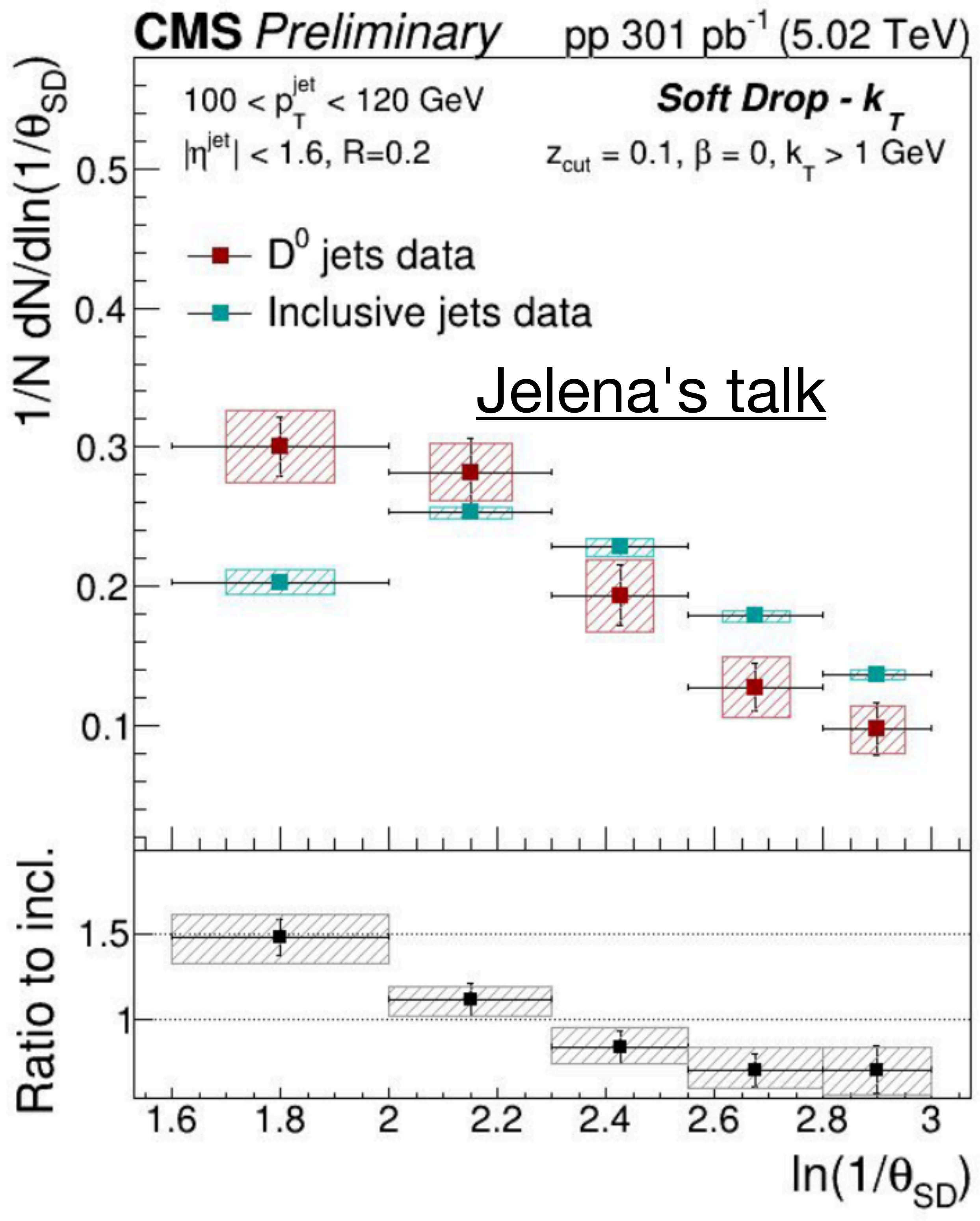
Heavy hadron decay daughters **do not** follow angular ordering

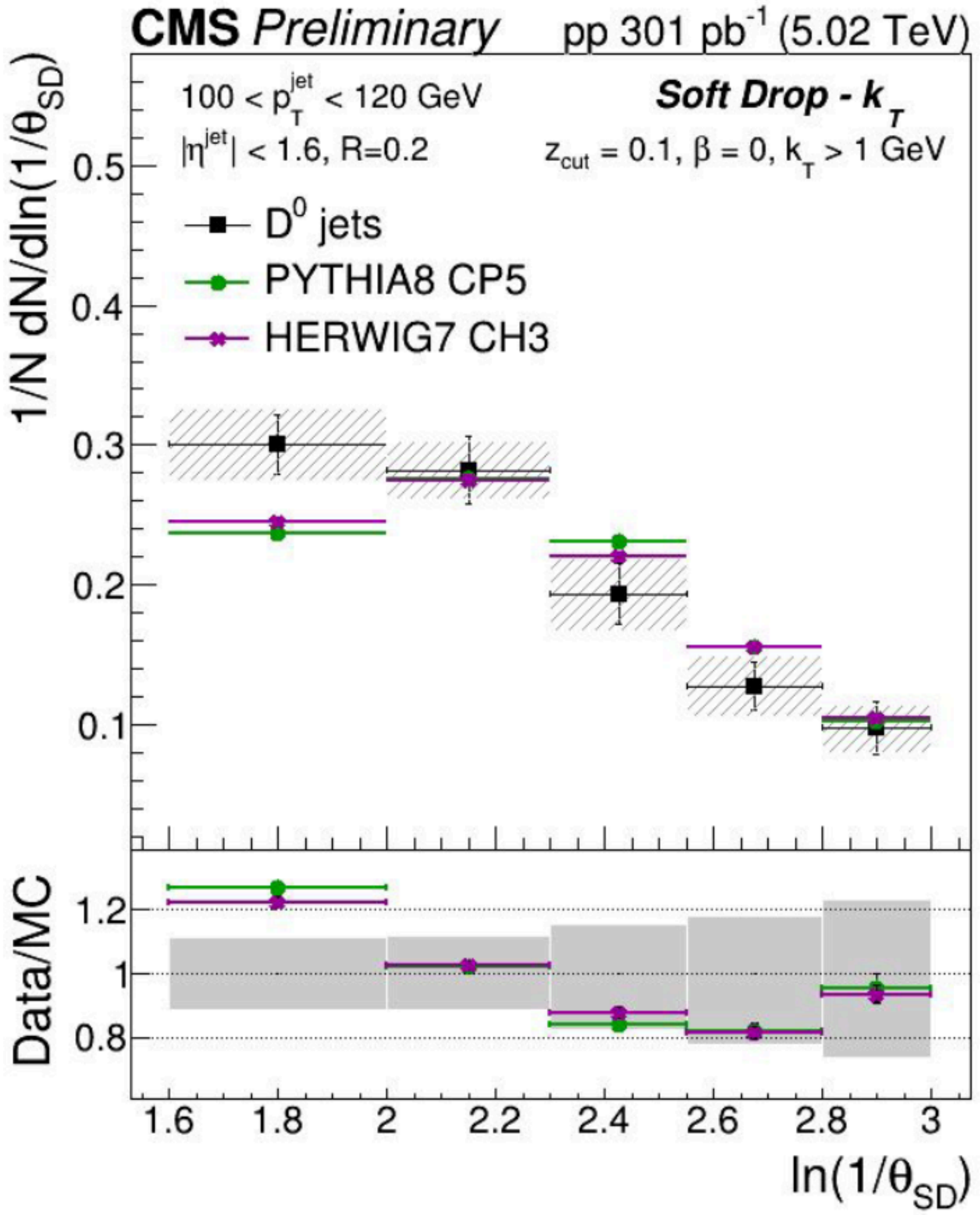


Zooming in

Lida's talk



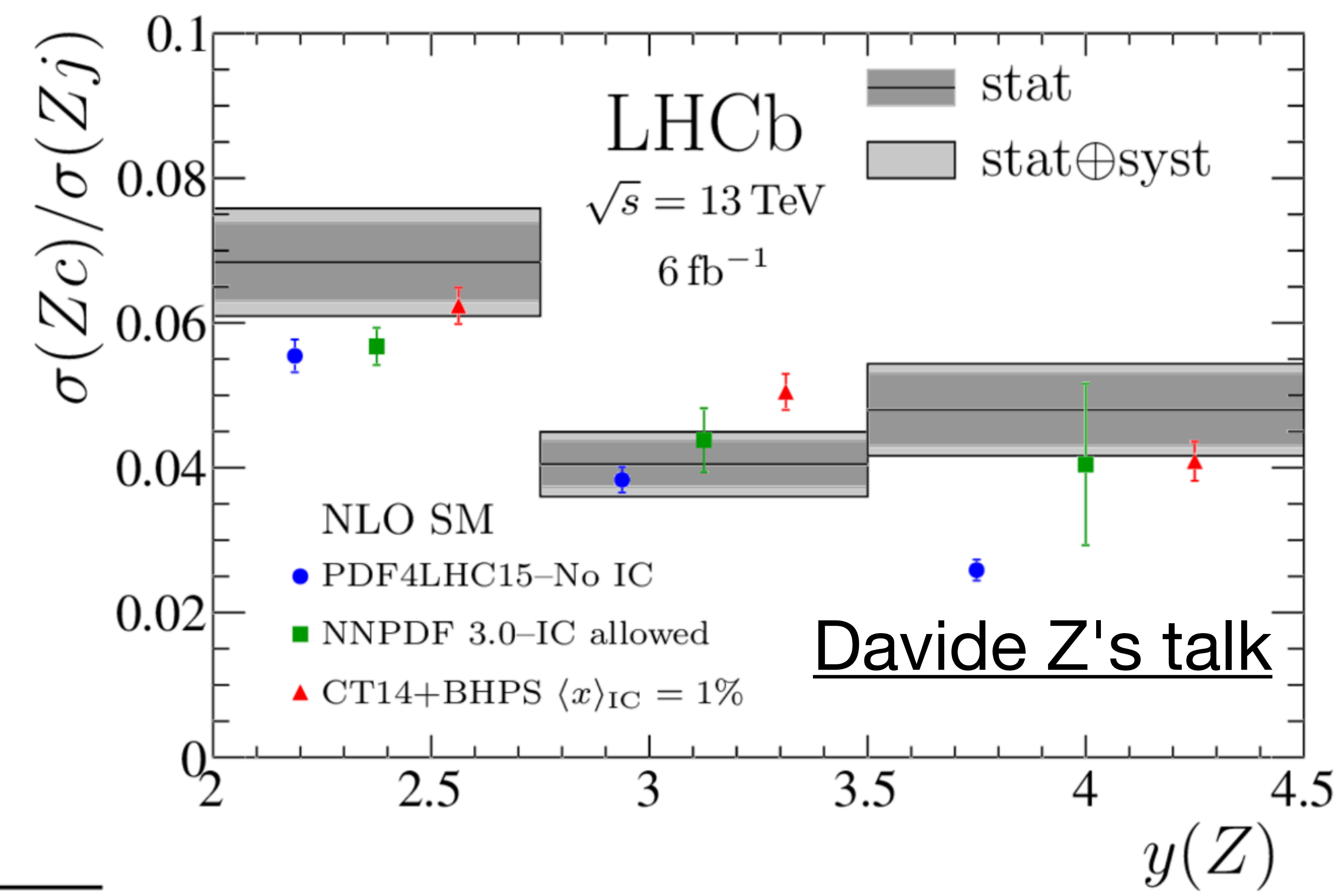




- Clear differences between inclusive and heavy flavor jets
  - More work still needed for full interpretation
  - *… but have potential to provide sensitivity to dead cone effects*

Zooming in

- Measurements of final states with heavy-flavor jets can be used to test model, and give sensitivity to the presence of intrinsic charm



Factorized changes to the modeling enable detailed studies of the importance of different effects!

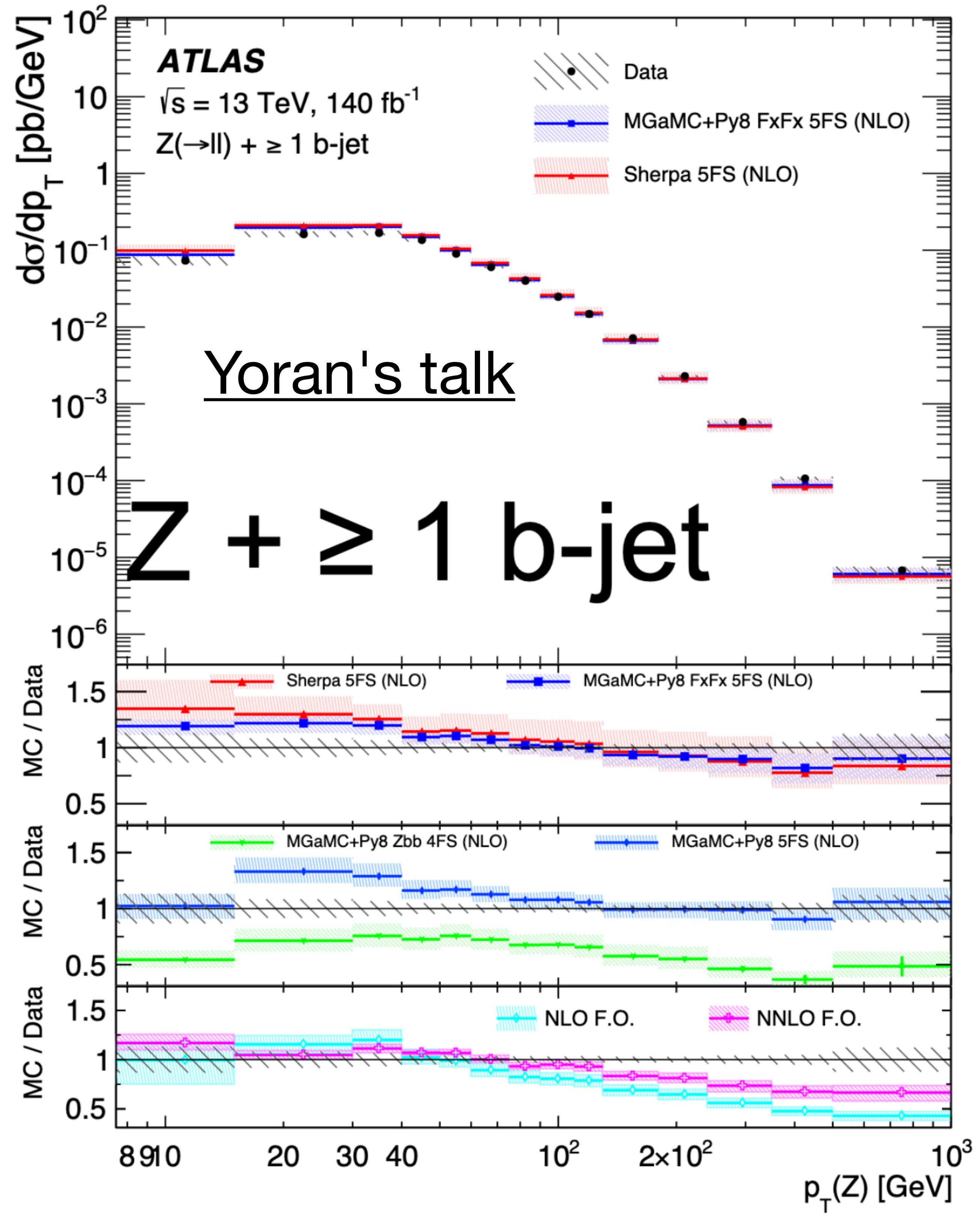
FS in matrix-element calculation

IC-component in proton PDFs

Higher order terms in QCD

Generator/settings	Flav. scheme	PDF	LHAPDF ID
		Main MC samples	
MGAMC+PY8 FxFx	5FS	NNPDF3.1 (NNLO) LuxQED	325100
SHERPA 2.2.11	5FS	NNPDF3.0 (NNLO)	303200
		Predictions to test various flavour schemes	
MGAMC+PY8	5FS	NNPDF2.3 (NLO)	229800
MGAMC+PY8 *Zbb*	4FS	NNPDF3.1 (NLO) PCH	321500
MGAMC+PY8 *Zcc*	3FS	NNPDF3.1 (NLO) PCH	321300
		Intrinsic charm (IC) predictions	
MGAMC+PY8 FxFx	5FS	NNPDF4.0 (NNLO) PCH (no IC)	332100
		NNPDF4.0 (NNLO)	331100
		NNPDF4.0 (NNLO) EMC+LHCbZc	– [24]
		CT18 (NNLO) (no IC)	14000
		CT18FC – CT18 BHPS3	14087
		CT18FC – CT18 MCM-E	14093
		CT14 (NNLO) (no IC)	13000
		CT14 (NNLO)IC – BHPS1	13082
		CT14 (NNLO)IC – BHPS2	13083
		Fixed-order predictions [3]	
NLO	5FS	PDF4LHC21	93000
NNLO	5FS	PDF4LHC21	93000

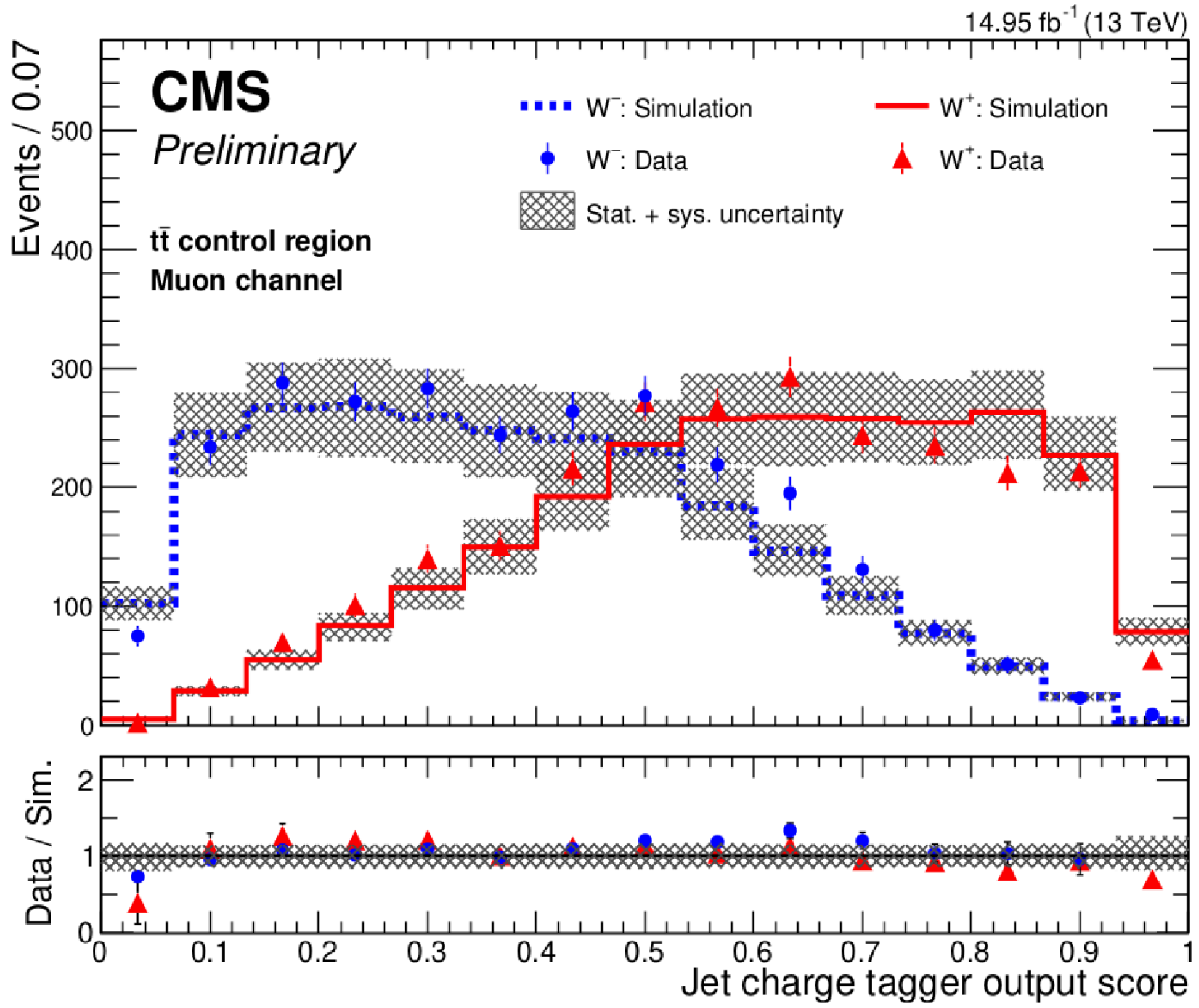
Test multiple theoretical predictions



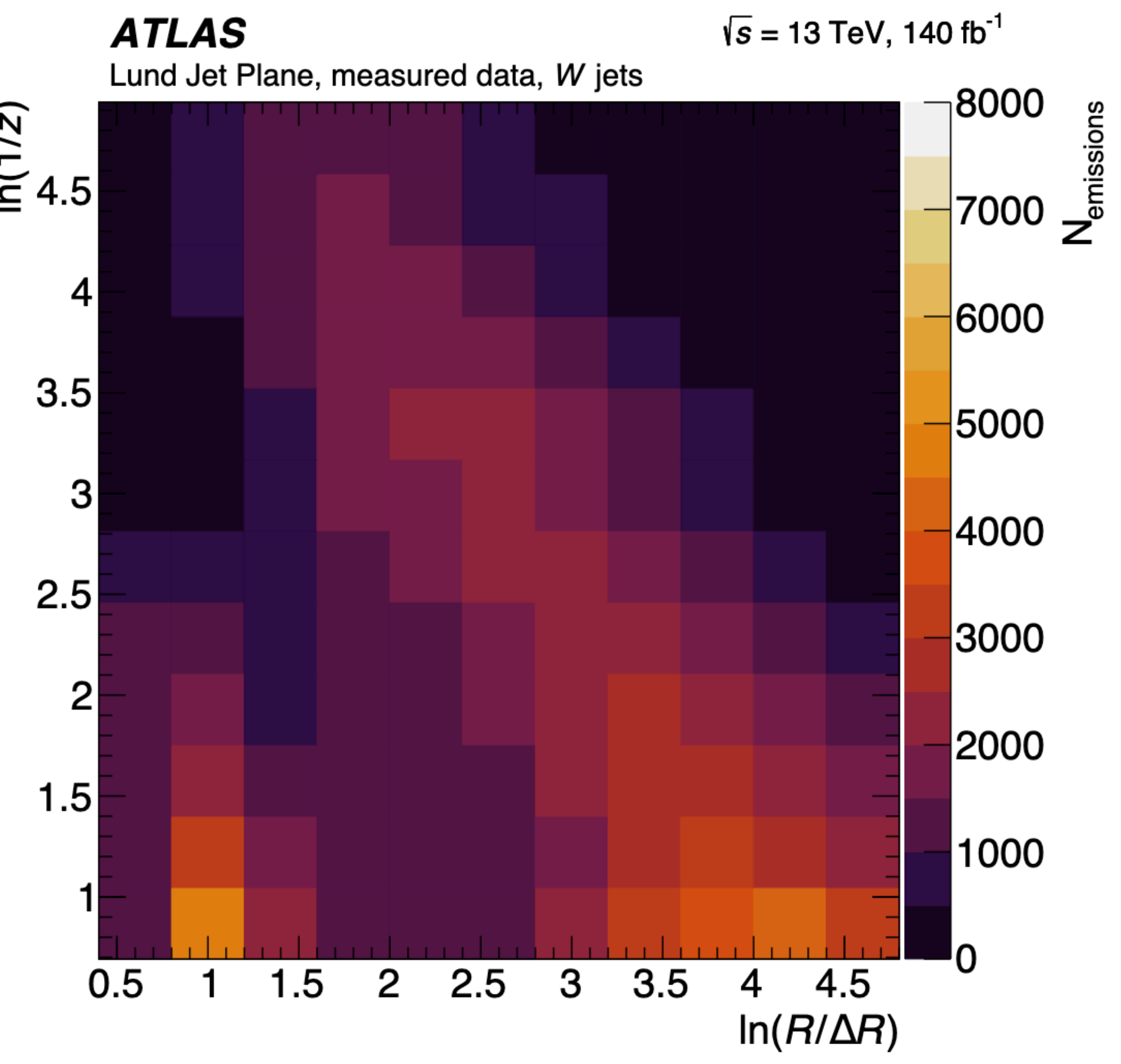
Zooming in

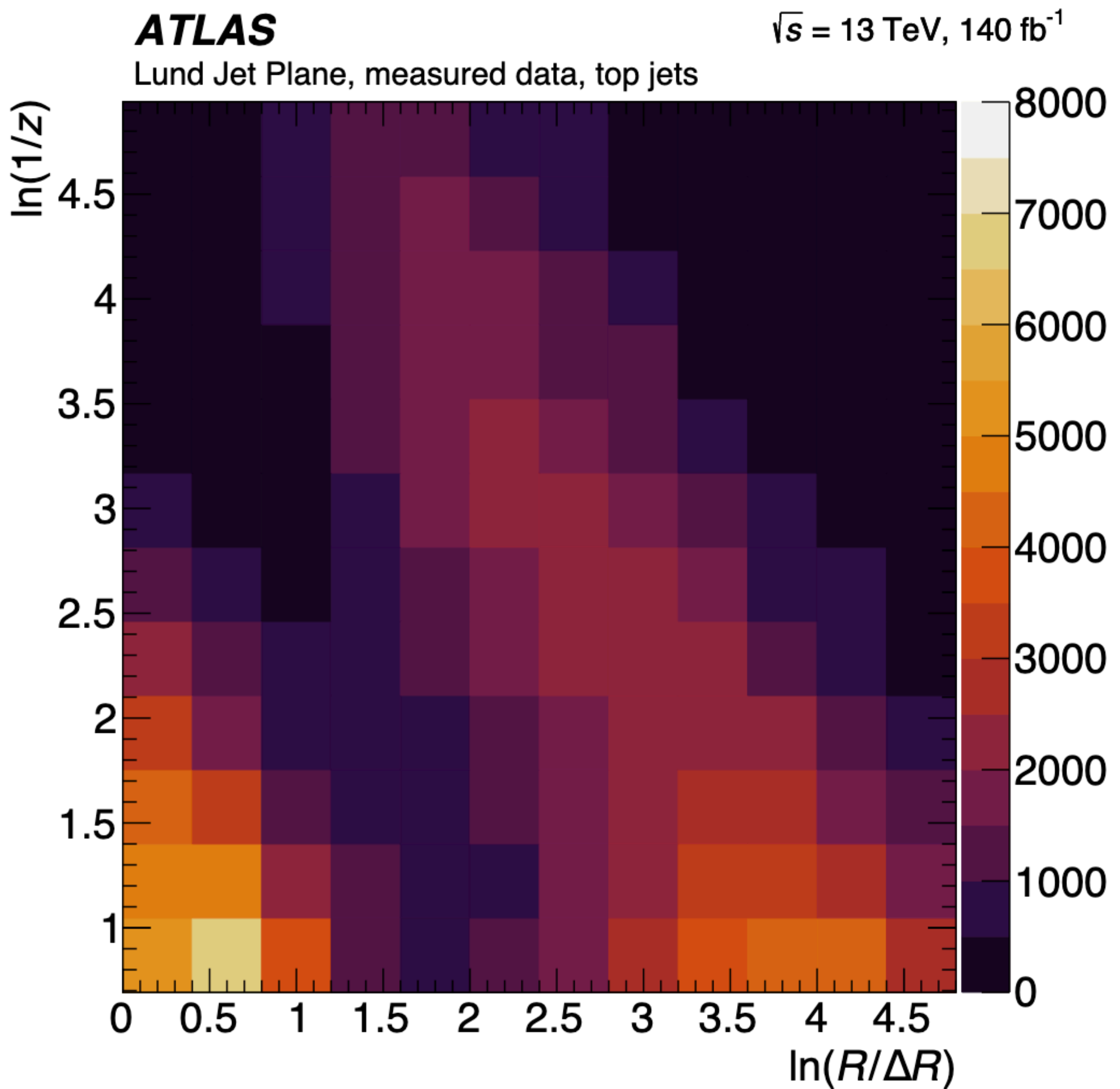
Komal's poster Donato's talk

- Not just aiming to identify 2-prong structure → aiming at distinguishing between different hadrons (and their charges)
  - Opens up more possibilities for electroweak measurements in semi- or fully-hadronic channels



Mario's talk

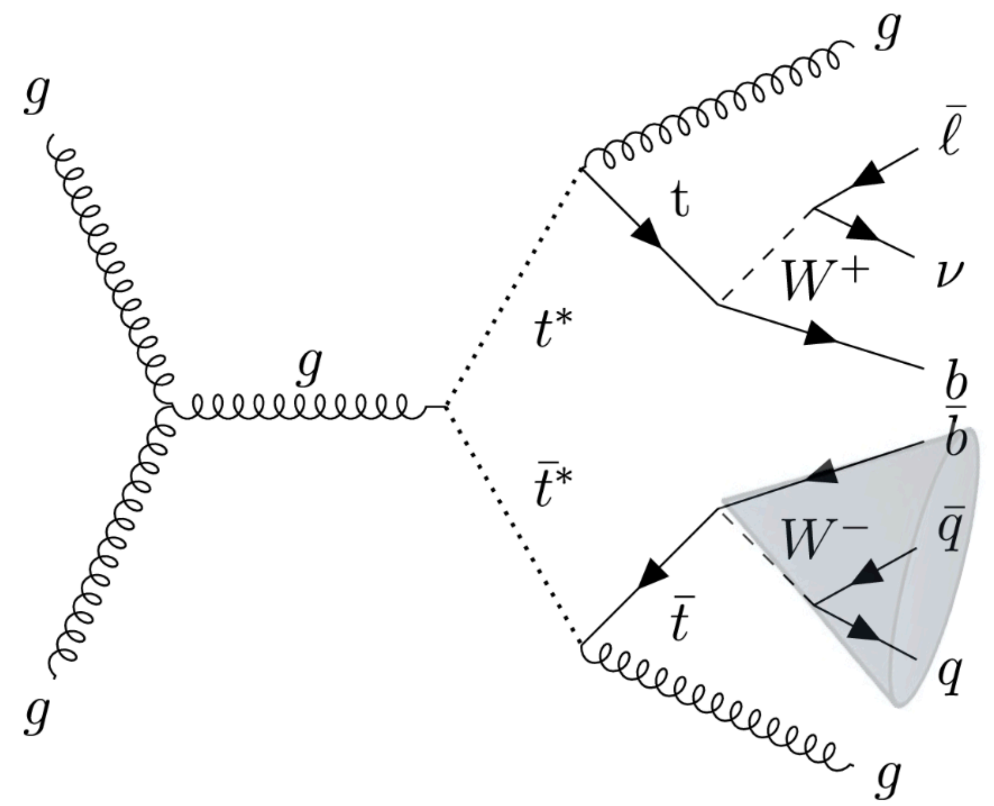


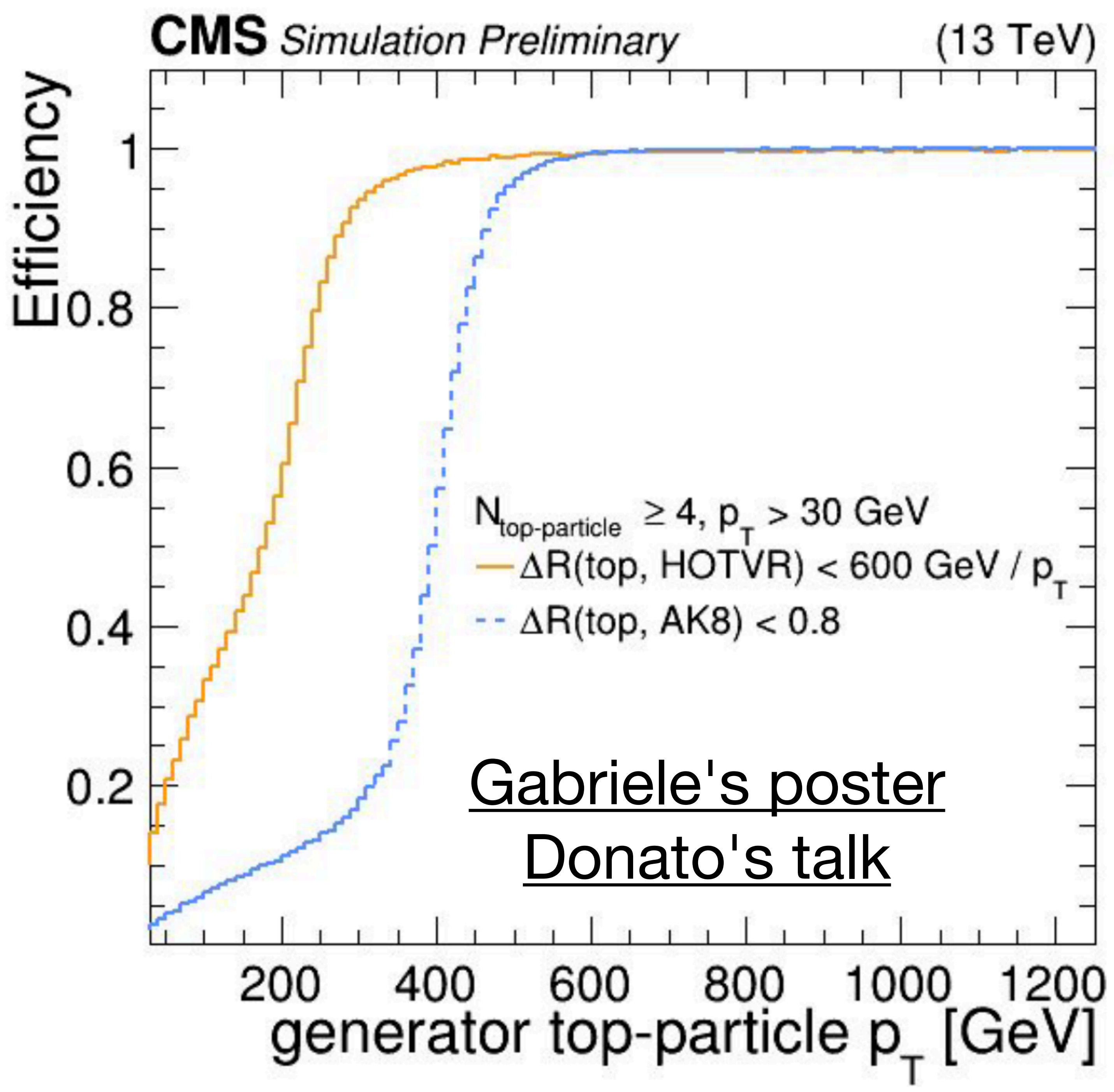


- Dedicated measurements of the substructure of boosted top jets
- Much more complex than q/g jets, but can give insight into the details of their jet formation

Zooming in

- Transition between resolved an boosted channels is difficult to cover efficiently
  - Can instead use variable radius jets to increase the reach of boosted jets while minimizing sensitivity to other effects

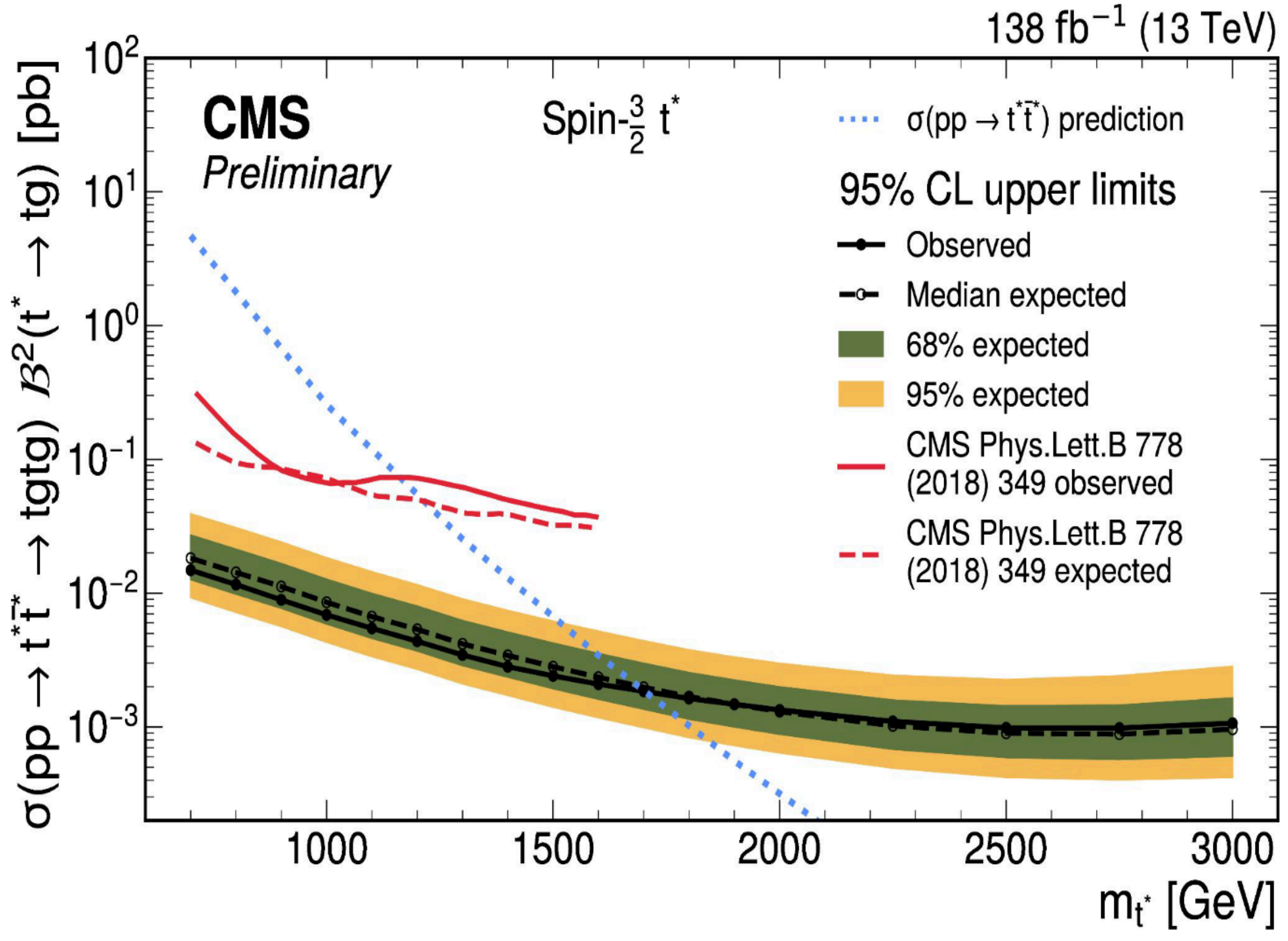




Gabriele's poster

Donato's talk

- HOTVR has been used by CMS to enhance sensitivity to models like t*

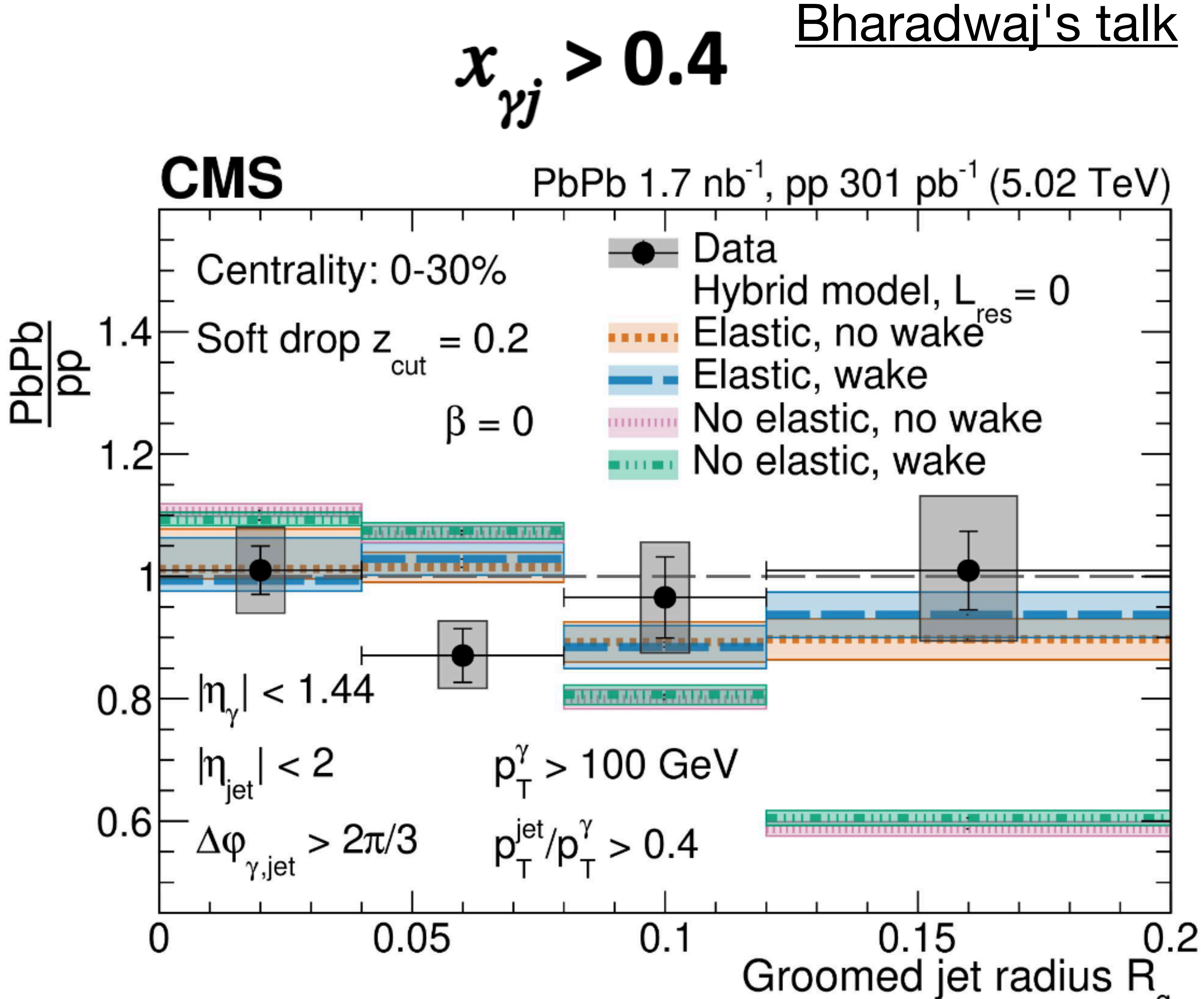


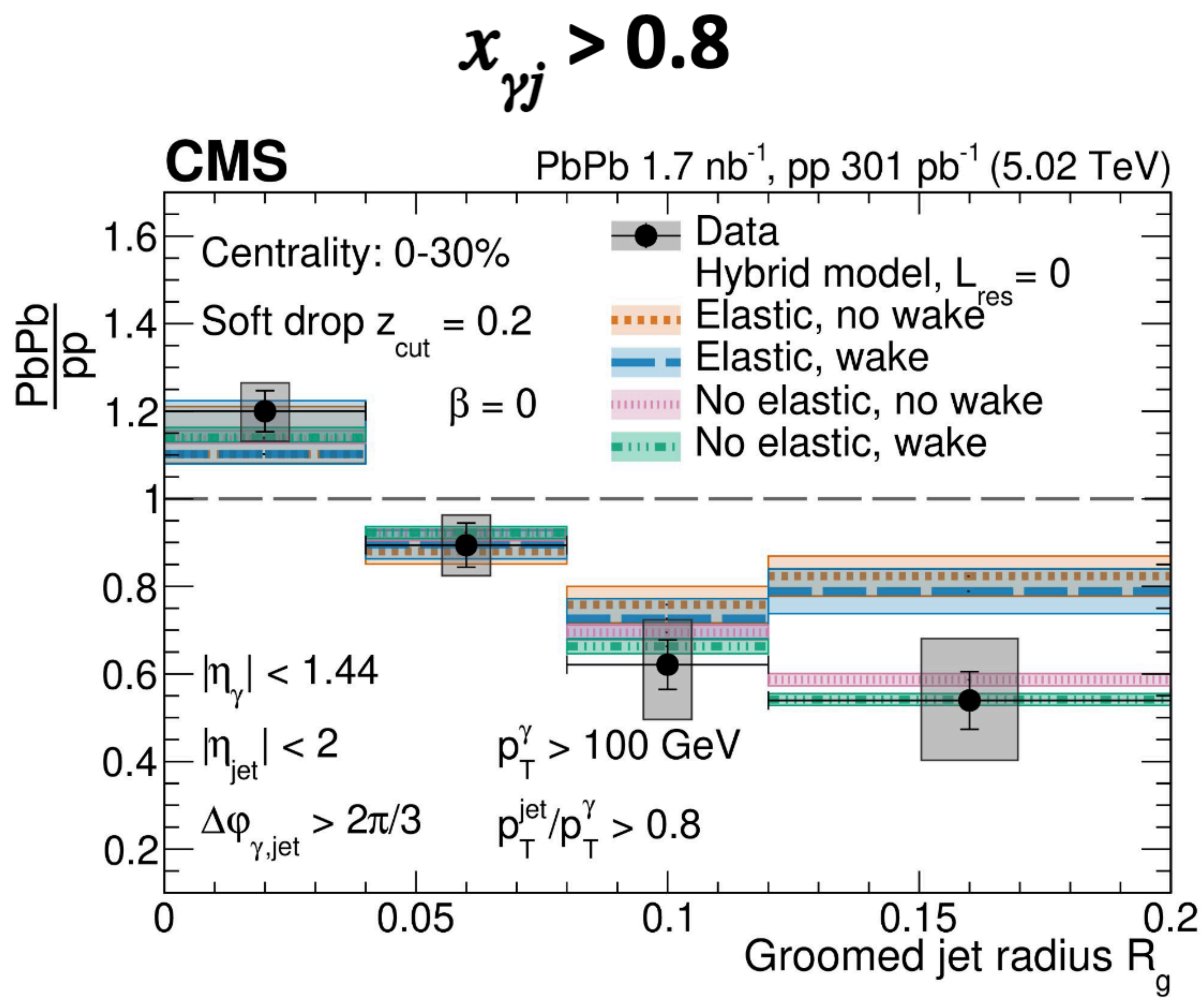
Zooming in

- Using photons as a colorless probe to tag jets
  - Don't expect it to be impacted by the medium → easier interpretation
- Different behavior depending on the p_T balance → see less suppression for more imbalanced events
- No single model describes all of the effects

- Aiming to understand the mechanism of energy loss in heavy ion collisions
- No single model describes all of the effects

Bharadwaj's talk

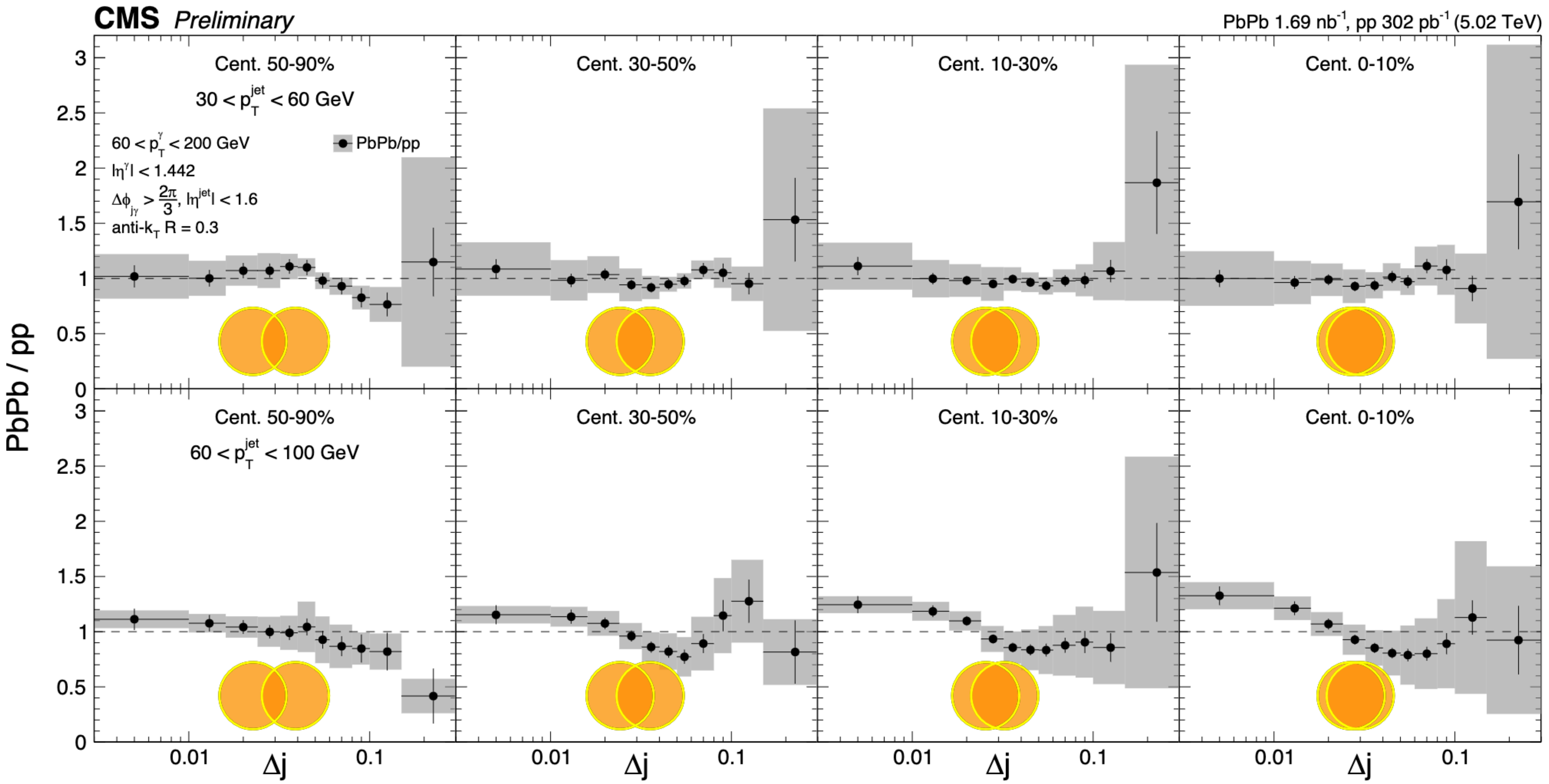


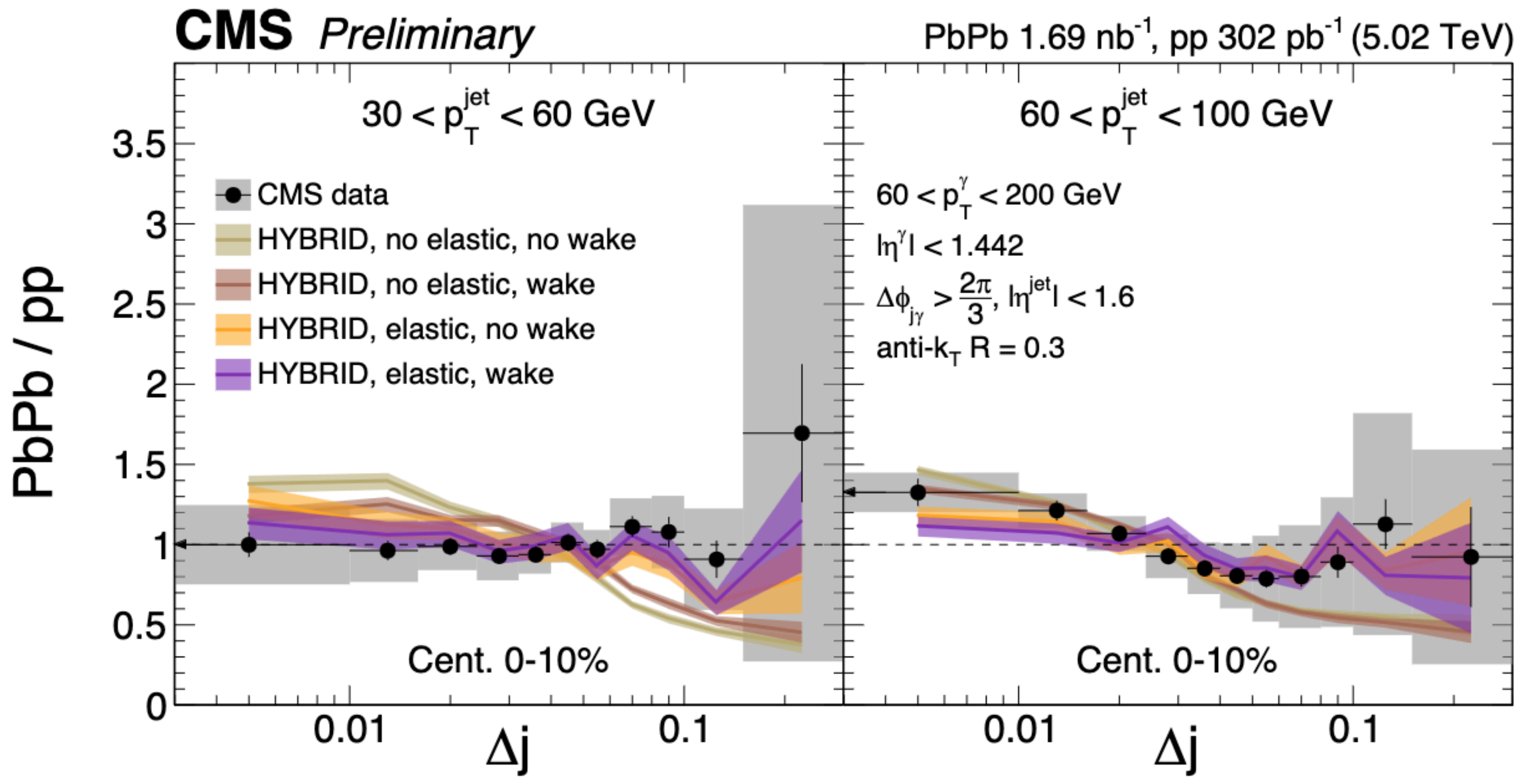


Molly's talk

Zooming in

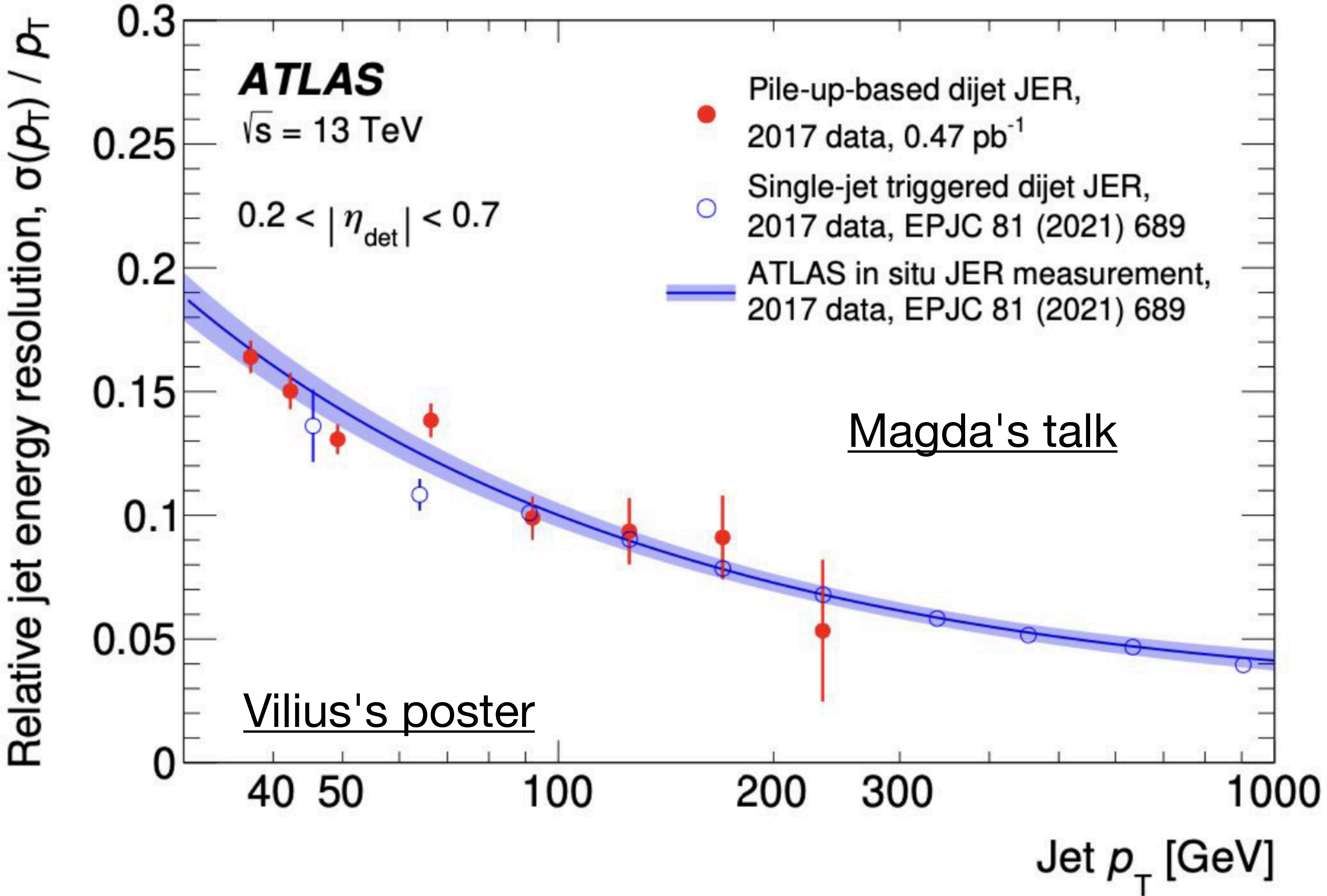
- Also using photon-tagged jets to study axis decorrelation (difference between winner-take-all and E-scheme axes)
- Some indication that wake effects could be important
    - *More measurements needed to understand all the effects*

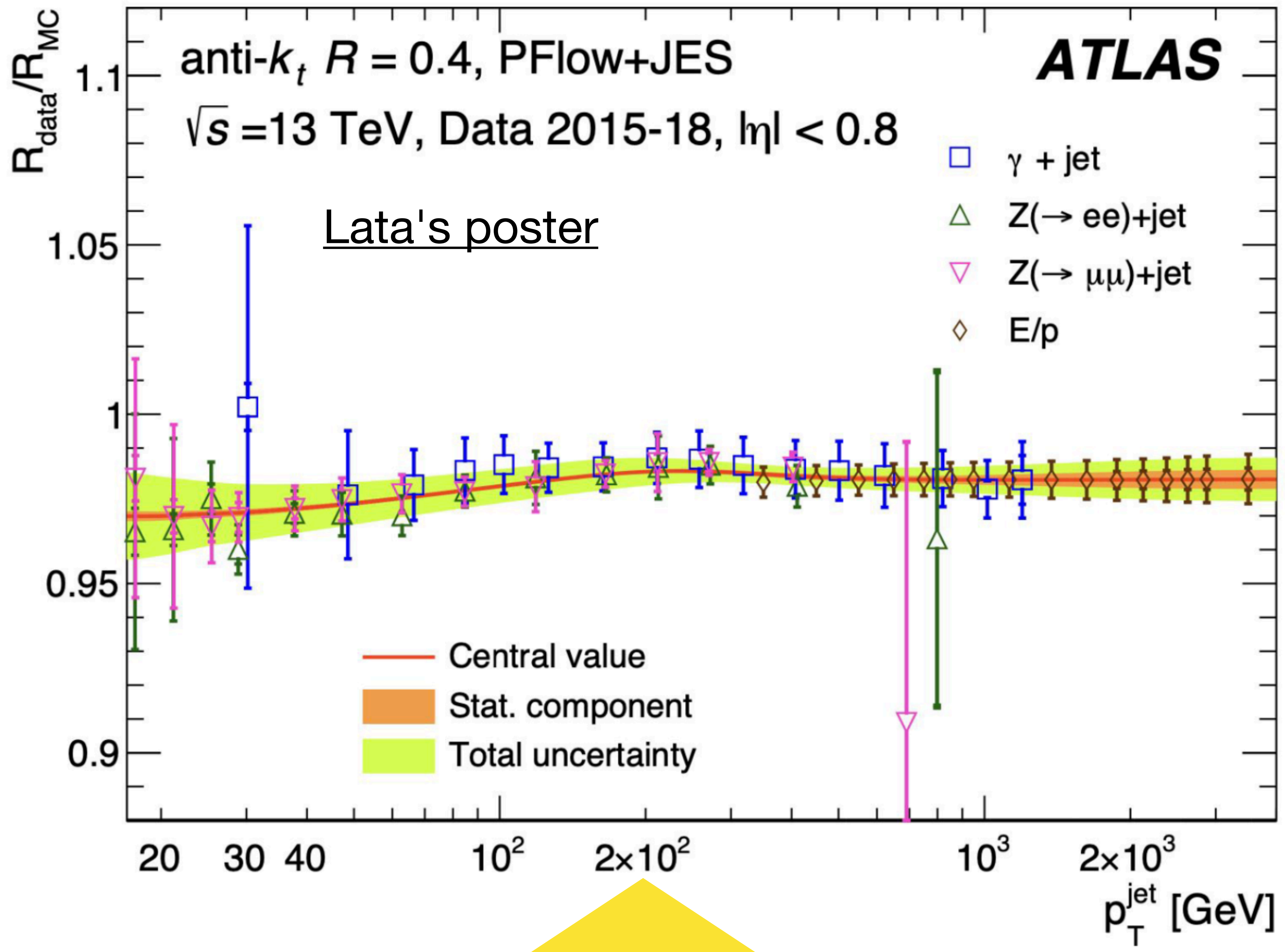




Making the most of it

- Using pile-up as a component of the ATLAS jet calibration
  - Not just a nuisance anymore → using it to beat large scale factors at low p_T

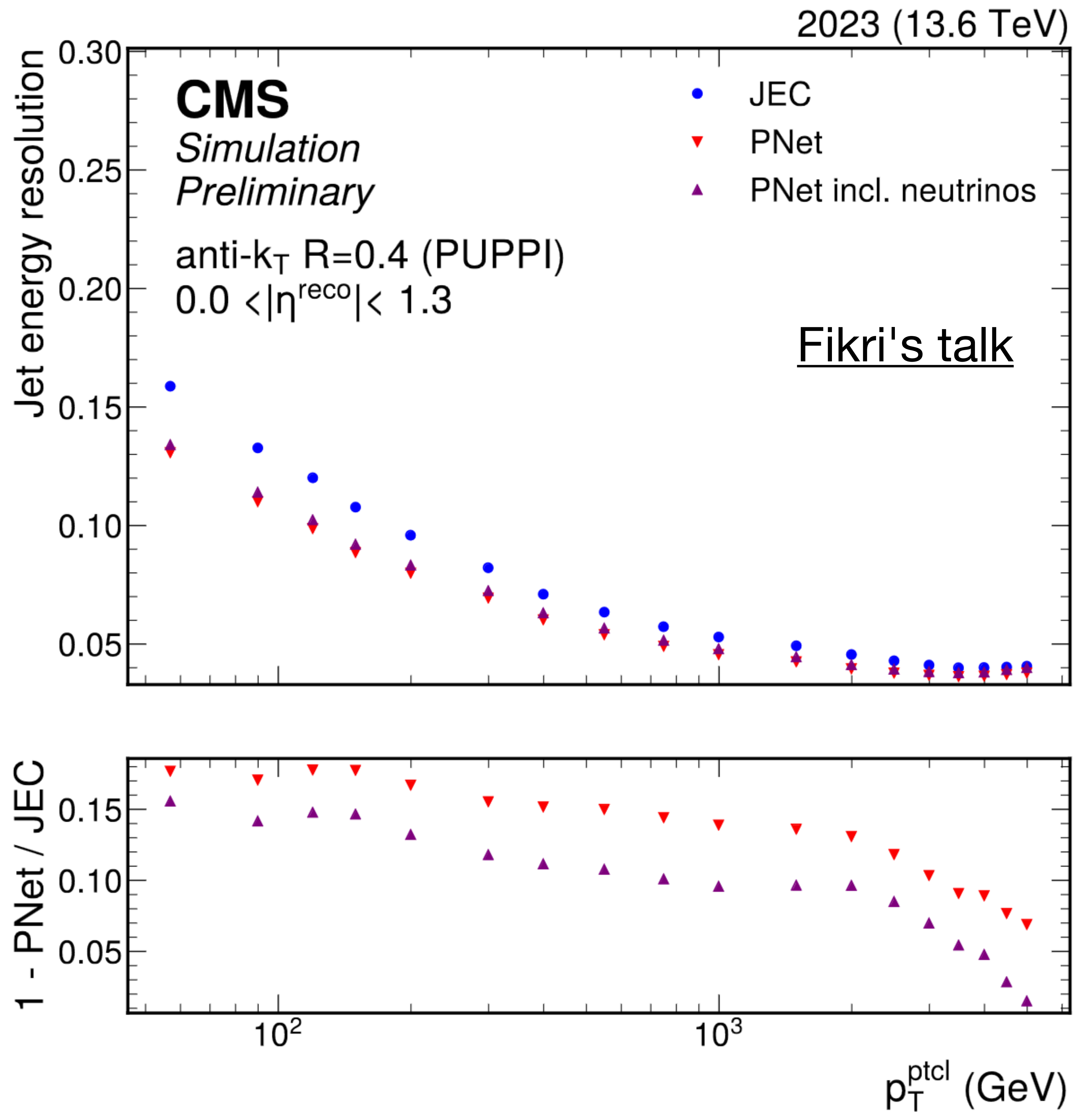


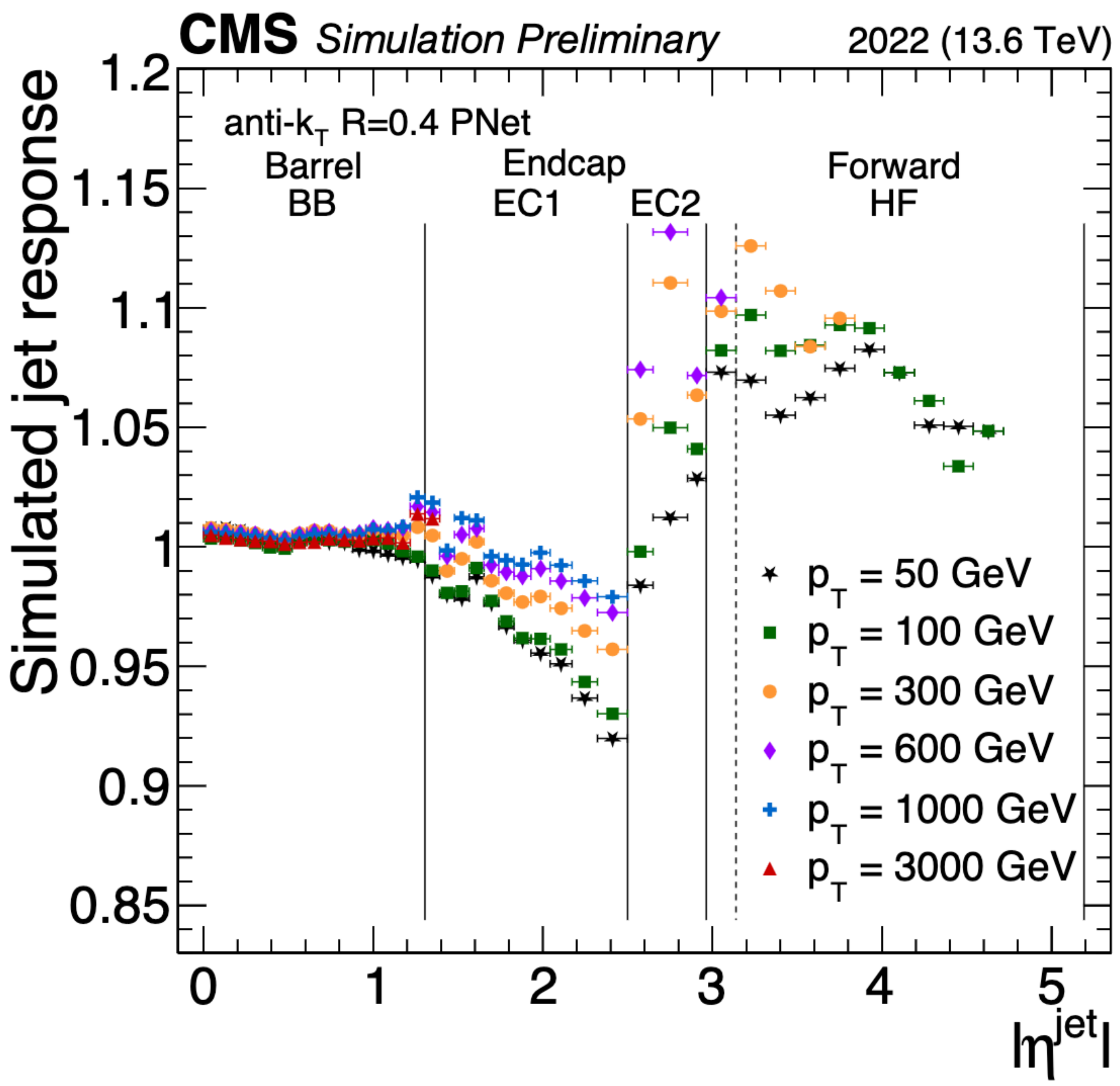


- Using single particle deconvolution to reduce jet uncertainties at high p_T
  - Applications to deriving in-situ jet calibrations with fewer steps for certain uses

Making the most of it

- CMS is using particle net to provide a regression on the jet energy scale
  - Significant improvement to the jet energy resolution!
  - More information about the jet constituents provides more accurate jet corrections

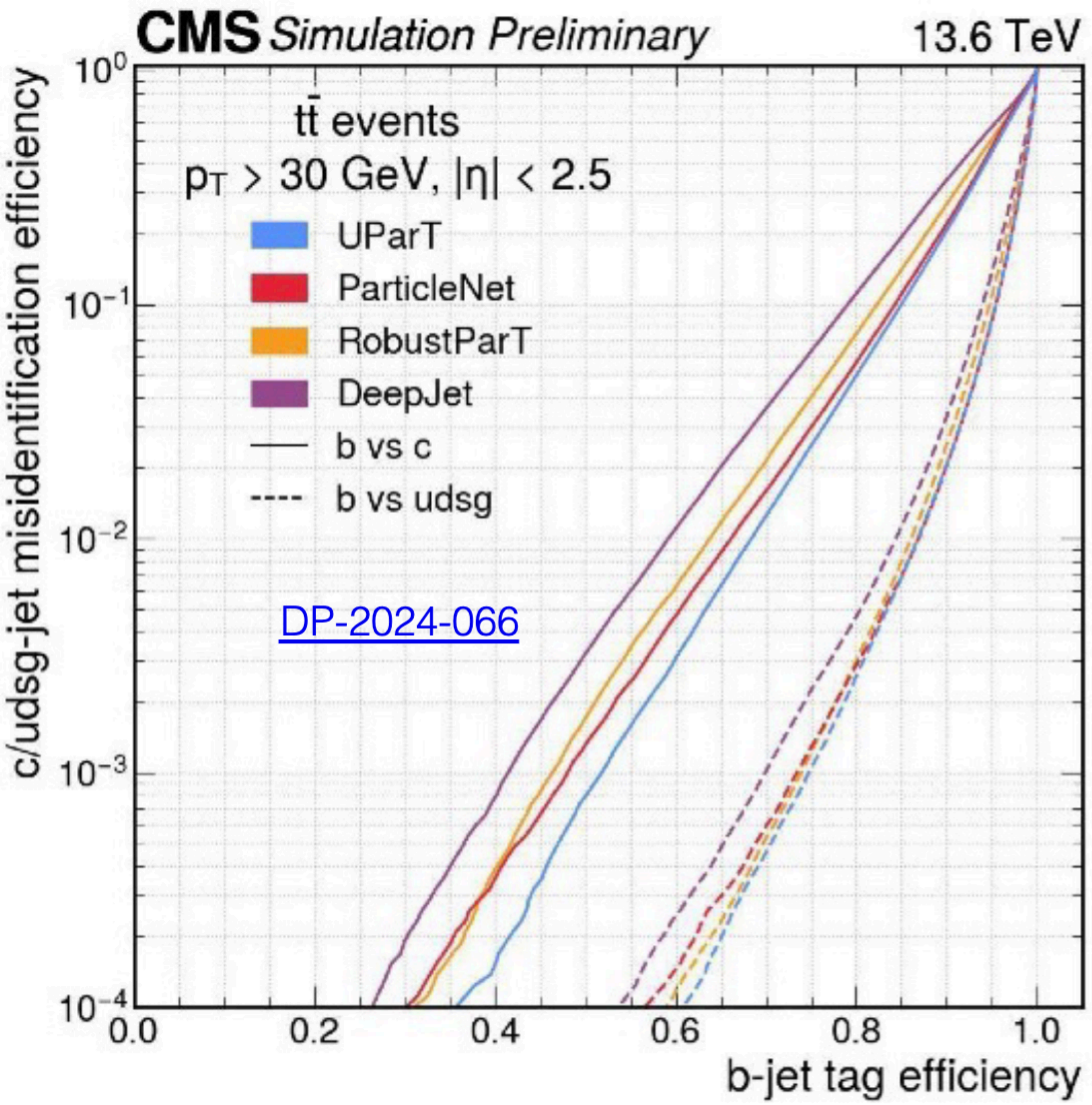




- *Challenging to make this work over the full phase space, but has potential to be used for the full MC calibration*

Making the most of it

- UParT uses more output nodes to enhance tagger performance
  - *Teaching the network more about the inputs provides better sensitivity*
- Also includes flavor-aware jet energy and resolution regression!
- Still a particle-net variant, but still finding ways to enhance the performance



Making the most of it

- Unbinned multidifferential unfolding techniques enable new types of open data

Dataset & Jupyter Notebooks

- Datasets:
  - https://zenodo.org/records/11507450
- Codebase:
  - https://gitlab.cern.ch/atlas-physics/public/sm-z-jets-omnifold-2024
- Notebooks:

1_basics.ipynb	Open in Colab
2_pseudo_results.ipynb	Open in Colab
3_results.ipynb	Open in Colab

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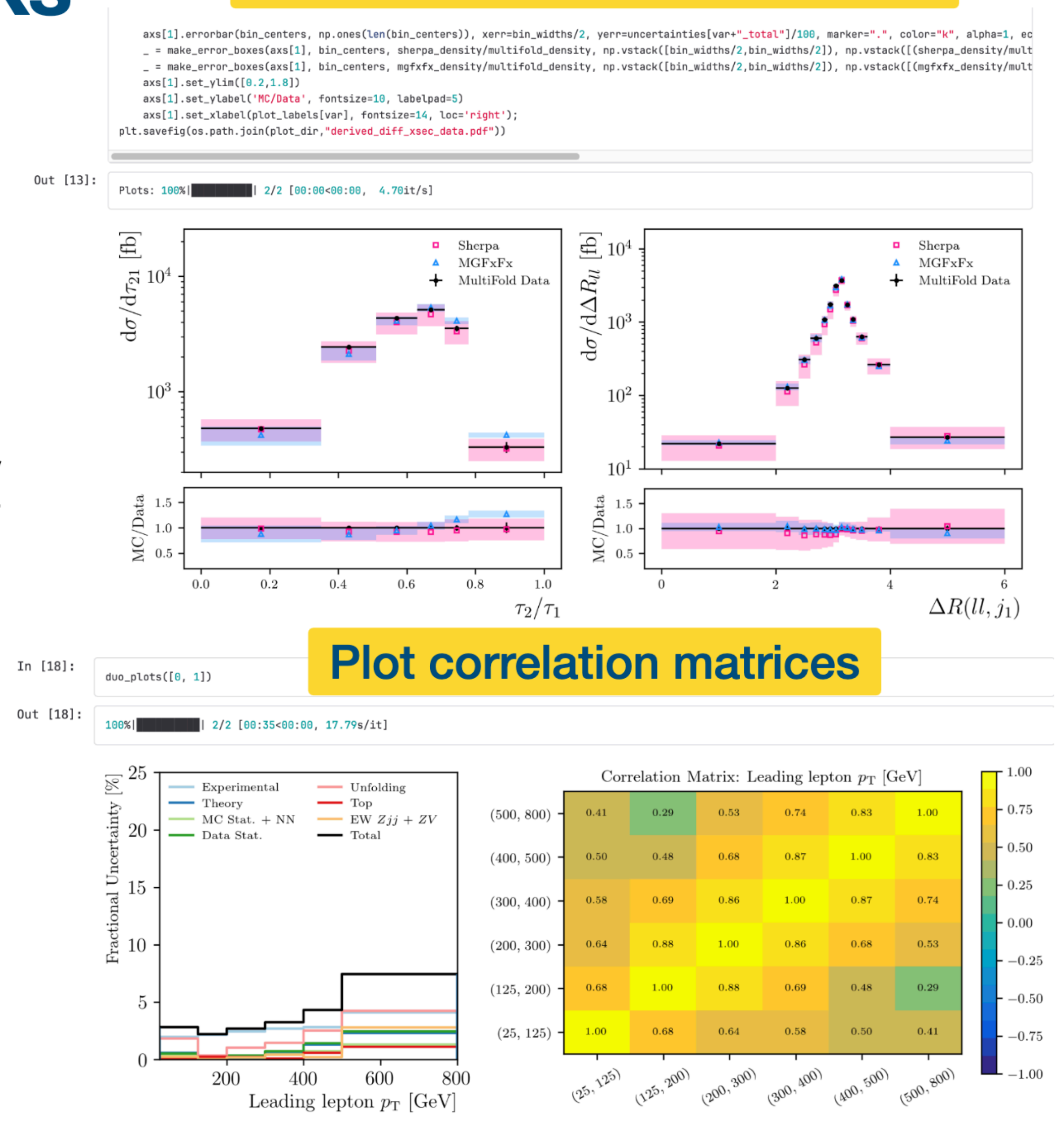
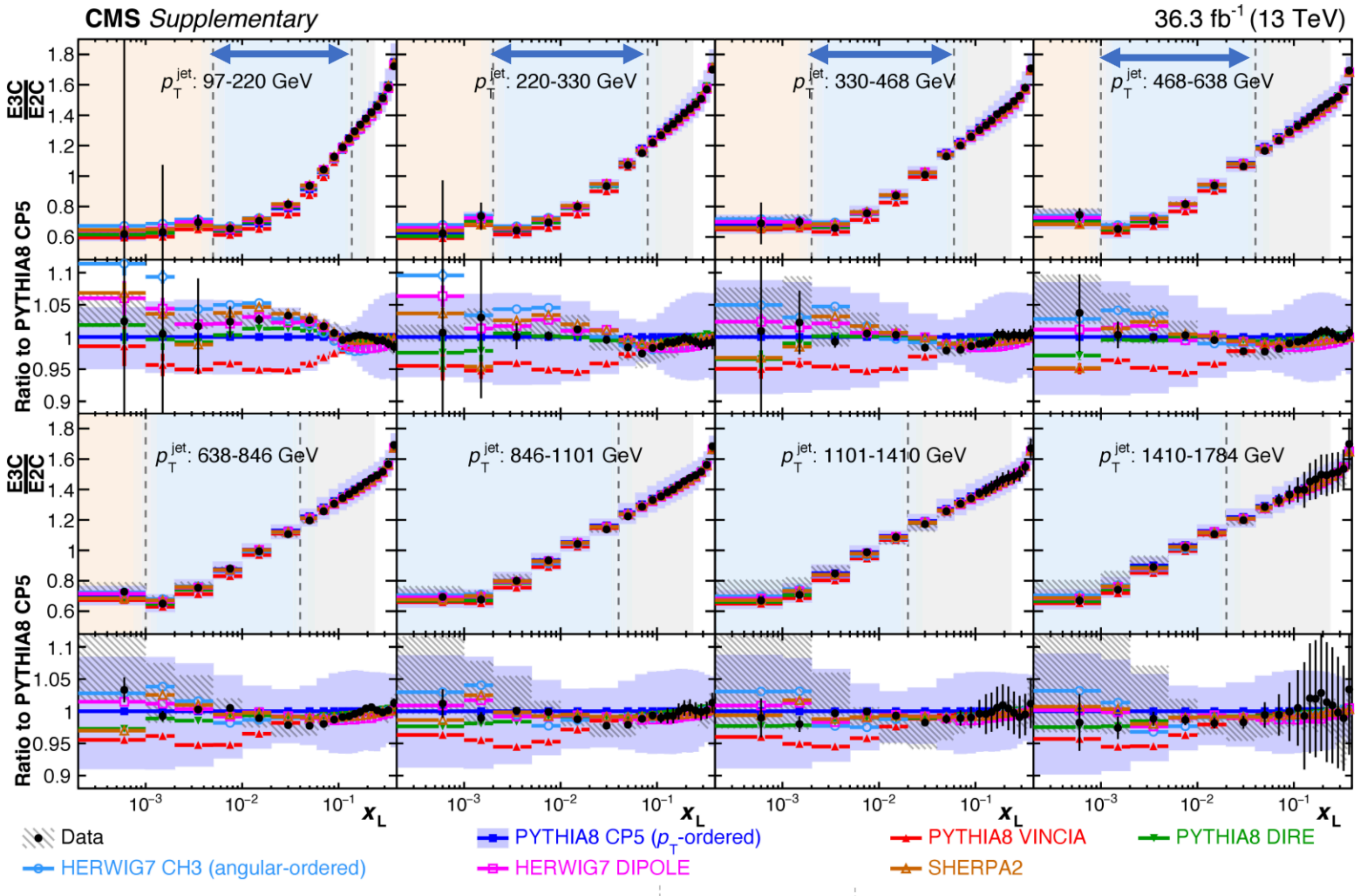
Construct derived observables

Plot correlation matrices



Kaustuv's talk

$Q \propto x_L \cdot p_{T,\text{jet}}$: Boundaries between regions shift to smaller x_L at high p_T

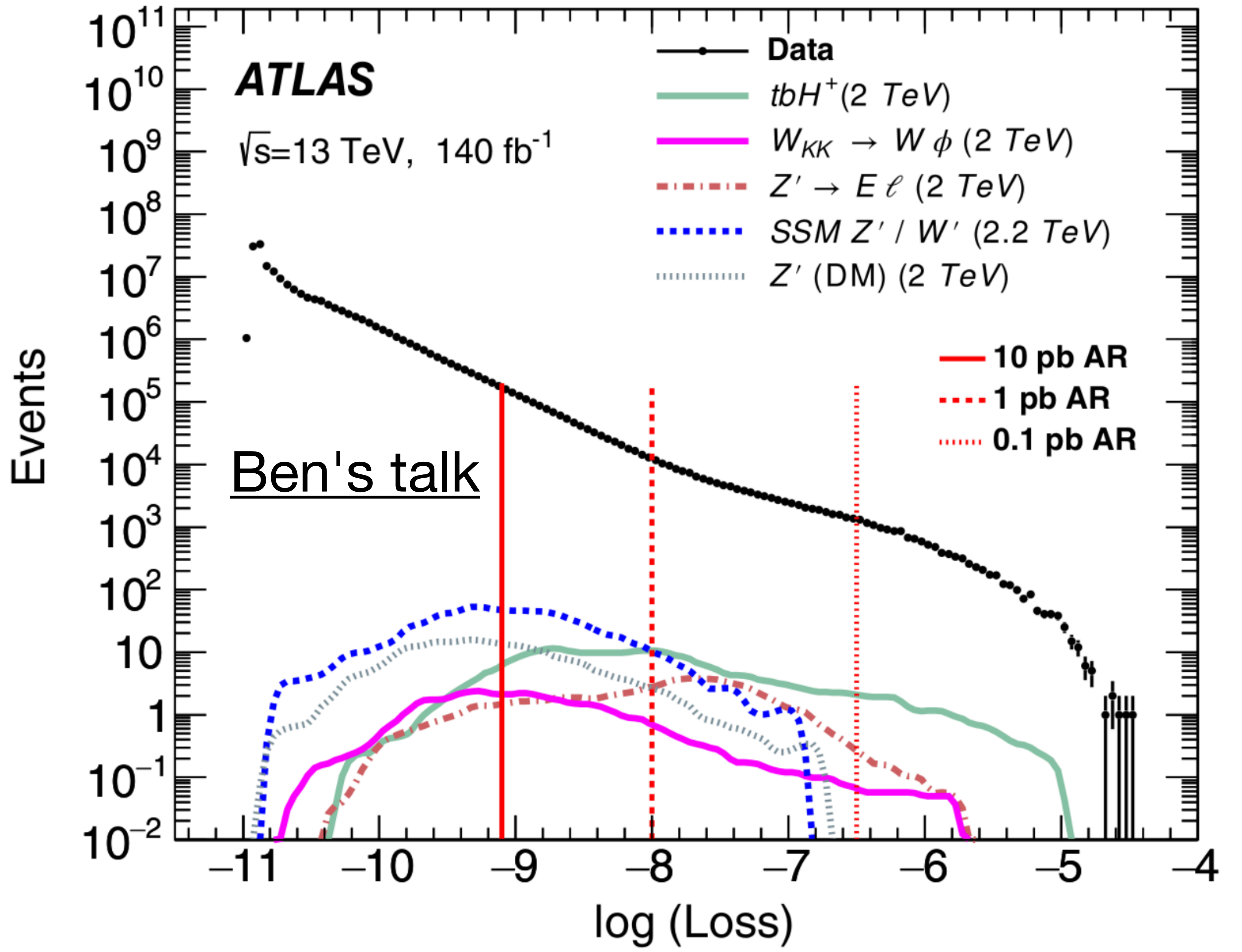


$x_L \simeq \frac{0.8}{\ldots}$ $x_L \simeq \frac{20}{\ldots}$

- Multiparticle correlations provide opportunities to explore jet formation from a new perspective
  - *Challenging to measure experimentally, but many potential applications!*

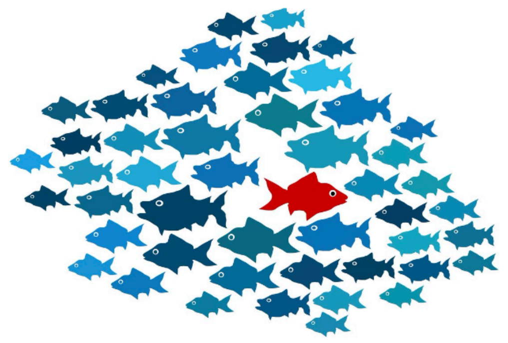
Making the most of it

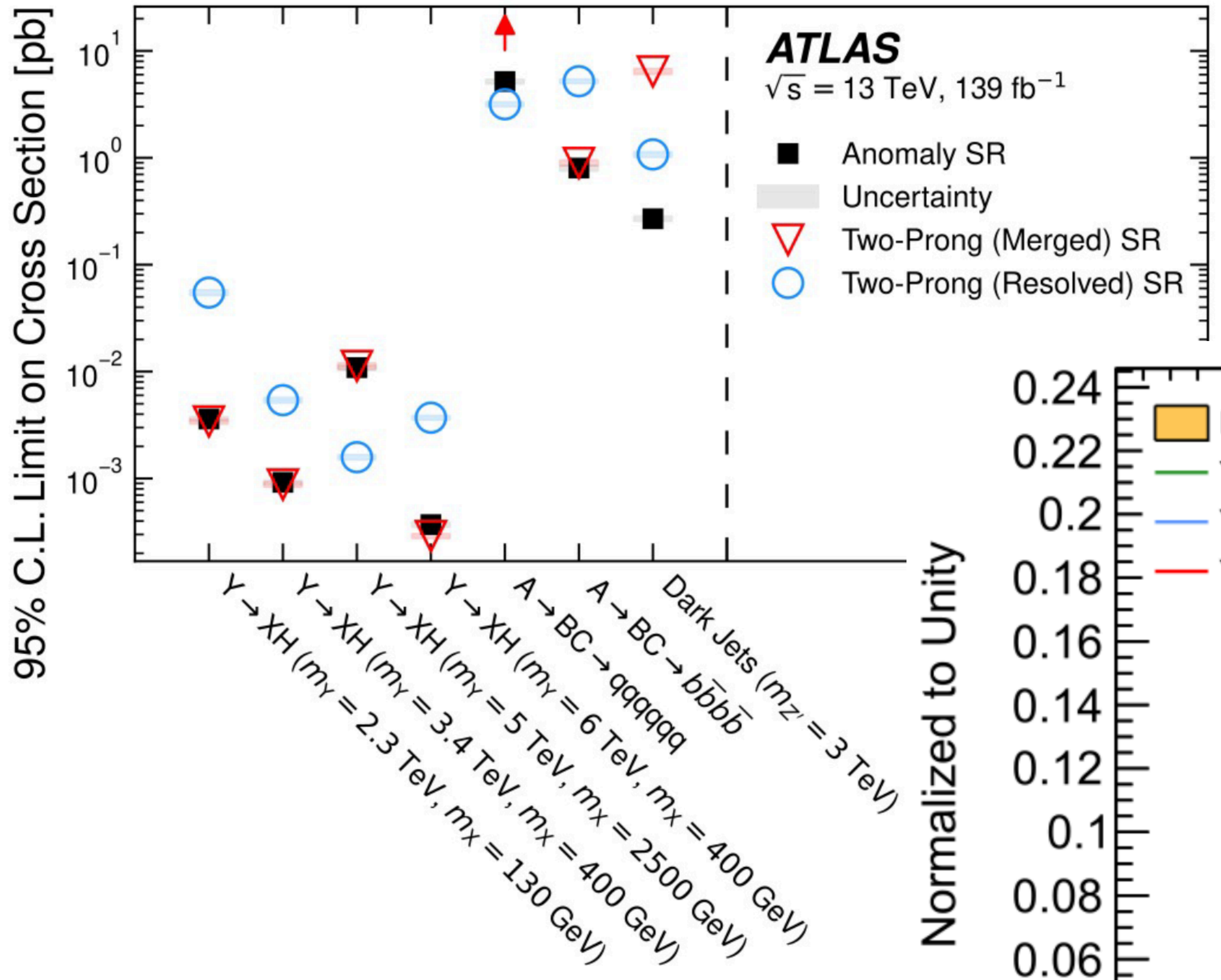
- Anomaly detection could help us find physics that we wouldn't have seen with a traditional search (or wouldn't have dedicated a search to)
- Many open questions about how we would interpret what we see (but this would be a good place to be)

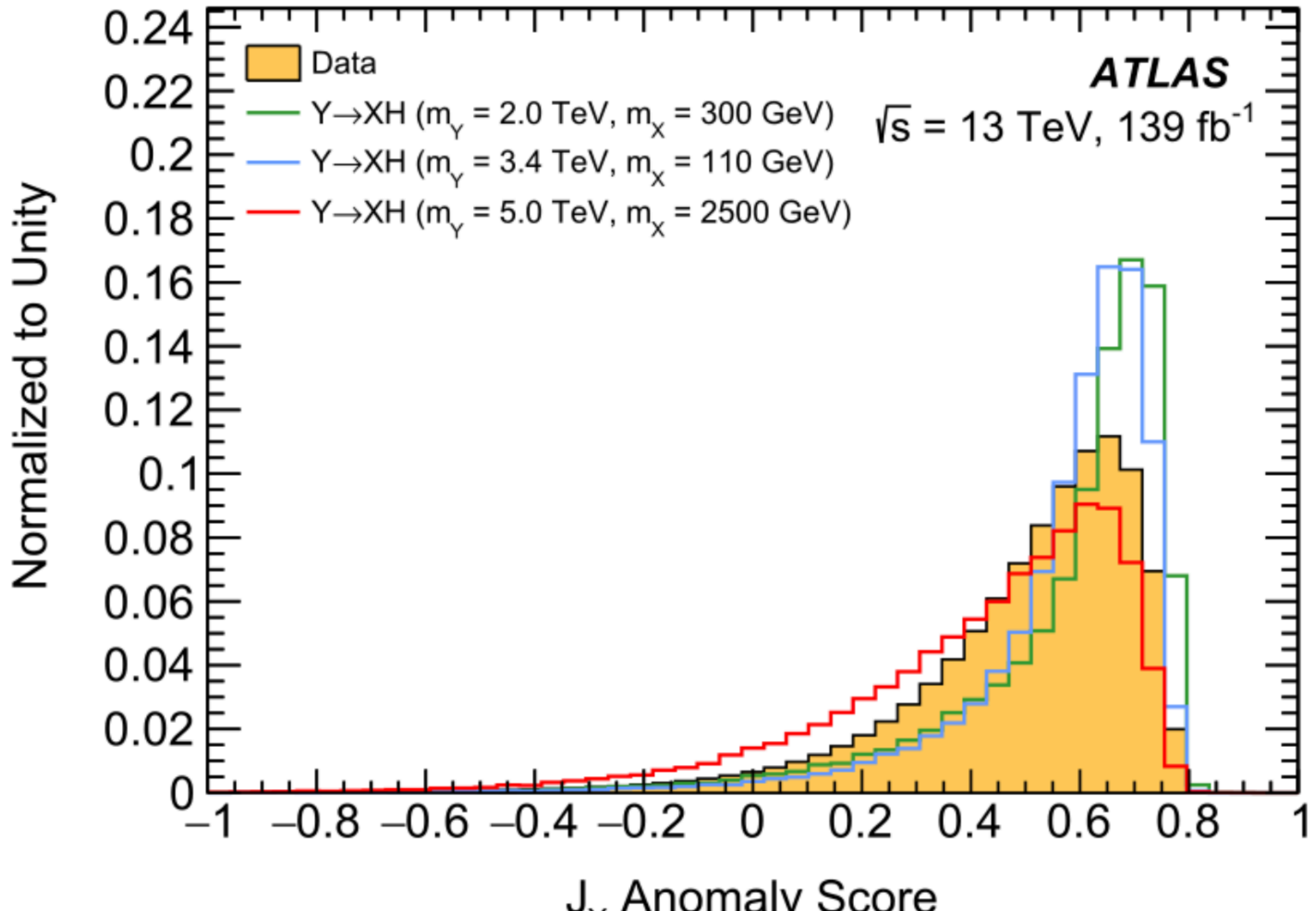


Florian's talk

Traditional search	Anomaly detection
• Targets a specific new physics signal model	• Makes no/few assumptions about the new physics
• Maximum sensitivity to this signal	• Smaller sensitivity compared to traditional search for the target signal
• Potentially very little sensitivity to different experimental signatures	• Sensitive to a wide range of new physics scenarii!

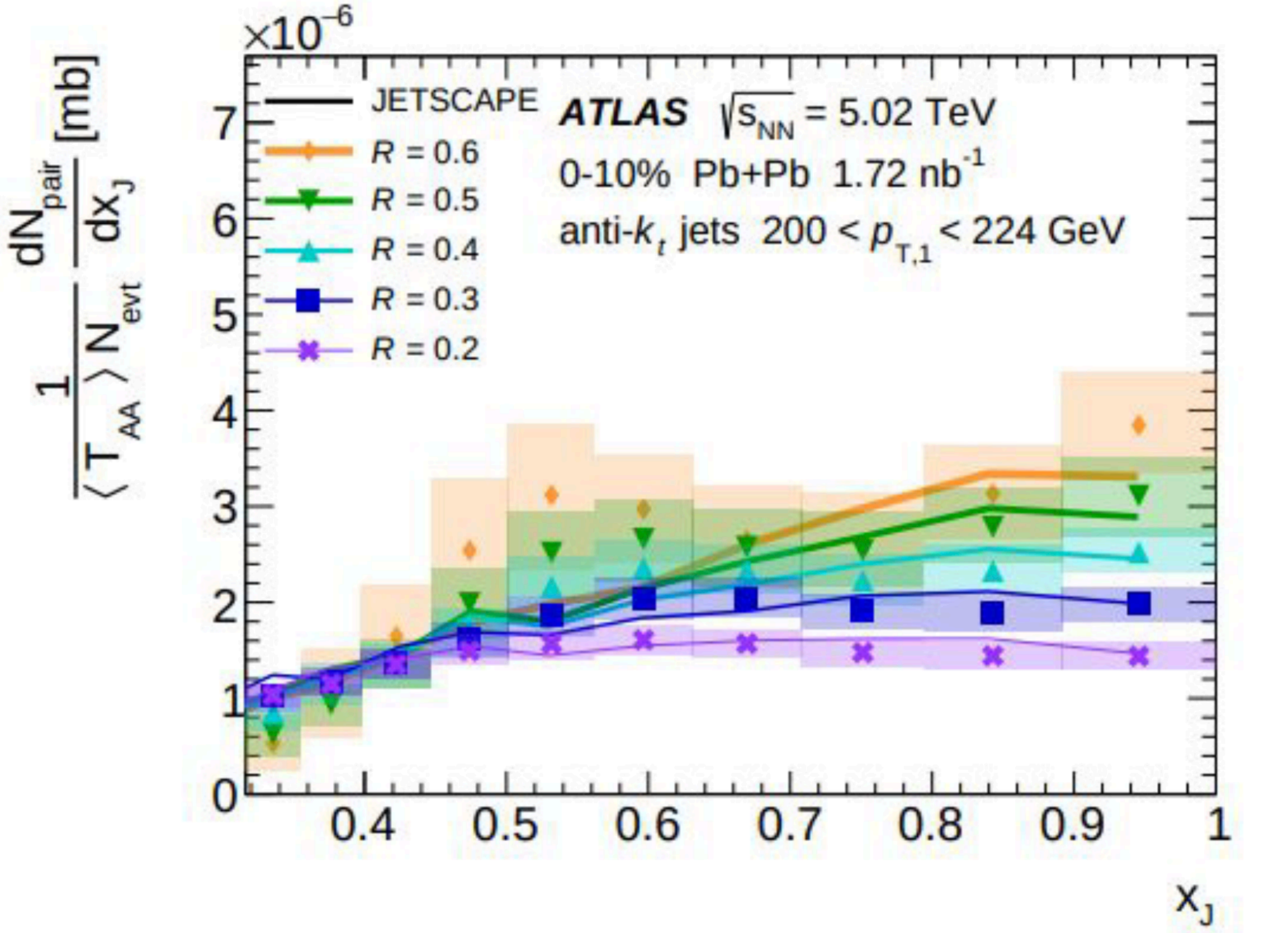


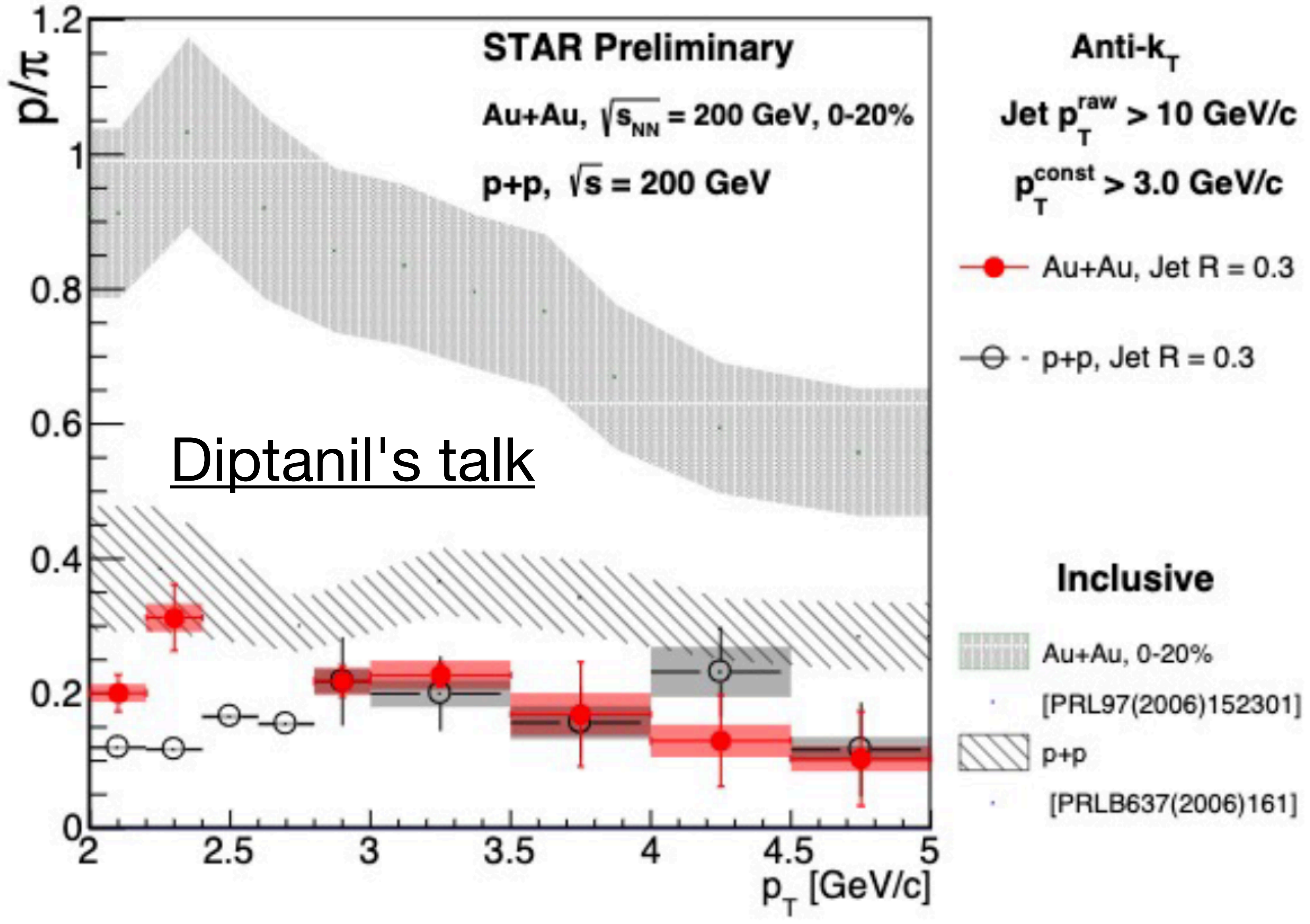




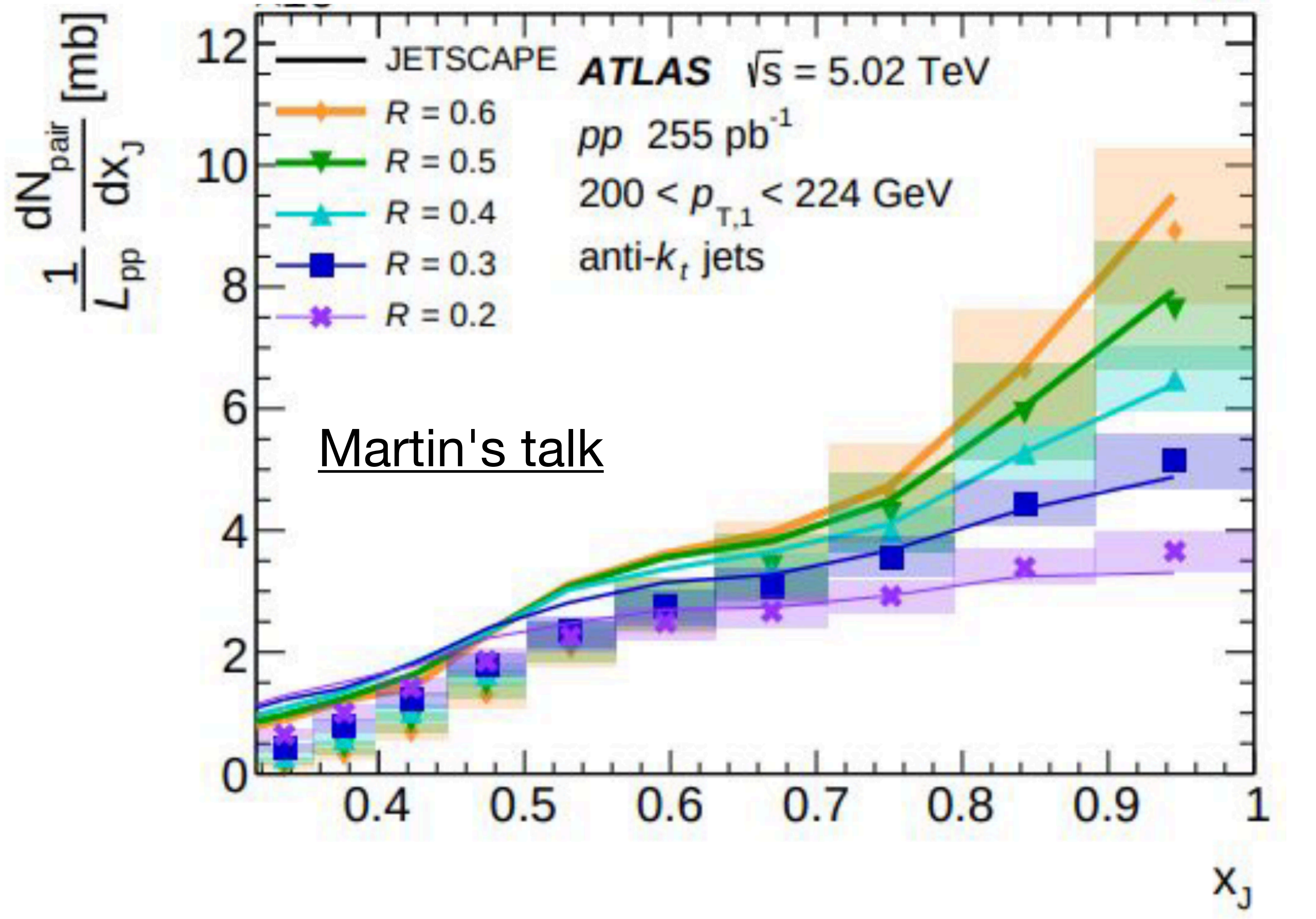
Understanding the space

- Energy loss in heavy ion collisions depends on the jet radius as well as the dijet balance
- Clear differences with respect to *pp* collisions

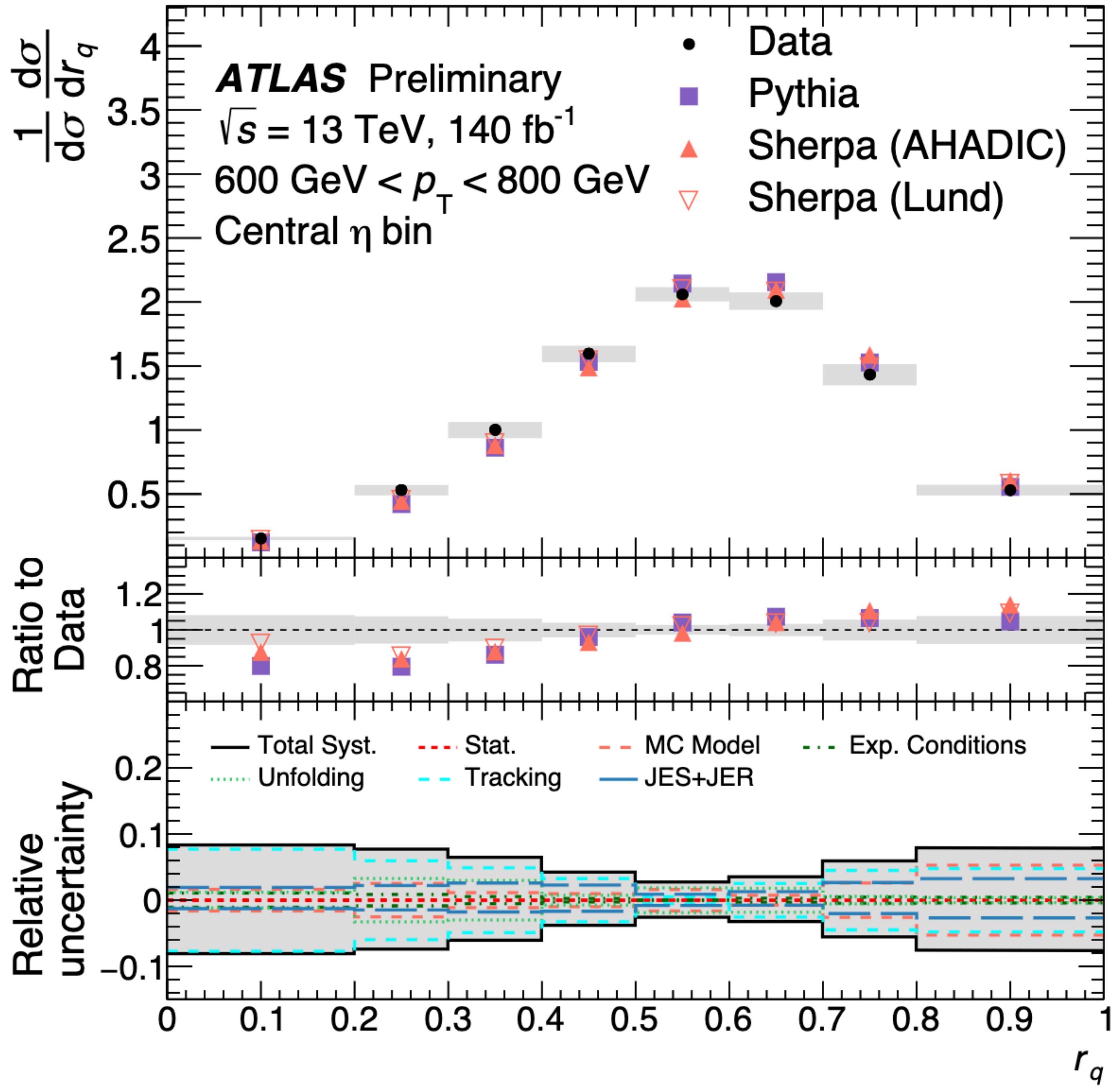




- Also trying to understand which hadrons are produced in jets, and how this changes with heavy ion collisions

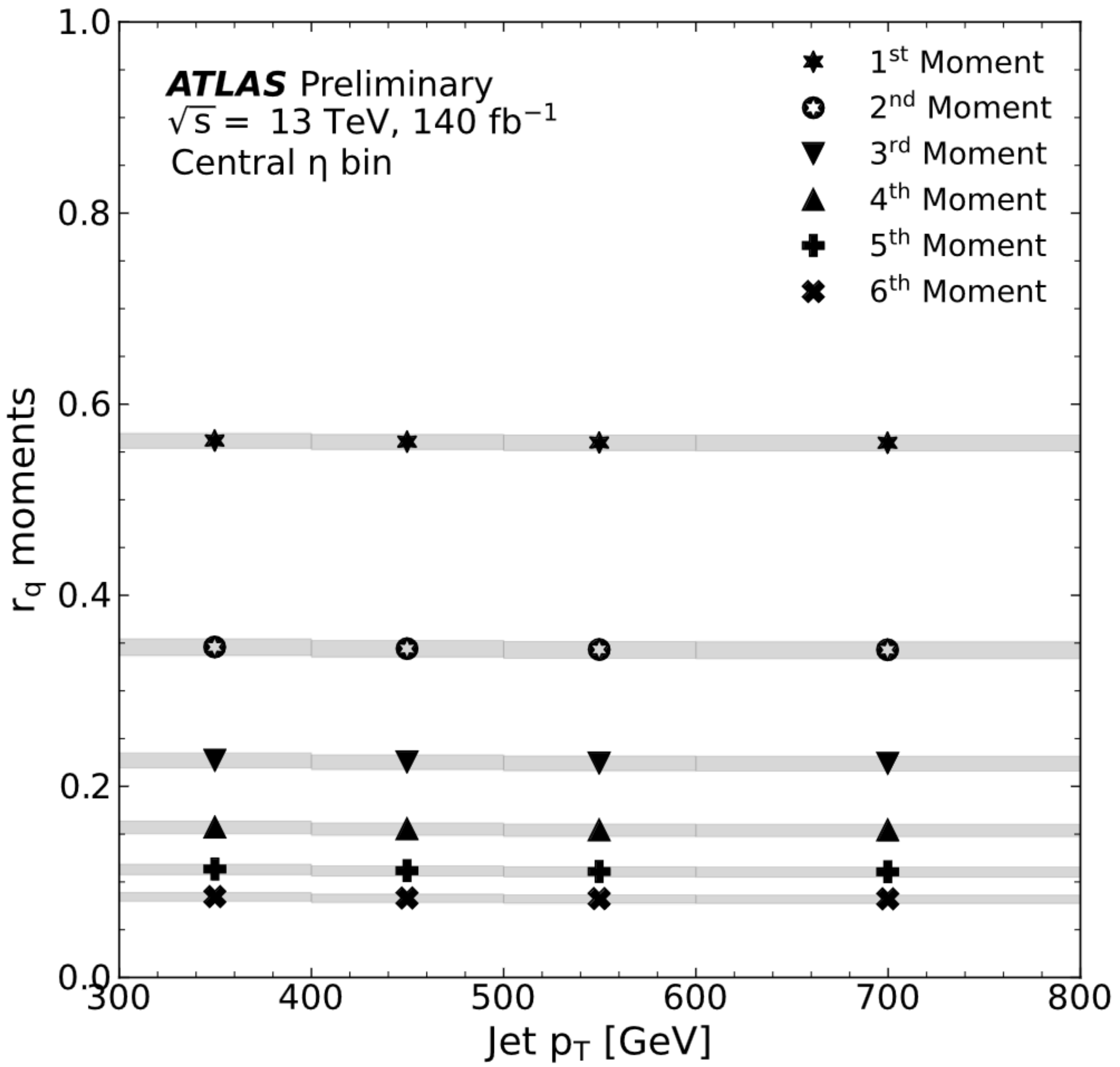


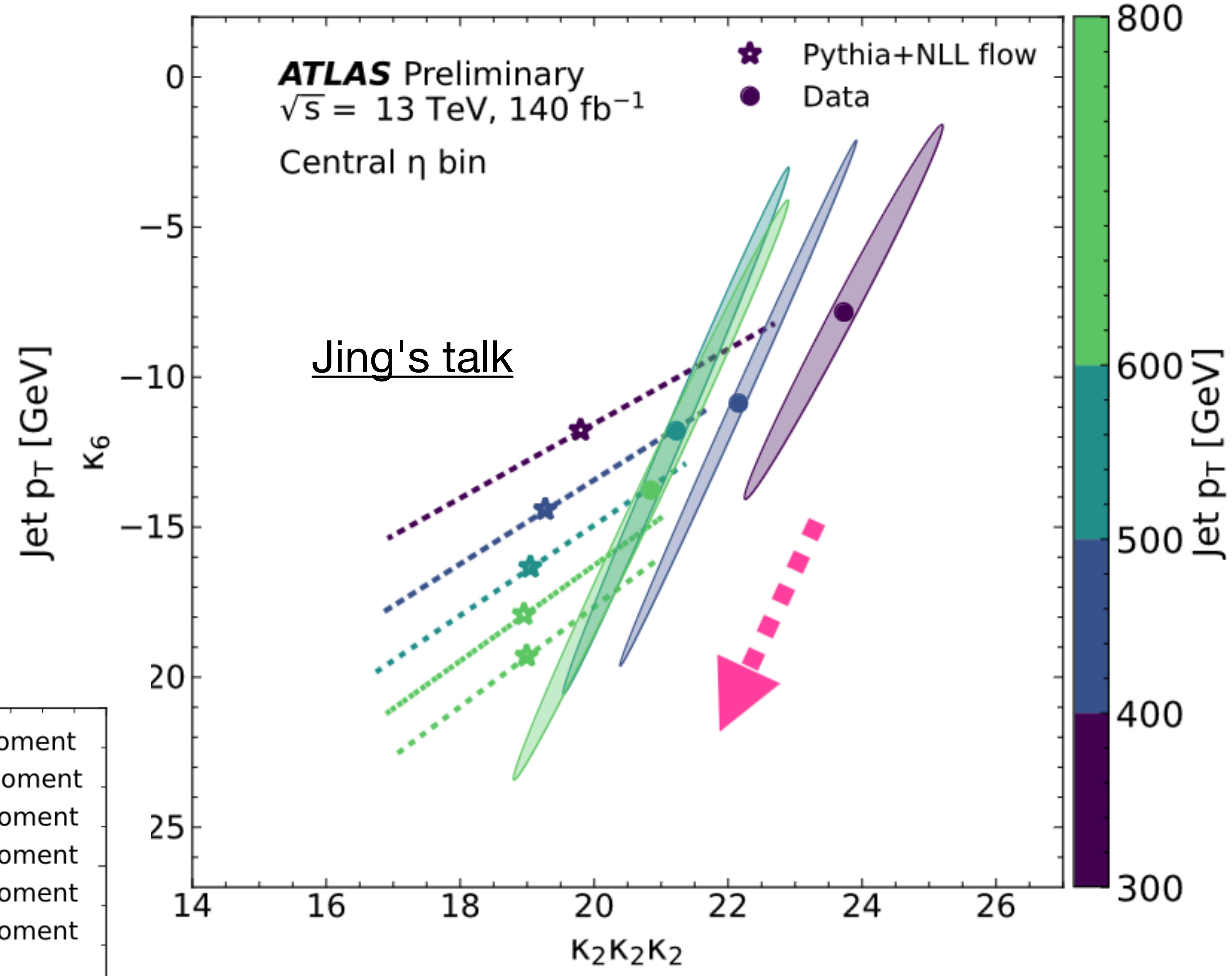
Understanding the space



Charged fraction of a jet seems like a simple fundamental quantity

Its moments evolve very slowly with the jet p_T

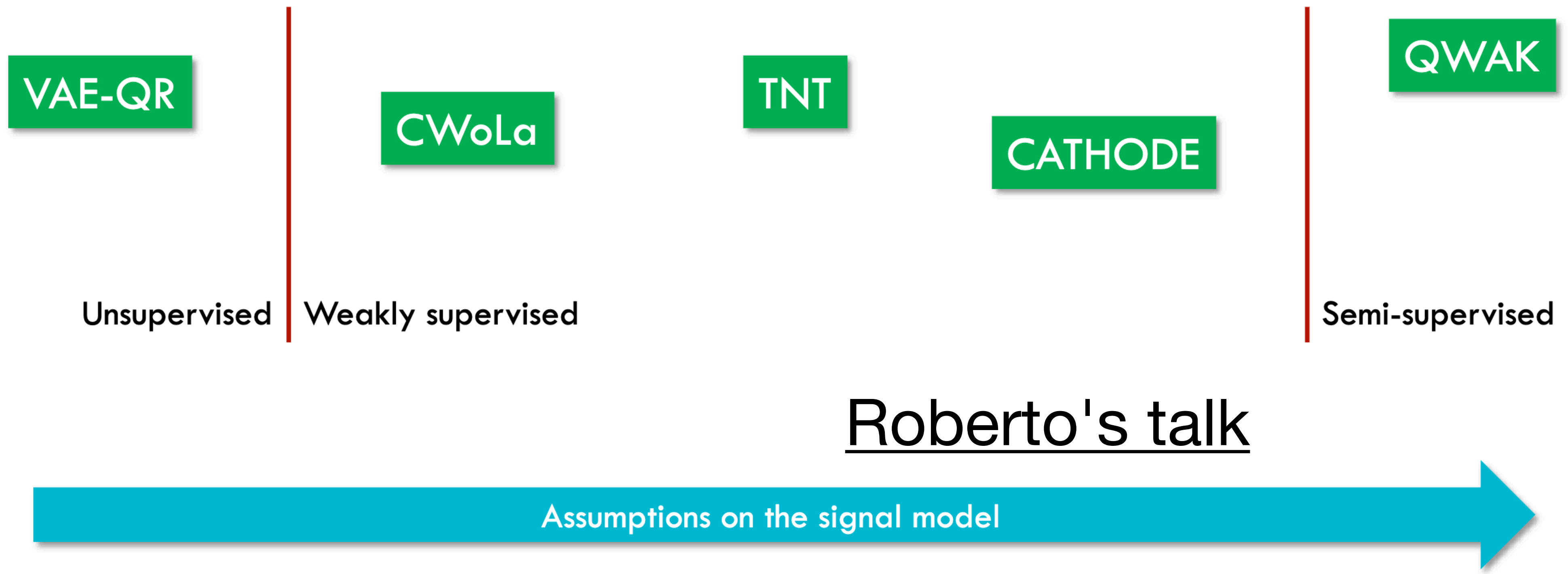




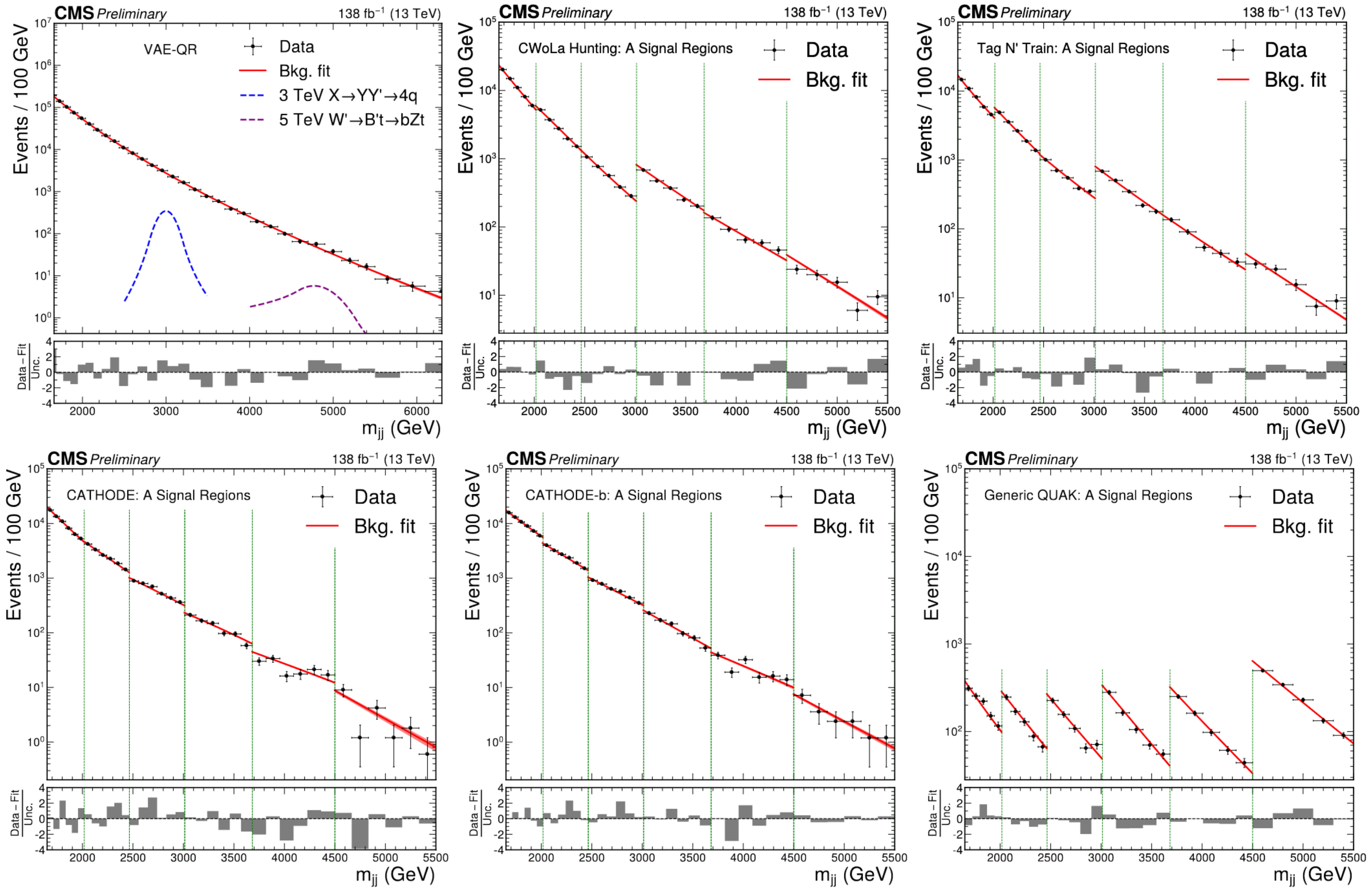
Correlations between cumulants reveal nonlinear mixings of moments, with deeper connections to QCD

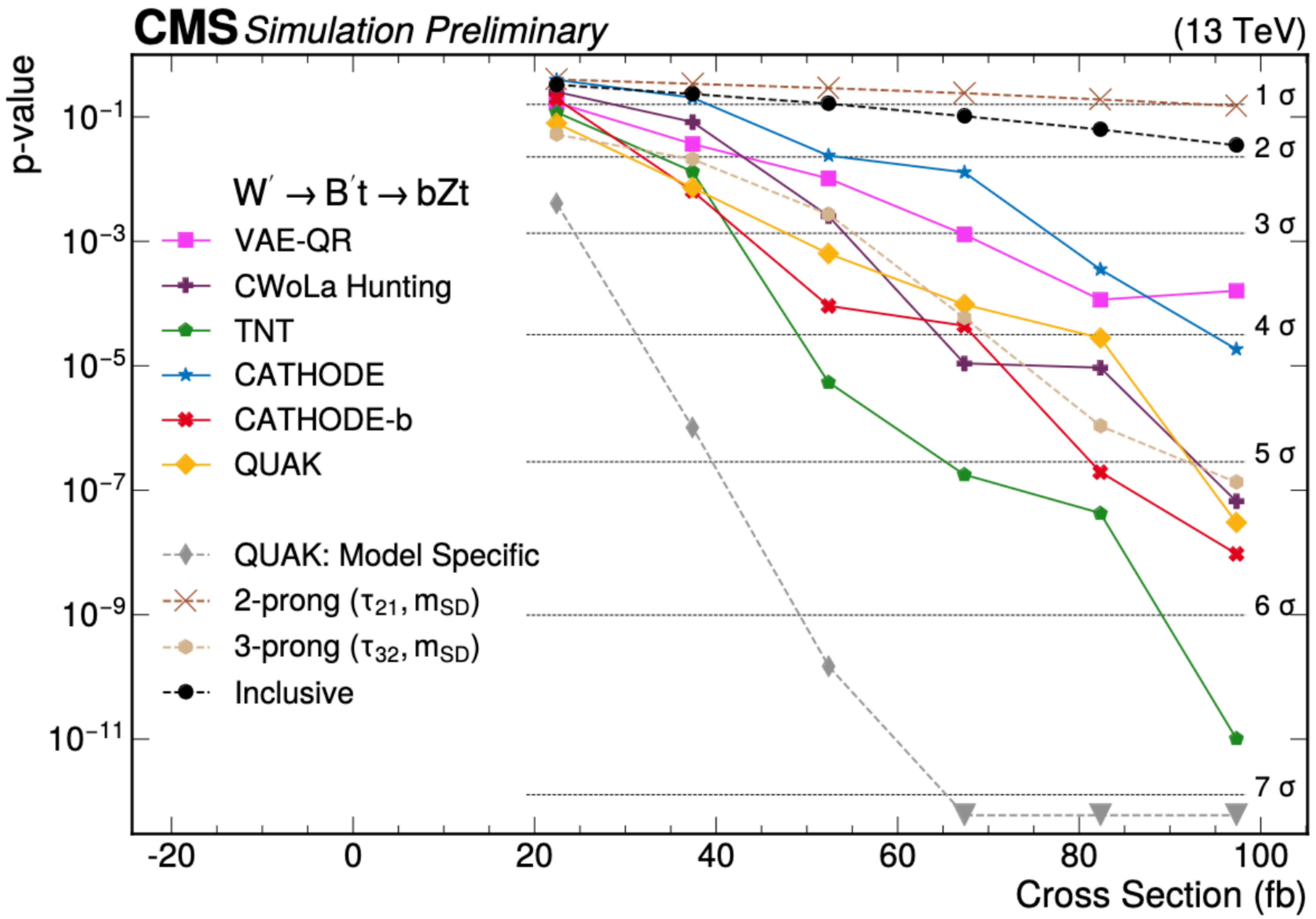
Understanding the space

- Many different model-agnostic search strategies on the market
- No single method outperforms the others
- Complementary sensitivity from different algorithms, and enables comparisons across a wide range of models



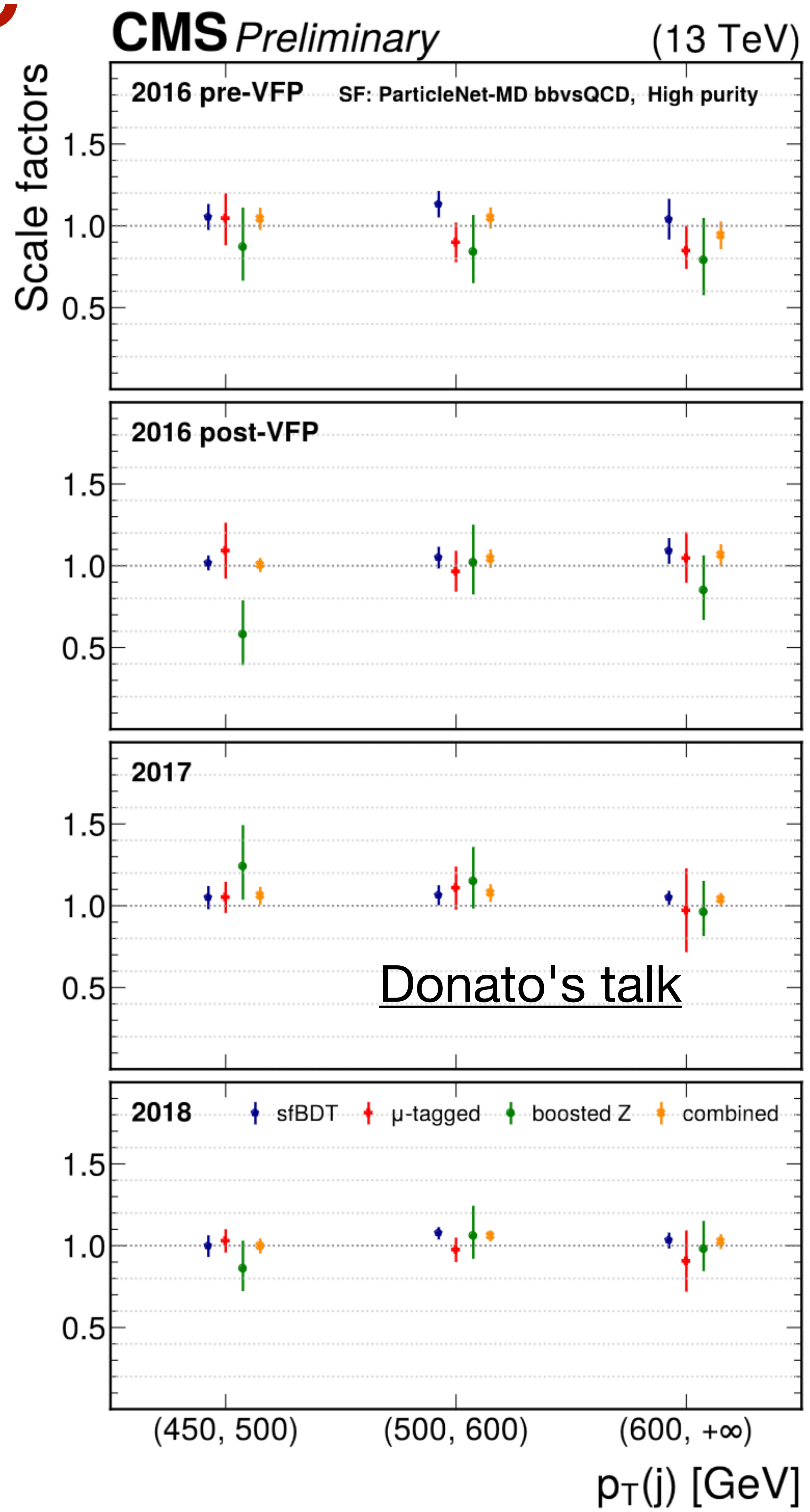
Even though these are model agnostic, can gain a lot through understanding their behavior across a wide range of models



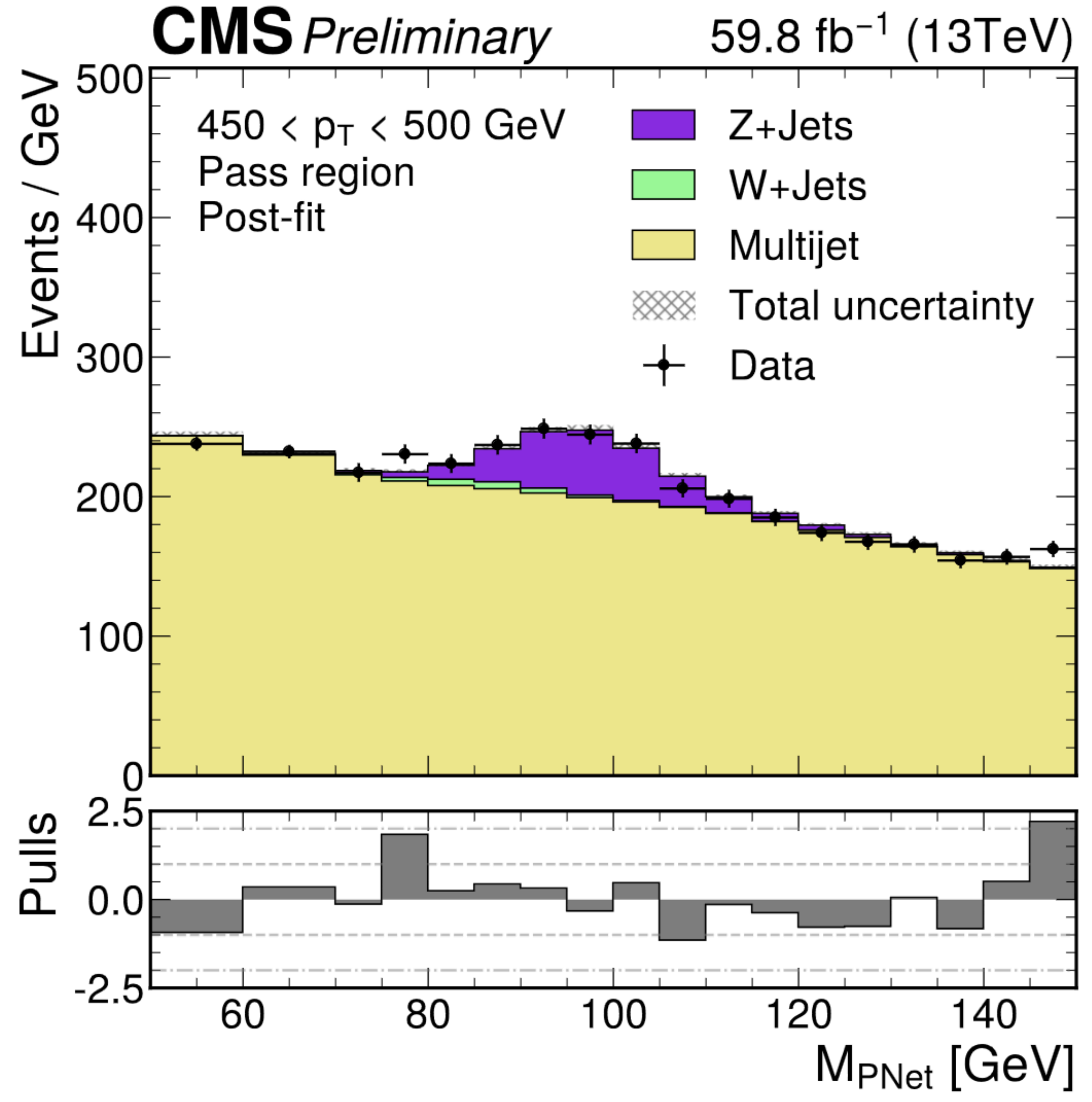


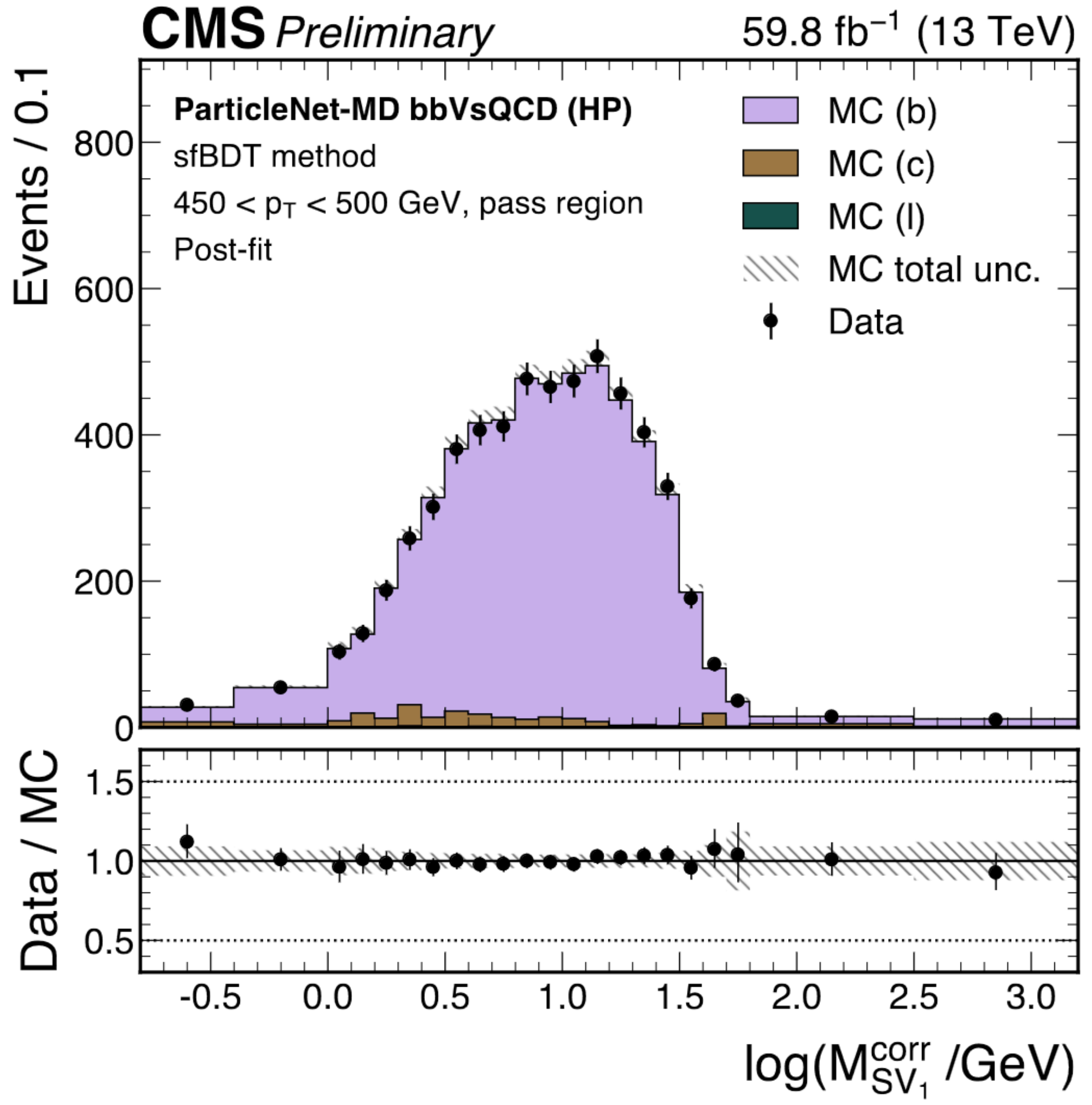
Understanding the space

- Need tagger calibrations
- Difficult to get for rare processes (like H->bb)
- Combining scale factors from multiple methods to get the tagger calibration
  - Using multiple topologies: g→bb and Z→bb
  - Good cross-check that scale factors are consistent
  - *Will improve with higher stats*



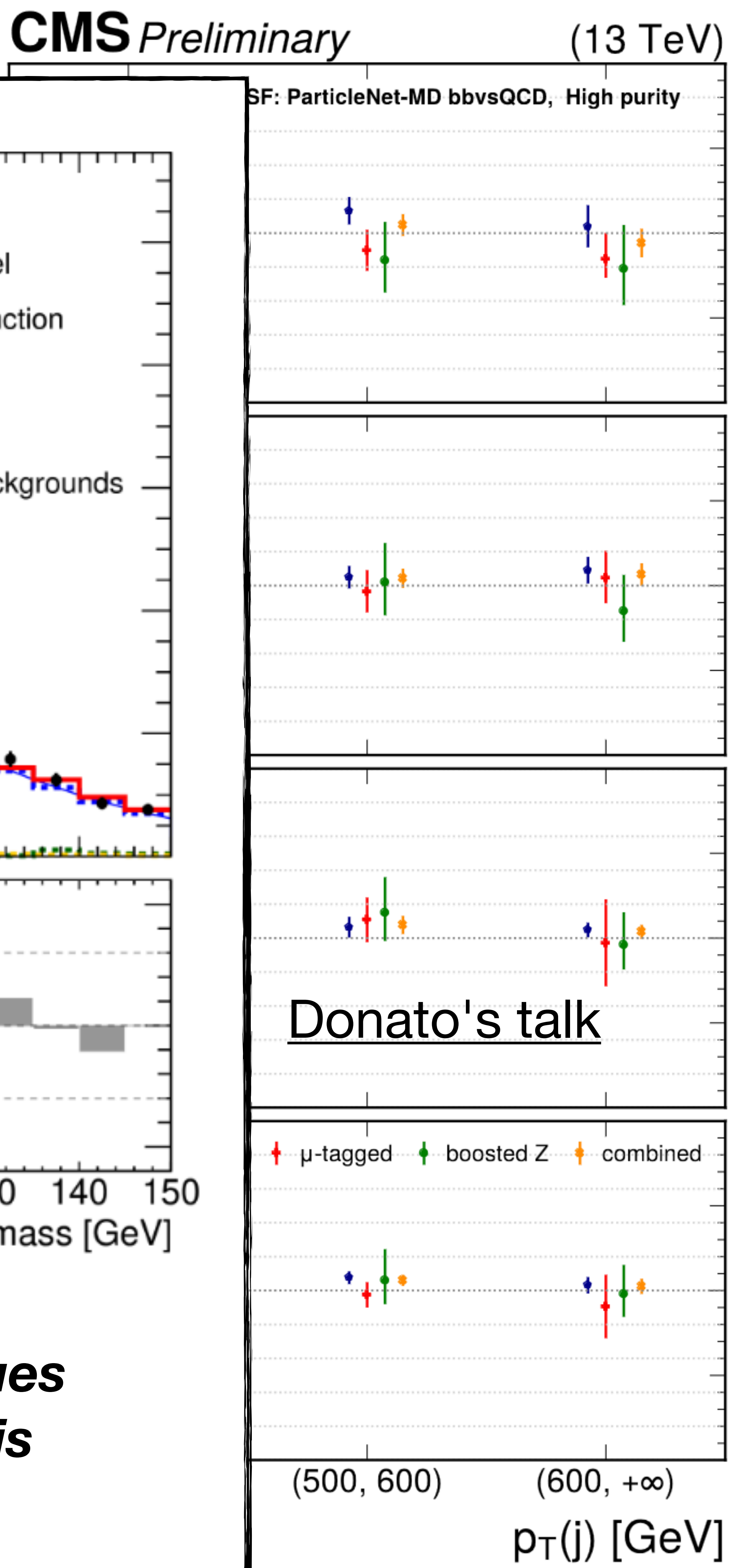
Donato's talk

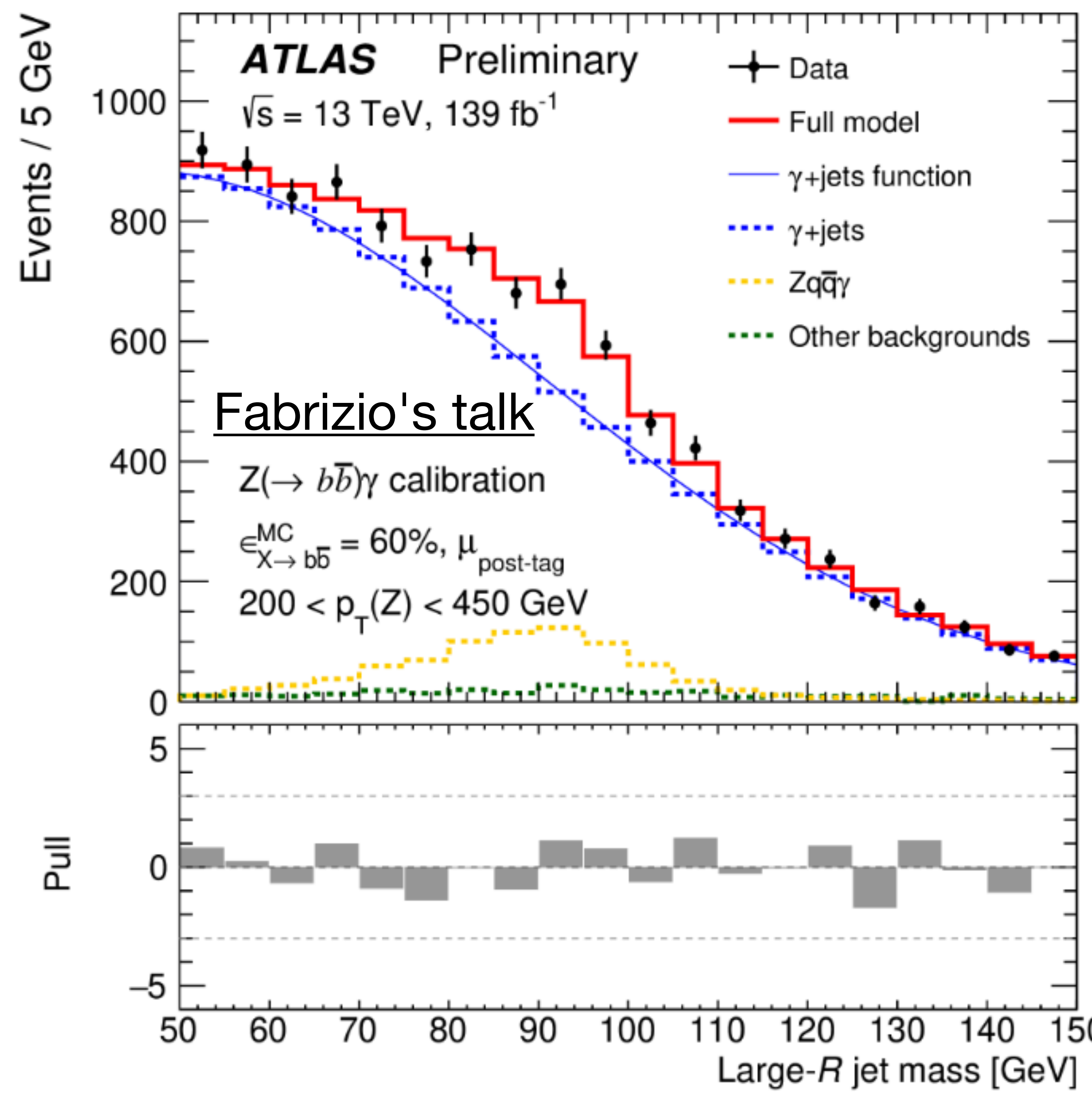




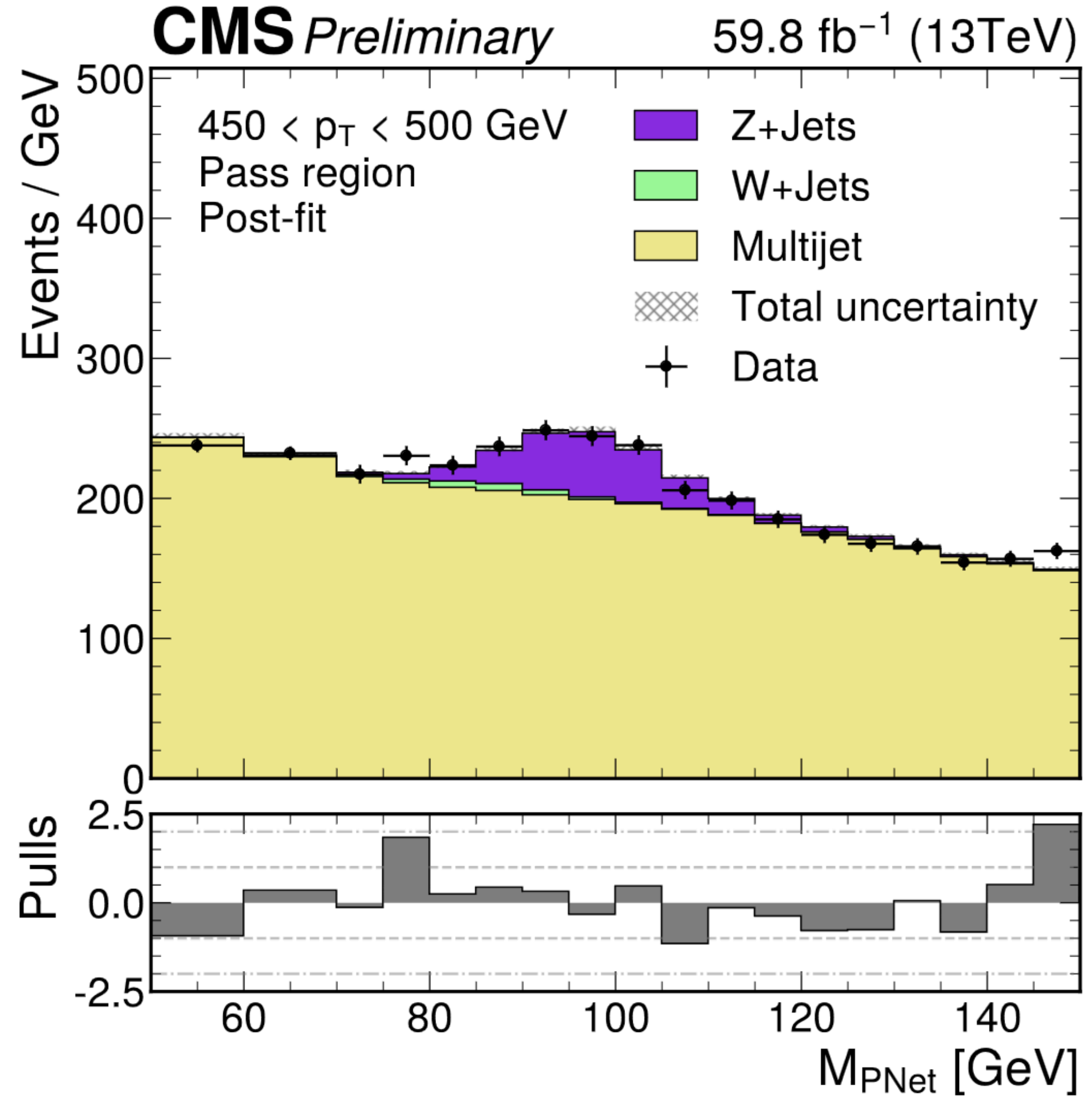
Understanding the space

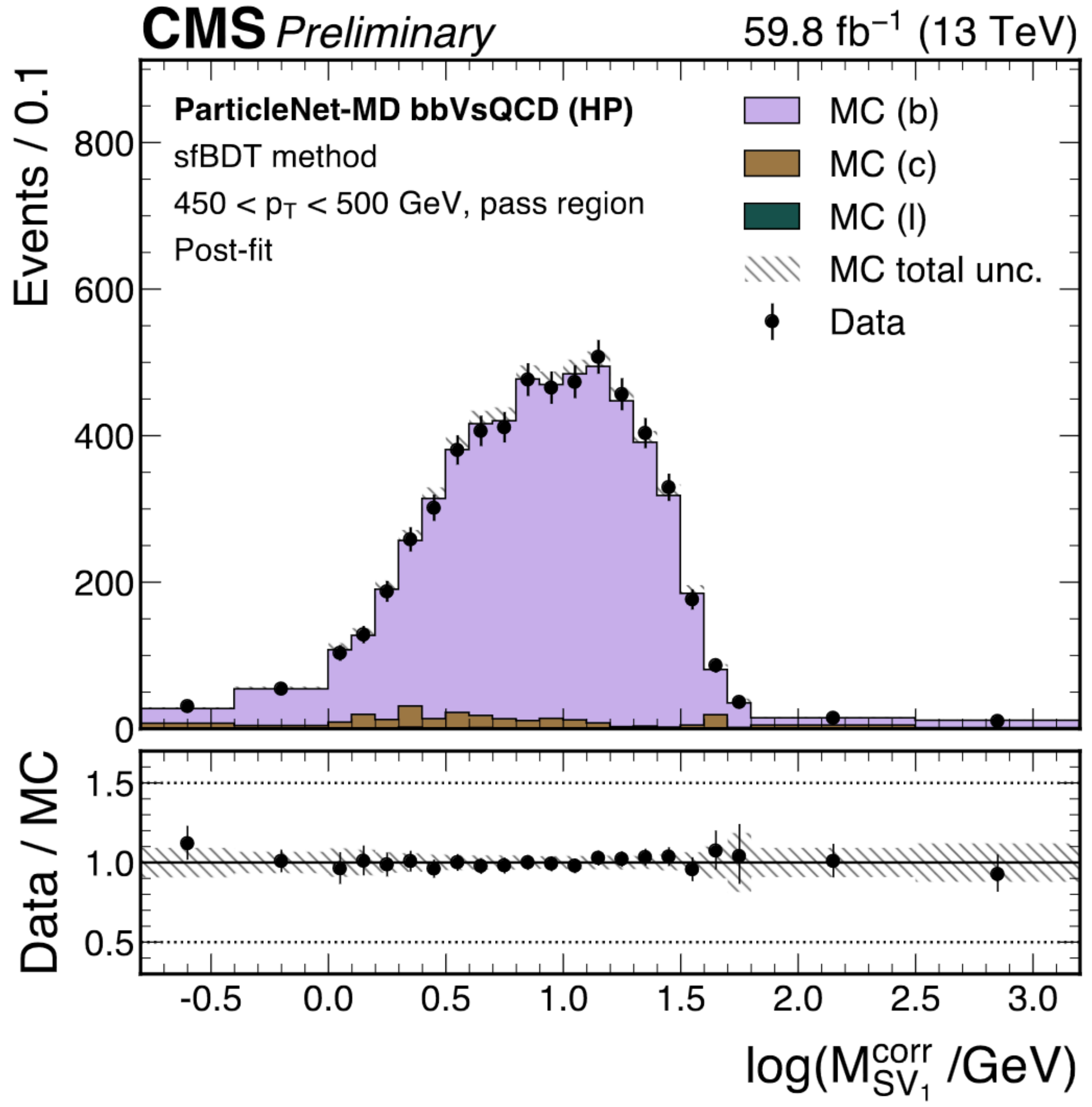
- Need tagger calib
- Difficult to get for H->bb)
- Combining scale methods to get th
  - Using multiple and Z→bb
  - Good cross-ch are consistent
  - *Will improve wi*





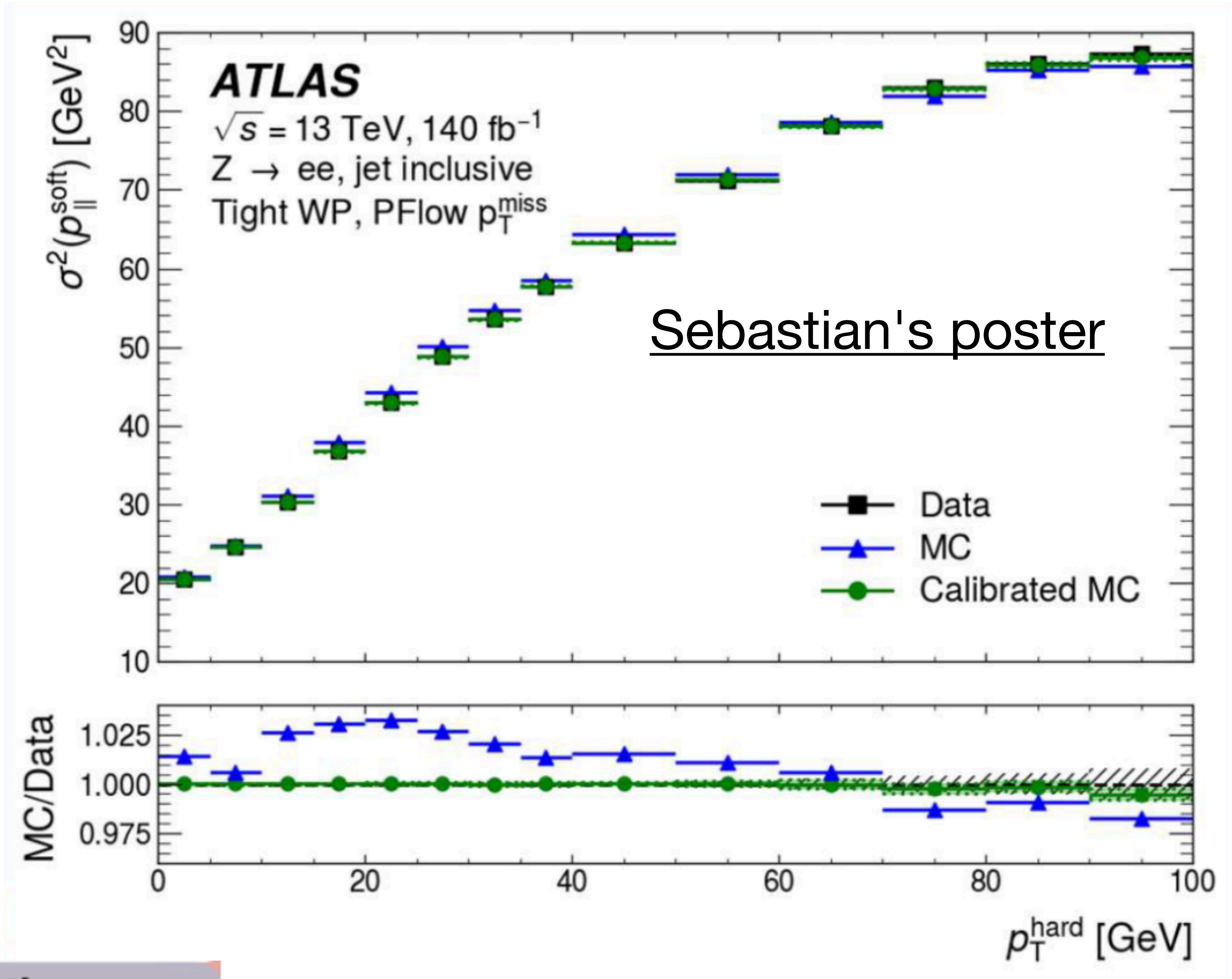
ATLAS is using similar techniques for the calibration (but g→bb is used for validation)

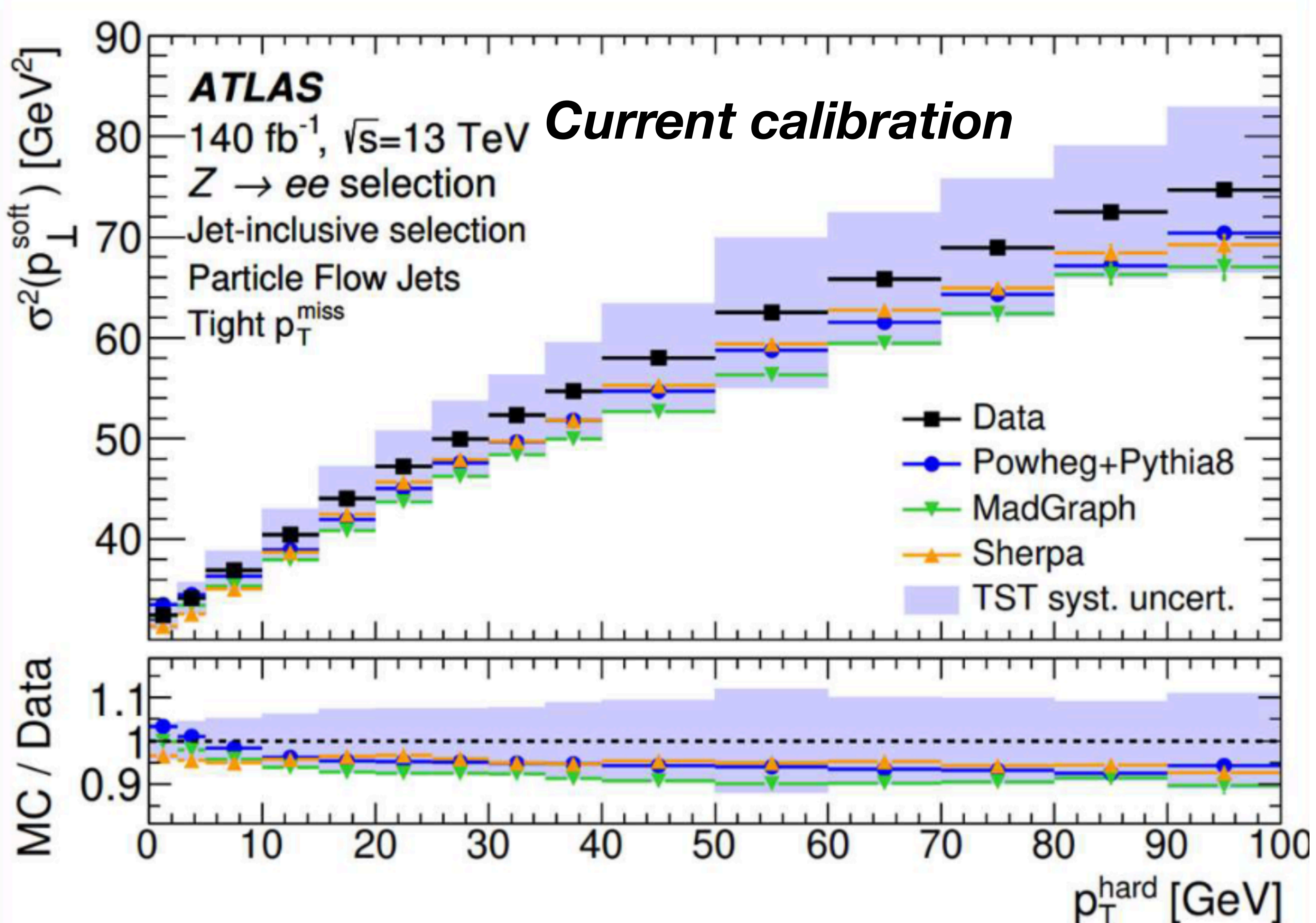


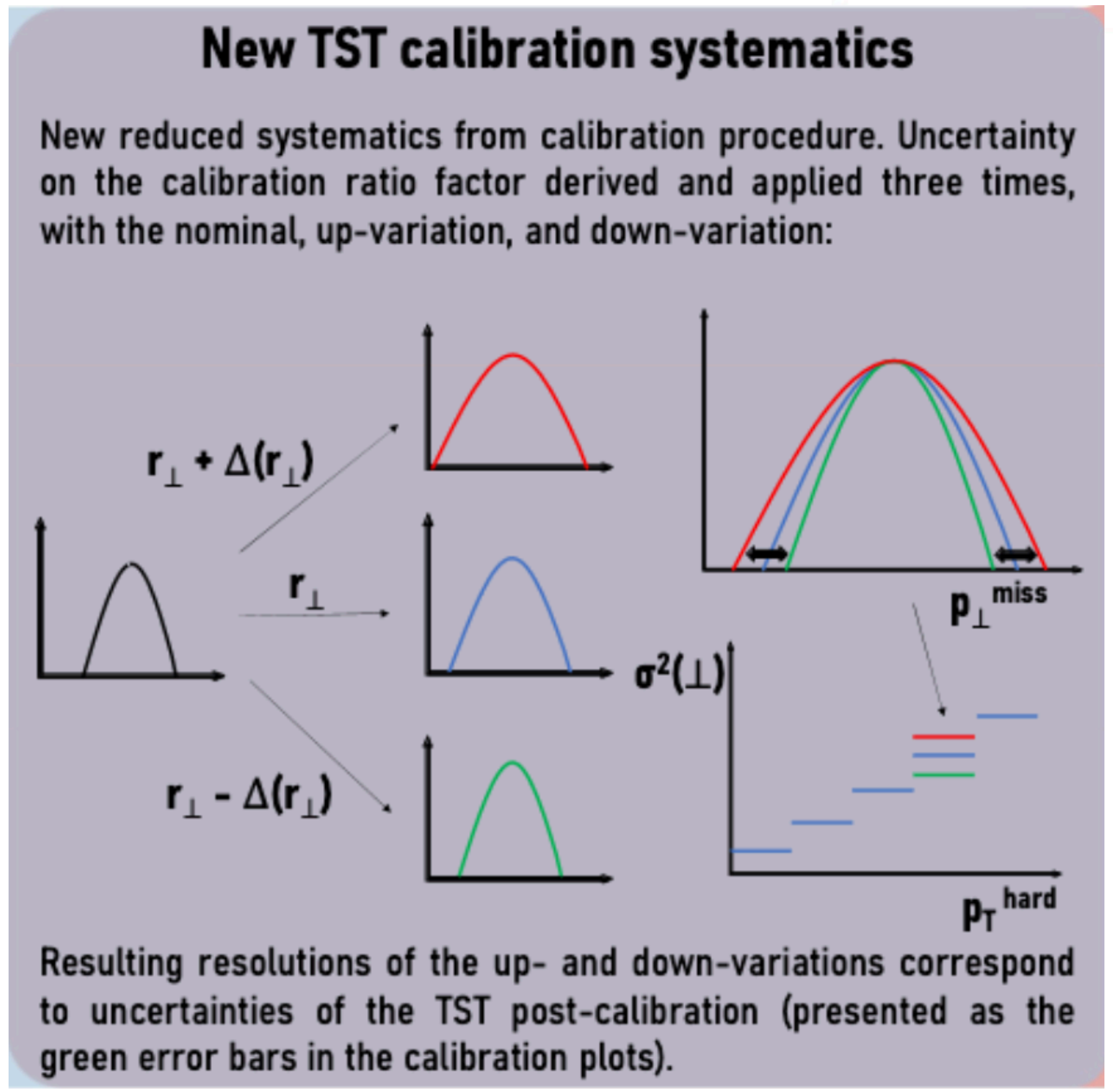


Understanding the space

- ATLAS is beginning to calibrate the MET
  - Calibration based on three components of the TST



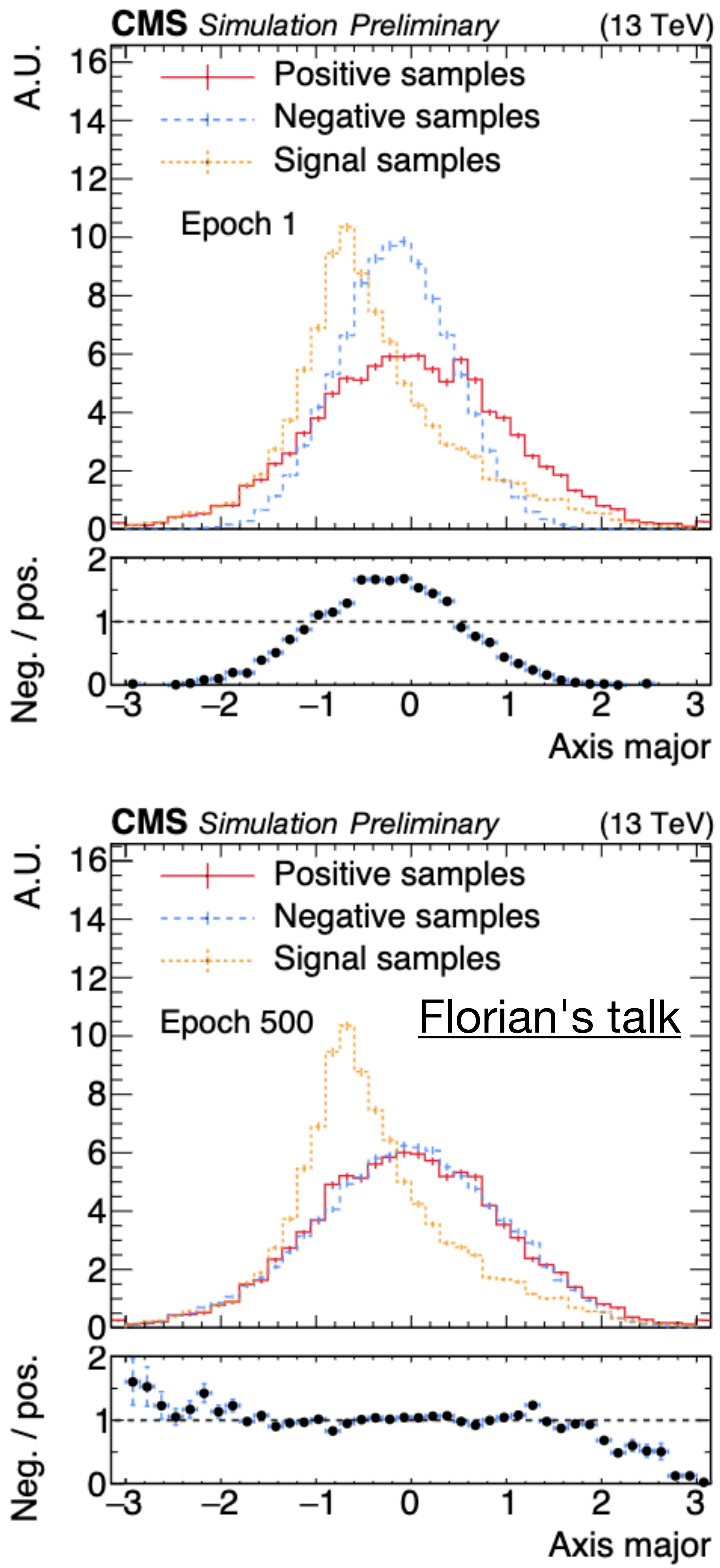


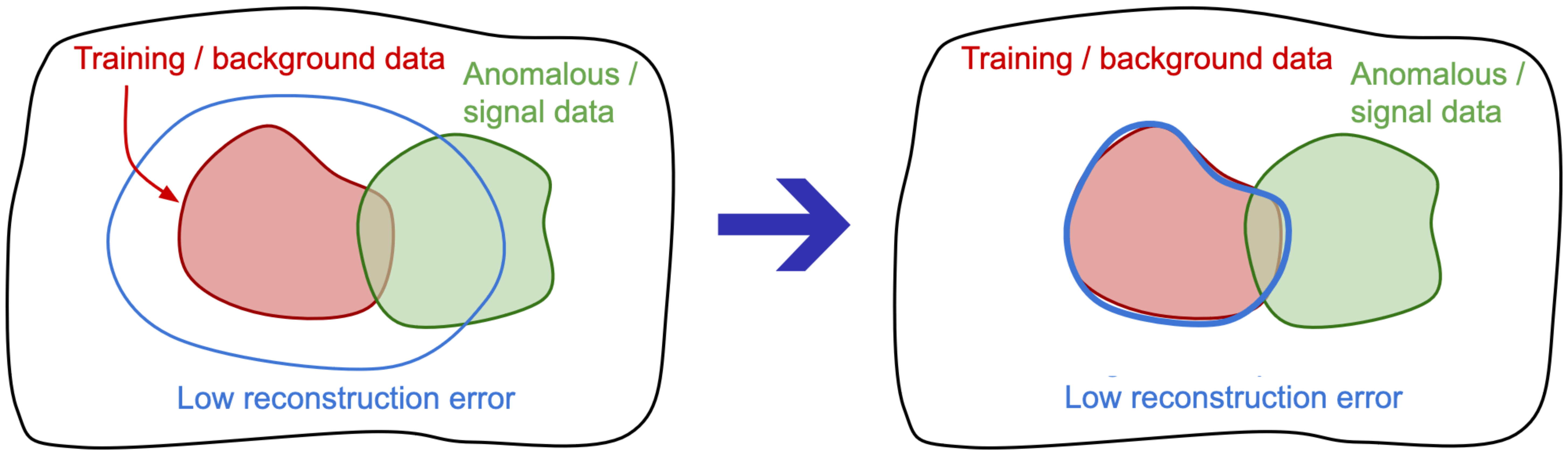


- *Potential to reduce the dominant systematic from MET!*

Understanding the space

- Trying to make sure we can control the behavior of the NNs that we train
  - If we know their limitations, can often account for this (with some cleverness)

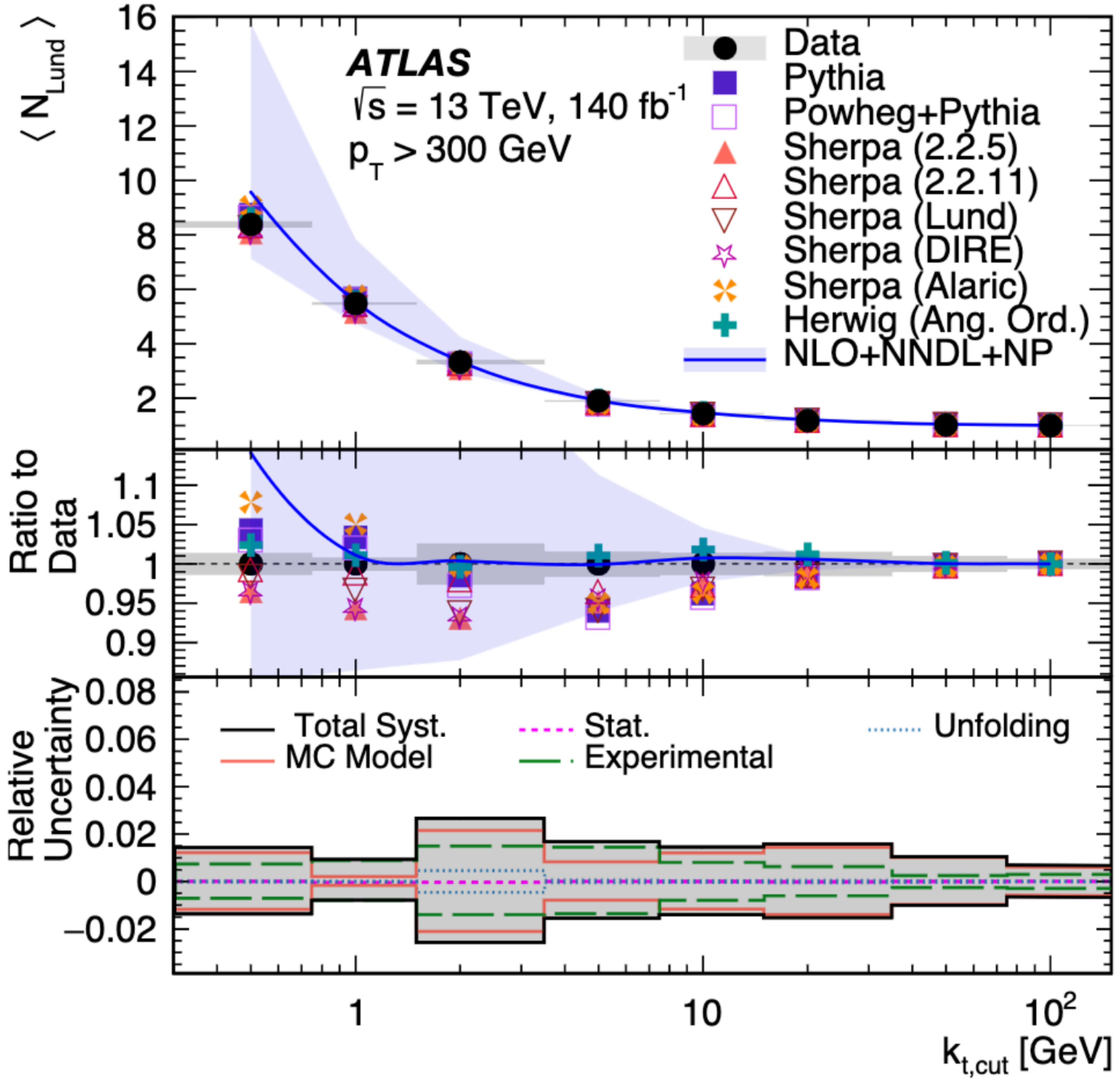


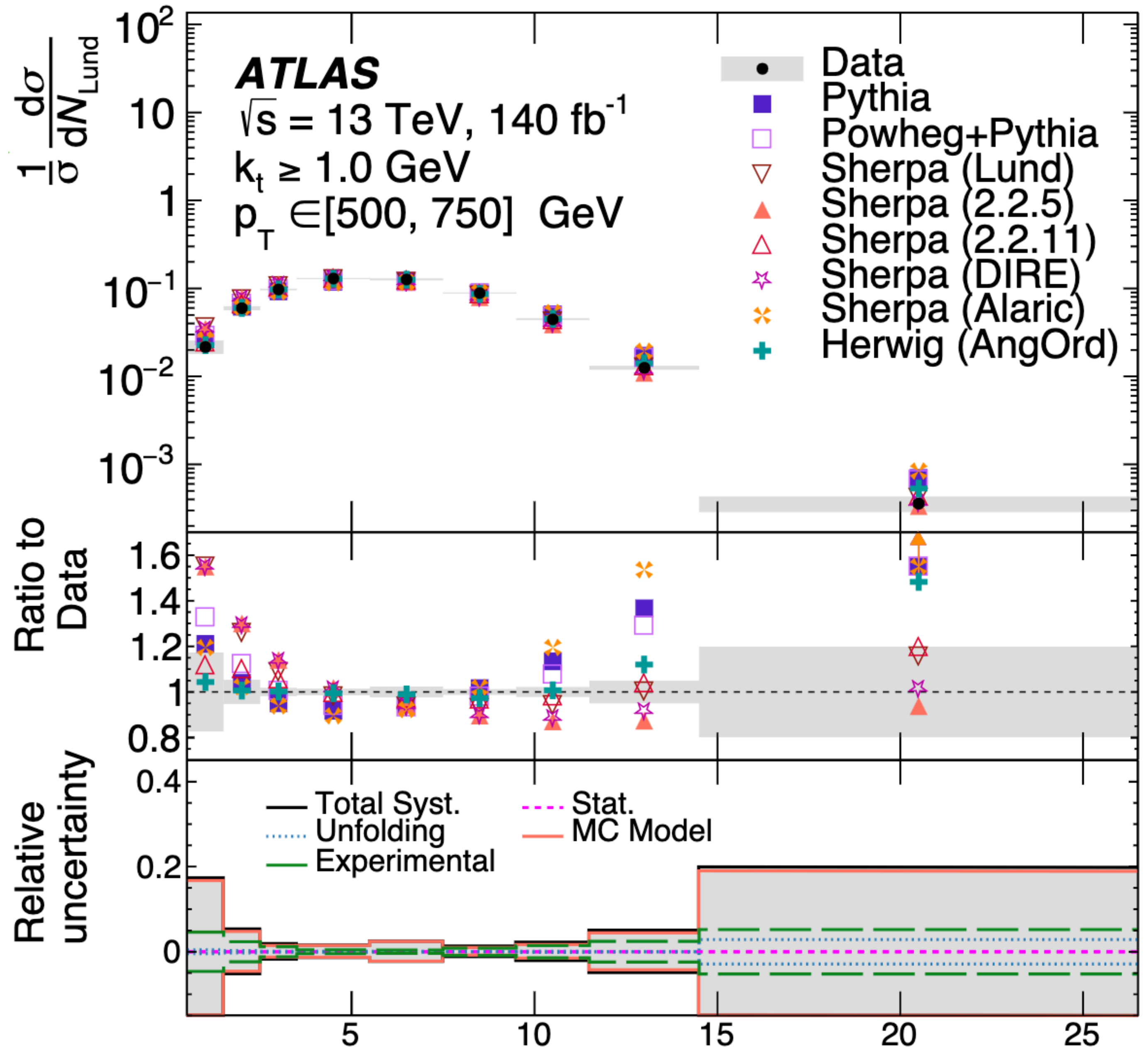


Understanding the space

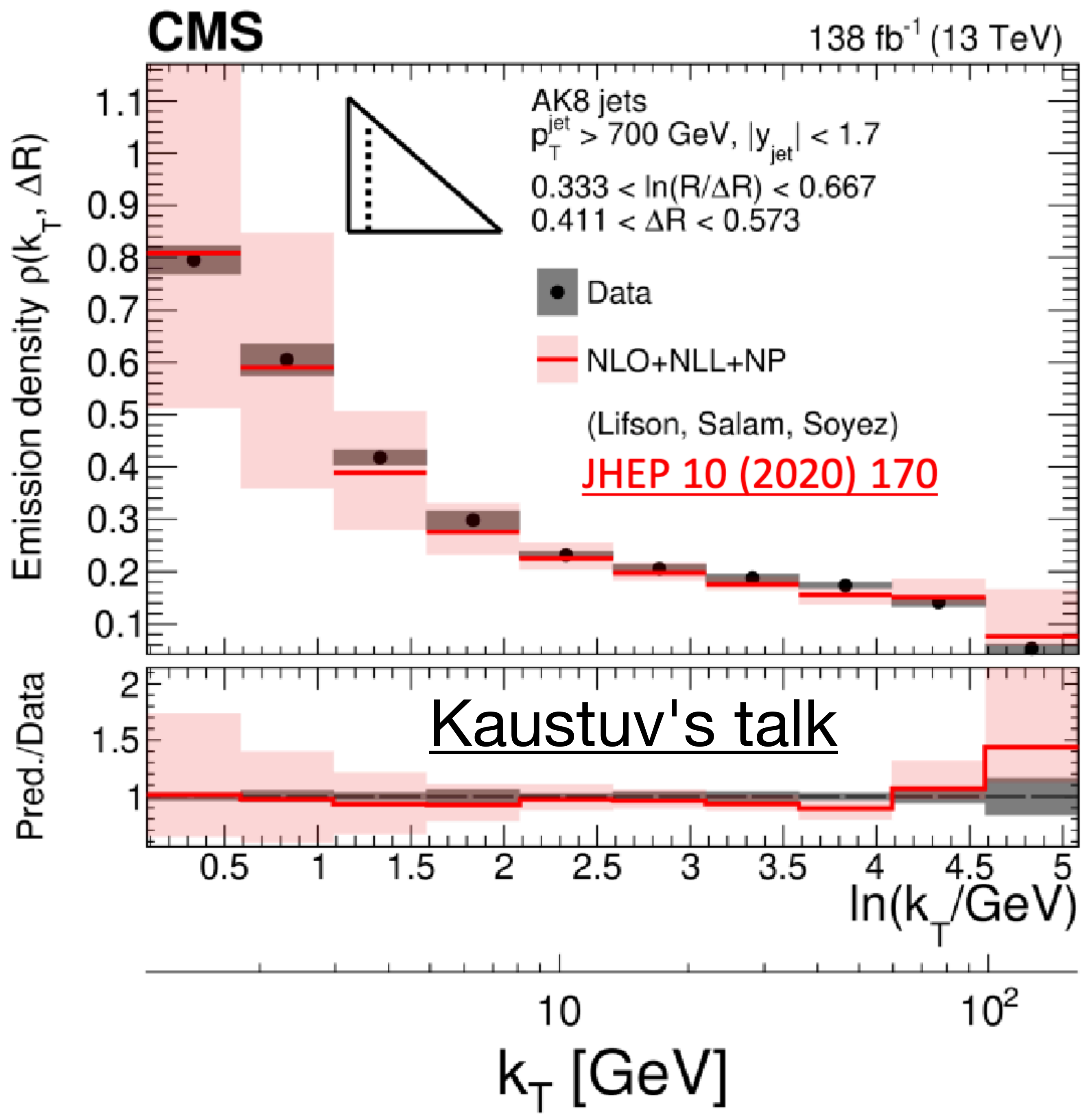
- The Lund plane provides a window into a variety of QCD dynamics

Jing's talk





Able to compare to analytical predictions!



Kaustuv's talk

- The Lund multiplicity is sensitive to NNDL effects, which are being included in higher accuracy MC predictions
  - *Providing experimental tests of new theoretical calculations*

Understanding the space

- Many discussions about the **robustness** of different ML-based taggers
- May be fine to sacrifice larger uncertainties to improve tagging performance
  - *Understanding where these differences come from could help us reduce modeling uncertainties for future taggers*

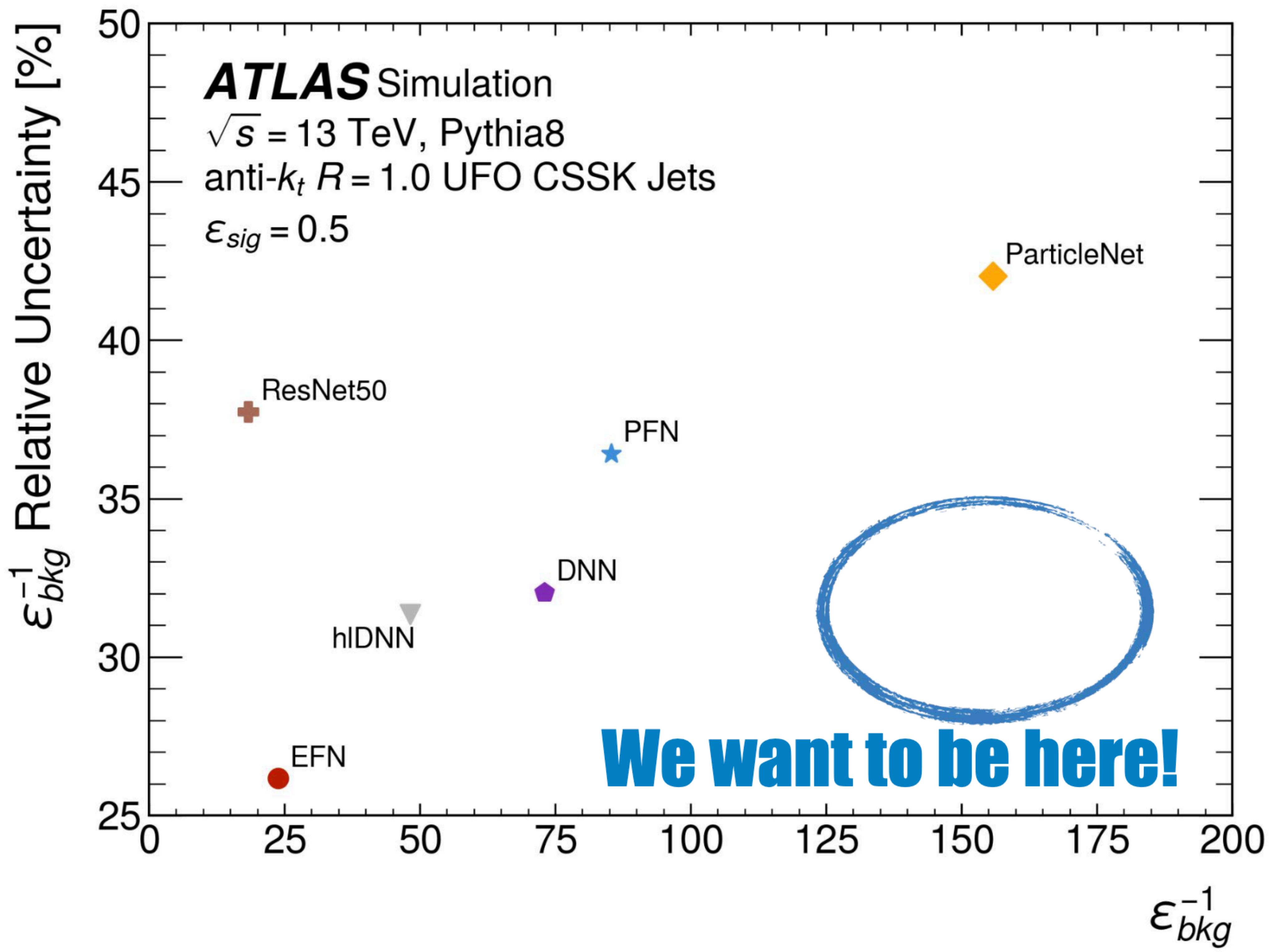
Rob's talk

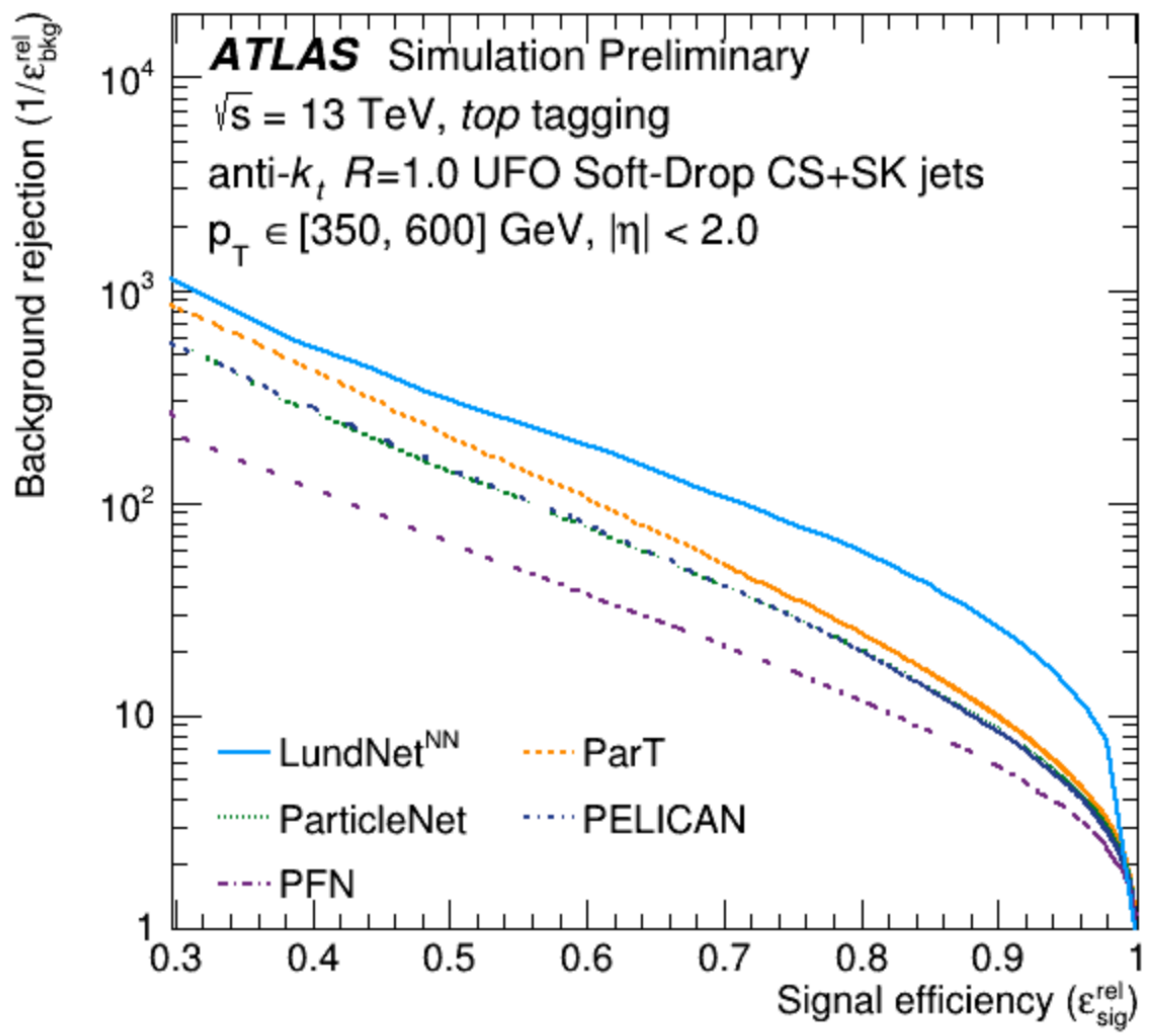
Understanding the space

- Still working to understand which networks are robust against modeling effects (and why)
  - Can no longer use a single metric to quantify the performance of a tagger

Kevin's poster

Have an idea for controlling uncertainties? These datasets are public!



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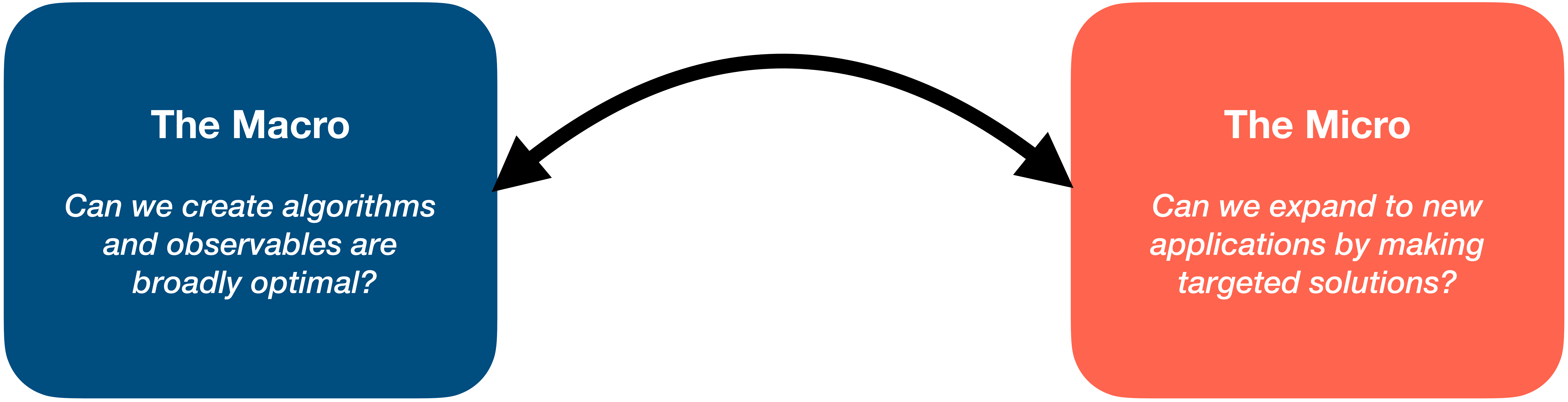
The Macro
Can we create algorithms and observables are broadly optimal?
The Micro
Can we expand to new applications by making targeted solutions?

BOOST

- 2010: These aren’t your daddy’s jets
- 2011: “First” data
- 2012: Kids in a candy store
- 2013: Bringing substructure into the mainstream
- 2014: if you ain’t boostin’ you ain’t livin’
- 2015: What a difference five years makes
- 2016: I got 99 problems but my BOOST ain’t one
- 2017: Deep thinking jets, they are among us
- 2018: DeepBOOST
- 2019: If you ain’t boostin’ in the morning, go back to bed!
- 2020: ..
- 2021: Jet vettin’ without jet settin’
- 2022: we are all about that boost (no treble)
- 2023: Through BOOST, all things are possible (so jot that down)
- 2024: BOOST for all, and all for BOOST