Introduction (experimental)

14th Annual Workshop on Boosted Object Phenomenology, Reconstruction, Measurements and Searches in High-Energy Physics

BOOST '22

Matt LeBlanc (CERN)

CERN

Sorry if you were expecting someone else.

Hey Matt I want to tell you this how do you be able to a good actor though in production can I ask

May 18, 2020, 1:30 AM

Hey Matt I always watch you on the TV the sitcom of friends and always I am doing drama at the moment I want to act with you is that ok with you

Jan 10, 2019, 9:14 PM

Hi joey...fan from India..

Jan 3, 2017, 10:28 AM

You should be together in the show friends Joey and Rachel just Match SOO good btw I LOVE YOU GUYS ❤️❤️u guys are my idols🙄❤️❤️❤️

Dec 23, 2020, 5:33 PM

Joey

Joey

Joey

Joey

Joey

Joey

Joey

Joey

Joey

Feb 18, 2017, 8:40 PM

Sure!

I'll try to find you at boost :)

Aug 5, 2022, 1:56 AM

… it happens quite often.

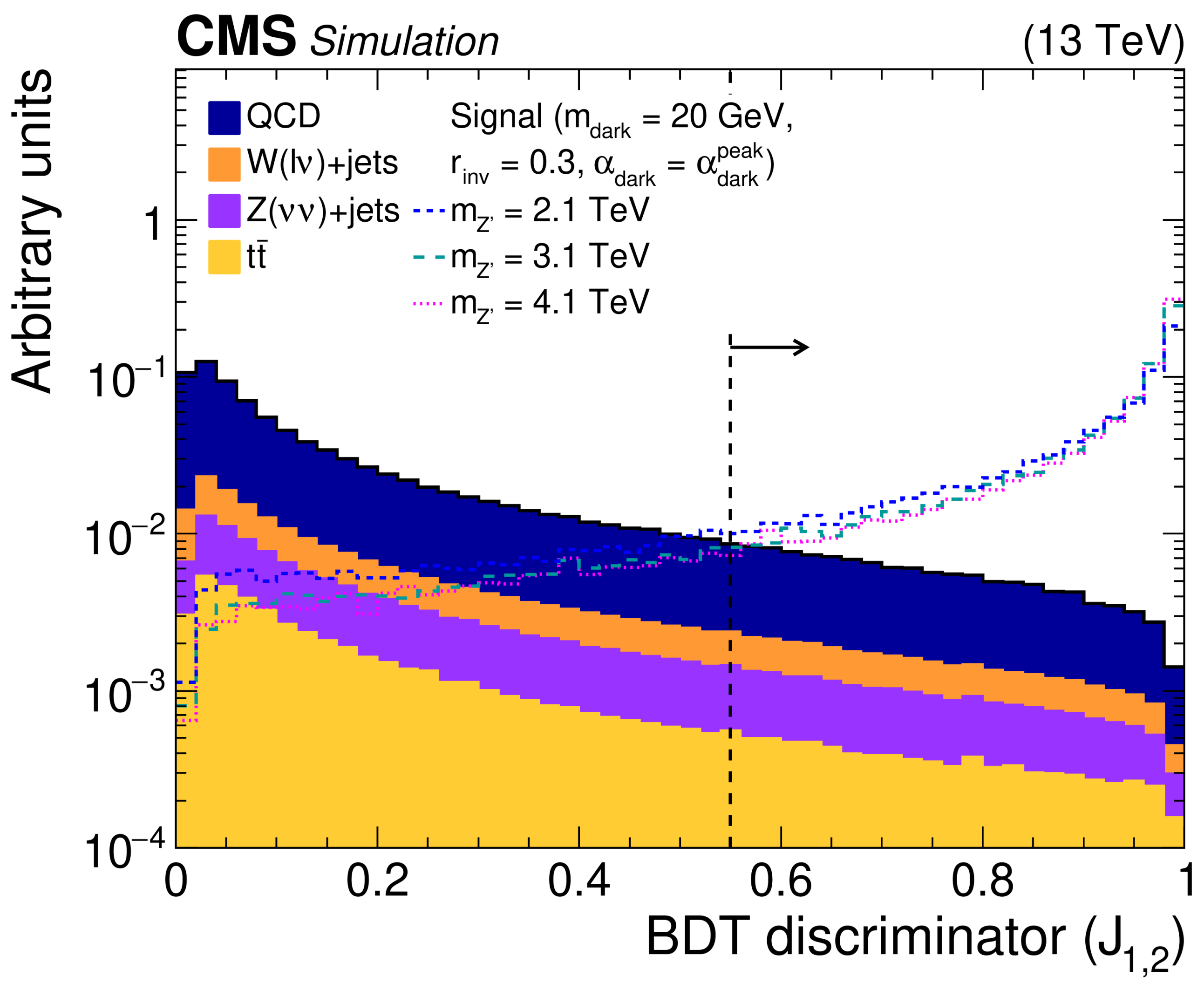
Why do we BOOST?

- We want to better understand the world around us.

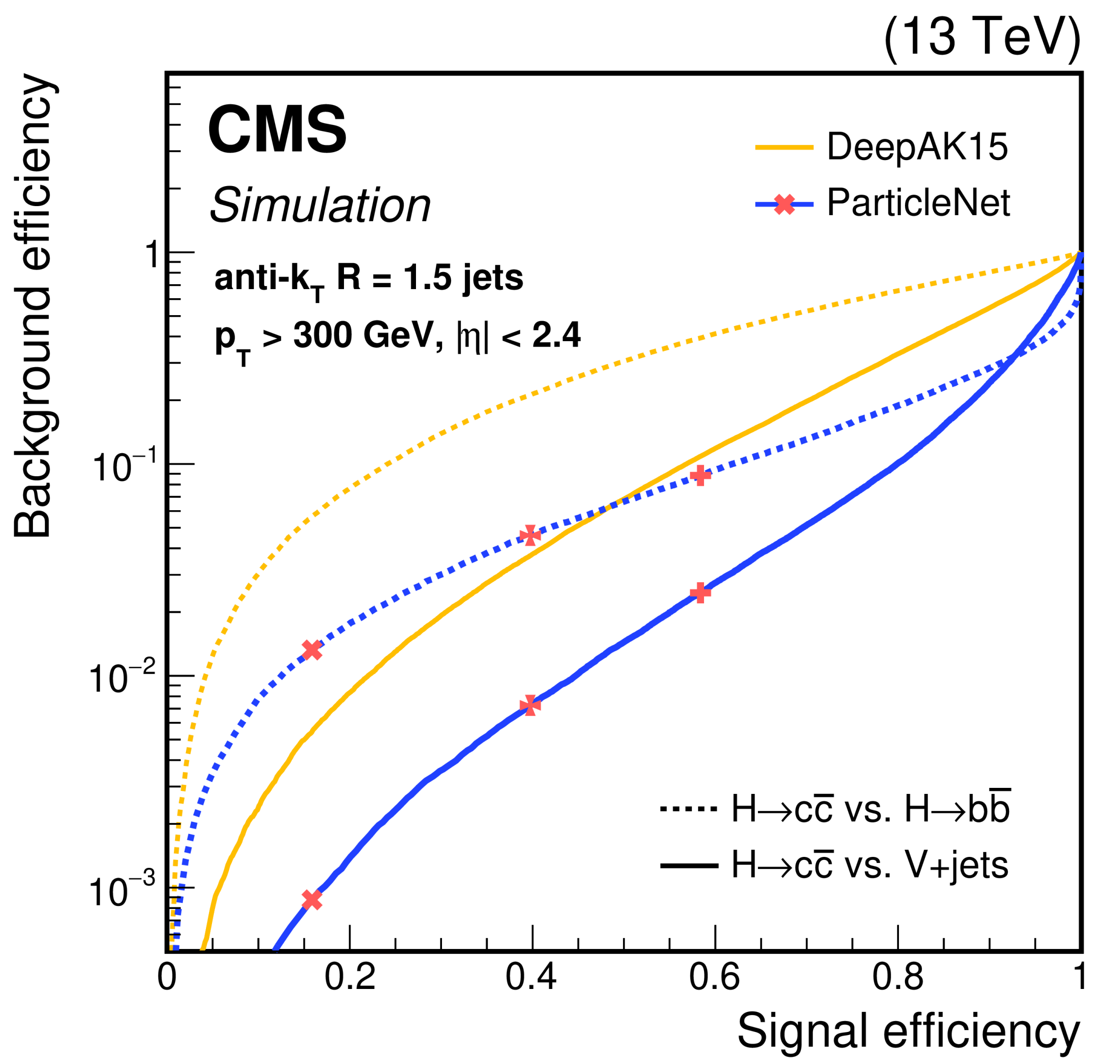
SMACS 0723 via https://www.nasa.gov/webbfirstimages, bullet cluster via https://chandra.harvard.edu/photo/2006/1e0657/more.html

Why do we boost?

- We want to better understand the world around us.
- Many of these questions imply the existence of particles beyond the Standard Model (BSM).
    - We **search** for them directly, and **develop new tools** to do so.



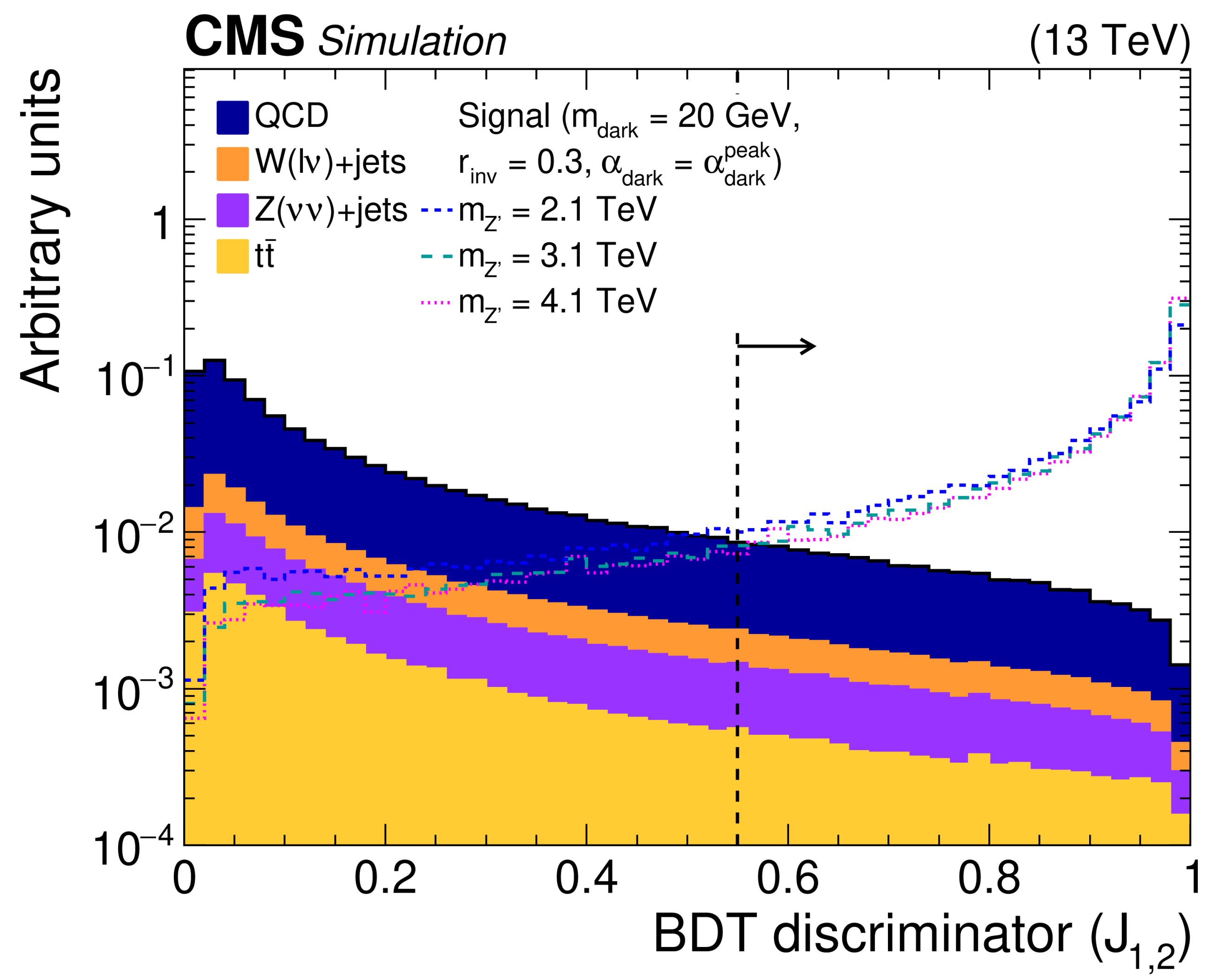
Maybe: you search for Dark Matter

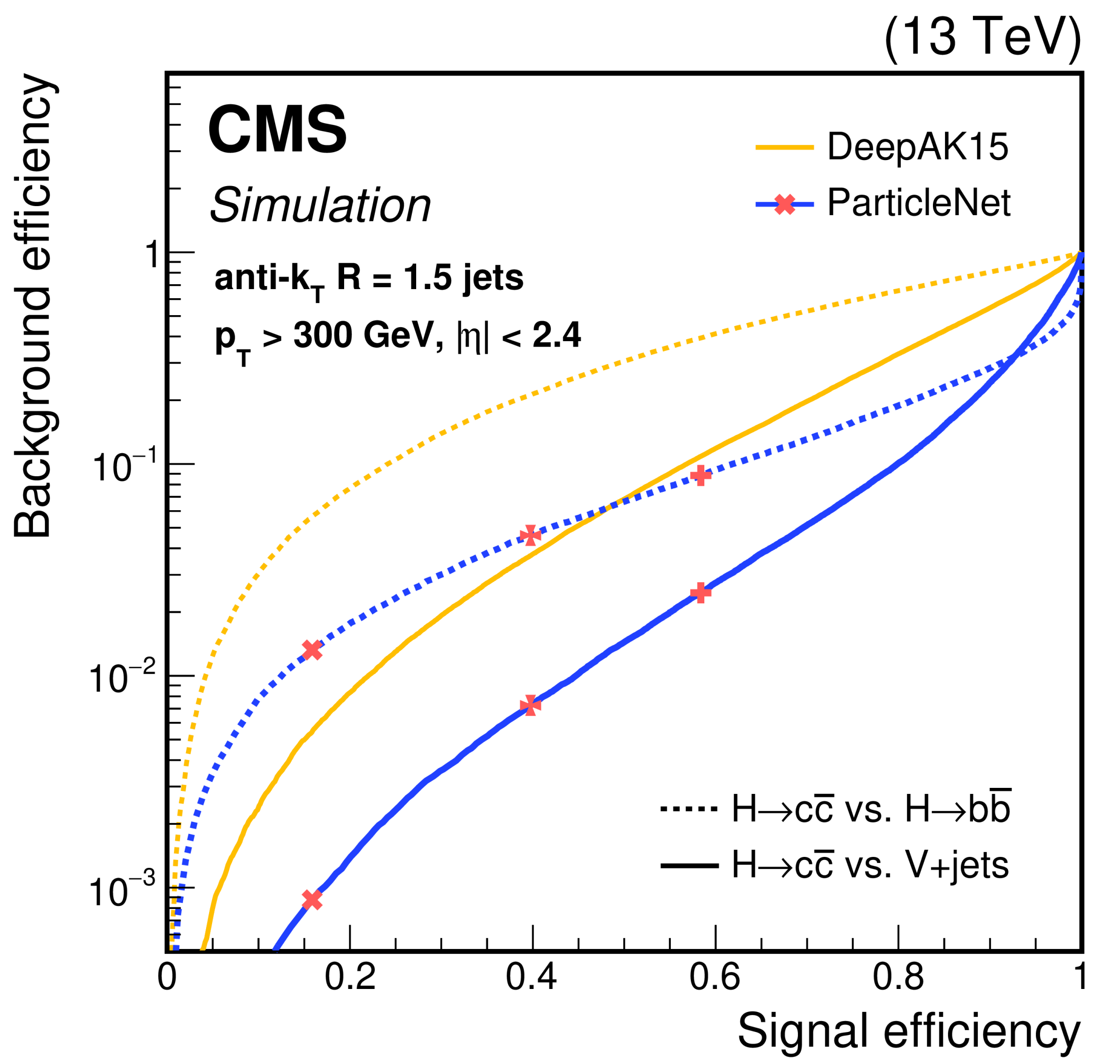


Maybe: you develop new tools

WHY DO WE BOOST ?

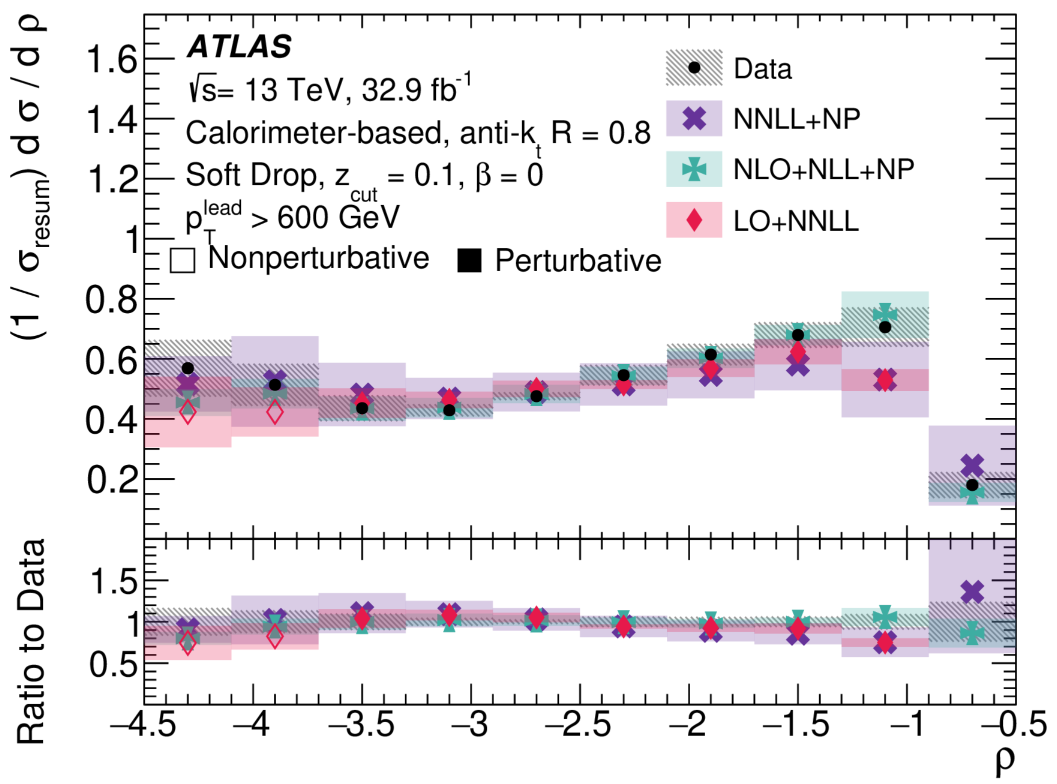
- We want to better understand the world around us.
- Many of these questions imply the existence of particles beyond the Standard Model (BSM).
  - We **search** for them directly, and **develop new tools** to do so.
- We want to improve our understanding the Standard Model (SM).
  - **Measurements** resolve tensions, improve **models** (MC & analytic), *etc.*
    - … ultimately help us test the SM with improved precision.

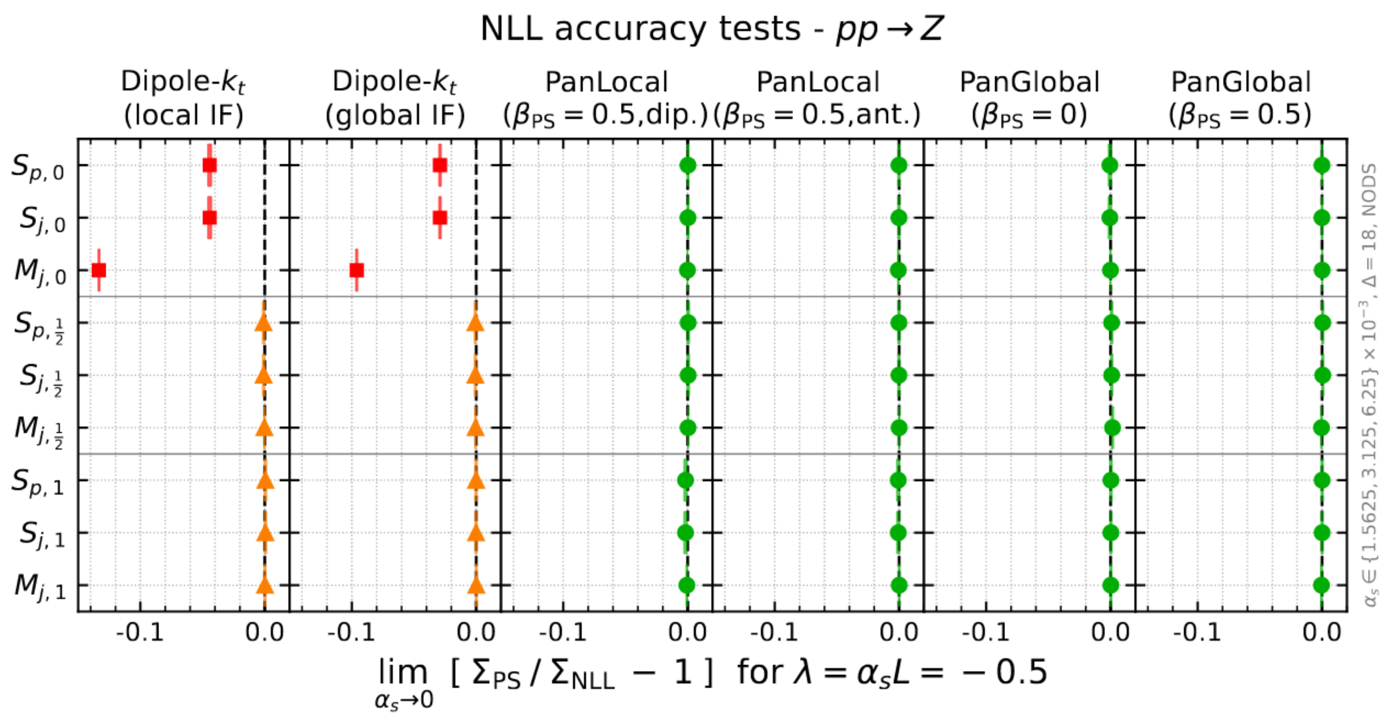


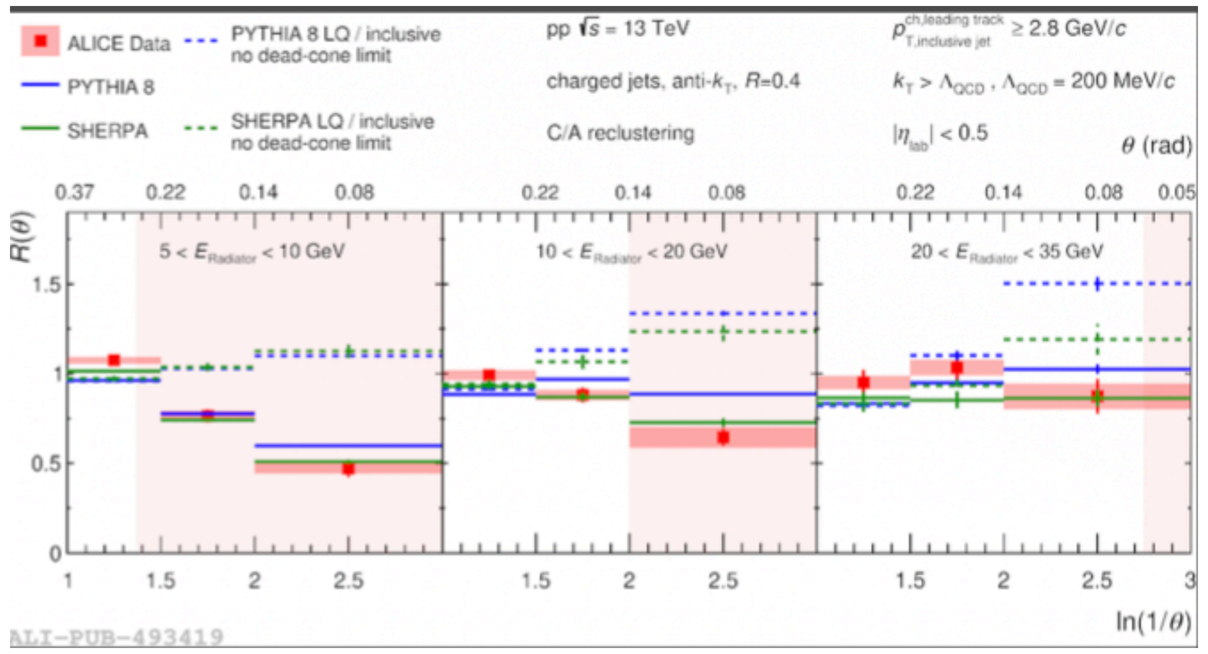


Maybe: you search for Dark Matter

Maybe: you develop new tools





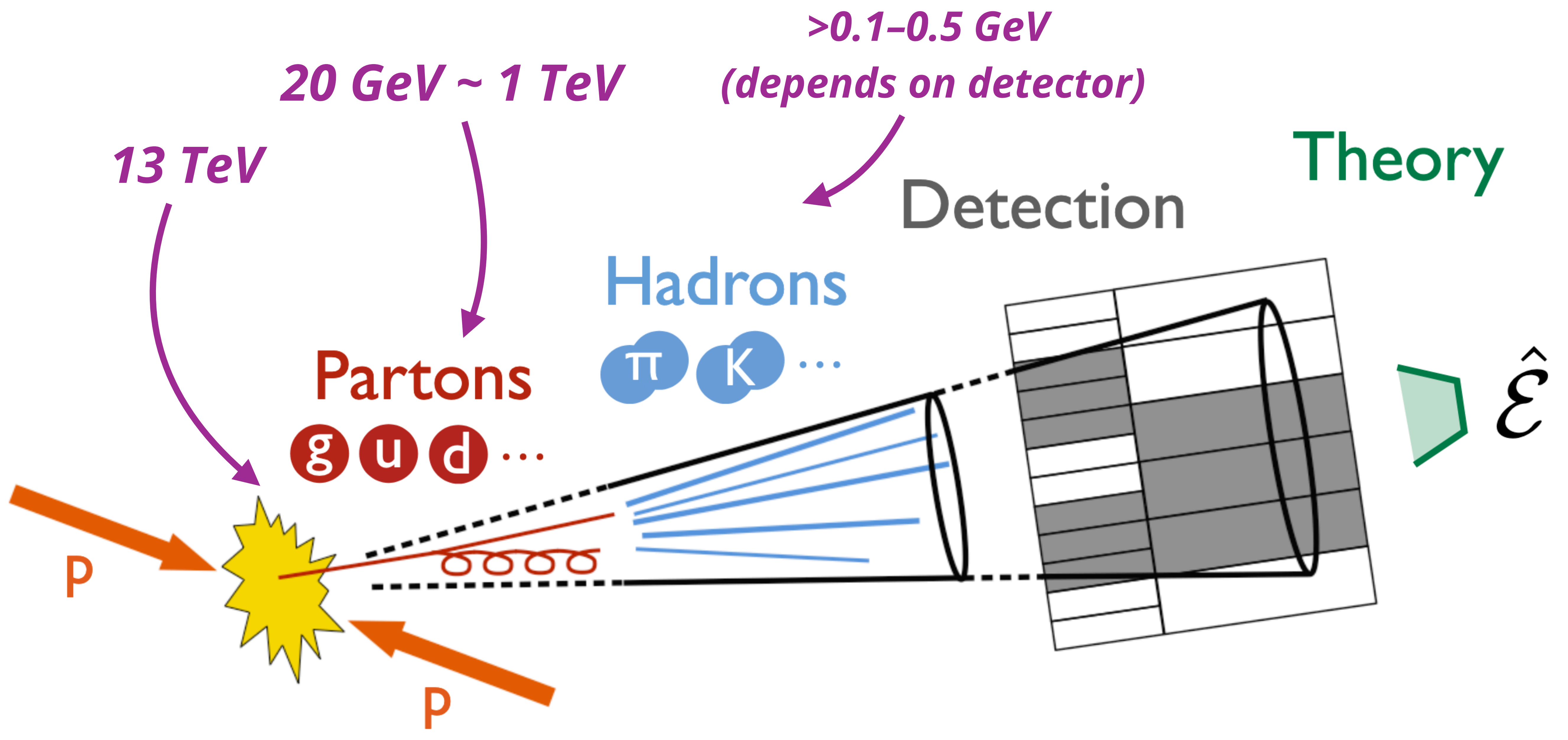


Maybe: you make precision measurements

Maybe: you improve our models

Why do we BOOST ?

- Jets & jet substructure allows us to **coherently probe QCD over several orders of magnitude** of energy.
  - … from the **hardest, TeV-scale** emissions at the LHC …
  - … through the **resummation-dominated** region we can study perturbatively …
  - … down to the **softest, MeV-scale** emissions produced by hadronisation and non-perturbative processes.



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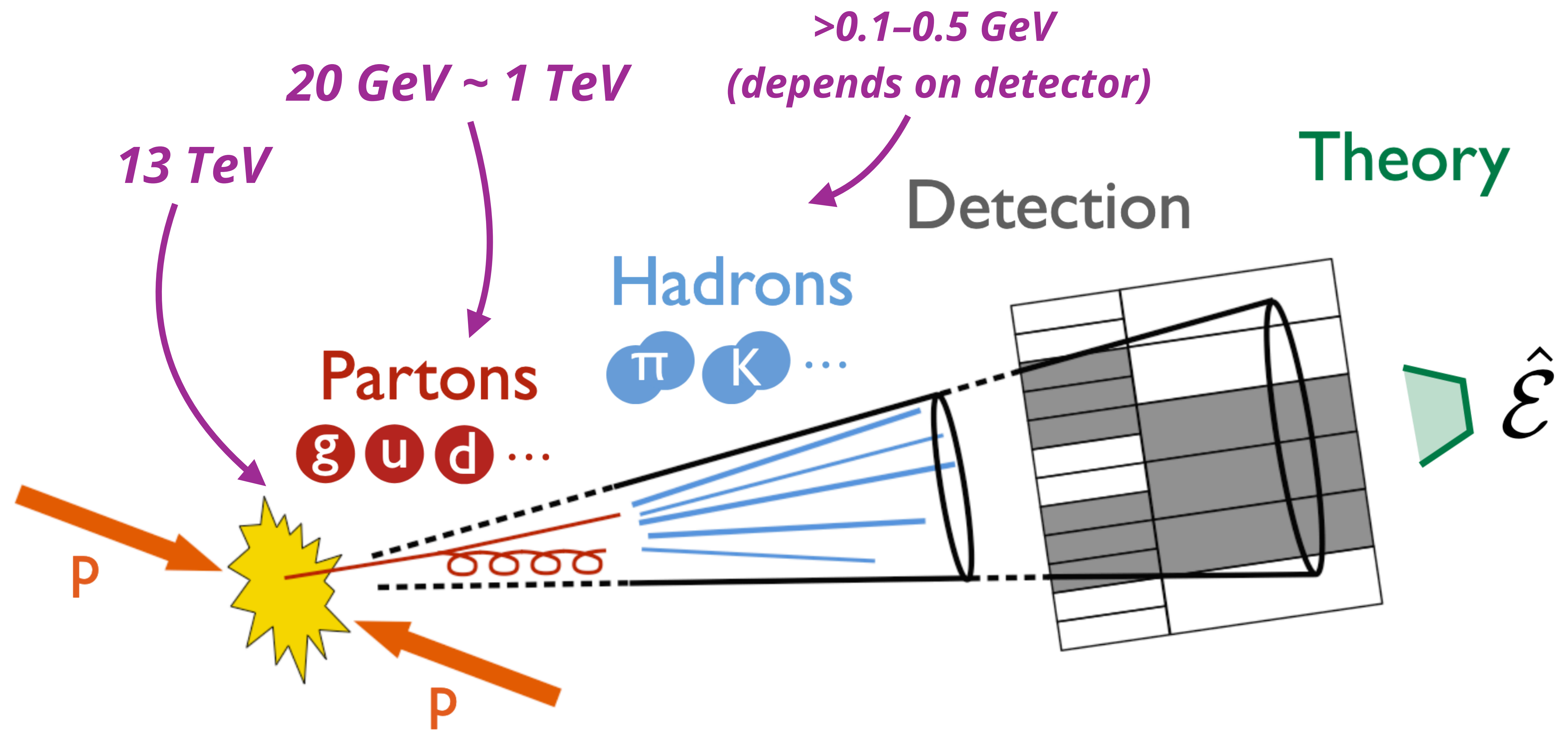
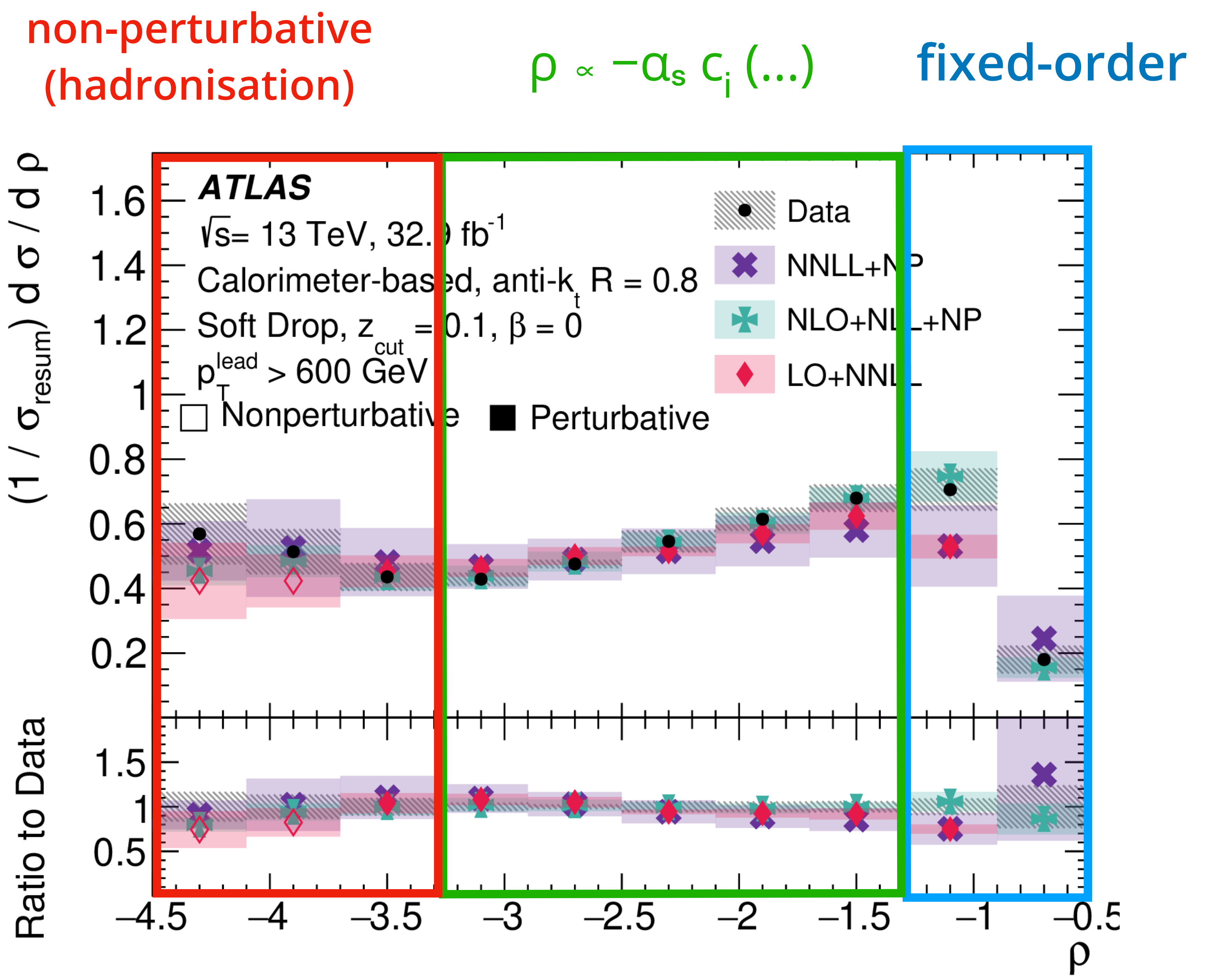
- **We often do this in a single analysis!**





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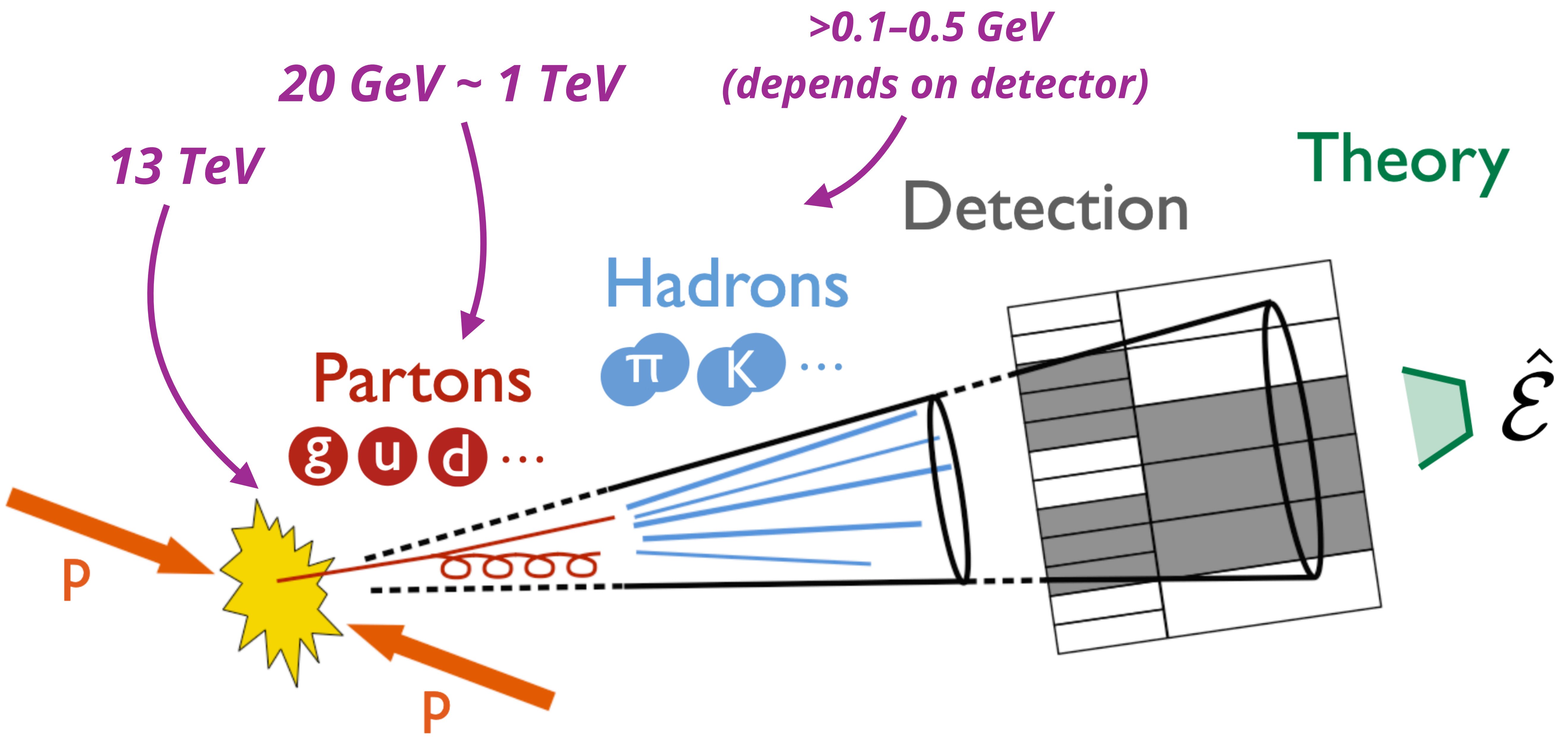
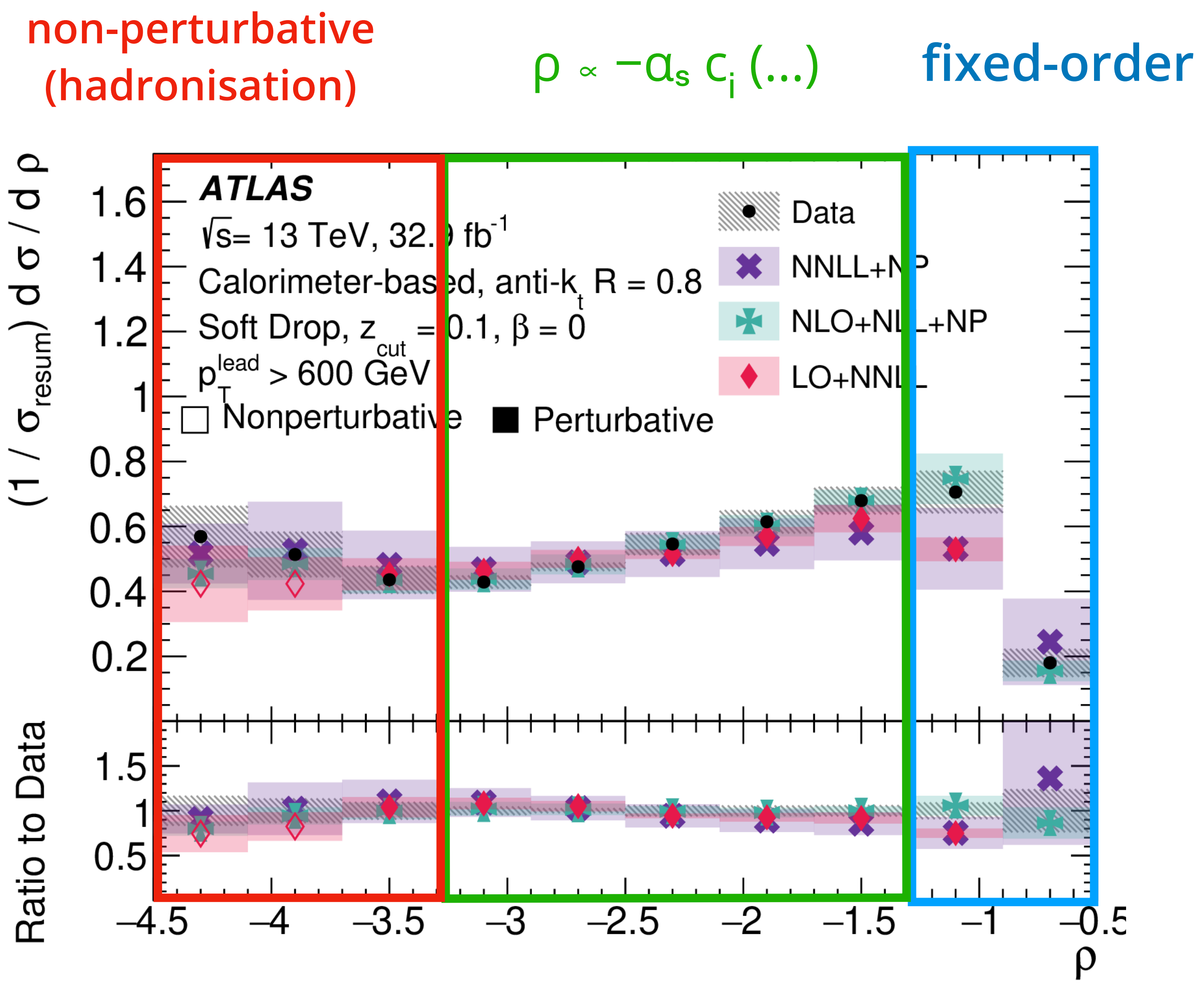
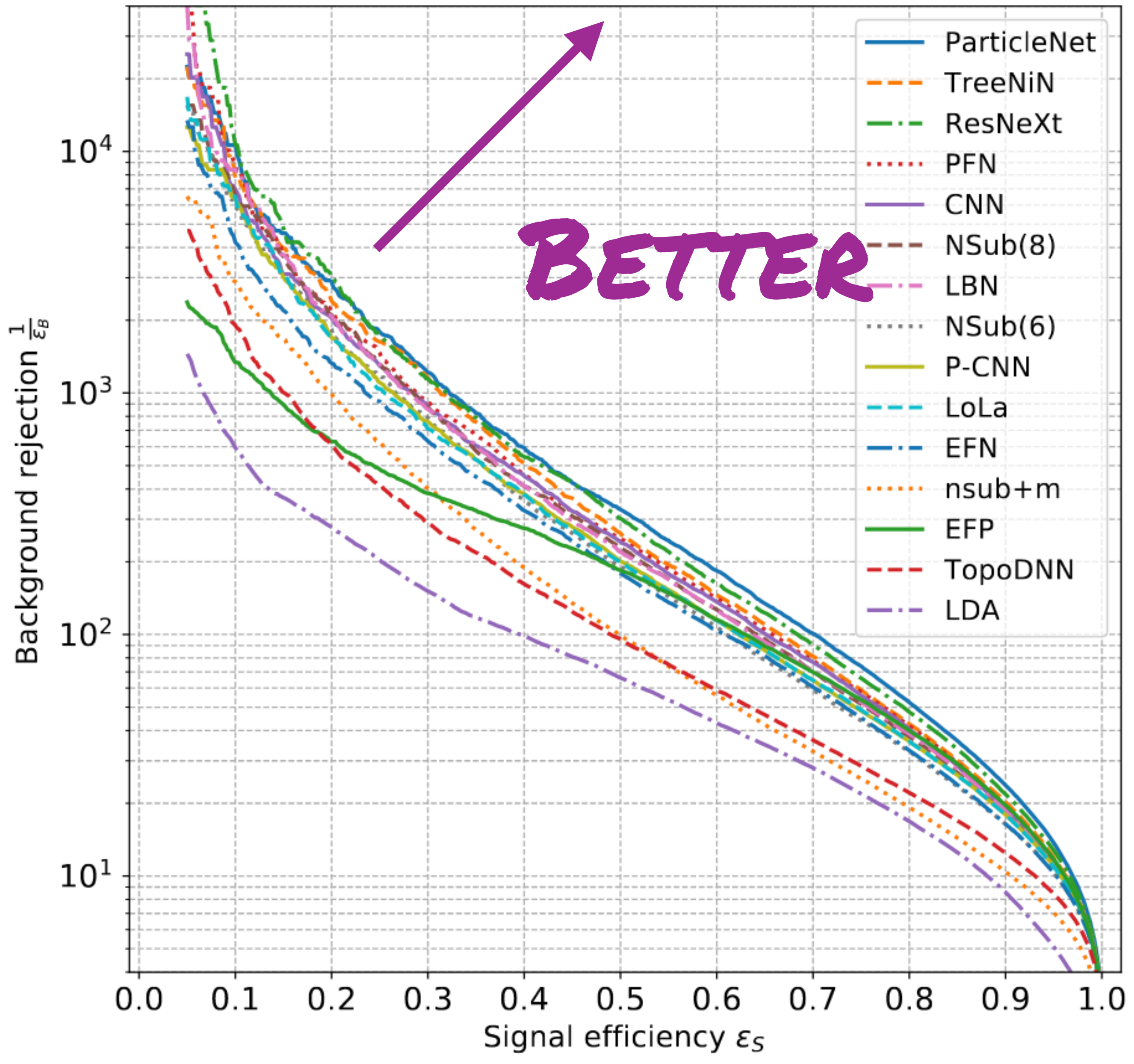
- **We often do this in a single analysis!**
- The **tactile nature** of Jets+JSS lends itself naturally to **ML/AI studies:**
  - Playground for classification, regression tasks with well-understood non-ML benchmarks.





Kasieczka et al. 1902.09914



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  - … from the **hardest, TeV-scale** … at
  - … re
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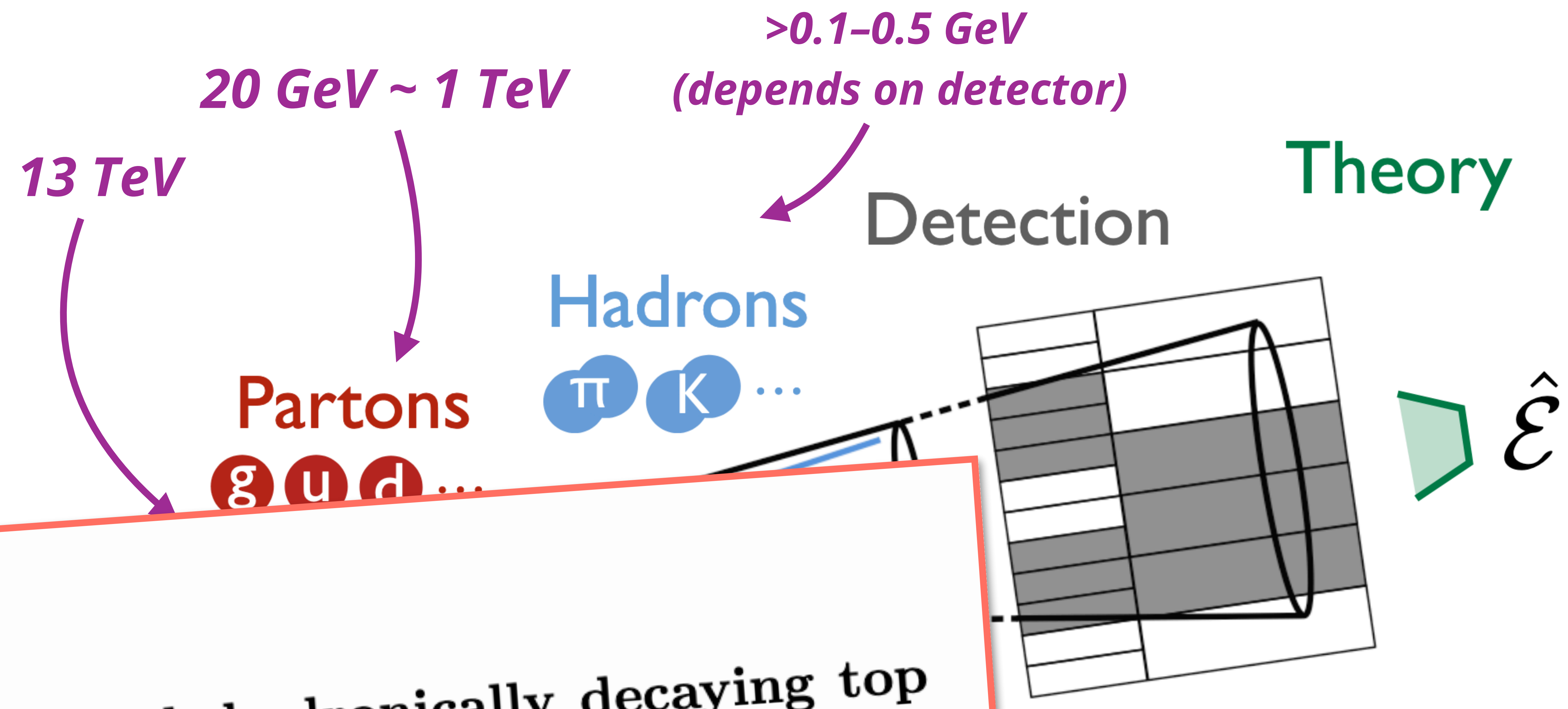
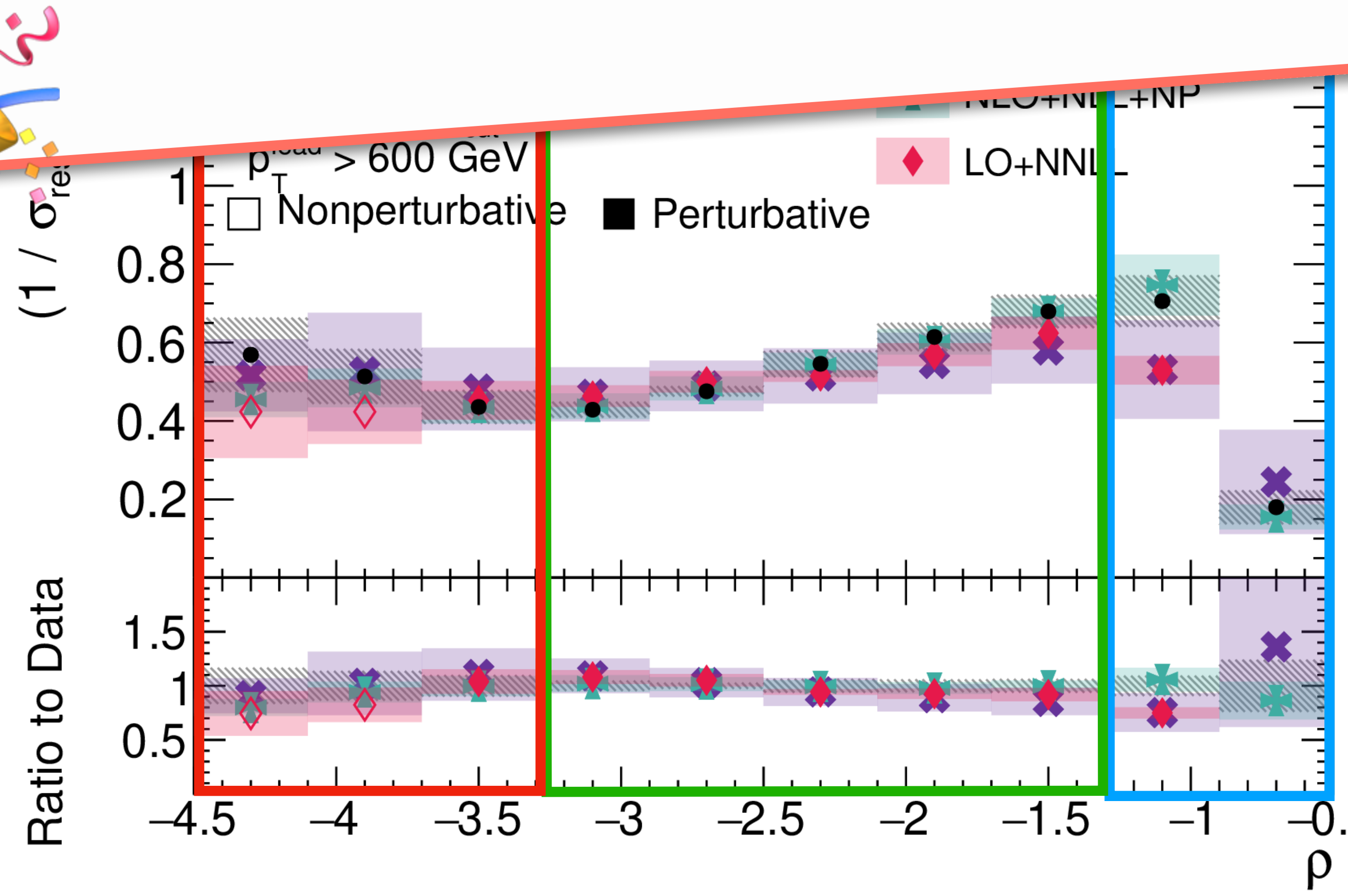
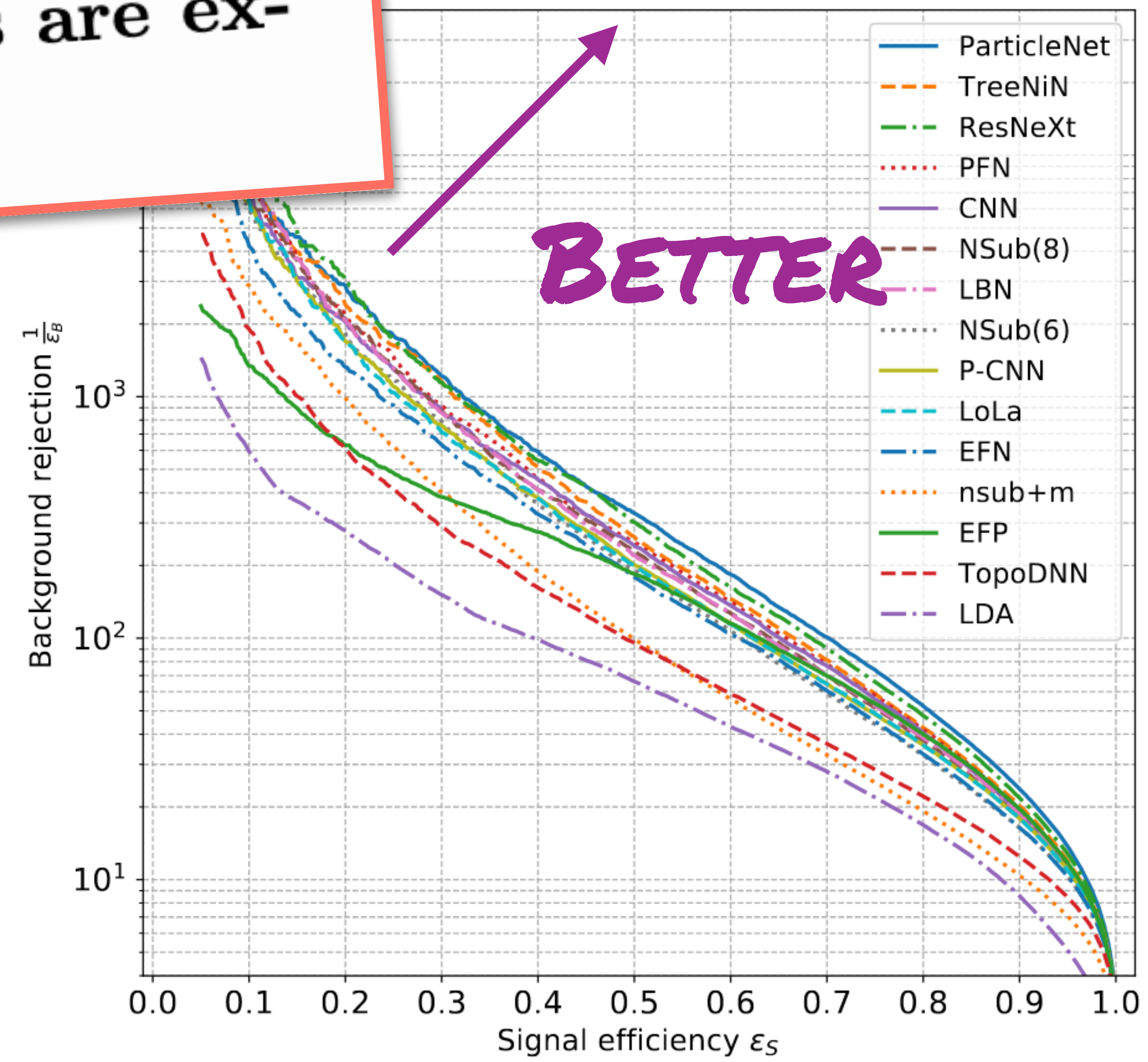


Abstract

Based on the established task of identifying boosted, hadronically decaying top quarks, we compare a wide range of modern machine learning approaches. Unlike most established methods they rely on low-level input, for instance calorimeter output. While their network architectures are vastly different, their performance is comparatively similar. In general, we find that these new approaches are extremely powerful and great fun.



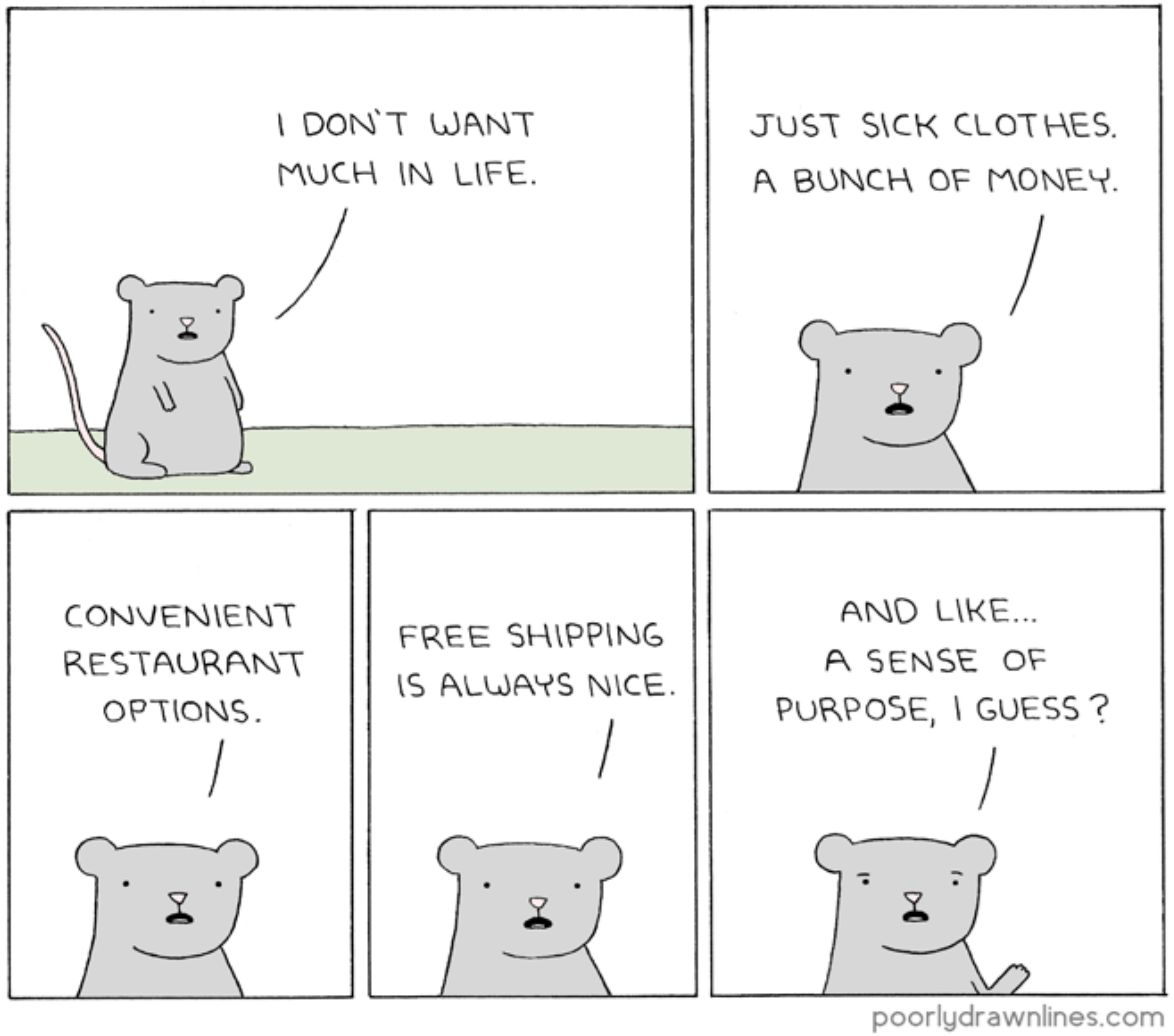
…zka et al. 1902.09914



QUICK TOUR OF A COUPLE SELECTED RUN 2 SEARCH RESULTS.

THESE WILL BE PRESENTED AFTER LUNCH TODAY — SO THIS IS VERY CURSORY / CHERRY-PICKED.

(I WILL SHOW ONLY ONE SET OF LIMITS IN THIS TALK!)

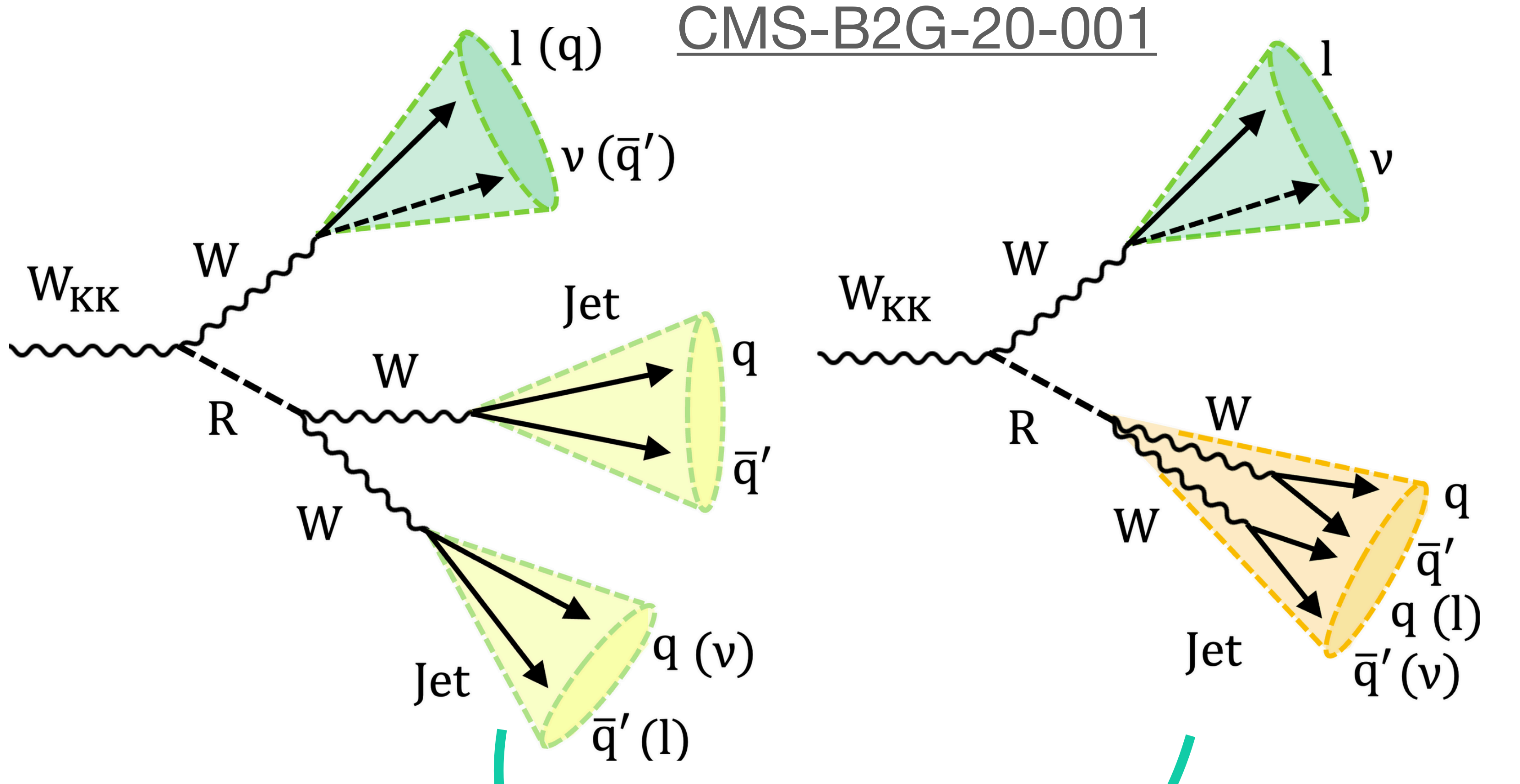


Lots of CMS ML/AI Jet Tagging Info:
CMS-JME-18-002

Run 2 Searches : CMS

CMS 3W Resonances

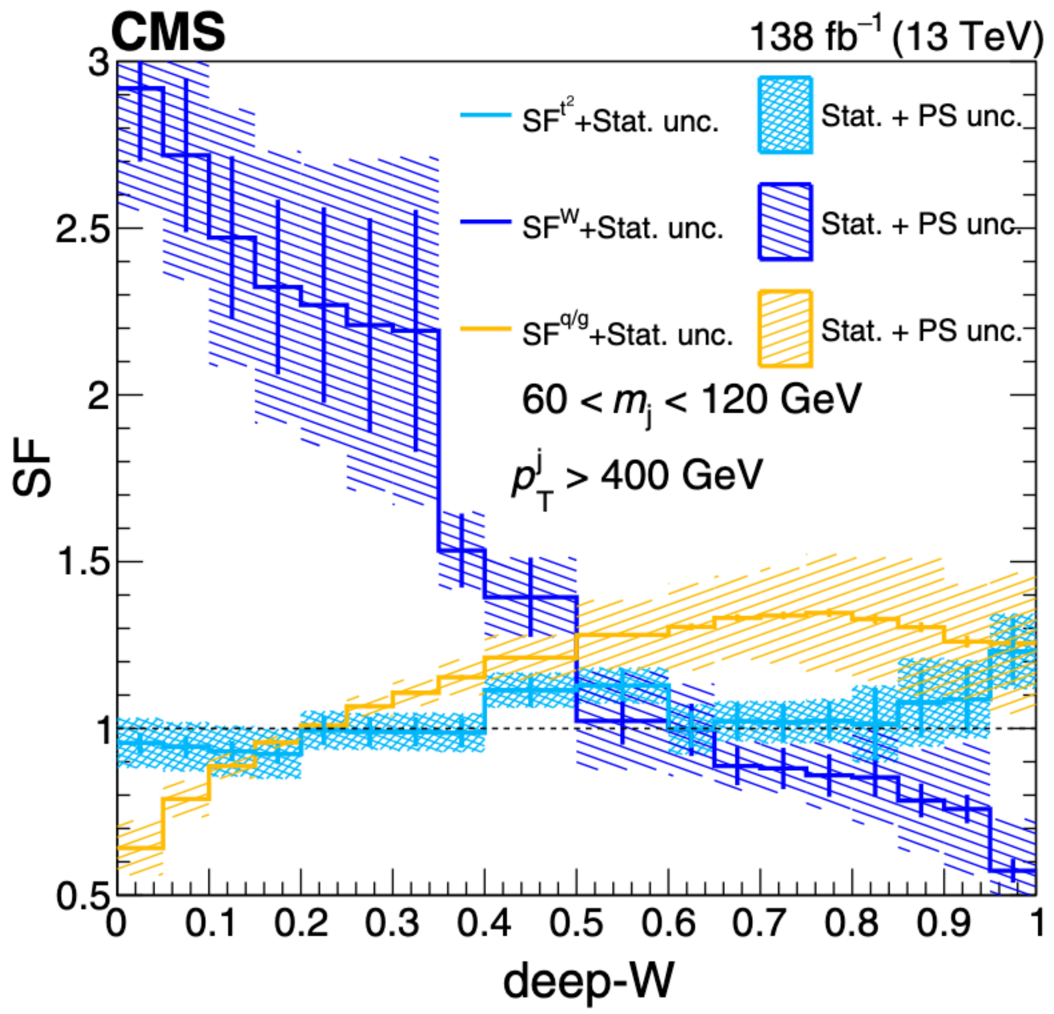
CMS-B2G-20-001



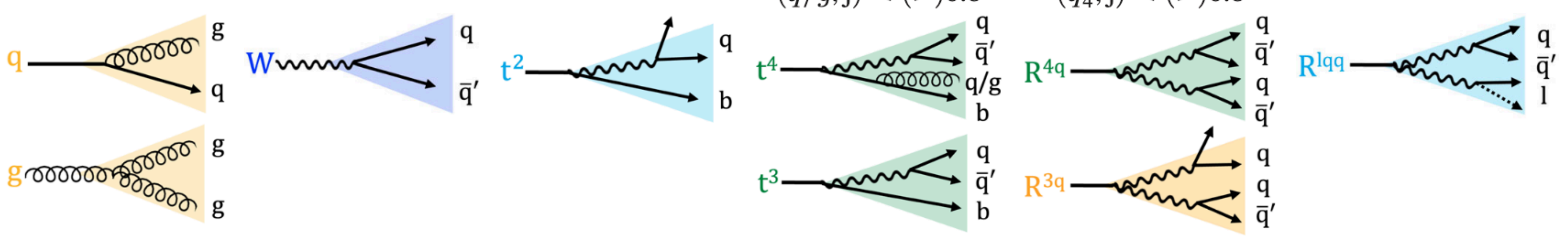
DeepAK8

Particle + SV CNNs

17 output nodes, calibrate 2



q/g	W	t^2	$t^{3,4}$	$R^{3,4q}$	$R^{\ell qq}$
$(q/g,\mathrm{j}) < 0.6$ … … … …	$(W,\mathrm{j}) < 0.6$ $(q_{1W},\mathrm{j}) < 0.8$ $(q_{2W},\mathrm{j}) < 0.8$ $(b_t,\mathrm{j}) > 0.8$ …	$(t,\mathrm{j}) < 0.6$ $(b_t,\mathrm{j}) < 0.8$ $(q_{1W},\mathrm{j}) < 0.8$ $(q_{2W},\mathrm{j}) > 0.8$ …	$(t,\mathrm{j}) < 0.6$ $(b_t,\mathrm{j}) < 0.8$ $(q_{1W},\mathrm{j}) < 0.8$ $(q_{2W},\mathrm{j}) < 0.8$ For t^4 (t^3): $(q/g,\mathrm{j}) <(>) 0.8$	$(R,\mathrm{j}) < 0.6$ $(q_1,\mathrm{j}) < 0.8$ $(q_2,\mathrm{j}) < 0.8$ $(q_3,\mathrm{j}) < 0.8$ For R^{4q} (R^{3q}) : $(q_4,\mathrm{j}) <(>) 0.8$	$(R,\mathrm{j}) < 0.6$ $(q_1,\mathrm{j}) < 0.8$ $(q_2,\mathrm{j}) < 0.8$ $(\ell,\mathrm{j}) < 0.8$ …



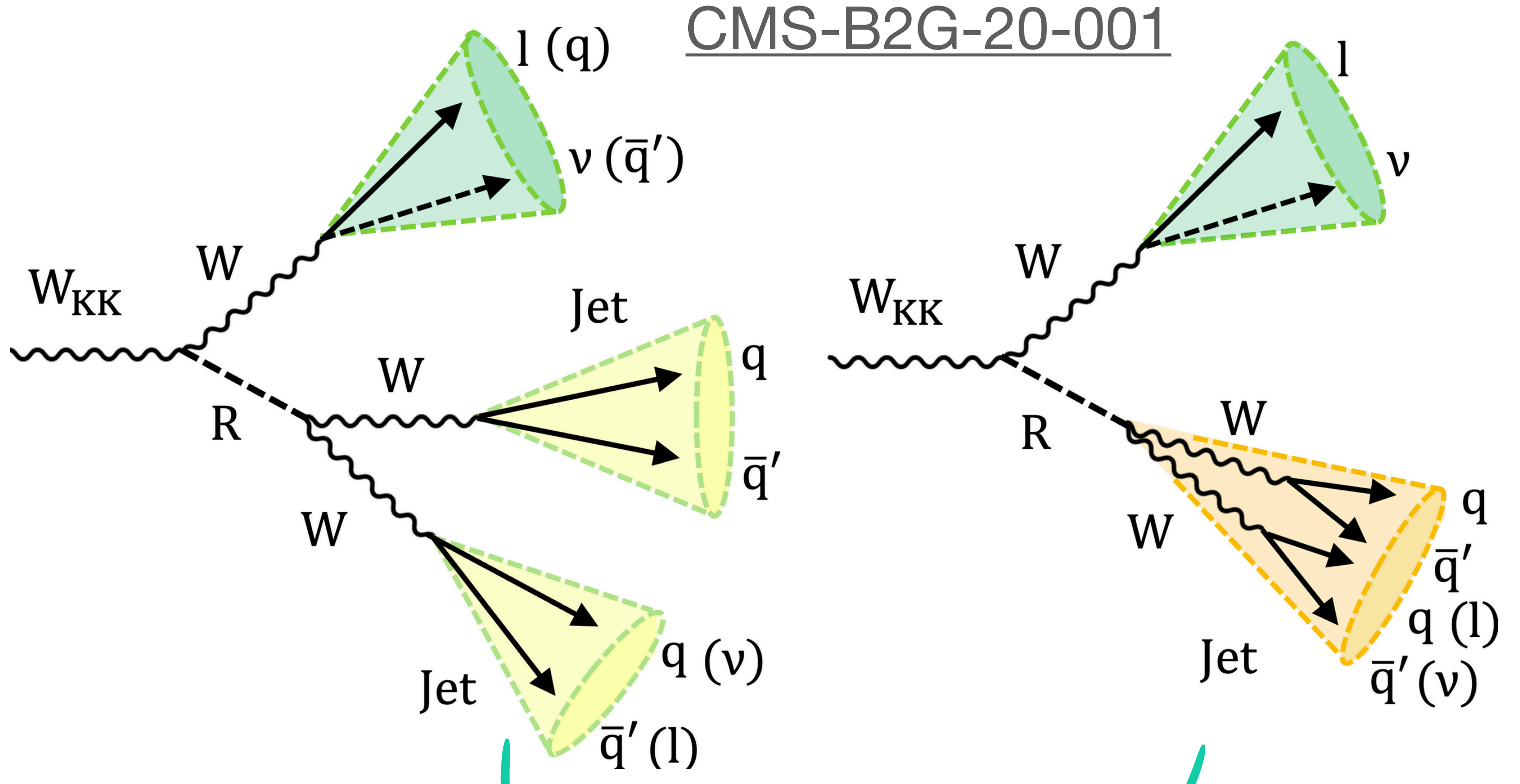
Sotiroulla and Denis will present the details from CMS after lunch today!

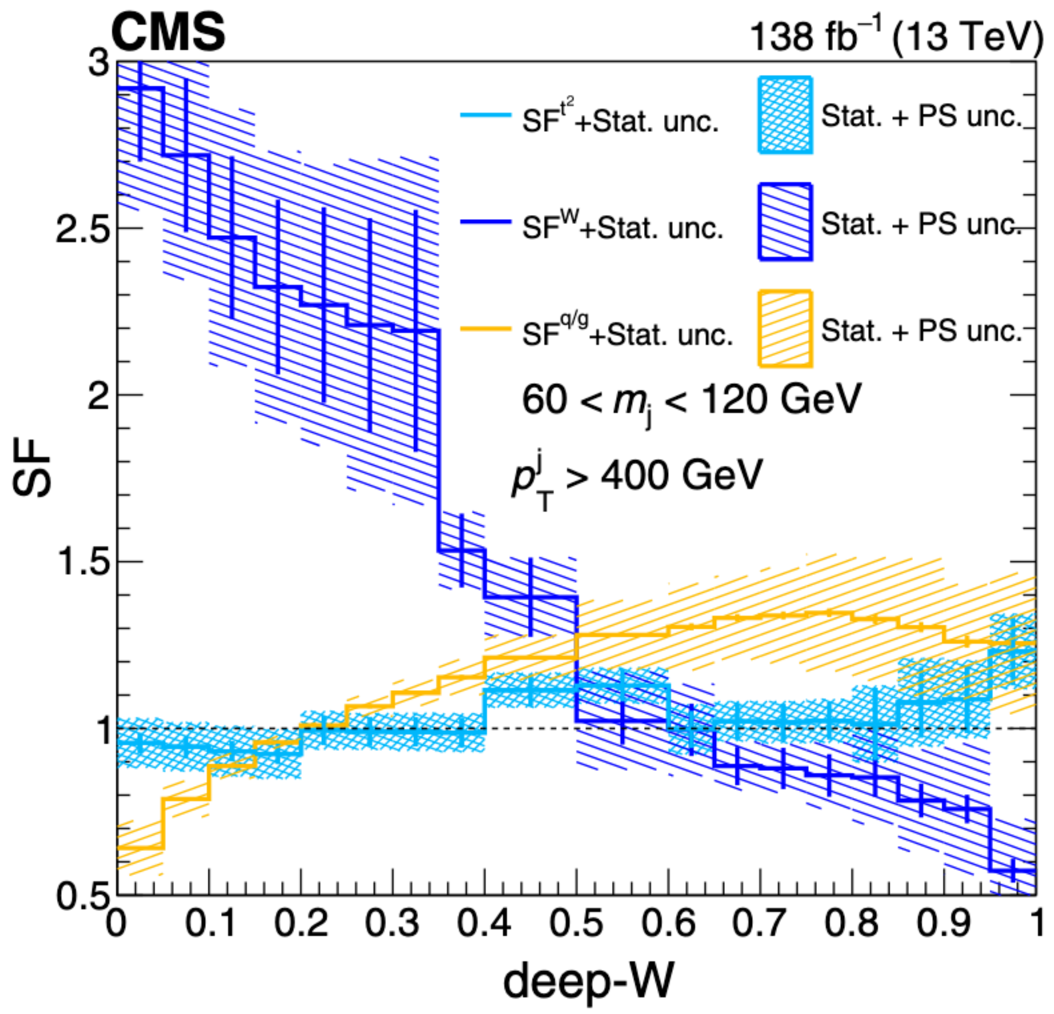
Lots of CMS ML/AI Jet Tagging Info: CMS-JME-18-002

Run 2 Searches : CMS

CMS 3W Resonances

CMS-B2G-20-001





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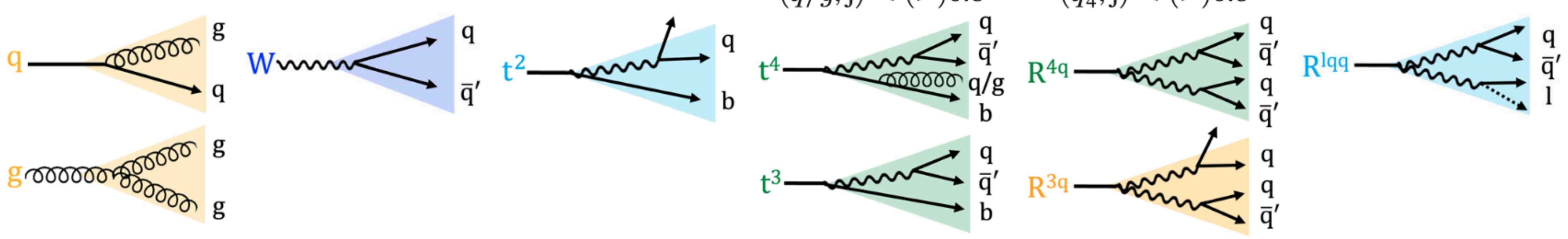
q/g	W	t^2	$t^{3,4}$	$R^{3,4q}$	$R^{\ell qq}$
$(q/g,\mathrm{j}) < 0.6$	$(W,\mathrm{j}) < 0.6$	$(t,\mathrm{j}) < 0.6$	$(t,\mathrm{j}) < 0.6$	$(R,\mathrm{j}) < 0.6$	$(R,\mathrm{j}) < 0.6$
...	$(q_{1W},\mathrm{j}) < 0.8$	$(b_t,\mathrm{j}) < 0.8$	$(b_t,\mathrm{j}) < 0.8$	$(q_1,\mathrm{j}) < 0.8$	$(q_1,\mathrm{j}) < 0.8$
...	$(q_{2W},\mathrm{j}) < 0.8$	$(q_{1W},\mathrm{j}) < 0.8$	$(q_{1W},\mathrm{j}) < 0.8$	$(q_2,\mathrm{j}) < 0.8$	$(q_2,\mathrm{j}) < 0.8$
...	$(b_t,\mathrm{j}) > 0.8$	$(q_{2W},\mathrm{j}) > 0.8$	$(q_{2W},\mathrm{j}) < 0.8$	$(q_3,\mathrm{j}) < 0.8$	$(\ell,\mathrm{j}) < 0.8$
...	...	...	For t^4 (t^3):	For R^{4q} (R^{3q}) :	...
			$(q/g,\mathrm{j}) <$ (>)0.8	$(q_4,\mathrm{j}) <$ (>)0.8	



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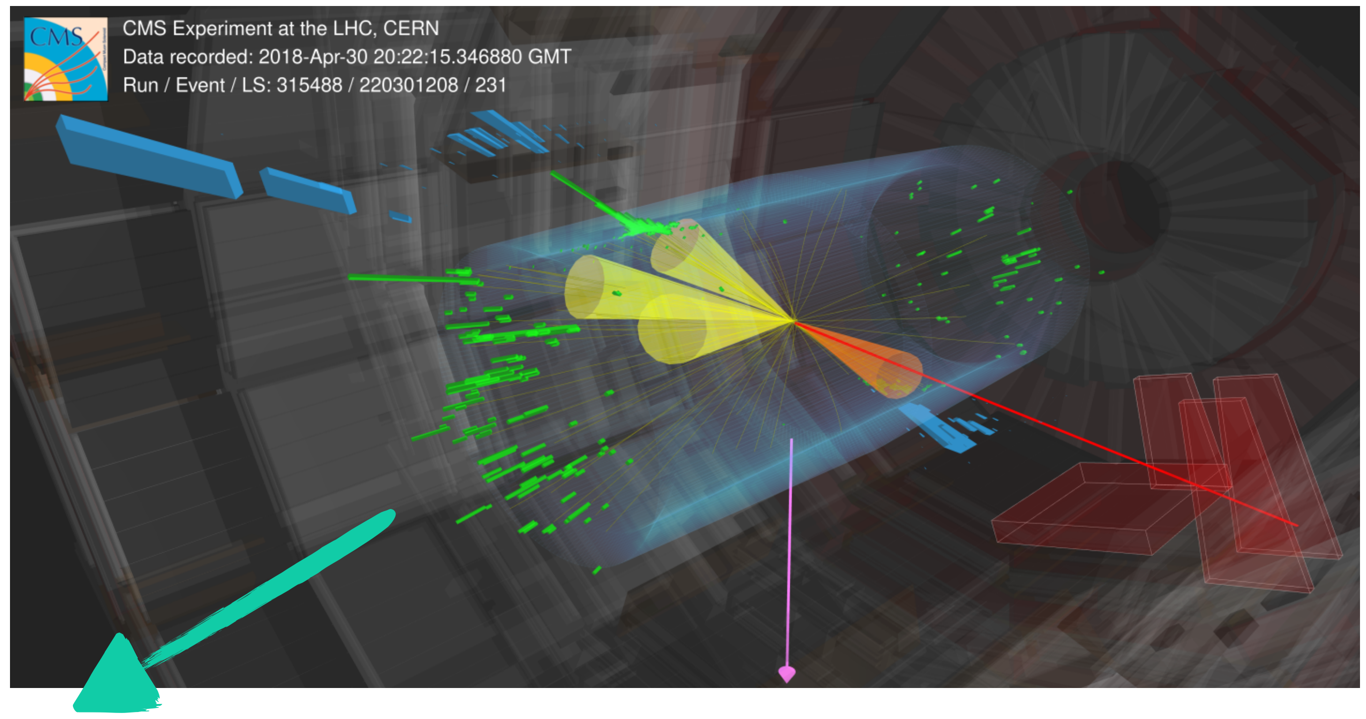
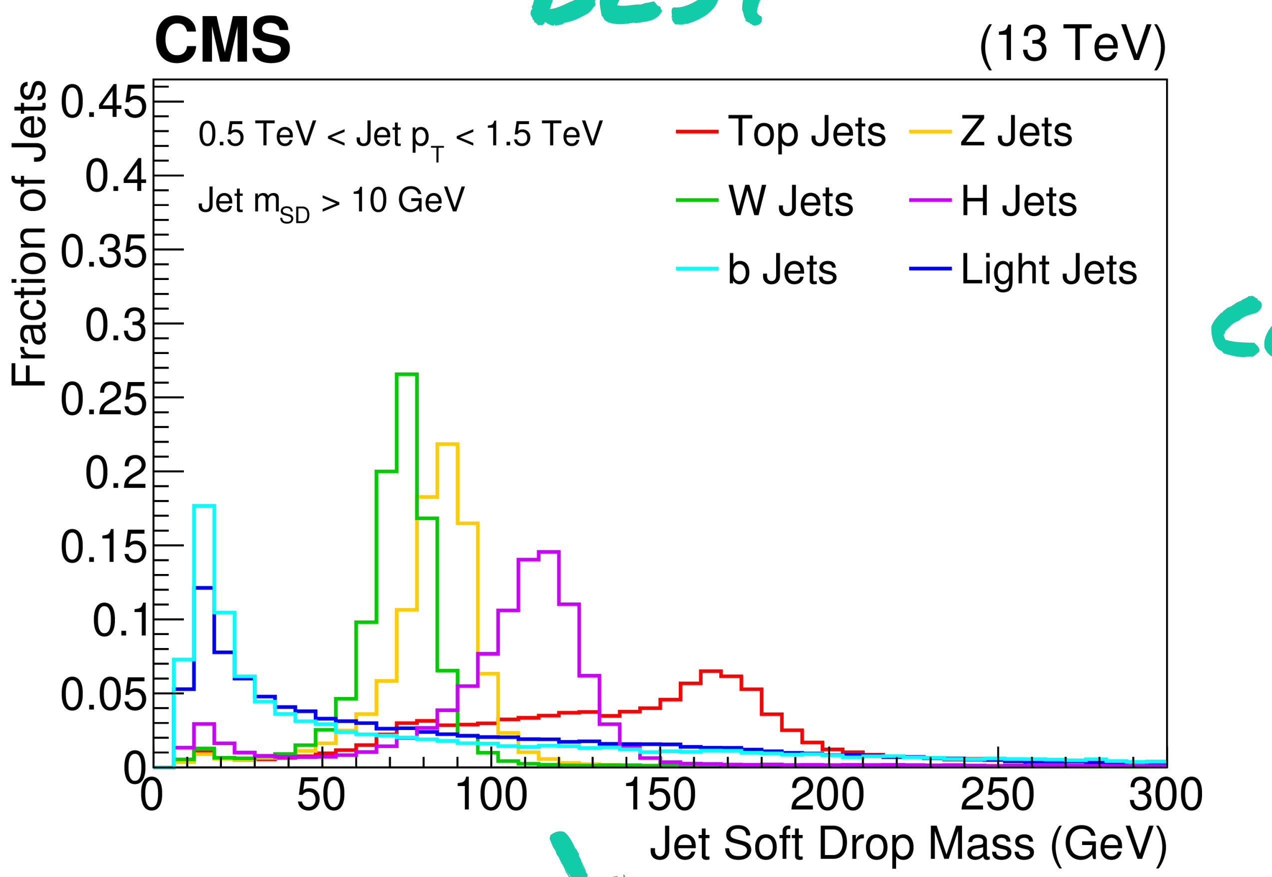


Boosted Event Shape Tagger

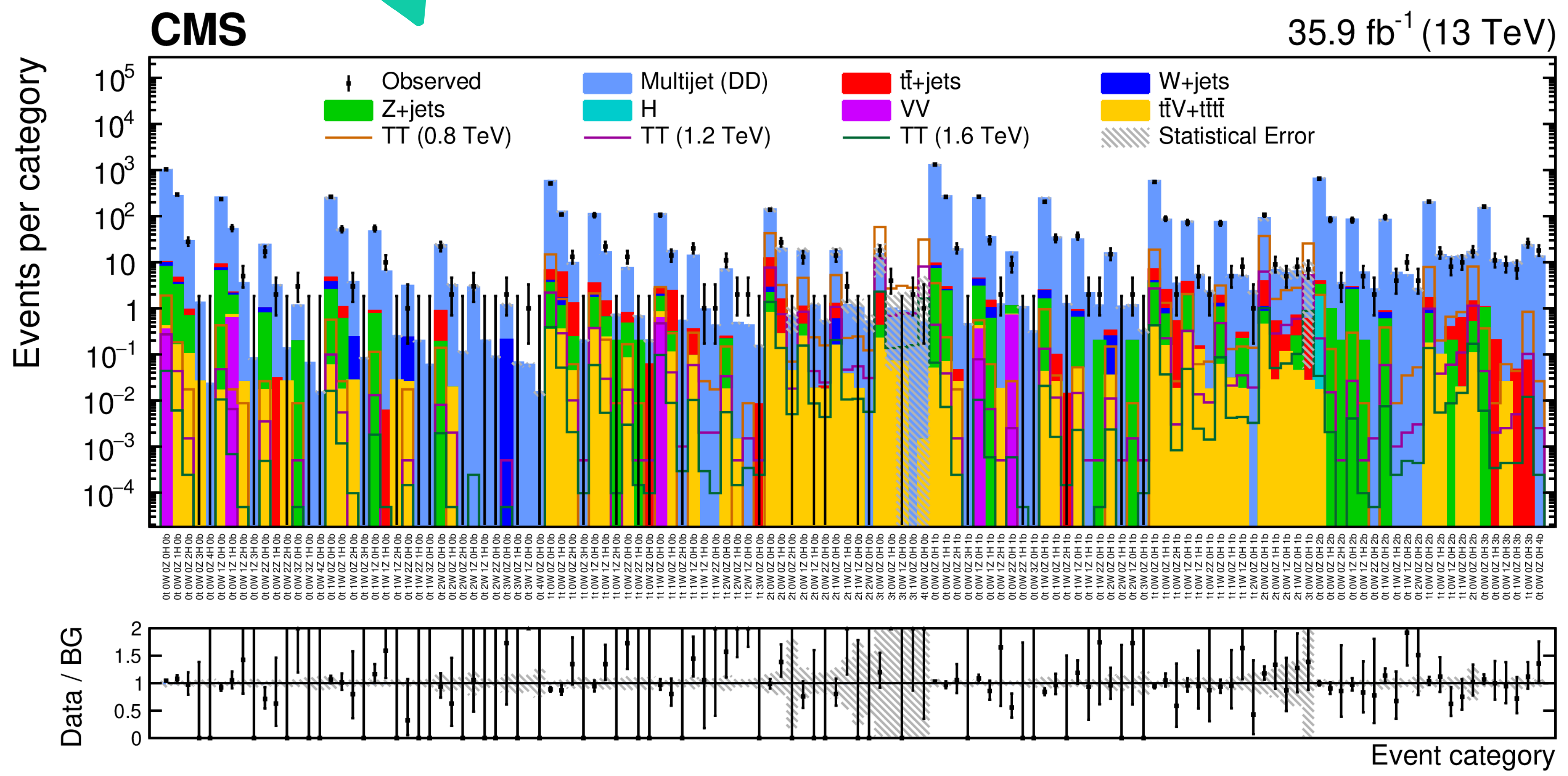
BEST



Boost 4 times, compare HL features

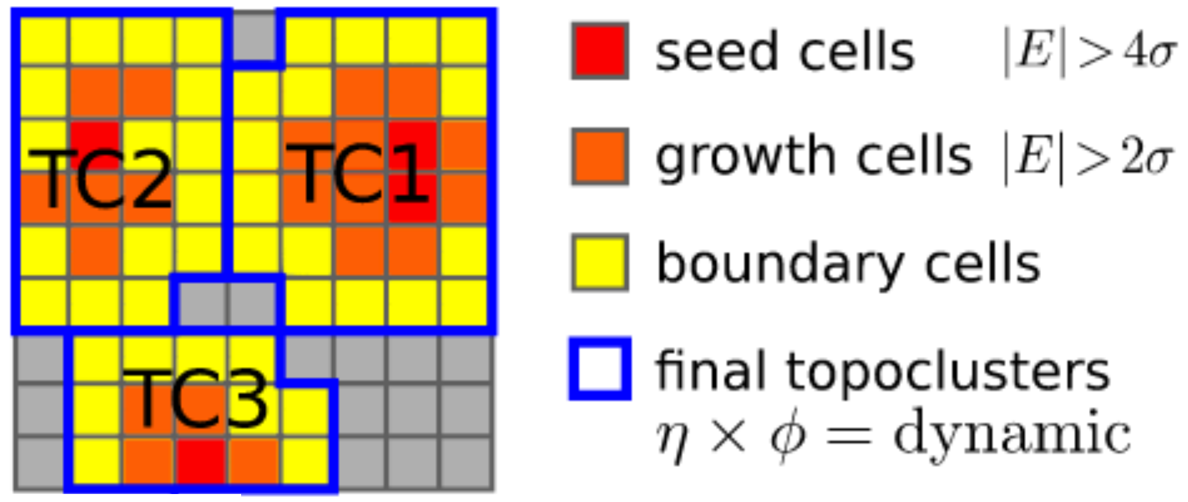
6 output nodes W/Z/H/t/b/other

CMS, B2G-18-005



Don't miss the BEST poster from Brendan!

Run 2 Searches : ATLAS

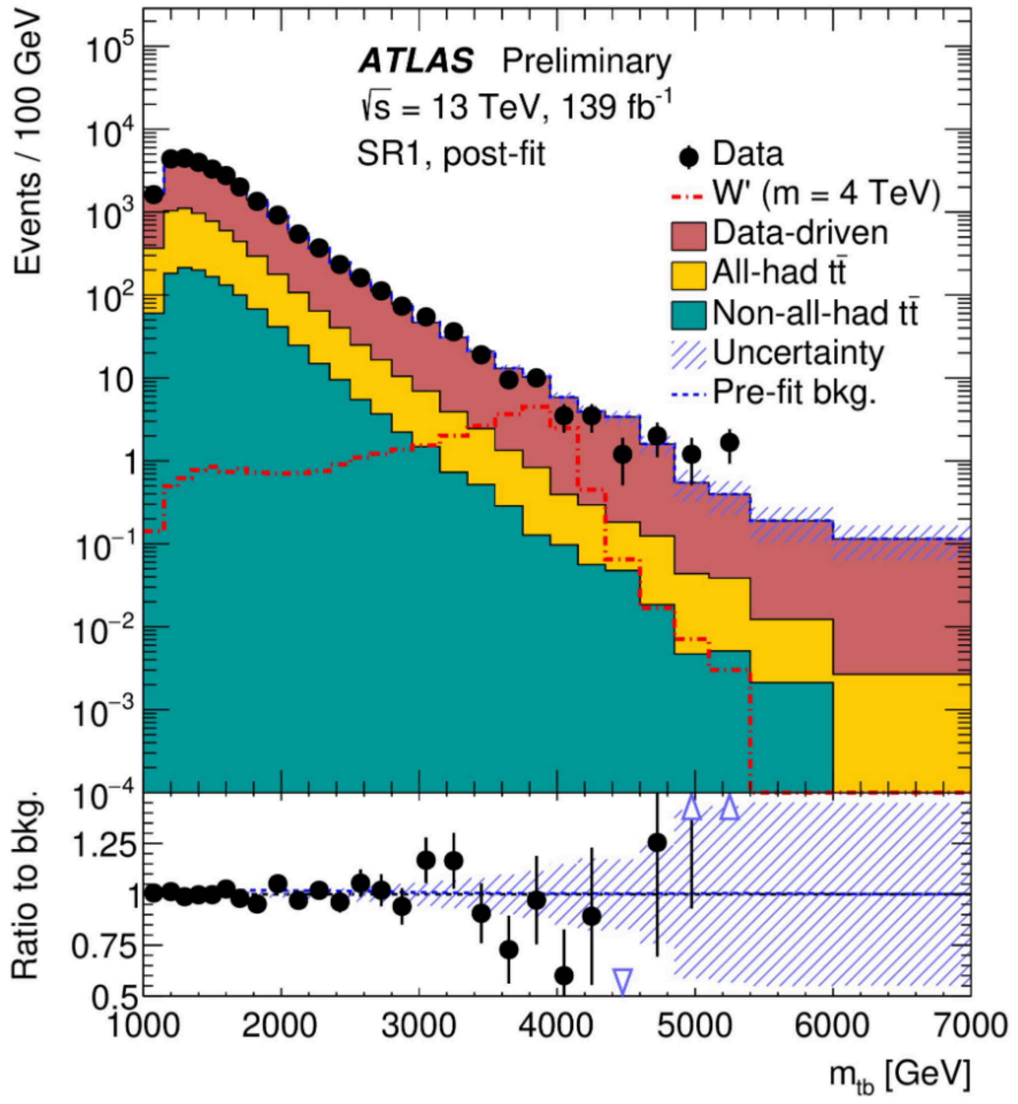


Topo-clusters

Trimmed Calo-Jet + High-Level DNN

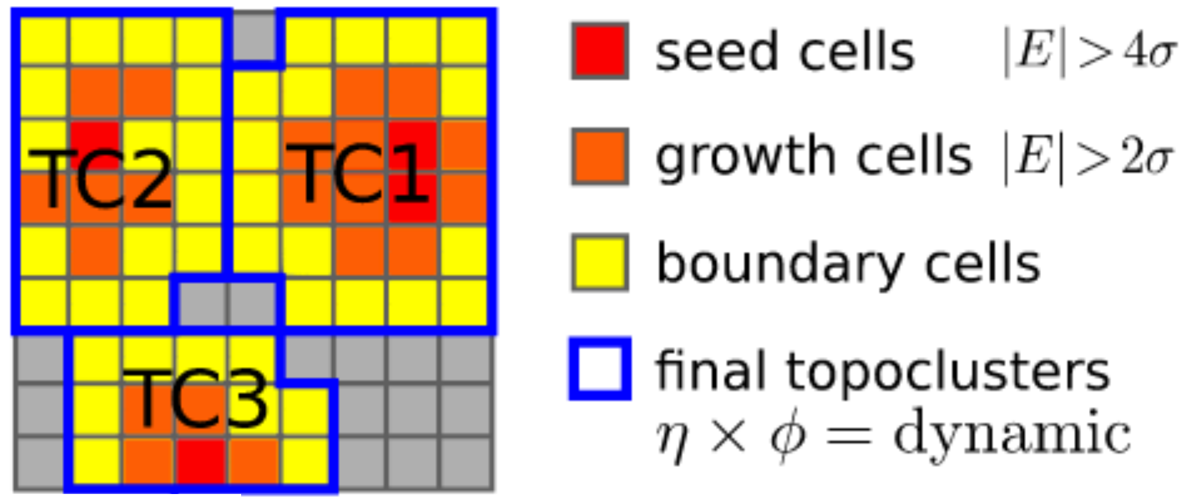
W' -> tb search

ATLAS-CONF-2021-043



Ali + Lars will present many ATLAS searches for boosted stuff, after lunch today!

Run 2 Searches: ATLAS



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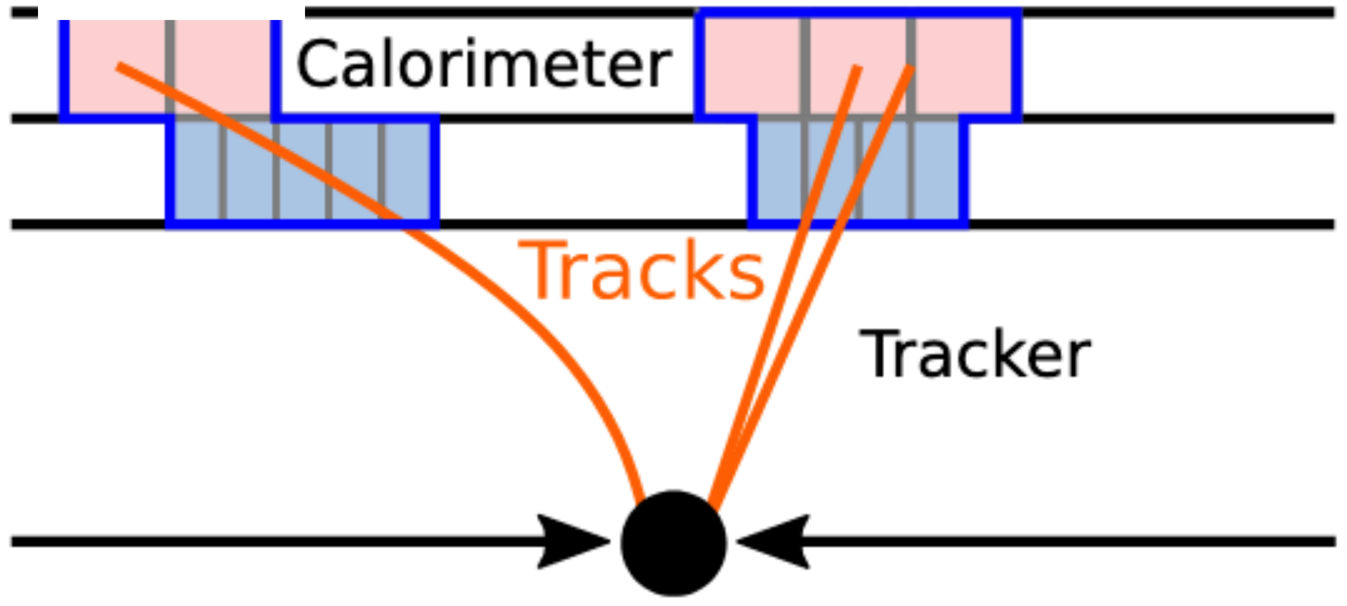
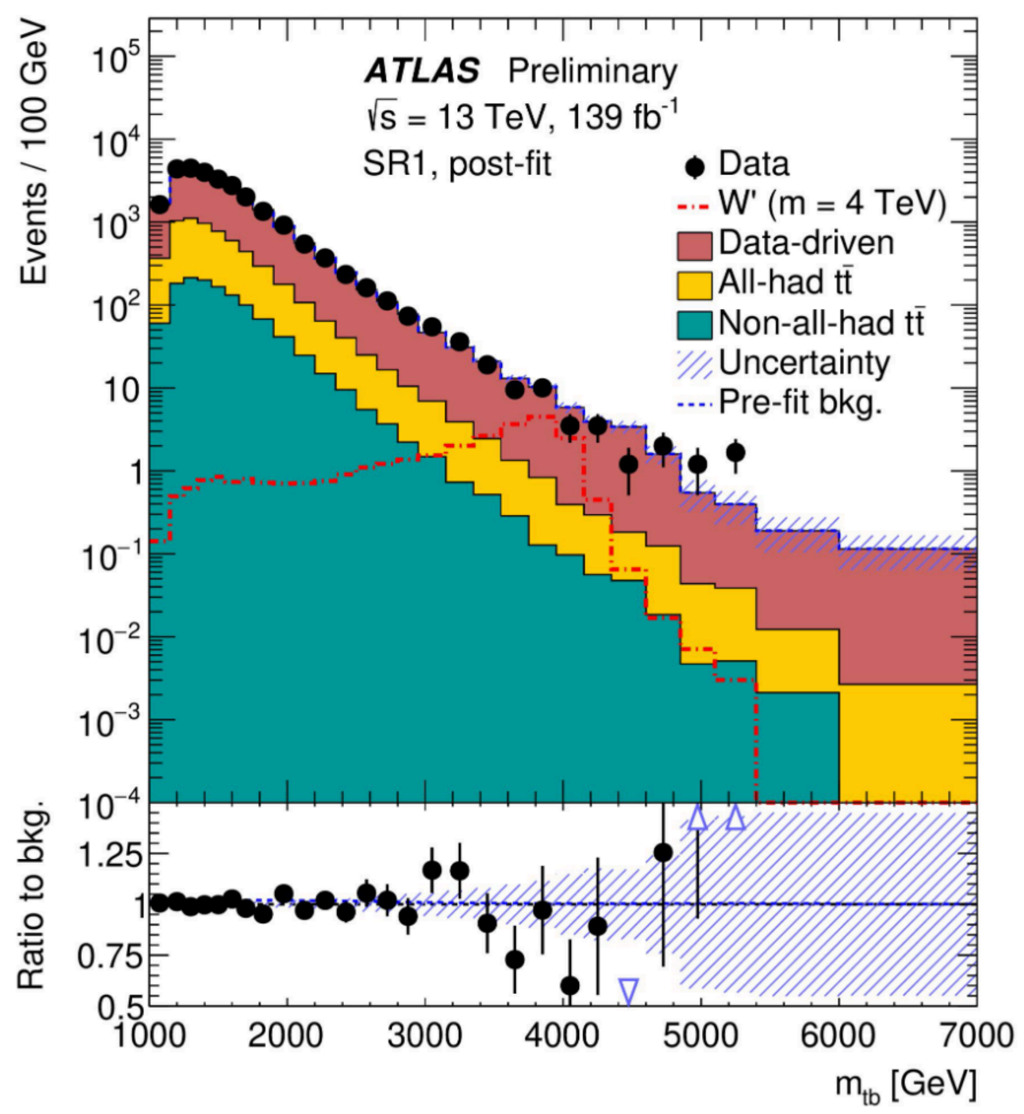


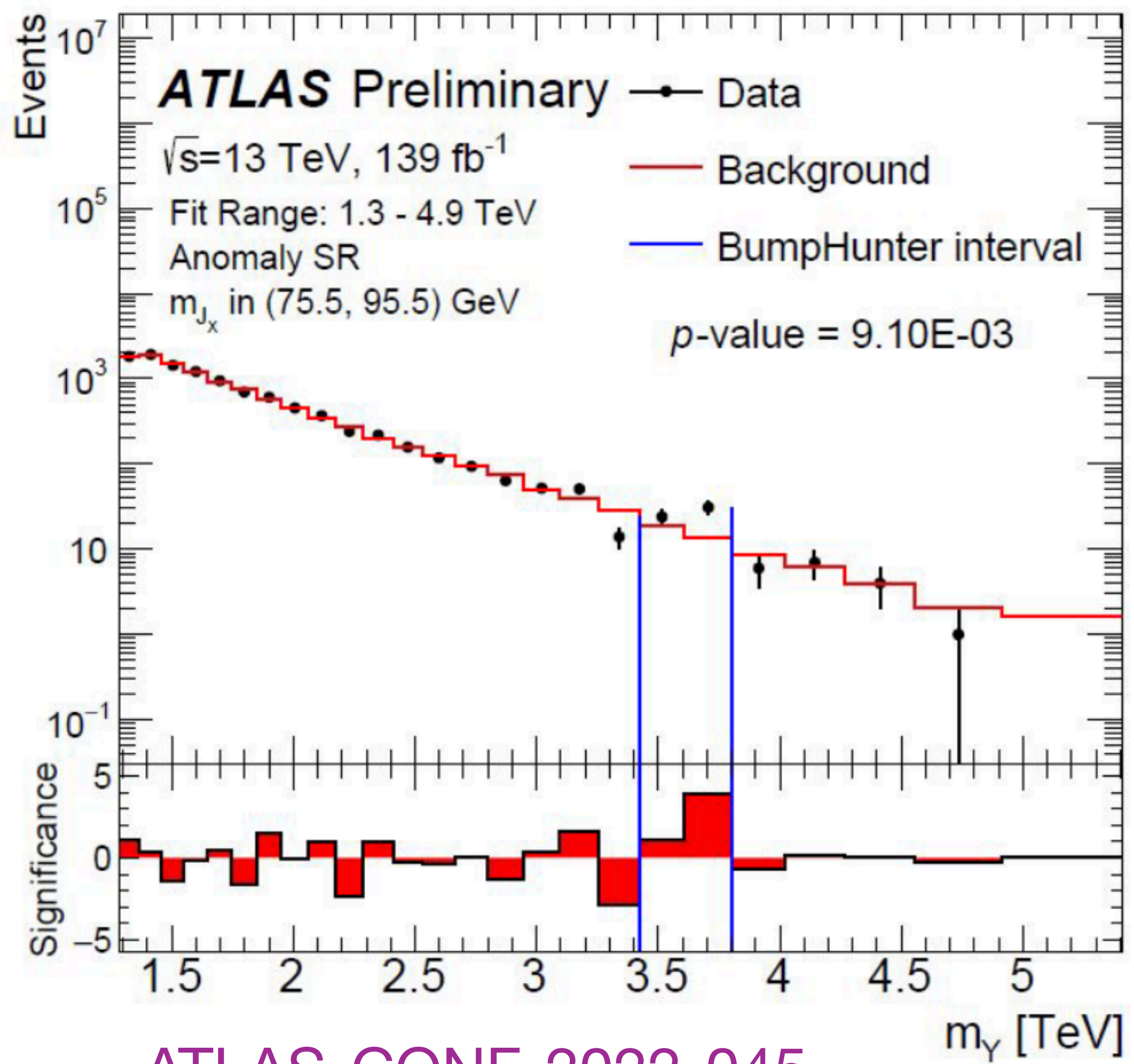
Combine tracking + Calorimeter info (Run 2 style, "TCCs")

Trimmed Calo-jet + High-Level DNN

W' -> tb search

ATLAS-CONF-2021-043





ATLAS-CONF-2022-045

Unsupervised Anomaly VRNN used to define Signal Region

Silvia has a poster about this!

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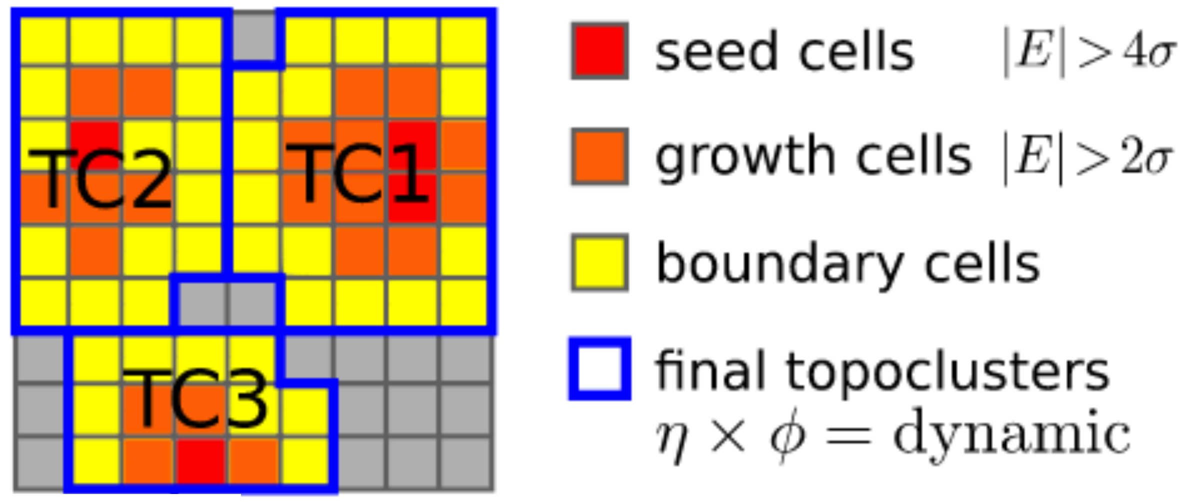
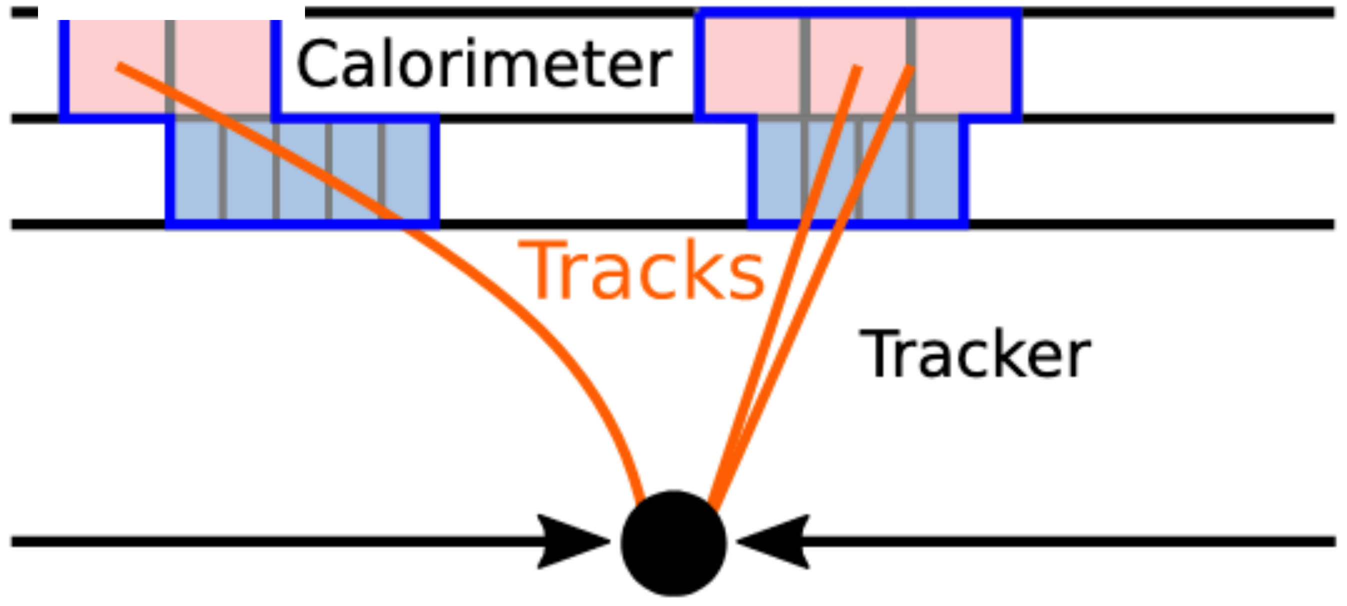
Run 2 Searches : ATLAS



Topo-clusters



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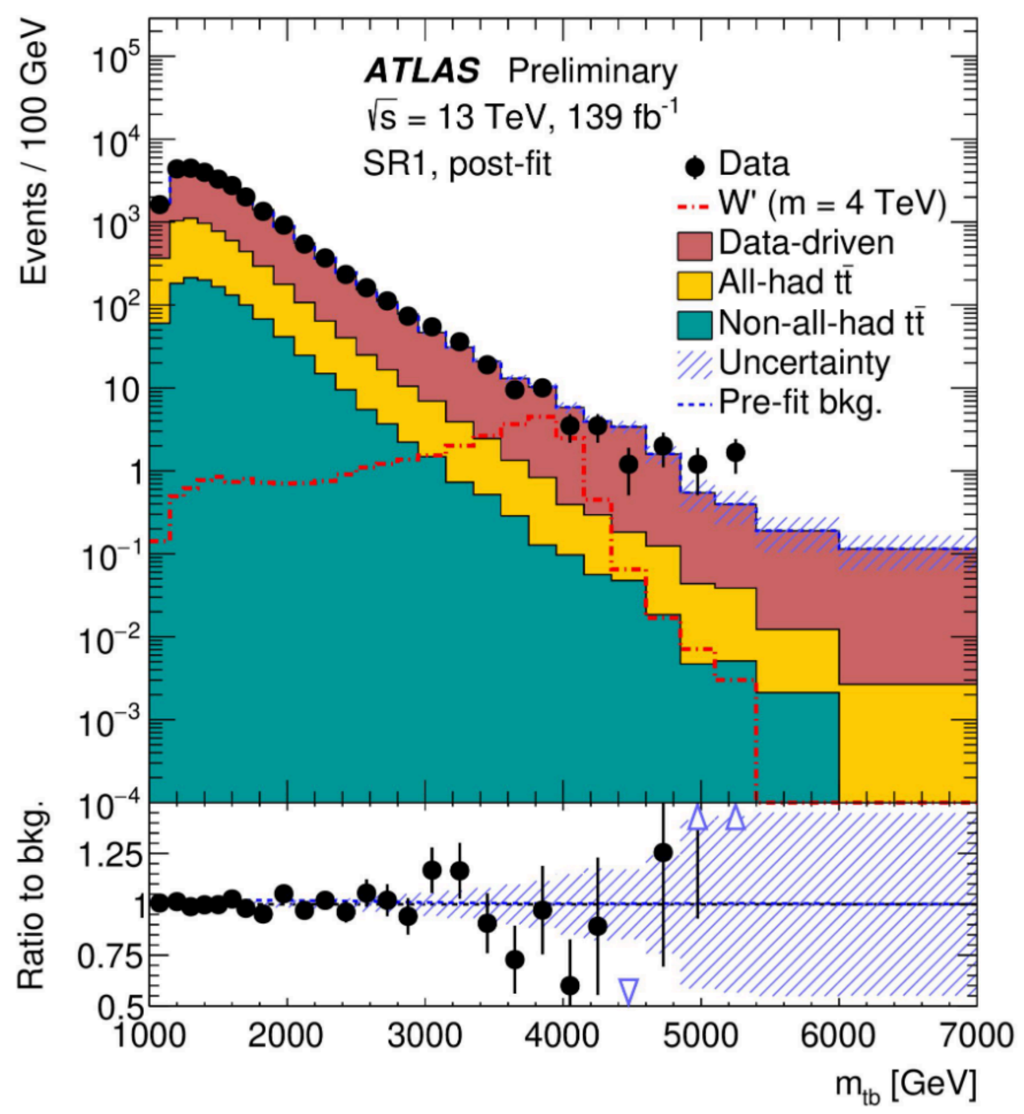
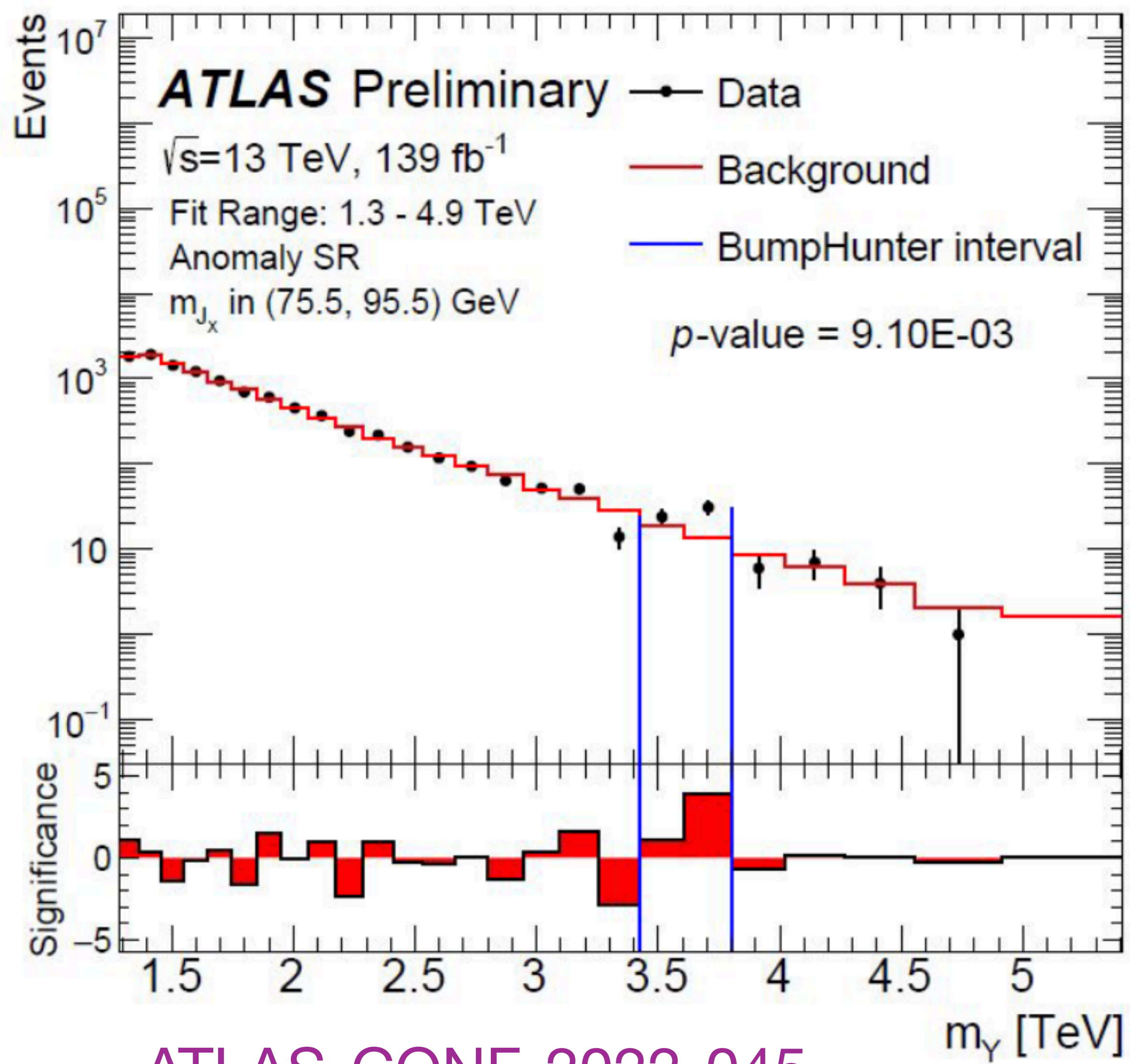
ATLAS-CONF-2021-043





ATLAS-CONF-2022-045

Unsupervised Anomaly VRNN Used to define Signal region

New Diboson resonances

Combination of 9 Run 2 analyses!

Analysis	leptons	$E_{T miss}$	jets	b-tags	Discr.
$WW/WZ \to qqqq$	0	Veto	≥2J	-	m_{VV}
$WZ \to \nu\nu qq$	0	Yes	≥1J	0	m_{VV}
$WZ \to \ell\nu qq$	1e, 1μ	Yes	≥2j, ≥1J	0, 1, 2	m_{VV}
$WZ \to \ell\ell qq$	2e, 2μ	-	≥2j, ≥1J	0	m_{VV}
$WZ \to \ell\nu\ell\ell$	3 ⊂ (e, μ)	Yes	-	0	m_{VV}
$WH \to qqbb$	0	Veto	≥2J	1, 2	m_{VH}
$ZH \to \nu\nu bb$	0	Yes	≥2j, ≥1J	1, 2	m_{VH}
$WH \to \ell\nu bb$	1e, 1μ	Yes	≥2j, ≥1J	1, 2	m_{VH}
$ZH \to \ell\ell bb$	2e, 2μ	Veto	≥2j, ≥1J	1, 2	m_{VH}
$\ell\nu$	1e, 1μ	Yes	-	-	m_T
$\tau\nu$	1τ	Yes	-	-	m_T
$\ell\ell$	≥2e, ≥2μ	-	-	-	$m_{\ell\ell}$

ATLAS-CONF-2022-028

Sometimes ATLAS & CMS use a simple, cut-based JSS approach … but sometimes, **they do not.**

Silvia has a poster about this!

Ali + Lars will present many ATLAS searches for boosted stuff, after lunch today!

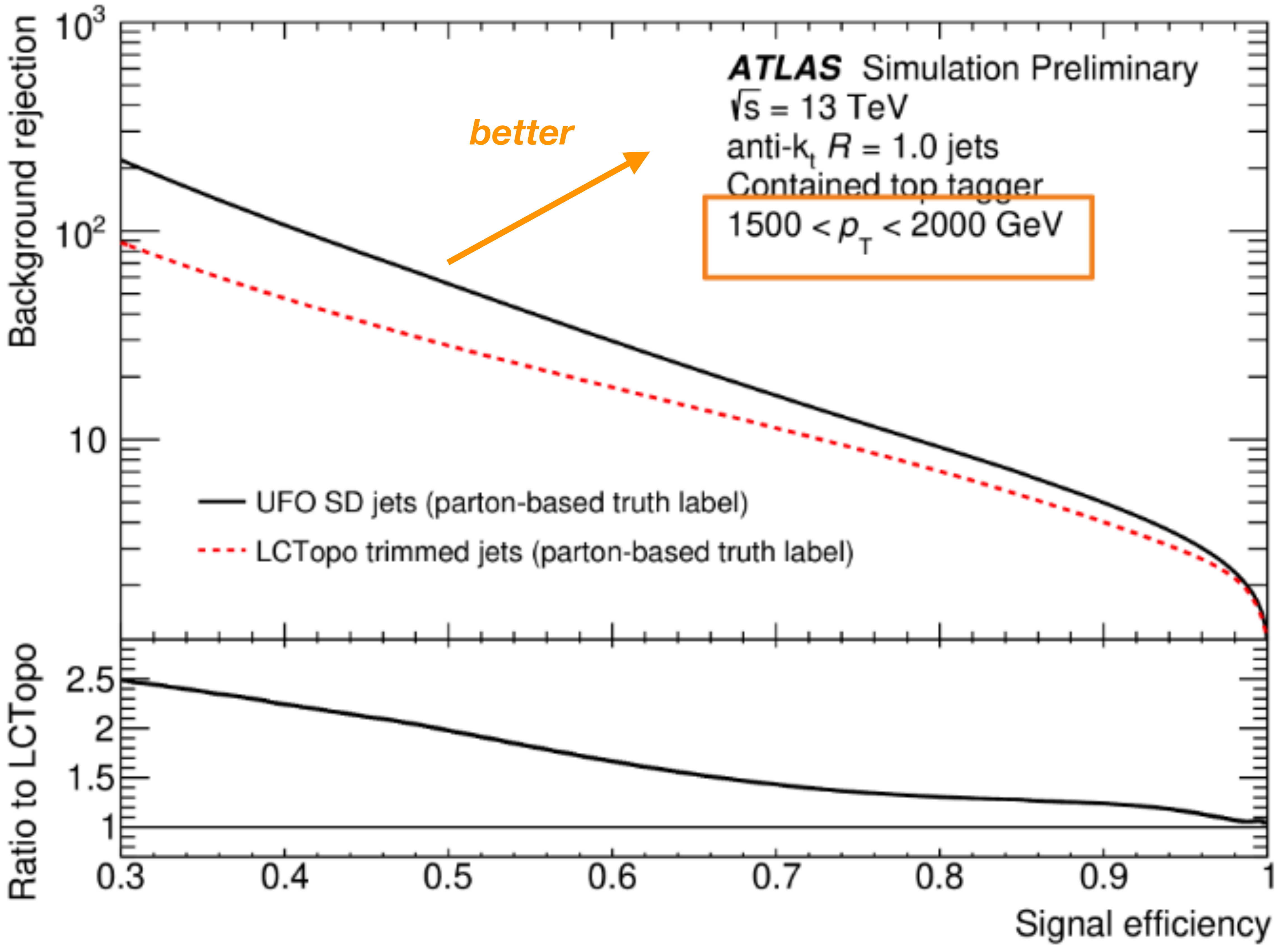
Run 2 searches did not find conclusive signs of BSM.

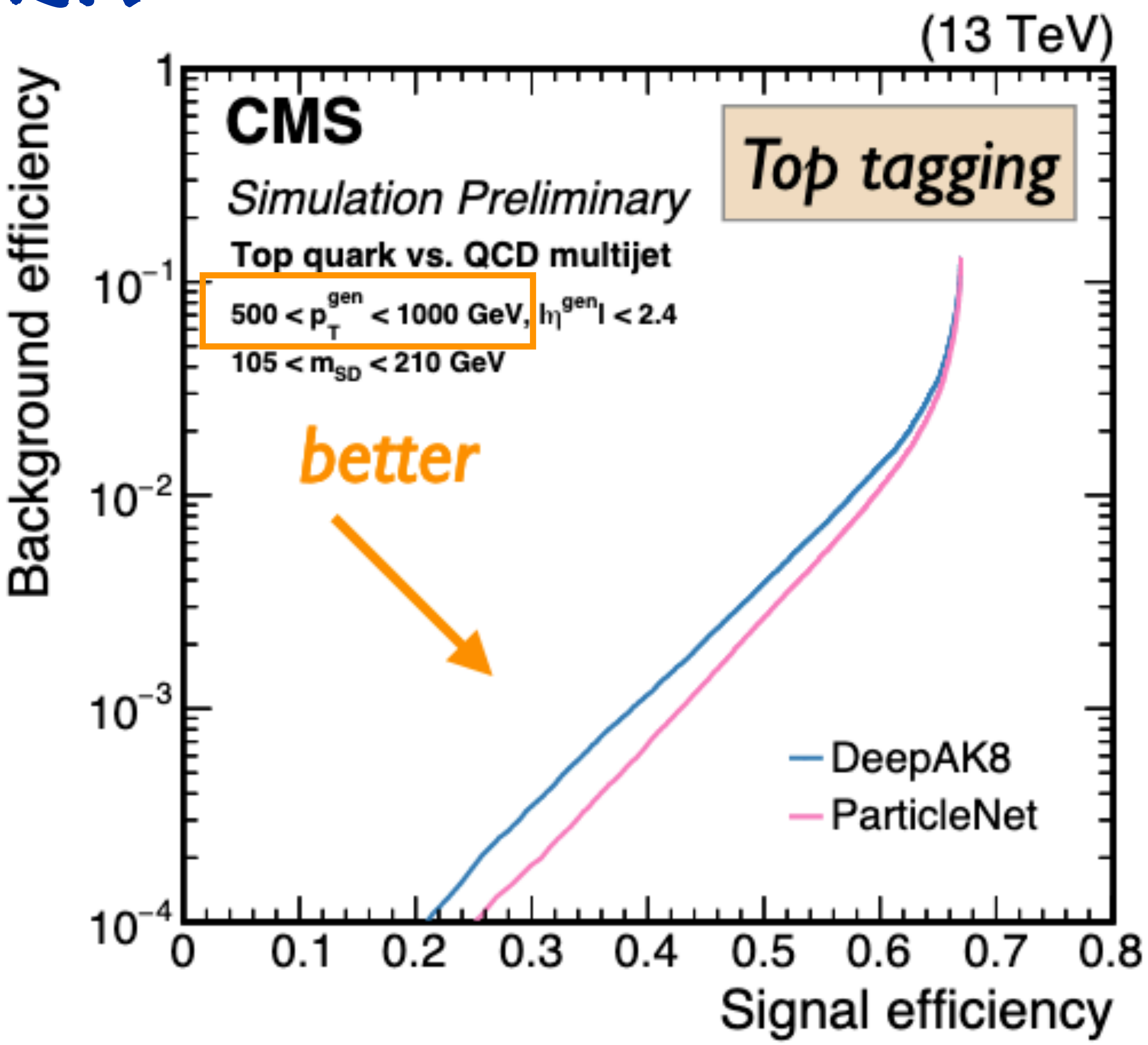
I will spare us looking at the summary plots: ATLAS, CMS

How can we BOOST our searches further in Run 3?

REMINDER: LAST YEAR

ATLAS + CMS : BOOSTING APART?





Different jet inputs (UFOS: track+calo objects, cluster splitting)

Different architectures (GNN vs. CNN)

- Big improvements to boosted object tagging on display from both ATLAS and CMS, but via completely different approaches! (Do not directly compare these plots to each-other!)

Metaphor

Seirinkan, Tokyo

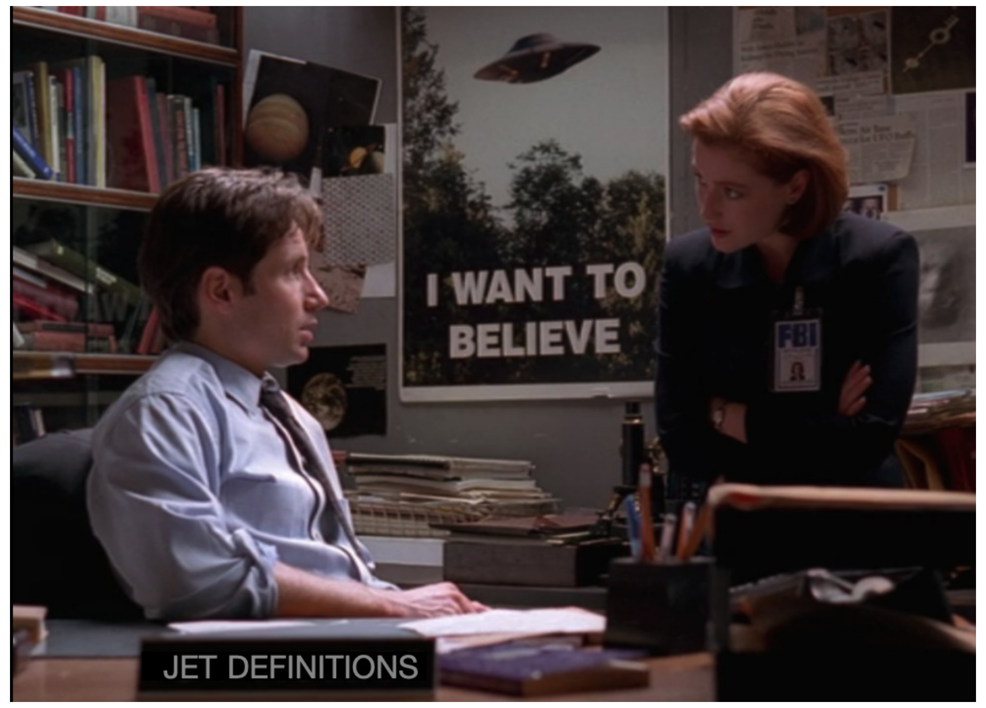
DevilCraft, Tokyo

(I think both look great.)

ATLAS UFOs

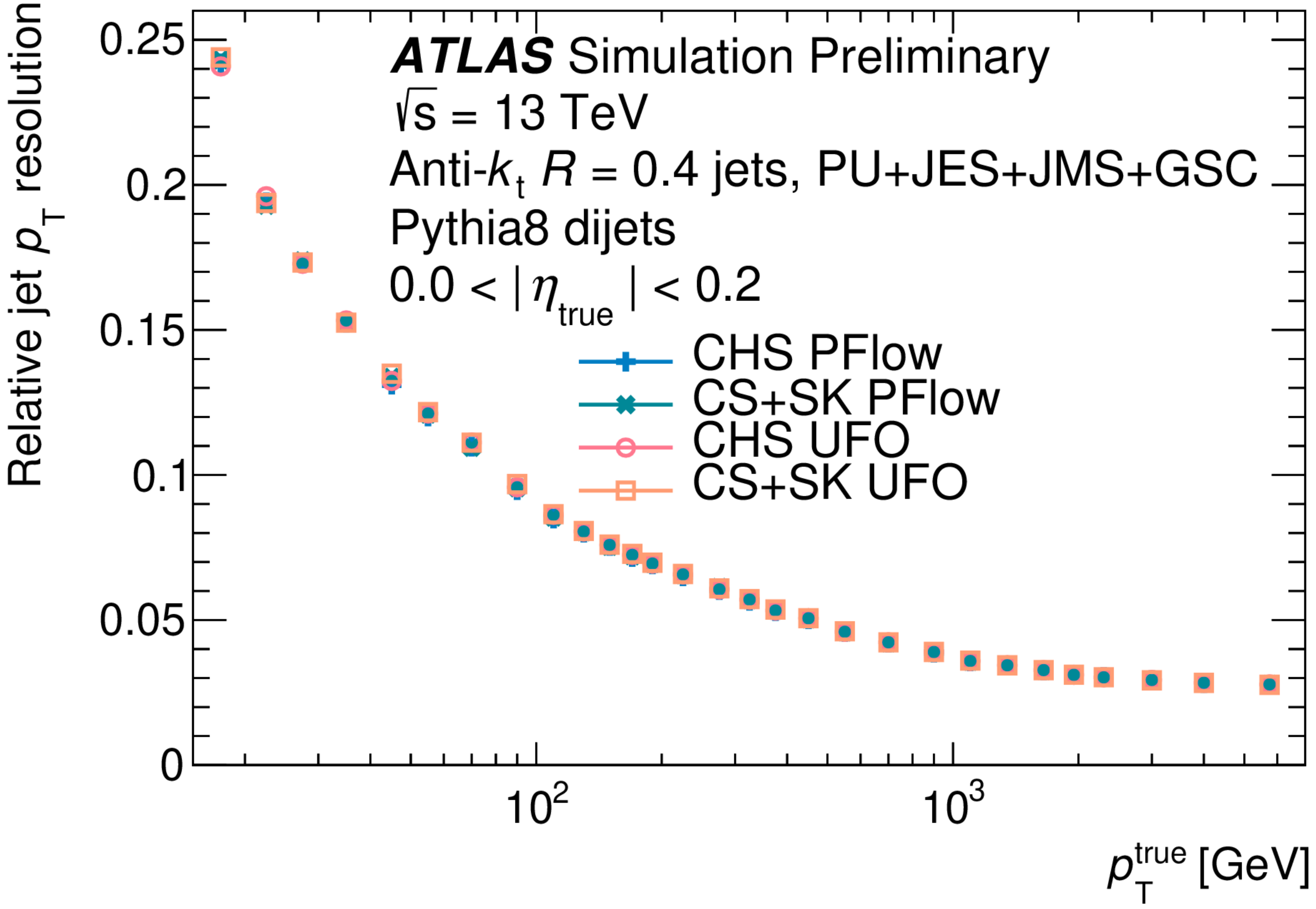
ATL-PHYS-PUB-2022-038 (Brand new!)

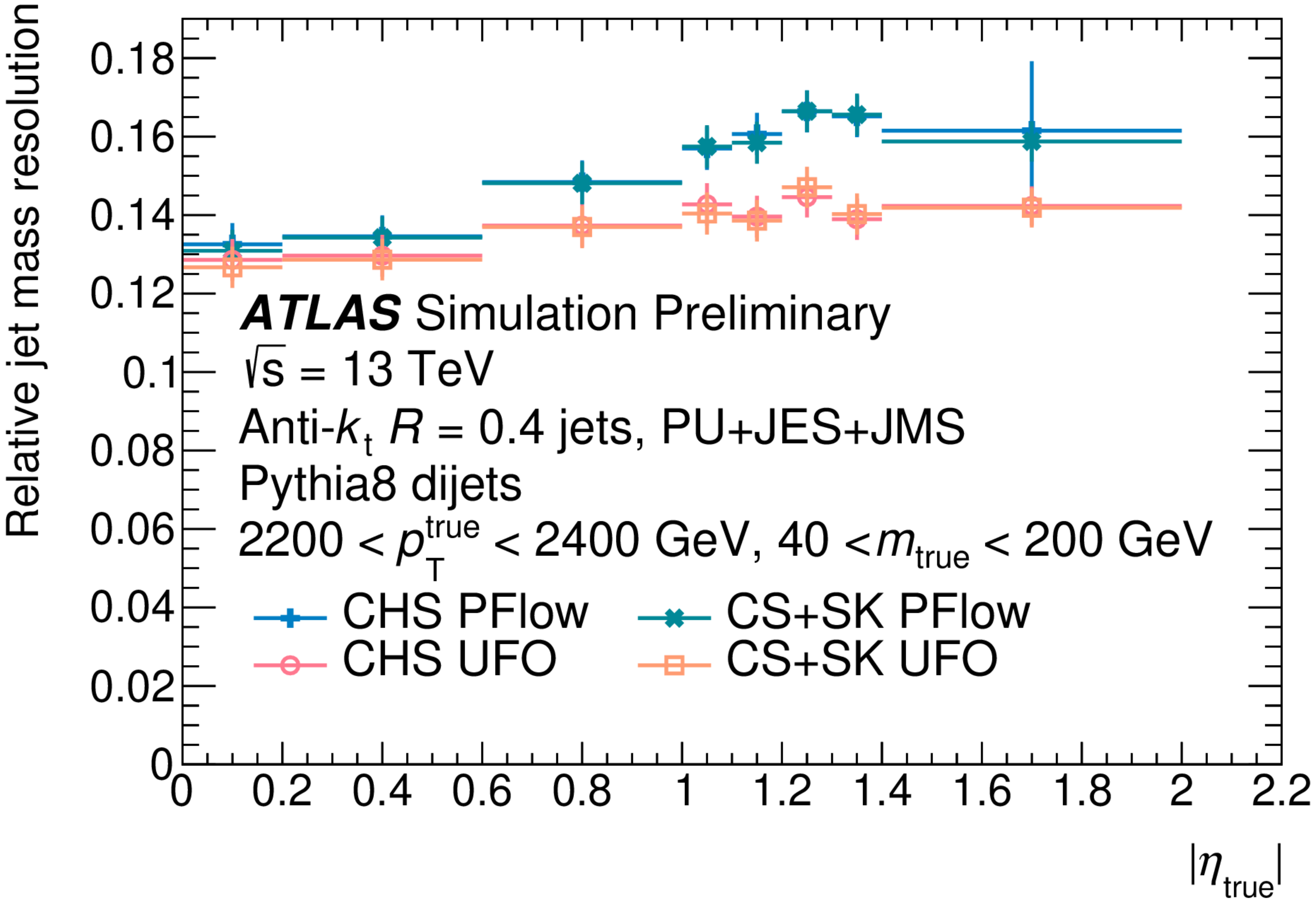
Don't miss Nathan's poster!



ATLAS Jet Definitions Group, LS2

ATLAS, Early Run 3



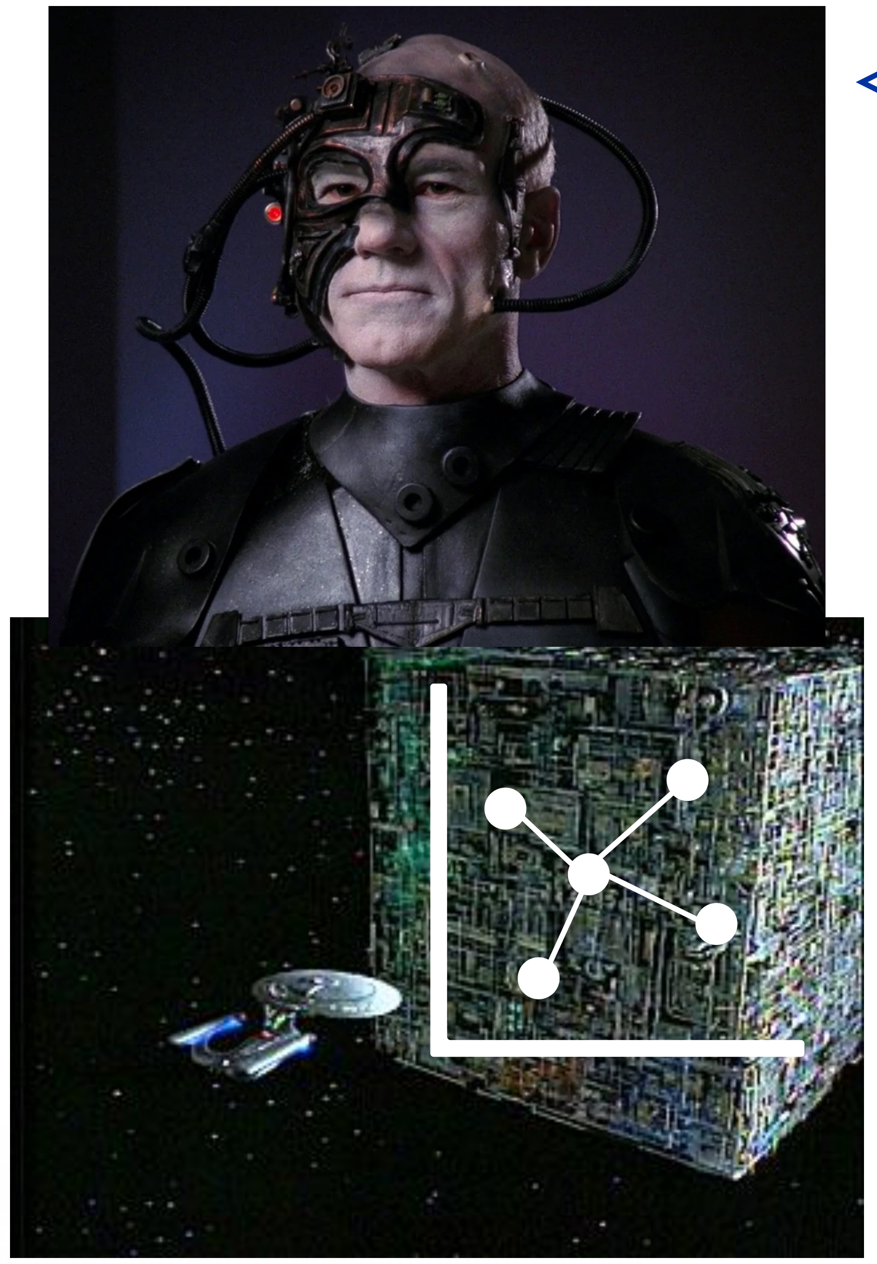


First R=0.4 UFO jet performance studies! → Performance equivalent to or better than R=0.4 PFlow jets.

H(cc)

CMS [HIG-21-008]

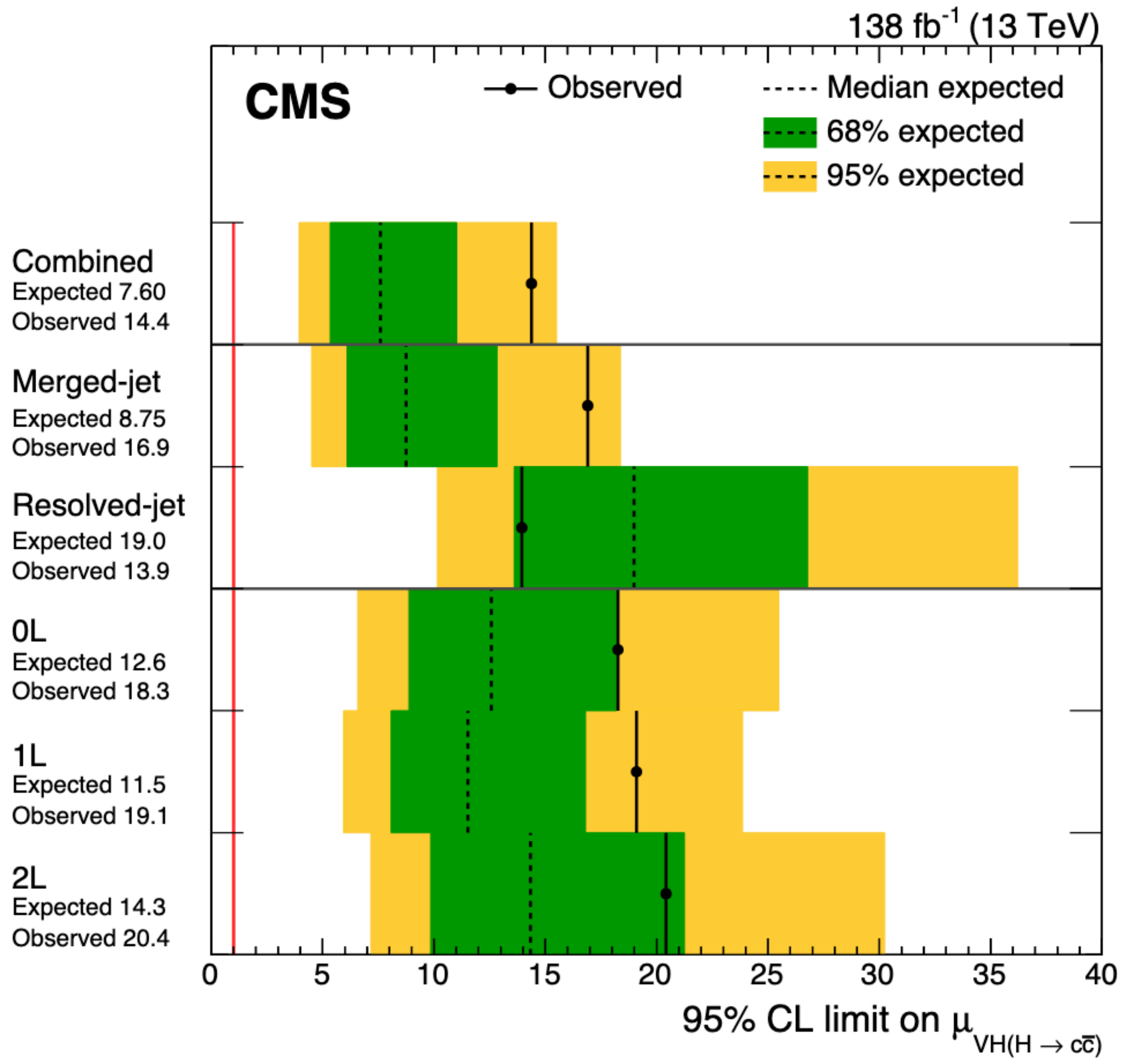
(New!)

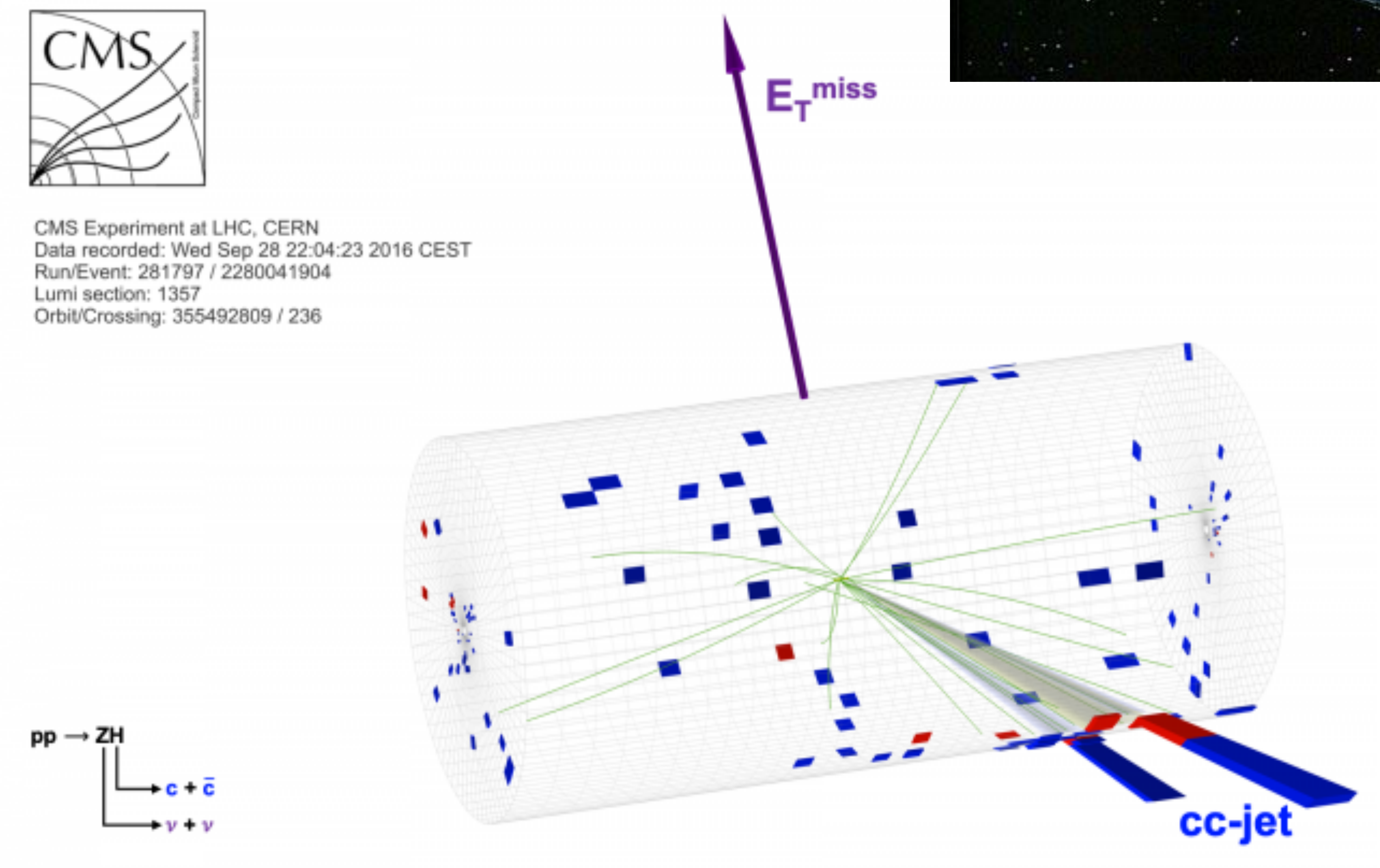


Higgs Boson,
You will be
assimilated.

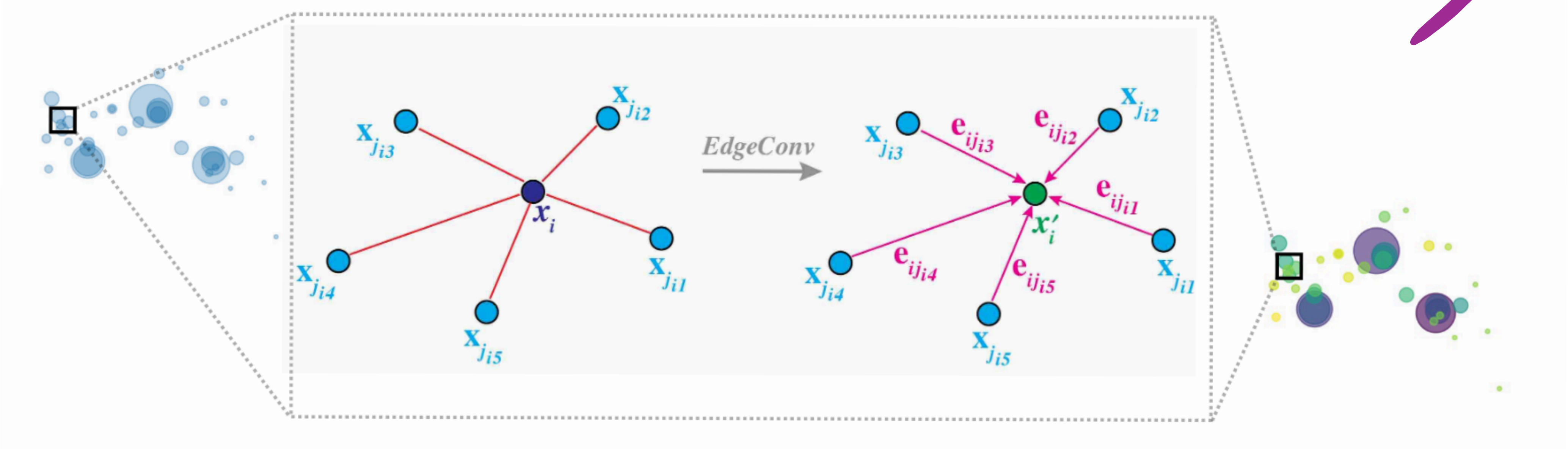
— ParticleNet

5% of cross-section in this category!





Particle kinematics + PID info
Graph Neural Network

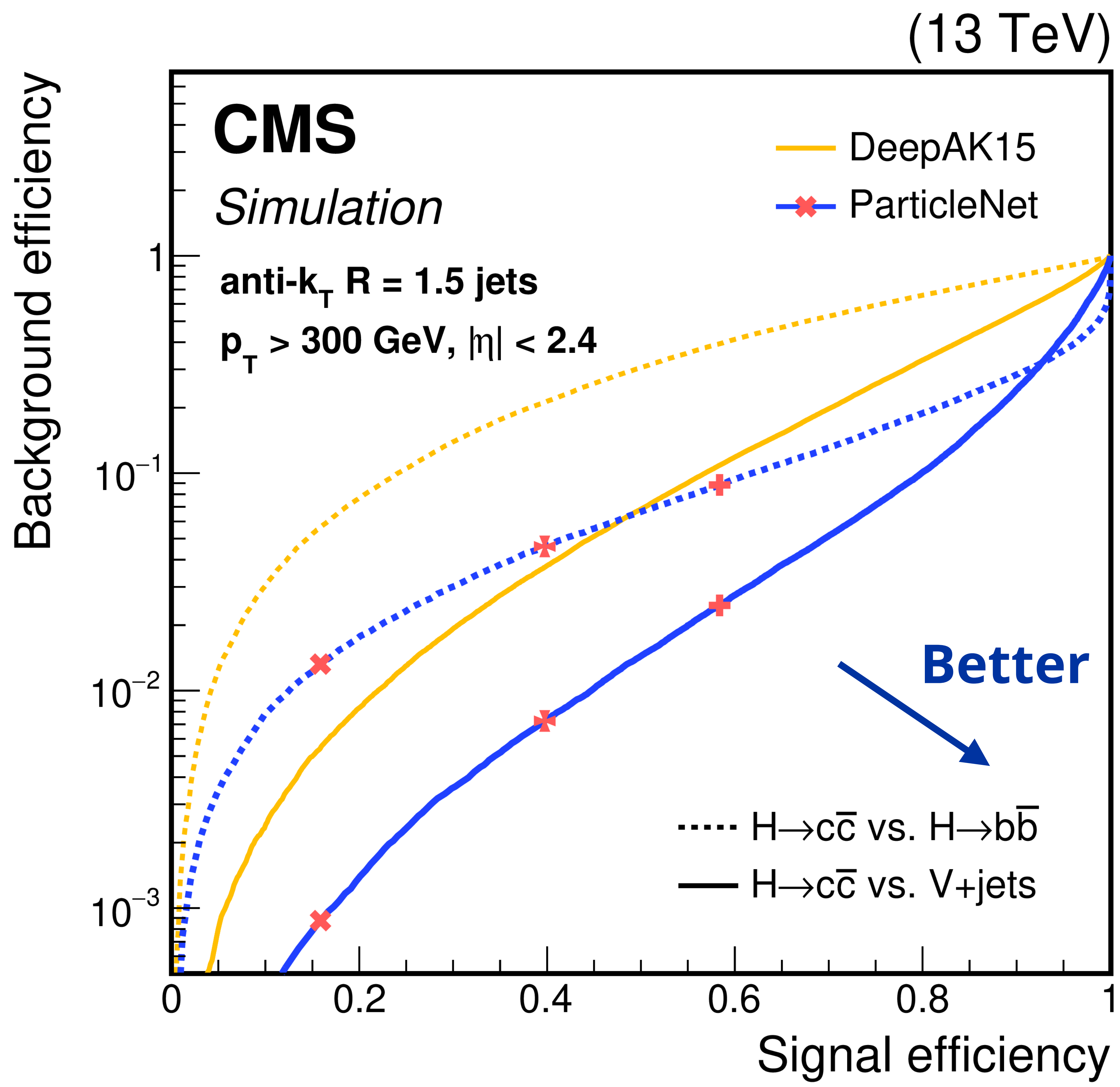


H(cc)

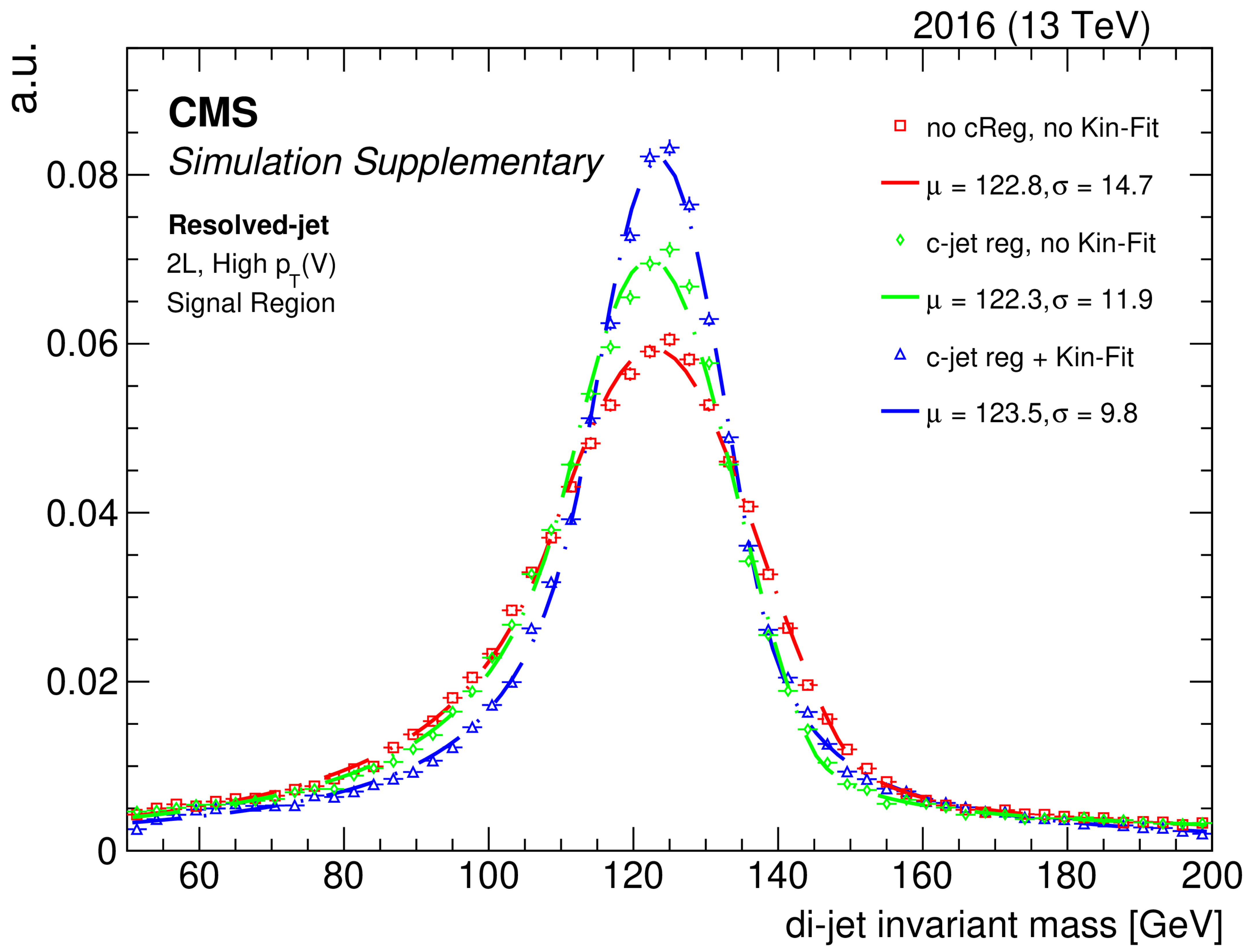
Qu & Gouskos 1902.08570

Regression: CMS DP-2021-017

CMS HIG-21-008 (New!)



4–7x improved rejection of H(bb) and V+jets vs. DeepAK8 (CNN)

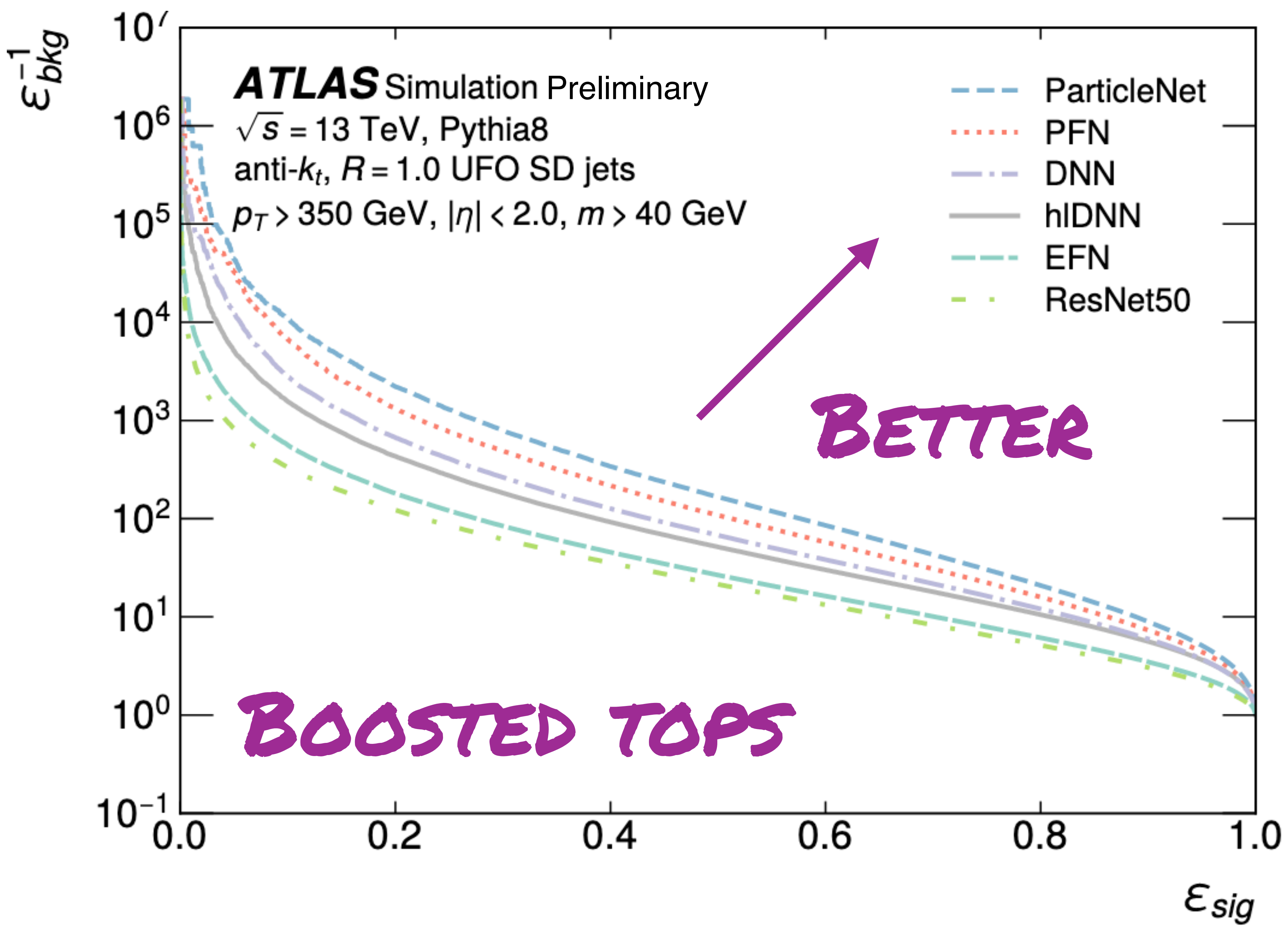


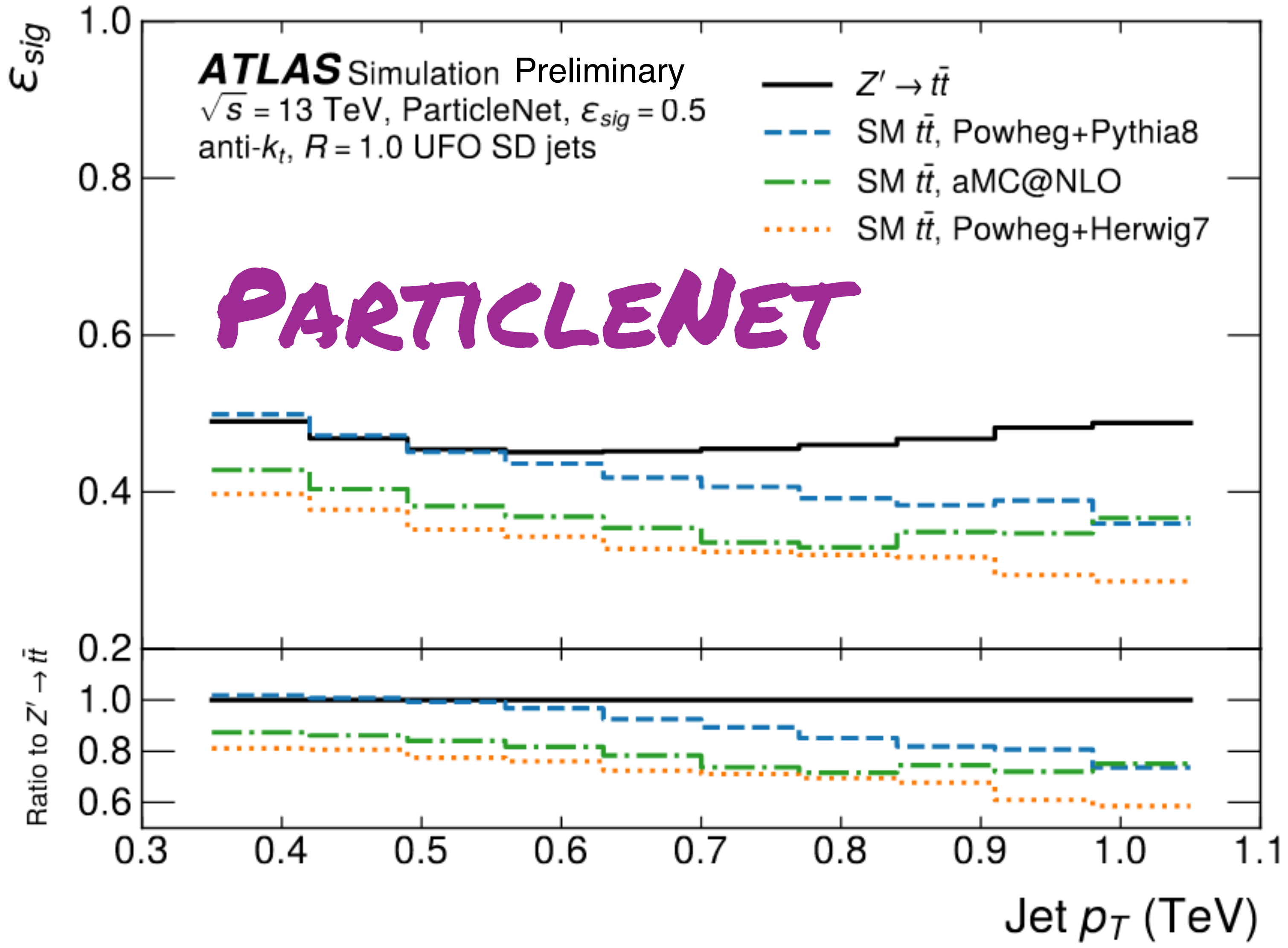
ParticleNet jet mass regression improves jet mass resolution by ~50%

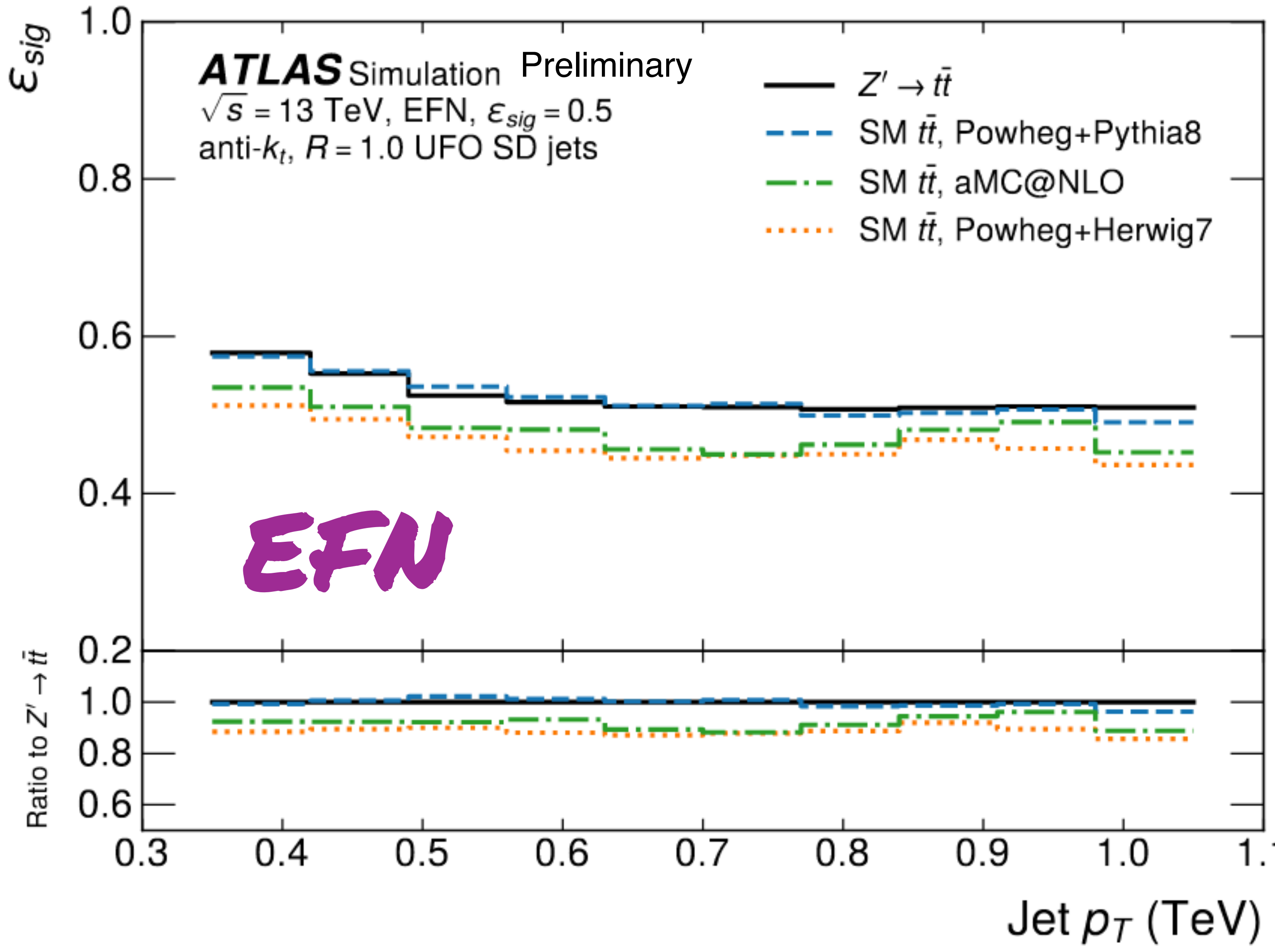
Breaking News!

ATLAS assimilated by ParticleNet!?

ATL-PHYS-PUB-2022-39 (New! Link doesn't work yet.)







Tobias will tell us about ATLAS's newest UFO-based top taggers on Wednesday Morning!

Interesting that ATLAS & CMS are converging on similar approaches — but we should be mindful that **AUC is not the only important metric!**

More aspects of our simulation enters the picture when we rely on low-level info.

(*c.f. Fig. 42-43,* **CMS-JME-18-002**)

Don't miss Kevin's poster!

Even more Breaking News!

ATLAS assimilated by ParticleNet *really badly*!?

ATL-PHYS-PUB-2022-39

(New! Link doesn't work yet.)

Coming soon:

ATLAS 13 TeV open sim

R=1.0 UFO Soft-Drop jets

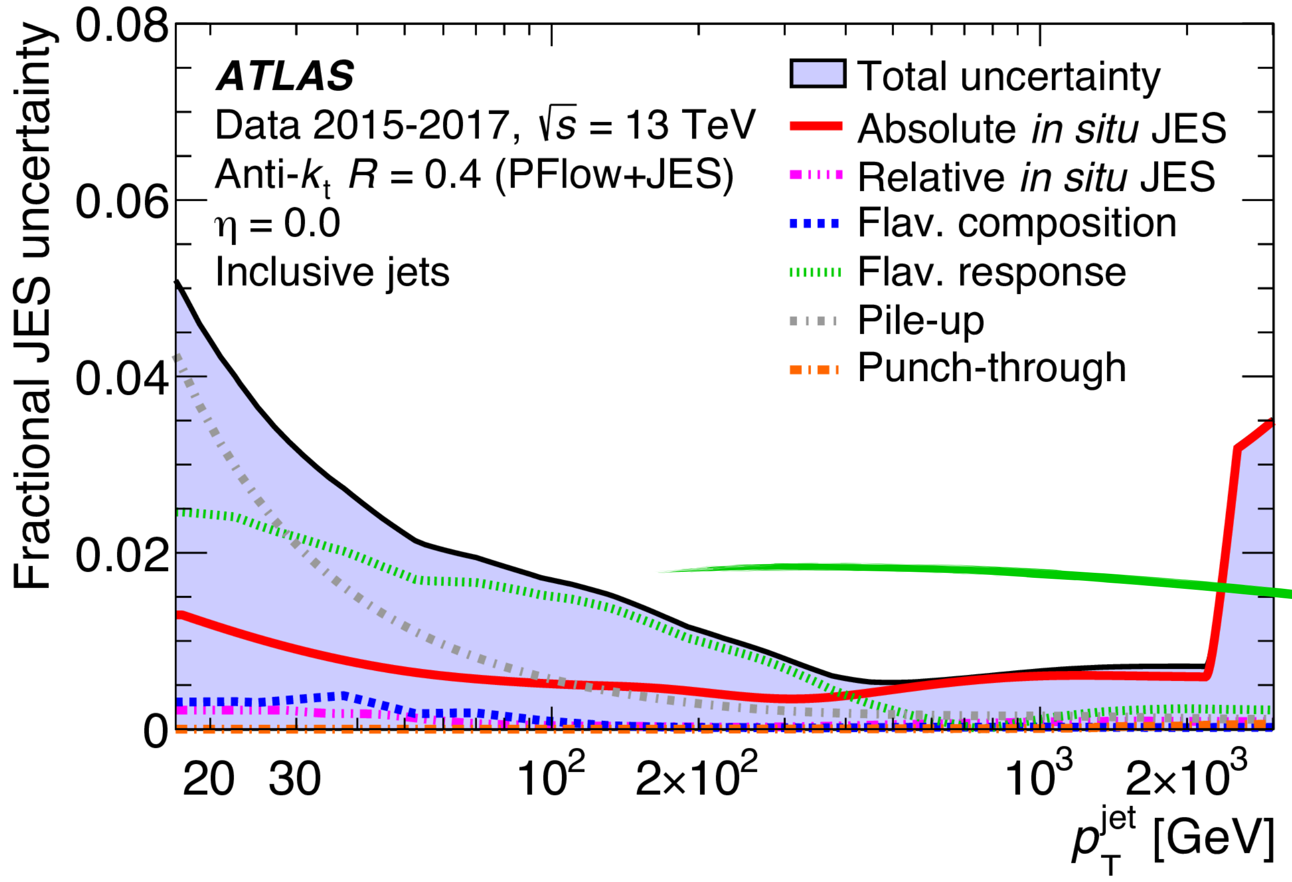
~ for ~

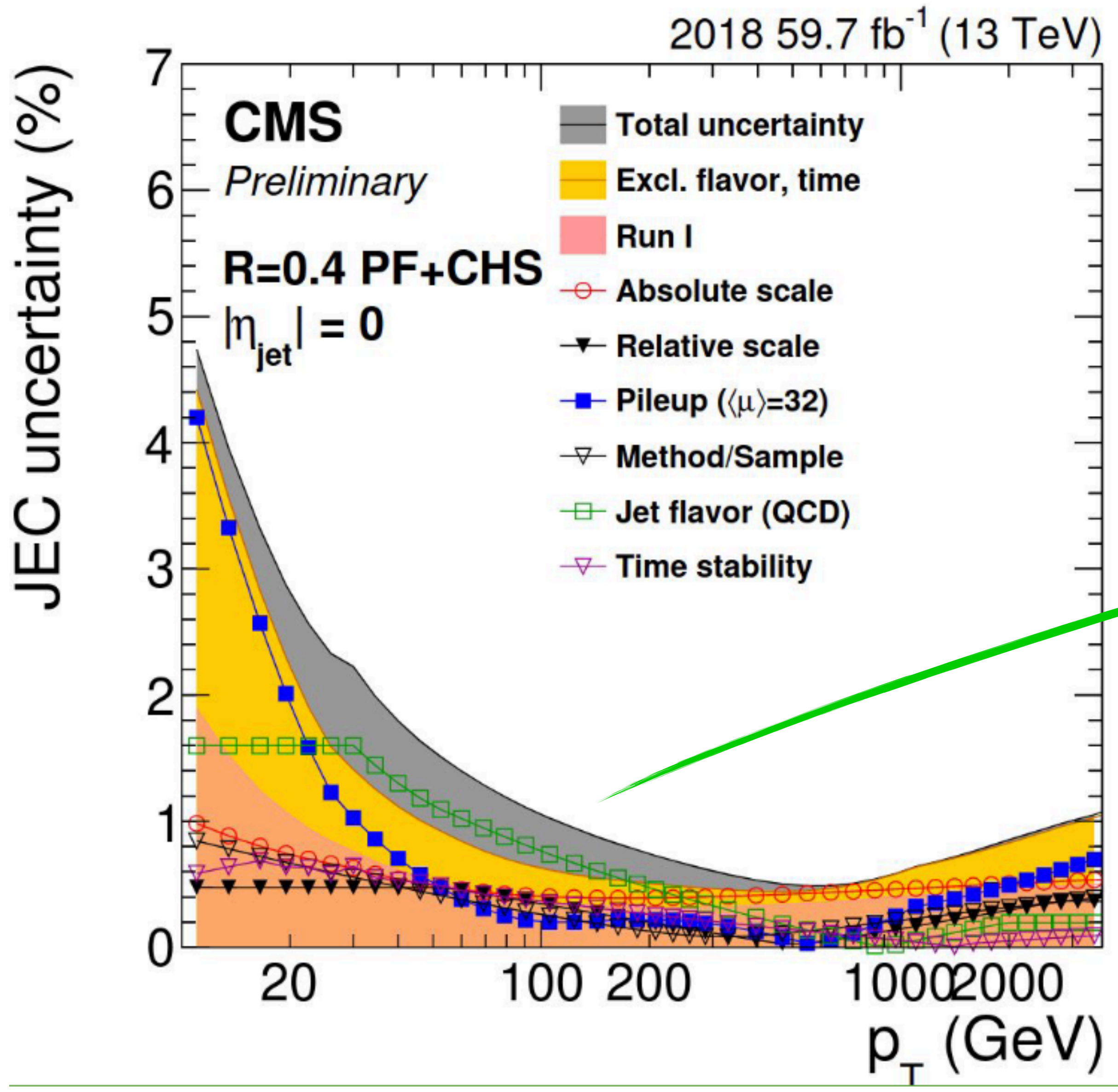
boosted top tagging, ML/AI studies!

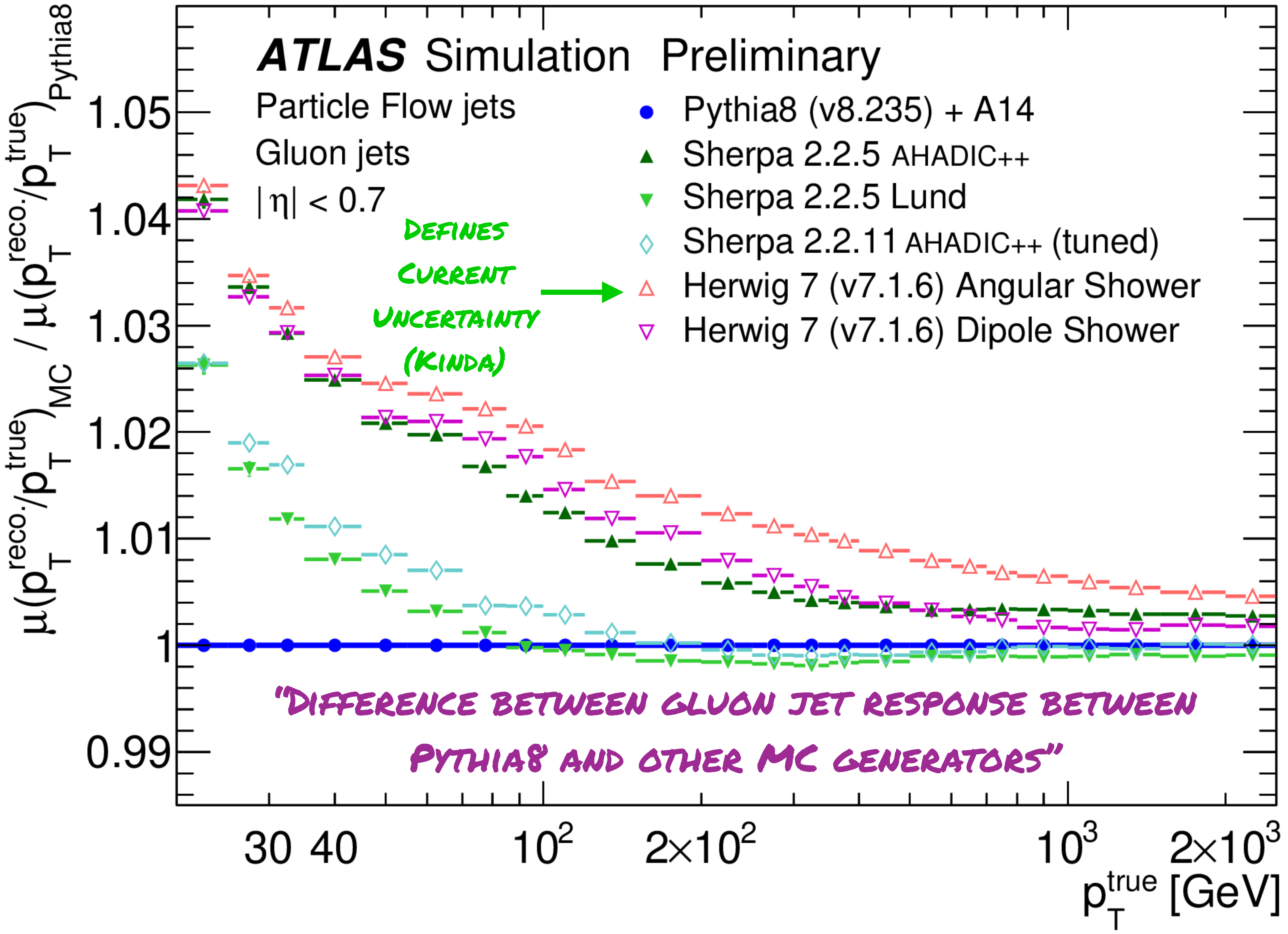
JES Flavour Response

ATLAS ATL-PHYS-PUB-2022-021 (New!)

JES Flavour Response uncertainty related to differences in gluon jet response in different generators: **limits precision in many LHC analyses**.





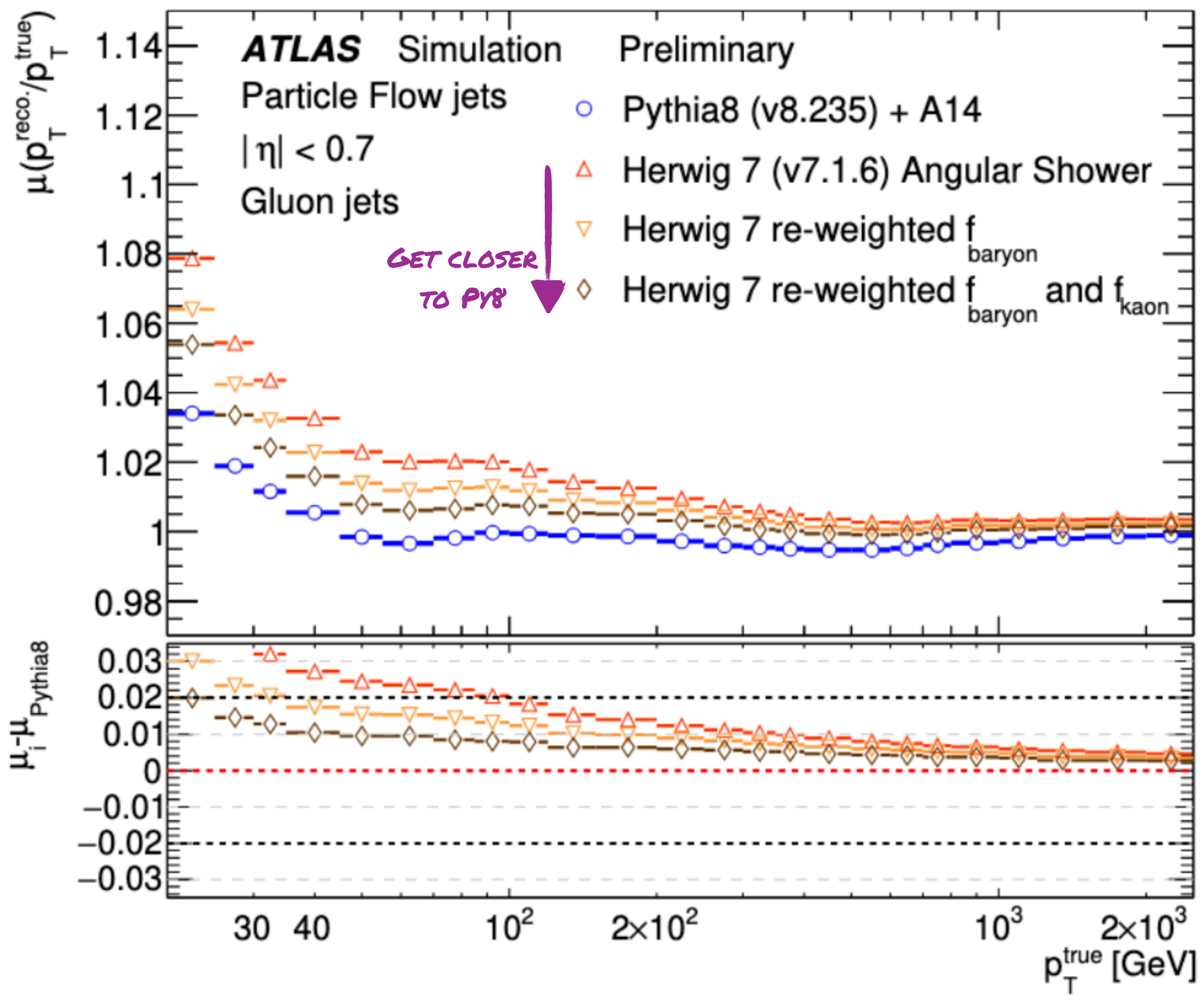


JES Flavour Response

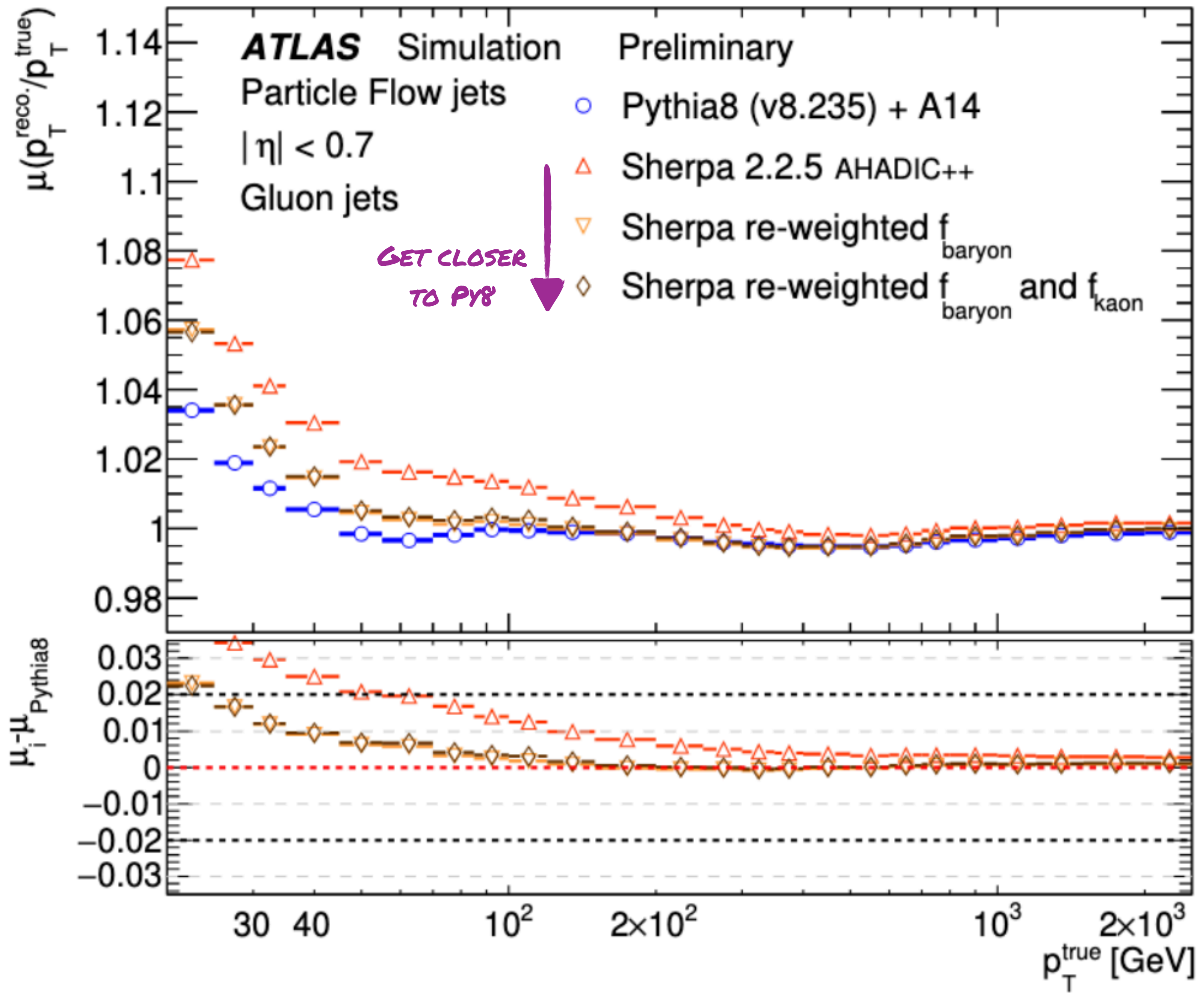
ATLAS ATL-PHYS-PUB-2022-021 (New!)

CHRIS WILL TELL YOU ALL ABOUT THIS + MORE ON THURSDAY AFTERNOON!

PYTHIA V8.235 VS. HERWIG V7.1.6



PYTHIA V8.235 VS. SHERPA 2.2.5



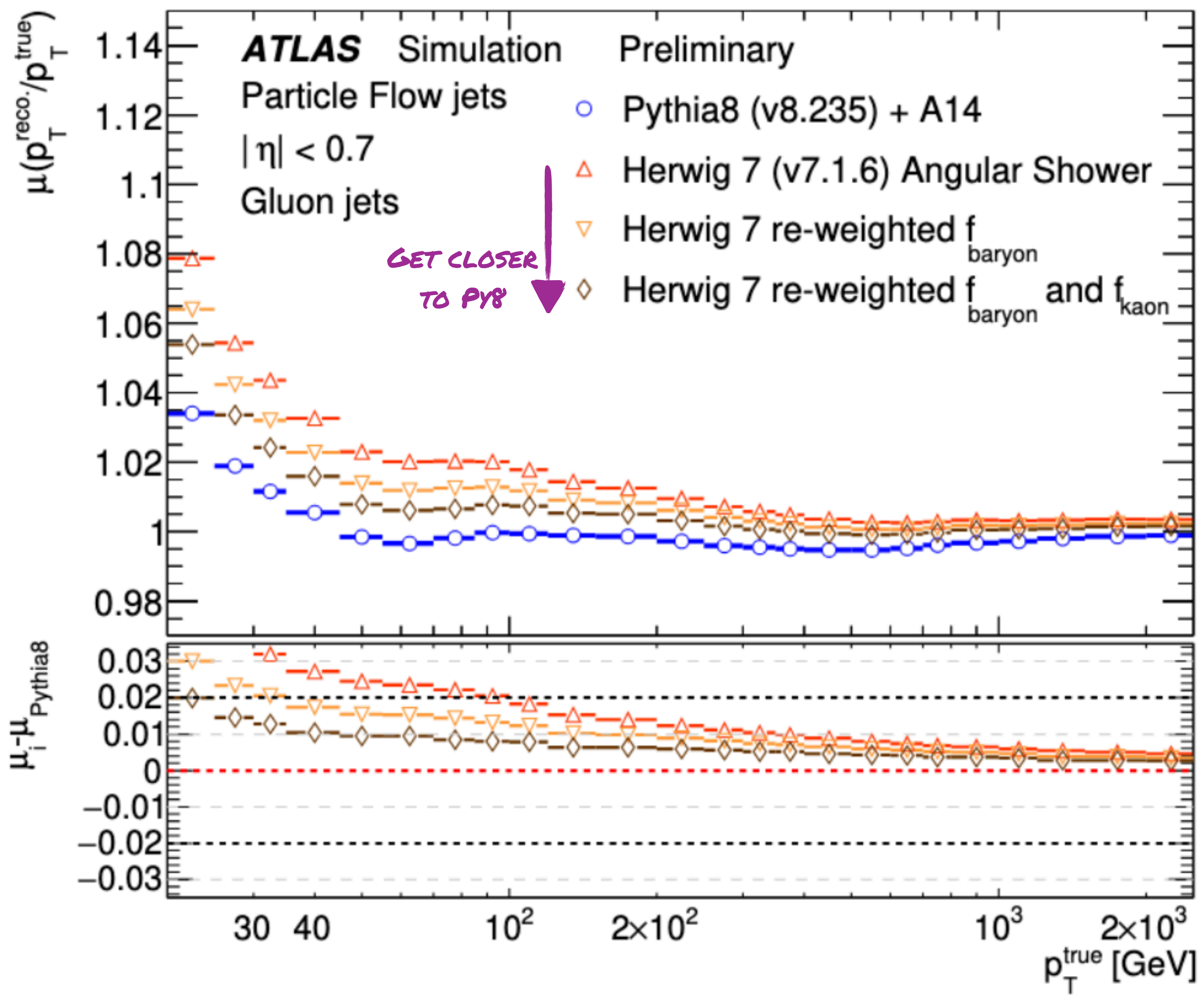
By re-weighting the **baryon and kaon fractions** within Herwig and Sherpa jets to match Pythia, the jet response in all generators can be made closer.

JES Flavour Response

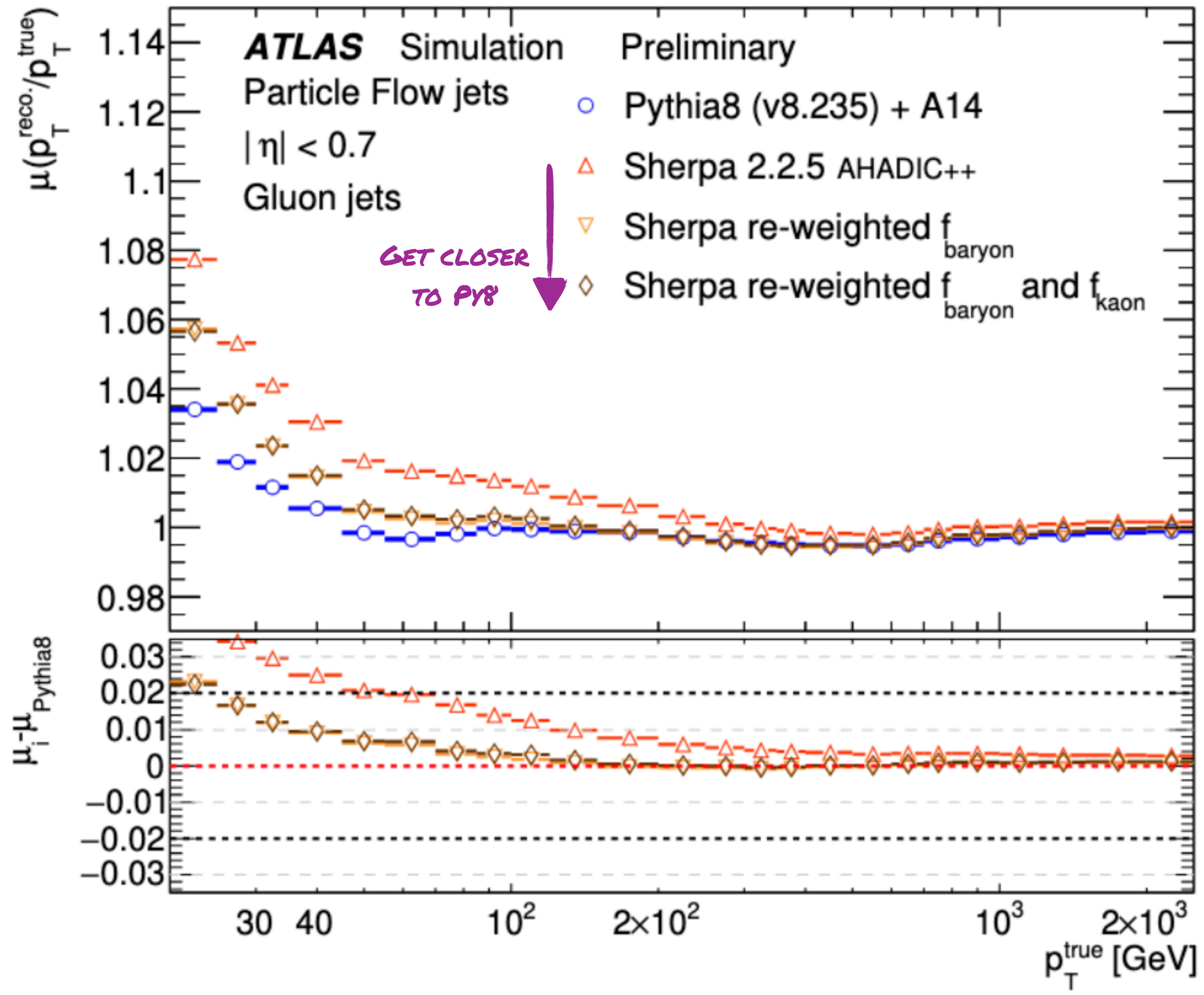
ATLAS ATL-PHYS-PUB-2022-021 (New!)

Chris will tell you all about this + more on Thursday afternoon!

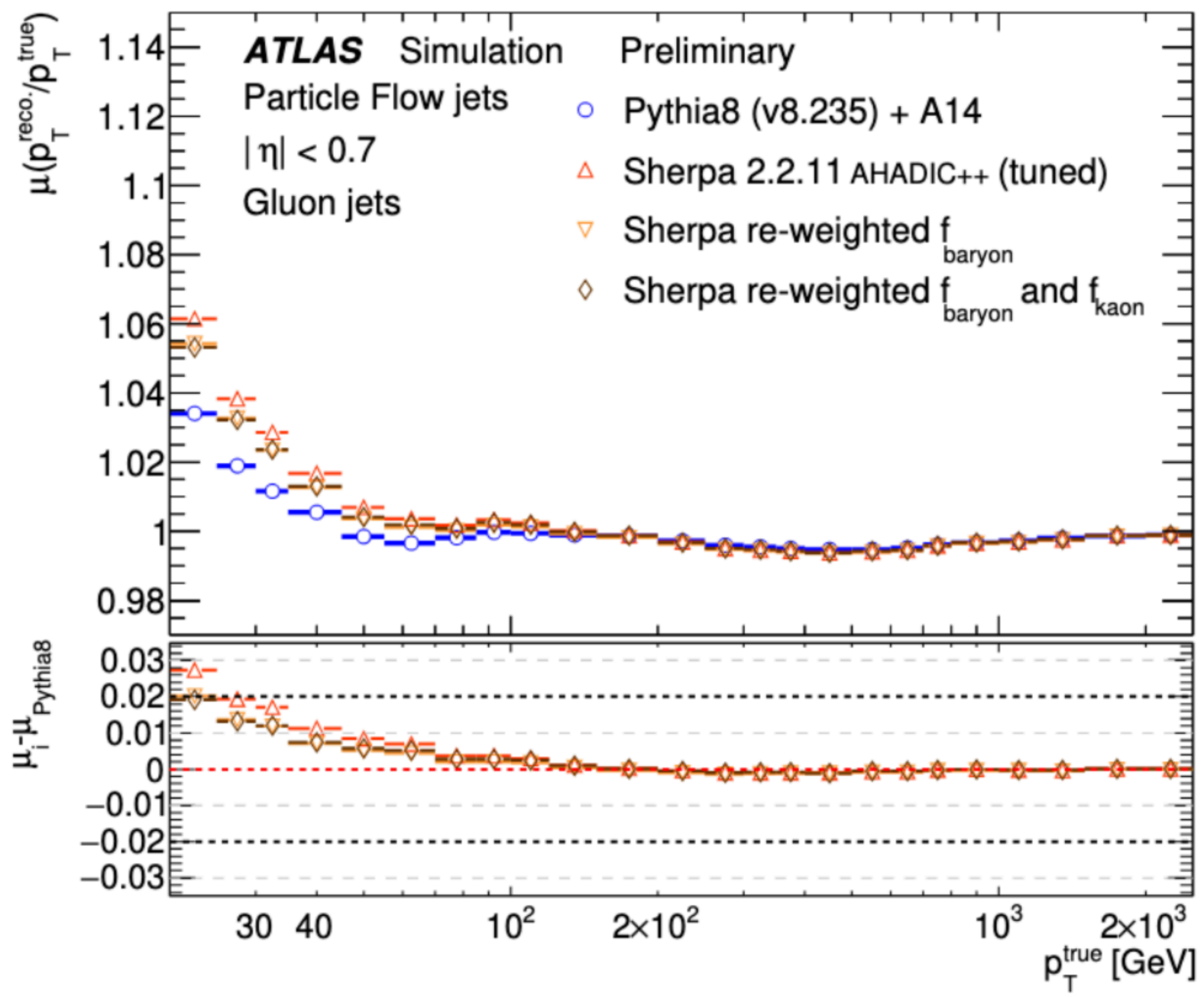
Pythia v8.235 vs. Herwig v7.1.6



Pythia v8.235 vs. Sherpa 2.2.5



Pythia v8.235 vs. Re-tuned Sherpa 2.2.5



By re-weighting the **baryon and kaon fractions** within Herwig and Sherpa jets to match Pythia, the jet response in all generators can be made closer.

Sherpa can also brought to Pythia out-of-the-box by re-tuning to LEP data!

JES Flavour Response

ATLAS ATL-PHYS-PUB-2022-021 (New!)

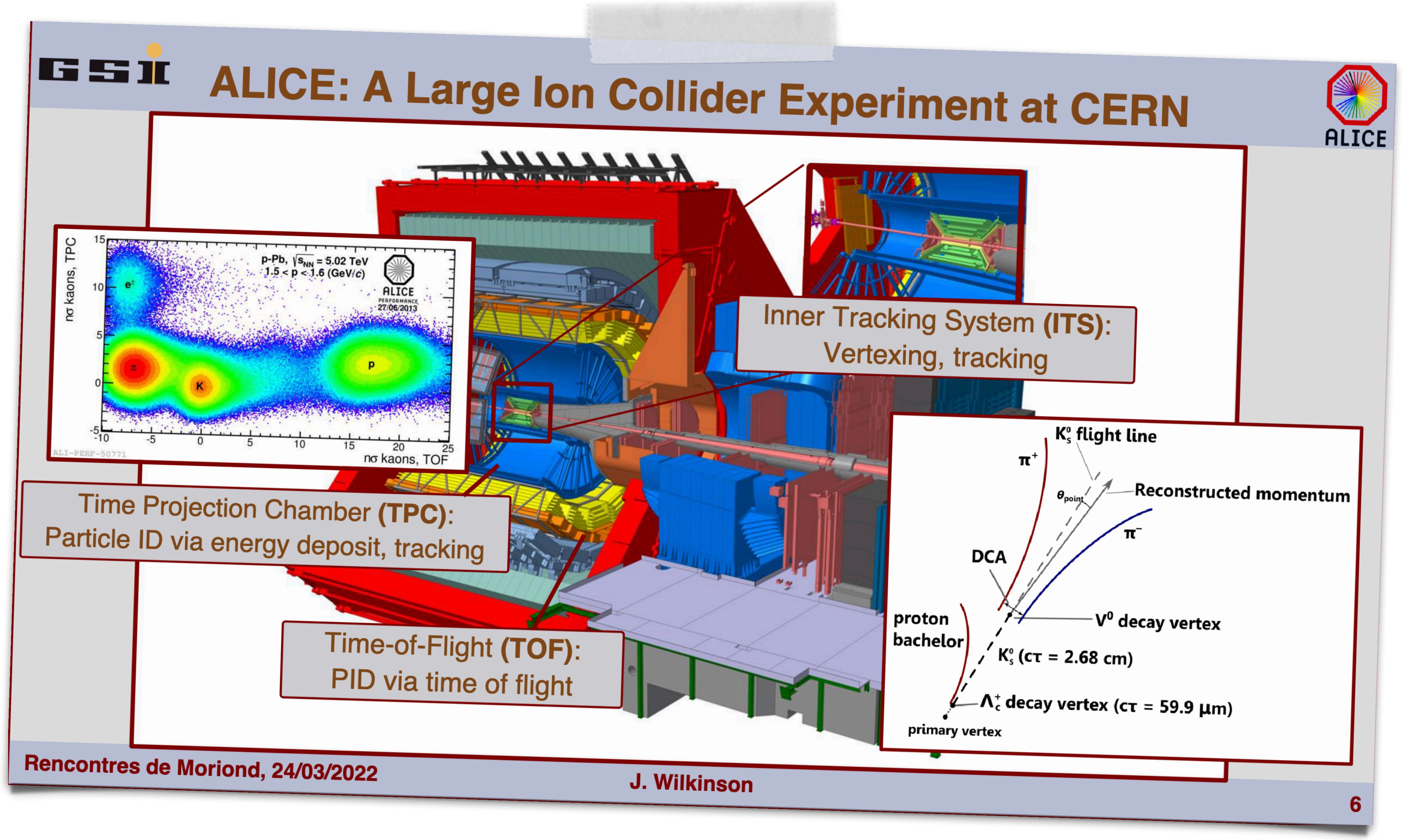
Chris will ask ALICE to do this on Thursday afternoon!

It also motivates the measurement of these quantities in LHC data to enable such tuning, as well as careful comparison to the LEP e^+e^- data. While ATLAS does have the ability to identify protons and $K^{\pm}$ at very low momenta [56] it is not designed for measurements in the p_{T} range of particles in jets at LHC. However, the ALICE detector is capable of good particle identification [57] and has already published spectra of identified particles in minimum bias collisions [58] and therefore precise measurements of the baryon and kaon energy fractions of jets are feasible. Such a measurement could have a significant impact on precision measurement of the LHC physics program.

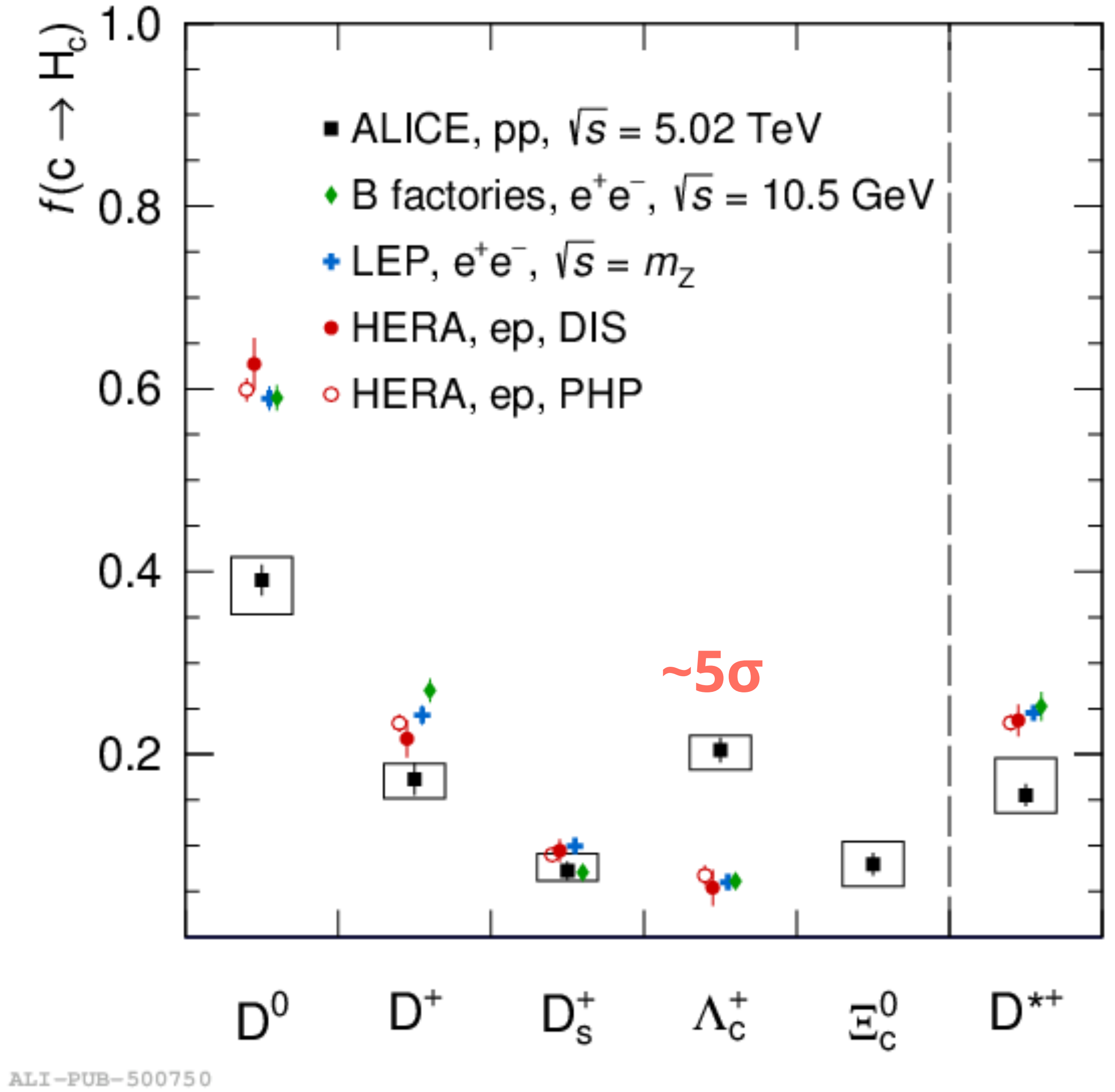
Gian will tell us about how ALICE have done this inclusively (so-far) on Tuesday afternoon!

Heavy Hadrons @ LHC

ALICE 2112.08156 CERN-EP-2021-088 CERN-EP-2022-171 (New!)



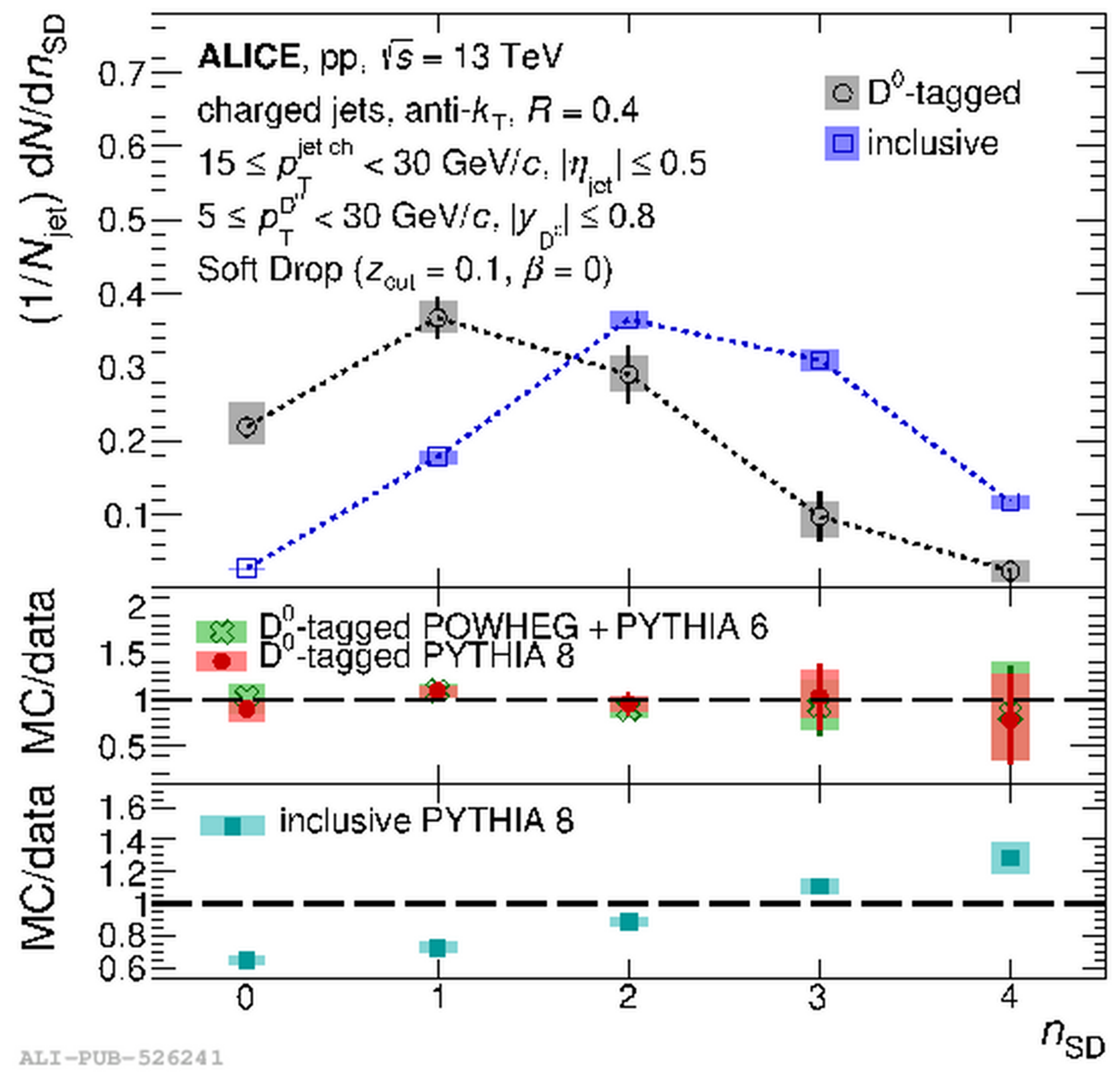
ALICE has complementary abilities to ATLAS & CMS — particularly PID.



Charm fragmentation fractions differ significantly from LEP, HERA!

… should include LHC data in tuning / validation!

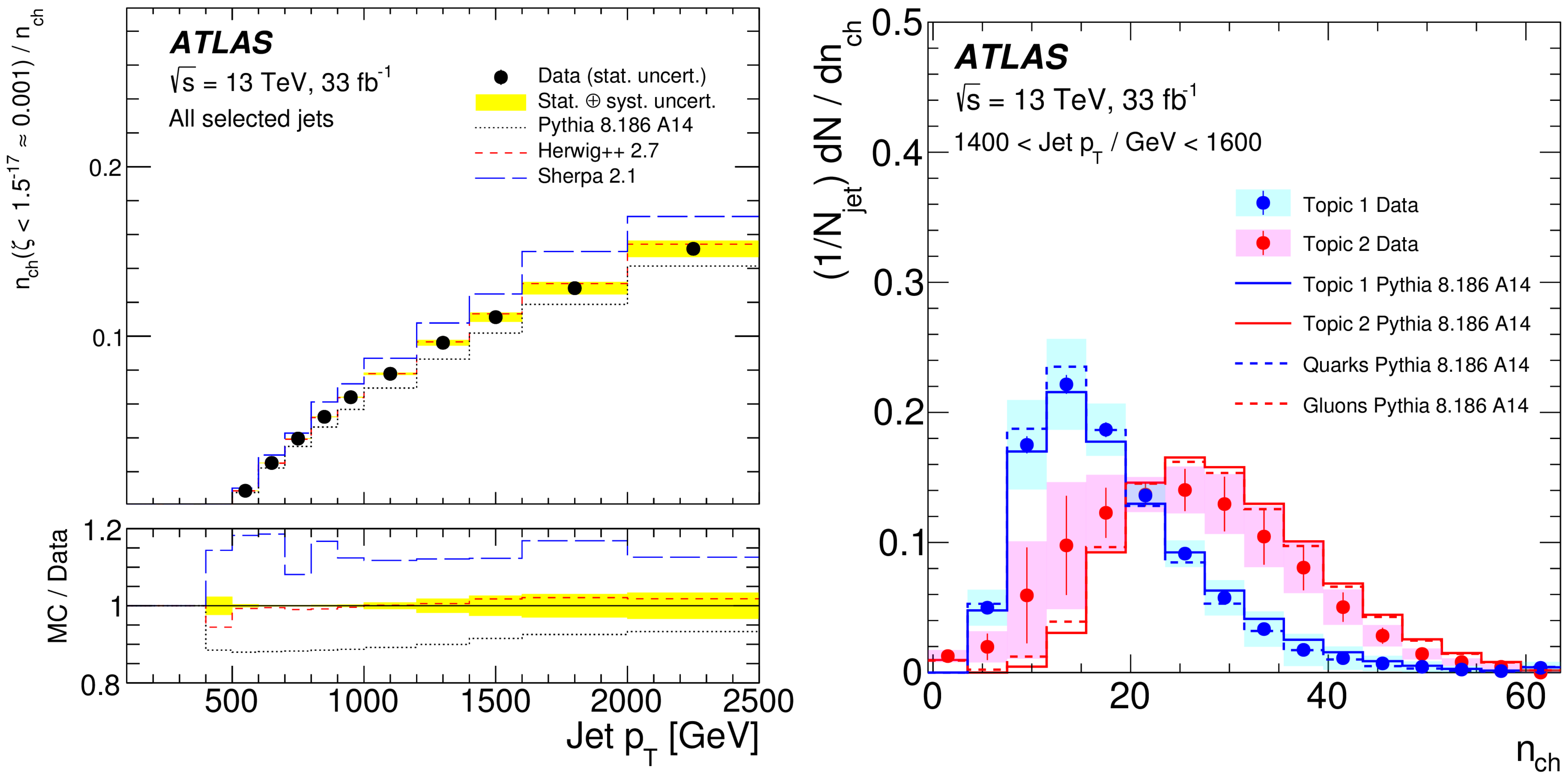
Soft-drop observables in D0-tagged jets! Brand new!



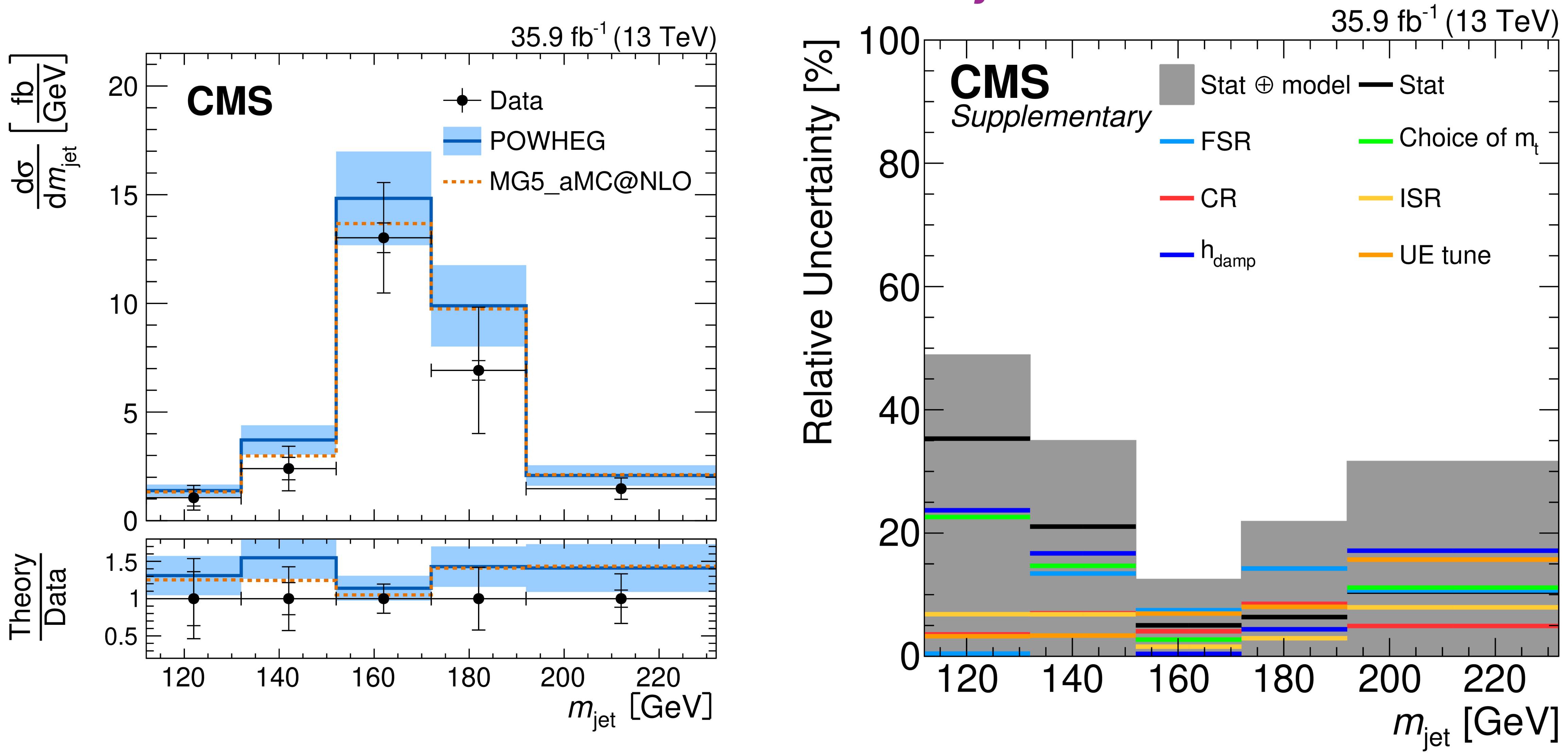
Gian will tell us about the latest from ALICE in pp on Tuesday afternoon! + Ezra in Pb+Pb on Thursday morning!

ATLAS, Phys. Rev. Lett. 124, 222002 (2020)   CMS, Phys. Rev. D 98, 092014 (2018)   ATLAS, Phys. Rev. D 100, 052011 (2019)   CMS, Phys. Rev. Lett. 124, 202001 (2020)

ATLAS Fragmentation Functions w/ jet topics extraction

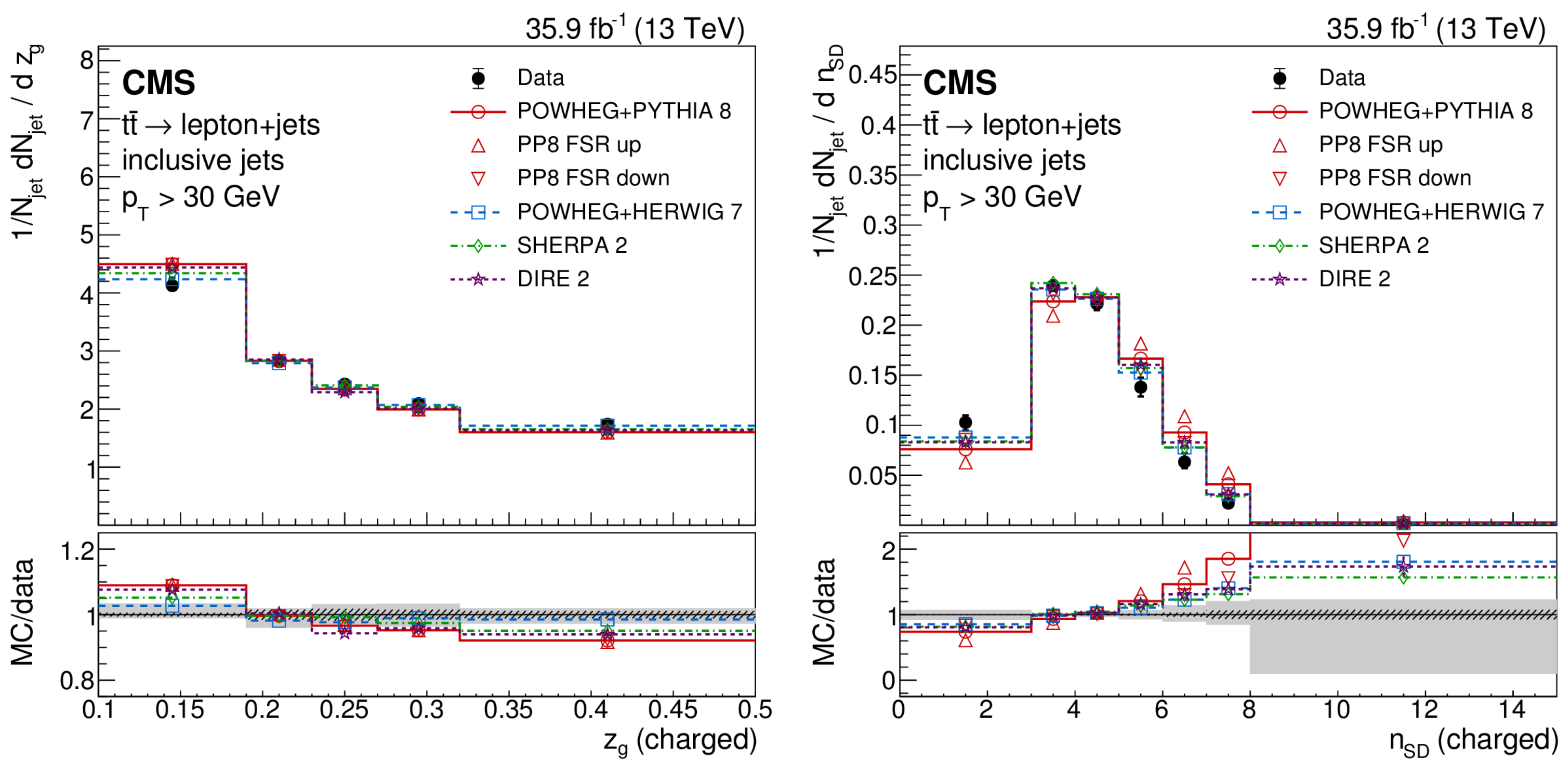


CMS m_t w/ XCone jets



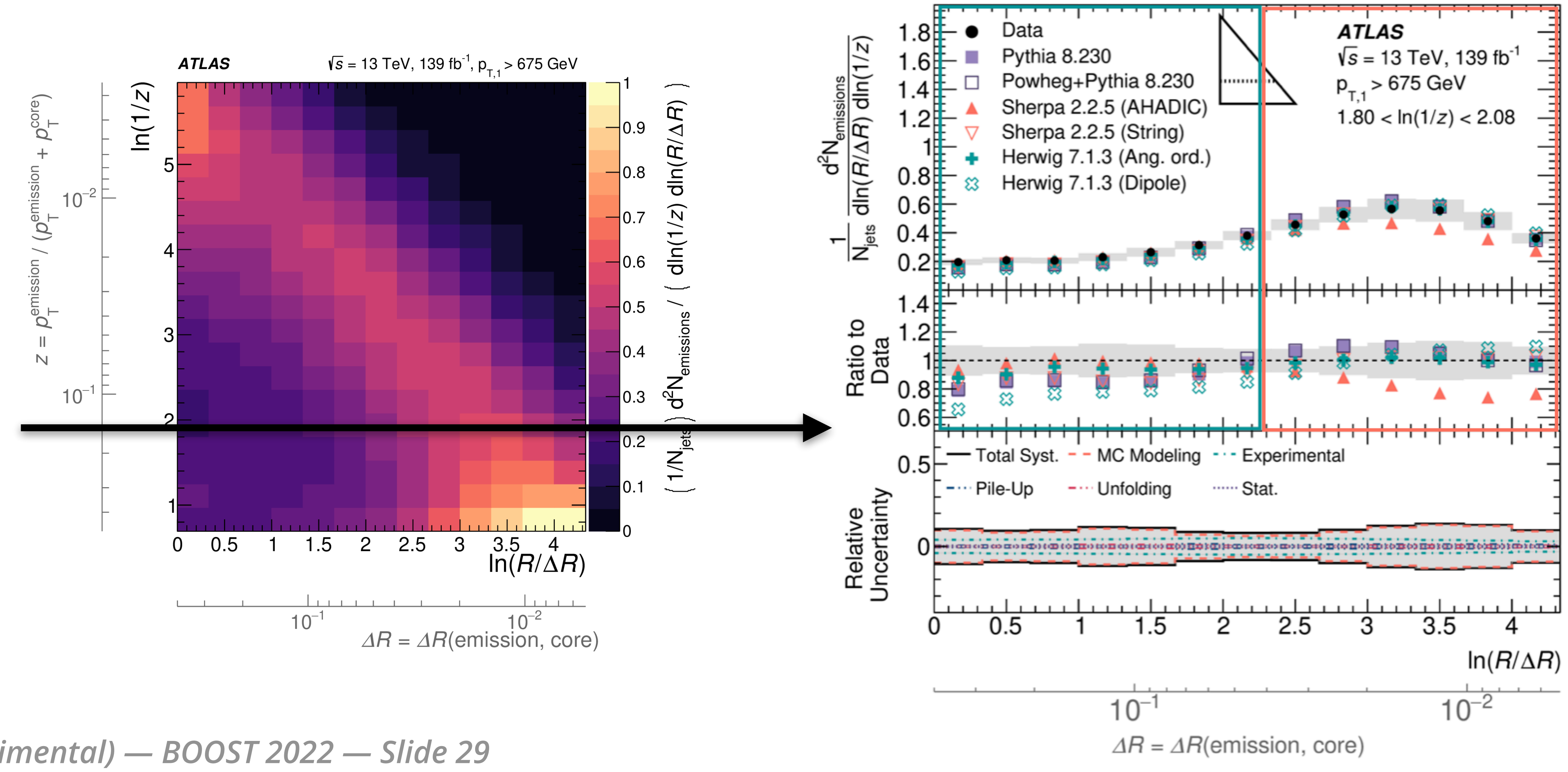
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

CMS jet shapes in ttbar



ATLAS Lund jet plane

Parton shower models differ   Hadronisation models differ



[CMS-SMP-20-010](CMS-SMP-20-010)

(311 public figures!)

CMS q/g Angularities

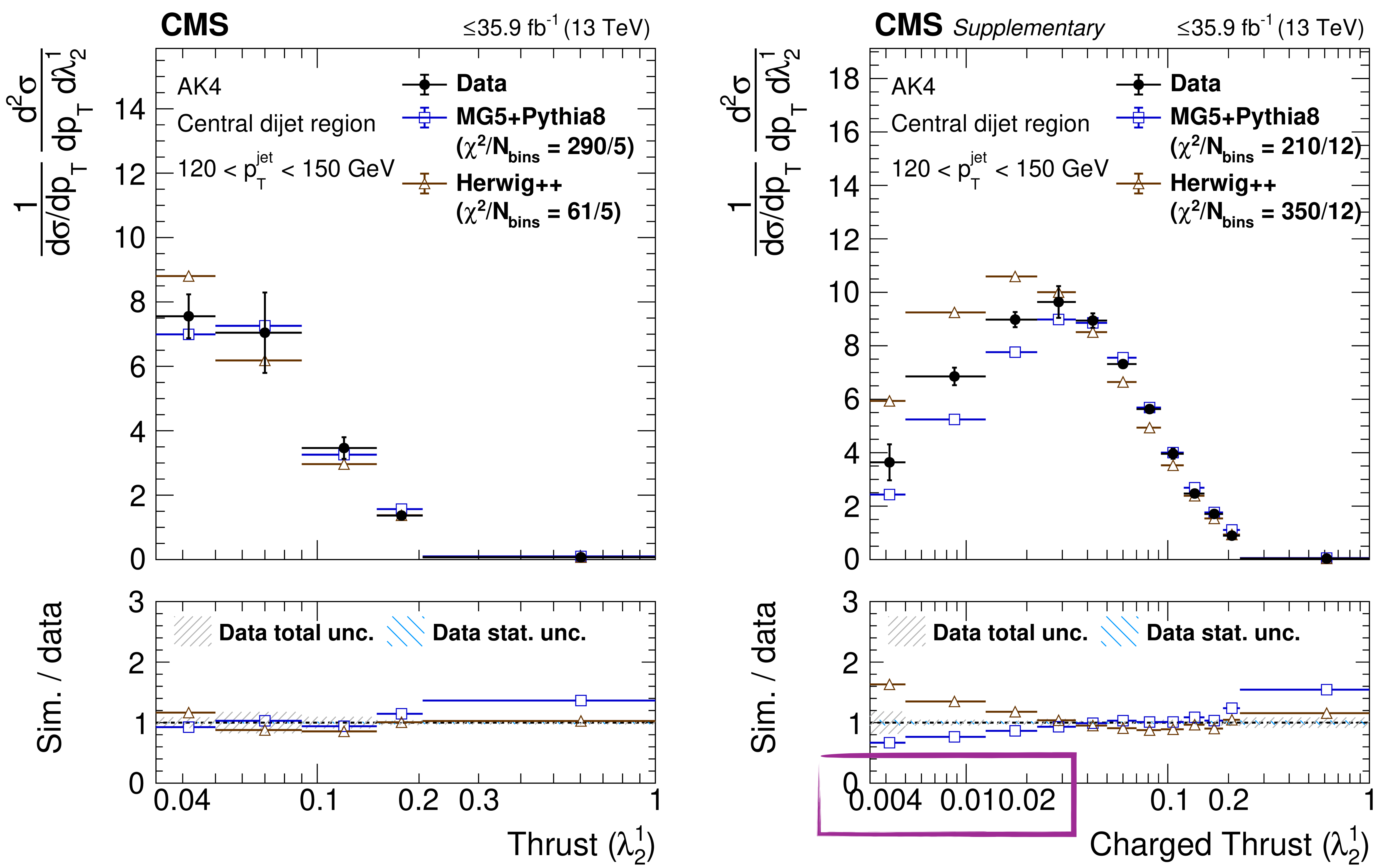
Daniel will tell you about the NLO+NLL' calculations on Tuesday morning!

Can make many comparisons from these results — here, note how **agreement improves for larger R, or with grooming**. Studying a dijet topology (q/g-like jet admixture) exposes mis-modelling at the **gluon-initiated jet enriched** region (large thrust).

Aside: JSS with Charged vs. All Particles

- Both ATLAS and CMS have made comparisons of **charged+neutral & charged-only measurements**.
- Measurements made using only inner-detector signals **improve experimental resolution & measurement precision.**
  - *"Smaller angles, softer signals, more bins."*
  - **Trade-off:** IRC safety. Recently, extra **NP-corrections or folding** made to **compare theory to charged-particle only** picture.
    - … but, we now have data/theory comparisons that would have otherwise not been possible (*e.g.* ATLAS LJP)!

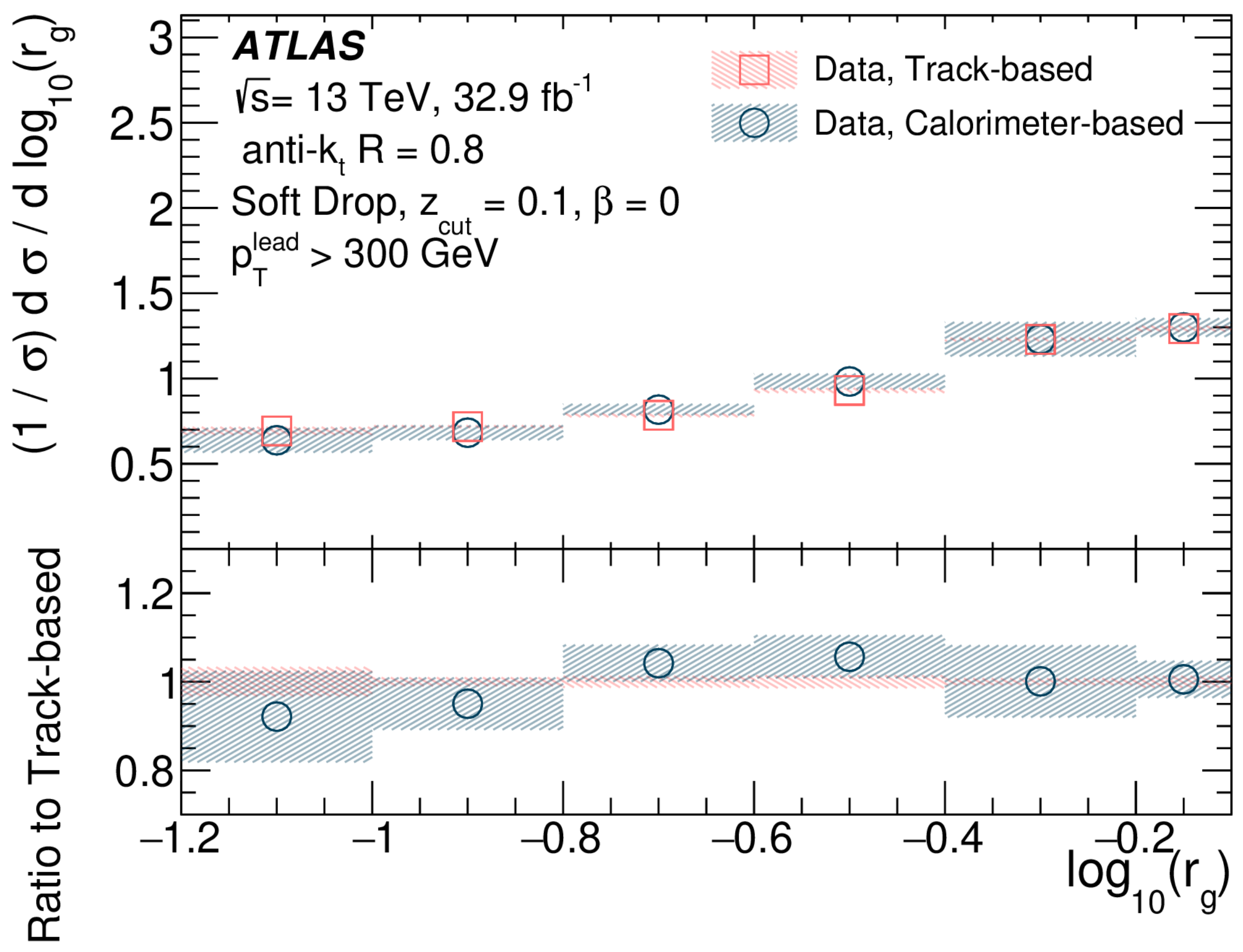
Yibei will tell you about the latest theoretical progress with track functions on Tuesday morning!



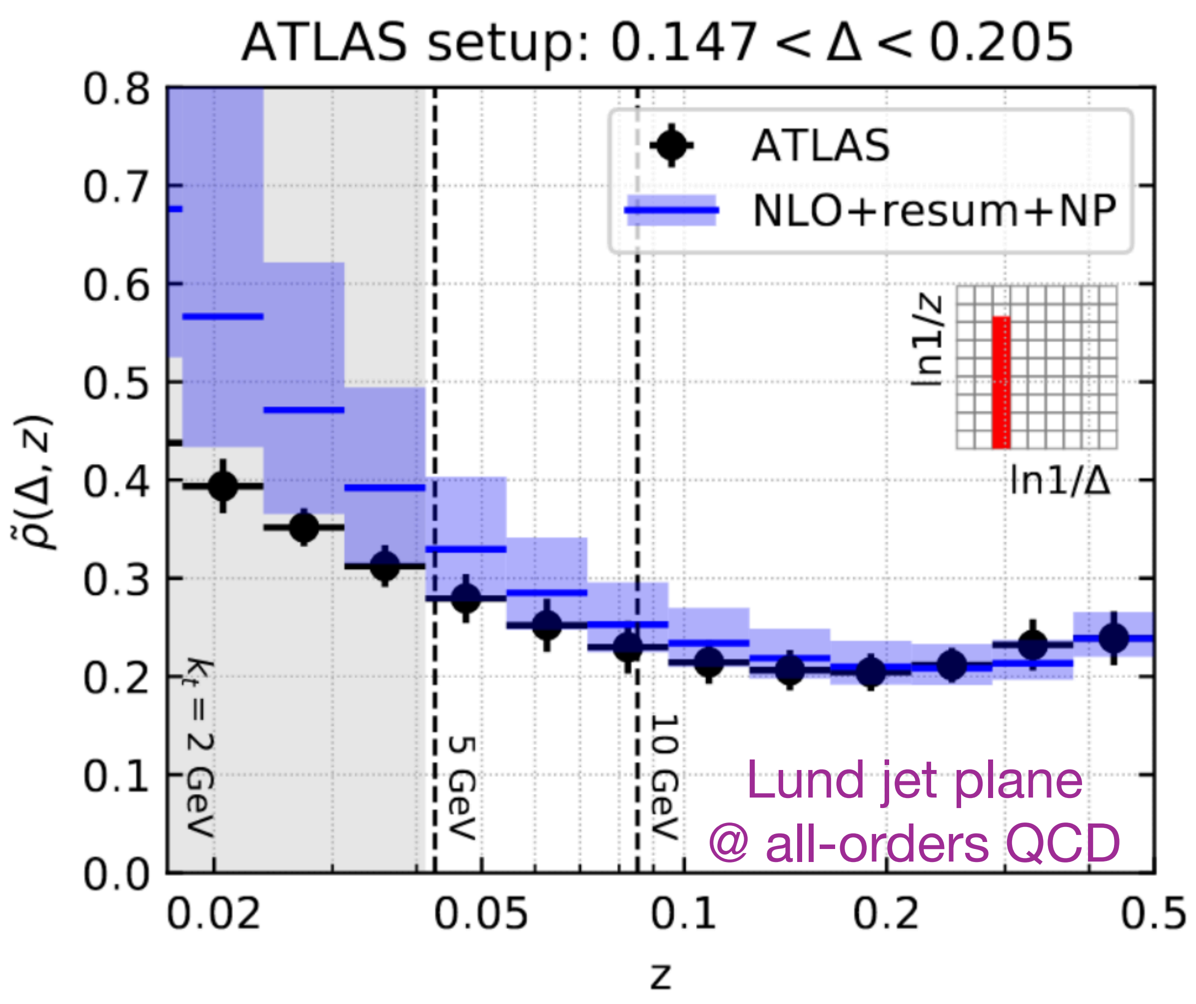
CMS, arXiv.2109.03340

Similar level of (dis)agreement — charged-only measurements can be more useful for MC tuning!

Extra reach into collinear region — sensitive to npQCD effects!



ATLAS Phys. Rev. D 101 (2020) 052007



Lifson, Soyez & Salam, JHEP 10 (2020) 170

Data from ATLAS Phys. Rev. Lett. 124 (2020) 222002

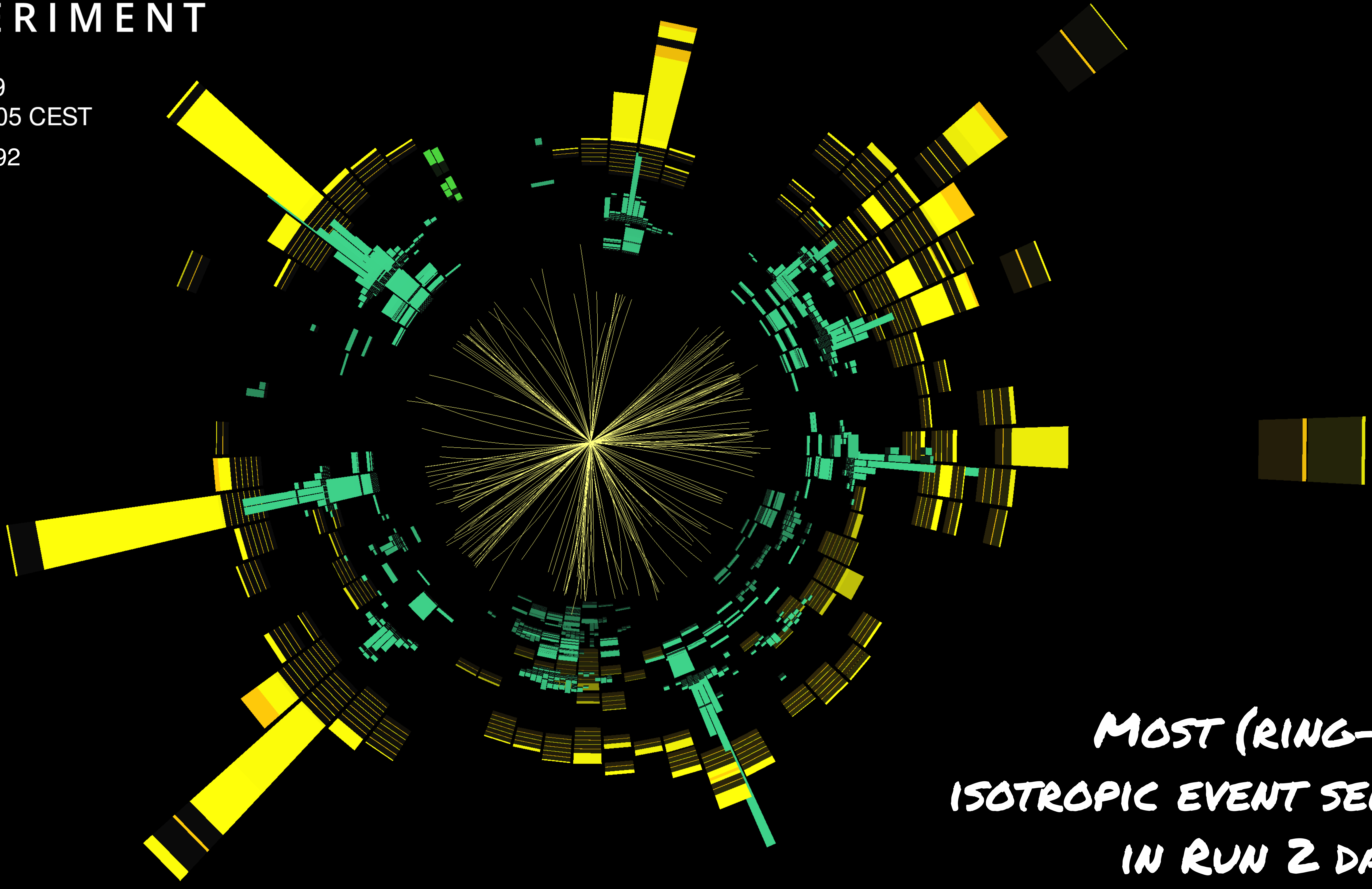
ATLAS EXPERIMENT

Run: 300687
Event: 1358542809
2016-06-02 18:19:05 CEST

1-IsoRing128 = 0.92
N_{jets} = 12

ATLAS-CONF-2022-056

(Branch New! Link doesn't work yet)

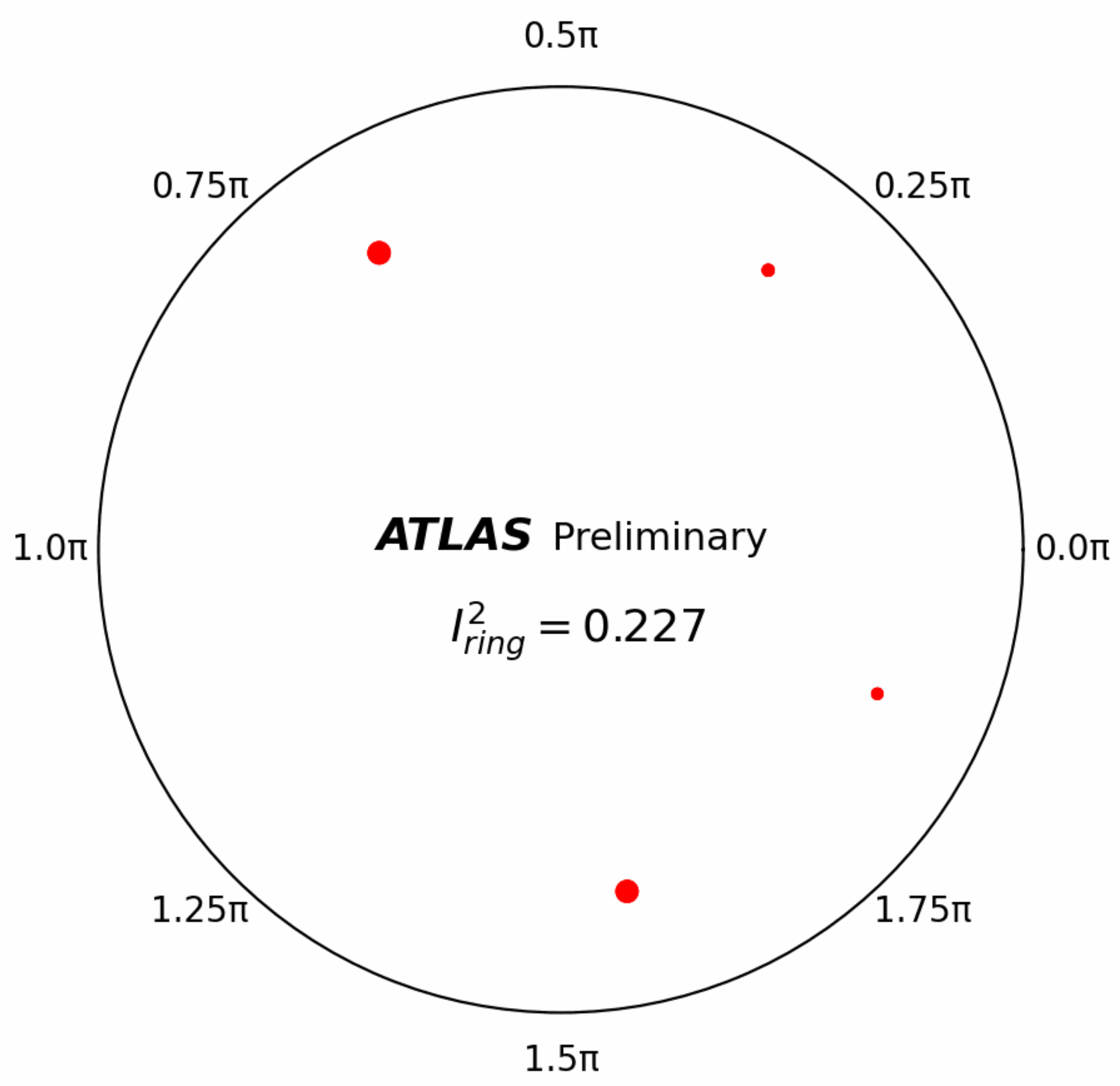


MOST (RING-LIKE) ISOTROPIC EVENT SELECTED IN RUN 2 DATASET!

ATLAS Multijet Event Isotropies w/ Optimal Transport

Many Event Shapes can be recast as 'Optimal Transport' problems + solved using (IRC-safe) techniques from Topology + Computer Vision.

This allows us to instead quantify the distance between events and isotropic radiation patterns, resulting in new + better-performing event shapes!

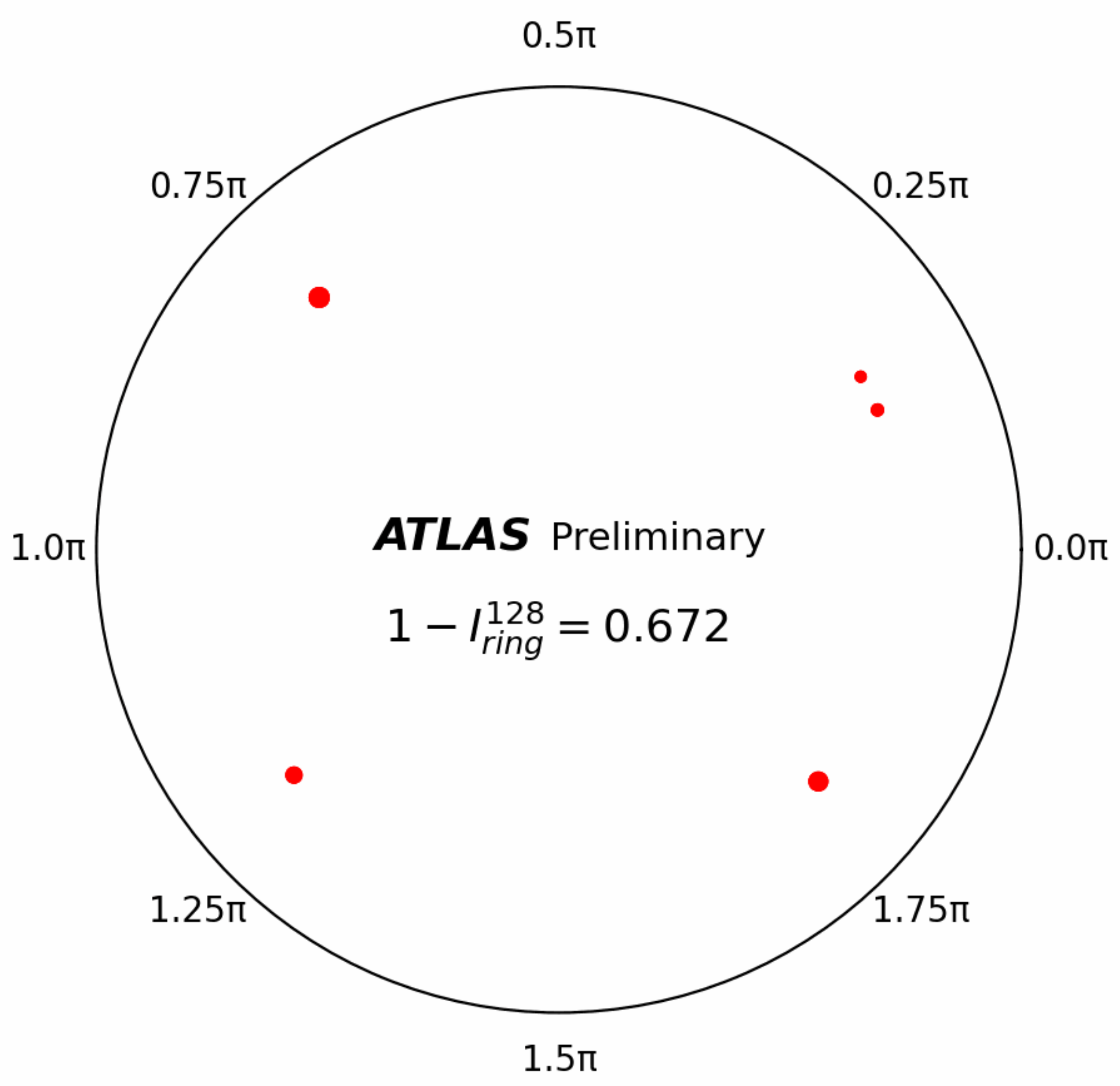


"Work" to re-arrange event into reference geometry: distance*energy

p-Wasserstein distance (a.k.a. EMD)

$$\text{EMD}_\beta(\mathcal{E}, \mathcal{E}') = \min_{\{f_{ij} \geq 0\}} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} \theta_{ij}^{\beta},$$

LINK TO ANIMATIONS



ATLAS-CONF-2022-056

Key Pheno Ideas:

EMDs (Wasserstein Distances between events)
Komiske, Metodiev + Thaler
1902.02346, 2004.04159

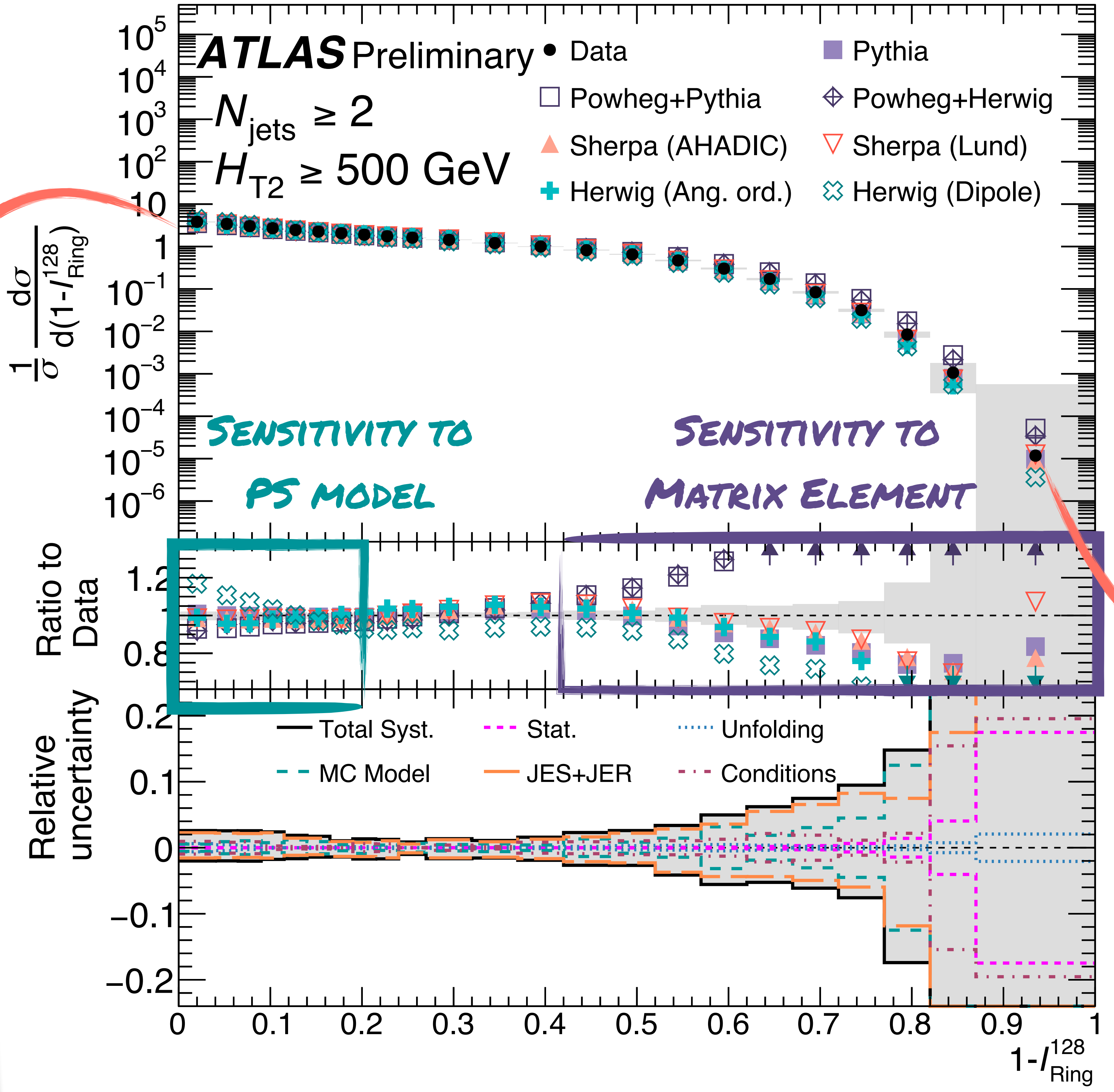
Event Isotropies
Cesarotti + Thaler
2004.06125

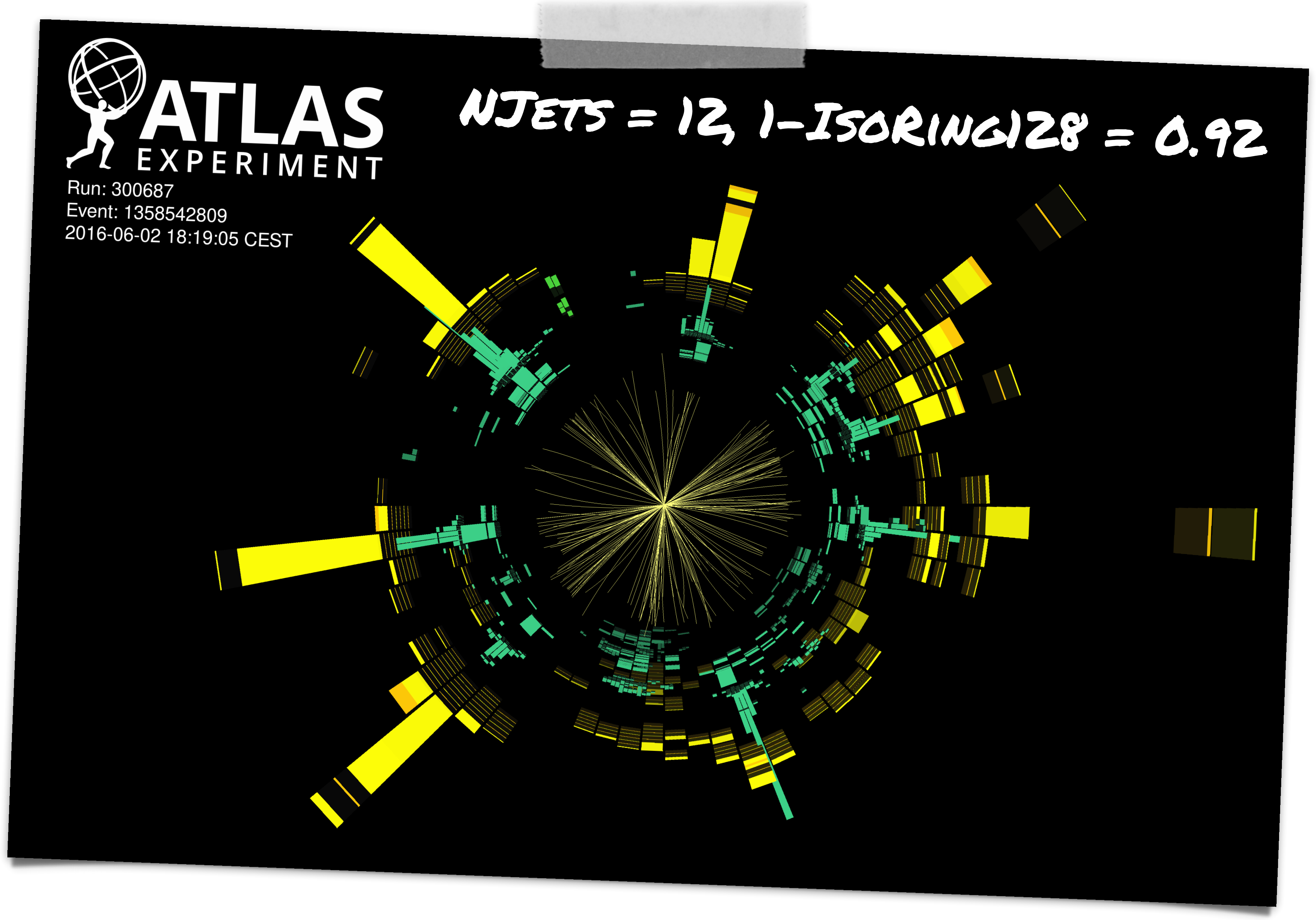
Results: I_{Ring}^{128}

ATLAS ATLAS-CONF-2022-056 (New!)

Manuel will tell you all about this + and other ATLAS multijet cross-section measurements, on Thursday morning!

Ring-like Isotropy

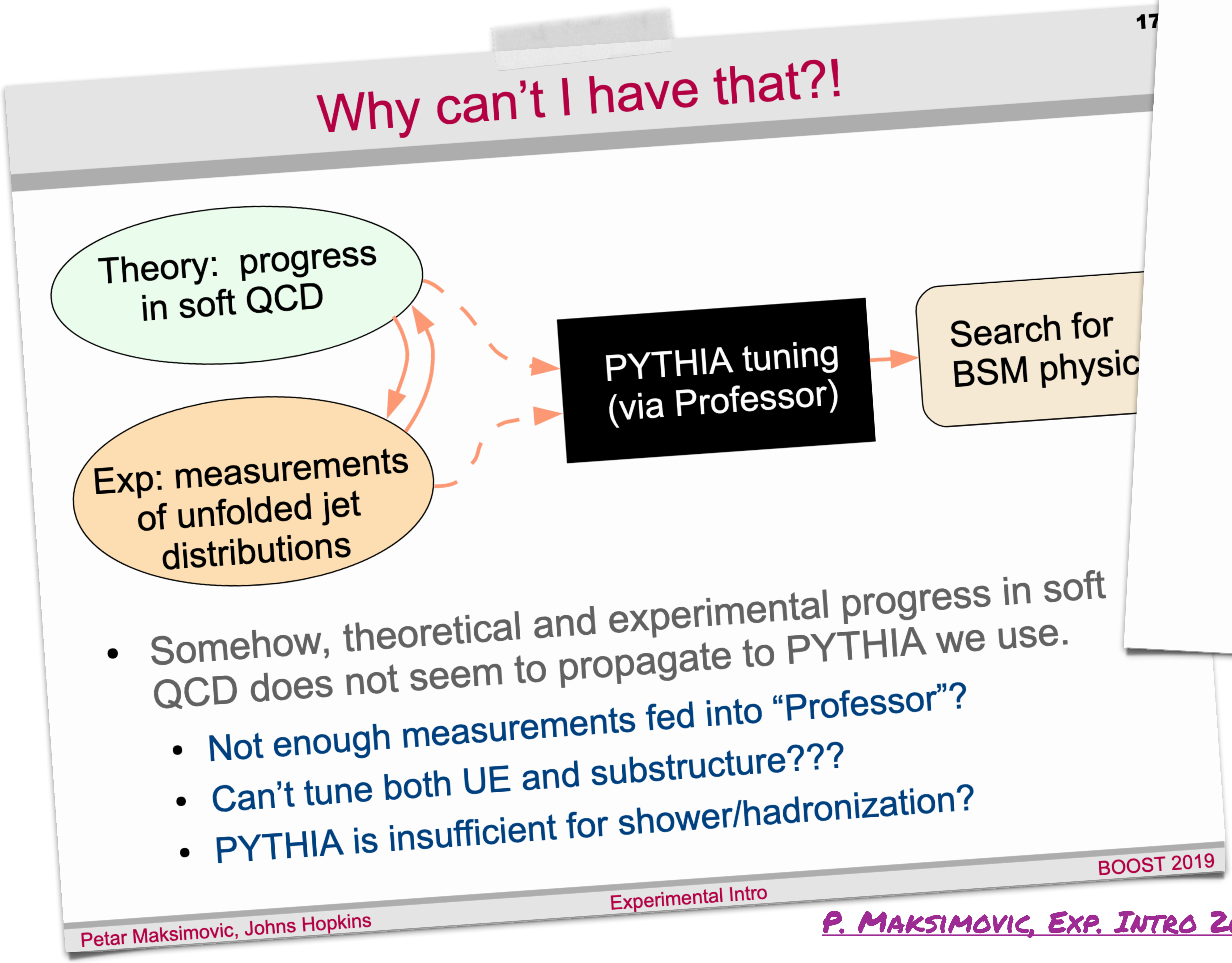




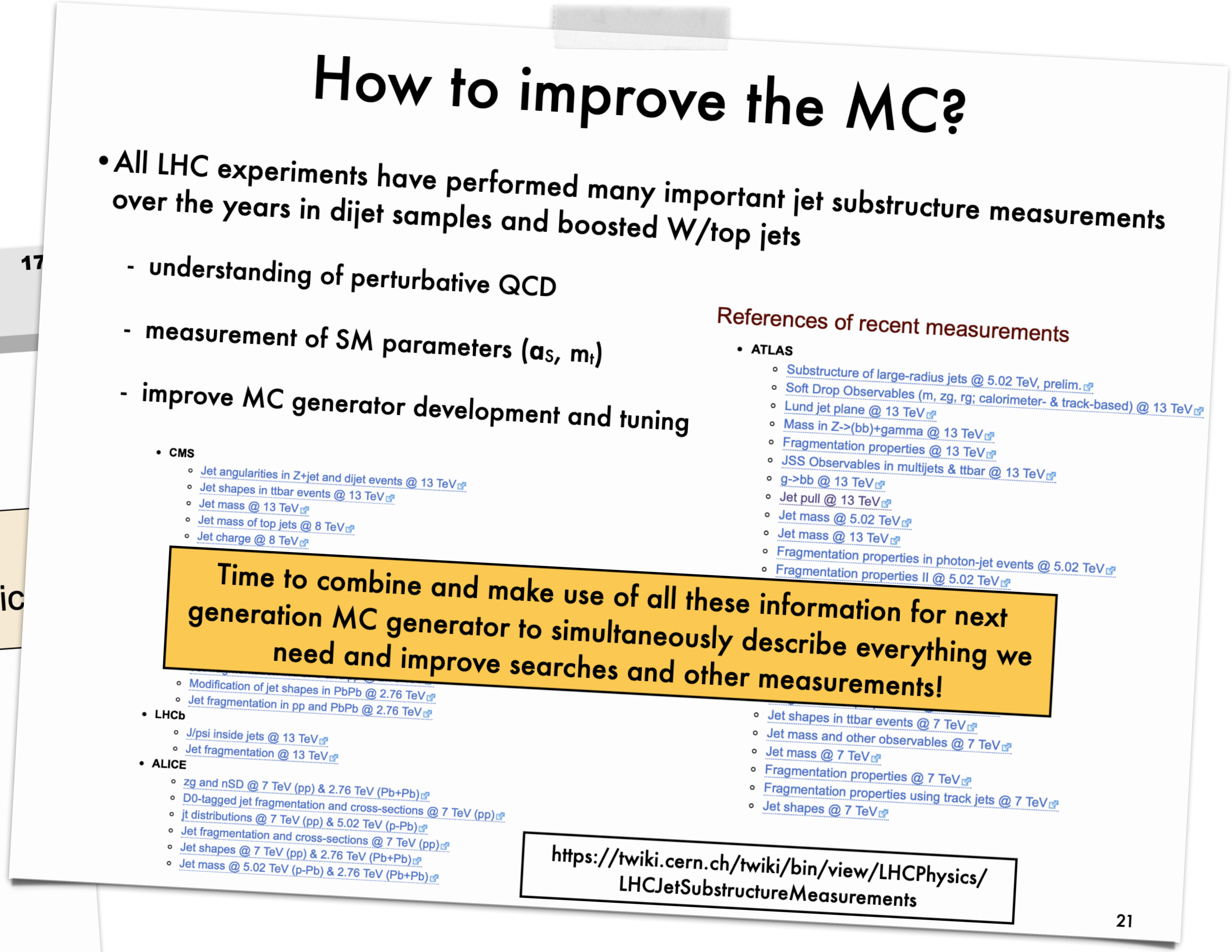
Dijets ⟷ Isotropic

Enhanced sensitivity to isotropic multijet configurations relative to other event shapes!

BOOSTING TUNES



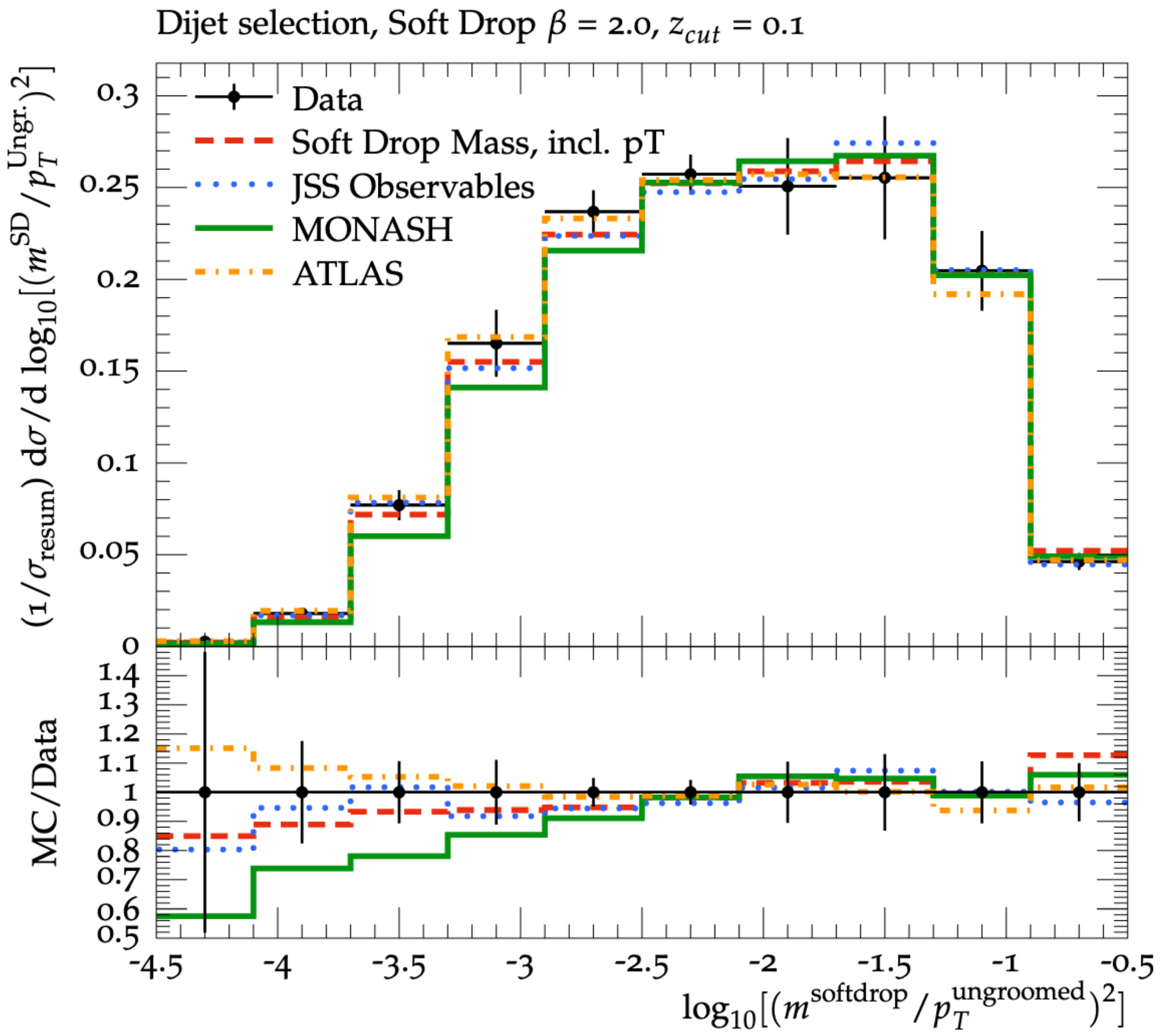
P. MAKSIMOVIC, EXP. INTRO 2019



J. NGADIUBA, EXP. INTRO 2021

Tune-y Tuesday?

- What can we learn from our existing oeuvre of measurements?
  - Unclear that all mis-modelling we observe can be solved by tuning NP parameters.
  - Can learn something about *e.g.* the universality of hadronisation
    - Compare w/ recent Sherpa tune to LEP data?
- Propose to have an initial chat for anyone interested during **Tuesday PM coffee break, before poster session**!



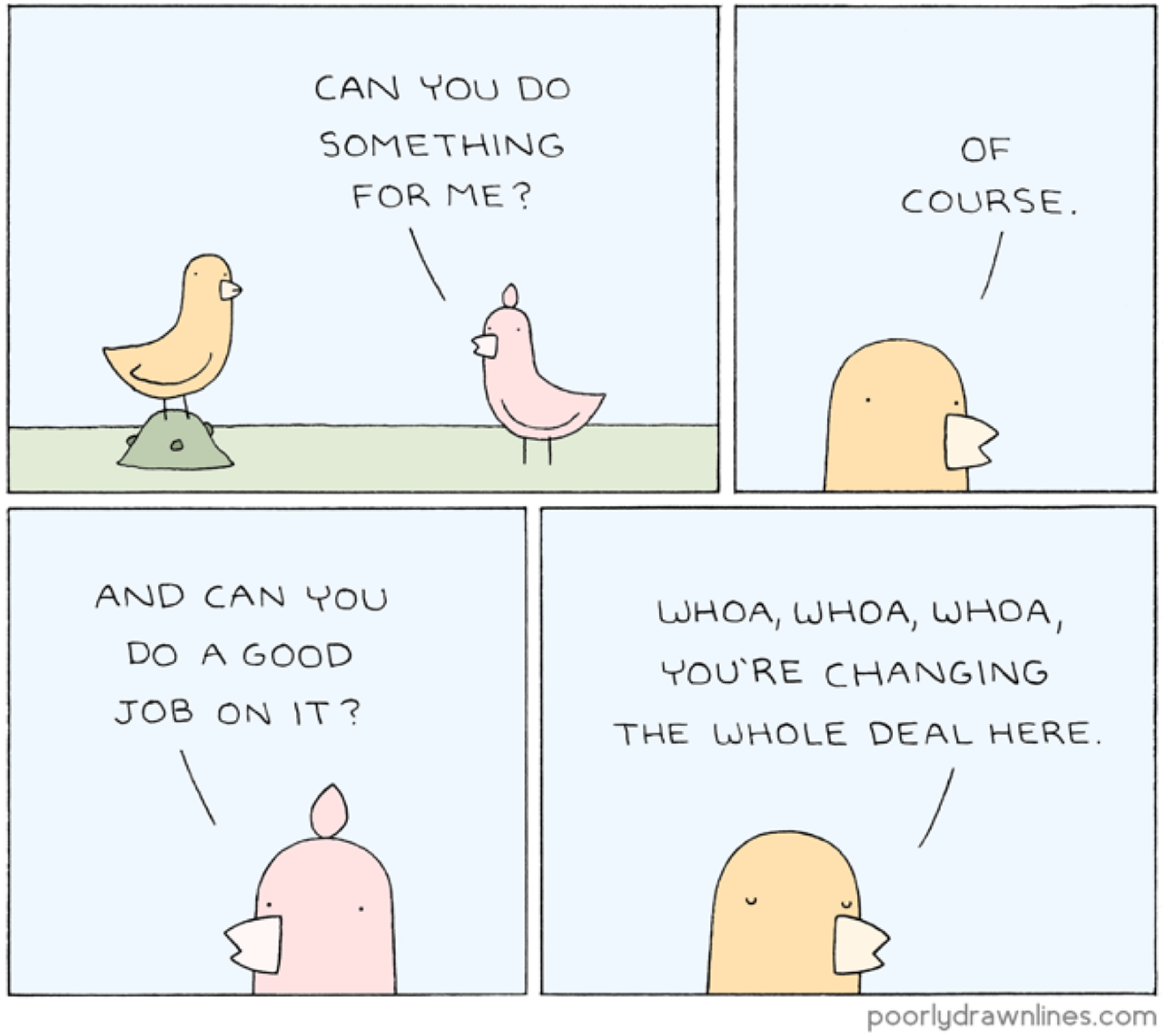
	Min. Value	Max. Value
SigmaProcess:alphaSvalue	0.12	0.15
BeamRemnants:primordialKThard	1.5	2.0
SpaceShower:pT0Ref	0.75	2.0
SpaceShower:pTmaxFudge	0.5	1.5
SpaceShower:pTdampFudge	1.0	1.5
SpaceShower:alphaSvalue	0.10	0.15
TimeShower:alphaSvalue	0.10	0.15
StringPT:sigma	0.3	0.37
MultipartonInteractions:pT0Ref	1.5	3.0
MultipartonInteractions:alphaSvalue	0.1	0.15

Table III.1: Choices of parameters to tune, and their maximum and minimum values.

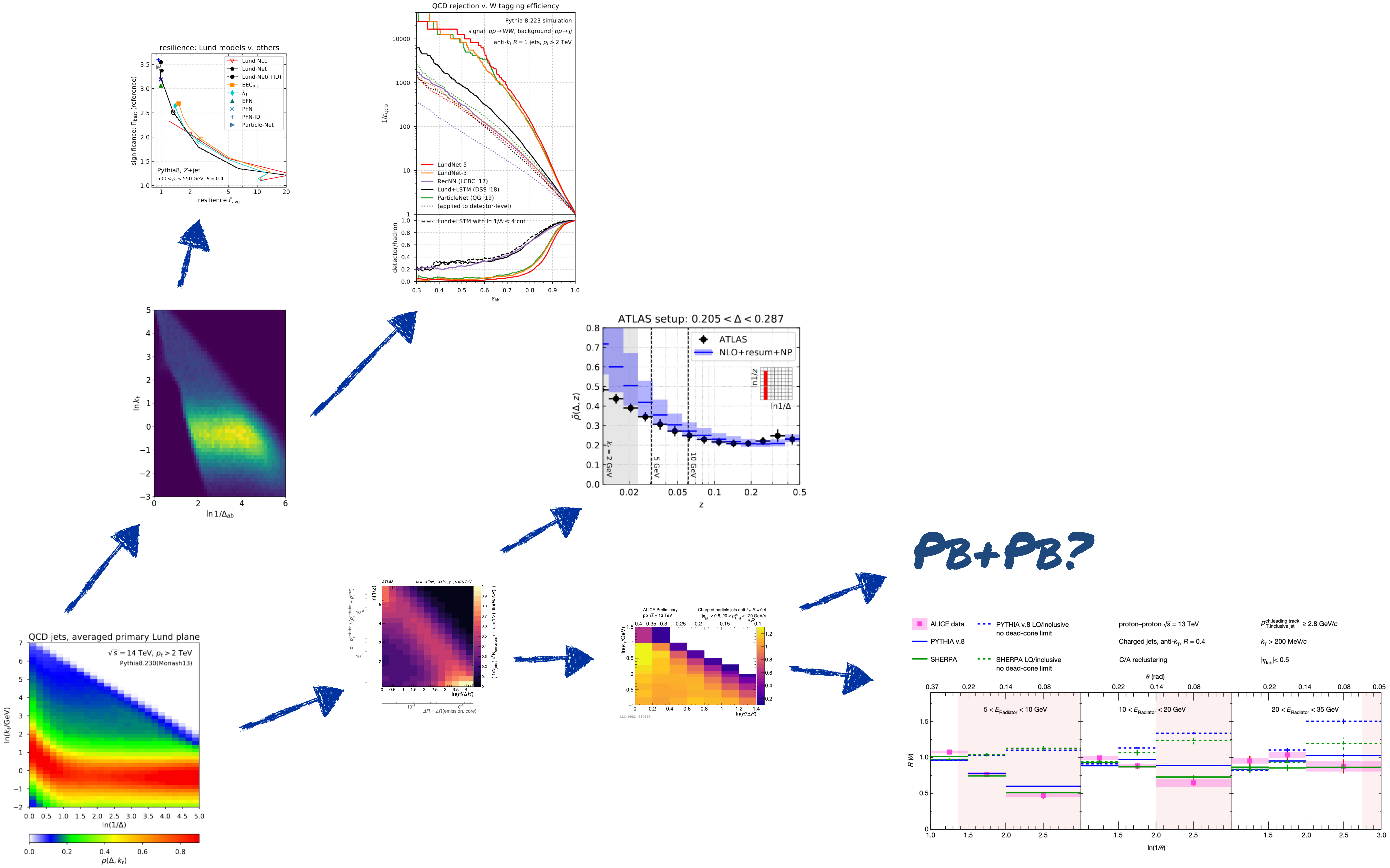
Les Houches '19, Chapter 3

How are we progressing toward our next milestones?

α_S, m_t, other stuff & the future

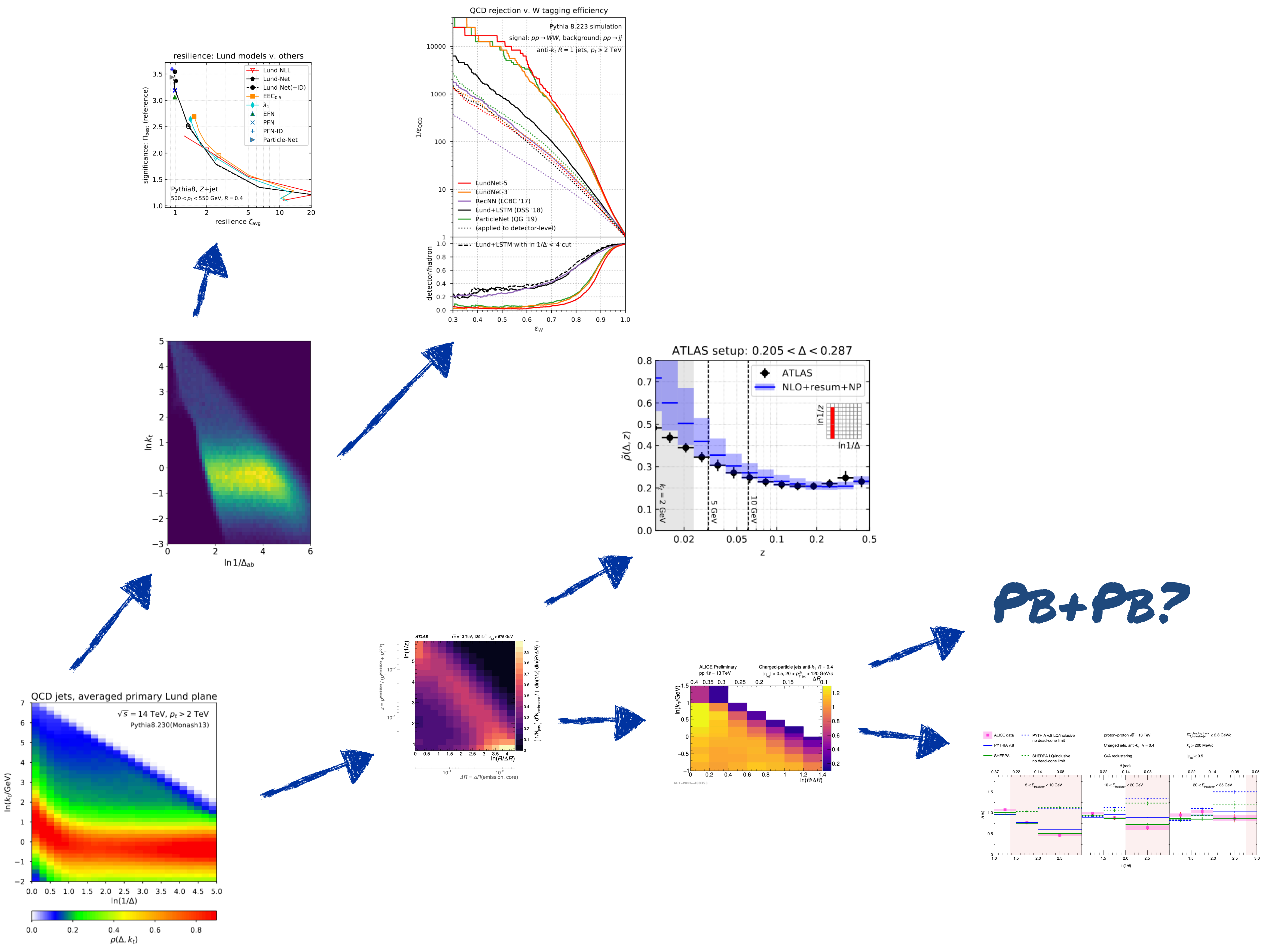


Lund Jet Plane — BOOSTing each other!

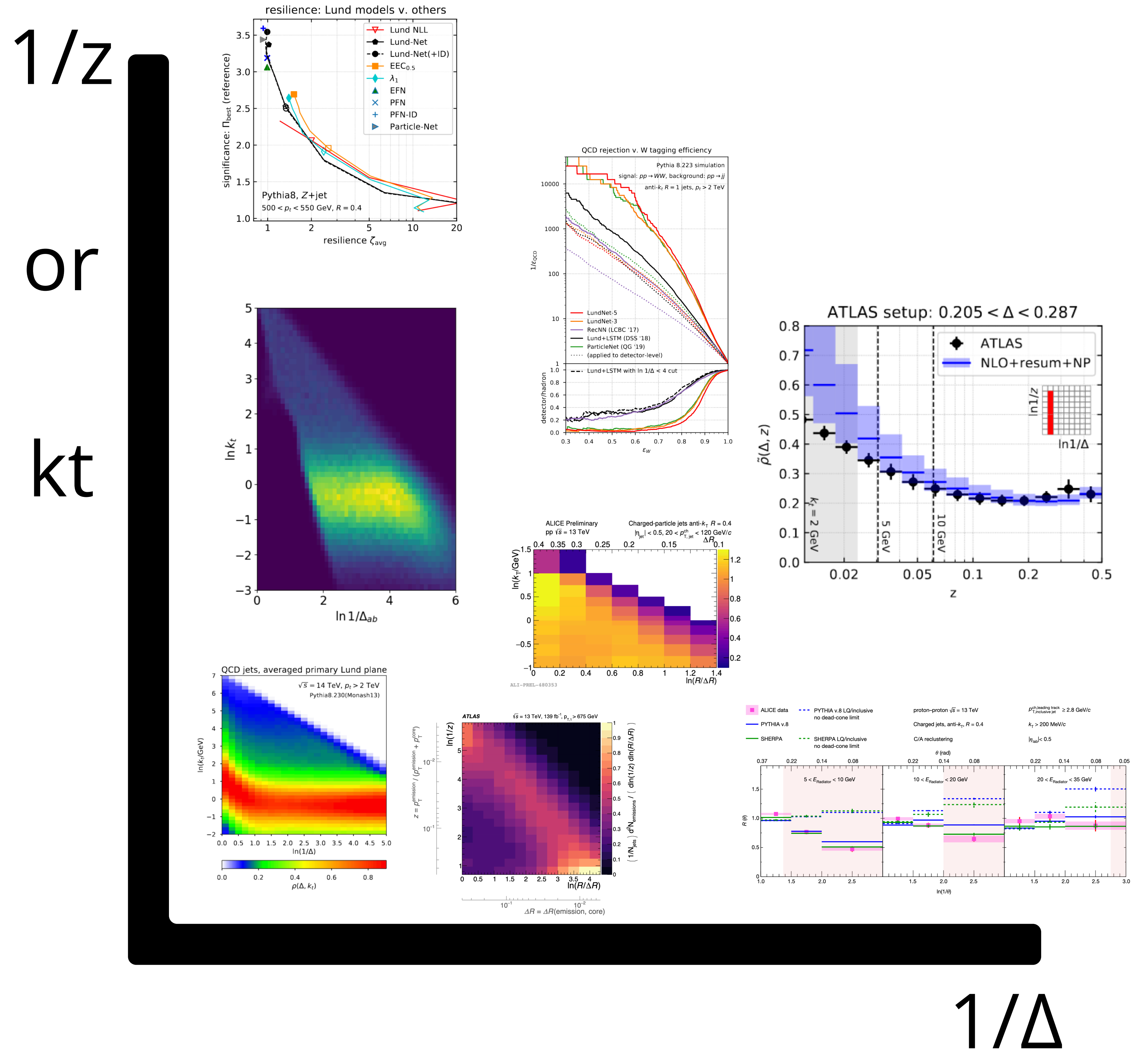


Beautiful exchanges between ***phenomenology****, multiple* ***experiments*** *and* ***AI/ML*** *results!*

Lund Jet Plane



Lund Jet Plane
Lund Jet Plane*

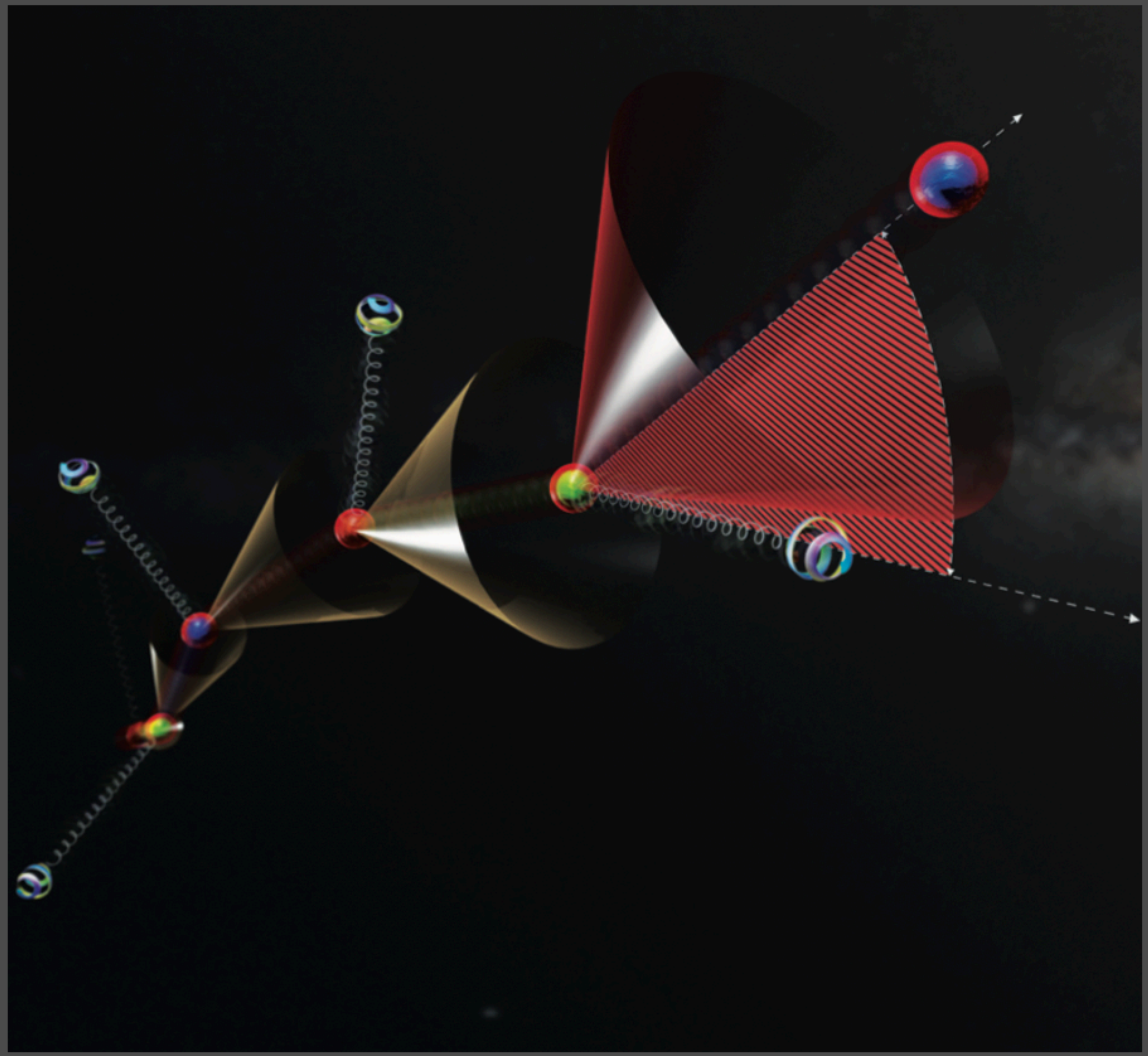


* I do not mean to imply that any results are 'non-perturbative'

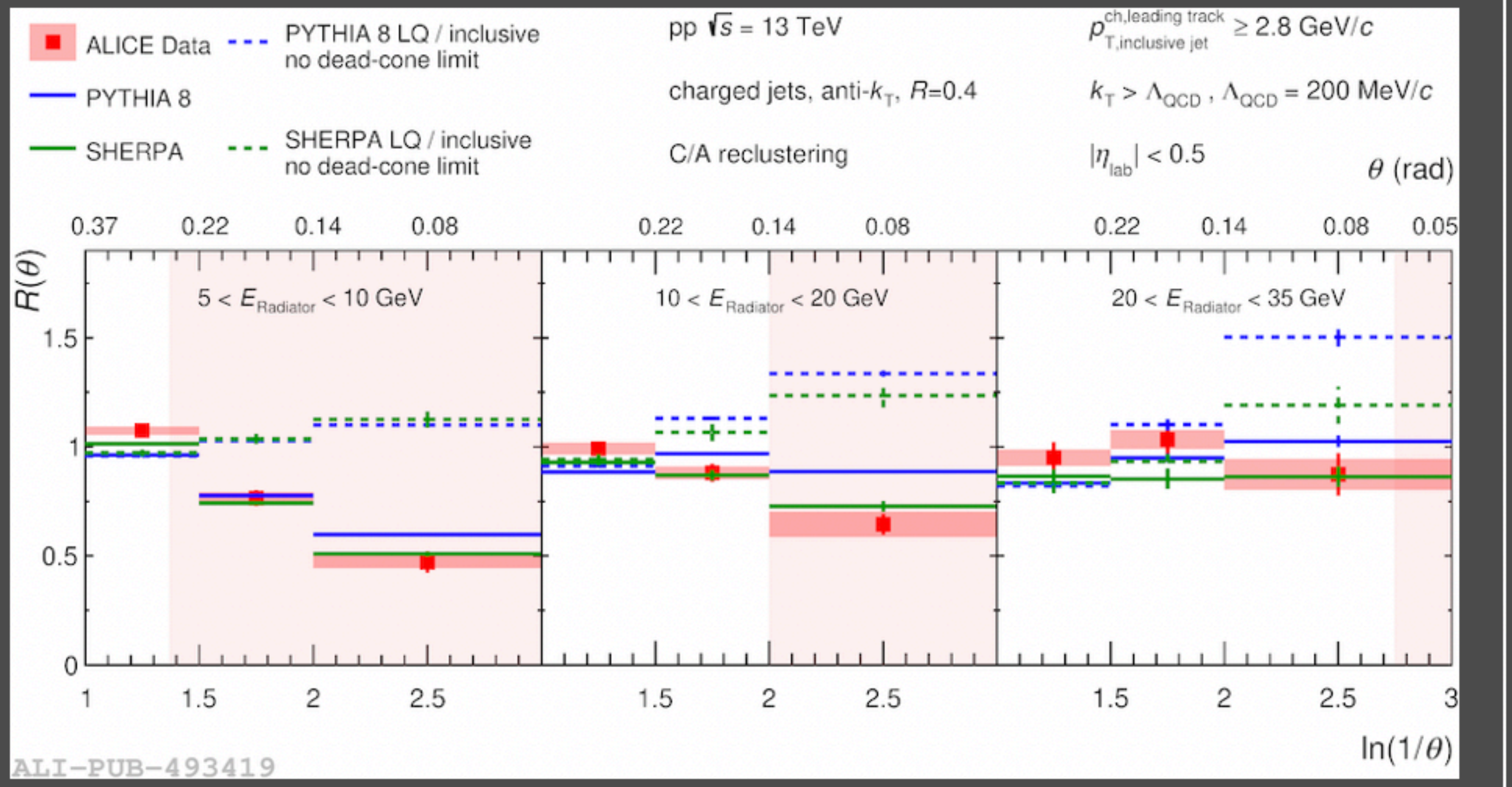
Direct Observation of Dead Cone Effect

ALICE 2106.05713

Nima will tell you all about this on Thursday morning!



Dead-cone effect in a parton shower. The cone size is inversely proportional to the quark's energy and increases as the quark's energy decreases with each subsequent emission.



The ratios of the angular distribution of gluon emissions from charm quarks to those from light quarks and gluons (where no dead cone is expected), shown in intervals of the emitting parton's energy at each emission vertex, $E_{Radiator}$. A significant suppression of gluon emissions from charm quarks is observed at small angles, with the suppression exhibiting an inversely proportional relation to the energy of the emitting charm quark.

First observation of a fundamental QFT (QCD) phenomenon

& experimental confirmation of nonzero charm quark mass!

Strong coupling from JSS (Prospects)

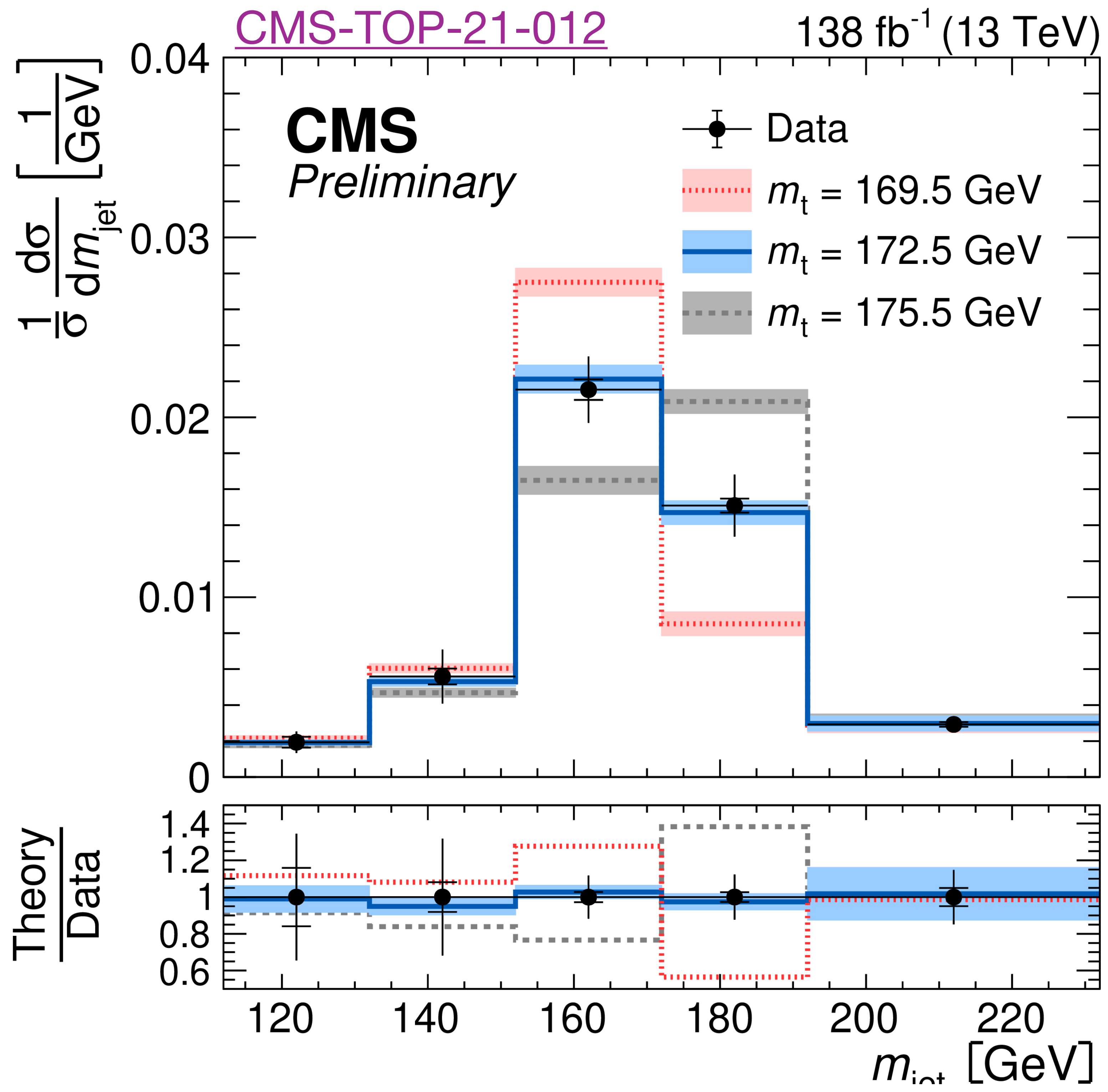
LEP Extractions	LHC Extractions	LHC Extractions from JSS
e^+e^- 🧑‍🍳👌	Underlying event, colour reconnection ✗	soft-drop grooming → mitigate soft/wide-angled contributions ✓
Thrust extraction sensitive in resummation-dominated region	Jet rates, cross-section ratios usually compared to fixed-order calculations ✗	Soft-drop mass prediction → precise resummation ✓

MLB : Tuesday Morning

Hofie : Thursday Morning!

Prediction: we will see the first α_S extractions from JSS during Run 3!

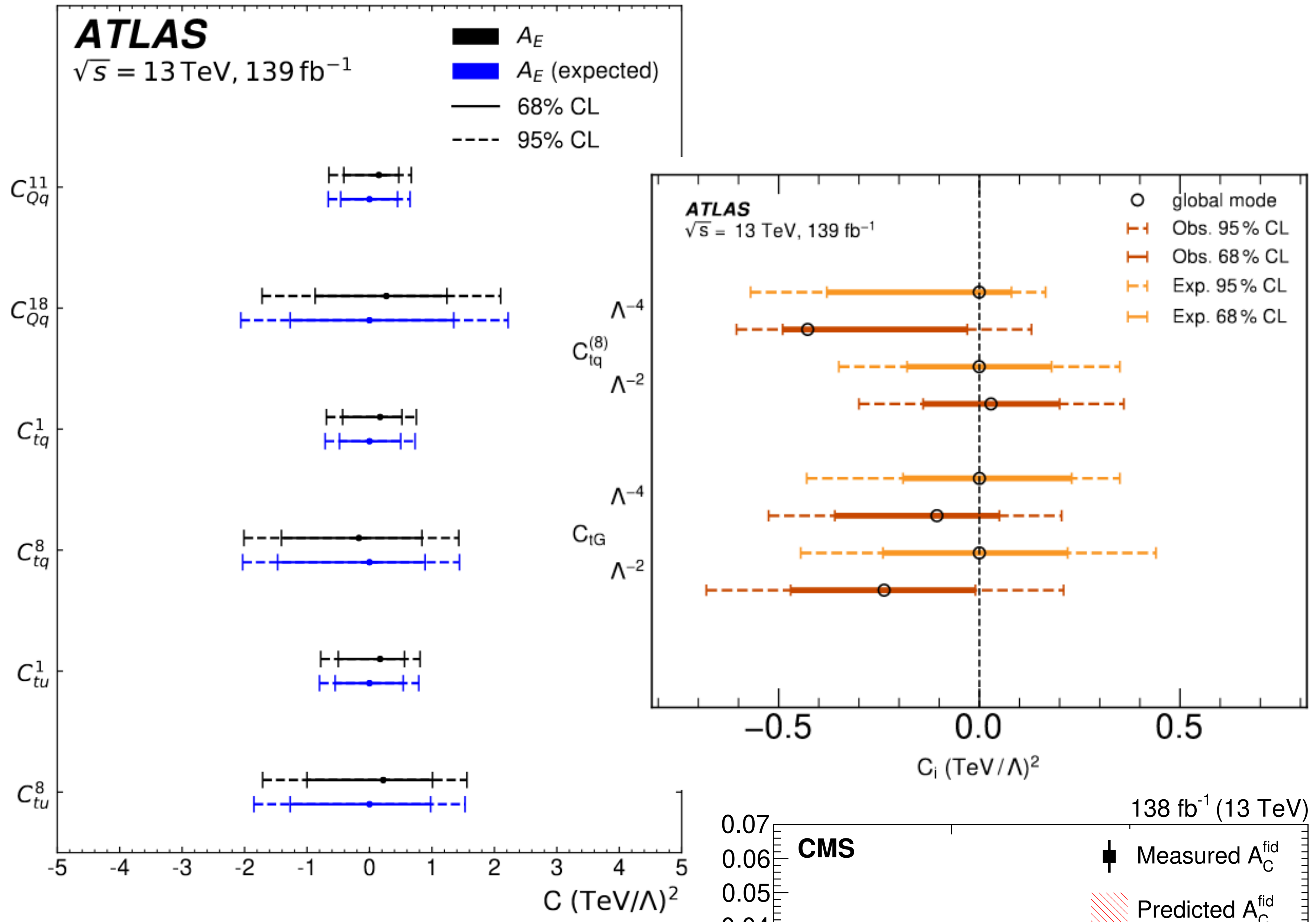
Top sector measurements w/ JSS

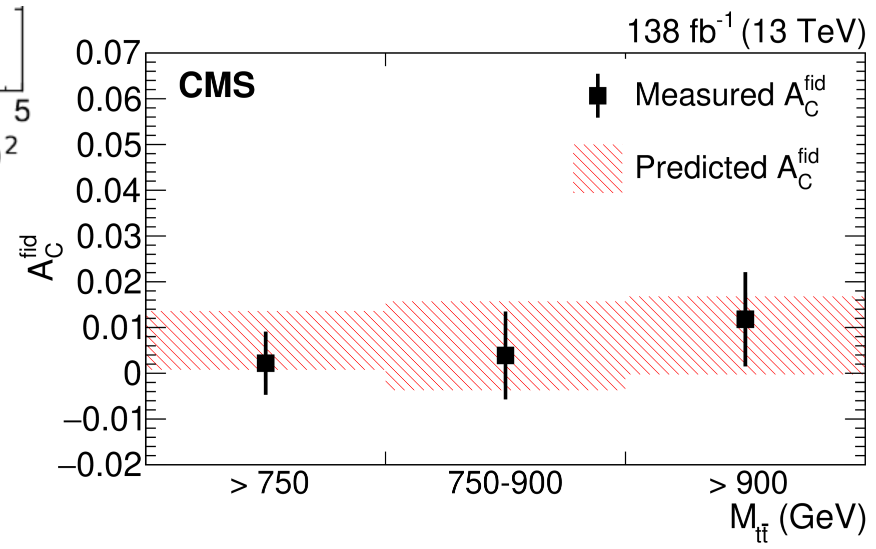


$$m_t = 172.76 \pm 0.22\,(\text{stat}) \pm 0.57\,(\text{exp}) \pm 0.48\,(\text{model}) \pm 0.24\,(\text{theo})\,\text{GeV}$$
$$= 172.76 \pm 0.81\,\text{GeV}.$$

Boosted M_{top}

Many other new results!





ATLAS-TOPQ-2019-28

ATLAS-TOPQ-2019-23

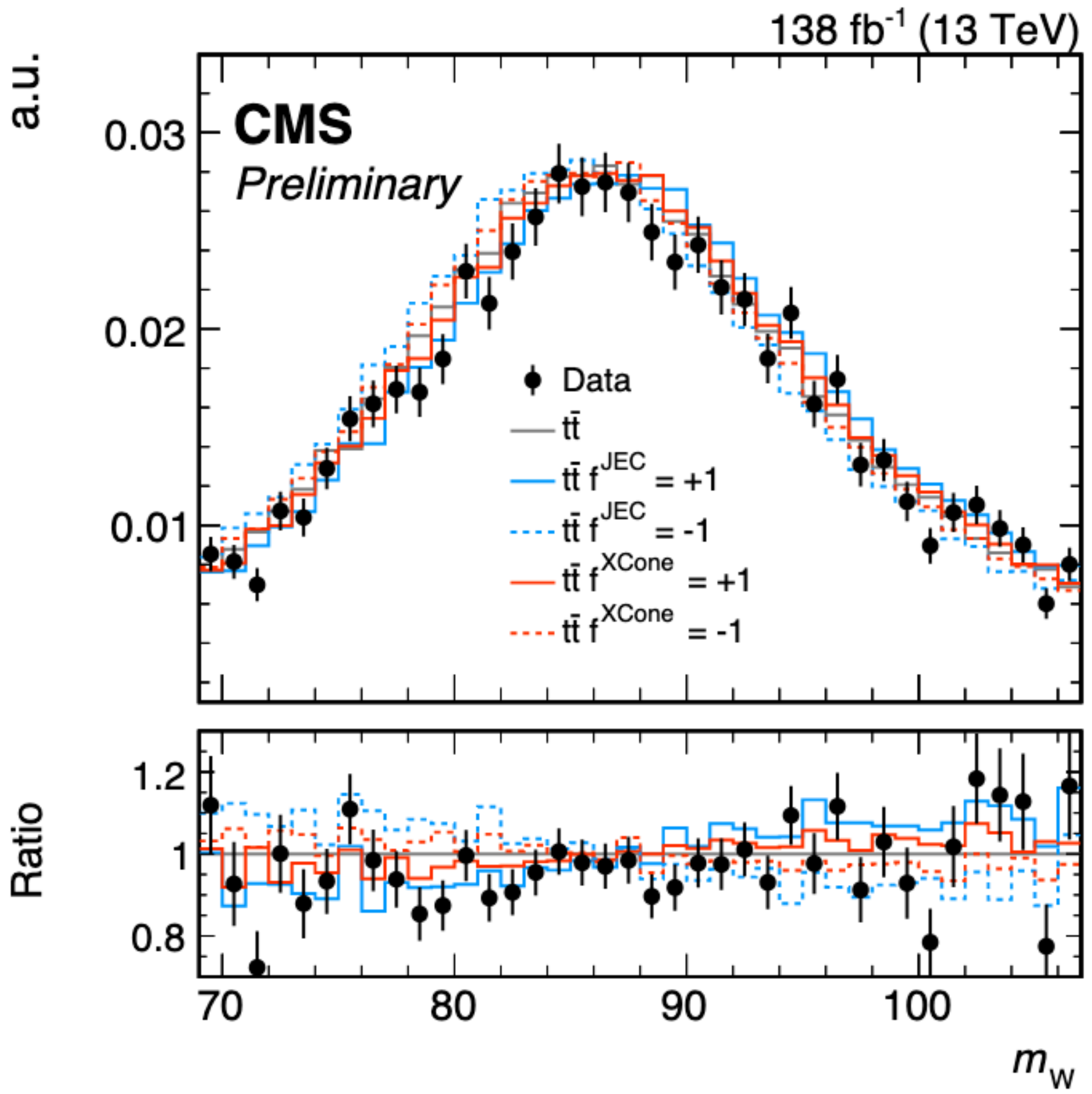
CMS-TOP-21-014

Alexander : Thursday Afternoon

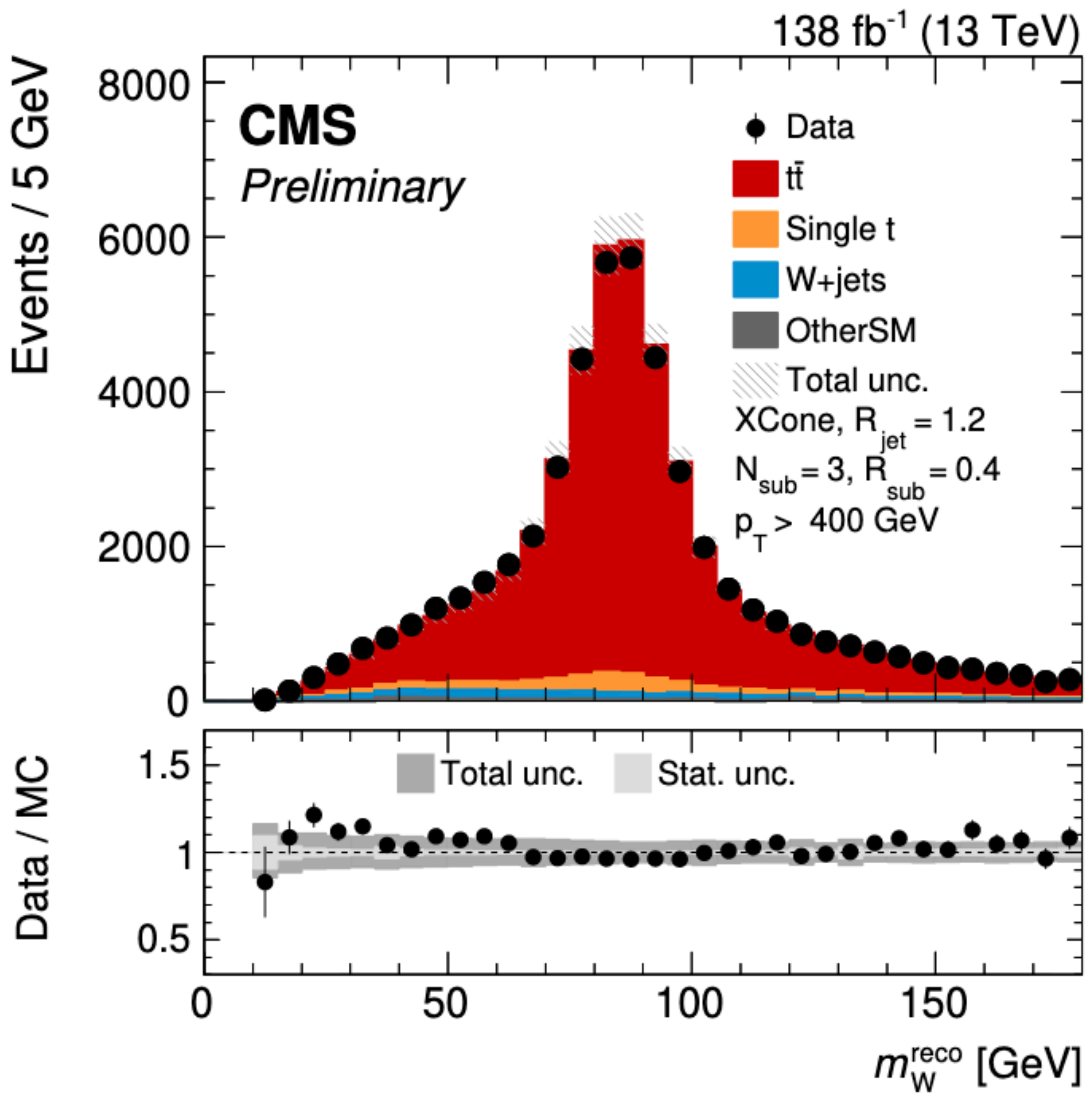
Kevin (after lunch) + Titas (Thurs. PM)

CMS Boosted Top Mass — Cool Details

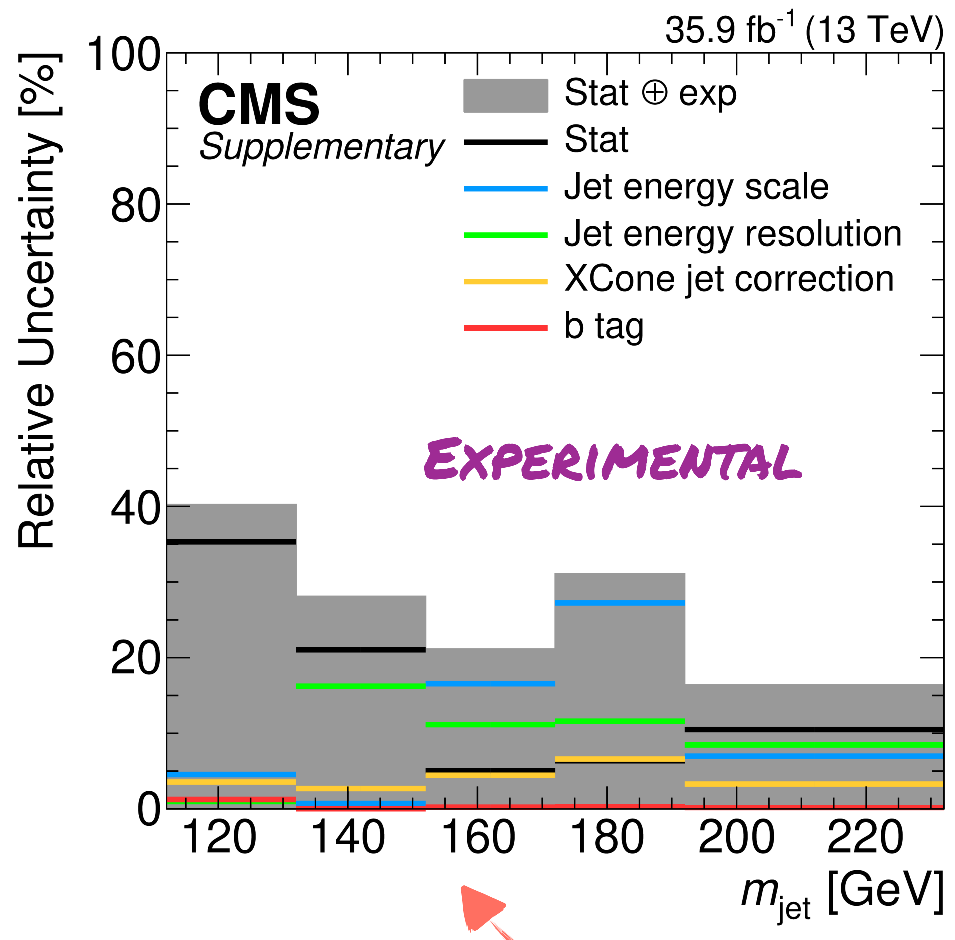
CMS-PAS-TOP-21-012

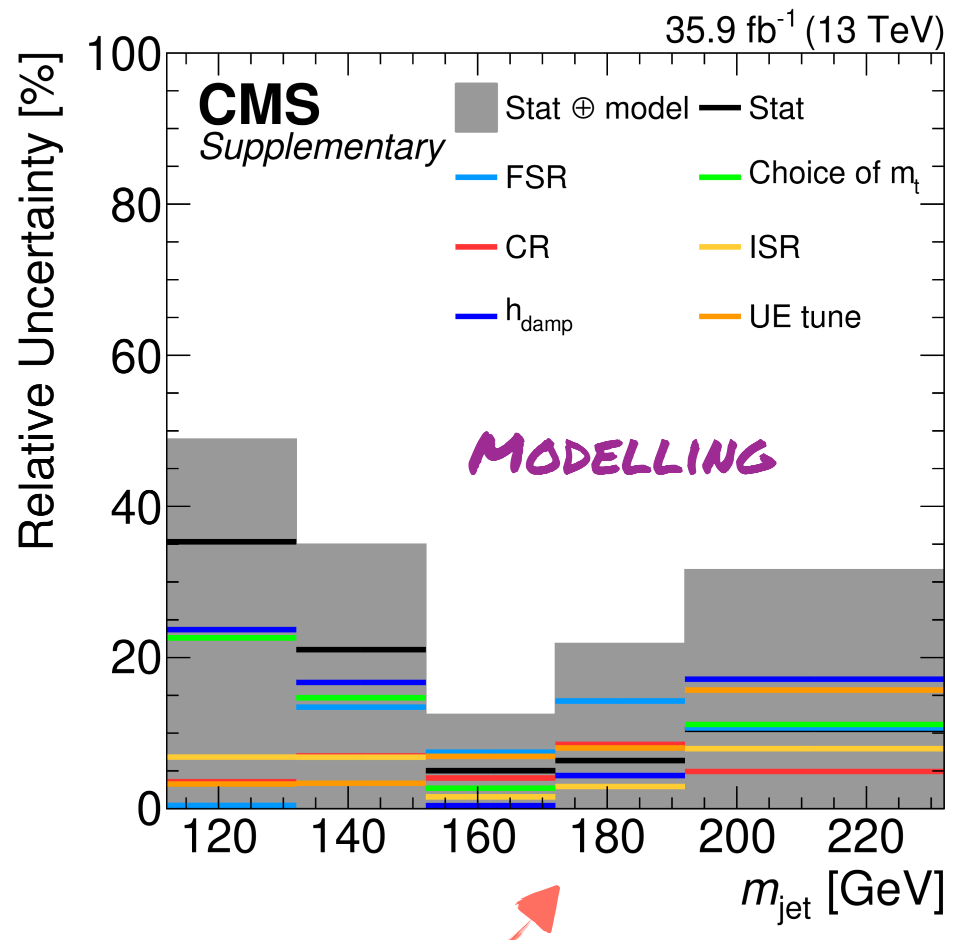


In situ JES/JMS calibration from boosted W's inside of tops



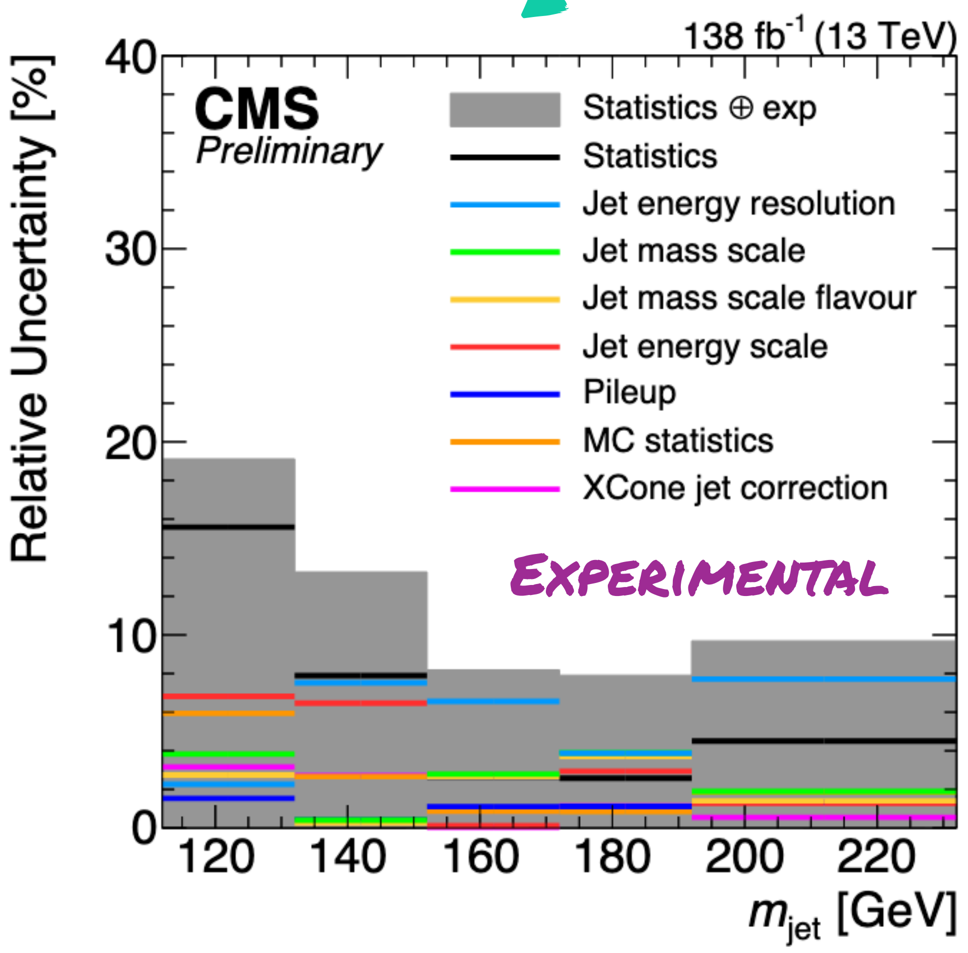
+ *re-tuned FSR $\alpha_S(M_Z)$ in fiducial region w/ τ_{32} (in backup)*

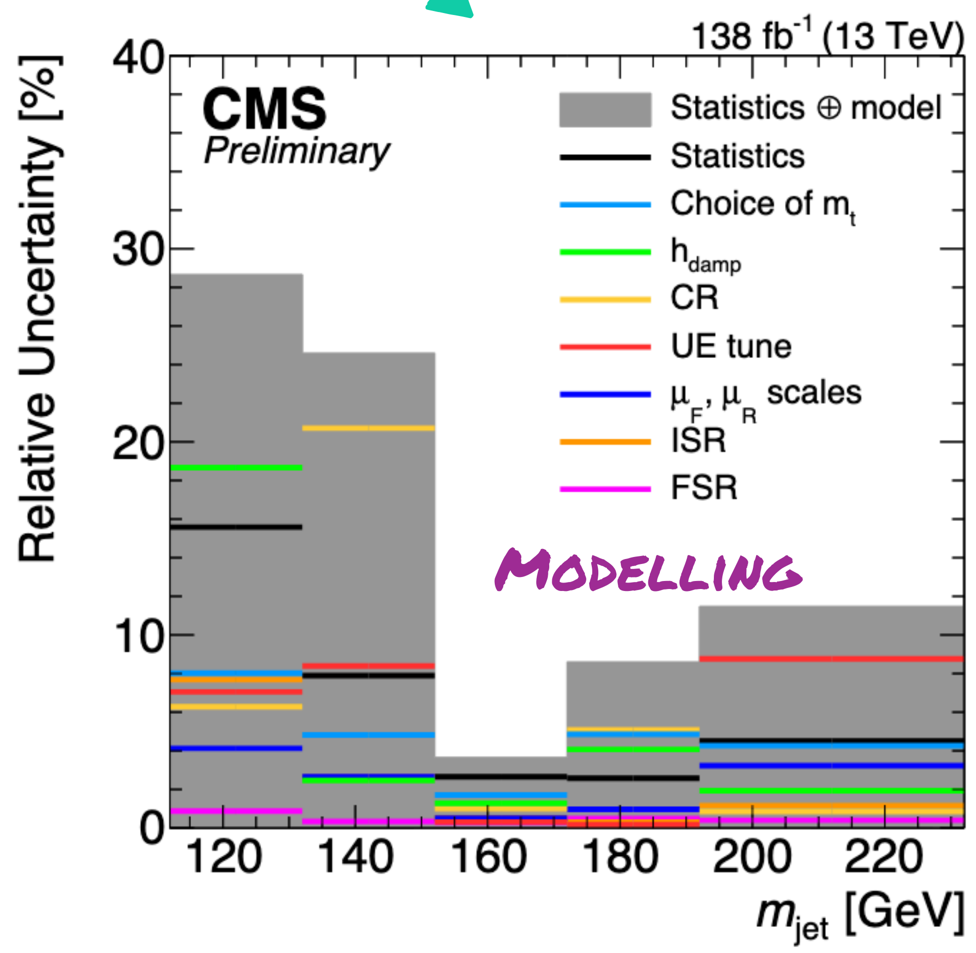




BOOST '19

NEW!

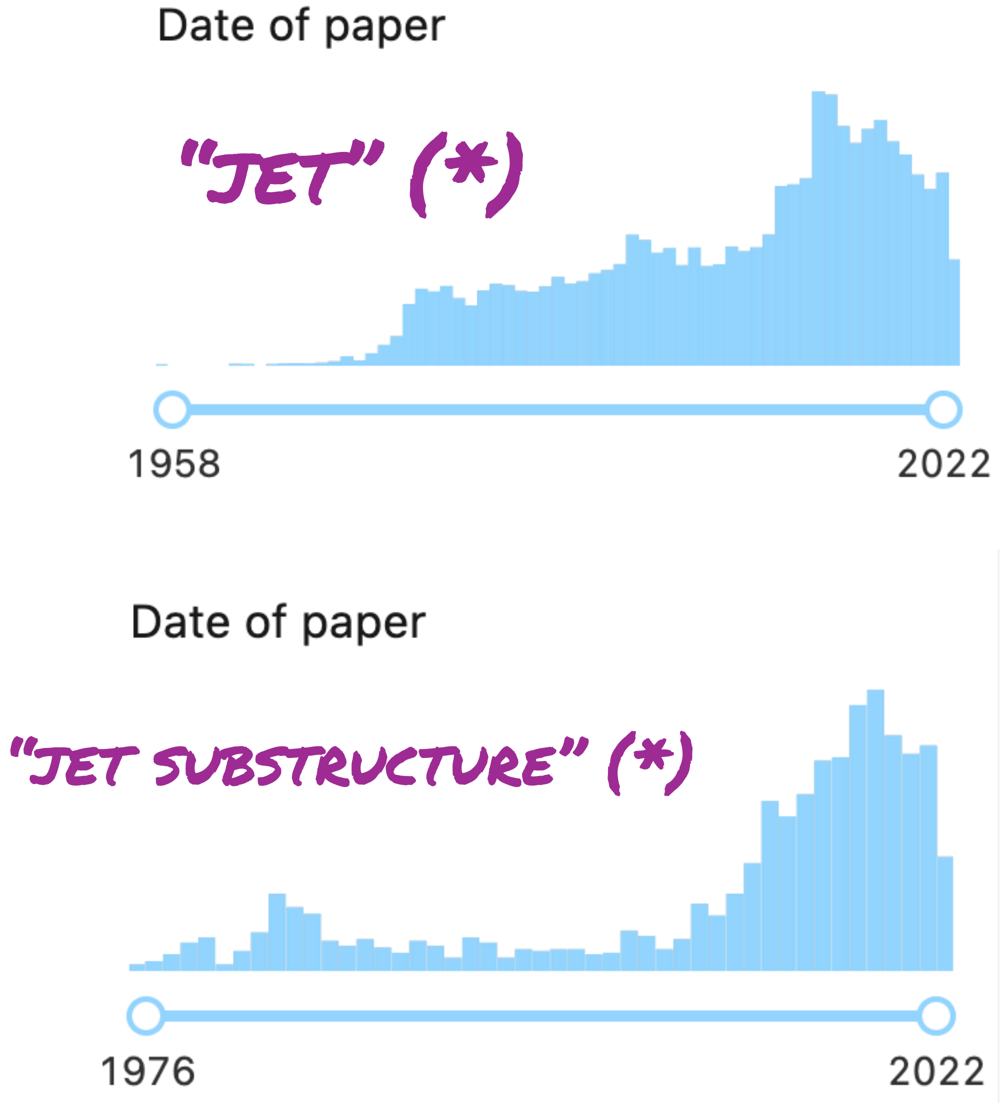


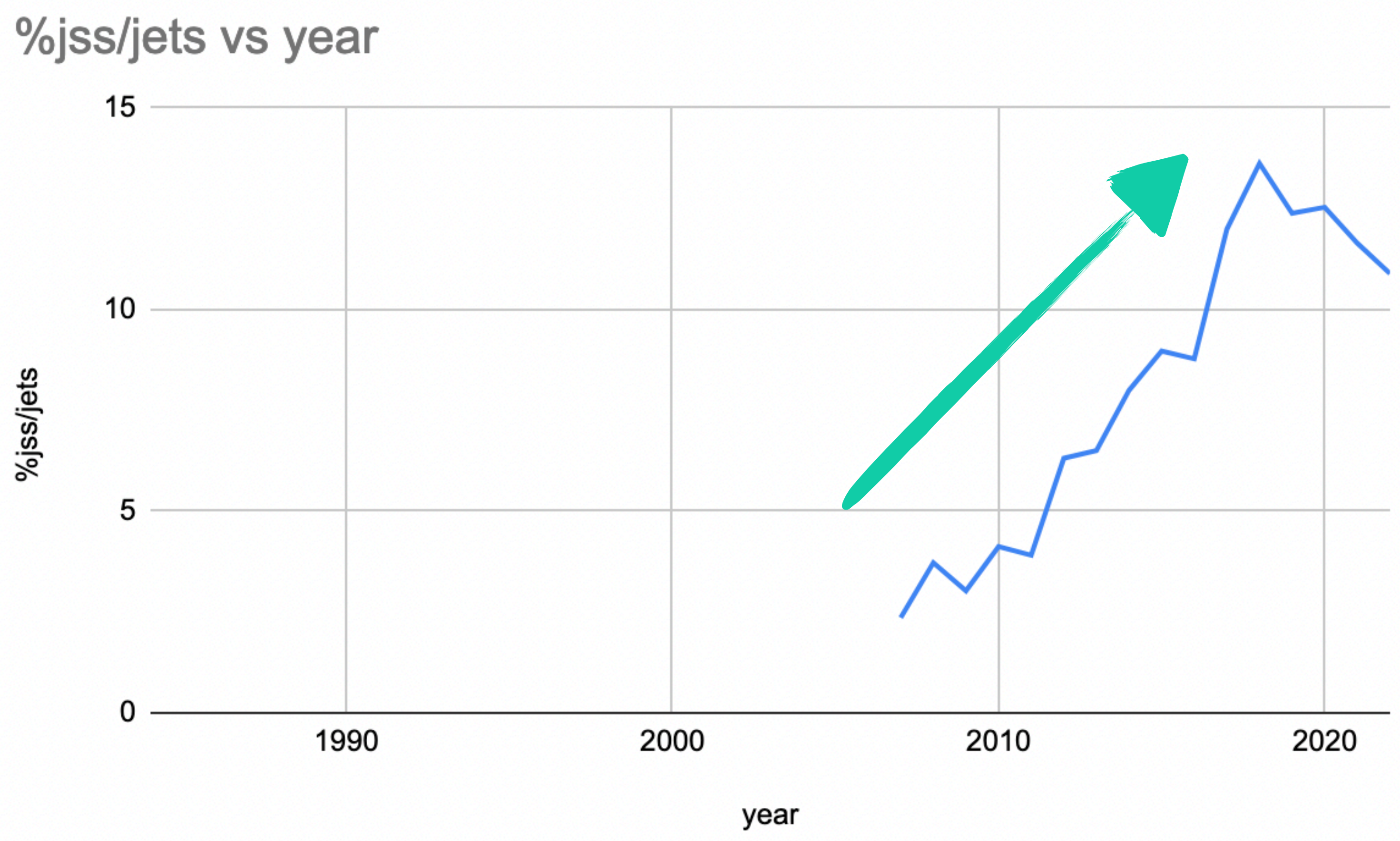


Alexander will tells us more (with increased precision), Thursday Afternoon!

BOOST is Expanding

BOOST 2022 is the fourteenth conference of a series of ***successful joint theory/experiment workshops*** *[...] to* ***generate new ideas & develop new approaches*** *on the* ***reconstruction and use of boosted decay topologies in particle physics*** *and beyond.*





"(Jet) Substructure" mentioned?

- ATLAS TDR (1999) ✗
- CMS TDR (2006) ✗
- ALICE Physics TDR (2005) ✗
- EIC CDR (2021) ✓
- ILC TDR (2013) ✓
- ILC Snowmass (2021) (19+ times!) ✓

Jet substructure has been established as a versatile + mainstream tool for many areas of collider physics!

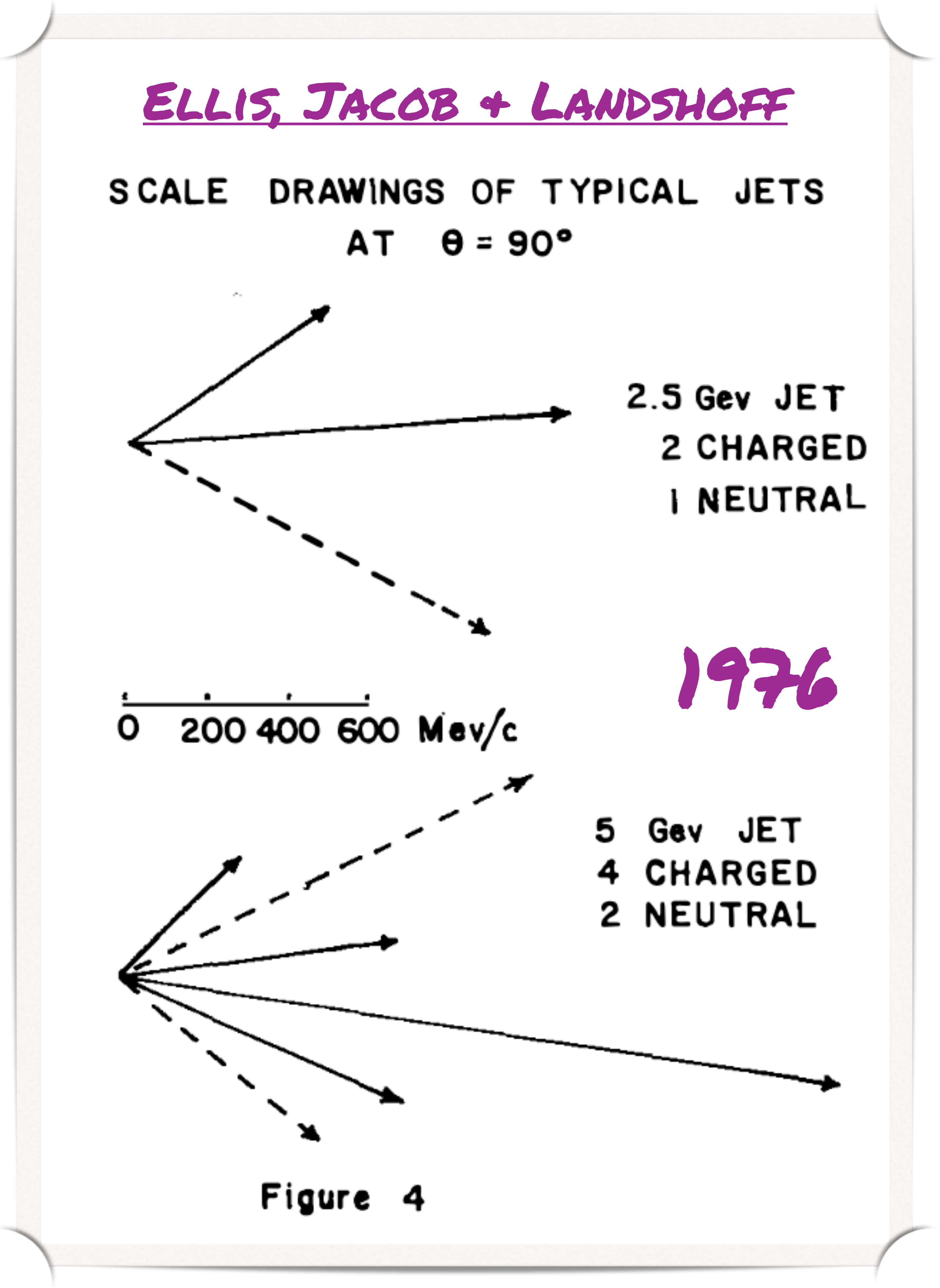
* "jet" not "blazar" not "black hole" not "Kerr" not "Supernovae" not "blazars" not "black holes" not "Radio" not "Galaxy" not "optical" not "accretion" not "GRB" not "gravitational"

** "jet substructure" or "soft drop" or "soft-drop" or "Lund jet plane" or "jet topics" or "Particle Flow Network" or "boosted top" or "boosted boson" or "jet fragmentation"

Boostin' is Legit

- JSS has been established as a **versatile** and **mainstream** tool for many areas of collider physics.
  - Proving ground for many **ML/AI studies** and other interdisciplinary techniques (**optimal transport, statistical demixing, etc.**)
  - Can coherently probe **huge range of energy scales** with a single analysis.
  - Helping to **push boundaries & beat projections** of what we can do with LHC data!

- JSS being considered explicitly in the design of **future detectors / facilities**.
  - Clemens will tell you about that on Friday afternoon!

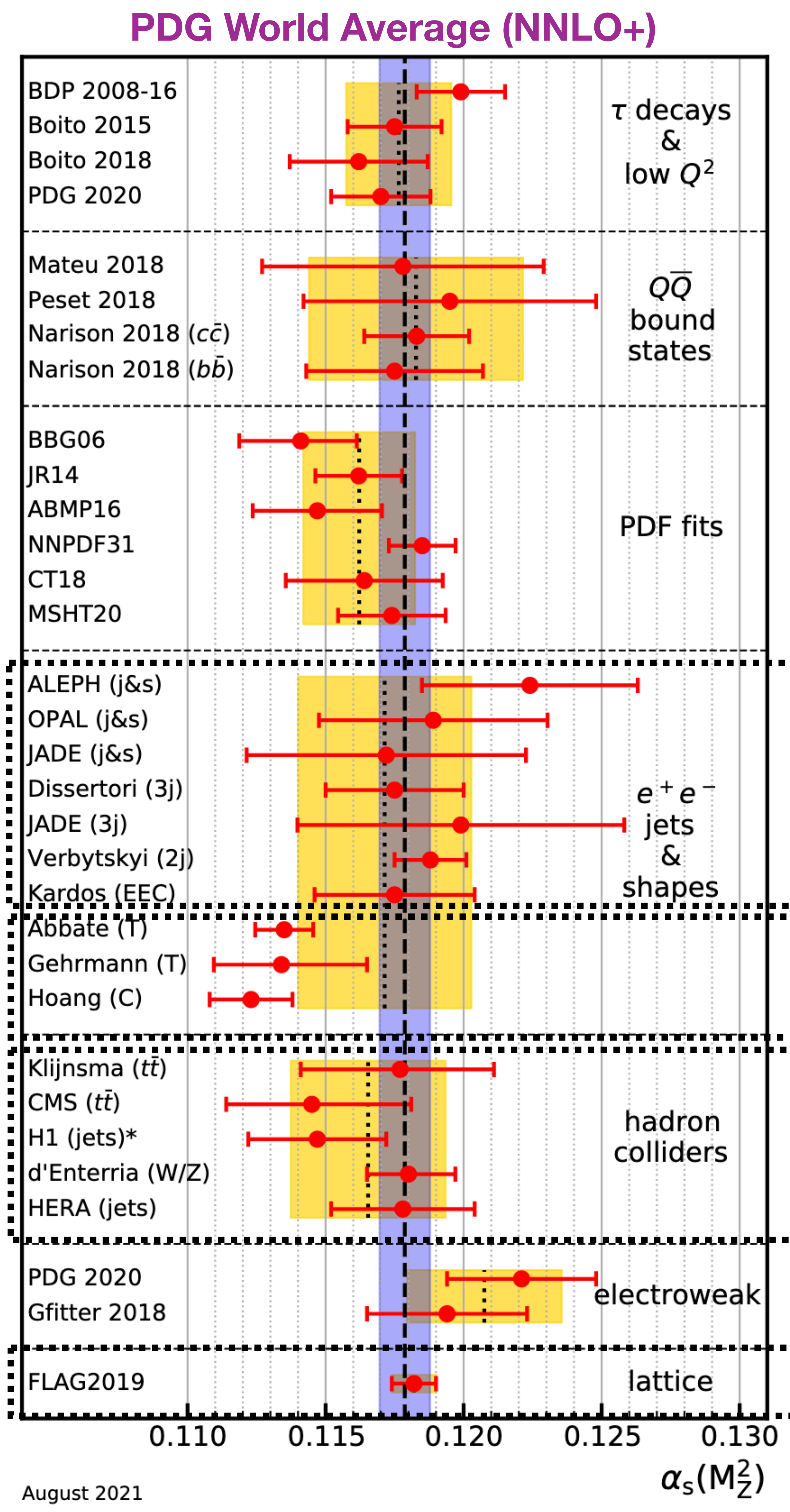


"BOOSTAMOS"

It means:

Let's **BOOST!**

Strong coupling



Fixed-order predictions, extractions from jet rates, etc.

Most precise collider extractions (LEP) in tension with other results…

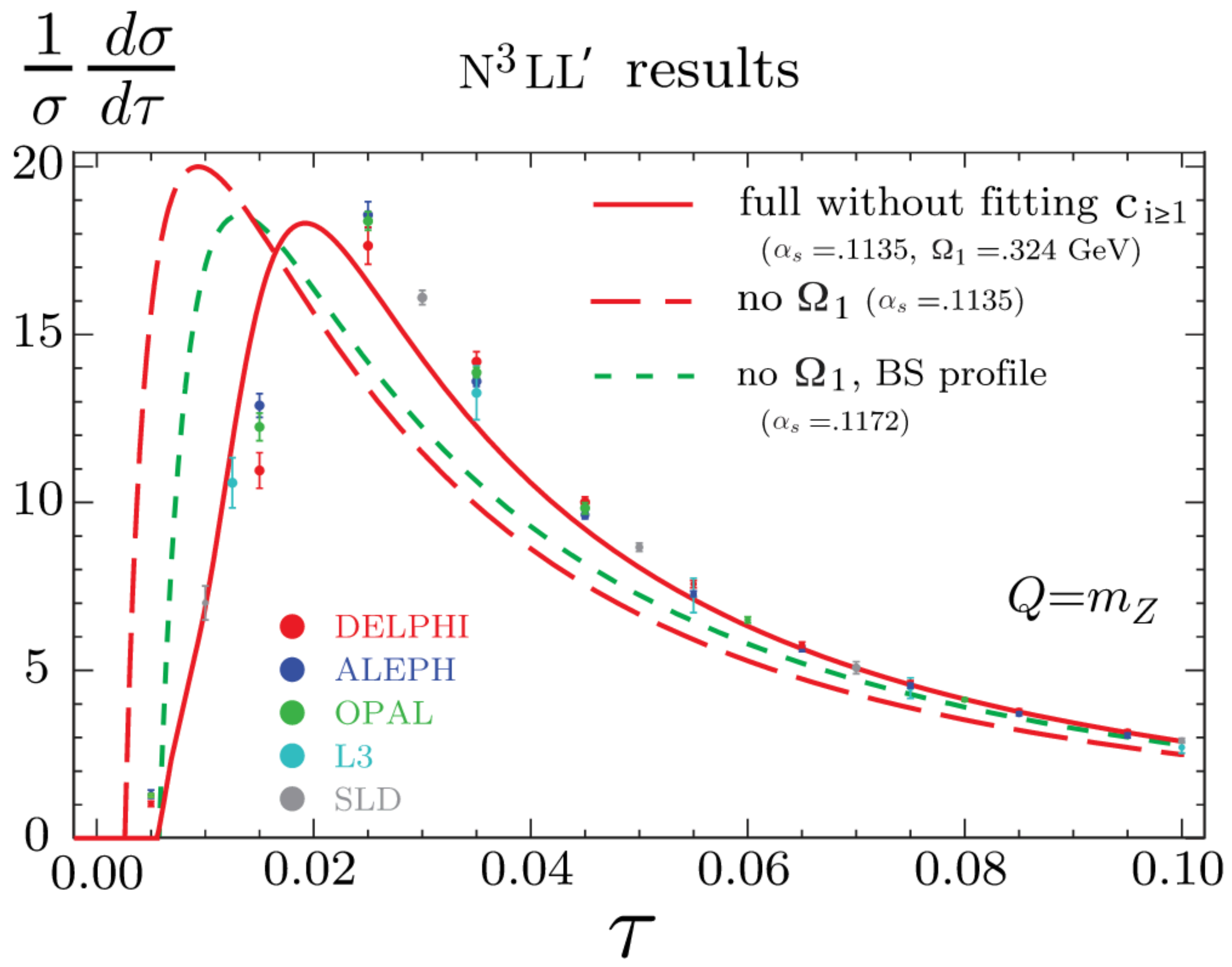
No LHC input from jets at NNLO+!

Lattice average most precise input.

The QCD coupling, α_S, is known with far less precision than those of other gauge field theories:

$\delta\alpha \sim 10^{-10} \ll \delta G_F \sim 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_S \sim 10^{-3}$

This **uncertainty is driven by tensions within the α_S world average**, and it is **becoming increasingly relevant** in predictions related to Higgs & top production, EWPOs, etc.



$\alpha_S(M_Z) = 0.1135 \pm 0.0010$ (e^+e^- thrust)

vs.

$\alpha_S(M_Z) = 0.1182 \pm 0.0008$ (lattice)

Tension > 3σ

Abbate et al. Phys.Rev.D 83 (2011) 074021

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

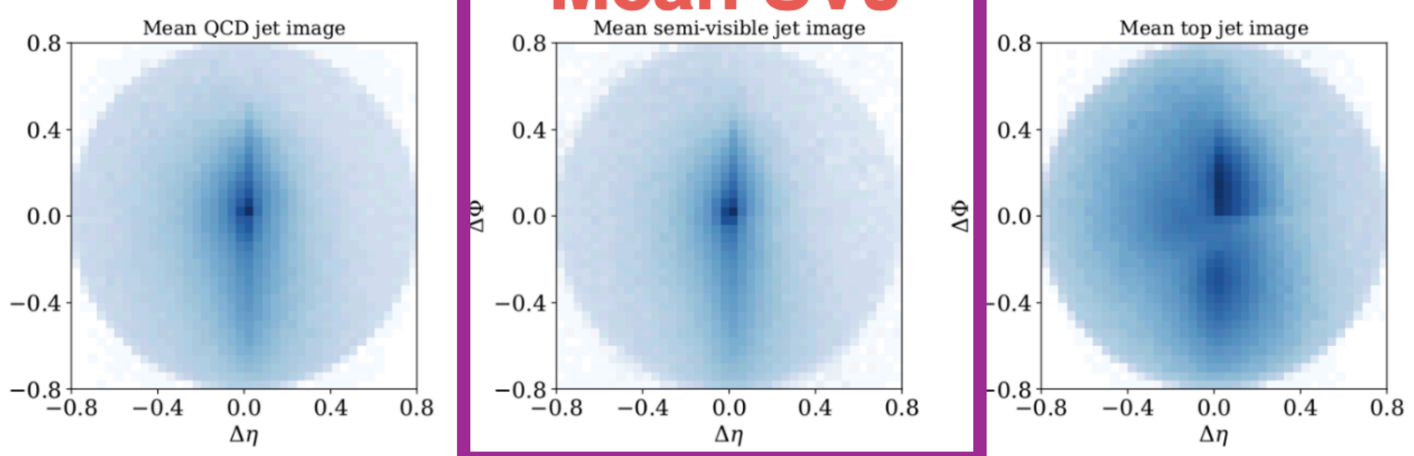
Semi-visible jets

July workshop @ ETH: https://indico.cern.ch/event/1133166/

Introduction

- Common feature for dark sector models with hadronization: **Final states of mostly soft particles, jets**
  - Semivisible jets are quite QCD-like:

Mean QCD image | Mean SVJ | Mean top jet image [source]



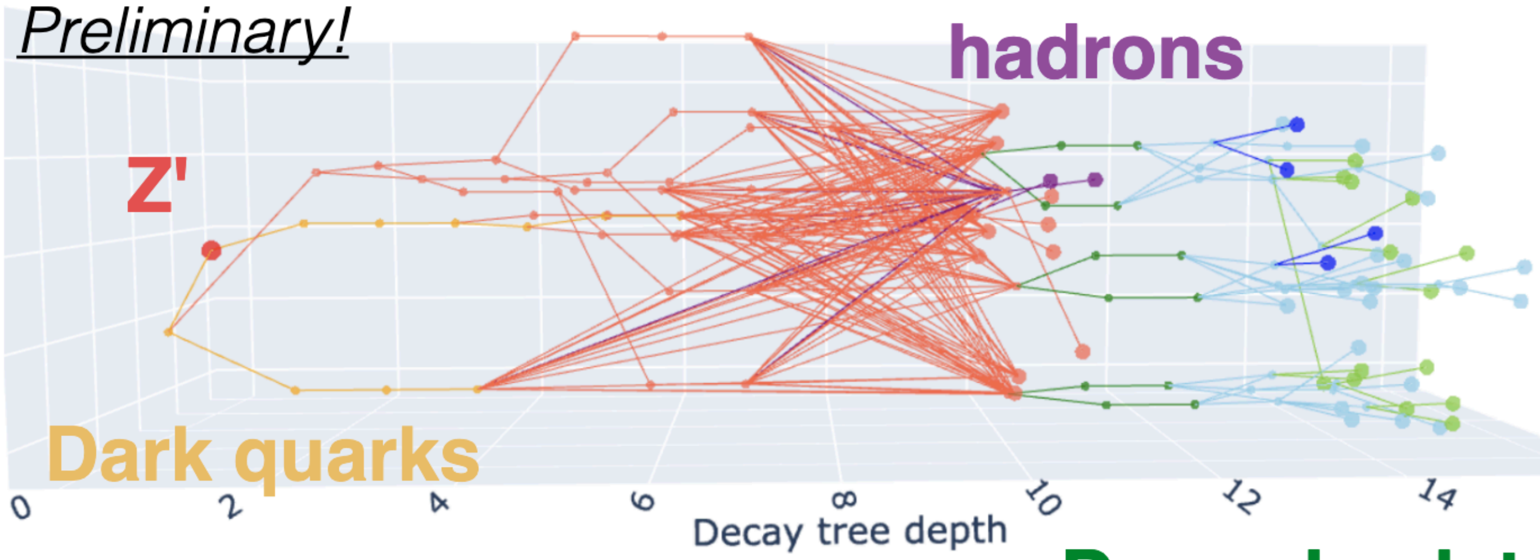
  - Using **jet substructure is virtually required** to achieve sensitivity
- Many existing substructure variables are based on identifying hard processes in the history of a jet - **prongs**
  - Not necessarily the signature of semivisible jets
- This talk: A collection of ideas, insights, and concerns identified during meetings of the Substructure Working Group

6 July 2022 - Thomas Klijnsma - Semivisible Jet Workshop (Zurich, Switzerland) Fermilab 2

Central challenge of substructure in SVJs

- We have long decay chains

Preliminary!



+ Detector folding

Play with plot in browser

- Features of the hadronization must survive through multiple stages in order to eventually appear in substructure variables
- Is a prong-centric view going to suit the SVJ topology?

6 July 2022 - Thomas Klijnsma - Semivisible Jet Workshop (Zurich, Switzerland) Fermilab 4

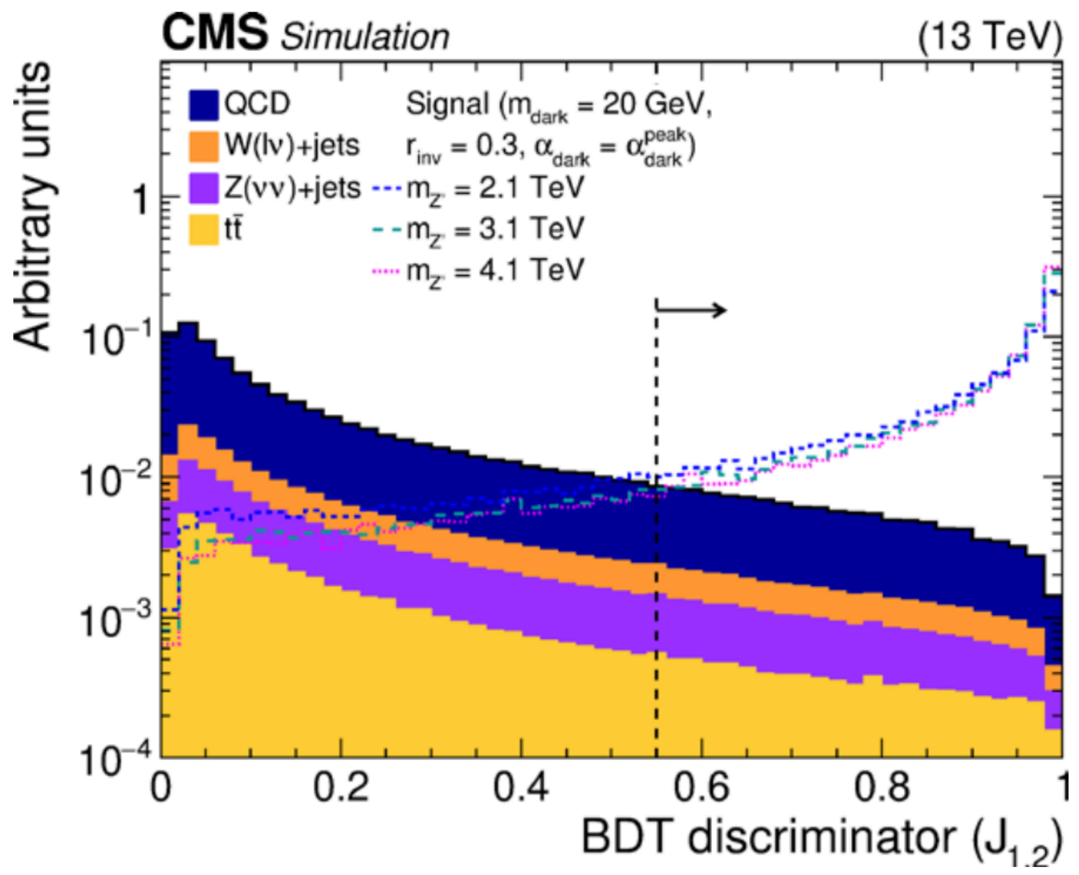
Picture strongly depends on details of model: Huge variance from one choice of parameters to another → *Organising the space of models is a big open question here, preventing systematic study.*

JSS of these models exhibits diverse pheno —I think there's a lot of room for members of the BOOST community to get involved!

Two SVJ pheno talks this week — Sukanya (Wed. Morning) + Jeremi (Wed. Afternoon) will tell us about their JSS!

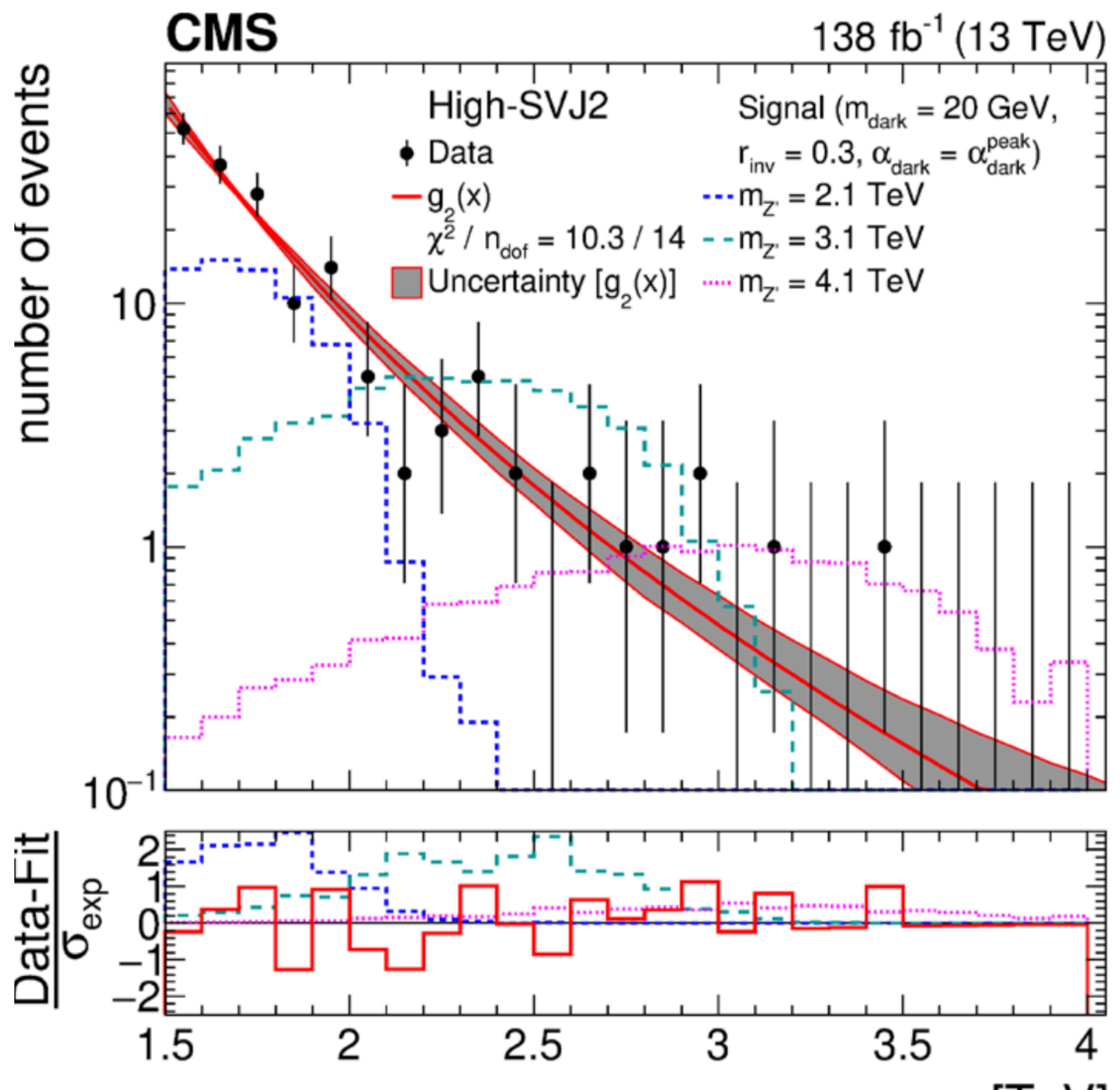
Semi-visible jets from CMS + ATLAS

CMS CMS-EXO-19-020, ATLAS CONF-2022-038 (New!)

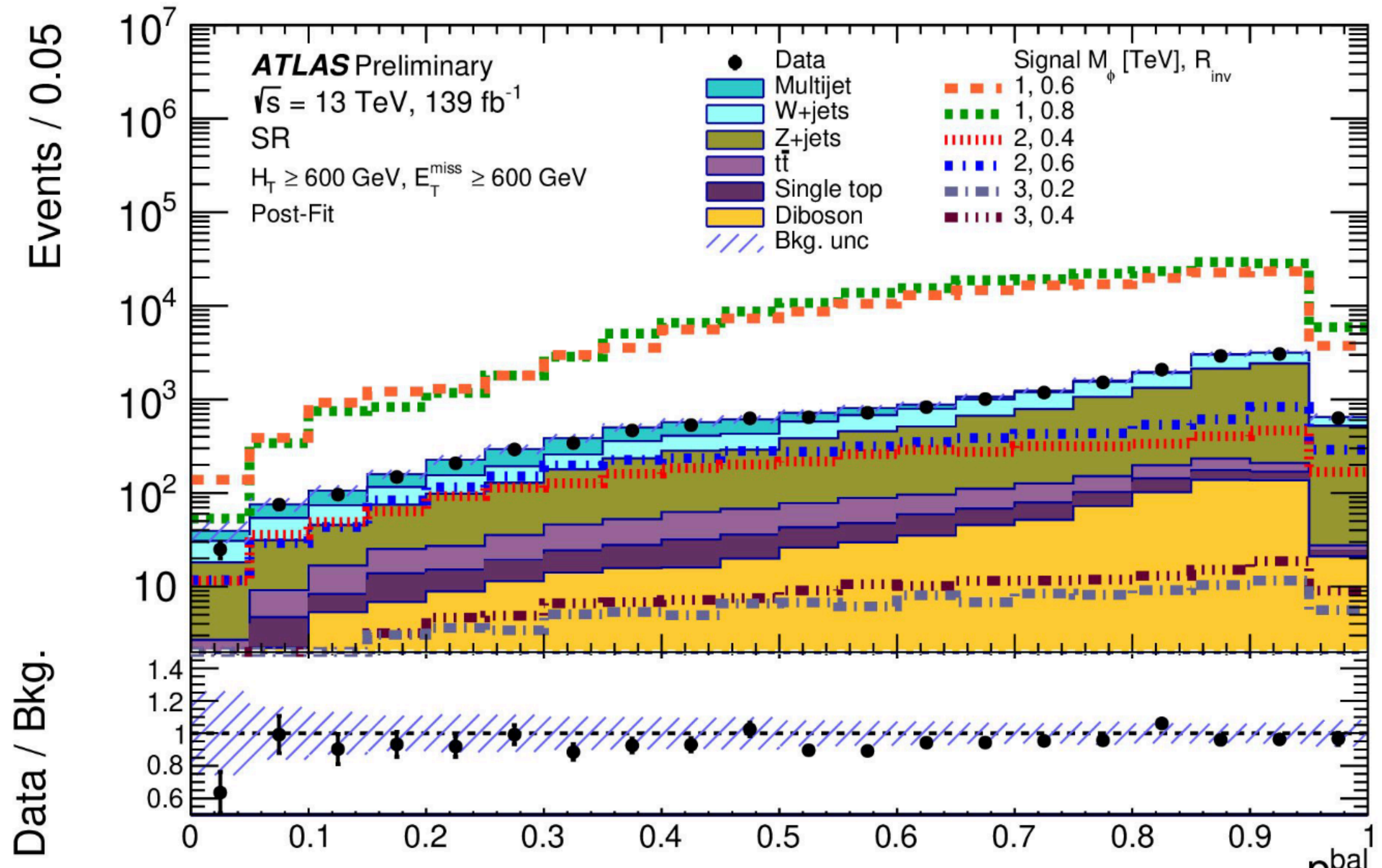


BDT:
tau_{ij}, ECFs, m_{SD}, girth, major/minor axes, flavour info, Δϕ(jet,MET)

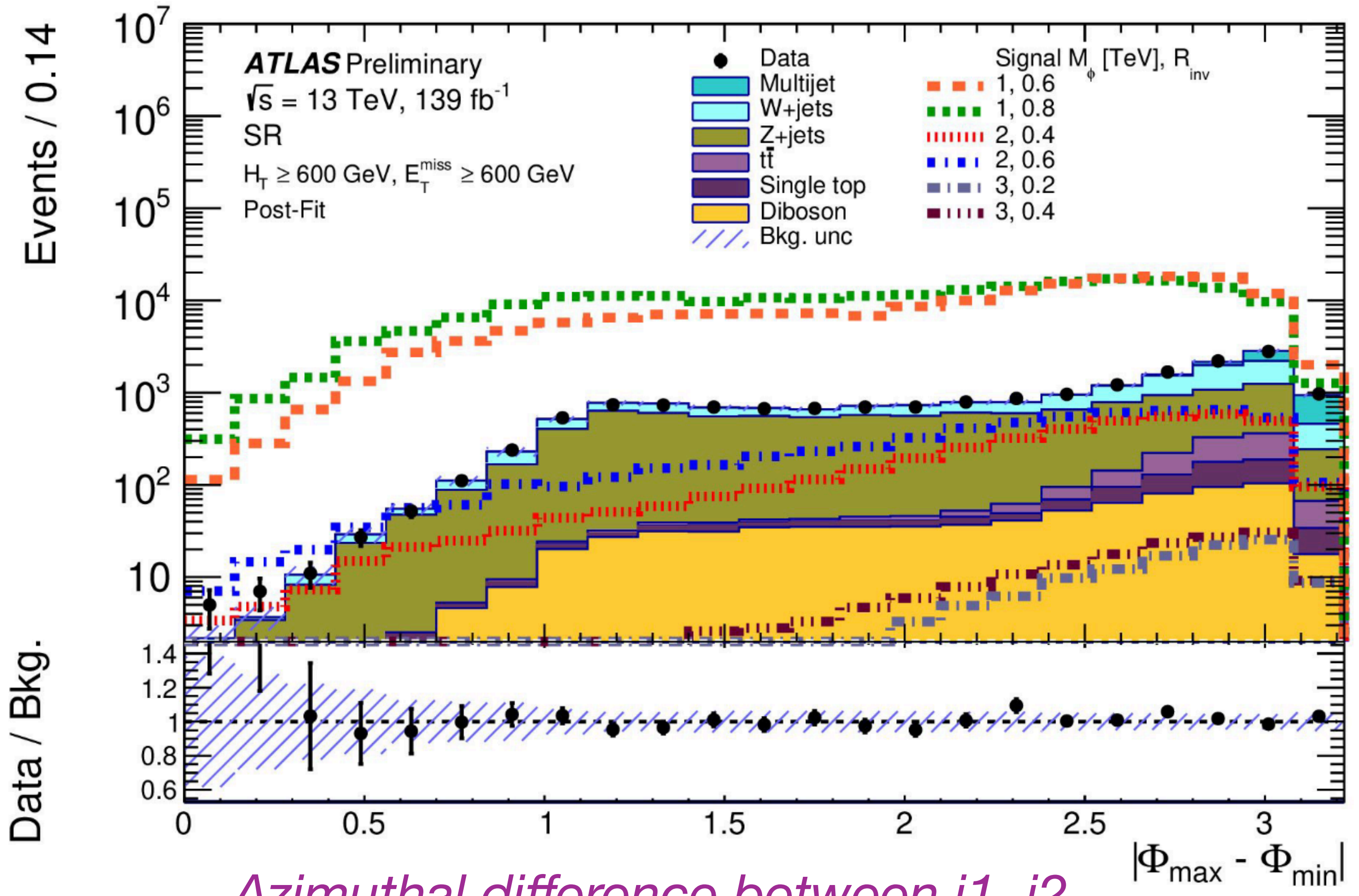
"Variables sensitive to multiplicity are excluded" (p.10)



Bump hunt in transverse mass

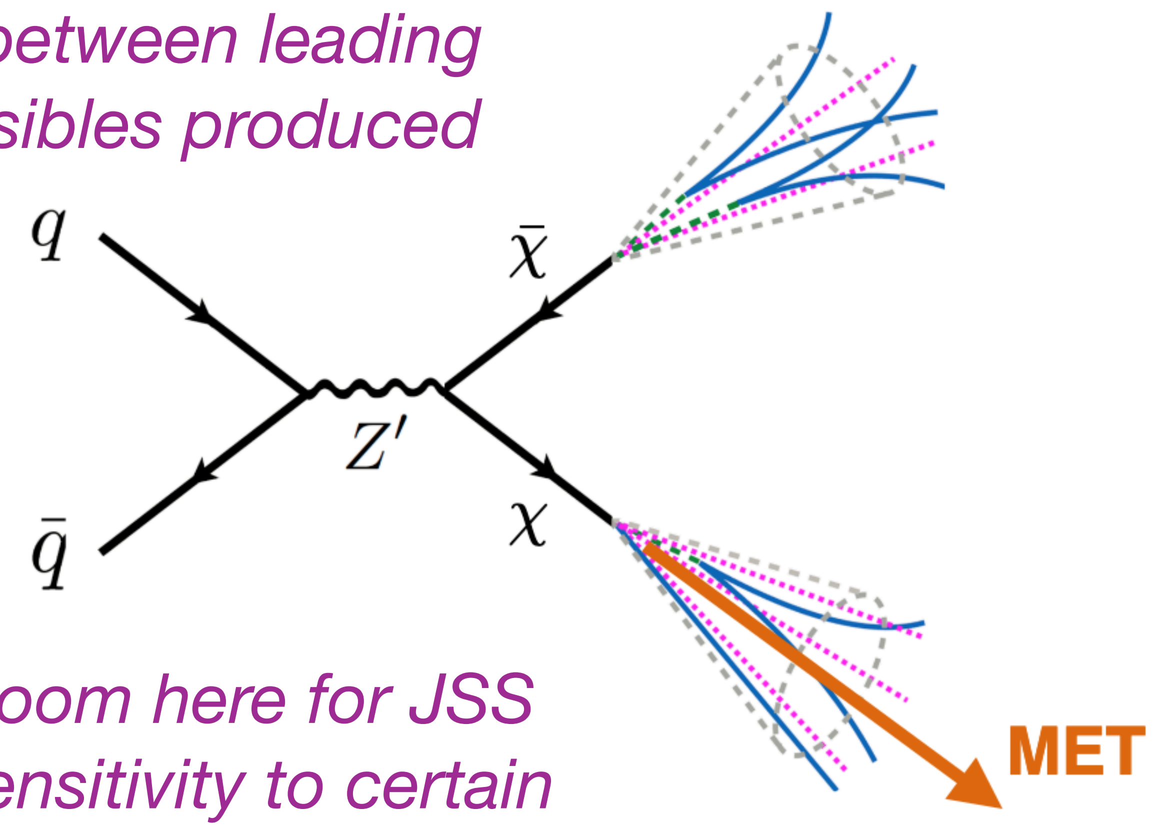


pT balance of j1, j2



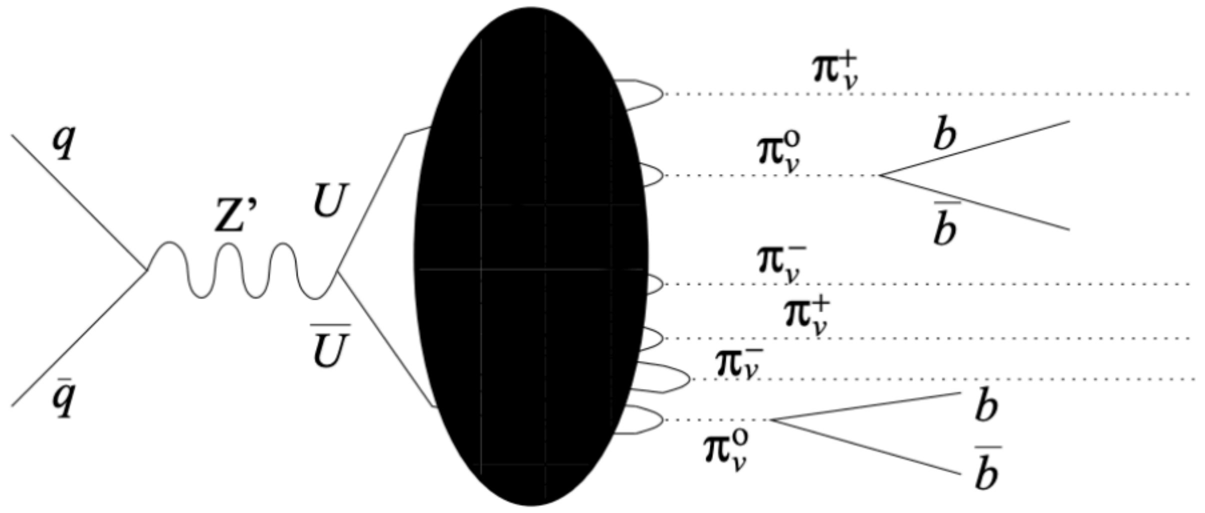
Azimuthal difference between j1, j2

Analyses currently rely heavily on imbalance between leading jets due to invisibles produced in shower …



… plenty of room here for JSS to improve sensitivity to certain sets of models.

S. Kulkarni @ SVJ '22



*SVJ can be enriched in **heavy flavour,** depending on hidden sector mass spectrum:*

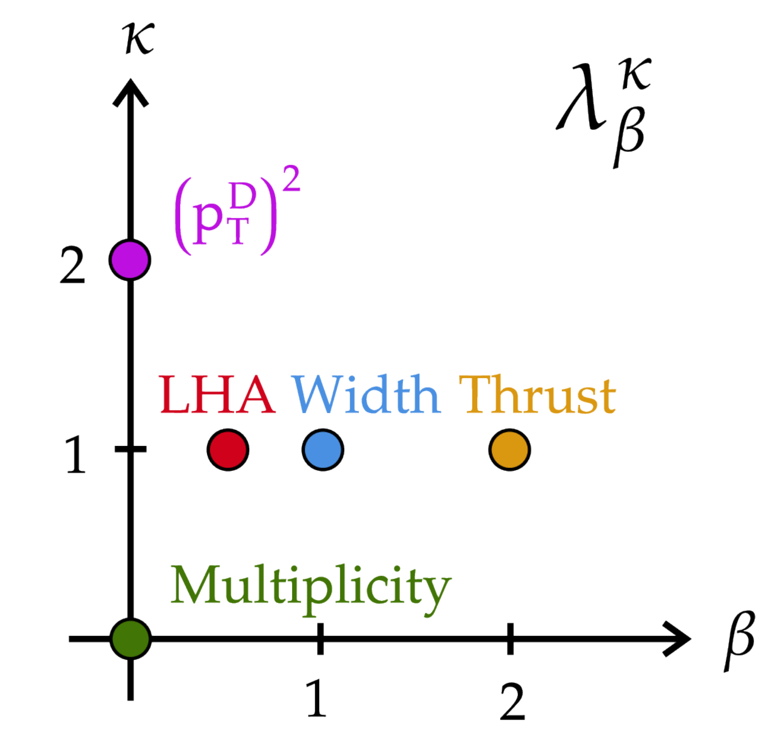
*Will **lepton jets** from BOOST '09 return!?*

CMS, arXiv.2109.03340

(311 public figures!)

CMS Q/G Angularities

- New measurement of **generalized angularities** from CMS!

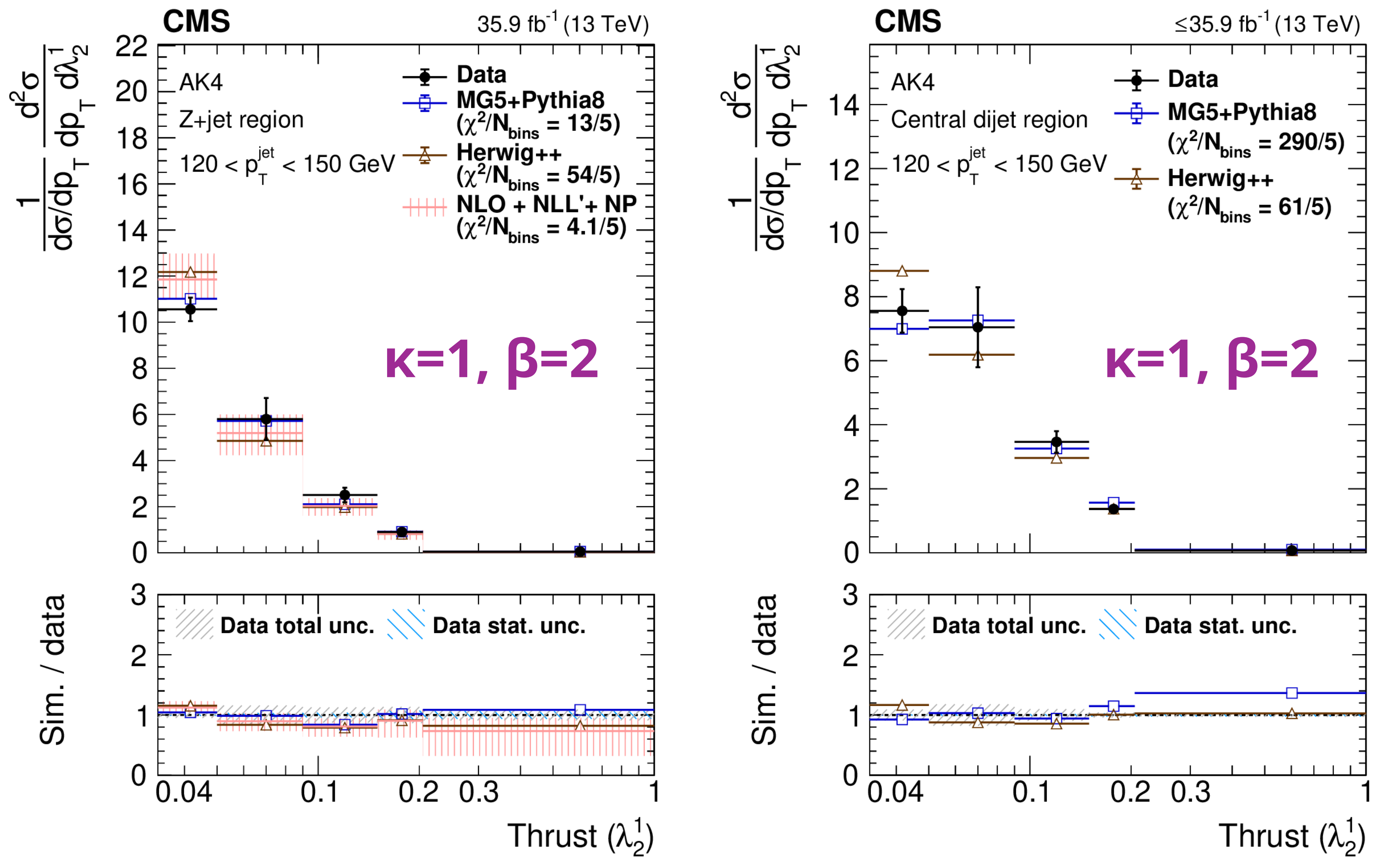


$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R}\right)^\beta,$$

Products of constituent relative p_T and angle, vary weight of each component

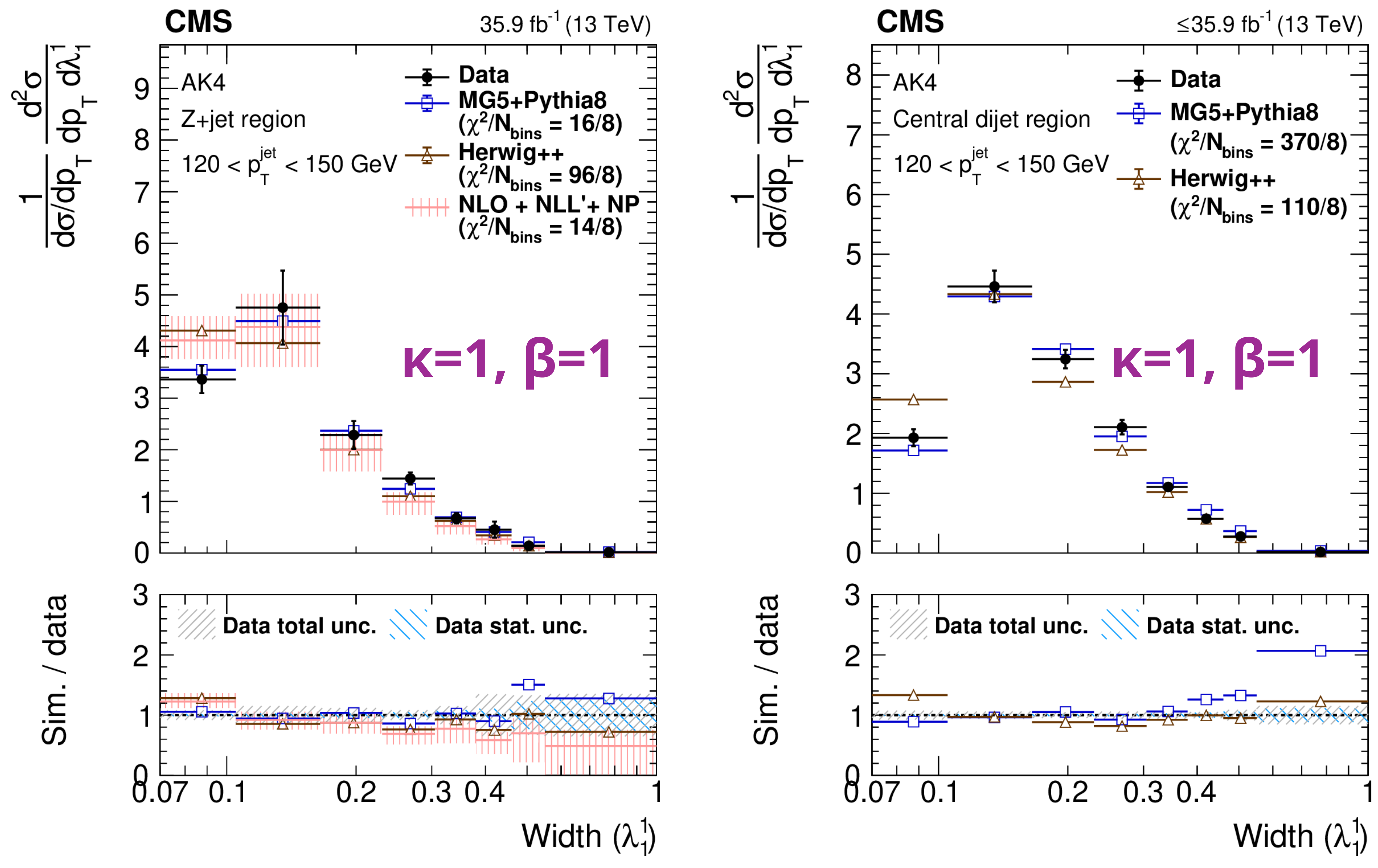
  - Explores differences between quark-enriched and gluon-enriched selections (Z+jets vs. dijets).
  - Exponents of energy/angular components can probe different aspects of QCD.

- Focusing on three angularities today which are **IRC-safe** (κ>0).



Larger angular exponent

Better agreement throughout



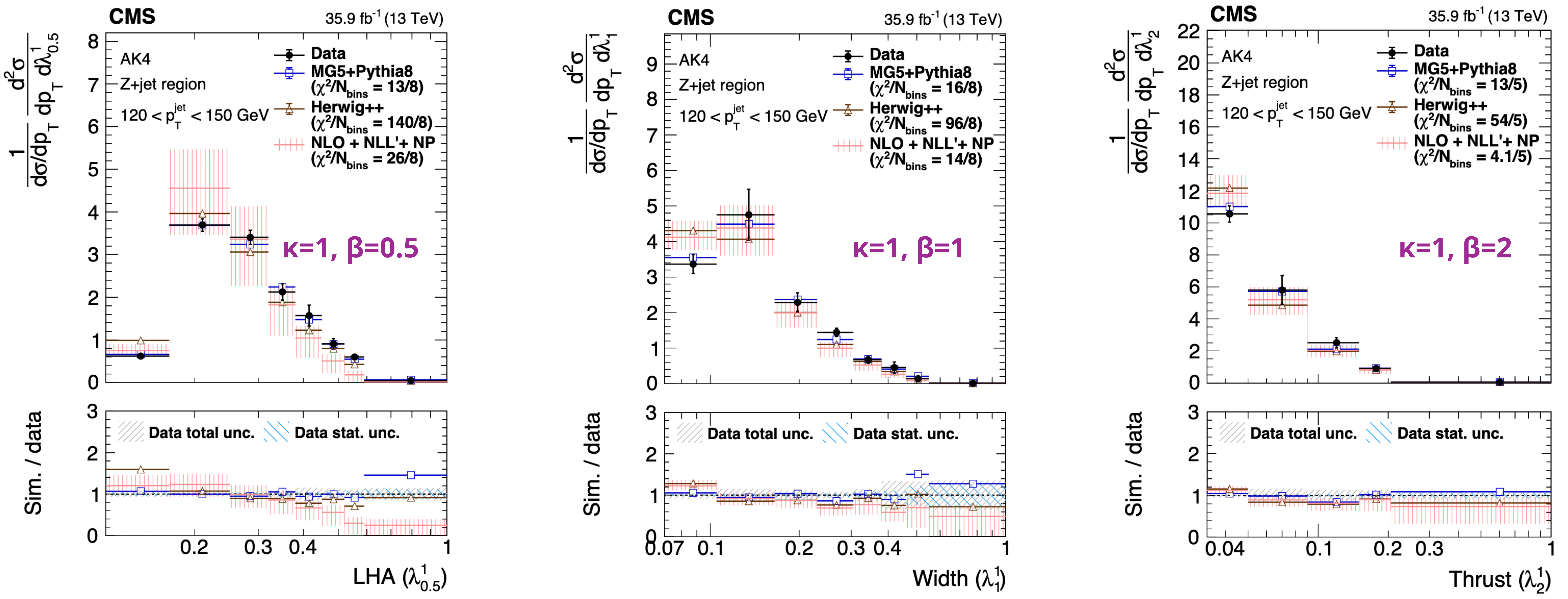
Smaller angular exponent

Deteriorating agreement for wide-angled contributions

CMS q/g Angularities

UNGROOMED

LOWER ANGULAR EXPONENT ⟷ LARGER ANGULAR EXPONENT



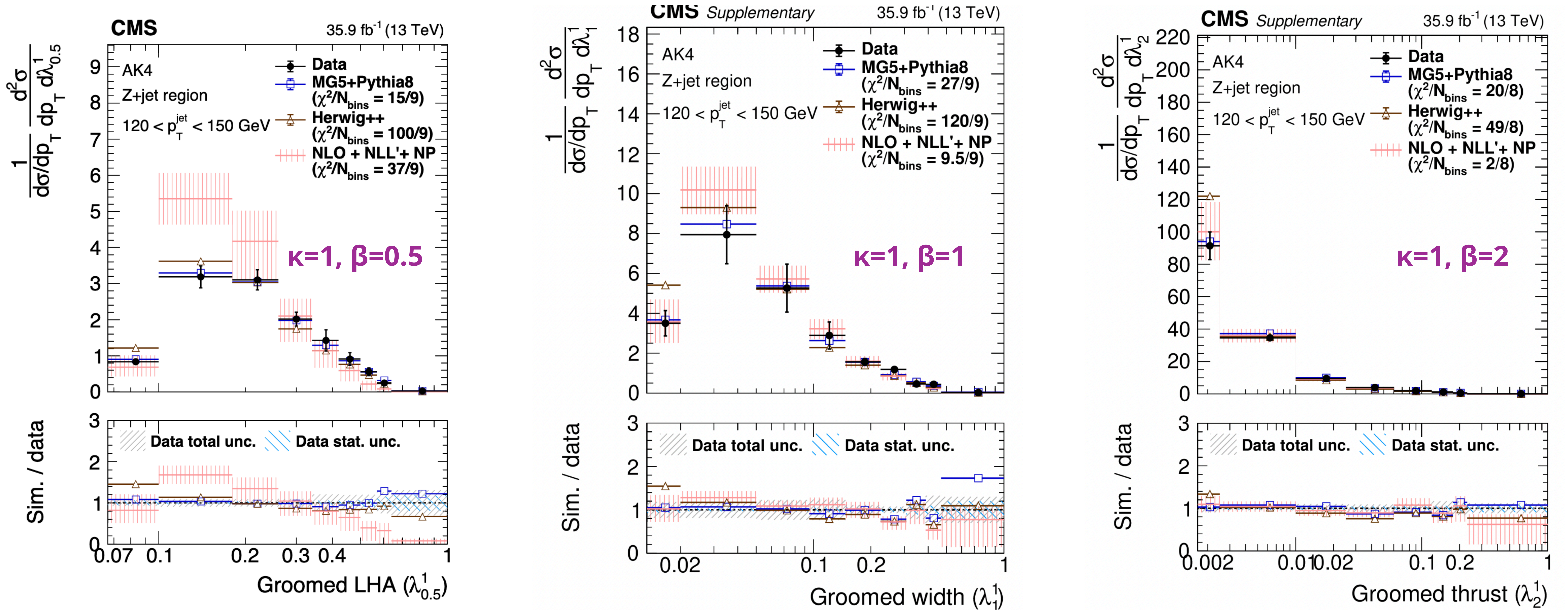
Predictions for three IRC-safe angularities available at NLO+NLL, **with & without soft-drop!** For ungroomed observables, **agreement improves for larger angular exponents.**

CMS, arXiv.2109.03340

CMS q/g Angularities

SOFT-DROP

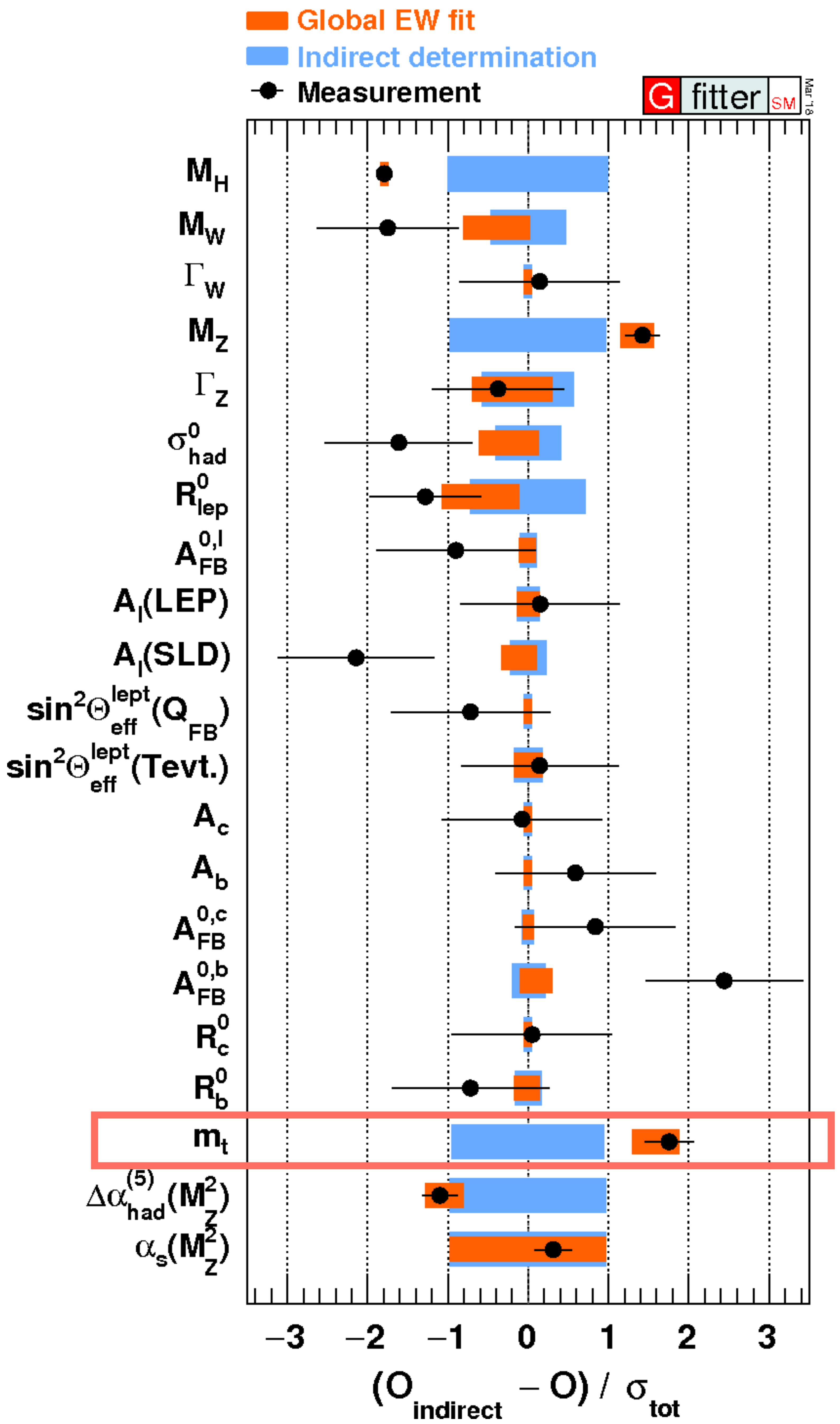
LOWER ANGULAR EXPONENT ⟷ LARGER ANGULAR EXPONENT



Removing **soft radiation** via soft-drop (z_{cut}=0.1, β=0) accentuates disagreements already observed in LHA: *description of soft-collinear splittings?*

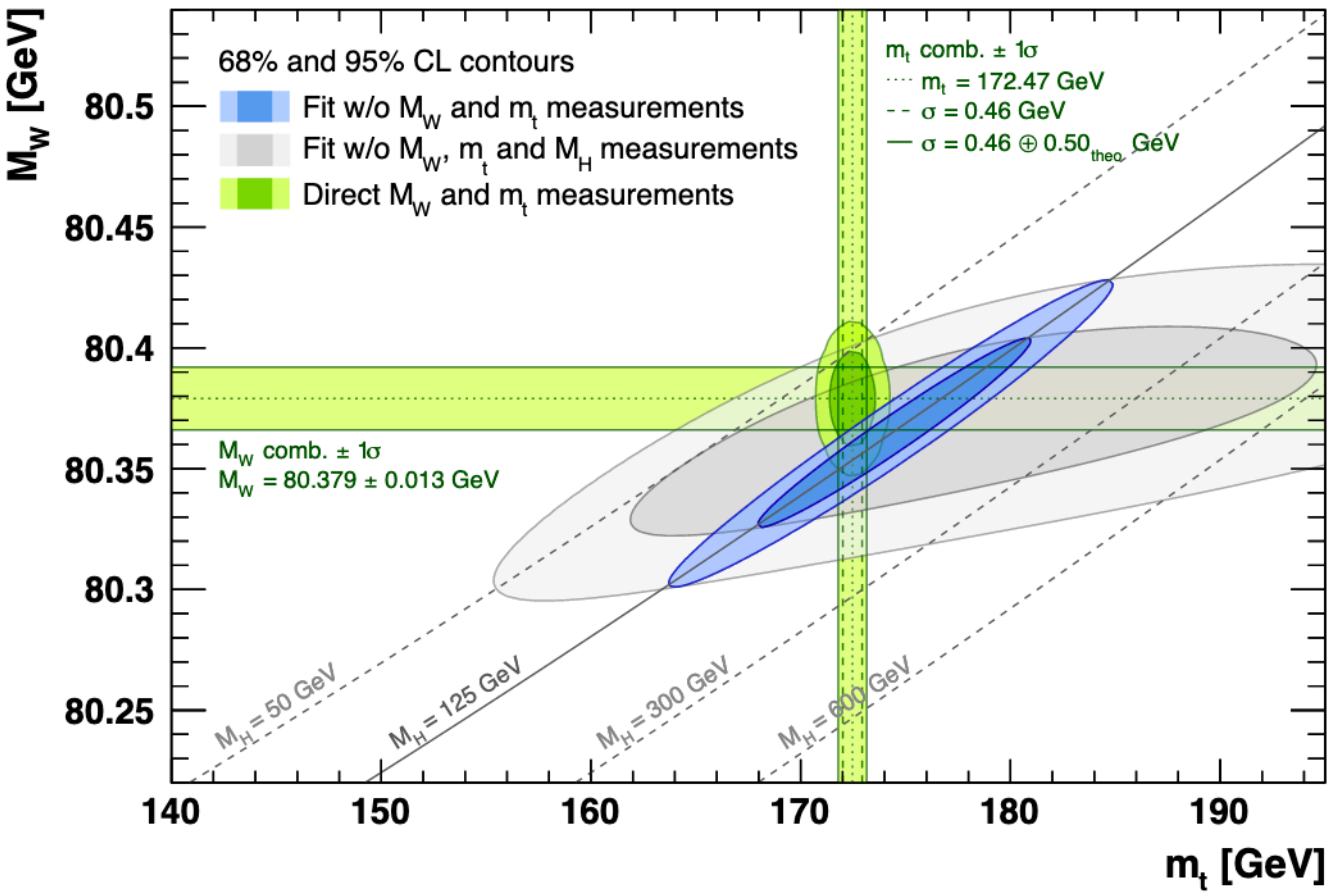
gFitter collab. 1803.01853

Global Electroweak Fit

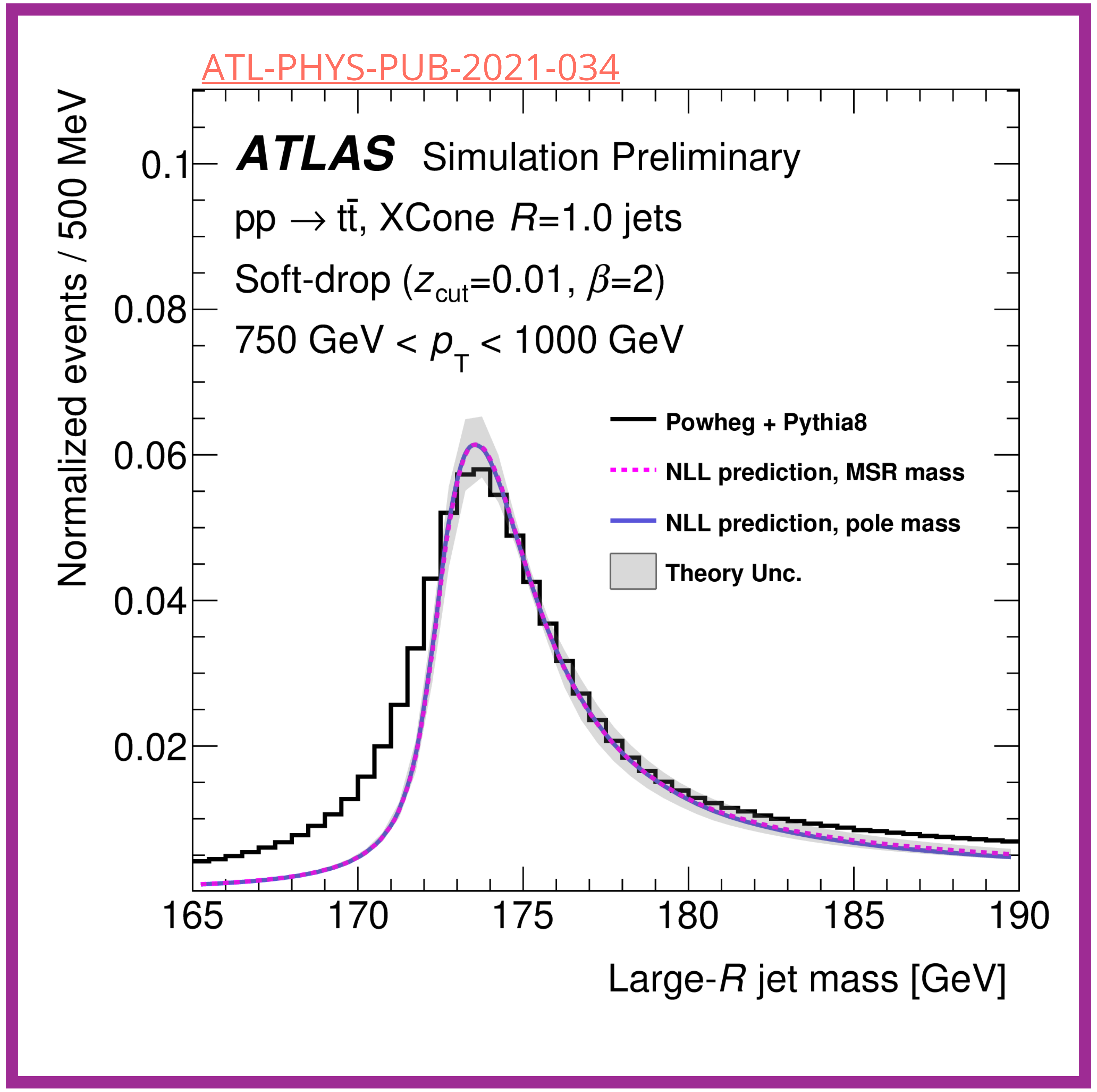


Where can we contribute most significantly to this picture?

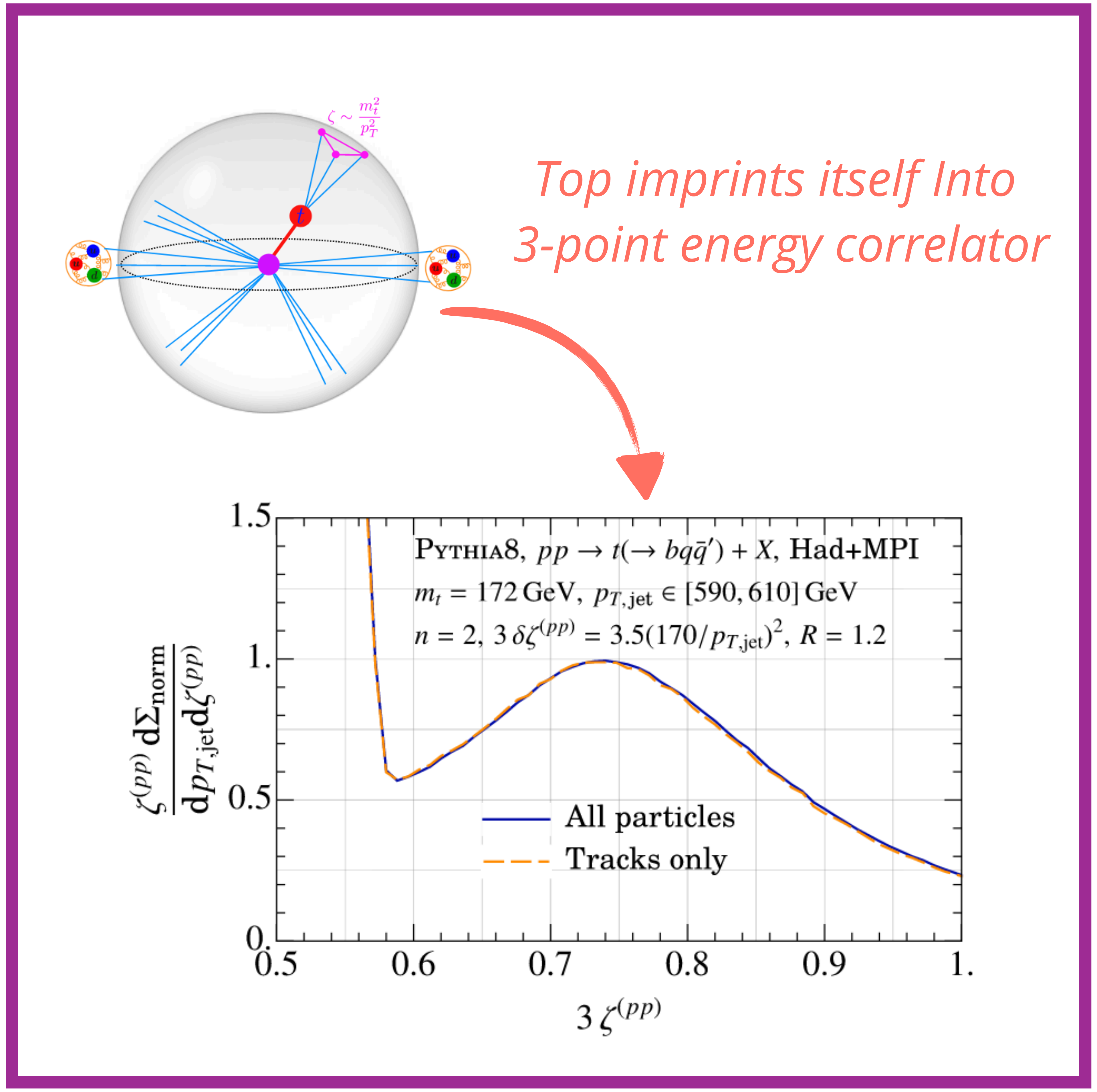
***m_t** is an obvious place to start BOOSTing!*



Top Mass w/ JSS : Indirect Prospects (near + far)



ATLAS @ BOOST21



Jack : Thursday Afternoon

CMS Boosted Top Mass — Cool Details, suite.

7. Studies of the final state radiation **13**

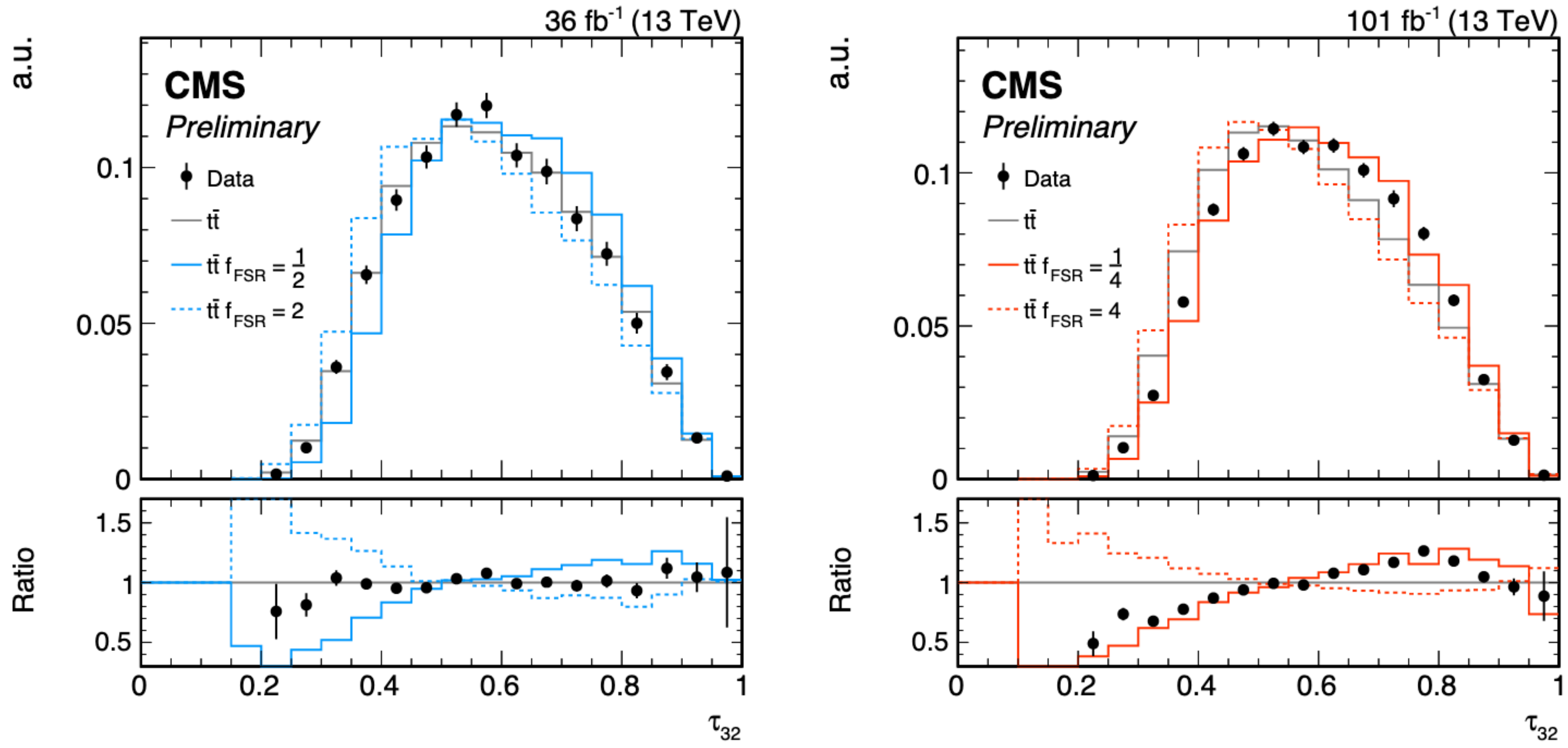
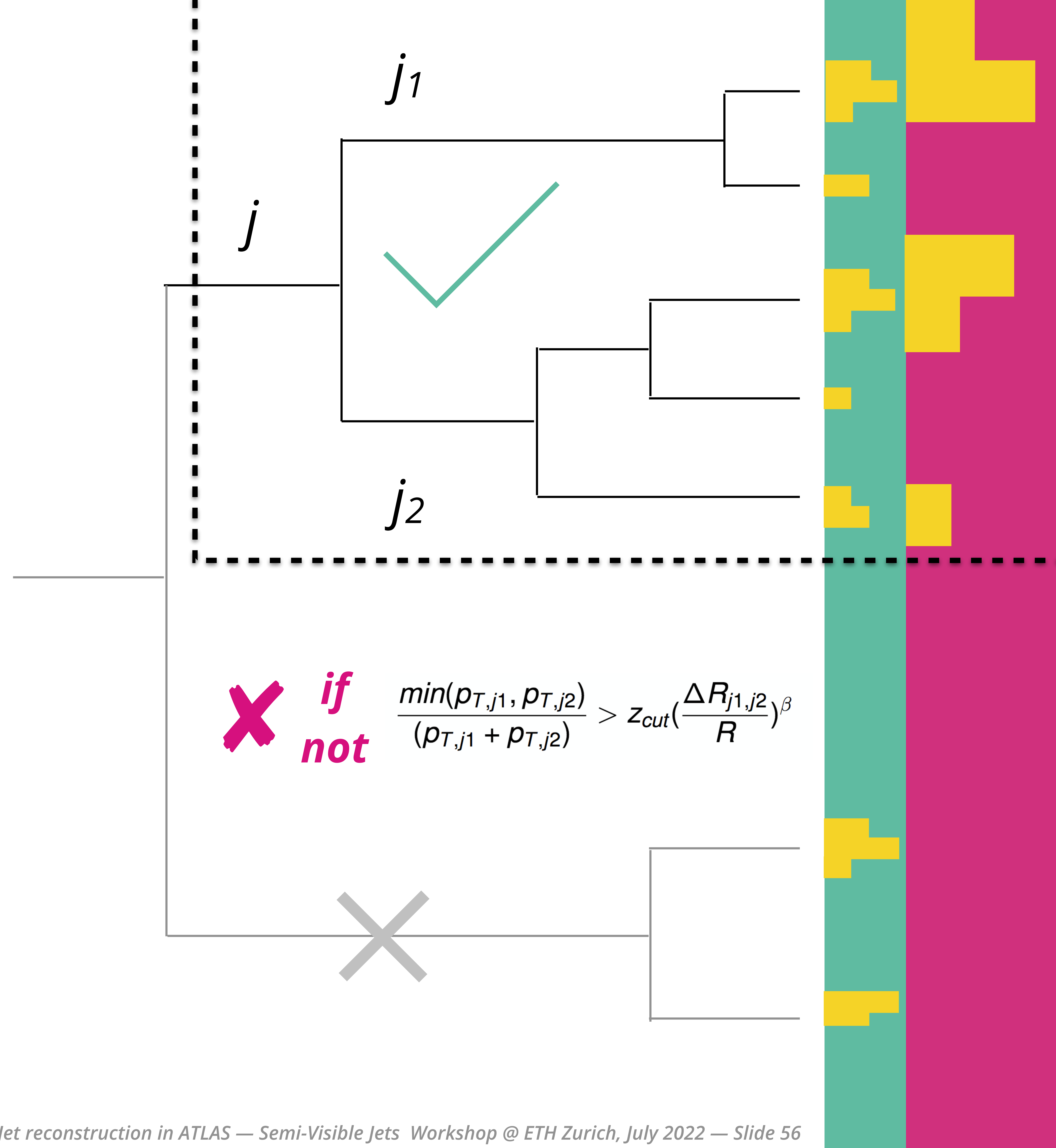


Figure 8: The normalised distributions in τ_{32} for AK8 jets with $m_{\text{jet}} > 140\,\text{GeV}$, from the hadronic decay of boosted top quarks. Shown are distributions for 2016 (left) and the combination of 2017 and 2018 (right). The background-subtracted data are compared to $\text{t}\bar{\text{t}}$ simulations with different parton shower and UE tunes and different values of f_{FSR}. The bottom panels show the ratio to the $\text{t}\bar{\text{t}}$ simulation with $f_{\text{FSR}} = 1$.

Soft-drop / mMDT

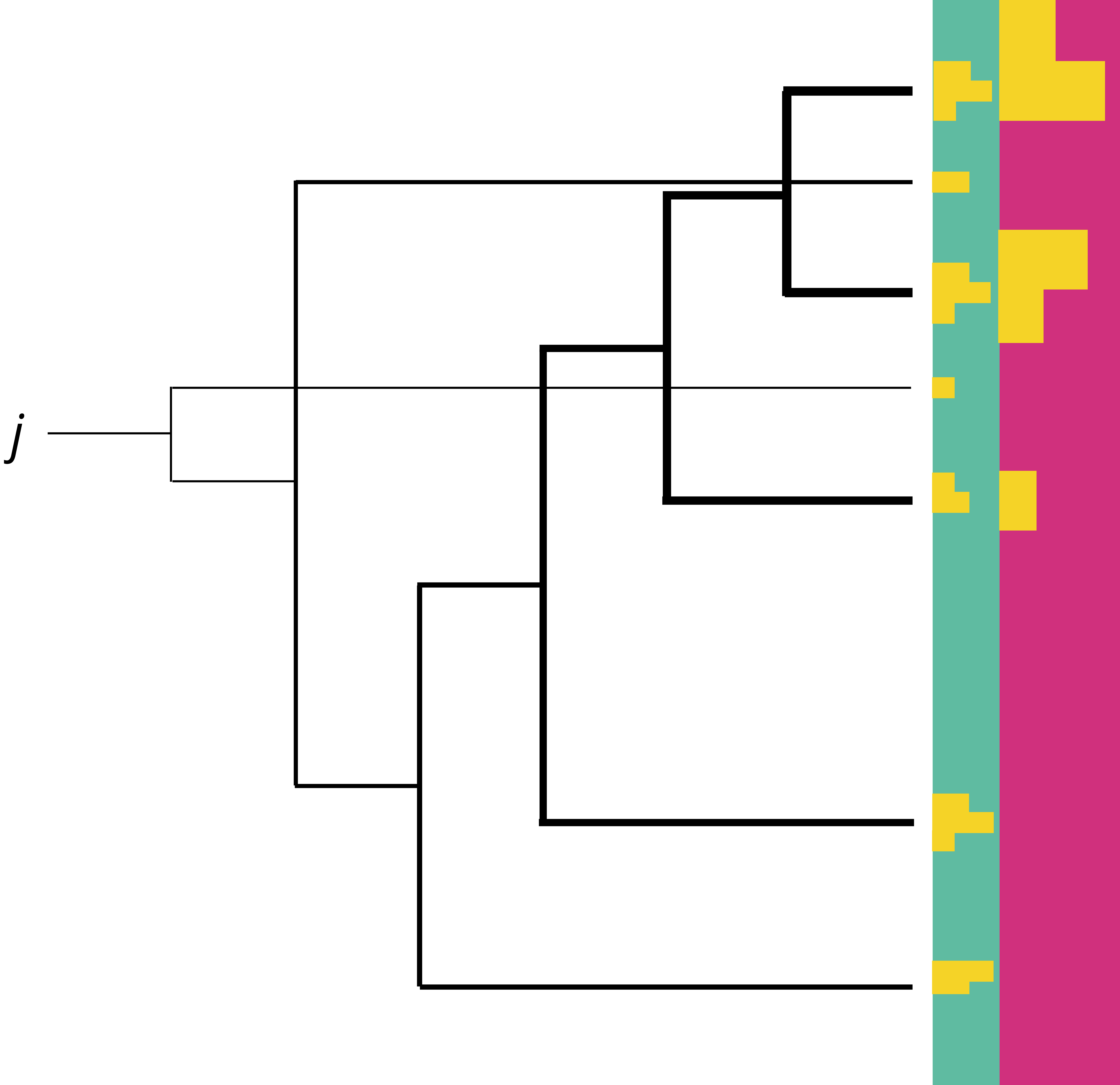
- This algorithm has played a central role in understanding JSS since its proposal in 2013 / 2014.
- **Recluster** jet constituents with **C/A algorithm**, then **remove soft & wide-angle radiation** failing SD condition.
  - Removes **Non-Global Logarithms:** first analytical predictions for JSS @>LL rely on the SD/mMDT procedure.
- Observables characterizing the hardest splitting in SD jets have been studied thoroughly by experiment and theory:
  - $\rho = \log_{10}(m_j / p_T^j)$
  - $z_g = p_T^{j2} / p_T^{j1}$
  - $R_g = \Delta R(j_1, j_2)$
- Many other schema for understanding JSS are built from this tree-based declustering technique (*e.g.* Lund jet plane).



Dasgupta, Fregoso, Marzani, Salam, JHEP09 (2013) 029,
Larkowski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146

Soft-drop / mMDT

1. **Begin with an anti-k_t jet.**
2. Recluster jet constituents using **Cambridge/Aachen (C/A)** algorithm **(angular-ordering)**.
3. **Iterating inward from widest-angle radiation**, discard subjets when they fail the Soft Drop condition.
   - Two parameters: z_{cut} and β.
4. When the SD condition is satisfied, **stop!**
   - **Soft** and **Wide-Angle** radiation is removed.



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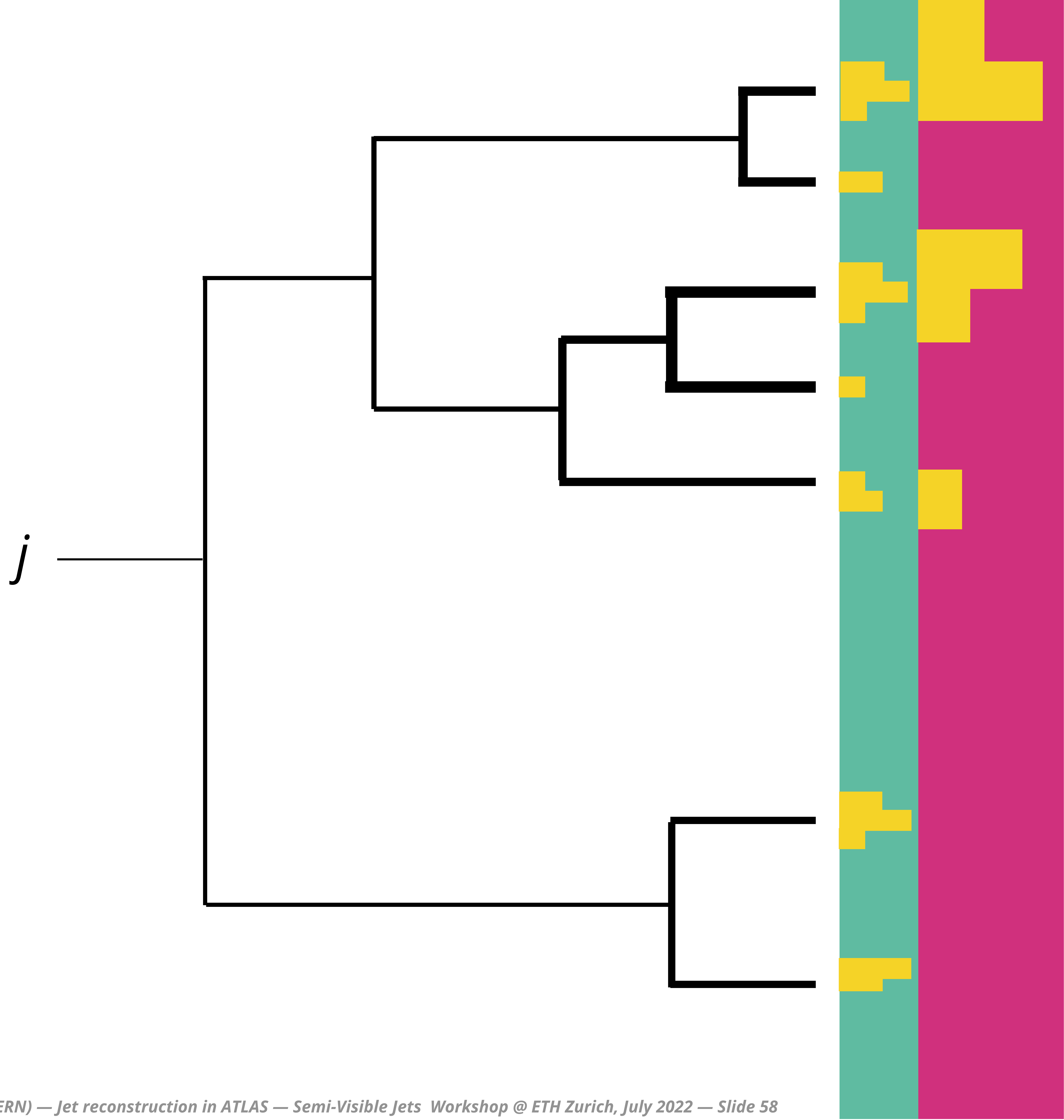

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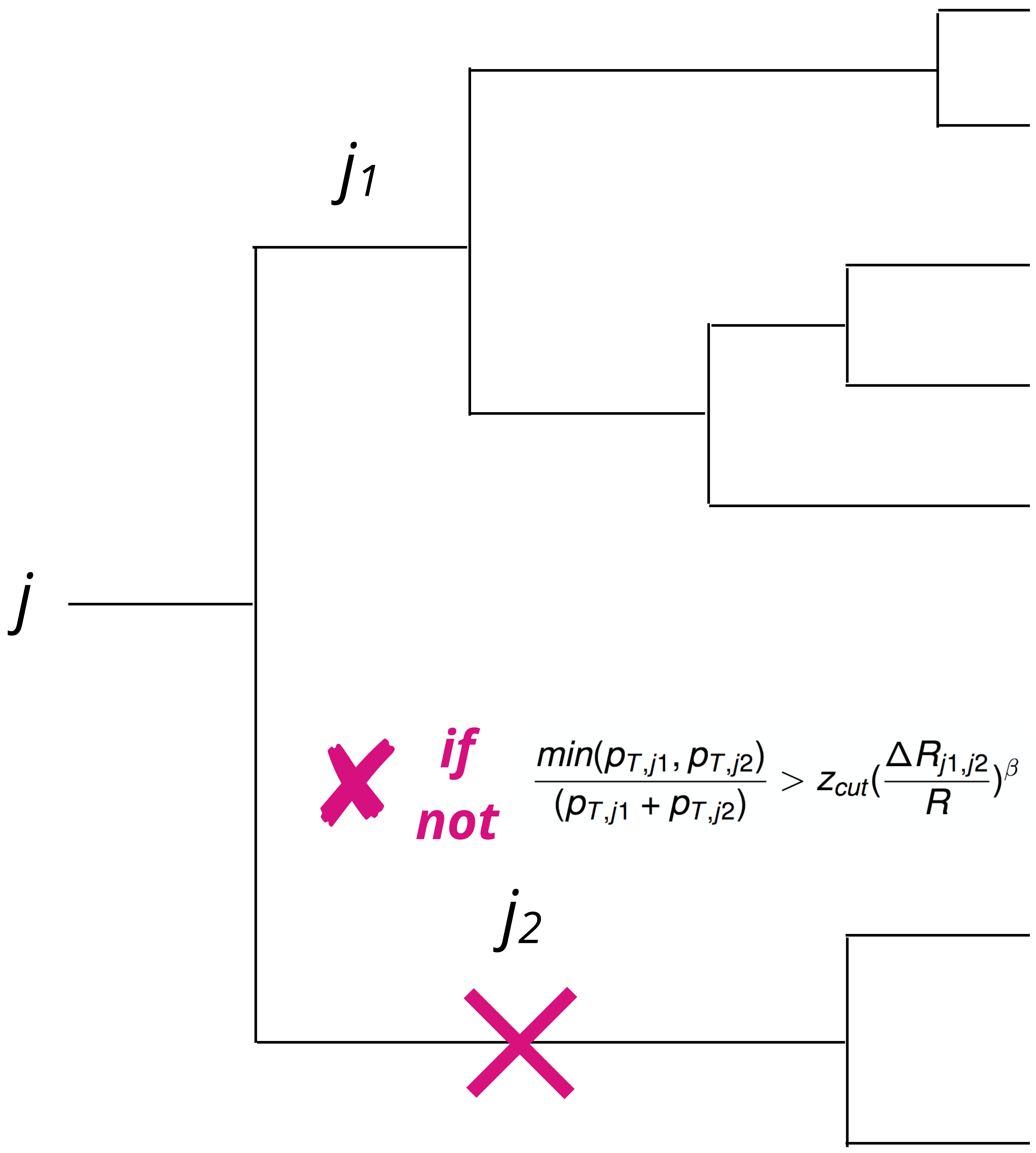

Dasgupta, Fregoso, Marzani, Salam, JHEP09 (2013) 029,
Larkowski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146

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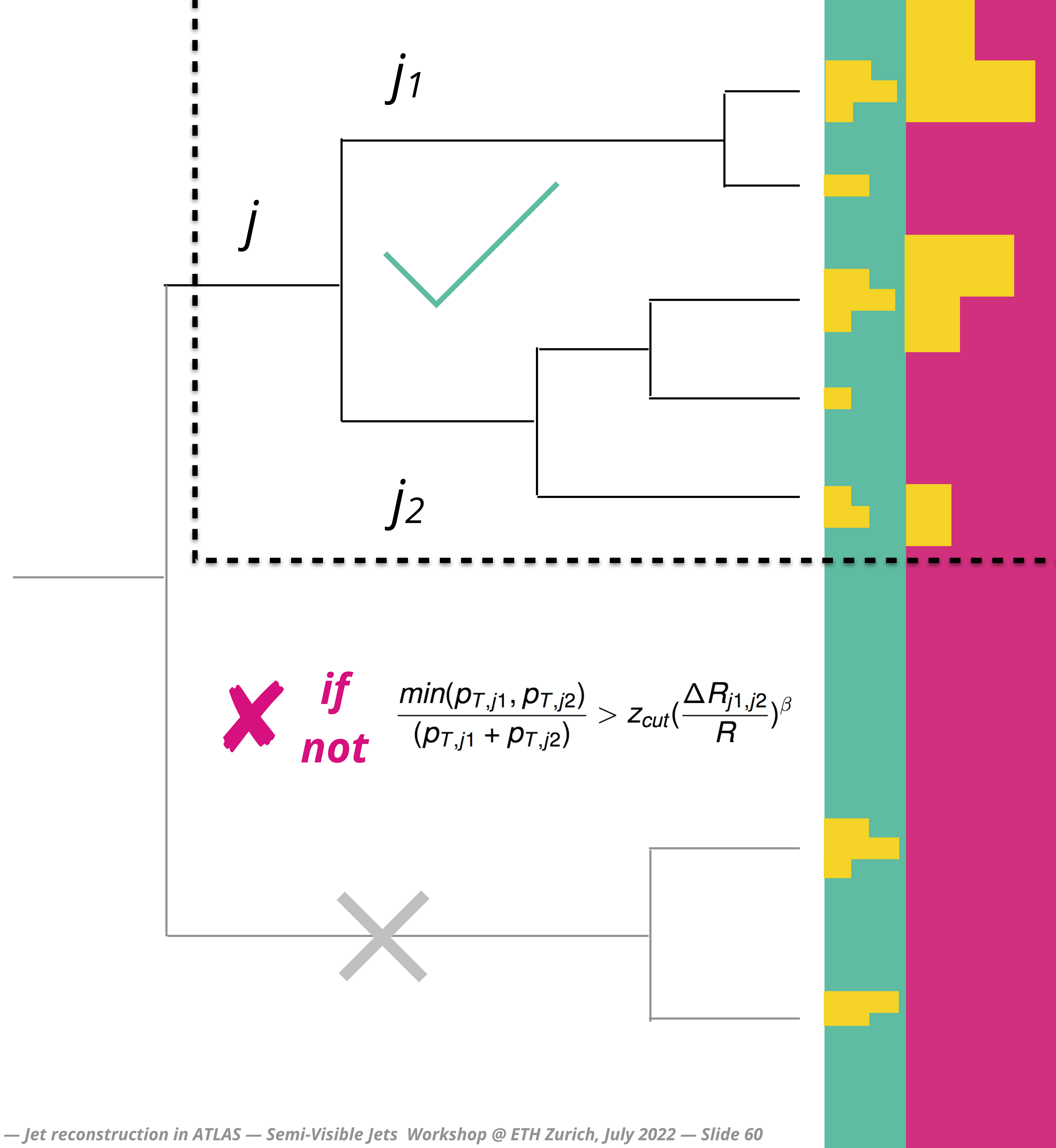


Dasgupta, Fregoso, Marzani, Salam, JHEP09 (2013) 029,
Larkowski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146

<u>Dreyer, Soyez, Salam 1807.04758</u>

Lund jet plane

QCD radiation within jets is approx. uniform in ln(E), ln(θ):

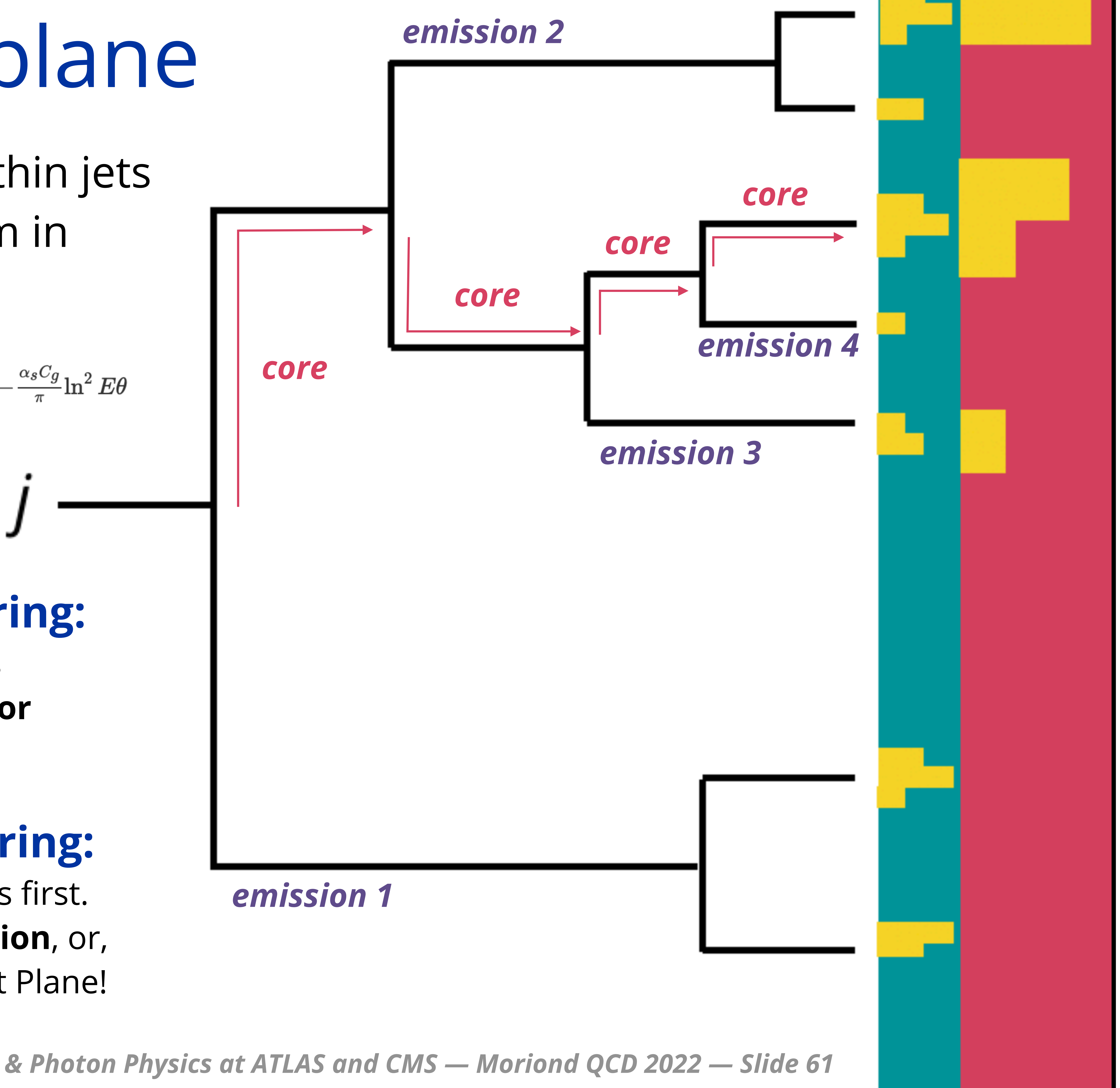
$$P(E,\theta) = \frac{2\alpha_s C_g}{\pi}\frac{1}{E\theta}e^{-\frac{\alpha_s C_g}{\pi}\ln^2 E\theta}$$

1. C/A Reclustering:

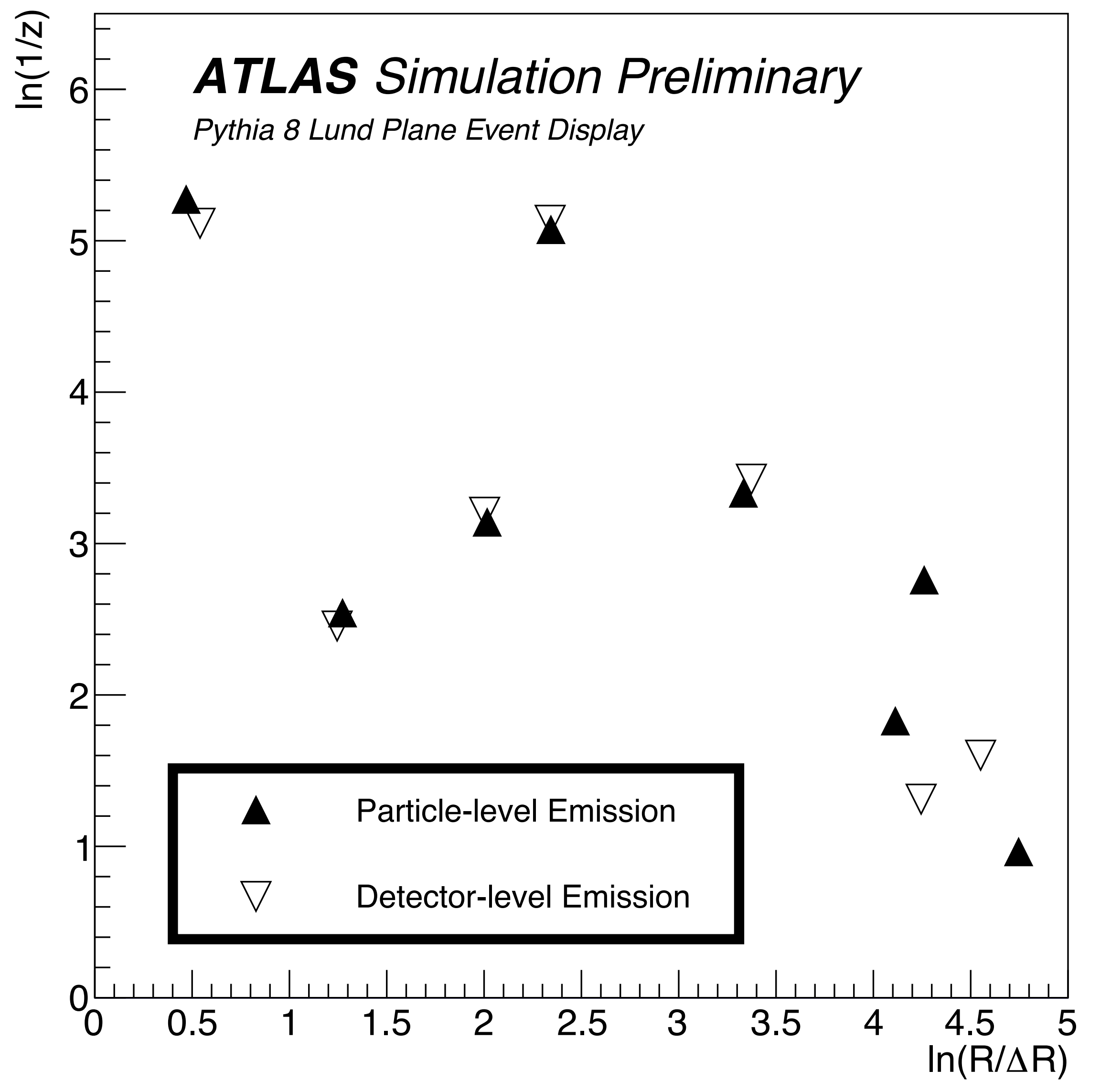
Combine closest pairs of **charged particles or tracks!**

2. C/A Declustering:

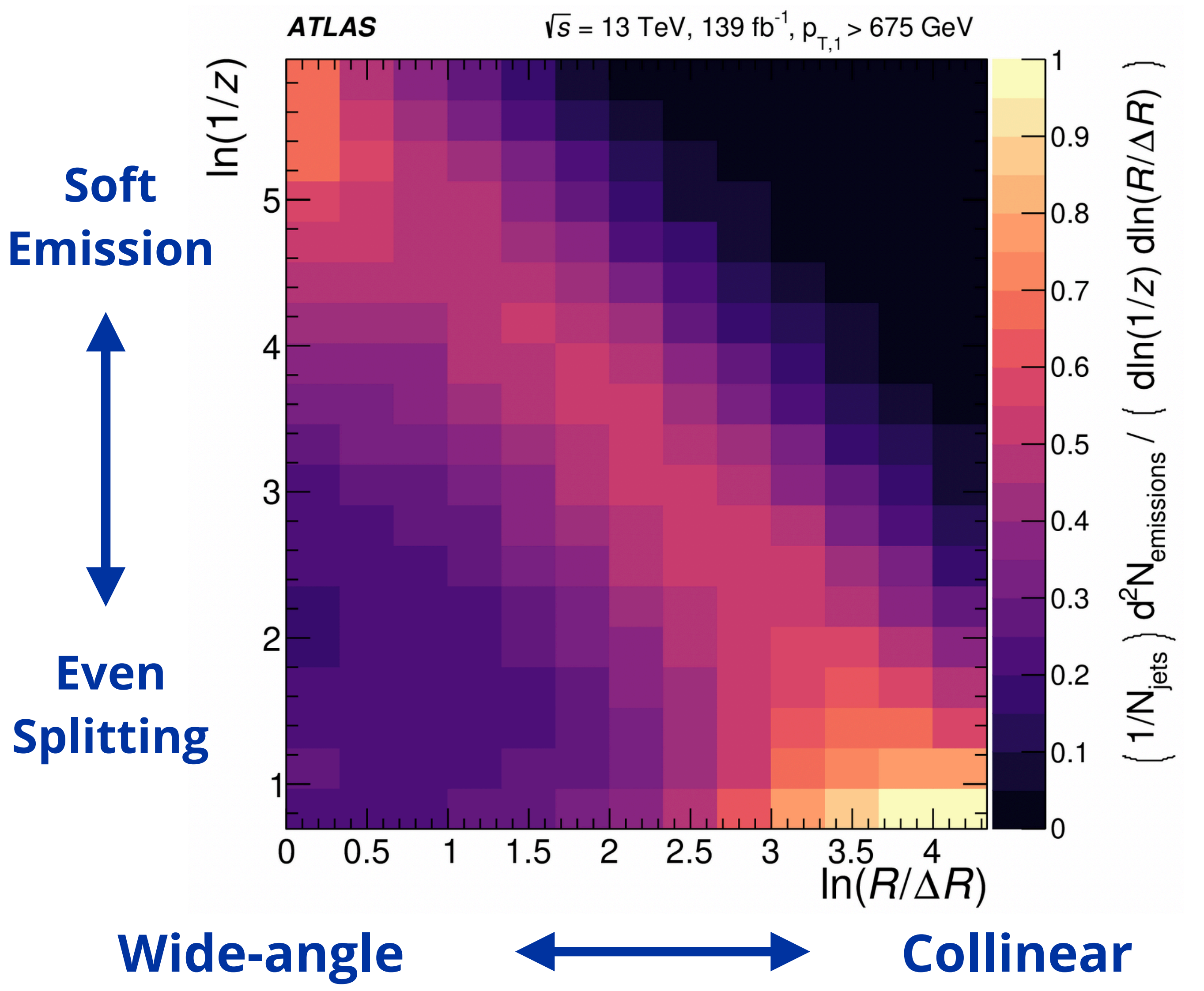
Unwind, widest angles first. Each step is an **emission**, or, a point in the Lund Jet Plane!



A single jet results in **a set of coordinate points** in the LJP …



… a collection of jets gives a **distribution**:

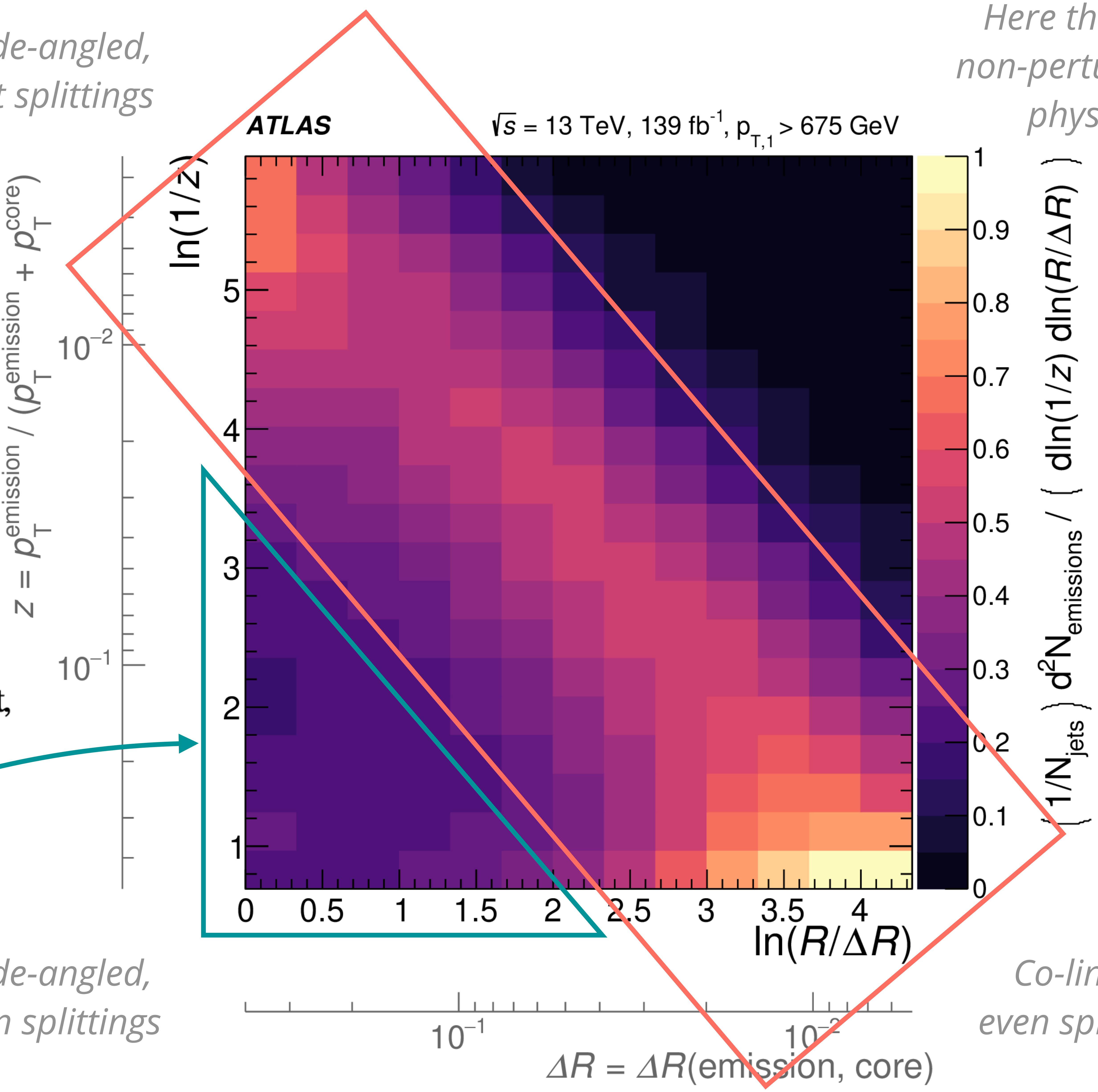


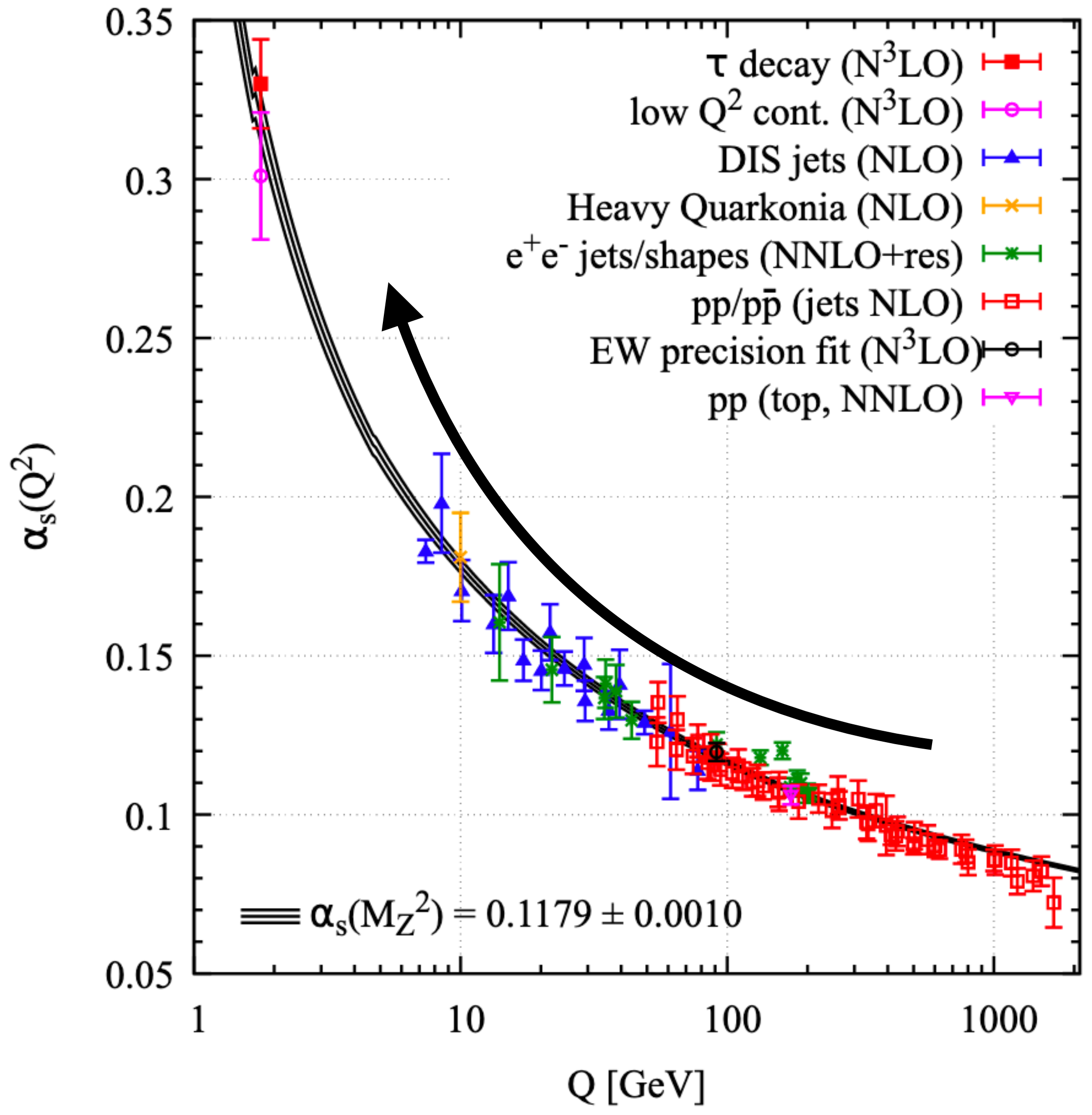
ATLAS Collab., Phys. Rev. Lett. 124, 222002 (2020), (HepData, Rivet)

The Lund jet plane

Wide-angled, soft splittings

Here there be non-perturbative physics.





$$\frac{1}{N_{jets}}\frac{d^2 N_{emissions}}{d\ln(1/z)\,d\ln(R/\Delta R)} \propto \text{constant},$$

Region of hard, wide-angle (perturbative) splittings.

Populated ~uniformly.

Wide-angled, even splittings

Co-linear, even splittings

Probability of emission enhanced for $k_t \sim z\,\Delta R \sim \Lambda_{QCD}$,

Sensitivity to choice of hadronisation models.

Multijet Event Isotropies with Optimal Transport in ATLAS

ATLAS-CONF-2022-056

Event shapes

Gluon observation
(JADE, 1980)

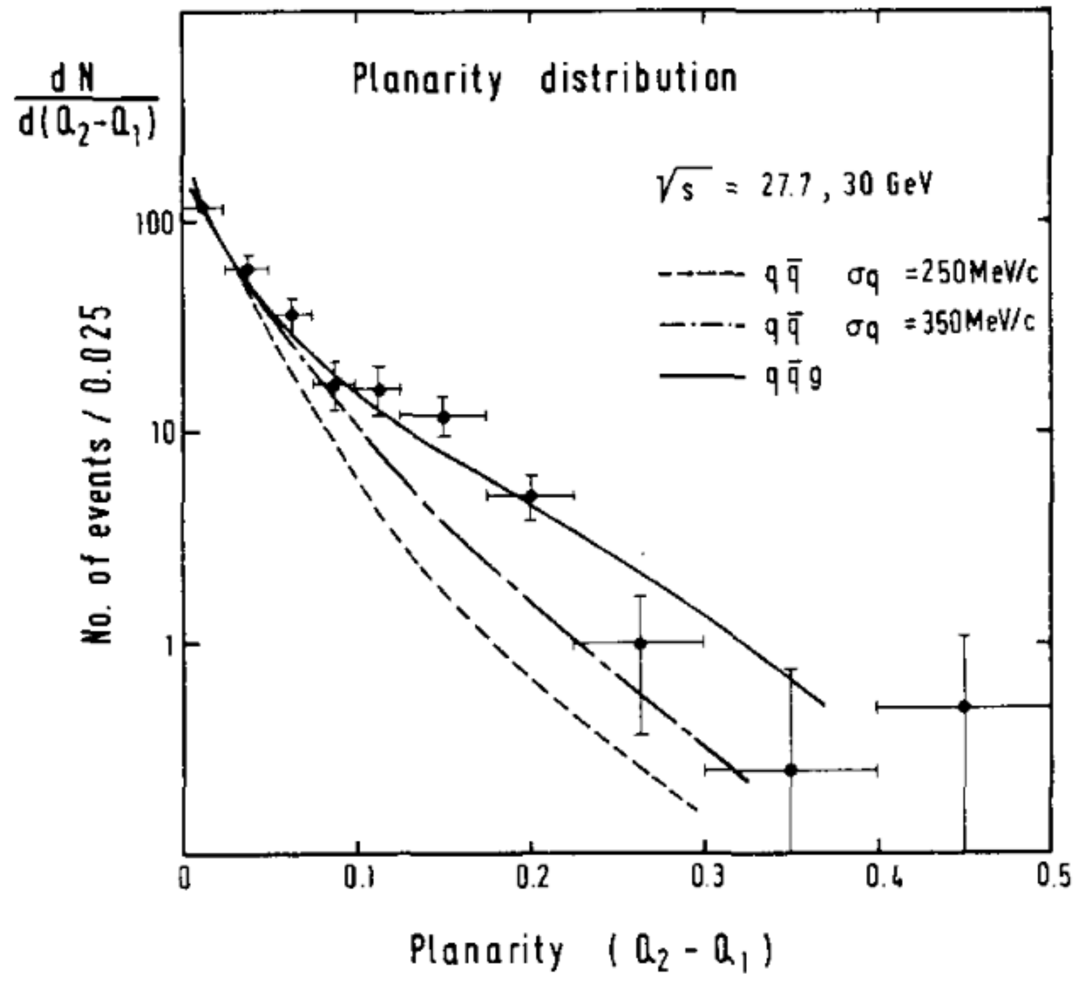
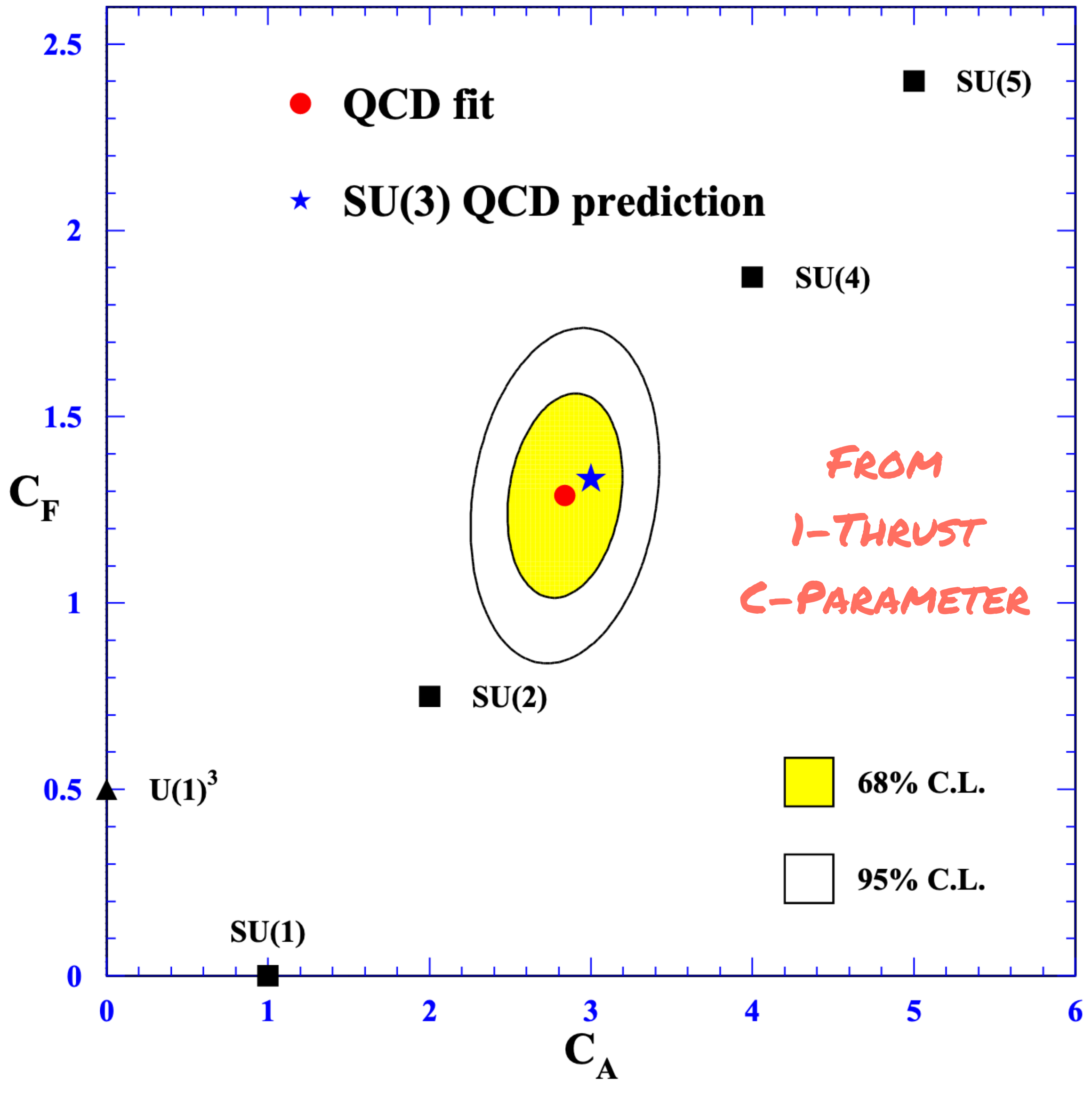


Fig. 3. The planarity distribution compared with model predictions.

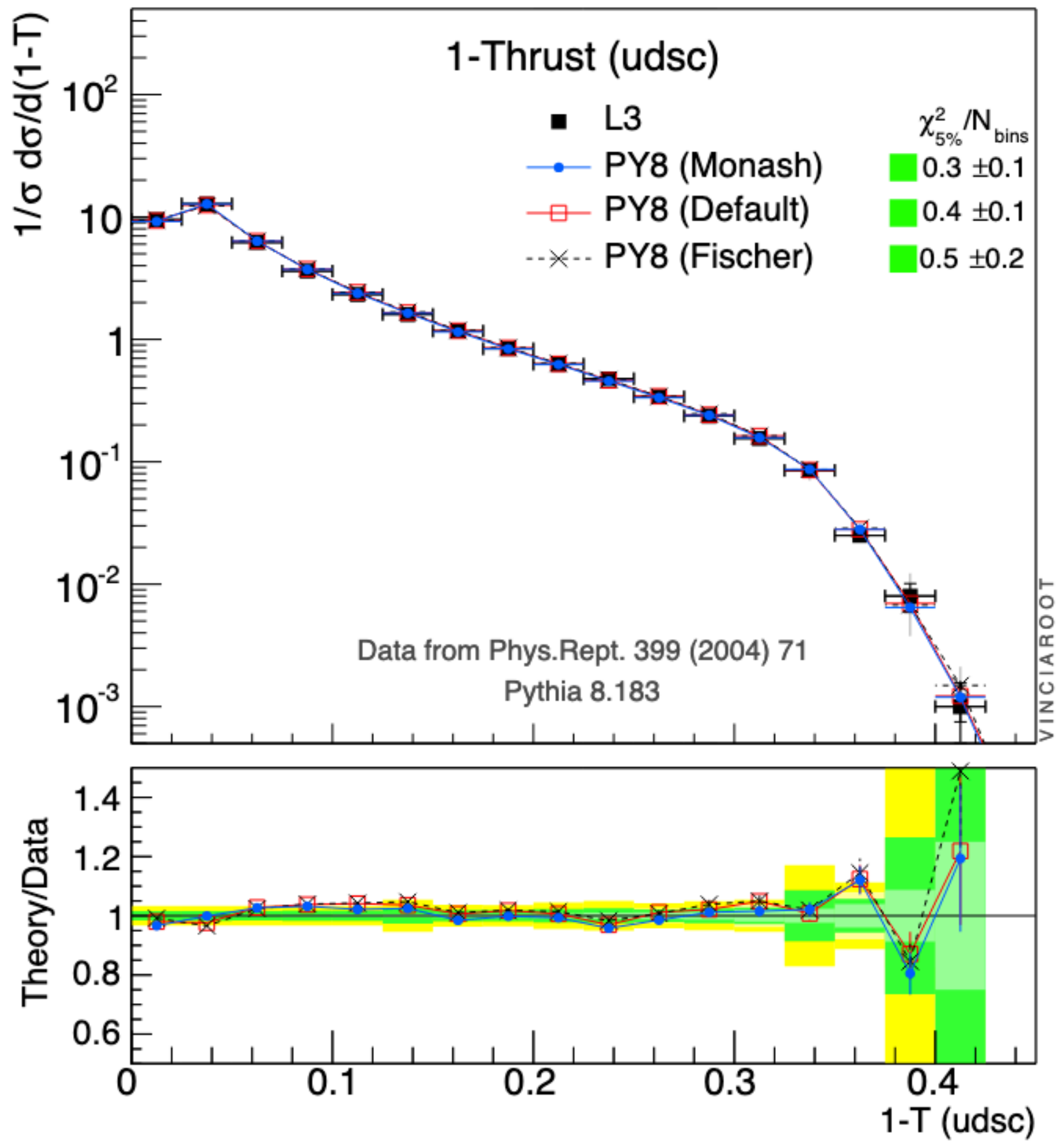
$$T_{\alpha\beta} = \sum_i P_{i\alpha} P_{i\beta} \Big/ \sum_i P_i^2 \,,$$

QCD Colour Factors
(Kluth et al. 2000)



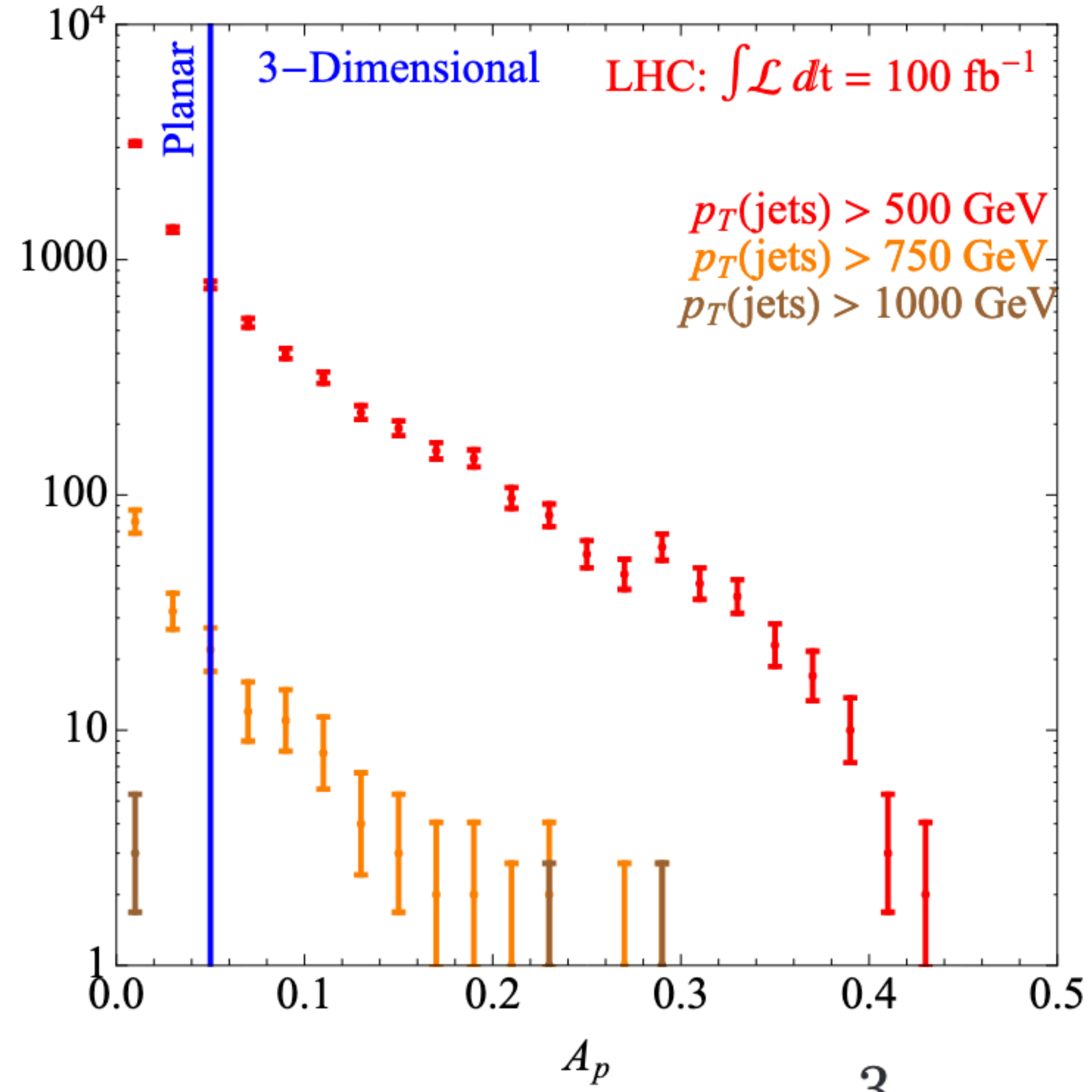
$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|} \right) \qquad C = 3(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1)$$

Monash tune
(Skands et al. 2014)



$$T = \max_{\vec{n}} \left(\frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|} \right)$$

BSM?
(Anchordoqui et al. 2011)



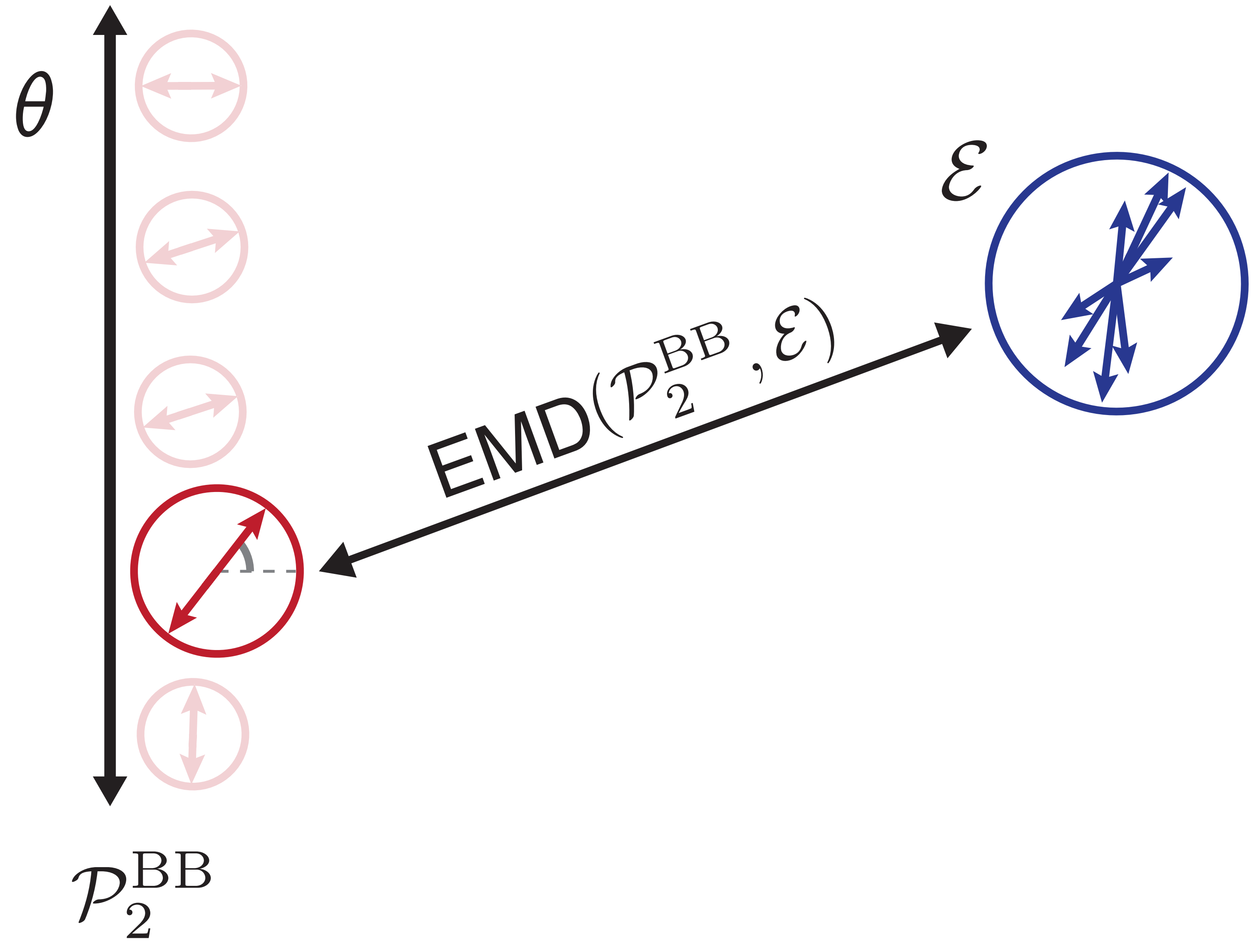
$$A_p = \frac{3}{2} Q_1,$$

Event shapes interpolate between collider event topologies.

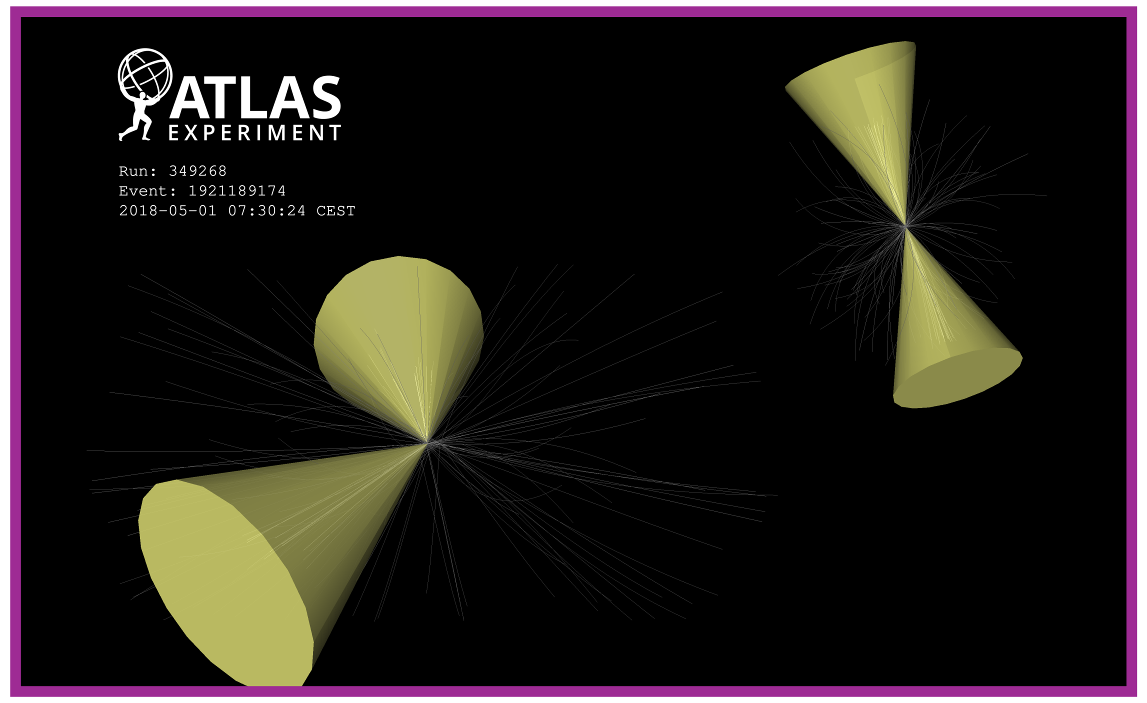
They have seen a wide variety of applications in collider physics for over 50 years.

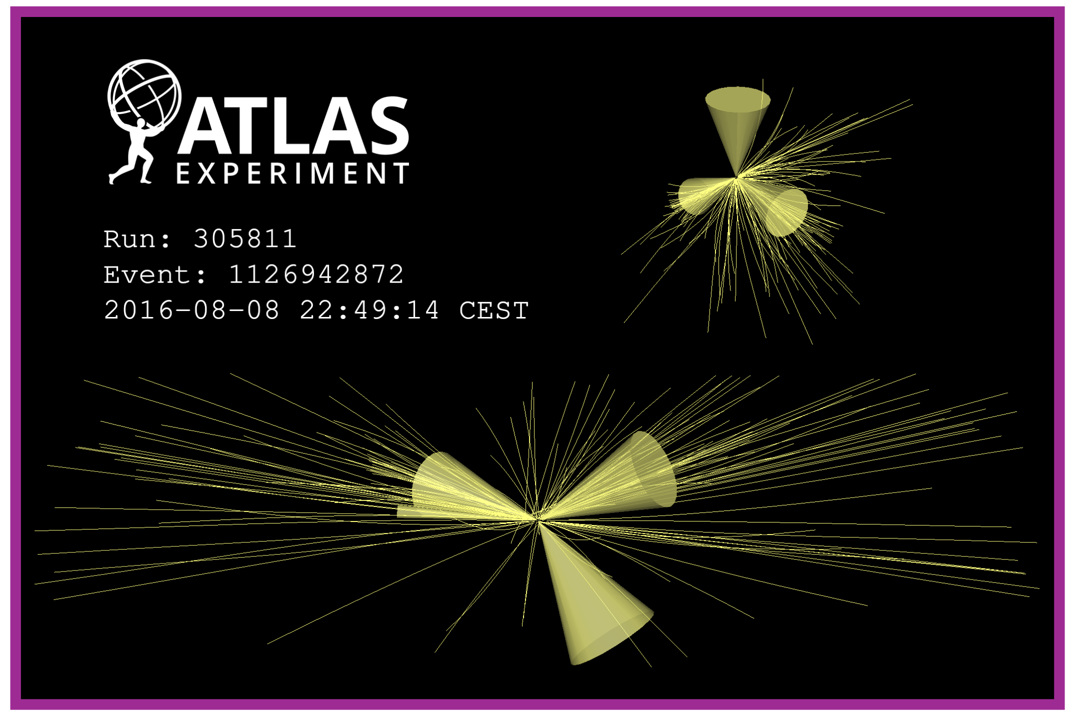
Transverse Thrust

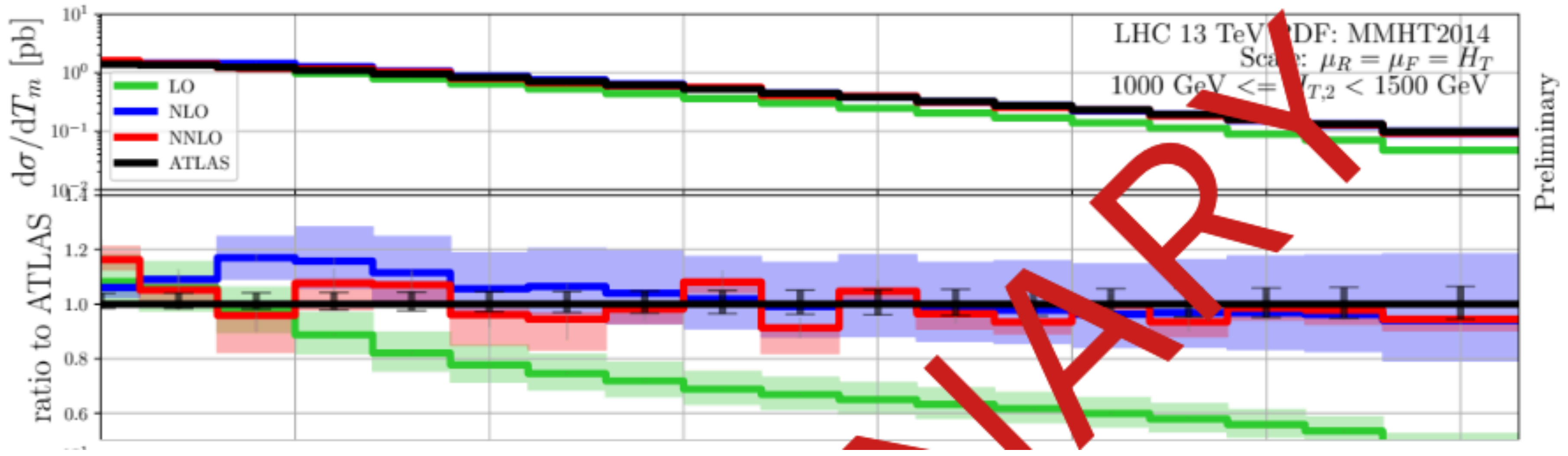
- **Transverse Thrust** is an extremely well-understood event shape in *pp* collisions.
  - Quantifies how "back-to-back" an event is.
    - Small values: back-to-back.
    - Largest values: Mercedes events
      - (c.f. Fig. 1 in STDM-2019-02), or event displays here.
- ***Are Mercedes events isotropic?***
  - Transverse thrust really just quantifies if an event is back-to-back, or *not back-to-back*.



Small Trans. thrust ⟷ Large Trans. thrust





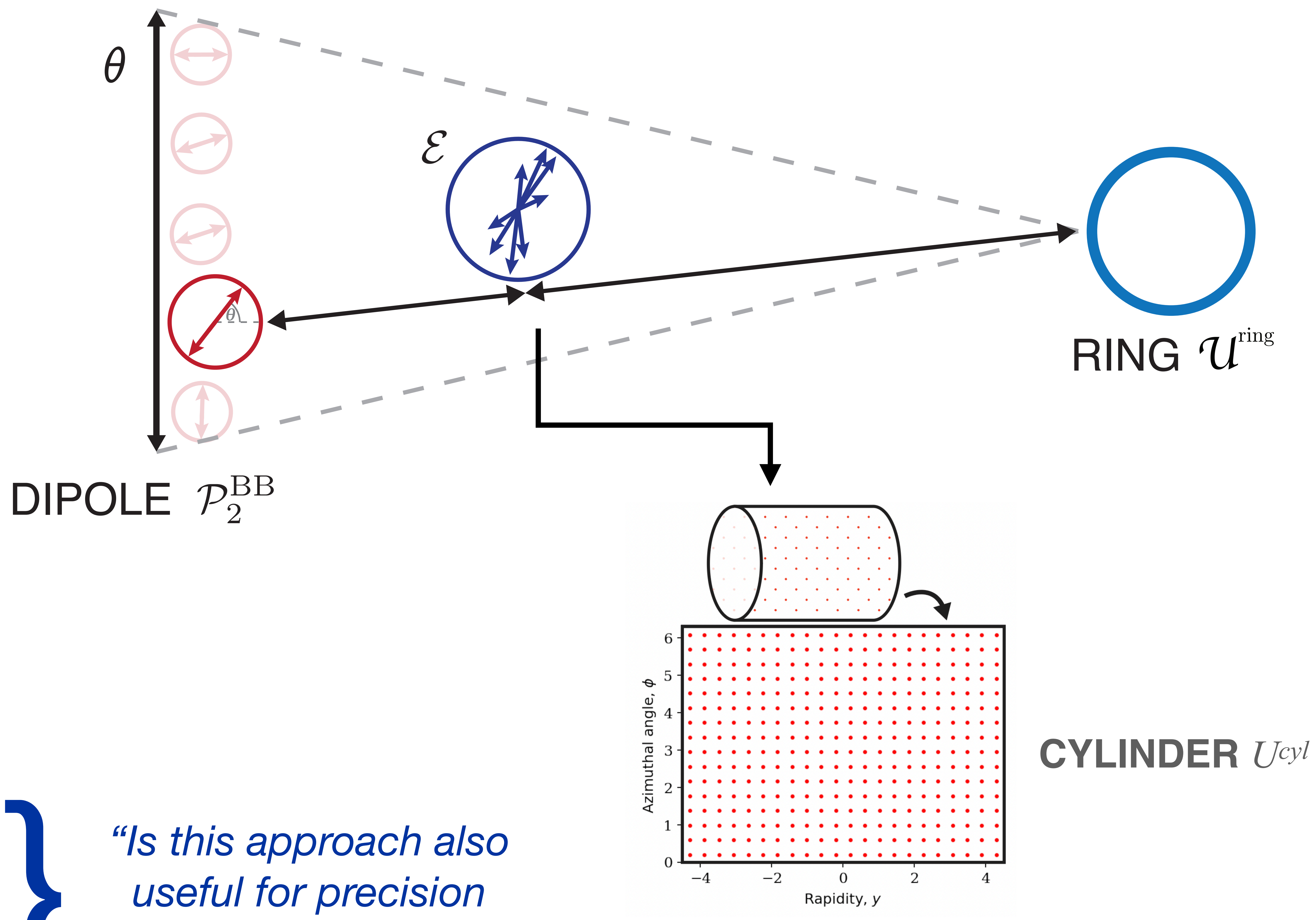


R. Poncelet @ Moriond QCD '22 Trans. Thrust w/ 2,3 jets @ NNLO

Event Isotropy

Cesarotti + Thaler, 2004.06125

- Quantifies how **far** the radiation pattern of a collider event is from a **isotropic** distribution.
  - Will define what I mean by **far** precisely on the next slide.
- We will be precise with what we mean by **isotropic**.
  - Isotropic in *transverse plane*? → **ring-like**
  - Isotropic in *rapidity-azimuth*? → **cylindrical**
- Original proposal motivated by certain BSM models that do not produce 'jetty' signatures.
  - Certain dark showers models, SUEP, low-mass instantons, etc.



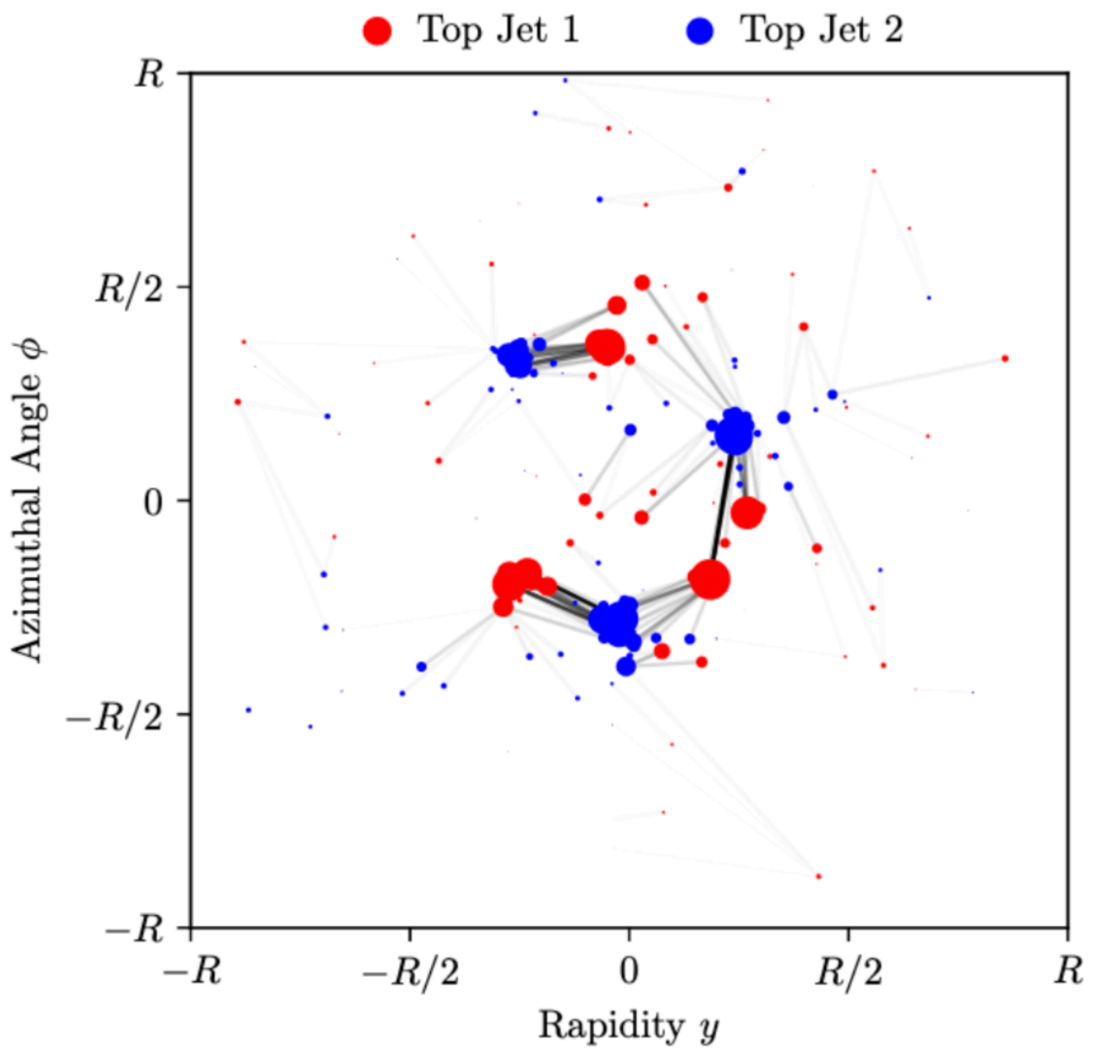
"Is this approach also useful for precision QCD studies?"

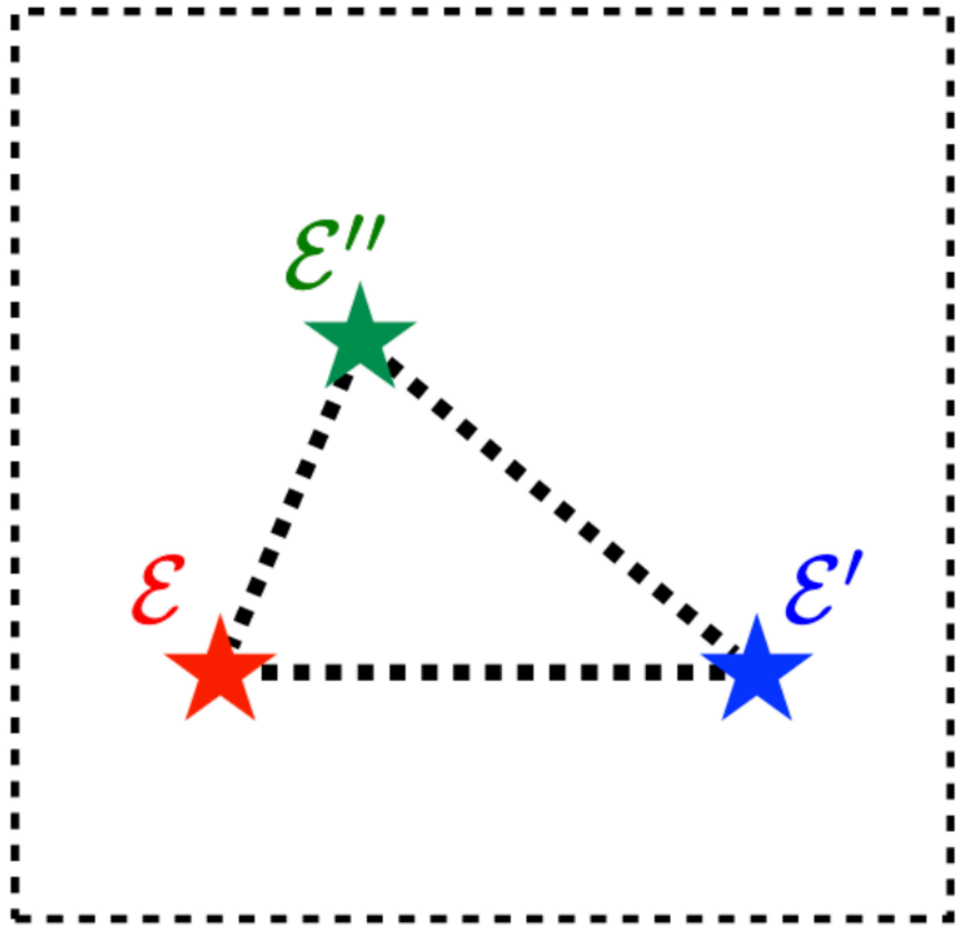
Energy-Mover's Distance (EMD)

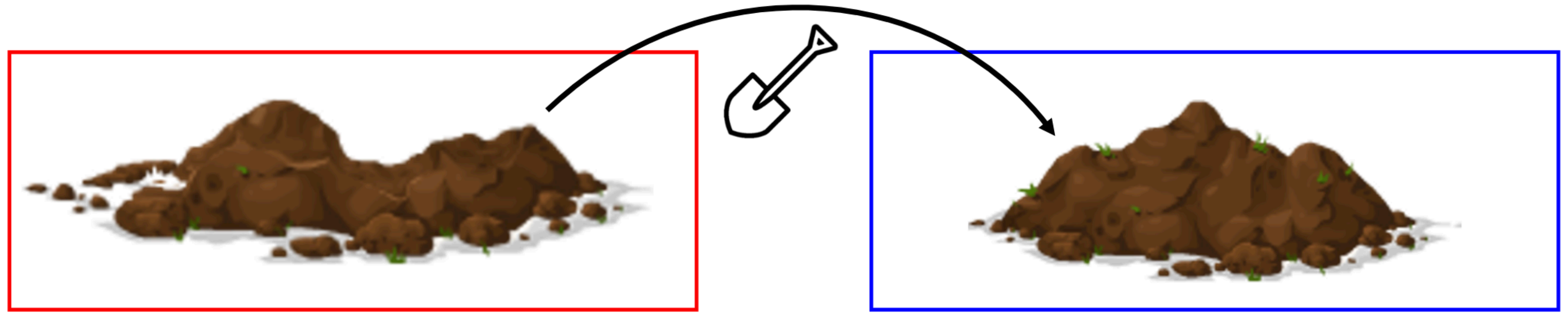
Komiske, Metodiev + Thaler, 2004.06125

$$\mathrm{EMD}_\beta(\mathcal{E},\mathcal{E}') = \min_{\{f_{ij}\geq 0\}} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij}\theta_{ij}^{\beta}$$

- Need to define a **IRC-safe distance metric** between collider radiation patterns.
  - EMD defines the **minimum work required to re-arrange one event into another**.
  - Given a metric, we can study collider physics using techniques from **topology**.
    - Corresponds to the ***p*-Wasserstein** class of metrics.
- This metric is often utilized in computer vision: formulated as **Optimal Transport** problems.
  - We can solve these problems with computer vision tools/libraries. 1, 2, 3
    - Some have even been adapted for particle physics use since this analysis began! 4, 5



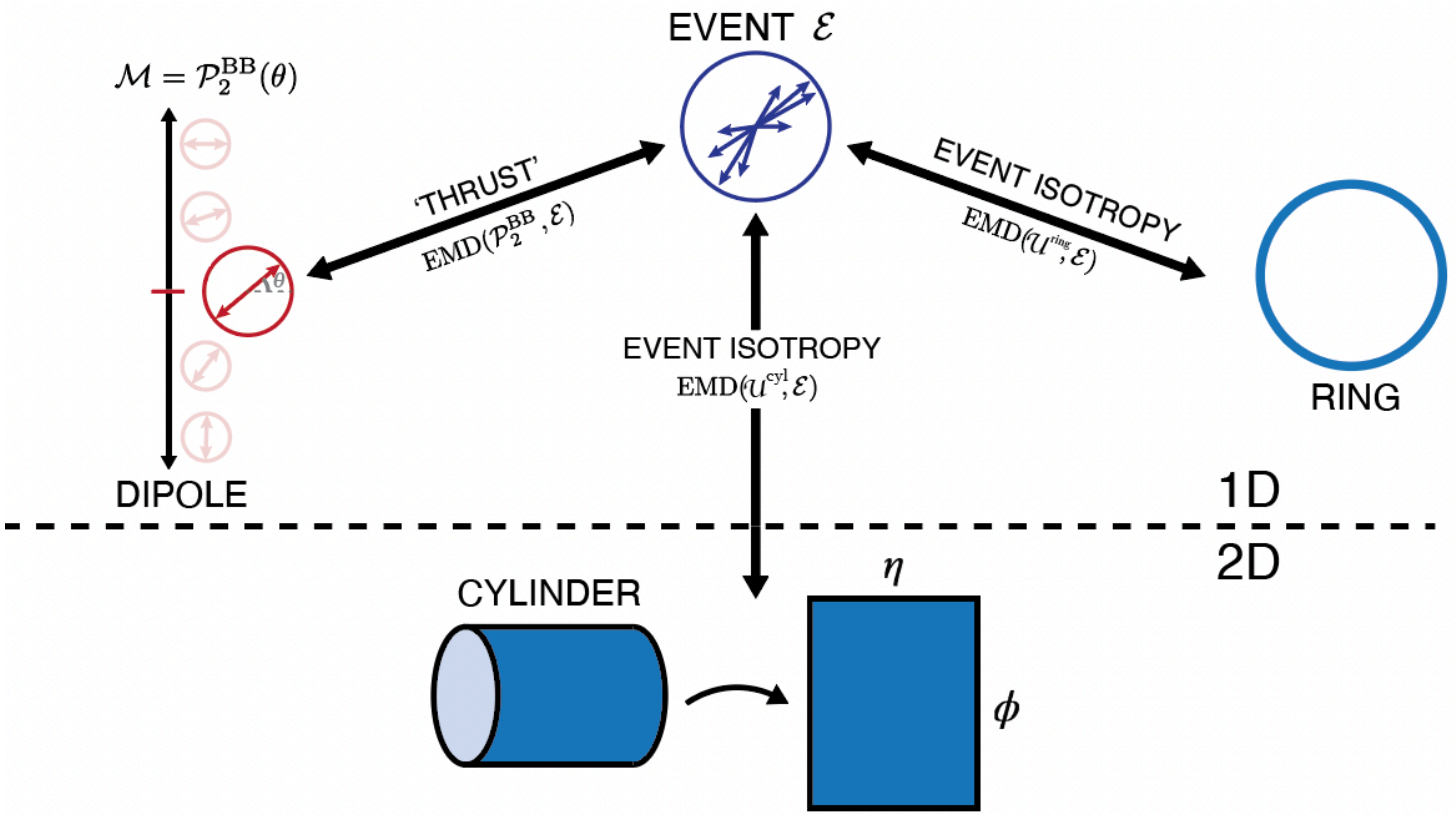




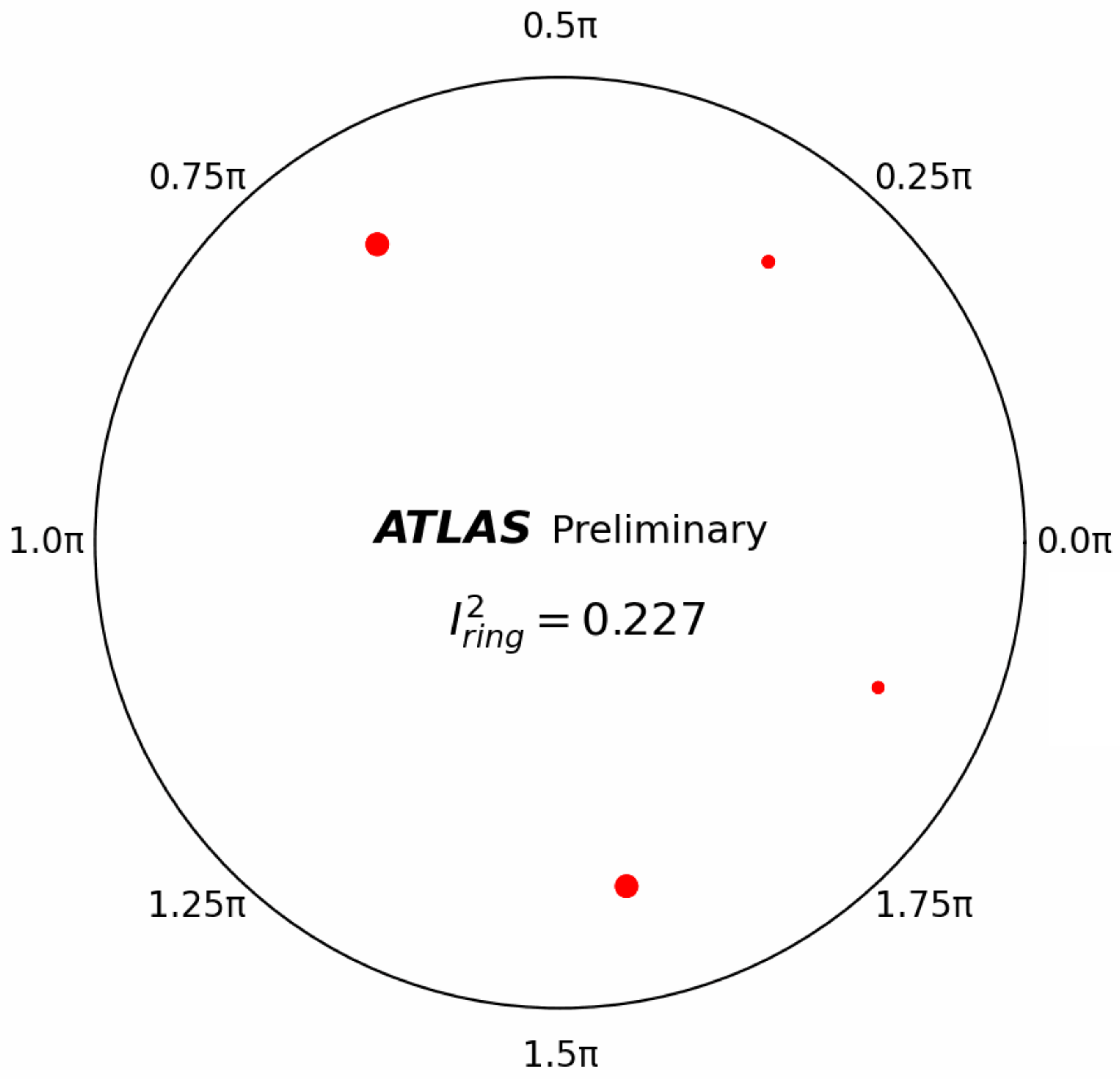
a.k.a. Earth-Mover's Distance

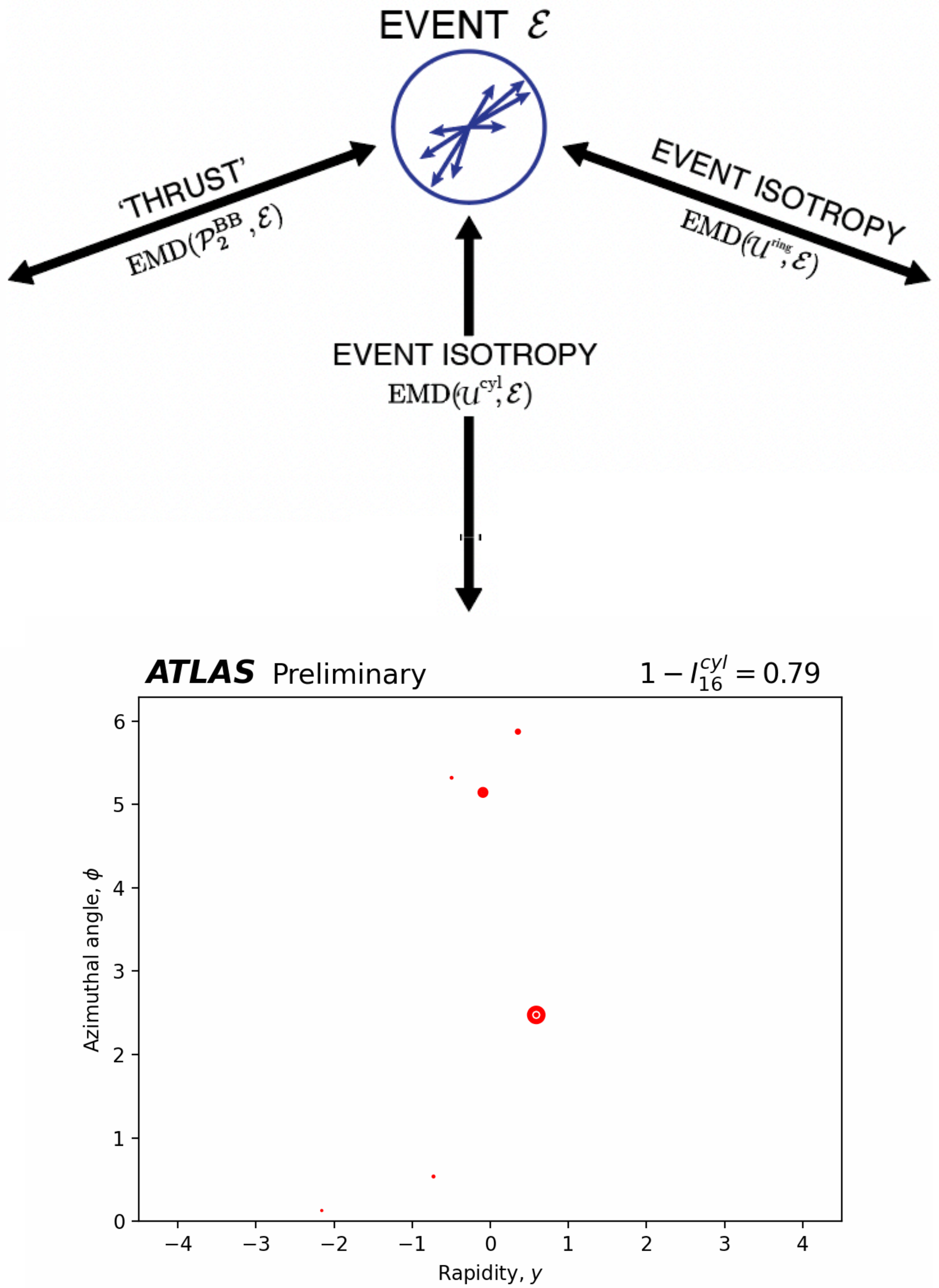
The Plan

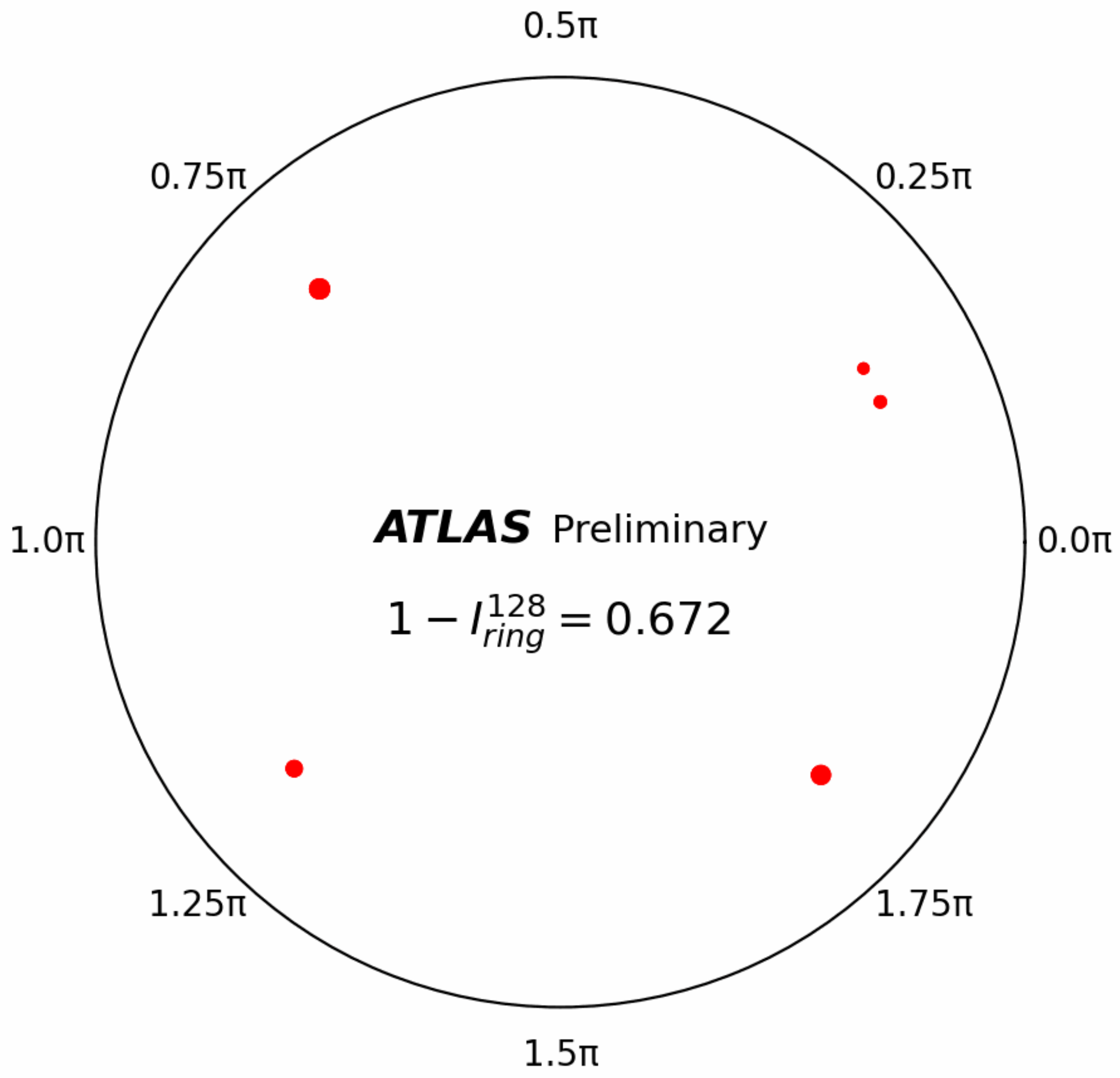
- **We measured three EMDs, per-event:**
  - The two maximally-distant 1D isotropies that conserve transverse momentum.
    - **IsoRing2** is equivalent to transverse thrust — can be used to directly evaluate performance of **IsoRing128**.
  - The 2D extension of isotropy into rapidity-phi space (**IsoCyl16**).
- Take calibrated R=0.4 PFlow jets with p_T > 60 GeV, $|y|$ < 4.4 as inputs to calculations.
  - Calculation also includes jet-based recoil vector to balance visible momenta.
- Measurement made in inclusive bins of jet multiplicity and $H_{T2} = p_{T,1}+p_{T,2}$.



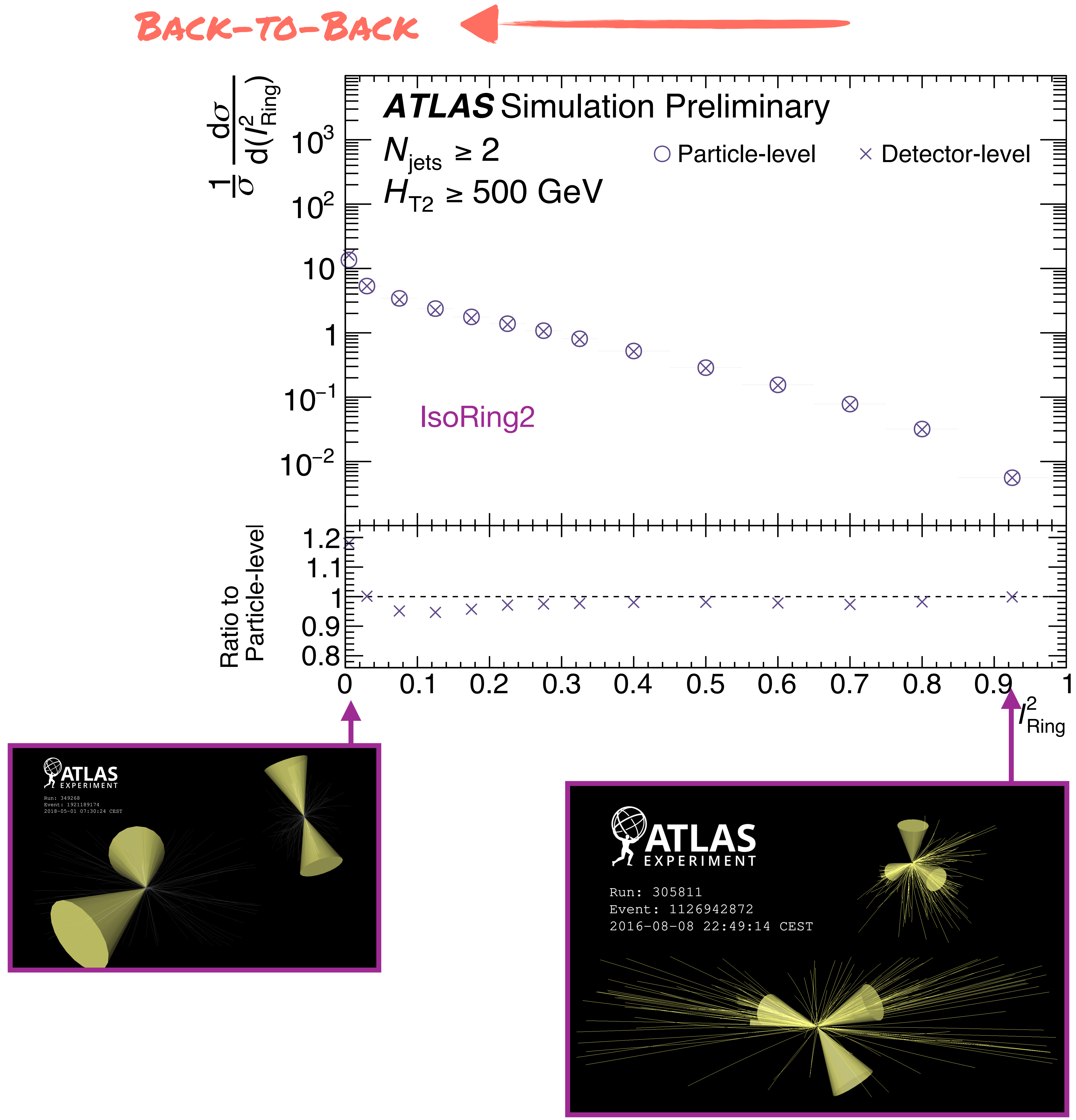
Animated Visualisations of OT Calculation

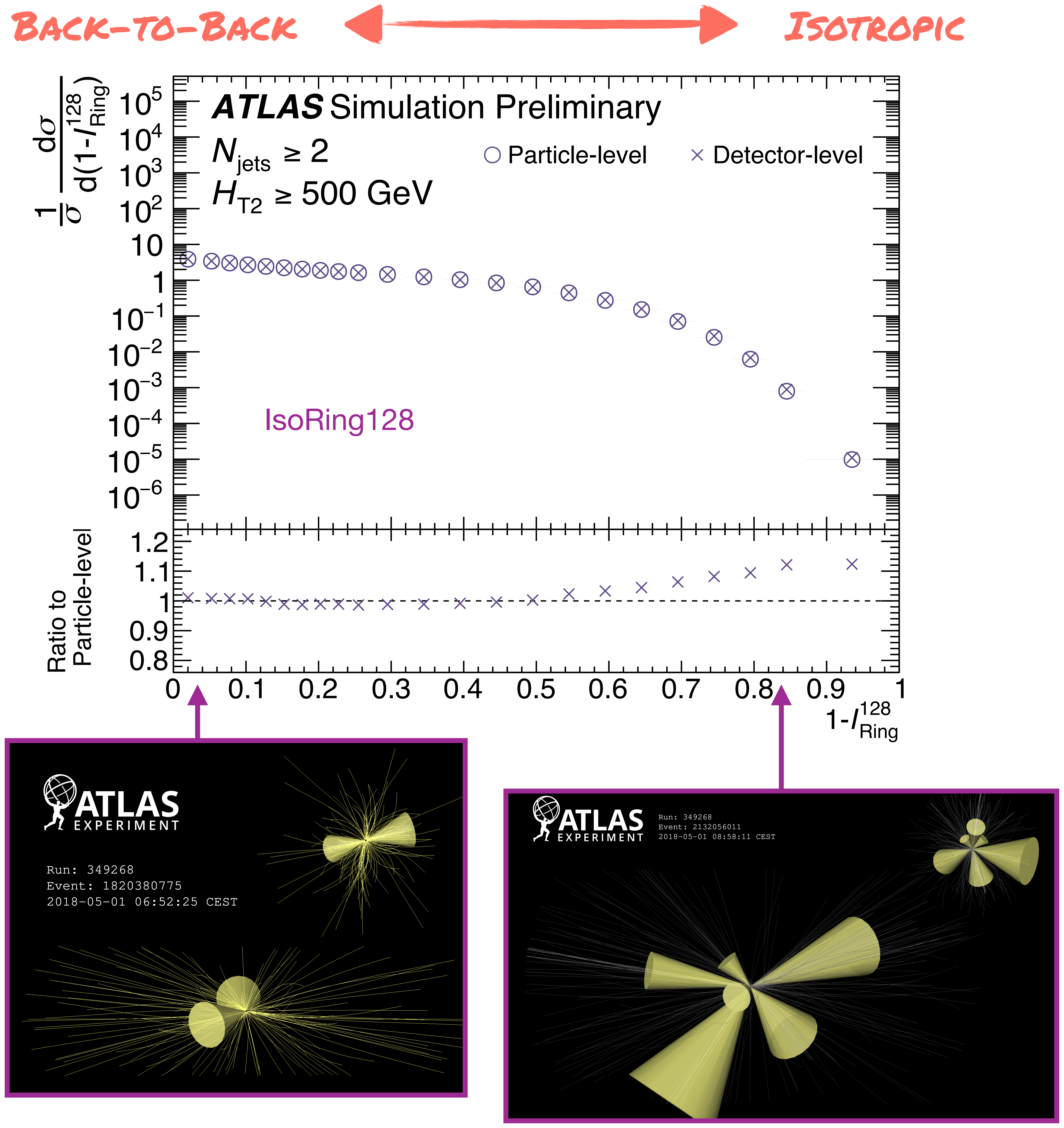




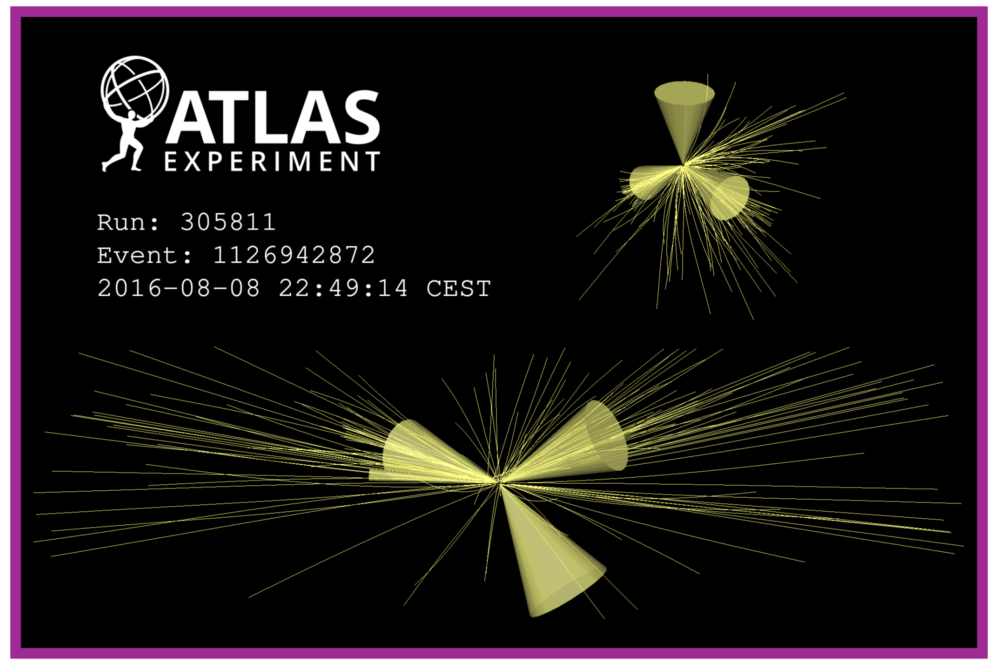


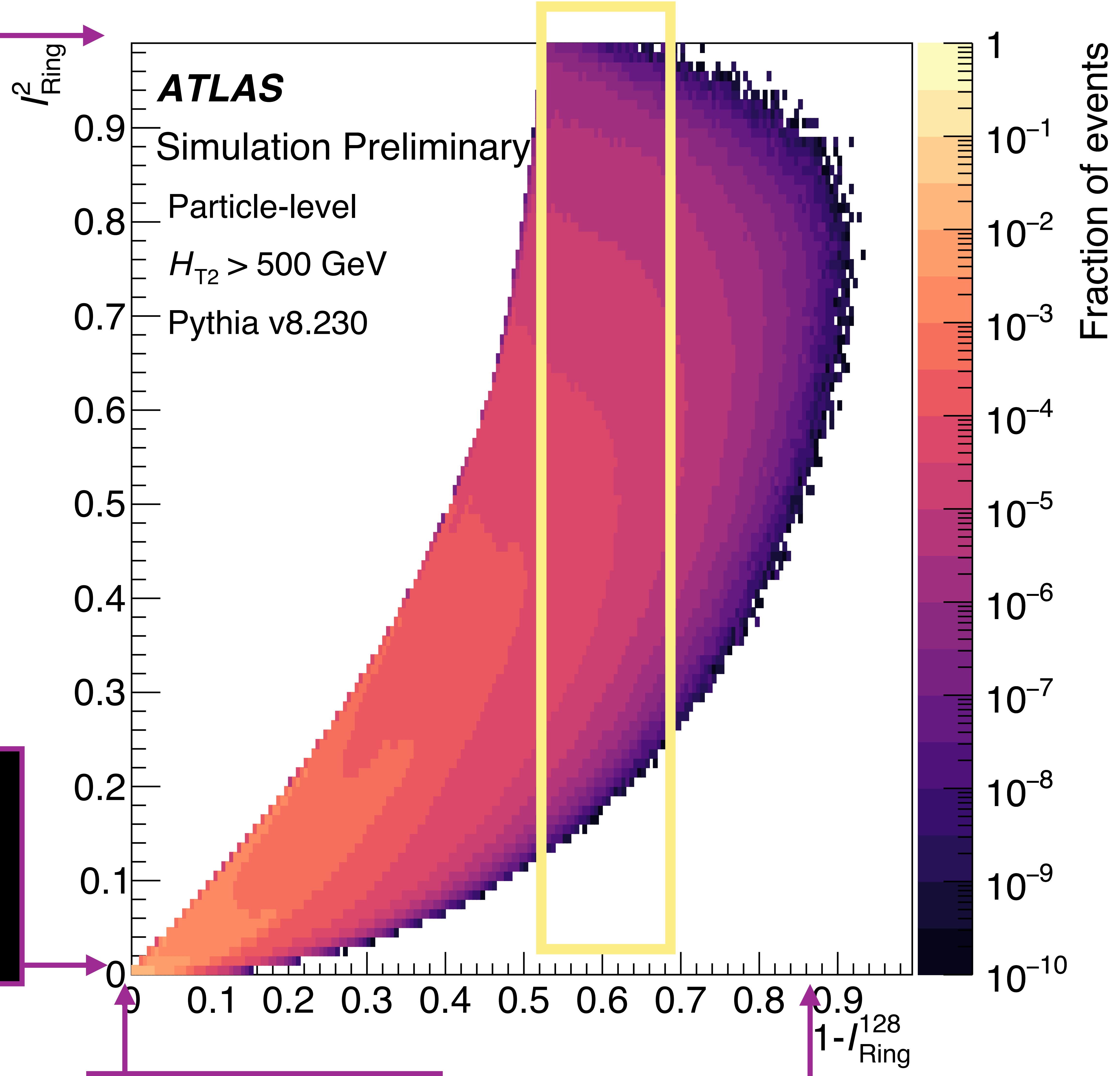
Animations are at this link :
https://cernbox.cern.ch/index.php/s/rYYF20n3je2rtXI

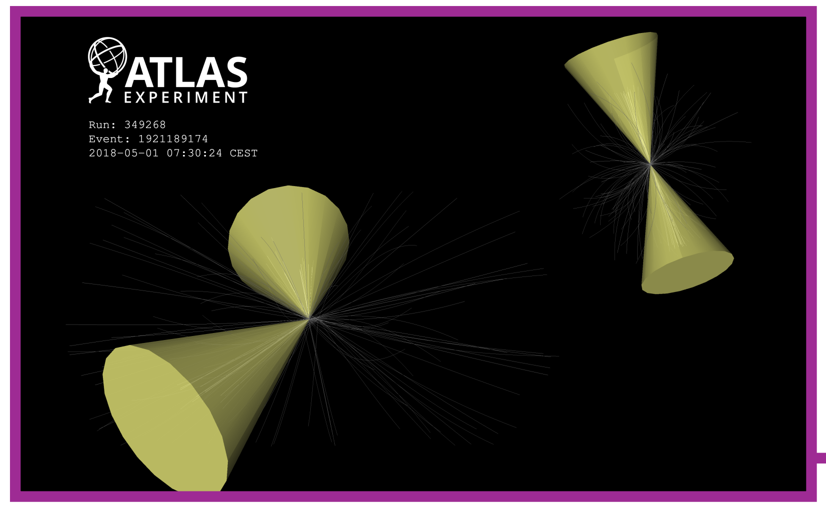


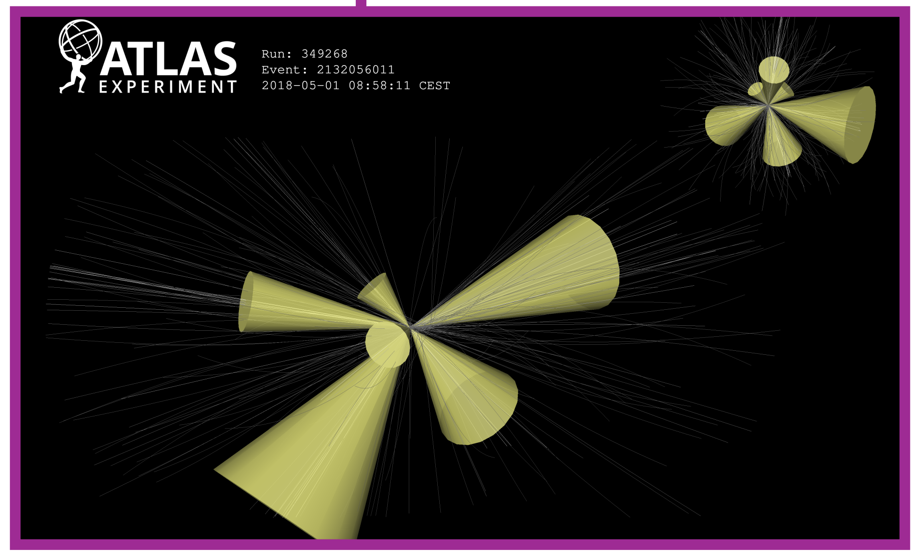


IsoRing2 and IsoRing128 take extreme values for ***qualitatively different*** events.
IsoRing128 takes extreme values for much *rarer* multijet final states (***increased dynamic range***).









Events that saturate IsoRing2 only have intermediate IsoRing128 values! (**“increased dynamic range”**)

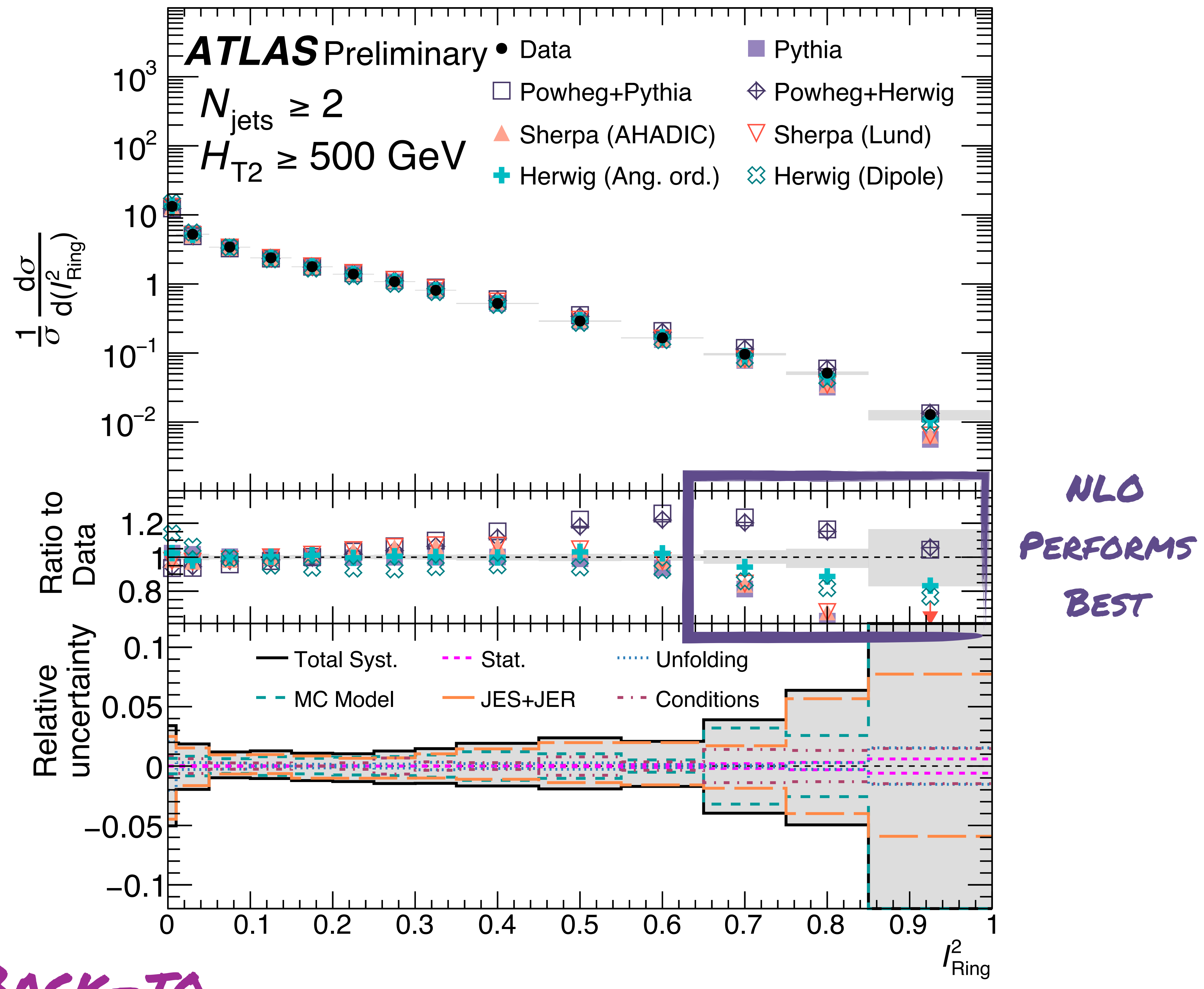
IsoRing128 saturated by “perfectly (and only perfectly) isotropic events.”

3-pronged configurations are **not isotropic in the same way** as a multijet event.

Results: I_{Ring}^{128} & I_{Ring}^{2}

ATLAS CONF-STDM-2022-12 (New!)

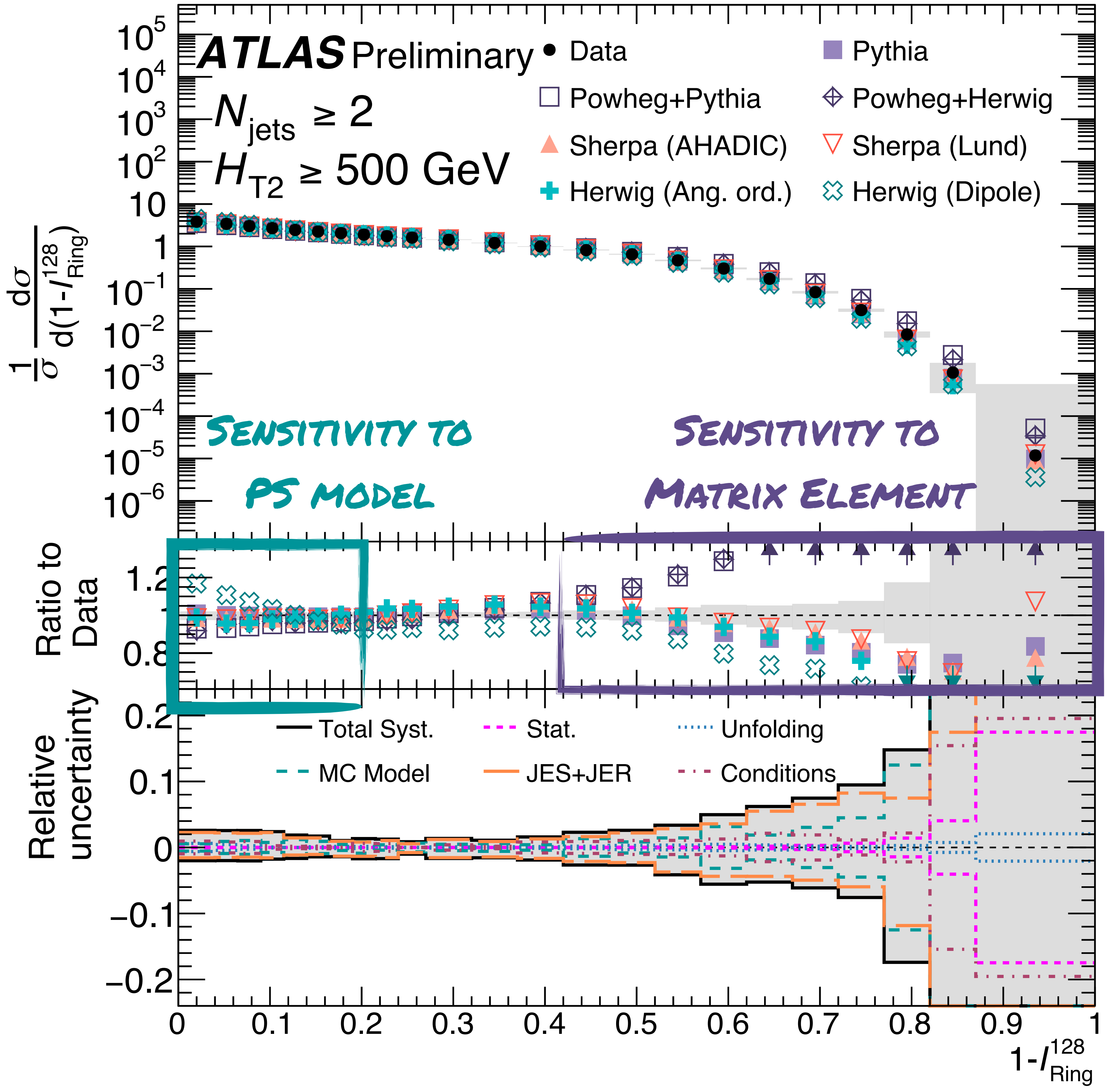
"Transverse Thrust"



NLO Performs Best

Back-to-Back ⟷ Trijets

Ring-like Isotropy



Larger Dynamic Range

Dijets ⟷ Isotropic


ATLAS
EXPERIMENT
Run: 349268
Event: 2132056011
2018-05-01 08:58:11 CEST
$1-I_{Ring}^{N=128} = 0.83$
$1-I_{Cyl}^{N=16} = 0.85$
$N_{jet} = 6$


ATLAS EXPERIMENT
Run: 349268
Event: 1921189174
2018-05-01 07:30:24 CEST
$I_{Ring}^{N=2}$ = 0.0001
N_{jet} = 2

Run: 359010
Event: 4395980669
2018-08-24 11:01:18 CEST

$1 - I_{Cyl}^{N=16} = 0.48$

$N_{jet} = 2$

Inset from Cesarotti & Thaler, 2004.06125

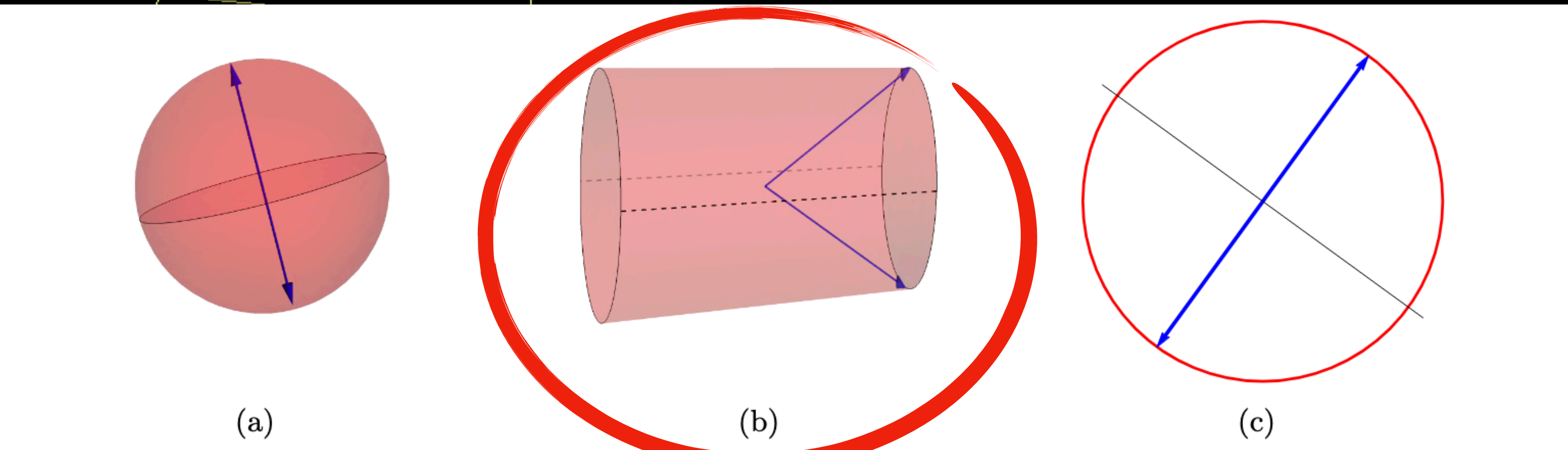


Figure 2. Event configurations that maximize event isotropy (i.e. least isotropic), assuming balanced (transverse) momentum. The optimal EMD transportation plan is determined by partitioning the uniform event, where the sphere (a) is partitioned into two hemispheres, the cylinder (b) is separated along the dashed lines at fixed ϕ and $\phi + \pi$, and the ring (c) is divided in half.