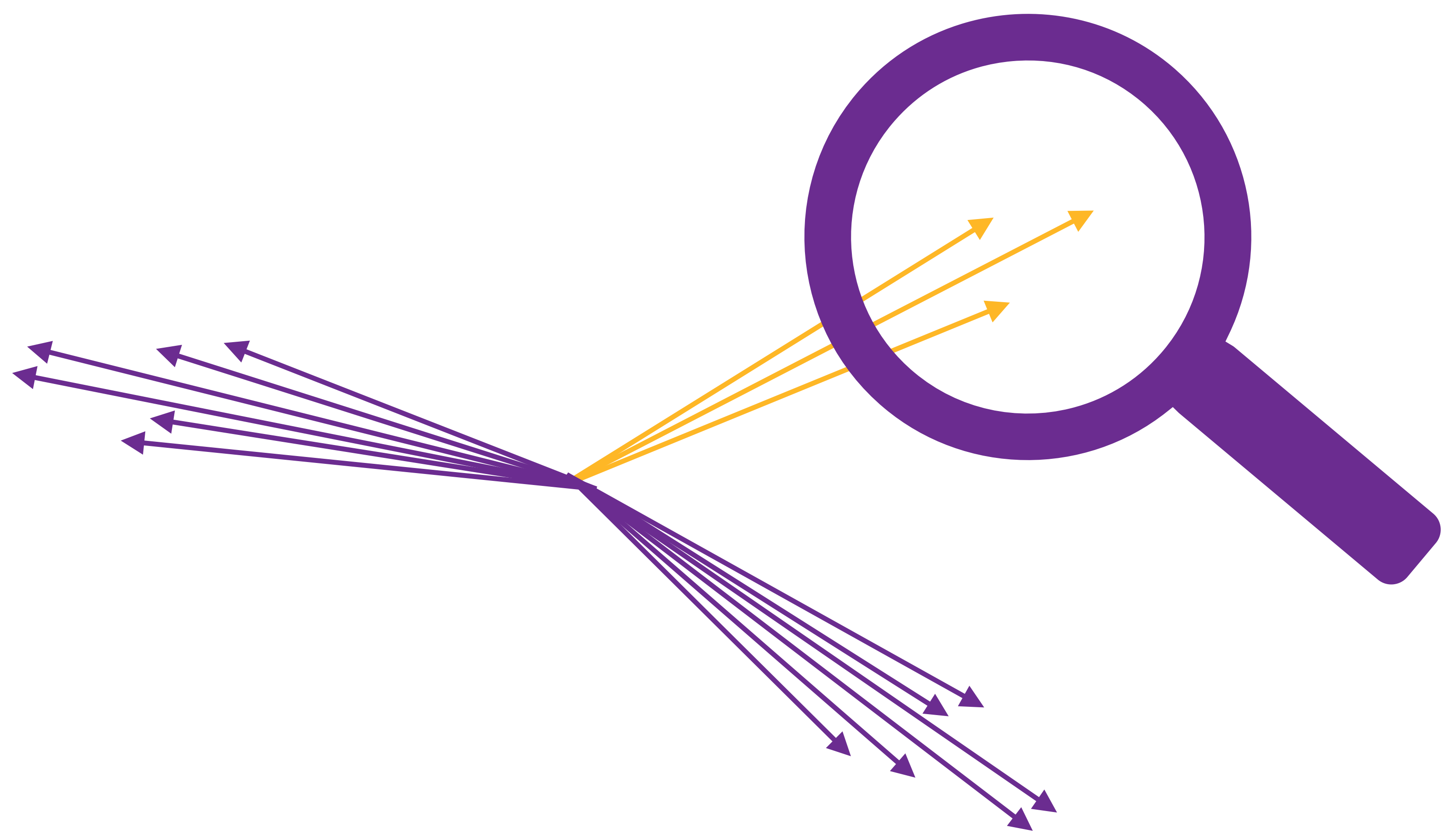


Perspectives on hadronic final states, from up close & far away

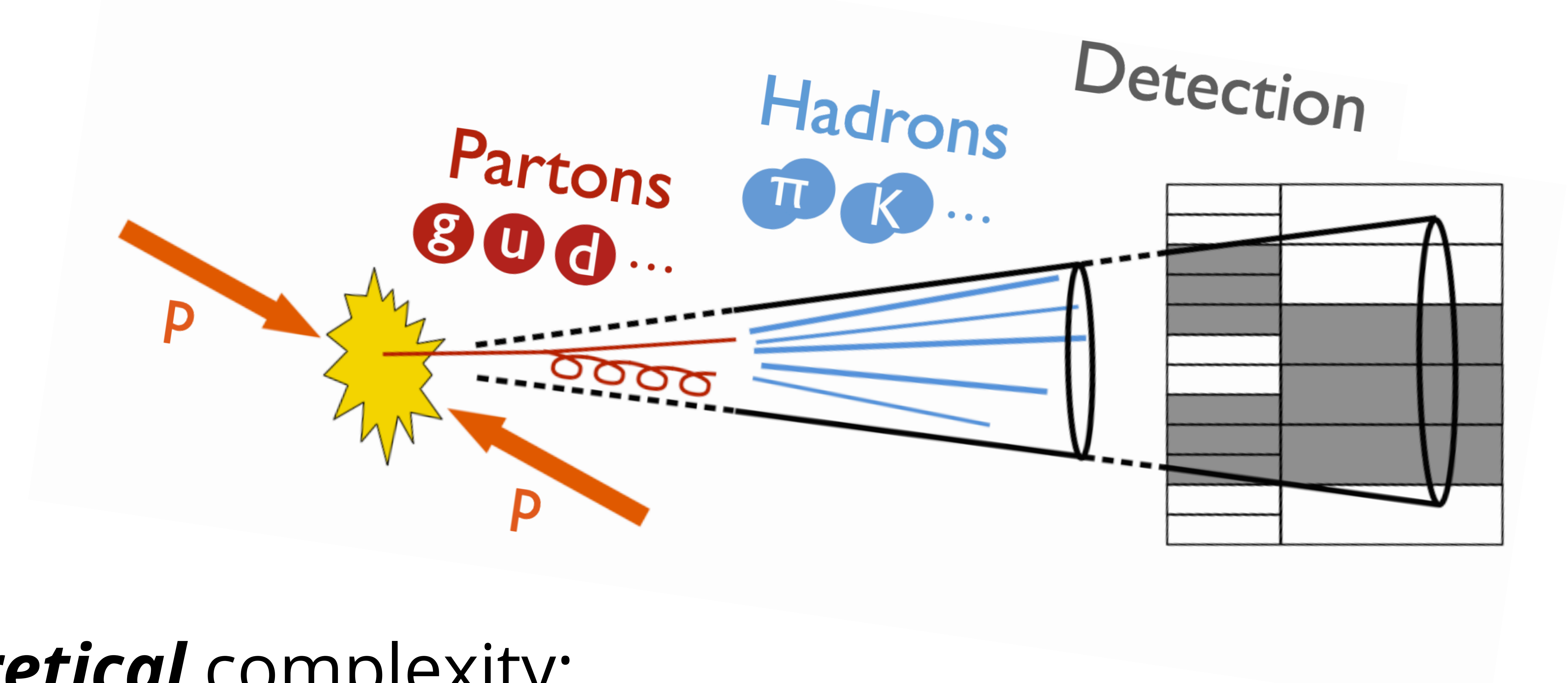
Università di Genova (Genoa, Italy), 2023.05.24

Matt LeBlanc (Manchester)
matt.leblanc@cern.ch, @TopPhysicist

MANCHESTER 1824
The University of Manchester

ATLAS EXPERIMENT

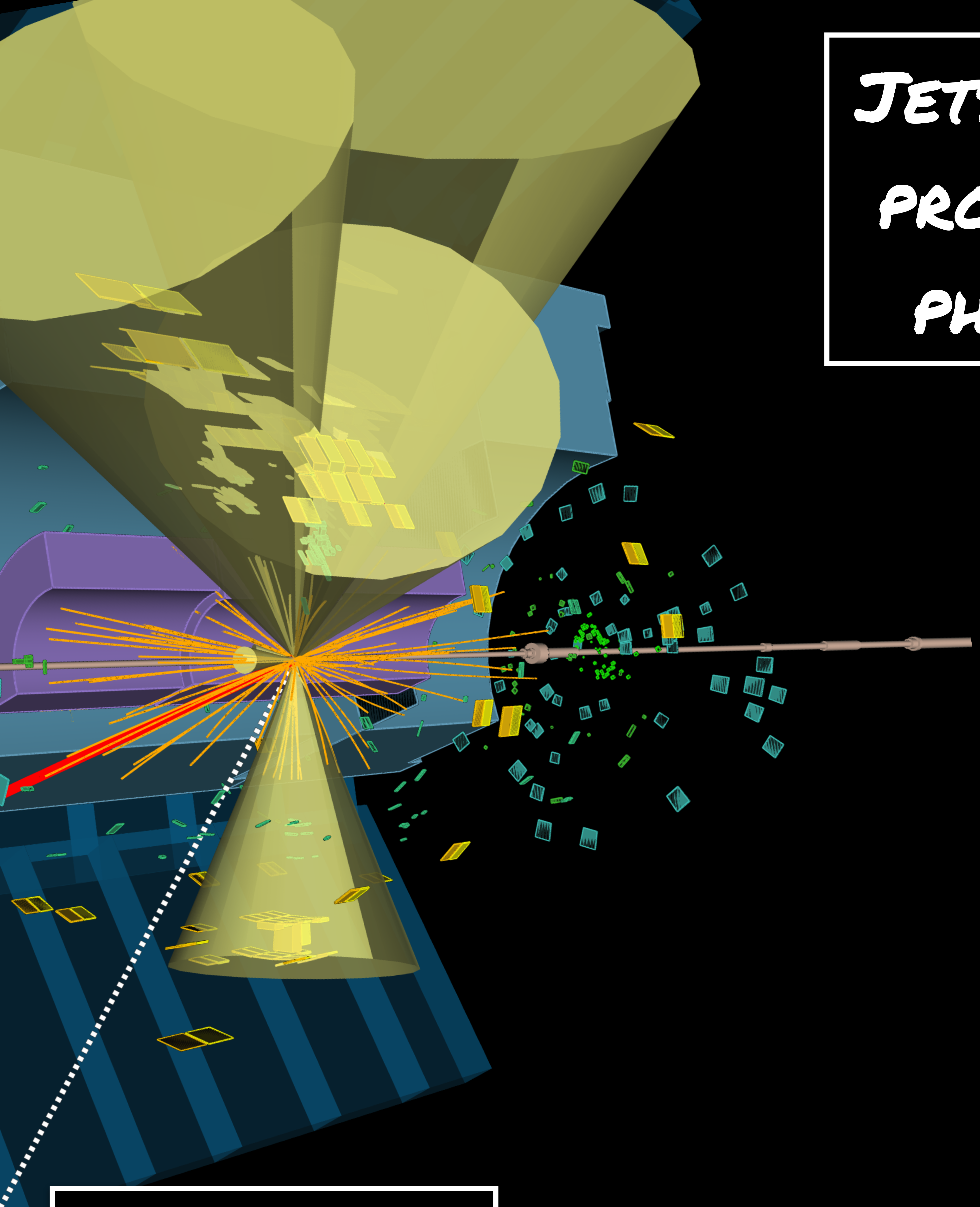
- **Jets are formed when high-energy quarks and gluons are produced in LHC collisions** (Proxy for parton momentum).
- ***Jets are complex: composite objects w/ multiple scales, large areas.***



- ***Theoretical*** complexity:
  - fixed-order aspects
  - resummation-dominated aspects
  - non-perturbative aspects
- ***Experimental*** complexity:
  - Calorimeter signals
  - Charged-particle tracks

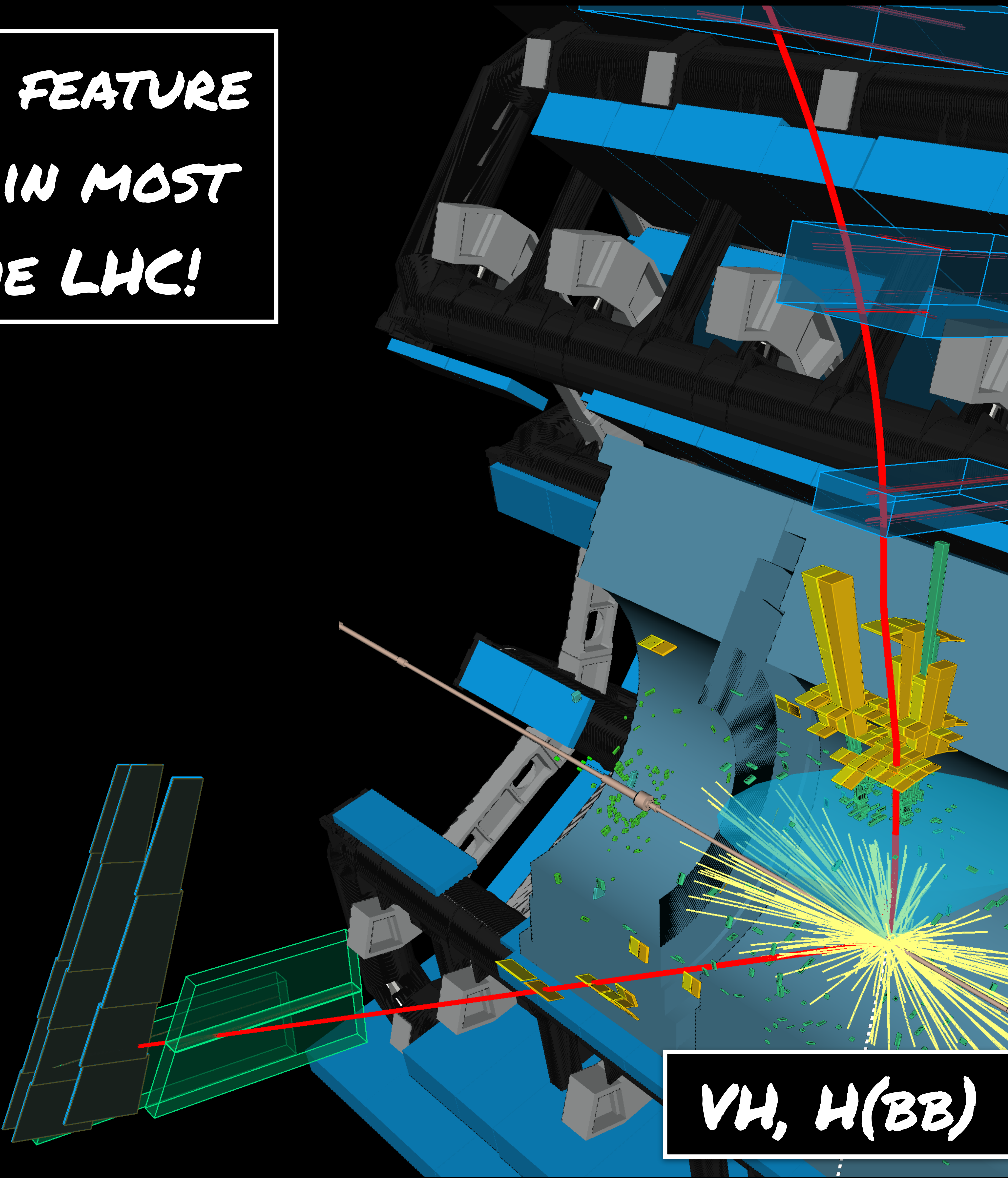
Cartoon from E. Metodiev

Jets and QCD feature prominently in most physics @ the LHC!



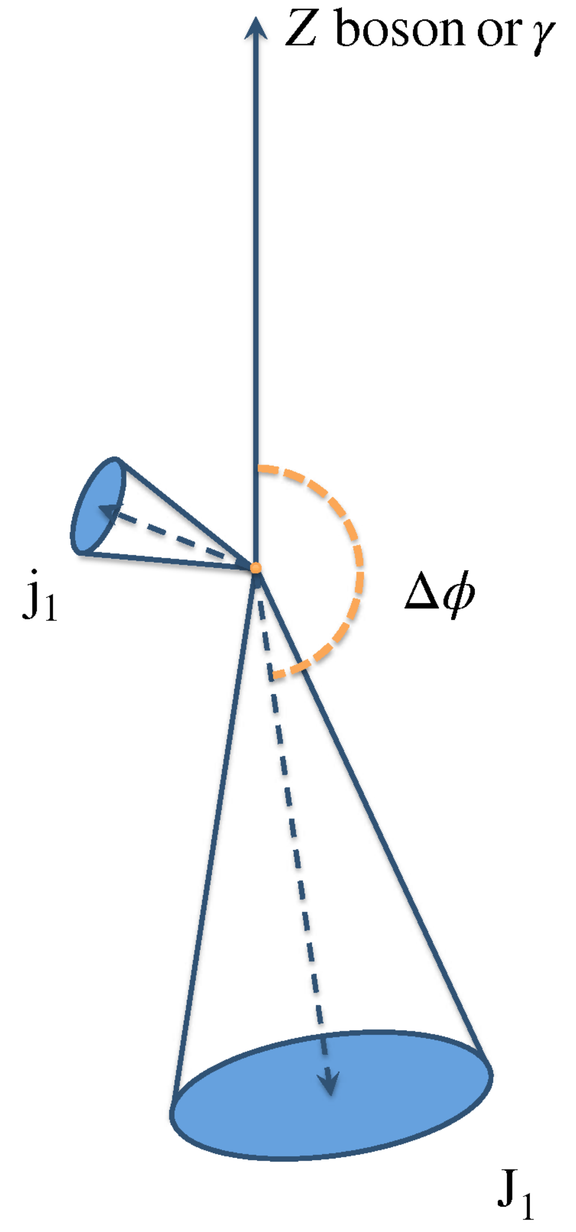
Top mass m_T

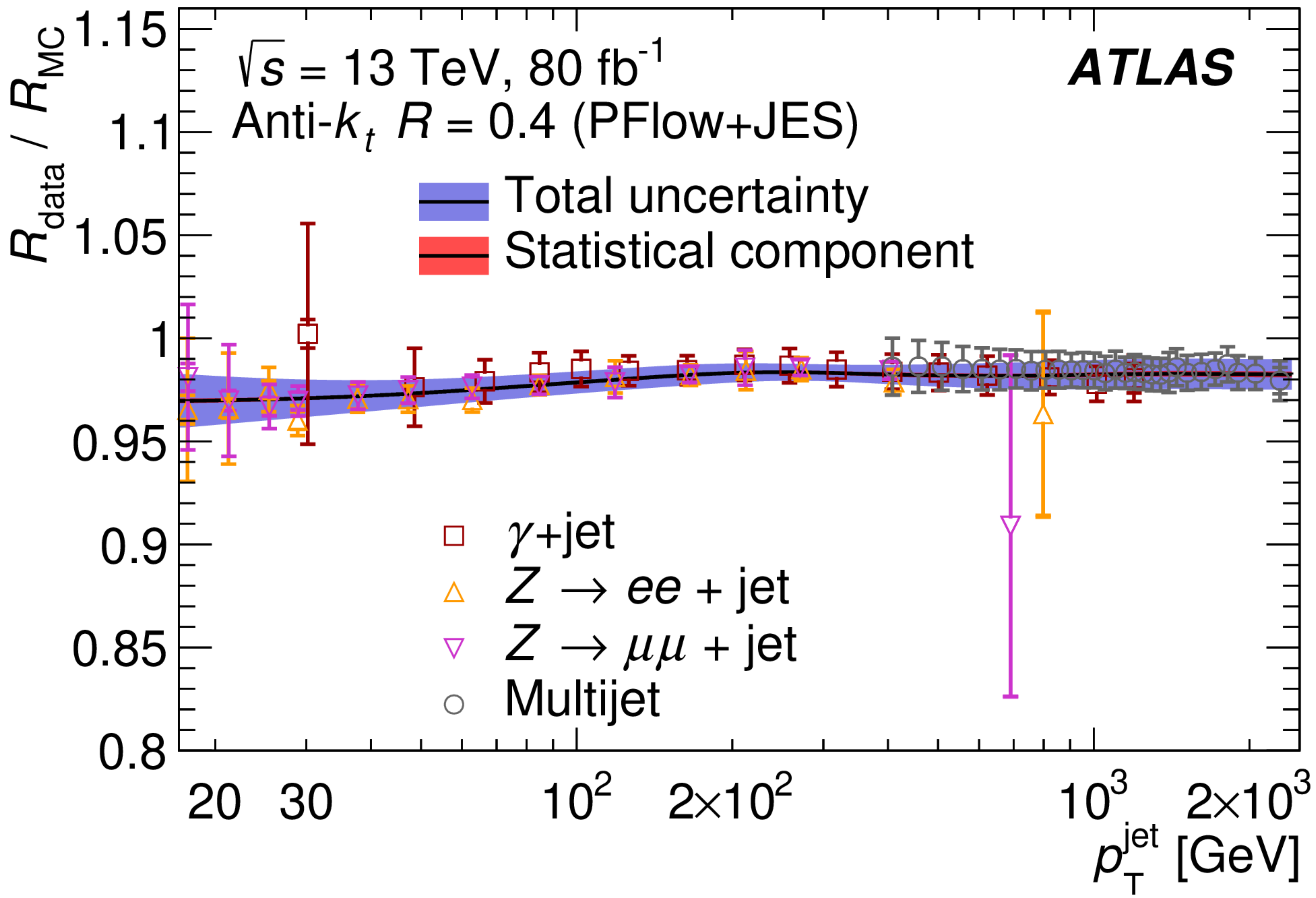
ATLAS, EPJC 79 (2019) 290

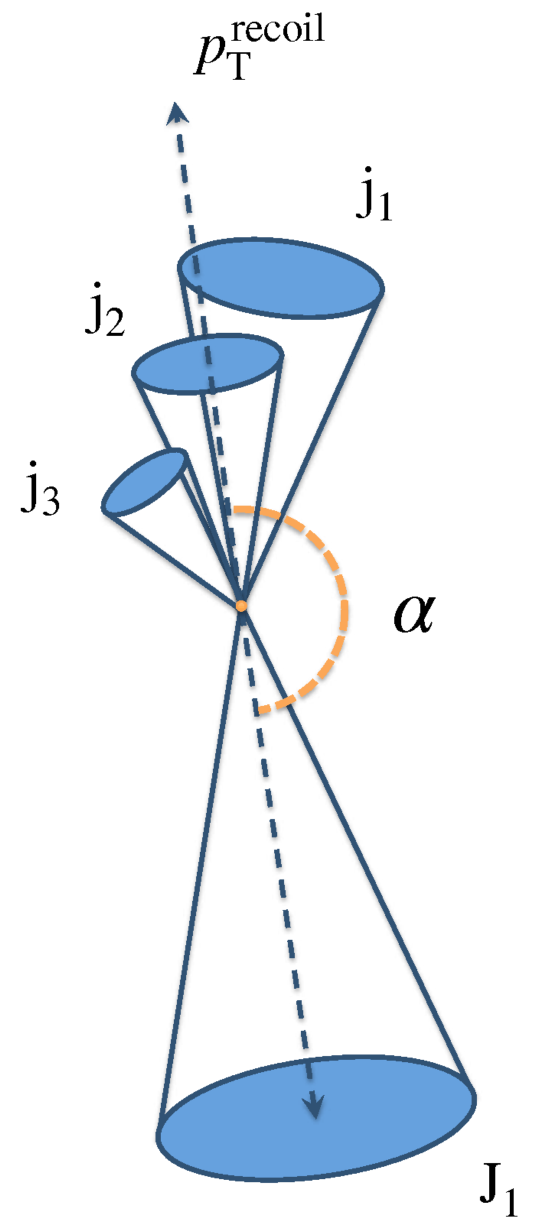


VH, H(bb)

ATLAS, PLB 816 (2021) 136204



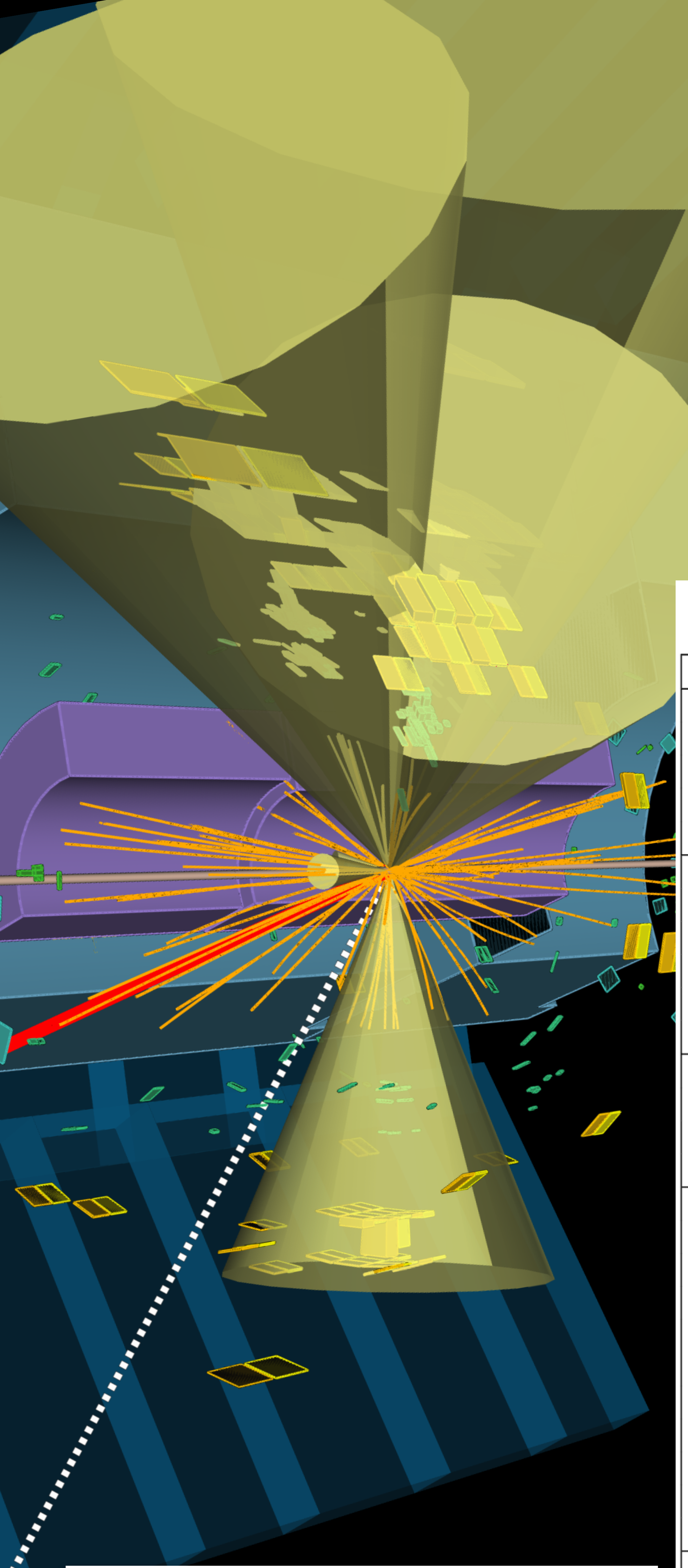




- Experimentalists at the LHC **work hard to calibrate the jet energy scale (JES)** using *in situ* balance measurements.
  - Not a topic for today, but one near & dear to me: ***ATLAS*** has recently achieved sub-% JES precision over the widest-ever kinematic range!

ATLAS JES **Run 2:** EPJC 81 (2021) 689 **Run 3 (brand new!)**: 2303.17312

JETS AND QCD FEATURE PROMINENTLY IN MOST PHYSICS @ THE LHC!



k		$\sqrt{s} = 8$ TeV $m_{top}^{\ell+jets}$ [GeV]
k	Results ($i = 0 \ldots, 5$)	172.08
0	Statistics	0.39
	– *Stat. comp.* (m_{top})	0.11
	– *Stat. comp.* (JSF)	0.11
	– *Stat. comp.* (bJSF)	0.35
1	Method	0.13 ± 0.11
2	Signal Monte Carlo generator	0.16 ± 0.17
3	Hadronization	0.15 ± 0.10
4	Initial- and final-state QCD radiation	0.08 ± 0.11
5	Underlying event	0.08 ± 0.15
6	Colour reconnection	0.19 ± 0.15
7	Parton distribution function	0.09 ± 0.00
8	Background normalization	0.08 ± 0.00
9	W/Z+jets shape	0.11 ± 0.00
10	Fake leptons shape	0
11	Data-driven all-jets background	
12	Jet energy scale	0.54 ± 0.02
13	Relative b-to-light-jet energy scale	0.03 ± 0.01
14	Jet energy resolution	0.20 ± 0.04
15	Jet reconstruction efficiency	0.02 ± 0.01
16	Jet vertex fraction	0.09 ± 0.01
17	b-tagging	0.38 ± 0.00
18	Leptons	0.16 ± 0.01
19	Missing transverse momentum	0.05 ± 0.01
20	Pile-up	0.15 ± 0.01
21	All-jets trigger	
22	Fast vs. full simulation	
	Total systematic uncertainty	0.82 ± 0.06
	Total	0.91 ± 0.06

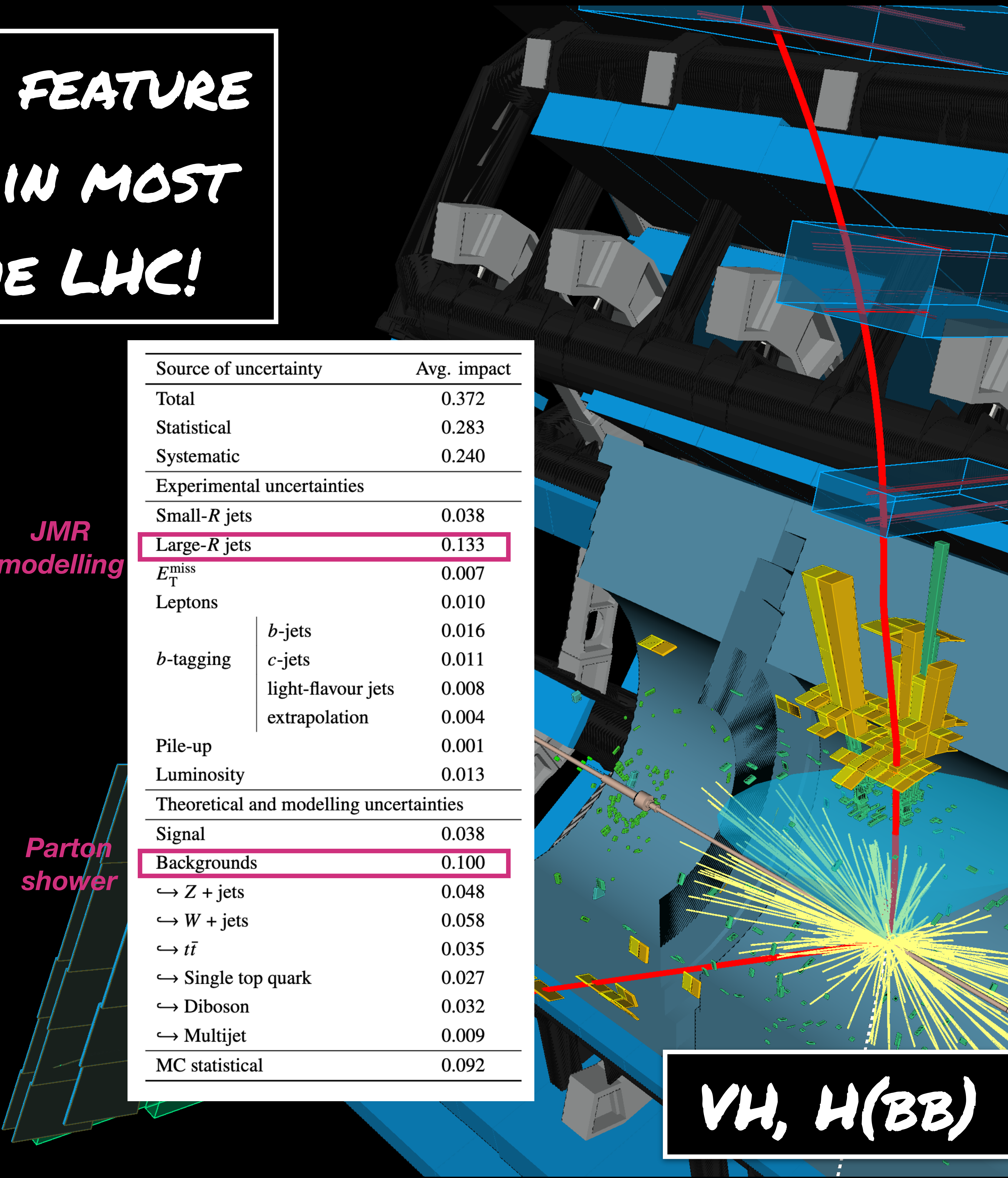
Modelling various aspects of QCD...

JES → Modelling here!

JMR modelling

Parton shower

Source of uncertainty		Avg. impact
Total		0.372
Statistical		0.283
Systematic		0.240
Experimental uncertainties		
Small-R jets		0.038
Large-R jets		0.133
E_T^{miss}		0.007
Leptons		0.010
b-tagging	b-jets	0.016
	c-jets	0.011
	light-flavour jets	0.008
	extrapolation	0.004
Pile-up		0.001
Luminosity		0.013
Theoretical and modelling uncertainties		
Signal		0.038
Backgrounds		0.100
↪ Z + jets		0.048
↪ W + jets		0.058
↪ $t\bar{t}$		0.035
↪ Single top quark		0.027
↪ Diboson		0.032
↪ Multijet		0.009
MC statistical		0.092



TOP MASS M_T

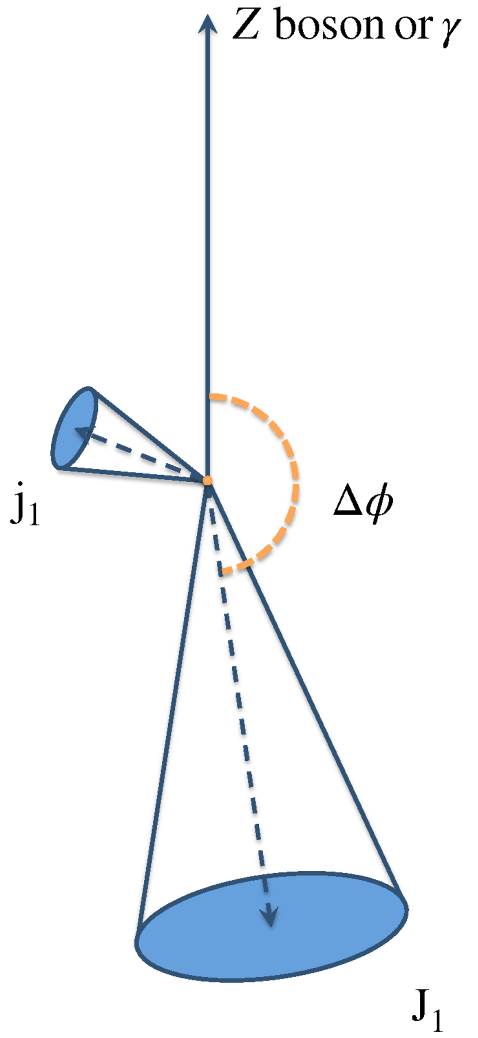
ATLAS, EPJC 79 (2019) 290

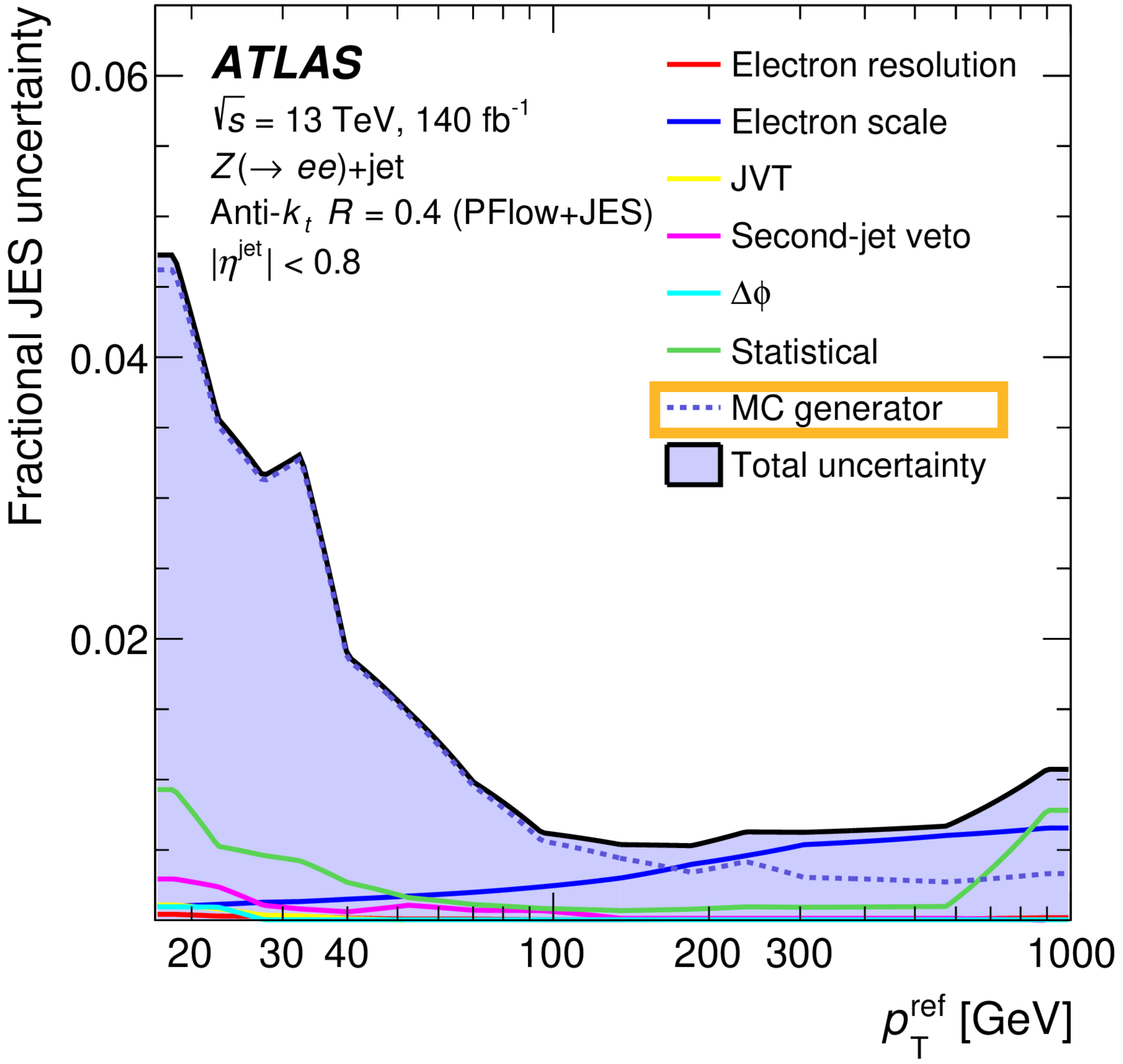
VH, H(BB)

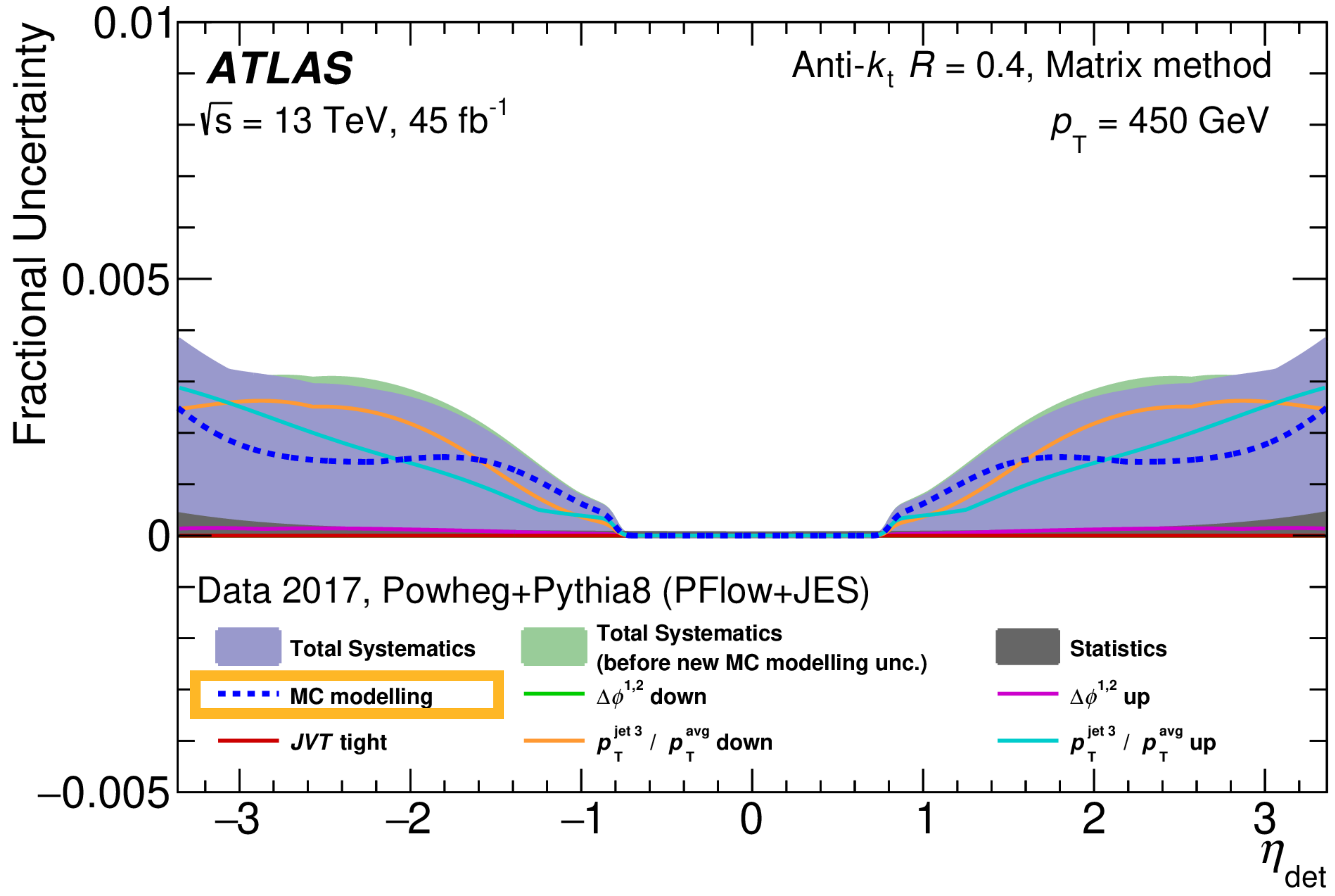
ATLAS, PLB 816 (2021) 136204

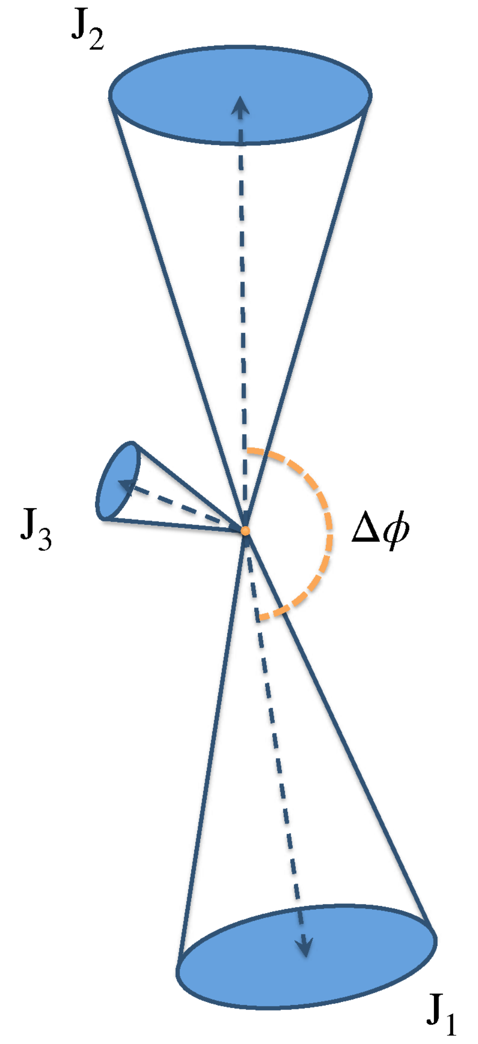
ATLAS Jet Energy Scale

ATLAS, 2303.17312 (brand new!)









- Even with our latest techniques, the *in situ* JES uncertainty is still driven by **the choice of nominal MC model** in many places…

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22	Fast vs. full simulation	
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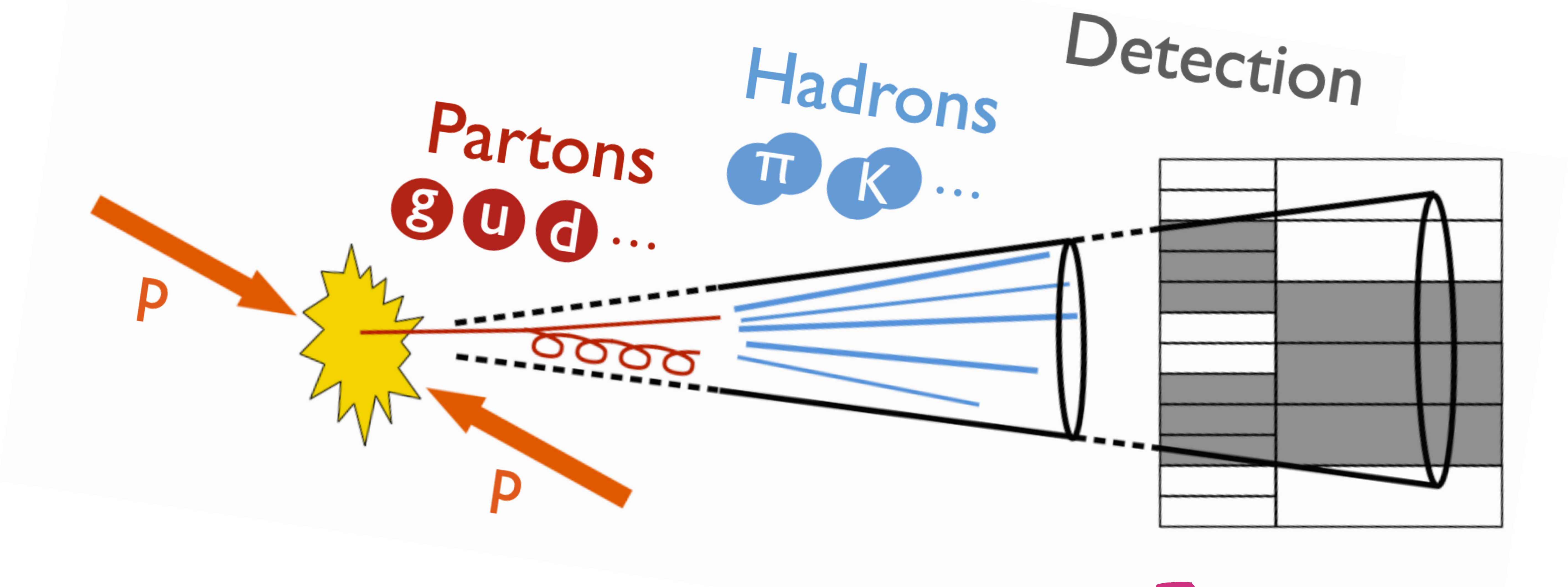
Various aspects of QCD…

JES/JER → Large parts from MC Modelling!

TOP MASS M_T

ATLAS, EPJC 79 (2019) 290



SIGNAL MC
PDFS

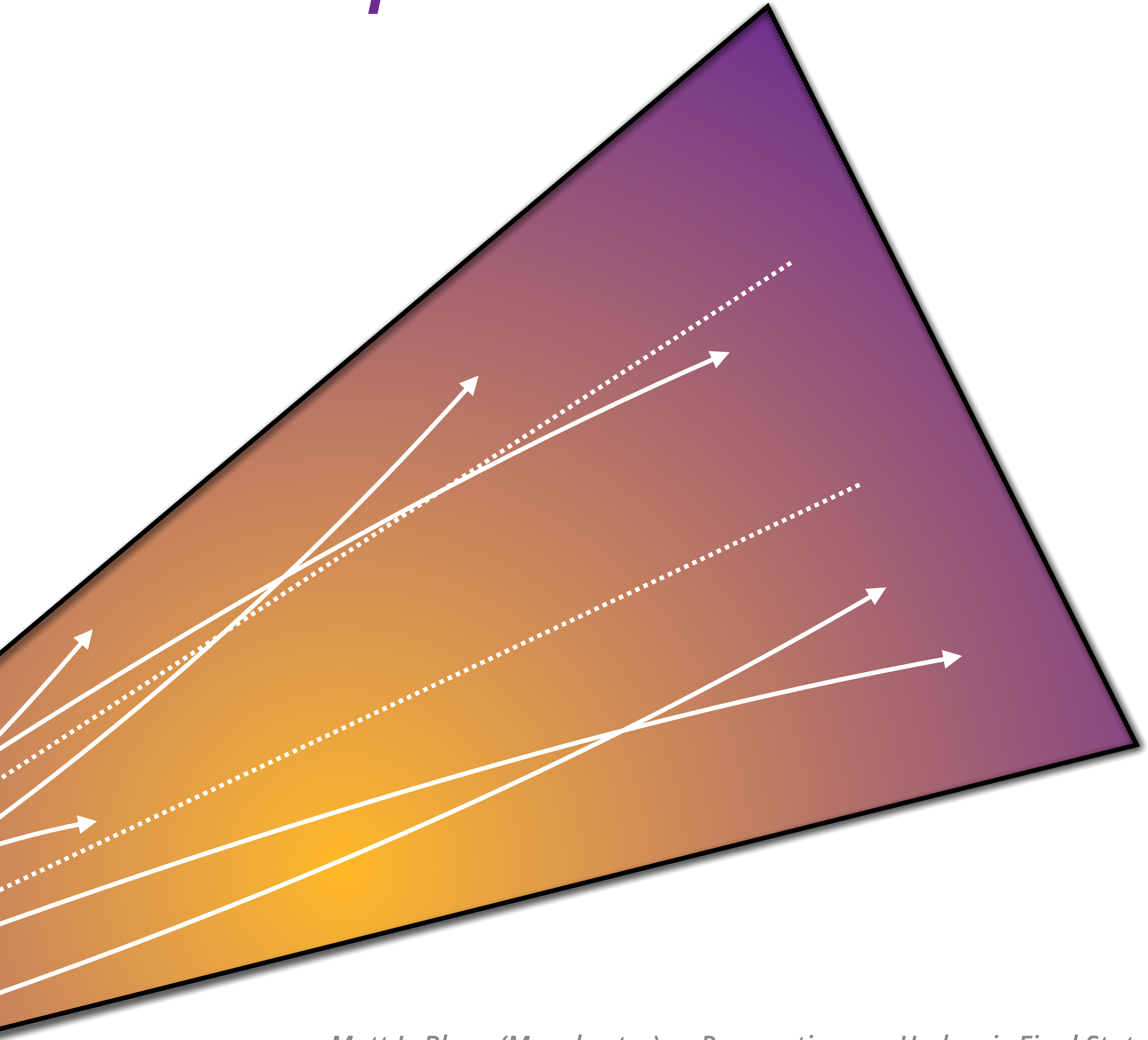
PARTON SHOWER
ISR

HADRONISATION
FSR
COLOUR REC. / UE

JET ENERGY SCALE
(OFTEN DRIVEN BY
PARTON SHOWER
+ HADRONISATION MODELLING)

CARTOON FROM
E. METODIEV

Perspectives on hadronic final states



From Up Close

Part 1: Jet Substructure

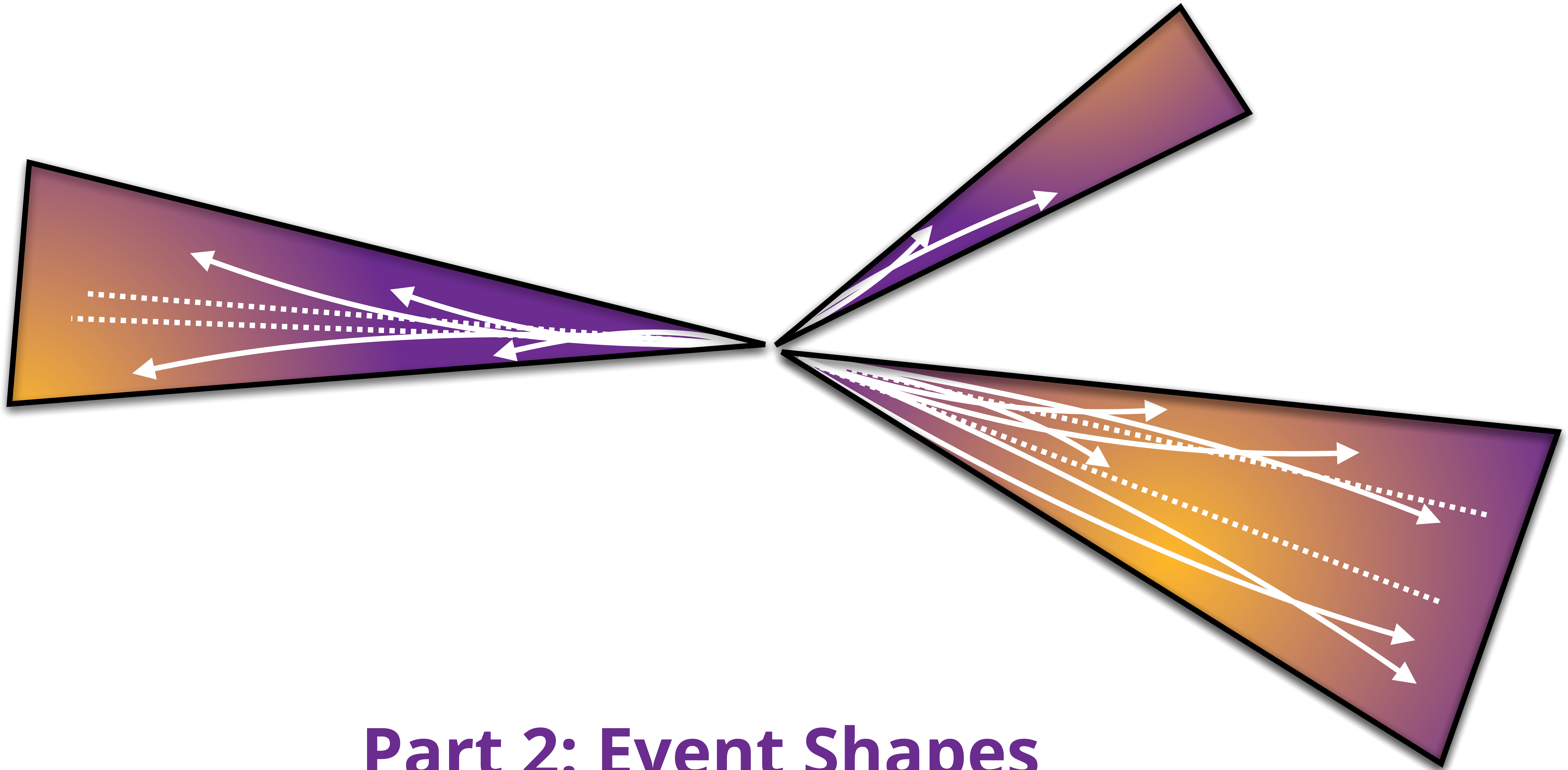
ATLAS soft-drop mass + observables

PRL 121, 092001 (2018), PRD 101, 052007 (2020)

ATLAS Lund jet plane

PRL 124, 222002 (2020)

Perspectives on hadronic final states



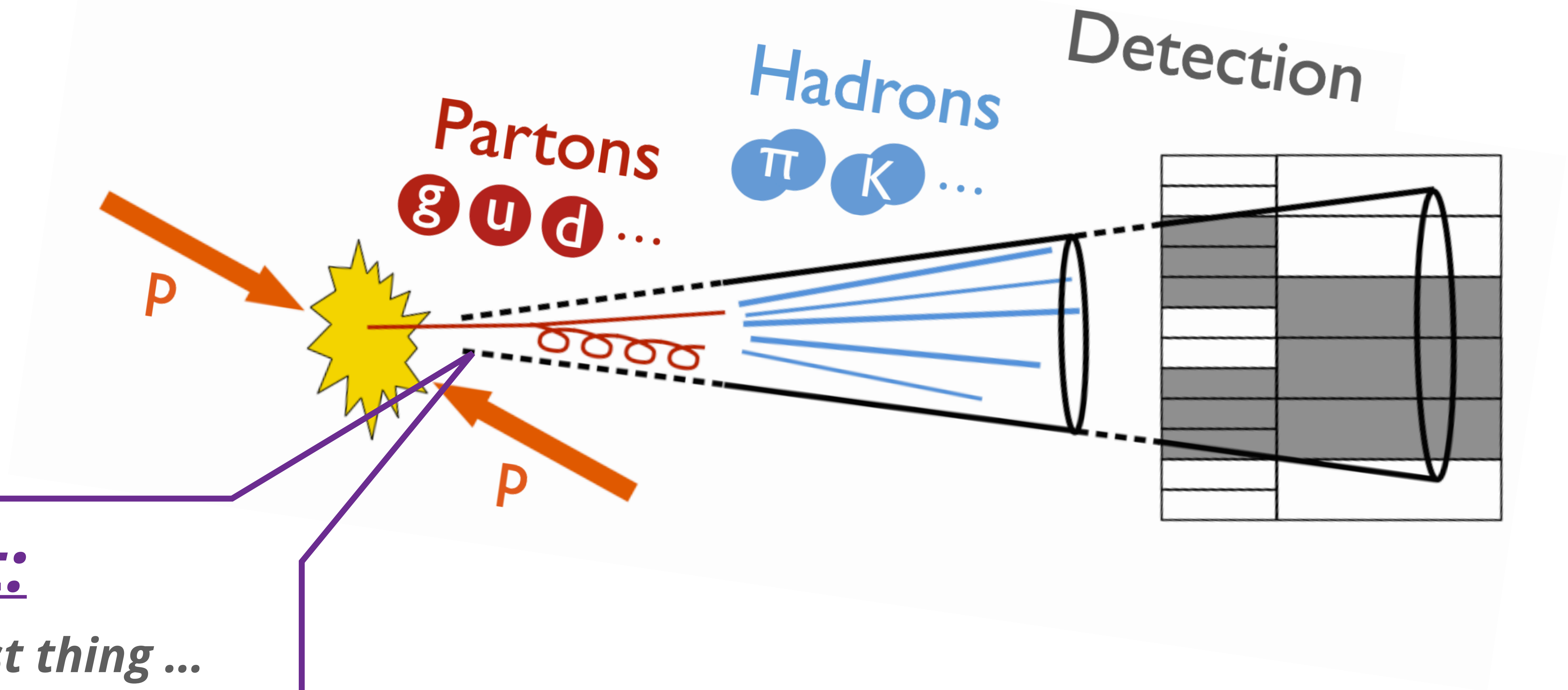
FROM UP CLOSE

+ FAR AWAY

Part 2: Event Shapes

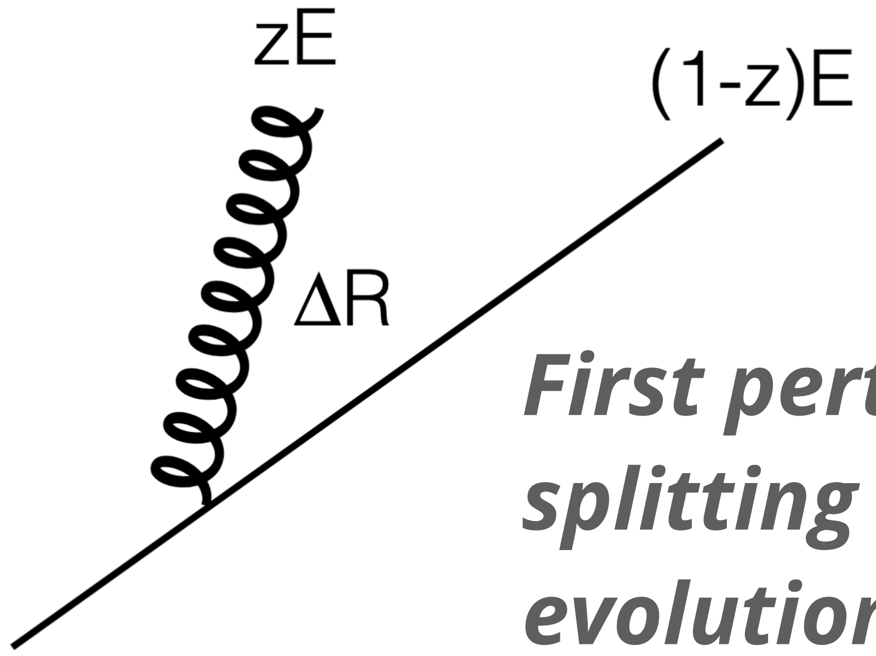
Multijet Event Isotropies w/ Optimal Transport

ATLAS-STDM-2020-20

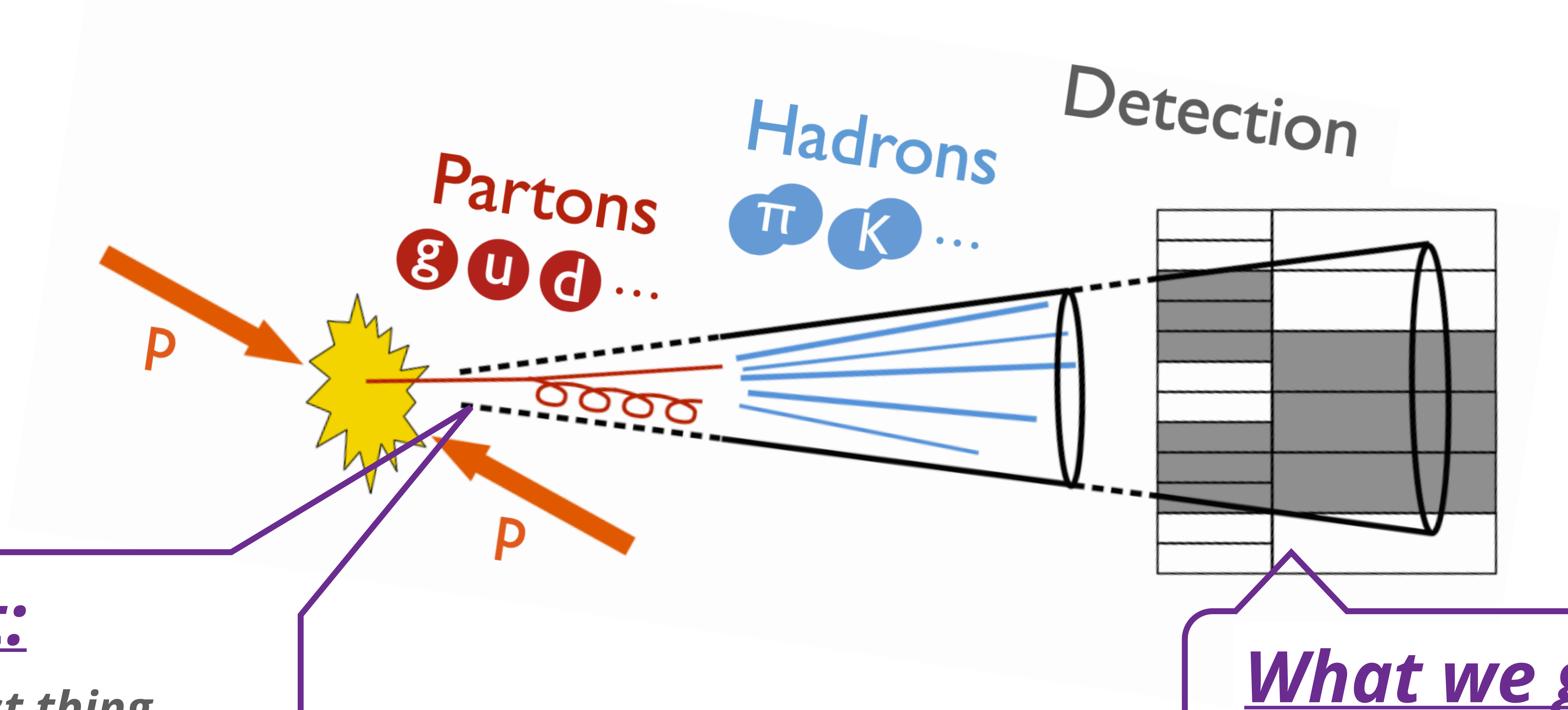


What we want:

Start with the easiest thing …



First perturbative splitting in jet's evolution.



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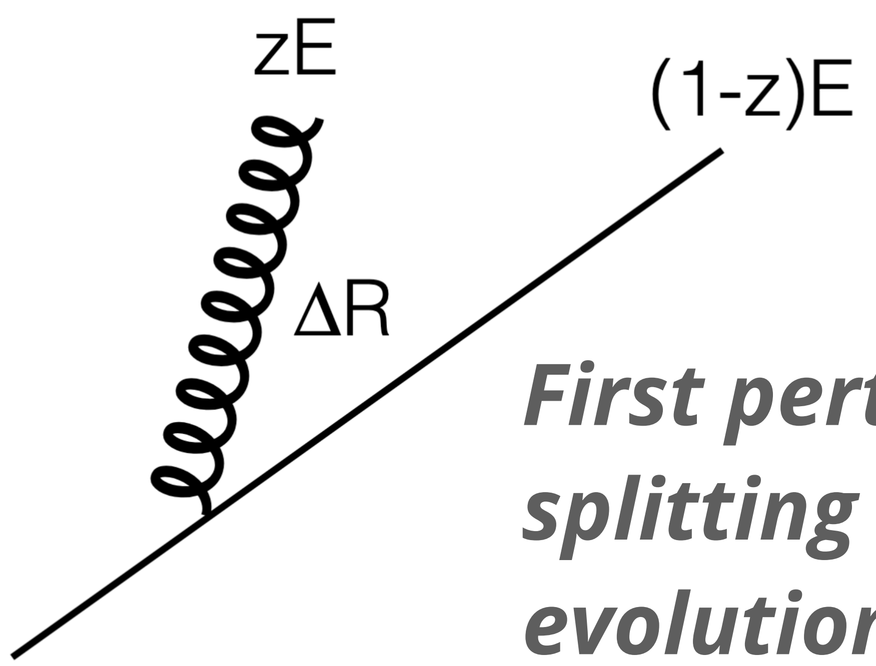
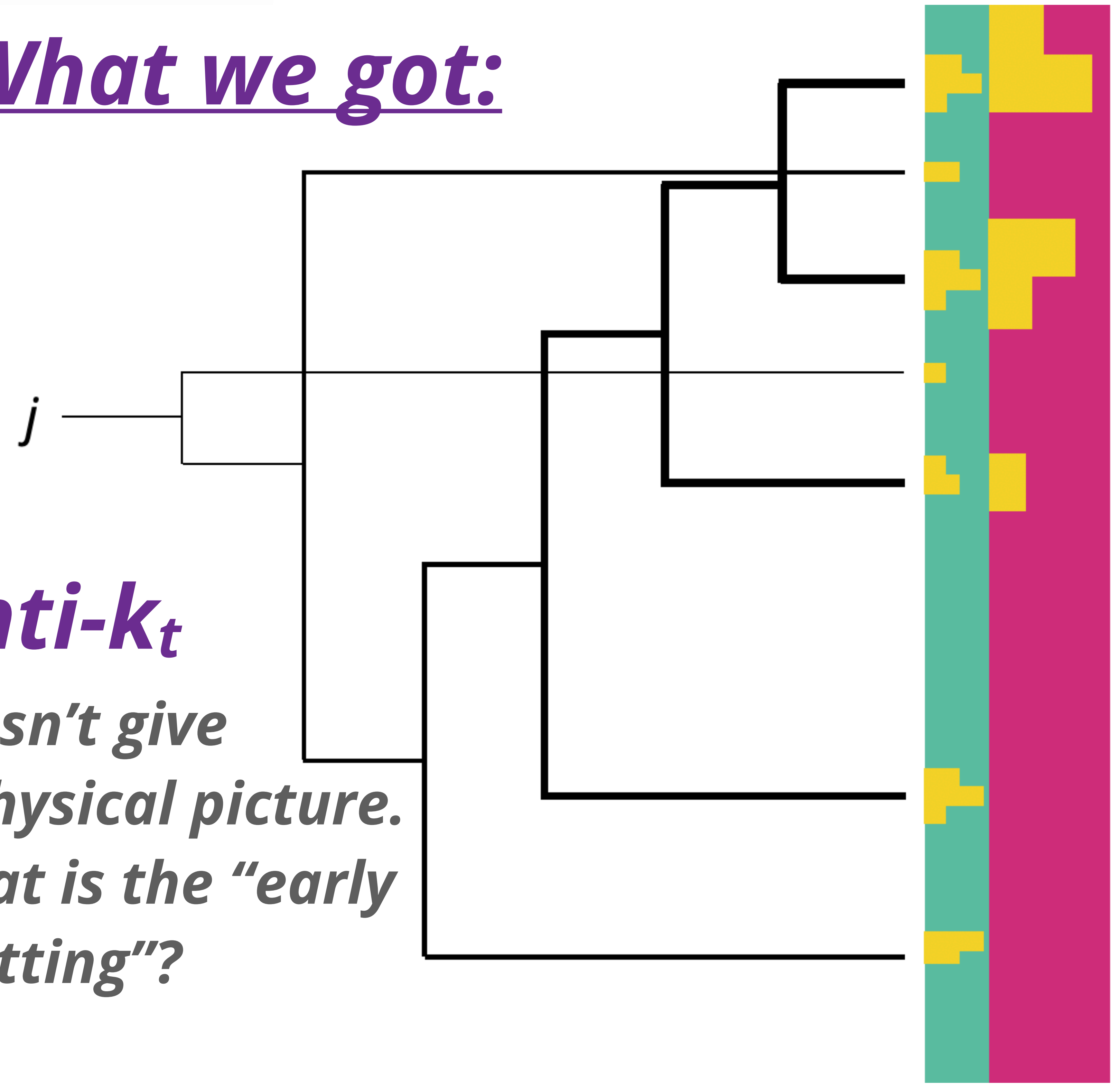
Start with the easiest thing …



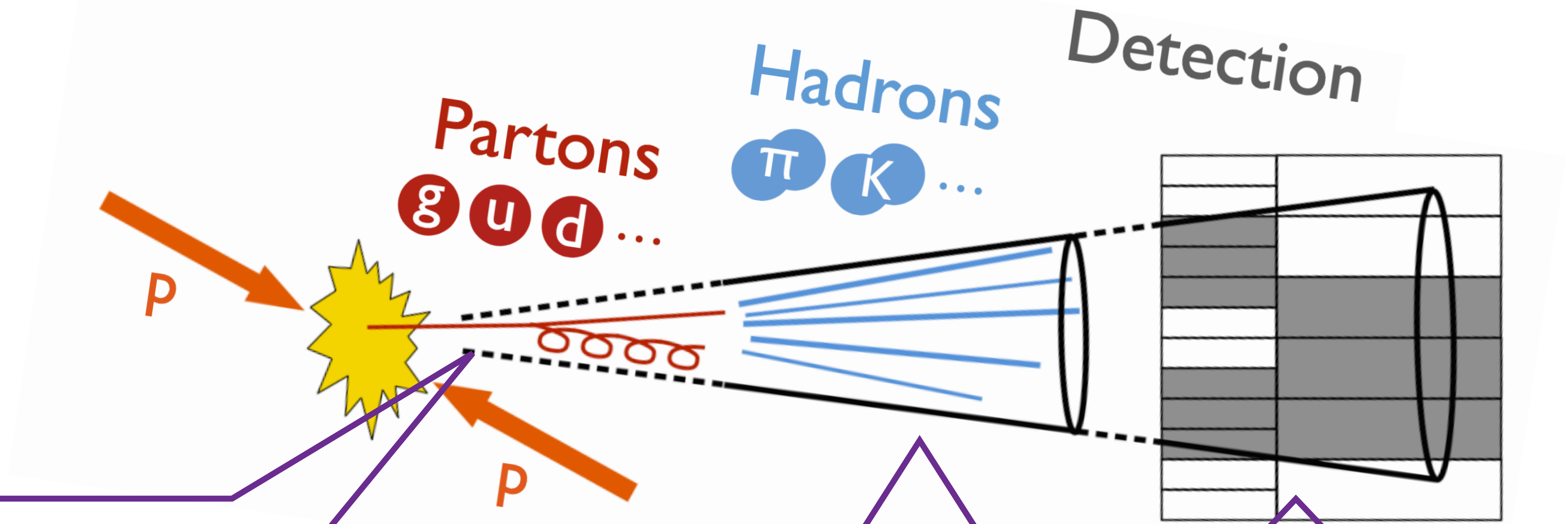
First perturbative splitting in jet's evolution.

What we got:



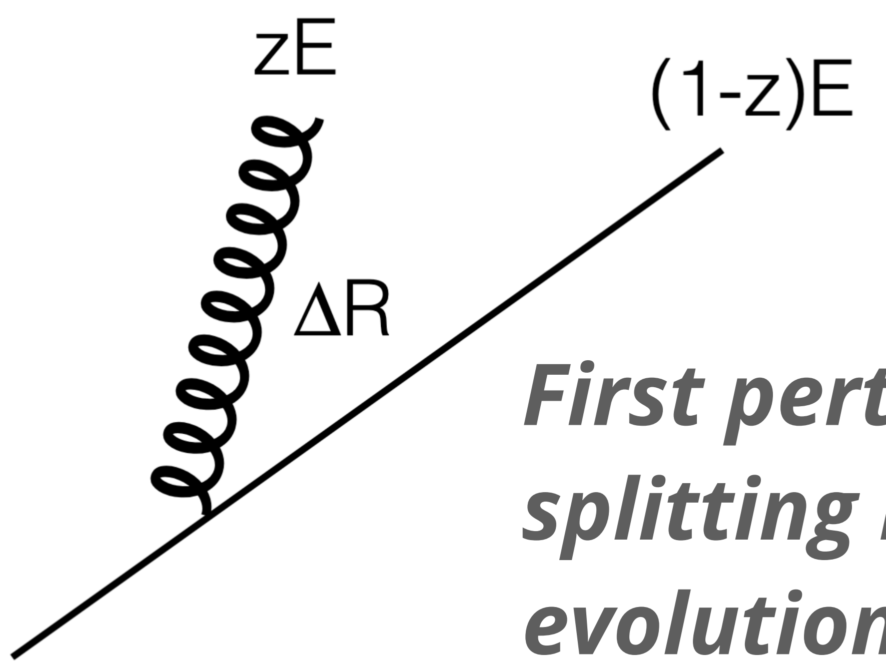
Anti-k_t

doesn't give a physical picture. What is the "early splitting"?



What we want:

Start with the easiest thing …



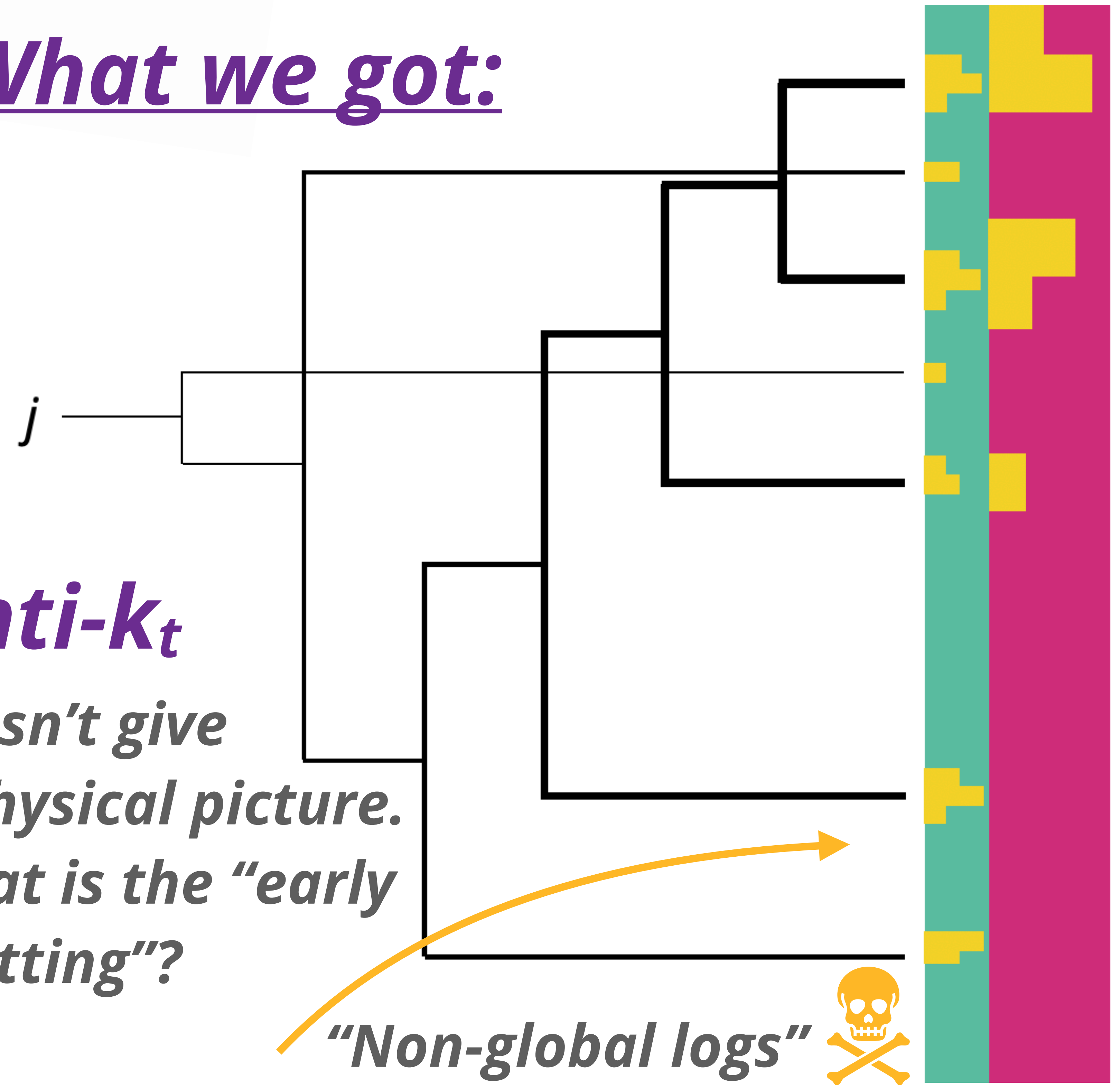
First perturbative splitting in jet's evolution.

What's the problem:

Large number of emissions from non-perturbative hadronisation processes obscure hard structure.

… and, early JSS tools were not theoretically amenable.

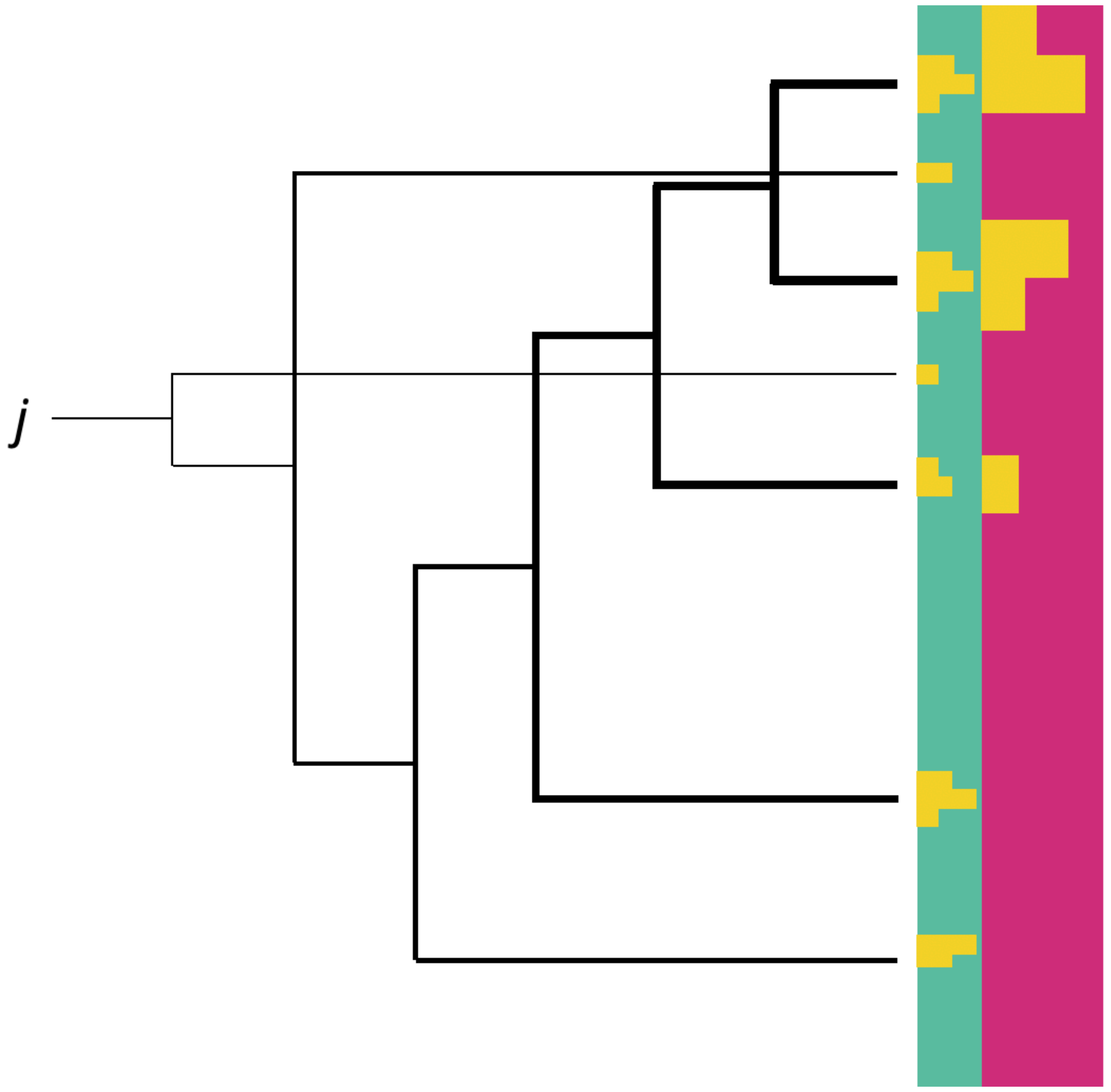
What we got:



Anti-k_t

doesn't give a physical picture. What is the "early splitting"?

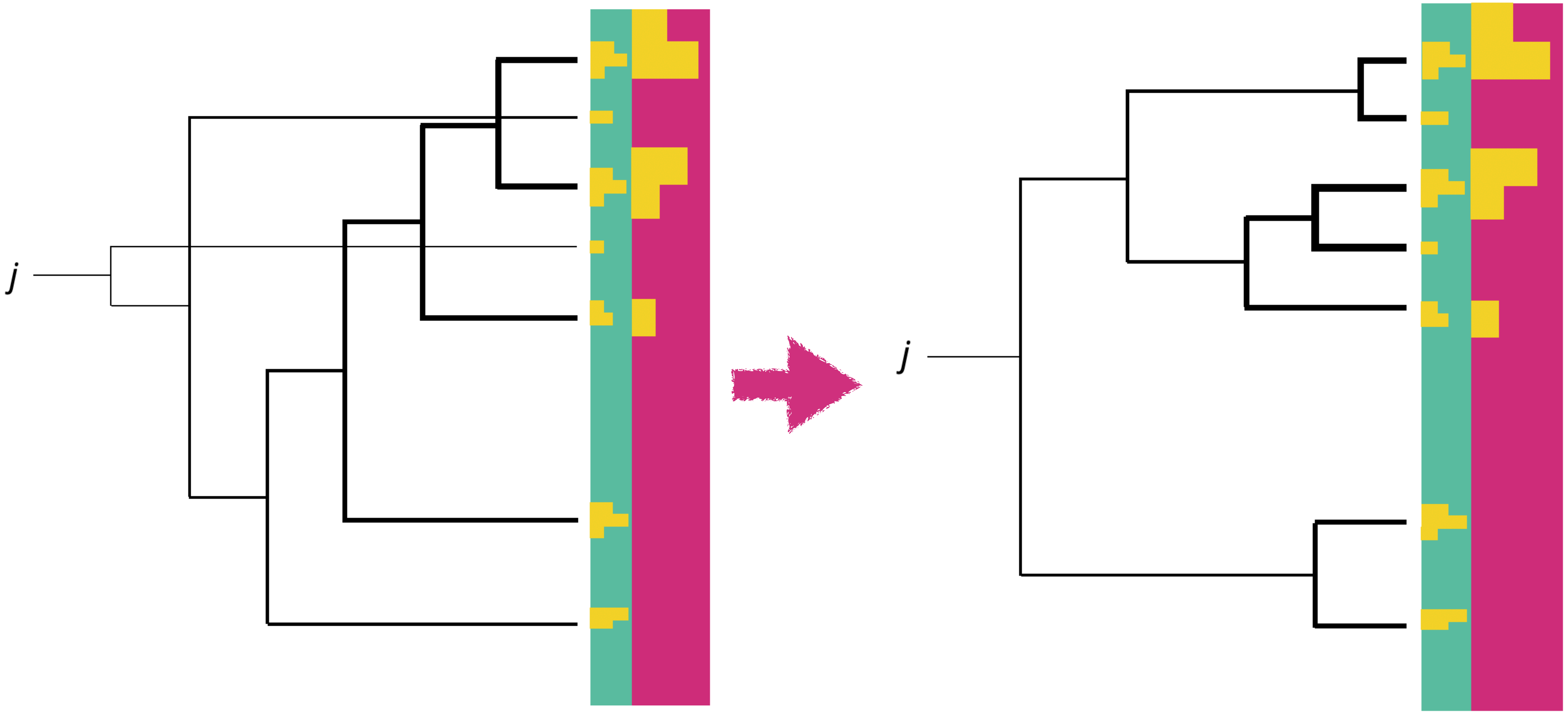
The Soft-Drop / modified Mass-Drop Algorithm



1. Start with anti-k_t jet.

Dasgupta, Fregoso, Marzani, Salam, JHEP 09 (2013) 029,
Larkowski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146

The Soft-Drop / modified Mass-Drop Algorithm



1. Start with anti-k_t jet.

2. Recluster with C/A algorithm. (Angle-ordered!)

Dasgupta, Fregoso, Marzani, Salam, JHEP 09 (2013) 029,
Larkowski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146

The Soft-Drop / modified Mass-Drop Algorithm

1. Start with anti-k_t jet.

2. Recluster with C/A algorithm. (Angle-ordered!)

3. Check soft-drop condition at each node, starting with the widest-angle emission.

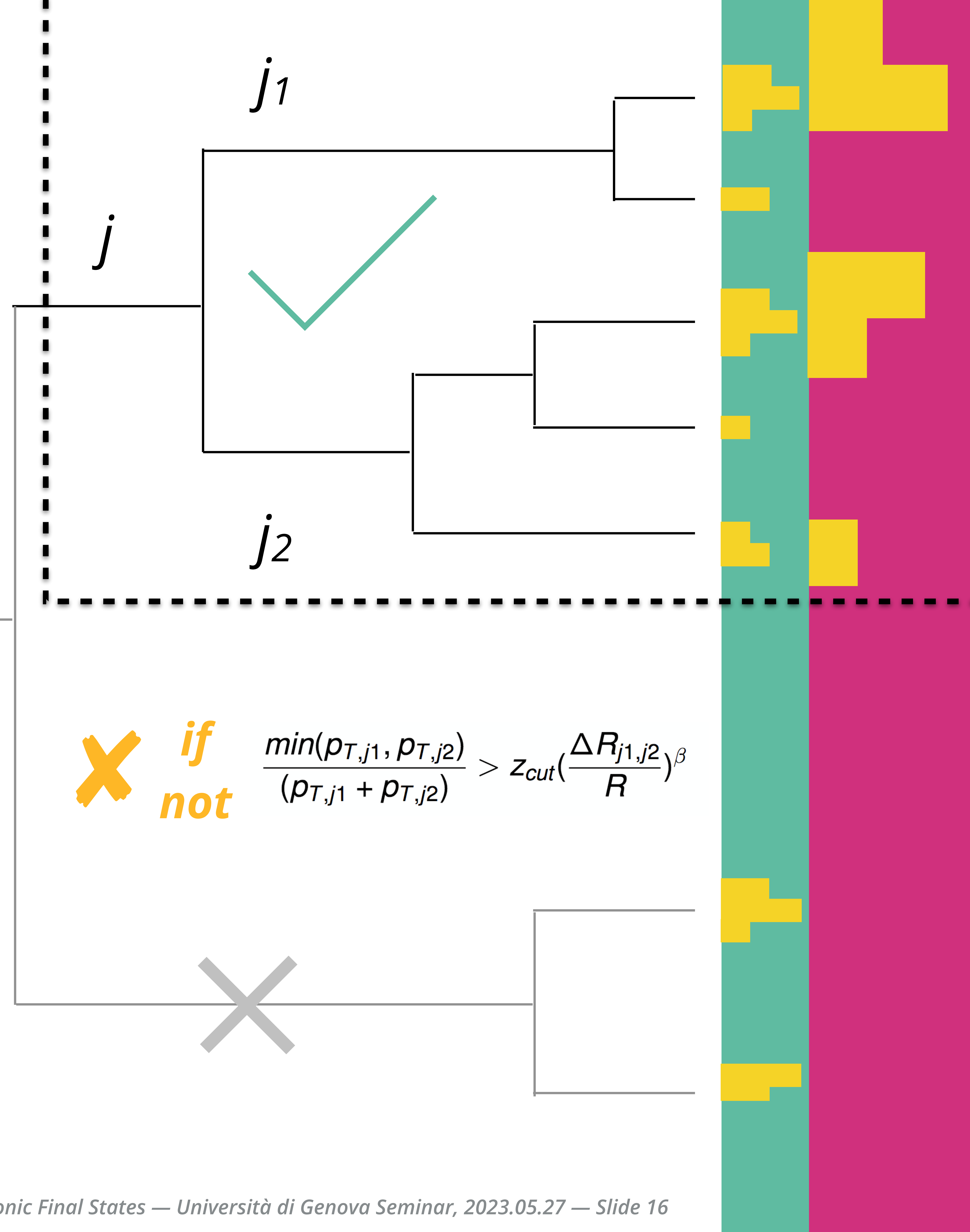
Stop when one passes!

Dasgupta, Fregoso, Marzani, Salam, JHEP 09 (2013) 029,
Larkowski, Marzani, Soyez, Thaler, JHEP 1405 (2014) 146

Precision Jet Substructure: Soft-Drop Observables

ATLAS, PRD 101, 052007 (2020), PRL 121, 092001 (2018)

- **Goal:** provide experimental testbed for the first high-accuracy (>LL) JSS predictions:
  - ***Mass*** $\rho = \log_{10}(m_j / p_T^j)$
    NLL 1704.02210 1712.05105
    **today* NNLL 1603.06375 1603.09338 1803.03645 1811.06983
  - ***Angle*** $R_g = \Delta R(j_1, j_2)$
    NLL 1908.01783
  - ***Balance*** $z_g = p_T^{j2} / p_T^{j1}$
    NLL 2106.04589



$$\frac{\min(p_{T,j1}, p_{T,j2})}{(p_{T,j1} + p_{T,j2})} > z_{cut}\left(\frac{\Delta R_{j1,j2}}{R}\right)^{\beta}$$

- JSS measurements made in **dijet events:**
  - No backgrounds, q/g admixture, broad kinematic range. **p_T ~ 300 GeV — 2 TeV**
  - Measured different ß values → **more/less NP-QCD**
  - Measured **calorimeter and track-based** signals

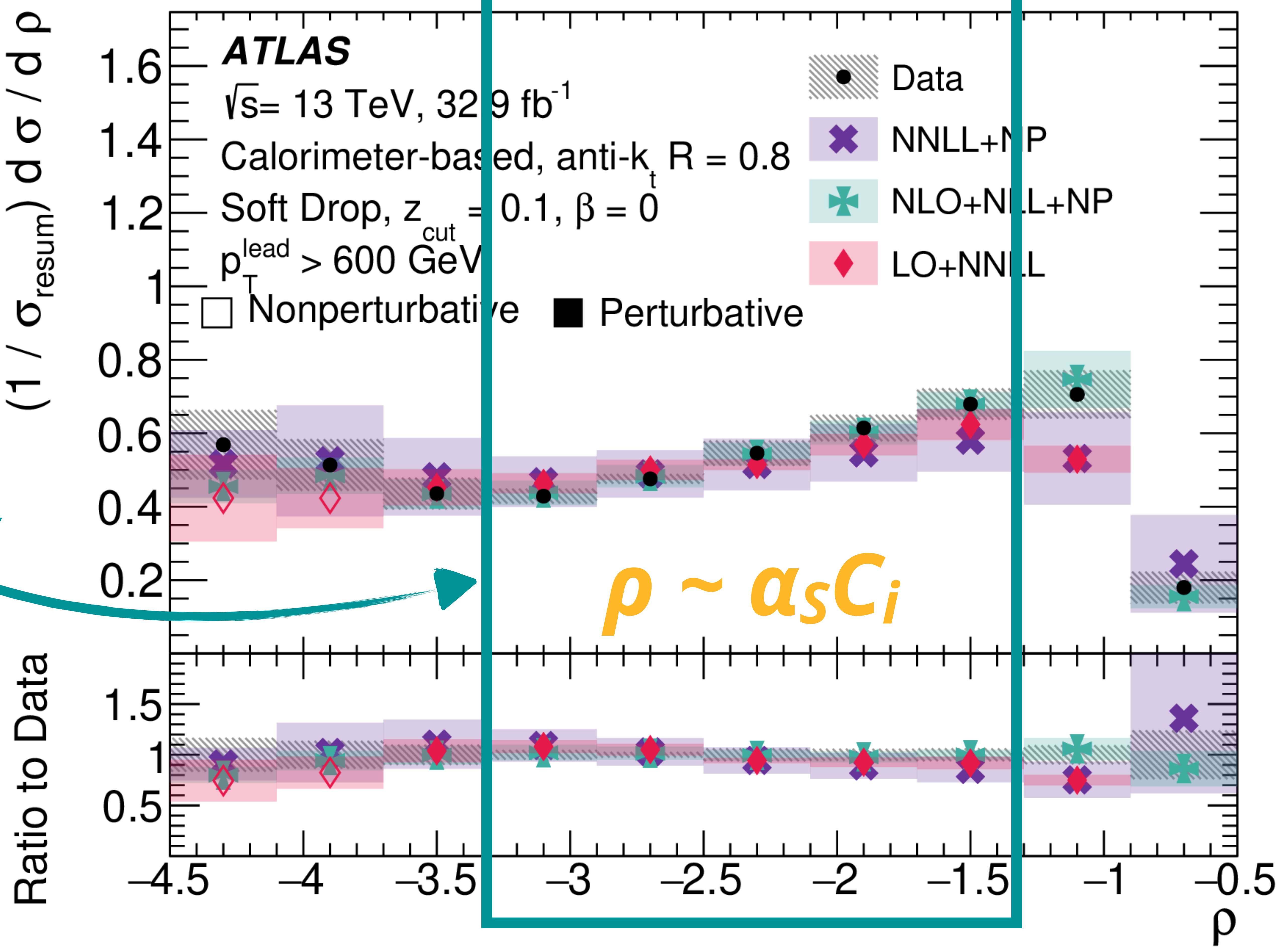
See also: CMS, JHEP 11 (2018) 113 (soft-drop mass)

Soft-Drop Jet Mass

ATLAS, PRD 101, 052007 (2020), PRL 121, 092001 (2018)

"Relative Mass"
$\rho = \log(m_{SD}^2/p_T^2)$

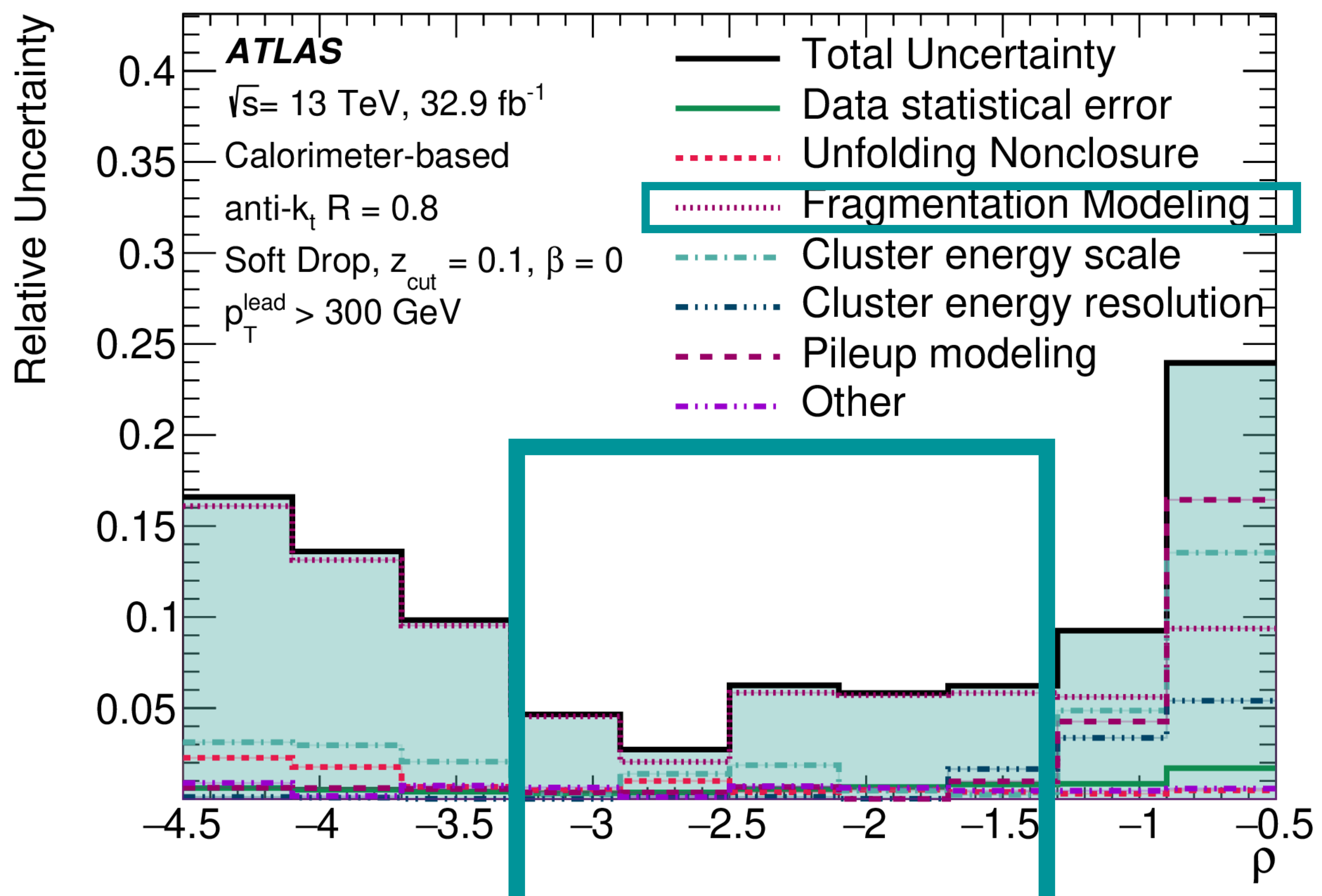
(npQCD) *Resummation-dominated* *(Fixed-order)*



Calculations target "resummation" region!

$\rho \sim \alpha_s C_i$

Good theoretical & experimental control! Comparable unc. in 'resummation region.'



MC setups differ significantly, leading to large systematics (particularly in NP-QCD region)

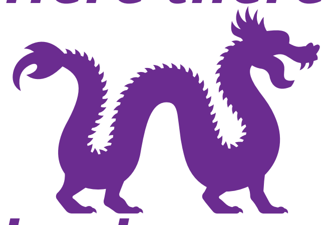
Marzani, Schunk & Soyez!

Soft-Drop Jet Mass: increasing NP-QCD

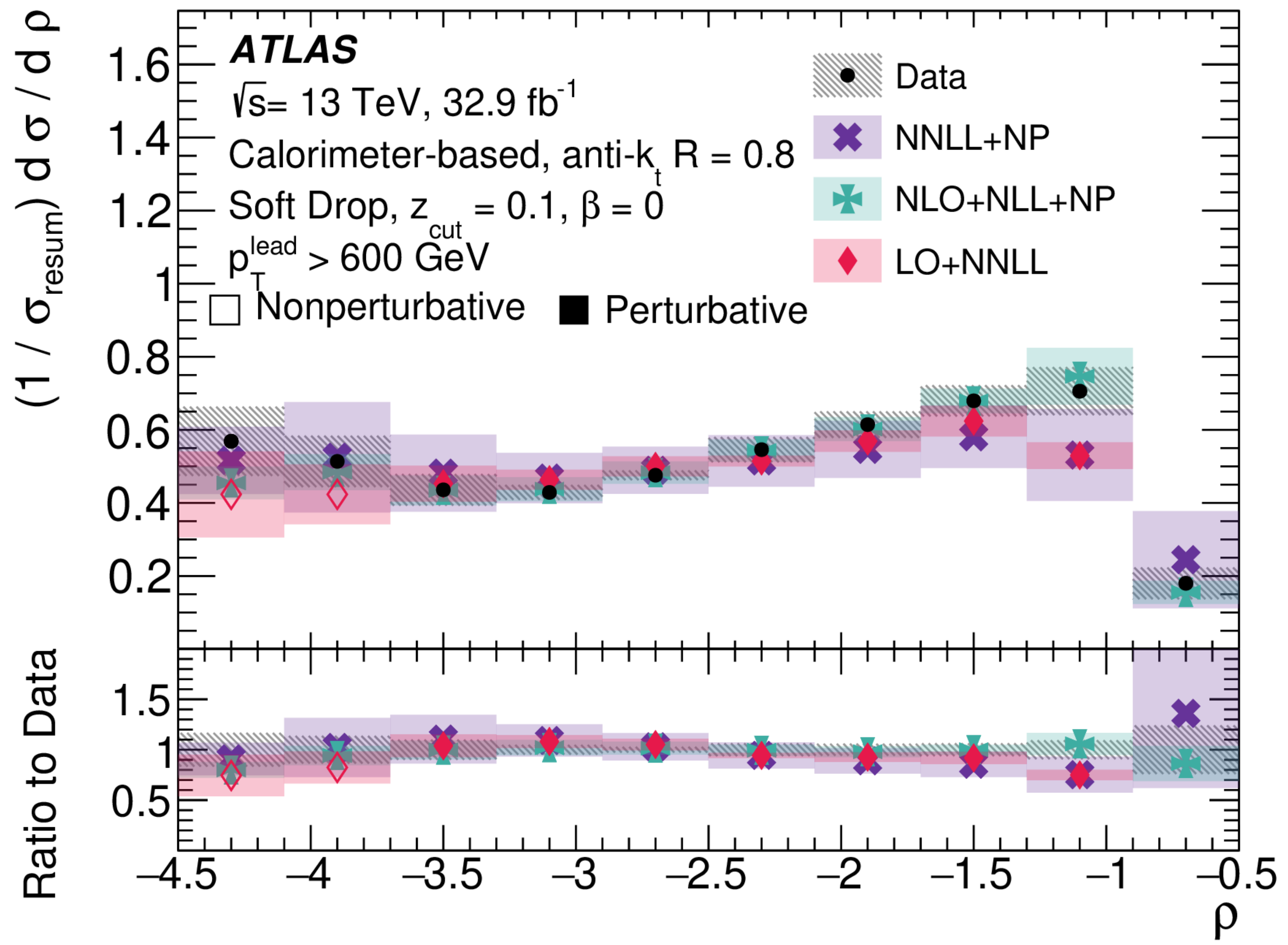
ATLAS, [PRD 101, 052007 (2020)], [PRL 121, 092001 (2018)]

"Relative Mass"
$\rho = \log(m_{SD}^2/p_T^2)$

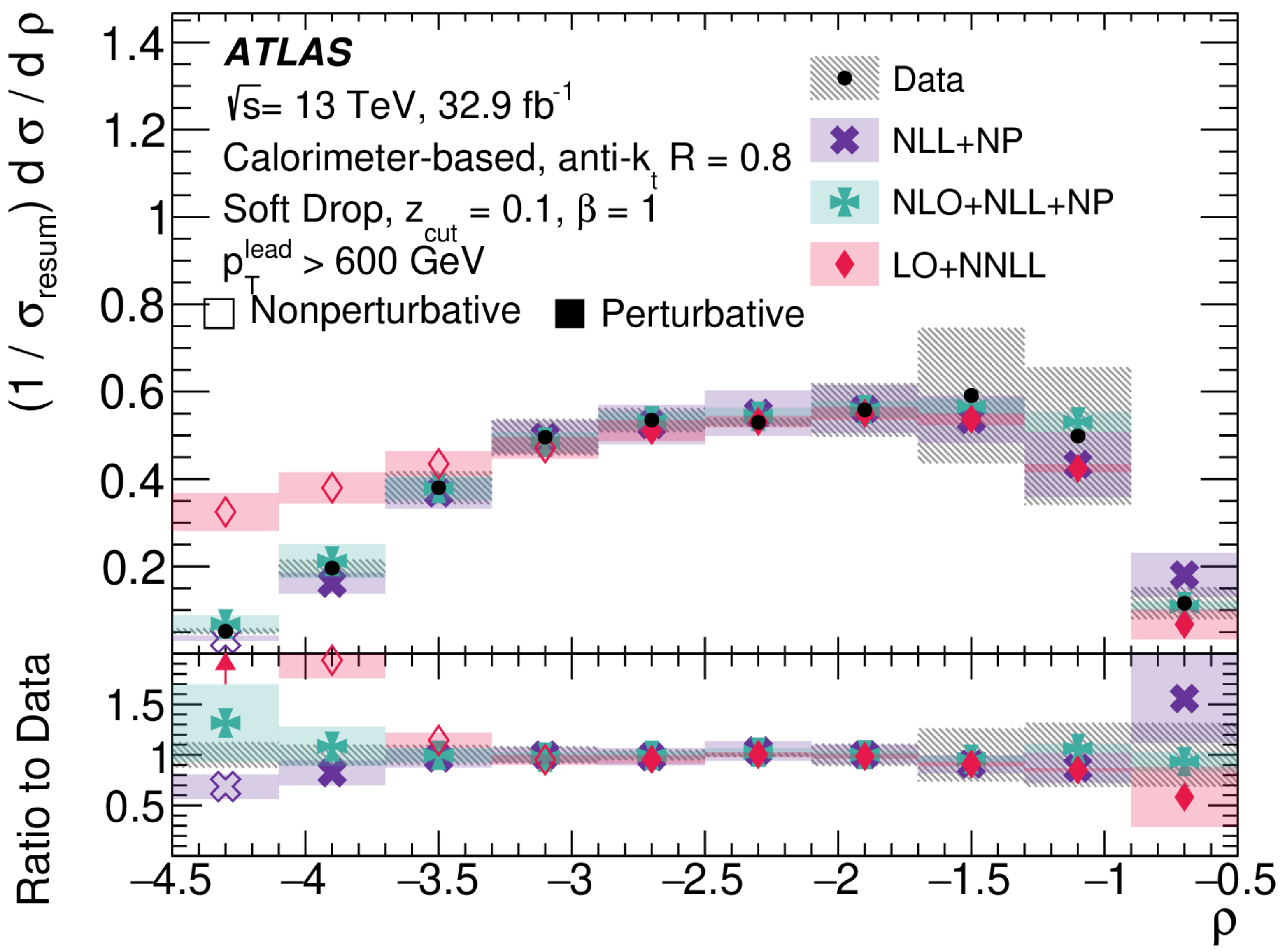
Permit more non-perturbative (soft, wide-angle) radiation

Here there

be dragons

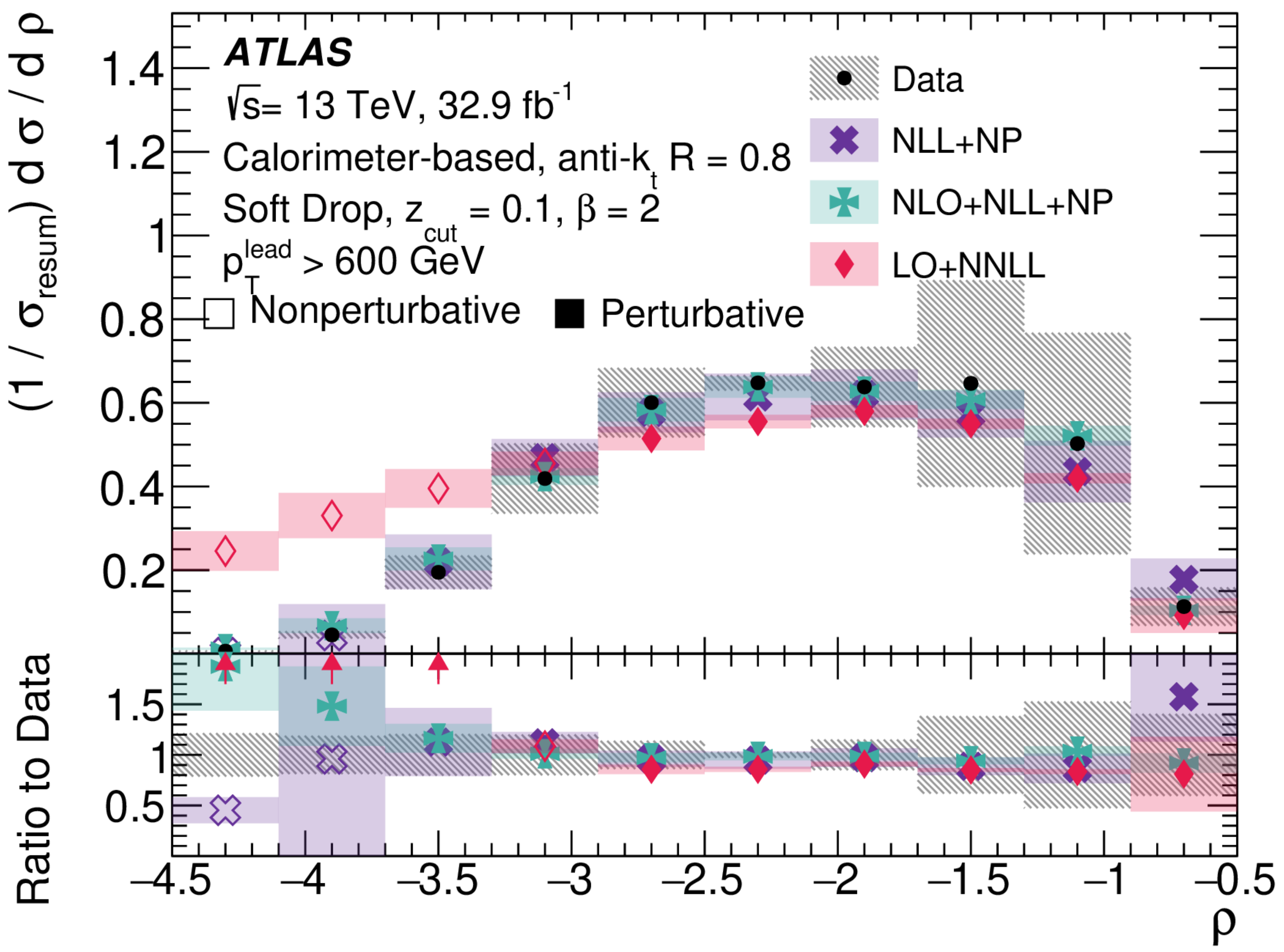
ß=0



ß=1



ß=2



Agreement deteriorates, 'well-understood' region shrinks, uncertainties increase!

Calo- and track-based JSS

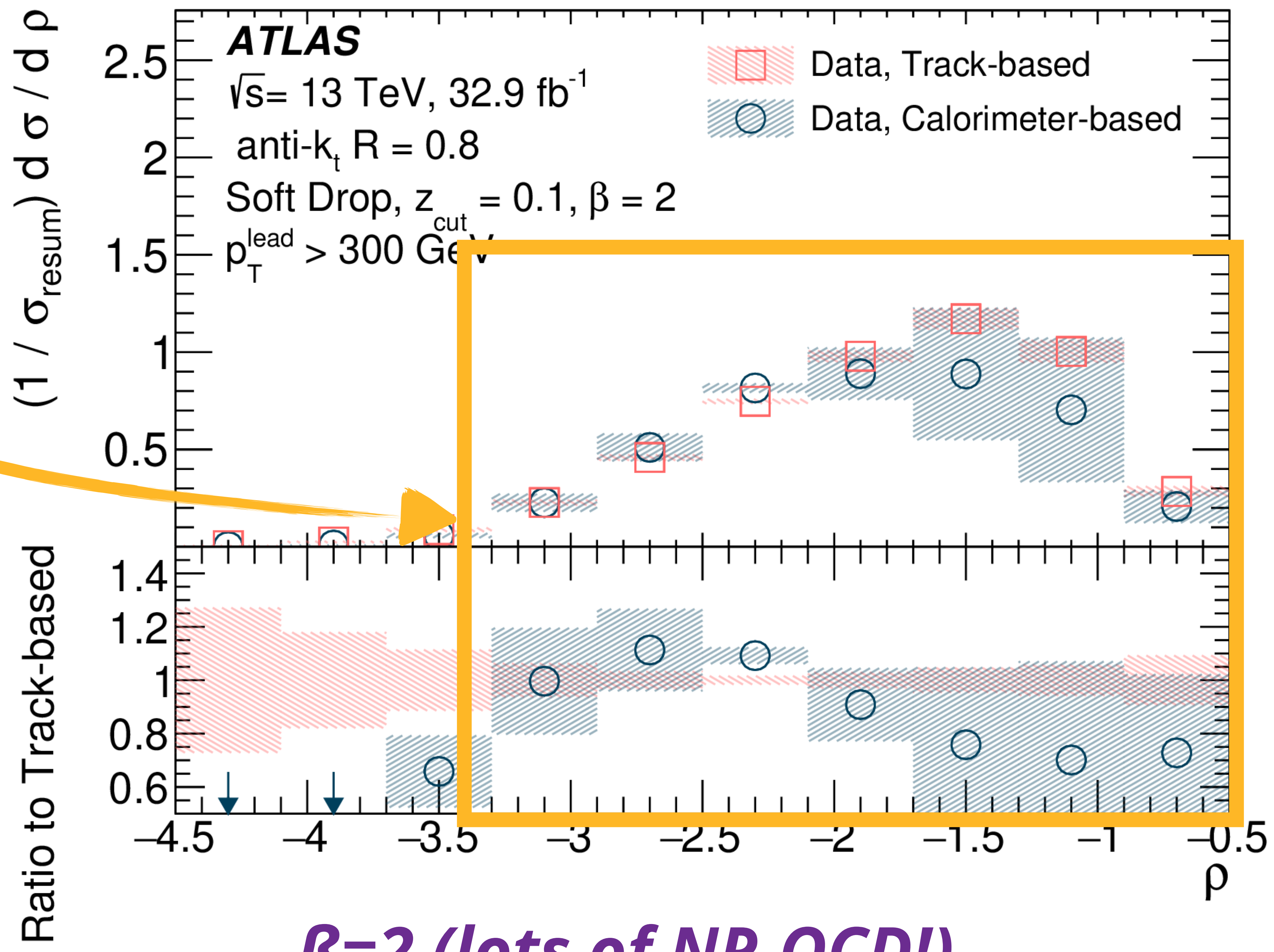
ATLAS, PRD 101, 052007 (2020)

- **Advantages:** Smaller angles, softer signals, better resolution (more bins).
- **Trade-offs:** IRC safety (collinear-unsafe).

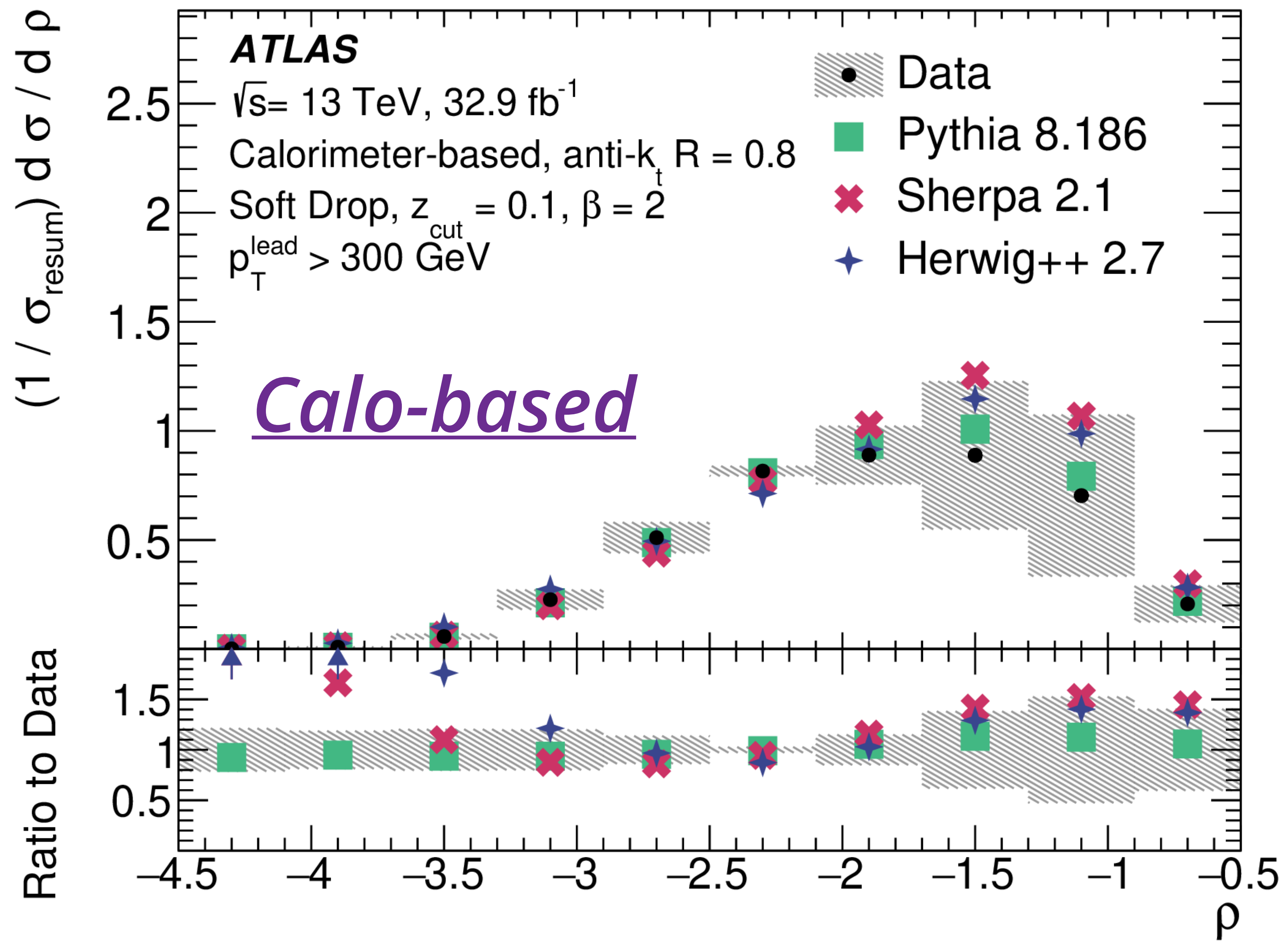
Track-based measurement provides a cross-check on calorimeter-based measurement.

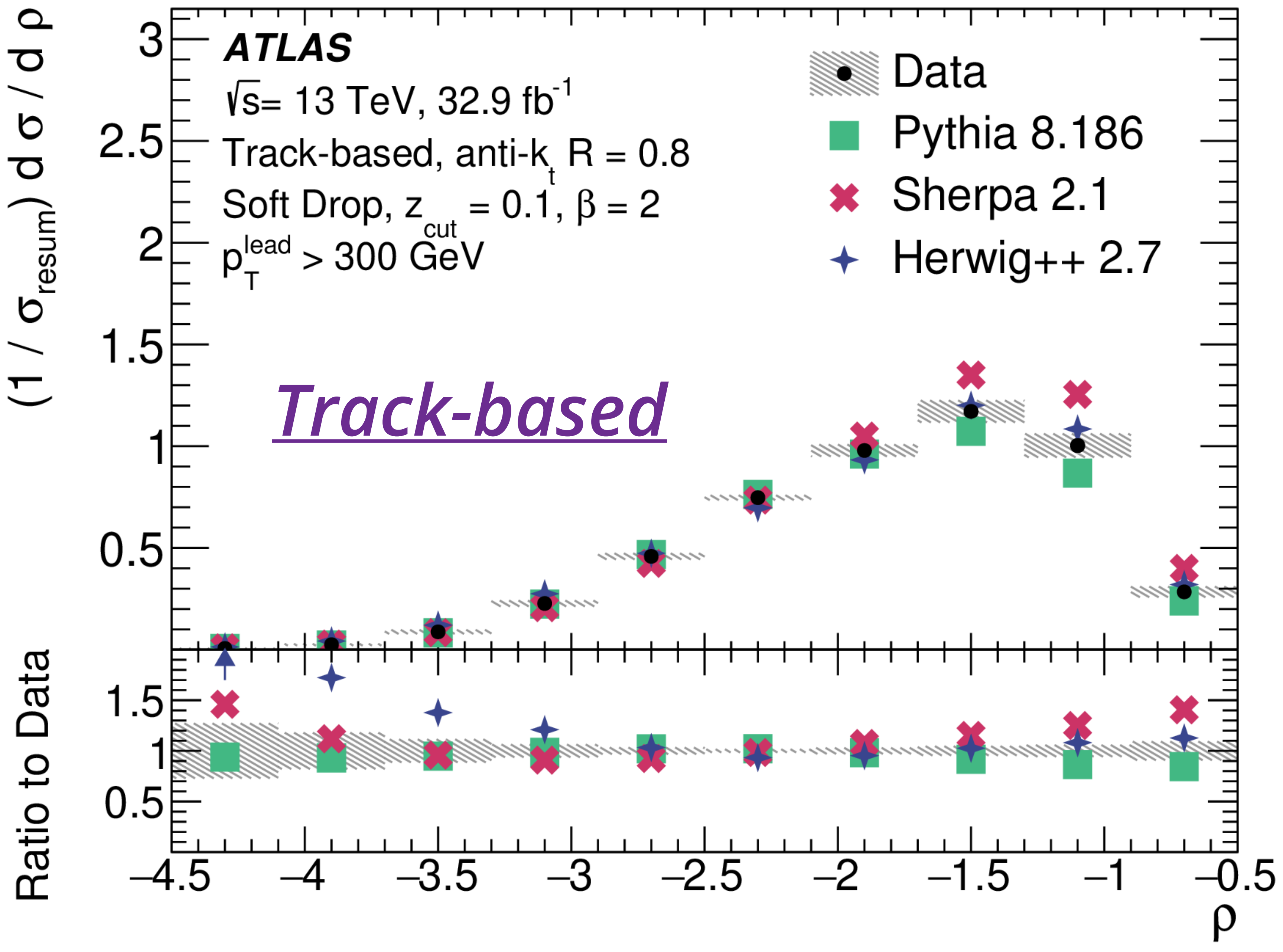
*Also, more precise reference data for **improving MC models.***

Reduced uncertainties!



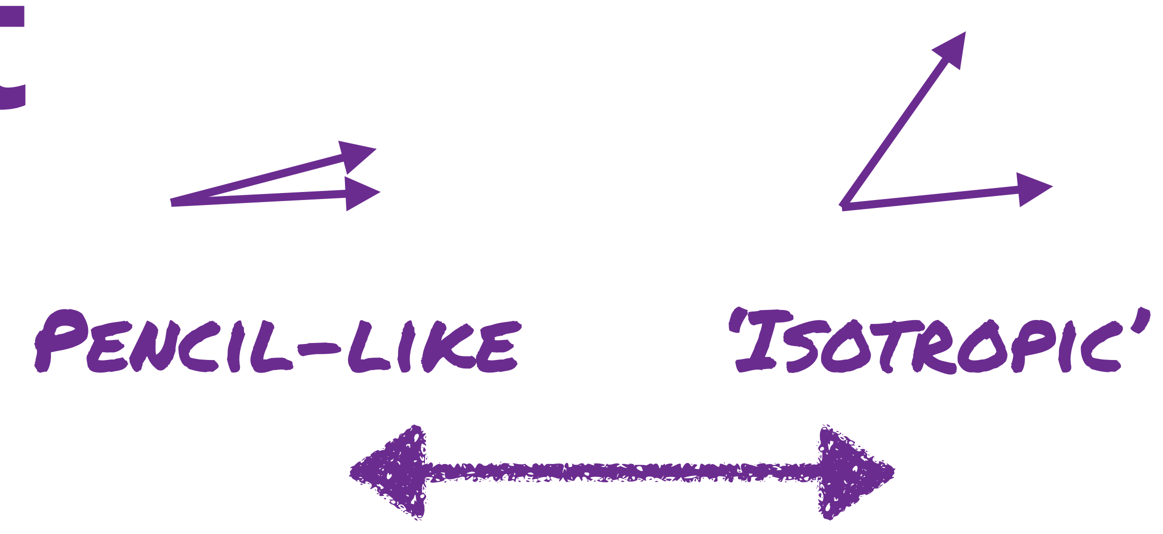
β=2 (lots of NP-QCD!)





Aside: CMS JSS Angularities Measurement

CMS, JHEP 01 (2022) 188

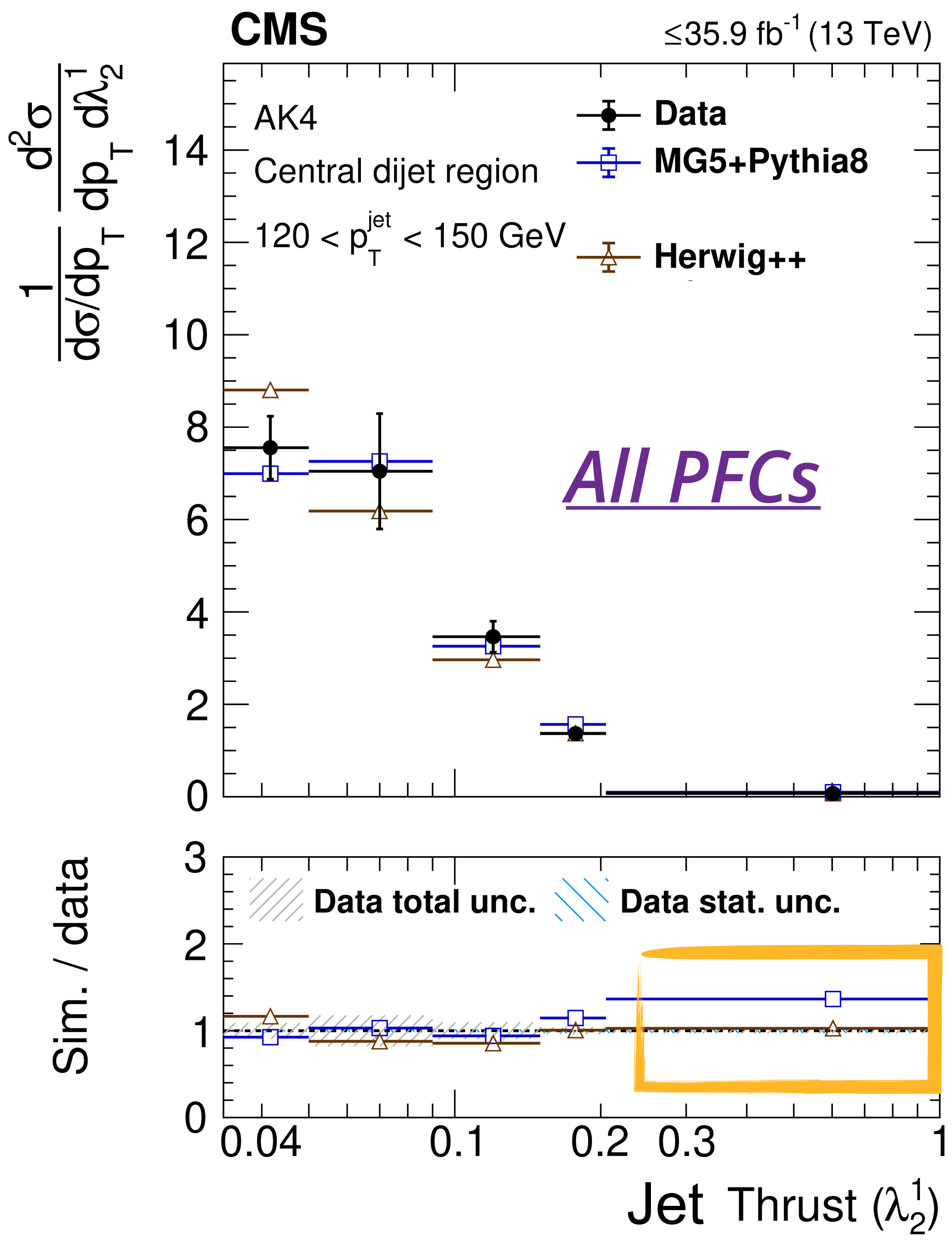


JSS Angularities

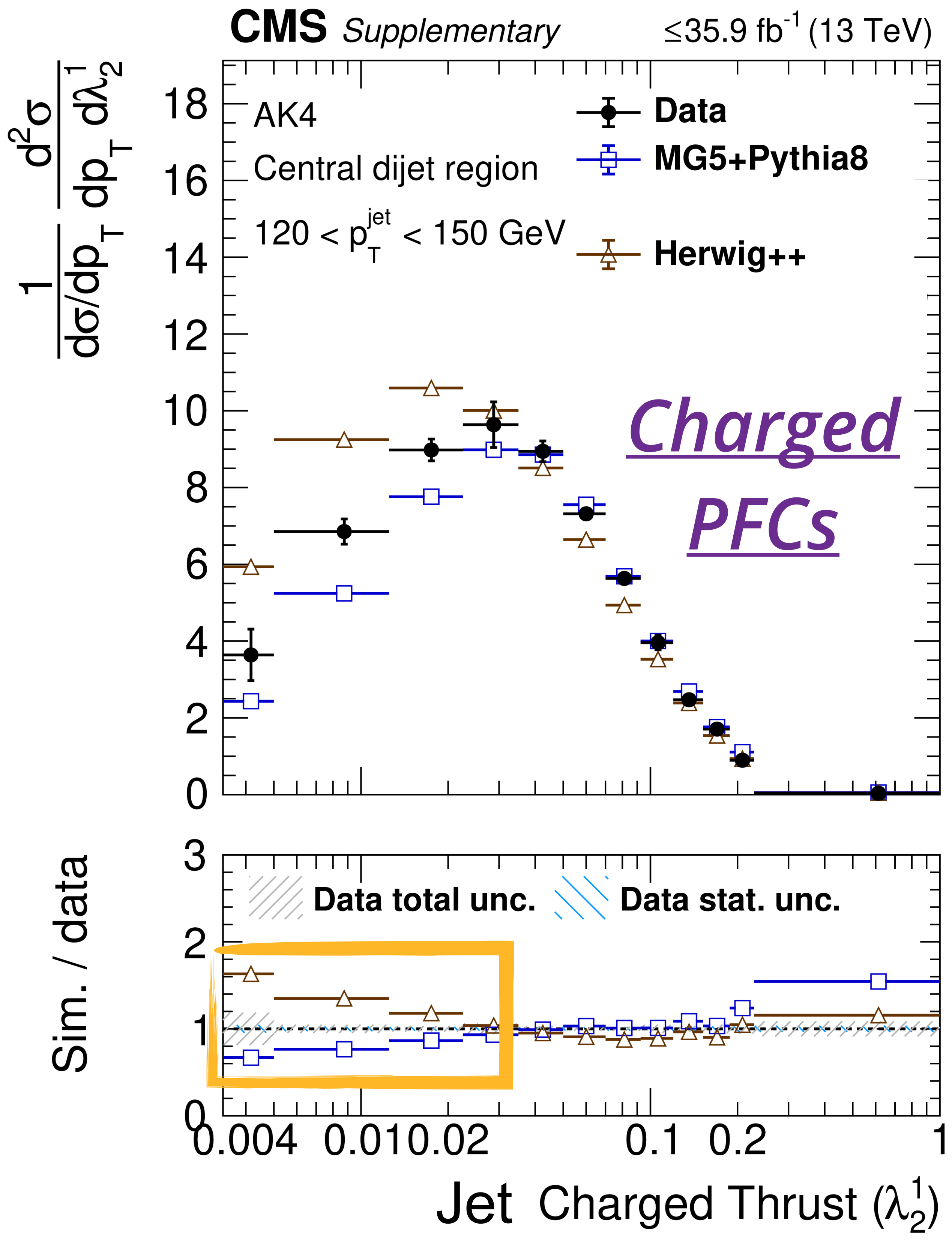
Products of relative constituent energies and angles, varying weight of each component

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

- Both ATLAS and CMS have made comparisons of **charged+neutral & charged-only pictures**.
  - Similar observations can be made using data from both collaborations
  - Perhaps surprising, given CMS's "particle-flow" reconstruction.



Similar levels of (dis)agreement!



*Charged picture has **significantly more reach** into collinear region (10x)!*

Local metaphor

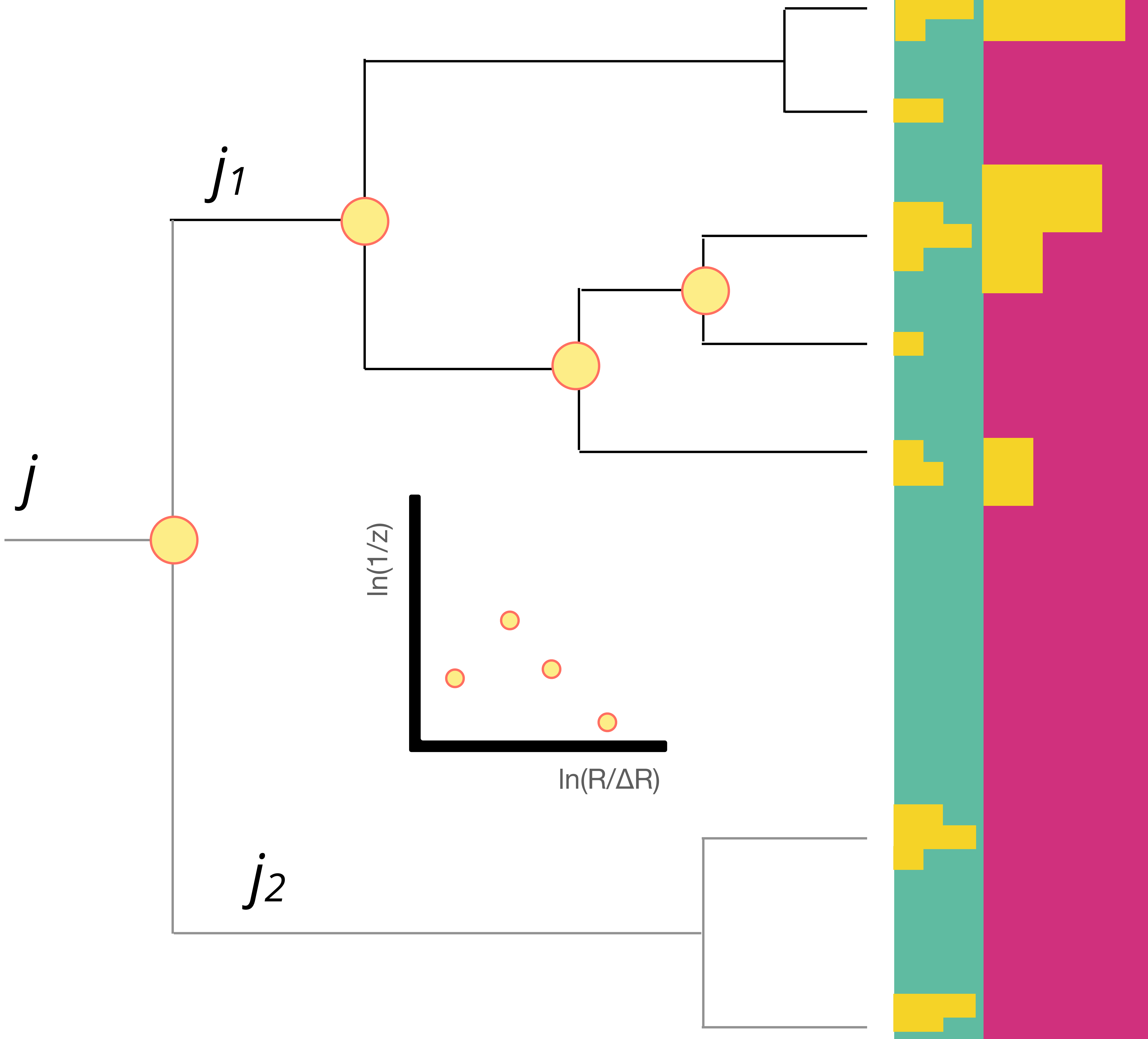
Calorimeter-only

Inner-Detector-only

Lund jet plane

Dreyer, Salam & Soyez JHEP 12 (2018) 064

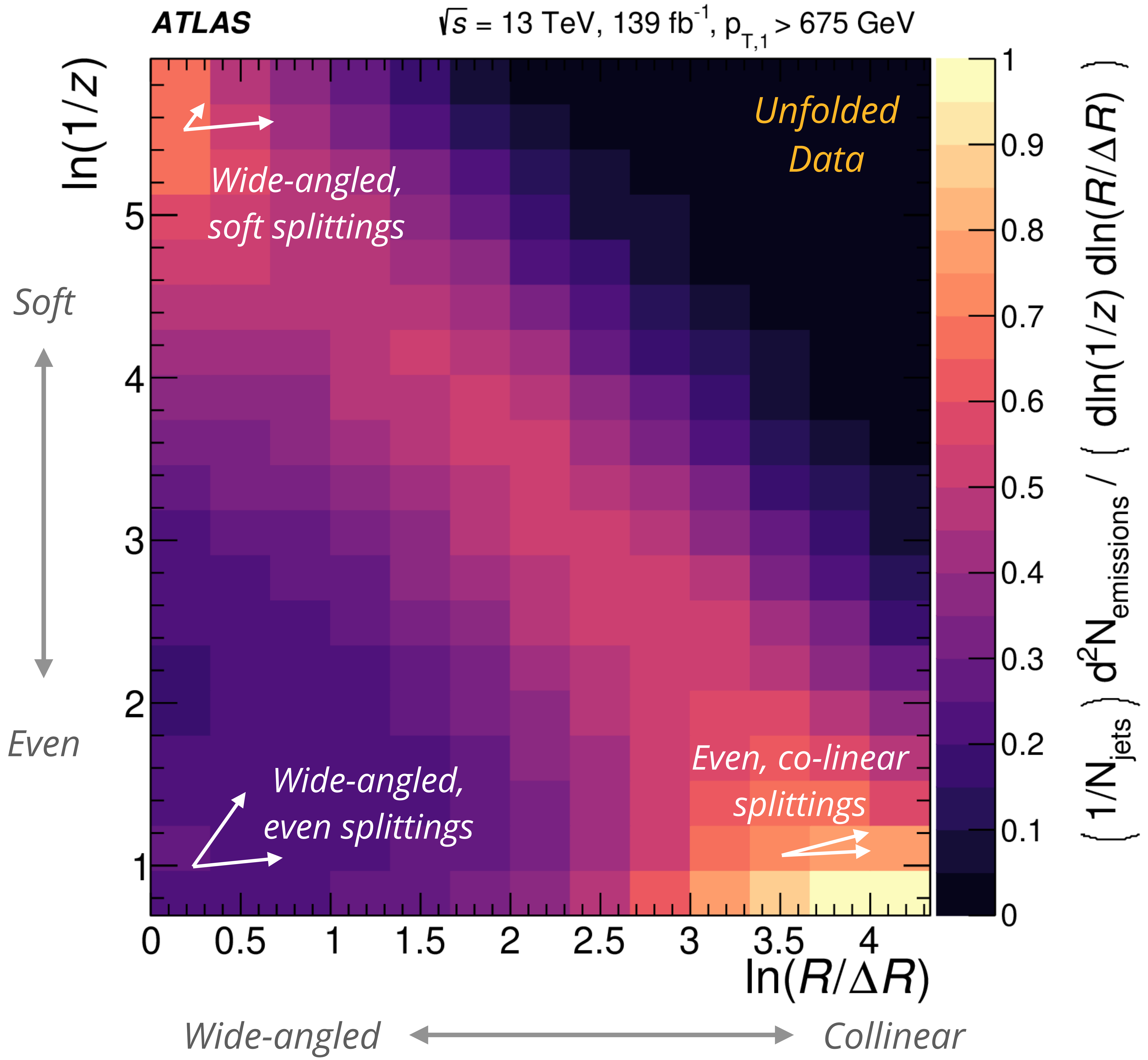
- **Lund Plane** : tool used by PSMC authors for 34 years & counting (Andersson et al. Z.Phys.C 43 (1989) 625)
- Newly applied to JSS by **Dreyer *et al.***
  - **Key concept:** probe entire angle-ordered emission history of originating parton.
  - Parameterise emissions of **angle-ordered picture** in terms of their **relative energies (*z*)** and **angles (*ΔR*).**
- Powerful, physics-forward representation of JSS:
  - ML/AI (1903.09644, 2012.08526), q/g tagging (2112.09140), PS development (1805.09327, 2205.02861), analytics (2007.06578), heavy-flavour (2106.05713, 2112.09650, 2202.05082)
    - *… we'll have a whole LJP workshop at CERN in July!*



Lund jet plane: data

ATLAS, PRL 124, 222002 (2020)

- Factorises different physics effects into different regions.
  - *Soft splittings vs. even splittings, wide-angled vs. collinear.*



Lund jet plane: data

ATLAS, PRL 124, 222002 (2020)

- Factorises different physics effects into different regions.
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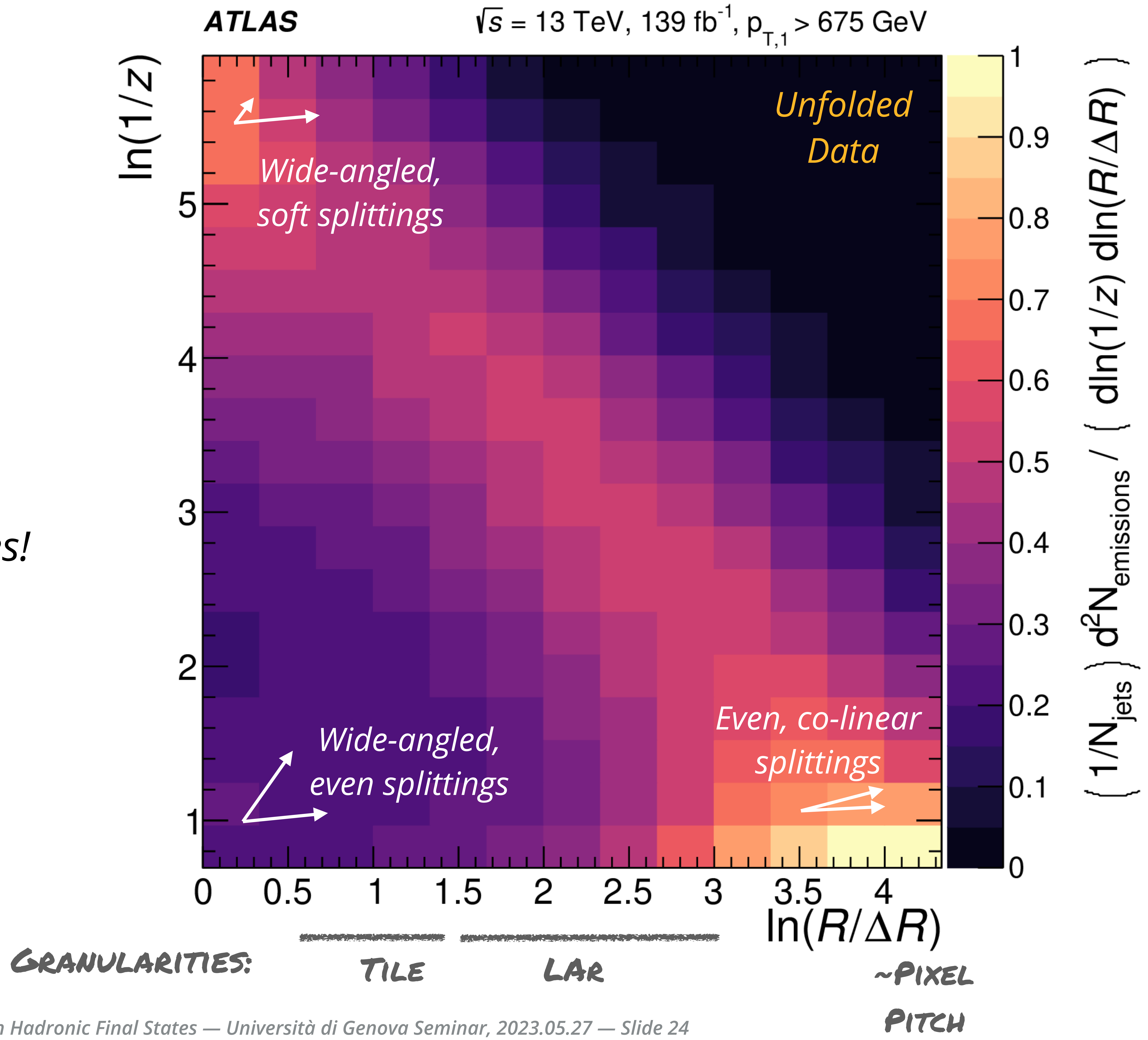
- Calorimeter granularity is too coarse to resolve the most collinear splittings.
  - *Use tracks in jets → smallest angular scales!*



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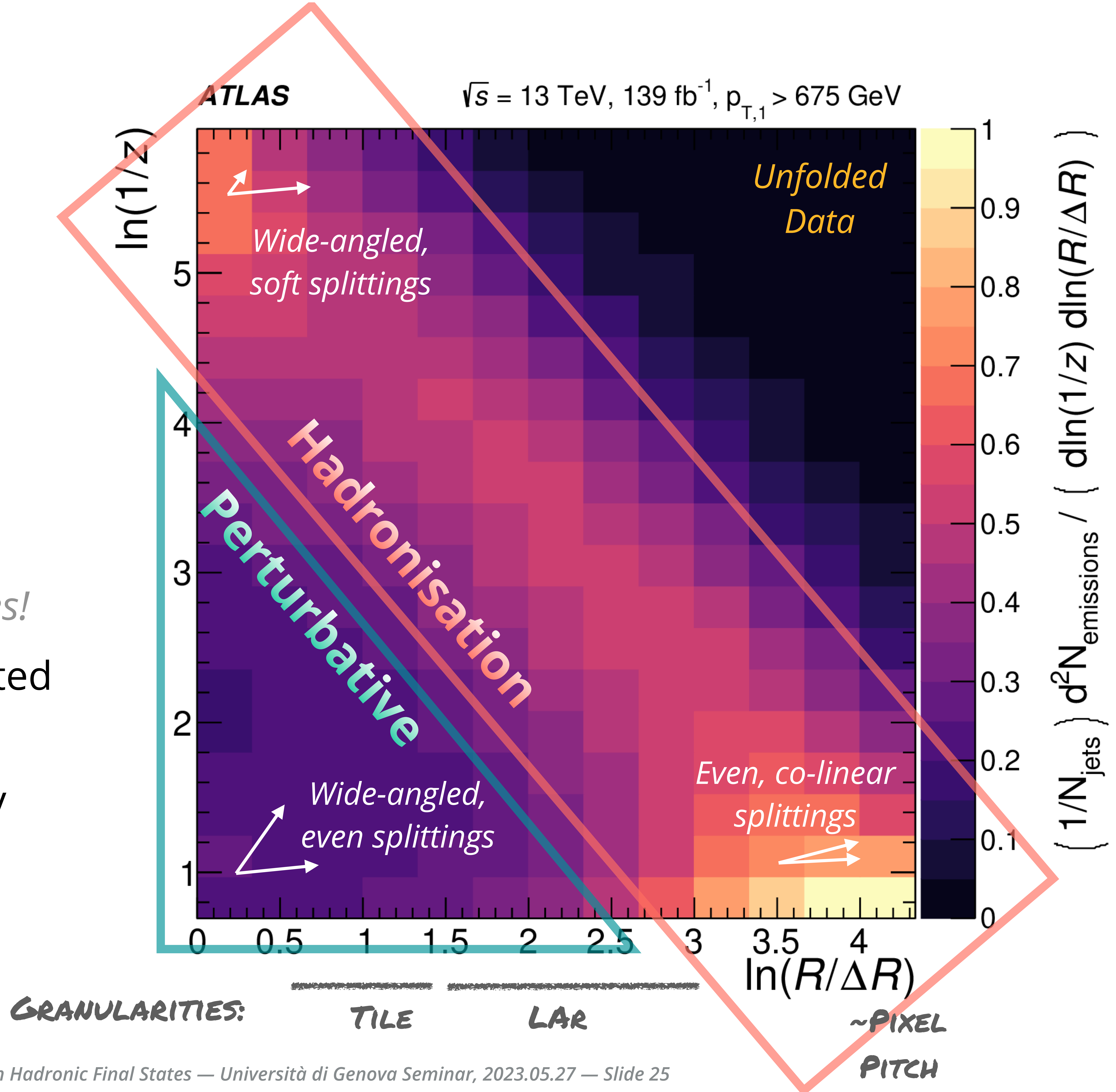
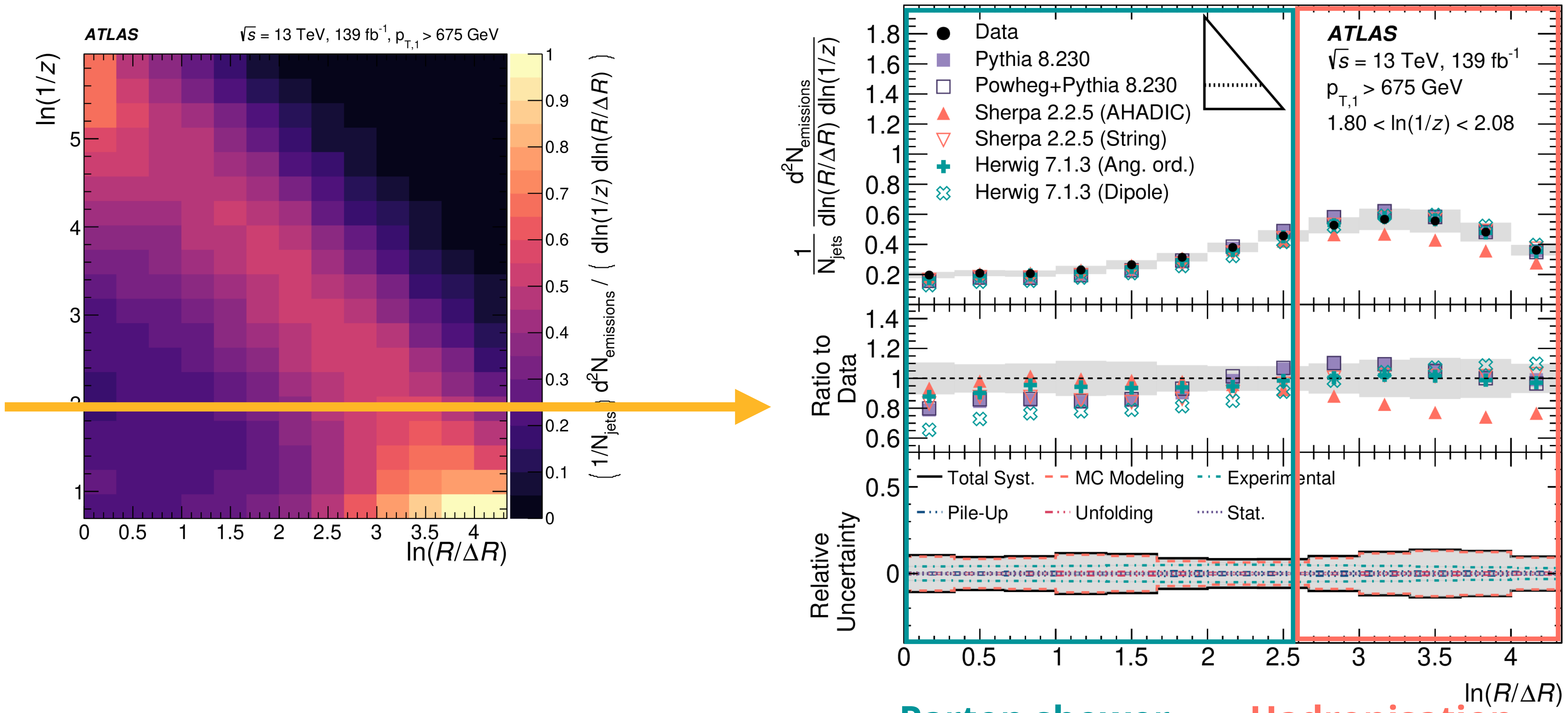
- Calorimeter granularity is too coarse to resolve the most collinear splittings.
  - *Use tracks in jets → smallest angular scales!*
  - **Perturbative region,** uniformly populated (lower-left corner).
  - **Non-Perturbative region,** enhanced by hadronisation (diagonal band).

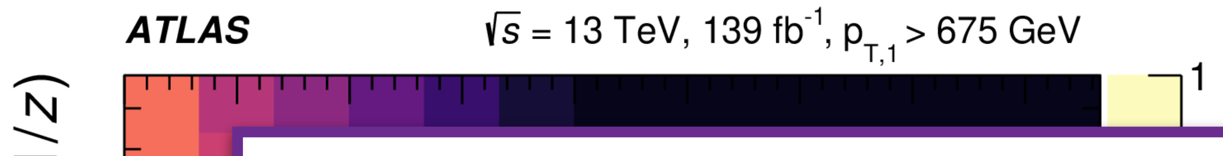


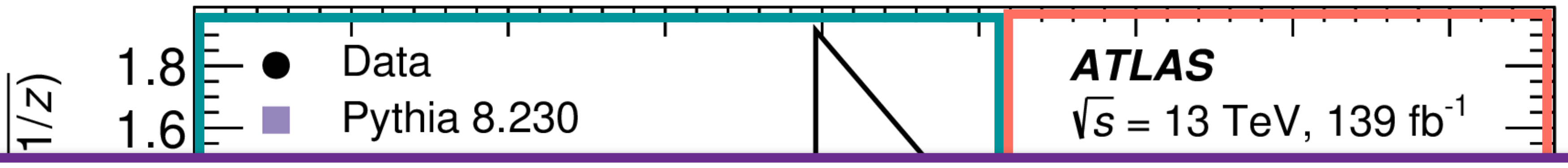


Parton shower models differ

Hadronisation models differ

- Easier to see factorised effects by slicing through LJP.
- Utility in data for improving MC models (*e.g.* hadronisation models → JES)
  - Can improve one aspect of simulation without disturbing another
  - Can mask non-perturbative aspects from classifiers





• Easier to see factorised
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→ JES)
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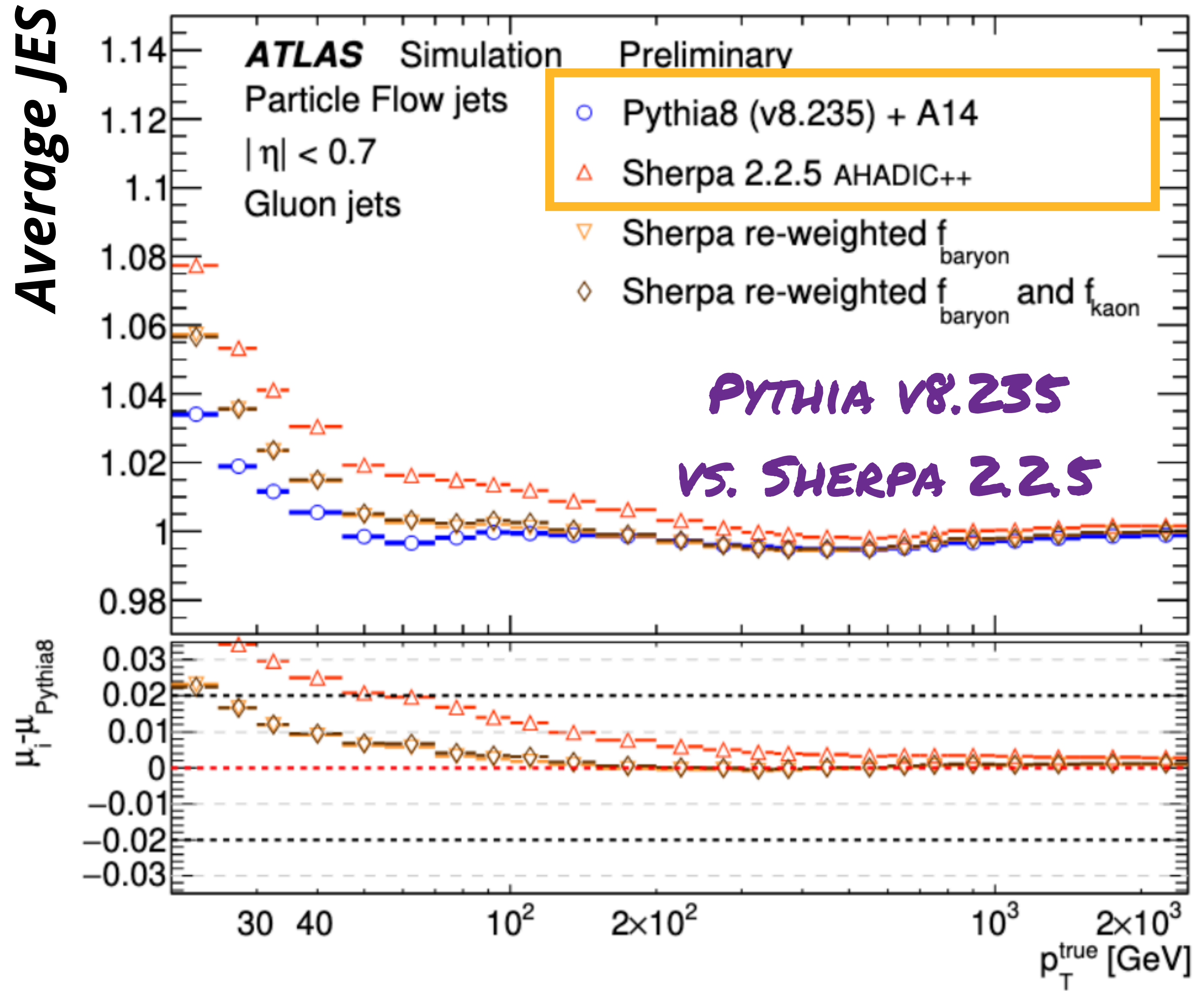
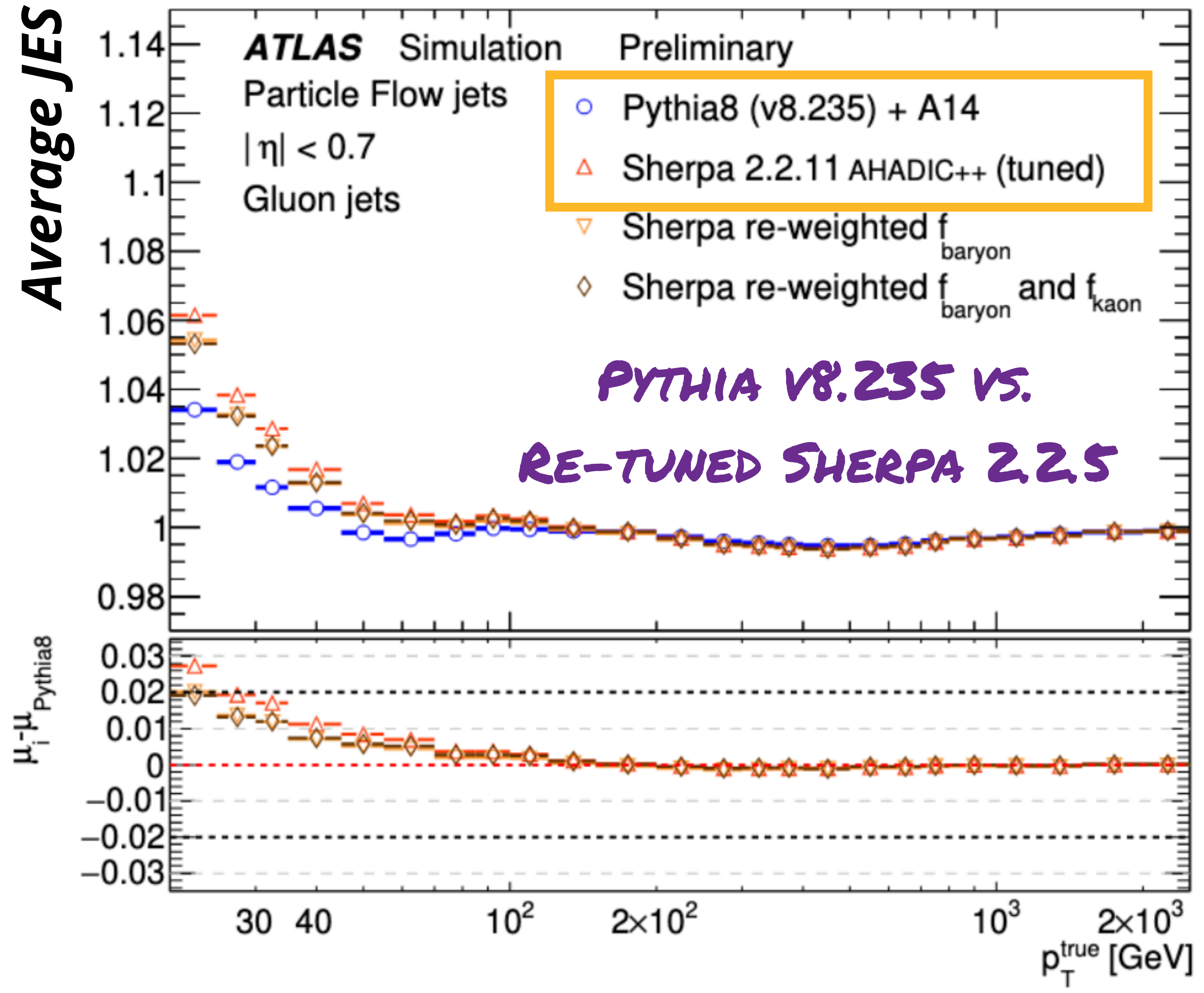
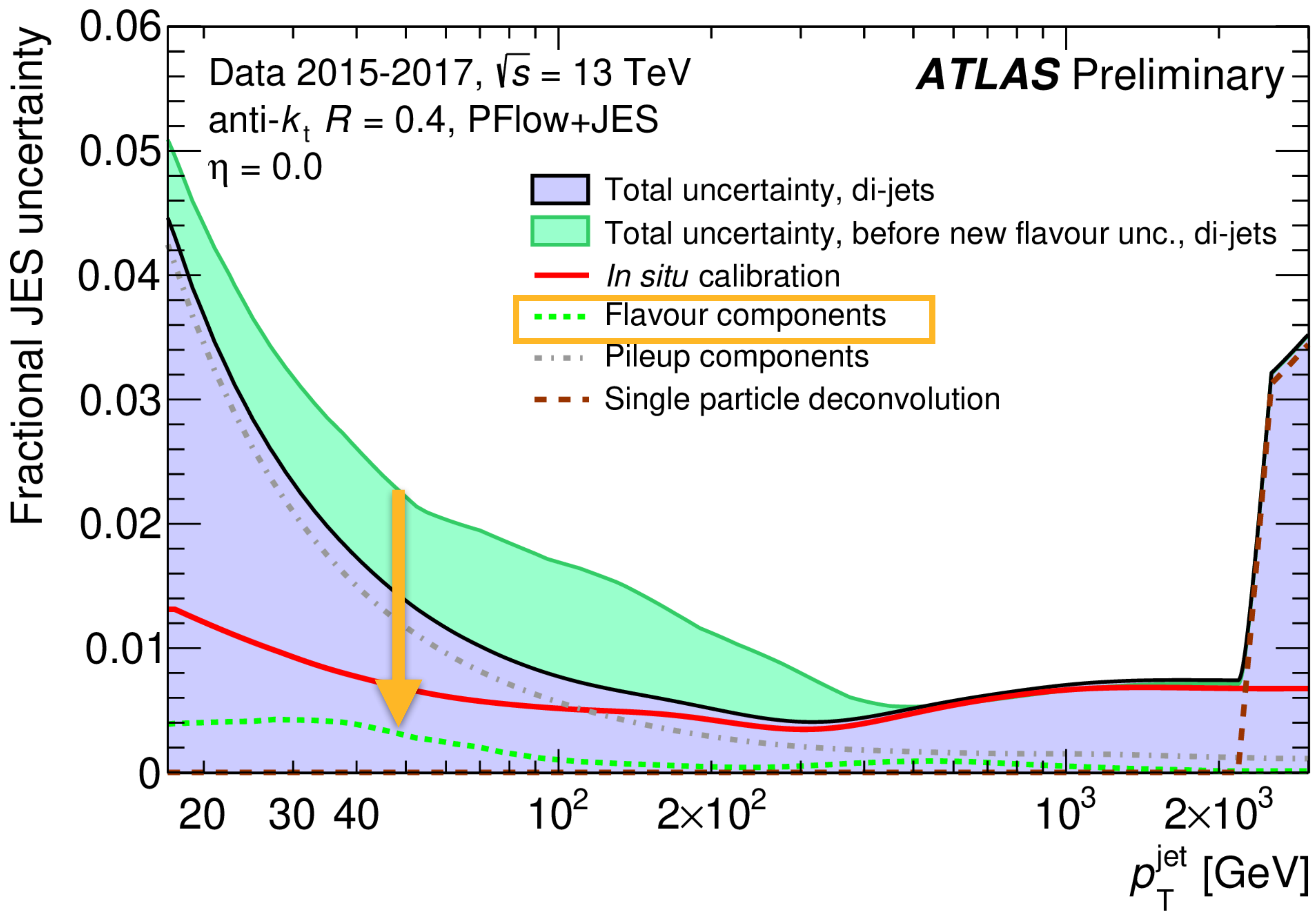
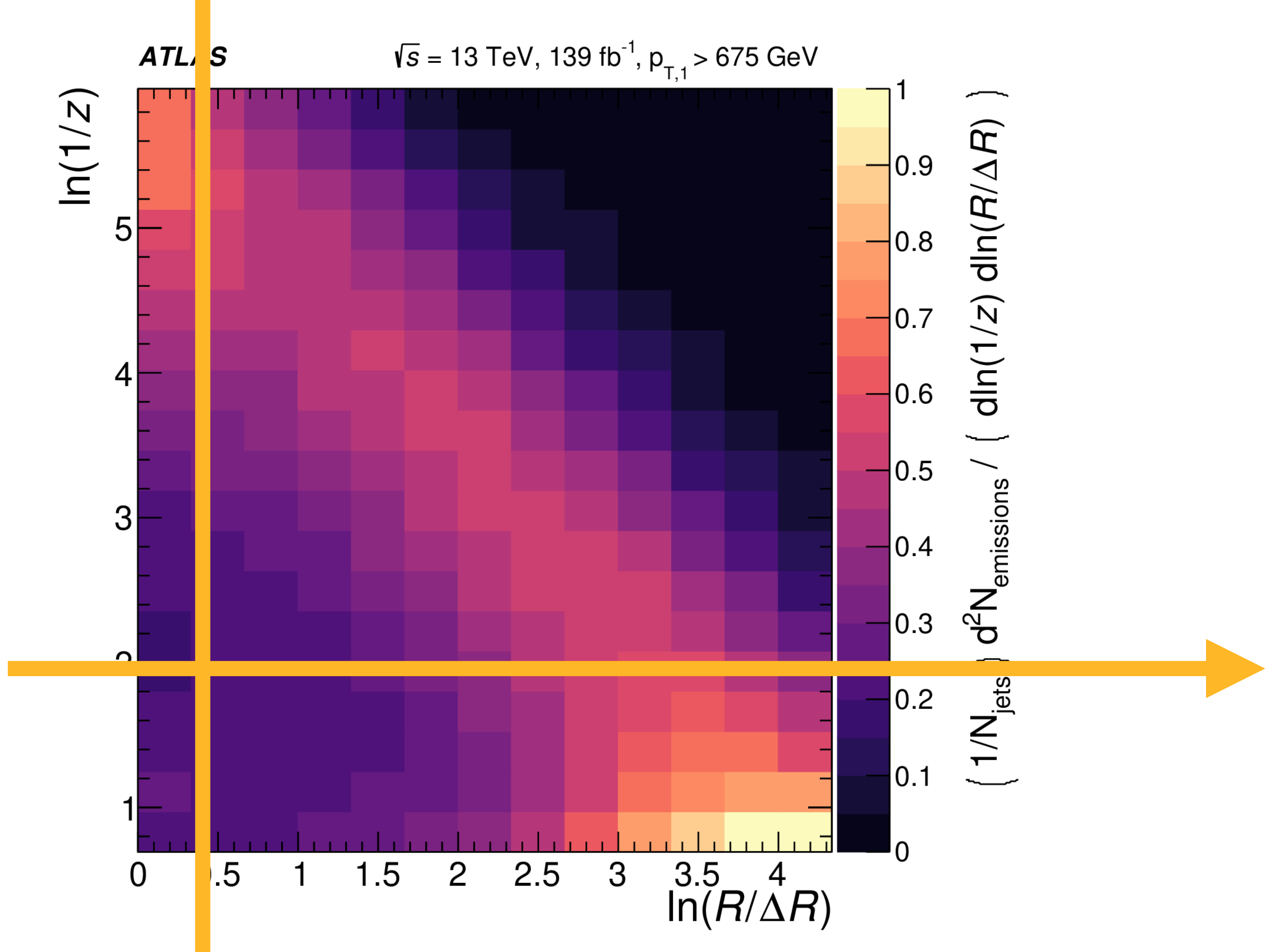


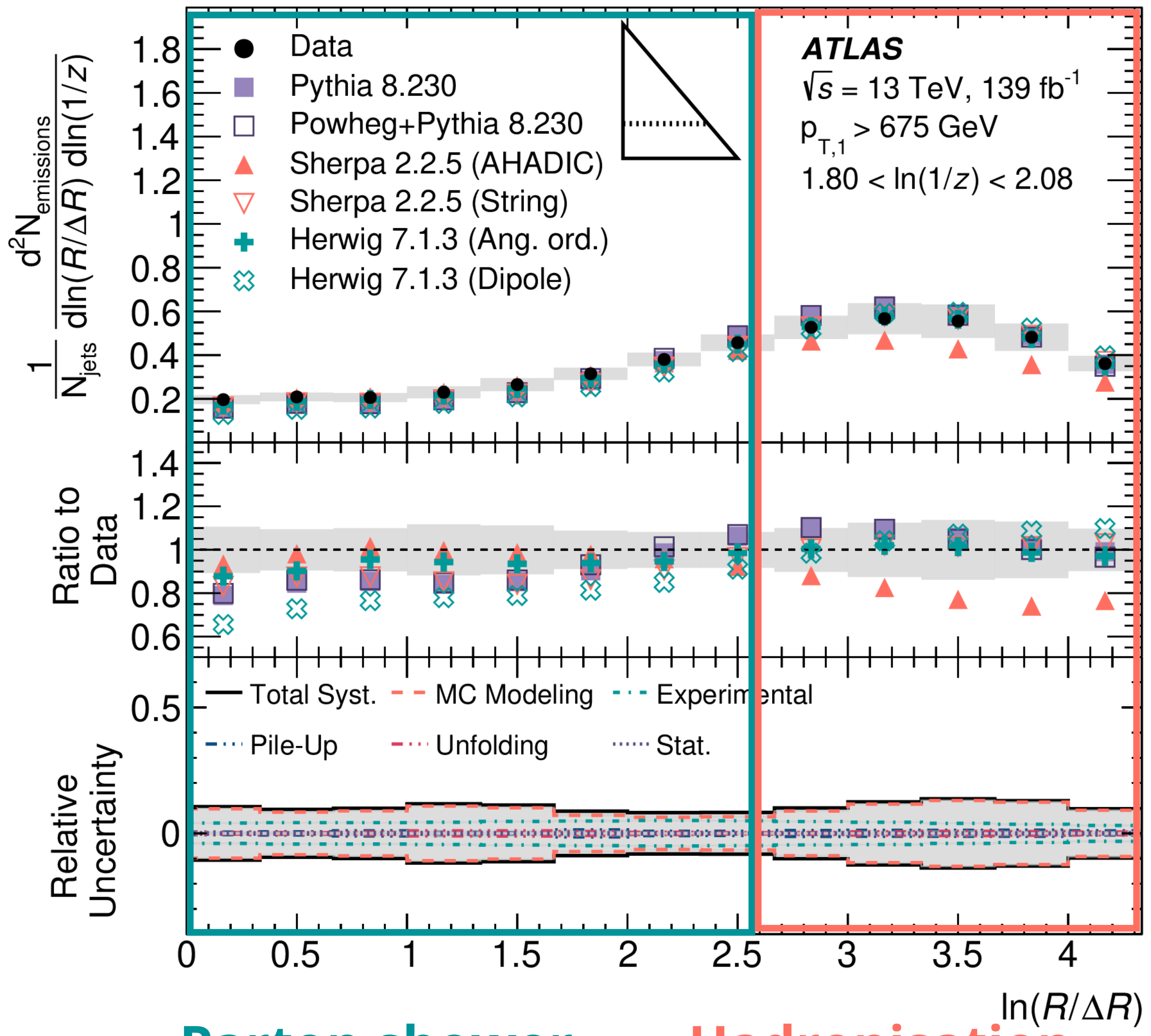




• Re-tuned Sherpa AHADIC hadronisation (*n.b.* tuned w/ LEP data) helps to **dramatically improve** JES flavour uncertainty **(*q vs. g* modelling)** for Run 3!

ATLAS, ATL-PHYS-PUB-2022-021





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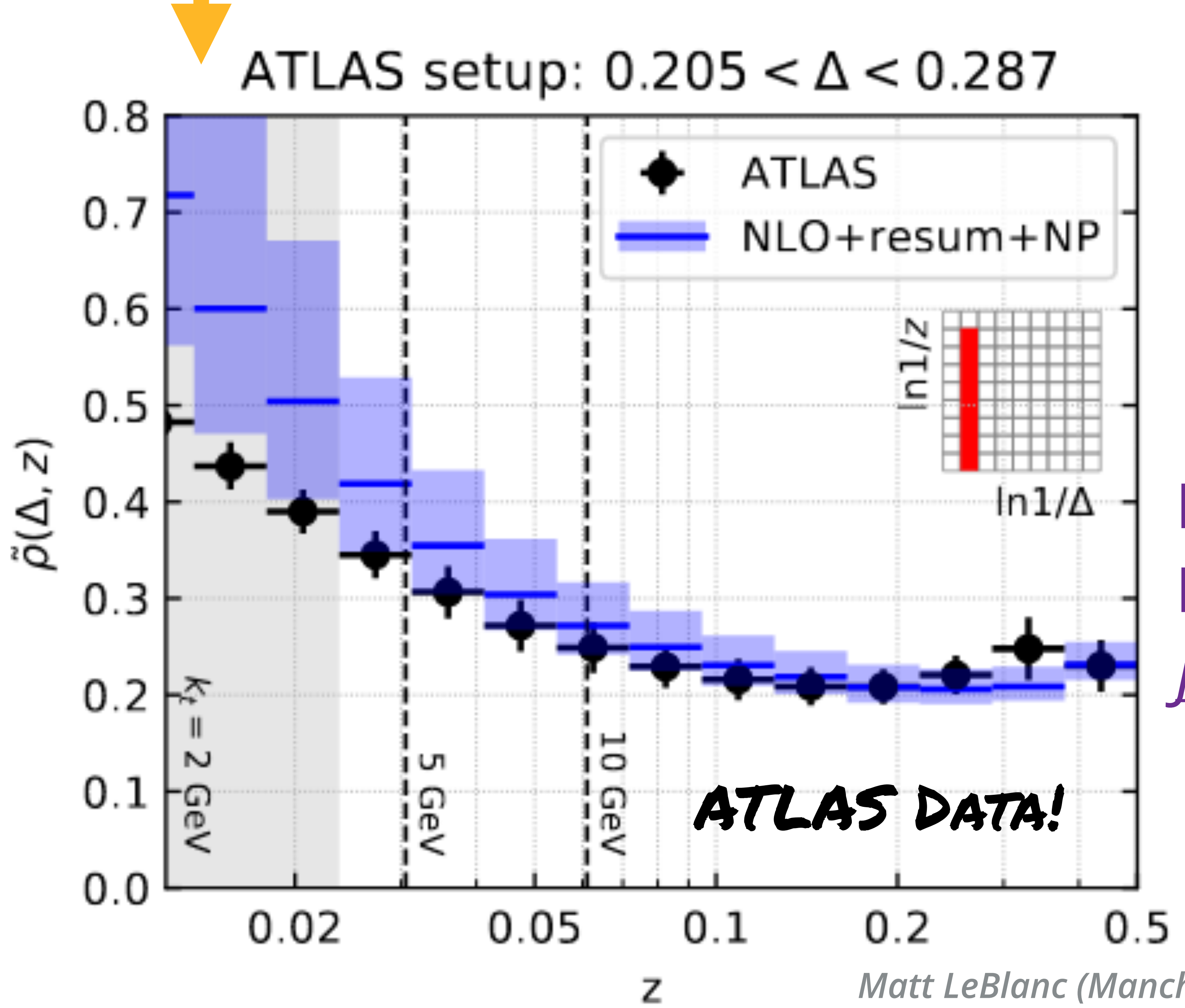


LJP @ NLL
Lifson, Salam, Soyez,
JHEP 10 (2020) 170

- Calculation with NLL resummation compared to measured data
  - **Non-perturbative corrections small** despite charged-only measurement.
  - Agrees well w/ measurement in perturbative region.

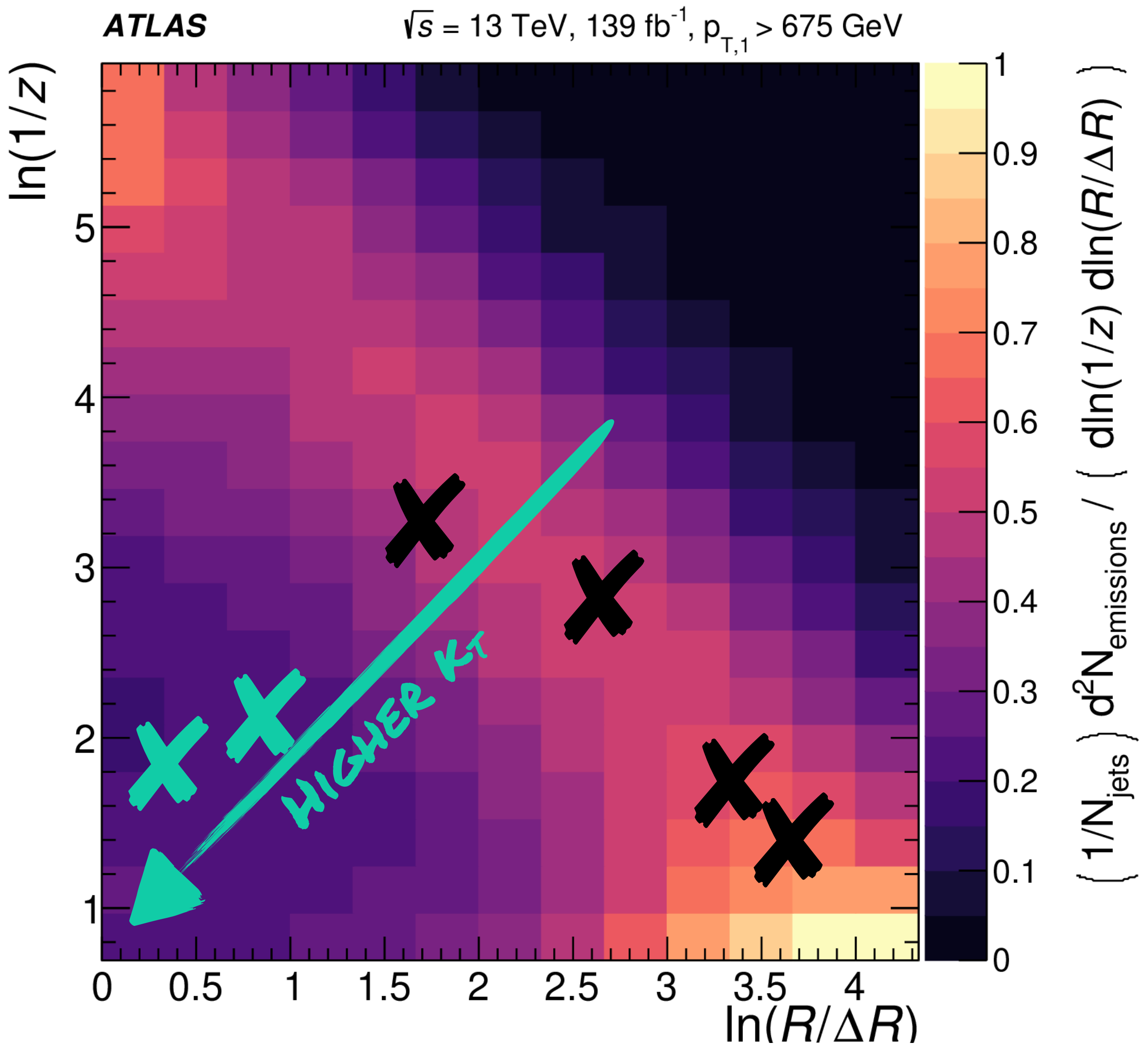
LJP + Parton Showers >LL

Dasgupta, Dreyer, Hamilton, Monni, Salam & Soyez, PRL 125, 052002 (2020)
https://gsalam.web.cern.ch/gsalam/panscales/

- Can the >NLL revolution for JSS be generalised?

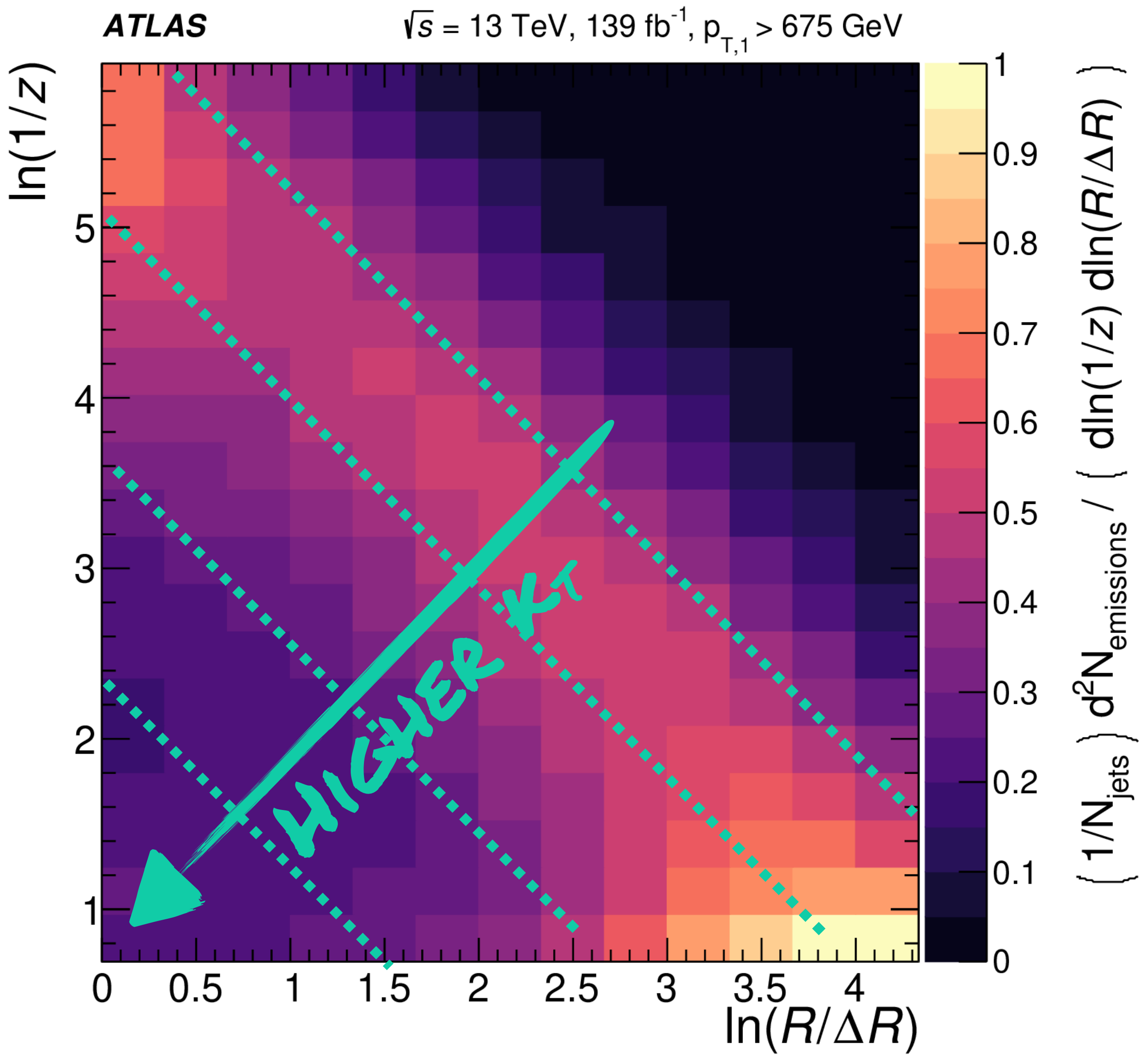
> *had LO → NLO → NNLO,*
> *now LL → NLL → NNLL!*
> ***want Parton Showers: LL → NLL***

- Parton Shower Monte Carlos are probably the most widely-used theoretical HEP tool.
  - We know that the current generation have limitations:
    - Only ~LL accurate
    - Do not provide realistic estimates of uncertainties
    - Performance difficult to evaluate — tuned to data (empirical)
- LJP can be used to construct observables sensitive to higher-order effects (PanScales, NLL).



DELTA-PHI BETWEEN TWO EMISSIONS WITH HIGHEST k_T

→ SPIN CORRELATIONS

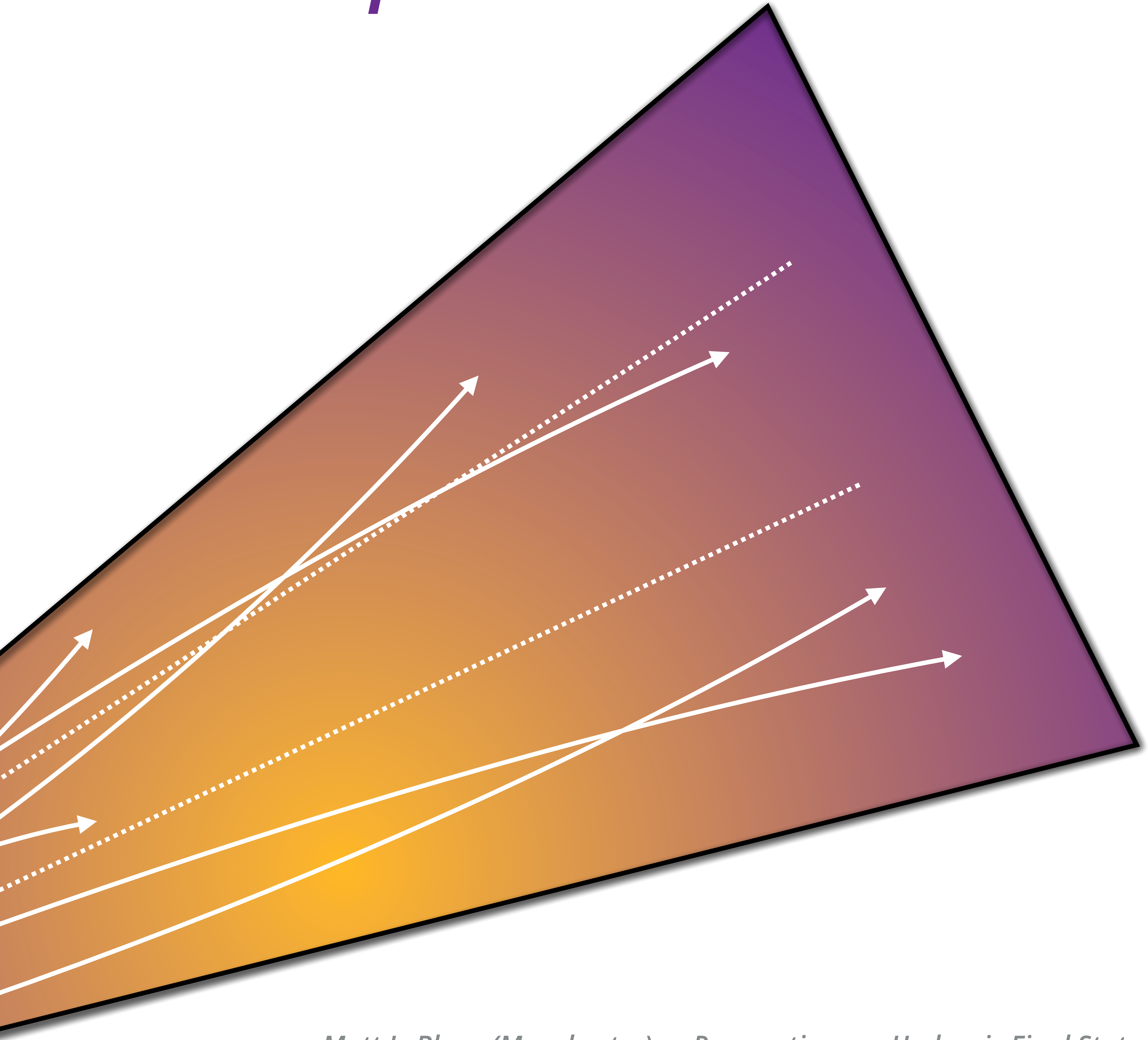


INCREASE k_T-CUT + INTEGRATE IN LJP (COUNT EMISSIONS)

→ SPLITTING FUNCTIONS (2→2, 2→3)

SEE ALSO LH19 2003.01700

Perspectives on hadronic final states



From Up Close

Part 1: Jet Substructure

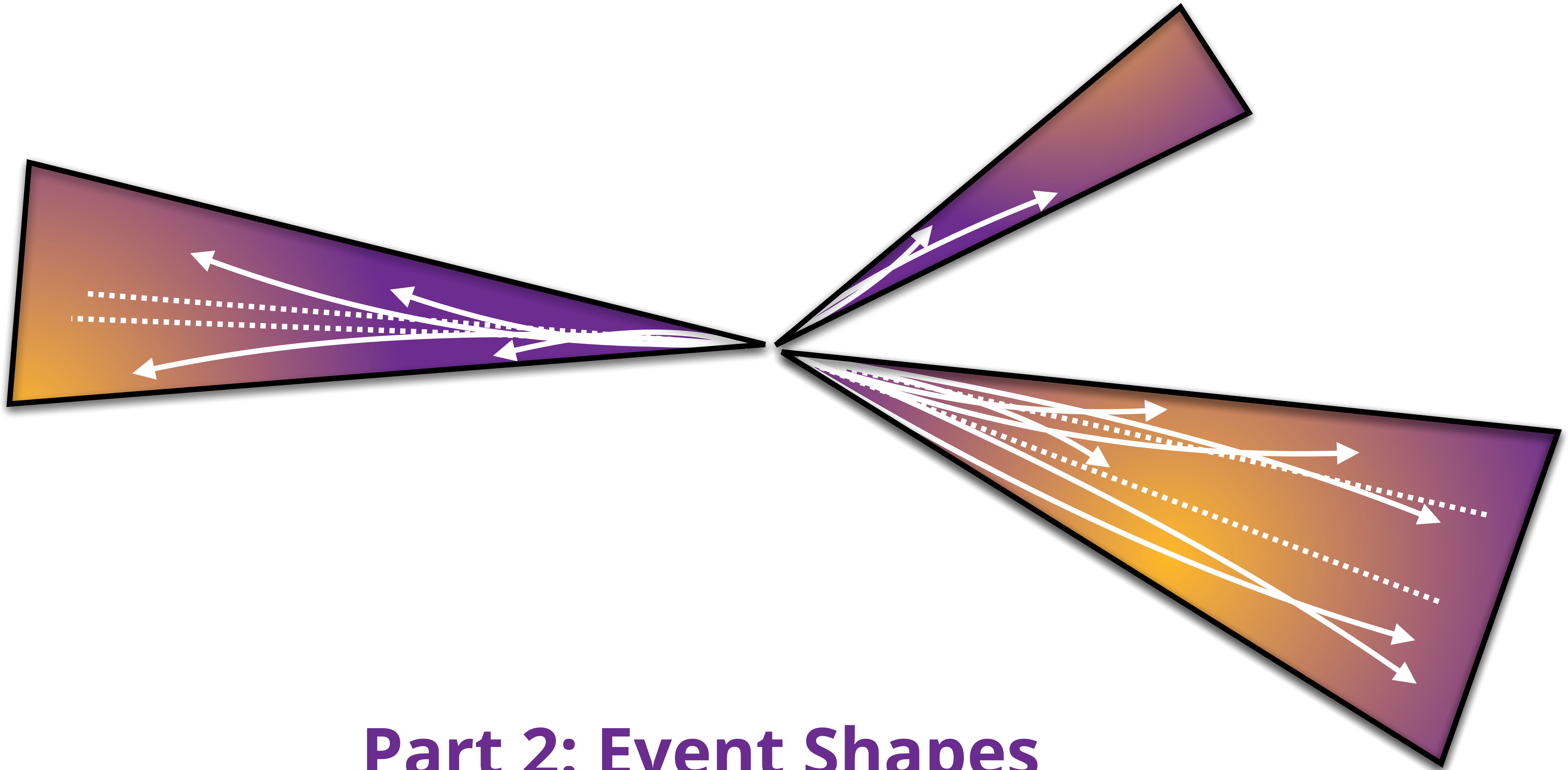
ATLAS soft-drop mass + observables

PRL 121, 092001 (2018), PRD 101, 052007 (2020)

ATLAS Lund jet plane

PRL 124, 222002 (2020)

Perspectives on hadronic final states



From Up Close

+ Far Away

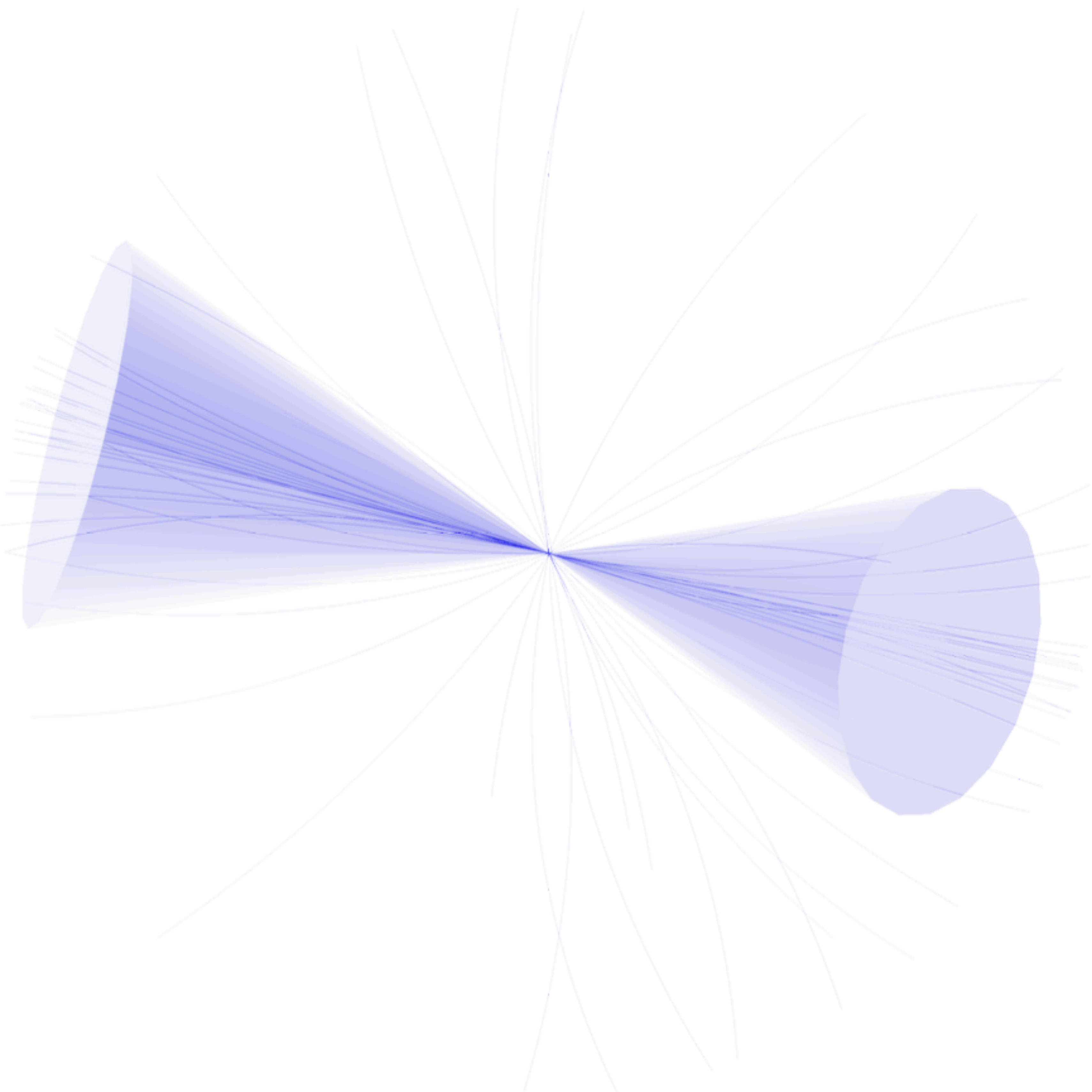
Part 2: Event Shapes

Multijet Event Isotropies w/ Optimal Transport

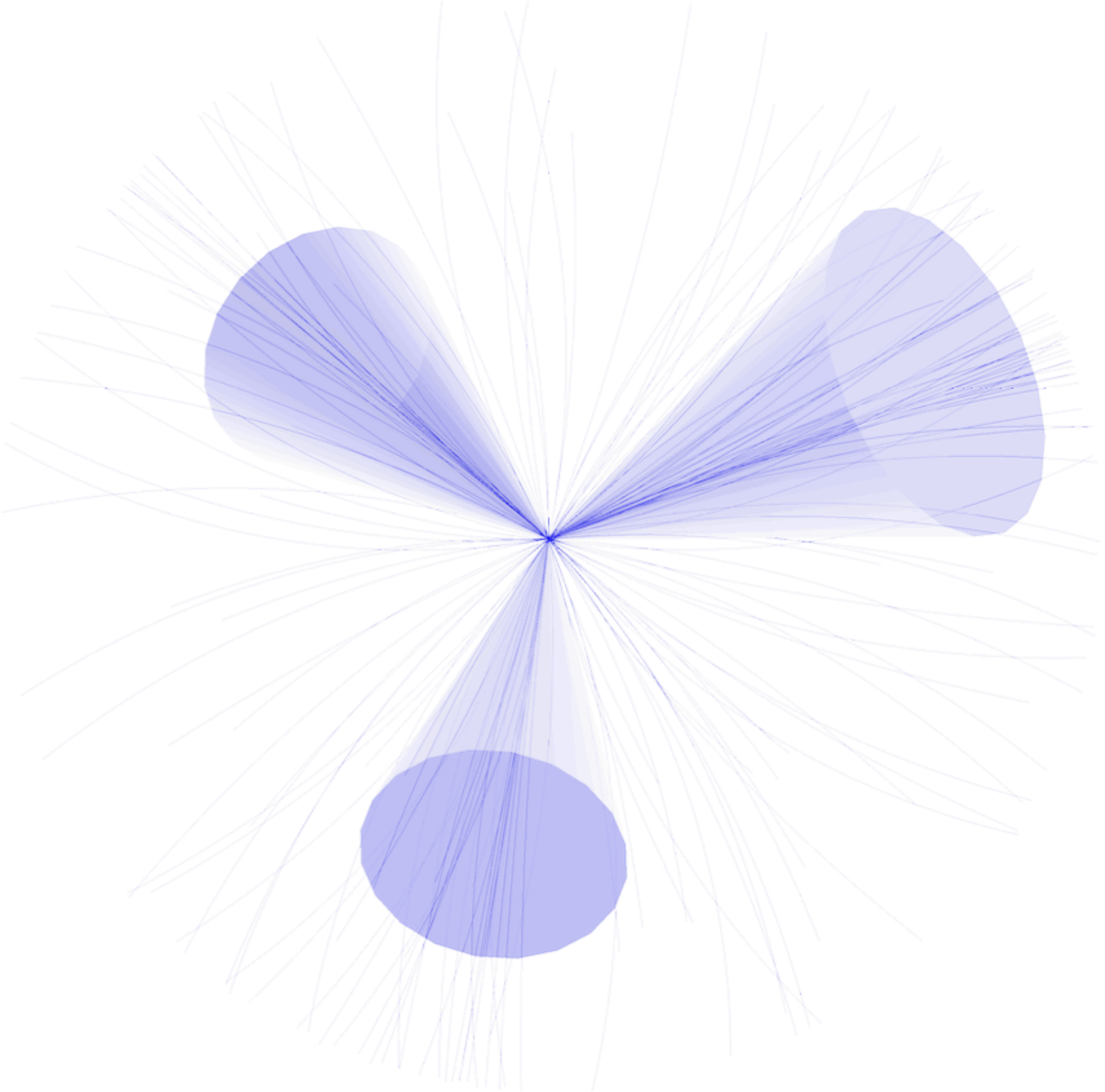
ATLAS-STDM-2020-20

Event shapes

... interpolate between collider event topologies.



Which event is more back-to-back?



Event shapes

… interpolate between collider event topologies.

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

Gluon observation

(JADE, 1980)

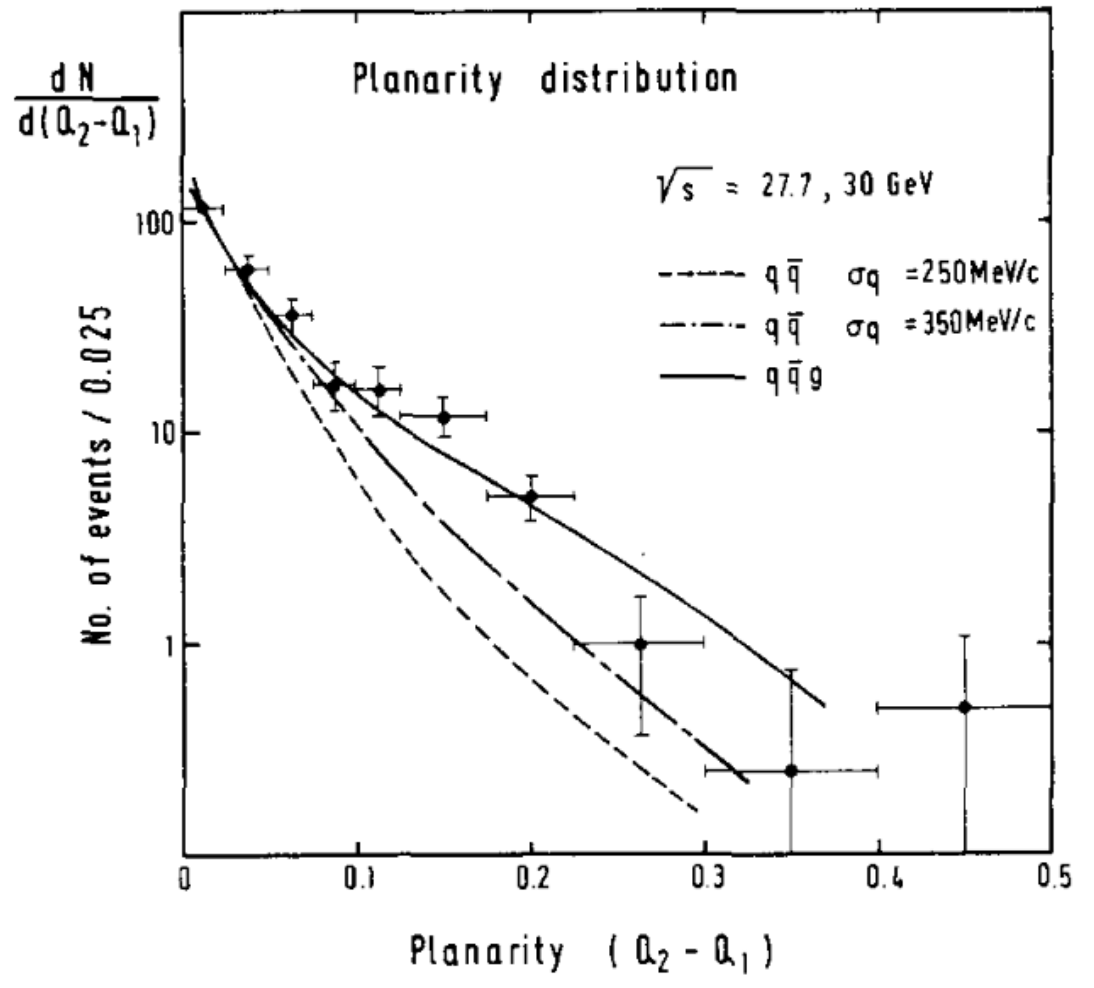
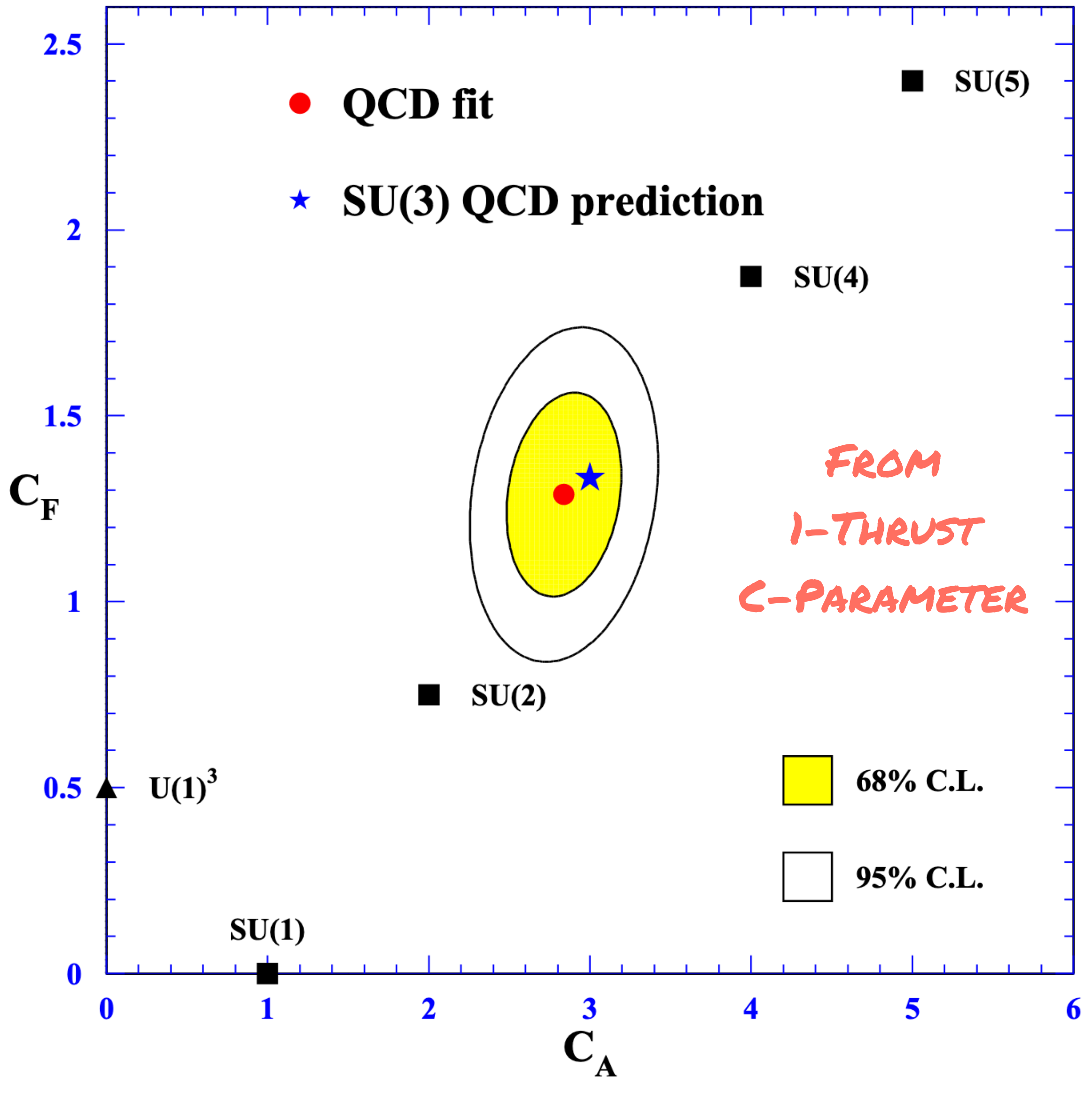


Fig. 3. The planarity distribution compared with model predictions.

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

QCD Colour Factors

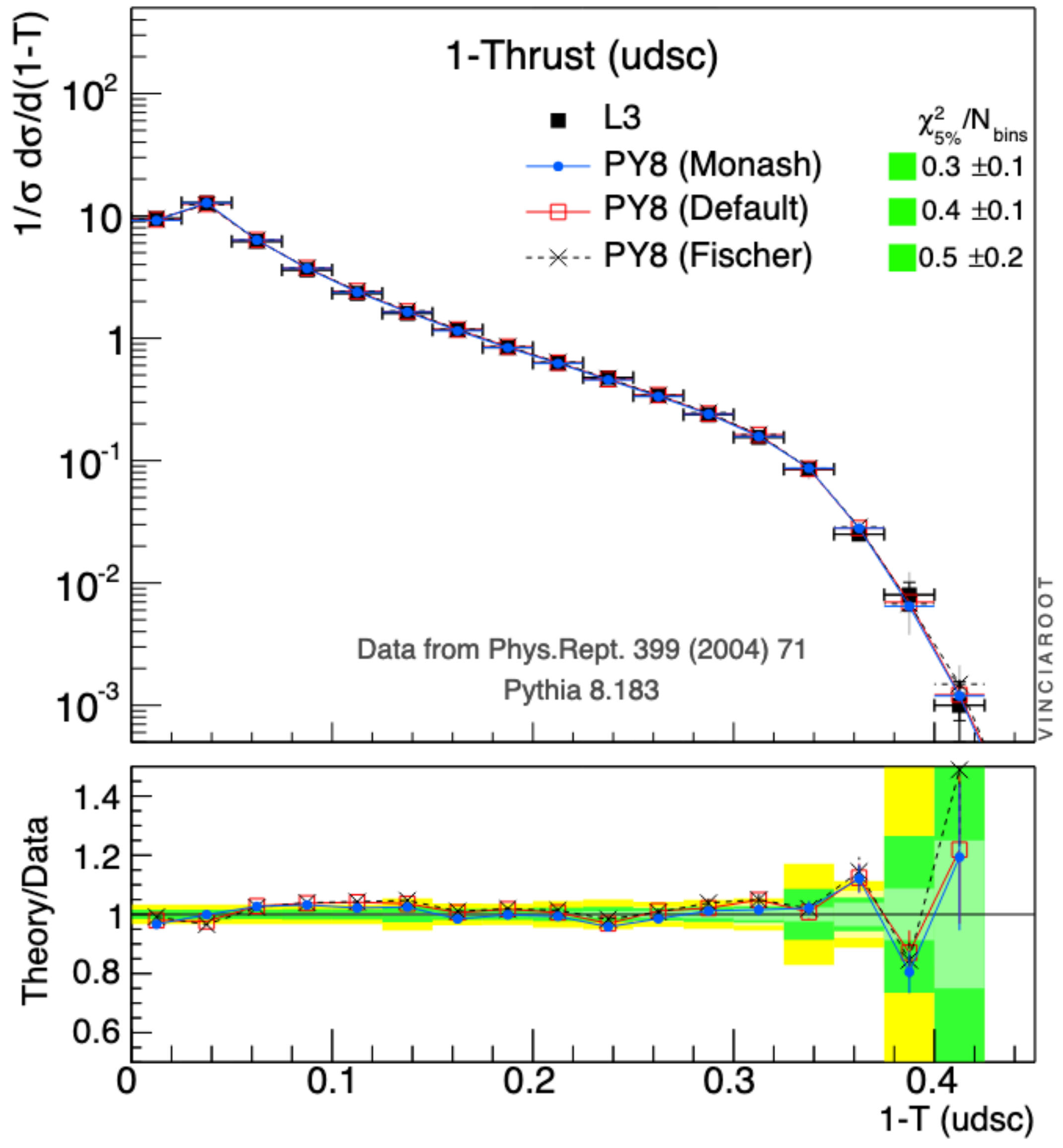
(Kluth et al. 2000)



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

Monash tune

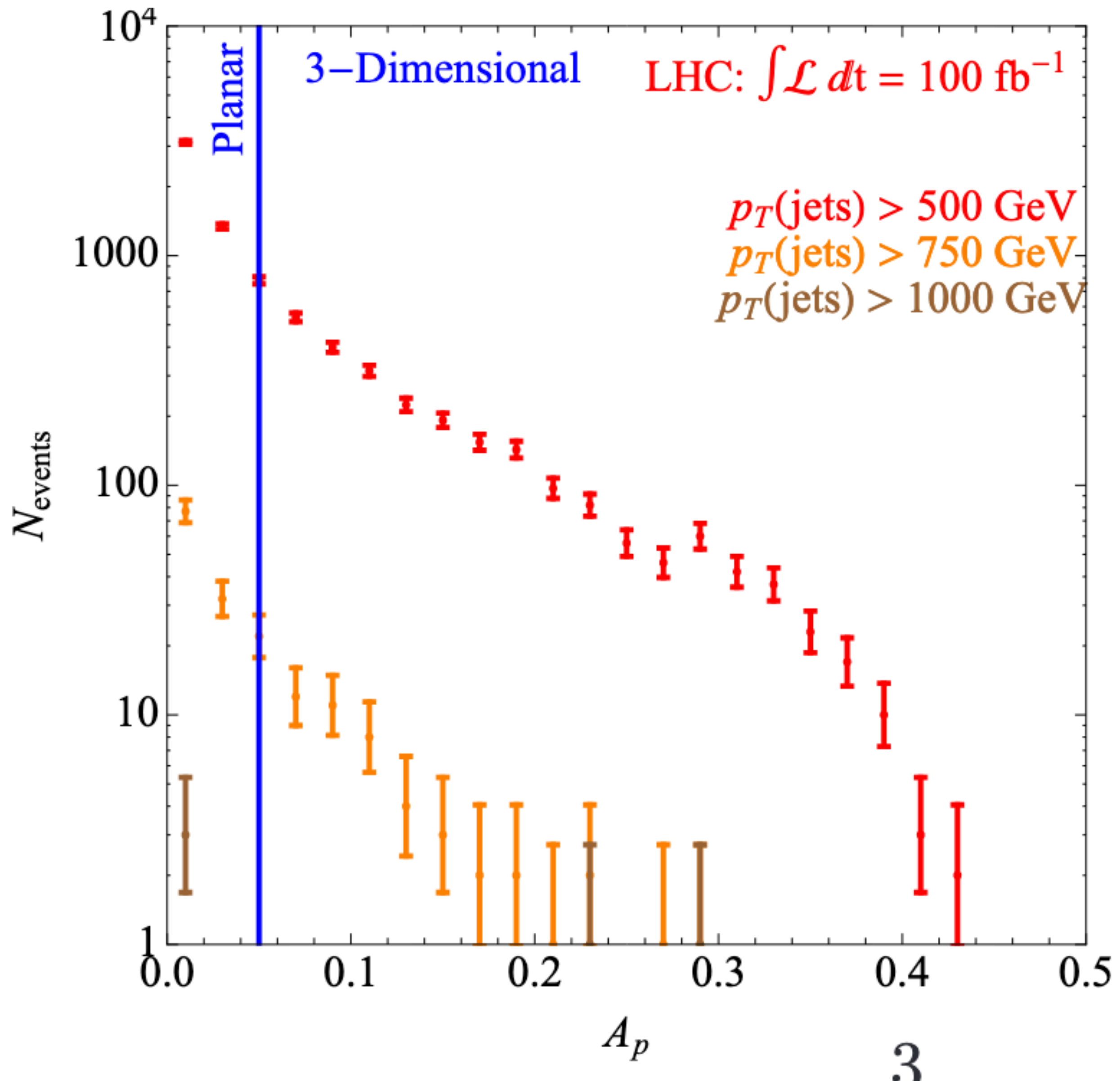
(Skands et al. 2014)



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

BSM?

(Anchordoqui et al. 2011)



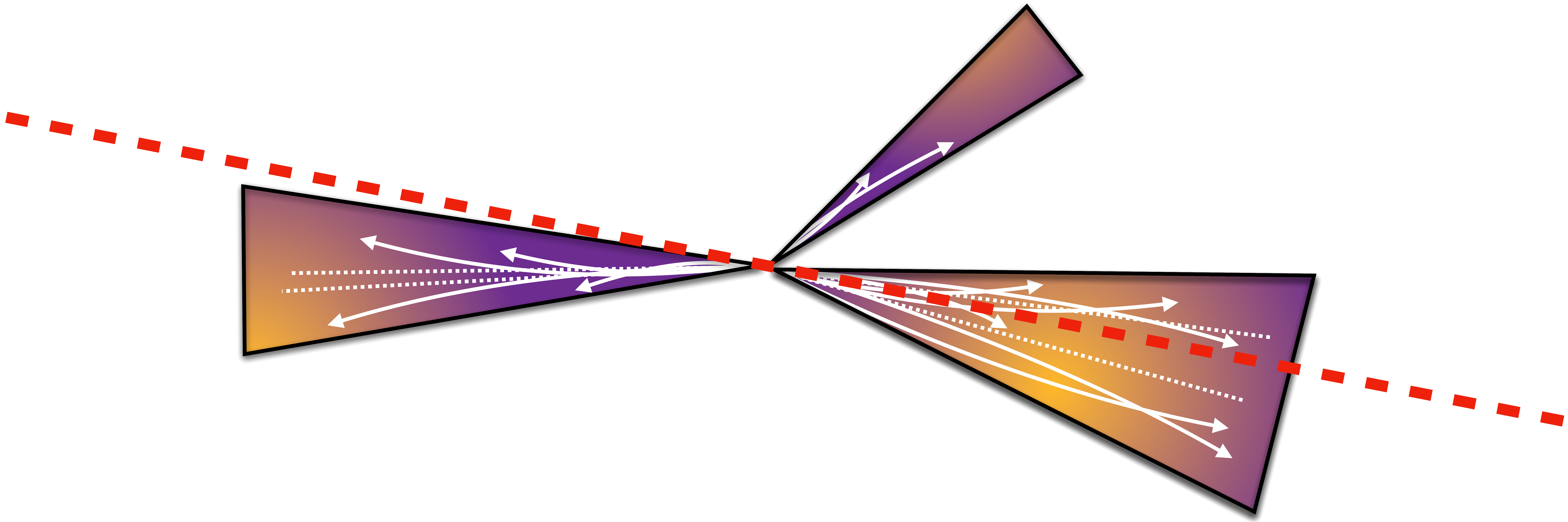
$$A_p = \frac{3}{2} Q_1 ,$$

Transverse thrust

One common definition of thrust:

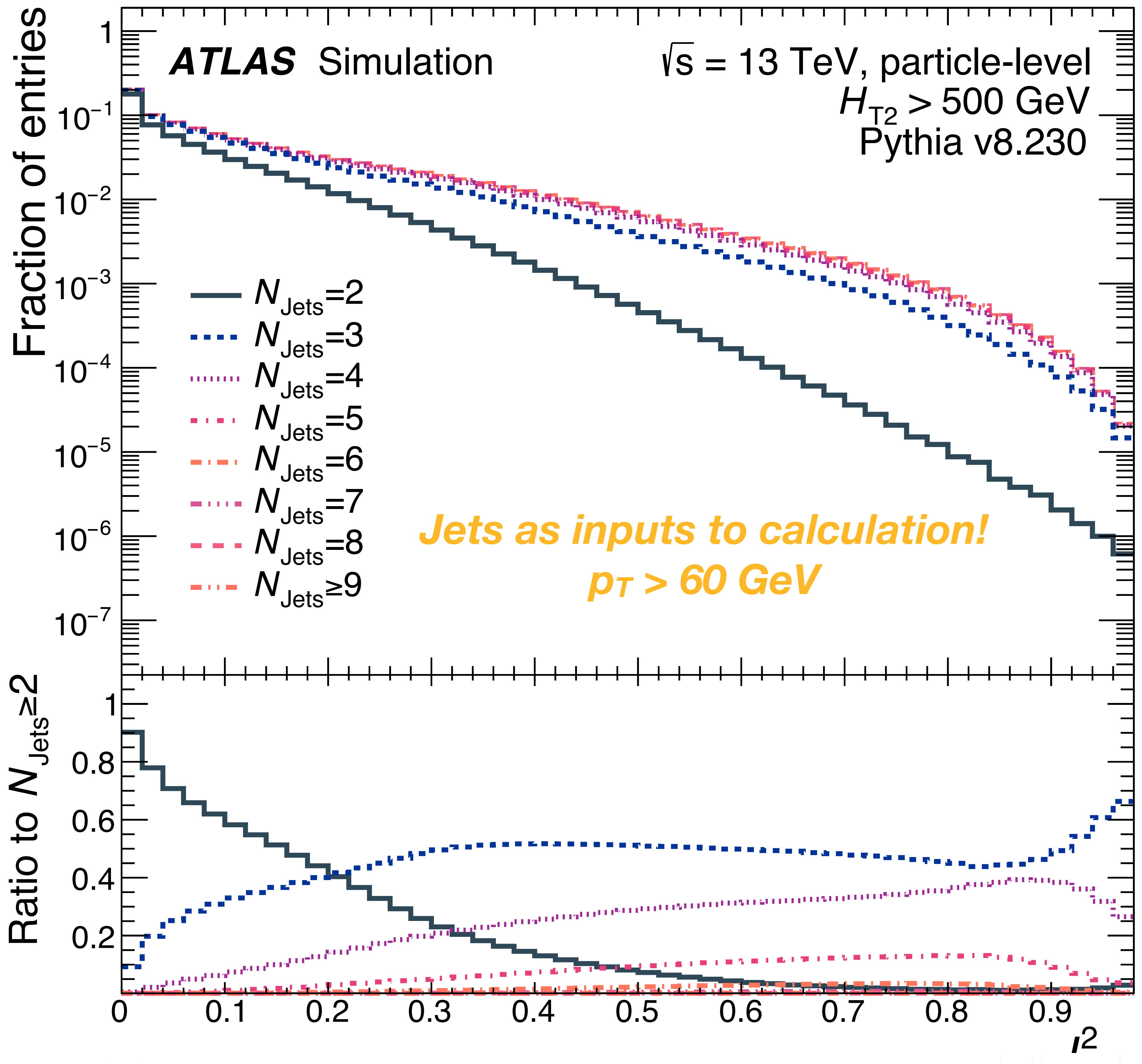
$$t(\mathcal{E}) = 2\min_{\hat{n}} \sum_{i=1}^{M} \frac{|\vec{p}_i|(1 - |\vec{n}_i \cdot \hat{n}|)}{E_{\text{total}}} \quad \hat{n}_i = \vec{p}_i/|\vec{p}_i|$$

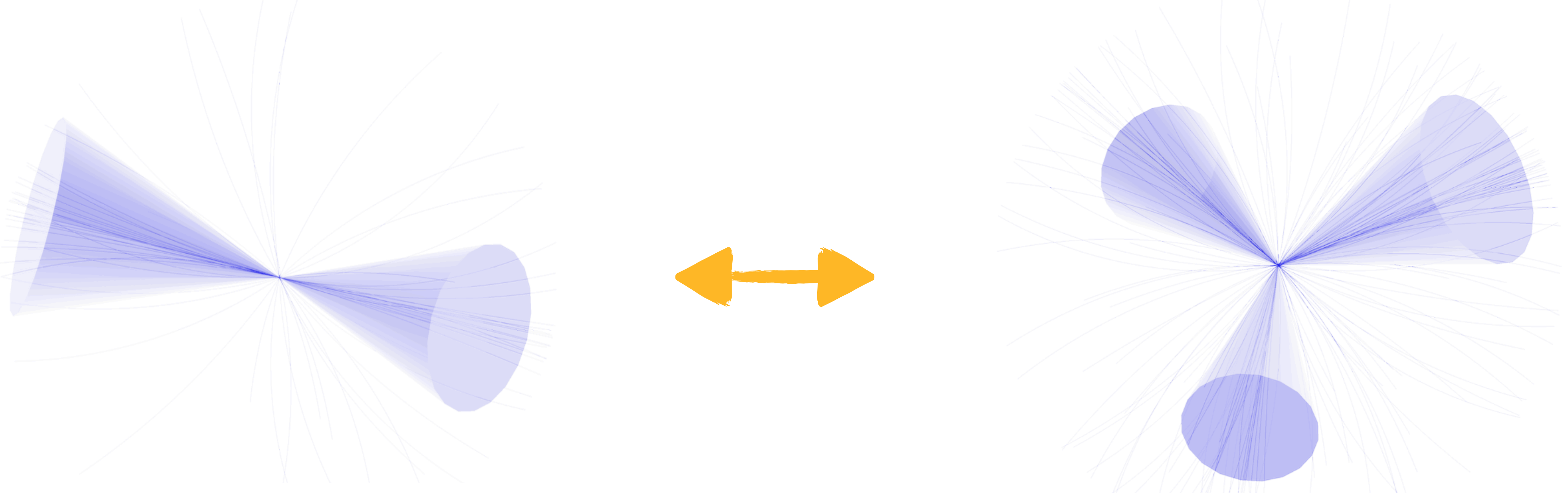
PROJECT EVENT ACTIVITY ONTO THE 'THRUST AXIS' THAT MINIMISES OBSERVABLE



Transverse thrust

- **Transverse Thrust** is an extremely well-understood event shape in *pp* collisions.
    - Quantifies how “back-to-back” an event is.
        - **<u>Small values:</u>** back-to-back
        - **<u>Large values:</u>** ‘Mercedes’
- ***Are Mercedes events isotropic?***



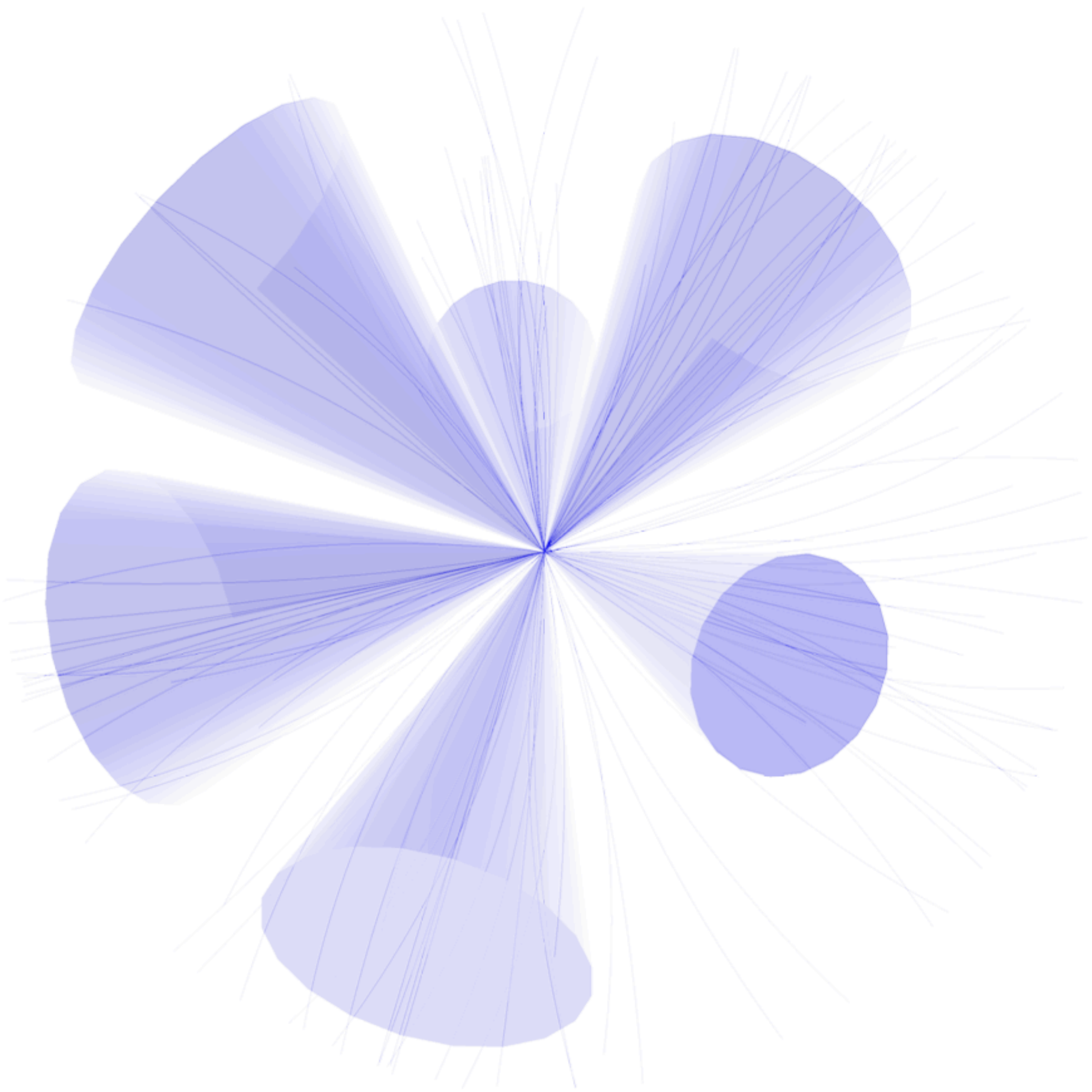


$$t(\mathcal{E}) = 2\min_{\hat{n}} \sum_{i=1}^{M} \frac{|\vec{p}_i|(1 - |\vec{n}_i \cdot \hat{n}|)}{E_{\text{total}}} \qquad \hat{n}_i = \vec{p}_i/|\vec{p}_i|$$

What about this event?

Does it have a large or small thrust value?

Is it isotropic?



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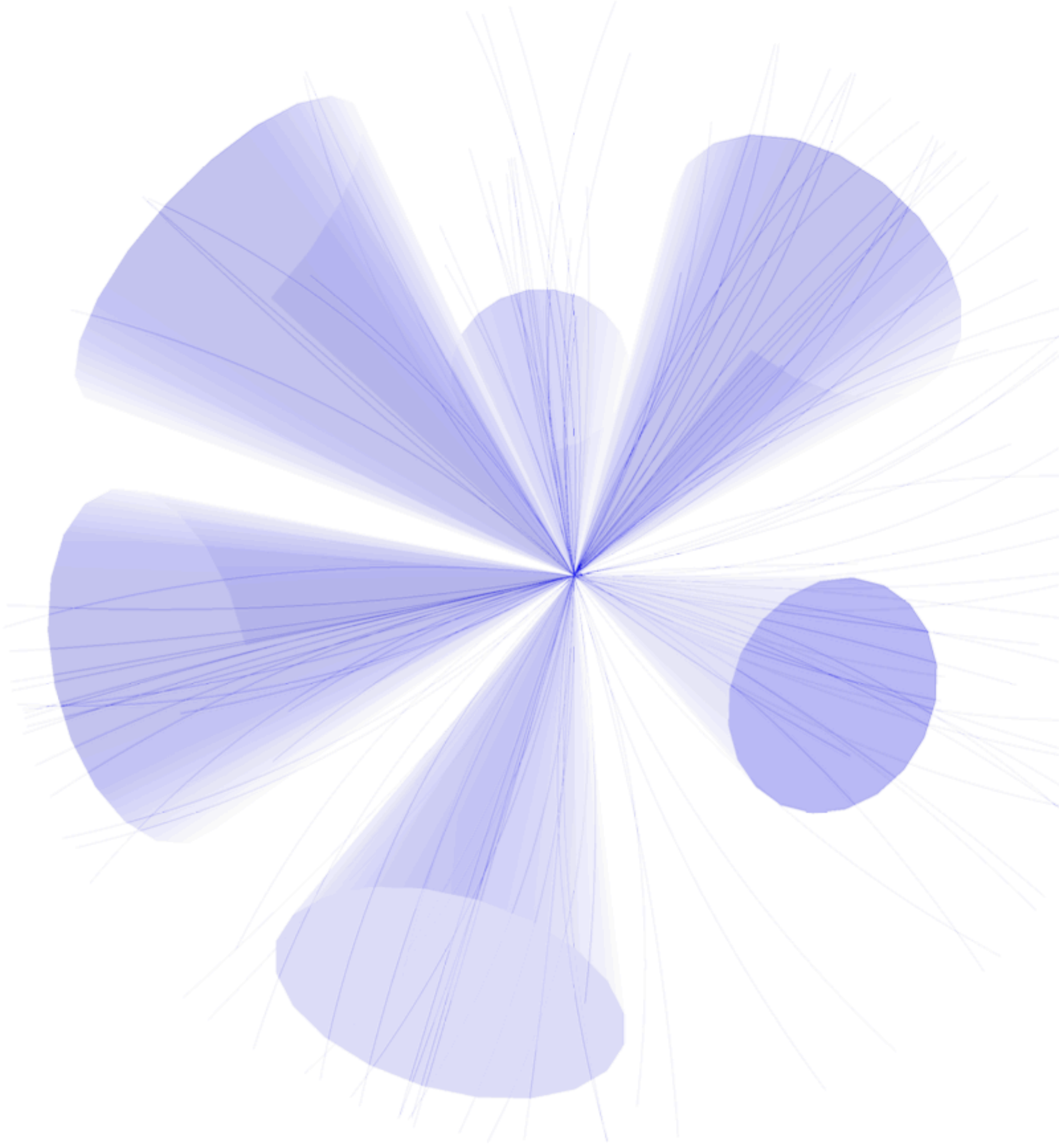
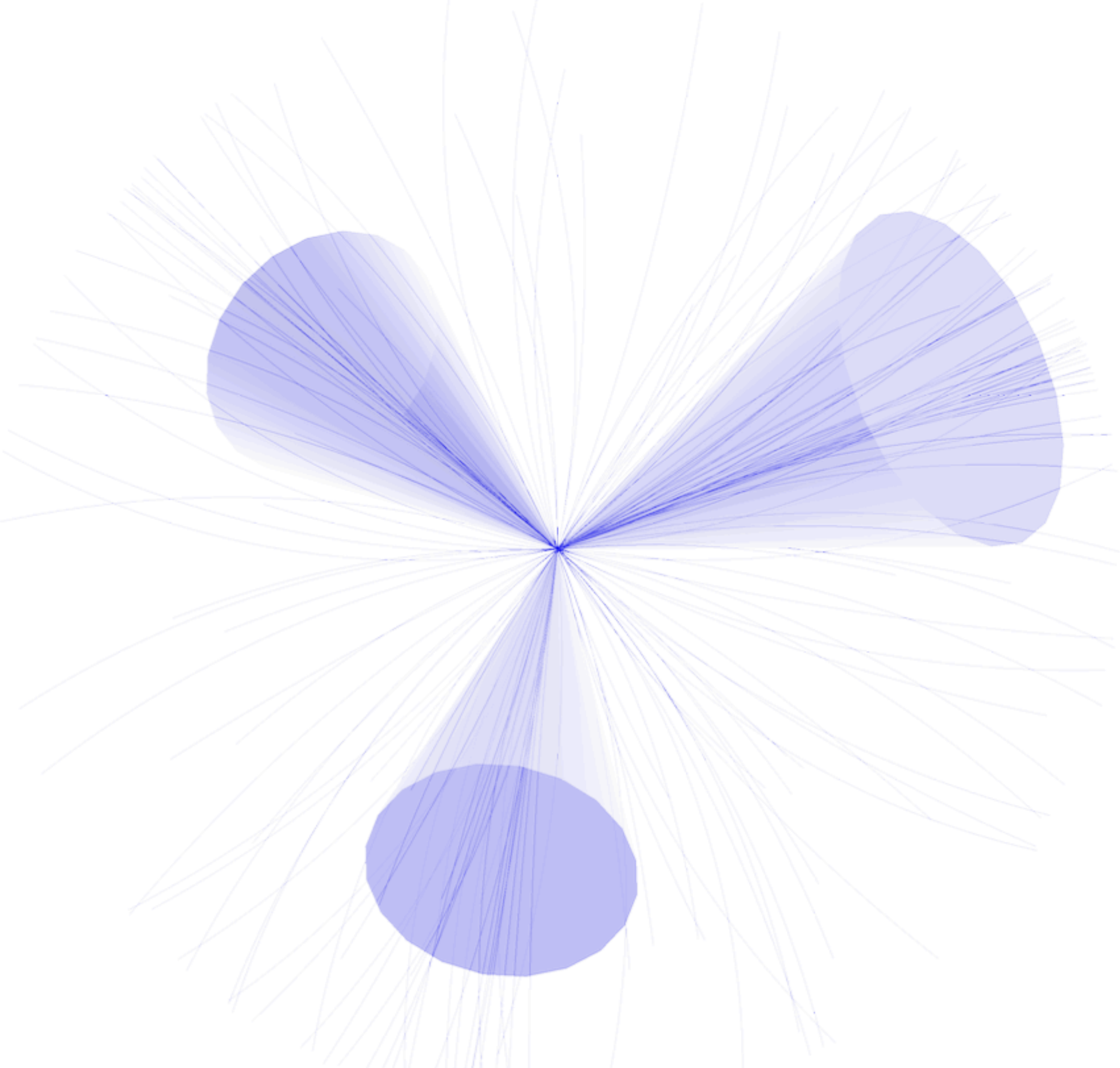
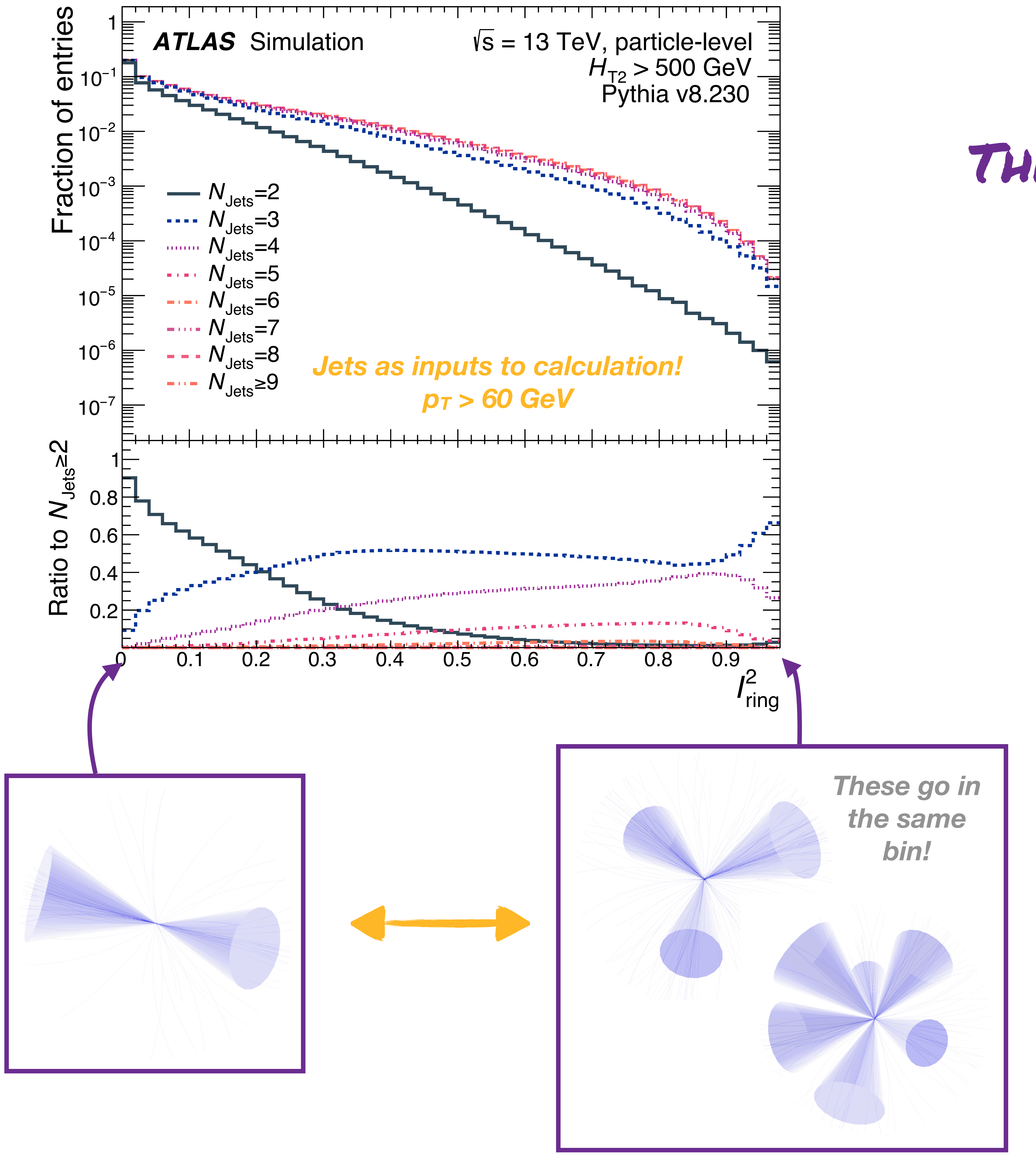


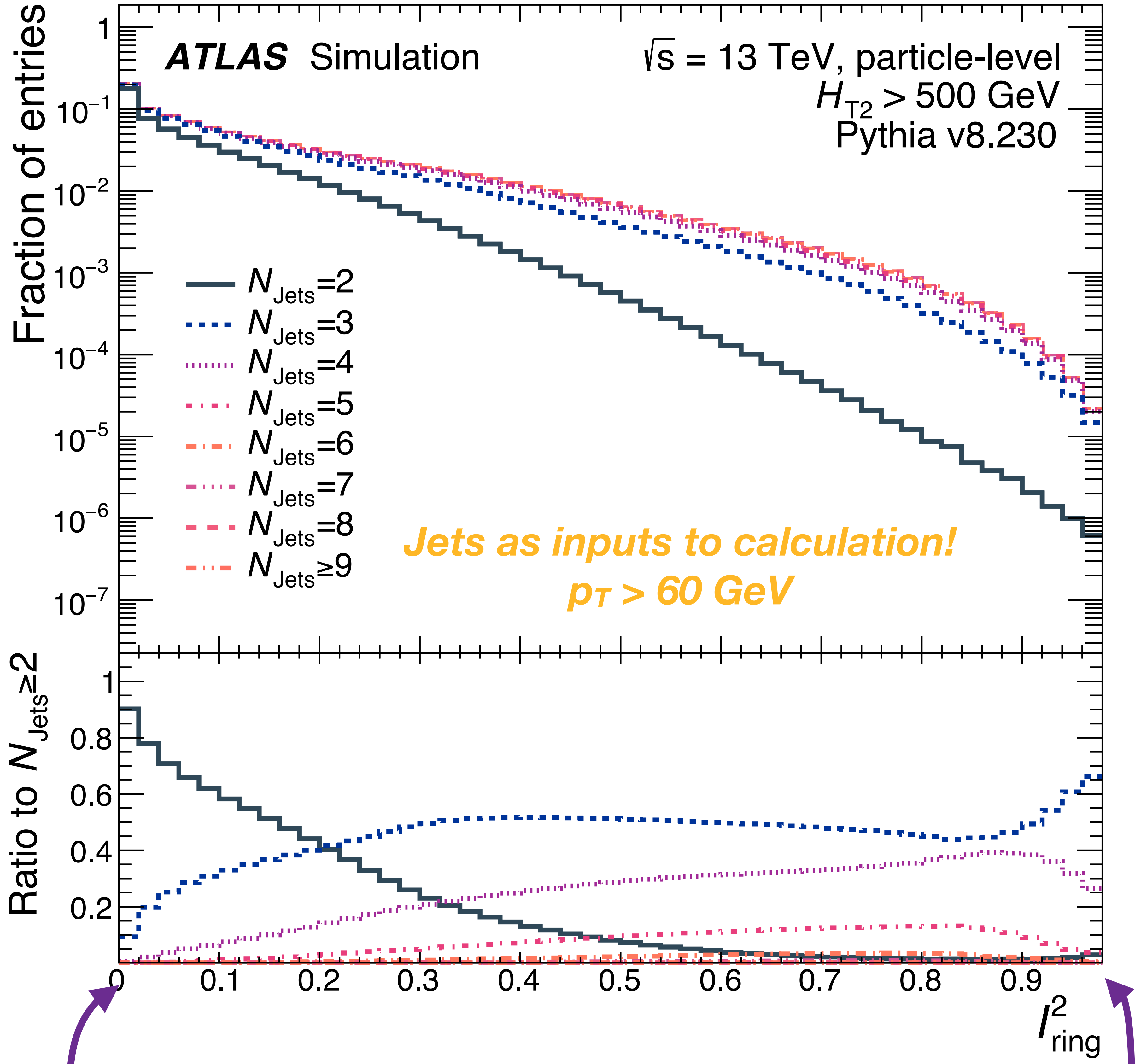


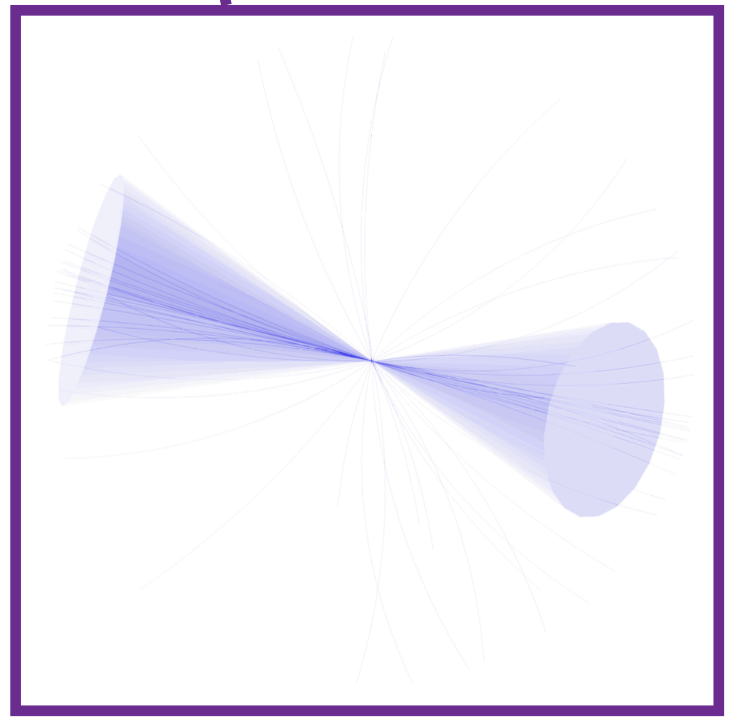
Is it larger or smaller than this one?

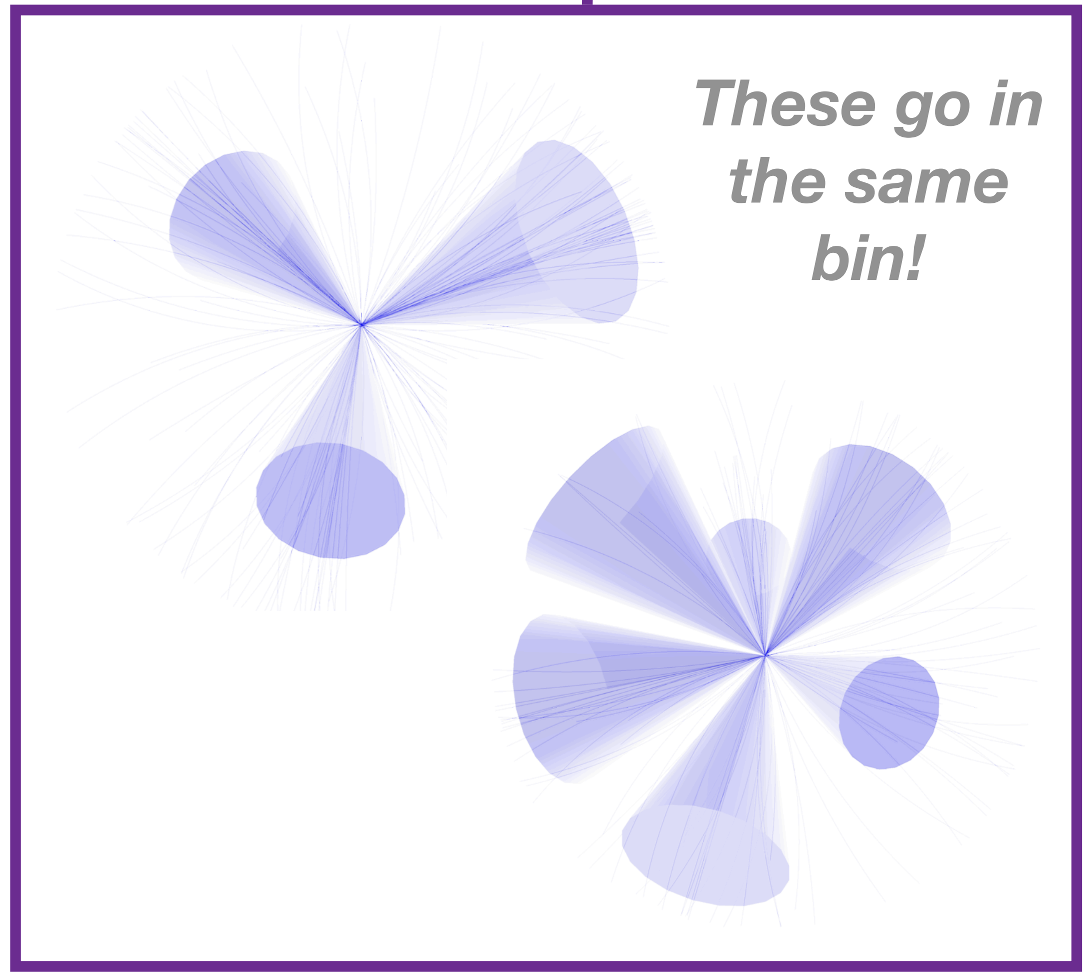
More or less isotropic?

Thrust picks out back-to-back events, not isotropic ones.









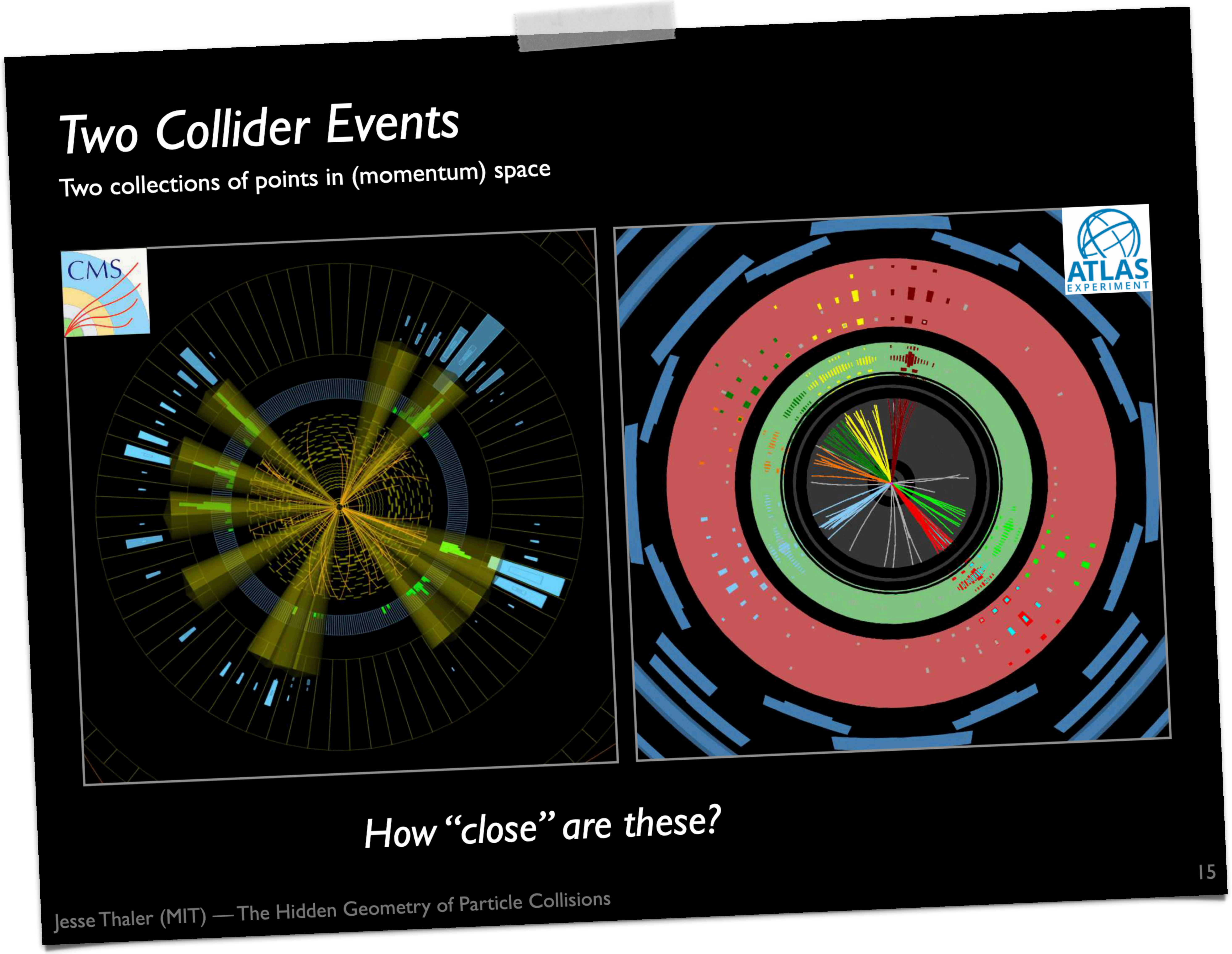
Thrust picks out back-to-back events, not isotropic ones.

To isolate isotropic configurations, we need a new tool:

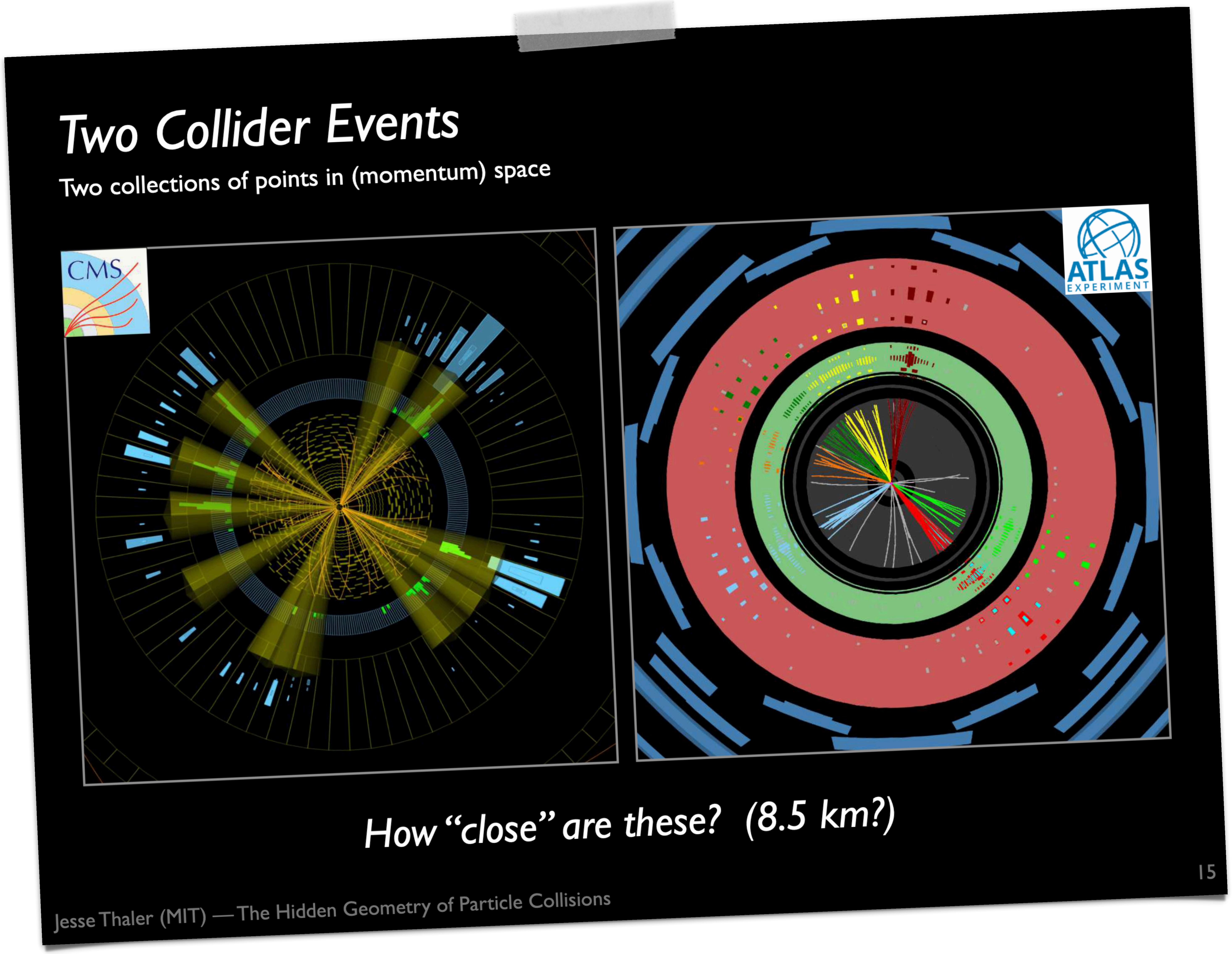
... a notion of "distance"!

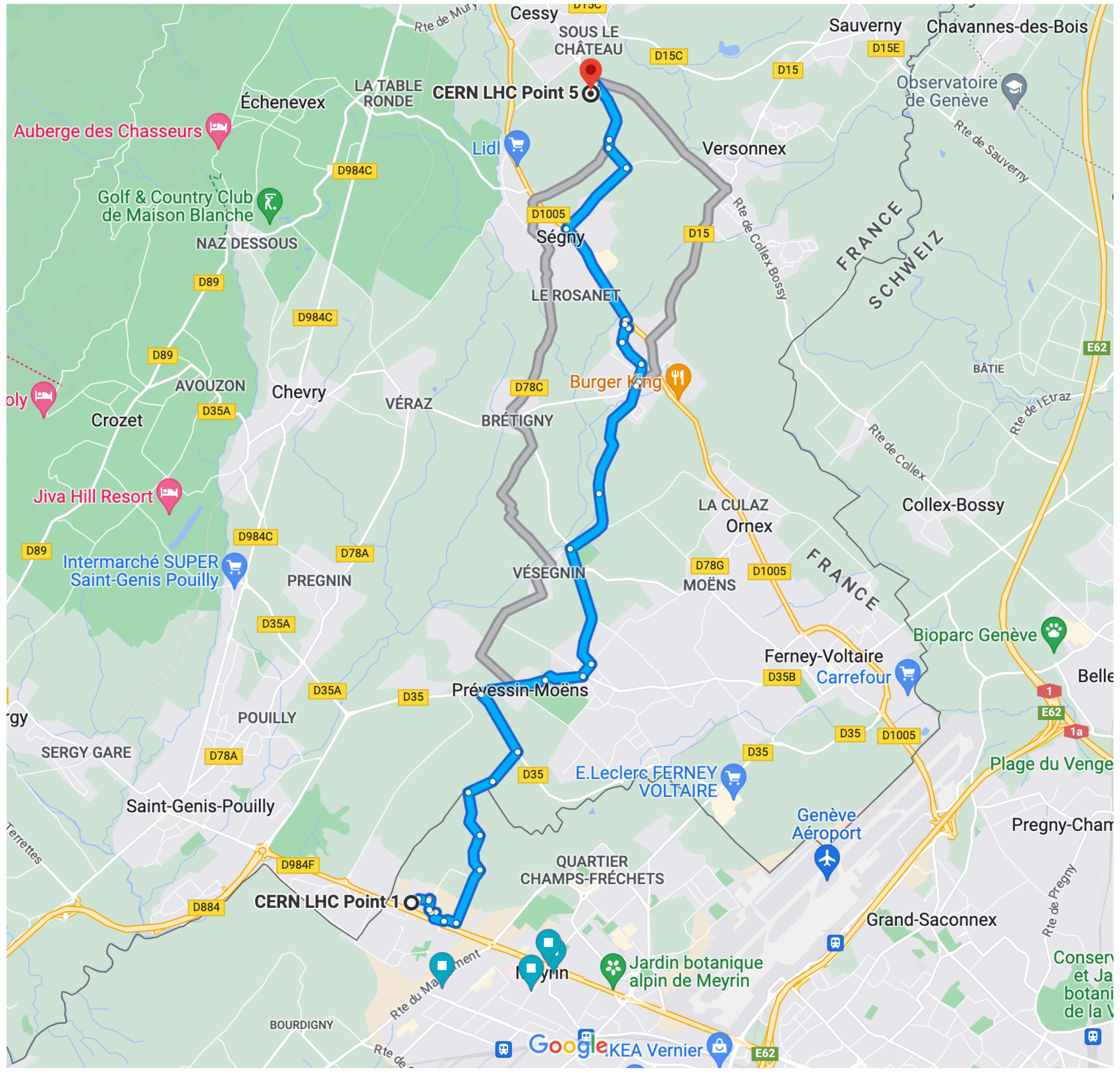
'Dad joke' from J. Thaler

Distance & QCD



Distance & QCD

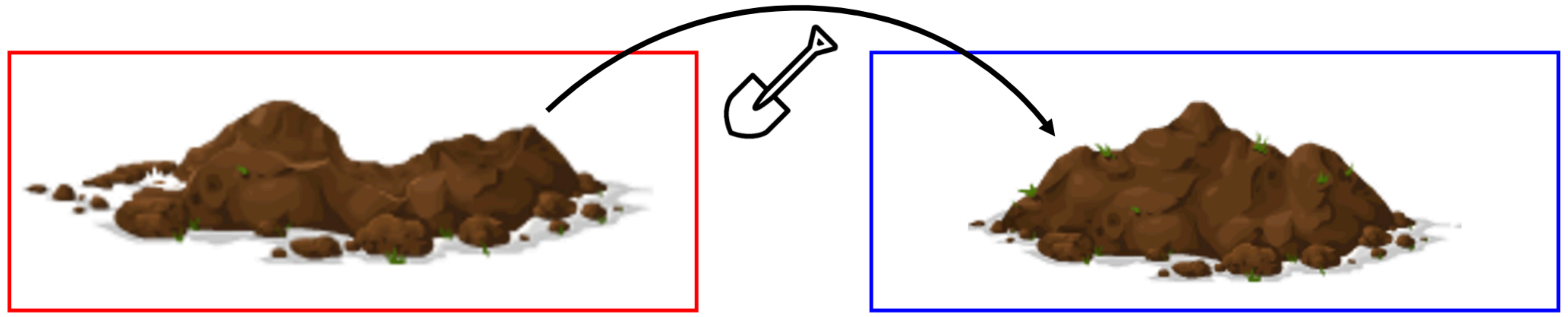




Energy-Mover's Distance (EMD)

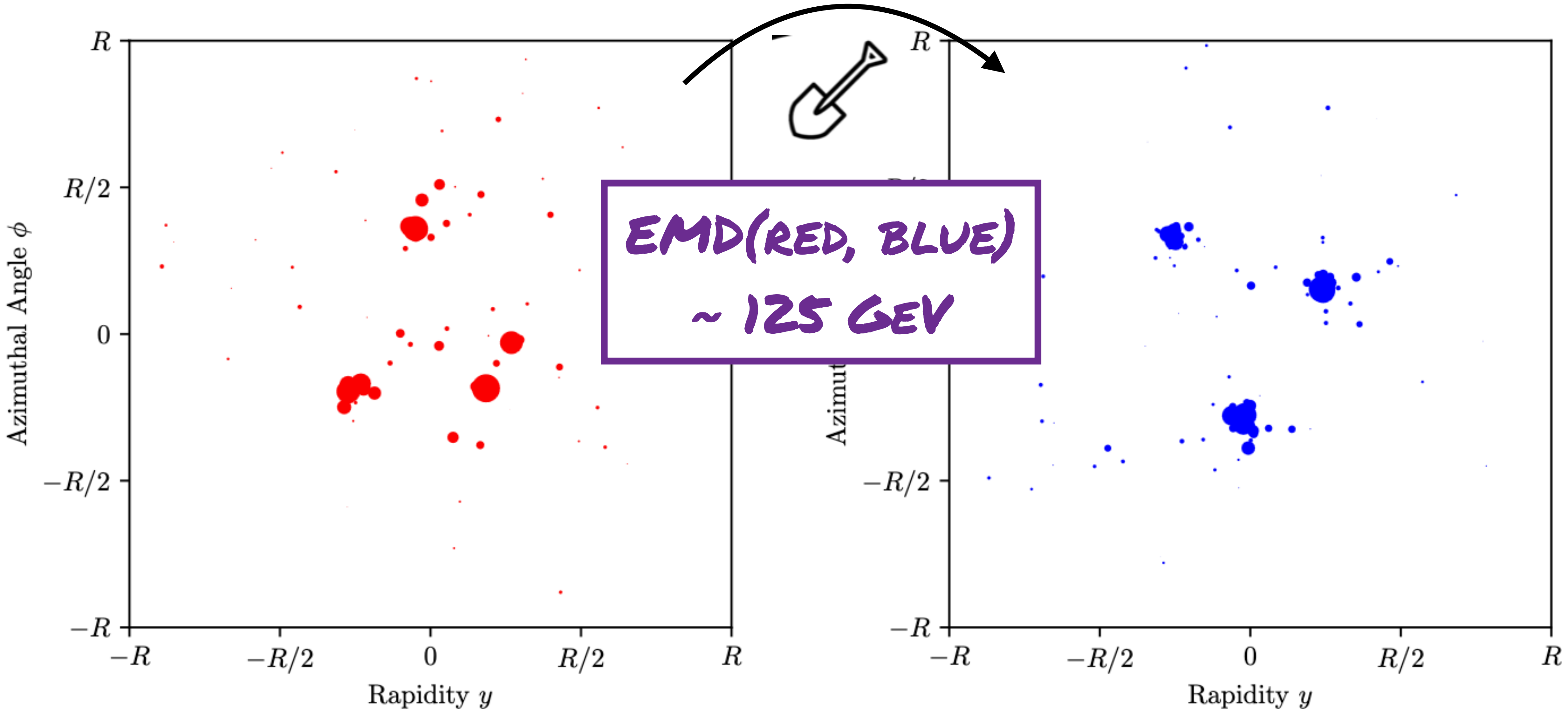
Komiske, Metodiev & Thaler, PRL 123, 041801 (2019), JHEP 07 (2020) 006

- Need **IRC-safe distance metric** between collider radiation patterns.
  - EMD defined as the **minimum 'work' required to re-arrange one event into another**.
    - Corresponds to the ***p*-Wasserstein** class of metrics.
- **Interdisciplinary tool for QCD analysis!**
  - EMDs used often in **computer vision**: problems solved w/ **Optimal Transport** techniques.
    - Common tools/libraries… 1, 2, 3
      - Some have been adapted for HEP! 4, 5

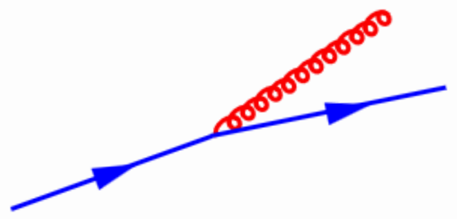


A.K.A. Earth-Mover's Distance

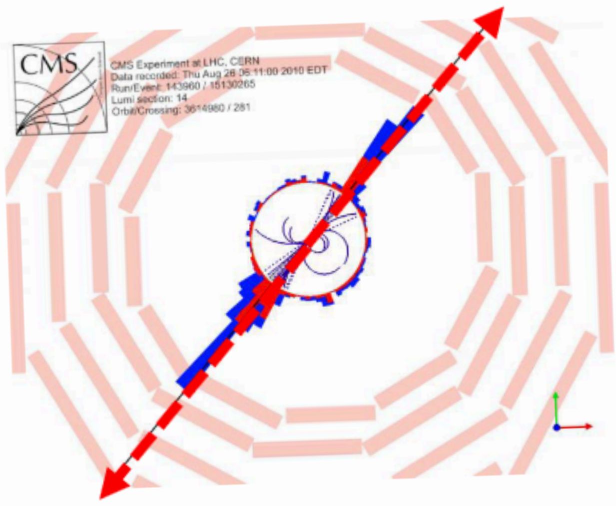
$$\mathrm{EMD}_\beta(\mathcal{E},\mathcal{E}') = \min_{\{f_{ij}\geq 0\}} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij}\,\theta_{ij}^{\beta}$$



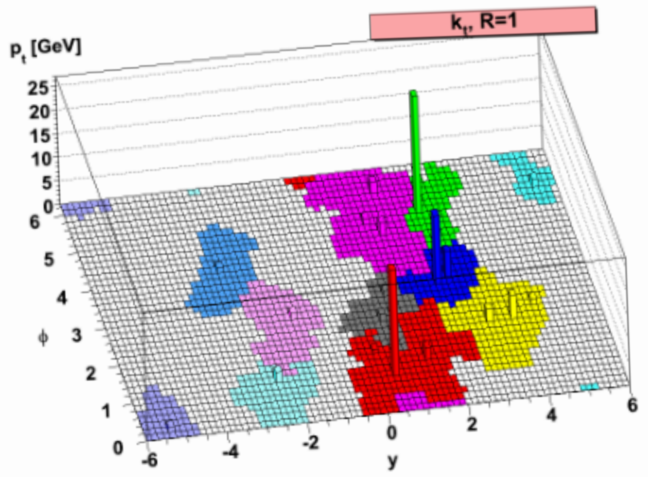
Six Decades of Collider Techniques



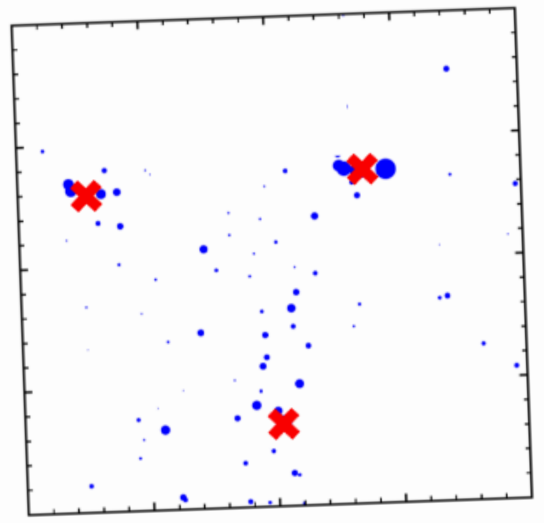
Taming infinities



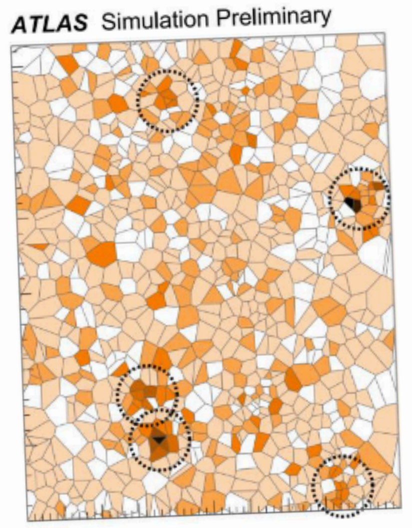
Event Shapes



Jet Algorithms



Jet Substructure



Pileup

1960

2020

1962-1964
Infrared Safety
[Kinoshita, JMP 1962]
[Lee, Nauenberg, PR 1964]

1977
Thrust, Sphericity
[Farhi, PRL 1977]
[Georgi, Machacek, PRL 1977]

1993
k_T jet clustering
[Ellis, Soper, PRD 1993]
[Catani, Dokshitzer, Seymour, Webber, NPB 1993]

1997-1998
C/A jet clustering
[Wobisch, Wengler, 1998]
[Doskhitzer, Leder, Moretti,Webber, JHEP 1997]

2010-2015
N-(sub)jettiness, XCone
[Stewart, Tackmann, Waalewijn, PRL 2010]
[Thaler, Van Tilburg, JHEP 2011]
[Stewart, Tackmann, Thaler, Vermilion, Wilkason, JHEP 2015]

2014-2019
Constituent Subtraction
[Berta, Spousta, Miller, Leitner, JHEP 2014]
[Berta, Masetti, Miller, Spousta, JHEP 2019]

And many more!

Thrust *via* OT

One common definition of thrust:

$$t(\mathcal{E}) = 2\min_{\hat{n}} \sum_{i=1}^{M} \frac{|\vec{p}_i|(1 - |\vec{n}_i \cdot \hat{n}|)}{E_{\text{total}}} \qquad \hat{n}_i = \vec{p}_i/|\vec{p}_i|$$

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Energy weight

Angular measure

$$f_{ij} = \frac{|\vec{p}_i|}{E_{\text{total}}} \qquad \theta_{ij}^2 = 2 n_i^{\mu} n_{j\mu} = 2(1 - |\vec{n}_i \cdot \hat{n}|)$$

Thrust *via* OT

ONE COMMON DEFINITION OF THRUST:

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ENERGY WEIGHT

ANGULAR MEASURE

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B=2 HERE

... WHAT IS E' ?

Thrust *via* OT

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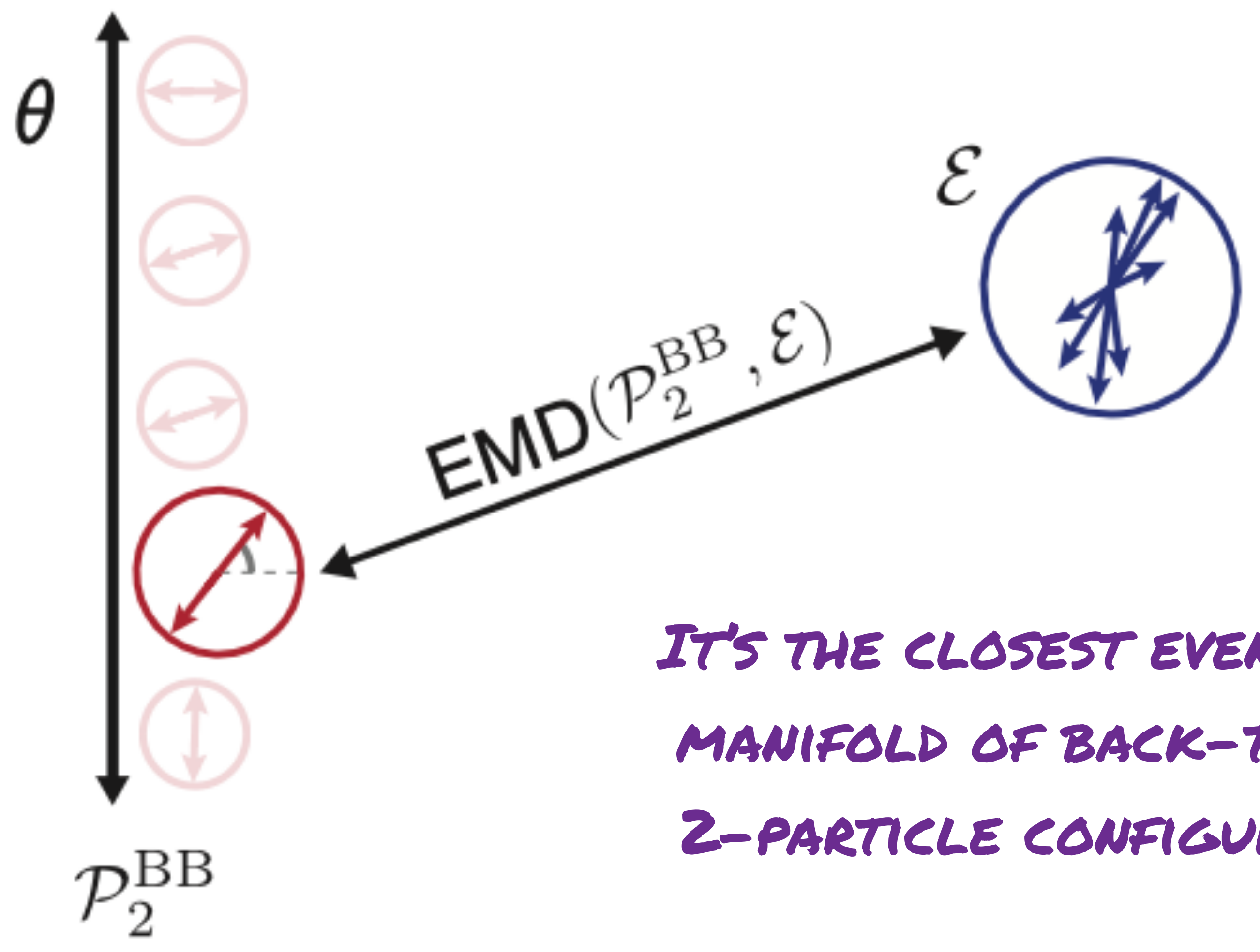
B=2 here

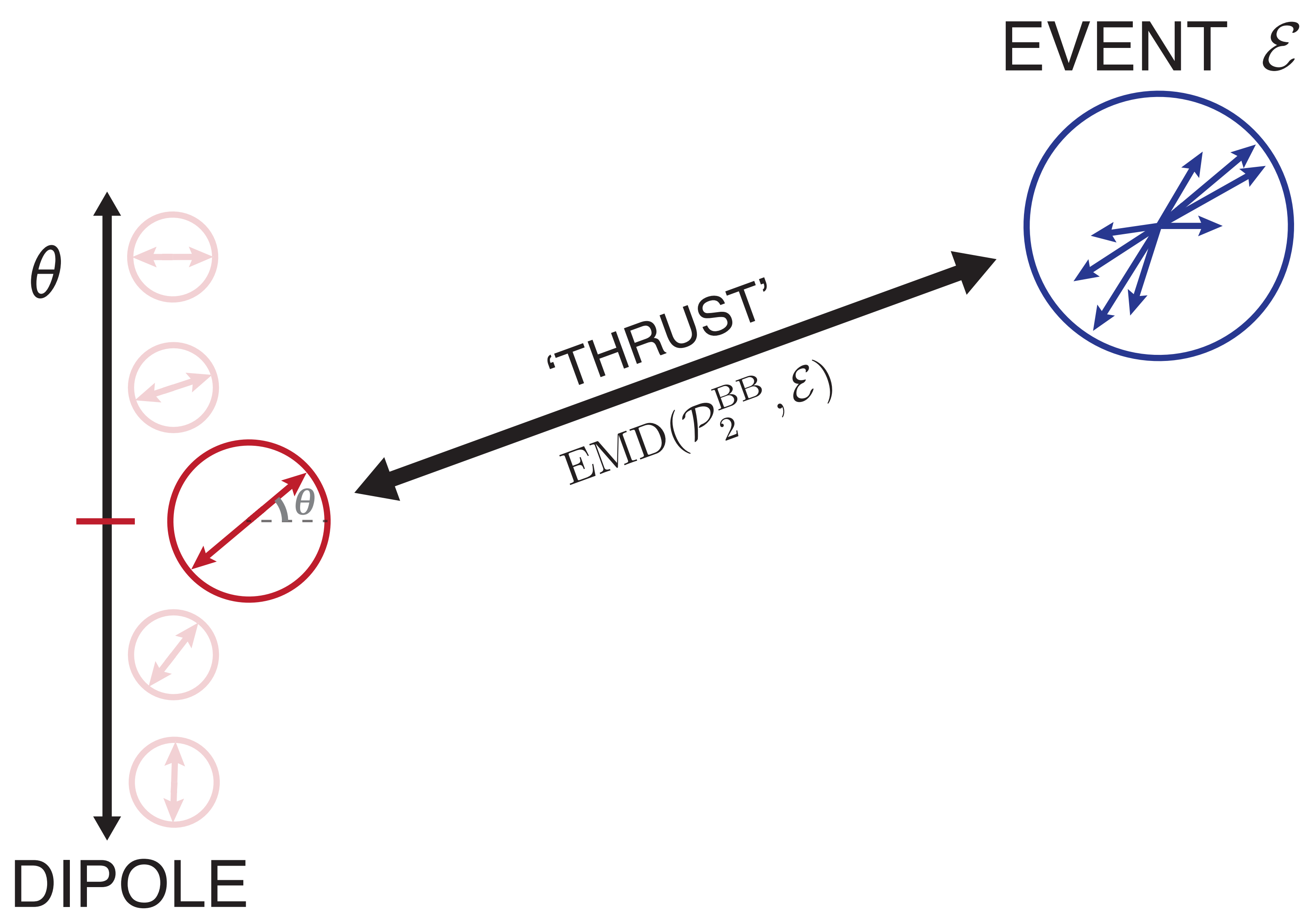
... what is E' ?



It's the closest event in the manifold of back-to-back 2-particle configurations!

Novel event shapes via OT: ‘event isotropy’

Cesarotti & Thaler, JHEP 08 (2020) 084
***ATLAS** (incl. Cesarotti, STA) ATLAS-STDM-2020-20*



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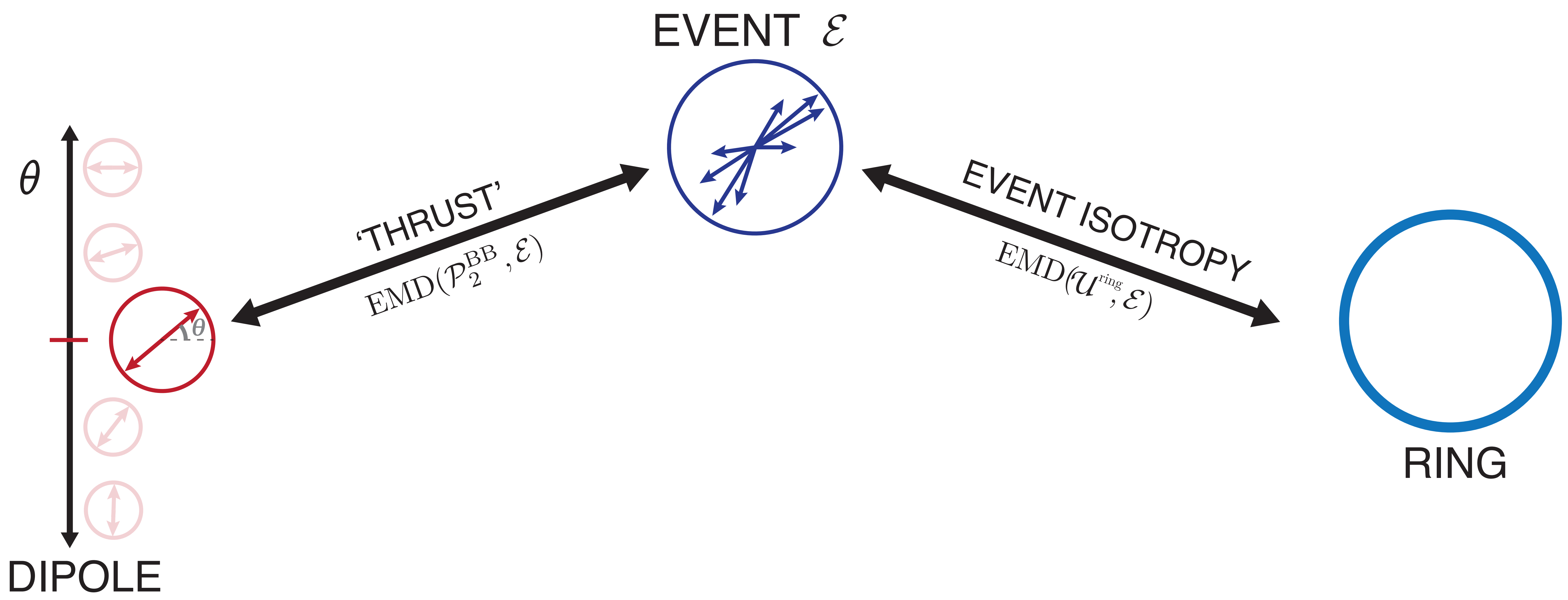

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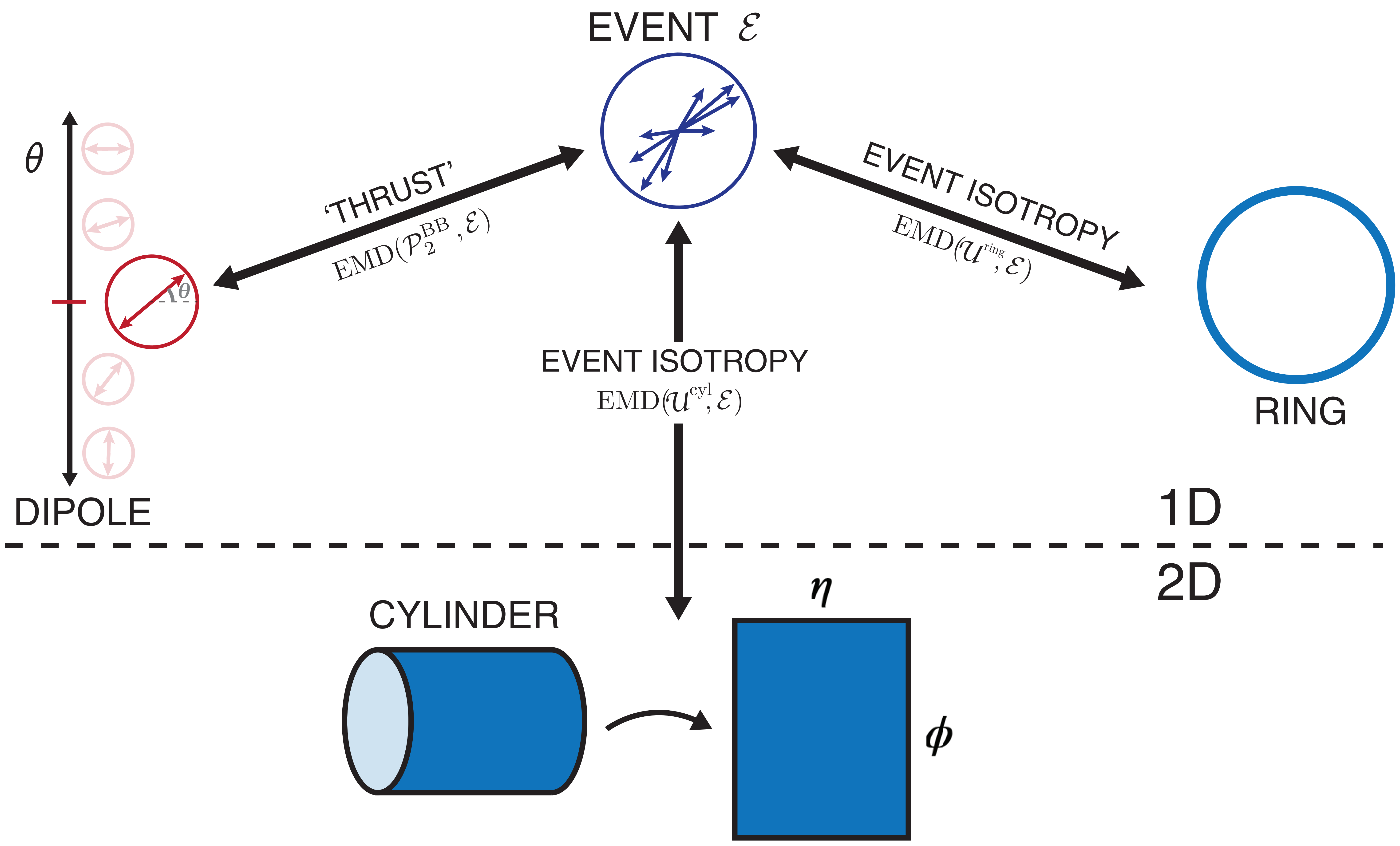

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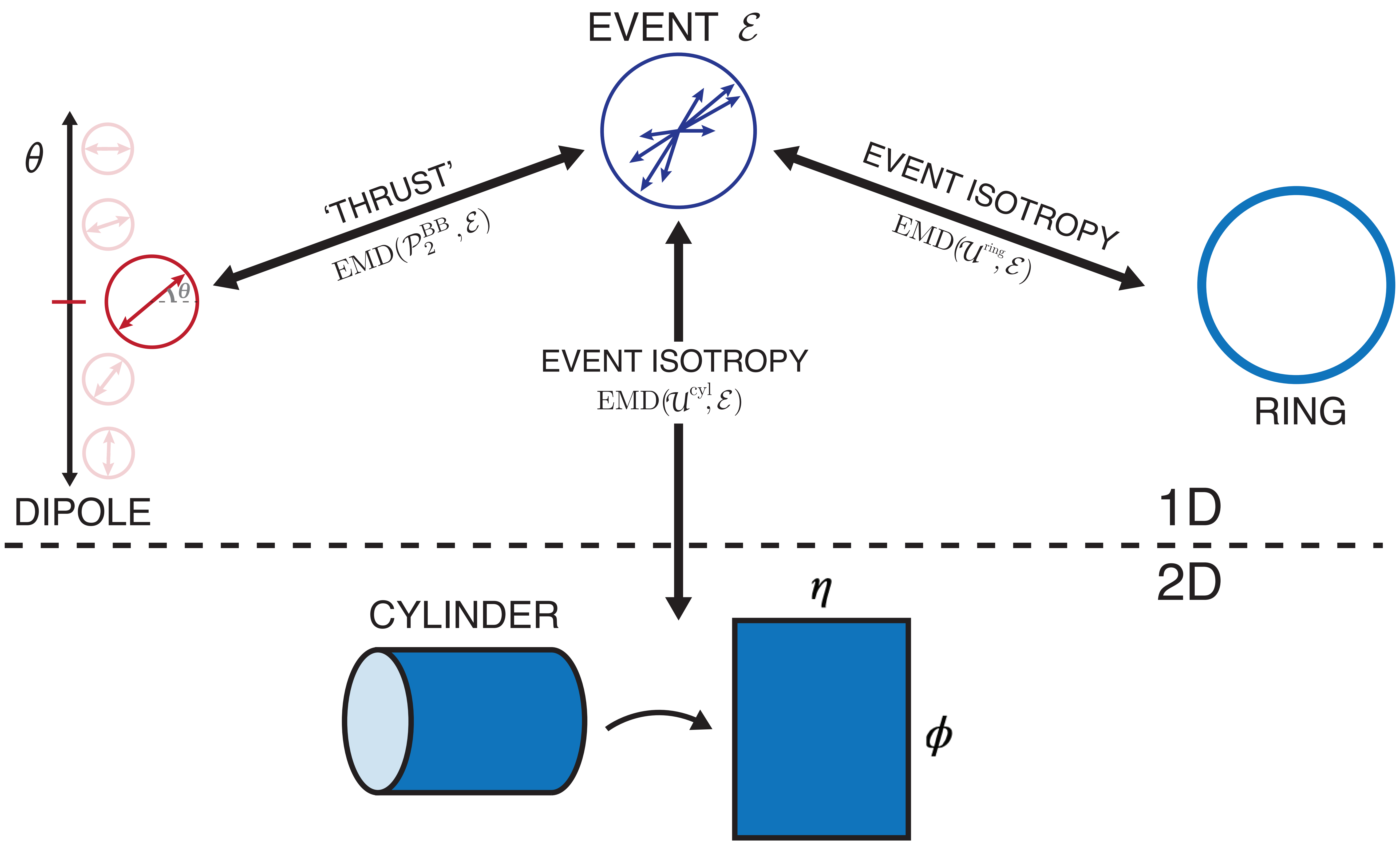
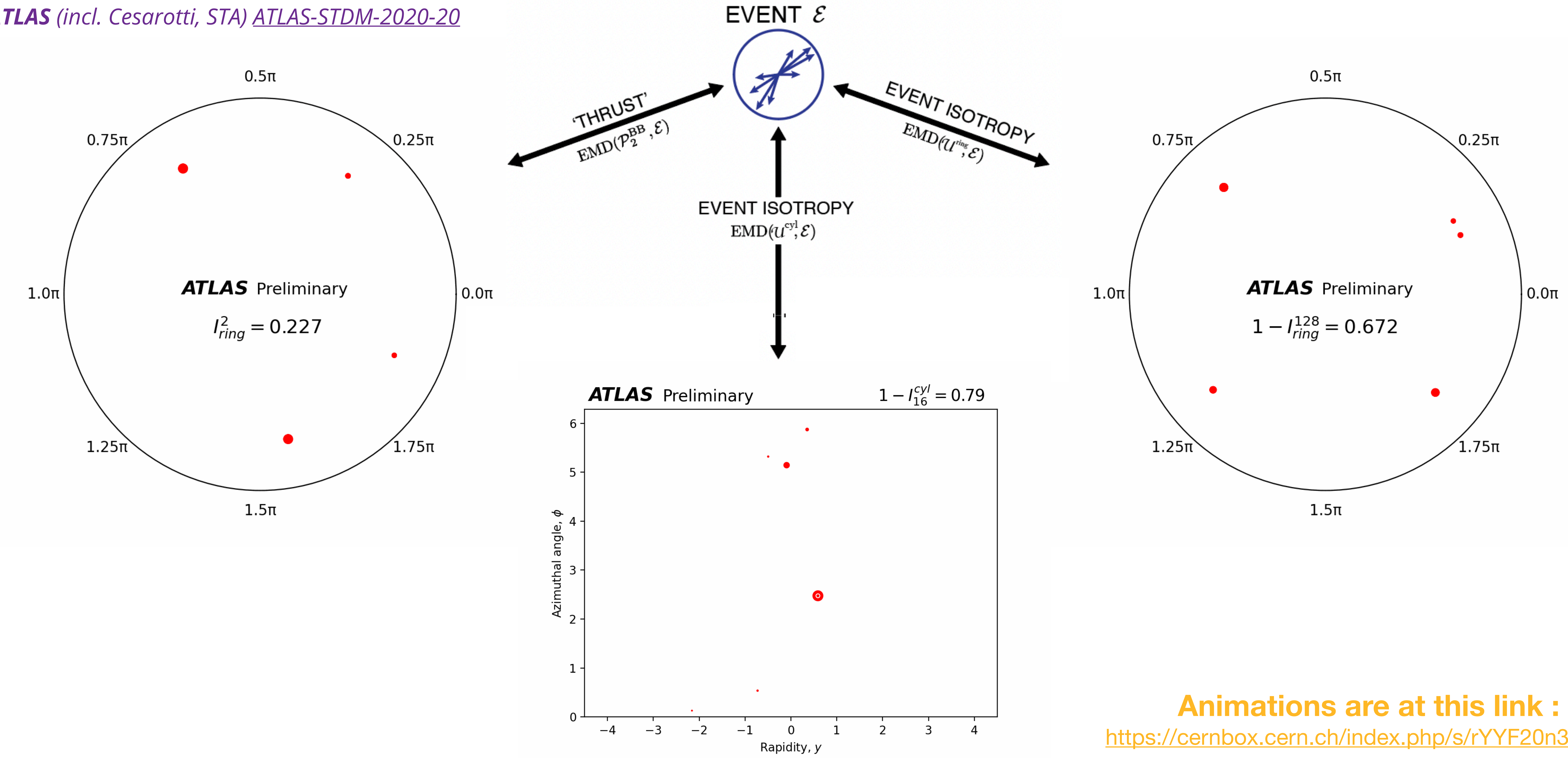


- **We measured 3 EMDs, per-event:**
    - Two most-distant 1D configurations conserving transverse momentum.
    - 2D extension of isotropy into rapidity-phi space (**IsoCyl16**).
- Used ***R*=0.4 PFlow jets** (p_T > 60 GeV, $|y|$ < 4.4) + recoil vector as inputs to EMD calculations.
- Measurements in inclusive bins of **jet multiplicity** and $\boldsymbol{H_{T2} = p_{T,1}+p_{T,2}}$.

Visualisation of OT calculation

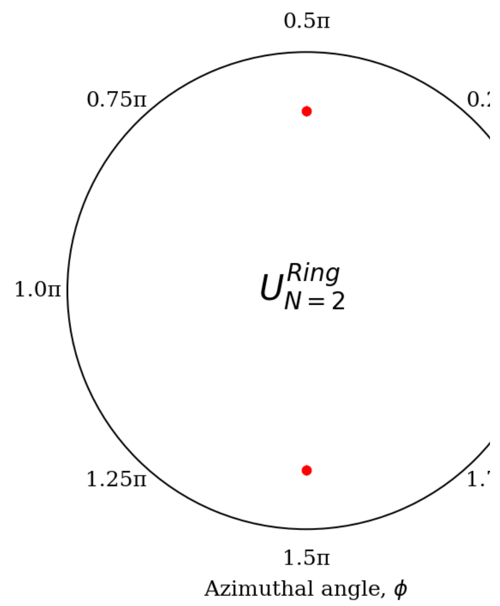
ATLAS *(incl. Cesarotti, STA)* *[ATLAS-STDM-2020-20]*

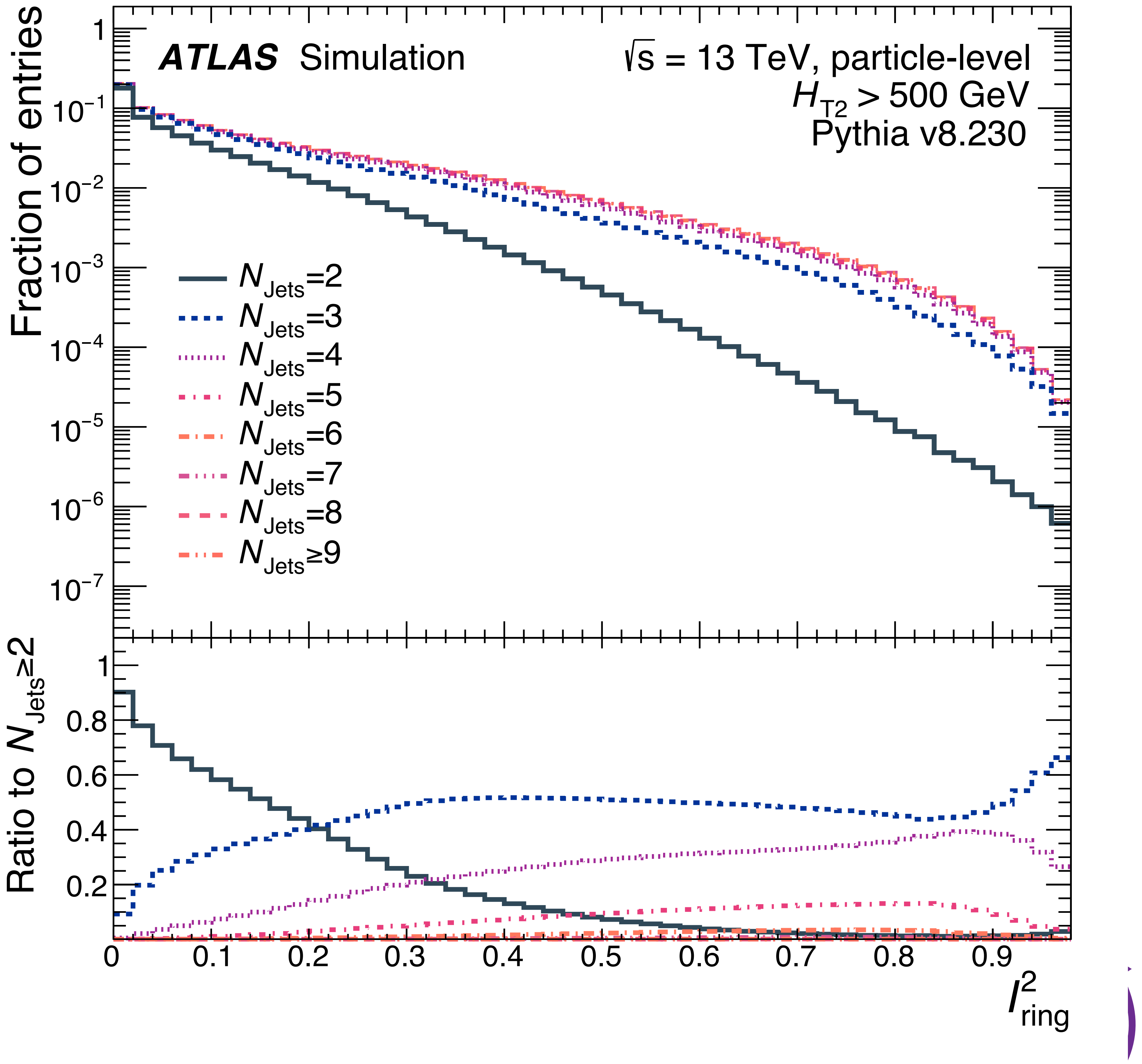


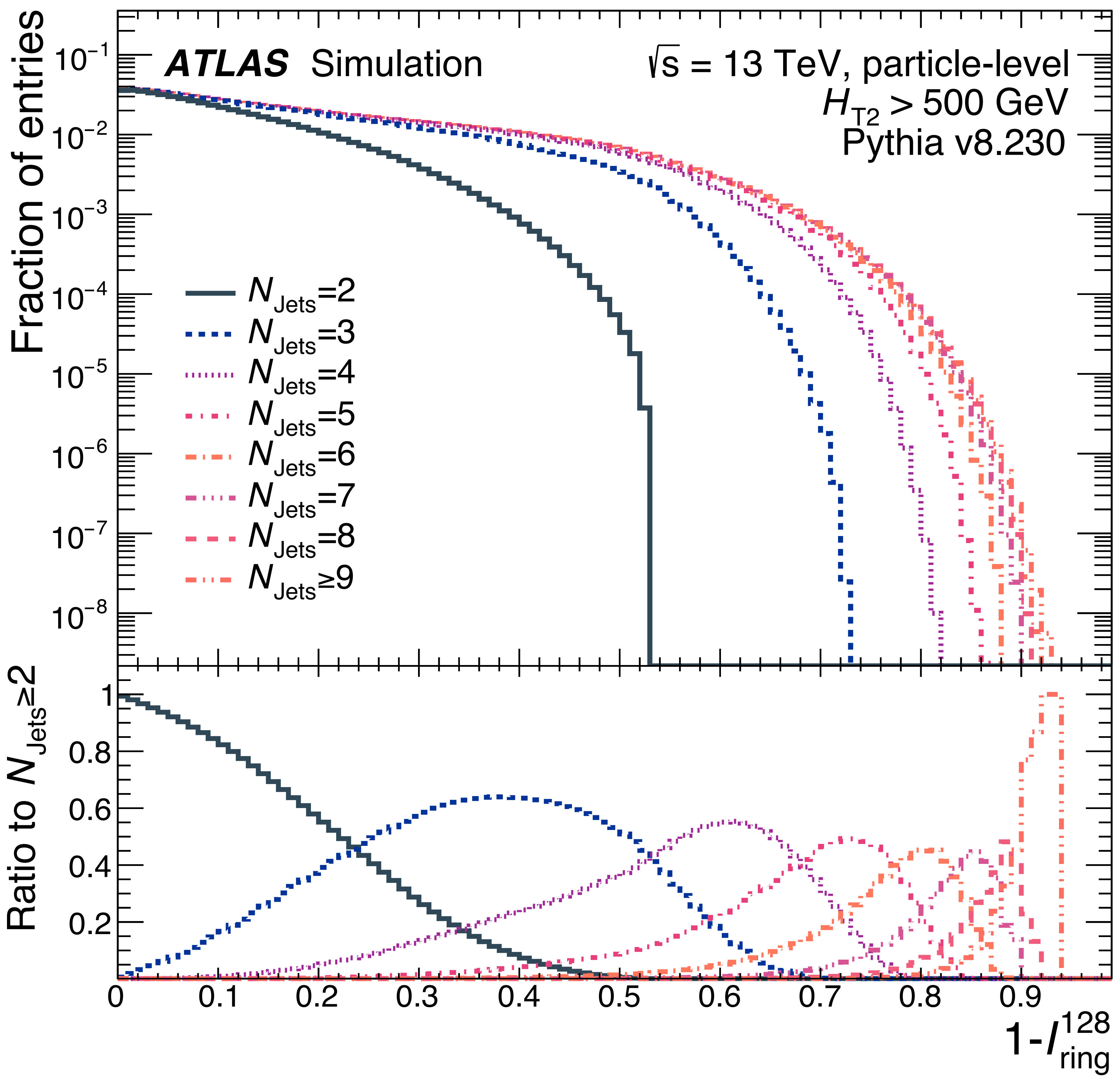
Animations are at this link :

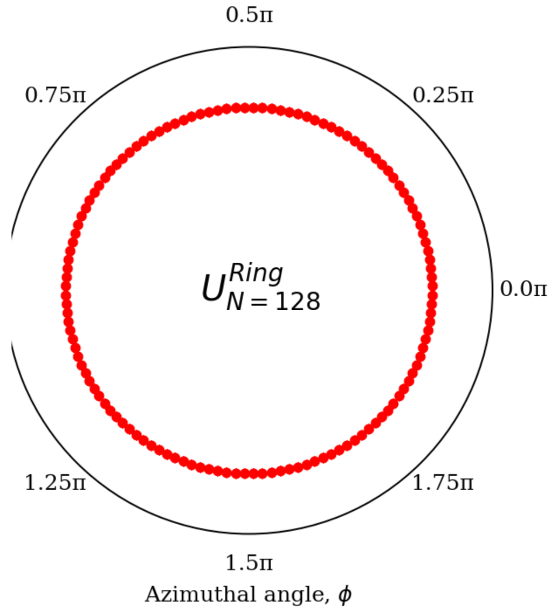
https://cernbox.cern.ch/index.php/s/rYYF20n3je2rtXI

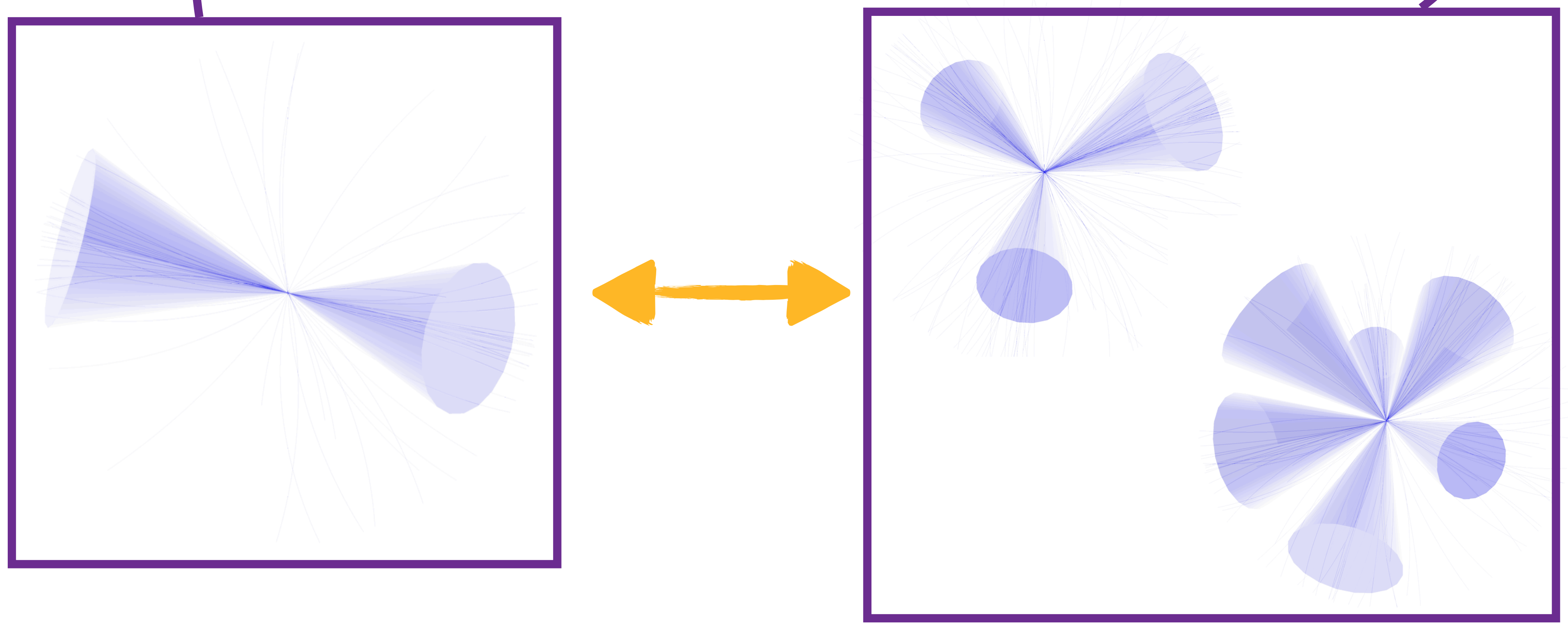
Different properties w/ different reference geometries…

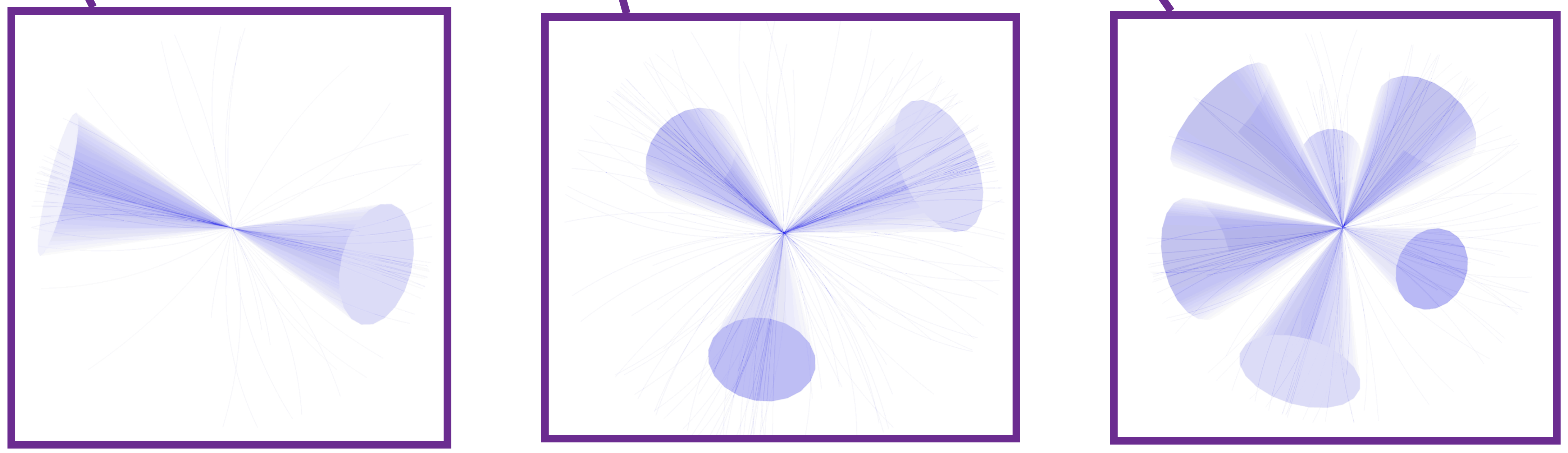


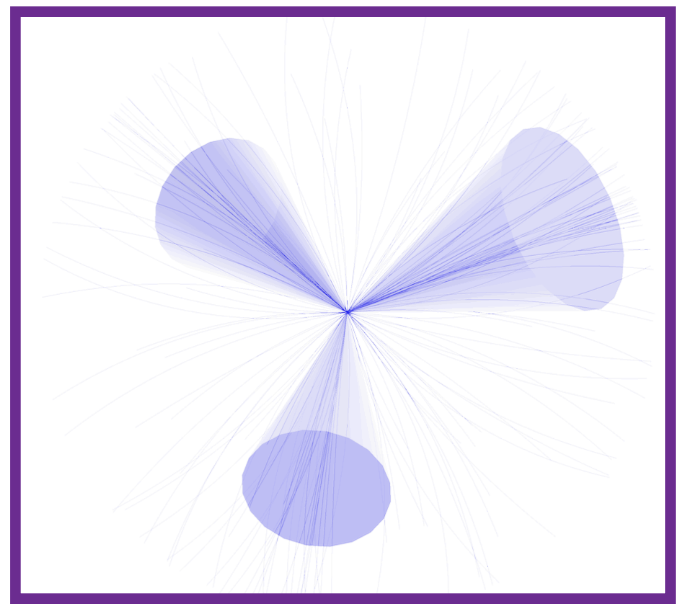


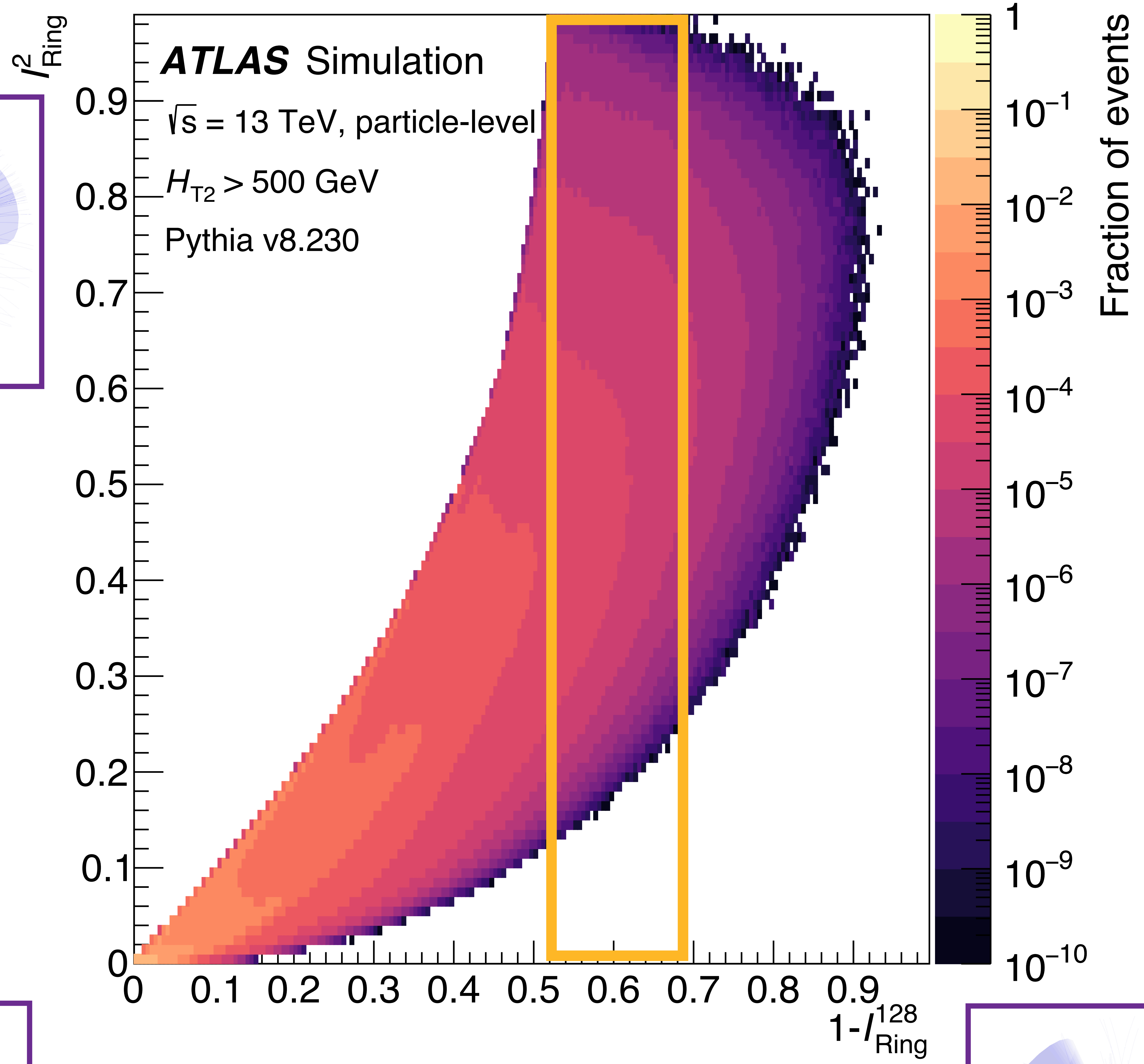


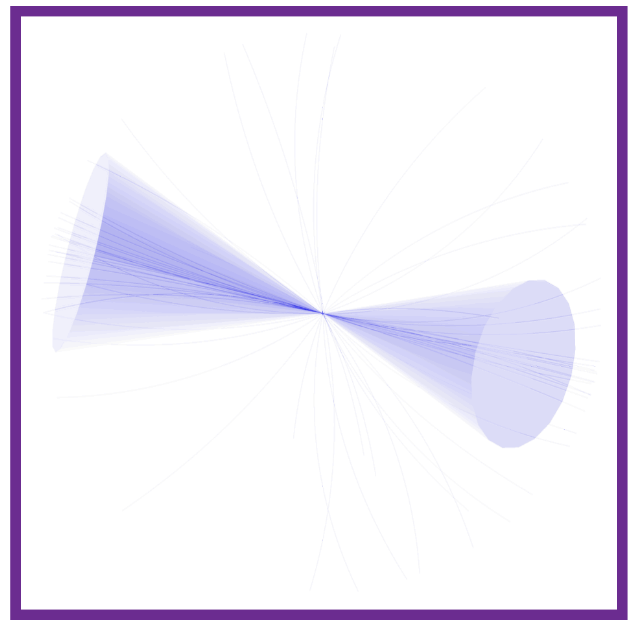


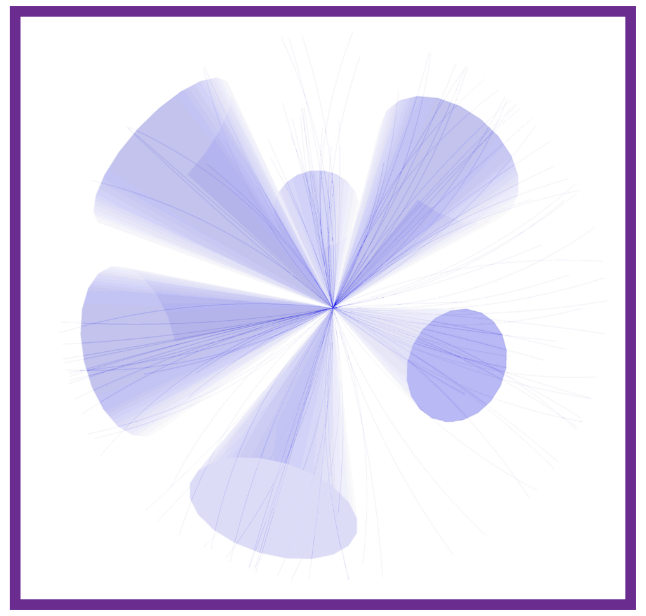










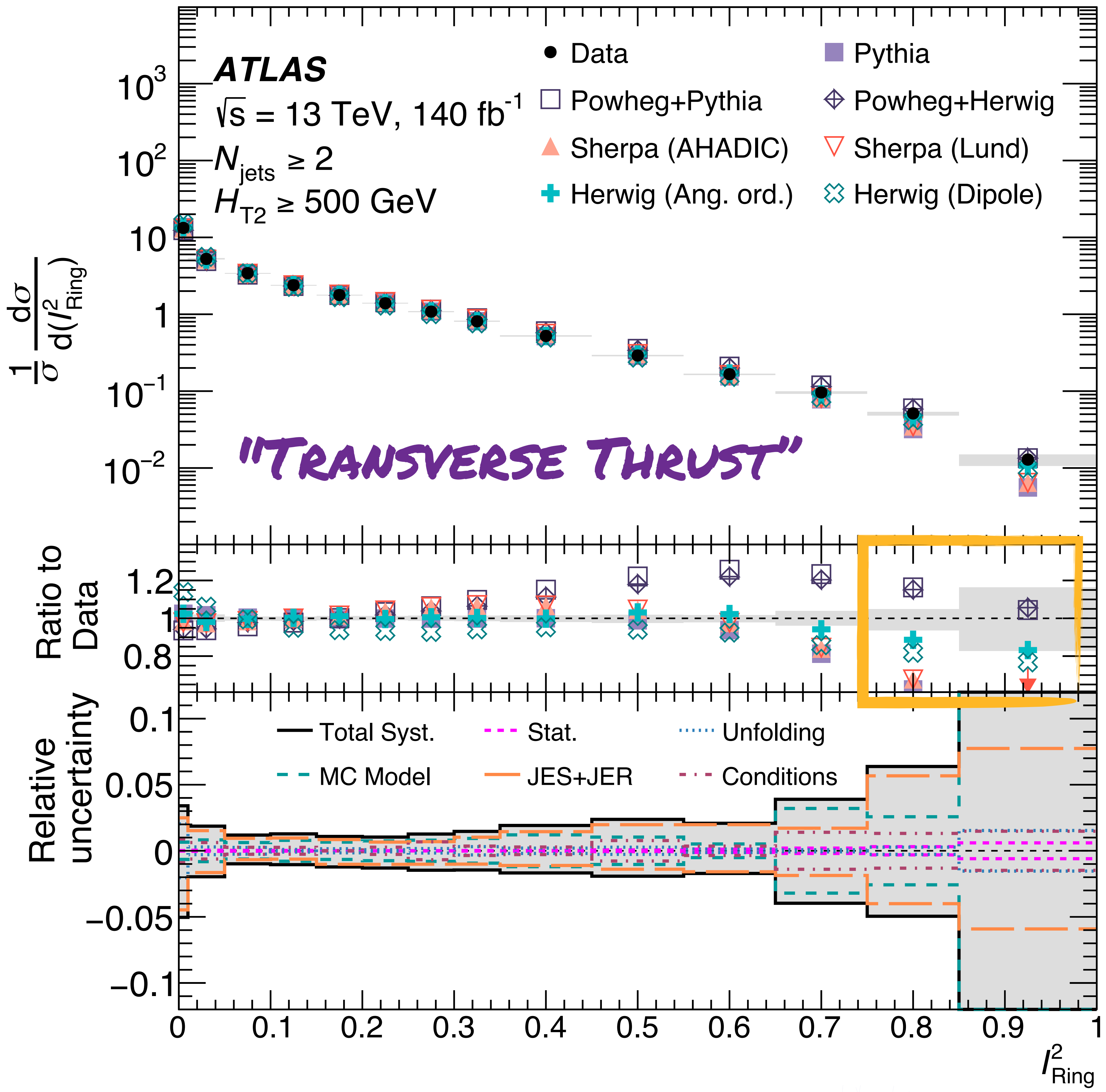


Events that saturate IsoRing2 only have intermediate IsoRing128 values!

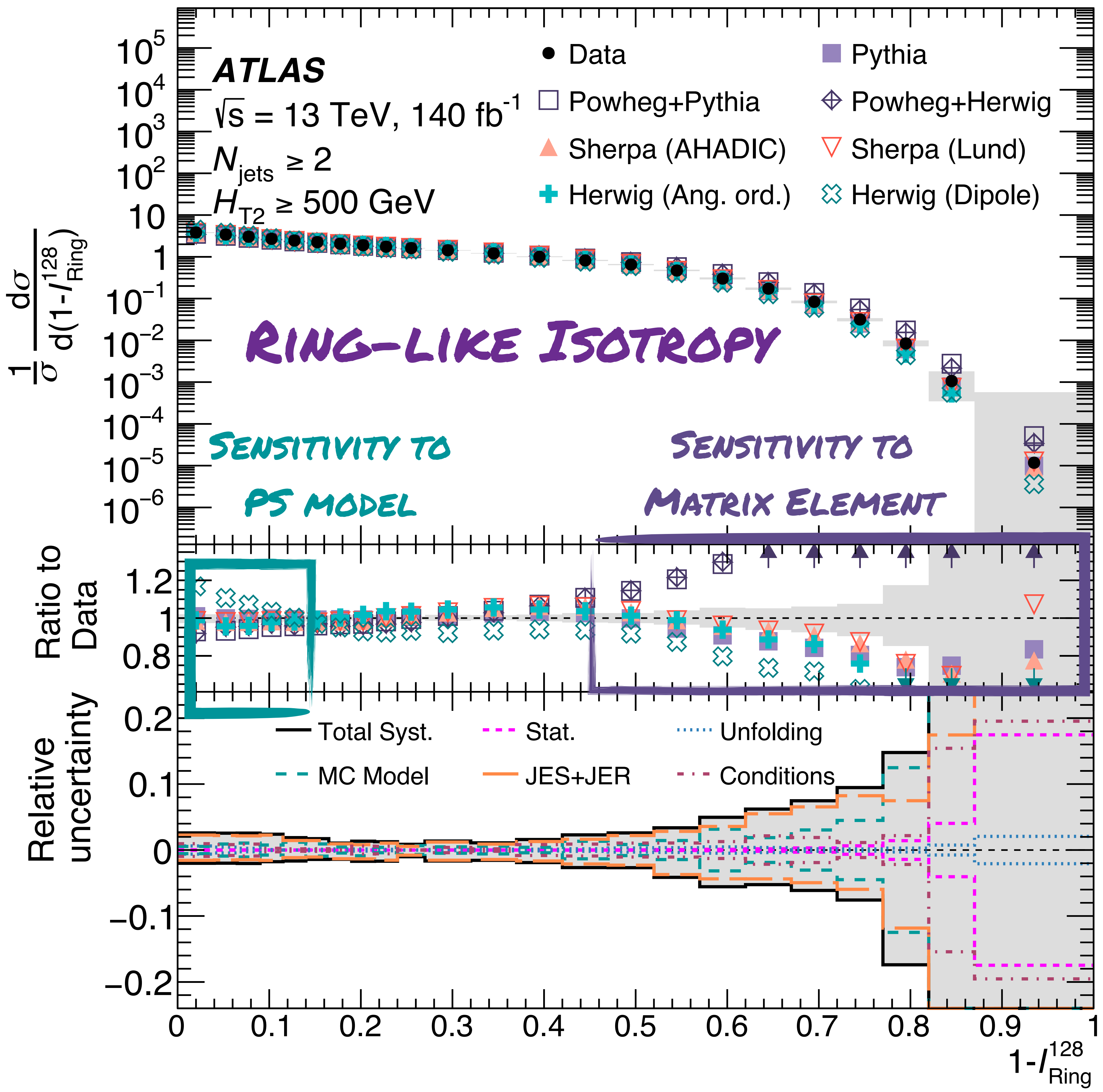
3-pronged configurations are **not "isotropic" in the same way** as a high-multiplicity multijet event.

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

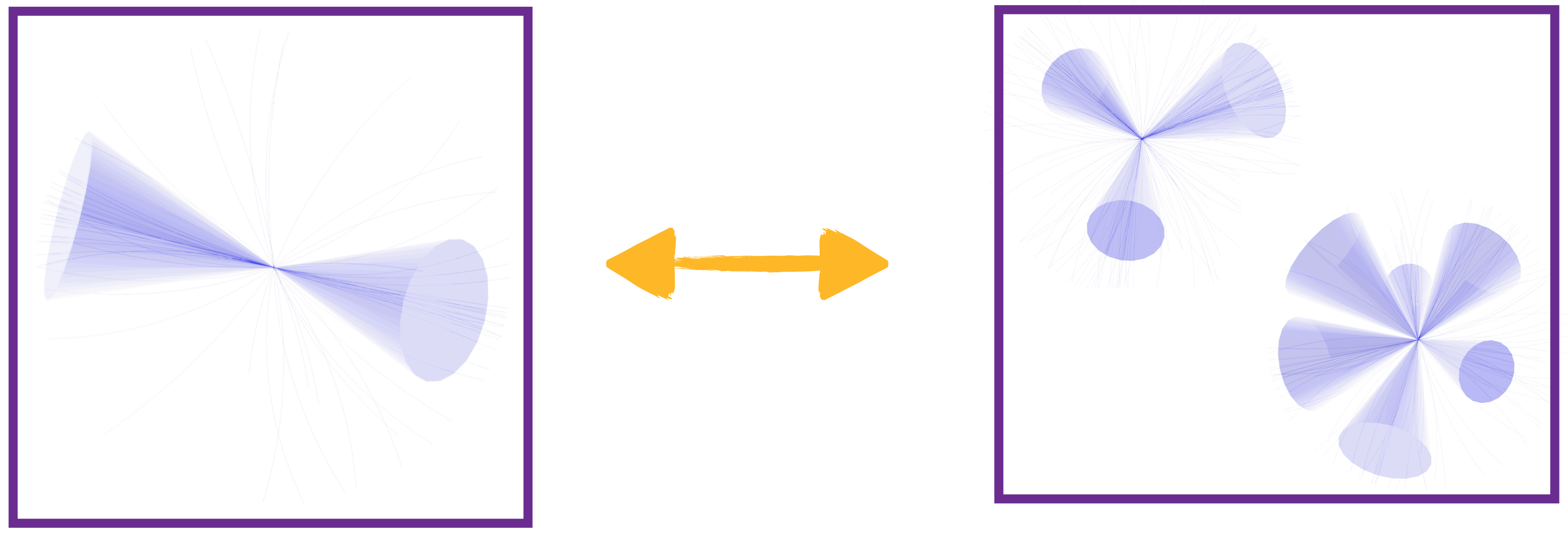
ATLAS, ATLAS-STDM-2020-20

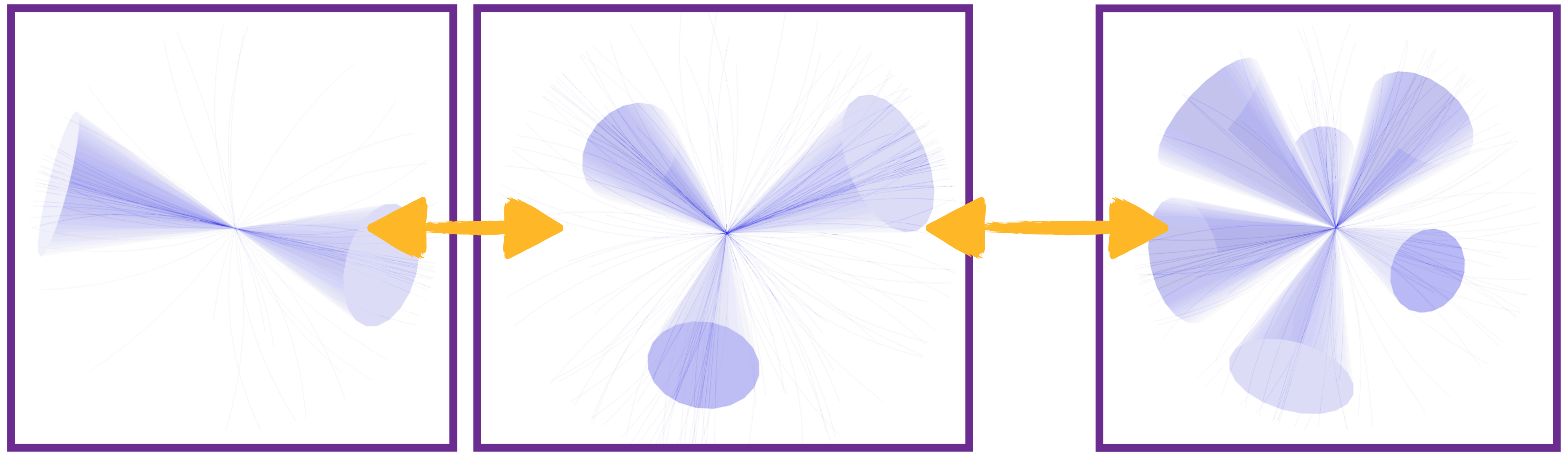


NLO performs best for 3-jet events



Larger dynamic range



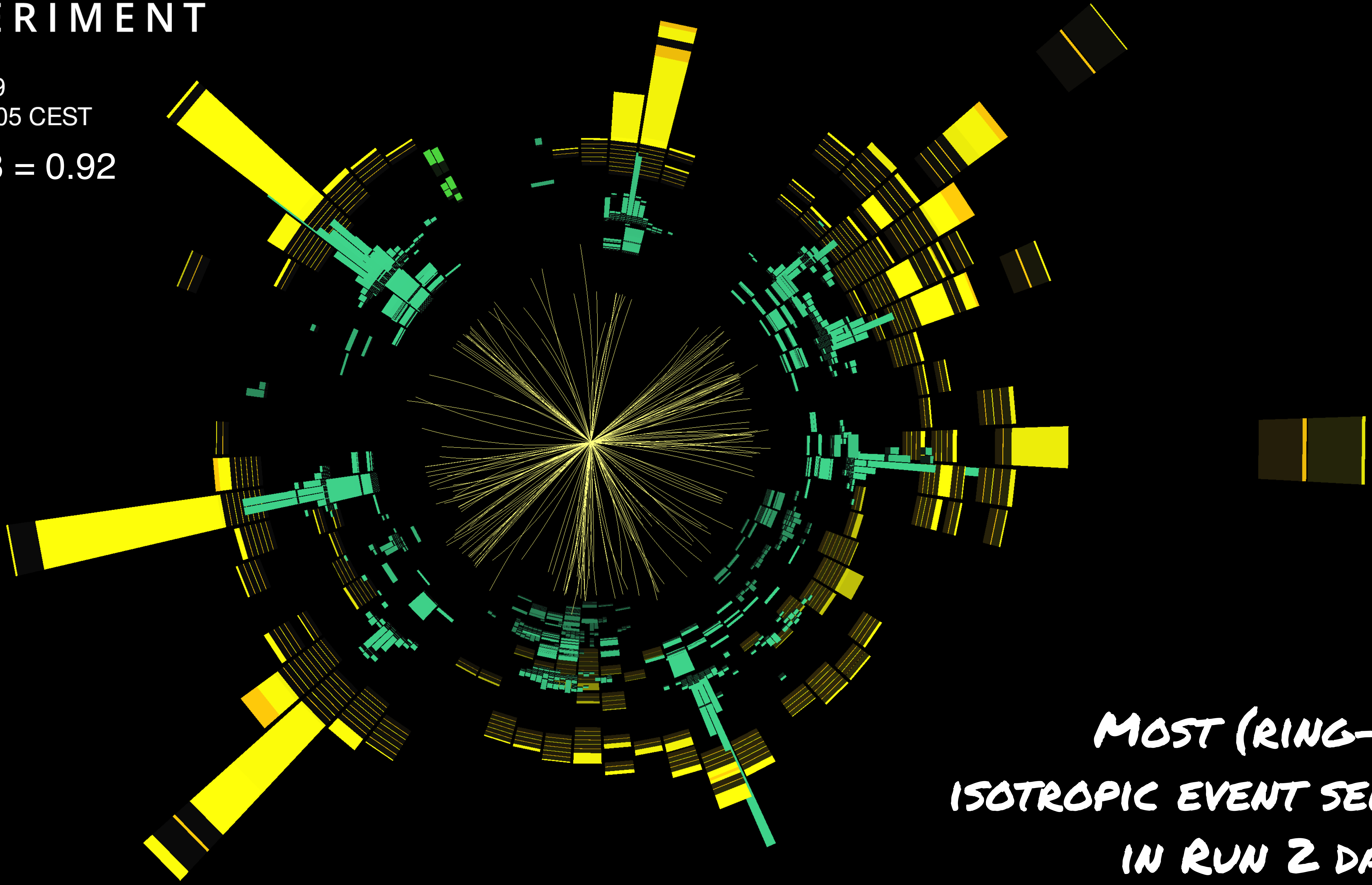


ATLAS-STDM-2020-20

ATLAS EXPERIMENT

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

1-IsoRing128 = 0.92
N_{jets} = 12



Most (ring-like) isotropic event selected in Run 2 dataset!

Results: I_{Ring}^{128} vs. N_{jets}

ATLAS, ATLAS-STDM-2020-20

Increase minimum jet requirement

Data/MC disagreement deteriorates at "dijet-like" end: soft activity in the event increases difficulty for MC generators

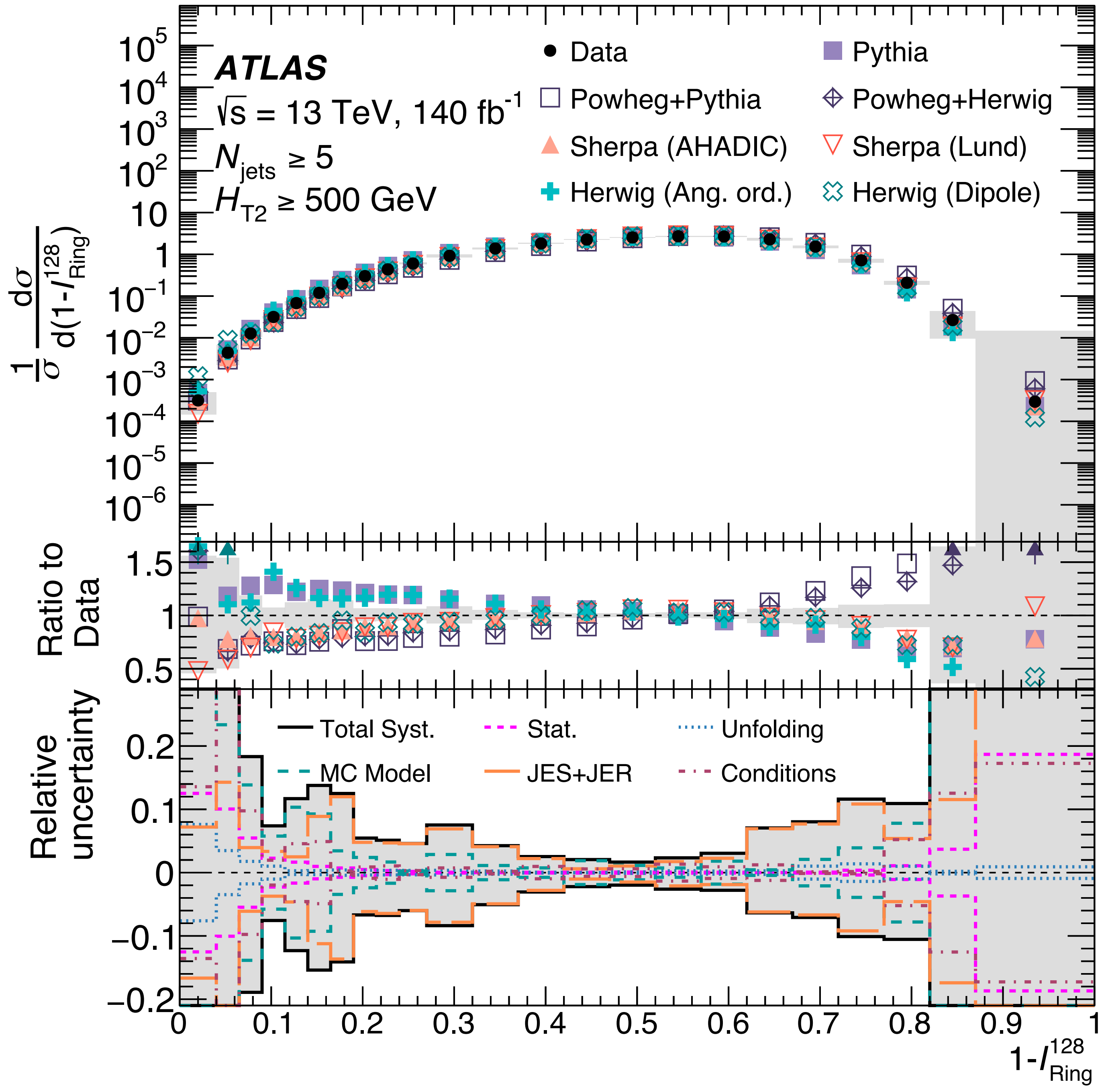
Events become more isotropic on-average as Njets is increased (expected scaling!)

Results: I_{Ring}^{128} vs. H_{T2}

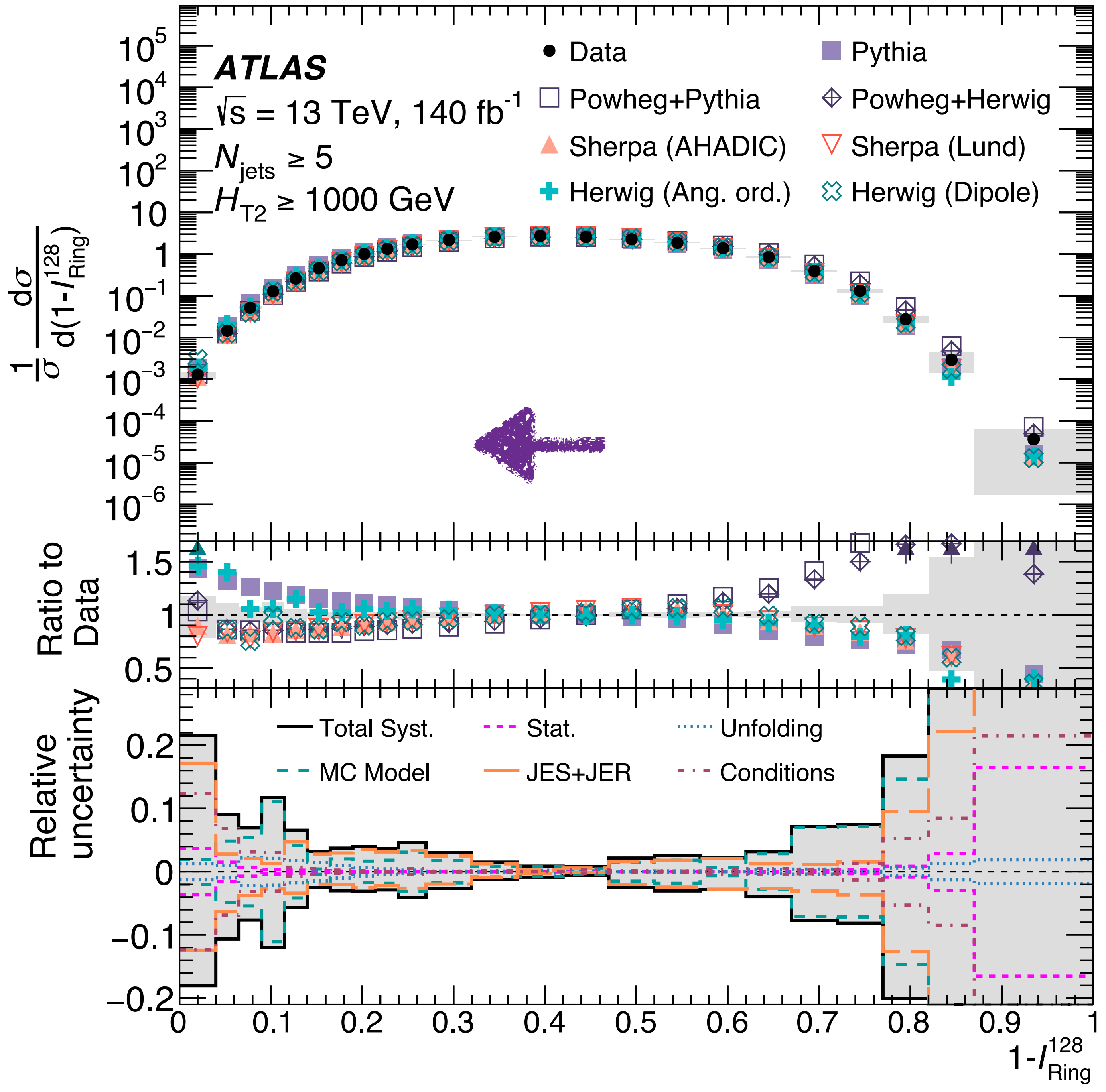
ATLAS *ATLAS-STDM-2020-20*

Increase minimum H_{T2} requirement

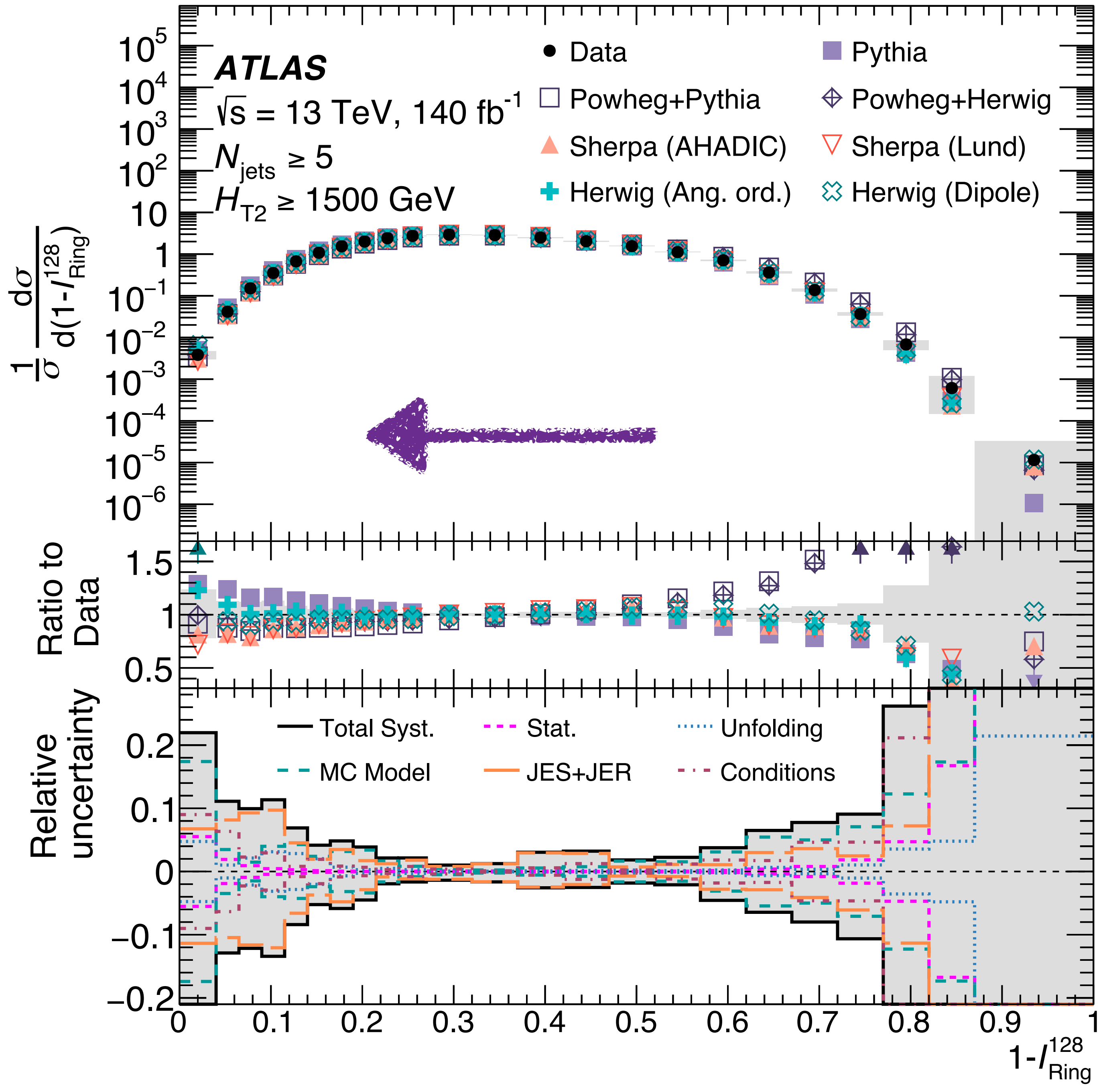
H_{T2} >= 500 GeV



H_{T2} >= 1000 GeV



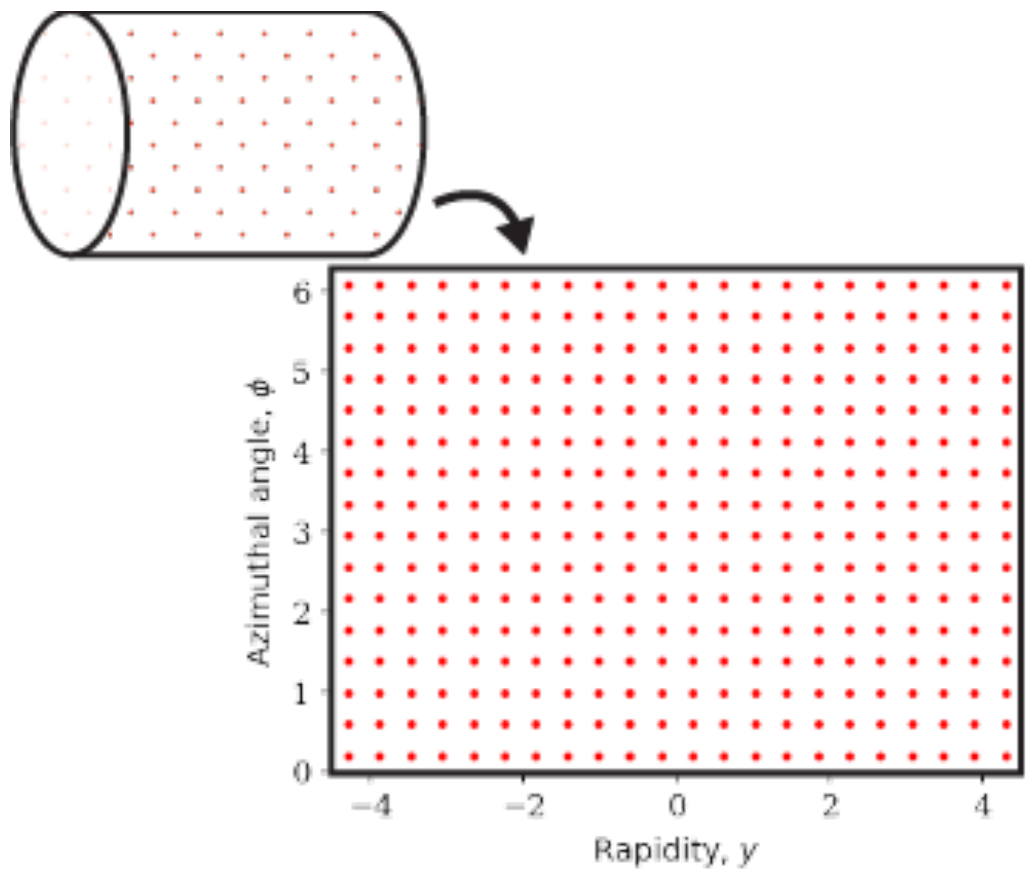
H_{T2} >= 1500 GeV

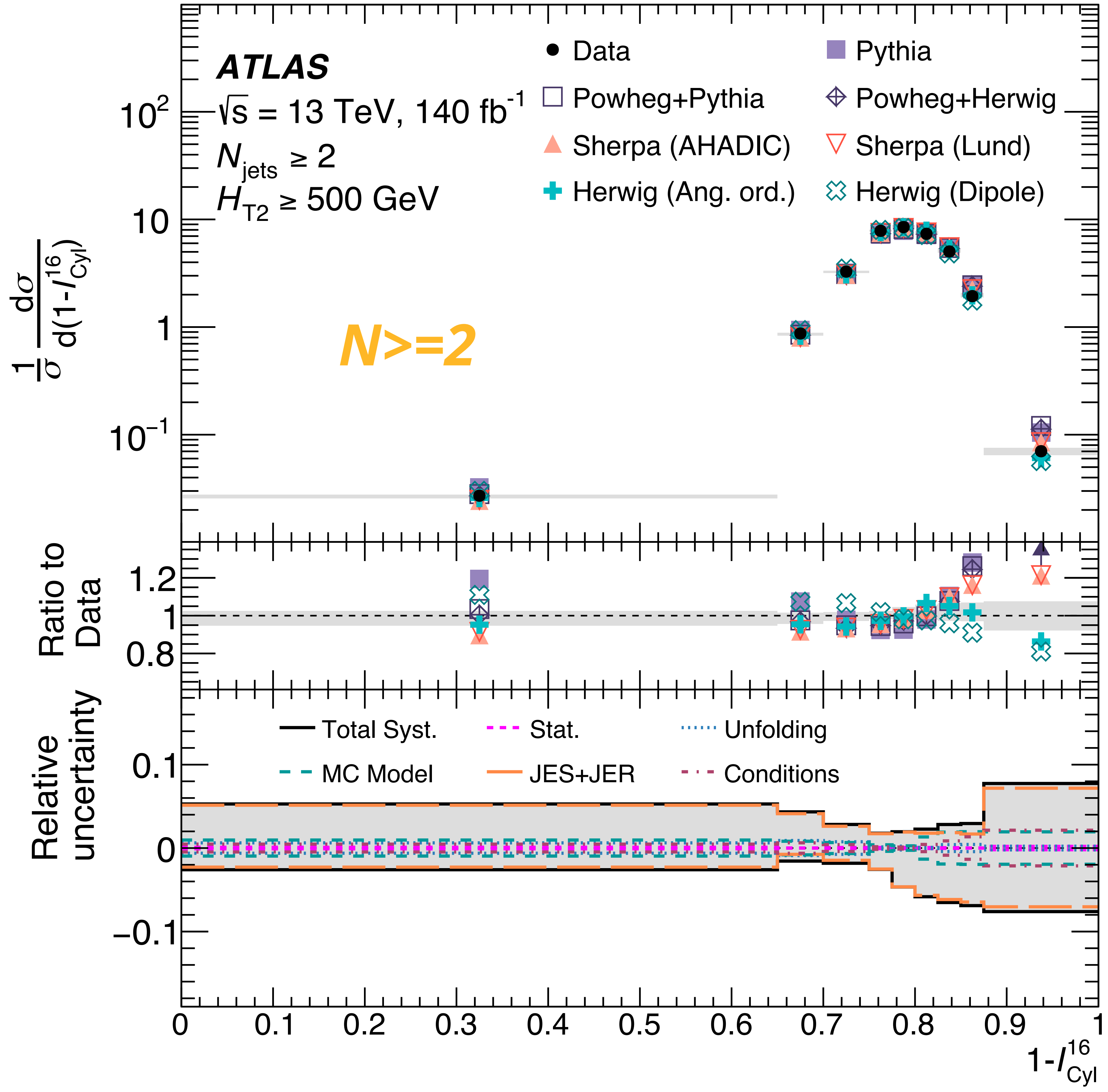


Data/MC disagreement improves at "dijet-like" end: events become more collimated with larger HT2, description is better despite large jet multiplicities.

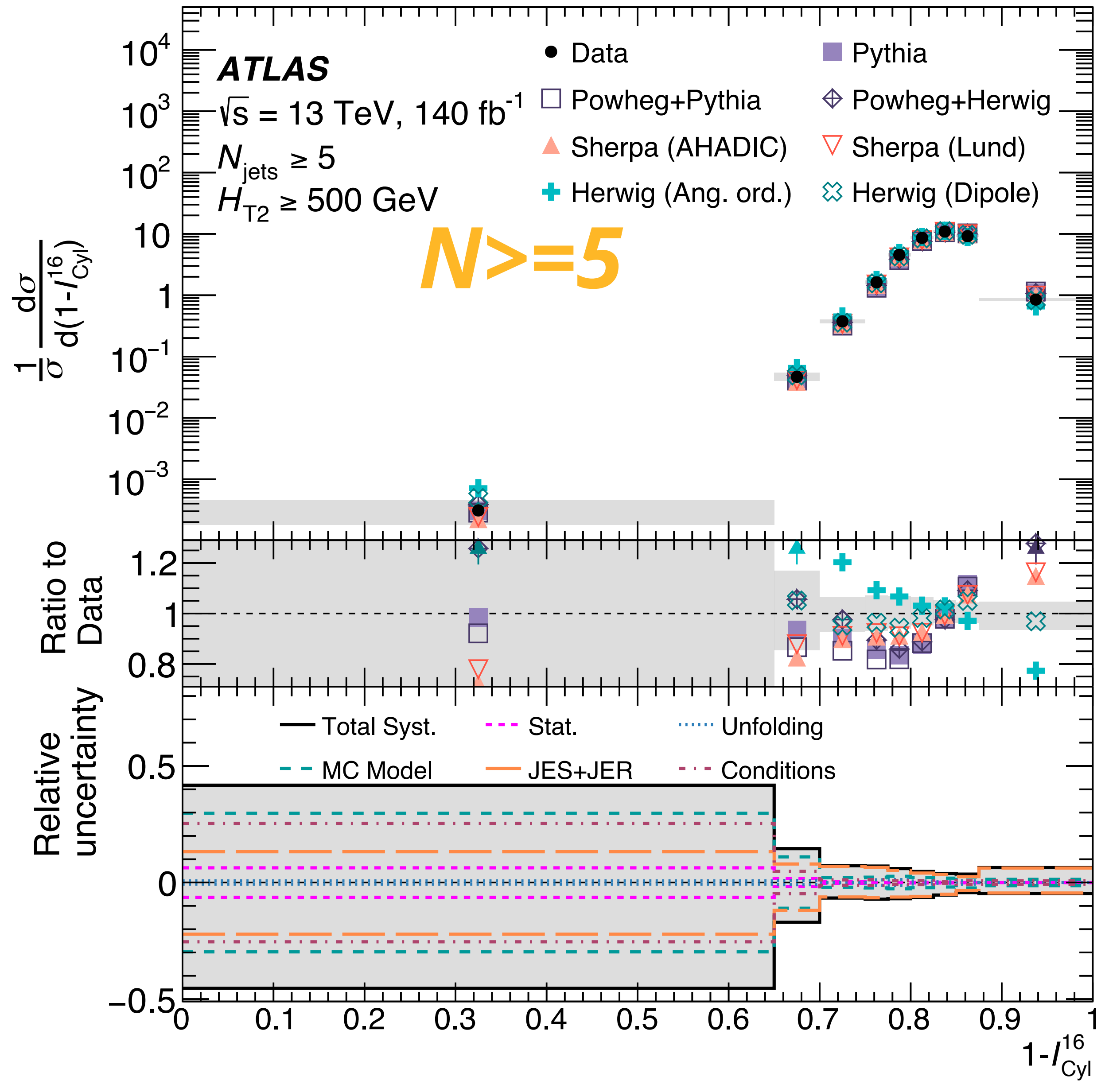
Results: I_{cyl}^{16}

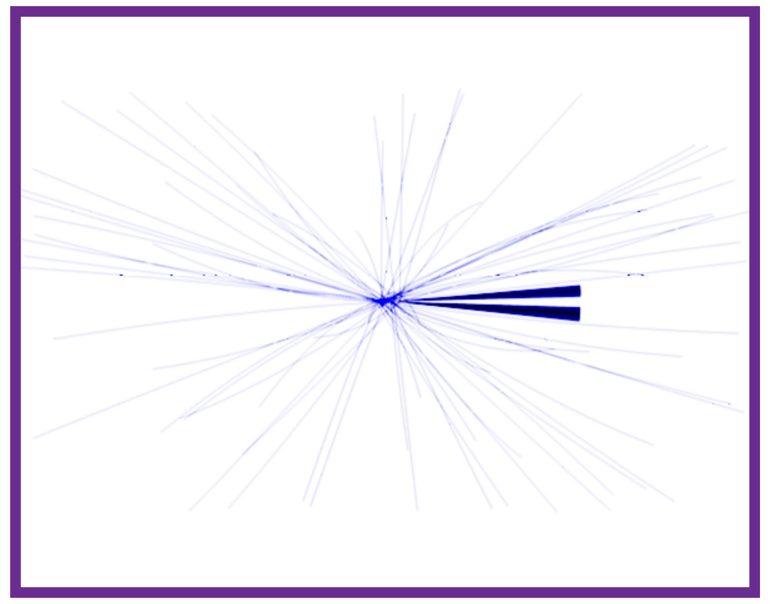
ATLAS *ATLAS-STDM-2020-20*



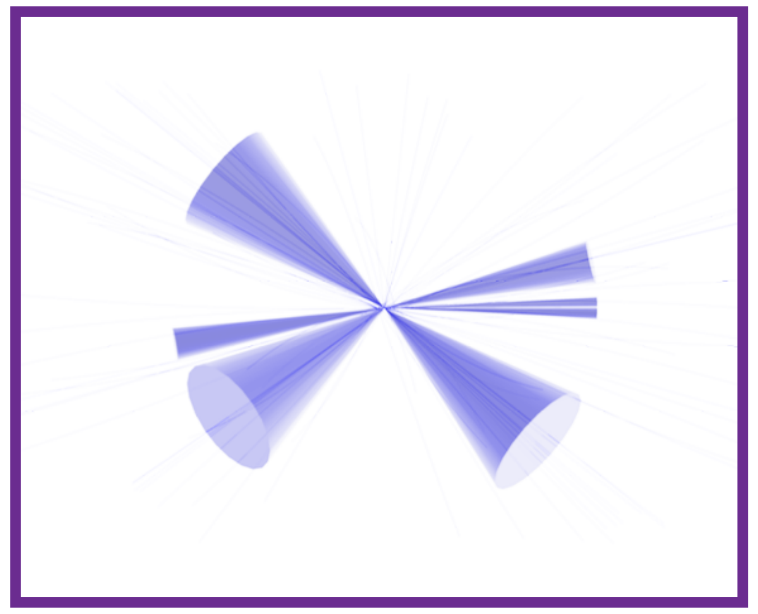


Increase N_{Jets}: isotropy increased significantly!





n.b. side view!



Concluding remarks

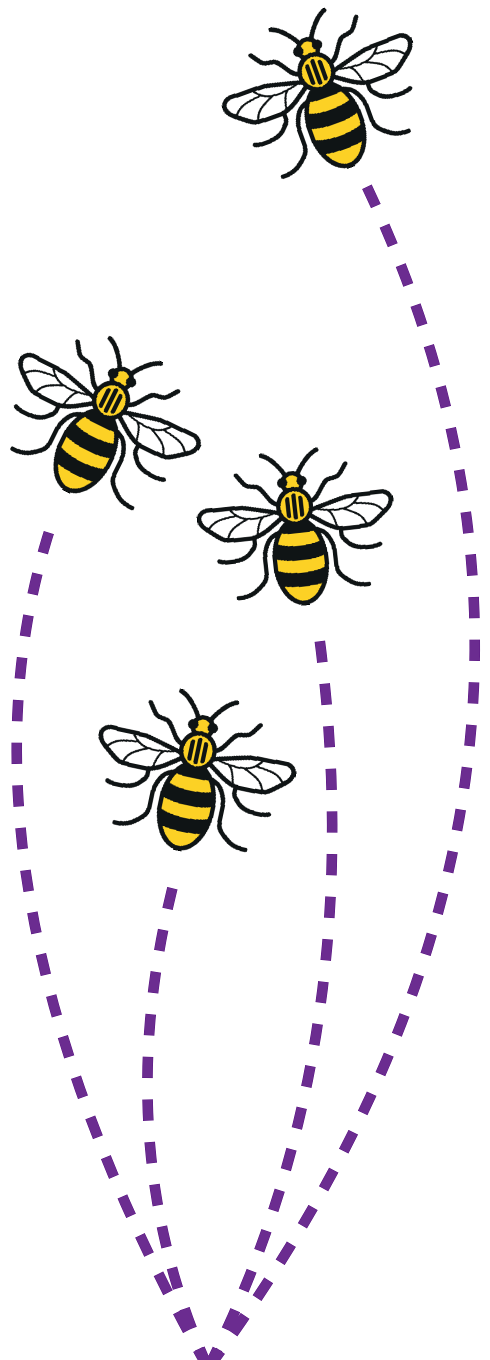
Comments by S. Marzani @ 2022.11.11 CERN QCD Seminar

- LHC Run3 does not give us any substantial increase in energy: but we will have more and more data;
- the theoretical focus is on making our tools better and better

Cross-pollination: bring field-specific developments to the broader pheno community

Understanding new tools: ML algorithms are reshaping the way we think analyses and searches

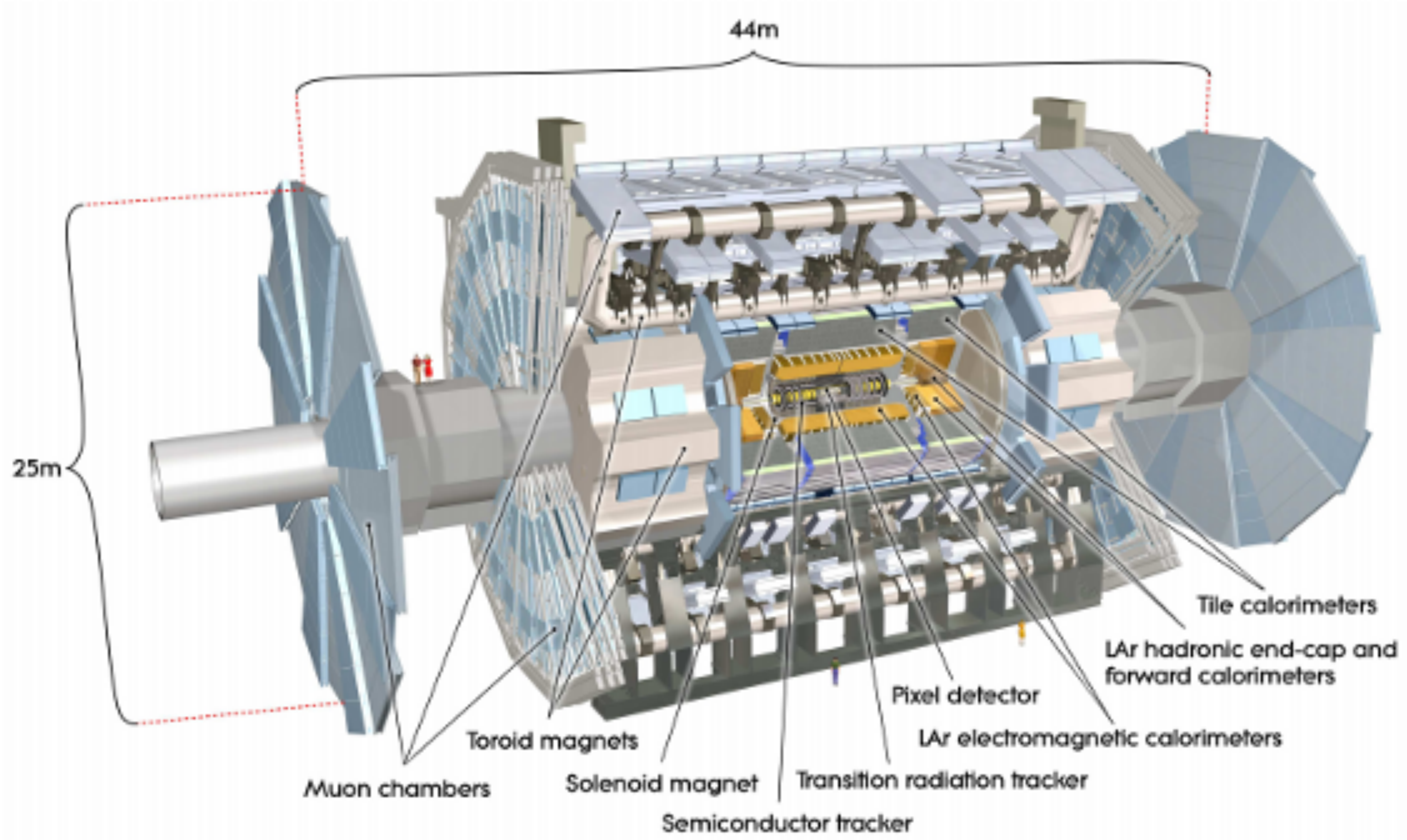
- This idea has already been **exemplified in QCD studies with Run 2 data!**
  - JSS programme demonstrates fruitful **interplay of theory & experiment**.
  - **New QCD measurements** of observables w/ novel properties resulting from direct collaboration between ***ATLAS*** and theory community.
- Crucial to **maintain this momentum!**
  - Run 3 is a moment of **reflection and opportunity** before HL-LHC era …
    - Keep asking each other : WHAT SHOULD WE DO NEXT?

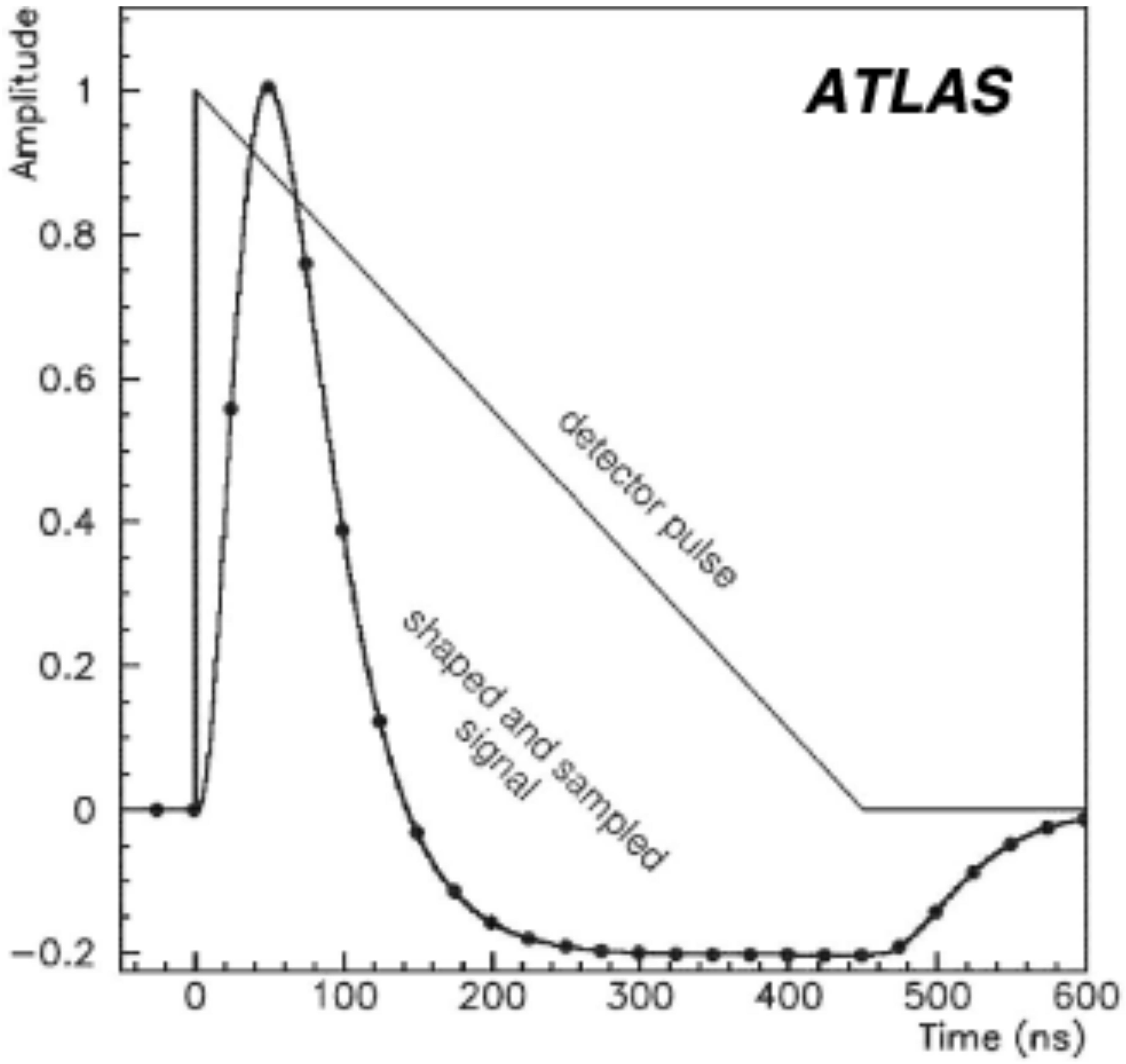


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

Thanks for Listening!

Auxiliary material.


44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Solenoid magnet
Transition radiation tracker
Muon chambers
Semiconductor tracker


ATLAS
Amplitude
Time (ns)
detector pulse
shaped and sampled signal

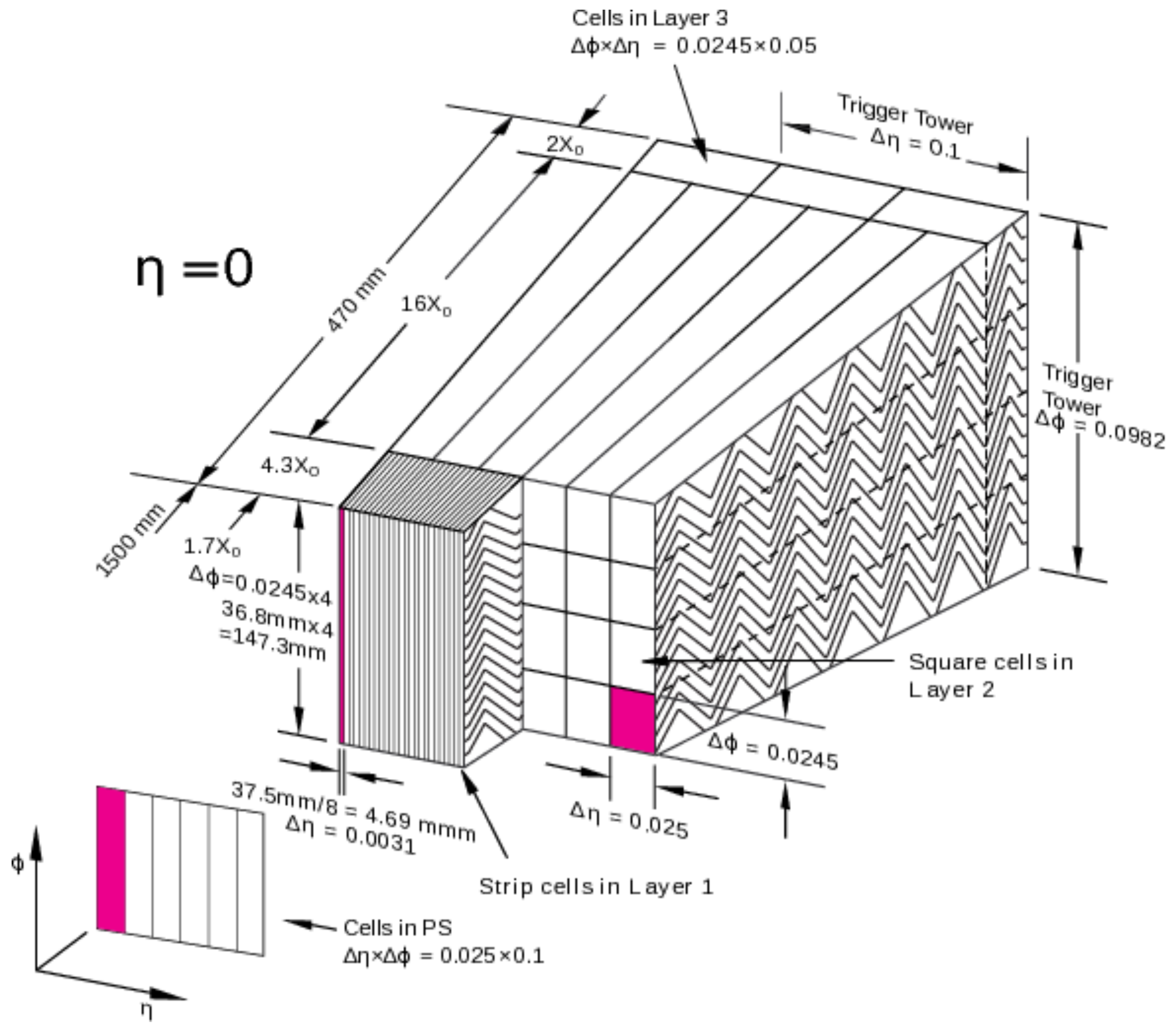
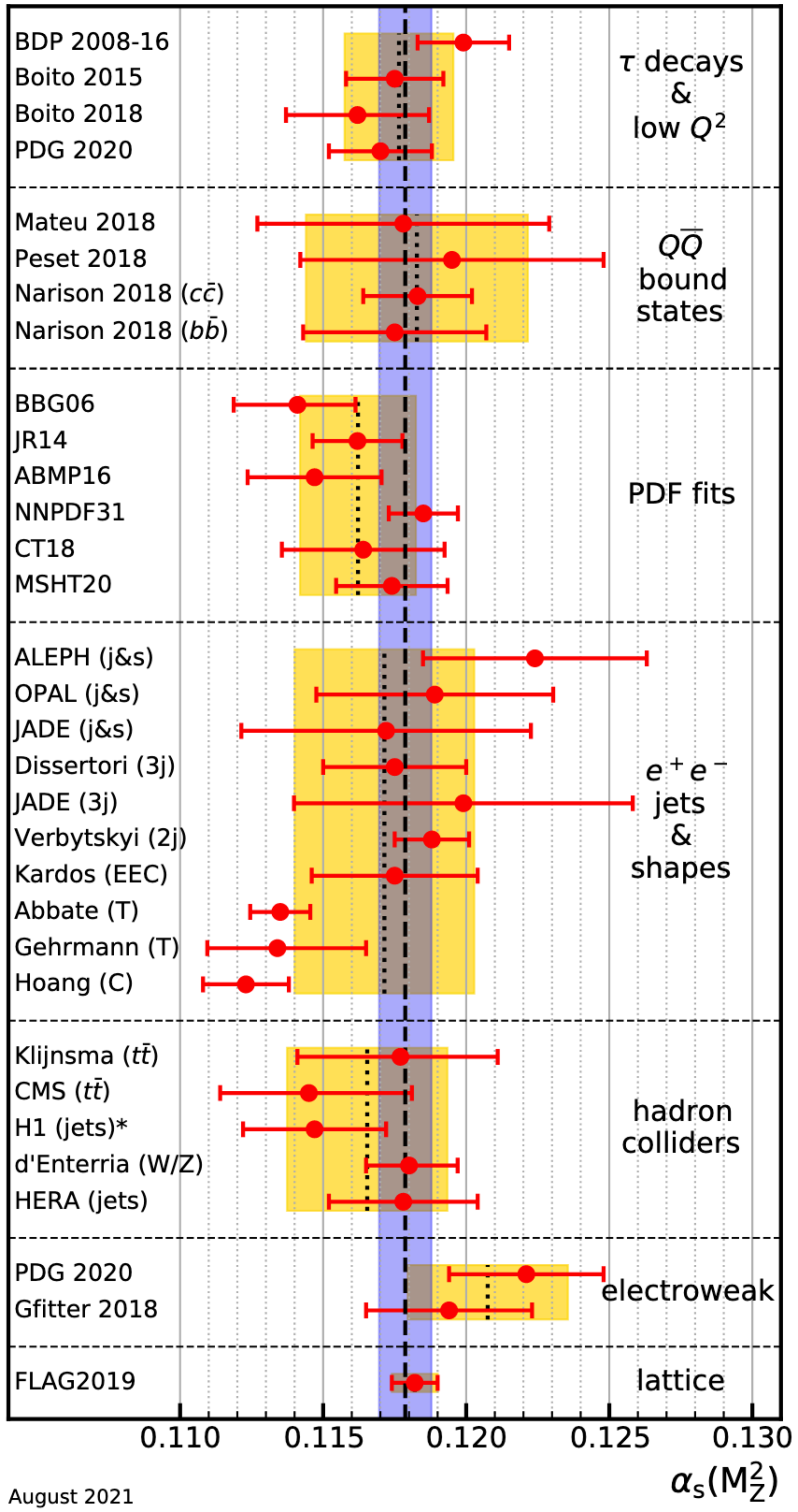

η =0
Cells in Layer 3
Δϕ×Δη = 0.0245×0.05
Trigger Tower
Δη = 0.1
2X₀
470 mm
16X₀
4.3X₀
1500 mm
1.7X₀
Δϕ=0.0245x4
36.8mmx4
=147.3mm
Trigger
Tower
Δϕ = 0.0982
Square cells in
Layer 2
Δϕ = 0.0245
Δη = 0.025
37.5mm/8 = 4.69 mmm
Δη = 0.0031
Strip cells in Layer 1
Cells in PS
Δη×Δϕ = 0.025×0.1
ϕ
η

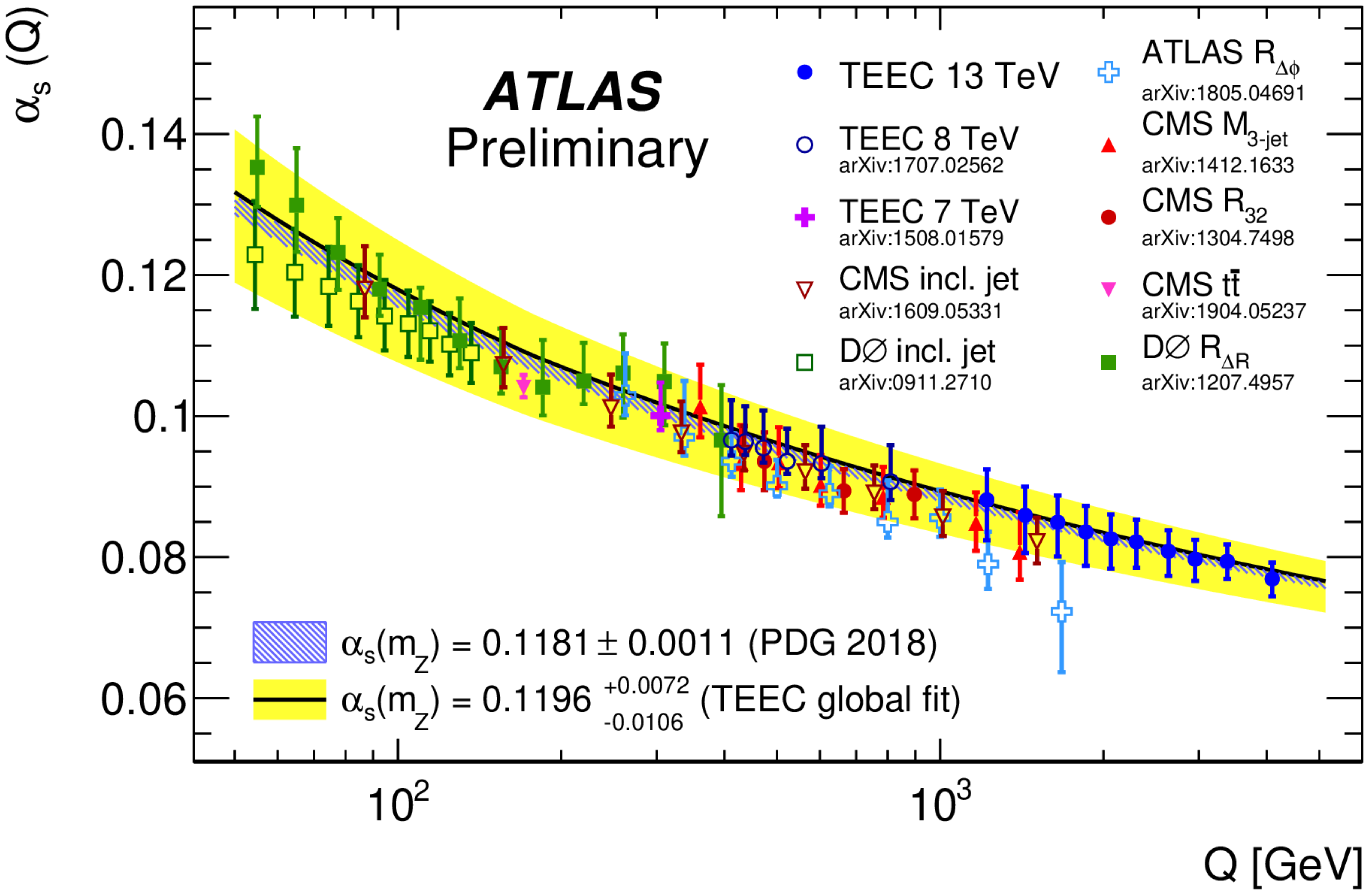
Table 1: The read-out granularity of the ATLAS calorimeter system [1], given in terms of $\Delta\eta\times\Delta\phi$ with the exception of the forward calorimeters, where it is given in linear measures $\Delta x\times\Delta y$, due to the non-pointing read-out geometry of the FCAL. For comparison, the FCAL granularity is approximately $\Delta\eta\times\Delta\phi = 0.15\times0.15(0.3\times0.3)$ at $\eta = 3.5(4.5)$. The total number of read-out cells, including both ends of the calorimeter system, with (without) pre-samplers is 187 652 (178 308).

Calorimeter	Module	Sampling (S_{calo})	N_{cells}	η-coverage	$\Delta\eta\times\Delta\phi$
Electromagnetic calorimeters	EMB		109 568	$\lvert\eta\rvert < 1.52$	
		PreSamplerB	7 808	$\lvert\eta\rvert < 1.52$	$0.025\times\pi/32$
		EMB1		$\lvert\eta\rvert < 1.4$	$0.025/8\times\pi/32$
				$1.4 < \lvert\eta\rvert < 1.475$	$0.025\times\pi/128$
		EMB2		$\lvert\eta\rvert < 1.4$	$0.025\times\pi/128$
				$1.4 < \lvert\eta\rvert < 1.475$	$0.075\times\pi/128$
		EMB3		$\lvert\eta\rvert < 1.35$	$0.050\times\pi/128$
	EMEC		63 744	$1.375 < \lvert\eta\rvert < 3.2$	
		PreSamplerE	1 536	$1.5 < \lvert\eta\rvert < 1.8$	$0.025\times\pi/32$
		EME1		$1.375 < \lvert\eta\rvert < 1.425$	$0.050\times\pi/32$
				$1.425 < \lvert\eta\rvert < 1.5$	$0.025\times\pi/32$
				$1.5 < \lvert\eta\rvert < 1.8$	$0.025/8\times\pi/32$
				$1.8 < \lvert\eta\rvert < 2.0$	$0.025/6\times\pi/32$
				$2.0 < \lvert\eta\rvert < 2.4$	$0.025/4\times\pi/32$
				$2.4 < \lvert\eta\rvert < 2.5$	$0.025\times\pi/32$
				$2.5 < \lvert\eta\rvert < 3.2$	$0.1\times\pi/32$
		EME2		$1.375 < \lvert\eta\rvert < 1.425$	$0.050\times\pi/128$
				$1.425 < \lvert\eta\rvert < 2.5$	$0.025\times\pi/128$
				$2.5 < \lvert\eta\rvert < 3.2$	$0.1\times\pi/128$
		EME3		$1.5 < \lvert\eta\rvert < 2.5$	$0.050\times\pi/128$
Hadronic calorimeters	Tile (barrel)		2 880	$\lvert\eta\rvert < 1$	
		TileBar0/1			$0.1\times\pi/32$
		TileBar2			$0.2\times\pi/32$
	Tile (extended barrel)		2 304	$0.8 < \lvert\eta\rvert < 1.7$	
		TileExt0/1			$0.1\times\pi/32$
		TileExt2			$0.2\times\pi/32$
	HEC		5 632	$1.5 < \lvert\eta\rvert < 3.2$	
		HEC0/1/2/3		$1.5 < \lvert\eta\rvert < 2.5$	$0.1\times\pi/32$
				$2.5 < \lvert\eta\rvert < 3.2$	$0.2\times\pi/16$
Forward calorimeters	FCAL		3 524	$3.1 < \lvert\eta\rvert < 4.9$	$\Delta x\times\Delta y$
		FCAL0		$3.1 < \lvert\eta\rvert < 3.15$	1.5 cm × 1.3 cm
				$3.15 < \lvert\eta\rvert < 4.3$	3.0 cm × 2.6 cm
				$4.3 < \lvert\eta\rvert < 4.83$	1.5 cm × 1.3 cm
		FCAL1		$3.2 < \lvert\eta\rvert < 3.24$	1.7 cm × 2.1 cm
				$3.24 < \lvert\eta\rvert < 4.5$	3.3 cm × 4.2 cm
				$4.5 < \lvert\eta\rvert < 4.81$	1.7 cm × 2.1 cm
		FCAL2		$3.29 < \lvert\eta\rvert < 3.32$	2.7 cm × 2.4 cm
				$3.32 < \lvert\eta\rvert < 4.6$	5.4 cm × 4.7 cm
				$4.6 < \lvert\eta\rvert < 4.75$	2.7 cm × 2.4 cm

α_s



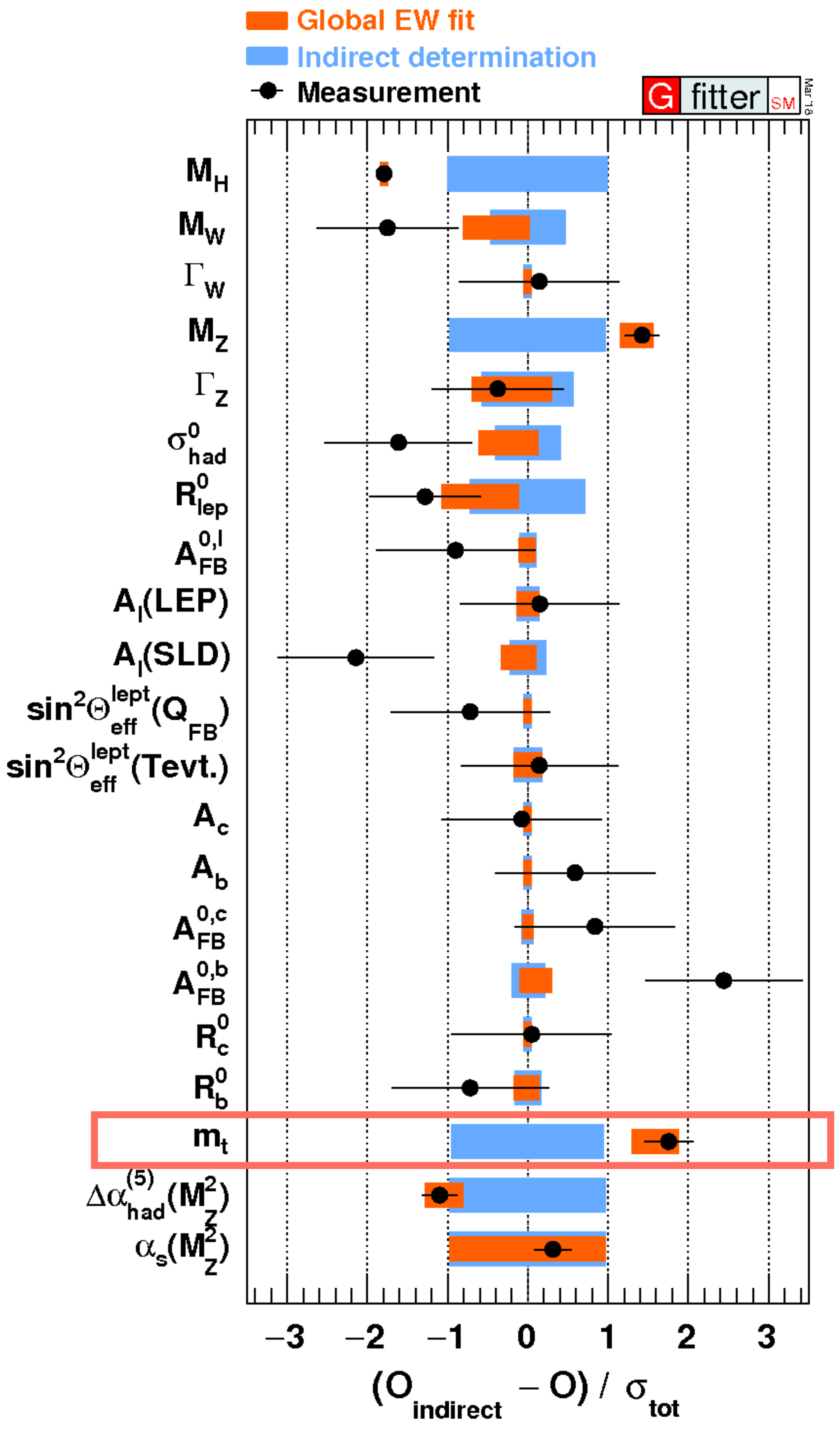
BDP 2008-16
Boito 2015
Boito 2018
PDG 2020
τ decays & low Q²
Mateu 2018
Peset 2018
Narison 2018 (cc̄)
Narison 2018 (bb̄)
QQ̄ bound states
BBG06
JR14
ABMP16
NNPDF31
CT18
MSHT20
PDF fits
ALEPH (j&s)
OPAL (j&s)
JADE (j&s)
Dissertori (3j)
JADE (3j)
Verbytskyi (2j)
Kardos (EEC)
Abbate (T)
Gehrmann (T)
Hoang (C)
e⁺e⁻ jets & shapes
Klijnsma (tt̄)
CMS (tt̄)
H1 (jets)*
d'Enterria (W/Z)
HERA (jets)
hadron colliders
PDG 2020
Gfitter 2018
electroweak
FLAG2019
lattice
0.110
0.115
0.120
0.125
0.130
αs(M²Z)
August 2021

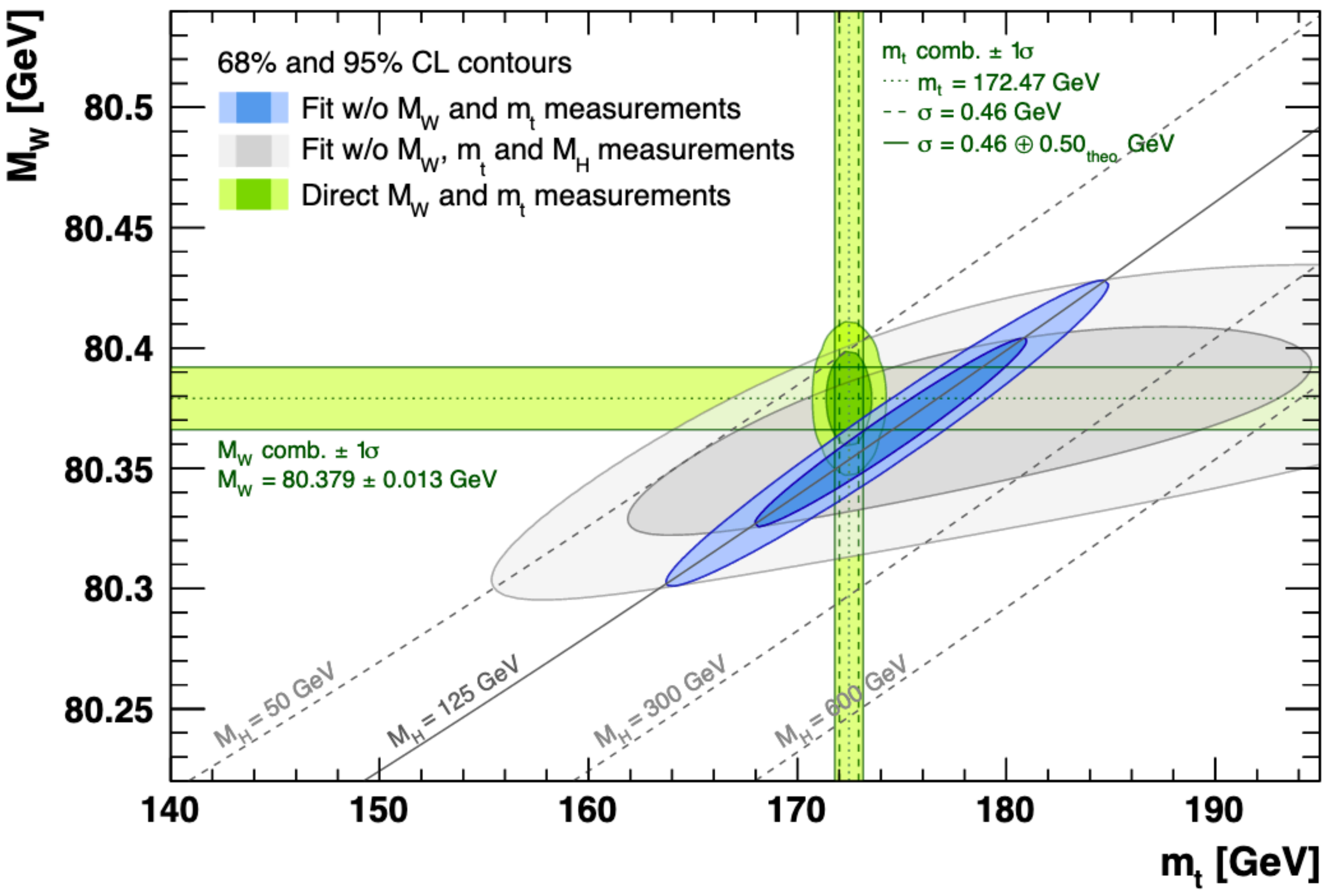


αs (Q)
ATLAS
Preliminary
TEEC 13 TeV
TEEC 8 TeV
arXiv:1707.02562
TEEC 7 TeV
arXiv:1508.01579
CMS incl. jet
arXiv:1609.05331
DØ incl. jet
arXiv:0911.2710
ATLAS RΔϕ
arXiv:1805.04691
CMS M3-jet
arXiv:1412.1633
CMS R32
arXiv:1304.7498
CMS tt̄
arXiv:1904.05237
DØ RΔR
arXiv:1207.4957
αs(mZ) = 0.1181 ± 0.0011 (PDG 2018)
αs(mZ) = 0.1196 +0.0072 -0.0106 (TEEC global fit)
0.14
0.12
0.1
0.08
0.06
10²
10³
Q [GeV]

gFitter collab. 1803.01853

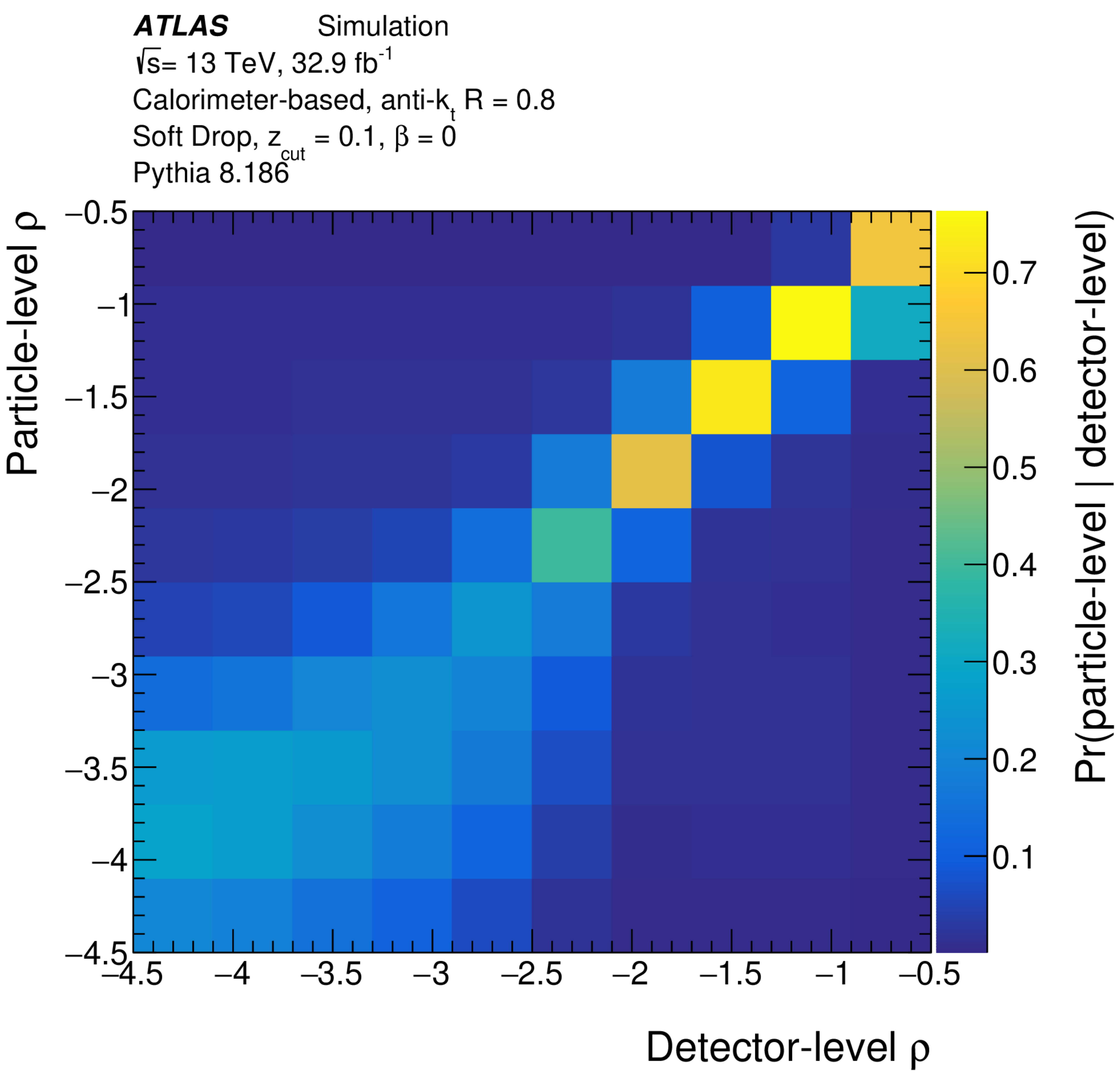
Global Electroweak Fit

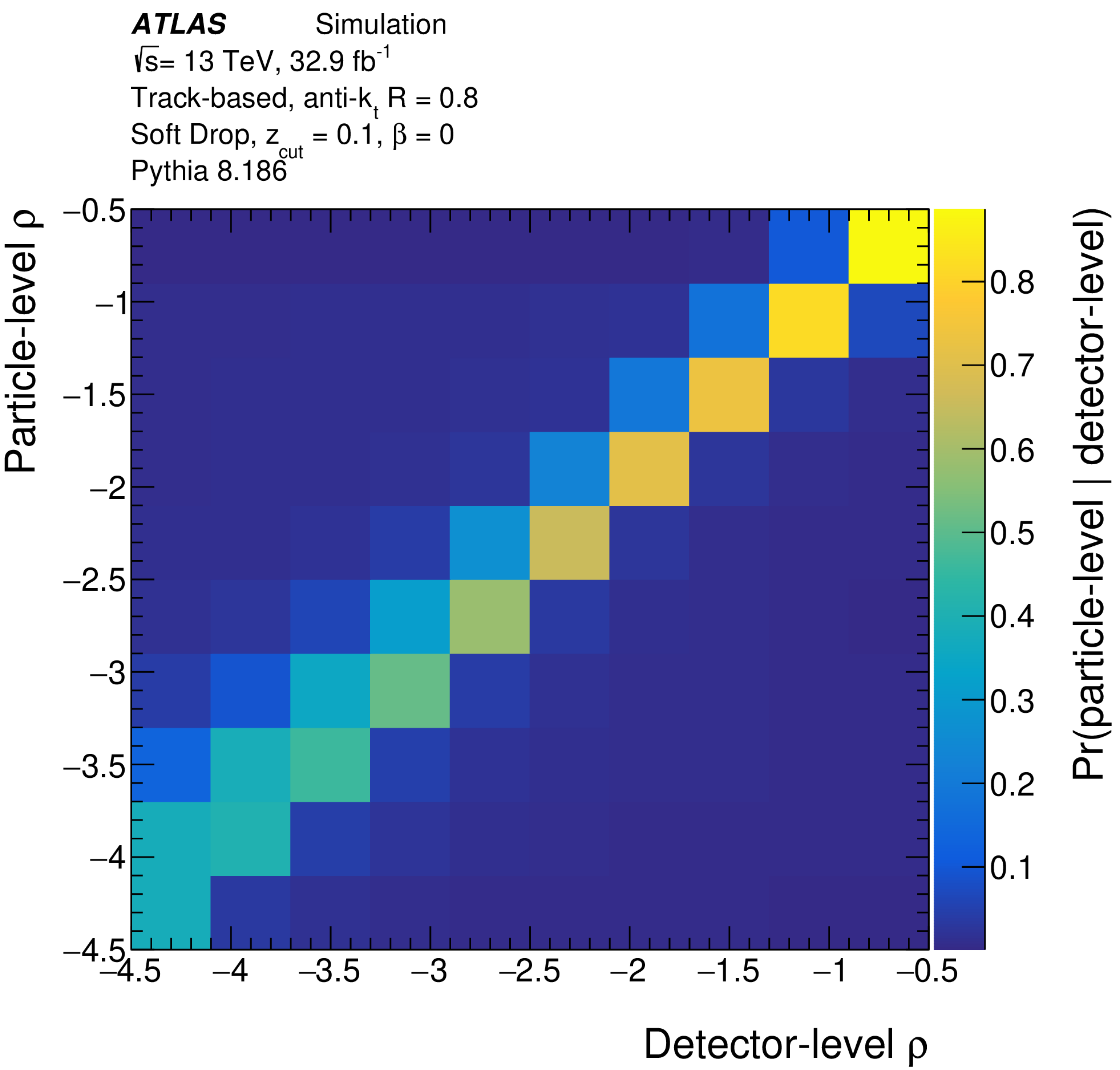




Soft-drop observables: calo vs. track response matrices

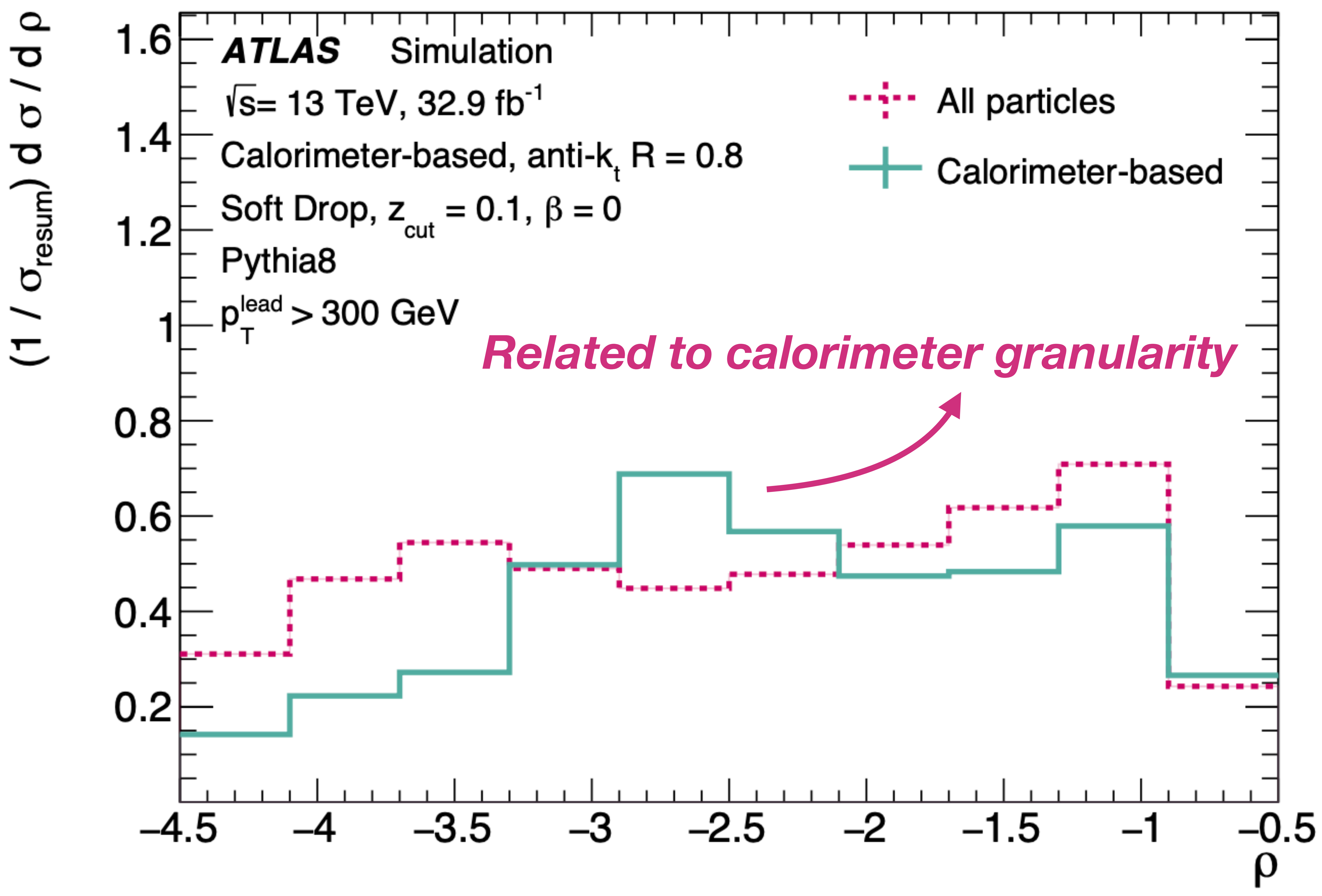
ATLAS, Phys. Rev. D 101, 052007 (2020), Phys. Rev. Lett. 121, 092001 (2018)



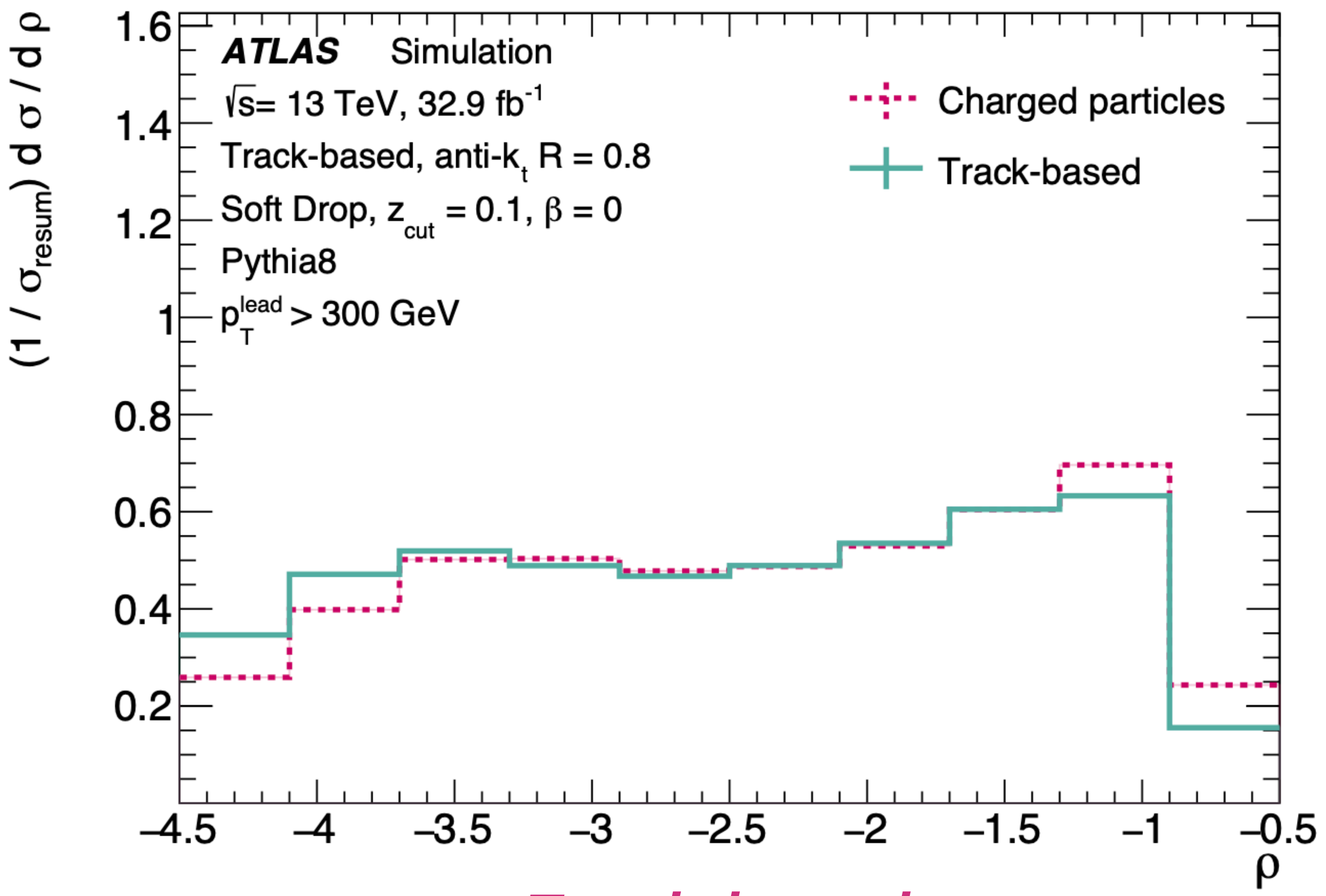


Soft-drop observables: calo vs. track before unfolding

ATLAS, Phys. Rev. D 101, 052007 (2020), Phys. Rev. Lett. 121, 092001 (2018)



Calo-based

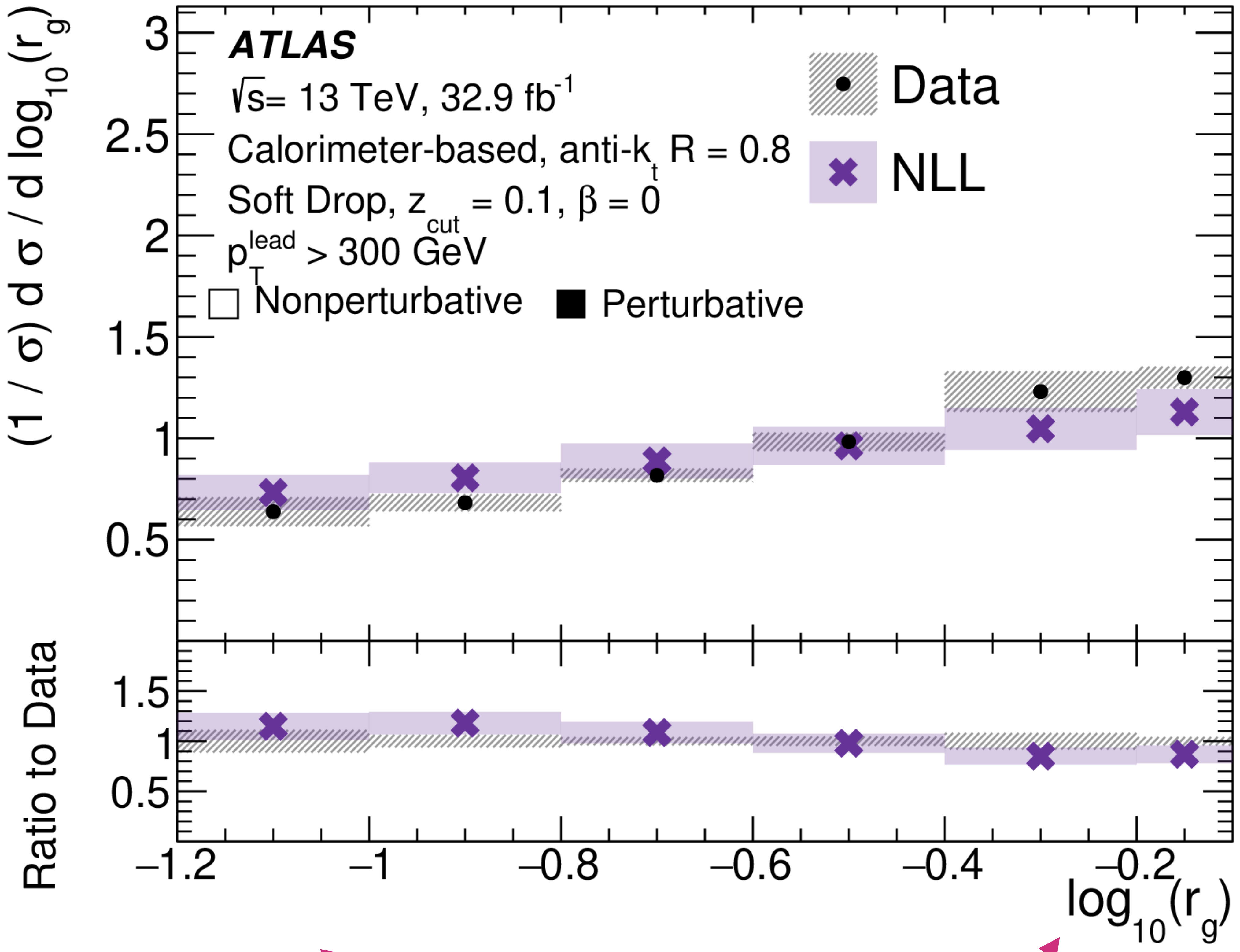


Track-based

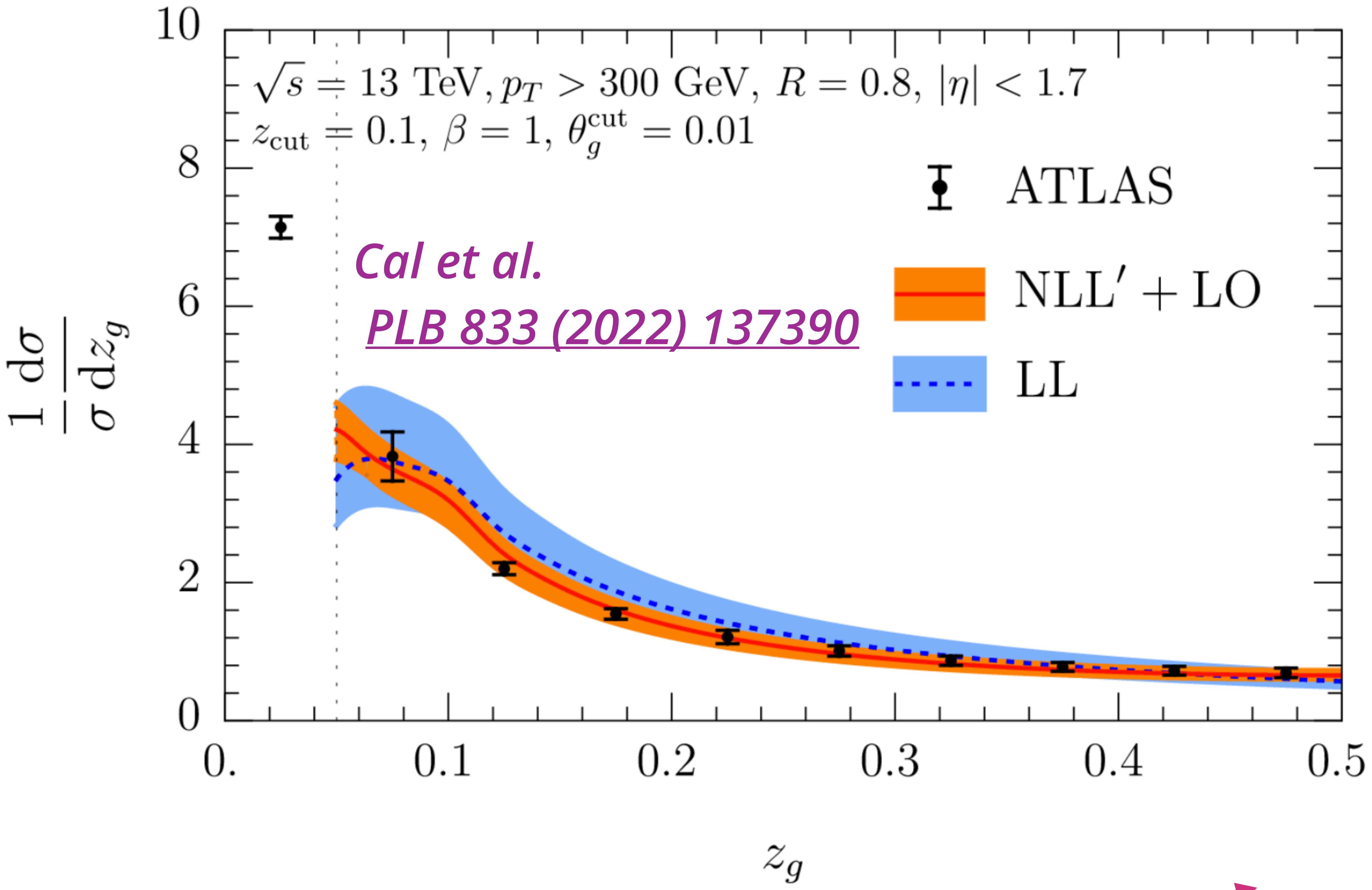
Soft-Drop Observables

ATLAS, Phys. Rev. D 101, 052007 (2020), Phys. Rev. Lett. 121, 092001 (2018)

"Groomed radius" $r_g = \Delta R(p_T^{j1}, p_T^{j1})$



"Energy balance" $z_g = p_T^{j2}/p_T^{j1}$



Cal et al. PLB 833 (2022) 137390

Collinear (npQCD) ⟷ Wide-angled

Soft splittings (npQCD) ⟷ Even splittings