BOOST Camp (Experimental)

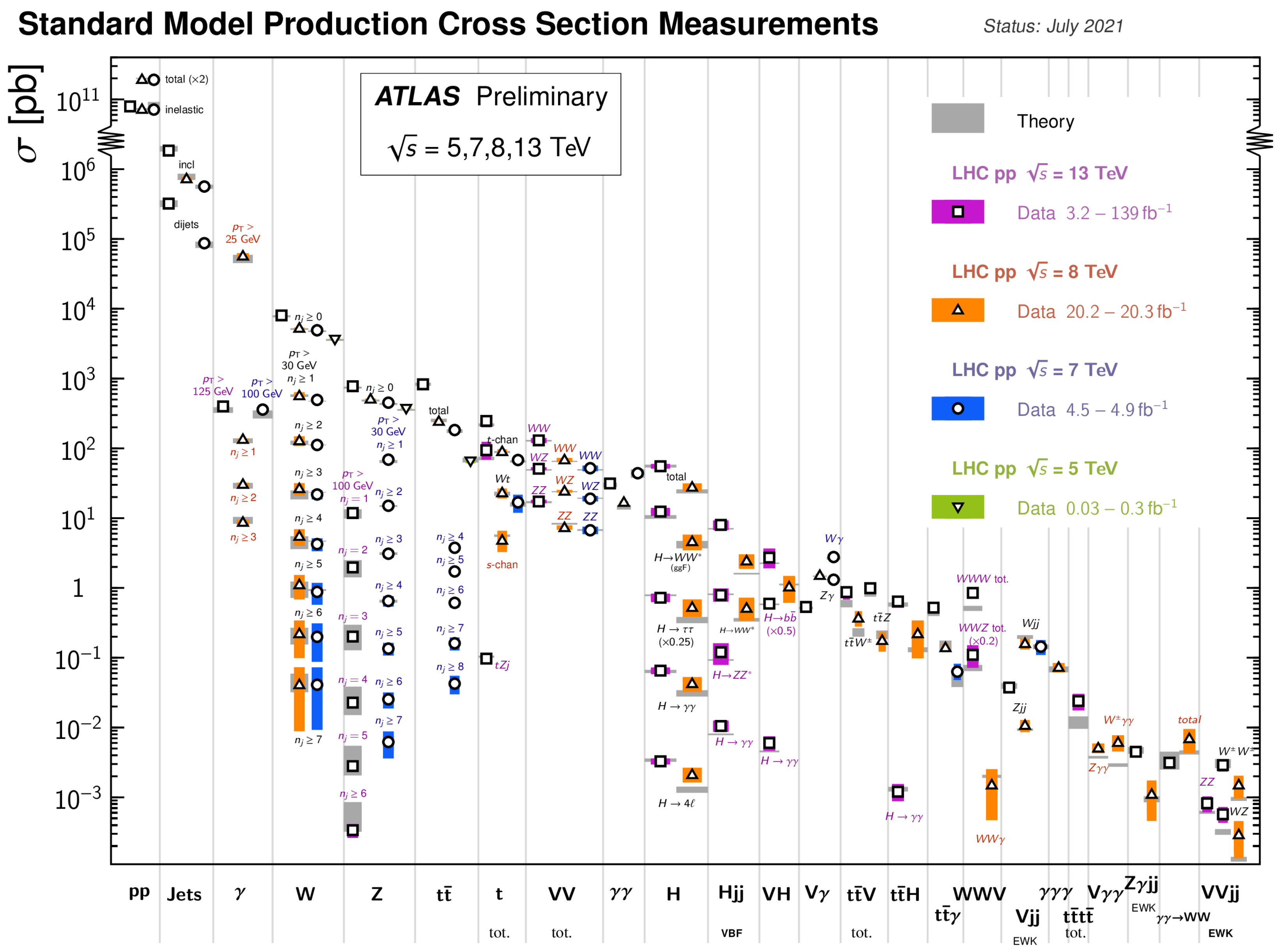
16th International Workshop on Boosted Object Phenomenology, Reconstruction, Measurements, and Searches at Colliders (BOOST 2024)

Genova, Italy, 29 July - 2 August 2024

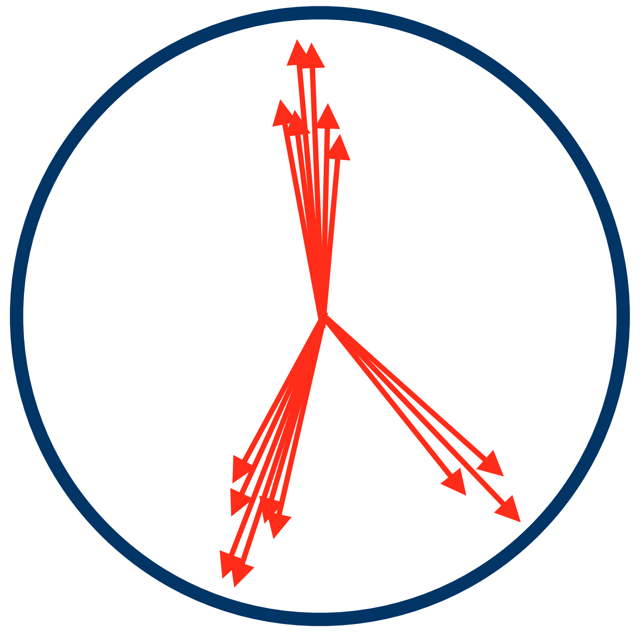
Matt LeBlanc (Brown University)

BROWN

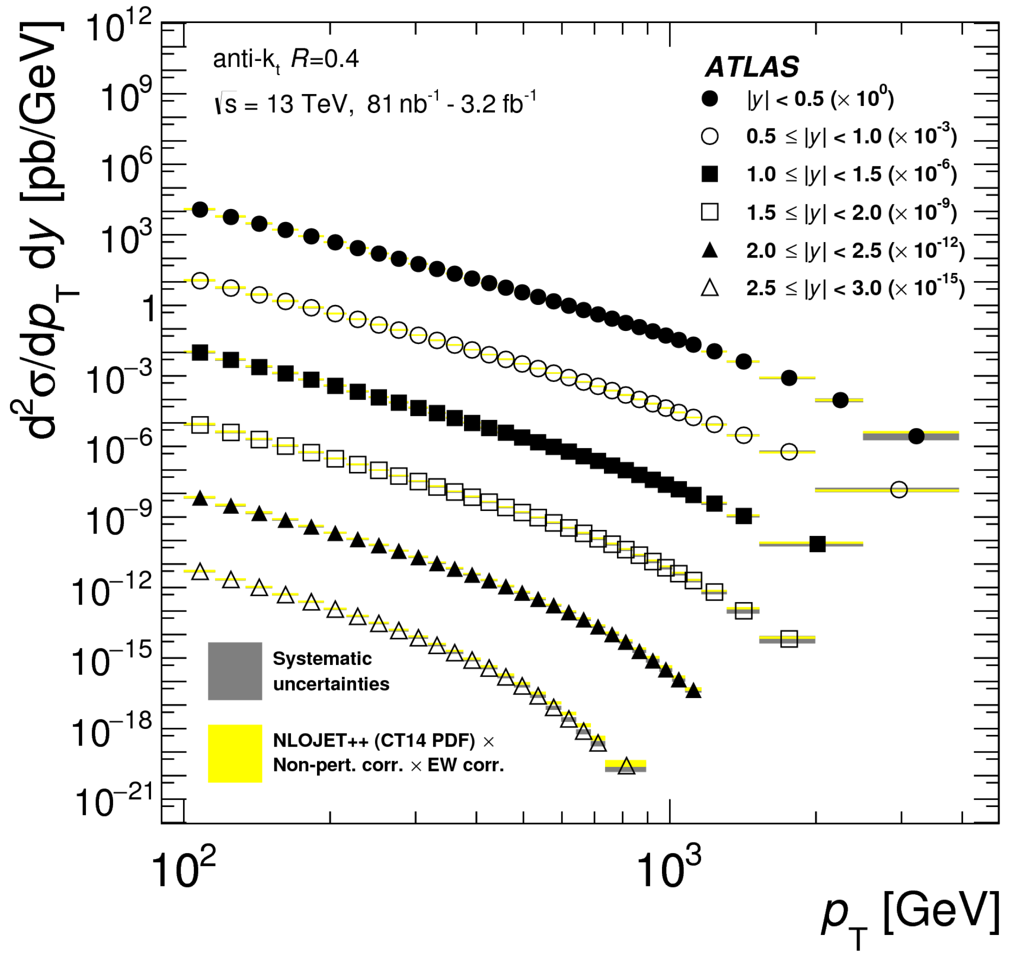
At the LHC, we can study **many processes**

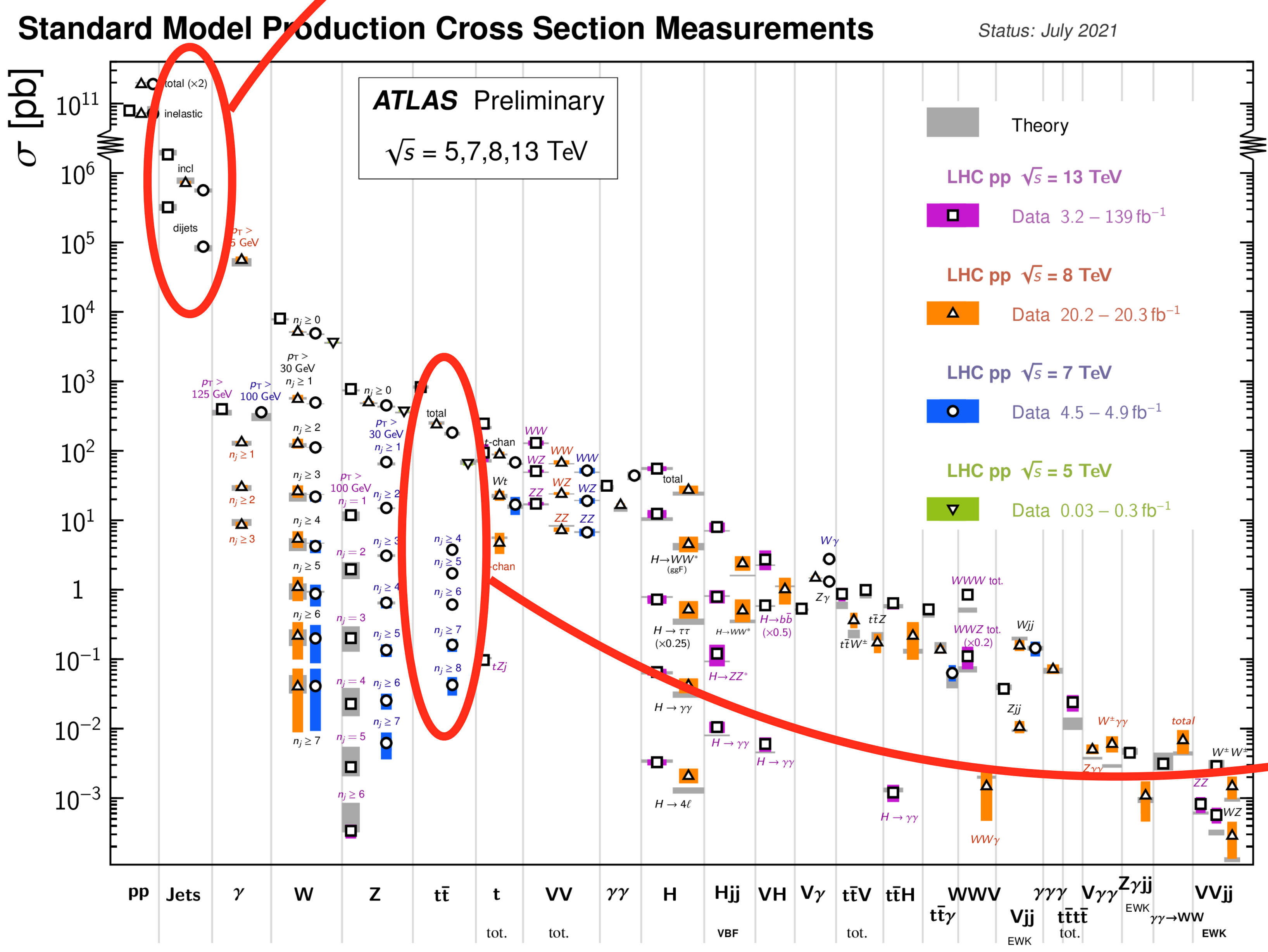


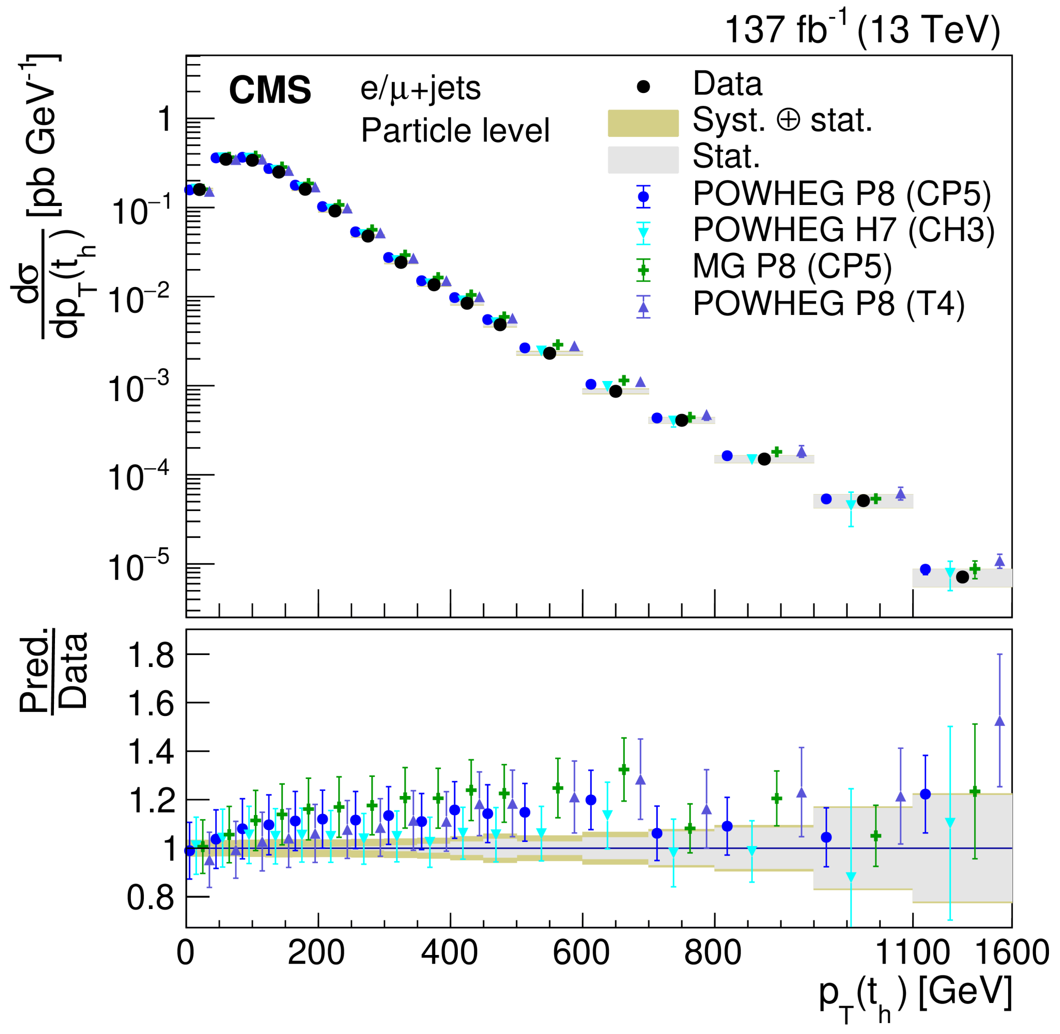
At the LHC, we can study **many processes** at **many scales** …



e.g. mutijets







e.g. top pairs

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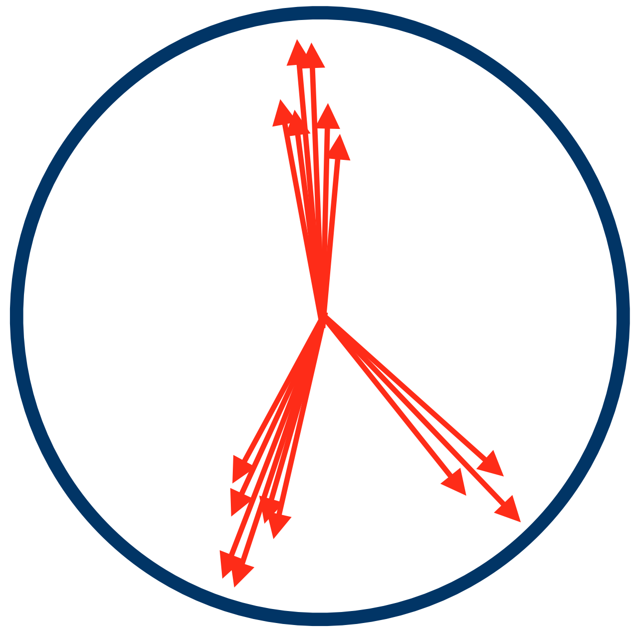

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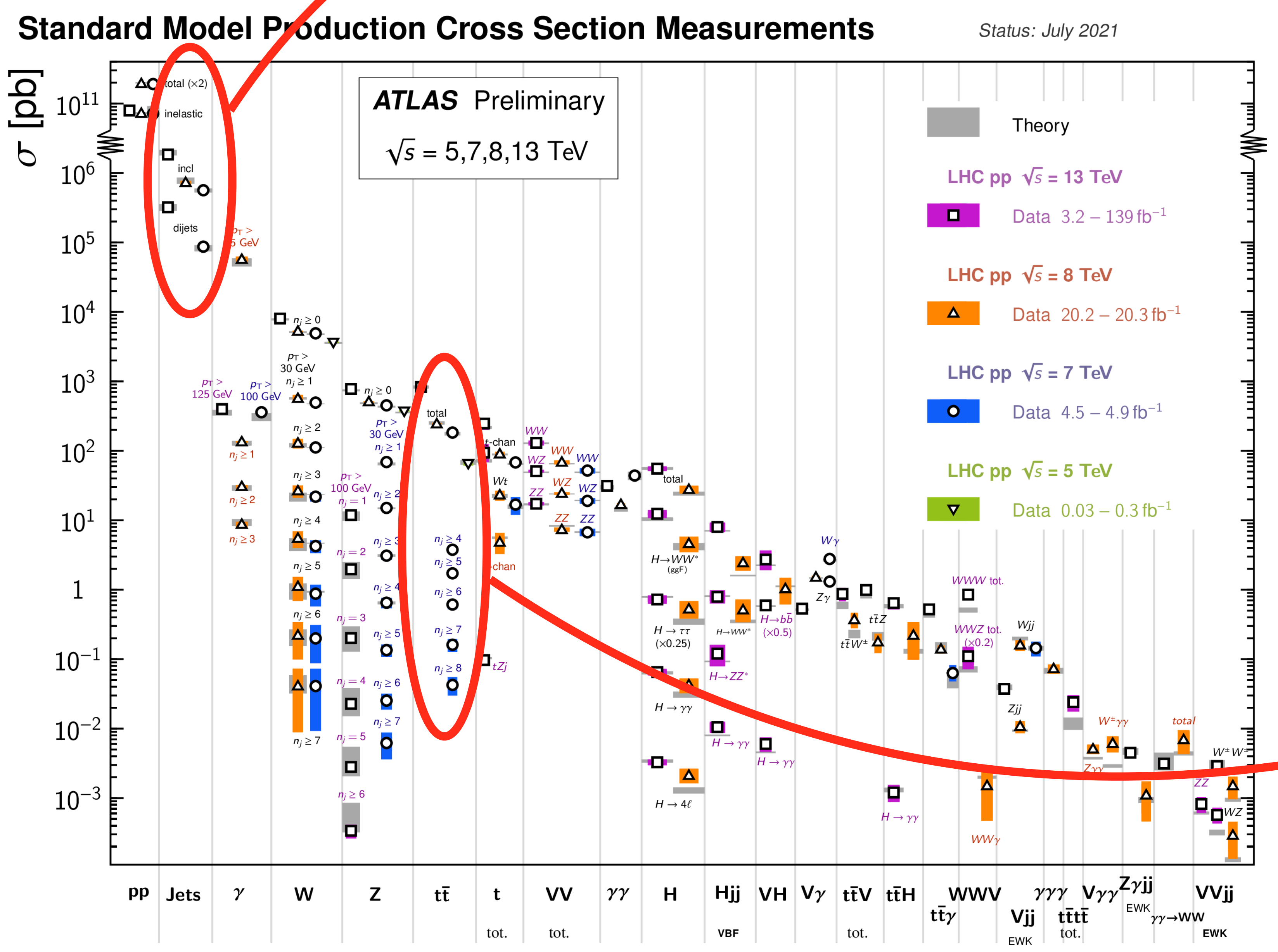

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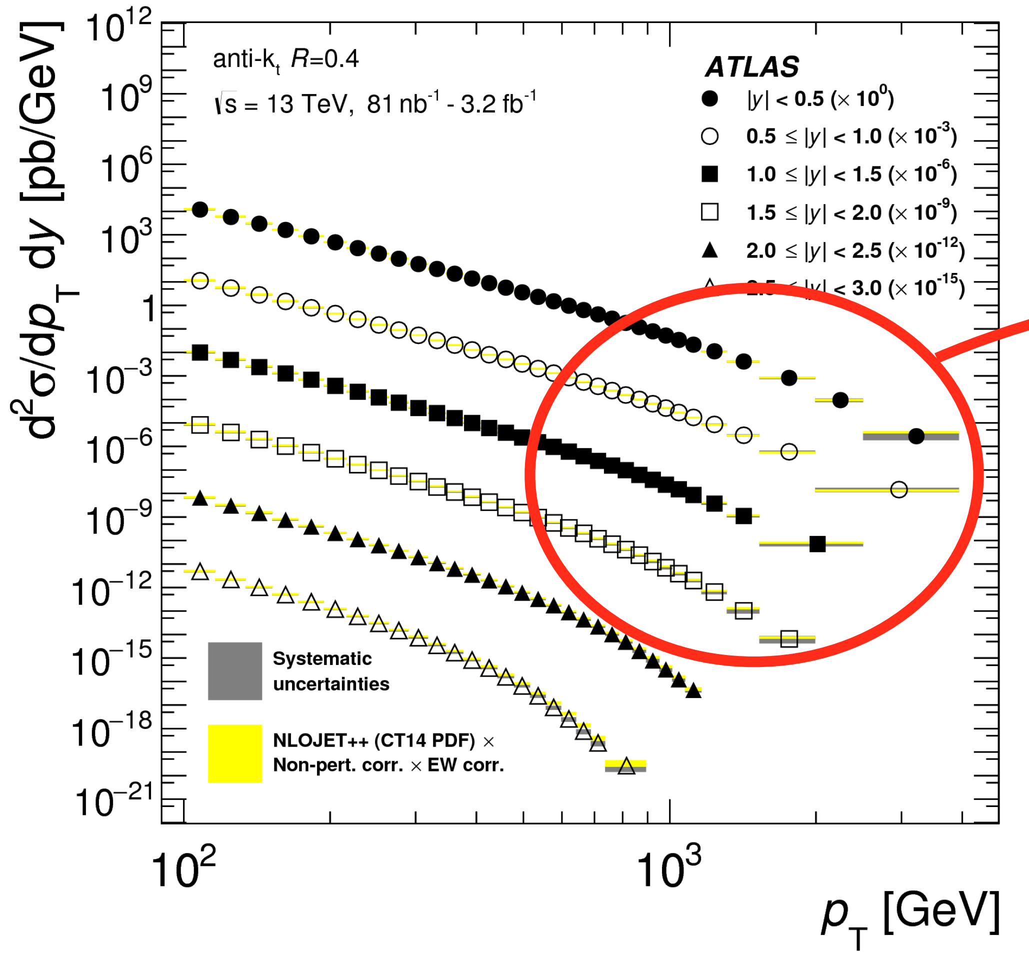
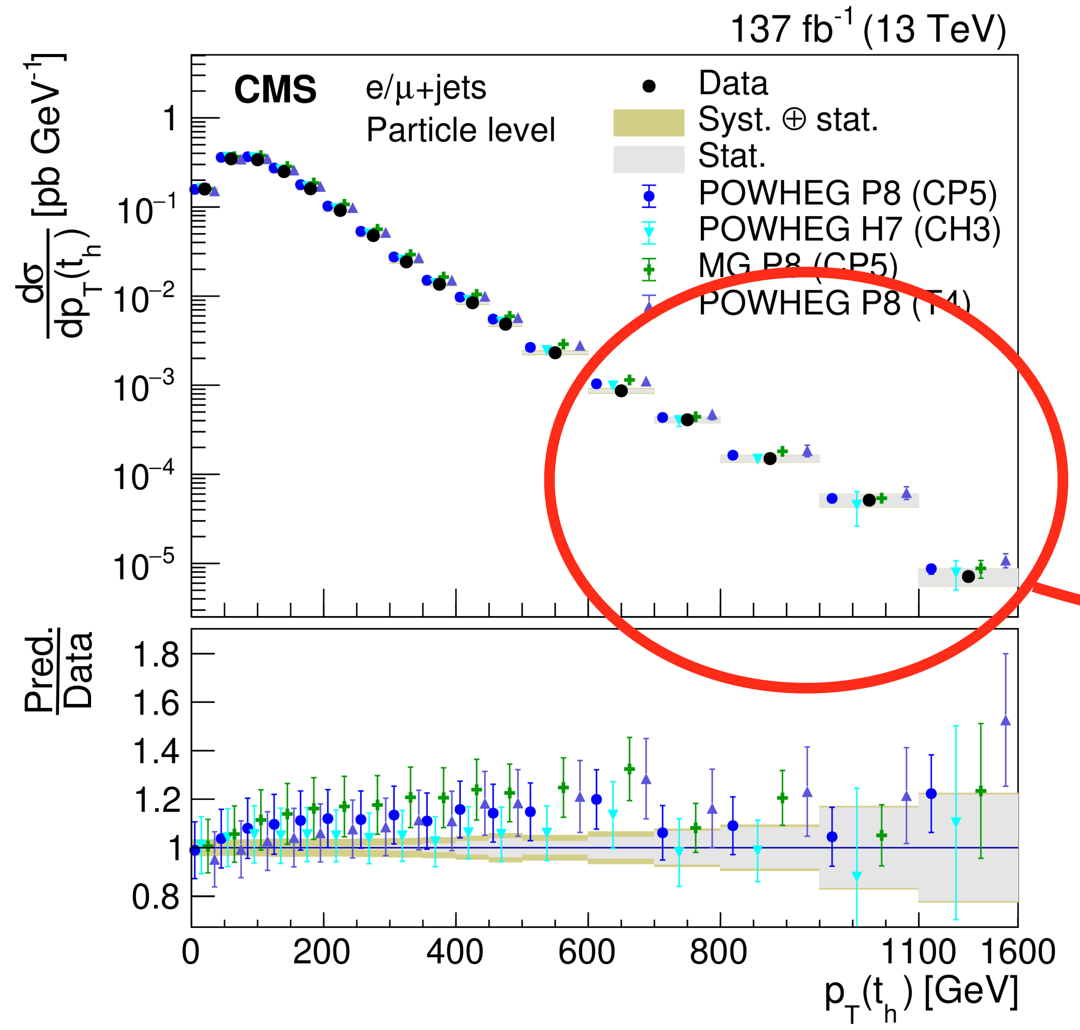
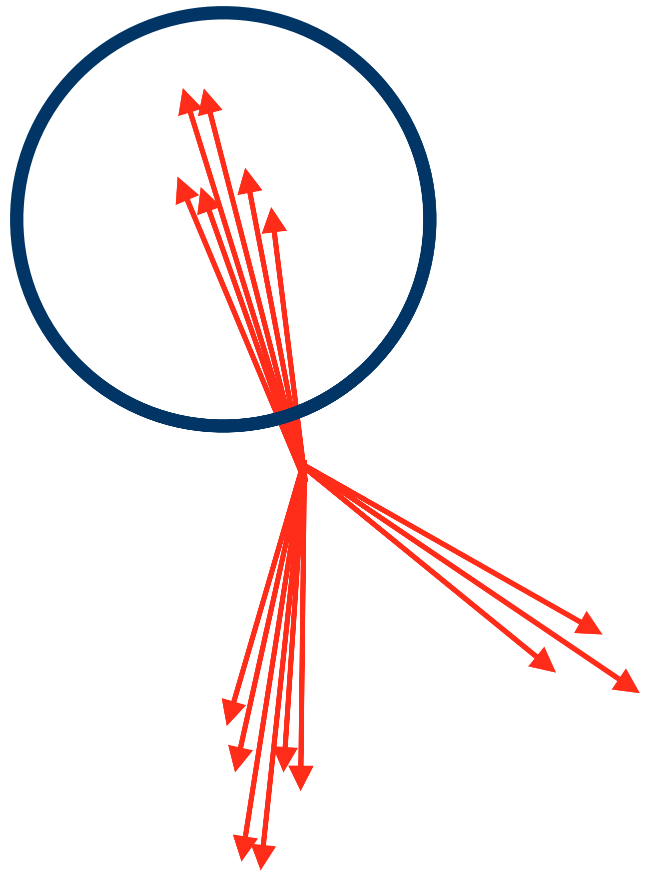
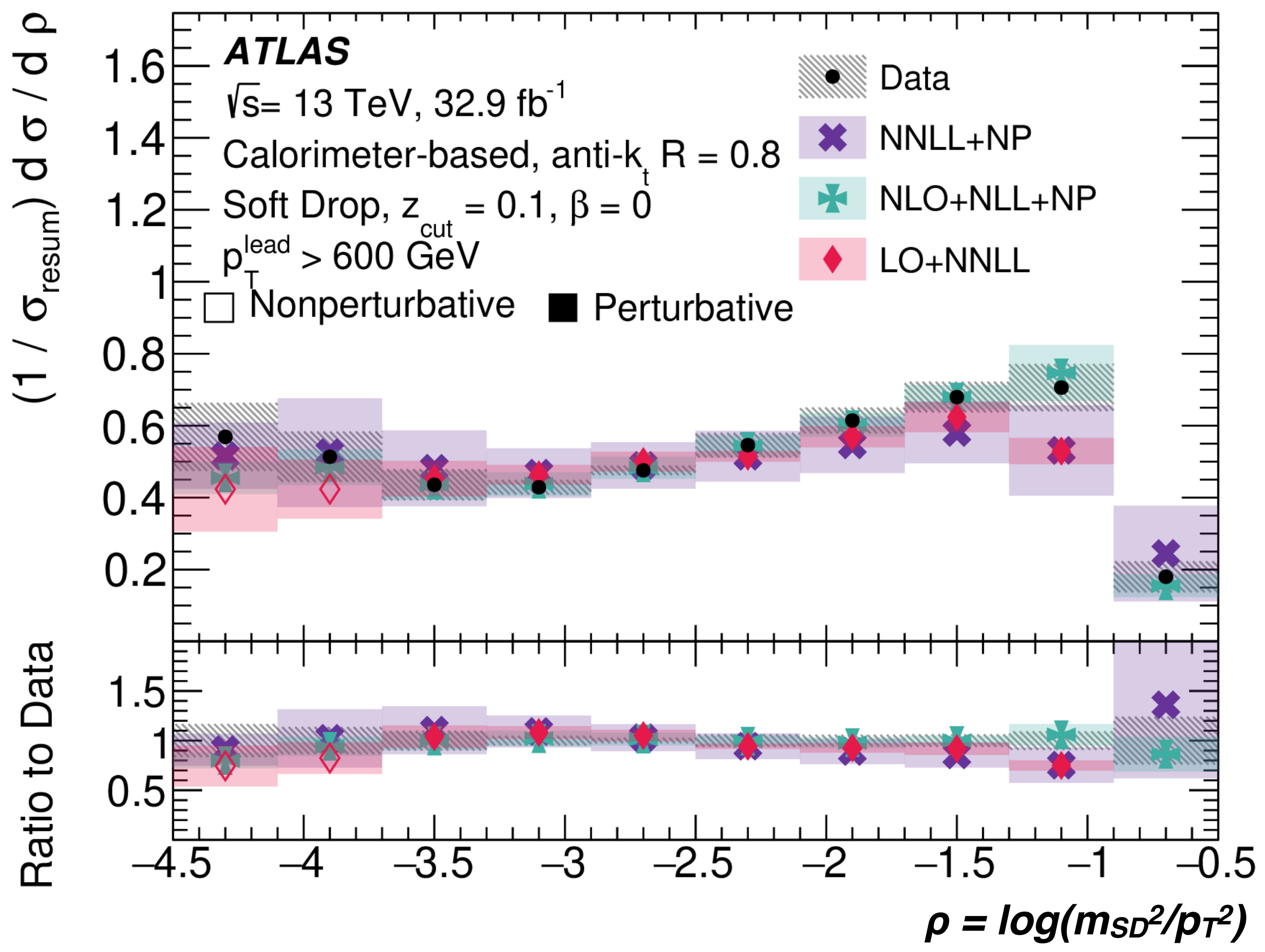


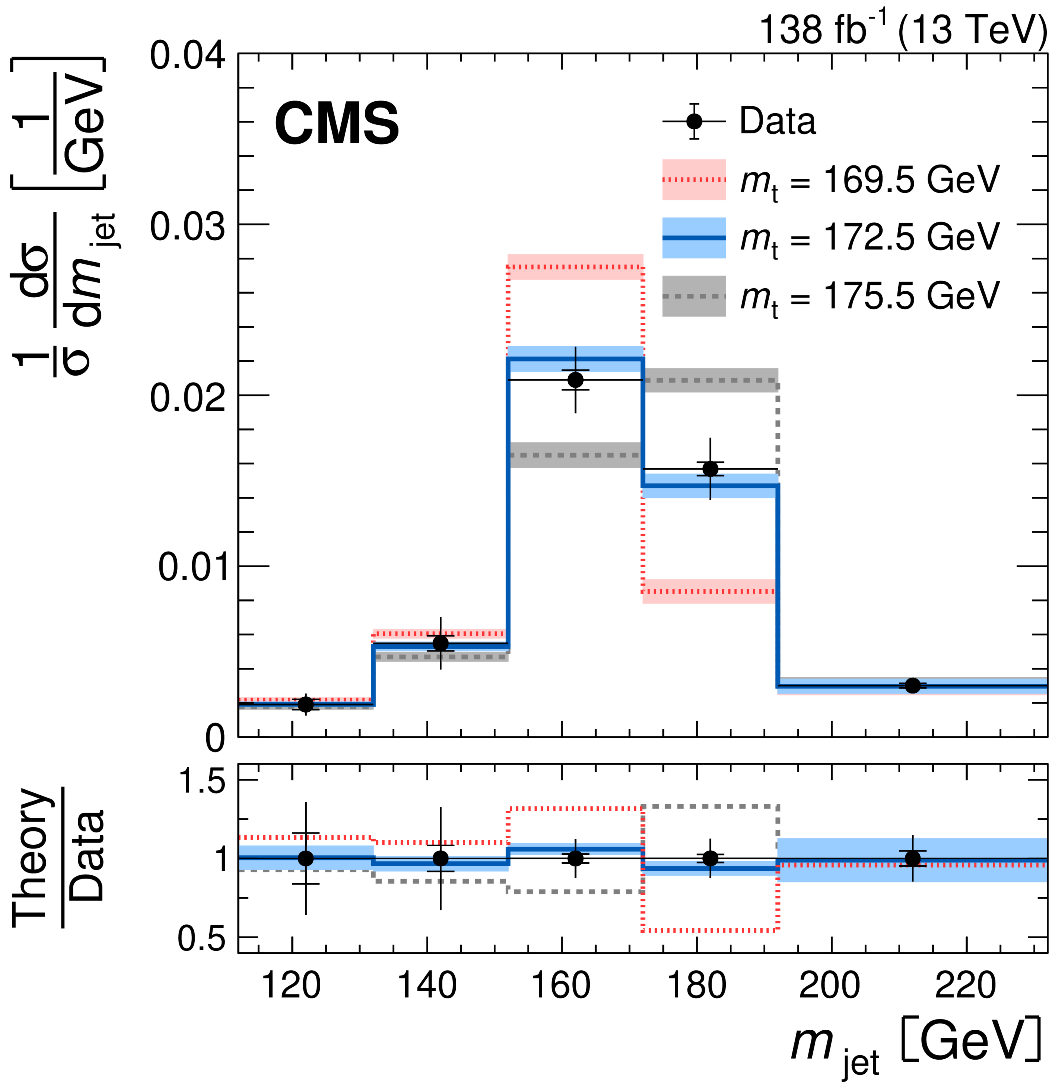


e.g. jet mass (groomed)

JSS







e.g. top mass (boosted)

… and at the highest scales: ***boostemos!***

(Let's boost.)

Today's map

- **Detectors**
  - ATLAS, CMS
    - Tracking detectors, calorimeters
    - Pile-up
    - Particle Flow
  - ALICE
    - Heavy ions concepts (Centrality, RAA)
  - DIS: H1 (HERA), EPIC (EIC)
- **Analysis techniques**
  - Tagging
  - Unfolding
- *Selected topics, some points might seem obvious to you — goal is for everyone to learn something.*

Genoese map circa 1457, pre-Columbus, Caboto

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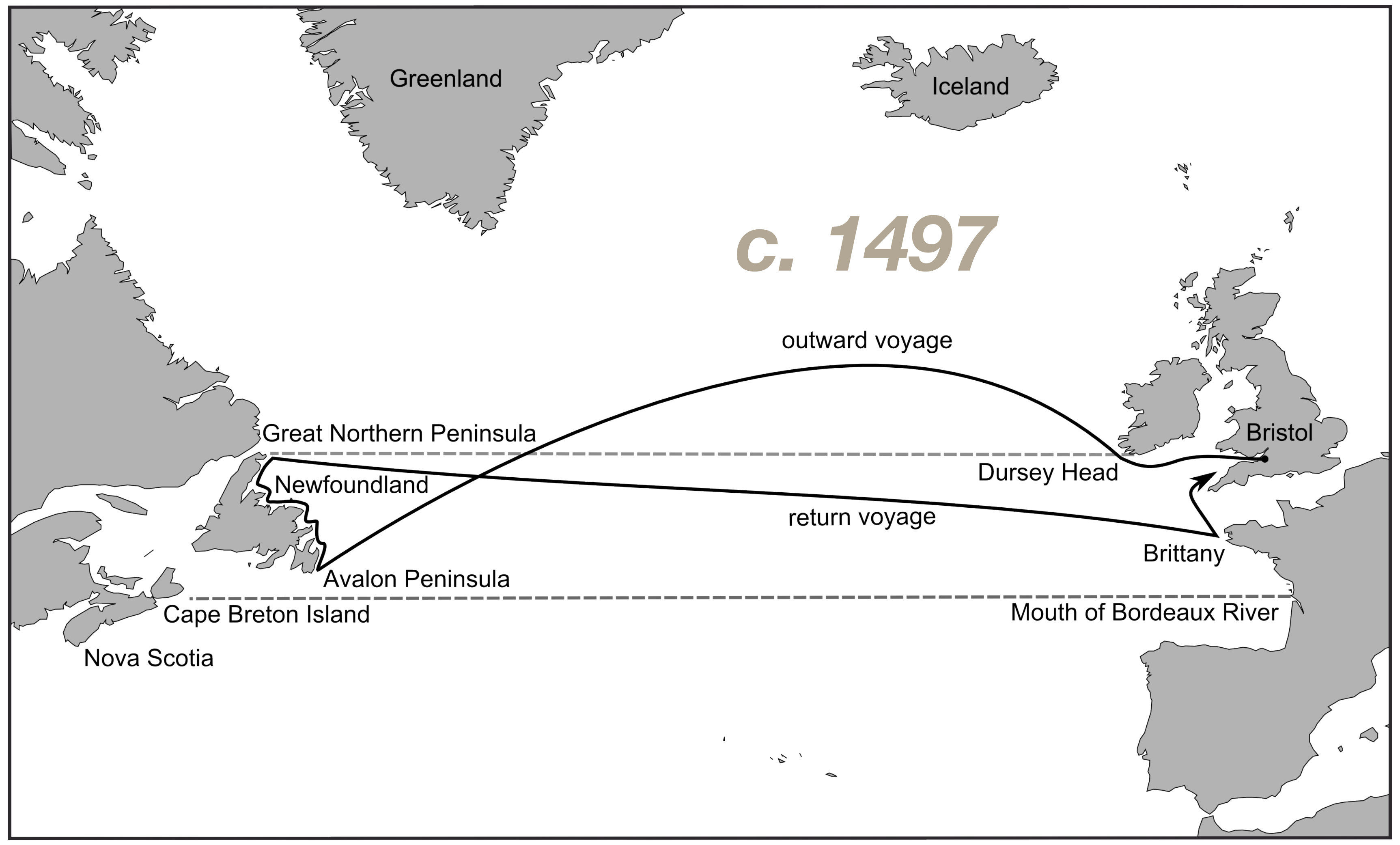

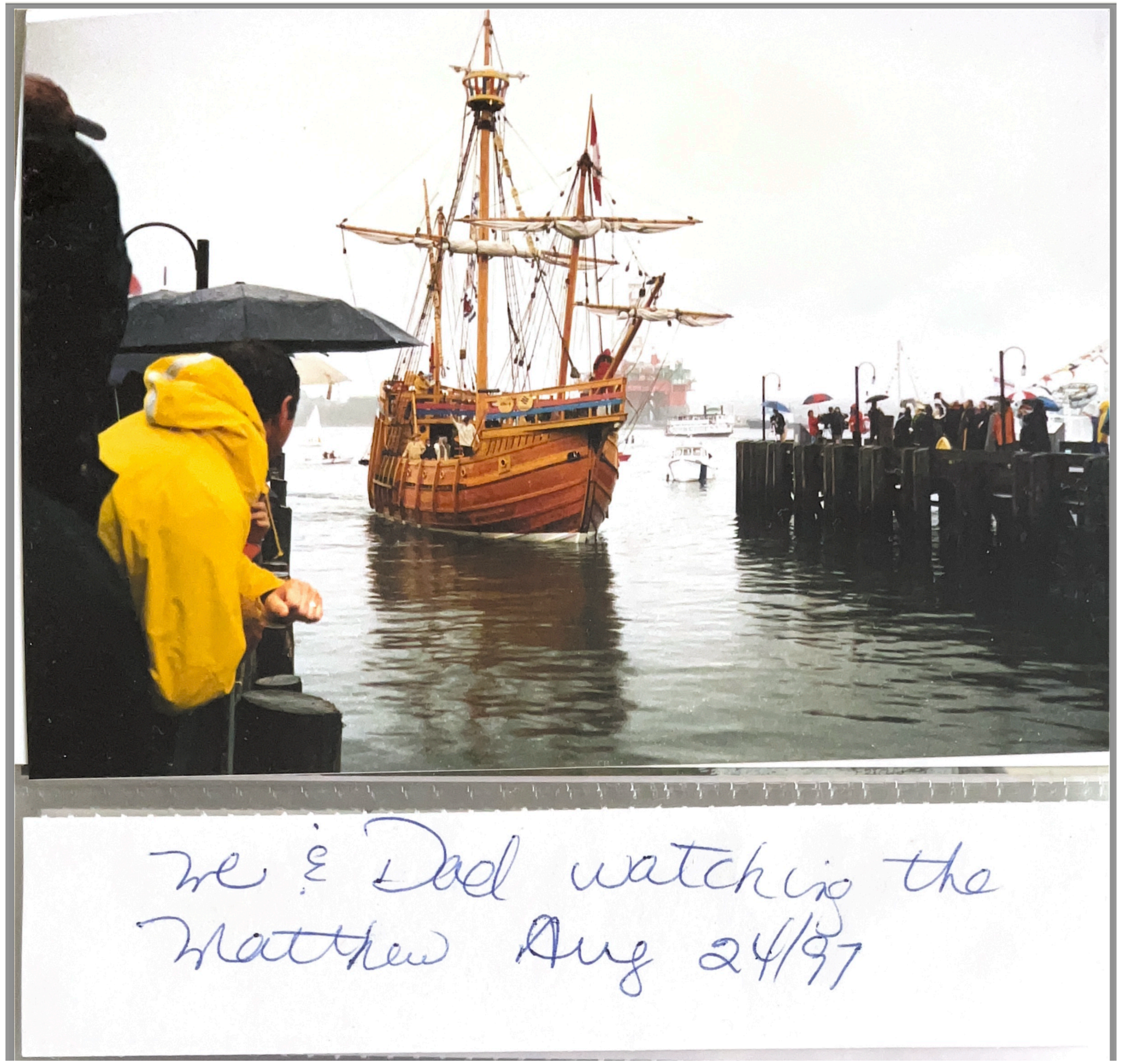

(Halifax 1997)

Monument in Fleming Park (Halifax, Nova Scotia)

Detectors + Reconstruction

Detectors + Reconstruction

Theory Intro
Berkeley, 2023

(Aiming to clarify some fundamentals earlier in the conference this year.)


LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km


13.6 TeV Run 3 *pp* centre-of-mass energy
5.02 TeV Run 3 Pb+Pb sqrt(s)
1 billion collisions per-second (40 MHz)
1.2E11 nominal protons per-bunch
2808 proton bunches per-beam
1232 superconducting dipole magnets
392 superconducting quadrupoles
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SUISSE
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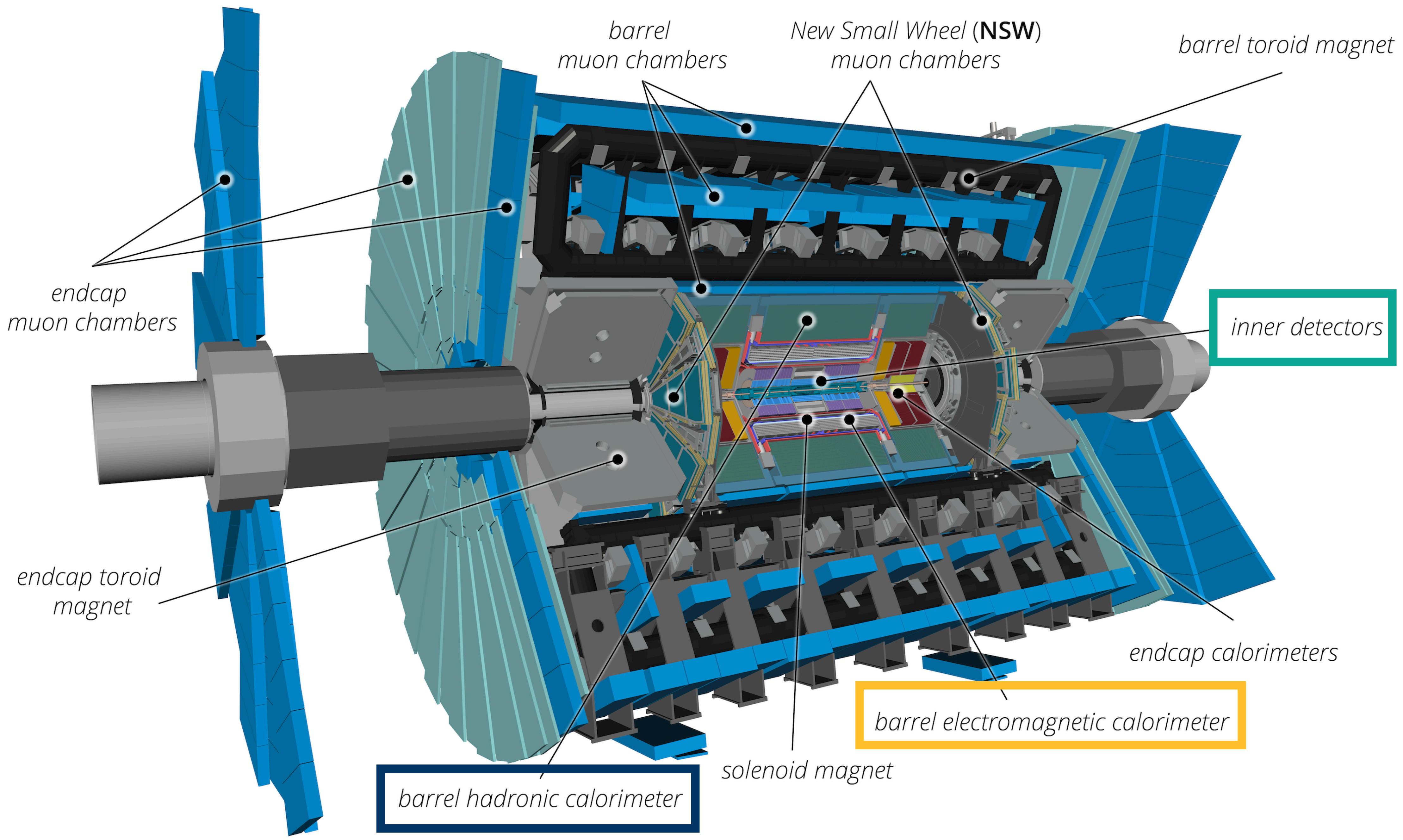
SPS 7 km
ALICE
LHC 27 km
Side View
Magnet
SciFi Tracker
RICH2
ECAL
HCAL
M2
M3
M4
M5
RICH1
UT
Vertex Locator
5m
10m
15m
20m
barrel muon chambers
New Small Wheel (NSW) muon chambers
barrel toroid magnet
endcap muon chambers
inner detectors
endcap toroid magnet
endcap calorimeters
barrel electromagnetic calorimeter
solenoid magnet
barrel hadronic calorimeter
CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16 m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels
a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

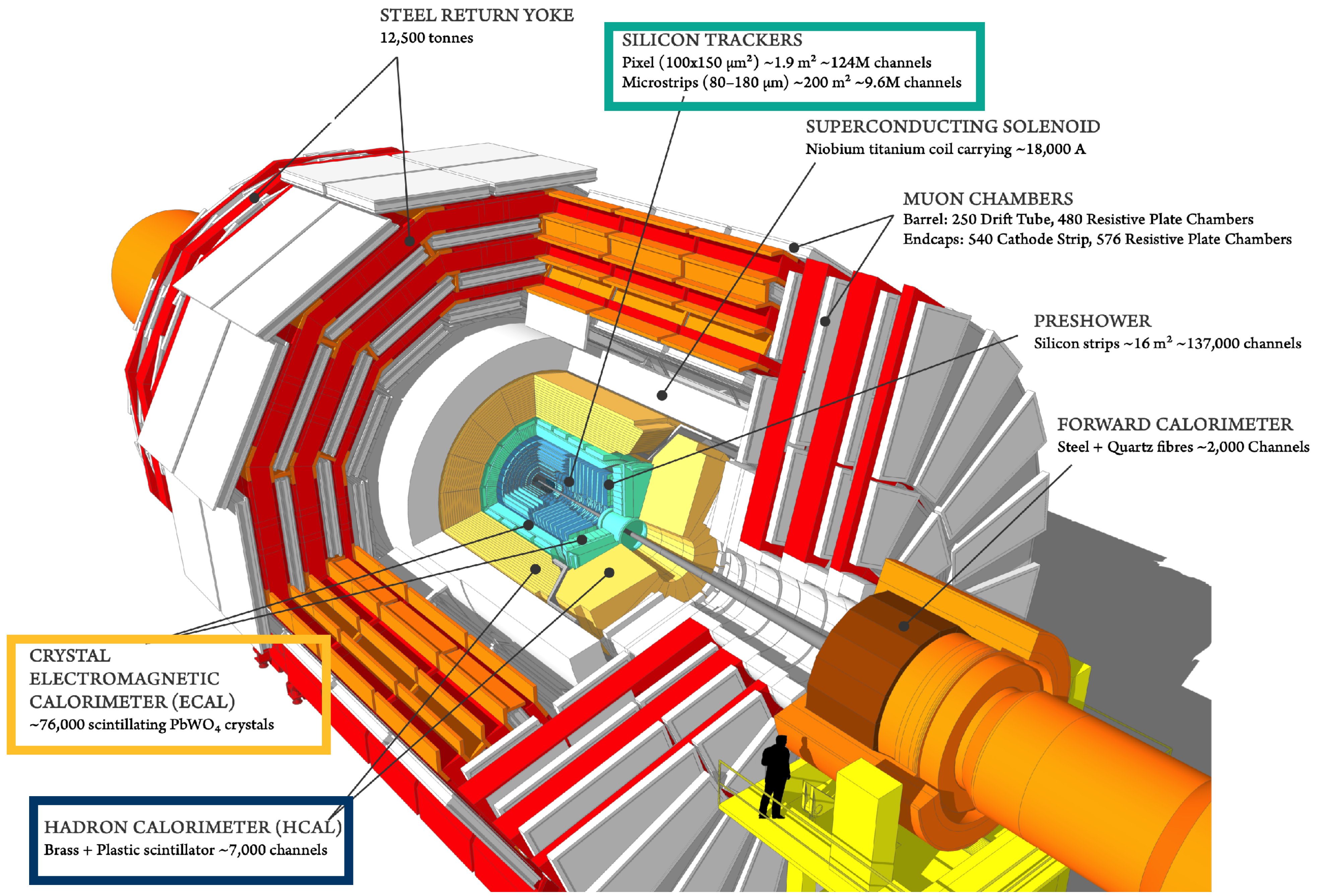
CMS & ATLAS

♫ *... are two of a kind / looking for whatever new particles they can find.* ♫

- General purpose detectors, similar design goals (discover Higgs + broad BSM sensitivity).
  - Implementations quite different in terms of technologies:

	ATLAS	CMS
Tracker	Silicon+Straw Tube	All-Silicon
ECal (Barrel)	Lead+LAr *Sampling,* *3 longitudinal segments* *+ Presampler*	PbWO4 Crystal *Homogeneous* *+ Preshower*
HCal (Barrel)	Fe+Scintillators *Sampling,* *3 readout depths*	Brass+Scintilators *Sampling,* *Run 2: 3 readout depths* *Run 3+: 7 readout depths*
Muons	Drift tubes, RPCs, sTGCs, MMs	Drift tubes, RPCs, CSCs, GEMs
Magnetic fields	2 T Solenoidal 2-6 Tm Toroidal	3.8 T Solenoid

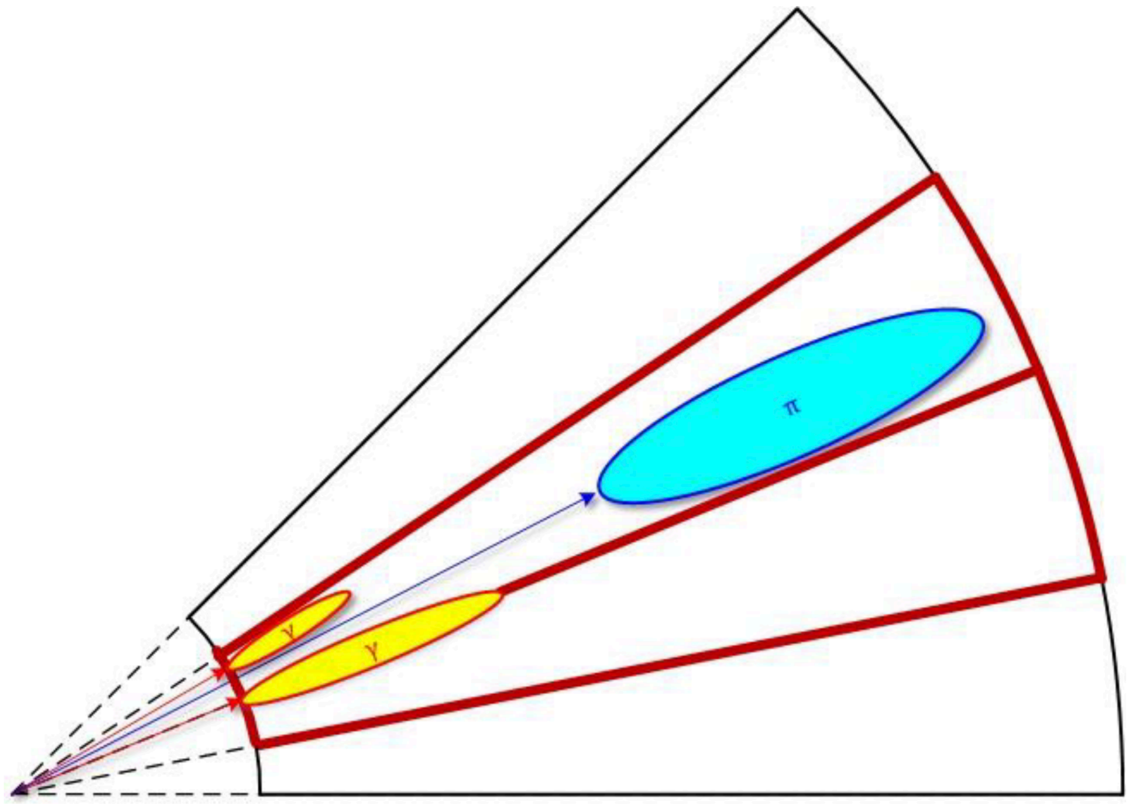


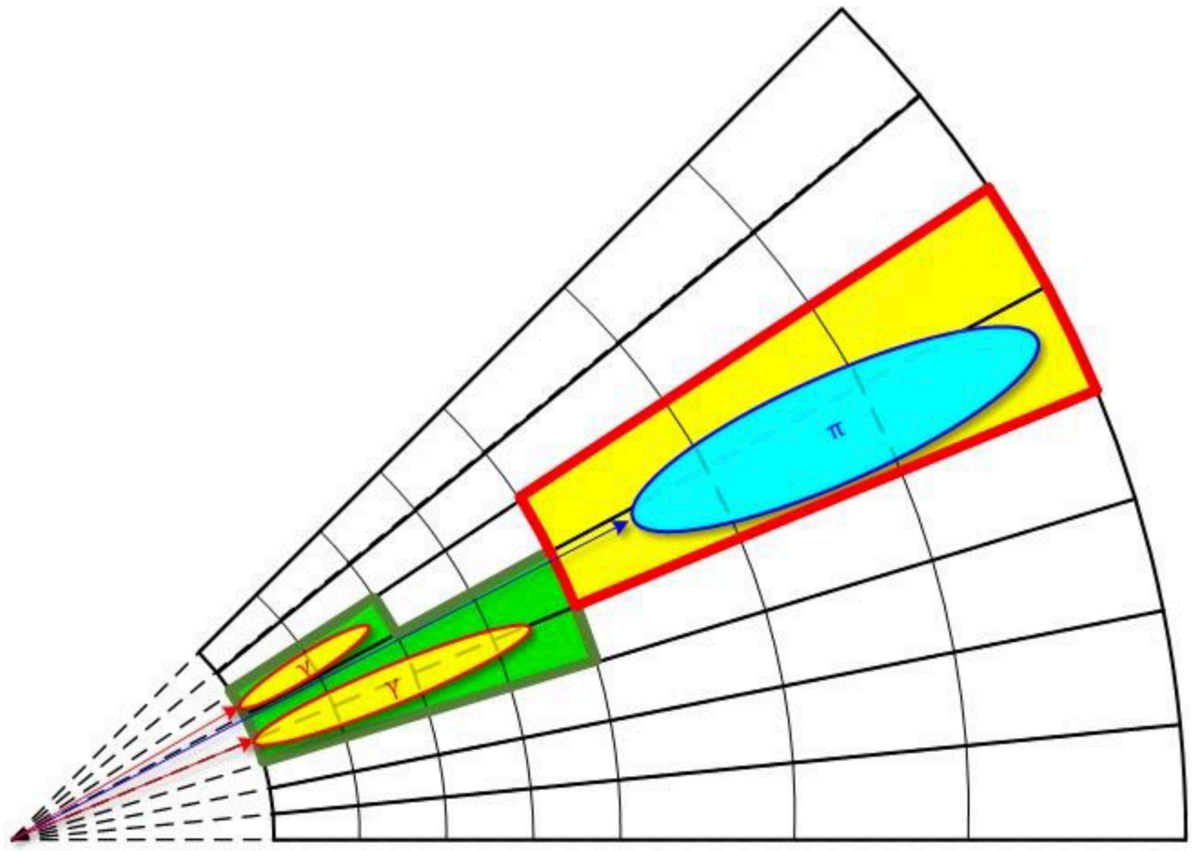


CMS & ATLAS: Segmentation

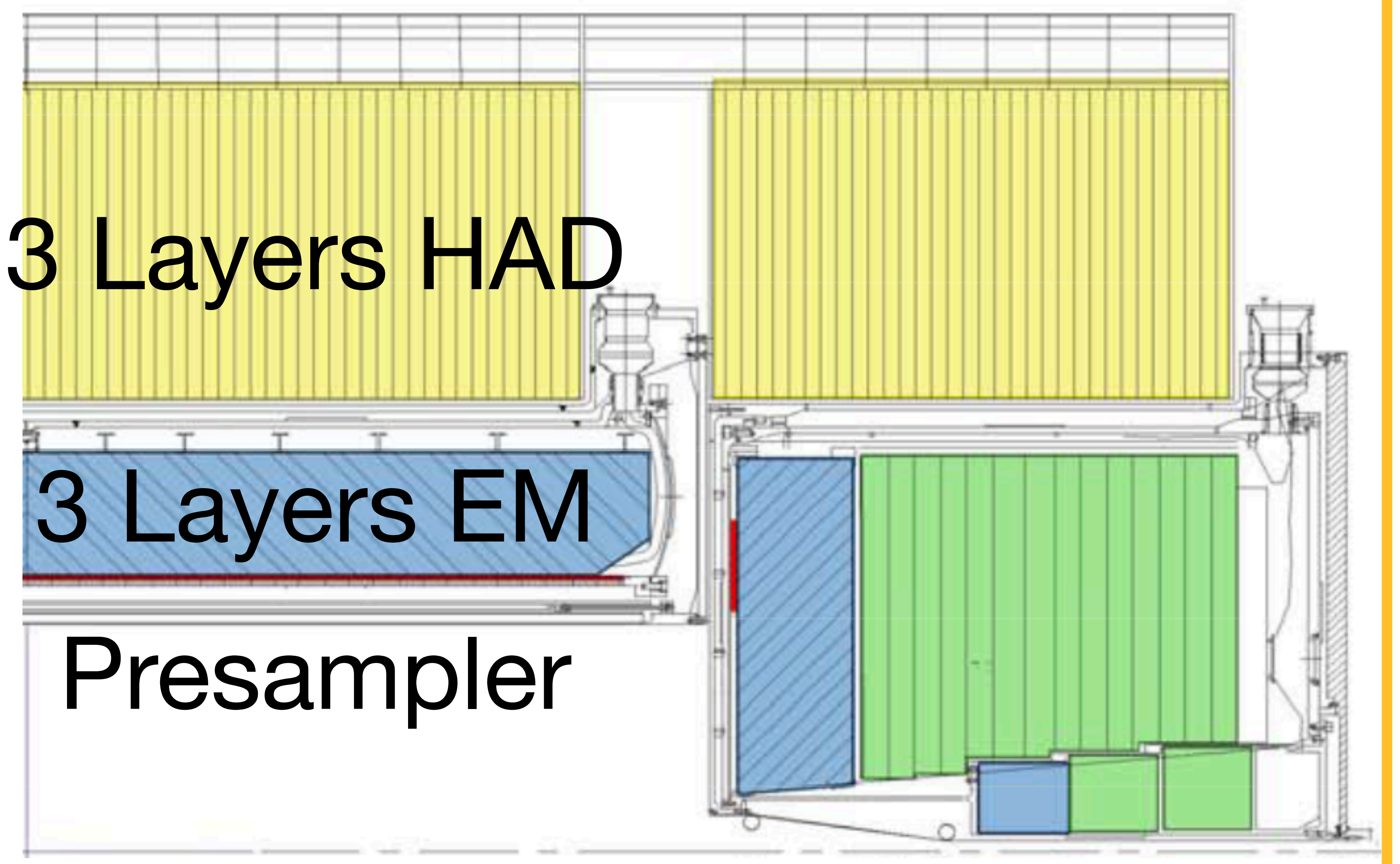
P. Loch @ UniGe 2017, https://dpnc.unige.ch/seminaire/talks/loch.pdf

- Longitudinal segmentation of calorimeters important for JSS reco at LHC.
  - Reconstruct kinematics & structure while reading out less volume:
    - Less electronics/detector noise
    - Less **pile-up** (next slide)
    - Better signal calibration shapes (EM/HAD) ATLAS Eur. Phys. J. C 77 (2017) 490, P. Loch @ H1, 1992

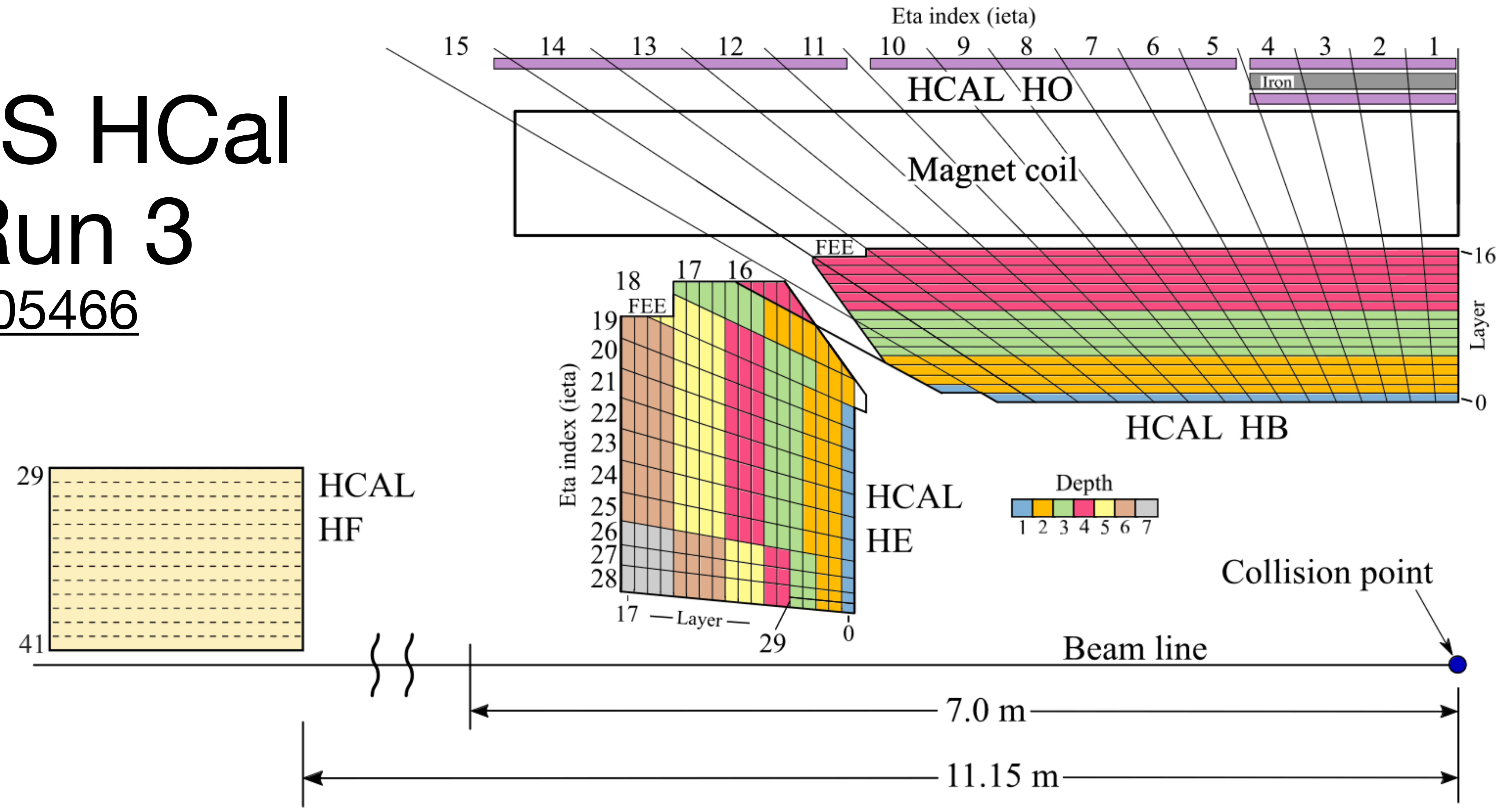




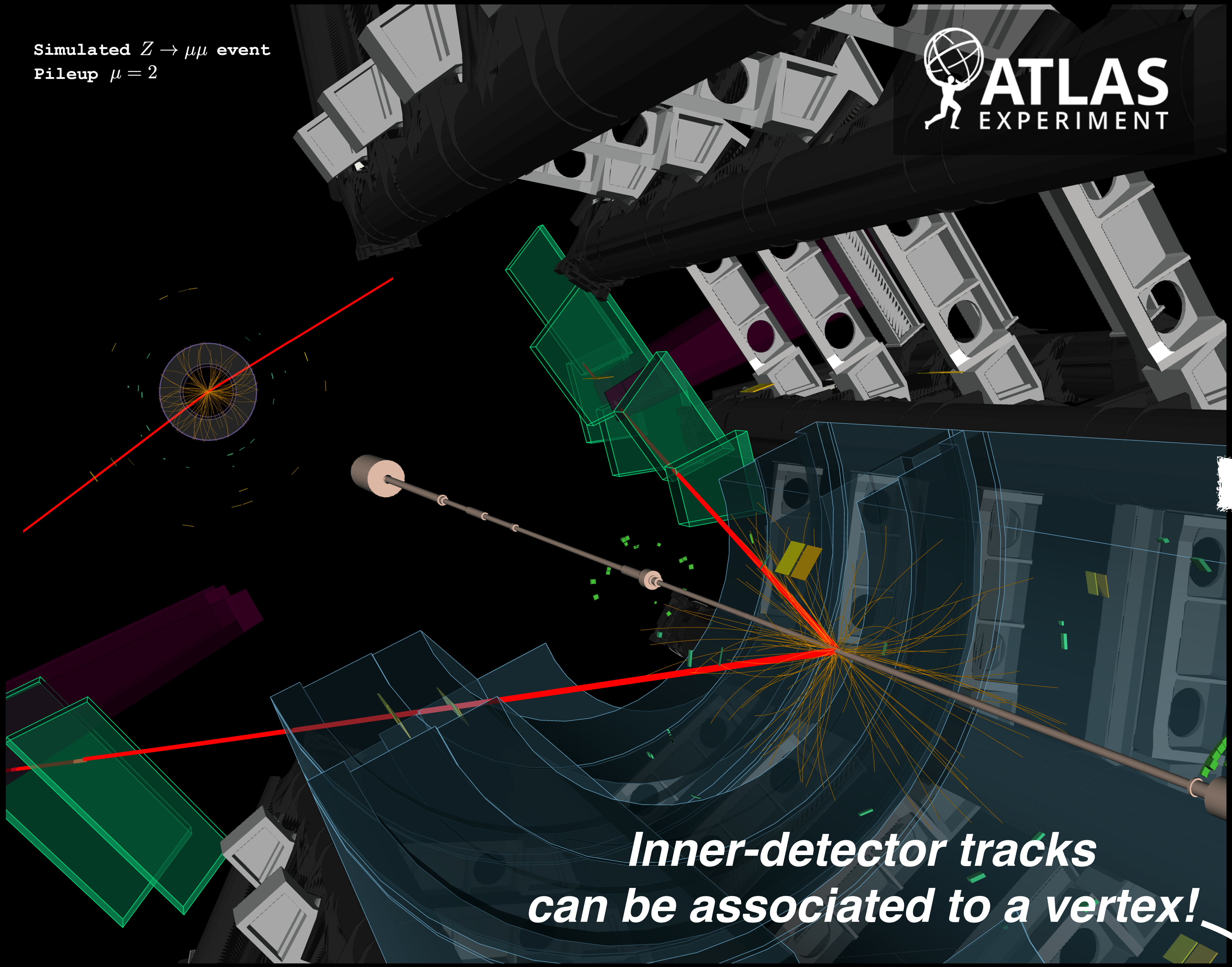
ATLAS
(from TP,
modifié par
M.-A. Dufour)

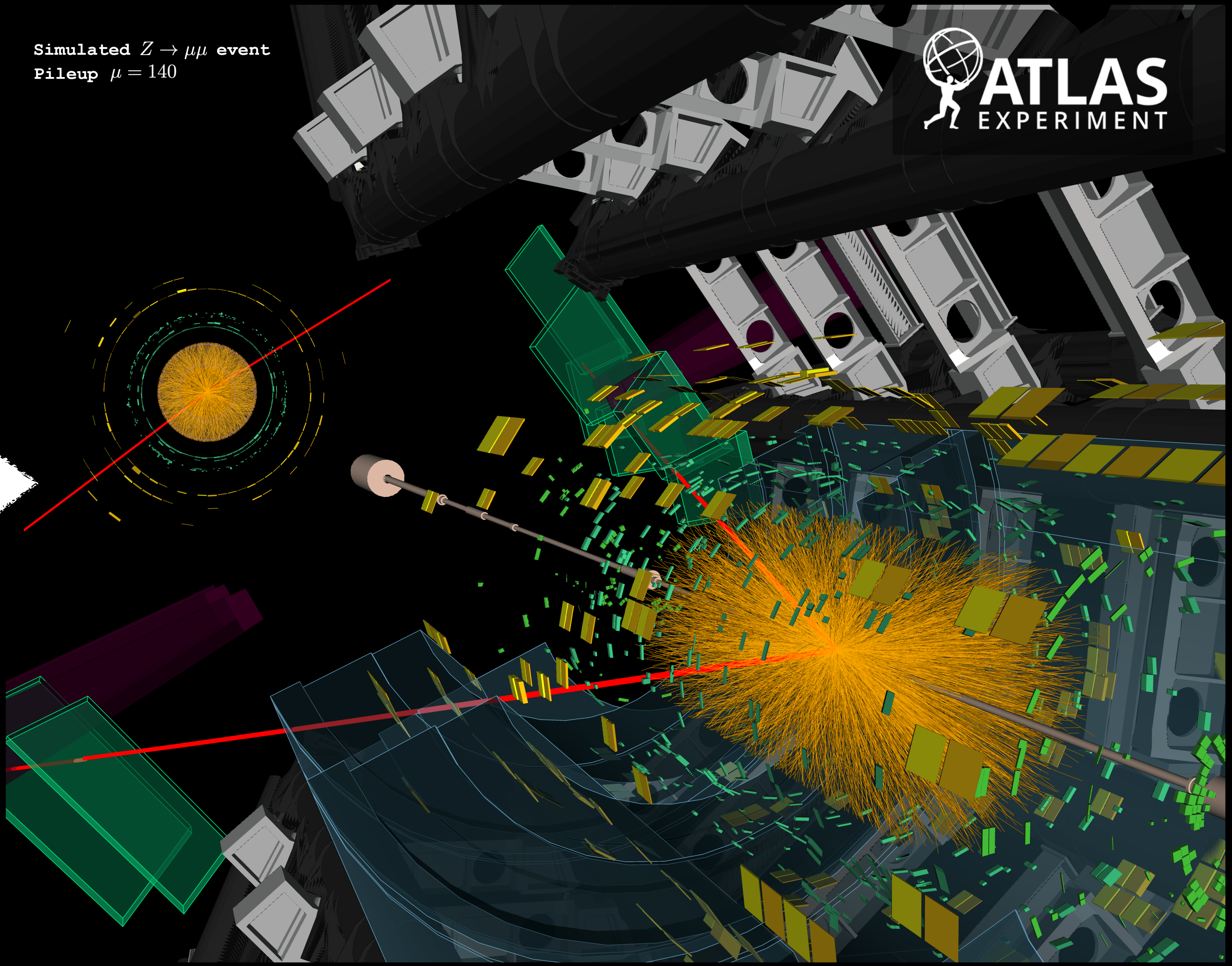


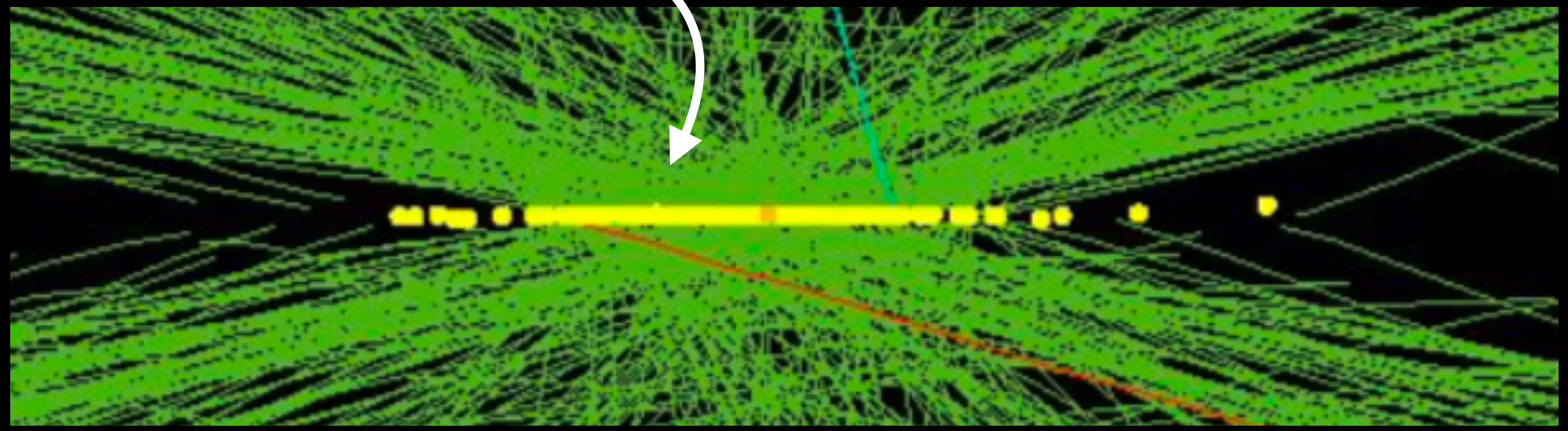
CMS HCal
in Run 3
2309.05466



“Pile-up” → uncorrelated, additional *pp* collisions in same bunch-crossing as signal process.







2010 pile-up
(μ ~ 2)

Run 4 pile-up
(μ ~ 140)

Pileup

CMS, JINST 15 (2020) P09018
ATLAS, Eur. Phys. J. C 81 (2021) 334

- Uncorrelated pp interactions that occur in the same bunch-crossing as the 'hard scattering' of interest
  - Effect on hadronic objects pronounced:
    - Jets have large catchment area
    - JSS sensitive to soft radiation
    - MET requires balanced energy flow
    - Spurious jets!
      (uncorrelated w/ signal of interest)
- Modern approach: **mitigate bit-by-bit, at each step** of reconstruction.
  - Constituent level (e.g. PUPPI, CS+SK)
  - Jet level (e.g. Soft-Drop grooming)

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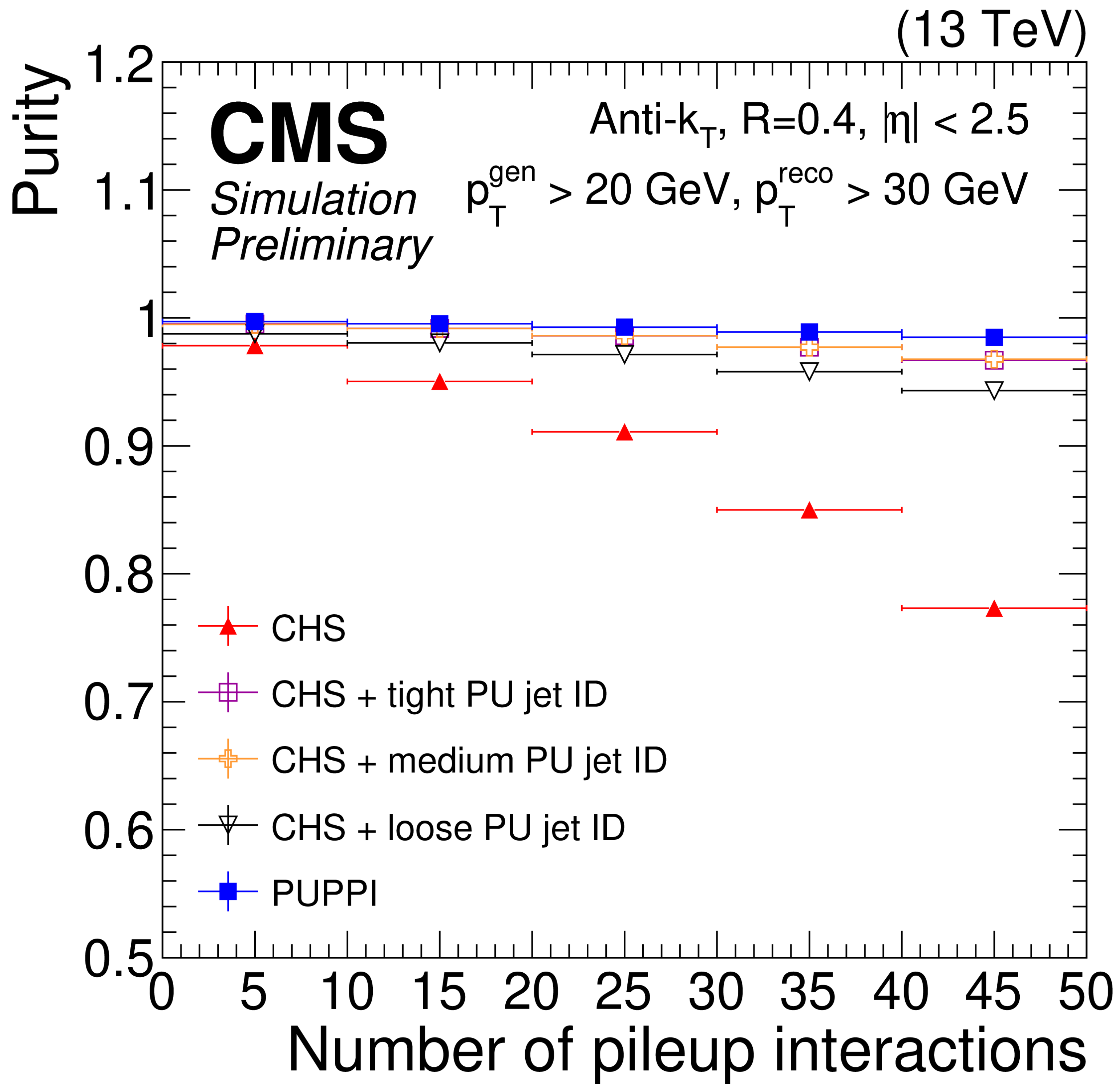
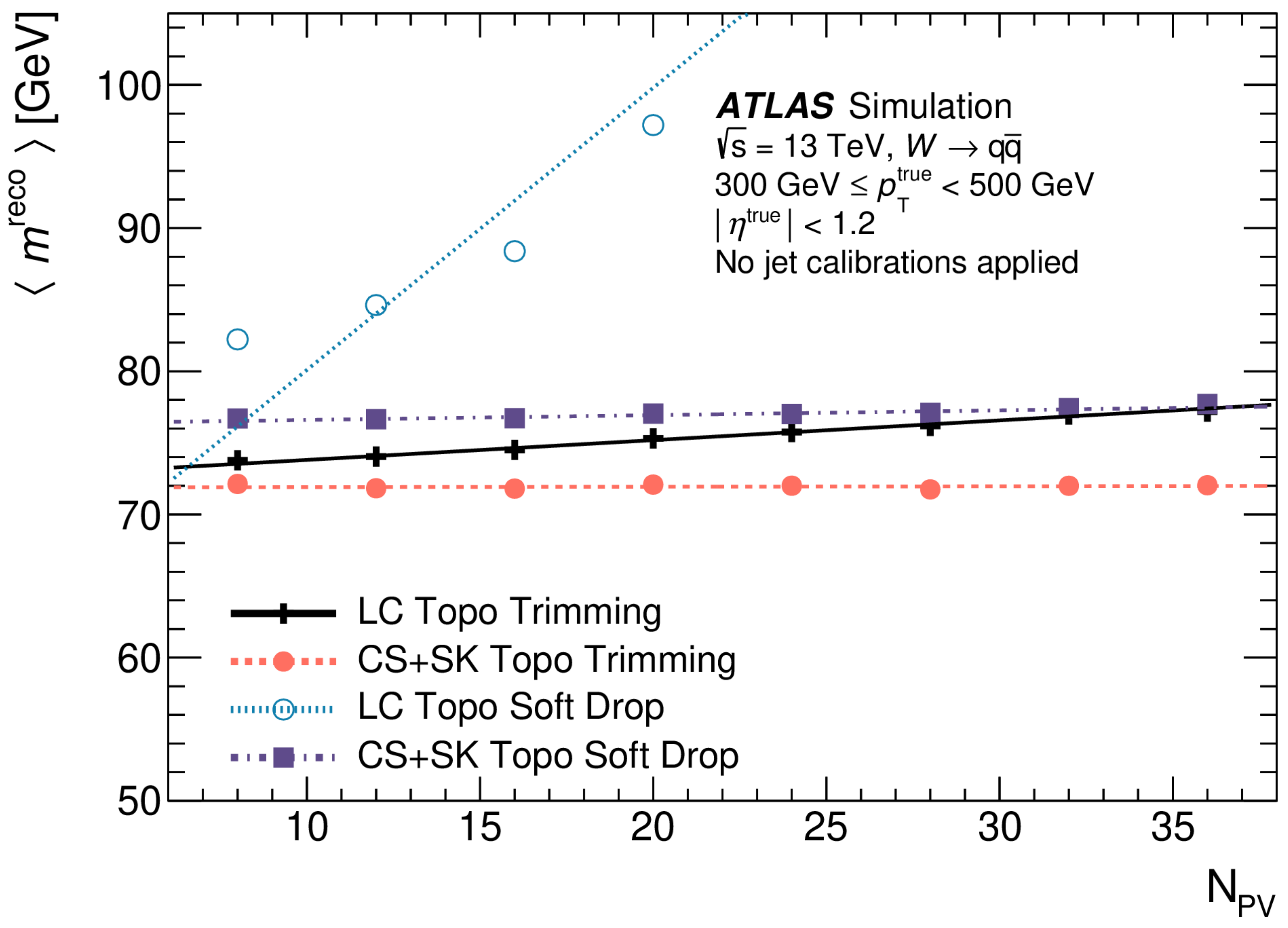


PUPPI improves on CHS+PU jet ID rejection of spurious jets.

(Closer to 1 is better!)



Average jet mass increases with pileup (Flat is good!)

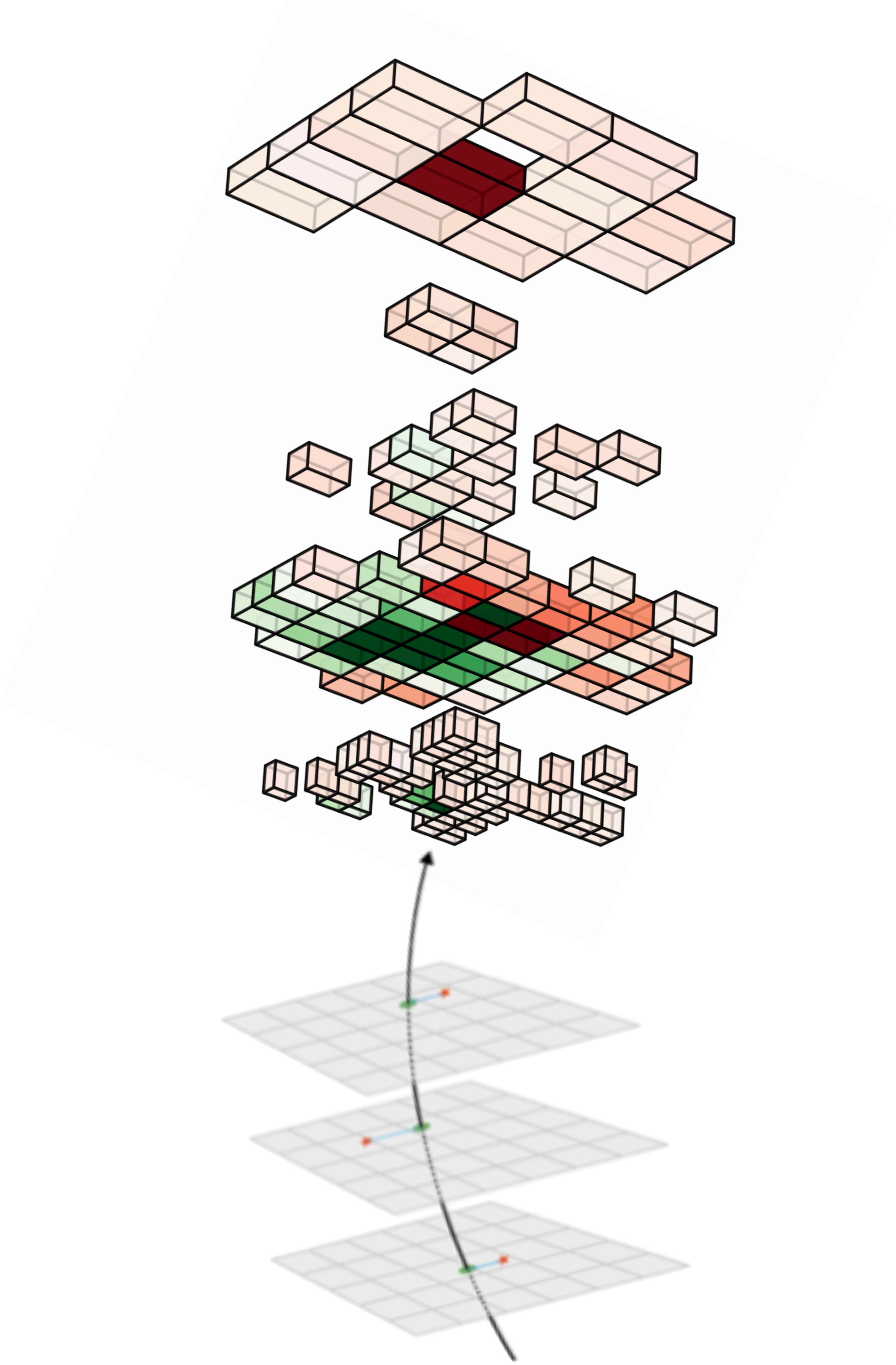
CMS & ATLAS : Particle Flow

Calorimeter

- Good energy resolution (**high-p_T** particles)
- Coarse angular resolution
- Susceptible to pile-up noise
- Retains neutral component
- Central+Forward coverage

Tracker

- Good energy resolution (**low-p_T**)
- Fine angular resolution
- Stable w.r.t. pile-up (vertex association)
- Lacks neutral energy flow
- Only central coverage until Run 4



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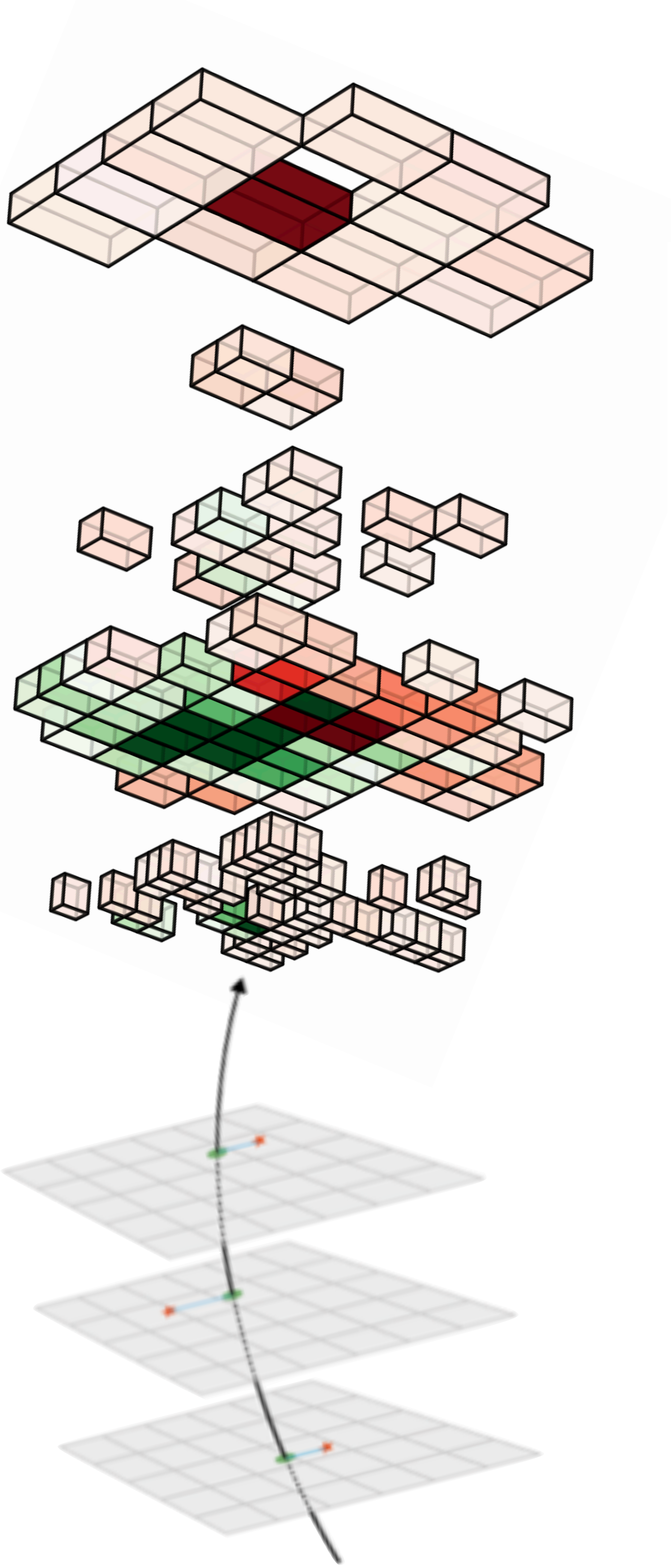
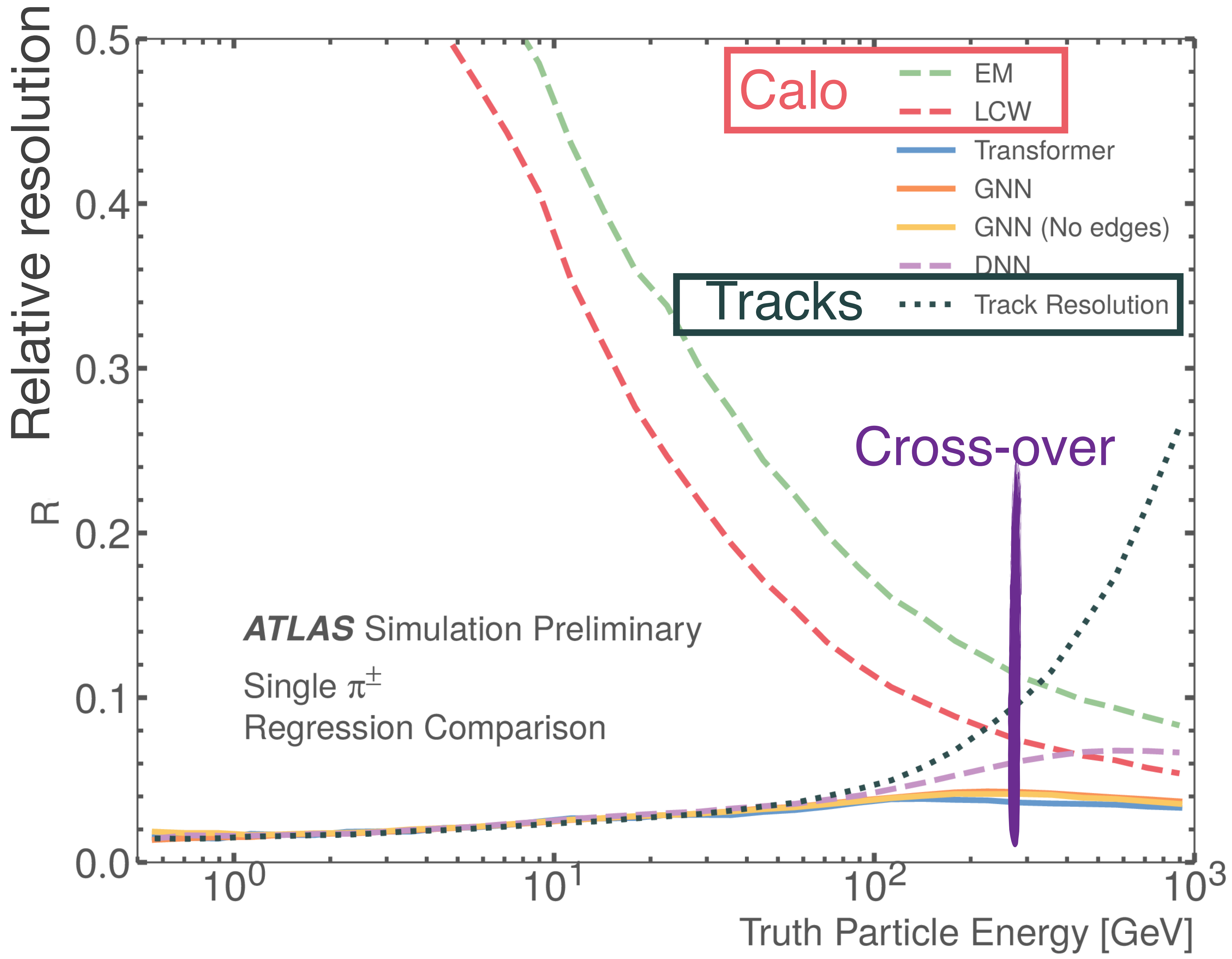


Both ATLAS & CMS now use Particle Flow algorithms for both small- and large-radius jet reconstruction!



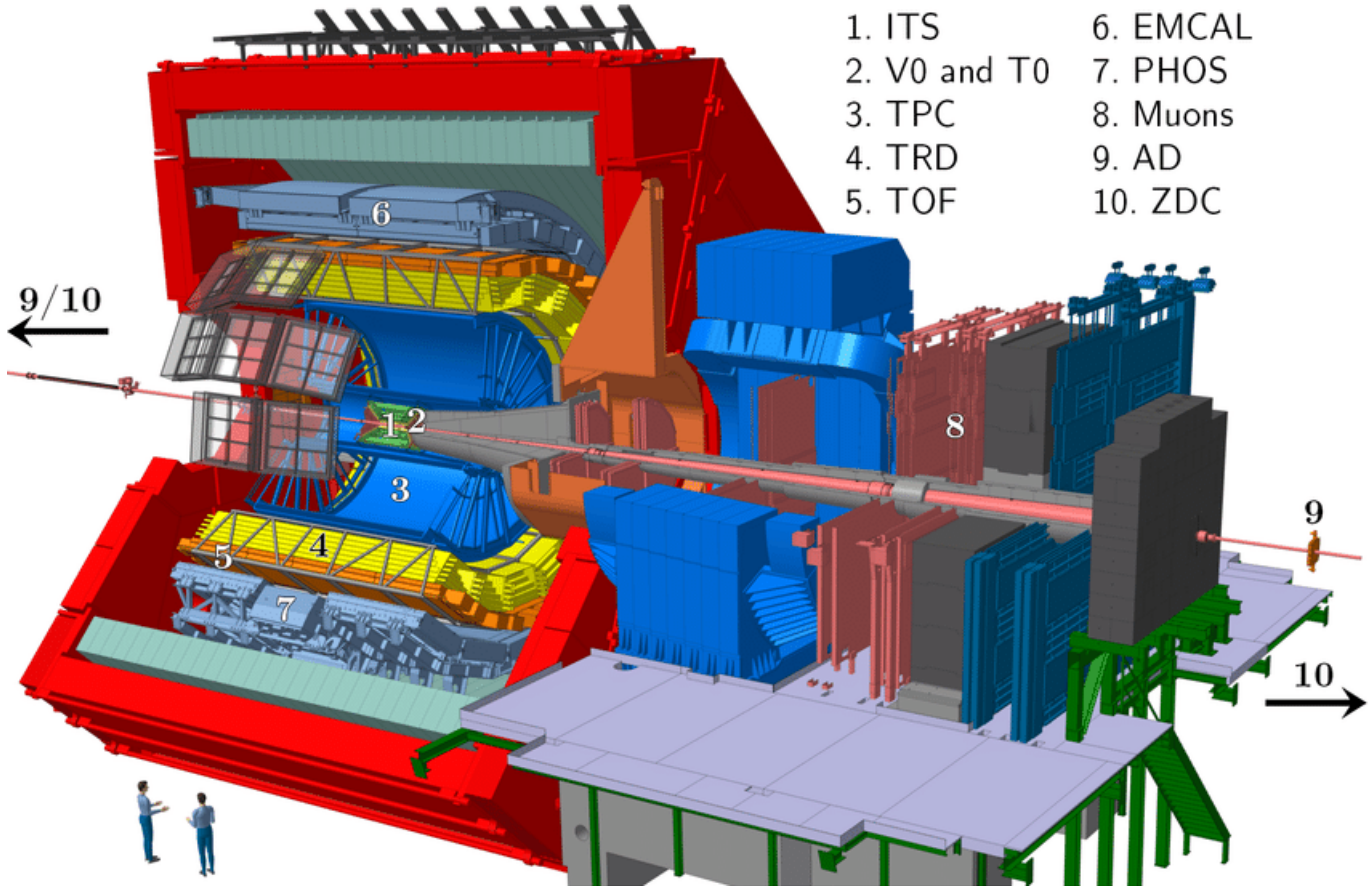
Cross-over point for CMS somewhere else: different magnetic field, tracker, calorimeter…

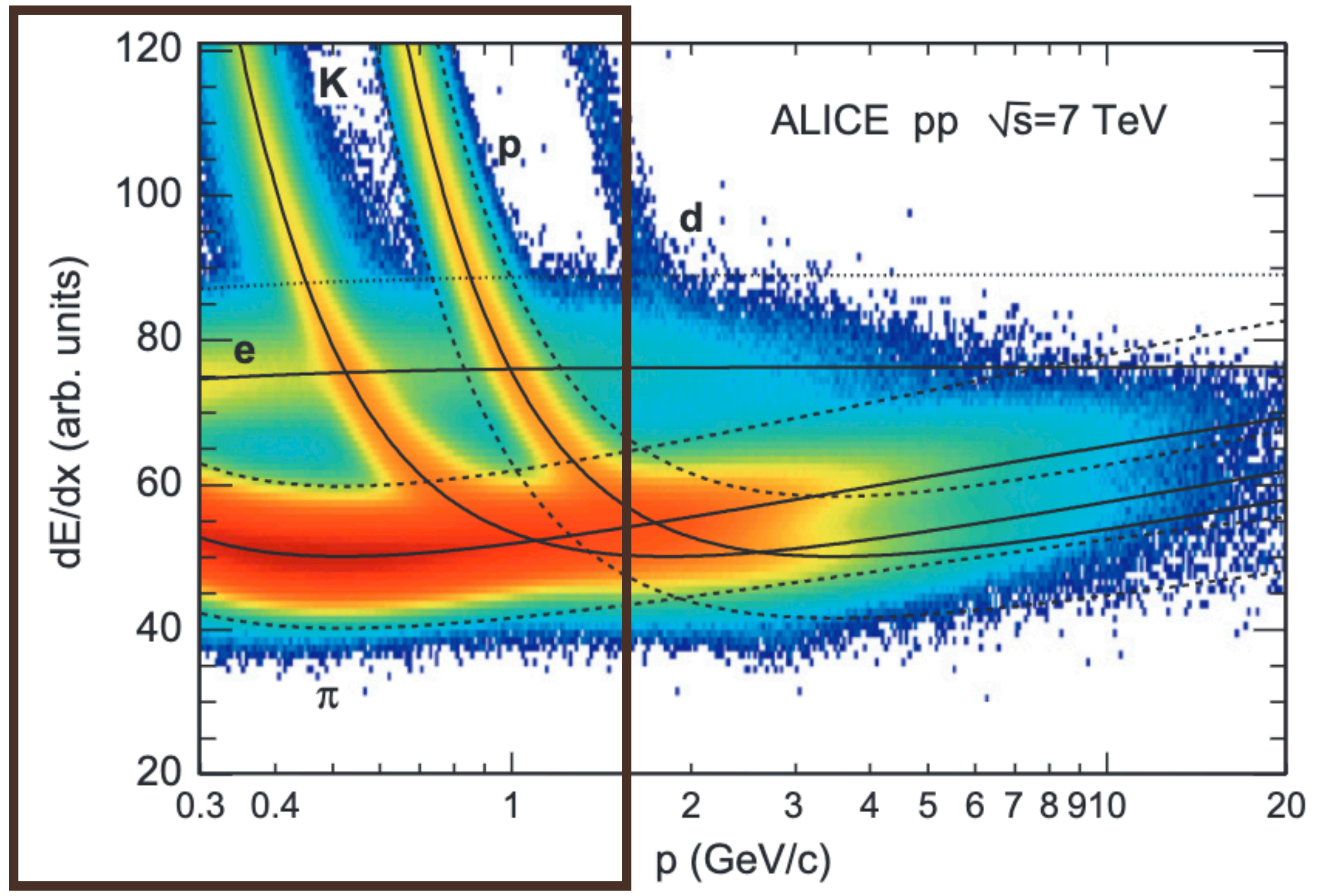
Heavy Ions + DIS

ALICE

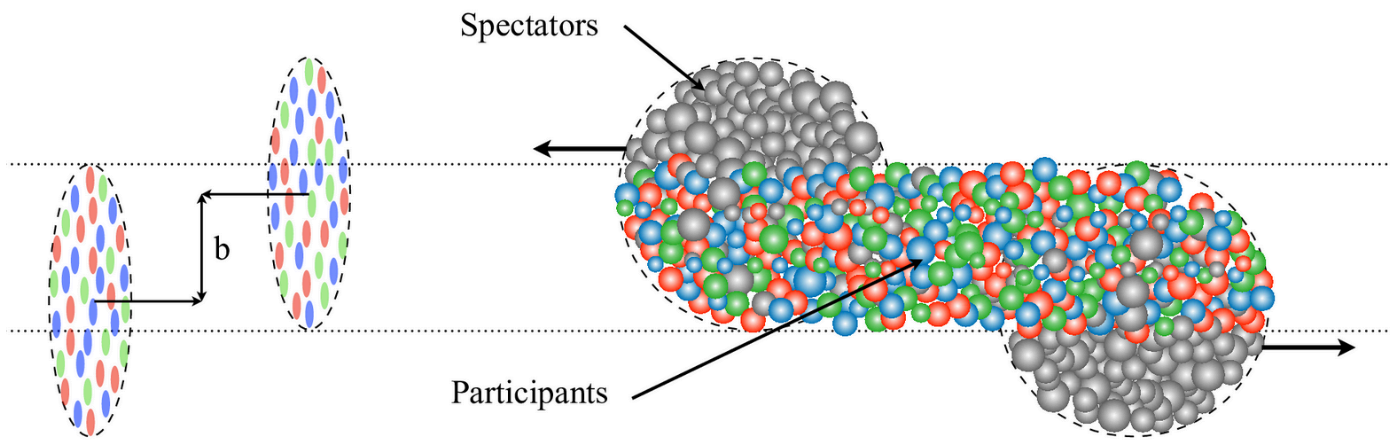
♬ ... looks at collisions of lead ions. ♬

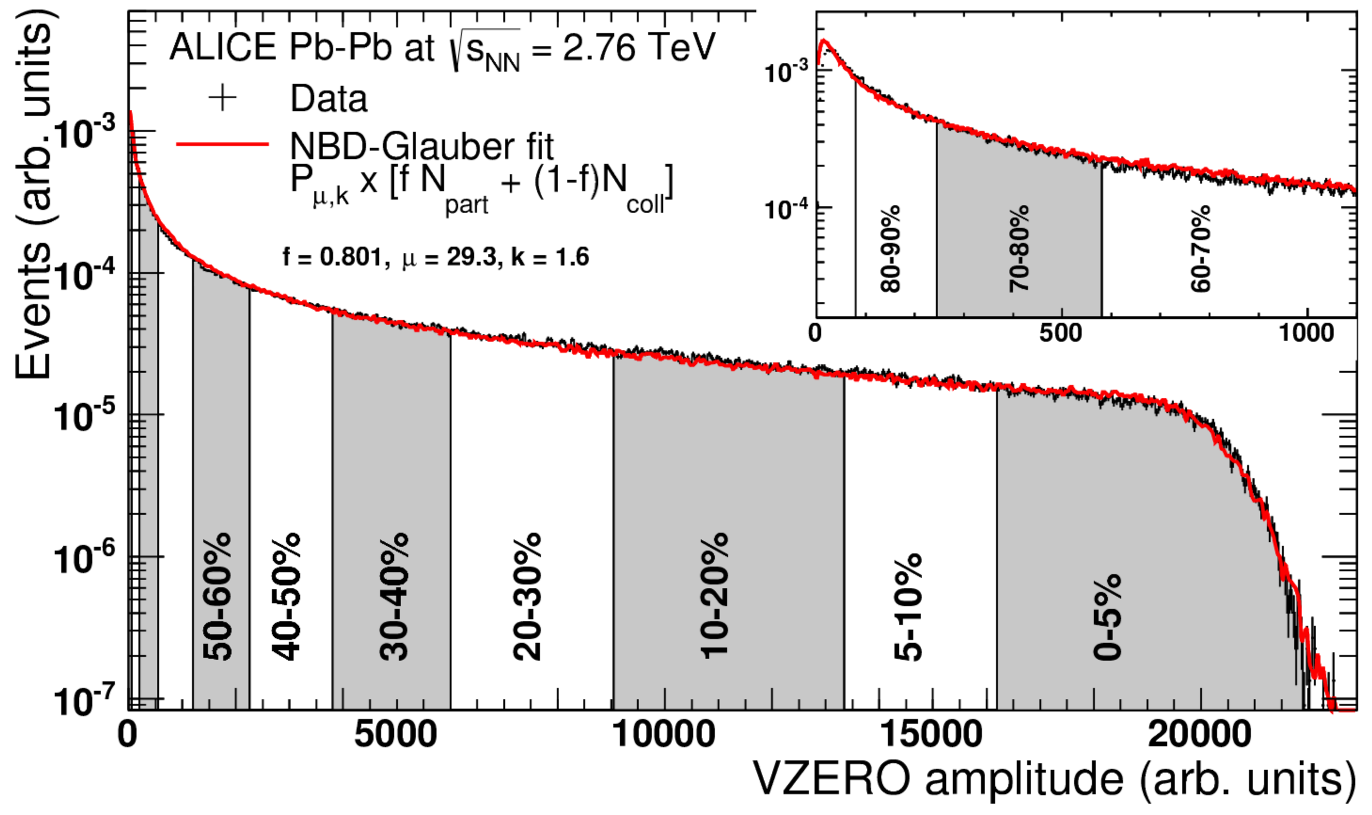
- Designed for heavy-ion physics studies.
  - TPC provides excellent dE/dx measurements → enhanced capability of particle ID studies
    - p/Pi/K separation @ 3σ, < 2 GeV
      - Enables D-hadron ID from TVs
  - TOF MRPC system extends PID to higher p_T's





- **Key concept** in HI collisions: **Centrality** related to overlap region of colliding nuclei.
  - Determined from V0 or ZDC subdetectors.





Ratios of Pb+Pb / pp (R_{AA})

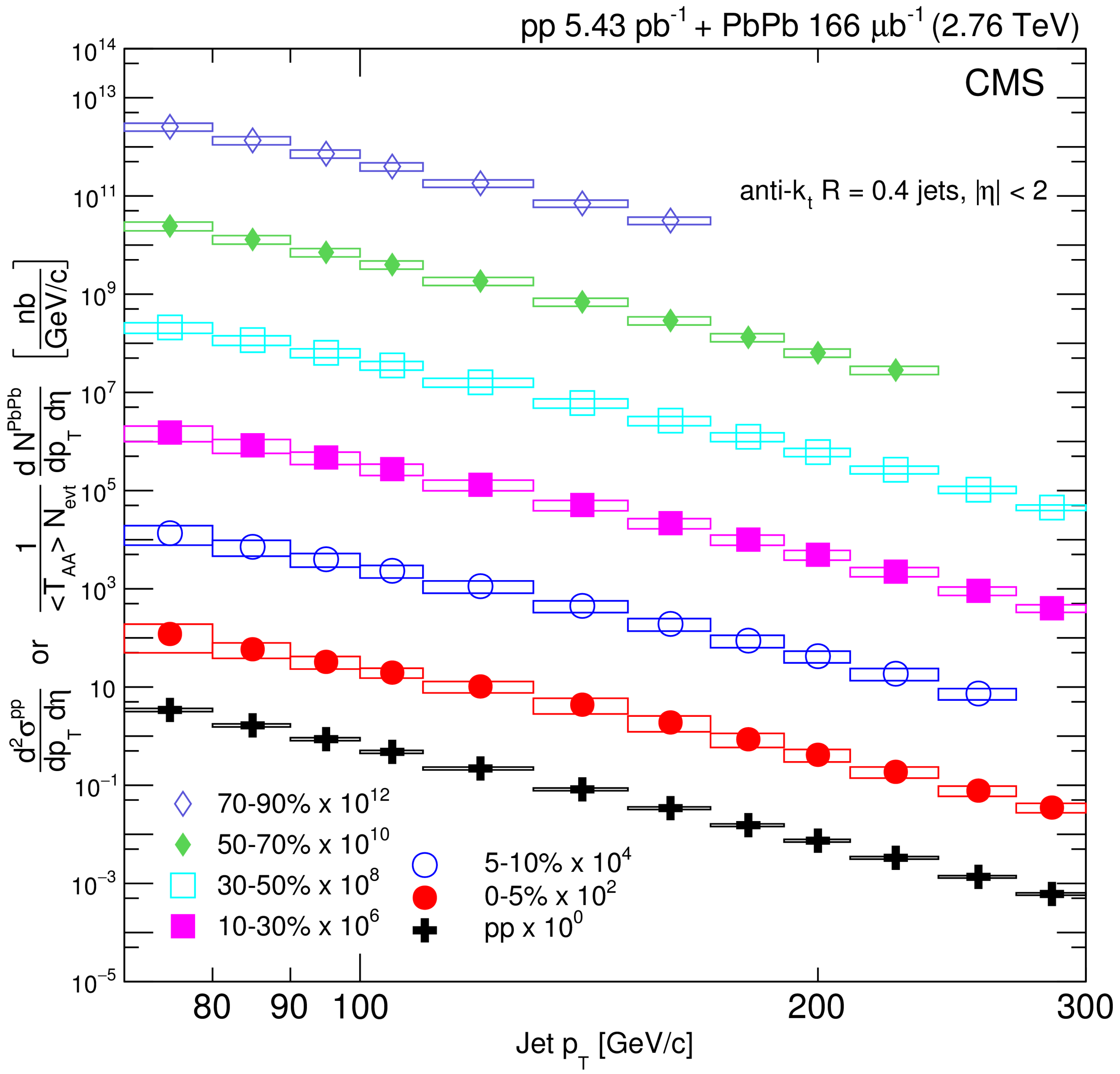
Example from CMS, Phys. Rev. C 96 (2017) 015202

Many HI results study the relative differences of systems **"in-medium"** (w/ QGP) and **"in-vacuum"** (*pp*) → Ratios!

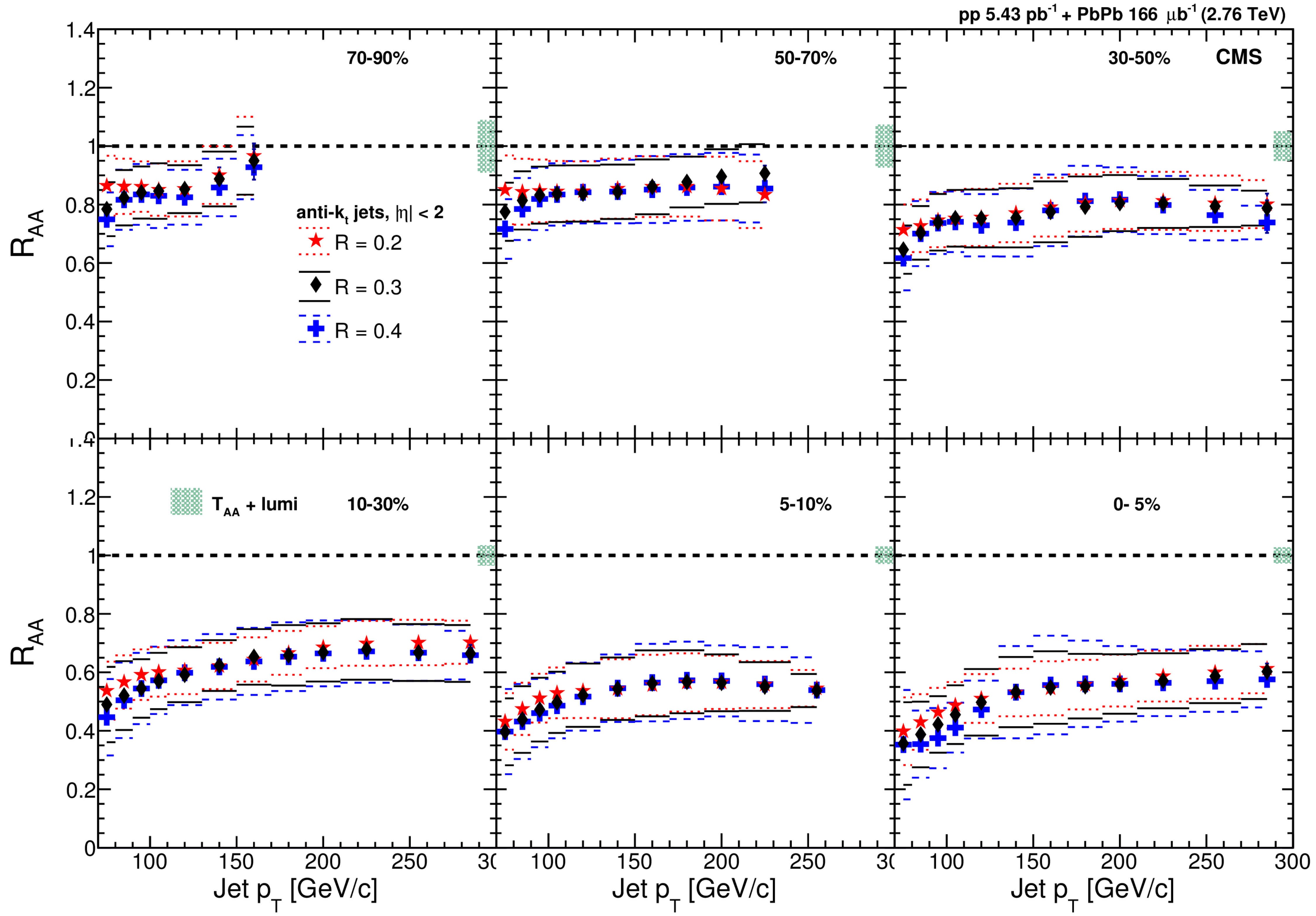
Pb+Pb

More to less central

pp



Least central: least modification



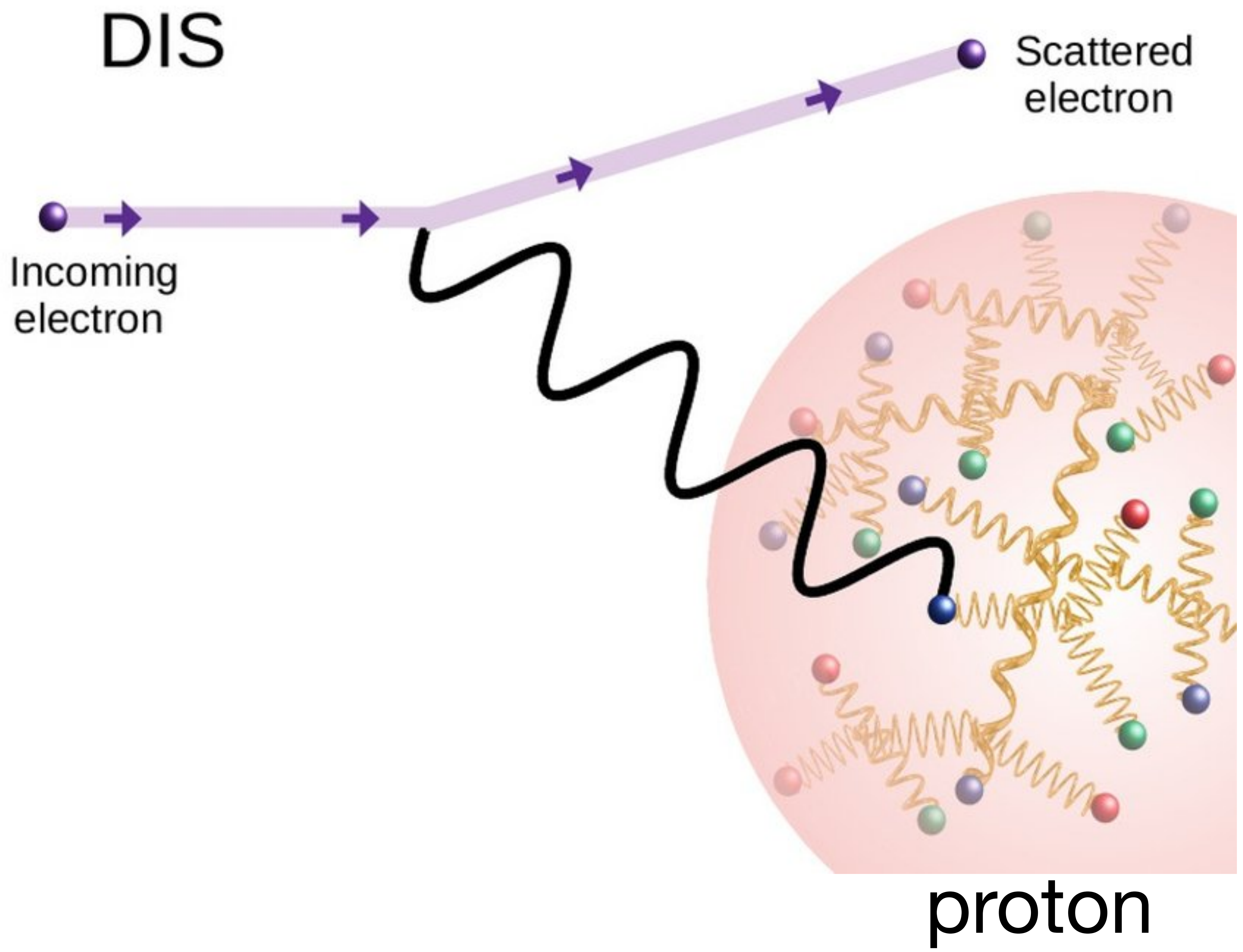
Most central: most modification

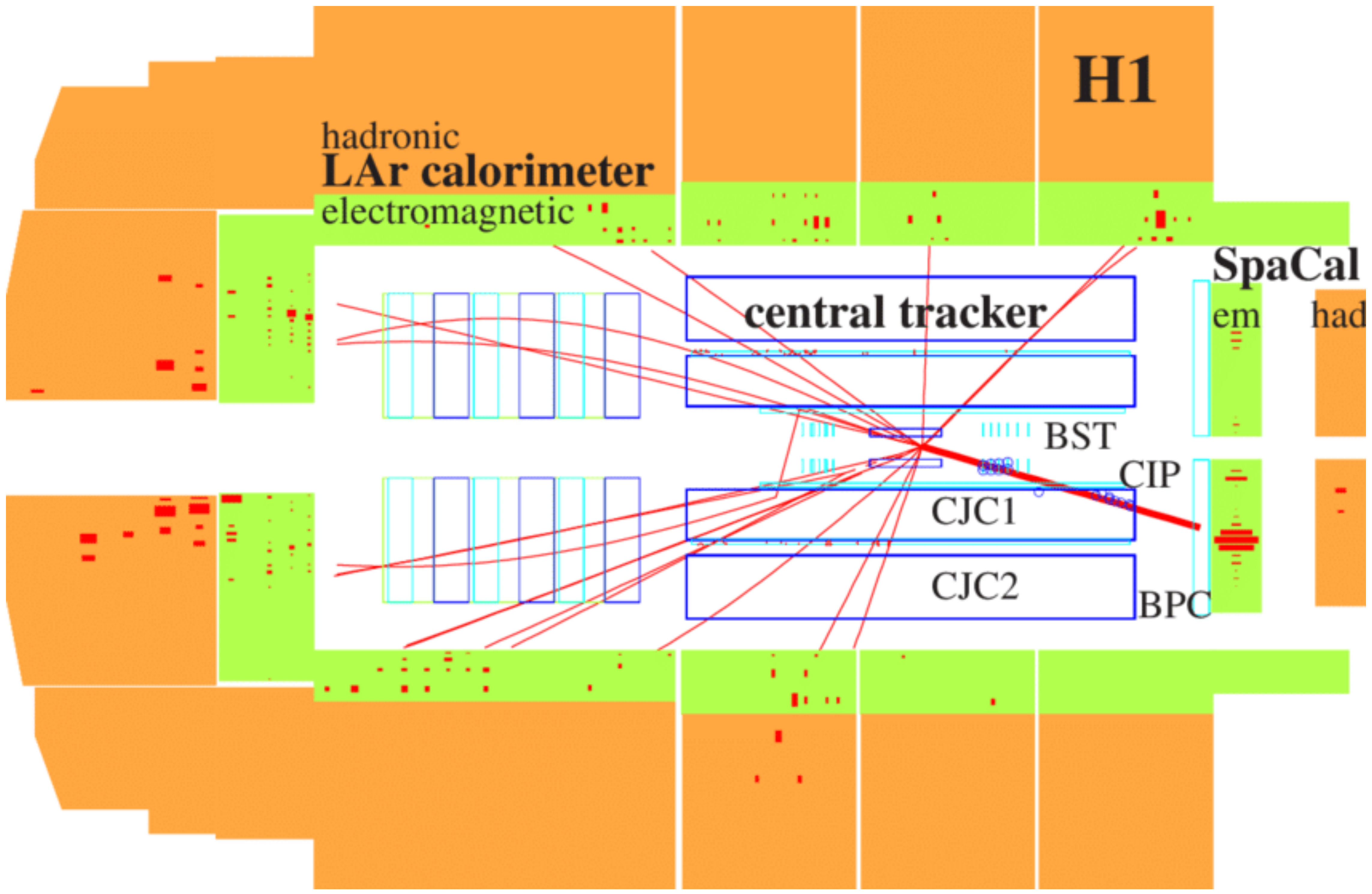
Deep Inelastic Scattering (DIS)

Special "zombie" prize for H1:
Bringing jet substructure back in time,
with three talks this year!

M. Światłowski @ BOOST '23

- HERA delivered sqrt(s)=320 GeV electron-proton collisions to H1 and ZEUS detectors (1992-2007).
- Long history of fragmentation measurements continues: 3 new H1 results shown last year!

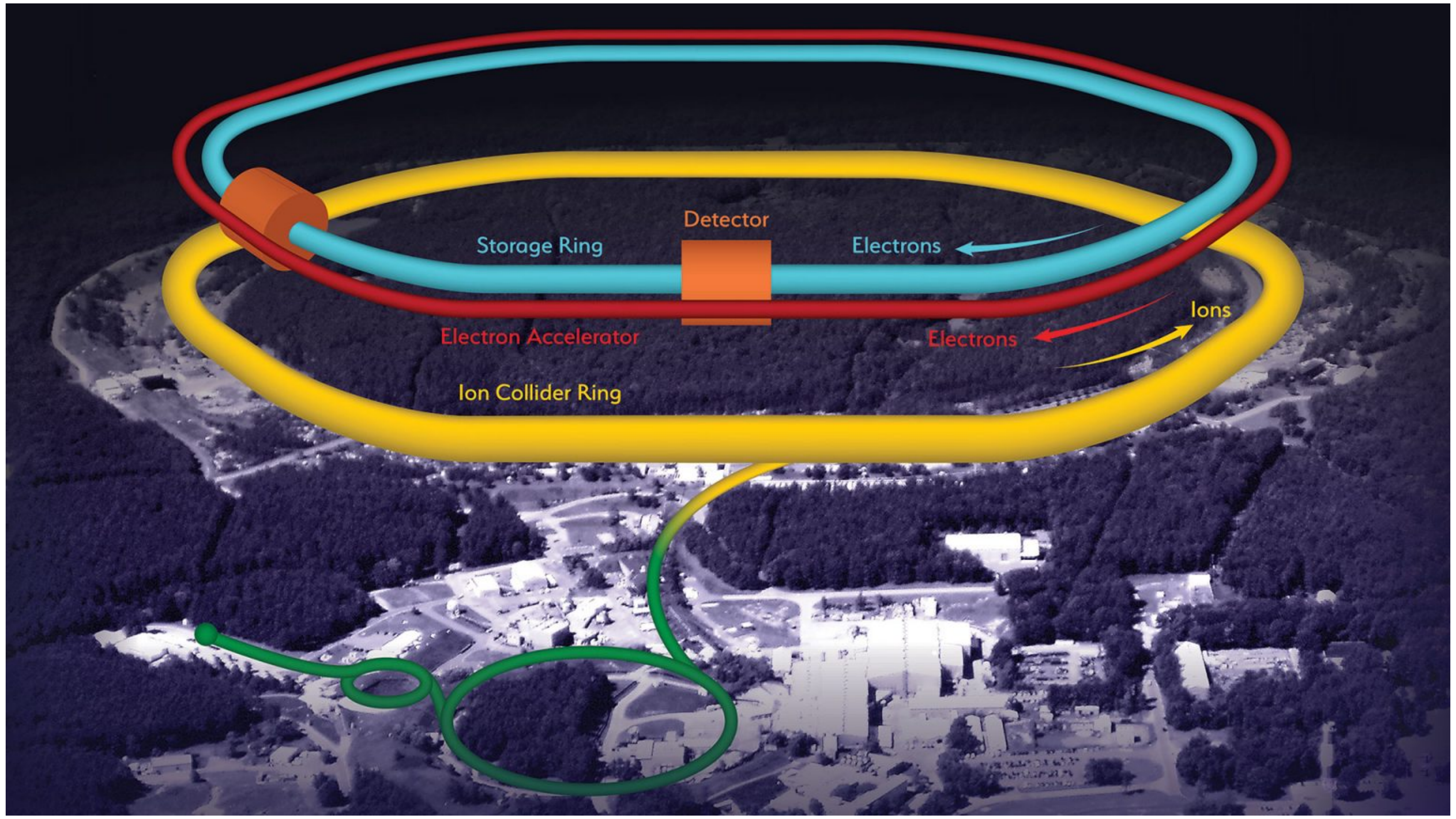




Electron-Ion Collider

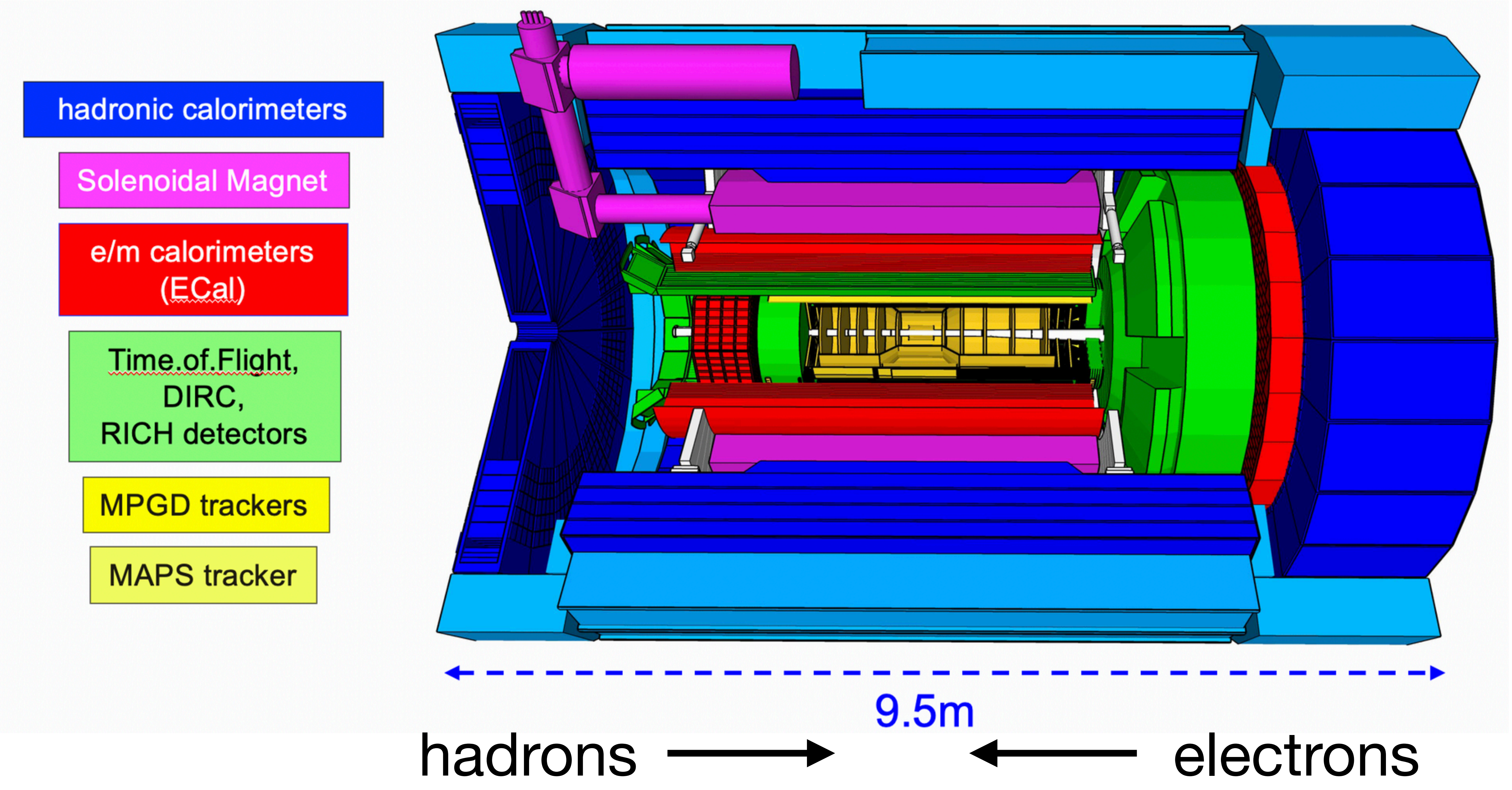
EIC Snowmass White Paper 2203.13199

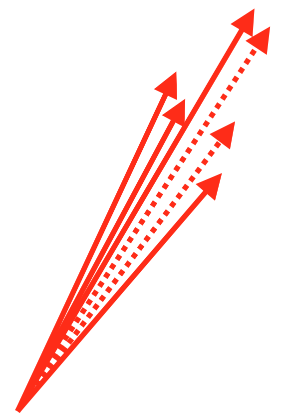
- EIC project is scheduled for construction at Brookhaven this decade.
    - e-p and e-nucleus deep inelastic scattering
    - polarized beams (spin physics studies)



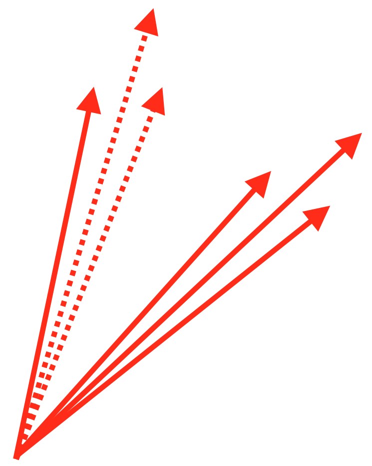
EPIC Detector Concept

- Tracker: MAPS, micro pattern gaseous detectors (MPGDs)
- ECal: Homogeneous $PbWO_4$
- Far-forward & far-backward roman pots, ZDC along beam line
- PID (→ p/Pi/K separation @ 3σ)
    - AC-LGAD ToF
    - Barrel: DIRC, <6 GeV
    - Backward: Aerogel RICH, <10 GeV
    - Forward: Gaseous RICH, <50 GeV



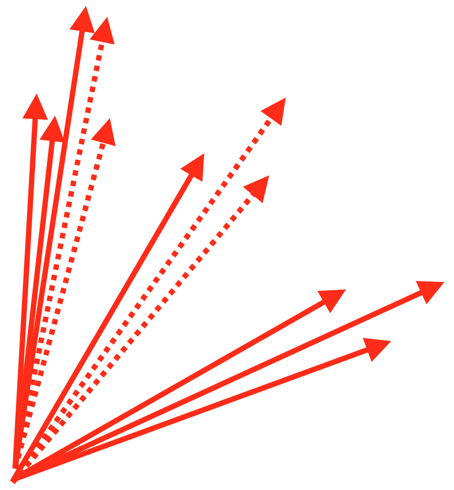


Quark? Gluon?



Higgs boson?

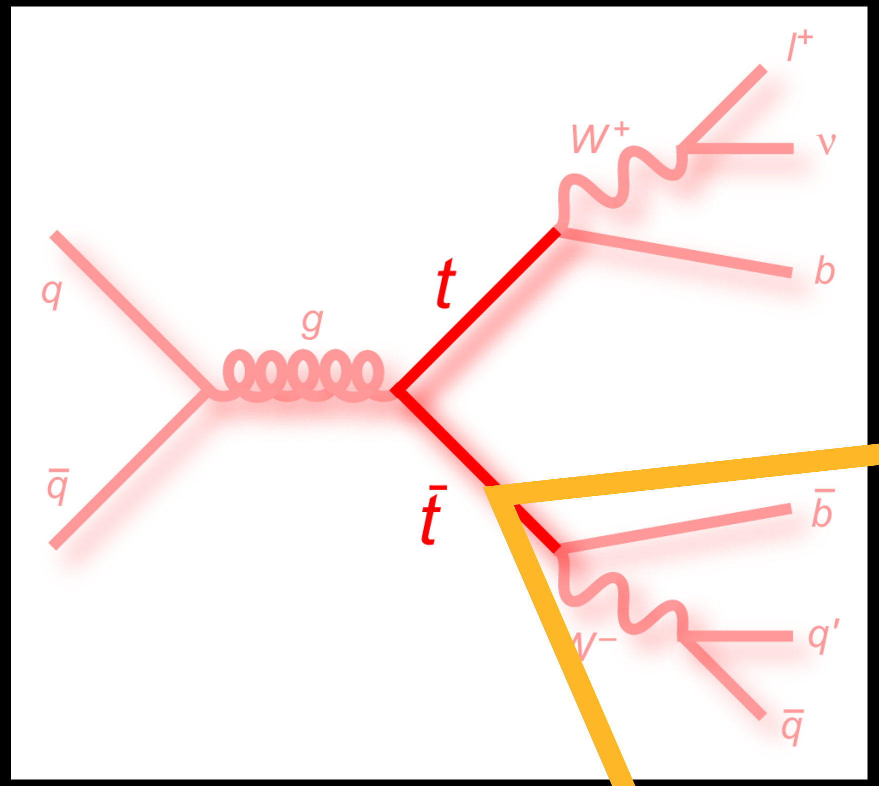
W/Z boson?

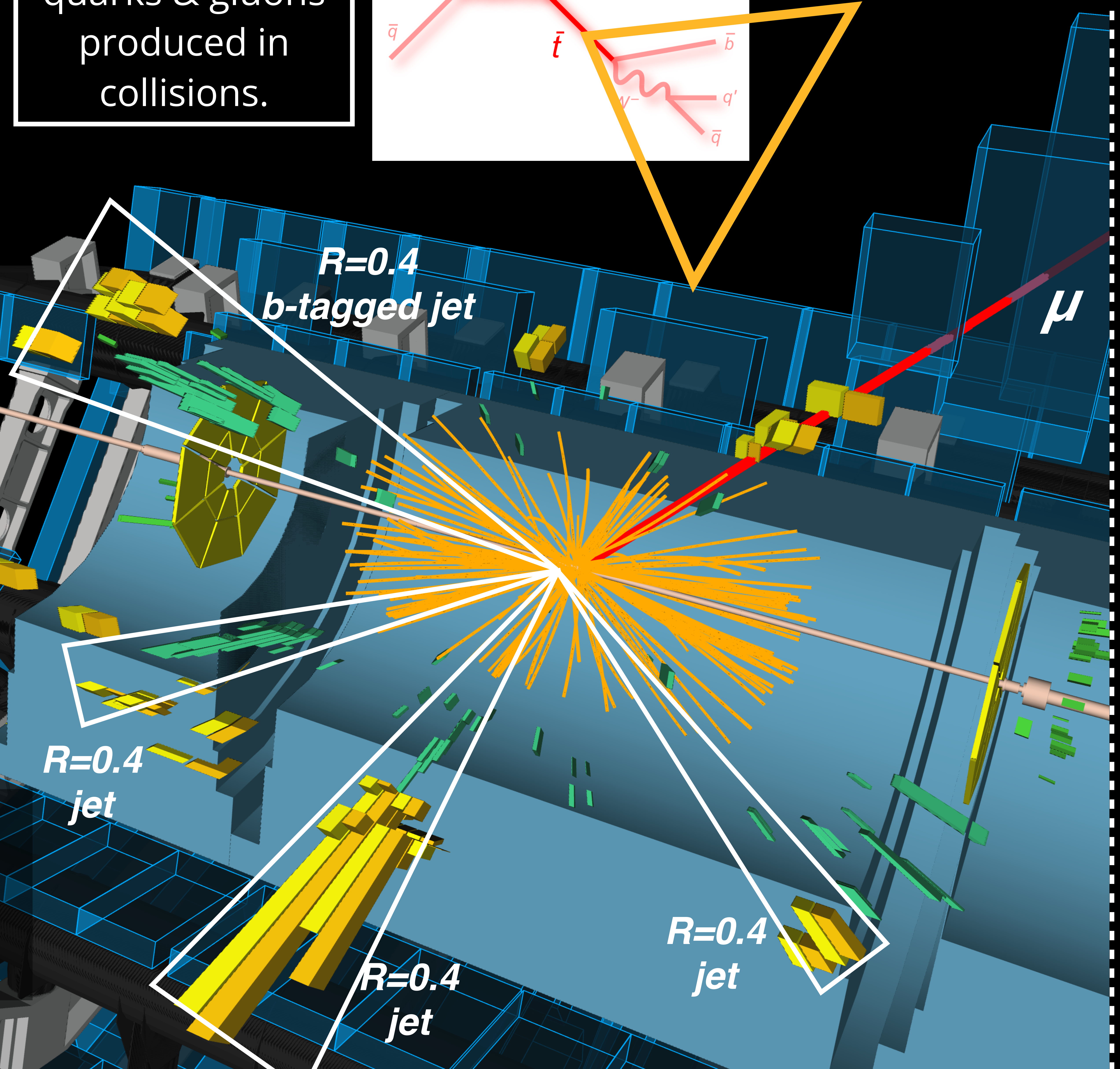


Top quark?

Tagging / Classification

Jets are proxies for high-energy quarks & gluons produced in collisions.





Jets are proxies for high-energy quarks & gluons produced in collisions.
q
q̄
g
t
t̄
W+
b
b̄
q'
BOOST!
… use "large-R" jets to collect the hadronic decays of heavy particles like top quarks!
R=0.4 b-tagged jet
μ
R=0.4 jet
R=0.4 jet
R=0.4 jet
R=0.4 b-tagged jet
μ
R=1.0 'large-R' ~3xR=0.4 Boosted top
pT ~ 600 GeV
m ~ 180 GeV

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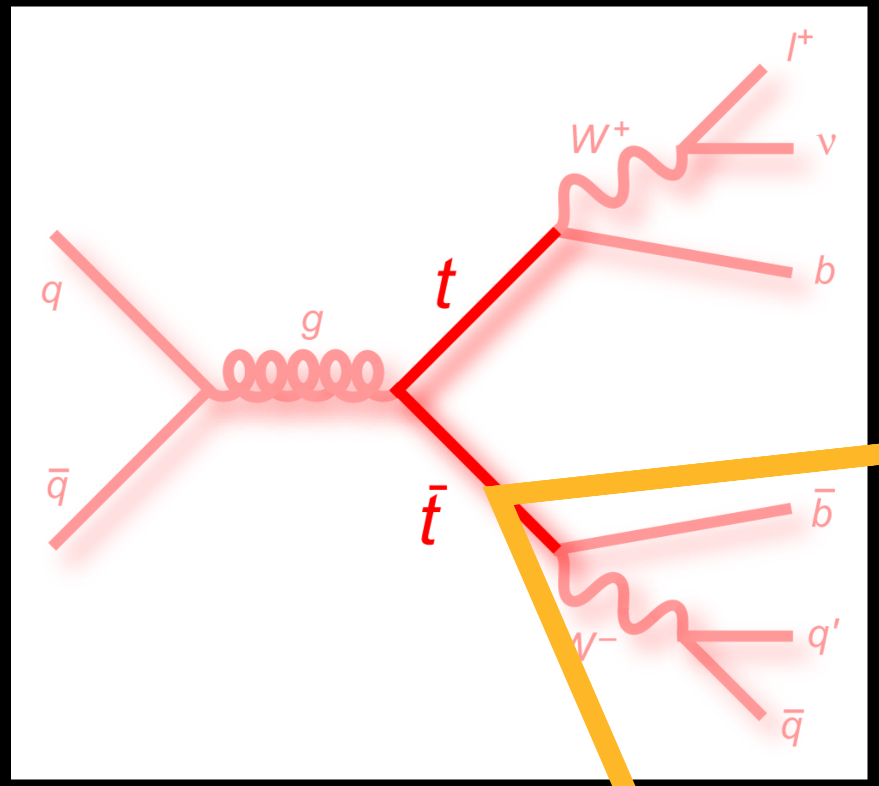
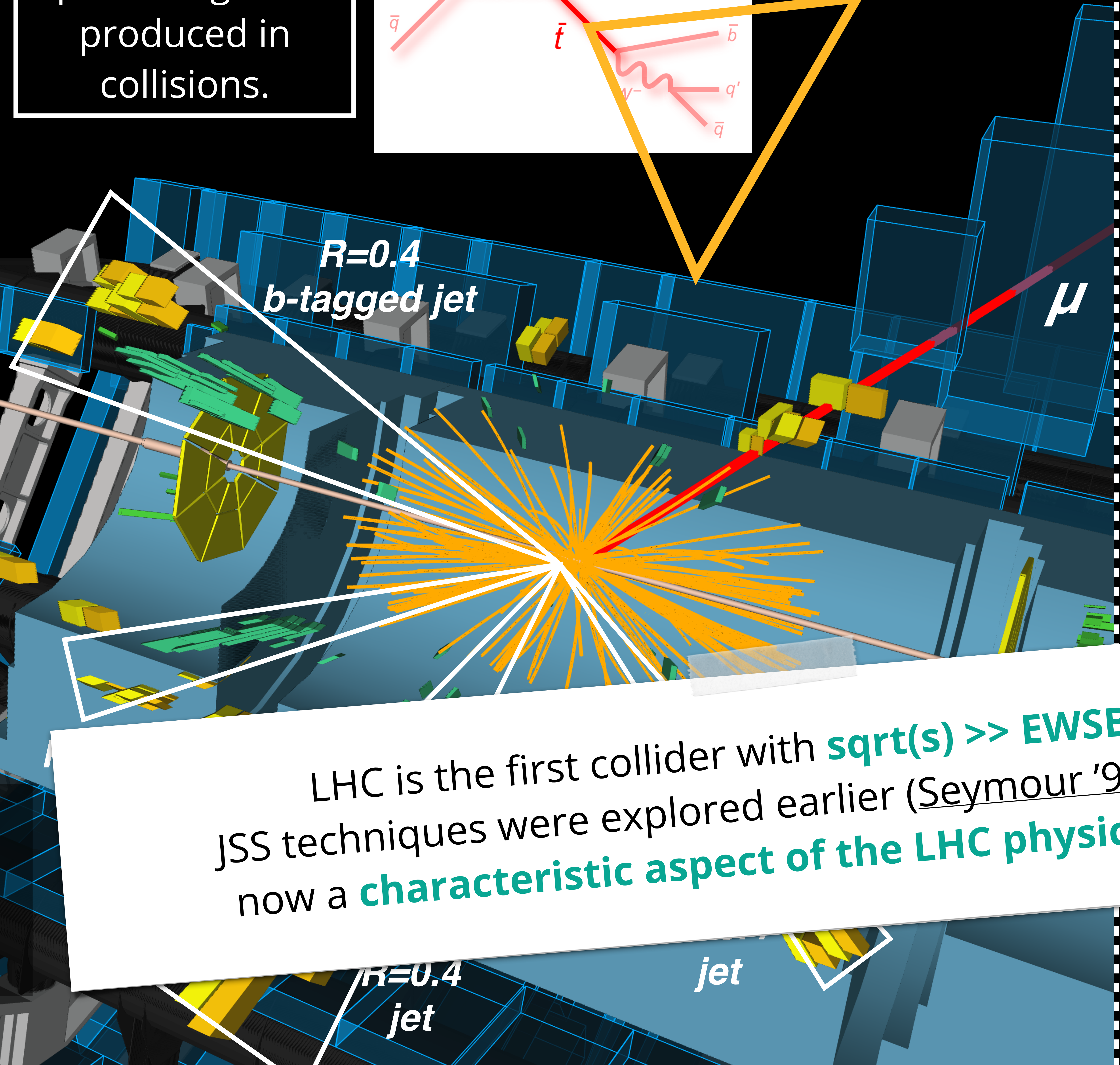
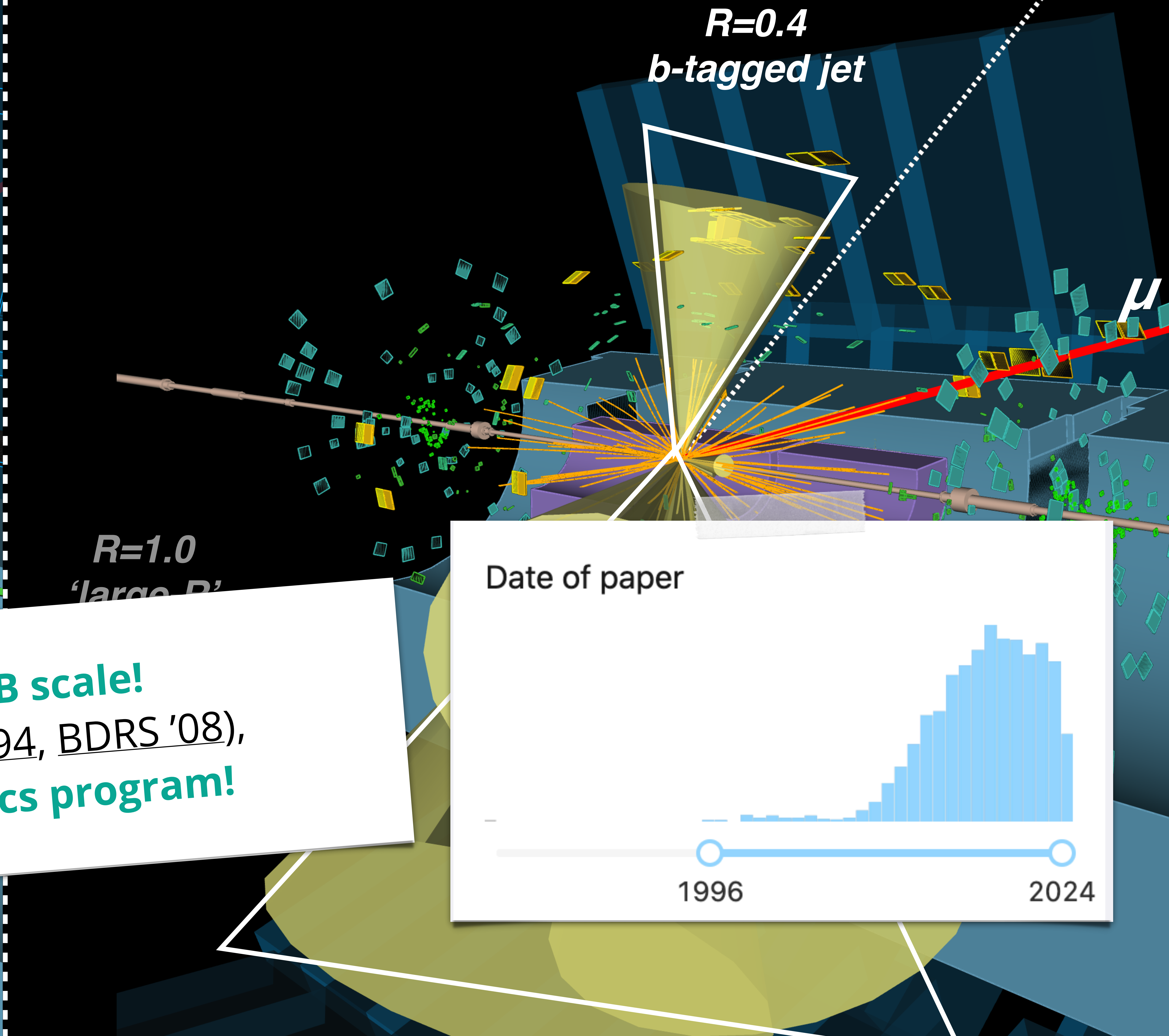


BOOST!

… use “large-R” jets to collect the hadronic decays of heavy particles like top quarks!

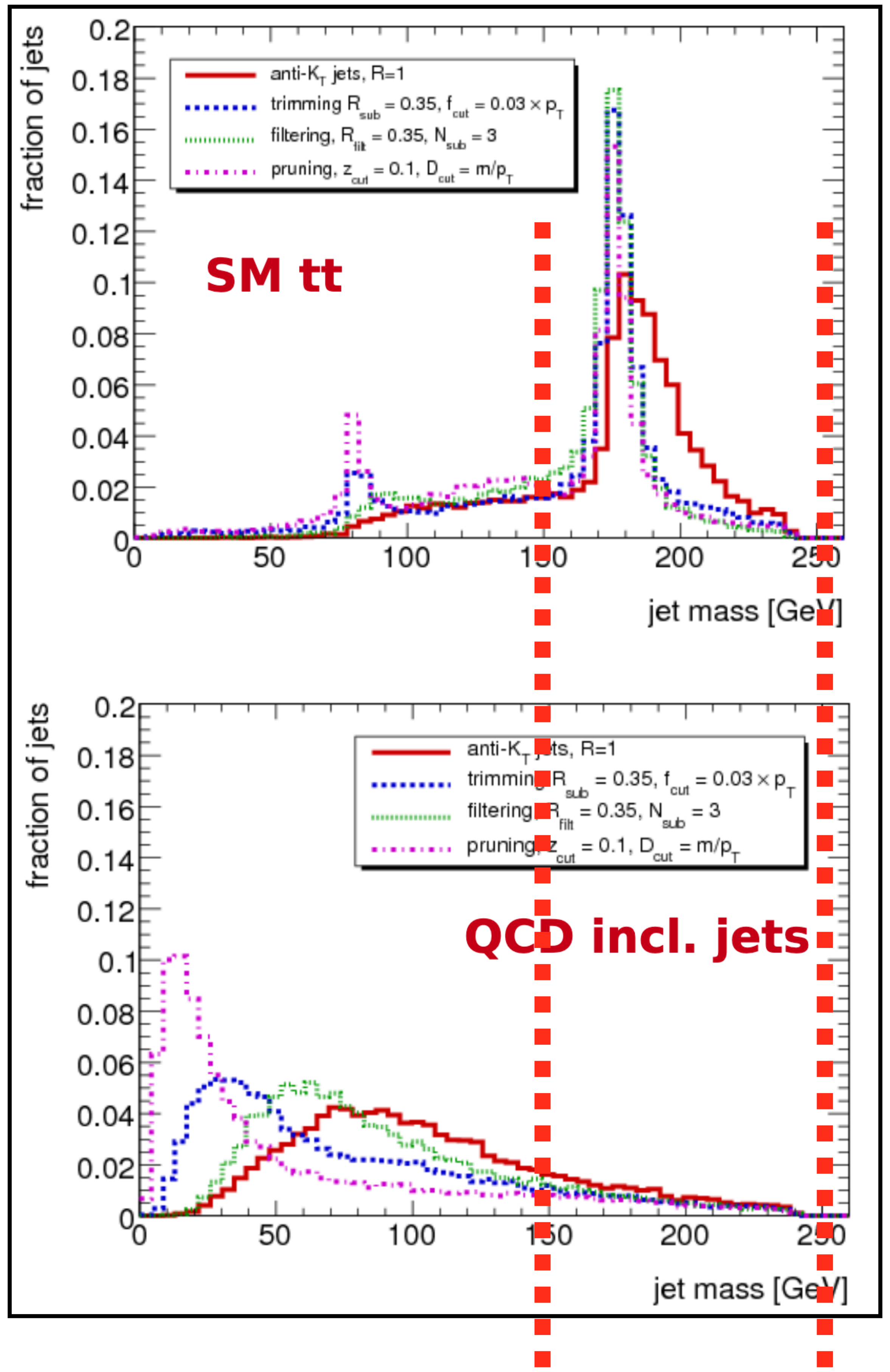




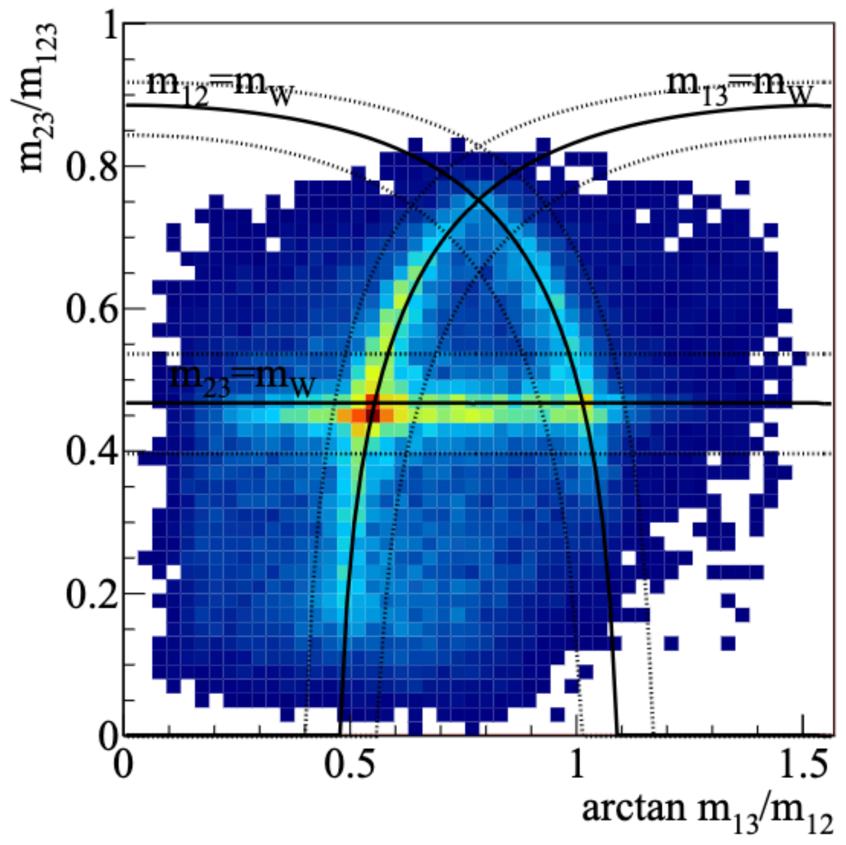
LHC is the first collider with **sqrt(s) >> EWSB scale!**
JSS techniques were explored earlier (Seymour ’94, BDRS ’08),
now a **characteristic aspect of the LHC physics program!**

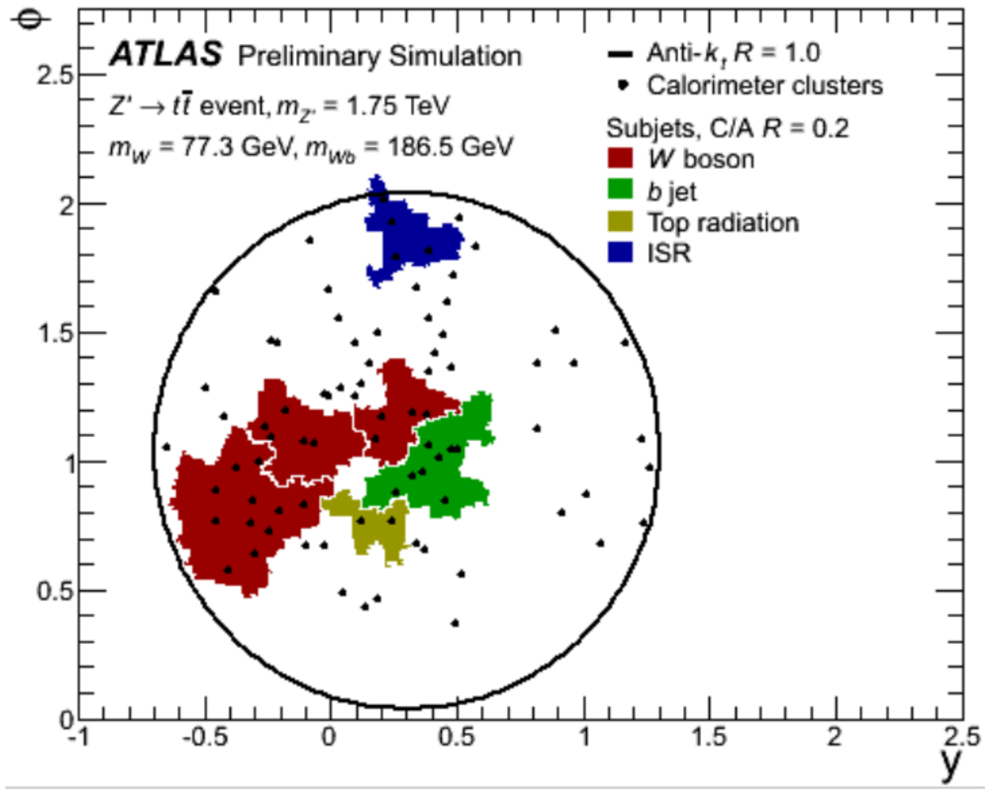
Then

M. Vos o.b.o. ATLAS+CMS, 2014



Cut on individual JSS observables





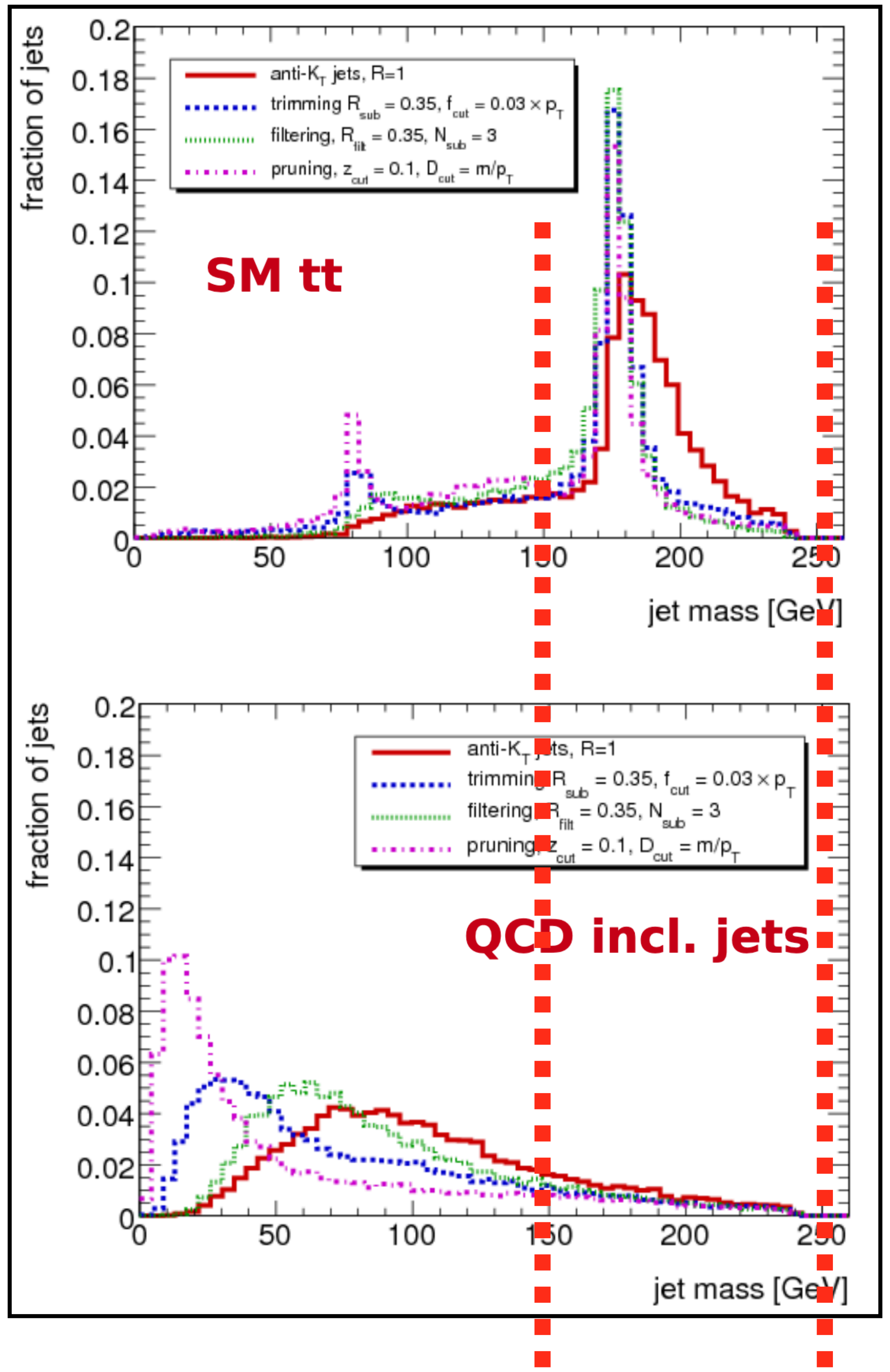
Rule-based

HepTopTagger, Shower Deconstruction

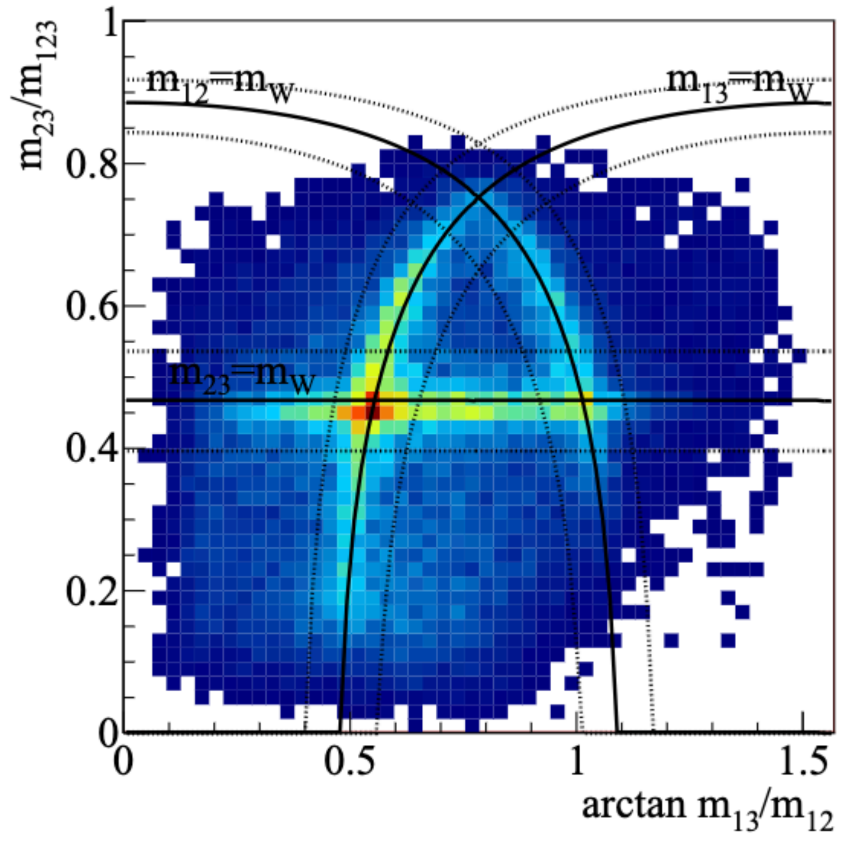
Then

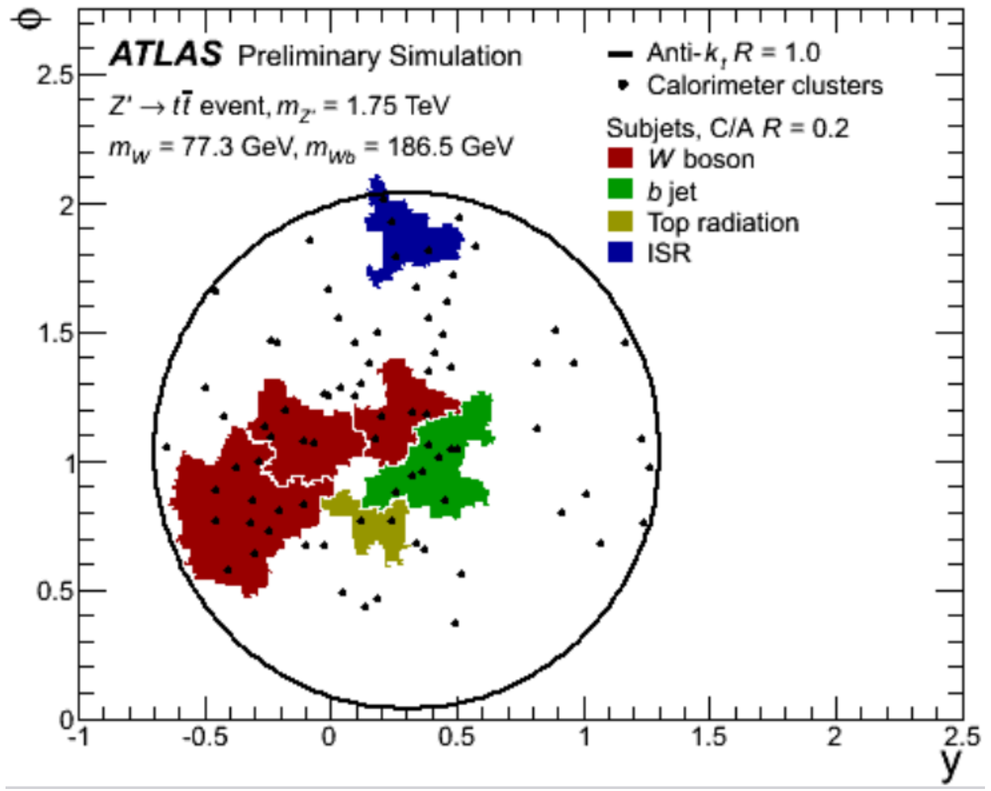
[M. Vos o.b.o. ATLAS+CMS](), 2014

Now

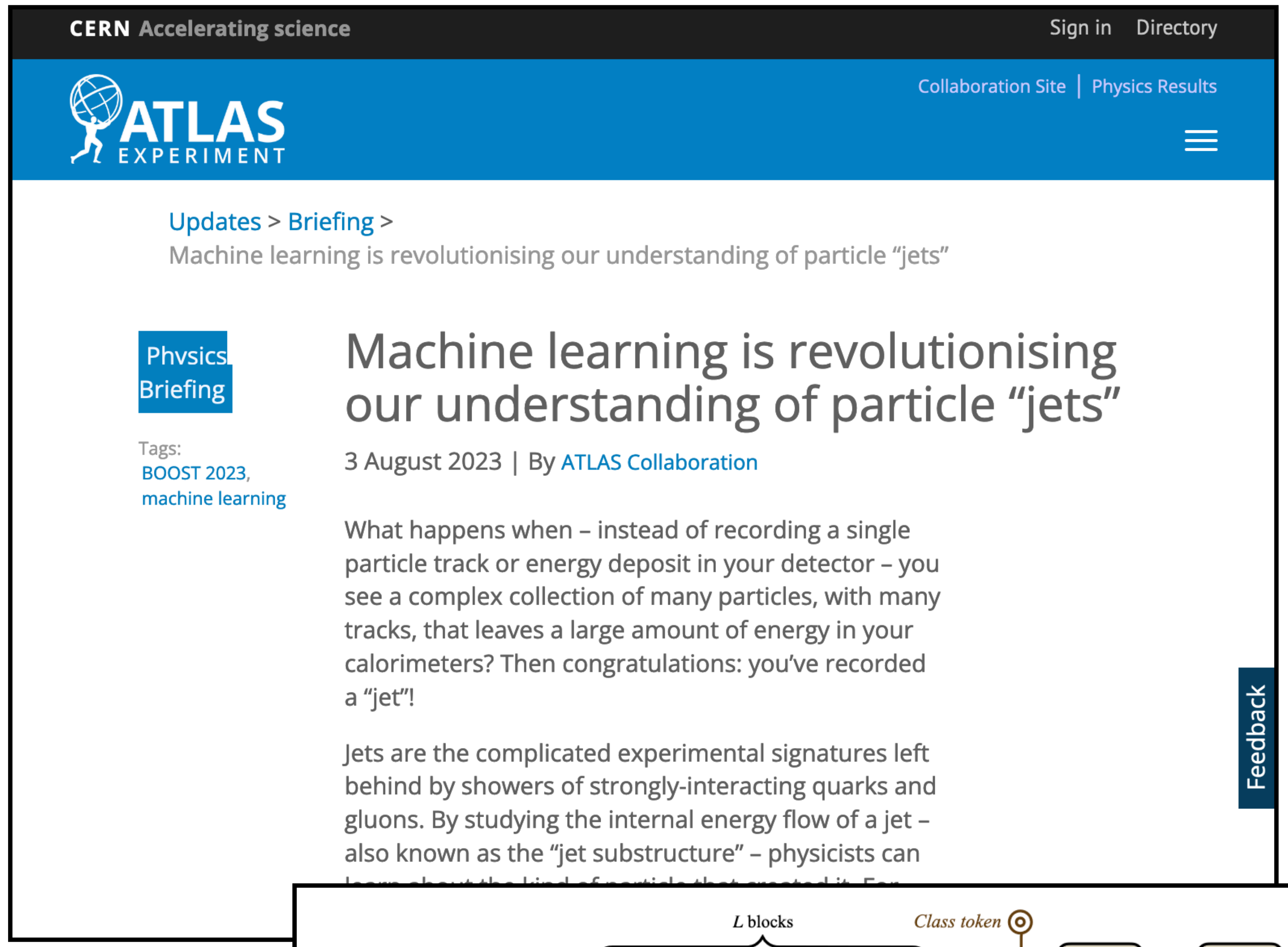


Cut on individual JSS observables





Rule-based
HepTopTagger, Shower Deconstruction


CERN Accelerating science
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ATLAS EXPERIMENT
Collaboration Site | Physics Results
Updates > Briefing >
Machine learning is revolutionising our understanding of particle "jets"

Physics Briefing

Tags:
BOOST 2023,
machine learning

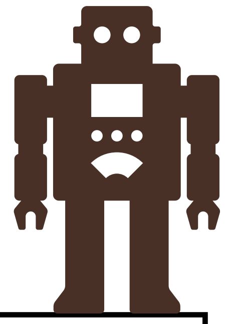
Machine learning is revolutionising our understanding of particle "jets"

3 August 2023 | By ATLAS Collaboration

What happens when – instead of recording a single particle track or energy deposit in your detector – you see a complex collection of many particles, with many tracks, that leaves a large amount of energy in your calorimeters? Then congratulations: you've recorded a "jet"!

Jets are the complicated experimental signatures left behind by showers of strongly-interacting quarks and gluons. By studying the internal energy flow of a jet – also known as the "jet substructure" – physicists can

Feedback



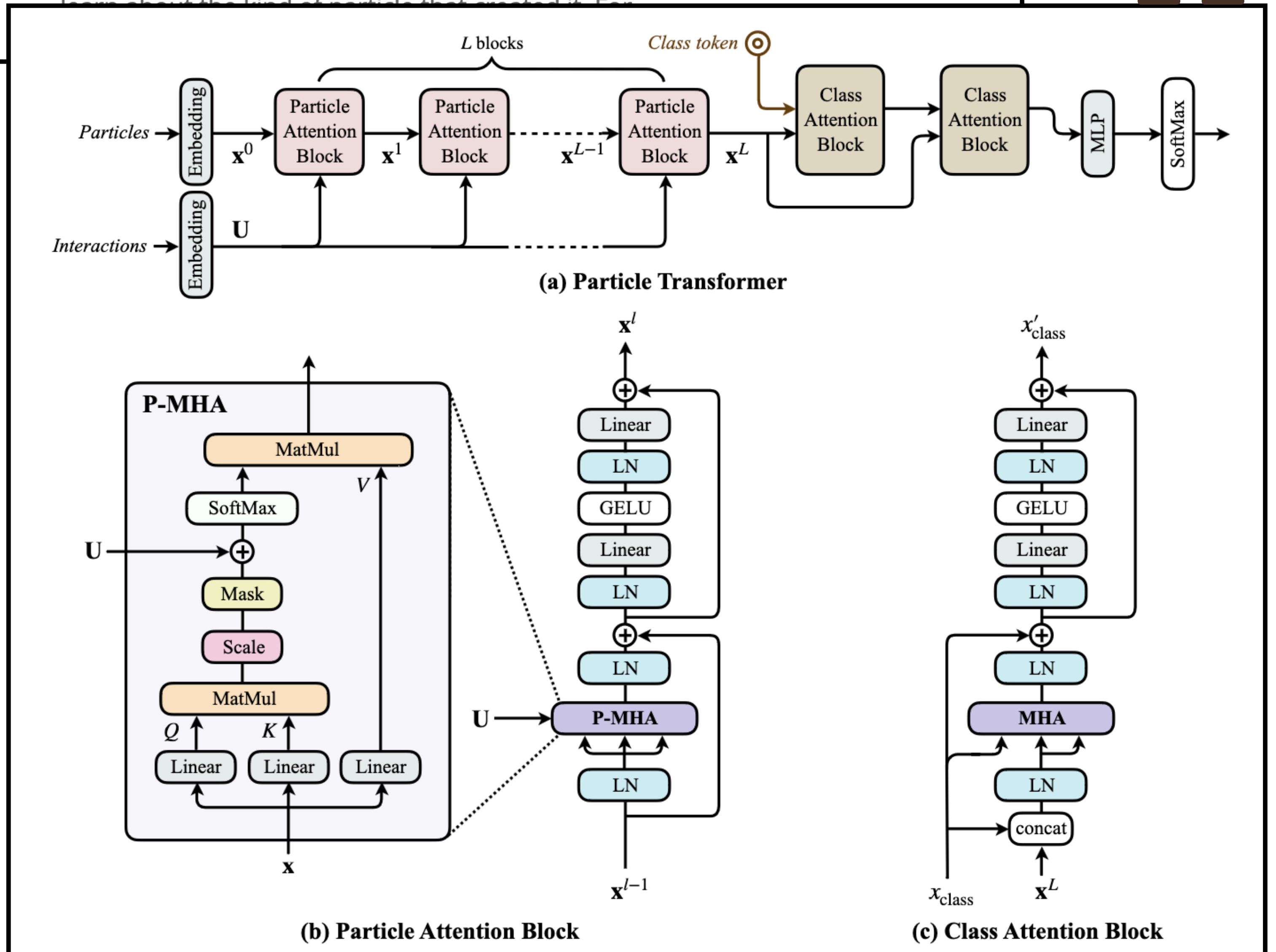


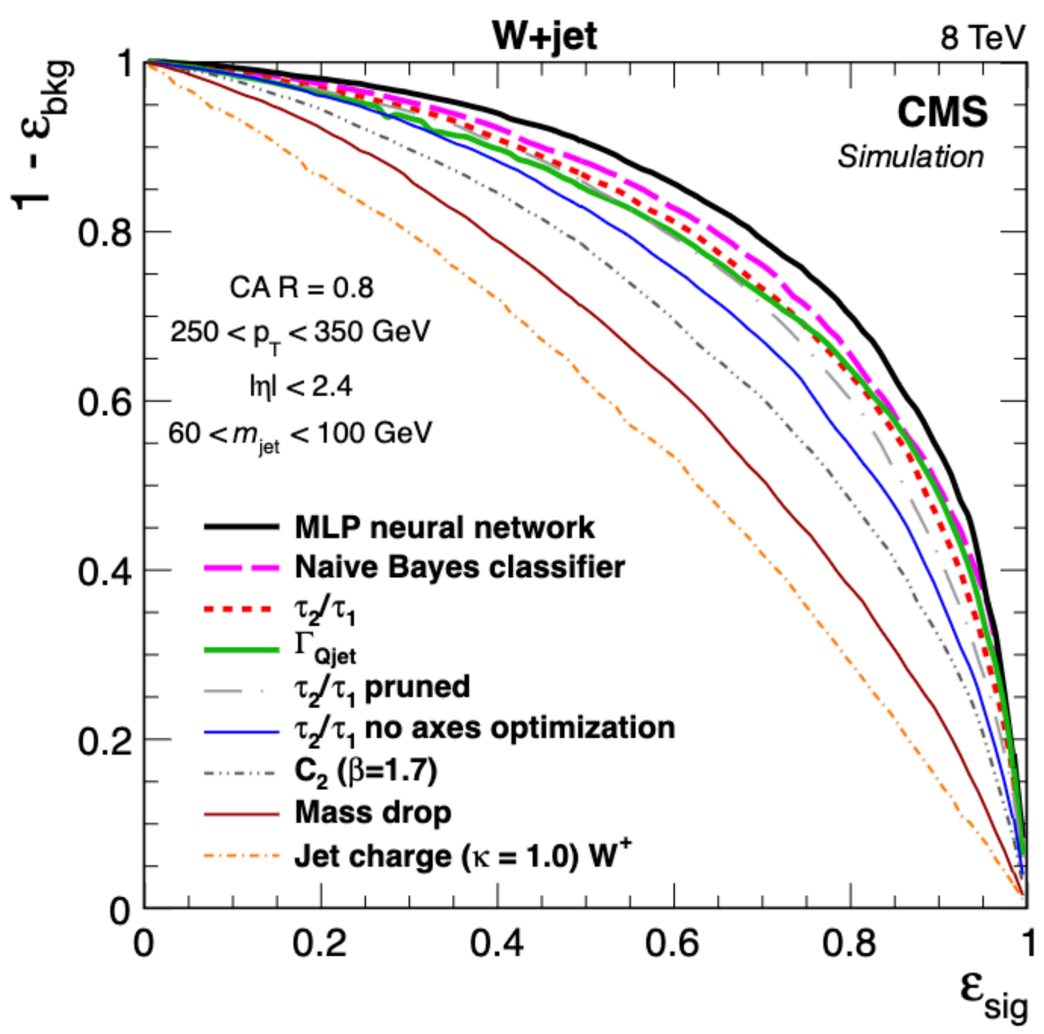
Figure 3. The architecture of (a) Particle Transformer (b) Particle Attention Block (c) Class Attention Block.

Boosted object tagging (nostalgic retrospective)

- Many different approaches are constantly being utilized in physics analysis: continuous development in this area for 16 BOOSTs (and counting!)

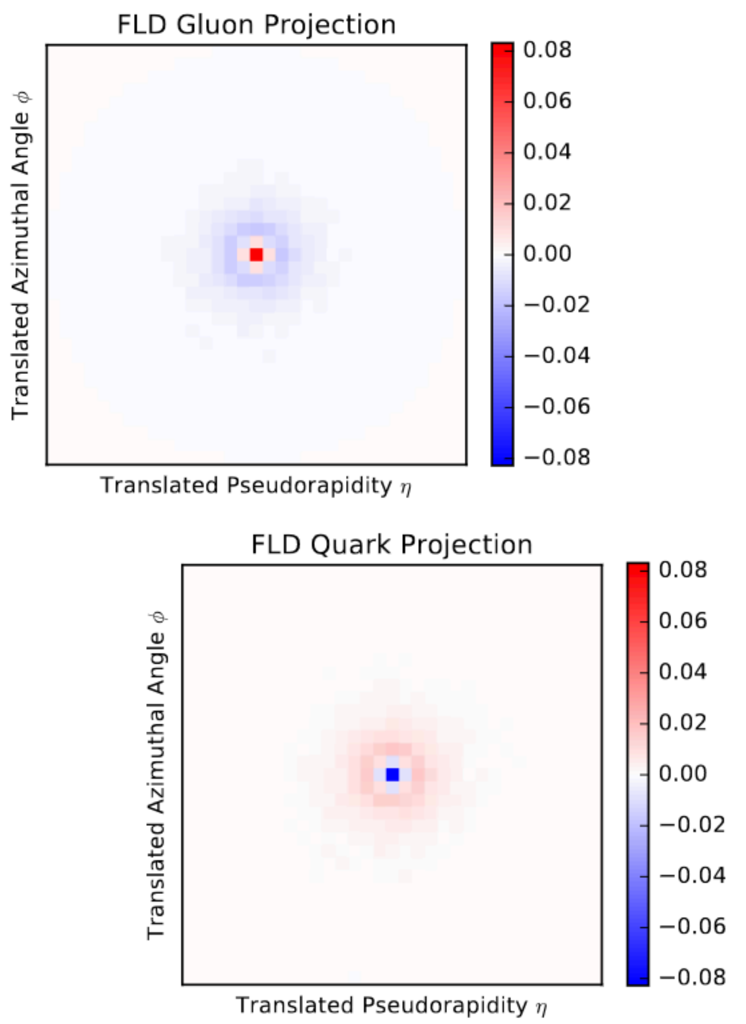
Expert features

e.g. CMS, 1410.4227



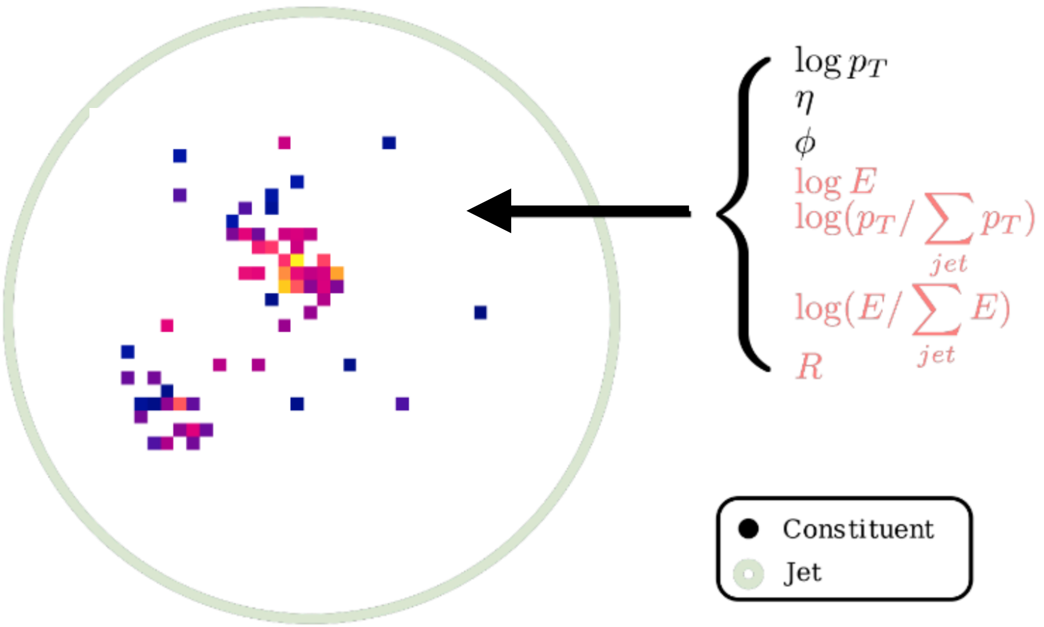
Images

e.g. Komiske et al. 1612.01551



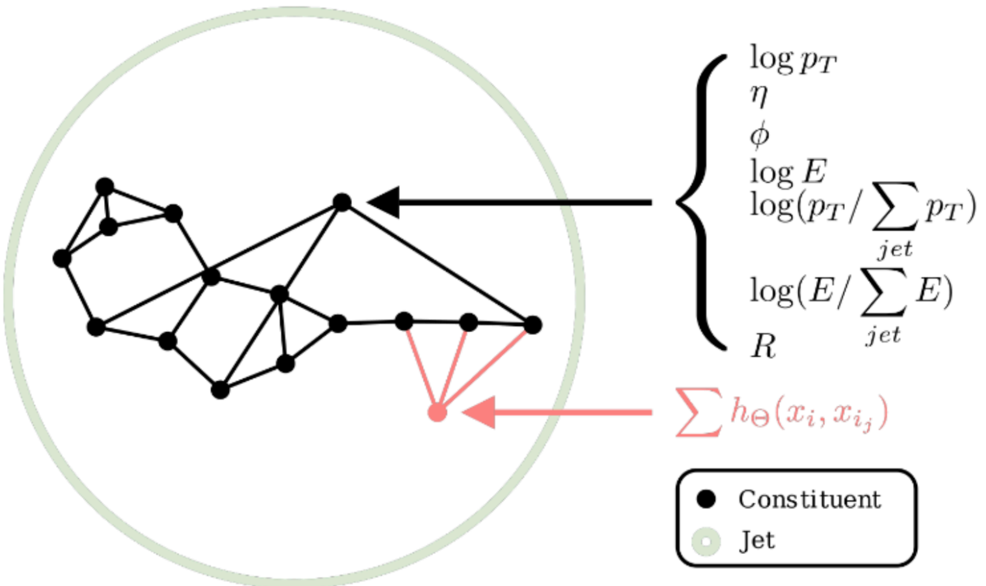
Point Cloud (PFN/EFN)

e.g. Komiske et al. 1810.05165



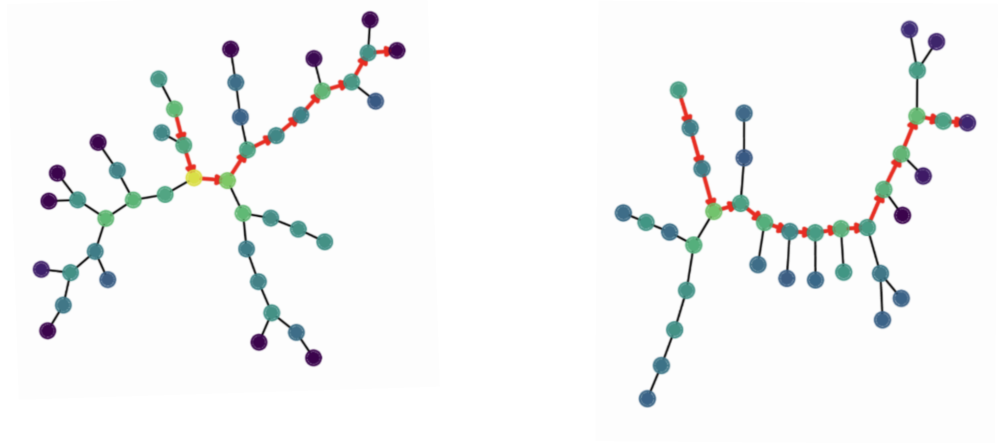
Graph (ParticleNet)

e.g. Gouskos & Qu 1902.08570



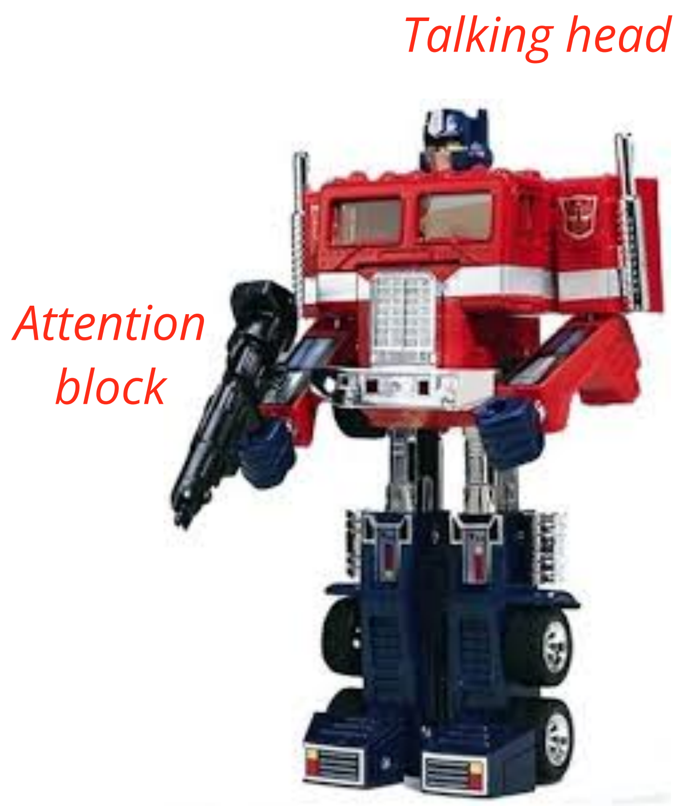
Graph definitions not unique — c.f. ATLAS LundNet tagger (C/A Graphics)

ATL-PHYS-PUB-2023-017



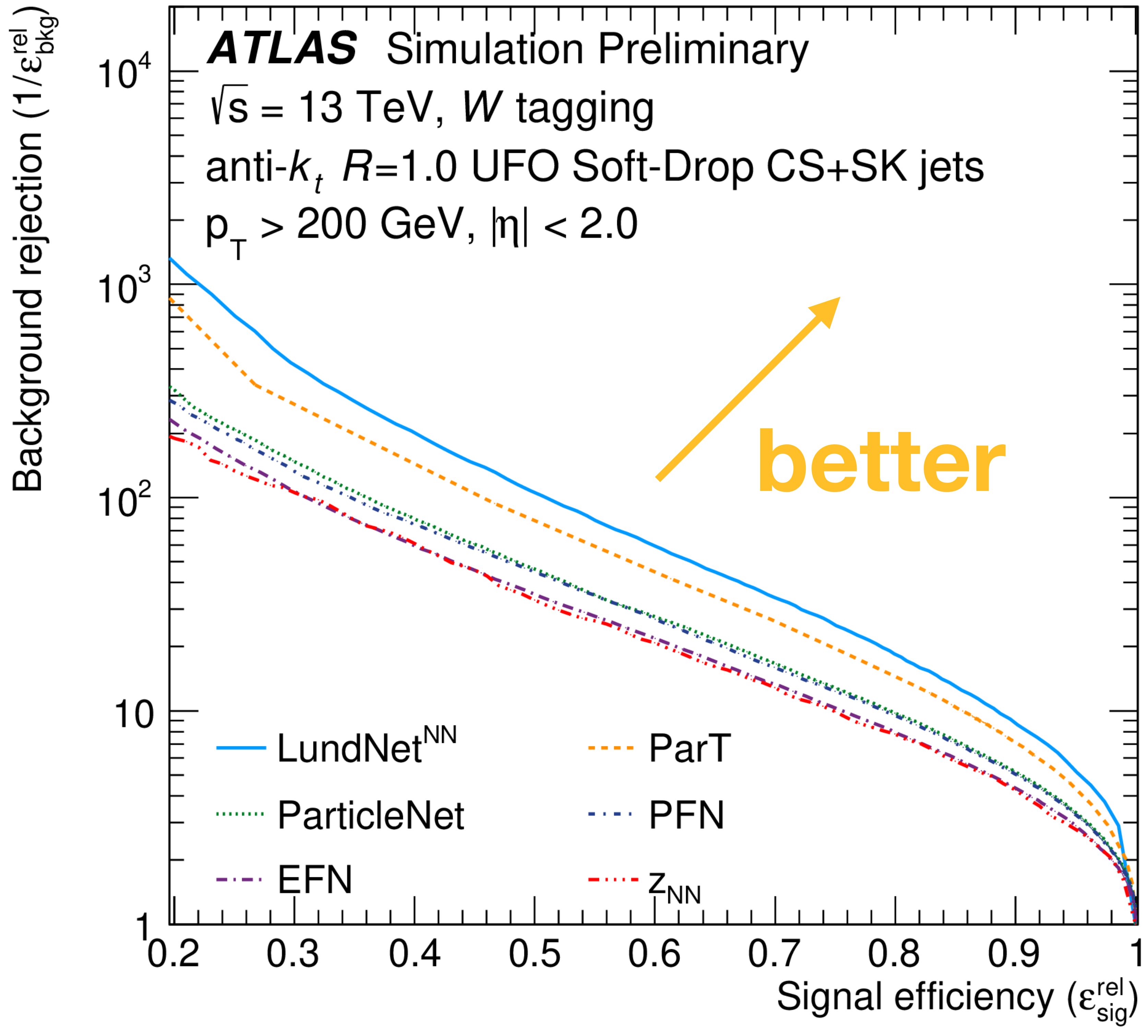
Transformers

e.g. Qu, Li & Quian 2202.03772

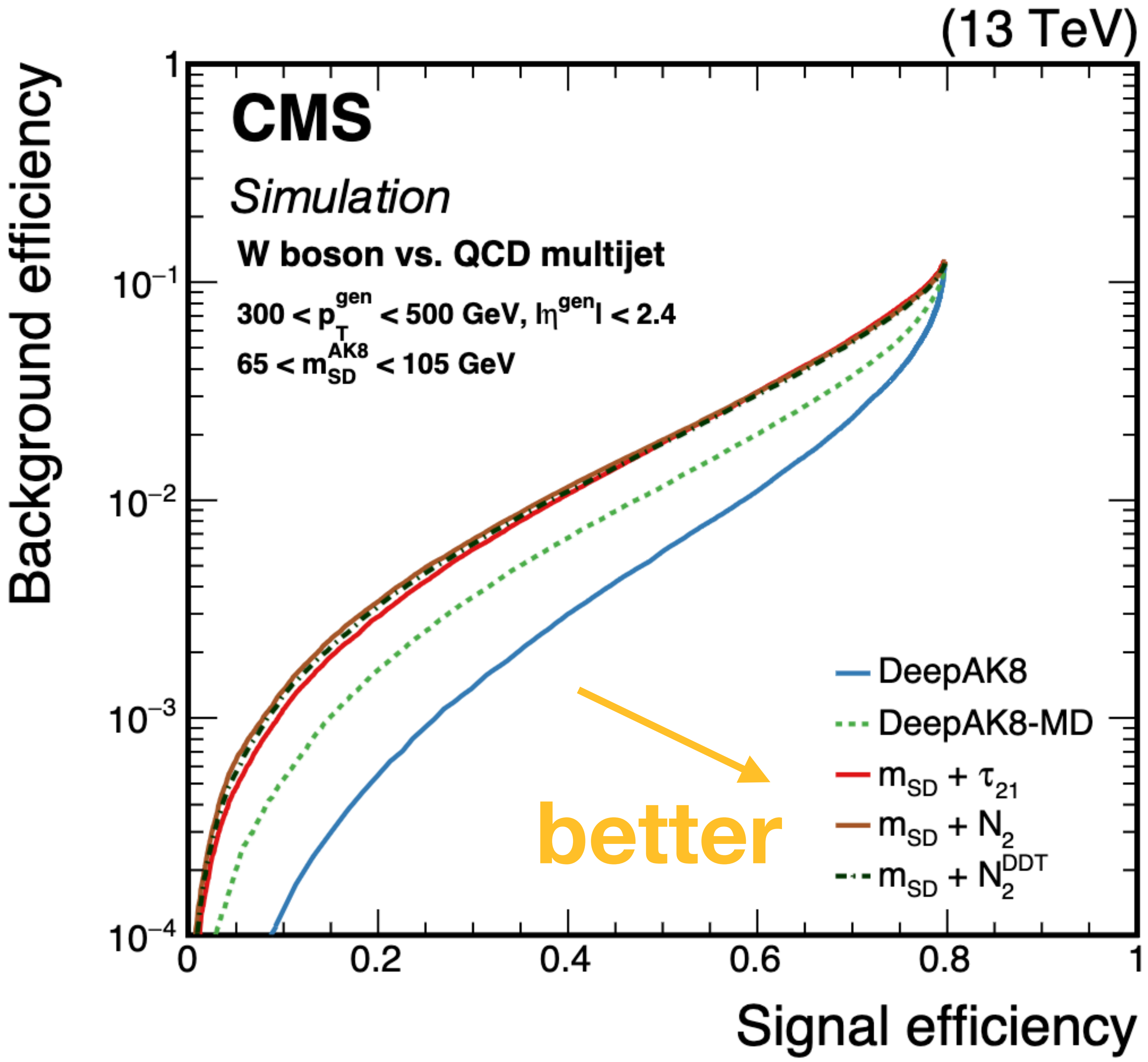


How to read a ROC curve

- Different people draw these with different ordinate quantities (efficiency *vs.* rejection)

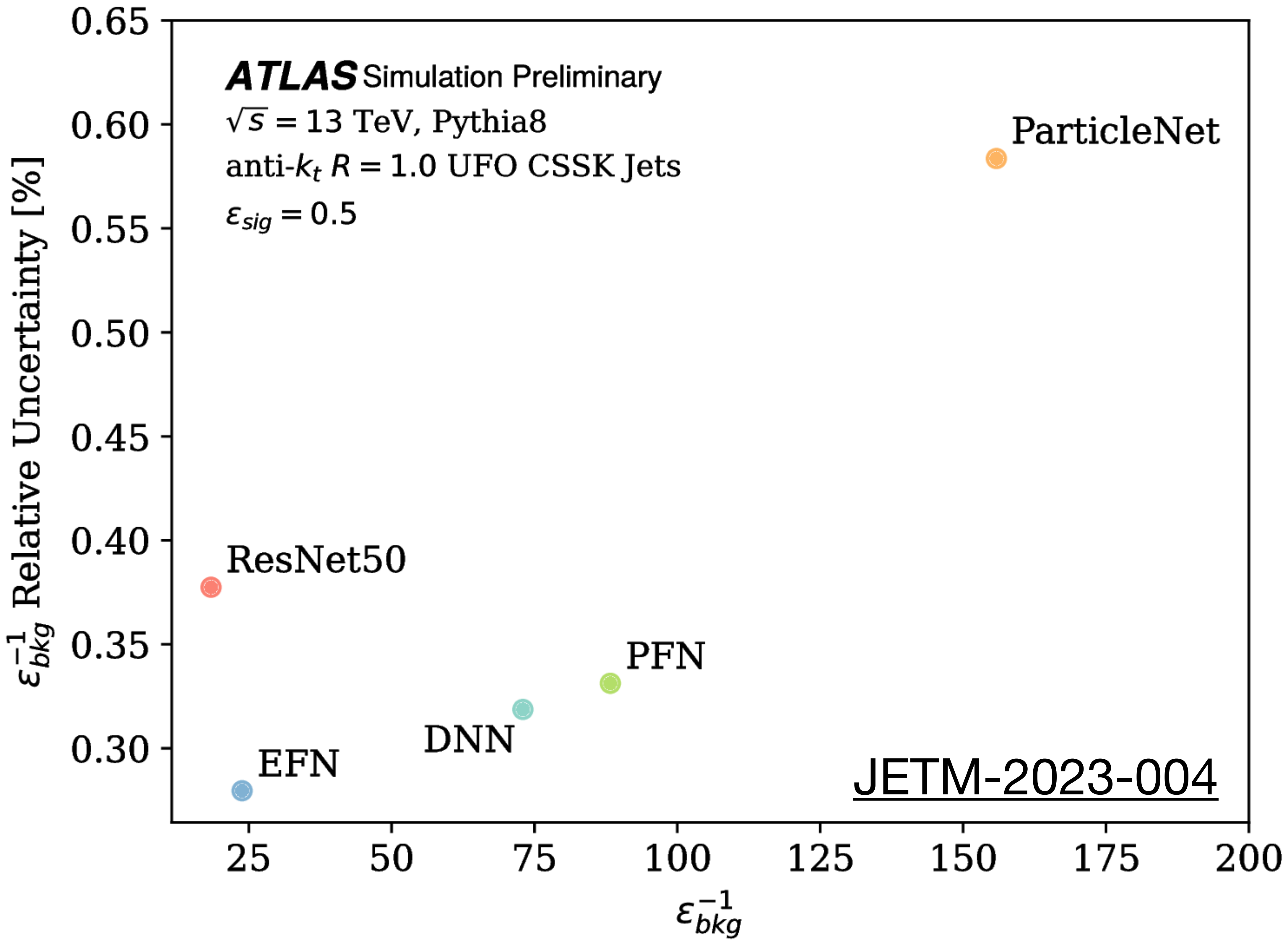


ATLAS, JETM-2023-003



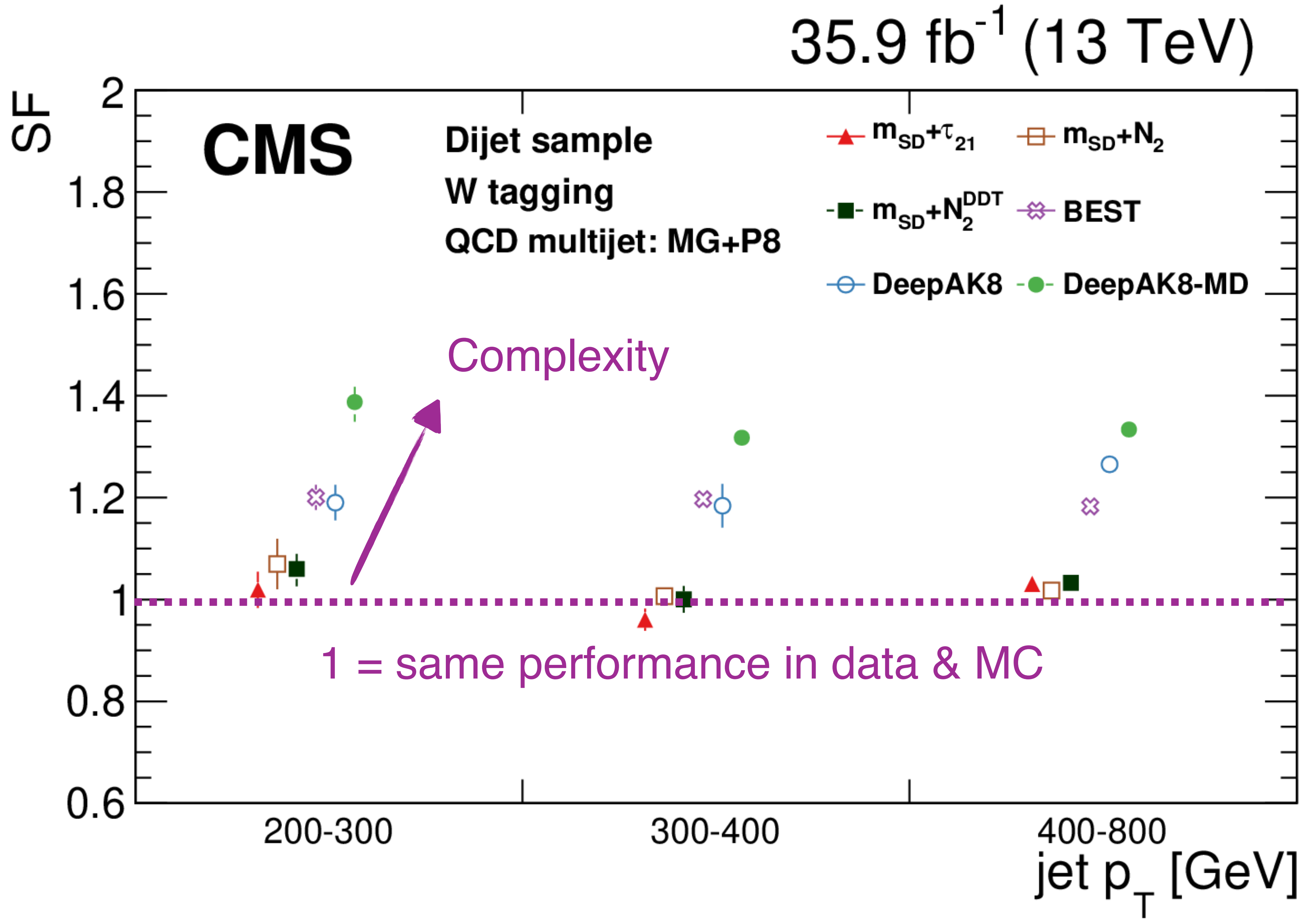
CMS, JINST 15 (2020) P06005

- Be mindful that AUC is not the only important metric!
- Trade-offs between power & precision: *Is performance being realized in data?*



ATLAS Top Tagging Study

Sensitivity to sources of uncertainty increases with tagger complexity.



Data/MC Scale Factors for CMS W-Tagger BG Efficiency

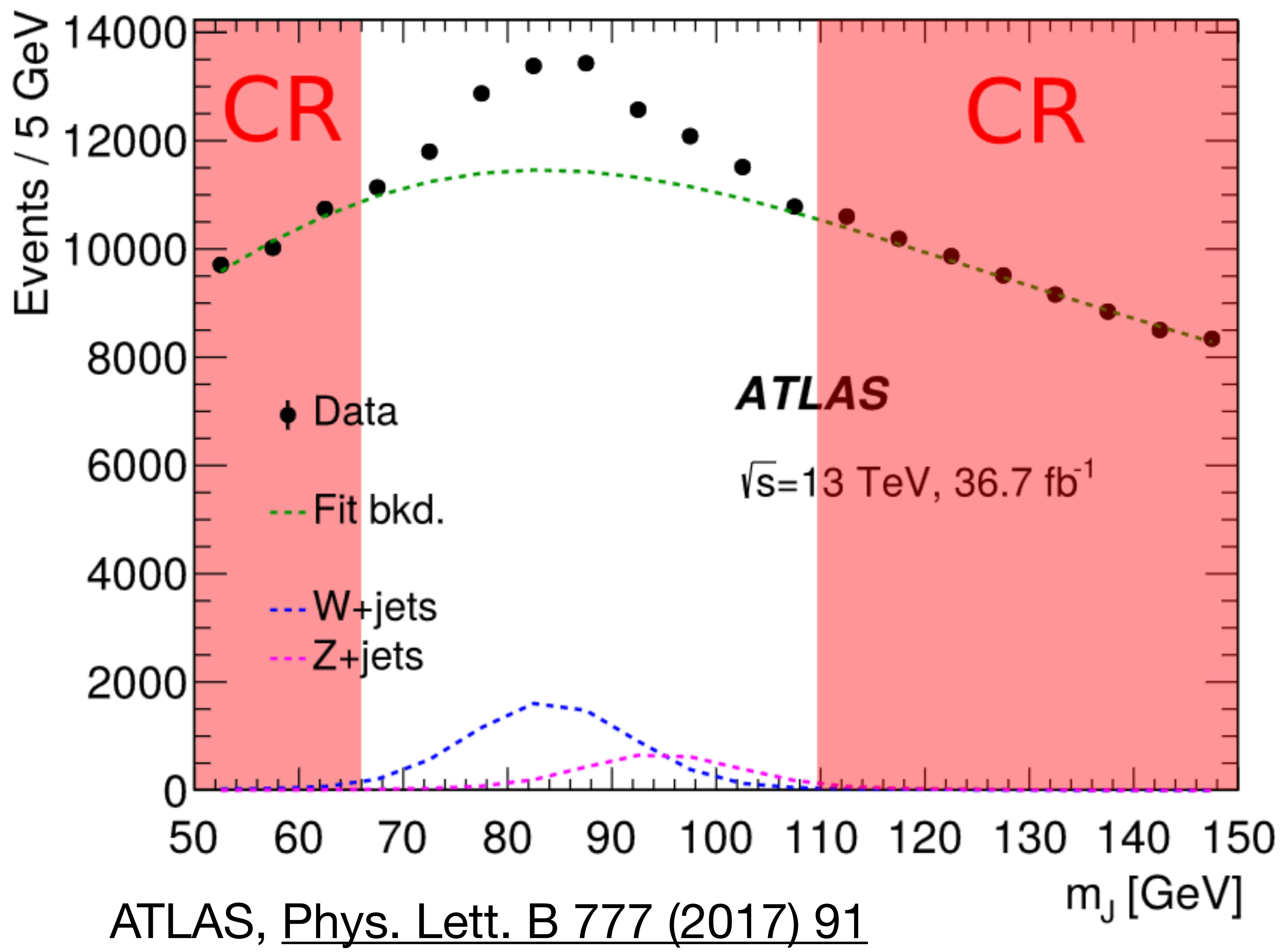
~30-40% Data/MC differences for most complex neural network in comparison!

(DeepAK8, DeepAK8-MD)

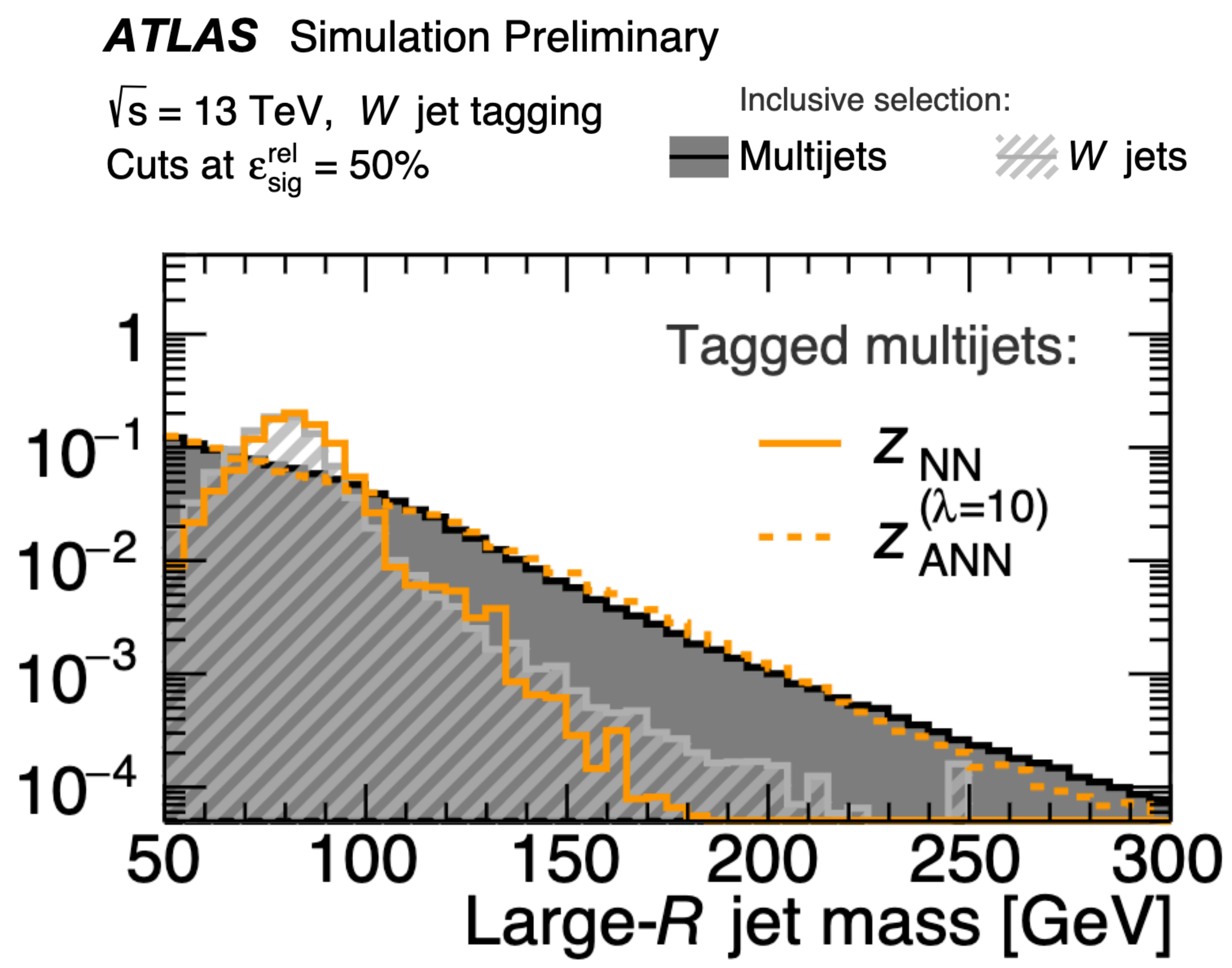
Mass decorrelation

- Certain background estimation strategies require taggers that do not sculpt the distribution of interest.
  - *e.g.* invariant mass spectrum → fit sideband regions to estimate contribution in signal region

- Can de-correlate tagger performance from observable of interest.
  - Analytical approaches (Dolen et al. JHEP 05 (2016) 156)
  - ML-based approaches (*e.g.* ANNs, ATL-PHYS-PUB-2021-029)



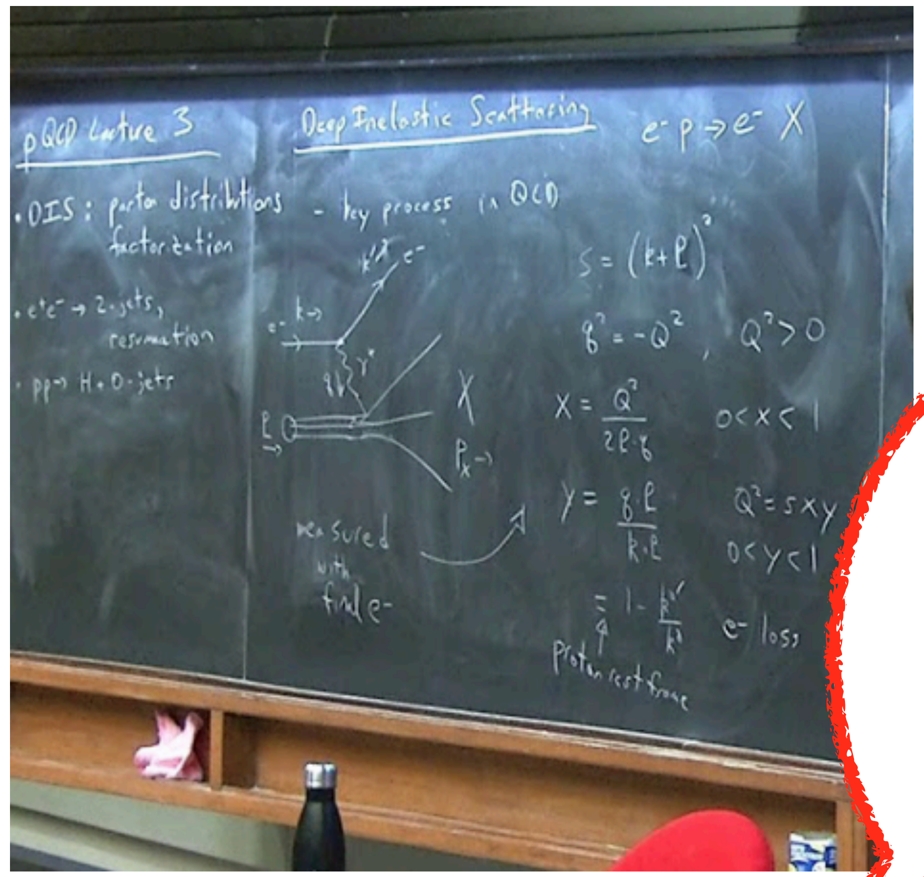
ATLAS, Phys. Lett. B 777 (2017) 91

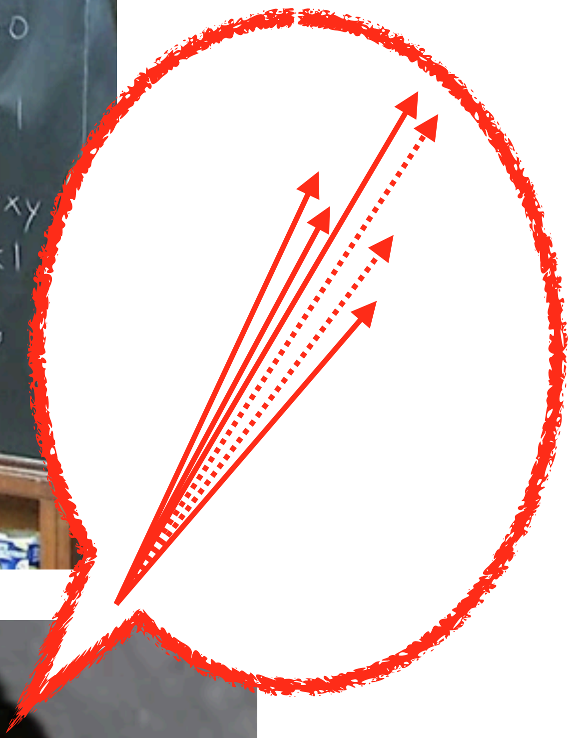


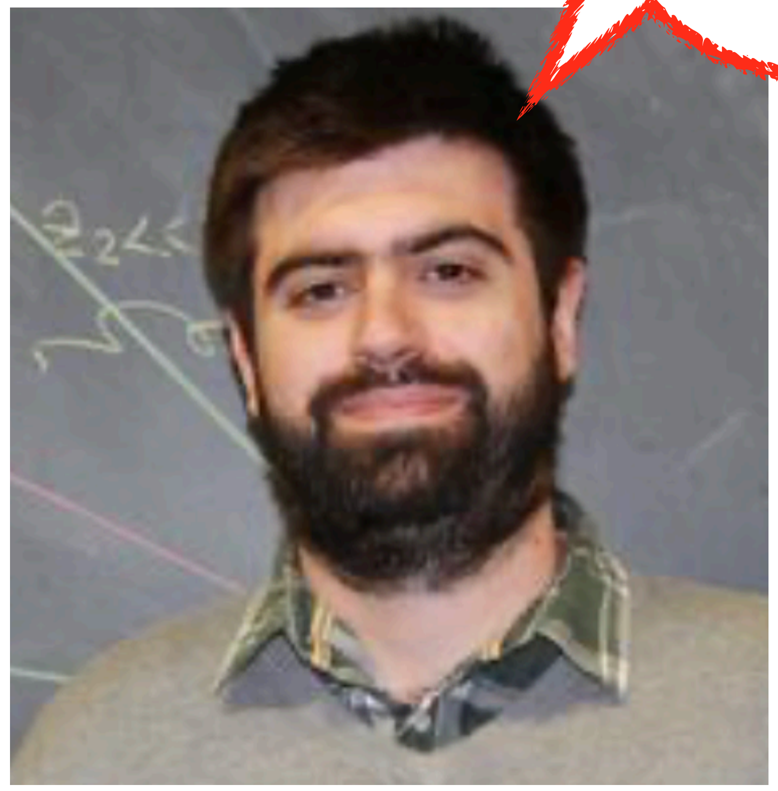
Unfolding

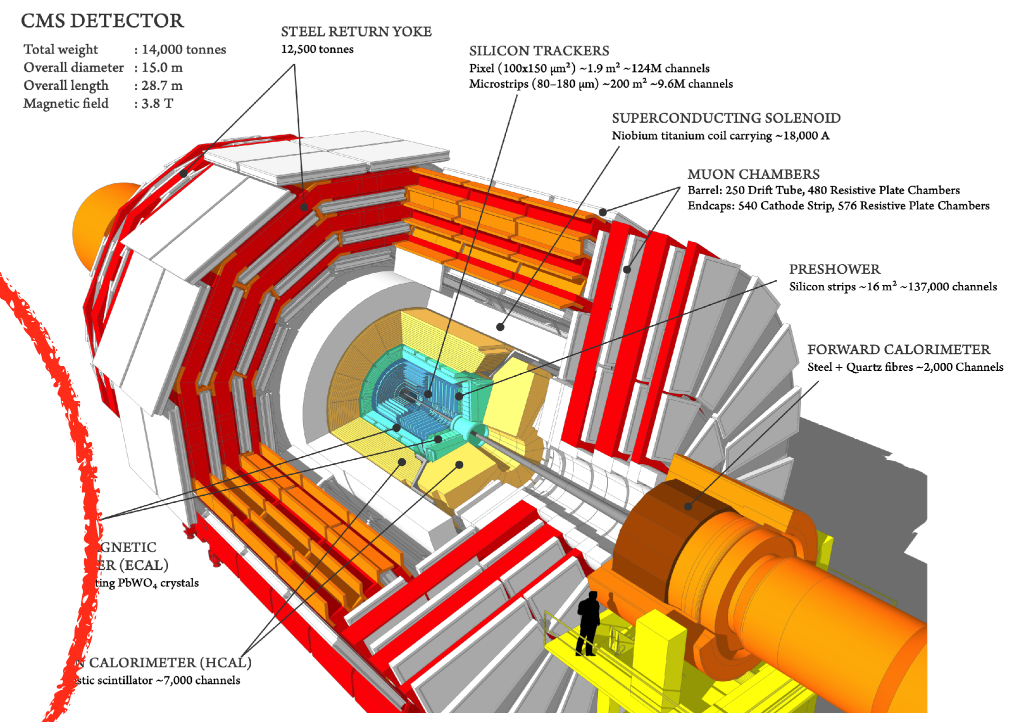
Theorist

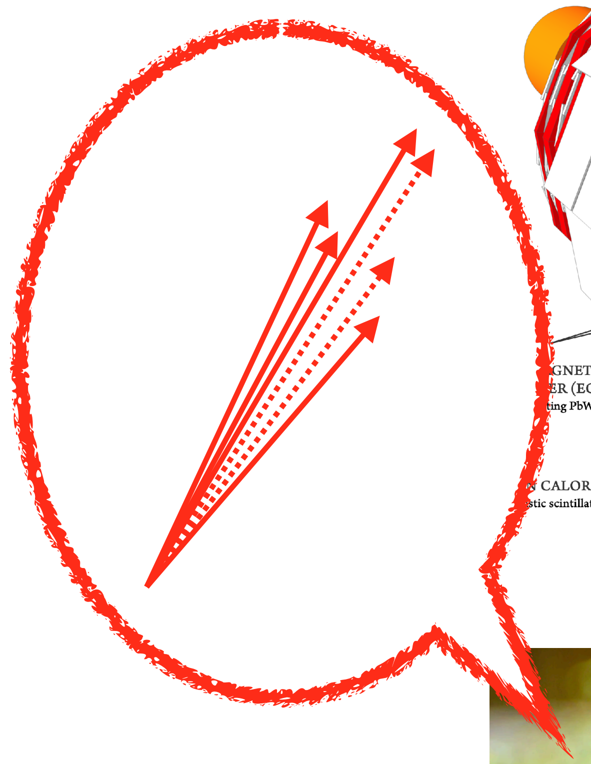
Experimentalist





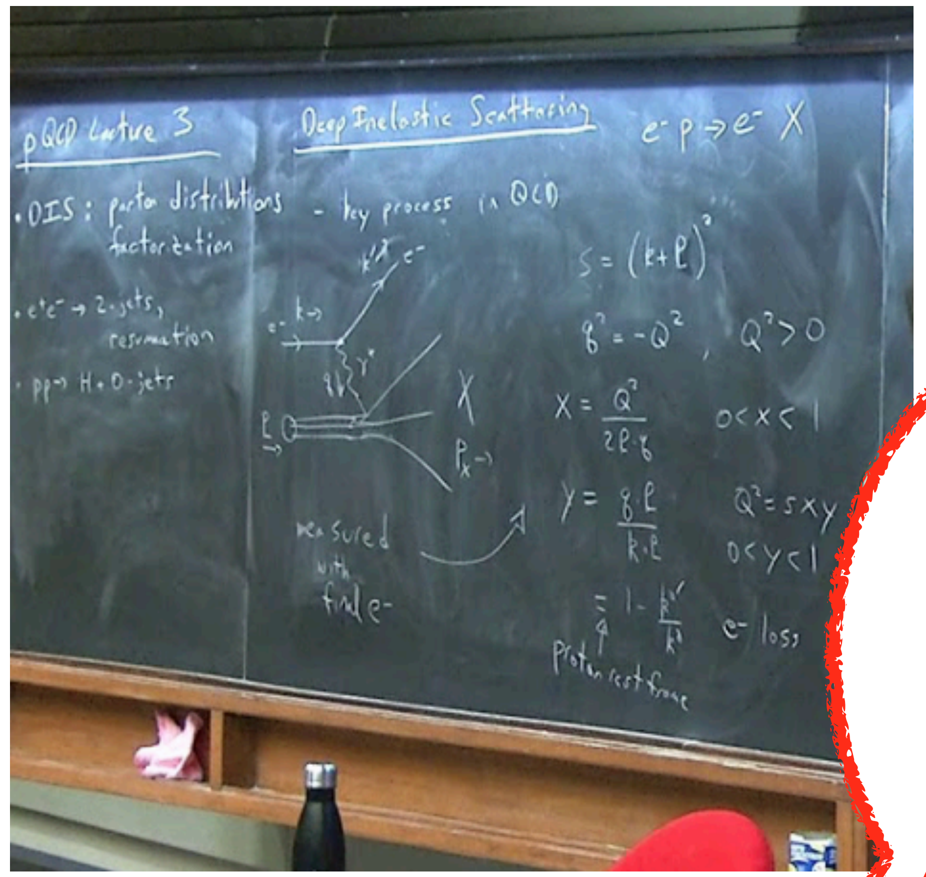


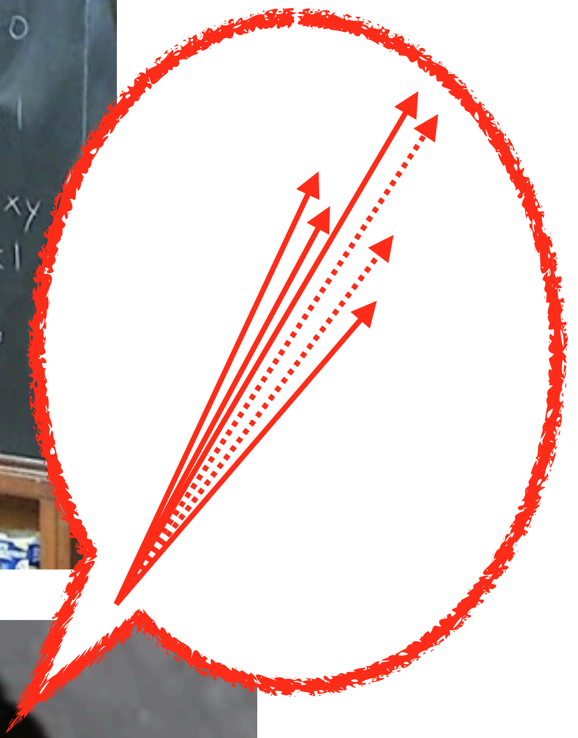


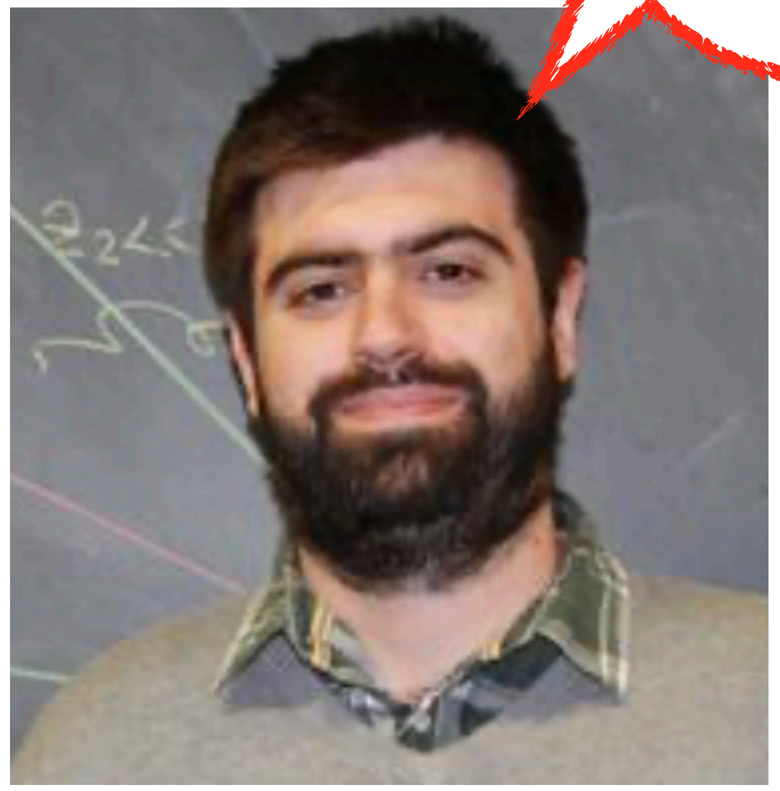


Theorist

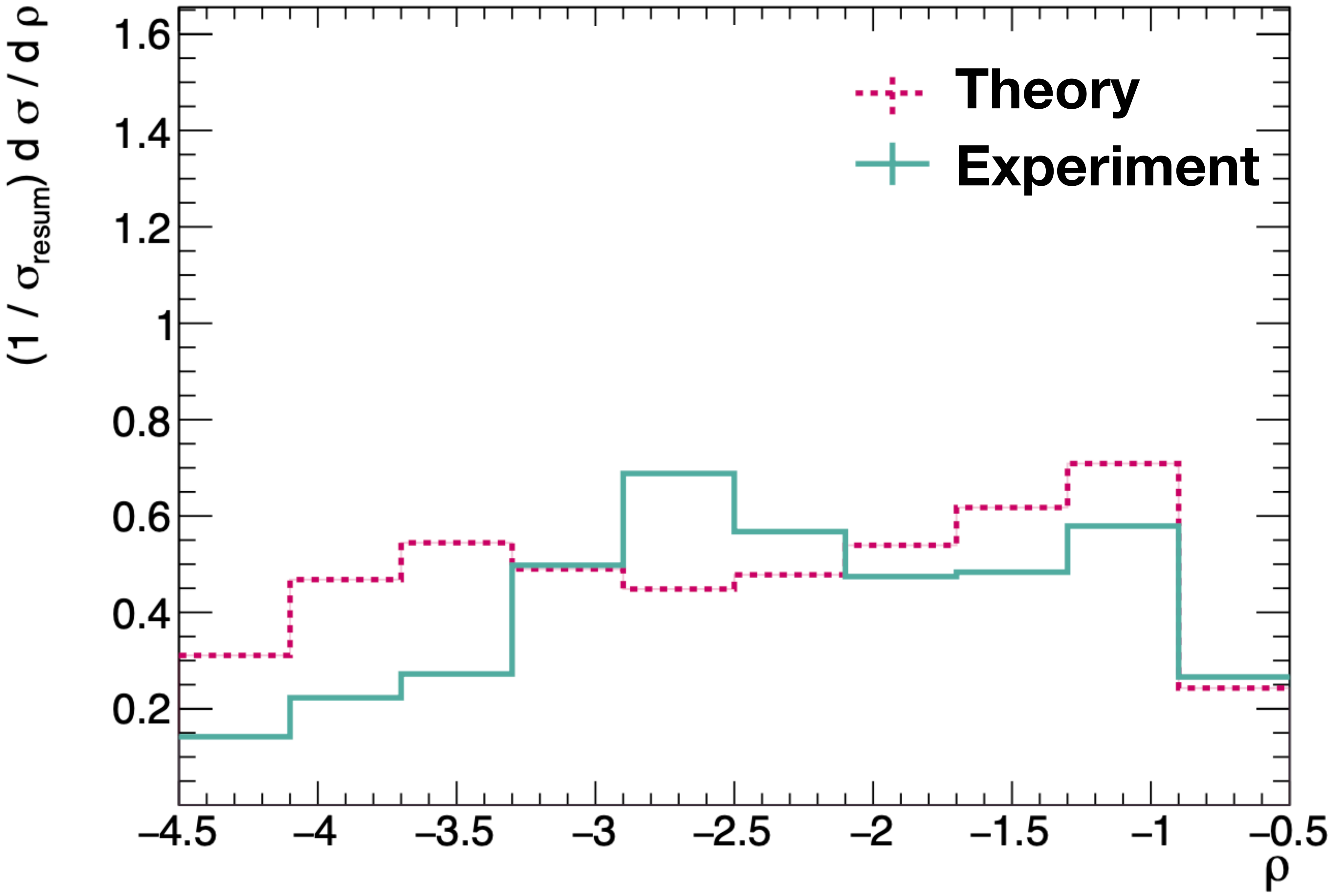
Experimentalist

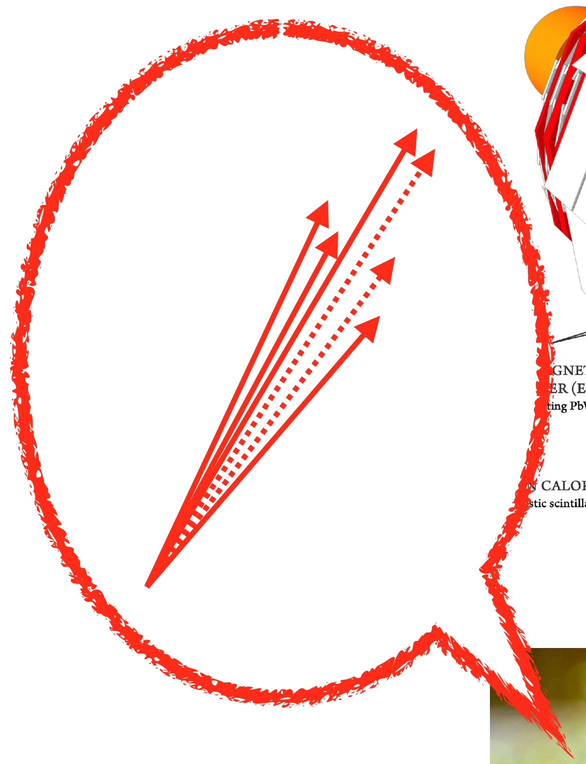


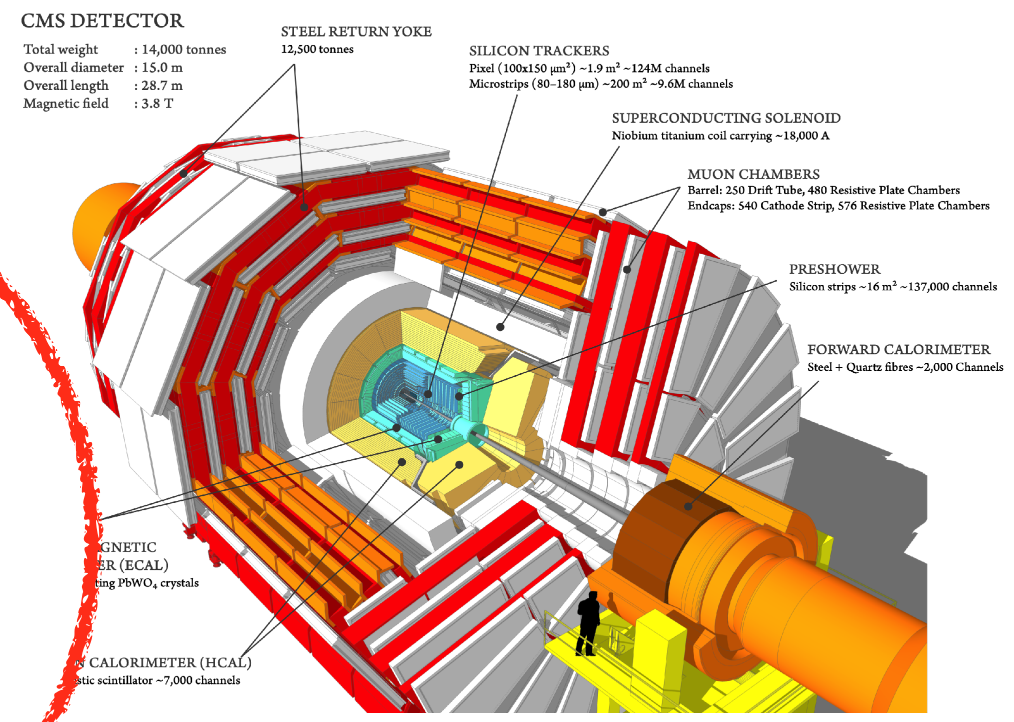




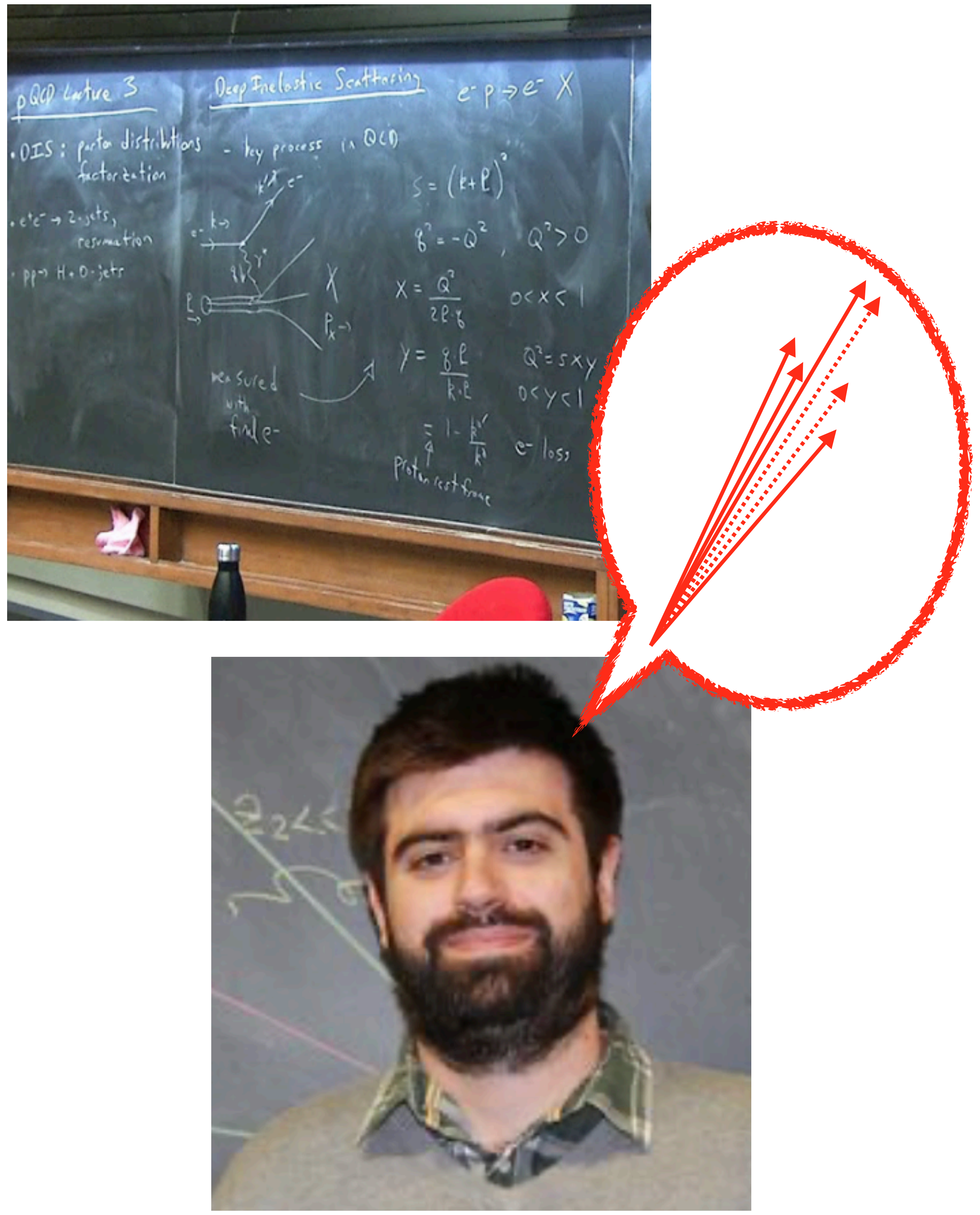
Theorist



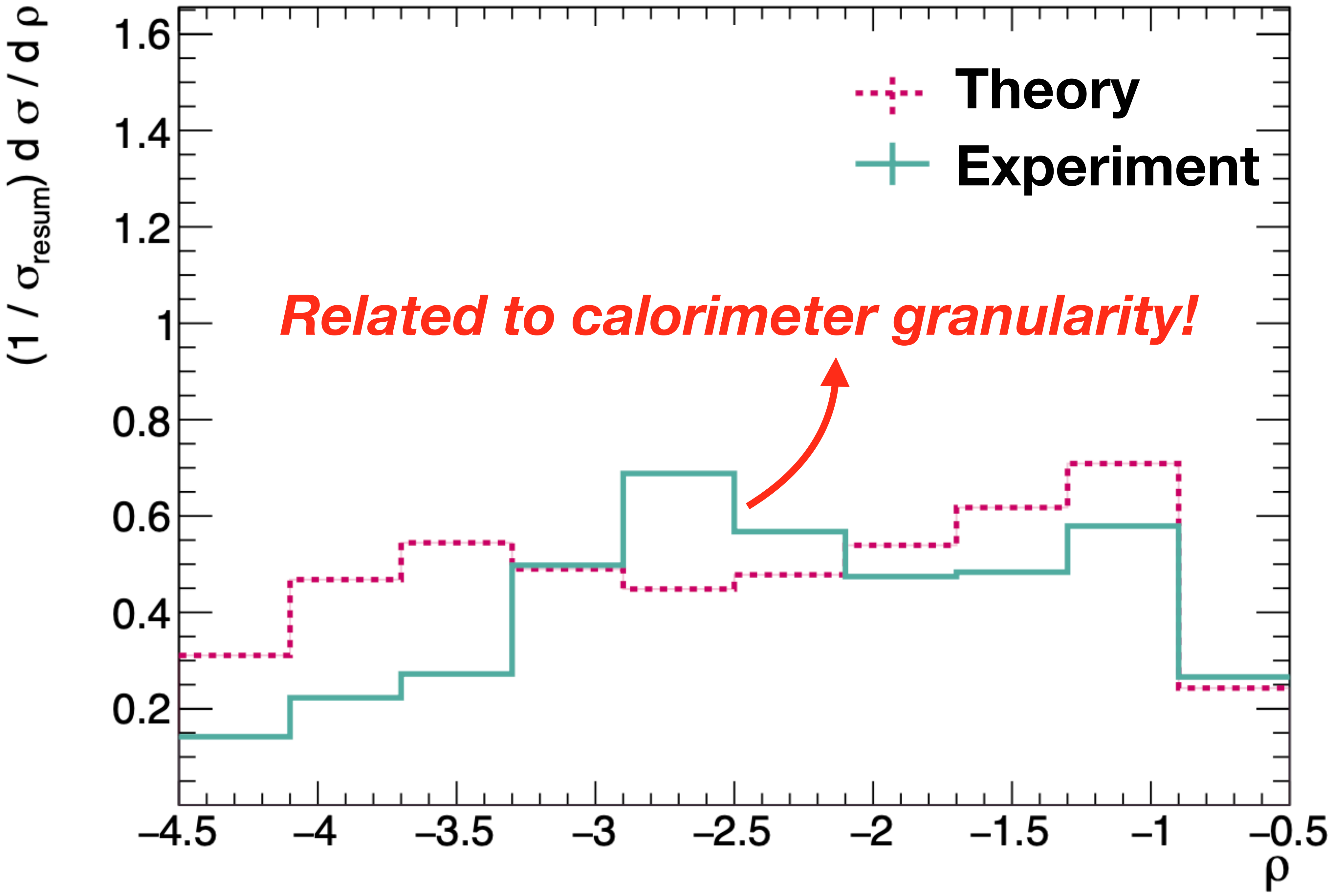


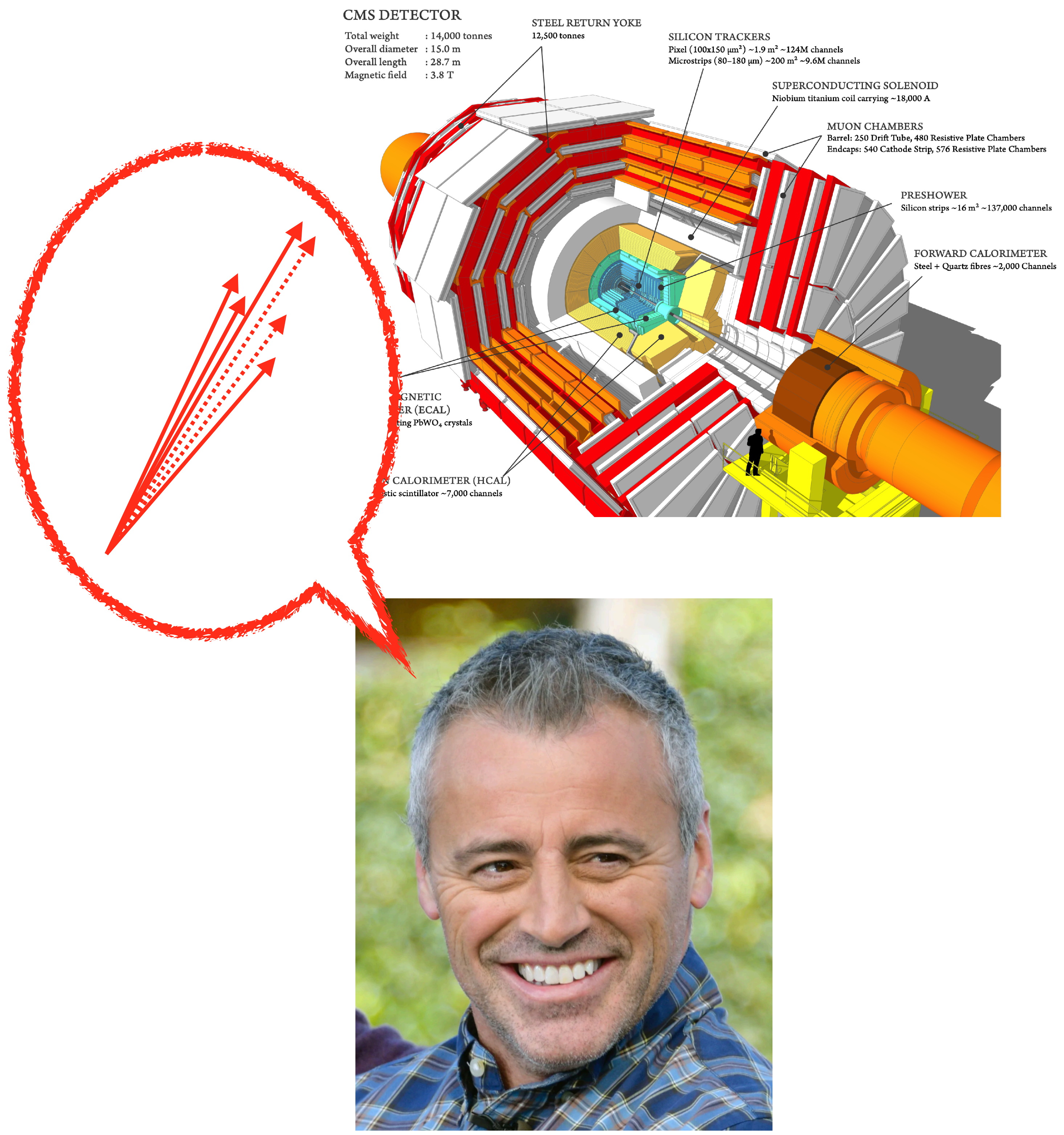


Experimentalist



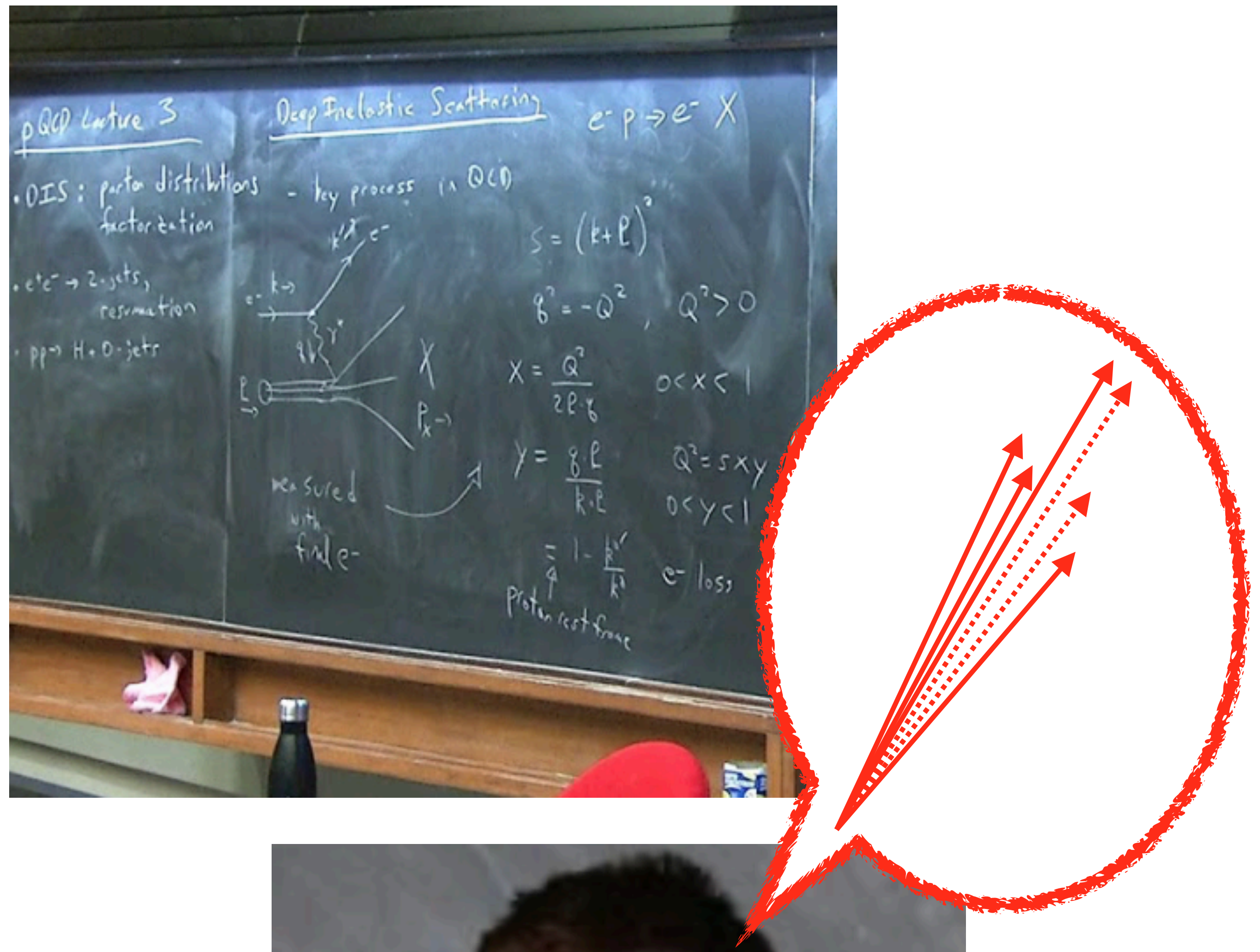
Theorist

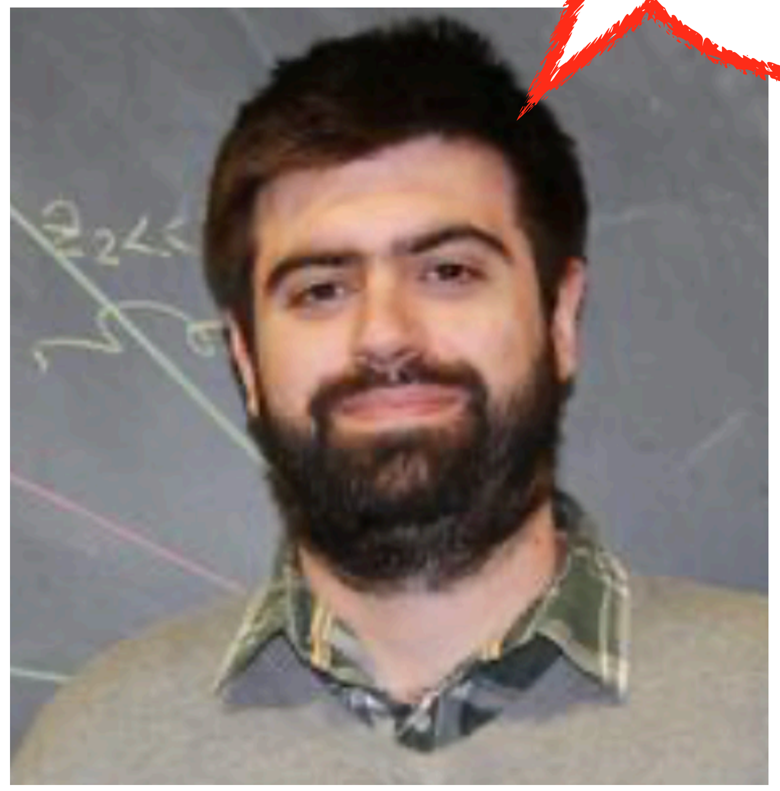




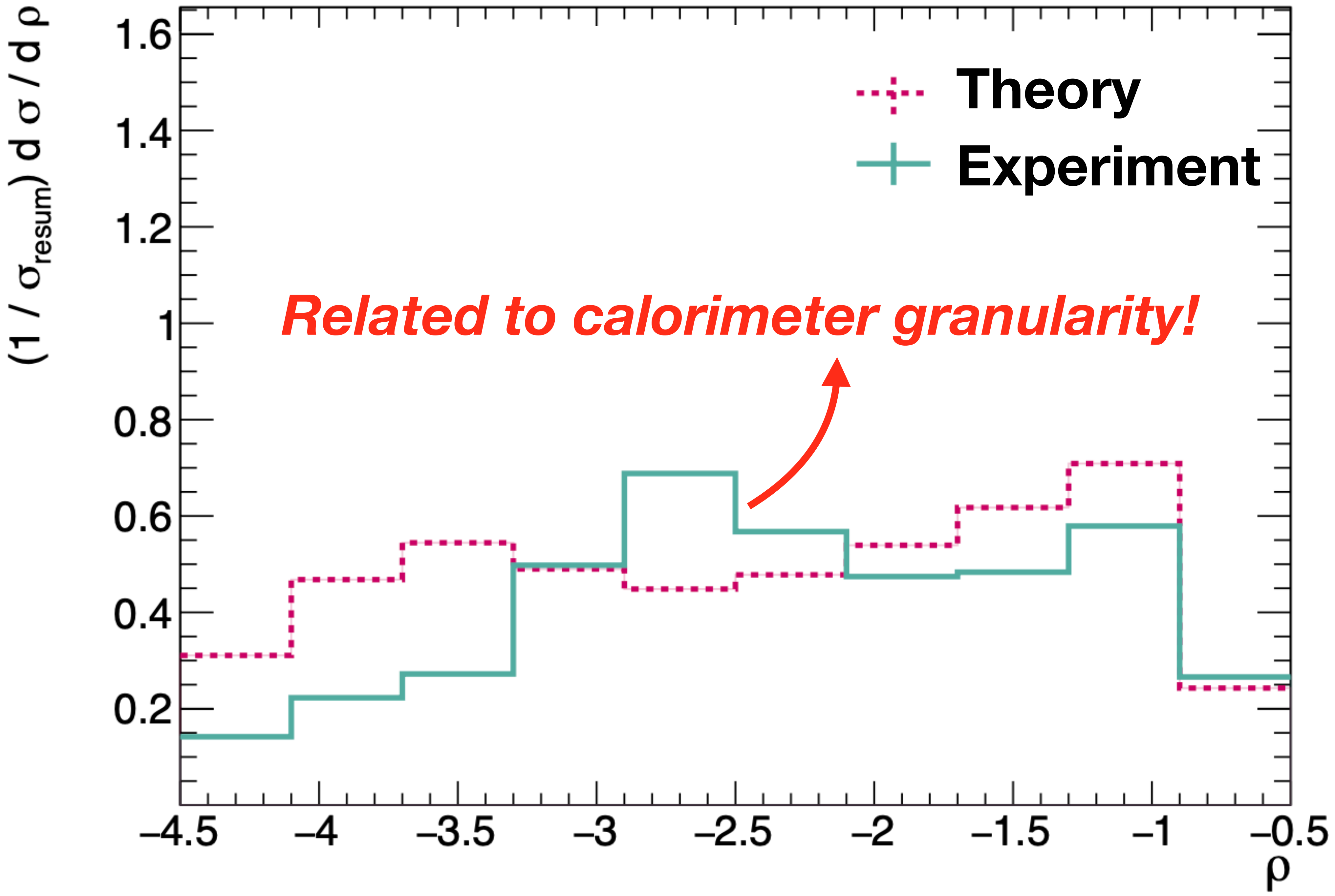
Experimentalist

Unfolding corrects for detector-related resolution & acceptance effects.





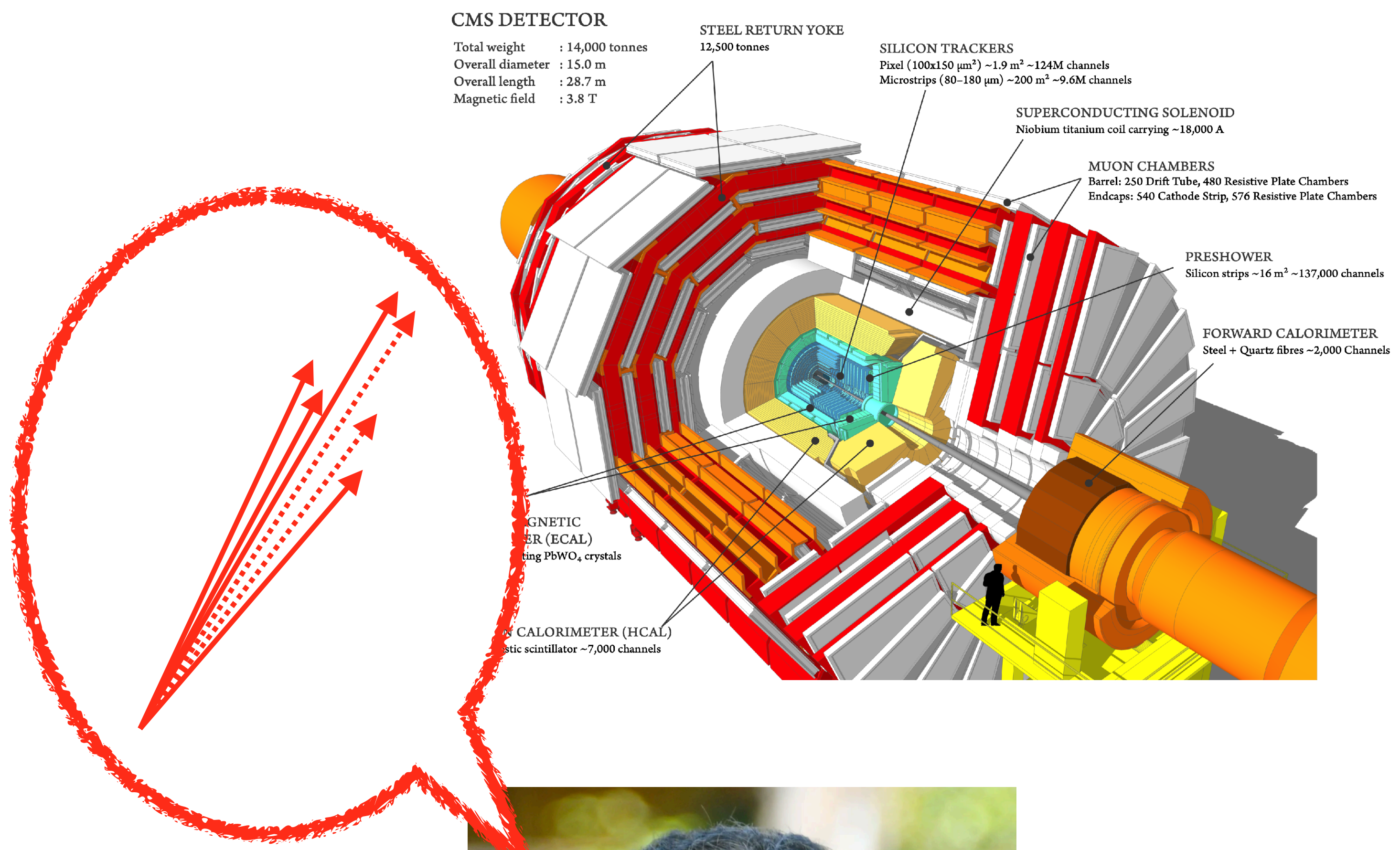
Theorist



n.b. Could also Fold the theory

But other advantages to having unloaded distributions

(Availability for MC tuning, PDF fits, CONTUR, etc.)

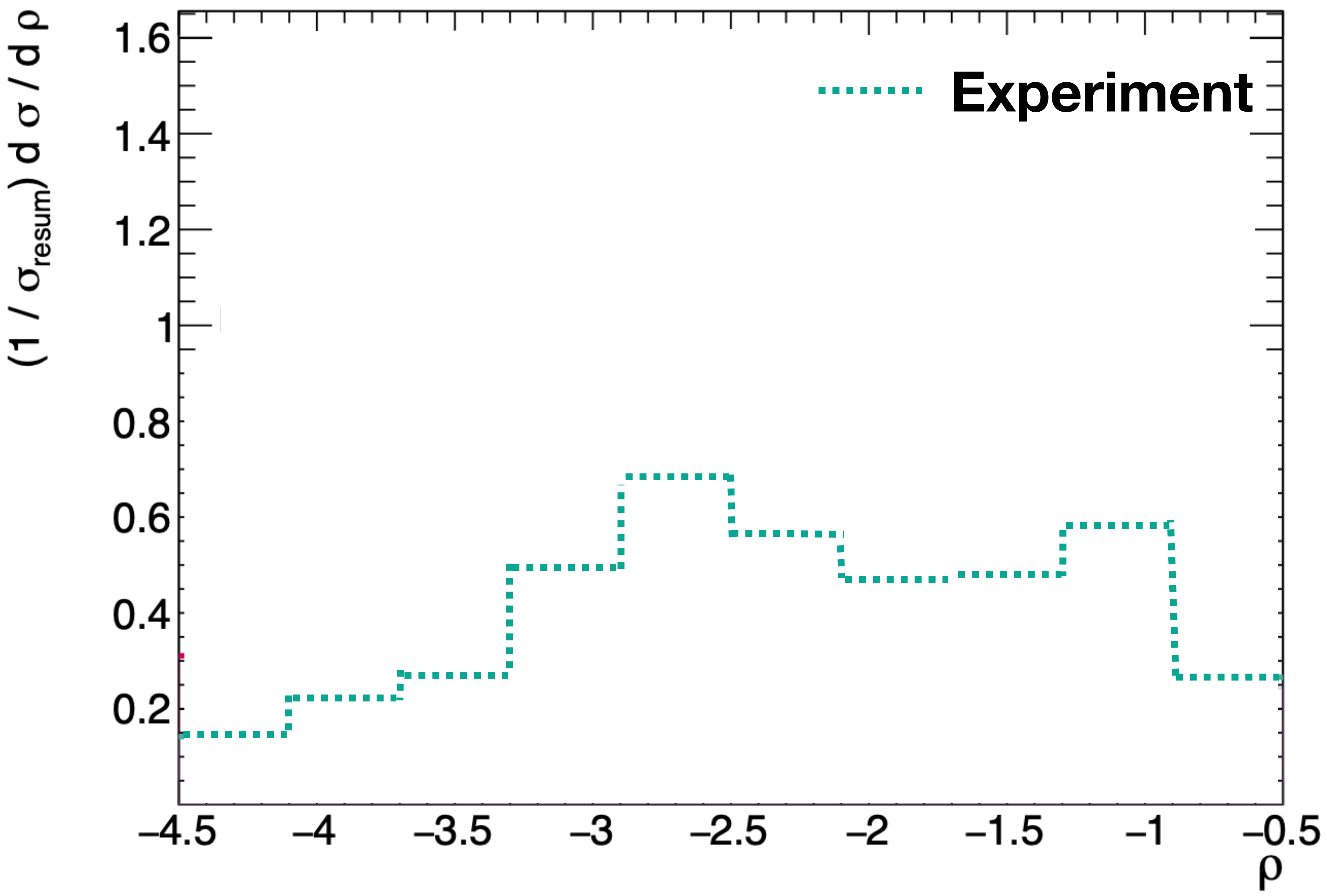


Experimentalist

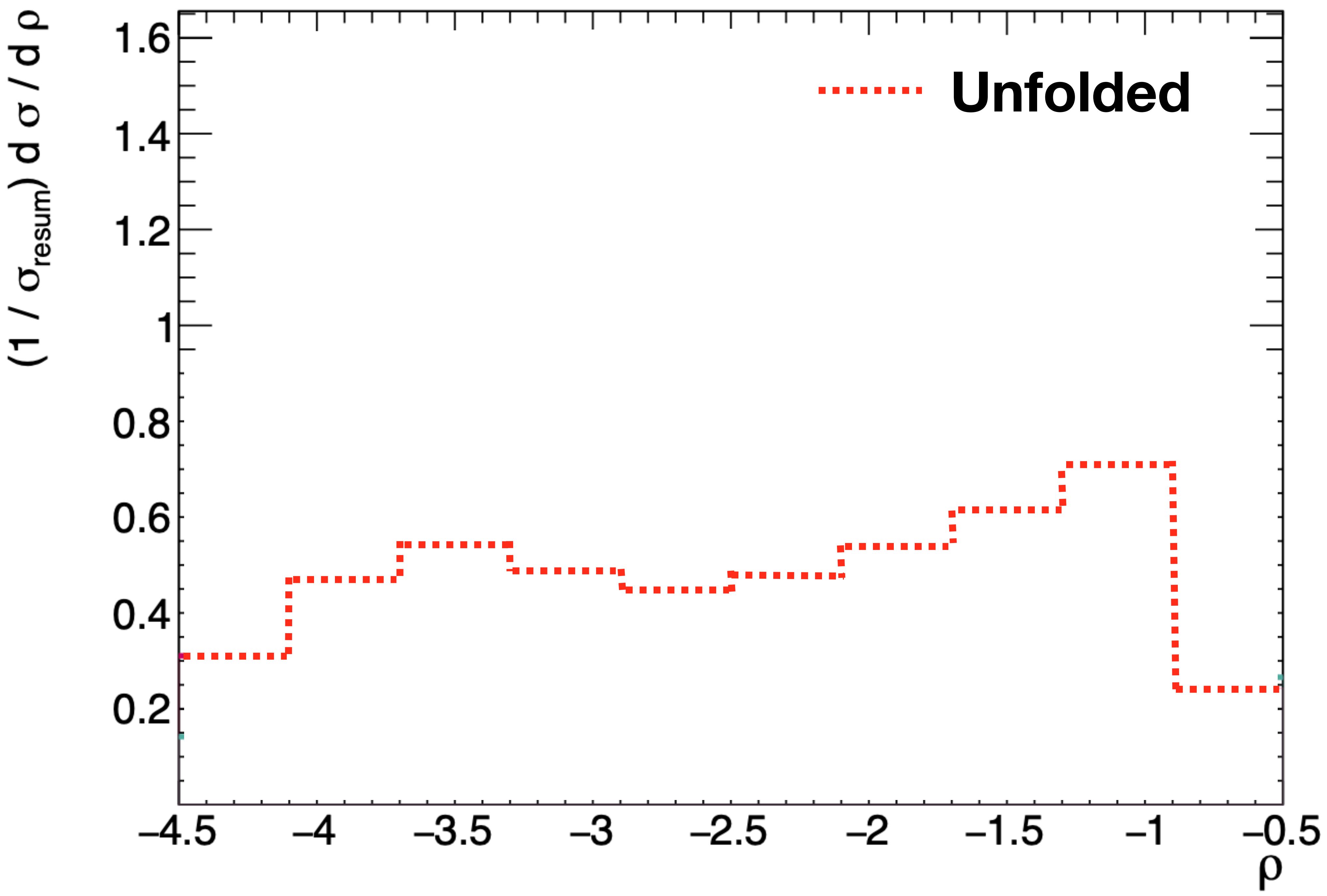
$$\mathbf{g} = K\boldsymbol{\lambda}$$

- $\mathbf{g}$: observed detector-level distribution (‘smeared’)
- $\boldsymbol{\lambda}$: desired particle-level distribution
- K : kernel / response function (map between spaces)

$$\mathbf{g} = K\boldsymbol{\lambda}$$

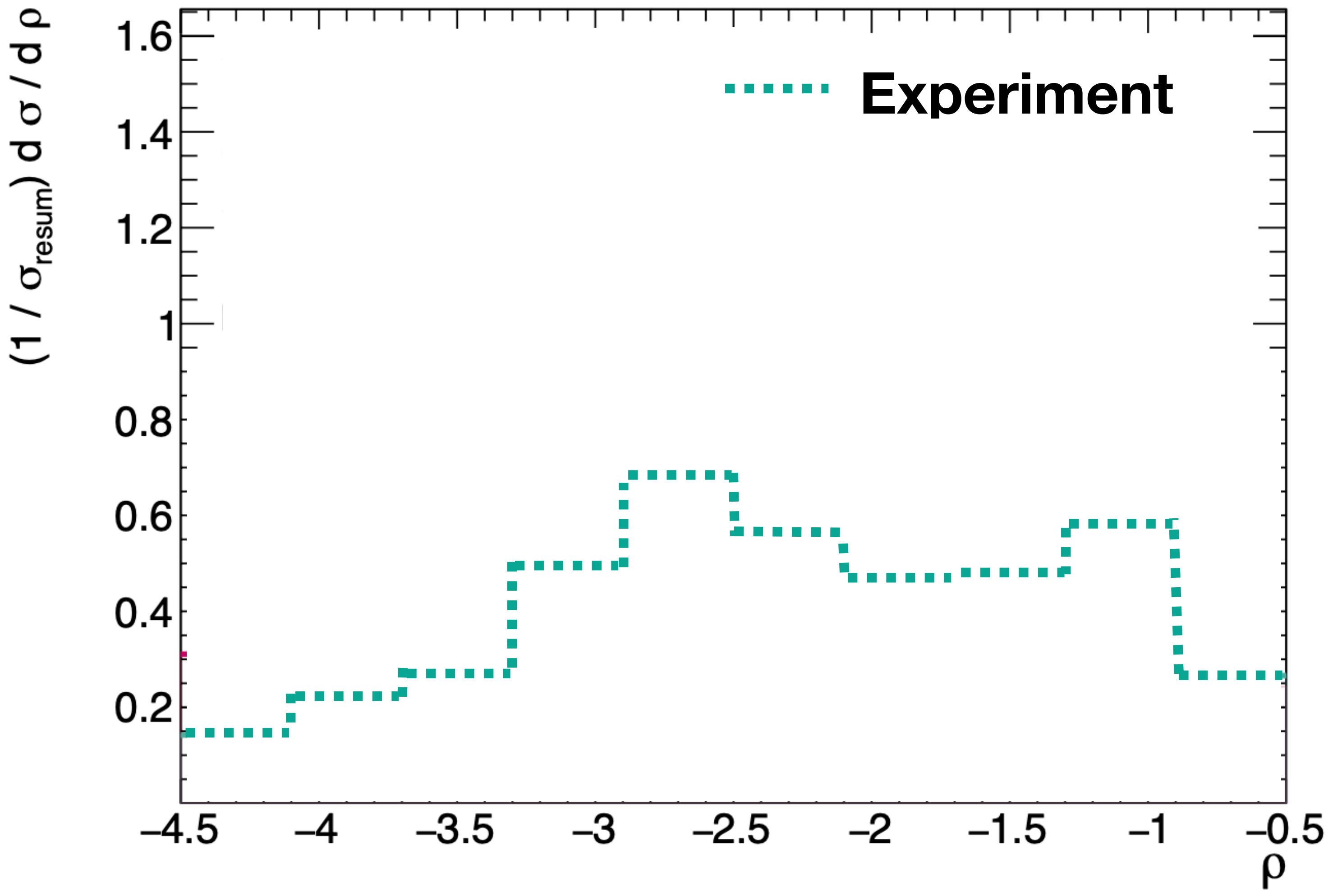


$= K$



- **g** : observed detector-level distribution (‘smeared’)
- **λ** : desired particle-level distribution
- K : kernel / response function (map between spaces)

$\mathbf{g} = K\boldsymbol{\lambda}$



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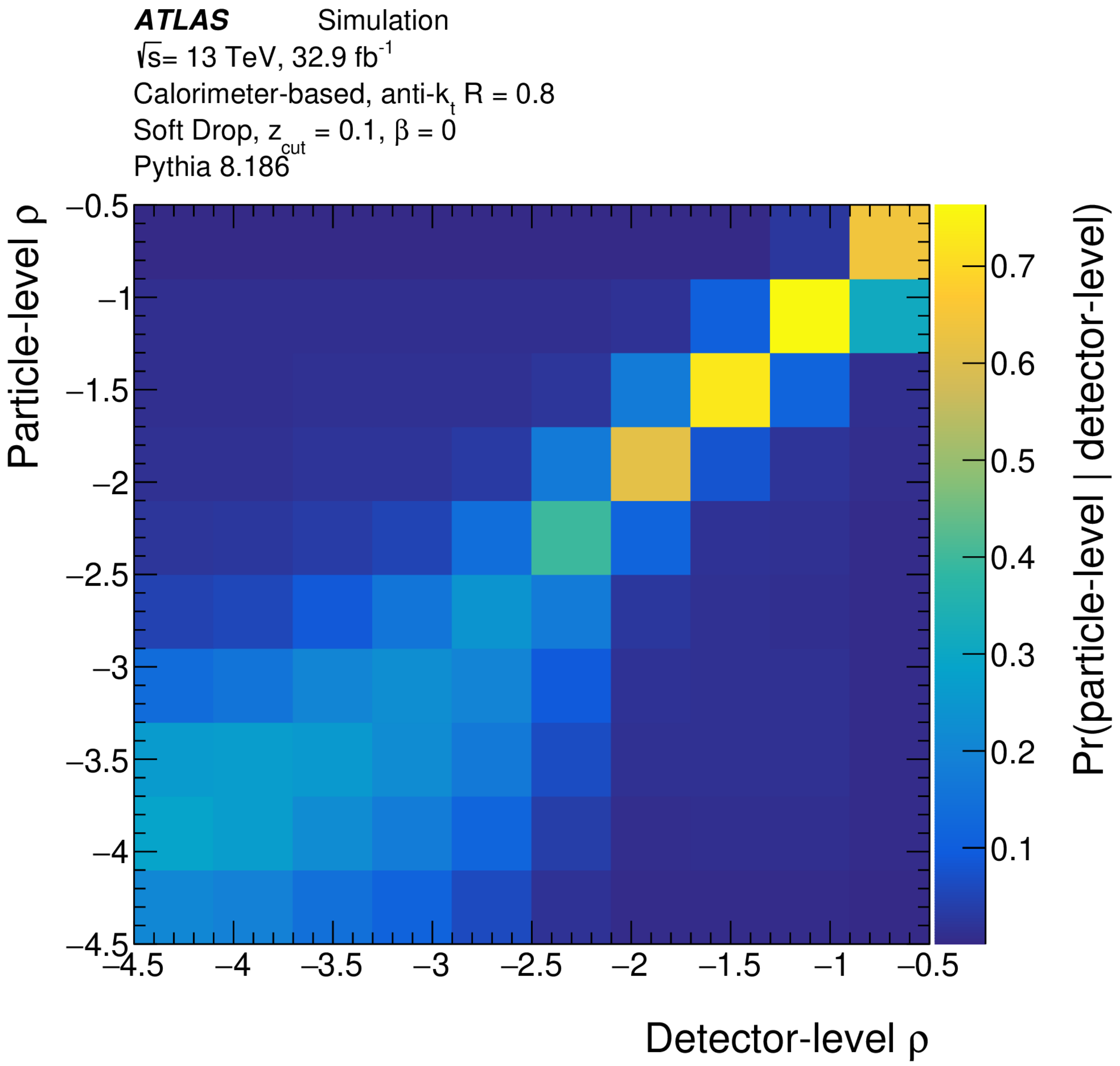
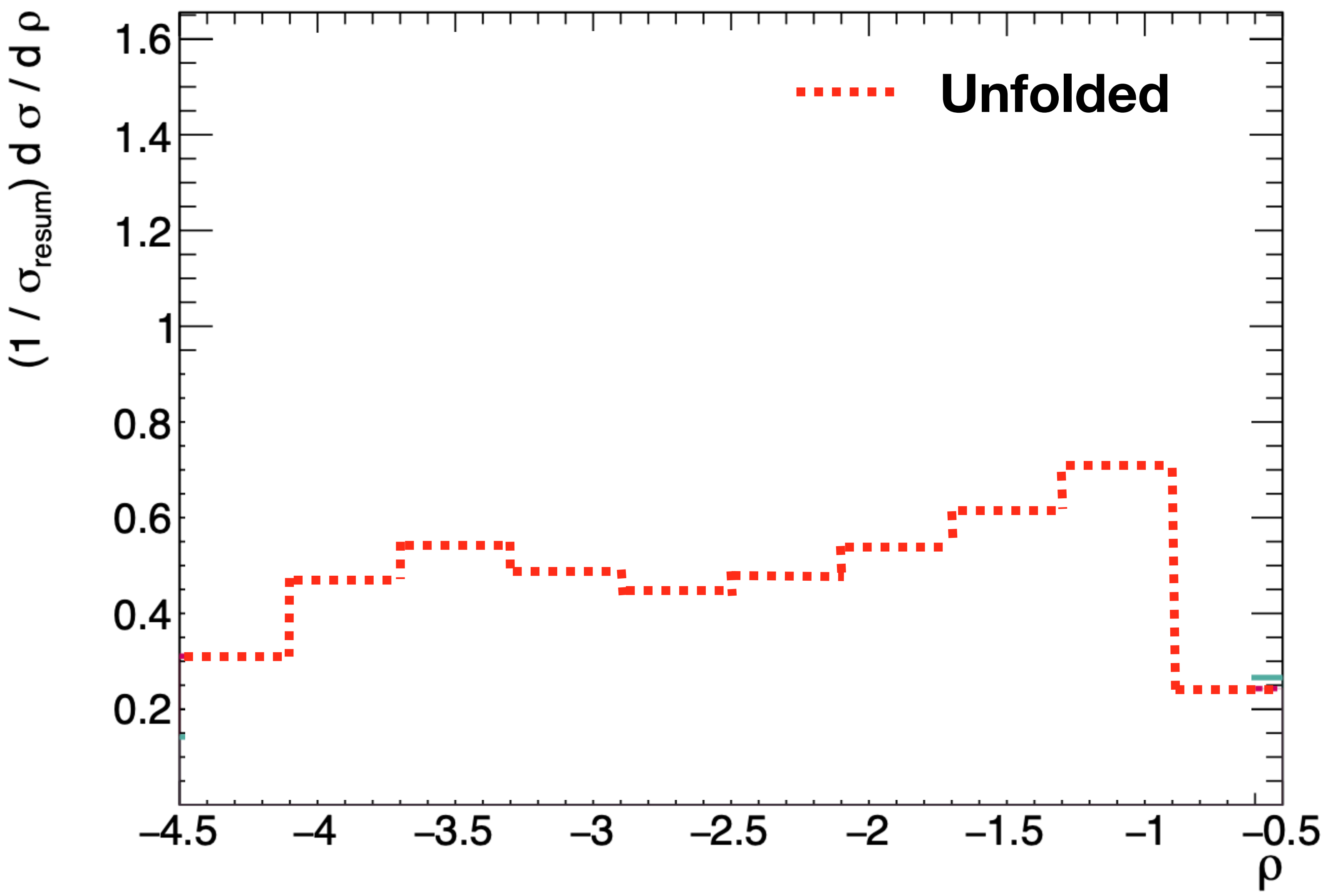




- **g** : observed detector-level distribution (‘smeared’)
- **λ** : desired particle-level distribution
- K : kernel / response function (map between spaces)

MC used to obtain K!
More migrations → more reliant on MC.
(Uncertainties from modeling, non closure etc.)

Unfolding methods & metrics (not exhaustive)

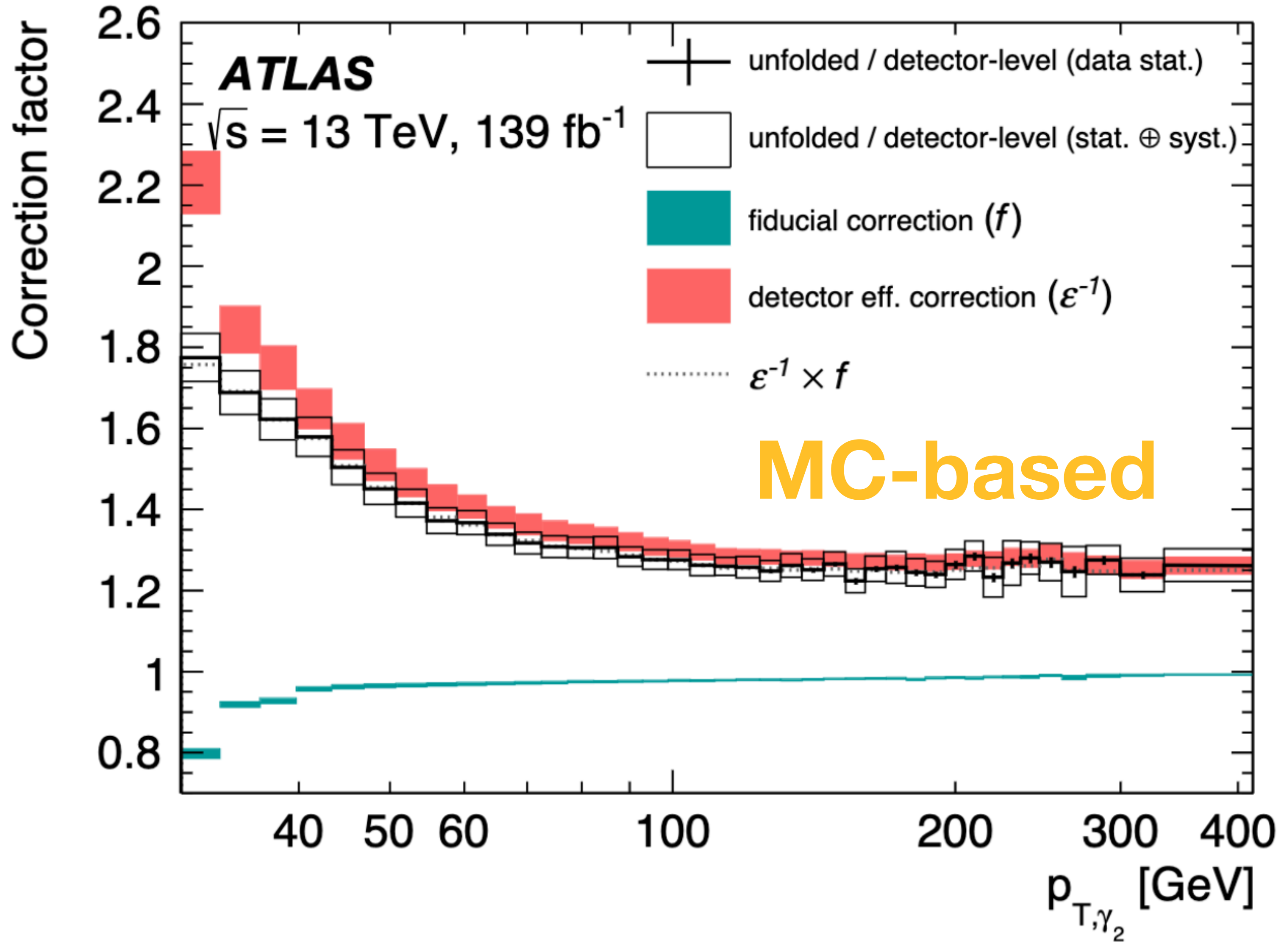
- Unfolding is an "ill-posed" inverse problem; many different approaches to solving it:
  - Binned (matrix-based):
    - Singular Value Decomposition (SVD)
    - Iterative Bayesian Unfolding (D'Agostini)
  - ML-based (see: 2211.01421 Sec. 5):
    - Classifier-reweighing: e.g. Omnifold
    - Generative: e.g. cINNs, flow matching, diffusion [1,2,3,4]
  - Regularization ou non?
- **Choice of method surprisingly contentious: not a good use of time to argue about them now.**
  - 2024 France-Berkeley Unfolding Workshop: https://indico.cern.ch/event/1357972/

- Often asking **similar questions** to assess the performance of these algorithms:
  - **How diagonal is the kernel?** (What is the experimental resolution? → determines bin granularity)
  - **Does changing the prior change the result? Is the method converging?** (→ Non-closure uncertainty)
  - **Is there sensitivity to the MC model used to construct the kernel? Hidden variables?** (→ MC modeling uncertainty, *etc.*)
- Questions tend to matter even more as the kernel becomes further off-diagonal.
  - If there is a large bias, estimates of uncertainties can be untrustworthy.

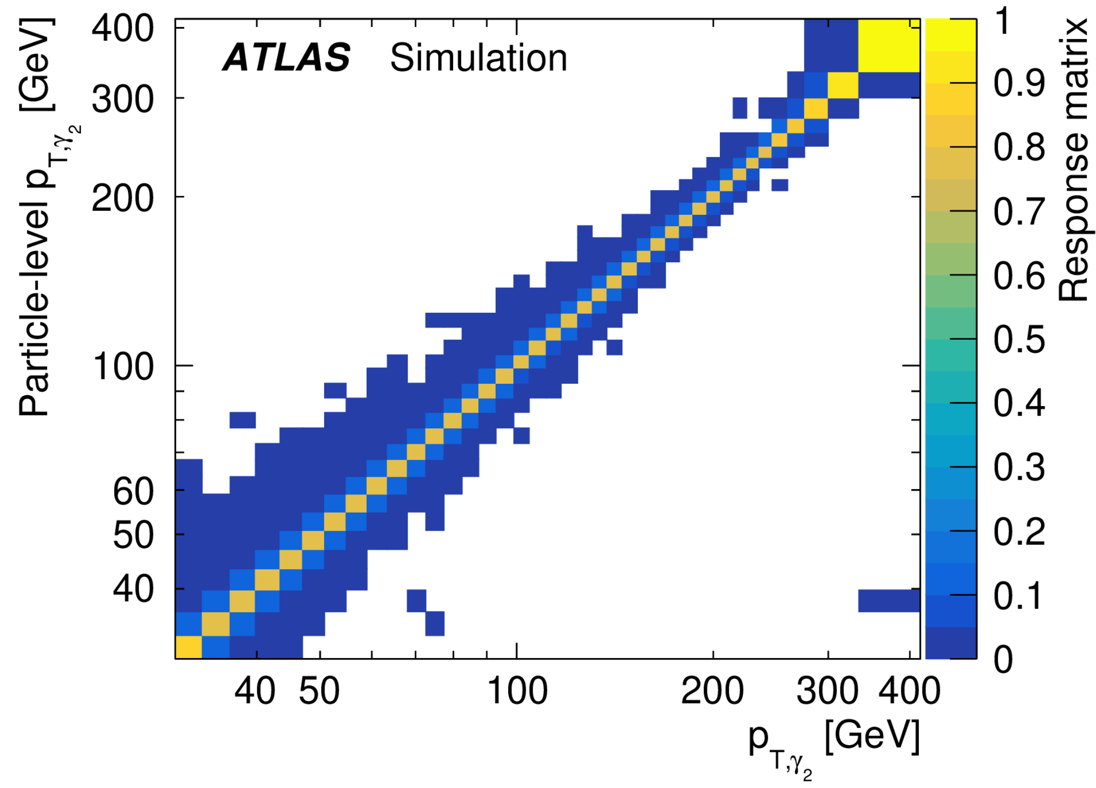
Other aspects: efficiency & purity (fakes) corrections

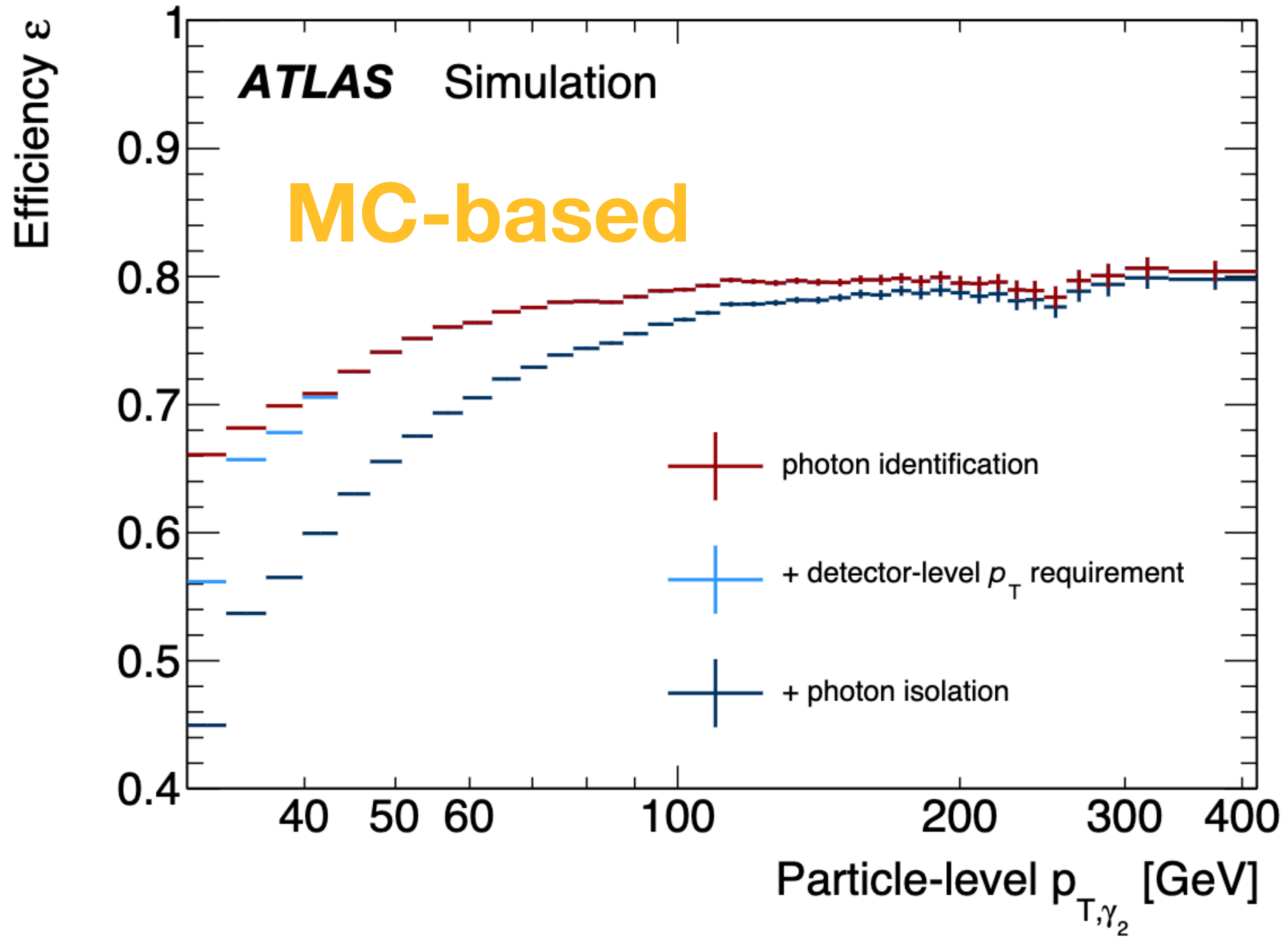
Nice examples — ATLAS Diphotons @ 13 TeV, JHEP 11 (2021) 169

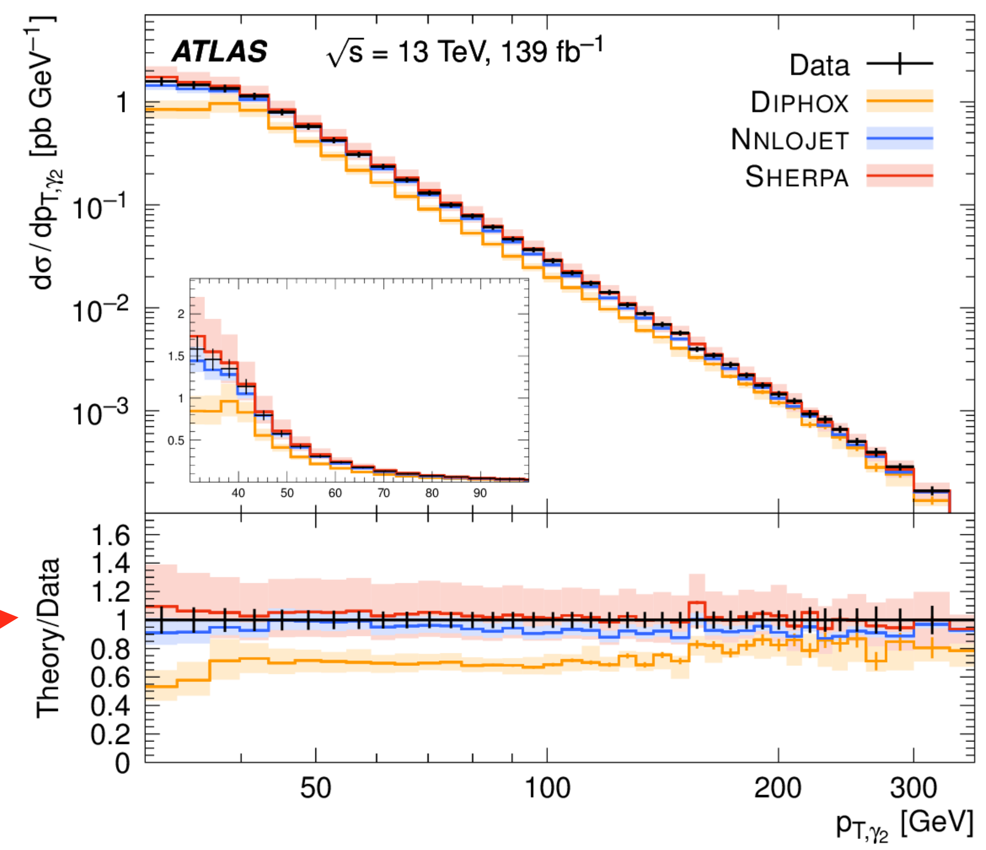
- Also need to account for acceptance-related effects (under/overflow):
  - **Fiducial ('fake-factor') corrections :** pass detector-level selection, not truth-level selection
  - **(In)Efficiency correction :** pass truth-level selection, not detector-level selection
- **Often estimated directly from MC.**
  - Can add 'sideband' under/overflow regions to kernel to decrease extrapolations, reliance on MC.



Regularized (Data-driven)



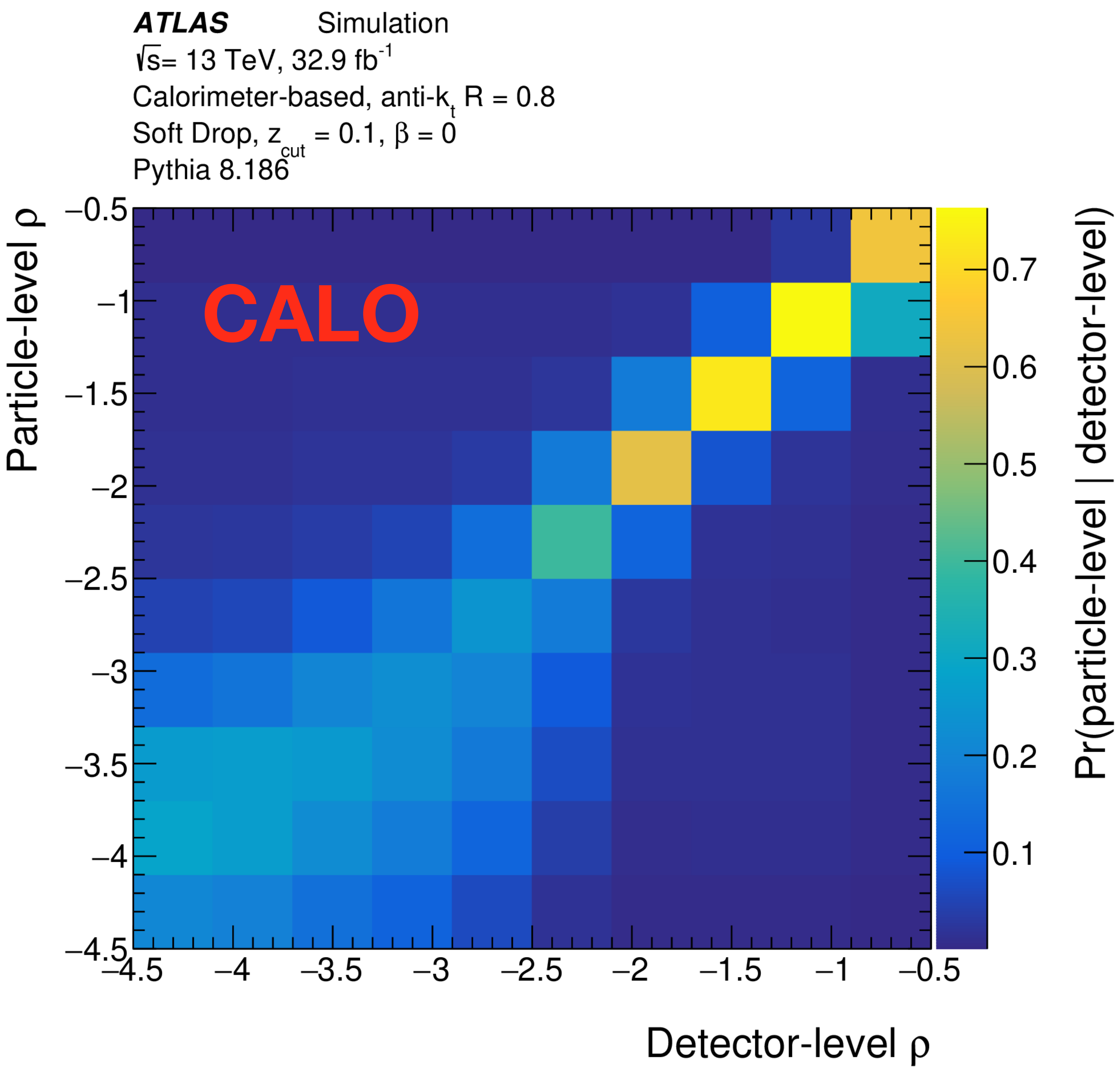


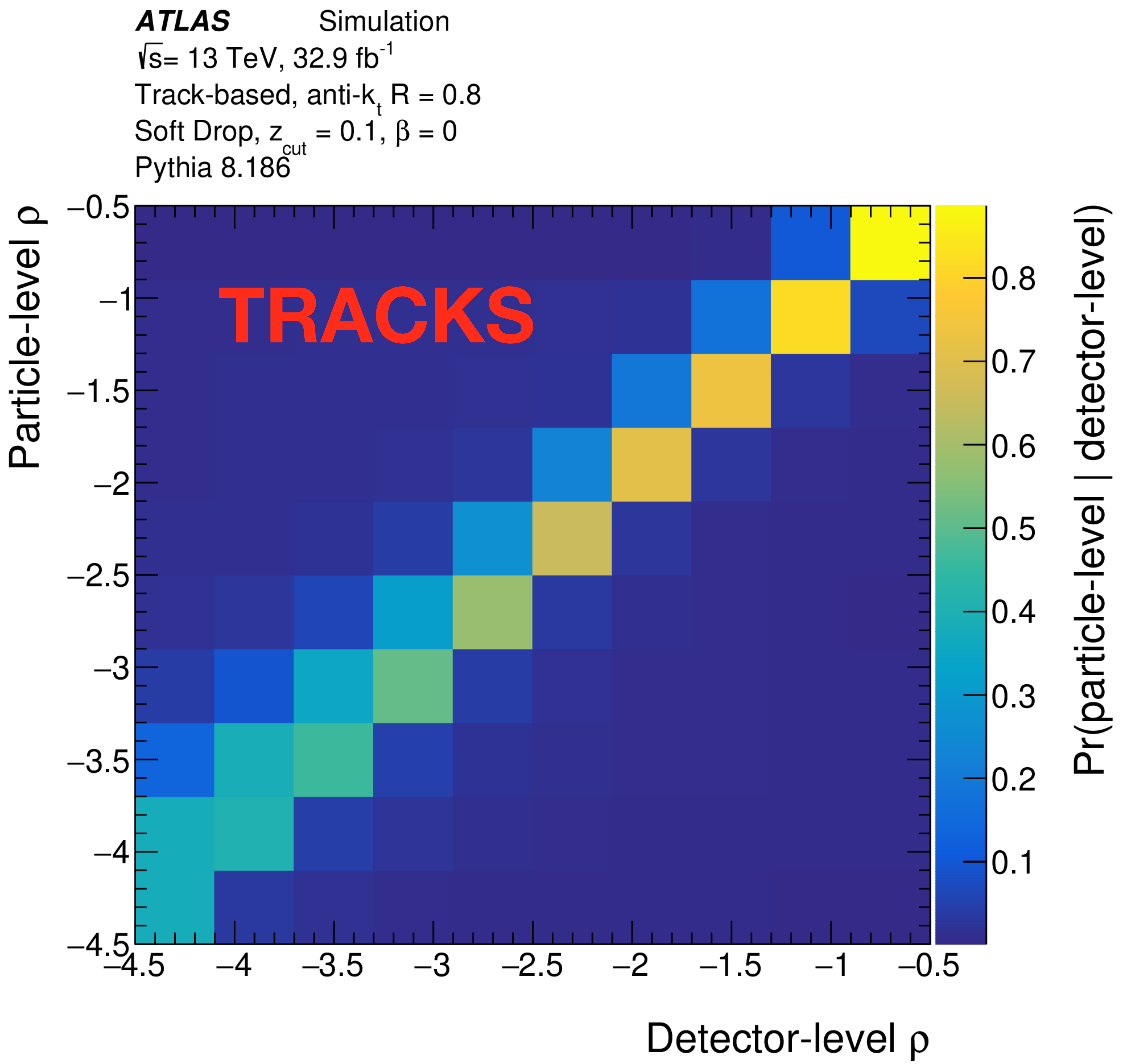


n.b. results end at 300 GeV, but matrix goes further!

Soft-drop observables: calo vs. track response matrices

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



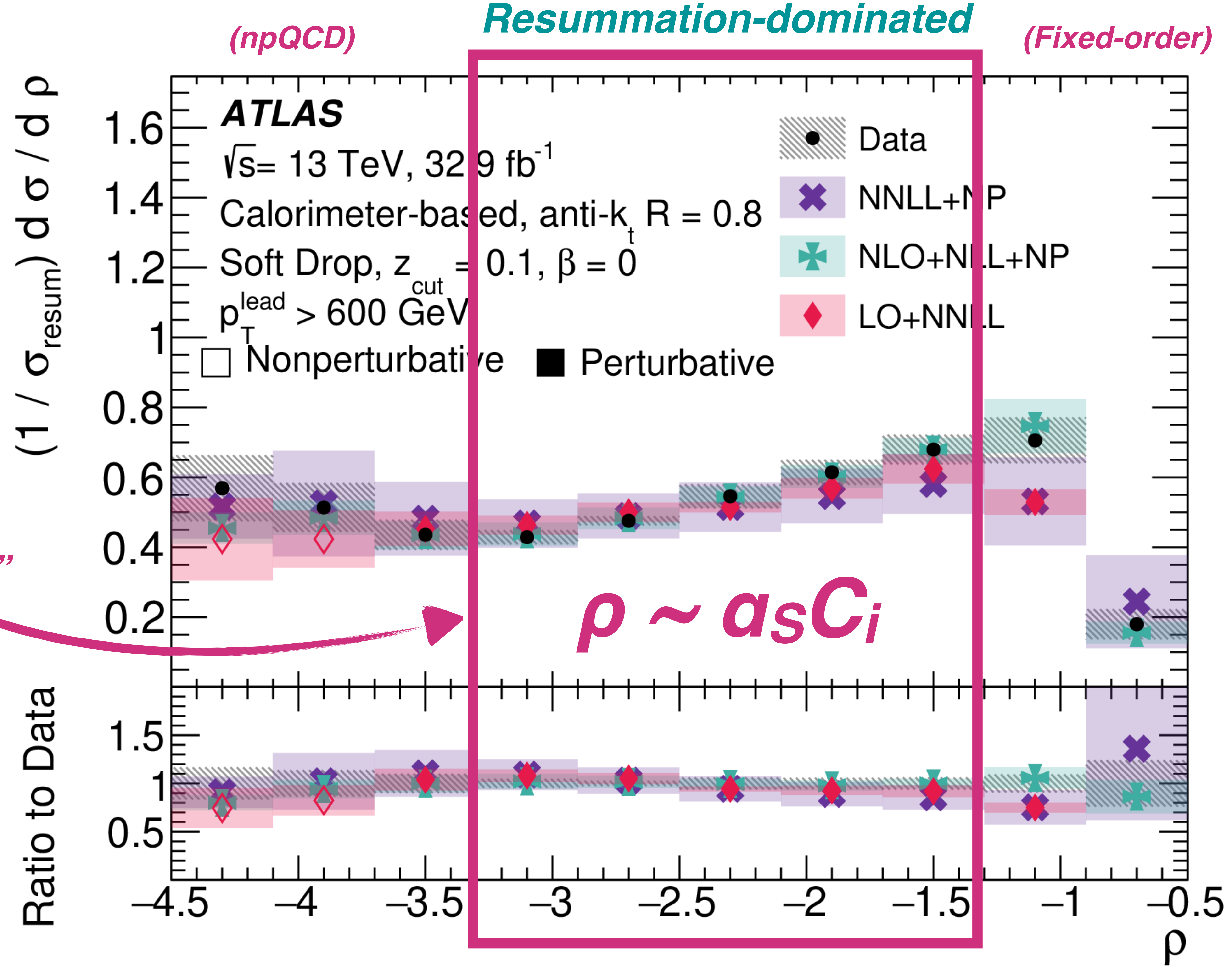


Soft-Drop Jet Mass

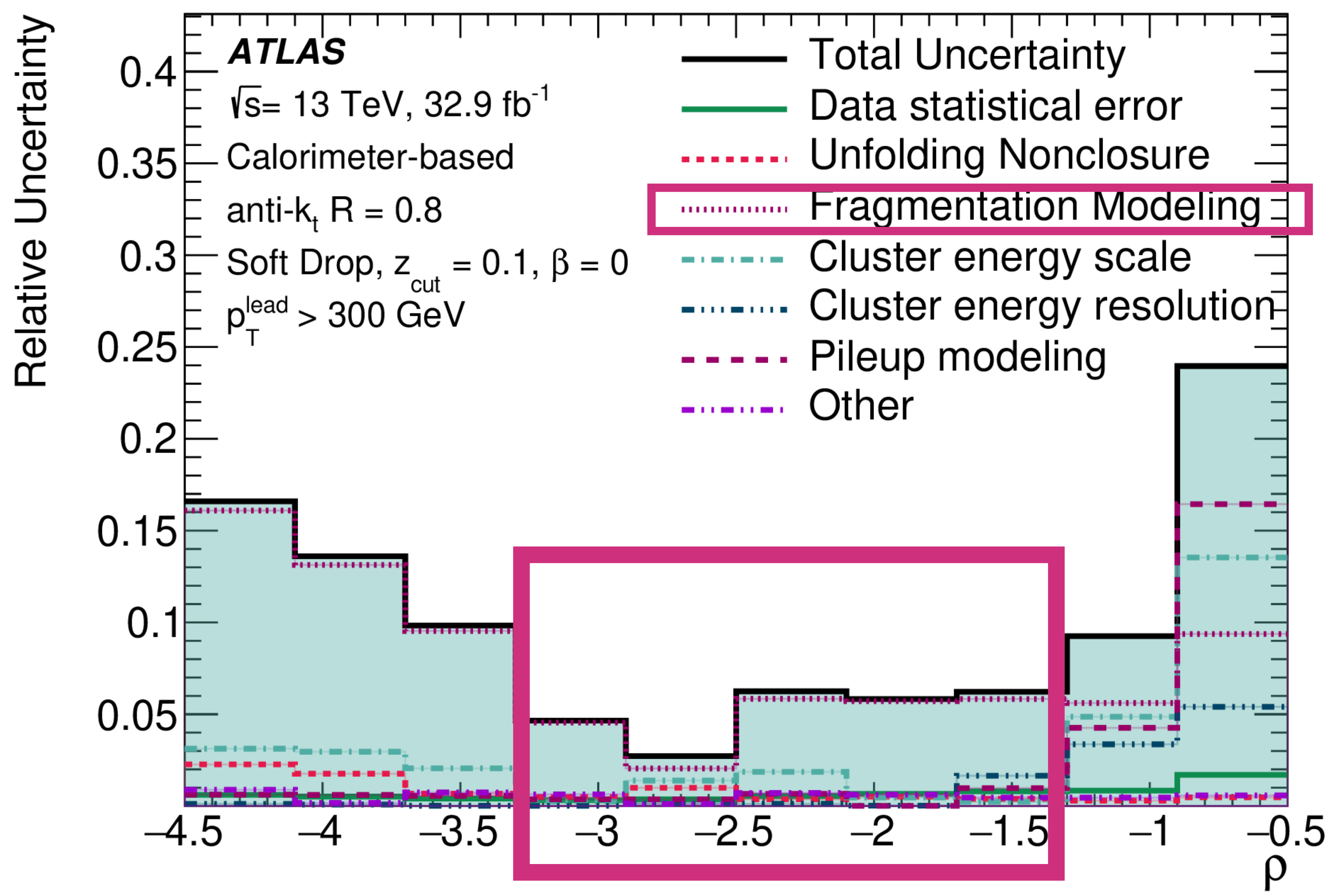
ATLAS, Phys. Rev. D 101, 052007 (2020),
& earlier, Phys. Rev. Lett. 121, 092001 (2018)

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

Resummation-dominated



Calculations target "resummation" region!



Unfolding w/ different MC setups leads to large systematics in NP-QCD region

Note: non-closure uncertainty still small in this region!

Concluding remarks

Recap:

- **Detectors:** increased segmentation allows for better signal calibration and less readout noise. Please remember this when you are thinking about future collider detectors!
- **Particle Flow:** optimal combination of calo & tracker signals important for JSS performance.
- **Pile-up:** best to mitigate a little in each step (cluster/track reco, constituent-, jet-level, *etc.*).
- **Heavy ions:** centrality quantifies the fraction of participating nucleons in a collision.
- **Jet Tagging:** many approaches being used simultaneously for different purposes: important to also understand older approaches, context in which they are used.
- **Unfolding:** different approaches are used, but we typically ask similar questions to assess performance.

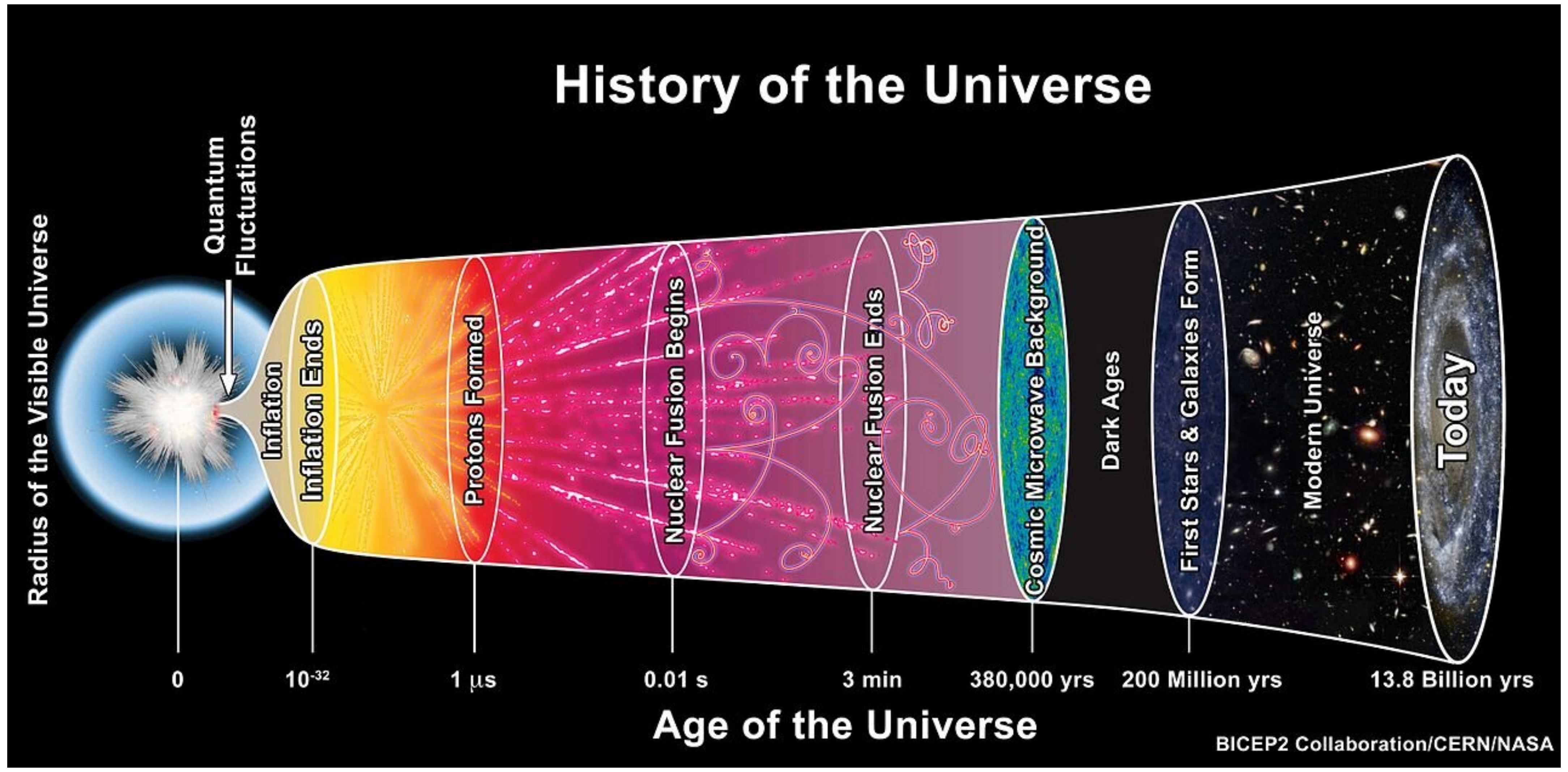
Let's BOOST!

Thanks for listening!

BROWN

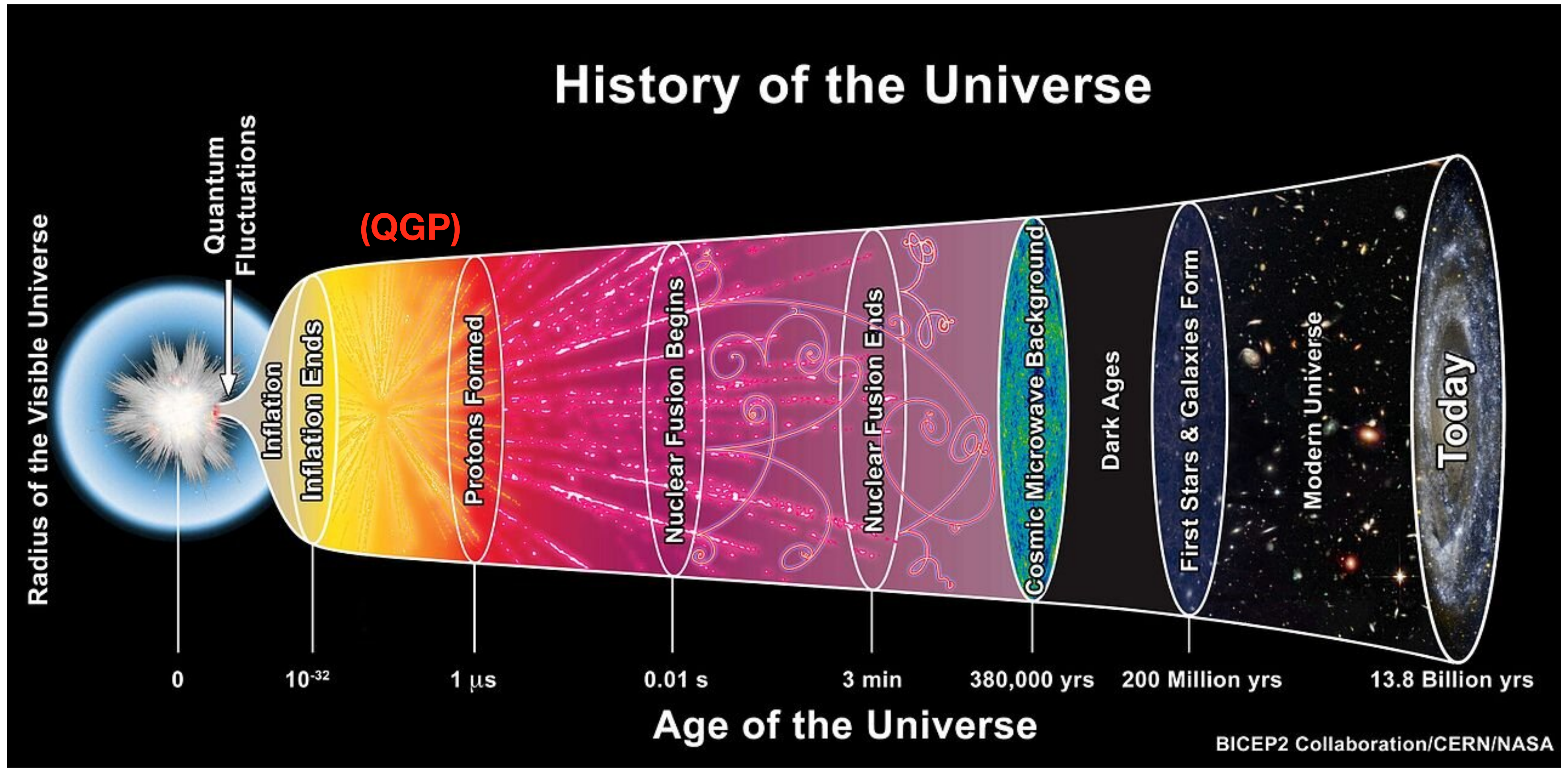
Auxiliary material

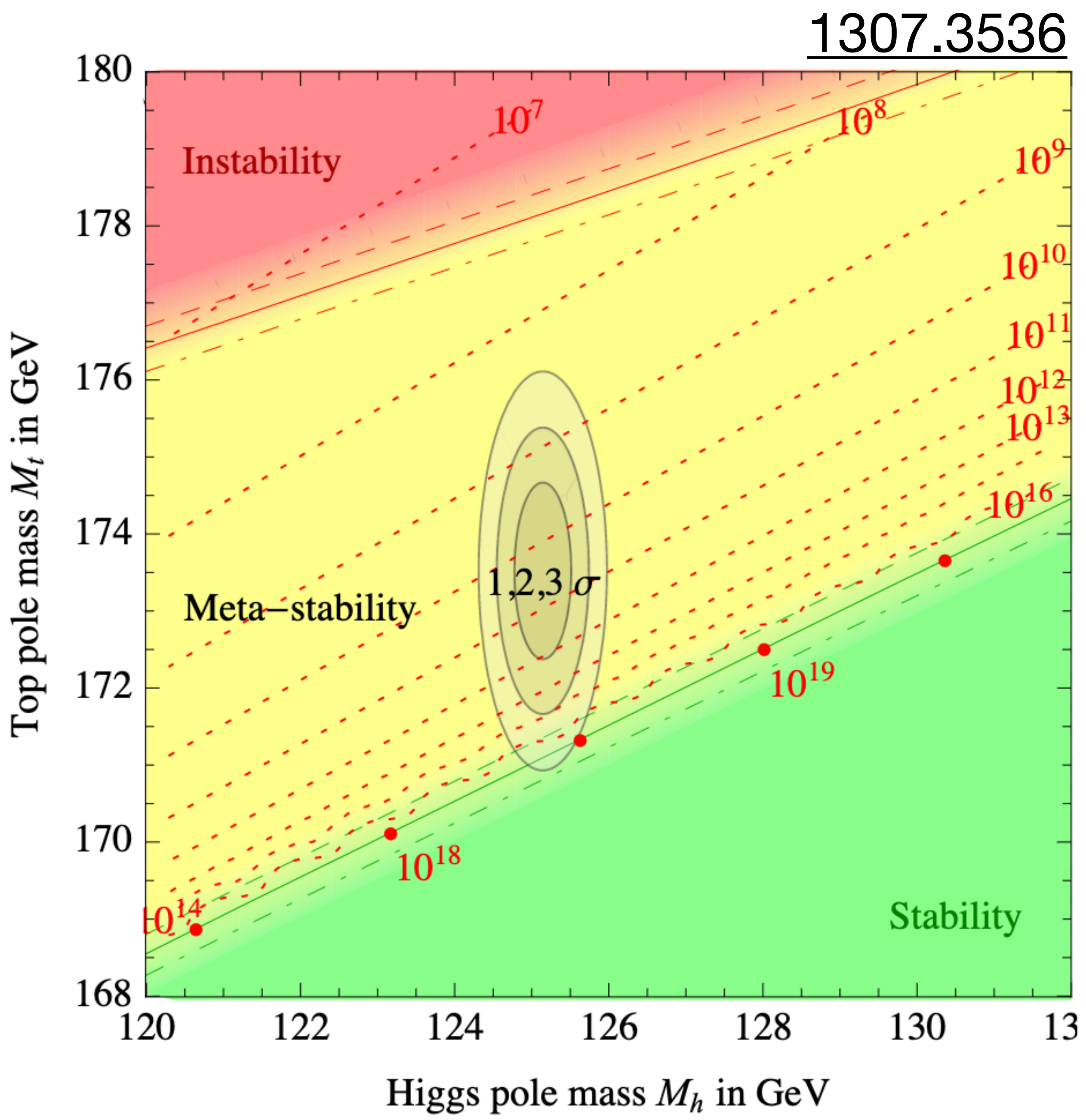
Particle Physicists learn about our universe by studying the properties of particles.

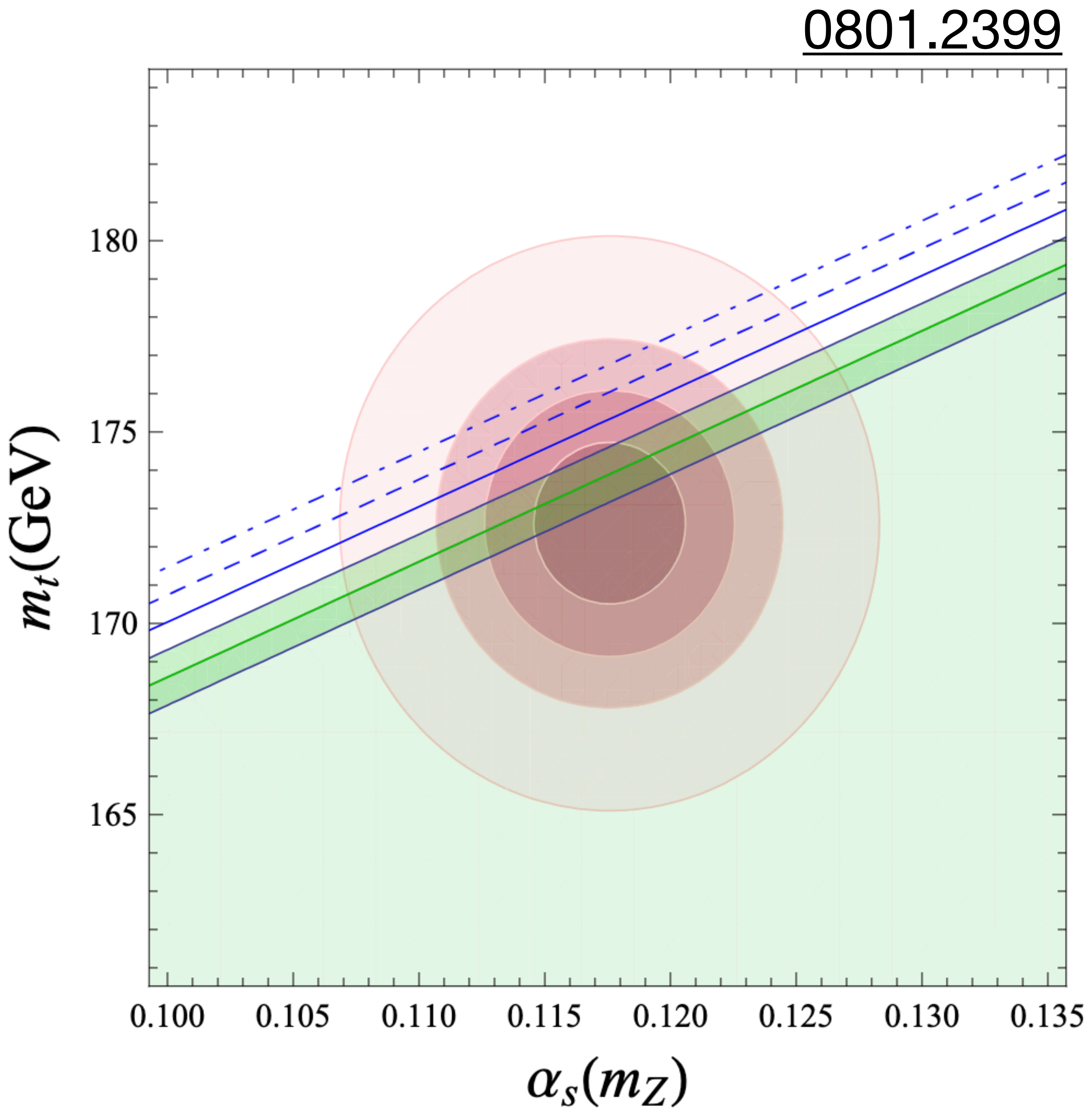


What was the nature of our early universe?

Particle Physicists learn about our universe by studying the properties of particles.





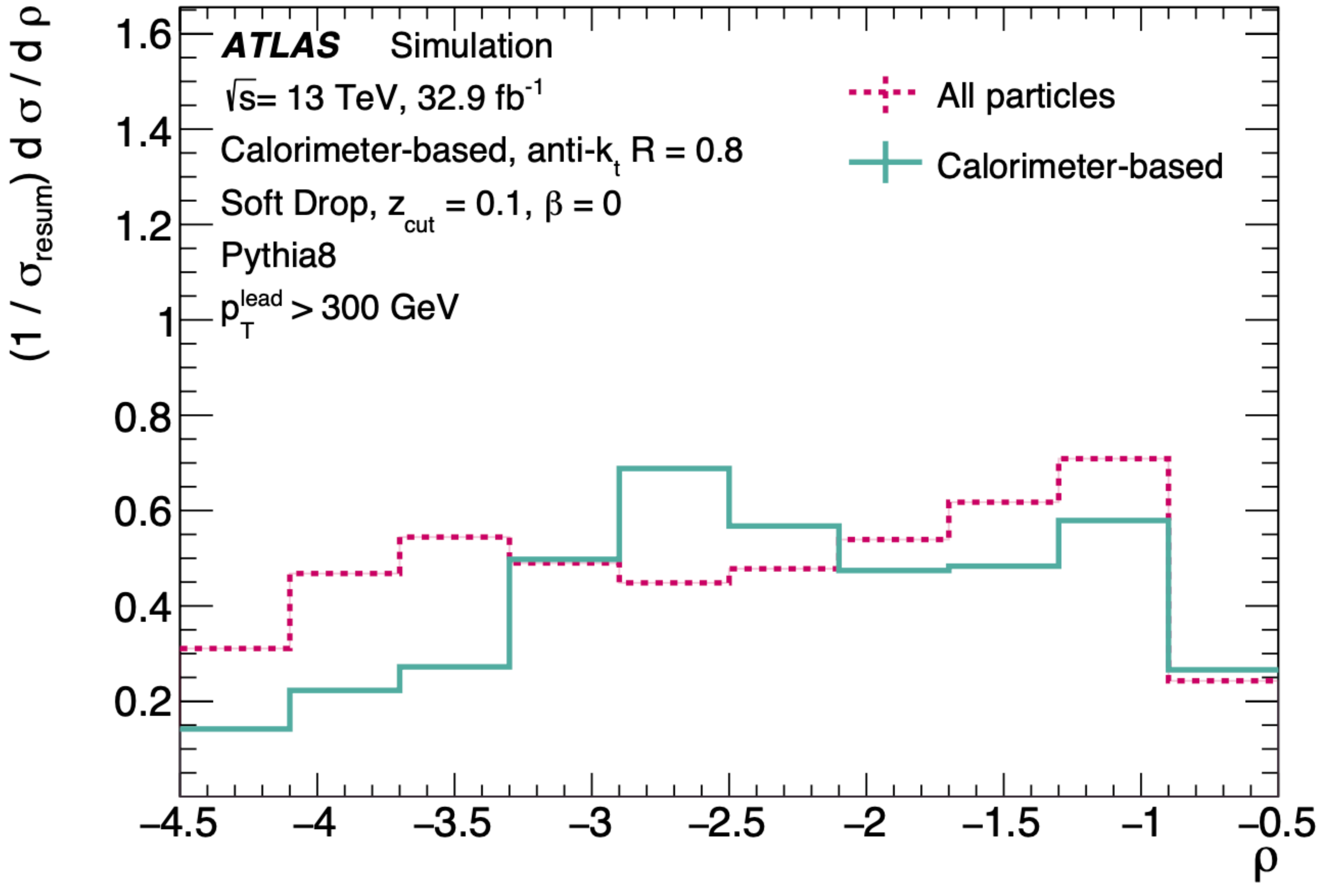


What was the nature of our early universe?

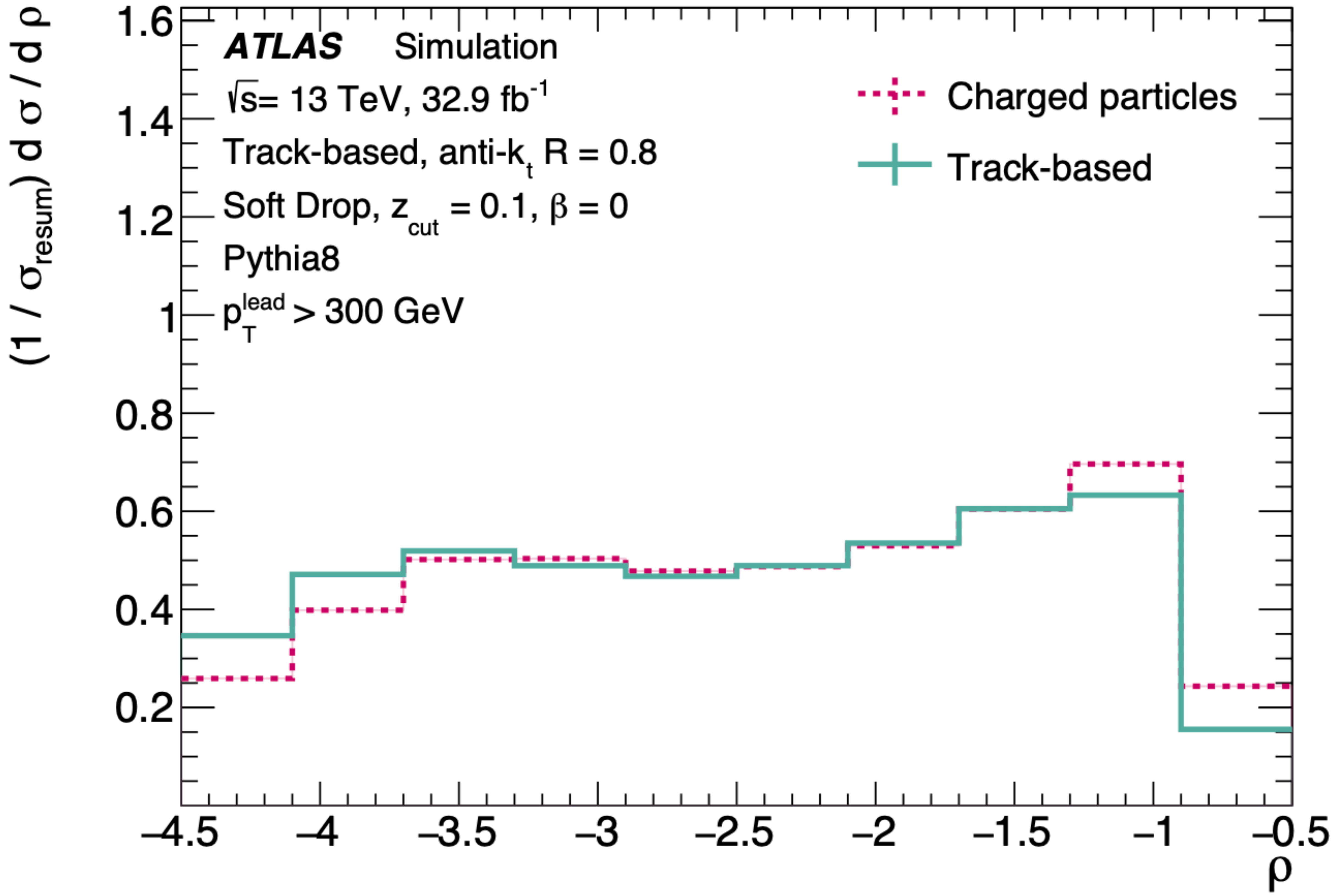
… and what is its ultimate fate?

Soft-drop observables: calo vs. track before unfolding

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



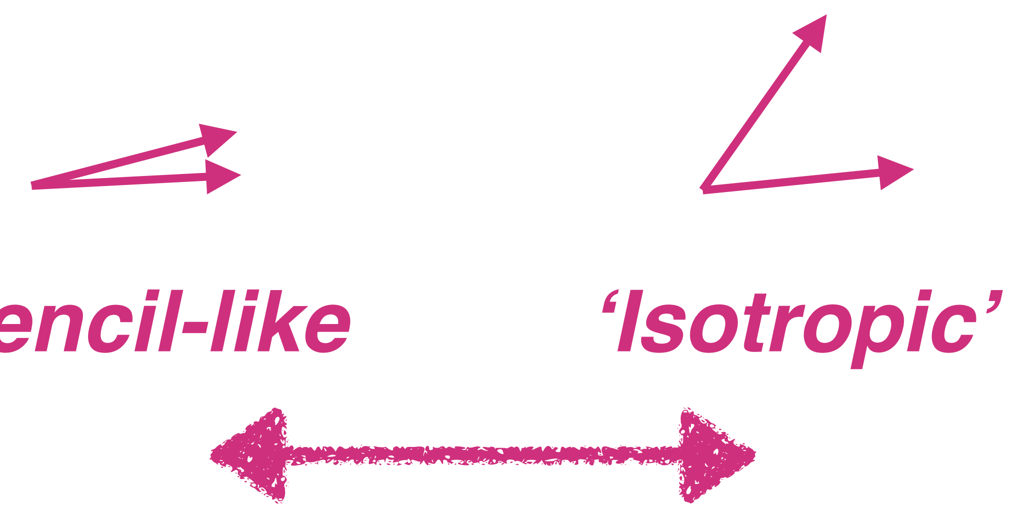
Calo-based



Track-based

Aside: CMS JSS Angularities Measurement

CMS, JHEP 01 (2022) 188

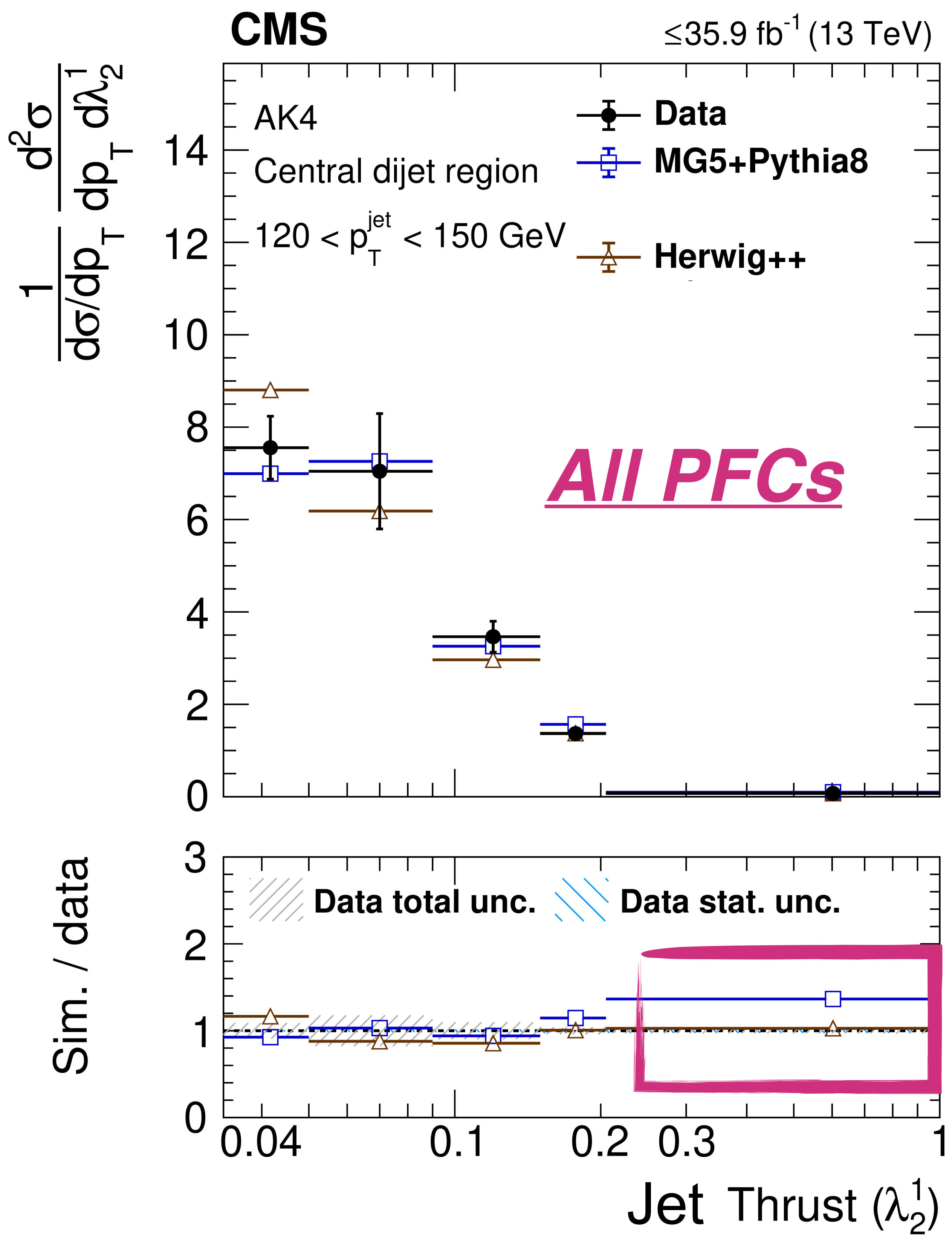


JSS Angularities

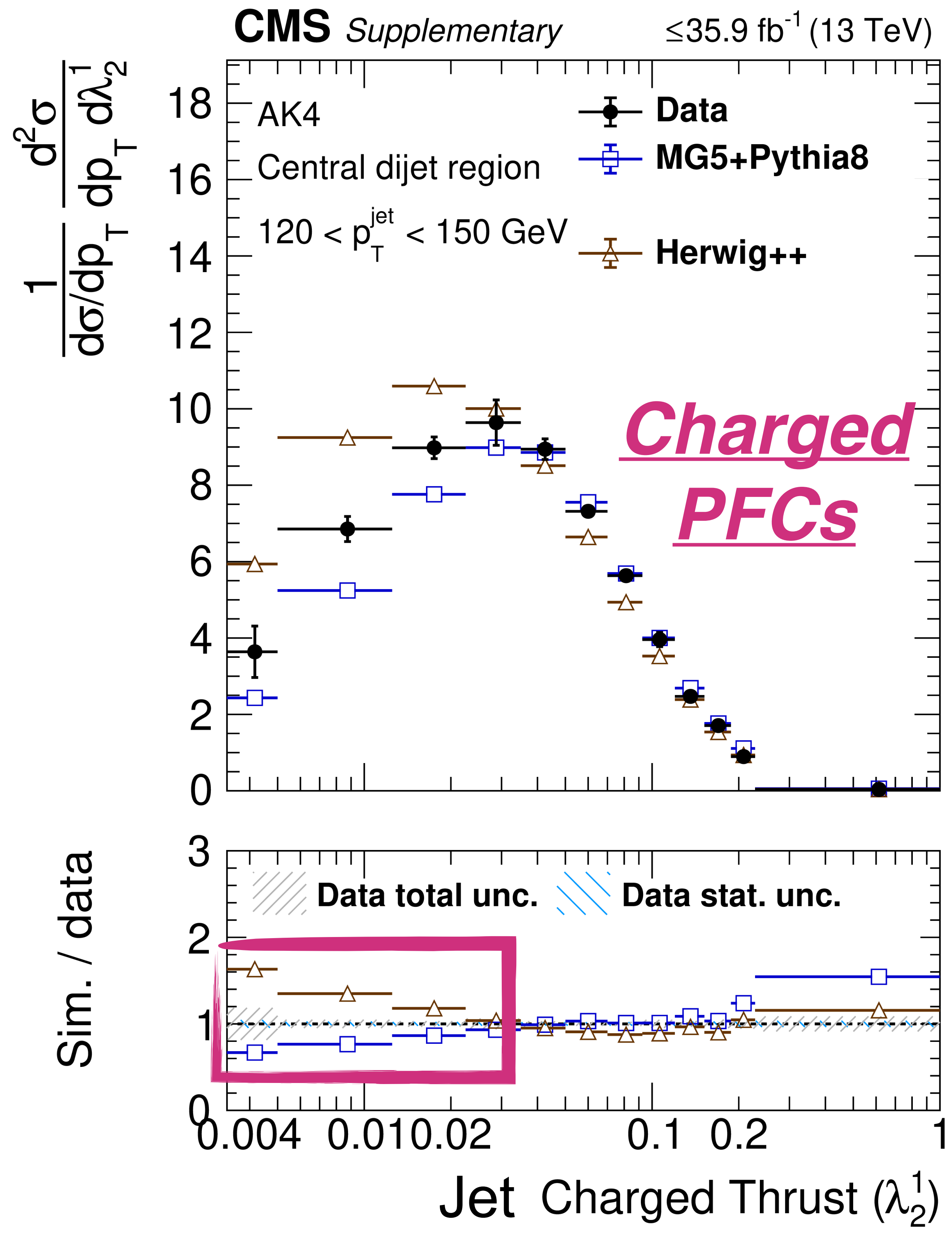
Products of relative constituent energies and angles, varying weight of each component

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

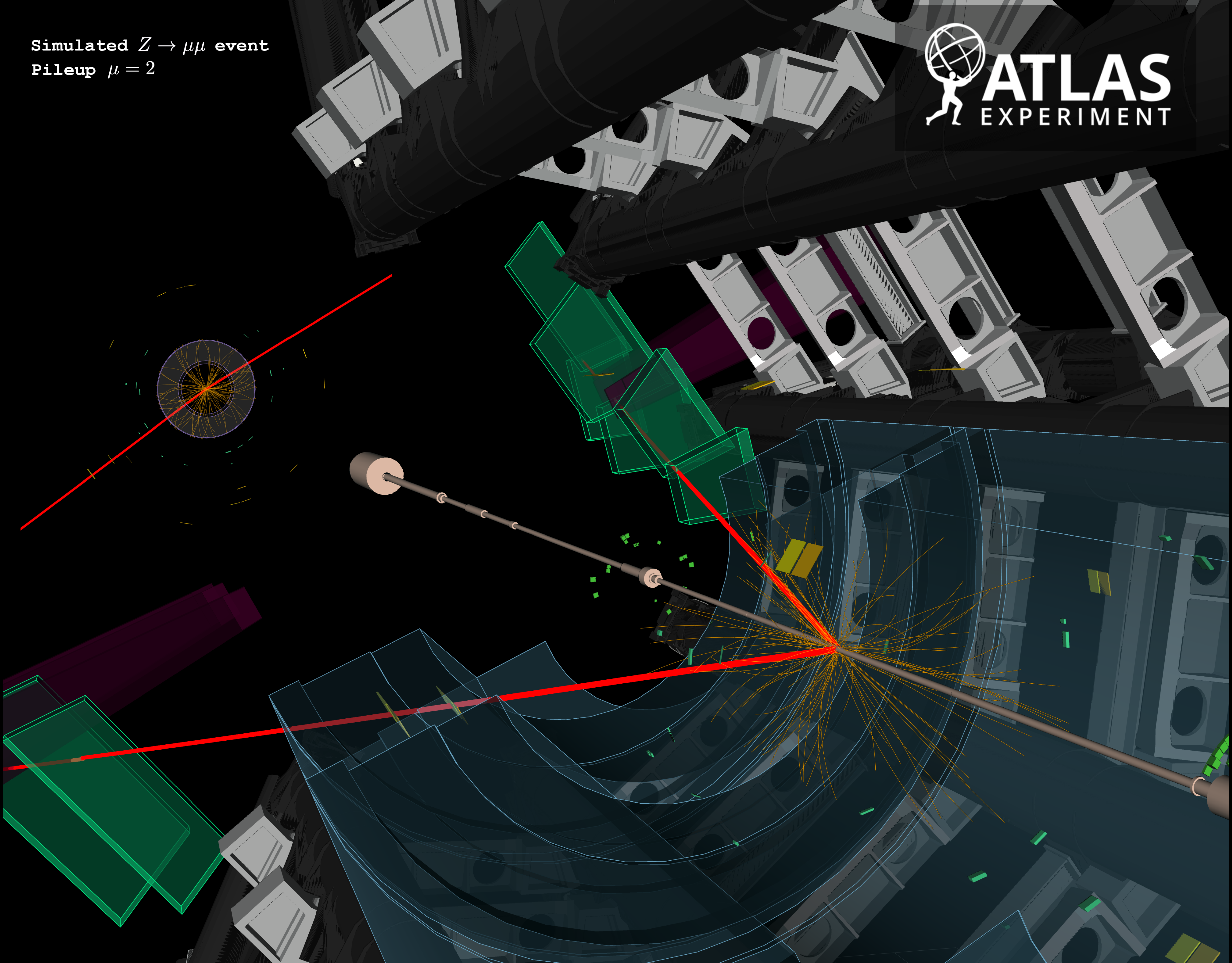
- Both ATLAS and CMS have made comparisons of **charged+neutral & charged-only pictures**.
  - Similar observations can be made using data from both collaborations
  - Perhaps surprising, given CMS's "particle-flow" reconstruction.

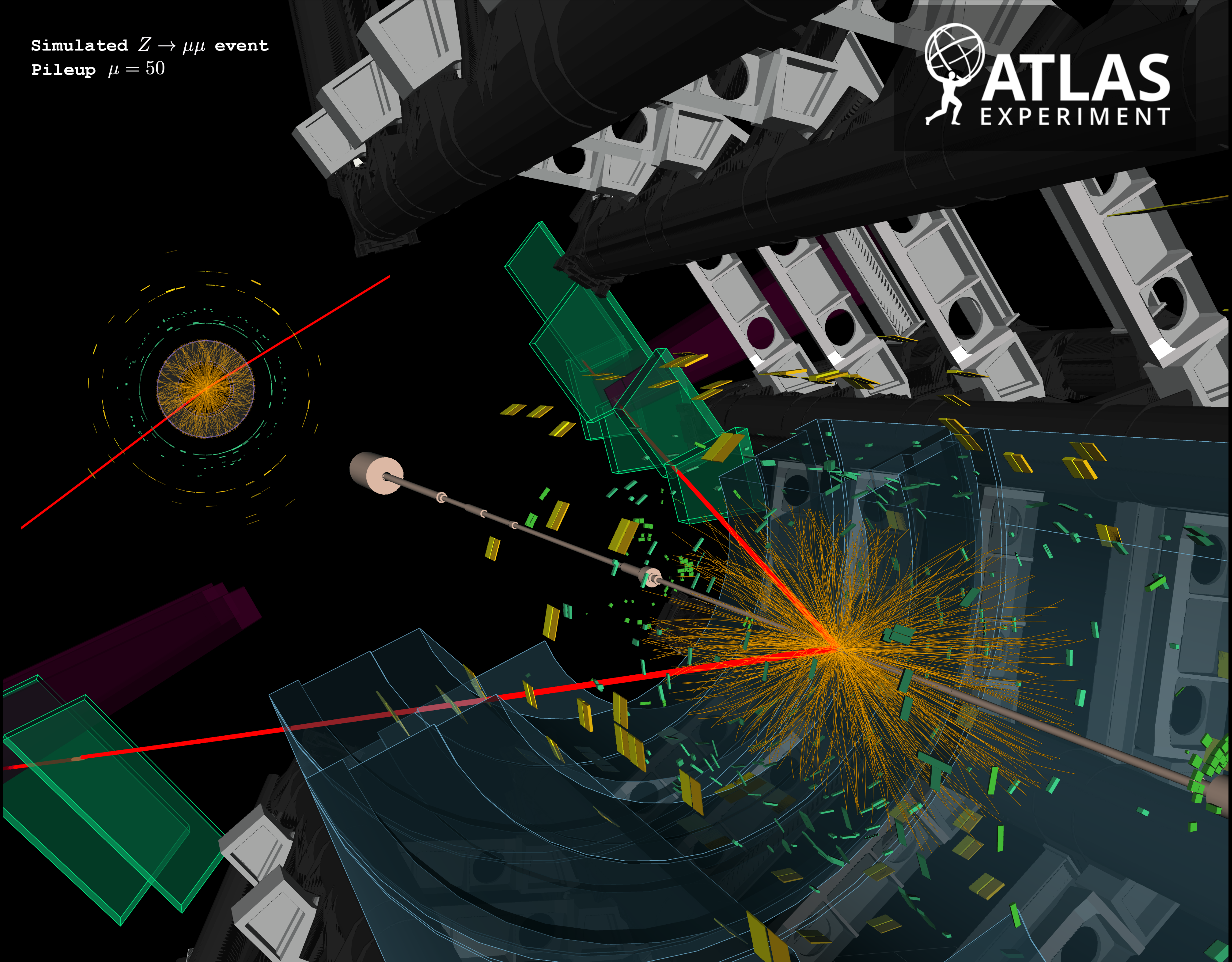


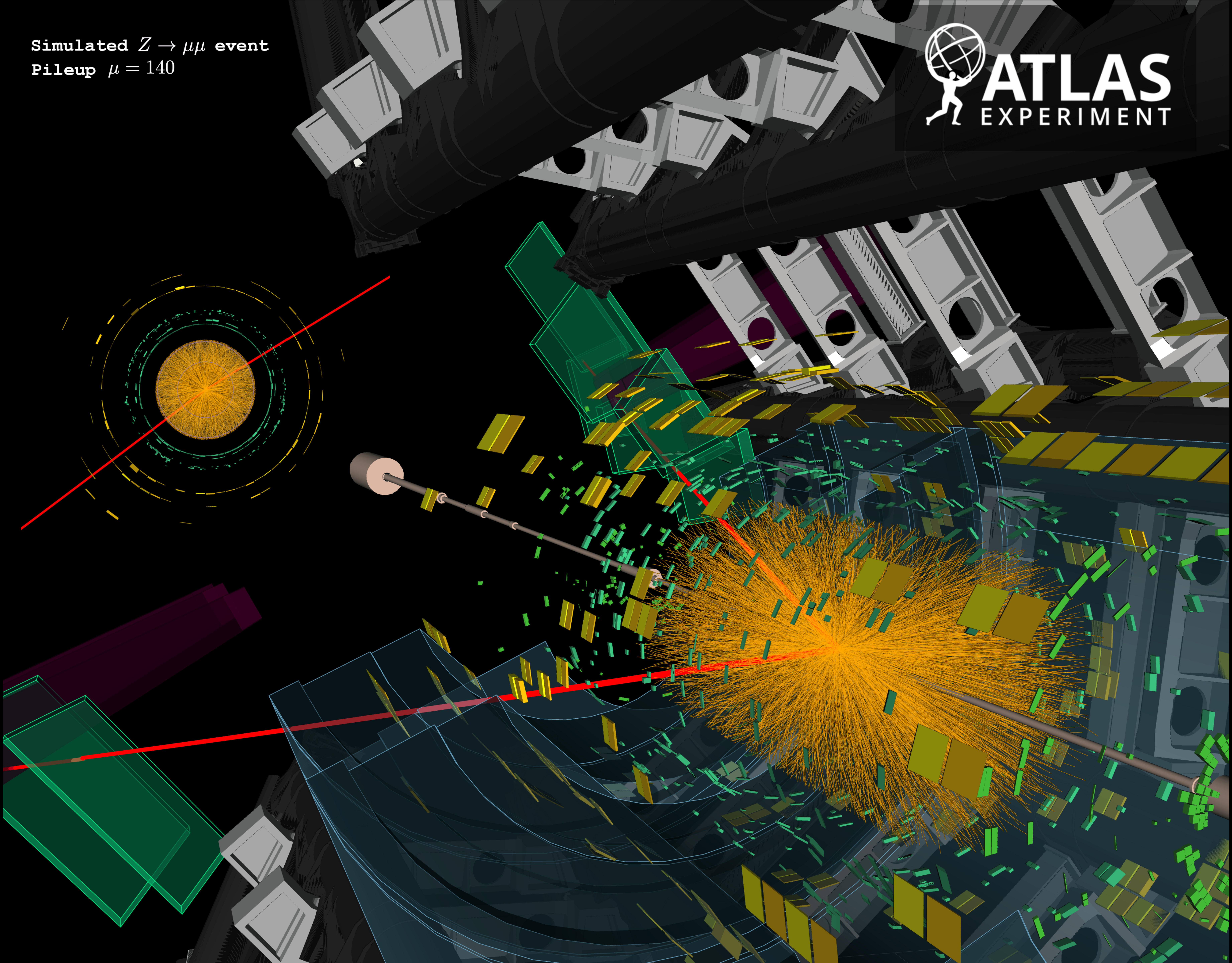
Similar levels of (dis)agreement!



Charged picture has ***significantly more reach*** *into collinear region!*


Simulated $Z \to \mu\mu$ event
Pileup $\mu = 2$
ATLAS
EXPERIMENT


Simulated $Z \to \mu\mu$ event
Pileup $\mu = 50$
ATLAS
EXPERIMENT

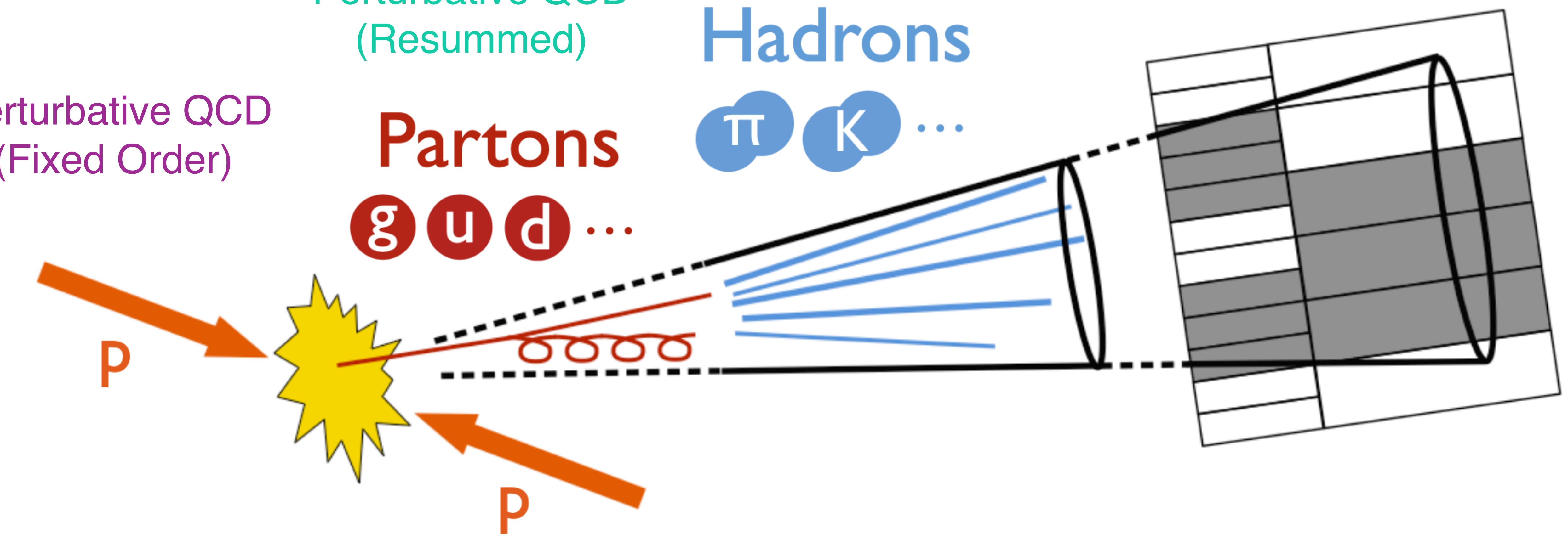

Simulated $Z \to \mu\mu$ event
Pileup $\mu = 140$
ATLAS
EXPERIMENT

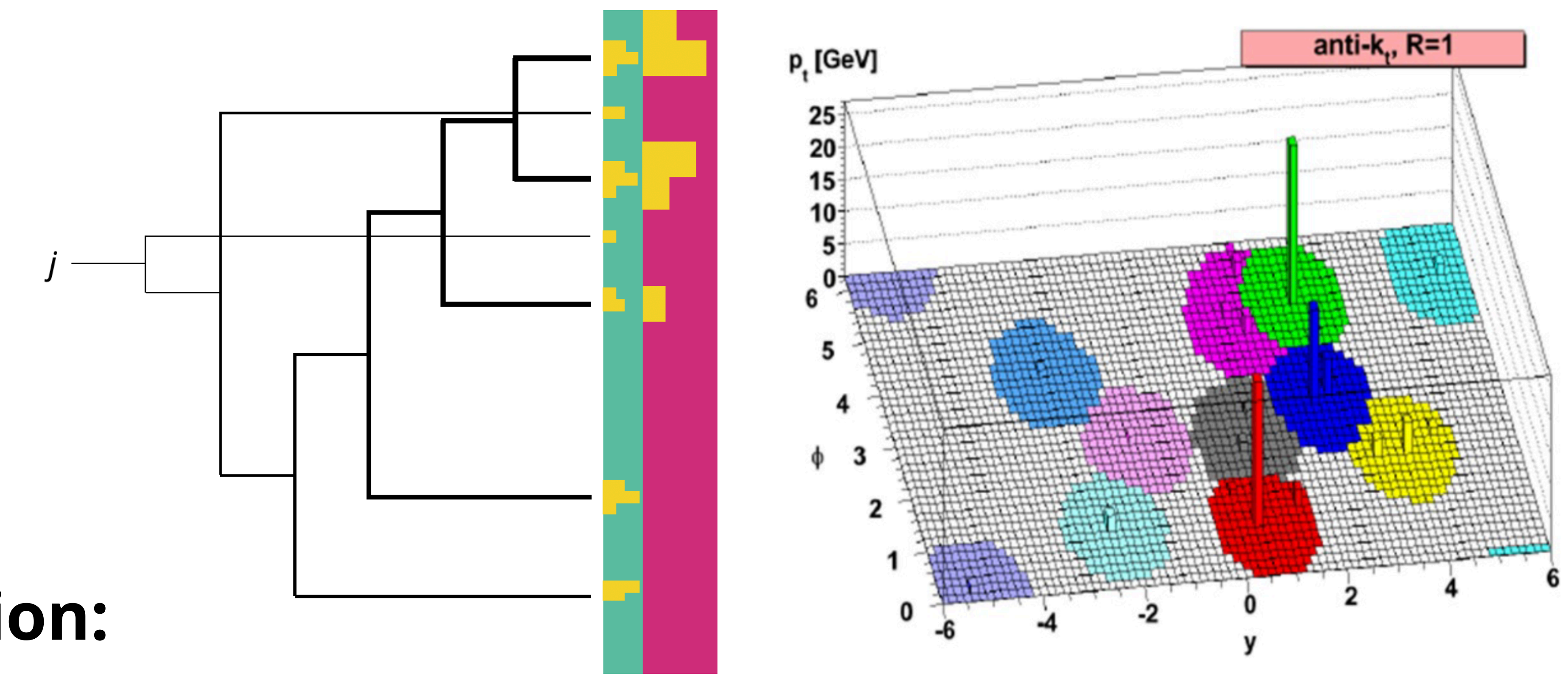

ATLAS EXPERIMENT
Run Number: 336852, Event Number: 883966264
Date: 2017-09-29 09:19:23 CEST
$\mu \sim 65$
beam

“What is a jet?”

Starting place for jet physics: Salam 0906.1833

- **Jets are formed when high-energy quarks and gluons are produced in LHC collisions.**
  - Interpreted as a proxy for parton momentum.
- ***Jets are complex:***
  - Multi-scale
  - Large area
  - Composite objects
  - Diverse signals:
    - Calorimetry
    - Charged-particle tracks
- Jets do not exist without their **definition:**
  - Recursive recombination algorithms (anti-kt, C/A, …)
    - Radius parameter (*R*)
  - Other choices …
    - Grooming? Pile-up mitigation? *Common complaint: too many choices*

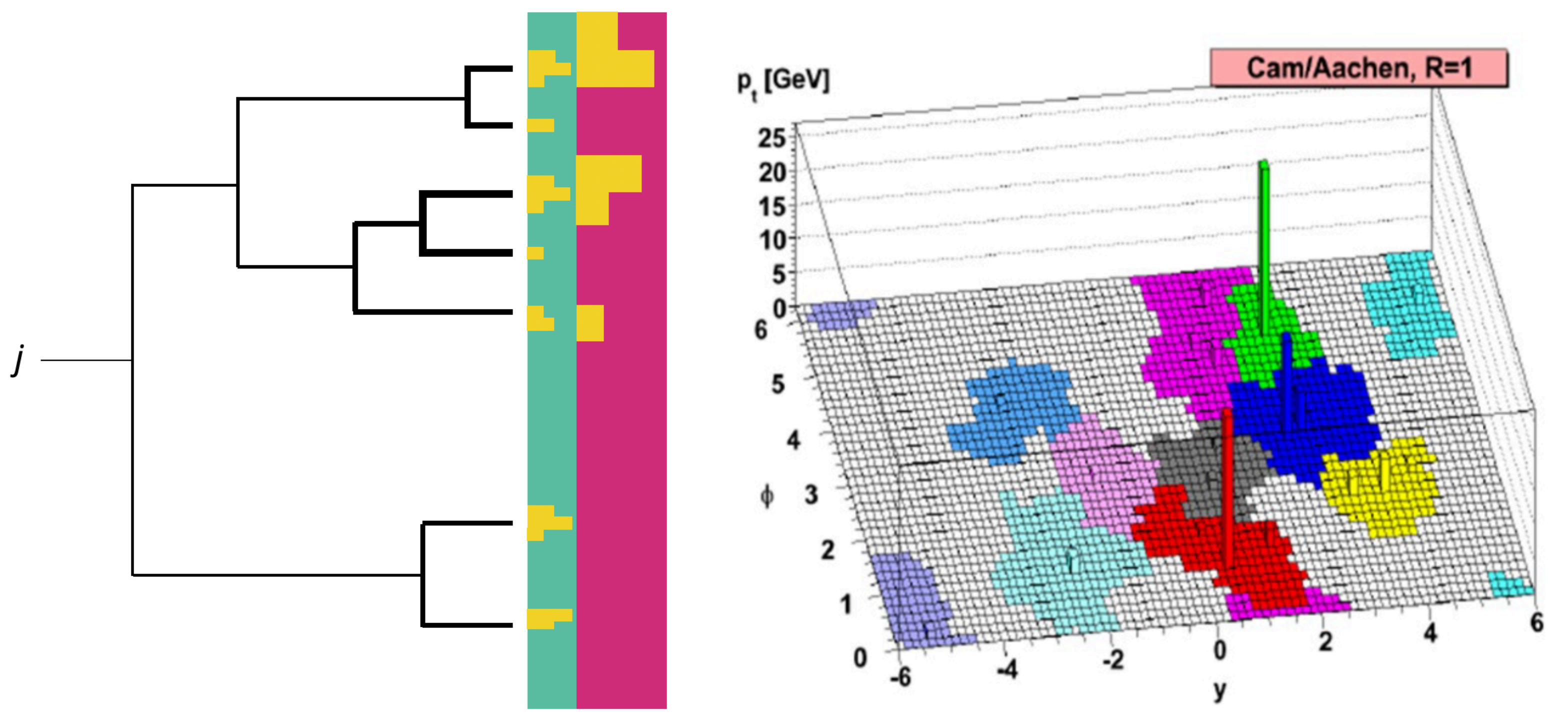




Anti-k_t

“Soft things into hard things”

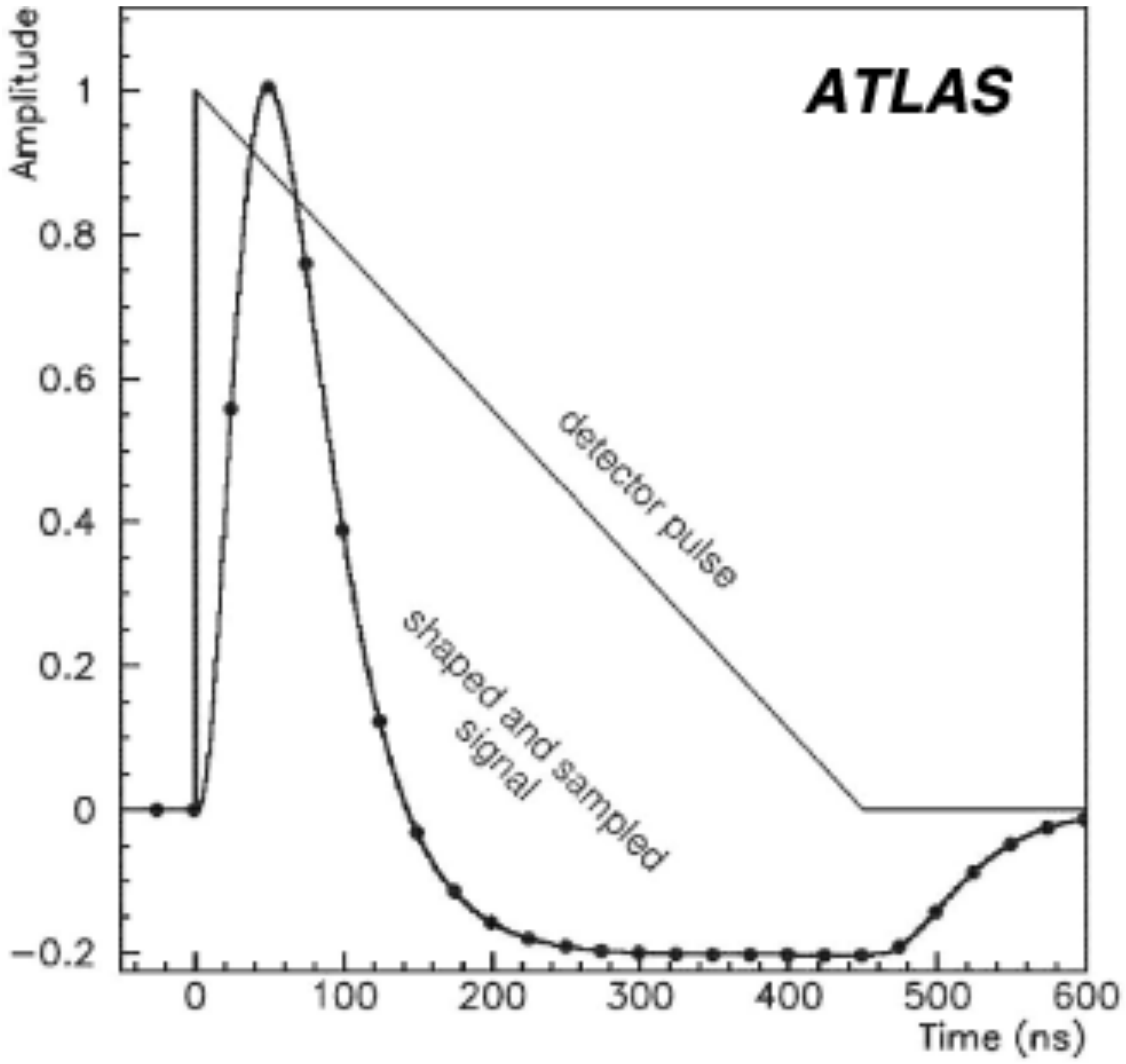
LHC daily driver



Cambridge / Aachen

“Angle-ordered”

Irregular shape: difficult to calibrate


ATLAS
Amplitude
Time (ns)
detector pulse
shaped and sampled signal
1
0.8
0.6
0.4
0.2
0
−0.2
0
100
200
300
400
500
600

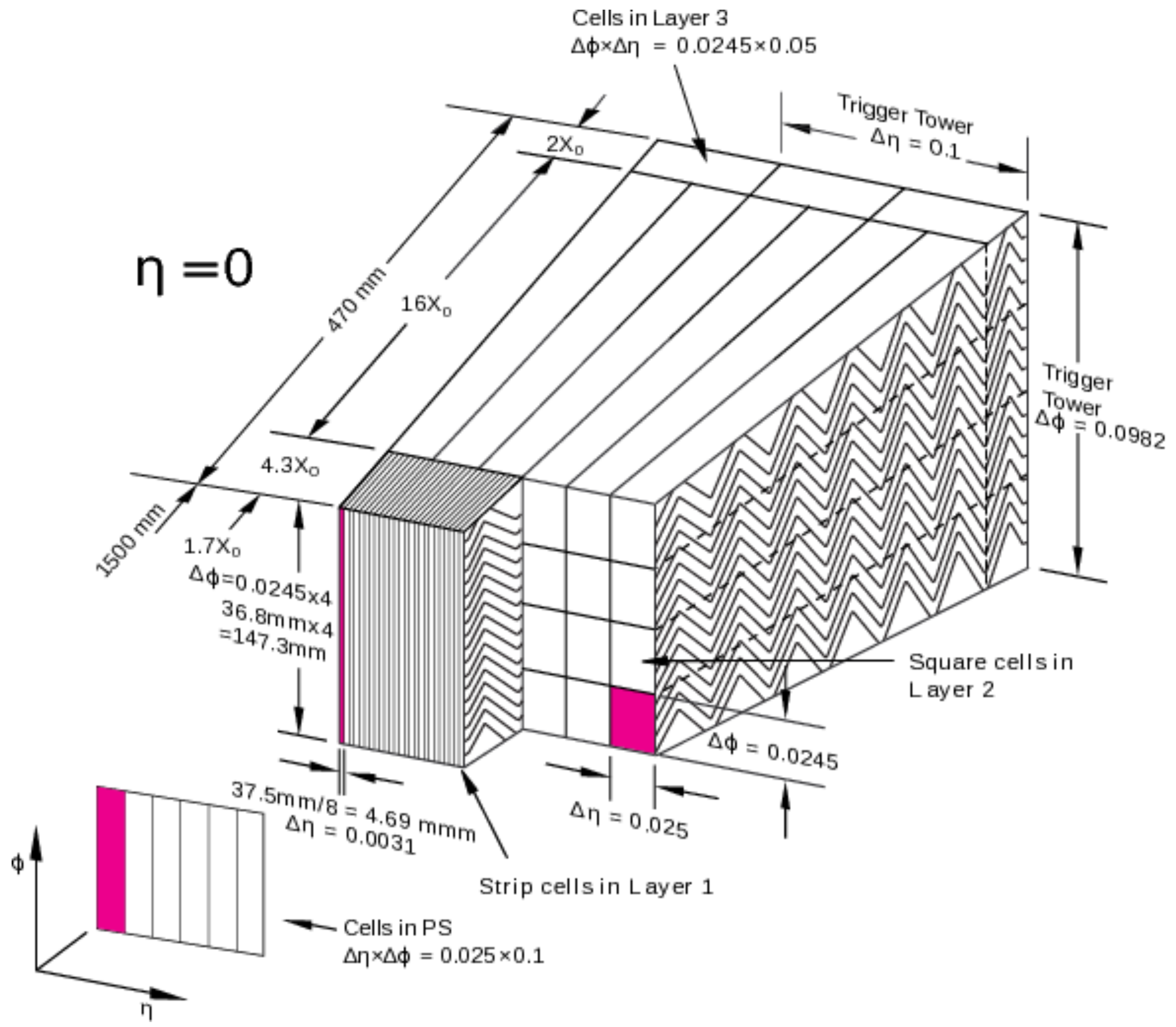
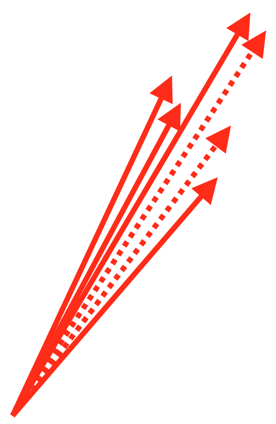
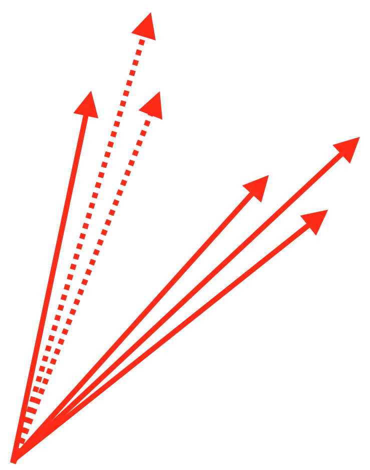

η =0
Cells in Layer 3
Δϕ×Δη = 0.0245×0.05
Trigger Tower
Δη = 0.1
2X₀
470 mm
16X₀
Trigger Tower
Δϕ = 0.0982
4.3X₀
1500 mm
1.7X₀
Δϕ=0.0245x4
36.8mmx4
=147.3mm
Square cells in Layer 2
Δϕ = 0.0245
37.5mm/8 = 4.69 mmm
Δη = 0.0031
Δη = 0.025
Strip cells in Layer 1
ϕ
η
Cells in PS
Δη×Δϕ = 0.025×0.1

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

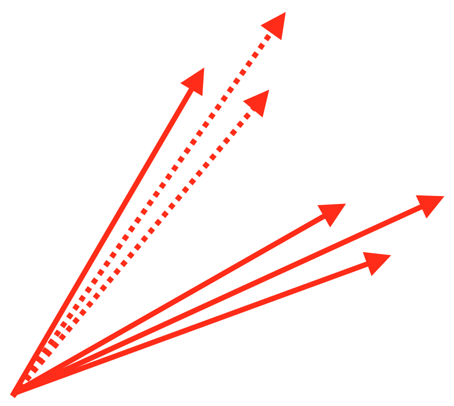


Quark? Gluon?



Higgs boson?

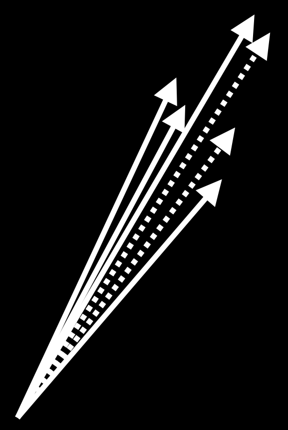
W/Z boson?



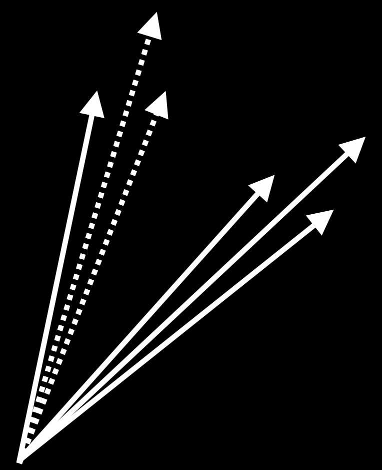
Top quark?

Tagging / Classification

Let's play a game!

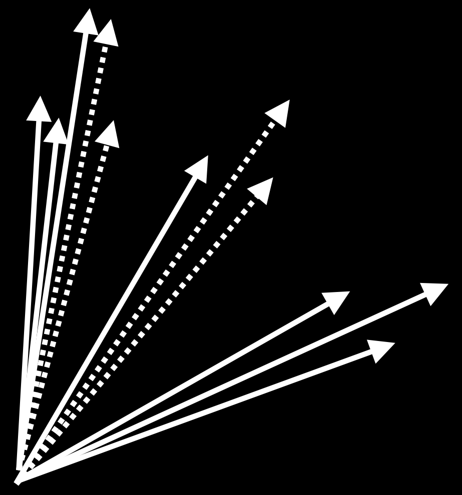


Quark? Gluon?

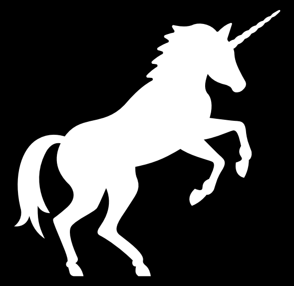


Higgs boson?

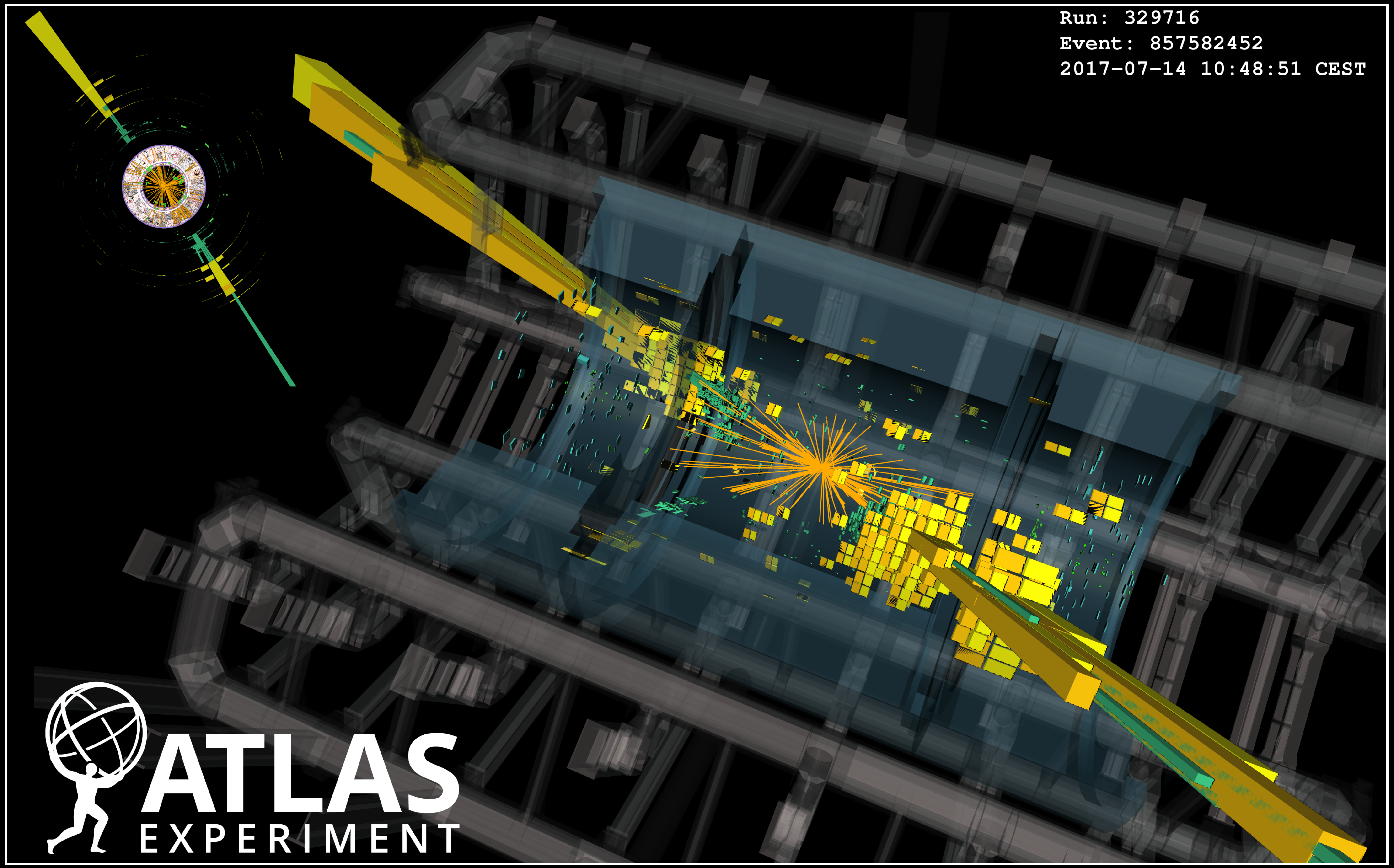
W/Z boson?

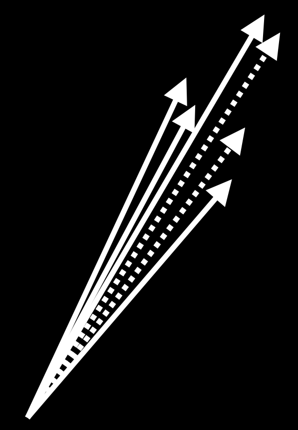


Top quark?

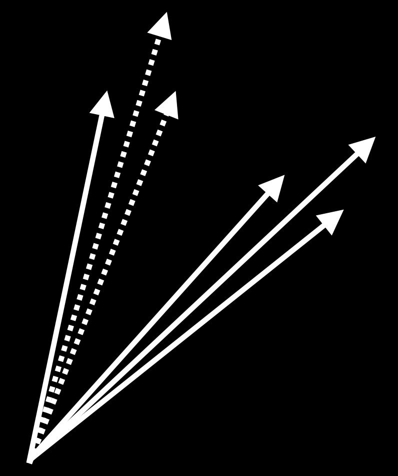


Something else?



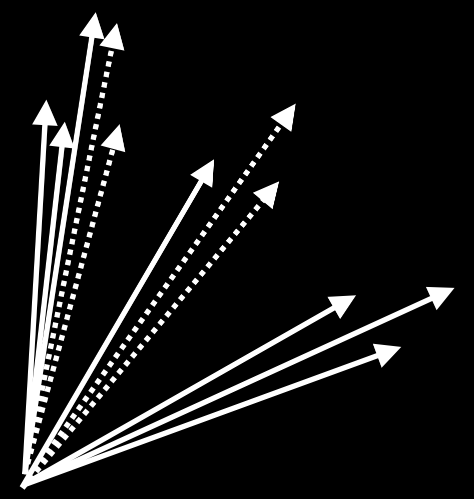


Quark? Gluon?

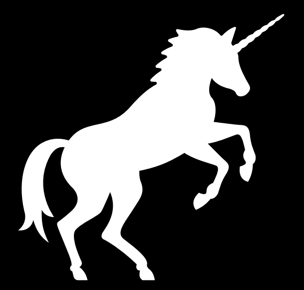


Higgs boson?

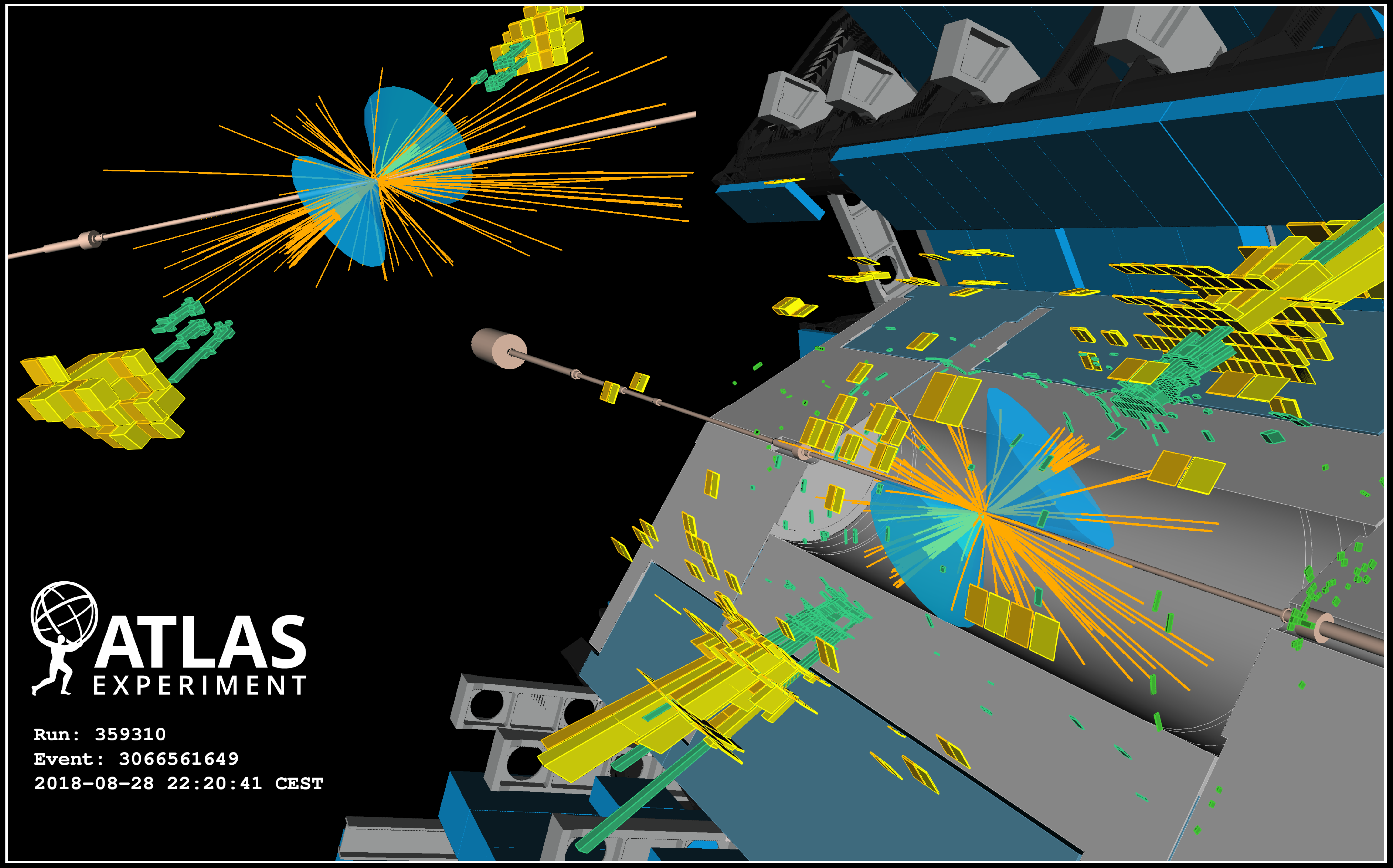
W/Z boson?

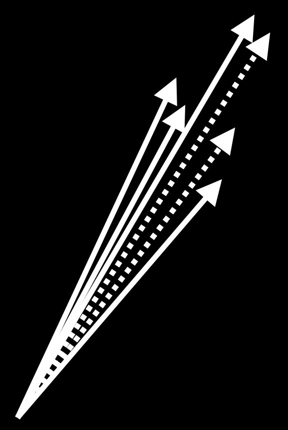


Top quark?

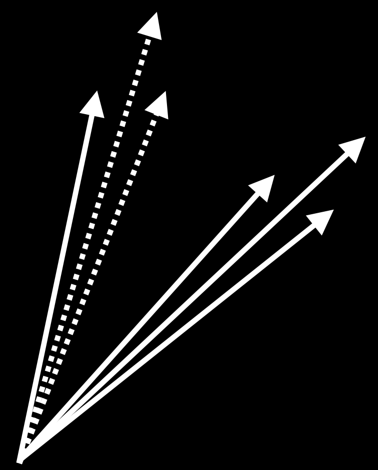


Something else?





Quark? Gluon?



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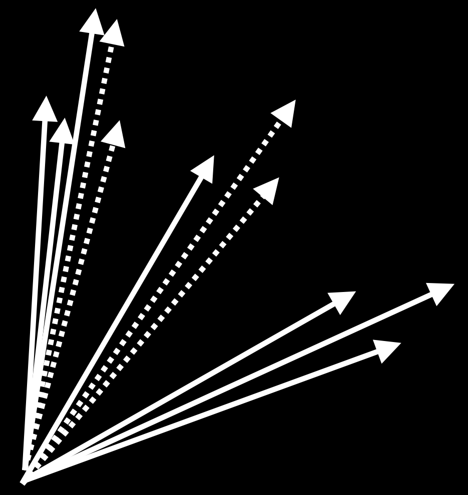
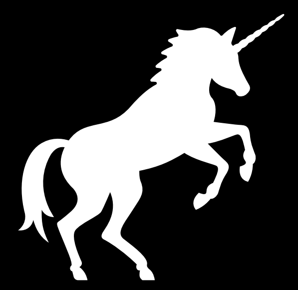
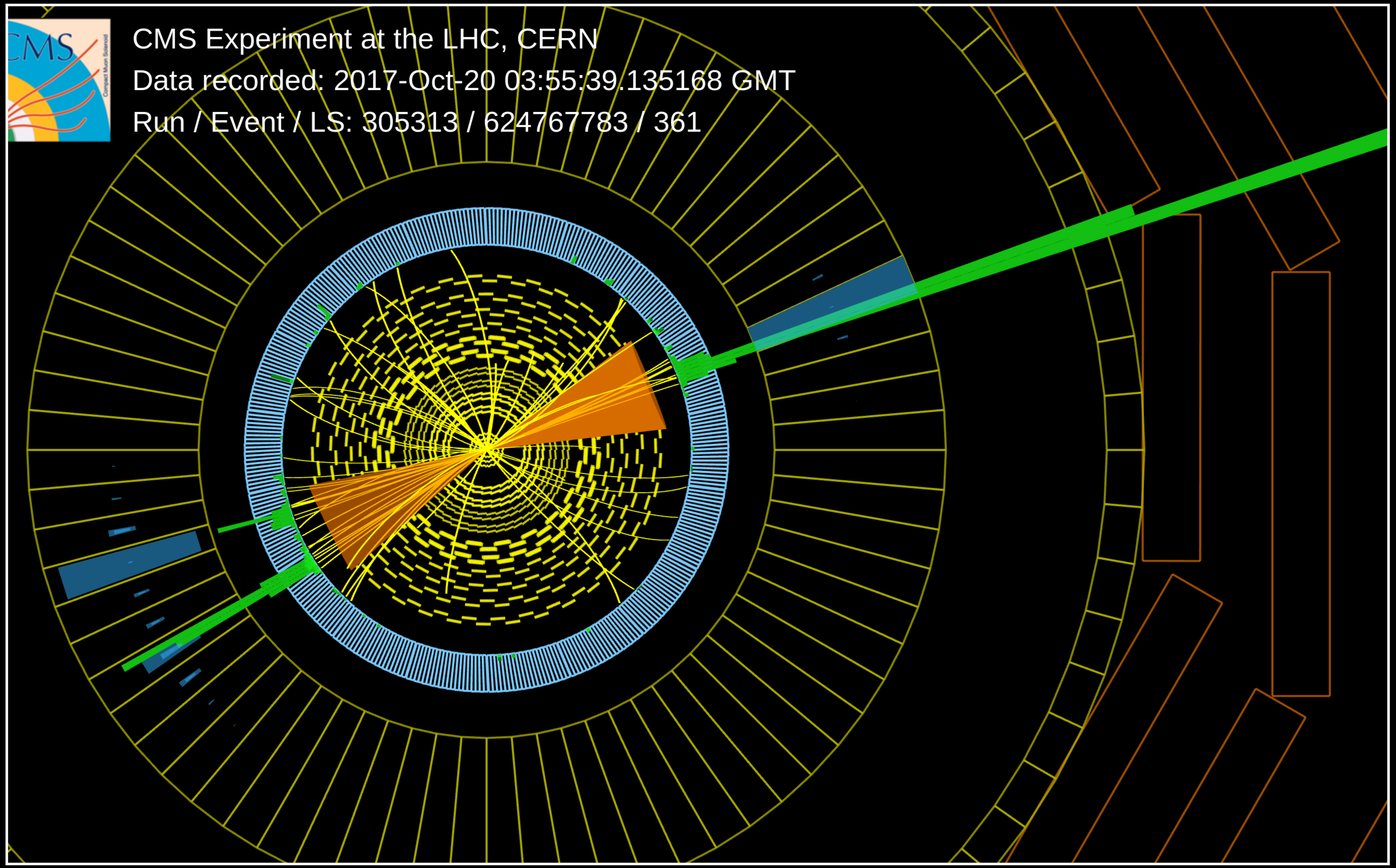
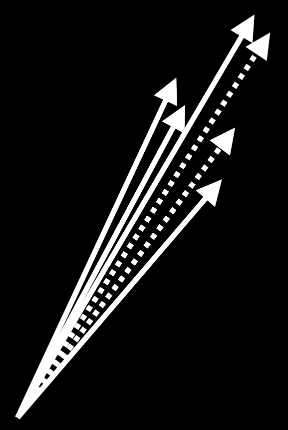


Top quark?

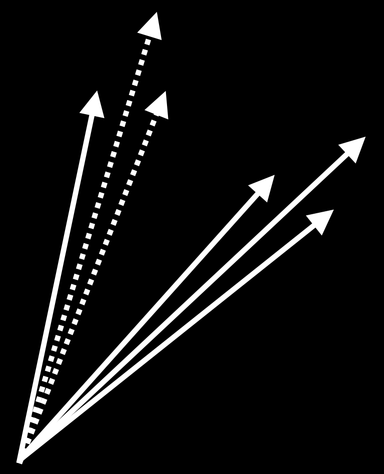


Something else?



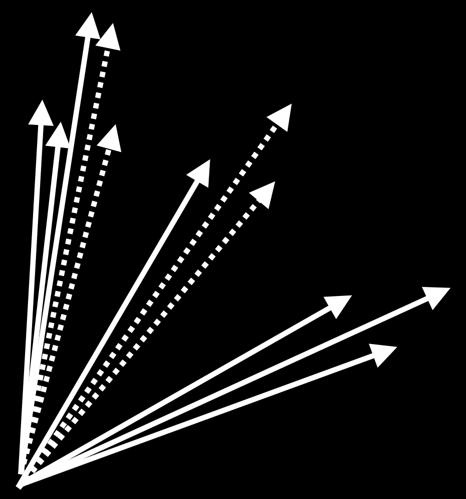


Quark? Gluon?

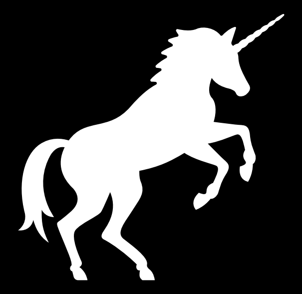


Higgs boson?

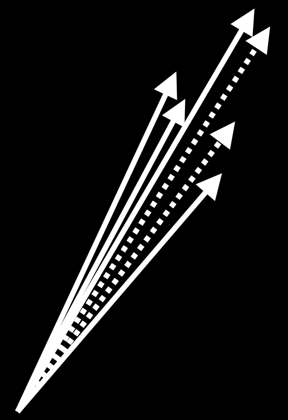
W/Z boson?



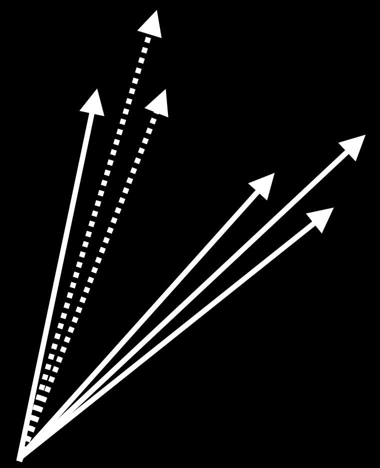
Top quark?



Something else?

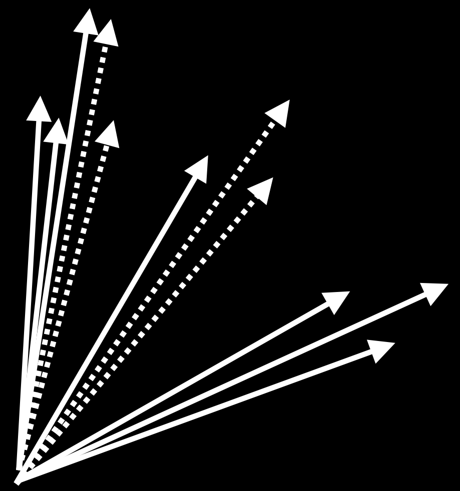


Quark? Gluon?



Higgs boson?

W/Z boson?

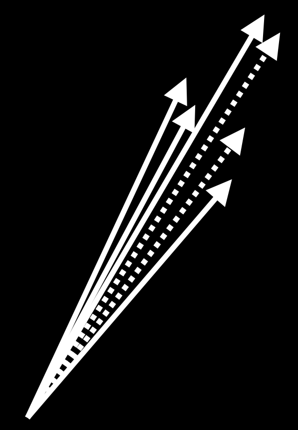


Top quark?

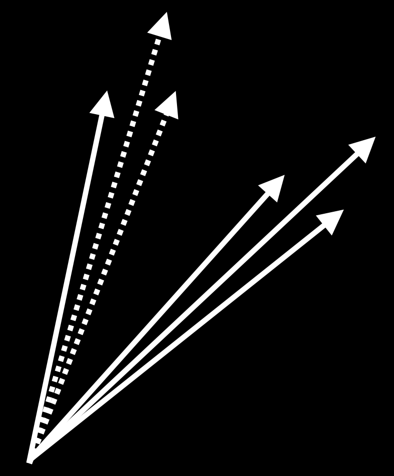
Something else?

(Dark Shower)

Event displays were from :
https://atlaspo.cern.ch/public/event_display/
https://cds.cern.ch/record/2714889

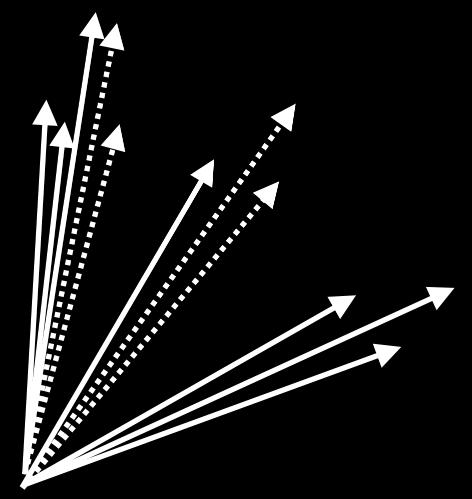


Quark? Gluon?

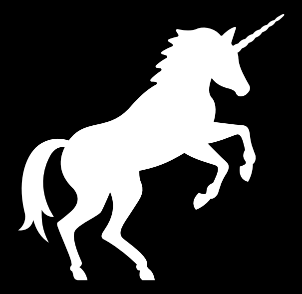


Higgs boson?

W/Z boson?



Top quark?

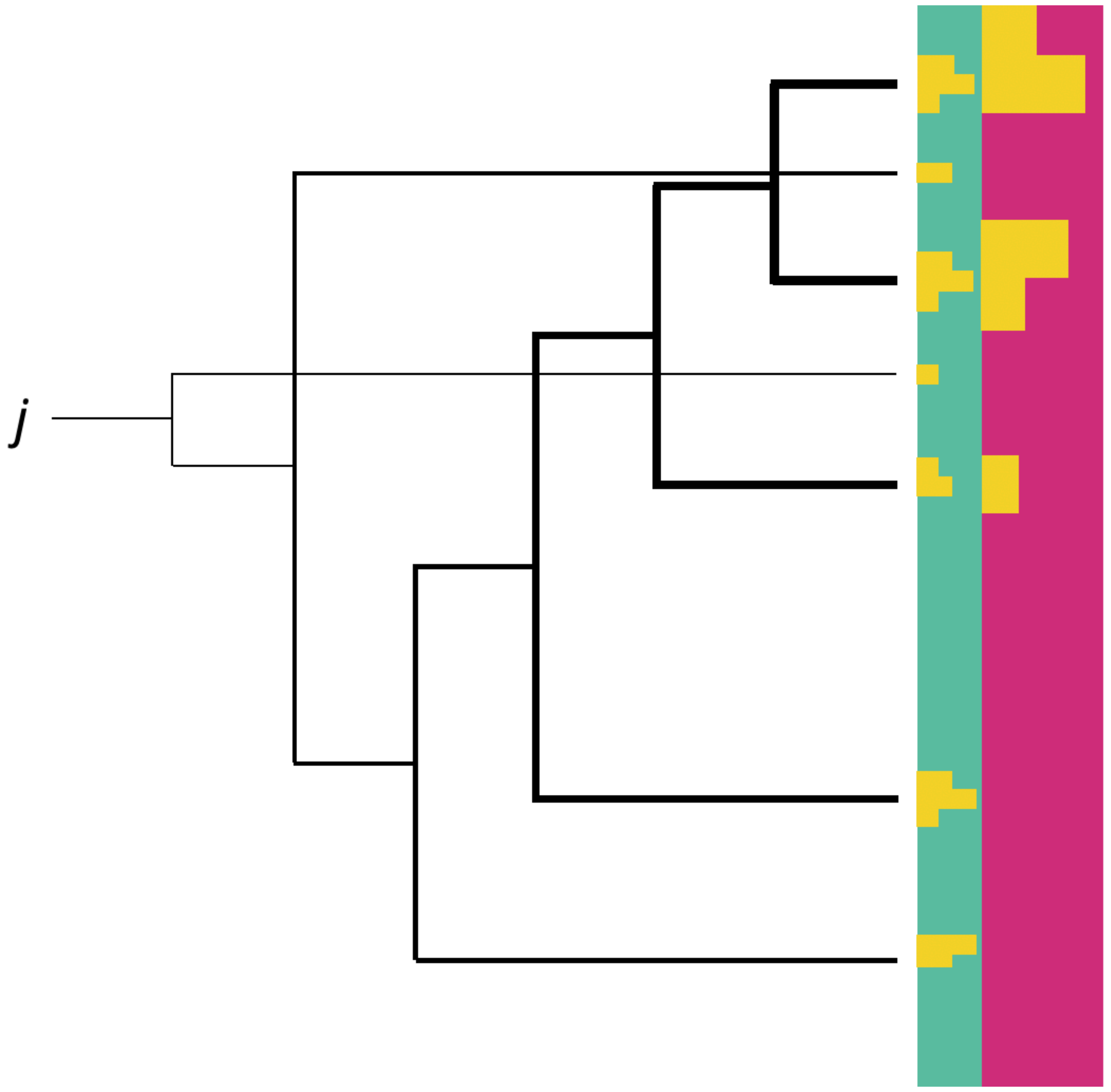


Something else?

(Dark Shower)

(Pause for laughter)

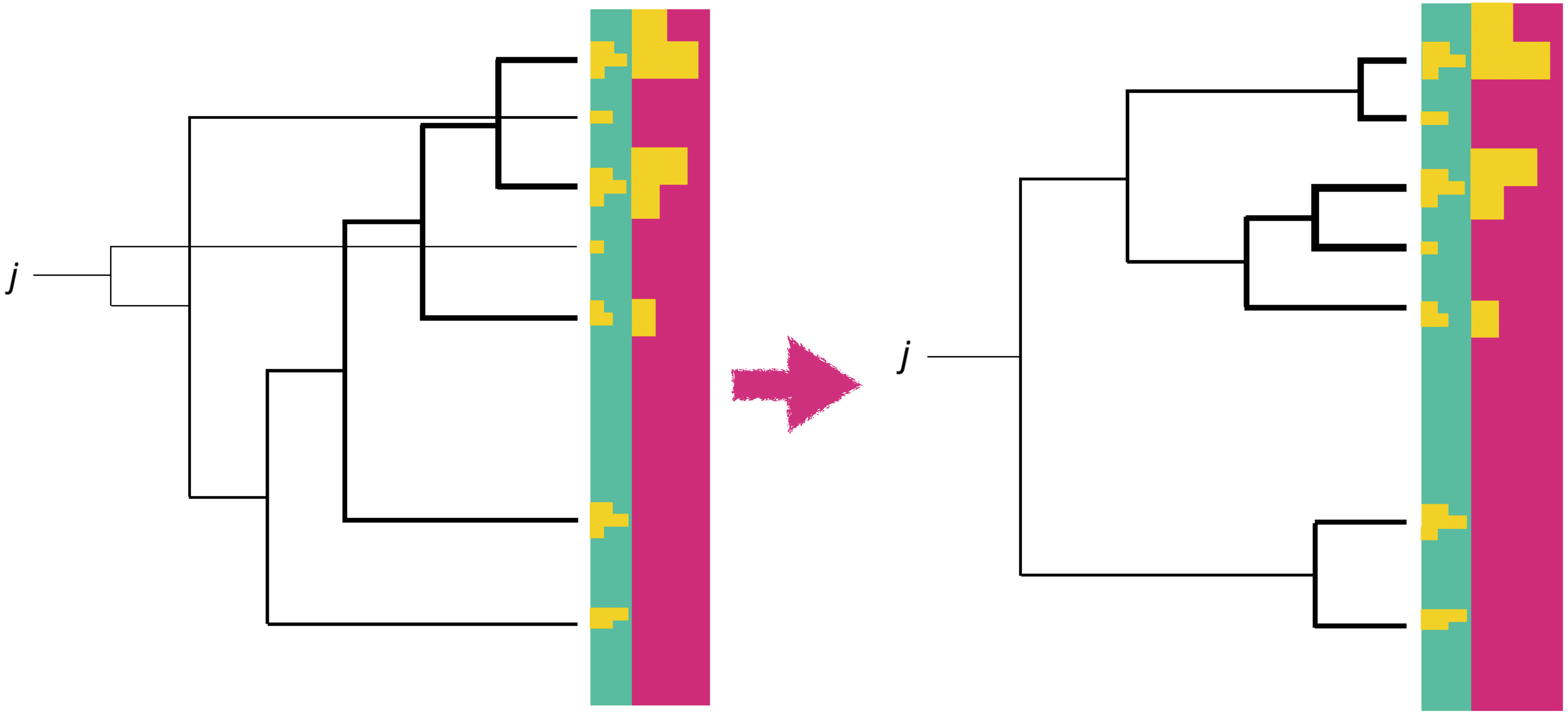
The Soft-Drop / modified Mass-Drop Algorithm



1. Start with anti-k_t jet.

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

Lund jet plane

Dreyer, Salam & Soyez [JHEP 12 (2018) 064]

- **Lund Plane** : tool used by Parton Shower community for >30 years (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.
        - Recluster jet with C/A algorithm
        - Parameterise emissions 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*,
      PSMC development *1805.09327*, *2205.02861*,
      analytics *2007.06578*,
      heavy-flavour *2106.05713*
      dead-cone *ALICE*, *Nature 605, 440–446 (2022)*
        - ***We had a whole LJP workshop at CERN in July!***