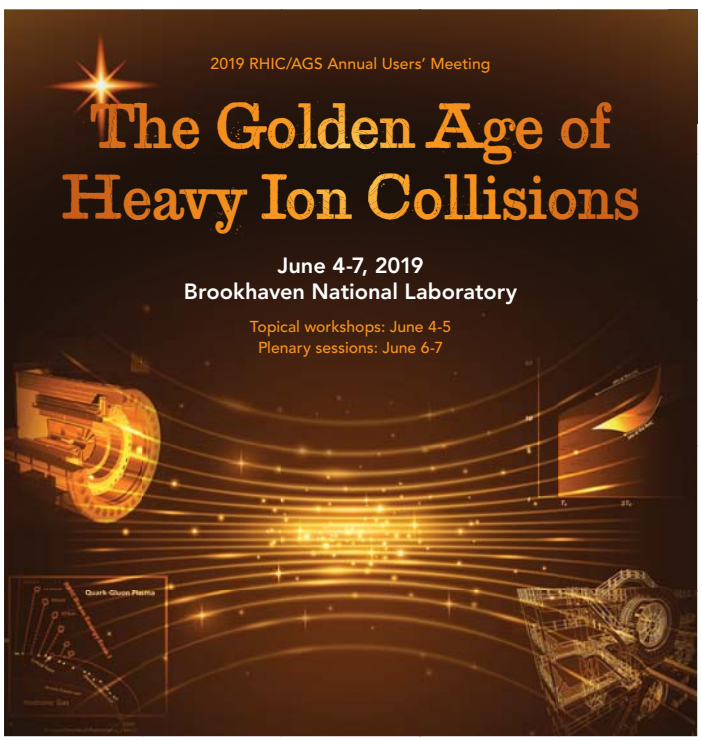
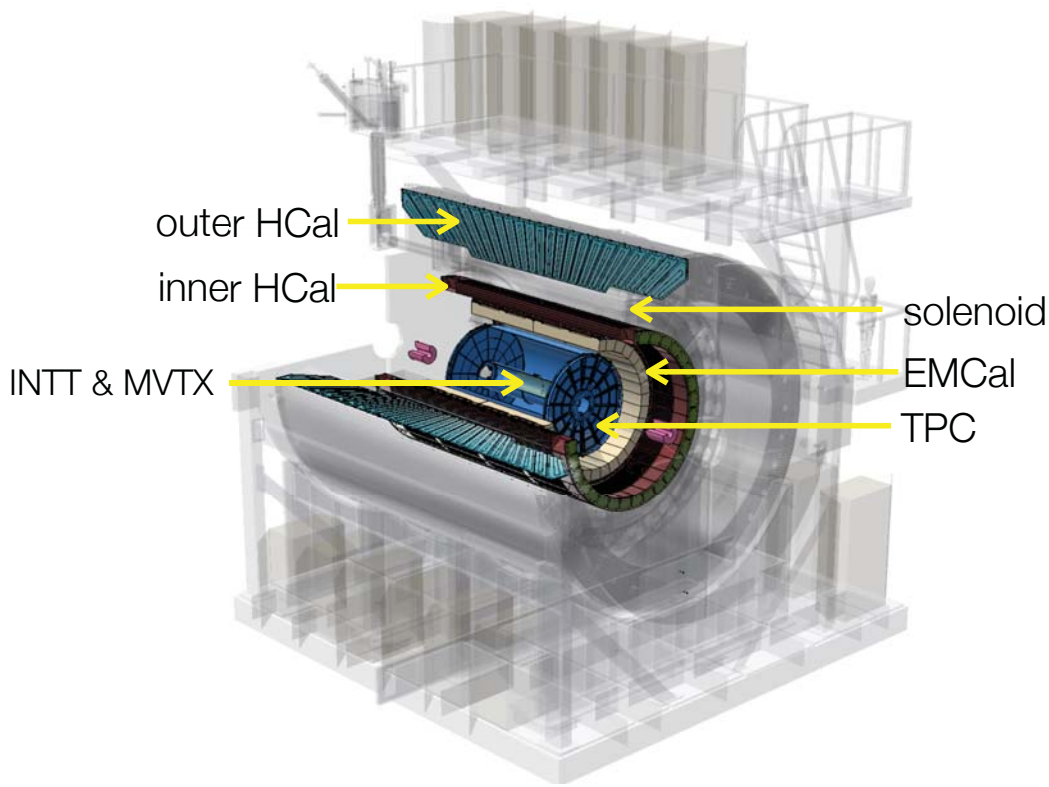
sPHENIX and its Capabilities on Jet Substructure at RHIC Energies

Dennis V. Perepelitsa
University of Colorado Boulder

RHIC/AGS Annual Users Meeting, 5 June 2019
Brookhaven National Laboratory





Jet Structure Topical Group

conveners Rosi Reed (Lehigh)

and Dennis Perepelitsa (Colorado)

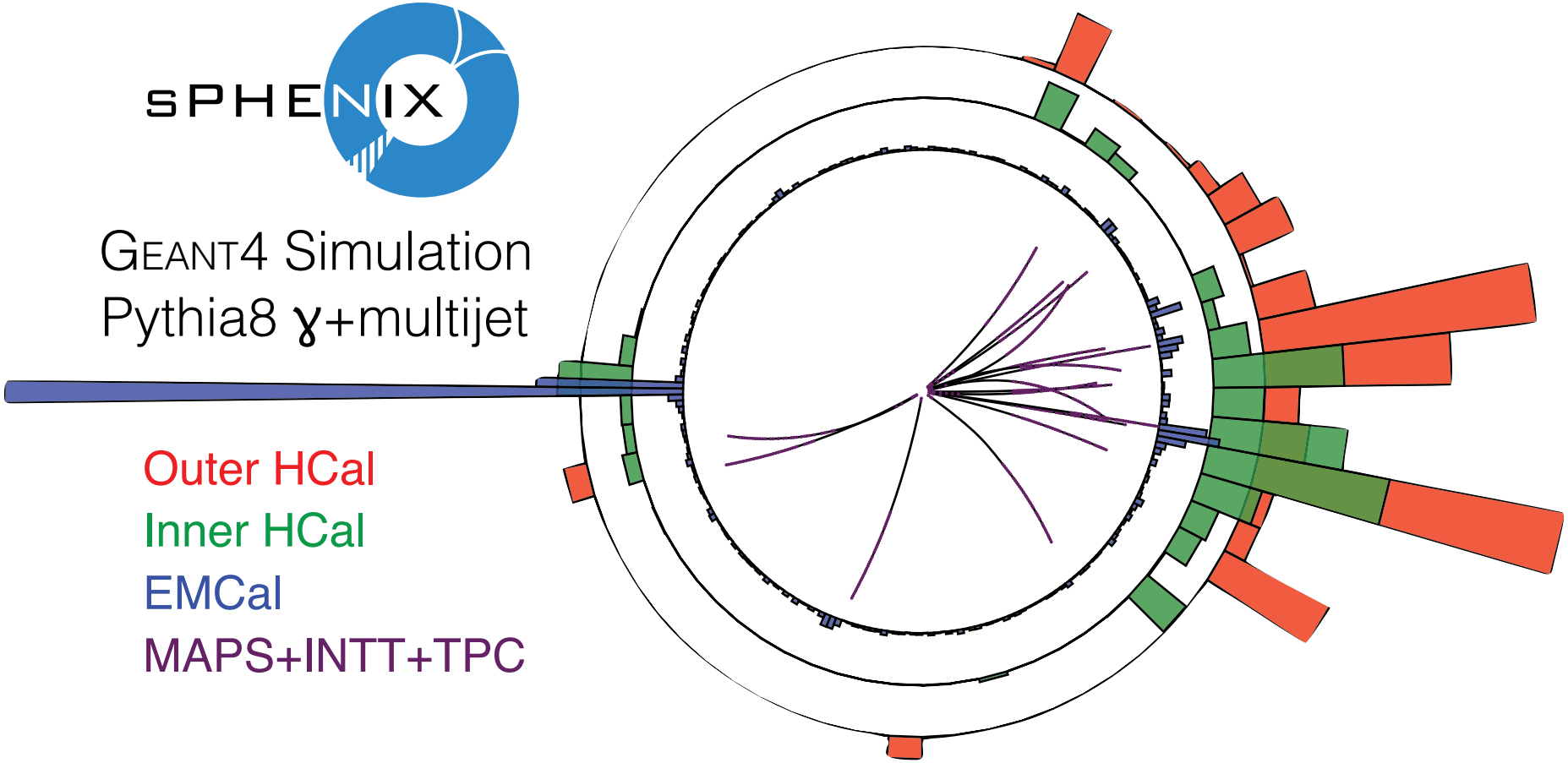
LEHIGH UNIVERSITY

purview: photon and jet reconstruction, performance, projections

sPHENIX

GEANT4 Simulation

Pythia8 γ+multijet

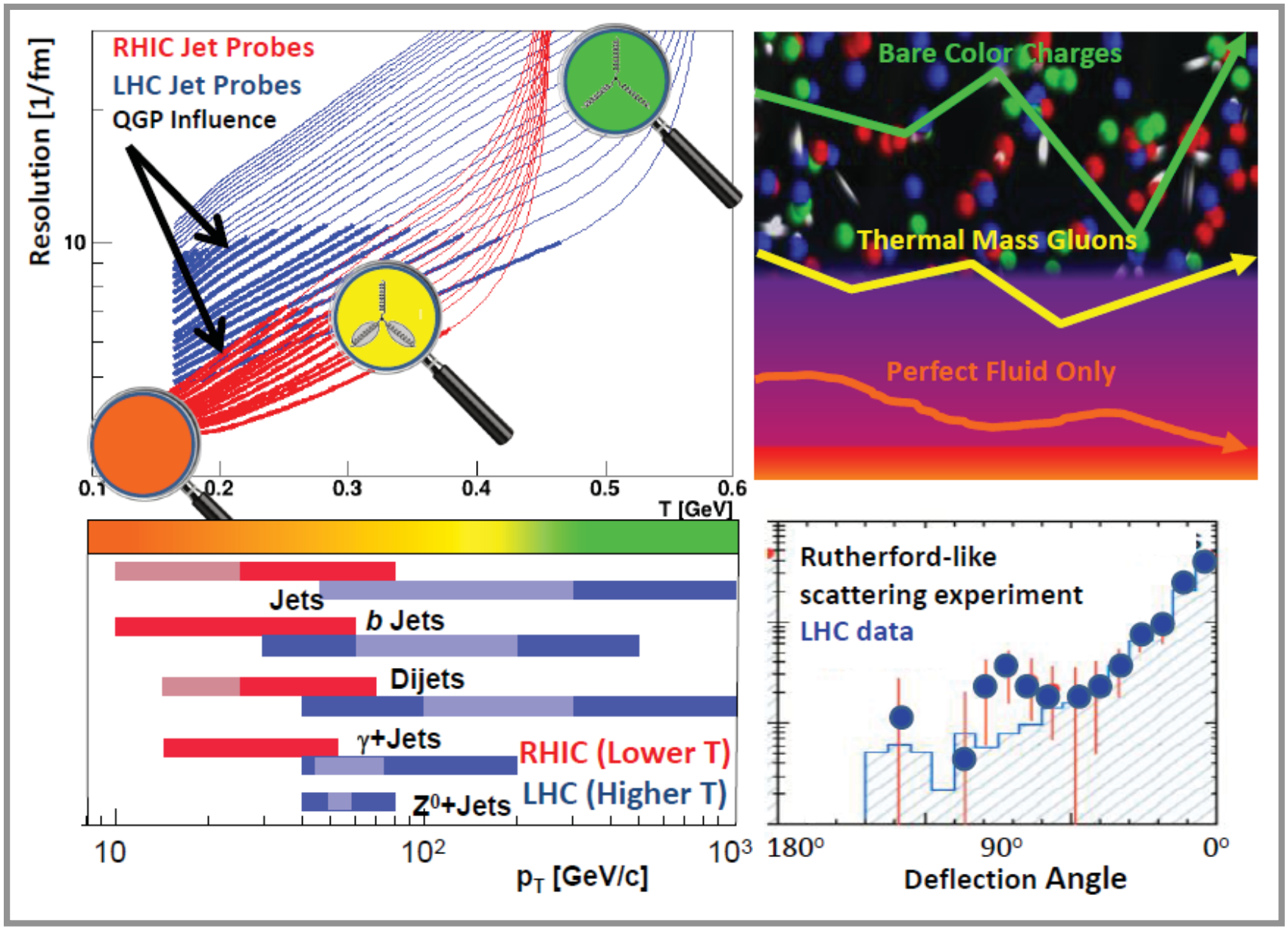


Outer HCal

Inner HCal

EMCal

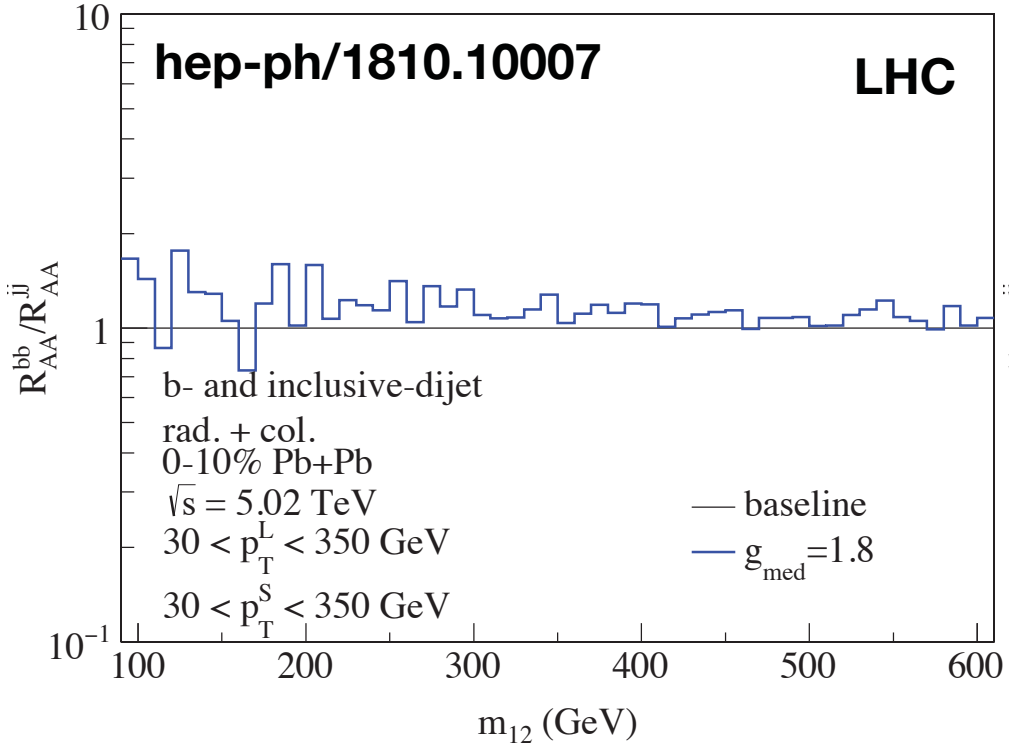
MAPS+INTT+TPC

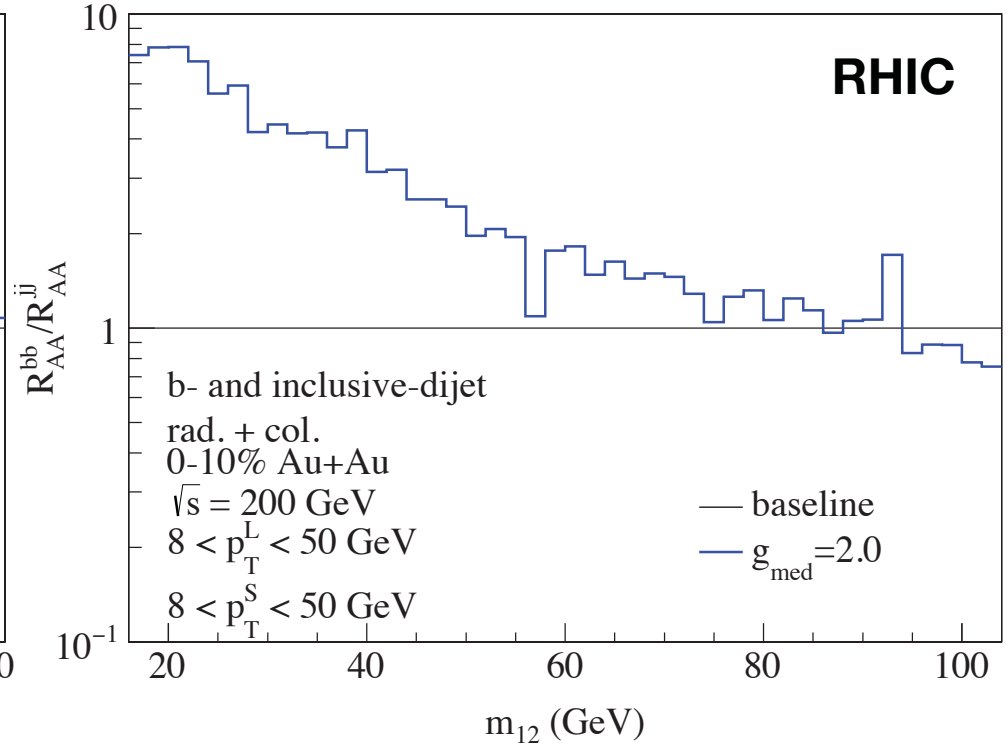


U.S. Long-range plan for nuclear physics, 2015

➡ Jet evolution dominated by medium scales at low kinematic end

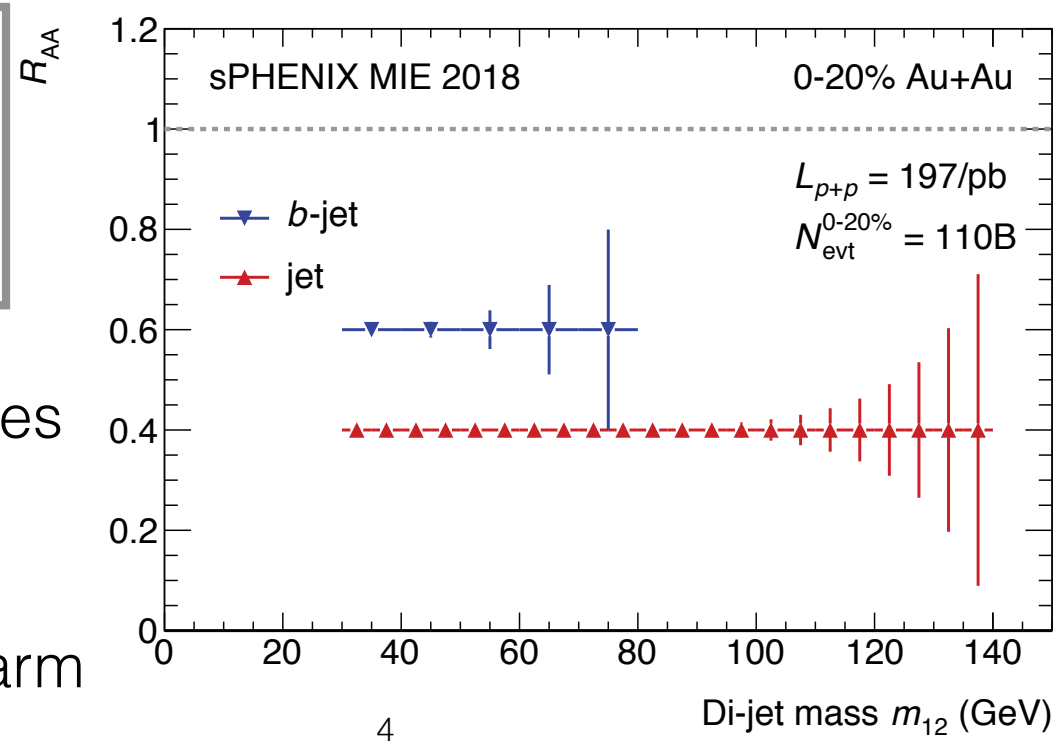
➡ Overlap with the LHC at the high kinematic end





Light and heavy flavor dijet production and dijet mass modification in heavy ion collisions

Zhong-Bo Kang,[1,2,3,*] Jared Reiten,[1,2,†] Ivan Vitev,[3,‡] and Boram Yoon[3,§]
[1] *Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*
[2] *Mani L. Bhaumik Institute for Theoretical Physics, University of California, Los Angeles, California 90095, USA*
[3] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
(Dated: February 22, 2019)



- In theory community, many examples of phenomena/observables more visible at RHIC:
  - ➡ sPHENIX provides crucial level arm

sPHENIX 5-Year Run Plan

Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

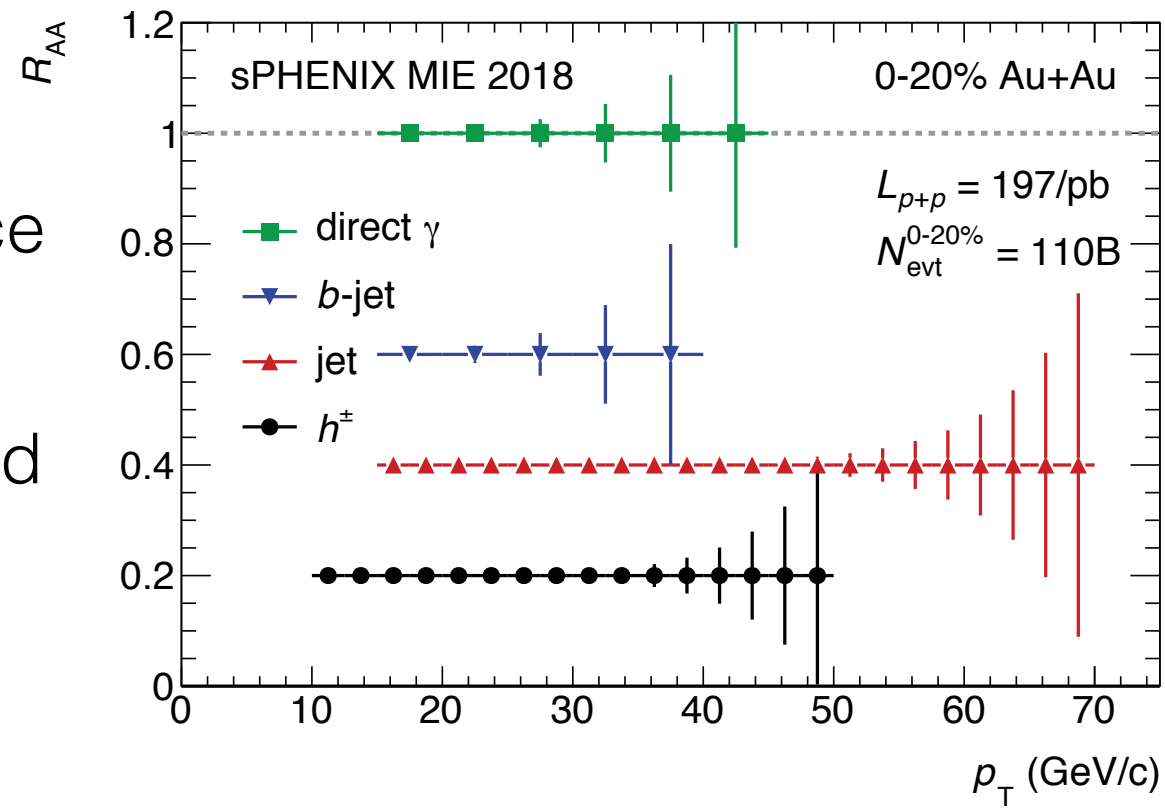
sPHENIX advantages:

➡ large, hermetic acceptance

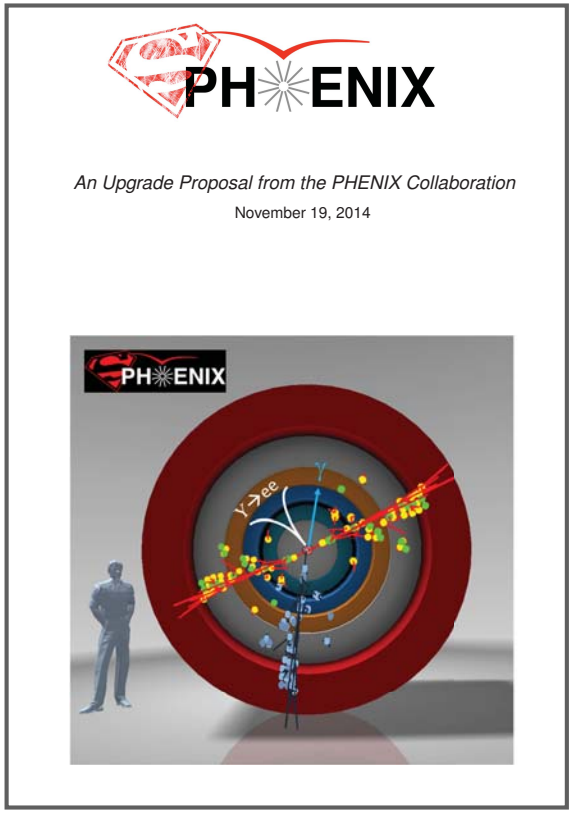
➡ huge data rate

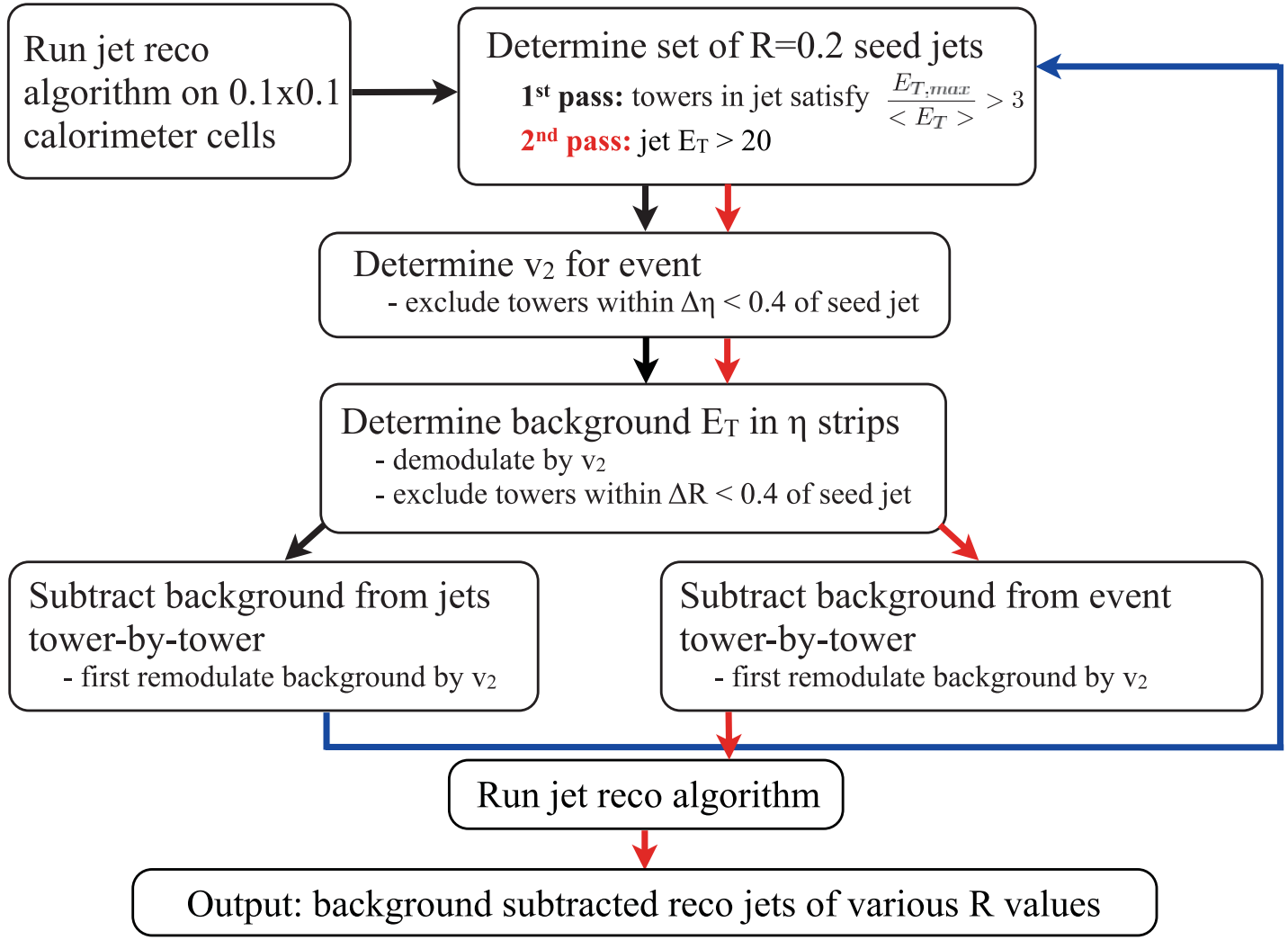
➡ hadronic calorimeter-based energy measurement

➡ unbiased triggering



Historical context





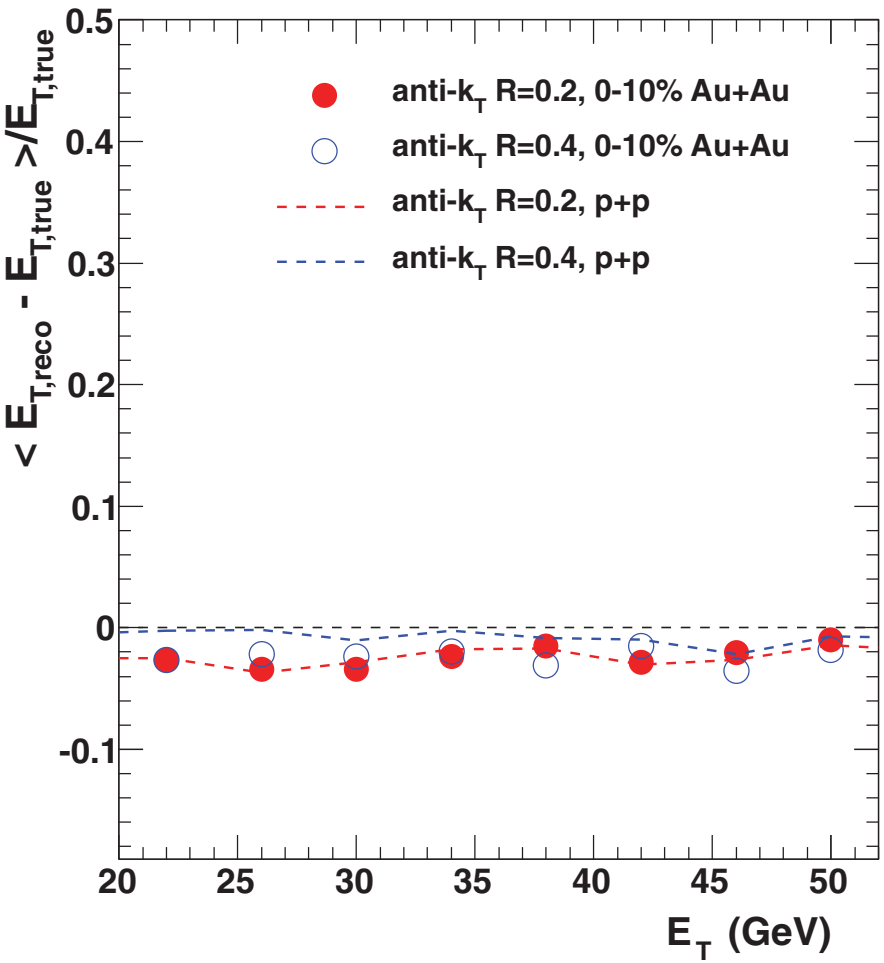
- Iterative algorithm to determine & subtract background based on ATLAS [PRC 86 (2012) 024908]

➡ proof of principle for calorimetric jet measurements in AA at RHIC

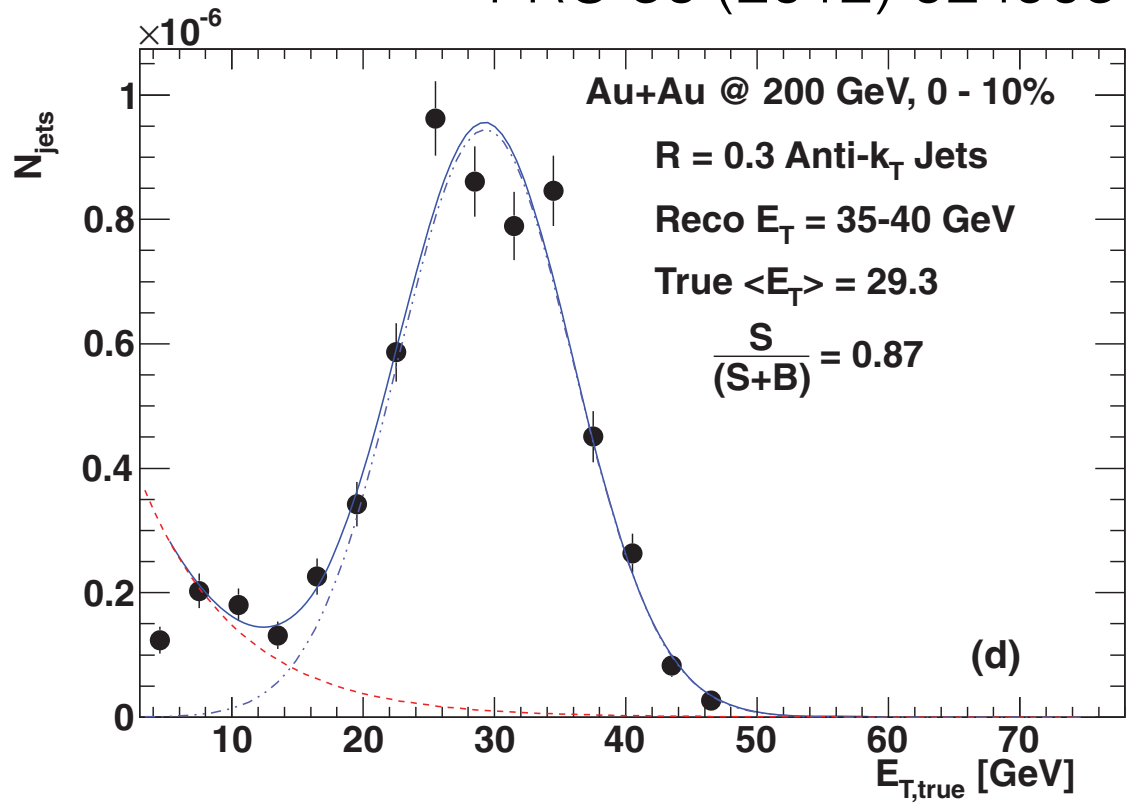
➡ historically “default”, but not unique, approach in sPHENIX

Historical context

(parameterized calorimeter response studies)



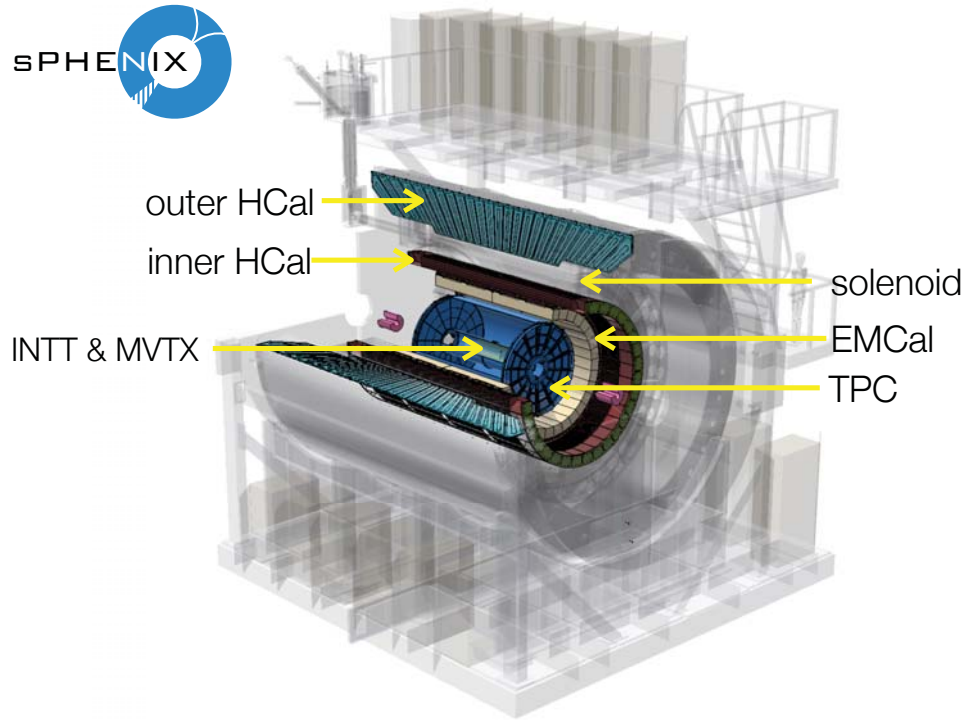
PRC 86 (2012) 024908



Test of subtraction on mean E_T response

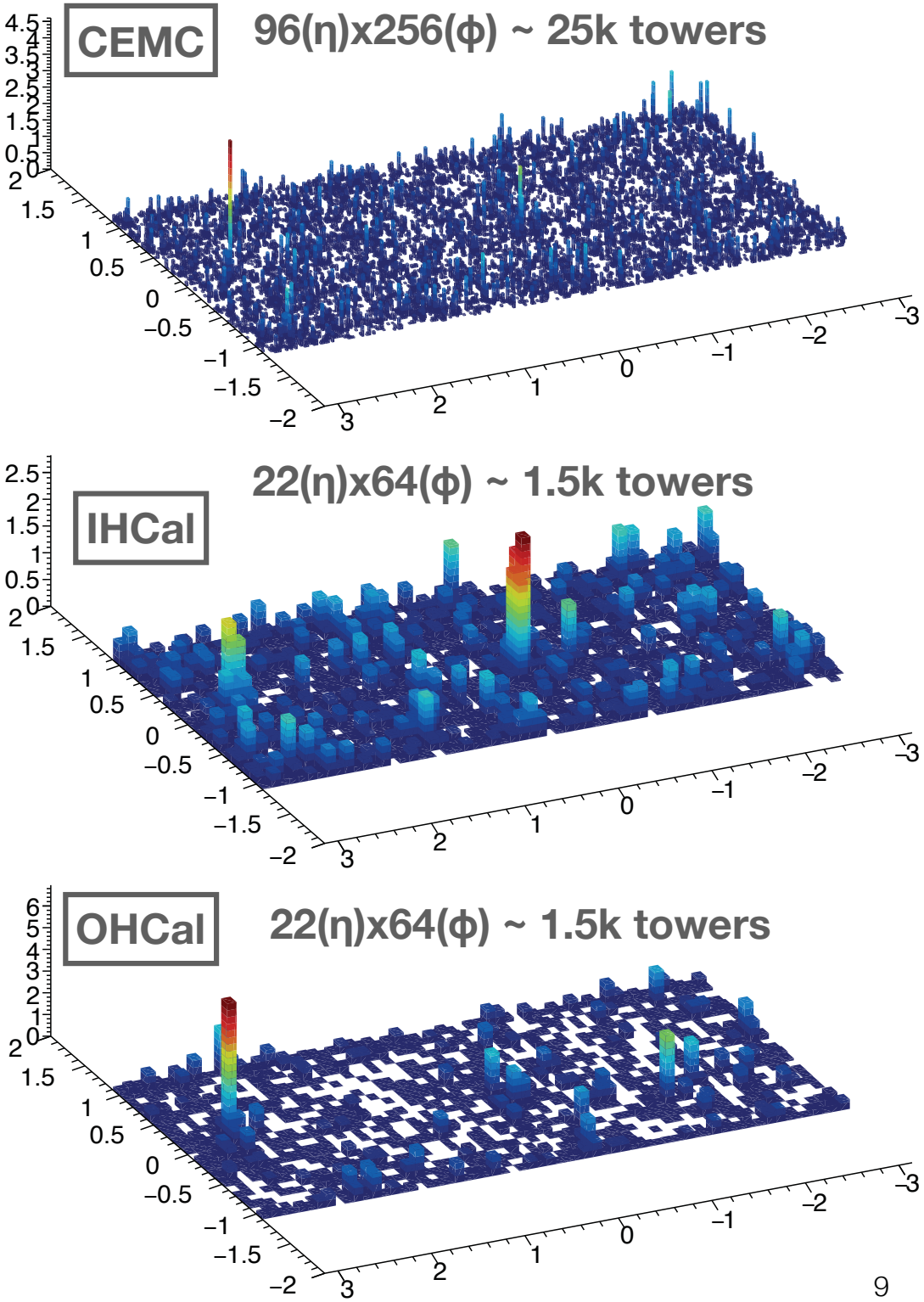
Select E_T^{reco} in some range —> what is E_T^{truth} distribution?

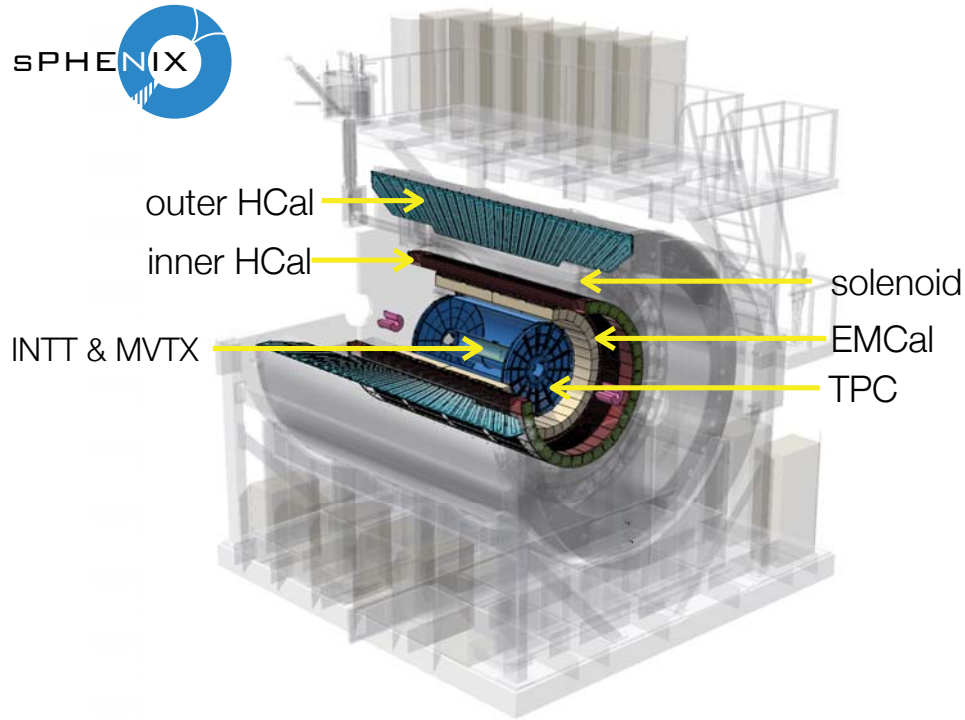
Modern implementation in sPHENIX, full GEANT4 simulation



Pythia QCD dijet event (p_T ~ 50 GeV)

embedded into b=1.2 fm (N_{coll} = 1048, 0-1%) Hijing event, at G4 hits level





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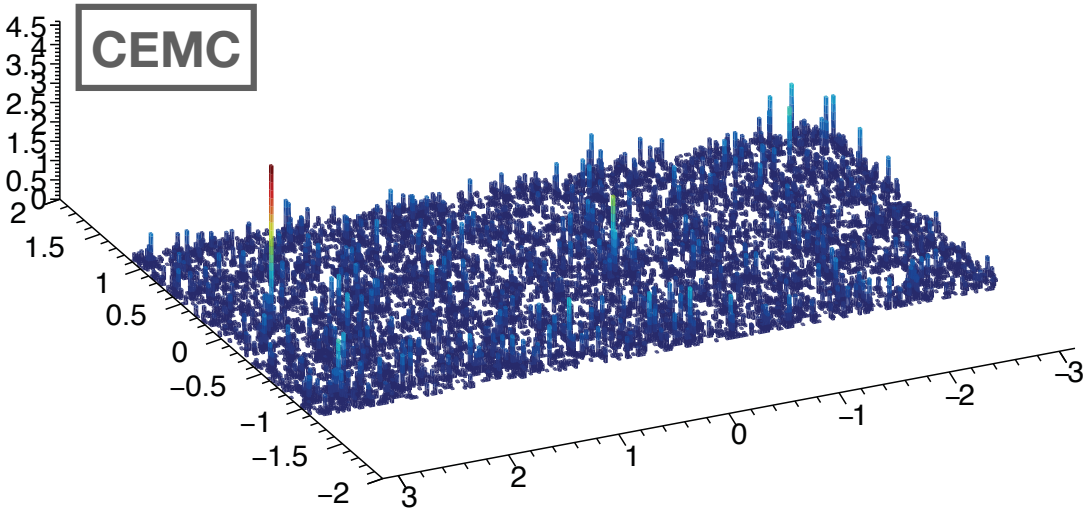
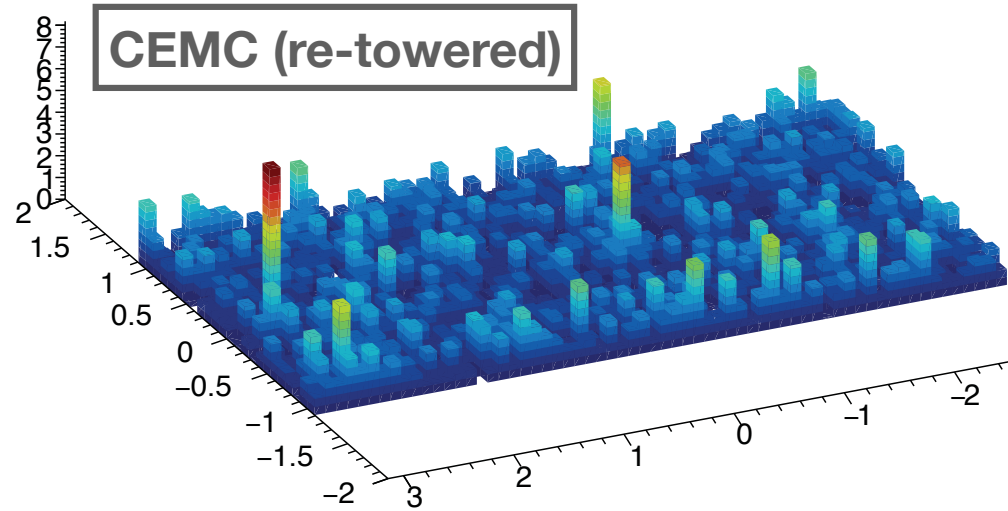
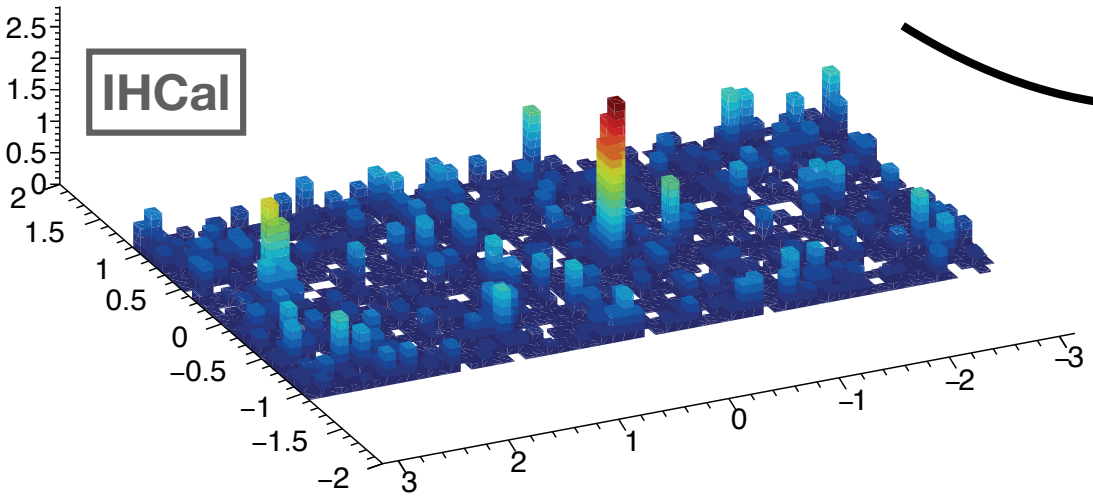
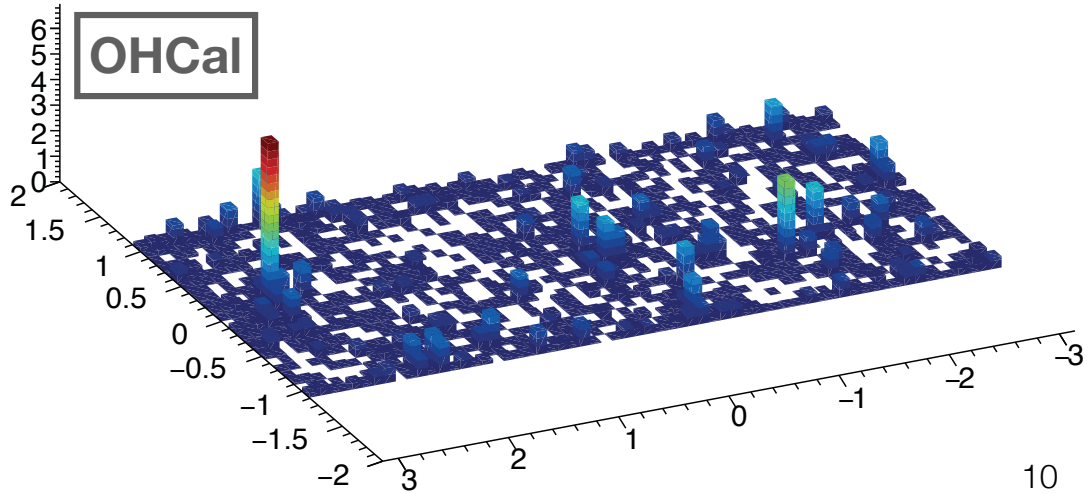
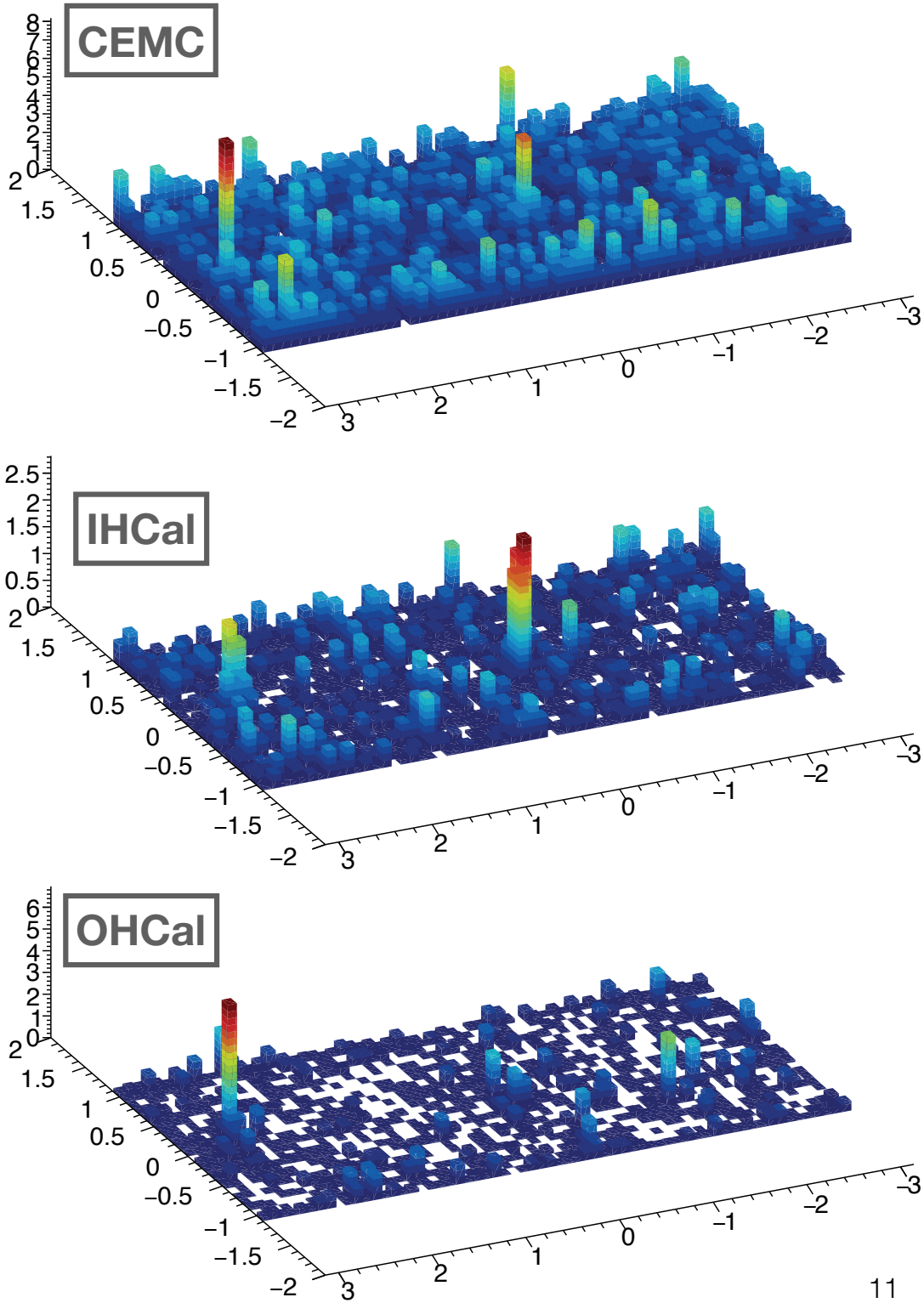




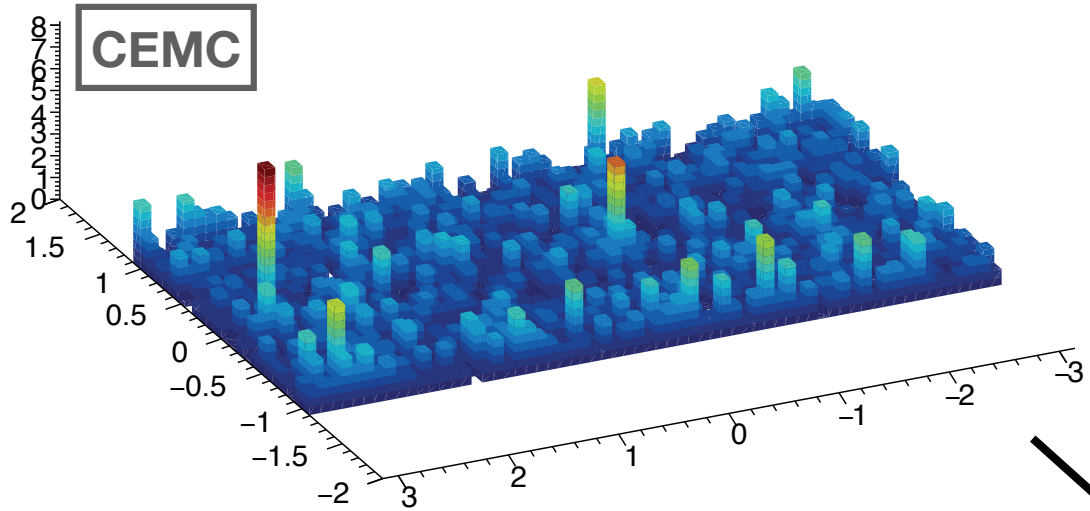




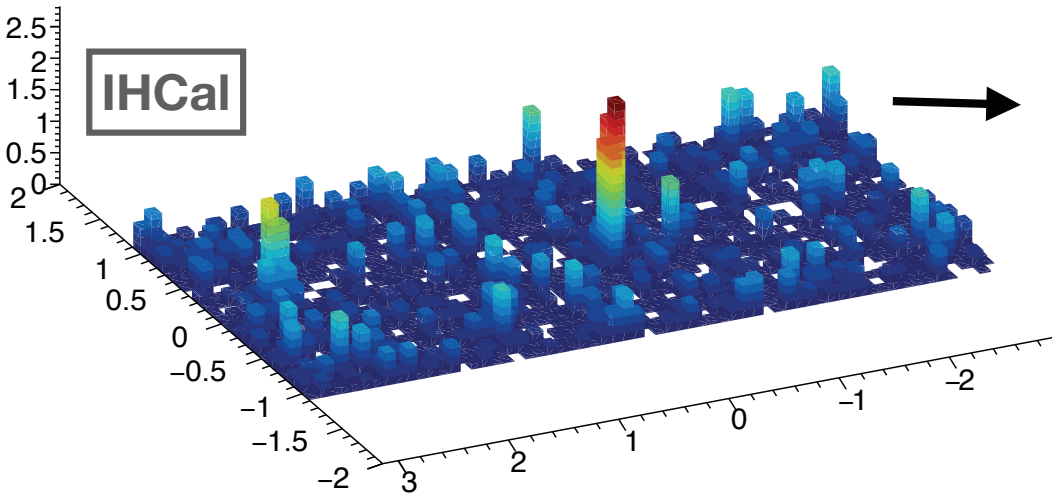
"Retower"(rebin) CEMC into abstract 0.1x0.1 towers

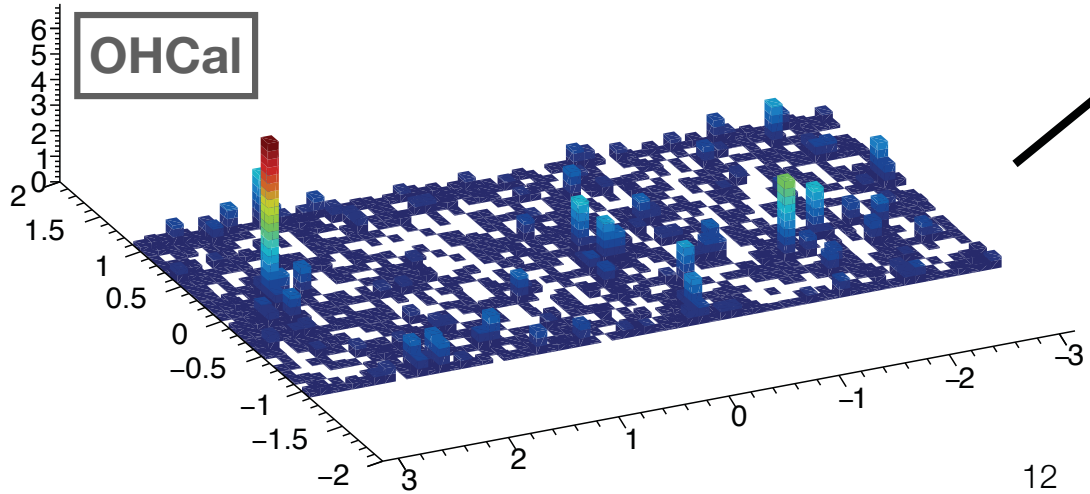


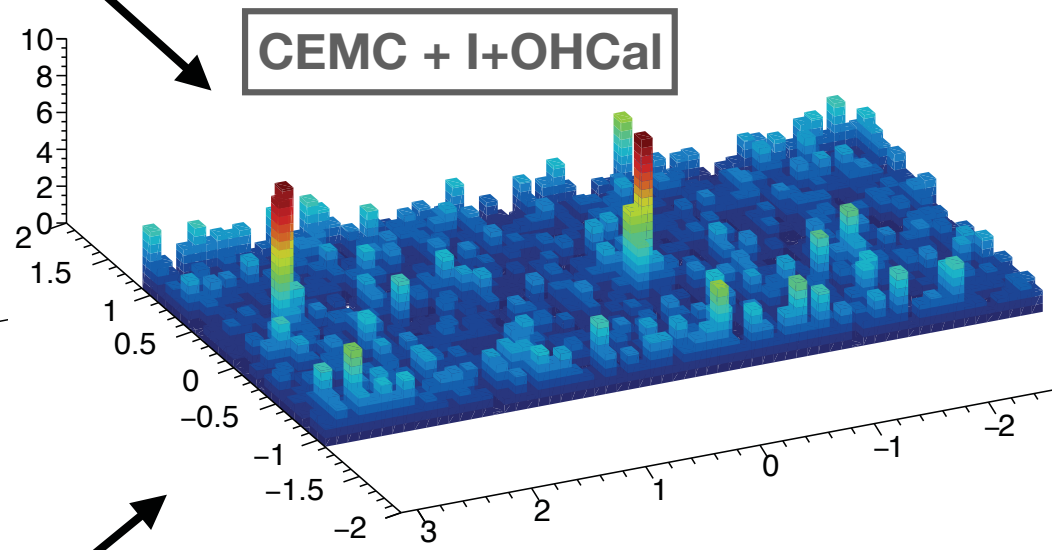
Run jet finding with R=0.2 on unsubtracted towers



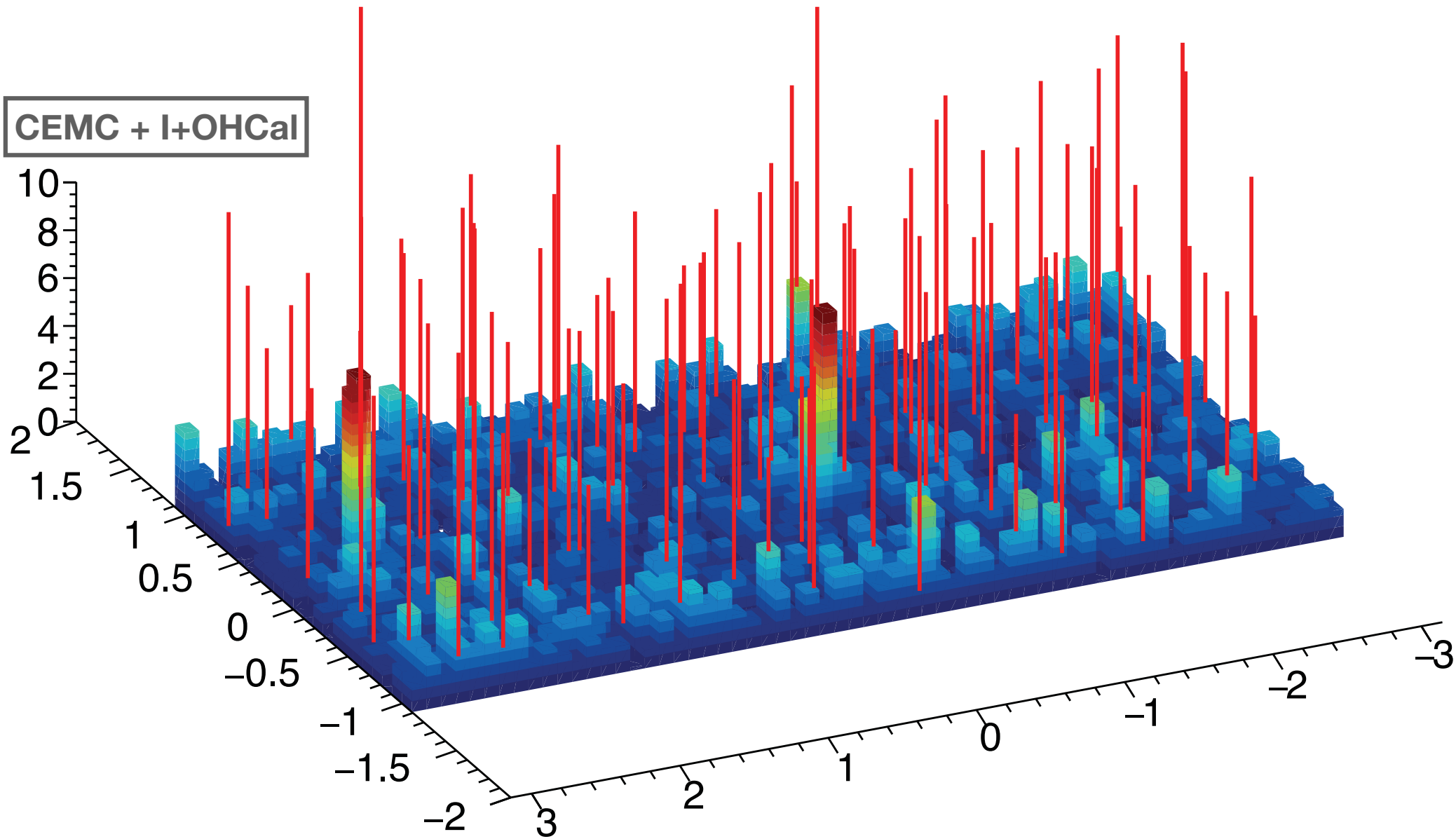
Can think of this as jet finding on a $\Delta\eta x \Delta\phi = 0.1x0.1$ grid





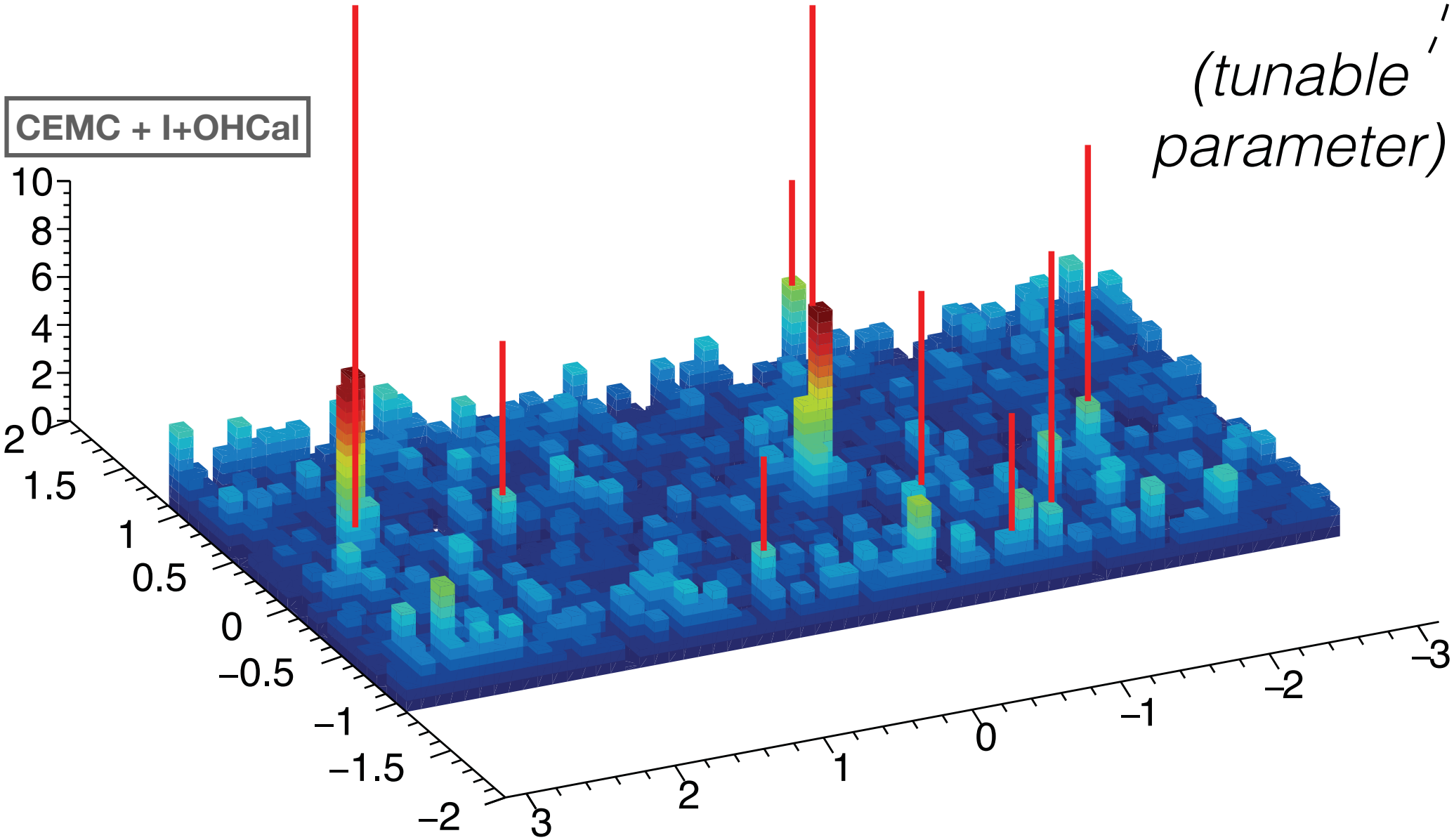


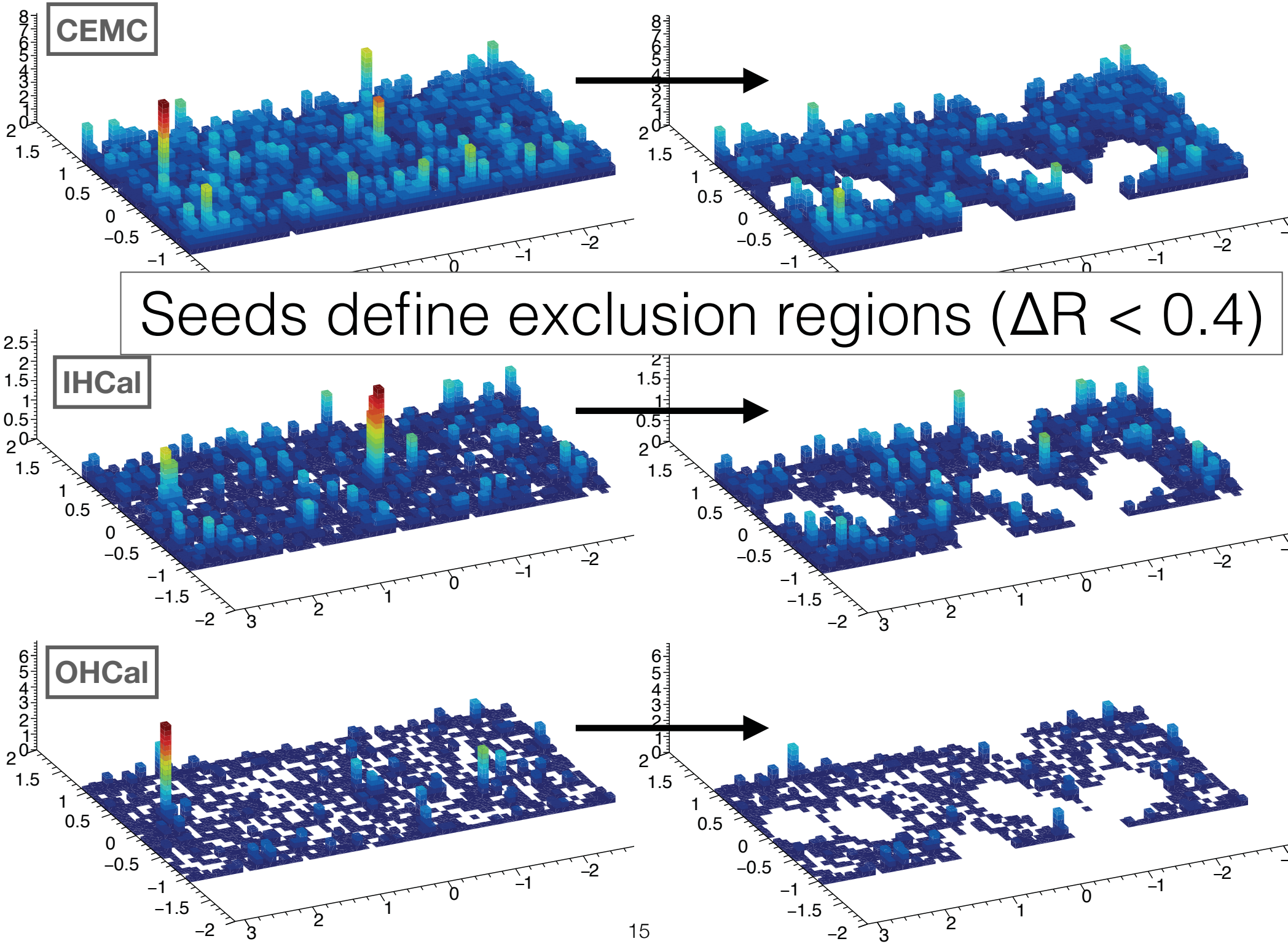
Position of R=0.2, p_T > 7 GeV jets (height ~ p_T)



Jets with $D = \max(E_T^{tower}) / \langle E_T^{tower} \rangle > 3$ serve as "seeds" in the first iteration

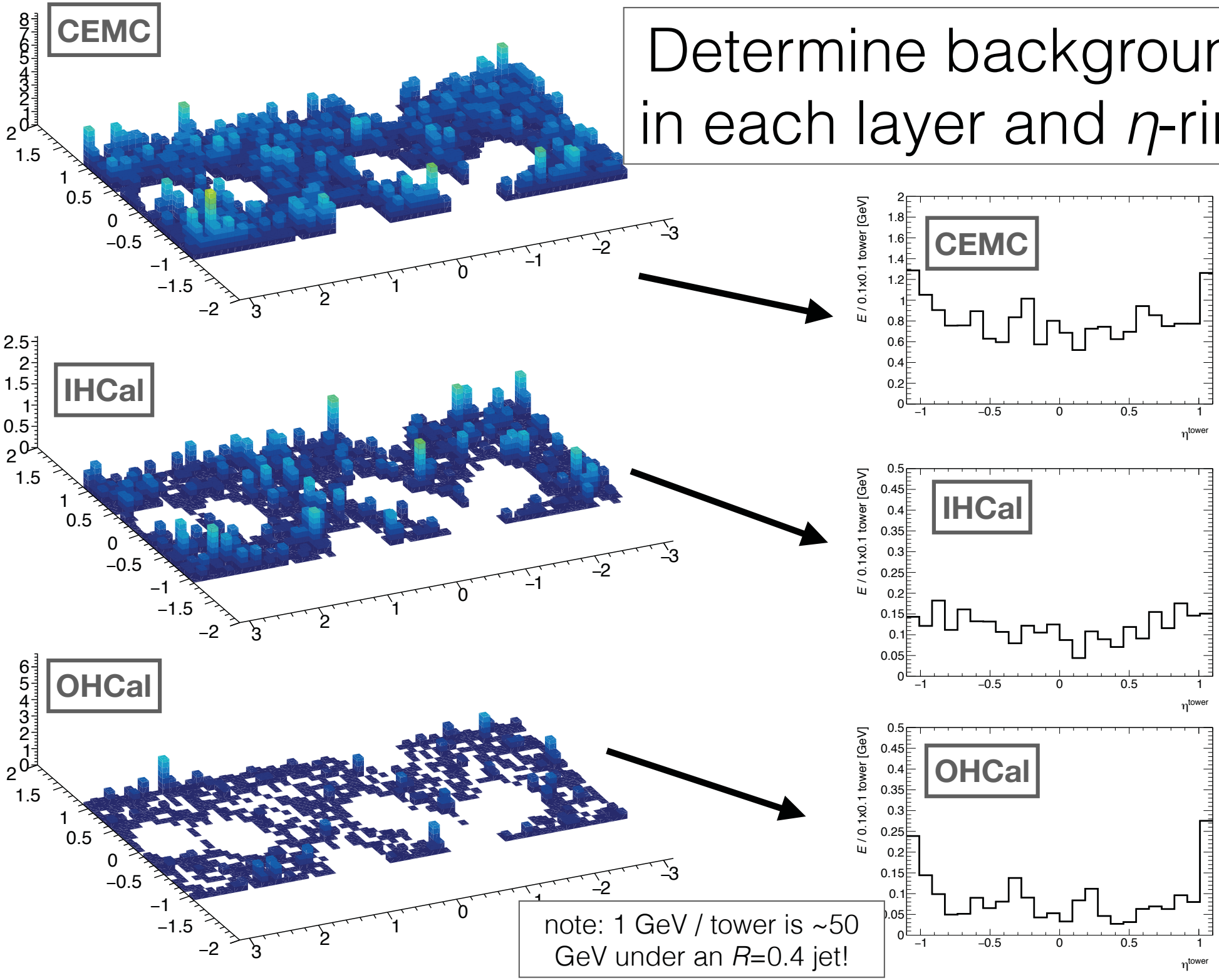
(tunable parameter)



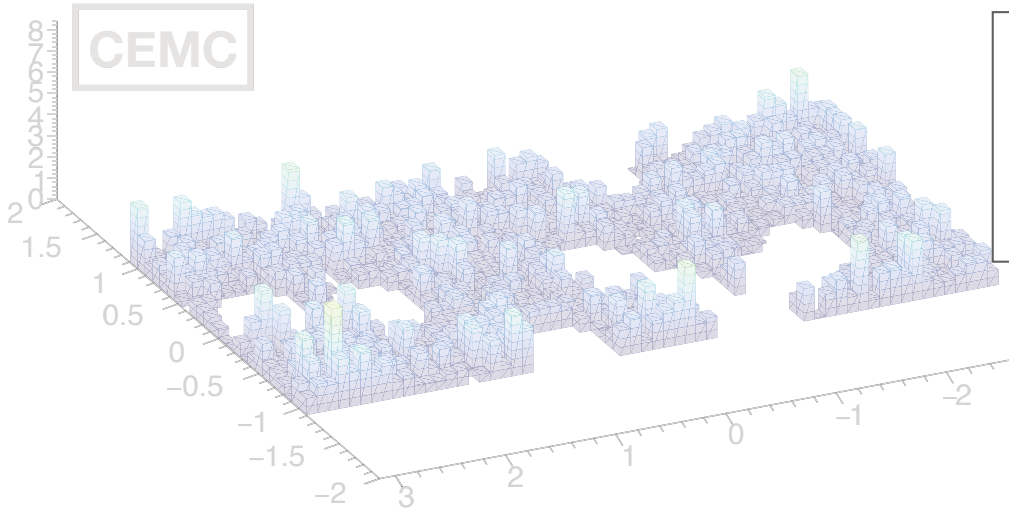


Seeds define exclusion regions ($\Delta R < 0.4$)

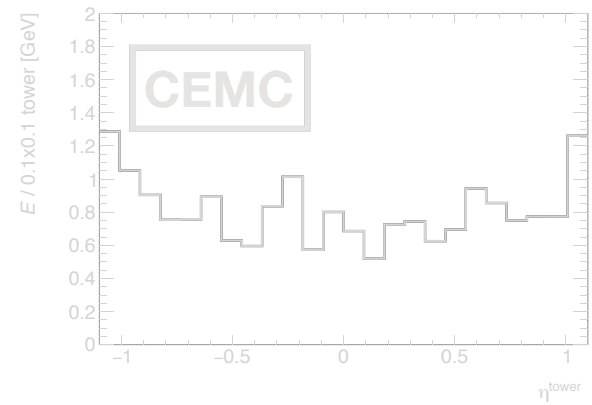
Determine background in each layer and η-ring

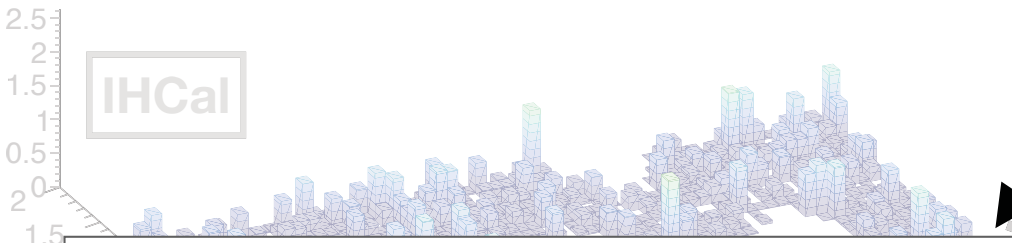


note: 1 GeV / tower is ~50 GeV under an R=0.4 jet!



Determine background in each layer and η-ring



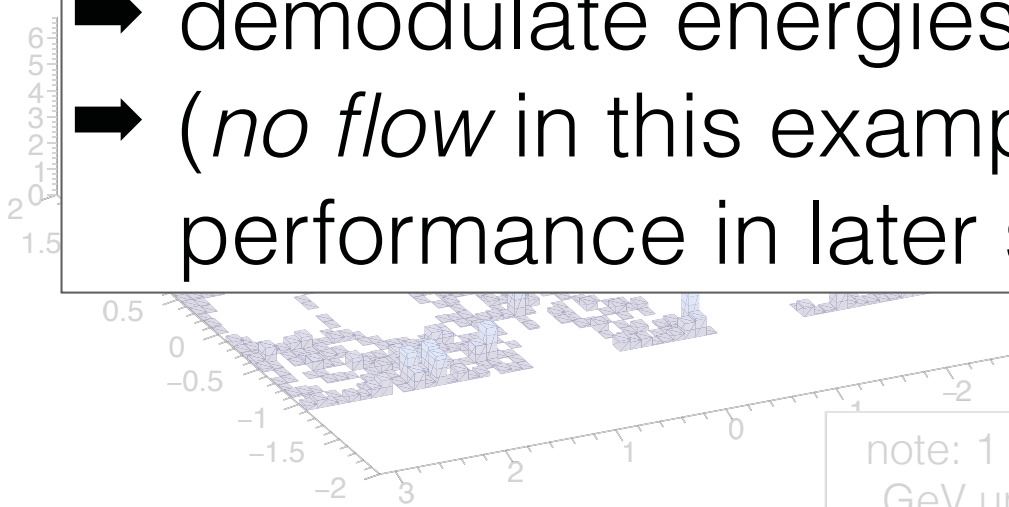


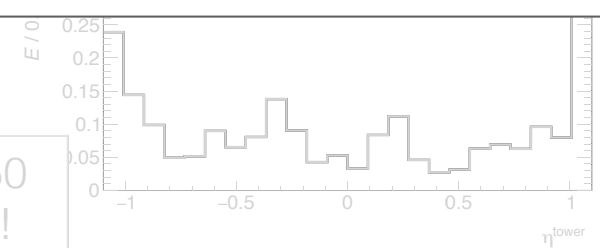
Determine event-wide Ψ_2 and v_2:

➡ estimate from η-rings without excluded towers

➡ demodulate energies before UE determination

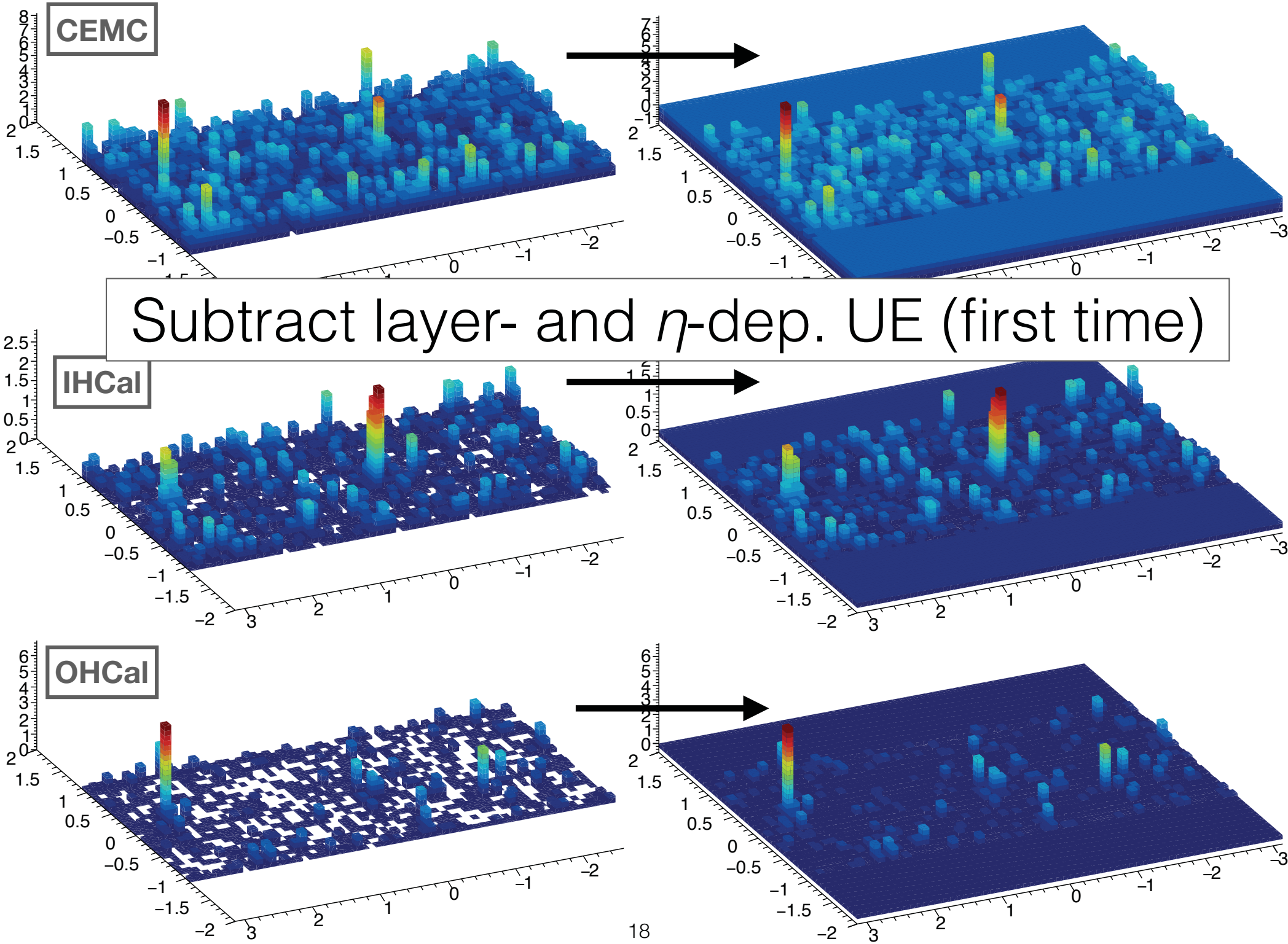
➡ (*no flow* in this example Hijing event, will show performance in later slides…)

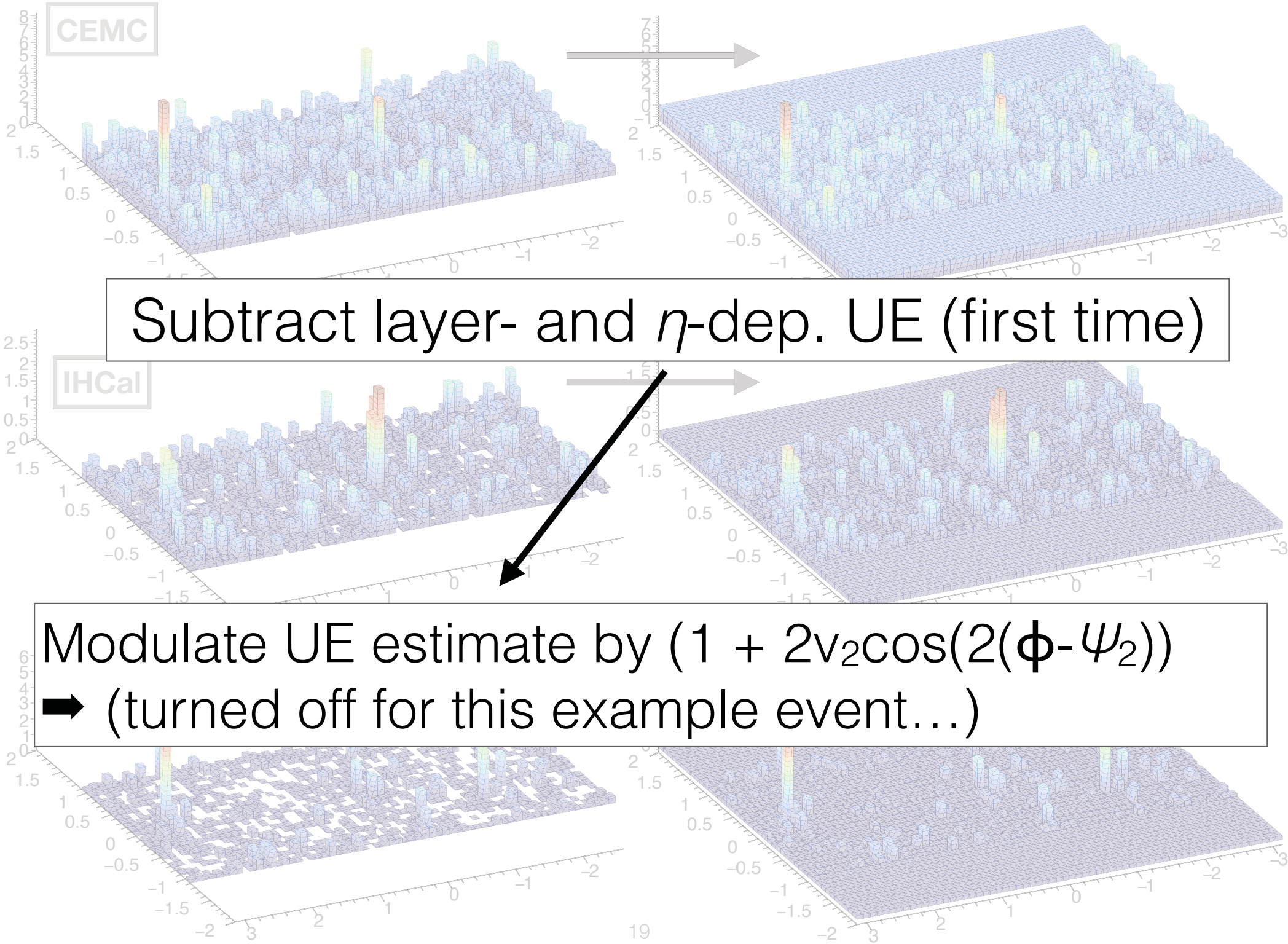




note: 1 GeV / tower is ~50 GeV under an R=0.4 jet!

Subtract layer- and η-dep. UE (first time)





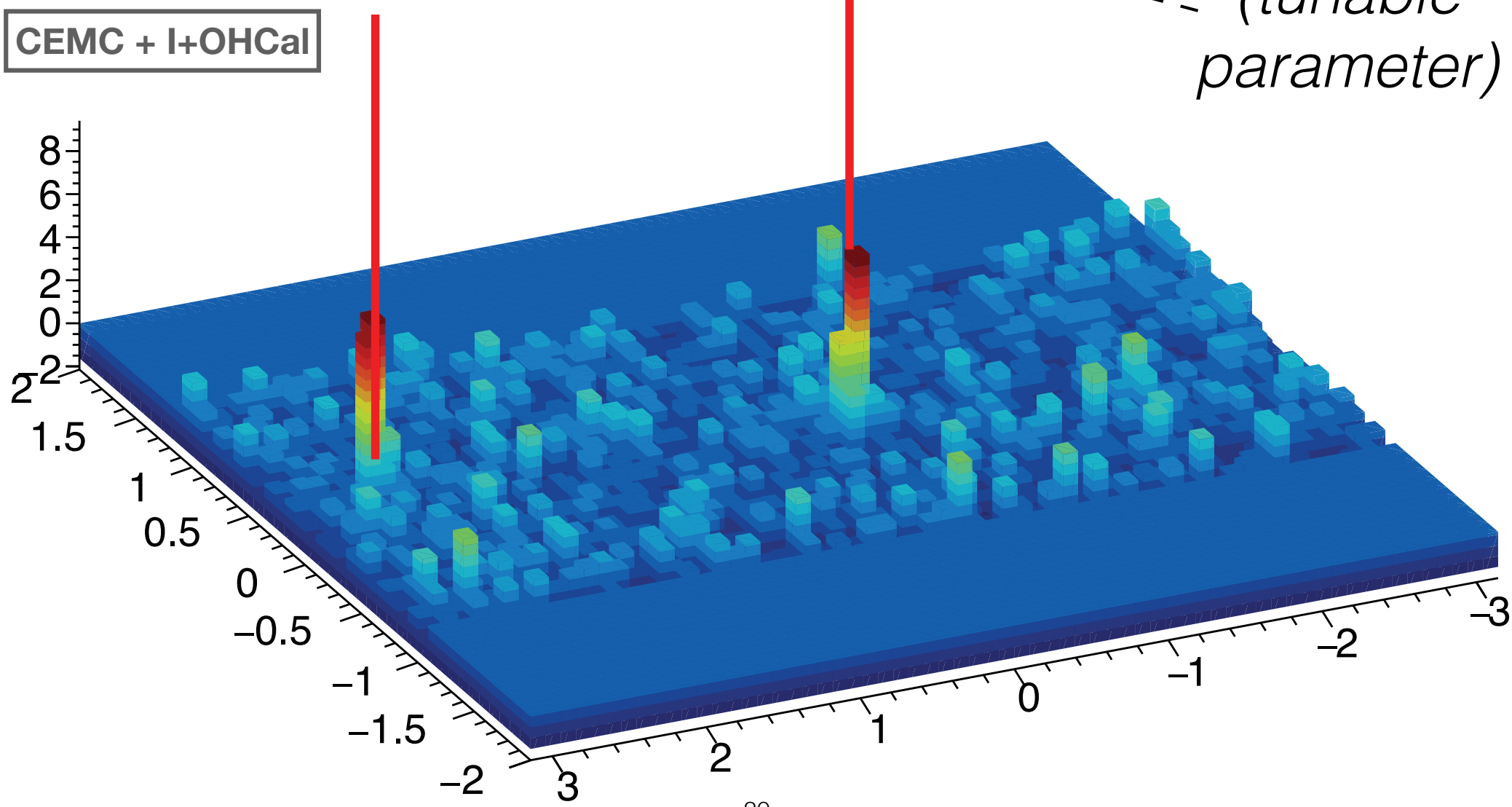
Subtract layer- and η-dep. UE (first time)

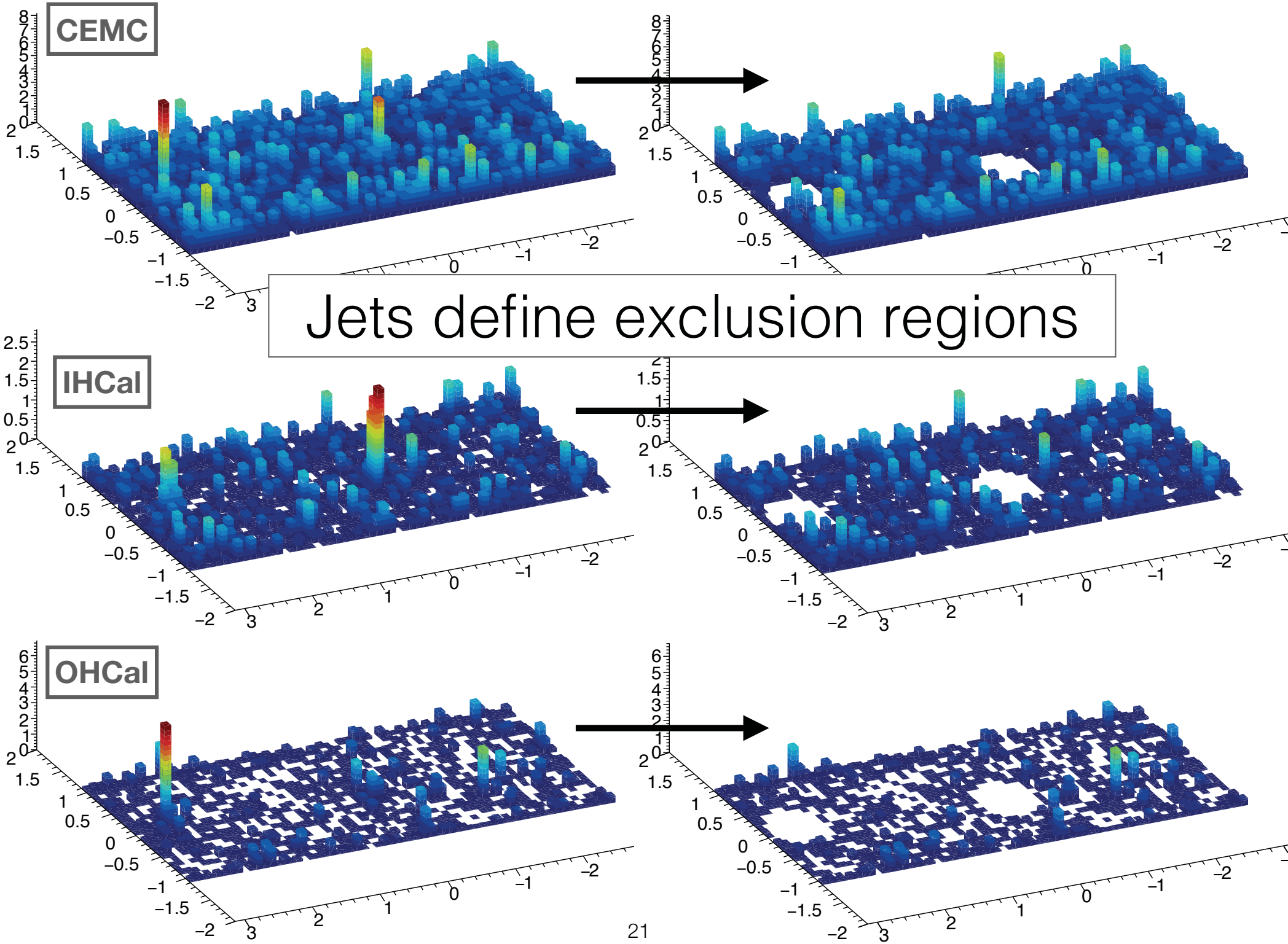
Modulate UE estimate by $(1 + 2v_2\cos(2(\phi - \Psi_2))$

➡ (turned off for this example event…)

Update jet kinematics (no new jet finding), keep only p_T > 10 GeV R=0.2 jets

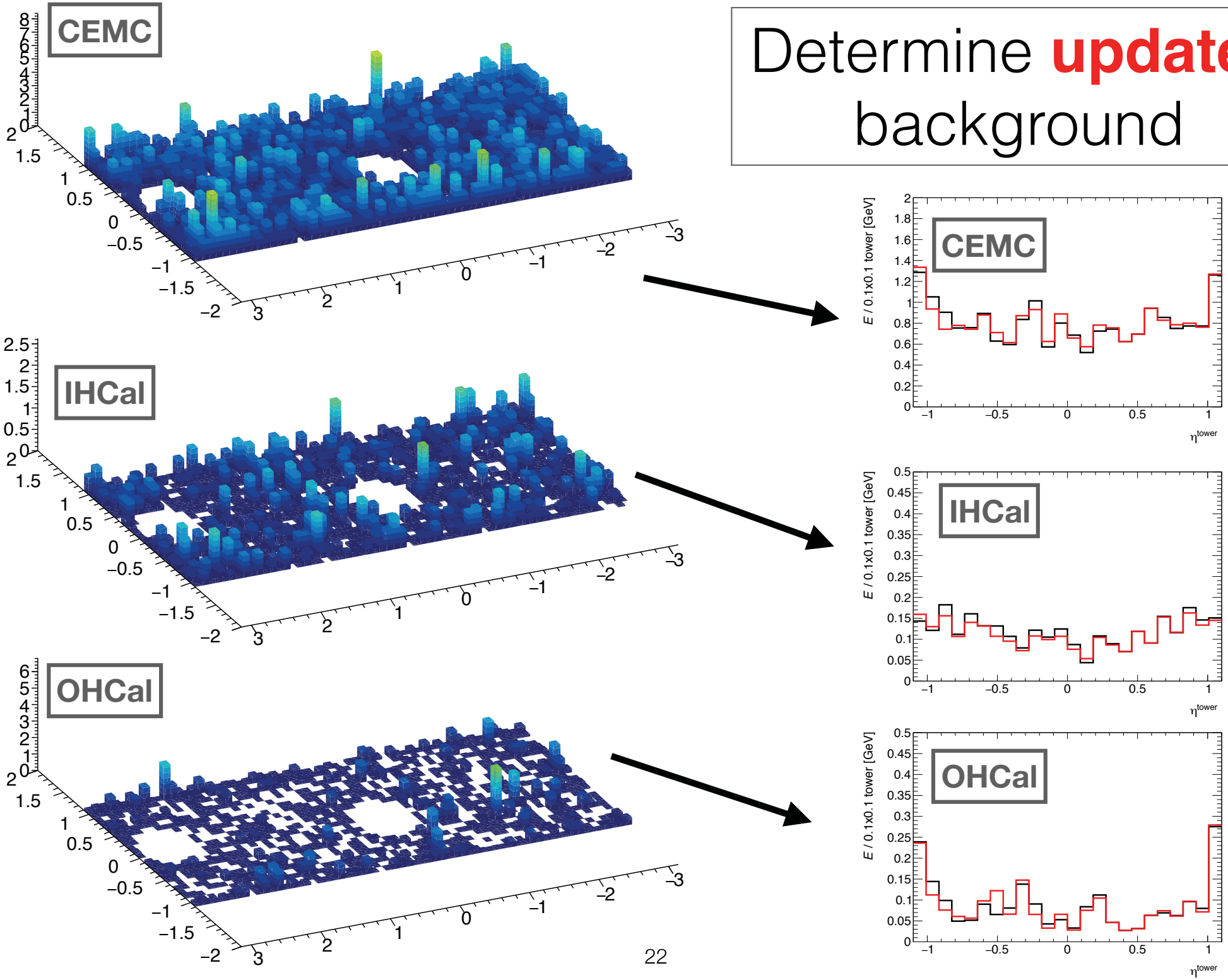
(tunable parameter)



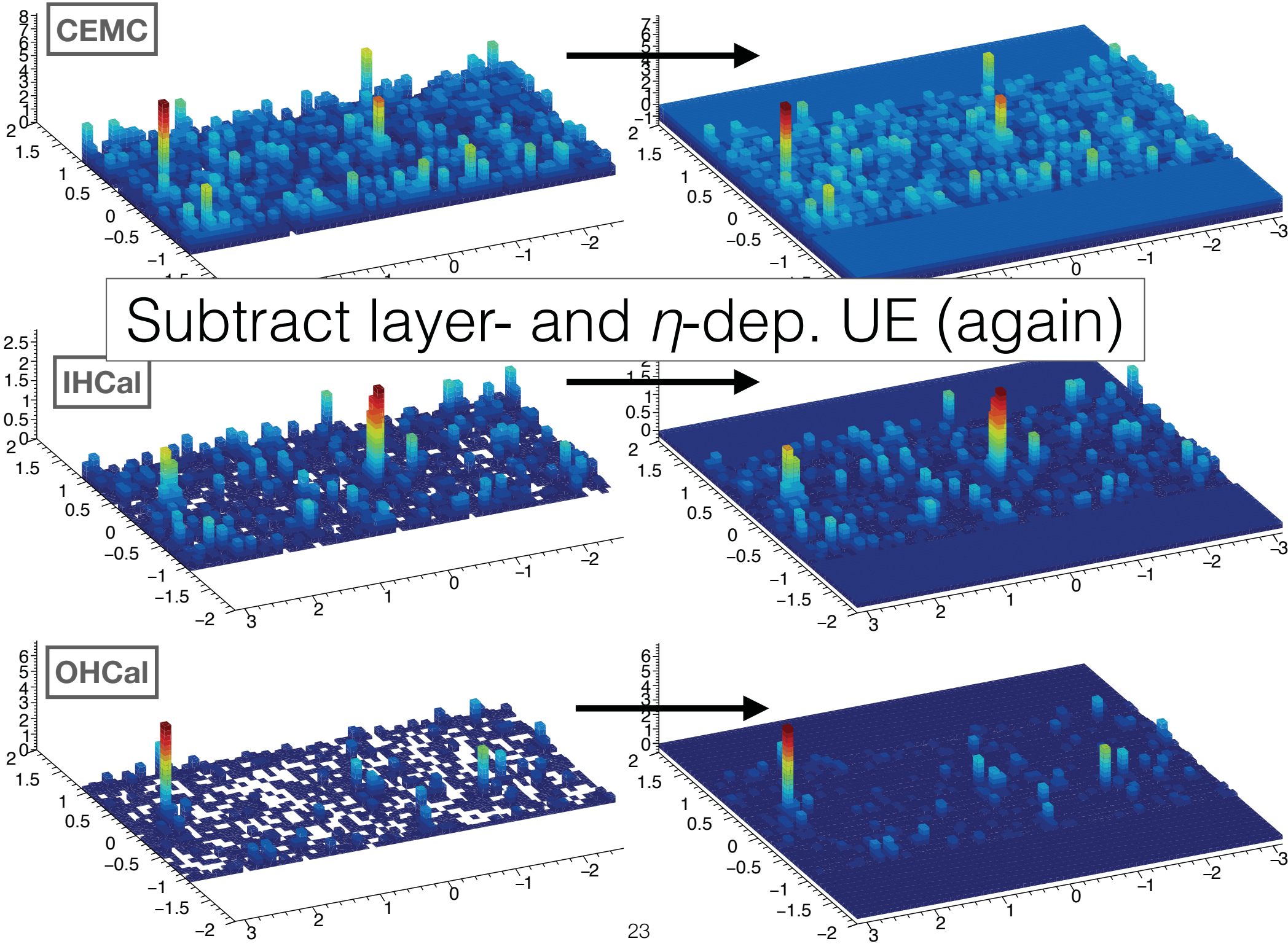


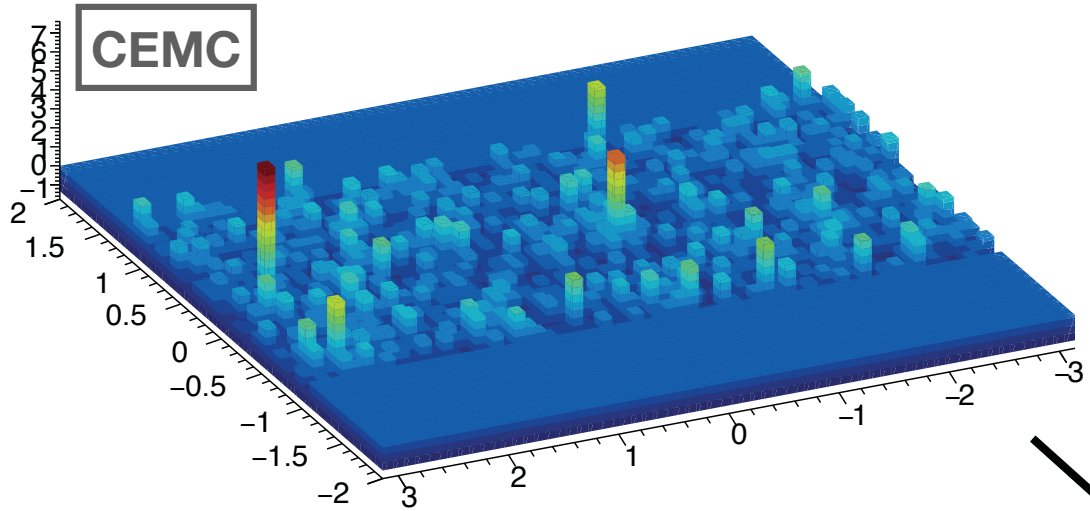
Jets define exclusion regions

Determine **updated** background

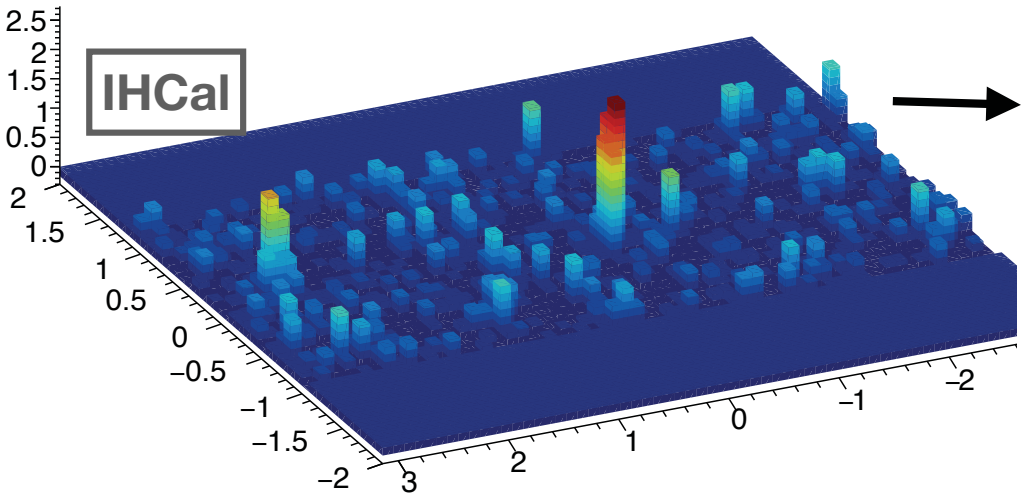


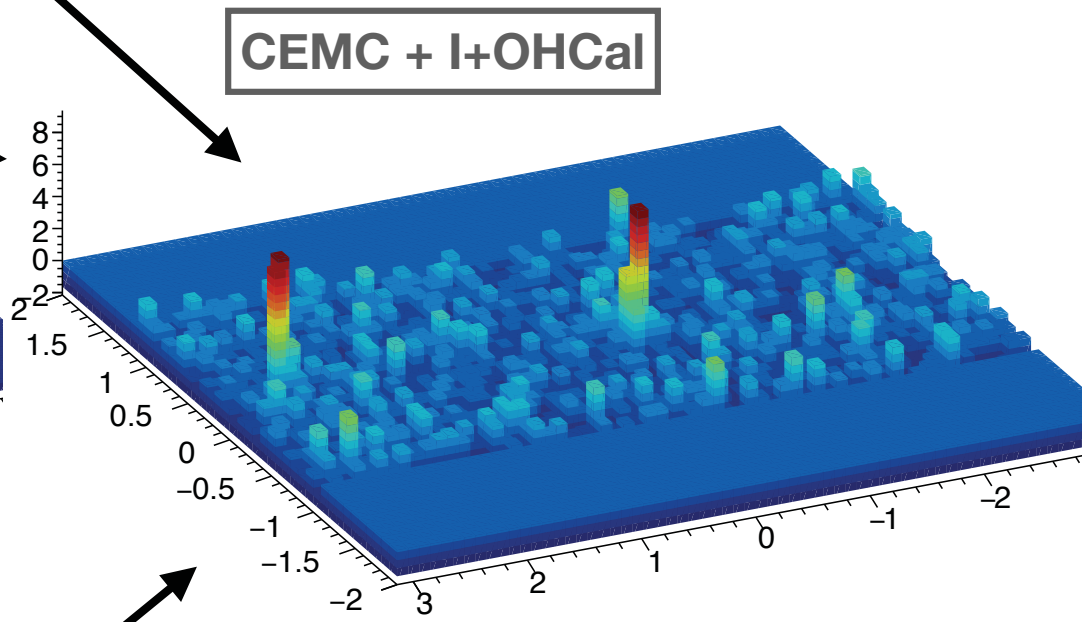
Subtract layer- and η-dep. UE (again)

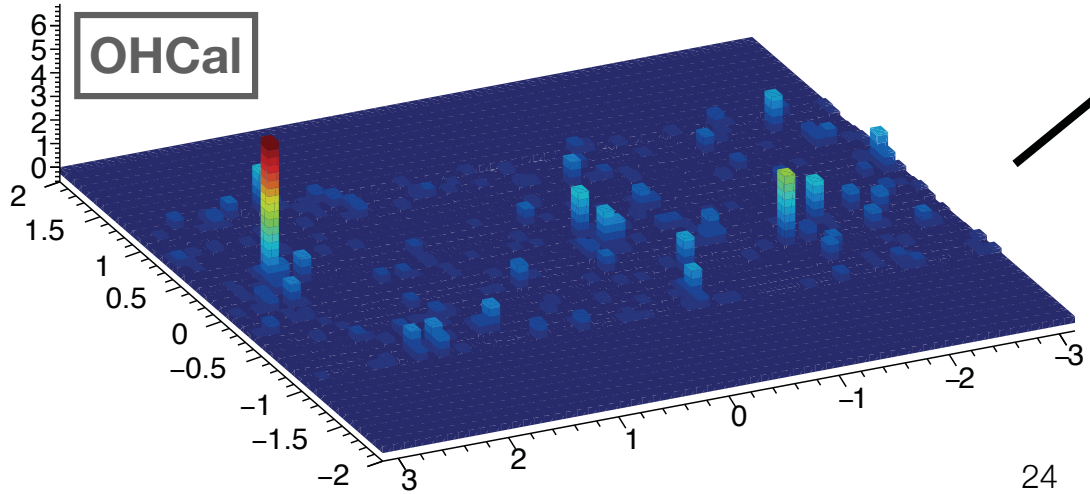


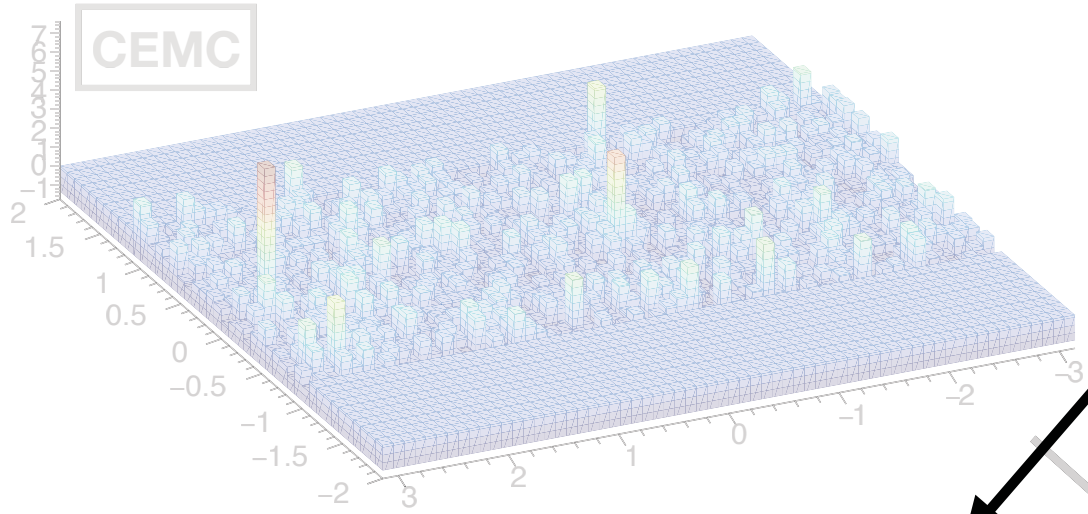


Run jet finding with R=0.2-0.5 on subtracted towers









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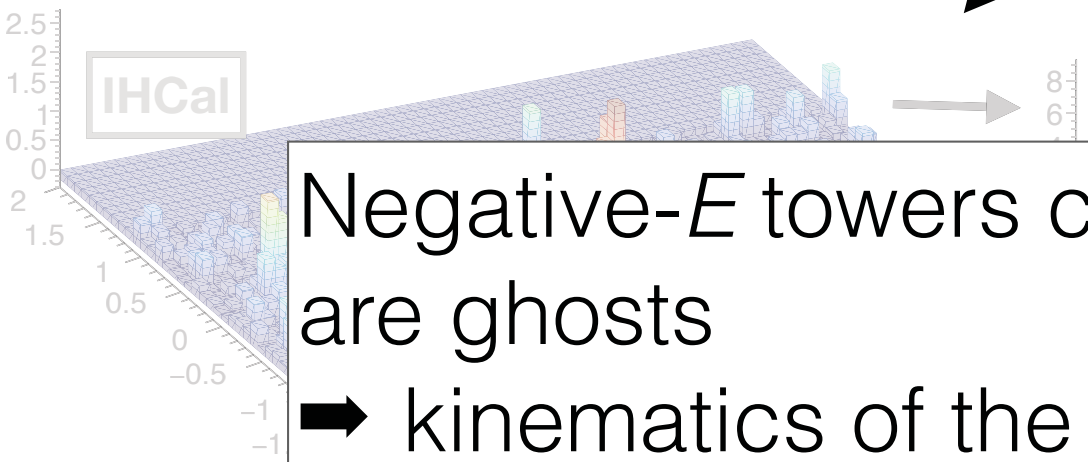
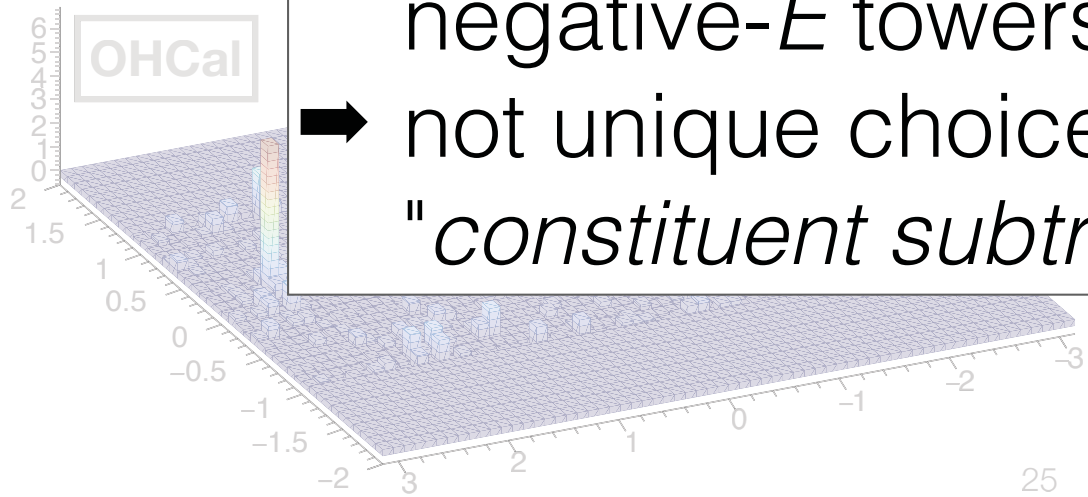
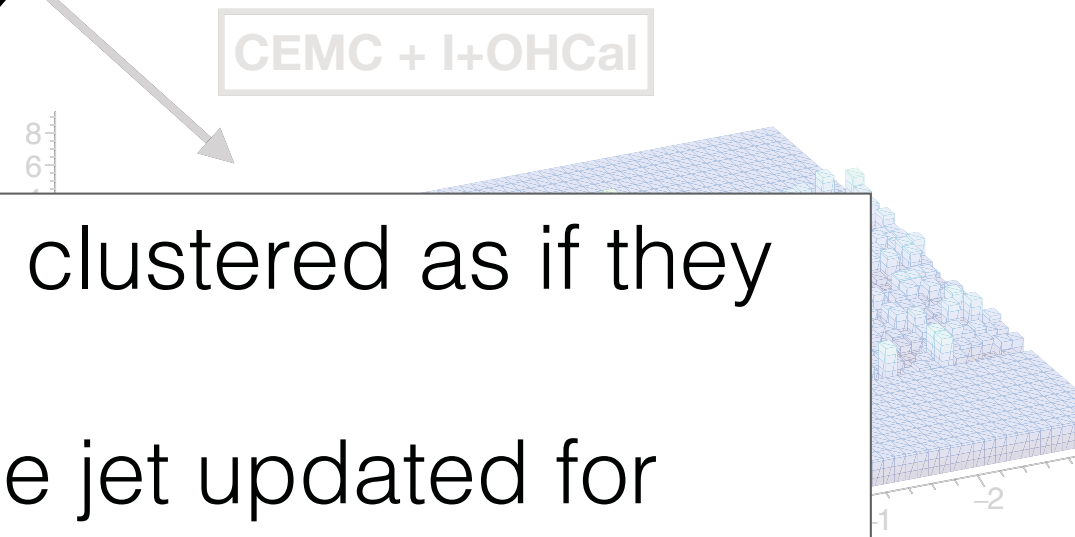




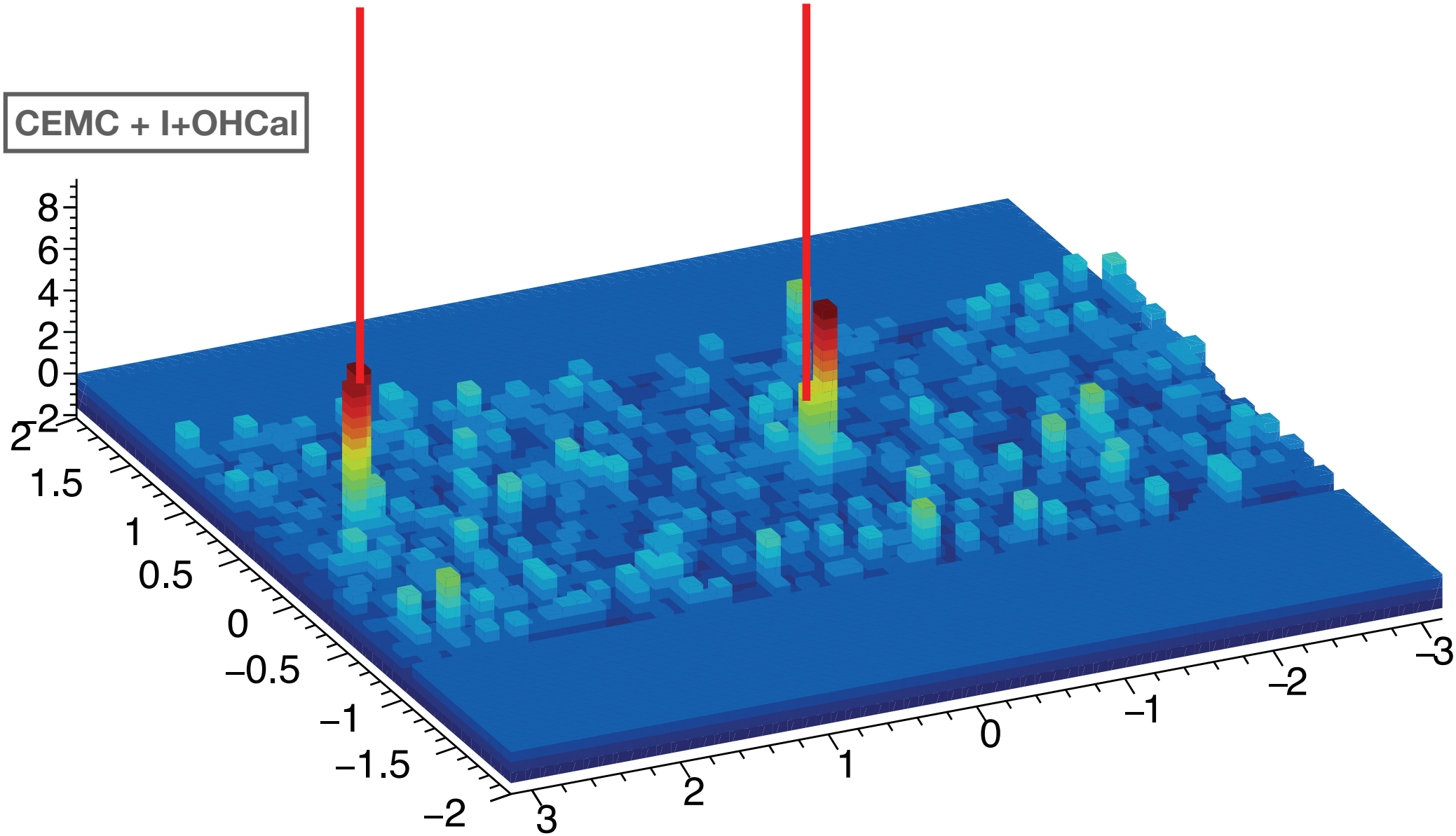


Negative-E towers clustered as if they are ghosts

➡ kinematics of the jet updated for negative-E towers afterwards

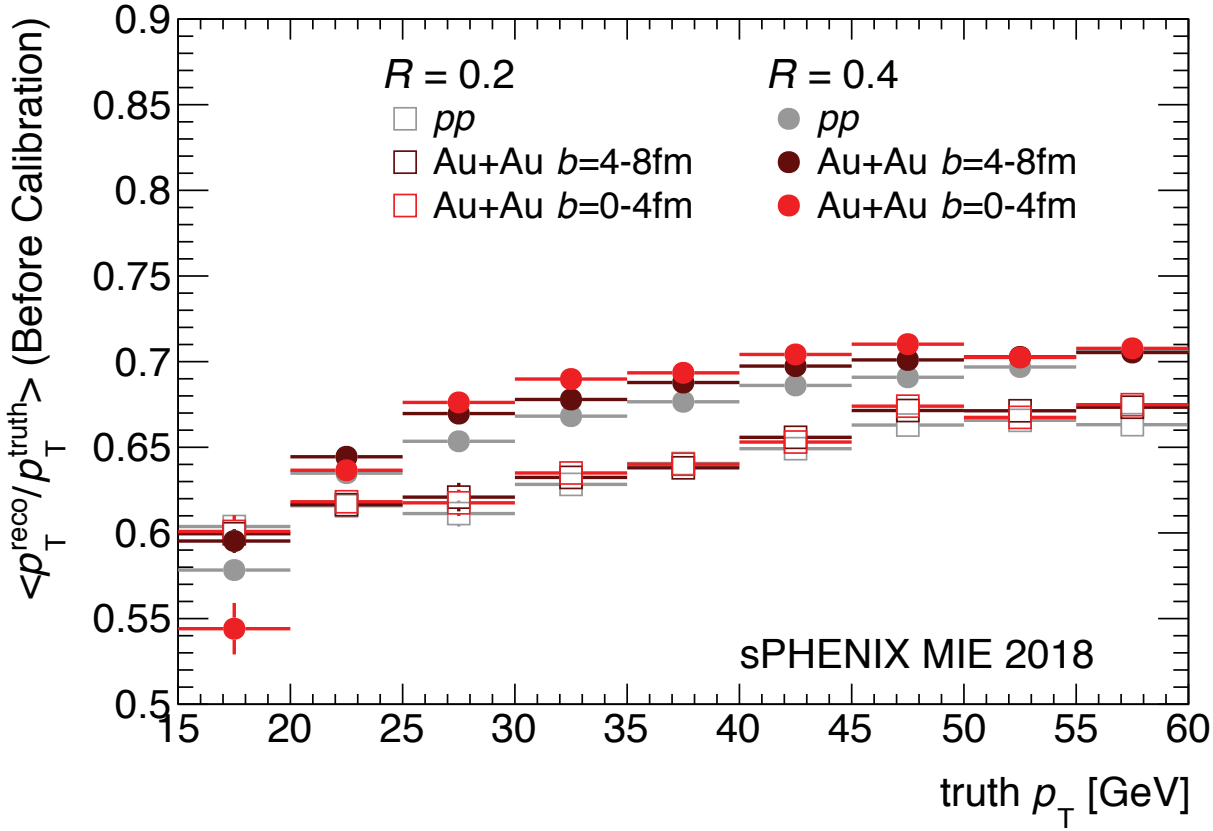
➡ not unique choice: can also apply "*constituent subtraction*" (later slides)

Final R=0.4, p_T > 10 GeV jets (height ~ p_T)



Jet performance summary (1/4)

(with some particular choice of seed parameters)

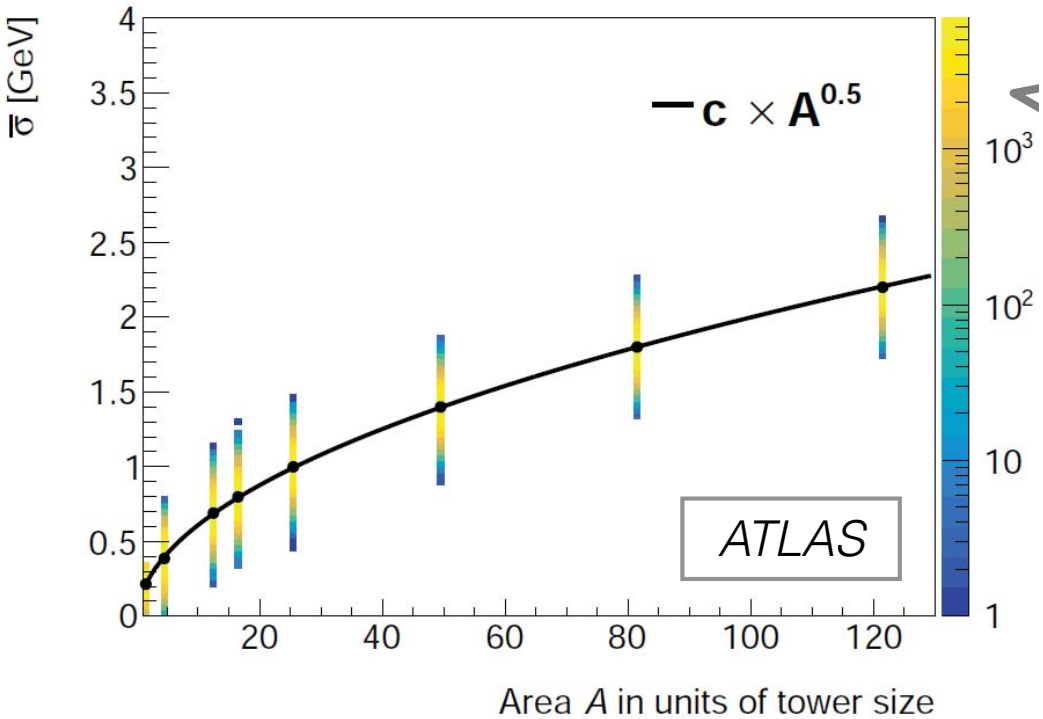


p_T response at "*EM*" scale, i.e. before jet-level calibration

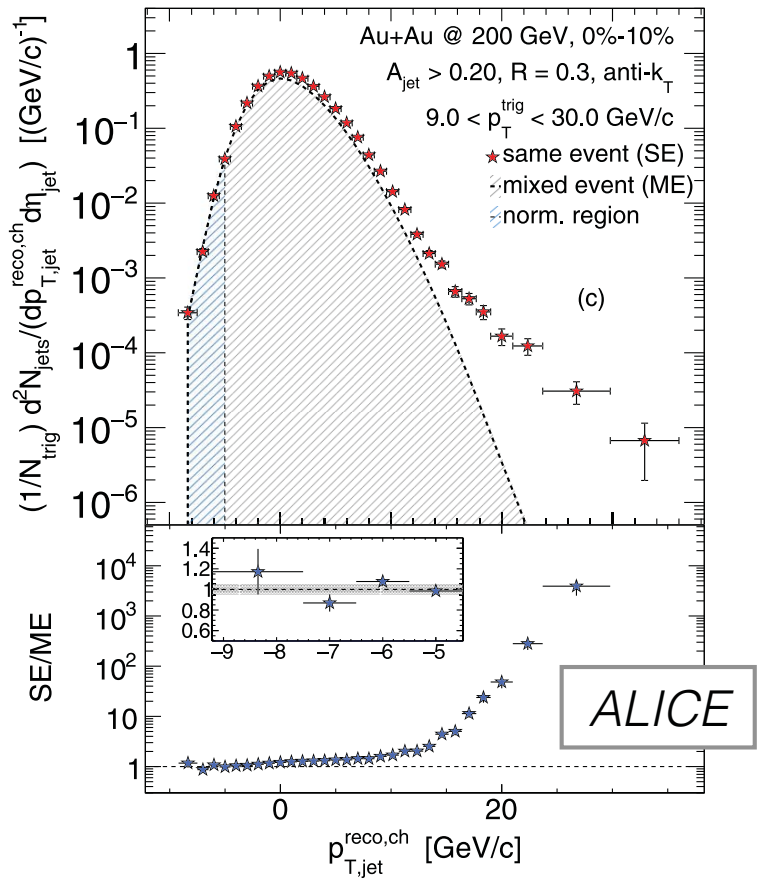
➡ reasonably (but imperfectly) independent of UE level

Major scientific goal is to push the achievable p_T^{jet} ever lower…

➡ increased sensitivity to flow treatment / reco. parameters



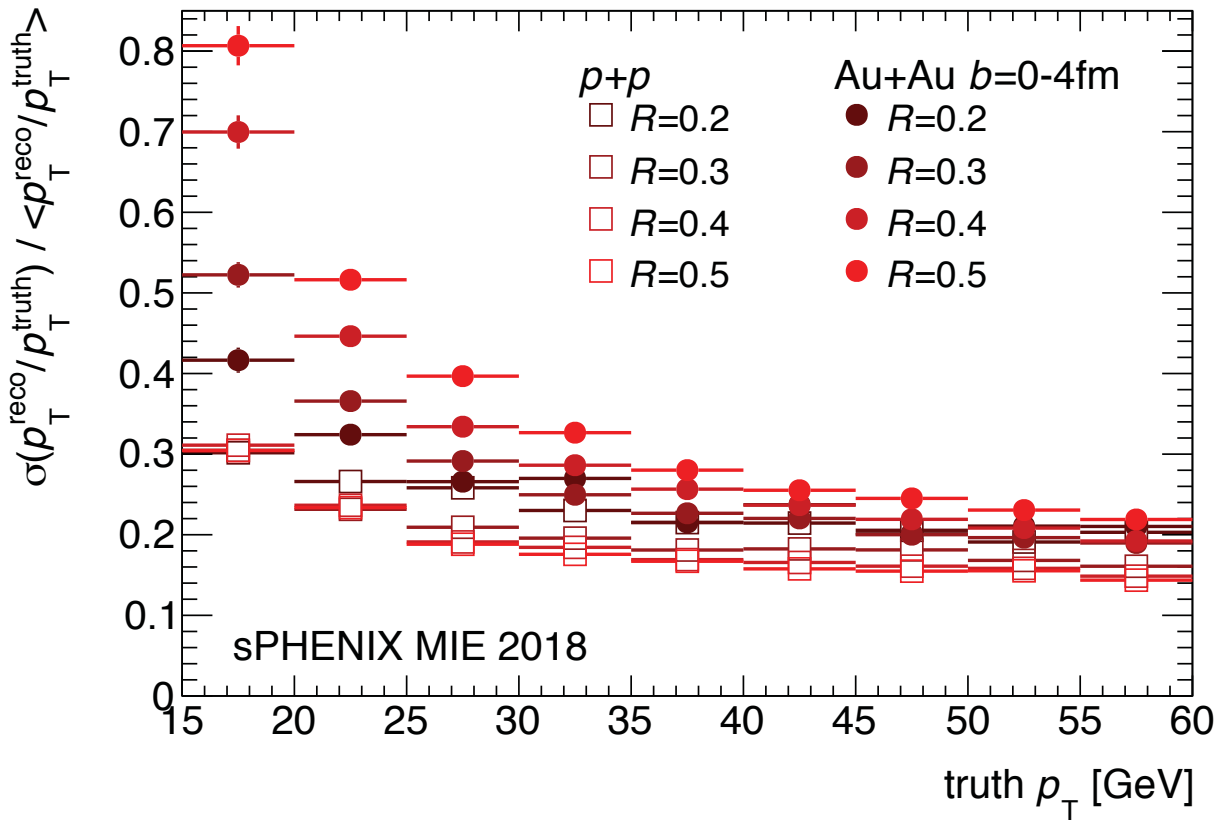
UE fluctuation spectrum in fixed cone sizes (ultimately will do in data)



construction of fluctuations from mixed events (semi-inclusive analyses)

Jet performance summary (2/4)

(with some particular choice of seed parameters)



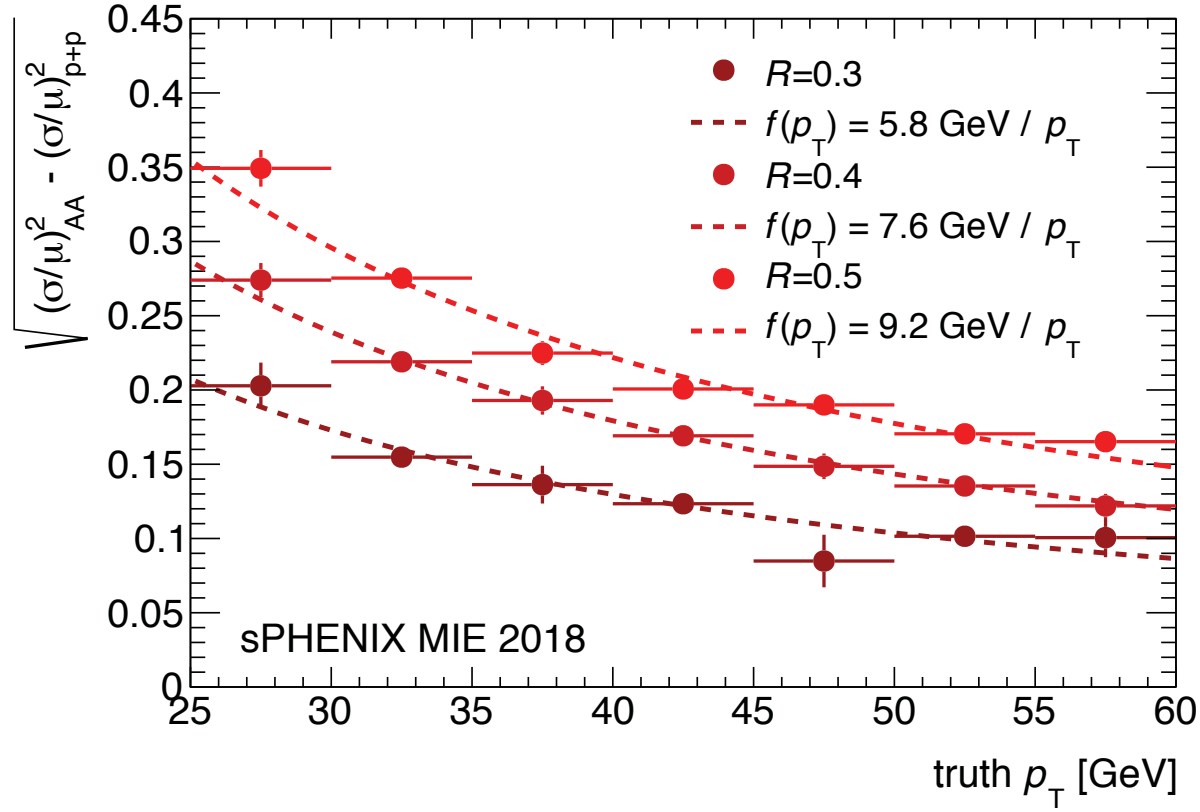
Resolution on *EM*-scale p_T response

➡ expected ordering in R and UE level

Deconvolution of UE term in Au+Au response

$$\frac{\sigma_{p_T}}{p_T} = \frac{n}{p_T} \oplus \frac{s}{\sqrt{p_T}} \oplus c$$

Noise Stochastic Constant



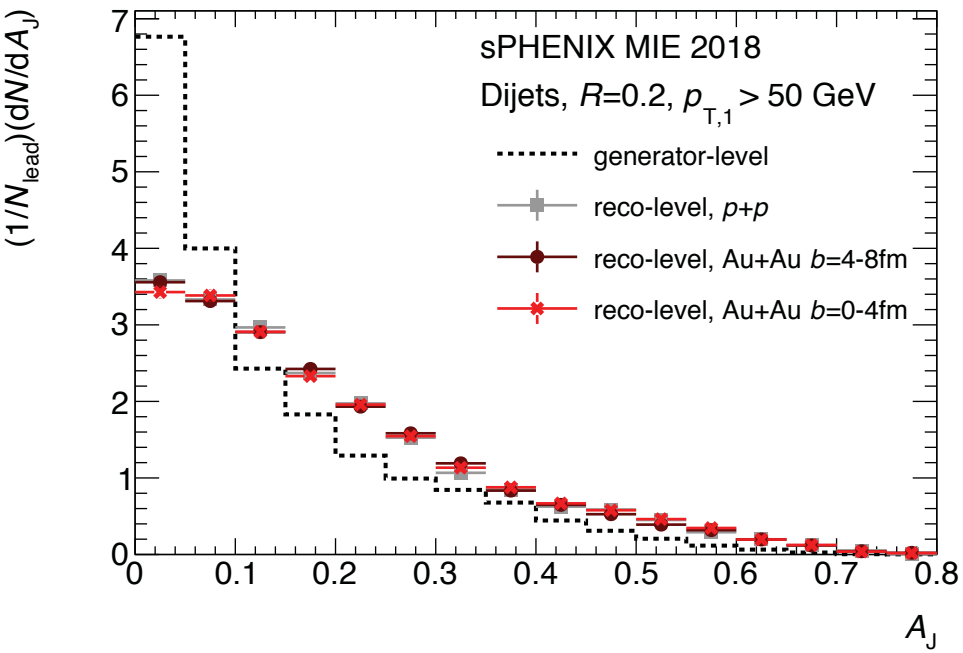
- One advantage of purely calorimetric measurement: reconstruction proceeds identically in *pp* and Au+Au

  ➡ can understand Au+Au response as *pp* response ⊗ UE

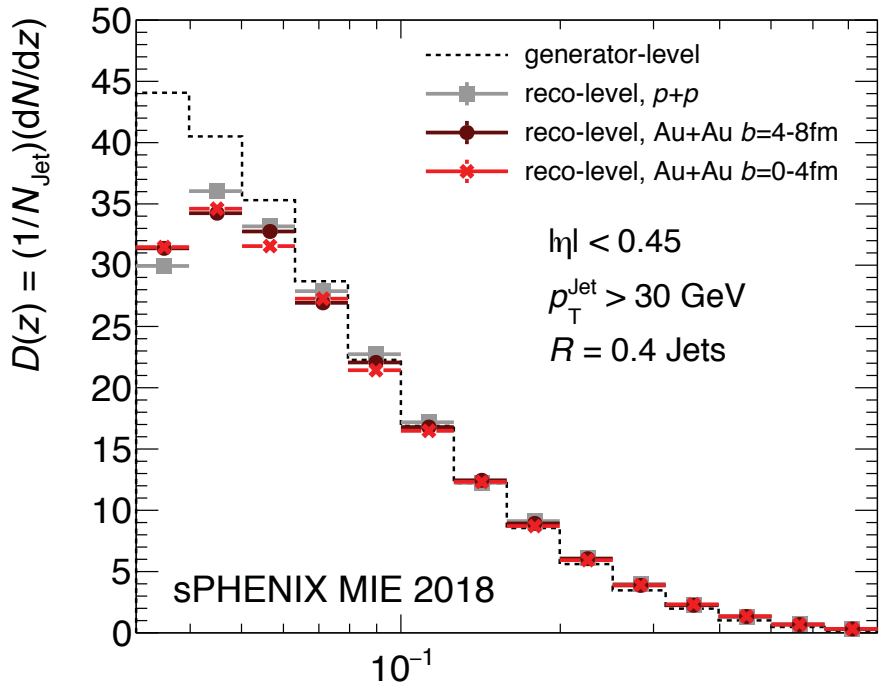
  ➡ identical, i.e. sensitivity of response to fragmentation, in both systems

Jet performance summary (3/4)

(with some particular choice of seed parameters)



di-jet p_T balance



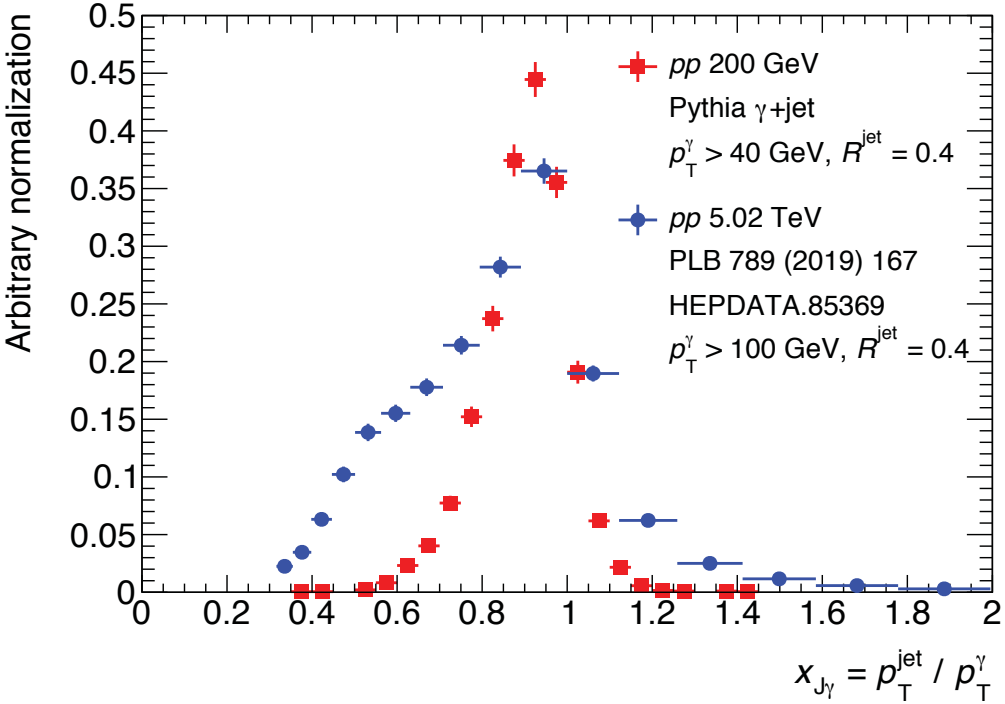
inclusive jet FF

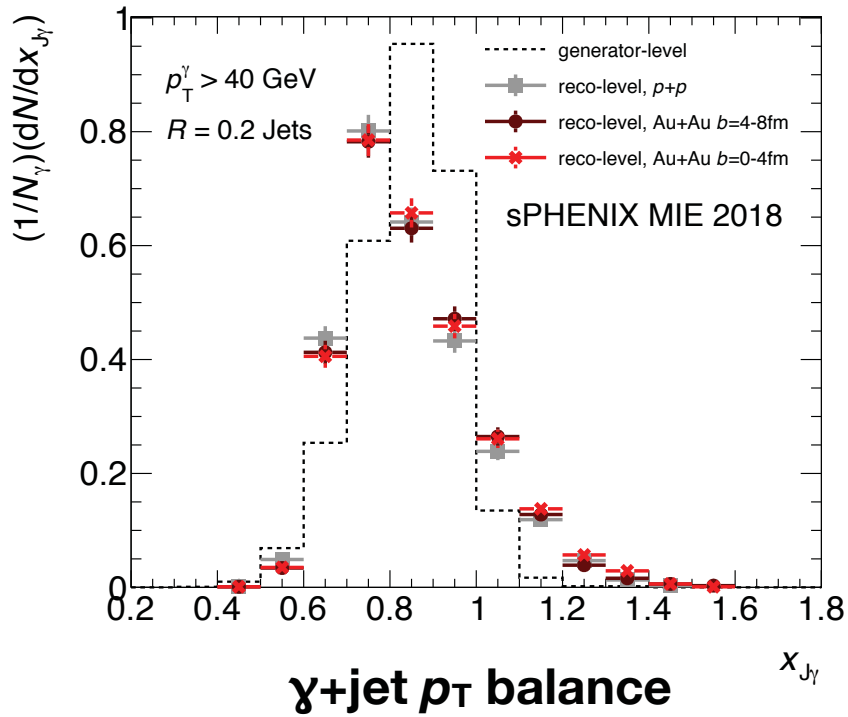
Good news: kinematic regions where p+p ~ Au+Au

➡ but want to make measurements in difficult regions too (detector corrections via unfolding, etc….)

Jet performance summary (4/4)

(with some particular choice of seed parameters)





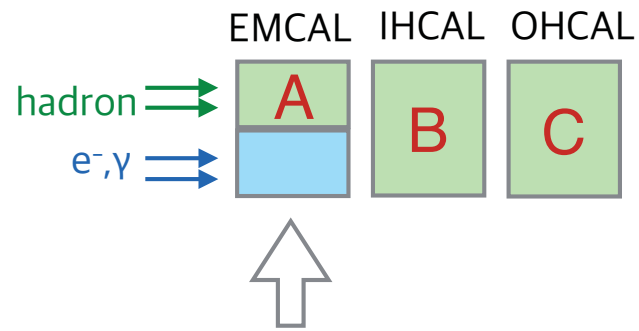
γ+jet physics at sPHENIX

- ➡ significantly tighter initial p_T & azimuthal correlation at RHIC
- ➡ best chance to compare jets at RHIC & LHC with similar "unquenched" <u>kinematics</u> / <u>flavor</u> / <u>cone size</u> ?
  - ➡ (JS TG involved in photon reco / ID…)

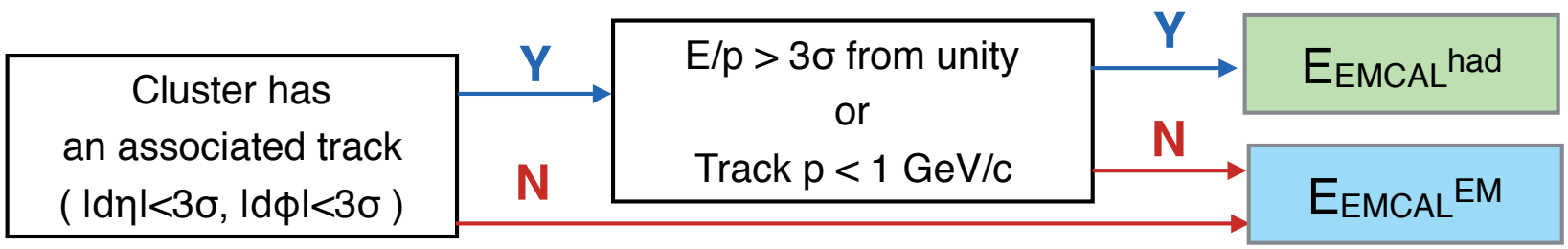
Jet energy calibration

[Songkyo Lee]

$$E^{RECO} = D \cdot (E_{EMCAL}^{EM} + A \cdot E_{EMCAL}^{had} + B \cdot E_{IHCAL} + C \cdot E_{OHCAL})$$



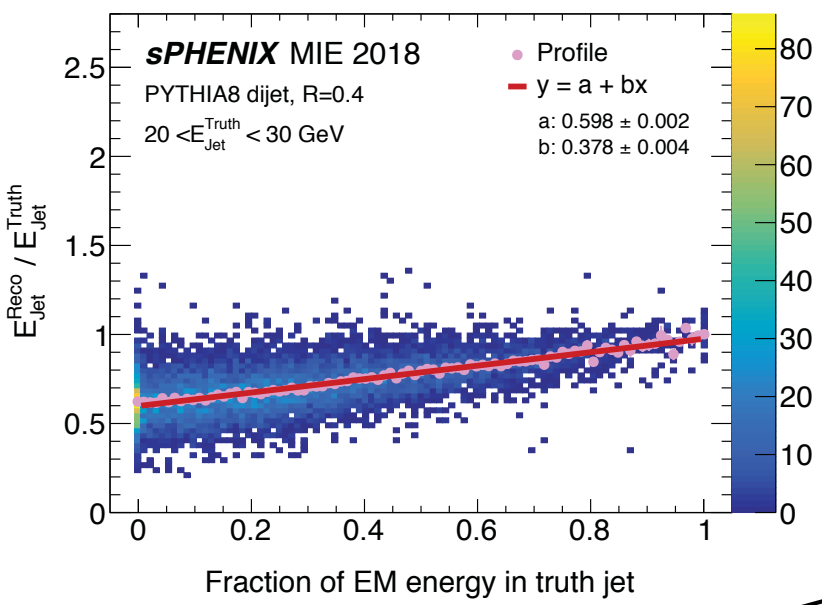
- Flow chart for EMCAL cluster selection

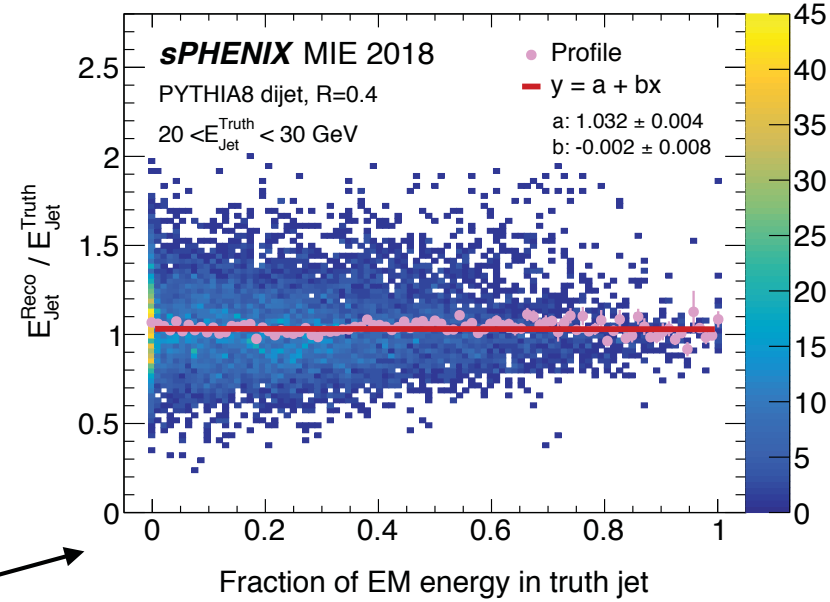


slide from Songkyo

Exploring calibration schemes based on multiplicative scale factors for each calorimeter layer

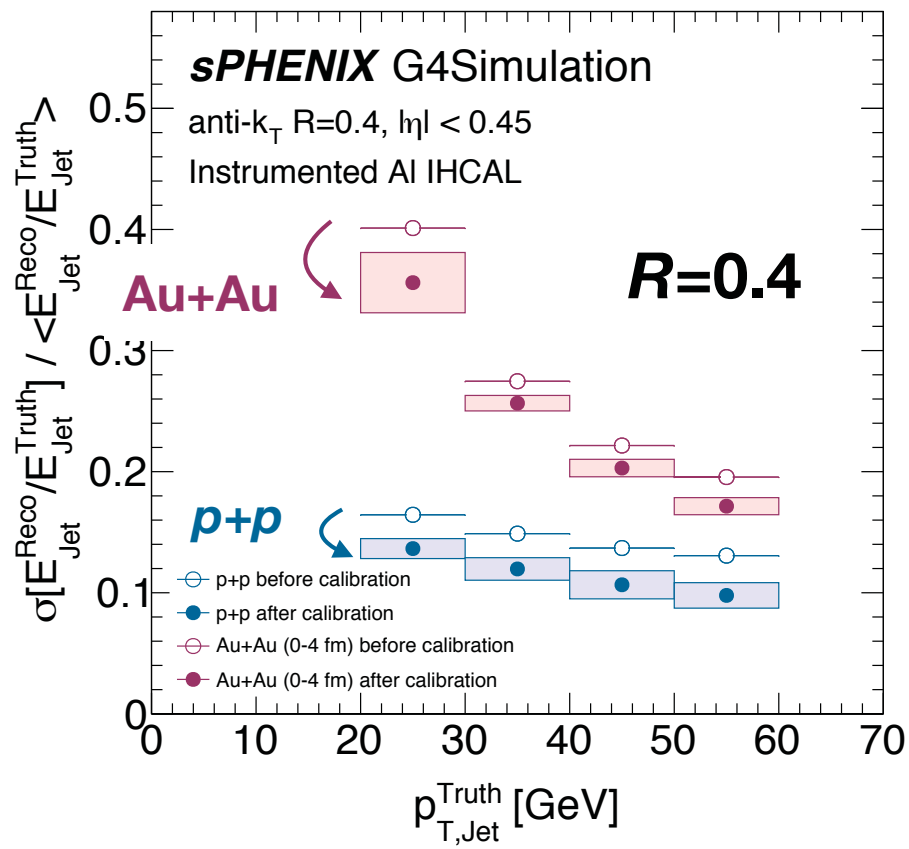
- separation of EMCal energy into e/ɣ (no track or E/p ~ 1 track) and hadronic (track with $E^{EM}/p < 1$)
- discussion of *in situ* validation with ɣ+jet events in *p*+*p*

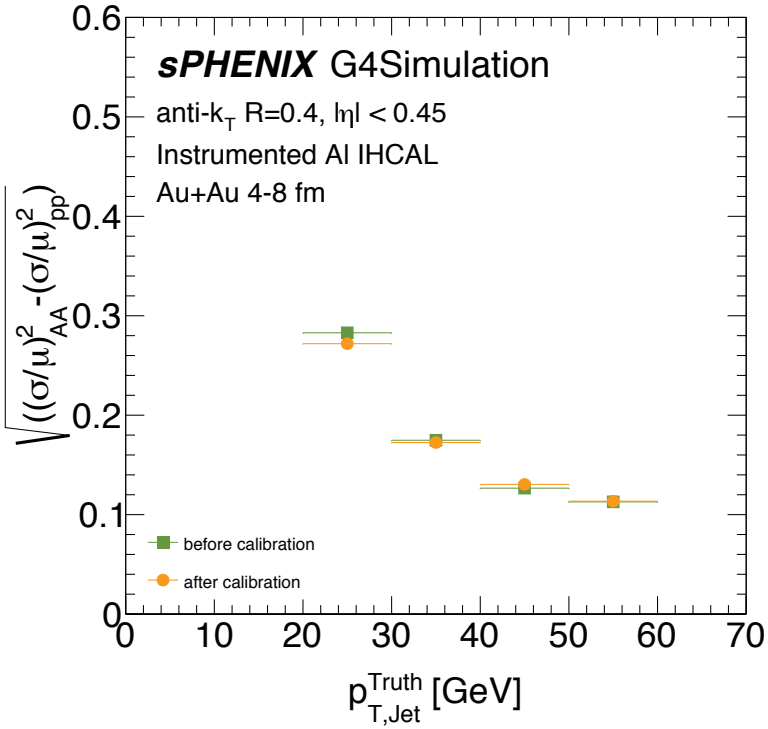




Response nearly independent of truth-EM fraction (i.e. fragmentation) in p+p

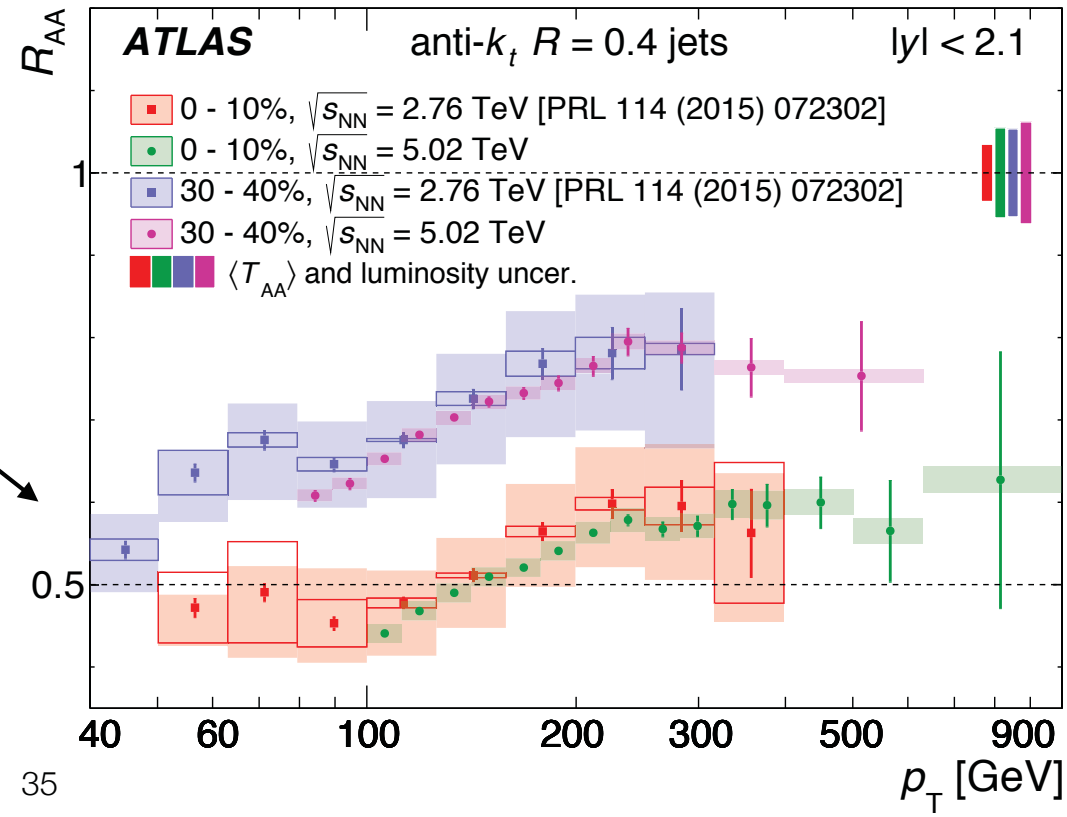
Layer-by-layer multiplicative calibration "commutes" with layer-by-layer subtraction in Au+Au

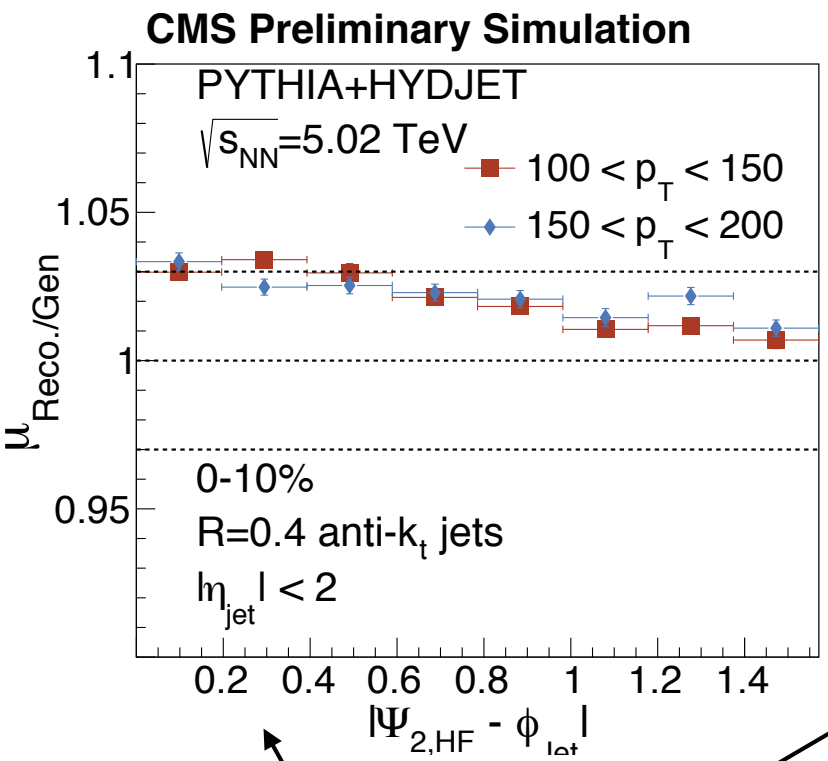


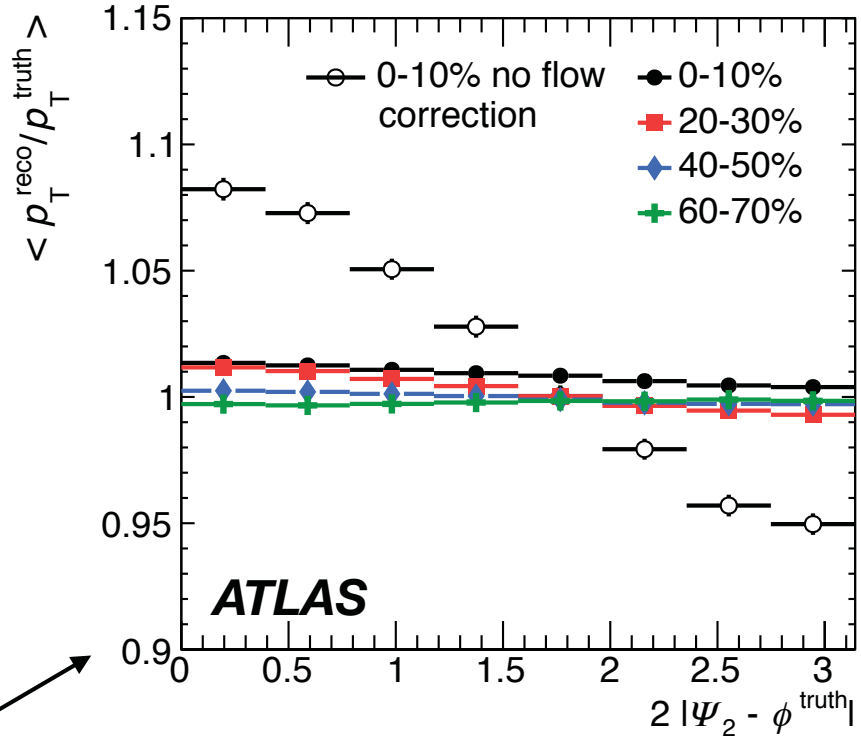


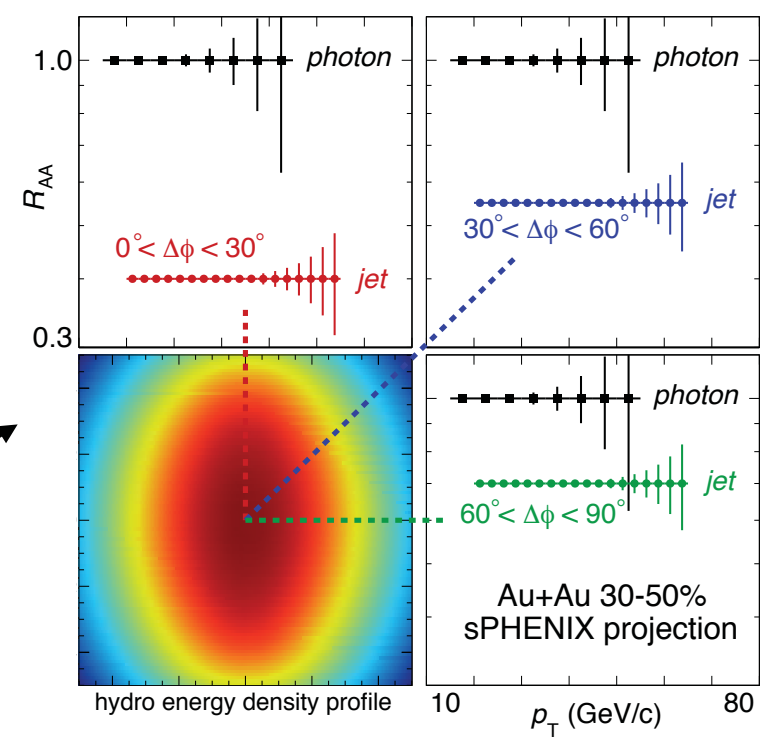
"factorization" holds before & after calibration

Goal from LHC experience: strong cancellation of common "pp"-like uncertainties







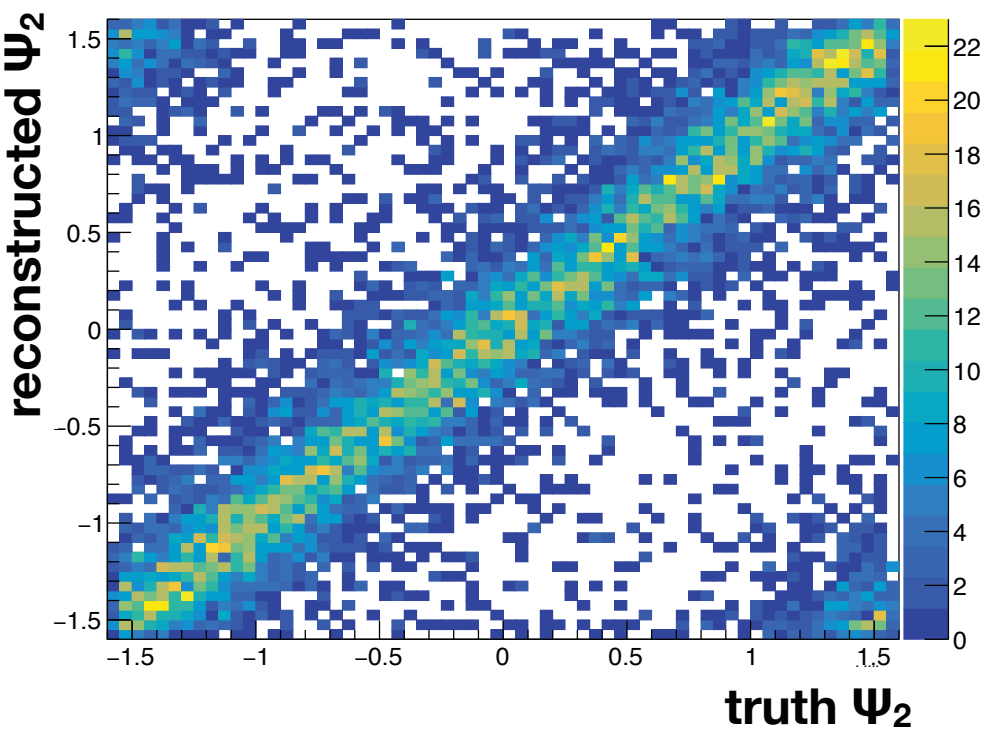


Goal from LHC experience: good control of event plane-dependent response

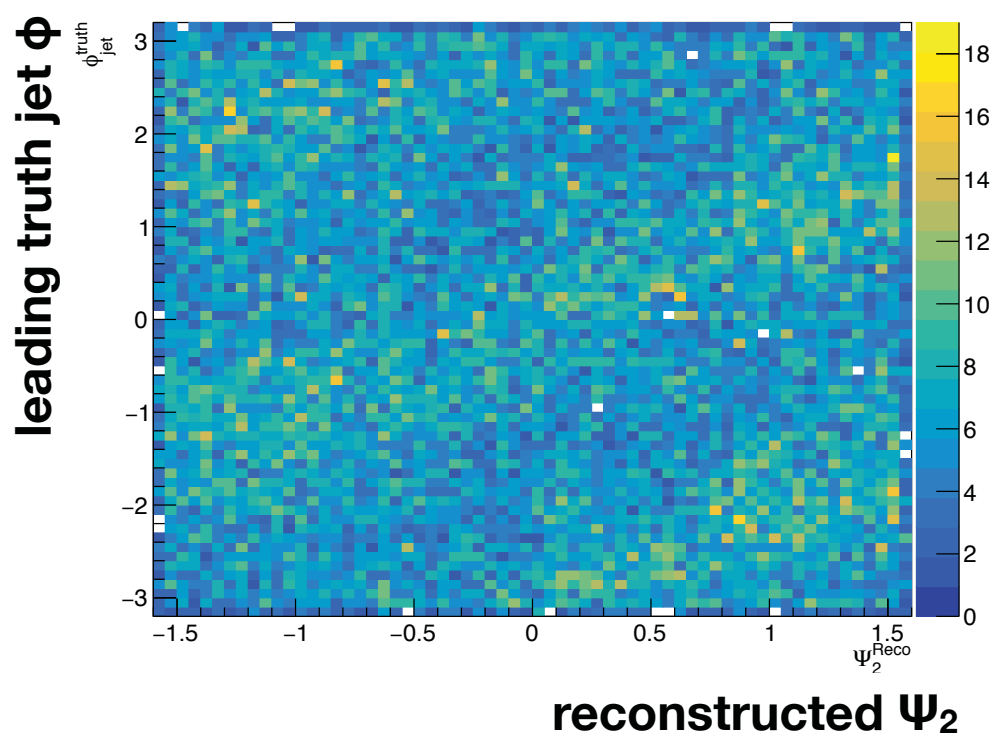
Important aspect of sPHENIX science case

Flow-aware UE subtraction

- Determine Ψ_2 and v_2 event-by-event in the calorimetry as part of UE estimation
- Test with Hijing + flow afterburner tuned to RHIC data



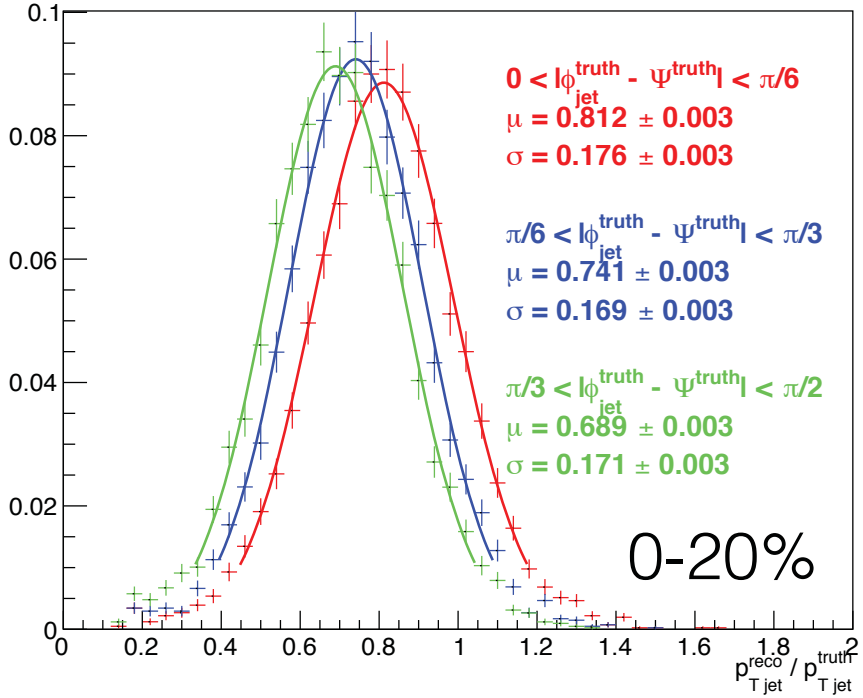
good reconstruction of true Ψ_2 in 0-20%



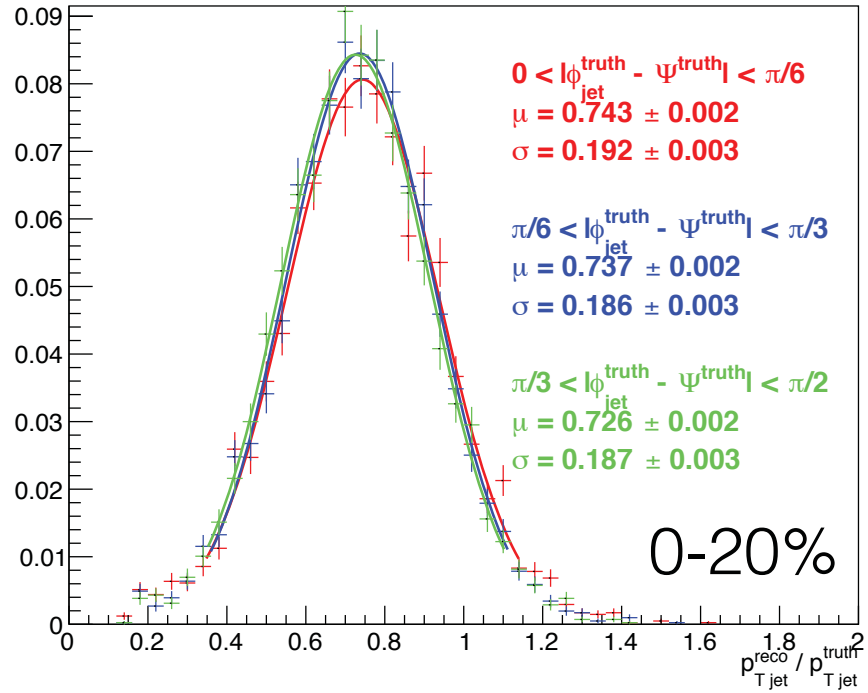
residual Ψ_2 -ϕ^{jet} correlation (both determined in same detector…)

ϕ-dependent jet performance

HI jet reco w/o flow determination…



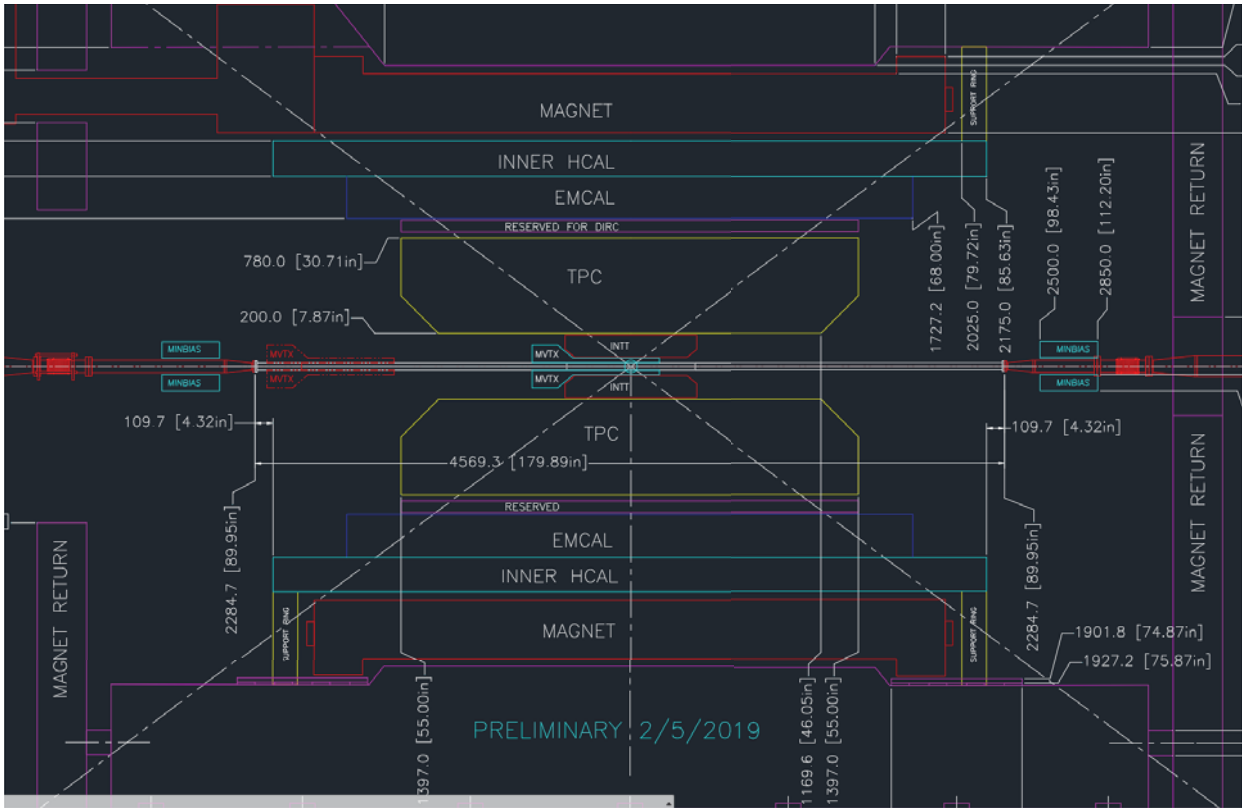
HI jet reco **WITH** flow determination

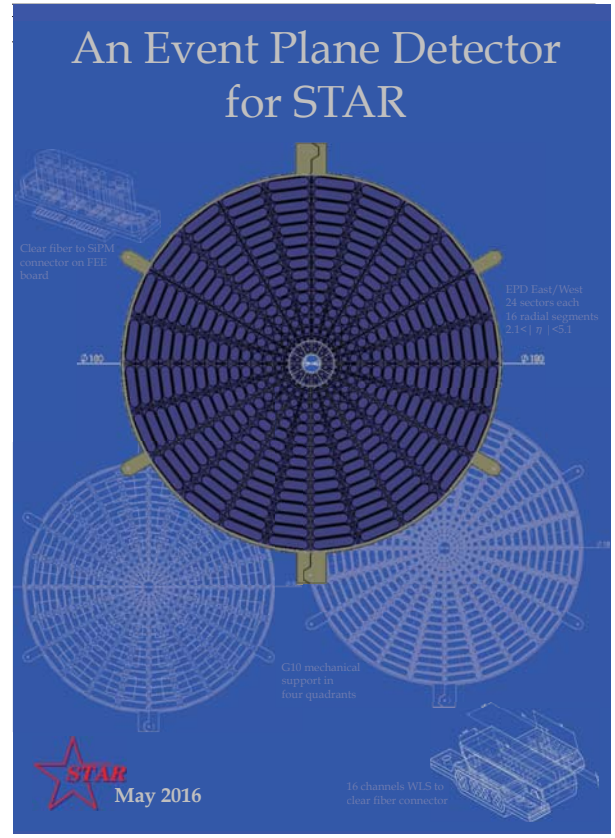


- Jet response vs. ($\phi^{jet,truth}$ - Ψ_2^{truth}): **in-plane**, **mid-plane**, **out-of-plane**
  - ➡ *left*: ~15% *E*-scale difference b/w in- vs. out-of-plane(!!)
  - ➡ *right*: including flow modulation reduces this to ~2%
    - ➡ enables reaction plane dependent jet measurements
    - ➡ control of flow likely sets the ultimate limit on low-p_T / large-*R* reach…

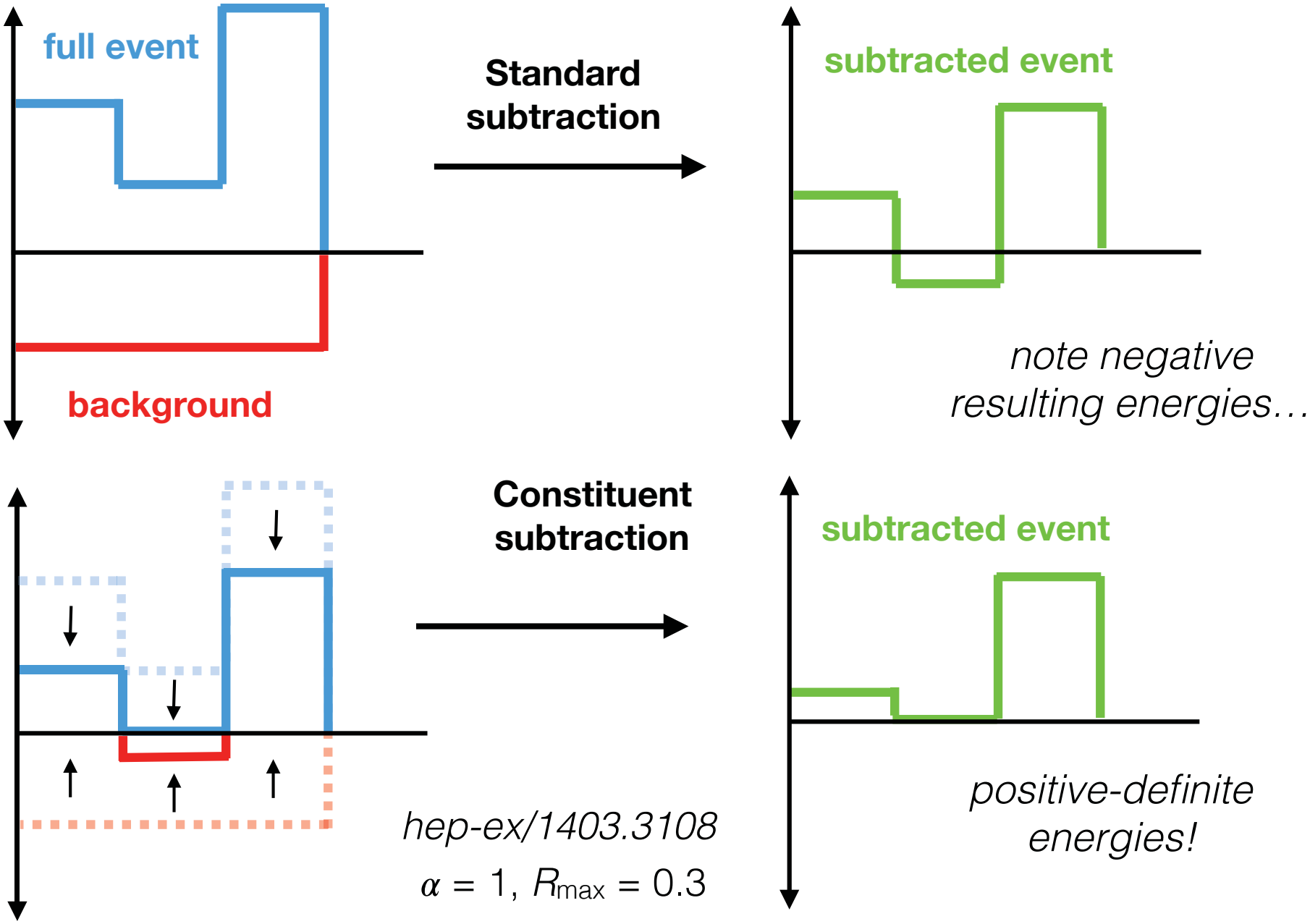
How to improve?

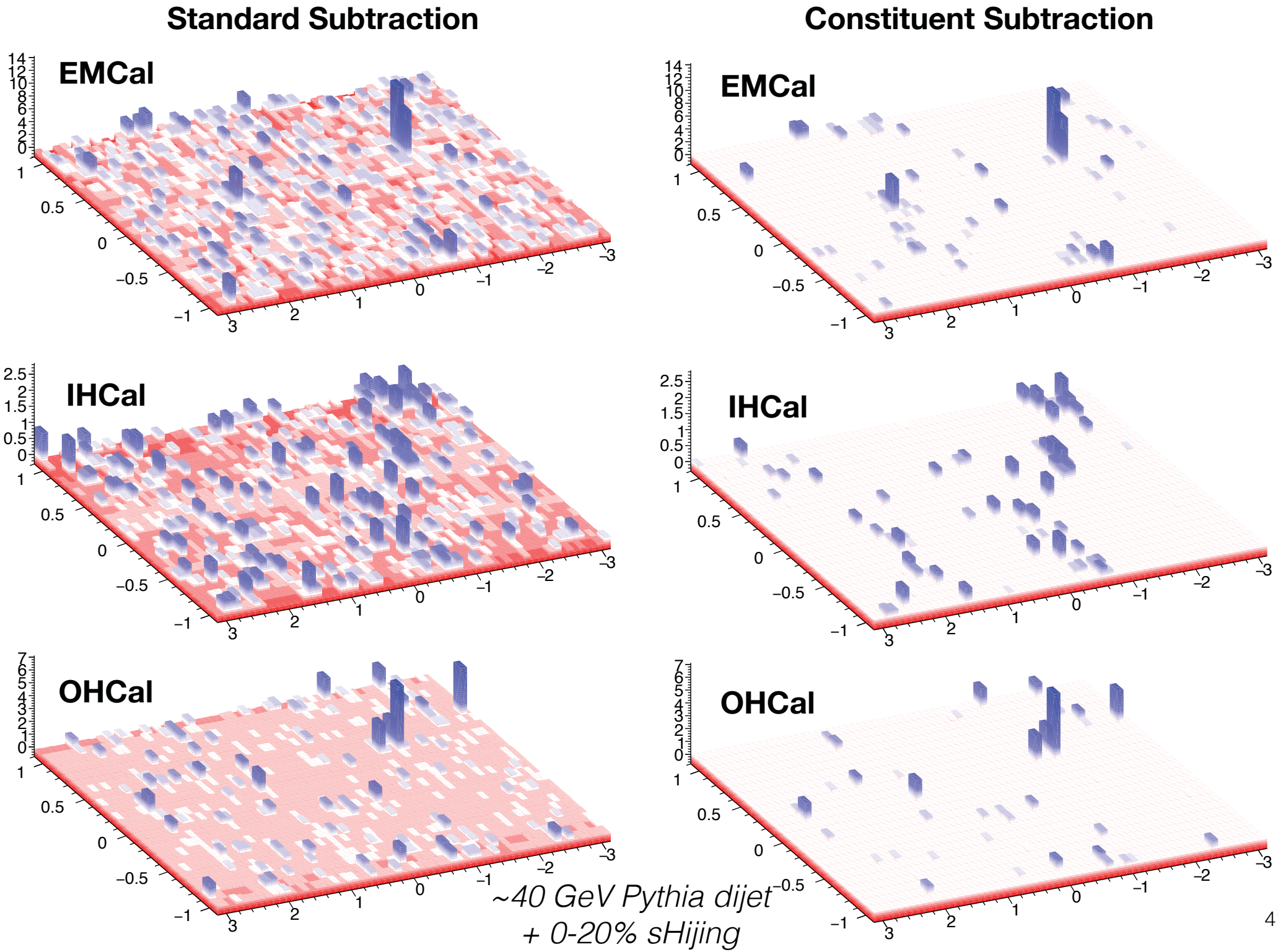
- Exploring other options:
  - ➡ fix event plane from TPC tracks ($p_T < p_T^{max}$),
  - ➡ new instrumentation (STAR EPD-like detector, forward EMCal),
  - ➡ etc.?



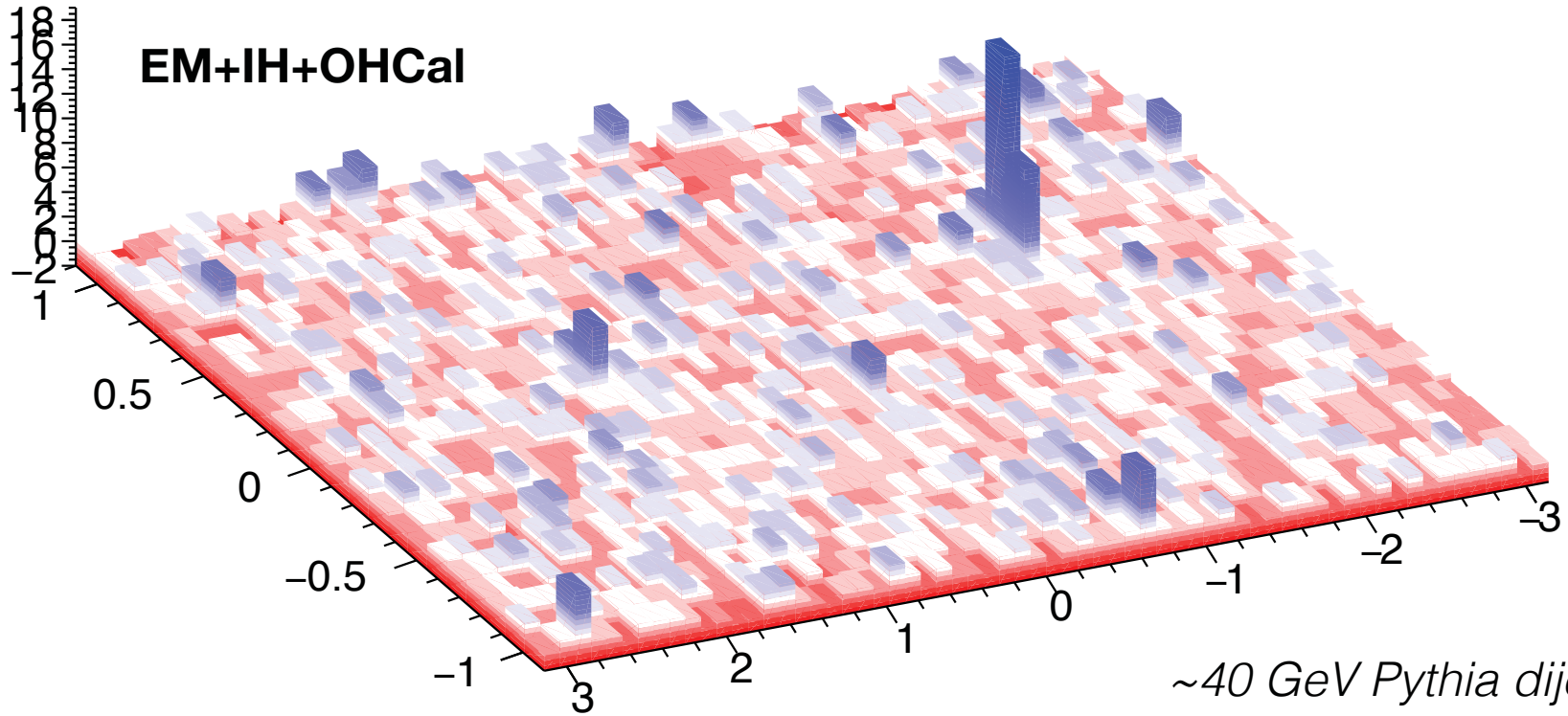


Our UE determination and subtraction "factorize": *Constituent subtraction* in sPHENIX



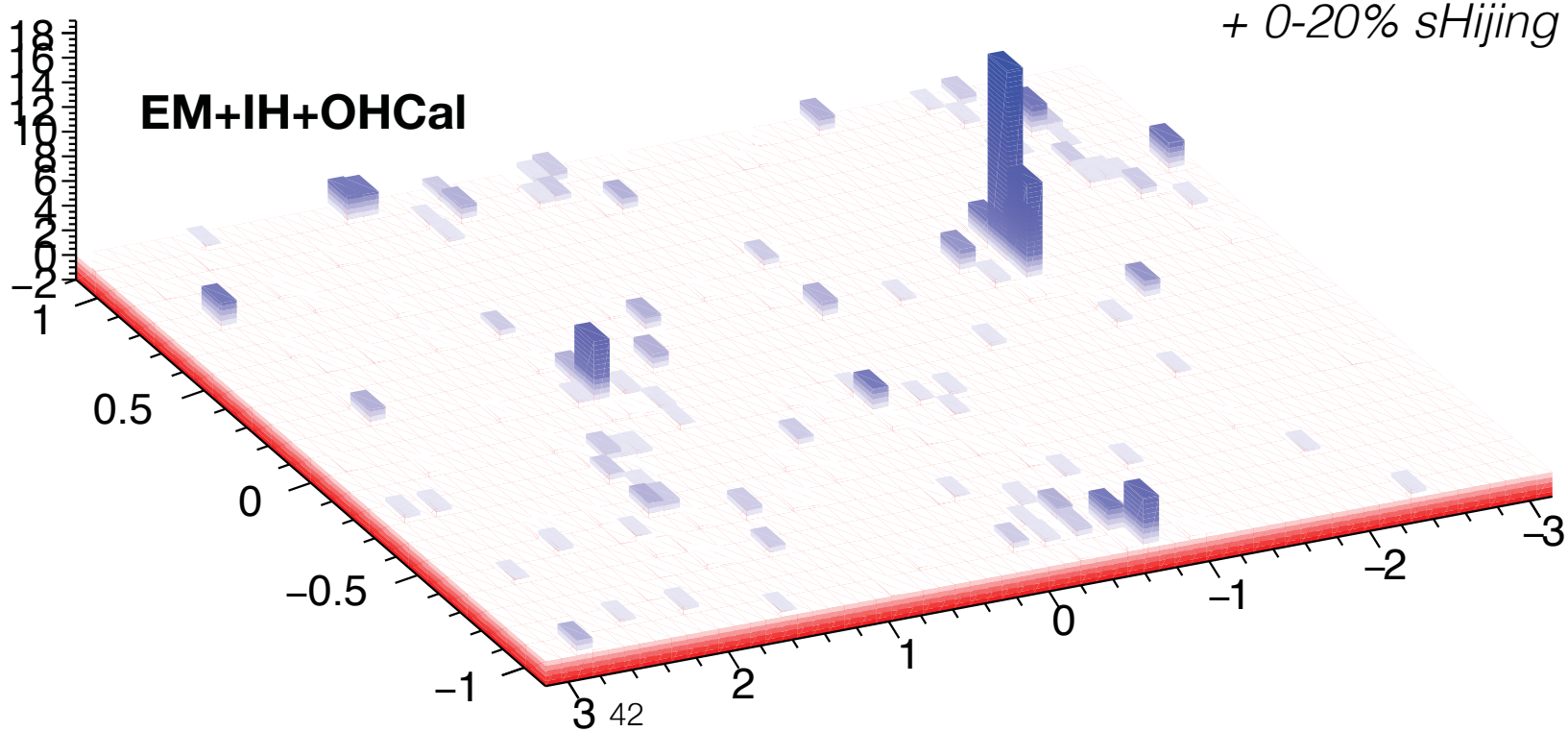

Standard Subtraction
Constituent Subtraction
EMCal
IHCal
OHCal
EMCal
IHCal
OHCal
~40 GeV Pythia dijet
+ 0-20% sHijing

Standard Subtraction

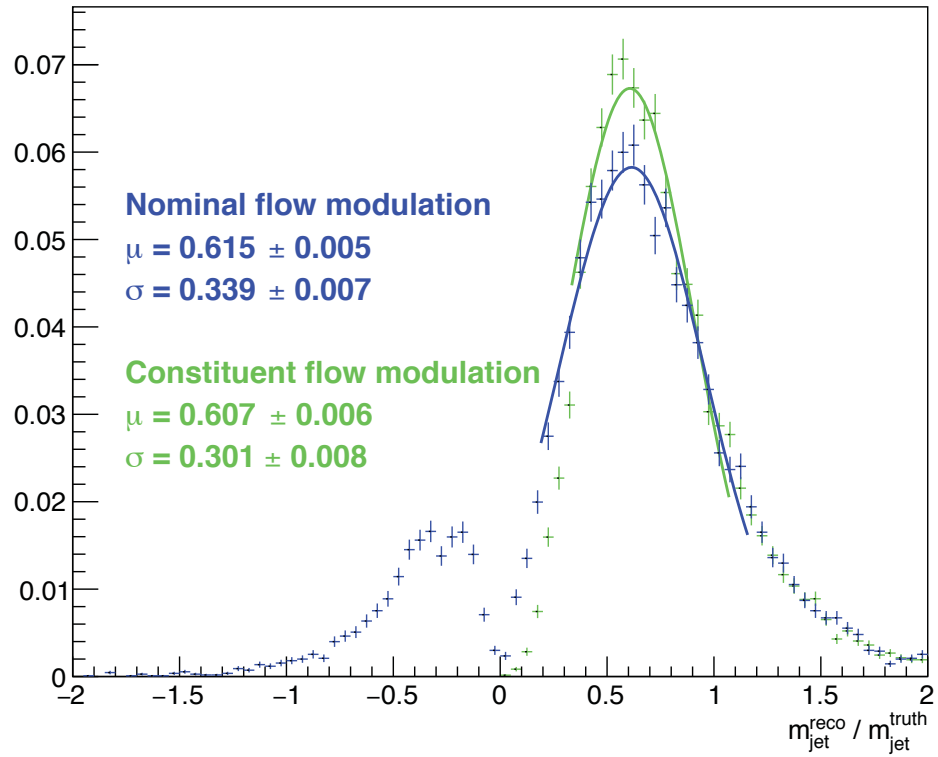


~40 GeV Pythia dijet
+ 0-20% sHijing

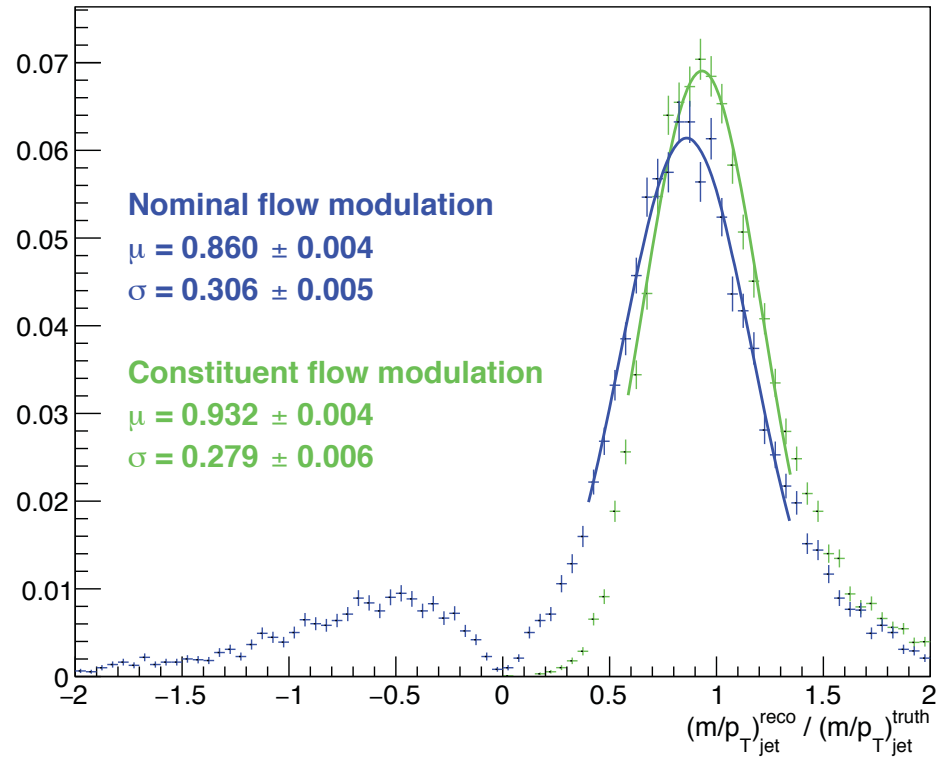
Constituent Subtraction



Comparison of mass response



Absolute (ungroomed) mass response

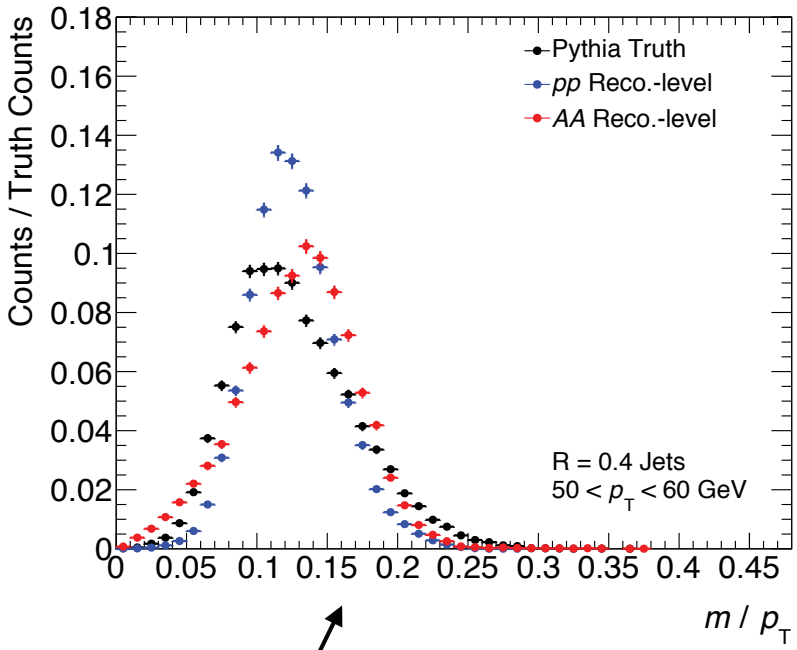


m/p_T response

- **Standard subtraction** w/ calo jets can result in $E_{jet} < |p_{jet}|$ due to resolution effects, e.g. $m_{jet}^2 < 0$ (represented here as $m_{jet} < 0$)
- **Constituent subtraction** has $m_{jet} > 0$ from pos-def. condition

  ➡ and better mass resolution & m/p_T scale

Competitive mass measurements



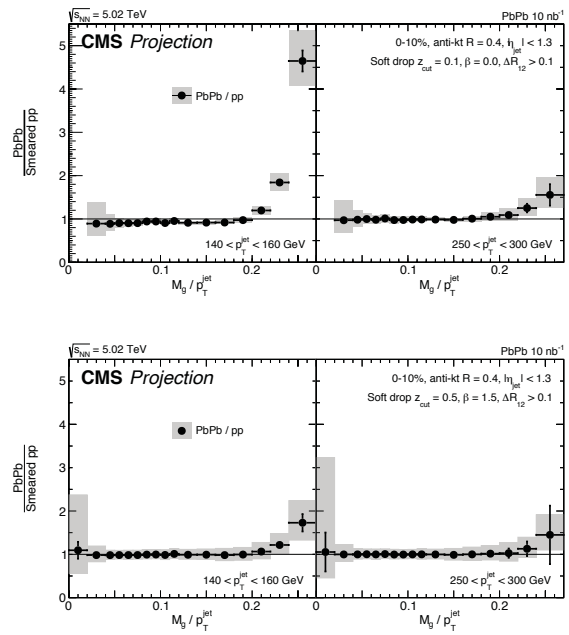
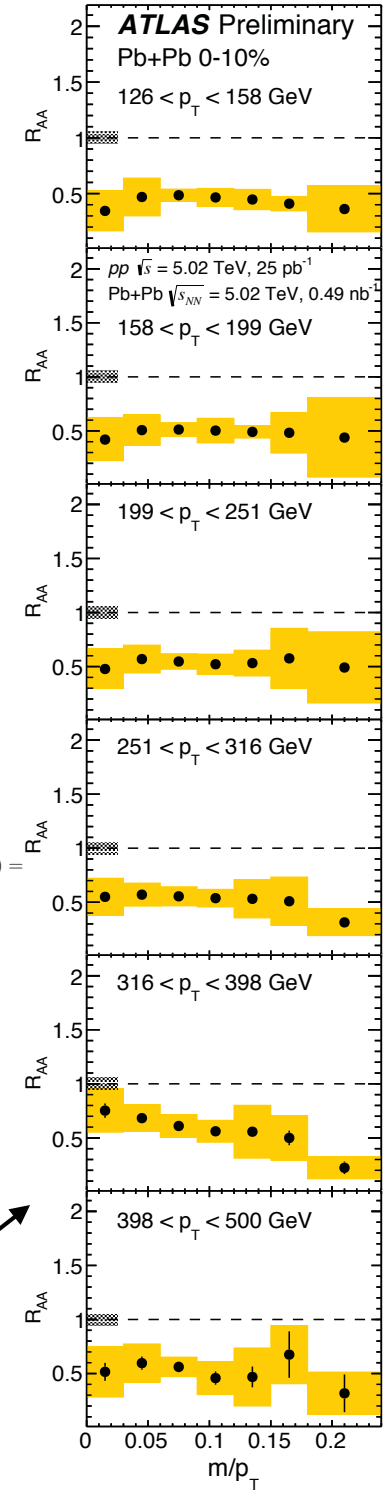


Fig. 37: Jet mass distribution with grooming setting $(z_{cut}, \beta) = (0.1, 0.0)$ (Upper panels) and $(z_{cut}, \beta) = (0.5, 1.5)$ (Lower panels). [8]

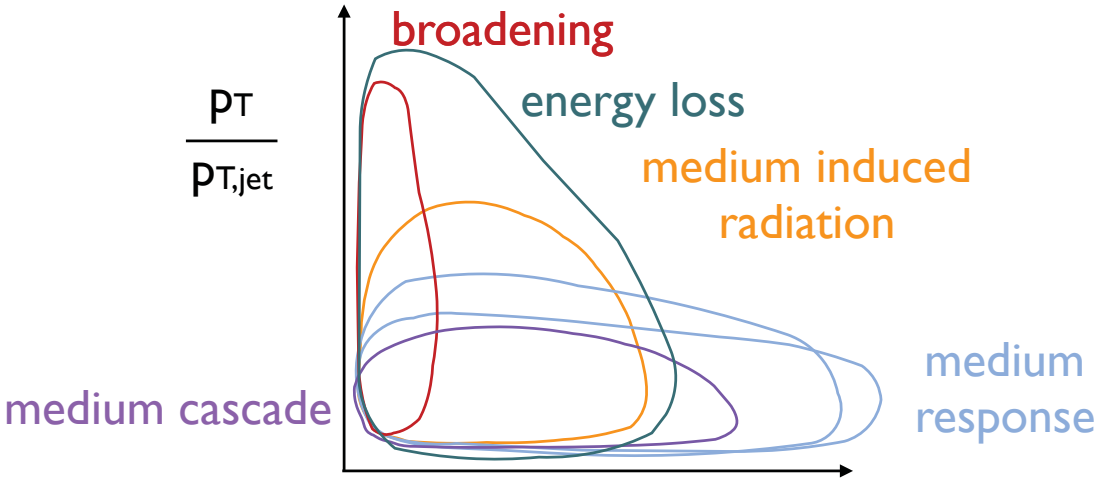


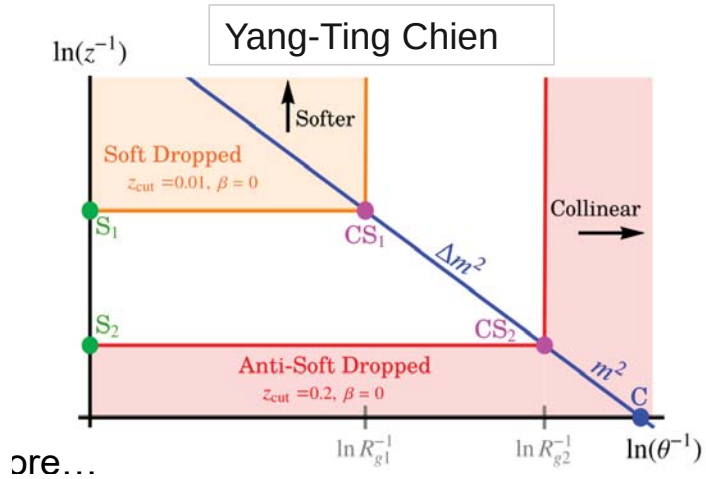
sPHENIX performance for m / p_T

Run 3+4 projection from CMS

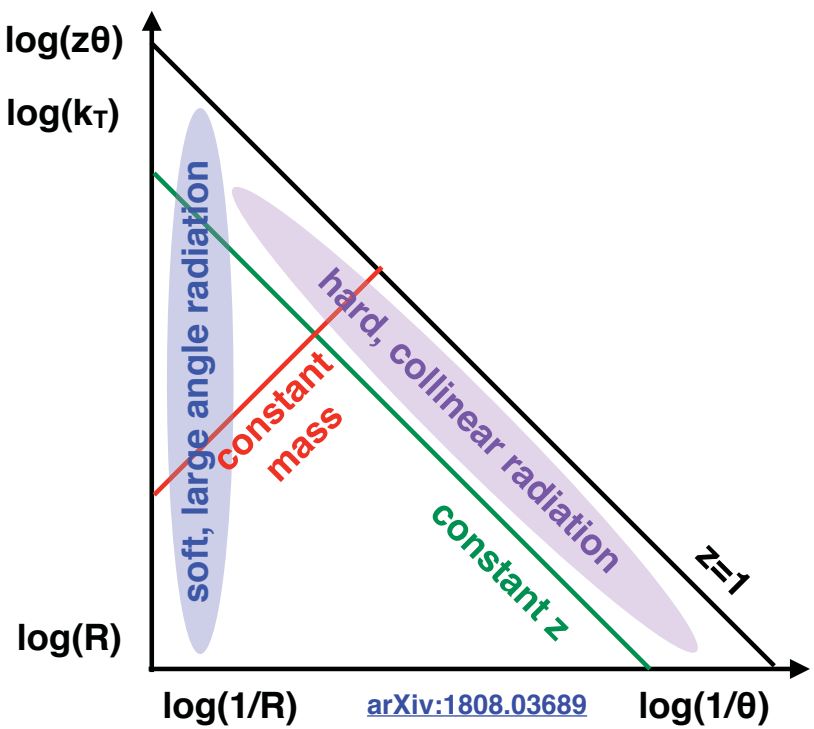
measurement from ATLAS

Jet substructure

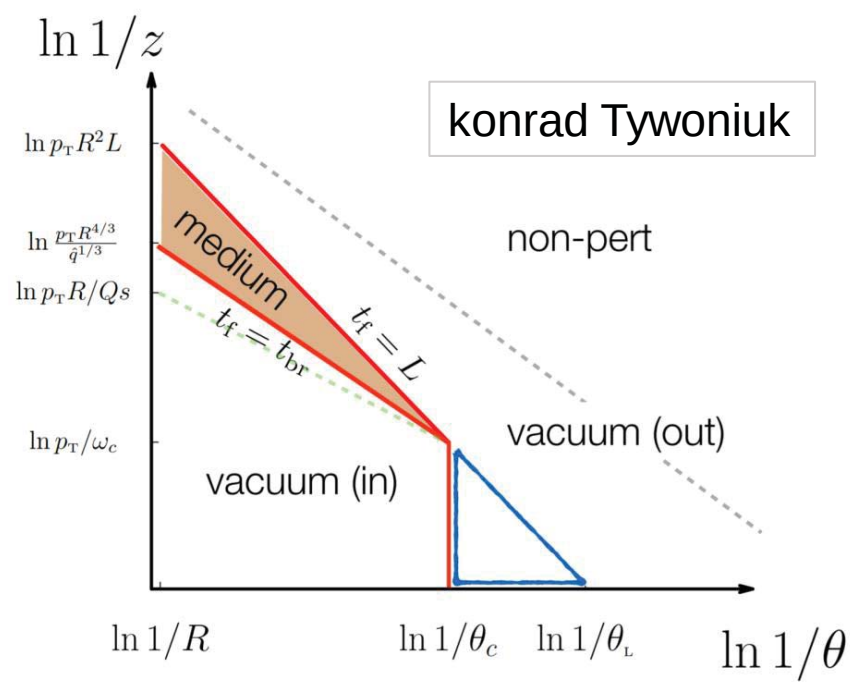




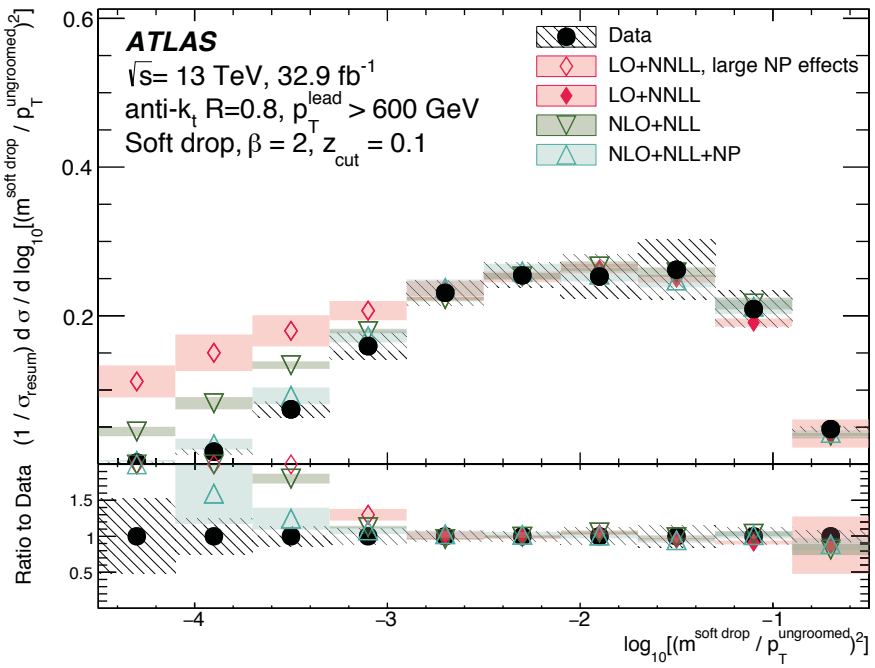
ore…

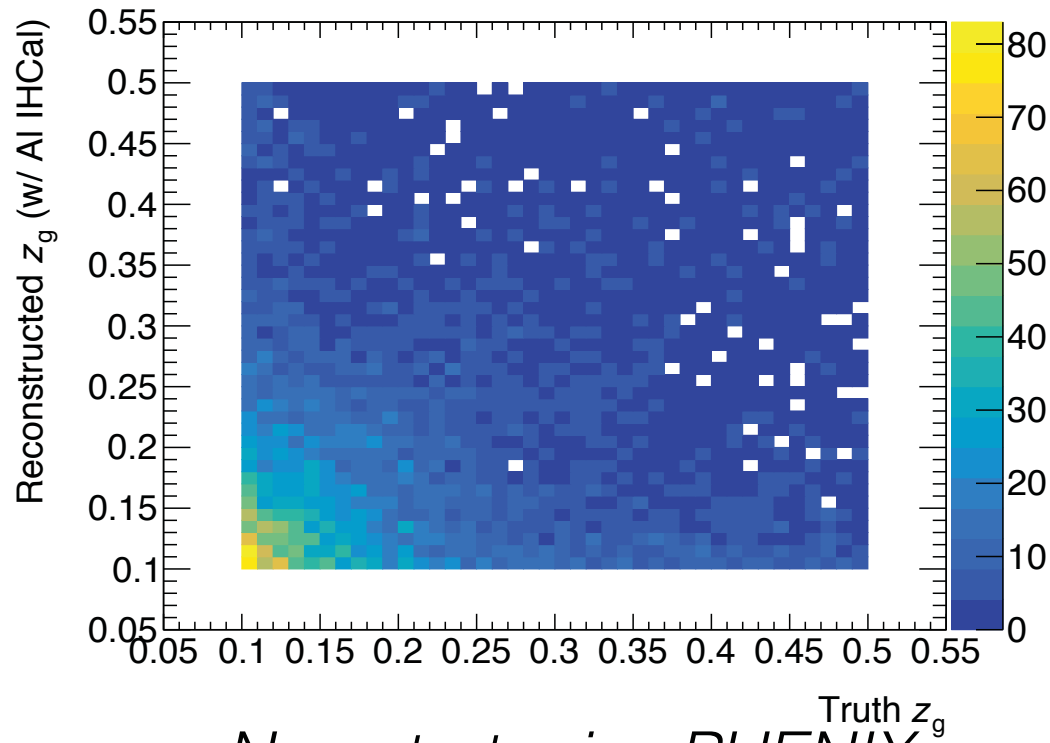


arXiv:1808.03689



Calorimetric substructure measurements(?)





LHC: at high-p_T, large-R, possible to do with calo alone

(unfolded SoftDrop mass)

Non-starter in sPHENIX

(z_g ~ 0.1 for p_T^{jet} = 30 GeV is response to 3 GeV hadrons…)

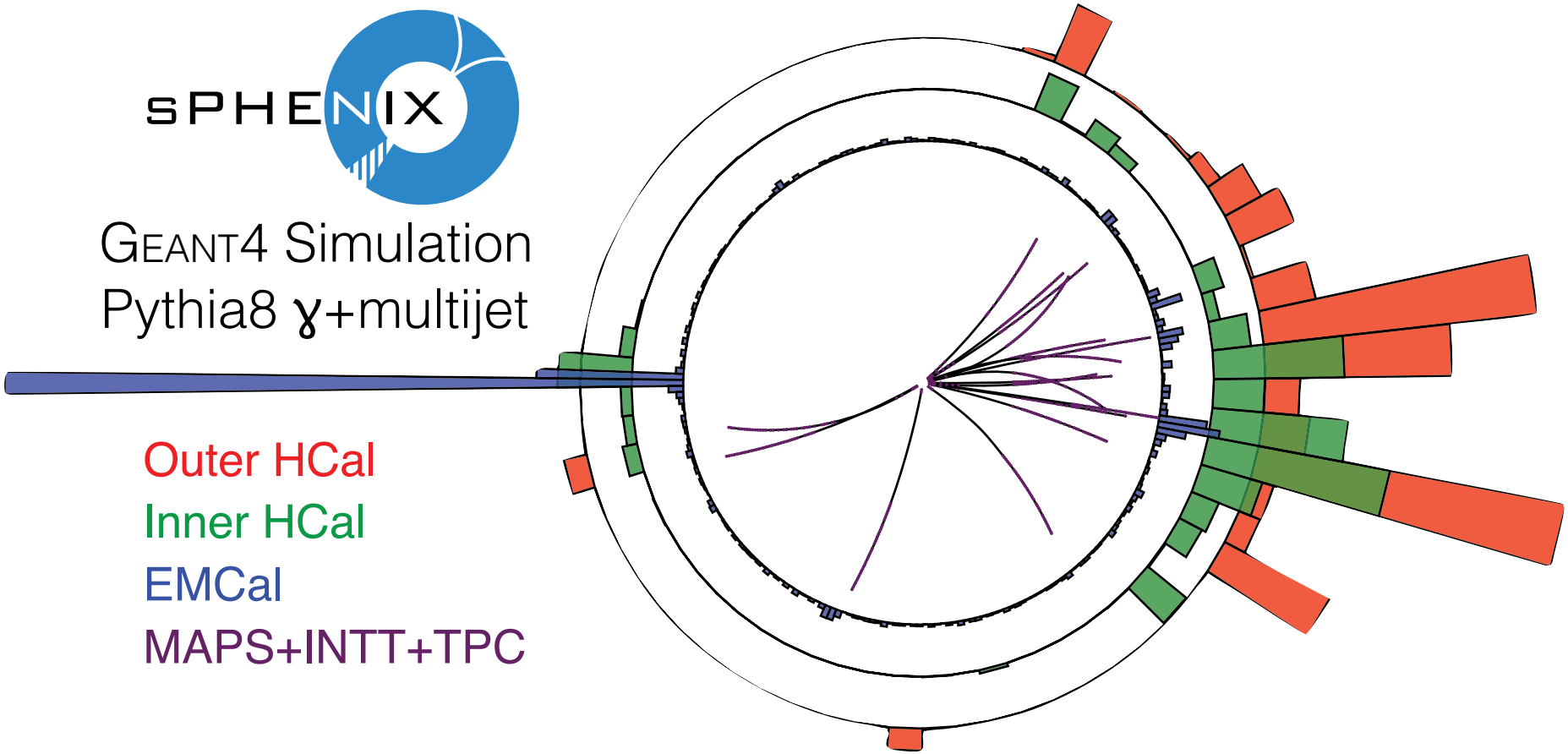
Next major effort in sPHENIX: track-assisted substructure / fully "particle flow"-style reconstruction

➡ PFlow: *what* improvements for *which* observables in *which* kinematic regions?

Join us!

sPHENIX

GEANT4 Simulation
Pythia8 γ+multijet



Outer HCal
Inner HCal
EMCal
MAPS+INTT+TPC