JETS and substructure, a review

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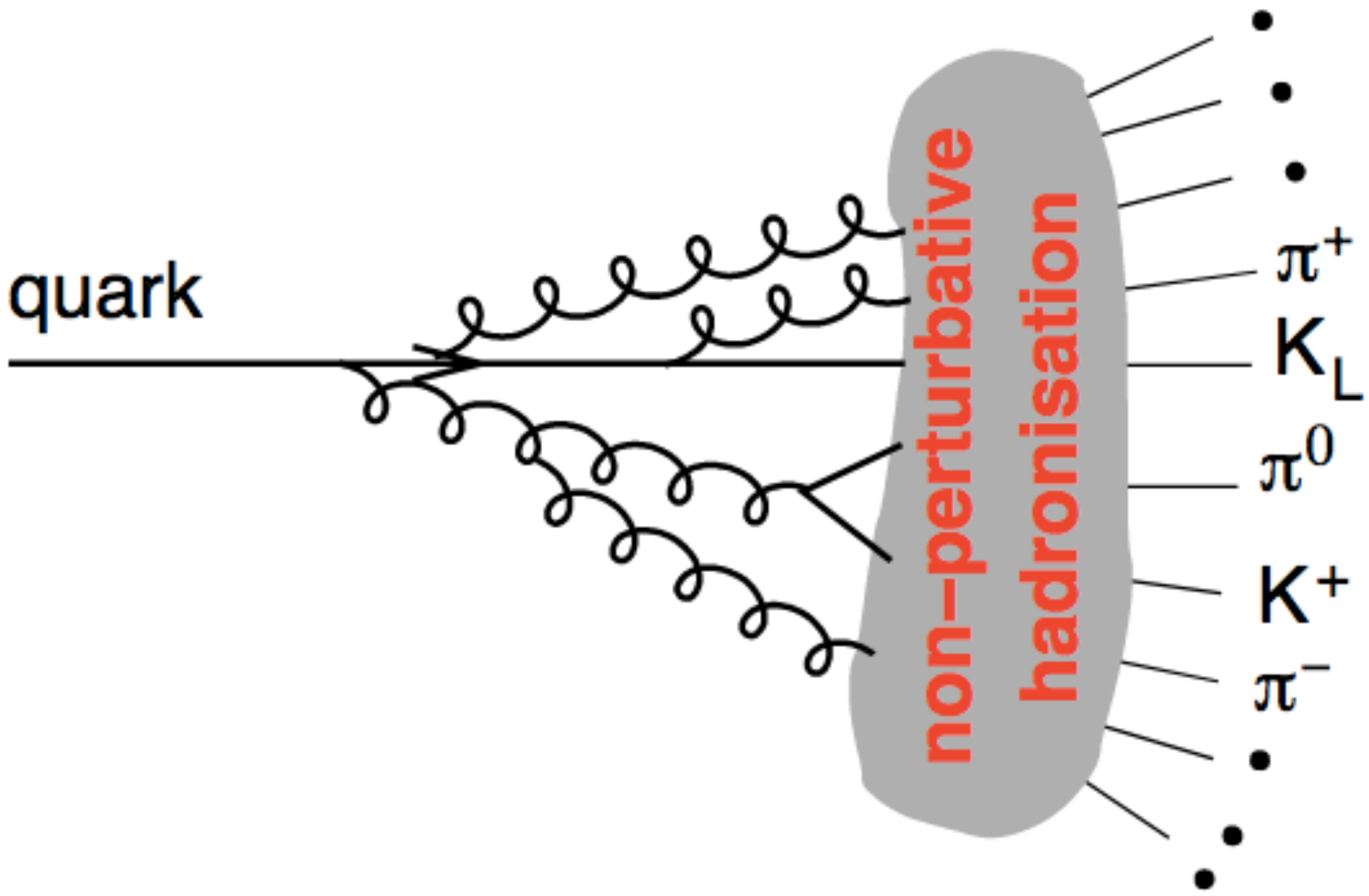
2nd JETSCAPE winter school,10th January 2019

College Station, Texas

The jet shower



Large radiation probability,
soft and collinear divergences

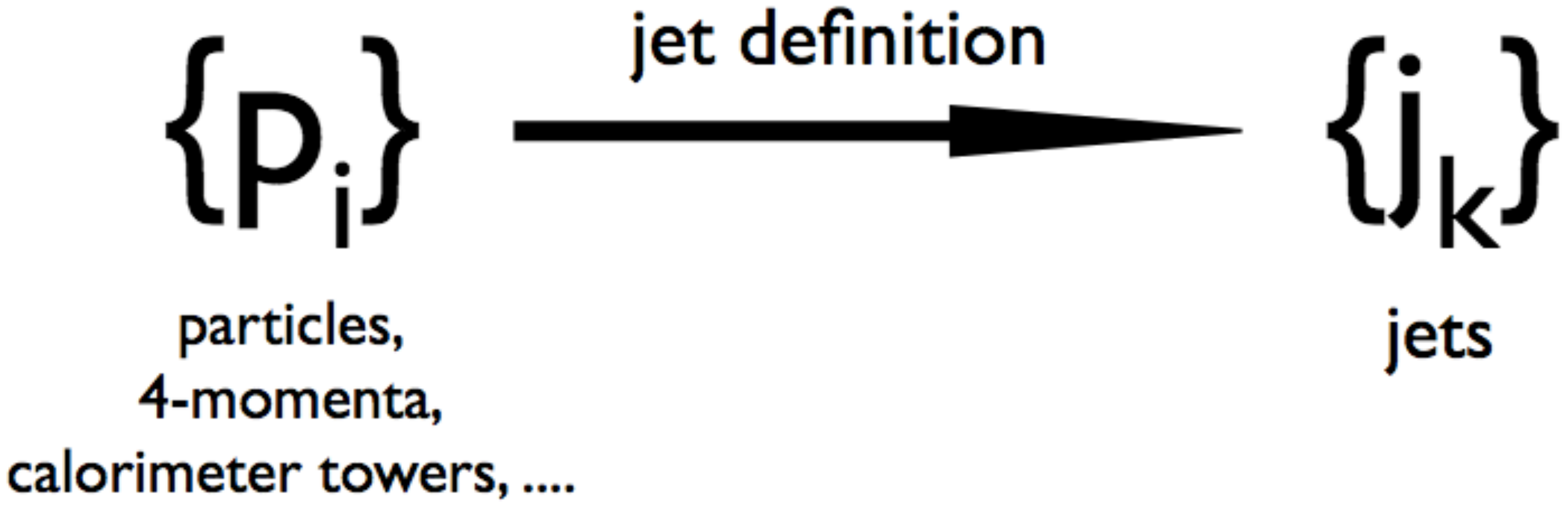
Gluon emission

$$\int \alpha_s \frac{dE}{E} \frac{d\theta}{\theta} \gg 1$$

Non-perturbative physics

$$\alpha_s \sim 1$$

The projection



Jets are energetic, collimated bunches of particles
A jet definition, is a projection of the hadronic level to partons (quarks and gluons)

Key requirement of the projection: infrared and collinear safety, to preserve calculability

Projections are not unique

Jet Definition: an example of a sequential recombination algorithm

Two parameters, *R* and $p_{t,min}$

(These are the two parameters in essentially every widely used hadron-collider jet algorithm)

$$d_{ij} = \min(p_{ti}^2, p_{tj}^2)\frac{\Delta R_{ij}^2}{R^2}, \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

Sequential recombination algorithm

1. Find smallest of d_{ij}, d_{iB}
2. If *ij*, recombine them
3. If *iB*, call i a jet and remove from list of particles
4. repeat from step 1 until no particles left

   Only use jets with $p_t > p_{t,min}$

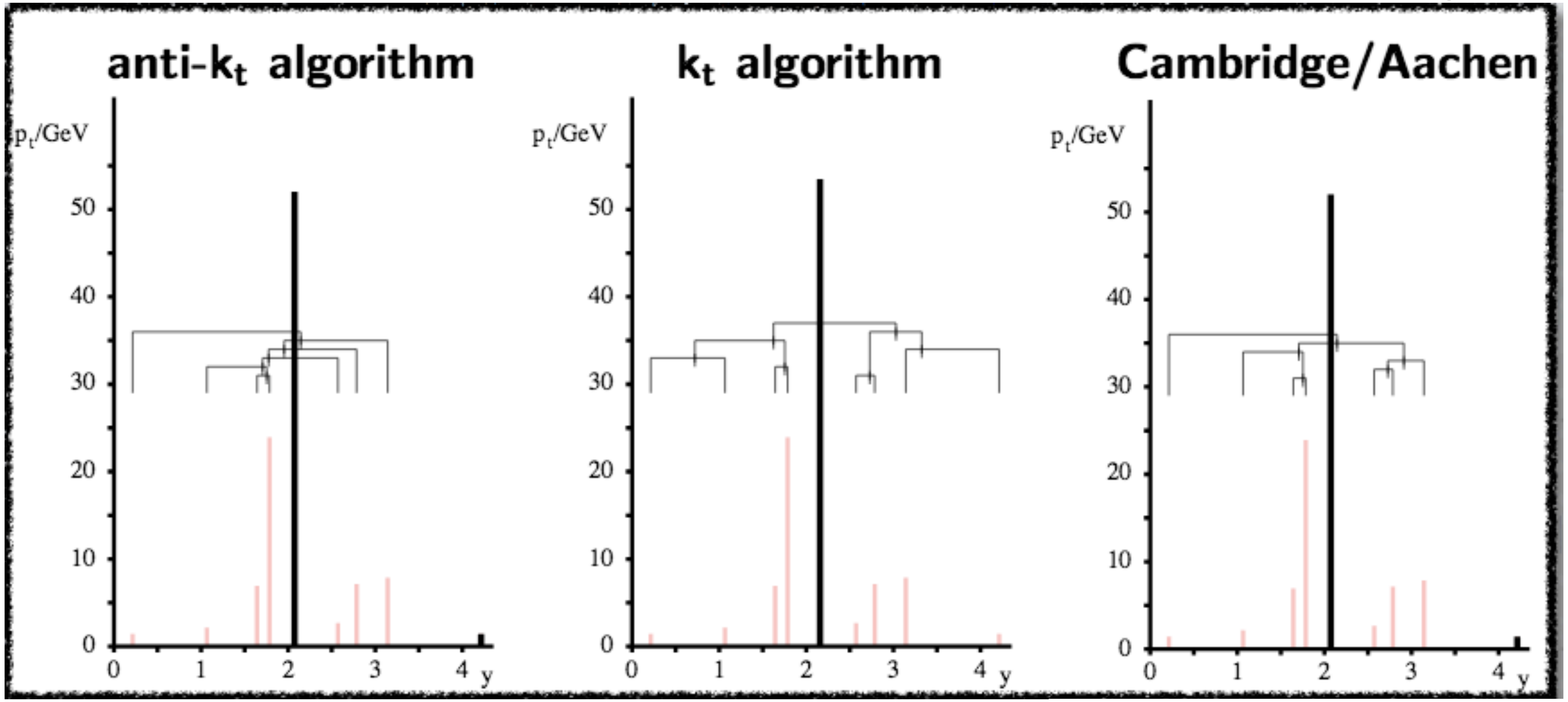
Inclusive k_t algorithm
S.D. Ellis & Soper, 1993
Catani, Dokshitzer, Seymour & Webber, 1993

The sequential recombination family of algorithms

Perfect cones

Ordered in k_T

Ordered in angle



$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

p = 1 k_t algorithm

S. Catani, Y. Dokshitzer, M. Seymour and B. Webber, Nucl. Phys. B406 (1993) 187
S.D. Ellis and D.E. Soper, Phys. Rev. D48 (1993) 3160

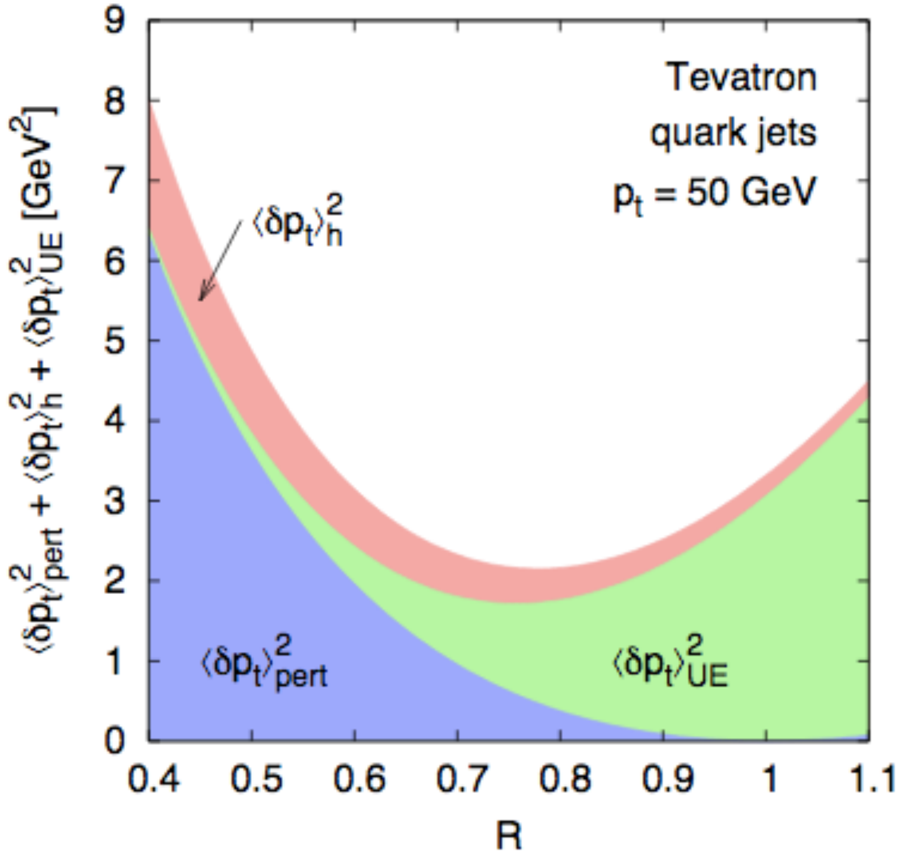
p = 0 Cambridge/Aachen algorithm

Y. Dokshitzer, G. Leder, S.Moretti and B. Webber, JHEP 08 (1997) 001
M.Wobisch and T.Wengler, hep-ph/9907280

p = -1 **anti-k_t algorithm**

MC, G. Salam and G. Soyez, arXiv:0802.1189

The perturbative and non-perturbative components of the jet

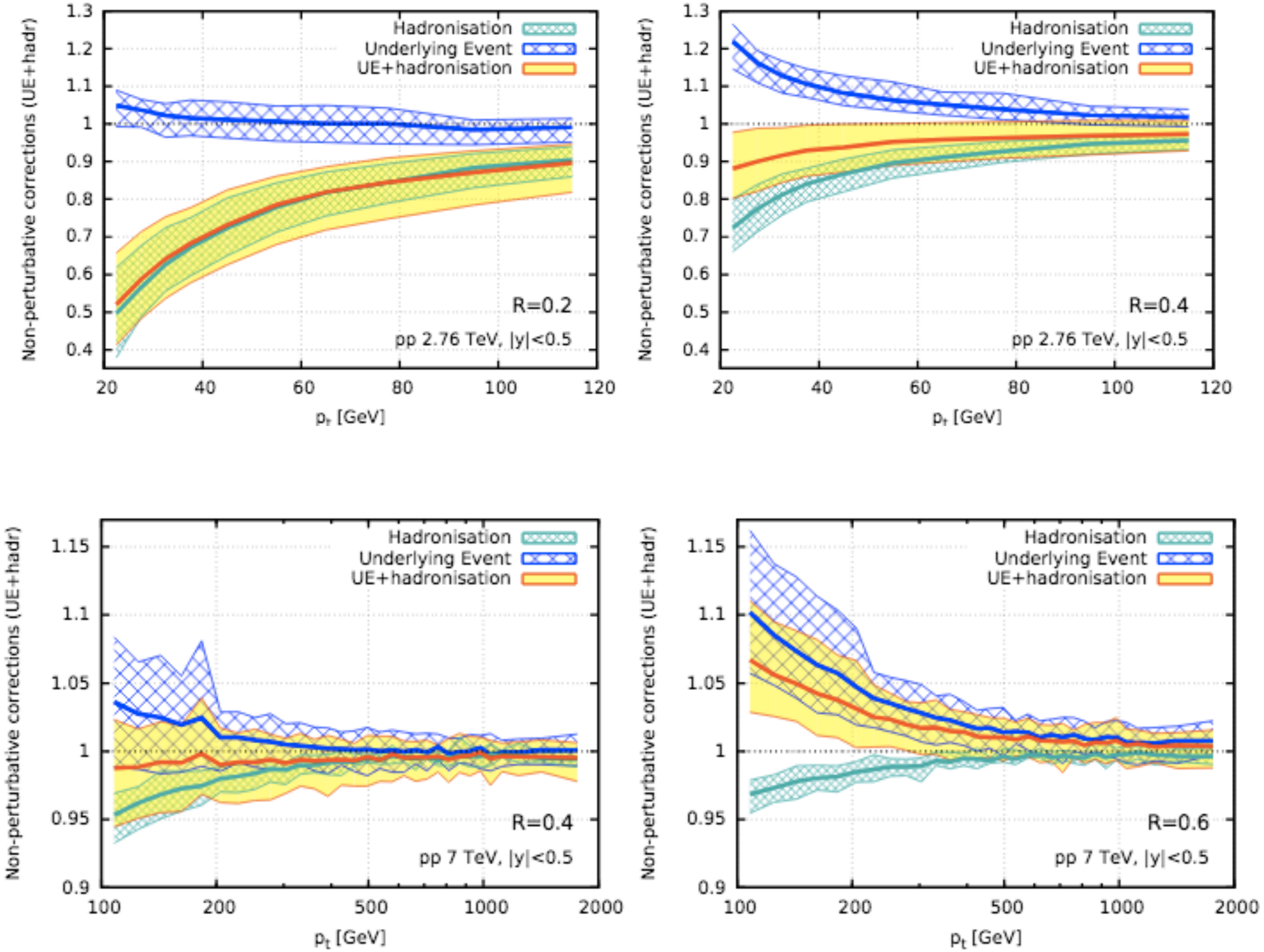


	Dependence of jet $\langle \delta p_t \rangle$ on			
	'partonic' p_t	colour factor	R	$\sqrt{s}$
perturbative radiation	$\sim \alpha_s(p_t)\, p_t$	C_i	$\ln R + \mathcal{O}(1)$	–
hadronization	–	C_i	$-1/R + \mathcal{O}(R)$	–
underlying event	–	–	$R^2 + \mathcal{O}(R^4)$	s^ω

Dasgupta, Magnea, Salam **JHEP 0802 (2008) 055**

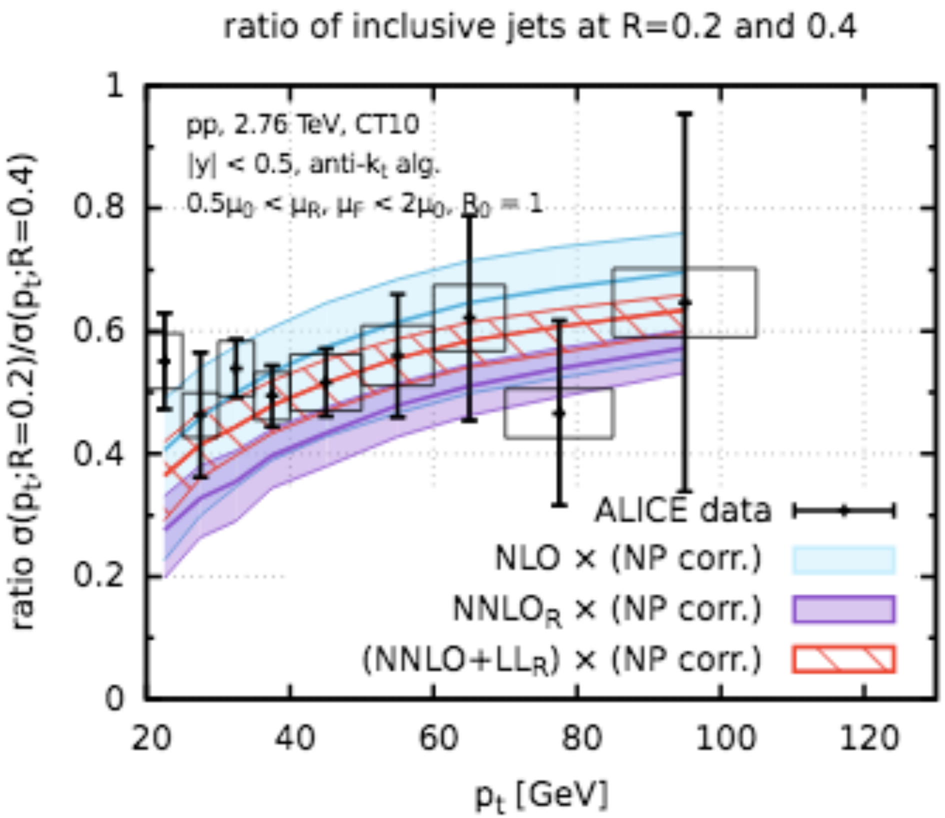
Optimal value of R depends in what component we want to study

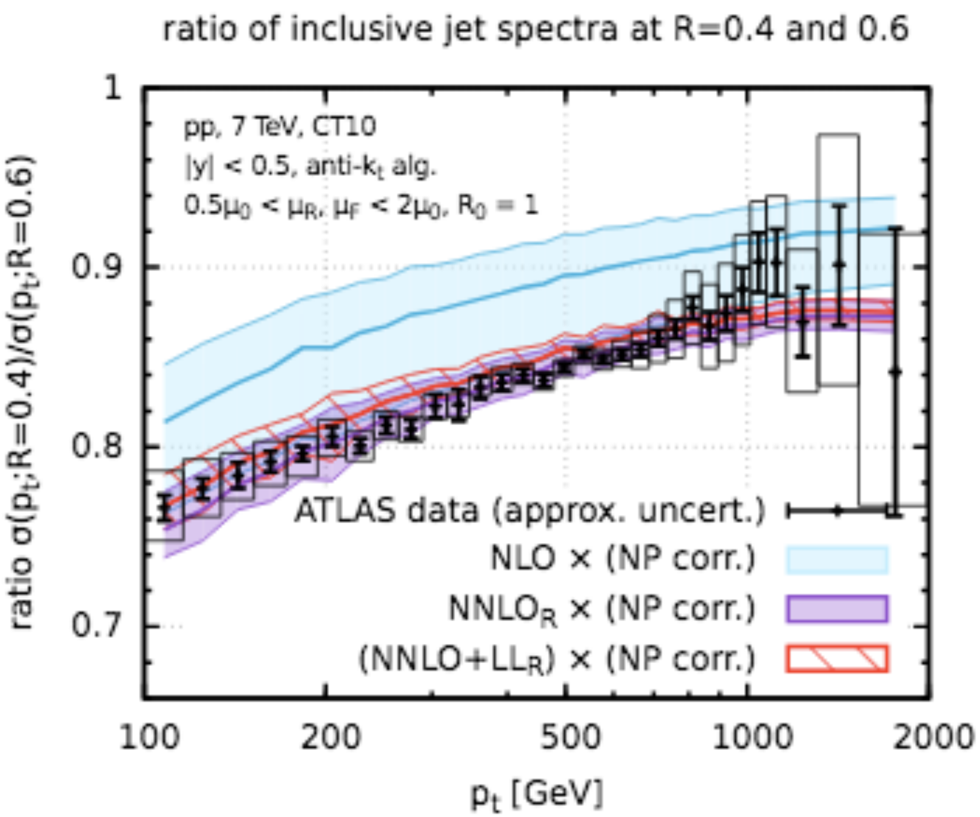
The perturbative and non-perturbative components of the jet



The region of low jet momentum is dominated by non-pertubative corrections

Ratio of cross sections for different R





Dasgupta, Dreyer,Salam,Soyez, **JHEP 1606 (2016) 057**

The ratio of xsections measured with different R is sensitive to the transverse energy profile

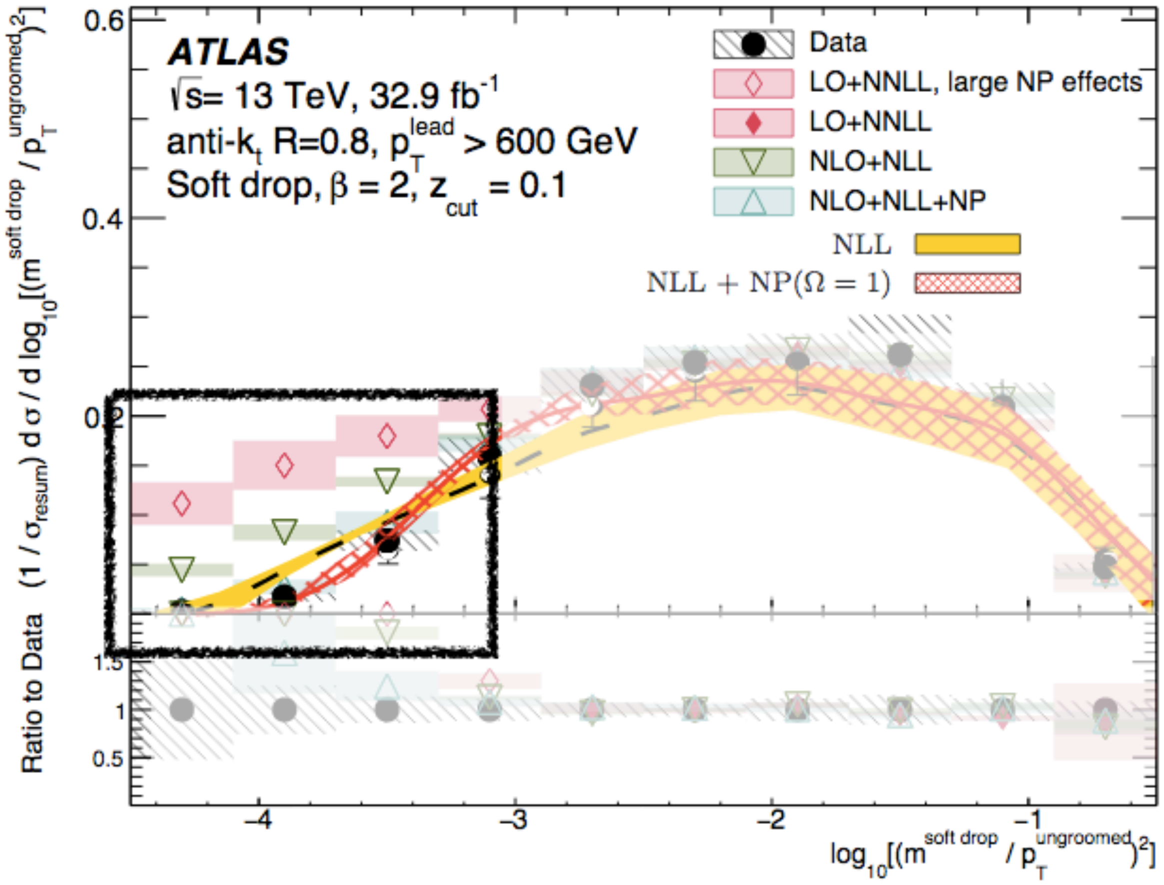
How to look inside a jet?

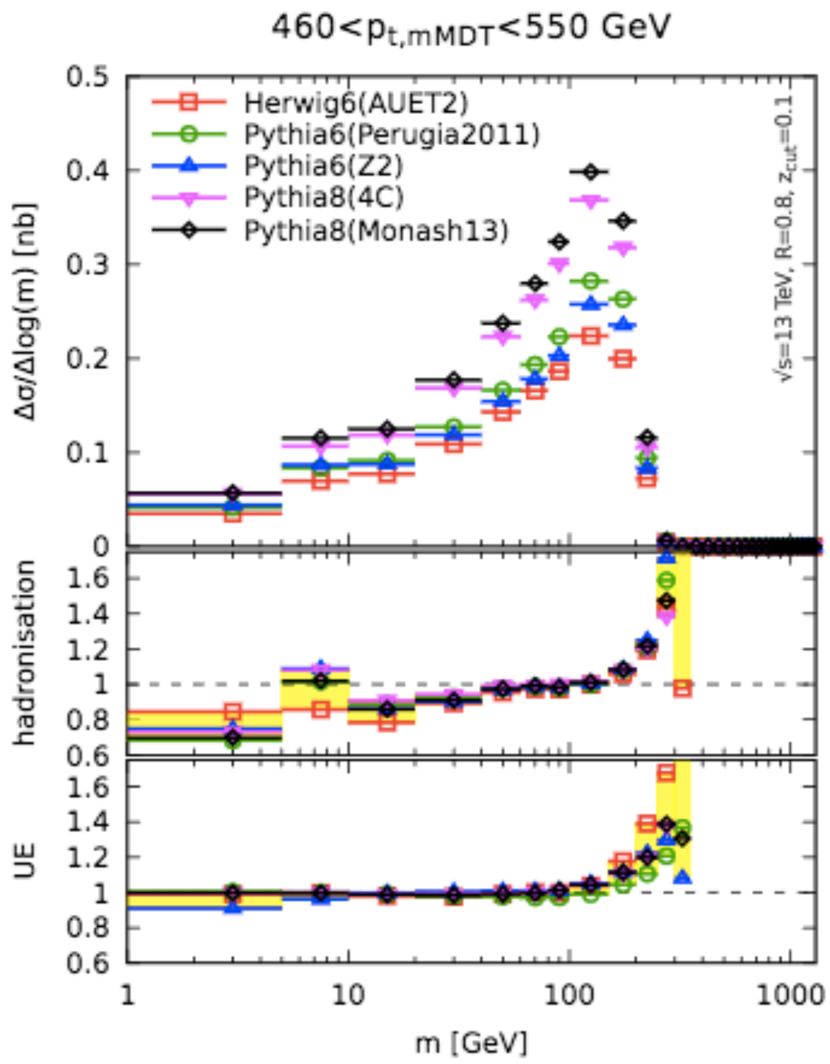
-Define jet shape variables: a function of the jet consitutents.
Examples: jet mass, angularity, pTD (generalized angularities), FF…

-Recluster the jet constituents with a hierarchical algorithm.
Unwind the clustering history of the jet to access the jet tree
Examples: n-subjettiness, zg, nSD,…groomed shapes in general…

Jet substructure pays a main role in LHC analysis, for instance in q/g discrimination or tagging of boosted objects.
In heavy ion collisions, we use it to probe the microscopic structure of QCD matter in AA

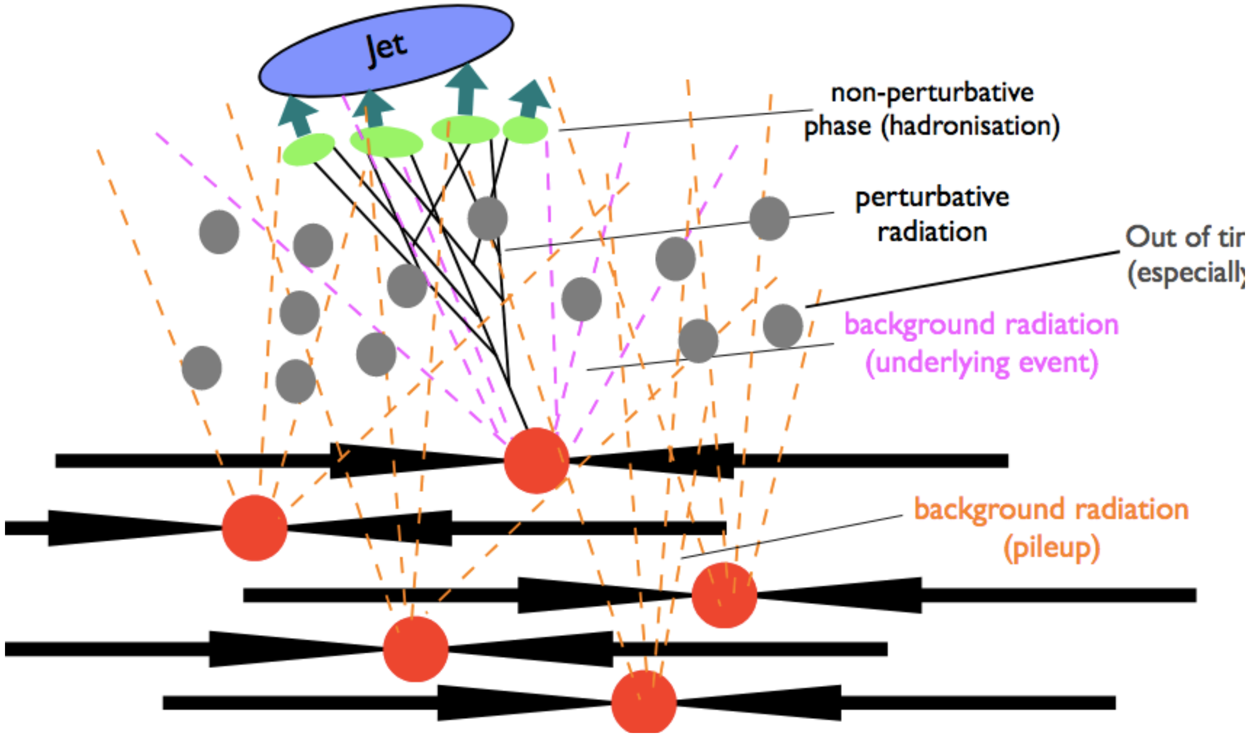
Jet shapes: differential constrain





Large region in mass where NP effects (yellow bands, right plot) are negligible
->great constrain to perturbative aspects of parton showers

Pileup subtraction



$$\Delta p_t = \rho A \pm (\sigma\sqrt{A})$$

Particles that are uncorrelated to the hard scattering will contaminate the jet.

The jet momentum can be adjusted, the jet area is the background susceptibility

The area-based equation below can be extended to shapes, to perform a zero-biased background subtraction, simultaneous in jet pt and shape

Salam,Cacciari et al

Other methods modify the event by removing particles according to some prescription. Not bias-free.

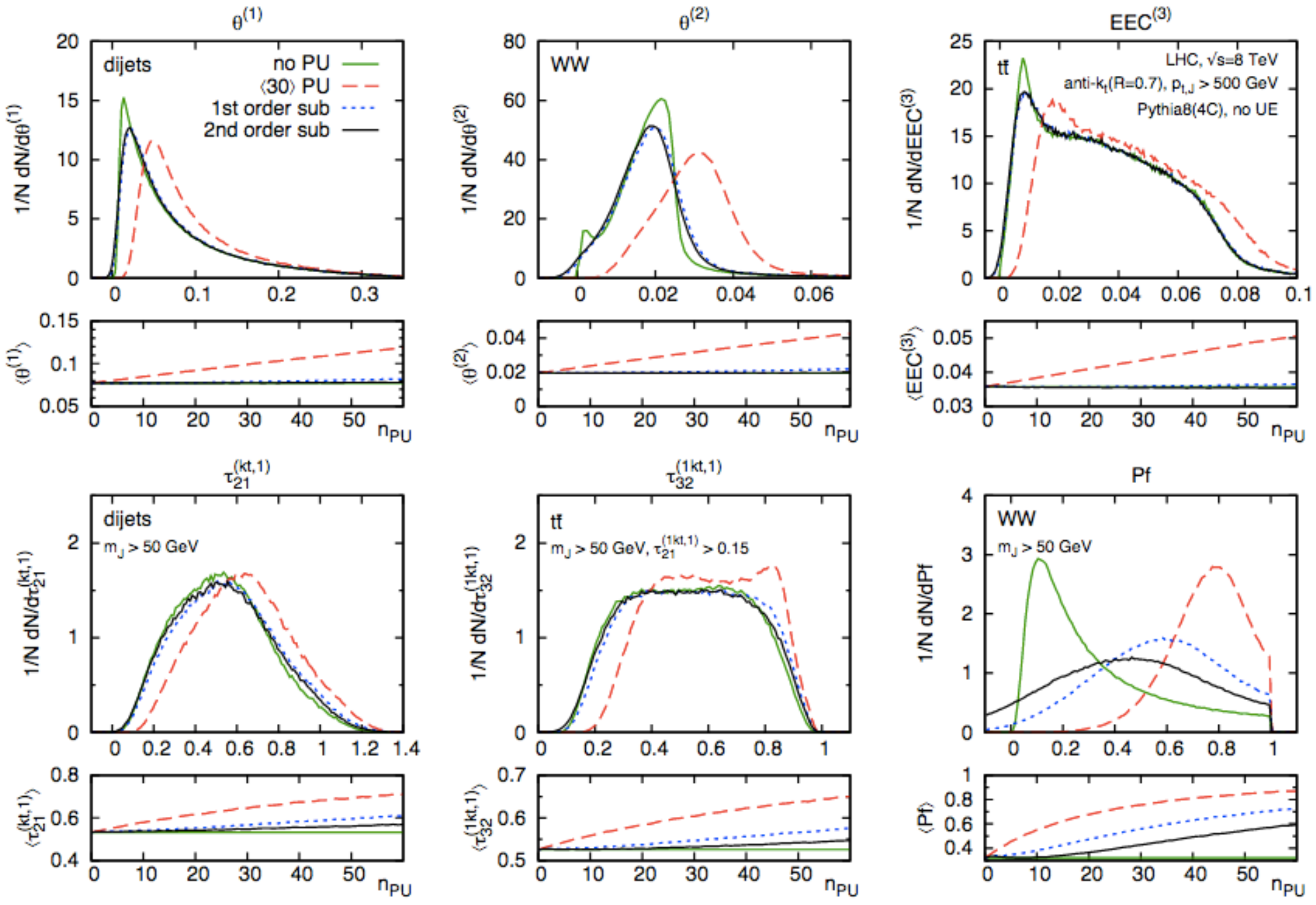
Constituent Subtraction (Berta, Spousta, Miller, Leitner, 1403.3108)

SoftKiller(MC, Salam, Soyez, 1407.0408)

PUPPI (Bertolini, Harris, Low, Tran, unpubl.)

…

Pileup subtraction



The event pileup is characterised by $\boldsymbol{\rho}$ and $\boldsymbol{\rho}_m$ Ghost particles are added uniformly in the acceptance, each mimicking a pileup-like component in a region of area A_g. The sensitivity of the shape to bkg is determined by calculating its derivatives with respect to the transverse momentum and mass of the ghosts. The value of the shape is then extrapolated by a Taylor series to zero pileup.

Soyez, Salam et al
Phys.Rev.Lett. 110 (2013) no.16, 162001

Jet grooming

Trimming

- Take jet with radius R
- Reclusters components into smaller subjets with radius $R_{sub} < R$
- Keep subjets that satisfy $p_{t,\,sub} > z_{cut}\, p_{t,\,jet}$

Pruning

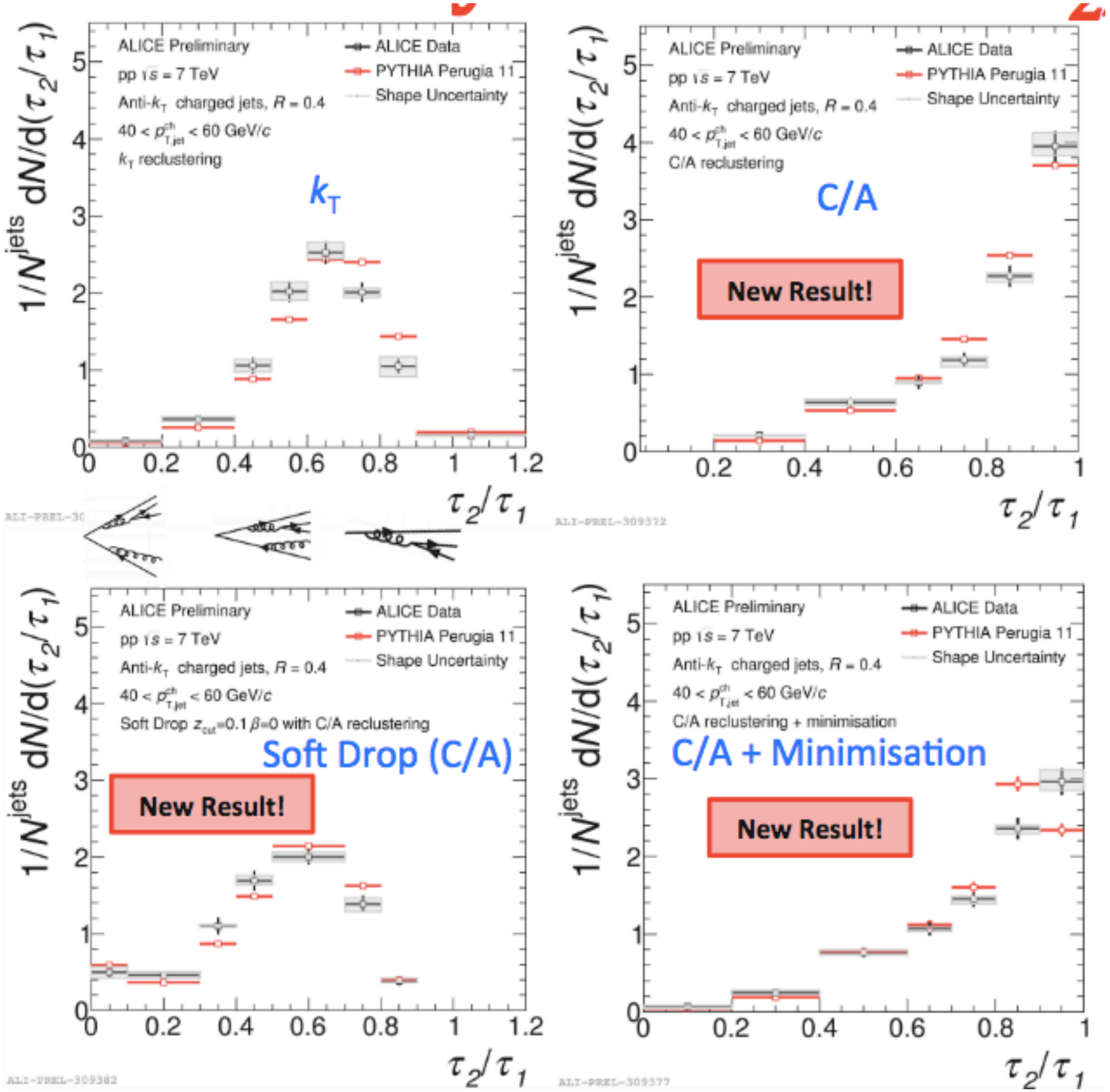
- Define pruning radius $R_{prun} = R_{cut} * 2\, m / p_t$
- For every step of clustering $j_1 + j_2 \to j_{12}$, check:
  - Wide-angle: $\Delta R_{12} > R_{prun}$
  - Soft: $\min(p_{t1}, p_{t2}) < z_{cut}\, p_{t,\,jet}$
- If either condition fails, eliminates softer subjet
- If both pass, continue clustering

SoftDrop (or mMDT)

- Decluster jet $j_{12} \to j_1 + j_2$
- Check condition $\min(p_{t1}, p_{t2})/p_{t,jet} > z_{cut}(\Delta R_{12}/R)^{\beta}$
  - z_{cut}, β: tunable values
- If condition fails, the softer subjet is removed
- If passes, stops recursion
- For β=0, it is mMDT

AIM: Limit contamination of QCD background in a controlled way while retaining the bulk of perturbative radiation ->interesting idea to export to HI!

Example of substructure in pp: N-Subjettiness



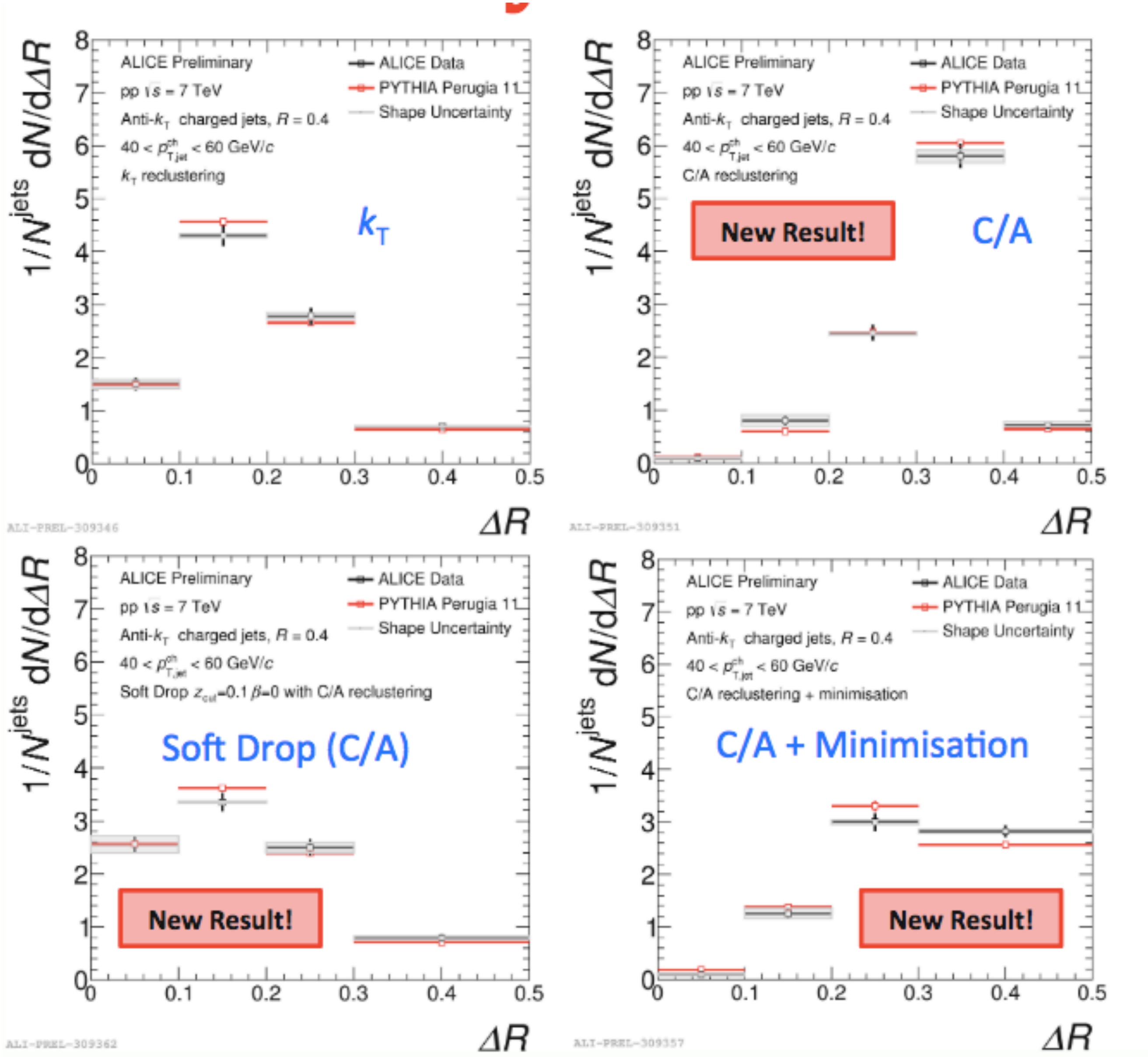
$$\tau_N = \frac{\sum_{i=1} p_{T,i} Min(\Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N})}{R_0 \sum_{i=1} p_{T,i}}$$

tau2/tau1->0 means that the jet is 2-prong
tau2/tau1->1 the jet has more prongs than just 2

tau2/tau1 measures how well the radiation is aligned relative to returned axes.

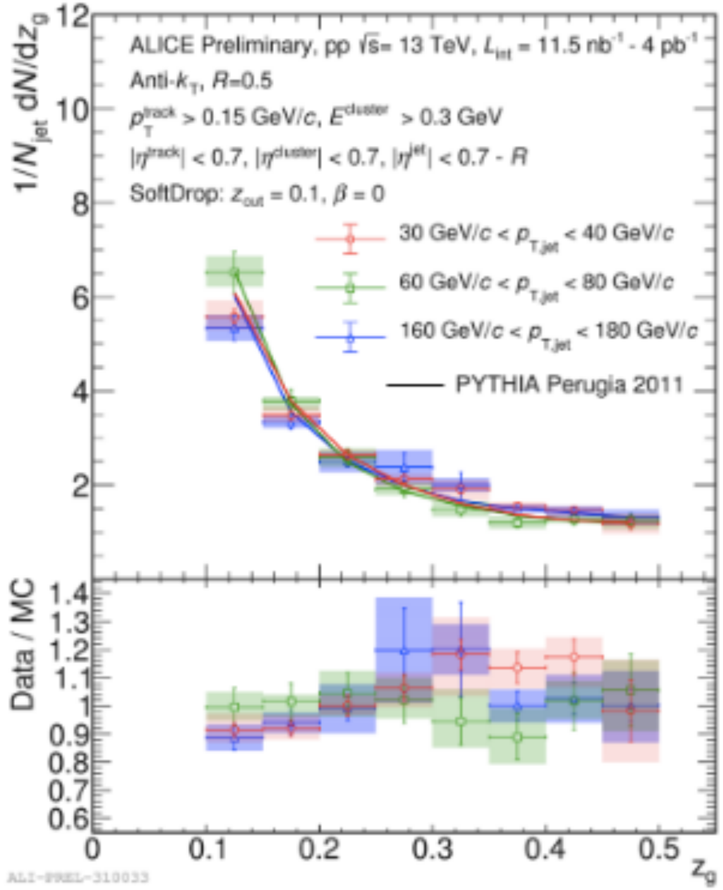
Changing the reclustering algorithm allows to probe different splittings in the jet

Example substructure in pp: aperture angle

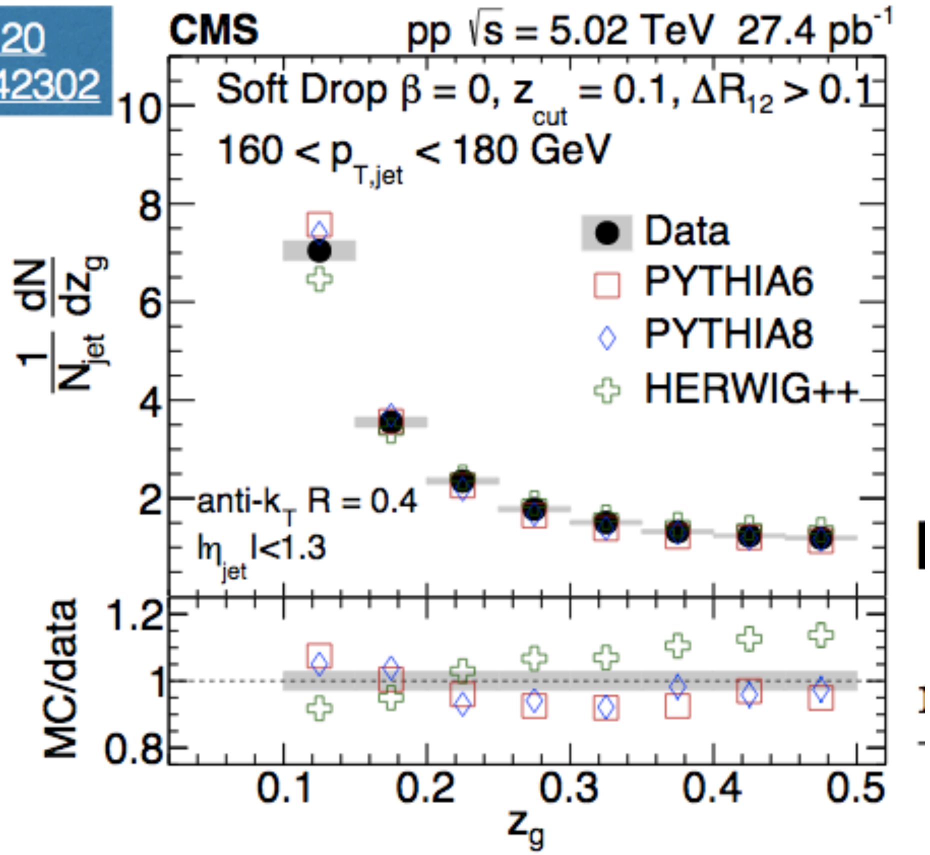


Angular separation of different splittings in the jet

Example of groomed substructure pp: momentum imbalance



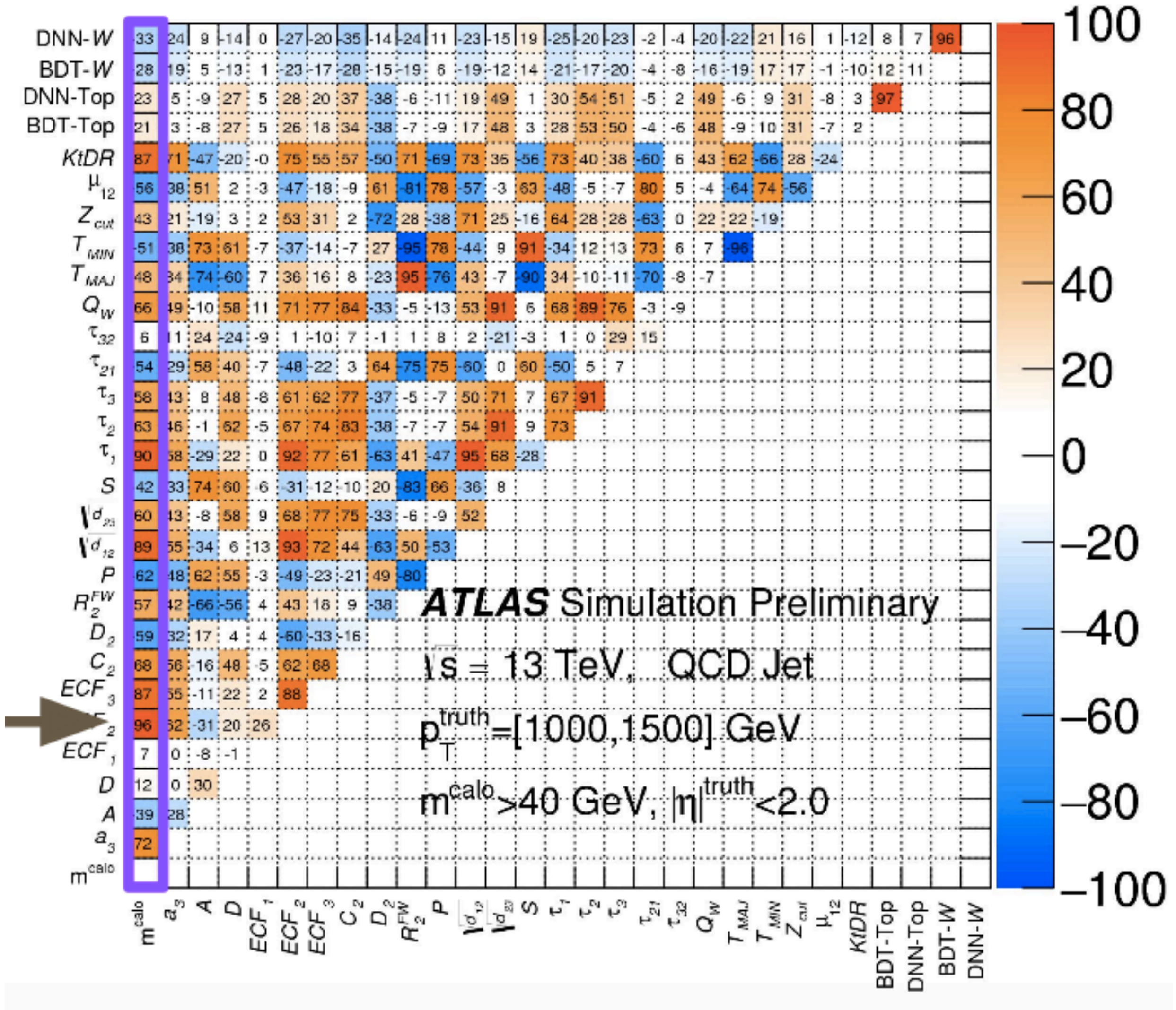
PRL 120 (2018) 142302



z_g is the momentum imbalance of the first pair of subjets that pass the mass drop condition

No jet p_T dependence, as expected if zg in vacuum is a valid proxy for the Altarelli-Parisi splitting kernel, universal 1/z behaviour

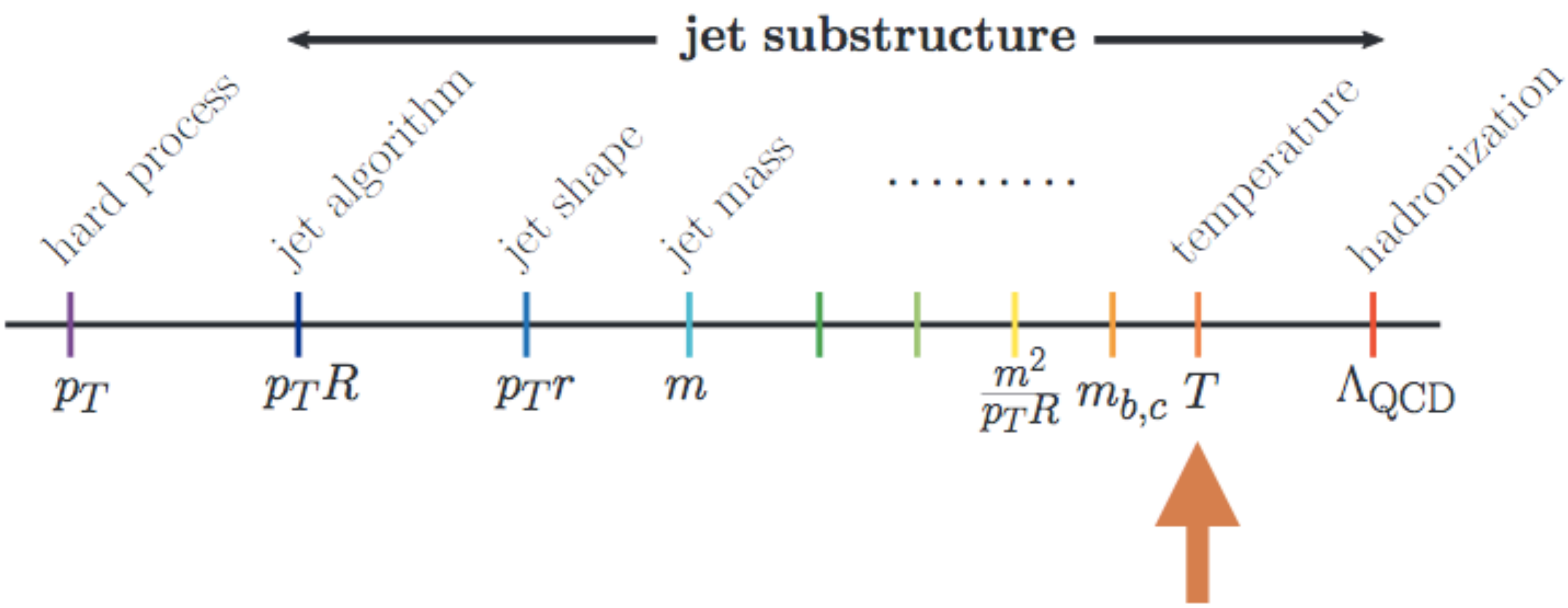
Jet substructure observables



Difficult to find a jet shape that is not correlated/anticorrelated with the jet mass

In order to extract maximal information (ie about jet quenching), the more uncorrelated the set of observables, the better

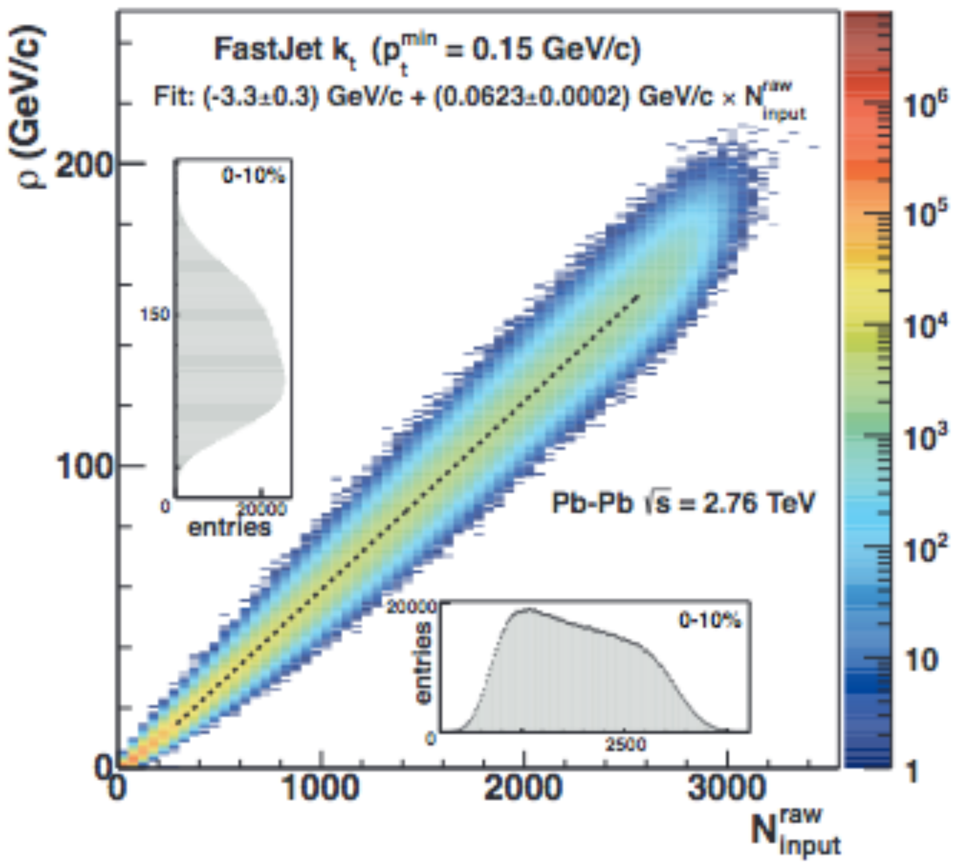
Jets in Heavy Ion Collisions



Several fundamental questions to answer

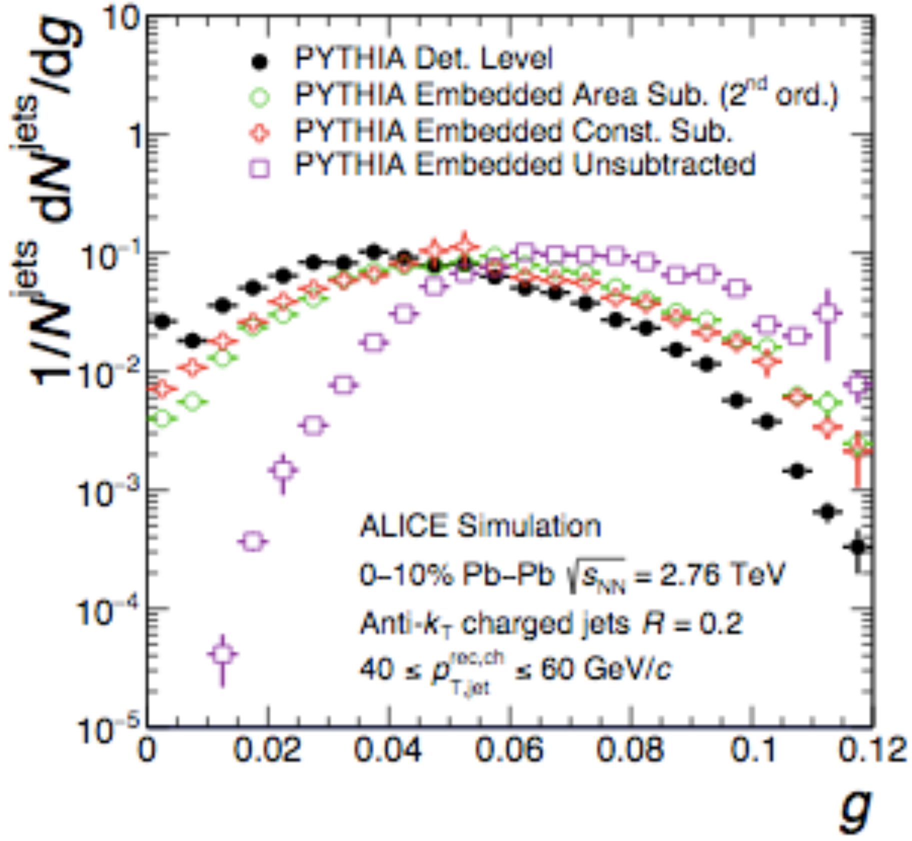
- Can we probe the partonic degrees of freedom within the strongly-coupled QGP? Do we have access to the Moliere regime? Can we detect scatterings off quasi-particles via large angle deflection of jets/constituents?
- Is color coherence at work and what are the critical angles?
- Is flavour hierarchy respected in medium?
- Related to the 3 previous points: how does energy loss depend on the jet substructure?
- Can we experimentally isolte specific aspects of the in-medium shower that are under better theoretical control?

Large pedestal background to subtract



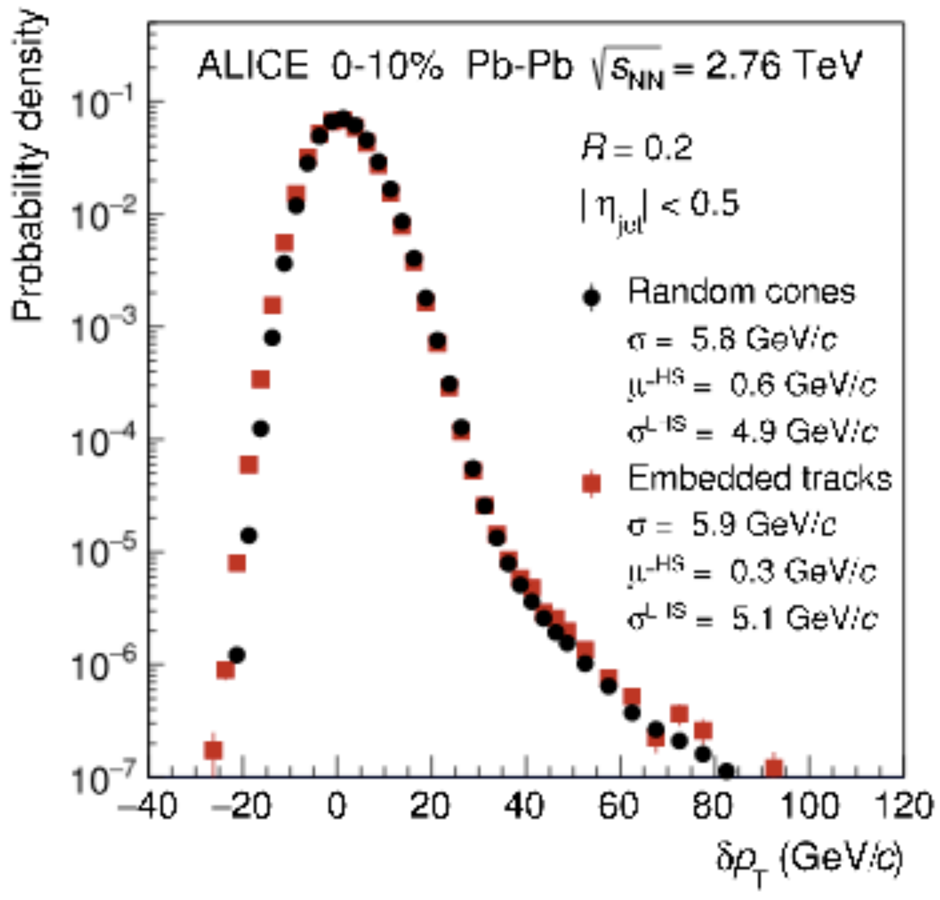
Large uncorrelated background per unit area

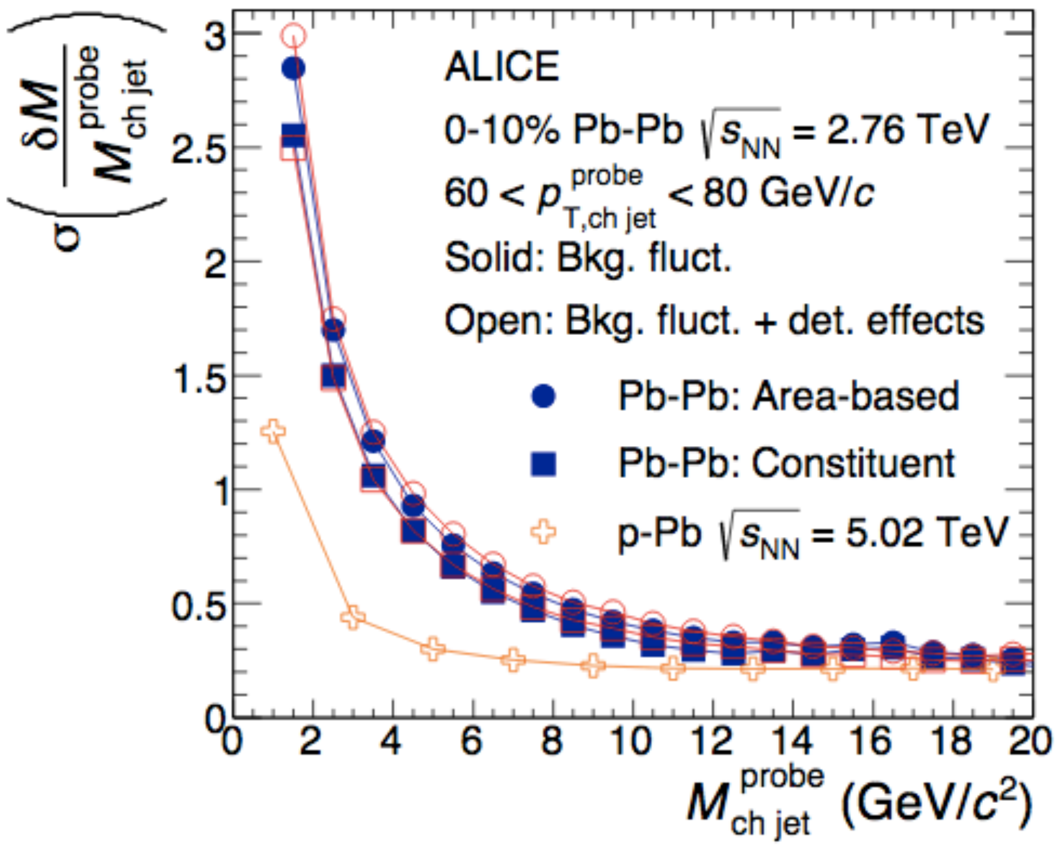
Pythia events embedded into PbPb data



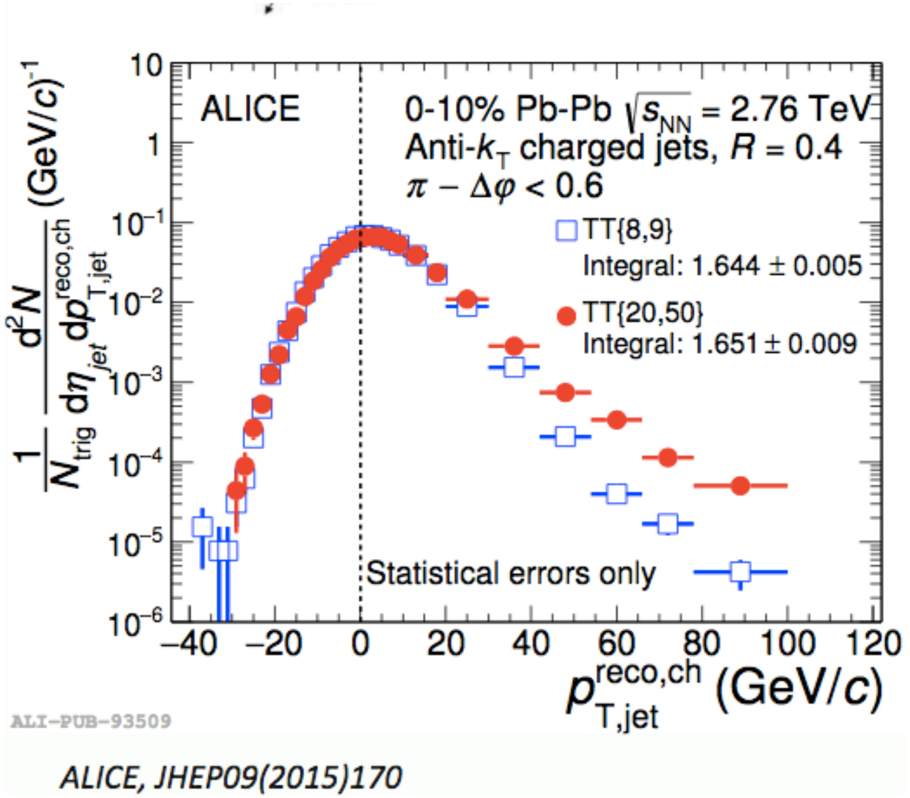
same techniques as in HEP

Jet energy and shape irresolution to unfold





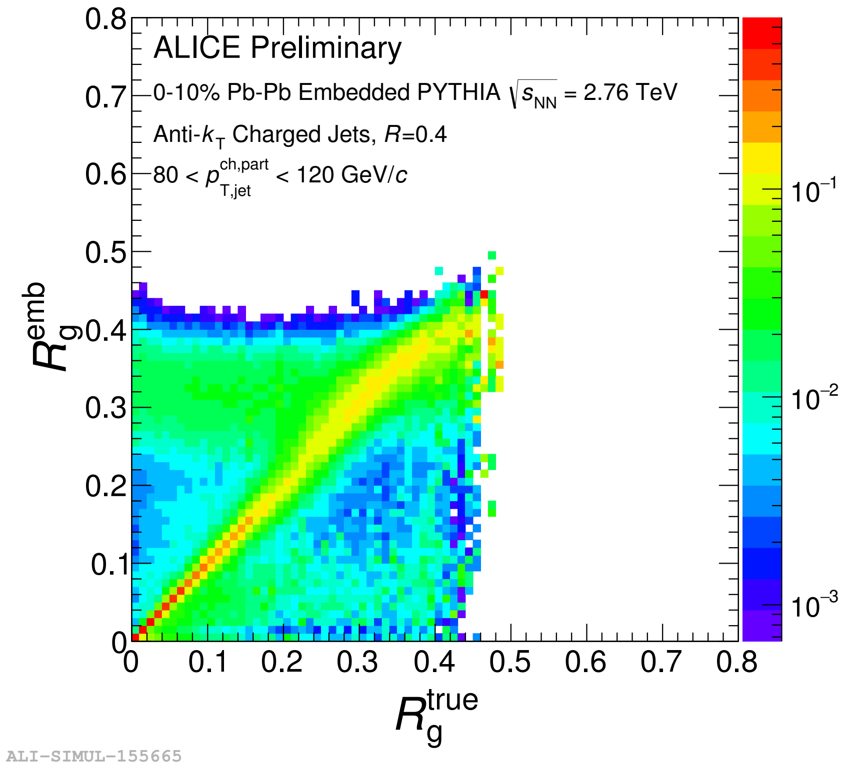
Large combinatorial background to suppress



Large fake jet contribution limits inclusive jet measurements at low jet pT/large R

Data-driven techniques based on semi-inclusive coincidence measurements can be applied to subtract combinatorial background
Jet event mixing, ML are other approaches under exploration

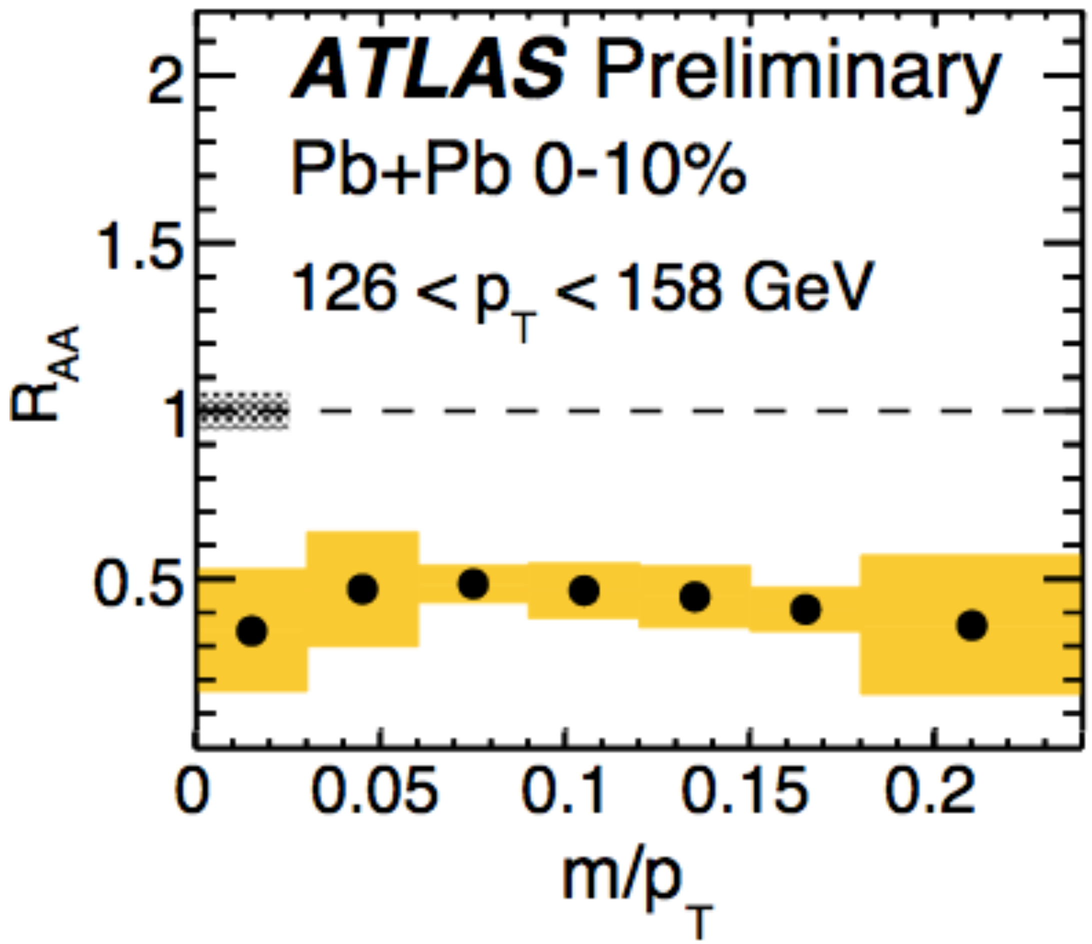
Background and detector response of the splitting aperture angle



The uncorrelated background generates fake subleading prongs at large angles (where area is maximal)

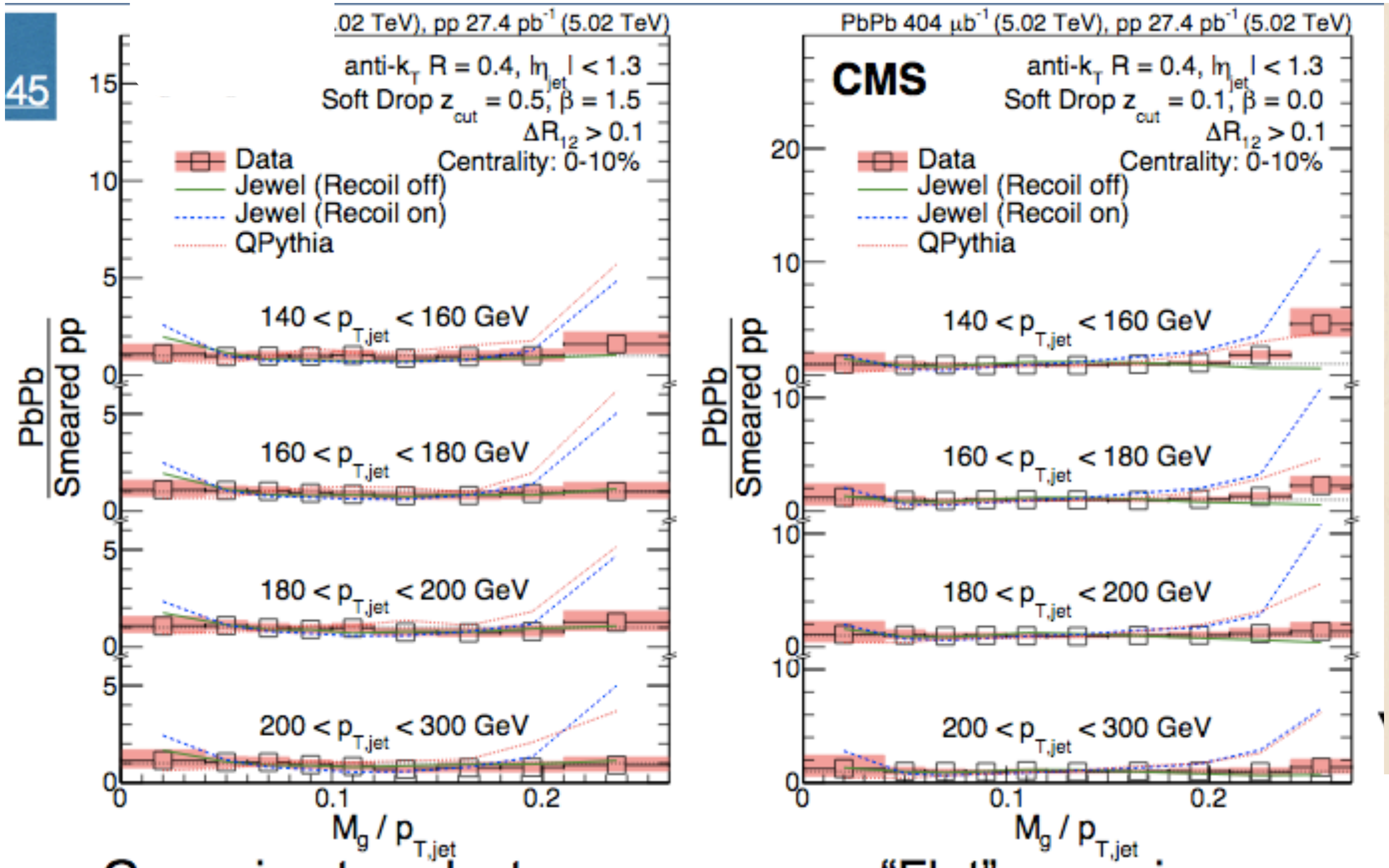
Does the energy loss depend on the jet shape?

ATLAS: mass from calorimeter towers



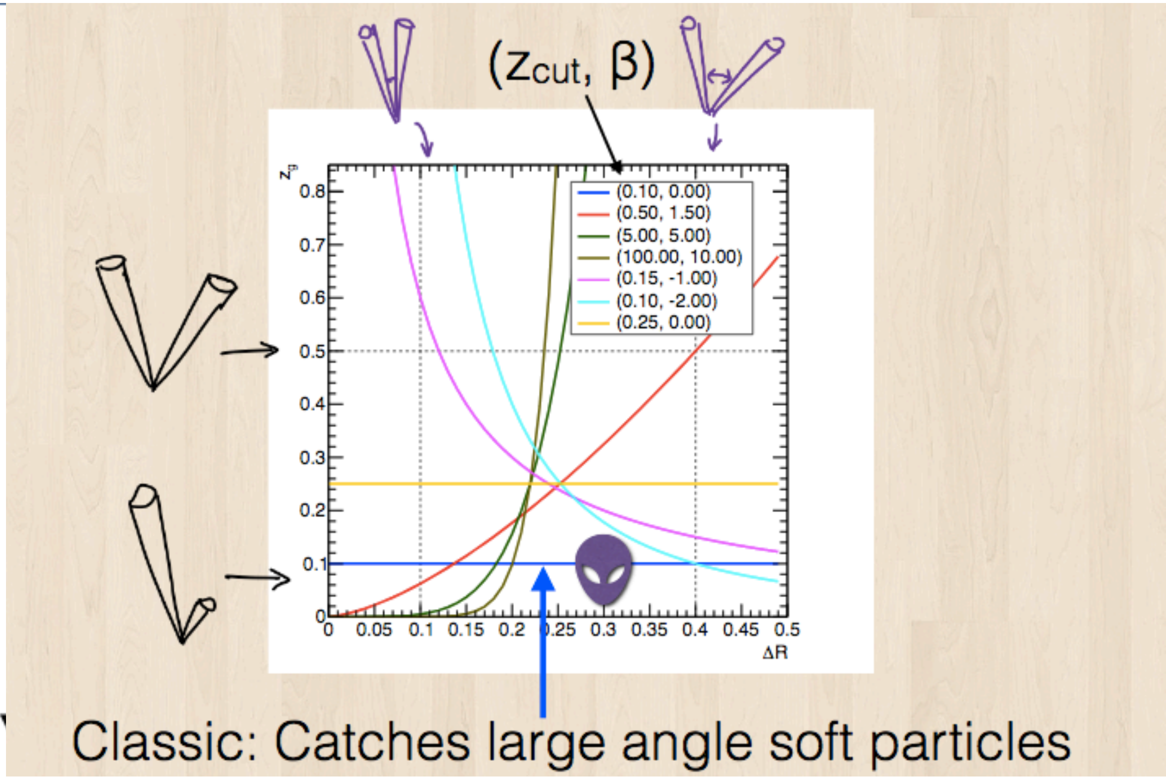
No apparent dependence observed

Does the energy loss depend on the jet shape?



Grooming to select core

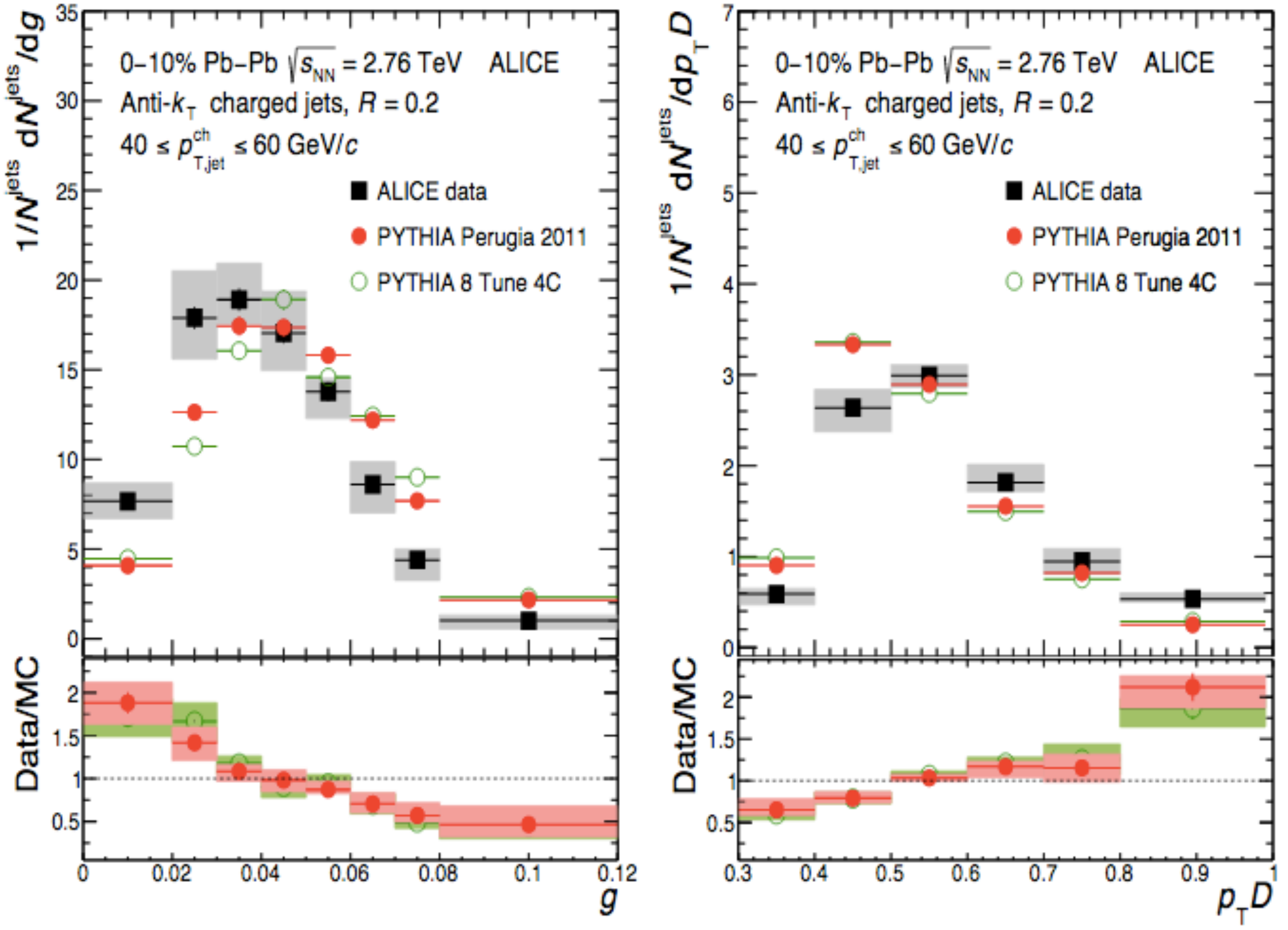
"Flat" grooming



Interesting exploration of the phase space of emissions

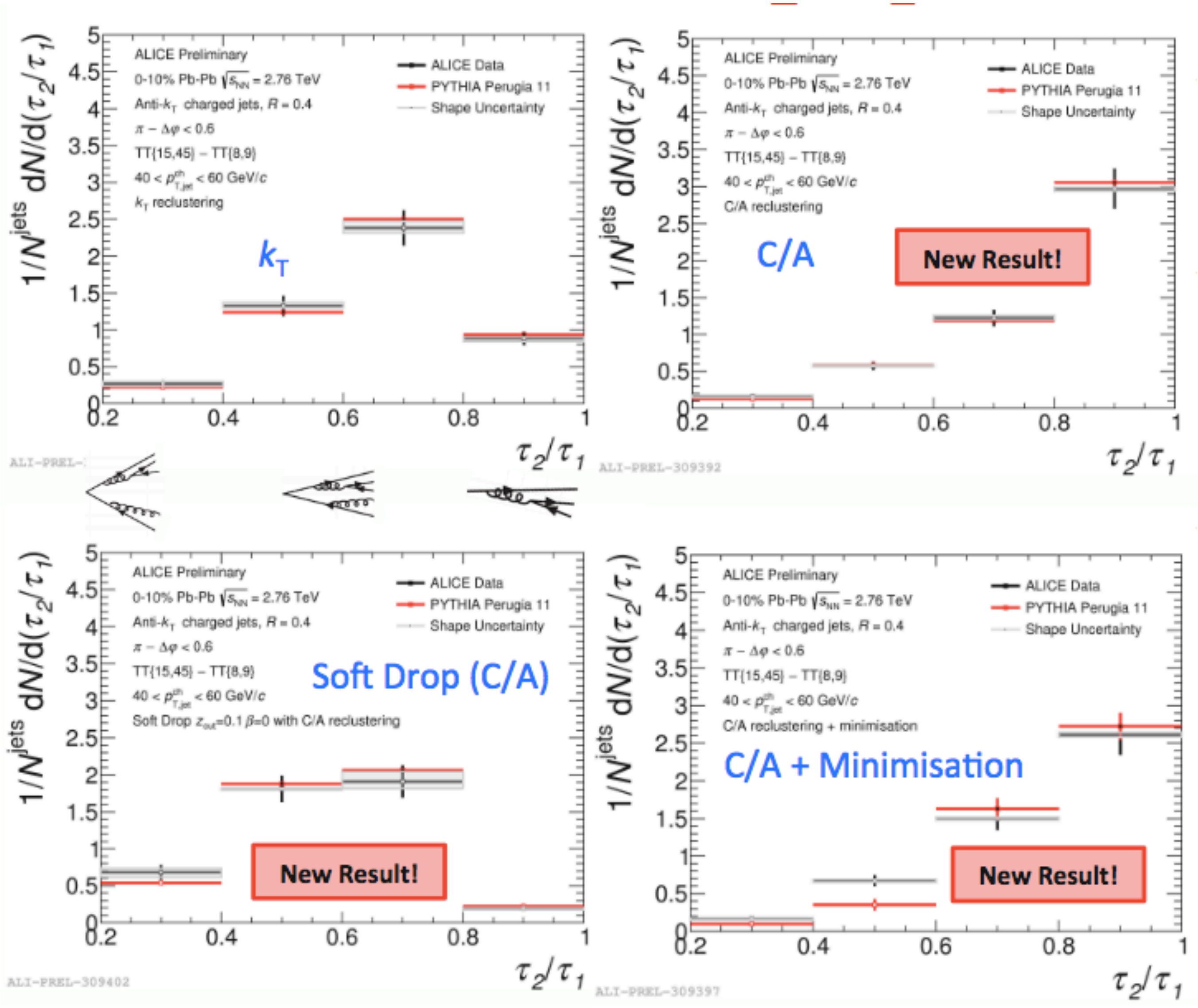
Some effects at the tails

Does the energy loss depend on the jet shape?



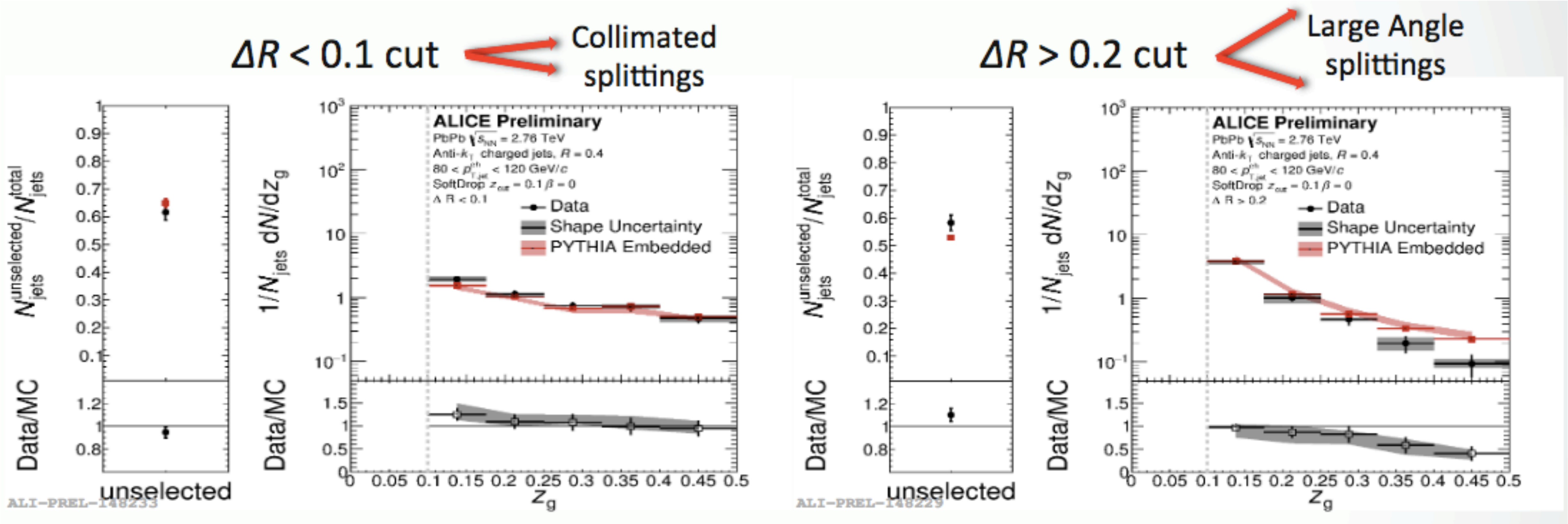
The jet cores seem to get narrower and harder in medium relative to vacuum, in agreement with a quark-like fragmentation

Does the energy loss depend on the jet shape?



The way radiation is aligned relative to the chosen splittings (a very different set of splittings was considered) does not change in medium relative to vacuum

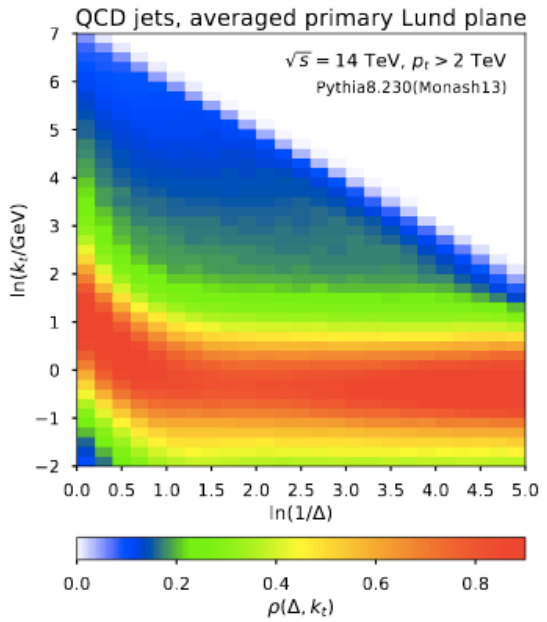
Momentum imbalance

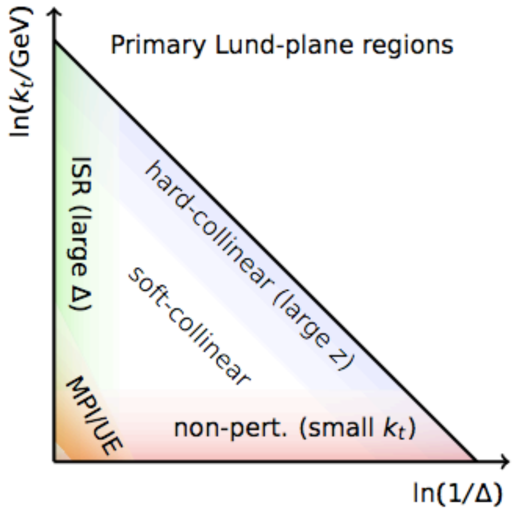


Suppression of symmetric splittings at large angles
Enhancement of collinear splittings
Interesting implications concerning formation time

The Lund plane

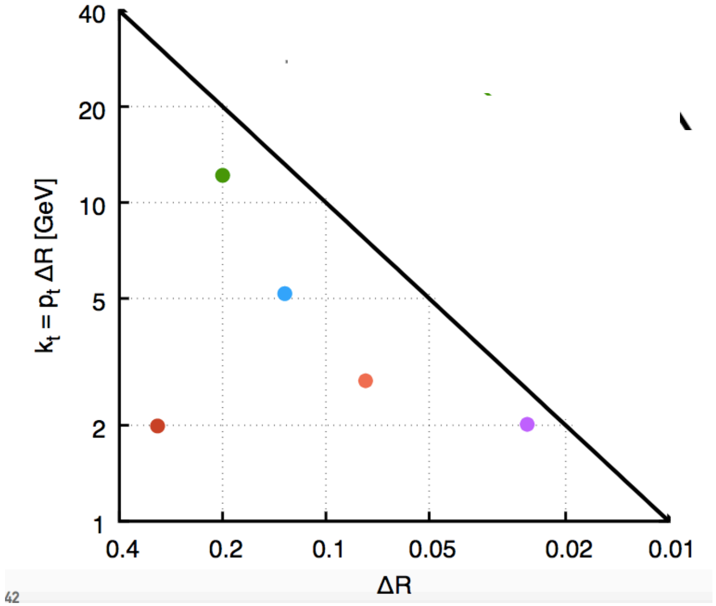
-A general 2D map of splittings, most of other substructure observables are derived from it
-Relevant scales like the splitting scale k_T, formation time, constant mass, can be marked as simple line cuts on the plane
-Powerful tool to isolate different physics ingredients in the jet quenching calculations (ideal tool for JETSCAPE)



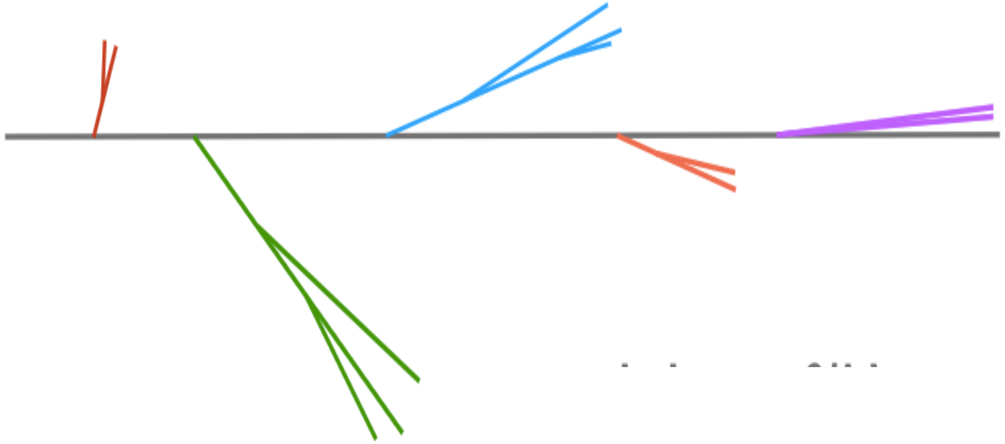


Dreyer, Salam, Soyez,
https://arxiv.org/pdf/1807.04758.pdf

The Lund plane in vacuum



plot from G.Salam, QM18



$$d^2P = 2\frac{\alpha_s(k_\perp)C_R}{\pi}dln(z\theta)dln(\frac{1}{\theta})$$

Iterative declustering:

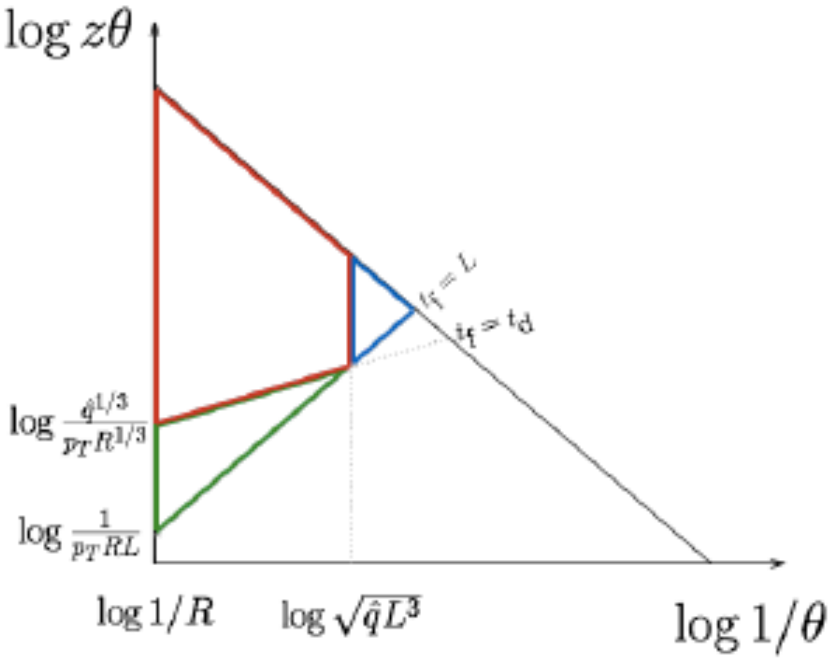
Unwind the CA clustering (angular ordering in vacuum)

At each step, register the k_T, ΔR coordinates

Follow the hardest branch at each step

In vacuum, flat 2D density except for variation of the coupling with k_T

The Lund plane in medium



Angular ordering not expected in medium, so using CA to recluster is an operational choice

New scales appear due to the medium and divide the phase space: formation time, decoherence time, decoherence angle…:

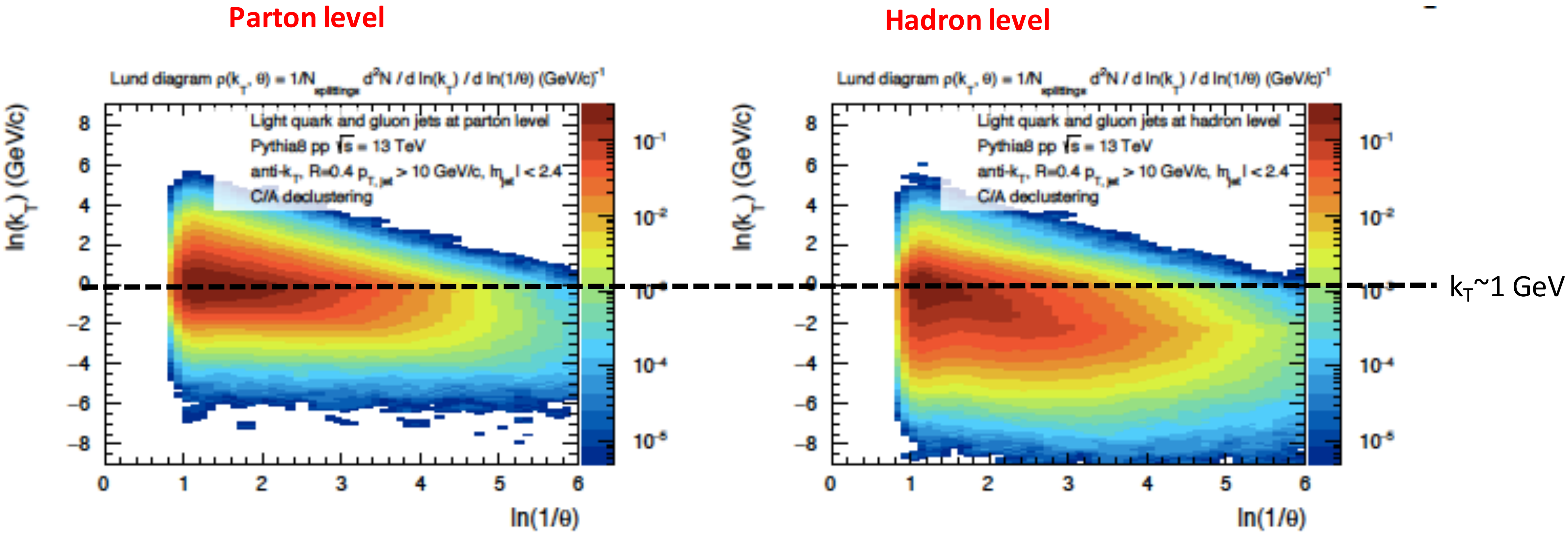
$t_f < t_d < L$ vacuum splittings inside the medium

In medium splittings with $t_d > L$:not resolved by the medium

$t_d \lesssim t_f$ splitting kinematics dominated by medium effects Lund plane not filled with the pQCD uniform probability

K.Tywoniuk et al, Novel tools and observables for jet physics in heavy ion collisons,
https://arxiv.org/pdf/1808.03689.pdf

Map different contributions: hadronization

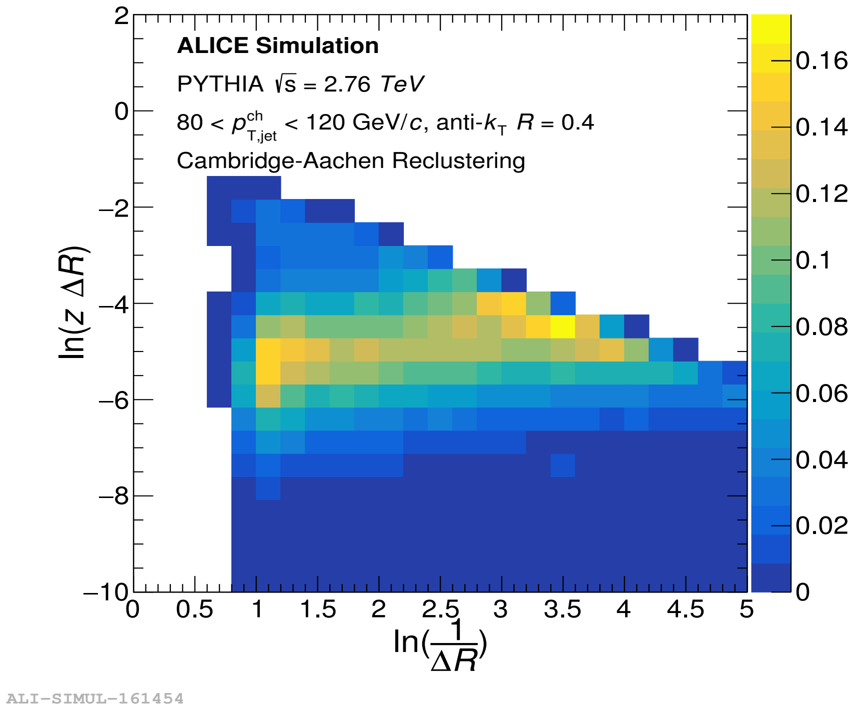


L.Cunqueiro, M.Ploskon, https://arxiv.org/pdf/1812.00102.pdf

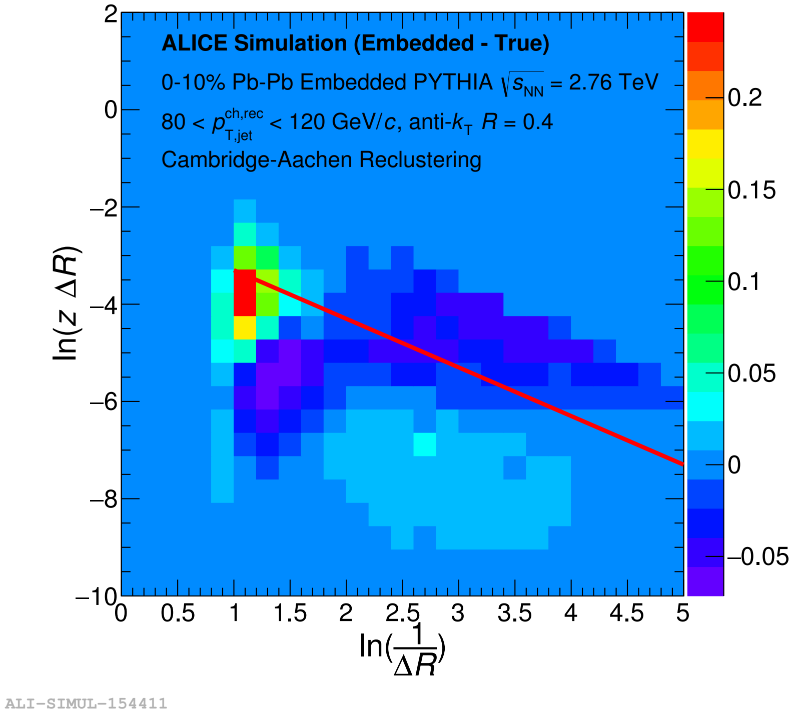
Non-perturbative effects can be removed/isolated by cutting at $\ln(k_T)>/<0$

Map different contributions: uncorrelated background

PYTHIA jets



PYTHIA jets embedded into 0-10% central Pb-Pb events

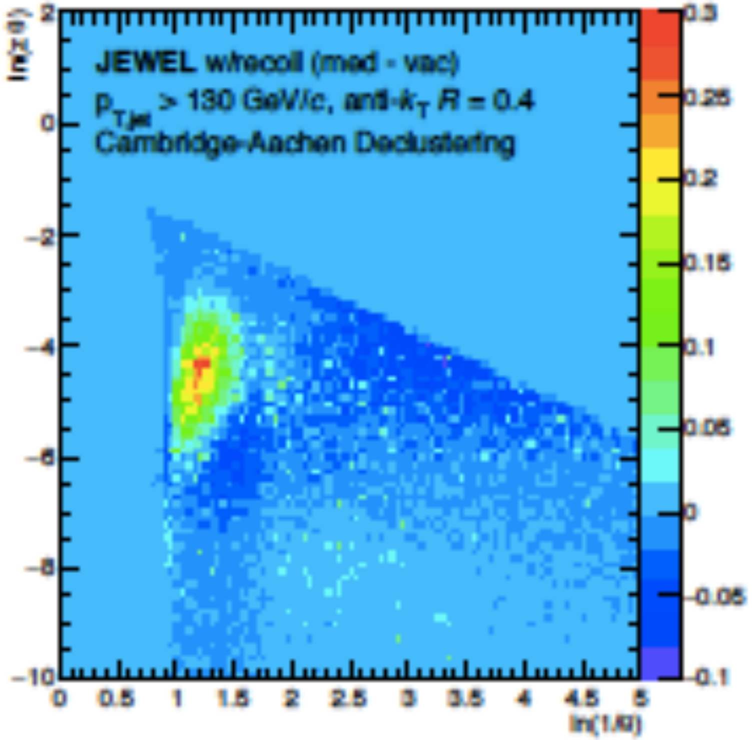


Fake splittings appear at large angles $\theta \sim R$ and lowish z

They contribute to the groomed signal (above red line representing SD condition $z_{cut} > 0.1$, $\beta=0$)

Map different contributions: correlated background

JEWEL MC: Medium - Vacuum



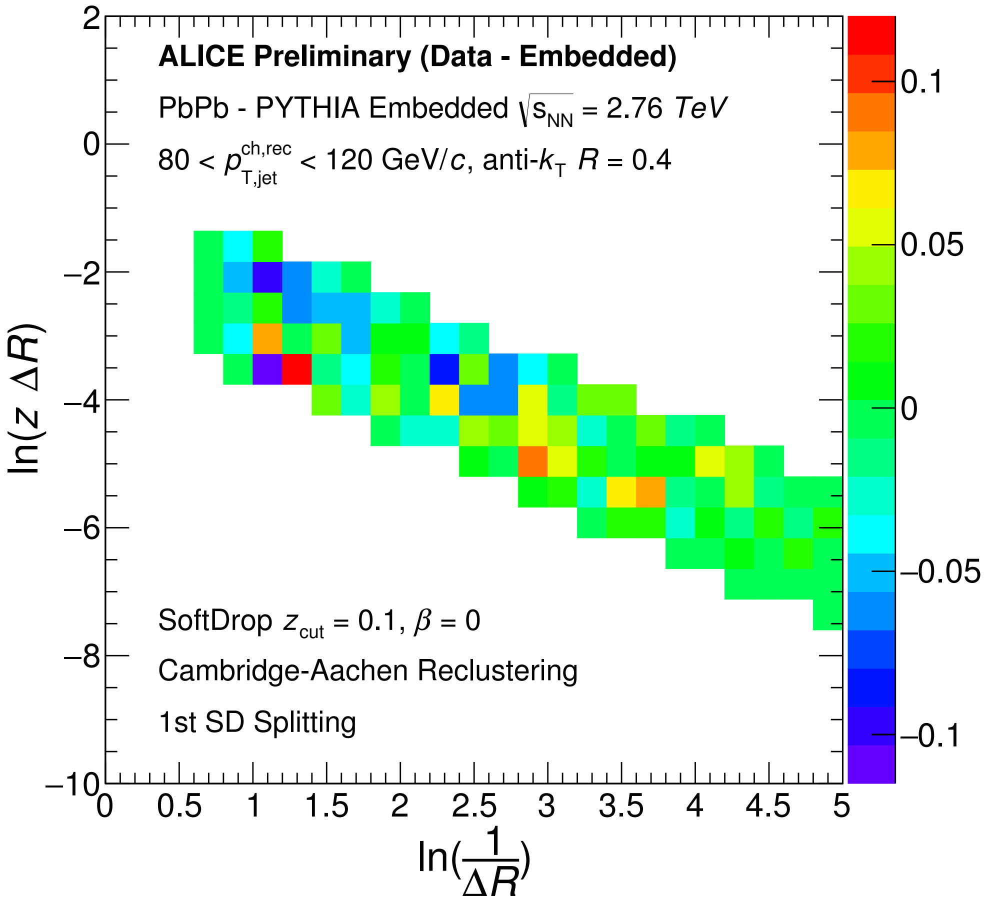
The correlated background or medium response is the background that gets "excited by the jet" and ends up in the jet cone.

As correlated bkg, it cannot be suppressed using standard techniques like event mixing or coincidence measurements.

K.Tywoniuk et al, Novel tools and observables for jet physics in heavy ion collisons,
https://arxiv.org/pdf/1808.03689.pdf

Lund plane in Pb-Pb , it can be measured

Probability density difference: Data - PYTHA embedded into Pb-Pb events

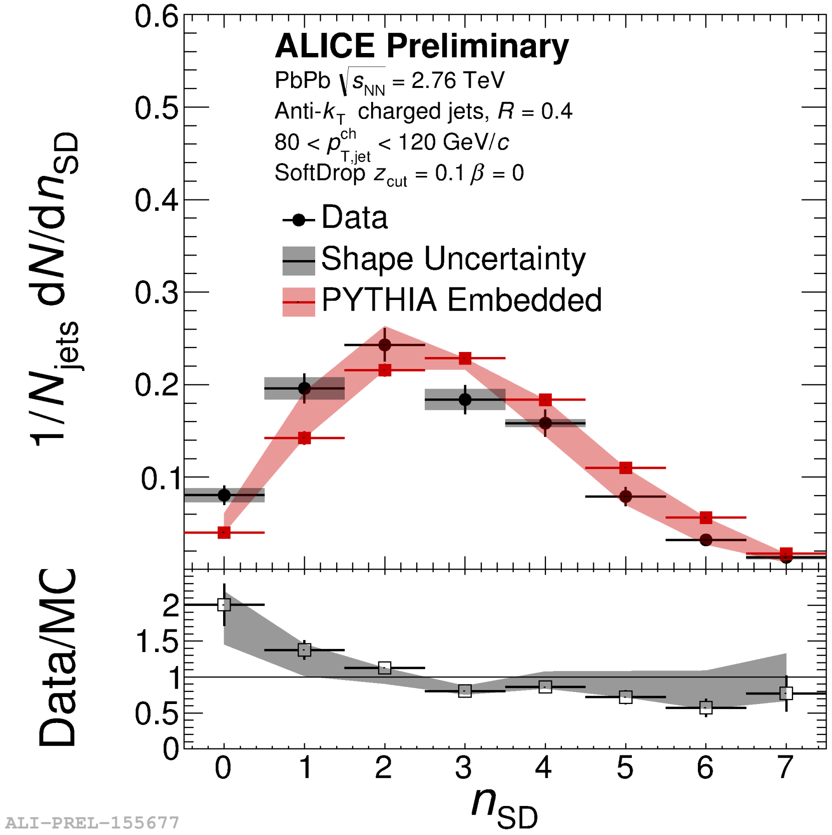


ALI−PREL−148246

Useful observable are 1D projections in bins of scale k_T

Quite differential, requires plenty of statistics

Lund plane: number of entries (splittings)



The density map of splittings is deformed in Pb-Pb relative to vacuum,
but this deformation is not accompanied by an increase in the number of hard splittings selected by SD.

Some thoughts on data to MC comparison in Heavy Ions in the context of JETSCAPE

1. The way jet observables are presented by the collaborations:

-Ideal: Fully corrected to particle level, can be directly compared to MC

-Not fully corrected observables. Sometimes unfolding is not possible, responses can be severely off-diagonal leading to unstable unfolding. Then, MC has to be smeared according to the responses the experiments provide.

Example case: ALICE measured the zg vs ΔR in a given jet pt bin at uncorrected level, and provides a 6D response (zg^{part}, ΔR^{part}, pT^{part}, zg^{emb}, ΔR^{emb}, p_T^{emb})

Some thoughts on data to MC comparison in Heavy Ions in the context of JETSCAPE

2. Strategies for MC to data comparison:

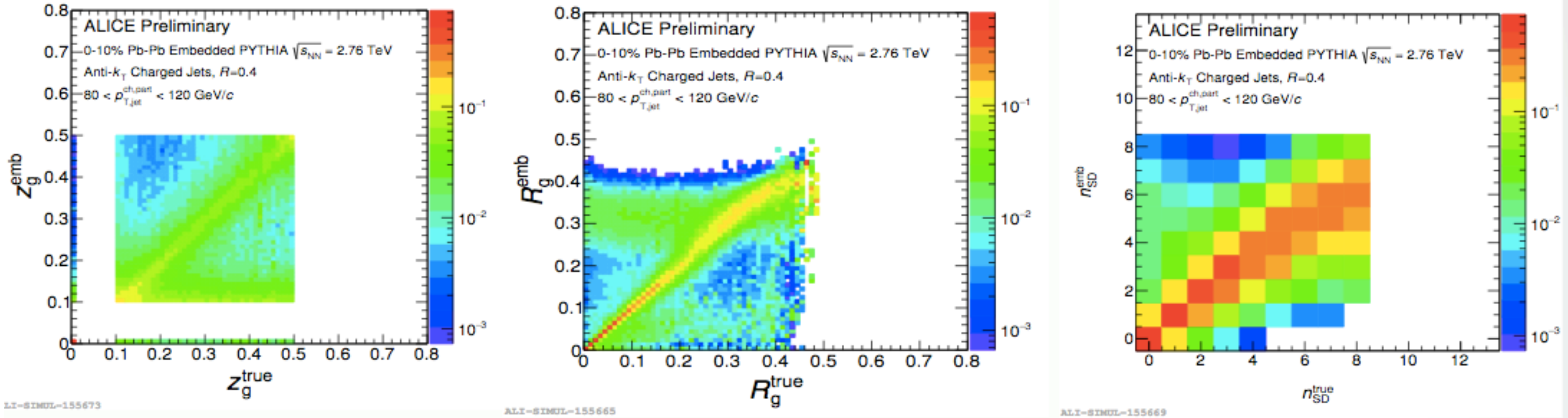
-Selective choice of observables when extracting fundamental properties like qhat : choose those that are less affected by model-dependent components like hadronization.

-Isolation of physics ingredients: the modular nature of JETSCAPE allows to test what physics ingredients contribute to what regions of the jet phase space and to test them experimentally.

A possible example: fill the Lund map switching on/off the different physics components of the JETSCAPE framework. Is there a region of the 2D phase space map that gets modified by a single physics ingredient? ->Then opportunity to test the model and propose an experimental observable.

- THANKS!

Fake splittings



- Uncorrelated background **adds splittings** at **low z_g**.
- Fake splittings **appear** at **large R_g** due to the background.
- n_{SD} appears relatively robust to the presence of background.

Fundamental question in the physics of heavy ion collisions:

How do collective phenomena and macroscropic properties of matter arise from the elementary interactions of a non-abelian quantum field theory?

Opportunities	Tools	Status
Constraining equilibrium properties of QCD matter (eos, η/s, ξ, τ_π ...	Flow and fluctuation measurements in AA	advanced
Measuring medium properties with hard auto-generated probes ($\hat{q}$, $\hat{e}$, T), ...	Quarkonia, R_{AA}'s, photons	in progress
Accessing microscropic structure of QCD matter in AA	Jet substructure, heavy flavor transport	in reach
Controlling initial conditions	pA (light AA) runs, npdf global fits, small-x	in reach
Testing hydrodynamization and thermalization	Combined jet and flow analyses	strategy t.b.d.
Understanding "heavy-ion like behavior" in small systems (pp, pA)	Flow, hadrochemistry, jets	recent surprises

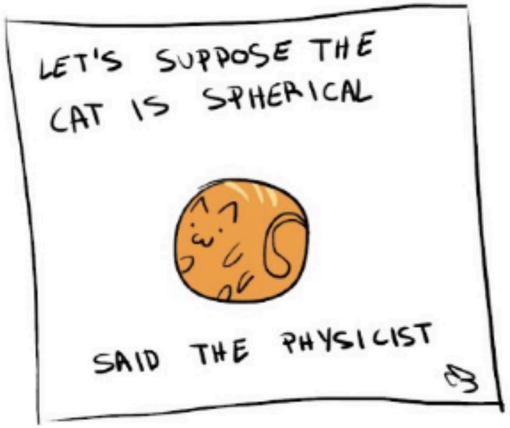
Slide stolen from Urs Wiedemann, Workshop on the physics of HL-LHC

(semi)-ANALYTIC

- Gives insight into what physics is relevant where (energy loss, decoherence, etc.)
- Can inspire what to measure
- Cannot capture all dimensions of full experimental analysis

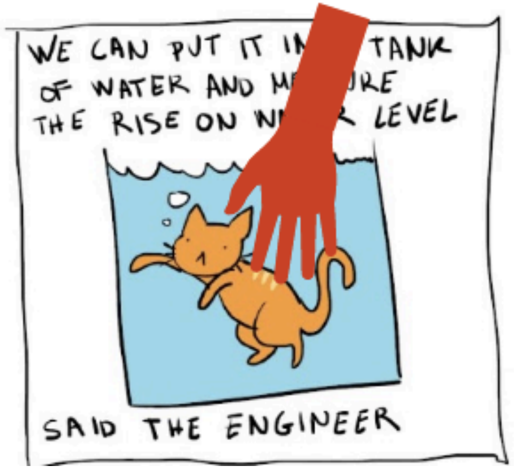
Monte Carlo Event Generator

- Gives ultimate realism (accuracy depends on what's inside)
- Can in principle include full medium embedding & subtraction (but that's often work in progress)
- Risks looking like a black box

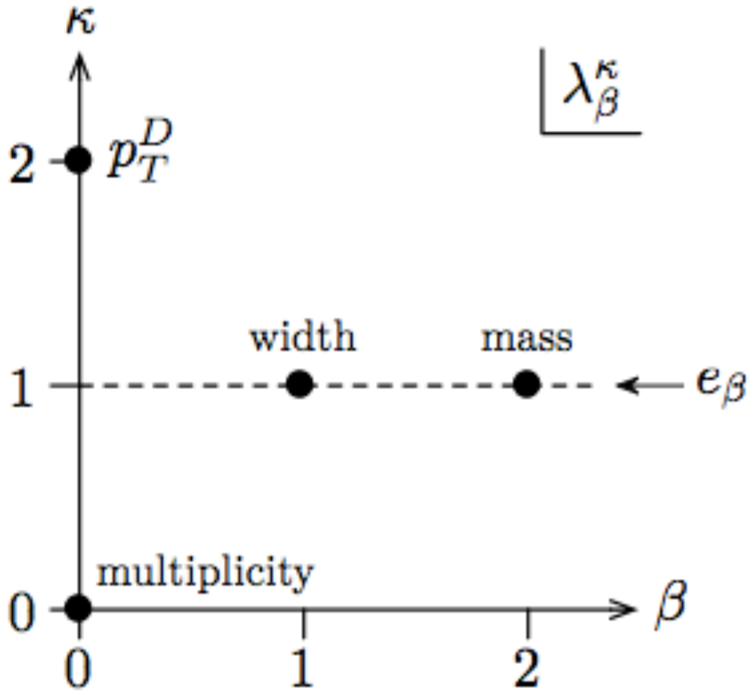


HOW TO CALCULATE THE VOLUME OF A CAT ?

[this morning's newsletter]



Jet shapes: generalized angularities



$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{R_i}{R_0}\right)^\beta$$

Diagram from Thaler et al

Exploring systematically the phase space of jet shapes

Plethora of techniques