JETS FOR THE LHC AND BEYOND

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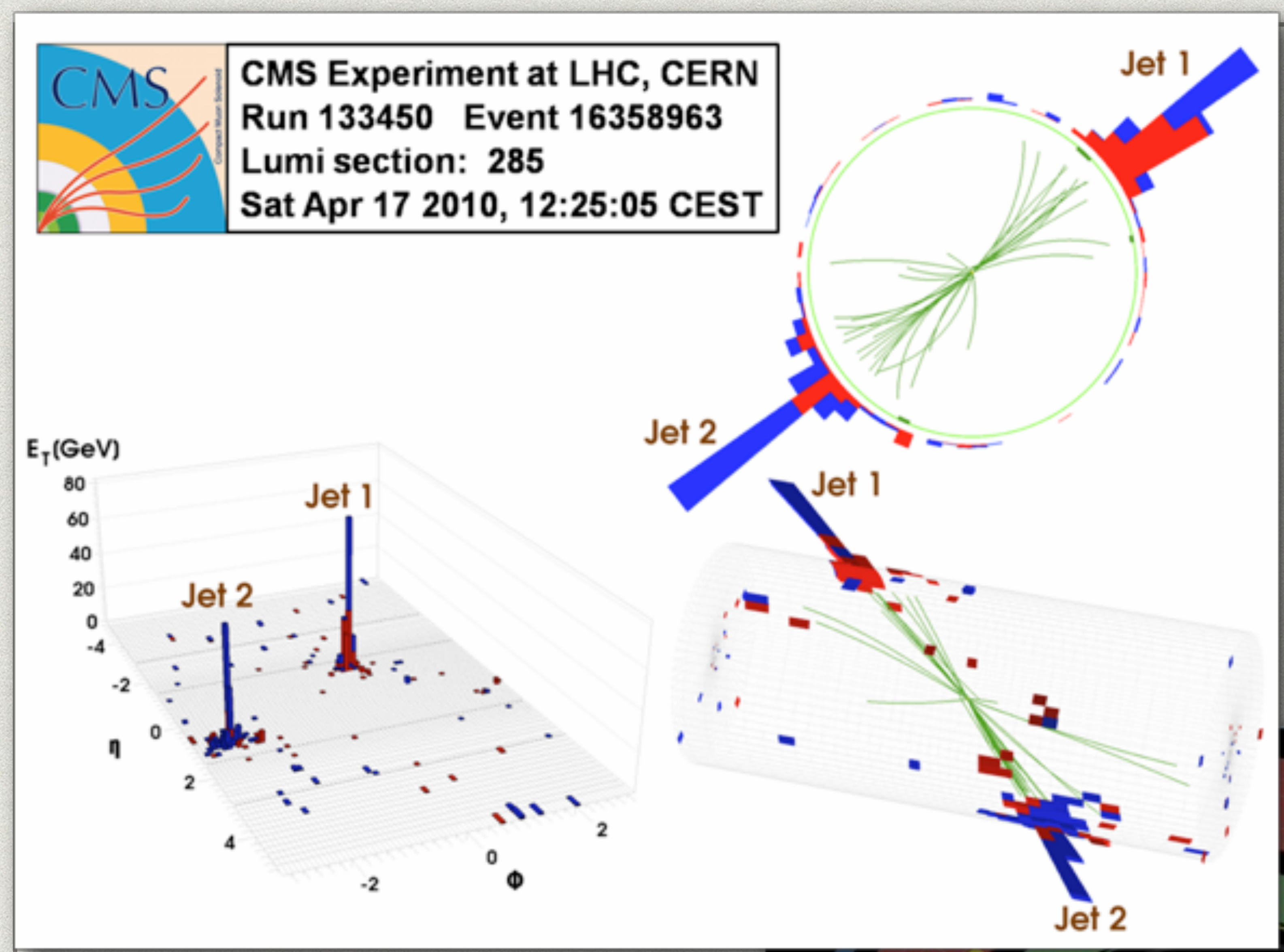
Outline

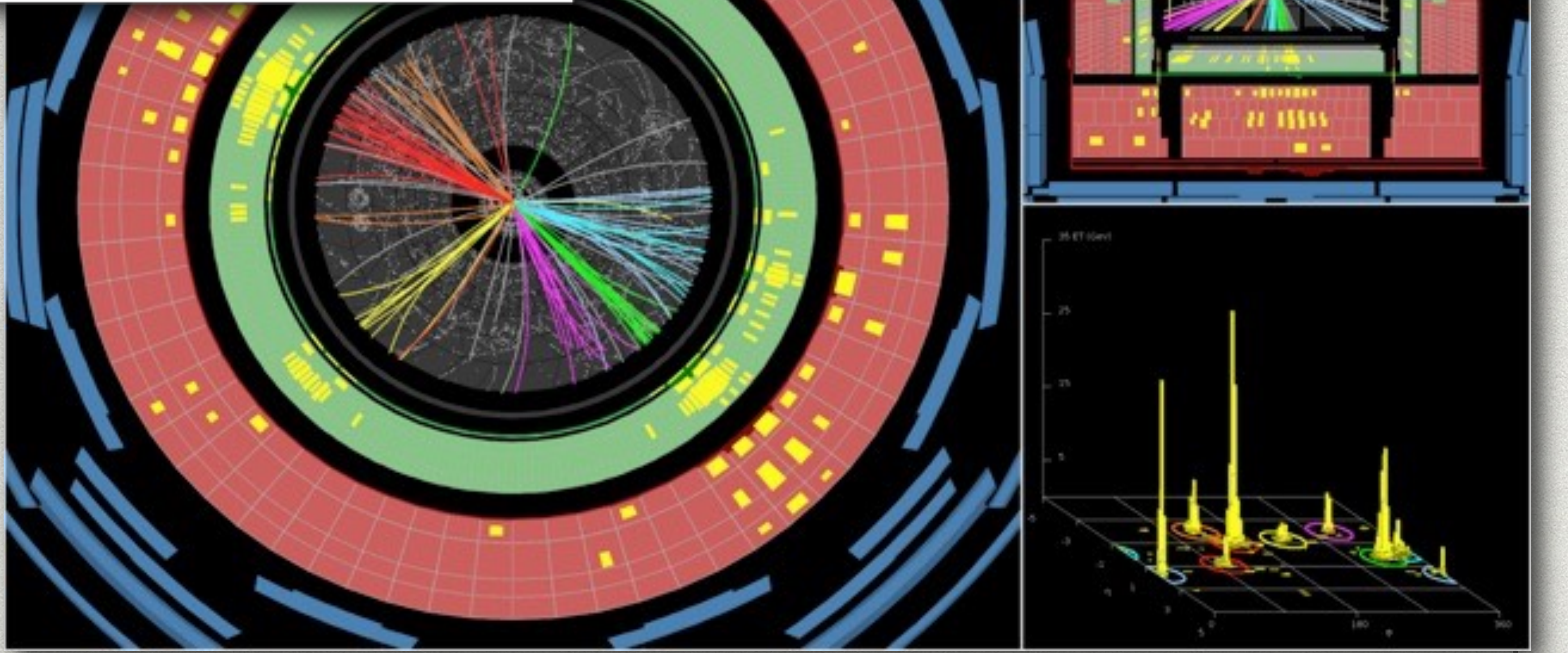
1. Introduction to jet physics
2. Jet substructure to look for boosted-objects
   a) example of a groomer: soft drop
   b) example of a tagger: N-subjettiness
3. Measuring jet substructure
   a) soft drop observables
   b) extraction of fundamental parameters
4. Final remarks

Introduction to jet physics



JETS

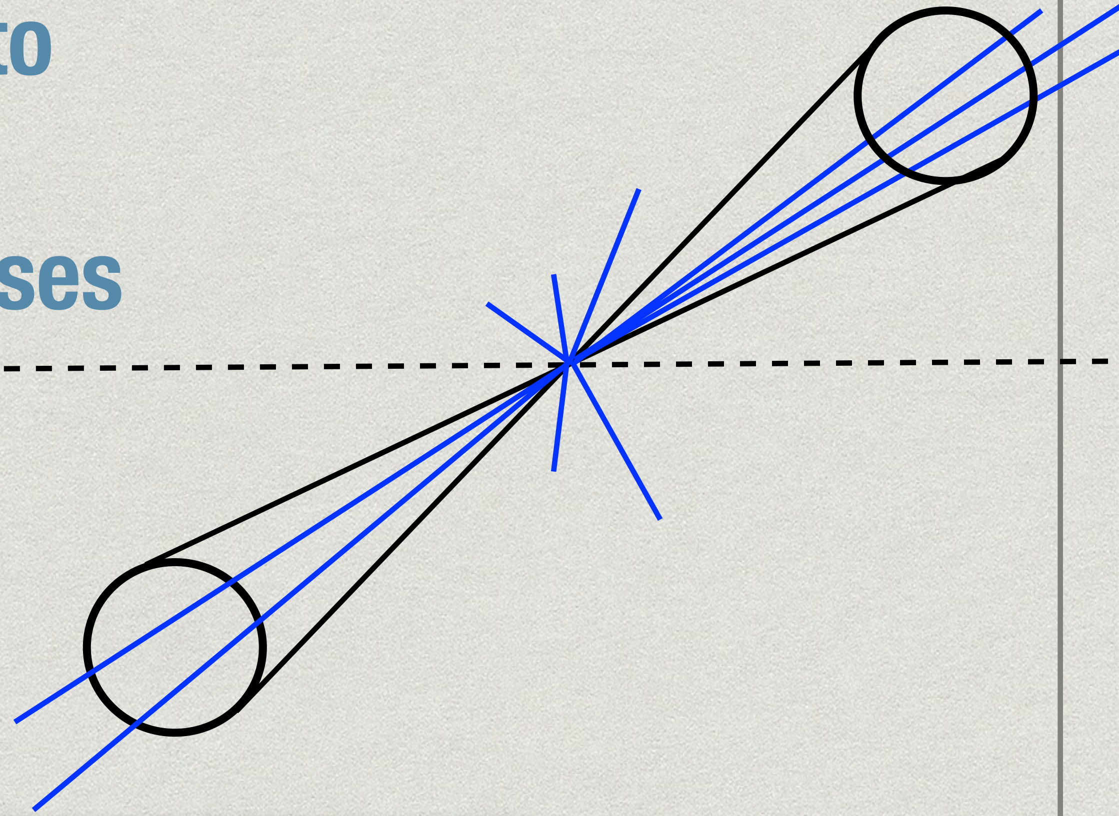
Collimated, energetic sprays of particles

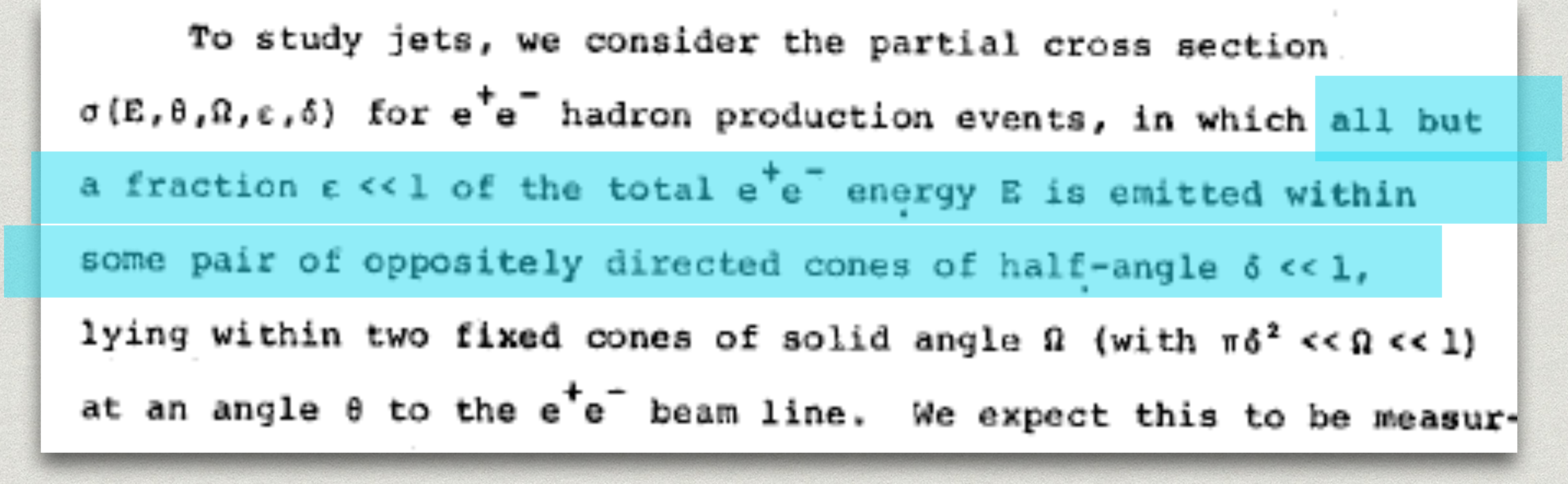


ubiquitous @LHC: more than 70% of ATLAS & CMS papers use jets in their analyses!

Jet definitions

- jet algorithms: sets of (simple) rules to cluster particles together
- implementable in experimental analyses and in theoretical calculations
- must yield to finite cross sections
- first example:





To study jets, we consider the partial cross section $\sigma(E,\theta,\Omega,\epsilon,\delta)$ for e^+e^- hadron production events, in which all but a fraction $\epsilon \ll 1$ of the total e^+e^- energy E is emitted within some pair of oppositely directed cones of half-angle $\delta \ll 1$, lying within two fixed cones of solid angle Ω (with $\pi\delta^2 \ll \Omega \ll 1$) at an angle θ to the e^+e^- beam line. We expect this to be measur-

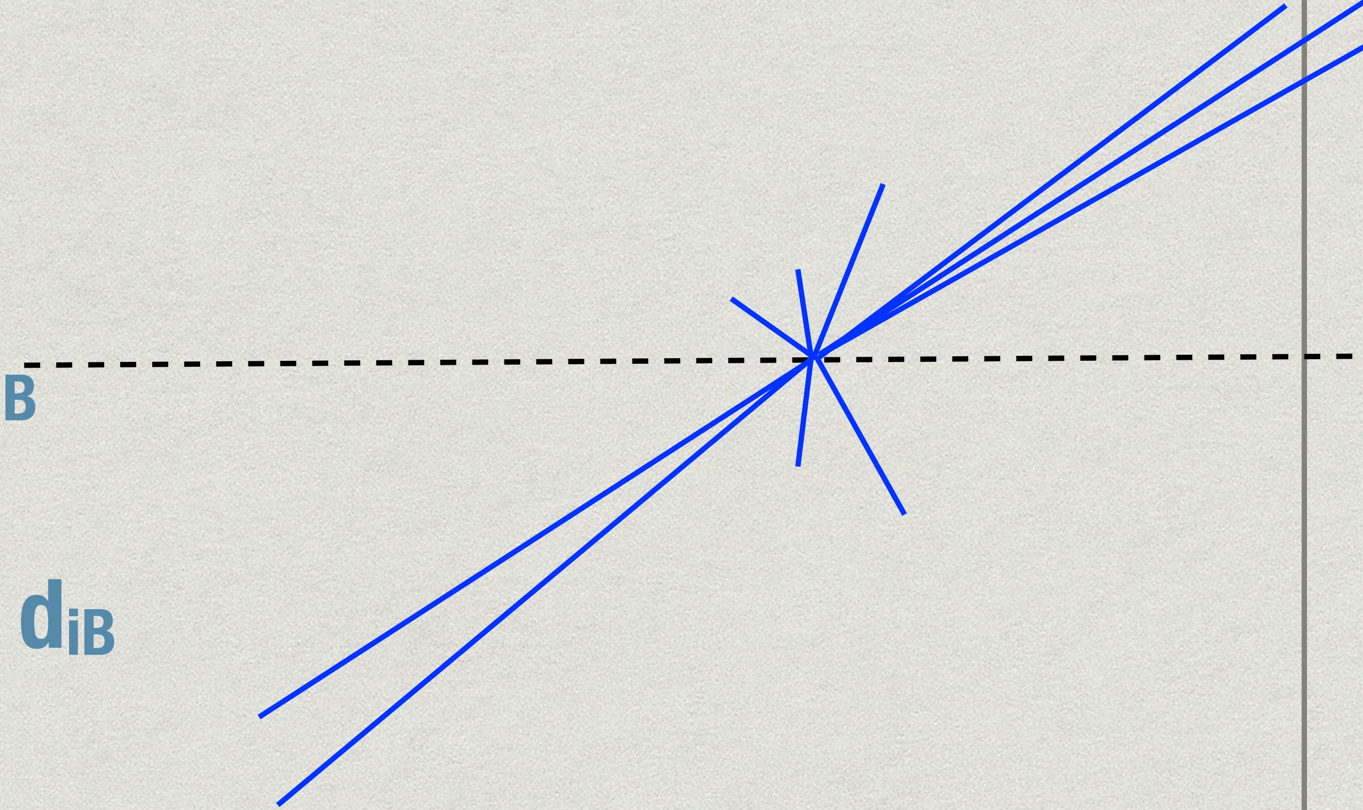
Sterman and Weinberg,
Phys. Rev. Lett. 39, 1436 (1977):

5

Sequential recombination

- Start with a list of particles, compute all distances d_{ij} and d_{iB}

- Find the minimum of all d_{ij} and d_{iB}

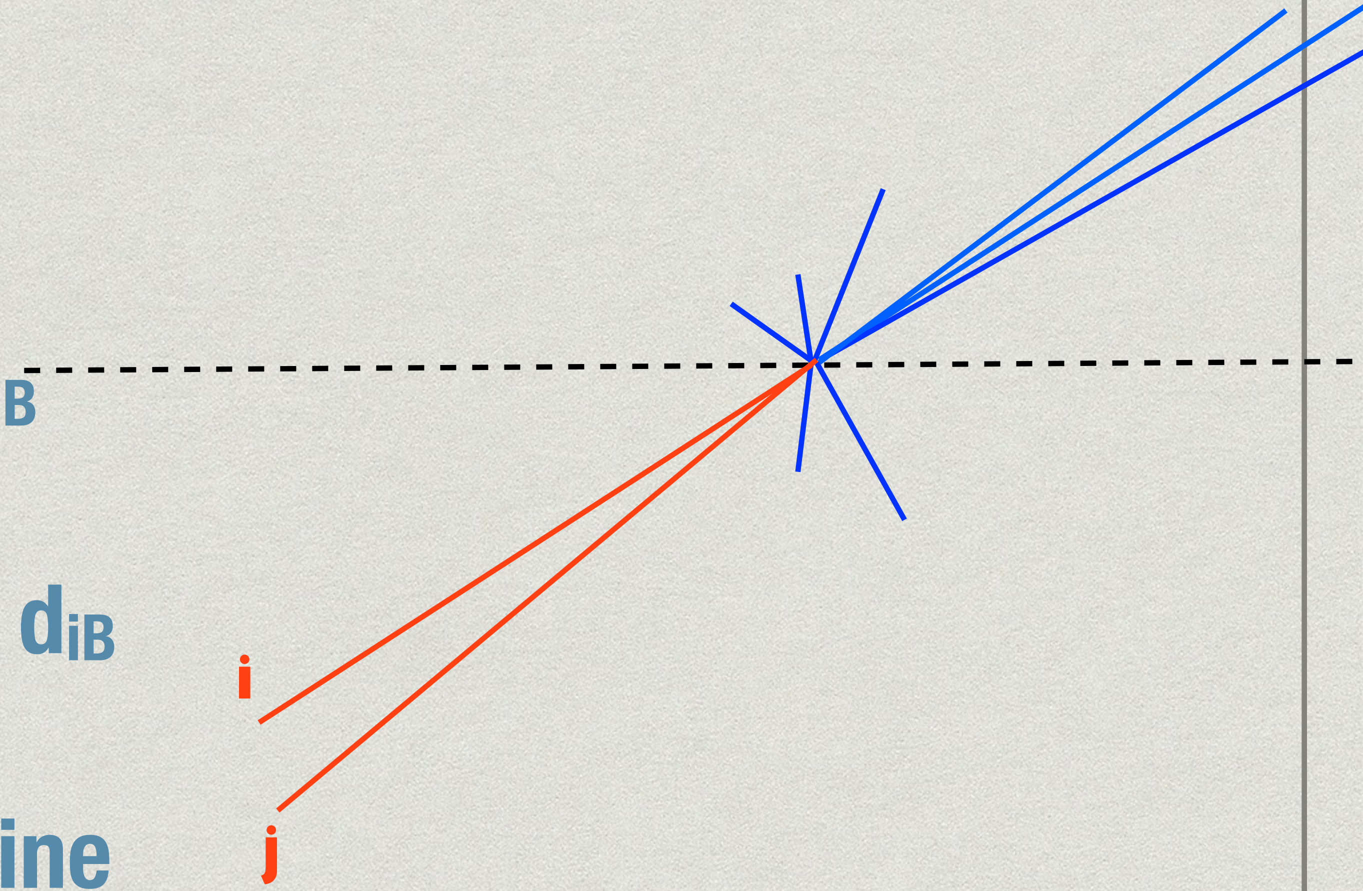


d_{ij} (weighted) distance between i j
d_{iB} external parameter or distance from the beam ...

for a complete review see G. Salam, Towards jetography (2009)

Sequential recombination

- Start with a list of particles, compute all distances d_{ij} and d_{iB}
- Find the minimum of all d_{ij} and d_{iB}
- If the minimum is a d_{ij}, recombine i and j and iterate



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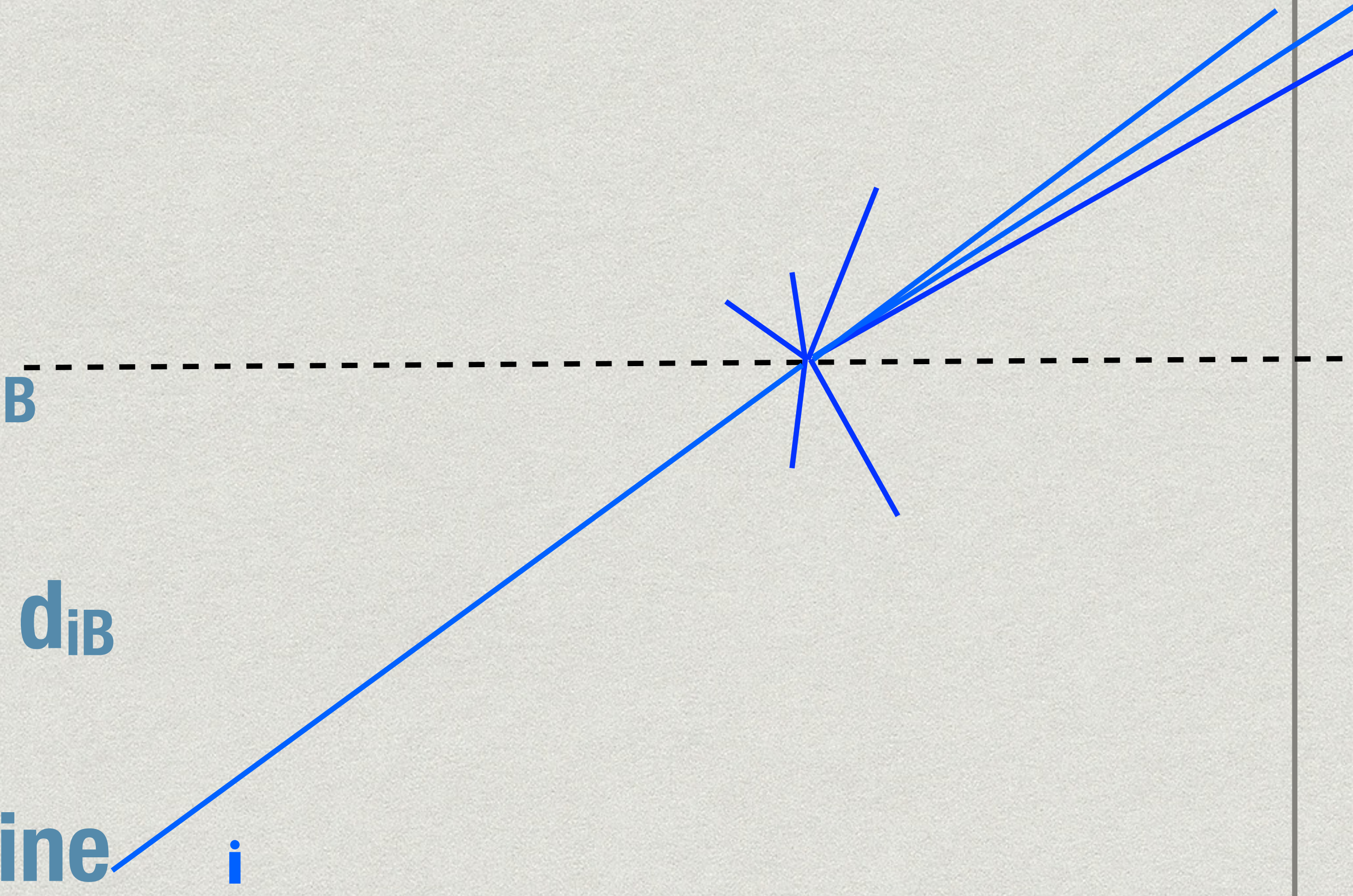

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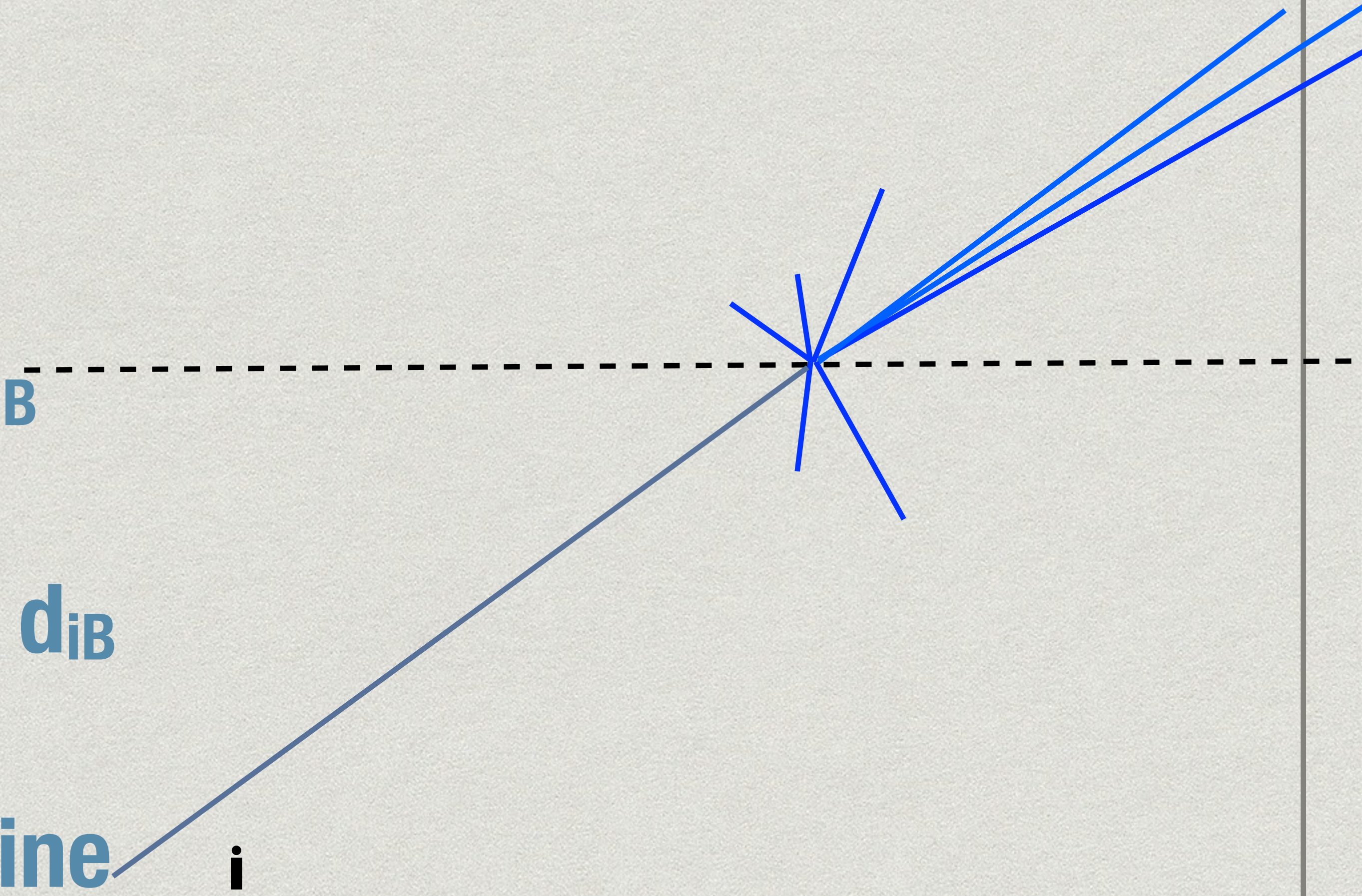
Sequential recombination

- Start with a list of particles, compute all distances d_{ij} and d_{iB}
- Find the minimum of all d_{ij} and d_{iB}
- If the minimum is a d_{ij}, recombine i and j and iterate
- Otherwise call i a final-state jet, remove it from the list and iterate



d_{ij} (weighted) distance between i j
d_{iB} external parameter or distance from the beam ...

Actual choice for the measure d_{ij} determines the jet algorithm

The generalised $\mathrm{k_t}$ family

- **Actual choice for the measure d_{ij} determines the jet algorithm**

$$d_{ij} = \min\left(p_{ti}^{2p}, p_{tj}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{ti}^{2p}$$

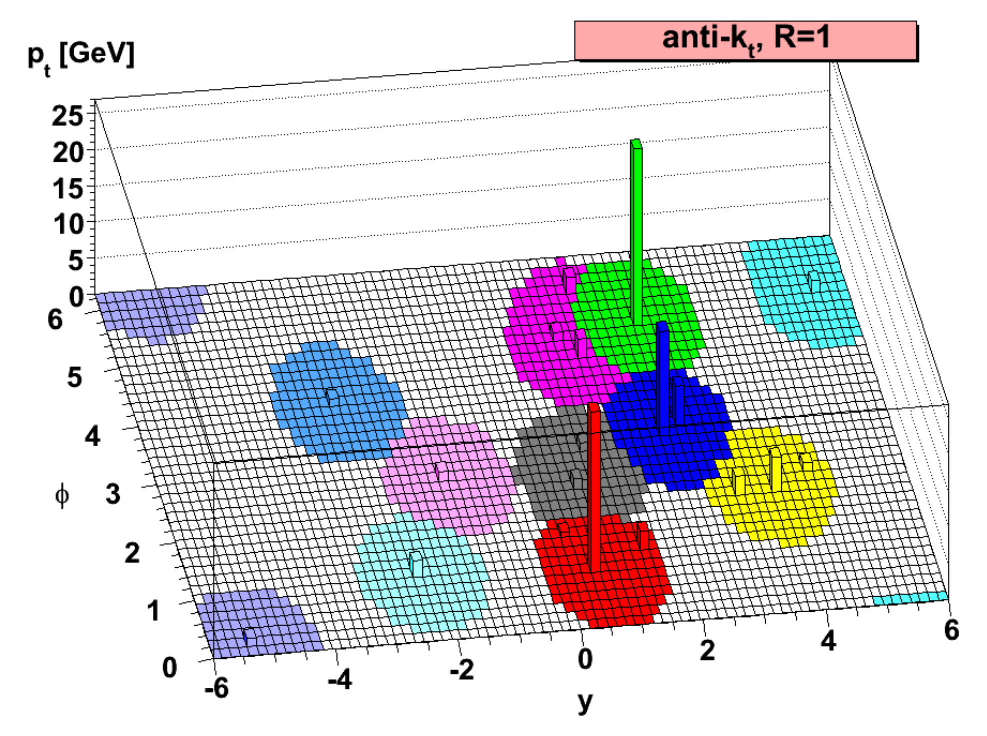
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

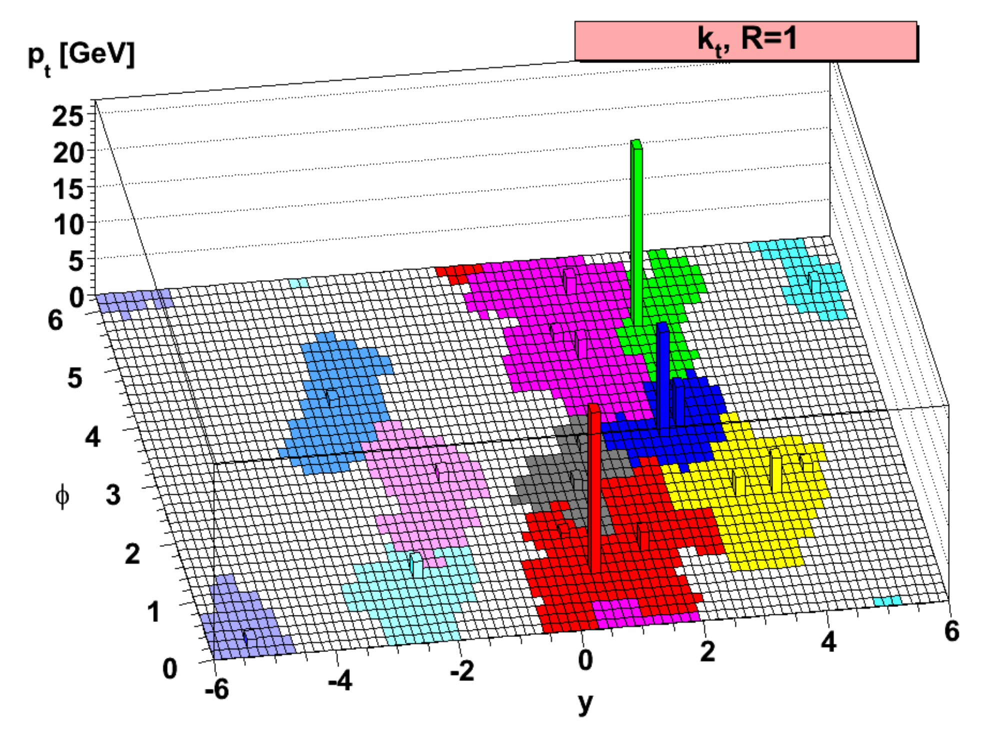
p = 1 $\mathrm{k_t}$ algortihm
(Catani *et al.*, Ellis and Soper)
p = 0 Cambridge / Aachen
(Dokshitzer *et al.*, Wobish and Wengler)
p = -1 anti-$\mathrm{k_t}$ algorithm
(Cacciari, Salam, Soyez)

- **Different algorithms serve different purposes**

Comparing clustering algorithms

- Anti-k_t clusters around hard particles giving round jets (default choice for ATLAS and CMS)
- k_t & C/A reflect the structure of QCD matrix elements
- Anti-k_t is less useful for substructure studies: often reclustering is done with C/A



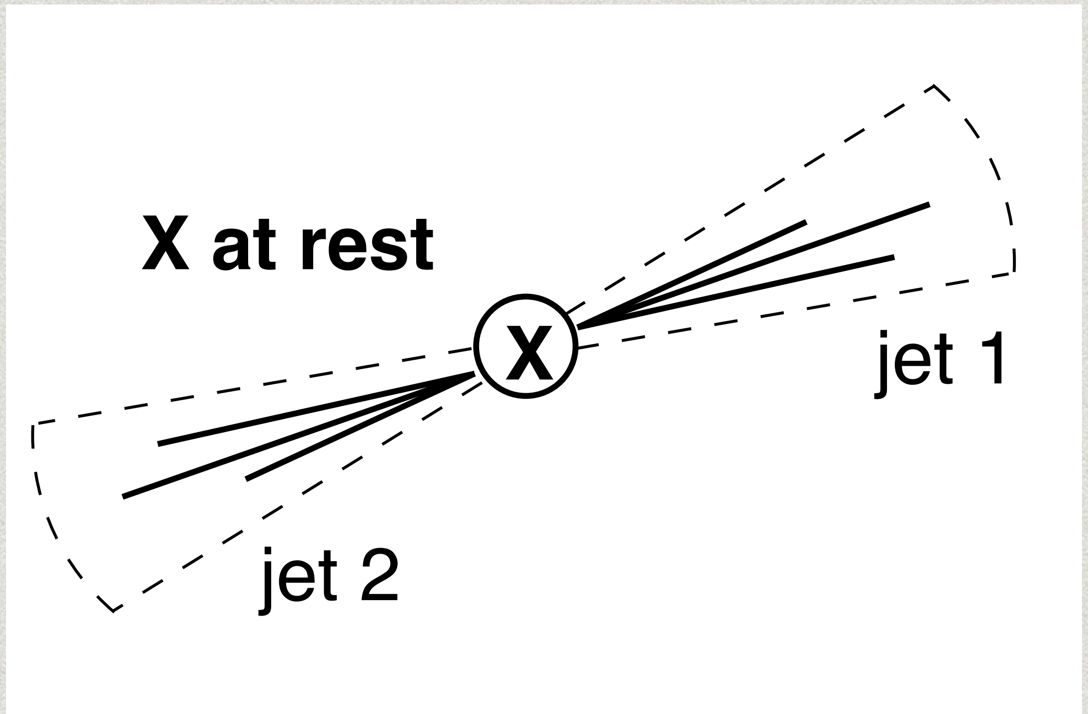


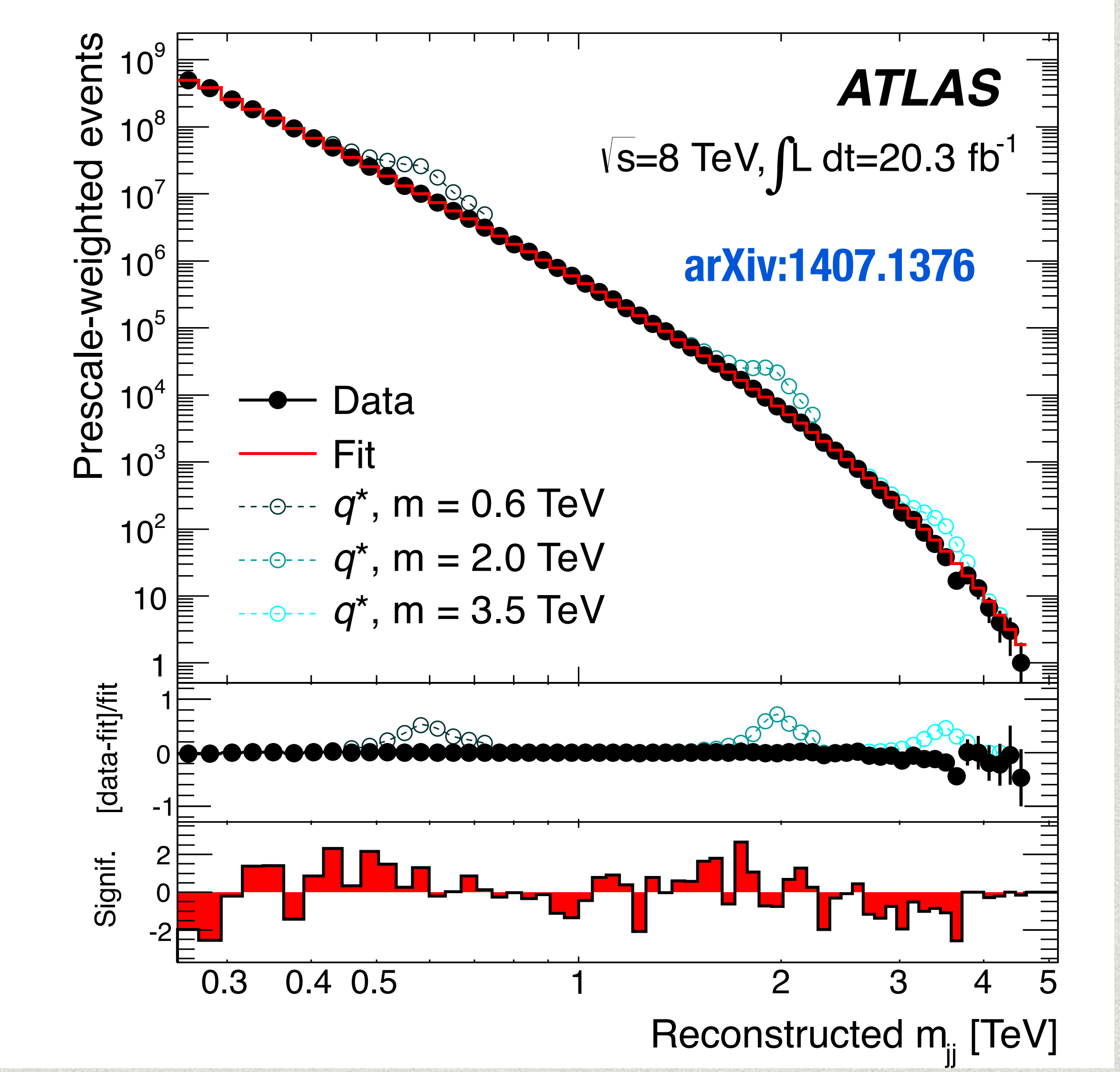
Cacciari, Salam, Soyez (2008)

Jet substructure to look for boosted-objects

Searching for new particles: resolved analyses

- the heavy particle X decays into two partons, reconstructed as two jets



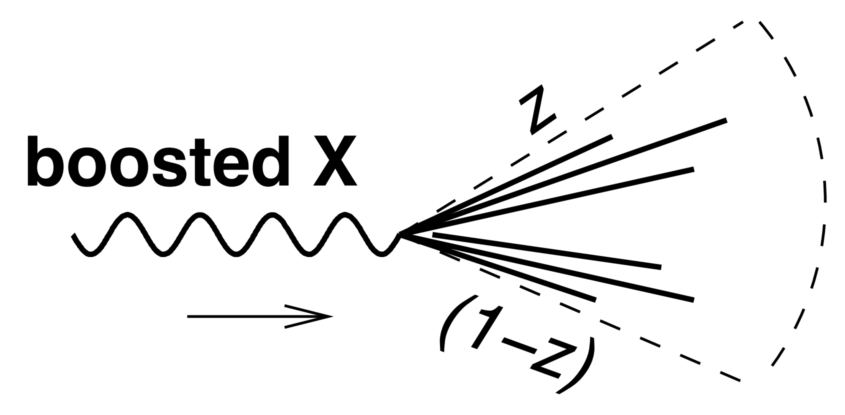


- look for bumps in the dijet invariant mass distribution

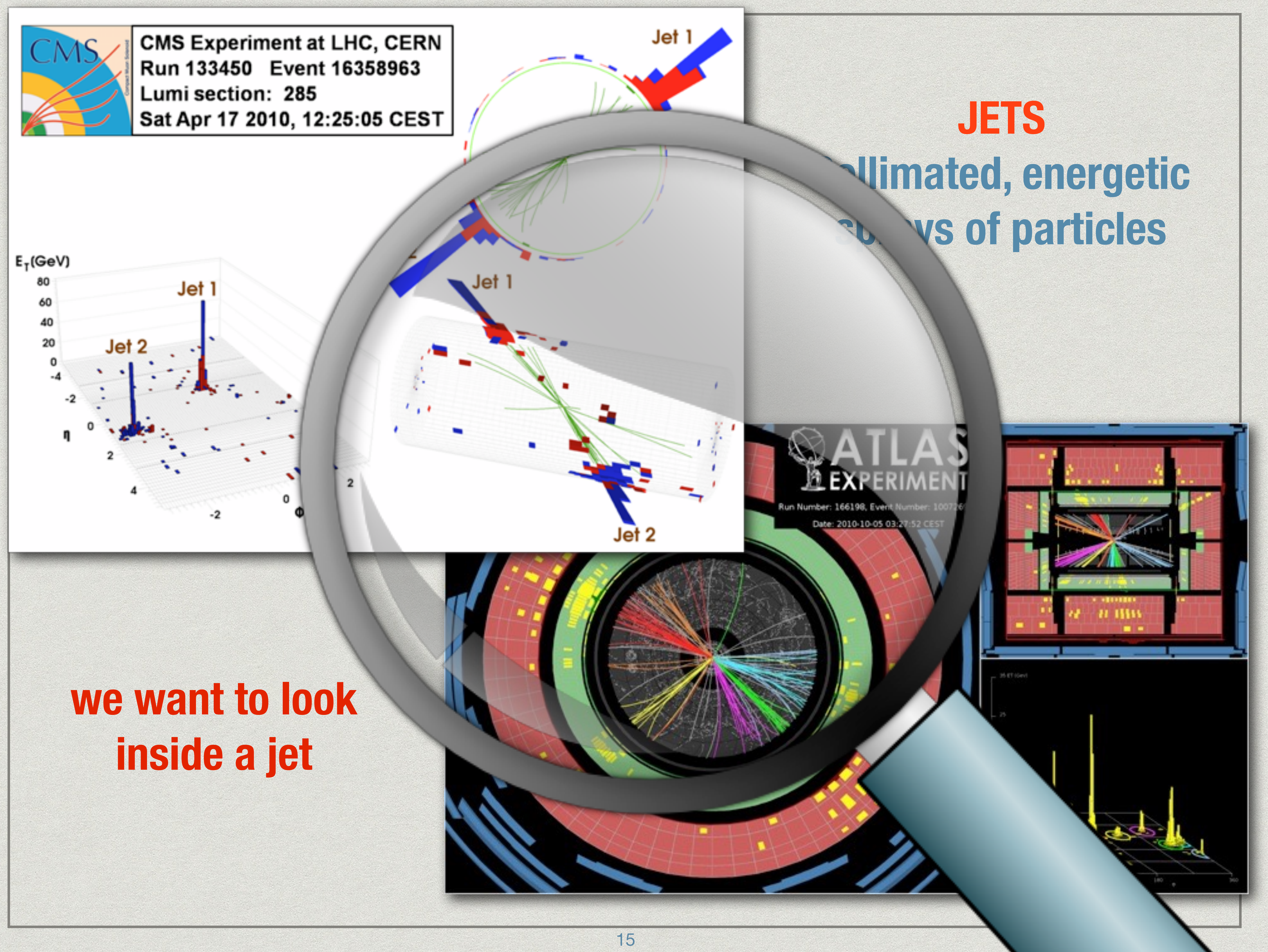
Searching for new particles: boosted analyses

- LHC energy (10^4 GeV) $\gg$ electro-weak scale (10^2 GeV)

- EW-scale particles (new physics, Z/W/H/top) are abundantly produced with a large boost



- their decay-products are then collimated
- if they decay into hadrons, we end up with localized deposition of energy in the hadronic calorimeter: a jet



JETS

collimated, energetic
sprays of particles

we want to look
inside a jet

JETS

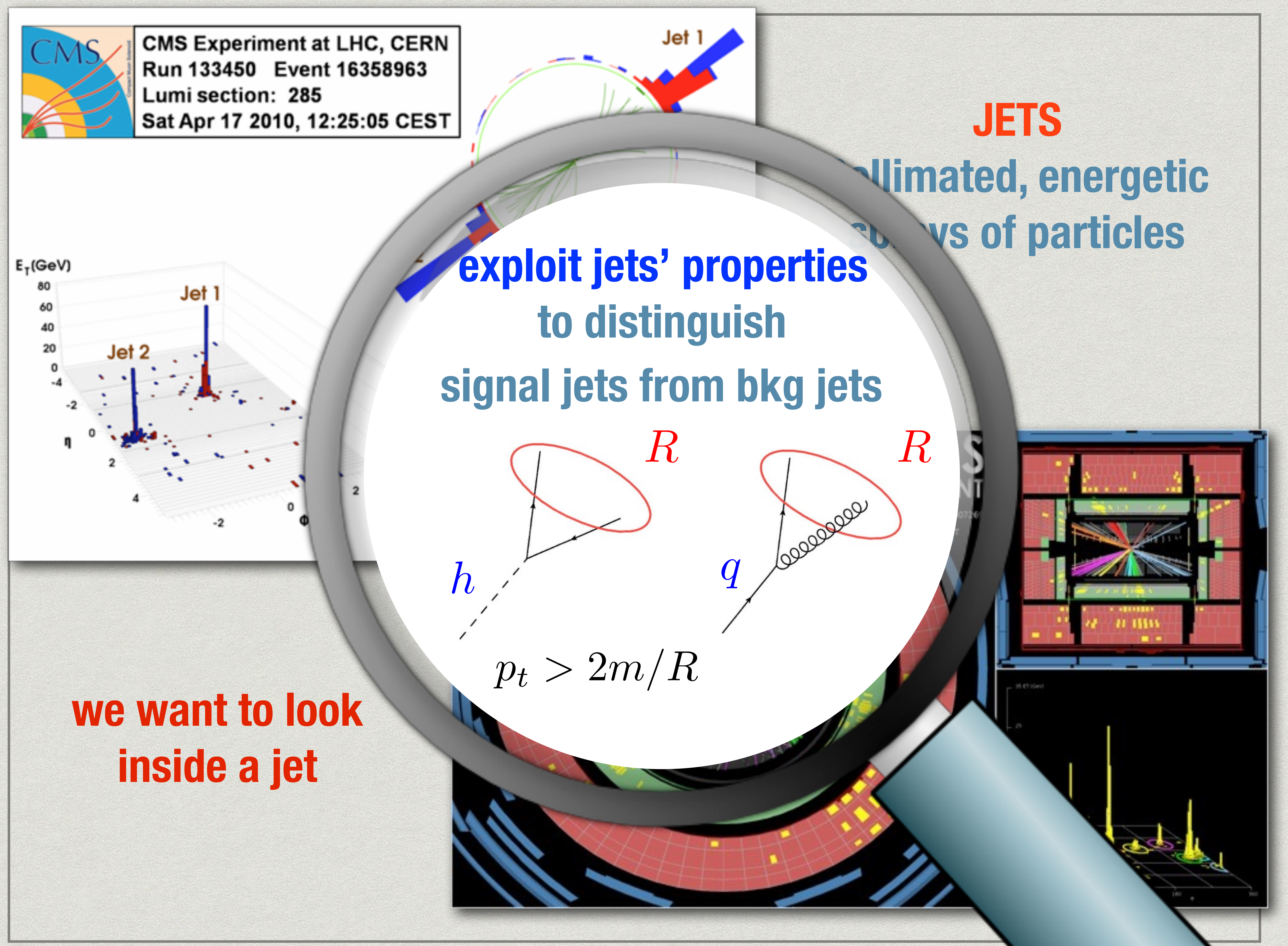
llimated, energetic

ys of particles

exploit jets' properties

to distinguish

signal jets from bkg jets



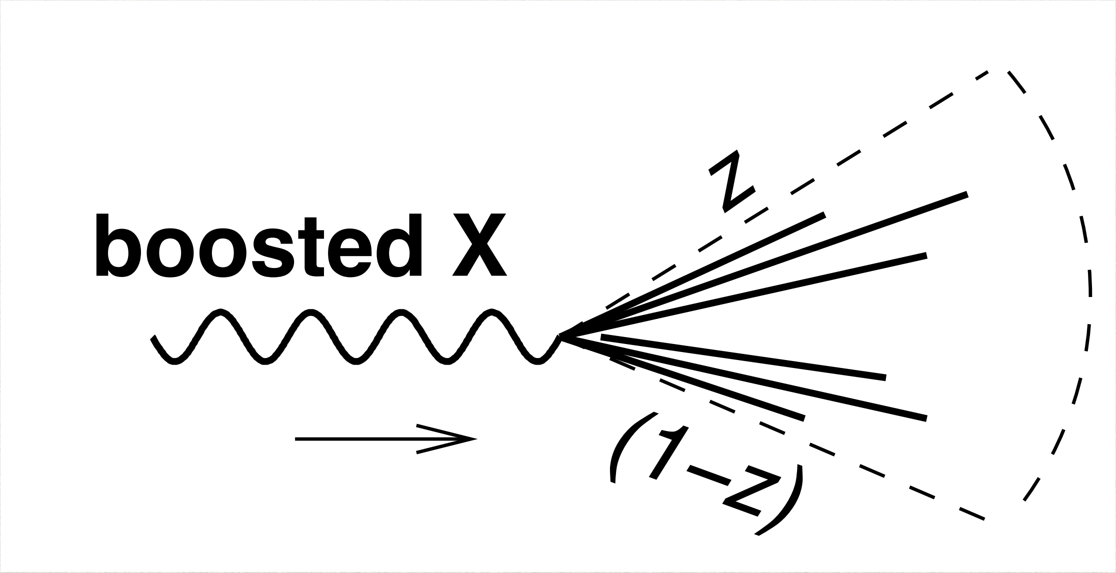
$$p_t > 2m/R$$

we want to look inside a jet

The jet invariant mass

- First jet-observable that comes to mind

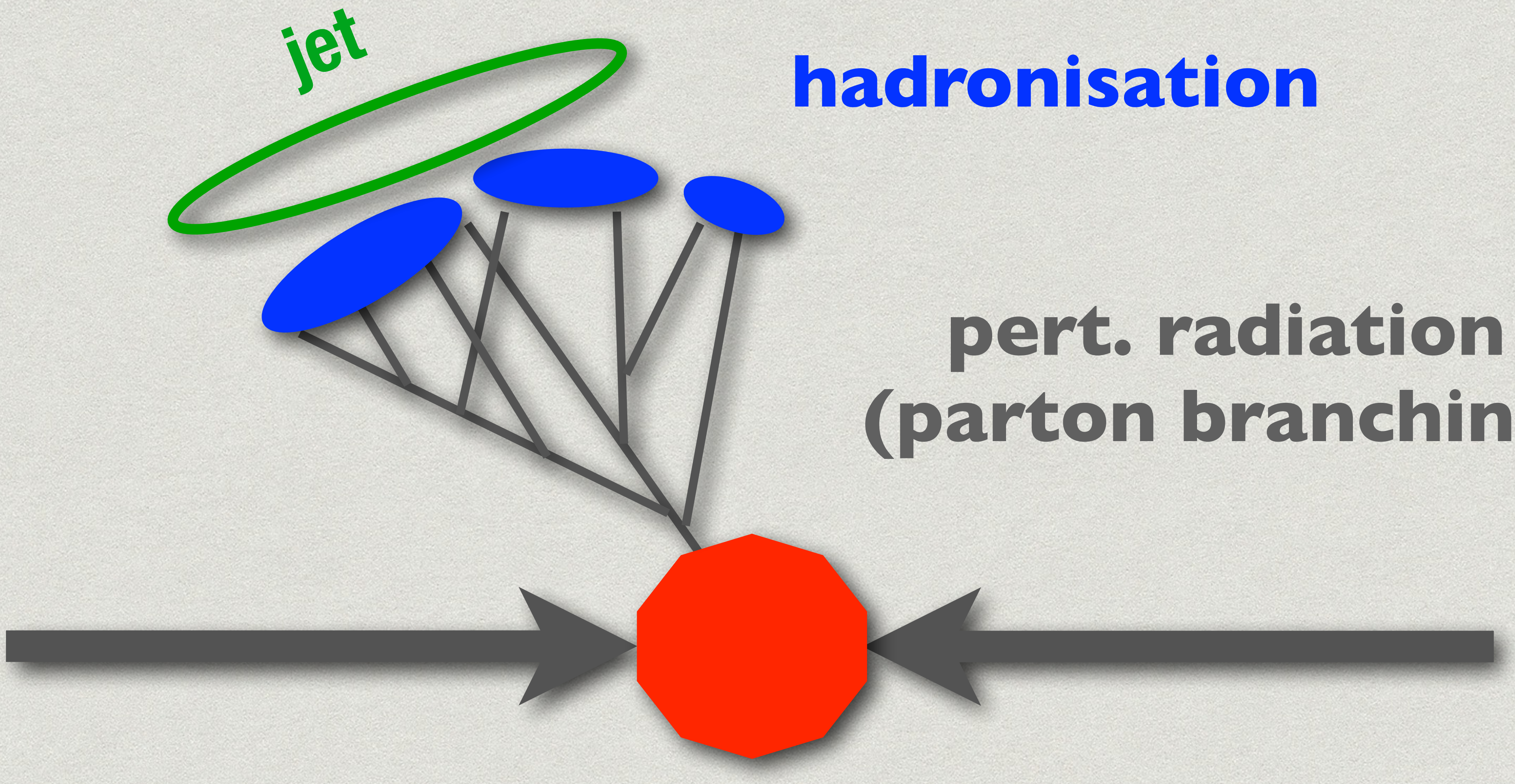
- Signal jet should have a mass distribution peaked near the resonance



- However, that's a simple partonic picture

A useful cartoon

inspired by G. Salam



hadronisation

**pert. radiation
(parton branching)**

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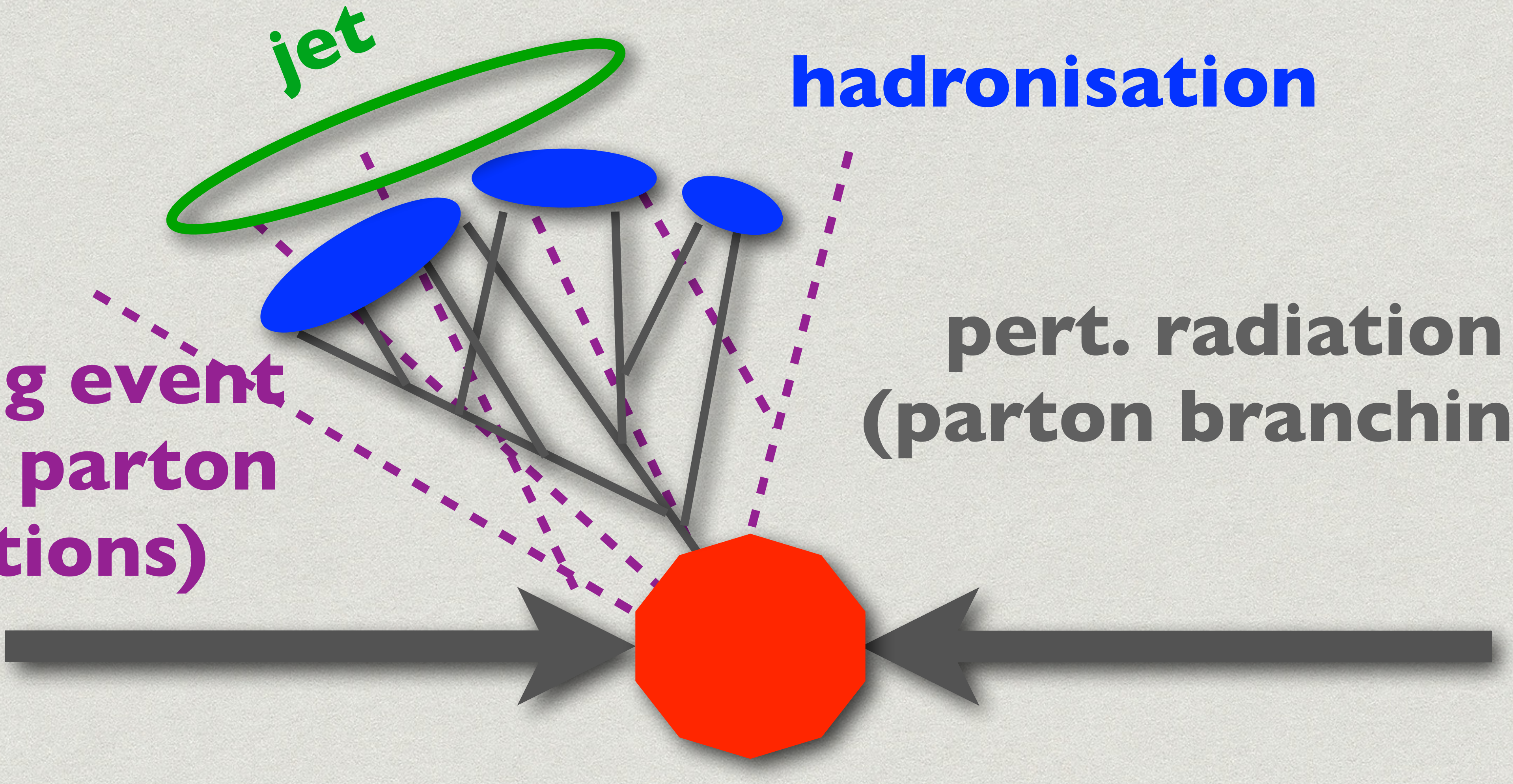

jet

hadronisation

pert. radiation
(parton branching)

underlying event
(multiple parton
interactions)

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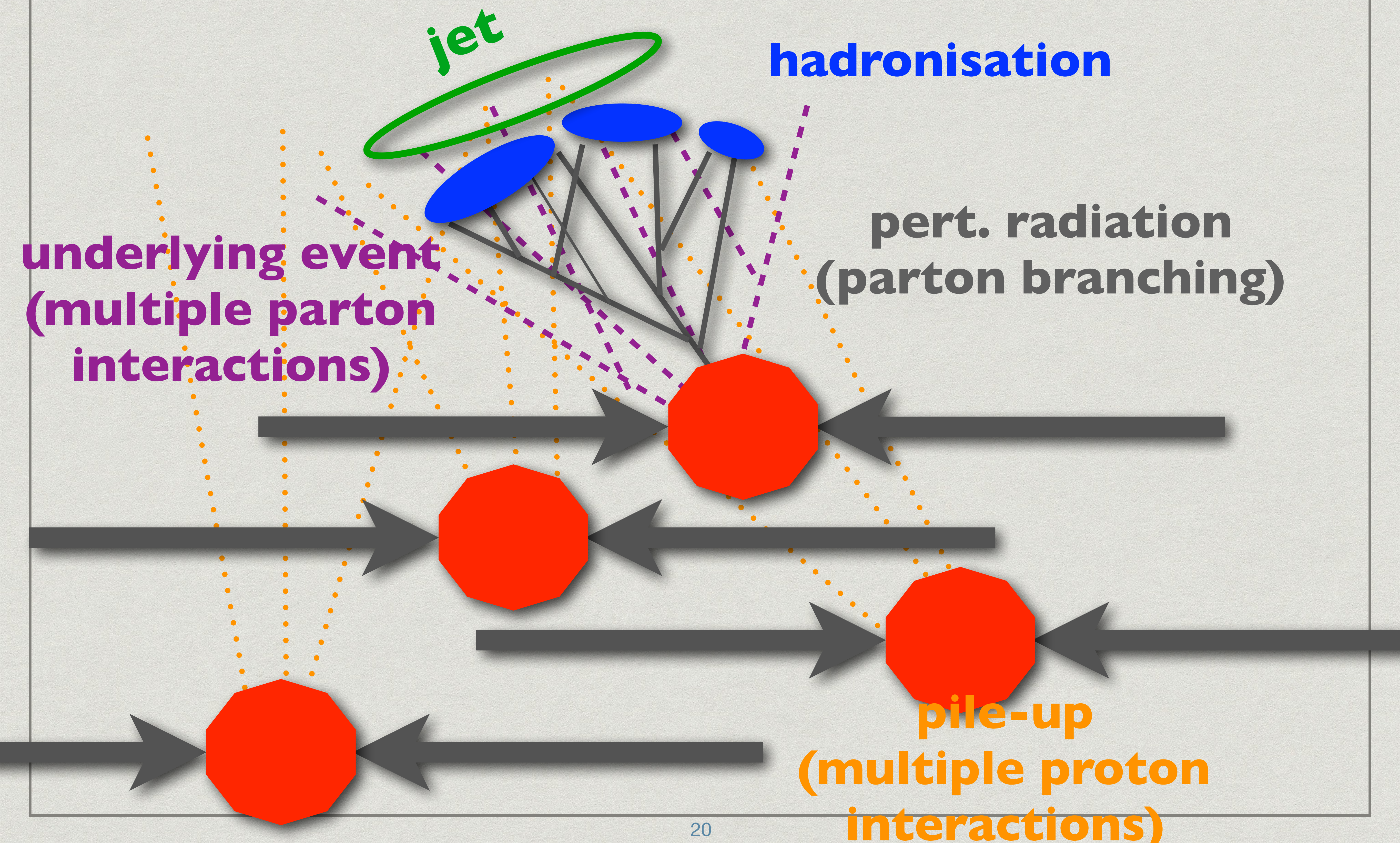


jet

hadronisation

pert. radiation (parton branching)

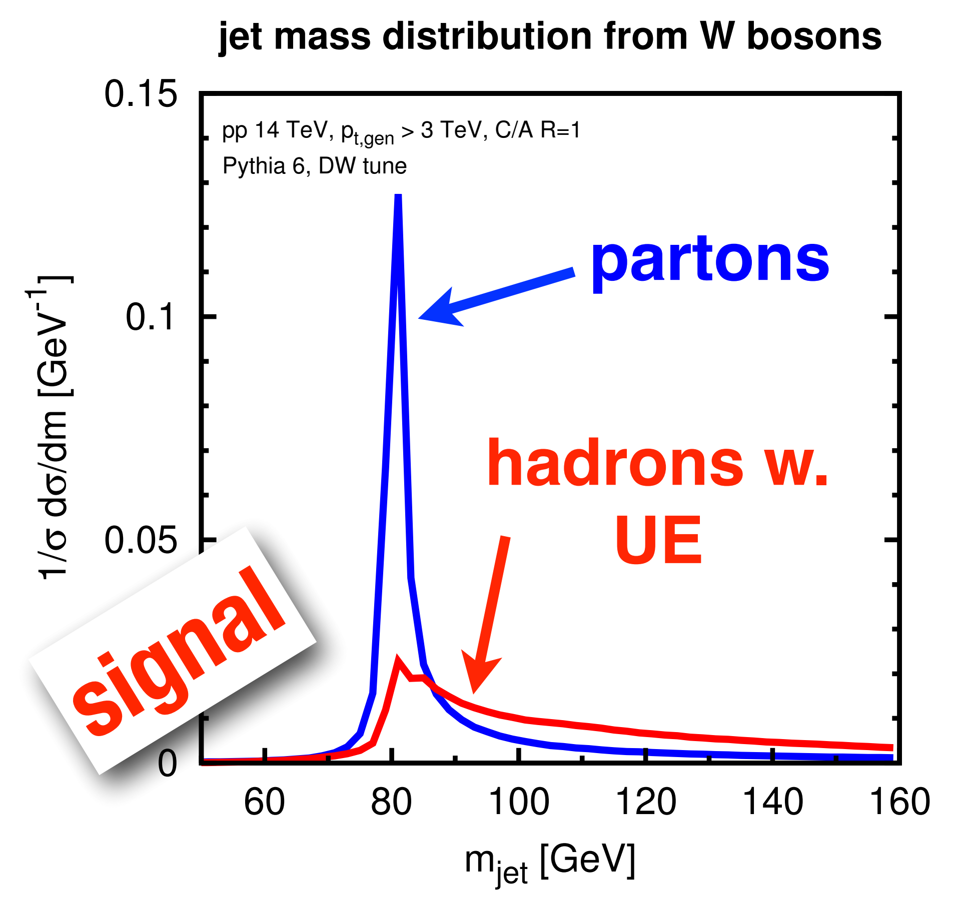
underlying event (multiple parton interactions)

pile-up (multiple proton interactions)

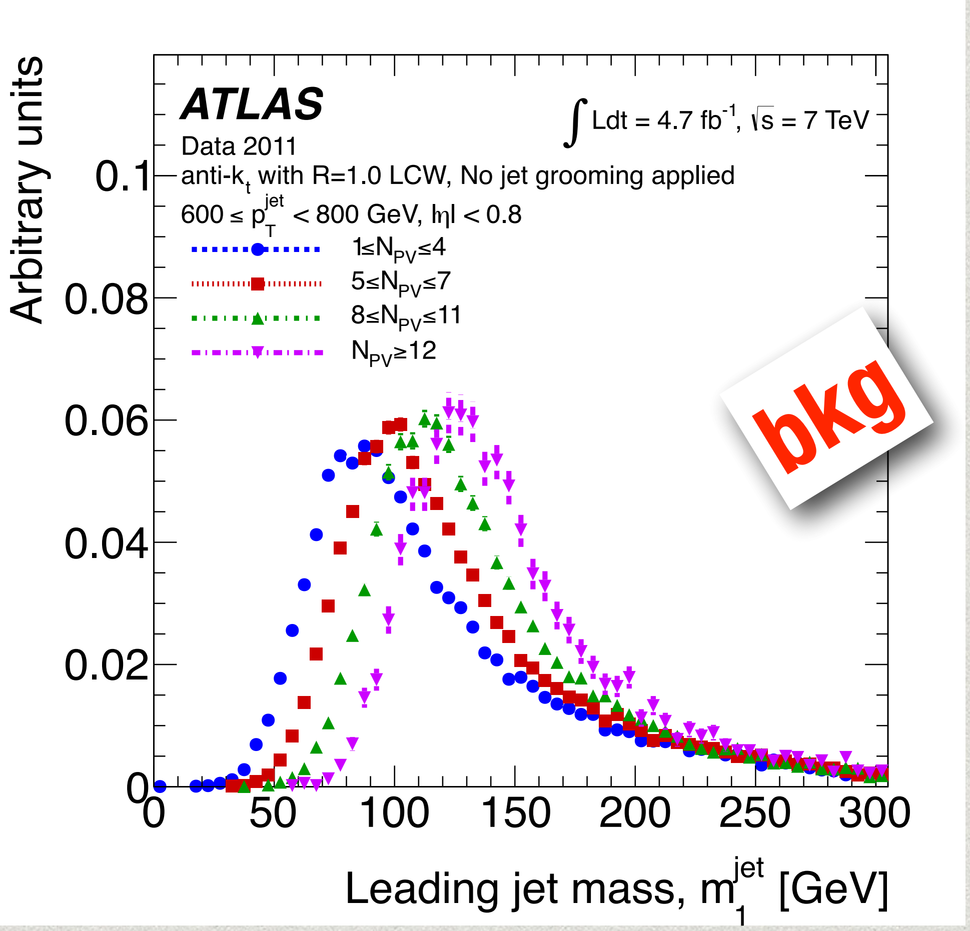
Effect on jet masses

- In reality perturbative and non-pert emissions broadens and shift the signal peak

- Underlying Event and pile-up typically enhance the jet mass (both signal and background)



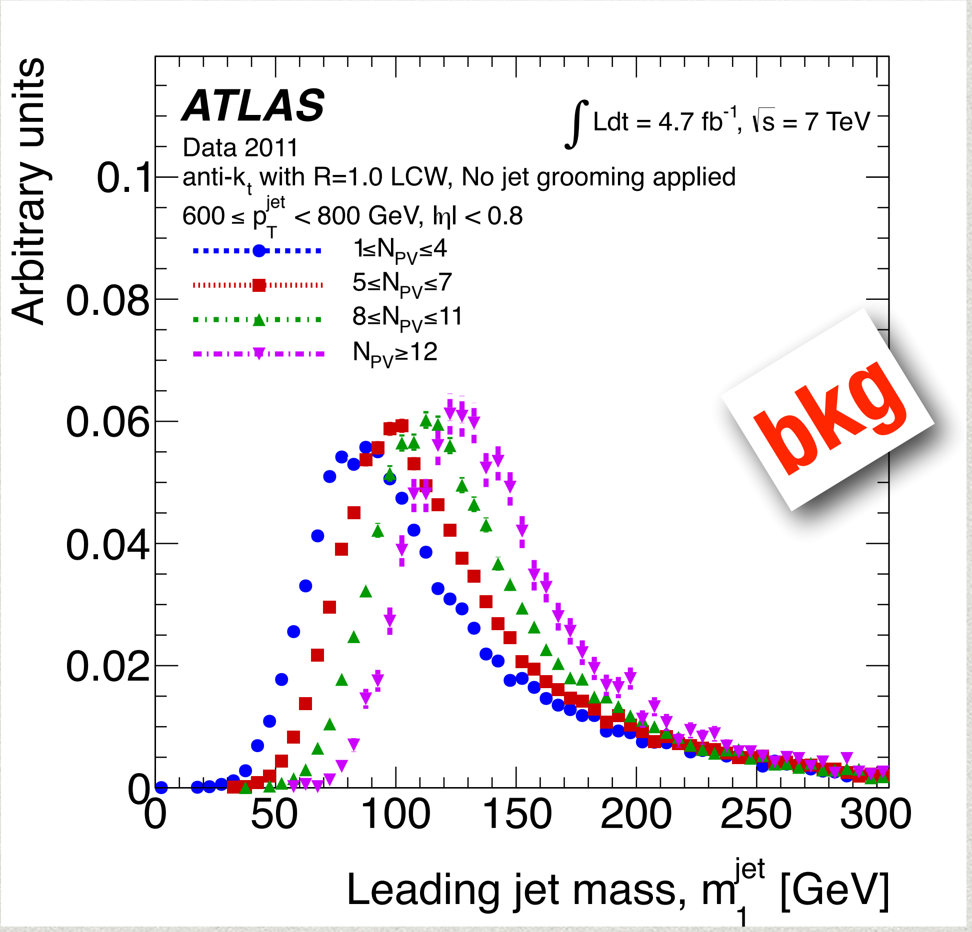
ATLAS, JHEP 1309 (2013) 076



Beyond the mass: substructure

- Let's have a closer look: background peaks in the EW region
- Need to go beyond the mass and exploit jet substructure
- **Grooming** and **Tagging**:

1. clean the jets up by removing soft junk
2. identify the features of hard decays and cut on them



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Beyond the mass: substructure

- Let's have a closer look: background peaks in the EW region
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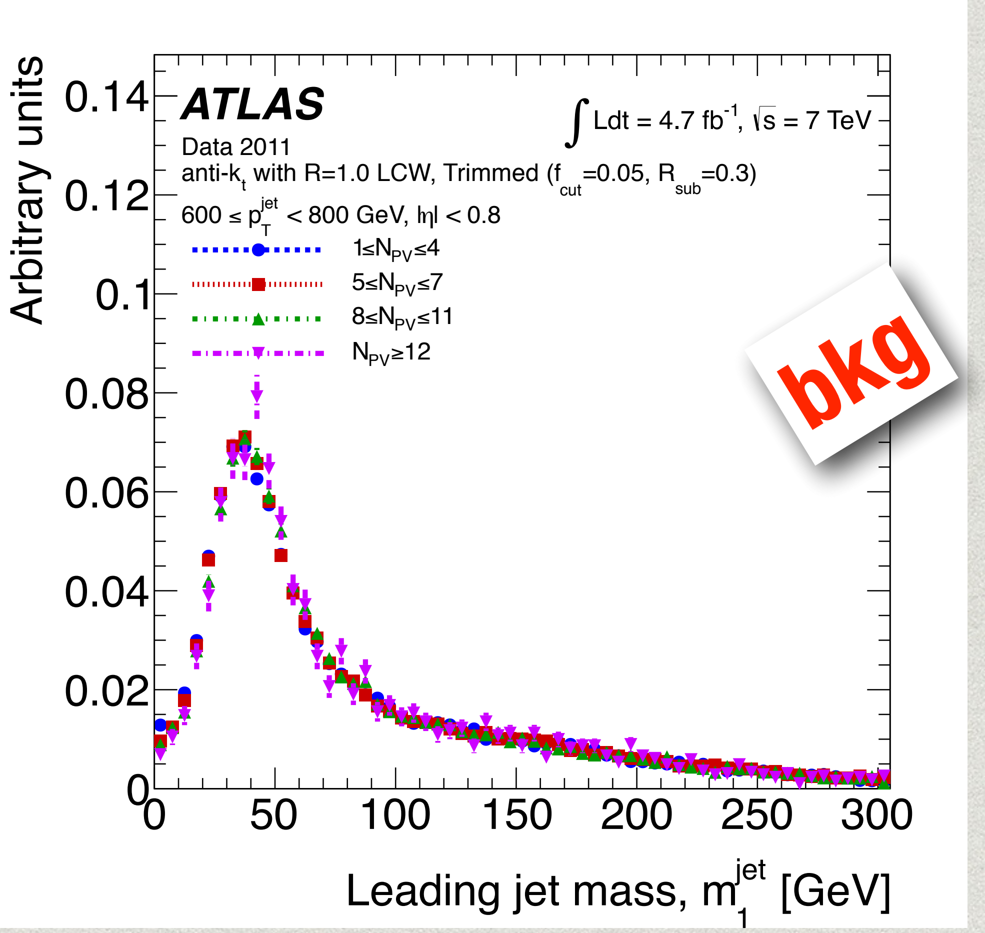
- **Grooming** and **Tagging**:

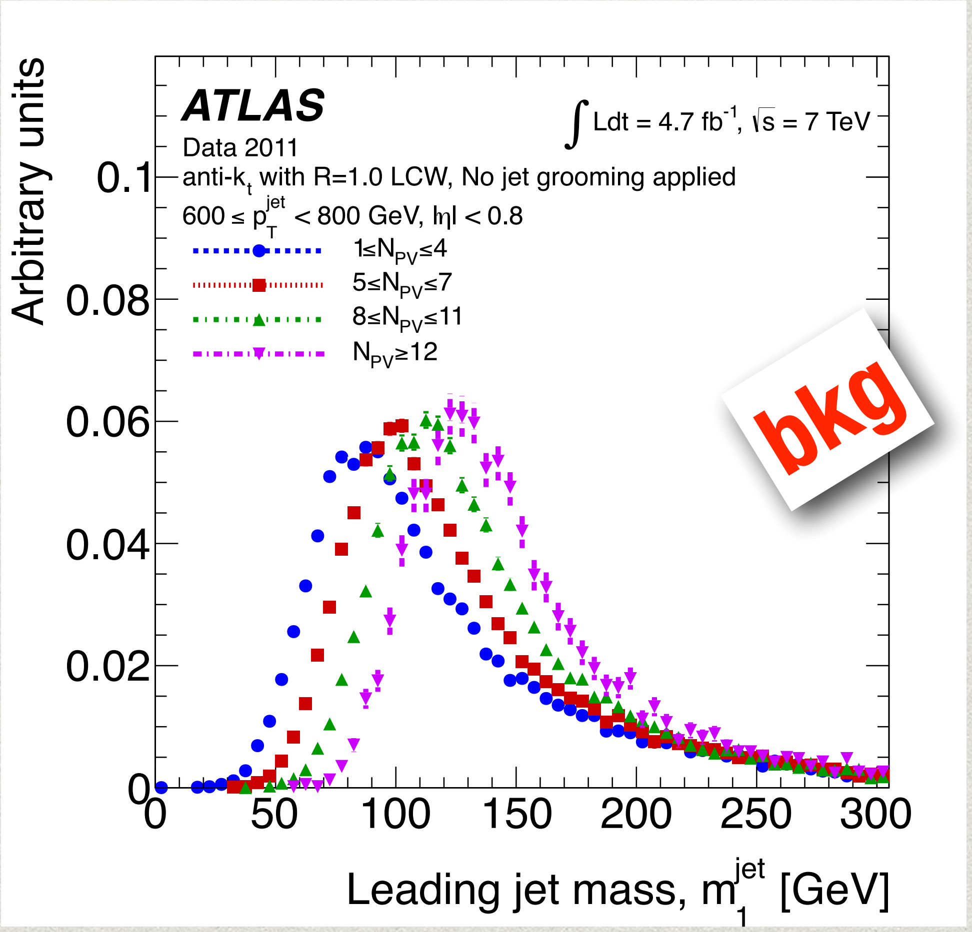
  1. clean the jets up by removing soft junk
  2. identify the features of hard decays and cut on them

- Grooming provides a handle on UE and pile-up



grooming

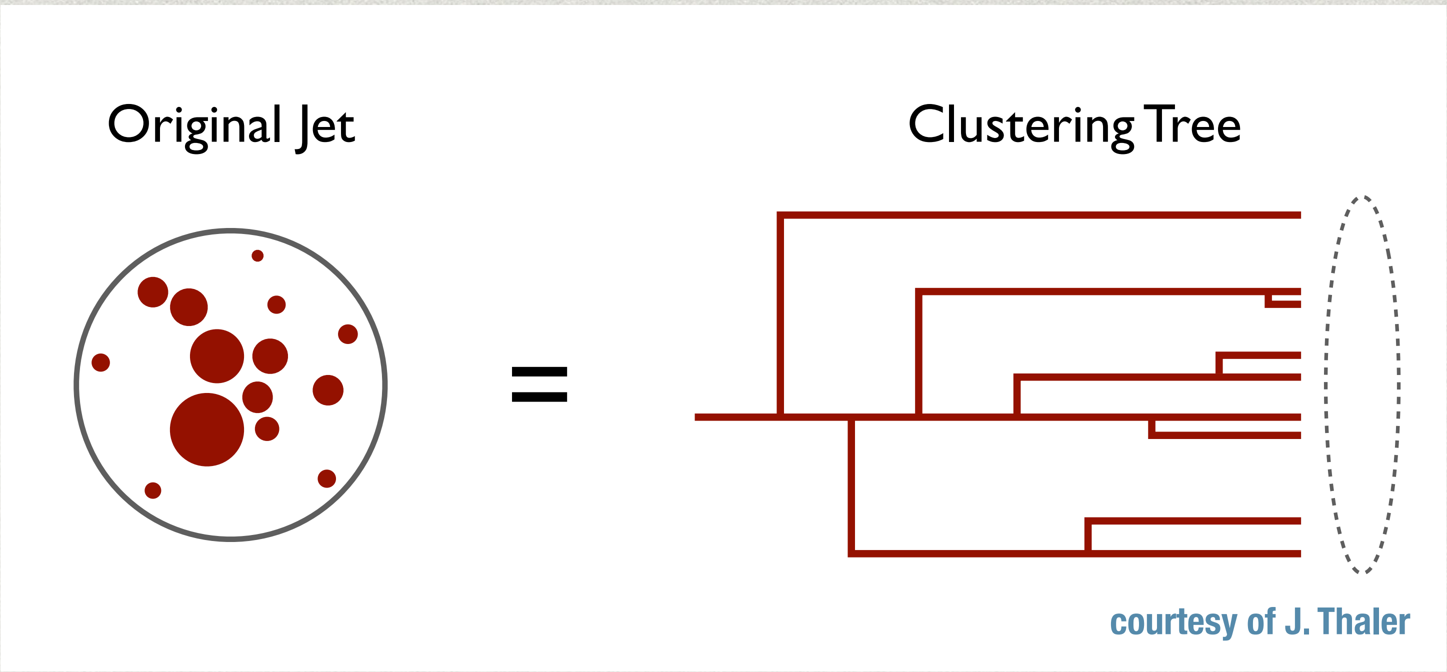
ATLAS, JHEP 1309 (2013) 076



Example of a groomer / prong-finder: Soft Drop

Soft Drop

Larkoski, SM, Soyez and Thaler (2014)



courtesy of J. Thaler

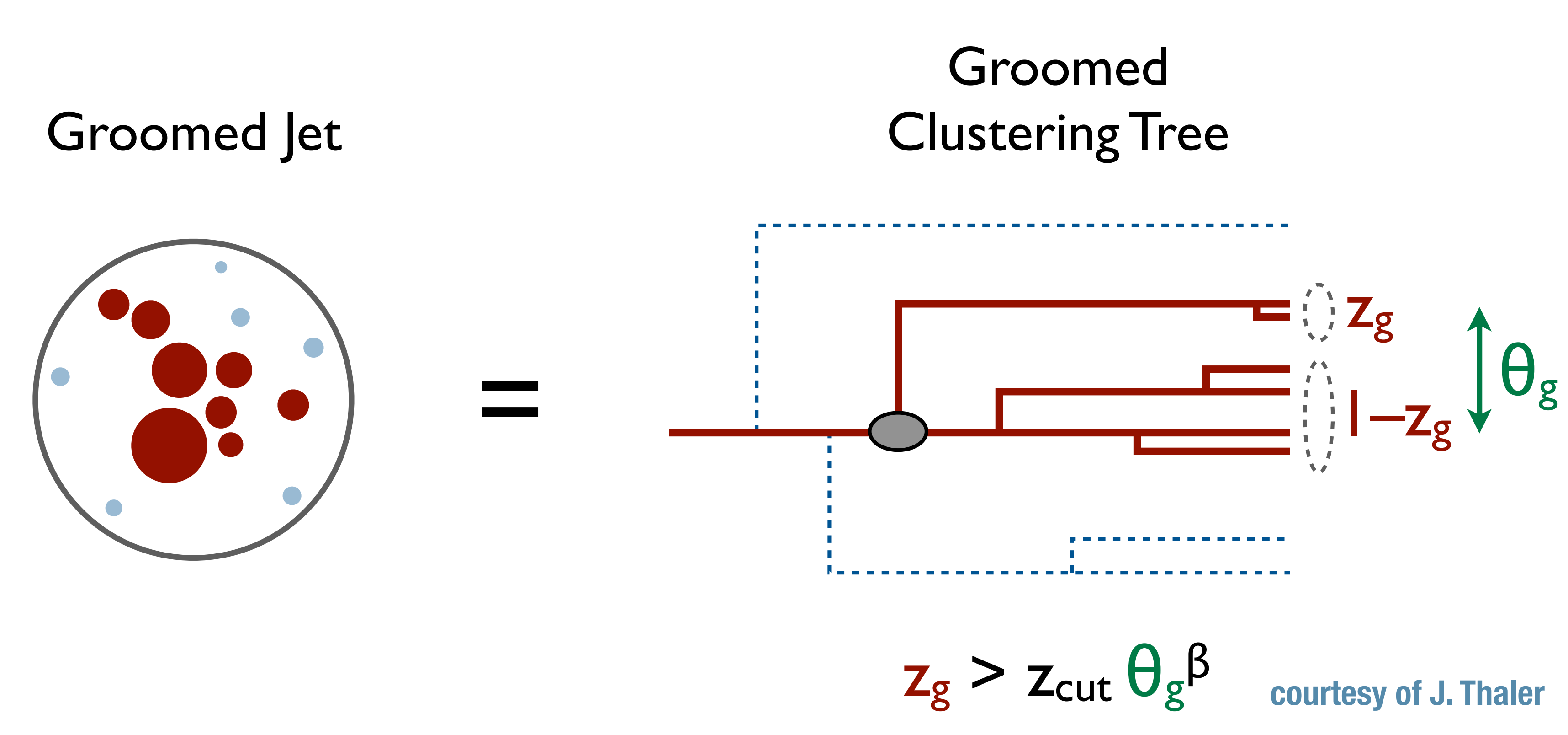
more information: clustering history

check momentum sharing

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

discard soft branches

$$z_g < z_{\text{cut}} \theta_g^\beta$$

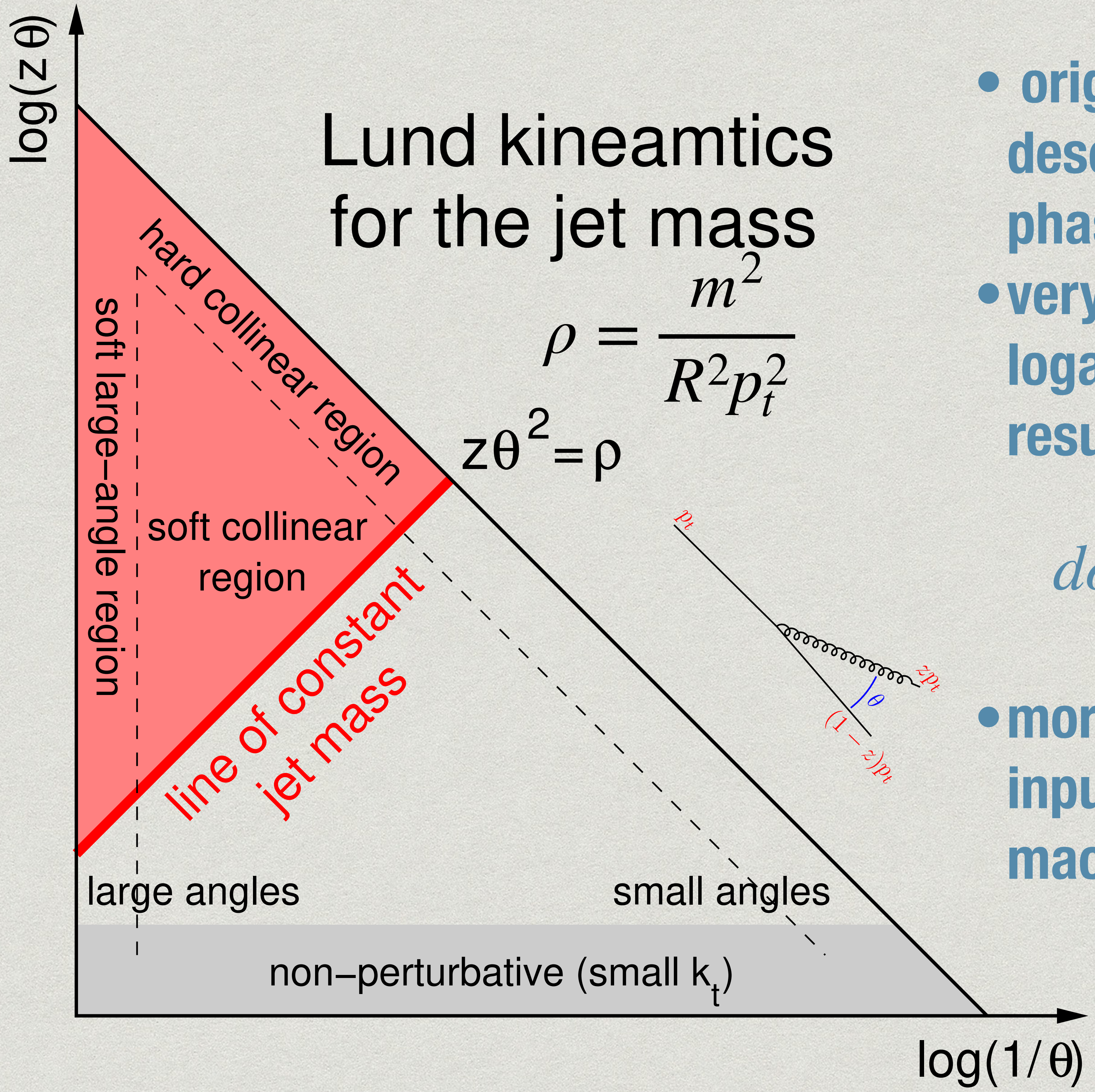


$z_g > z_{\text{cut}} \theta_g^\beta$

courtesy of J. Thaler

Butterworth, Davison, Rubin and Salam (2008); Dasgupta, Fregoso, SM and Salam (2013); Tseng and Evans (2013)

Lund plane



Lund kineamtics for the jet mass

$$\rho = \frac{m^2}{R^2 p_t^2}$$

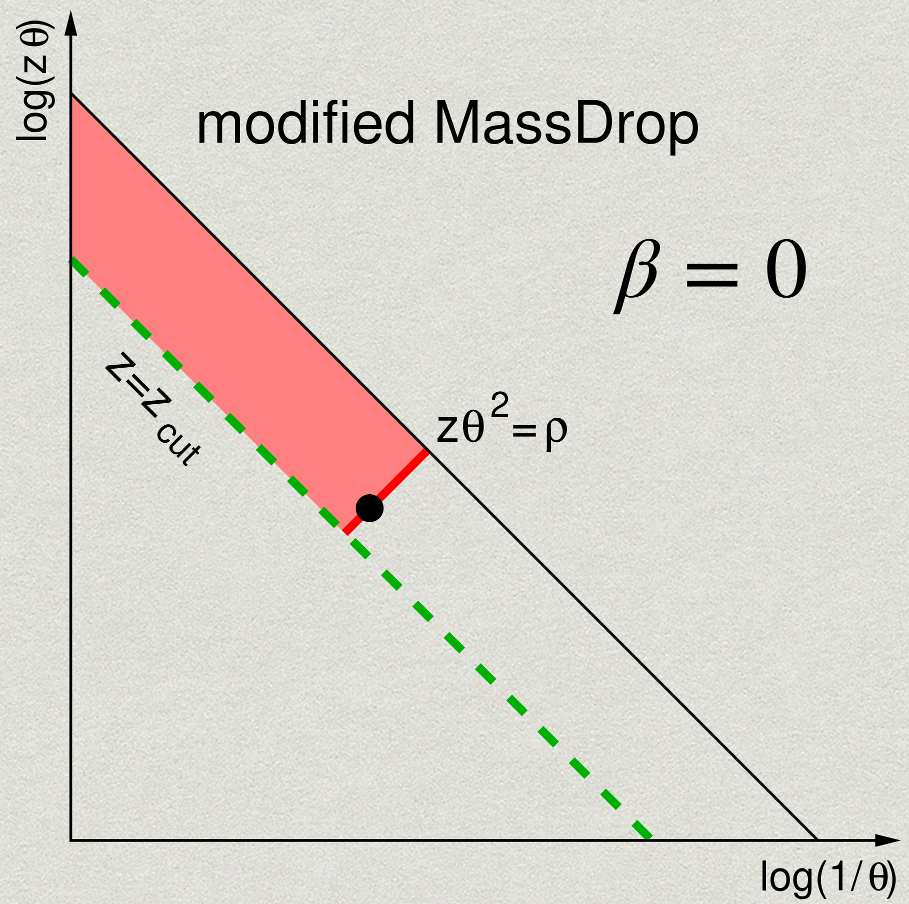
- originally introduced to describe parton shower phase space
- very helpful to understand logarithmic structure for resummation

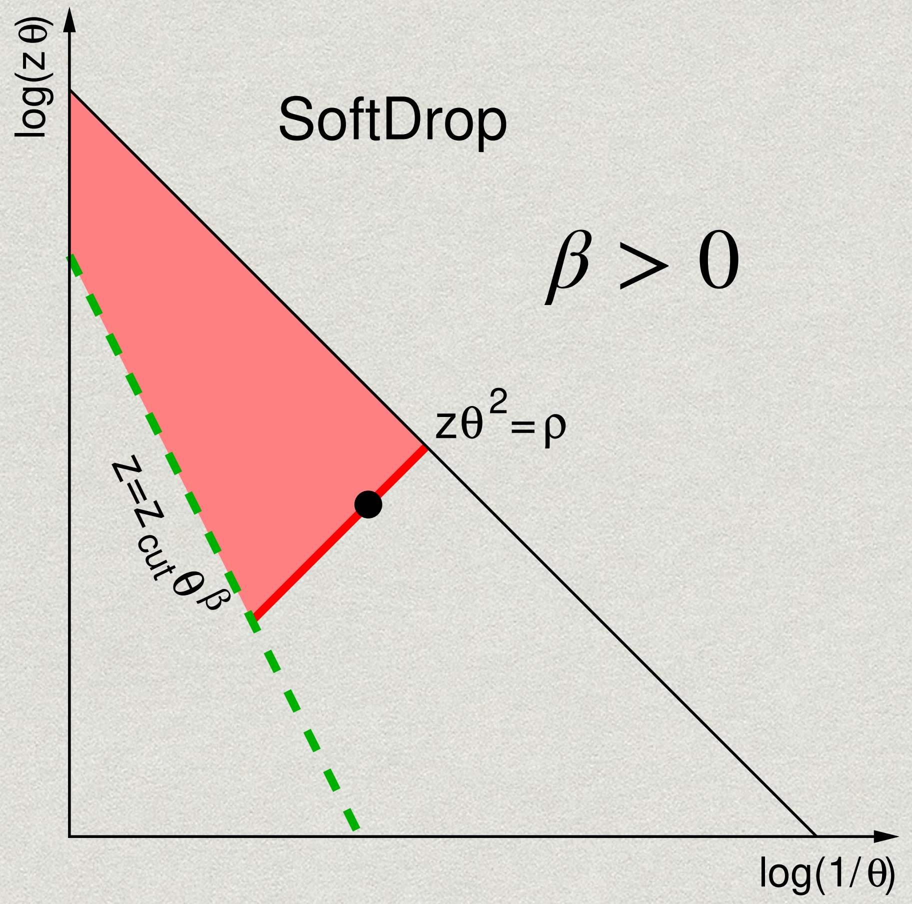
$$d\sigma = \alpha_s(k_t) C_i \frac{dk_t}{k_t} \frac{d\theta}{\theta}$$

- more recently employed as input for for machine-machine-learning algorithms

Dryer, Salam, Soyez (2018)

Kinematics of Soft Drop



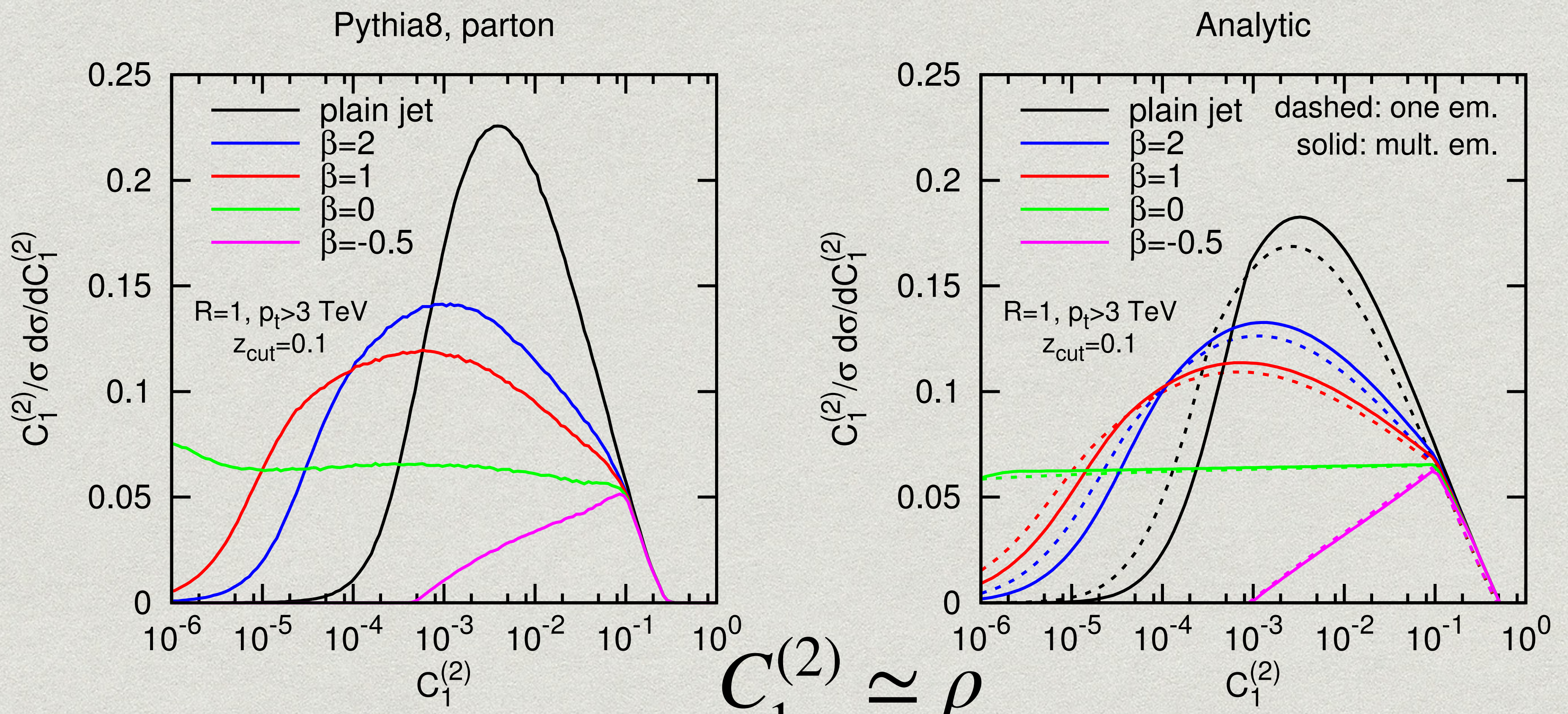


more grooming **less grooming**

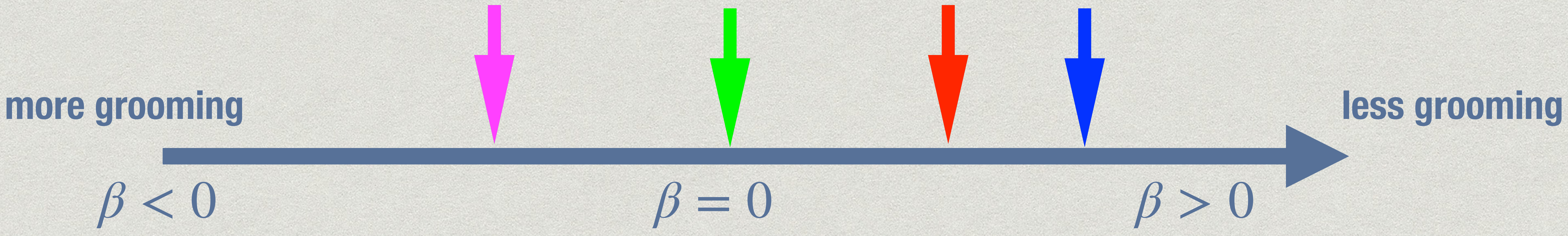
$\beta < 0$ $\beta = 0$ $\beta > 0$

- Soft Drop kinematic plane as a function of the angular exponent
- the region below the green line is groomed away
- this understanding can be easily translated into analytic resummation formulae

Groomed jet properties



$$C_1^{(2)} \simeq \rho$$



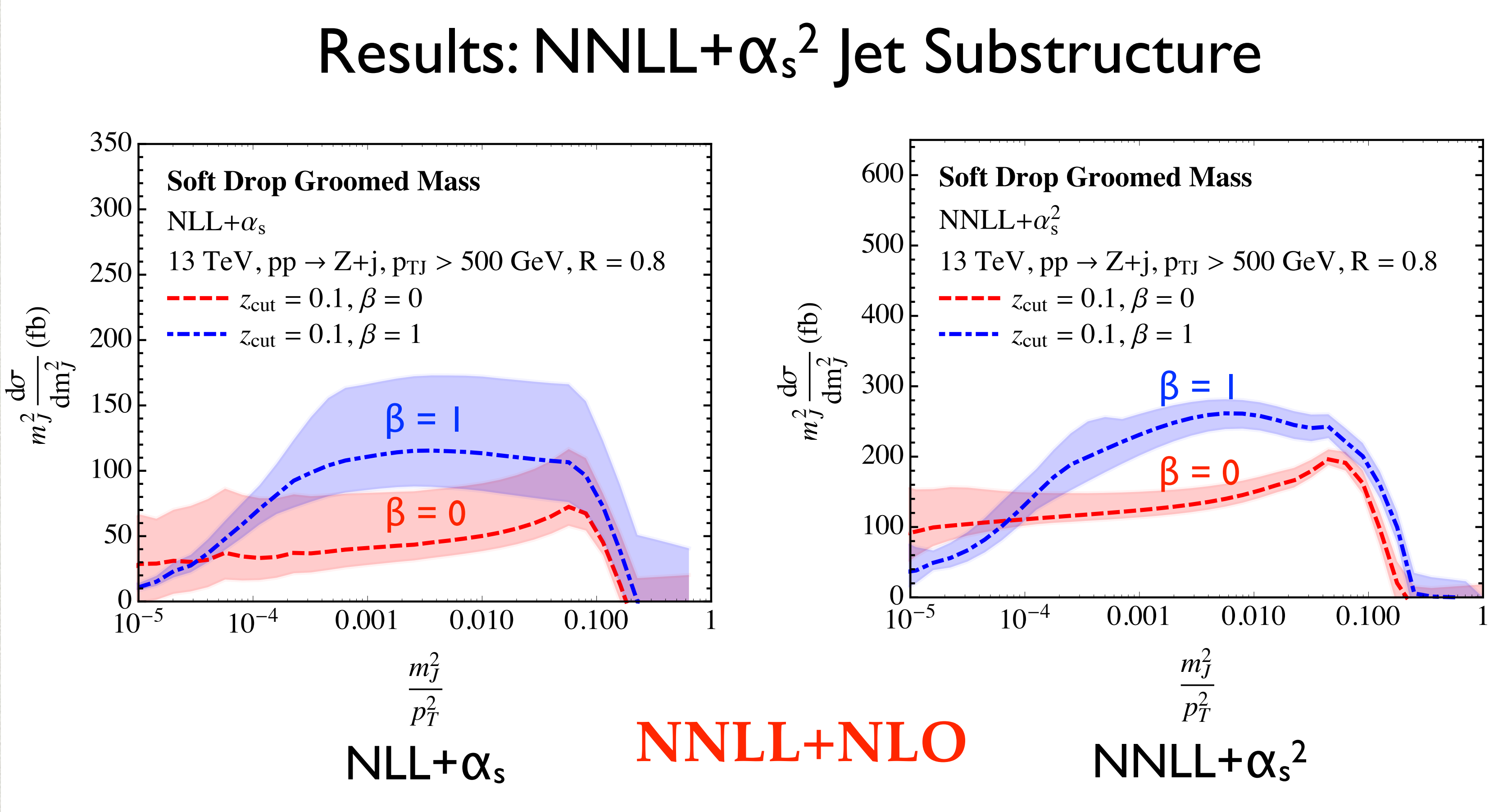
more grooming

less grooming

$\beta < 0$ $\beta = 0$ $\beta > 0$

- smooth distributions
- flatness in bkg can be achieved for β=0
- now the standard choice for CMS

Soft drop at NNLL



Results: NNLL+α_s^2 Jet Substructure

NLL+α_s

NNLL+NLO

NNLL+α_s^2

Frye, Larkoski, Schwartz, Yan (2016)

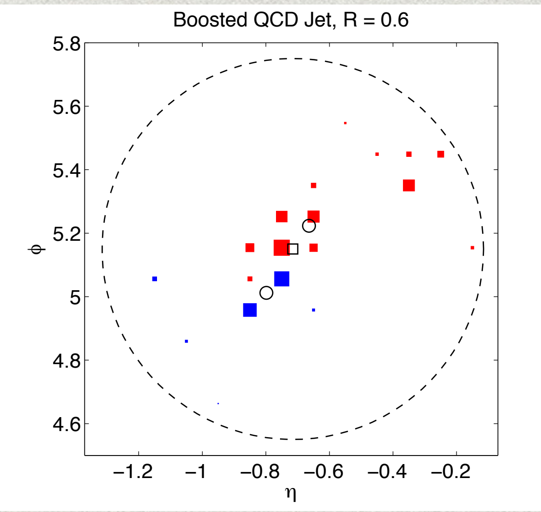
- soft-drop mass: something we can calculate
- reduced sensitivity to non-pert effects
- going to NNLL reduces scale variation but small changes in the shape
- for β=0 LL is zero, so state-of-the art NNLL is actually NLL

Example of a tagger: jet shapes

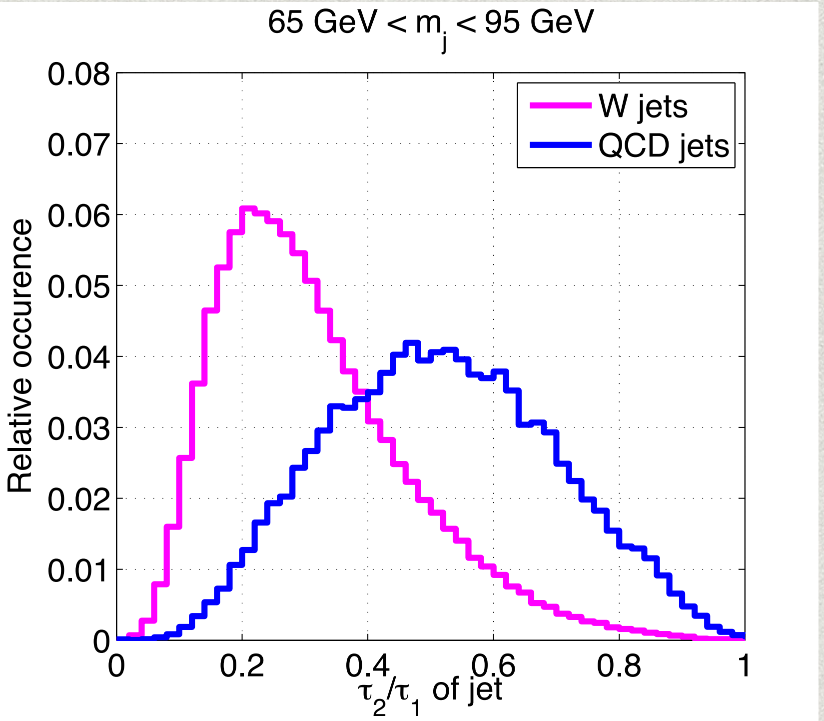
Tagging W bosons

- jet shapes measure the distribution of radiation inside a jet in order to distinguish signal from background
- standard analyses typically use a two-step approach
- first a mass window is identified (e.g. around m_W)
- a cut on a shape is imposed
- N-subjettiness is widely used for this purpose

Thaler and Van Tilburg (2010)



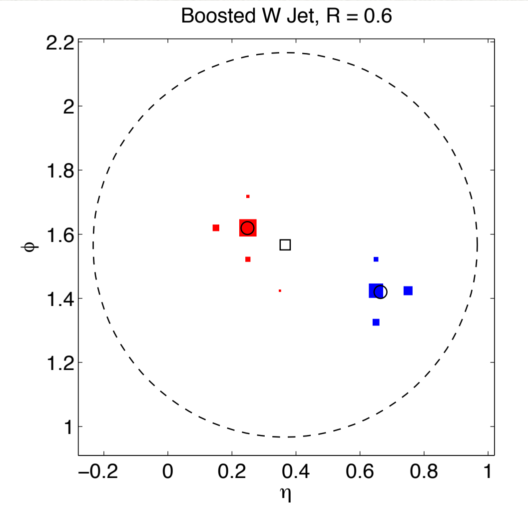
$$\tau_{21} = \frac{\tau_2^{(\beta)}(\text{jet; axes})}{\tau_1^{(\beta)}(\text{jet; axes})} = \frac{\sum_{i\in\text{constits}} z_i \min(\theta_{i,a_{2,1}}^{\beta}, \theta_{i,a_{2,2}}^{\beta})}{\sum_{i\in\text{constits}} z_i\, \theta_{i,a_{1,1}}^{\beta}}$$



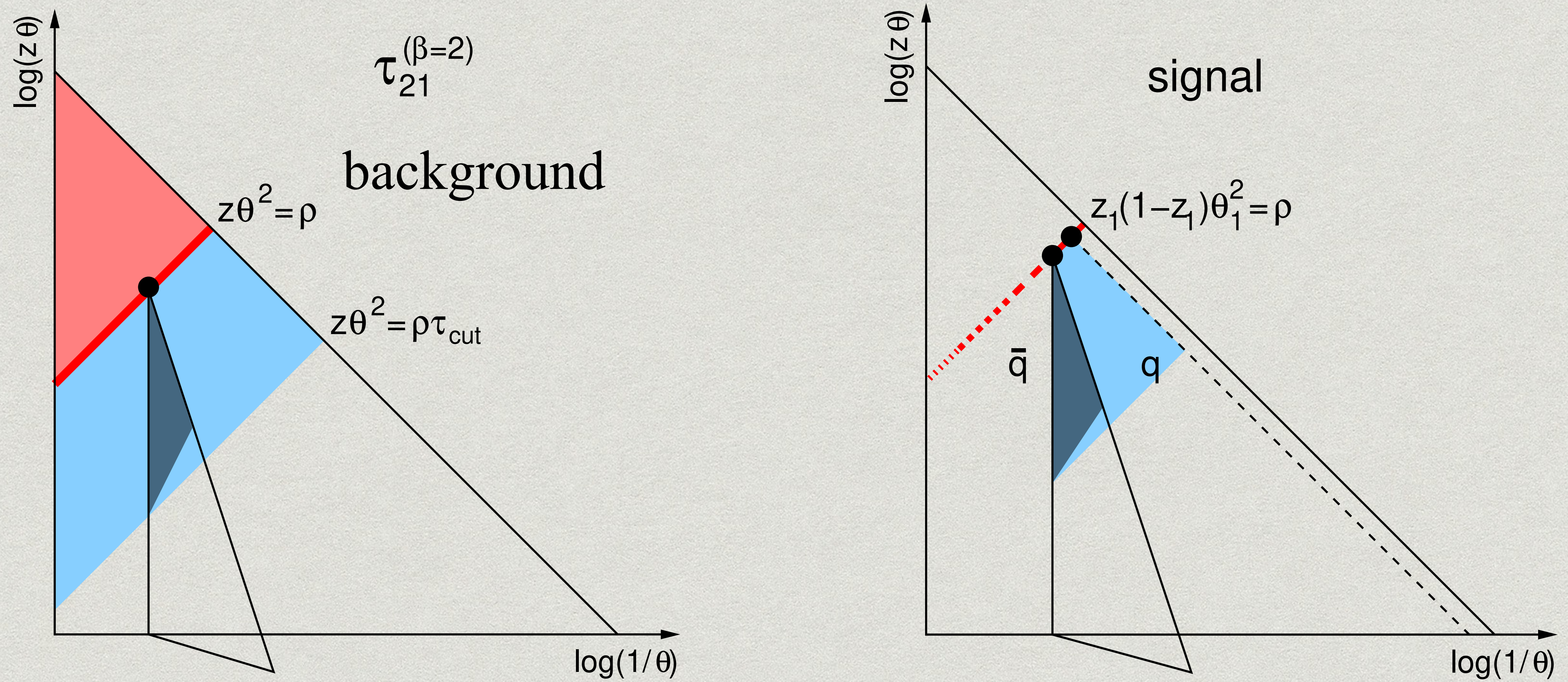
<u>specific choices:</u>

- axes?
- angular exponent (β=1 vs β=2)?
- plain or groomed jets
  (or both: dichroic ratios)?

Salam, Schunk, Soyez (2016)

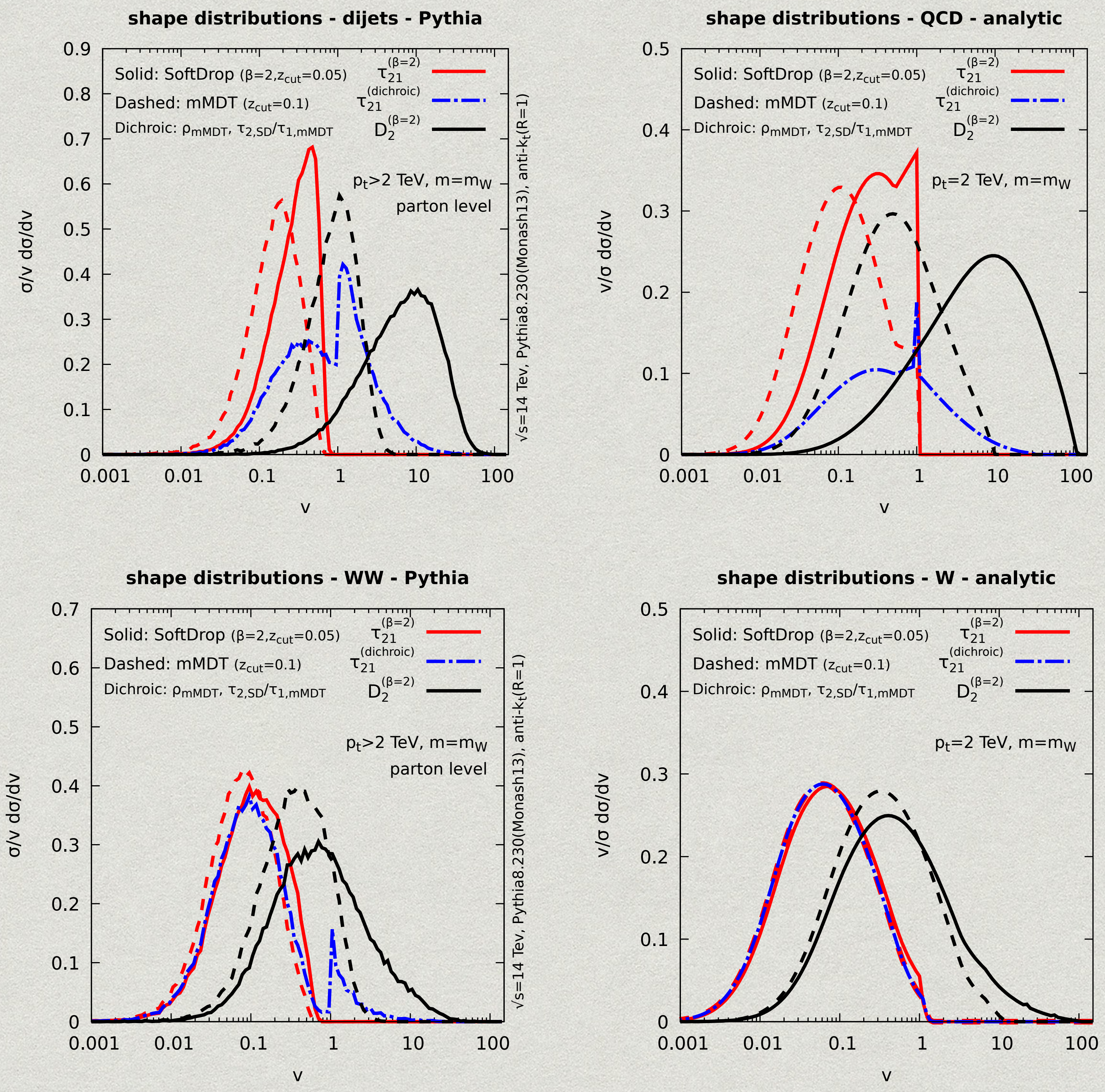


Kinematics of τ_{21}



- note that Lund diagrams become more complicated because we are sensitive to two emissions (mass and shape)
- the shape can be set by emission off the leading parton or by a splitting of the primary emission (which generates the extra fin)
- also in this case we can translate the above into analytic expressions
- we can also add grooming and consider different shapes

Analytics vs parton shower



- region of large v difficult to model in resummation but recent progress has been made

Napoletano, Soyez (2018)

- QCD jet shapes significantly affected by grooming, while signal ones less so
- Grooming does clean the jet up but tend to decrease separation, i.e. performance

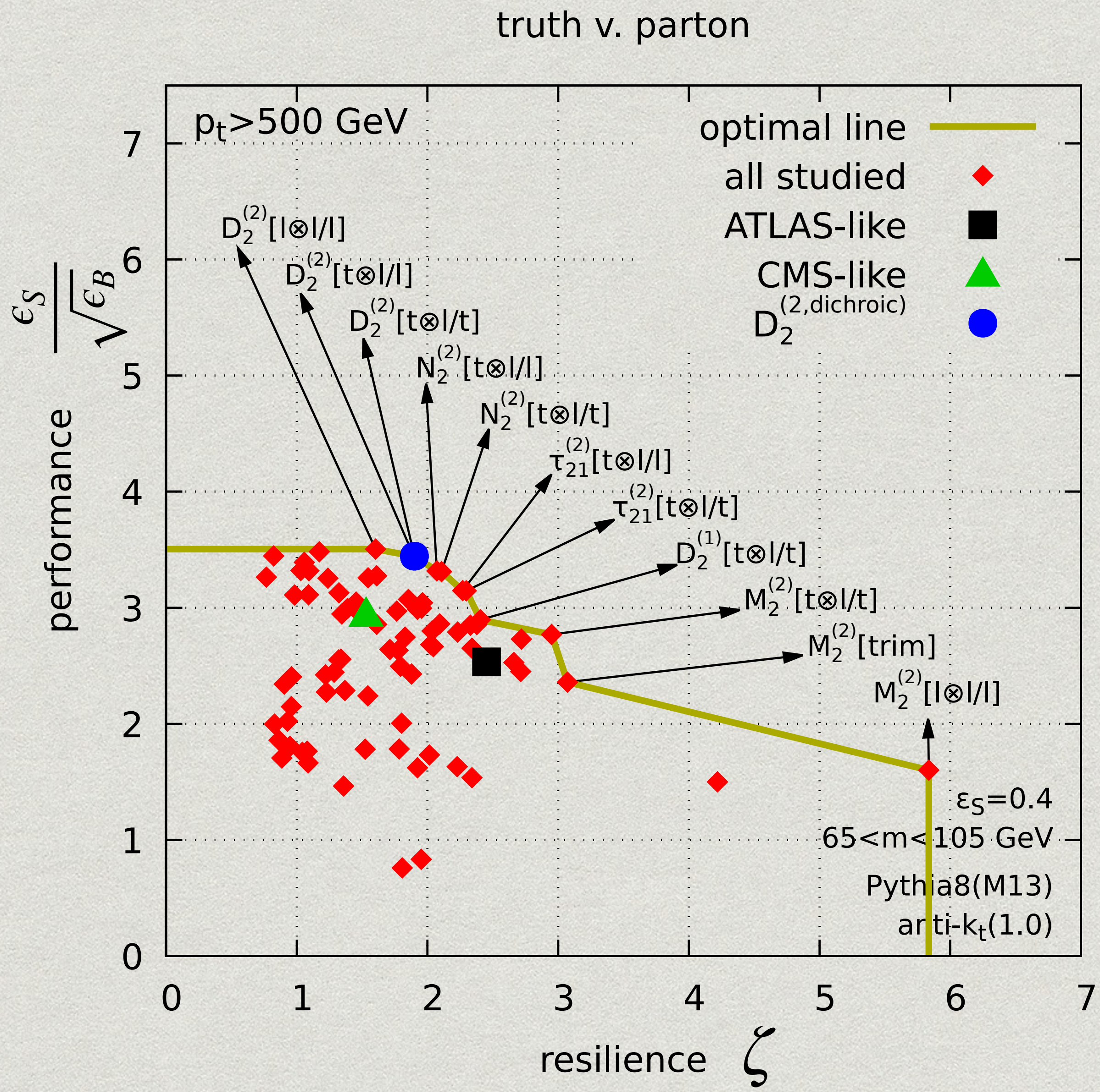
Performance and resilience

- resilience measures a tagger's robustness against non-perturbative effects (hadronisation and UE)
- it is defined in terms of signal/background efficiencies with/without non-pert. contributions

$$\zeta = \left(\frac{\Delta\epsilon_S^2}{\langle\epsilon\rangle_S^2} + \frac{\Delta\epsilon_B^2}{\langle\epsilon\rangle_B^2} \right)^{-1/2}$$

$$\Delta\epsilon_{S,B} = \epsilon_{S,B} - \epsilon'_{S,B},$$

$$\langle\epsilon\rangle_{S,B} = \frac{1}{2}\left(\epsilon_{S,B} + \epsilon'_{S,B}\right)$$

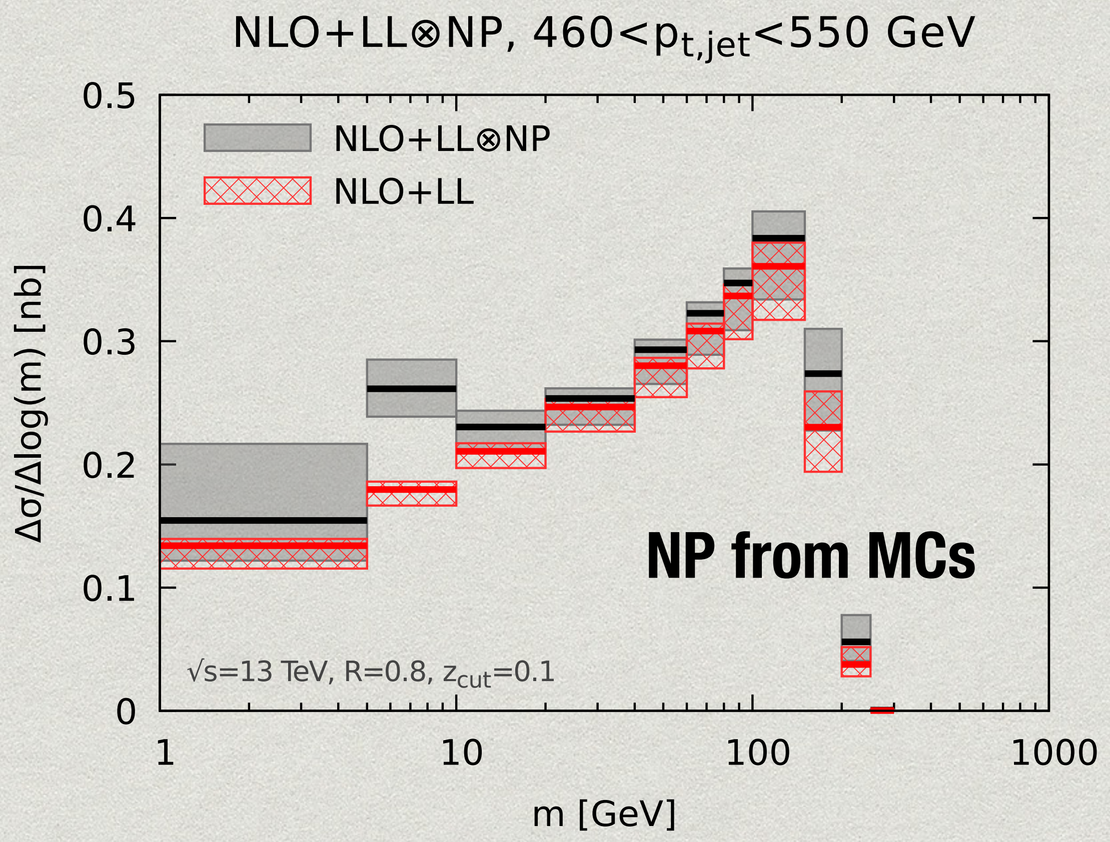


Measuring jet substructure

Soft Drop observables

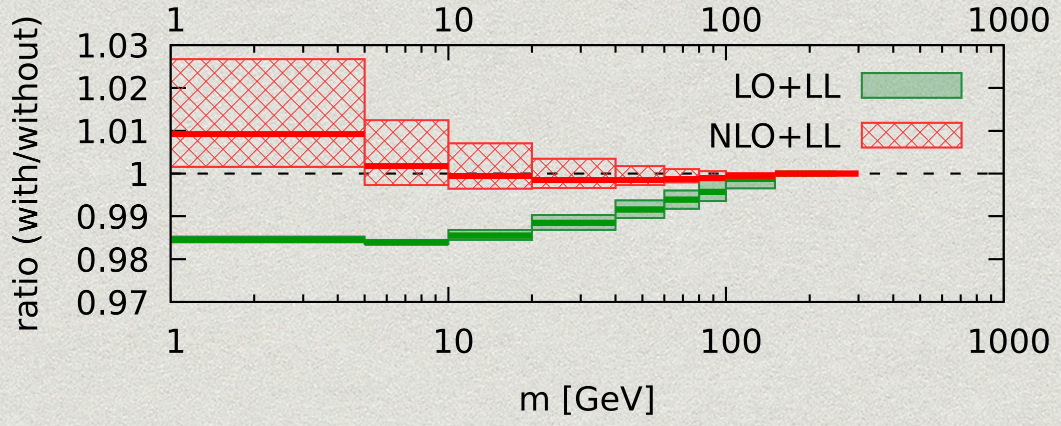
Theory predictions

SM, Schunk, Soyez (2017)

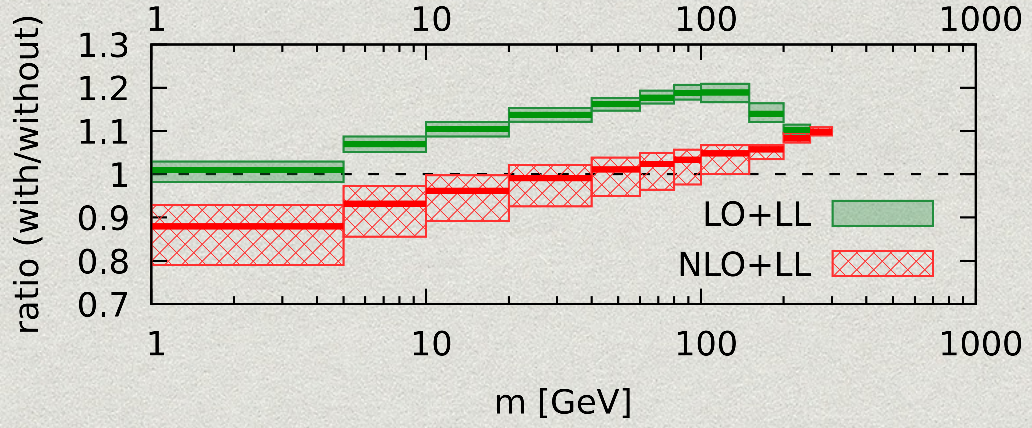


NP from MCs

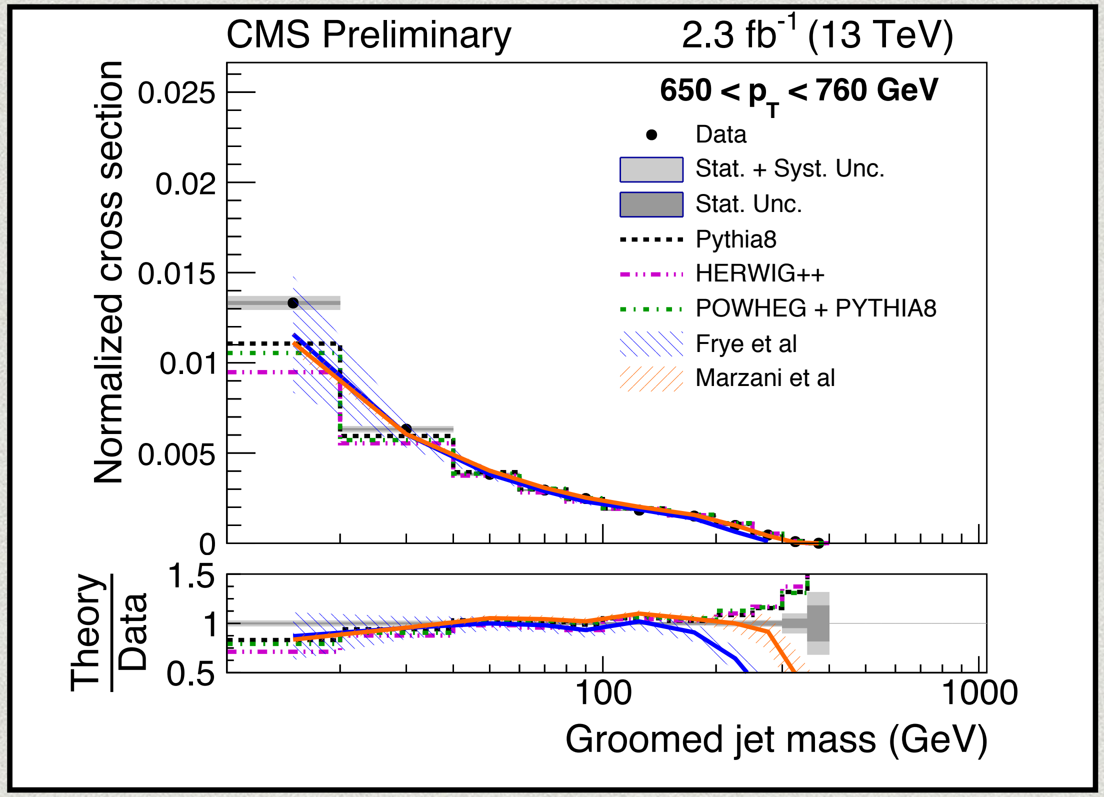
- let's start wit the simplest observable: jet mass
- large range of masses where NP corrections are small and we can trust resummation

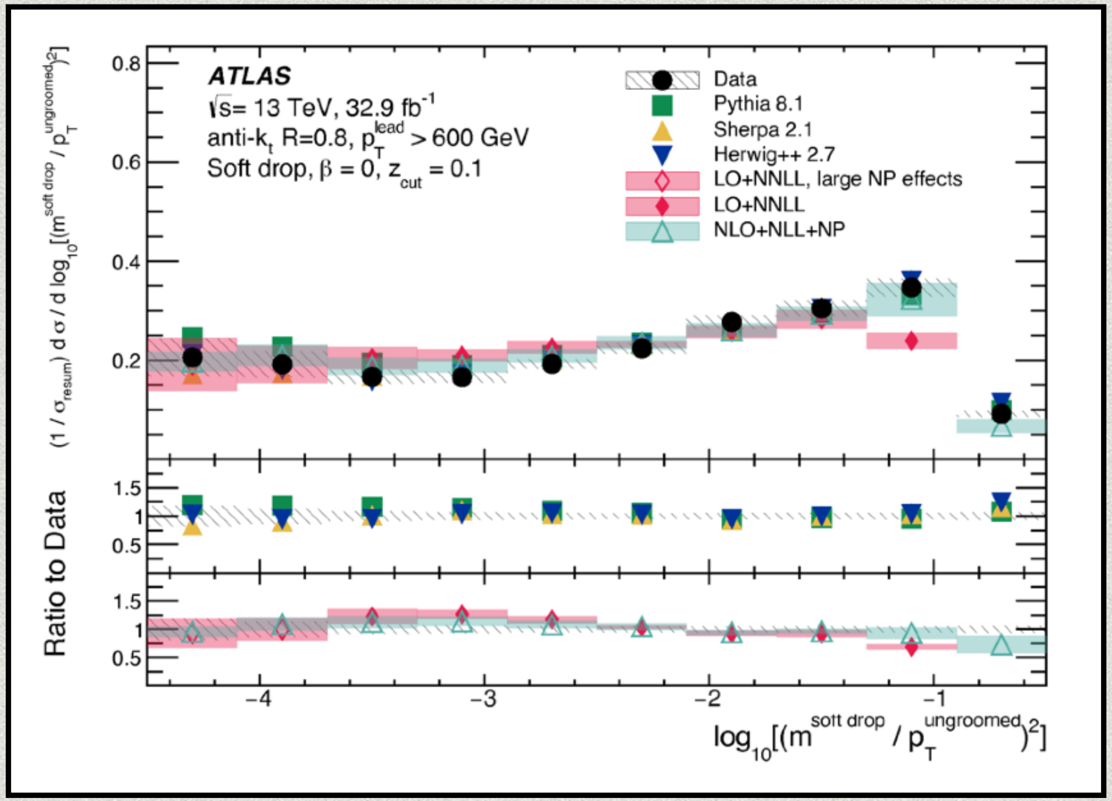


- what's the impact of finite z_c contributions (formally LL)?
- what's the impact of logs of z_c (formally N^kLL)?
- conclusions will change if we move away from z_c=0.1
-

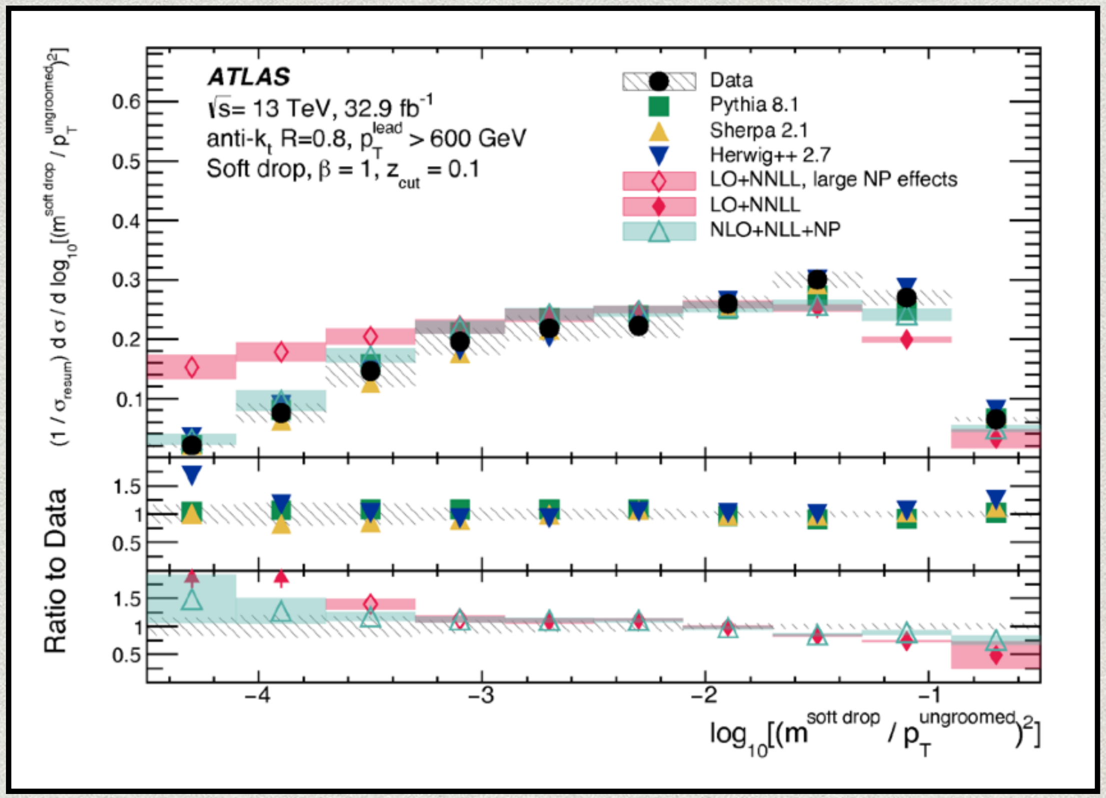


and the DATA!





CMS-PAS-16-010



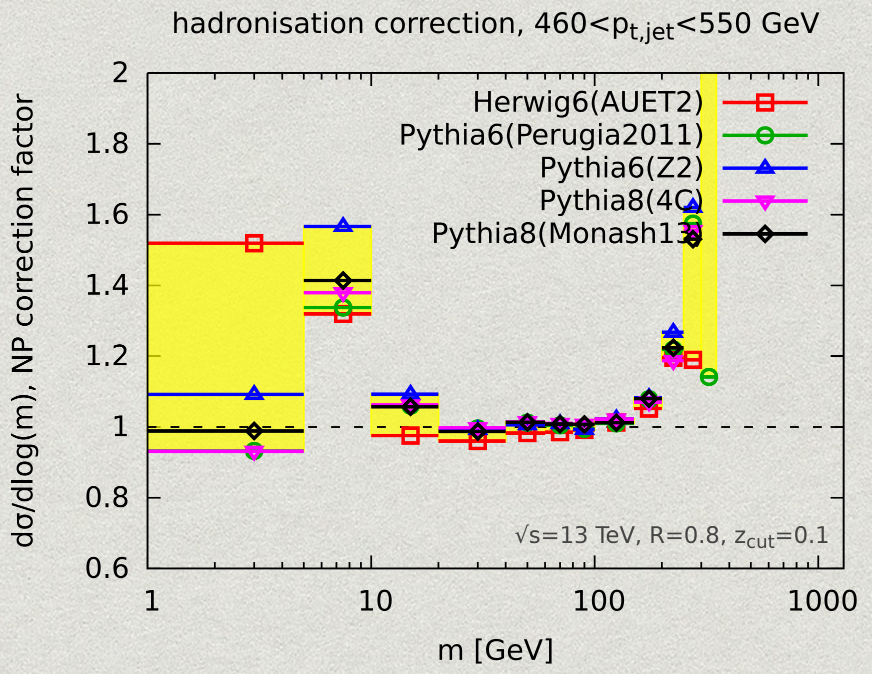
- CMS & ATLAS measurements
- NNLL is a small correction
- importance of FO for the tail
- ATLAS did β survey

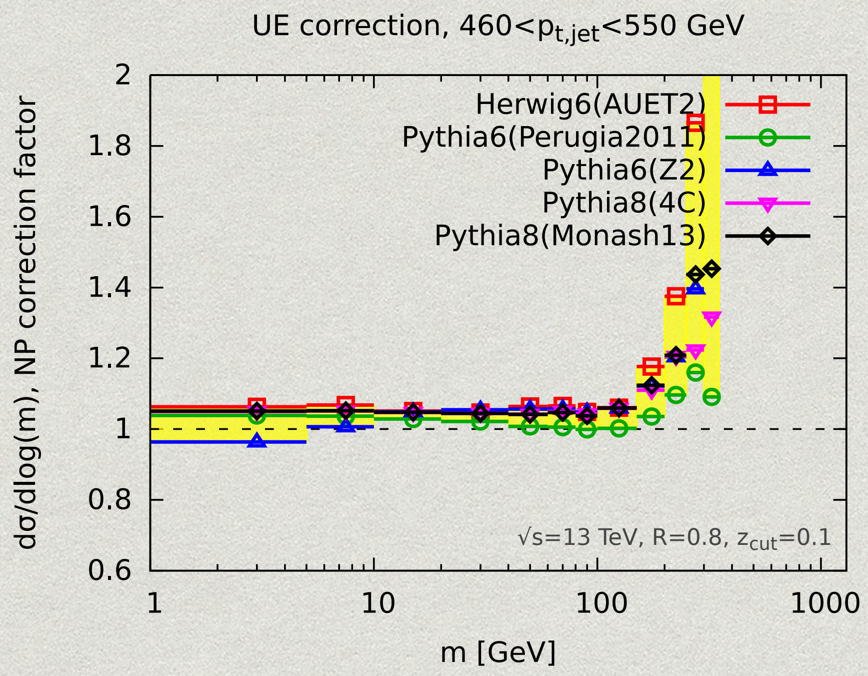
ATLAS: arXiv:1711.08341

Why unfolded measurements ?

What is the value of SM measurements and their comparison to theory, especially for “discovery” tools?

- understanding systematics (e.g. kinks and bumps)
- where non-perturbative corrections are small, test perturbative showers in MCs
- at low mass, hadronisation is large but UE is small: TUNE!

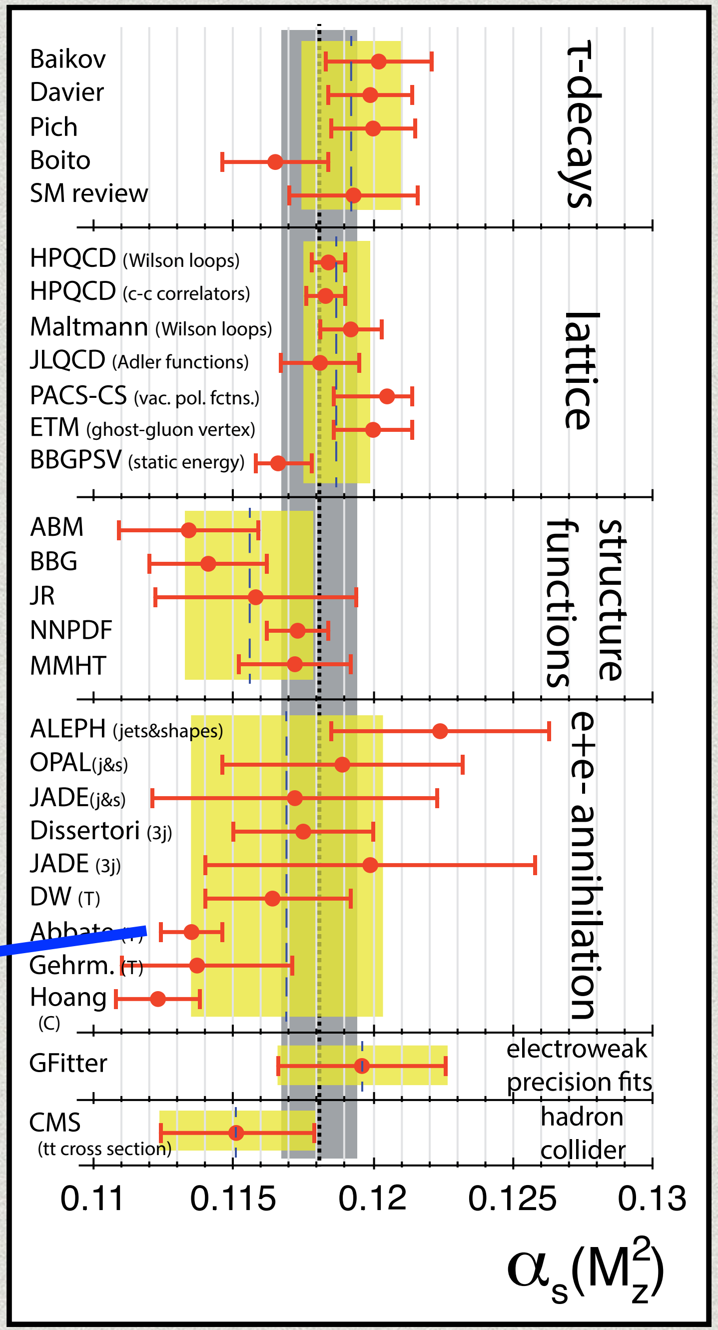




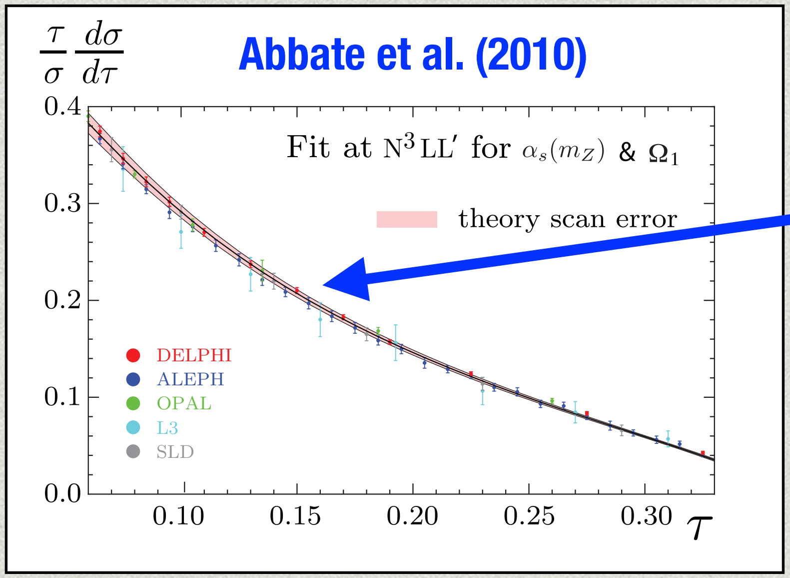
Extraction of Standard Model parameters

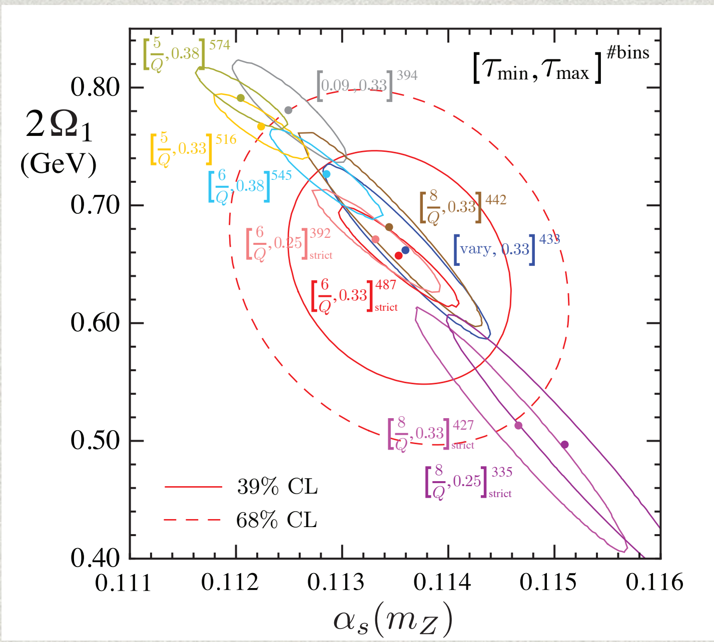
Strong coupling

- current precision below 1%, dominated by lattice extractions
- LEP event shapes also very precise (5%), however they are in tension with the world average
- Thrust (and C parameter) known with outstanding accuracy

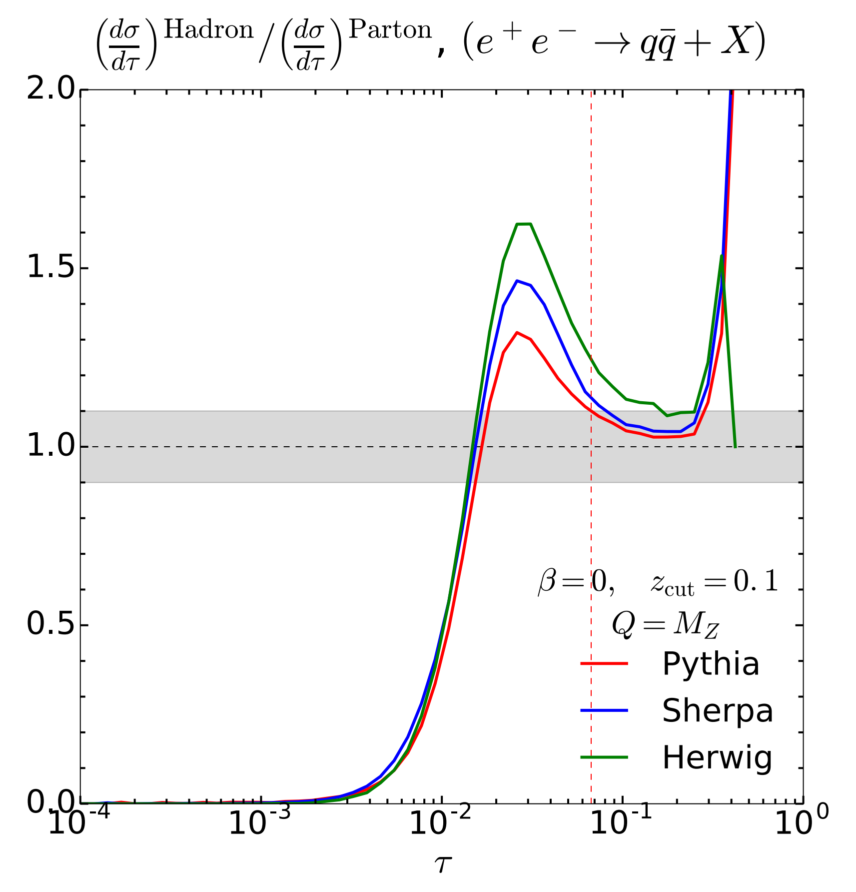


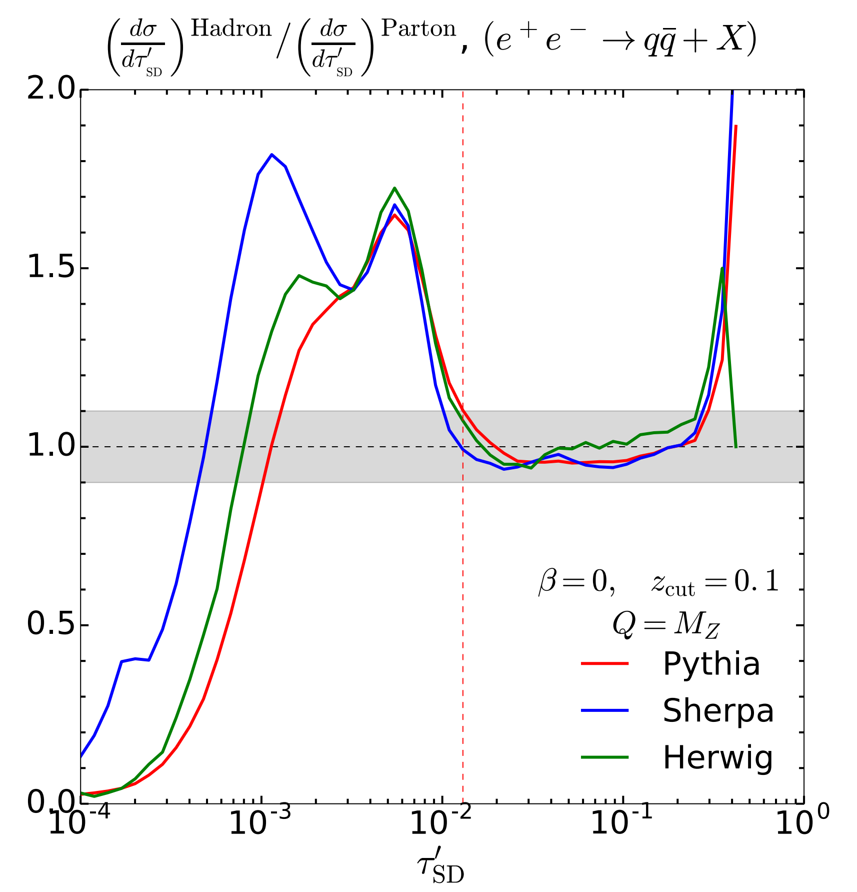
- Strong correlations with non-pert. parameter





Soft-drop thrust





Baron, SM, Theeuwes (2018)

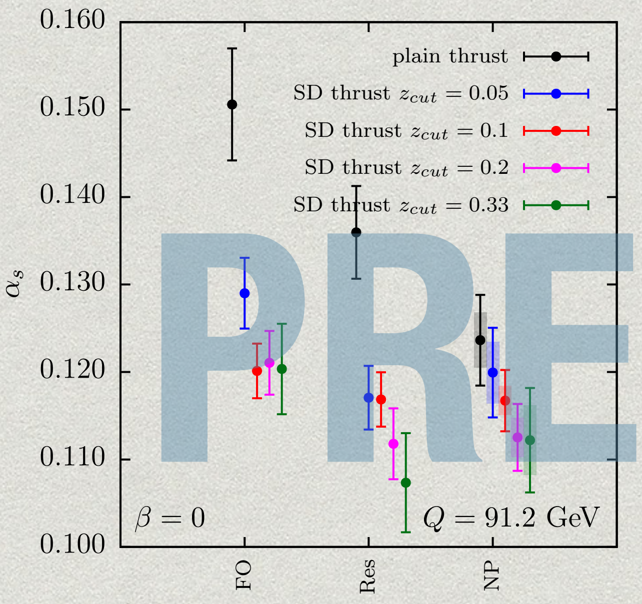
- noticeable reduction of non-pert. corrections may allow to disentangle the degeneracy
- can we compute it at the same accuracy as standard event shapes?
- NNLO calculations recently performed

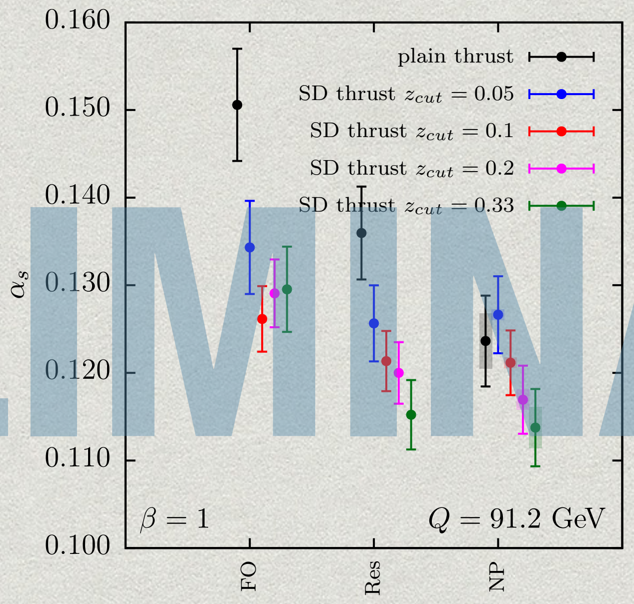
Kardos, Somogyi, Trocsanyi (2018)

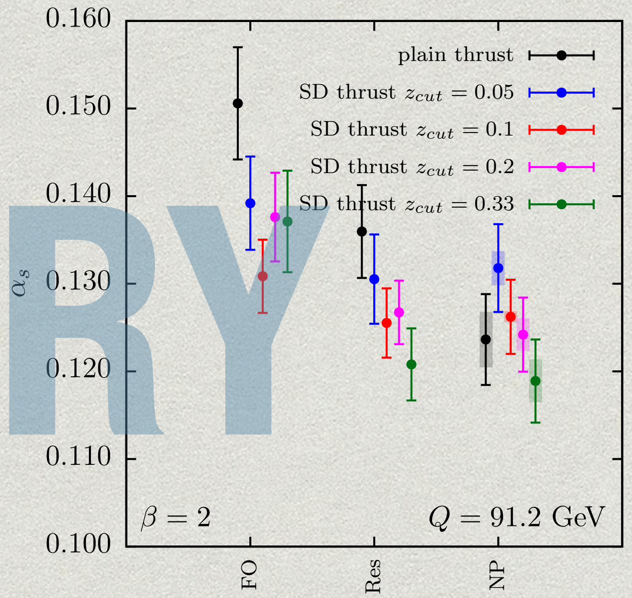
α_s with soft-drop thrust

SM, Reichelt, Schumann, Soyez and Theeuwes, (soon to appear)

PRELIMINARY





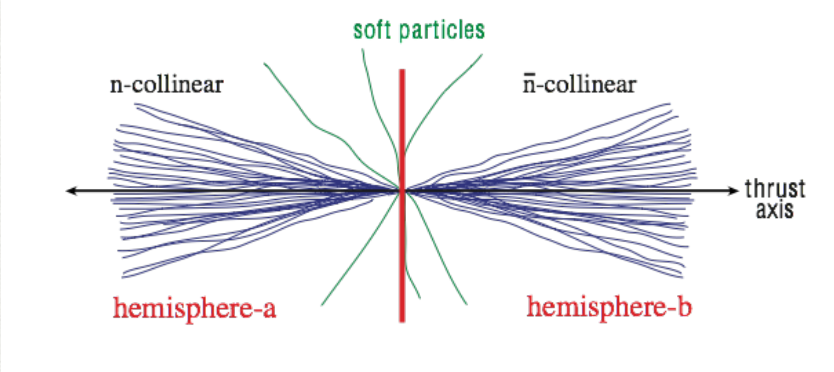


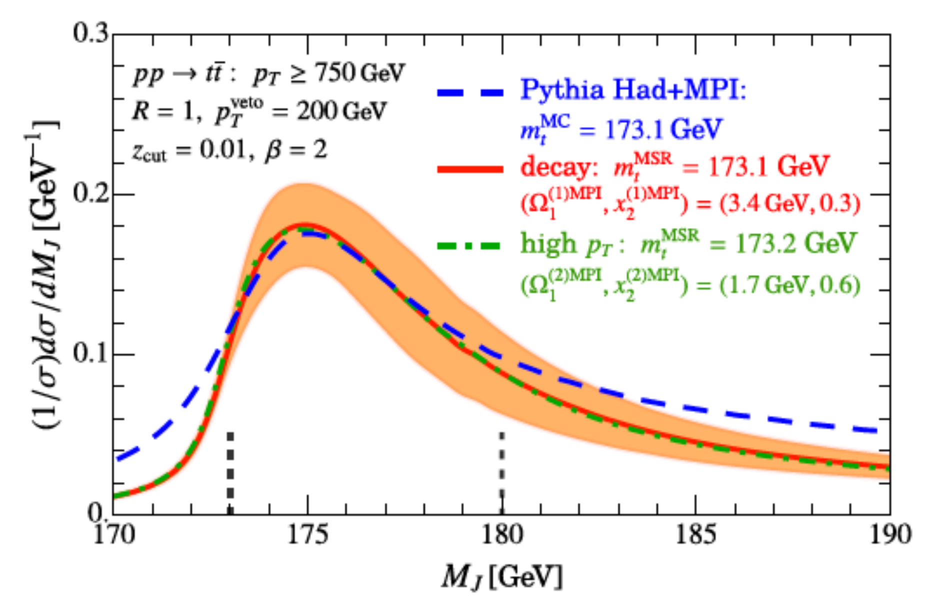
- fits to pseudo-data generated by SHERPA
- preliminary results shows reduced dependence on non-pert. corrections
- subleading effects are under investigation
- general question: is there a natural way to define soft-drop event shapes?
- bottom-up soft drop allows one to groom an entire event

Dreyer, Necib, Soyez, Thaler (2018); Baron (in preparation)

m_t with soft-drop jets

- determination of other fundamental parameters may benefit from grooming, e.g. the top quark mass
- in the context of e^+e^- collisions SCET factorisation theorems allow for a precision-determination of the top-jet mass
- the picture at pp collisions is polluted by wide-angle soft radiation
- grooming "turns" pp observables into e^+e^- ones





Hoang, Mantry, Pathak, Stewart (2017)

Final remarks

Summary & Outlook

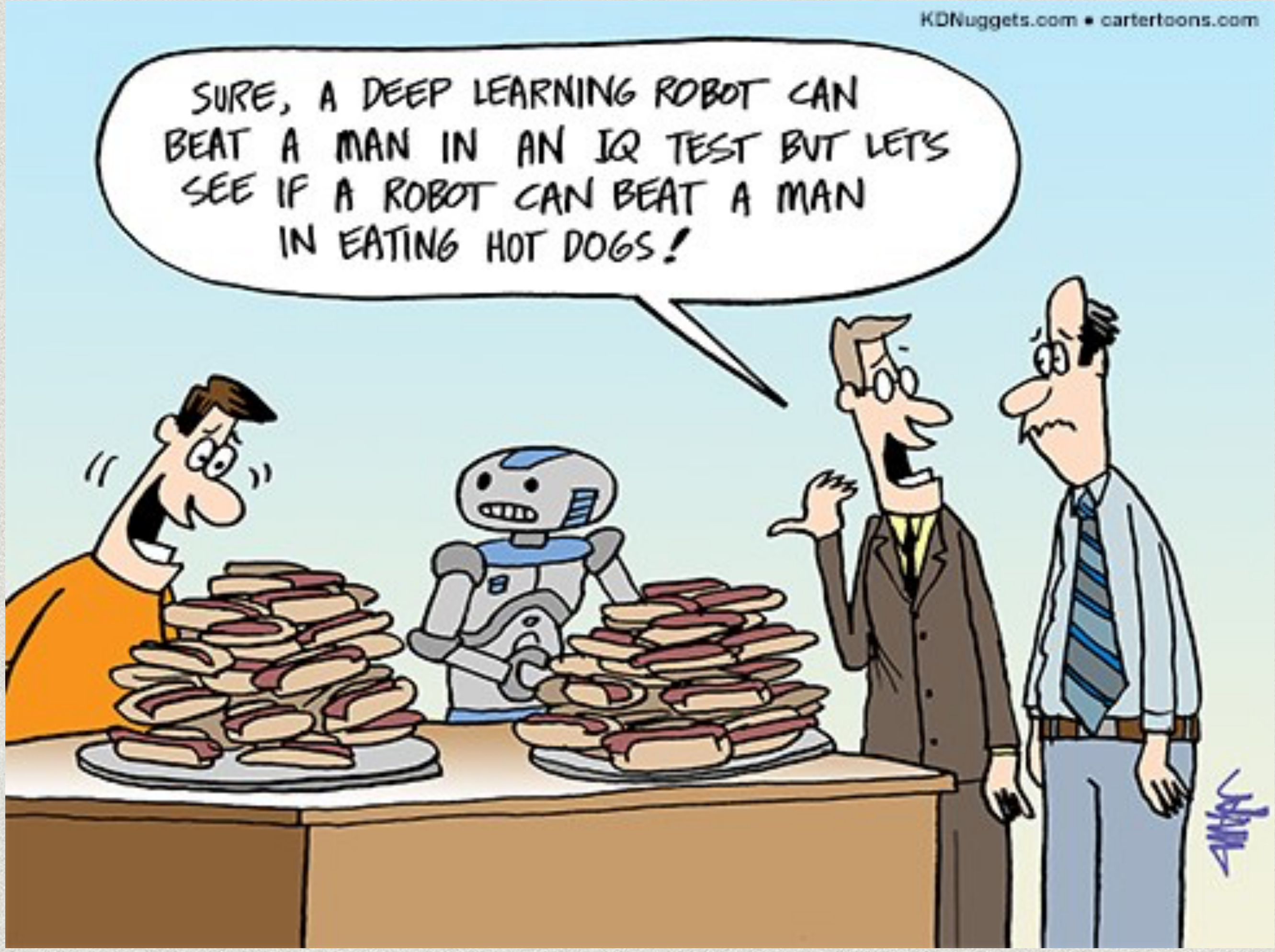
- importance of substructure studies
- soft drop: theoretical status and physics opportunities

- Open questions

   1. higher-order corrections (i.e. beyond NLO) and grooming?
   2. in the boosted regime electro-weak corrections are significant
   3. in the opposite direction: non-perturbative physics and hadronisation in particular. Is “standard” ? and what does standard even mean?

Humans vs machines

- Jet physics (and particle physics!) undergoing a revolution
- ideas / techniques from machine (deep) learning continuously poured into the field
- I had to make a choice and concentrated on humans for this talk



- Food for thoughts:
  - what are the machine-learning ideas best suited for particle physics? (images, language…)
  - are we scared of black boxes? (should we?)
  - can we make black boxes more transparent?

Thank you !

Looking inside jets: an introduction to jet substructure and boosted-object phenomenology

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