LOOKING INSIDE JETS

Simone Marzani
University at Buffalo,
The State University of New York

Università degli Studi di Genova
December 20th 2016

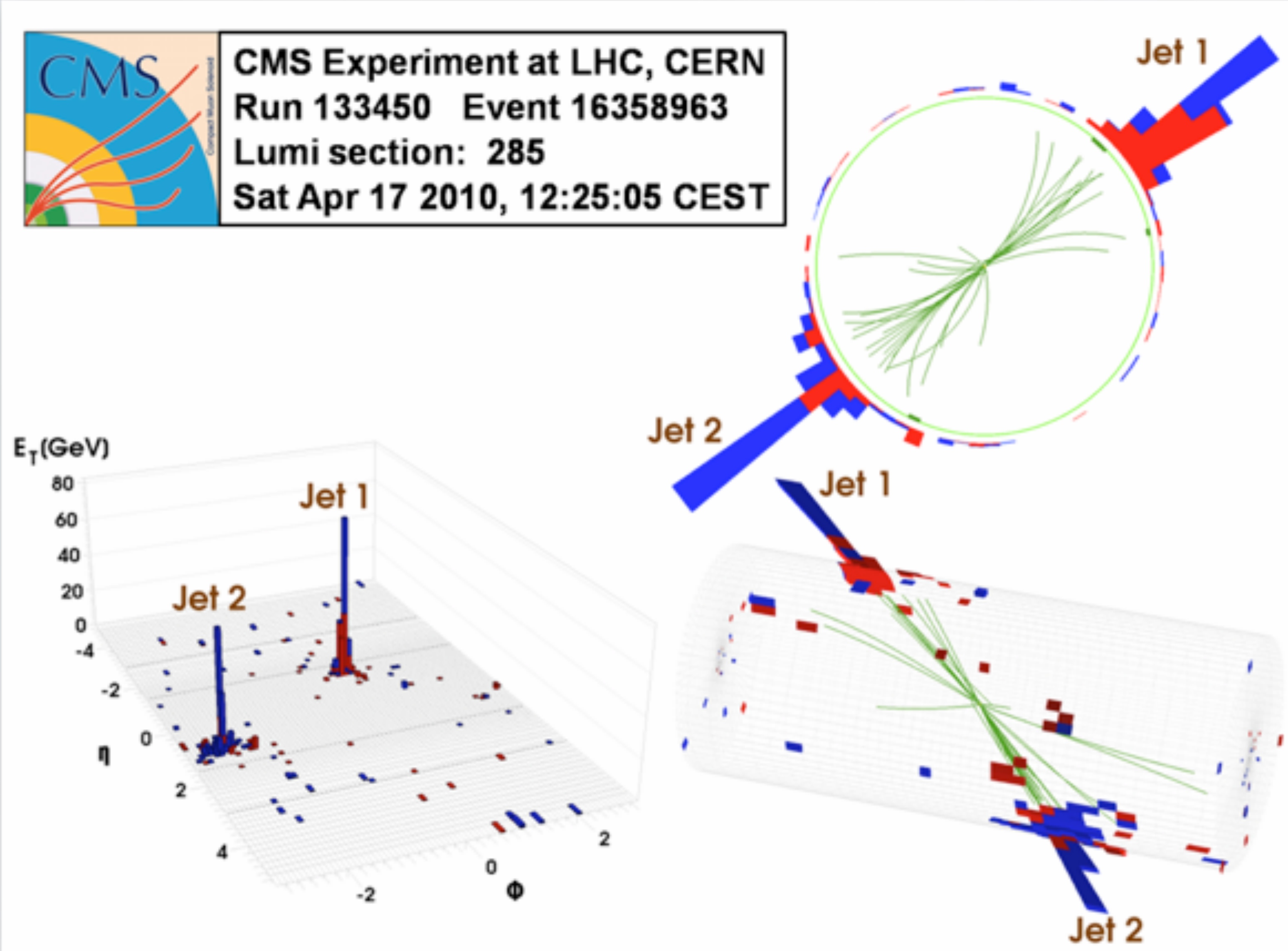
Outline

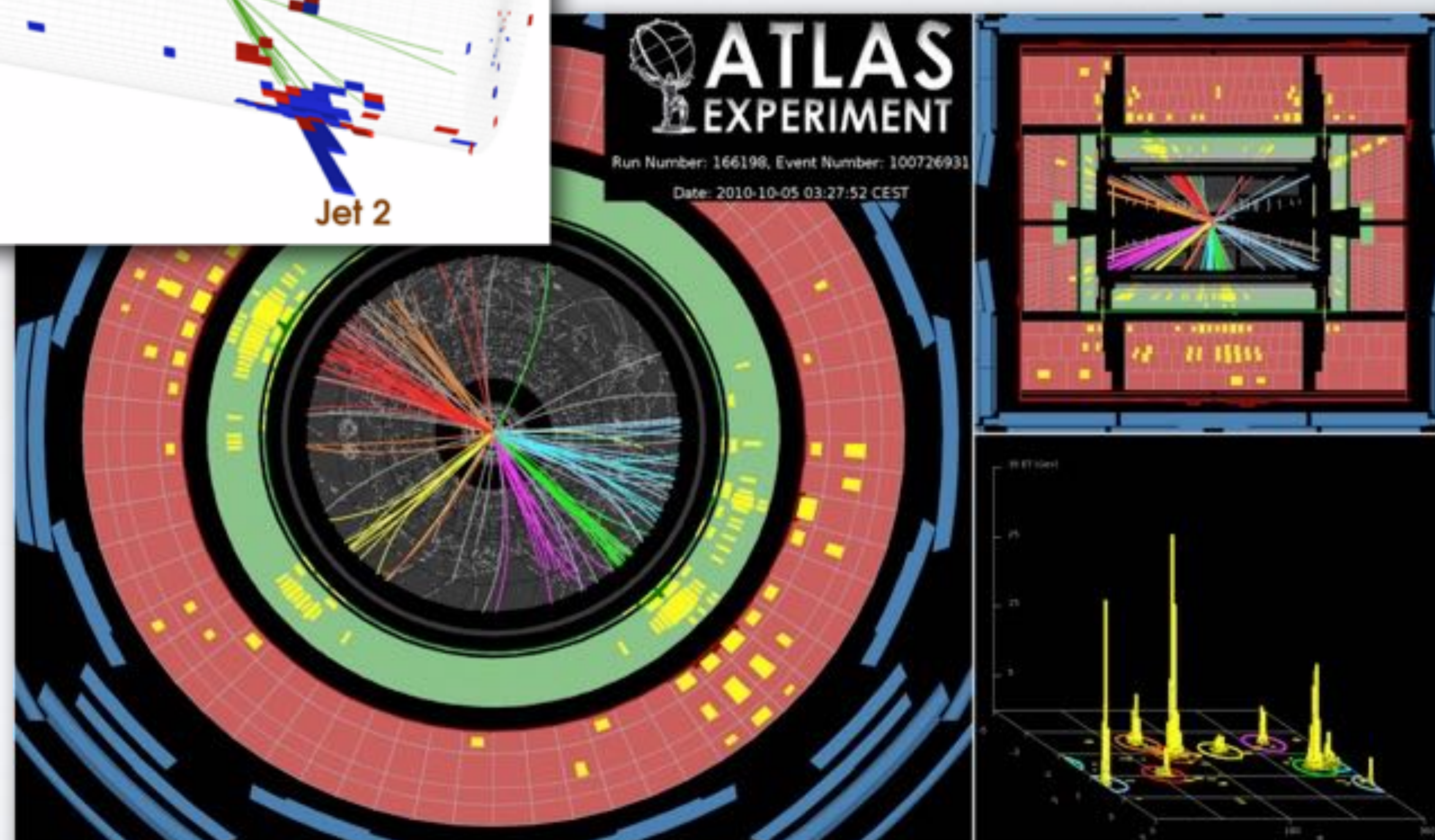
- Looking inside jets: an introduction
- Theoretical understanding of taggers and groomers
- Back to phenomenology: W tagging with DDT
- Exposing the QCD splitting function

What is a jet ?

JETS

Collimated, energetic sprays of particles

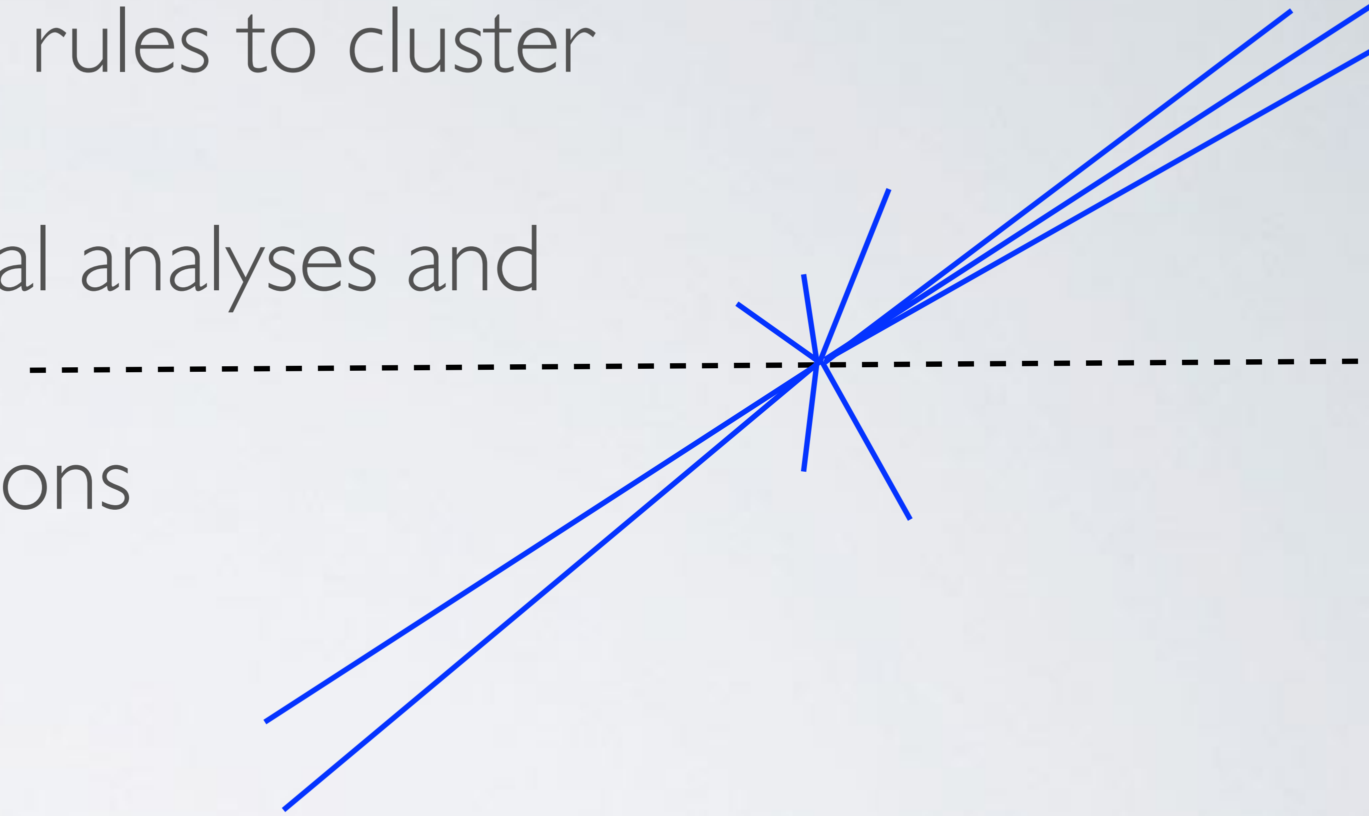




ubiquitous @LHC: more than 70% of ATLAS & CMS papers use jets in their analyses!

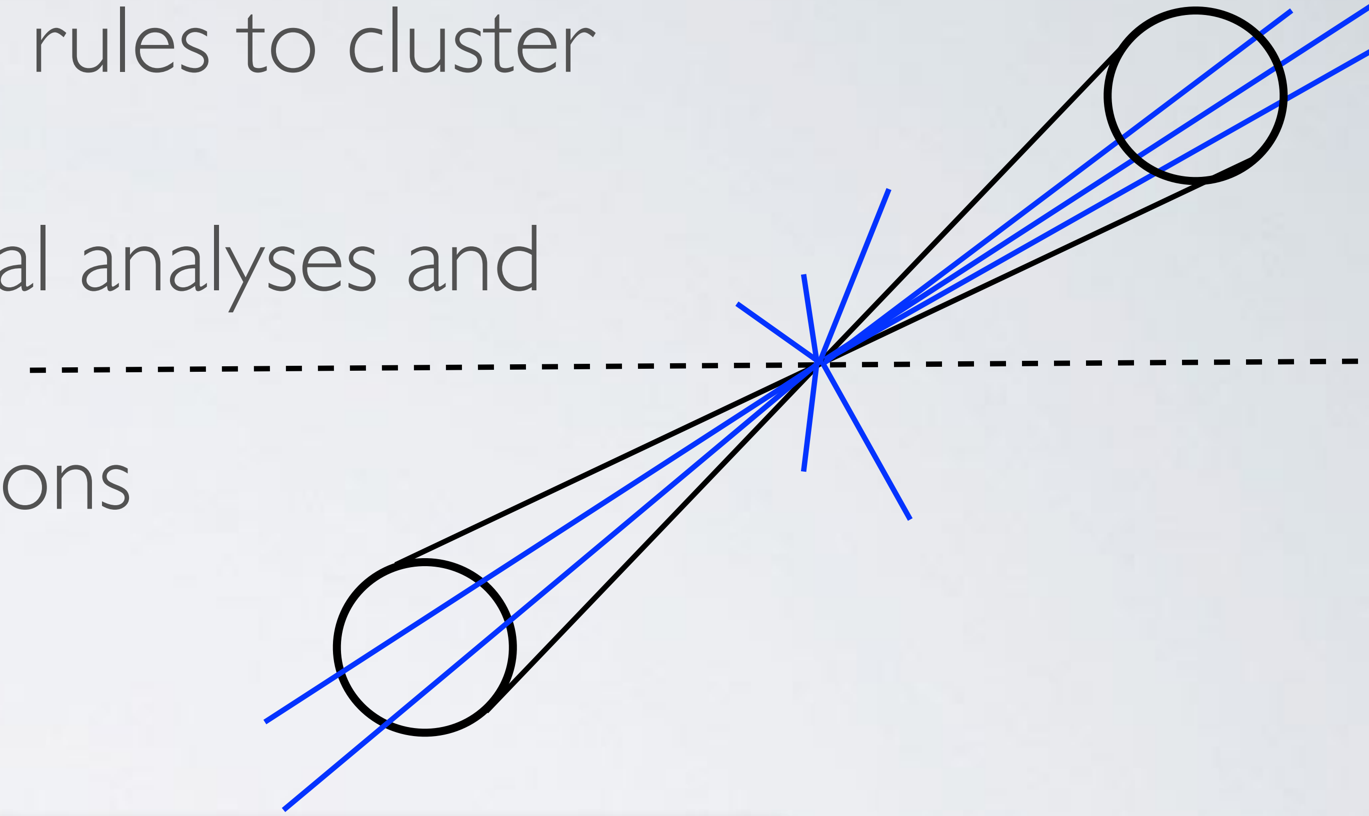
Jet definition(s)

- 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 :



Jet definition(s)

- 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 :

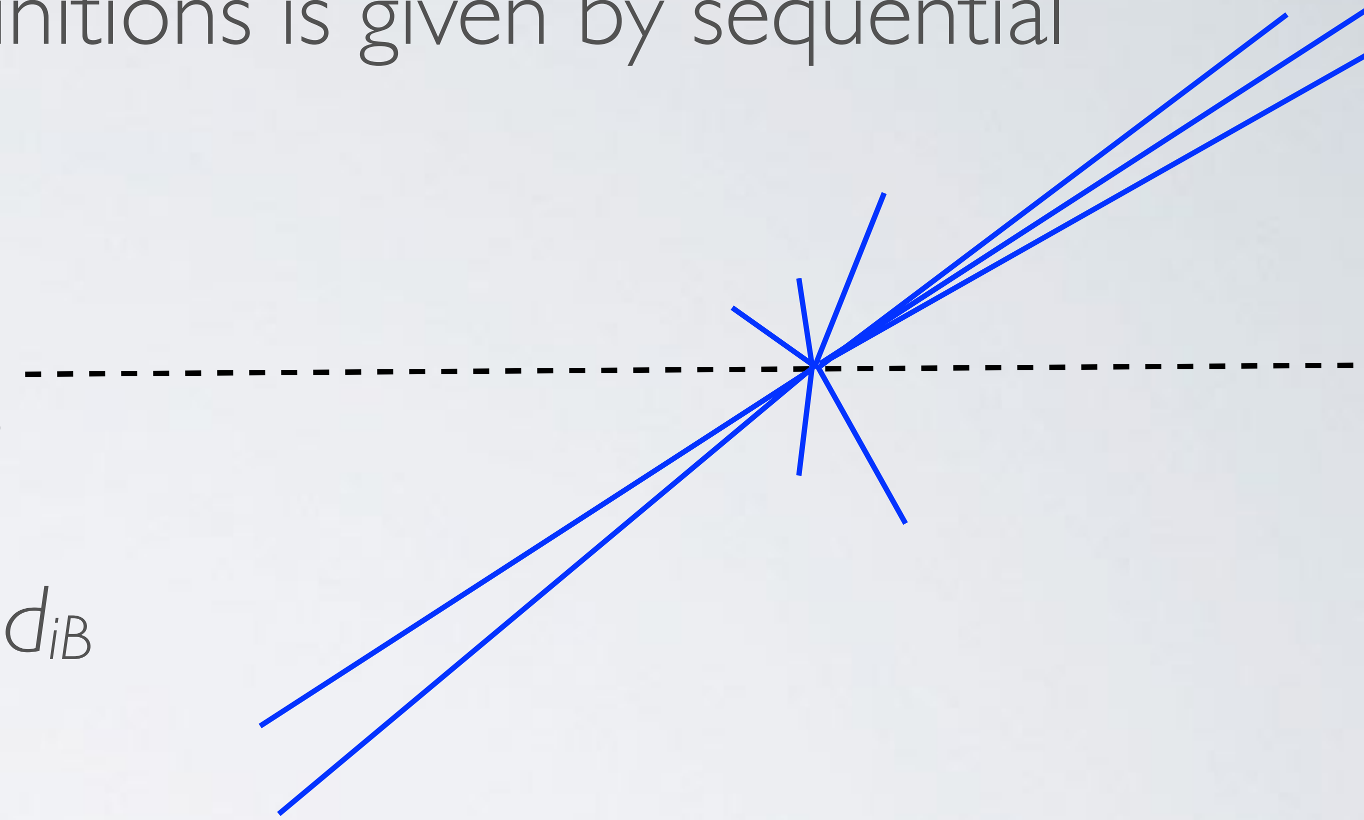


> To study jets, we consider the partial cross section $\sigma(E,\theta,\Omega,\varepsilon,\delta)$ for e^+e^- hadron production events, in which all but a fraction $\varepsilon \ll 1$ of the total e^+e^- energy E is emitted within some pair of oppositely directed cones of half-angle $\delta \ll 1$, 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):

Sequential recombination

- A large class of modern jet definitions is given by sequential recombination algorithms
- Start with a list of particles, compute all distances d_{ij} and d_{iB}
- Find the minimum of all d_{ij} and d_{iB}

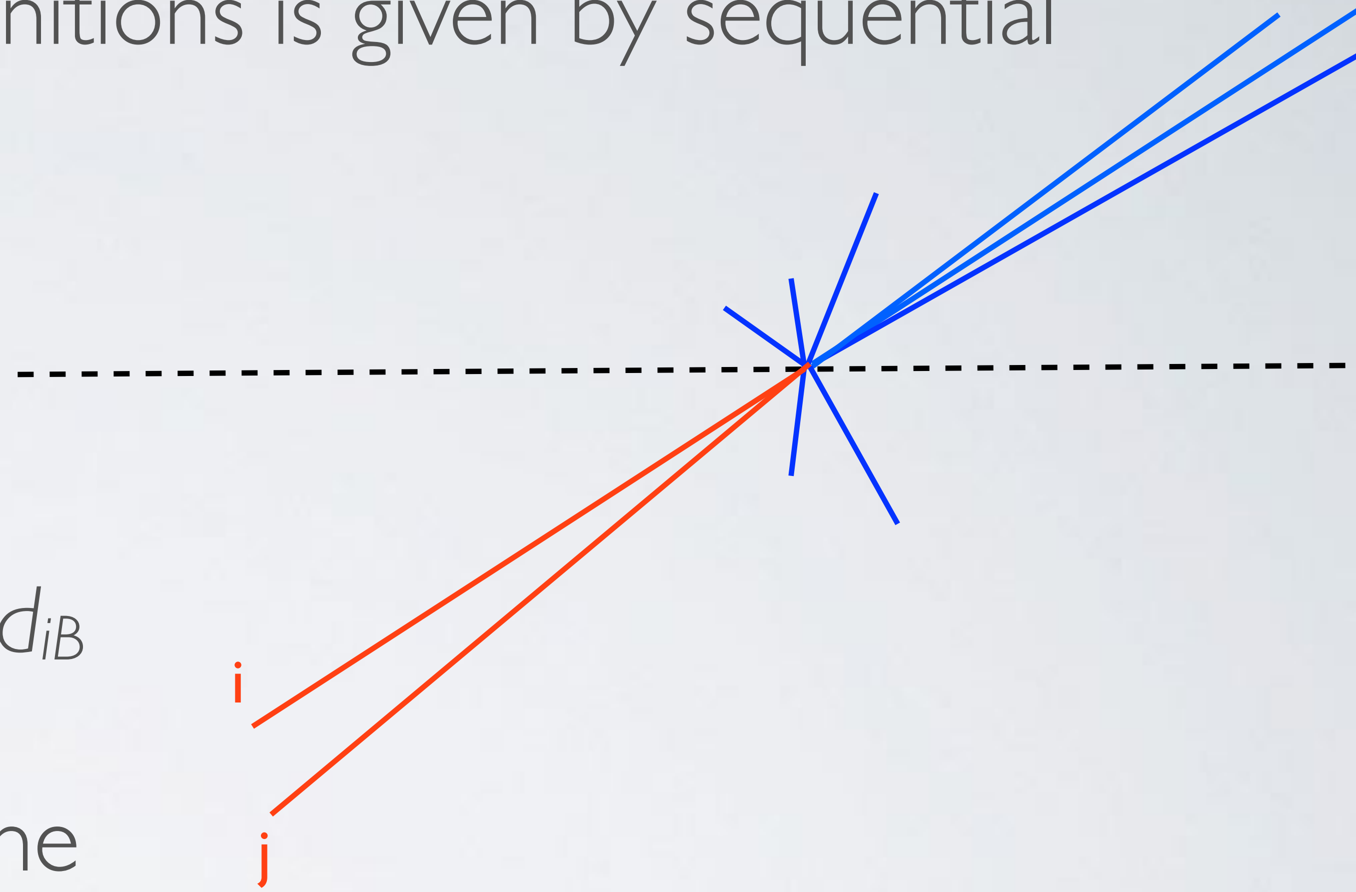


d_{ij} (weighted) distance between i j
d_{iB} external parameter or distance from the beam ...

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

Sequential recombination

- A large class of modern jet definitions is given by sequential recombination algorithms
- 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

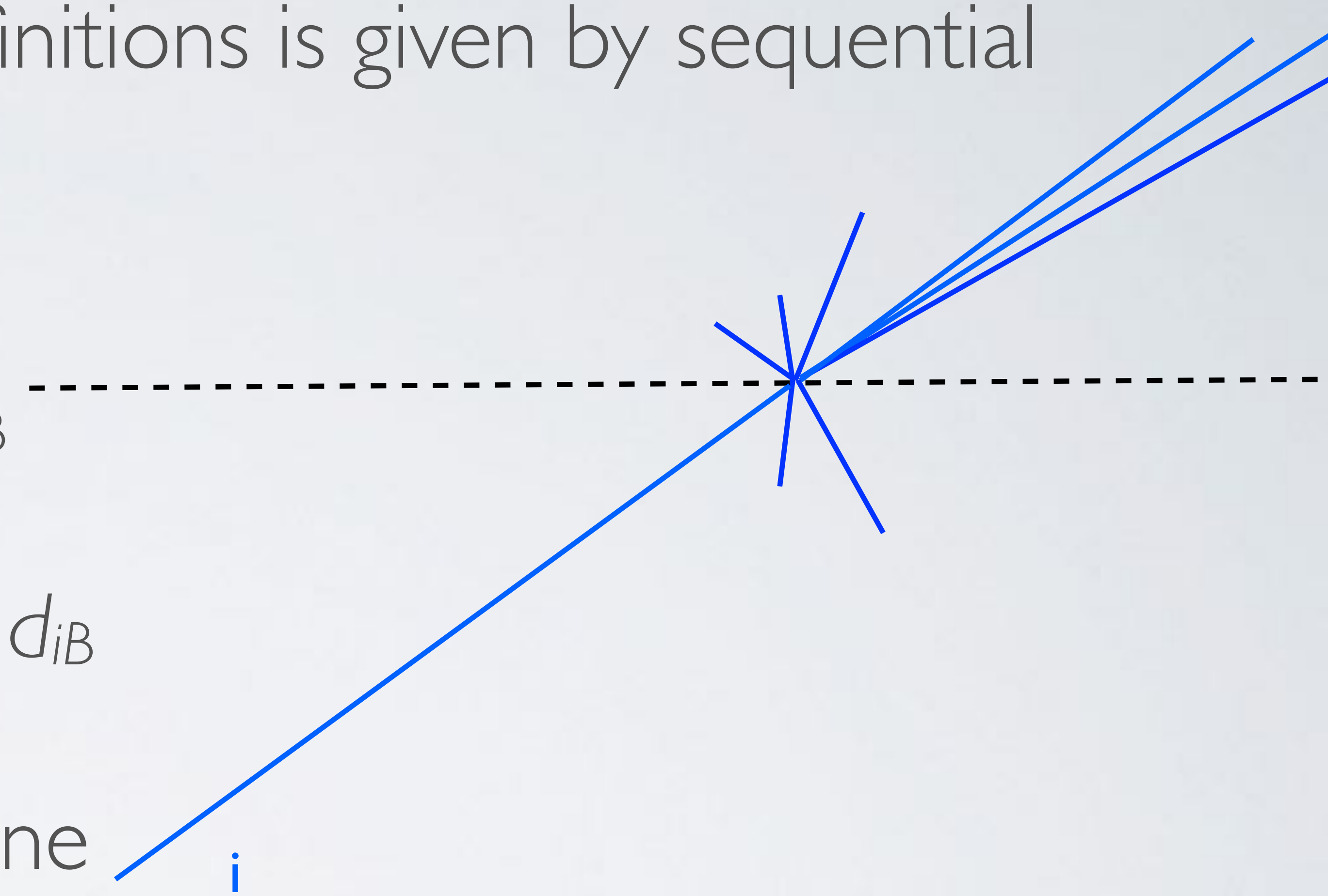


d_{ij} *(weighted) distance between i j*
d_{iB} external parameter or distance from the beam ...

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

Sequential recombination

- A large class of modern jet definitions is given by sequential recombination algorithms
- 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

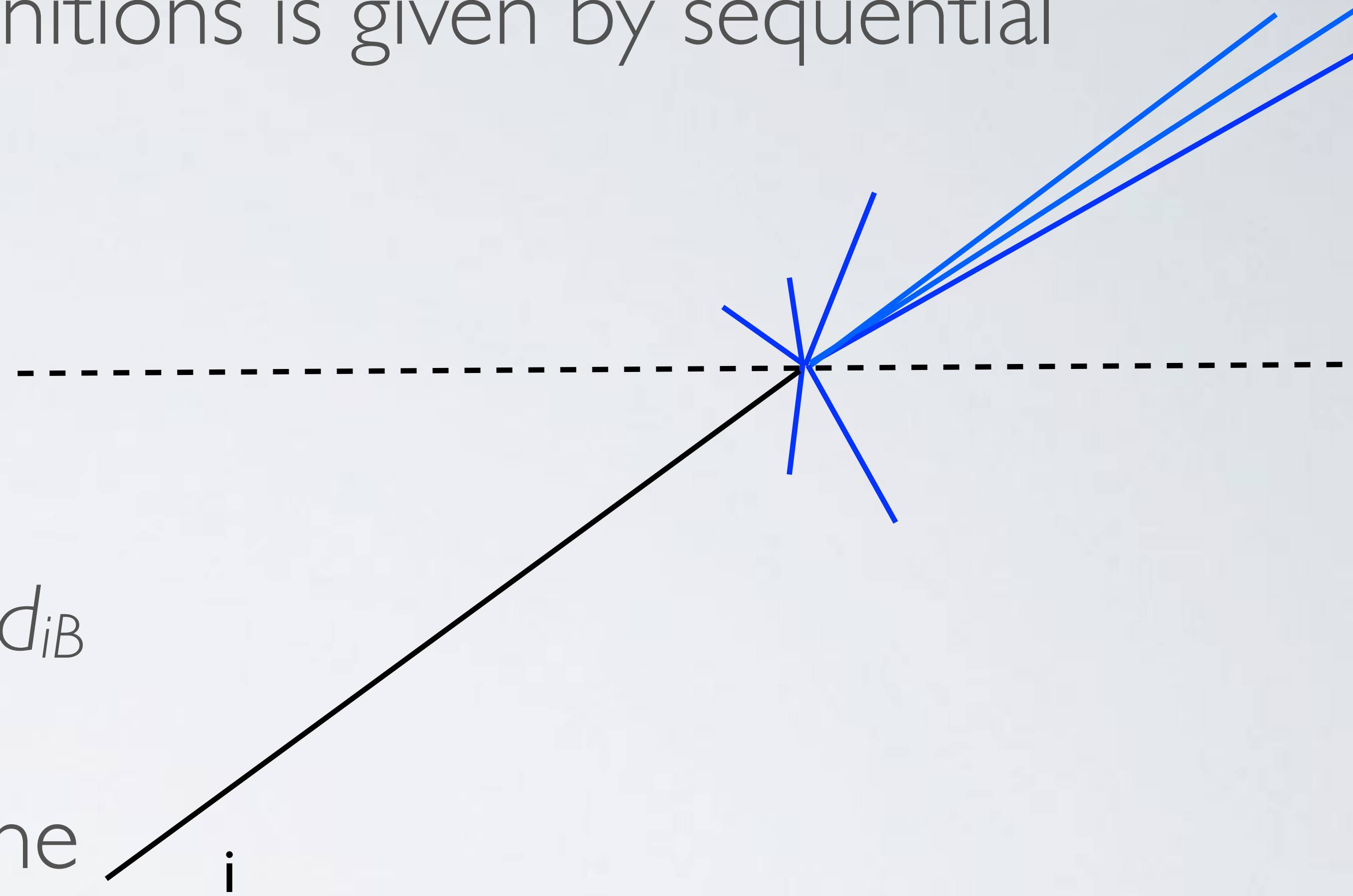


d_{ij} *(weighted) distance between i j*
d_{iB} external parameter or distance from the beam ...

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

Sequential recombination

- A large class of modern jet definitions is given by sequential recombination algorithms
- 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

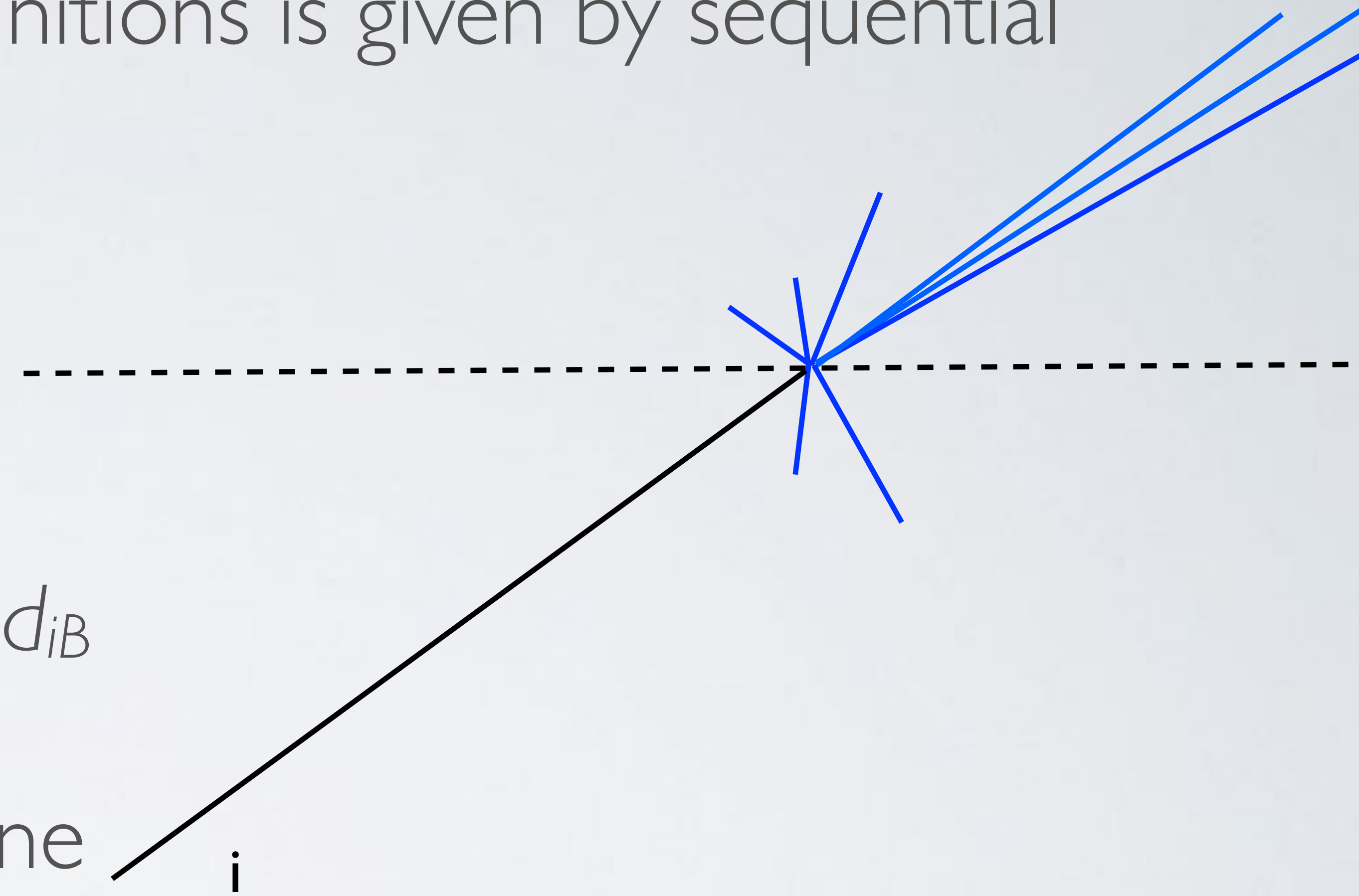


d_{ij} *(weighted) distance between i j*
d_{iB} external parameter or distance from the beam ...

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

Sequential recombination

- A large class of modern jet definitions is given by sequential recombination algorithms
- 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

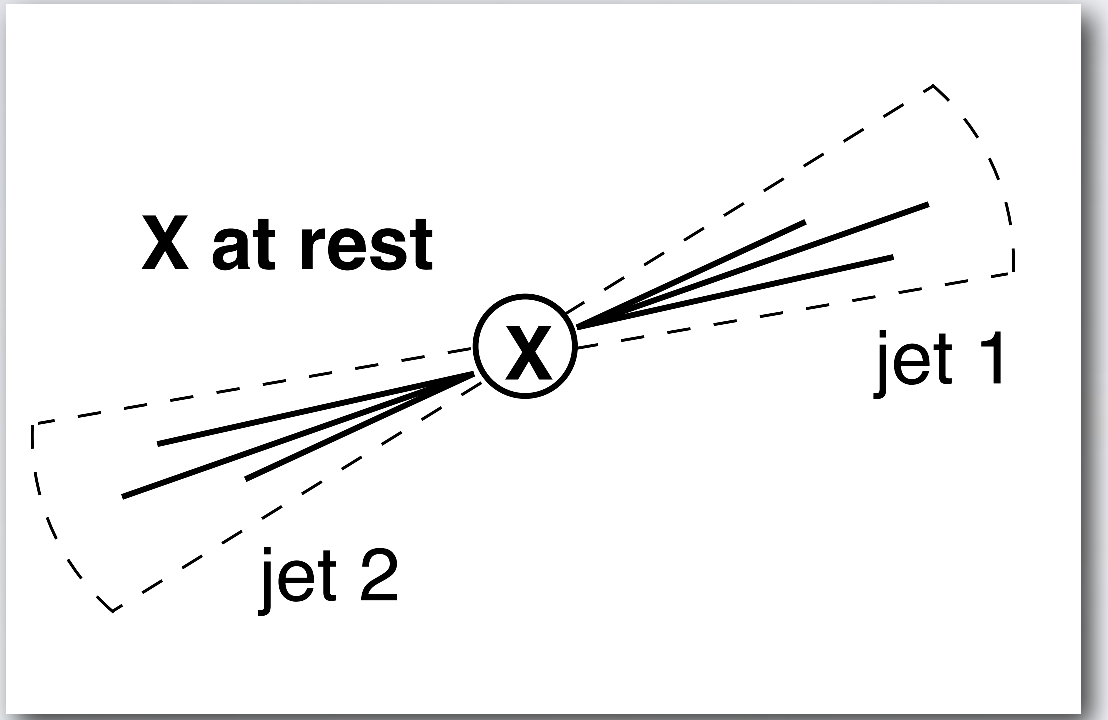


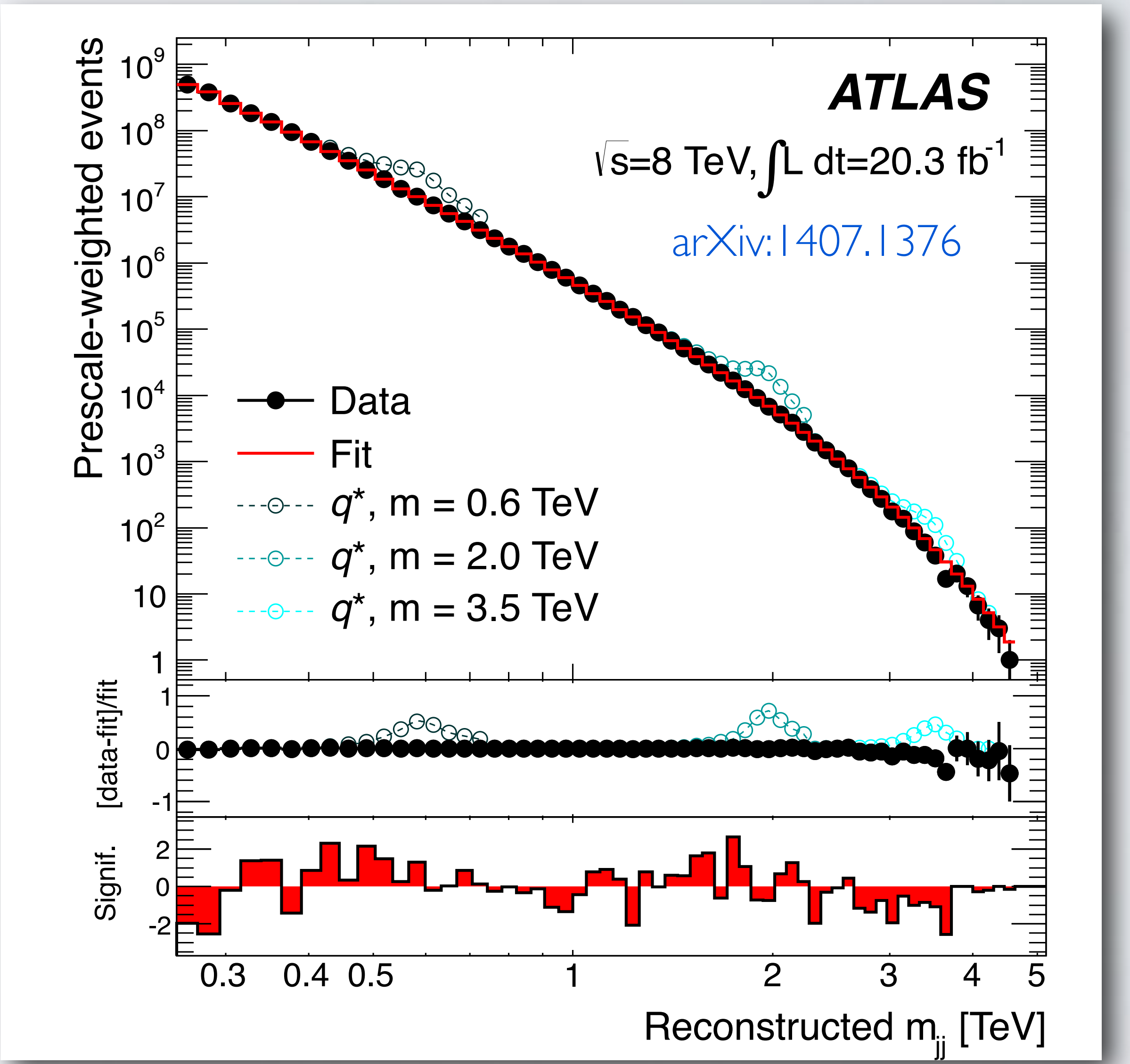
d_{ij} *(weighted) distance between i j*
d_{iB} external parameter or distance from the beam ...

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

Searching for new particles: resolved analyses

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

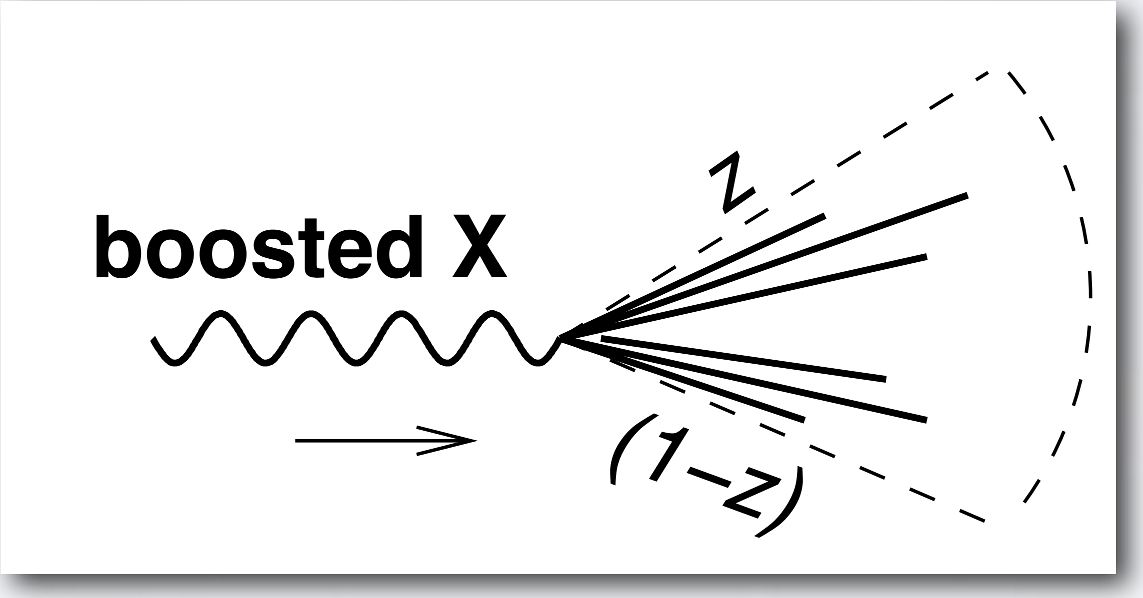




- look for bumps in the dijet invariant mass distribution

Searching for new particles: boosted analyses

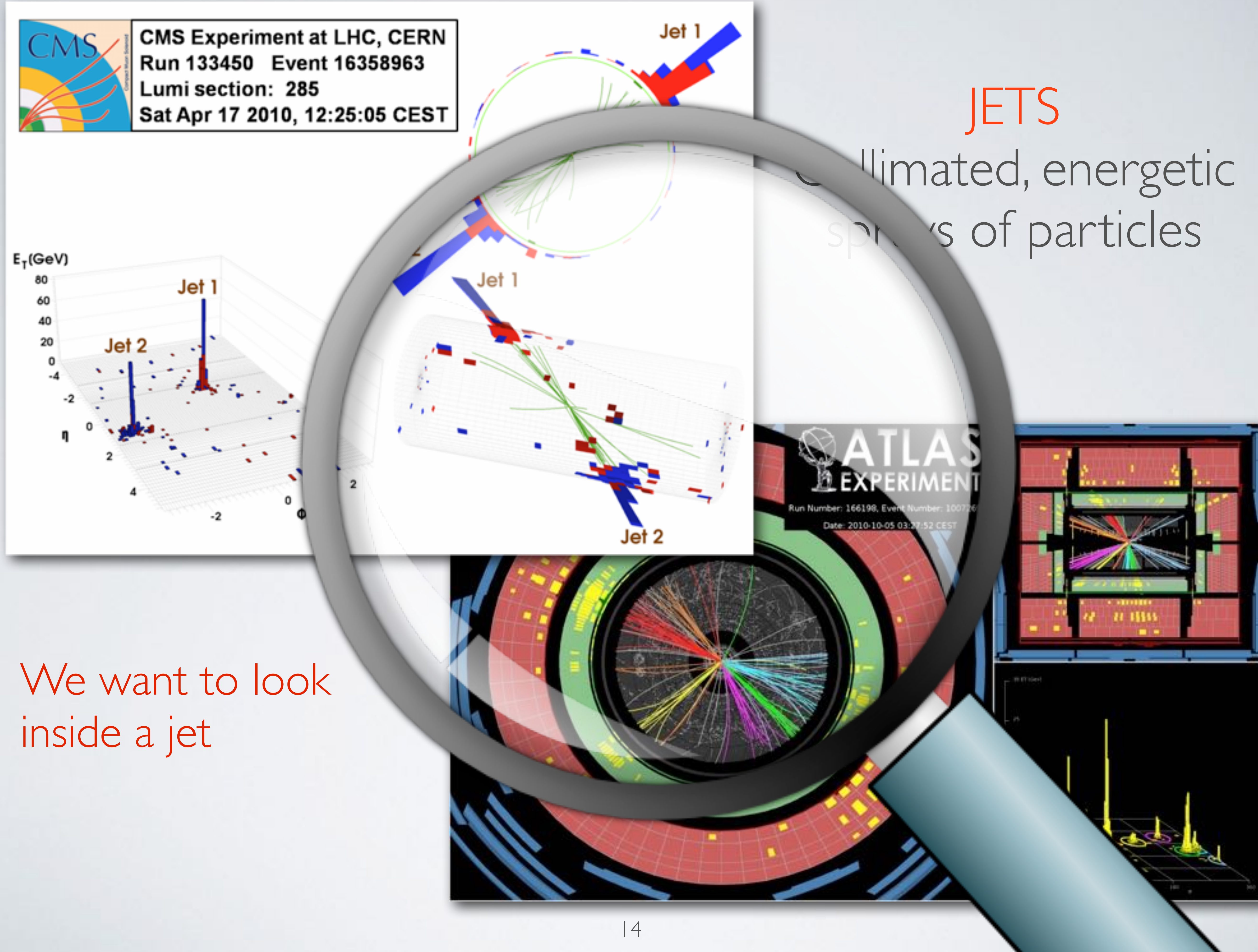
- LHC energy (10^4 GeV) $\gg$ electro-weak scale (10^2 GeV)
- EW-scale particles (new physics, Z/W/H/top) are abundantly produced with a large boost



- 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

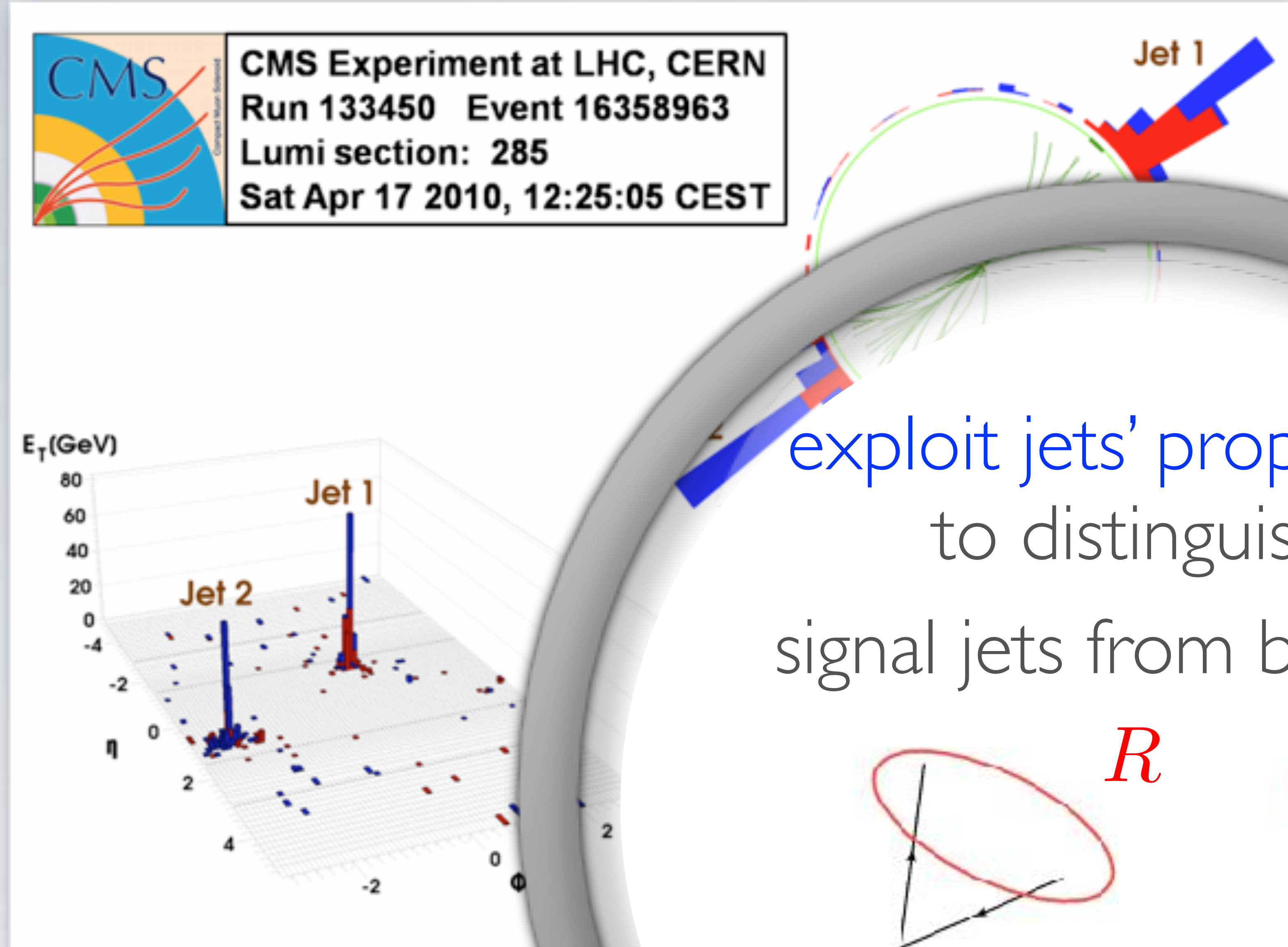


We want to look inside a jet

JETS

llimated, energetic

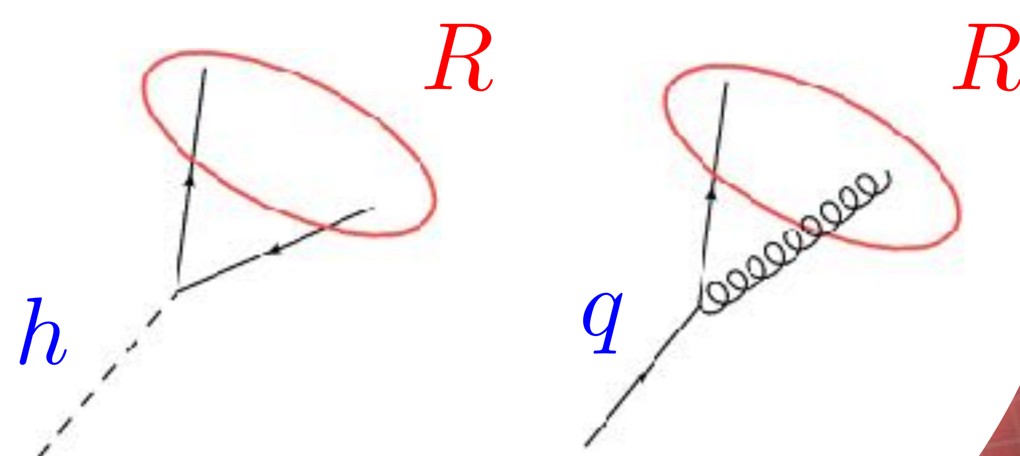
s of particles



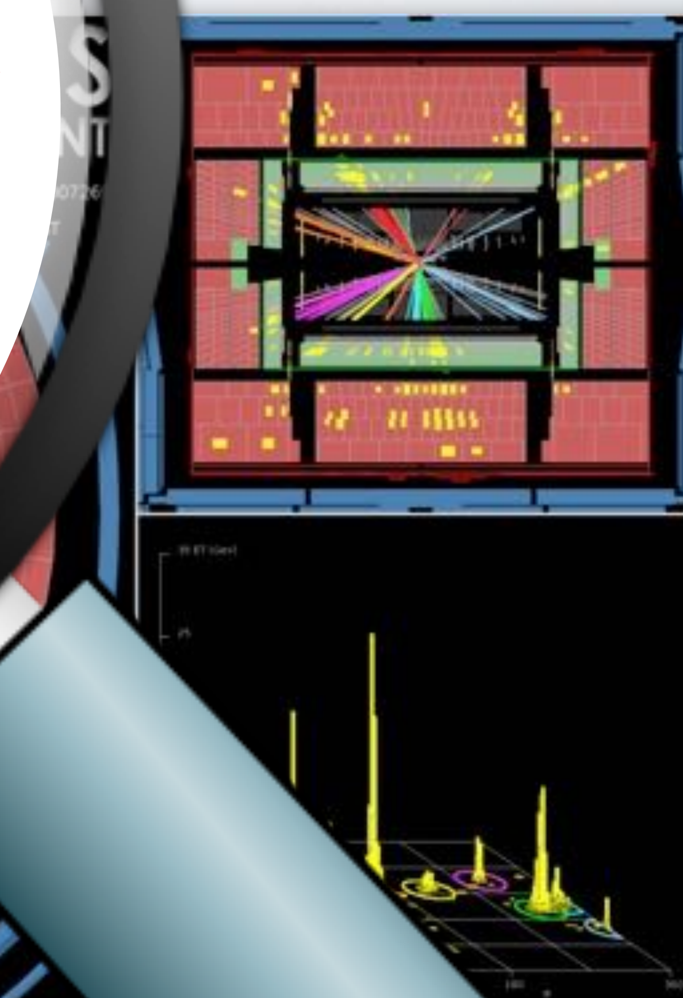
exploit jets' properties

to distinguish

signal jets from bkg jets



$$p_t > 2m/R$$

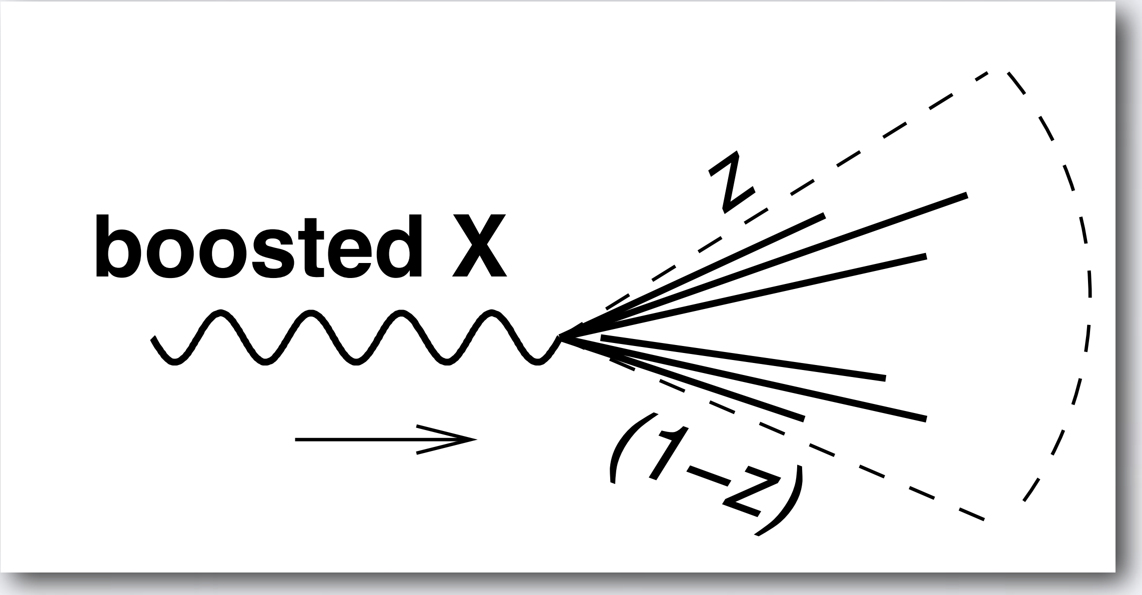


We want to look inside a jet

Looking inside jets

Signal-jet mass

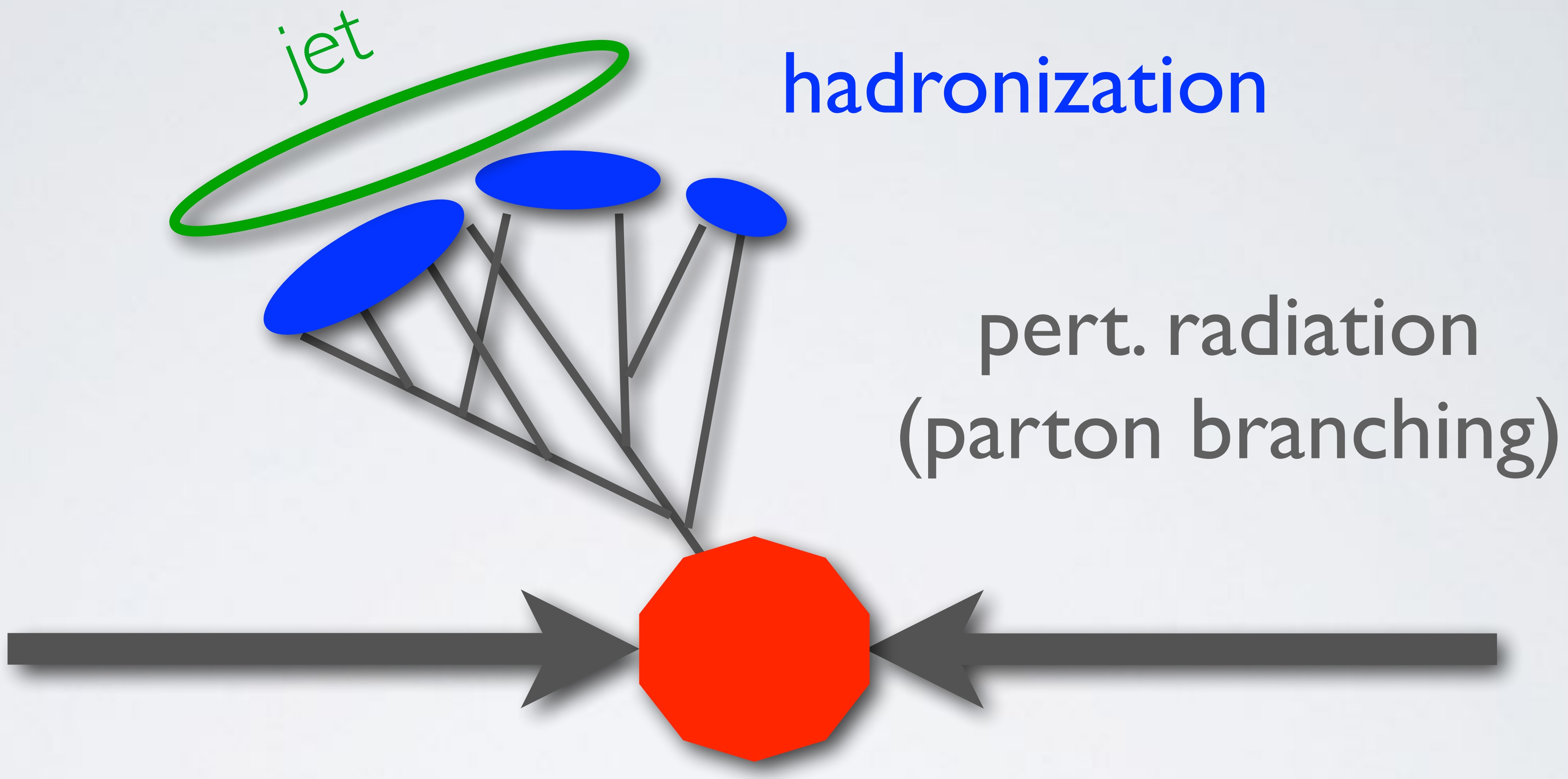
- First jet-observable that comes to mind
- Signal jet should have a mass distribution peaked near the resonance



- However, that's a simple partonic picture

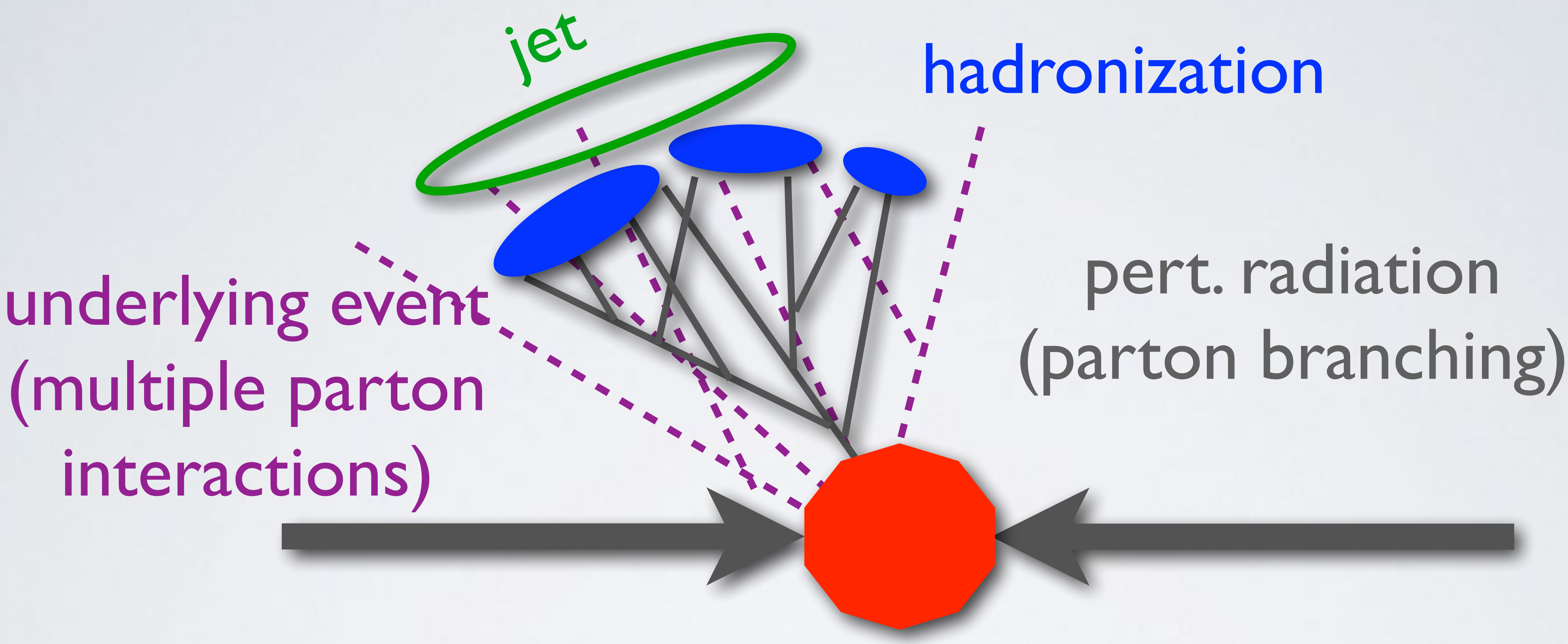
A useful cartoon

inspired by G. Salam



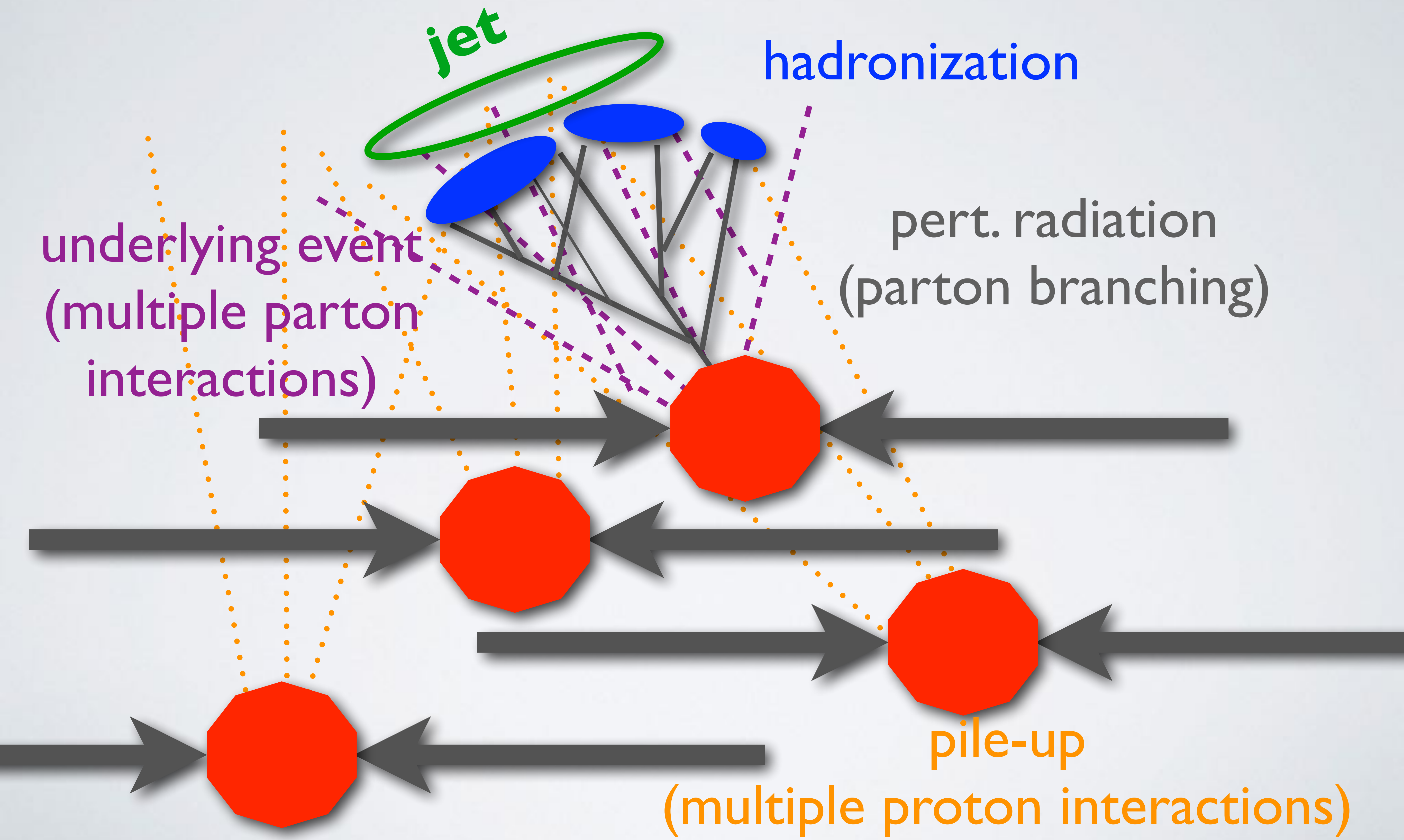
A useful cartoon

inspired by G. Salam



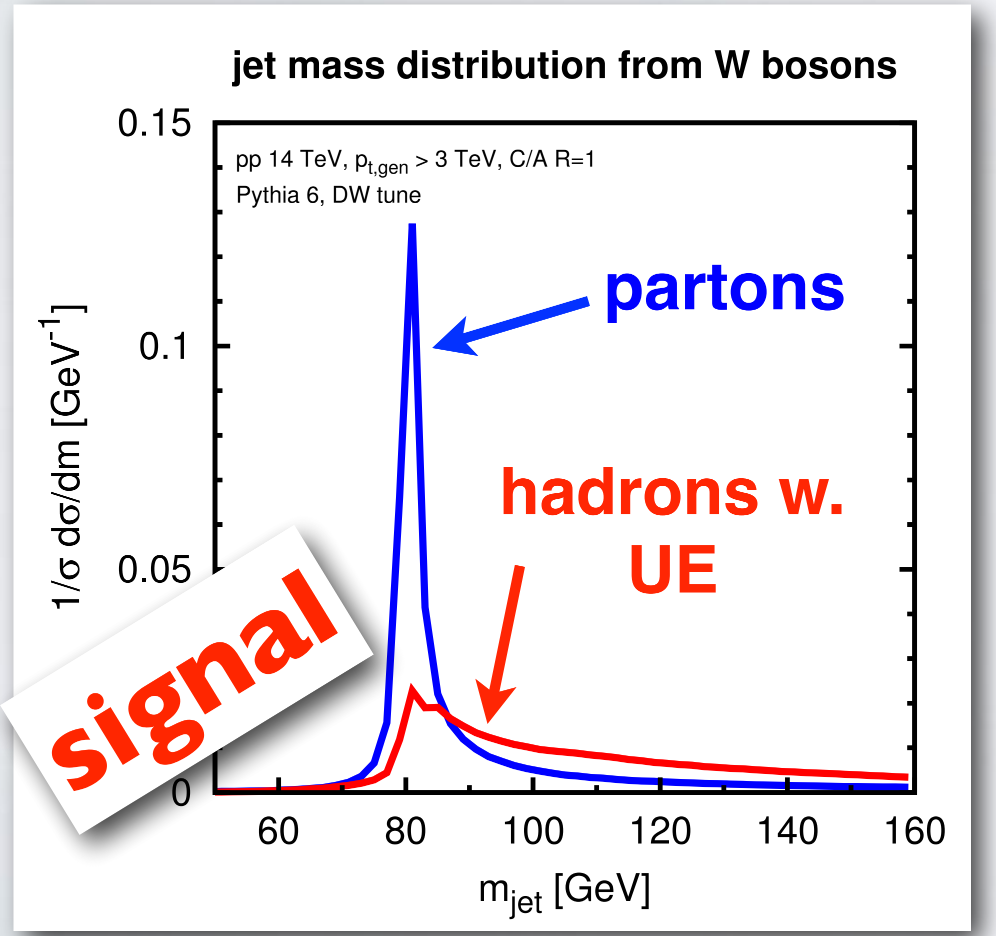
A useful cartoon

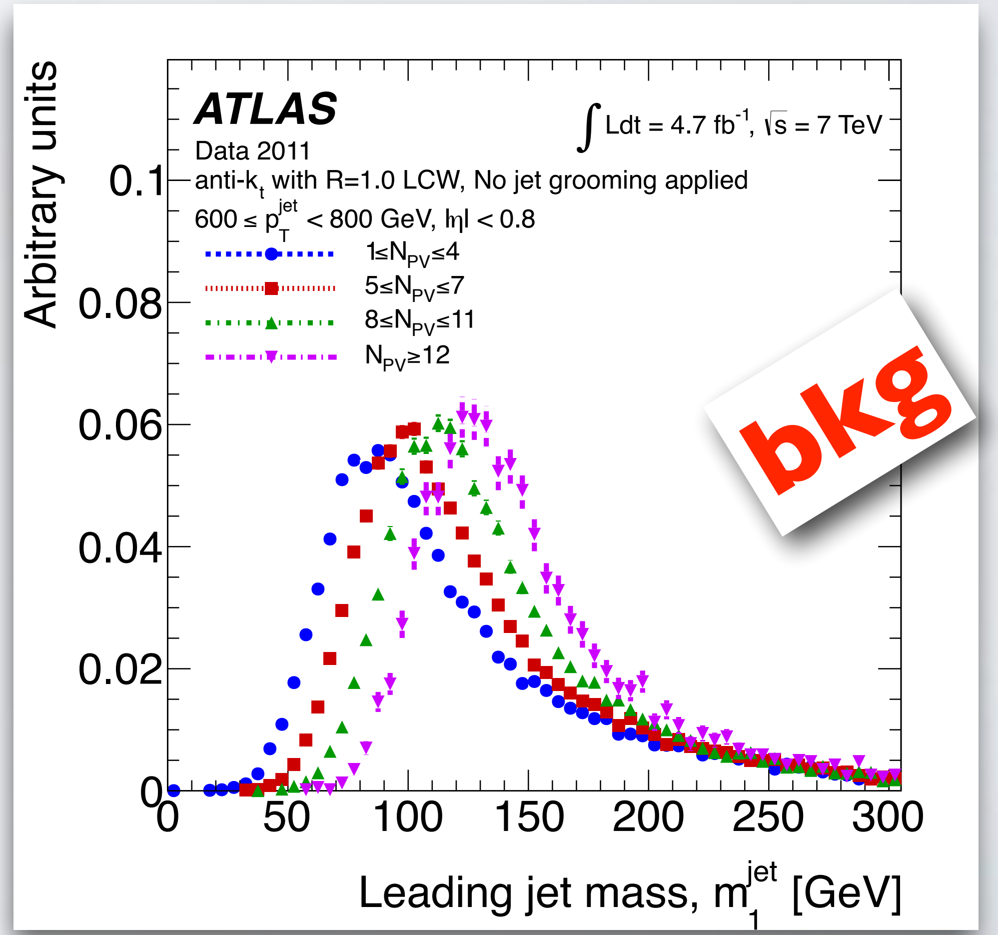
inspired by G. Salam



Effect of 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)

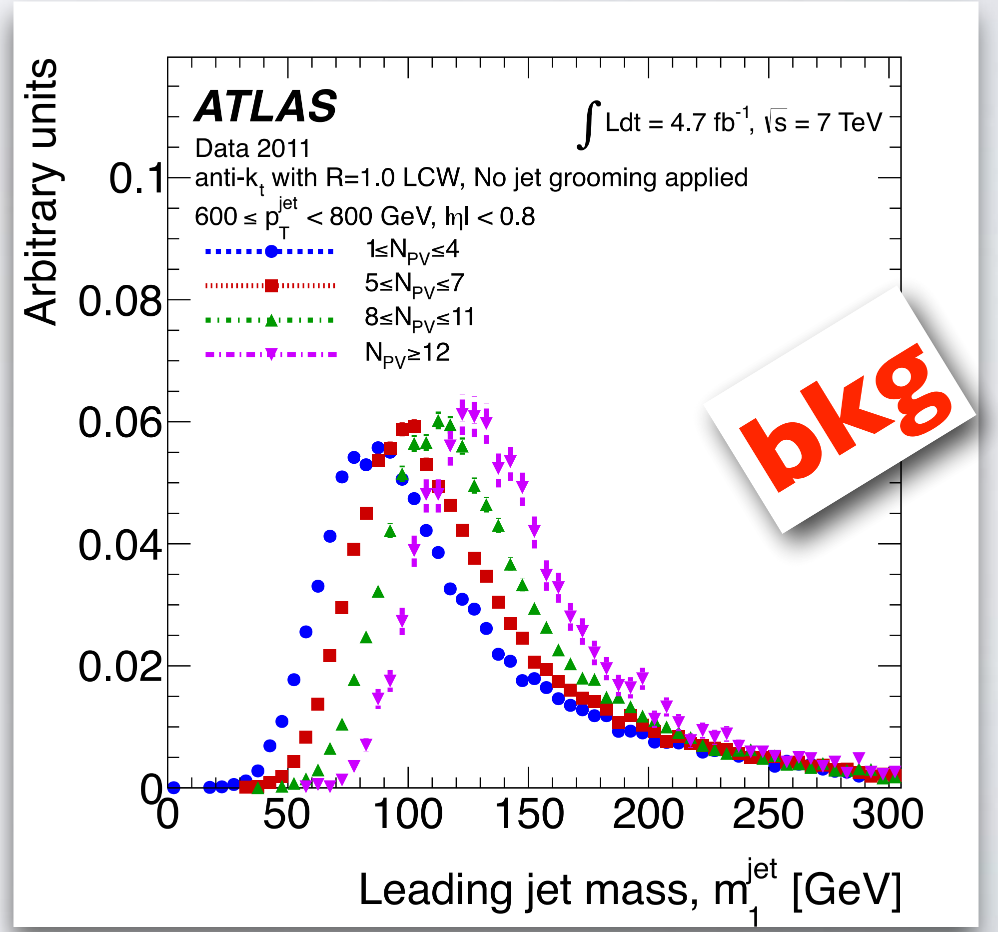




ATLAS, JHEP 1309 (2013) 076

Beyond the mass: substructure

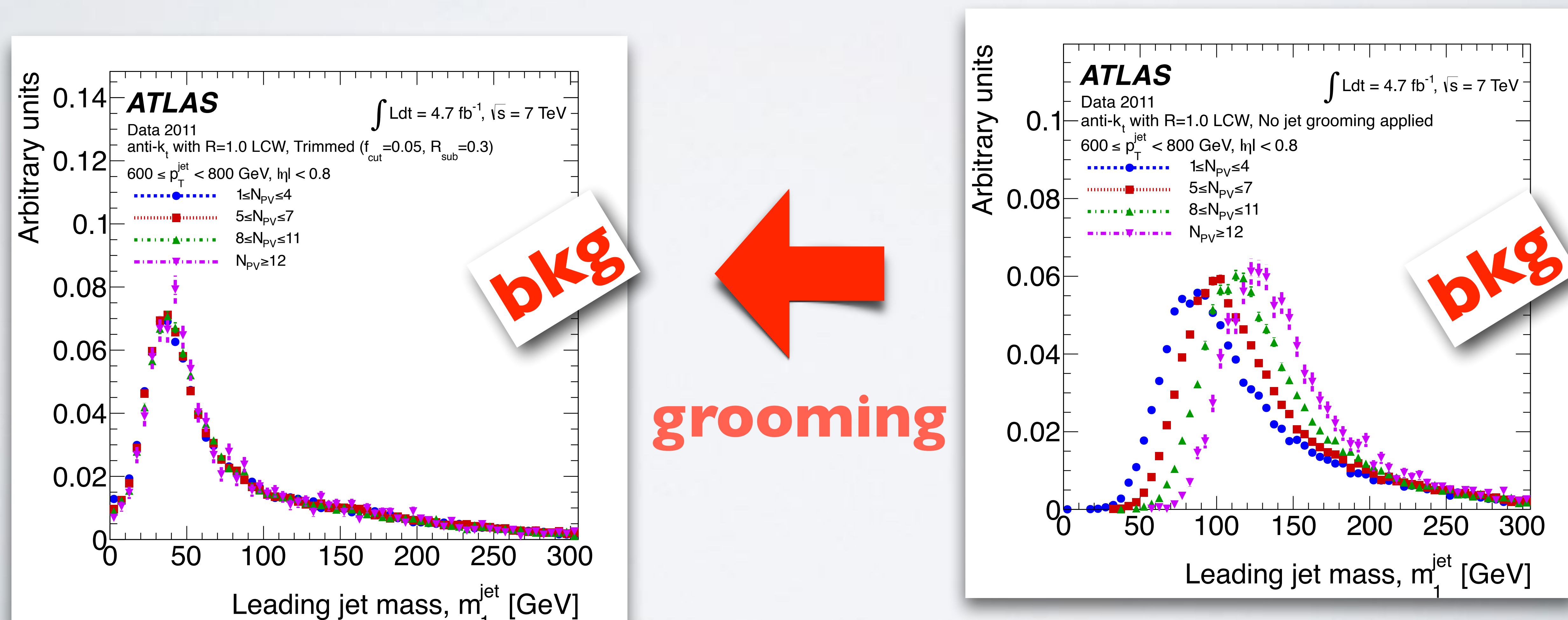
- Let's have a closer look: background peaks in the EW region
- Need to go beyond the mass and exploit jet substructure
- Grooming and Tagging:
  1. clean the jets up by removing soft junk
  2. identify the features of hard decays and cut on them



ATLAS, JHEP 1309 (2013) 076

Beyond the mass: substructure

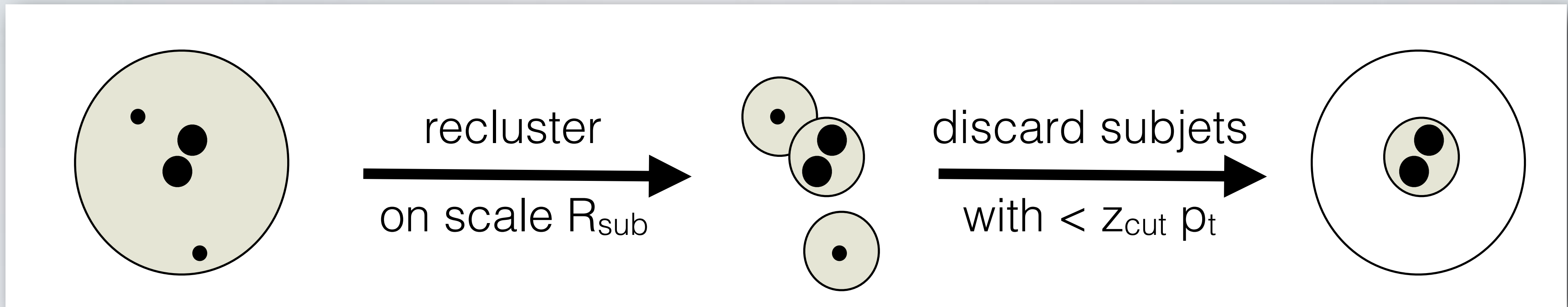
- Let's have a closer look: background peaks in the EW region
- Need to go beyond the mass and exploit jet substructure
- Grooming and Tagging:
  1. clean the jets up by removing soft junk
  2. identify the features of hard decays and cut on them
- Grooming provides a handle on UE and pile-up



ATLAS, JHEP 1309 (2013) 076

Trimming

Krohn, Thaler and Wang (2010)



1. Take all particles in a jet and re-cluster them with a smaller jet radius $R_{sub} < R$

2. Keep all subjets for which $p_t^{subjet} > z_{cut}\, p_t$

3. Recombine the subjets to form the trimmed jet

A theorist's worry

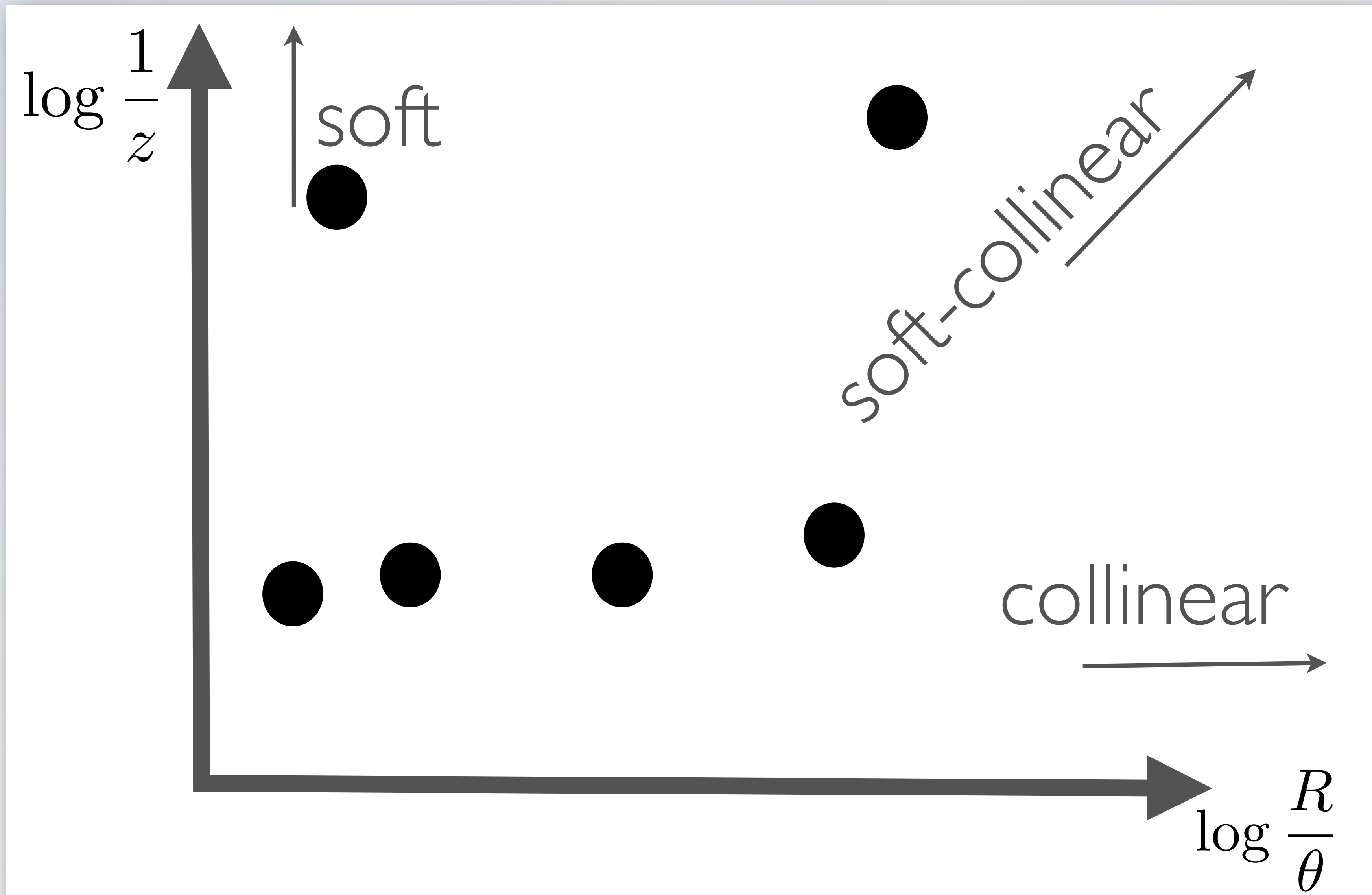
- Complicated algorithms with many parameters
- Are we giving up on calculability / precision QCD ?

- First comprehensive QCD study of these algorithms

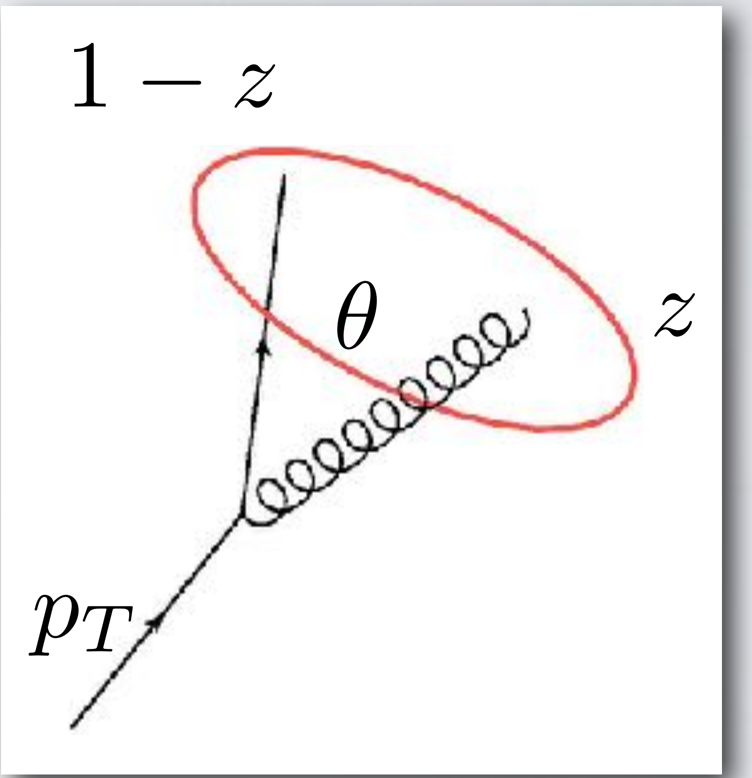
Dasgupta, Fregoso, SM, Powling EPJ C (2013)
Dasgupta, Fregoso, SM, Salam, JHEP 1309 029 (2013)

Theoretical understanding of jet substructure

Soft-gluon phase space



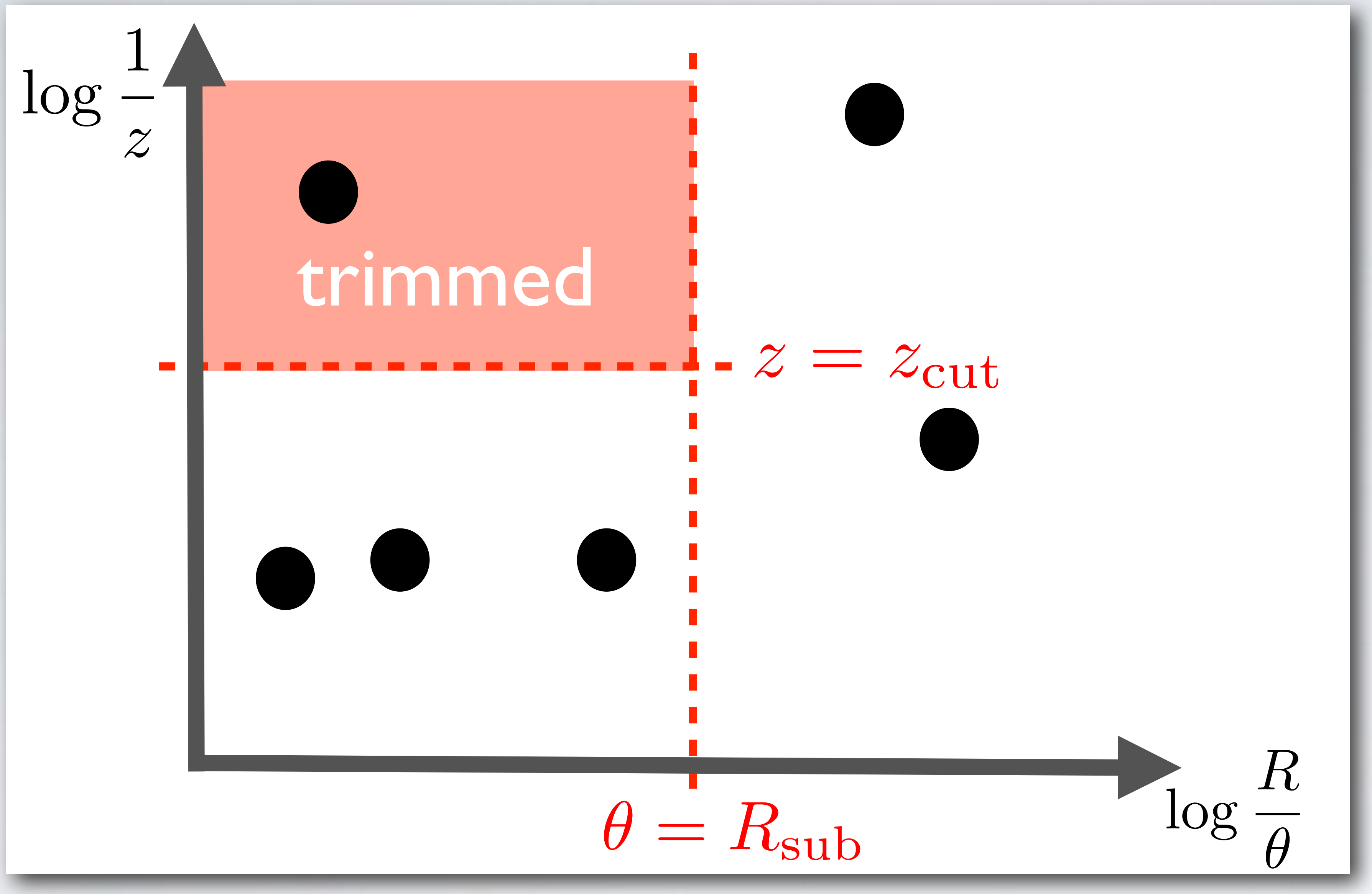
Soft gluons off a hard parton (a quark for definiteness)



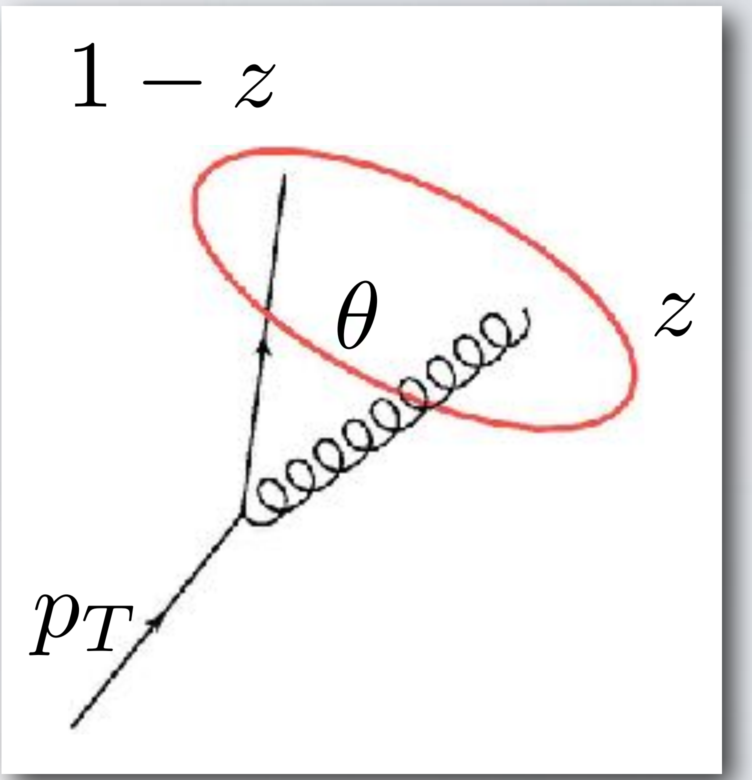
Emission probability is uniform in the (log z, log θ) plane:

$$dP_i \sim \frac{\alpha_s}{\pi} C_r \frac{dz_i}{z_i} \frac{d\theta_i}{\theta_i}$$

Trimming

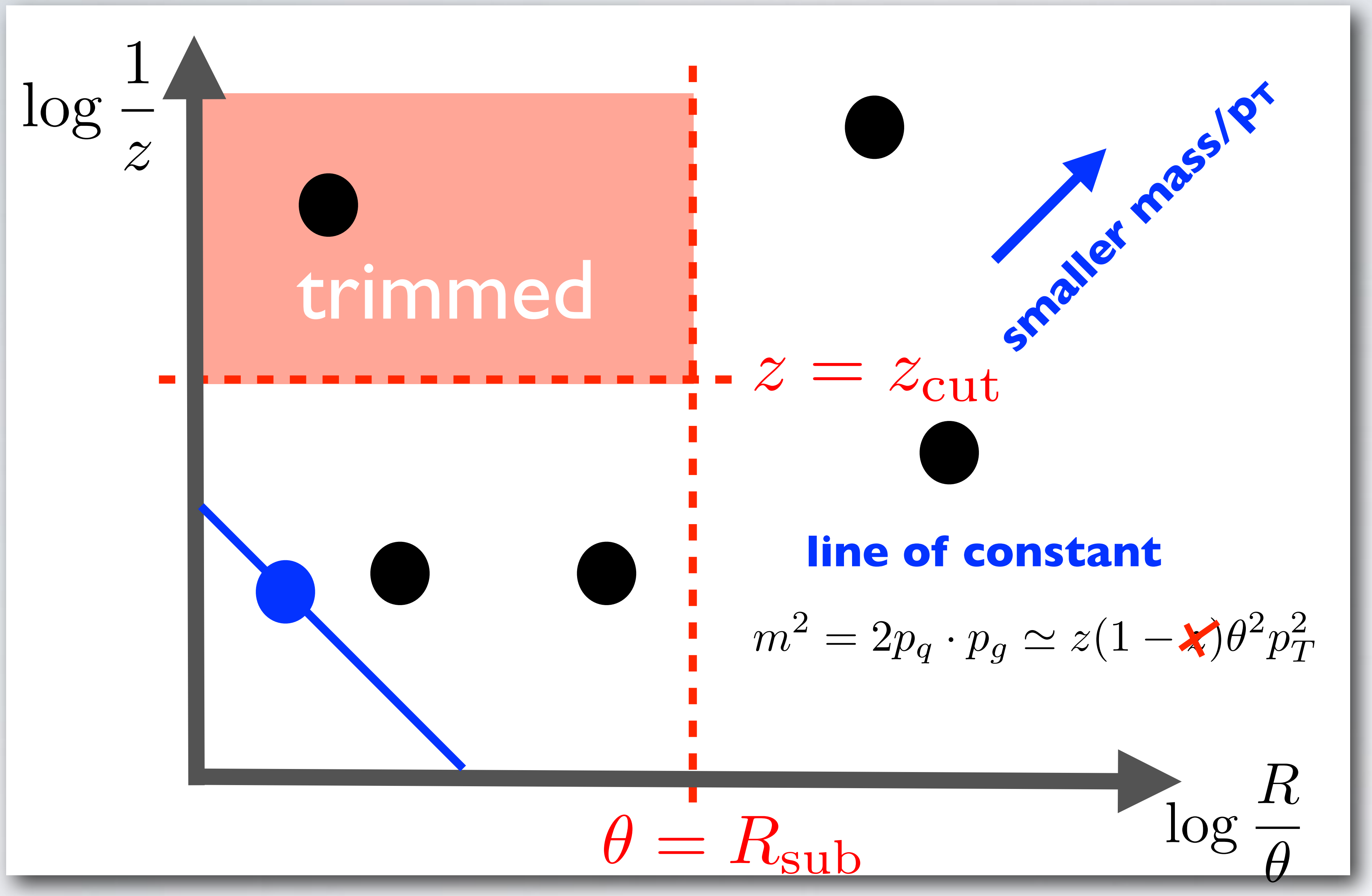


Soft gluons off a hard parton (a quark for definiteness)

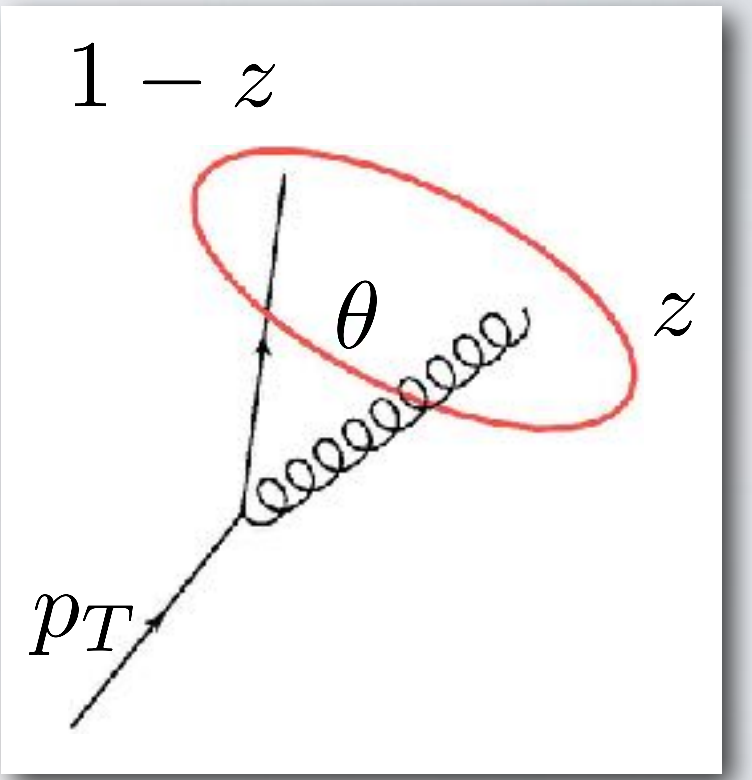


- The action of a groomer is to remove some of the allowed phase space (typically soft and soft-collinear)
- What are the consequences for physical observables, e.g. the jet mass ?

Trimming

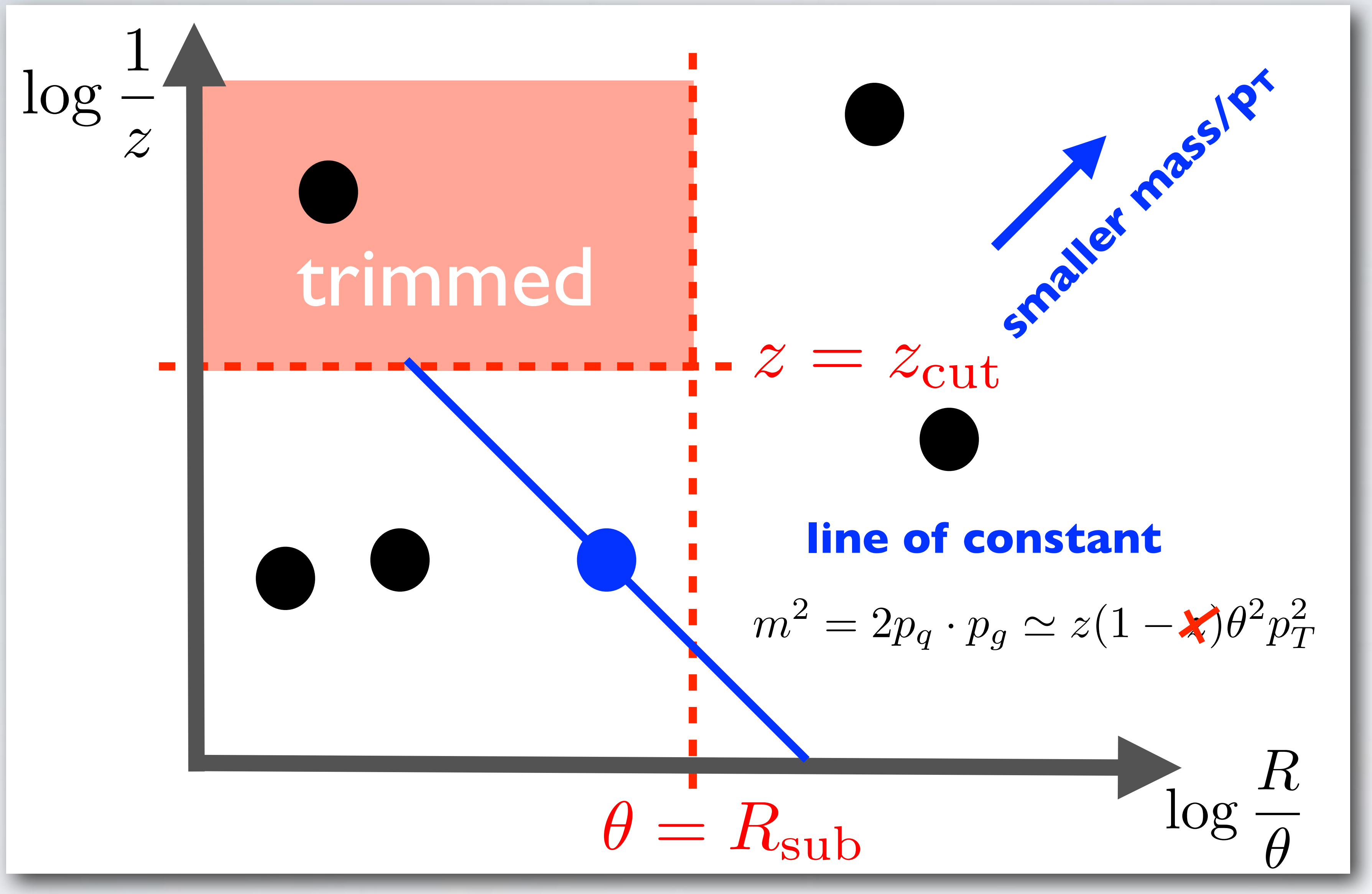


Soft gluons off a hard parton (a quark for definiteness)

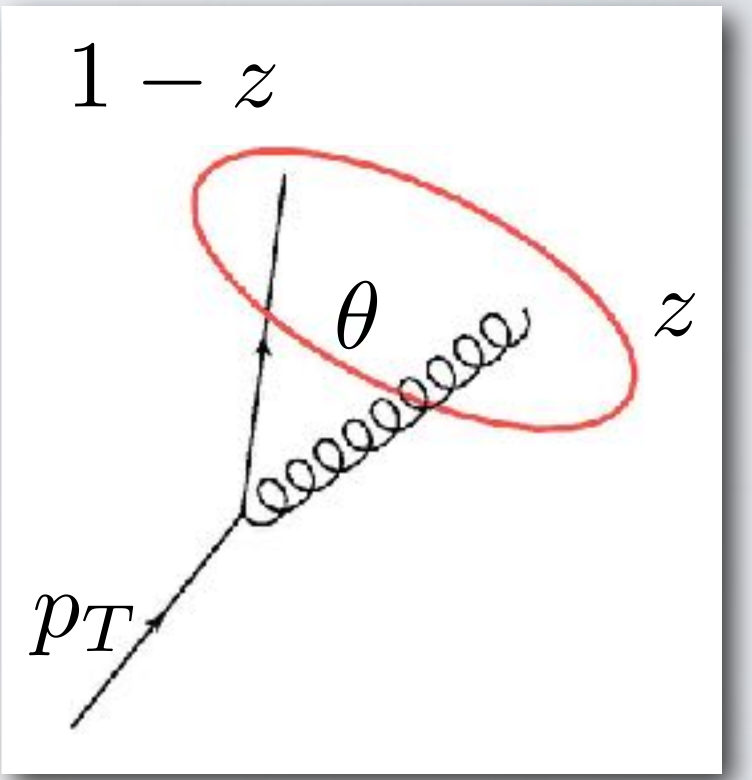


- The action of a groomer is to remove some of the allowed phase space (typically soft and soft-collinear)
- What are the consequences for physical observables, e.g. the jet mass ?

Trimming

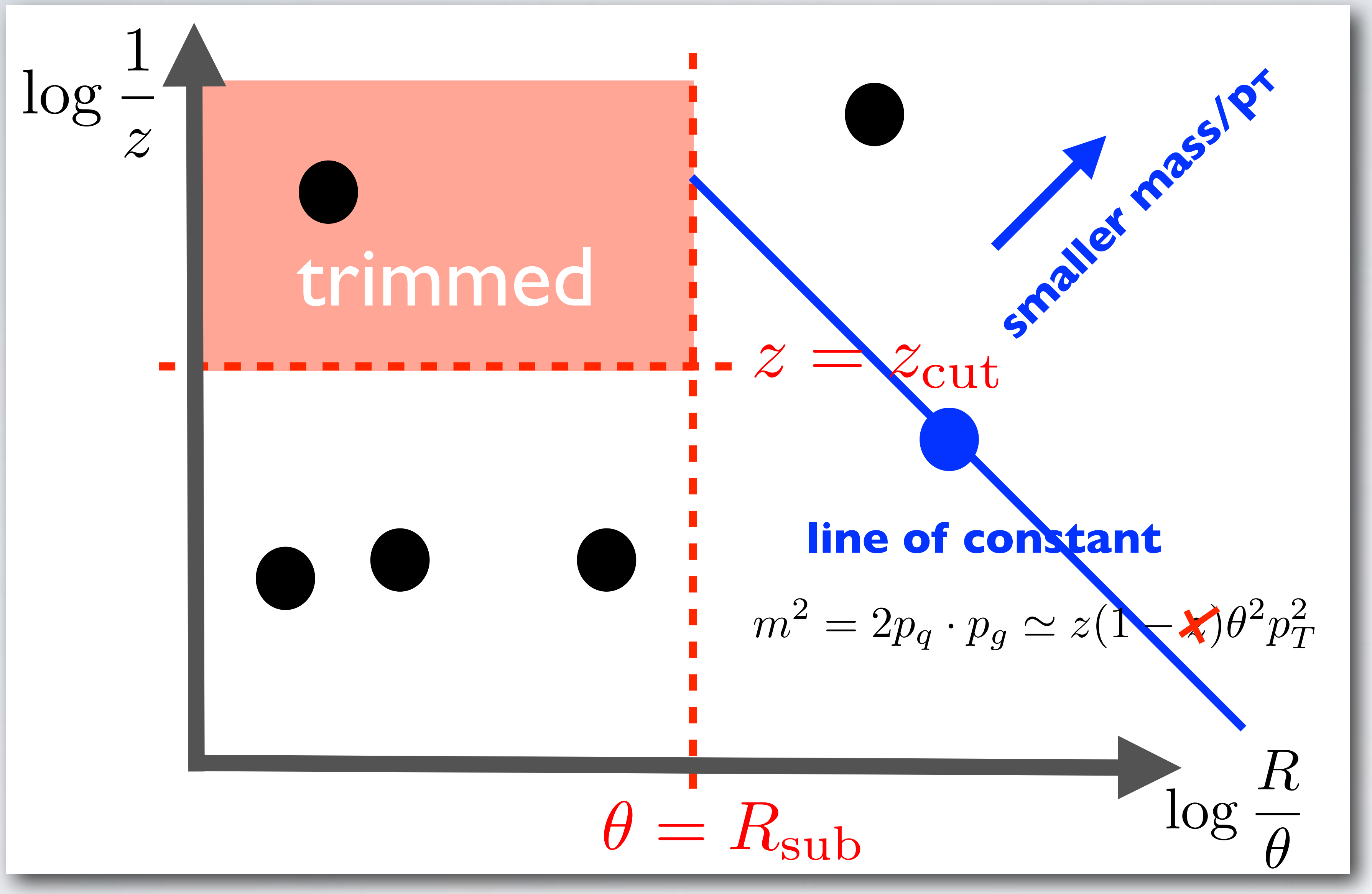


Soft gluons off a hard parton (a quark for definiteness)

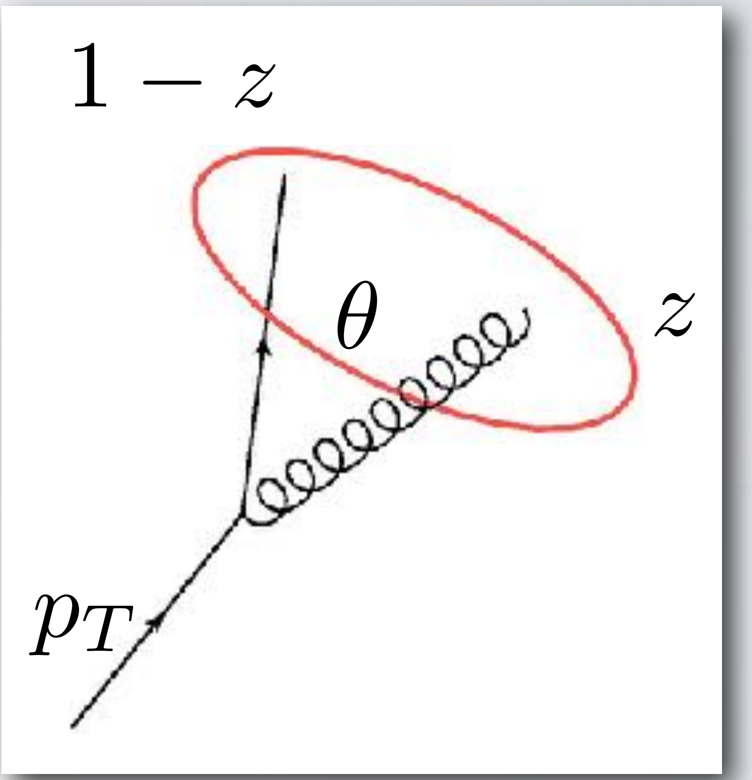


- The action of a groomer is to remove some of the allowed phase space (typically soft and soft-collinear)
- What are the consequences for physical observables, e.g. the jet mass ?

Trimming

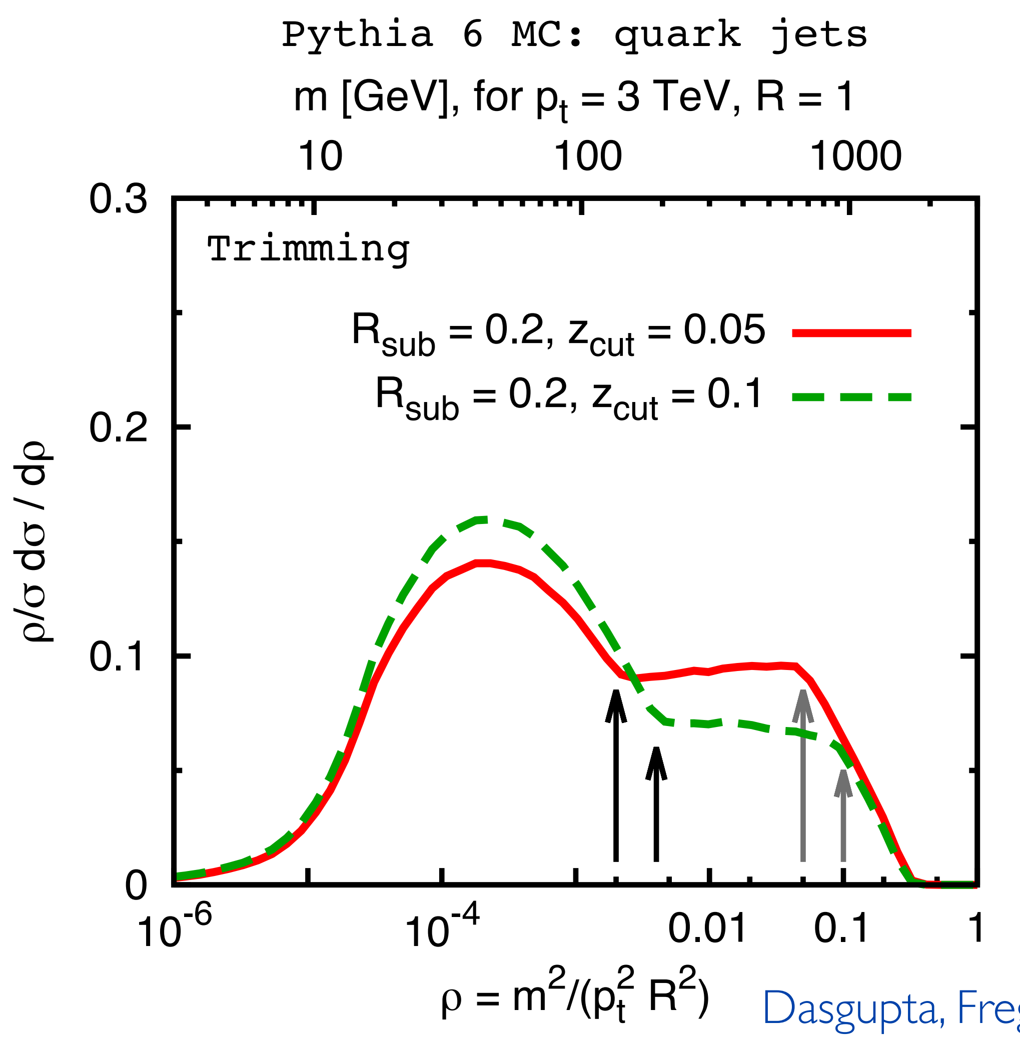


Soft gluons off a hard parton (a quark for definiteness)



- The action of a groomer is to remove some of the allowed phase space (typically soft and soft-collinear)
- What are the consequences for physical observables, e.g. the jet mass ?

Trimmed mass: MC vs analytics

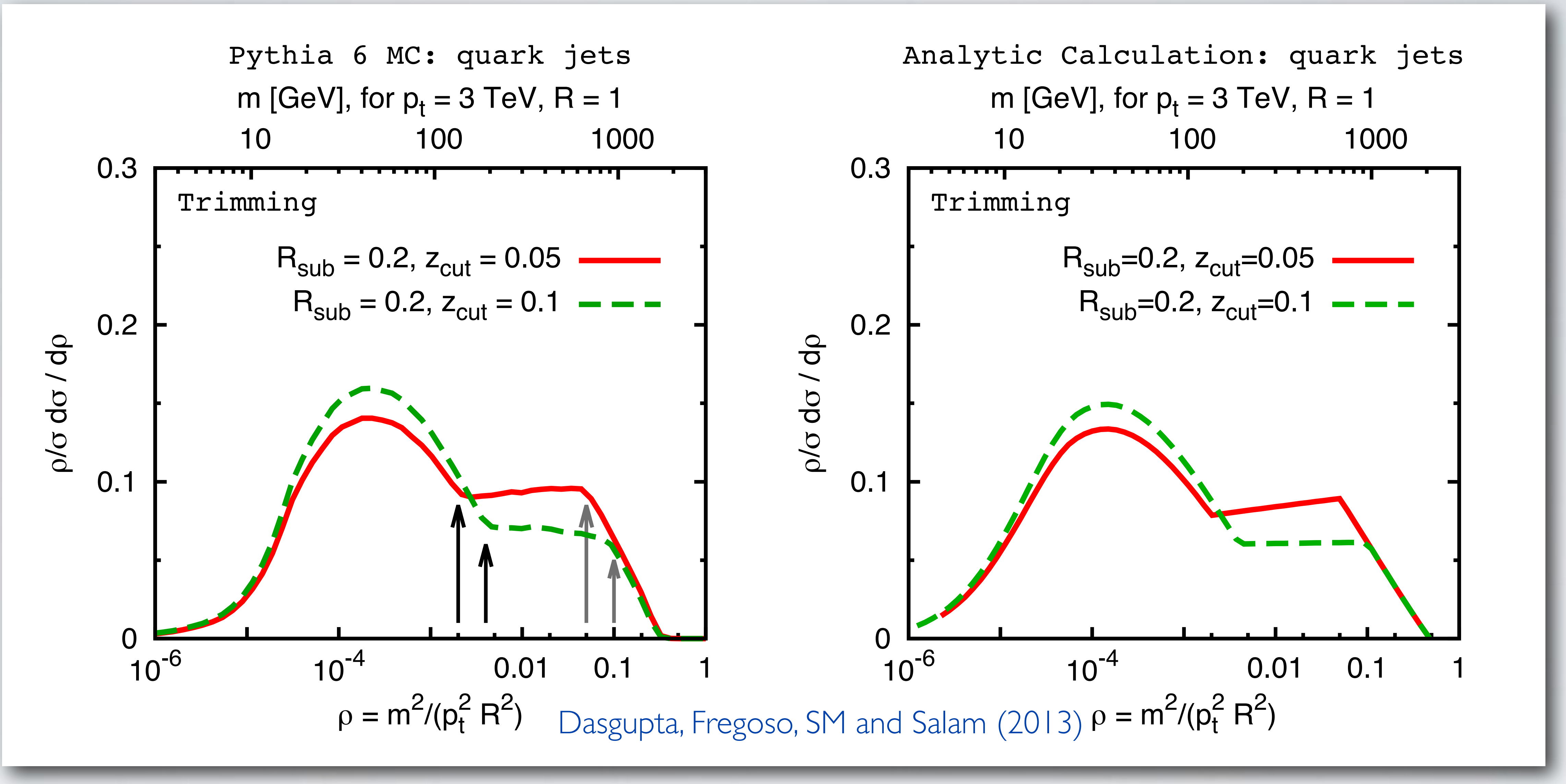


Dasgupta, Fregoso, SM and Salam (2013)

- Trimming is active (and aggressive) for $z_{cut} < \boldsymbol{\rho} < R_{sub}^2/R^2\, z_{cut}$
- Not active below because of fixed R_{sub}

Trimmed mass: MC vs analytics

Modified LL (MLL): LL + hard collinear + running coupling

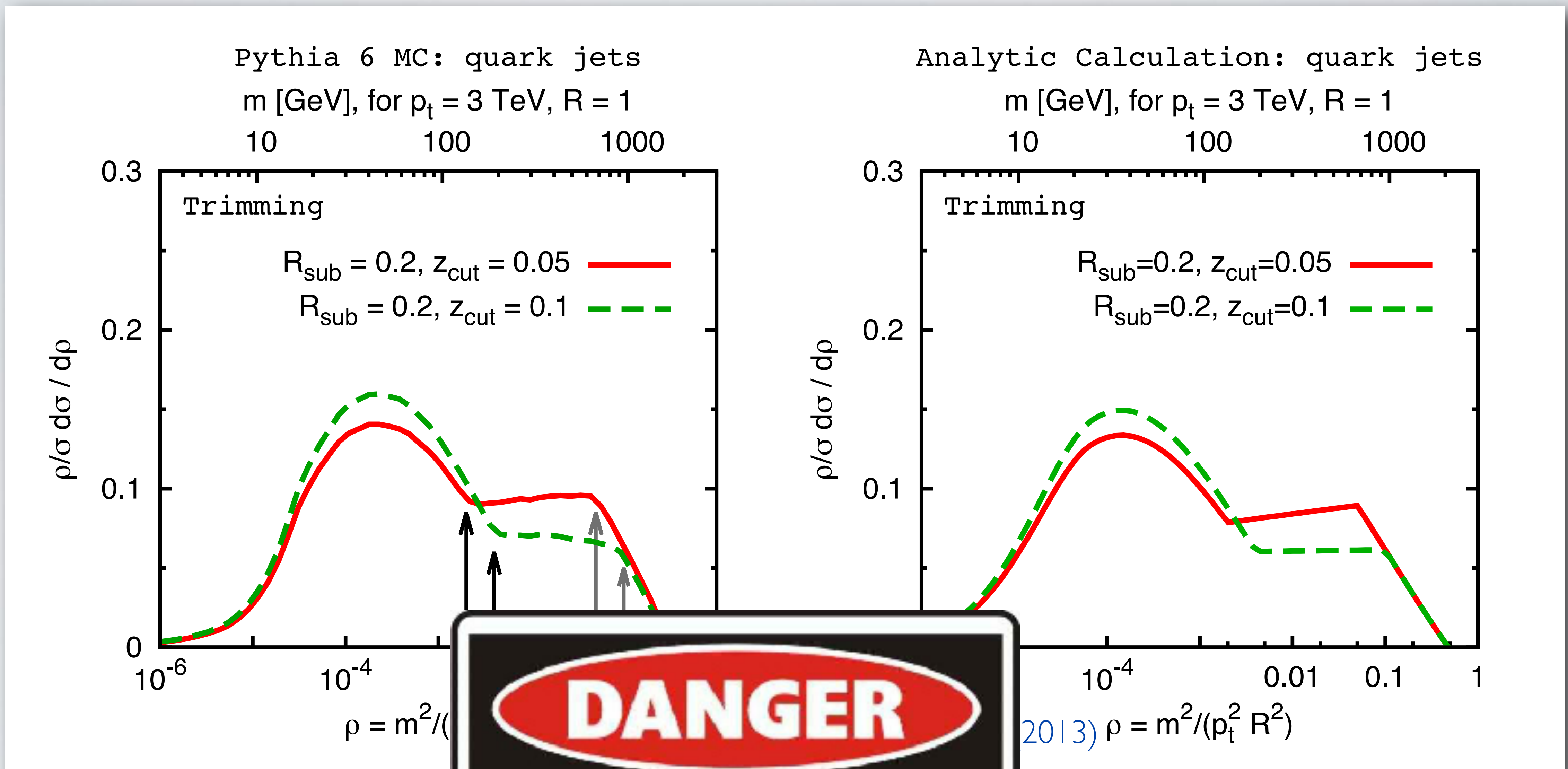


Dasgupta, Fregoso, SM and Salam (2013)

- Trimming is active (and aggressive) for $z_{cut} < \boldsymbol{\rho} < R_{sub}^2/R^2\ z_{cut}$
- Not active below because of fixed R_{sub}

Trimmed mass: MC vs analytics

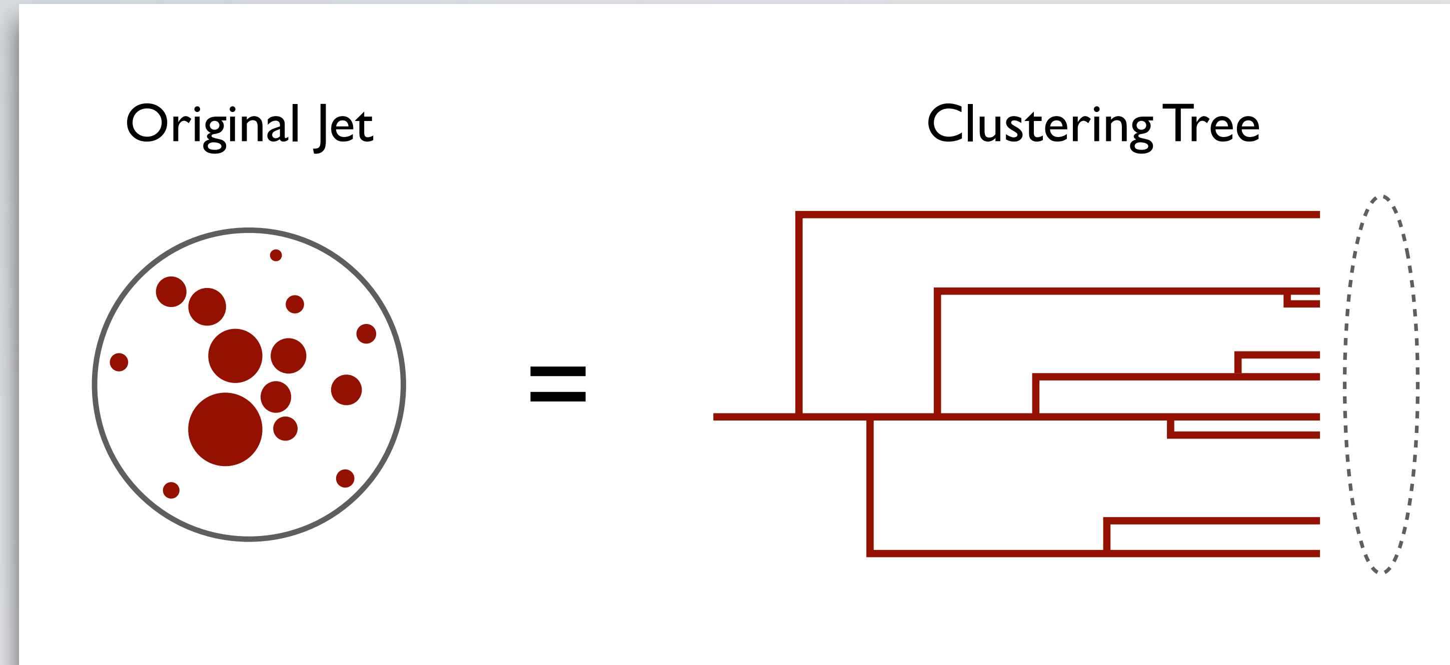
Modified LL (MLL): LL + hard collinear + running coupling



- Trimming is active ... $z_{cut} < \rho < R_{sub}^2/R^2 \, z_{cut}$
- Not active below ...

Soft Drop: understanding at work

Larkoski, SM, Soyez and Thaler (2014)



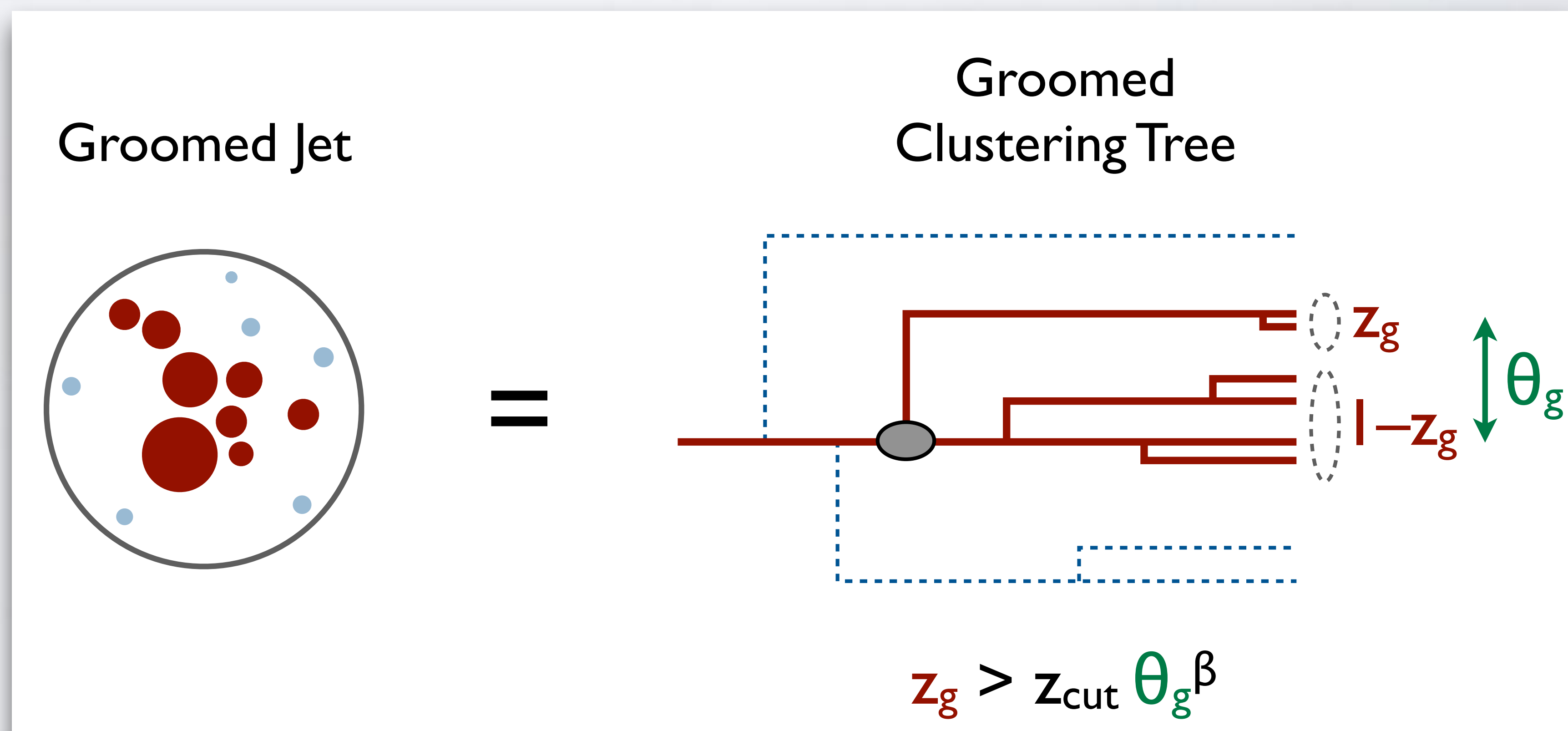
Go back in the jet clustering history

check momentum sharing

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

discard soft branches, i.e

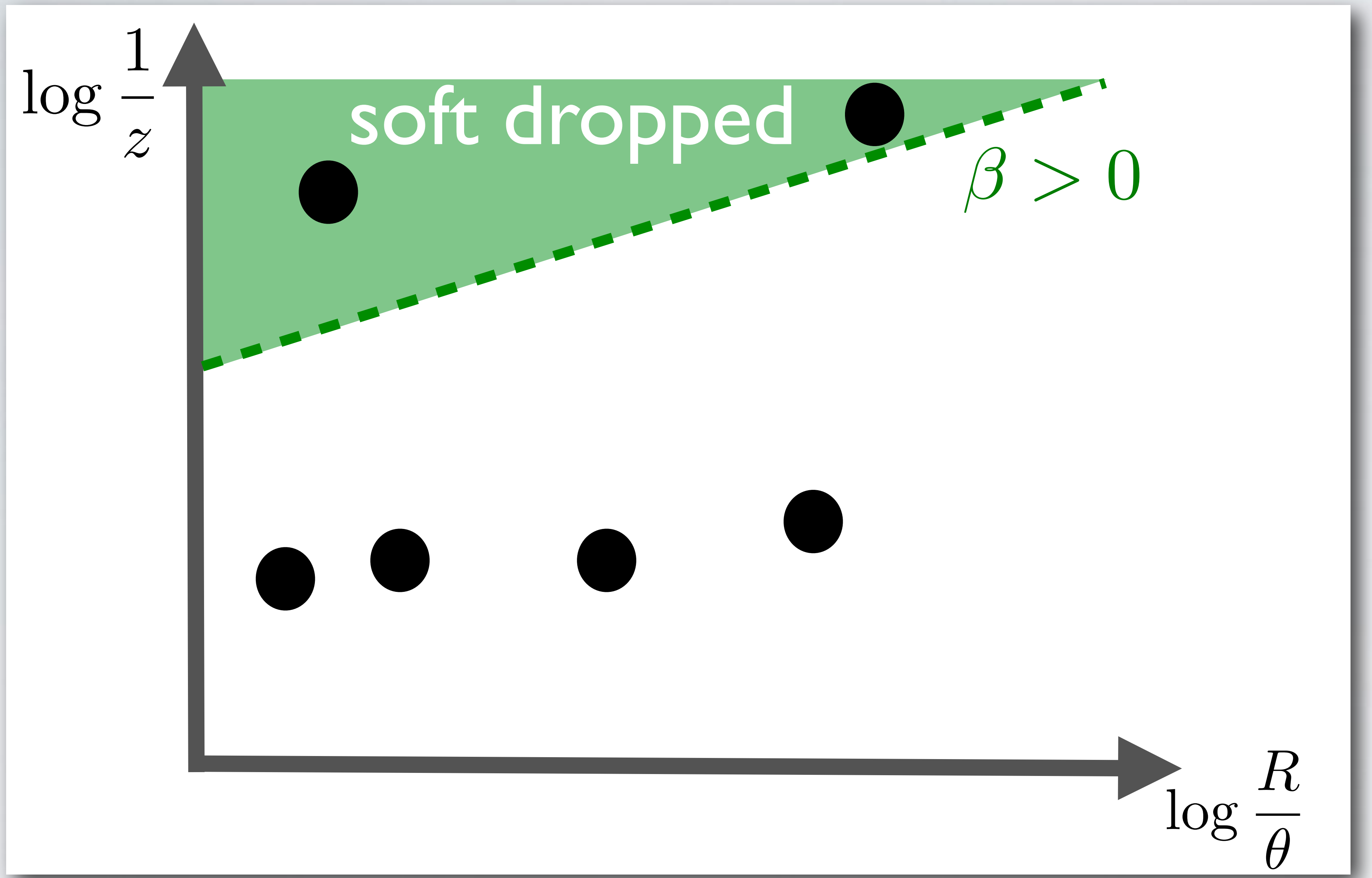
$$z_g < z_{\mathrm{cut}} \theta_g^\beta$$



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

courtesy of J. Thaler

Soft Drop as a groomer

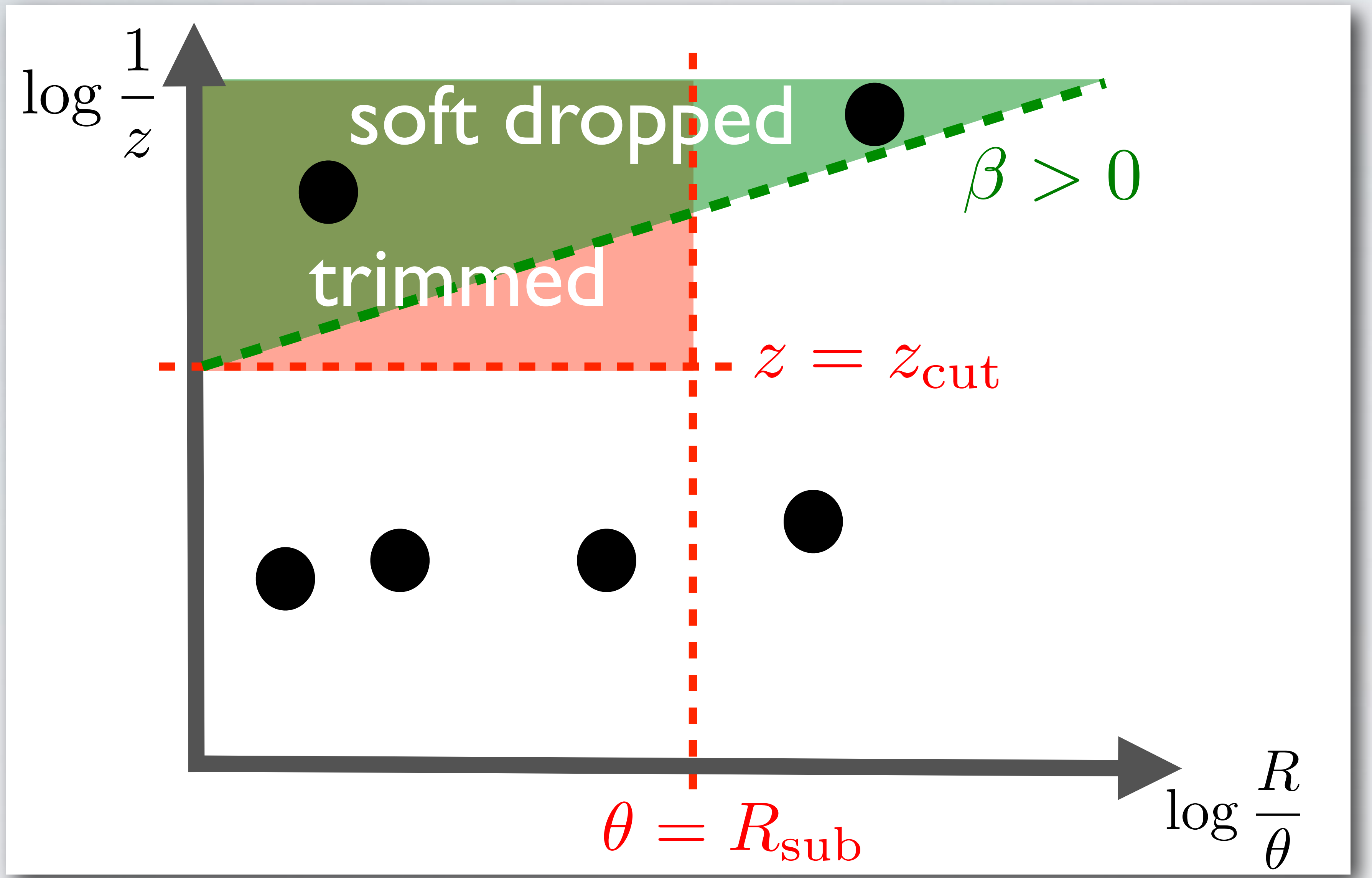


- useful to consider the soft-gluon phase space
- soft-drop condition becomes

$$z > z_{\text{cut}} \left(\frac{\theta}{R}\right)^{\beta}$$

- soft drop always removes soft radiation entirely (hence the name)
- for β>0 soft-collinear is partially removed

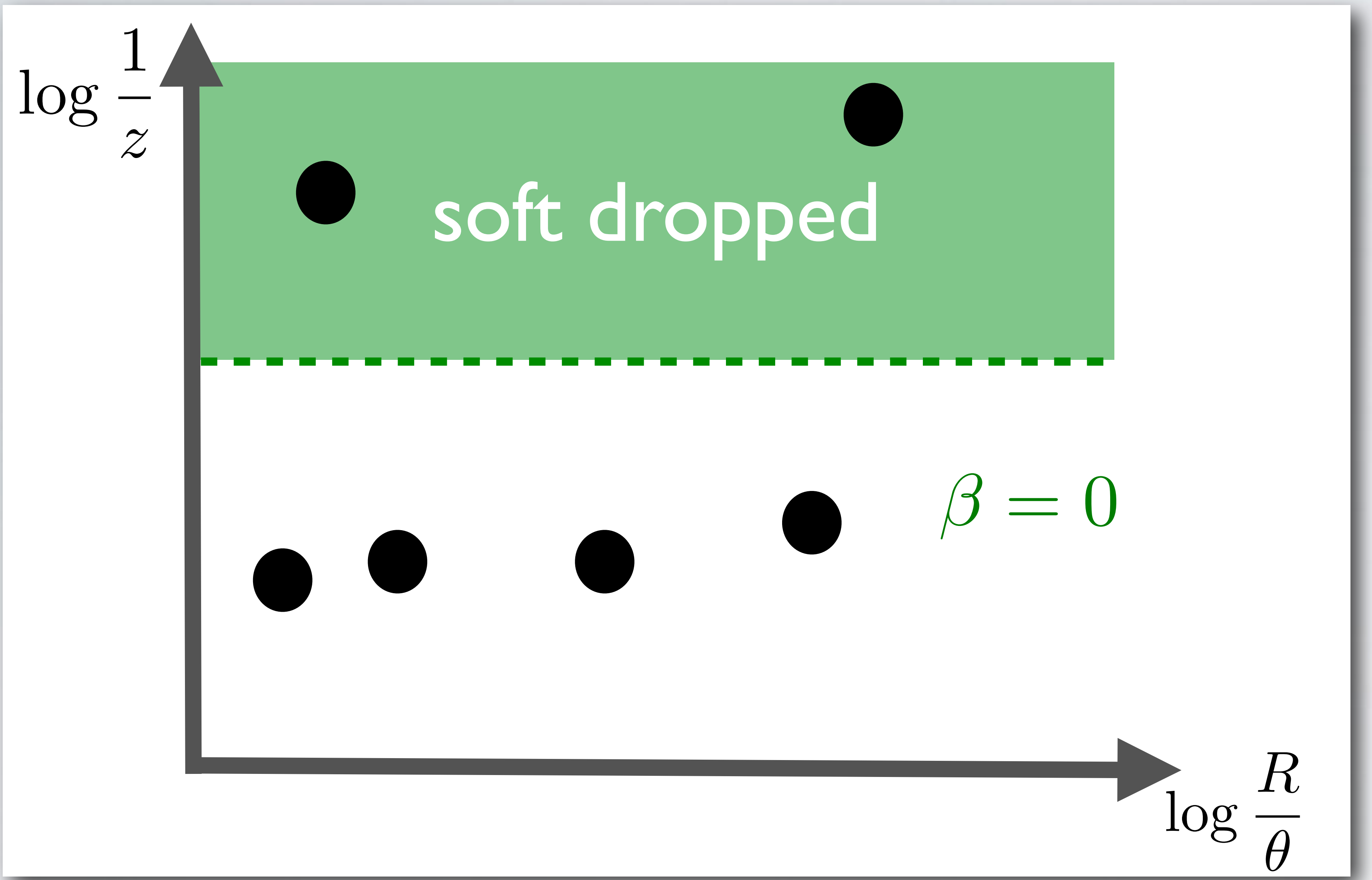
Soft Drop vs Trimming



- trimming had an abrupt change of behavior due to fixed R_{sub}
- in soft-drop angular resolution controlled by the exponent β
- phase-space appears smoother

Soft drop in grooming mode (β>0) works as a dynamical trimmer

Soft Drop and mMDT

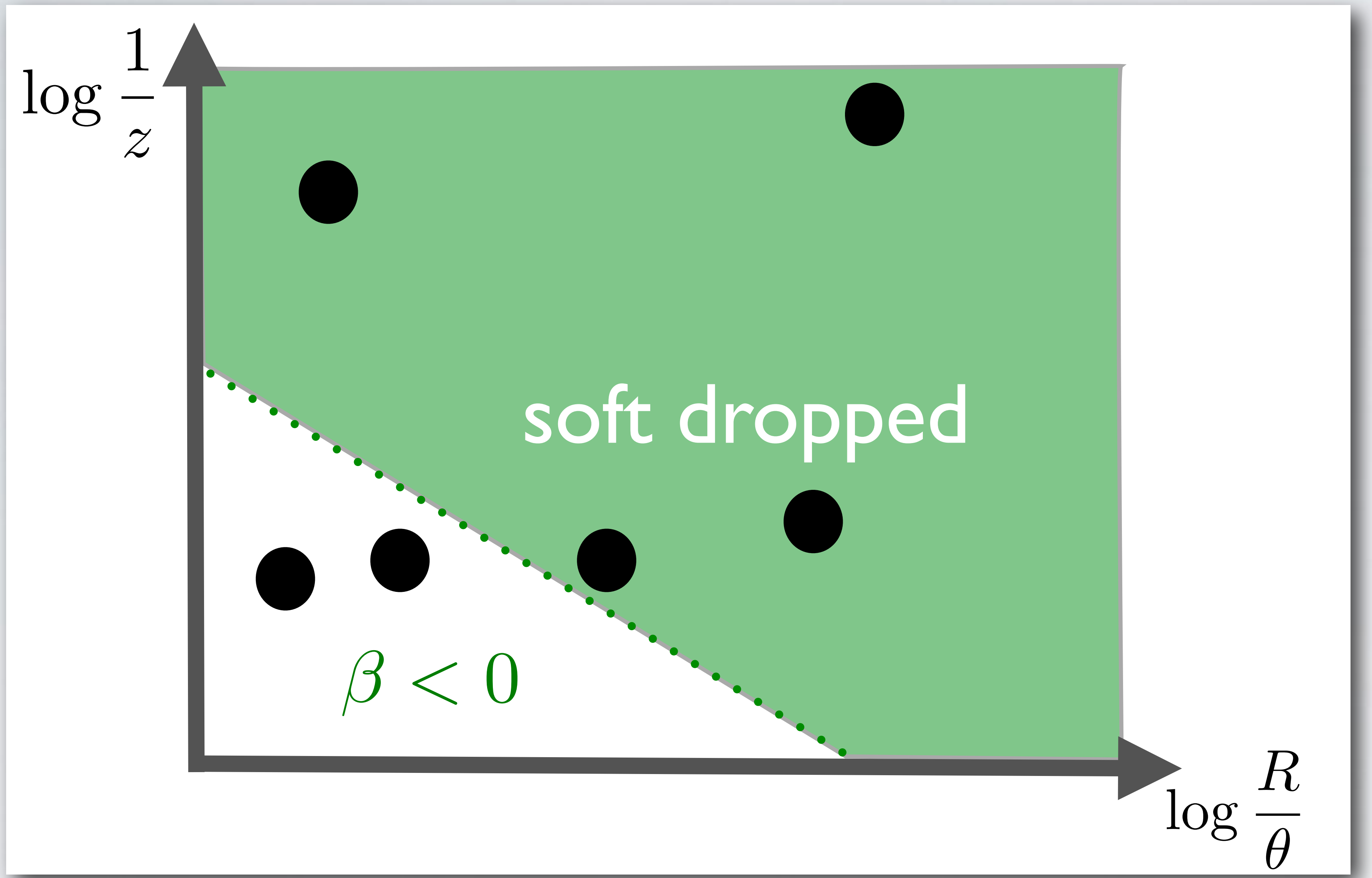


- useful to consider the soft-gluon phase space
- soft-drop condition becomes

$$z > z_{\text{cut}} \left(\frac{\theta}{R}\right)^{\beta}$$

- soft drop always removes soft radiation entirely (hence the name)
- for β=0 soft-collinear is also entirely removed (mMDT limit)

Soft Drop as a tagger

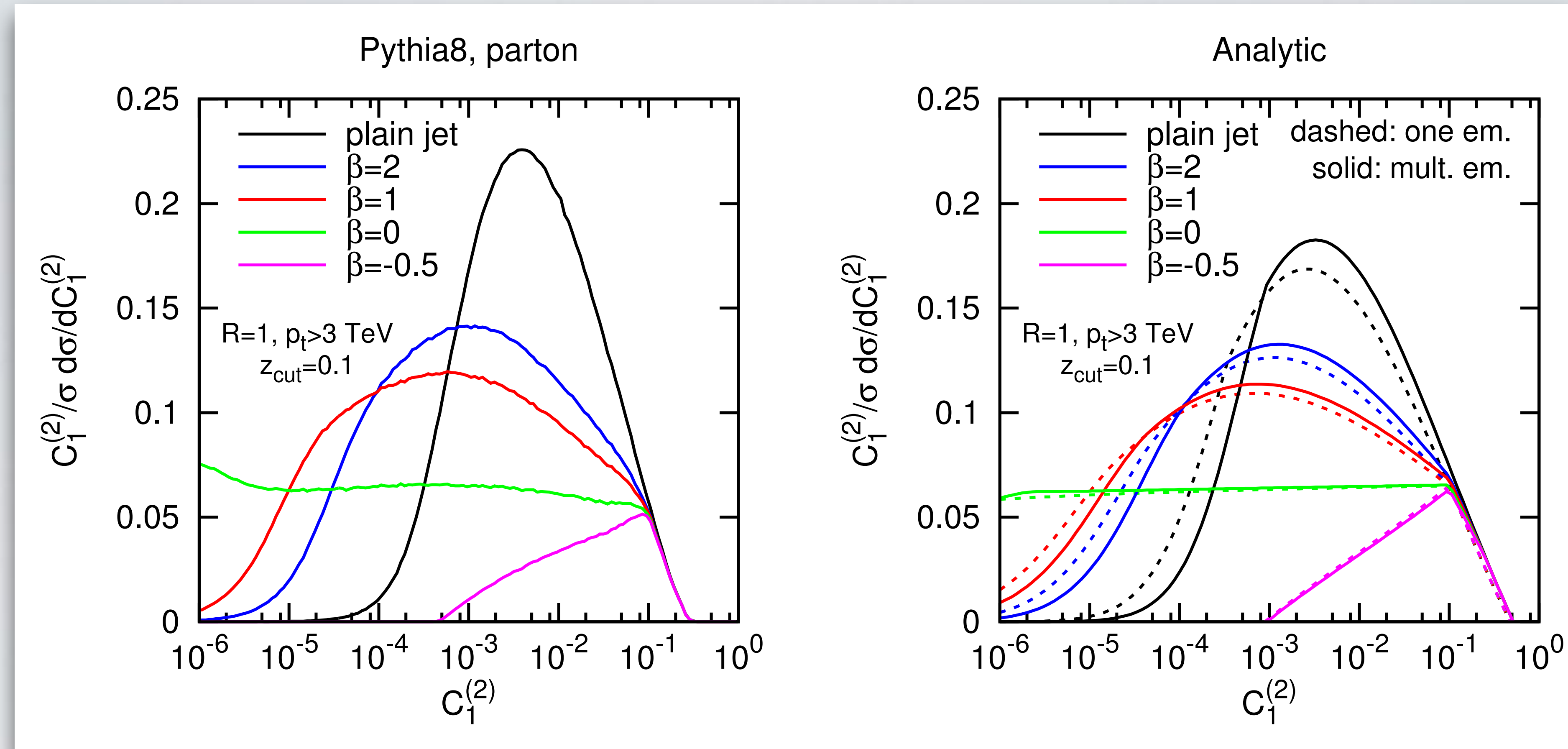


- useful to consider the soft-gluon phase space
- soft-drop condition becomes

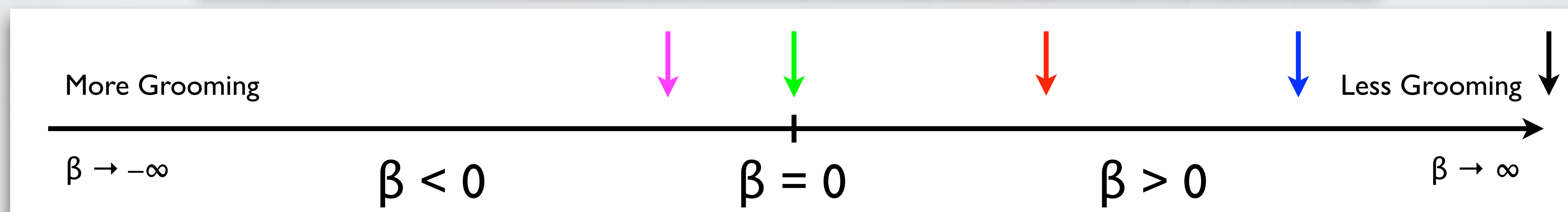
$$z > z_{\text{cut}} \left(\frac{\theta}{R} \right)^{\beta}$$

- soft drop always removes soft radiation entirely (hence the name)
- for β<0 some hard-collinear is also partially removed

Groomed jet properties



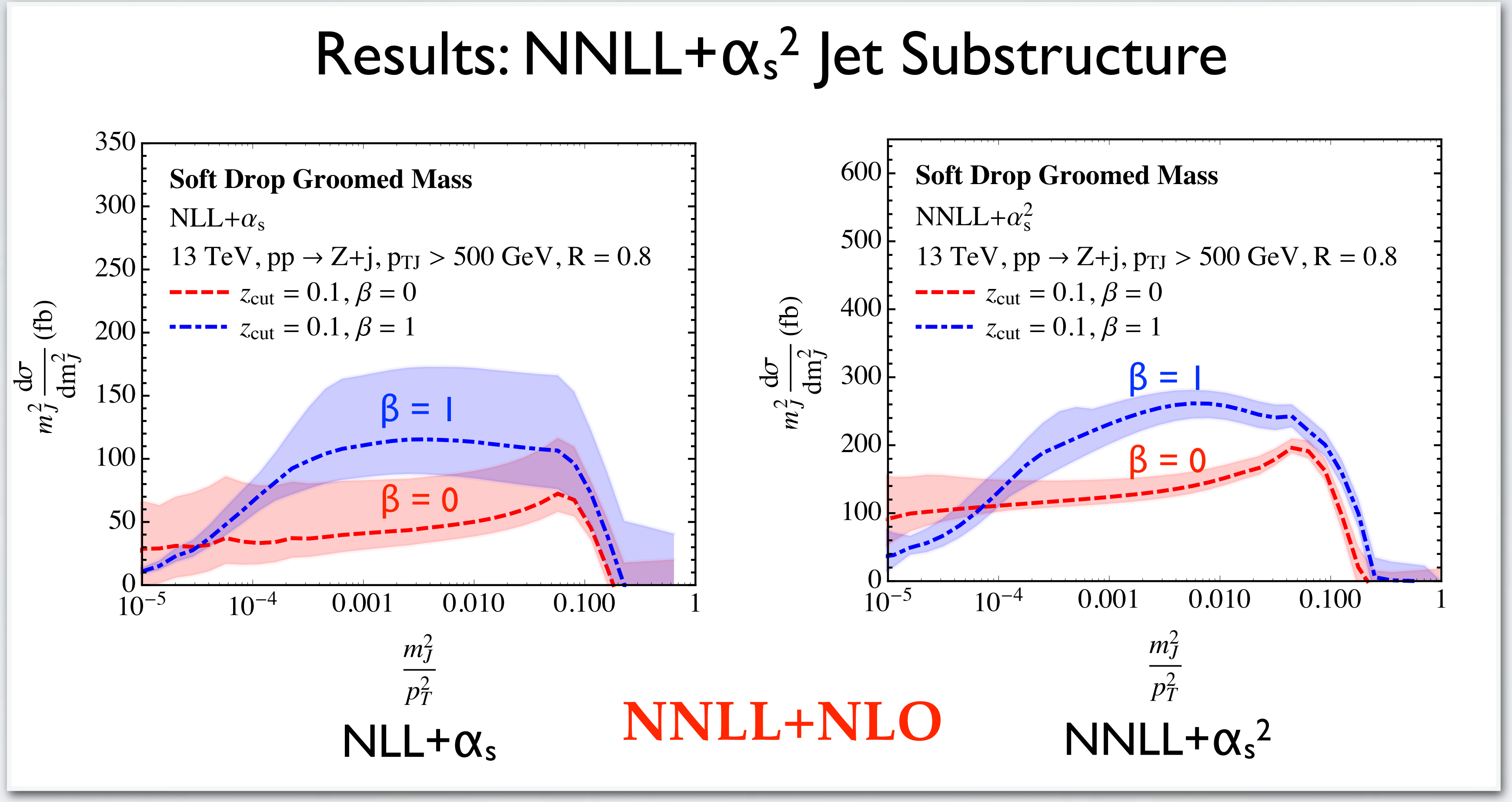
$C_1^{(2)} \simeq m^2/p_T^2$



courtesy of J. Thaler

- no more kinks
- flatness in bkg can be achieved for **β**=0
- it's becoming the *standard choice* for CMS

Soft drop at NNLL

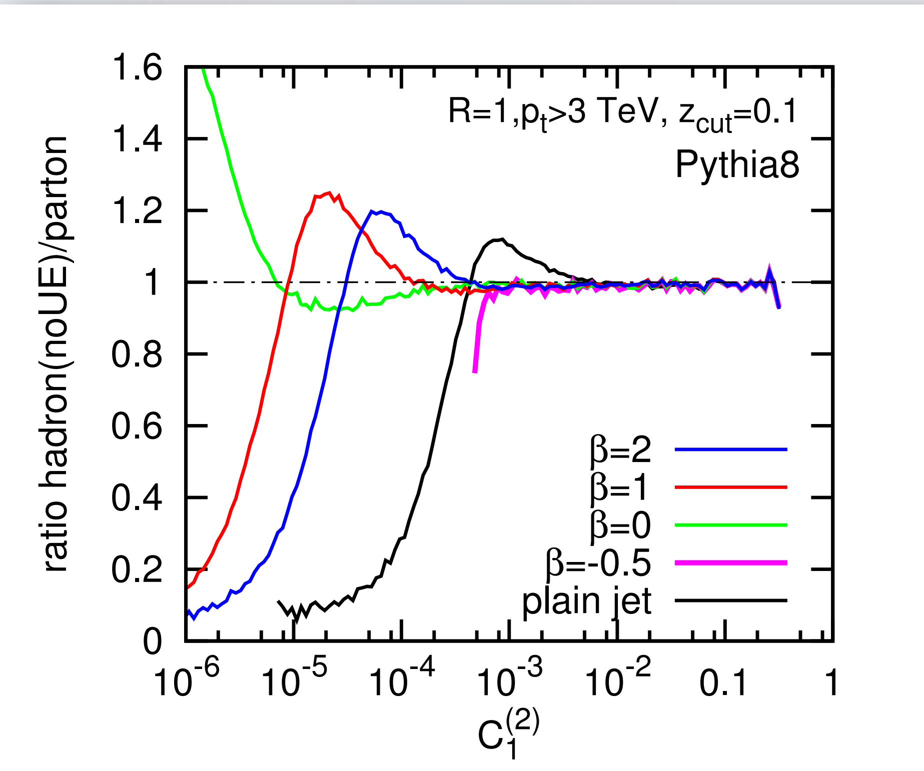


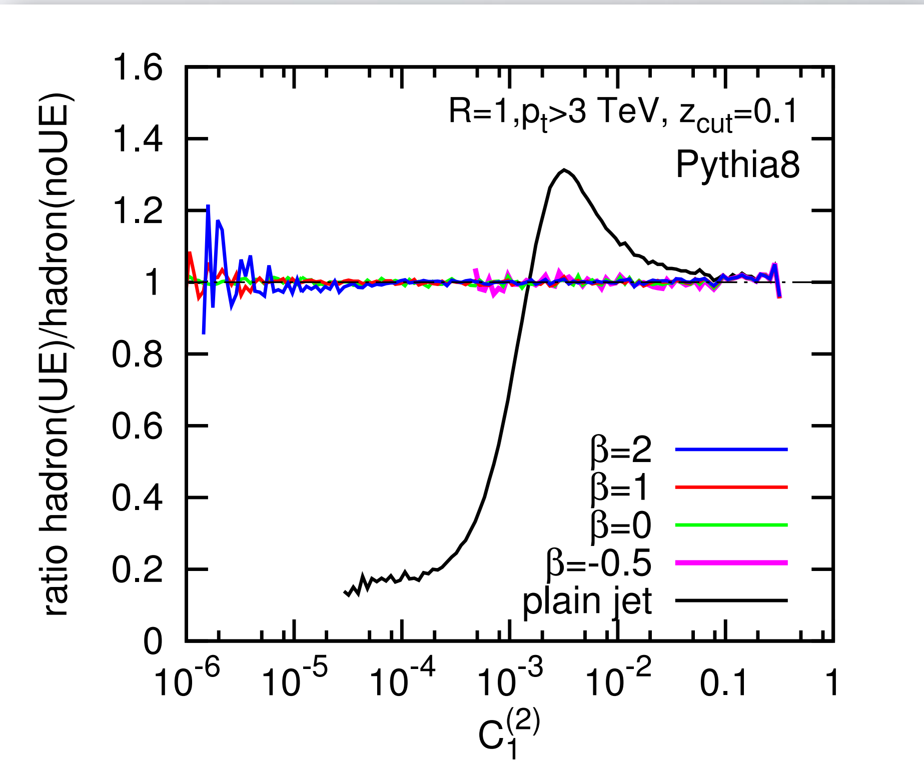
Frye, Larkoski, Schwartz, Yan (2016)

- 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
- let's compare to data! soon!

Non-perturbative physics

soft drop largely reduces sensitivity to non-perturbative physics



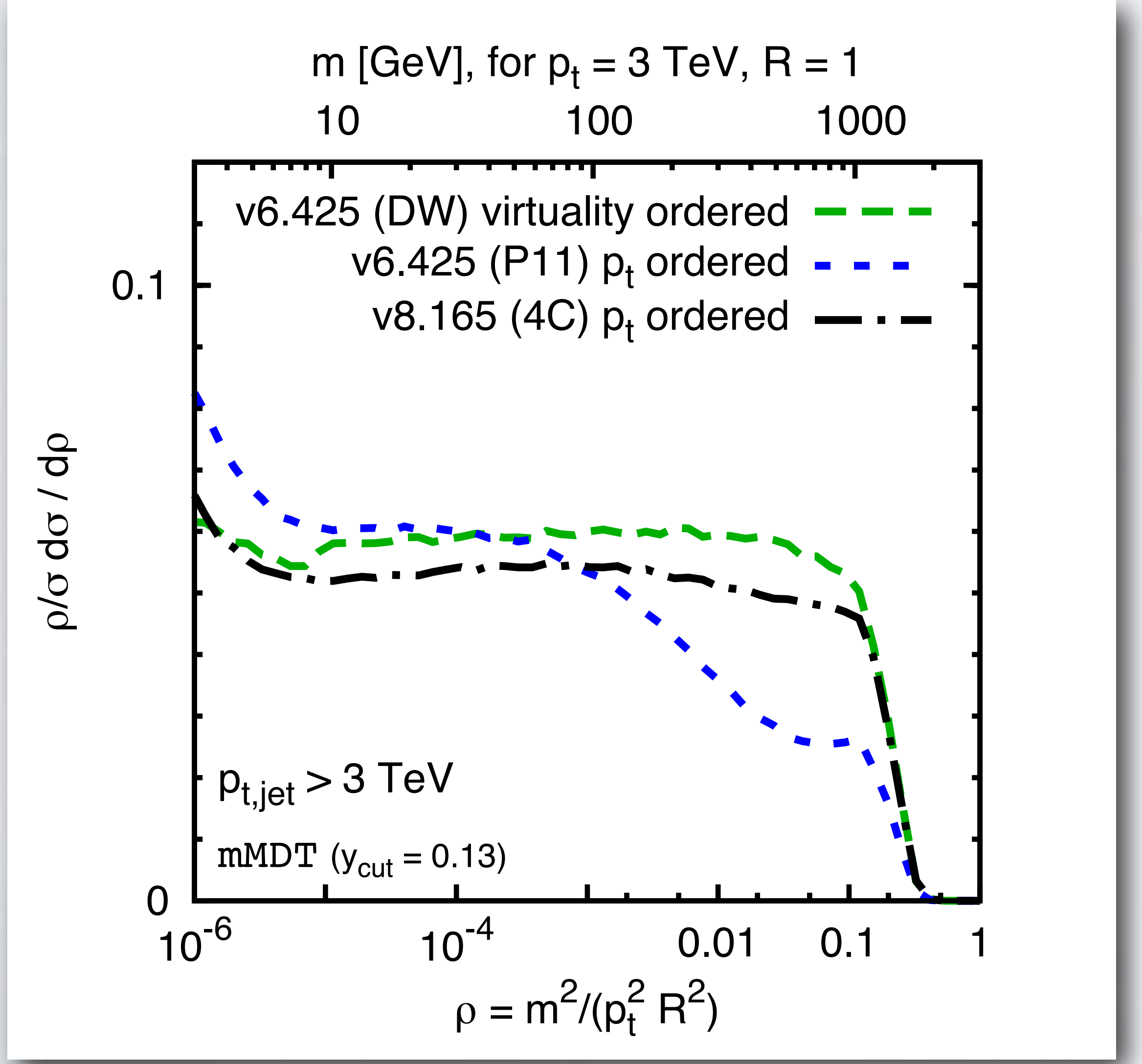


Can we use it for precision physics ?

Soft-drop thrust to determine α_s and resolve disturbing discrepancy with world average

Analytics to check MCs

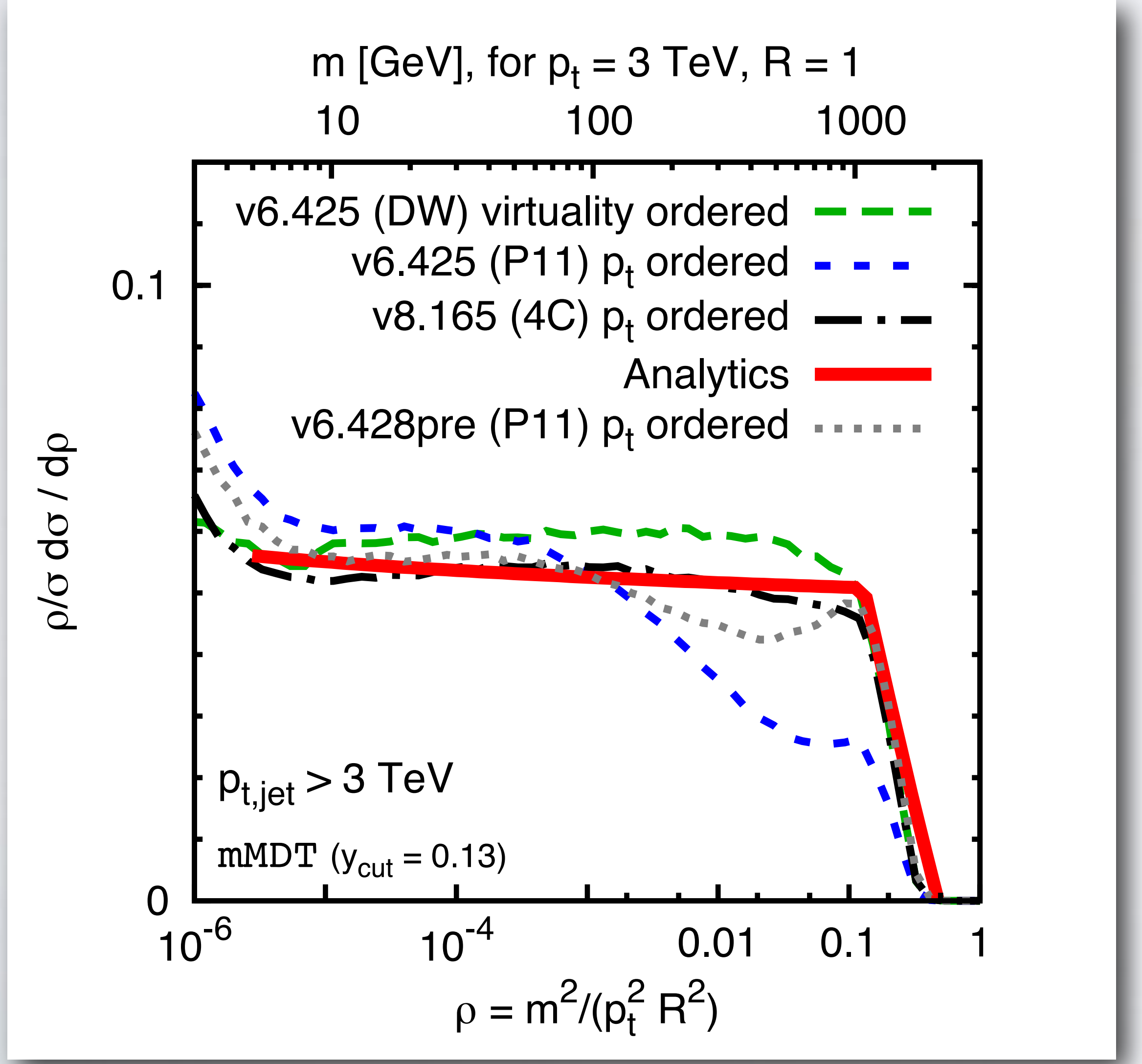
- How solid are MC descriptions of jet substructure ?
- Take something we analytically understand very well (mMDT)



- Take the spread as the uncertainty ?
- But we also have an analytic calculation

Analytics to check MCs

- How solid are MC descriptions of jet substructure ?
- Take something we analytically understand very well (mMDT)



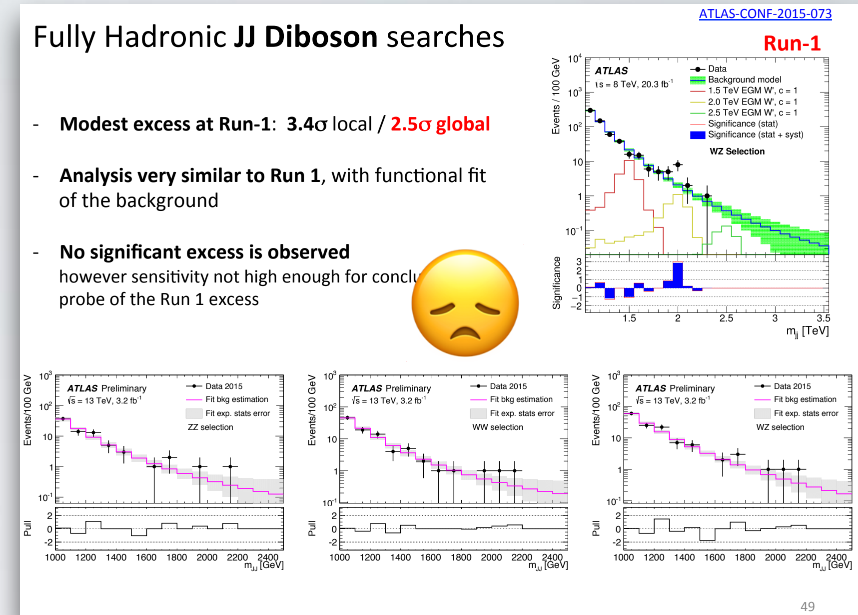
- Take the spread as the uncertainty ?
- But we also have an analytic calculation
- Problem in the shower: fixed by the Authors in the 6.428pre version

Back to phenomenology

W tagging with jet shapes

groom to remove contamination

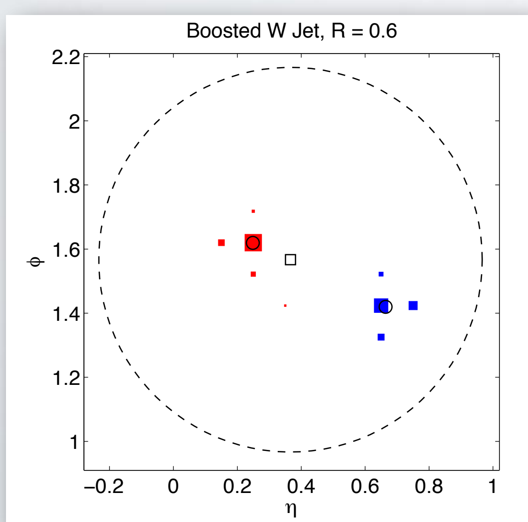
e.g. with soft drop

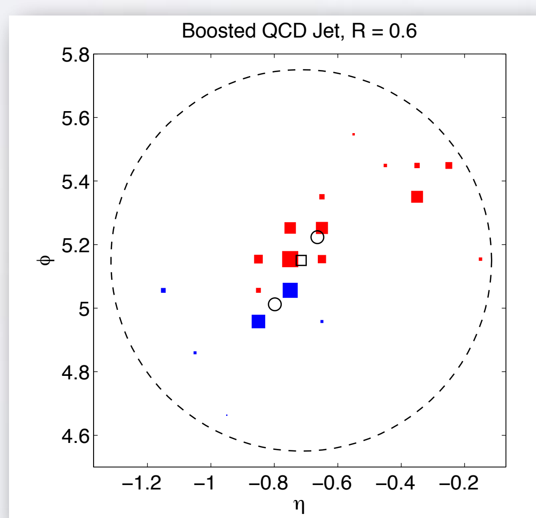


Marumi Kado
(LAL, Orsay and CERN)

select mass window about the resonance

use a shape to determine prong structure



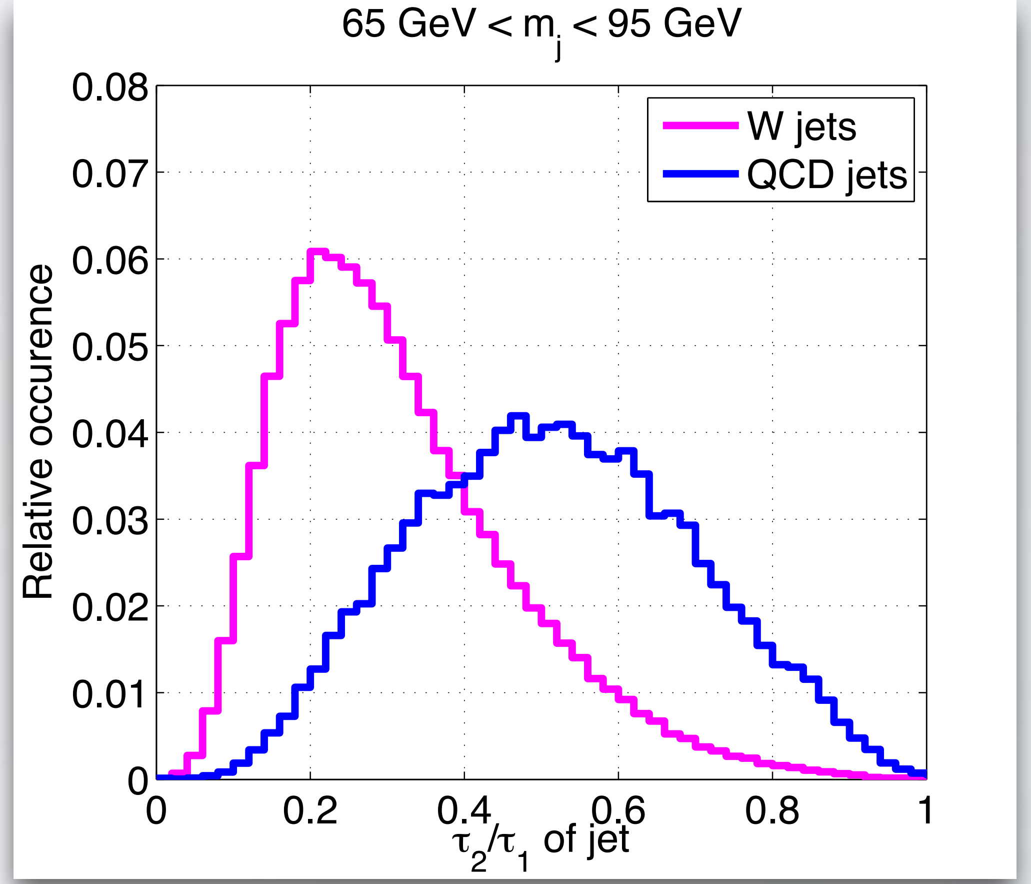


e.g. with *N*-subjettiness

N-subjettiness for W tagging

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

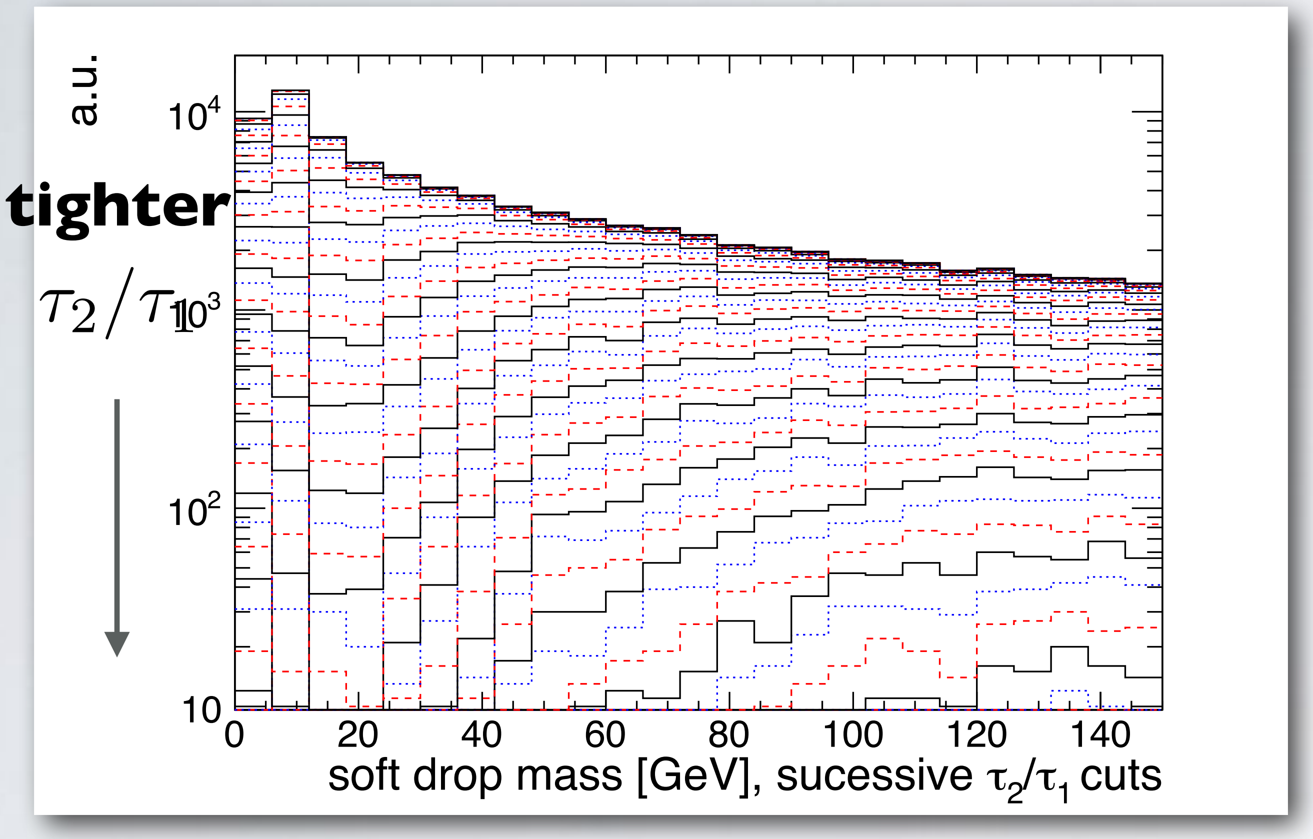
Thaler and Van Tilburg (2011)



Fine-print

- β:
  - give more or less weight to large/small angles
  - $\beta \sim 2$ seems slightly preferred in MC simulations
  - $\beta \sim 1$ should be less sensitive to non-perturbative effects and P
- choice of axes:
  - optimal, declustering, winner-takes-all, ...
  - For a given β, generalised-$k_t(p = 1/\beta)$~optimal
  - use WTA for $\beta \leq 1$
- choice of jet:
  - What to do with soft-and-large-angle emissions?
  - apply on full jet? (more discrimination, more NP Sensitive)
  - apply on groomed jet? (less discrimination, less NP Sensitive)

N-subjettiness and mass



- τ_{21} cut sculpts the mass distribution
- the background develop an artificial peak
- discrimination power goes down

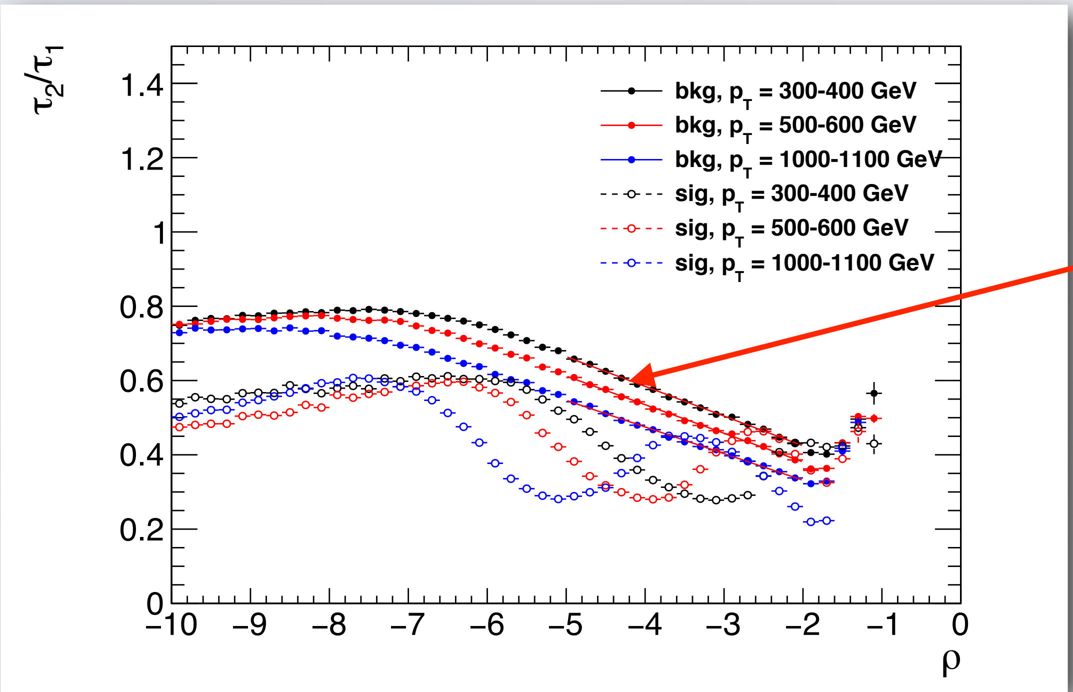
Dolen, Harris, SM, Rappoccio, Tran

see also Kasienczka *et al.* JHEP 1506 (2015) 203

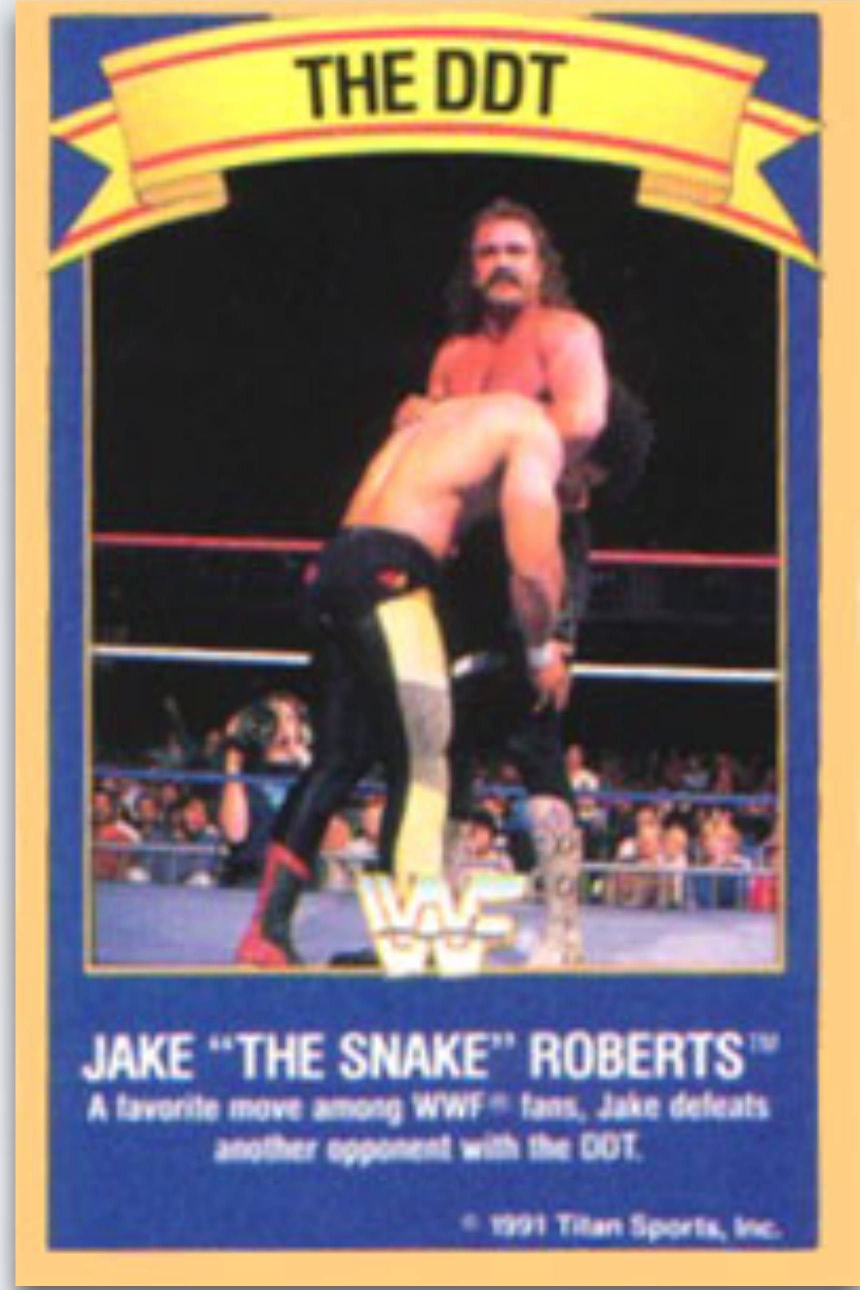
- flat bkg was a built-in feature of soft drop
- we would like to de-correlate mass and shape, so that a flat cut does not lead to a significant sculpting of the mass distribution

Designing De-correlated Taggers

- to understand what's going on plot average τ_{12} as a function of log(mass)



concentrate on bkg



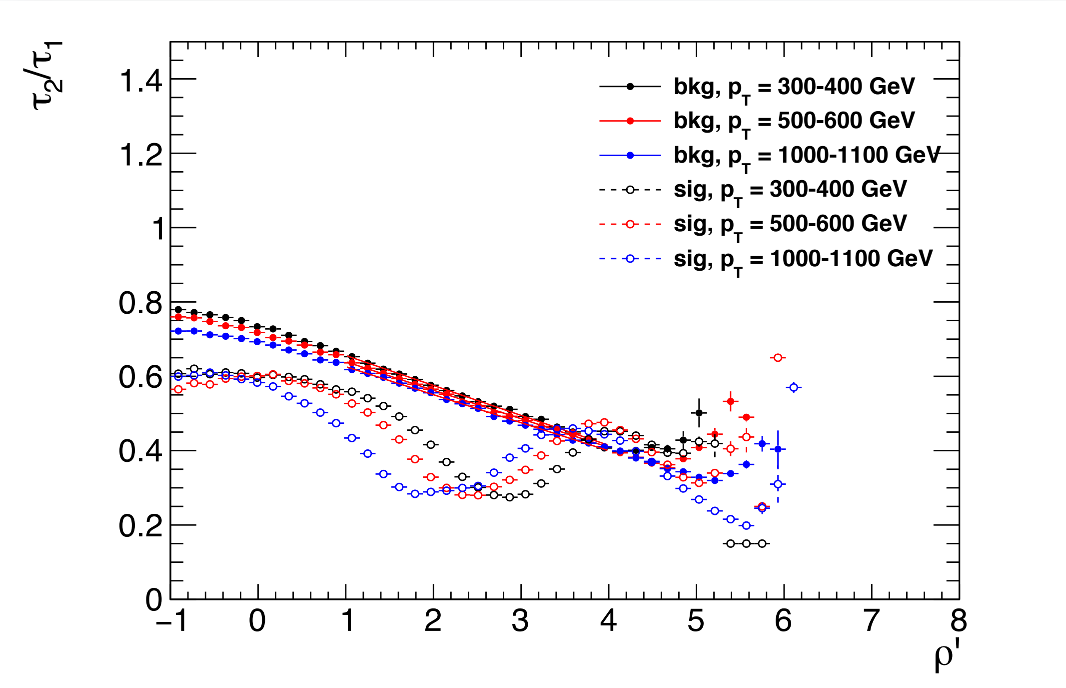
Dolen, Harris, SM, Rappoccio, Tran (2016)

- There exists a region of linear relation
- Can we understand this from first principle ?

see work by Larkoski, Moult, Neill & Dasgputa, Schunk, Soyez

Designing De-correlated Taggers

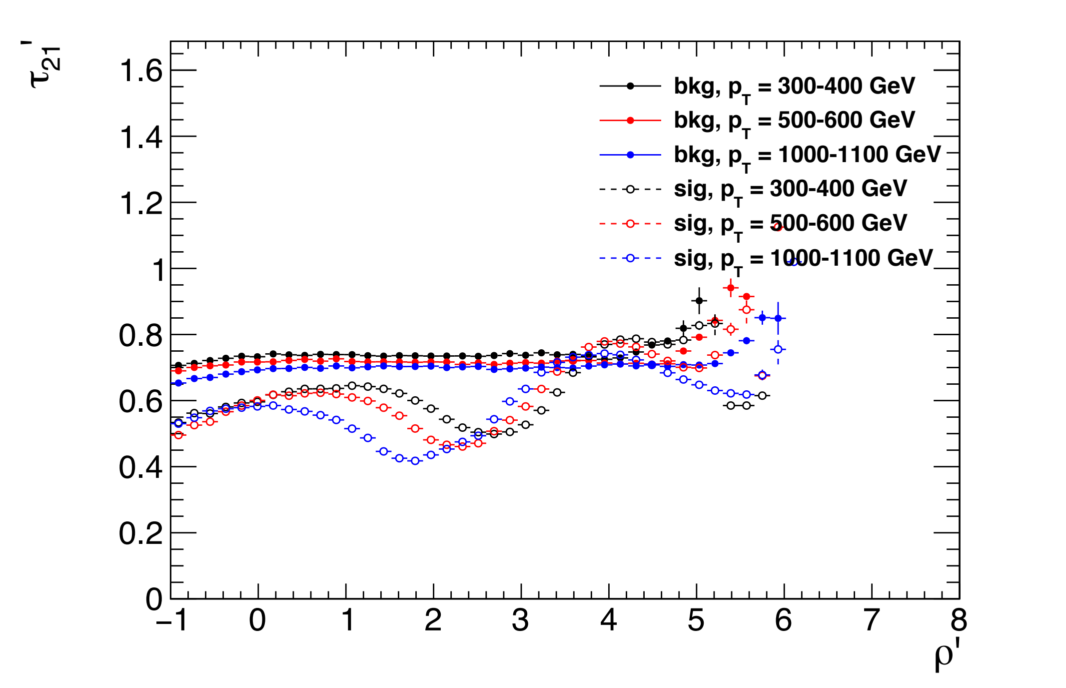
- Here we limit ourselves to a pheno study
- First shift the variable to account for p_T dependence



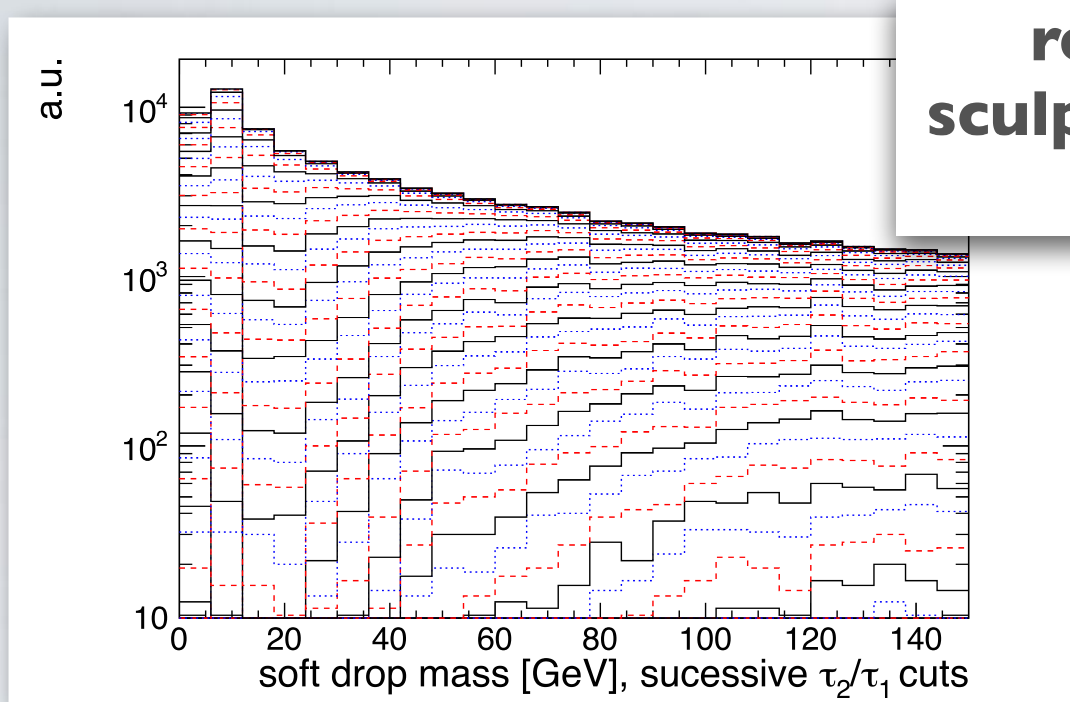
Dolen, Harris, SM, Rappoccio, Tran (2016)

- Then fit the slope and change the variable to

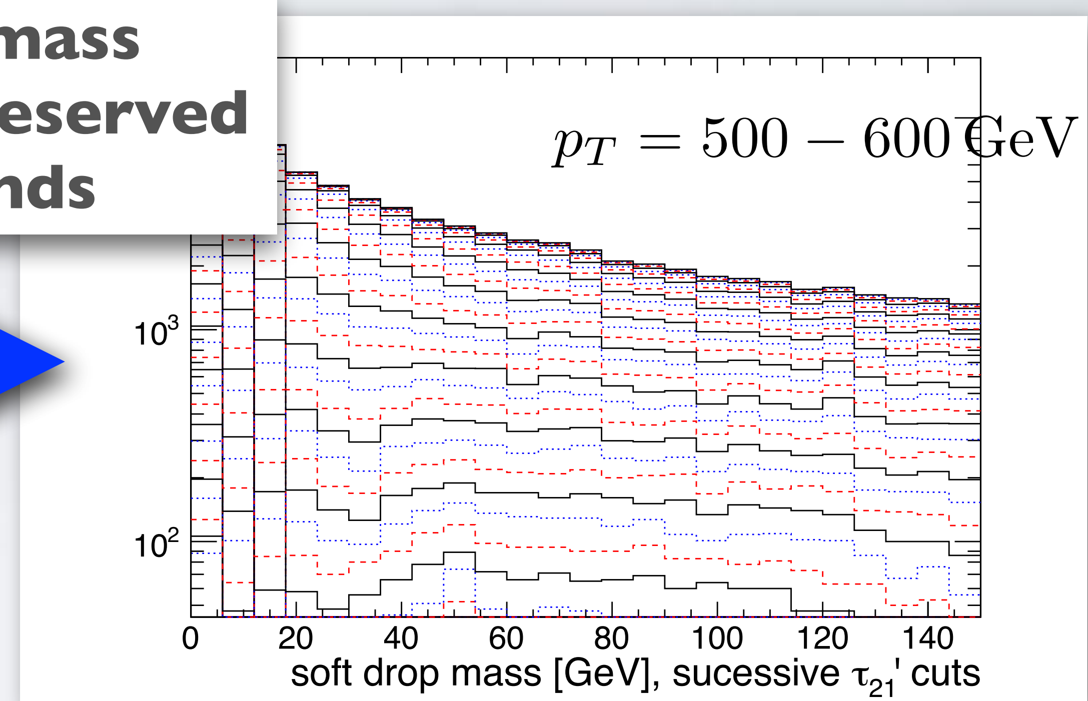
$$\tau'_{21} = \tau_2/\tau_1 - M \times \rho',$$

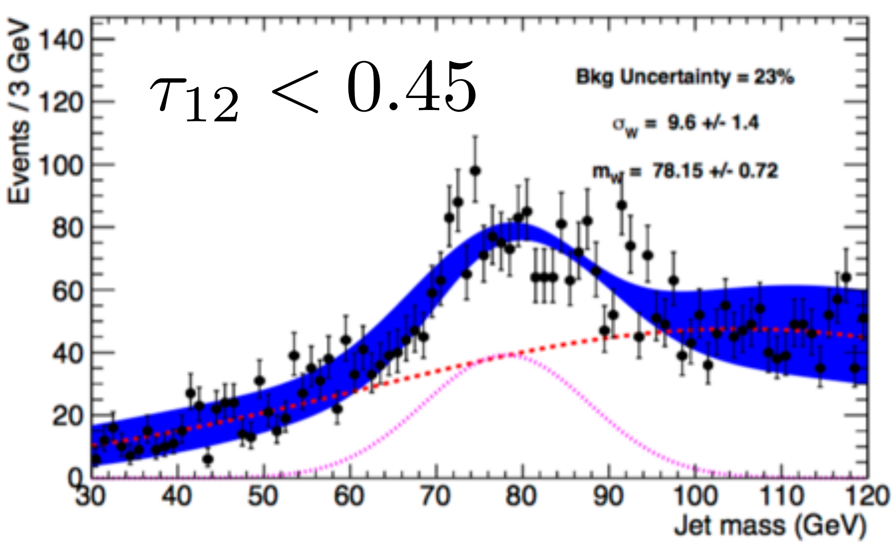


DDT: results

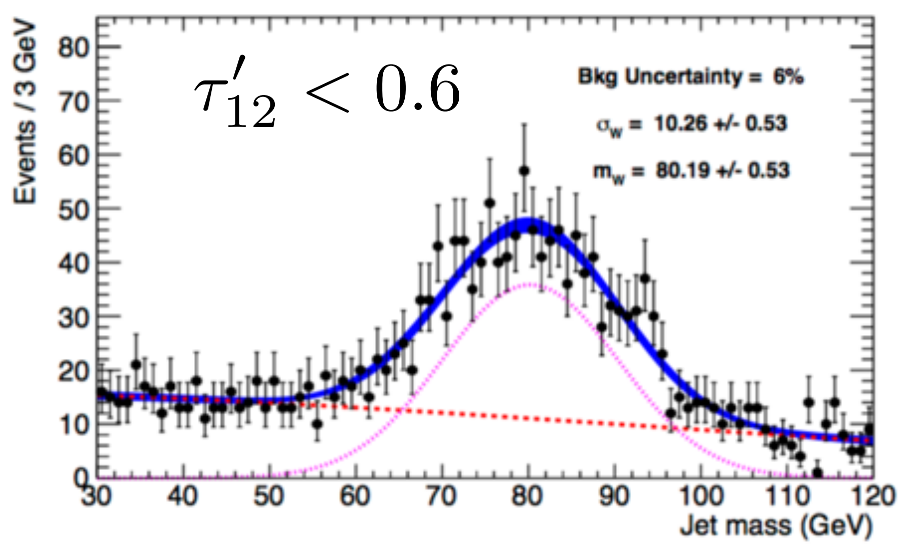


reduced mass sculpting, preserved side-bands





Bkg normalization unc: 23%



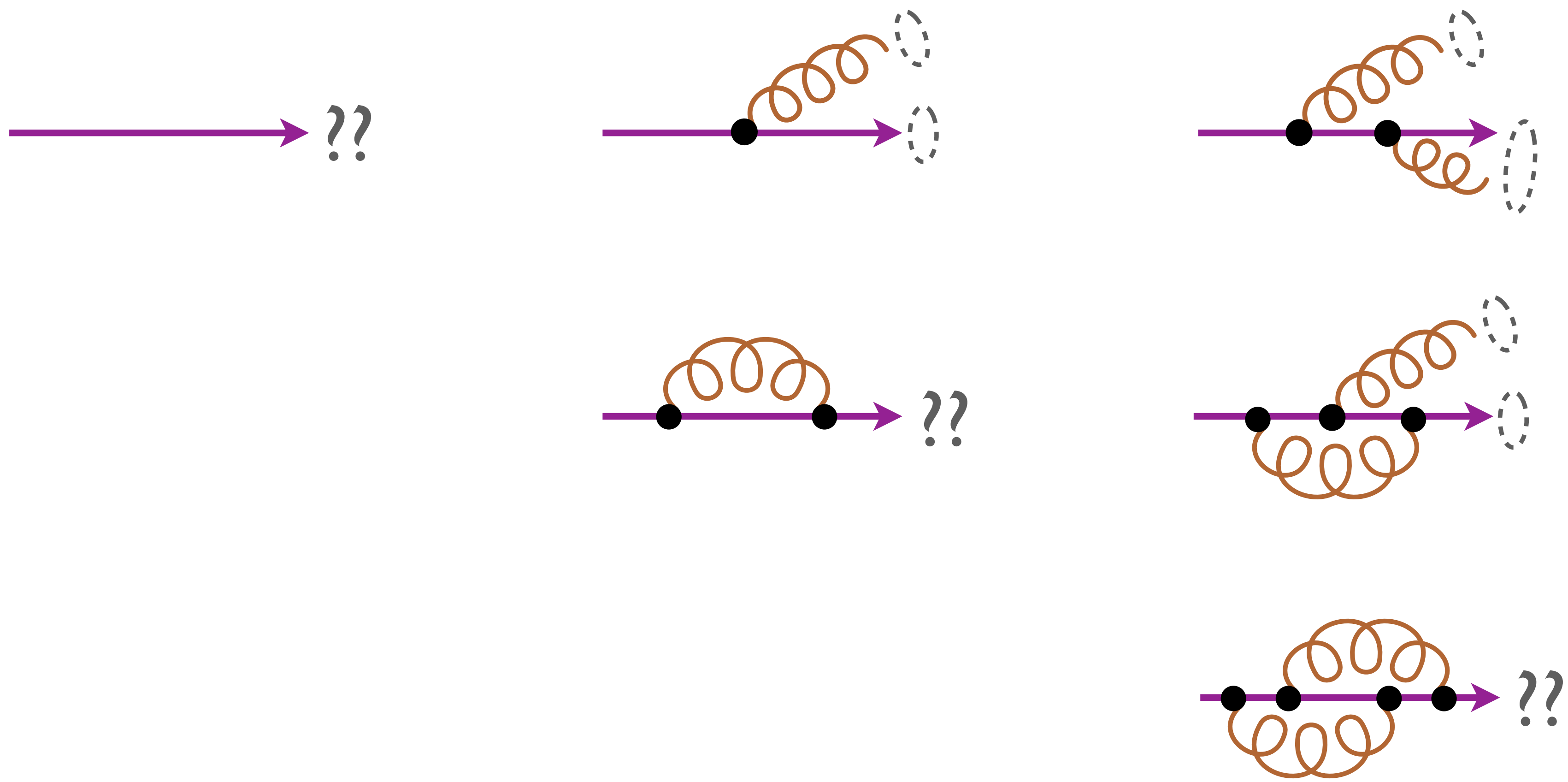
Bkg normalization unc: 6%

- M = 2 TeV
- roughly same signal efficiency
- bkg better behaved
- reduced systematics

Exposing the QCD splitting function

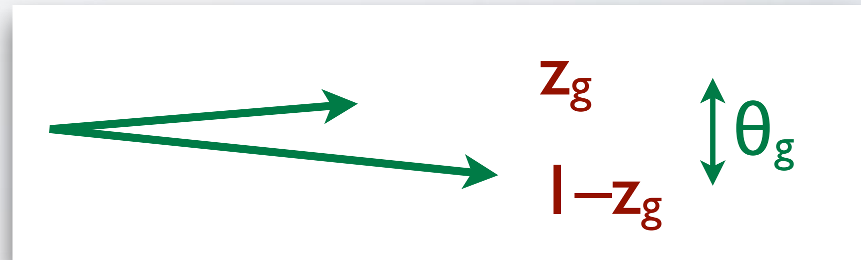
Momentum sharing z_g

$$\frac{1}{\sigma}\frac{d\sigma}{dz_g} = \left(\textit{undefined}\right) + \alpha_s\left(\textit{infinity}\right) + \alpha_s^2\left(\textit{infinity}^2\right) + \dots$$



courtesy of J. Thaler

- z_g not IRC safe because Born is ill-defined
- avoid singularity requiring opening angle



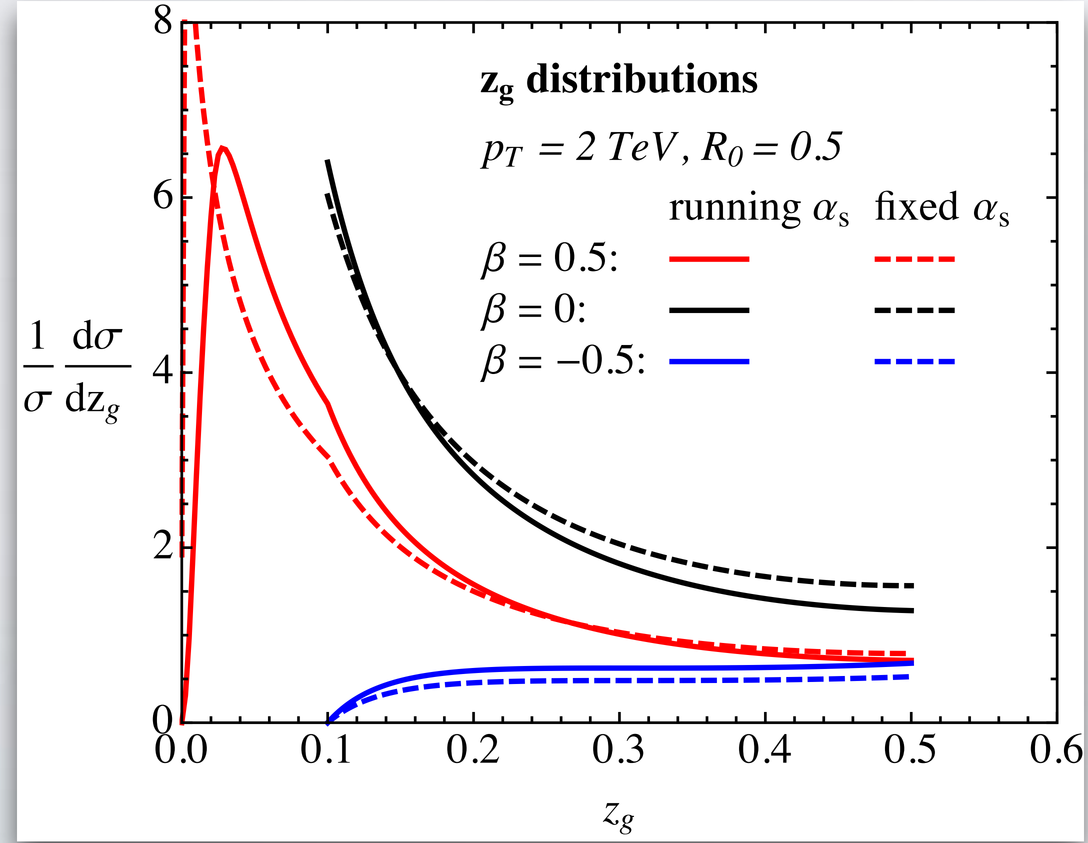
Sudakov safety

$$p(z_g) = \frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}z_g} = \int \mathrm{d}r_g\, p(r_g)\, p(z_g|r_g)$$

all-order distribution: emissions at zero angle are exponentially suppressed

finite conditional probability for r_g>0

If this procedure gives a finite result, z_g is said Sudakov safe



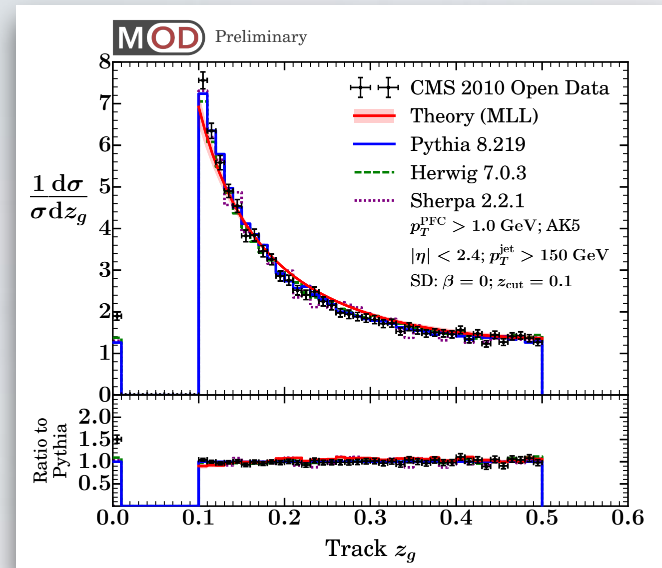
As β varies, we move from an IRC safe situation (β<0) to IRC unsafe (but Sudakov safe!) regime (β>0)

Larkoski, Thaler (2013)
Larkoski, SM, Thaler (2015)

remarkable result at β=0

Measuring z_g

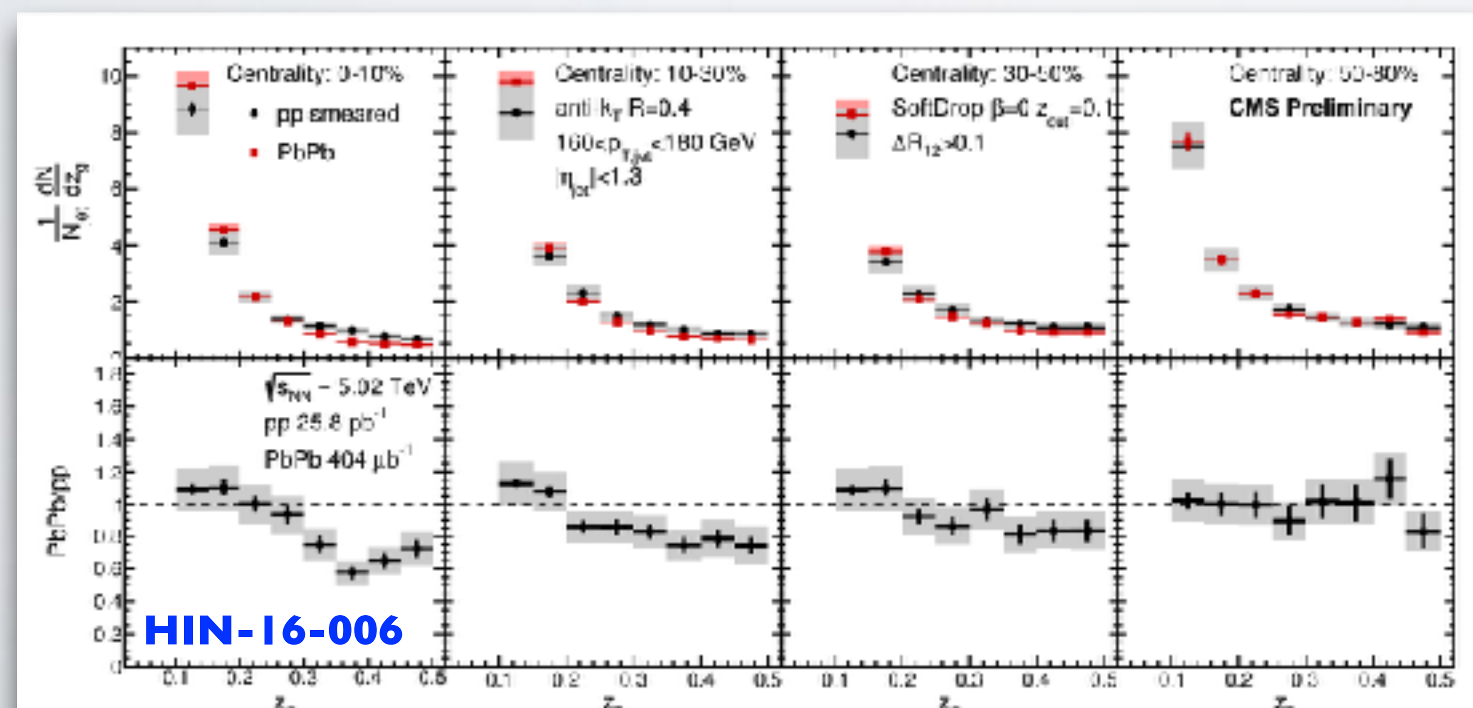
- exposes the QCD splitting function

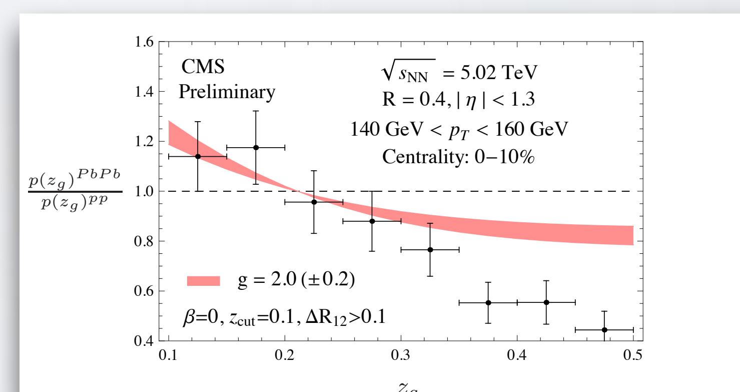


$$\frac{1}{\sigma}\frac{d\sigma}{dz_g} = \frac{\overline{P}_i(z_g)}{\int_{z_{\rm cut}}^{1/2} dz\,\overline{P}(z)}\Theta(z_g - z_{\rm cut}) + \mathcal{O}(\alpha_s)$$

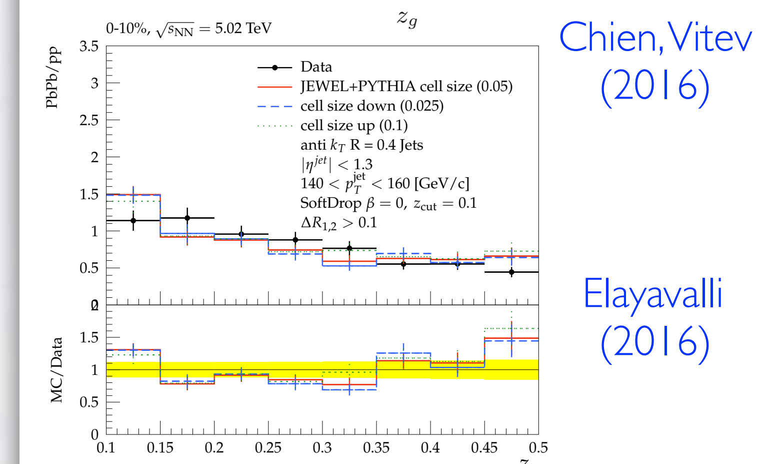
Larkoski, SM, Thaler (2015)
Larkoski, SM, Thaler, Tripathee, Xue (soon)

- now used as a probe for medium induced modification in heavy ion collisions





Chien, Vitev (2016)

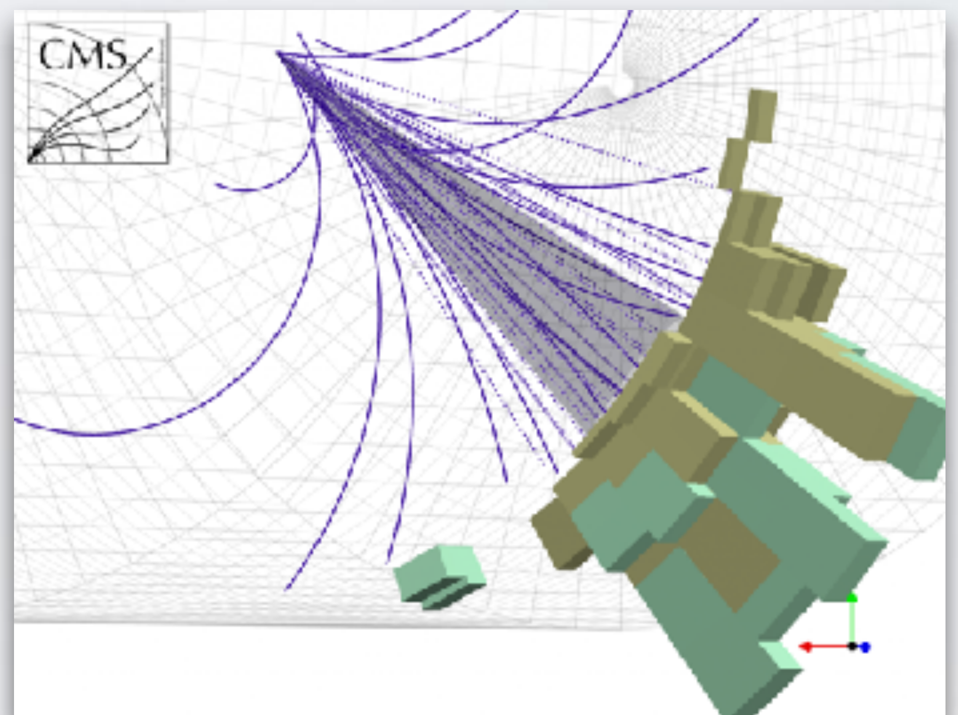


Elayavalli (2016)

Jet substructure at LHC

more robust

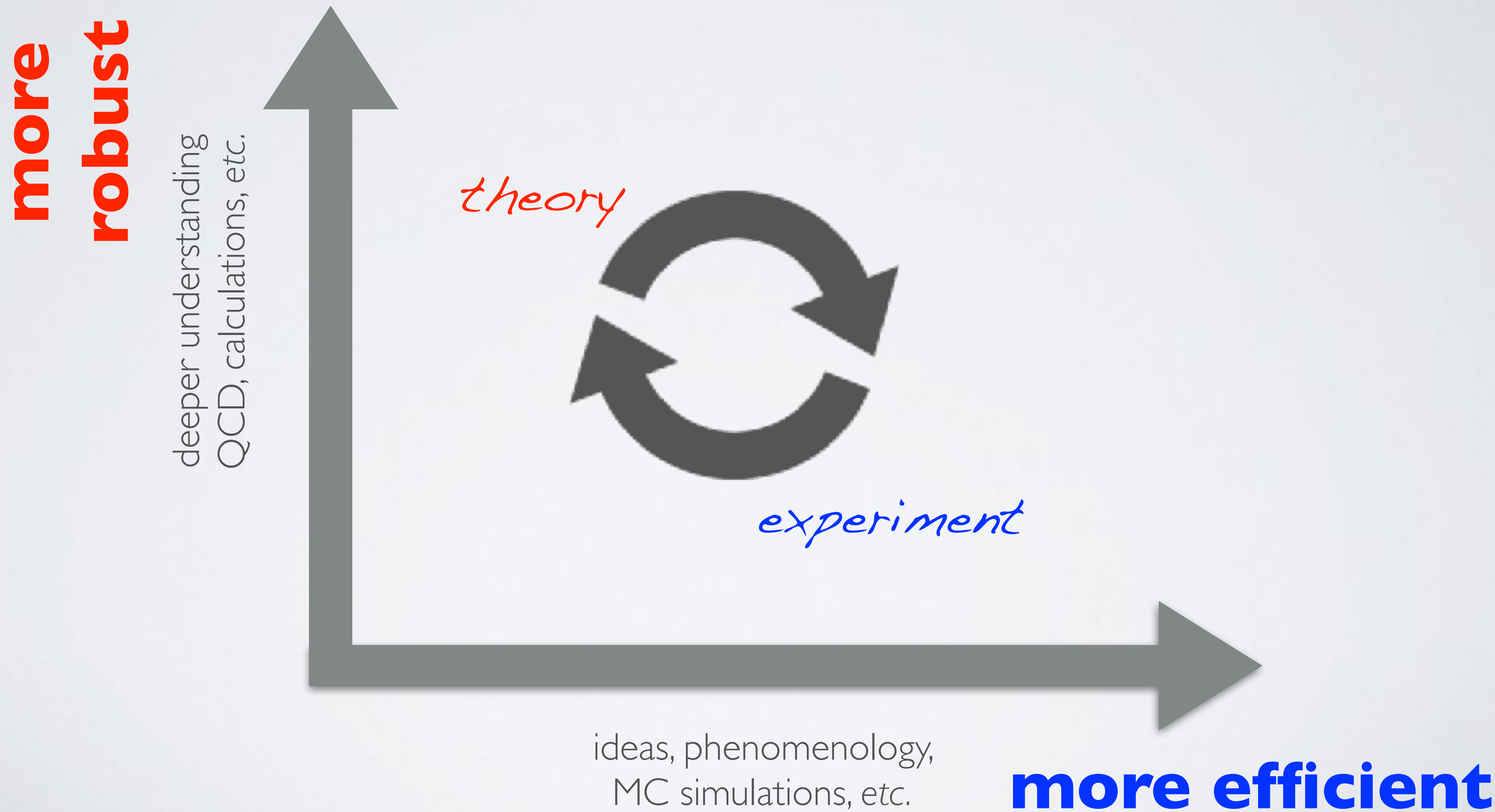
deeper understanding
QCD, calculations, *etc.*



ideas, phenomenology,
MC simulations, *etc.*

more efficient

Jet substructure at LHC



Thank you !

and Merry Christmas !