JET SUBSTRUCTURE

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Multi-Boson Interactions
August 24th - 26th 2016
Madison, WI

Good to be back !

2007 CTEQ Summer School

The Coordinated Theoretical-Experimental Project on QCD

(CTEQ)

**will organize and conduct the fourteenth
CTEQ Summer School on QCD Analysis and Phenomenology
at**

**Madison, Wisconsin USA
30 May - 7 June 2007**

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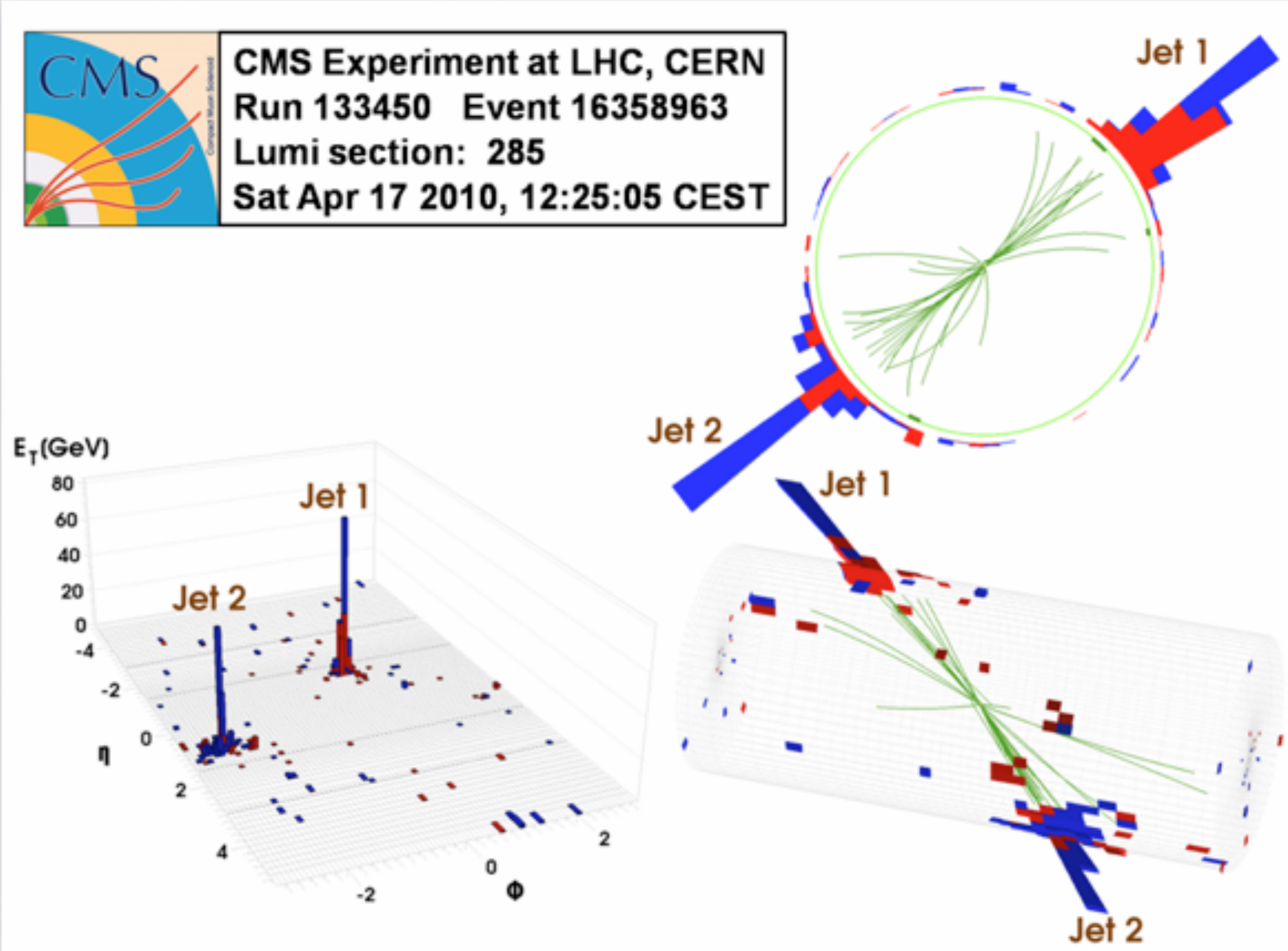
Outline

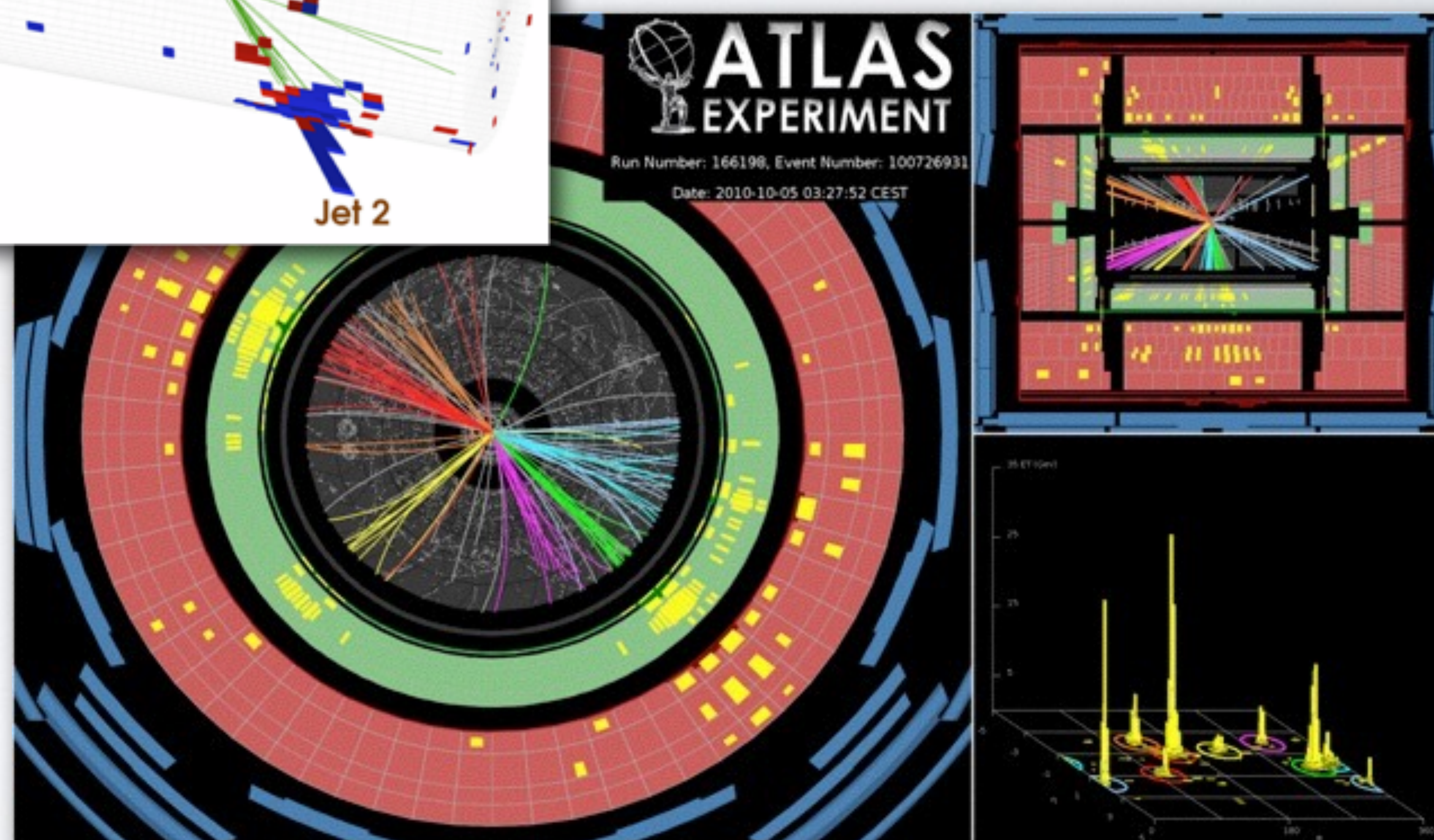
- Looking inside jets: an introduction
- Theoretical understanding of taggers and groomers
- Back to phenomenology: *W* tagging with DDT
- News from BOOST 2016

Looking inside jets

JETS

Collimated, energetic sprays of particles

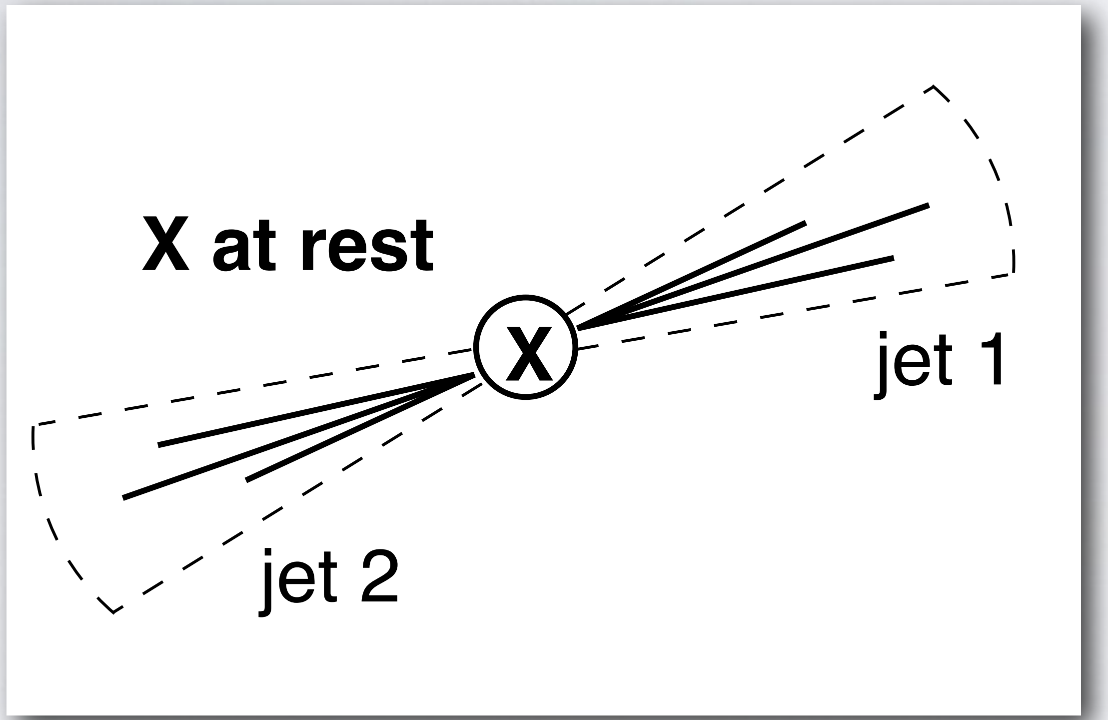


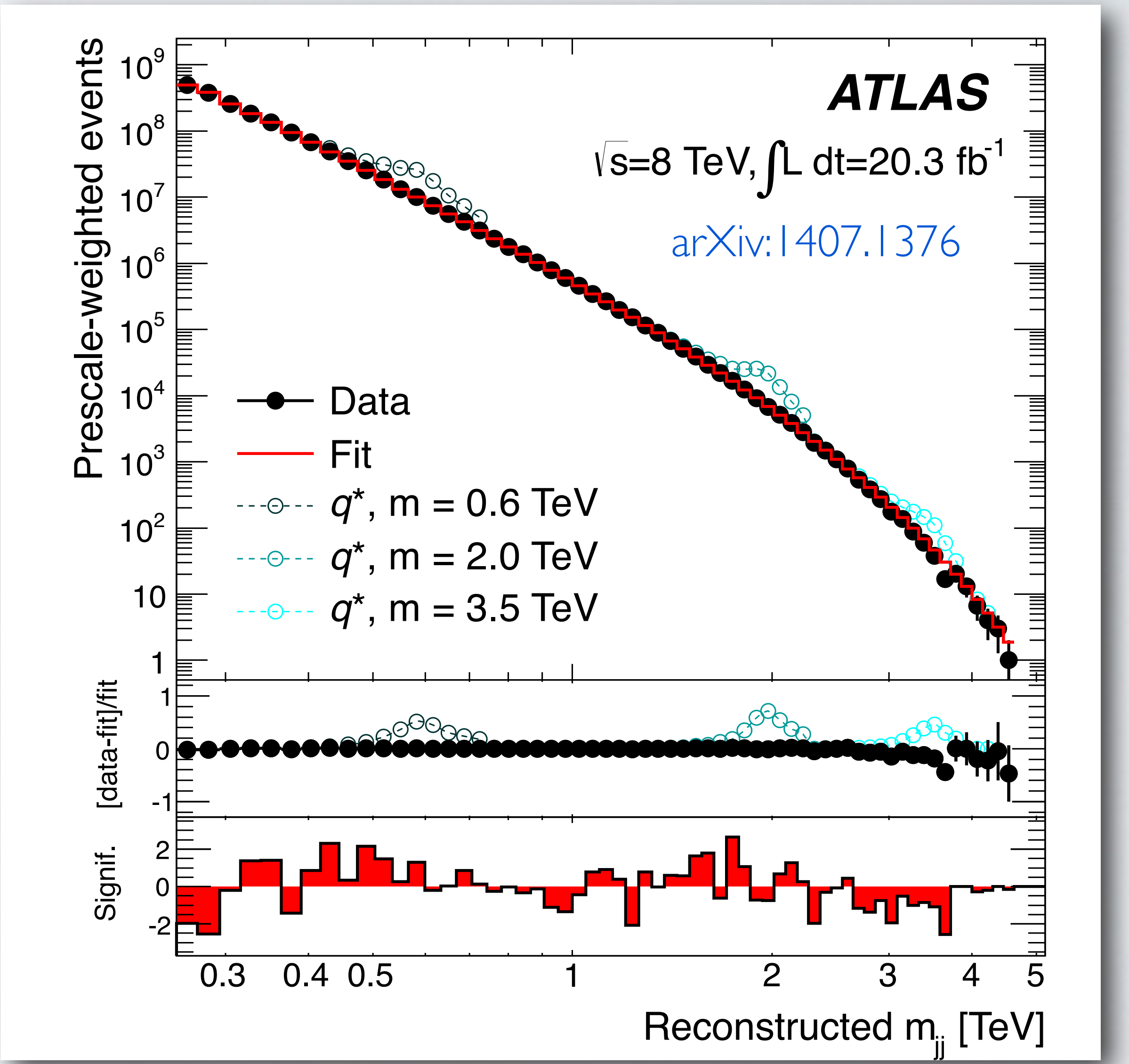


ubiquitous @LHC: more than 70% of ATLAS & CMS papers use jets in their analyses!

Searching for new particles: resolved analyses

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

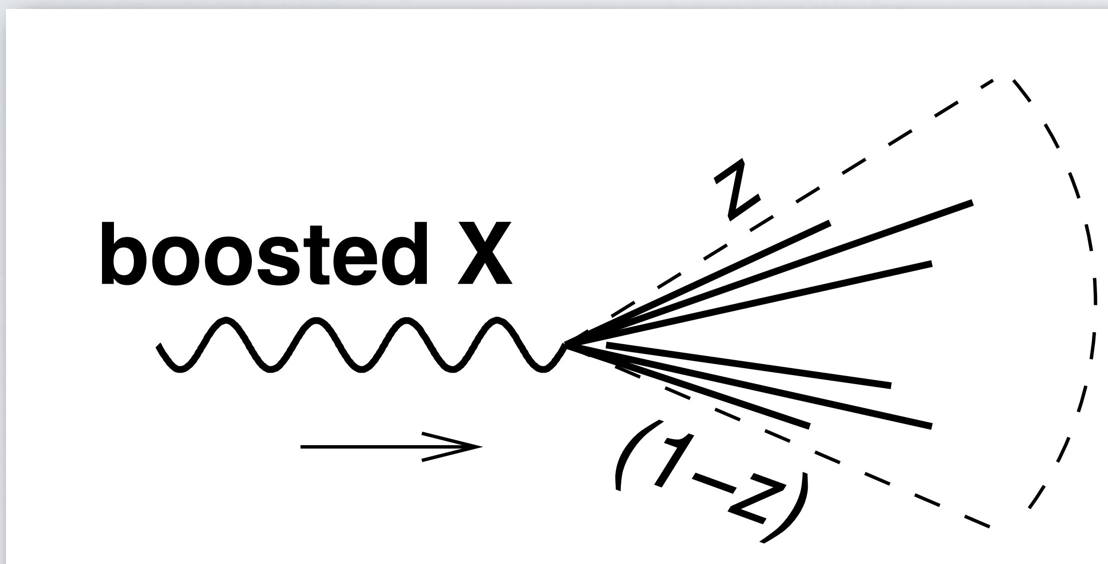


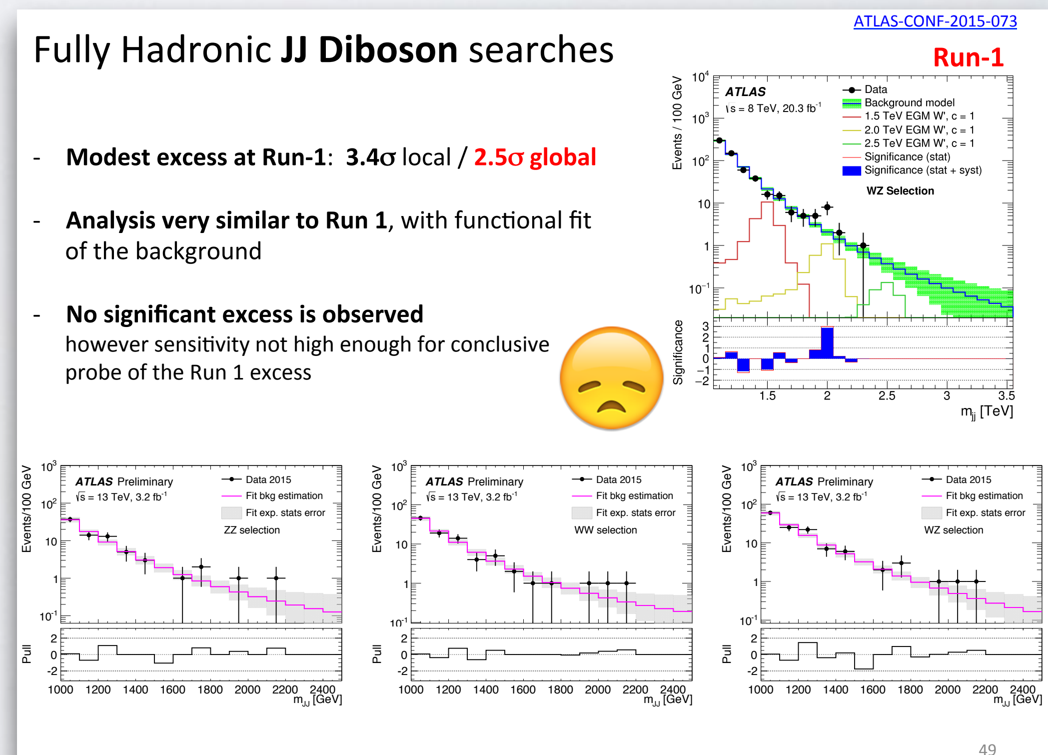


- look for bumps in the dijet invariant mass distribution

Searching for new particles: boosted analyses

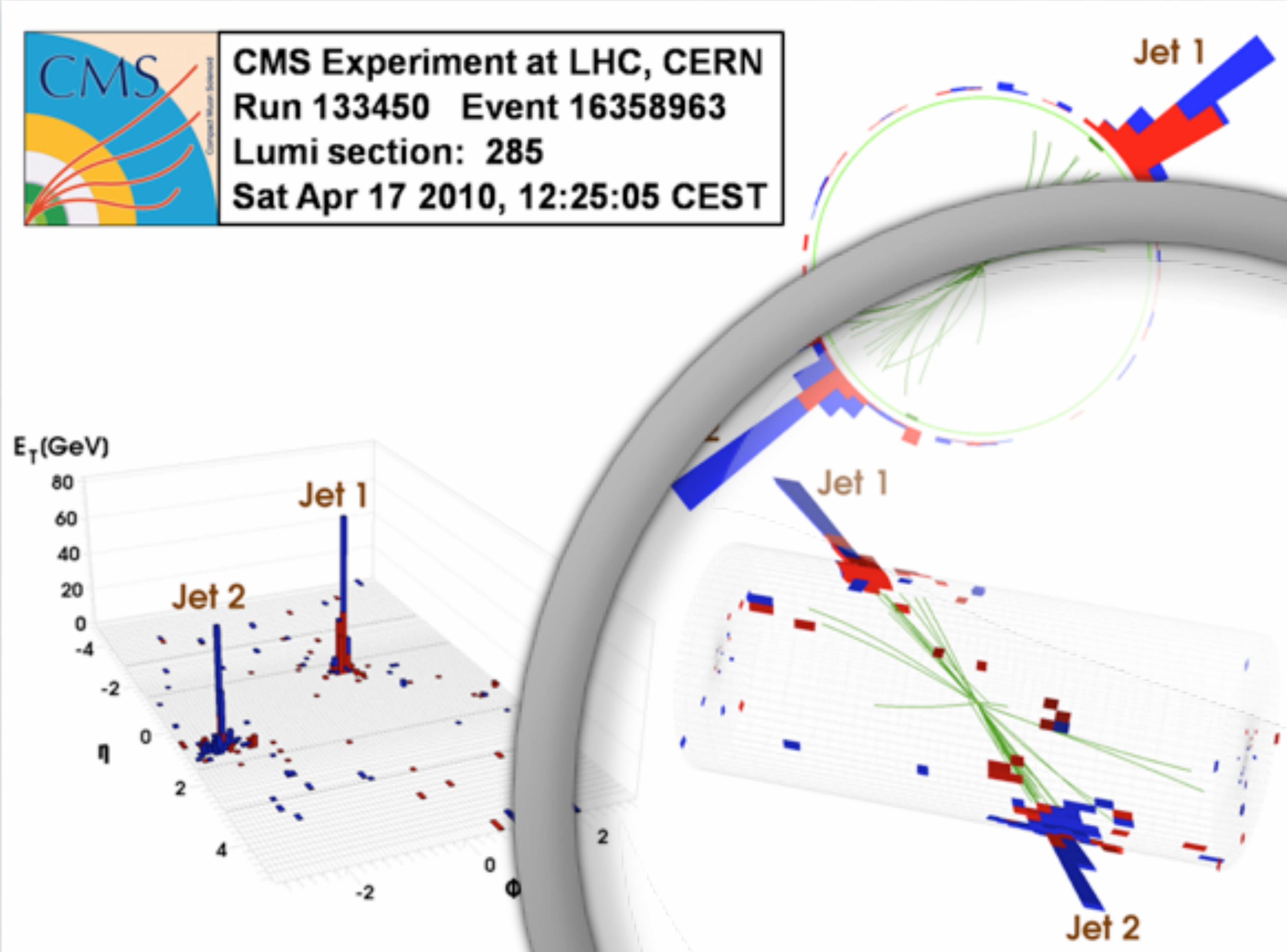
- LHC energy (10^4 GeV) $\gg$ electro-weak scale (10^2 GeV)
- EW-scale particles (new physics, Z/W/H/top) are abundantly produced with a large boost





- 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

Marumi Kado
(LAL, Orsay and CERN)



JETS

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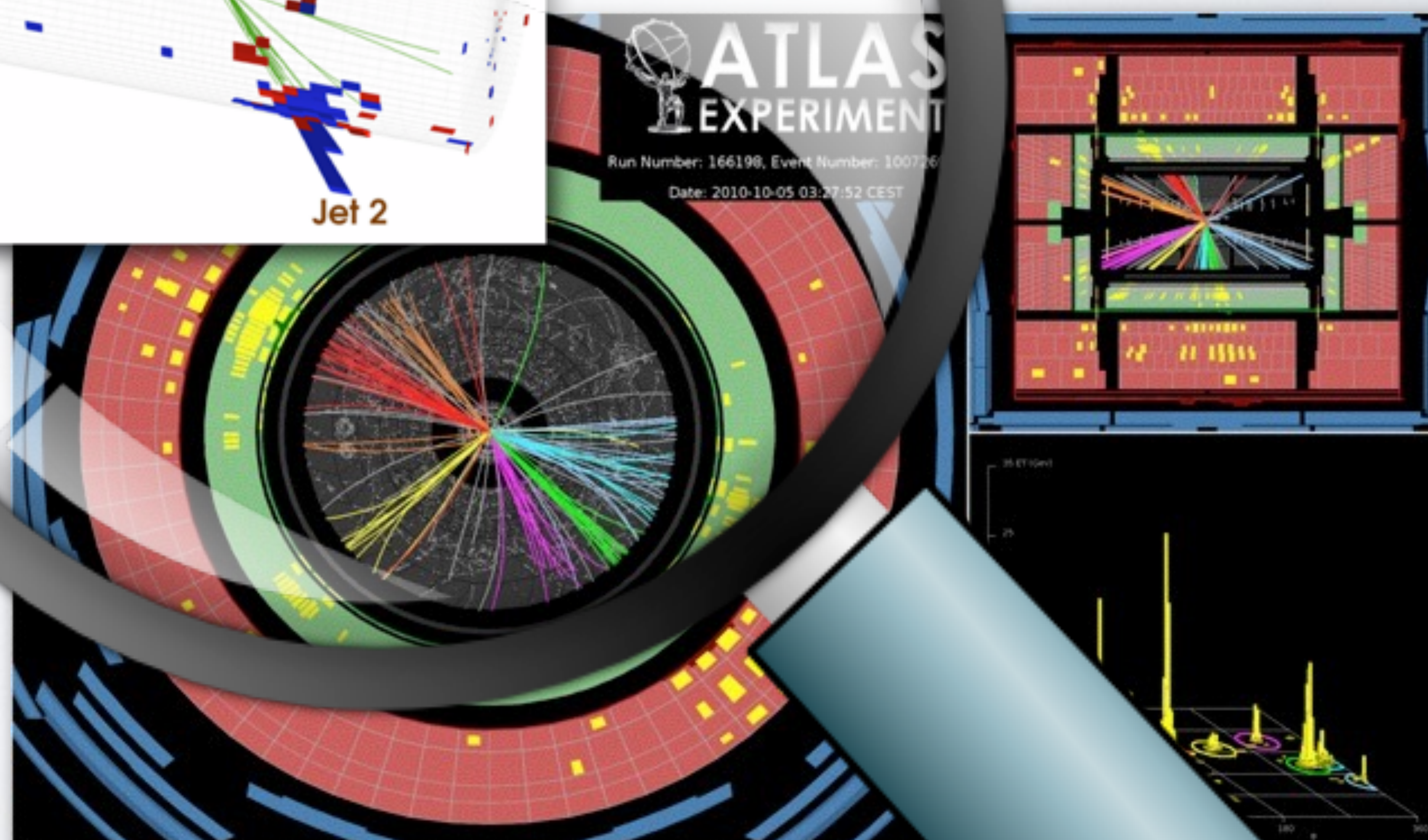
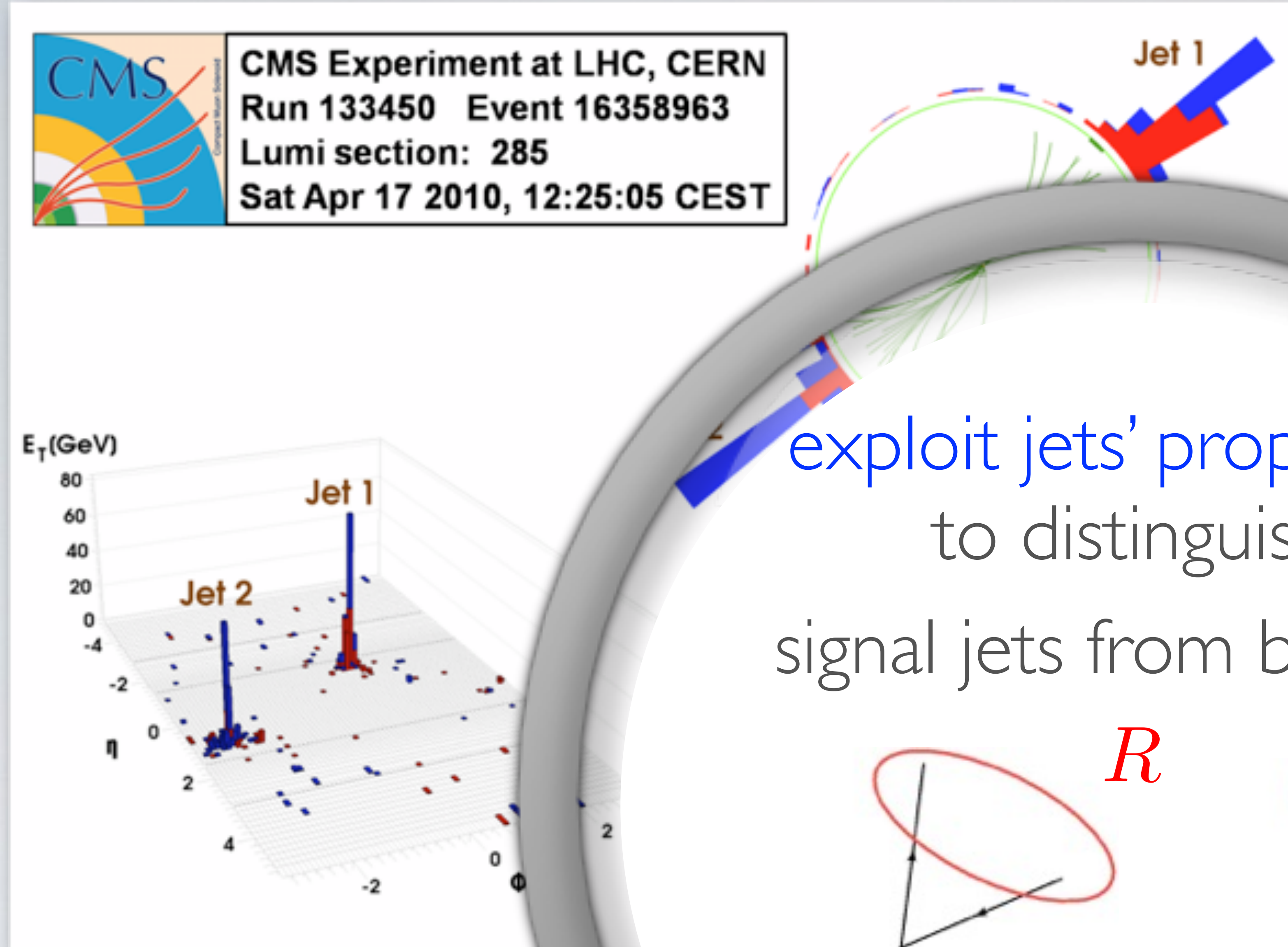


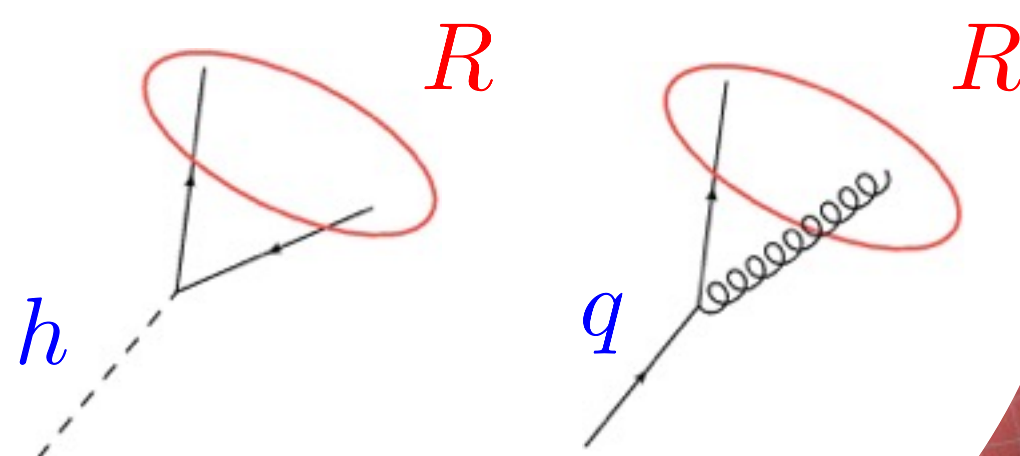
We want to look inside a jet



JETS

...llimated, energetic
...s of particles

exploit jets' properties
to distinguish
signal jets from bkg jets



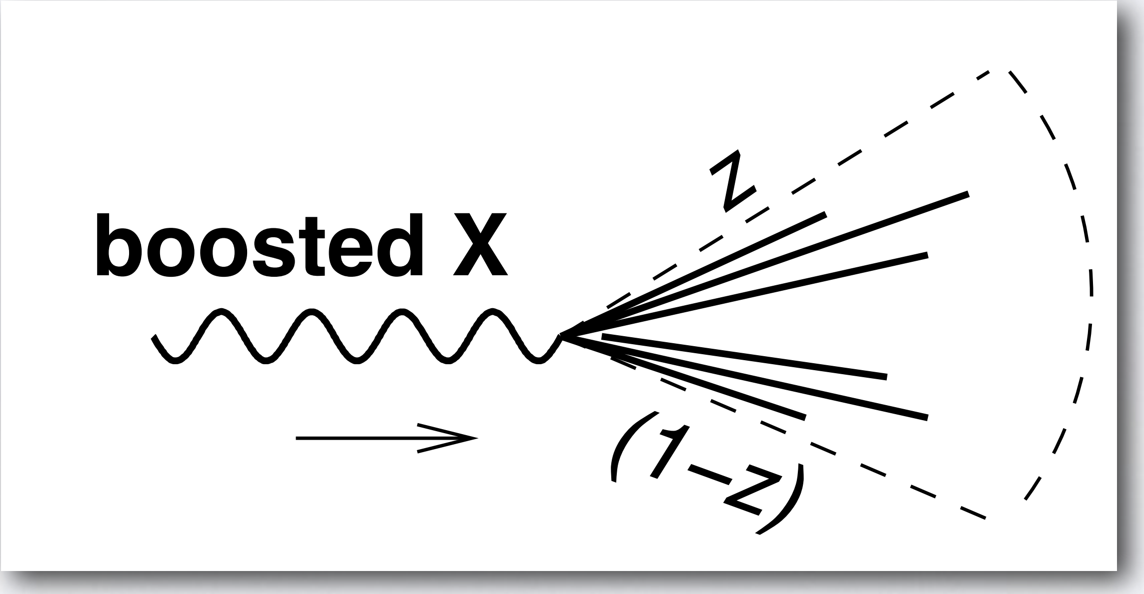
$$p_t > 2m/R$$

We want to look inside a jet

Signal-jet mass

- First jet-observable that comes to mind

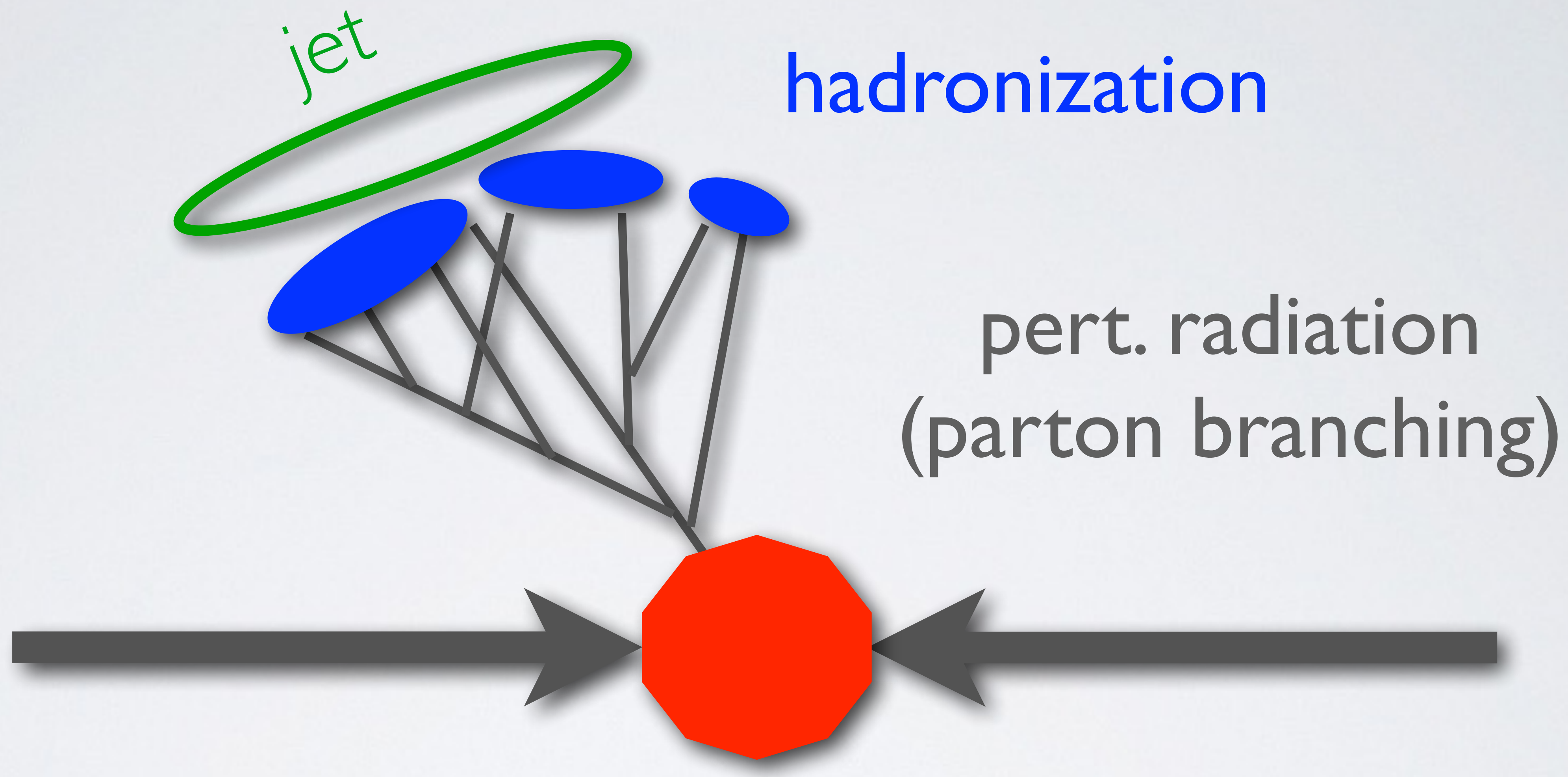
- Signal jet should have a mass distribution peaked near the resonance



- However, that's a simple partonic picture

A useful cartoon

inspired by G. Salam



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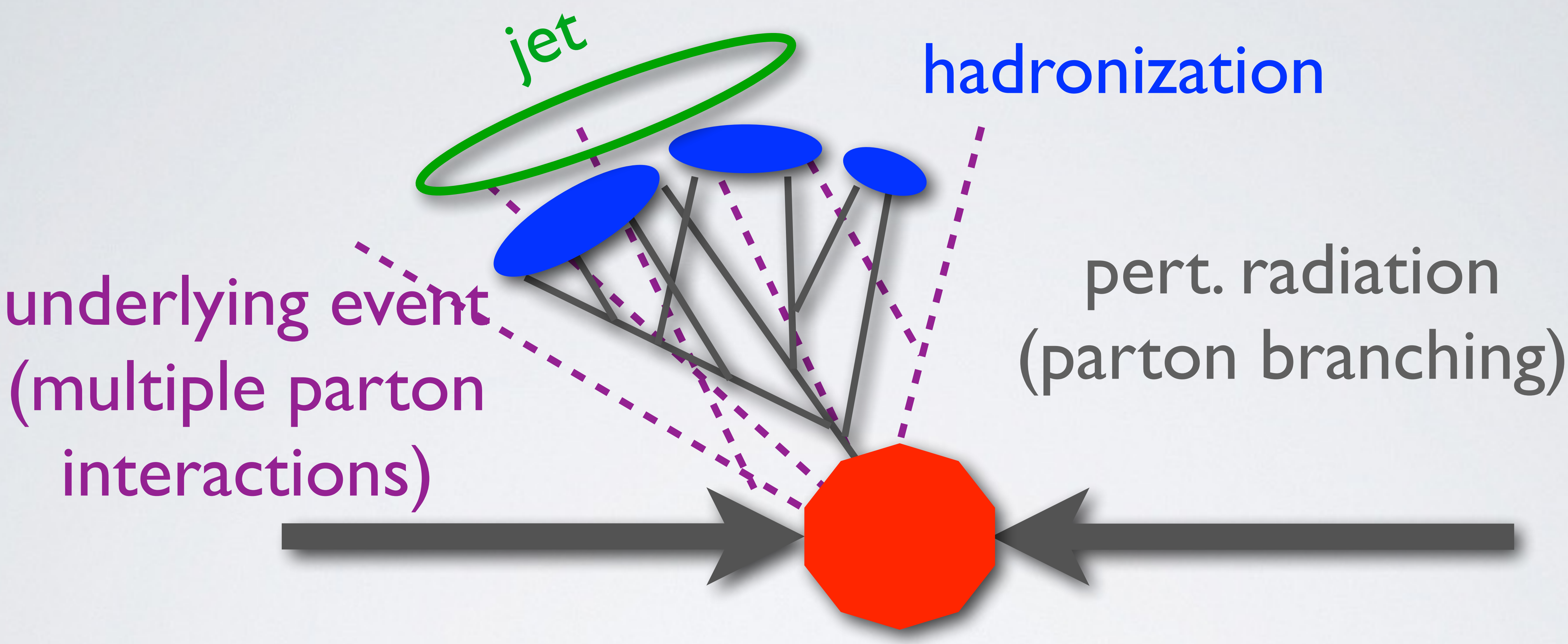

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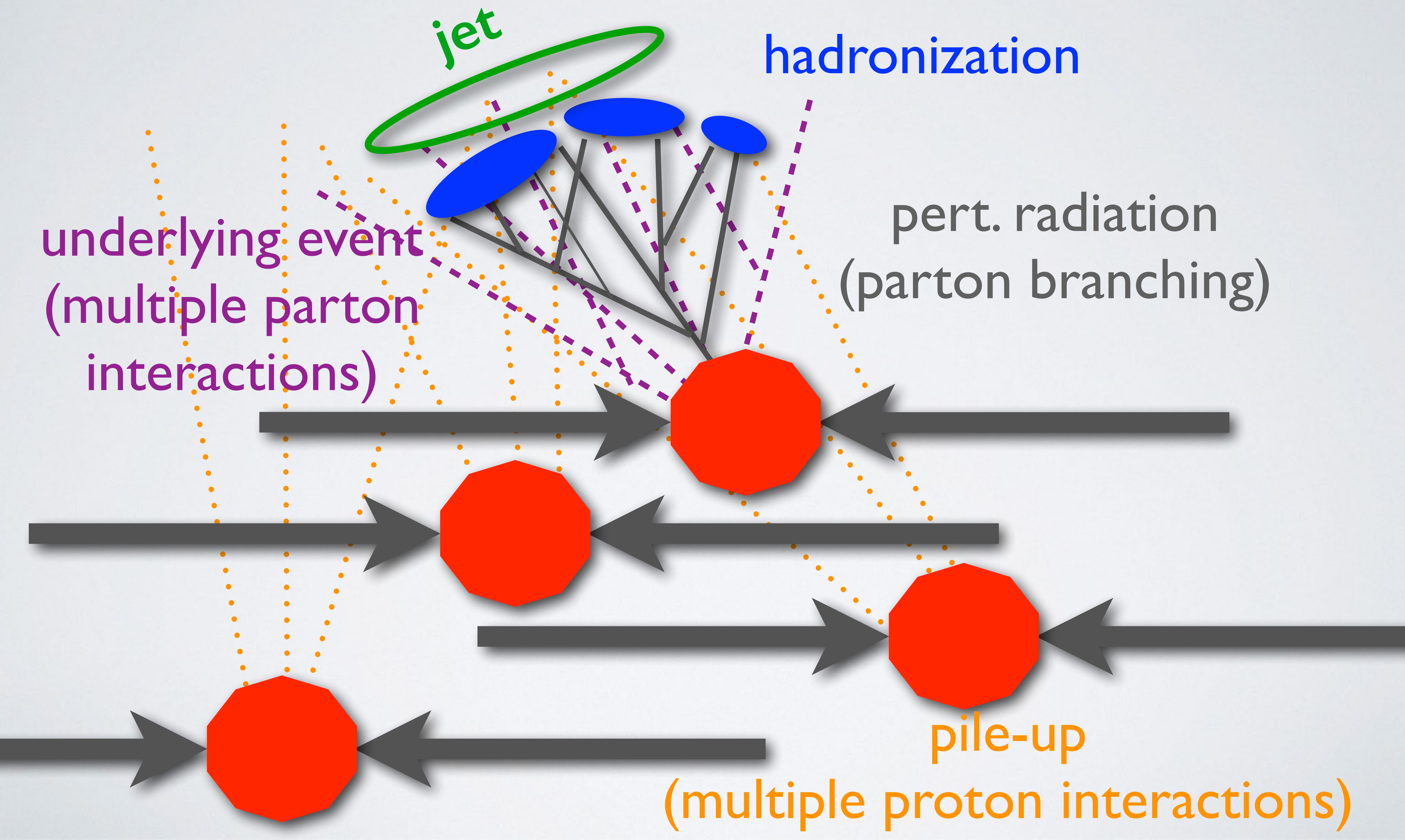
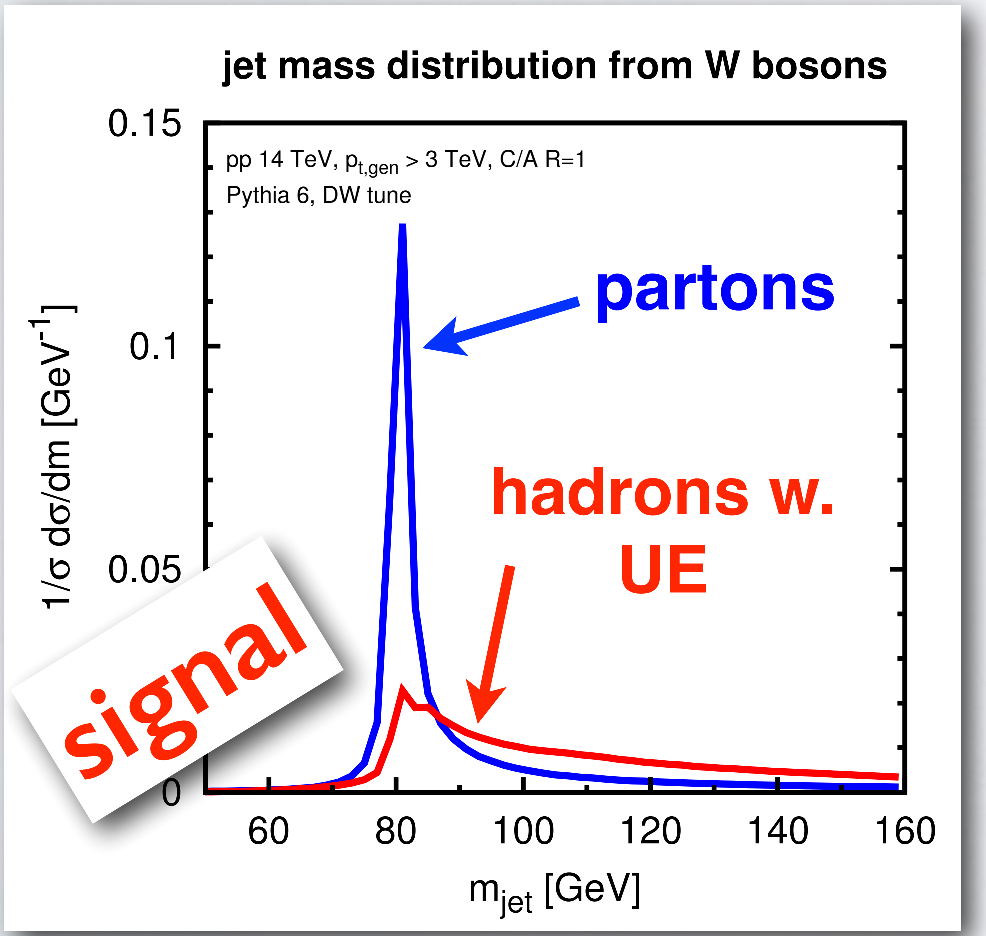
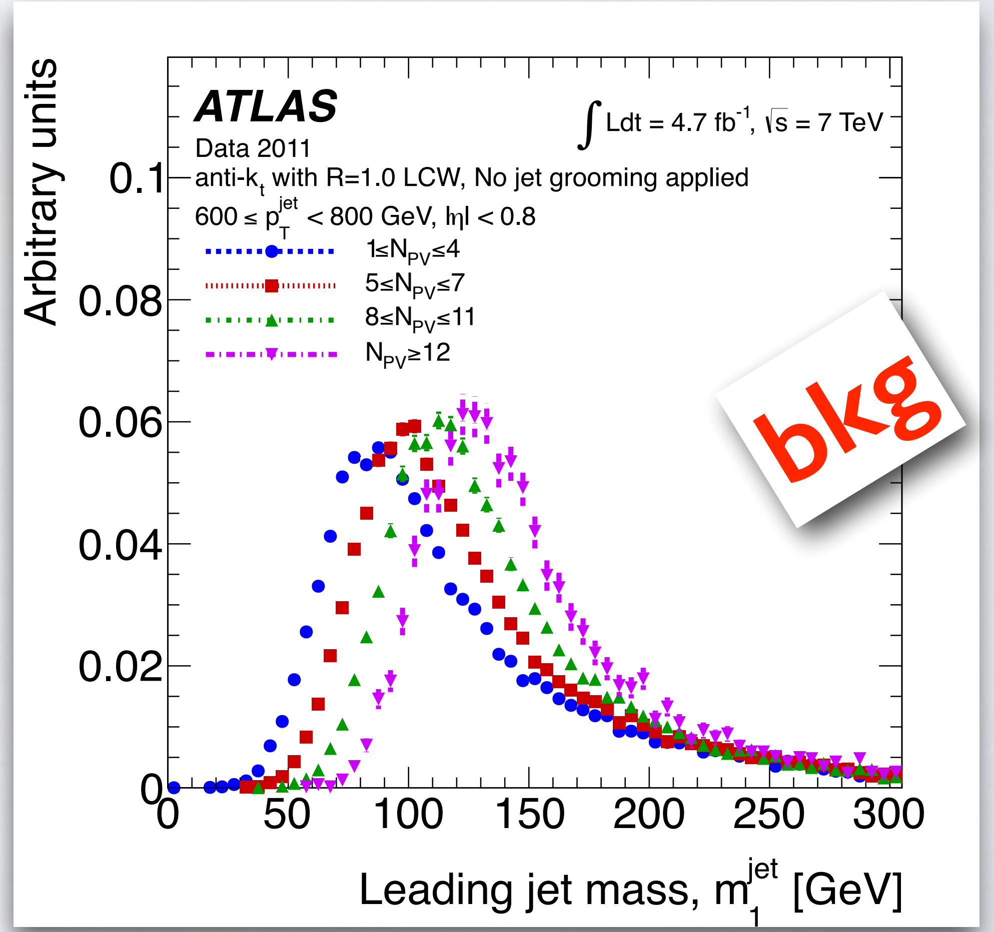


Effect of jet masses

- 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)

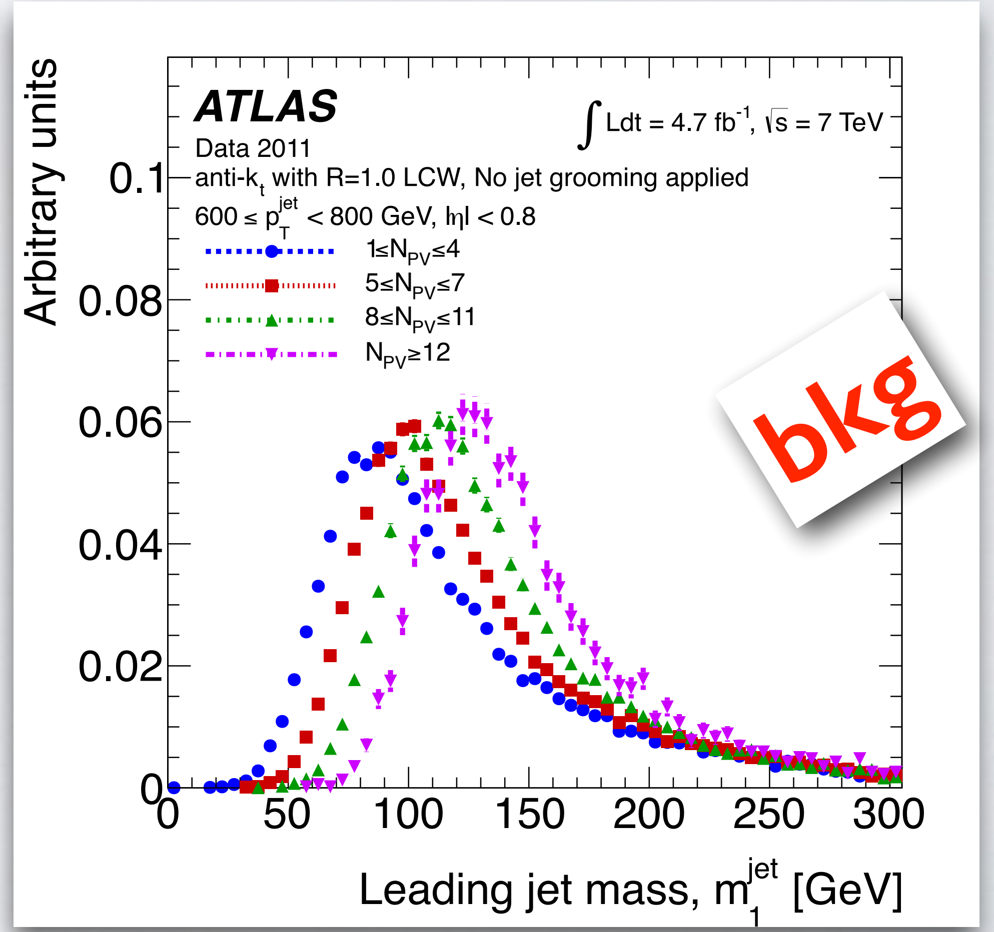




ATLAS, JHEP 1309 (2013) 076

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



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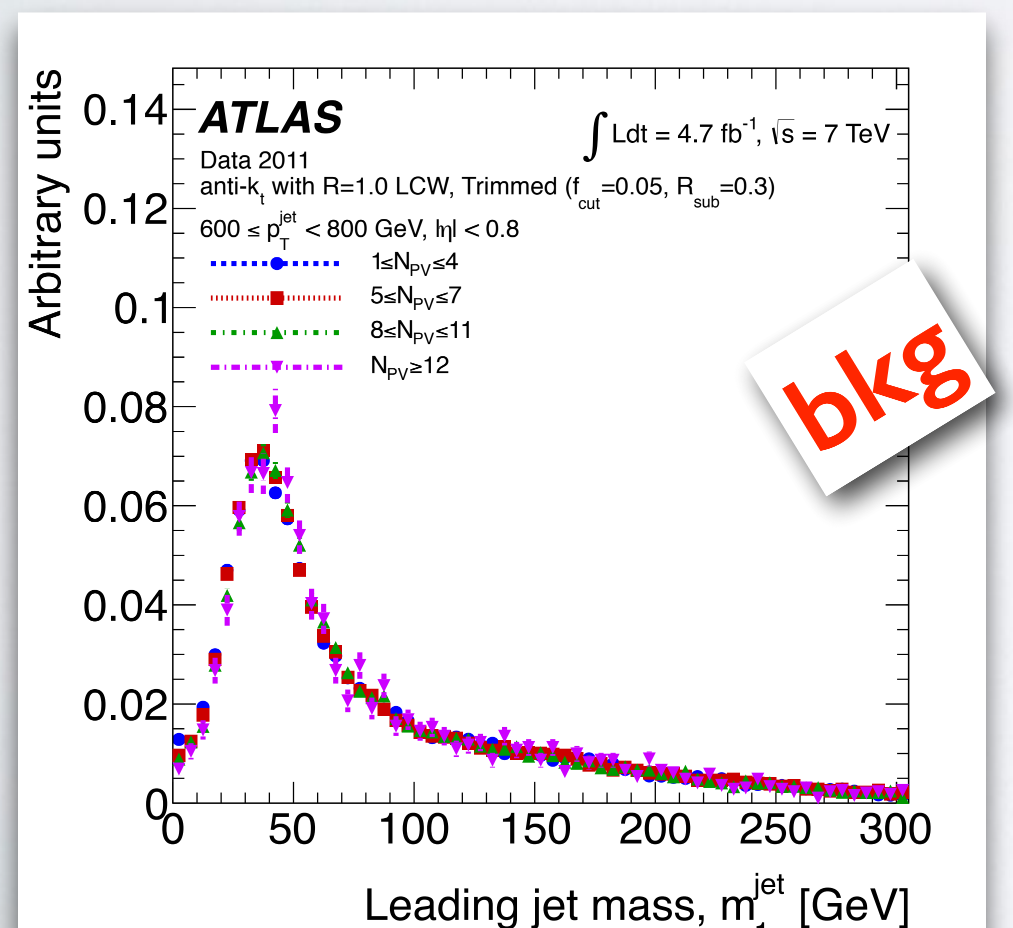
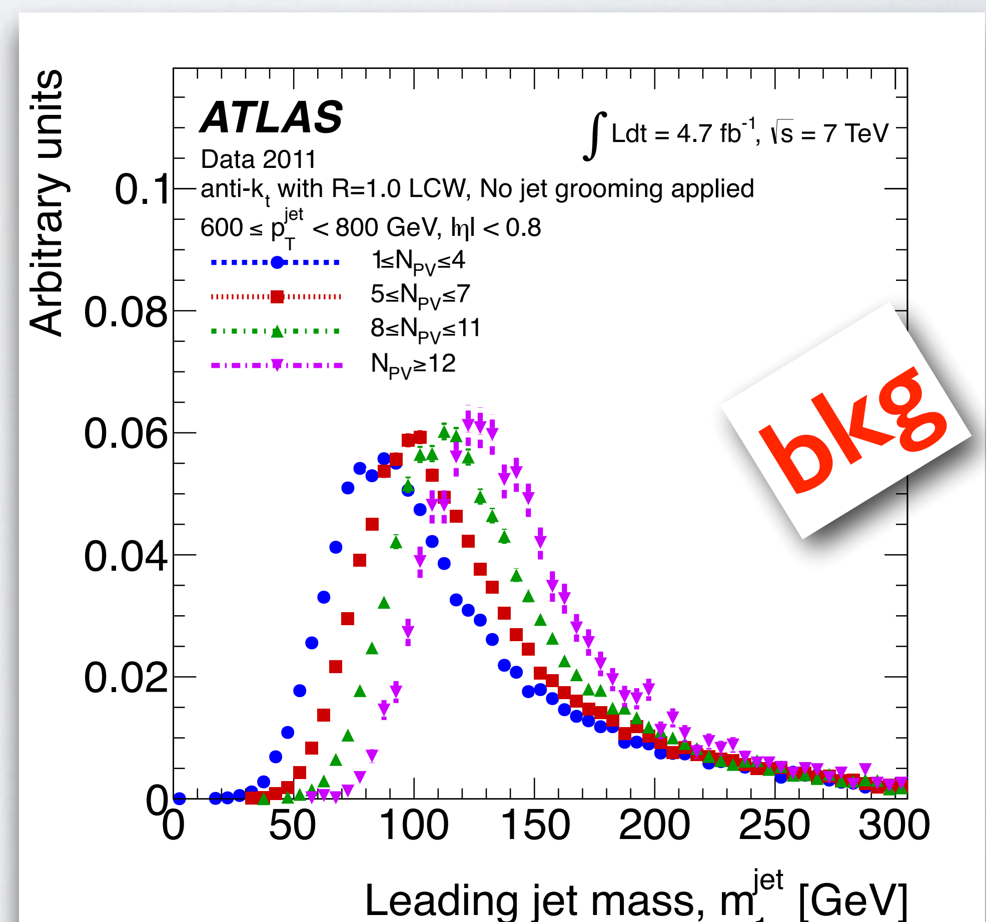
- Grooming and Tagging:
  1. clean the jets up by removing soft junk
  2. identify the features of hard decays and cut on them
- Grooming provides a handle on UE and pile-up



grooming



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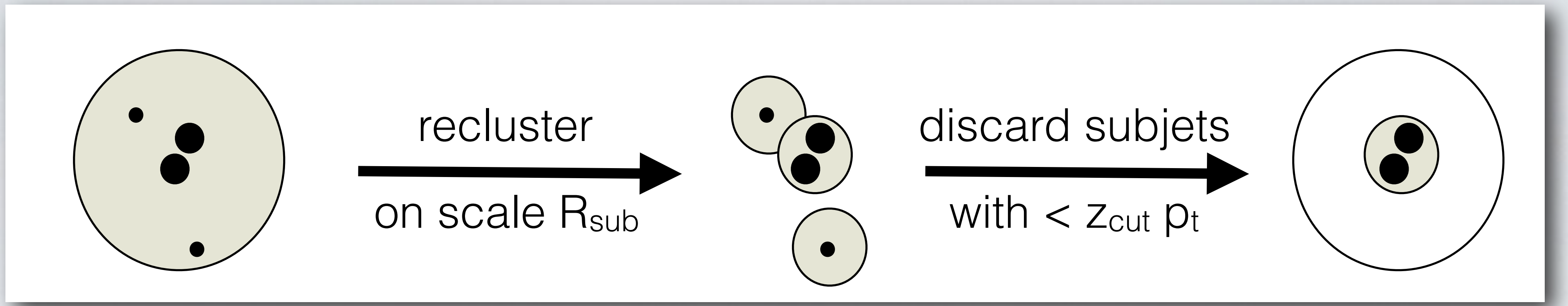
Trimming

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

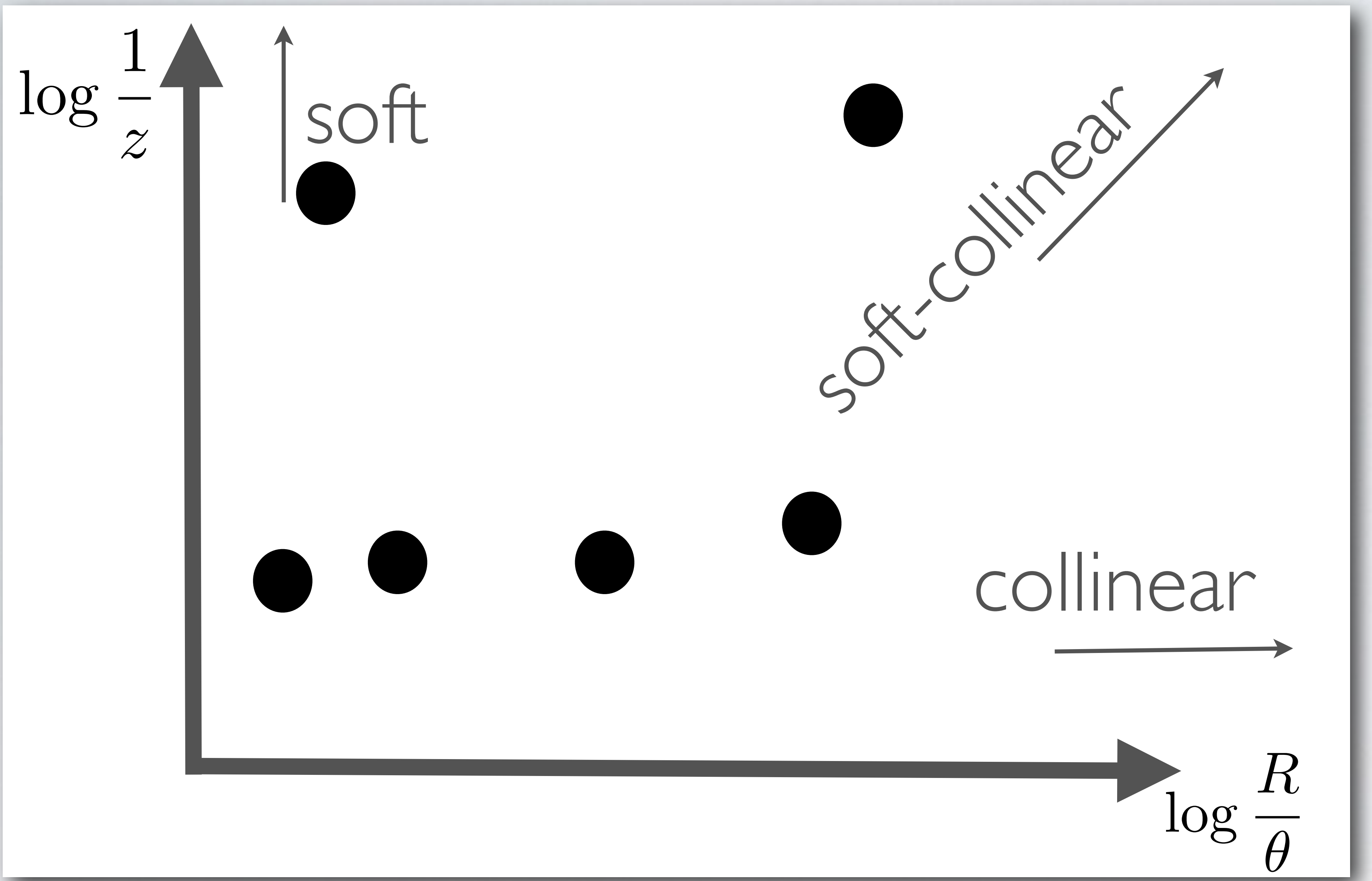
- Complicated algorithms with many parameters
- Are we giving up on calculability / precision QCD ?

- First comprehensive QCD study of these algorithms

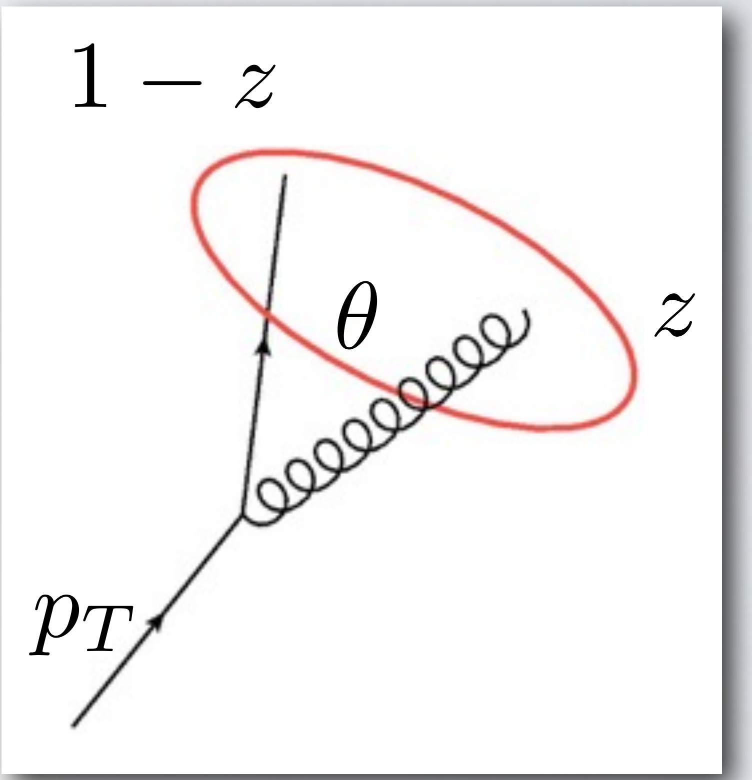
Dasgupta, Fregoso, SM, Powling EPJ C (2013)
Dasgupta, Fregoso, SM, Salam, JHEP 1309 029 (2013)

Theoretical understanding of jet substructure

Soft-gluon phase space



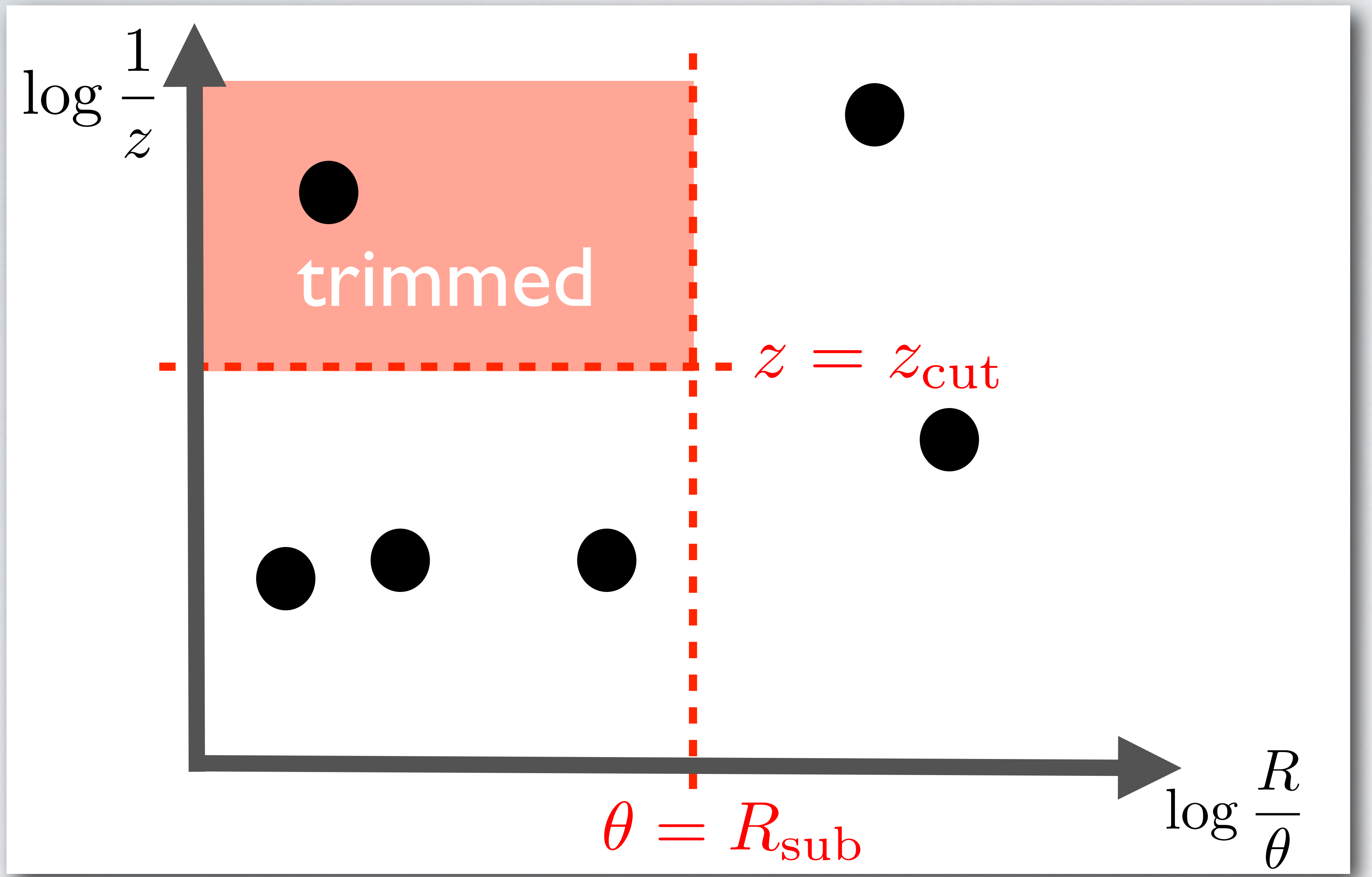
Soft gluons off a hard parton (a quark for definiteness)



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



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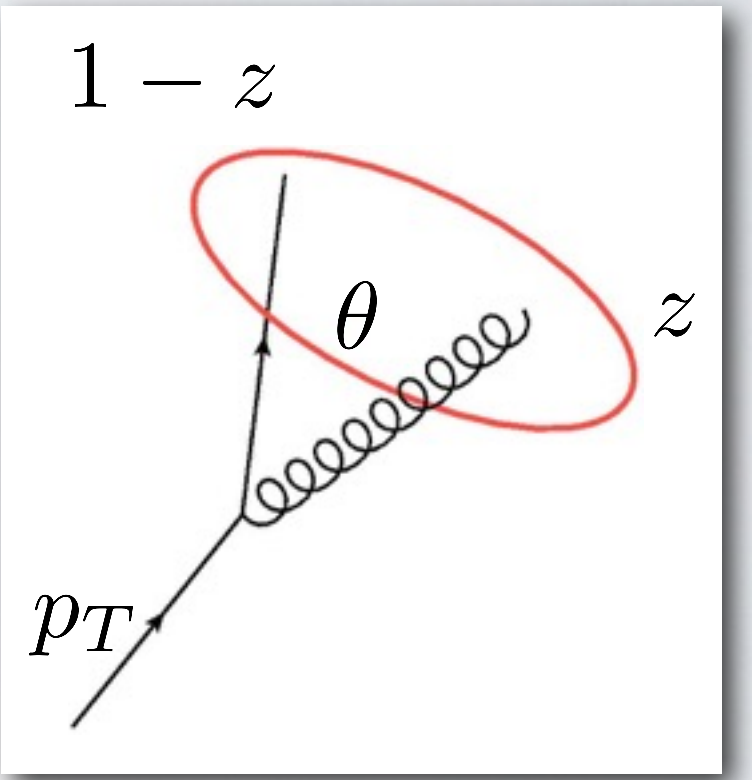
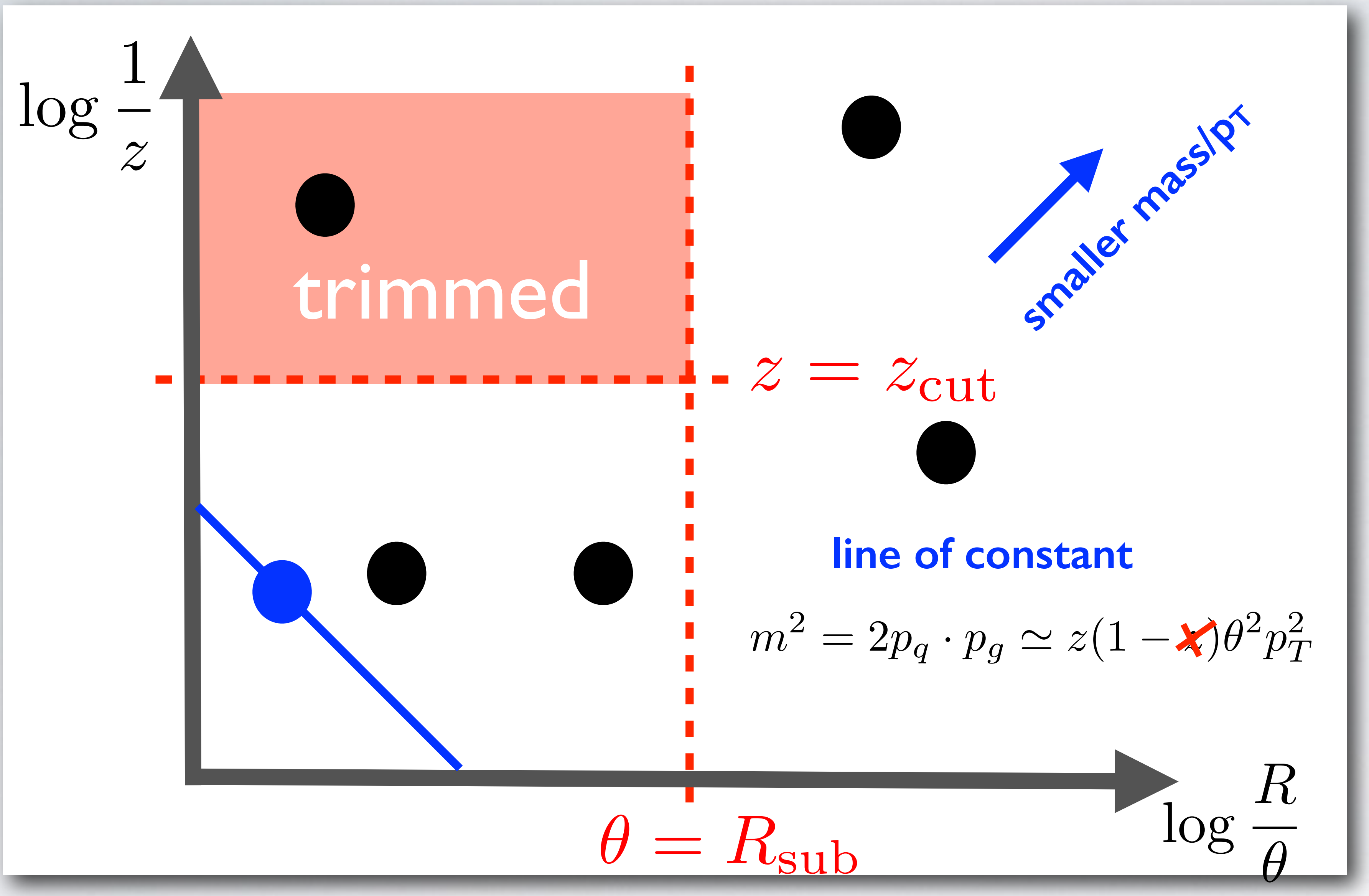


- The action of a groomer is to remove some of the allowed phase space (typically soft and soft-collinear)
- What are the consequences for physical observables, e.g. the jet mass ?

Trimming



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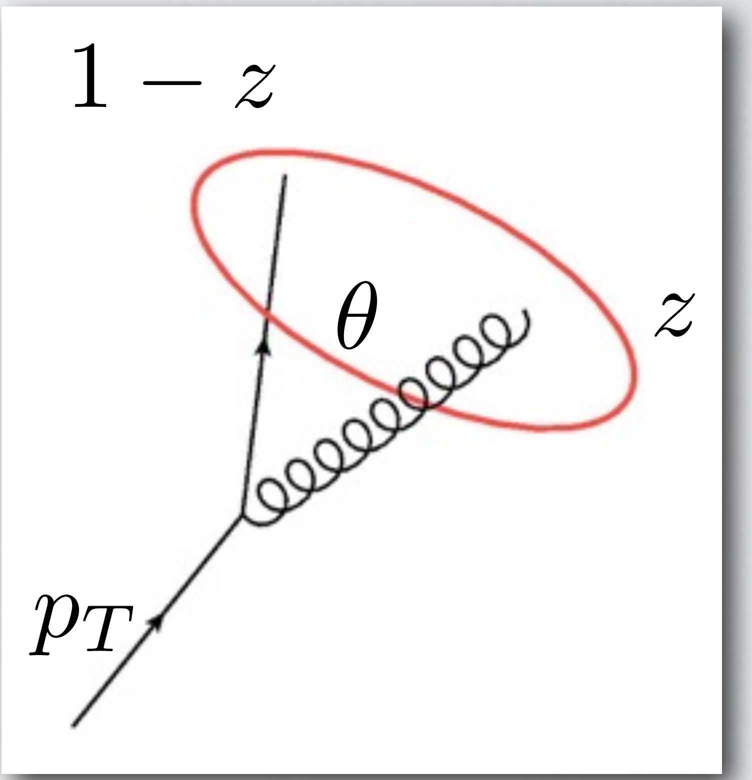

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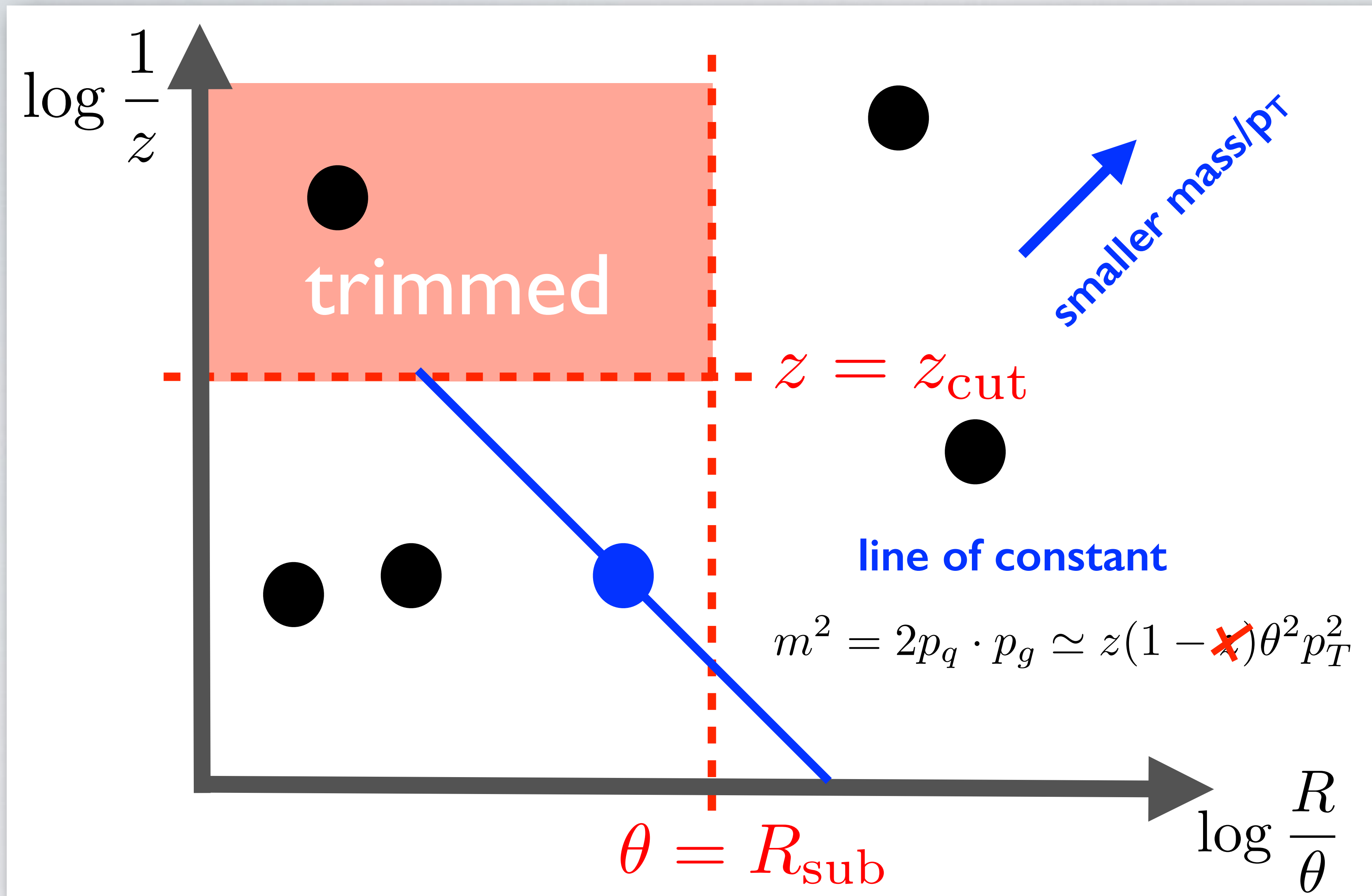

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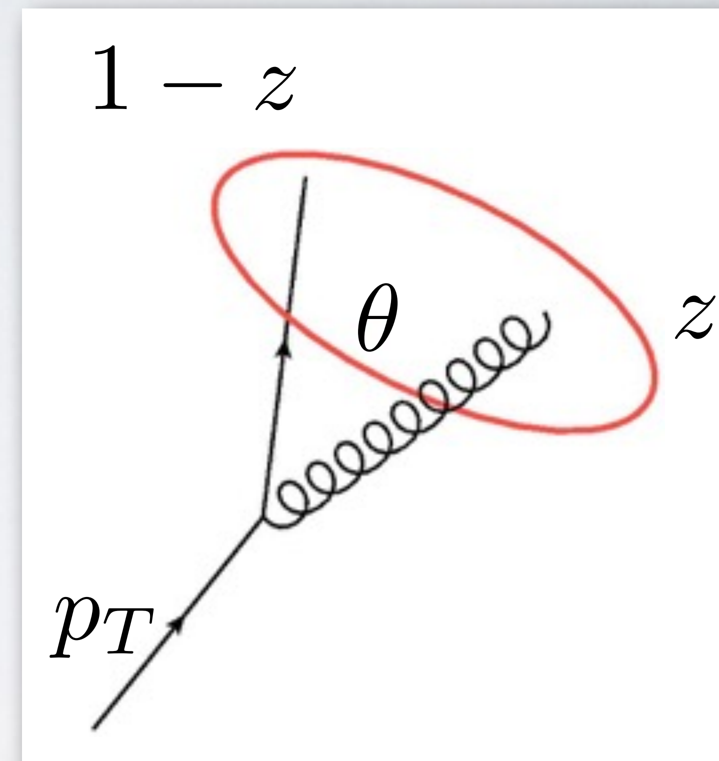

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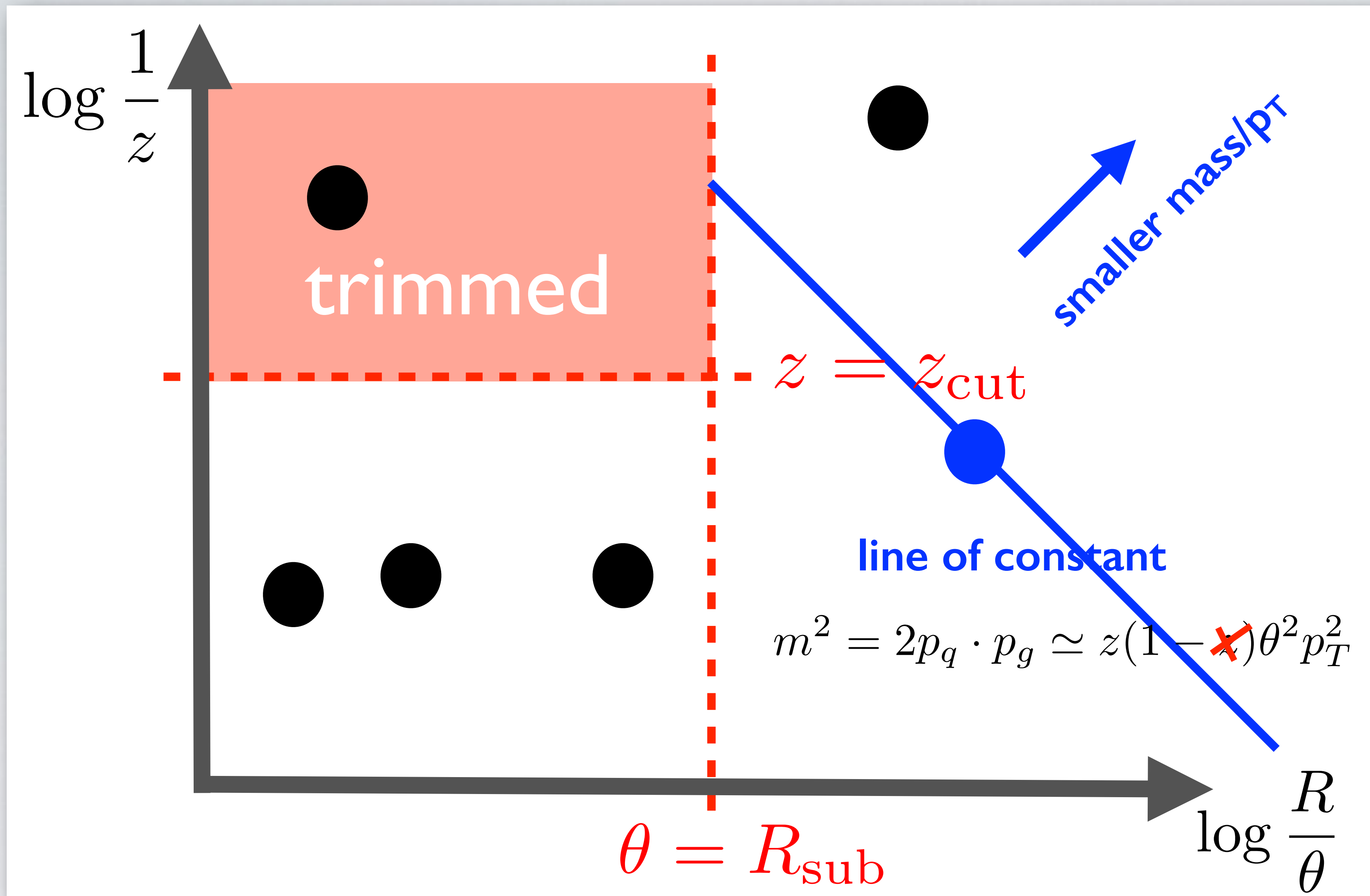

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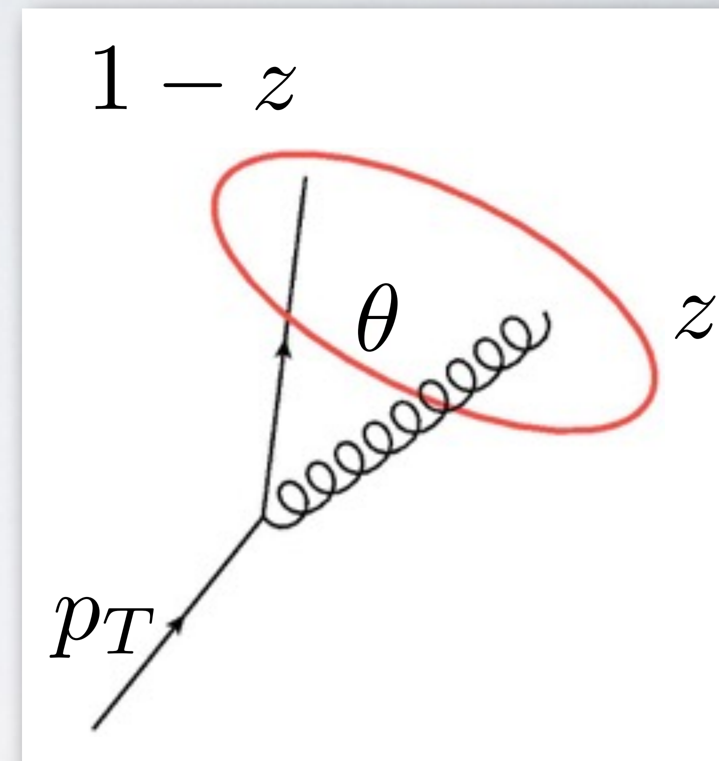

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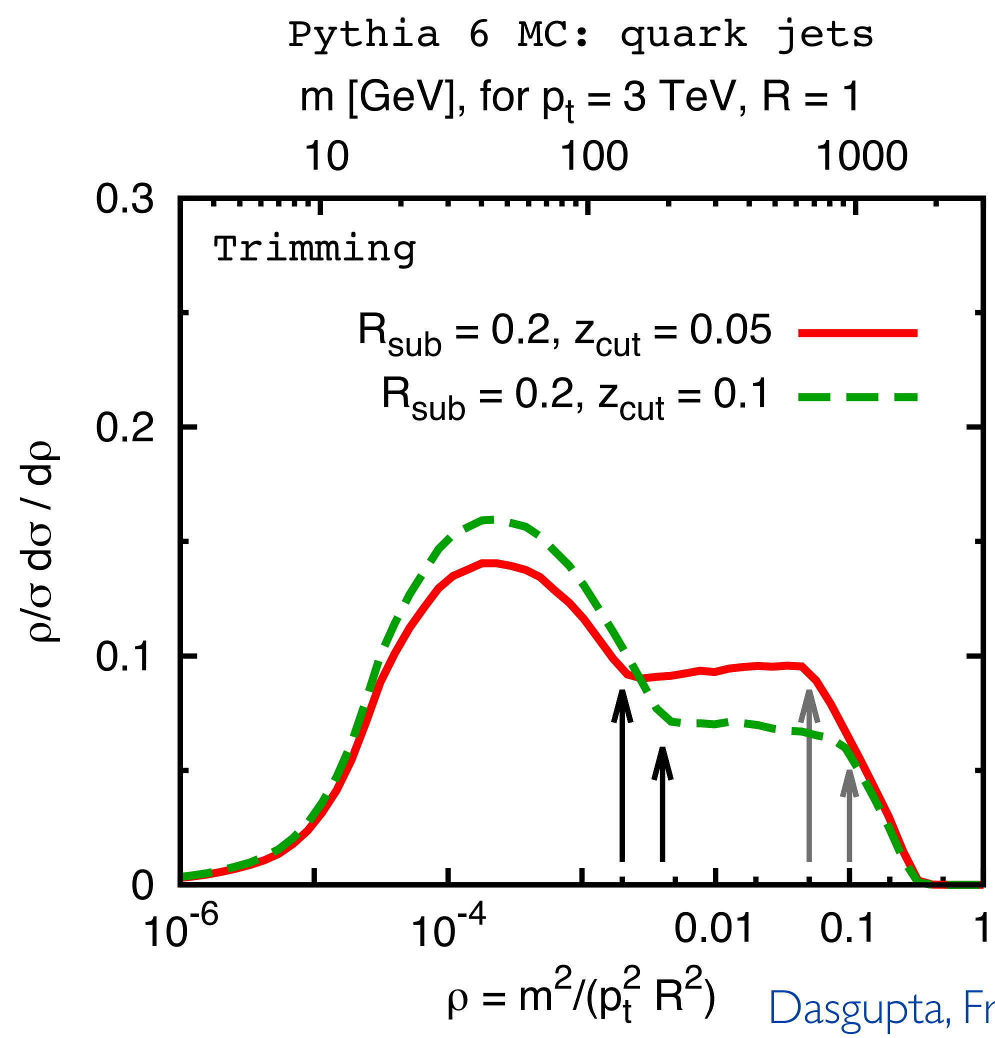
Trimmed mass: MC vs analytics

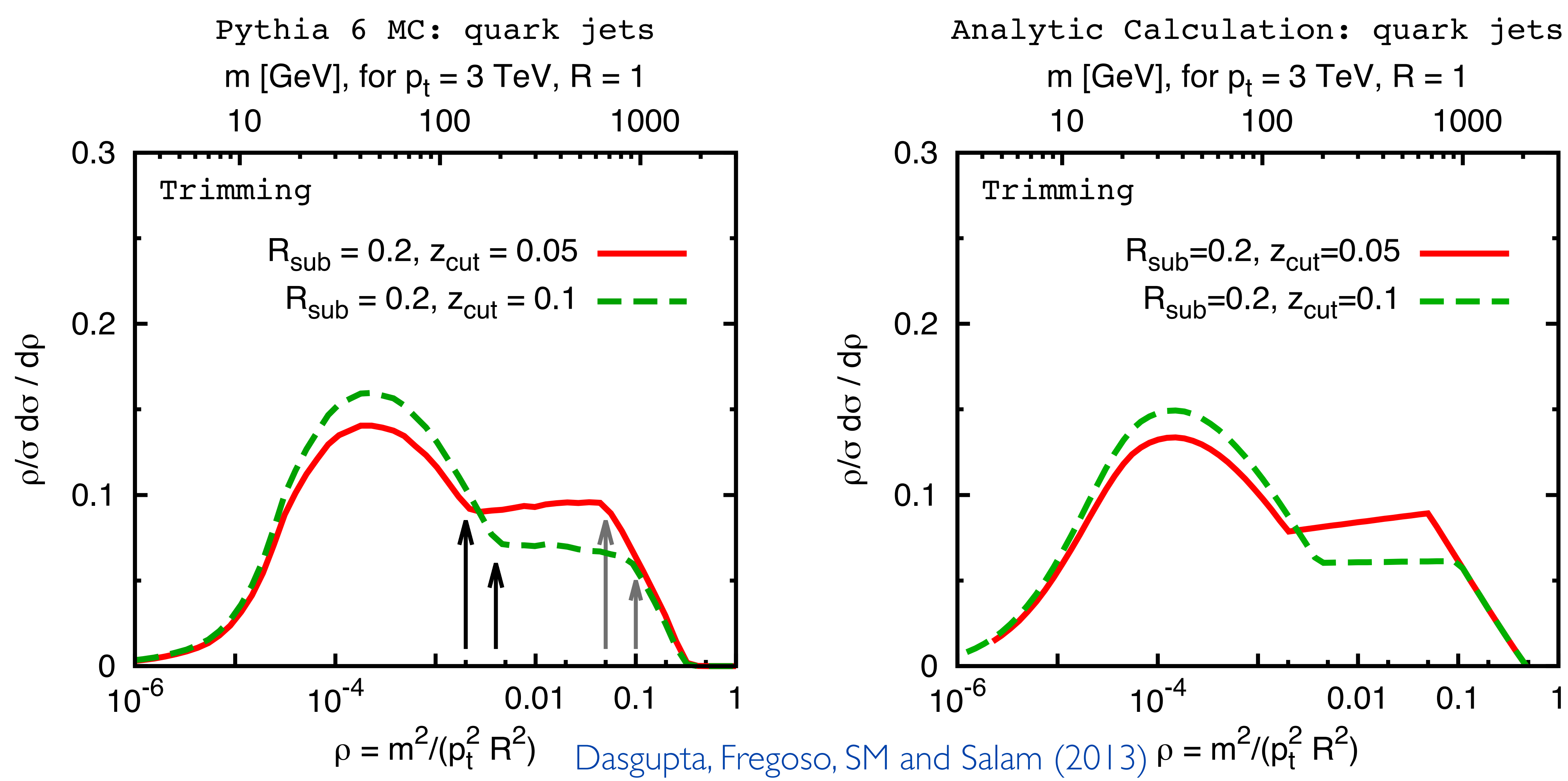


Dasgupta, Fregoso, SM and Salam (2013)

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

Trimmed mass: MC vs analytics

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



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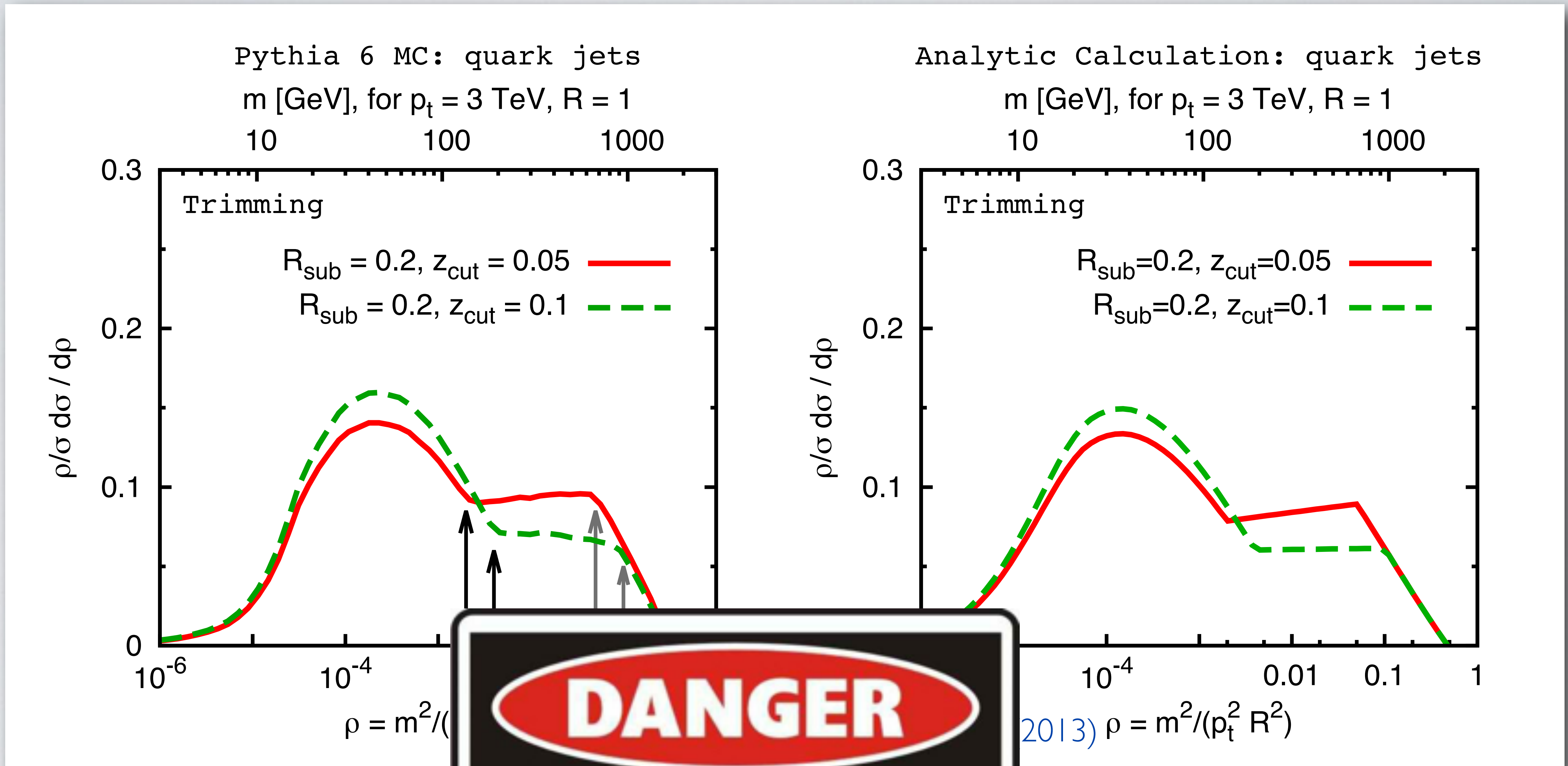
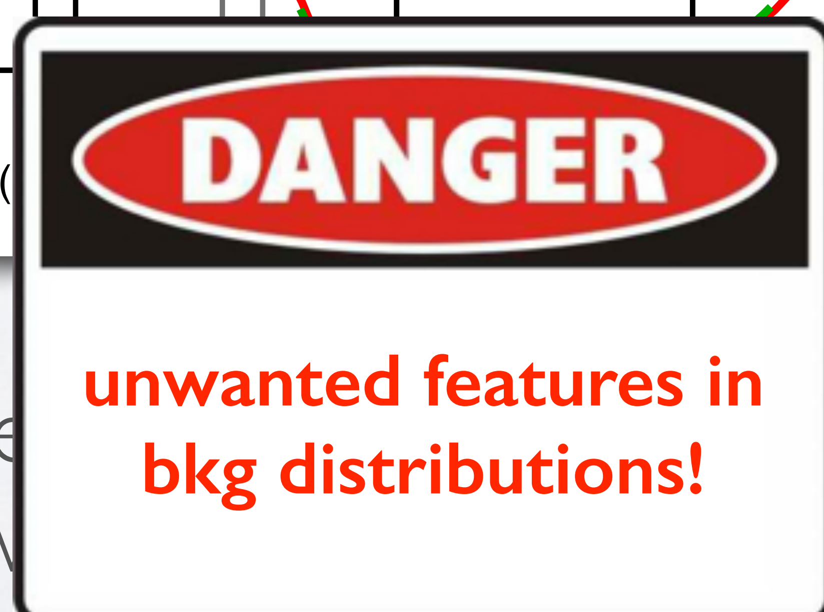


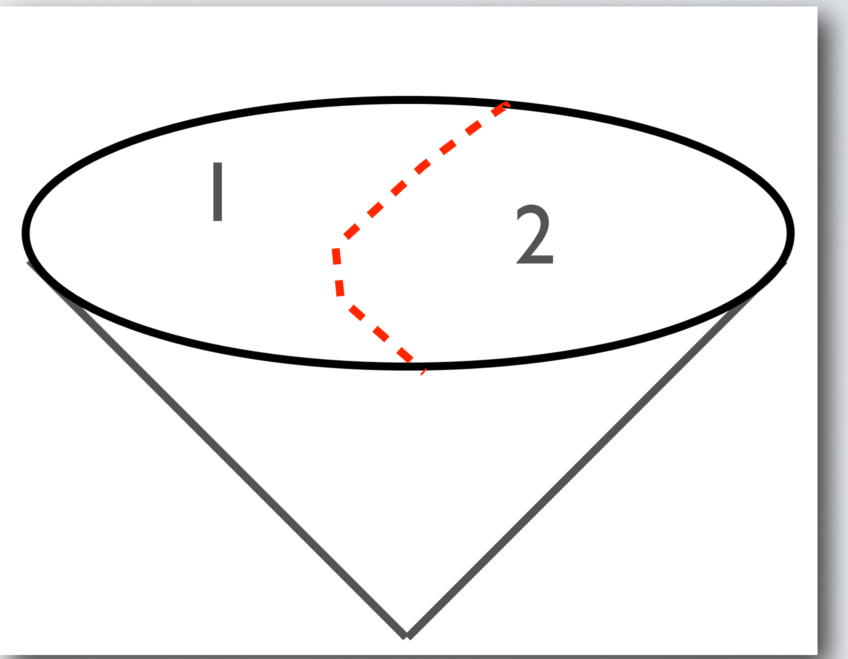


- Trimming is active ... $z_{cut} < \rho < R_{sub}^2/R^2\ z_{cut}$
- Not active below ...

Analytic understanding at work: Soft Drop

Larkoski, SM, Soyez and Thaler (2014)

1. Undo the last stage of the C/A clustering. Label the two subjets j_1 and j_2.



2. If $$\frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

then deem j to be the soft-dropped jet.

3. Otherwise redefine j to be the harder subjet and iterate.

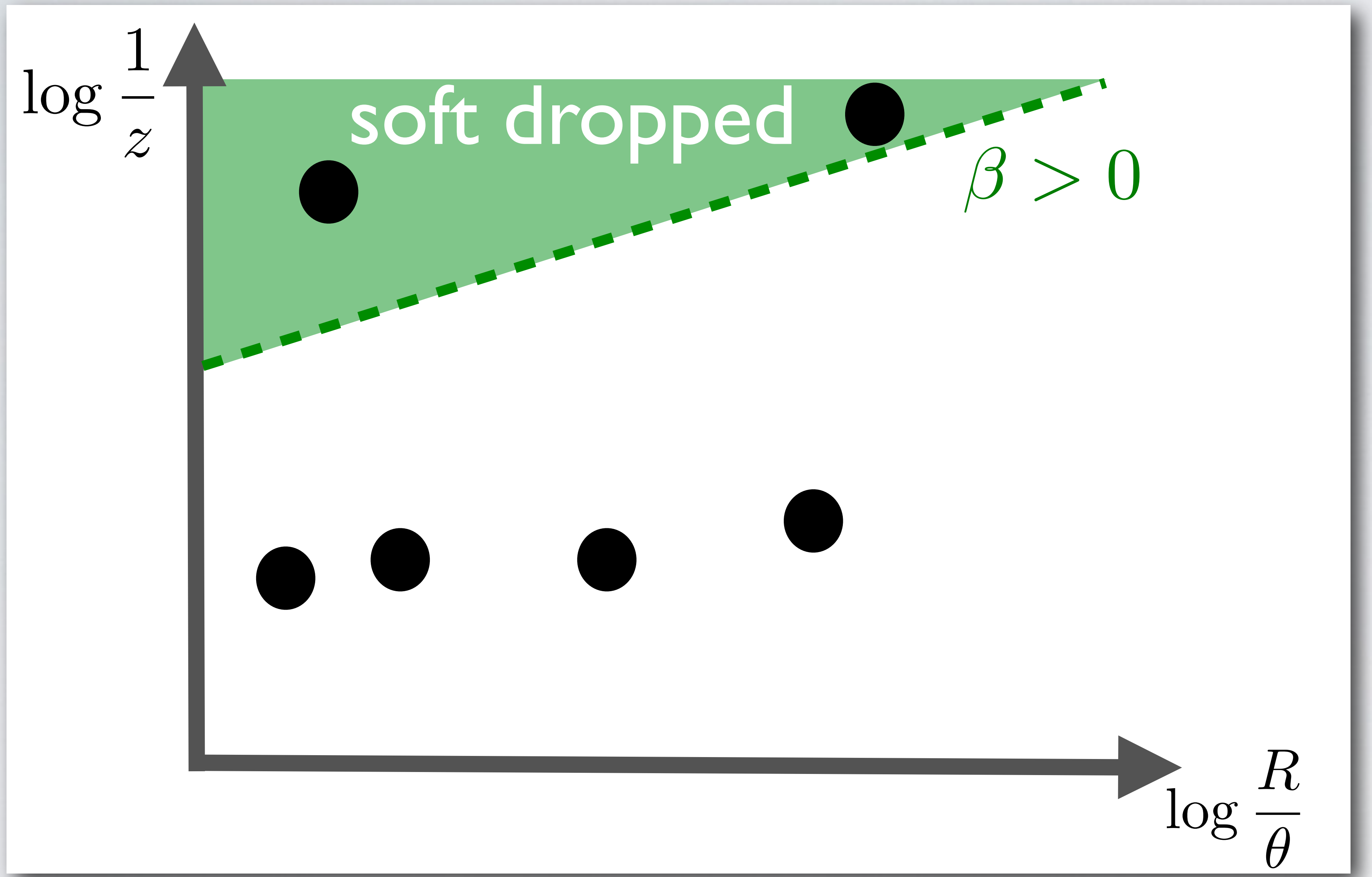
1-prong jets can be either kept (grooming mode) or discarded (tagging mode)

- Generalization of the (modified) Mass Drop procedure
- no mass drop condition (not so important)
- mMDT recovered for β=0
- some inspiration from semi-classical jets

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

Tseng and Evans (2013)

Soft Drop as a groomer

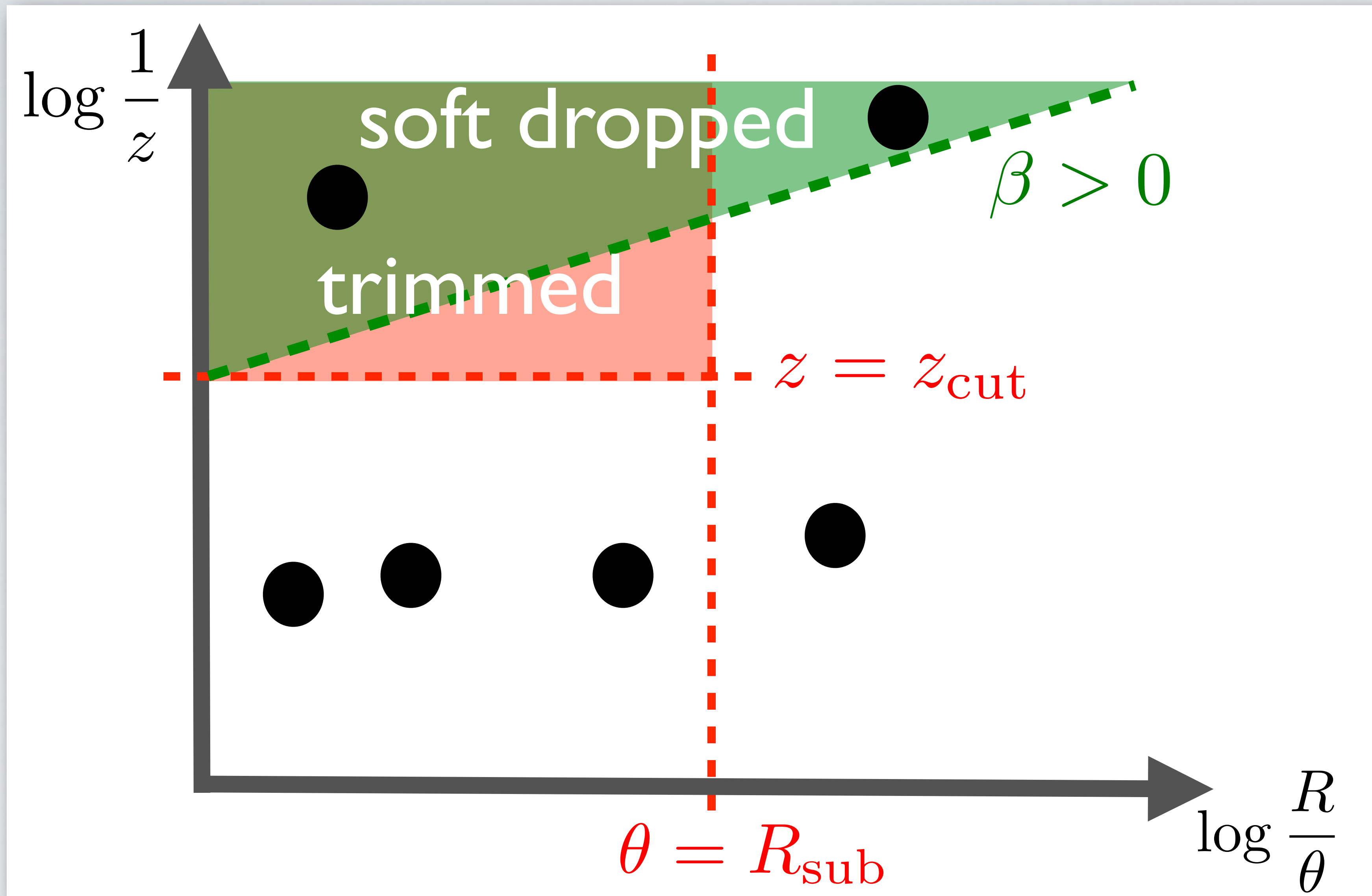


- useful to consider the soft-gluon phase space
- soft-drop condition becomes

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

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

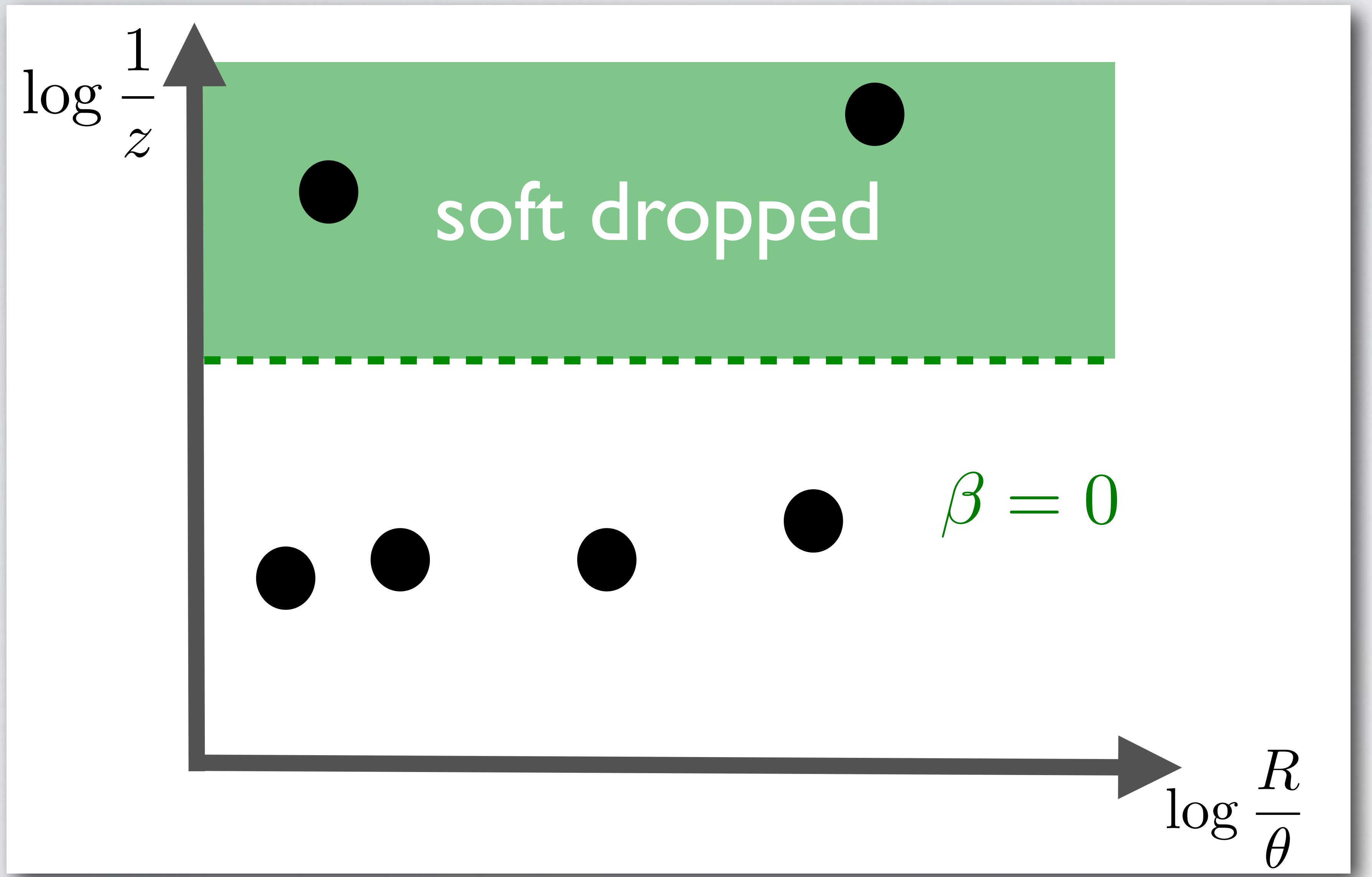
Soft Drop vs Trimming



- 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



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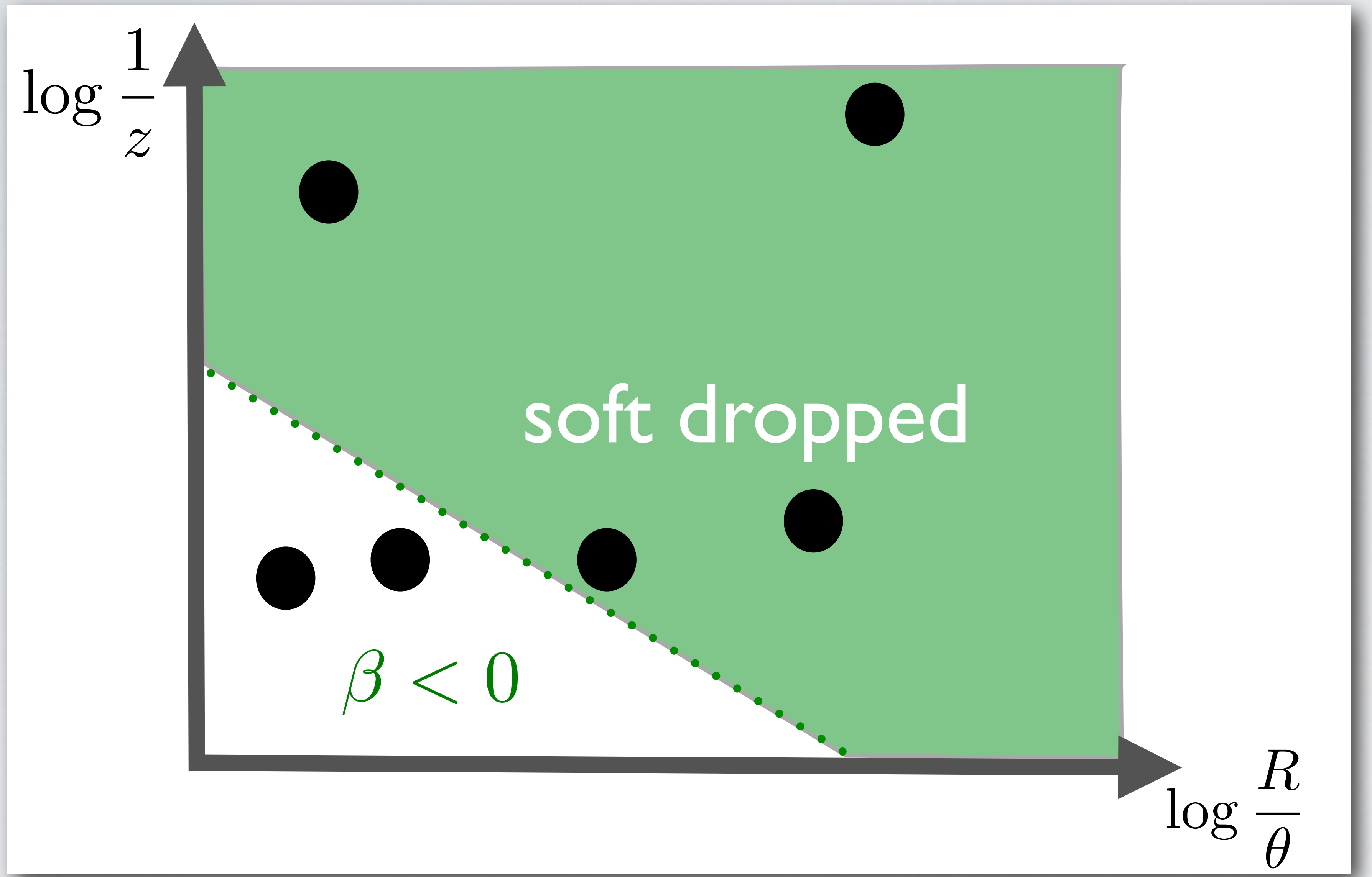
- for β=0 soft-collinear is also entirely removed (mMDT limit)

Soft Drop as a tagger



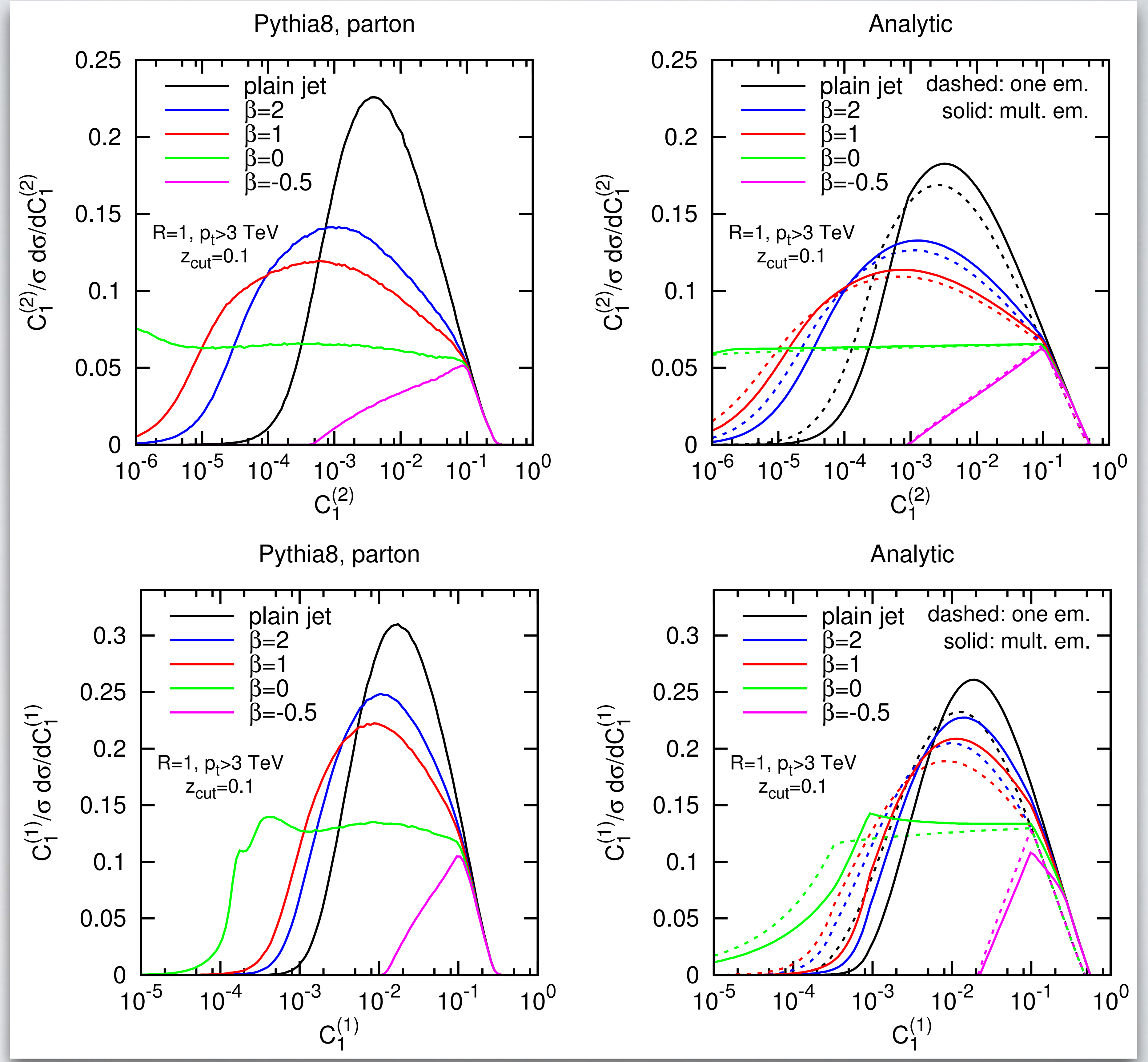
- useful to consider the soft-gluon phase space
- soft-drop condition becomes

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

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

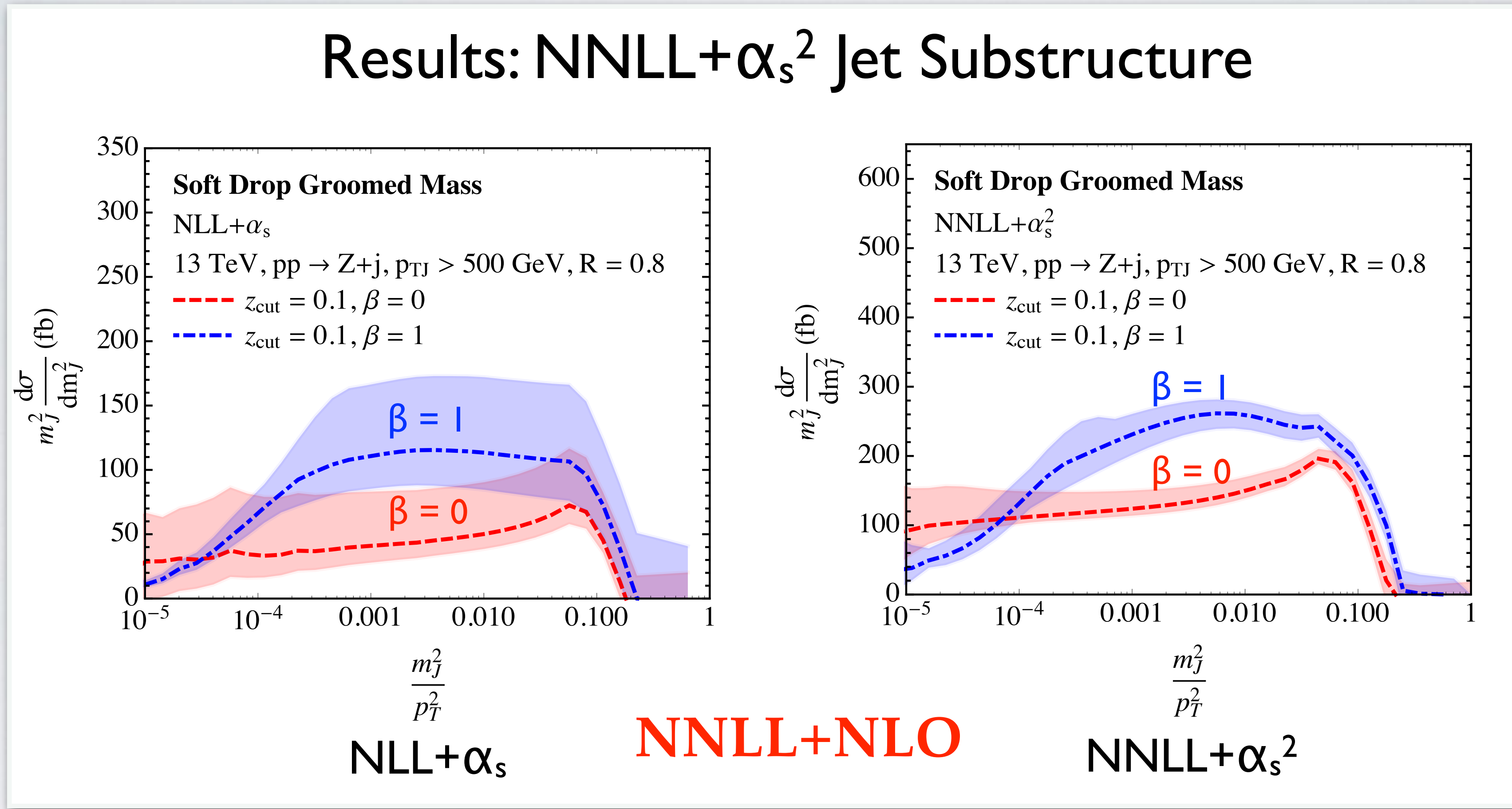
Calculating groomed-jet properties

- An example: two-point energy correlation functions



- no more kinks
- flatness in bkg can be achieved for **β**=0

Soft drop at NNLL

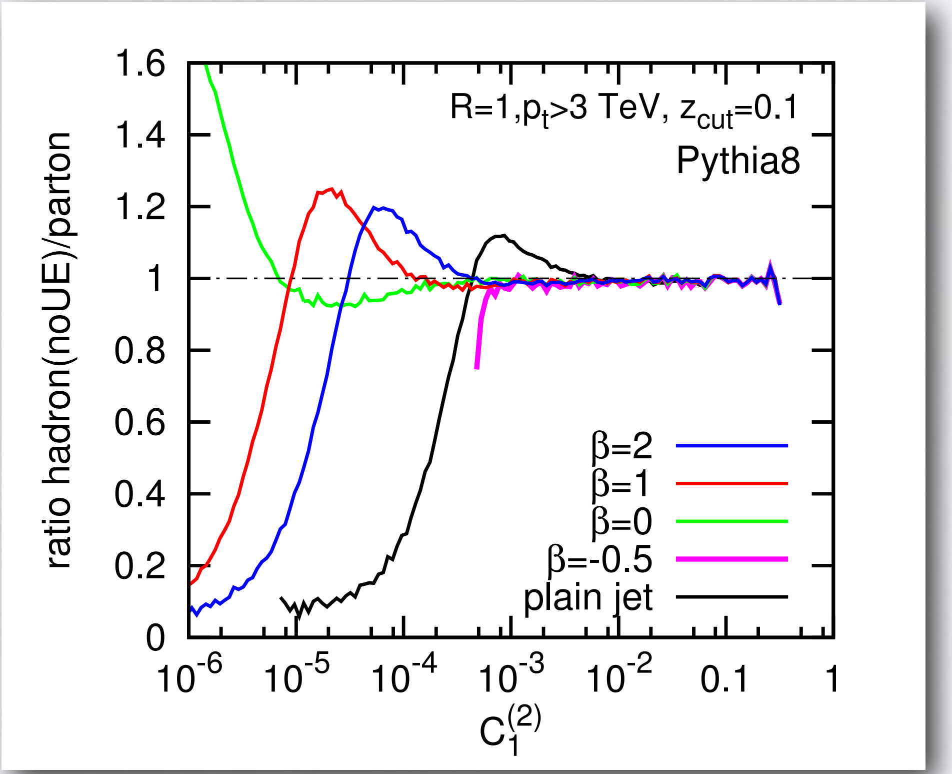


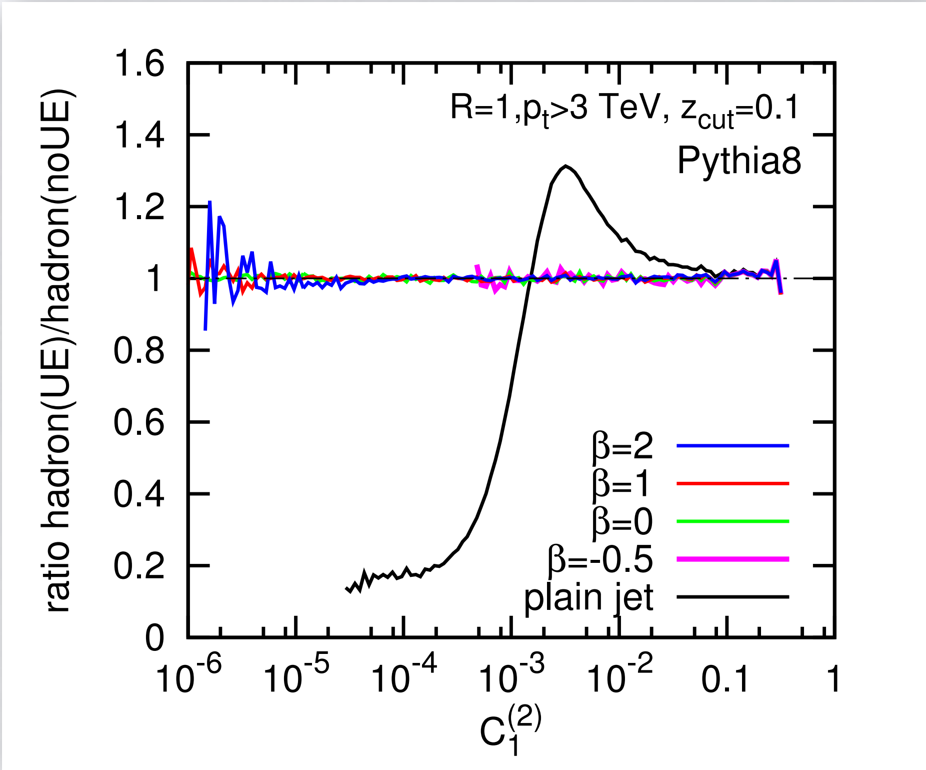
Frye, Larkoski, Schwartz, Yan (2016)

- 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

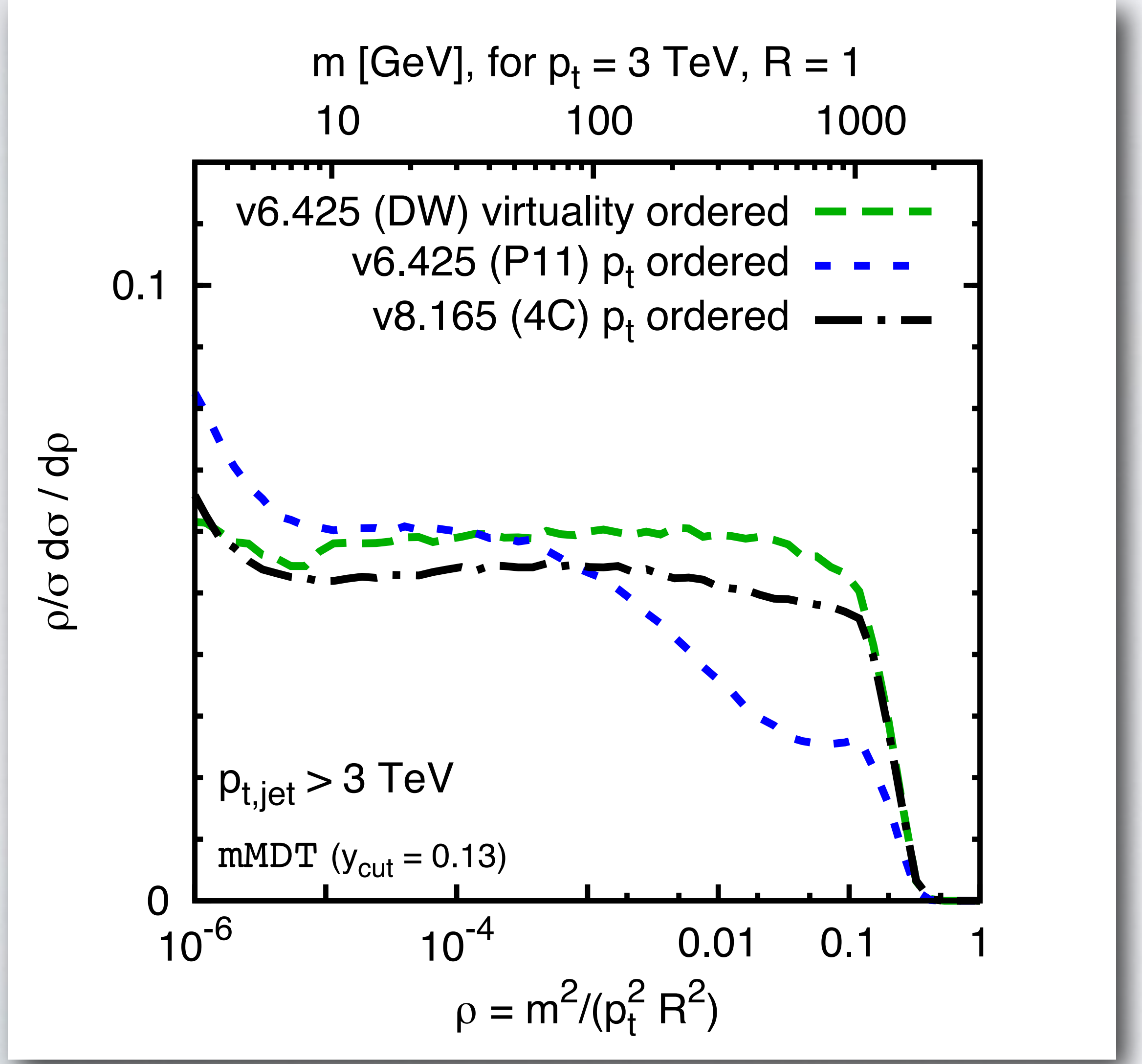
soft drop largely reduces sensitivity to non-perturbative physics





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

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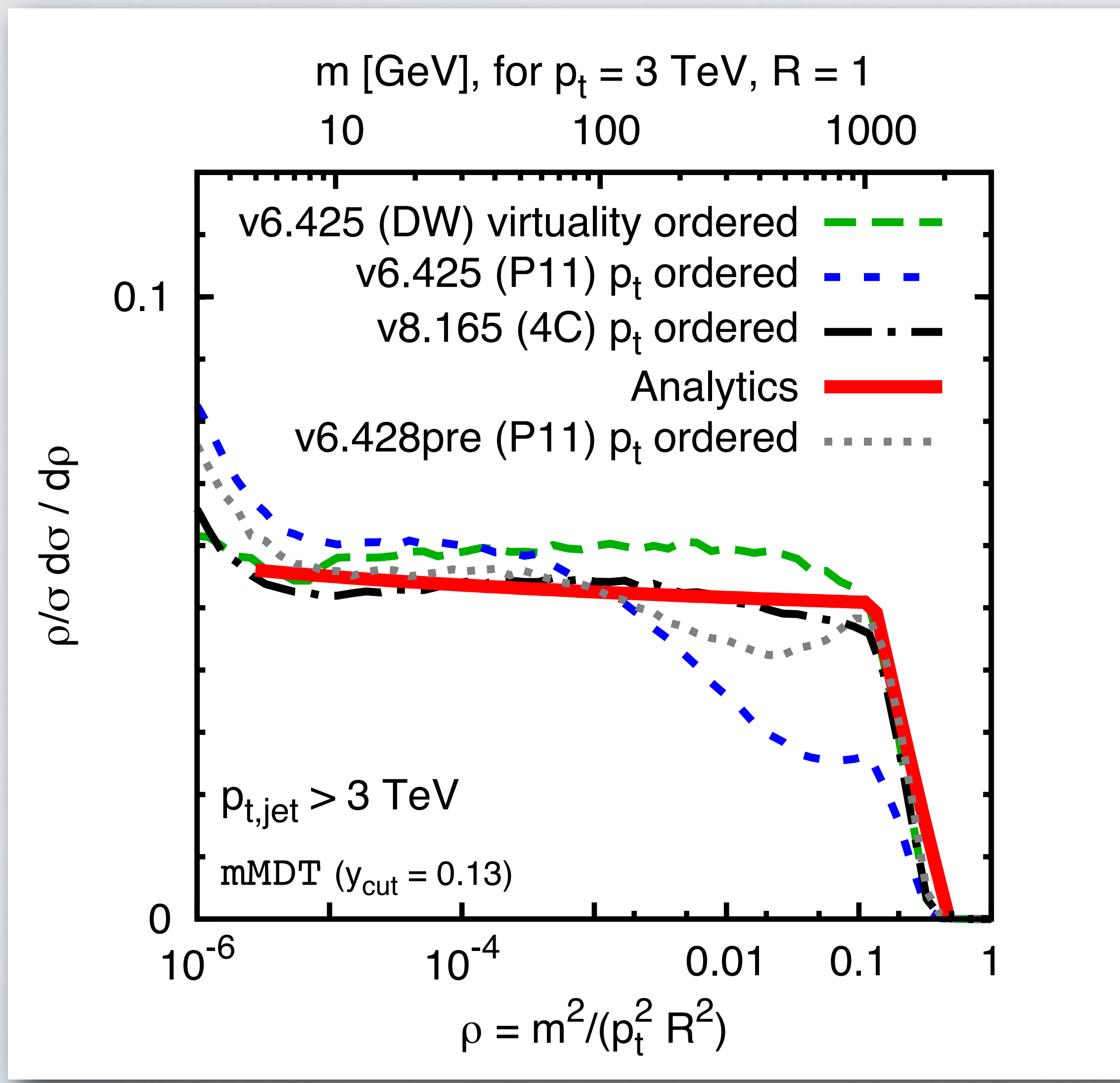


- Take the spread as the uncertainty ?
- But we also have an analytic calculation

- Problem in the shower: fixed by the Authors in the 6.428pre version

Back to phenomenology

Tagging with jet shapes

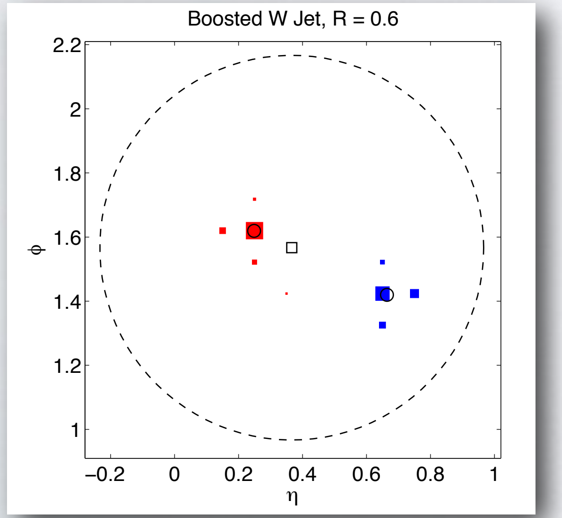
groom to remove contamination

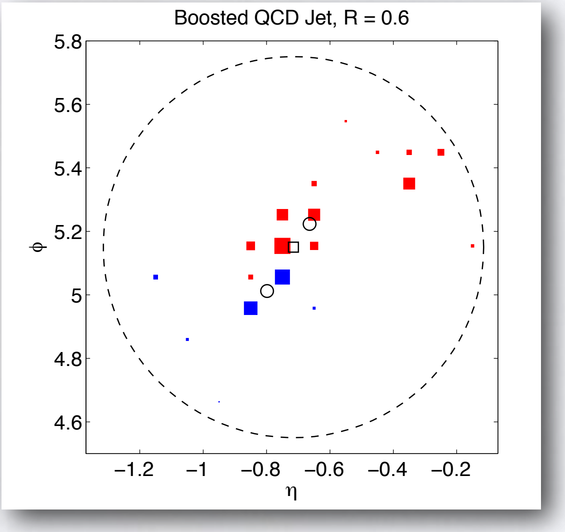
e.g. with soft drop

select mass window about the resonance

use a shape to determine prong structure

e.g. with *N*-subjettiness

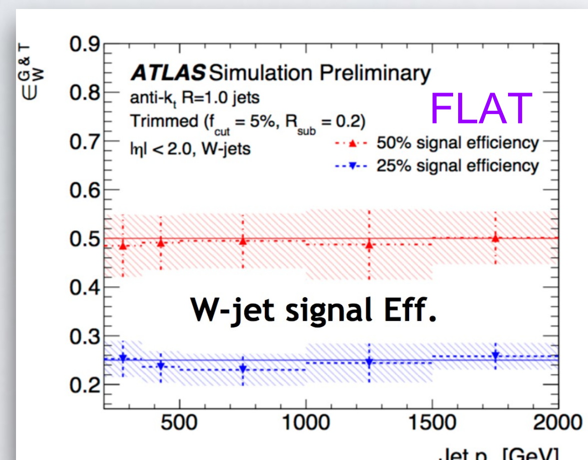


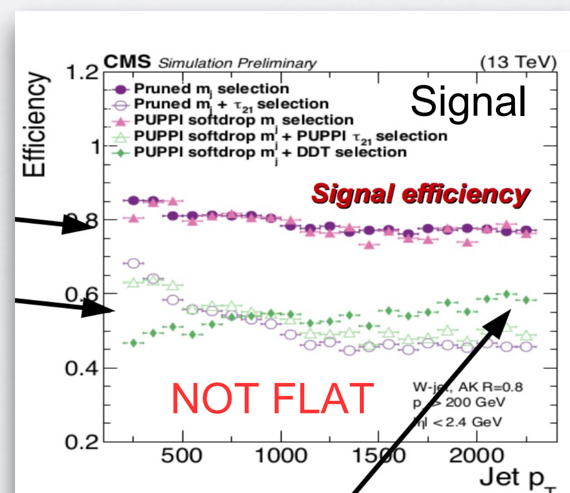


W tagging philosophies

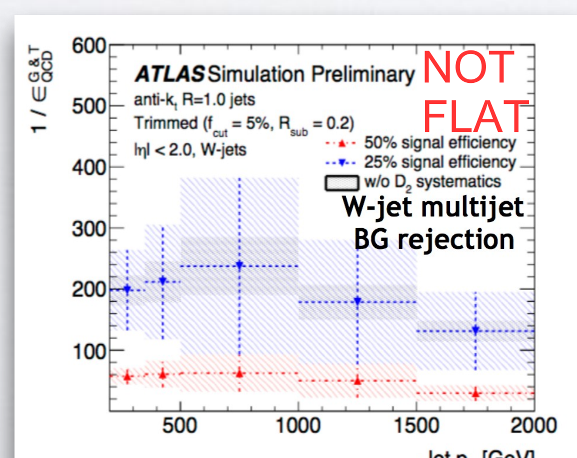
- ATLAS :
  - Tune for flat eff vs p_T
  - $\varepsilon(p_T, m_{trim}, D_2)$
    - Cut on m_{trim}/D_2 vs p_T

- CMS :
  - Tune for flat bakground
  - $\varepsilon(\tau_2/\tau_1^{DDT})=C$

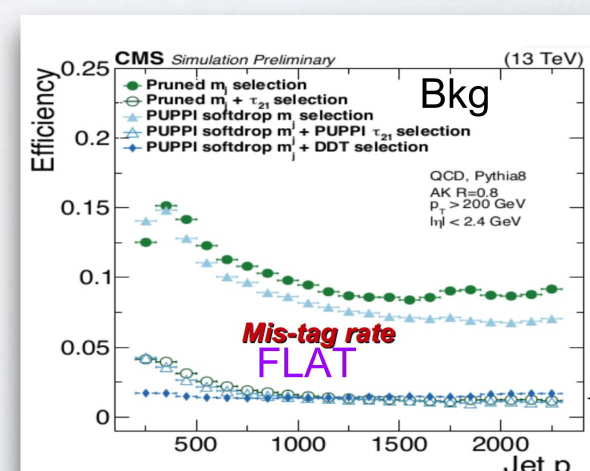




credits: Phil Harris



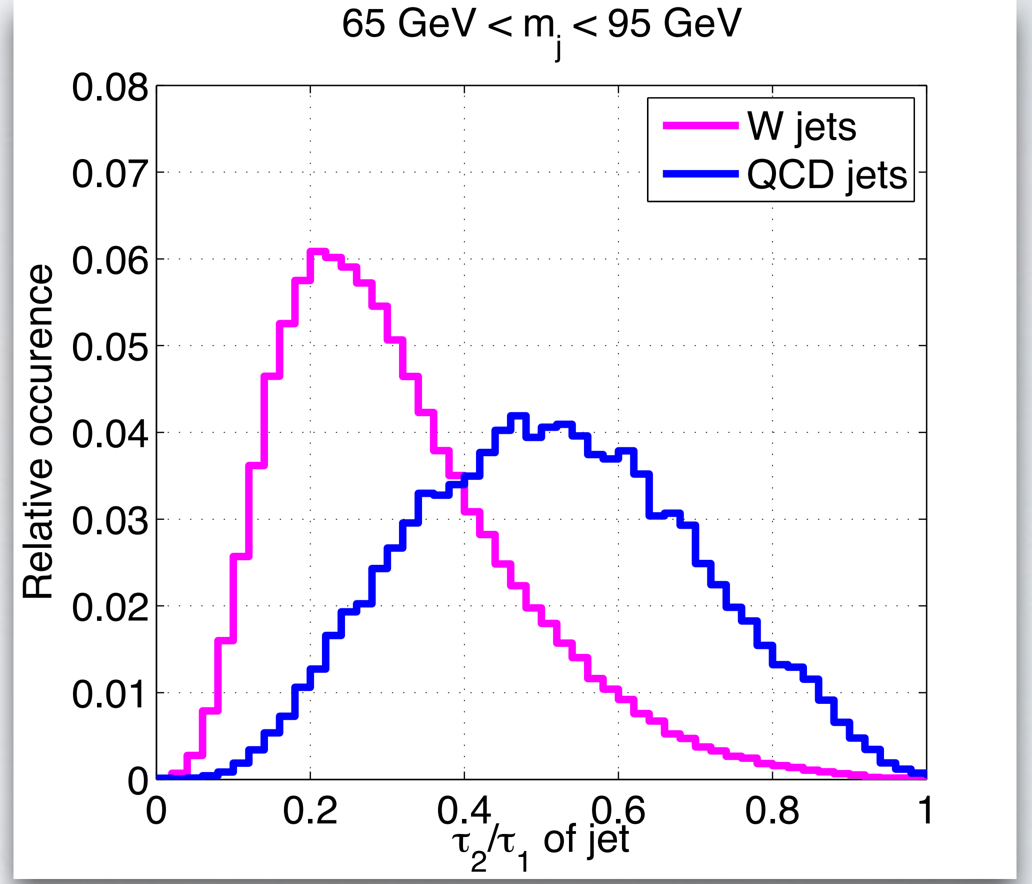
I'll be discussing the CMS approach



N-subjettiness for W tagging

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

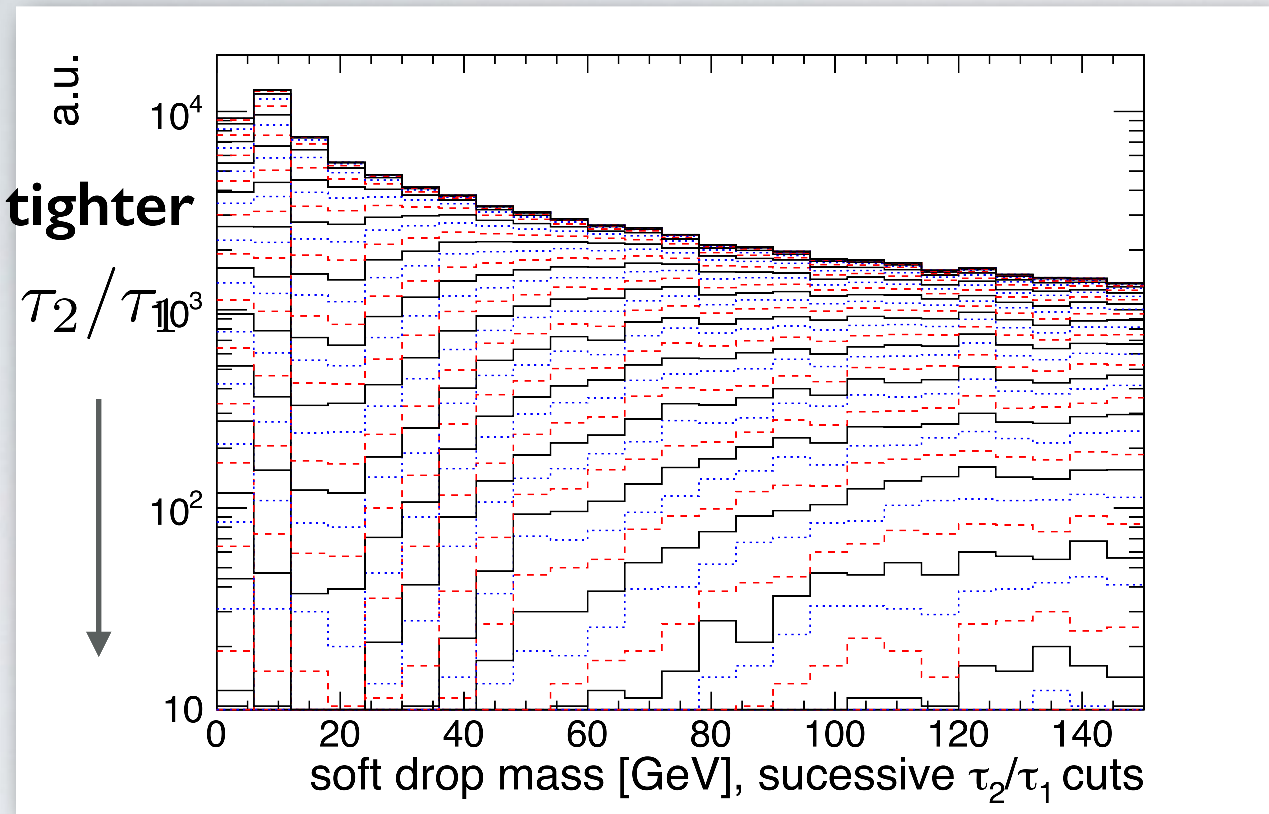
Thaler and Van Tilburg (2011)



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

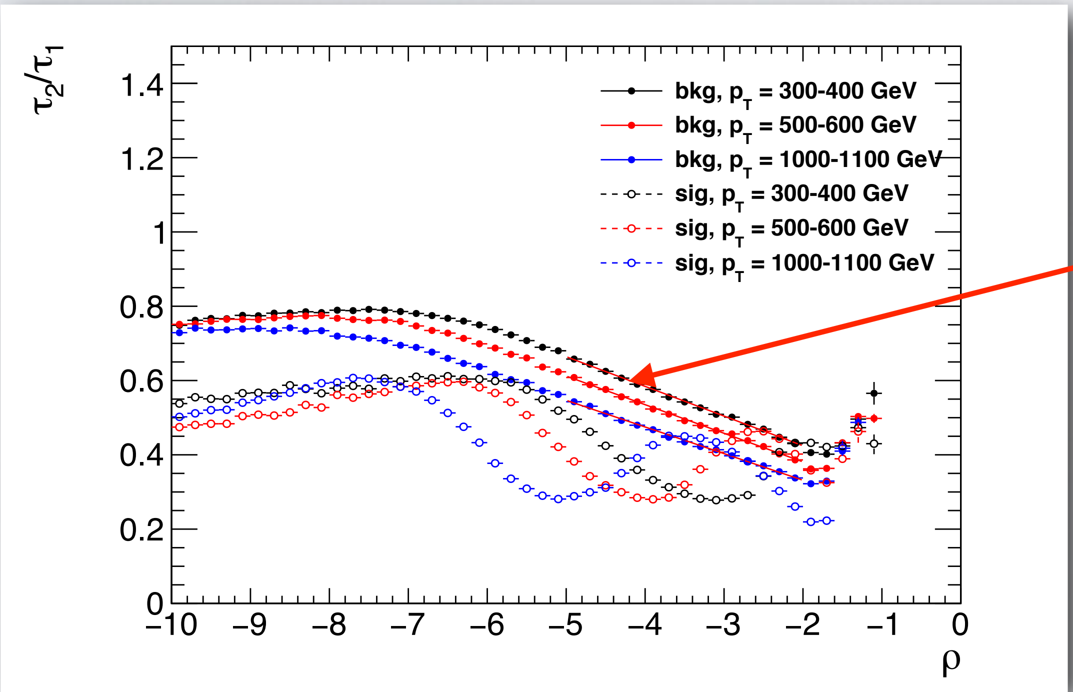
Dolen, Harris, SM, Rappoccio, Tran

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

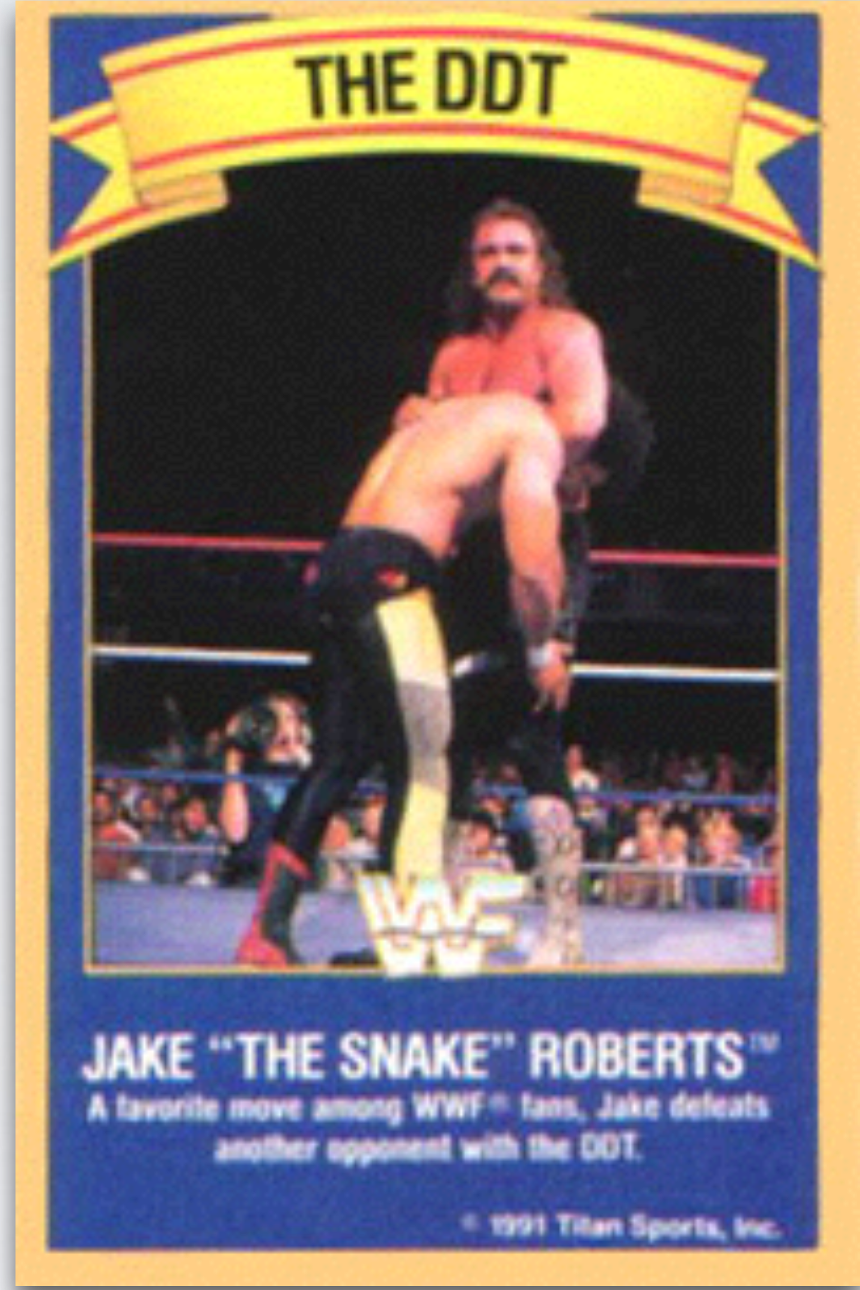
- flat bkg was a built-in feature of mMDT/soft drop :-(
- we would like to de-correlate mass and shape, so that a flat cut does not lead to a significant sculpting of the mass distribution

Designing De-correlated Taggers

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



concentrate on bkg

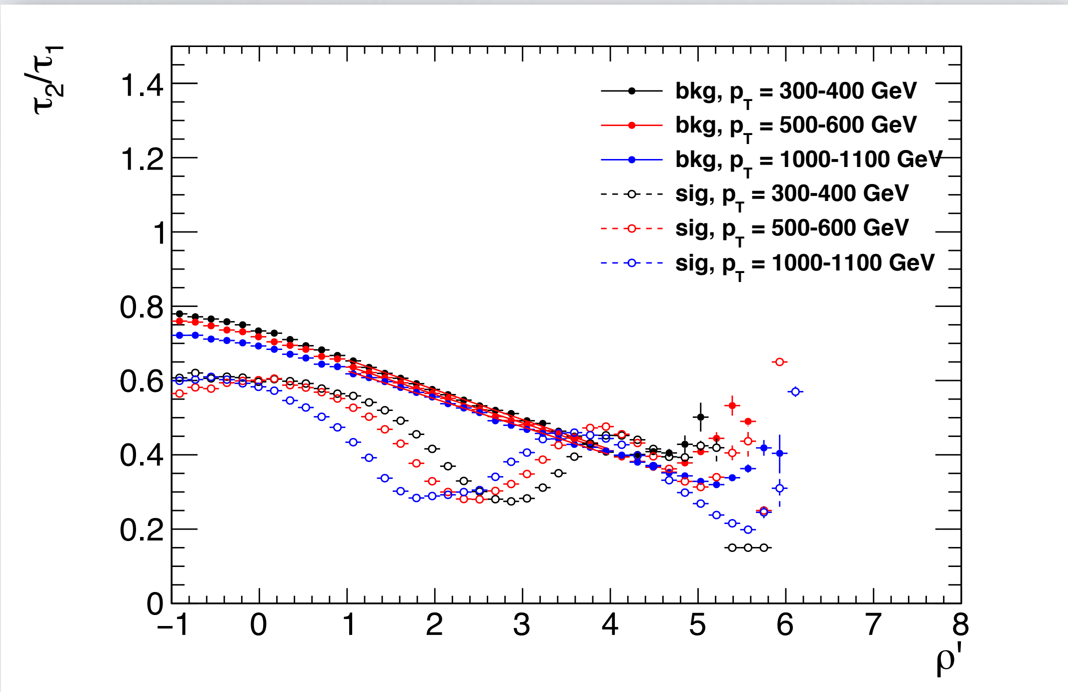


- There exists a region of linear relation
- Can we understand this from first principle ?

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

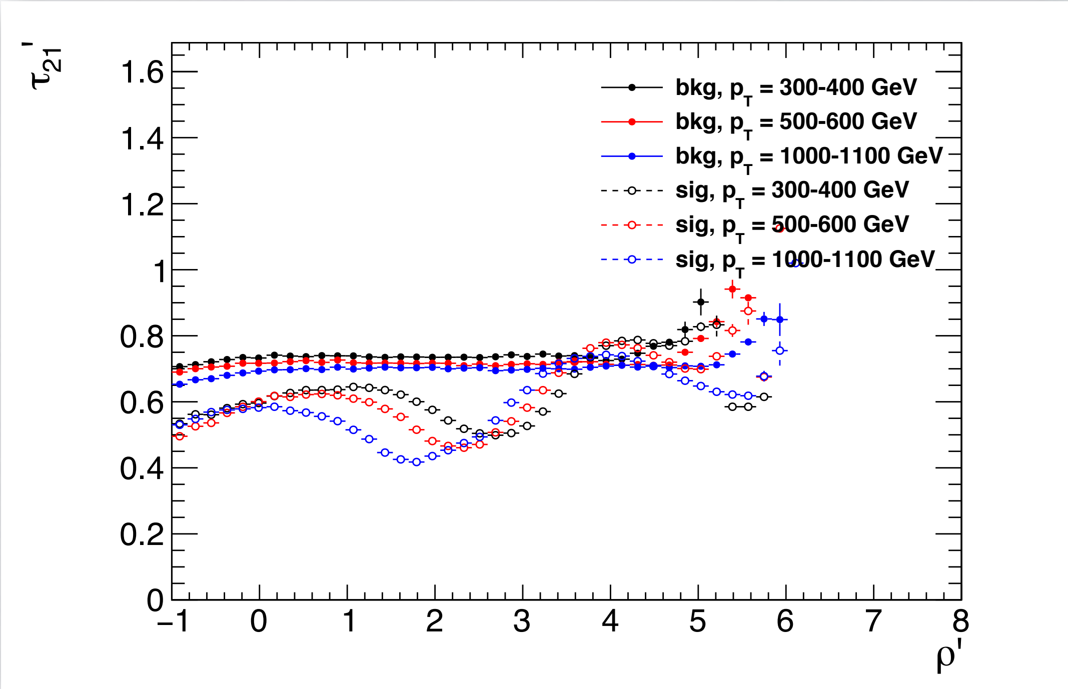
Designing De-correlated Taggers

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



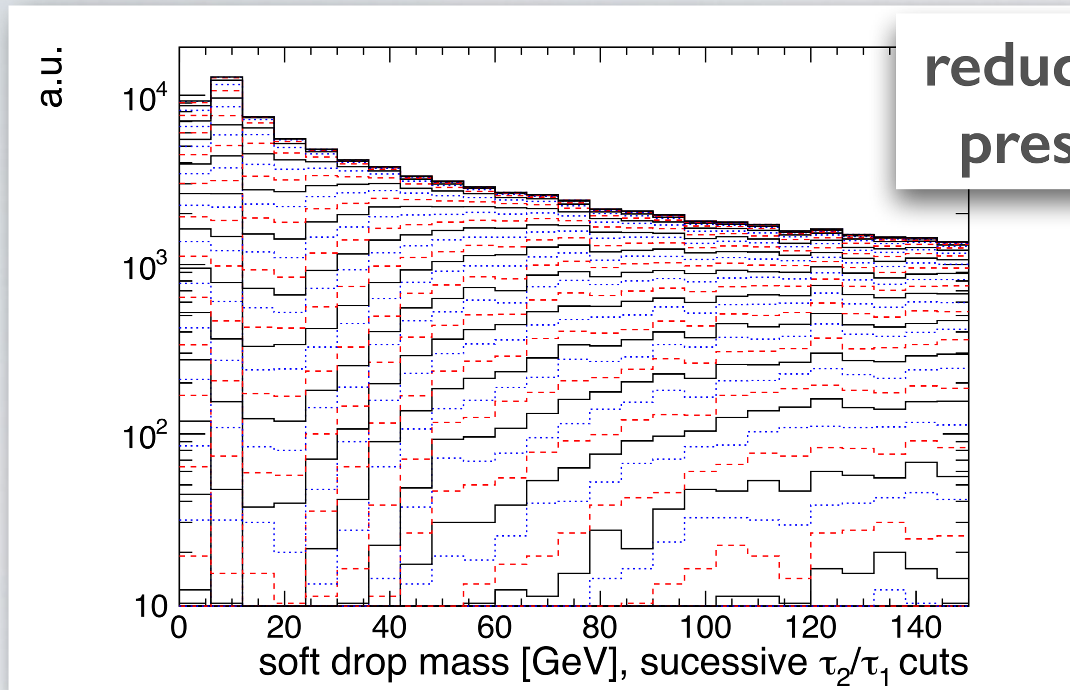
- Then fit the slope and change the variable to

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

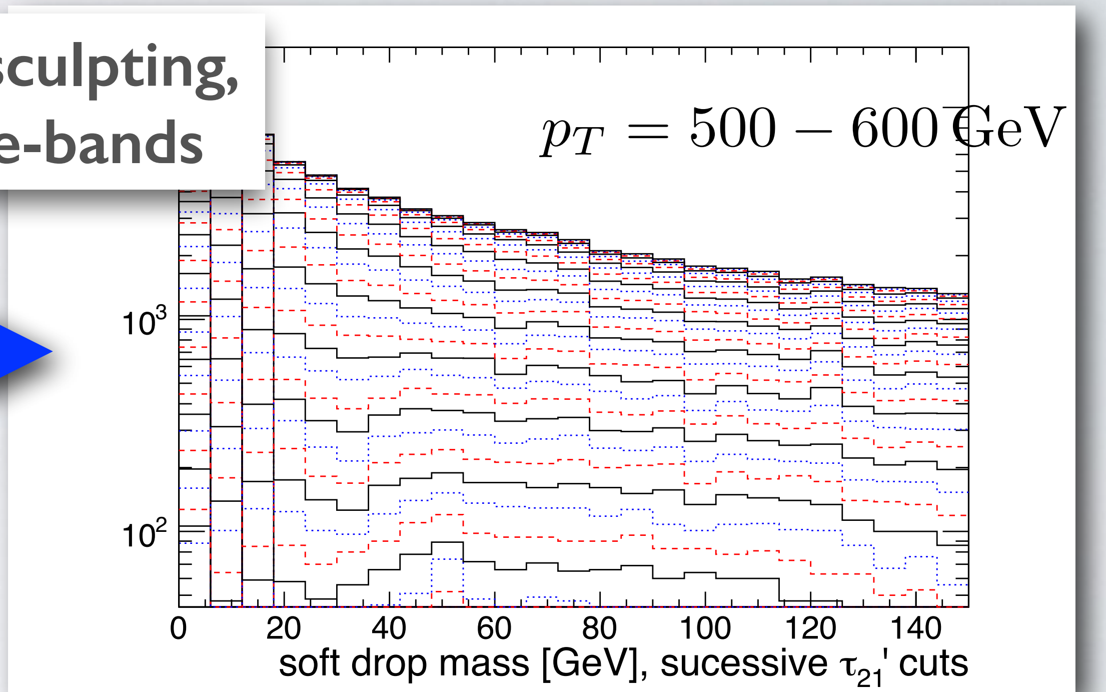


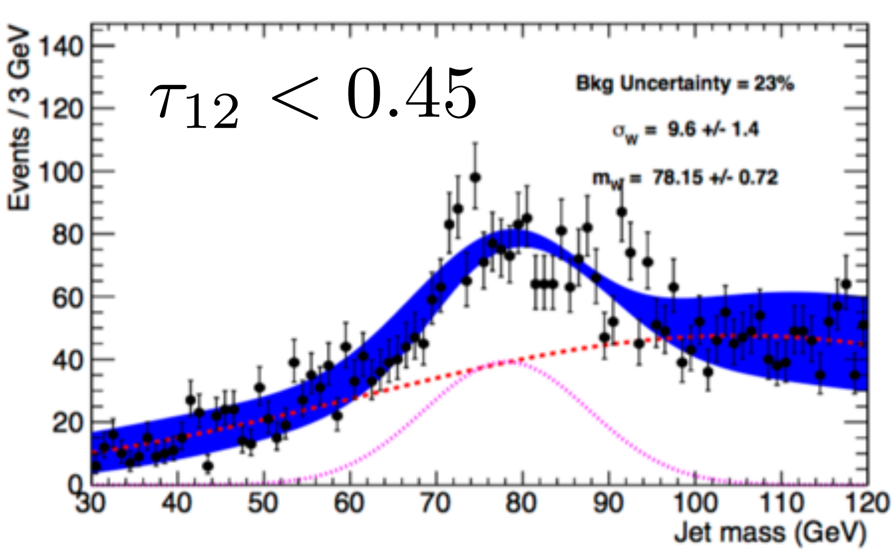
Dolen, Harris, SM, Rappoccio, Tran

DDT: results

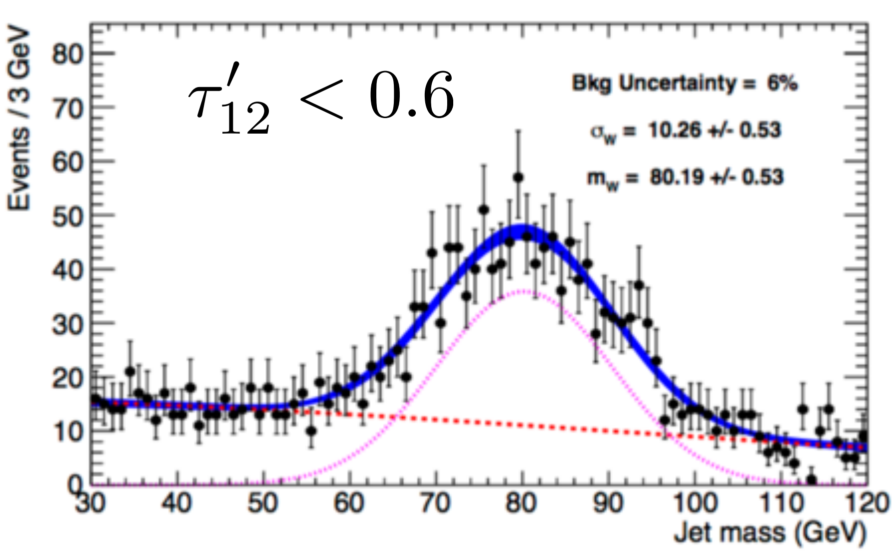


reduced mass sculpting, preserved side-bands





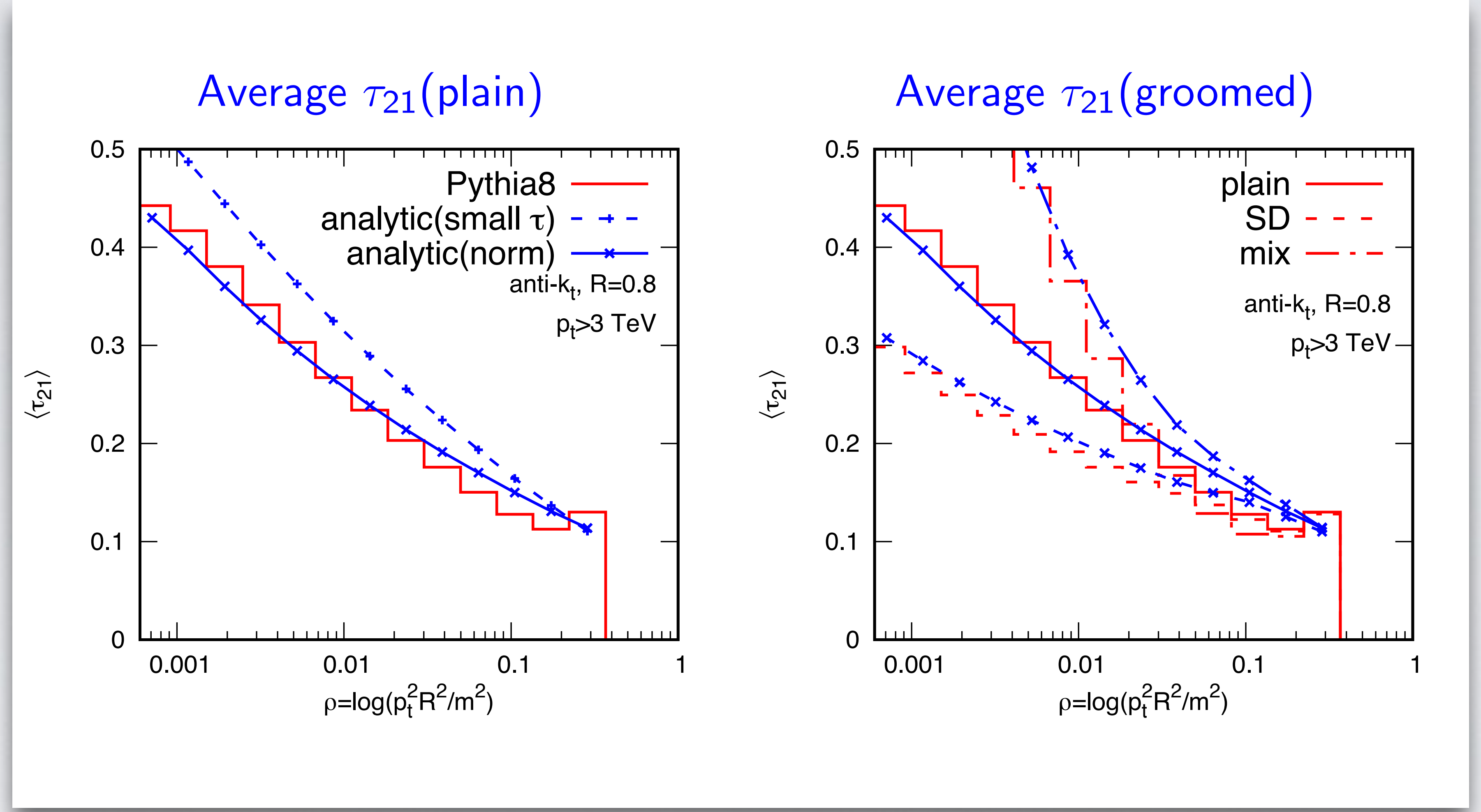
Bkg normalization unc: 23%



Bkg normalization unc: 6%

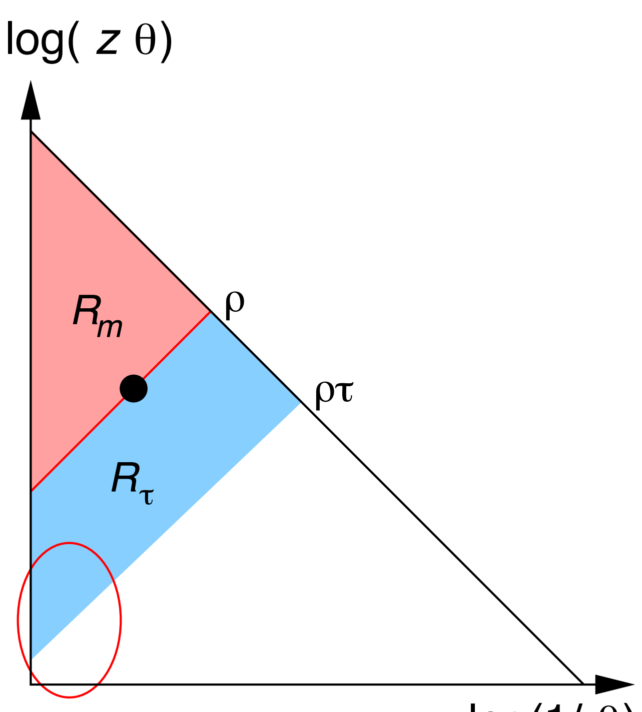
- M = 2 TeV
- roughly same signal efficiency
- bkg better behaved
- reduced systematics

Towards analytic DDT



work in progress with people in Paris and Buffalo

News from Boost 2016 (I)



Jet mass with a cut on τ_{21}:

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho}\bigg|_{<\tau} = R'_m \exp(-R_m - R_\tau)$$

Extra suppression

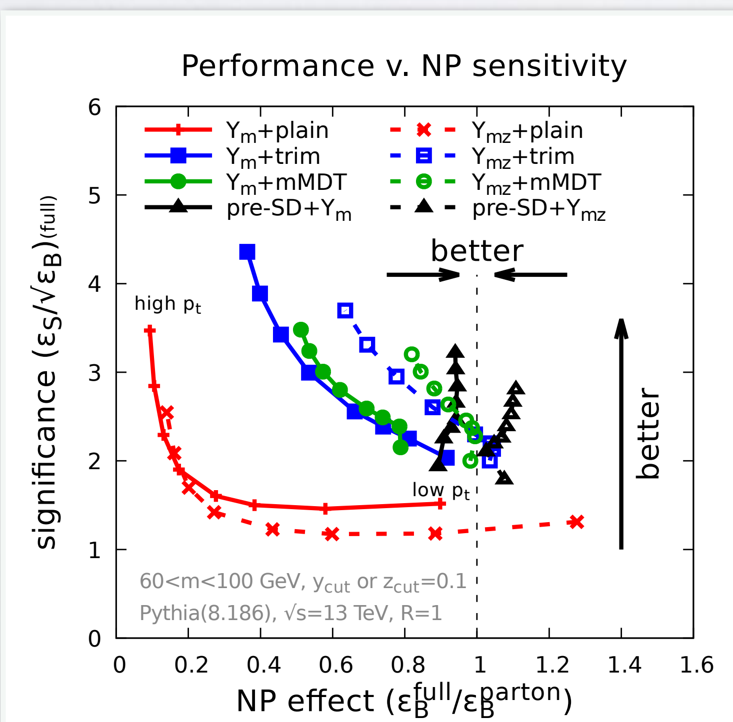
$$R_m \sim \frac{\alpha_s C_R}{2\pi}\log^2(1/\rho)$$

becomes $\quad R_m + R_\tau \sim \frac{\alpha_s C_R}{2\pi}\log^2(1/\tau\rho)$

Soft-and-large-angle radiation:

- performance gain (R_τ)
- large NP effects

Large NP effects vs performance gain what is the trade-off?



- mMDT to get 2 prongs
  Use that for ρ and τ_1
- "Gentle" SD to reduce NP effect
  Use that for τ_2

$$\tau_{21} = \frac{\tau_2(\text{SD})}{\tau_1(\text{mMDT})}$$

work in progress by
Dasgupta, Schunk and Soyez

News from Boost 2016 (II)

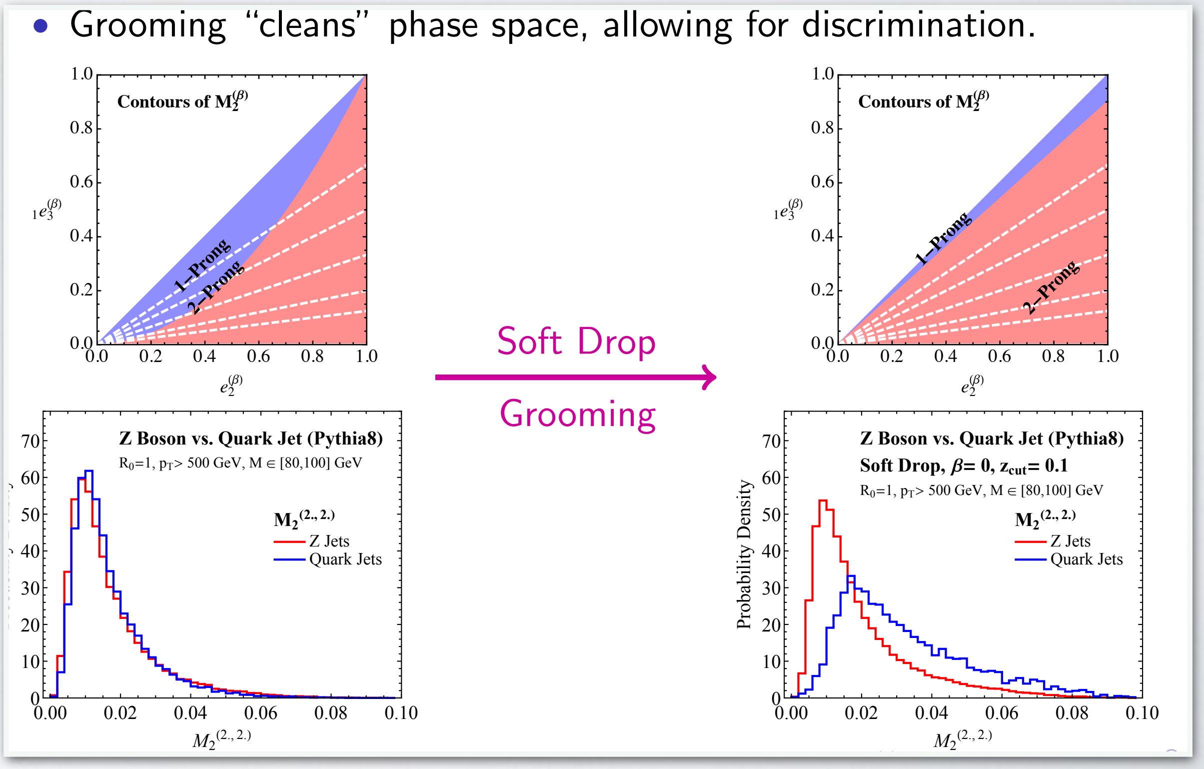
- "traditional" jet shapes not necessary well-suited for grooming
- design new variables

General Energy Correlation Functions

$$\boxed{{}_i e_j^{(\beta)} = \frac{1}{p_{TJ}^j} \sum_{1 \le n_1 < \cdots < n_j \le n} p_{Tn_1} p_{Tn_2} \cdots p_{Tn_j} \min \left(\prod_{s,t}^{i} R_{st}^{\beta} \right)}$$

- new shapes to perform boson tagging

$$M_2^{(\beta)} = \frac{{}_1 e_3^{(\beta)}}{e_2^{(\beta)}}$$

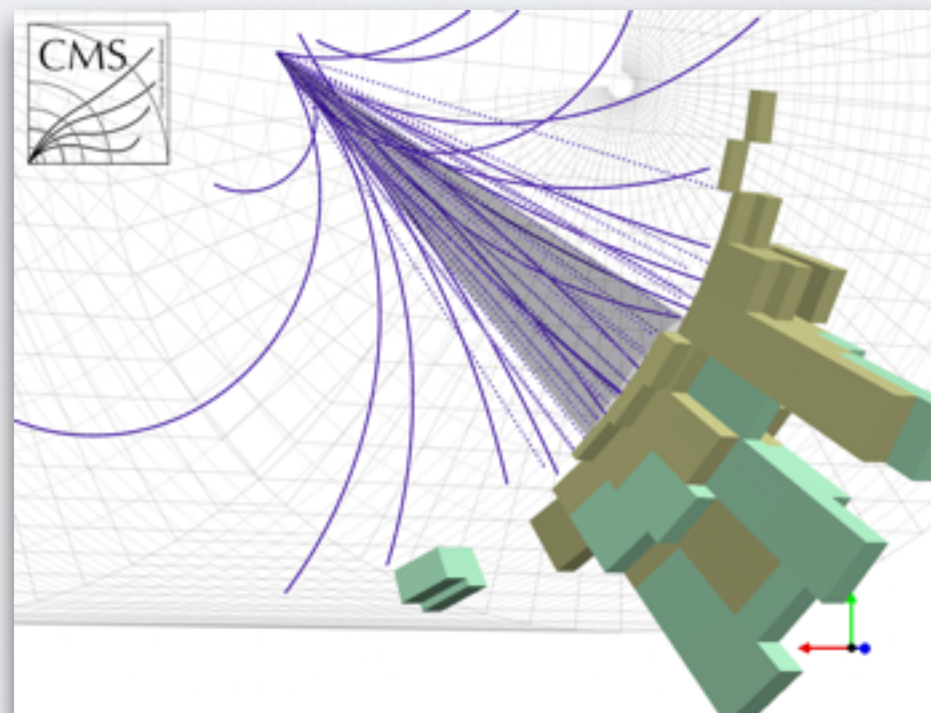


work in progress by Moult, Necib and Thaler

Jet substructure Taggers at LHC Run II

more robust

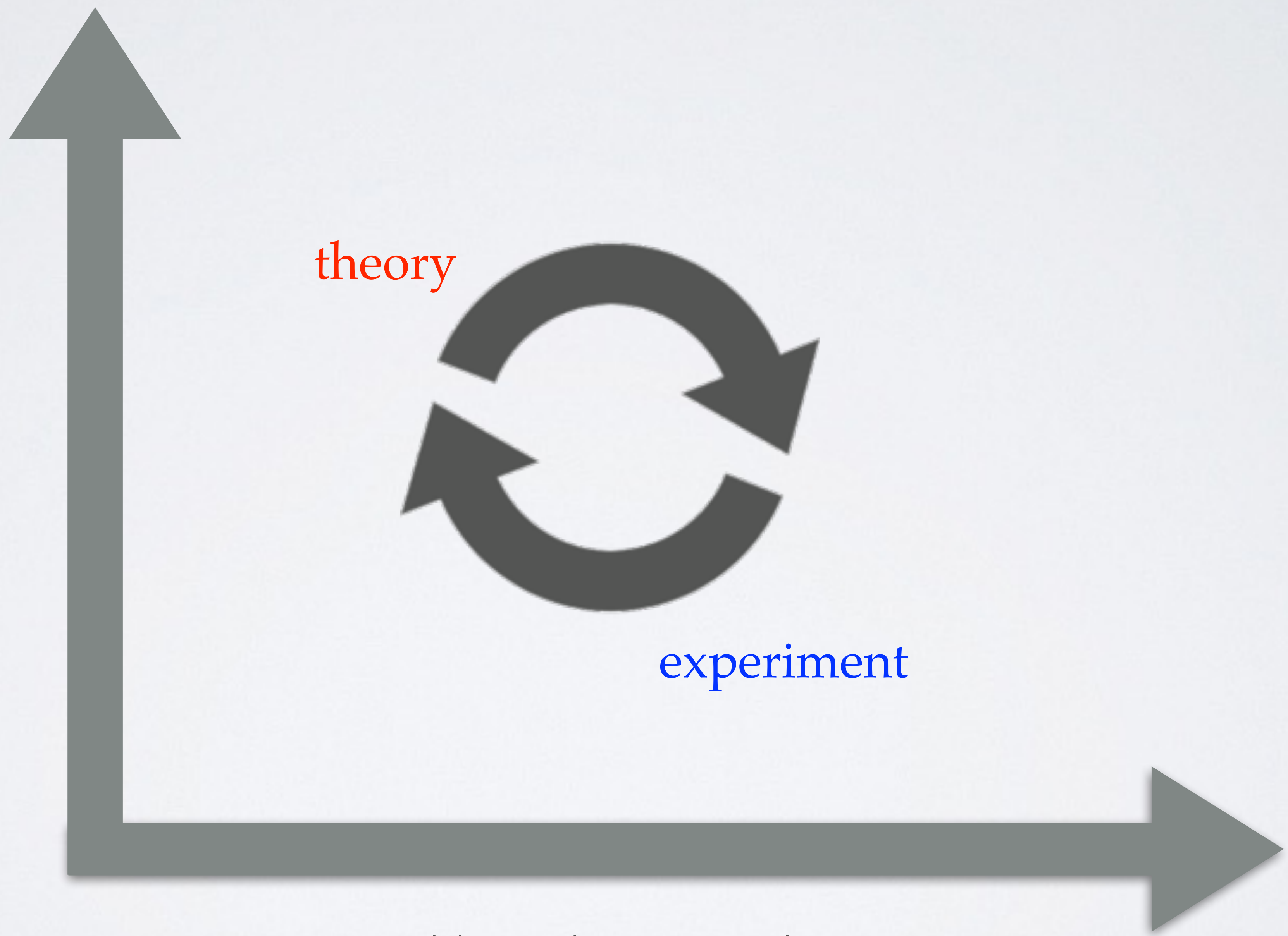
deeper understanding
QCD, calculations, *etc.*



ideas, phenomenology,
MC simulations, *etc.*

more efficient

Jet substructure Taggers at LHC Run II



Thank you !