DISSECTING JETS

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

MC4BSM 2017
SLAC
May 11th -13th 2017

Outline

- Looking inside jets: an introduction

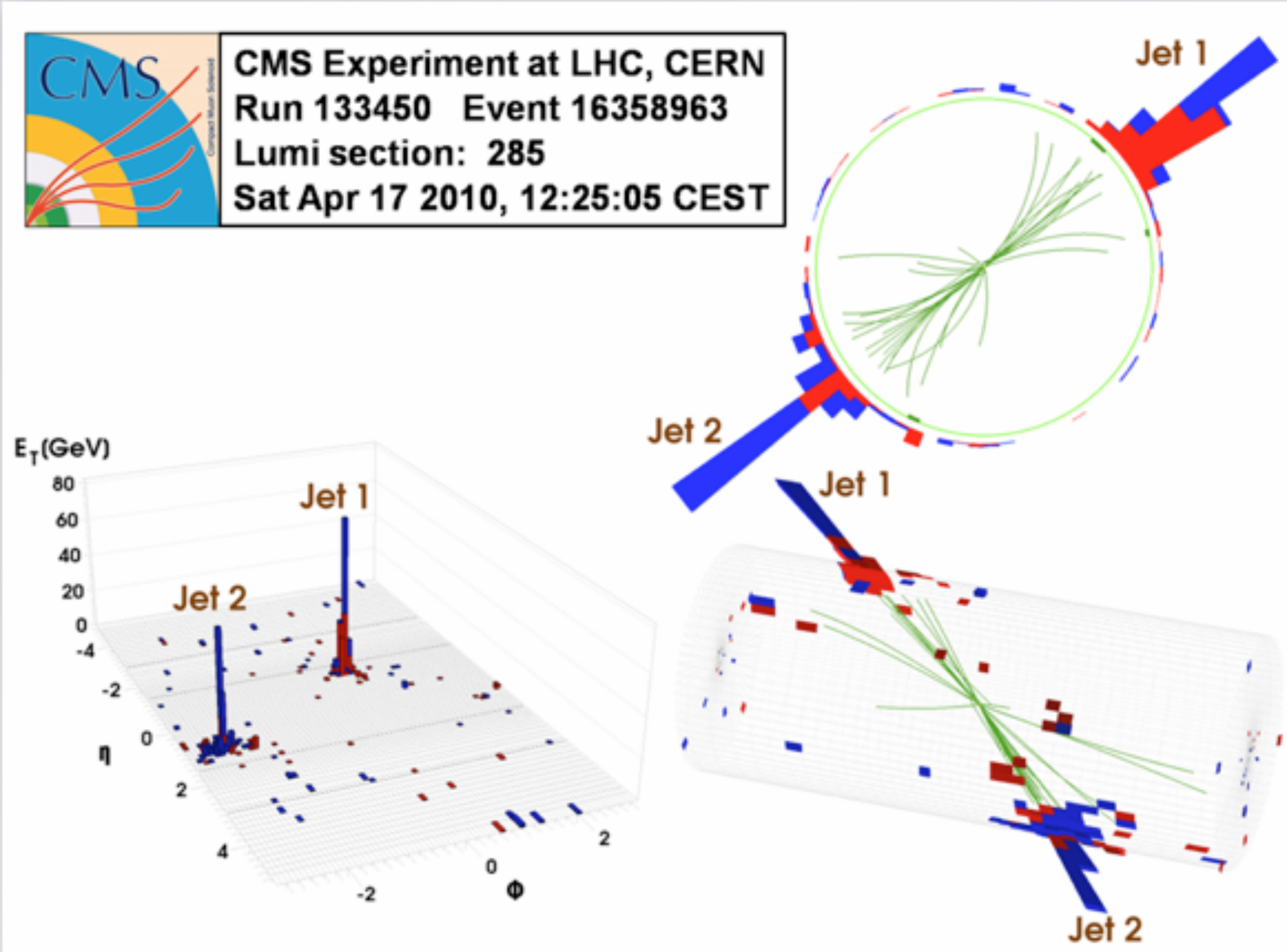
- Two examples:
  - groomed jet mass
  - prongs' momentum balance z_g

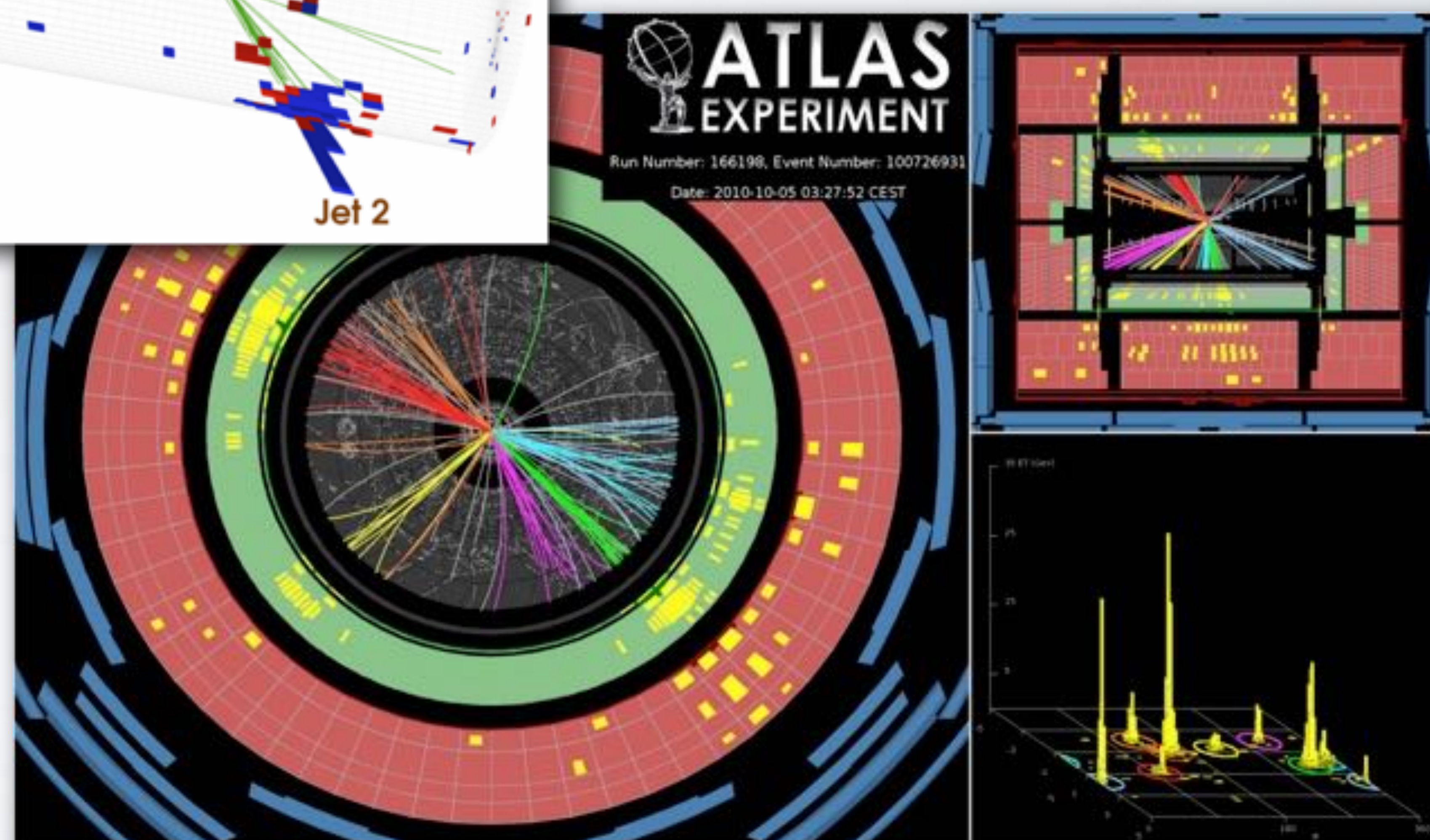
- Conclusions

Looking inside jets

JETS

Collimated, energetic sprays of particles

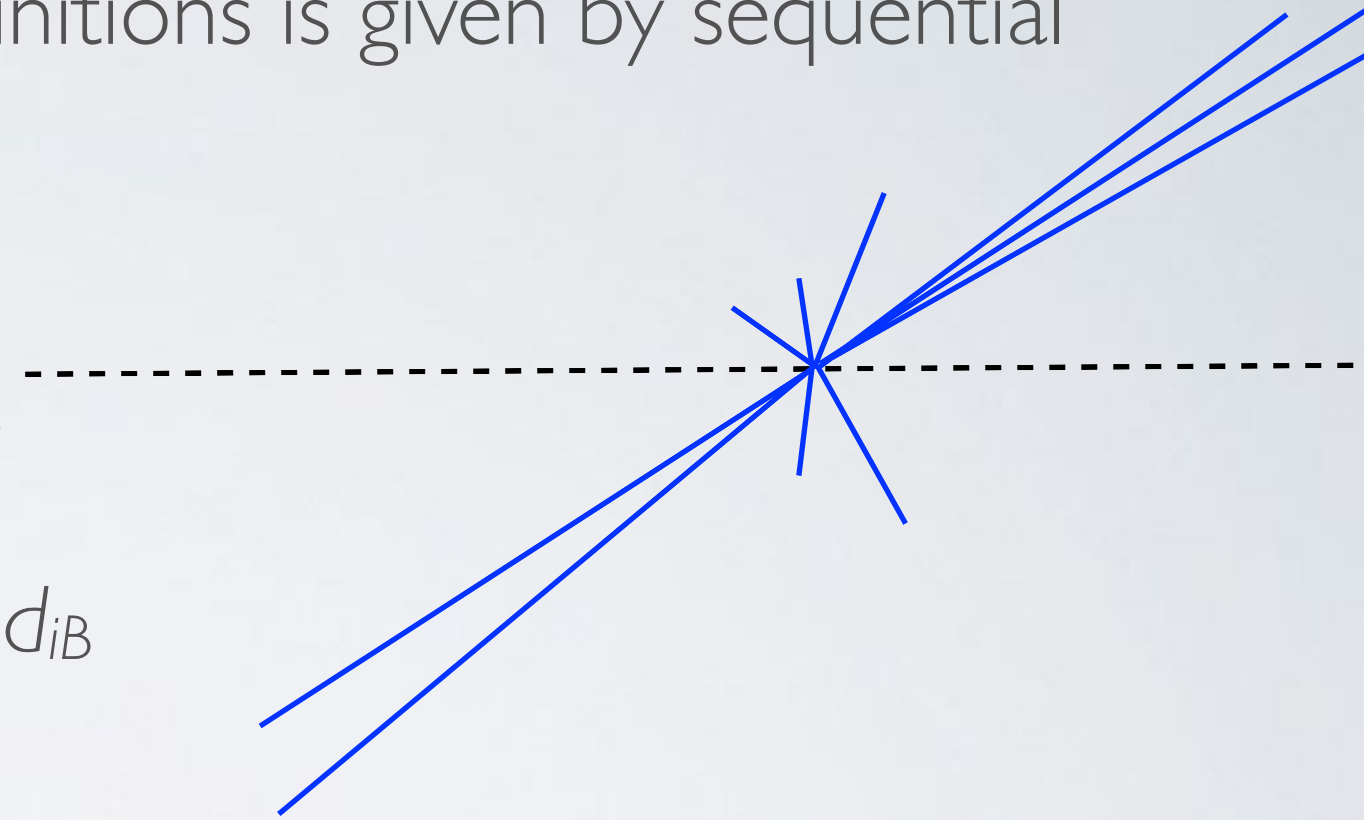




ubiquitous @LHC: more than 70% of ATLAS & CMS papers use jets in their analyses!

Jet definitions

- 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}

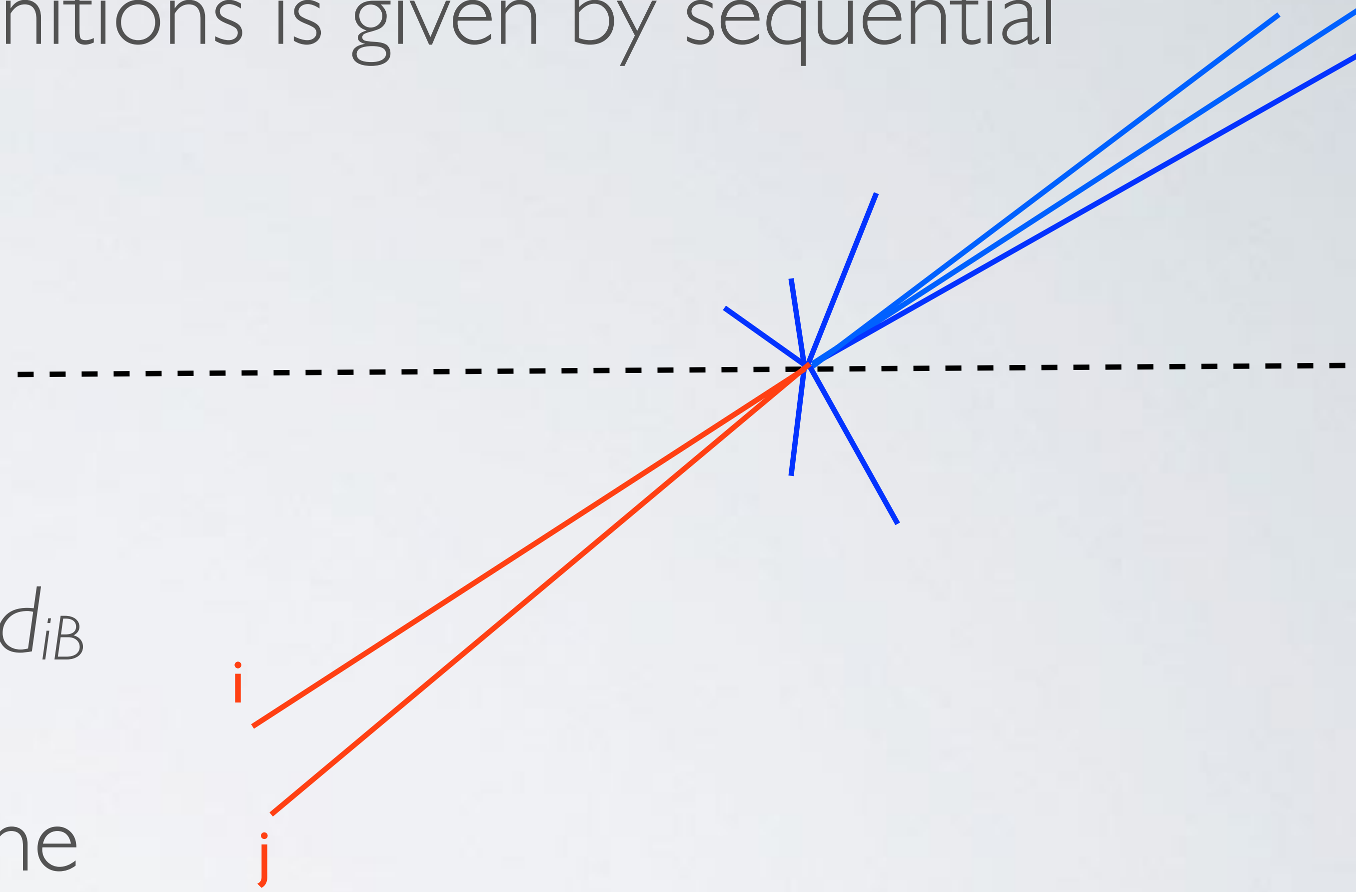


d_{ij} (weighted) distance between i j
d_{iB} external parameter or distance from the beam ...

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

Jet definitions

- 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

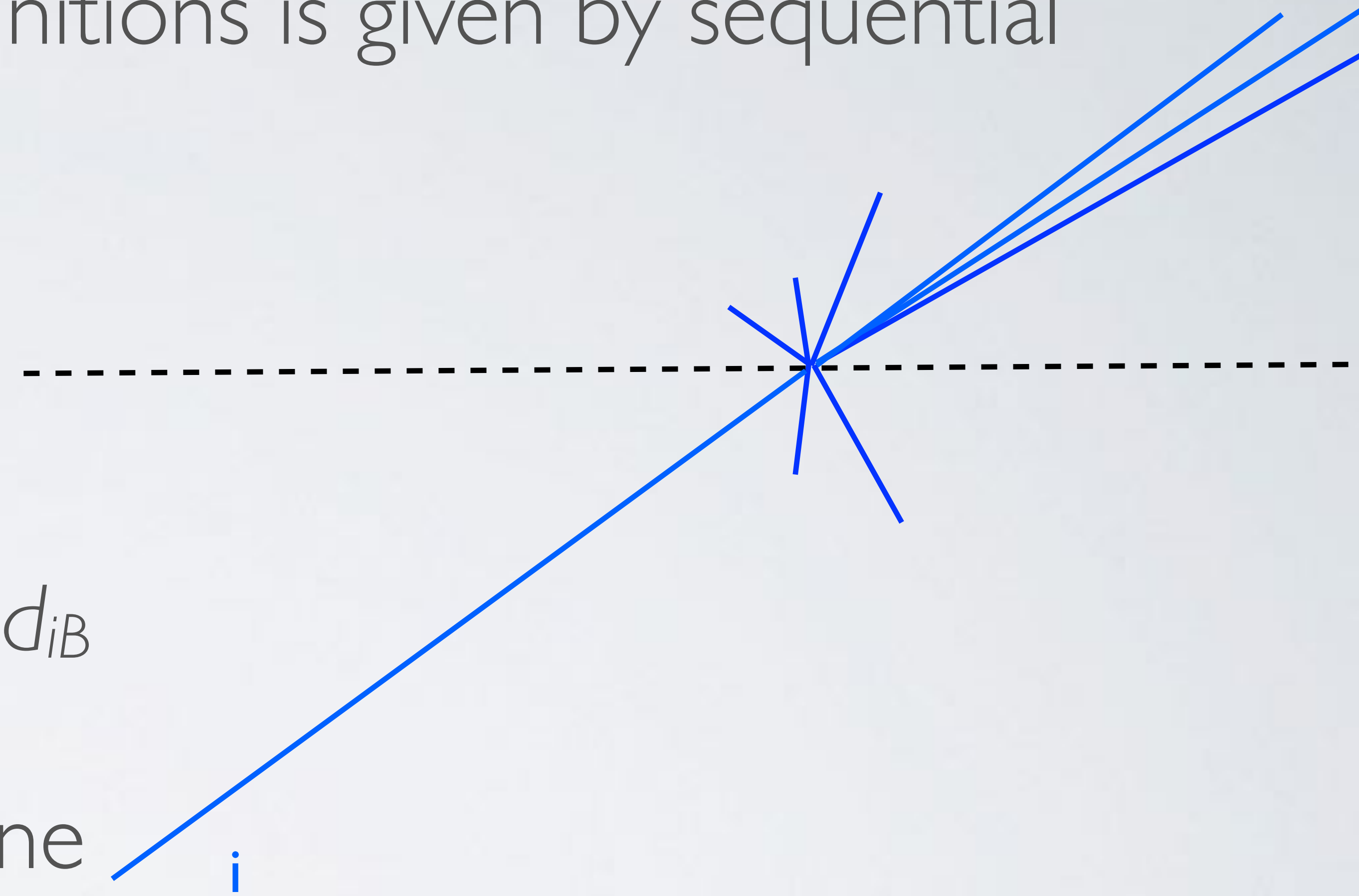


d_{ij} *(weighted) distance between i j*
d_{iB} external parameter or distance from the beam ...

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

Jet definitions

- 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



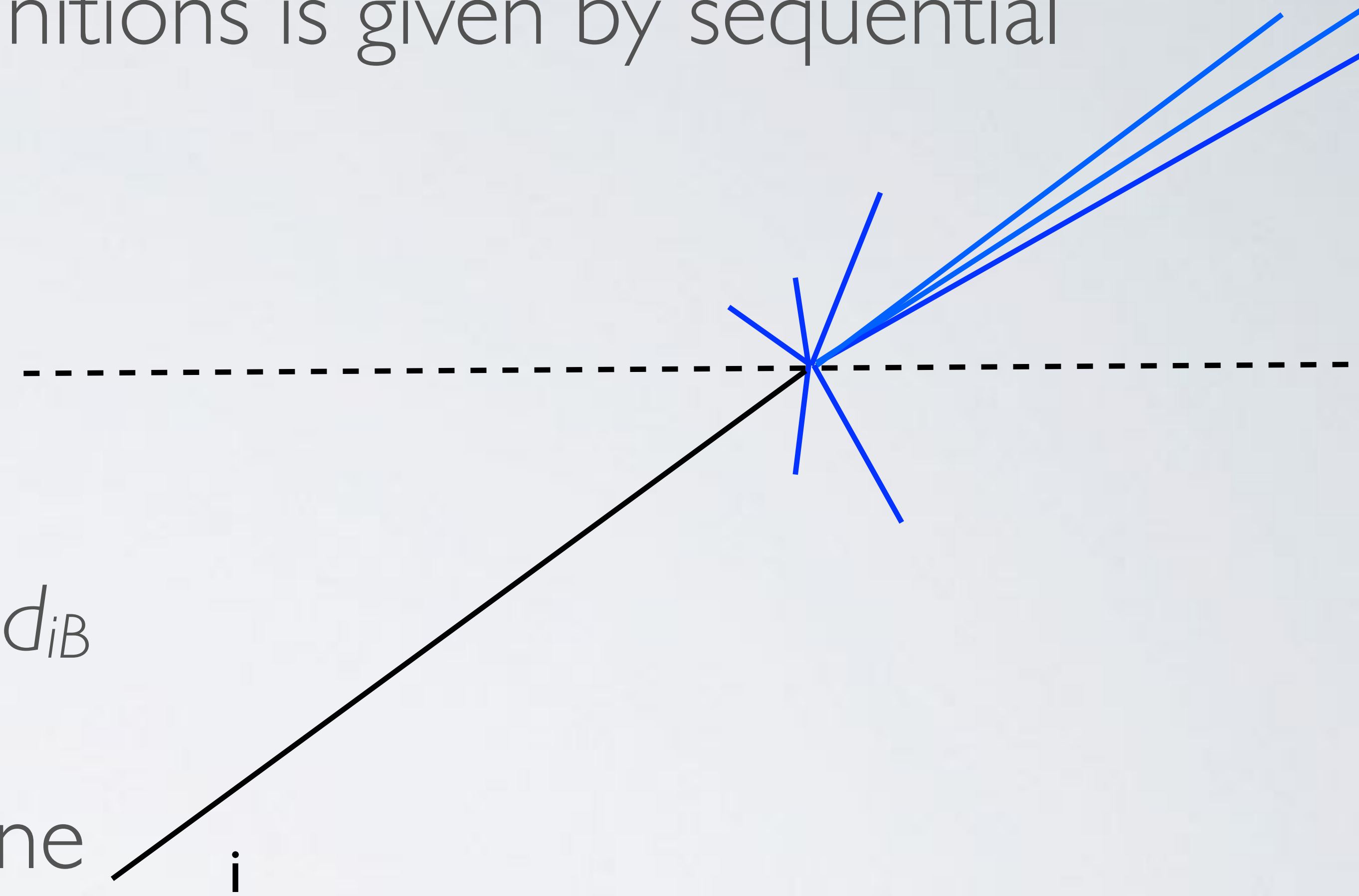
d_{ij} *(weighted) distance between i j*
d_{iB} external parameter or distance from the beam ...

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

Jet definitions

- 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

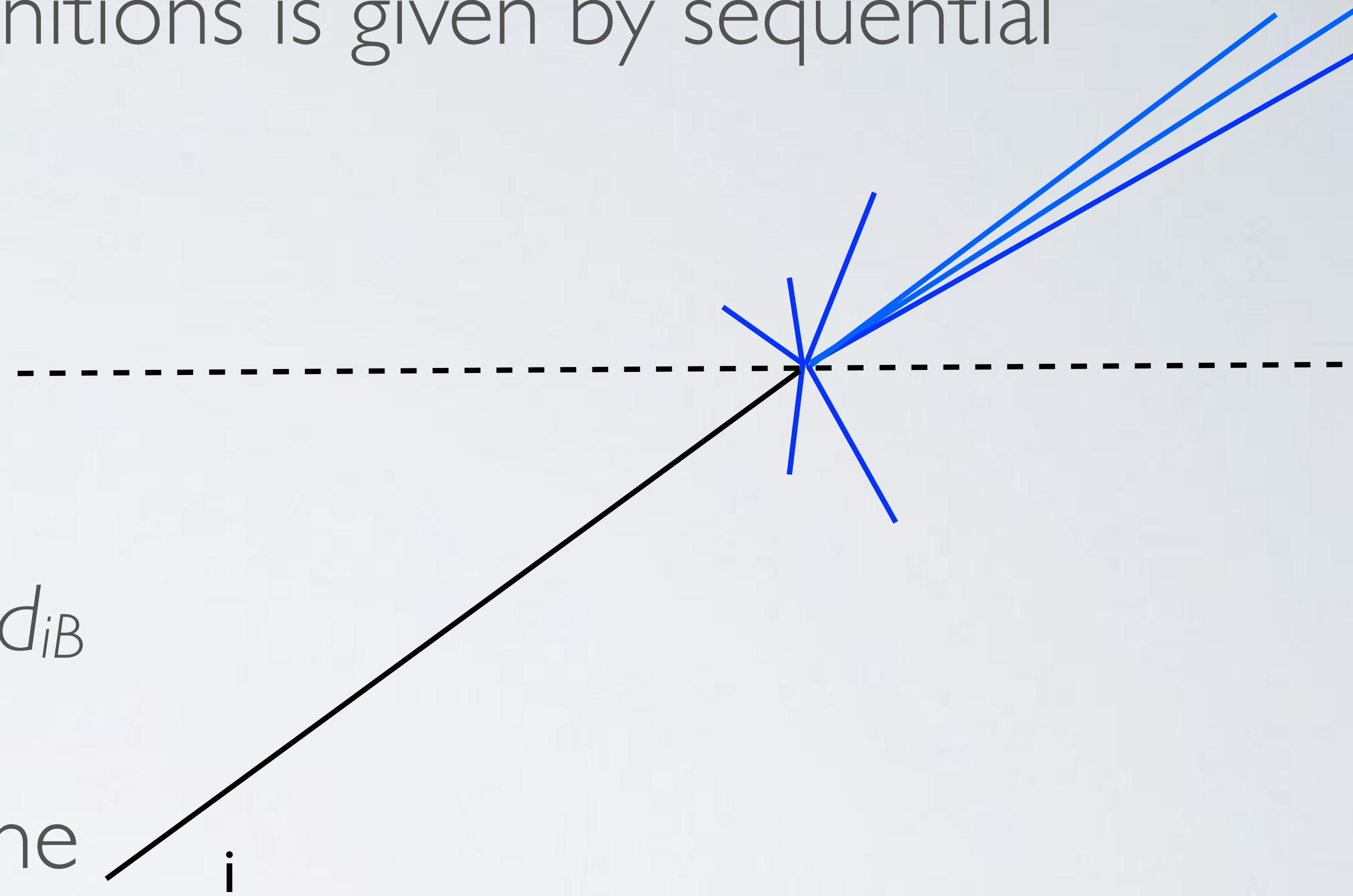
- Otherwise call *i* a final-state jet, remove it from the list and iterate

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)

Jet definitions

- 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

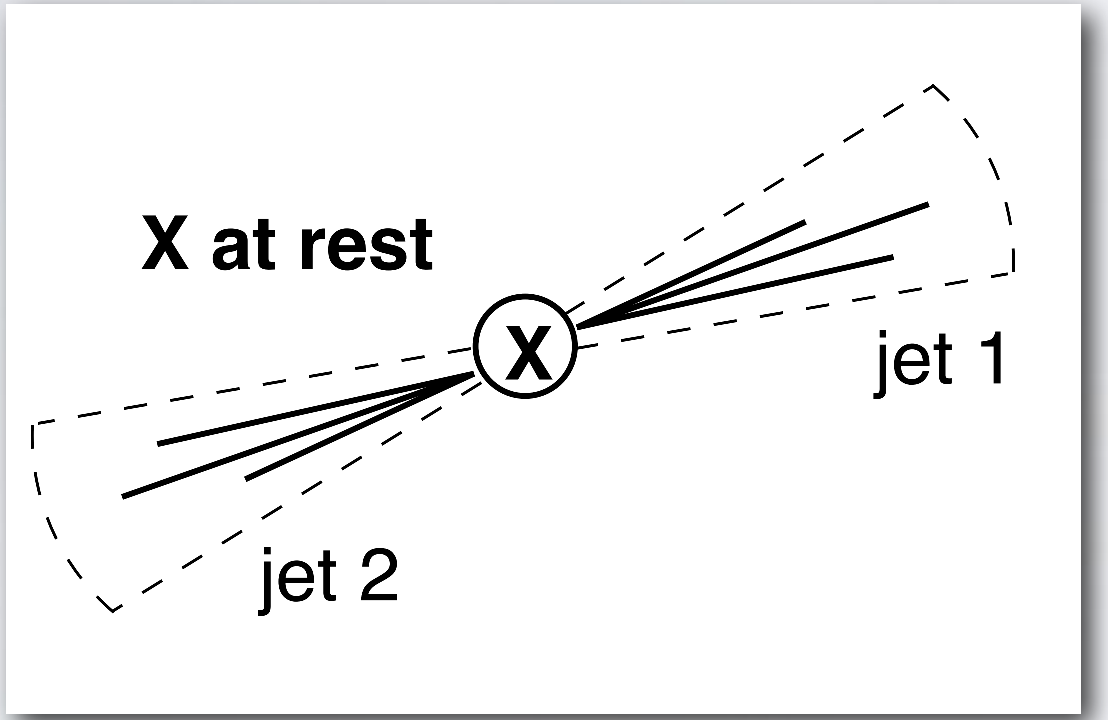


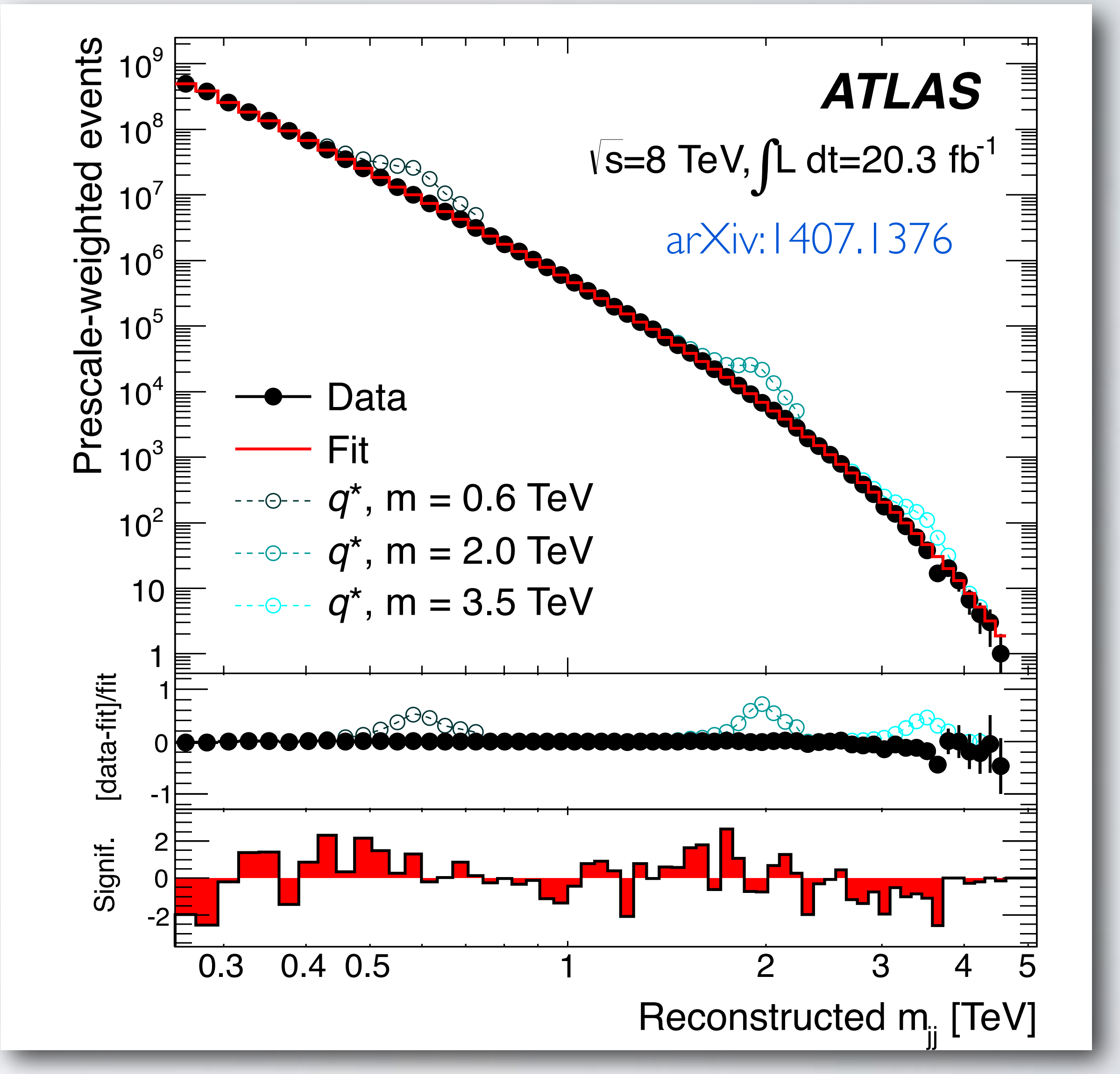
d_{ij} *(weighted) distance between i j*
d_{iB} external parameter or distance from the beam ...

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



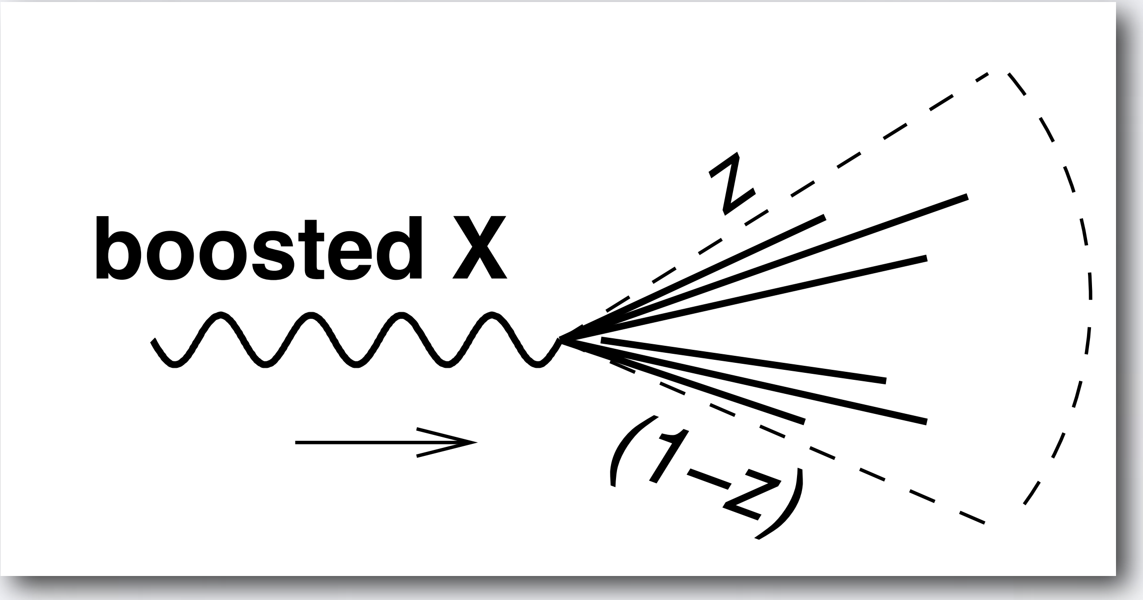


- look for bumps in the dijet invariant mass distribution

Searching for new particles: boosted analyses

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

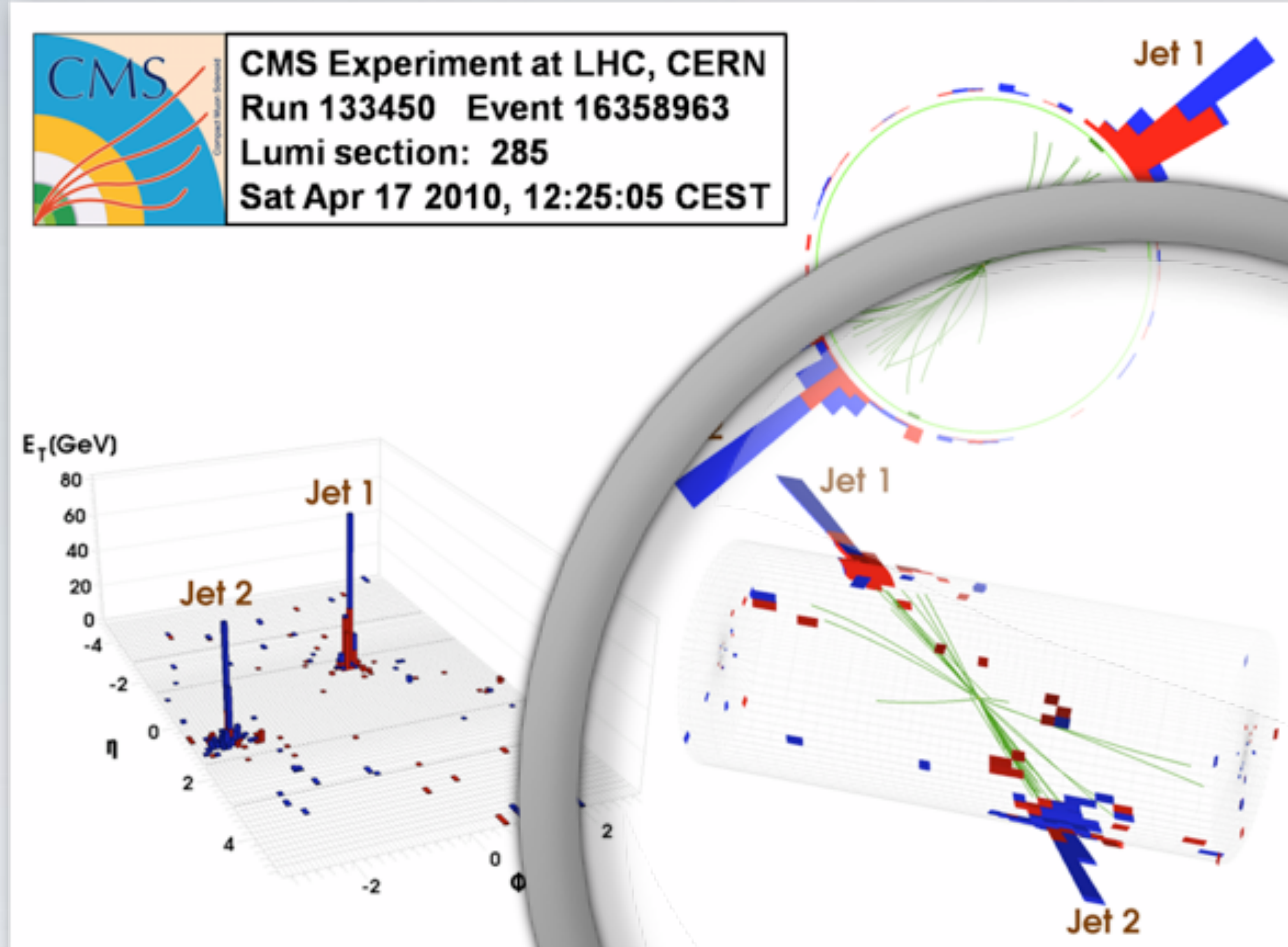
- EW-scale particles (new physics, Z/W/H/top) are abundantly produced with a large boost

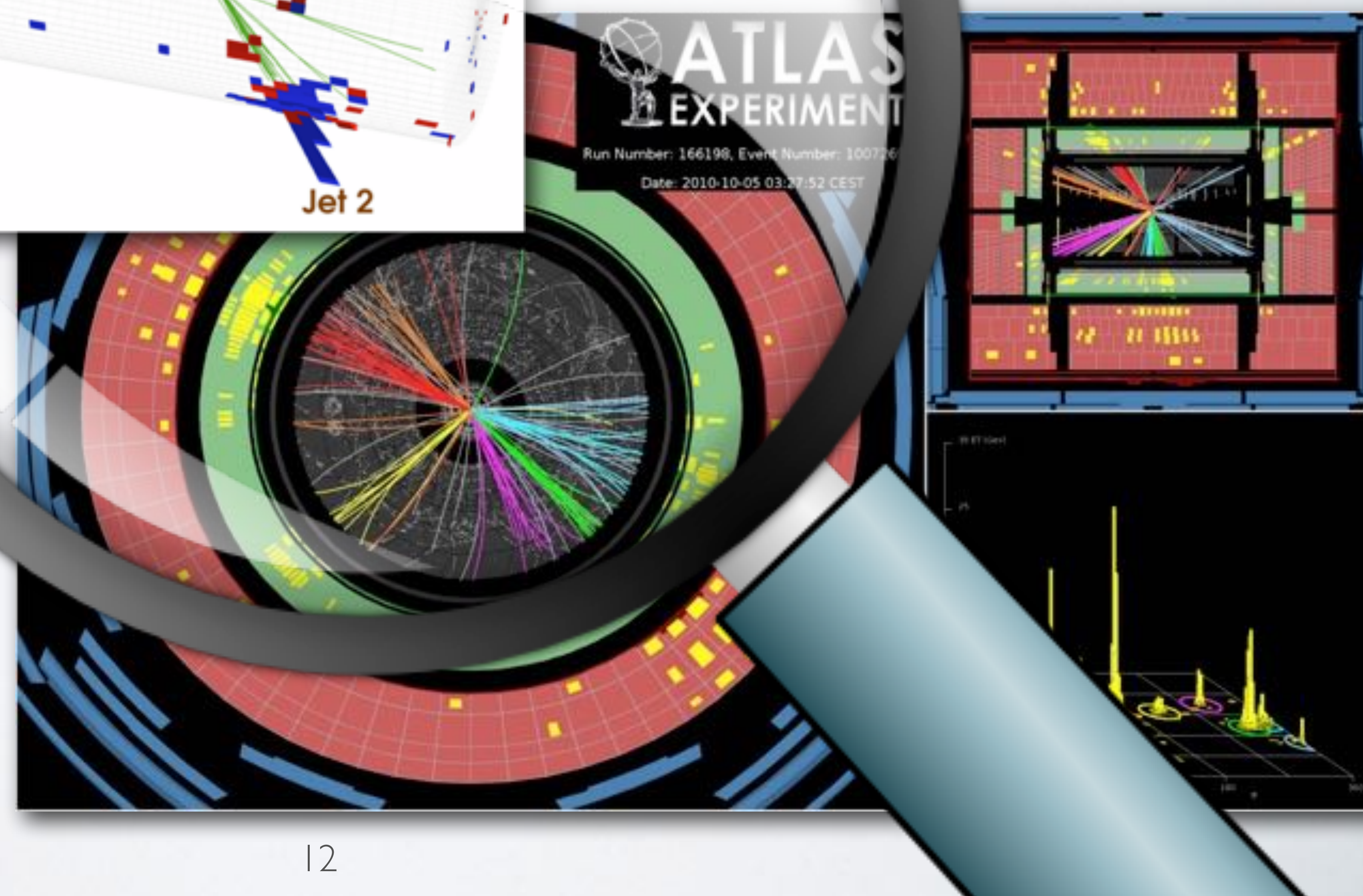


- their decay-products are then collimated
- if they decay into hadrons, we end up with localized deposition of energy in the hadronic calorimeter: a jet

JETS

Collimated, energetic sprays of particles



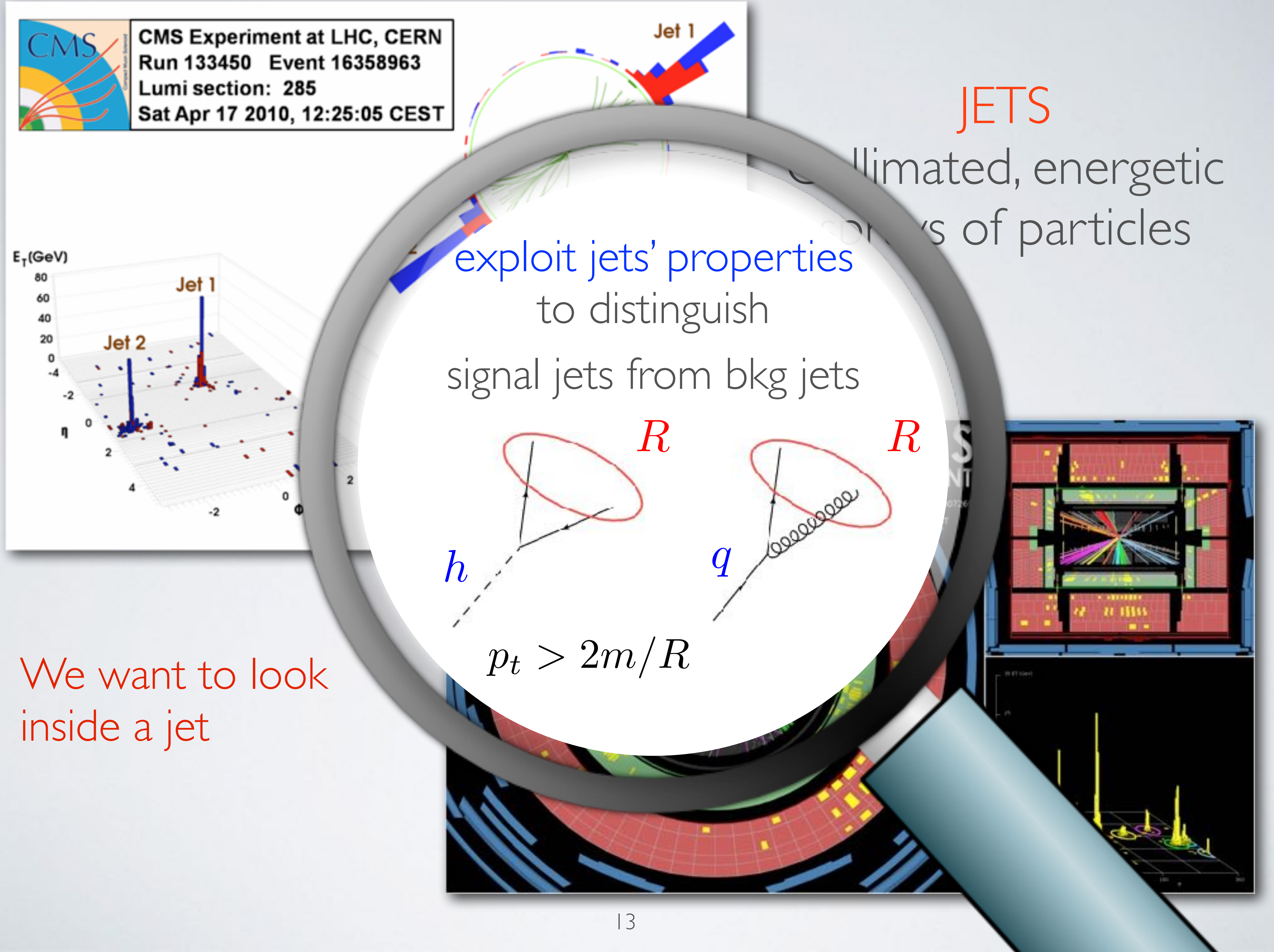


We want to look inside a jet

JETS

llimated, energetic

s of particles



exploit jets' properties

to distinguish

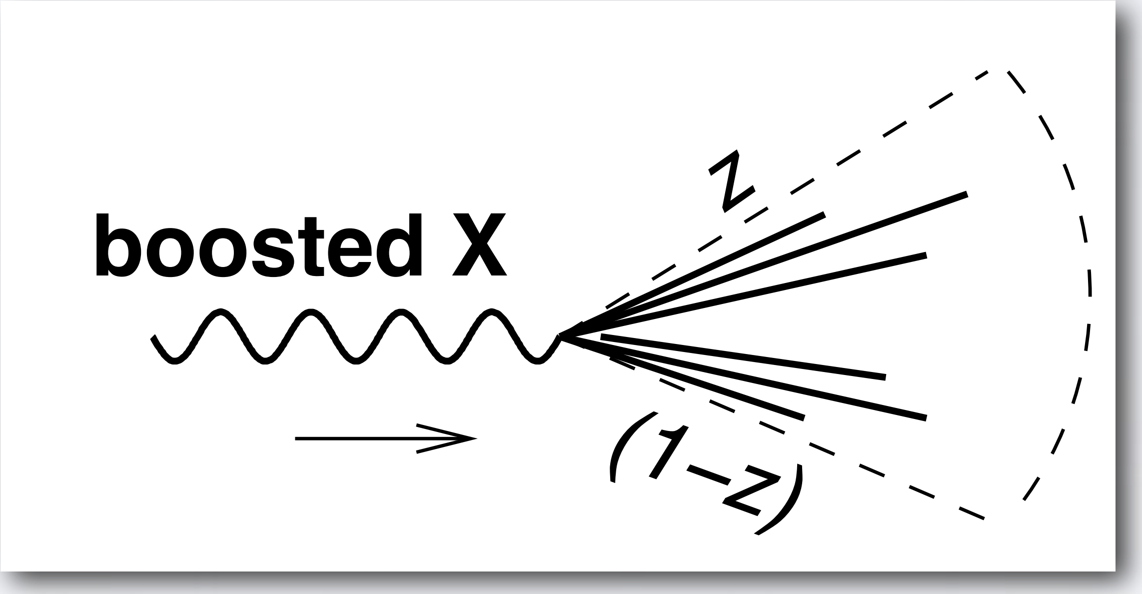
signal jets from bkg jets

$$p_t > 2m/R$$

We want to look inside a jet

Signal-jet mass

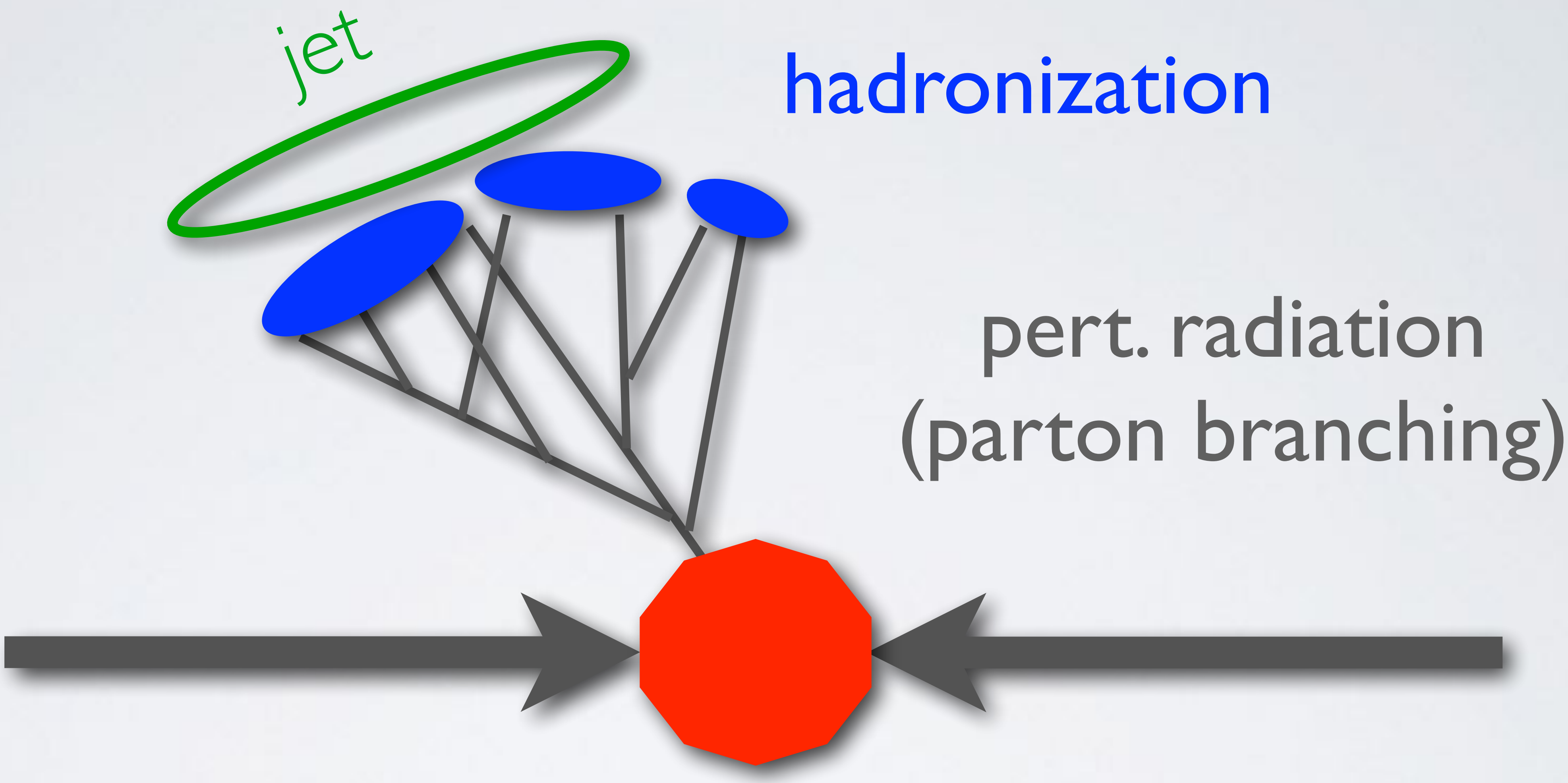
- First jet-observable that comes to mind
- Signal jet should have a mass distribution peaked near the resonance



- However, that's a simple partonic picture

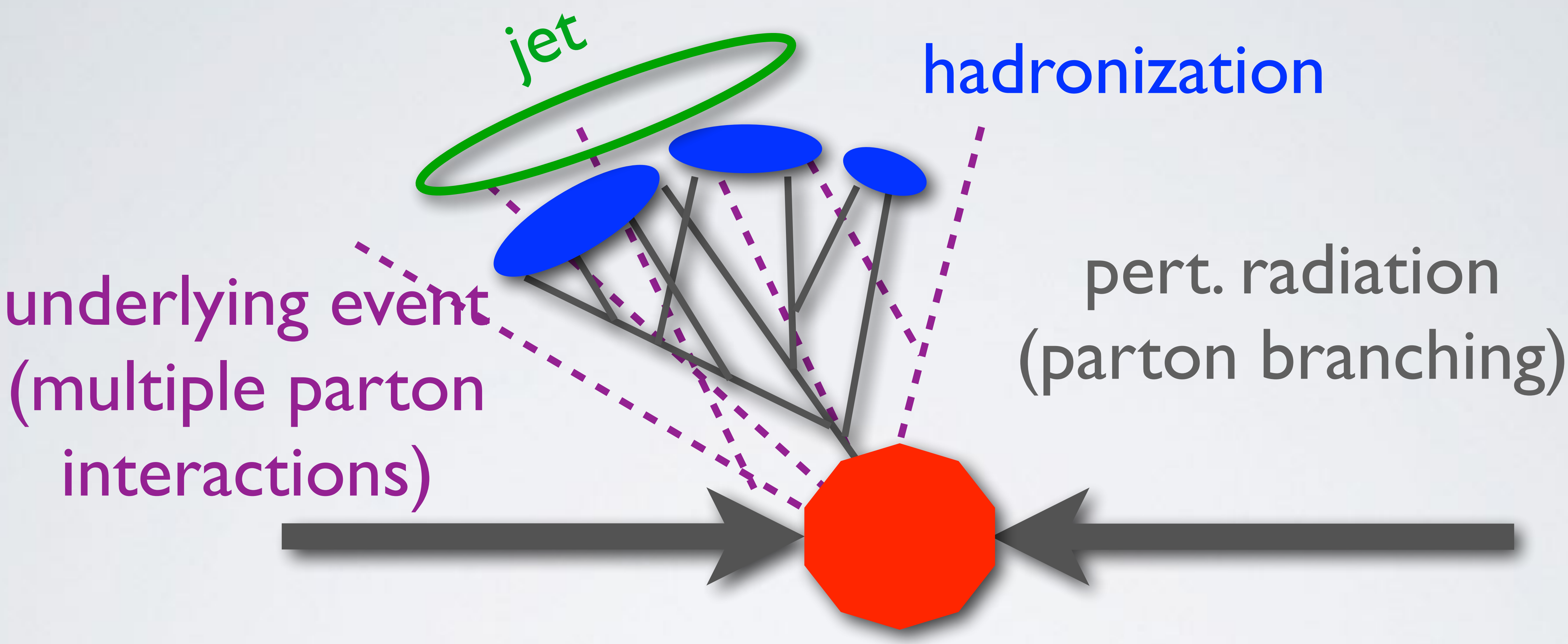
A useful cartoon

inspired by G. Salam



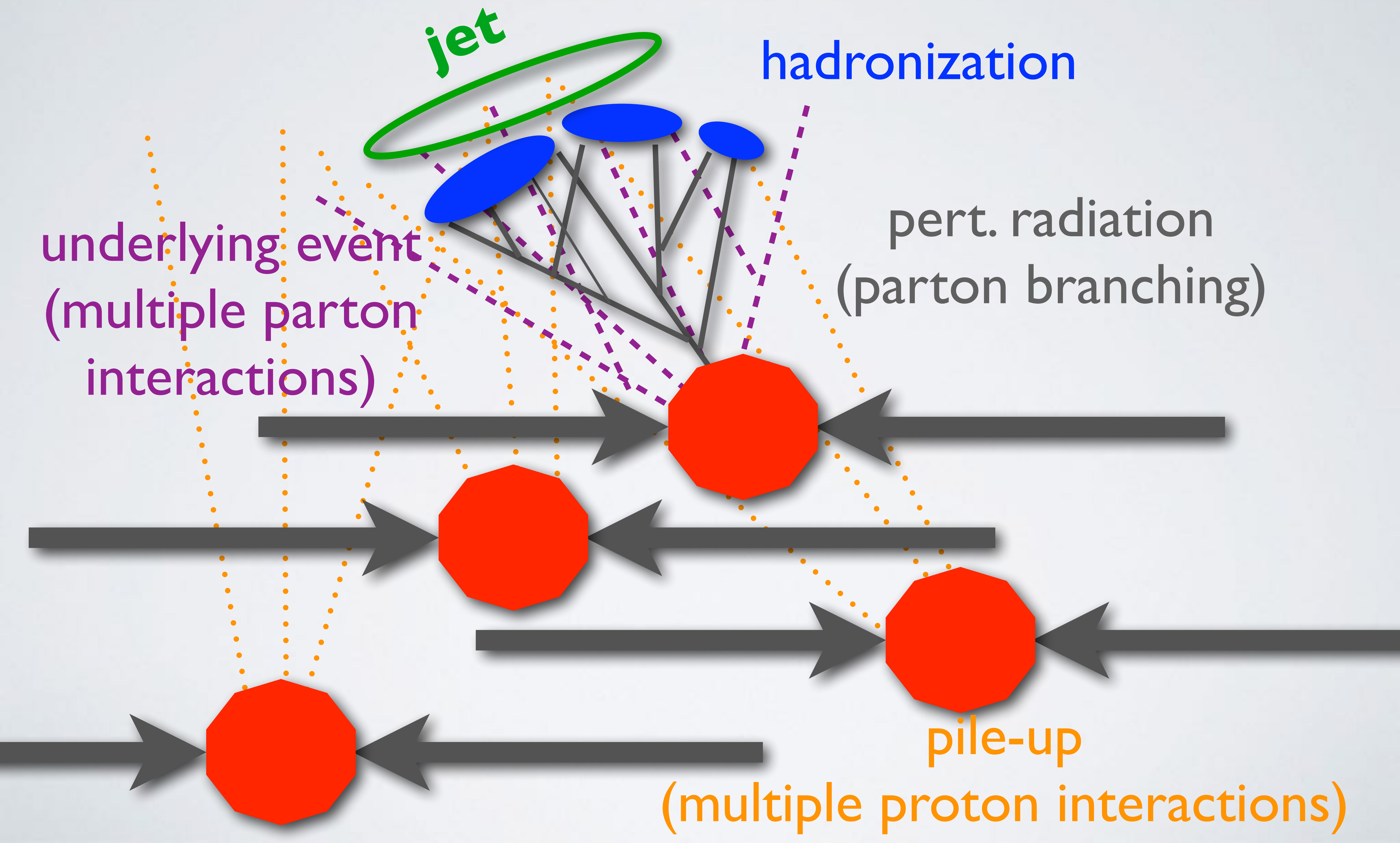
A useful cartoon

inspired by G. Salam



A useful cartoon

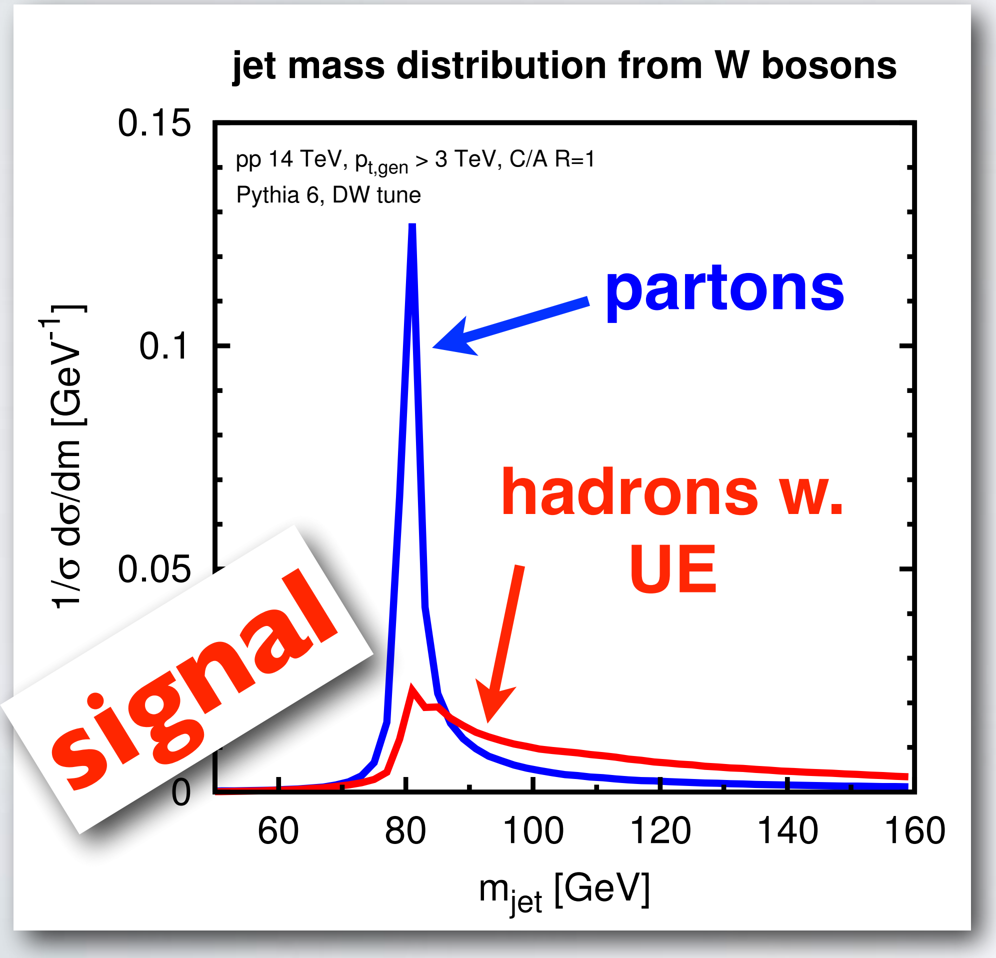
inspired by G. Salam

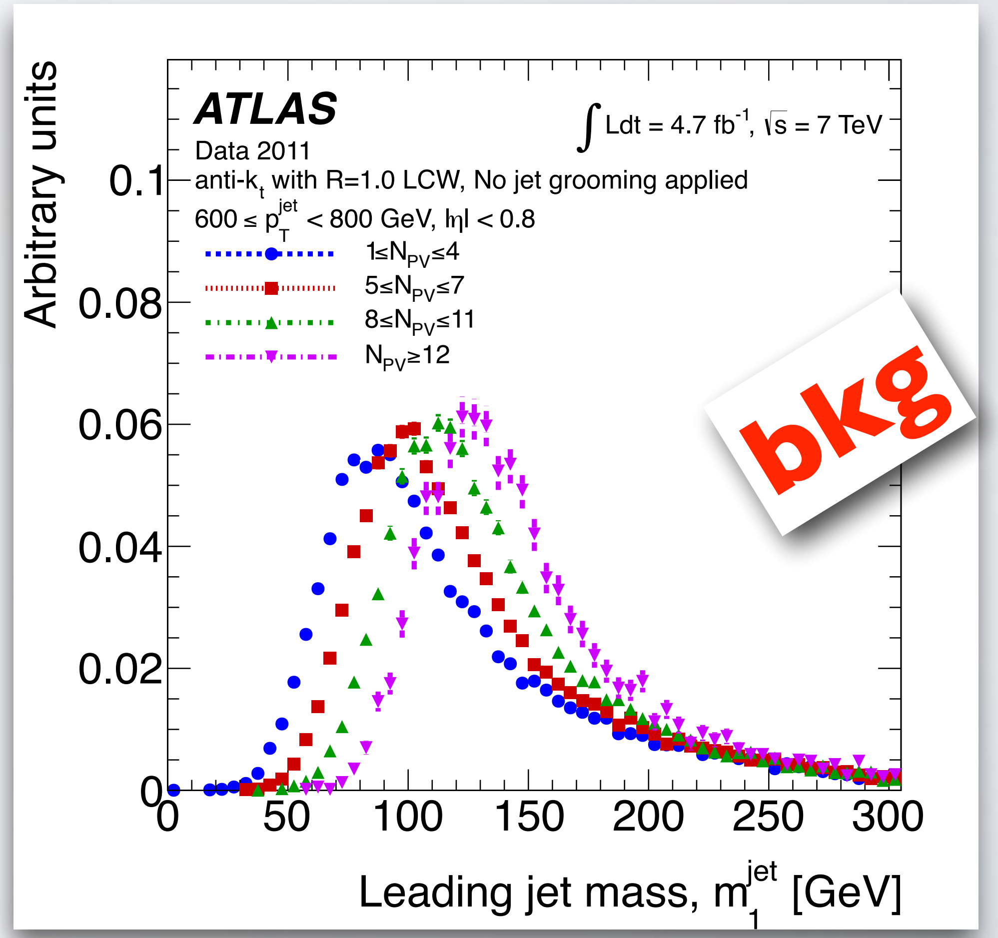


Effect on jet masses

- 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)



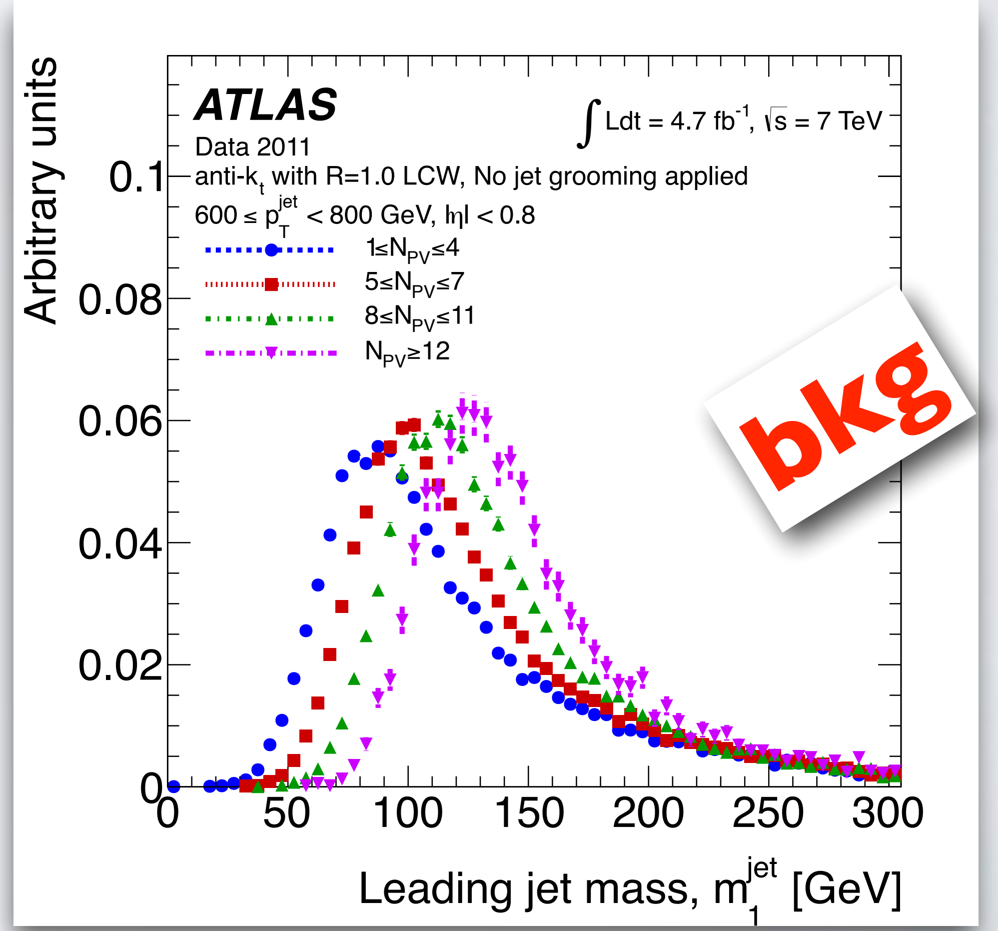


ATLAS, JHEP 1309 (2013) 076

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:

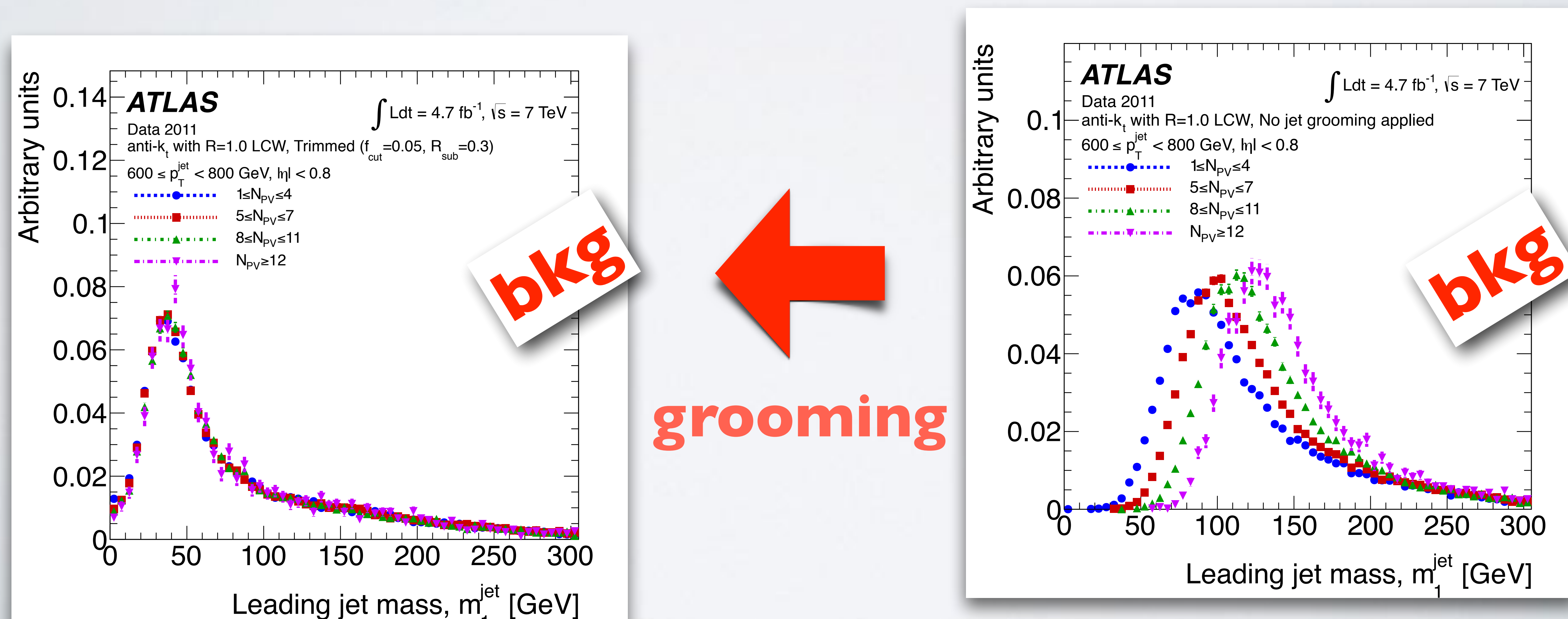
  1. clean the jets up by removing soft junk
  2. identify the features of hard decays and cut on them



ATLAS, JHEP 1309 (2013) 076

Beyond the mass: substructure

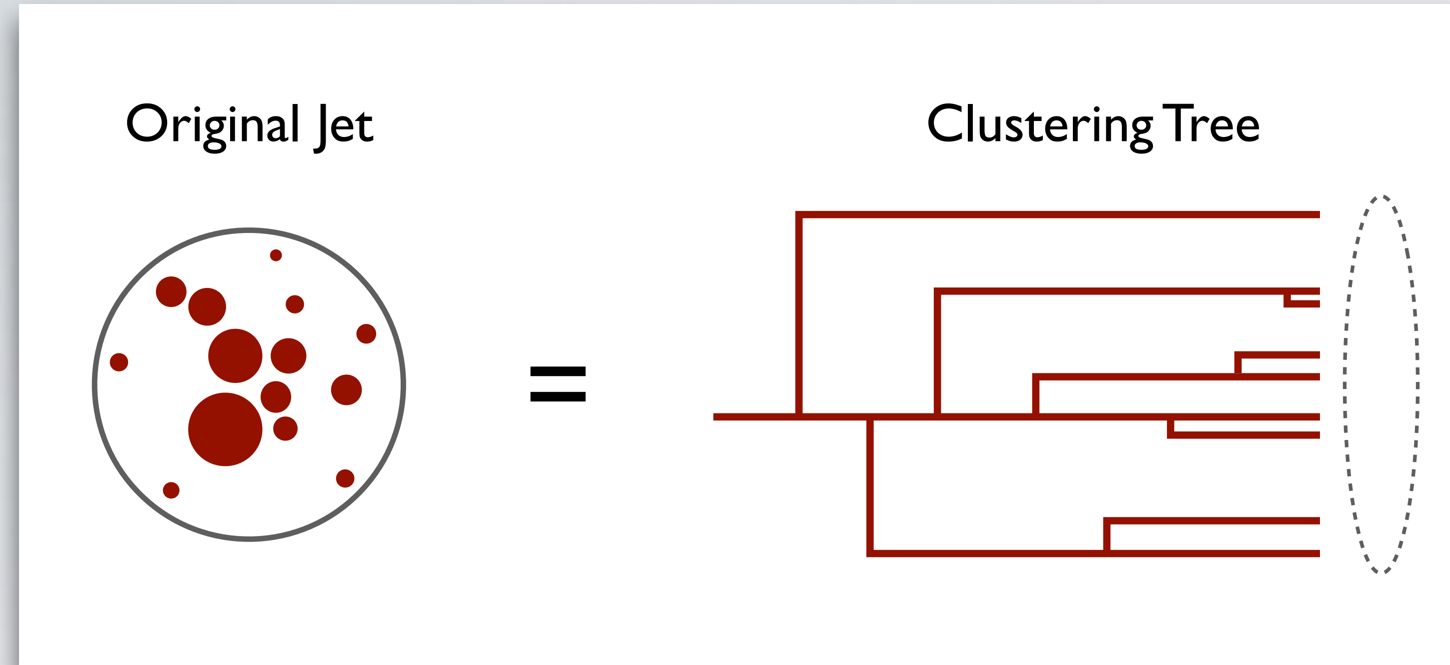
- Let's have a closer look: background peaks in the EW region
- Need to go beyond the mass and exploit jet substructure
- Grooming and Tagging:
  1. clean the jets up by removing soft junk
  2. identify the features of hard decays and cut on them
- Grooming provides a handle on UE and pile-up



ATLAS, JHEP 1309 (2013) 076

Soft Drop

Larkoski, SM, Soyez and Thaler (2014)



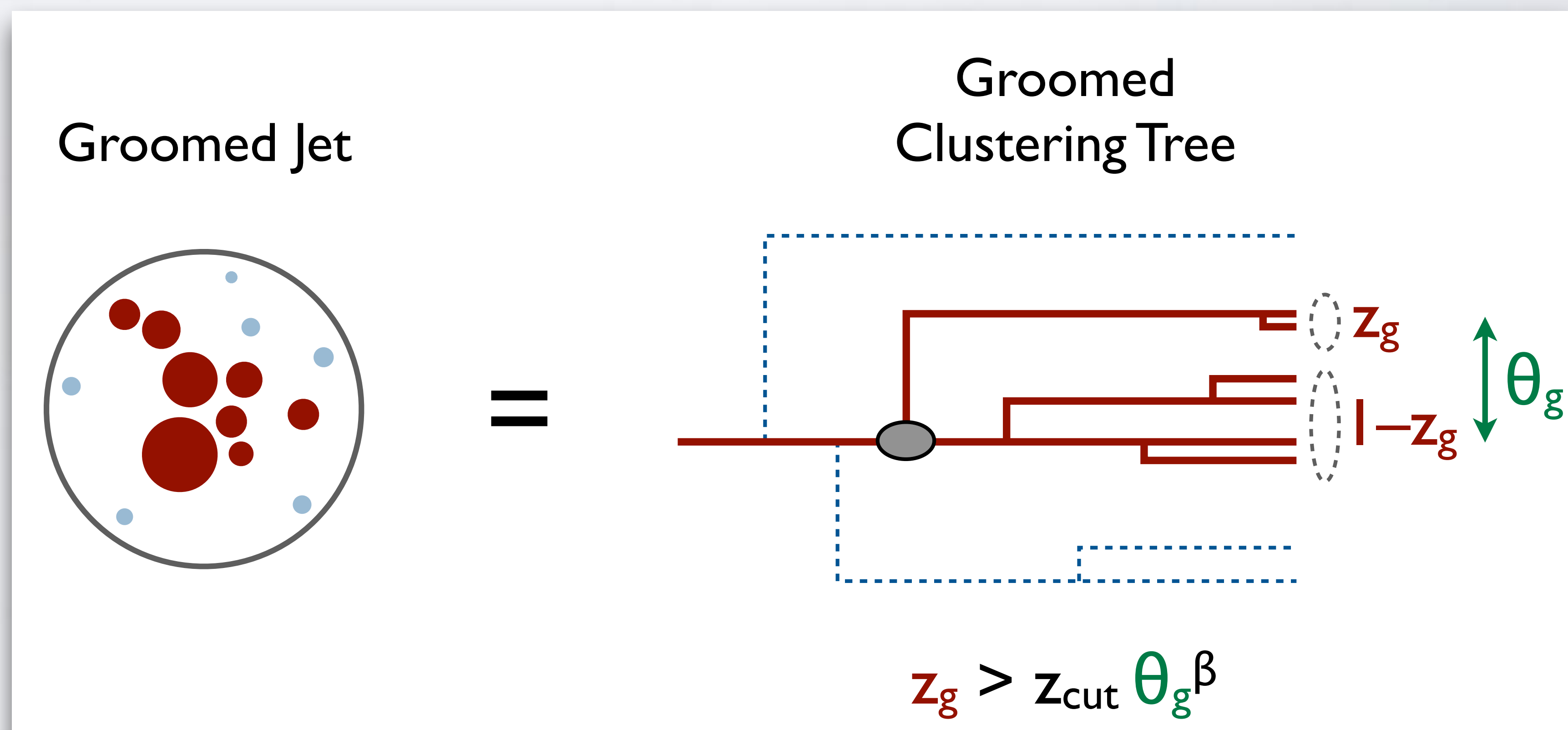
more information: clustering history

check momentum sharing

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

discard soft branches, i.e

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

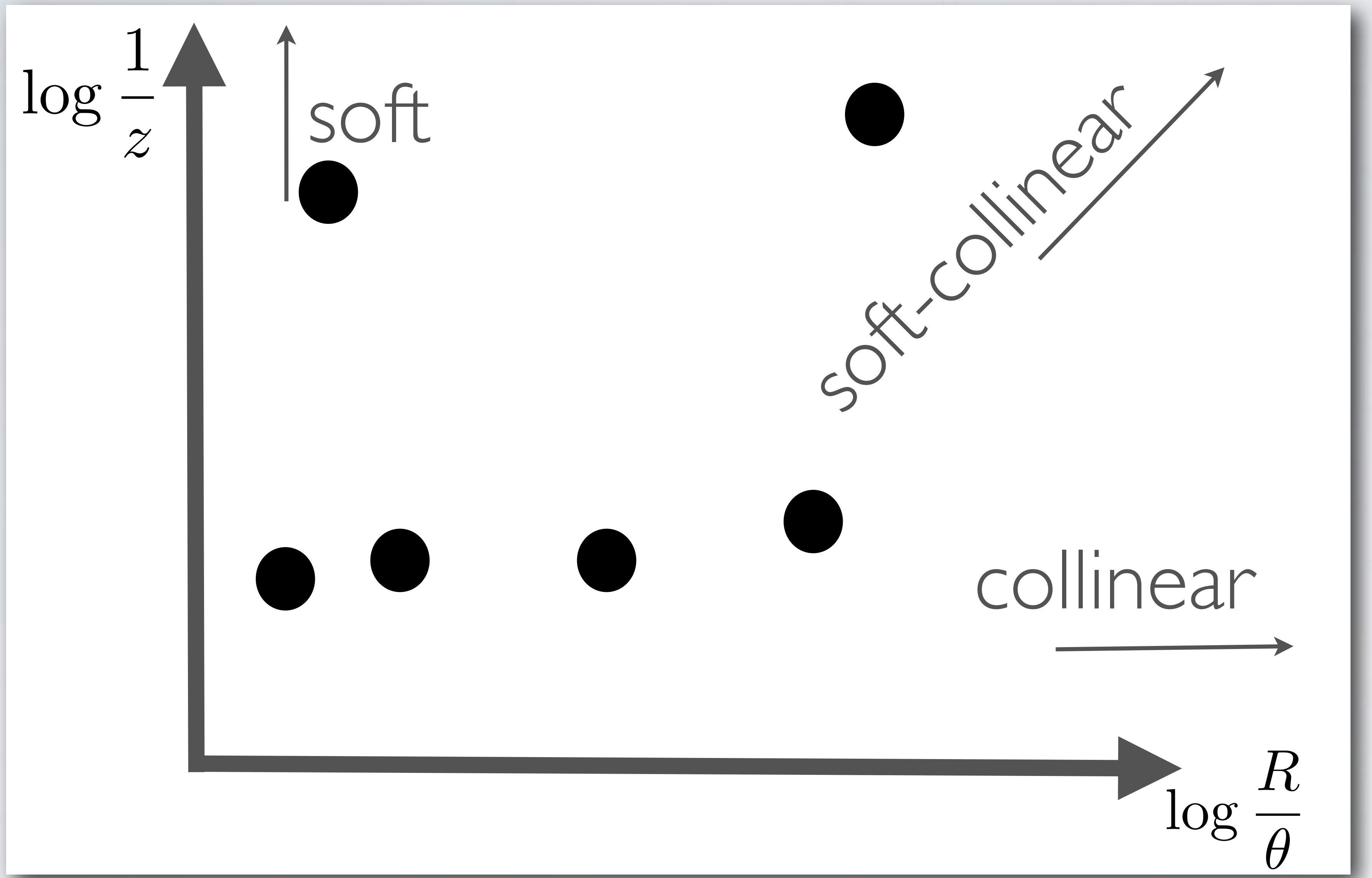


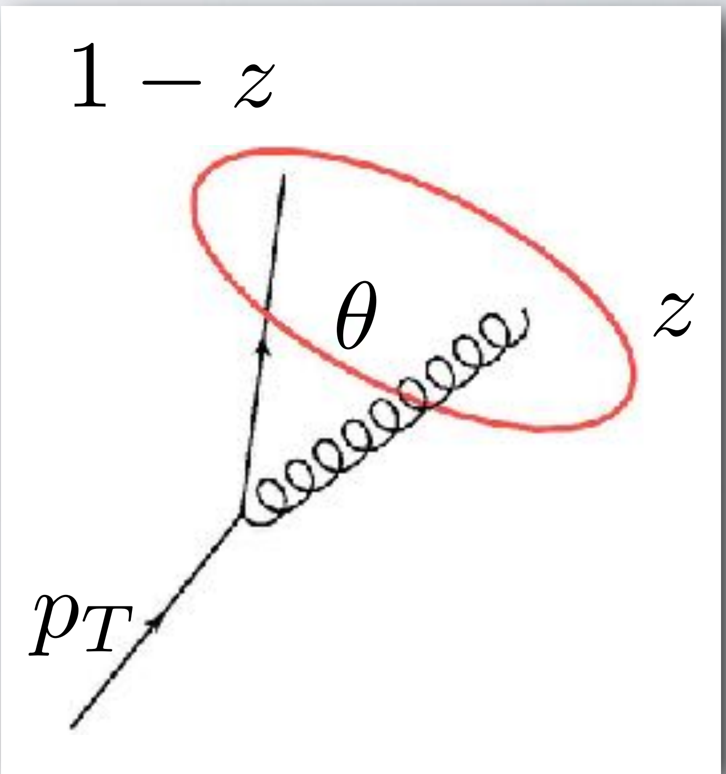
Butterworth, Davison, Rubin and Salam (2008)
Dasgupta, Fregoso, SM and Salam (2013)
Tseng and Evans (2013)

courtesy of J. Thaler

Soft-gluon phase space

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

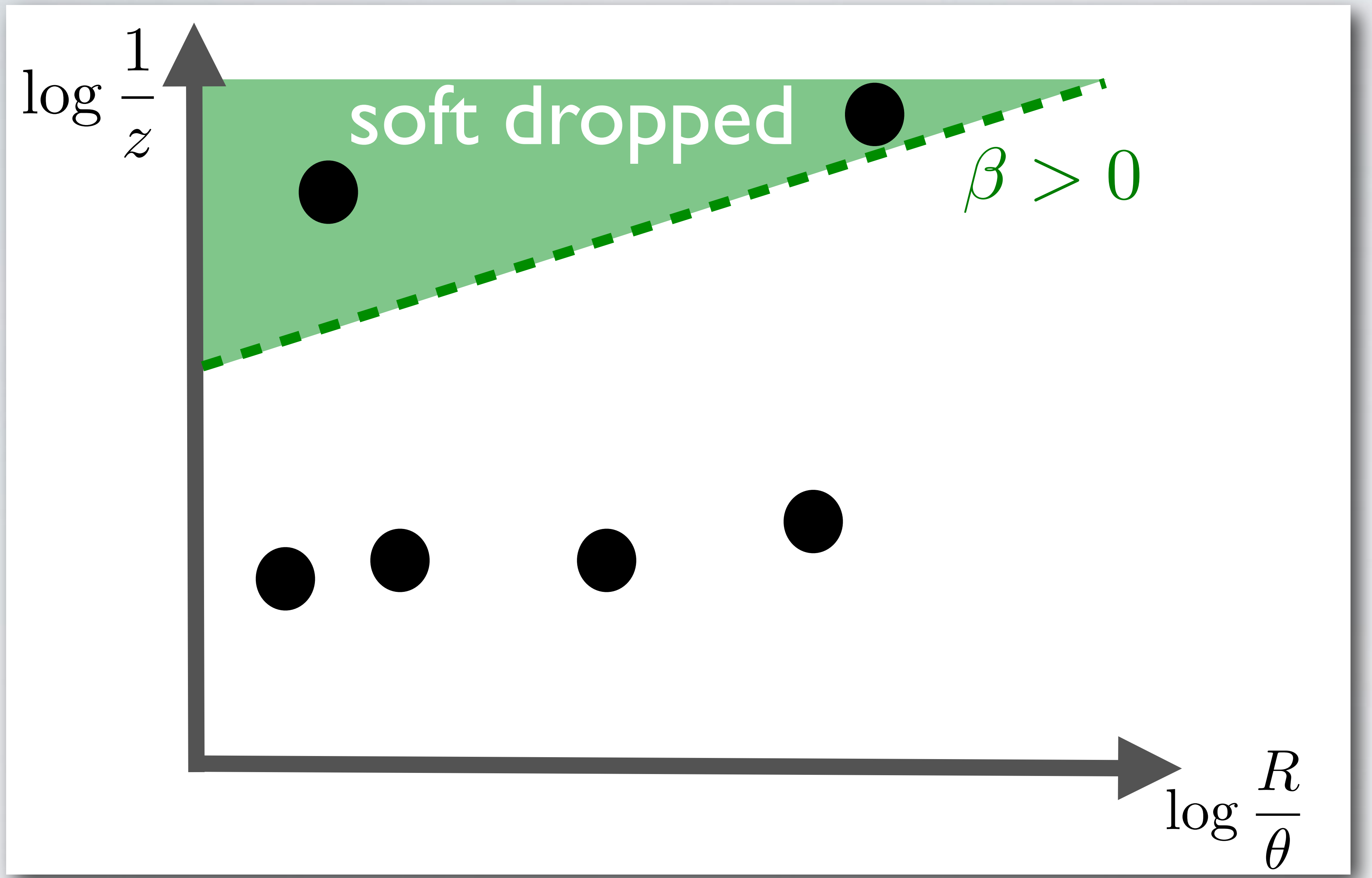




Emission probability is uniform in the (log z, log θ) plane:

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

Soft Drop as a groomer

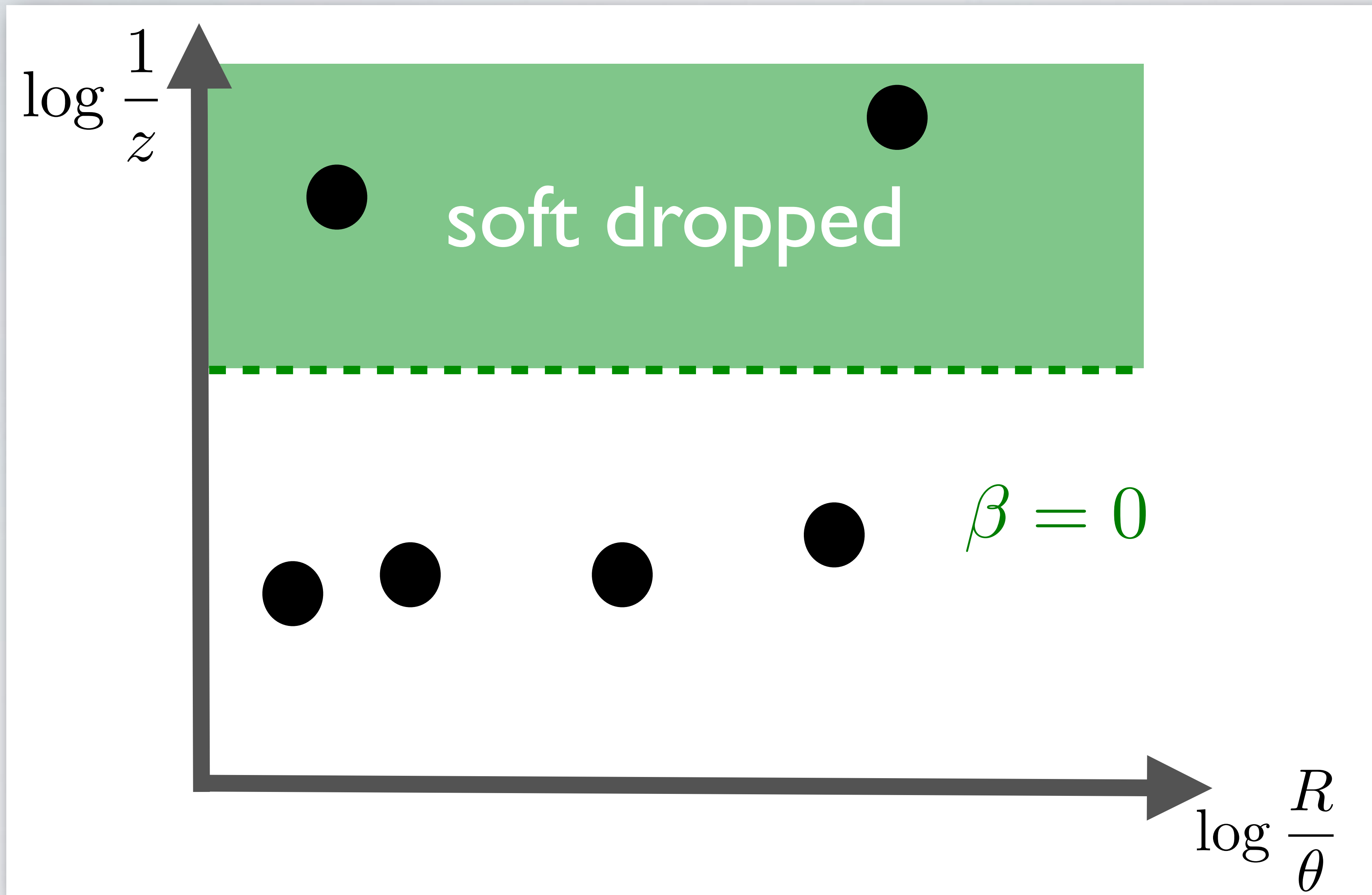


- useful to consider the soft-gluon phase space
- soft-drop condition becomes

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

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

Soft Drop and mMDT

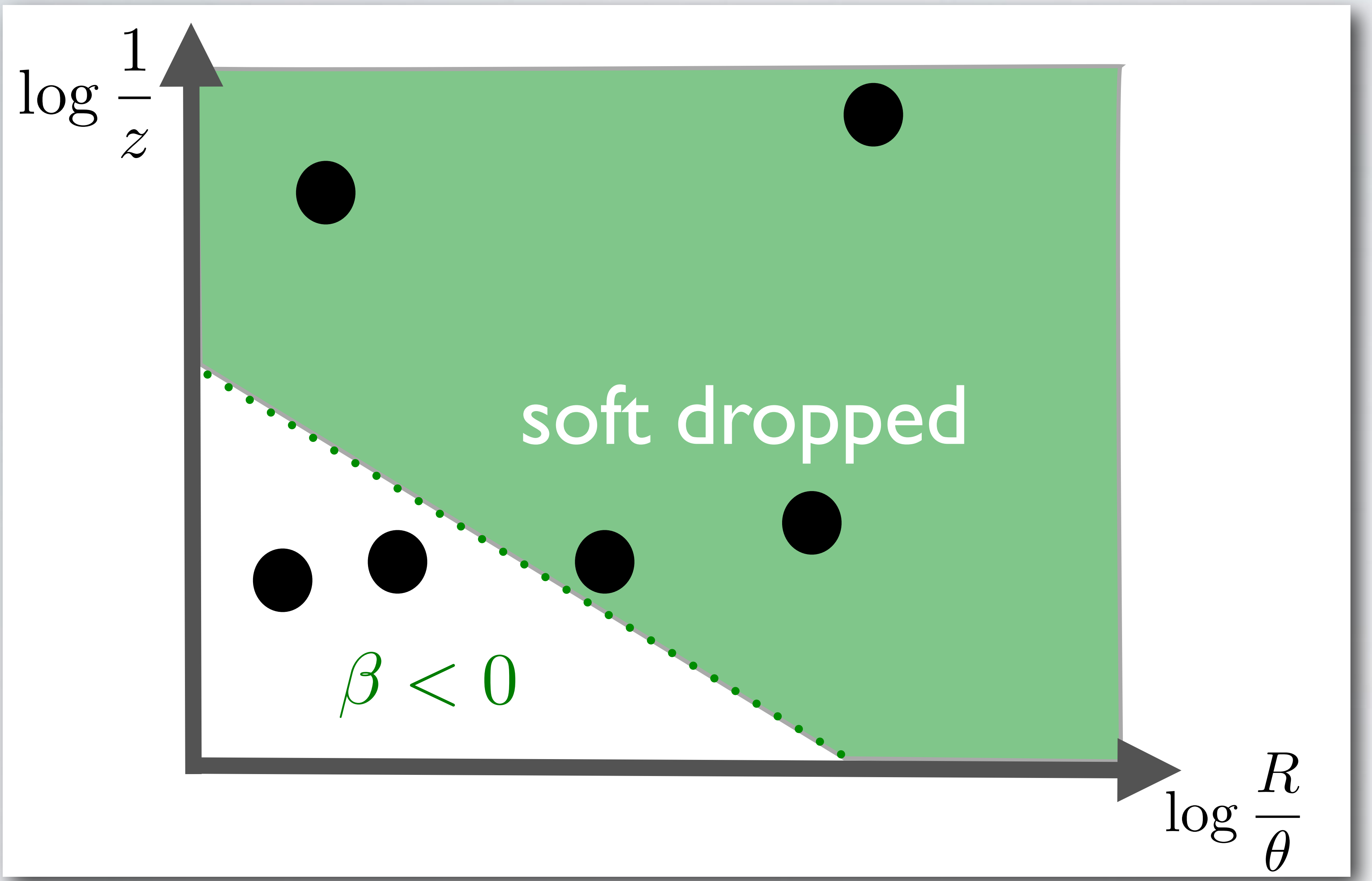


- useful to consider the soft-gluon phase space
- soft-drop condition becomes

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

- 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

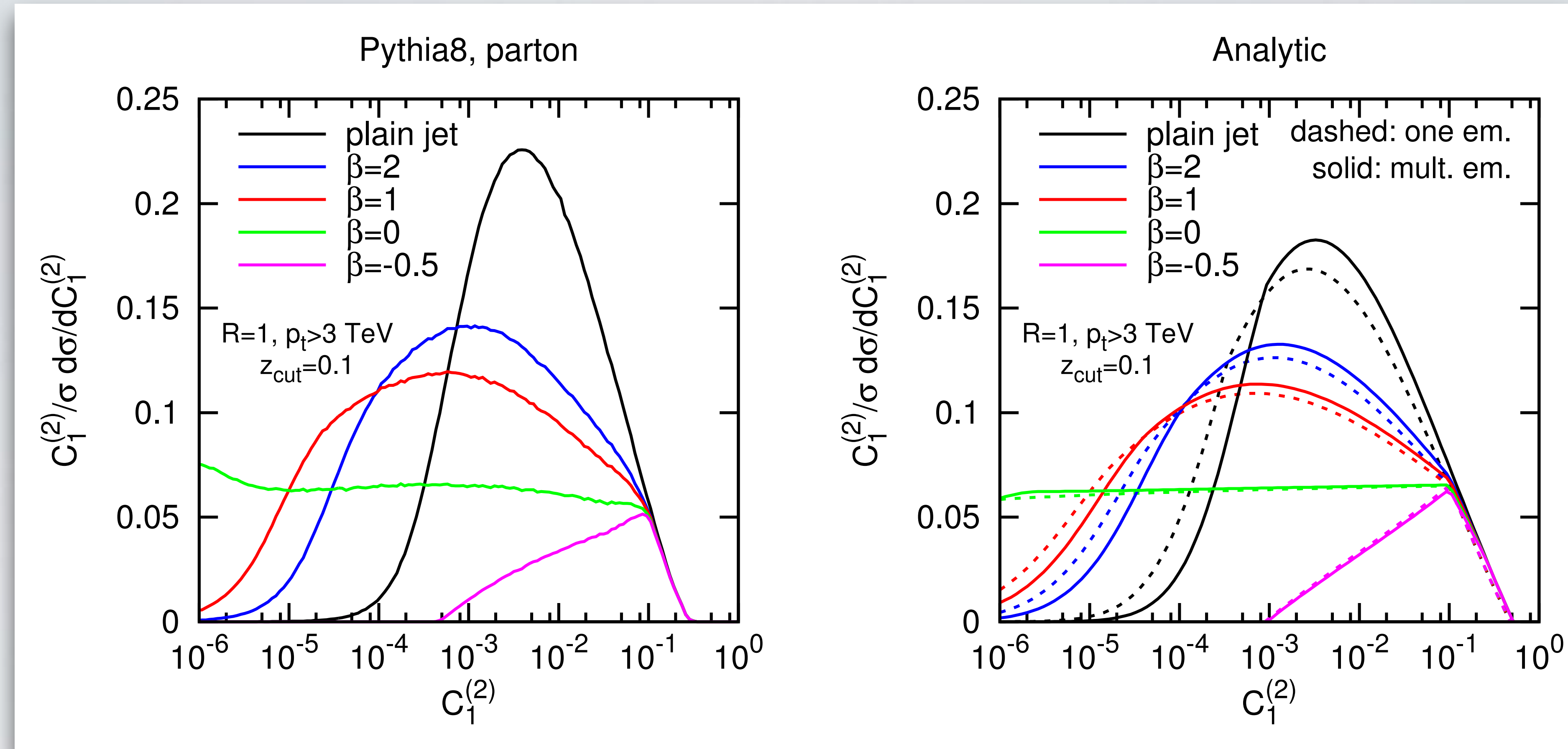


- useful to consider the soft-gluon phase space
- soft-drop condition becomes

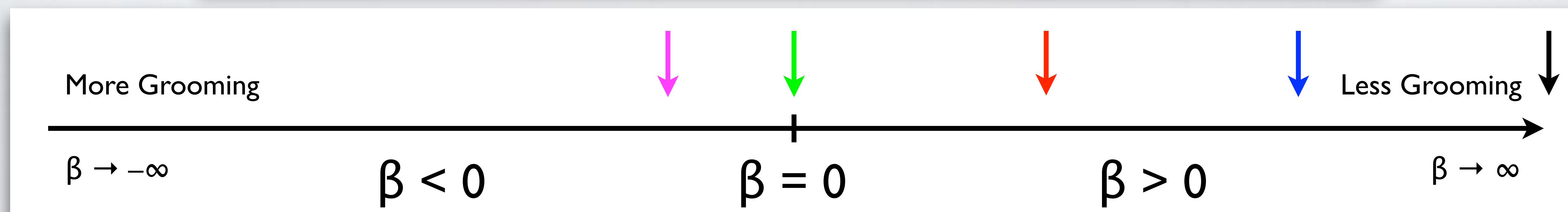
$$z > z_{\rm cut} \left(\frac{\theta}{R}\right)^{\beta}$$

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

Groomed jet properties



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

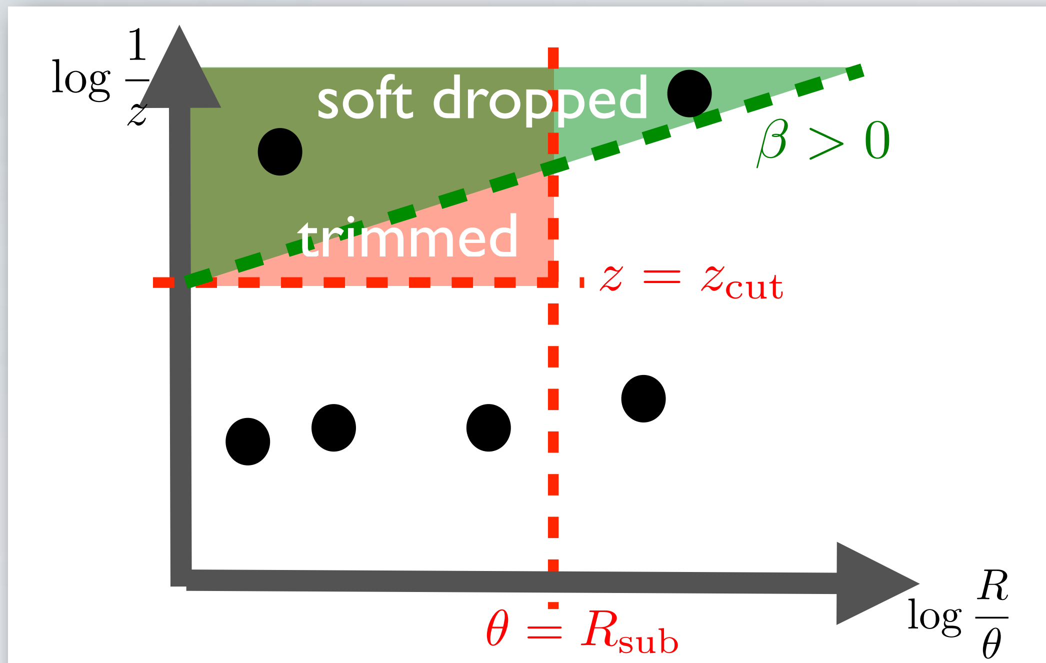


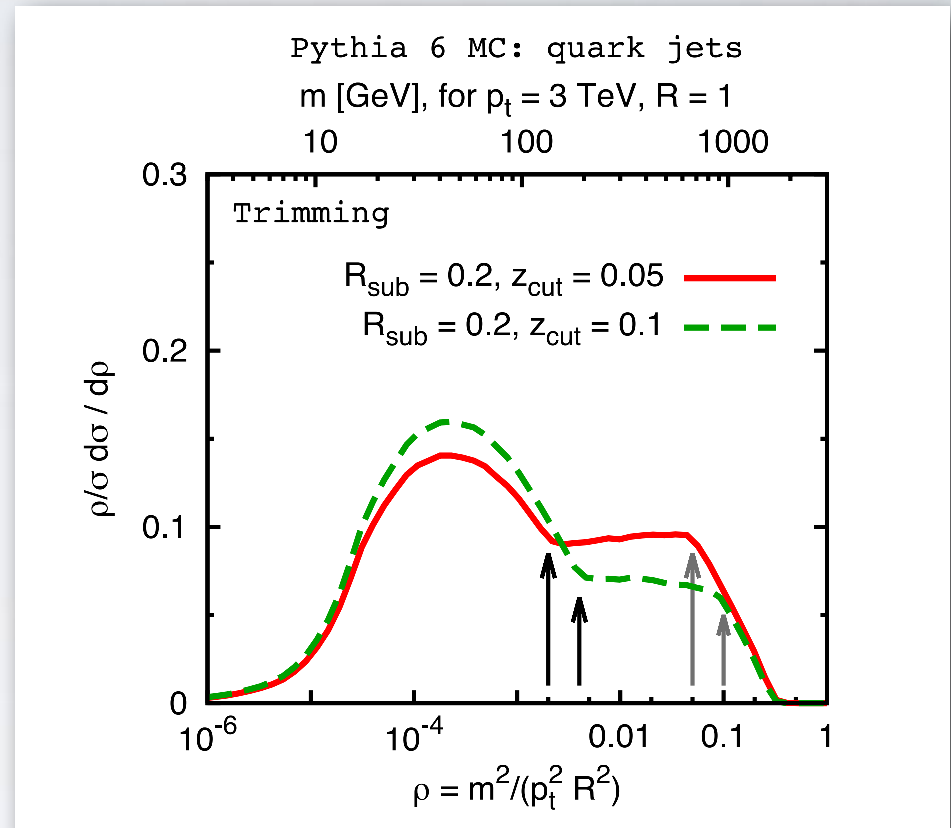
courtesy of J. Thaler

- smooth distributions
- flatness in bkg can be achieved for **β**=0
- it's becoming the *standard choice* for CMS

Soft Drop vs Trimming

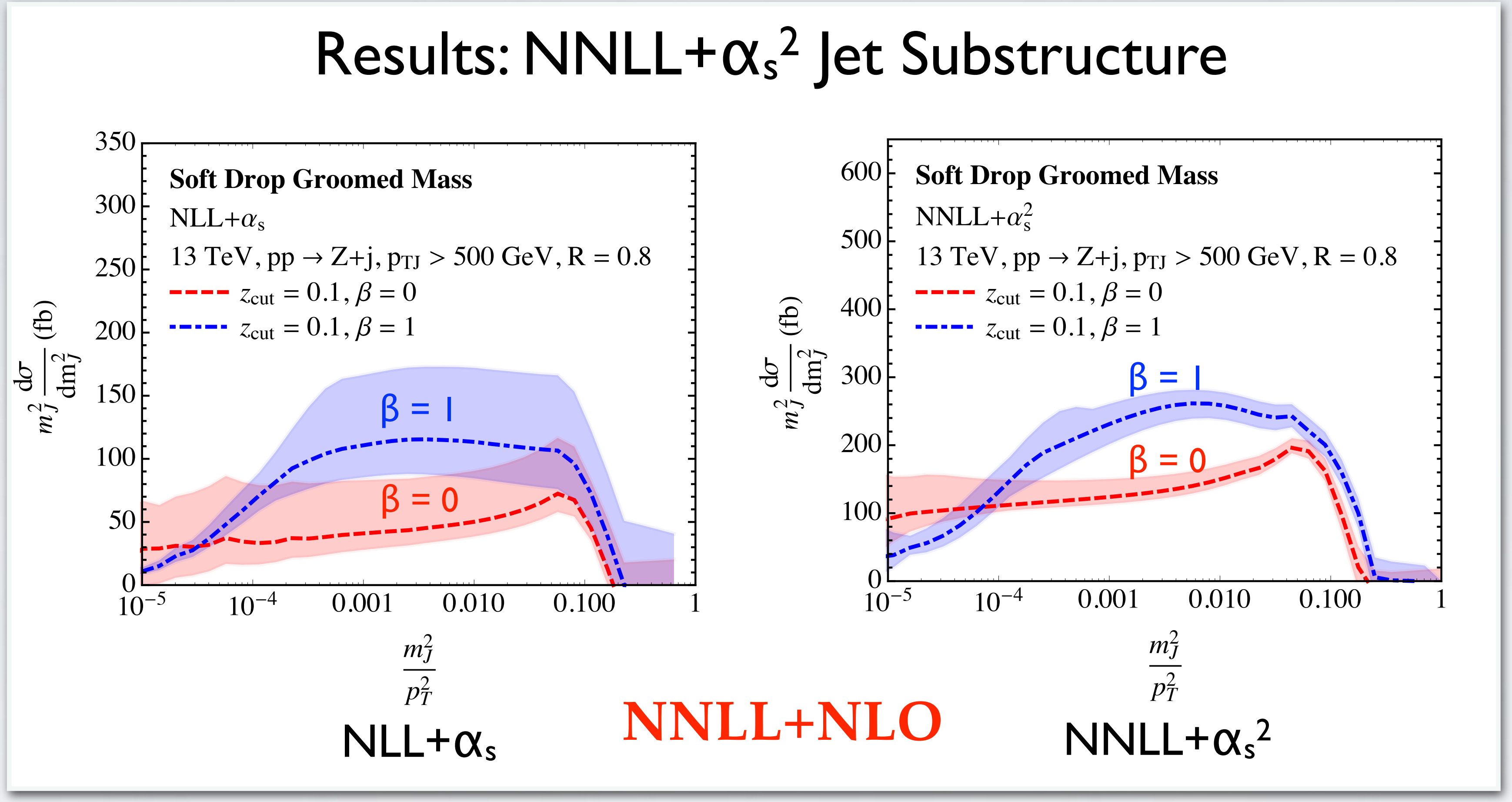
Soft drop in grooming mode (β>0) works as a dynamical trimmer





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

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
- for β=0 LL is zero, so state-of-the art NNLL is actually NLL

The groomed jet mass

Towards theory / data comparison

- the time is mature for theory / data comparison
- reduced sensitivity to non-pert physics (hadronization and UE) should make the comparison more meaningful
- substructure measurements of QCD jets can pin down poorly constrained gluon radiation (tuning)
- pick the observable we know the most about:

JET MASS for β=0 soft-dropped (i.e. mMDT) jets

Upcoming CMS measurement,
however, as usual:

Towards theory / data comparison

- the time is mature for theory / data comparison
- reduced sensitivity to non-pert physics (hadronization and UE) should make the comparison more meaningful
- substructure measurements of QCD jets can pin down poorly constrained gluon radiation (tuning)
- pick the observable we know the most about:

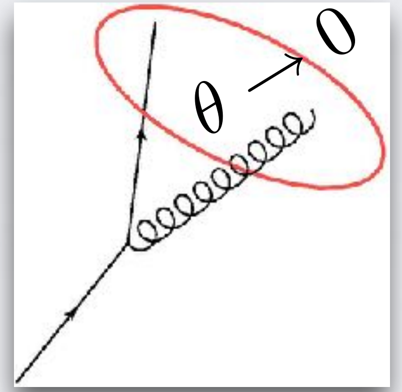
JET MASS for β=0 soft-dropped (i.e. mMDT) jets

Upcoming CMS measurement, however, as usual:

p_T vs p_T^{mMDT}

SM, Schunk, Soyez (2017)

- first choice: transverse momentum before or after grooming ?
- for **β**=0 the groomed p_T spectrum is not IRC safe (but it's Sudakov safe, see later)

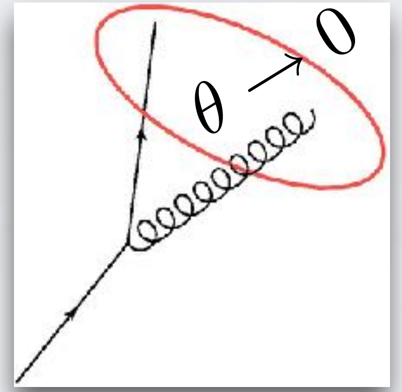


groomed away if $z < z_{\rm cut}$ leaving the collinear pole from the virtual uncancelled

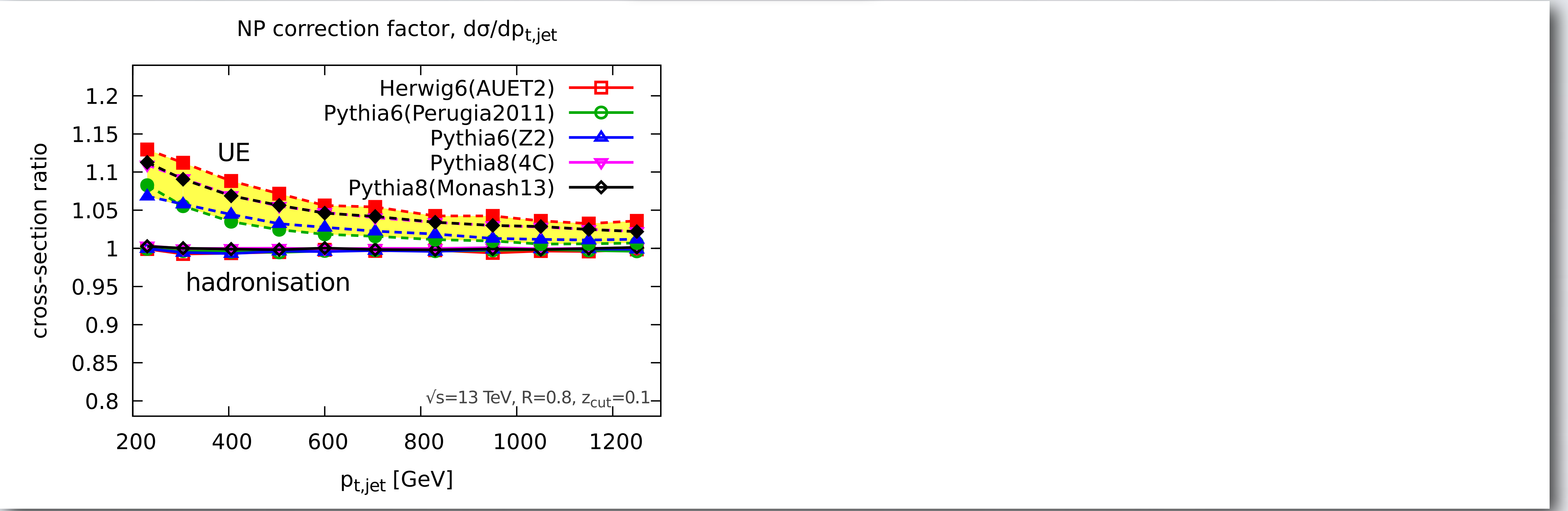
p_T vs p_T^{mMDT}

SM, Schunk, Soyez (2017)

- first choice: transverse momentum before or after grooming ?
- for β=0 the groomed p_T spectrum is not IRC safe (but it's Sudakov safe, see later)



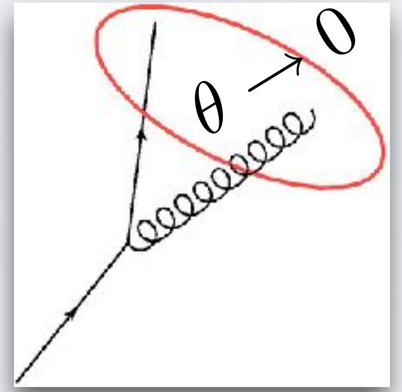
groomed away if $z < z_{cut}$ leaving the collinear pole from the virtual uncancelled



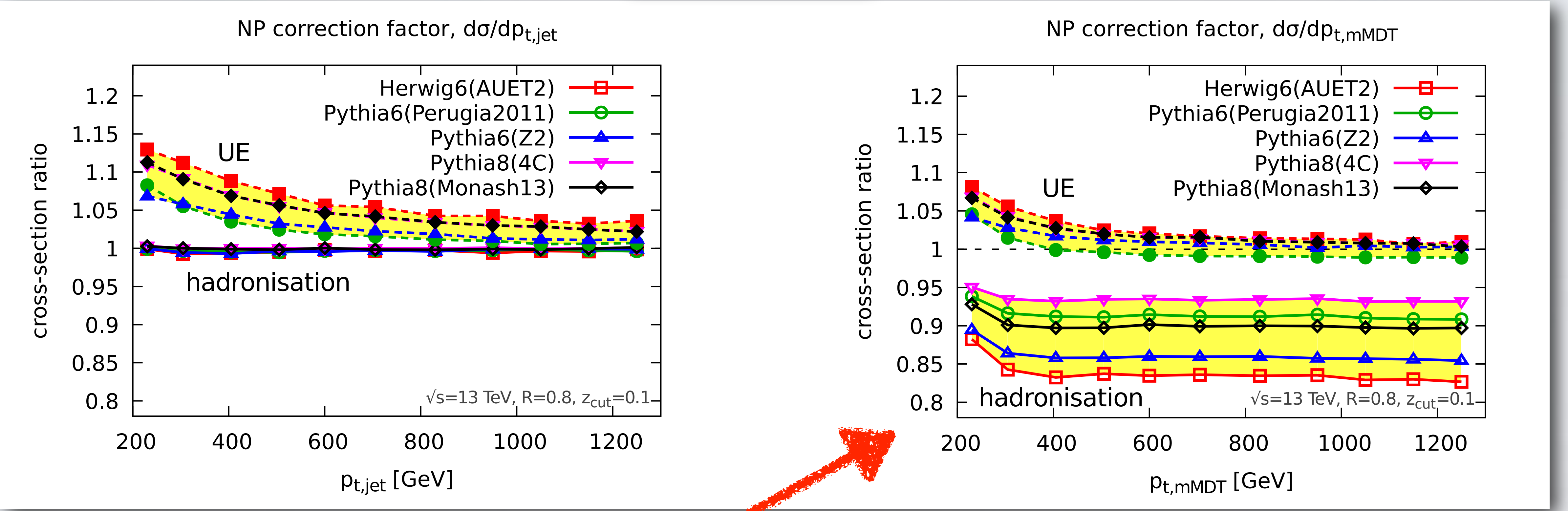
p_T vs p_T^{mMDT}

SM, Schunk, Soyez (2017)

- first choice: transverse momentum before or after grooming ?
- for β=0 the groomed p_T spectrum is not IRC safe (but it's Sudakov safe, see later)



groomed away if $z < z_{\rm cut}$ leaving the collinear pole from the virtual uncancelled



- large hadronization because of IRC unsafely
- UE (and pile-up?) resilient because of grooming

Jet mass with p_T^{mMDT}

SM, Schunk, Soyez (2017)

- mass distribution IRC safe in both cases
- however, resummation is different event at LL!
- nitty gritty details (for who's interested)

Jet mass with p_T^{mMDT}

SM, Schunk, Soyez (2017)

- mass distribution IRC safe in both cases
- however, resummation is different event at LL!
- nitty gritty details (for who's interested)

- At LO we have one emission: no changes wrt p_T
- More interesting structure at NLO

$$\rho \frac{d\sigma^{\mathrm{LL,NLO},C_F^2 a}}{d\rho} = \left(\frac{\alpha_s C_F}{\pi}\right)^2 \rho \int_{p_{t1}}^{p_{t2}} dp_{t,\mathrm{jet}}\, \sigma_q(p_{t,\mathrm{jet}})$$
$$\cdot \int_0^1 \frac{d\theta_1^2}{\theta_1^2} \int_0^1 dz_1\, p_{gq}(z_1) \Big[\Theta\left(z_{\mathrm{cut}} > z_1\right) \Theta\left((1-z_1)p_{t,\mathrm{jet}} > p_{t1}\right) - 1\Big]$$
$$\cdot \int_0^1 \frac{d\theta_2^2}{\theta_2^2} \int_0^1 dz_2\, p_{gq}(z_2) \Theta\left(z_2 > z_{\mathrm{cut}}\right) \Theta\left(1 - z_2 > z_{\mathrm{cut}}\right) \Theta\left(\theta_1^2 > \theta_2^2\right) \delta\left(\rho - z_2\theta_2^2\right).$$

gluon 1 fails mMDT
but cannot carry away too much

gluon 2 sets the mass

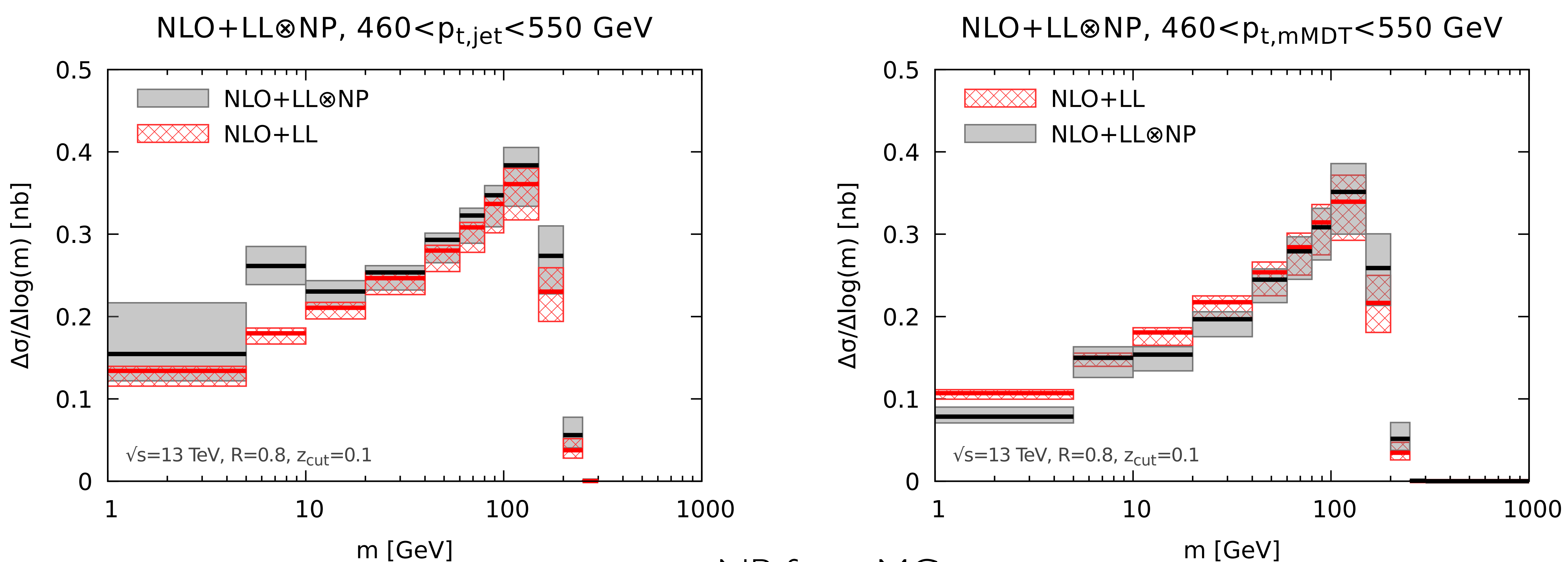
$$= \int_{p_{t1}}^{p_{t2}} dp_{t,\mathrm{jet}}\, \sigma_q(p_{t,\mathrm{jet}}) R_q' \Big[- R_q - R_{q\to g} \Big]$$
$$- \int_{p_{t1}}^{\min\left[p_{t2}, \frac{p_{t1}}{1-z_{\mathrm{cut}}}\right]} dp_{t,\mathrm{jet}}\, \sigma_q(p_{t,\mathrm{jet}})\, R_q' \,\frac{\alpha_s C_F}{\pi} \log\frac{1}{\rho} \int_{1-\frac{p_{t1}}{p_{t,\mathrm{jet}}}}^{z_{\mathrm{cut}}} dz_1\, p_{gq}(z_1).$$

p_T result and new piece

Phenomenology

- mass distribution IRC safe in both cases
- however, resummation is different event at LL!

SM, Schunk, Soyez (2017)

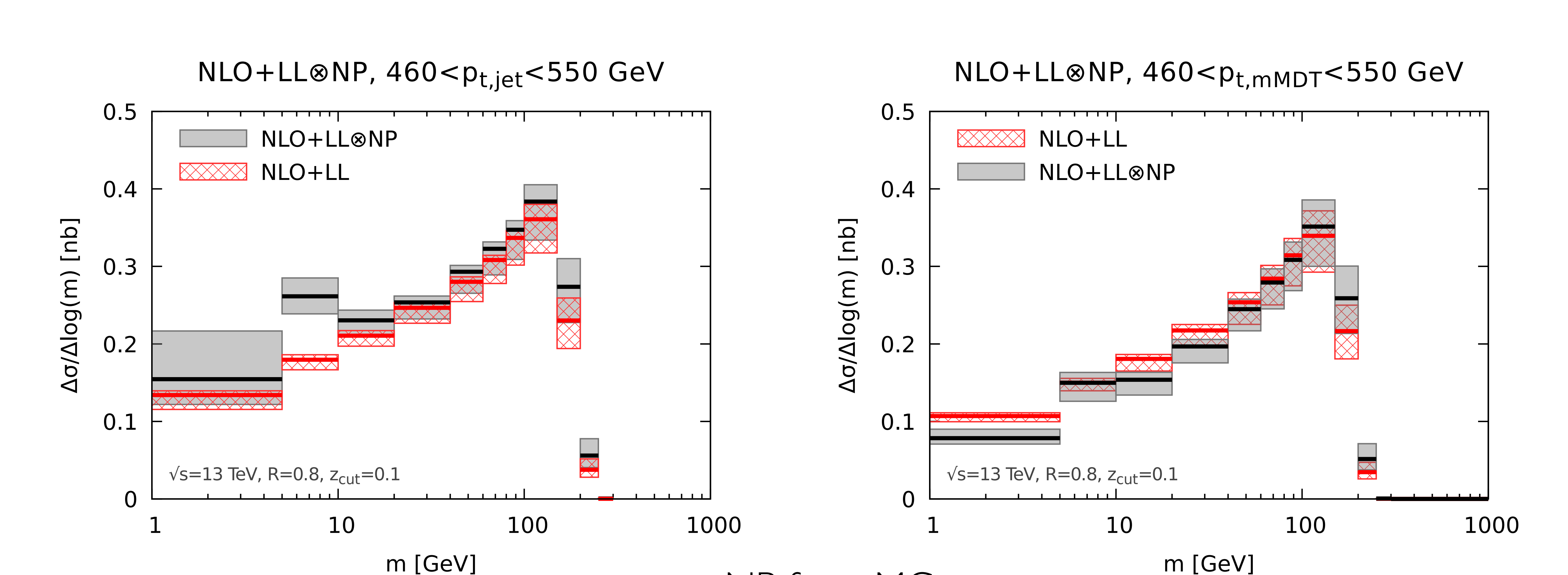


NP from MCs

Phenomenology

SM, Schunk, Soyez (2017)

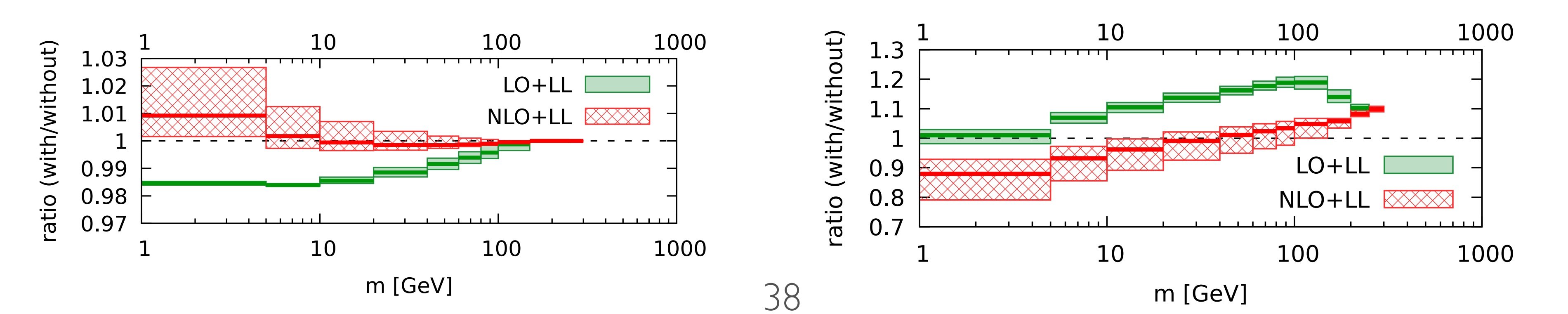
- mass distribution IRC safe in both cases
- however, resummation is different event at LL!



NP from MCs

- Is z_c=*0.1*: big or small ?

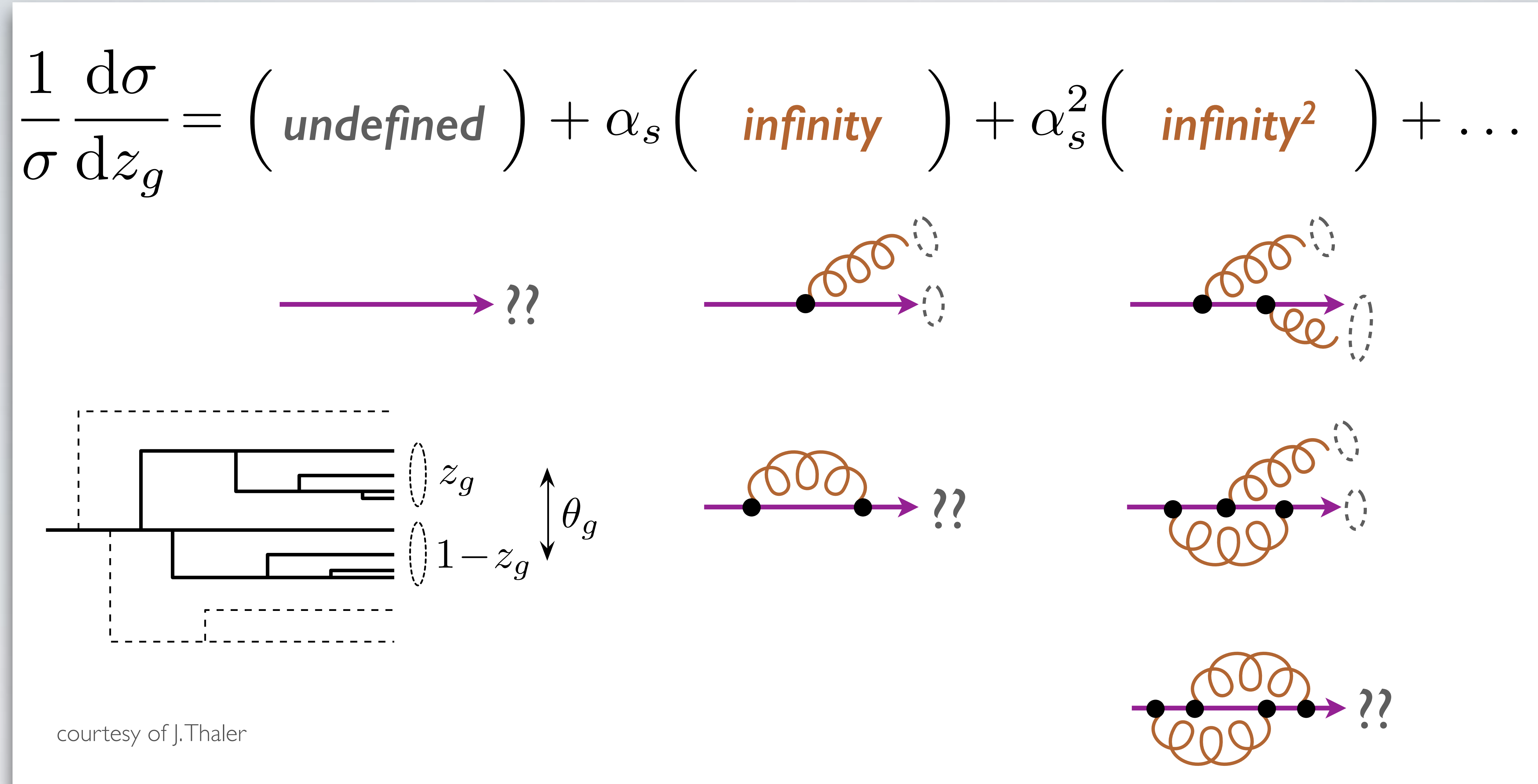
finite z_c effects



logs of z_c resummed

The prongs' momentum balance z_g

Momentum sharing z_g



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

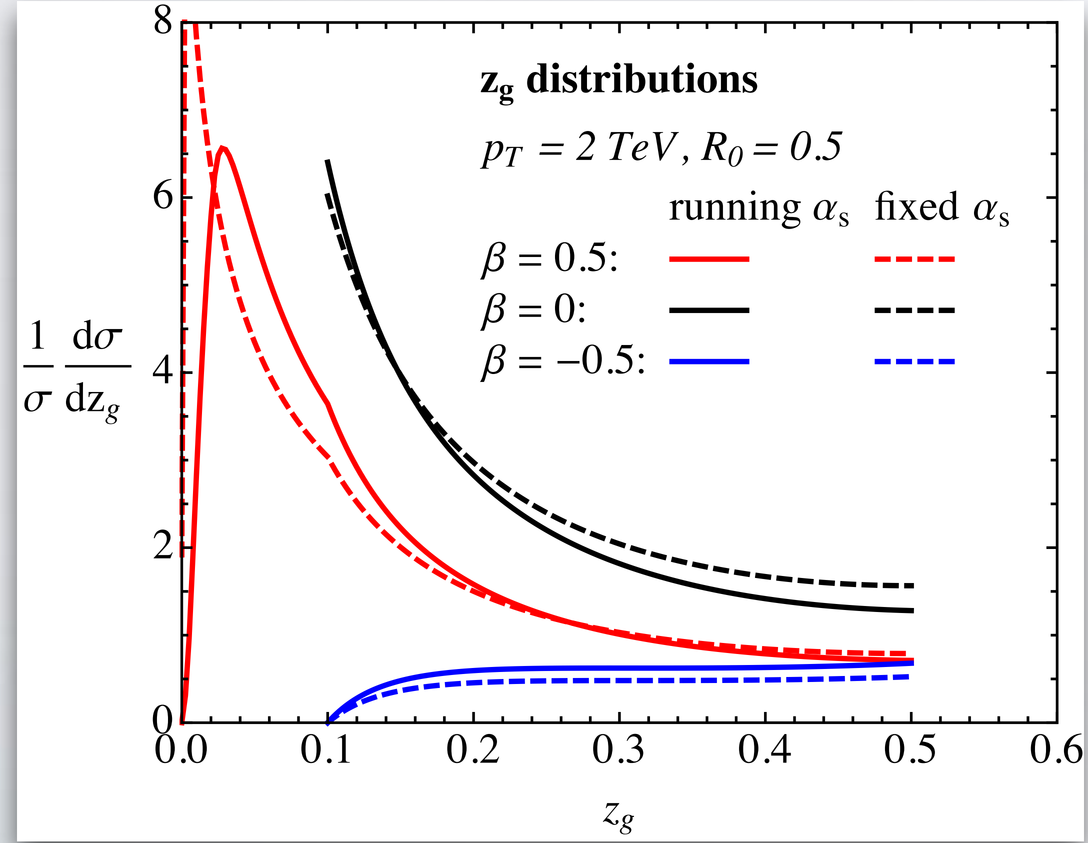
Sudakov safety

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

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



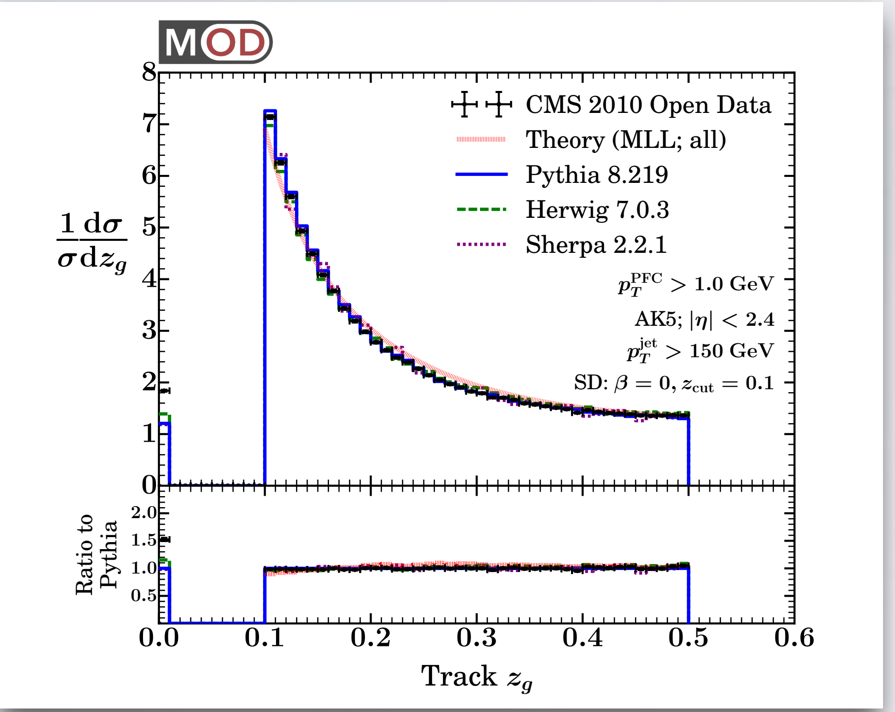
As β varies, we move from an IRC safe situation (β<0) to IRC unsafe (but Sudakov safe!) regime (β>0)

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

remarkable result at β=0

Measuring z_g

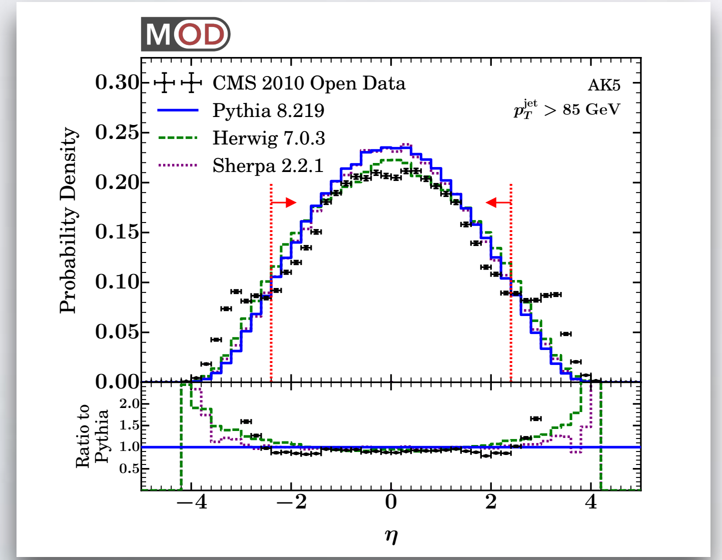
- exposes the QCD splitting function

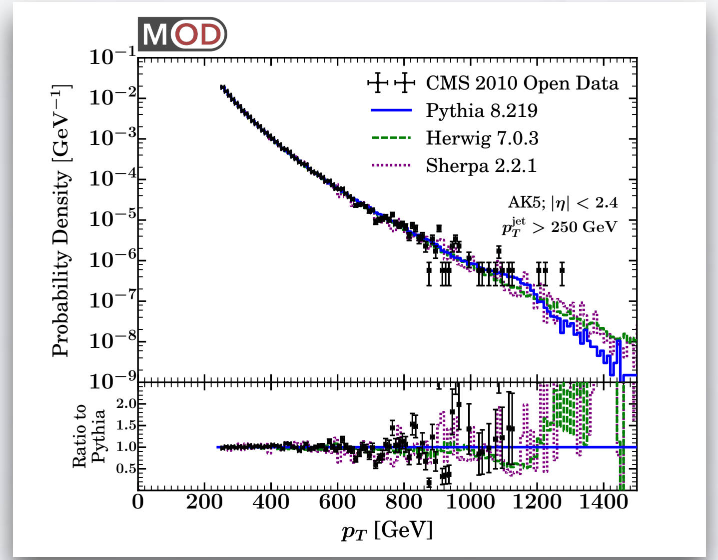


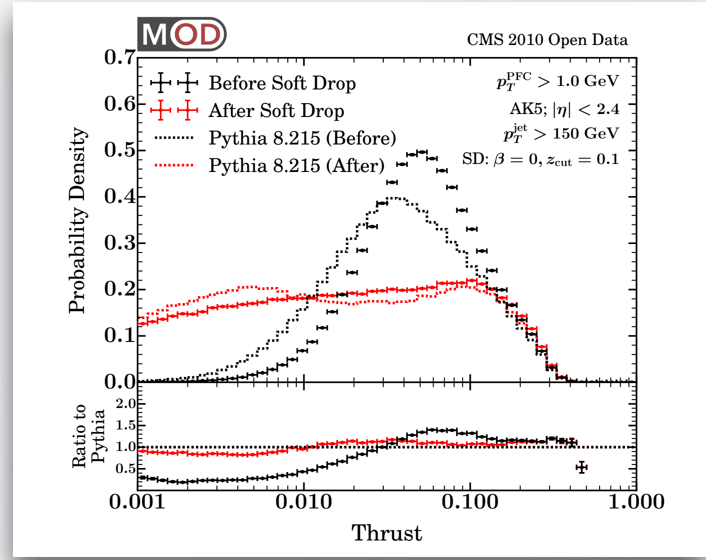
$$\frac{1}{\sigma}\frac{d\sigma}{dz_g} = \frac{\overline{P}_i(z_g)}{\int_{z_{\mathrm{cut}}}^{1/2} dz\, \overline{P}(z)}\Theta(z_g - z_{\mathrm{cut}}) + \mathcal{O}(\alpha_s)$$

Larkoski, SM, Thaler (2015)
Larkoski, SM, Thaler, Tripathee, Xue (2017)

- first research-level physics study that utilizes CMS Open Data





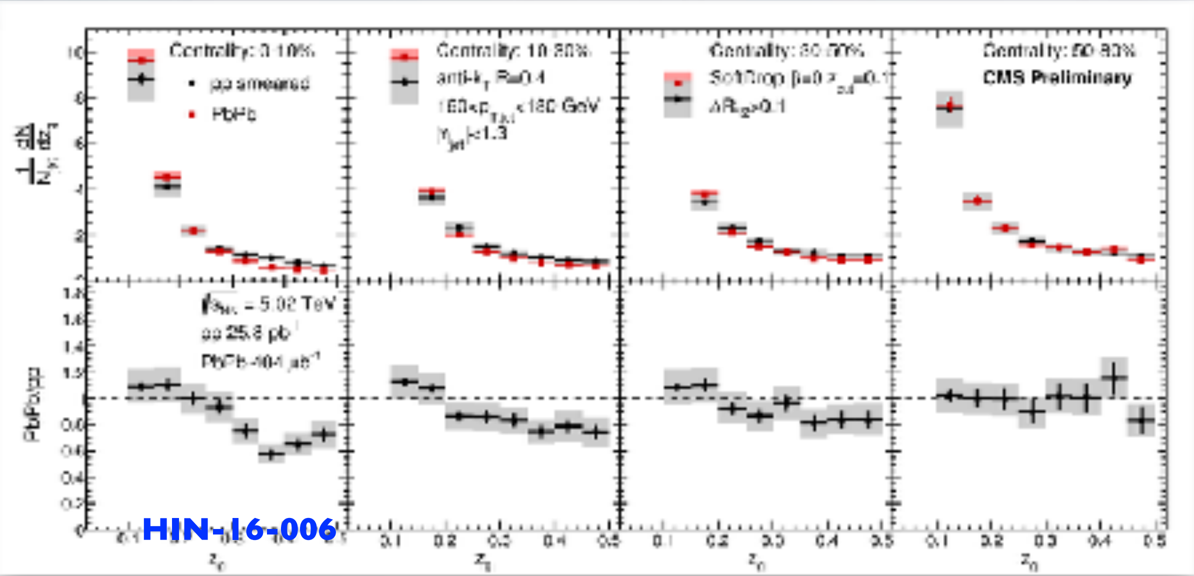


Tripathee, Xue, Larkoski, SM, Thaler (2017)

Heavy-ion applications

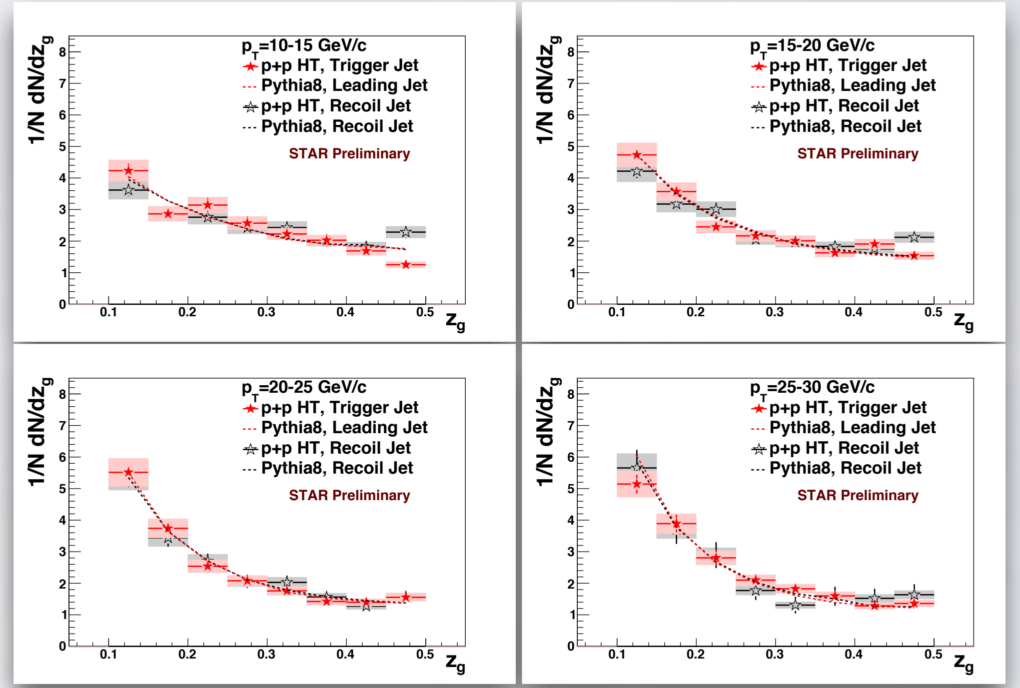
- now used as a probe for medium induced modification in heavy ion collisions

$$\mathcal{P}_{i\to jl}(x,k_\perp) = \mathcal{P}^{vac}_{i\to jl}(x,k_\perp) + \mathcal{P}^{med}_{i\to jl}(x,k_\perp)$$

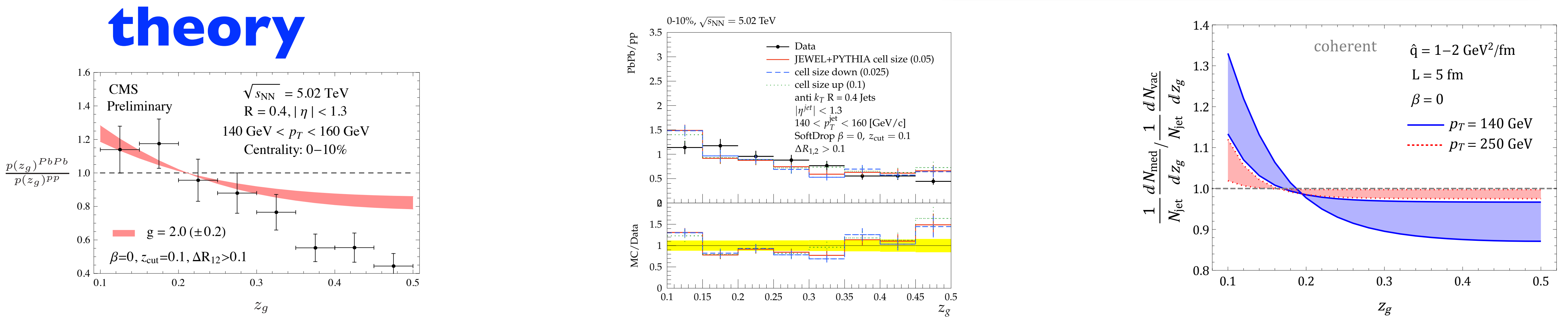


CMS Pb-Pb

STAR Au-Au



theory



Chien, Vitev (2016

Elayavalli (2016)

Mehtar-Tani, Tywoniuk (2016)

Summary

- Importance of substructure studies
- Soft drop: theoretical status and physics opportunities

Summary

- Importance of substructure studies
- Soft drop: theoretical status and physics opportunities

- Things I didn't have time to discuss:

  - quark / gluon discrimination

    Andersen *et al.* ``Les Houches 2015: Physics at TeV Colliders Standard Model Working Group Report", arXiv:1605.04692
    Gras *et al.* ``Systematics of quark/gluon tagging", arXiv:1704.03878
    Elder *et al.* ``Generalized Fragmentation Functions for Fractal Jet Observables", arXiv:1704.05456
    Frye *et al.* ``Casimir Meets Poisson: Improved Quark/Gluon Discrimination with Counting Observables", arXiv:1704.06266

    (note that *et al.* always includes Jesse Thaler!)

  - first-principle taggers:

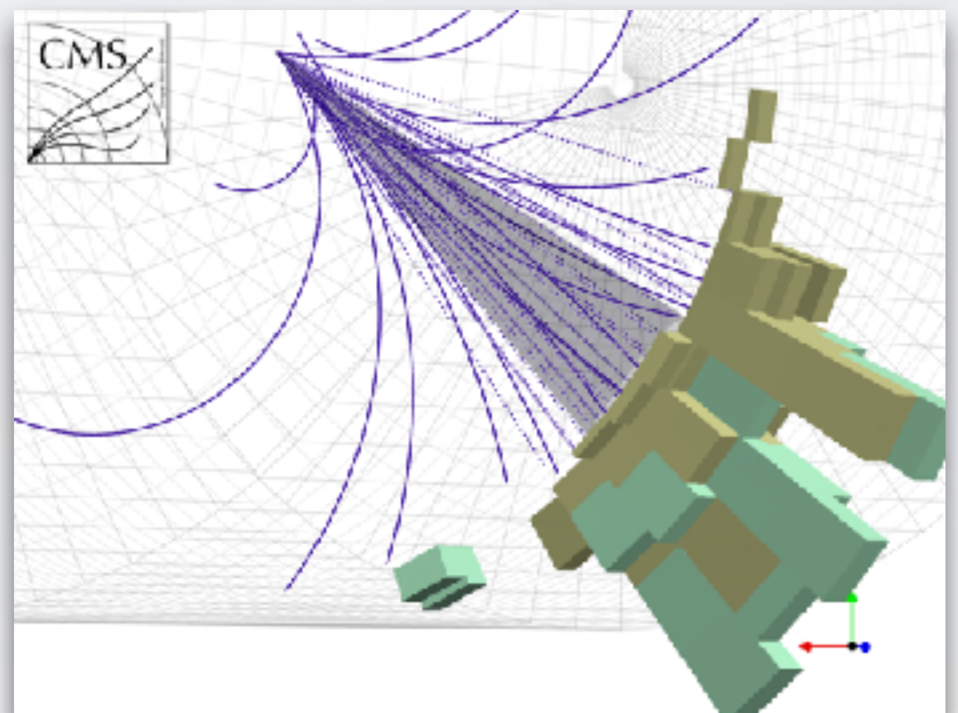
    Salam, Schunk, Soyez ``Dichroic subjettiness ratios to distinguish colour flows in boosted boson tagging", arXiv:1612.03917

  - machine learning (see Ben Nachman talk)

Jet substructure at LHC

more robust

deeper understanding
QCD, calculations, *etc.*



ideas, phenomenology,
MC simulations, *etc.*

more efficient

Jet substructure at LHC

more robust

deeper understanding
QCD, calculations, *etc.*

ideas, phenomenology,
MC simulations, *etc.*

more efficient

Thank you !