DISSECTING JETS

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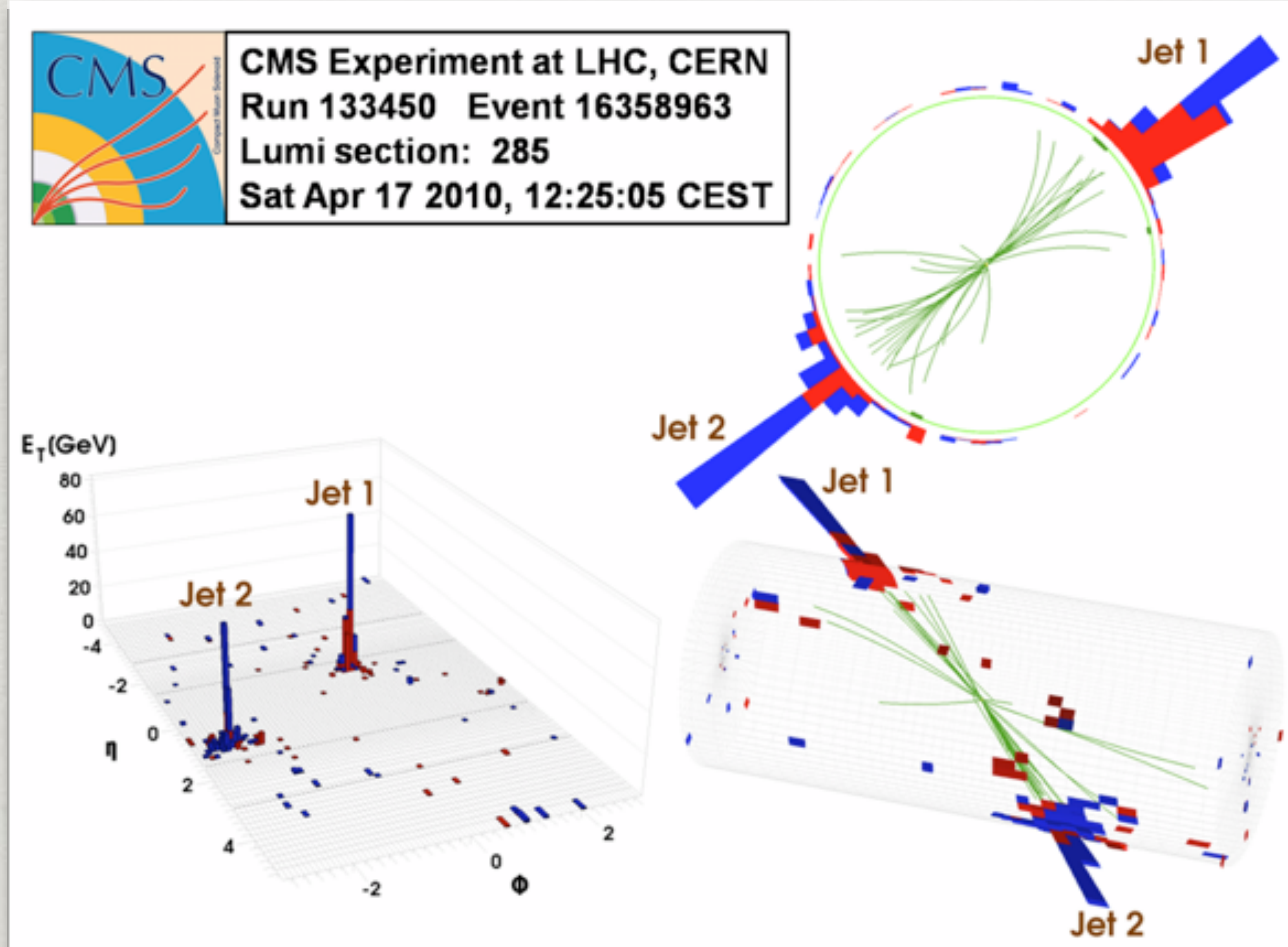
Outline

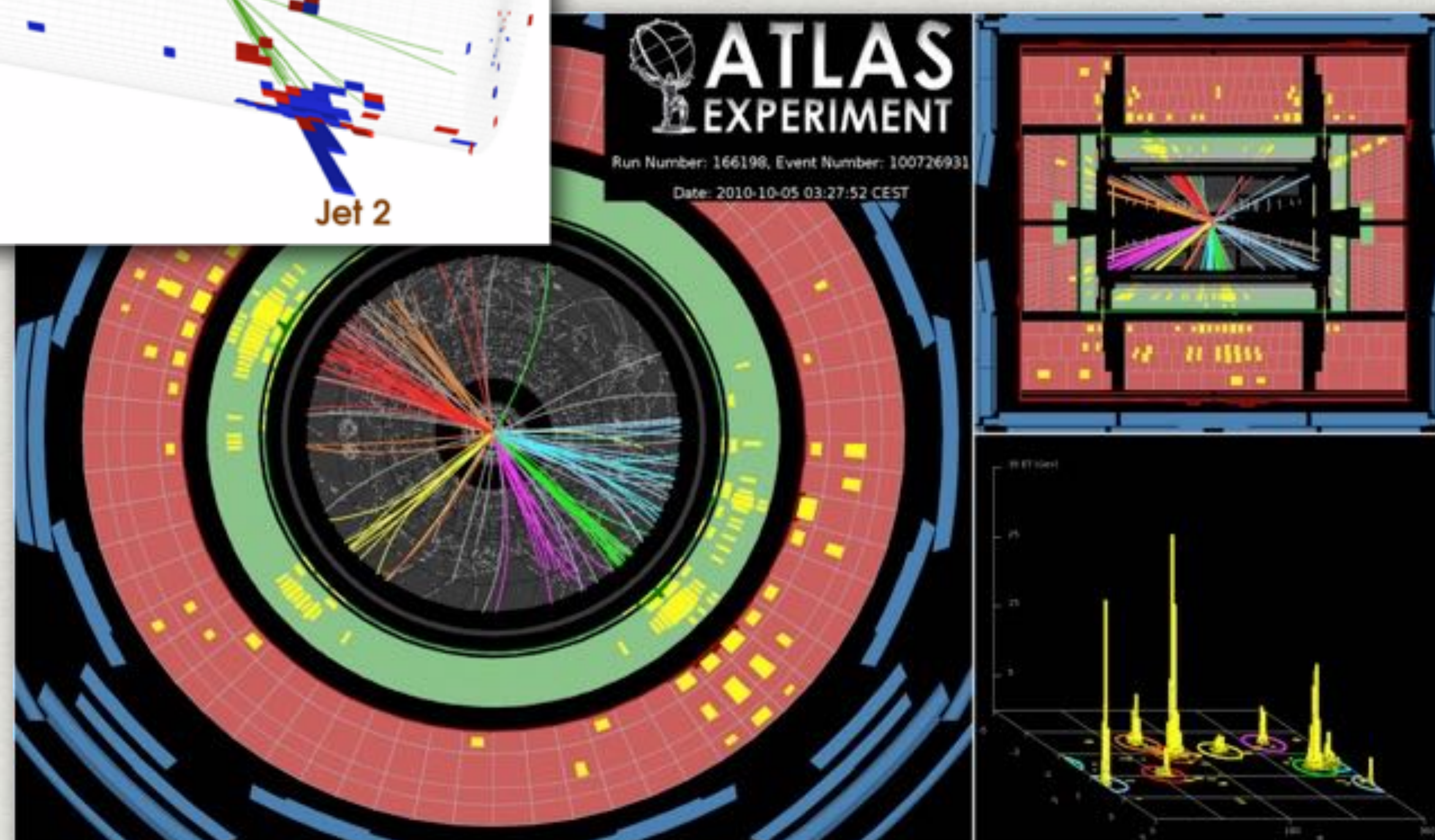
- An introduction to jet substructure
- Soft drop
- The groomed jet mass
- The prongs' momentum balance z_g
- Conclusions and Outlook

Jet substructure: an introduction



JETS

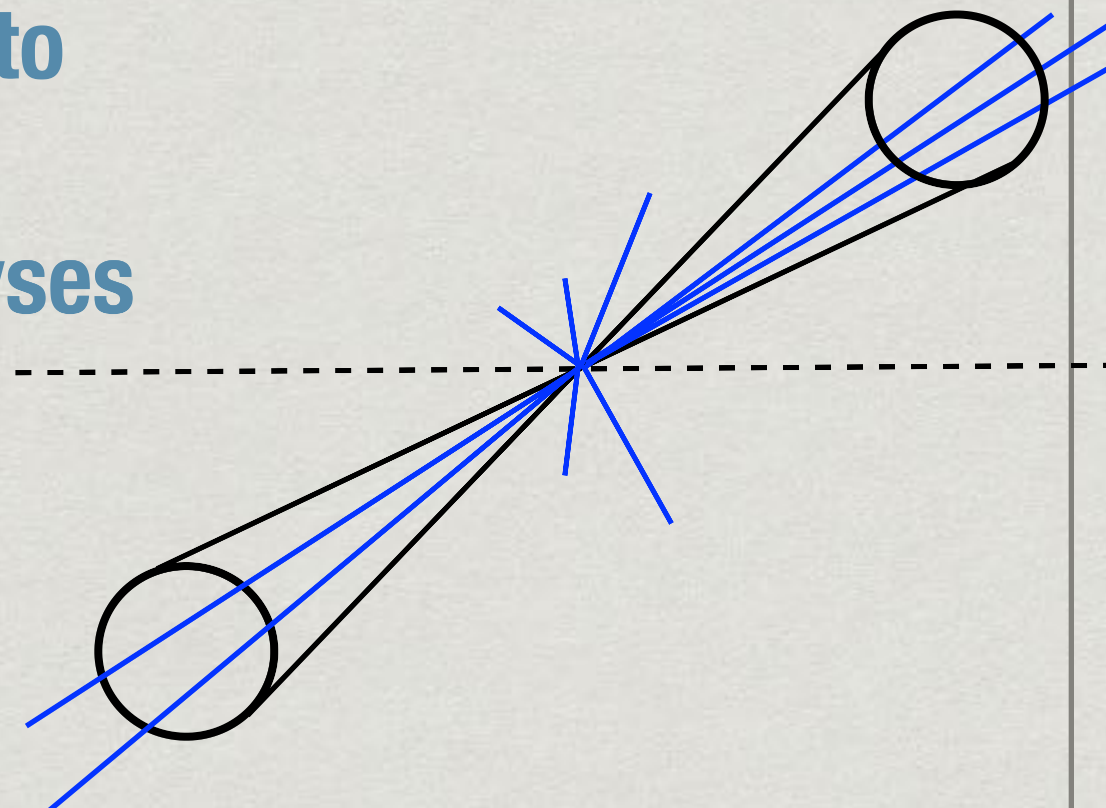
Collimated, energetic sprays of particles



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 $\sigma(E,\theta,\Omega,\varepsilon,\delta)$ 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):

5

Aside: IRC safety

For an observable's distribution to be calculable in [fixed-order] perturbation theory, the observable should be infra-red safe, i.e. insensitive to the emission of soft or collinear gluons. In particular if $\vec{p}_i$ is any momentum occurring in its definition, it must be invariant under the branching

$$\vec{p}_i \rightarrow \vec{p}_j + \vec{p}_k$$

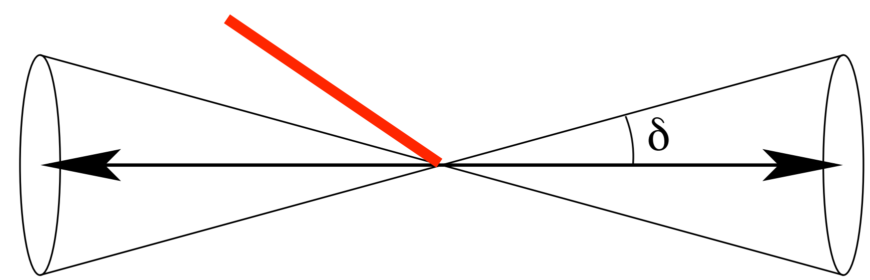
whenever $\vec{p}_j$ and $\vec{p}_k$ are parallel [collinear] or one of them is small [infrared]. [QCD and Collider Physics (Ellis, Stirling & Webber)]

Sterman-Weinberg jet definition

- **in soft or collinear limit the Θ-functions disappear**
- **R-V cancellation occurs leading to a finite cross-section: IRC safety**

The *original* (finite) jet definition

An event has 2 jets if at least a fraction $(1-\epsilon)$ of event energy is contained in two cones of half-angle δ.



subtract 3-jet component

$$\sigma_{2-jet} = \sigma_{q\bar{q}}\left[1 + \frac{2\alpha_s C_F}{\pi}\int \frac{dE}{E}\frac{d\theta}{\theta}\left(R\left(\frac{E}{Q},\theta\right)\right.\right.$$
$$\left.\left.\times\left(1 - \Theta\left(E-\epsilon Q\right)\Theta\left(\theta-\delta\right)\right) - V\left(\frac{E}{Q},\theta\right)\right)\right]$$

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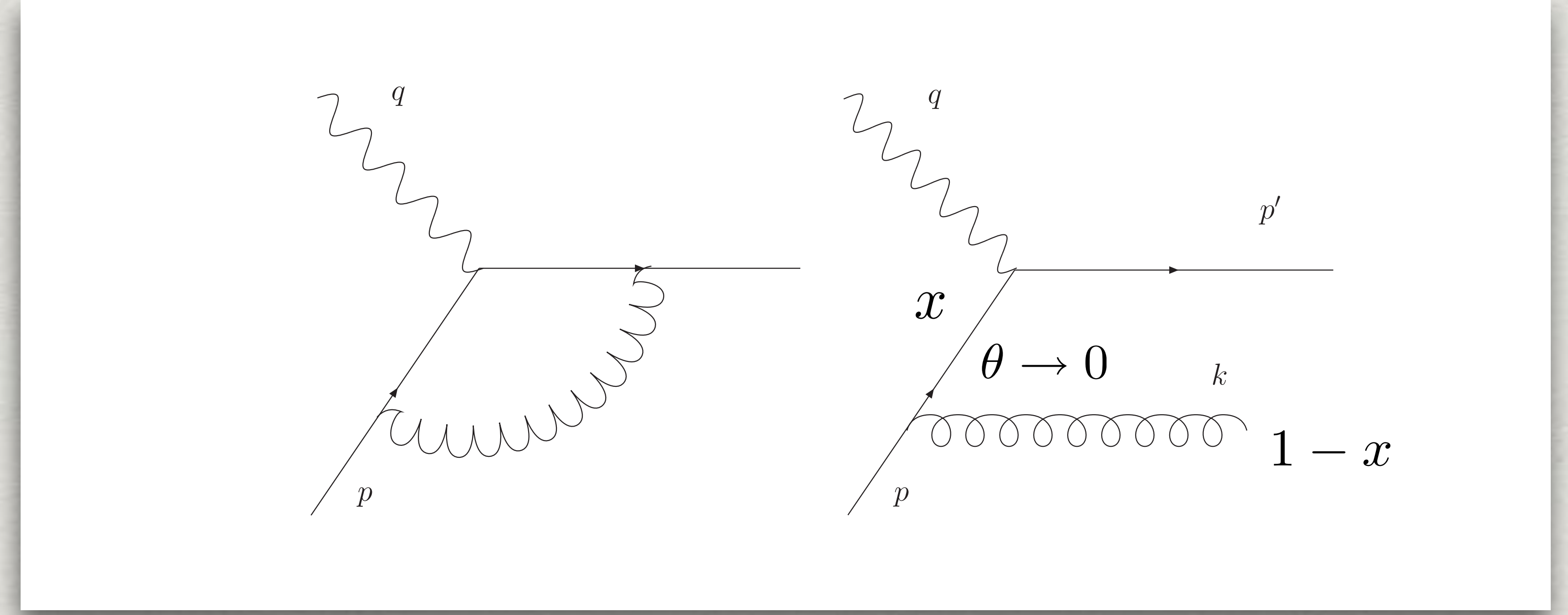
Partonic cross-sections

- in soft or collinear limit the Θ-functions disappear
- R-V cancellation occurs leading to a finite cross-section: IRC safety



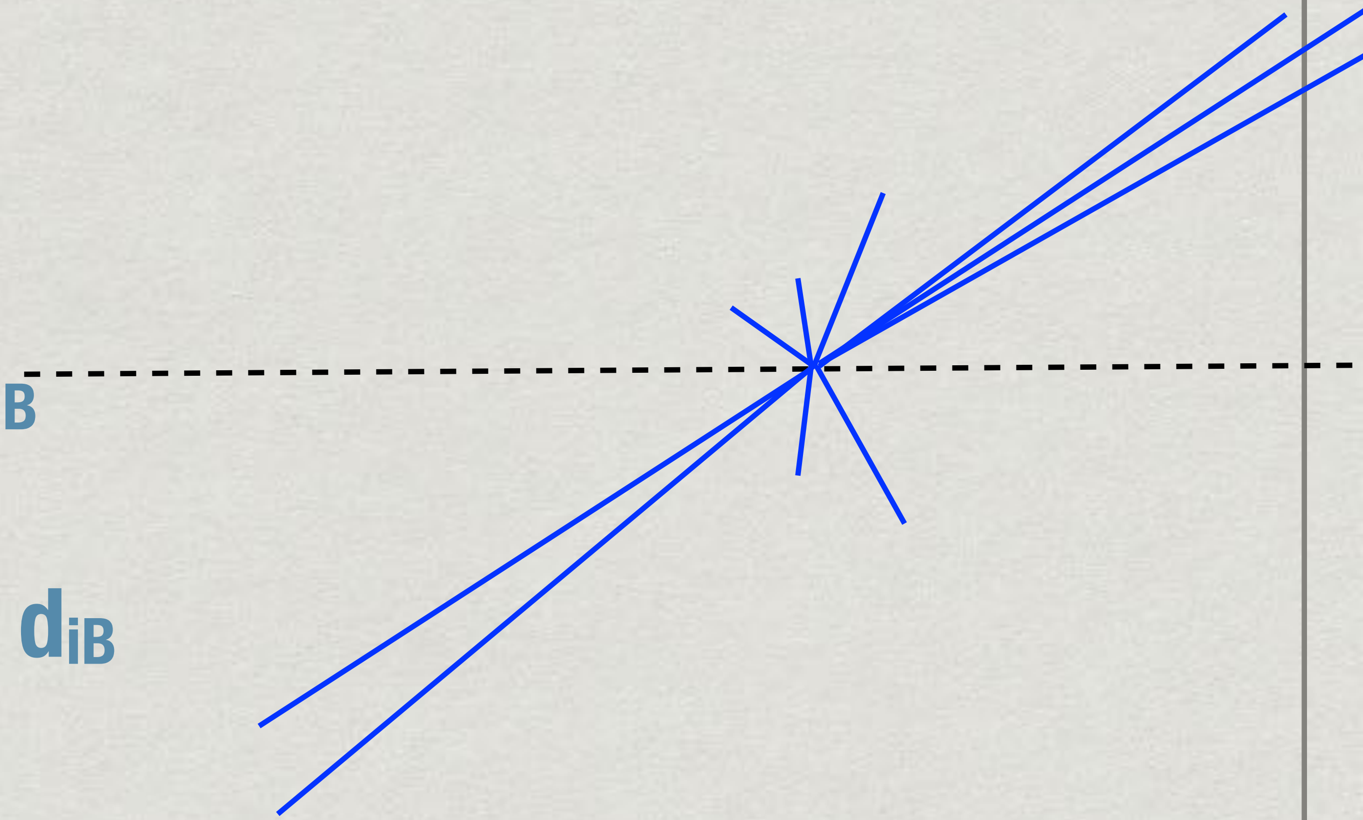
- IRC unsafe example: partonic x-sections
- an arbitrary collinear emission carries away momentum fraction 1-x
- collinear divergencies absorbed by pdfs

$$\hat{\sigma} = \sigma_0 \left[\delta(1-x) + \frac{\alpha_s}{\pi} \left(\int \frac{d\theta}{\theta} \left(P(x) + K\delta(1-x)\right) + C(x) \right) \right]$$

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

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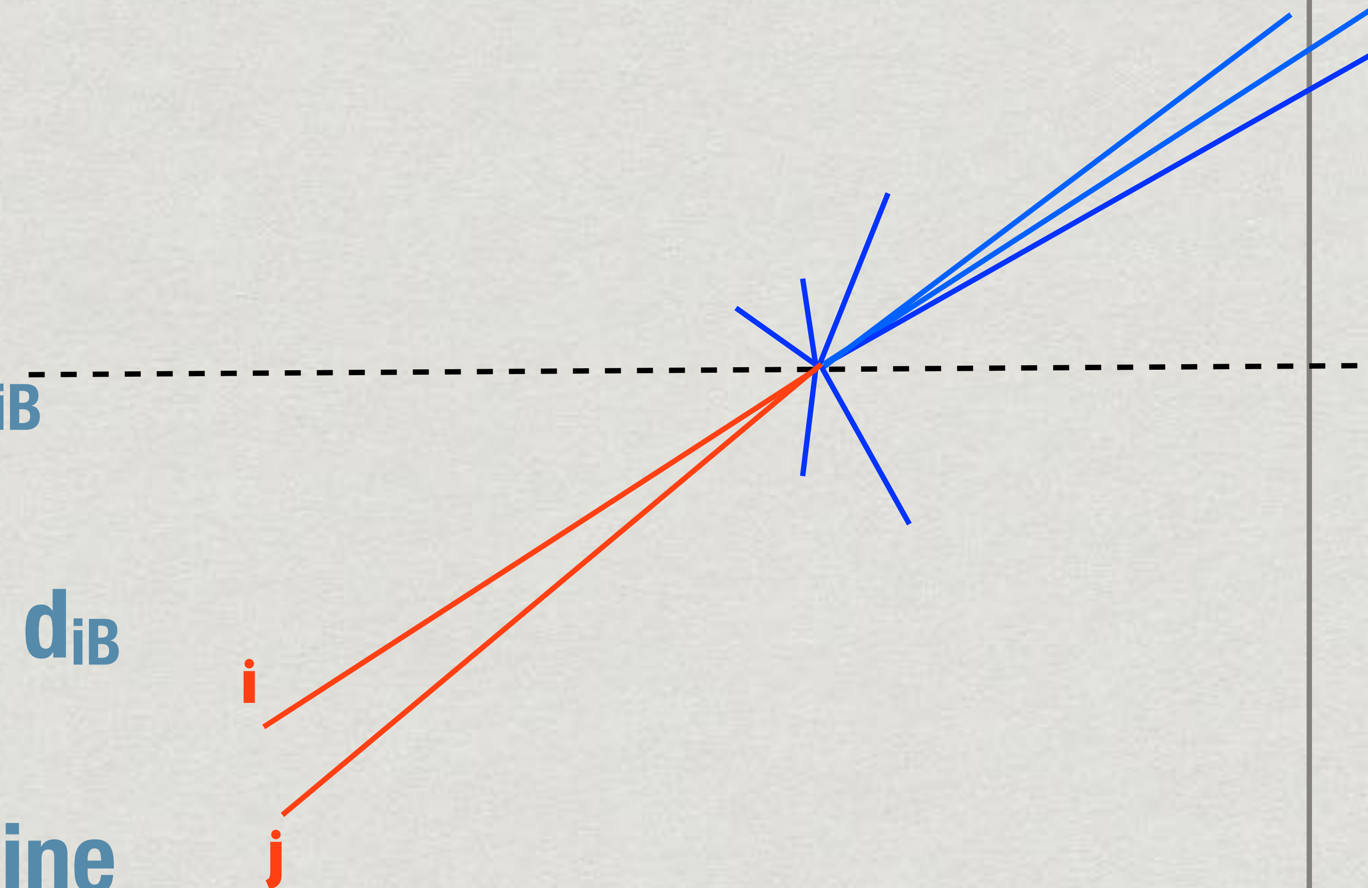

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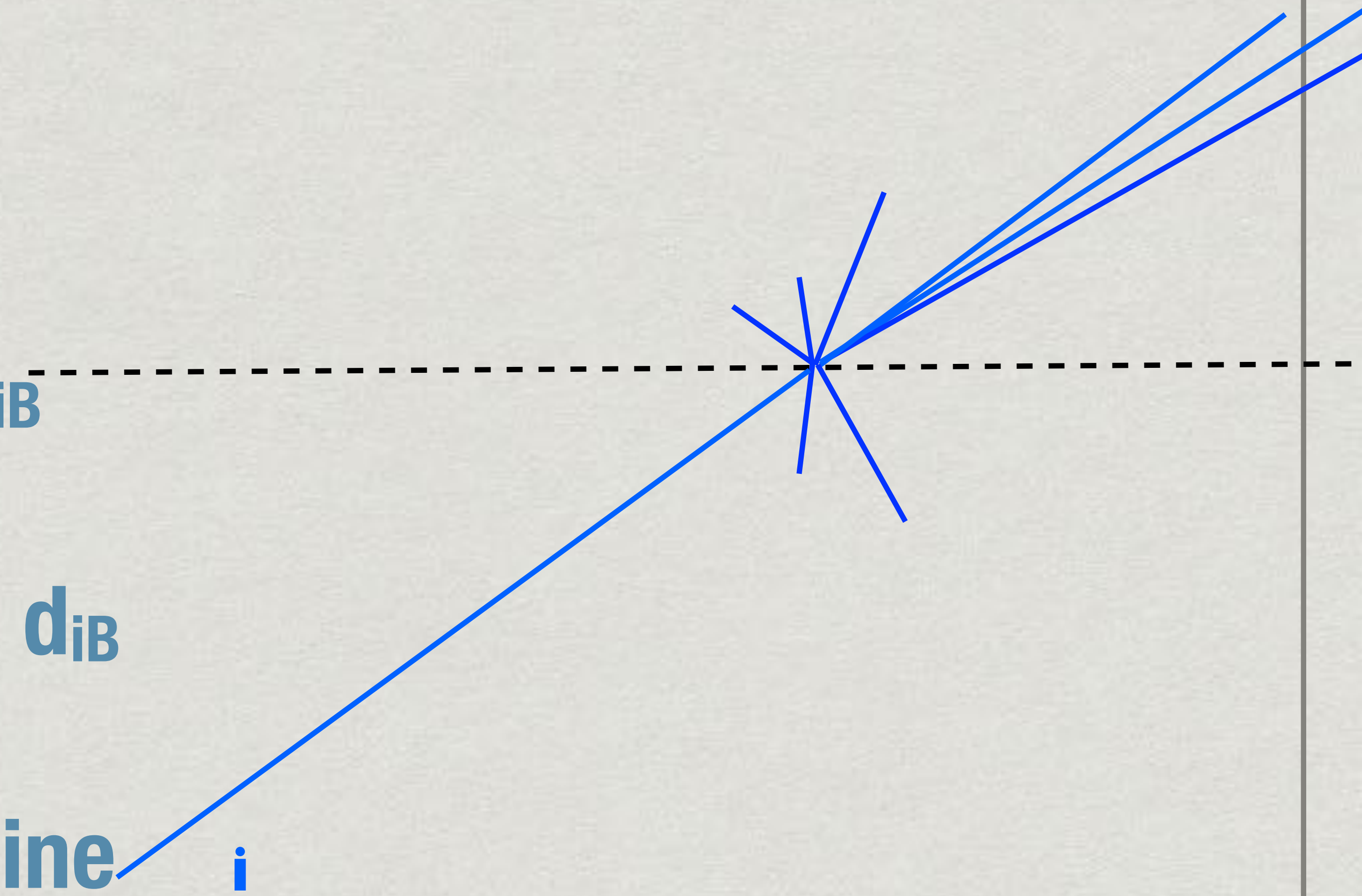

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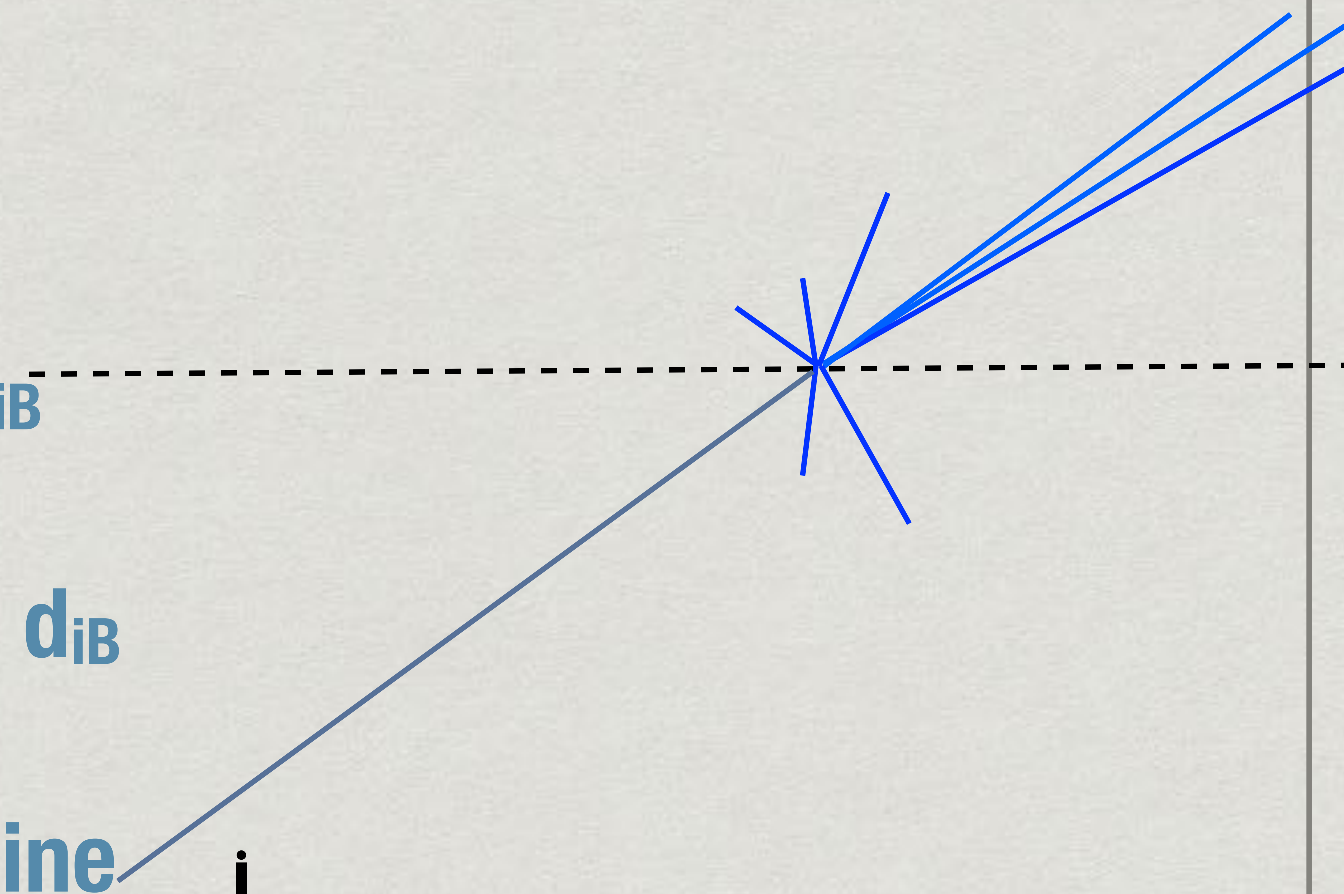
Sequential recombination

- 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

Most common jet algorithms

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

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

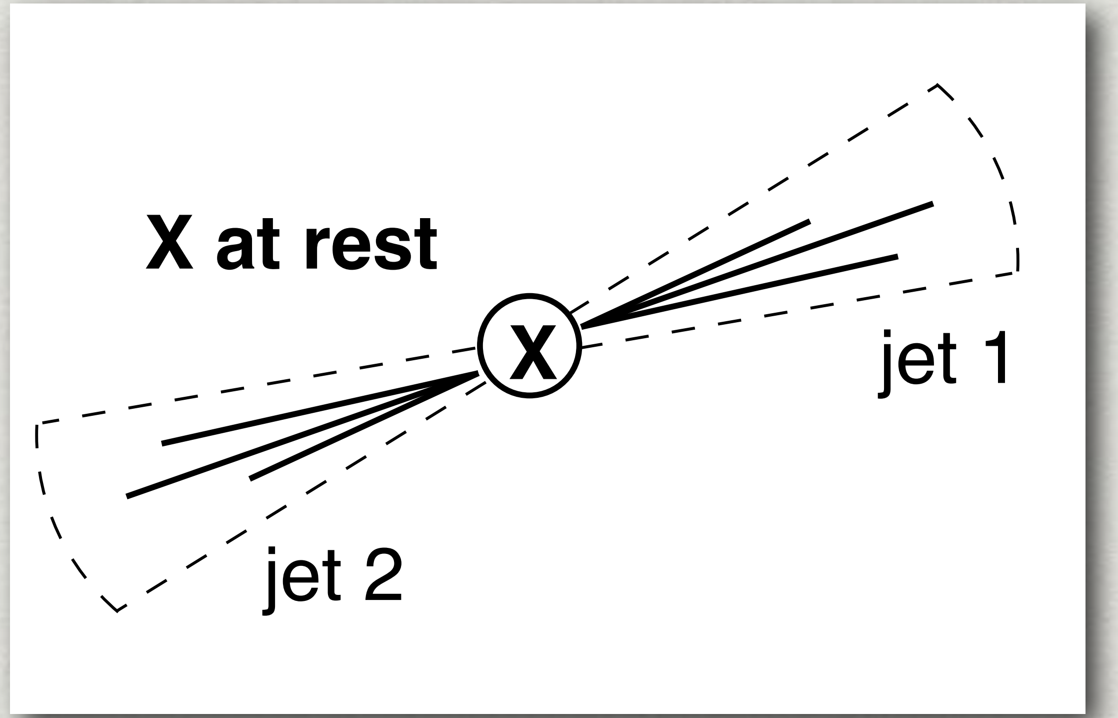
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

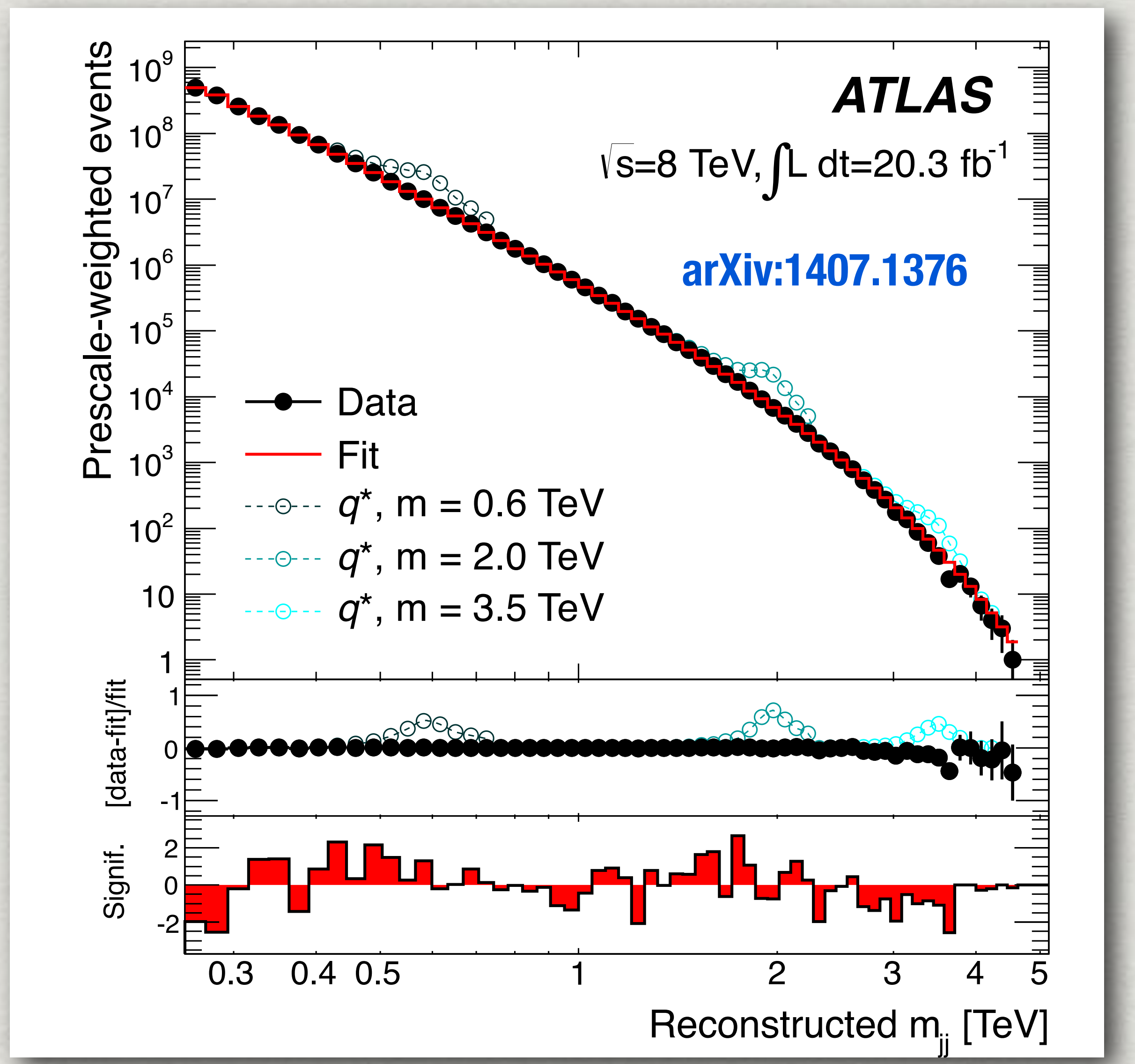
p = 1 k_t algortihm
(Catani *et al.*, Ellis and Soper)
p = 0 Cambridge / Aachen
(Dokshitzer *et al.*, Wobish and Wengler)
p = -1 anti-k_t algorithm
(Cacciari, Salam, Soyez)

- **Different algorithms serve different purposes**
- **Anti-k_t clusters around hard particles giving round jets (default choice for ATLAS and CMS)**
- **Anti-k_t is less useful for substructure studies, while k_t & C/A reflect the structure of QCD matrix elements**

Searching for new particles: resolved analyses

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



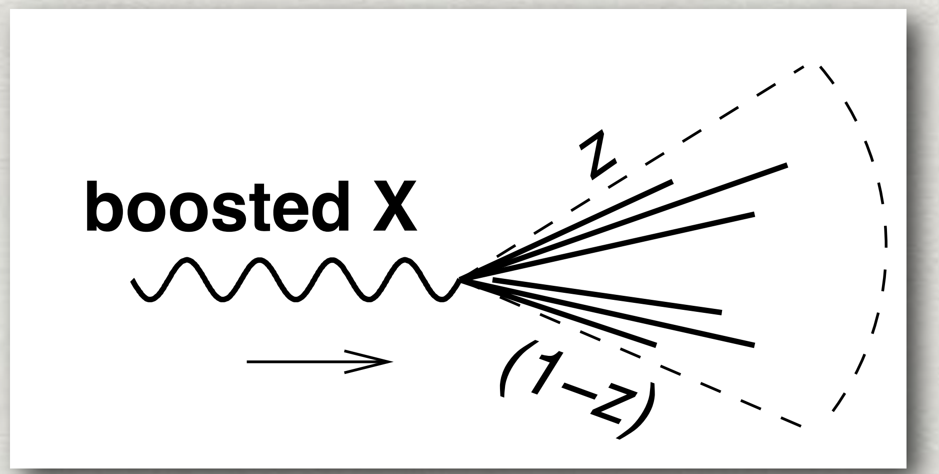


- look for bumps in the dijet invariant mass distribution

Searching for new particles: boosted analyses

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

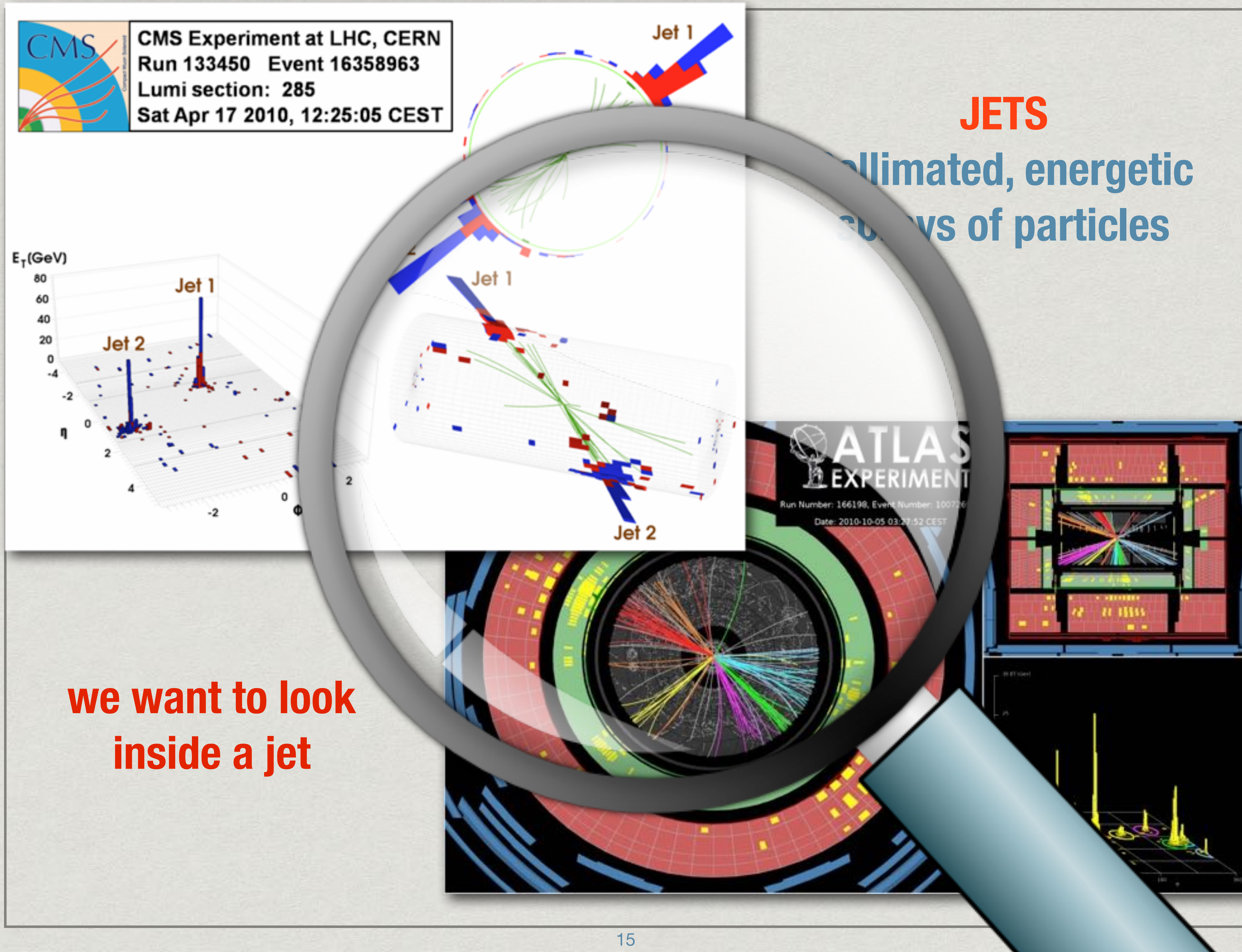
- EW-scale particles (new physics, Z/W/H/top) are abundantly produced with a large boost



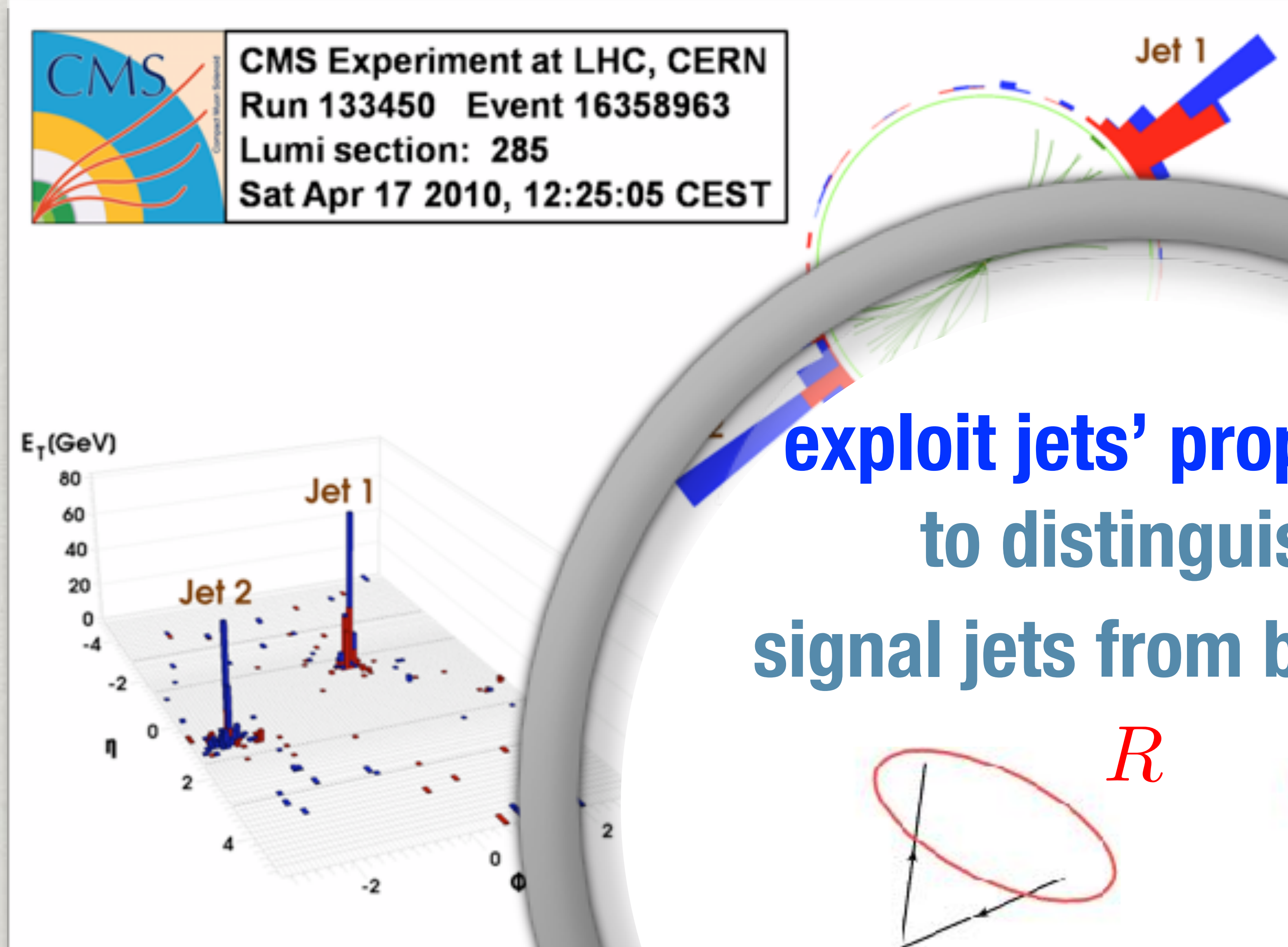
- their decay-products are then collimated
- if they decay into hadrons, we end up with localized deposition of energy in the hadronic calorimeter: a jet

JETS

collimated, energetic sprays of particles



we want to look inside a jet



JETS

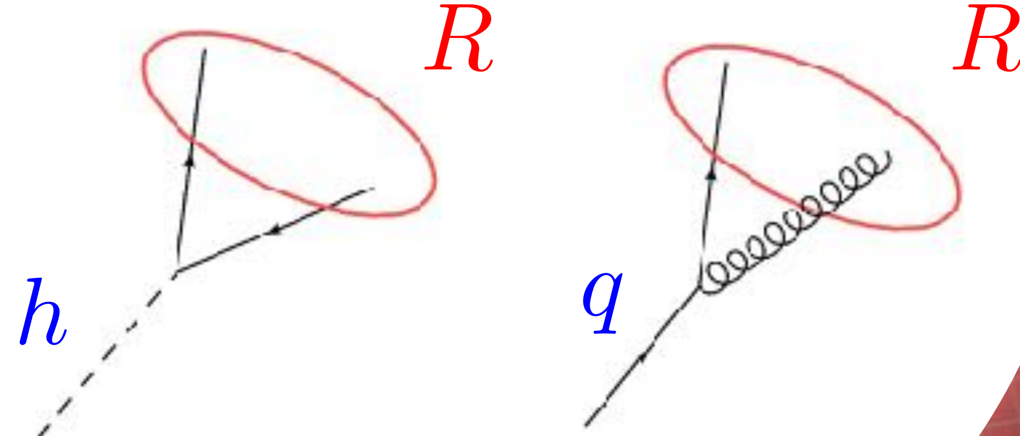
llimated, energetic

ys of particles

exploit jets' properties

to distinguish

signal jets from bkg jets

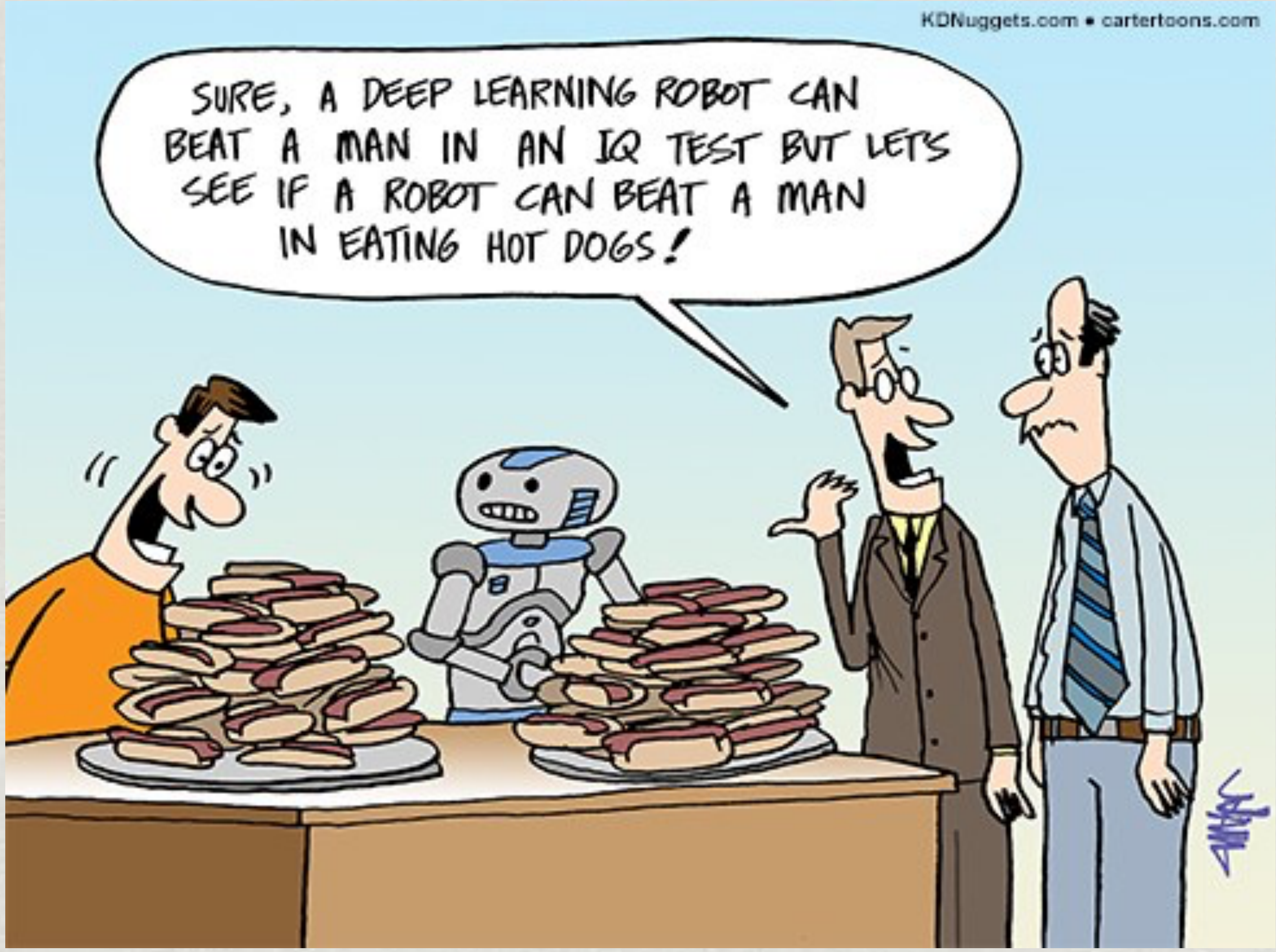


$$p_t > 2m/R$$

we want to look inside a jet

Humans vs machines

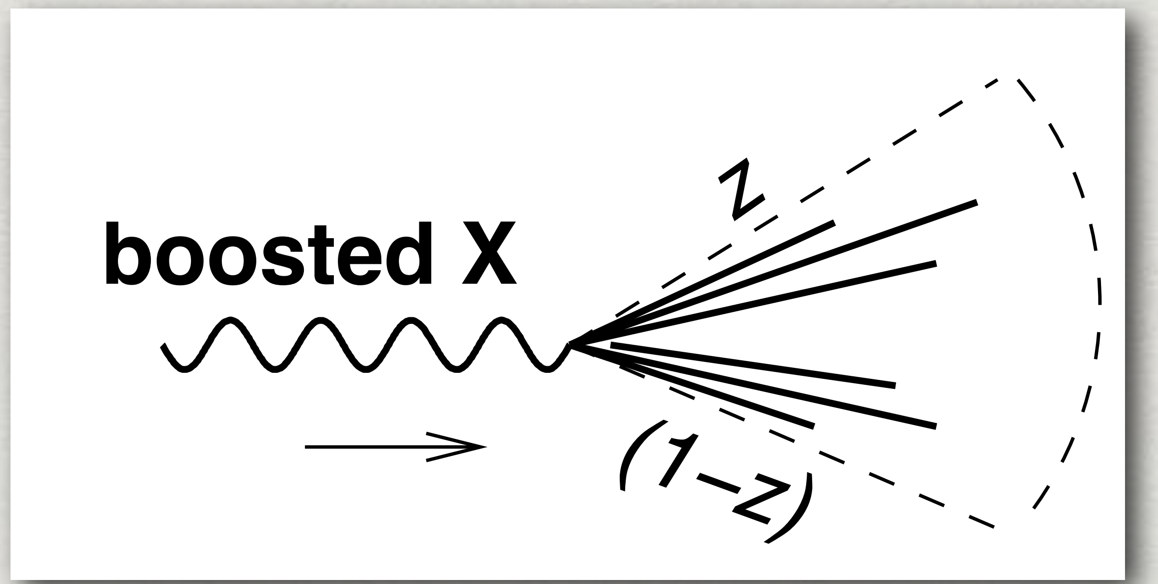
- Jet physics (and particle physics!) undergoing a revolution
- ideas / techniques from machine (deep) learning continuously poured into the field
- I had to make a choice: will concentrate on humans for this talk



- **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?

The jet invariant mass

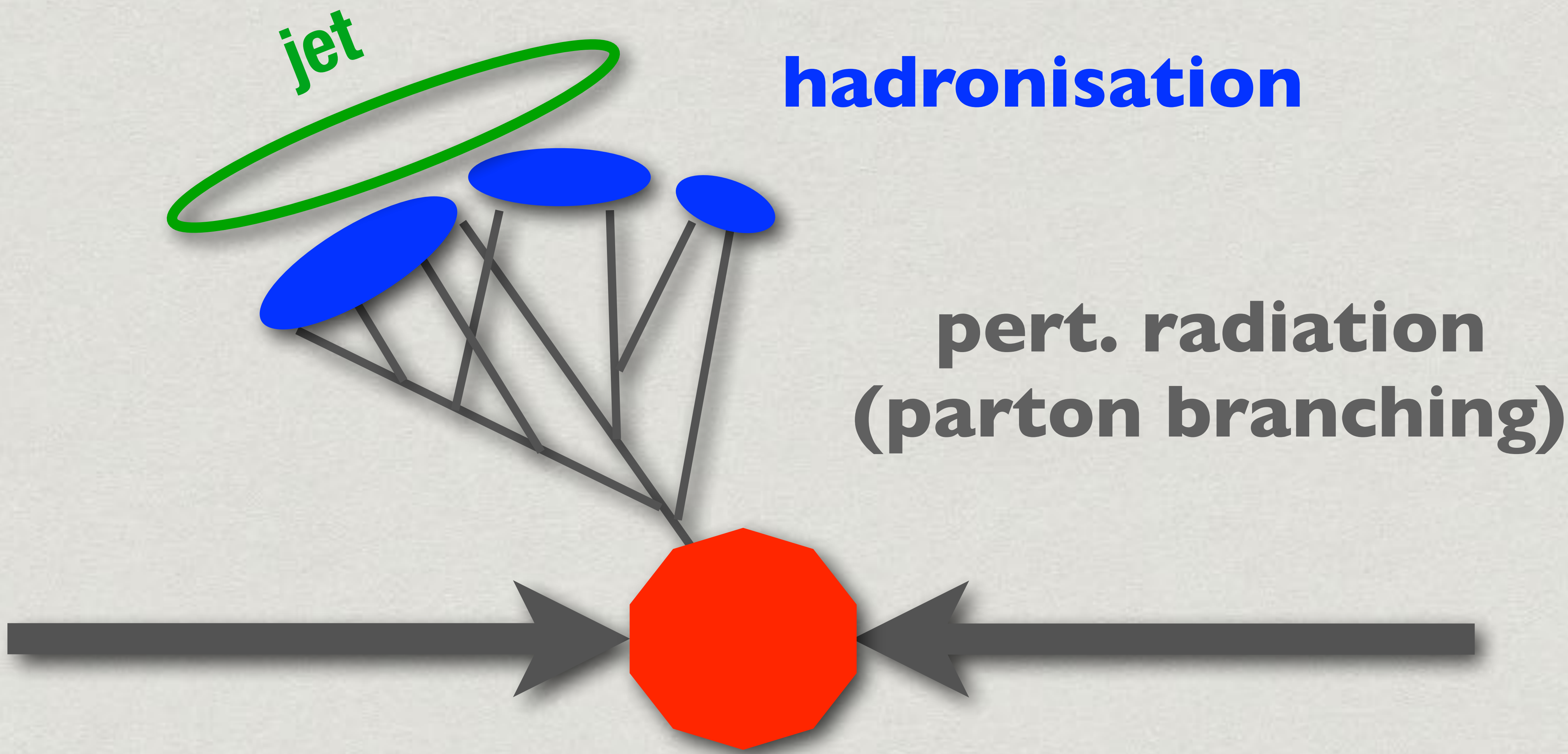
- First jet-observable that comes to mind
- Signal jet should have a mass distribution peaked near the resonance



- However, that's a simple partonic picture

A useful cartoon

inspired by G. Salam



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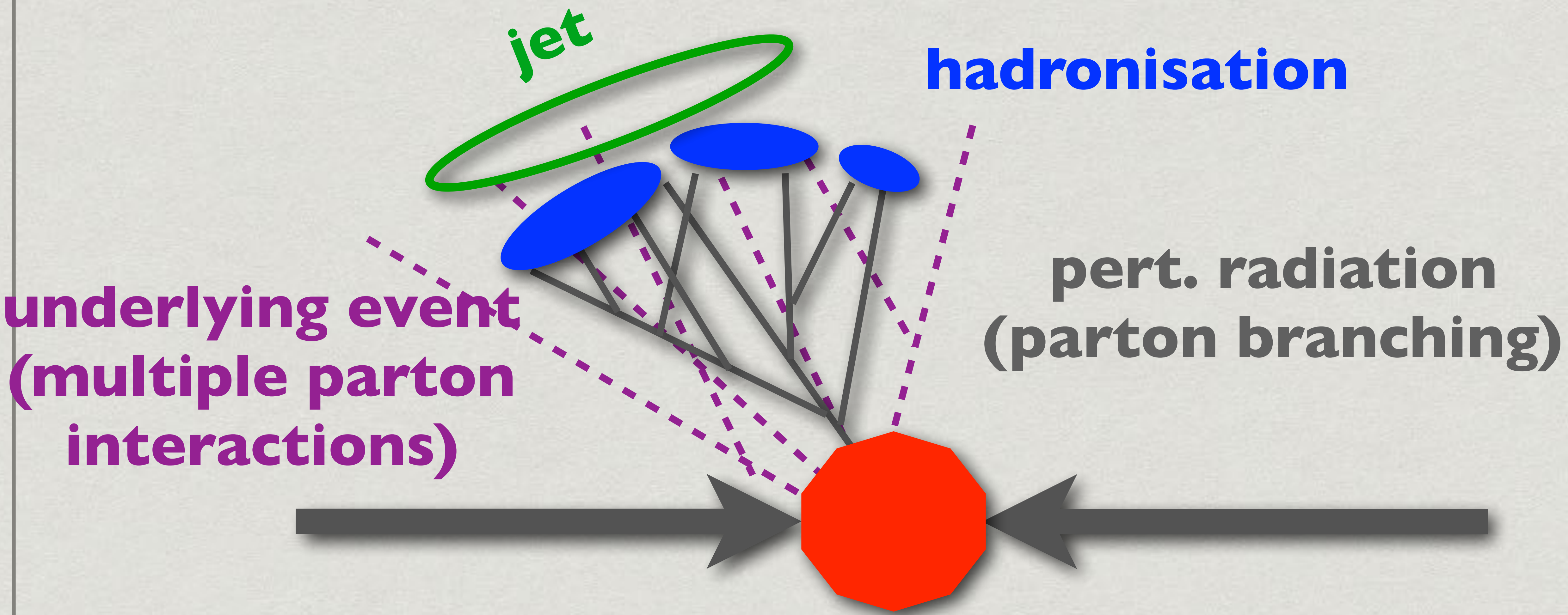

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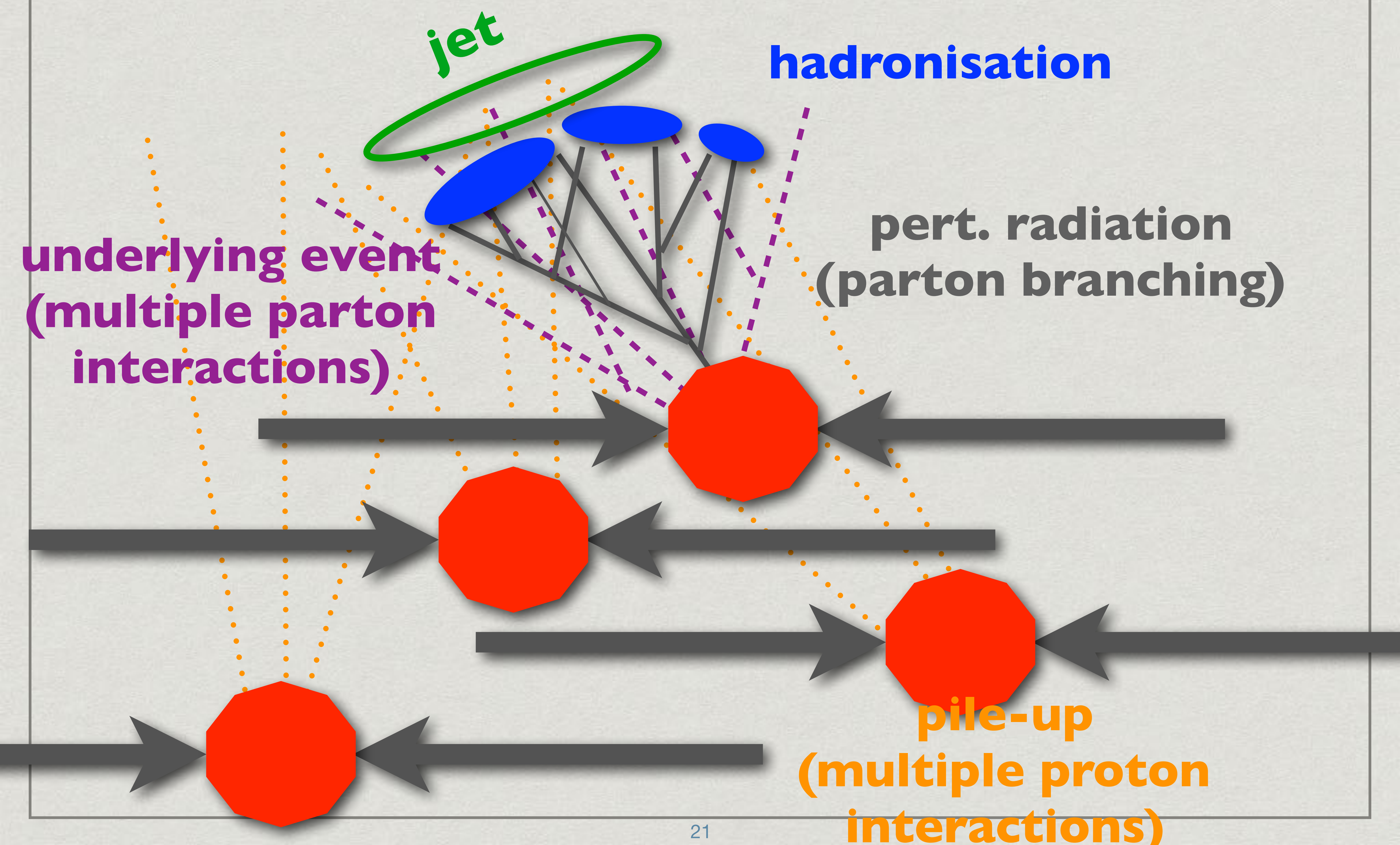
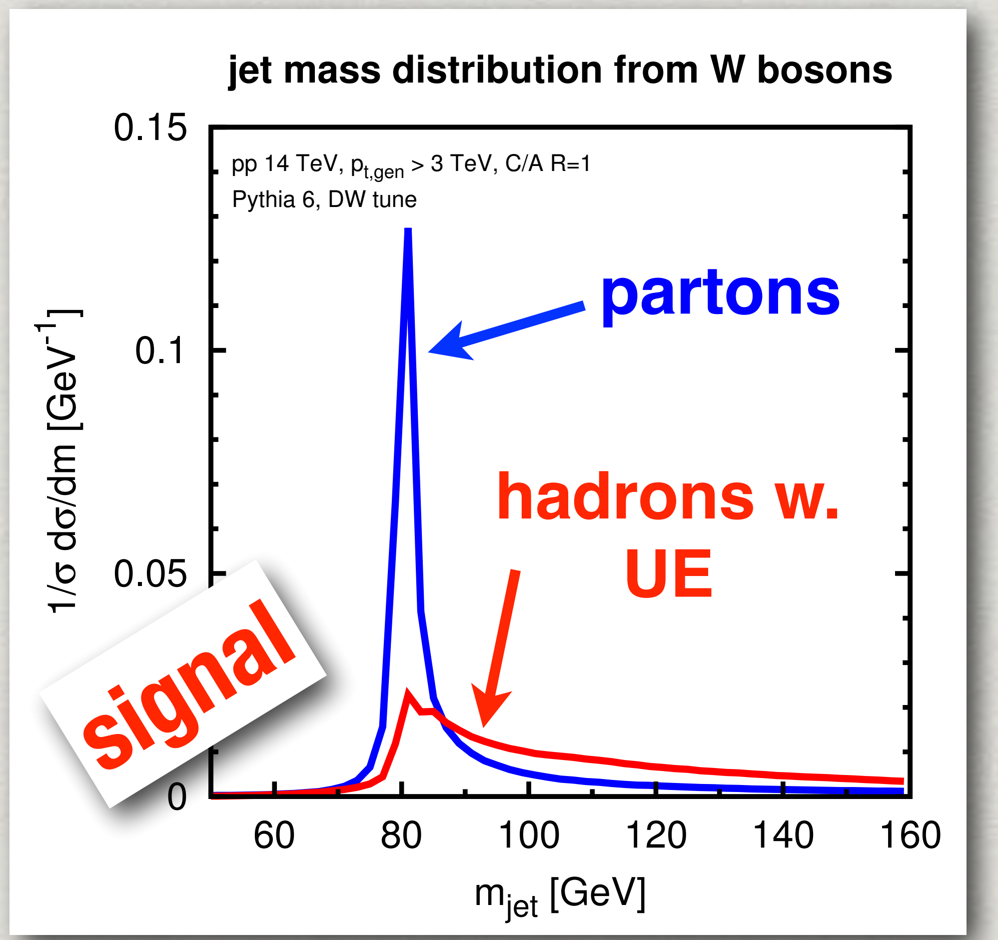
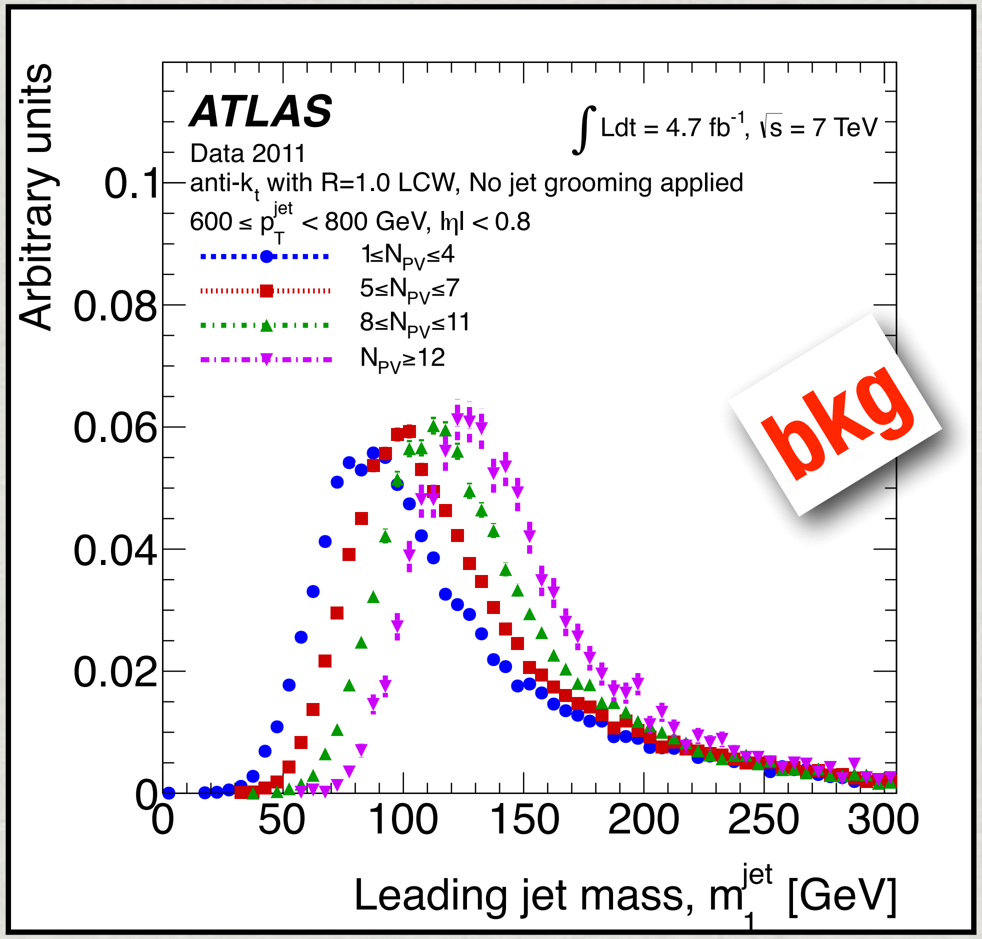


Effect on jet masses

- 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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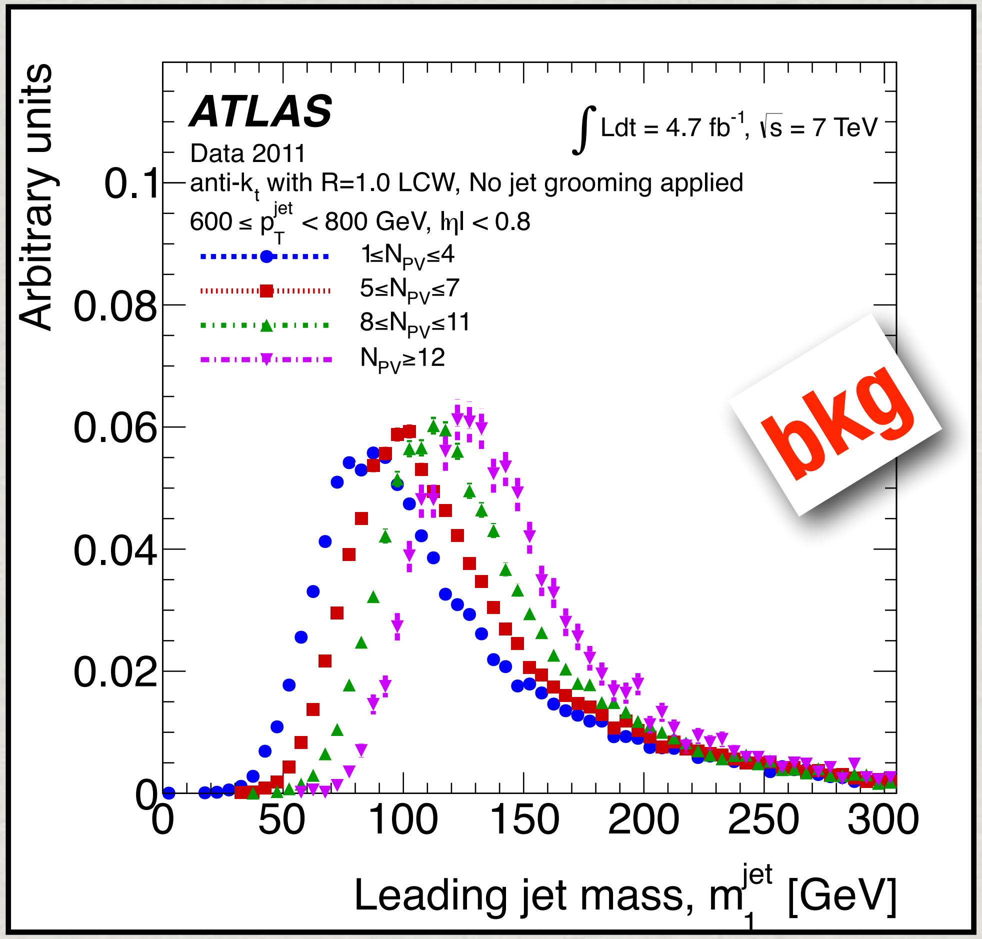

Beyond the mass: substructure

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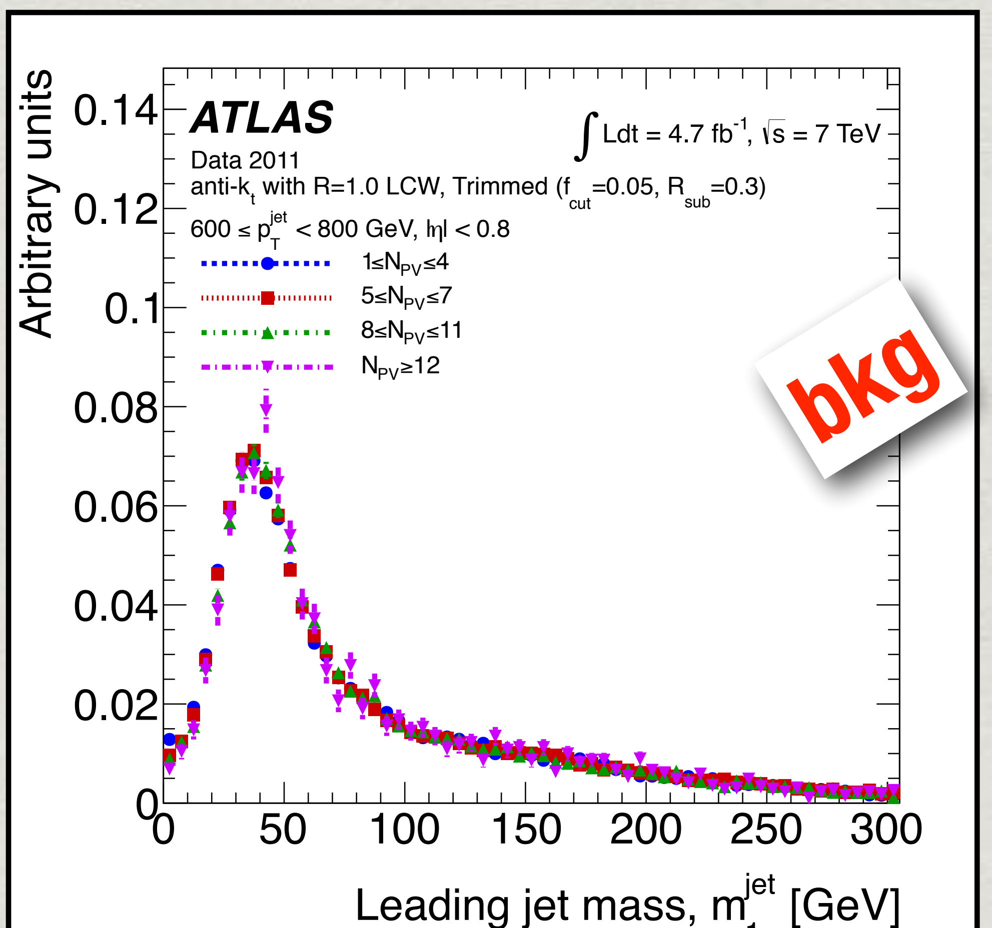
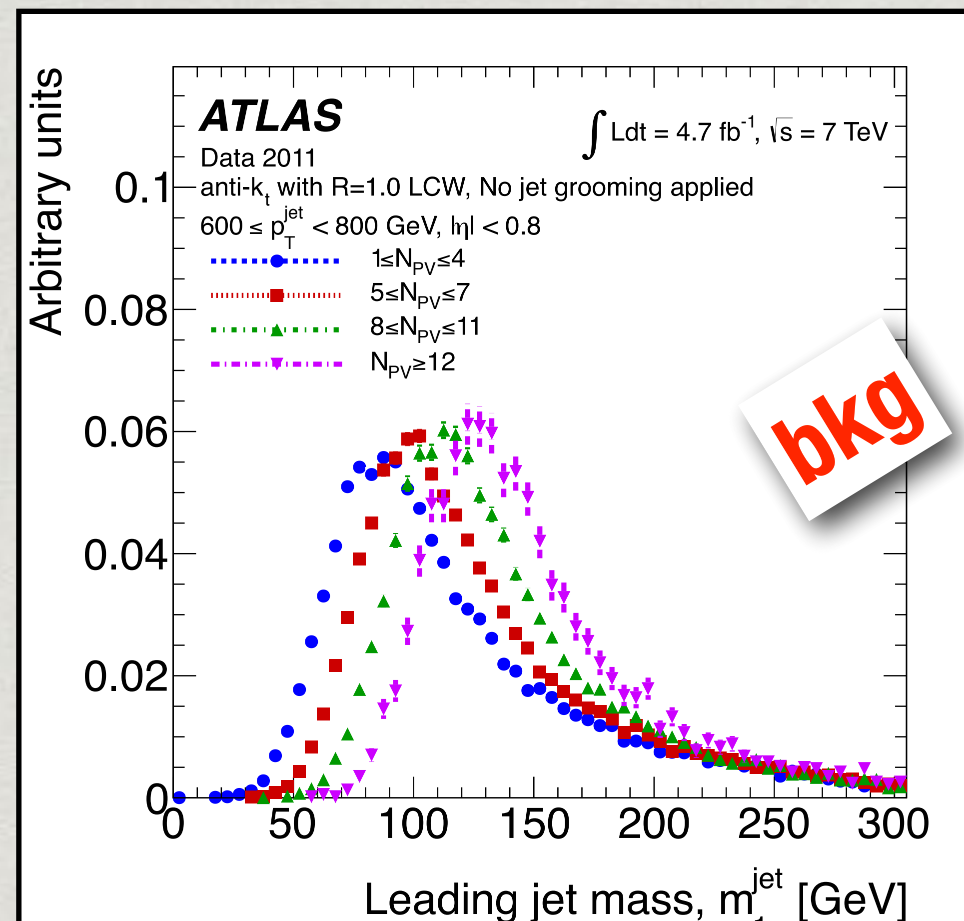
- Need to go beyond the mass and exploit jet substructure
- **Grooming** and **Tagging**:
  1. clean the jets up by removing soft junk
  2. identify the features of hard decays and cut on them
- Grooming provides a handle on UE and pile-up



grooming

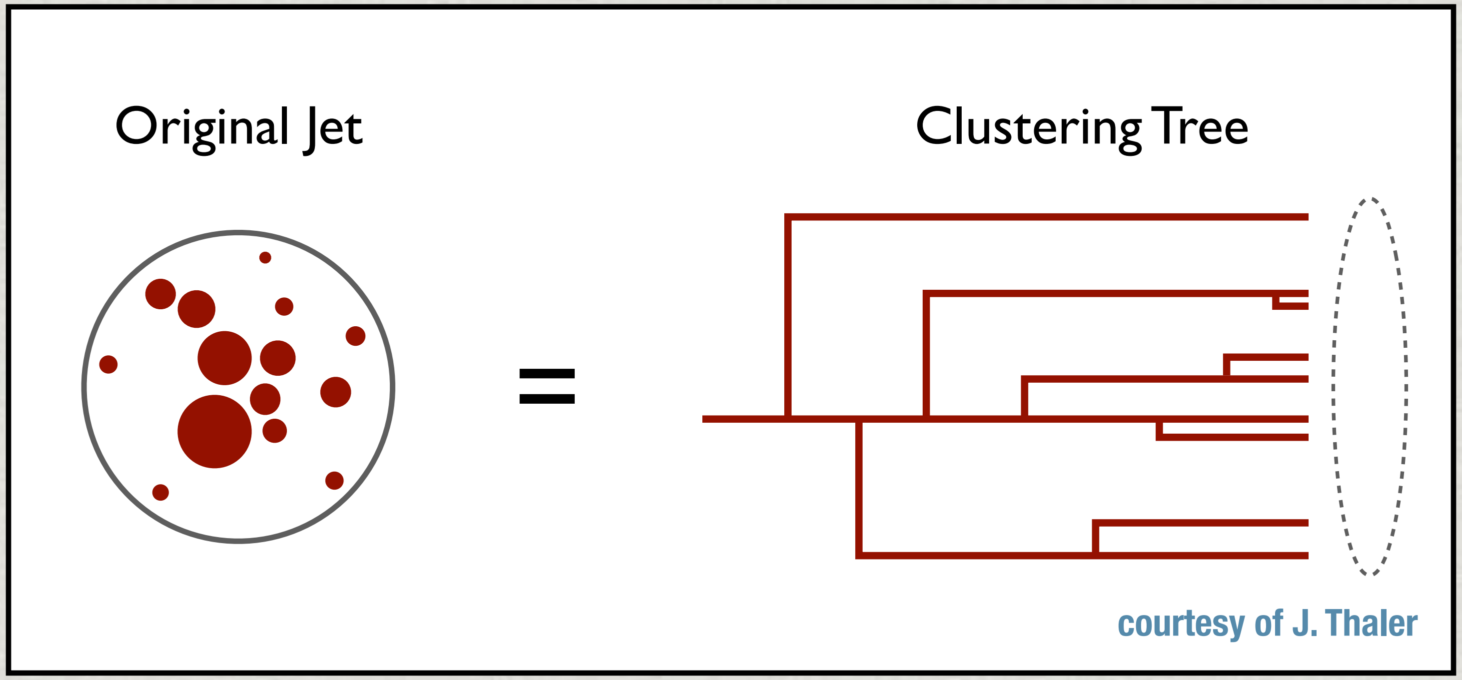
ATLAS, JHEP 1309 (2013) 076



Soft Drop

Soft Drop

Larkoski, SM, Soyez and Thaler (2014)



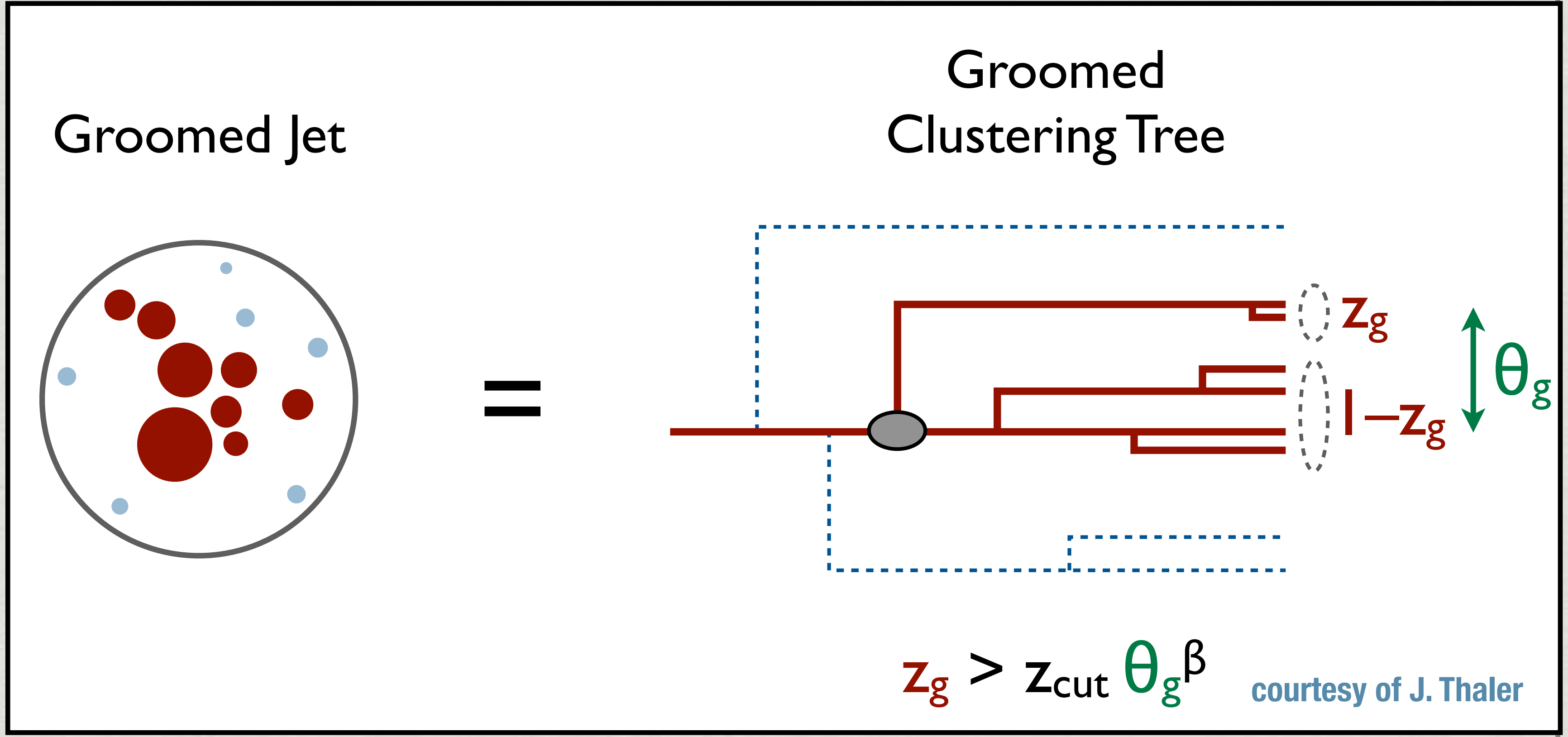
more information: clustering history

check momentum sharing

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

discard soft branches

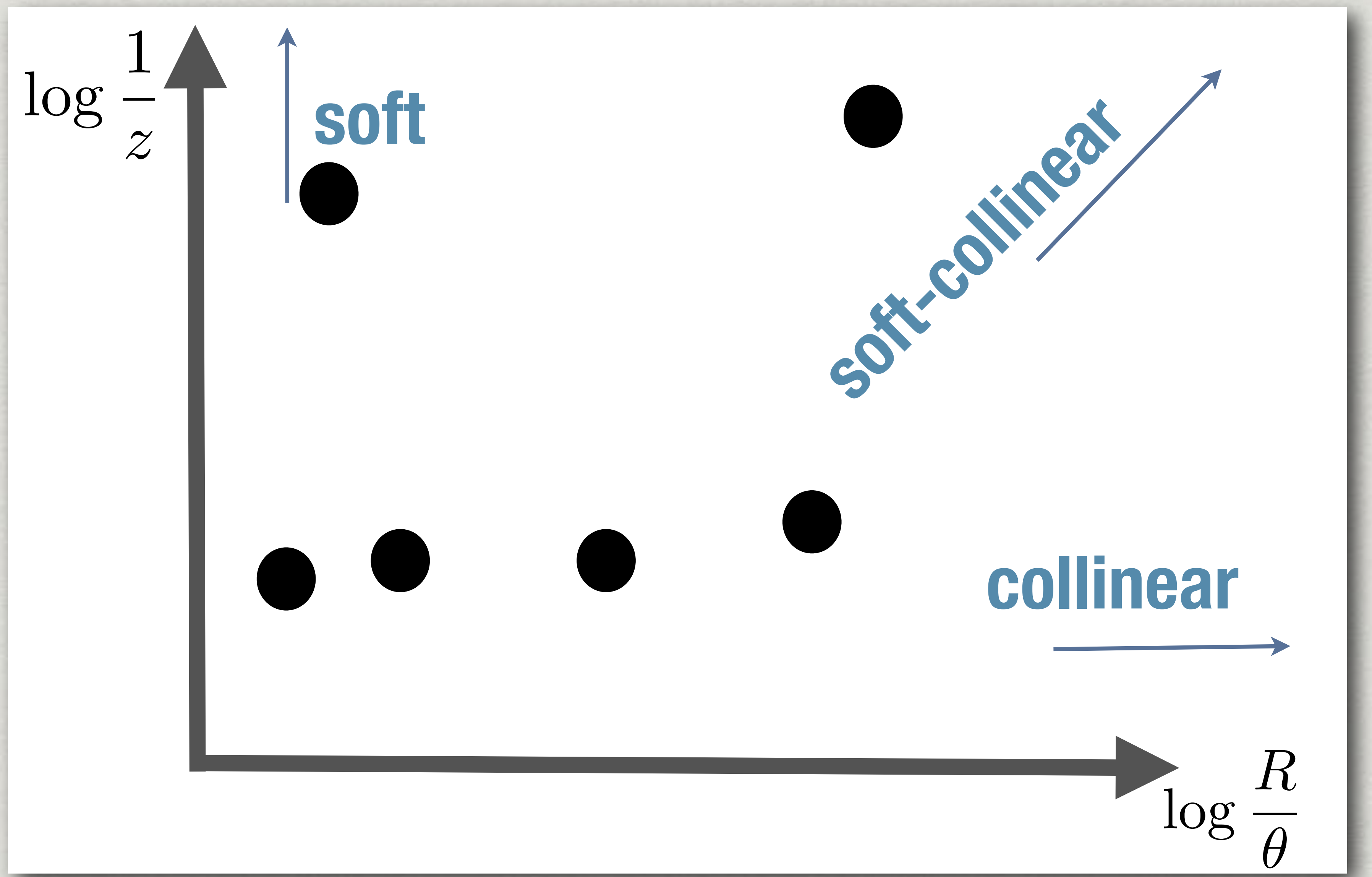
$$z_g < z_{\rm cut}\,\theta_g^\beta$$

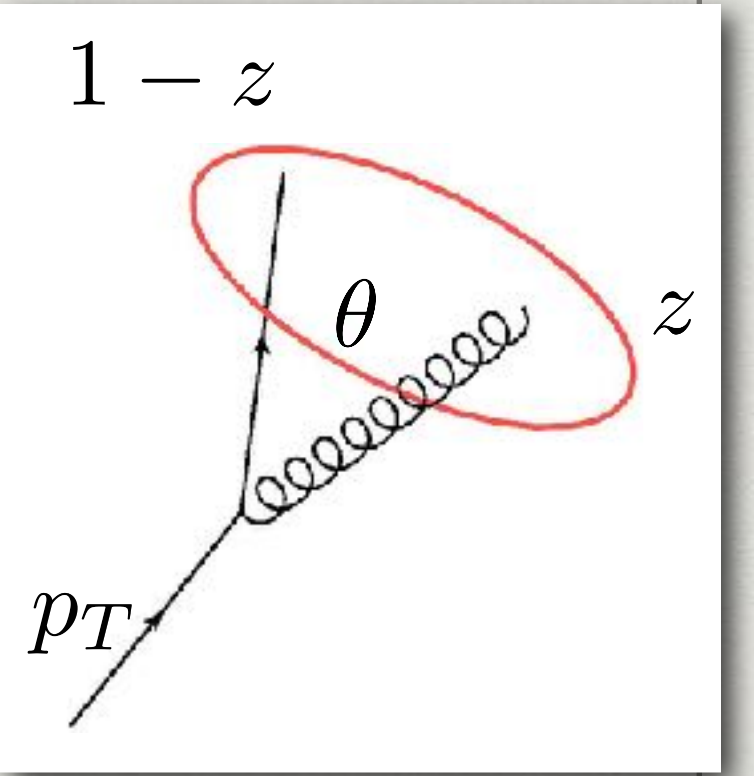


Butterworth, Davison, Rubin and Salam (2008); Dasgupta, Fregoso, SM and Salam (2013); Tseng and Evans (2013)

Soft-gluon phase space

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

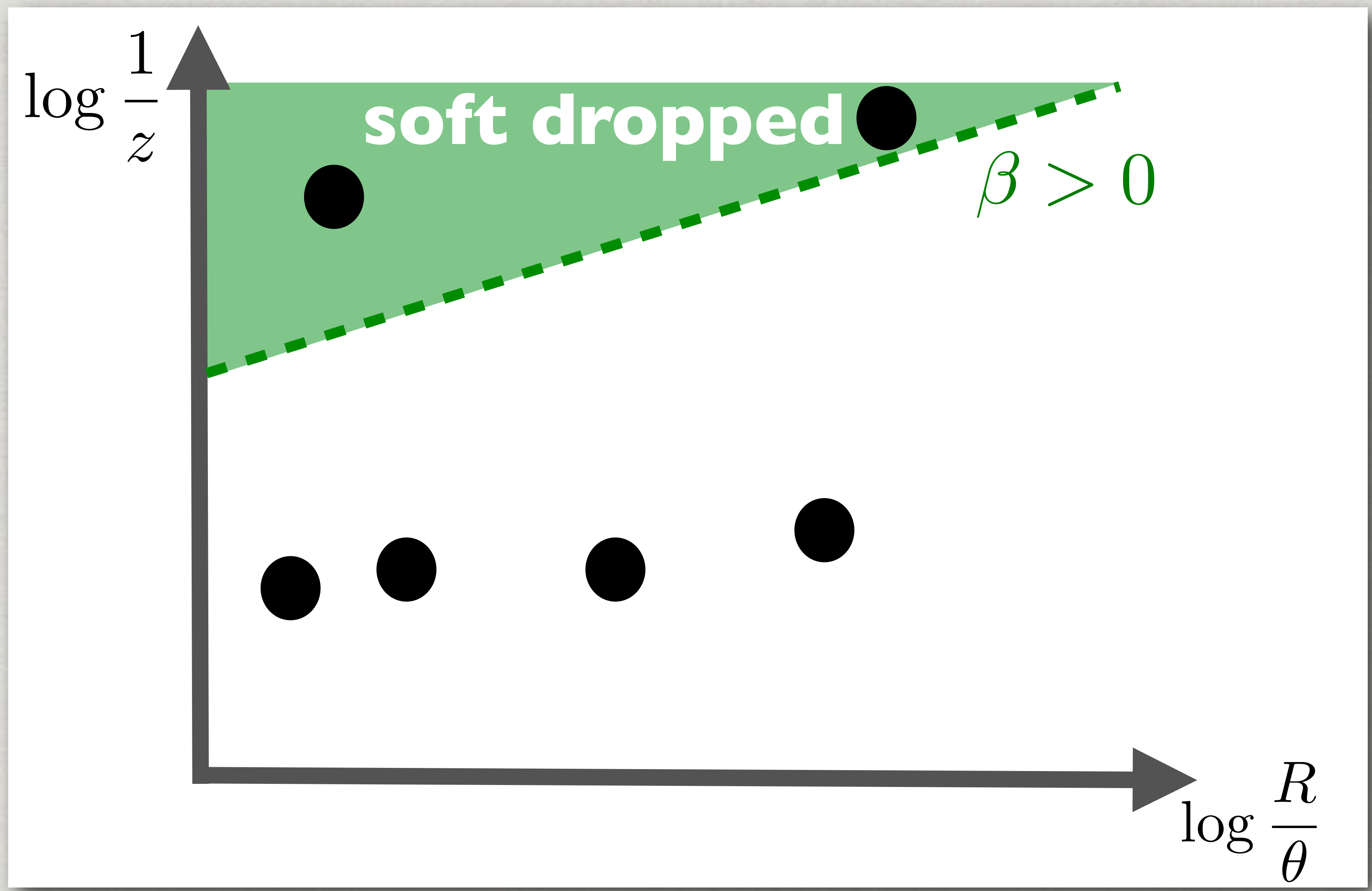




Emission probability is uniform in the (log z, log θ) plane: **cross-sections proportional to areas**

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

Soft Drop phase-space

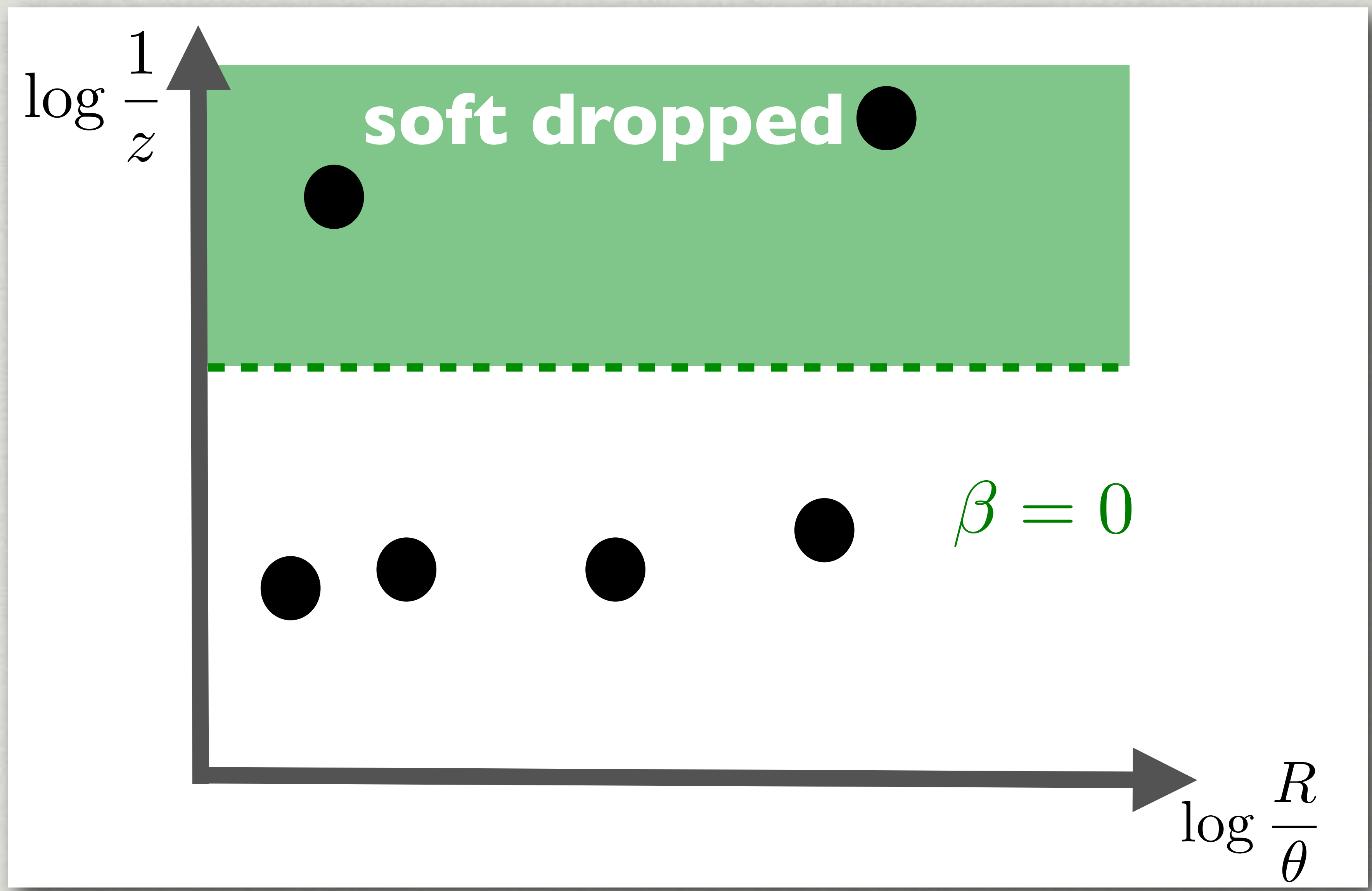


- useful to consider the soft-gluon phase space
- soft-drop condition becomes

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

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

Soft Drop phase-space



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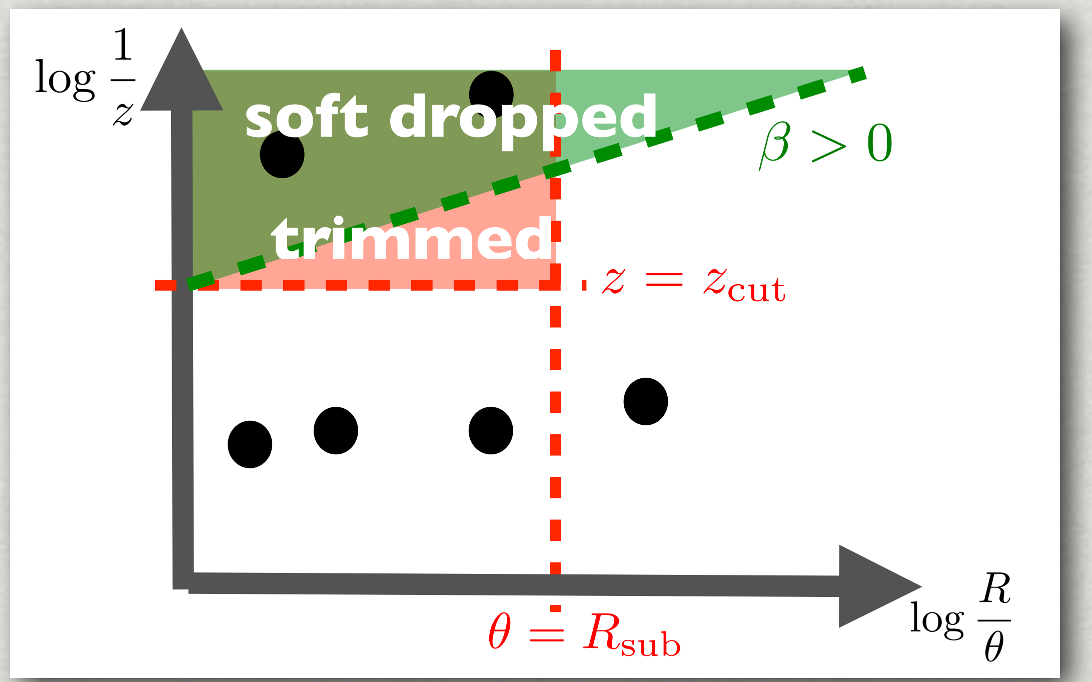
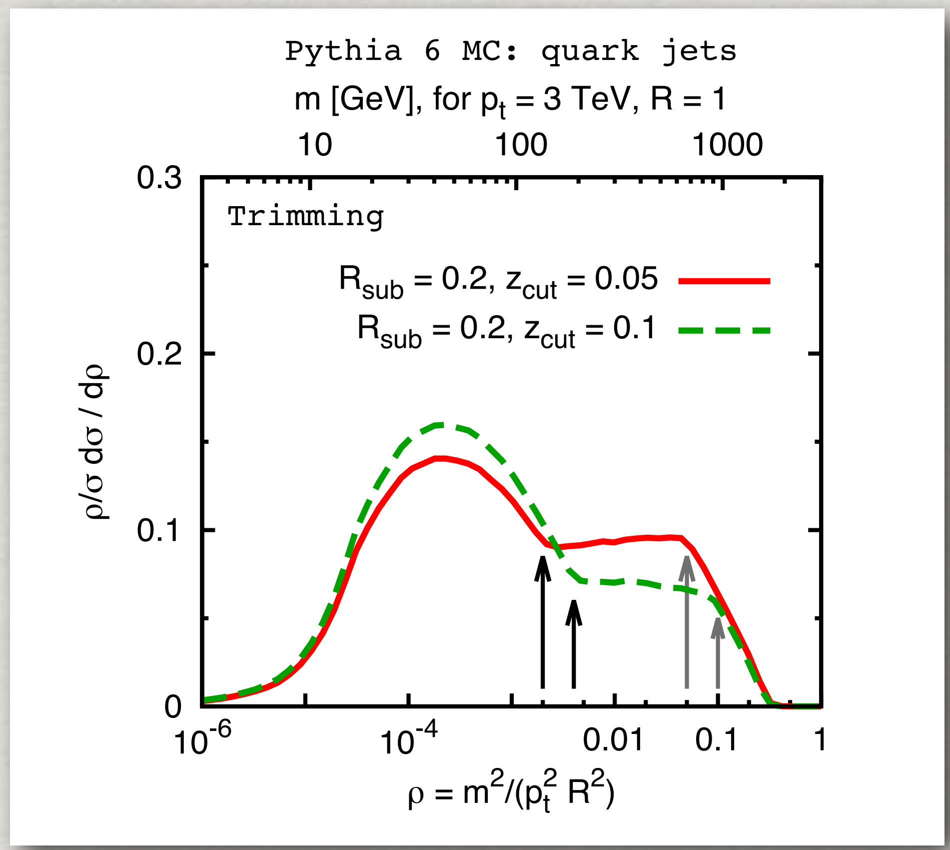
- for β=0 soft-collinear is totally removed

Soft Drop vs Trimming

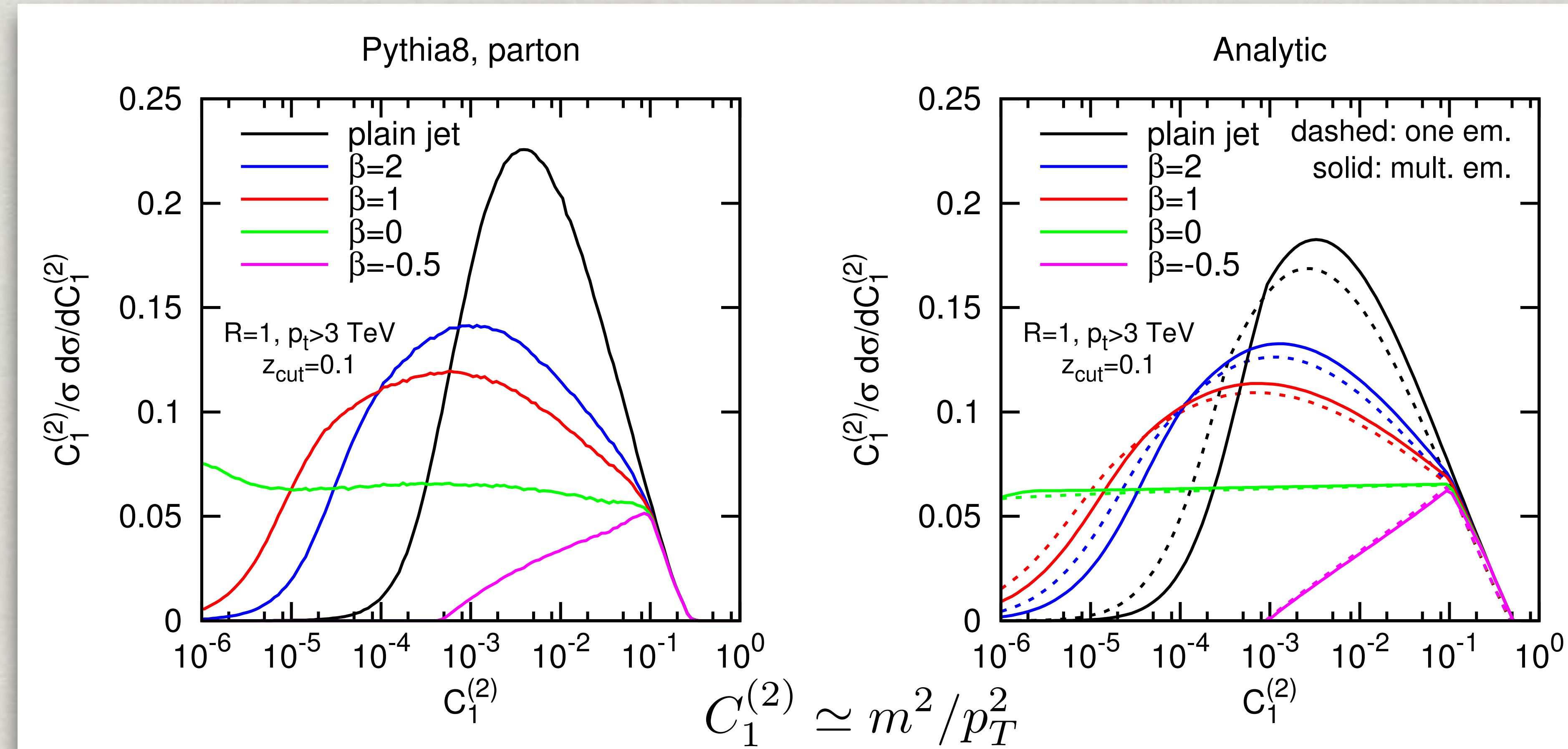
Soft drop in grooming mode (β>0) works as a dynamical trimmer

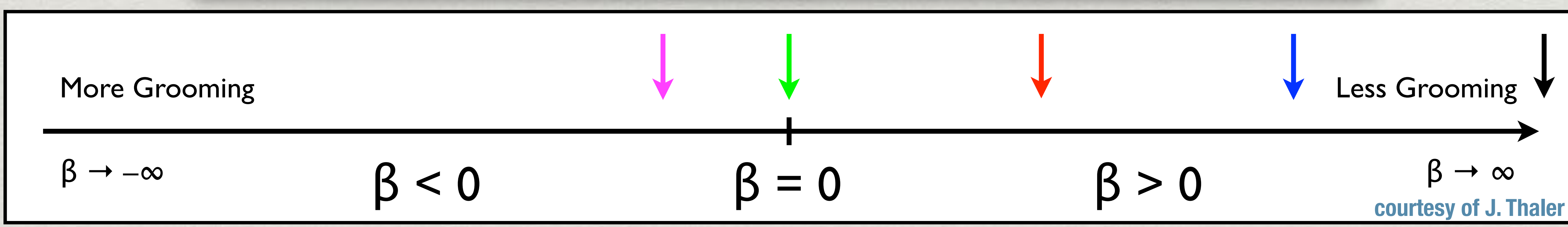




- trimming has an abrupt change of behaviour due to fixed R_{sub}
- loss of efficiency at high p_T
- in soft-drop angular resolution controlled by the exponent β
- phase-space appears smoother

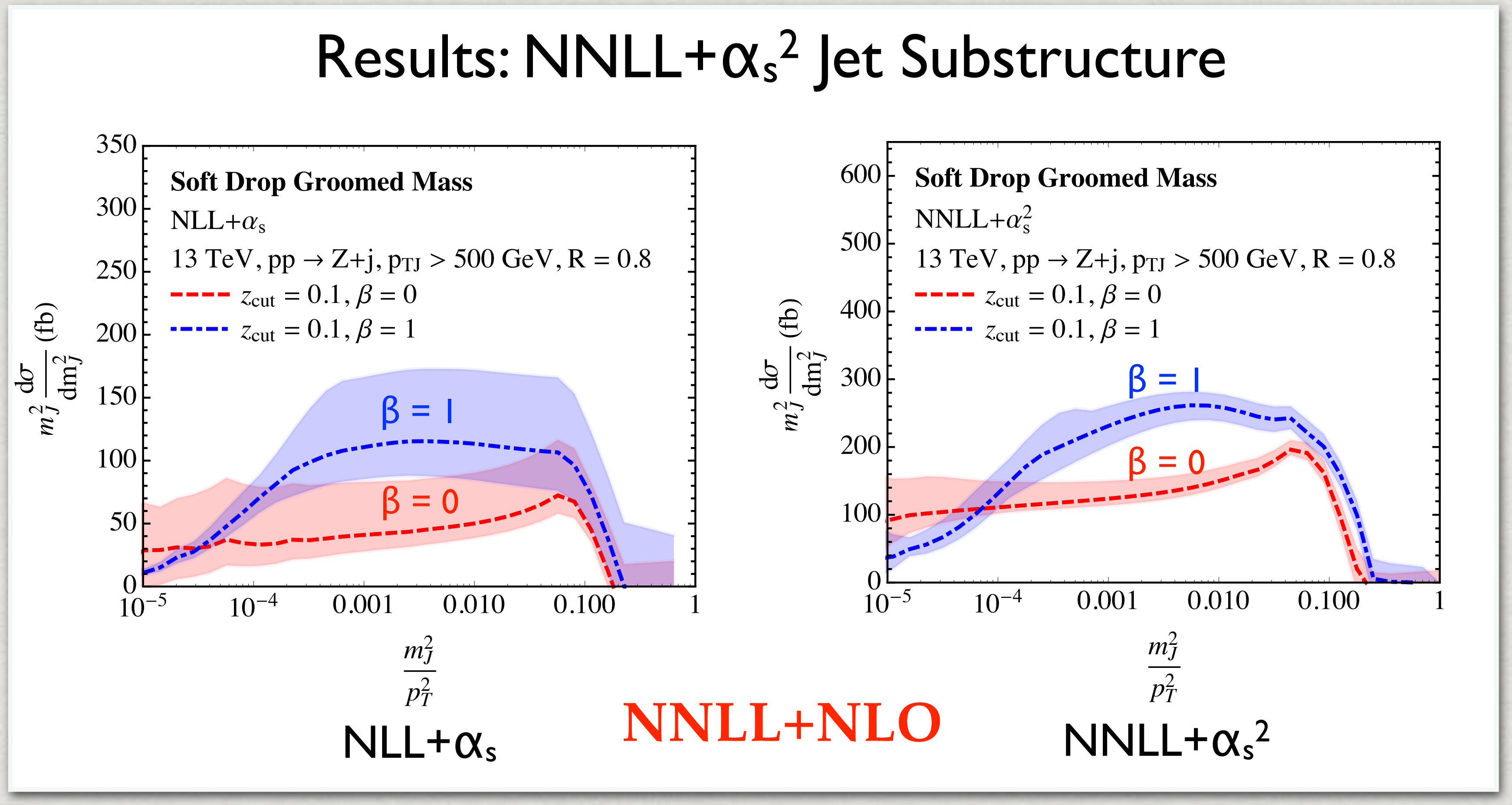
Groomed jet properties





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

Soft drop at NNLL



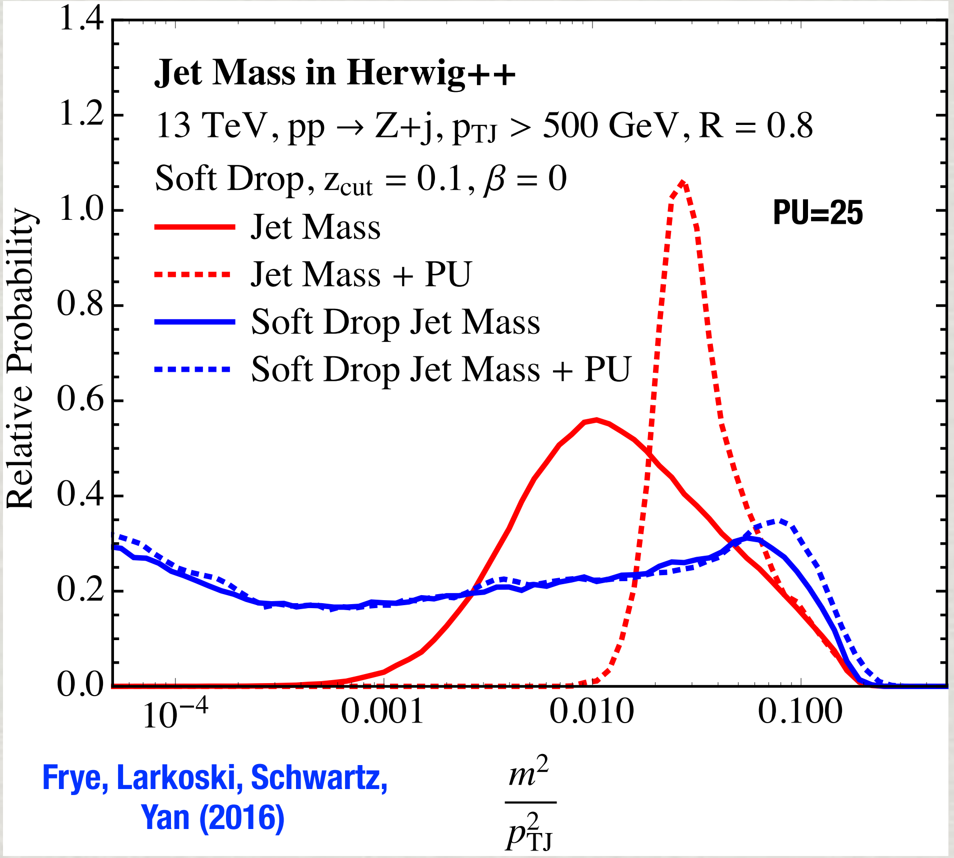
Frye, Larkoski, Schwartz, Yan (2016)

- 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
- 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 (hadronisation and UE) should make the comparison more meaningful
- pick the observable we know the most about:



Frye, Larkoski, Schwartz, Yan (2016)

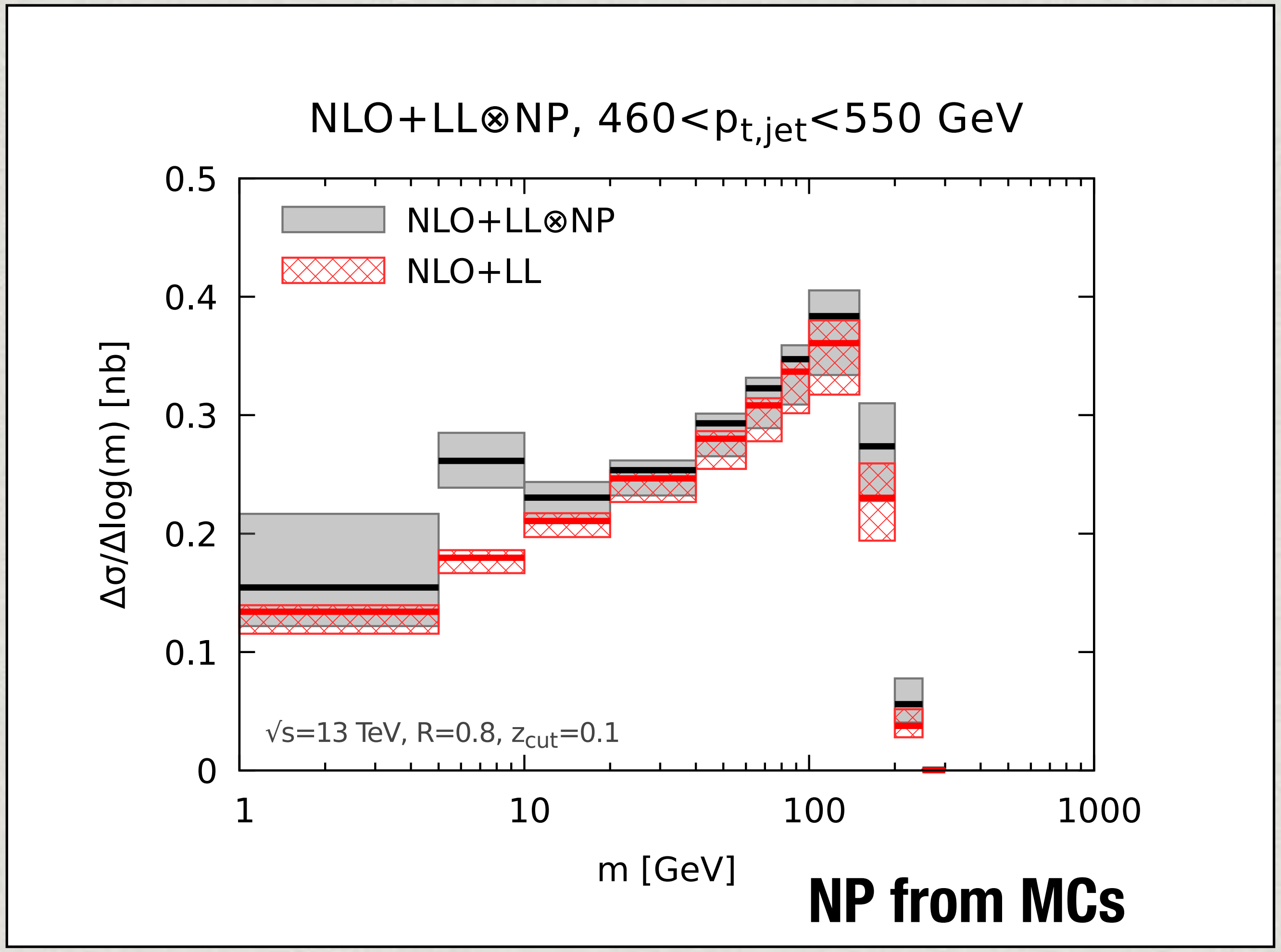
take a jet and measure its p_t

soft-drop it

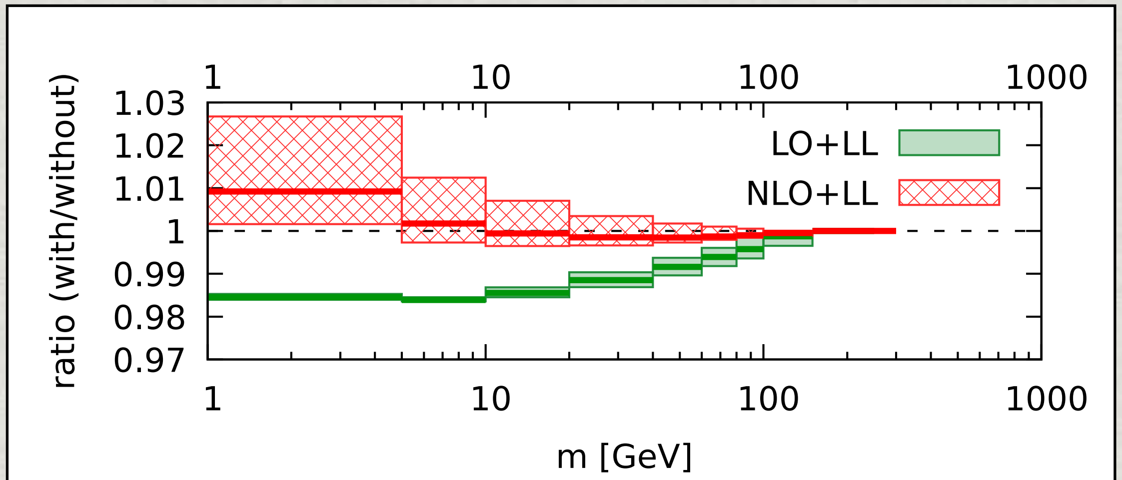
measure its mass

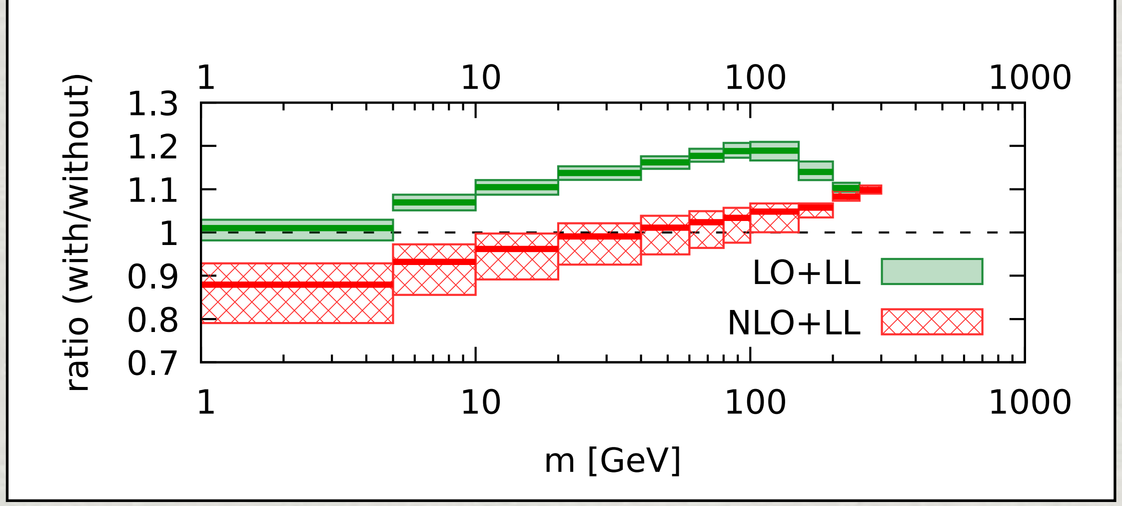
Theory predictions

SM, Schunk, Soyez (2017)



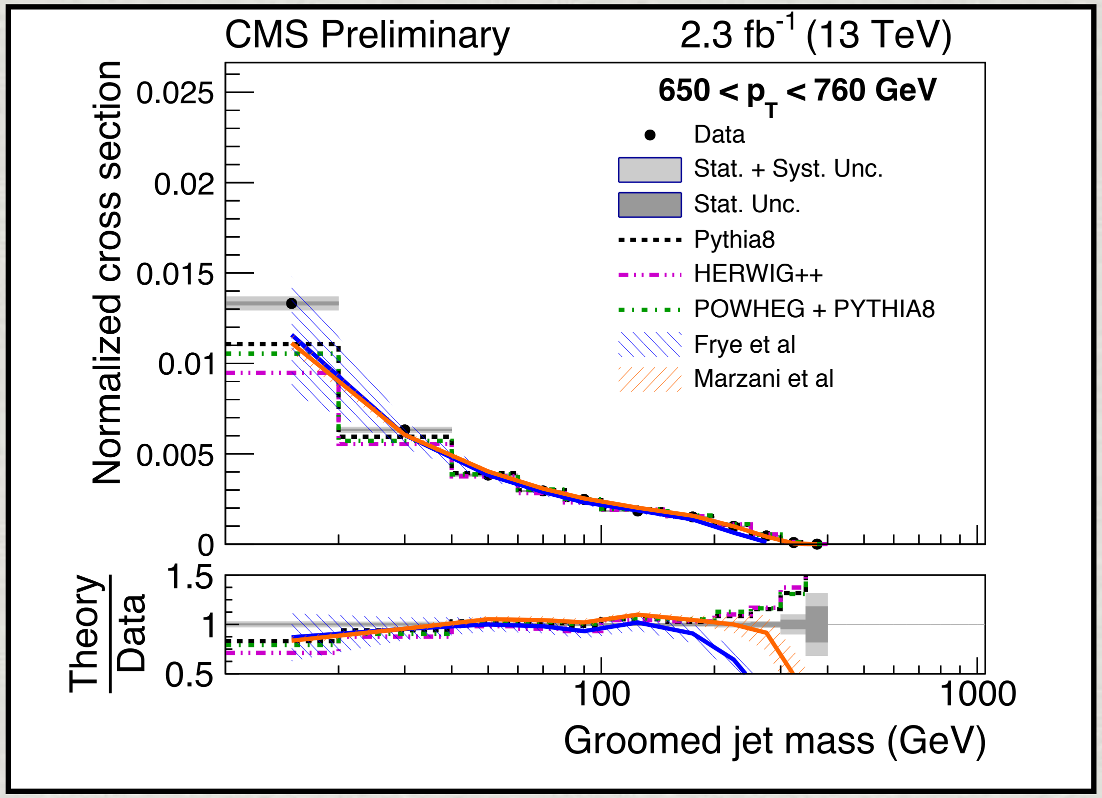
- large range of masses where NP corrections are small and we can trust resummation



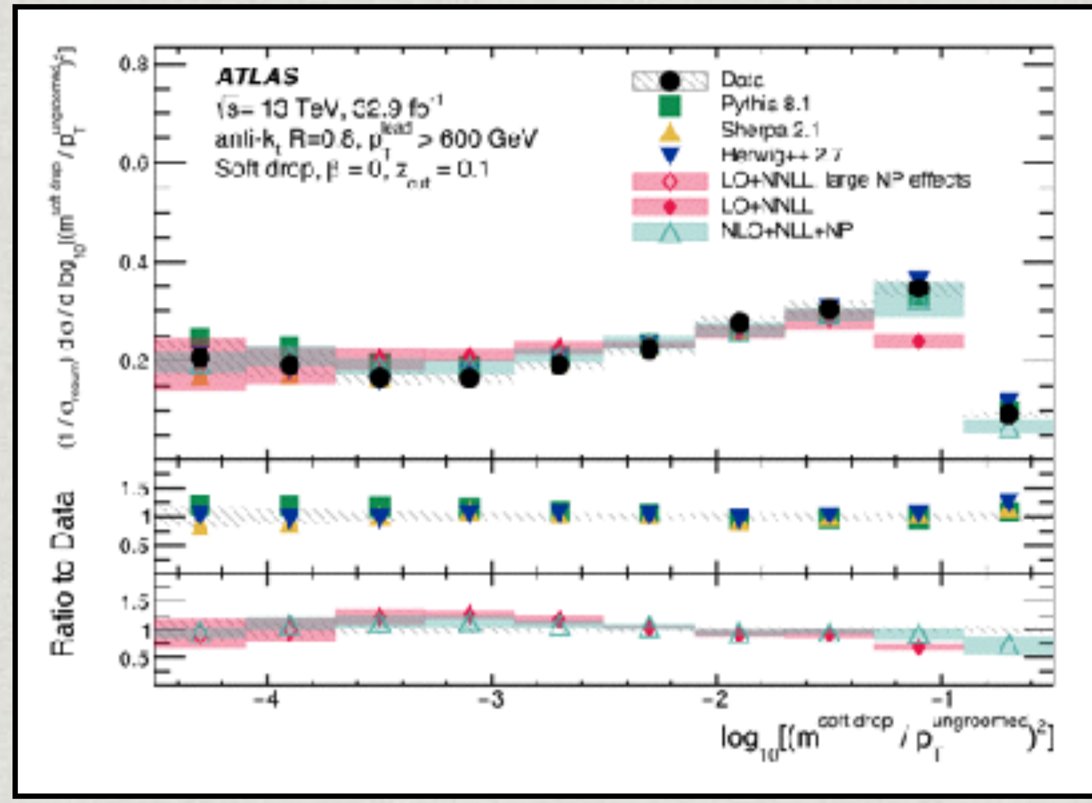


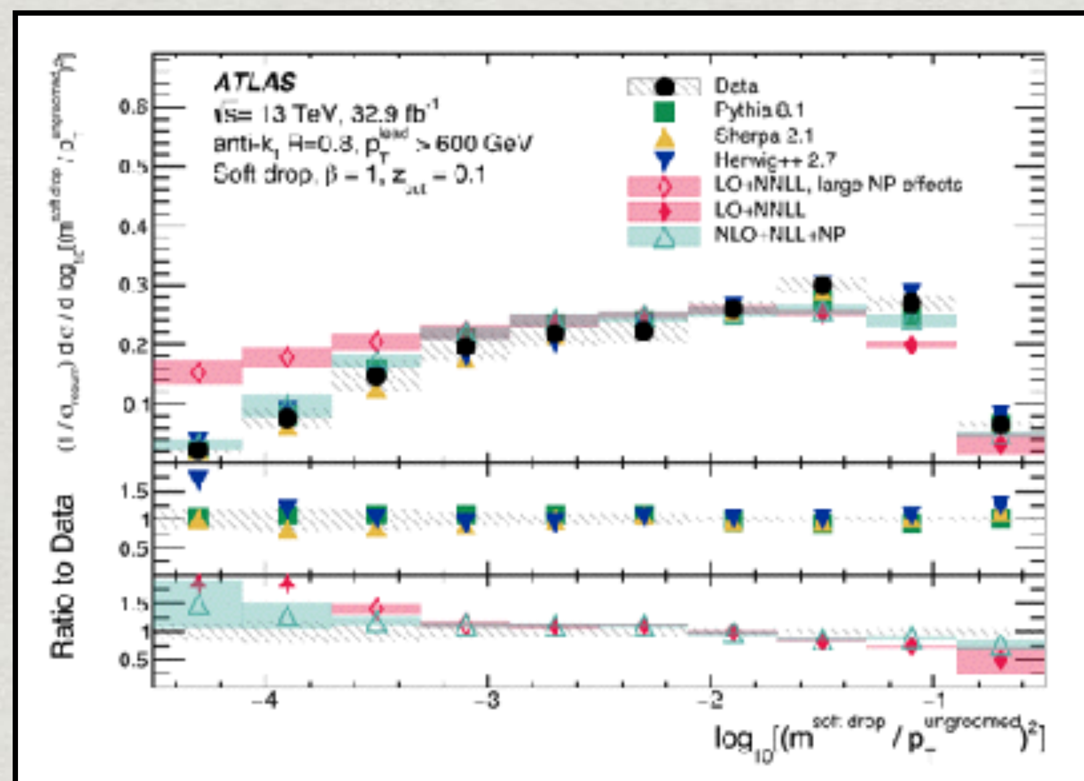
- what's the impact of finite z_c contributions (formally LL)?
- what's the impact of logs of z_c (formally N^kLL)?
- conclusions will change if we move away from z_c=0.1

and the DATA!



CMS-PAS-16-010





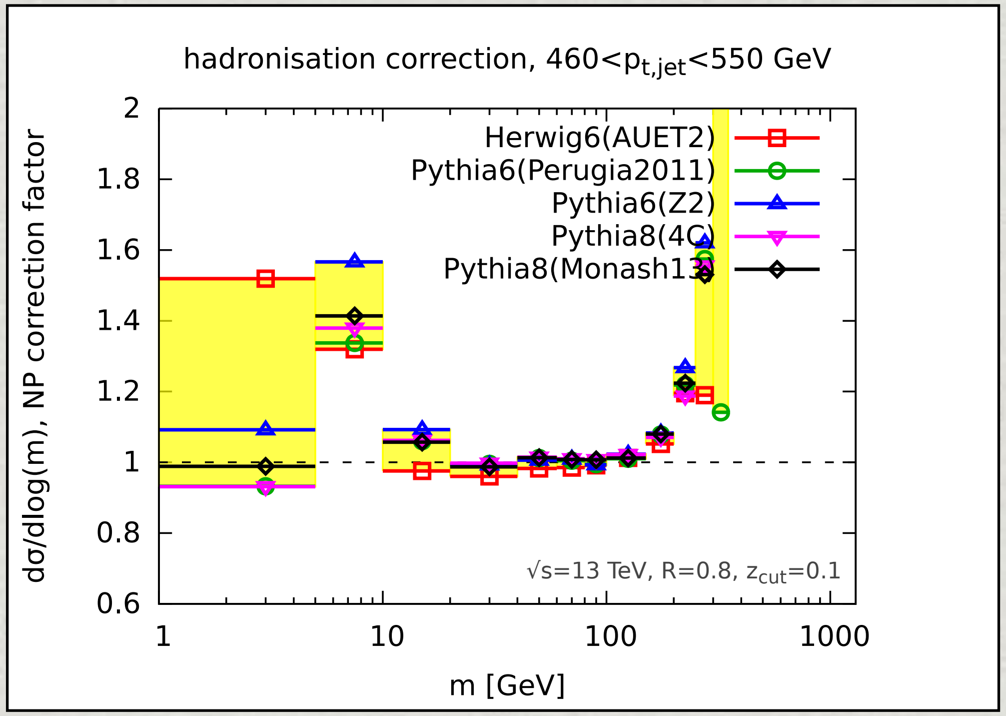
- CMS & ATLAS measurements
- NNLL is a small correction
- importance of FO for the tail
- ATLAS did β survey

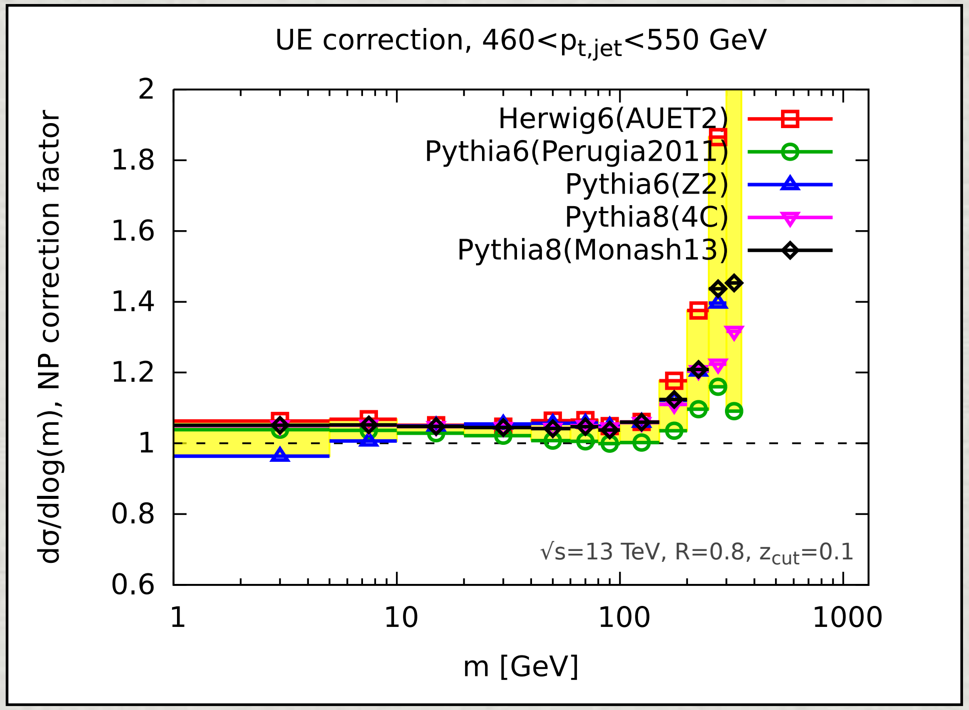
ATLAS: arXiv:1711.08341

Why unfolded measurements ?

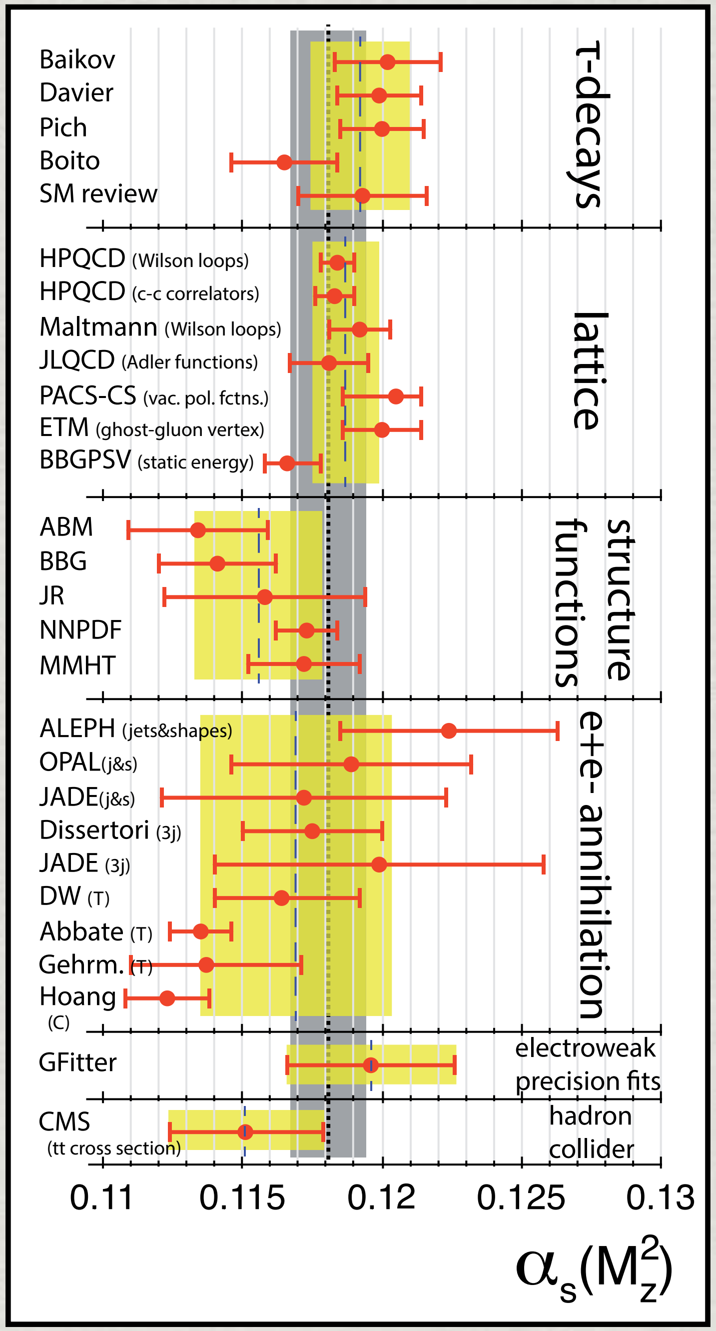
What is the value of SM measurements and their comparison to theory, especially for “discovery” tools?

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

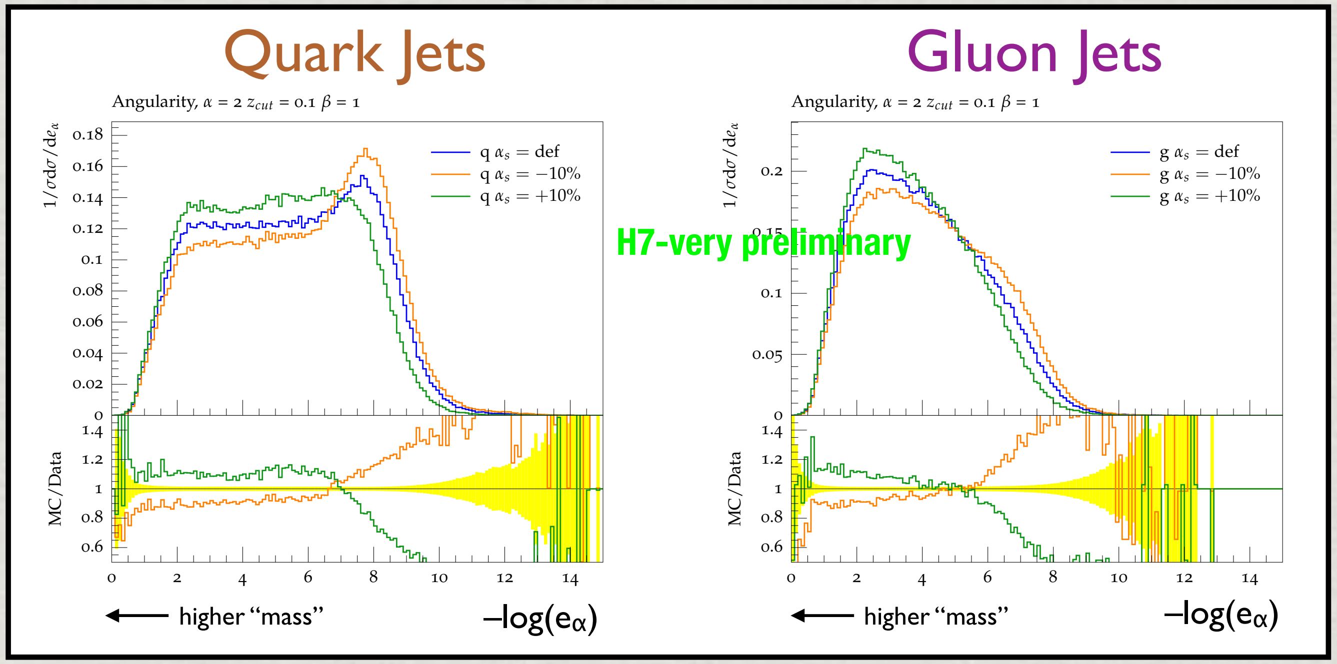




(not so) crazy idea



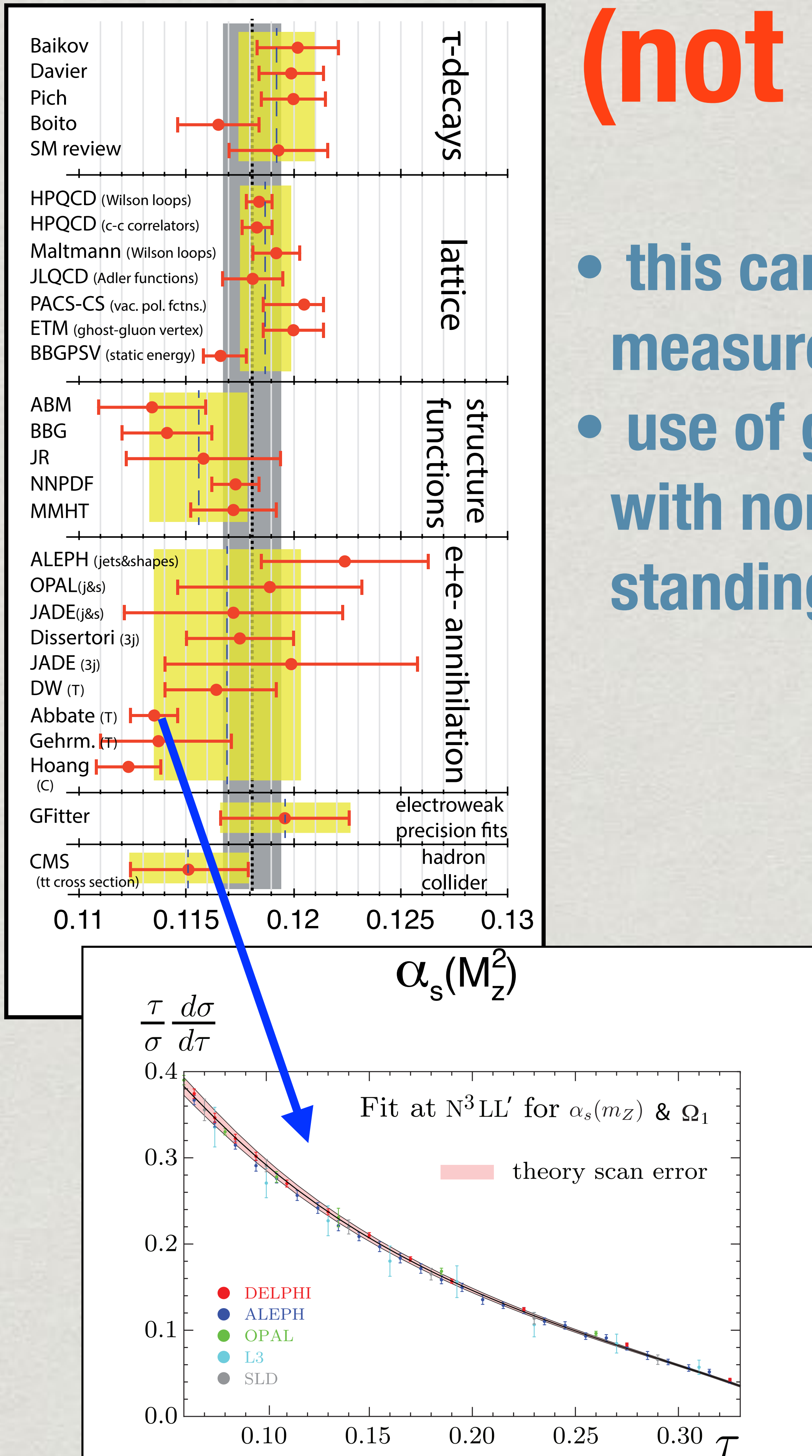
- Can we measure the strong coupling using jet substructure?
- target at LHC: 10-20%?



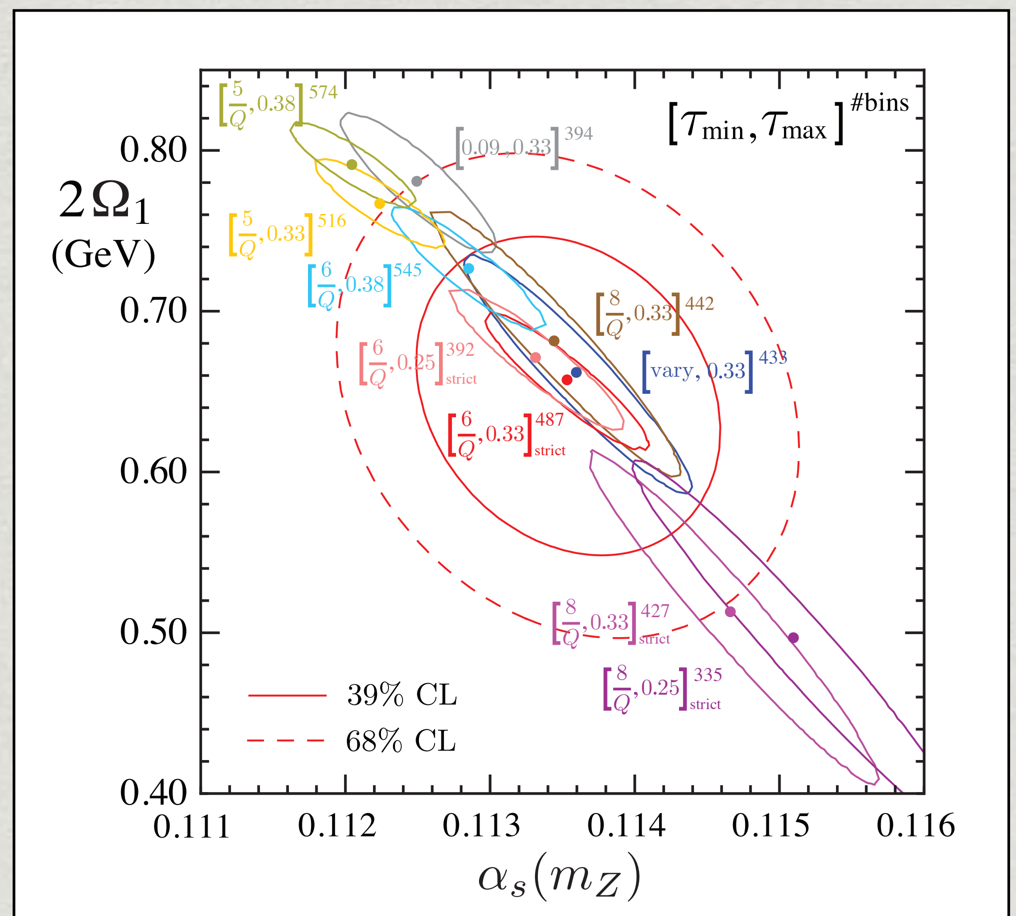
- α_s dependence is apparent
- many challenges experimental resolution, theory uncertainty, non-pert effects, q/g fractions, normalisation, PDFs, etc.

Les Houches 2017 study

(not so) crazy idea

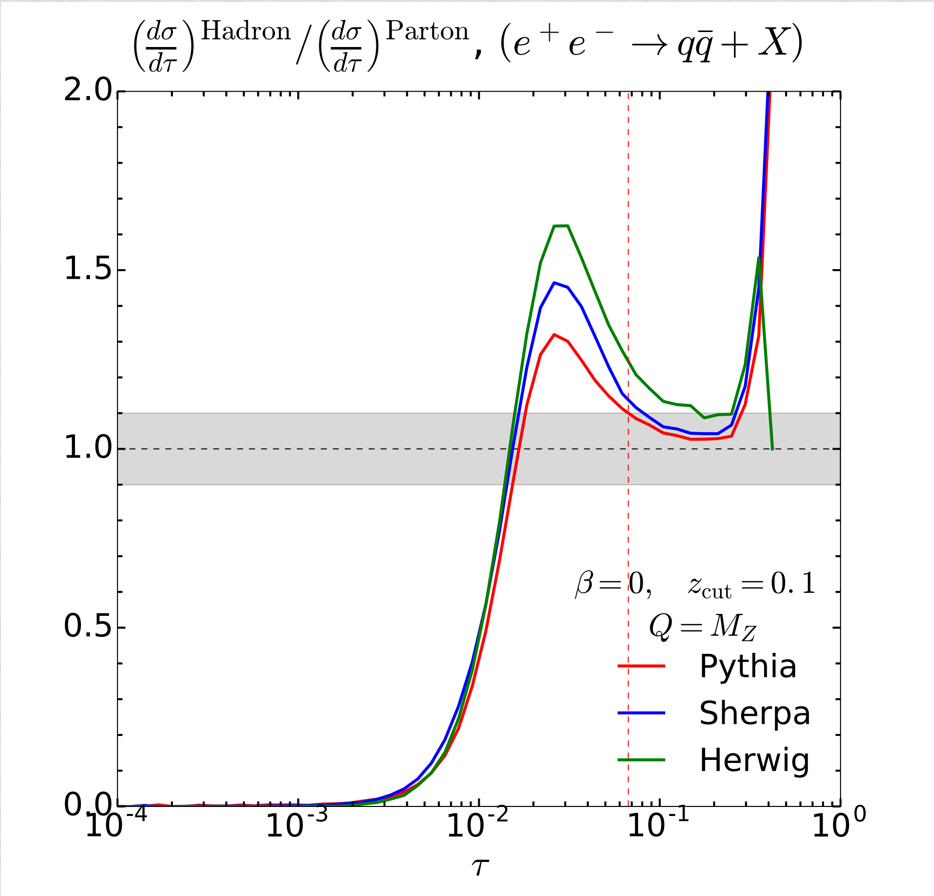


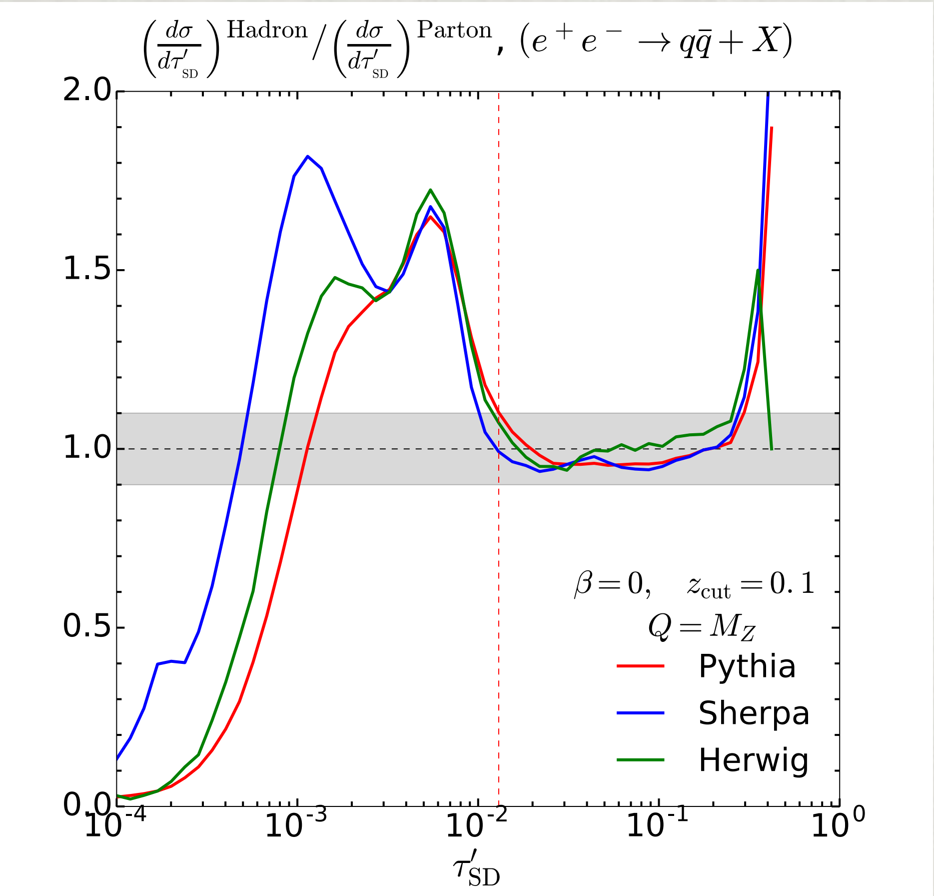
- this can pave the way for a more competitive measurement in e+e-
- use of grooming may help breaking degeneracy with non-perturbative effects and resolve long-standing puzzle



Abbate et al. (2010)

Soft-drop thrust

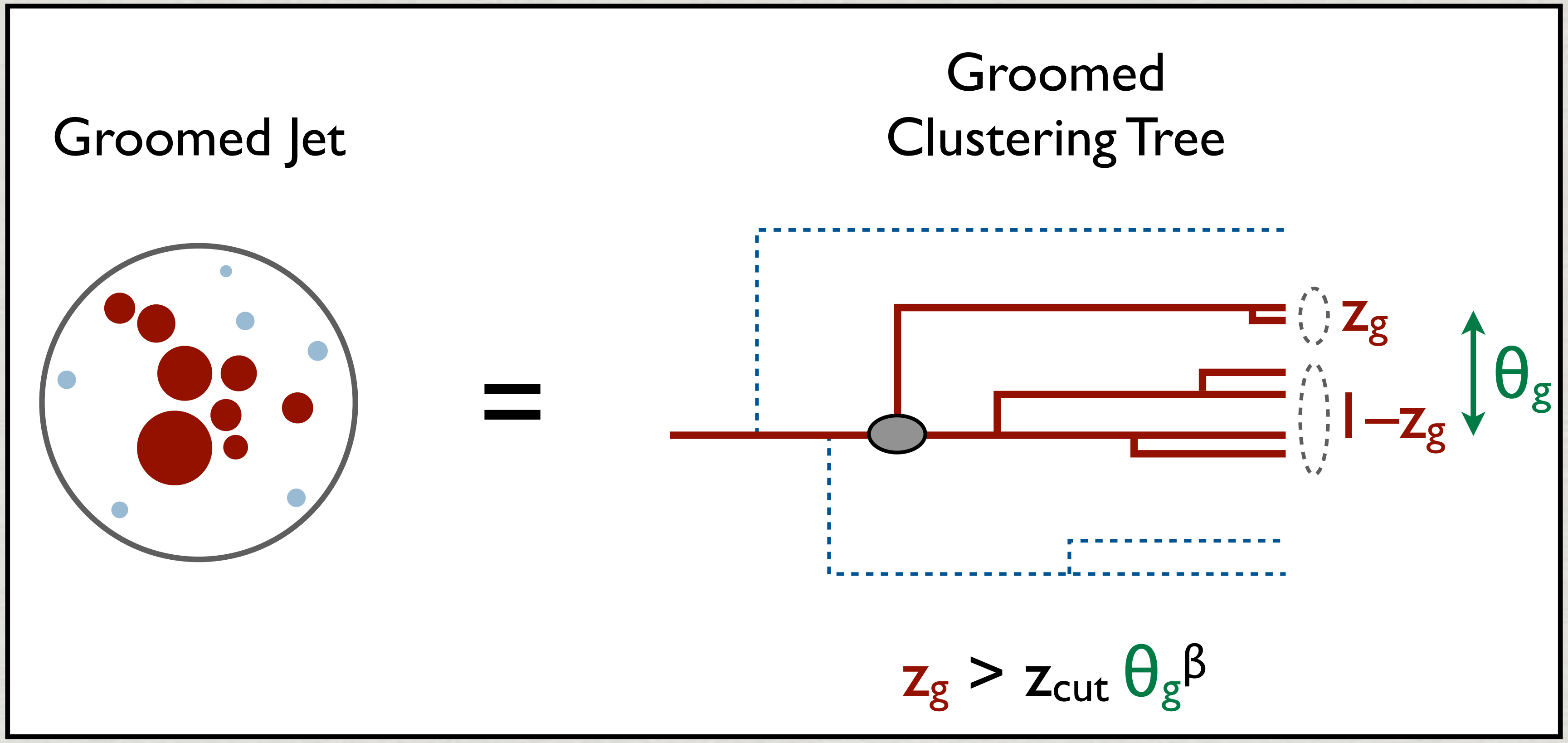




- noticeable reduction of non-pert. corrections
- can we compute it at the same accuracy as standard event shapes?
- non-trivial effects when $\tau \sim z_{\text{cut}}$: related observables such as jet masses may perform better

Baron, SM, Theeuwes (2018)

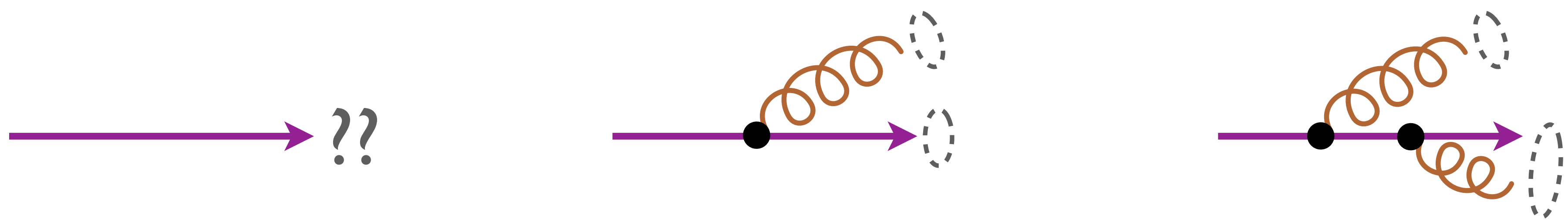
The prongs' momentum balance z_g

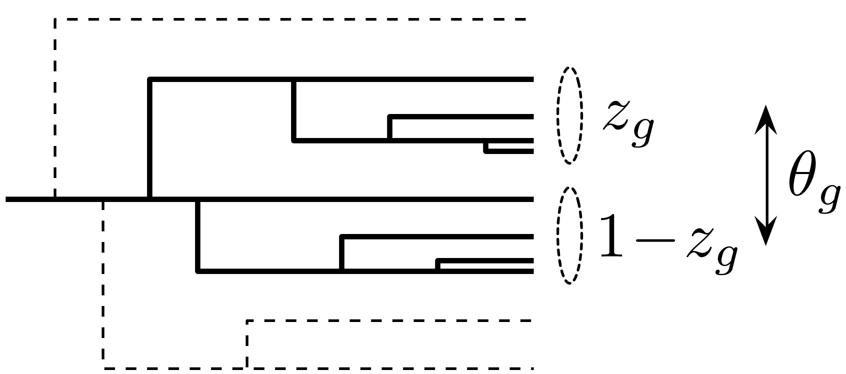


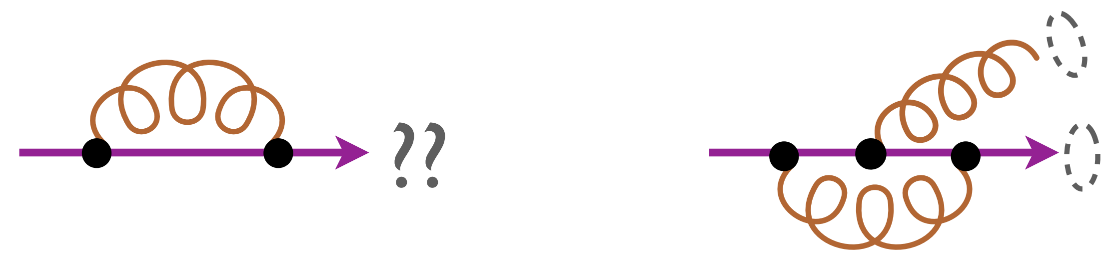
$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

Momentum sharing z_g

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

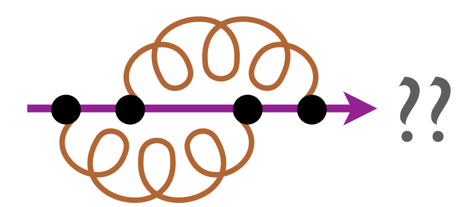






courtesy of J. Thaler

z_g not IRC safe because Born is ill-defined



$$\frac{d\sigma_i}{dz_g} = \textbf{??} + \frac{\alpha_s C_i}{\pi}\int_0^R \frac{d\theta}{\theta}\left[P_i(z_g)\Theta(z_g - z_c) + \textbf{??} \int_0^1 dz P_i(z)\left(\Theta(z_c - z) - 1\right)\right]$$

we can avoid the singularity requiring opening angle

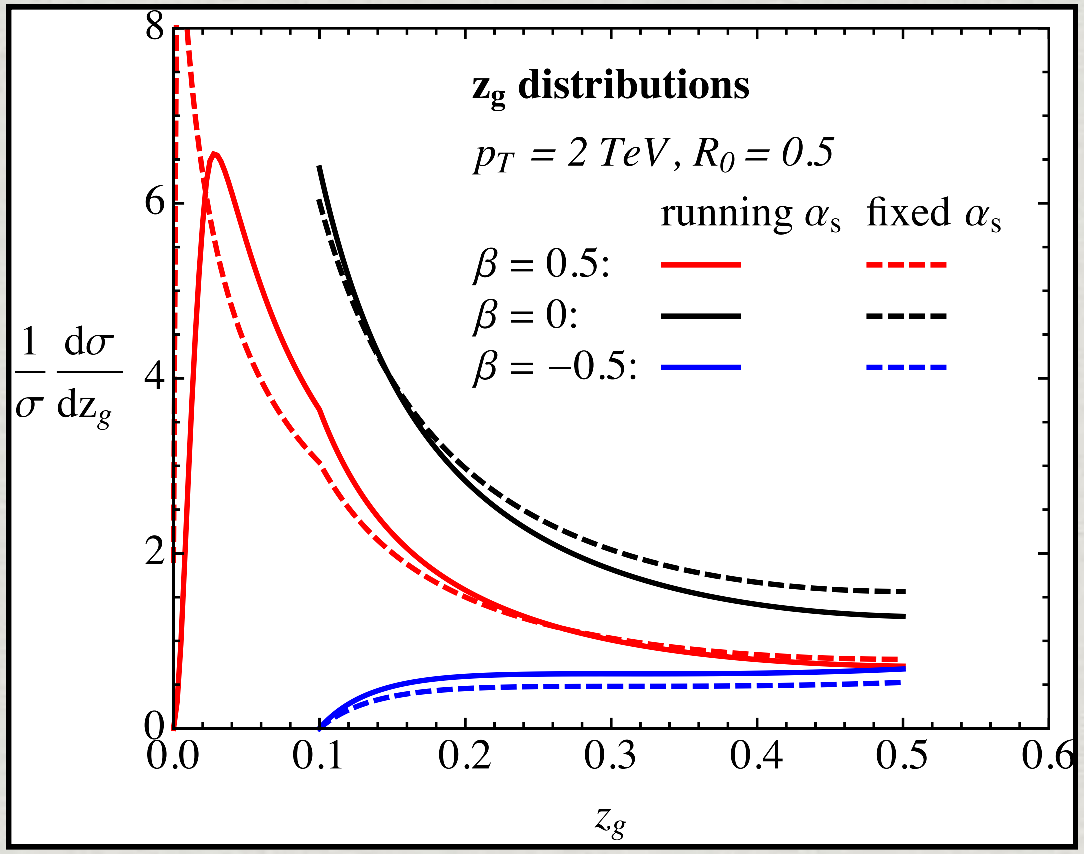
Sudakov safety

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

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



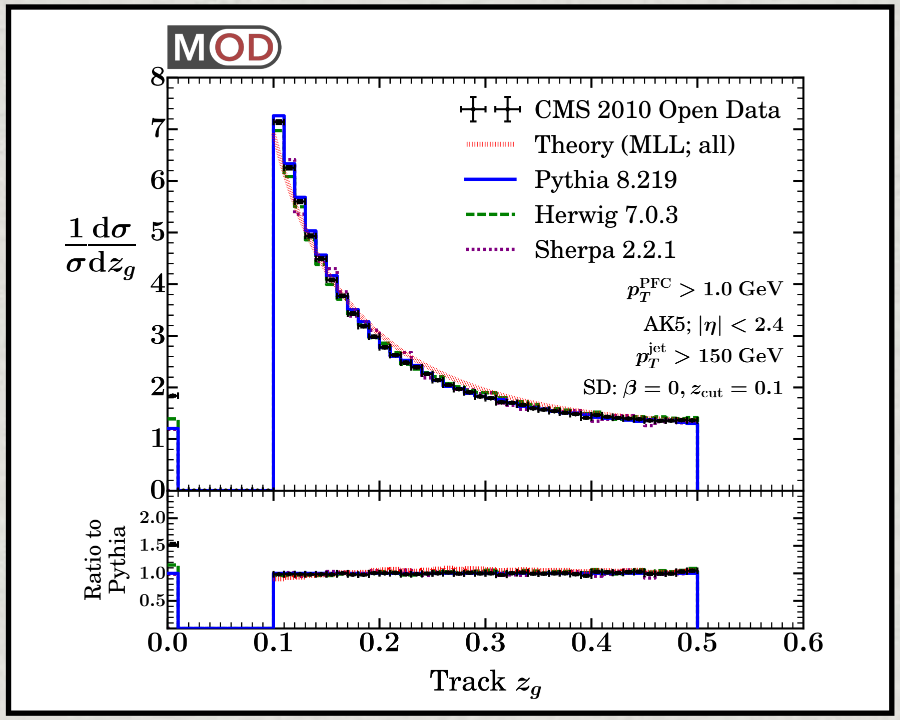
- as β varies, we move from an IRC safe situation (β<0) to IRC unsafe (but Sudakov safe!) regime (β>0)

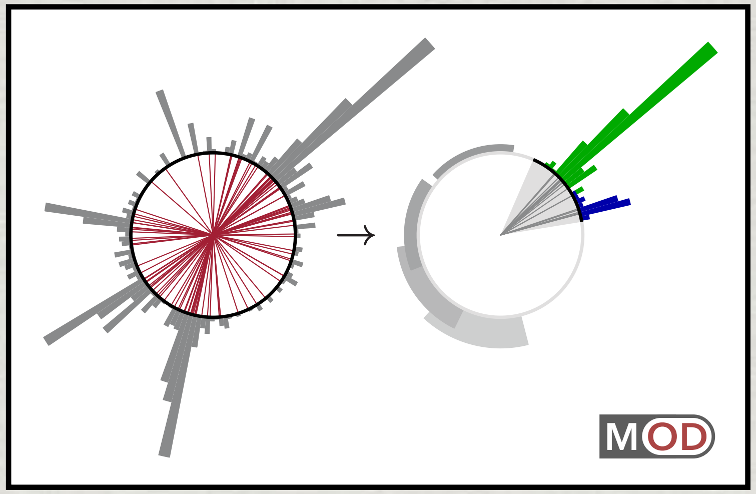
Larkoski, Thaler (2013); Larkoski, SM, Thaler (2015)

- remarkable result at β=0

Measuring z_g

- exposes the QCD splitting function



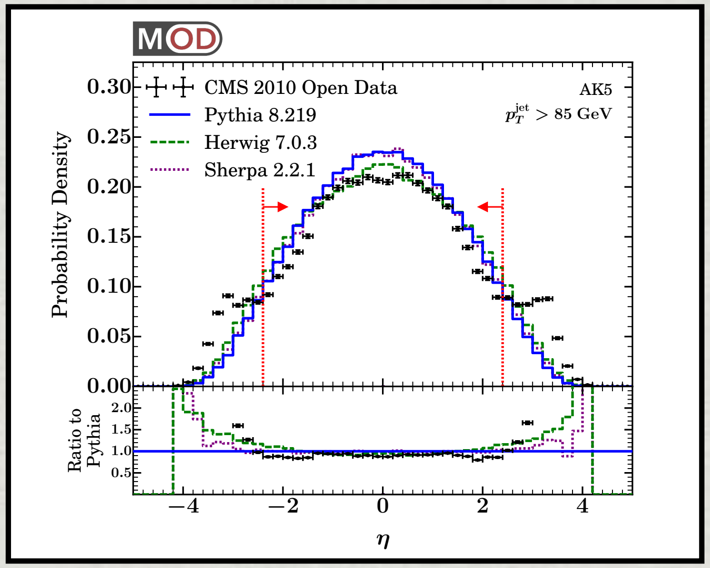


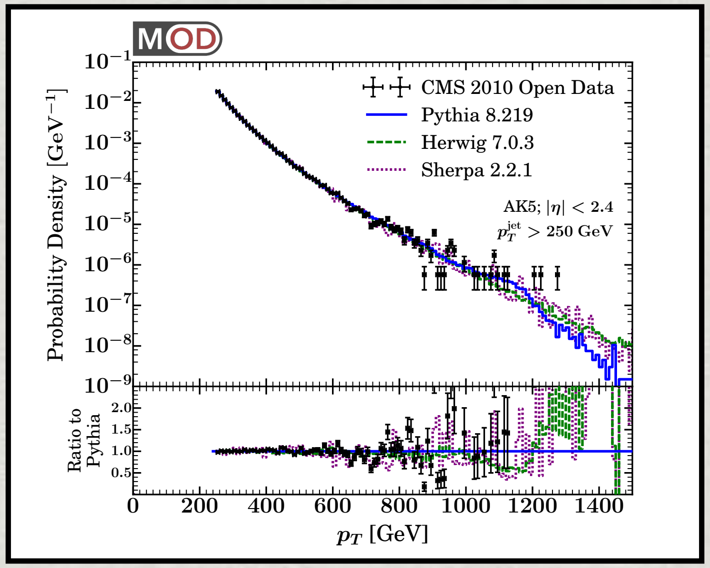
$$\frac{1}{\sigma}\frac{d\sigma}{dz_g} = \frac{\overline{P}_i(z_g)}{\int_{z_{\rm cut}}^{1/2} dz\, \overline{P}(z)}\Theta(z_g - z_{\rm cut}) + \mathcal{O}(\alpha_s)$$

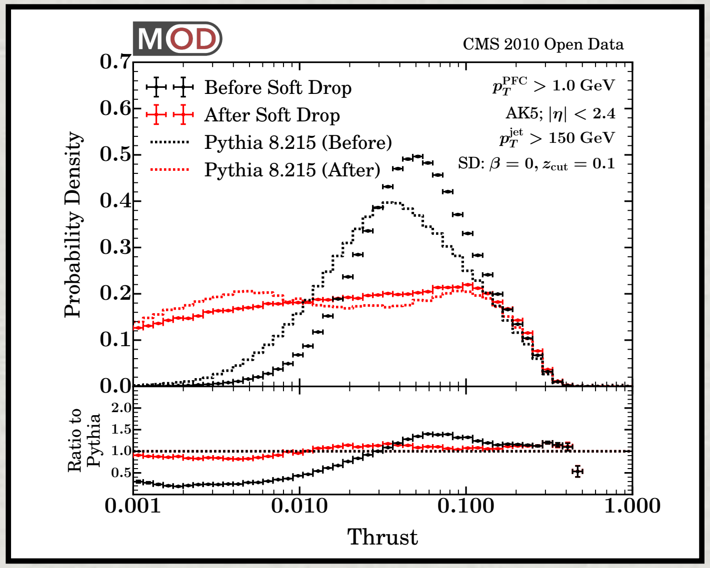
Larkoski, SM, Thaler (2015)

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

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





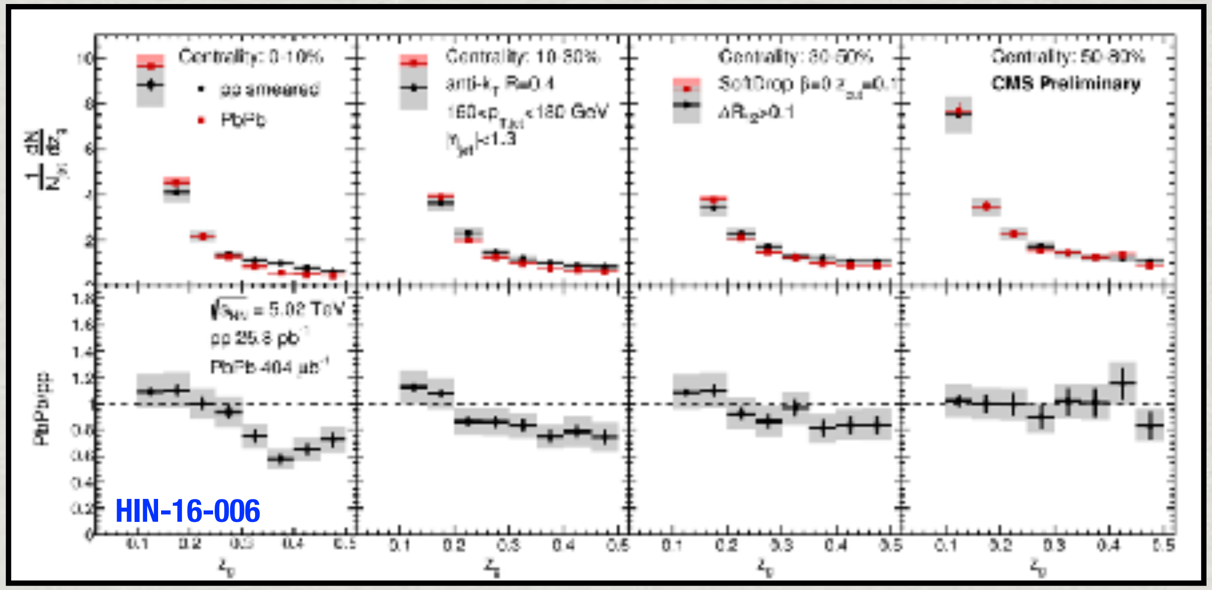


Tripathee, Xue, Larkoski, SM, Thaler (2017)

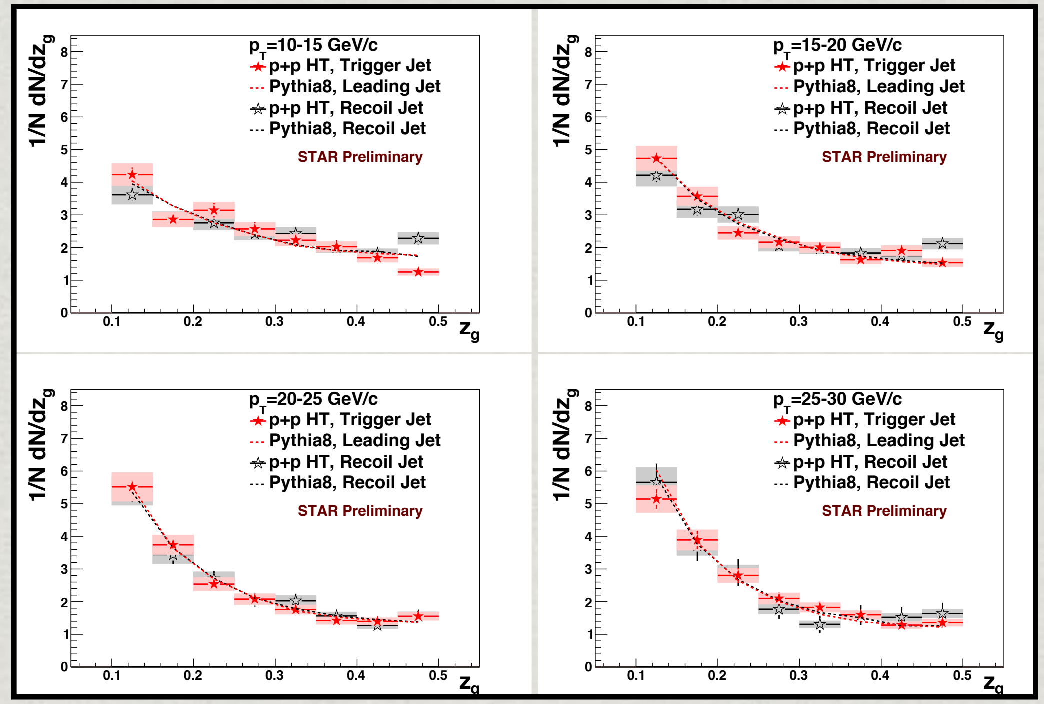
Heavy-ion applications

- also a probe for medium induced modification in heavy ion collisions

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

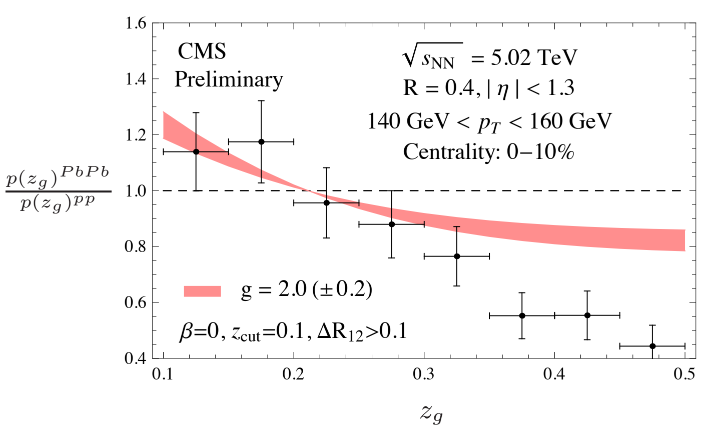


CMS Pb-Pb

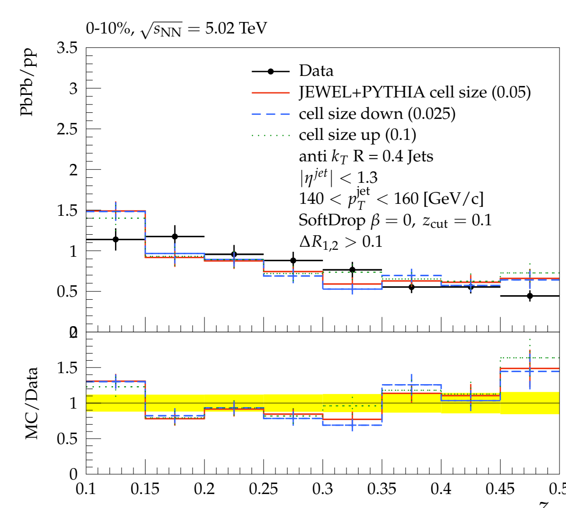


STAR Au-Au

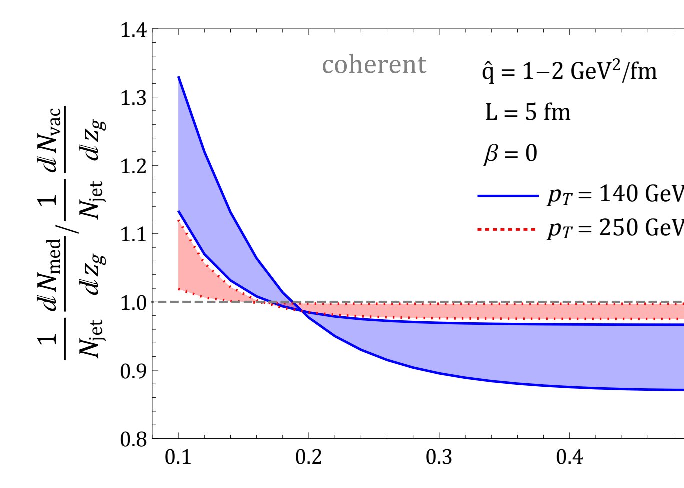
theory



Chien, Vitev (2016)



Elayavalli (2016)



Mehtar-Tani, Tywoniuk (2016)

Summary & Outlook

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

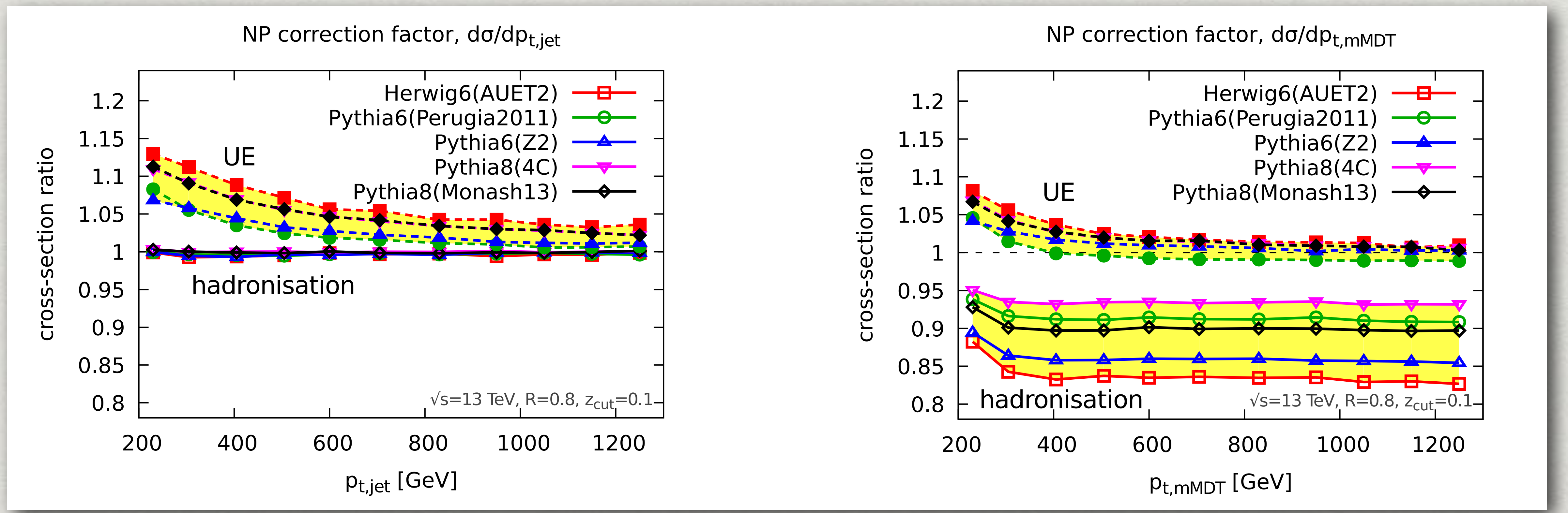
- Open questions
  1. higher-order corrections (i.e. beyond NLO) and grooming?
  2. in the boosted regime electro-weak corrections are significant
  3. in the opposite direction: non-perturbative physics and hadronisation in particular. Is “standard” ? and what does standard even mean?

     Particular relevant when we deal with Sudakov-safe observables: let me give a final example

p_T vs p_T^{mMDT}

SM, Schunk, Soyez (2017)

- transverse momentum before / after grooming
- for β=0 (β≤0) the groomed p_T spectrum is not IRC safe (but it's Sudakov safe)

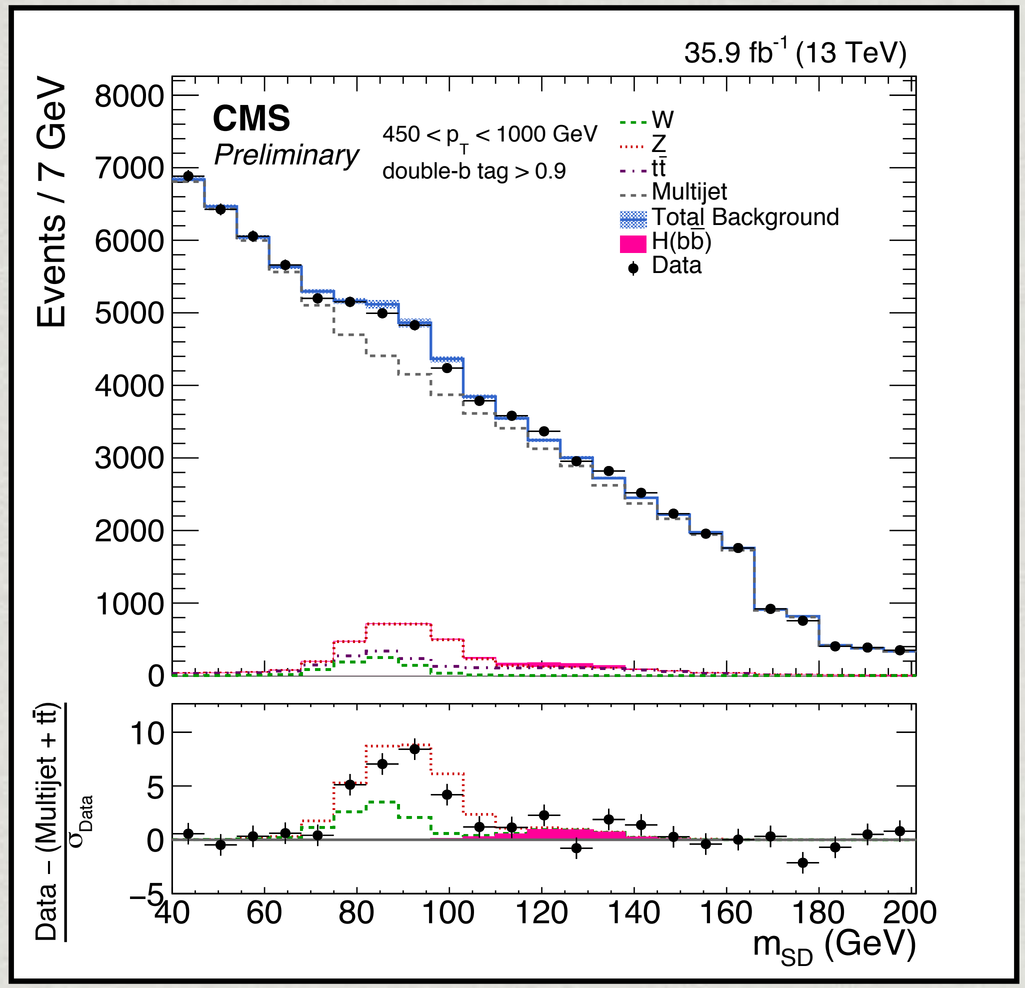


- large hadronisation because of IRC unsafety
- UE (and pile-up?) resilient because of grooming

Jet substructure at LHC

more robust

deeper understanding
QCD, calculations, etc.



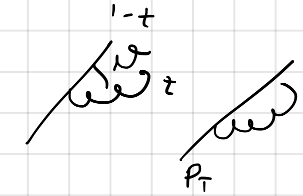
ideas, phenomenology,
MC simulations, etc.

more efficient

Thank you !

The jet transverse momentum after soft drop

Calculate p_T^{SD}



$$\frac{d\sigma}{dp_T} = \delta(p_T - p_T^{\varphi})$$

$$+ \left[\int dz\, P(z) \int \frac{d\vartheta}{\vartheta}\left[\Theta(R-\vartheta)\,\Theta(z - z_c\vartheta^\beta) - 1\right]\right]\delta(p_T - p_T^{\varphi})$$

$$+ \int dz\, P(z) \int \frac{d\vartheta}{\vartheta}\,\Theta(\vartheta - R)\,\delta(p_T - (1-z)p_T^{\varphi})$$

$$+ \int dz\, P(z) \int \frac{d\vartheta}{\vartheta}\,\Theta(R-\vartheta)\,\Theta(z_c\vartheta^\beta - z)\,\delta(p_T - (1-z)p_T^{\varphi})$$

$$= \delta(p_T - p_T^{\varphi})$$

$$+ \int dz\, P(z) \int \frac{d\vartheta}{\vartheta}\,\Theta(R-\vartheta)\Big\{\left[\Theta(z - z_c\vartheta^\beta) - 1\right]\delta(p_T - p_T^{\varphi}) + \Theta(z_c\vartheta^\beta - z)\,\delta(p_T - (1-z)p_T^{\varphi})\Big\}$$

$$+ \int dz\, P(z) \int \frac{d\vartheta}{\vartheta}\,\Theta(\vartheta - R)\left[\delta(p_T - (1-z)p_T^{\varphi}) - \delta(p_T - p_T^{\varphi})\right]$$

collinear finite $\vartheta > R$

soft-finite for cancellation $z \to 0$ $\equiv \frac{d\sigma^{out}}{dp_T}$

$$= \delta(p_T - p_T^{\varphi}) + \int dz\, P(z) \int \frac{d\vartheta}{\vartheta}\left[\Theta(R-\vartheta)\,\Theta(z_c\vartheta^\beta - z) + \Theta(\vartheta - R)\right]\left[\delta(p_T - (1-z)p_T^{\varphi}) - \delta(p_T - p_T^{\varphi})\right]$$

always finite for $z \to 0$ because of cancellation

collinear finite for $\beta > 0$. divergent for $\beta = 0$