Jets and their structure

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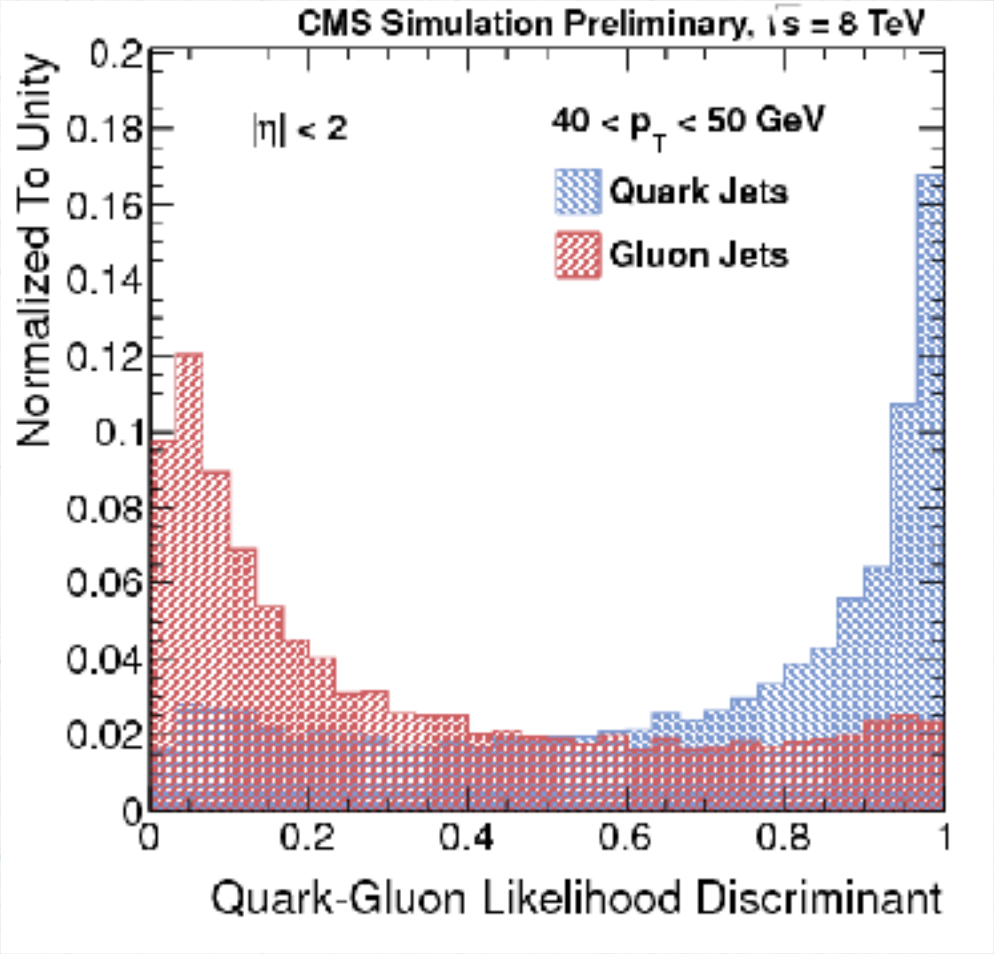
Lecture plan

* lecture 1: jets and jet algorithms
* lecture 2: calculating jet properties
* lecture 3: jet substructure
* lecture 4: more advanced topics & curiosities

Lecture 4

* defining and distinguishing quarks from gluons (in a meaningful way)
* Casimir scaling and beyond
* Unsafe but calculable!



what is a quark jet?

what is a quark jet?

From lunch/dinner discussions

Ill-Defined

What people sometimes think we mean

Quark as noun

Quark as adjective

Well-Defined

What we mean

A quark parton

A Born-level quark parton

The initiating quark parton in a final state shower

An eikonal line with baryon number 1/3 and carrying triplet color charge

A quark operator appearing in a hard matrix element in the context of a factorization theorem

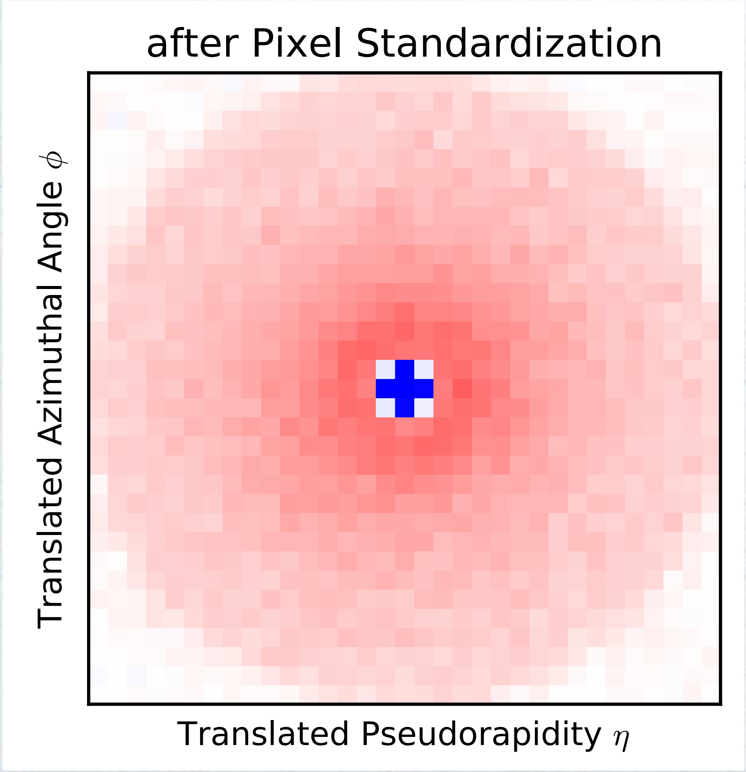
A parton-level jet object that has been quark-tagged using a soft-safe flavored jet algorithm (automatically collinear safe if you sum constituent flavors)

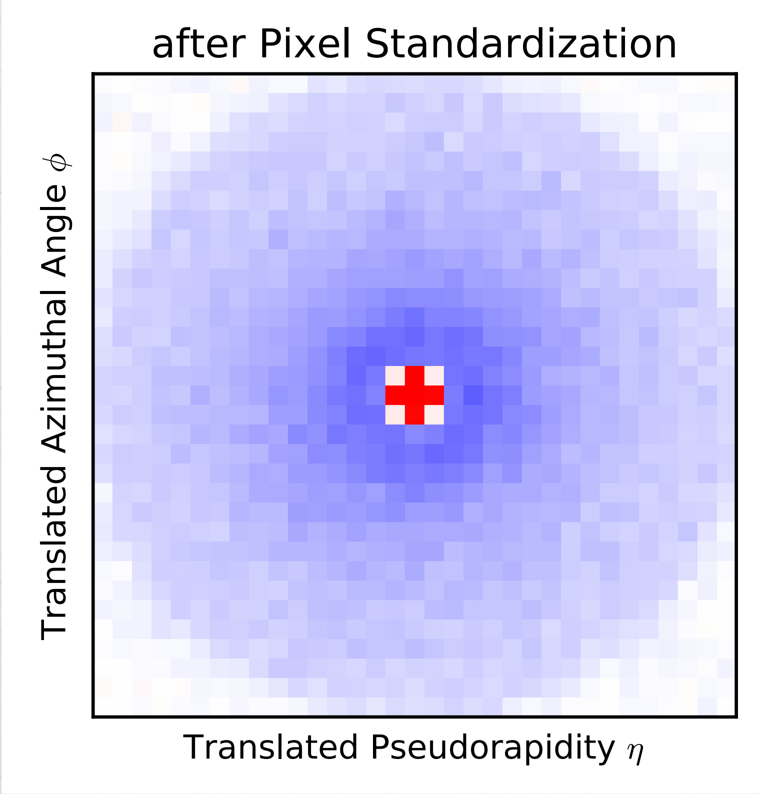
A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)

for a review see arXiv:1704.03878

q/g radiation pattern

* first expectation: quark and gluon radiation controlled by their Casimir
* $C_A > C_F$ so we expect gluons to radiate more

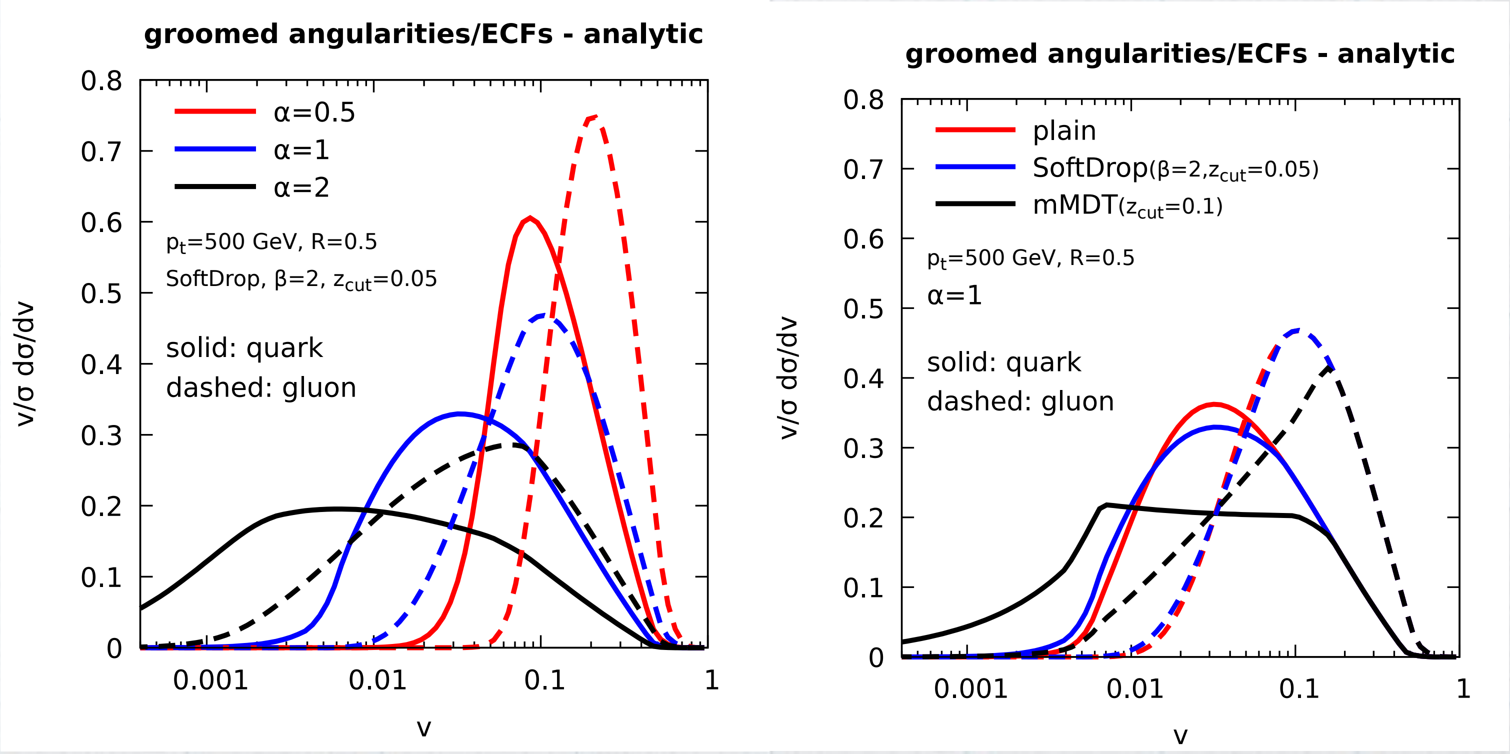




q/g discrimination with shapes

* we can use jet shapes to probe the radiation
* we expect gluon jets to exhibit on average a larger value of a jet shape
* the shape can be an angularity

$$v = \lambda_{1,\alpha}$$



Casimir scaling

* the efficiency of this q/g tagger can be estimated analytically

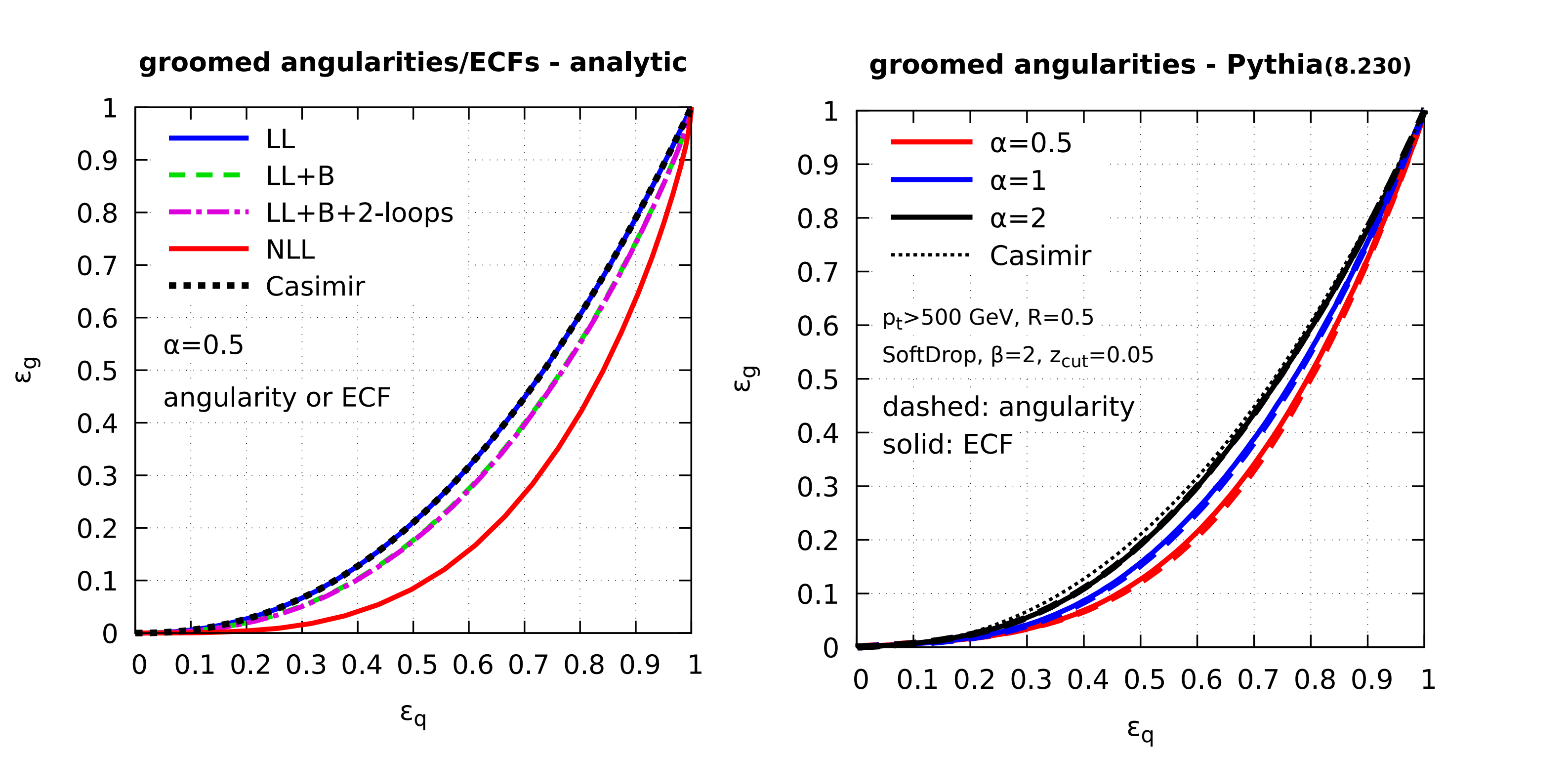
$$\epsilon_q = \int_0^{v_{cut}} dv \frac{d\sigma}{dv} = e^{-\frac{\alpha_s C_F}{\pi} a \log^2 v_{cut} + \dots}$$

$$\epsilon_g = \int_0^{v_{cut}} dv \frac{d\sigma}{dv} = e^{-\frac{\alpha_s C_A}{\pi} a \log^2 v_{cut} + \dots} = \epsilon_q^{\frac{C_F}{C_A}}$$

* at LL we find a universal relation between quark and gluon efficiencies

higher-order corrections

* the inclusion of higher logarithmic terms improves the discrimination power
* for instance, hard collinear contribution $B_g \neq B_q$
* however, analytic results are perhaps too optimistic



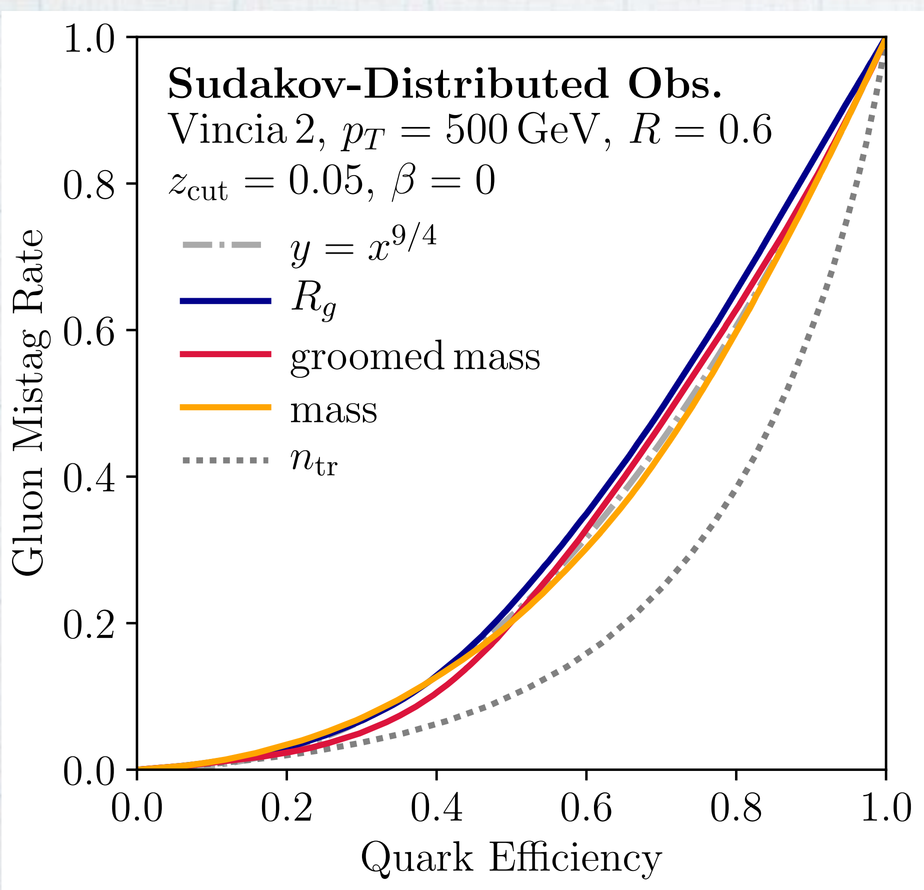
beyond Casimir scaling

* counting observables outperform Casimir scaling

$$\frac{1}{\sigma}\frac{d\sigma}{dn} = e^{-\nu}\frac{\nu}{n!} \Longrightarrow \quad \langle n \rangle = \sigma^2 = \nu \Longrightarrow \quad w_{rel} \sim \frac{\sigma}{\nu} \sim \frac{1}{\sqrt{n}}$$

Poisson distribution

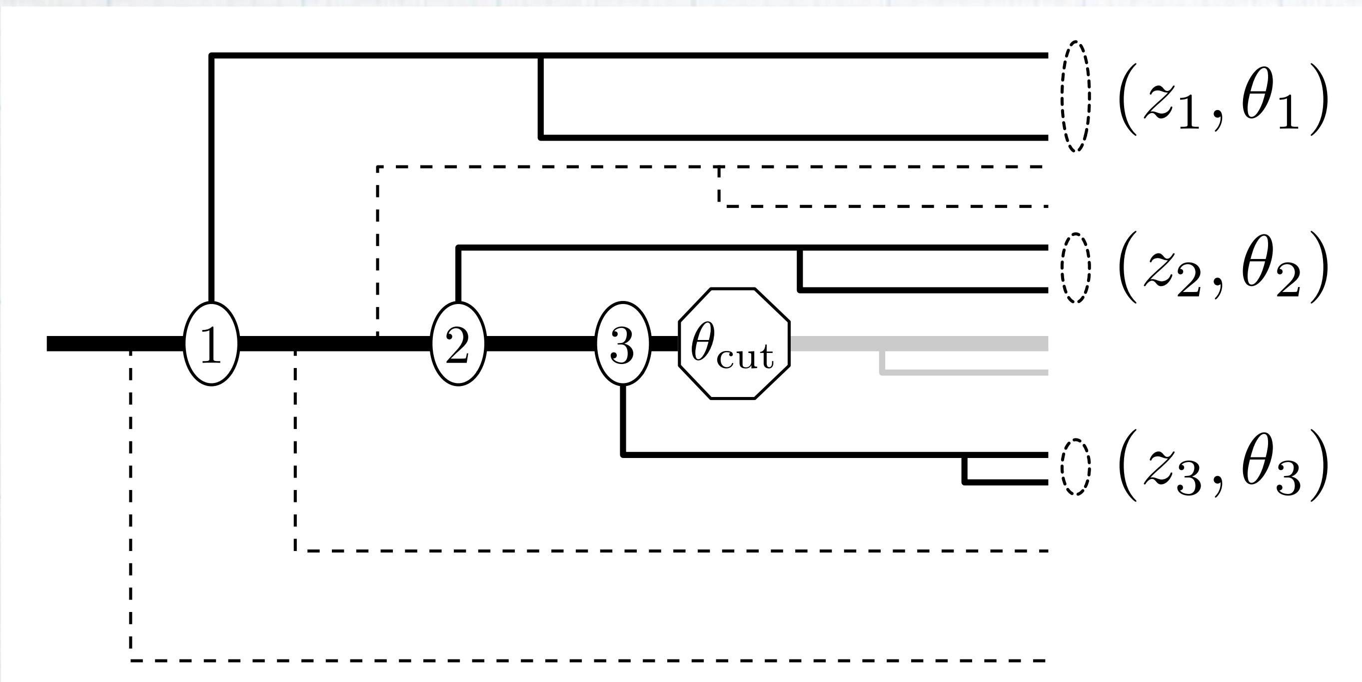
central theorem limit



* number of charged tracks is one of the most powerful q/g discriminant but it's not IRC safe

$$\frac{\langle n_{tr}\rangle_g}{\langle n_{tr}\rangle_q} \simeq \frac{C_A}{C_F}$$

iterative soft-drop



* iteratively apply soft-drop, recording the pairs (z_i, θ_i) that pass the condition, (you need θ_{cut} unless $\beta<0$)

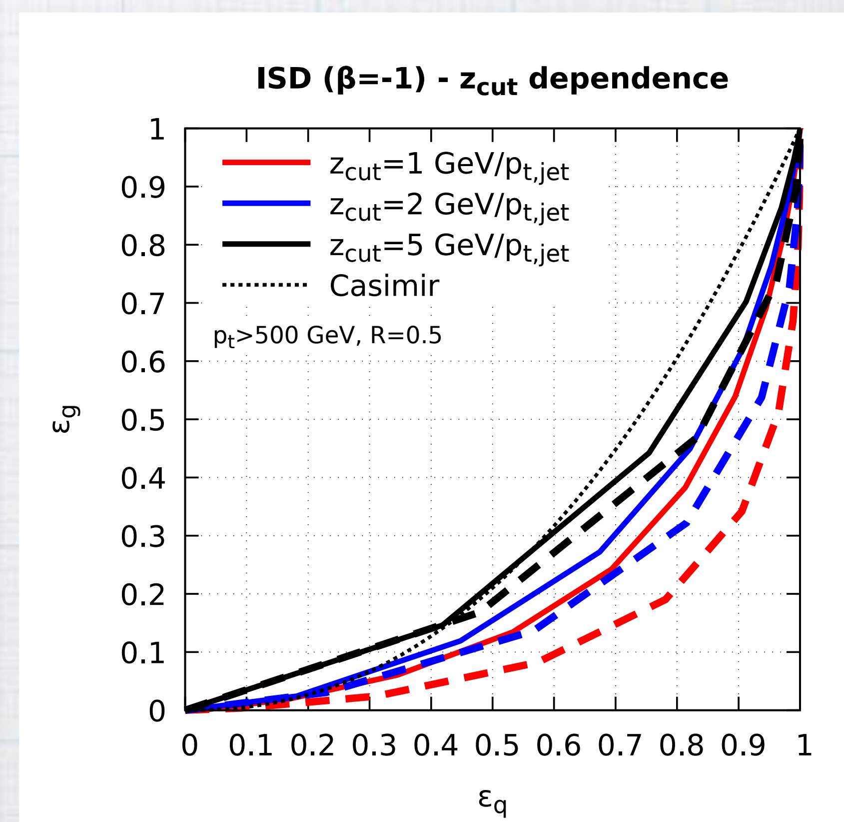
Frye, Larkoski, Thaler, Zhou (2017)

* IRC-safe counting observable

* Poisson distributed

$$\frac{1}{\sigma}\frac{d\sigma}{dn_{ISD}} = e^{-\nu}\frac{\nu^{n_{ISD}}}{n_{ISD}!}$$

with $$\nu = \frac{\alpha_s}{2\pi}\int_0^1 \frac{d\theta^2}{\theta^2}\int_0^1 dz P_i(z)\Theta(z > z_{cut}\theta^\beta)$$



Casimir meets Poisson

* Given that the ISD multiplicity is Poisson-distributed, its mean value is given by ν

* hence at LL

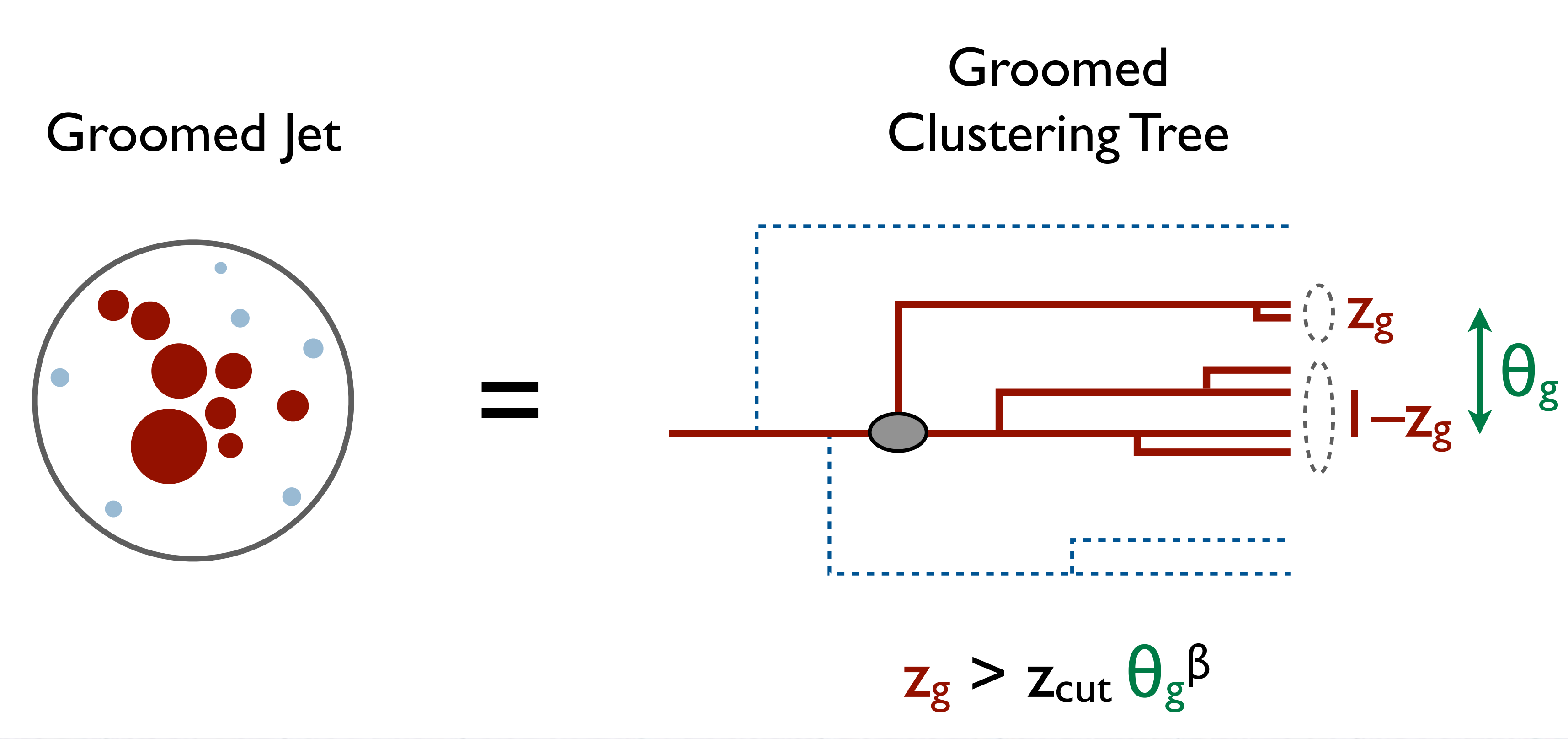
$$\frac{\langle n_{ISD} \rangle_g}{\langle n_{ISD} \rangle_q} = \frac{\nu_g}{\nu_q} \simeq \frac{C_A}{C_F}$$

* same as track multiplicity, but maintaining IRC safety!

homework 7

* compute the LL (fixed-coupling) expression for ISD v in two cases:
  * $\beta<0$
  * $\beta>0$ with a cut on the minimal angular separation θ_{cut}

the prongs' momentum balance



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

in perturbation theory

$$\frac{1}{\sigma}\frac{d\sigma}{dz_g} = \frac{\alpha_s}{2\pi}\int_0^1 \frac{d\theta^2}{\theta^2}\int_0^1 dz\, P_i(z)\, \Theta(z > z_{cut}\theta^\beta)\, \delta(z - z_g)$$

$$= \frac{\alpha_s}{\pi} P_i(z_g) \int_0^1 \frac{d\theta}{\theta} \Theta(z_g > z_{cut}\theta^\beta)$$

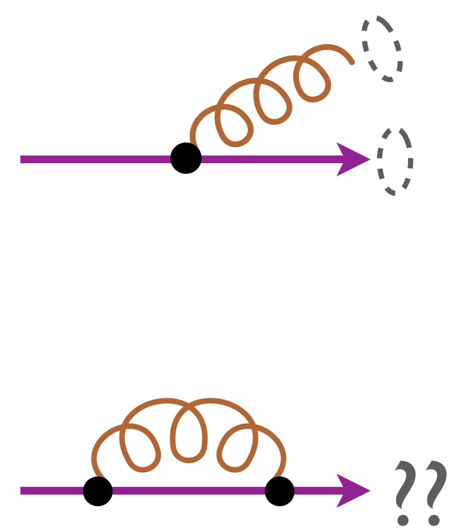
* this is finite only if β<0

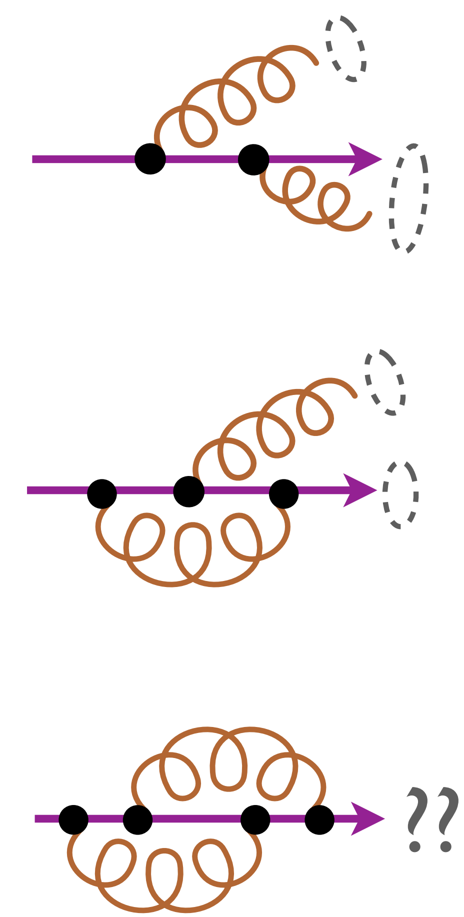
$$\frac{1}{\sigma}\frac{d\sigma}{dz_g} = \frac{\alpha_s}{|\beta|\pi} P_i(z_g) \log\frac{z_g}{z_{cut}} \Theta(z_g > z_{cut})$$

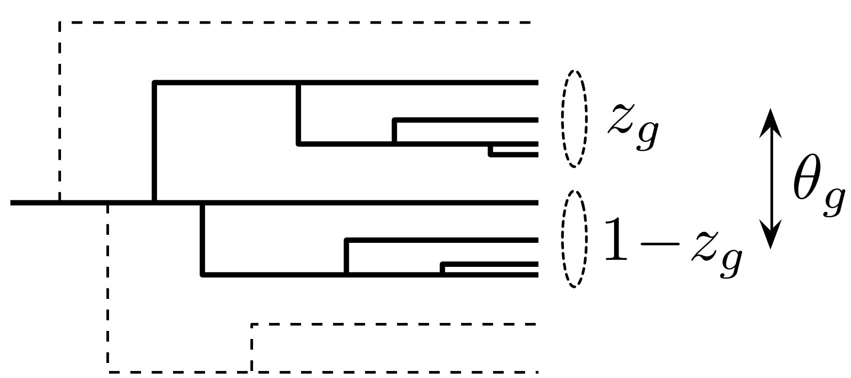
* we cannot take the β->0 limit: indeed the observable is IRC safe only if β<0
* however, we can try and make sense of the observable also in the IRC unsafe regime

in perturbation theory

$$p(z_g) = \Big(\ \text{undefined}\ \Big) + \alpha_s \Big(\ \text{infinity}\ \Big) + \alpha_s^2 \Big(\ \text{infinity}^2\ \Big) + \ldots$$







z_g not IRC safe because Born is ill-defined

Sudakov safety

* in order to resolve singularity, we can demand an opening angle, i.e. we study the conditional probability $p(z_g|\theta_g)$

* we then write

$$p(z_g) = \int_0^1 d\theta_g p(z_g\,|\,\theta_g)p(\theta_g)$$

* if the above expression is finite, we say that z_g is IRC unsafe but Sudakov safe

why Sudakov?

* how is that possible? We need to compute the distribution of the companion observable to all-orders

$$p(z_g) = \int_0^1 d\theta_g p^{FO}(z_g \,|\, \theta_g) p^{resum}(\theta_g)$$

finite conditional probability for $\theta_g > 0$

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

* we now need an all-order expression for the angular variable

calculation

putting things together

- for β≥0, we have

$$p^{FO}(z_g \,|\, \theta_g) = \frac{p^{FO}(z_g, \theta_g)}{p^{FO}(\theta_g)} = \frac{P_i(z_g)}{\int_{z_{cut}\theta^\beta}^{1} dz\, P_i(z)}$$

$$p^{resum}(\theta_g) = \frac{d}{d\theta_g} e^{\left[-\frac{\alpha_s}{\pi}\int_{\theta_g}^{1}\frac{d\theta}{\theta}\int_0^1 dz\, P_i(z)\,\Theta\left(z > z_{cut}\theta^\beta\right)\right]}$$

- the final integral can be done for all values of β, but the β=0 is particularly simple and reveals fascinating properties

the β=0 case

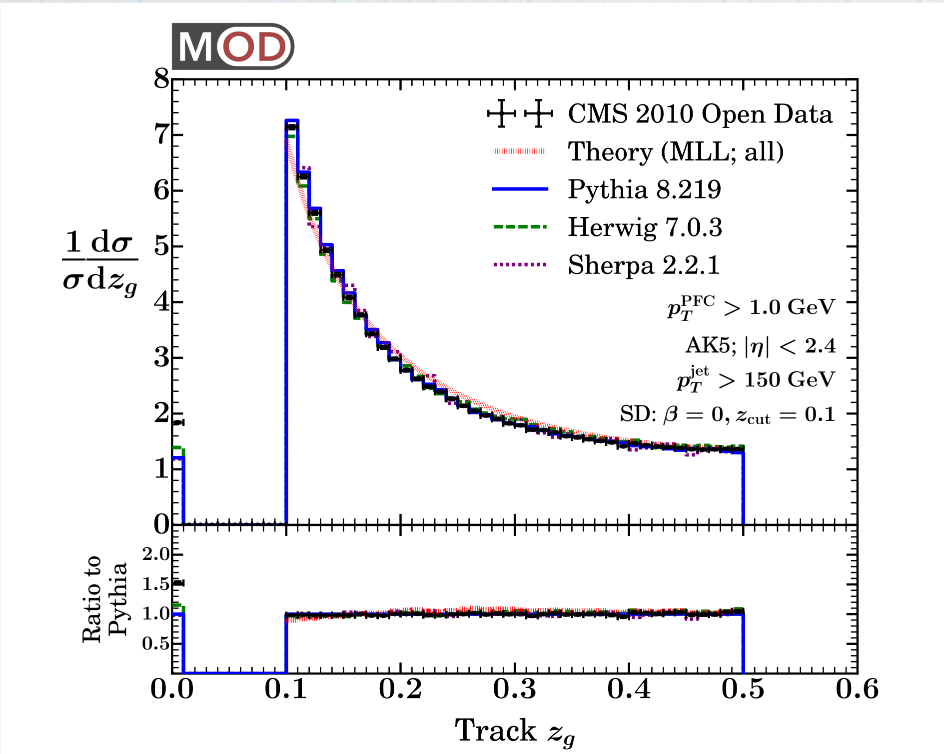
* we have

$$\frac{1}{\sigma}\frac{d\sigma}{dz_g} = \frac{P_i(z_g)}{\int_{z_{cut}}^{1} dz\, P_i(z)} \int_0^1 d\theta_g \frac{d}{d\theta_g} e^{\left[-\frac{\alpha_s}{\pi}\int_{\theta_g}^{1}\frac{d\theta}{\theta}\int_0^1 dz\, P_i(z)\,\Theta\left(z > z_{cut}\right)\right]}$$

$$= \frac{P_i(z_g)}{\int_{z_{cut}}^{1} dz\, P_i(z)}$$

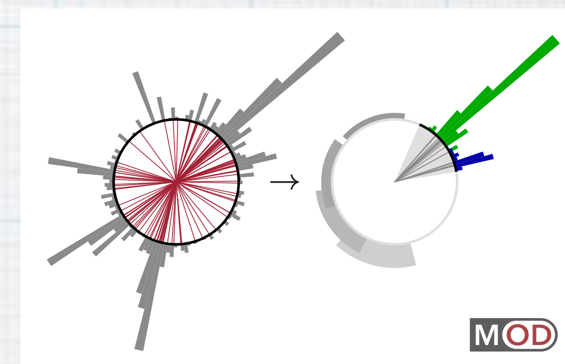
* finite result that show NO dependence on the strong coupling!
* it's just the QCD splitting function

what do the say say?



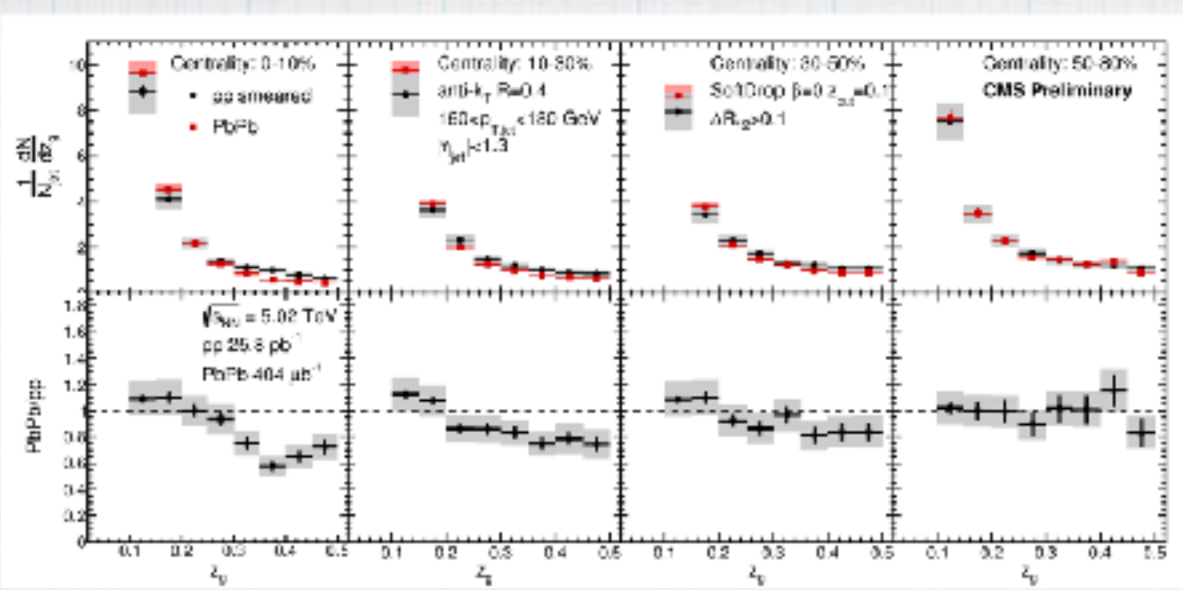
* first research-level physics study that utilises CMS Open Data

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

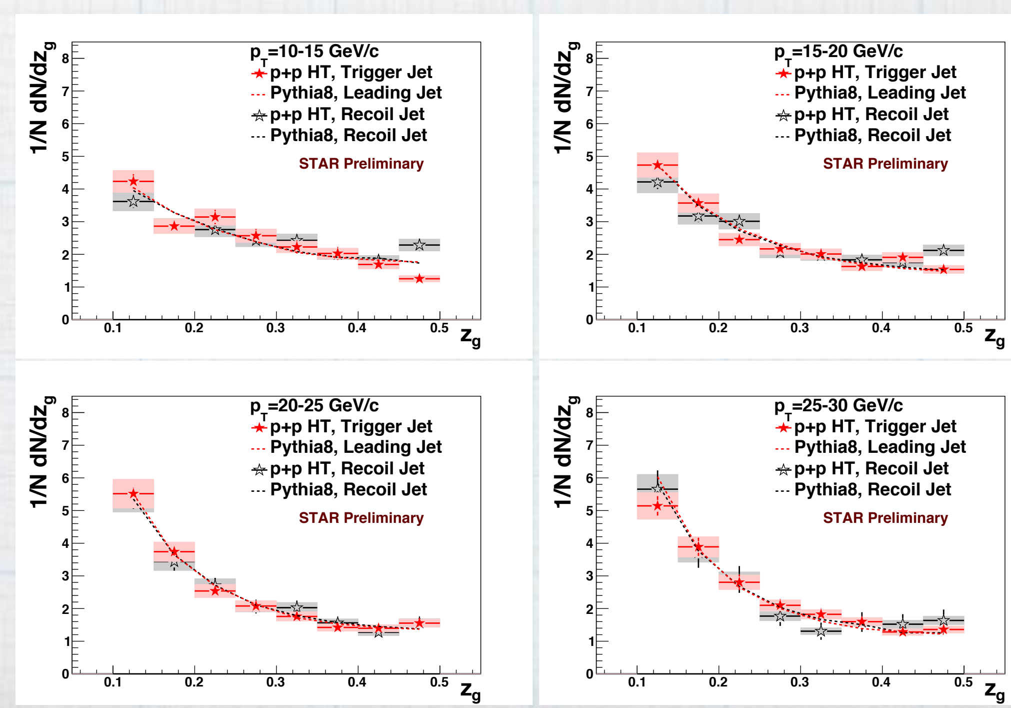


* also a probe of the quark gluon plasma

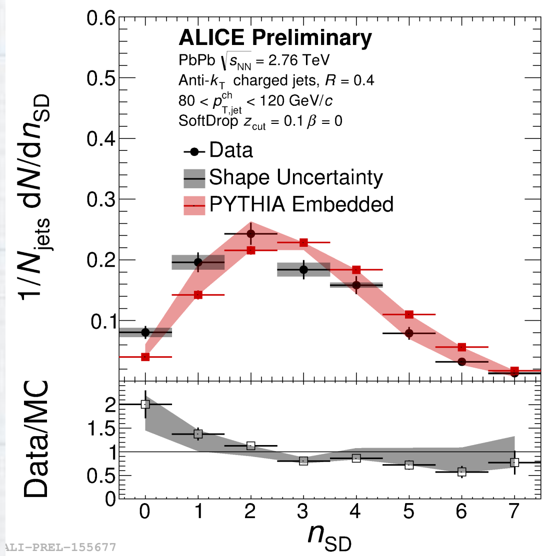
STAR Au-Au

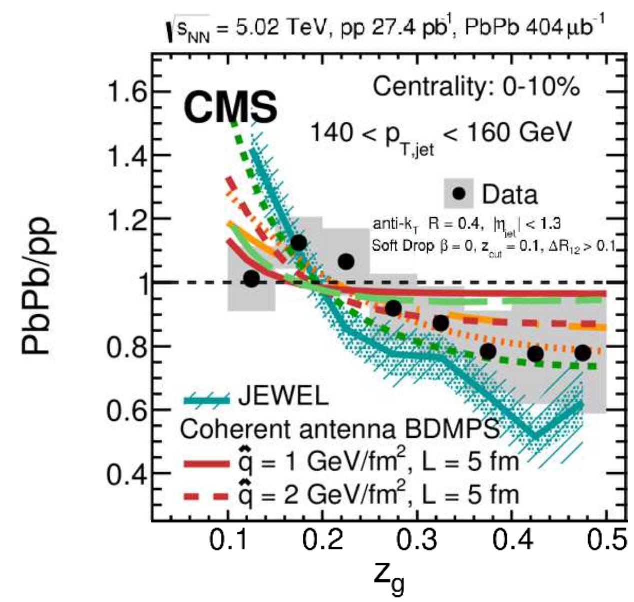


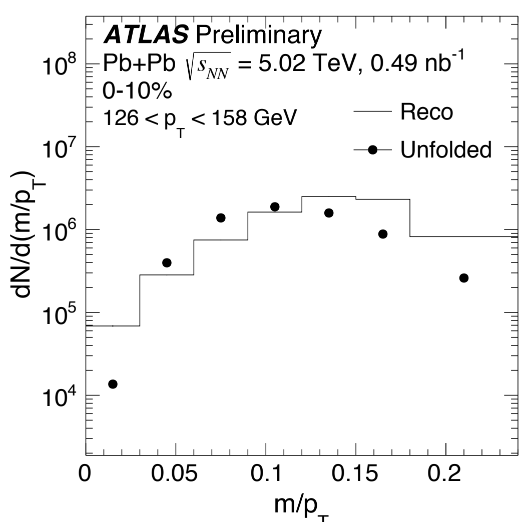
CMS Pb-Pb

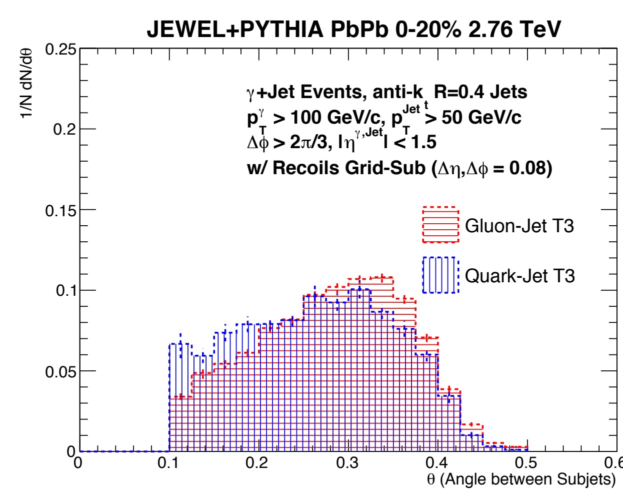


jet substructure goes nuclear









courtesy of Jesse Thaler

* jets offer a unique probe of the quark-gluon plasma
* theoretical and experimental results are pouring in

homework 8

- Compute the Sudakov-safe integral for $\beta>0$ and show that you obtain a non-analytic expansion in the square-root of α_s.
- Repeat the exercise for the IRC safe case $\beta<0$ and show that its expansion is now analytic in α_s and it reproduces the first-order result discussed during the lecture.

resources

* SM, M. Spannowsky, G. Soyez, "Looking inside jets: an introduction to jet substructure and boosted-object phenomenology"
* the BOOST report series
* Les Houches reports 2015 & 2017
* G. Salam: "Towards jetography"
* G. Soyez: "Pileup mitigation at the LHC: a theorist's view"
* Gras et al. "Systematics of quark/gluon tagging"