Part 4: The Substructure (R)evolution

Last time: Quarks vs. Gluons — 1-prong jets

Core difference: C_F vs. C_A

Analytically tractable in strongly-ordered limit

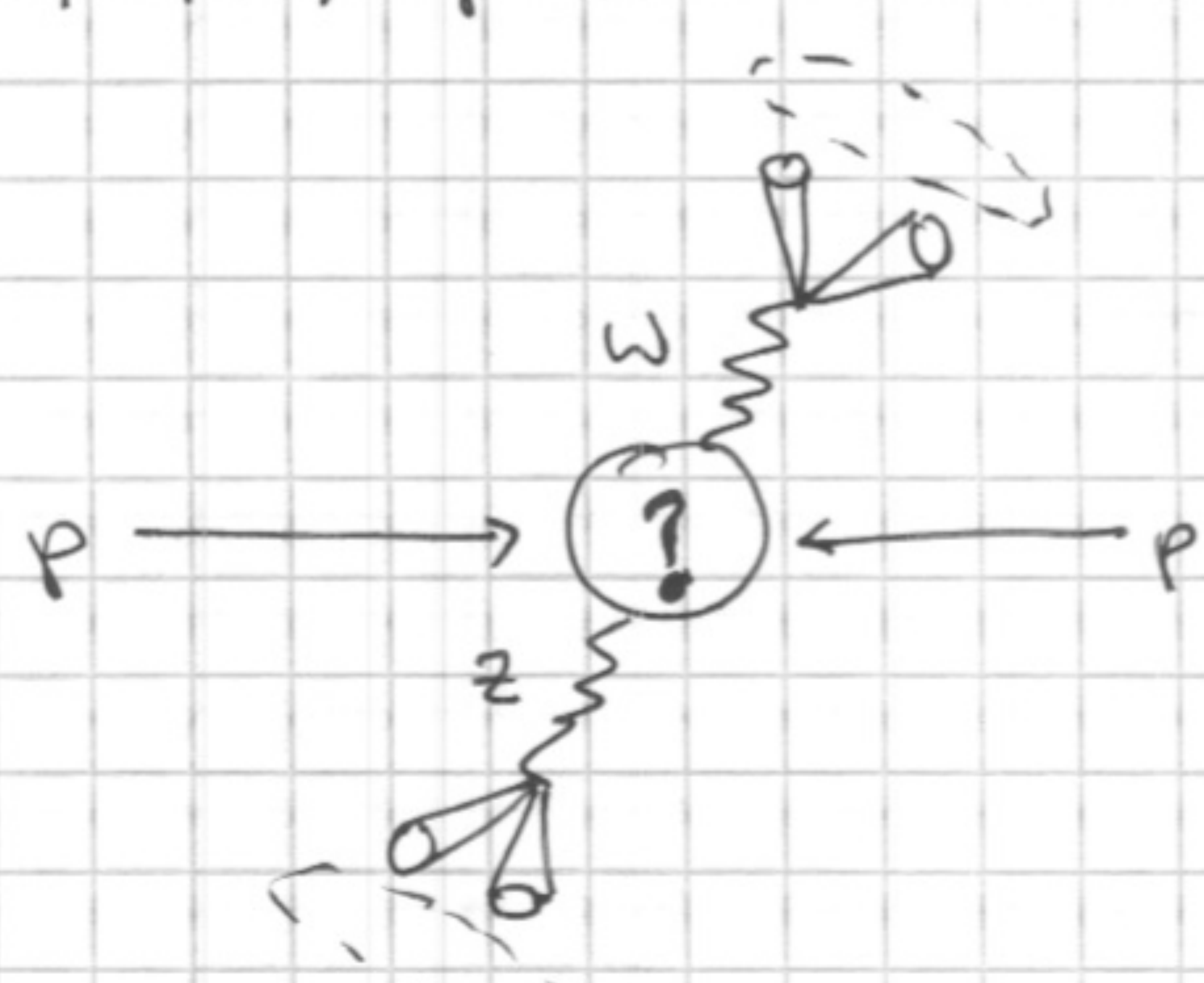
This time: { W / Z / Higgs — 2-prong jets; top quark — 3-prong jets

Active research area to gain analytic control.

Physics to exploit: In extreme kinematic circumstances, W/Z/H/top can look like single jet.

E.g. ATLAS diboson excess

$m_X \approx 2\, p_{T(W/Z)}$



$$p_{TZ} \approx p_{T1} + p_{T2} \qquad m_Z^2 \approx p_{T1}\, p_{T2}\, R_{12}^2$$

For $p_{TZ} \gg \dfrac{2 m_Z}{R_{jet}}$, boosted boson looks like single jet

Common misconception:

"W/Z/H jet has mass of 80/91/125 GeV
whereas quarks & gluons are massless"

Wrong! quark & gluon <u>jets</u> are massive.

Exercise: using soft-collinear limit, show that

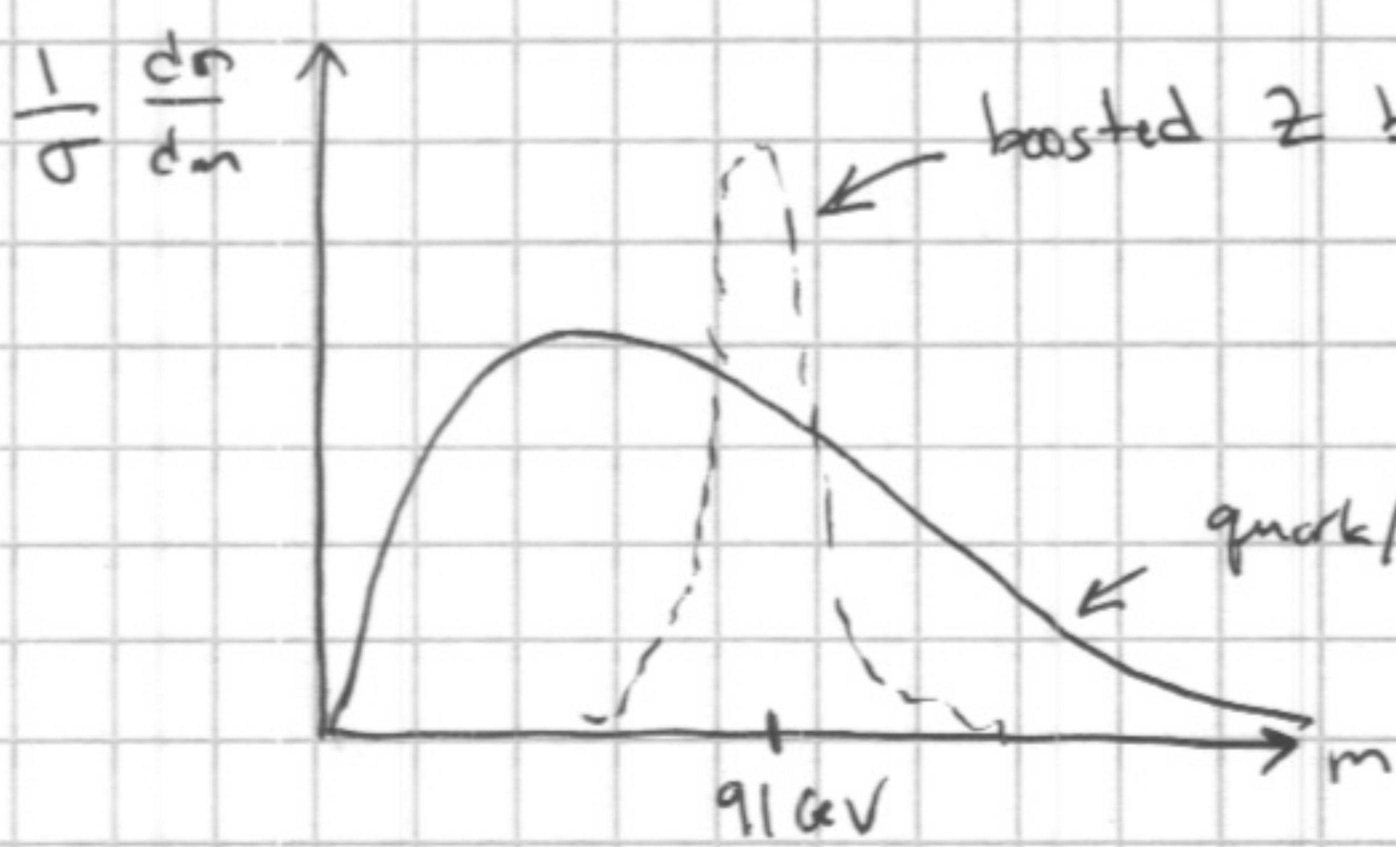
$$\langle m_{jet}^2 \rangle \approx \frac{\alpha_s C_{F,A}}{\pi} p_{T\,jet}^2 R^2$$

vs.

$$m_{W/Z/H}^2 \approx \frac{1}{2} p_{T\,jet}^2 R_{12}^2$$

Need observables to distinguish these two cases.

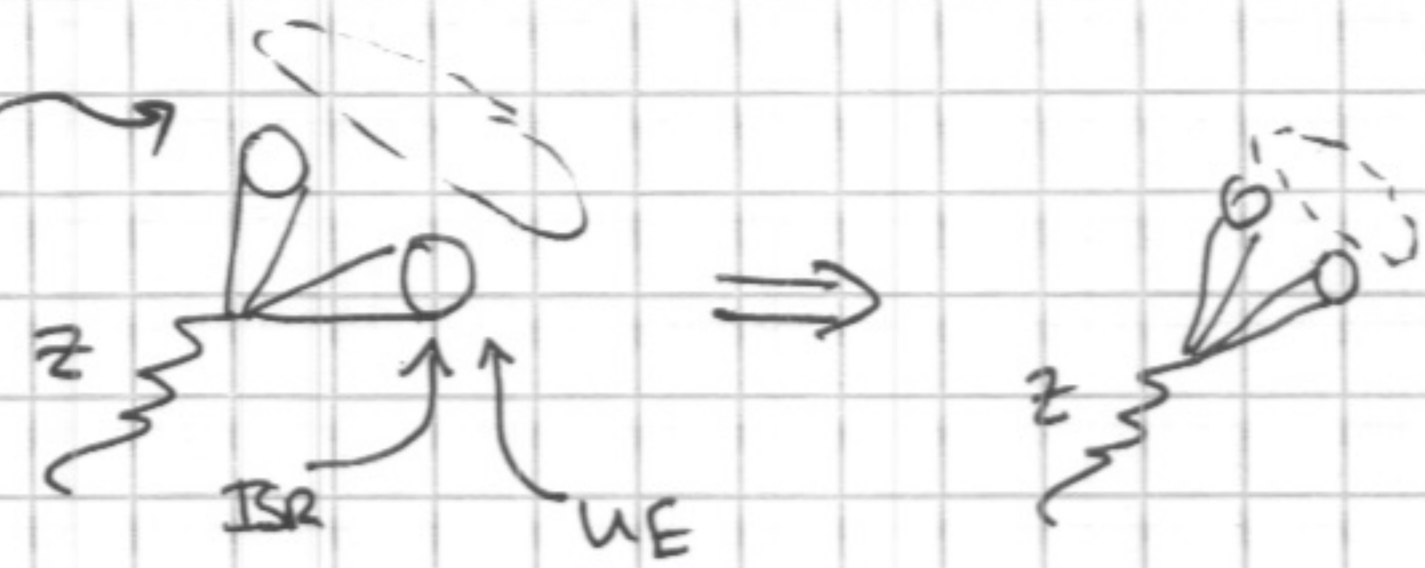
Obvious choice: Jet mass



Jet Substructure: Expanding toolbox of approaches to tag origin of jet

Broad Categories of Substructure Techniques

Jet Cleaning:

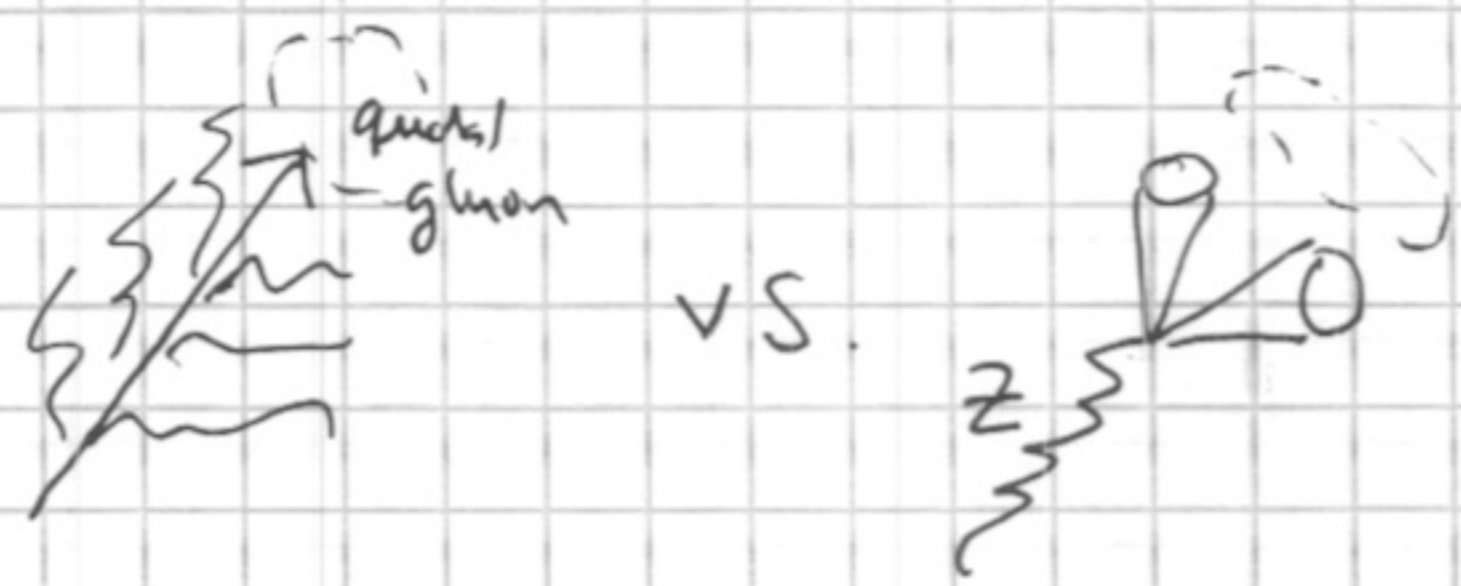


Remove contamination to improve resonance mass resolution

→ Pileup Mitigation: Address uniform contamination

→ Jet Grooming: Address "lumpy" contamination

Jet Discrimination:



Identify prong-like structures within jet

→ Leading order: Identify N-prong kinematics

→ Subleading order: Measure radiation around N prongs.

Over past 8 years, $\mathcal{O}(5\text{-}20)$ good ideas in each of these categories.

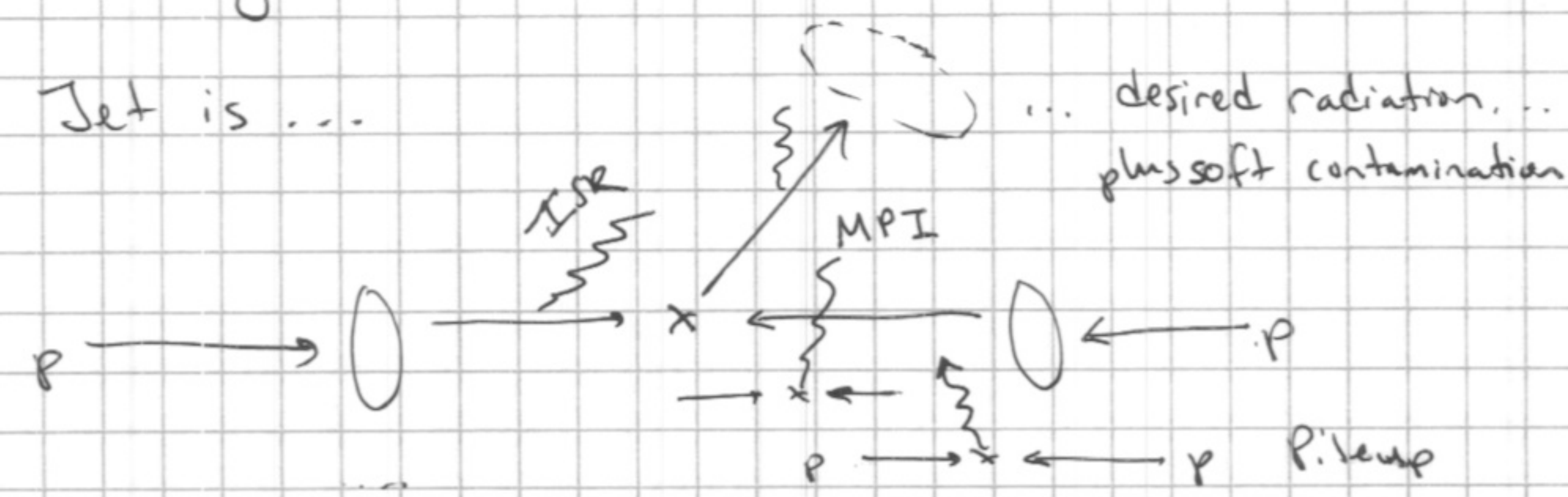
(Precursor work by Seymour in 1990's.)

I'll show you 3 examples and explain how they work.

No attempt to be exhaustive.
New ideas welcome!

Jet Cleaning: Recall lecture 1

Jet is ...

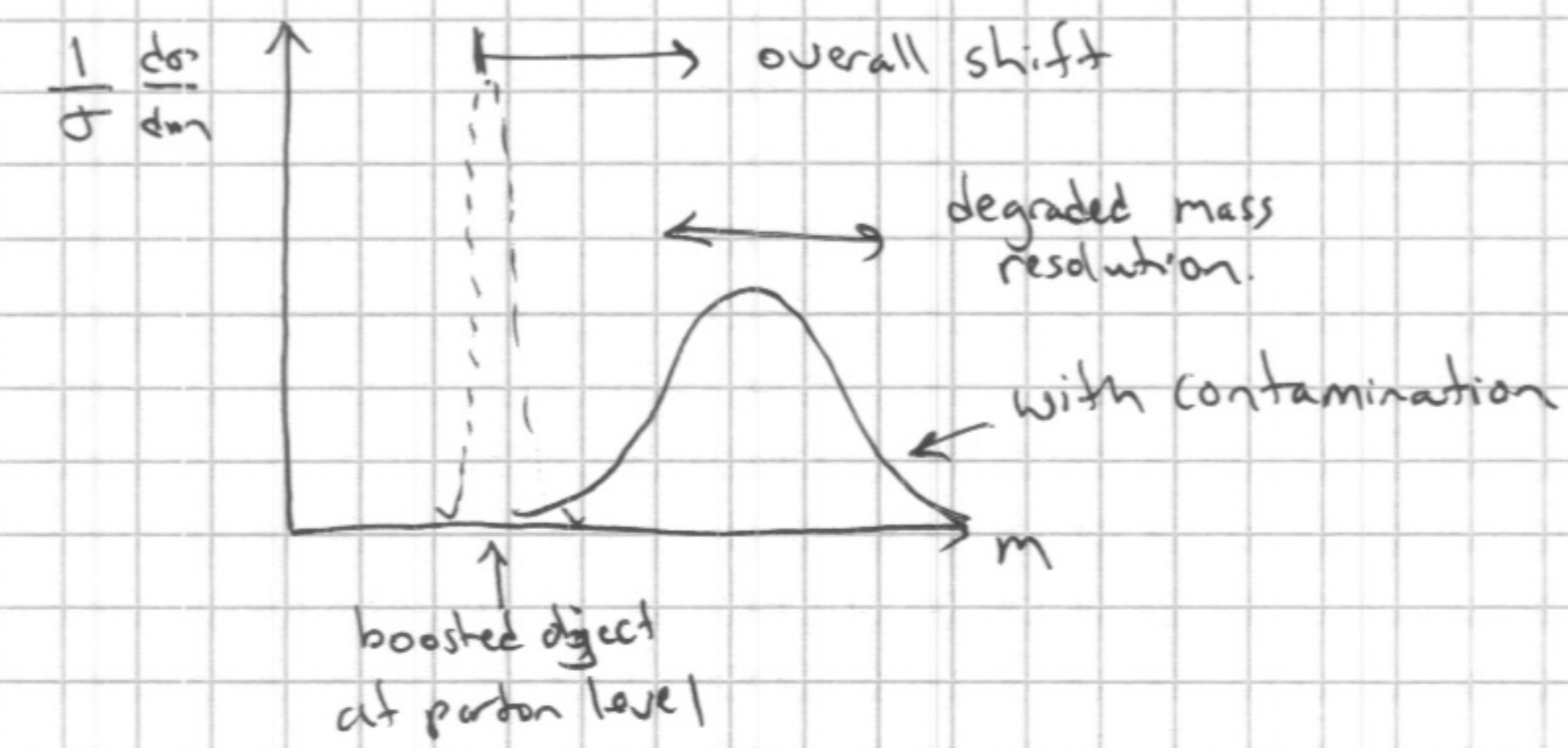


Easiest to understand is pileup, which is uncorrelated radiation from secondary collisions

Charged pileup: Easy to remove with good enough tracking

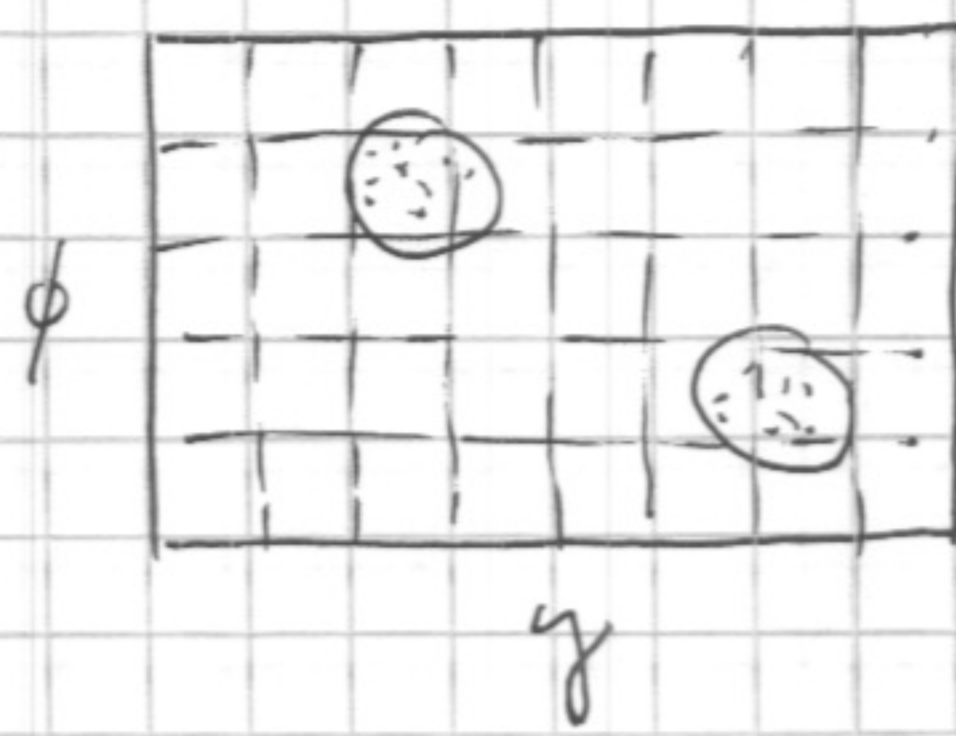
Neutral pileup: Try to remove statistically.

Why does it matter?



Method 1: Soft Killer (2014)

Take event and divide into patches



Starting from the softest p_T particle, remove until half the patches are empty.

One free parameter (patch size)

IRC safe? Nope, but appears to work well in practice.

Why does this work?

Balance between having pileup contamination and removing "good" particles.

When half the patches are empty, median contamination is zero.

(See also Area Substraction, Jet Cleansing, PUPPI, Constituent Subtraction ...)

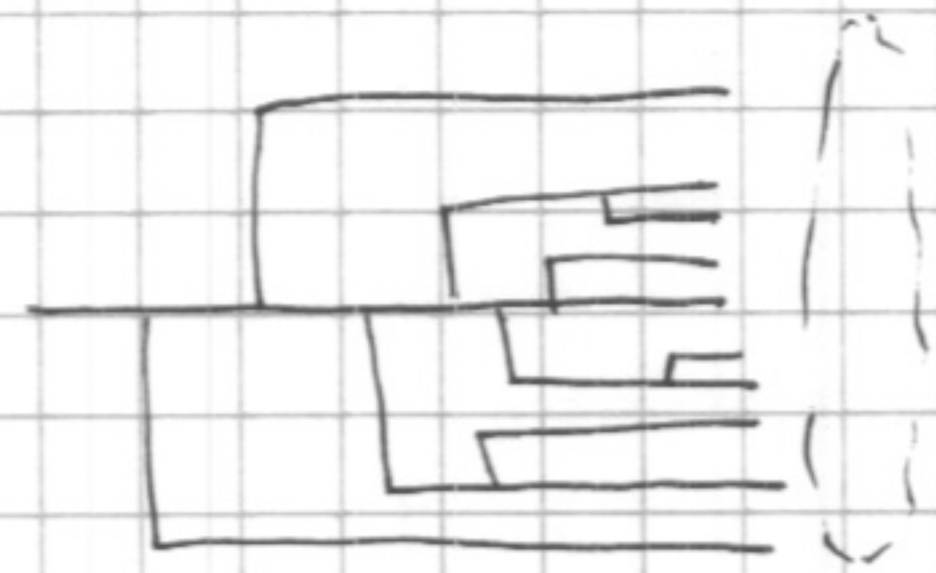
for other Pileup Mitigation Strategies

Method 2: Soft Drop (2014)

started substructure industry with $H \to b\bar{b}$

[Inspired by BDRS (2008),
mMDT (2013) & Semi-classical Jets (2013)]

Take a jet and recluster with C/A algorithm to form an angular-ordered tree



Decluster the jet, discarding the softer branch, ...

... until "soft drop condition" is satisfied.

$$z > z_{cut}\, \theta^{\beta}$$

$$z \equiv \frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} \qquad \theta = \frac{R_{12}}{R}$$

← look familiar?

Accomplishes three things:

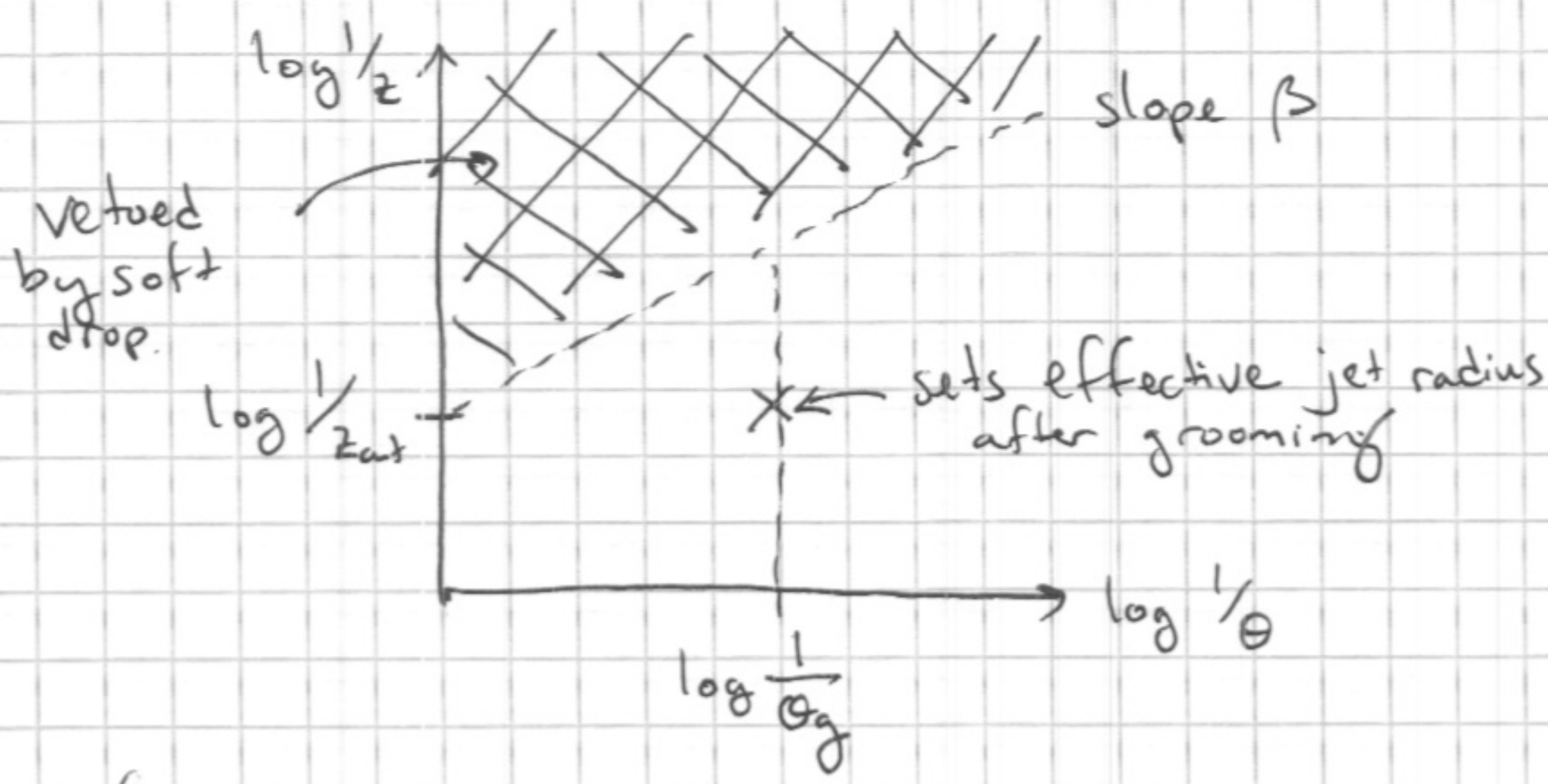
1) Removes soft radiation from periphery of jet (because C/A tree)
2) Dynamically shrinks jet radius to match hard core

} Jet Cleaning

3) Gives two prong kinematics through $\underbrace{z_g, \theta_g}_{\text{values that pass soft drop}}$ observables

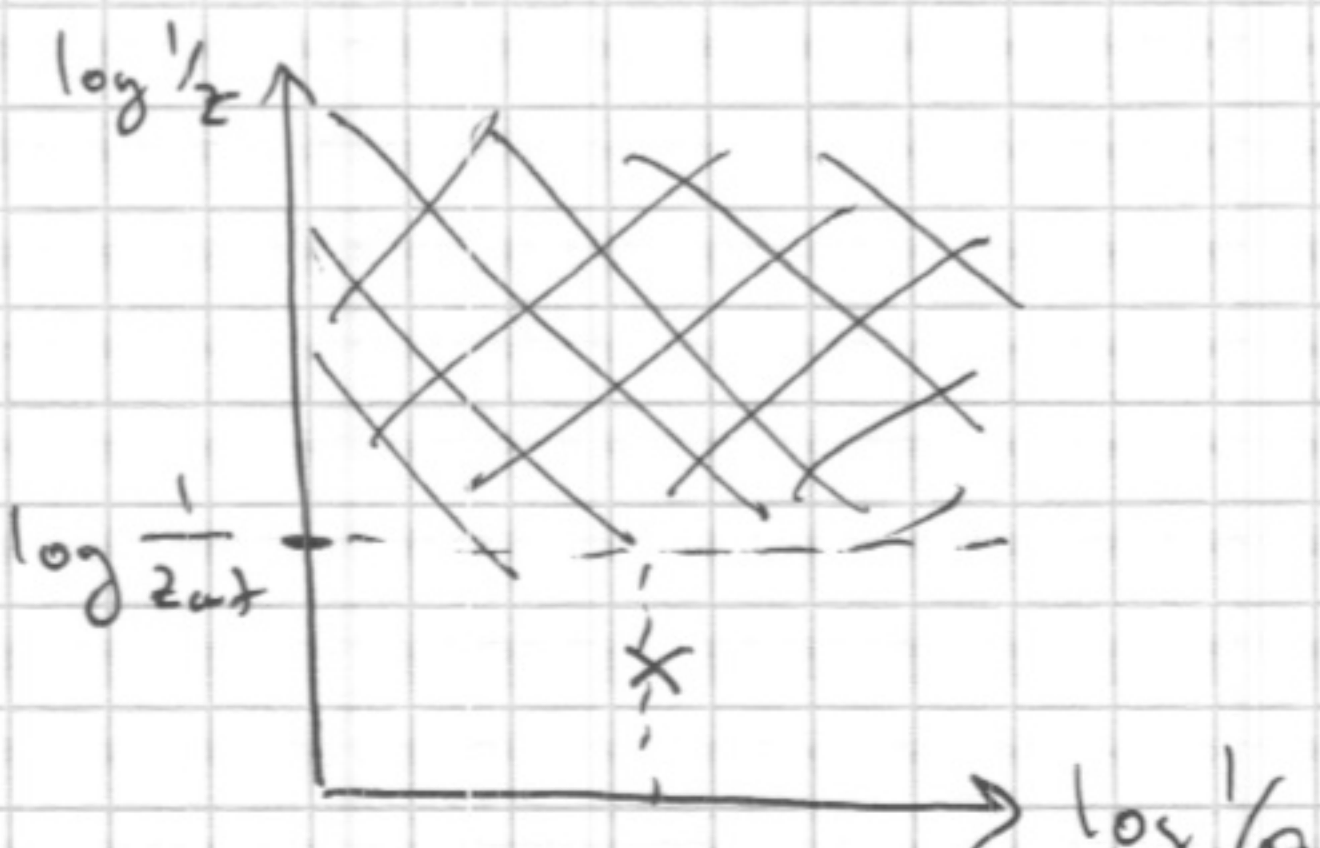
} Jet Discrimination

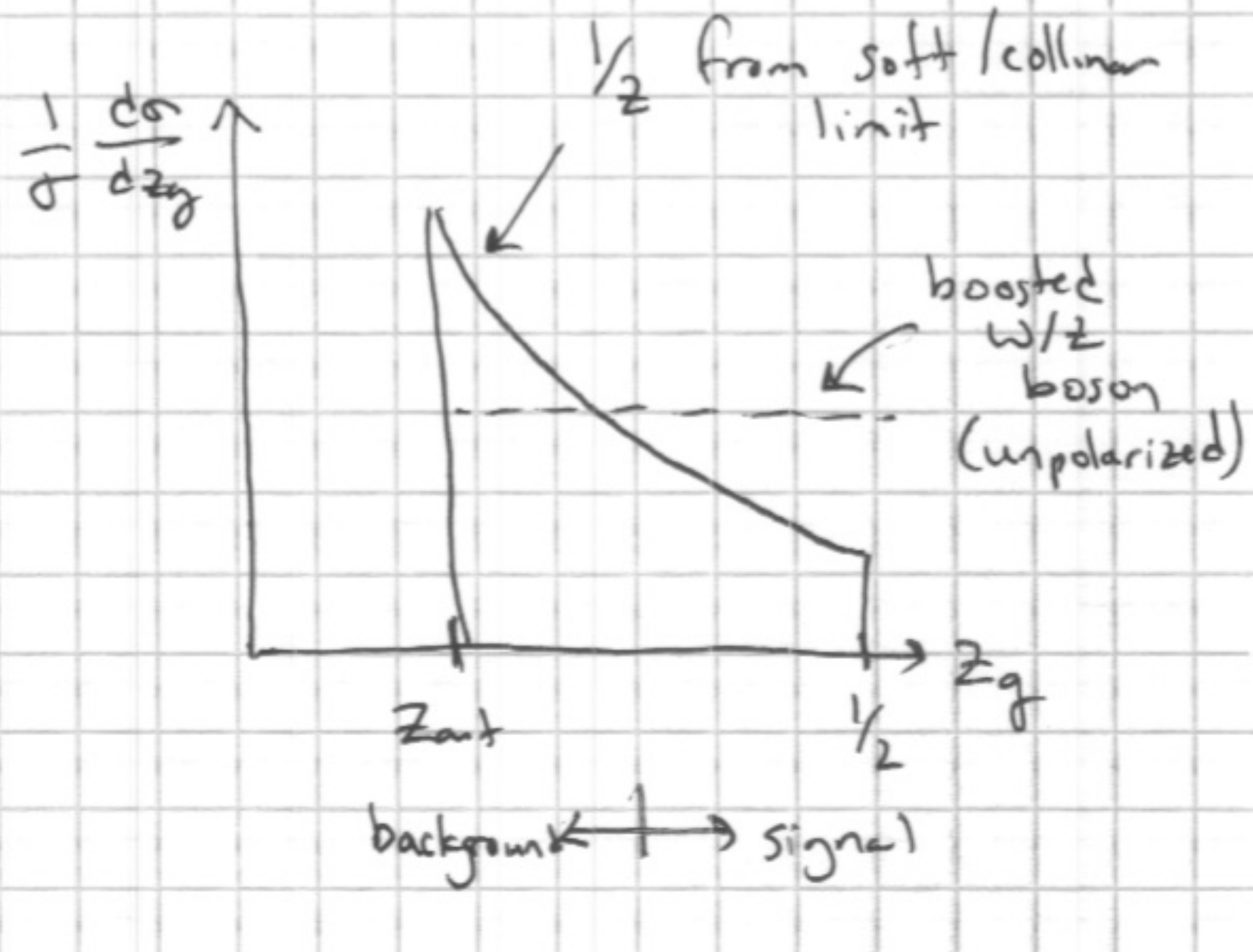
Let's see this in $\left(\log \frac{1}{\theta}, \log 1/z\right)$ plane.



(Can you use results of last lecture to calculate $\rho(\theta_g)$?)

ATLAS diboson excess effectively uses $\beta = 0$ grooming (i.e. original BDRS method) and uses z_g as discriminant.





Is z_g IRC safe?

Well, not really... soft safe, but collinear confusion.

$\longrightarrow$ z_g undefined $\qquad$ $\xrightarrow{z_g}$ $\longrightarrow 1-z_g$ perfectly fine, if $\theta_g > 0$

Turns out that you can do a trick to calculate z_g.

$$p(z_g) = \int d\theta_g \; \underbrace{p(\theta_g)}_{\text{resum using techniques of last lecture}} \; p(z_g \mid \theta_g)$$

$p(z_g \mid \theta_g) = \frac{1}{\text{norm}} \frac{1}{z_g} \Theta(z_g > z_{cut}) + \mathcal{O}(\alpha_s)$

(for $\beta = 0$, doesn't care about θ_g value.)

$$= \frac{1}{\text{norm}} \frac{1}{z_g} \Theta(z_g > z_{cut})$$

bizarre! No α_s at leading order

No C_A or C_F.

Just soft singular structure of QCD.

(For $\beta > 0$, turns out expansion parameter is $\sqrt{\alpha_s}$. Ask me offline.)

(See also filtering, trimming, pruning, jet reclustering ...

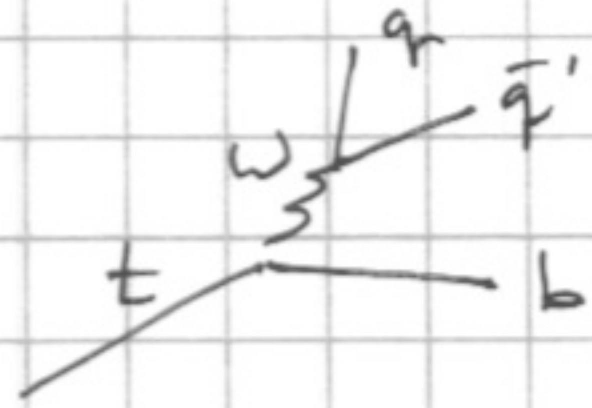
for other jet grooming strategies)

Method 3: N-subjettiness (2010)

[Inspired by N-jettiness (2010), recall XCone jet algorithm in lecture 2]

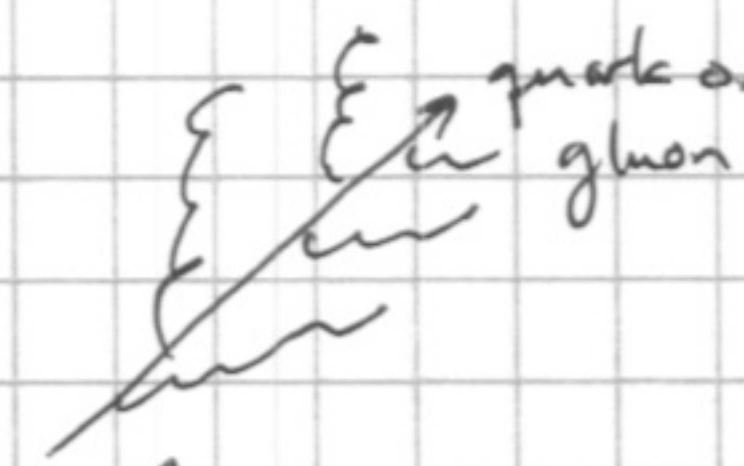
Want observable that goes to zero for a jet with exactly N prongs.

e.g.



3-prong

vs.

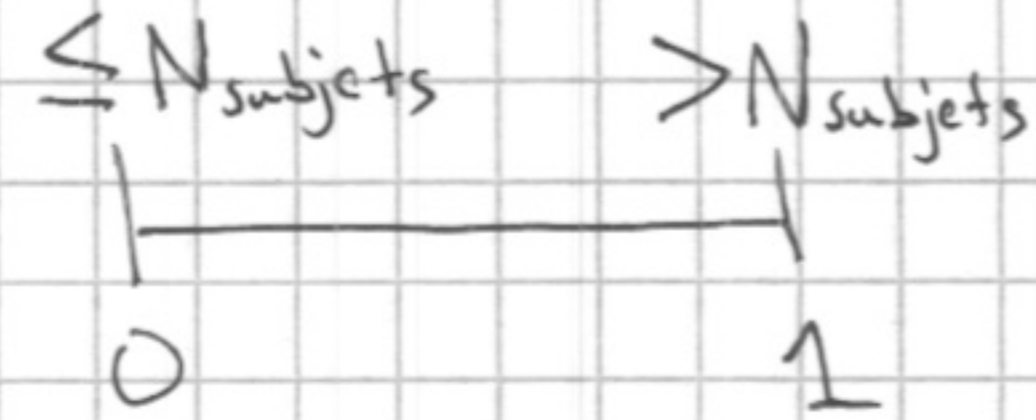


1-prong

$$\tau_N^{(\beta)} = \frac{1}{d_0} \sum_{i \in \text{jet}} p_{T_i} \min\{R_{i1}, R_{i2} \cdots R_{iN}\}^{\beta}$$

N axes chosen by some method, e.g. by minimizing τ_N

$\tau_N^{(\beta)}$:



Why does it work?

Actually, by itself τ_N is not an effective discriminant...

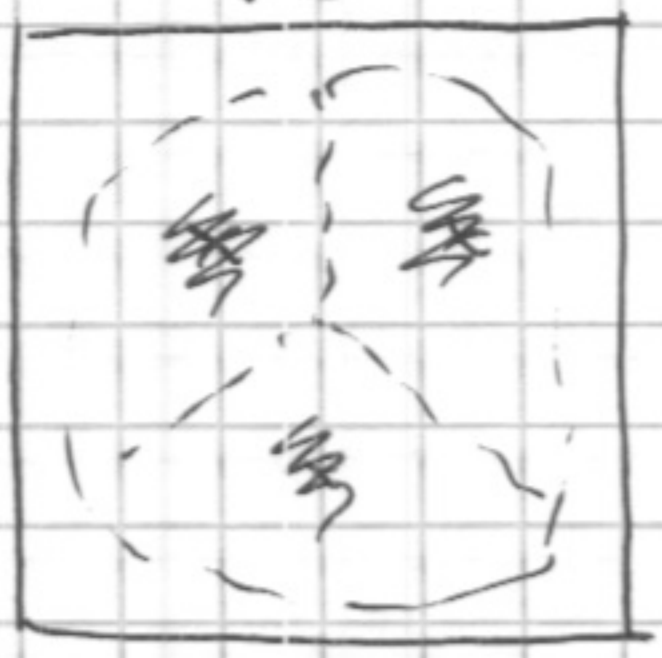
But τ_N / τ_{N-1} is rather good.

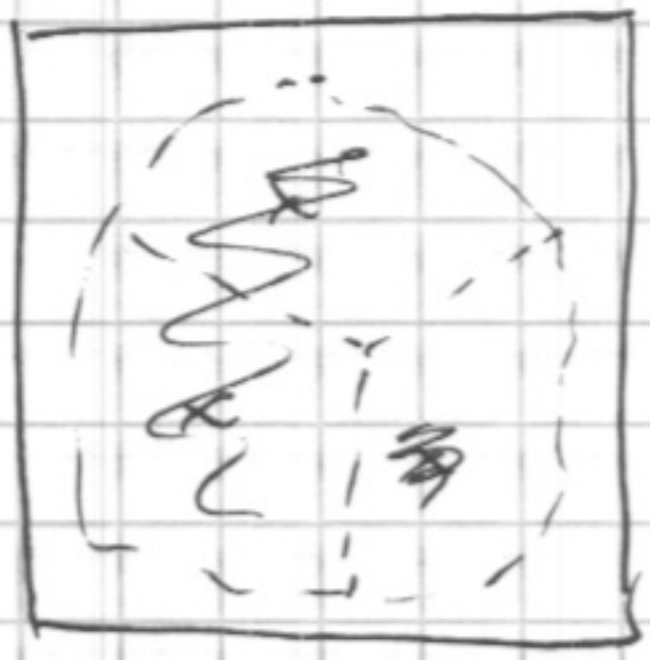
Consider a boosted top ($t \to bW$, $W \to jj$)
versus QCD jet with $m_{jet} \approx 170$ GeV

top jet

QCD jet

τ_3

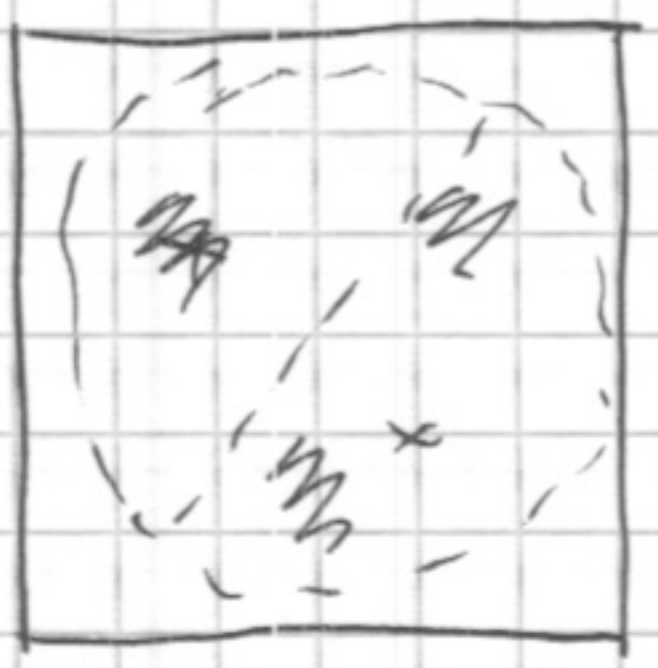




Axes "lock on" to correct substructure.
τ_3 is small

Indeterminant substructure
τ_3 is ambiguous.

τ_2



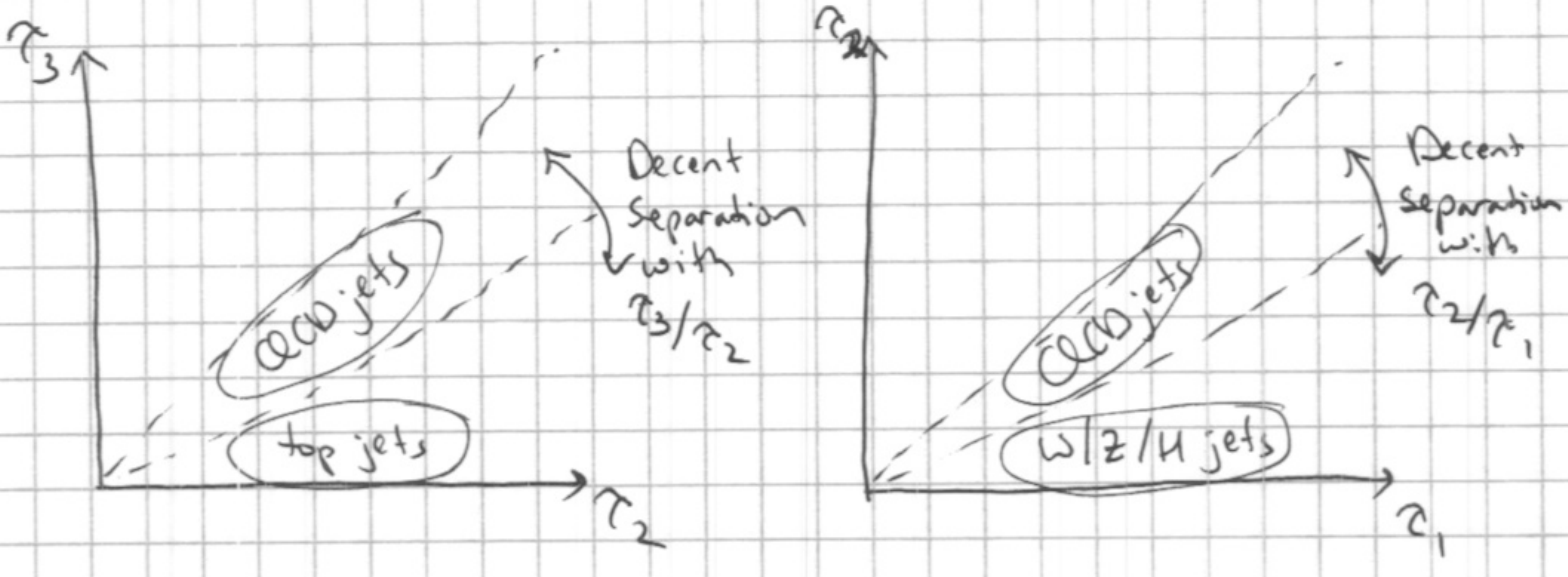
Not very 2-prong-like
τ_2 is large

Still indeterminant substructure
$\tau_2 \approx \tau_3$ is ambiguous.

$$\tau_3/\tau_2 \to 0 \qquad \tau_3/\tau_2 \sim \mathcal{O}(1)$$

(For boosted W/Z/H $\quad \tau_2/\tau_1 \to 0$ while $\tau_2/\tau_1 \sim \mathcal{O}(1)$)

Using power counting methods you can make this logic more rigorous (see "D_2" for 2-prong, calculable observable)



Can use the β exponent to further refine discrimination power.

(See also Y-splitter, angularities, planar flow, energy correlation functions, subjet counting, angular structure functions, jet charge, jet pull, dipolarity, Zernike Coefficients, rest frame Fox-Wolfram moments, ... for other discriminant observables.)

(See more aggressive strategies in JHUTopTagger, HEPTopTagger, Template Method, Wavelets, Q-jets, Telescopic Jets, Shower Deconstruction ...)

I have given you a brief tour of the field of jet substructure. Much more happening as part of BOOST workshop series (last week in Zurich!) Active area, and still room for new ideas.

Current hot topics:

- → Jet Physics from Deep Learning
- → Multivariate approaches
- → Resummation of Non-global logarithms
- → Small radius jets.
- → ...