QCD CALCULATIONS FOR JET SUBSTRUCTURE

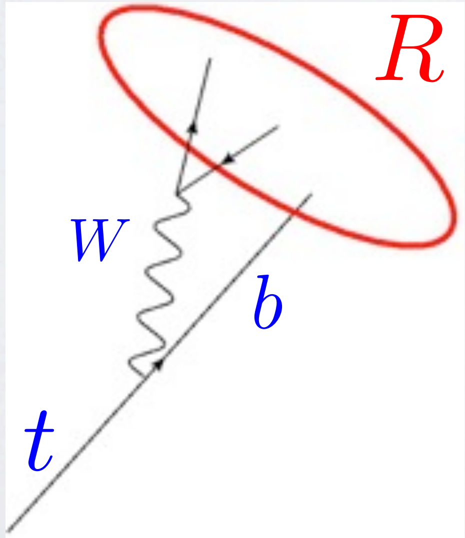
Simone Marzani
Institute for Particle Physics Phenomenology
Durham University

RADCOR 2013
11th International Symposium on Radiative Corrections
(Applications of Quantum Field Theory to Phenomenology)
22nd-27th September 2013

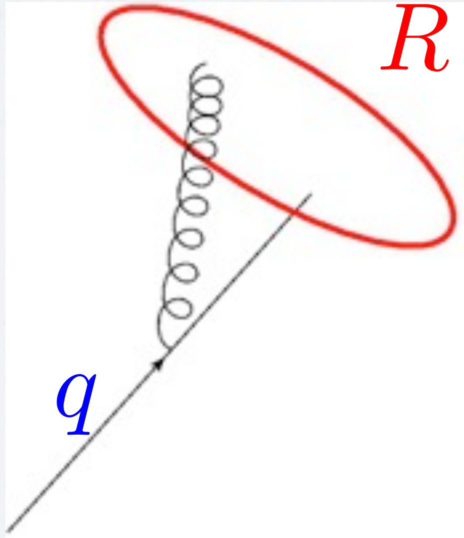
with
M. Dasgupta, A. Fregoso, G. P. Salam and A. Powling
arXiv:1307.0007 and 1307.0013

The boosted regime

- The LHC is exploring phenomena at energies above the EW scale
- Z/W/H/top can no longer be considered heavy particles
- These particles are abundantly produced with a large boost
- Their hadronic decays are collimated and can be reconstructed within a single jet. Need to distinguish:



from QCD



$$p_t \gg m$$

Grooming and tagging

- The last few years have seen a rapid development in substructure techniques: O(10-20) powerful methods to tag jet substructure

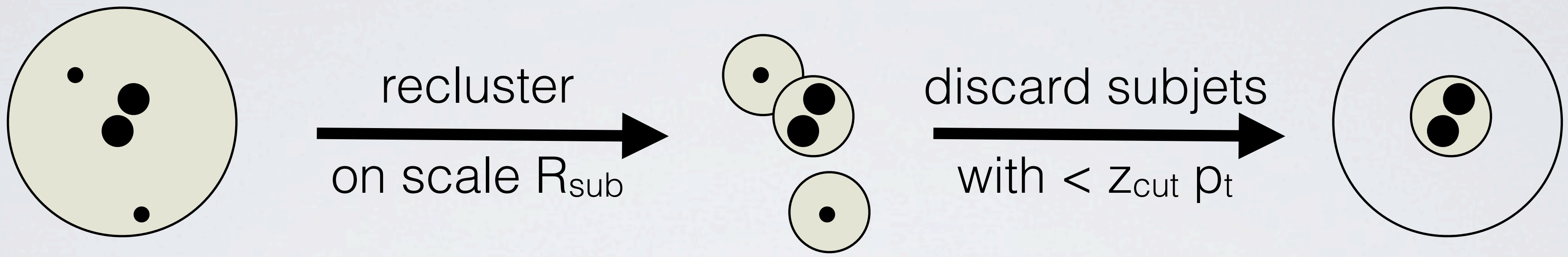
- Many of the methods have been tried out in searches and work; they will be crucial for searches in the years to come

- Many methods can lead to some confusion
- Do we understand how / why they work ?
- Only analytic understanding can give this field *robustness*

Where to start ?

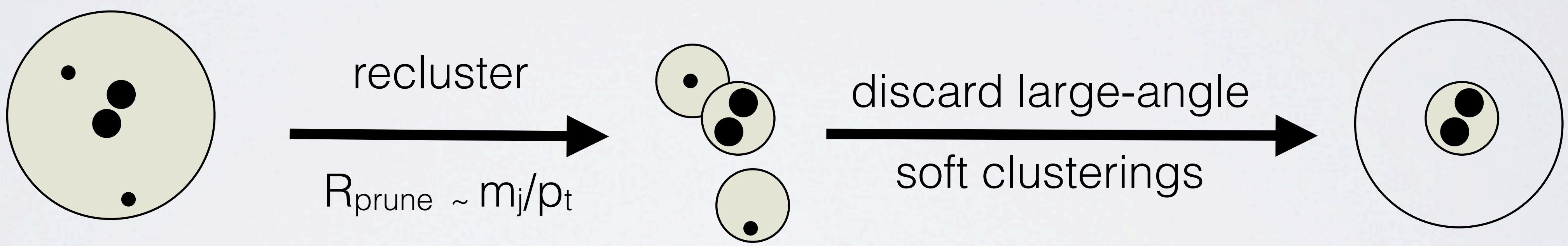
Cannot possibly study all tools
These 3 are widely used
We concentrate on background (QCD jets)

Trimming



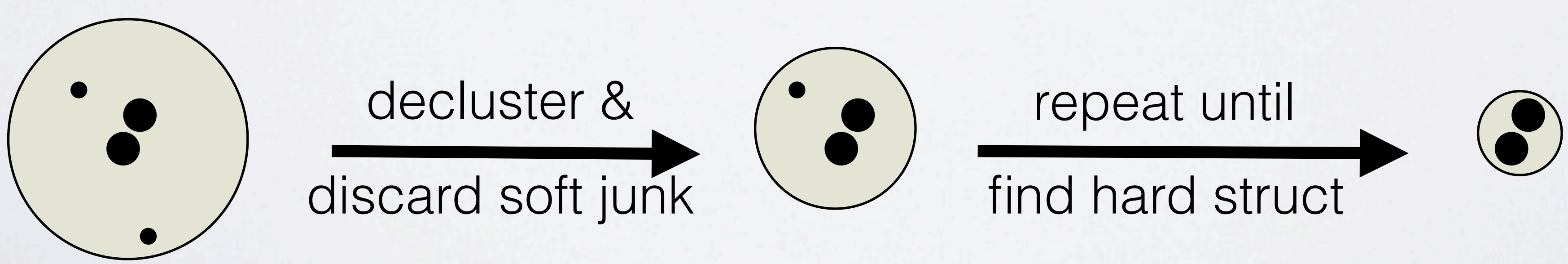
Krohn, Thaler and Wang (2010)

Pruning



Ellis, Vermillion and Walsh (2009)

Mass-drop tagger (MDT, aka BDRS)



Butterworth, Davison, Rubin and Salam (2008)

Our understanding so far

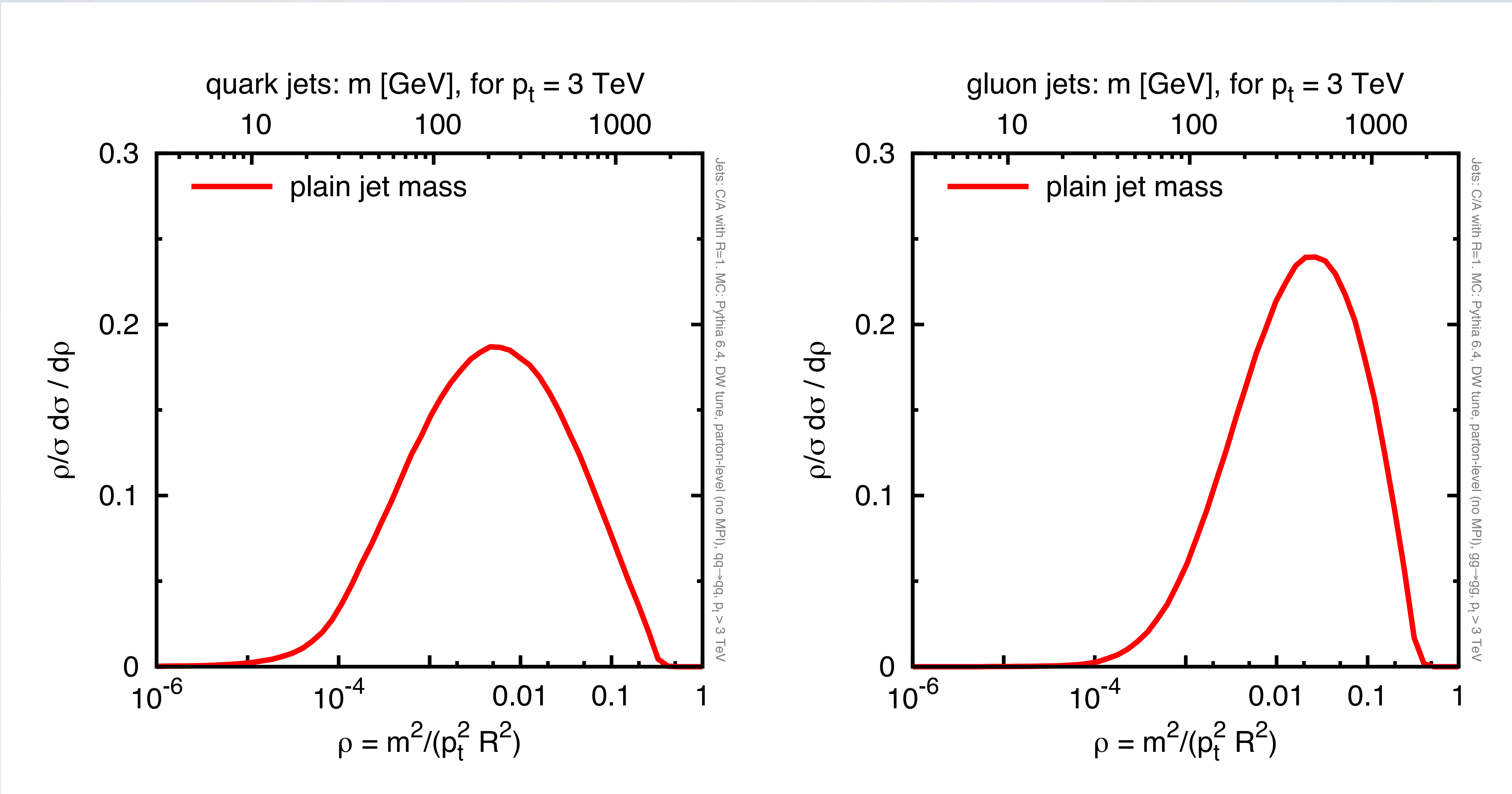
Boost 2010 proceedings:

The [Monte Carlo] findings discussed above indicate that while [pruning, trimming and filtering] have qualitatively similar effects, there are important differences. For our choice of parameters, pruning acts most aggressively on the signal and background followed by trimming and filtering.

- To what extent are the taggers above similar ?
- How does the statement of aggressive behaviour depend on the taggers' parameters and on the jet's kinematics ?

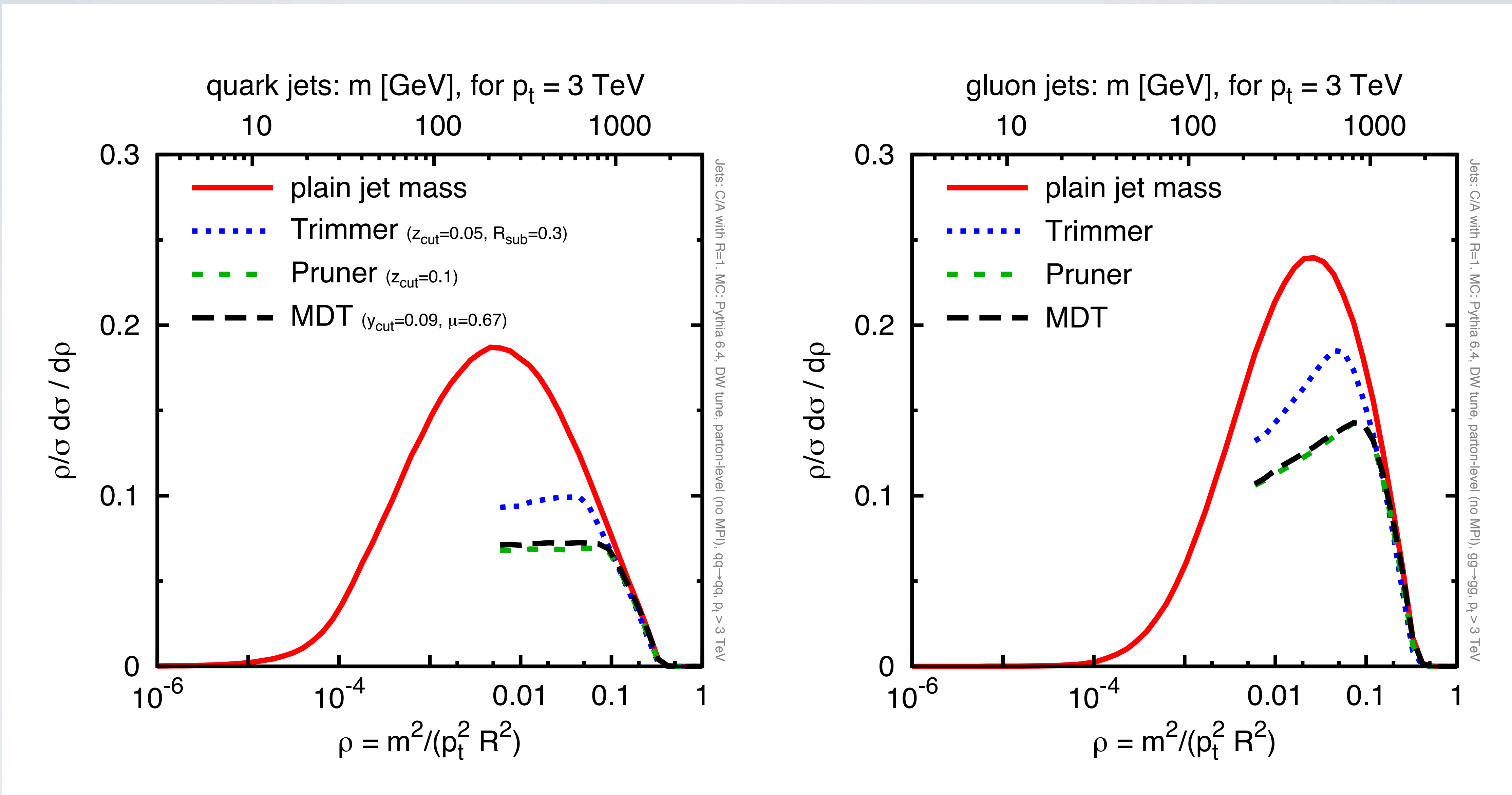
- The "right" MC study can be instructive

Comparison of taggers



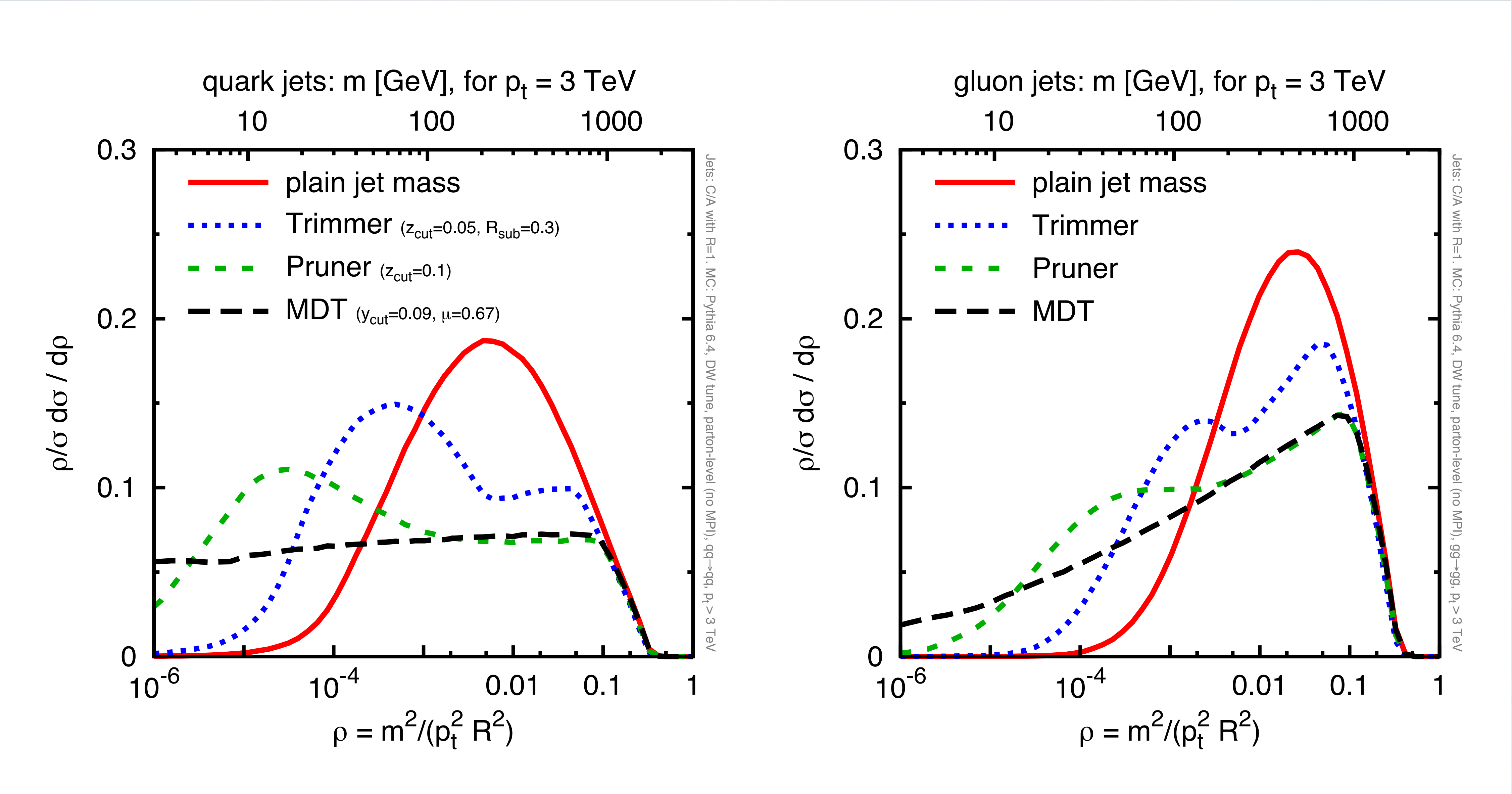
Plain jet mass: characteristic Sudakov peak

Comparison of taggers



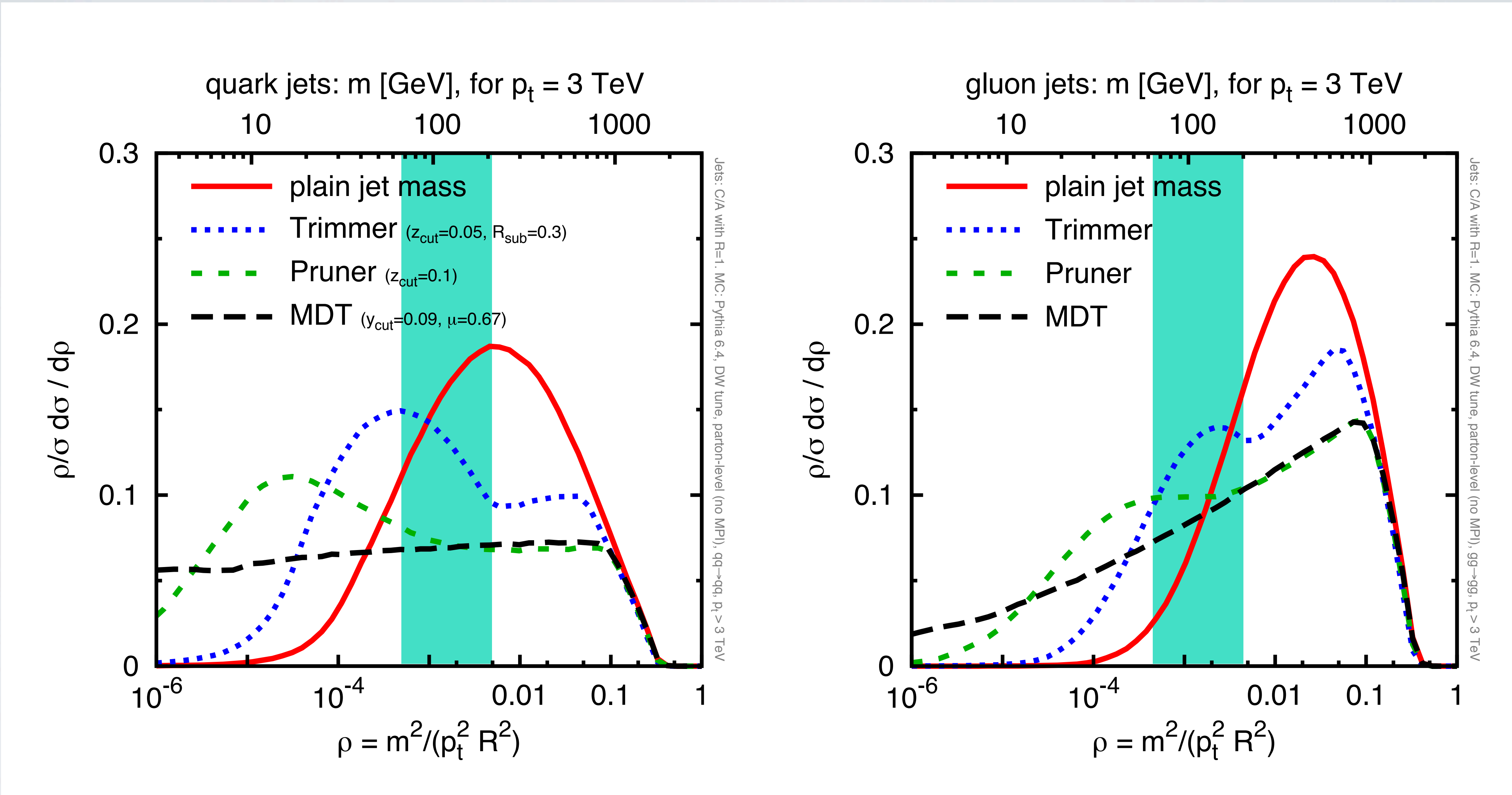
Different taggers appear to behave quite similarly

Comparison of taggers



But only for a limited kinematic region !

Comparison of taggers



Let's translate from QCD variables to ``search'' variables:

ρ → m, for p_t = 3 TeV, R = 1.0

Questions that arise

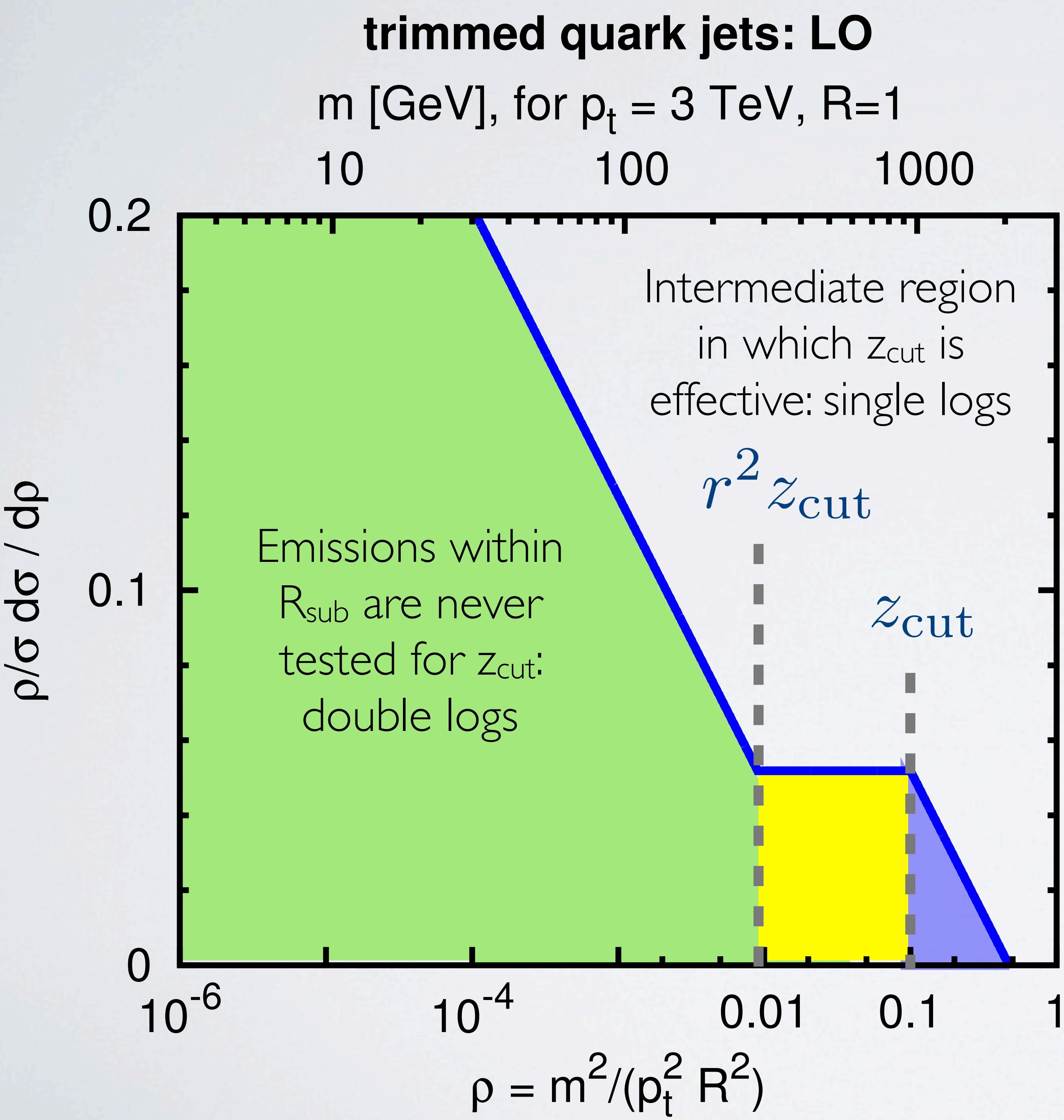
- Can we understand the different shapes (flatness vs peaks) ?
- What's the origin of the transition points ?
- How do they depend on the taggers' parameters ?

- What's the perturbative structure of tagged mass distributions ?
- Cumulative distribution for plain jet mass contains (soft & collinear) double logs

$$\Sigma(\rho) \equiv \frac{1}{\sigma}\int^{\rho} \frac{d\sigma}{d\rho'} d\rho' \sim \sum_n \alpha_s^n \ln^{2n}\frac{1}{\rho} + \ldots$$

- Do the taggers ameliorate this behaviour ?
- If so, what's the applicability of FO calculations ?

Trimming at LO



$$\boxed{\frac{\rho}{\sigma}\frac{d\sigma^{(\rm trim,LO)}}{d\rho} =}$$

$$\frac{\alpha_s C_F}{\pi}\left(\ln\frac{r^2}{\rho} - \frac{3}{4}\right)$$

$$\frac{\alpha_s C_F}{\pi}\left(\ln\frac{1}{z_{\rm cut}} - \frac{3}{4}\right)$$

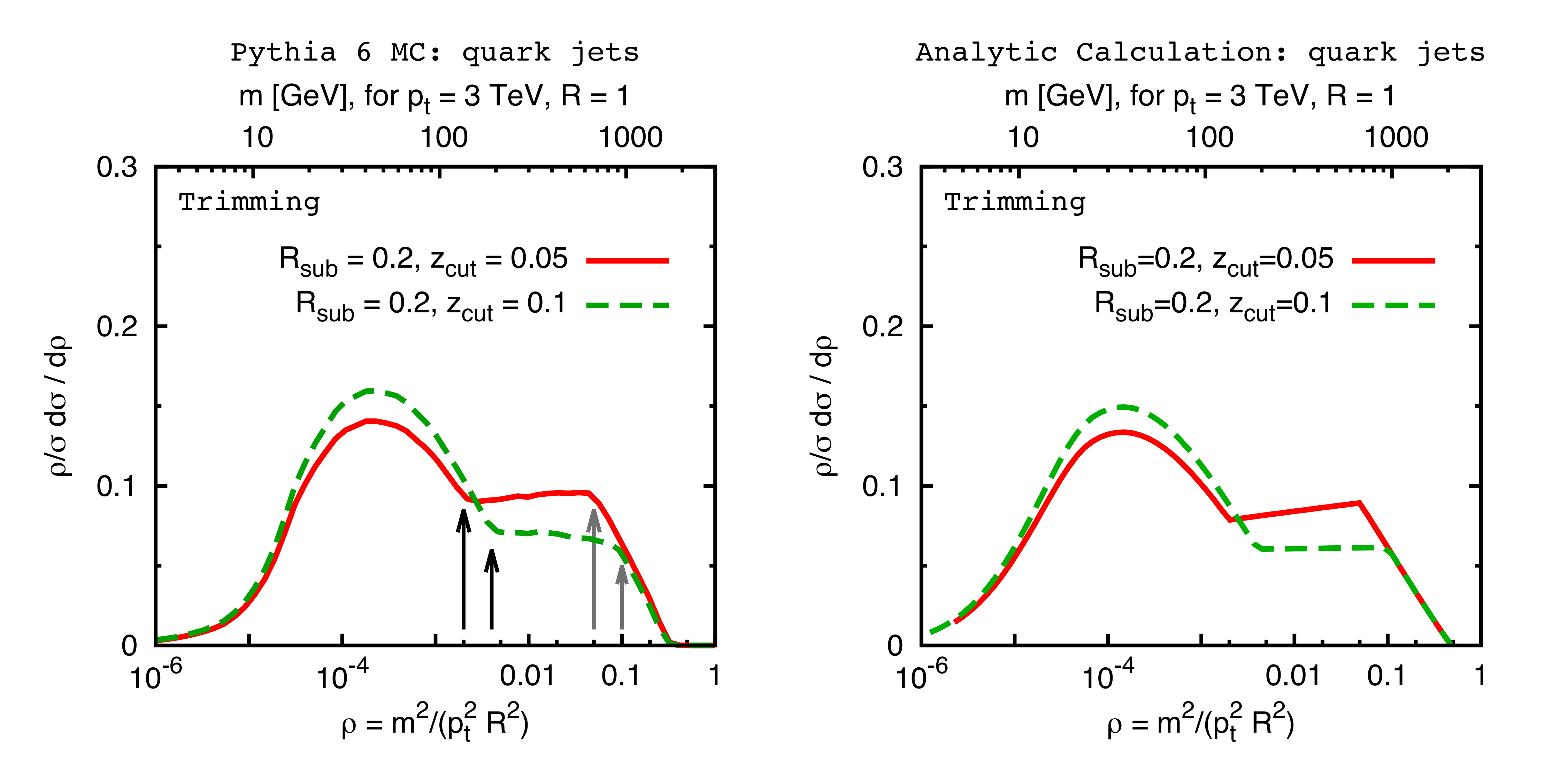
$$\frac{\alpha_s C_F}{\pi}\left(\ln\frac{1}{\rho} - \frac{3}{4}\right)$$

$$r = \frac{R_{\rm sub}}{R}$$

Trimming: all orders

One gets exponentiation of LO (+ running coupling)

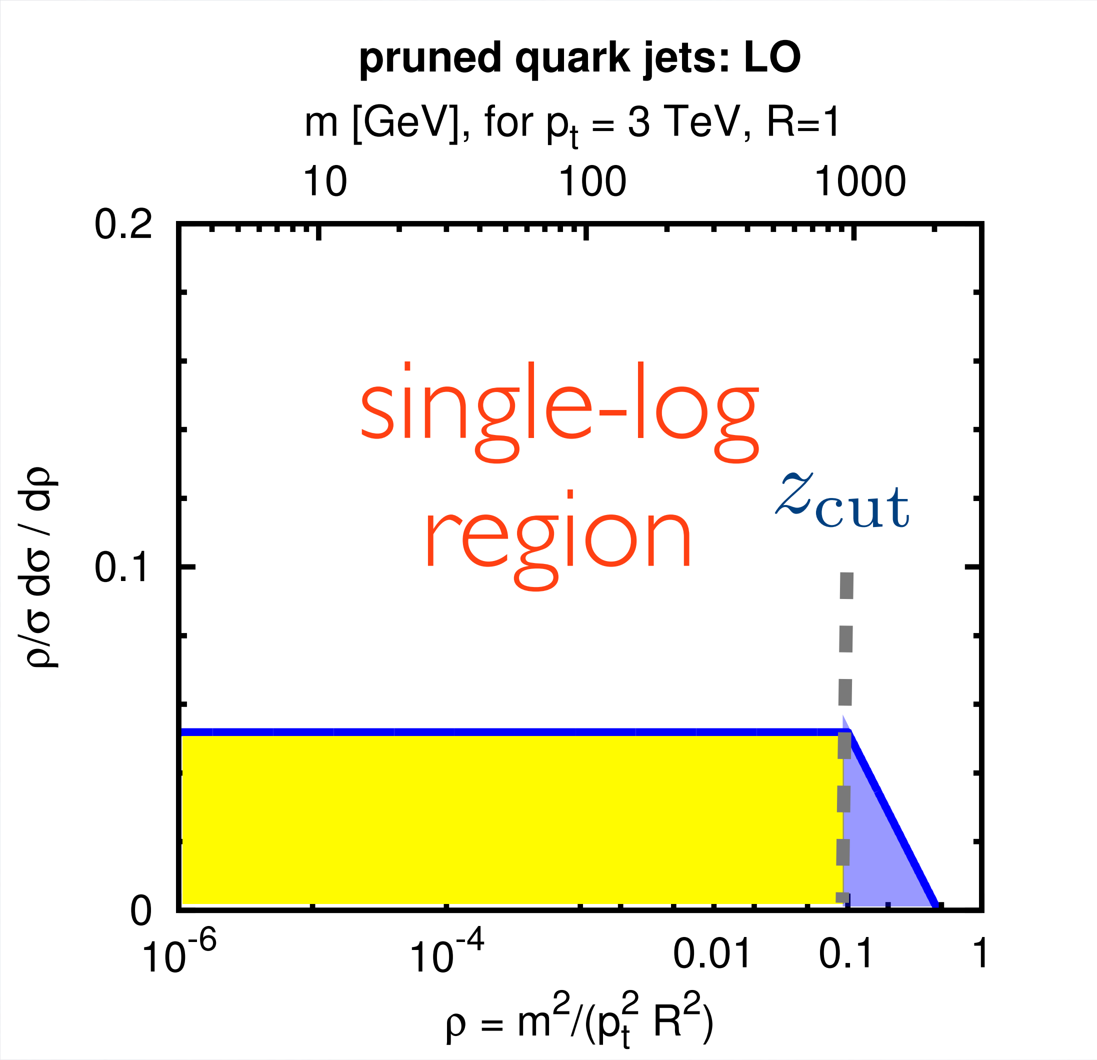
$$\frac{d\sigma^{\text{trim,resum}}}{d\rho} = \frac{d\sigma^{\text{trim,LO}}}{d\rho} \exp\left[-\int_\rho d\rho' \frac{1}{\sigma} \frac{d\sigma^{\text{trim,LO}}}{d\rho'}\right]$$



All-order calculation done in the small-z_{cut} limit

Pruning & MDT at LO

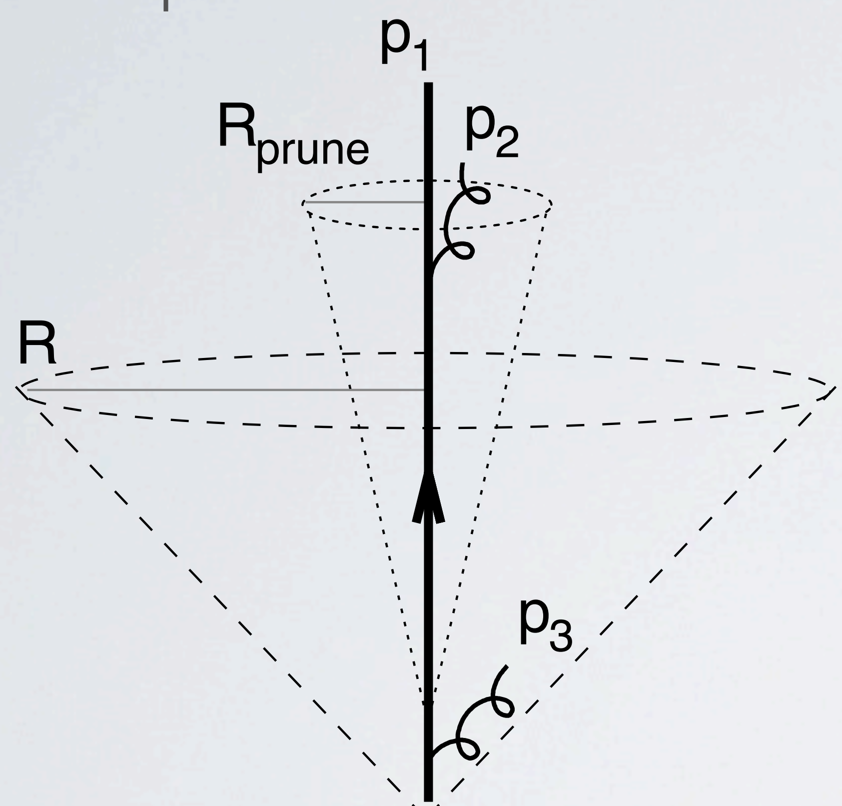
- The pruning radius is set dynamically: $R_{prune} < d_{ij}$
- The 2 prongs are always tested for z_{cut}: single logs



MDT result is identical to LO pruning (in the small-y_{cut} limit)

Structures beyond LO

All-order MDT and pruning distributions are NOT given by exponentiation of LO

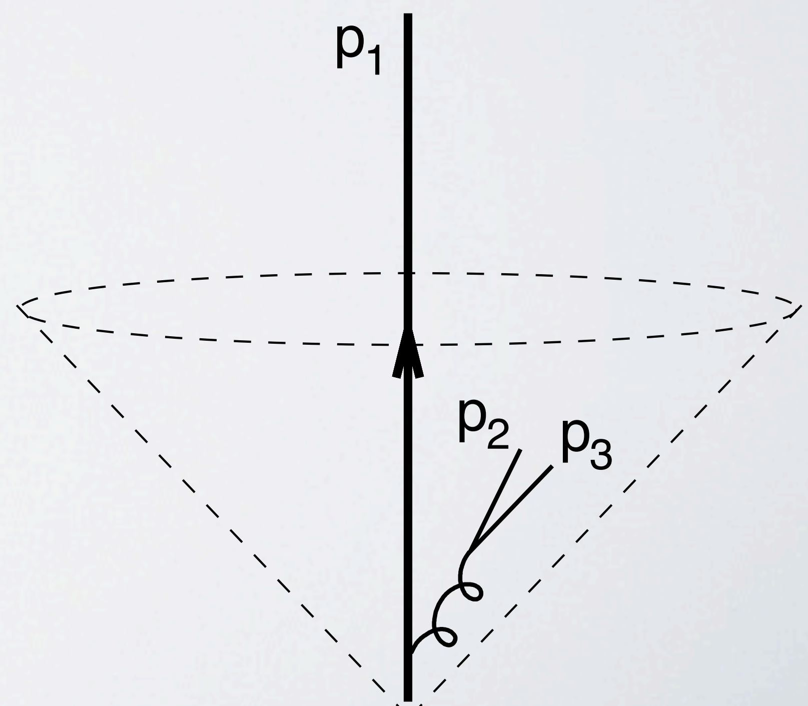


What pruning sometimes does

Chooses R_{prune} based on a soft p_3 (dominates total jet mass), and leads to a *single narrow subjet* whose mass is also dominated by a soft emission (p_2, within R_{prune} of p_1, so not pruned away).

What MDT does wrong

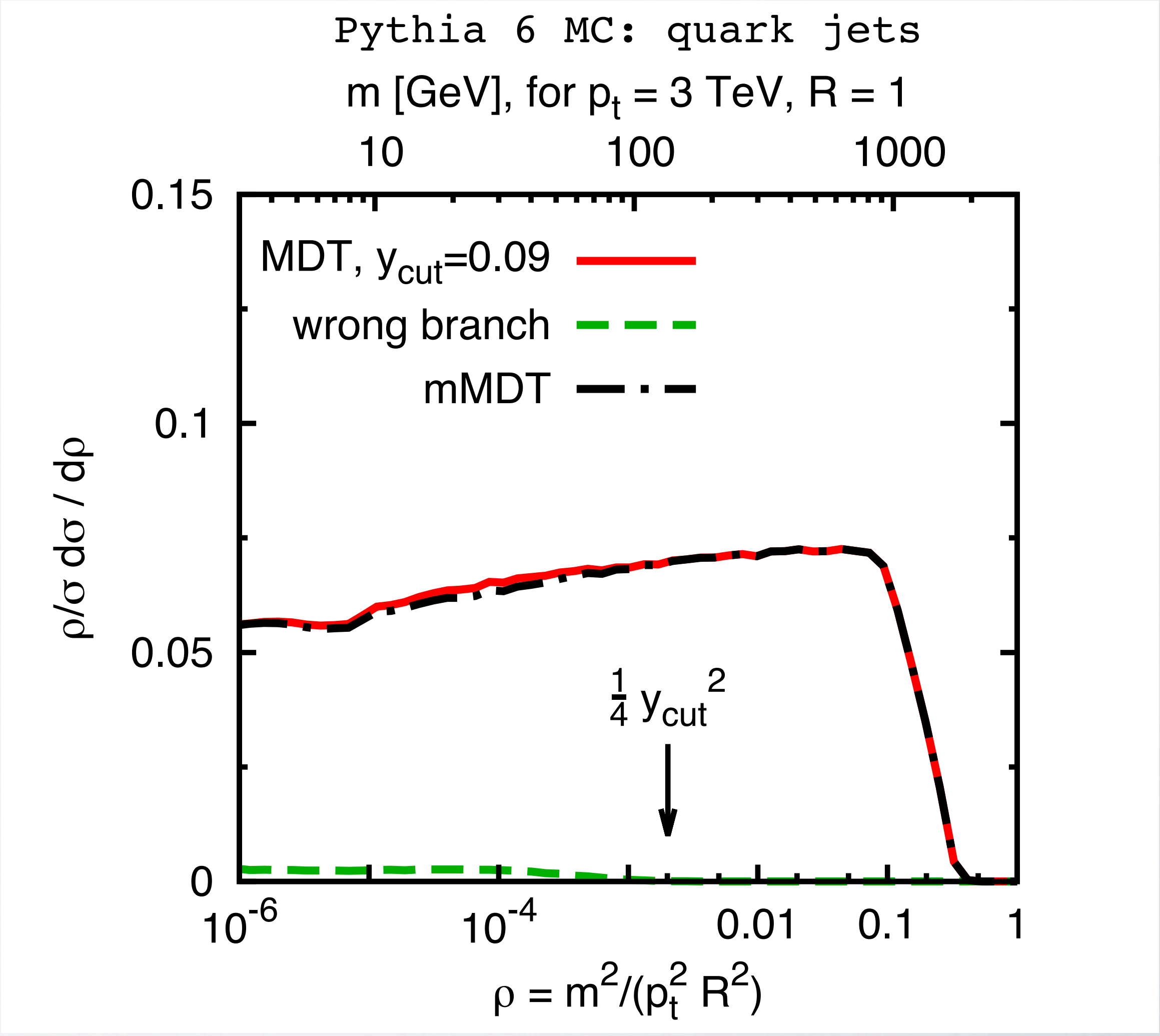
If the energy condition fails, MDT iterates on the more massive subjet. It can *follow a soft branch* ($p_2+p_3 < y_{cut}\, p_{tjet}$), when the "right" answer was that the (massless) hard branch had no substructure



The modified Mass Drop Tagger

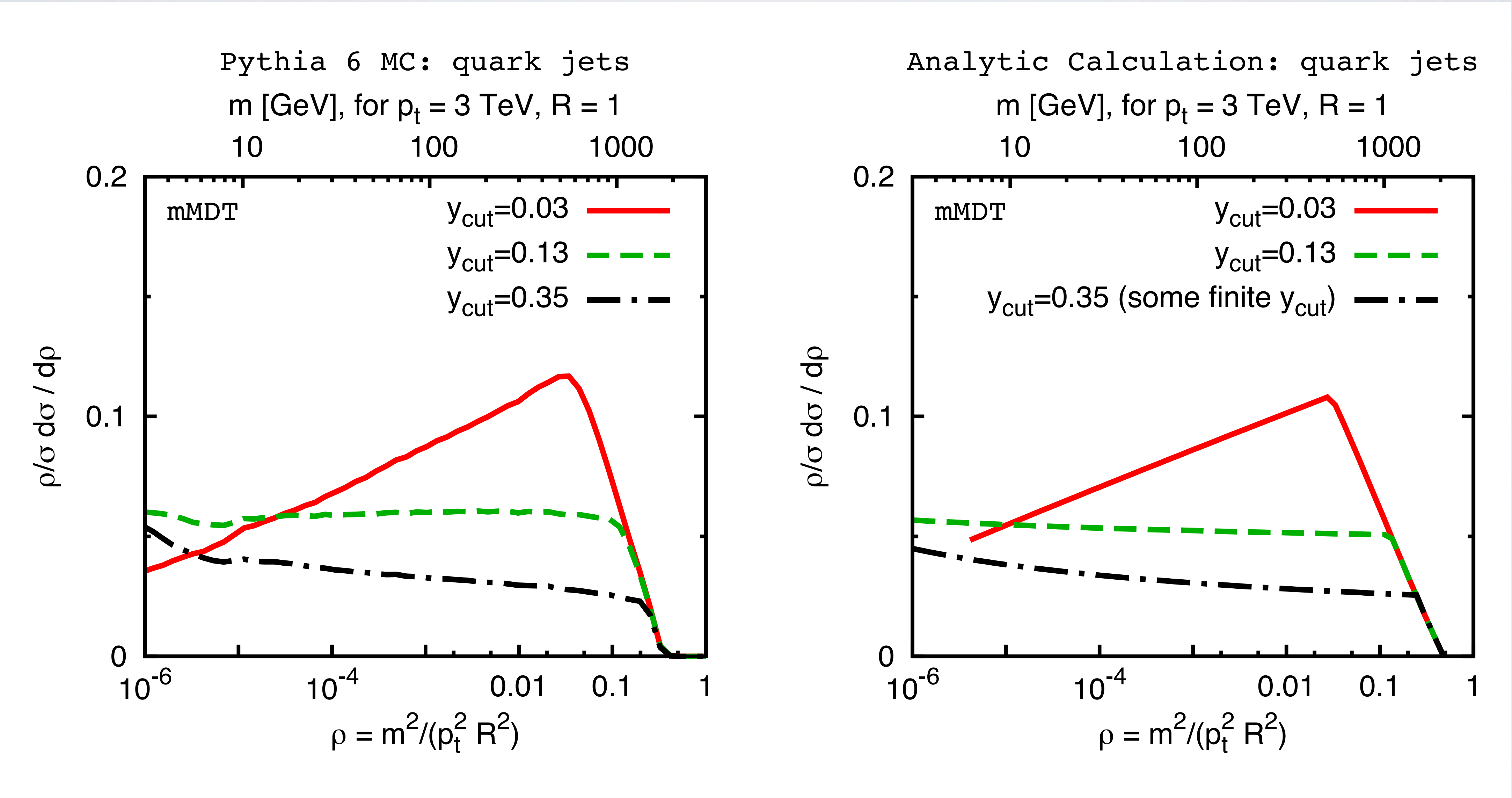
- The soft-branch issue can be considered a flaw of the tagger
- It worsens the logarithmic structure $\sim\alpha_s^2 L^3$
- It makes all-order treatment difficult
- It calls for a modification: always follow be the subjet with highest transverse mass

- In practice the soft-branch contribution is very small
- However, this modification makes the all-order structure particularly interesting



All-order structure of mMDT

- In the small y_{cut} limit, it is just the exponentiation of LO
- The mMDT has single logs to all orders (i.e. $\alpha_s^n L^n$)

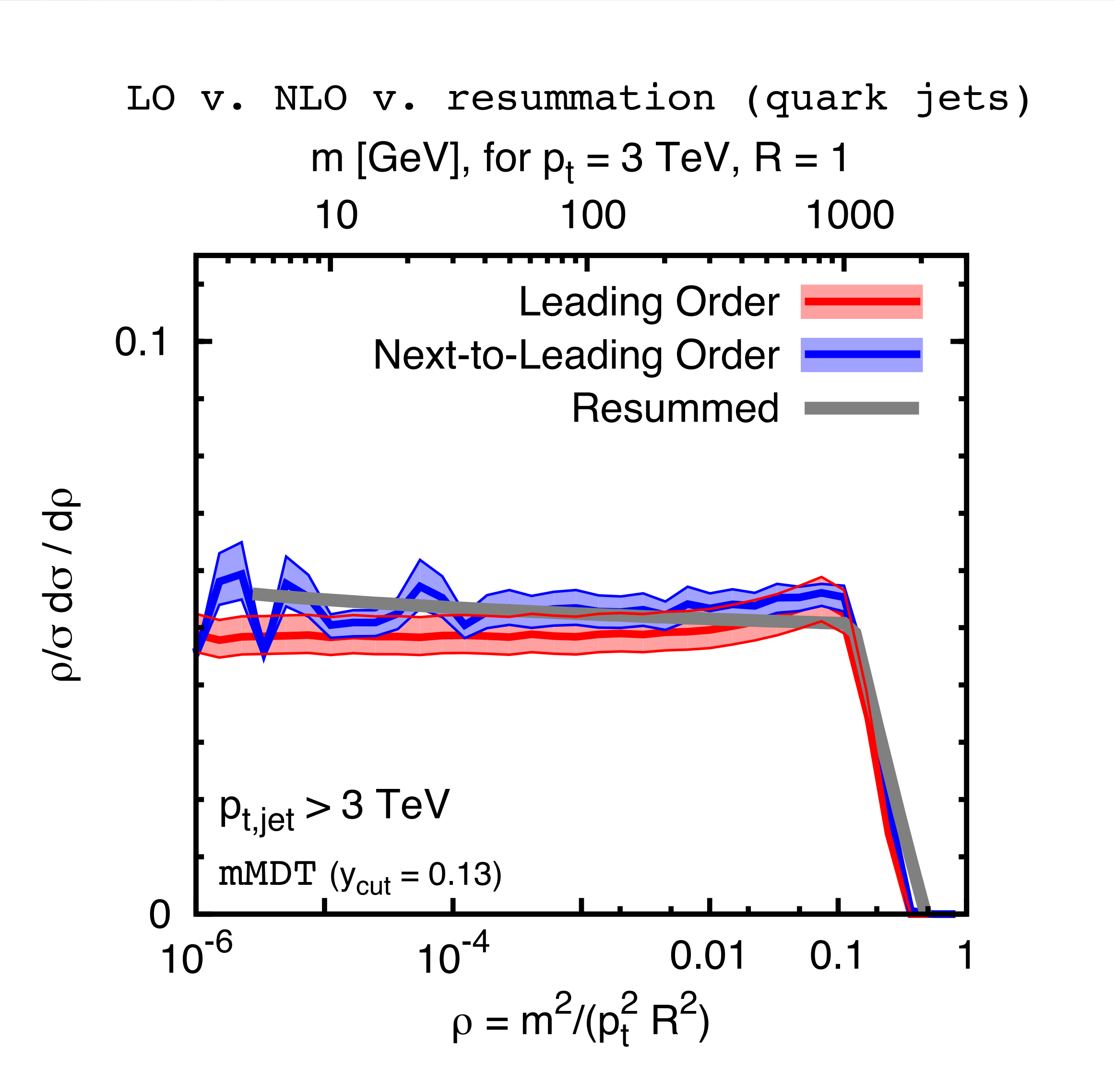


Remarkable agreement !

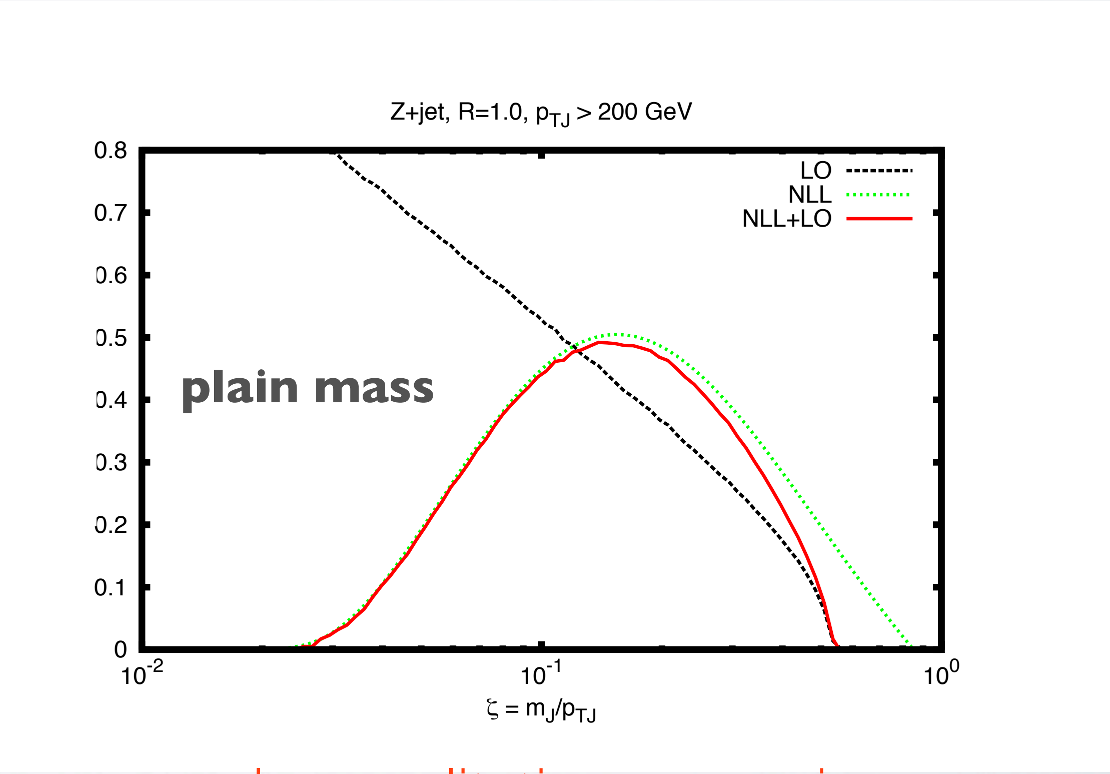
Interesting feature: flat mass distribution (more in backup slides)

All-order structure of mMDT

- In the small y_{cut} limit, it is just the exponentiation of LO
- The mMDT has single logs to all orders (i.e. $\alpha_s^n L^n$)



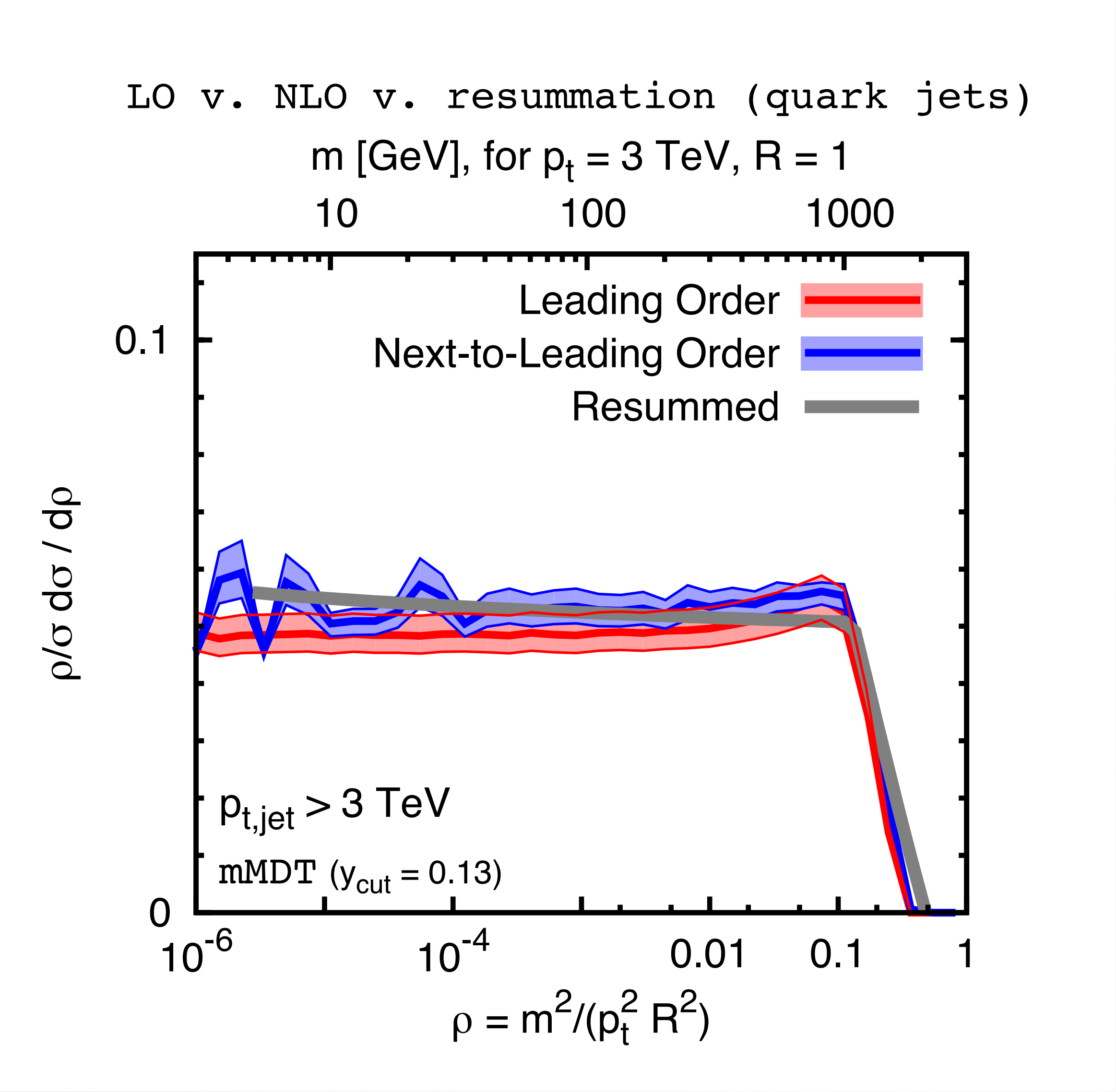
- Single logs: extended validity of FO calculations



only a qualitative comparison: different process/kinematics!

All-order structure of mMDT

- In the small y_{cut} limit, it is just the exponentiation of LO
- The mMDT has single logs to all orders (i.e. $\alpha_s^n L^n$)



- Single logs: extended validity of FO calculations

- Single logs of collinear origin
- Remarkable consequence: mMDT is free of non-global logs!

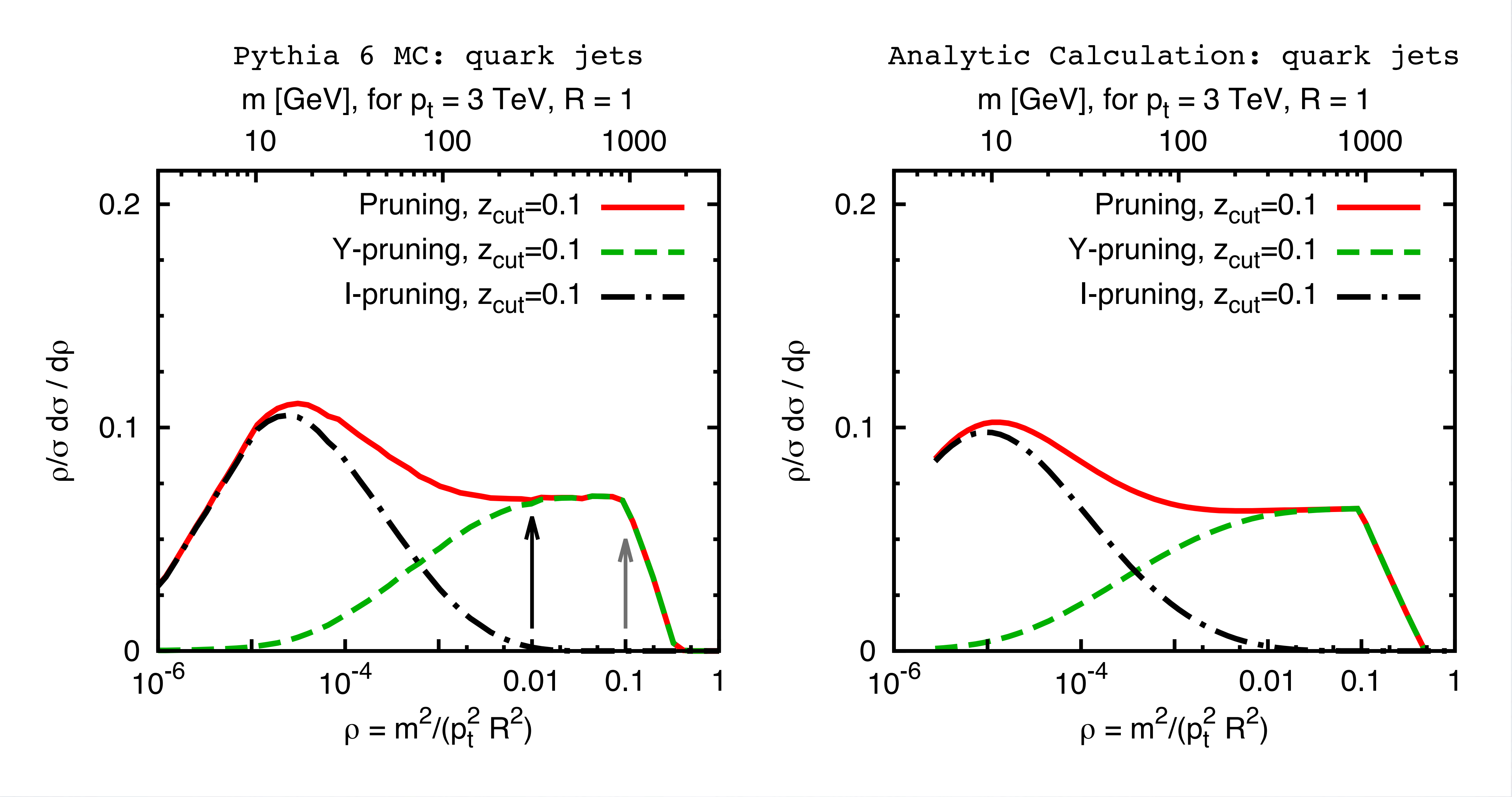
Pruning: I & Y components

- Pruning @ NLO ~α_s^2 L^4 (like plain jet mass)
- Single-pronged component (I-pruning) is active for ρ < z_{cut}^2
- A simple modification: require at least one successful merging with $\Delta R > R_{prune}$ and $z > z_{cut}$ (Y-pruning)

- It is convenient to resum the two components separately
- Y-pruning: essentially Sudakov suppression of LO ~ α_s^n L^{2n-1}
- I-pruning: convolution between the pruned and the original mass ~ α_s^n L^{2n}

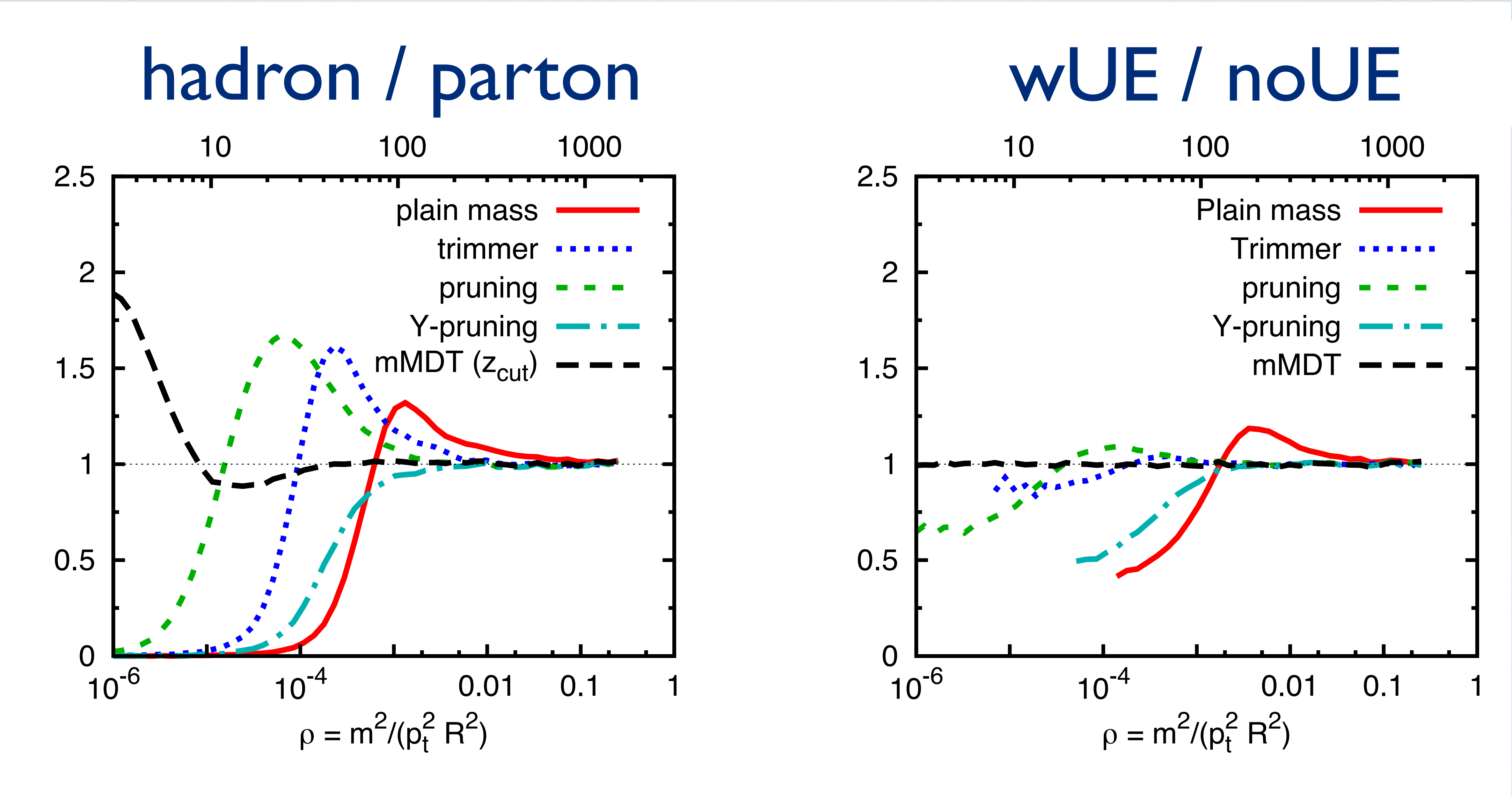
All-order results

- Full Pruning: single-log region for $z_{cut}^2 < \rho < z_{cut}$
- We control $\alpha_s^n L^{2n}$ and $\alpha_s^n L^{2n-1}$ in the expansion
- NG logs present but deferred to NNLO



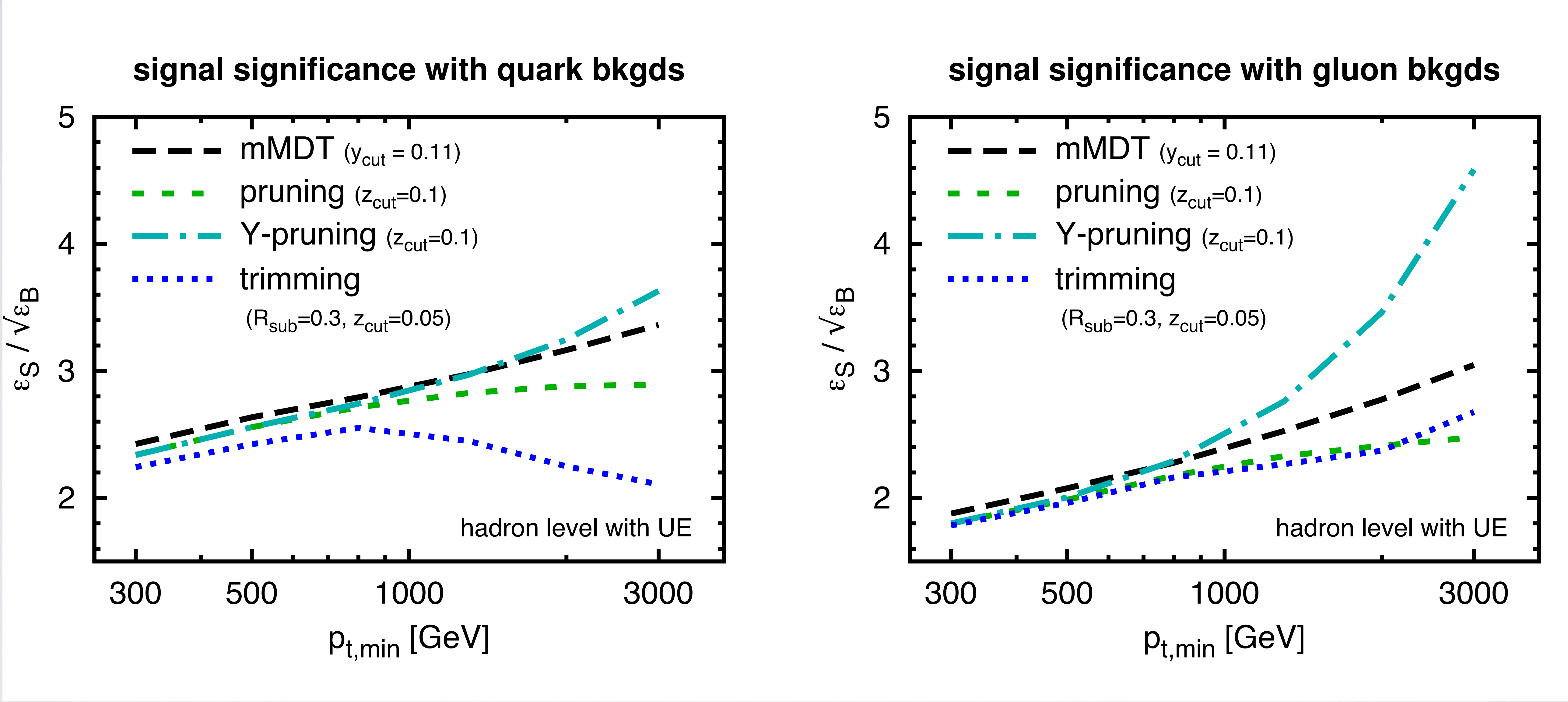
All-order calculation done in the small-z_{cut} limit

Non-perturbative effects



- Most taggers have reduced sensitivity to NP physics
- mMDT particularly so (it's the most calculable)
- Y-pruning sensitive to UE because of the role played by the fat jet mass

Performances for finding signals (Ws)



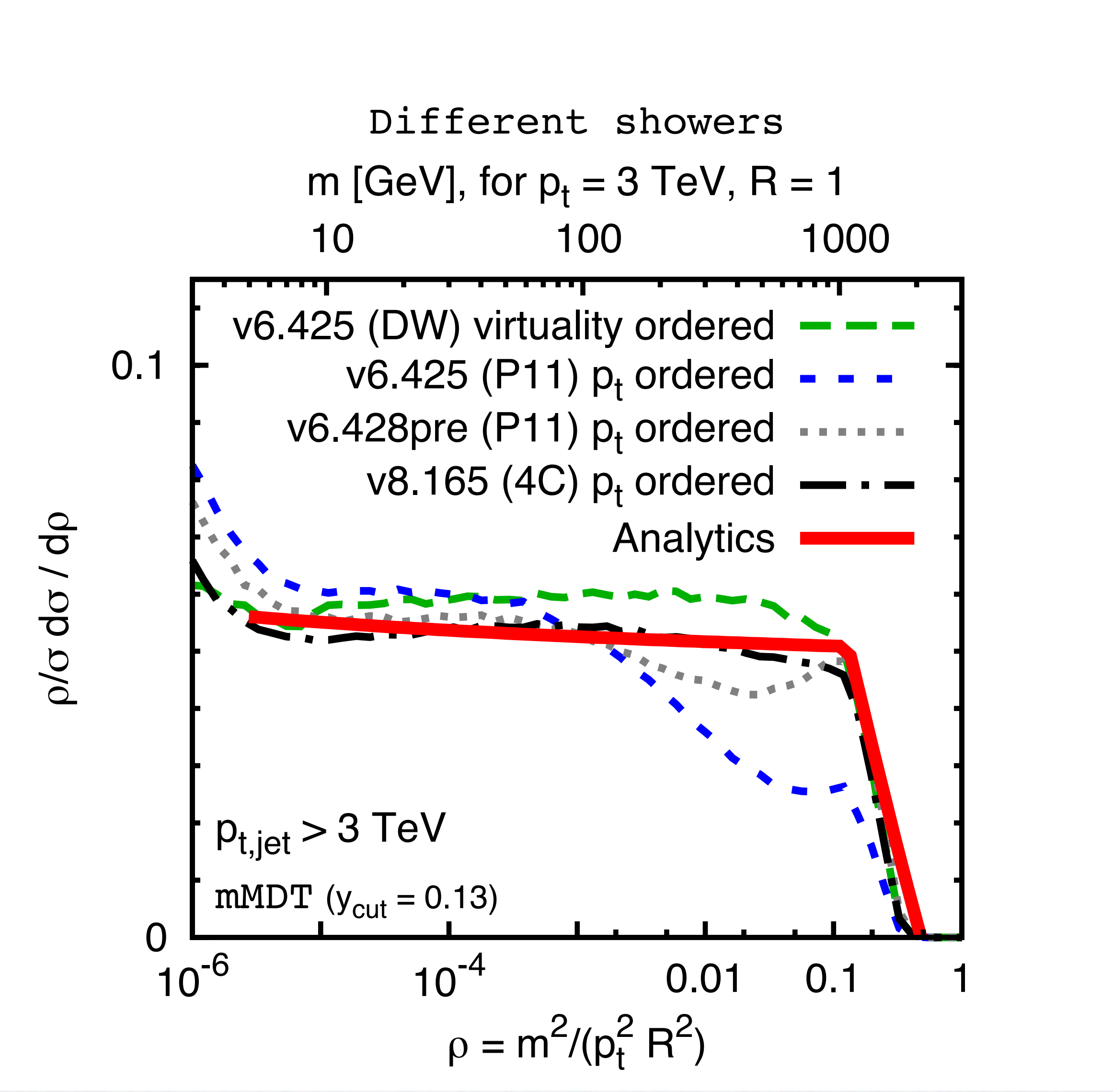
Y-pruning gives a visible improvement

In summary ...

- Analytic studies of the taggers reveal their properties
- Particularly useful if MCs don't agree

In summary ...

- Analytic studies of the taggers reveal their properties
- Particularly useful if MCs don't agree



In summary ...

- Analytic studies of the taggers reveal their properties
- Particularly useful if MCs don't agree

- They also indicate how to develop better taggers

- Y-pruning:
- improved log behaviour wrt pruning ($\alpha_s^n L^{2n-1}$ vs $\alpha_s^n L^{2n}$)
- better rejection of QCD background

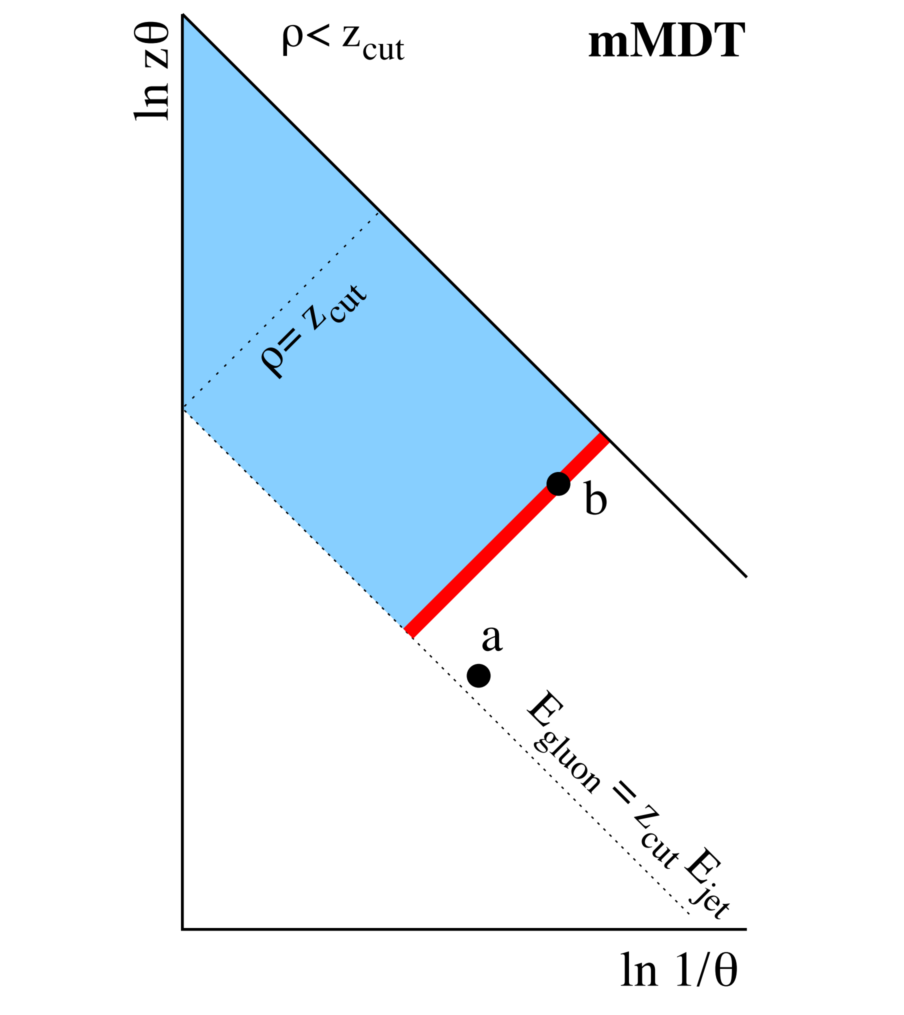
- mMDT:
- exceptionally simple structure (single logs, no non-global)
- reduced sensitivity to non-perturbative physics

BACKUP SLIDES

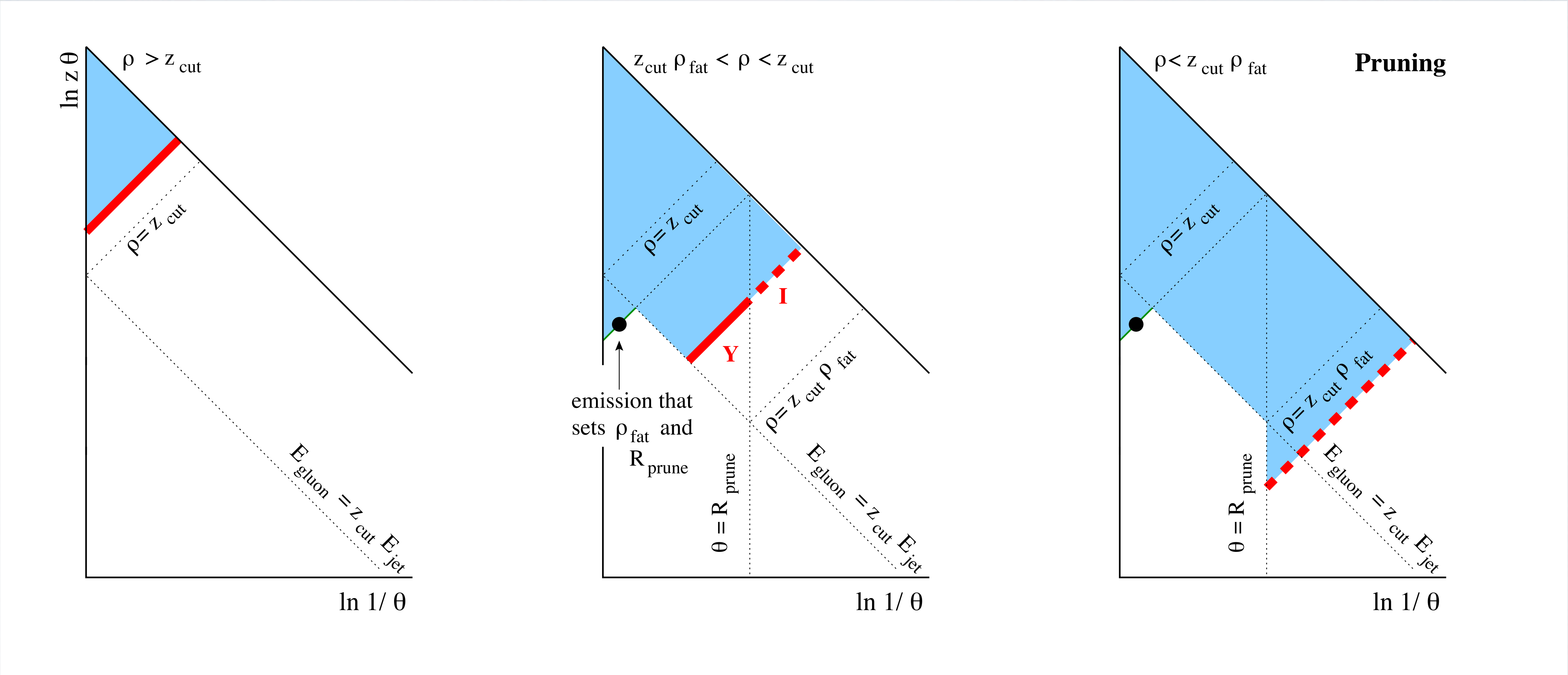
Summary table

	highest logs	transition(s)	Sudakov peak	NGLs	NP: $m^2 \lesssim$
plain mass	$\alpha_s^n L^{2n}$	—	$L \simeq 1/\sqrt{\bar{\alpha}_s}$	yes	$\mu_{\rm NP}\, p_t\, R$
trimming	$\alpha_s^n L^{2n}$	$z_{\rm cut},\ r^2 z_{\rm cut}$	$L \simeq 1/\sqrt{\bar{\alpha}_s} - 2\ln r$	yes	$\mu_{\rm NP}\, p_t\, R_{\rm sub}$
pruning	$\alpha_s^n L^{2n}$	$z_{\rm cut},\ z_{\rm cut}^2$	$L \simeq 2.3/\sqrt{\bar{\alpha}_s}$	yes	$\mu_{\rm NP}\, p_t\, R$
MDT	$\alpha_s^n L^{2n-1}$	$y_{\rm cut},\ \frac{1}{4}y_{\rm cut}^2,\ y_{\rm cut}^3$	—	yes	$\mu_{\rm NP}\, p_t\, R$
Y-pruning	$\alpha_s^n L^{2n-1}$	$z_{\rm cut}$	(Sudakov tail)	yes	$\mu_{\rm NP}\, p_t\, R$
mMDT	$\alpha_s^n L^n$	$y_{\rm cut}$	—	no	$\mu_{\rm NP}^2/y_{\rm cut}$

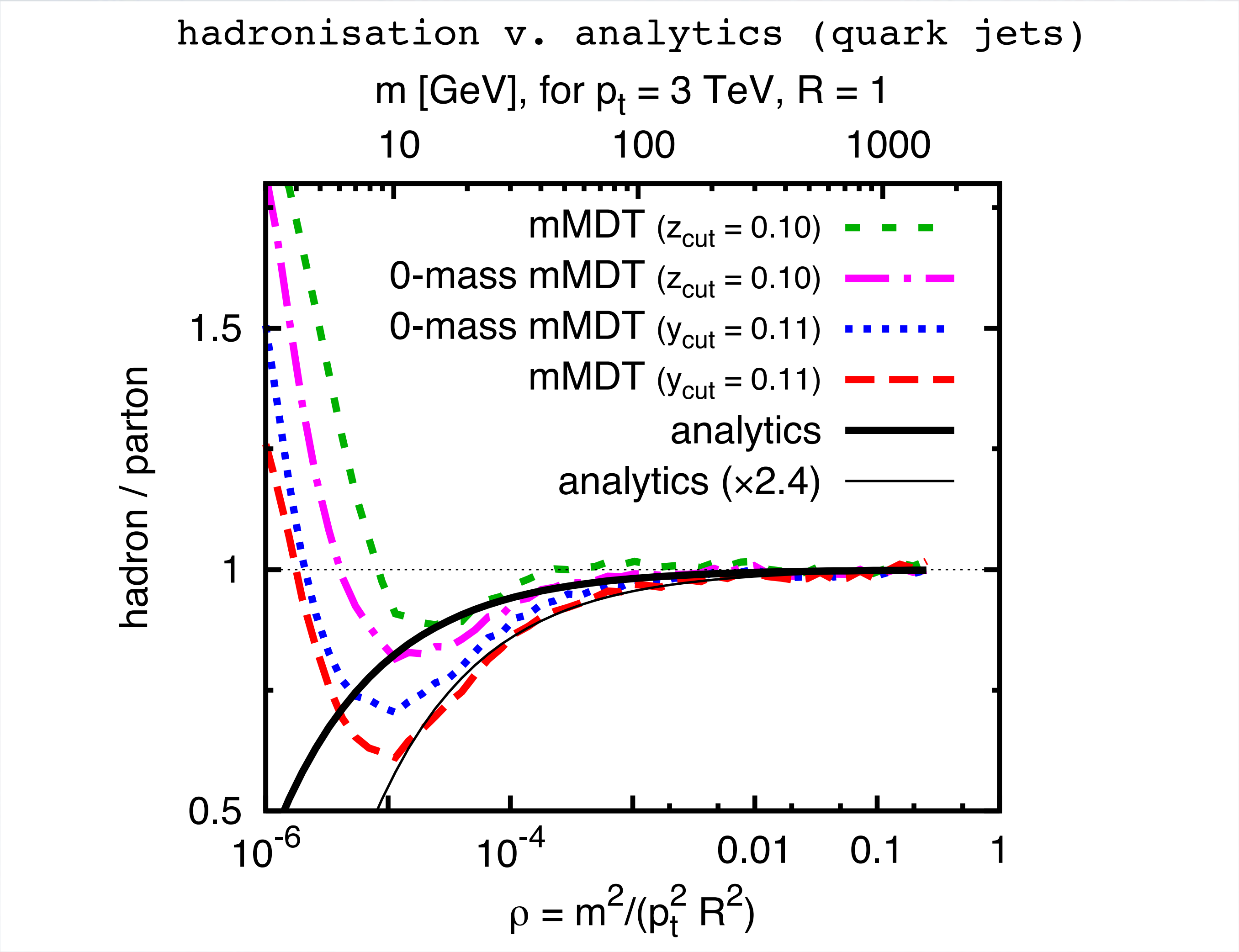
Lund diagrams for mMDT



Lund diagrams for pruning



Hadronisation effects for mMDT



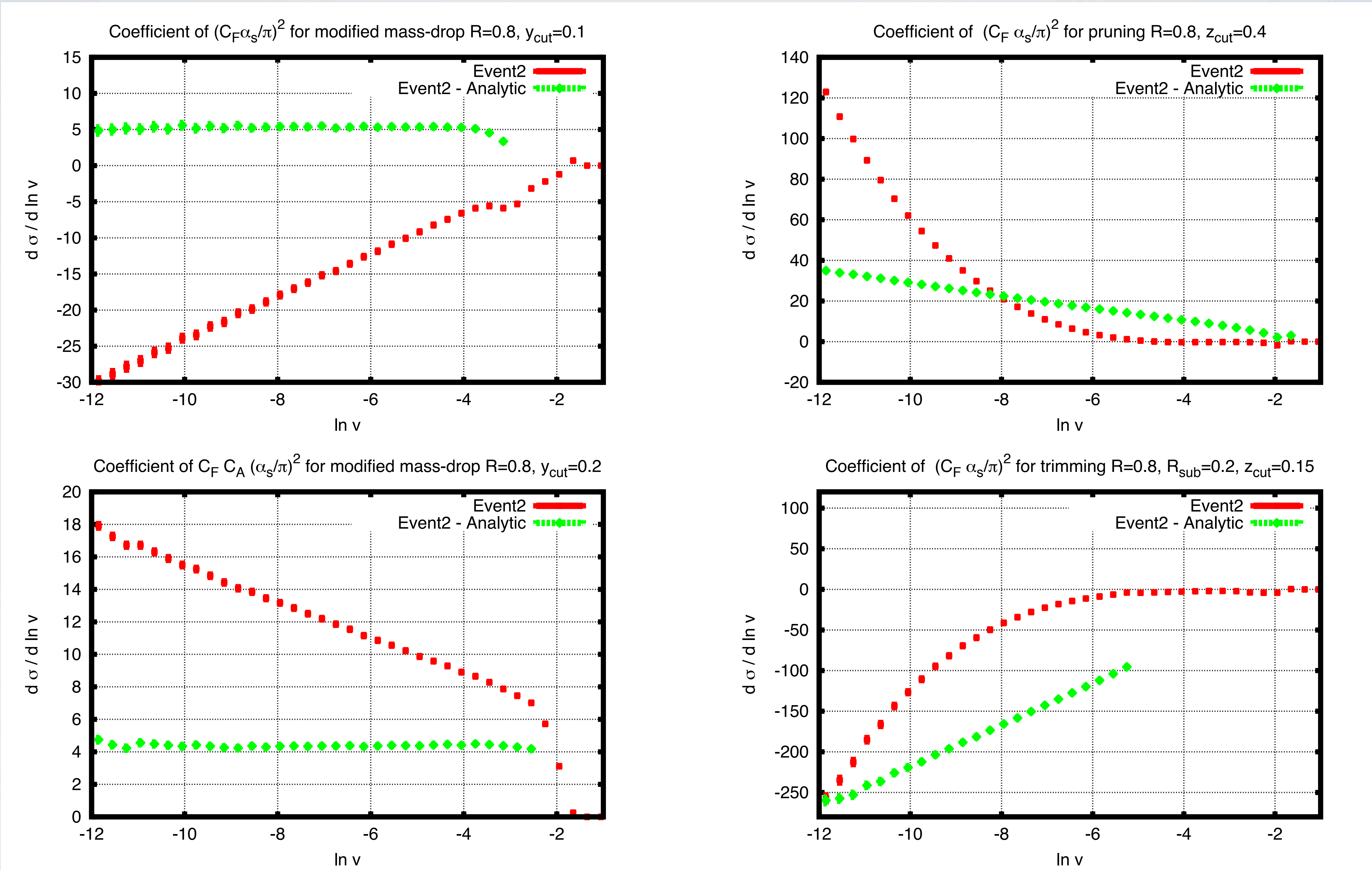
Hadronisation produces:

1. a shift in the squared jet mass
2. a shift in the jet's (or prong's) momentum

Same power behaviour but with competing signs:

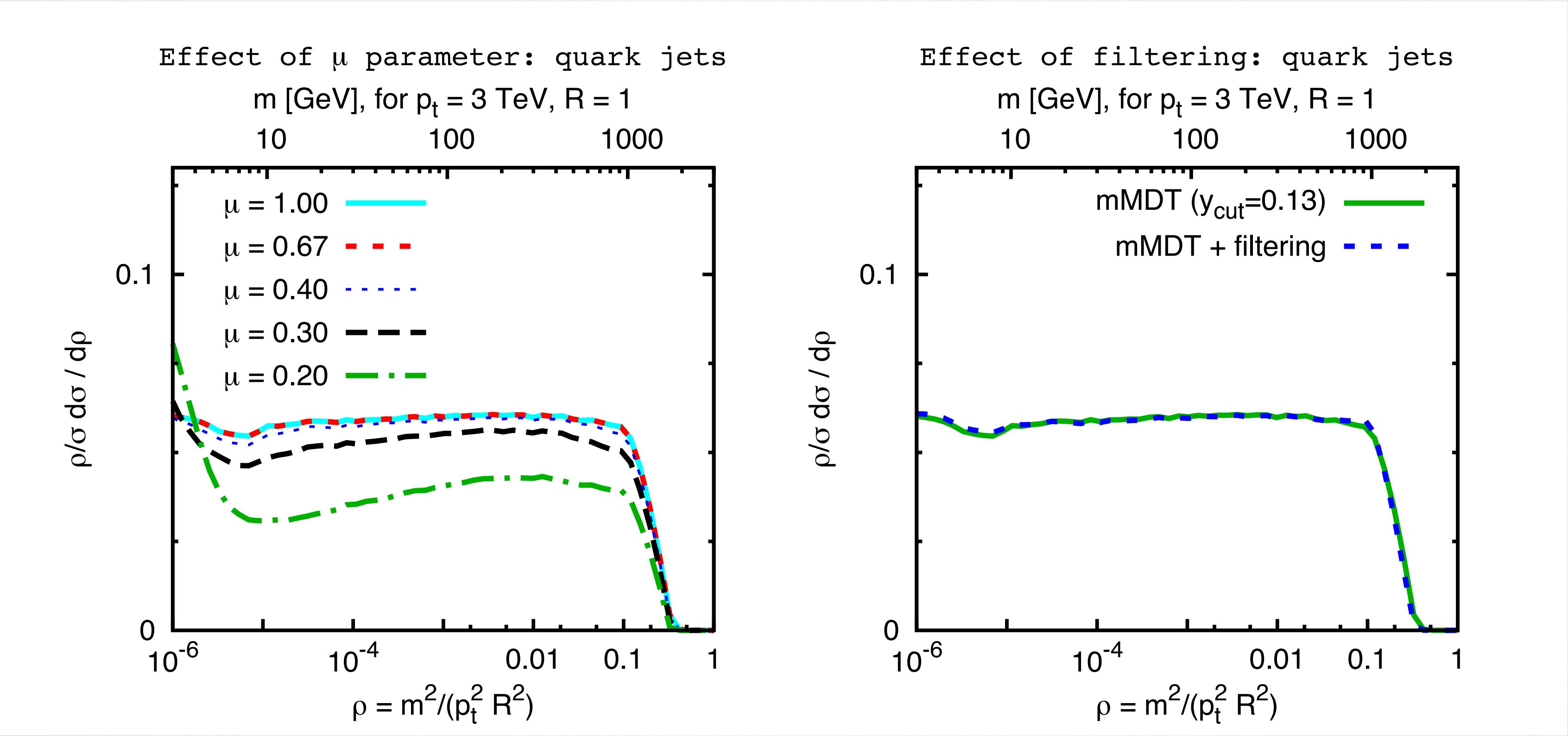
$$\frac{d\sigma^{\rm NP}}{dm} \simeq \frac{d\sigma^{\rm PT}}{dm}\left[1 + a\frac{\Lambda_{\rm NP}}{m}\right]$$

Examples of NLO checks

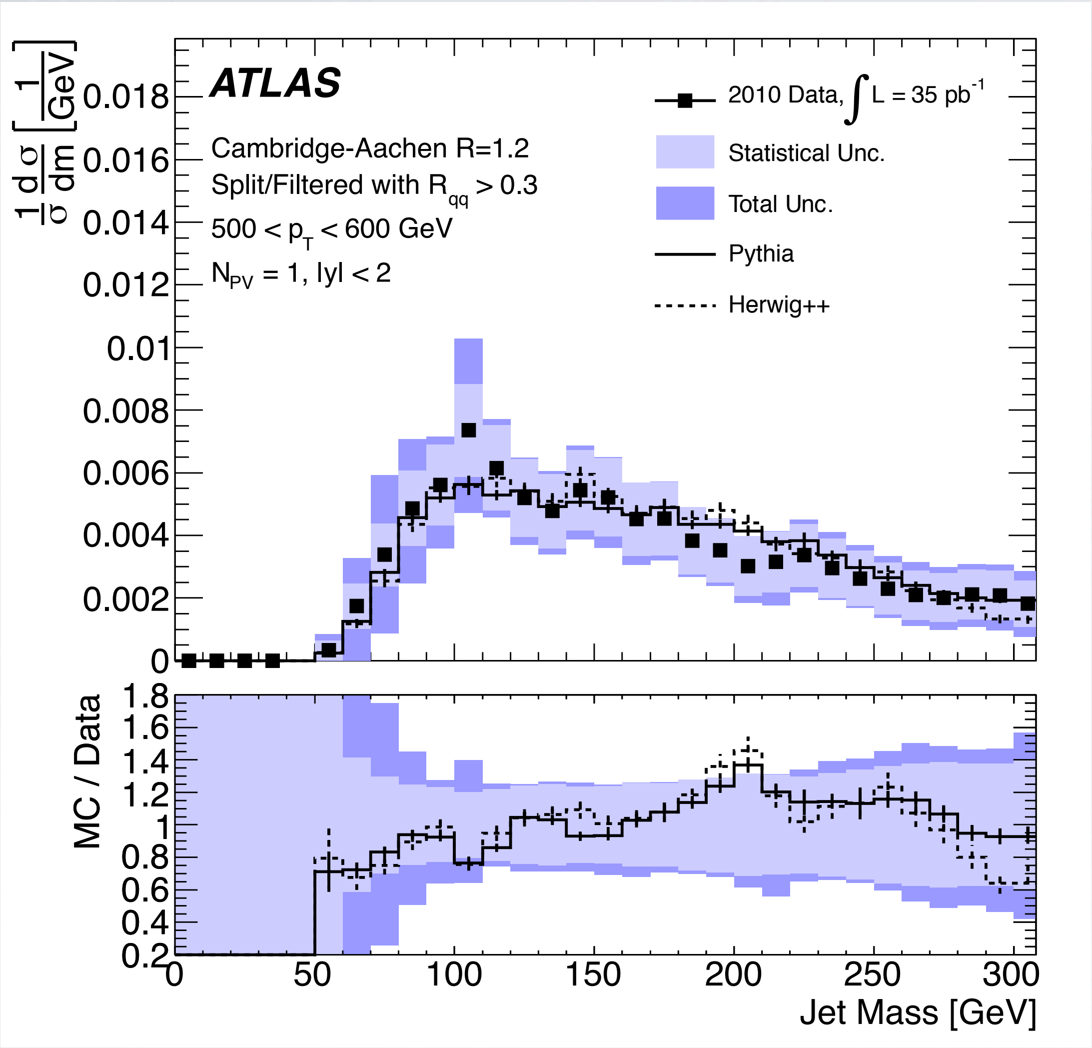


Other properties of mMDT

- Flatness of the background is a desirable property (data-driven analysis, side bands)
- y_{cut} can be adjusted to obtain it (analytic relation)
- Role of μ, not mentioned so far
- It contributes to subleading logs and has small impact if not too small (μ>0.4)
- Filtering only affects subleading ($N^{nfilt}LL$) terms

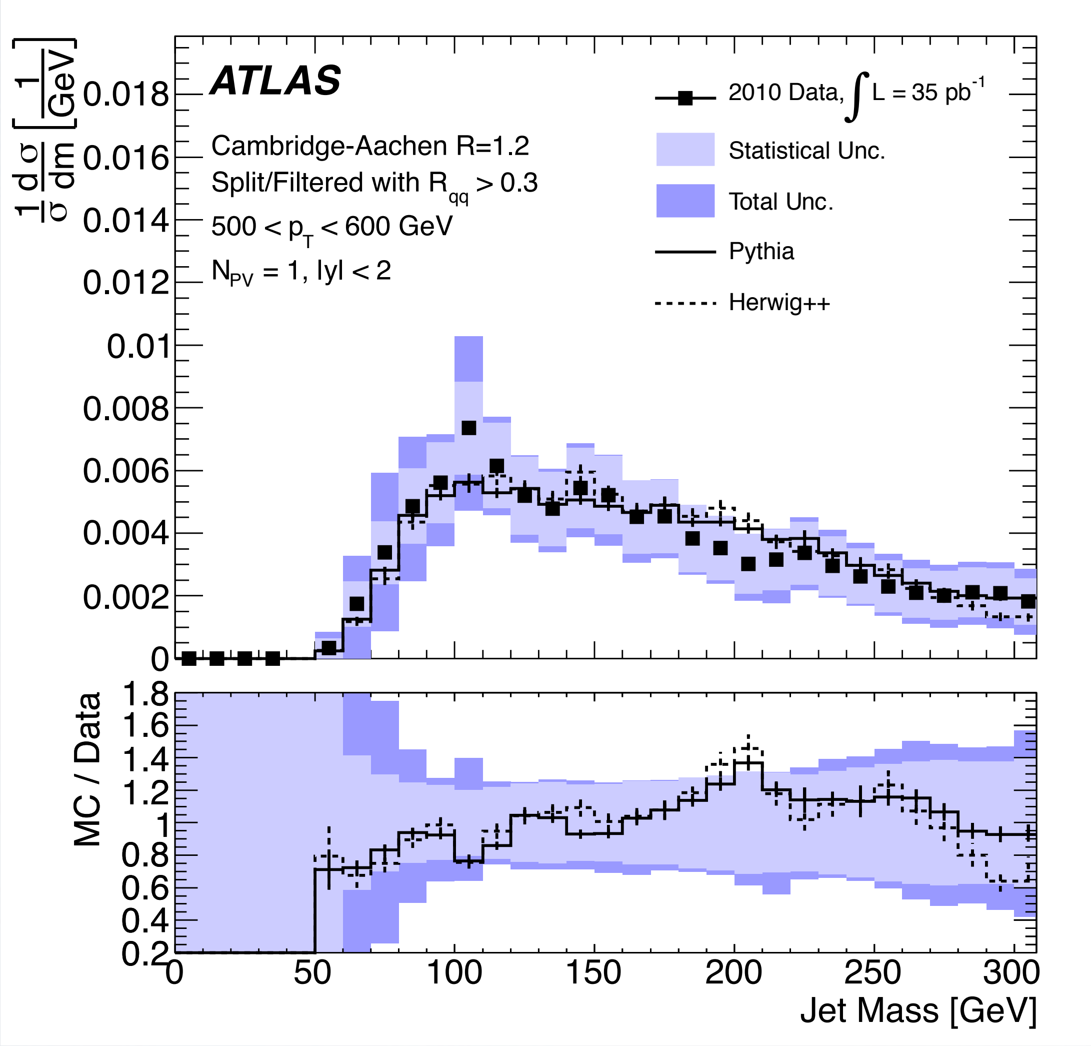


ATLAS MDT

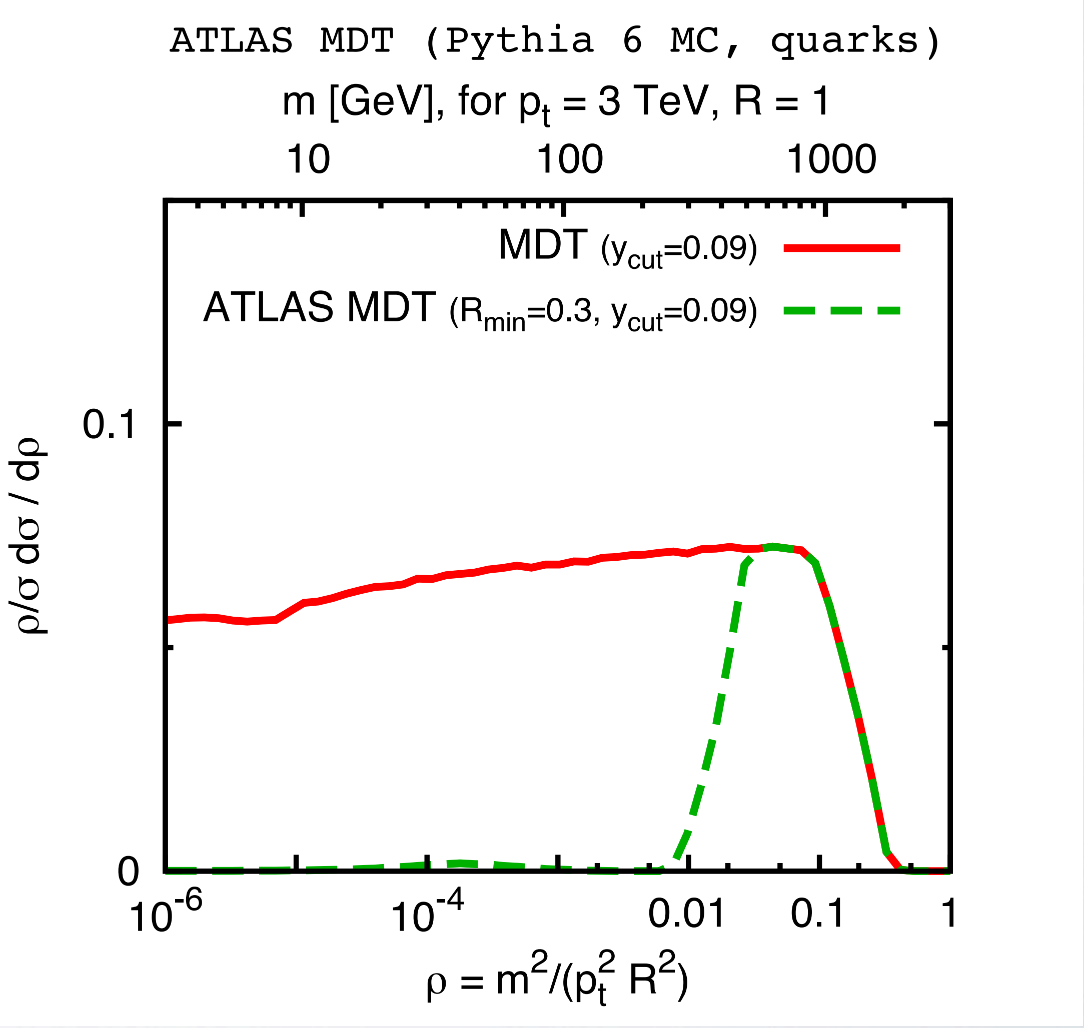


- ATLAS measured the jet mass with MDT
- Different version of the tagger with R_{min}=0.3 between the prongs

ATLAS MDT



- ATLAS measured the jet mass with MDT
- Different version of the tagger with R_{min}=0.3 between the prongs



- This cut significantly changes the tagger's behaviour: mass minimum
- The single-log region is reduced (and can even disappear)
- We hope that future studies will be able to avoid this