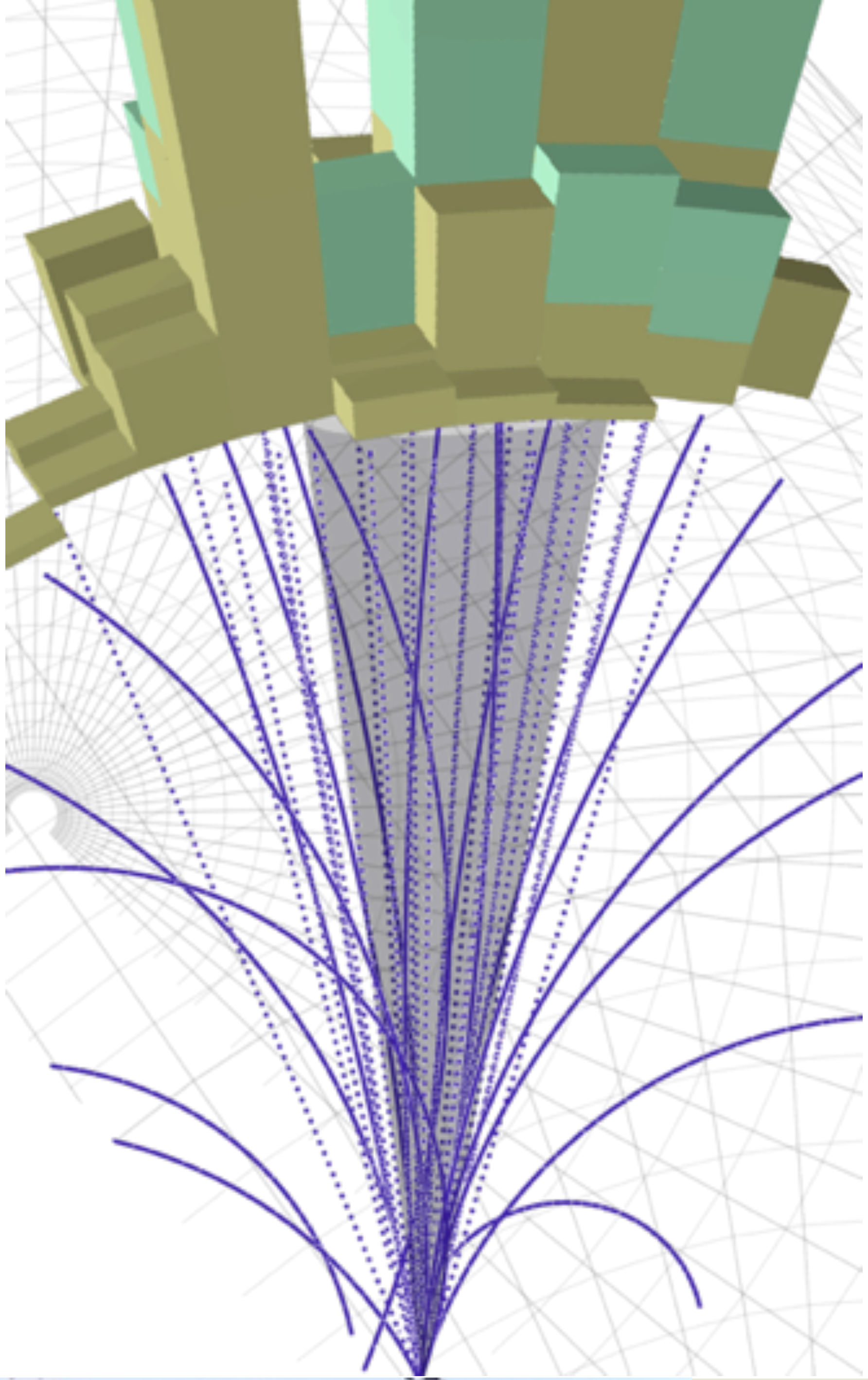
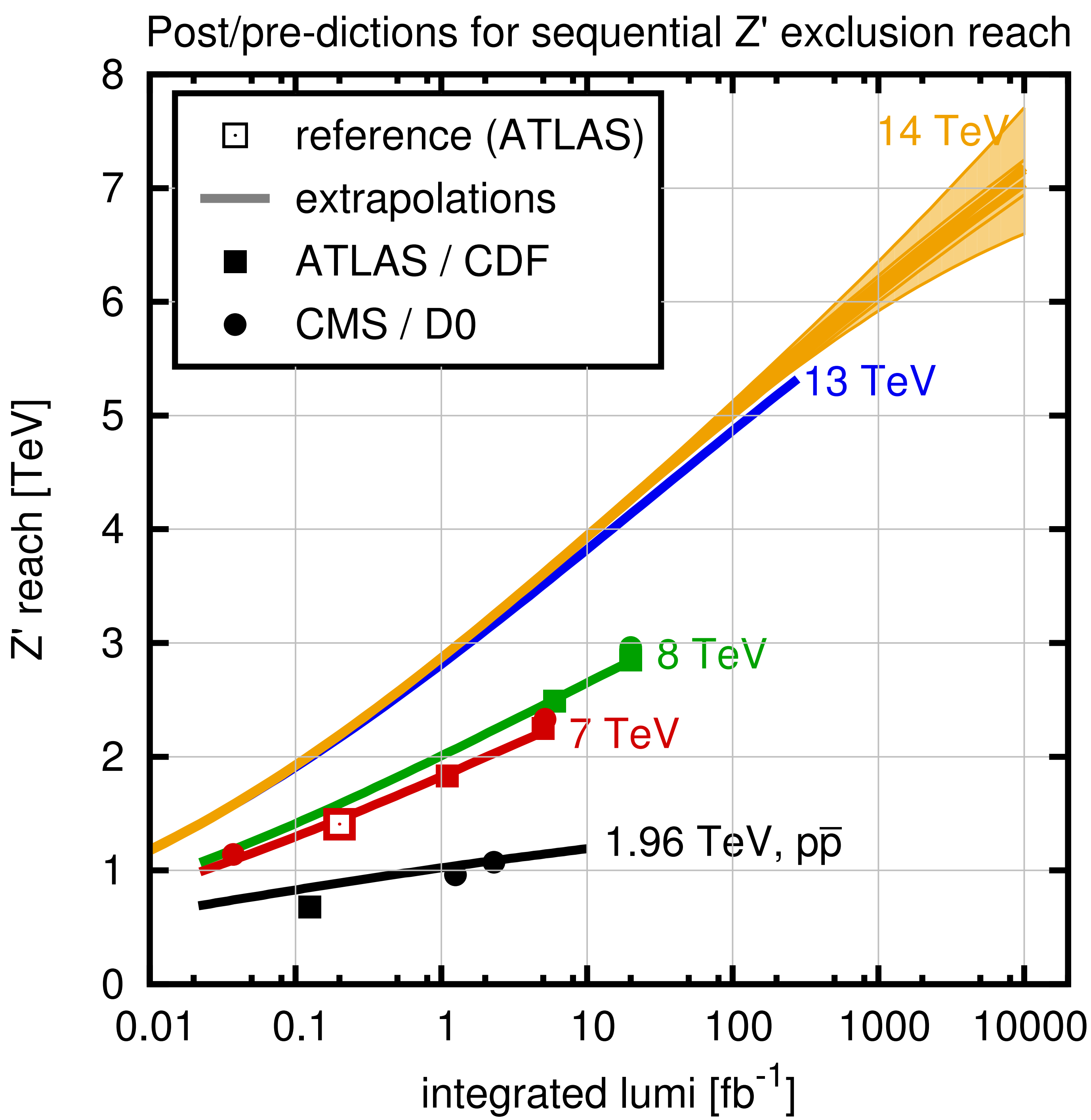


Analytics for jet substructure

Gavin Salam (CERN)
based on work with Dasgupta, Fregoso & Marzani

Physics challenges in the face of LHC-14
Madrid, September 2014

LHC reach v. lumi

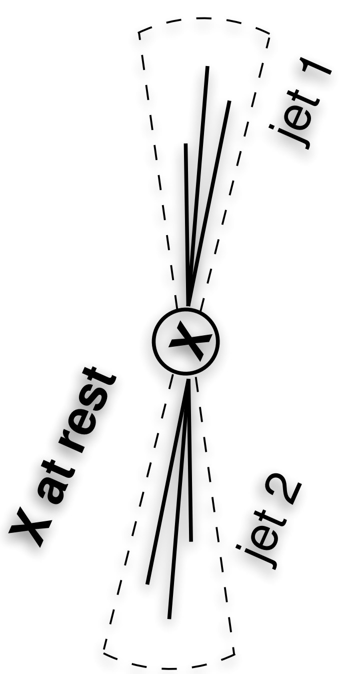


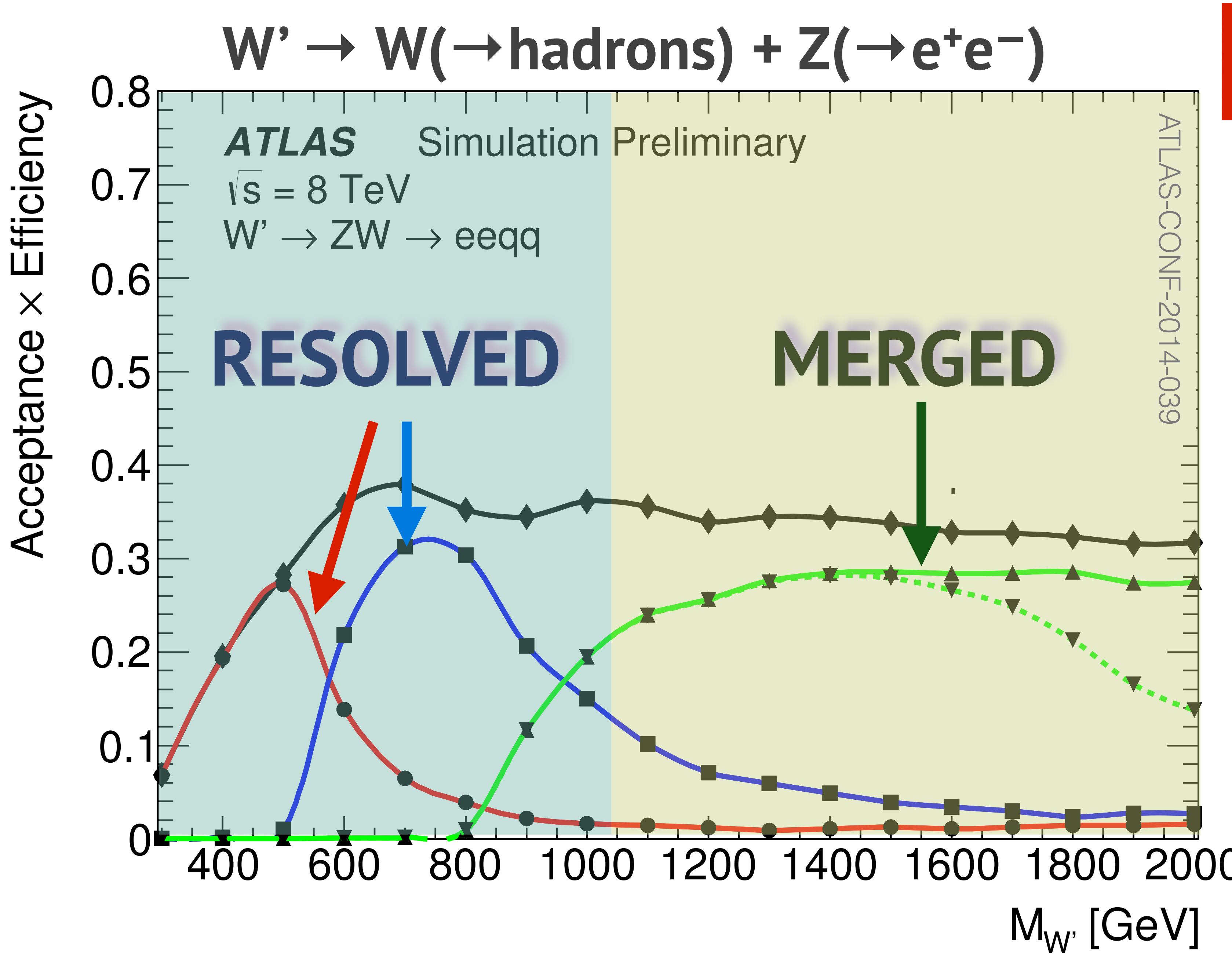
LHC8 → HL-LHC14
x ~2.2 in mass

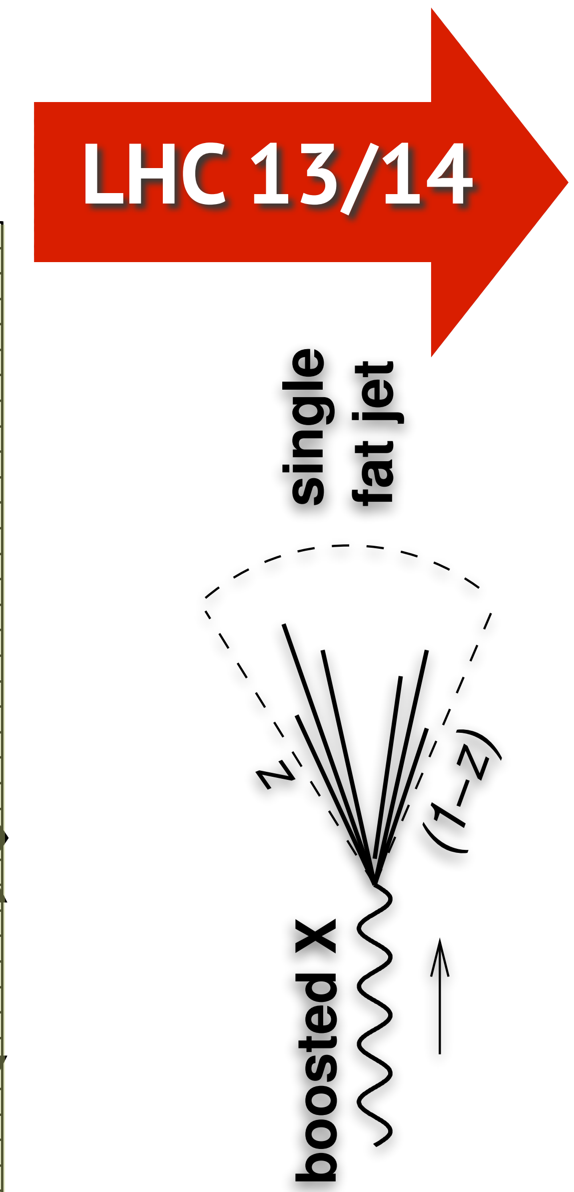
Tevatron → LHC8
x ~3 in mass

http://cern.ch/collider-reach with A. Weiler

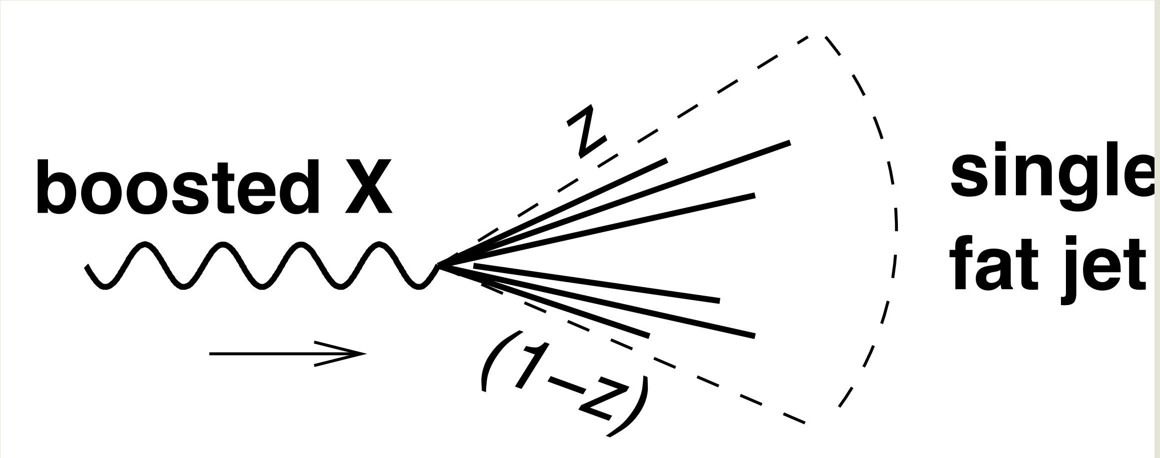
Boosted searches







Most obvious way of detecting a boosted decay is through the mass of the jet

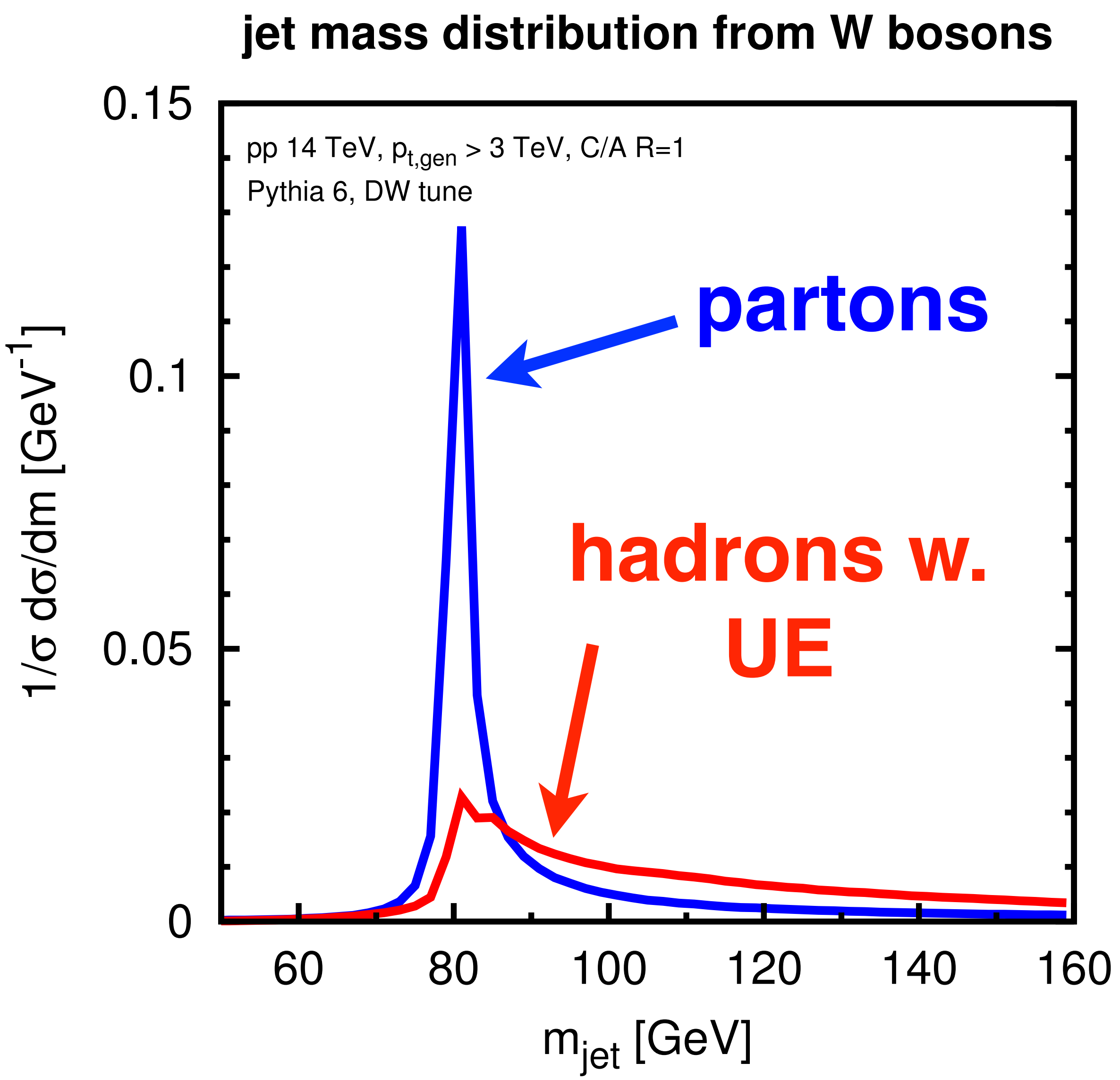


But jet mass is **poor** in practice:

e.g., narrow W resonance highly smeared by QCD radiation

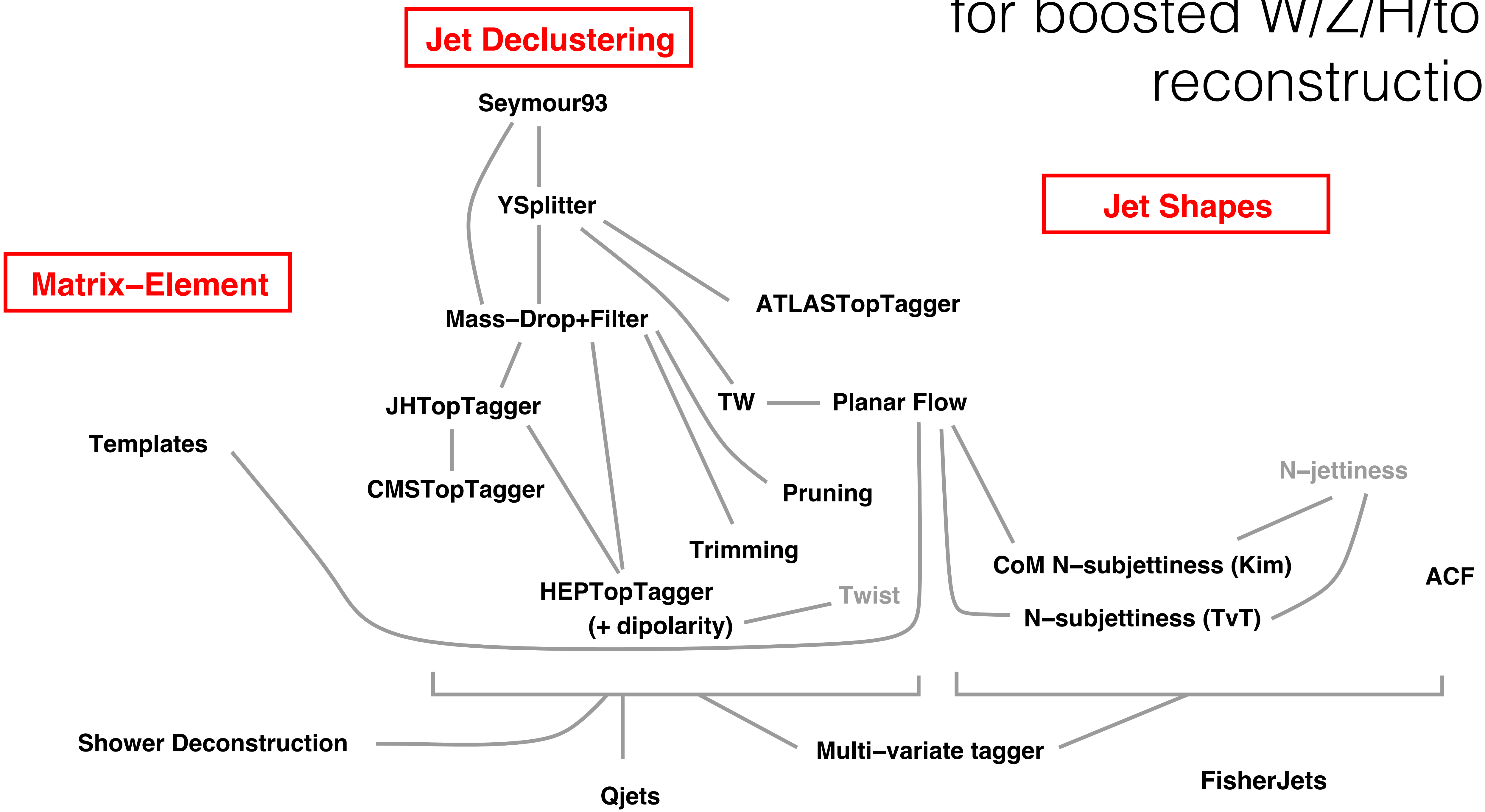
(mainly underlying event/ pileup)

cf. calculations by Rubin '10



Very active research field

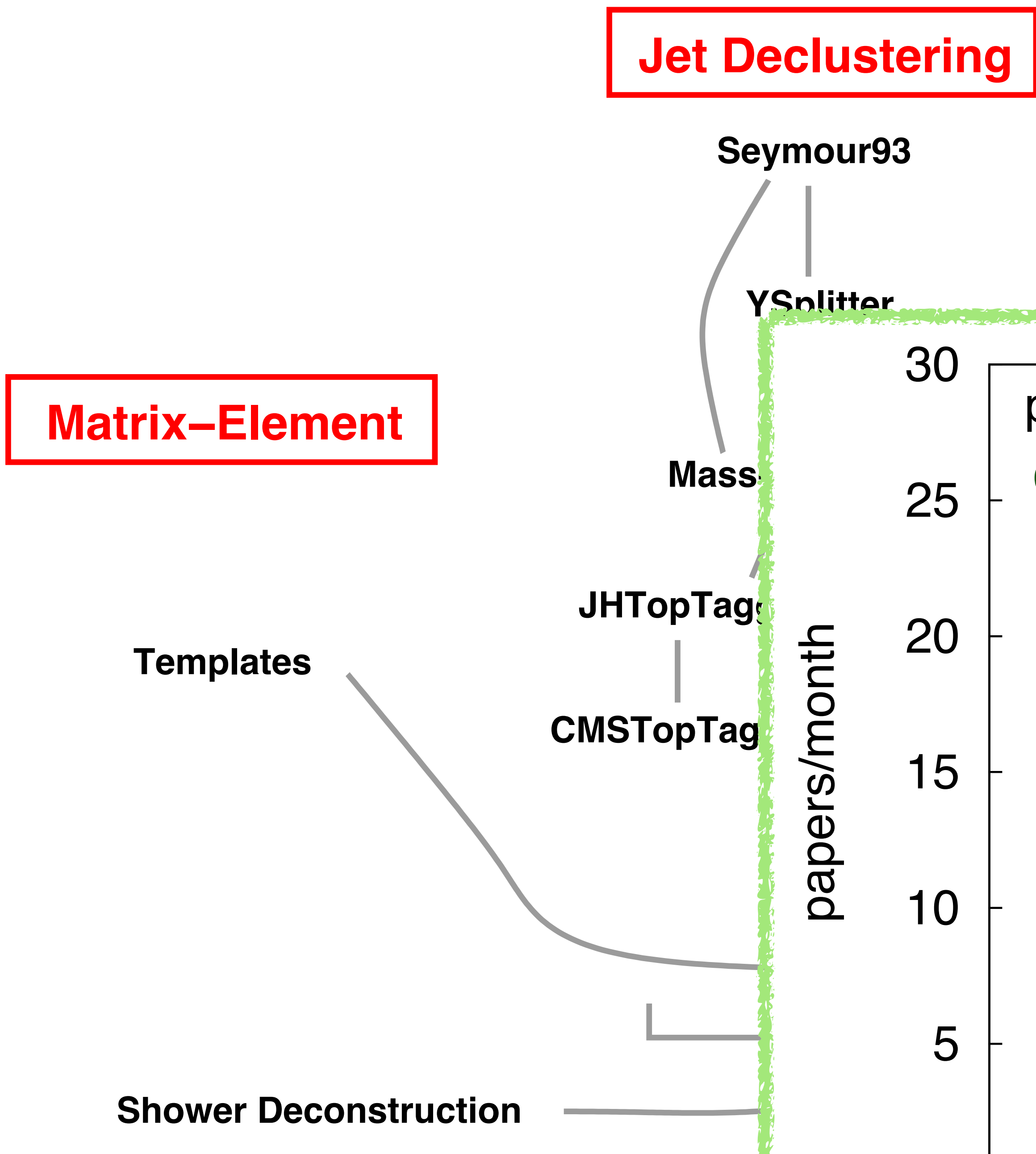
Some of the tools developed for boosted W/Z/H/top reconstruction

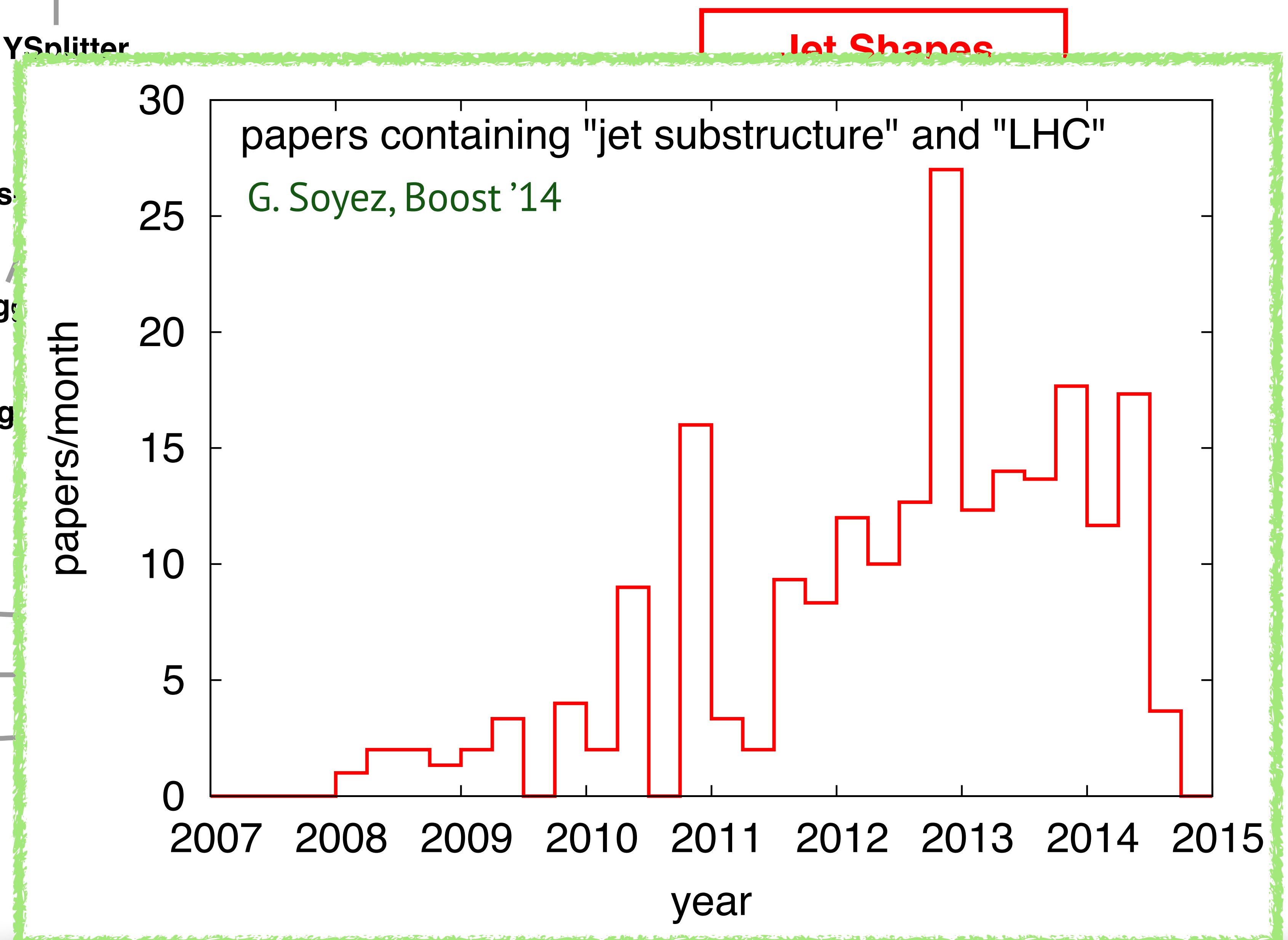


apologies for omitted taggers, arguable links, etc.

Very active research field

Some of the tools developed for boosted W/Z/H/top reconstruction





To fully understand “Boost” you want to study
all possible signal (W/Z/H/top/…) and QCD jets.

But you need to start somewhere.
We chose the QCD jets because:

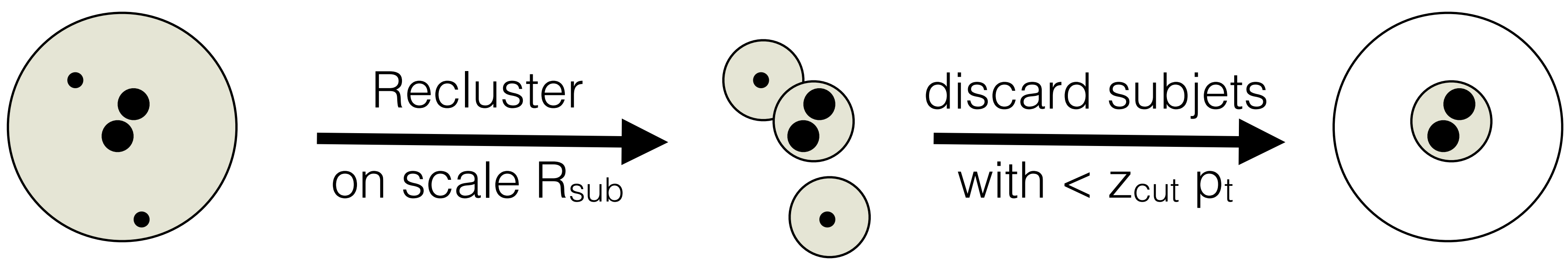
(a) they have the richest structure.

(b) once you know understand the QCD jets,
the route for understanding signal jets becomes clear too.

arXiv:1307.0007
Dasgupta, Fregoso, Marzani & GPS
+Dasgupta, Fregoso, Marzani & Powling, 1307.0013

Cannot possibly study all tools
These 3 are widely used

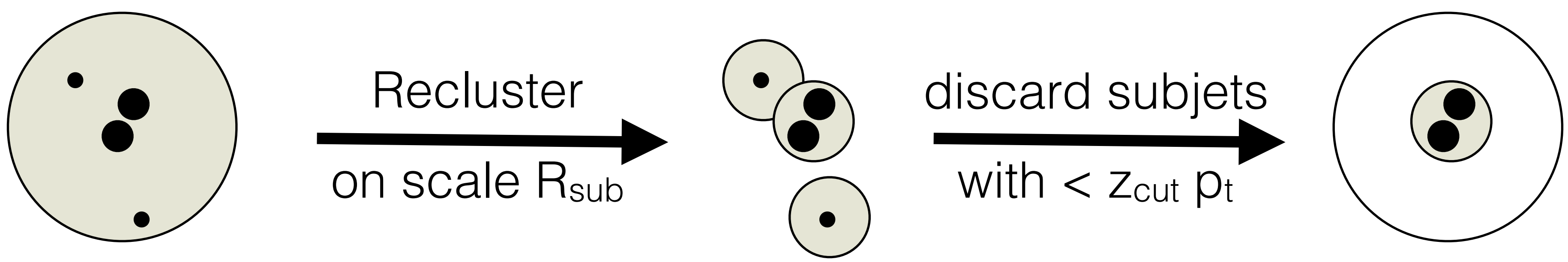
Trimming



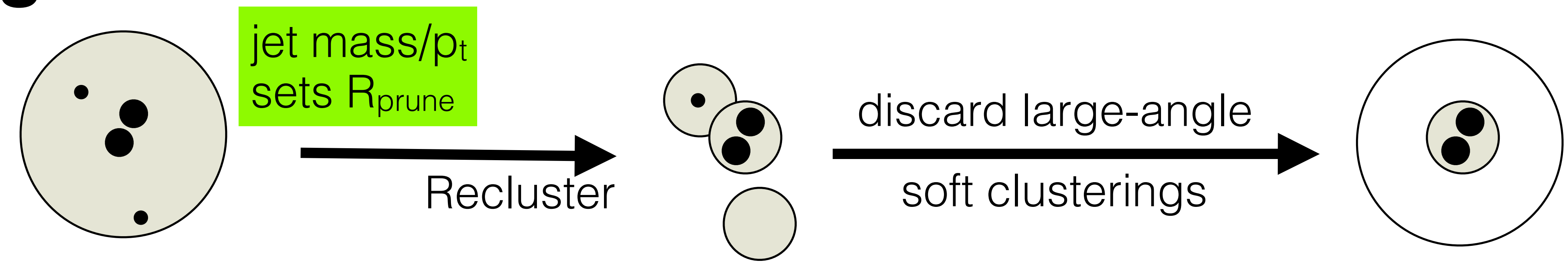
study 3 taggers/groomers

Cannot possibly study all tools
These 3 are widely used

Trimming



Pruning



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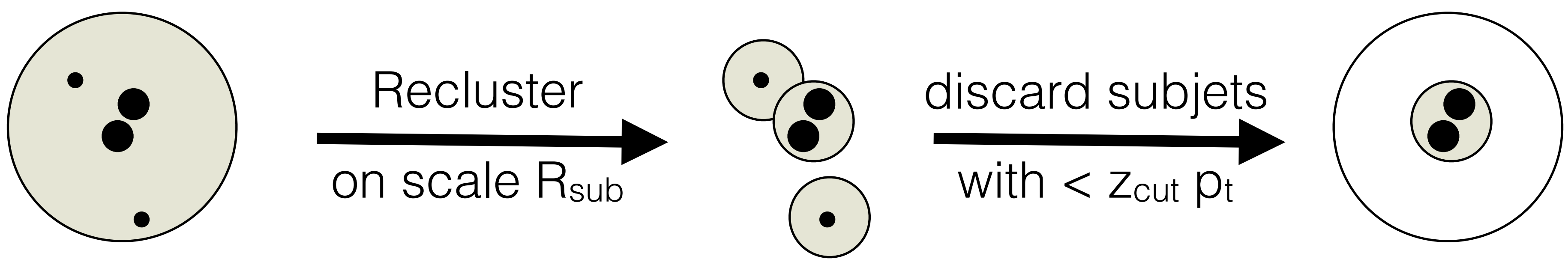

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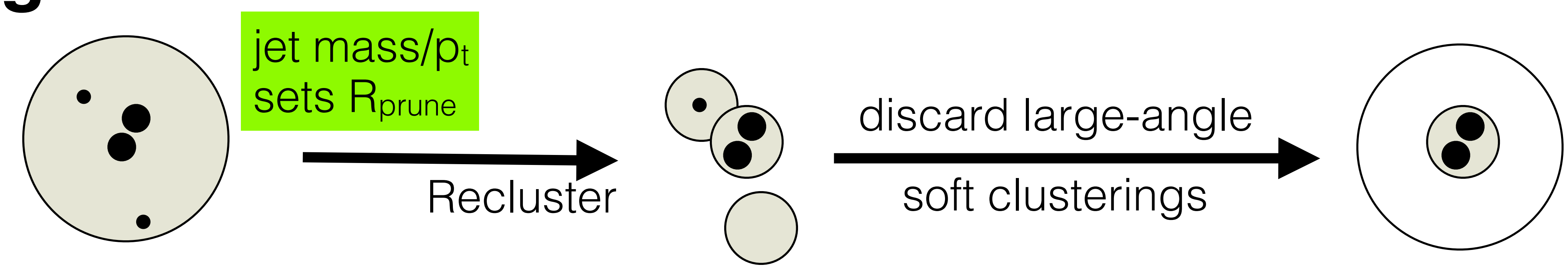
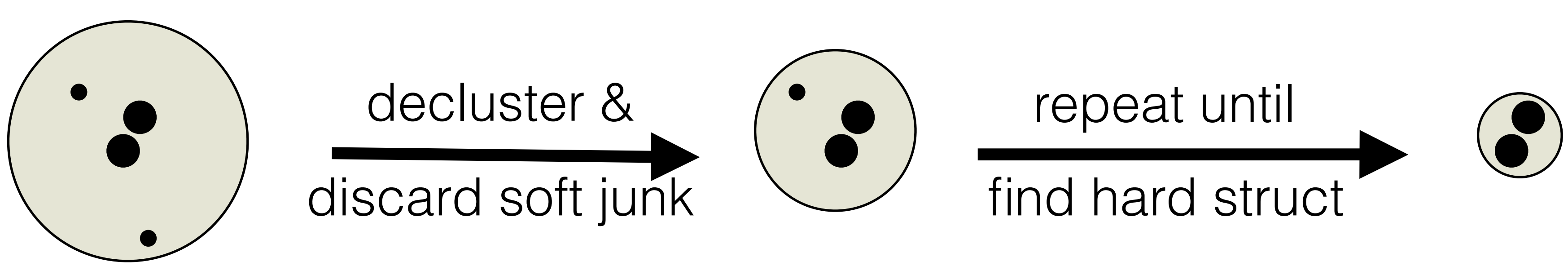


Mass-drop tagger (MDT, aka BDRS)



The key variables

For phenomenology

Jet mass: *m*

[as compared to W/Z/H or top mass]

For QCD calculations

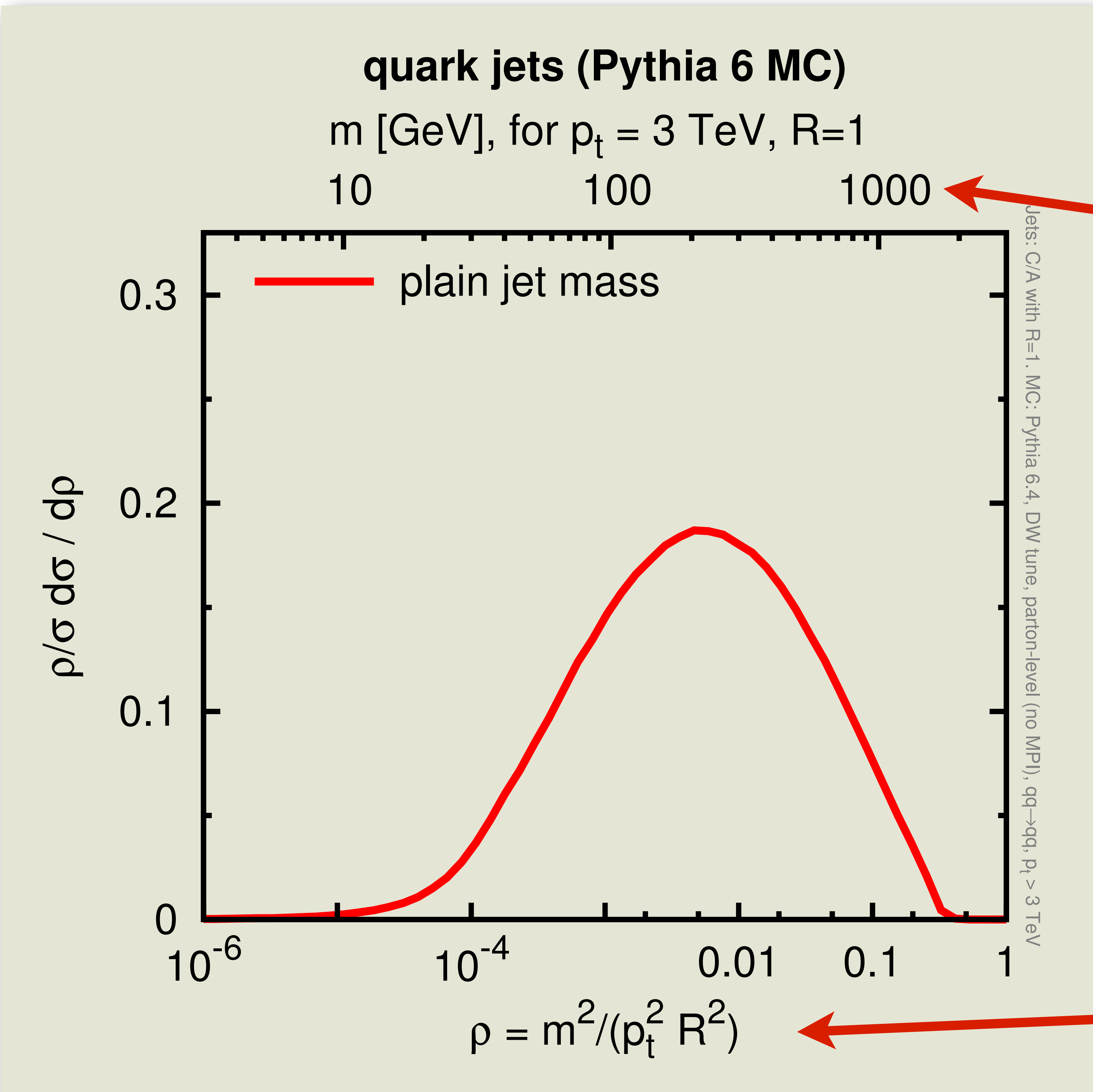
$$\rho = \frac{m^2}{p_t^2 R^2}$$

[R is jet opening angle – or radius]

Because ρ is invariant under boosts along jet direction

The "right" MC study can already be instructive

(testing on quark [background] jets)



Physical mass for 3 TeV, R=1 jets

ρ ~ Rescaled mass²

(i.e. the QCD variable)

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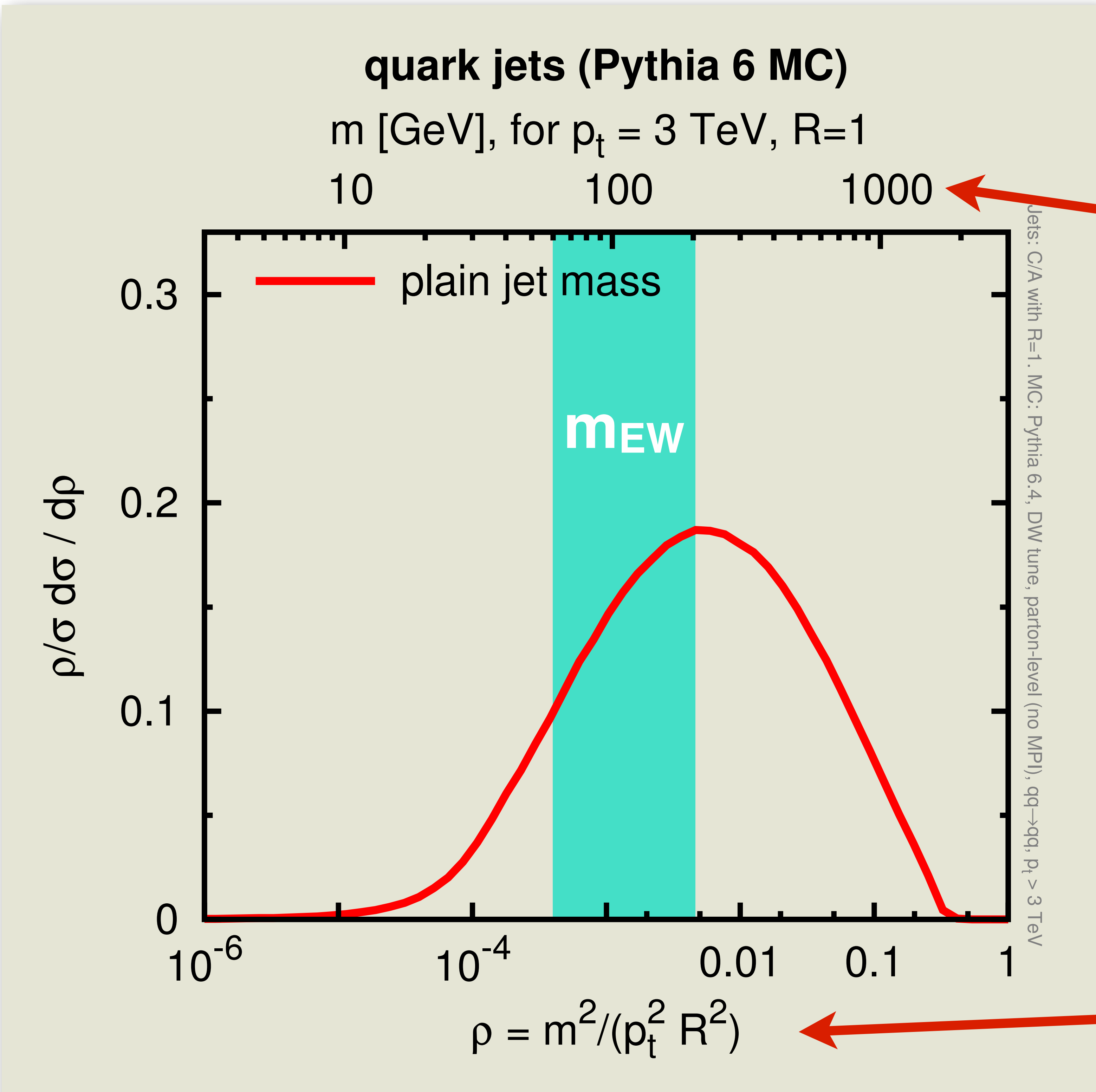

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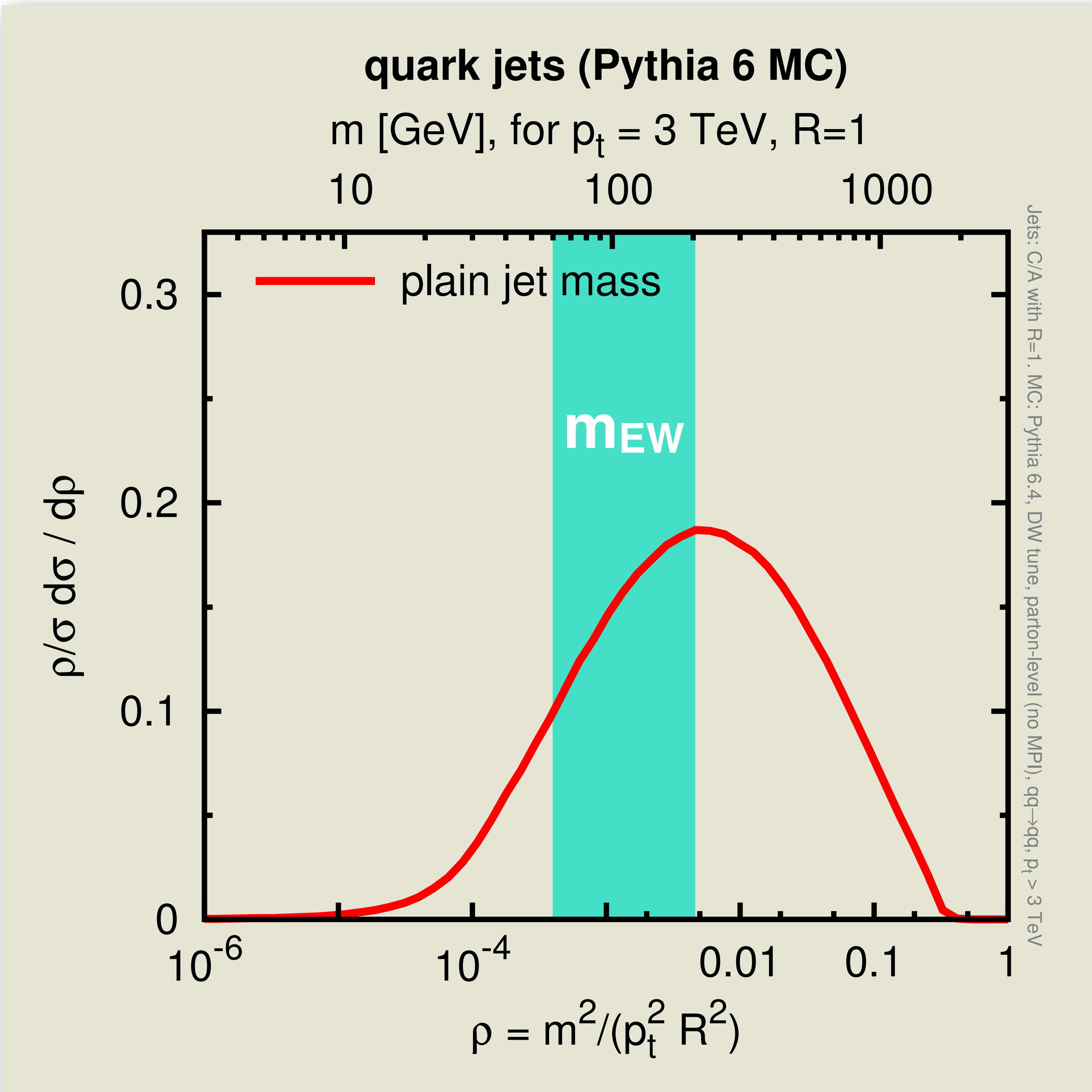

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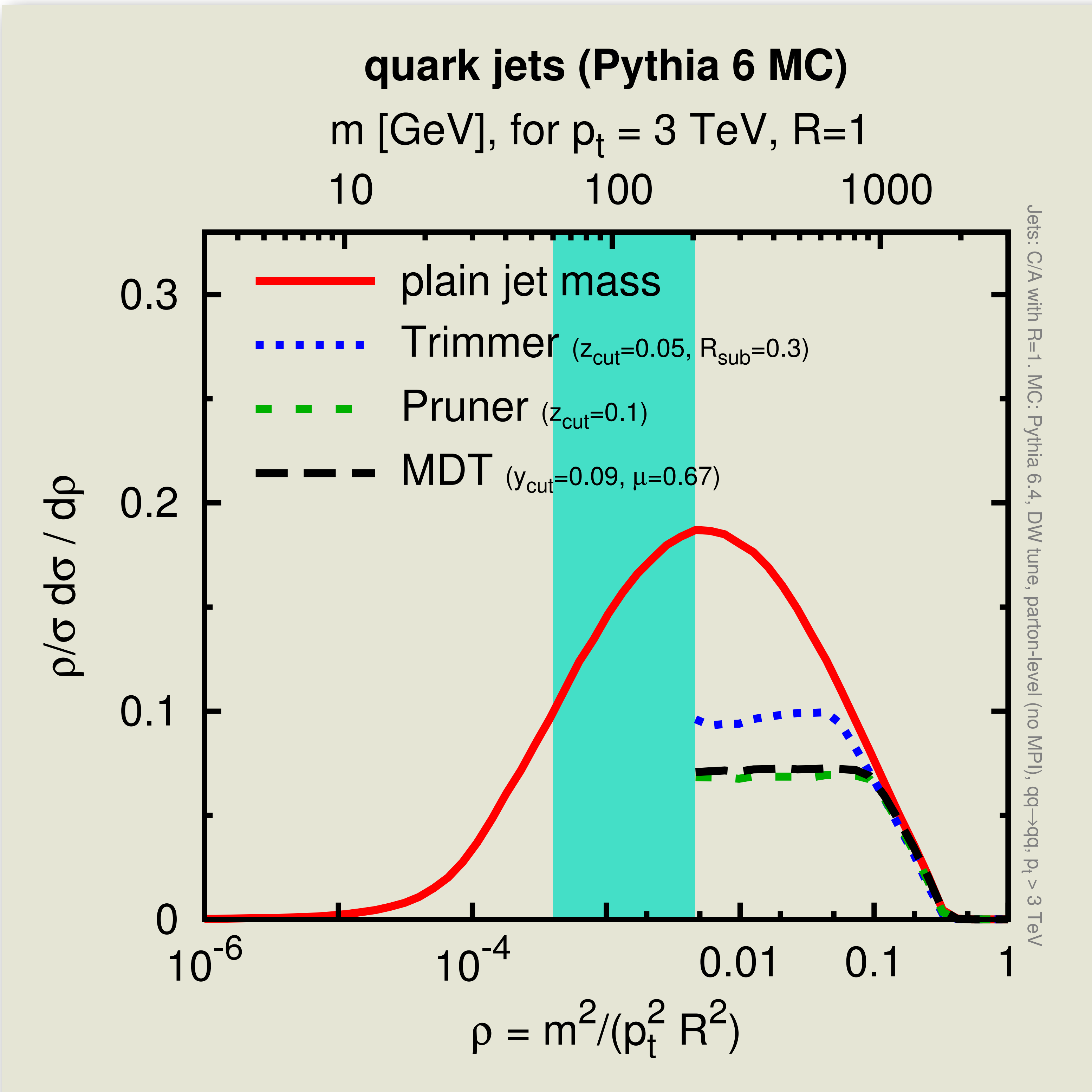
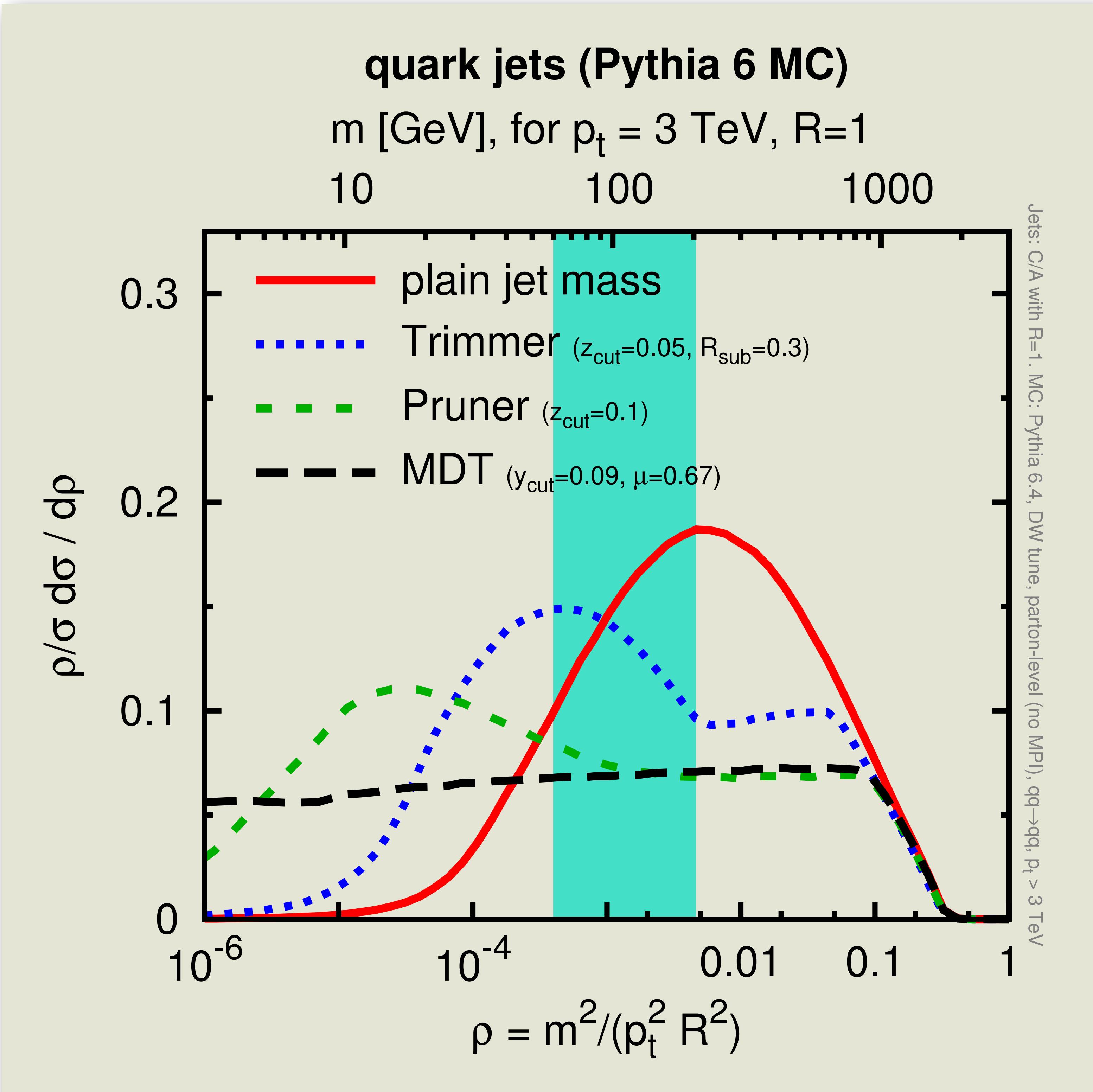


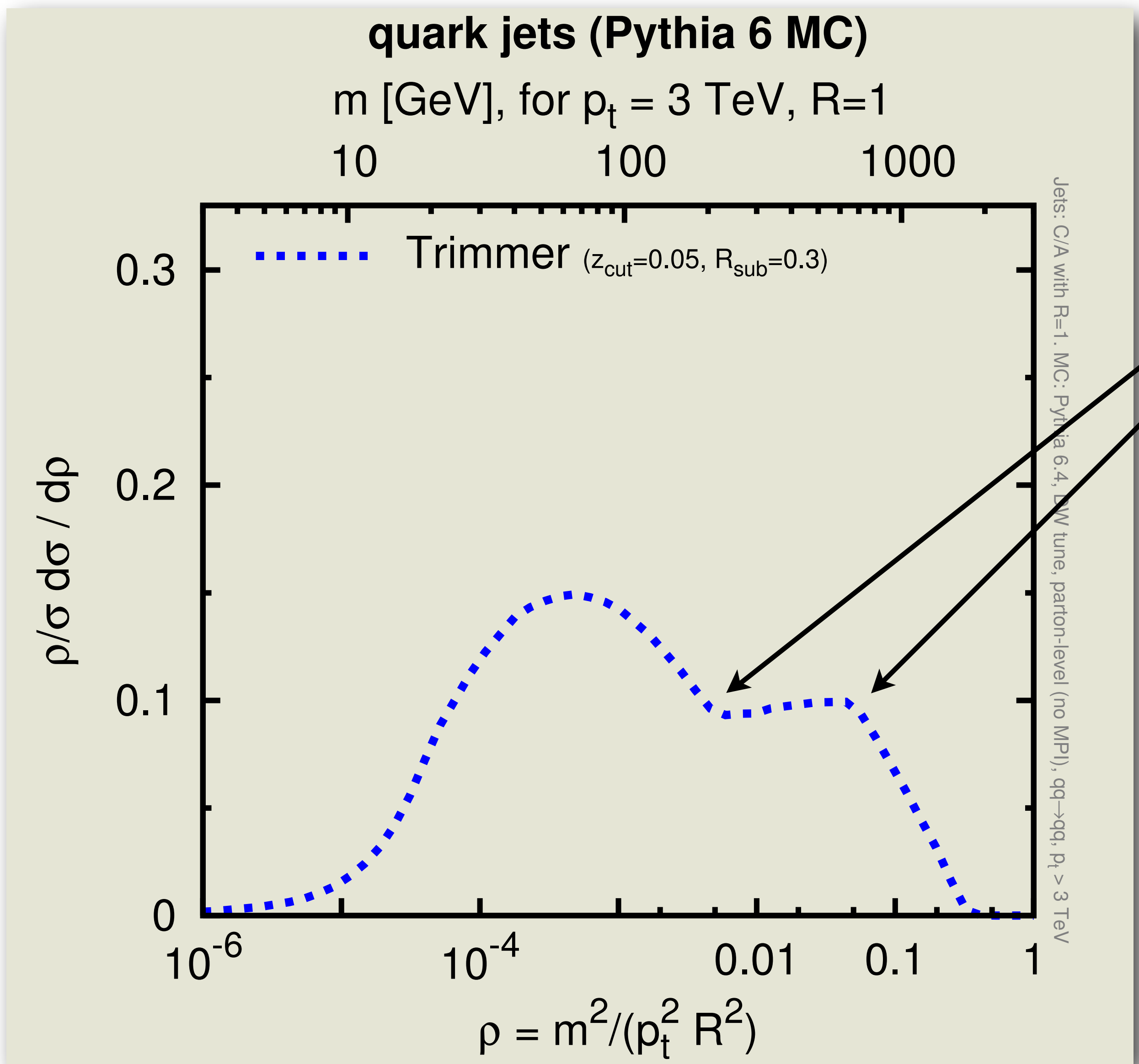
Different taggers can be quite similar

The "right" MC study can already be instructive
(testing on quark [background] jets)



But only for a limited range of masses

What might we want to find out?



Where exactly are the kinks? How do their locations depend on z_{cut}, R_{sub}?

Kinks are especially dangerous for data-driven backgrounds

What physics is relevant in the different regions?

Because then you have an idea of how well you control it

And maybe you can make better taggers

Key calculations related to plain jet mass

- Catani, Turnock, Trentadue & Webber, '91: **heavy-jet mass in e^+e^-**
- Dasgupta & GPS, '01: **hemisphere jet mass in e^+e^-** (and DIS) (→ non-global logs)
- Appleby & Seymour, '02; Delenda, Appleby, Dasgupta & Banfi '06: **impact of jet boundary** (→ clustering logs)
- Gehrmann, Gehrmann de Ridder, Glover '08; Weinzierl '08
  Chien & Schwartz '10: **heavy-jet mass in e^+e^- to higher accuracy**
- Rubin '10**: filtering for jet masses**
- Li, Li & Yuan '12,
  Dasgupta, Khelifa-Kerfa, Marzani & Spannowsky '12,
  Chien & Schwartz '12,
  Jouttenus, Stewart, Tackmann, Waalewijn '13:
  jet masses at hadron colliders
- Hatta & Ueda '13: non-global logs beyond large-N_C limit
- Forshaw, Seymour et al '06-'12, Catani, de Florian & Rodrigo '12: factorization breaking terms (aka super-leading logs)

Jet masses are hard!
Will tagging/grooming make them impossible?

Matt Schwartz @ Boost 2012

Trimming

Krohn, Thaler & Wang '09

Take all particles in a jet of radius **R** and recluster them into subjets with a jet definition with radius

$$R_{sub} < R$$

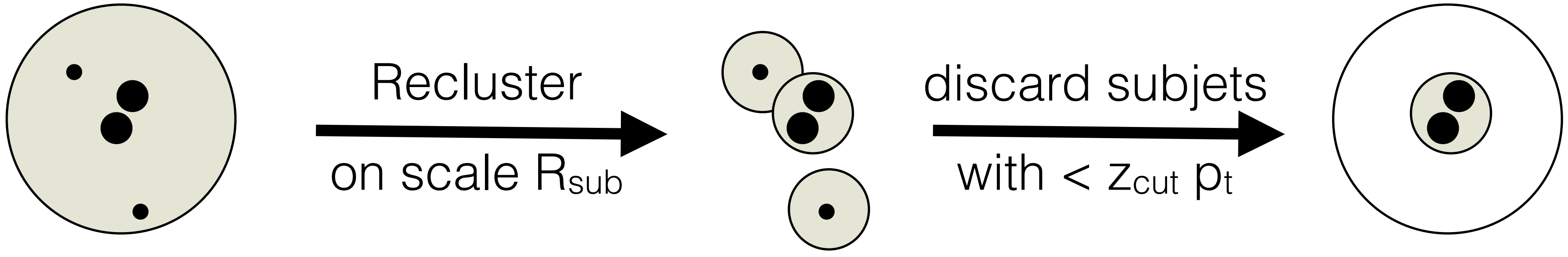
The subjets that satisfy the condition

$$p_t^{(subjet)} > z_{cut}\, p_t^{(jet)}$$

are kept and merged to form the trimmed jet.

two parameters:
R_{sub} and z_{cut}

Use z_{cut} because signals (bkgds) tend to have large (small) z_{cut}



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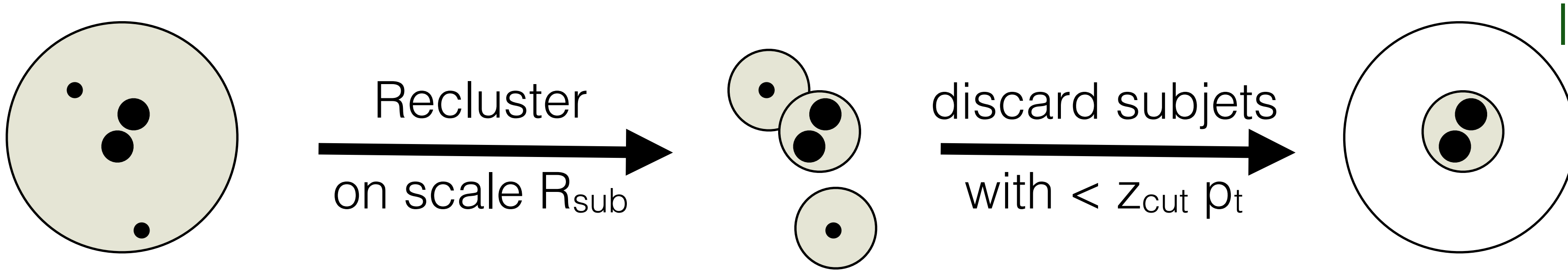
Our approximations

- $\rho \ll 1$
  logs of ρ get resummed
- pretend $R \ll 1$
- $z_{cut} \ll 1$,
  but ($\log z_{cut}$) not large

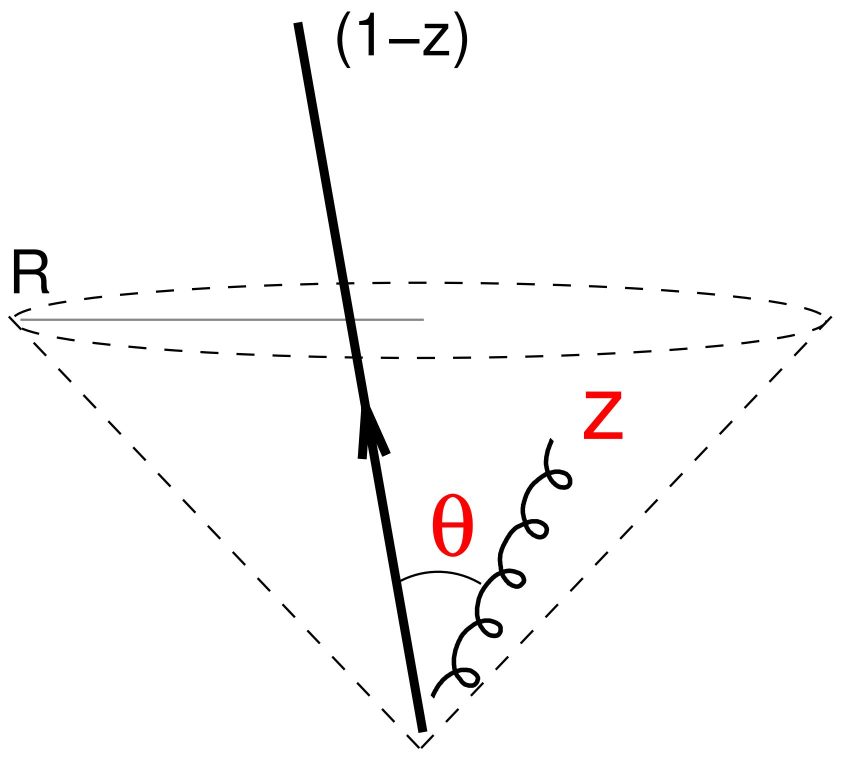
These approximations are not as "wild"as they might sound.

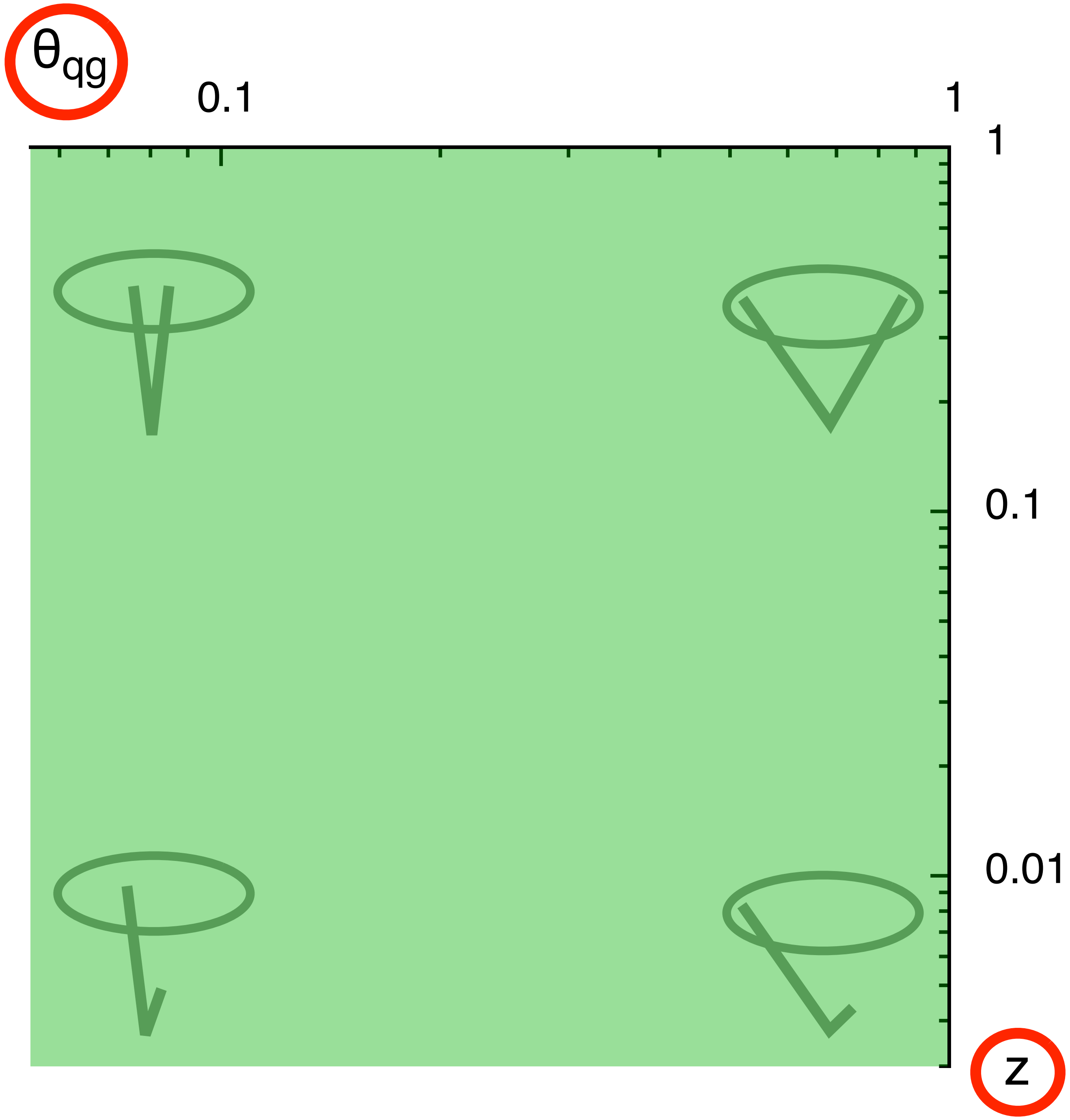
They can also be relaxed.

But our aim for now is to understand the taggers — we leave highest precision calculations till later.



At $O(\alpha_s)$, a quark jet emits a gluon. We study this as a function of the gluon momentum fraction **z** and the quark-gluon opening angle **θ**





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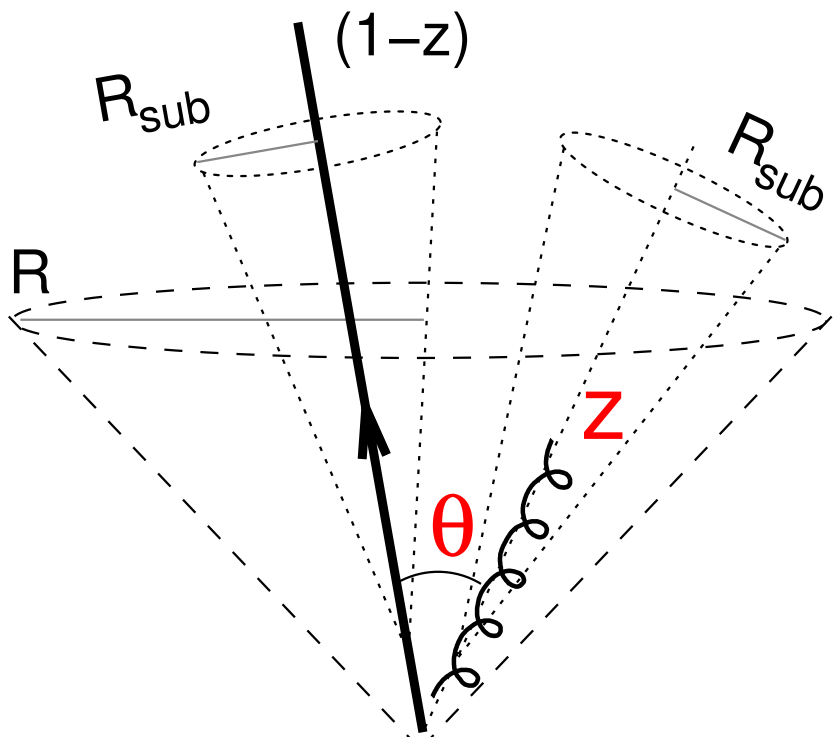

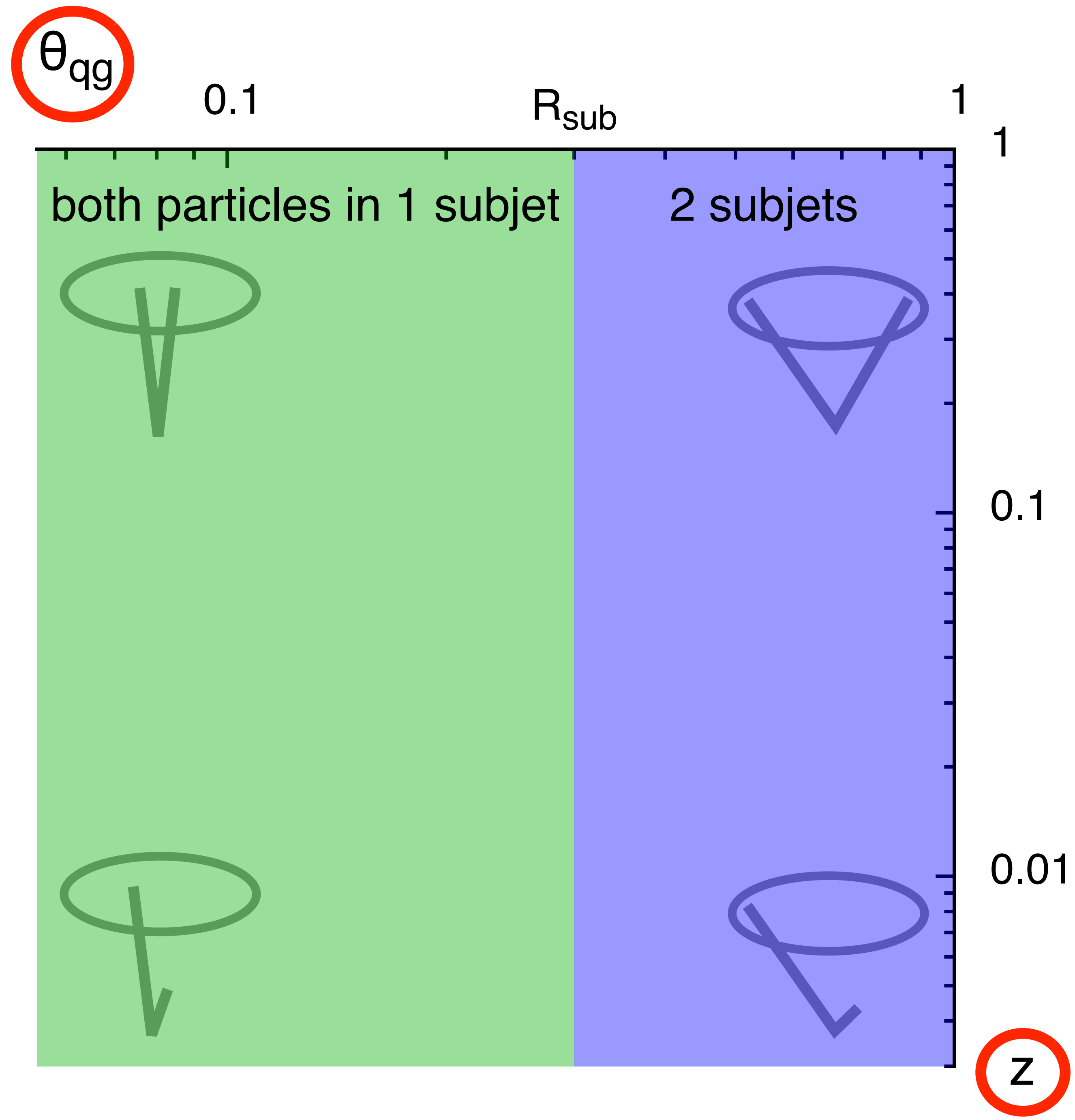

Leading Order — 2-body kinematic plane

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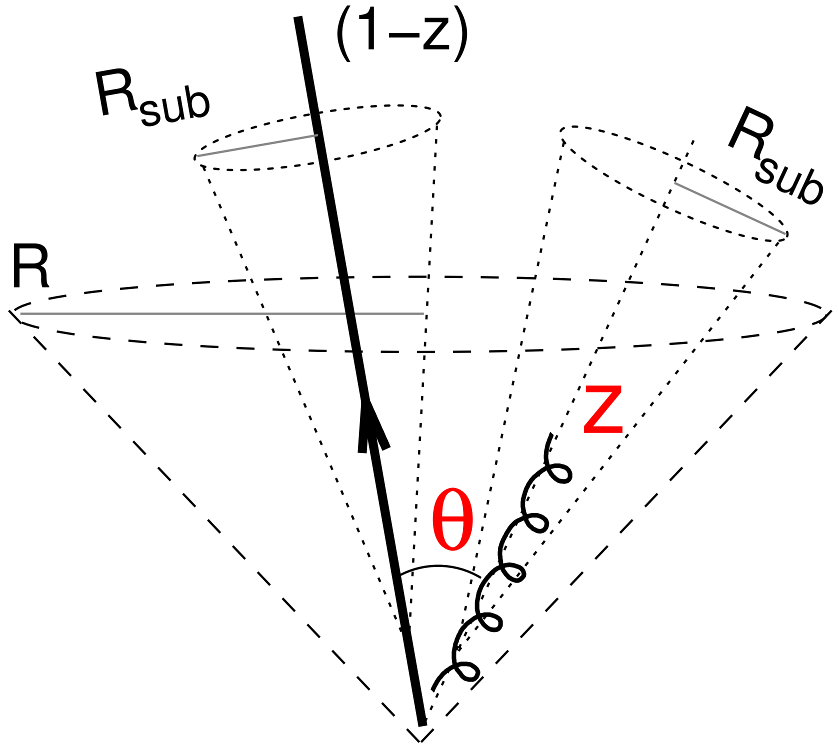
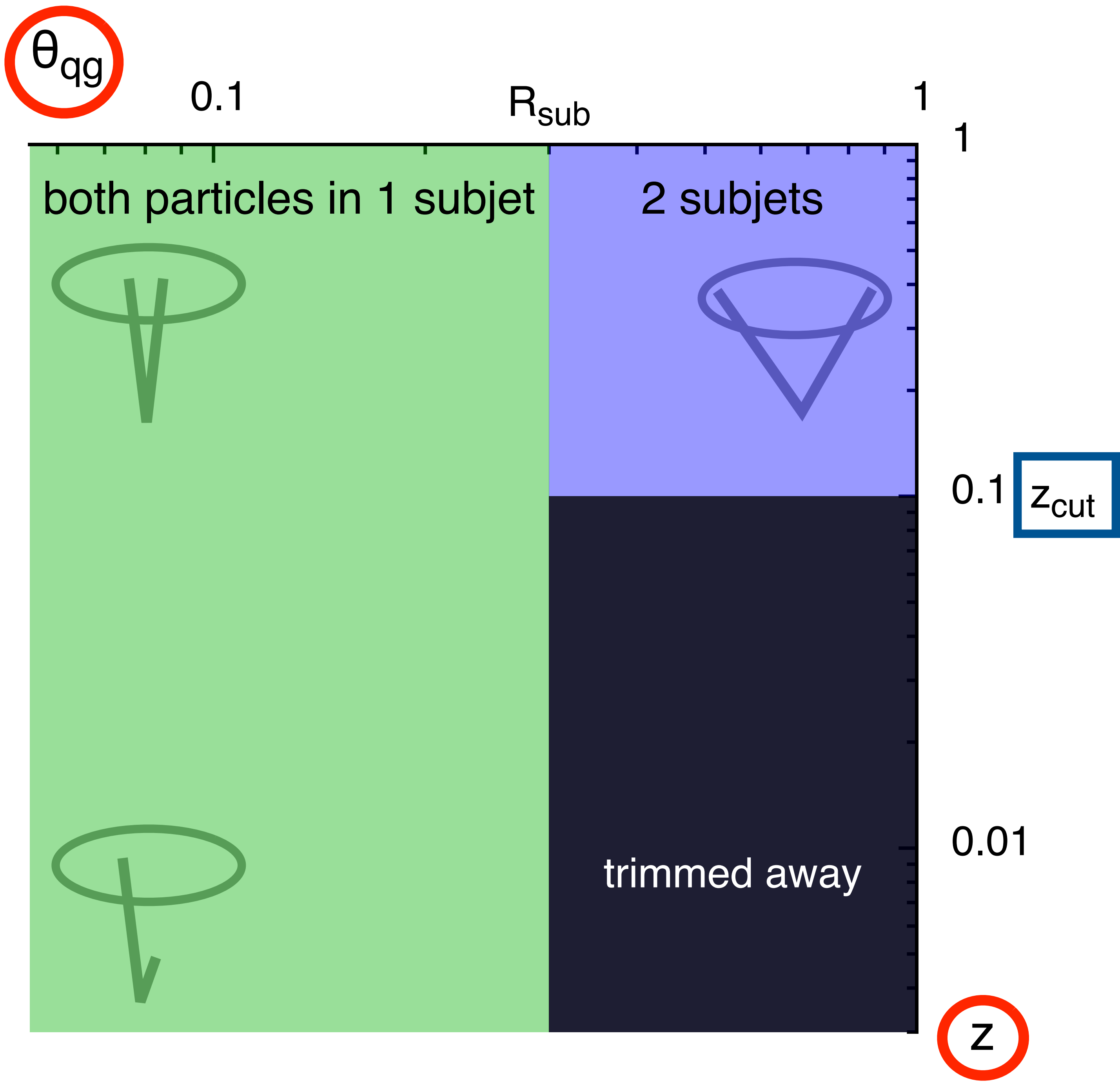
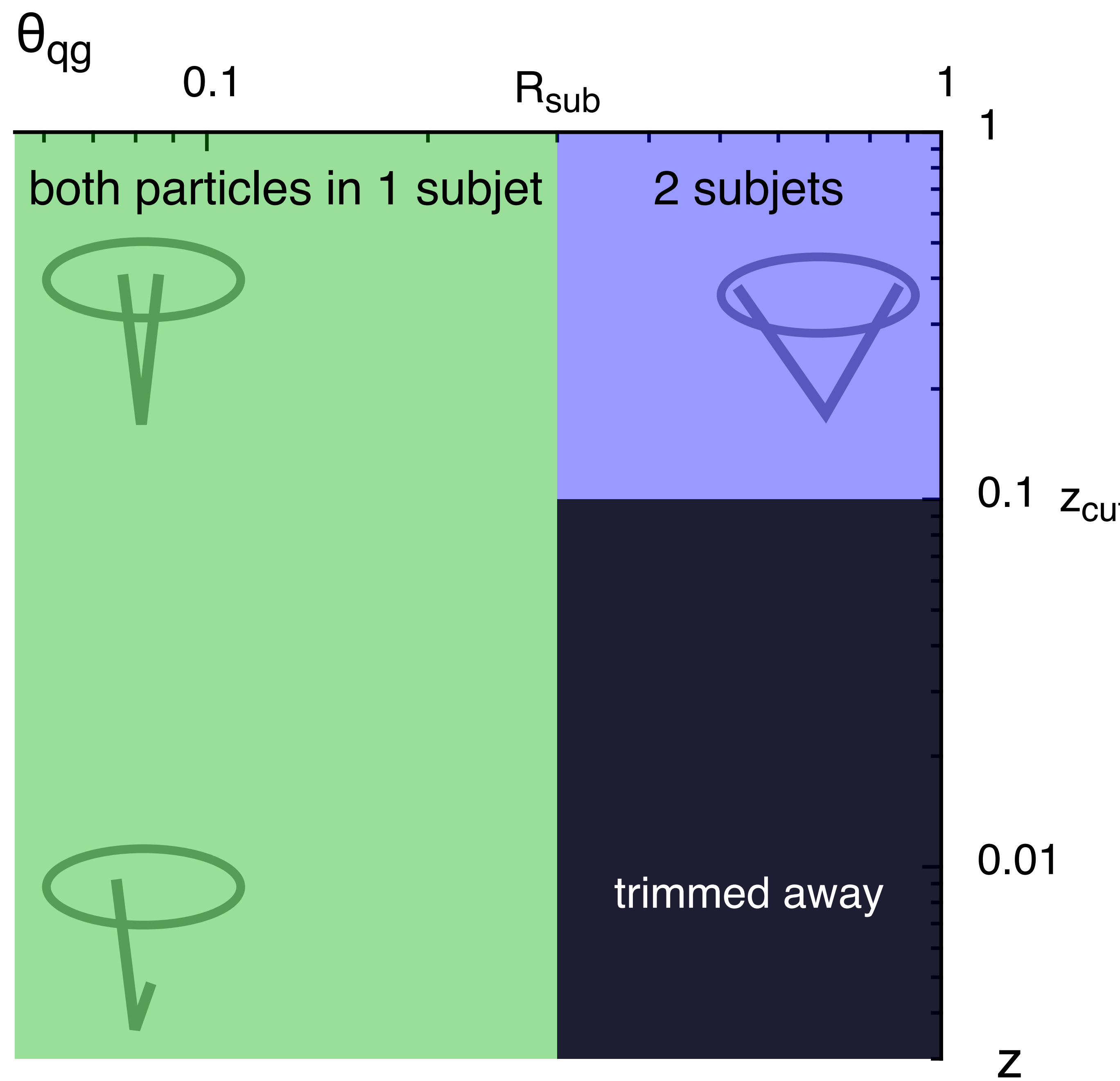




matrix element

$$\frac{\alpha_s C_F}{\pi} \frac{d\theta^2}{\theta^2} \frac{dz}{z}$$

emission probability ~ constant
in log θ – log *z* plane



jet mass

$$\rho = z(1-z)\theta^2$$

length of **fixed-ρ contour** gives LO differential cross section

matrix element

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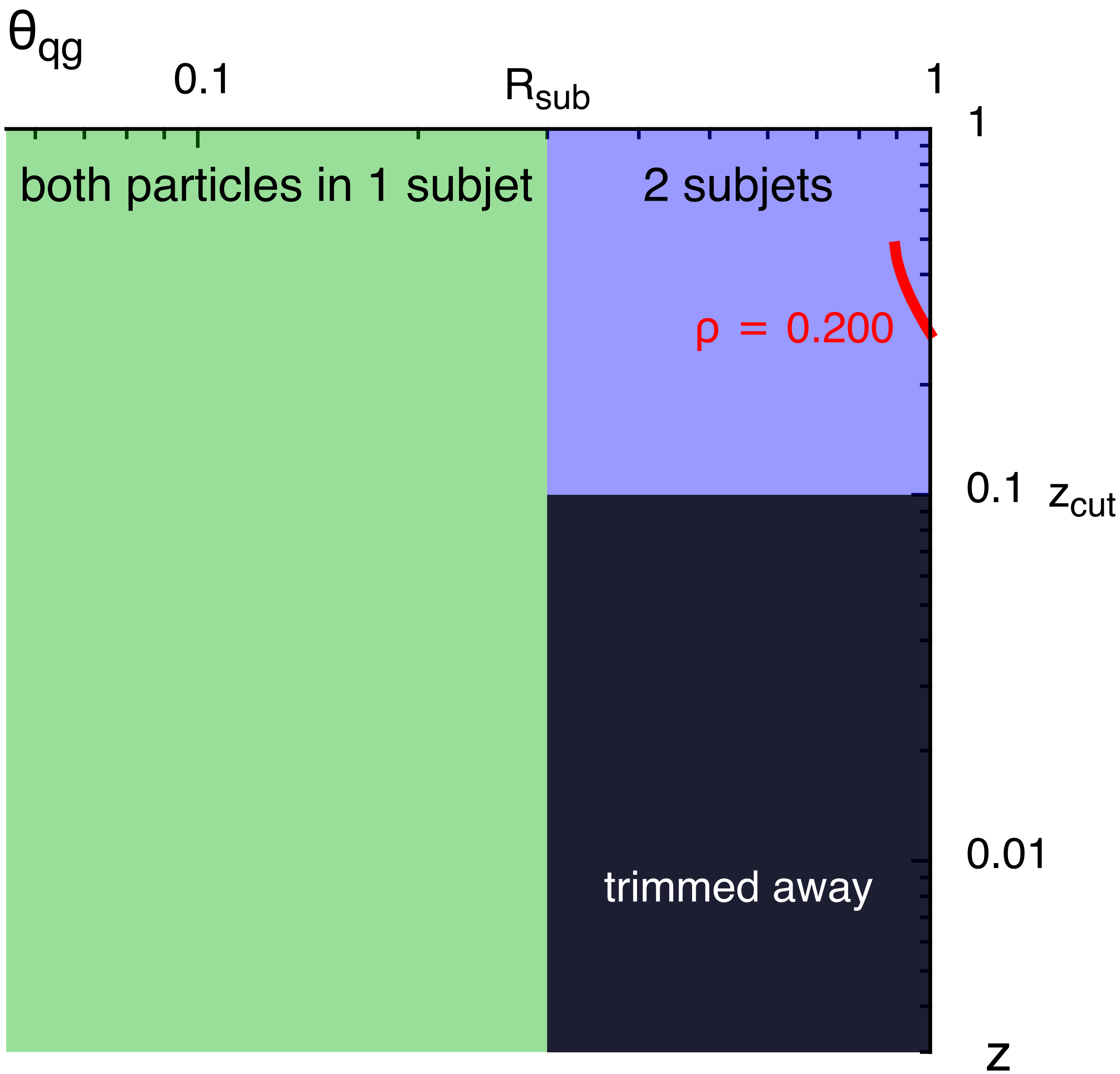

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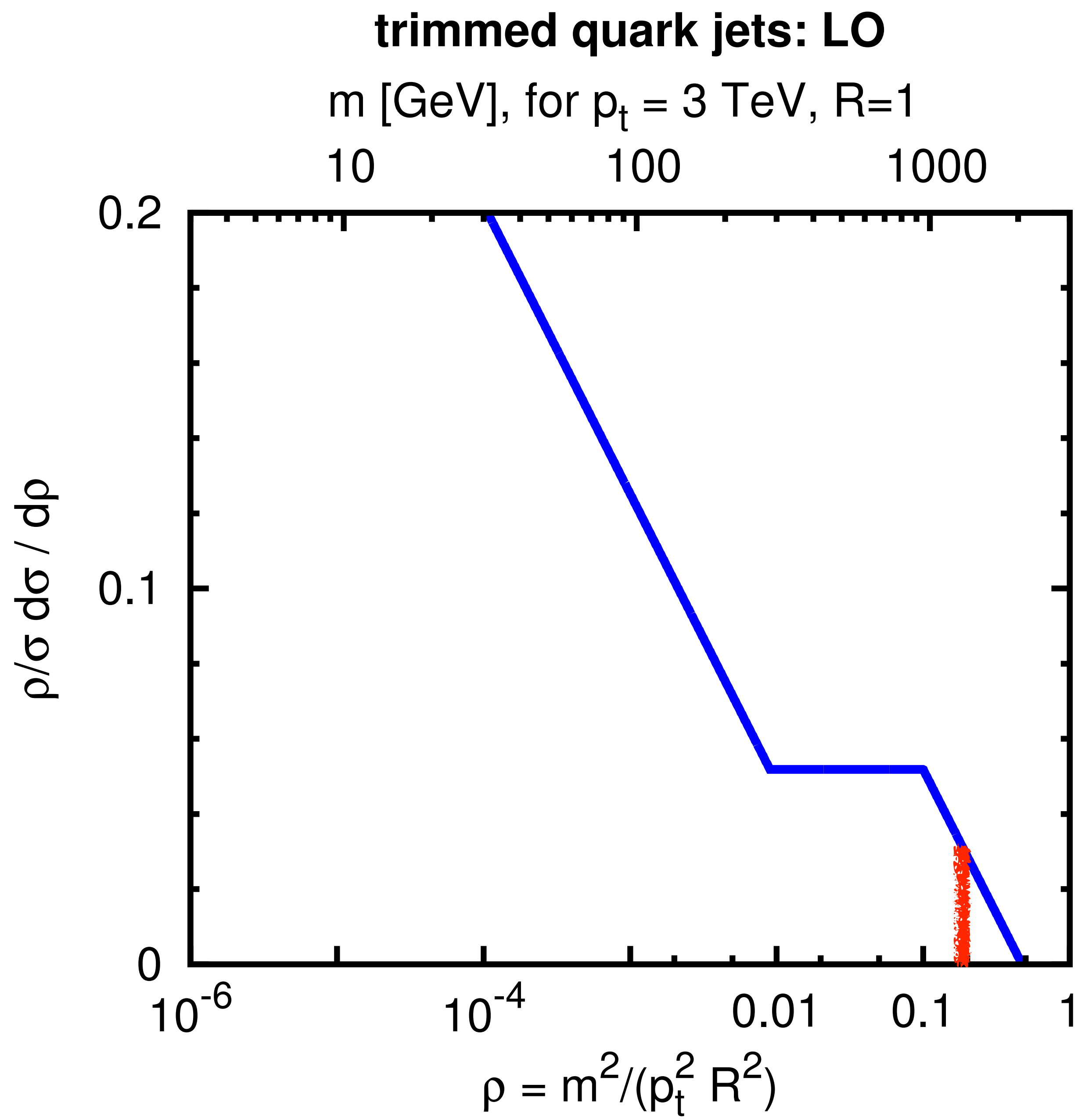

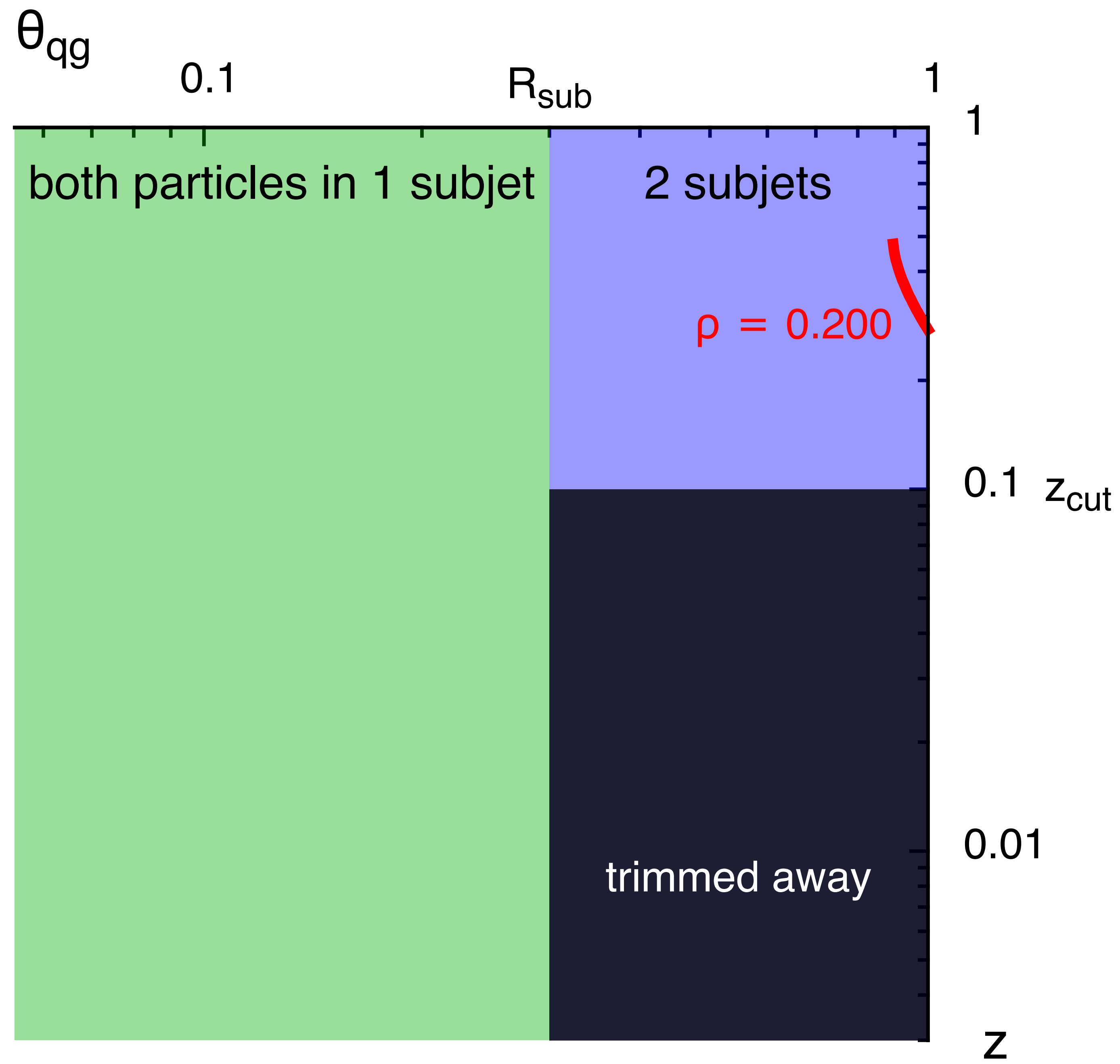

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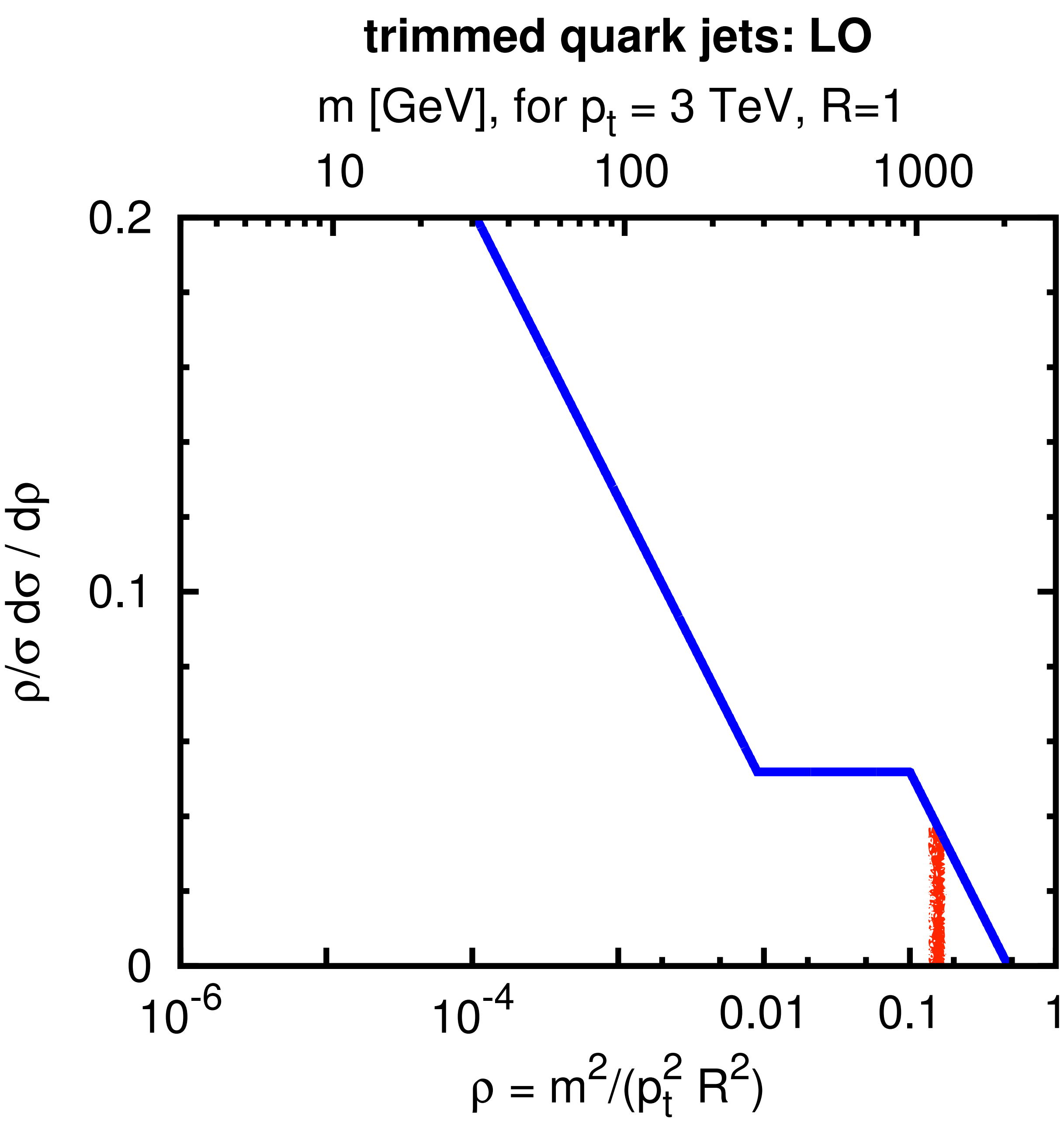

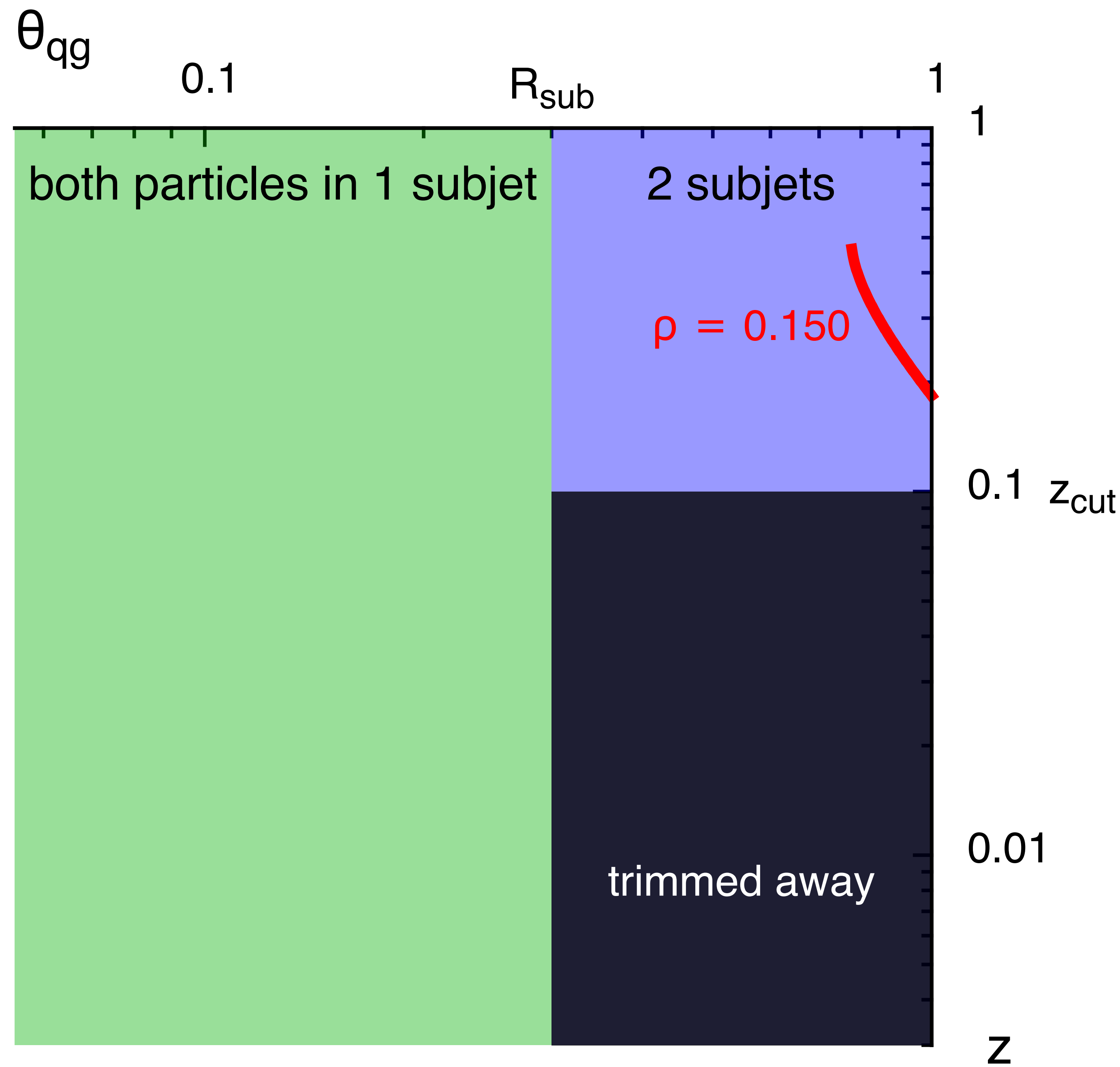

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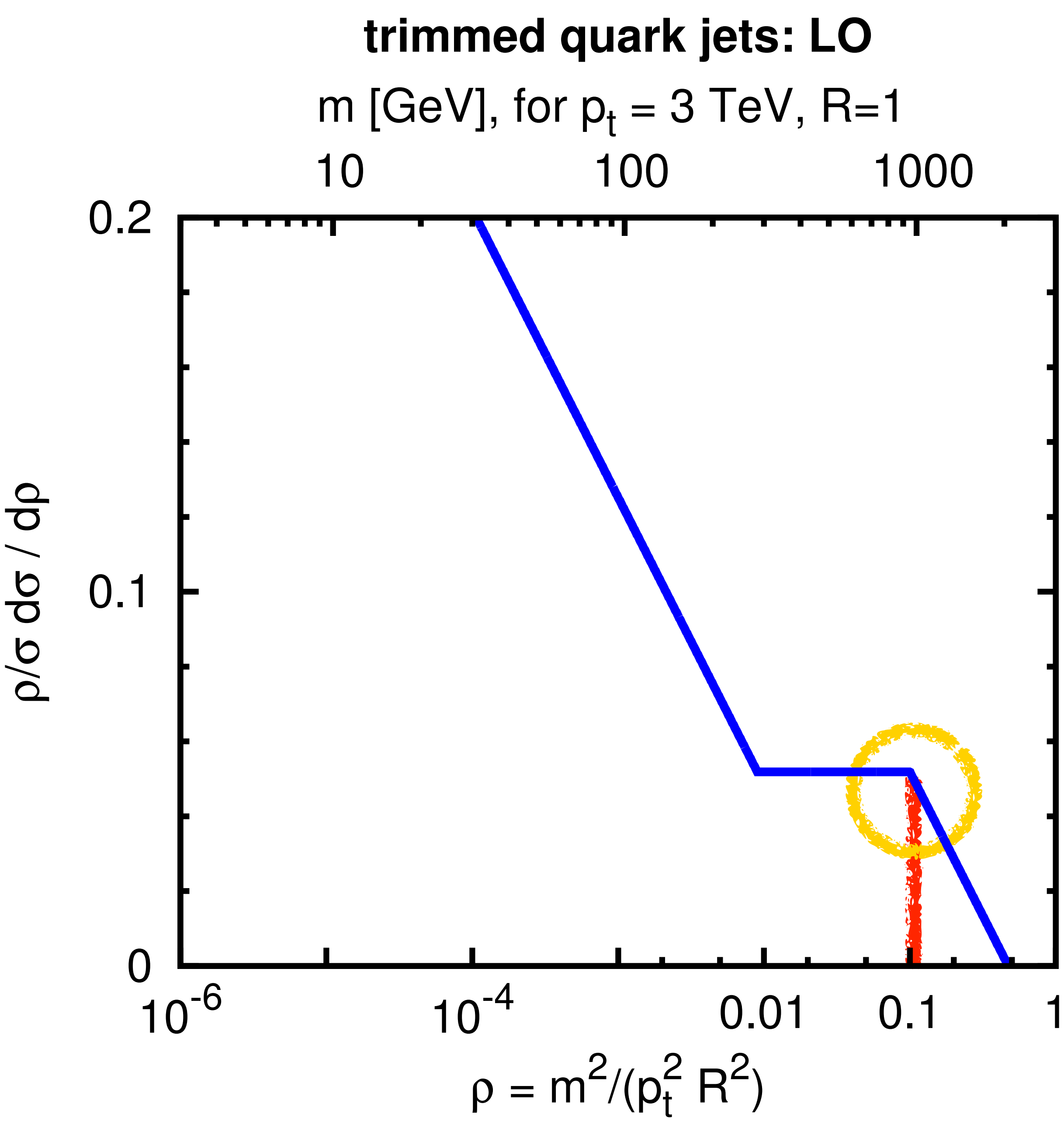

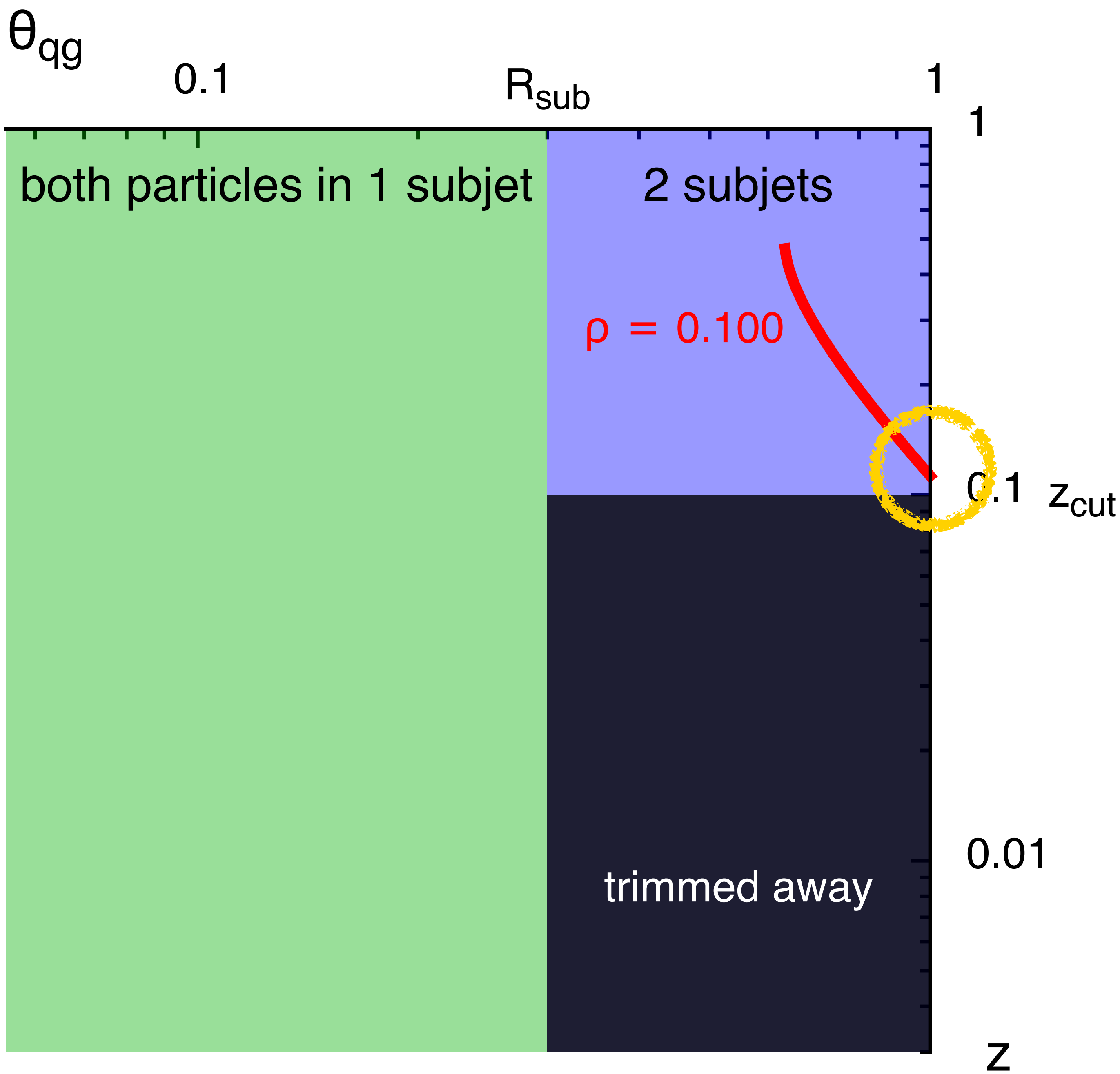

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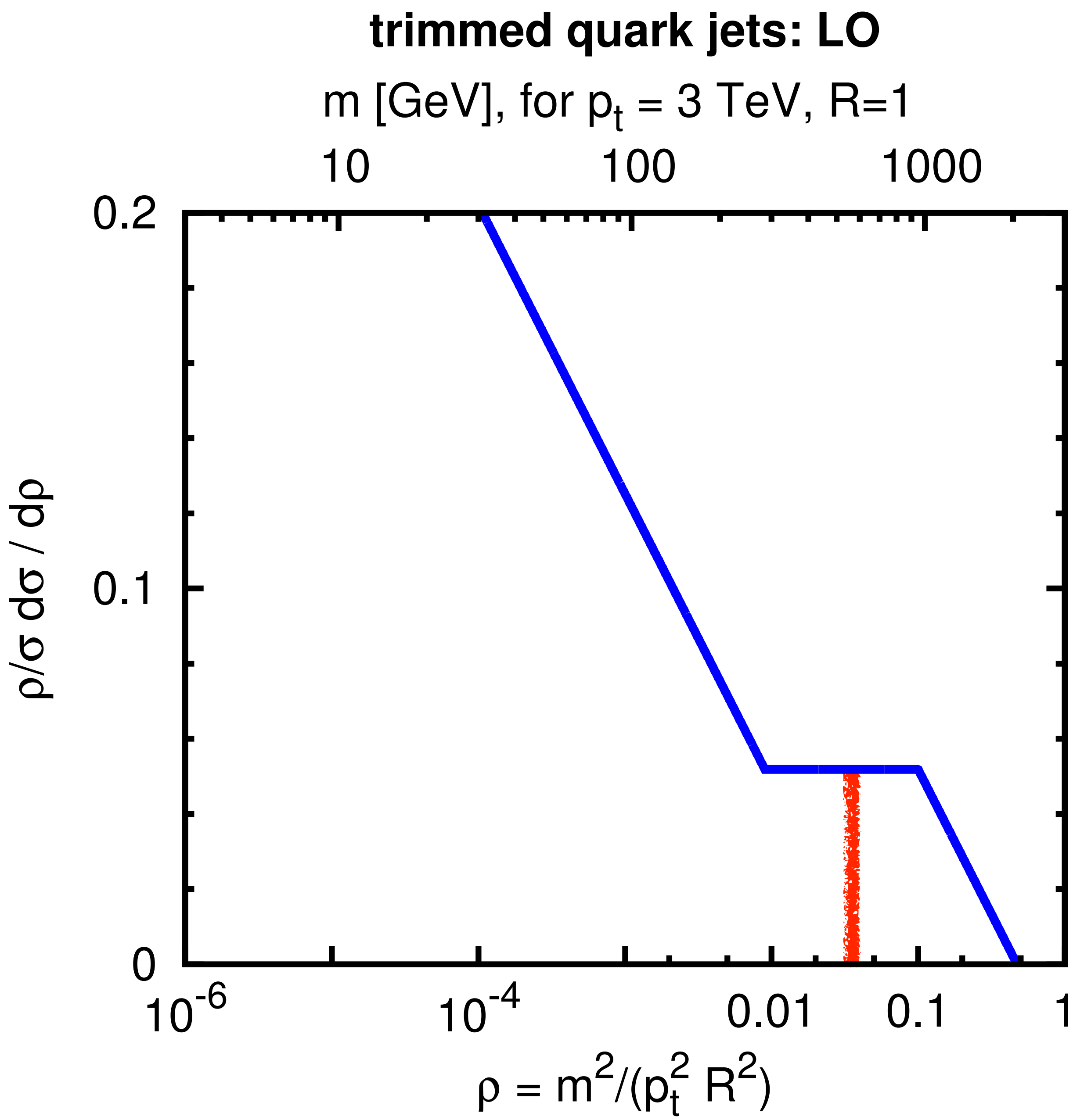

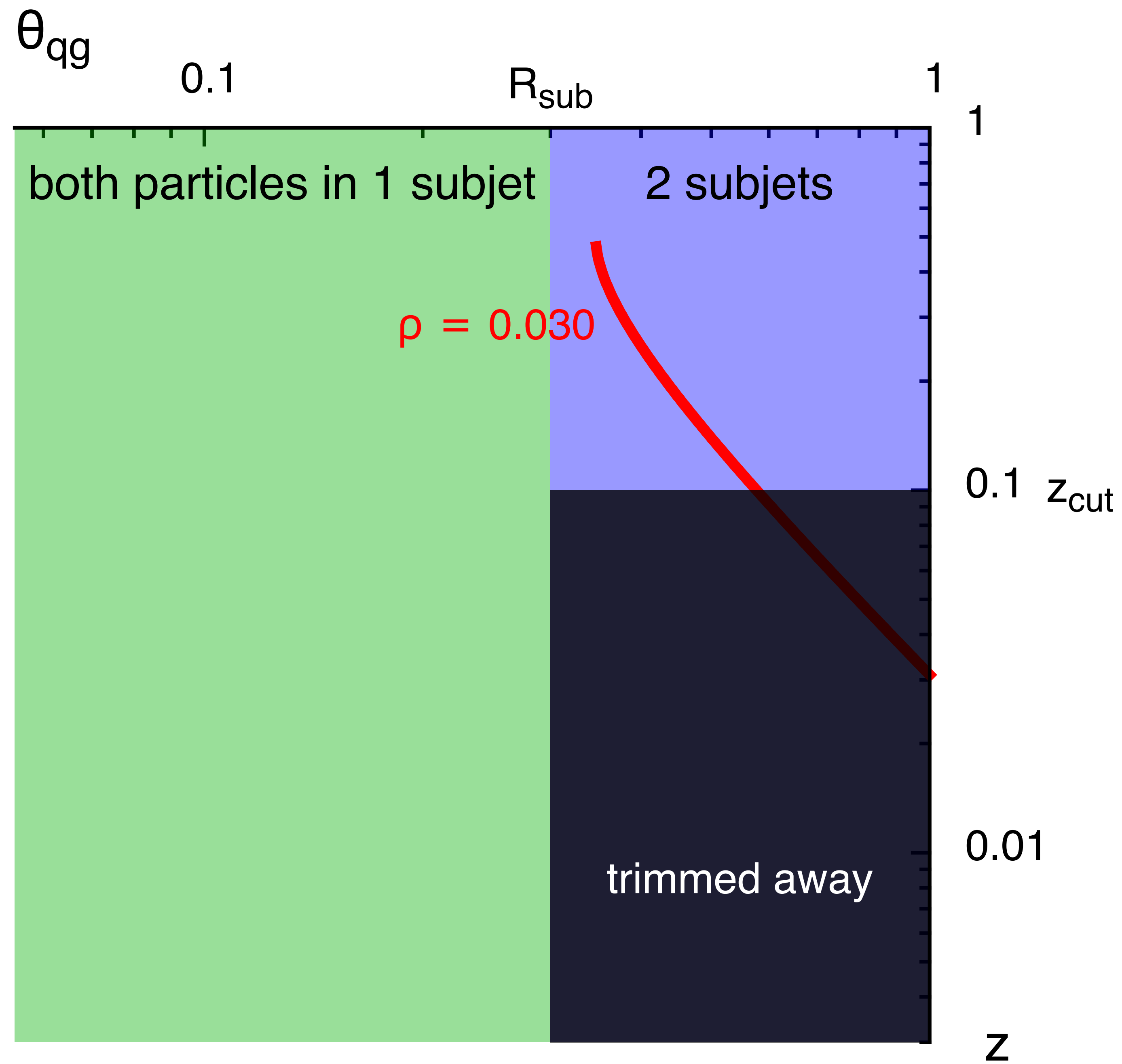

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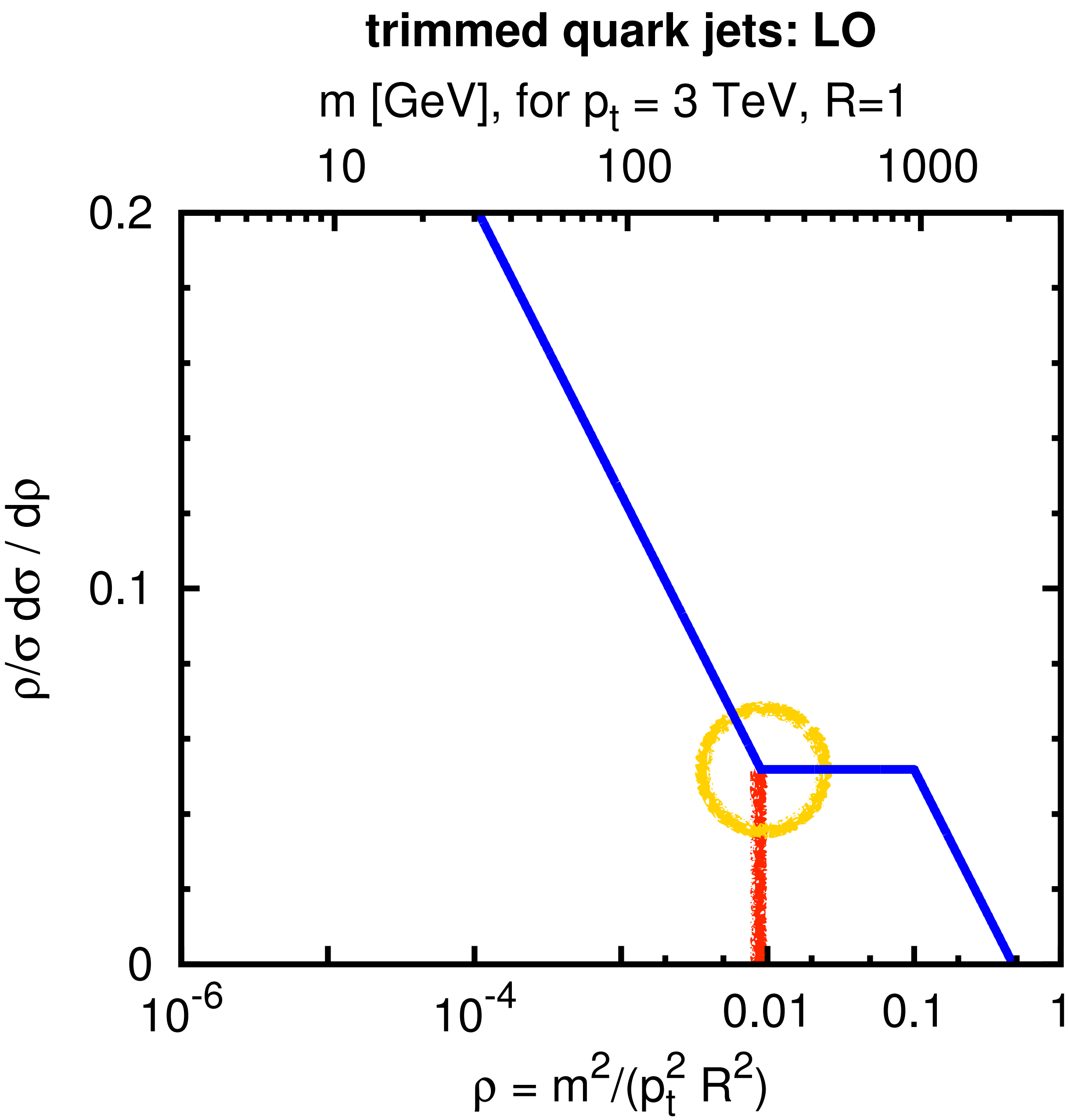

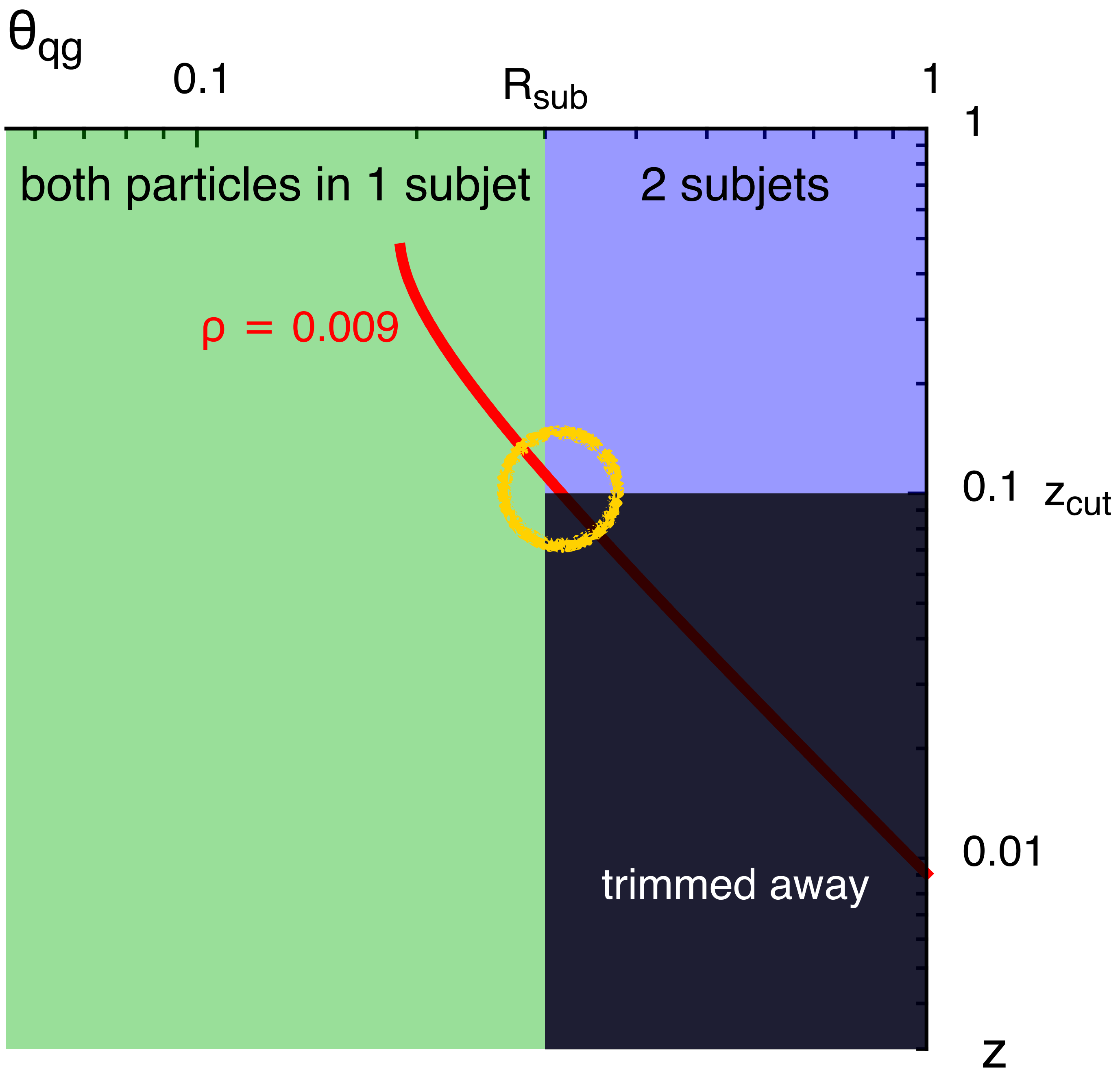

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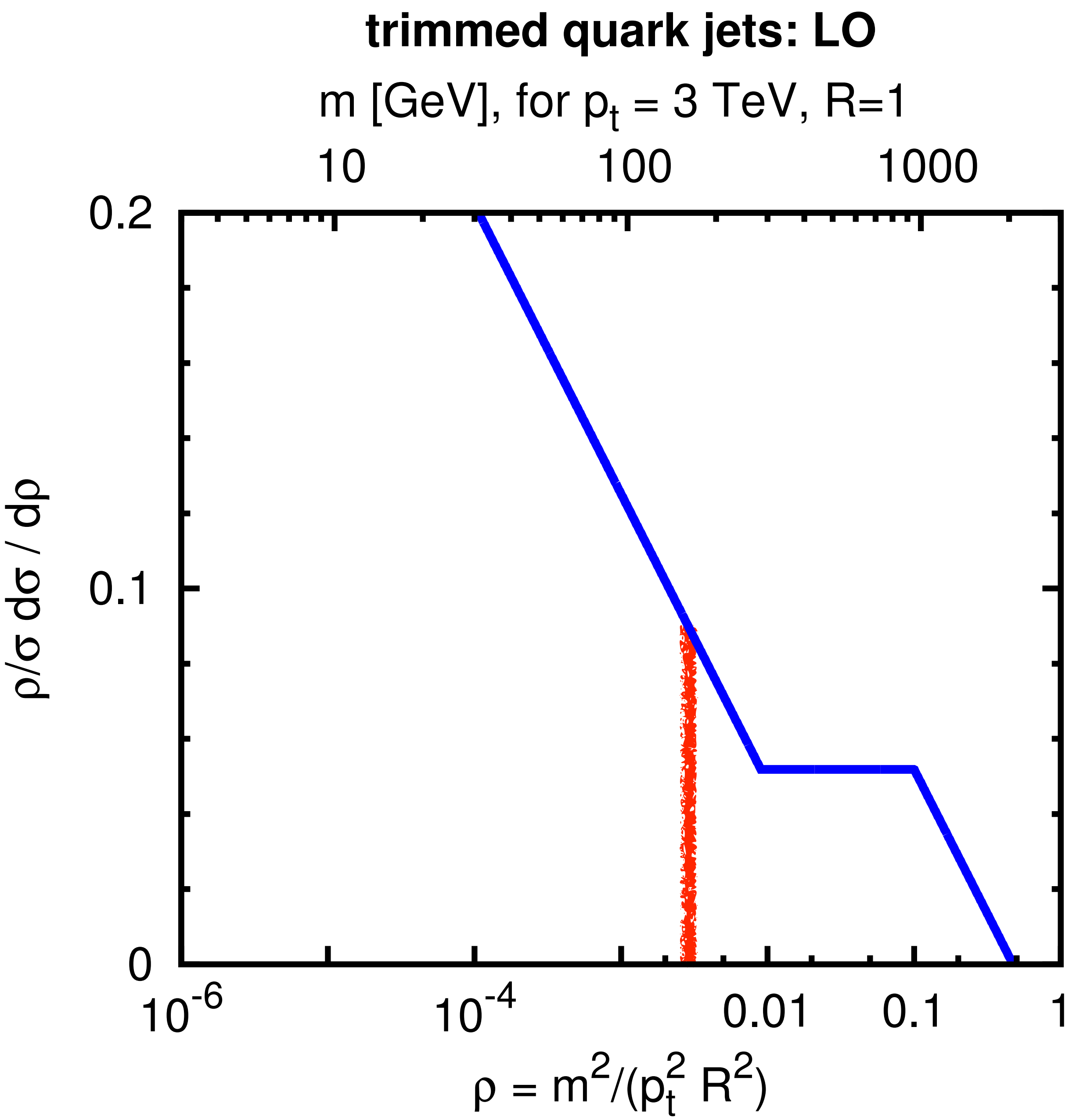

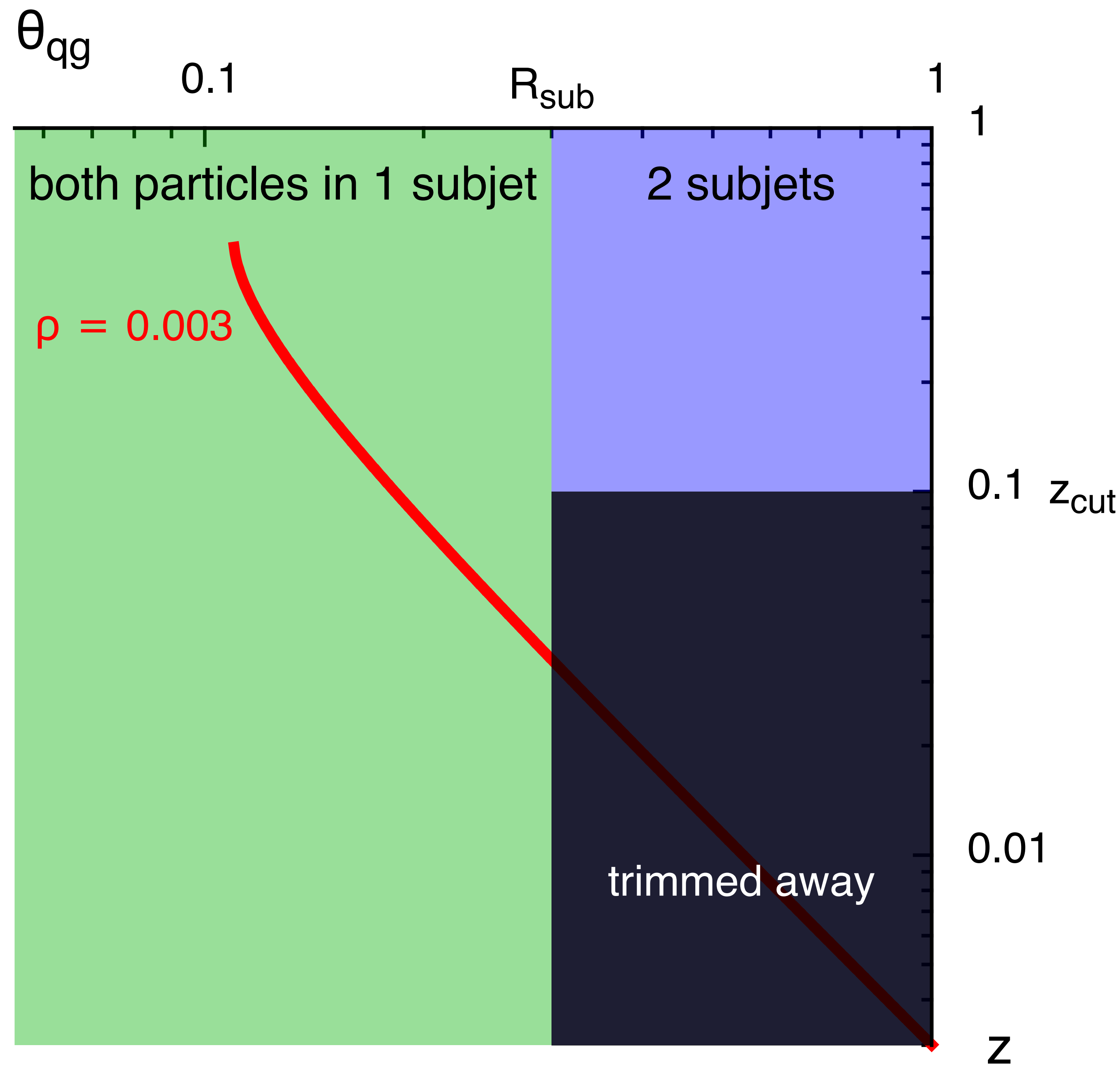

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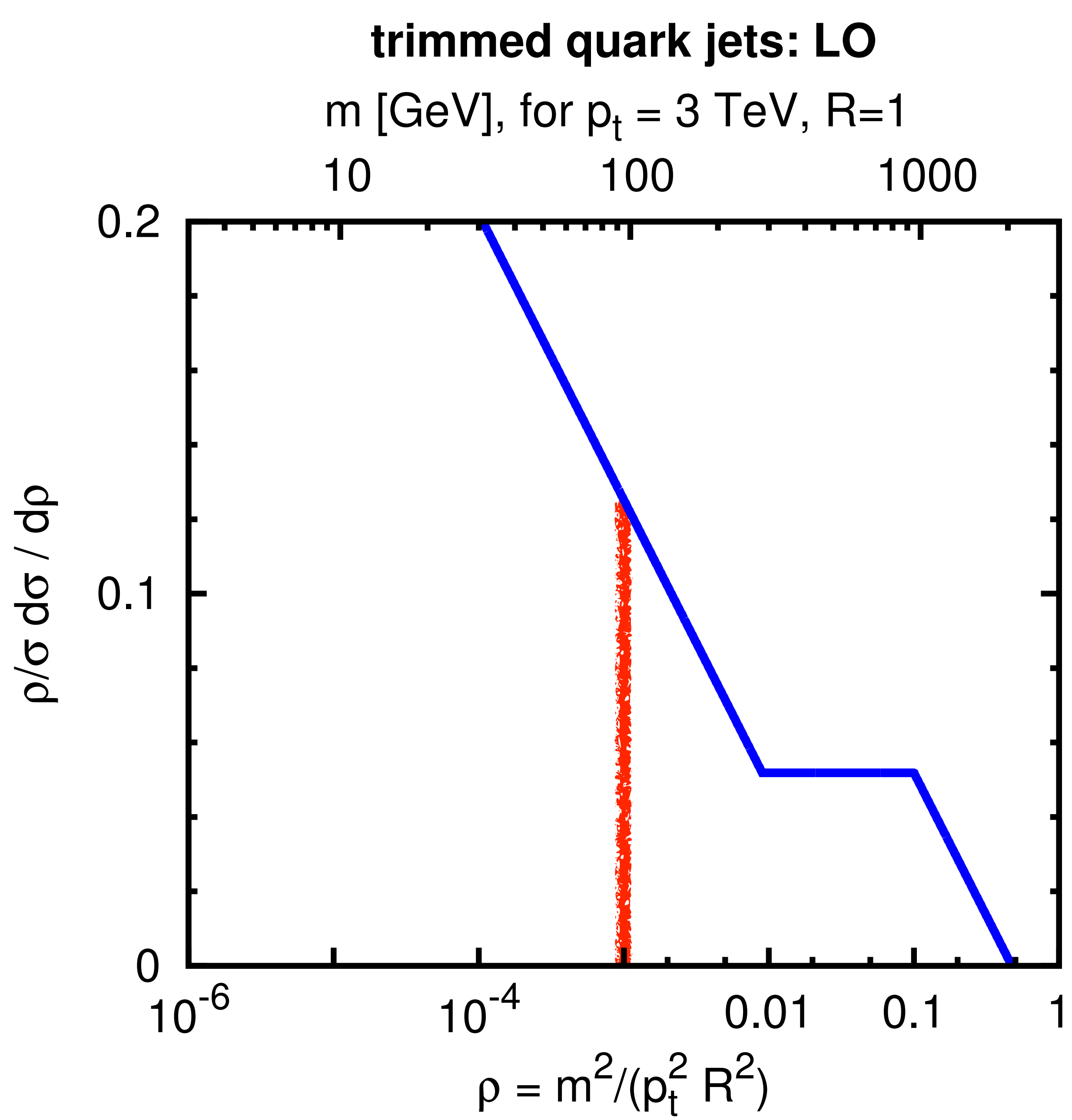
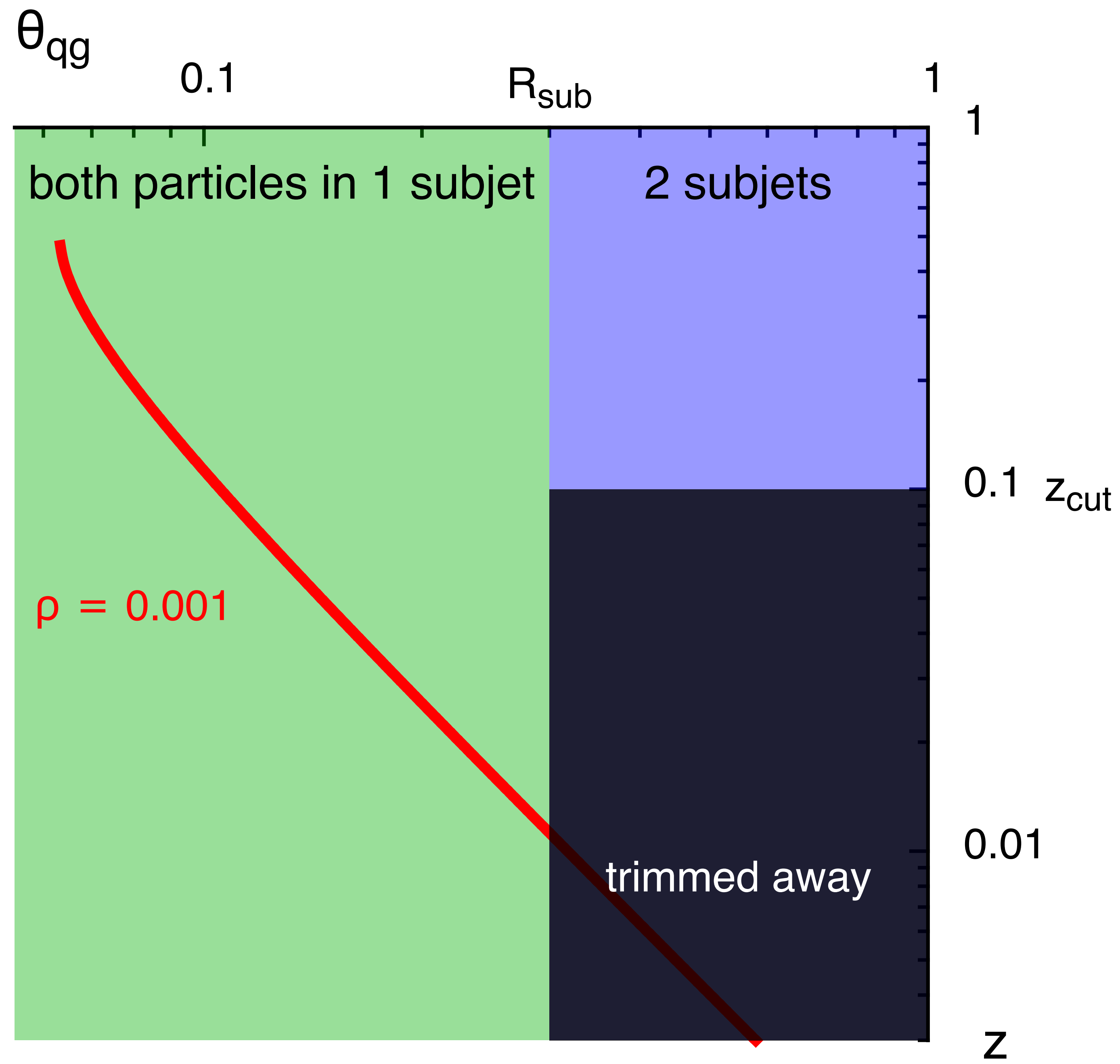
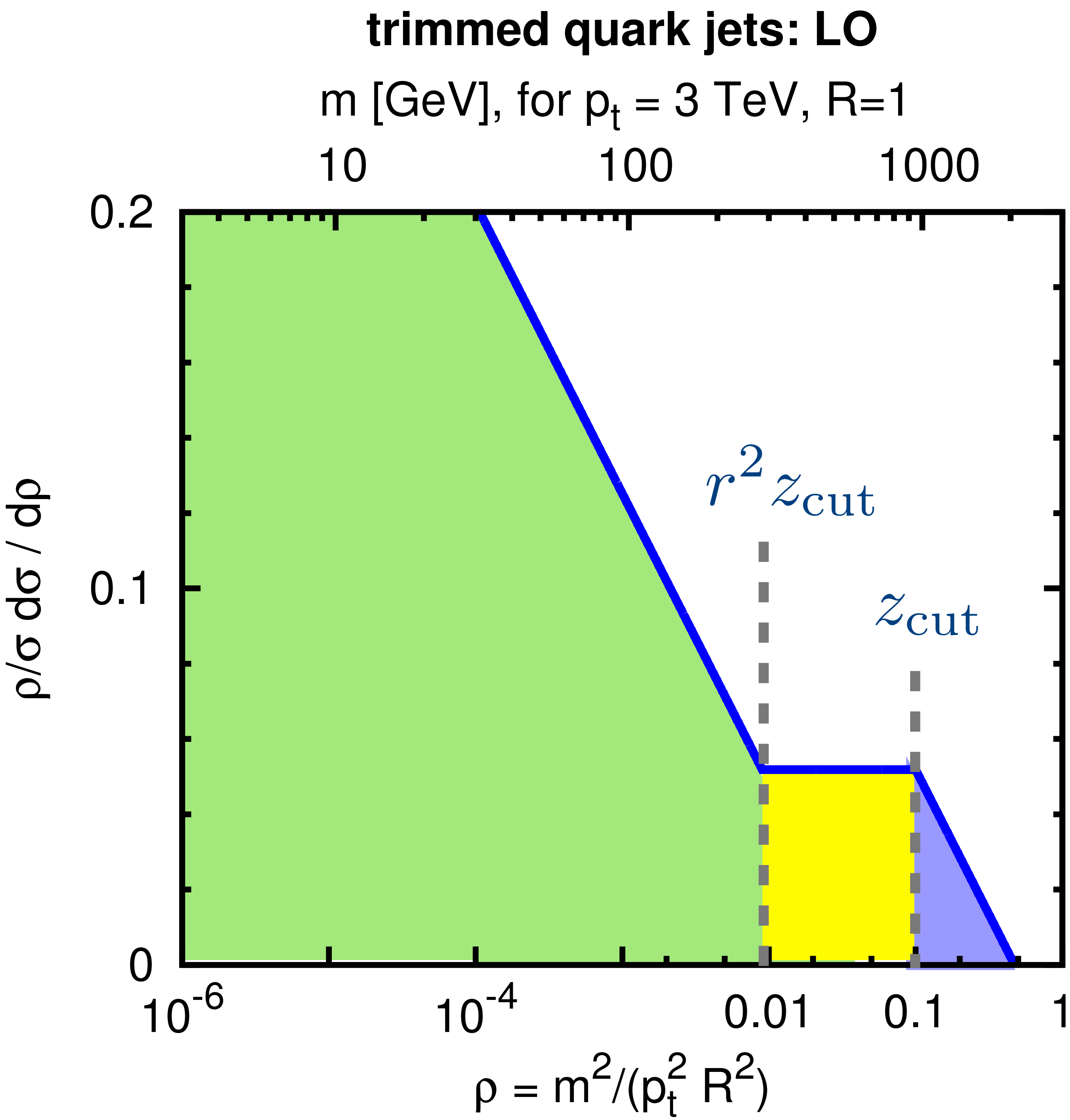






$$\frac{\rho}{\sigma}\frac{d\sigma^{(\mathrm{trim,LO})}}{d\rho} =$$

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

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

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

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

continue with all-order resummation of terms

$$\alpha_s^n \ln^m \rho$$

$\rightarrow$ all orders in α_s

Inputs

QCD pattern of multiple soft/collinear emission

Analysis of taggers' behaviour for 1, 2, 3, … n, emissions

→ Establish which simplifying approximations to use for tagger & matrix elements →

Output

approx. formula for tagger's mass distribution for $\rho \ll 1$

$$\frac{\rho}{\sigma}\frac{d\sigma}{d\rho} = \sum_{n=1}^{\infty} c_{nm}\, \alpha_s^n \ln^m \rho$$

keeping only terms with largest powers of ln ρ, e.g. $m = 2n$, $2n$-1

Trimming

$$\rho^{\text{trim}}(k_1, k_2, \ldots k_n) \simeq \sum_i^n \rho^{\text{trim}}(k_i)$$

$$\sim \max_i \{\rho^{\text{trim}}(k_i)\}$$

Trimmed jet reduces (~) to sum of trimmed emissions

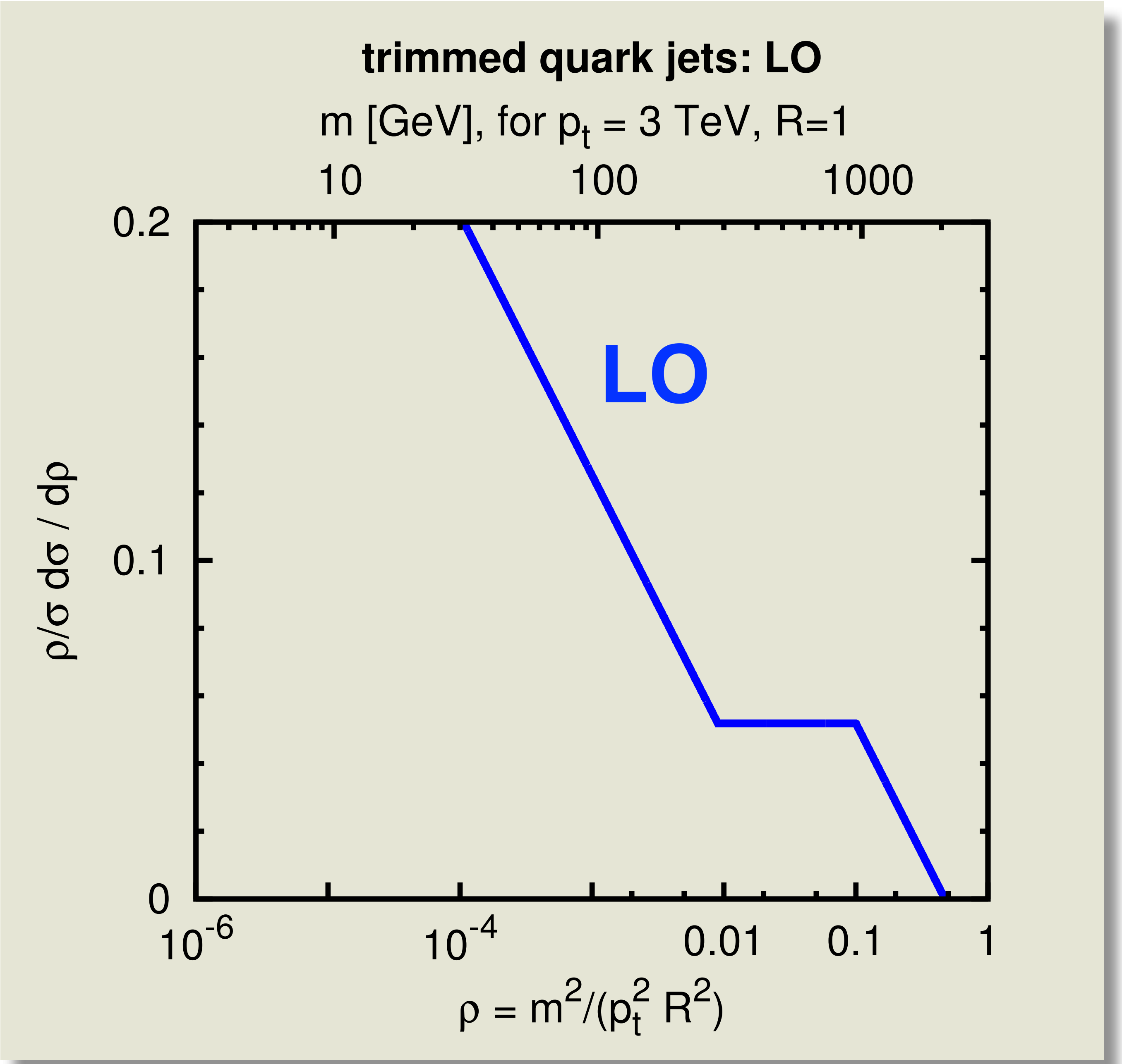
Matrix element

$$\sum_n \frac{1}{n!} \prod_i^n \frac{d\theta_i^2}{\theta_i^2} \frac{dz_i}{z_i} \frac{\alpha_s(\theta_i z_i p_t^{\text{jet}}) C_F}{\pi}$$

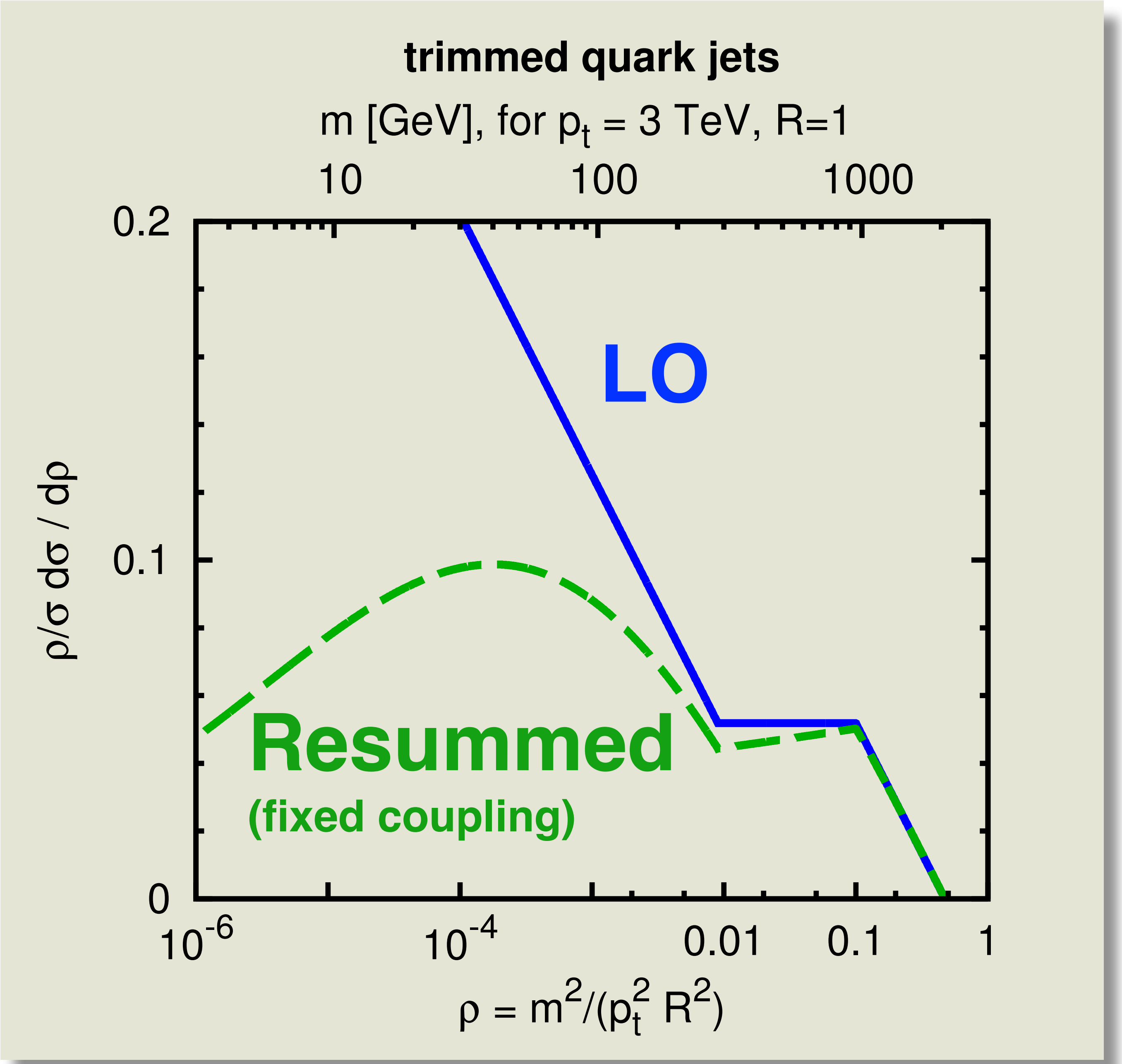
+ virtual corrections, essentially from unitarity

can use QED-like independent emissions, as if gluons don't split

$$\frac{d\sigma^{\text{trim,resum}}}{d\rho} = \frac{d\sigma^{\text{trim,LO}}}{d\rho}$$

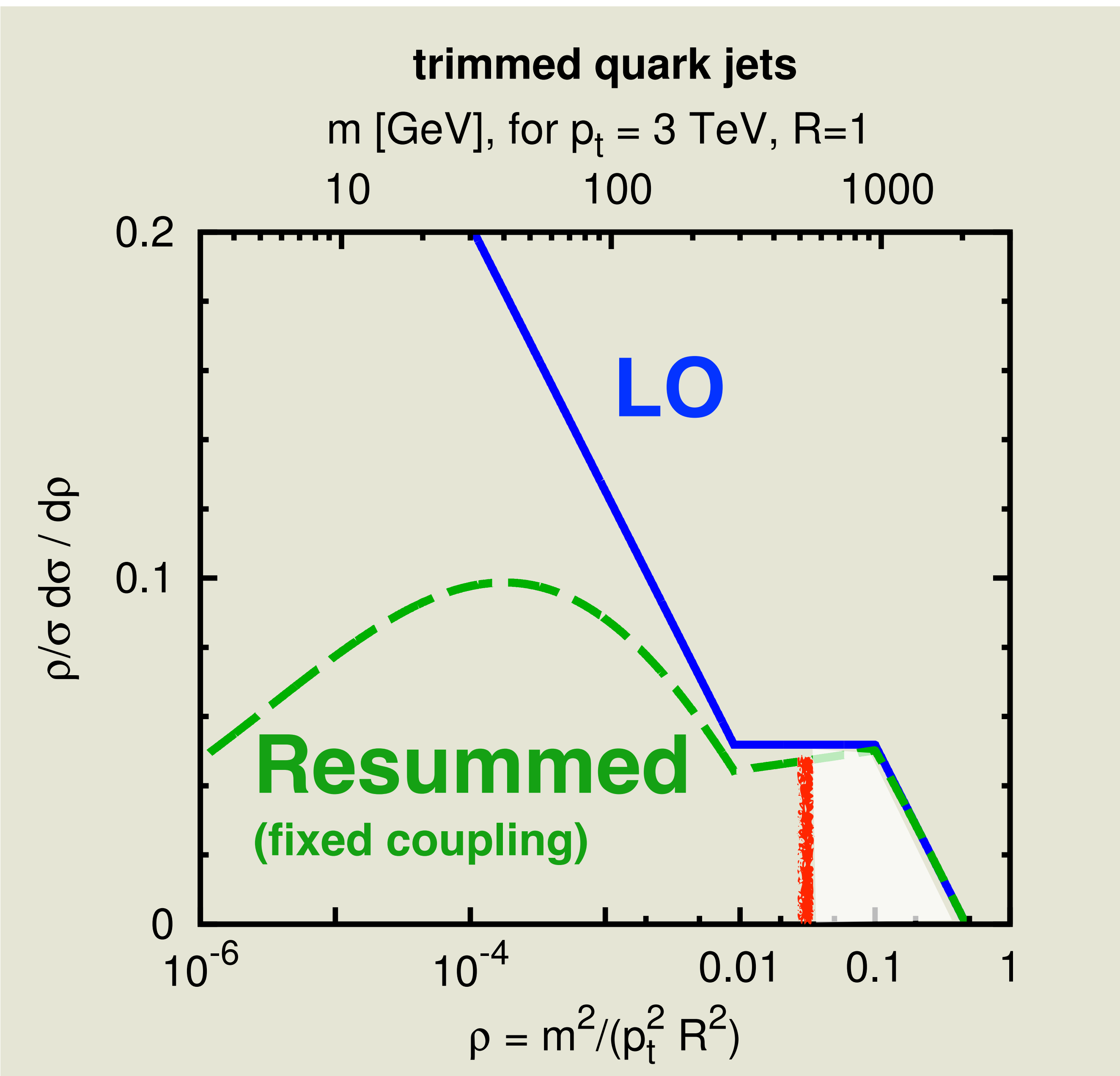


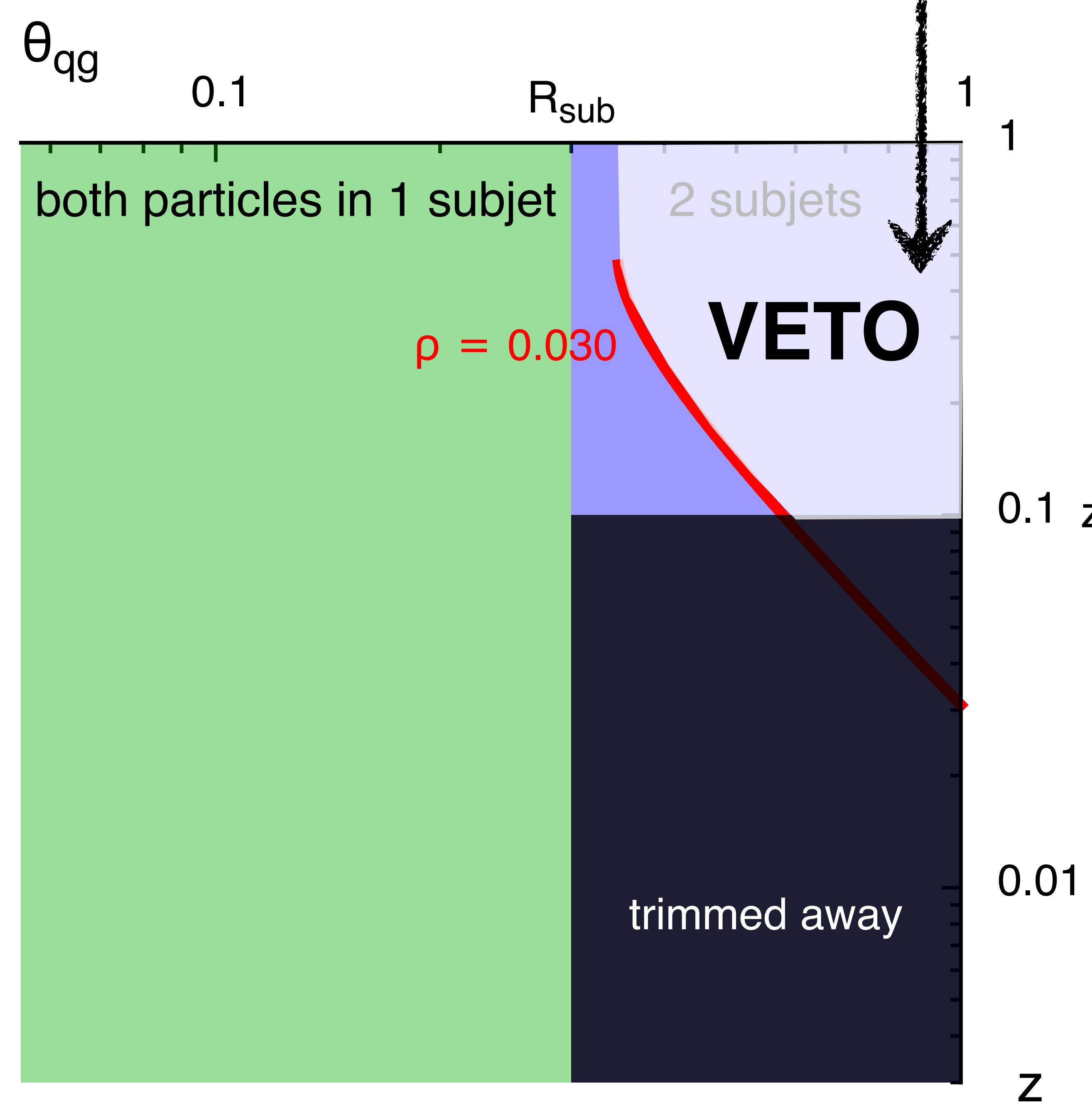
$$\frac{d\sigma^{\text{trim,resum}}}{d\rho} = \frac{d\sigma^{\text{trim,LO}}}{d\rho} \exp\left[-\int_\rho d\rho' \frac{1}{\sigma} \frac{d\sigma^{\text{trim,LO}}}{d\rho'}\right]$$



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

Sudakov





Trimming at all orders

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

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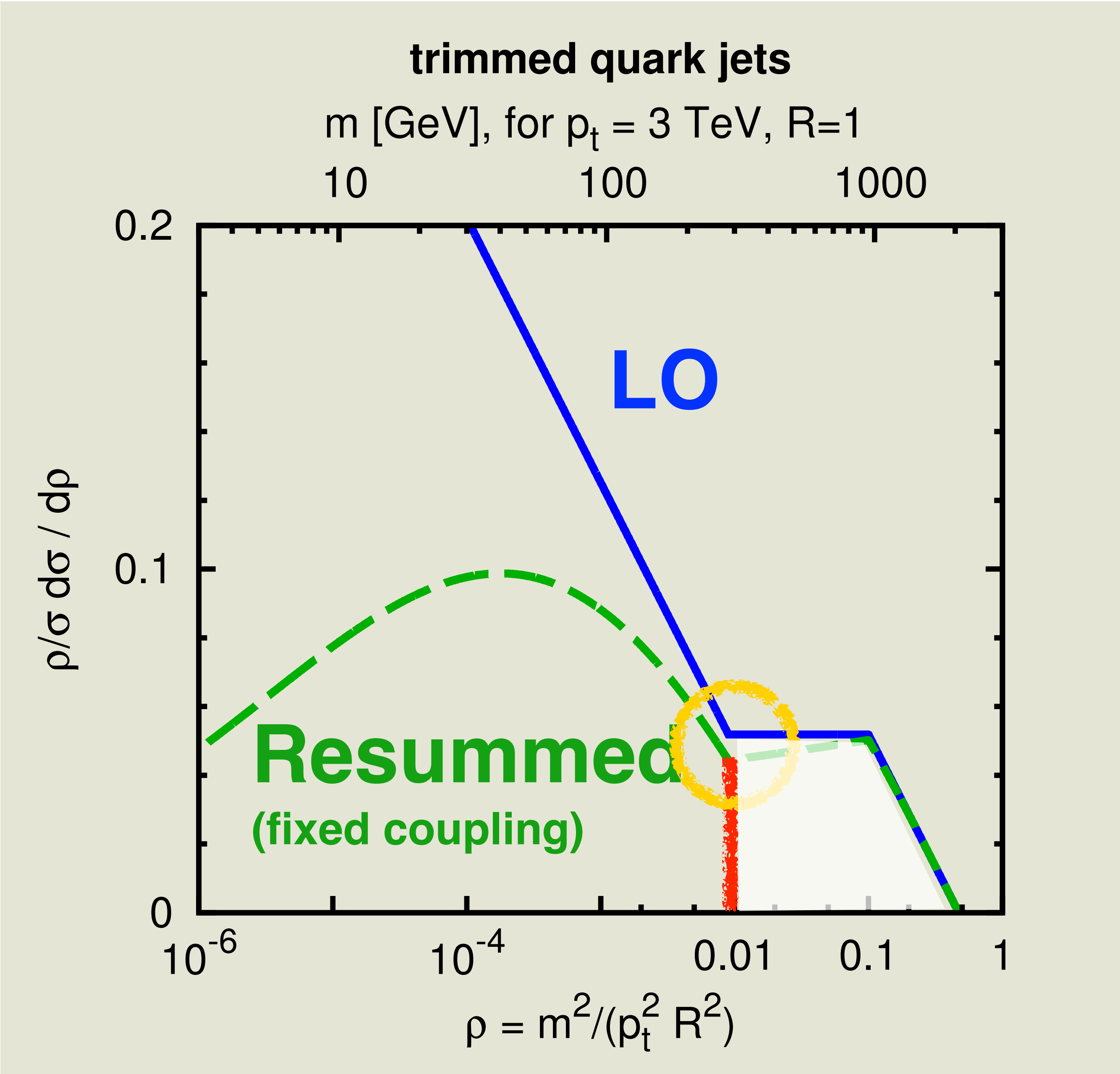

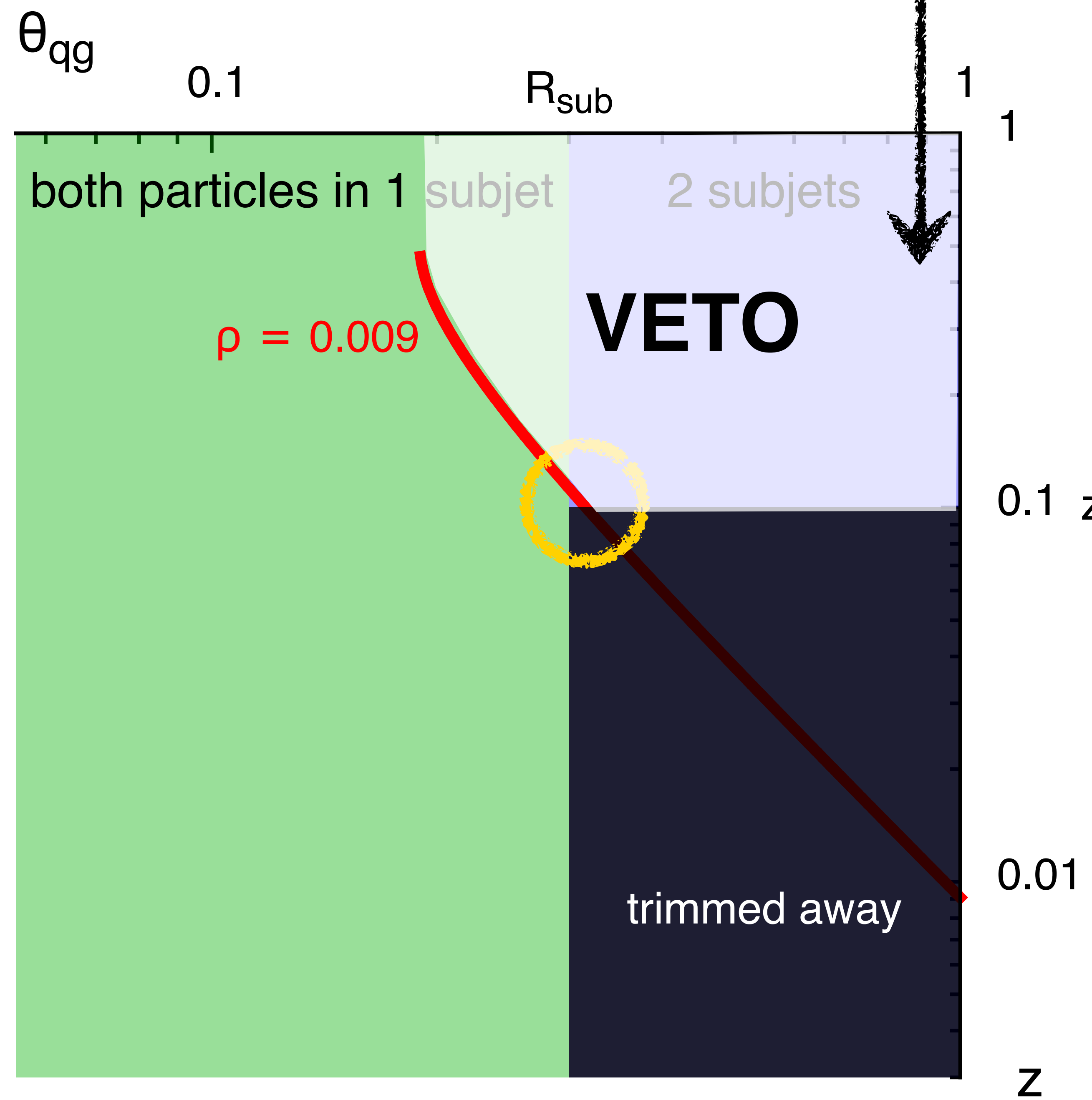

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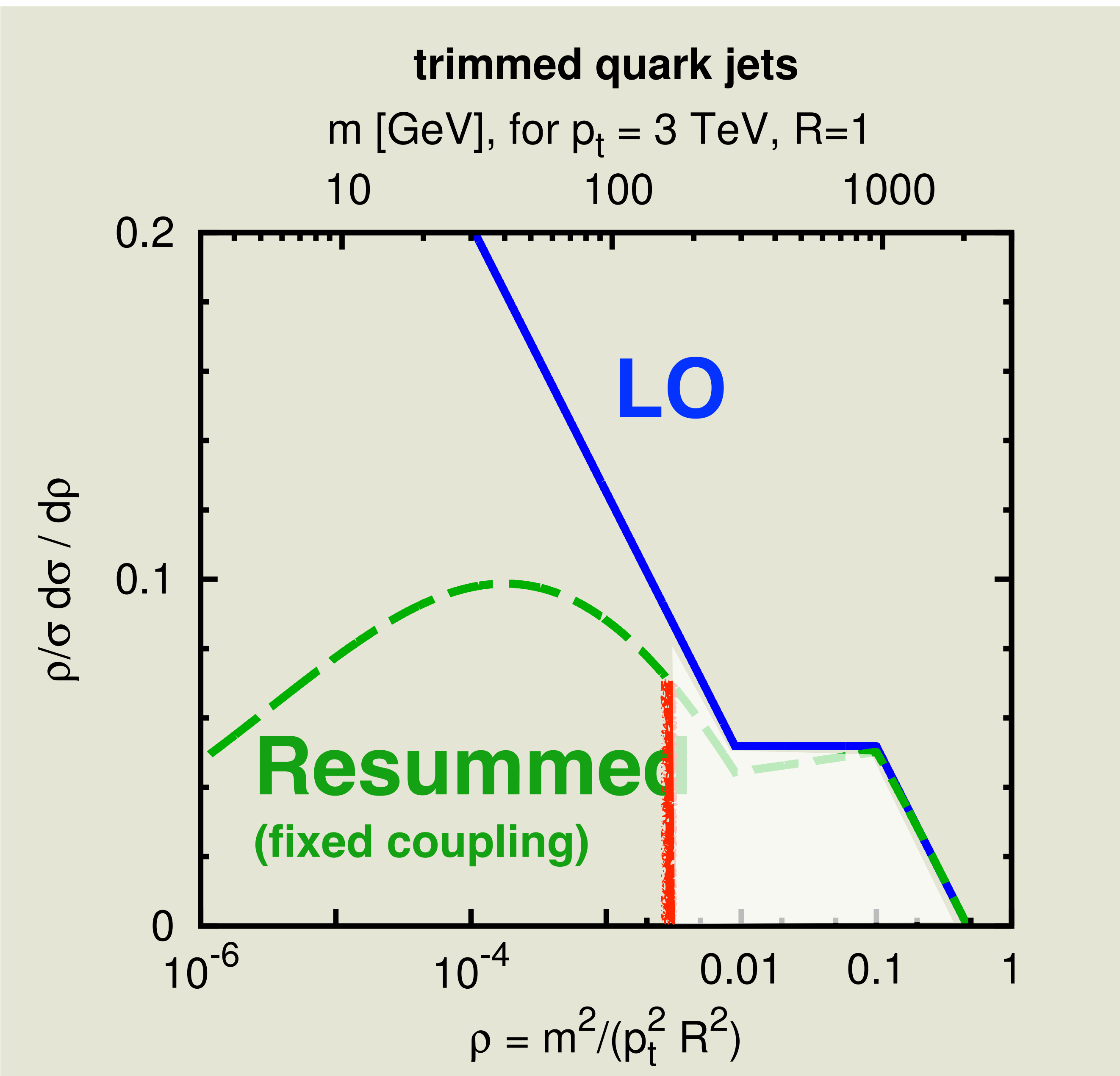

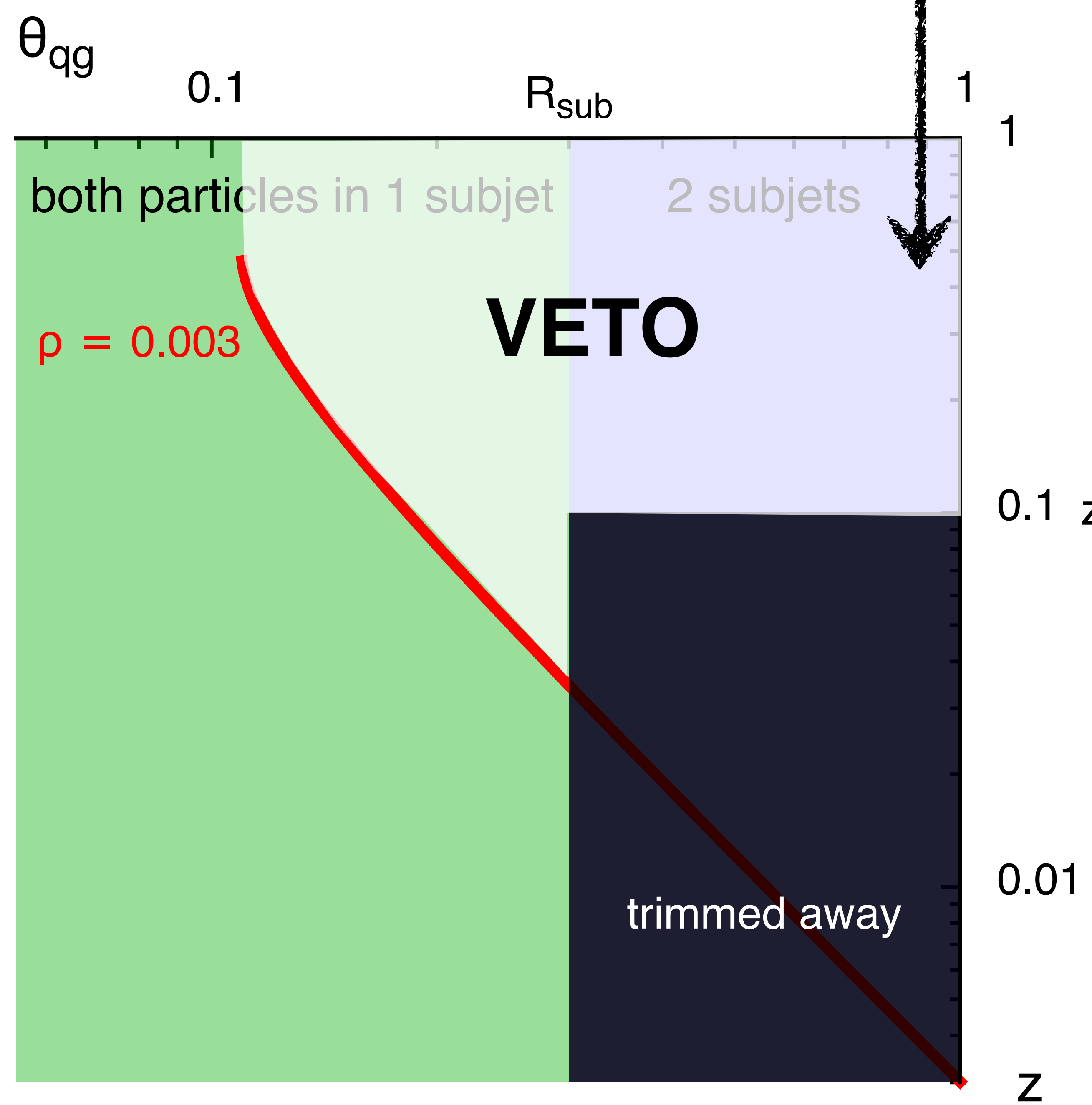

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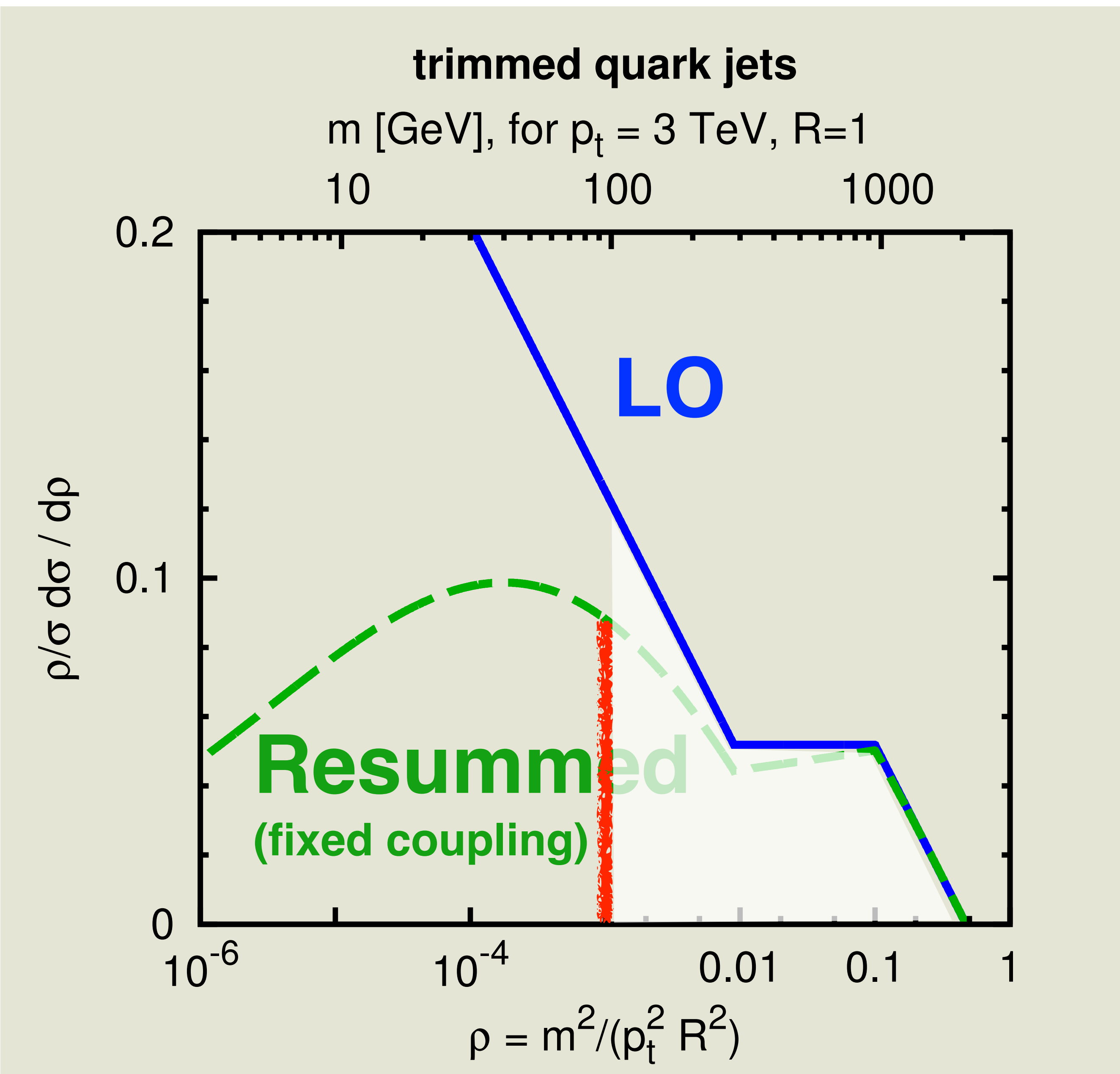

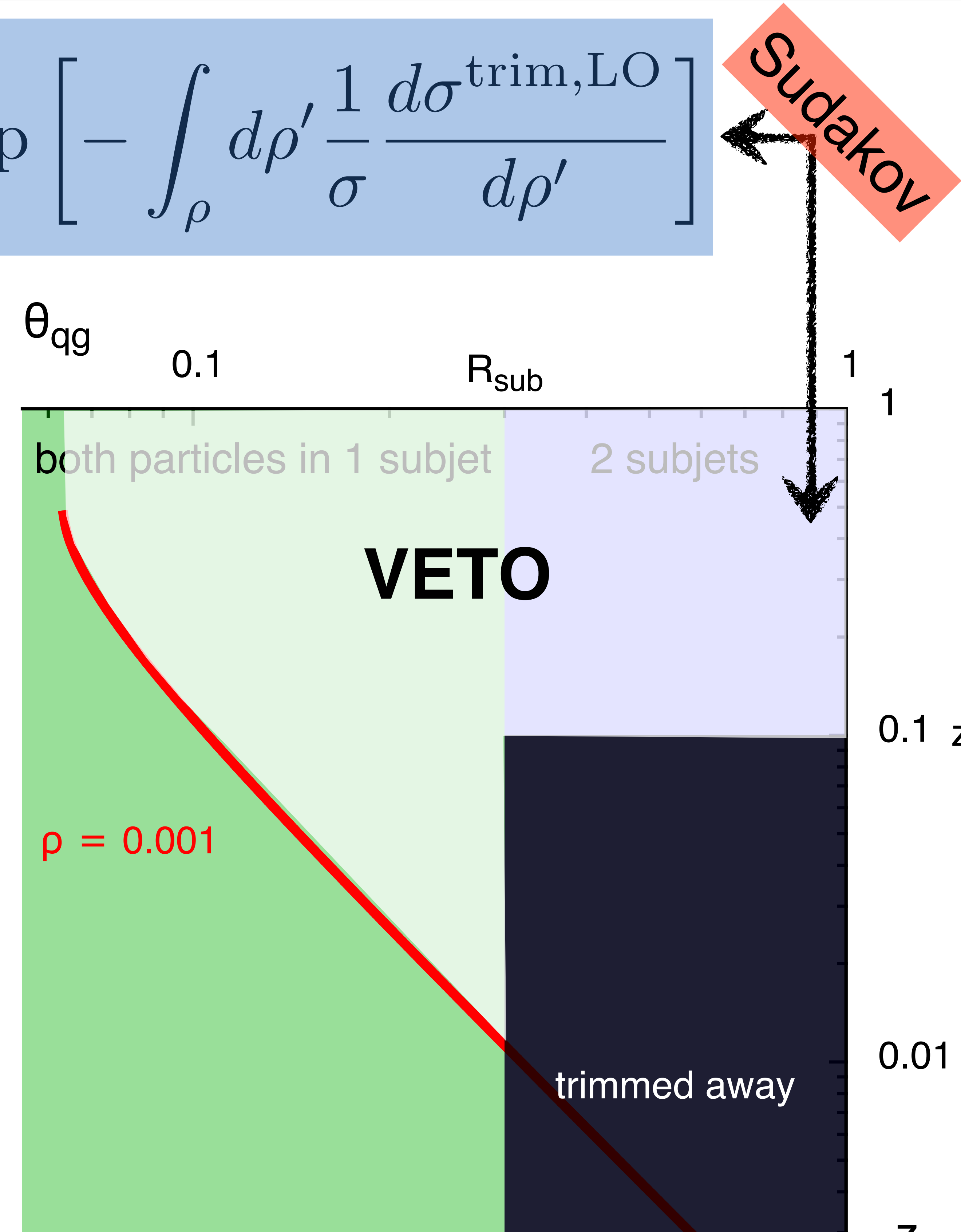

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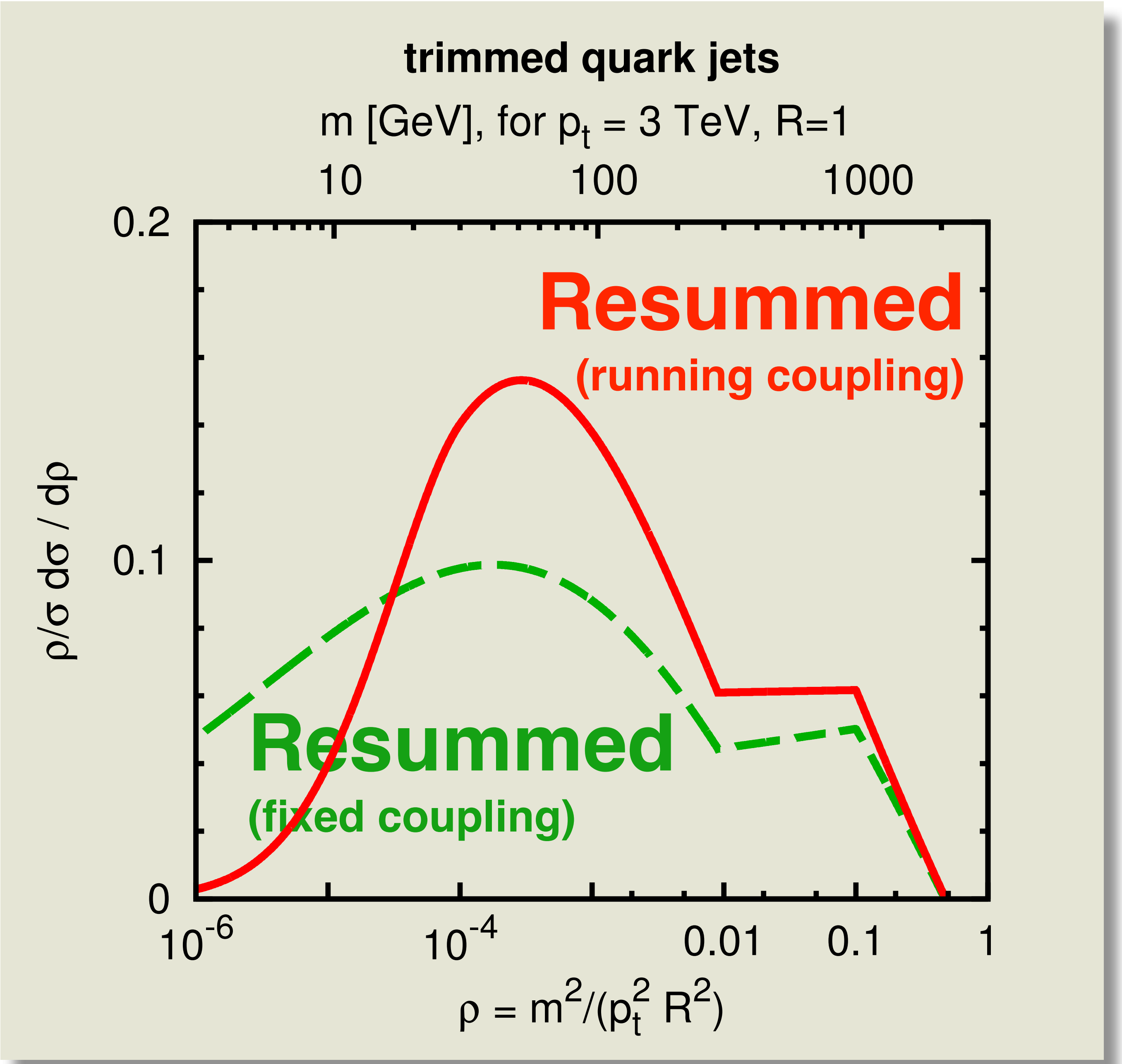

Full resummation also needs treatment of running coupling

What logs, what accuracy?

Express accuracy for "cumulative dist^n" $\Sigma(\rho)$:

$$\Sigma(\rho) = \int_0^{\rho} d\rho' \frac{1}{\sigma} \frac{d\sigma}{d\rho'}$$

Use shorthand L = log 1/ρ

Trimming's **leading logs** (LL, in Σ) are:

$$\alpha_s L^2,\ \alpha_s^2 L^4,\ \ldots.\ \text{I.e. } \boldsymbol{\alpha_s^n L^{2n}}$$

Just like the jet mass

We also have **next-to-leading logs** (NLL): $\boldsymbol{\alpha_s^n L^{2n-1}}$

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Express accuracy for "cumulative dist^n" Σ(ρ):

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Just like the jet mass

We also have **next-to-leading logs** (NLL): $\boldsymbol{\alpha_s^n L^{2n-1}}$

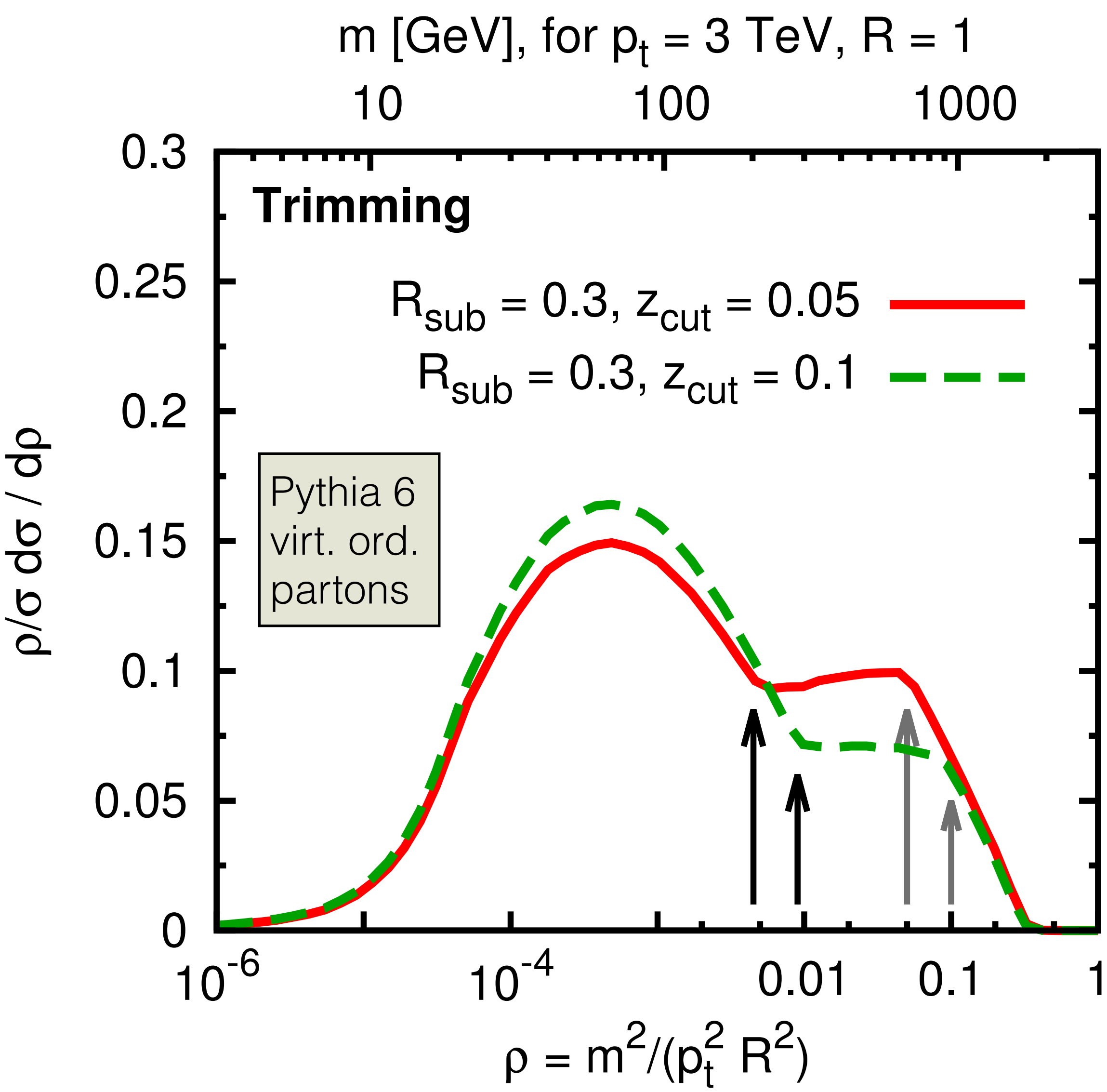
Could we do better? Yes: NLL in ln Σ:

$$\ln \Sigma:\ \alpha_s^n L^{n+1} \text{ and } \alpha_s^n L^n$$

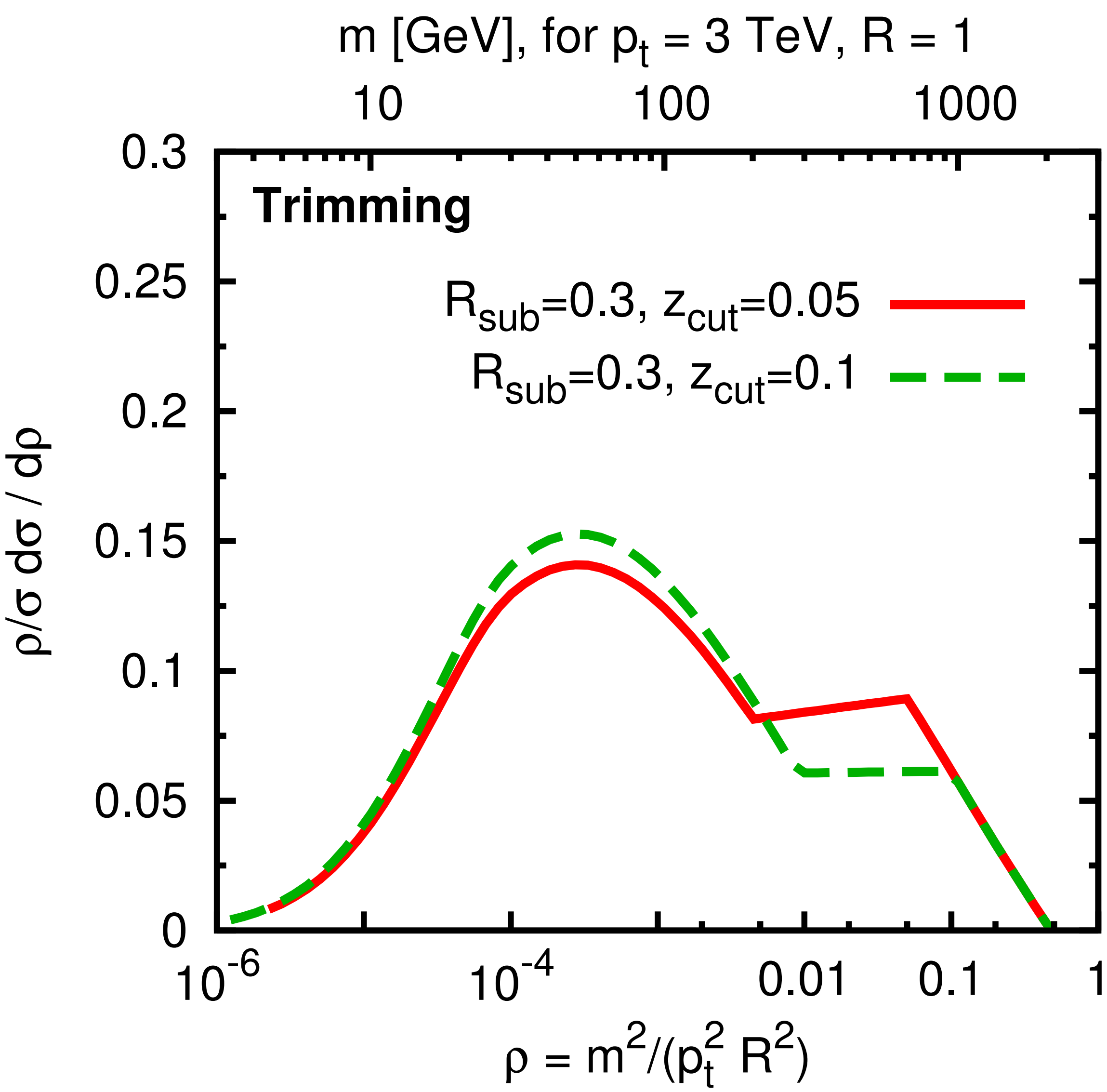
Trimmed mass is like plain jet mass (with R → R_{sub}), and this accuracy involves **non-global logs, clustering logs**

Trimming: MC v. analytics

Monte Carlo



Analytic

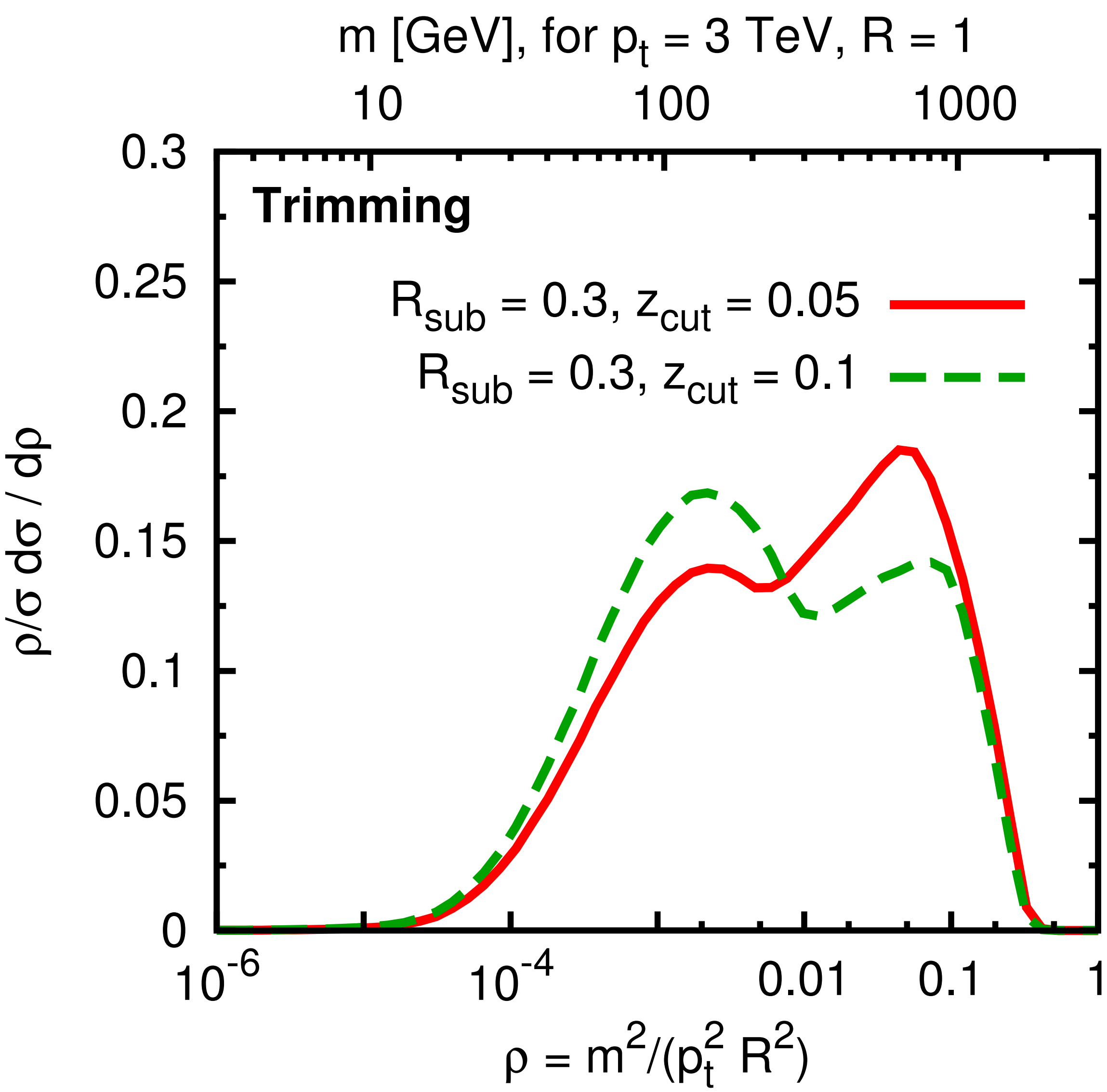


Non-trivial agreement!

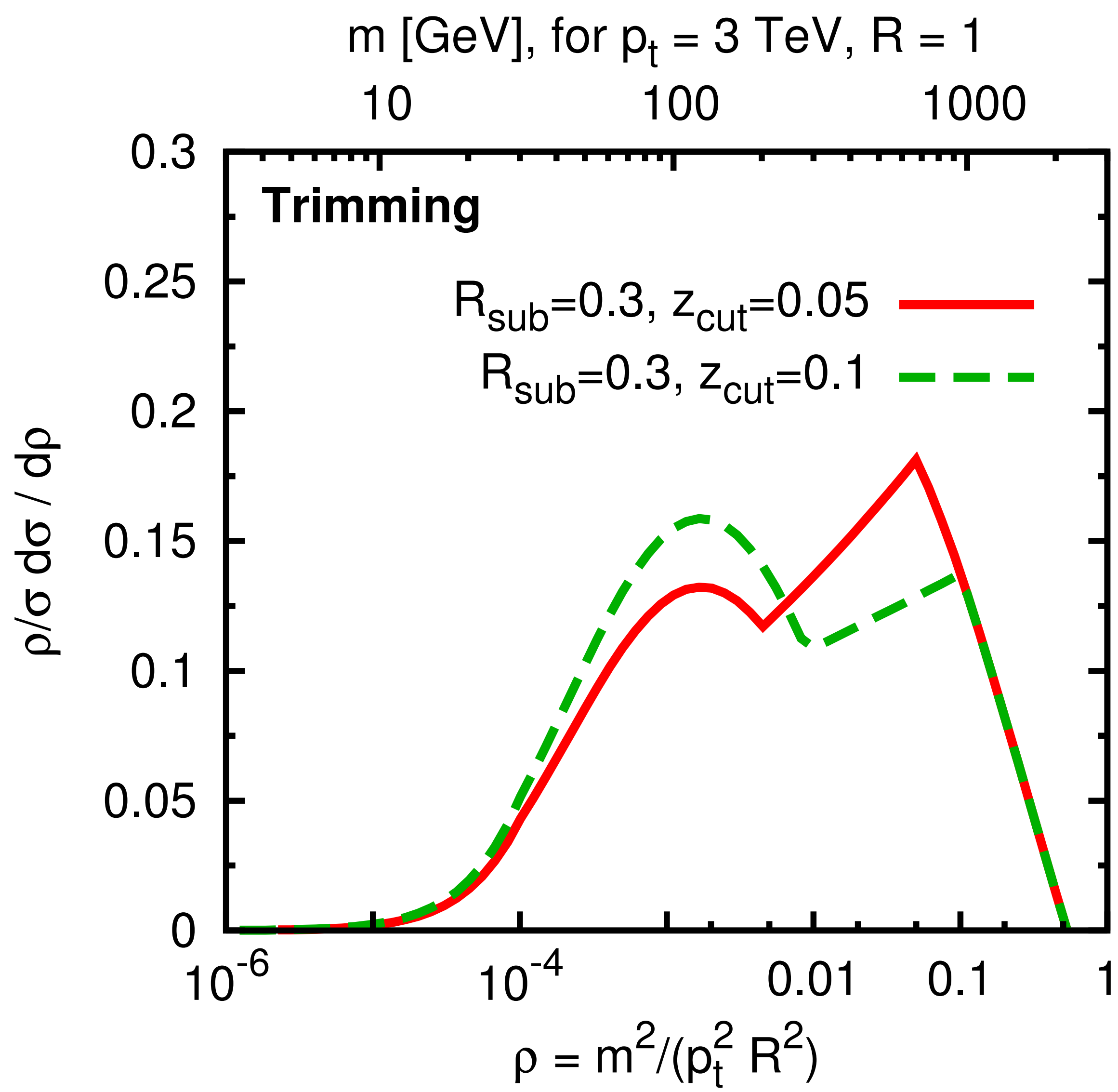
(also for dependence on parameters)

Trimming: MC v. analytics

Monte Carlo



Analytic



Non-trivial agreement!
(also for dependence on parameters)

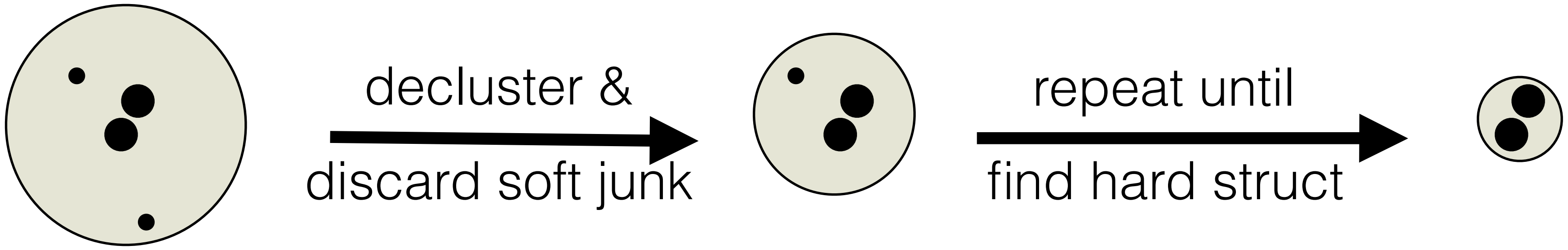
Mass-Drop Tagger

Butterworth, Davison, Rubin & GPS '08

For a jet clustered with C/A:

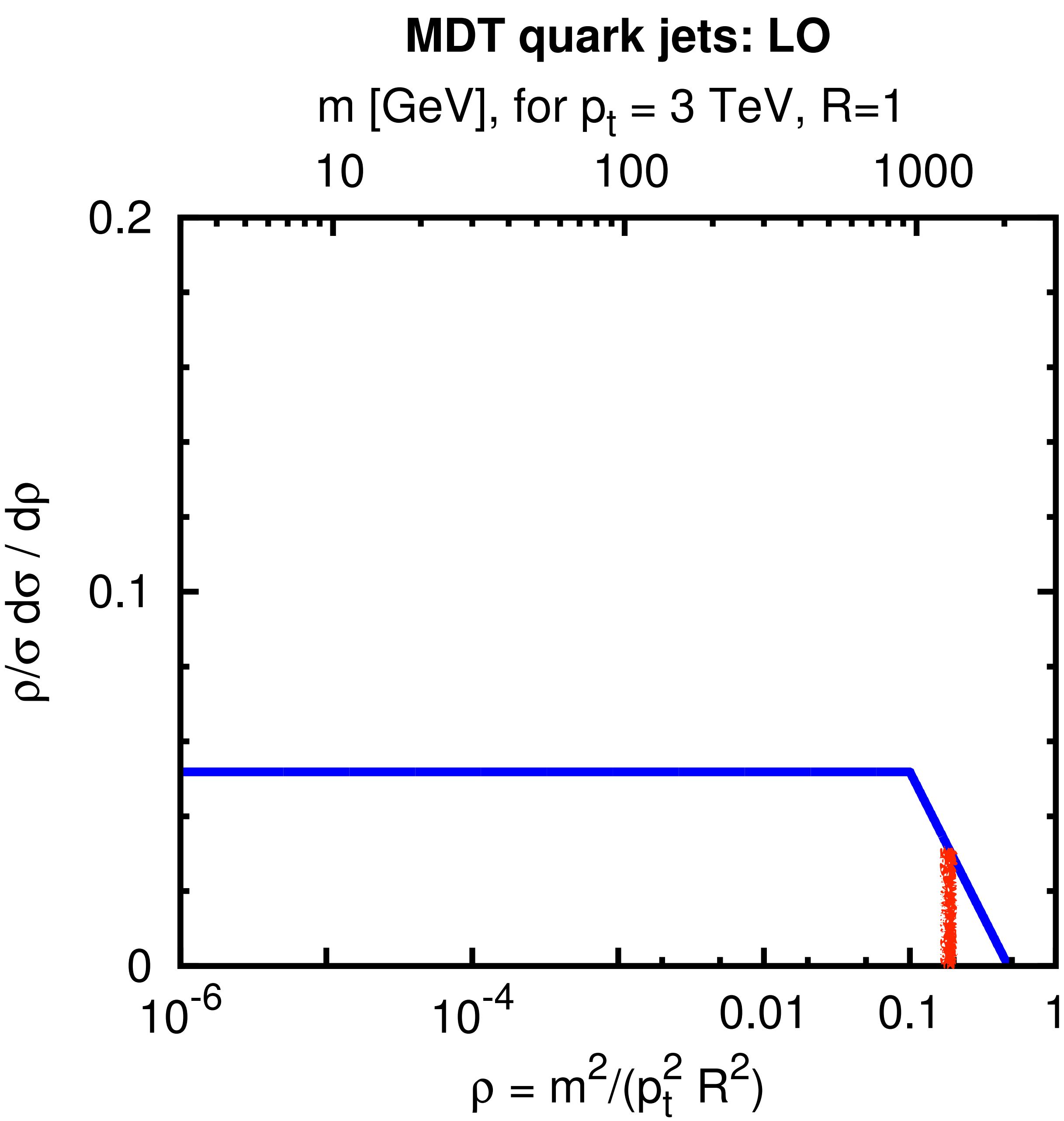
1. undo last clustering step to break jet (mass m) into two subjets with $m_1 > m_2$
2. If significant mass-drop ($m_1 < \mu m$) and subjet energy-sharing not too asymmetric
$$\min(p_{t1}^2, p_{t2}^2)\Delta R_{12}^2 < y_{\rm cut} m^2$$
jet is **tagged**.
3. Otherwise discard subjet 2, and go to step 1 with jet → subjet 1.

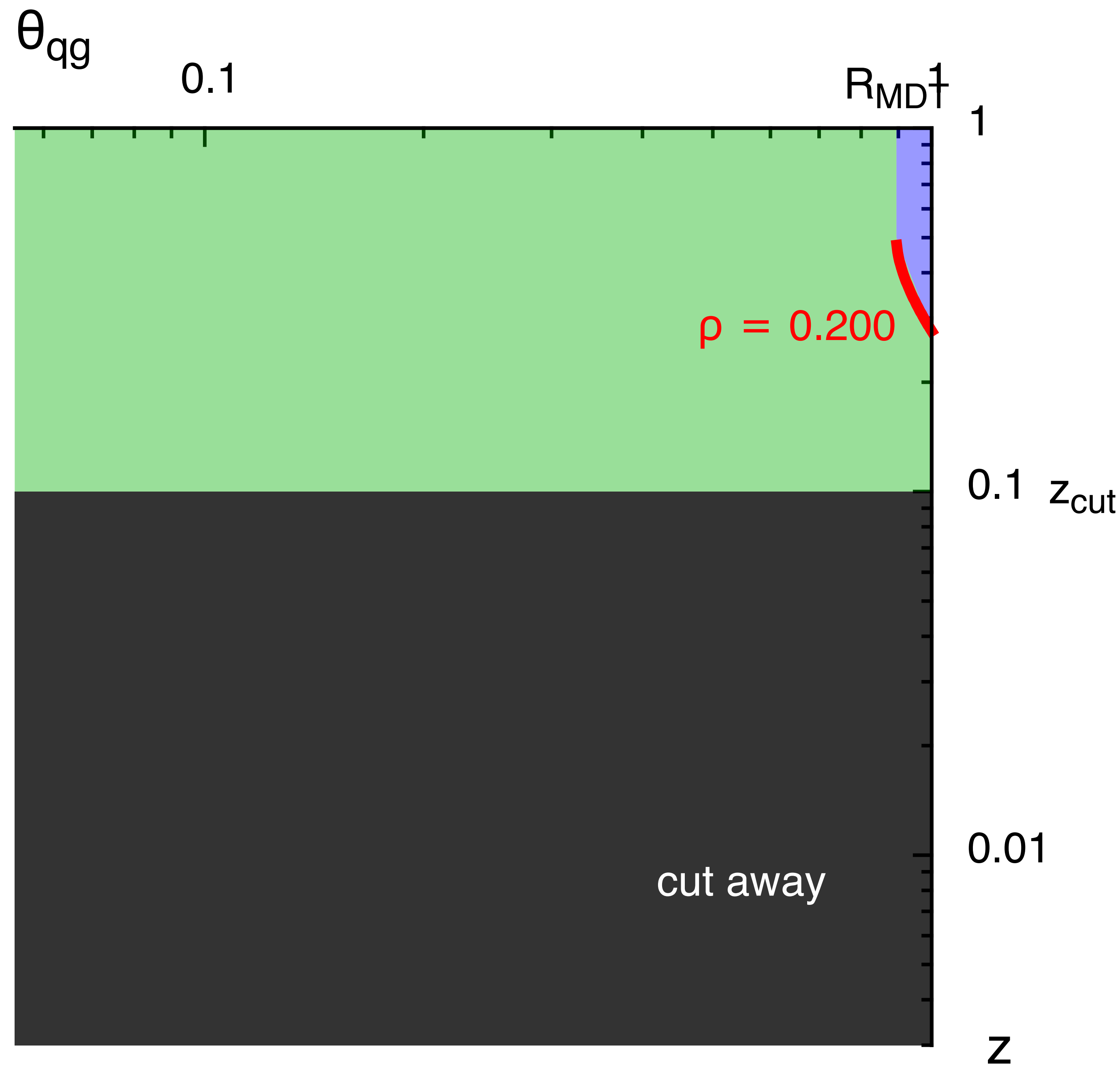
two parameters: μ and $y_{\rm cut}$ ($\sim z_{\rm cut}$)



Mass-Drop Tagger at LO

Jet is always split to give two subjets, and so y_{cut} ($\sim z_{cut}$) is always applied.





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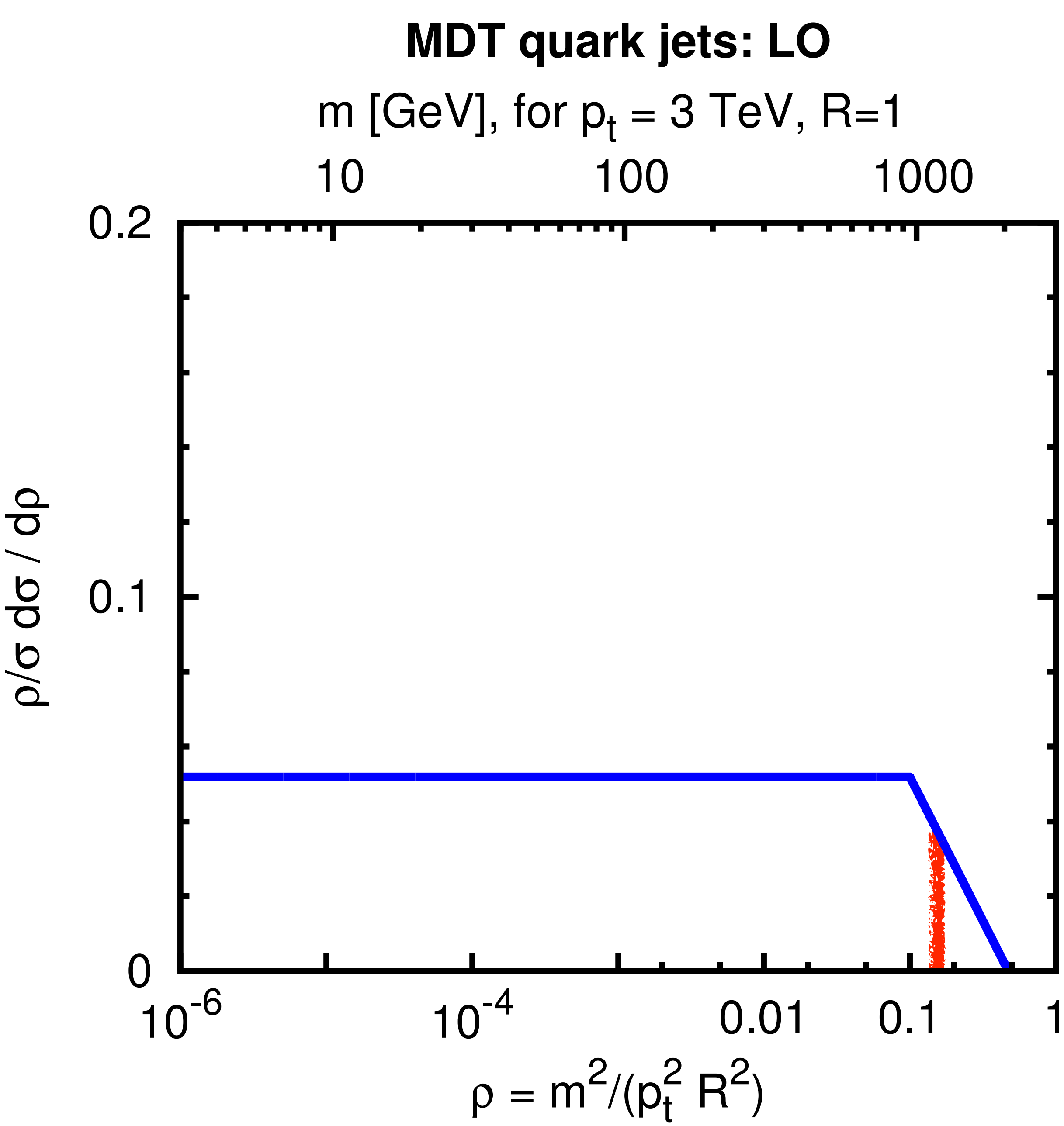

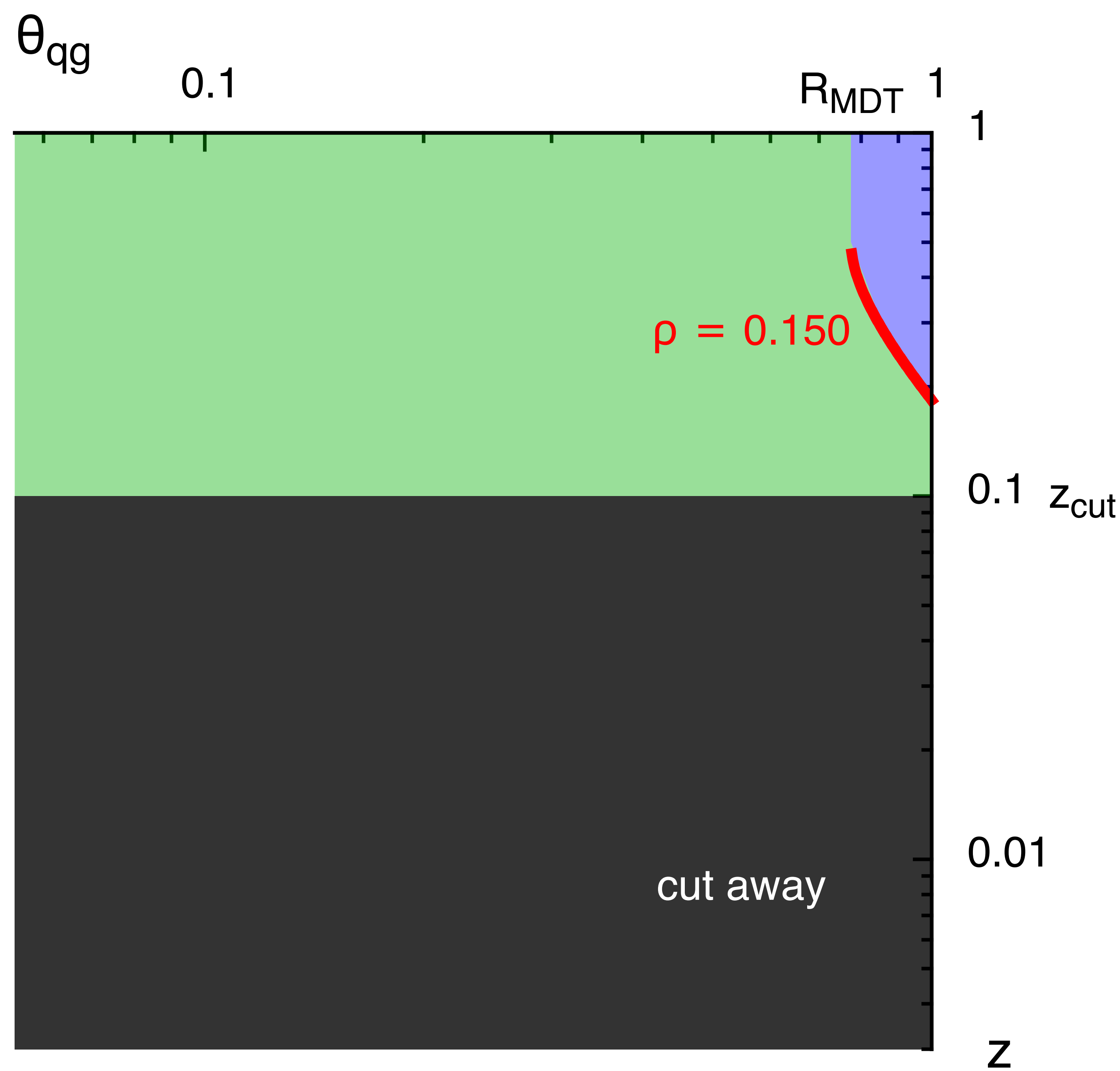

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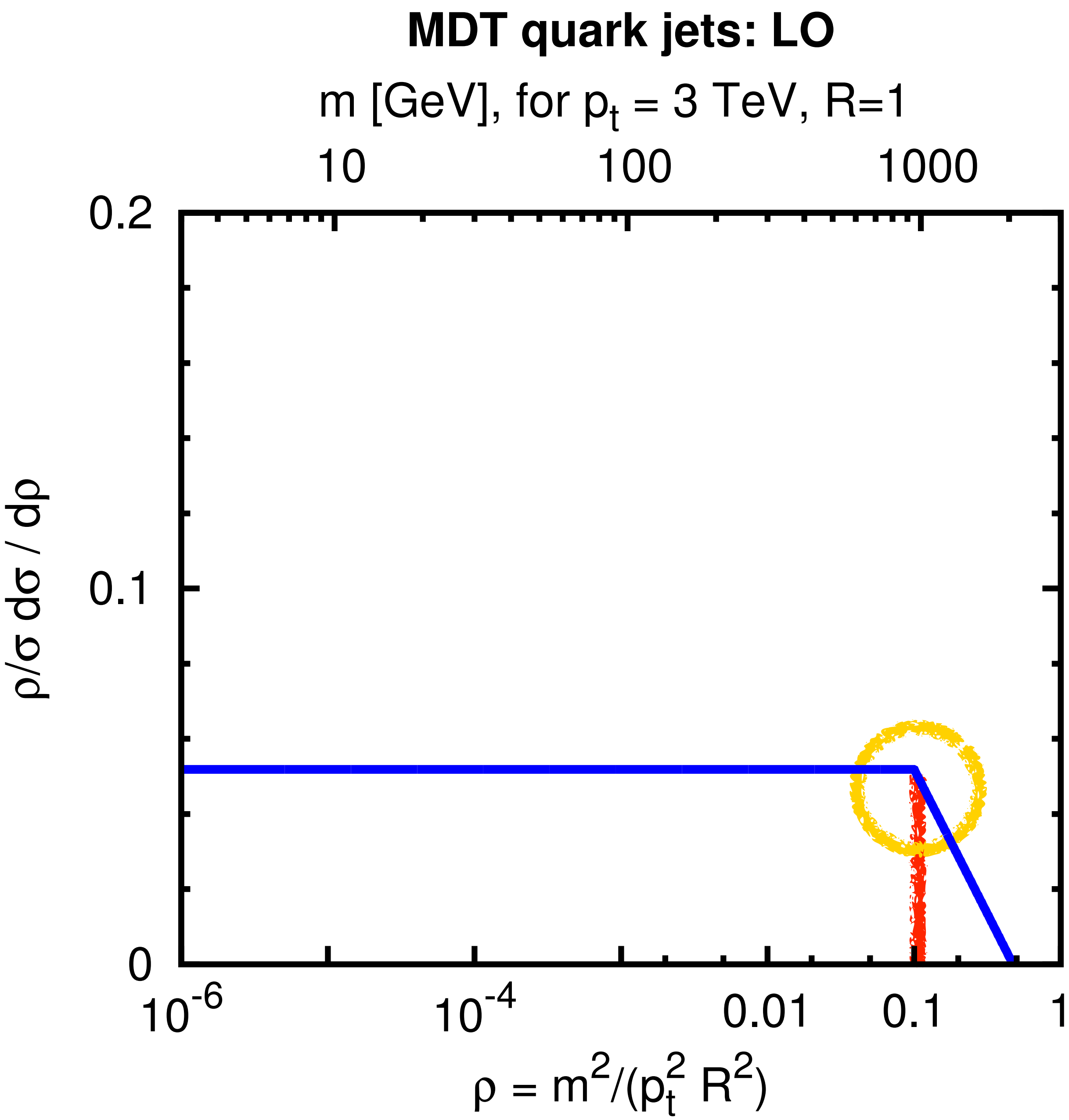

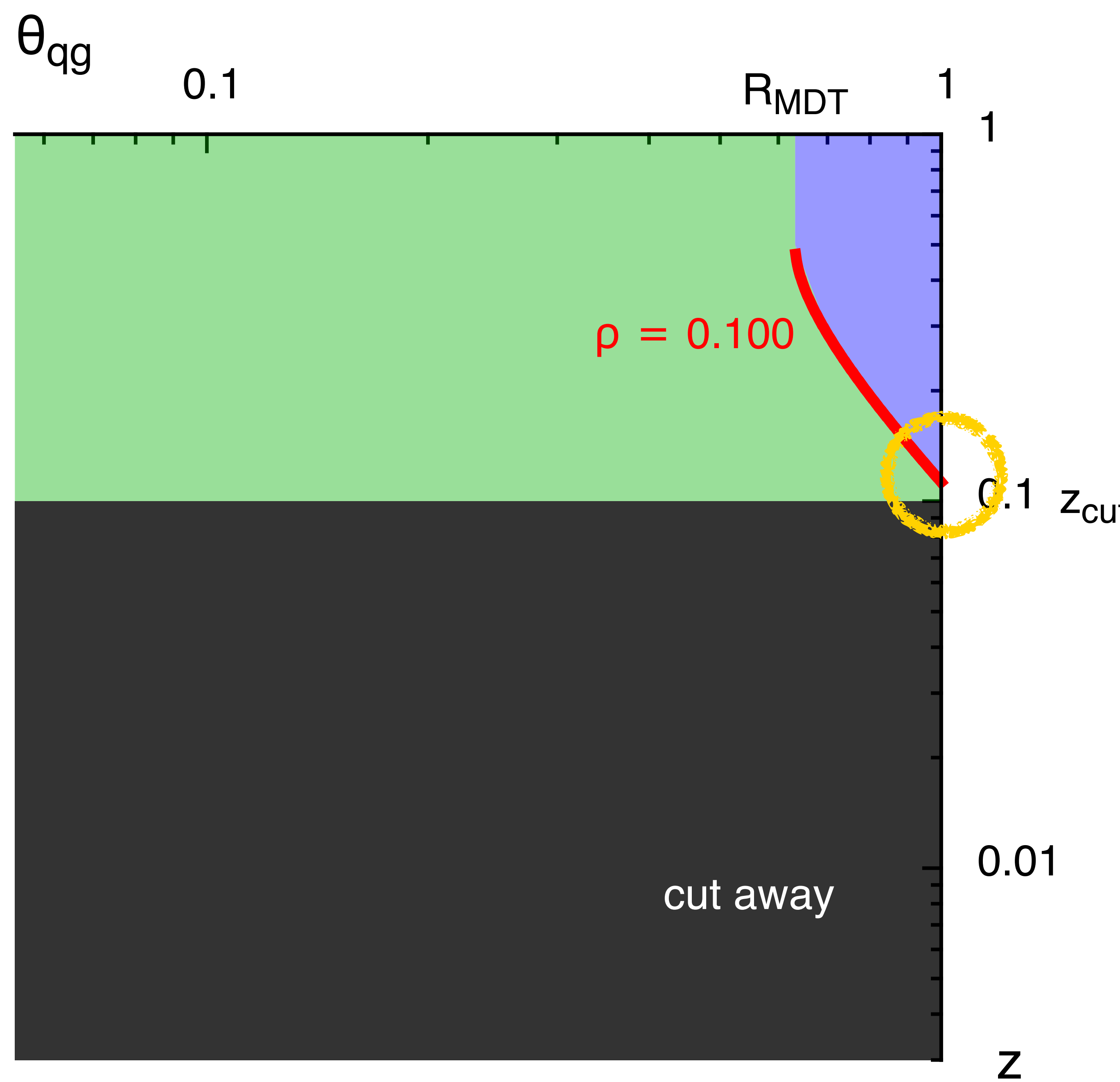

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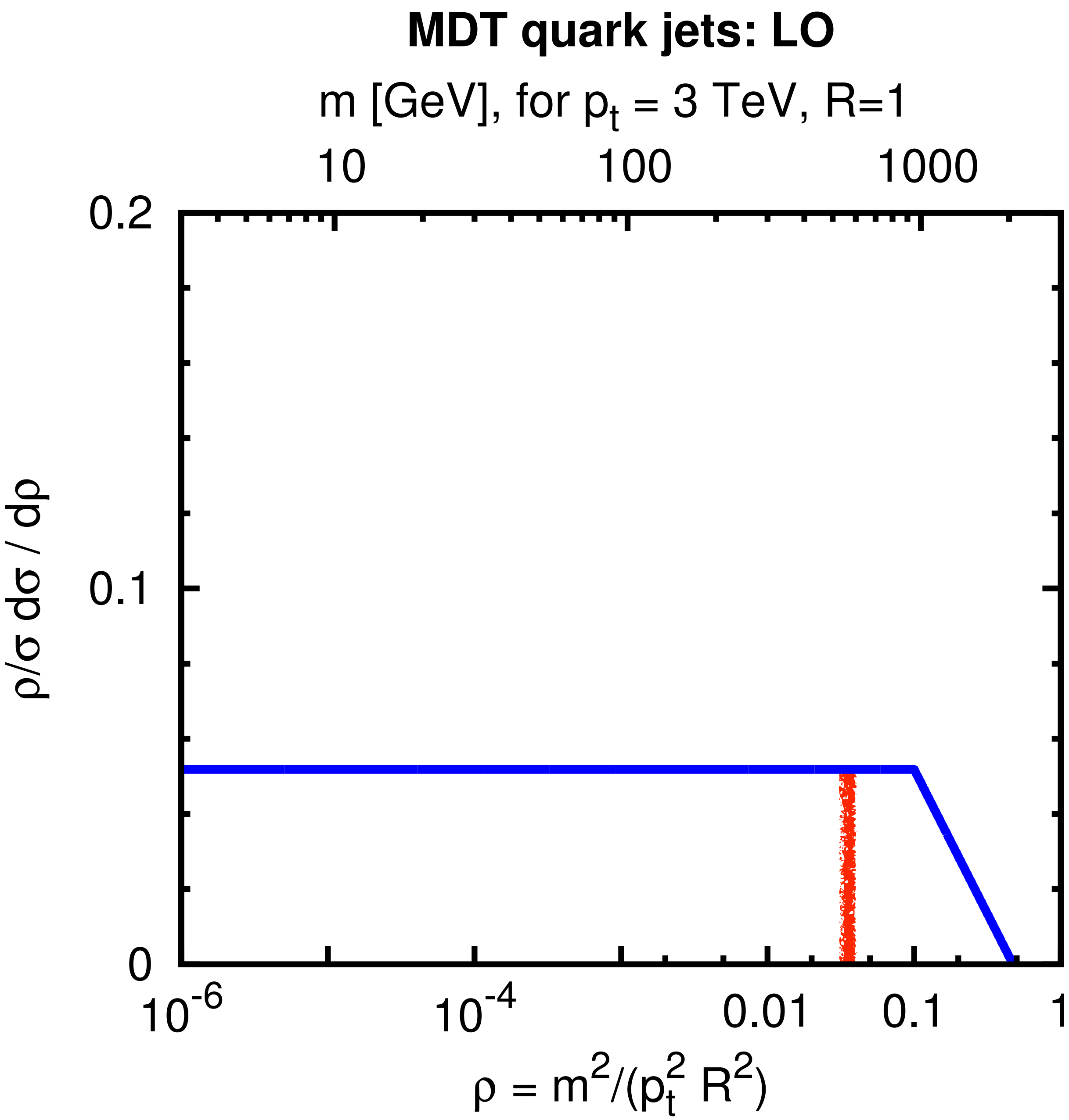

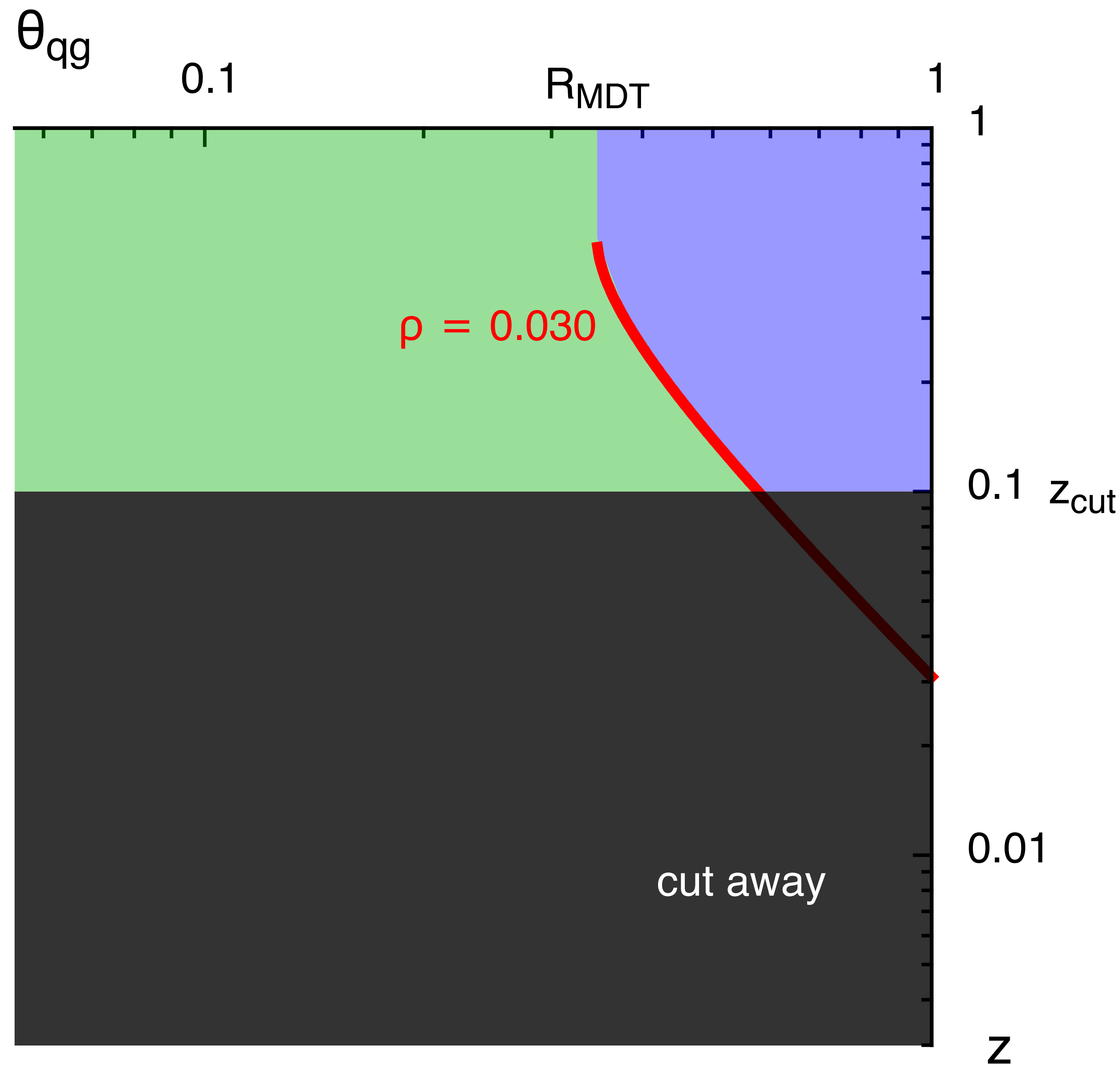

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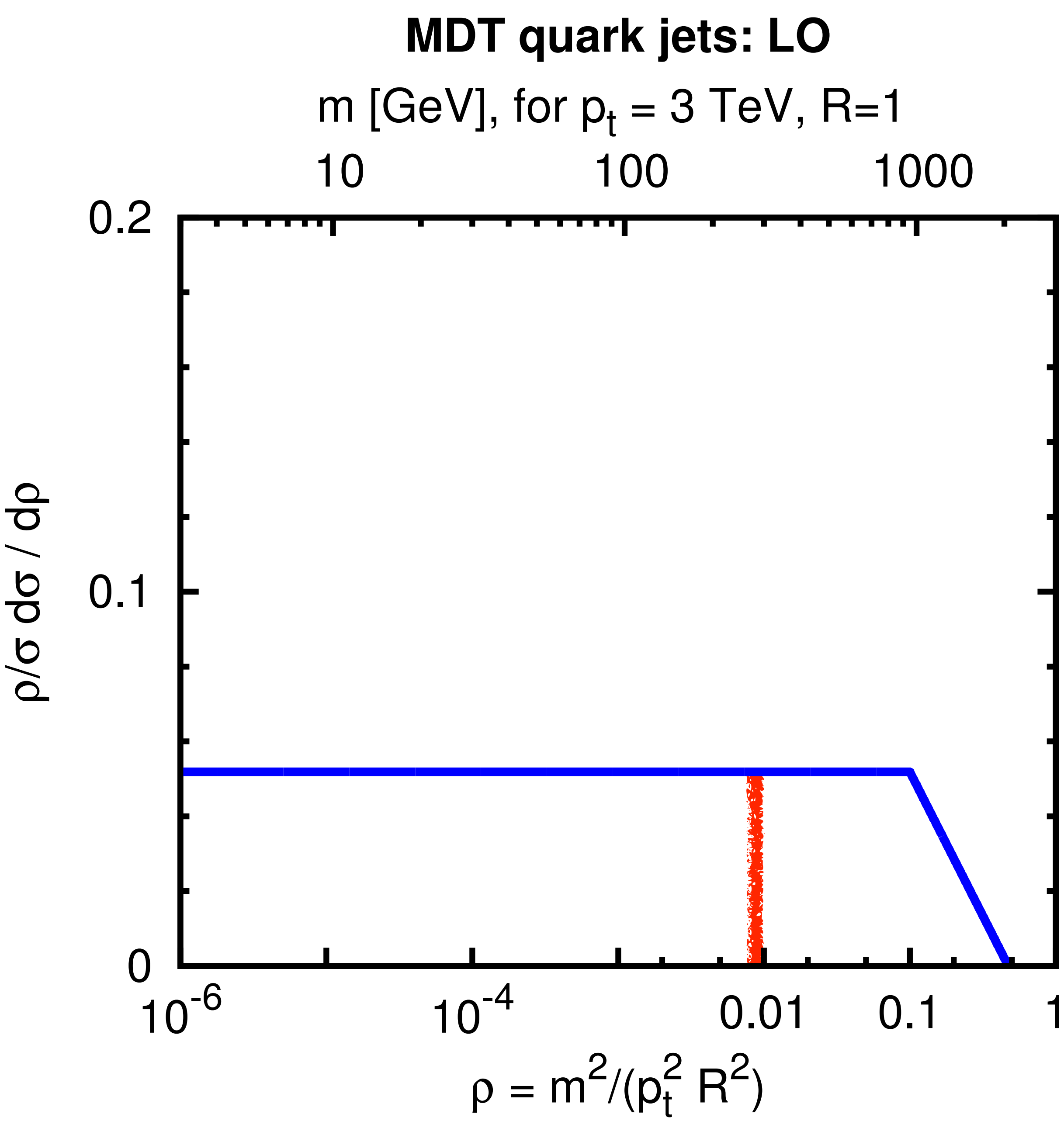

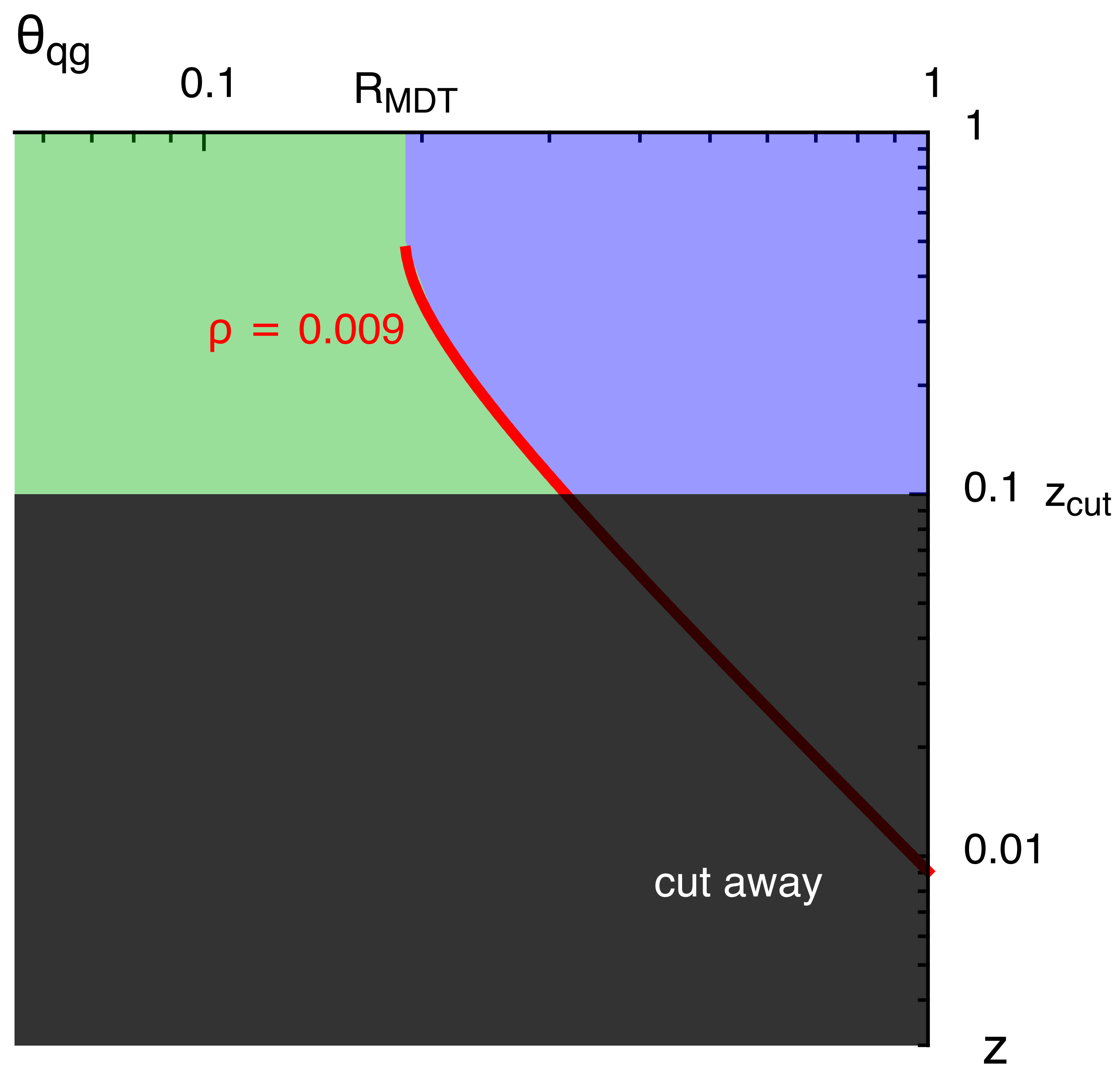

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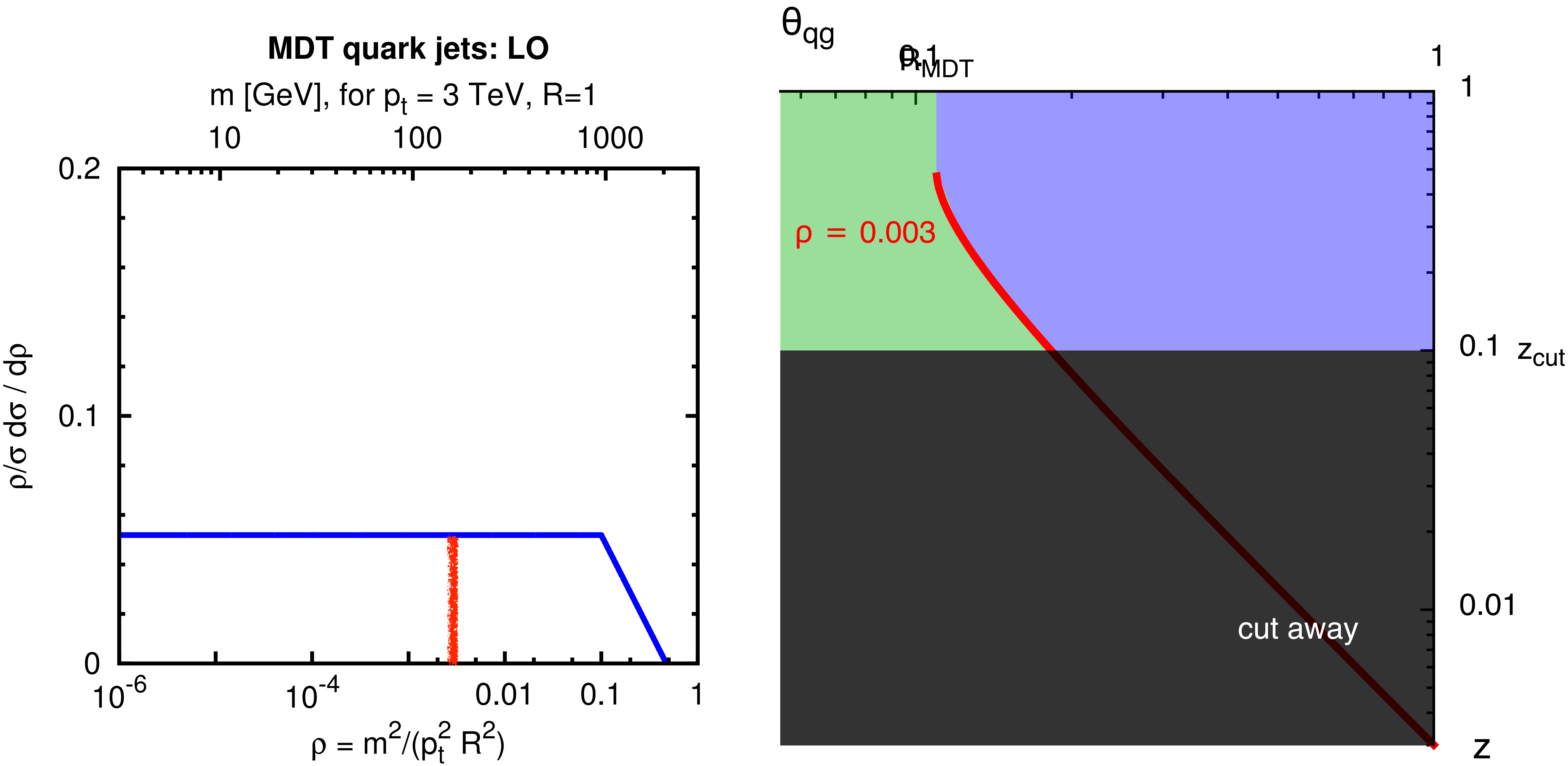

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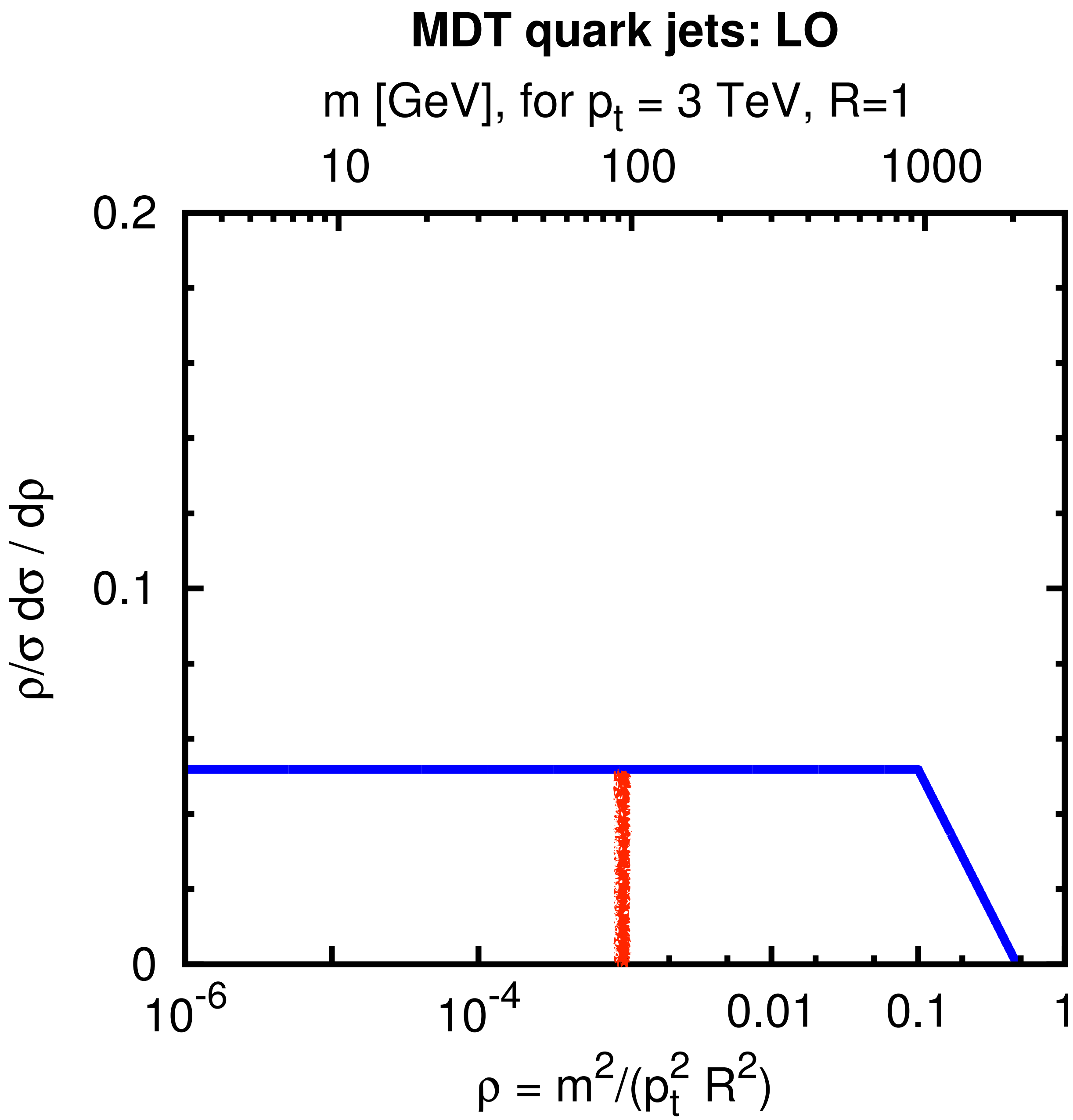
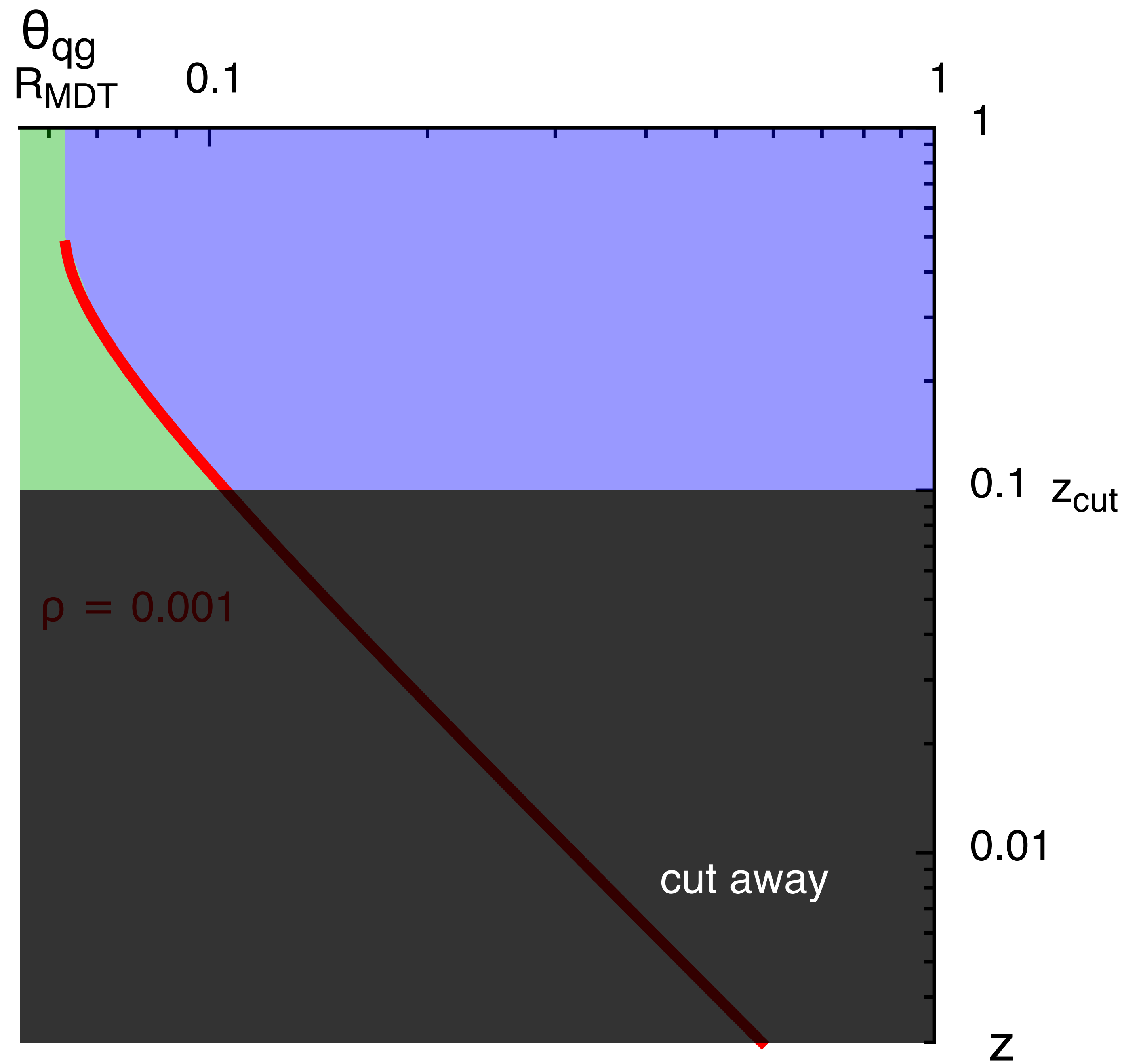
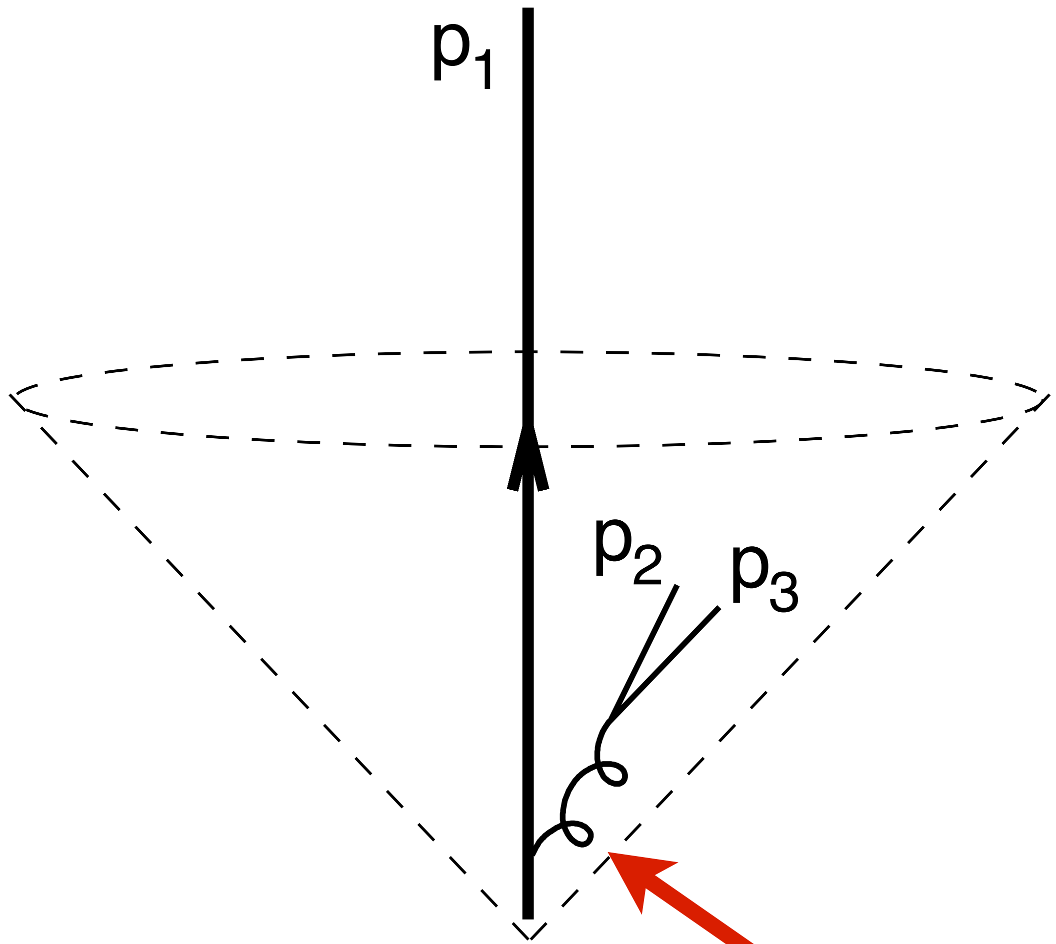






What MDT does wrong beyond LO:

Follows a soft branch ($p_2+p_3 < y_{cut}\, p_{jet}$) with "accidental" small mass, when the "right" answer was that the (massless) hard branch had no substructure

Subjet is soft, but has more substructure than hard subjet

MDT's leading logs (LL, in Σ) are:

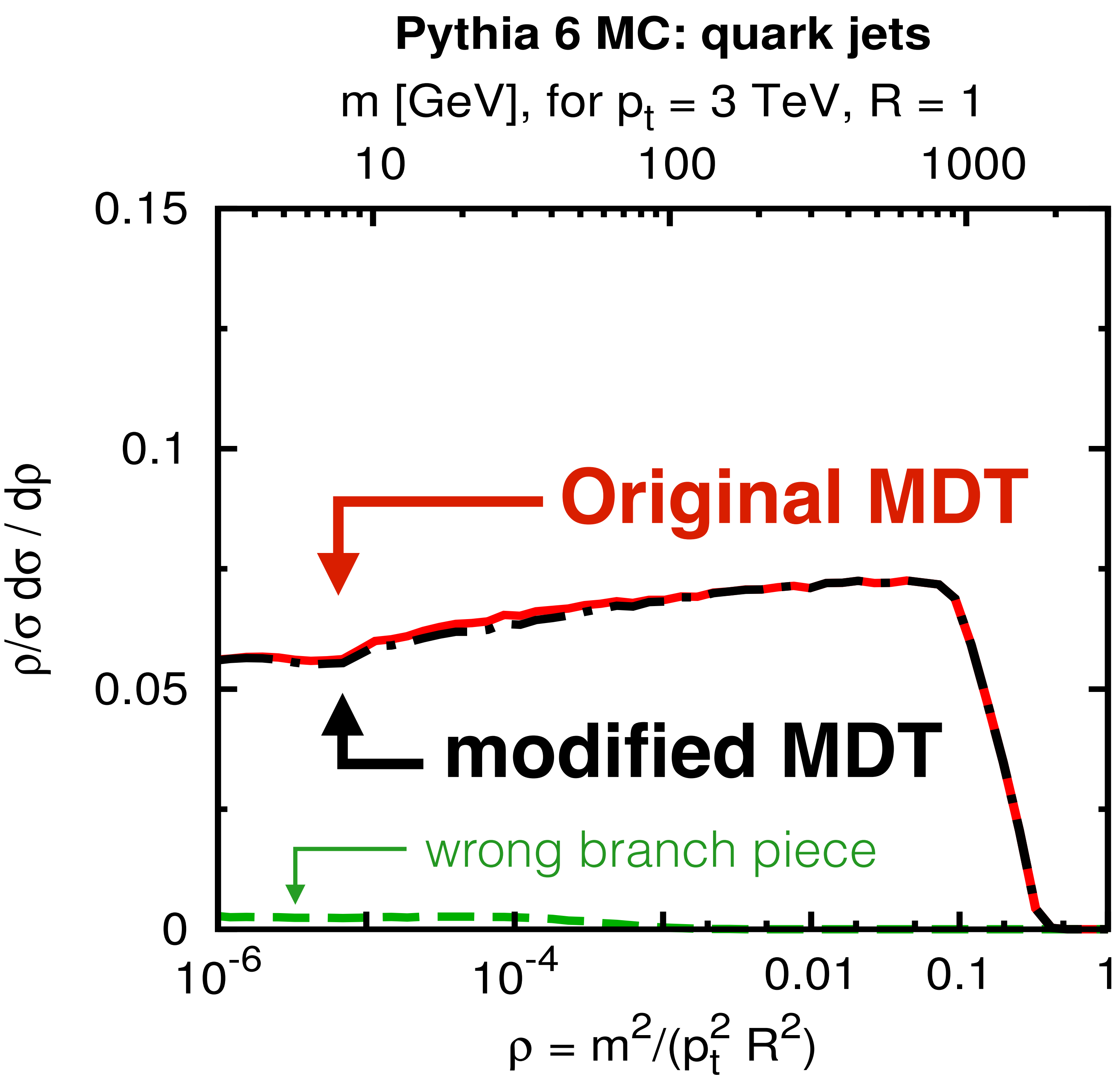
$$\alpha_s L,\ \alpha_s^2 L^3,\ \ldots .\ \text{I.e.}\ \boldsymbol{\alpha_s^n L^{2n-1}}$$

quite complicated to evaluate

A simple fix: **“modified”** Mass Drop Tagger:

When recursing, **follow branch with larger (m^2+p_t^2)**

(rather than the one with larger m)



Modification has almost no phenomenological impact, but big analytical consequences...

At most "single logs", at all orders, i.e.

$$\alpha_s L,\ \alpha_s^2 L^2,\ \ldots.\ \text{I.e. } \boldsymbol{\alpha_s^n L^n}$$

Logs exclusively collinear – much simpler than jet mass

➡ no non-global logs

➡ no clustering logs

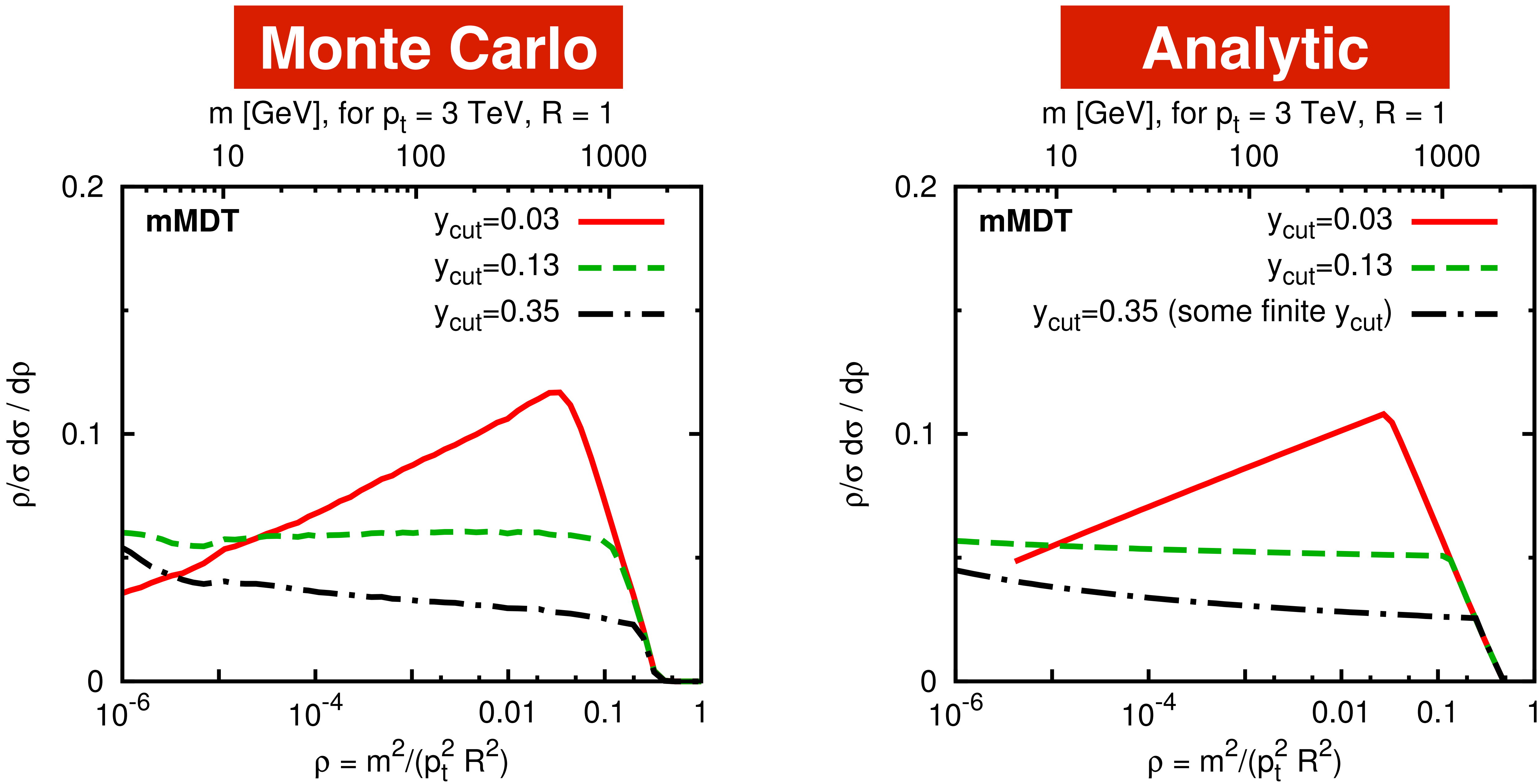
➡ no super-leading (factorization-breaking) logs

First time anything like this has been seen

Fairly simple formulae; e.g. [fixed-coupling]

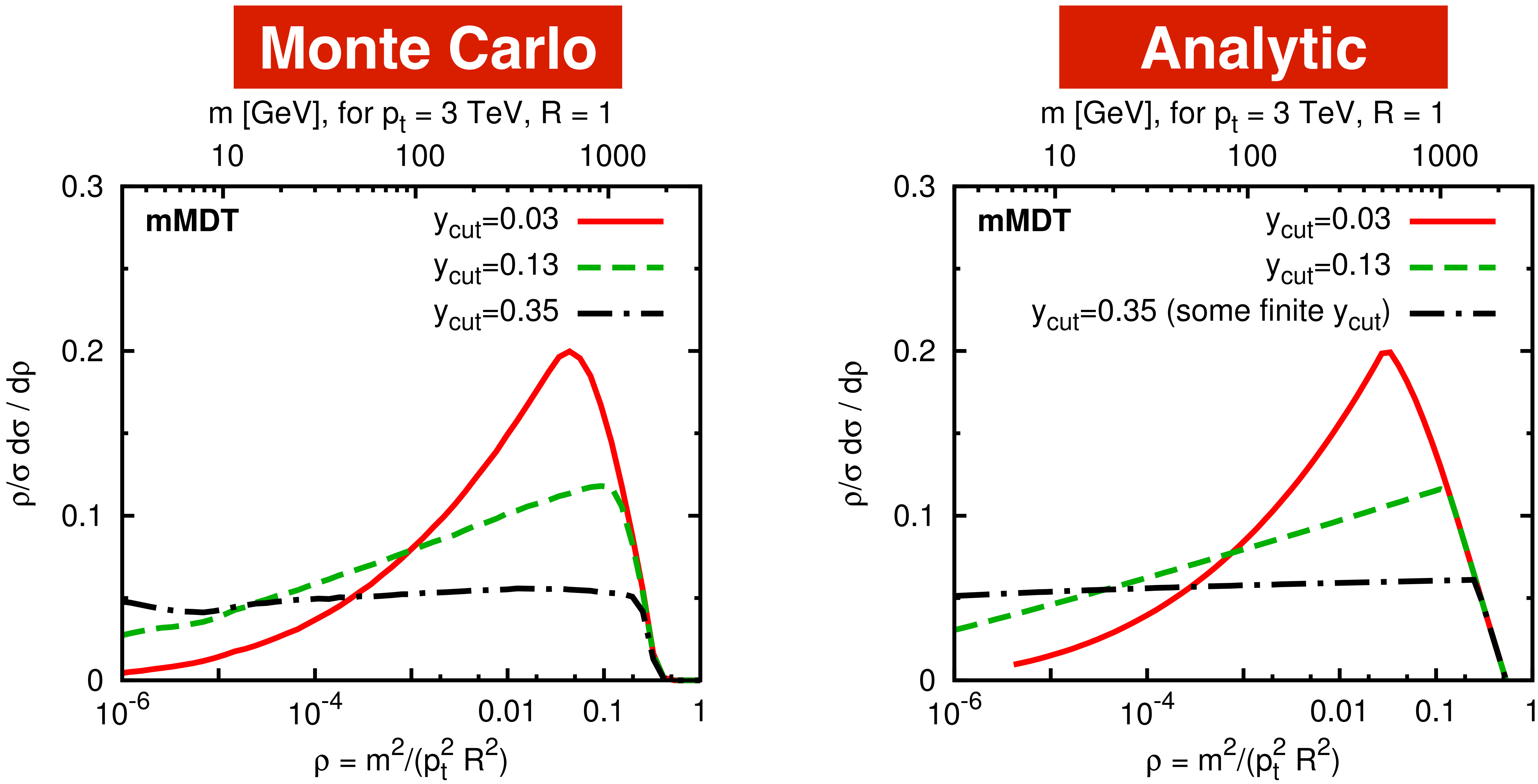
$$\Sigma^{(\text{mMDT})}(\rho) = \exp\left[-\frac{\alpha_s C_F}{\pi}\left(\ln\frac{y_{\text{cut}}}{\rho}\ln\frac{1}{y_{\text{cut}}} - \frac{3}{4}\ln\frac{1}{\rho} + \frac{1}{2}\ln^2\frac{1}{y_{\text{cut}}}\right)\right]$$

mMDT MC v. Resummation



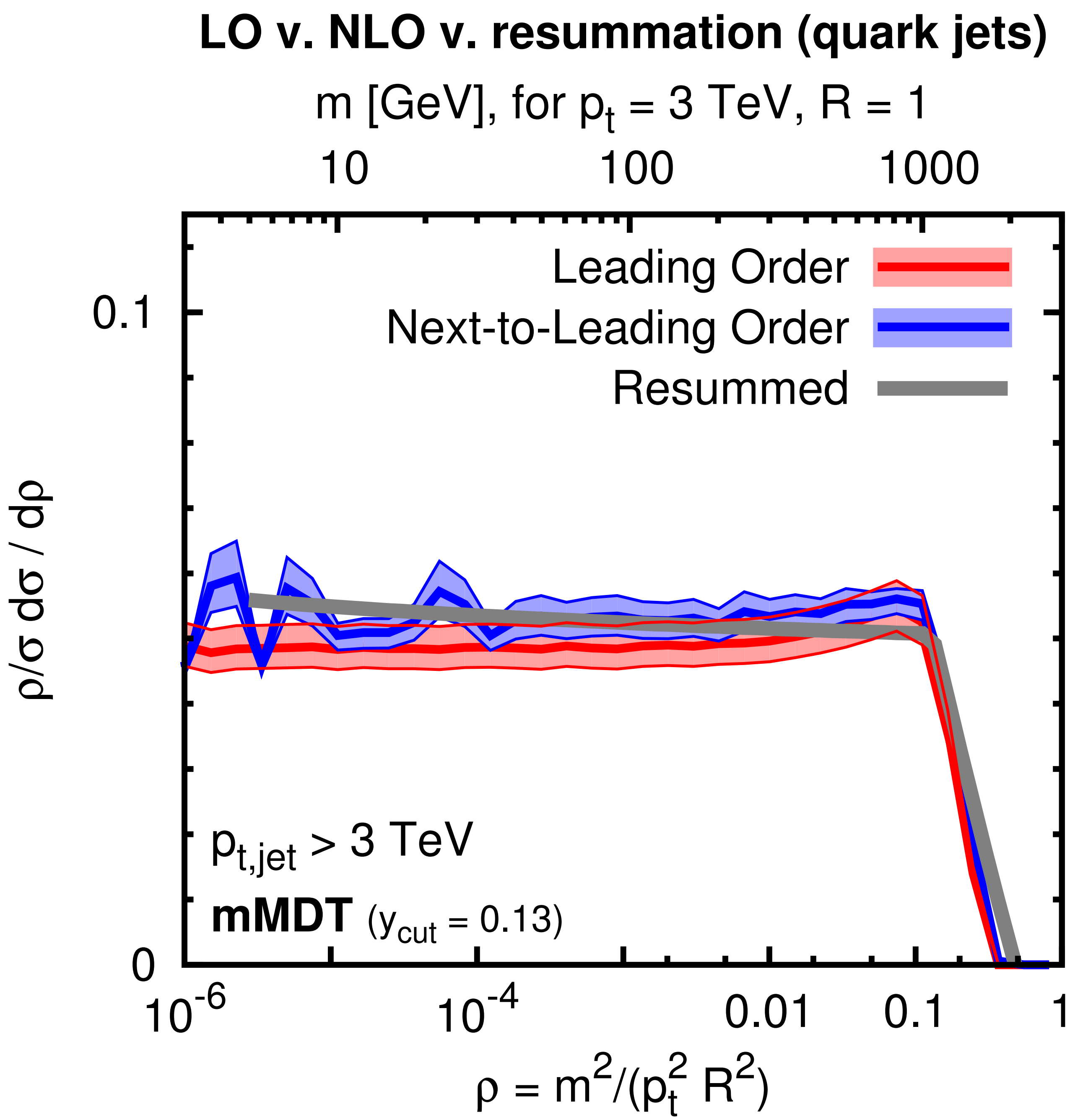
[mMDT is closest we have to a scale-invariant tagger, though exact behaviour depends on q/g fractions]

mMDT MC v. Resummation



[mMDT is closest we have to a scale-invariant tagger, though exact behaviour depends on q/g fractions]

mMDT resummation v. fixed order

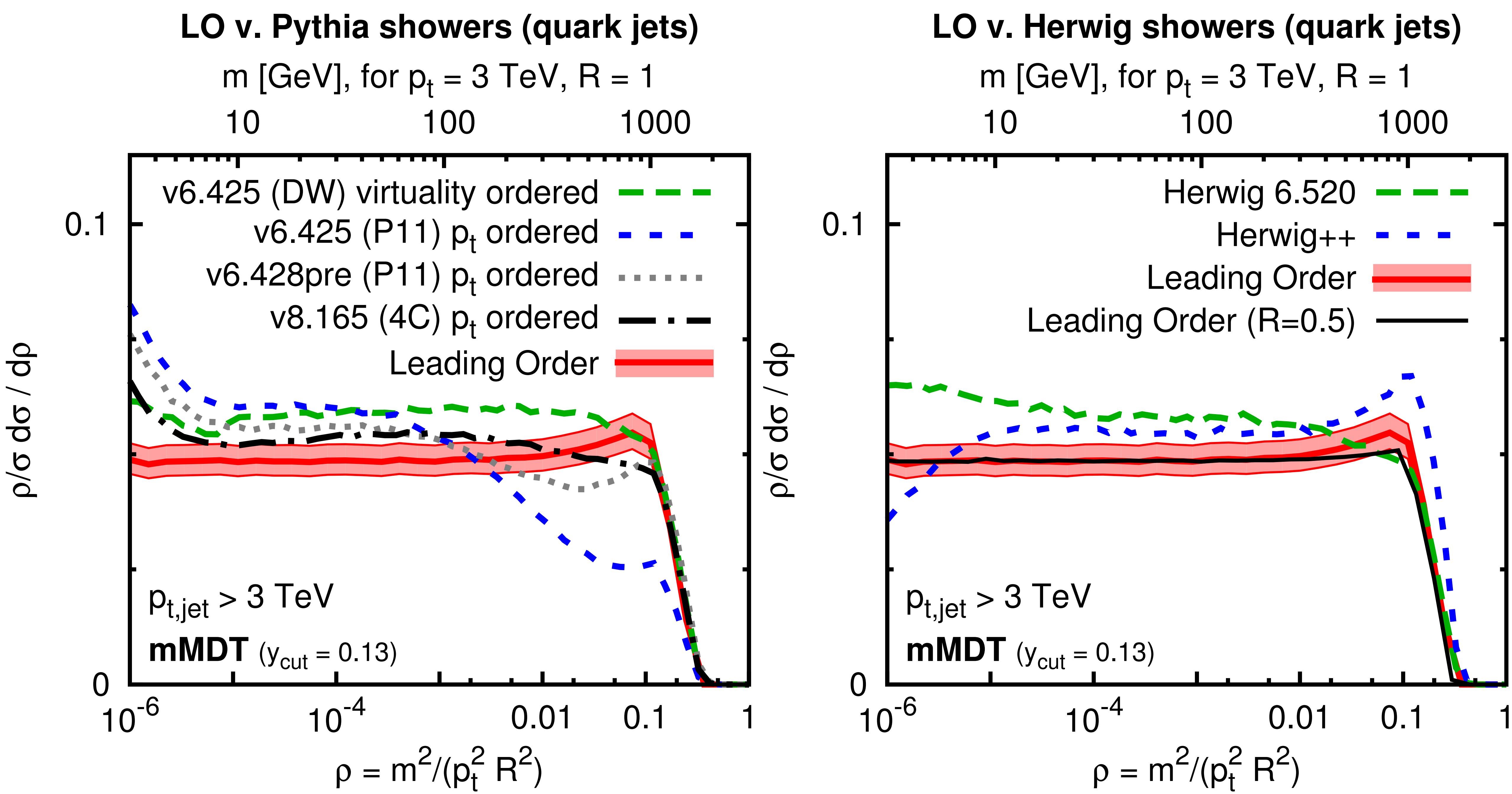


NLO from NLOJet++

Because we only have single logs, fixed-order is valid over a broader than usual range of scales

(helped by fortuitous cancellation between running coupling and single-log Sudakov)

mMDT: comparing many showers



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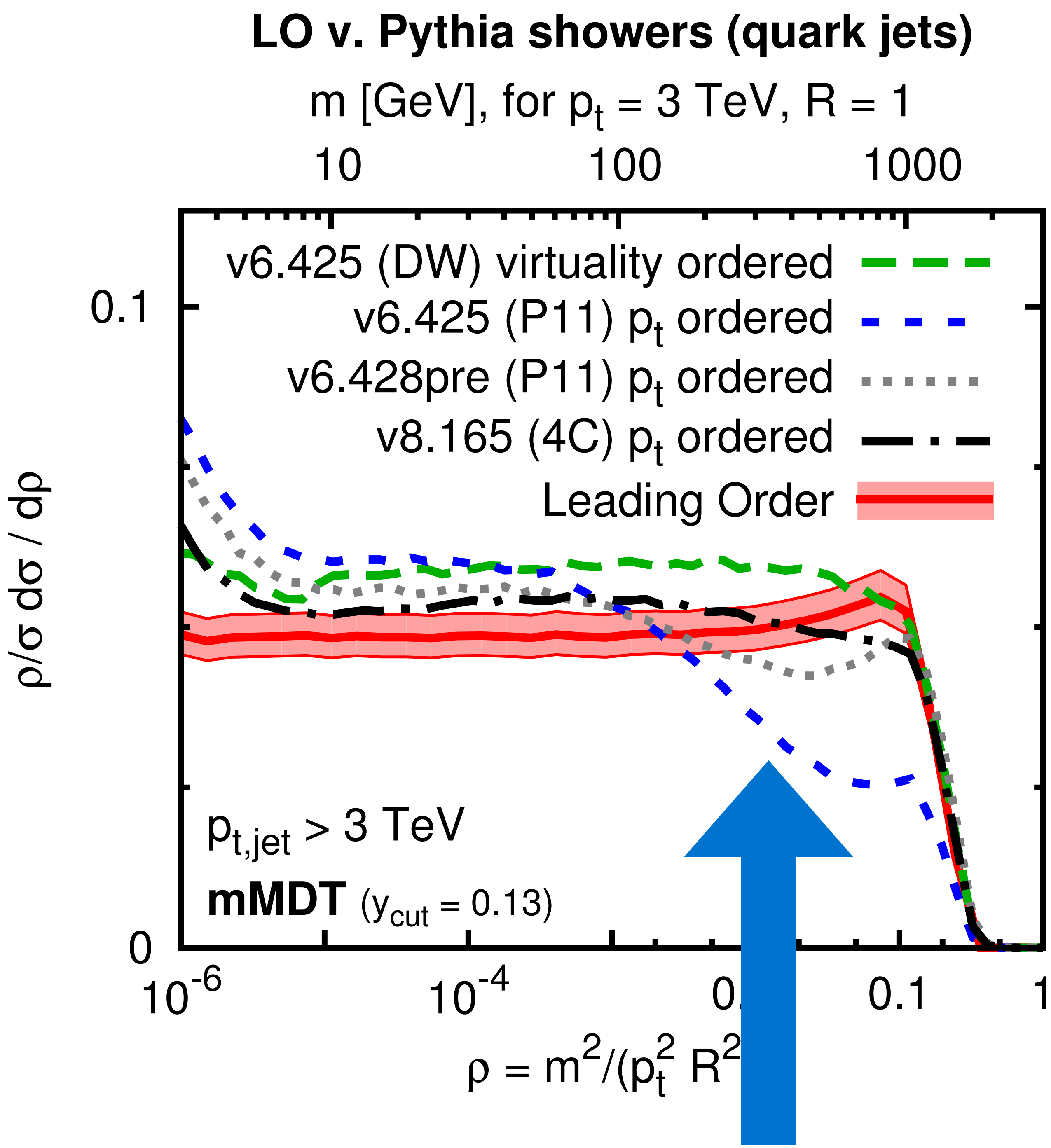
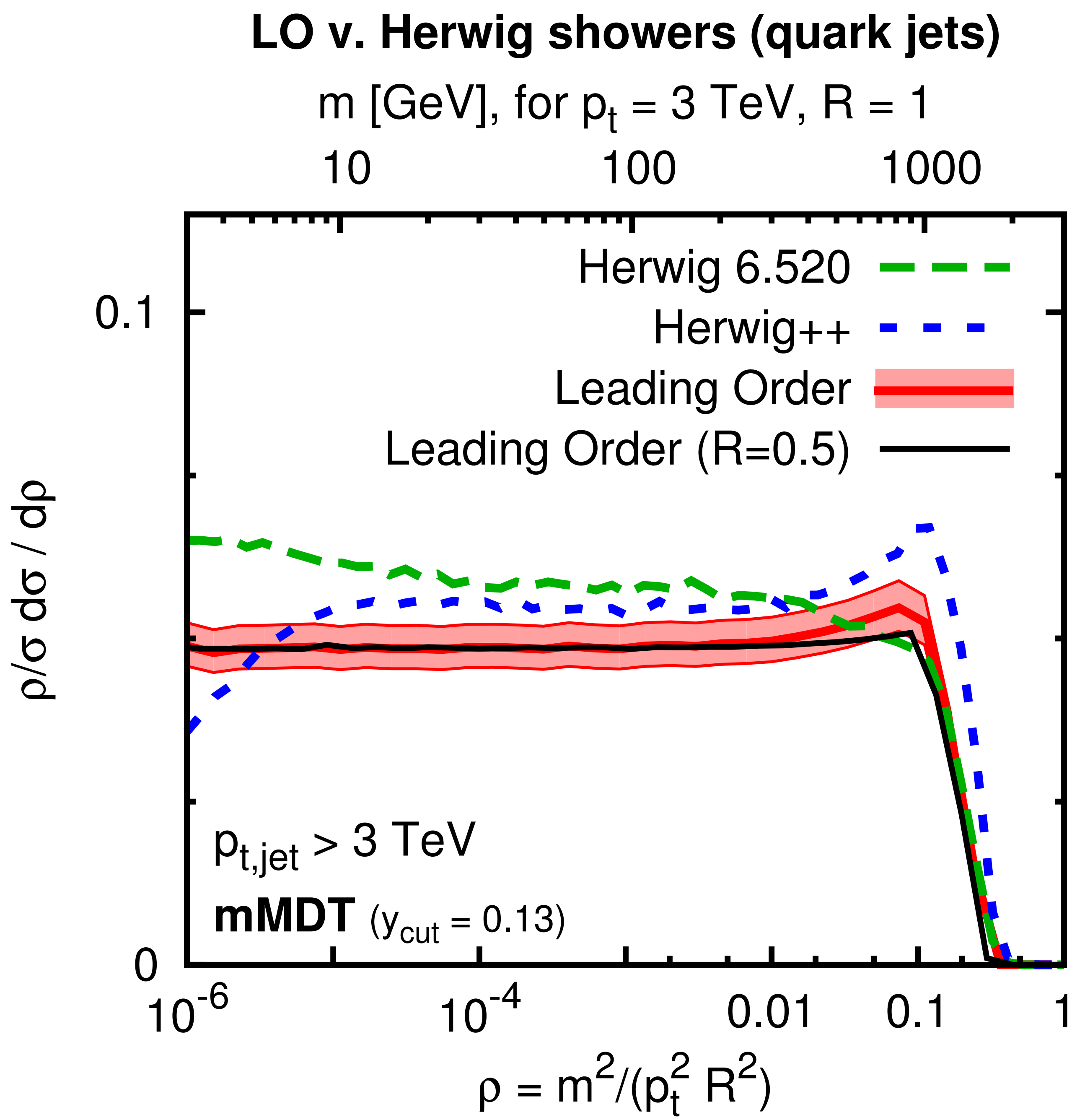
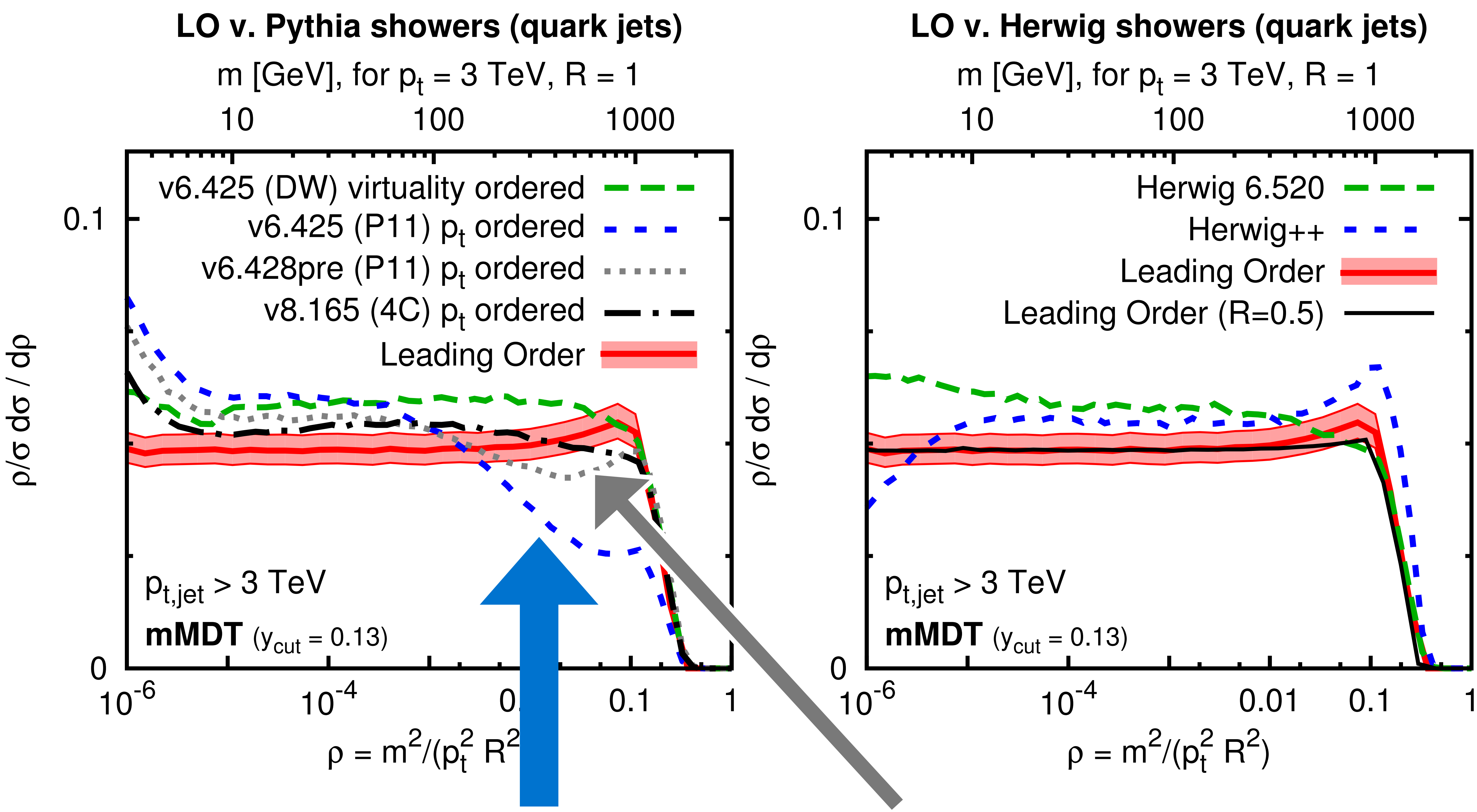




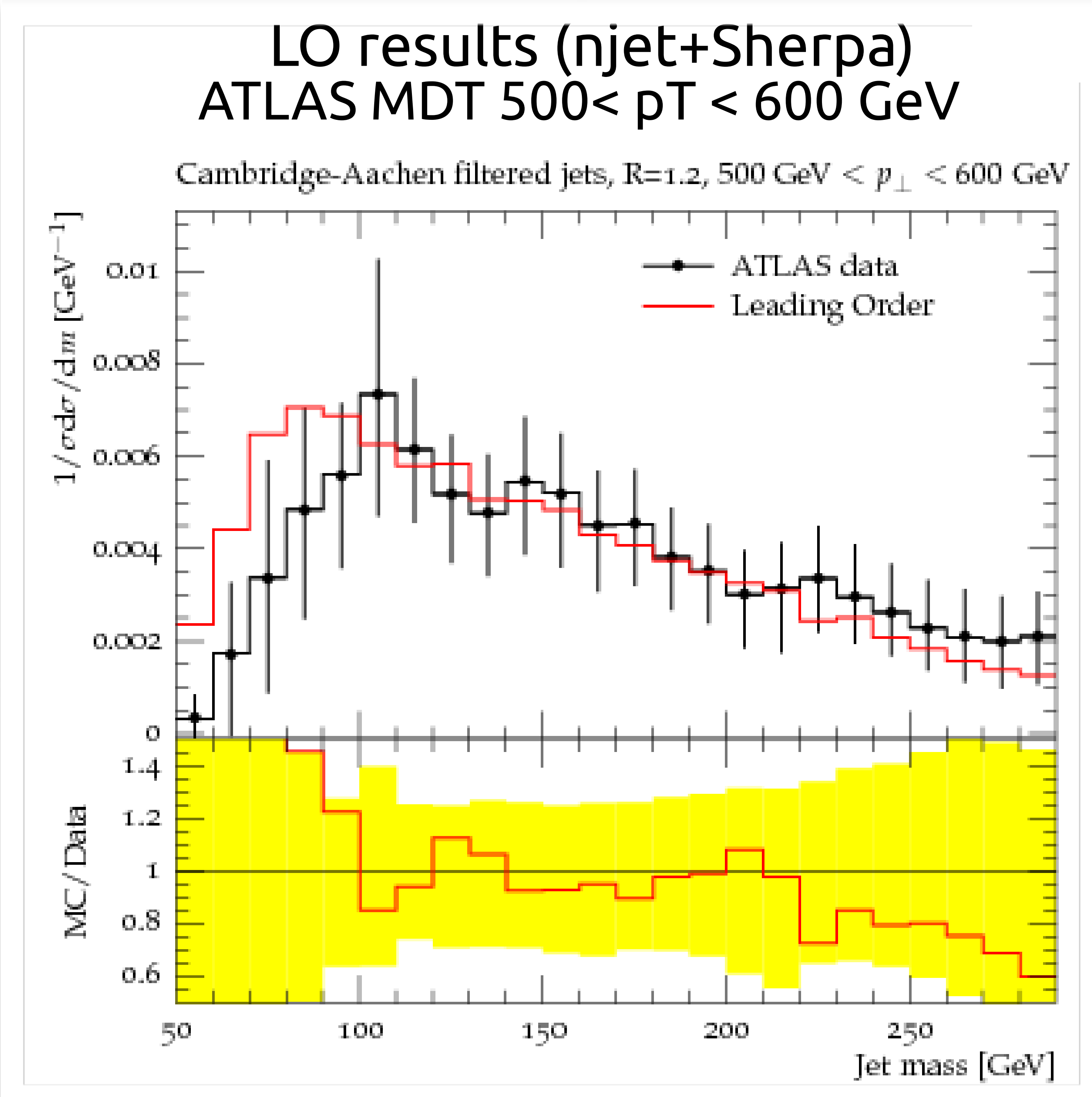
Issue found in Pythia 6 p_t-ordered shower → promptly identified and fixed by Pythia authors!

mMDT: comparing many showers



Issue found in Pythia 6 p_t-ordered shower → promptly identified and fixed by Pythia authors!

comparing to data



Dasgupta, Siodmok & Powling, in prep.

Since LO quite close to full resummation, you can try comparing LO directly to data.

Remarkable agreement!

[see backup for non-pert effects]

Looking beyond

mMDT has a single-logarithmic (pure collinear) distribution that's free of non-global logs

A generalisation is **Soft Drop**

Uncluster C/A jets as with mMDT, but stop only if

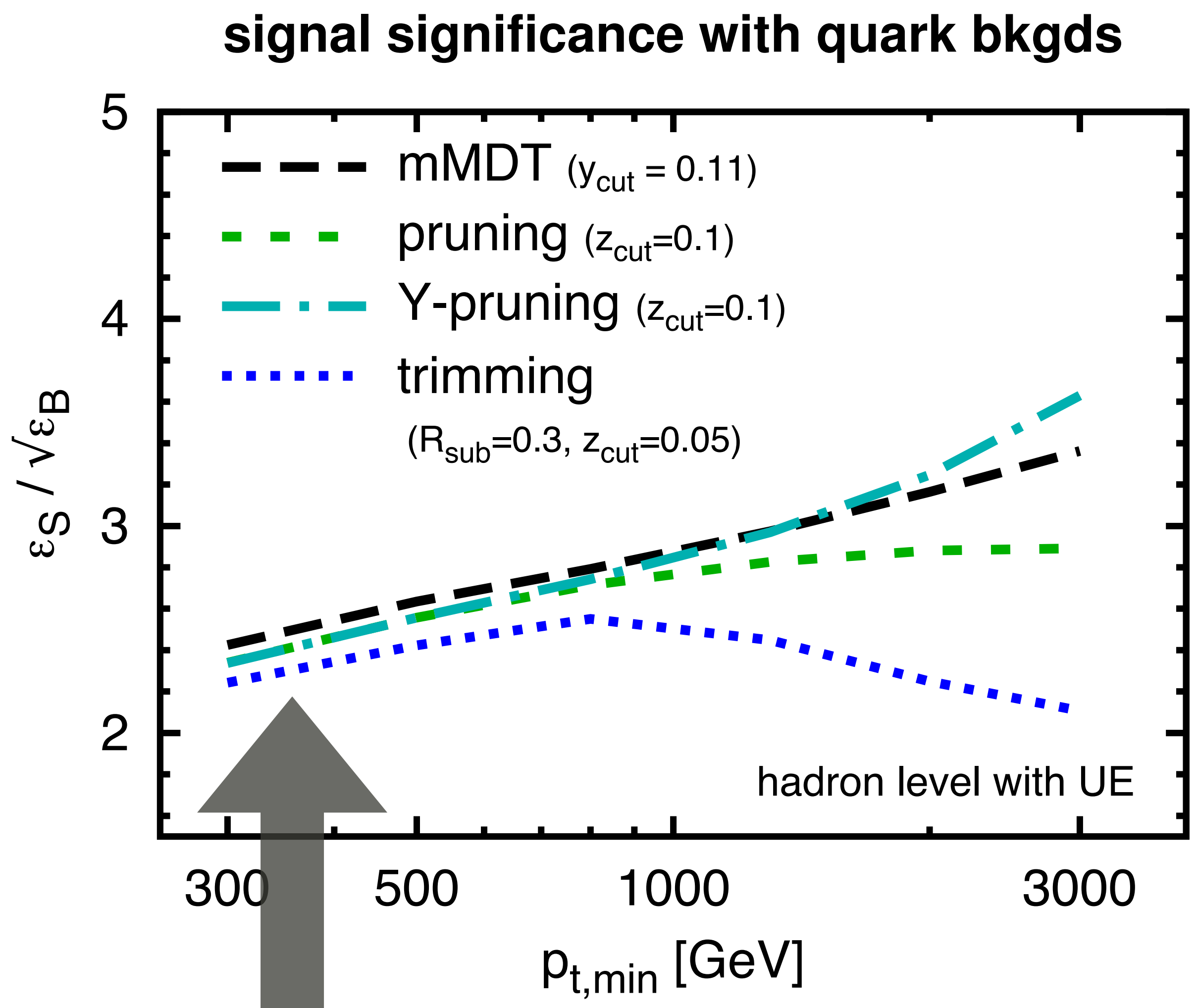
$$\frac{\min(p_{t1}, p_{t2})}{p_t} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

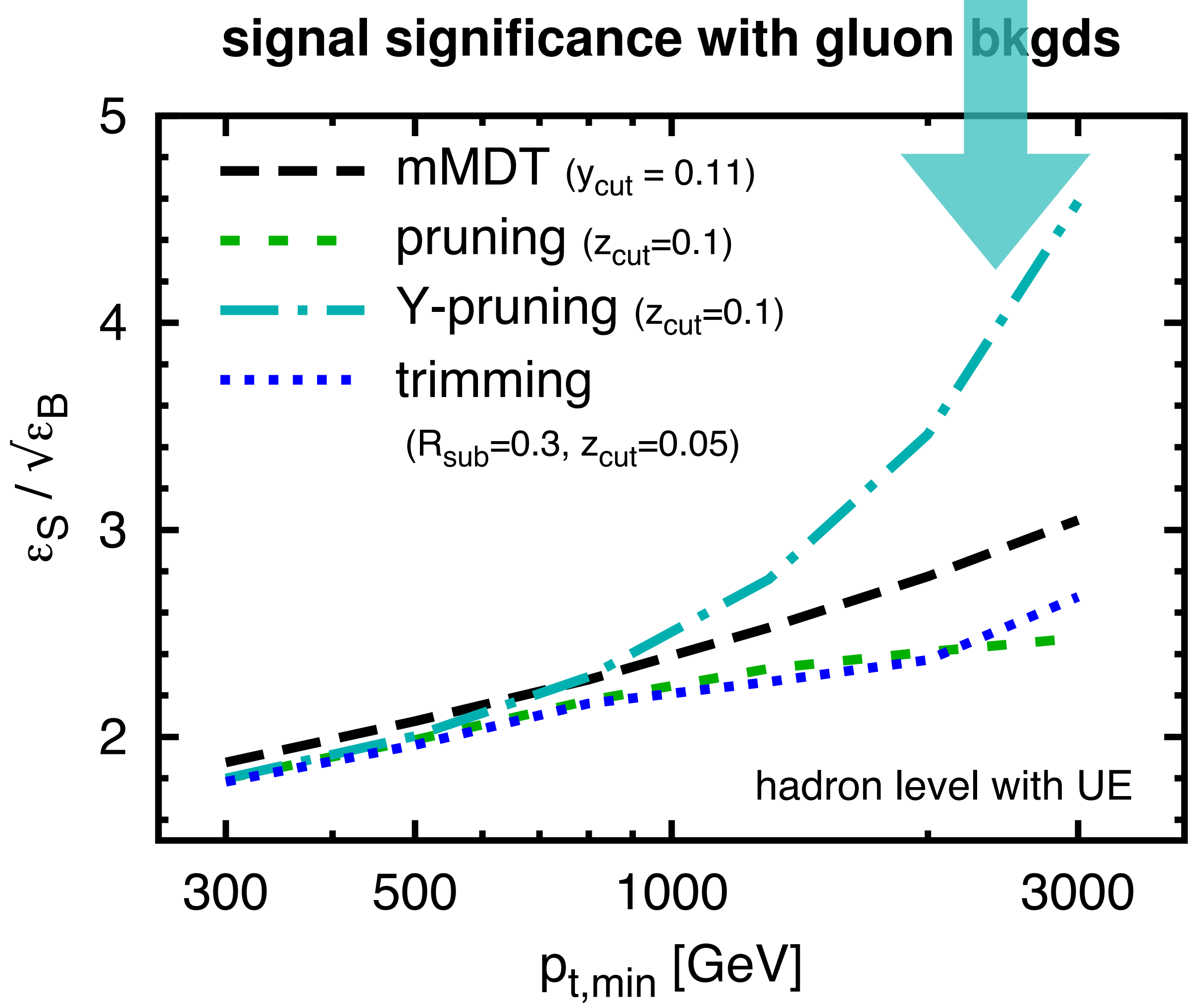
For $\beta > 0$, get double-log dist^n without NG logs
[mMDT corresponds to $\beta = 1$]

Larkoski, Marzani, Soyez, Thaler '14

Performance for finding signals (S/√B)

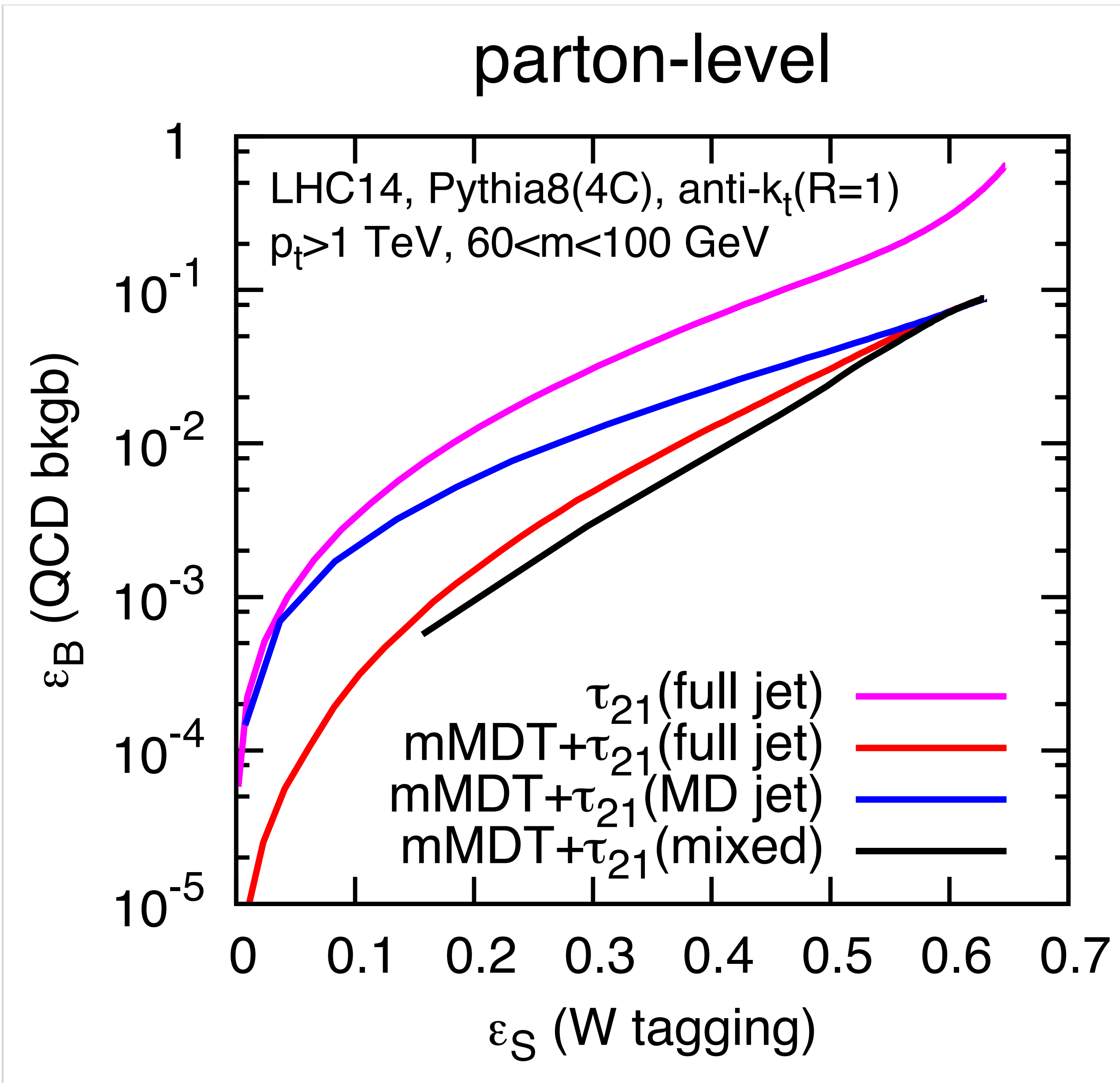
At high p_t, substantial gains from new Y-pruning
(probably just indicative of potential for doing better)





At low p_t (moderate m/p_t), all taggers quite similar

Combining variables



Experiments often combine [trimming/pruning/MDT/etc.] with a shape cut, typically N-subjettiness,

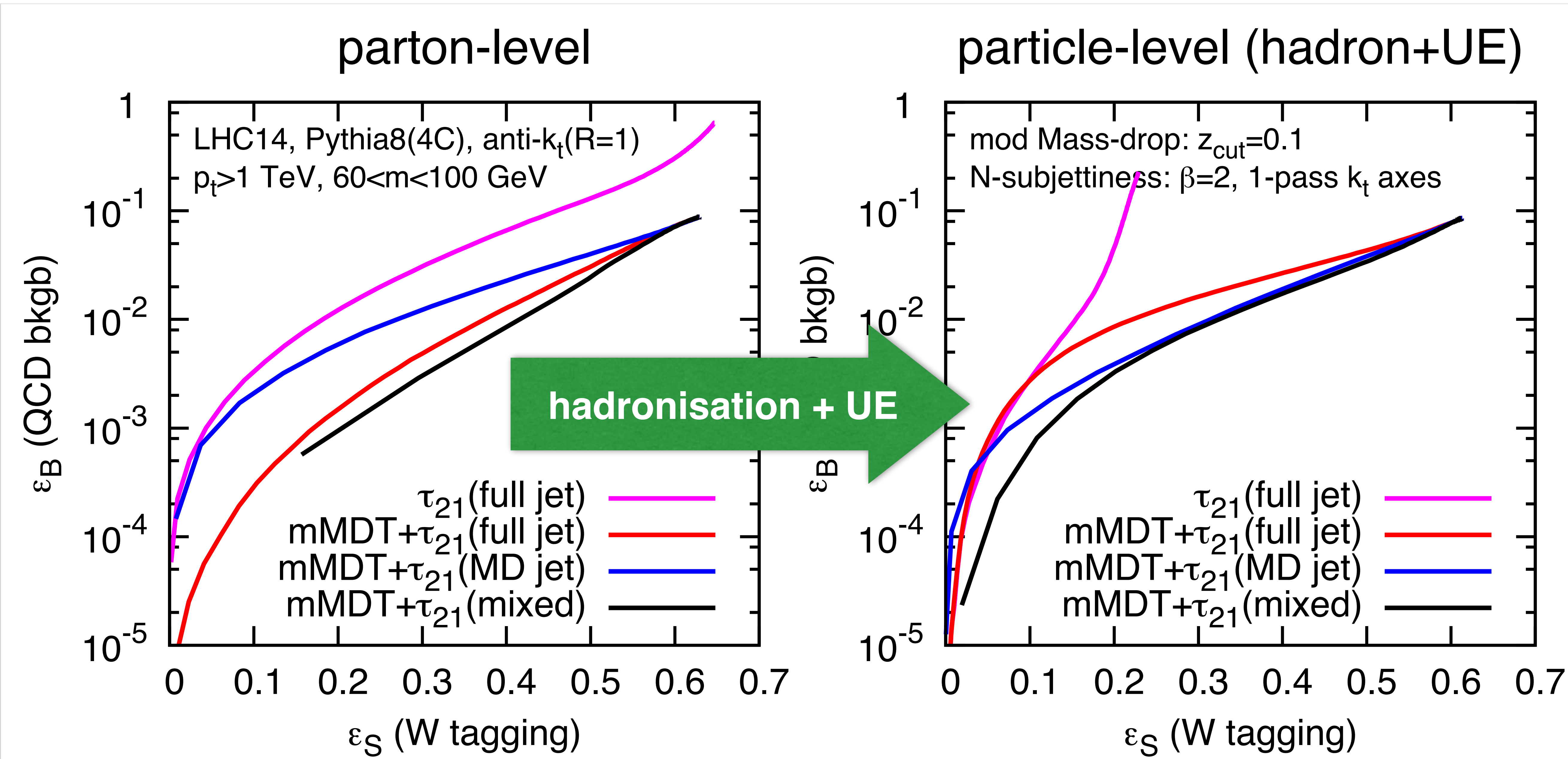
$$\tau_{21} = \tau_2 / \tau_1$$

Next: understand τ_{21}.
Qu.: apply before or after MMDT?

Prelim. answer: take τ_2 from full jet, τ_1 from mMDT jet

Work in progress, Dasgupta, GPS, Soyez & Sarem-Schunk

But: non-pert effects change picture



Work in progress, Dasgupta, GPS, Soyez & Sarem-Schunk

Summary

- Taggers may be quite simple to write, but potentially involved to understand.
- Contrast this with p_t cuts for standard jet analyses – (mostly) simple
- Still, many taggers/groomers are within calculational reach.
- Calculations help put the field on solid ground & potentially open road to new, better tools

Summary table

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

NEW

Special: only single logarithms (L = ln ρ)
→ more accurately calculable

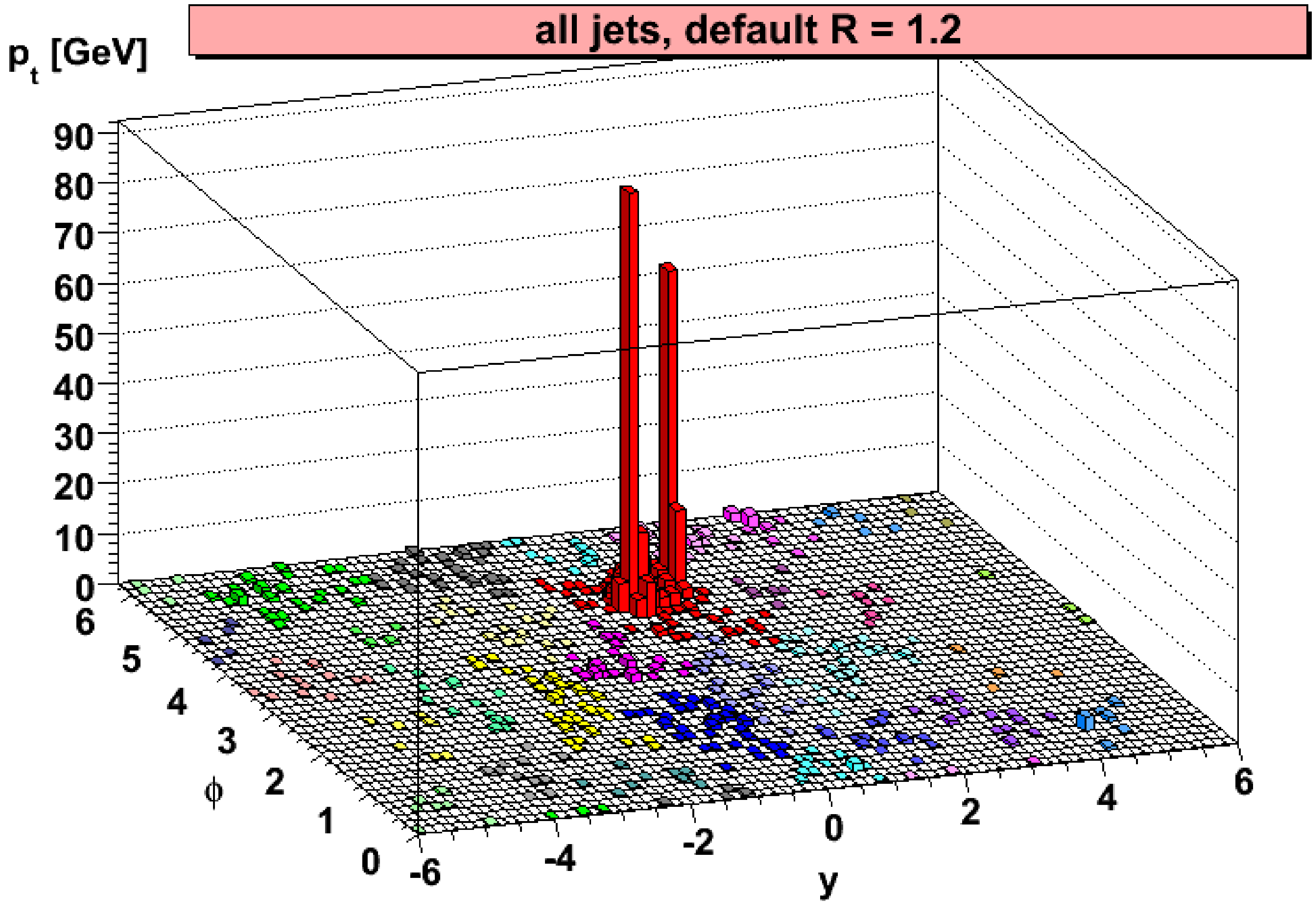
Special: better exploits signal/bkgd differences

EXTRAS

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

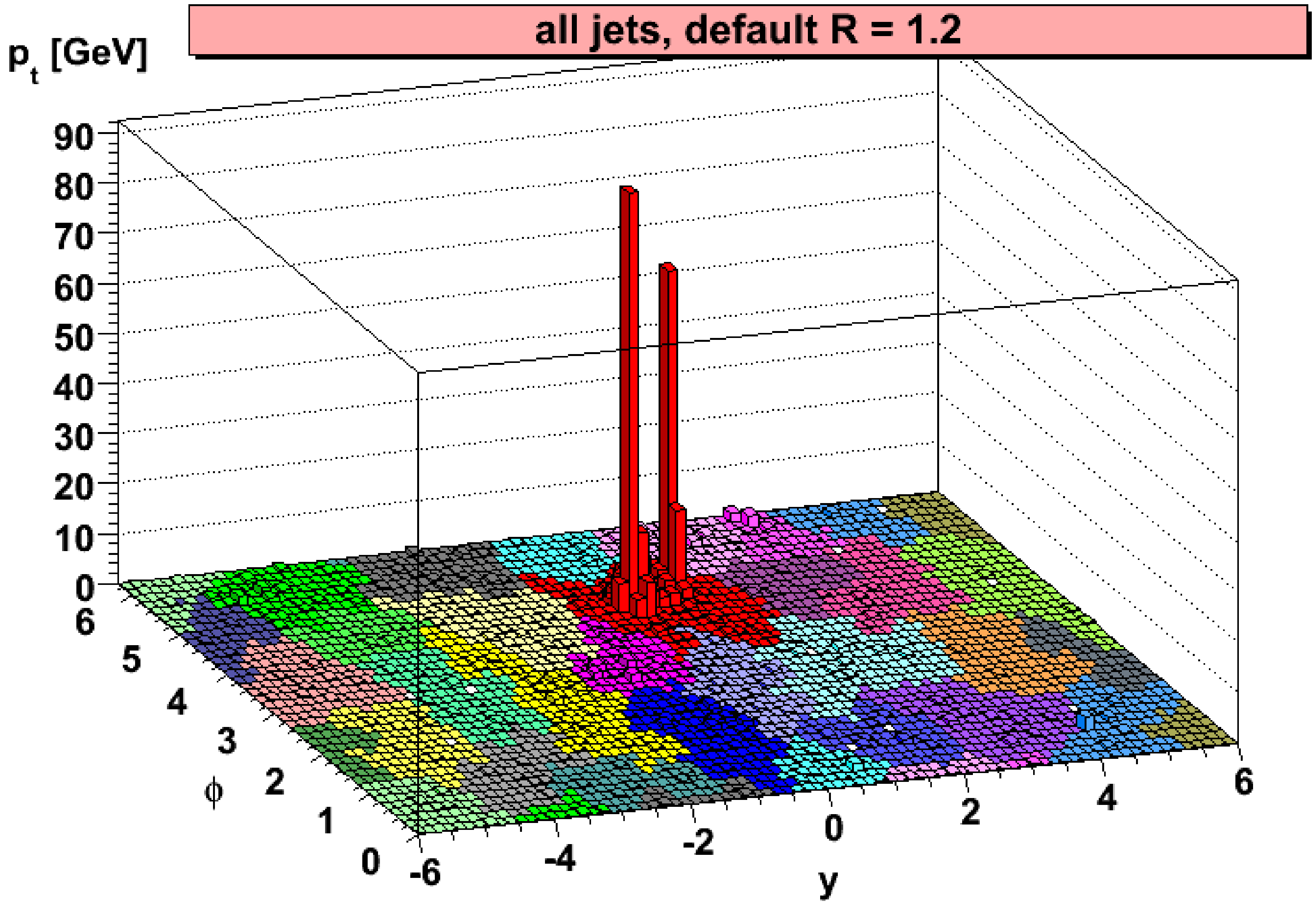
Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

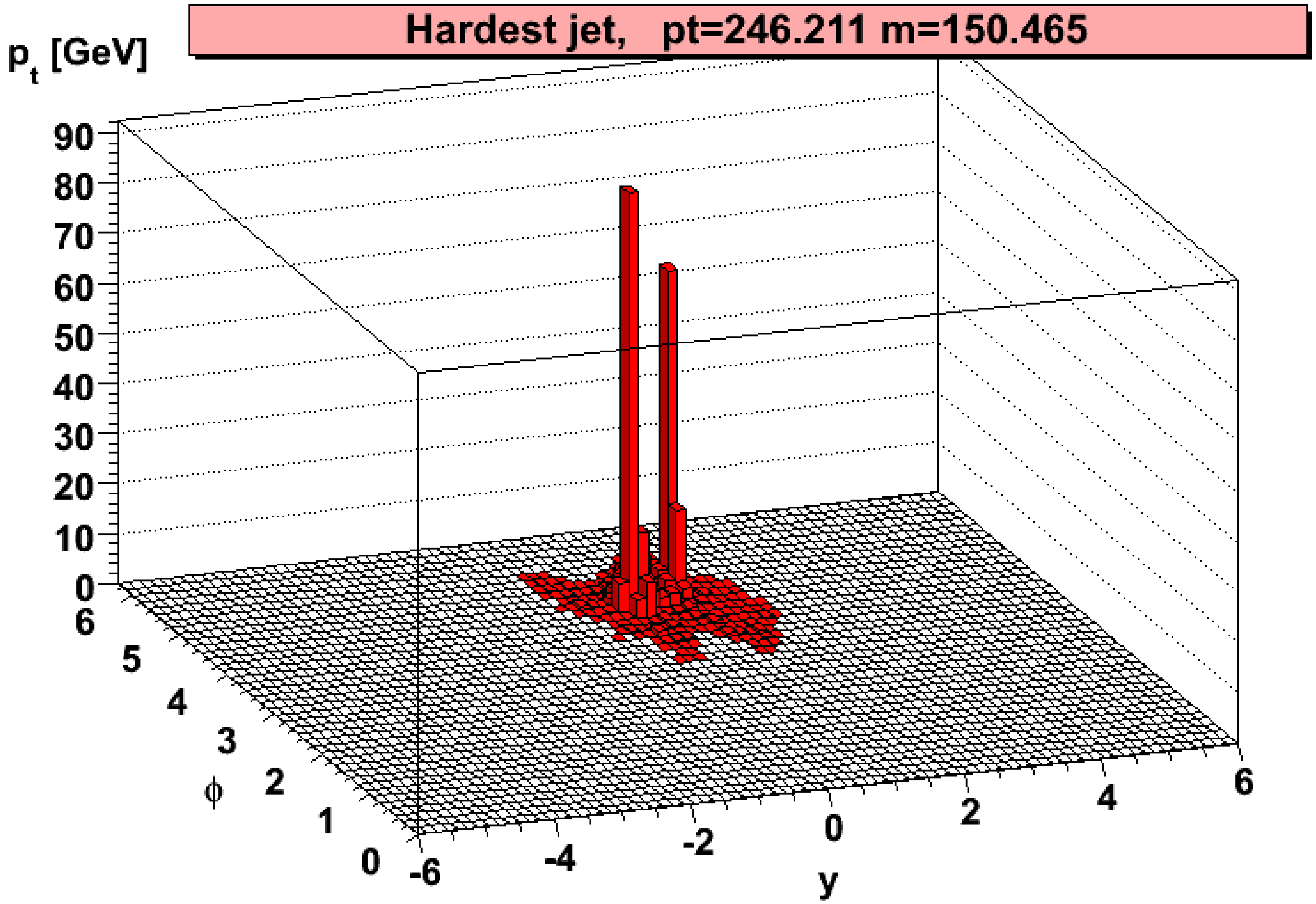
Fill it in, → show jets more clearly

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

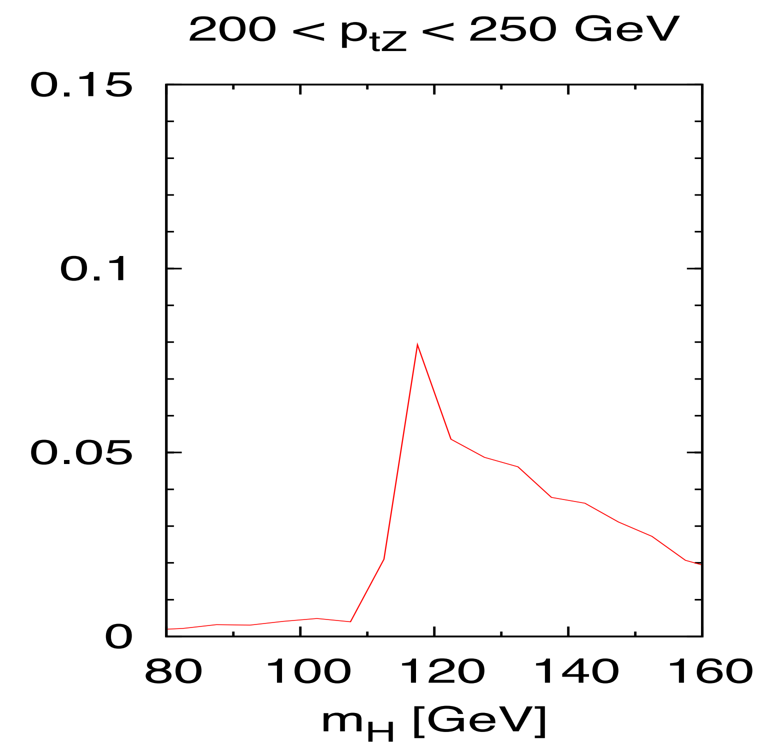
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

SIGNAL



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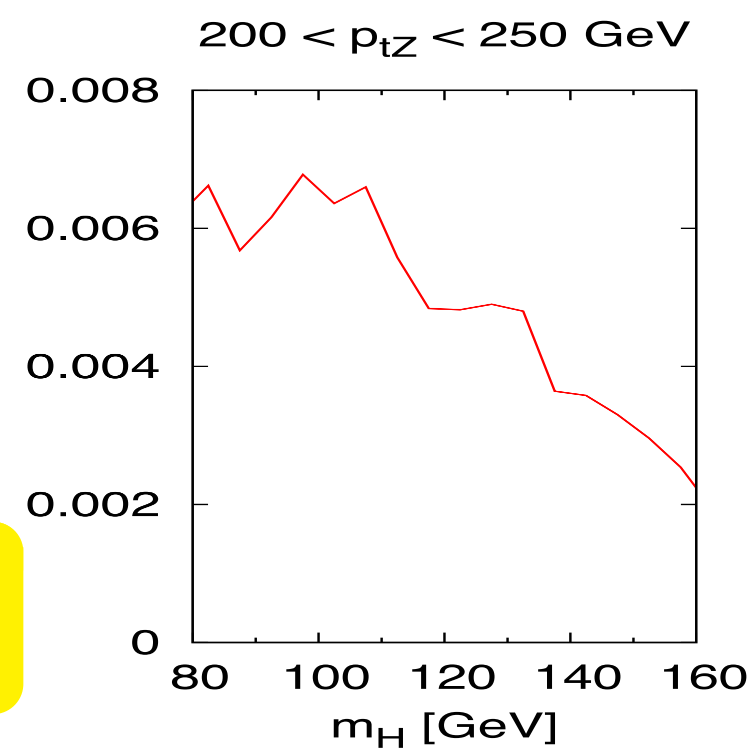

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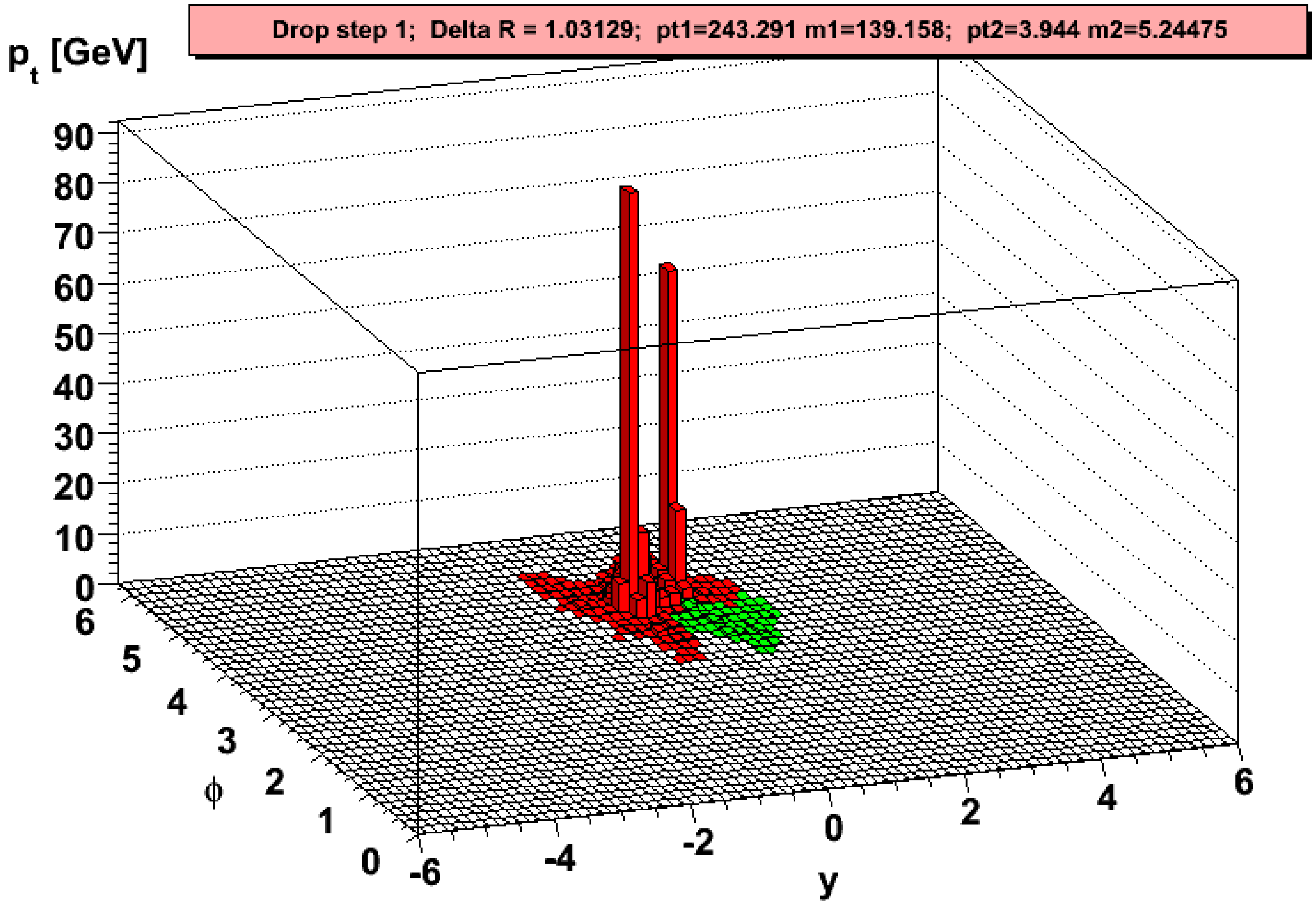
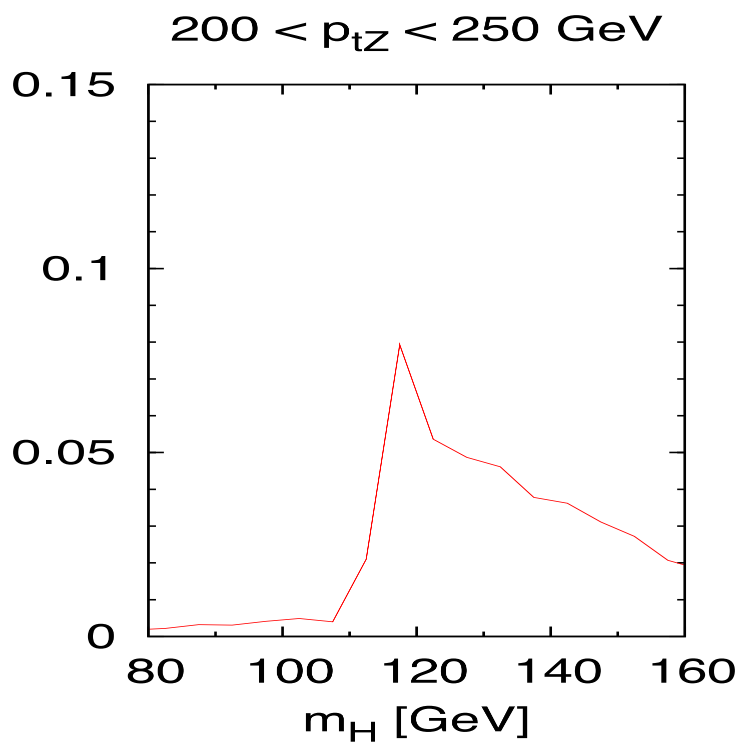
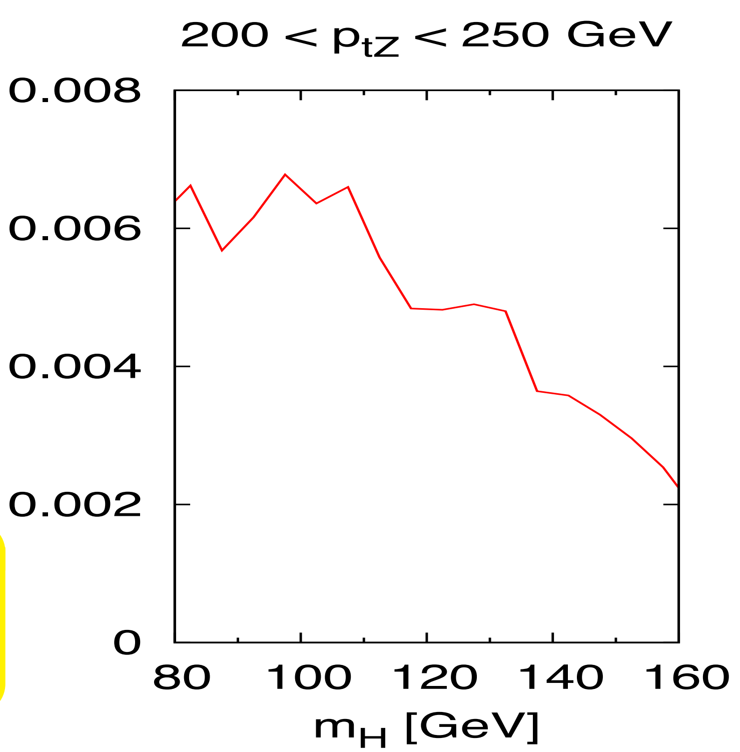


SIGNAL



Zbb BACKGROUND



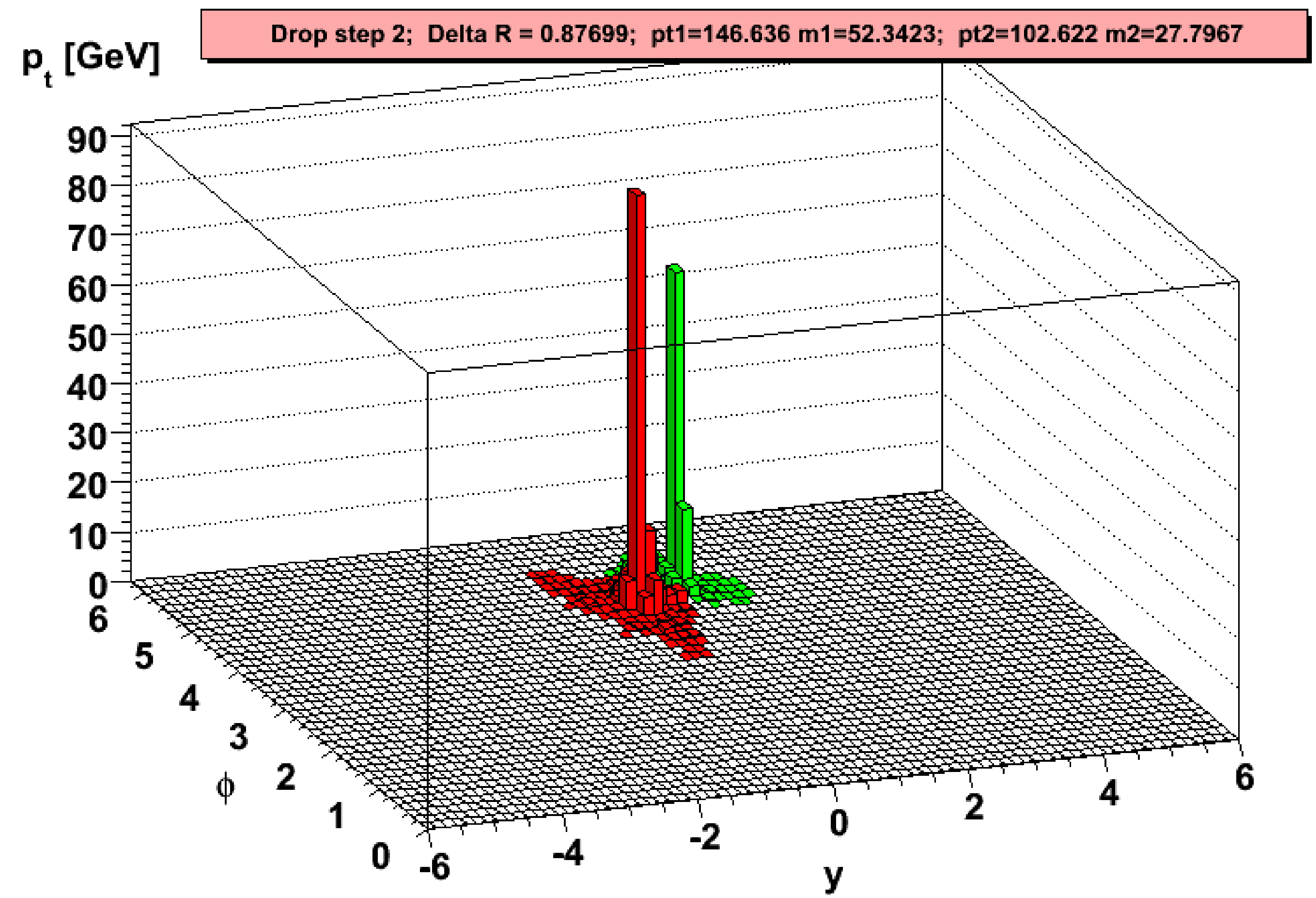
split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

Butterworth, Davison, Rubin & GPS '08

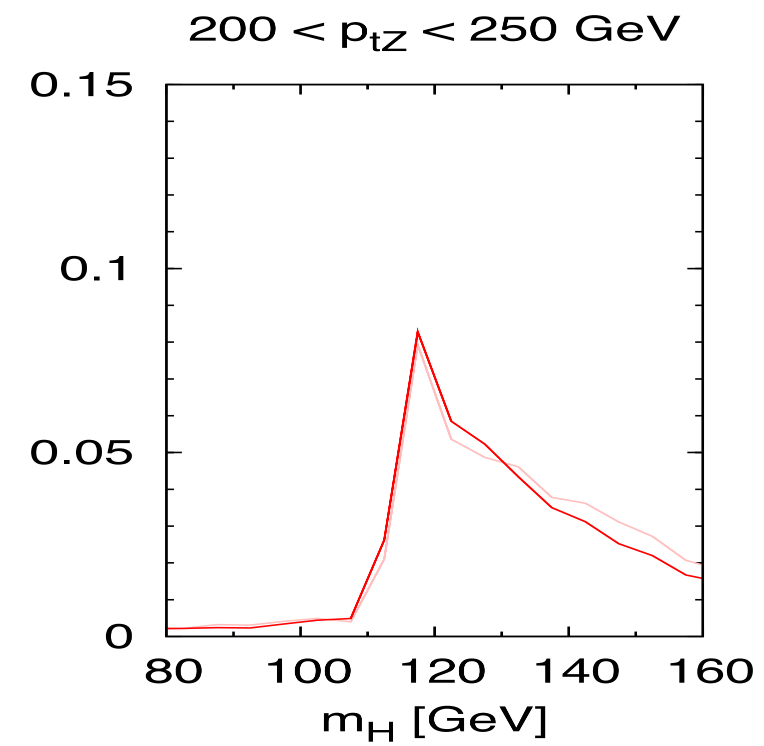
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



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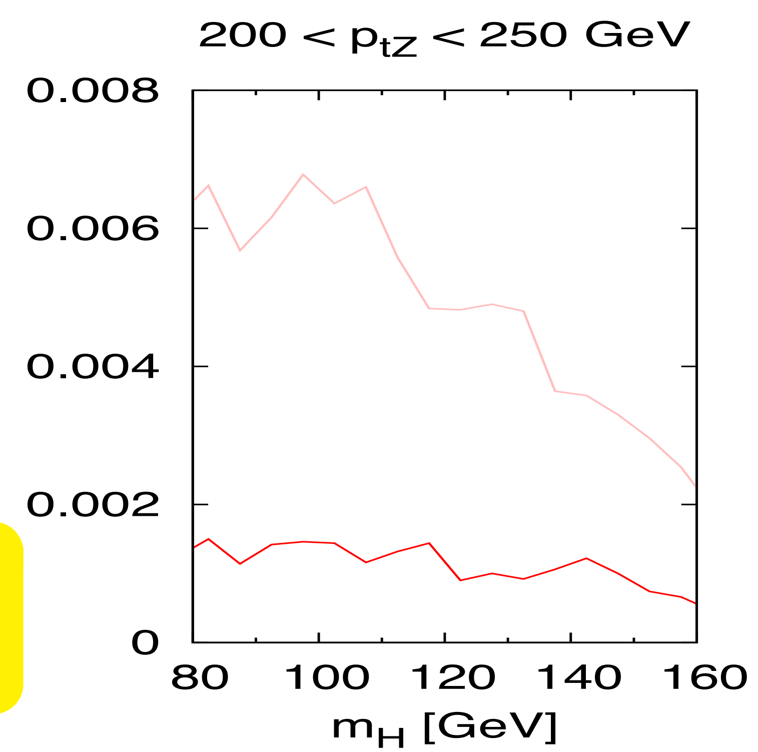


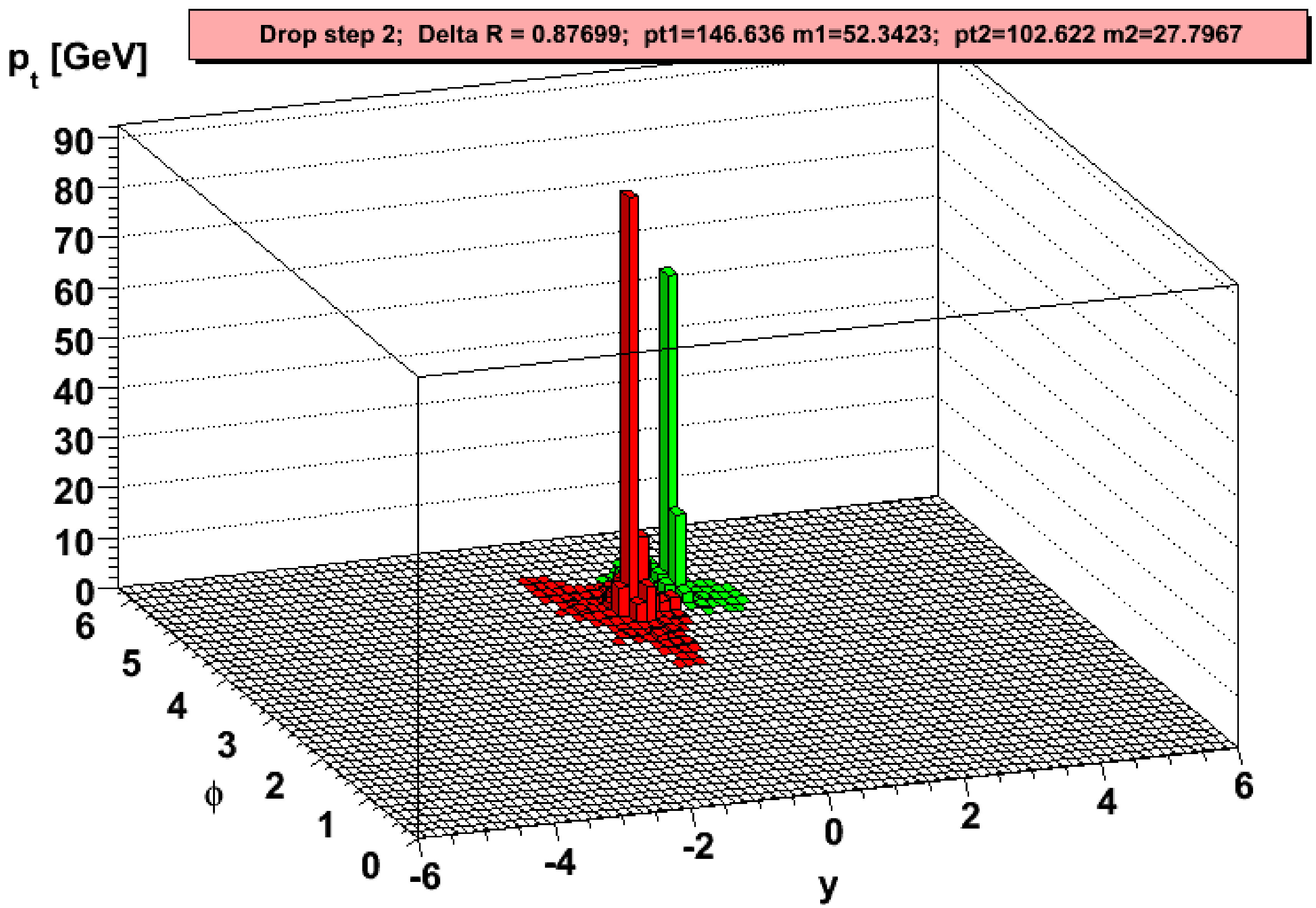
split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

Butterworth, Davison, Rubin & GPS '08

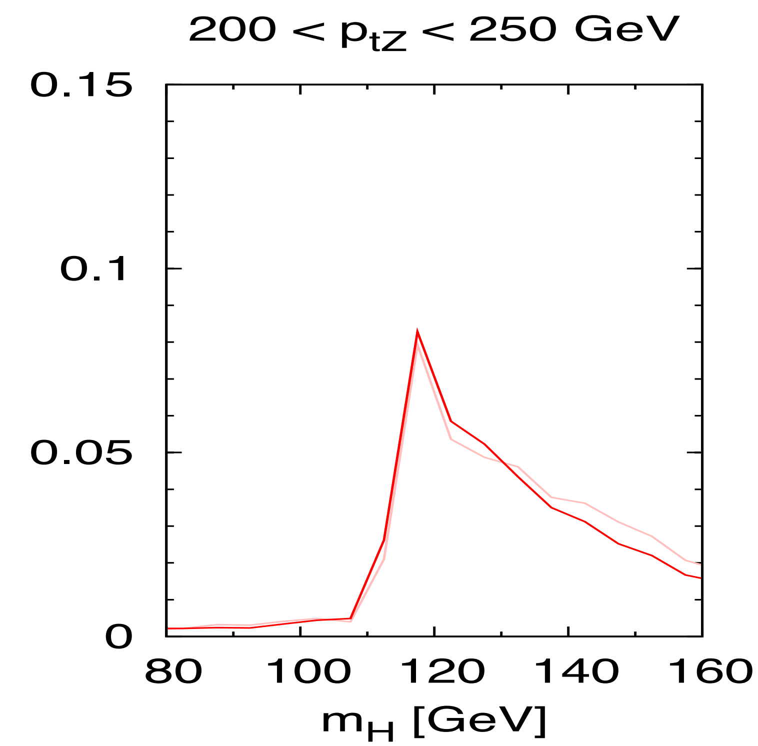
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

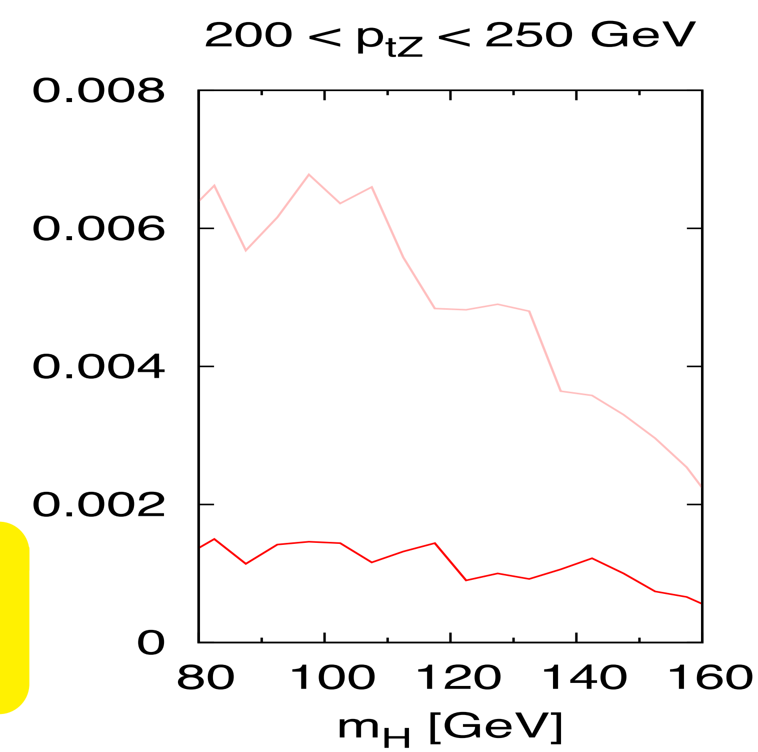
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND



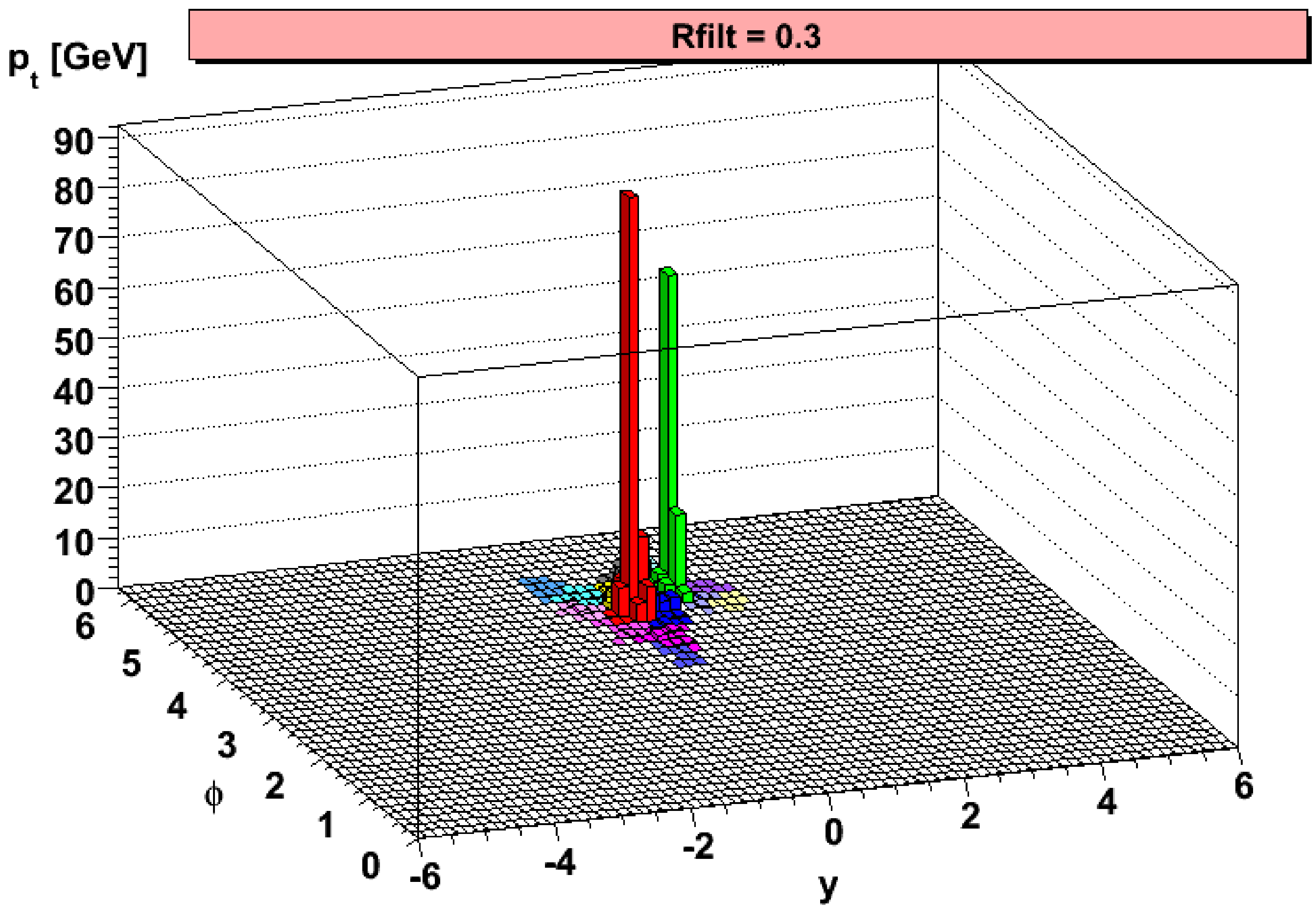
check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

Butterworth, Davison, Rubin & GPS '08

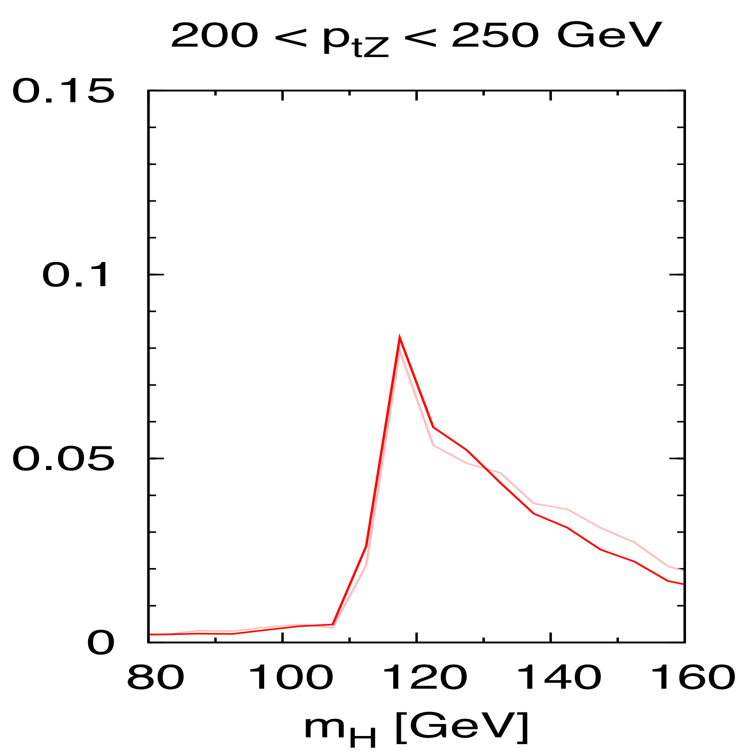
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

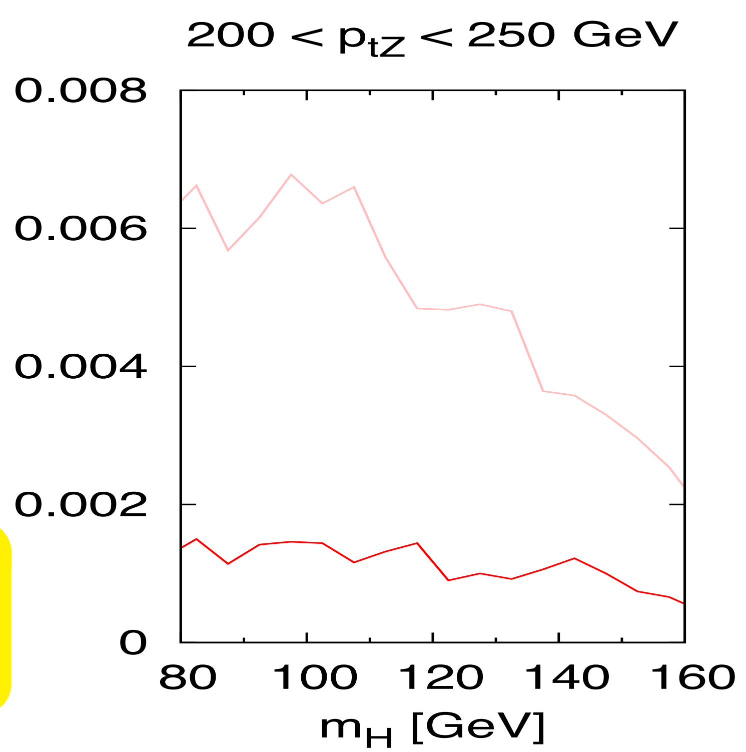
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND



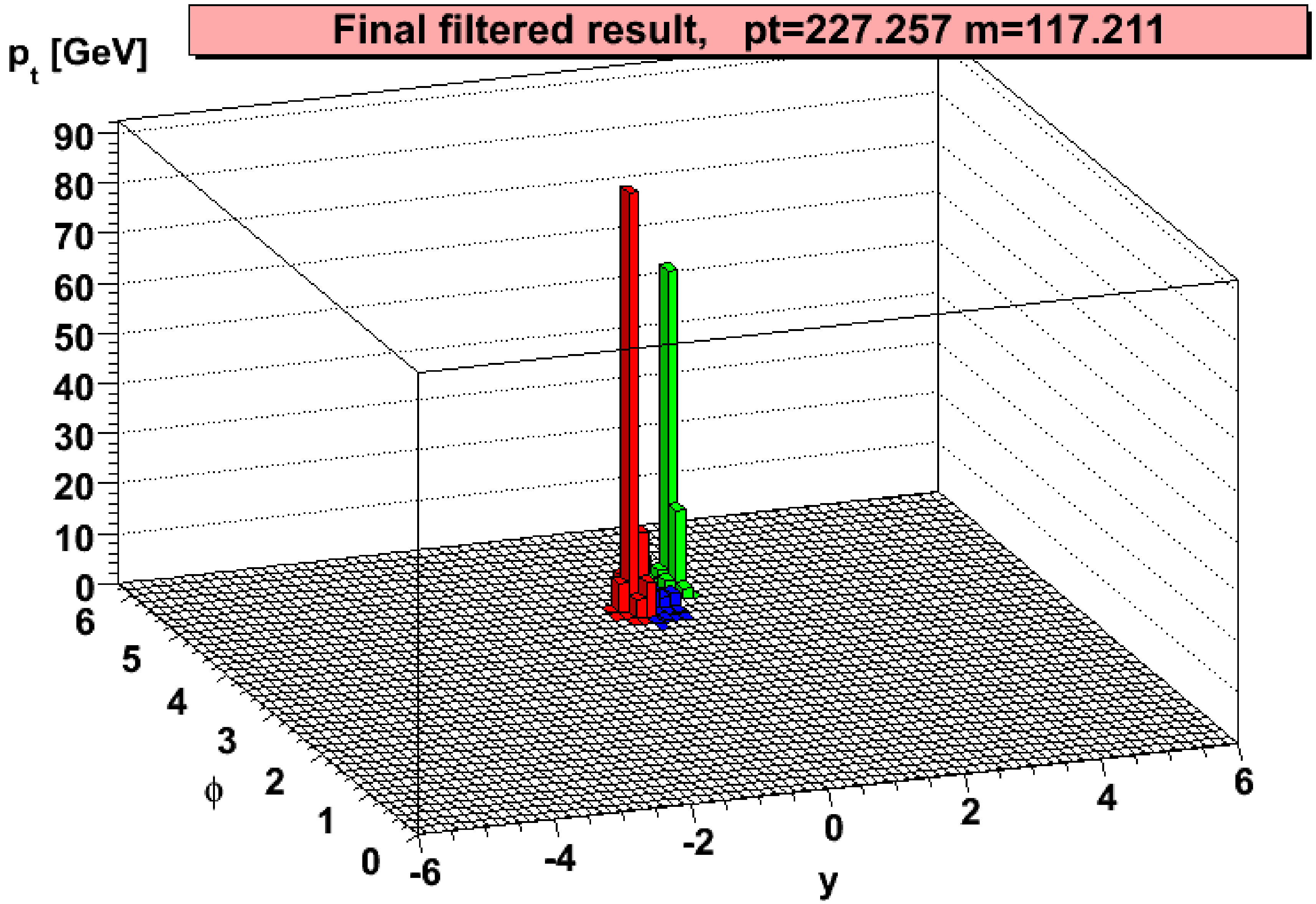
$R_{filt} = 0.3$

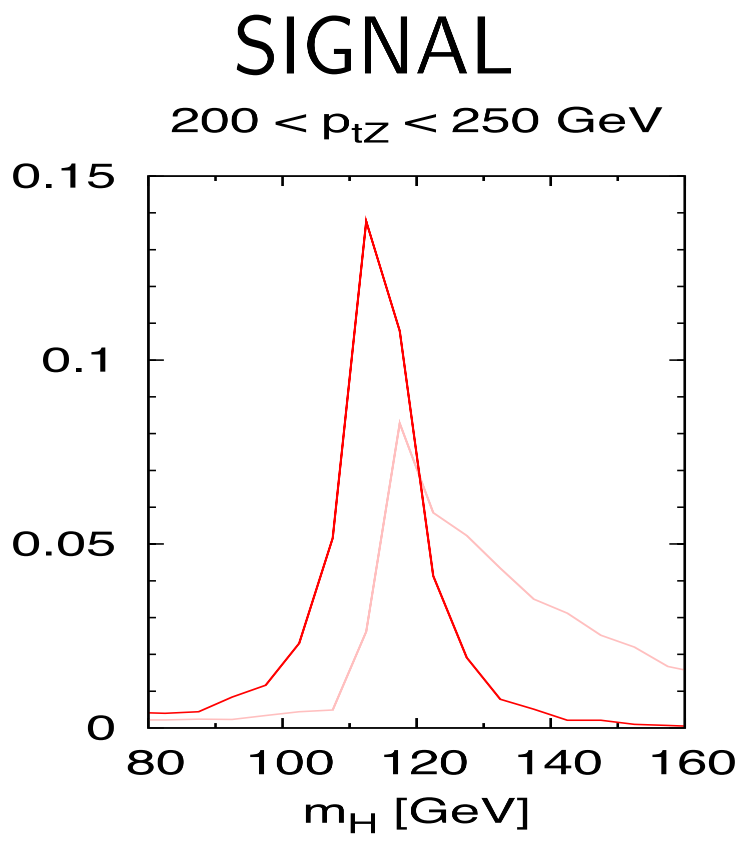
Butterworth, Davison, Rubin & GPS '08

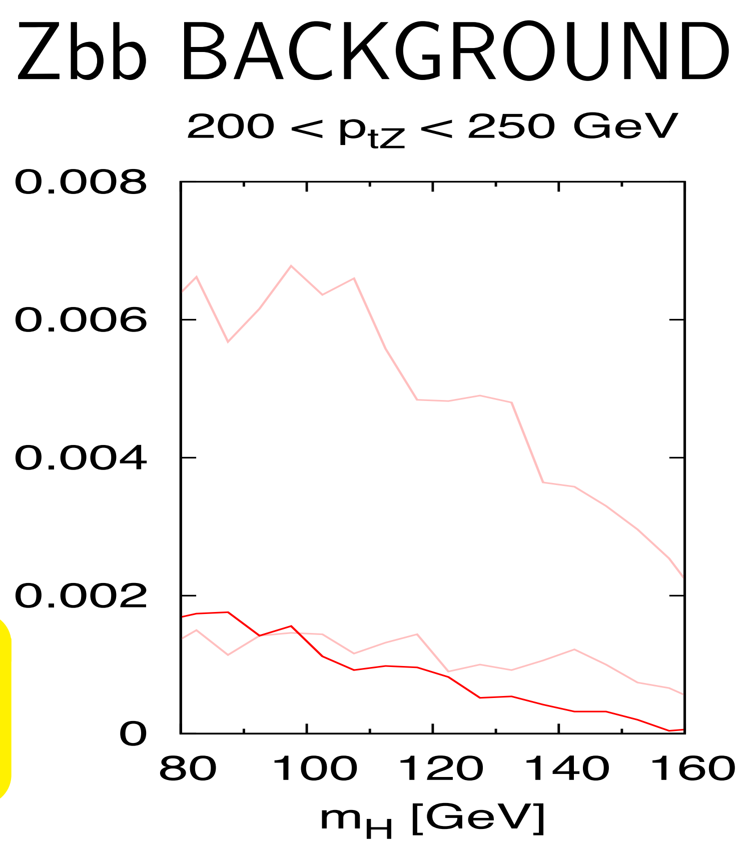
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







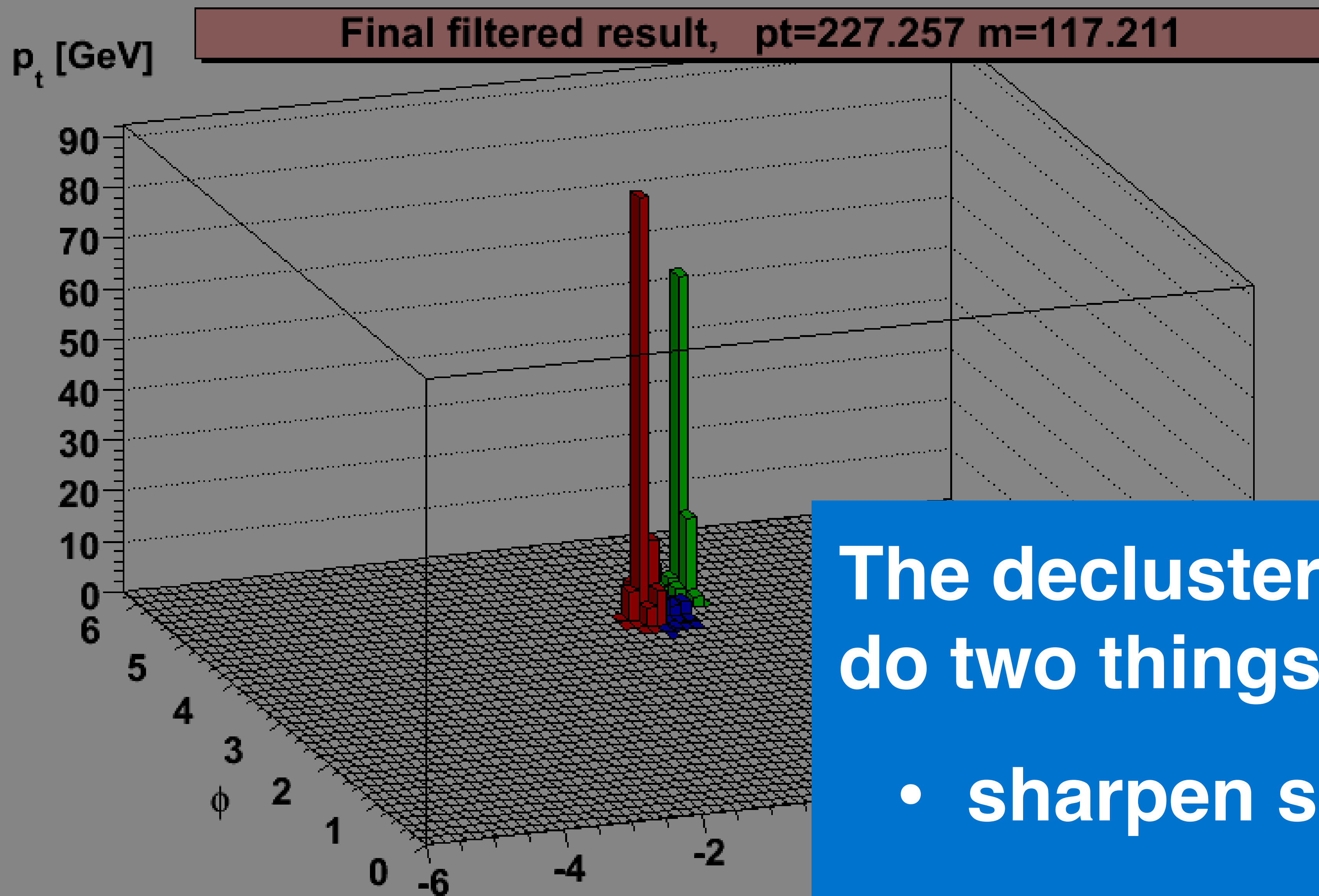
$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

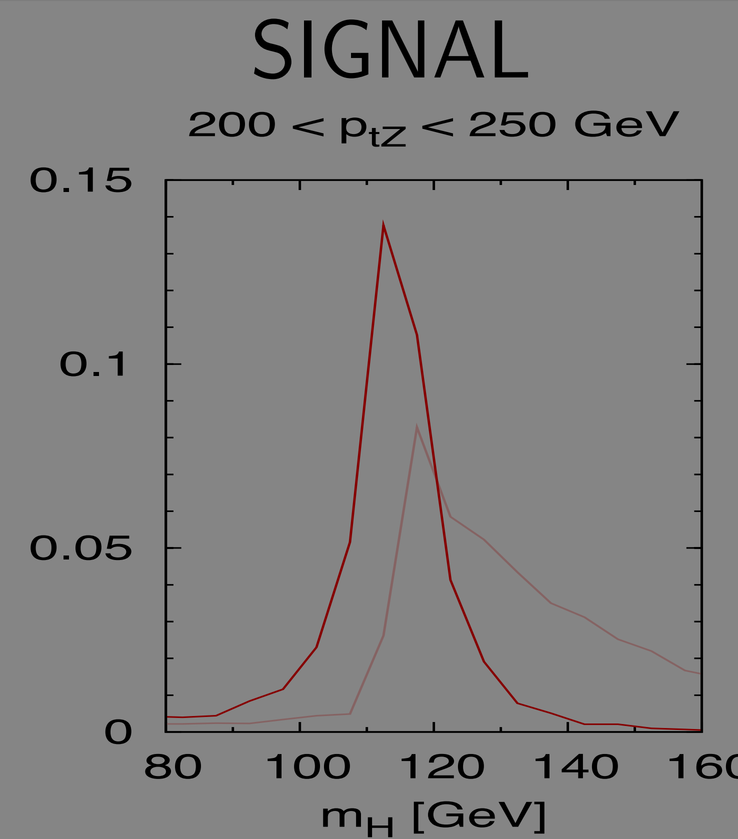
Butterworth, Davison, Rubin & GPS '08

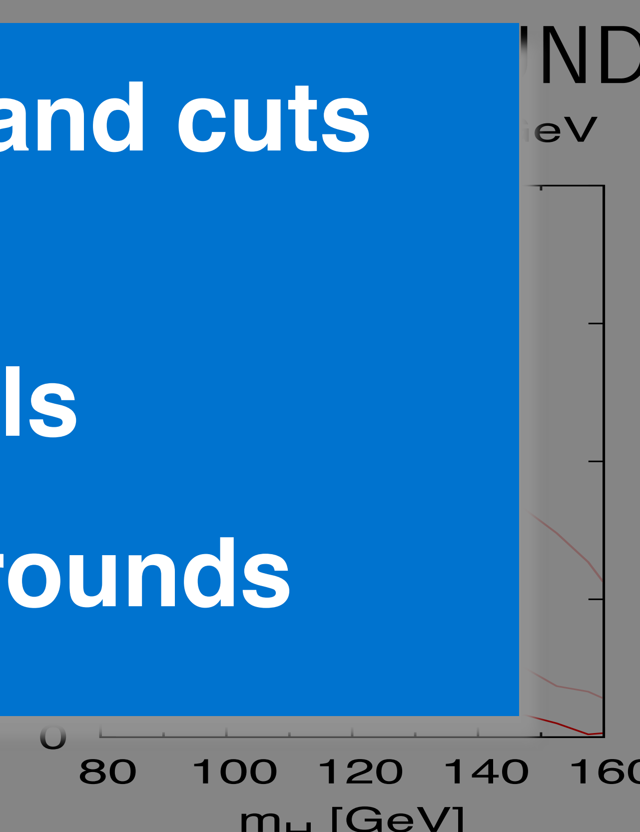
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







The declustering and cuts do two things

- **sharpen signals**
- **reduce backgrounds**

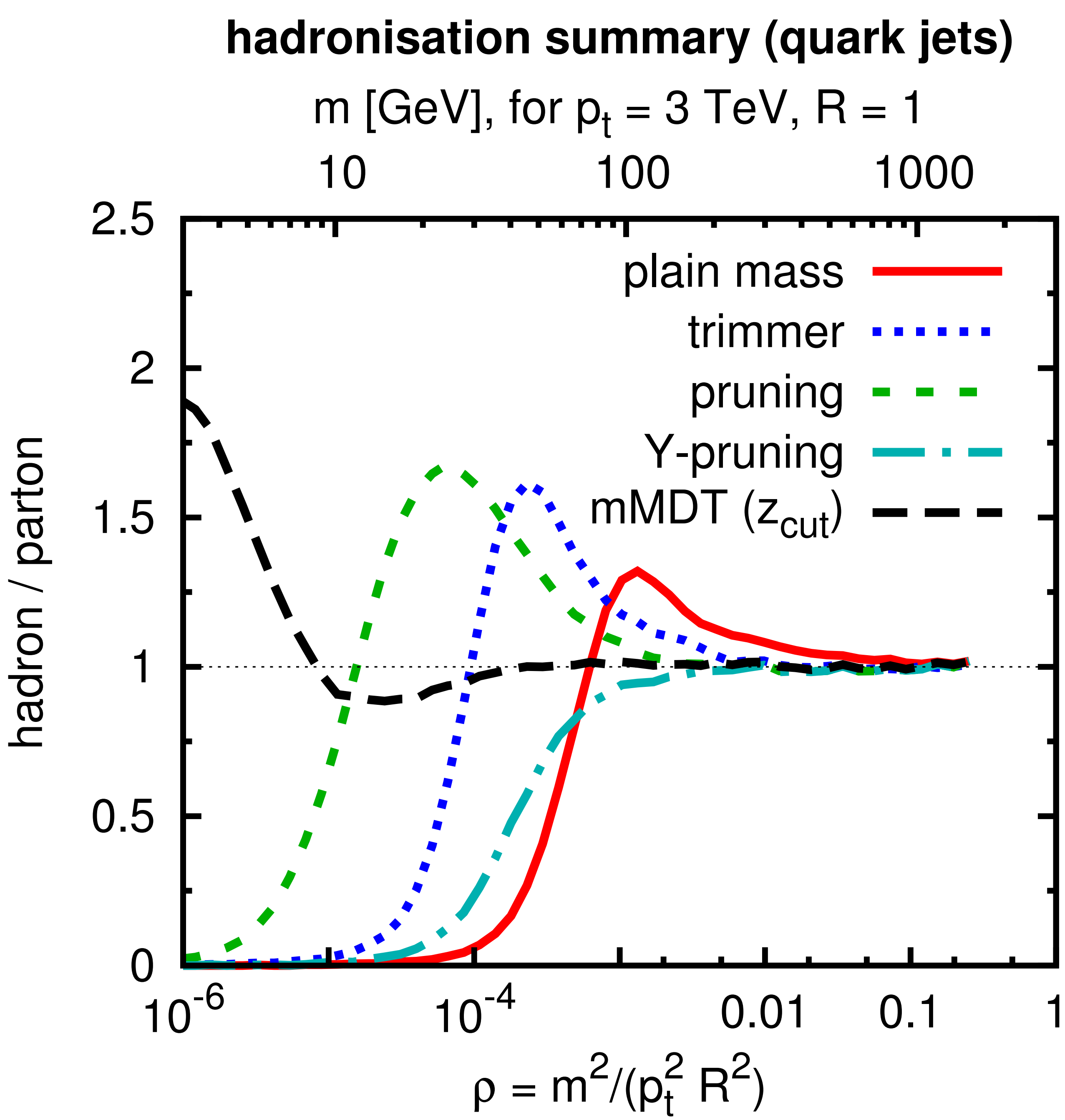
$R_{filt} = 0.3$: take 3 hardest, **m =**

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

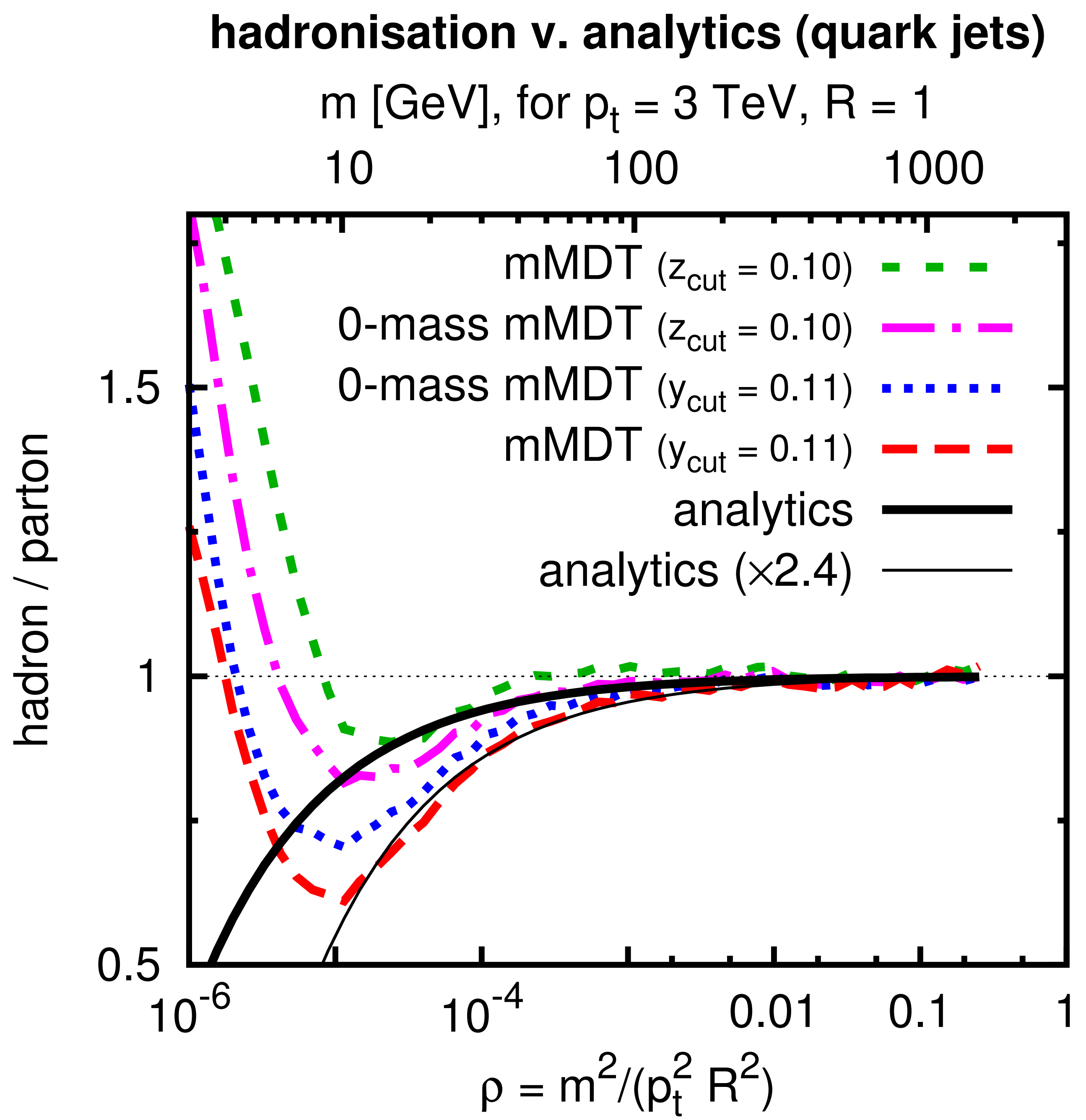
What about non-perturbative effects?

[on 3 TeV jets?!]



Nearly all taggers have large hadronisation effects:

15 – 60%
for m = 30 – 100 GeV



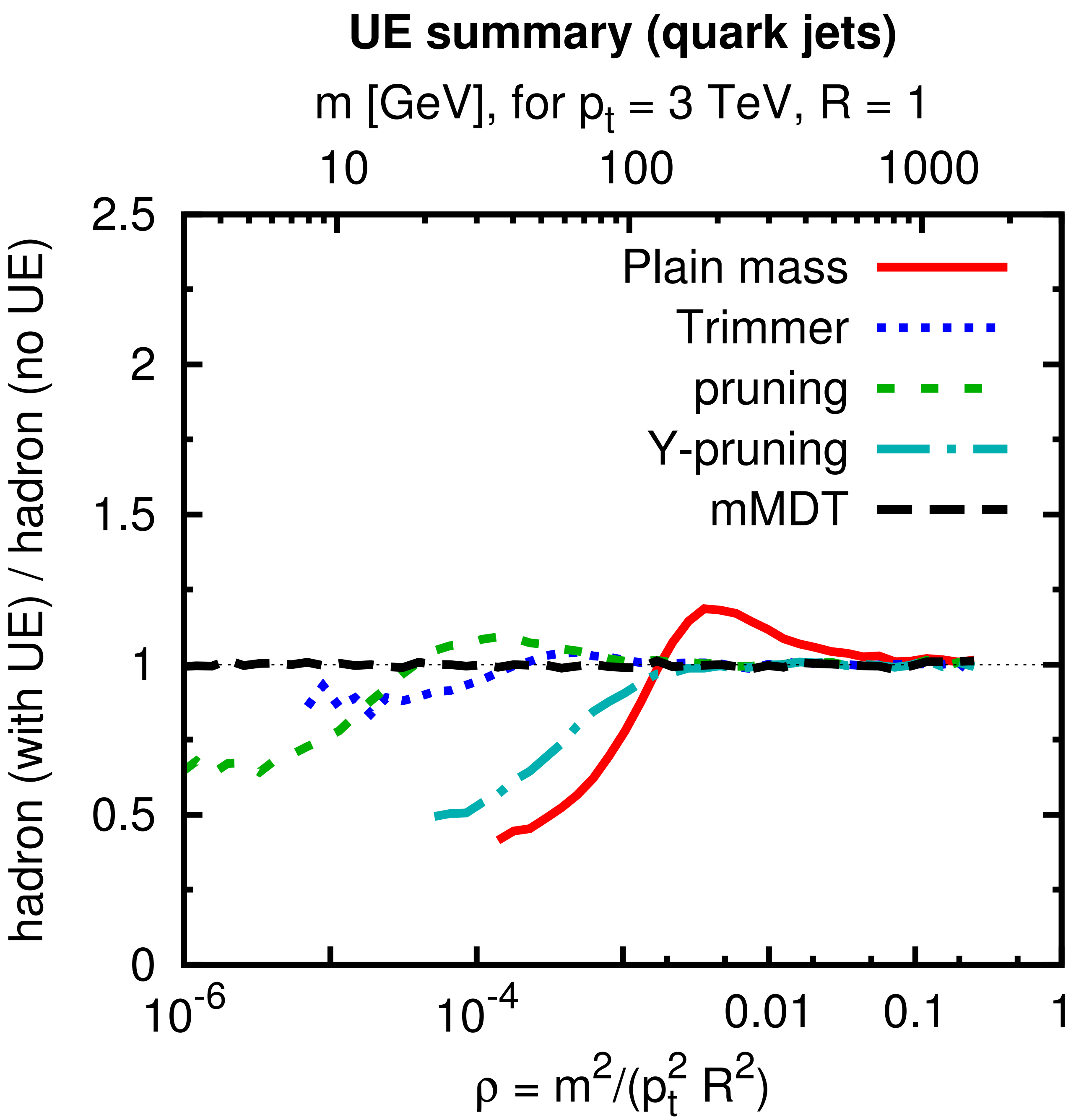
Exception is (m)MDT.

In some cases just few % effect.

m-dependence of hadronisation even understood analytically!

$$\frac{d\sigma}{dm}^{\text{hadron}} \simeq \frac{d\sigma}{dm}^{\text{parton}} \left(1 - c\frac{\Lambda}{m}\right)$$

Underlying Event (UE)



Underlying event impact much reduced relative to jet mass

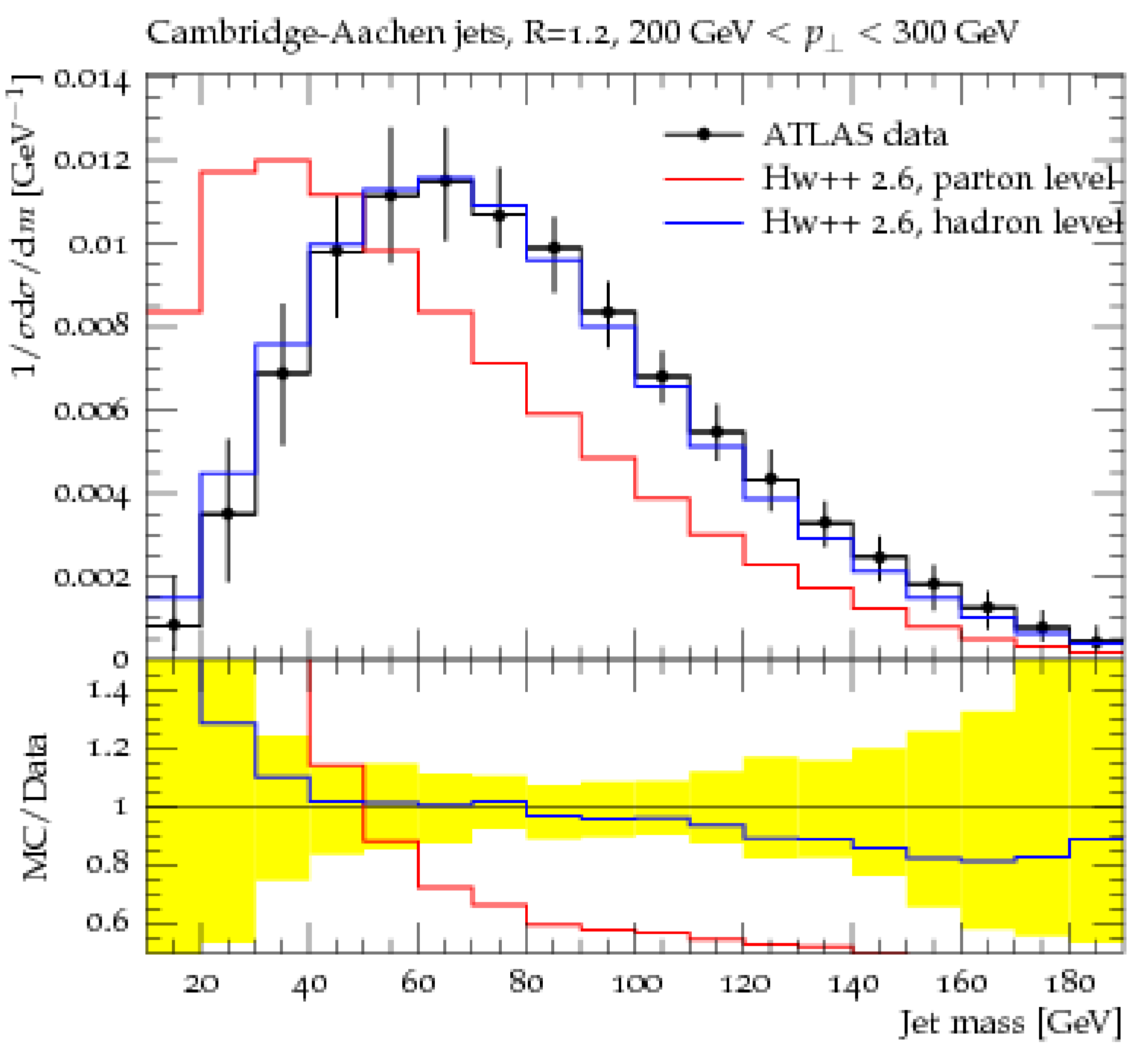
Almost zero for mMDT (this depends on jet p_t)

mMDT phenomenology

ATLAS measurment of the jet mass with MDT [JHEP 1205 (2012)]

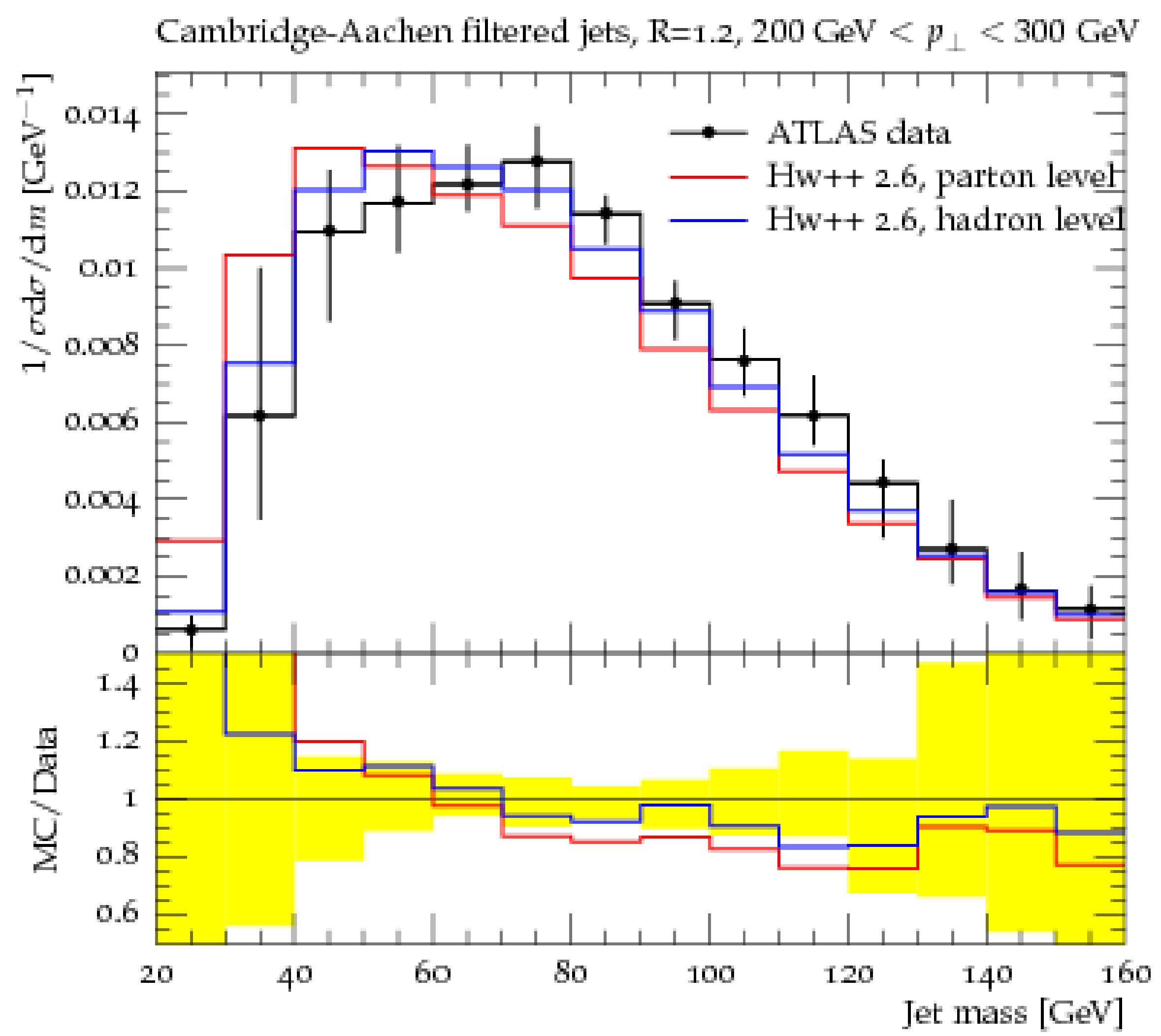
Hadronization + MPI effects

Plain Mass



significant effcts

ATLAS MDT



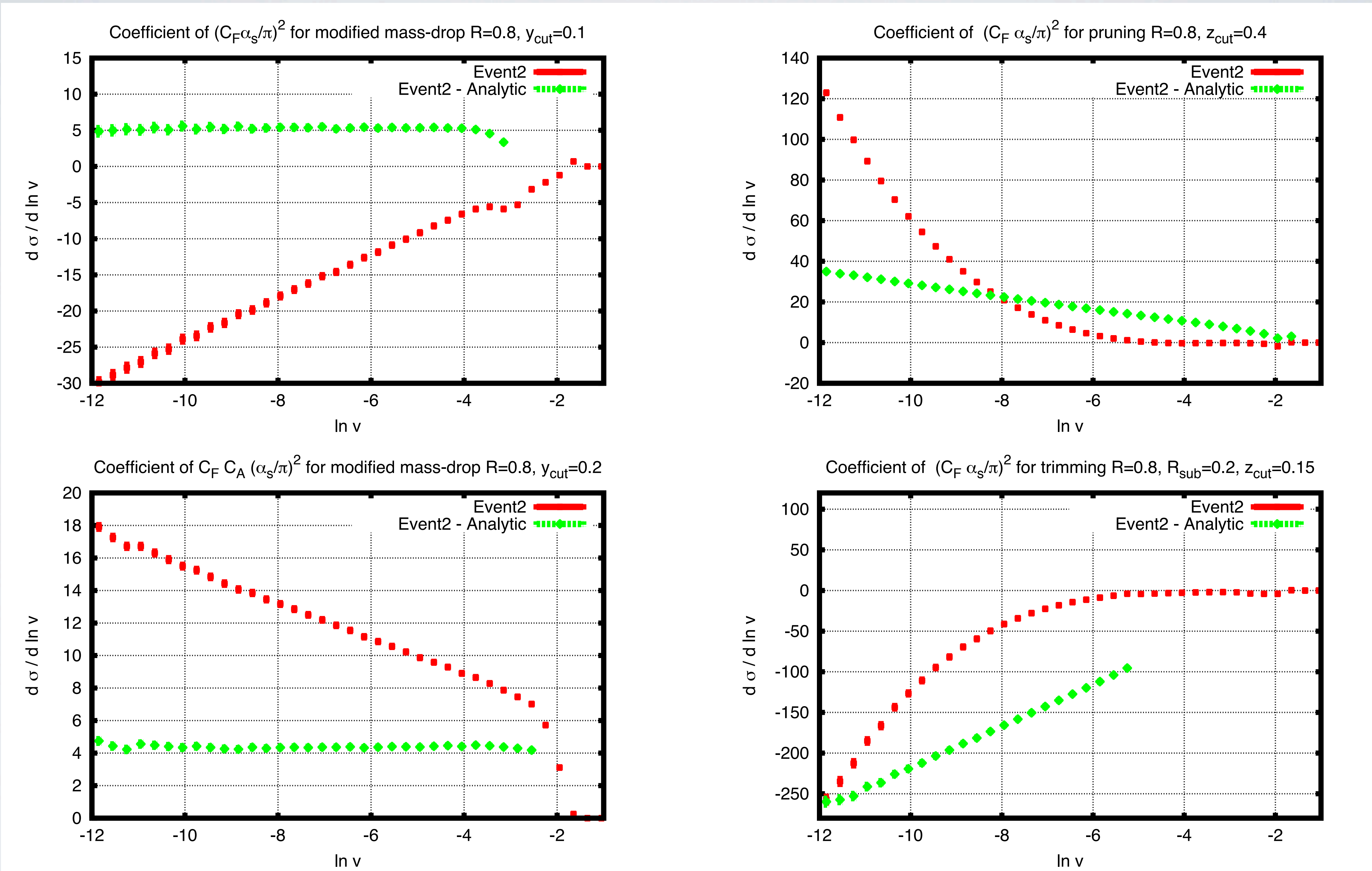
visible effcts (small m)

red line – parton level
blue line – hadron level

mMDT – not very sensitive to hadronization!

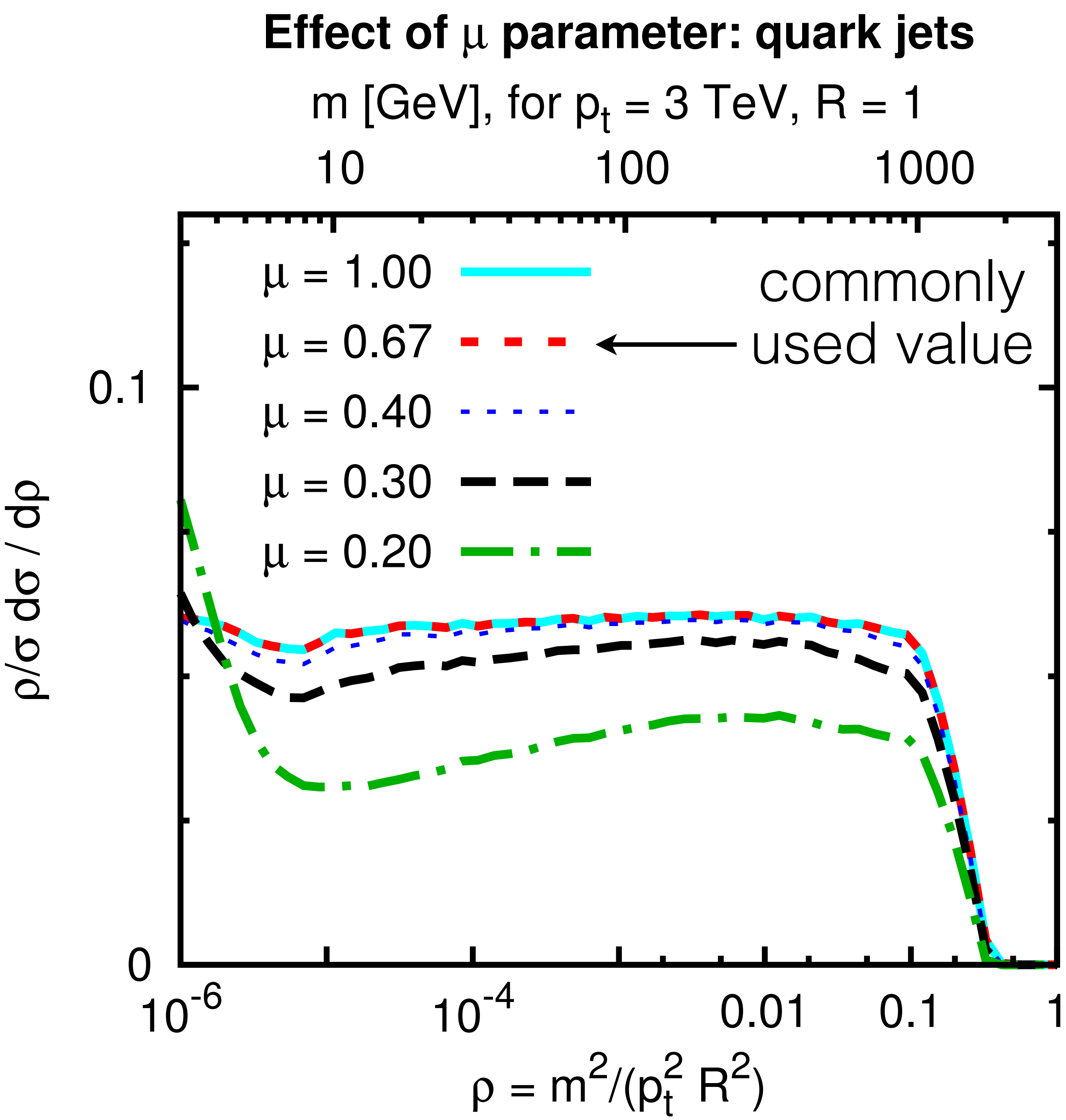
Dasgupta, Siodmok & Powling, in prep.

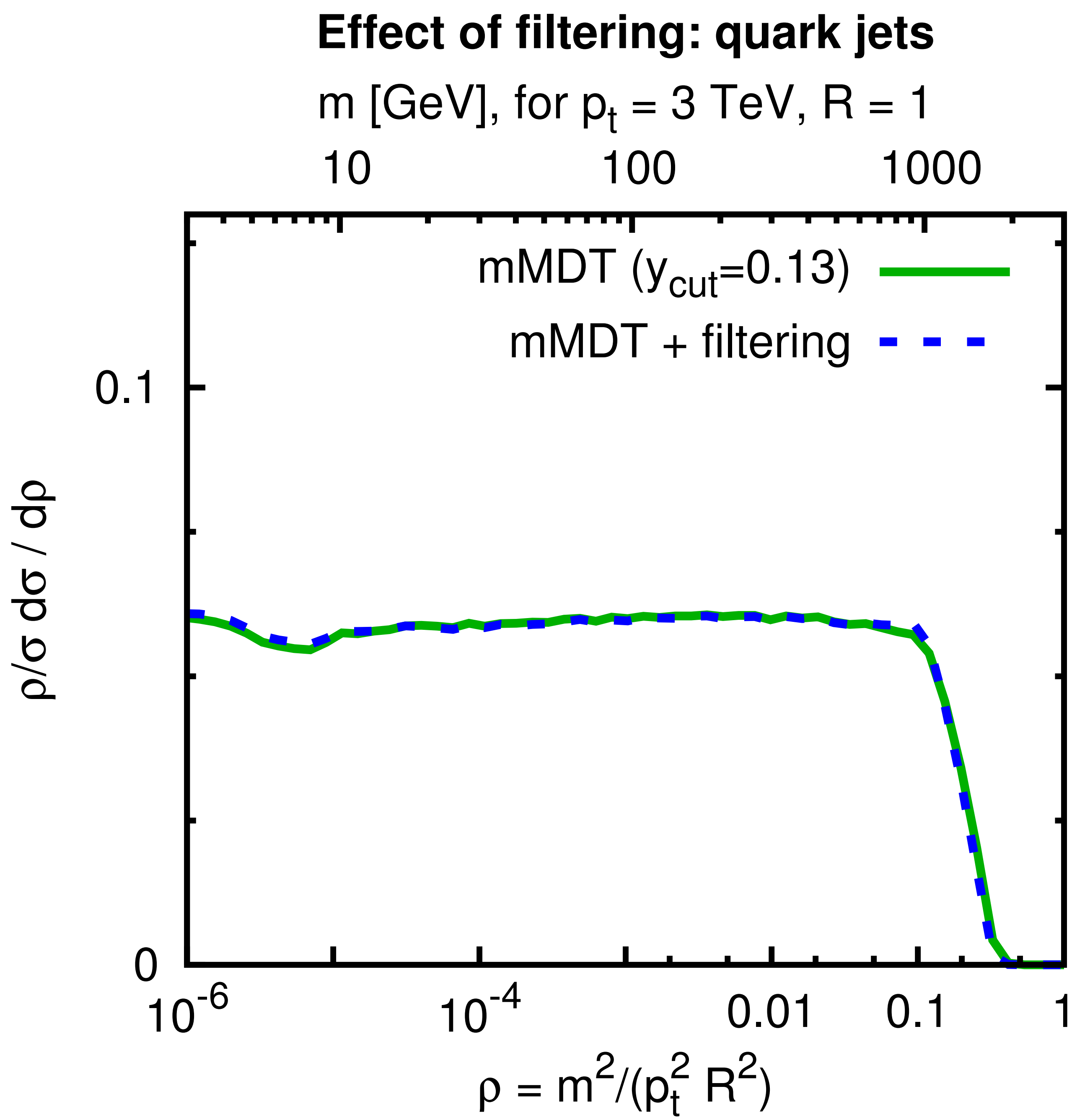
Examples of NLO checks



Dasgupta, Fregoso, Marzani & Powling, 1307.0013

mMDT: impact of μ and of filtering





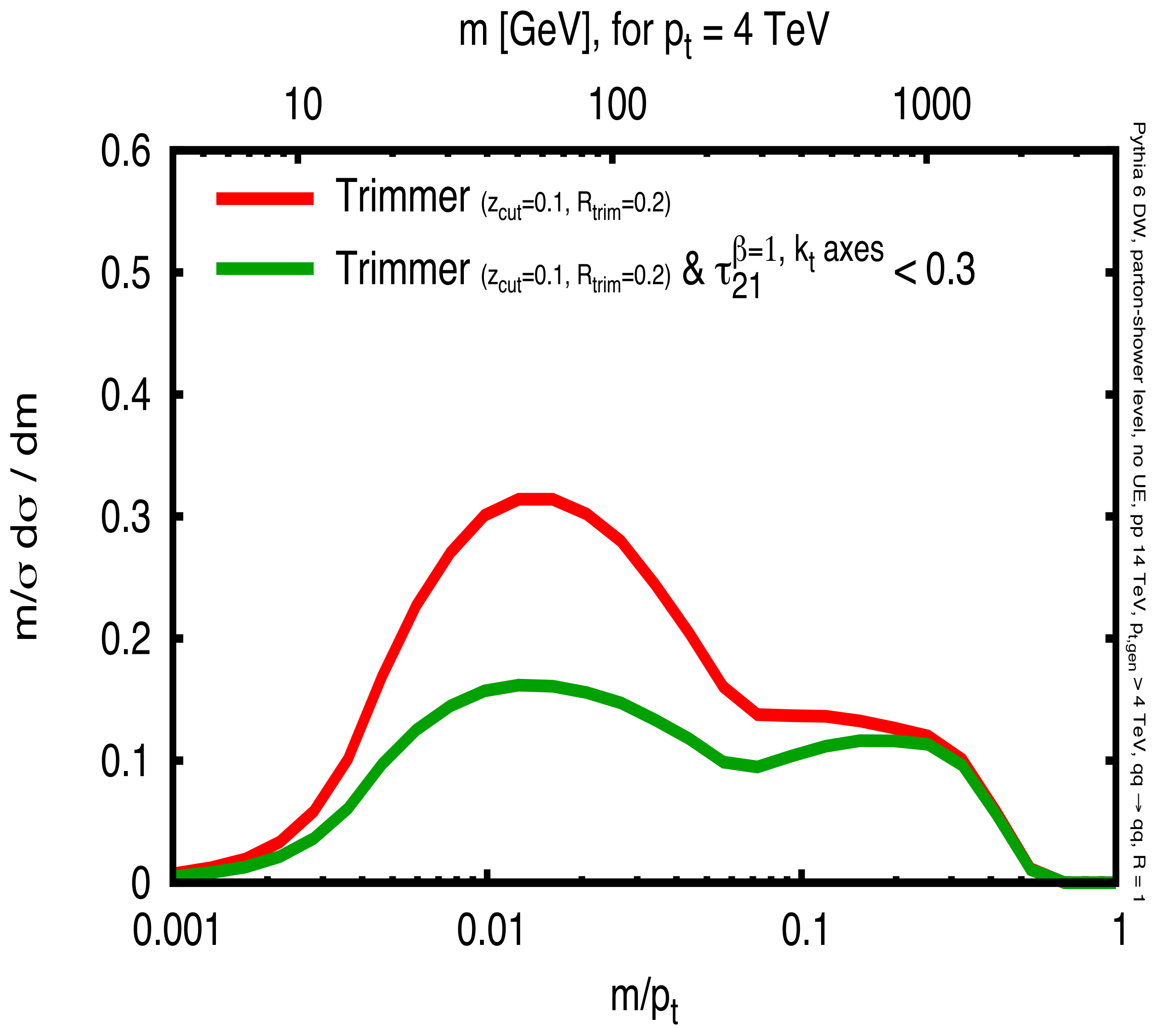
μ parameter basically irrelevant (simpler tagger discards it)

filtering leaves results unchanged (up to and incl. NNLL)

What about cuts on shapes/radiation

E.g. cuts on N-subjettiness, tight mass drop, etc.?

- These cuts are nearly always for a jet whose mass is somehow groomed. All the structure from the grooming persists.
- So tagging & shape must probably be calculated together



Pruning

Ellis, Vermillion & Walsh '09

Take a jet and define

$$R_{\text{prune}} = m / p_t$$

Recluster with k_t or C/A alg.
At each i+j clustering step, if

$$p_{ti} \text{ or } p_{tj} < z_{\text{cut}}\, p_{t(i+j)\text{asdf}}$$

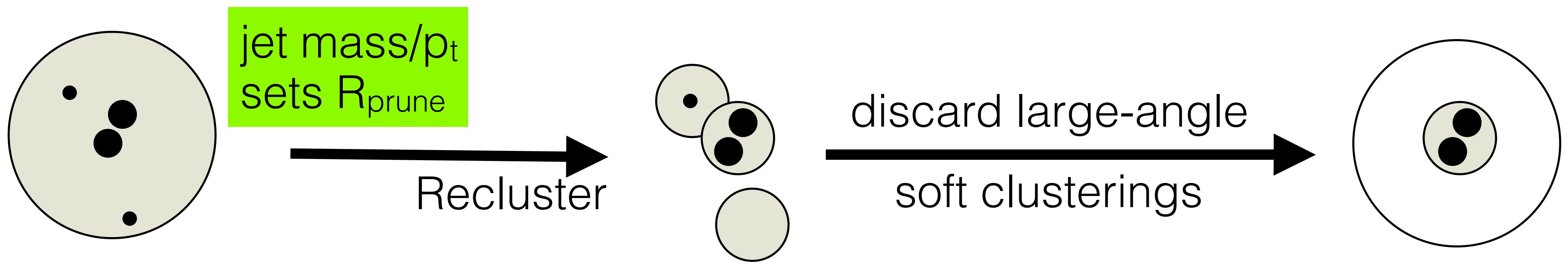
$$\Delta R_{ij} > R_{\text{prune}}$$

discard softer prong.

Acts similarly to filtering, but with **dynamic subjet radius**

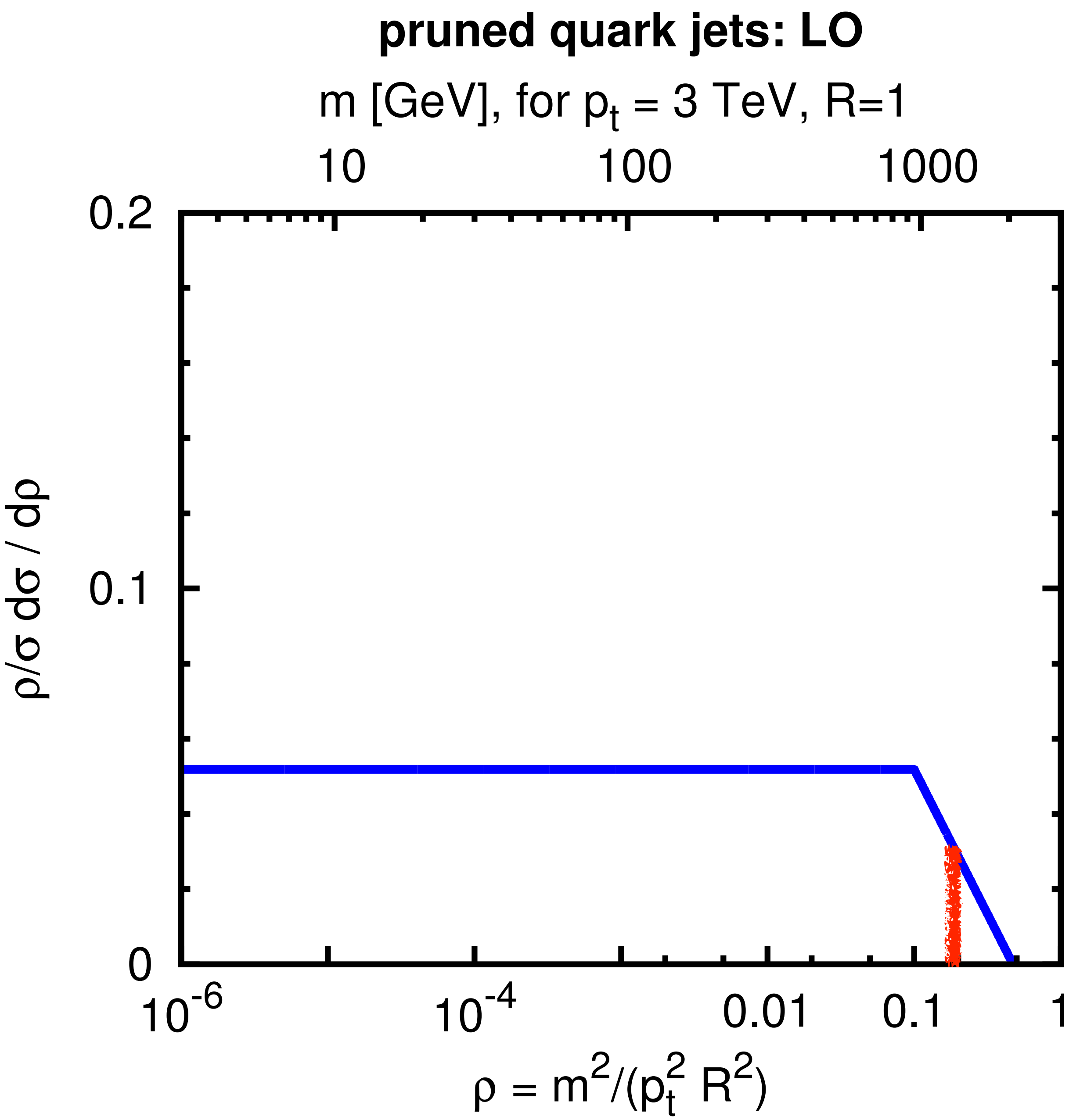
one (main) parameter: z_{cut}

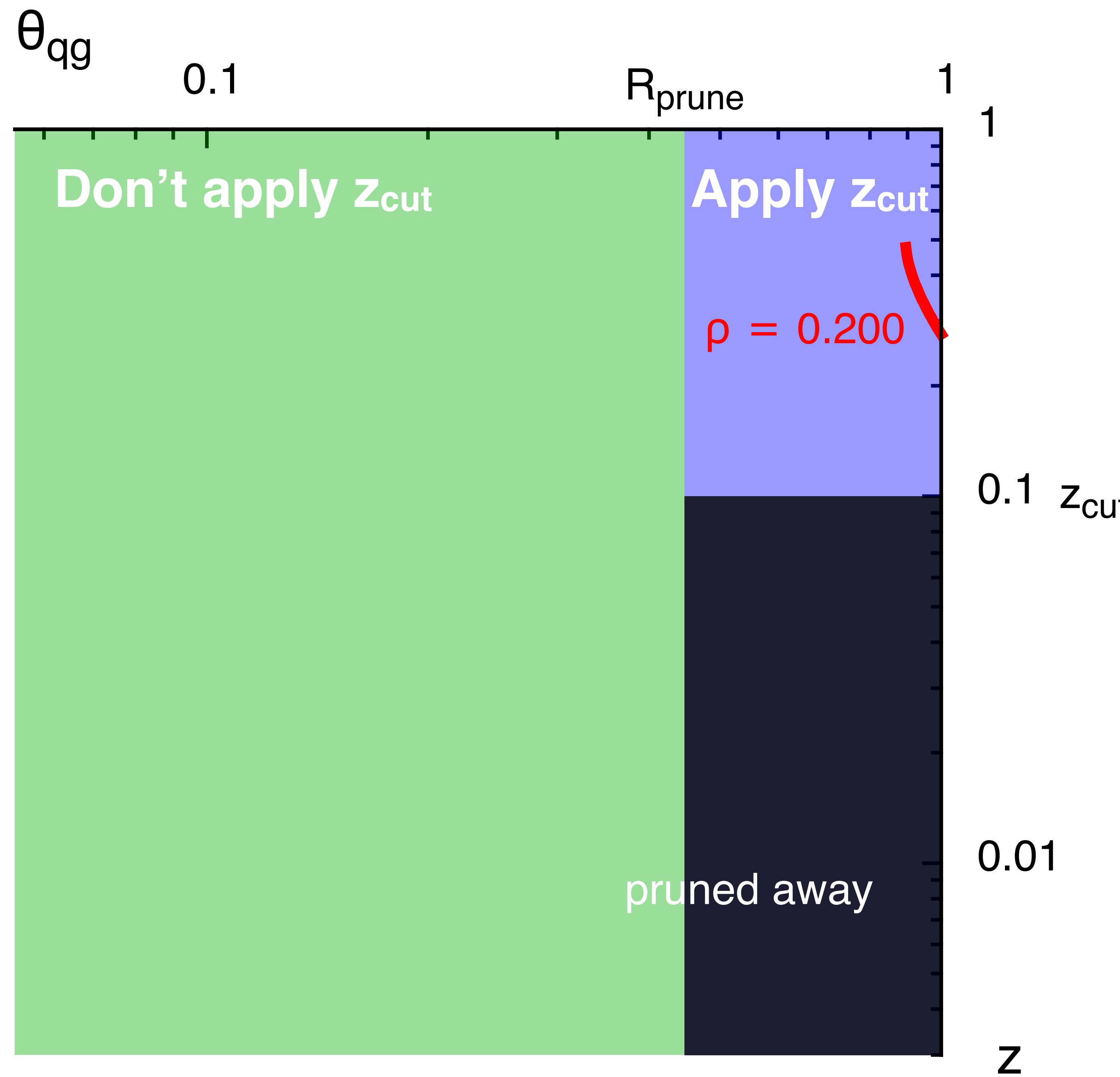
we'll study variant with C/A reclustering



Pruning at LO

Dynamical choice of R_{prune} means that two prongs are always separated by > R_{prune}. So, unlike trimming, z_{cut} always applied.





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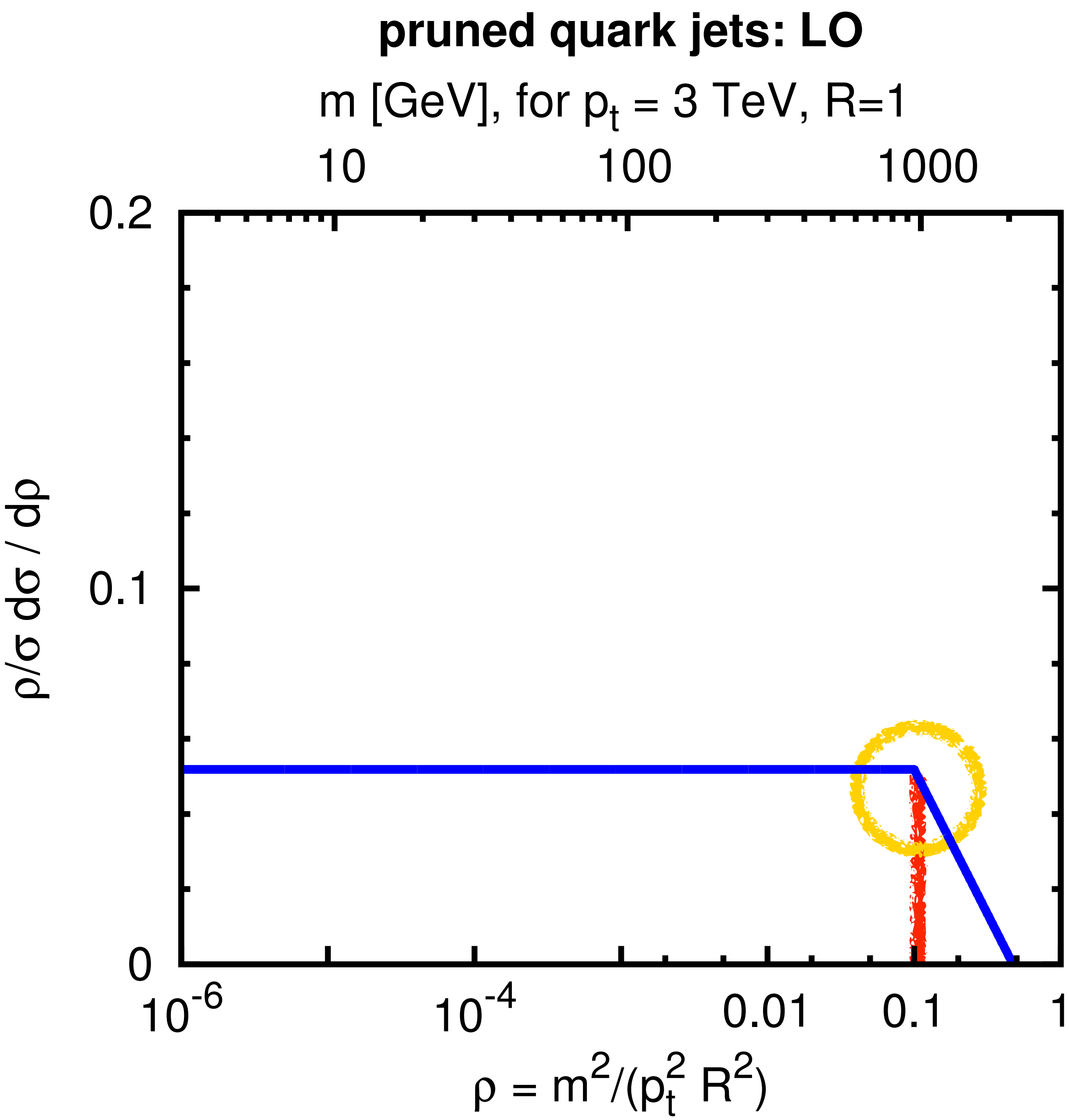

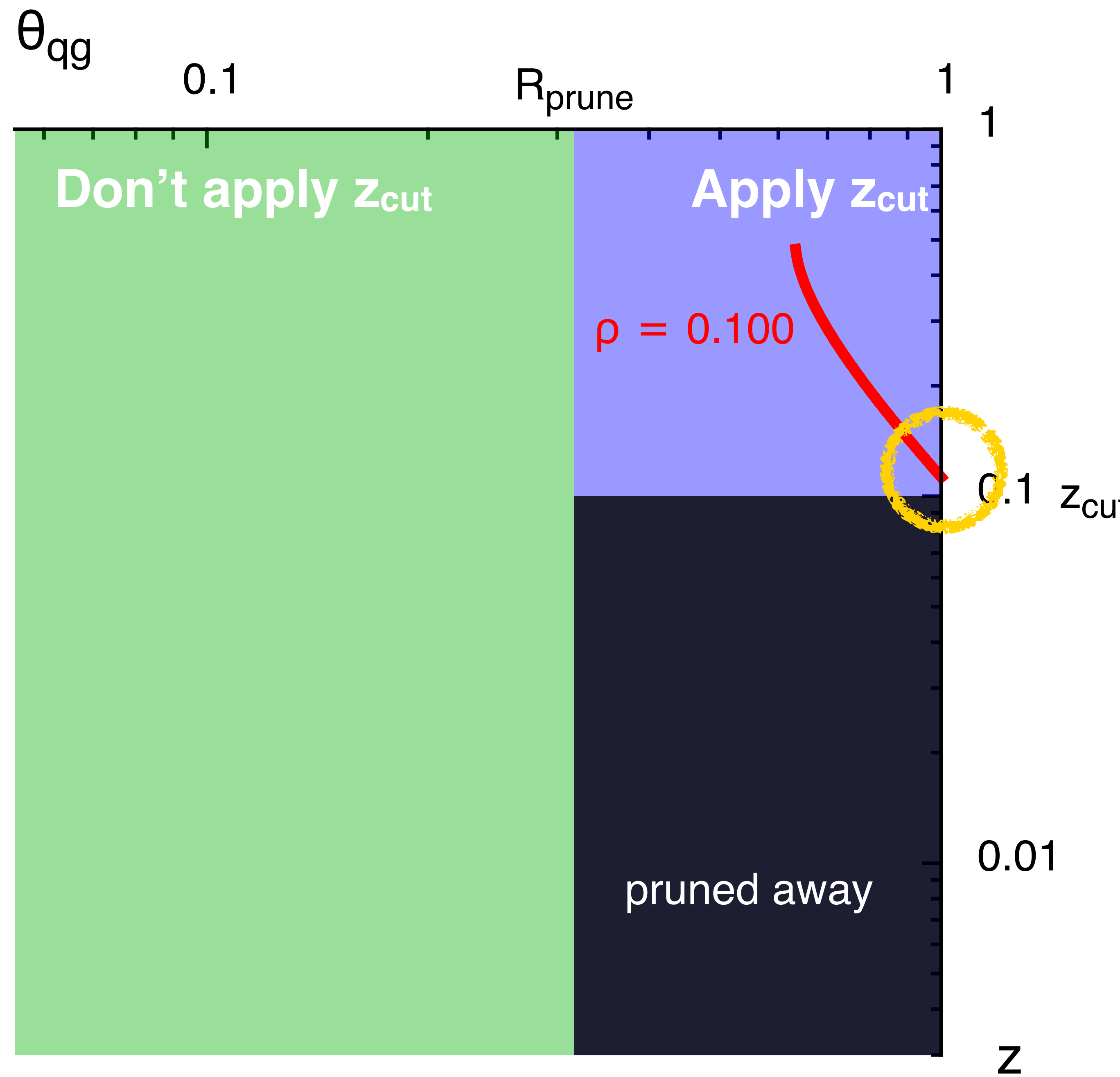

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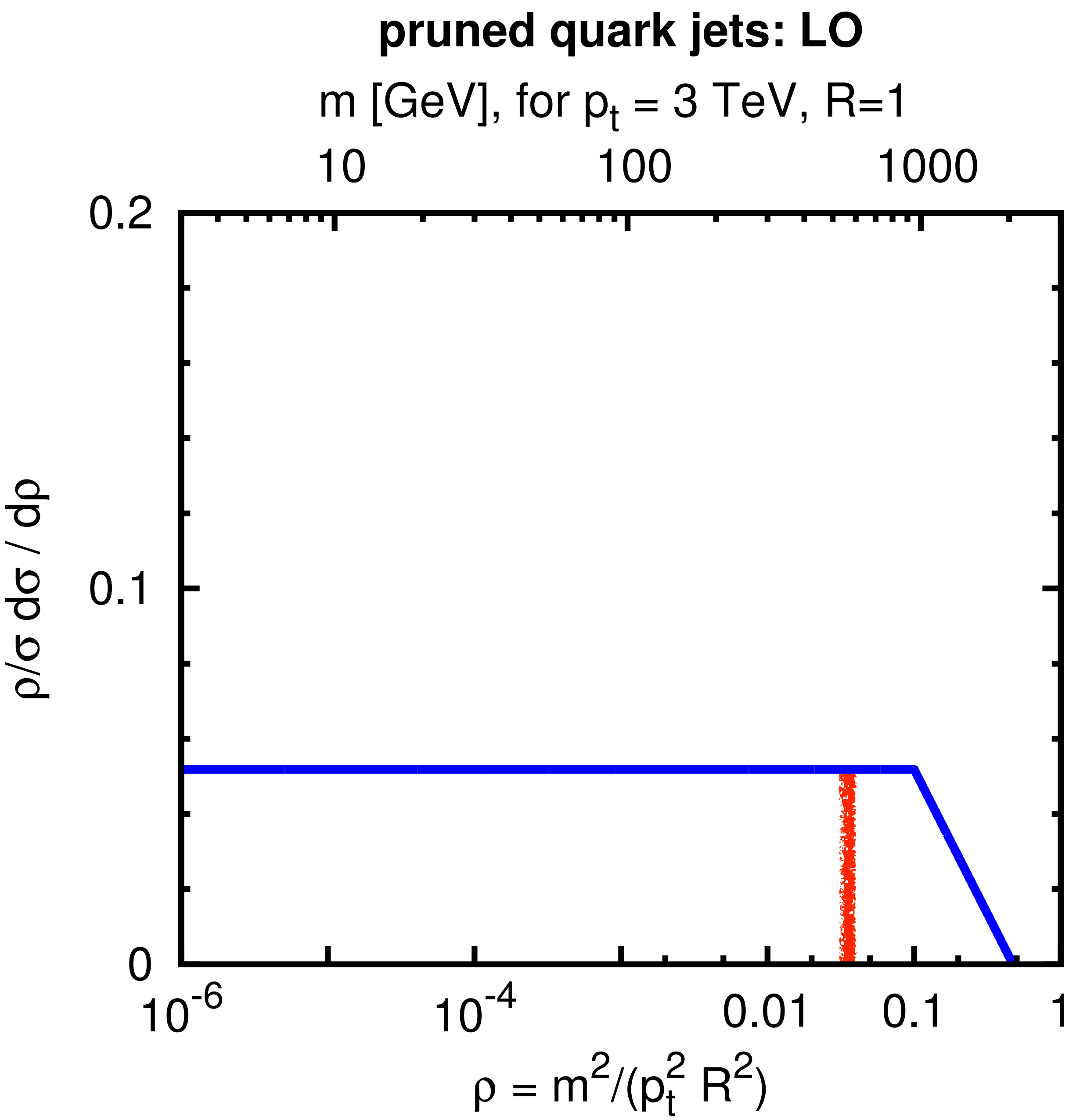

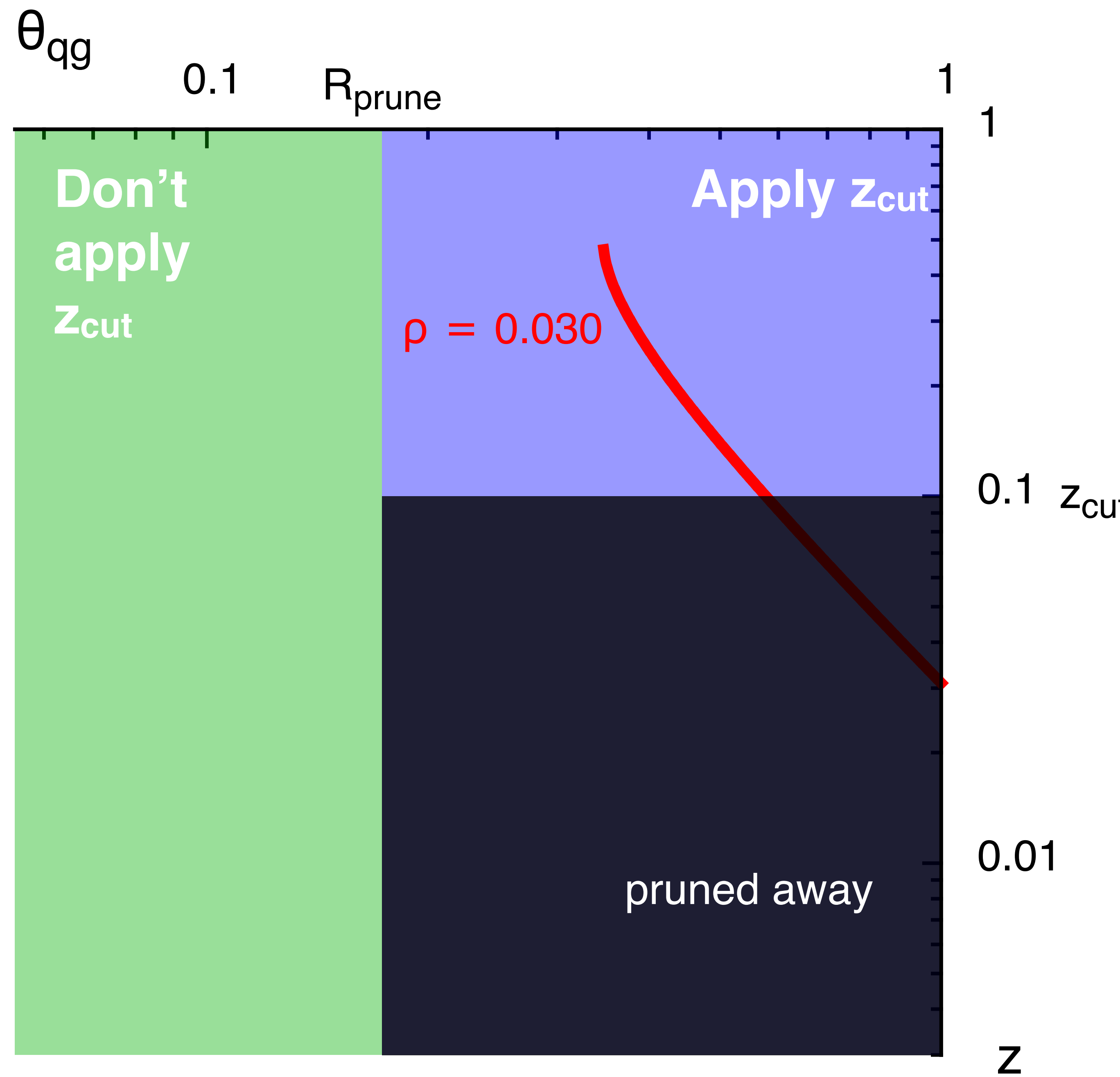

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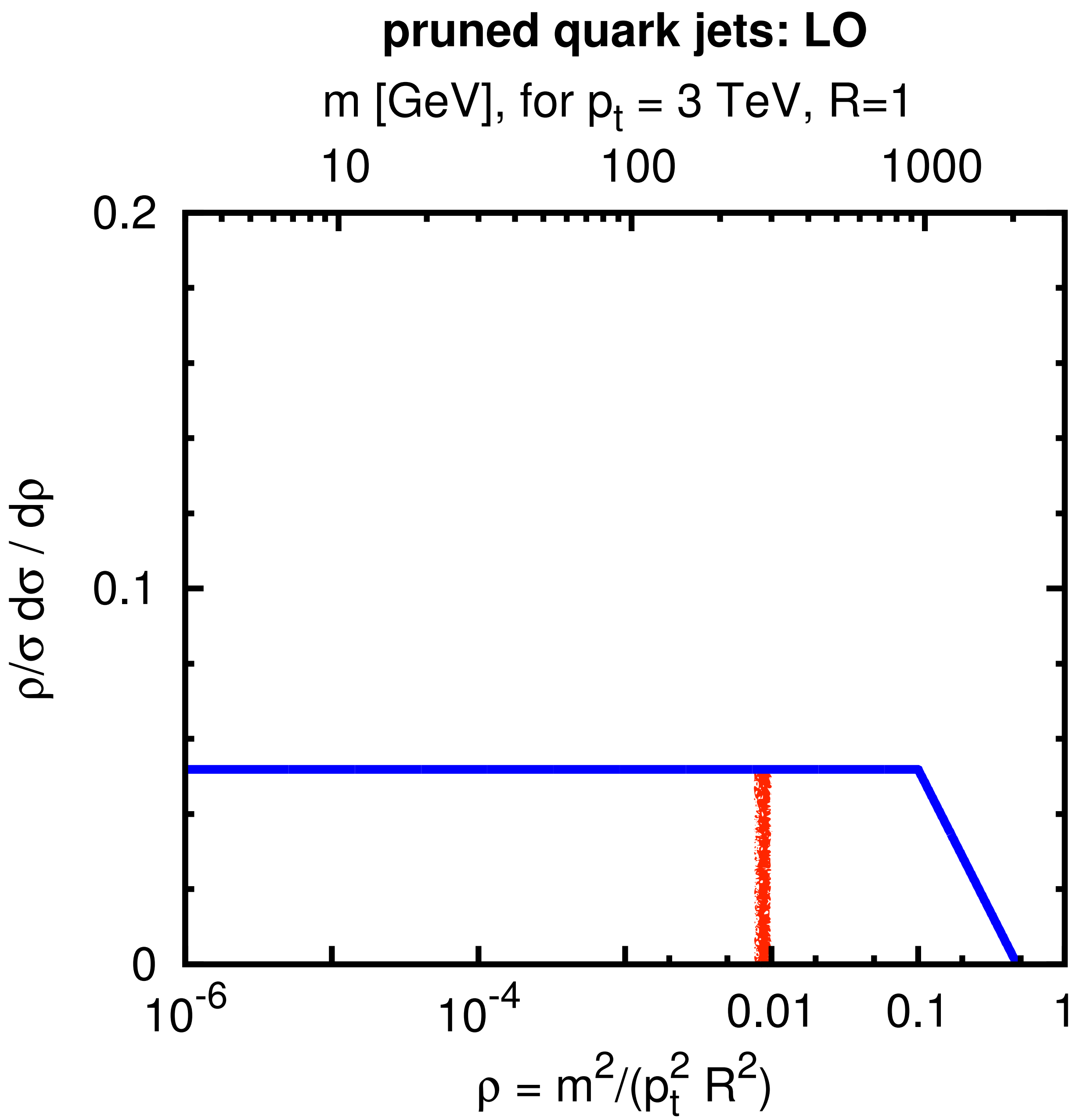

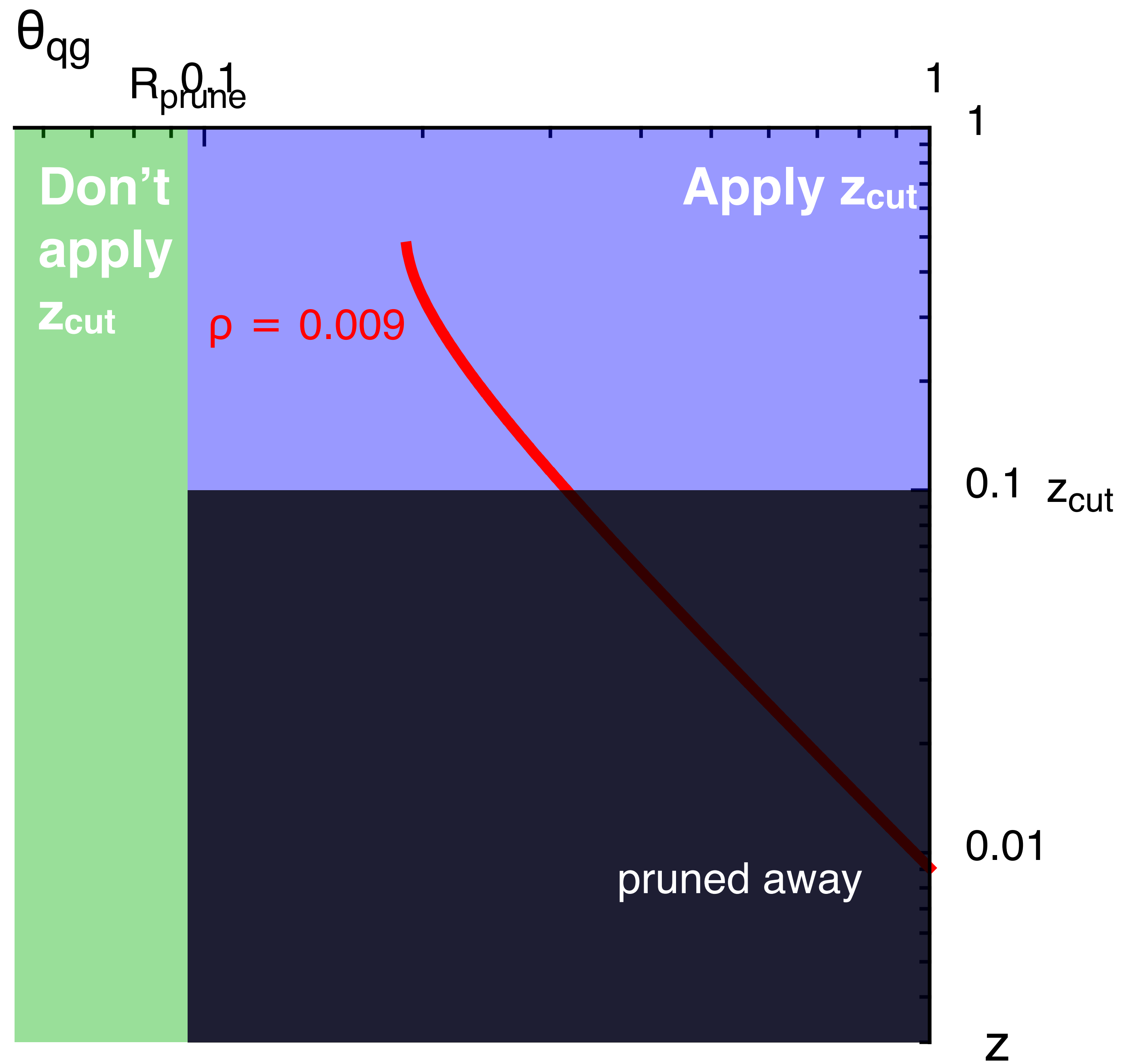

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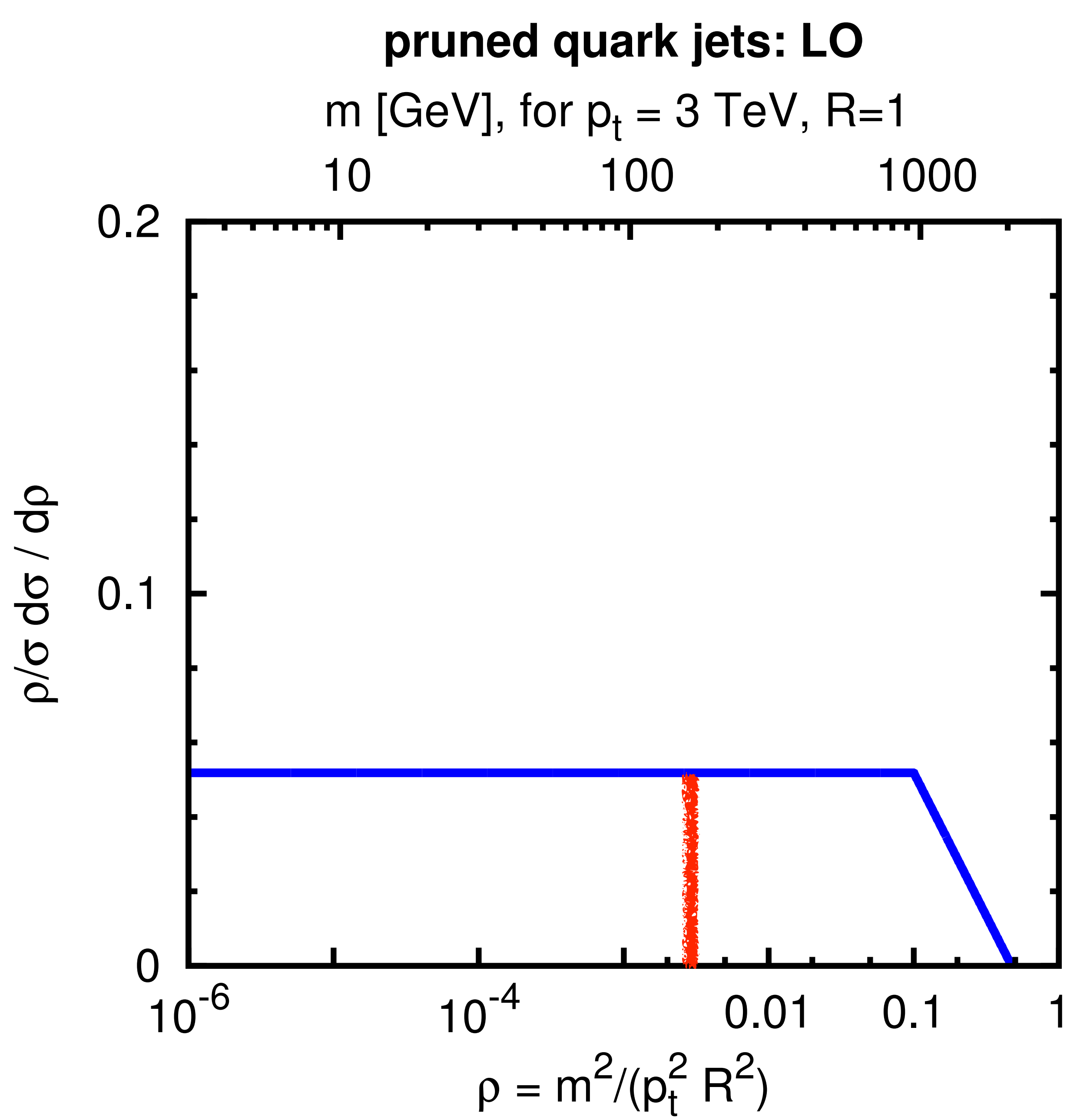

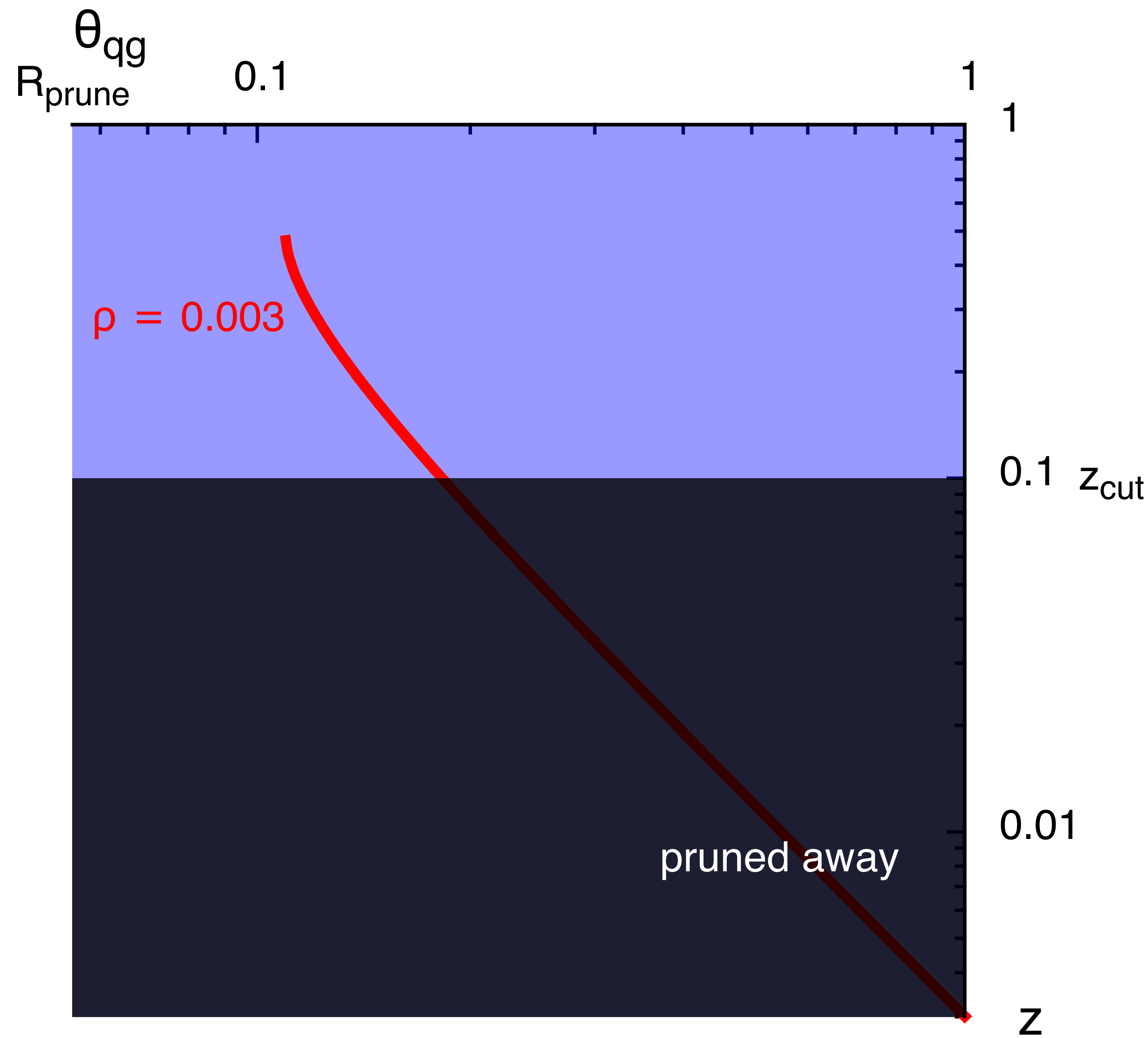

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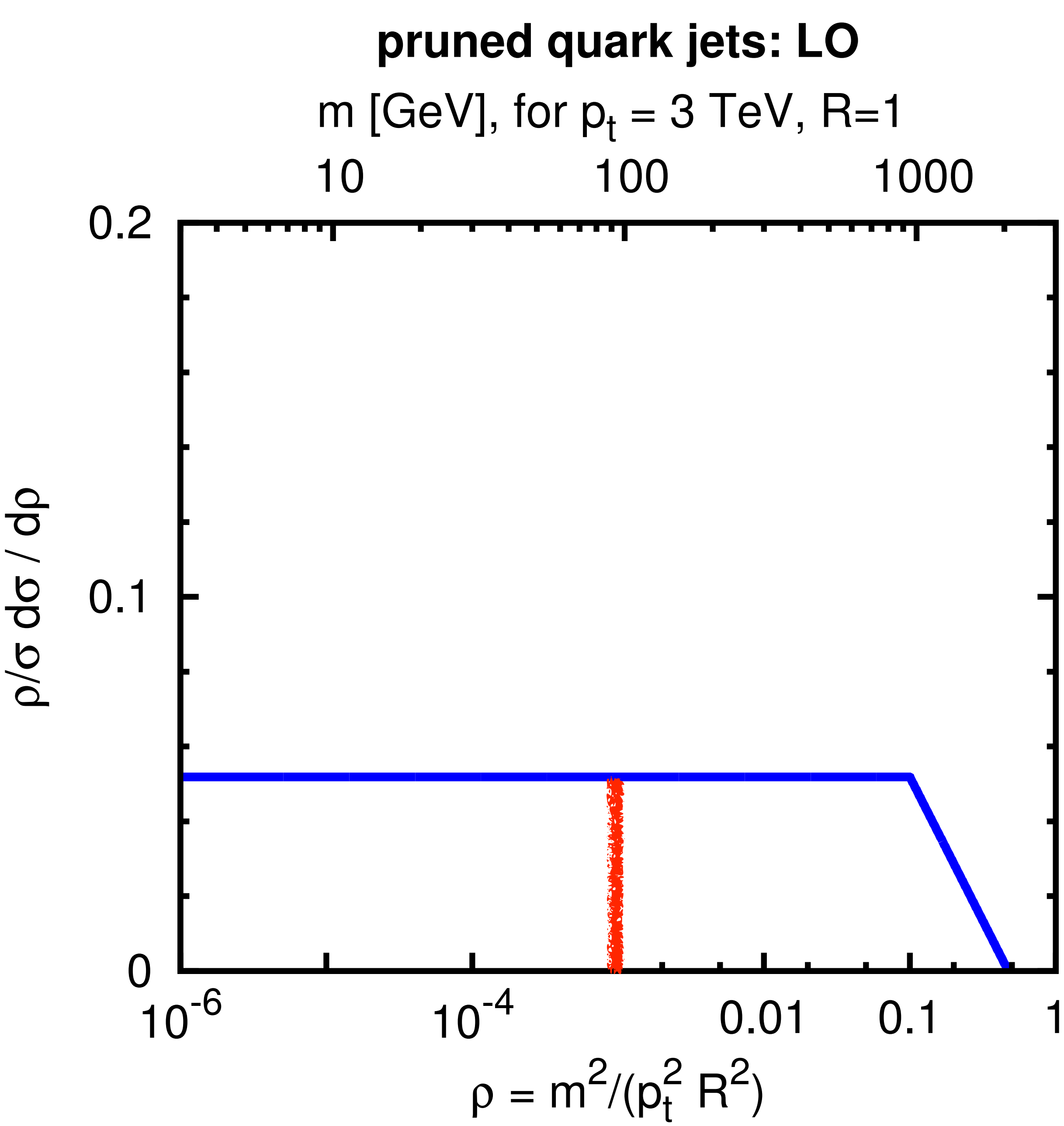
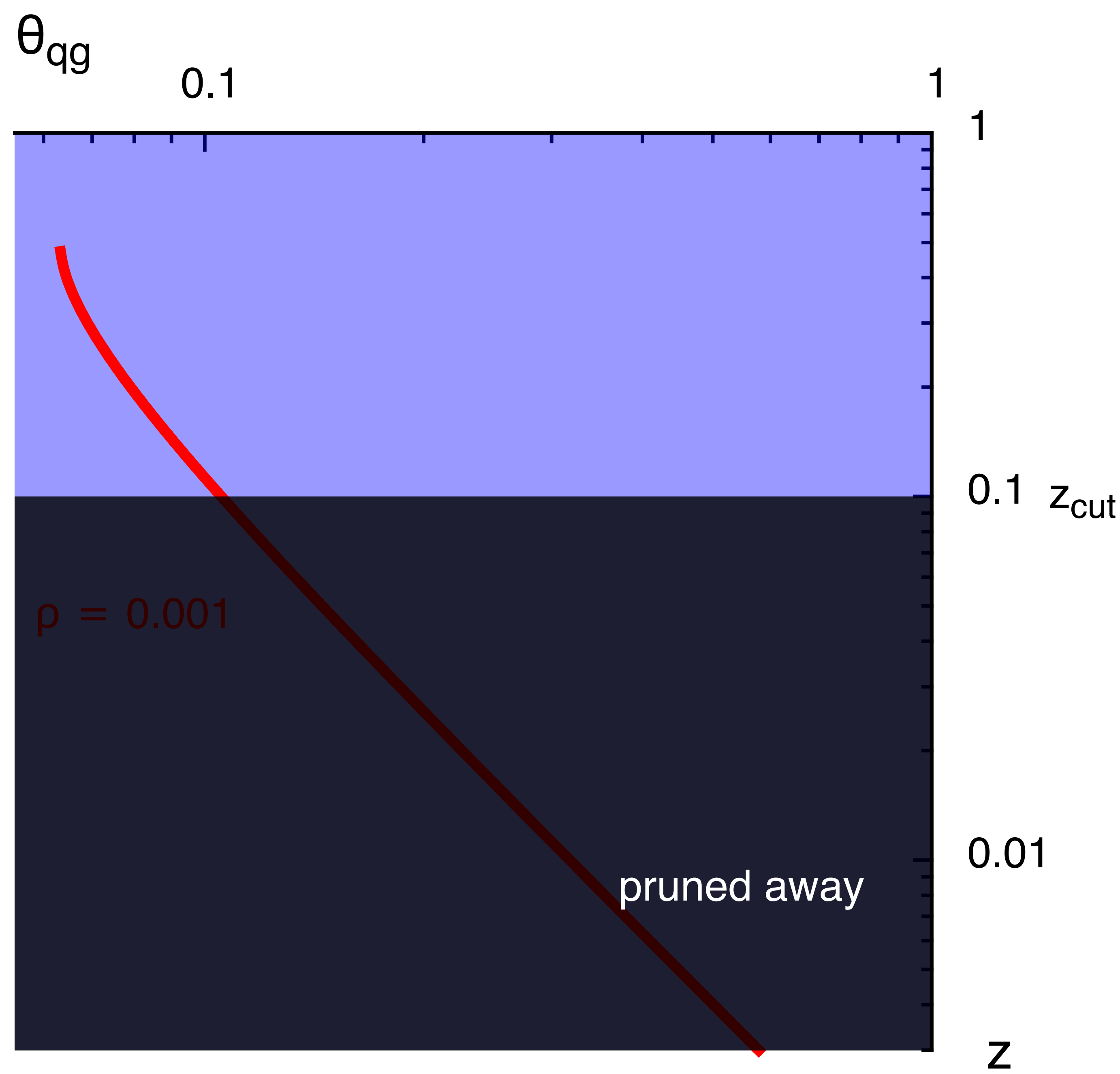
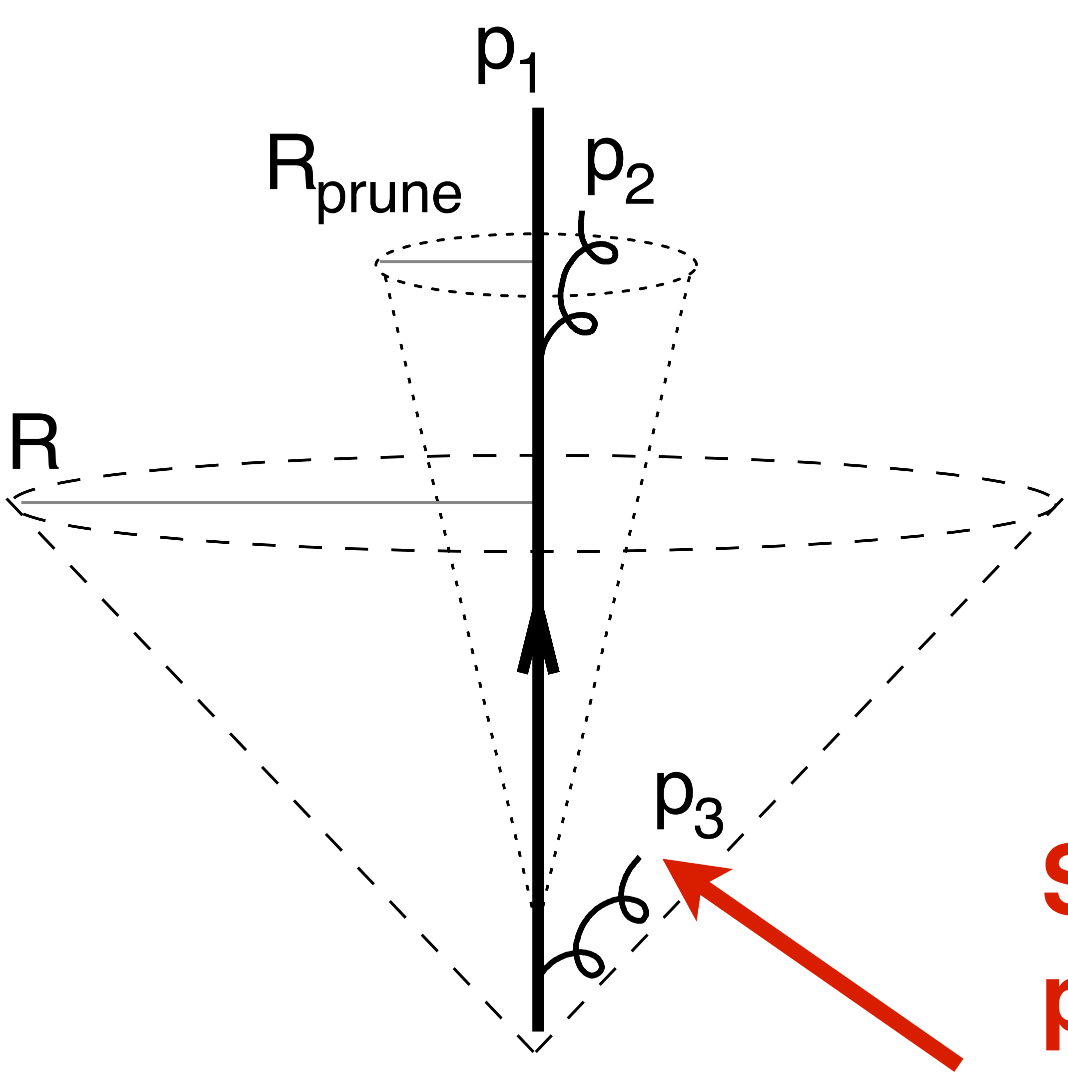




pruning beyond 1st order: consider multiple emissions



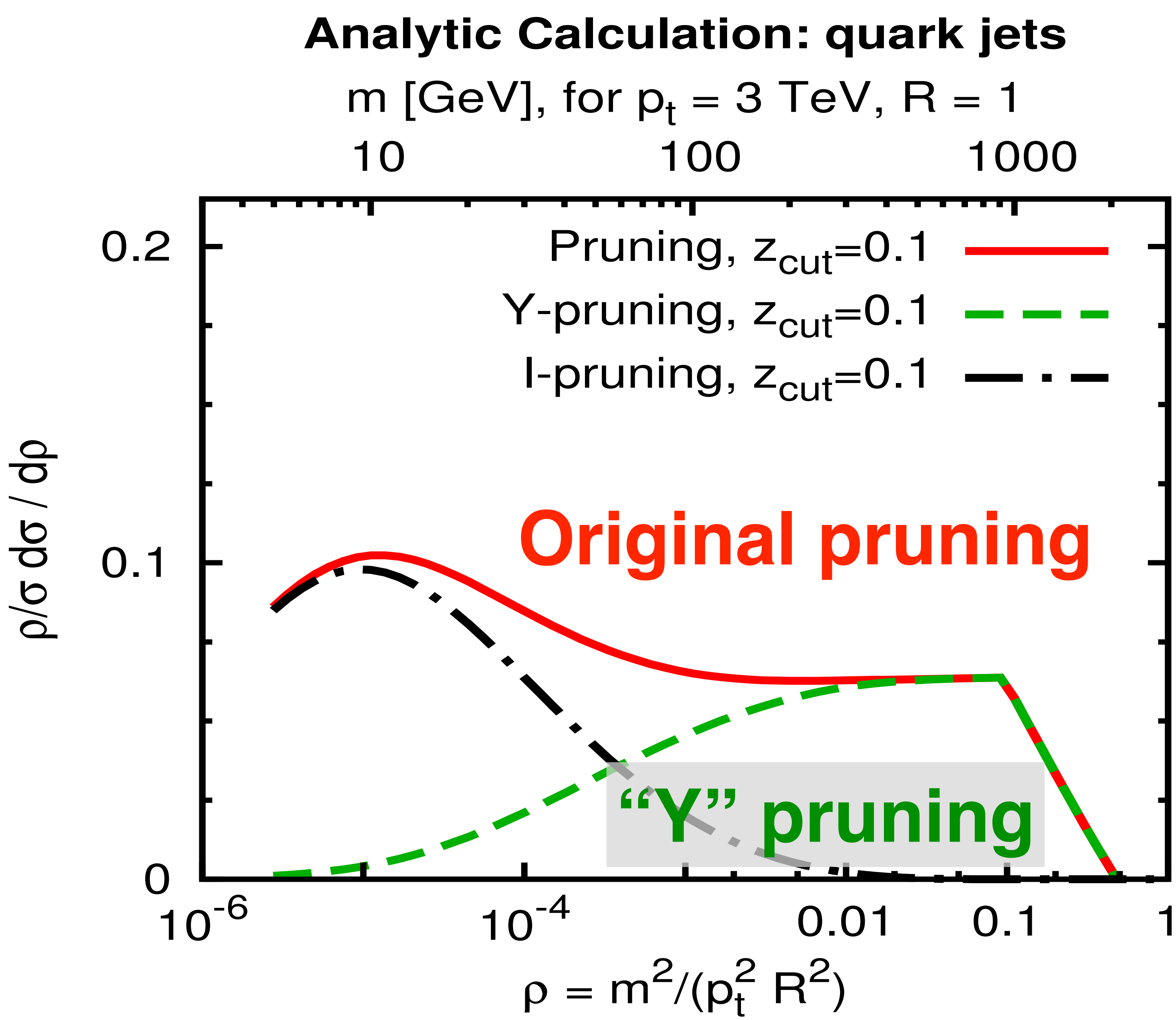
What pruning sometimes does

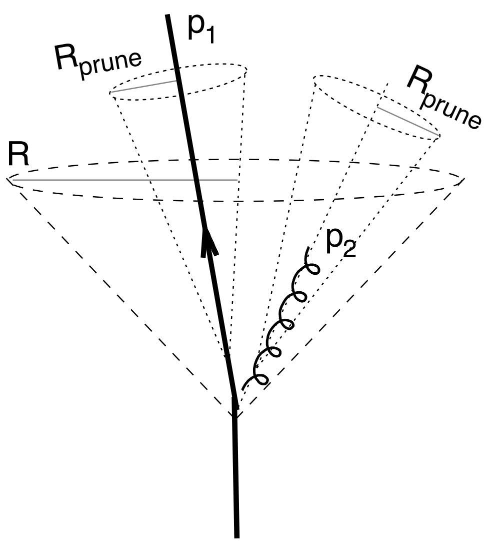
Chooses R_{prune} based on a soft p_3 (dominates total jet mass), and leads to a single narrow subjet whose mass is also dominated by a soft emission (p_2, within R_{prune} of p_1, so not pruned away).

Sets pruning radius, but gets pruned away → "wrong" pruning radius → makes this ~ trimming

A simple fix: “Y” pruning

Require at least one successful merging with $\Delta R > R_{prune}$ and $z > z_{cut}$ — forces 2-pronged (“Y”) configurations





“Y” pruning ~ an isolation cut on radiation around the tagged object — **exploits W/Z/H colour singlet**

What logs, what accuracy?

At leading order pruning (≡ Y-pruning): **no double logs**!

$$\alpha_s L, \text{ but no } \alpha_s L^2$$

Full Pruning's leading logs (LL, in Σ) are:

$$\alpha_s L,\ \alpha_s^2 L^4,\ \ldots\text{. I.e. } \boldsymbol{\alpha_s^n L^{2n}}$$

we also have NLL

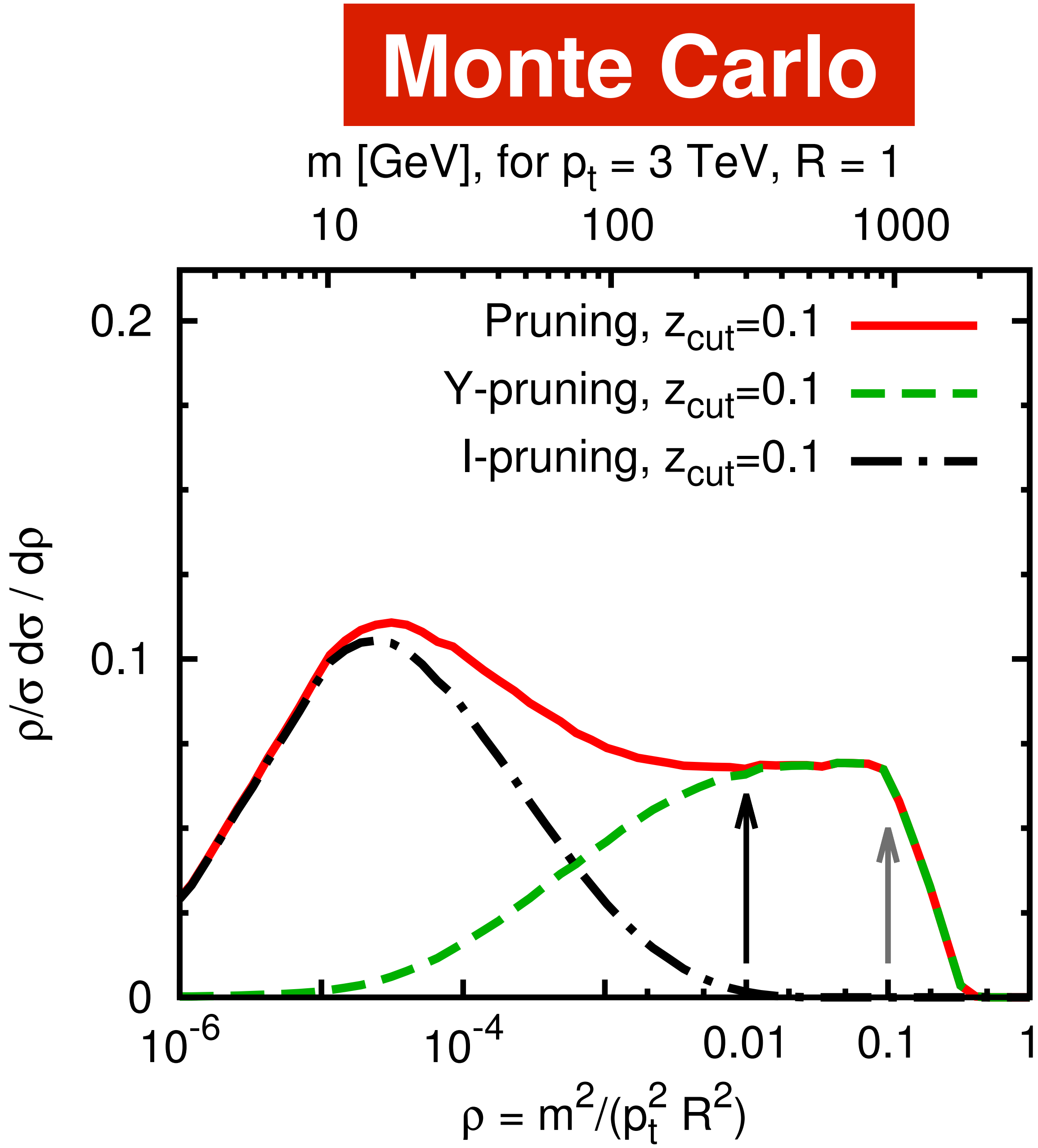
Y-Pruning's leading logs (LL, in Σ) are:

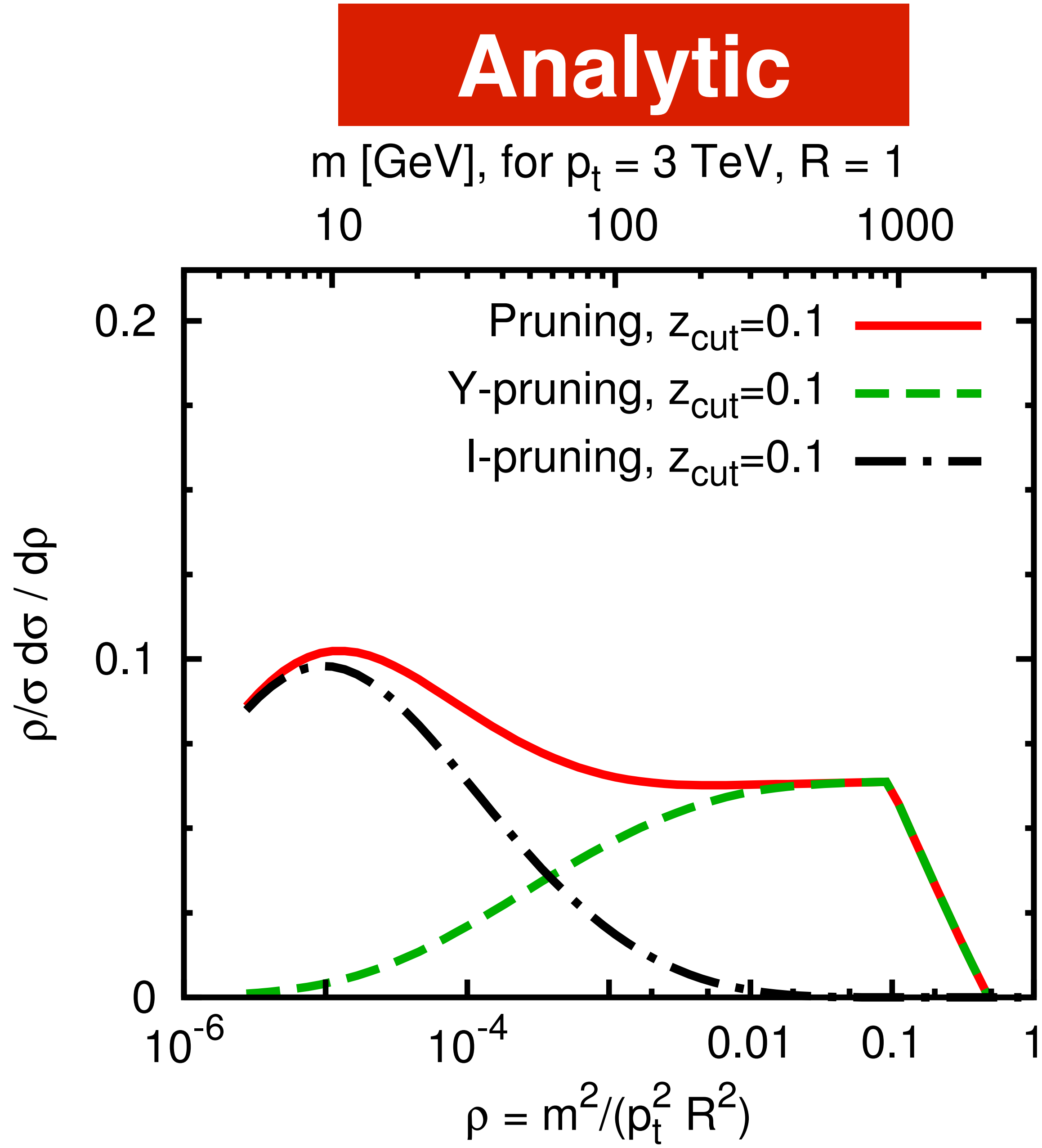
$$\alpha_s L,\ \alpha_s^2 L^3,\ \ldots\text{. I.e. } \boldsymbol{\alpha_s^n L^{2n-1}}$$

we also have NLL

Could we do better? Yes: NLL in ln Σ, but involves **non-global logs, clustering logs**

Pruning





Non-trivial agreement!

(also for dependence on parameters)