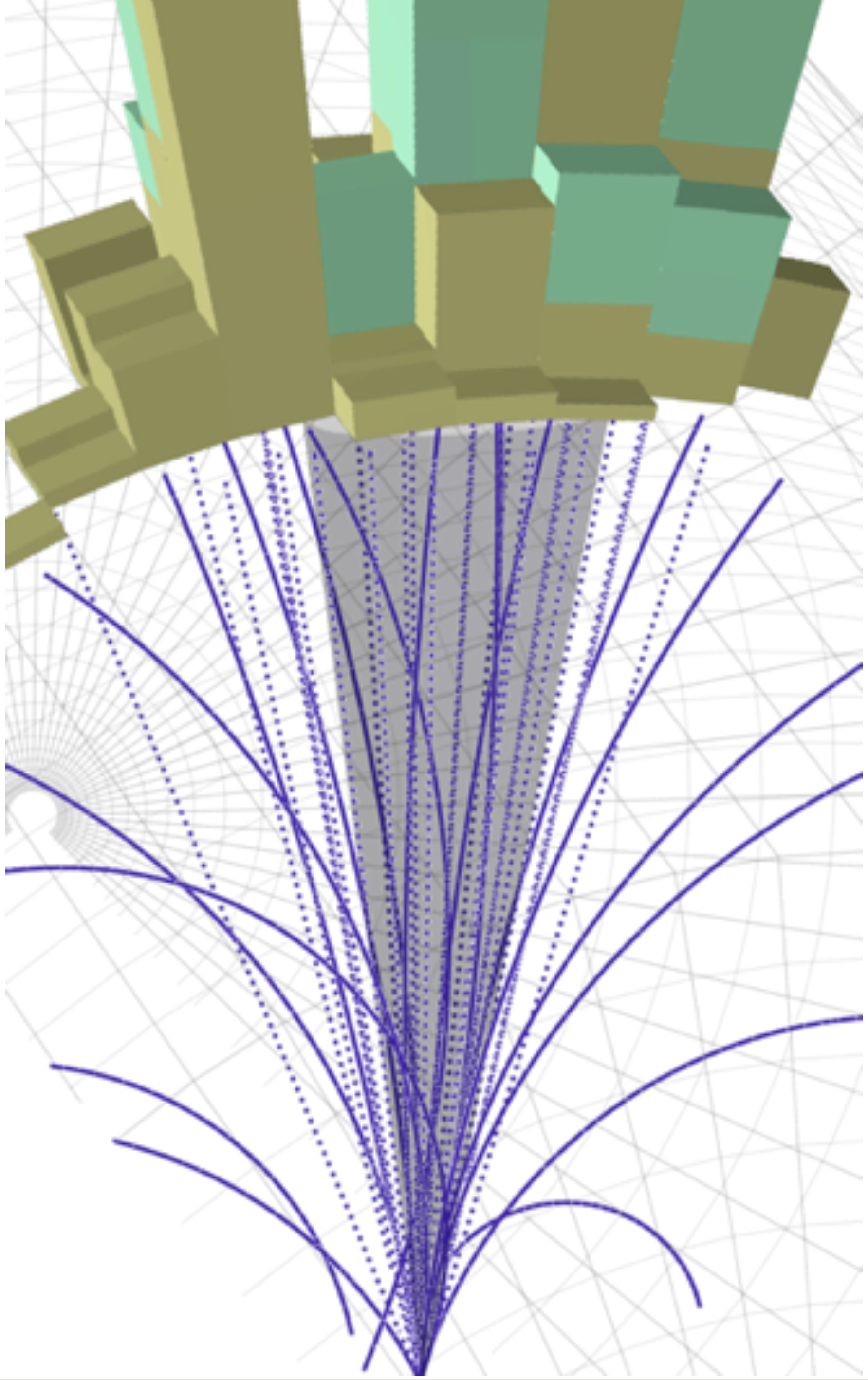


Towards an understanding of jet substructure

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

CFHEP@IHEP / CHEP@PKU, Beijing
30 April 2014

Broad Context

(after 3 years of LHC operation at 7 & 8 TeV)

Higgs discovered

Nothing Beyond Standard Model (BSM) so far,
with many limits now well above 1 TeV

Standard Model measurements

Surprises in heavy-ion (and pA) collisions

What is programme for coming years?

Investigate Higgs in fine detail

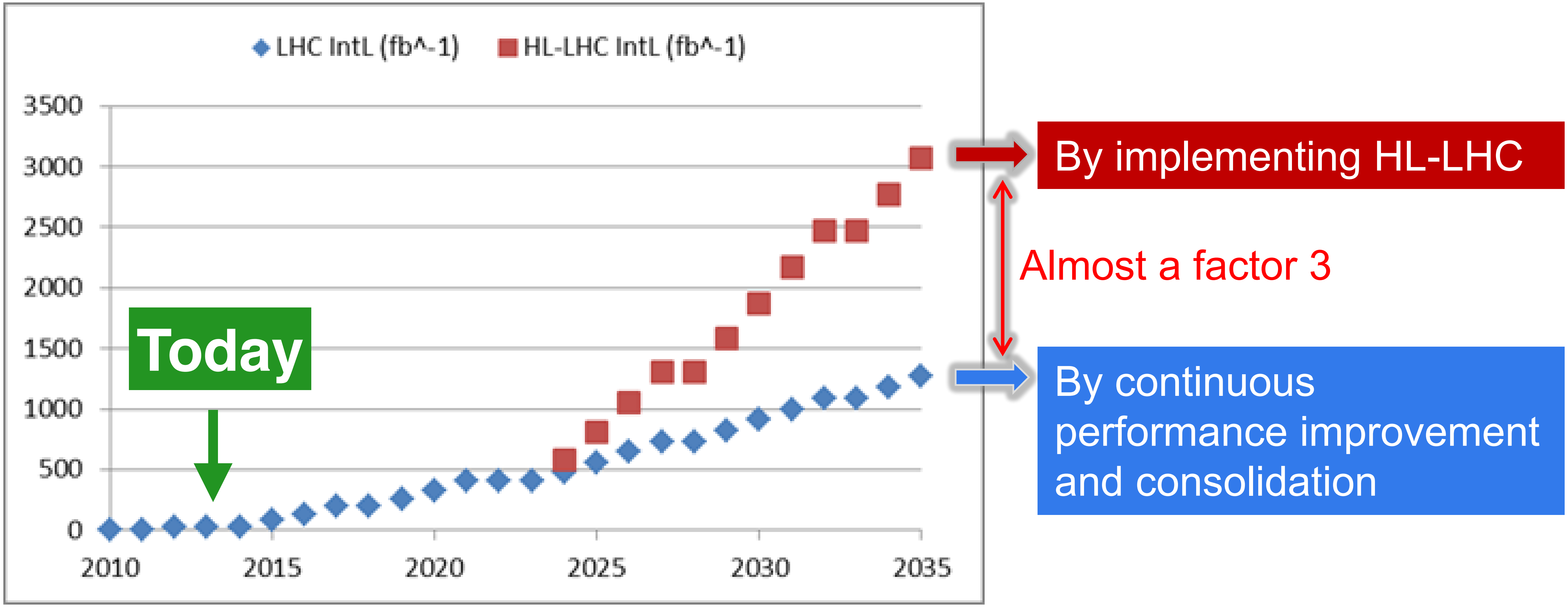
Push BSM search much further
(including through flavour physics)

Highly precise Standard Model measurements

Continue the study of heavy ions

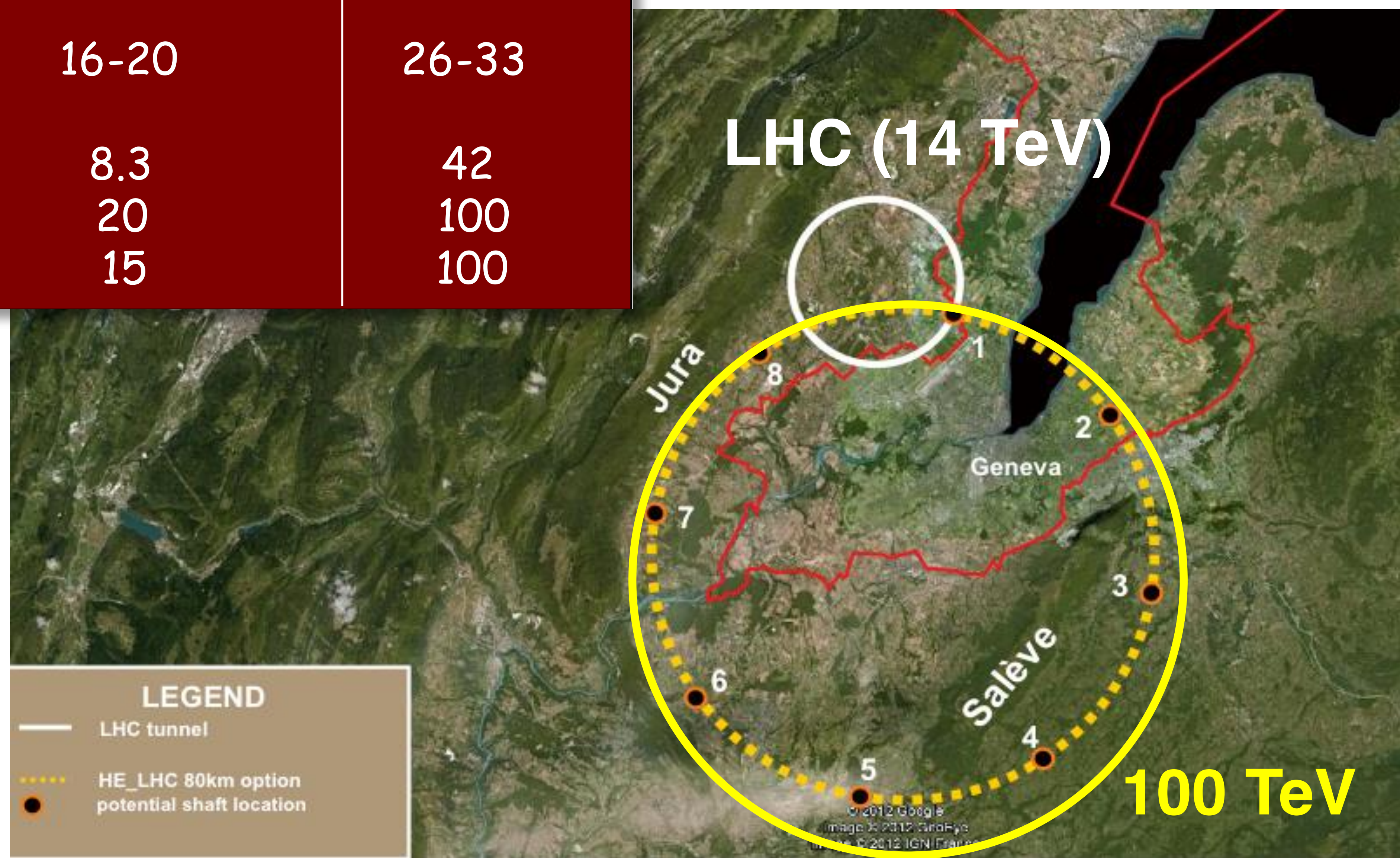
Only at the start of a long programme

in 2015 almost double the energy → 13–14 TeV
over 20 years: 150 times more data



Even longer term – a 100 TeV collider?

Facility	Ring (km)	Magnets (T)	$\sqrt{s}$ (TeV)
(SSC)	87	6.6	40
LHC	27	8.3	14
HE-LHC	27	16-20	26-33
FHC	80 80 100	8.3 20 15	42 100 100



These are endeavours involving ~10,000 people

How does a theorist contribute?

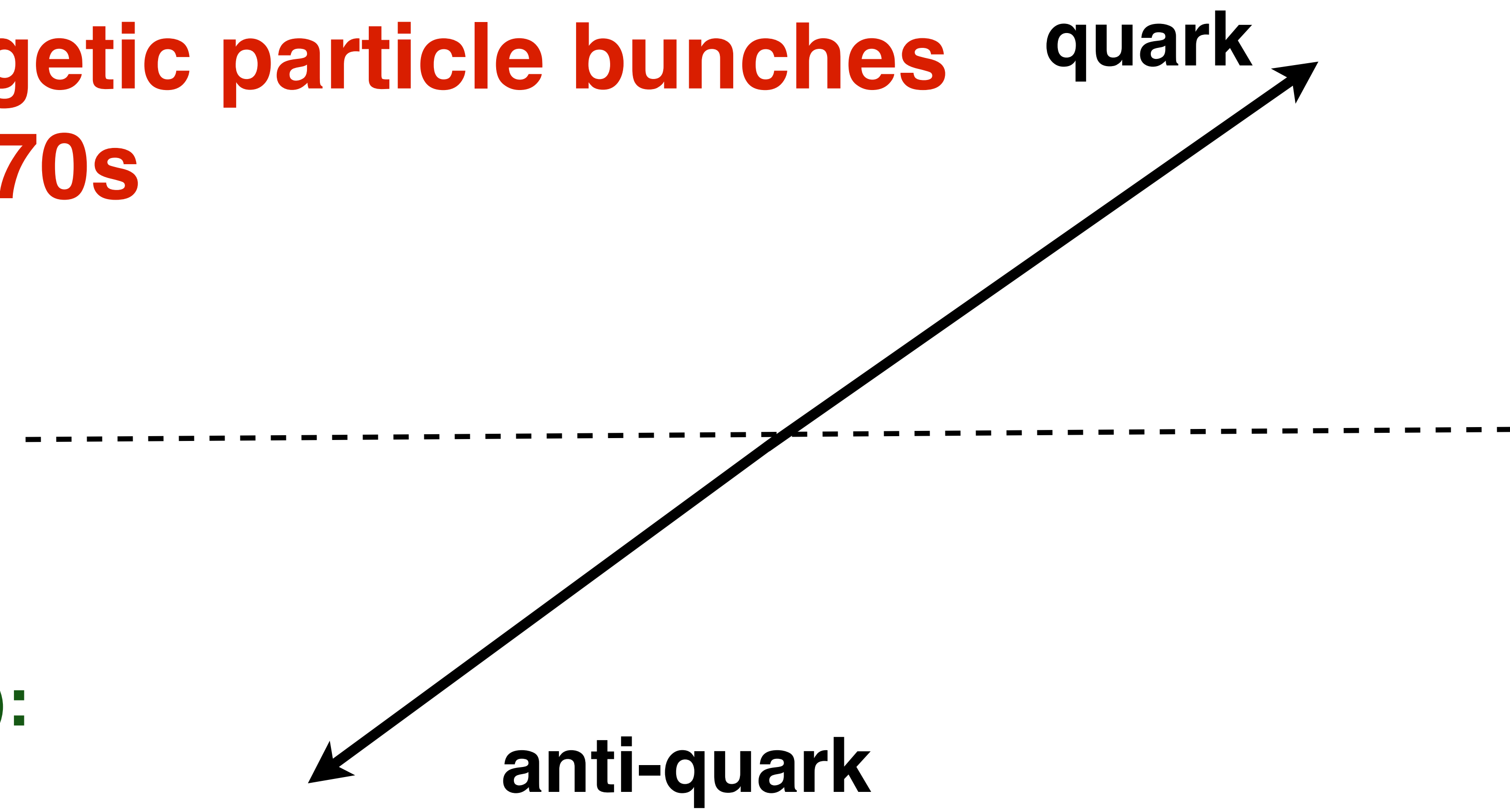
Devising models of new physics, to be searched for

Predicting the structure of events

Establishing the implications of existing data
(for new physics, for the Standard Model)

Thinking of new ways to exploit the data
→ this talk, specifically with **jets**

Jets — collimated energetic particle bunches date back to the late 1970s



Sterman and Weinberg,
Phys. Rev. Lett. 39, 1436 (1977):

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-

$$\sigma(E,\theta,\Omega,\varepsilon,\delta) = (d\sigma/d\Omega)_0\,\Omega\left[1 - (g_E^2/3\pi^2)\left\{3\ln\delta + 4\ln\delta\,\ln 2\varepsilon + \frac{\pi^3}{3} - \frac{5}{2}\right\}\right]$$

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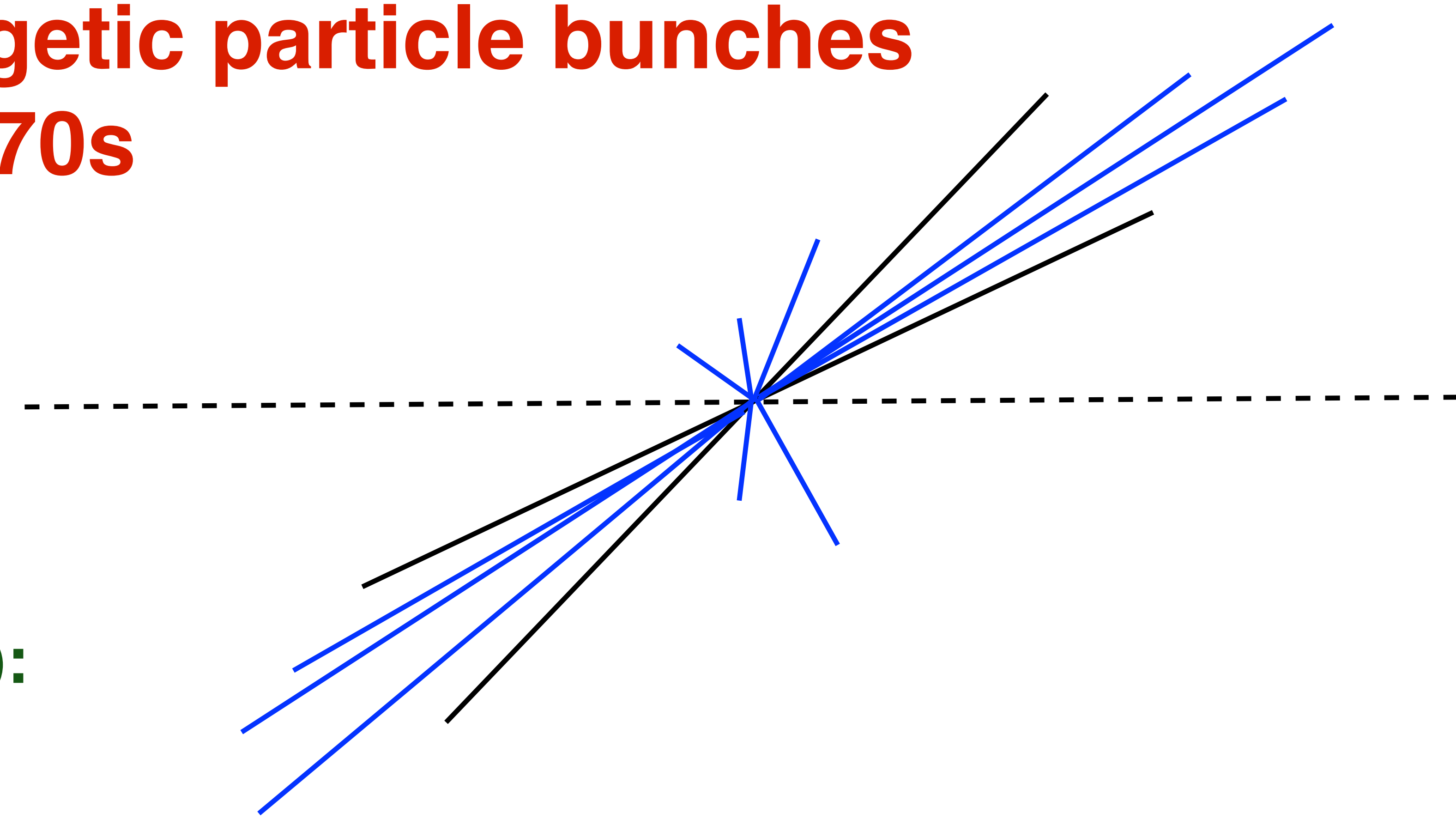

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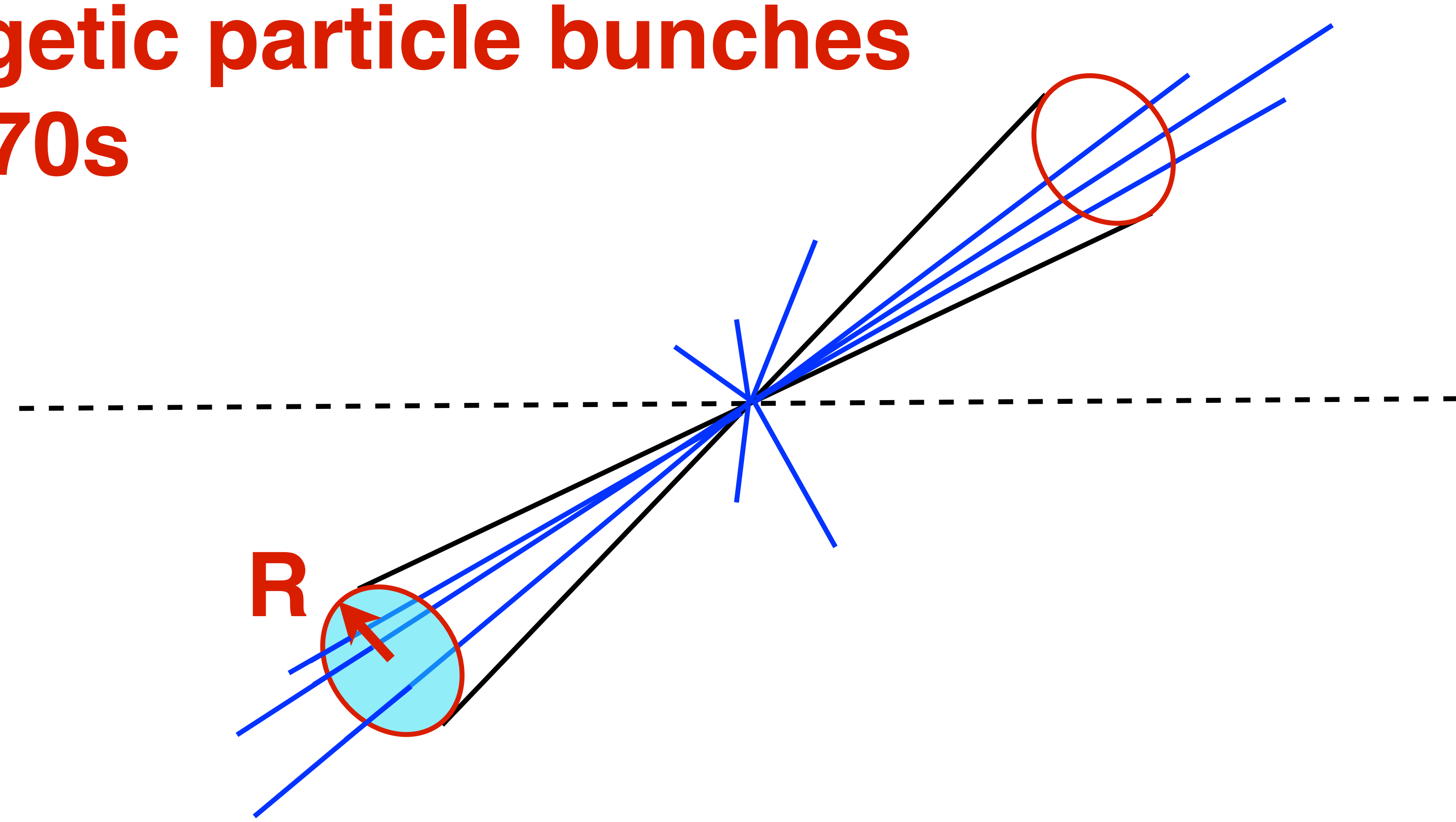
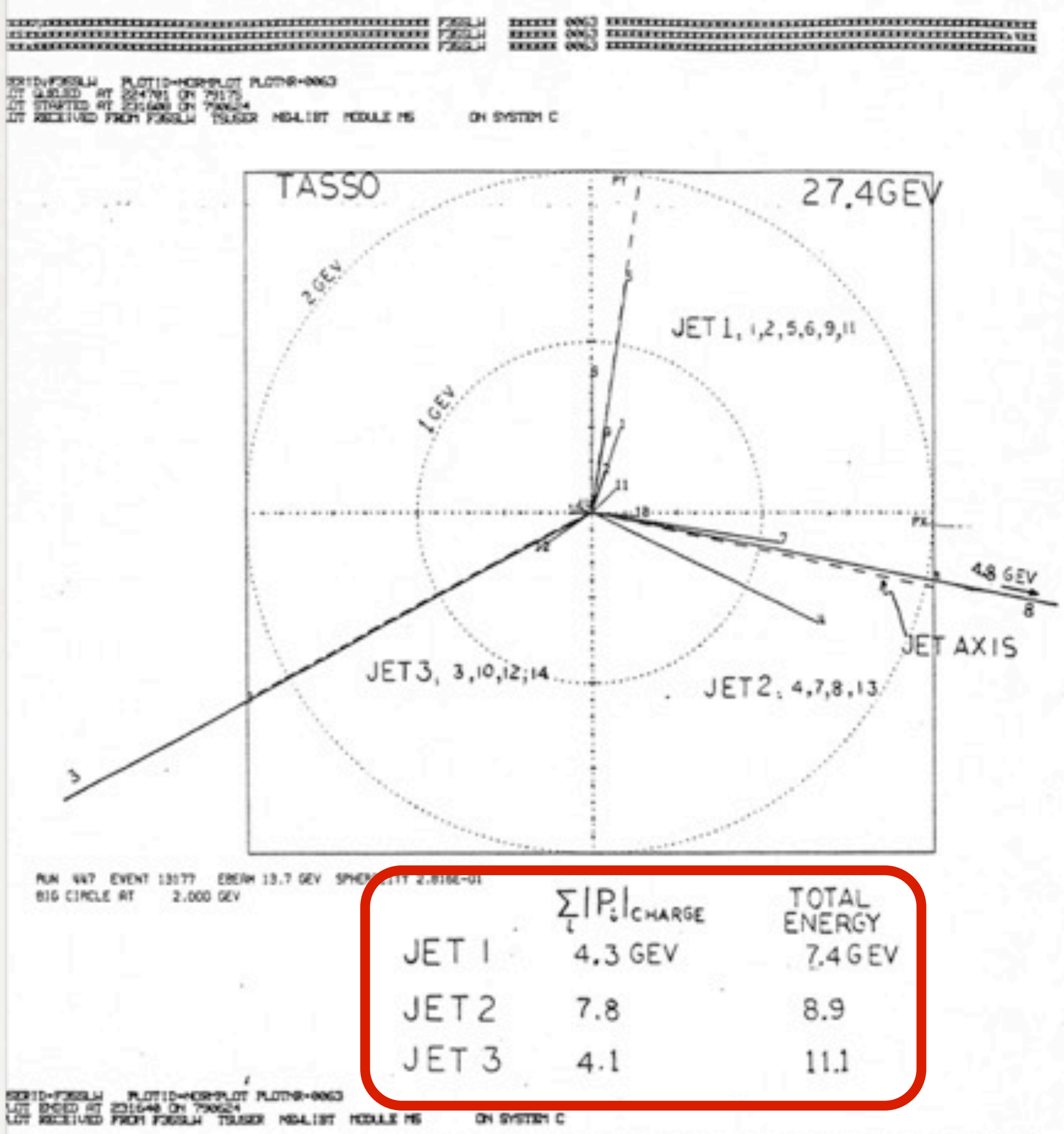


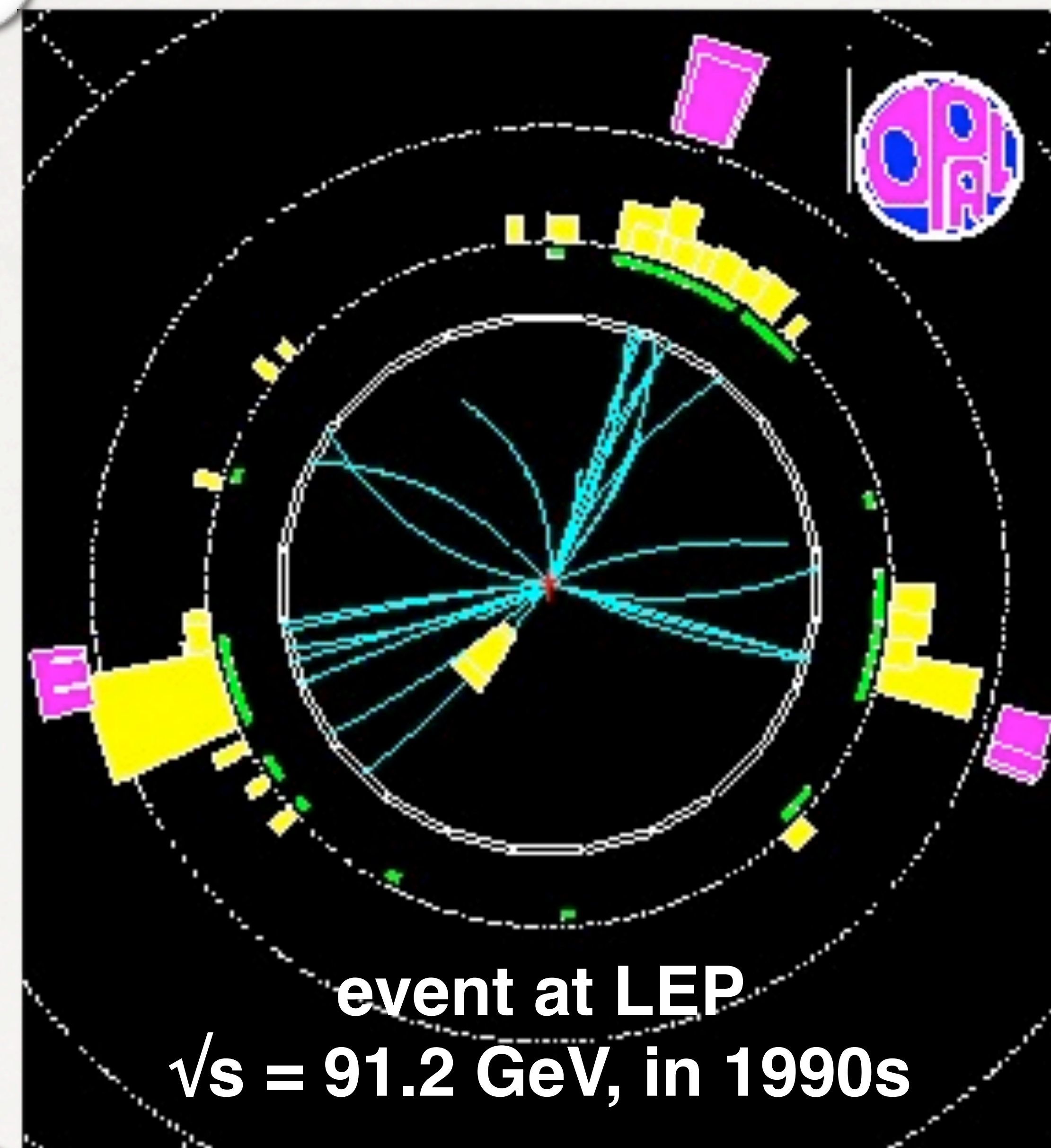
For many uses, jets, still today, effectively "measured" by capturing radiation with a cone of ~ fixed opening angle **R**

And they've been used and studied at every collider since



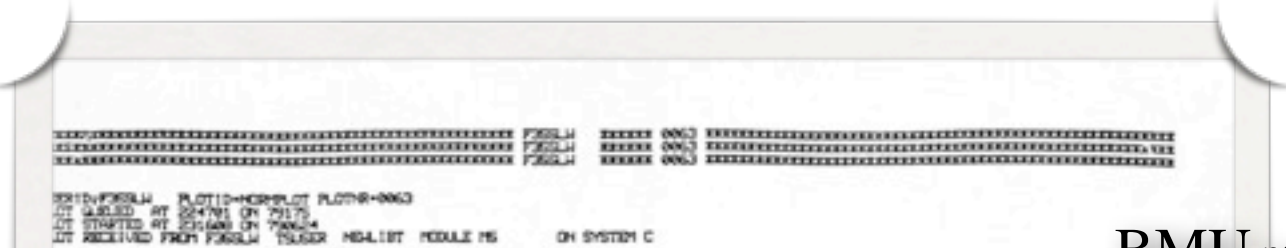
gluon discovery:

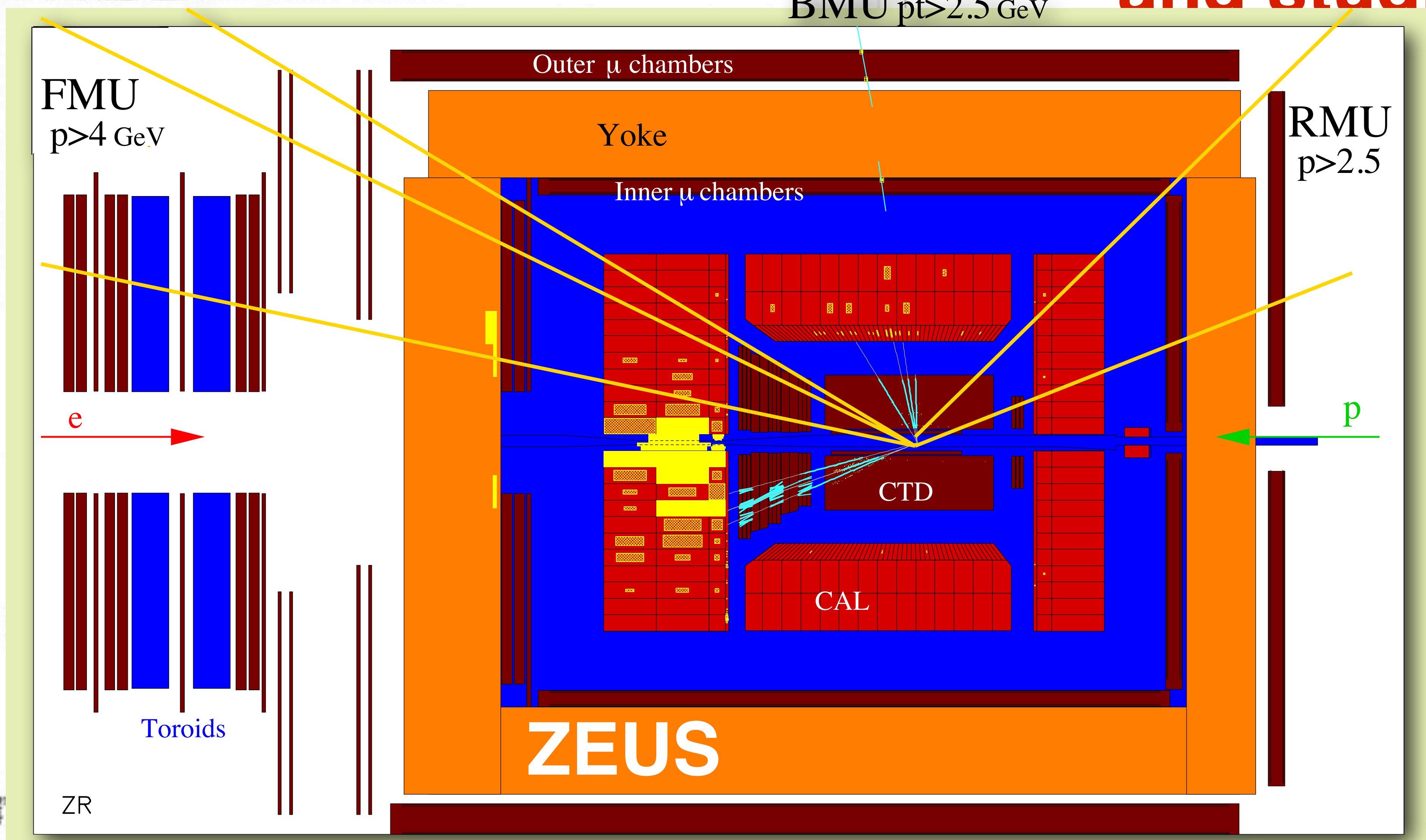
event at TASSO
√s = 27.4 GeV, in 1979



event at LEP
√s = 91.2 GeV, in 1990s

And they've been used and studied at every er since





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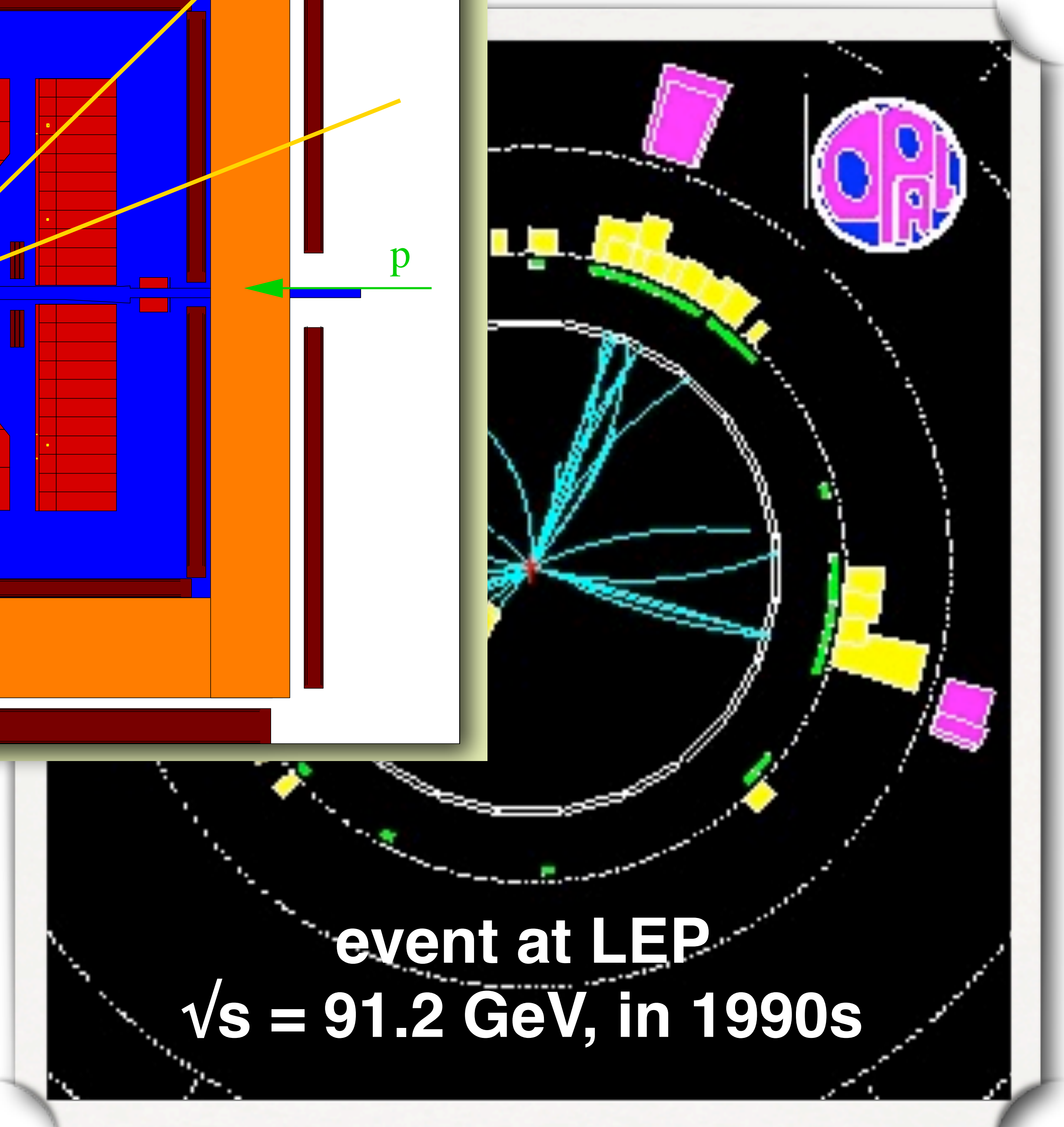

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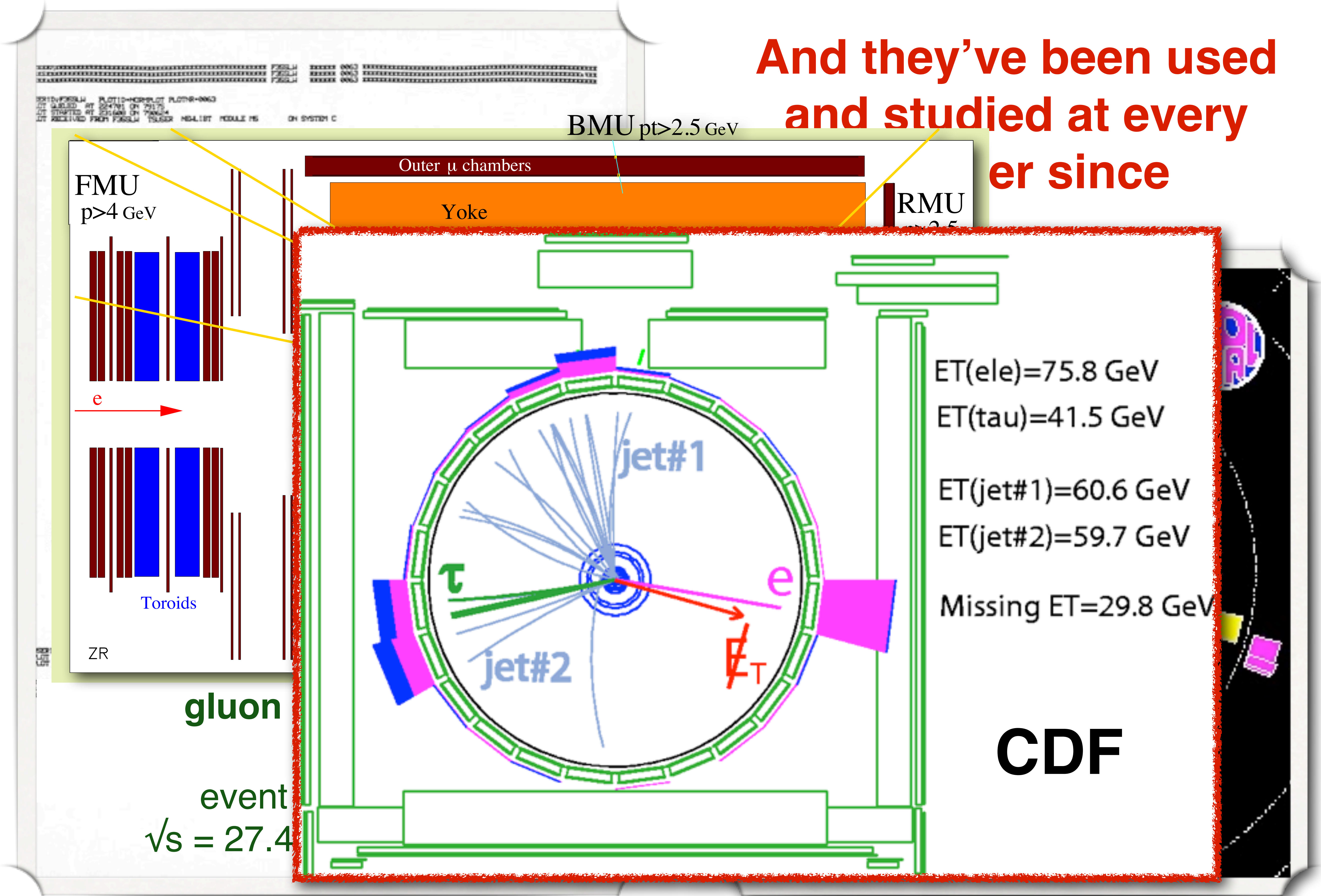
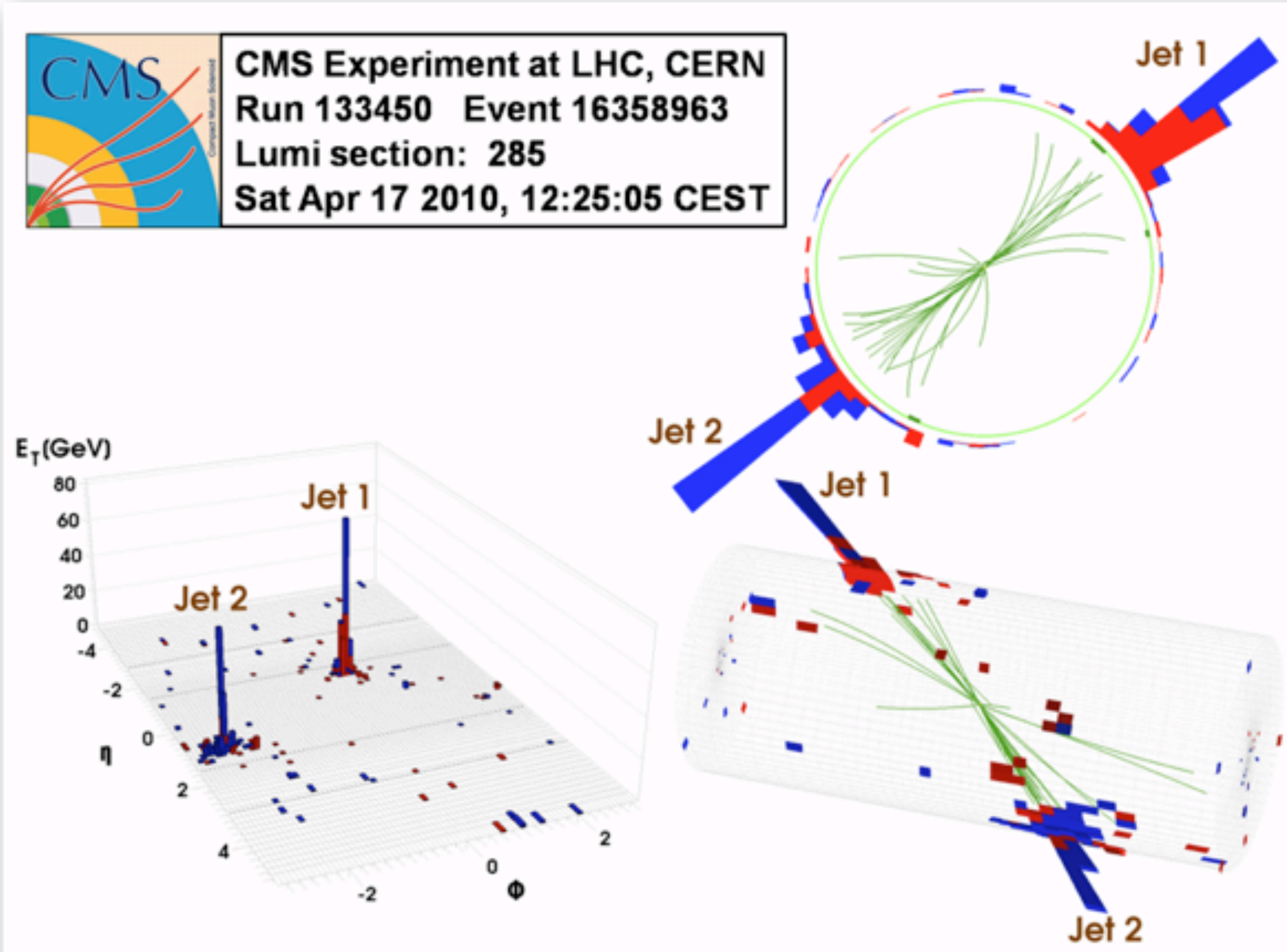
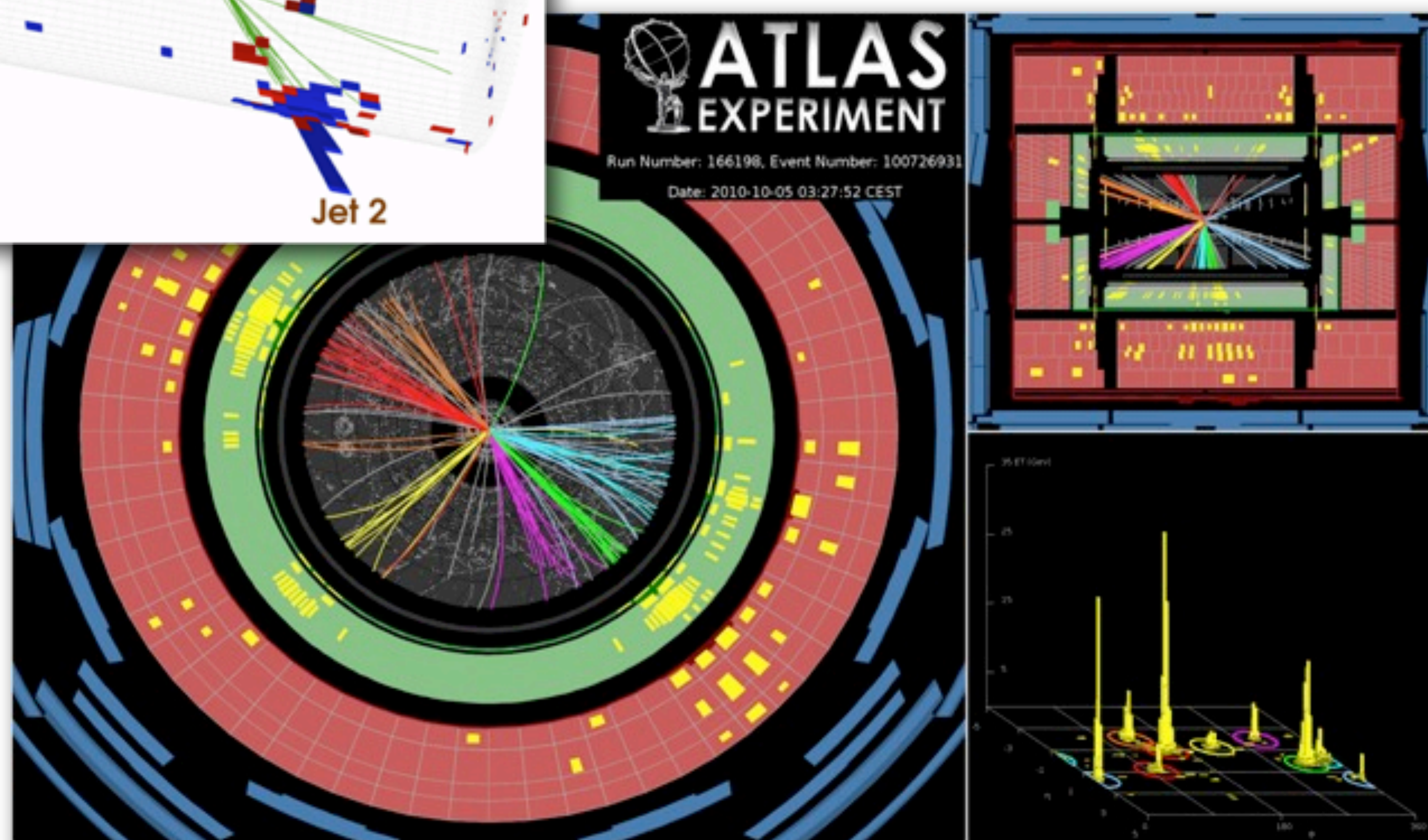
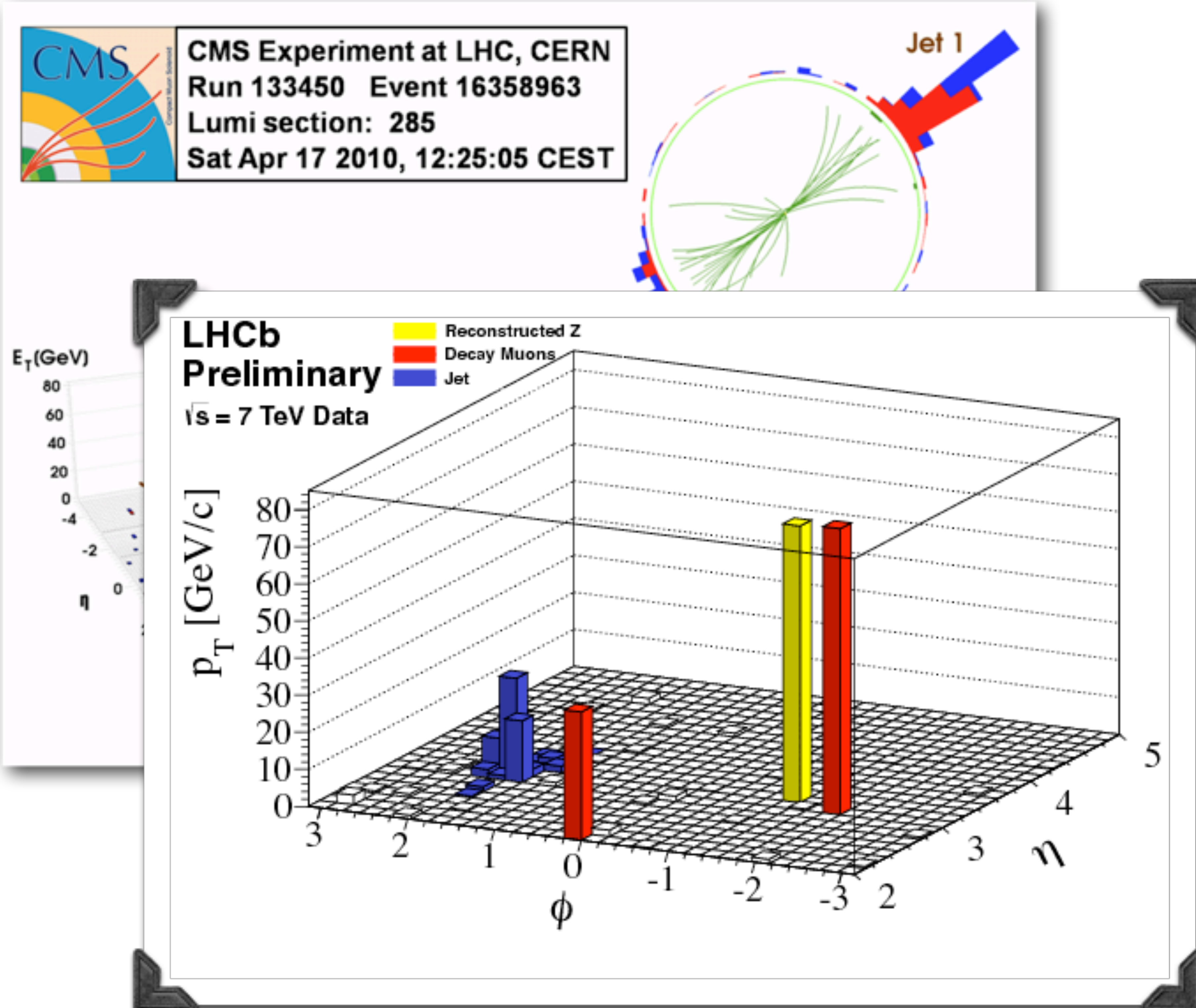
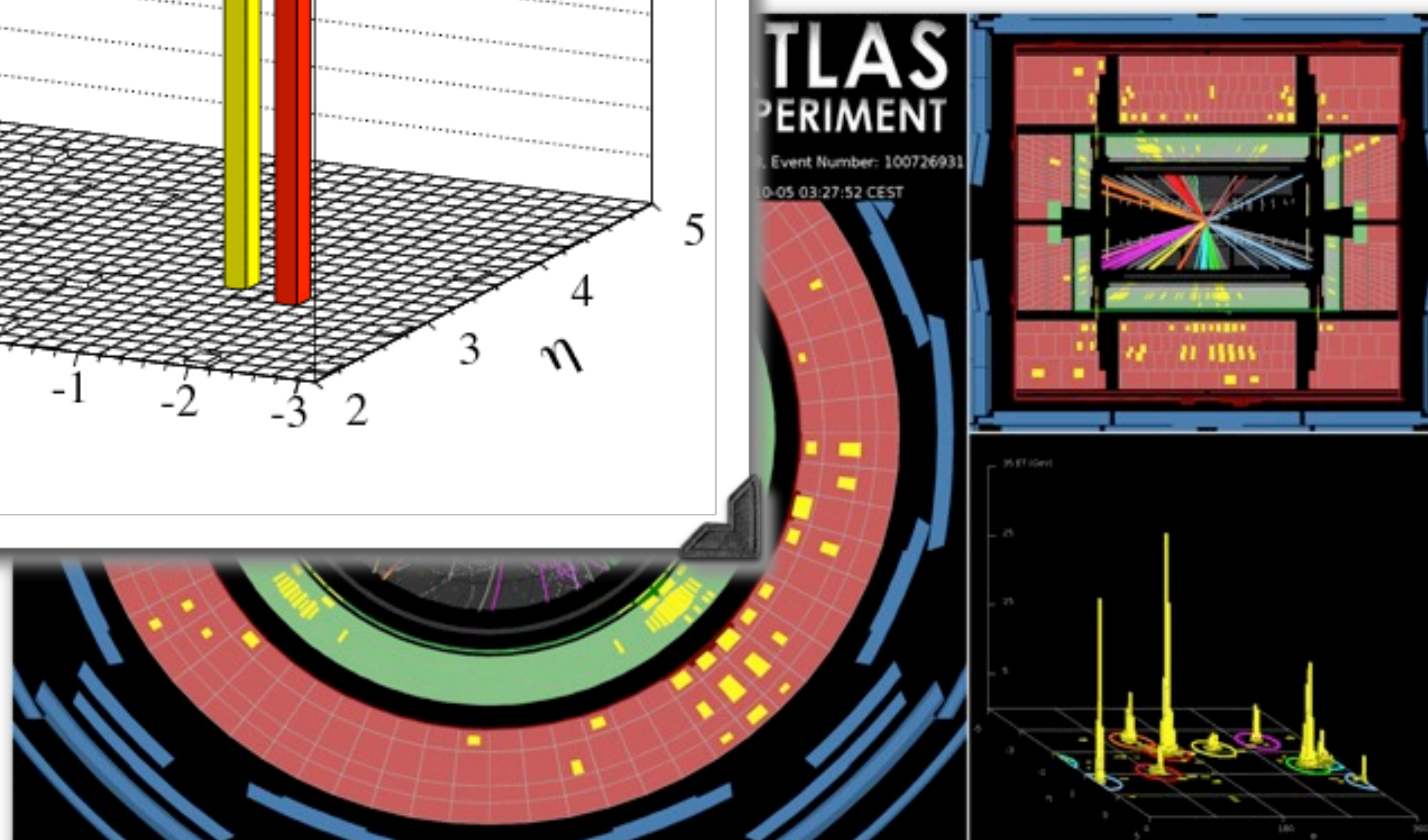




including,
extensively,
at the LHC
(~60–70% of ATLAS
& CMS papers use jets)







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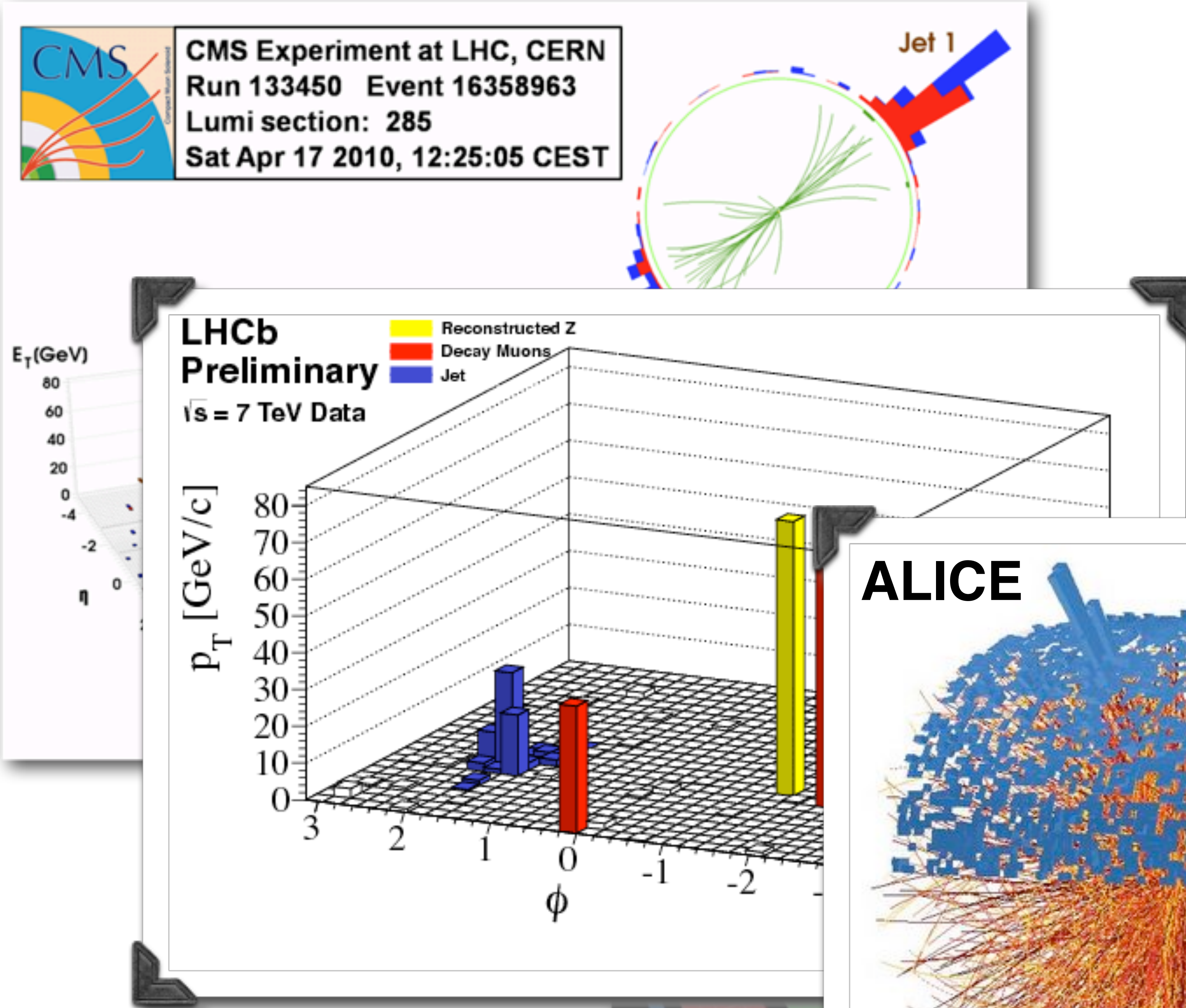
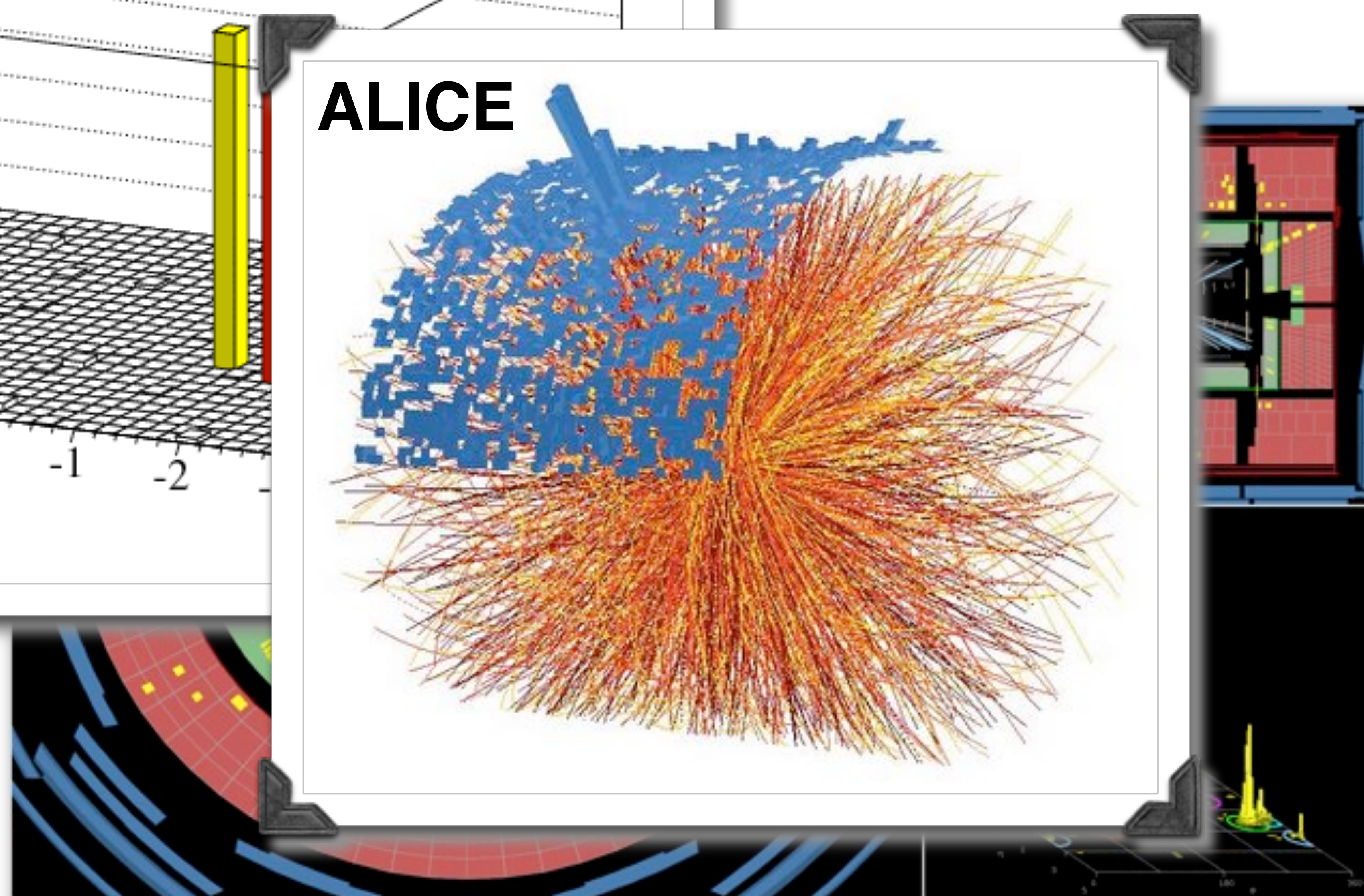
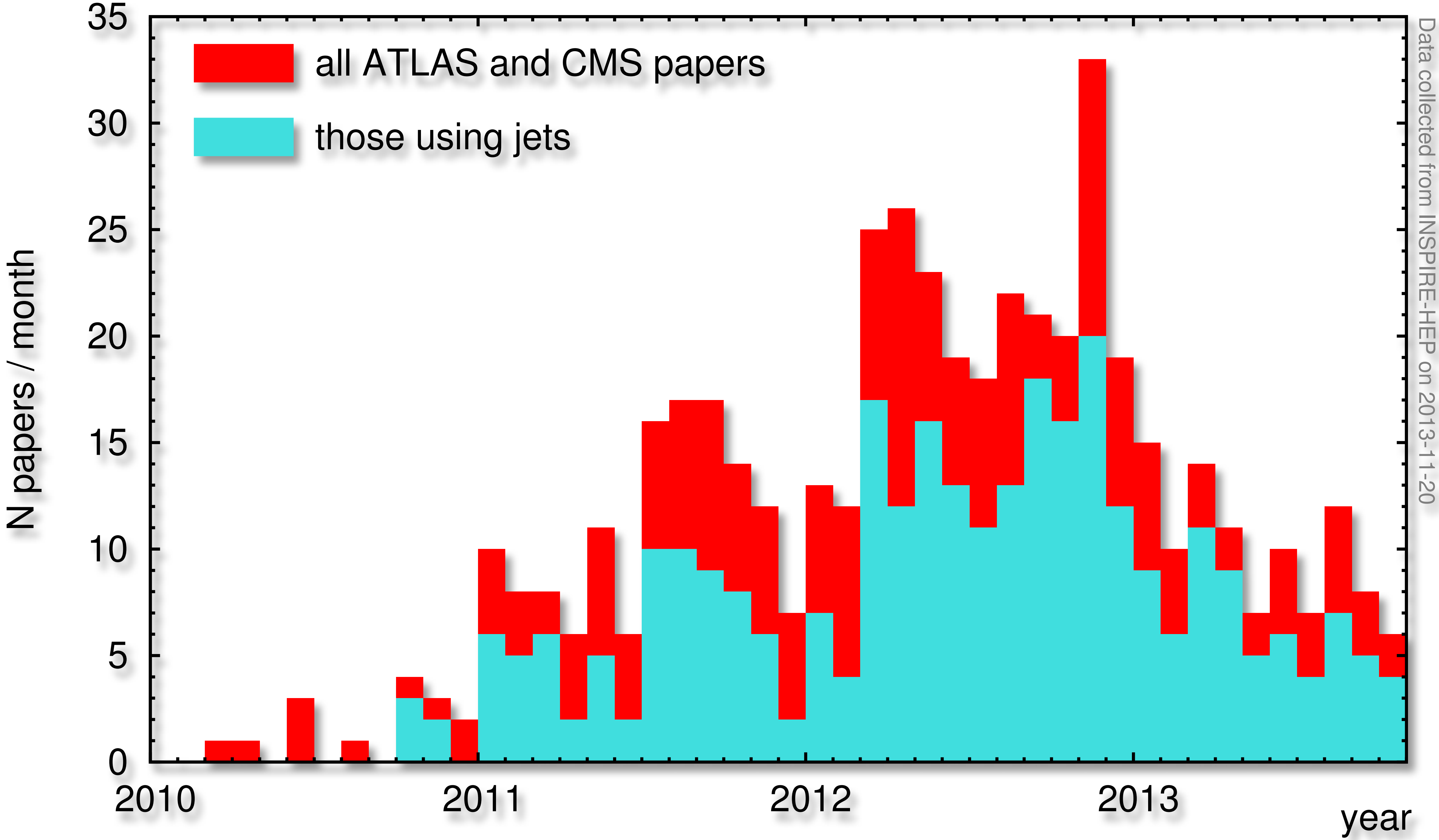




including,
extensively,
at the LHC
(~60–70% of ATLAS
CMS papers use jets)

60-70% of recent ATLAS and CMS papers use jets in their analyses, i.e. any time they want a quark or gluon to be present (or absent) in an event



Most LHC jet uses fall under the (historical) category

"a jet is basically a parton"

e.g. from a heavy-object decay, ISR, etc.

If radiation is modelled correctly in the Monte Carlos,
most experimenters don't even need to think (much) about jets.
Just build on standard jet tools: FastJet (Cacciari, GPS, Soyez '05–'14),
anti-k_t (idem '08), area subtraction of pileup (idem, '06–'12)
and the hard work of experimental calibration

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But as LHC moves to search “harder” for new physics,
we start to need to push analyses to their boundary, e.g.

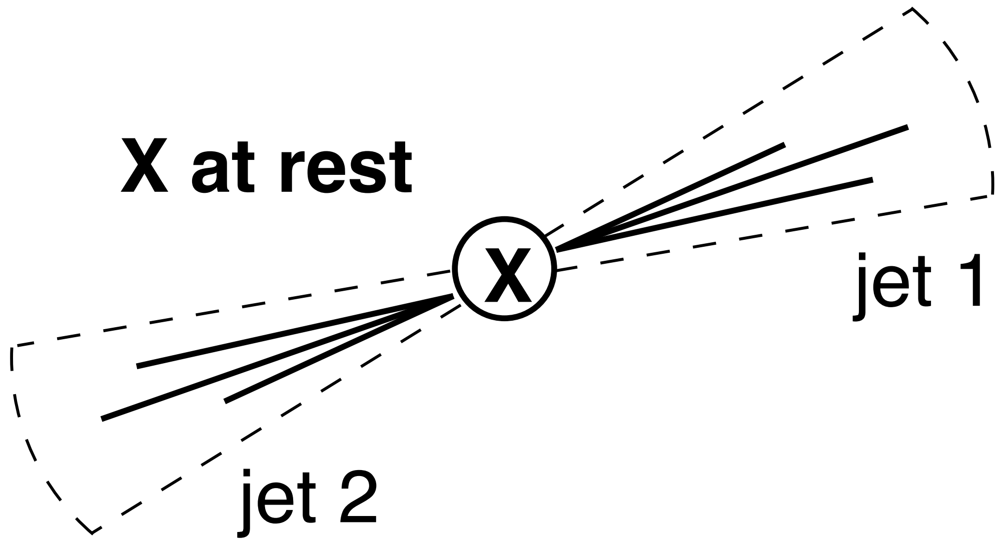
Enhance sensitivity to small signal/background
Explore very highest p_t’s
Learn how to handle complex final states

➜ for that, you need advanced jet techniques

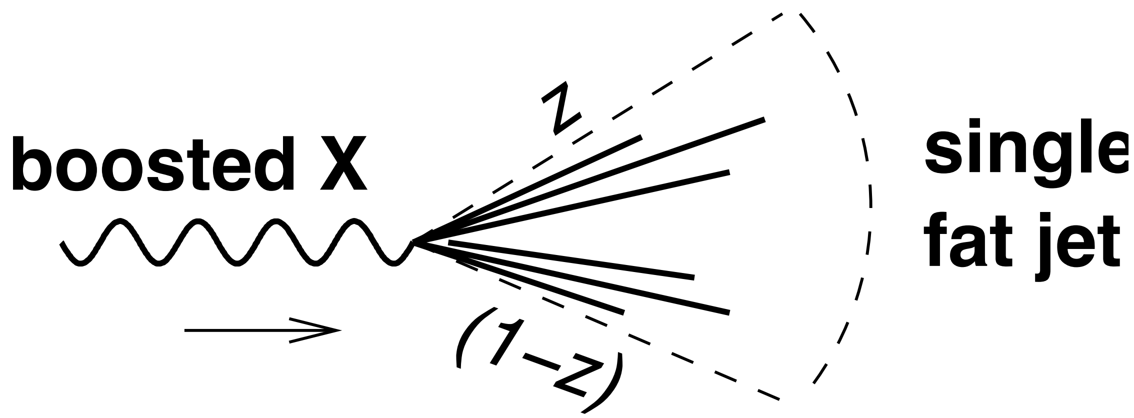
Boosted hadronic decays

(X = W, Z, H, top, new particle)

Normal analyses: two quarks from $X \to q\bar{q}$ reconstructed as two jets



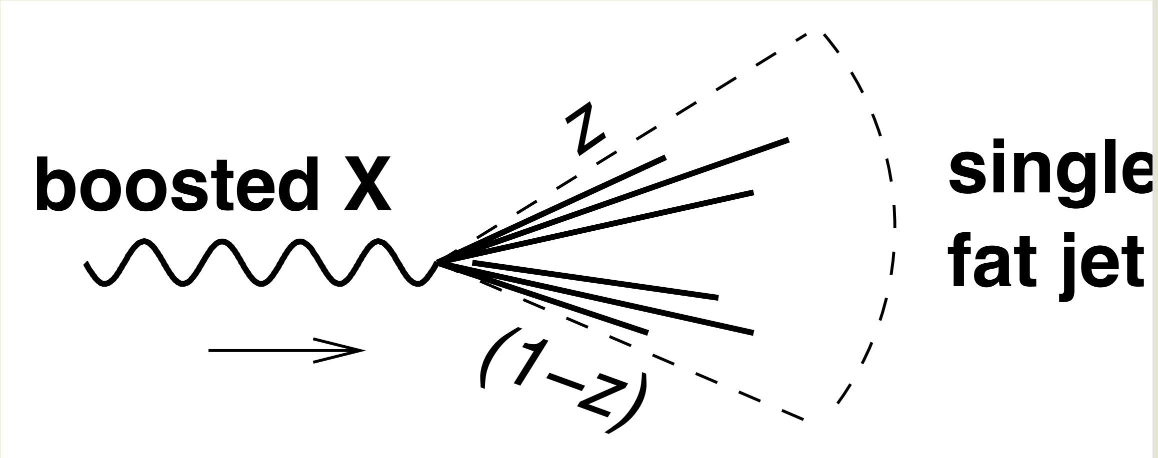
High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet



Happens for $p_t \gtrsim 2m/R$

$p_t \gtrsim 320$ GeV for $m = m_W$, $R = 0.5$

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

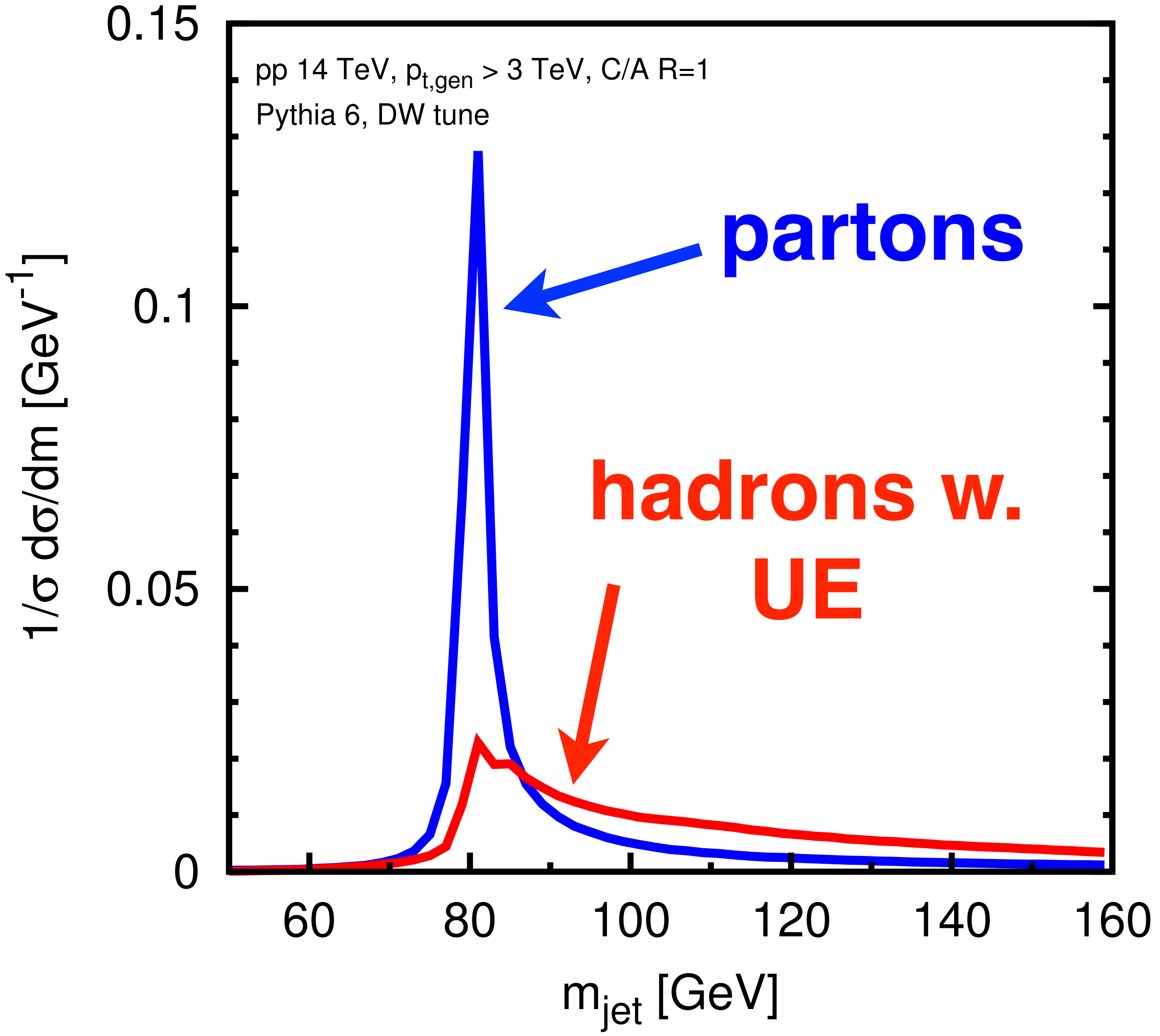


But jet mass is **poor** in practice:

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

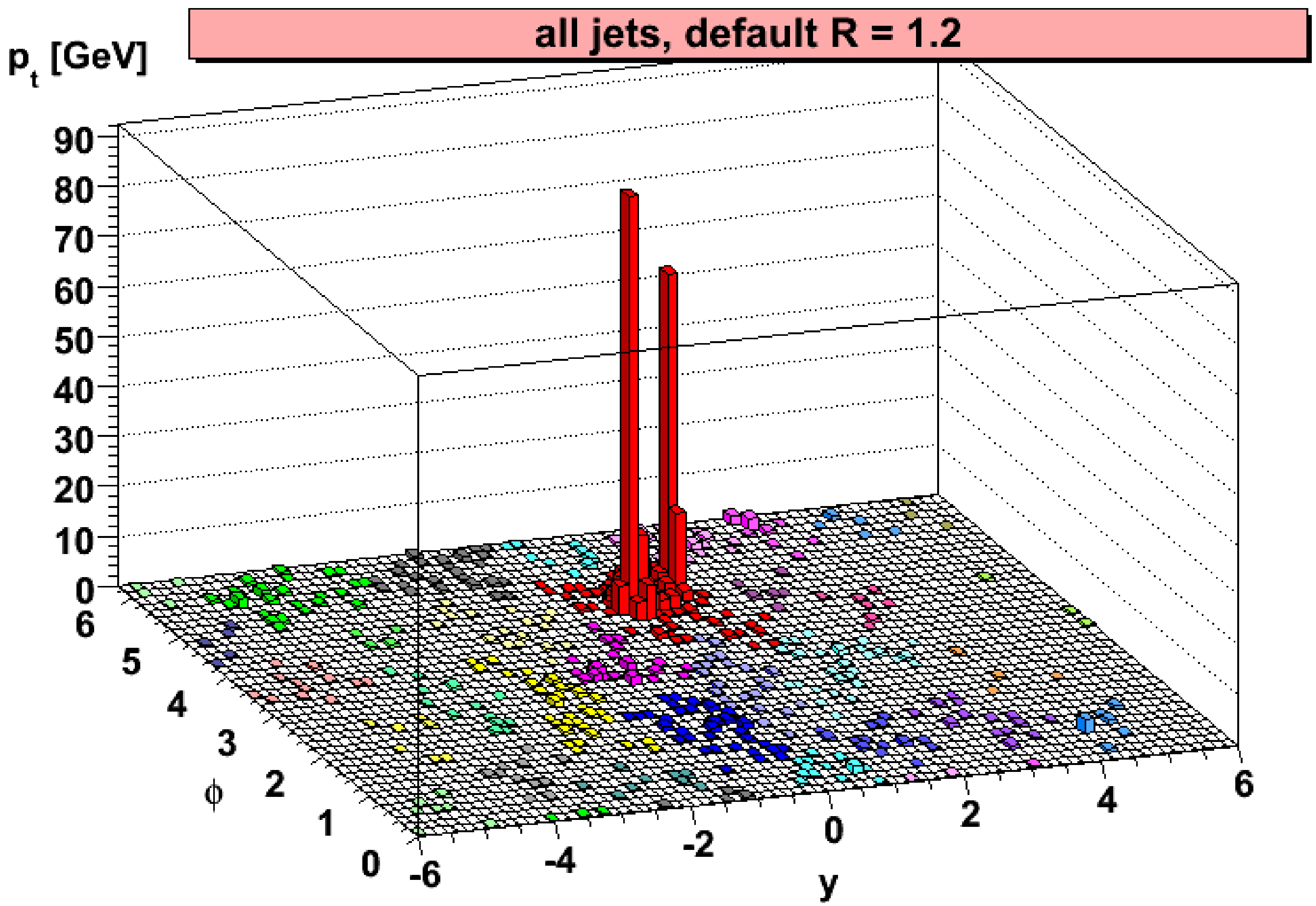
(mainly underlying event/ pileup)

jet mass distribution from W bosons



SIGNAL

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Zbb BACKGROUND

Cluster event, C/A, R=1.2

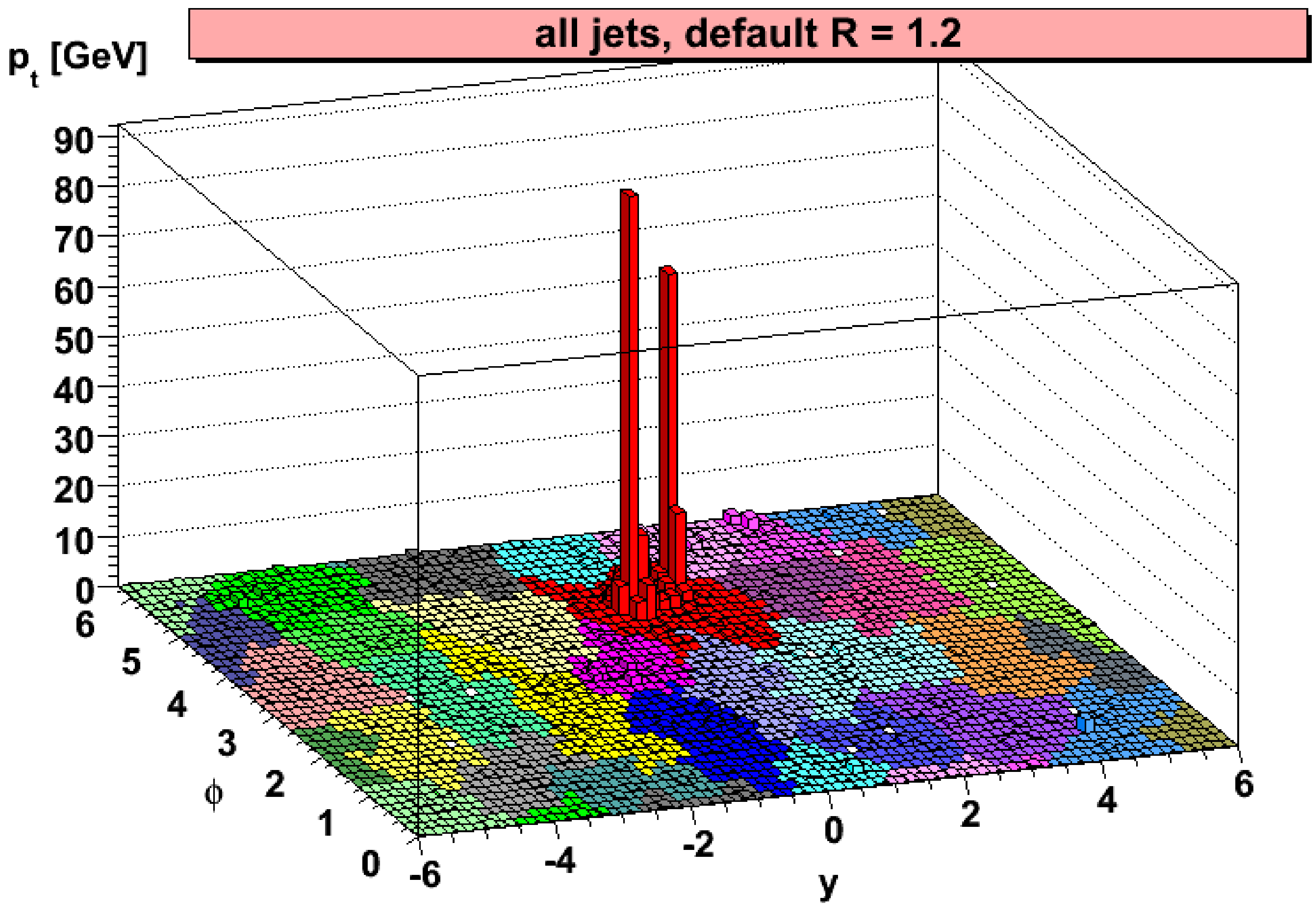
Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

SIGNAL



Zbb BACKGROUND

Fill it in, → show jets more clearly

Butterworth, Davison, Rubin & GPS '08

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

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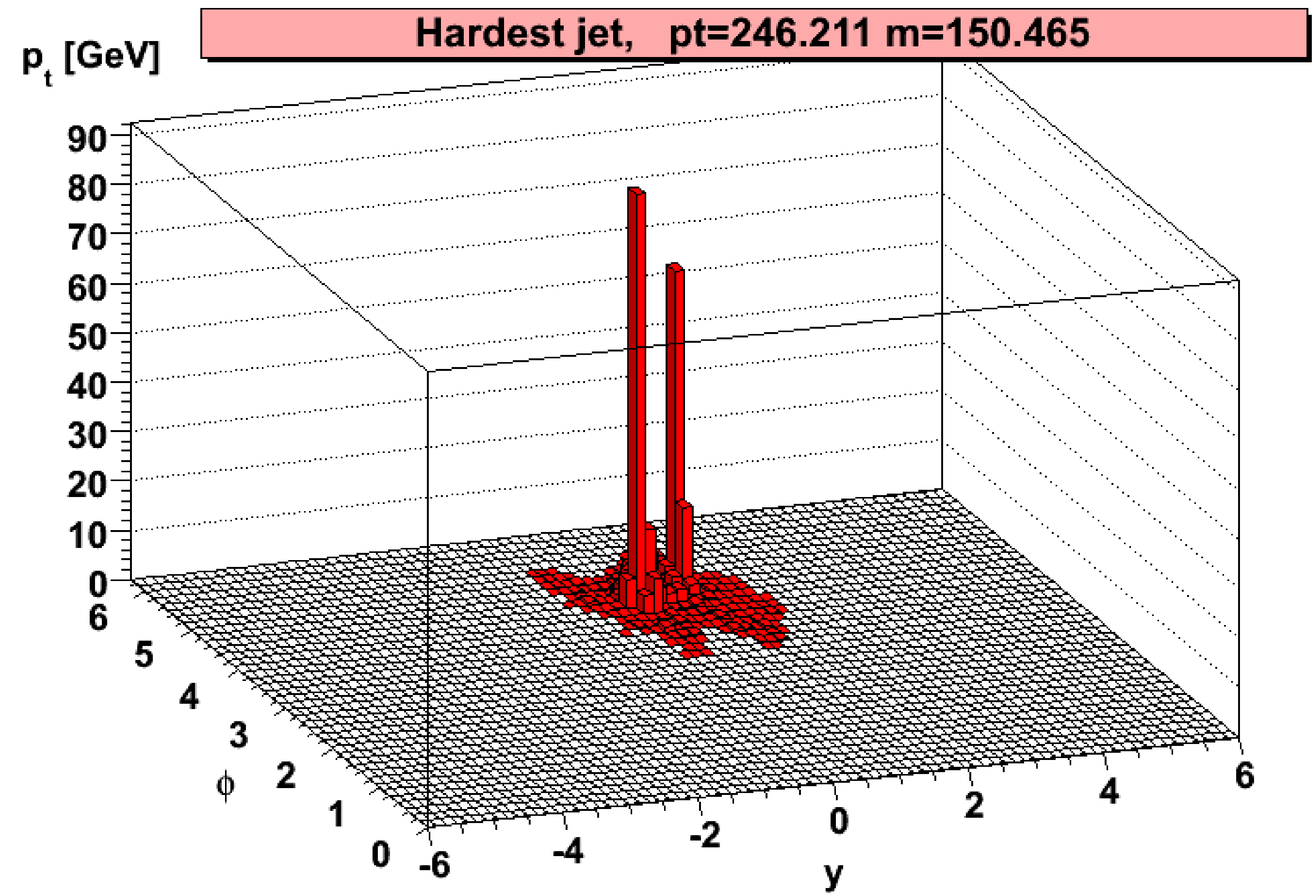
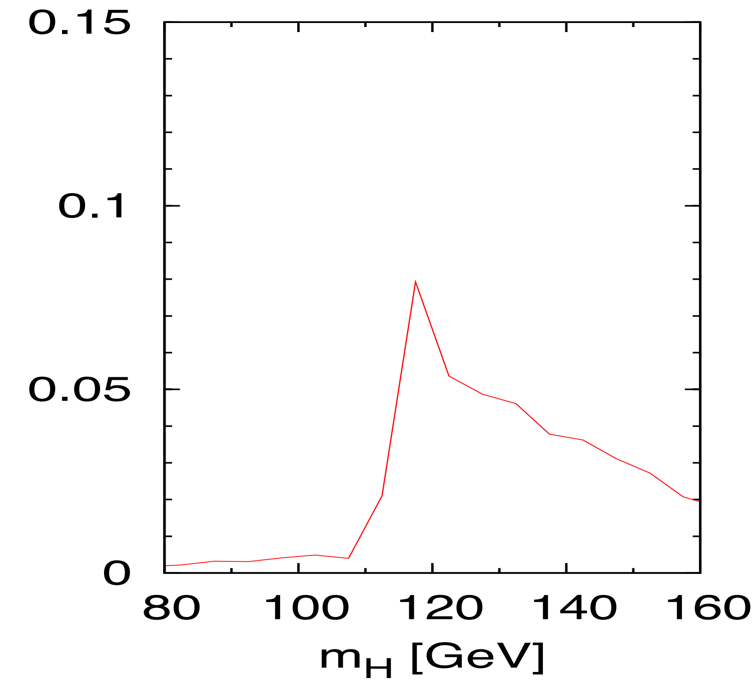


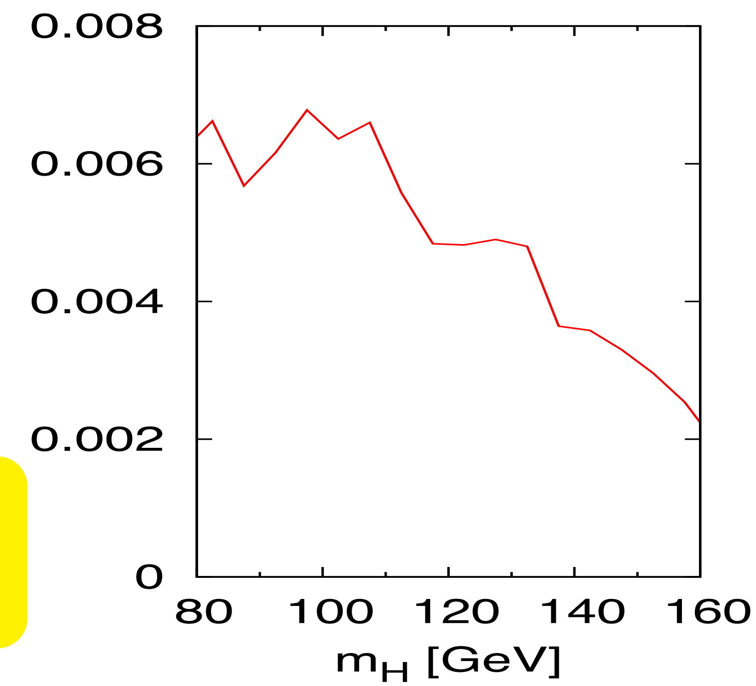
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

$200 < p_{tZ} < 250$ GeV



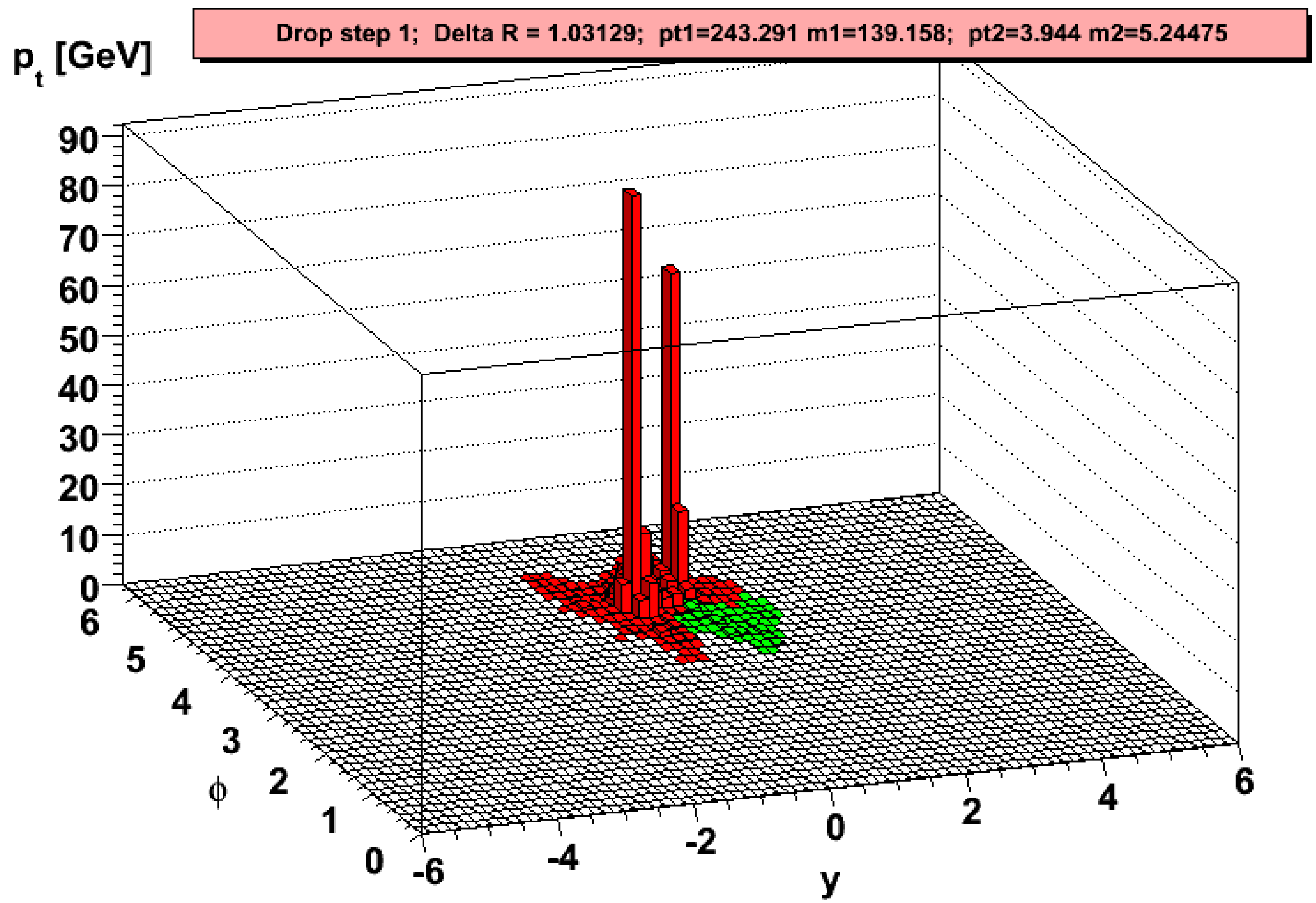
Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08

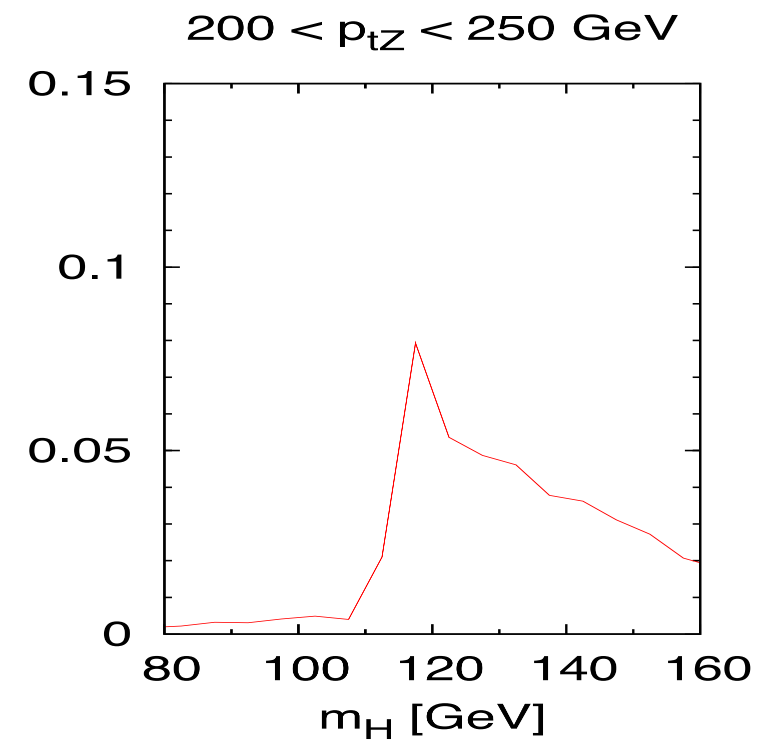
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



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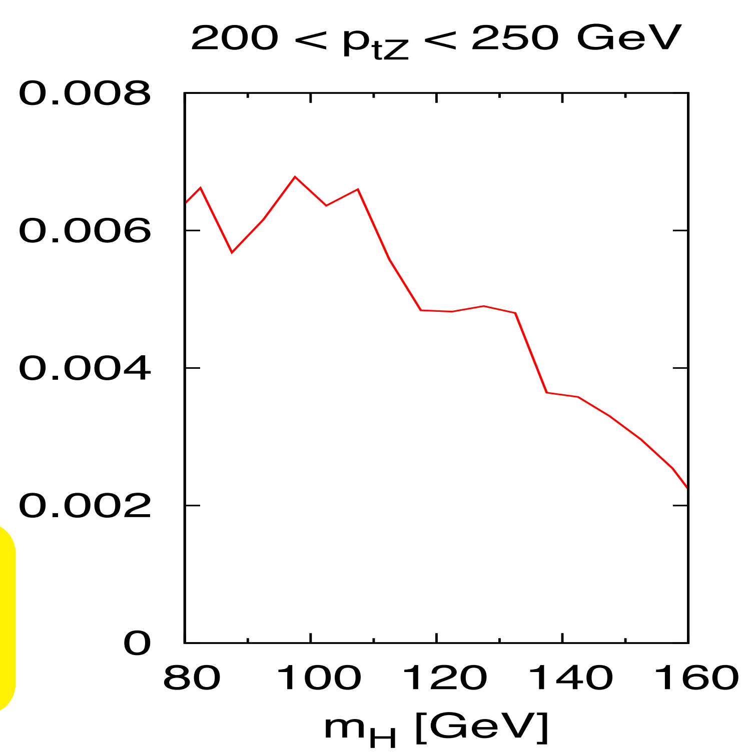

split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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

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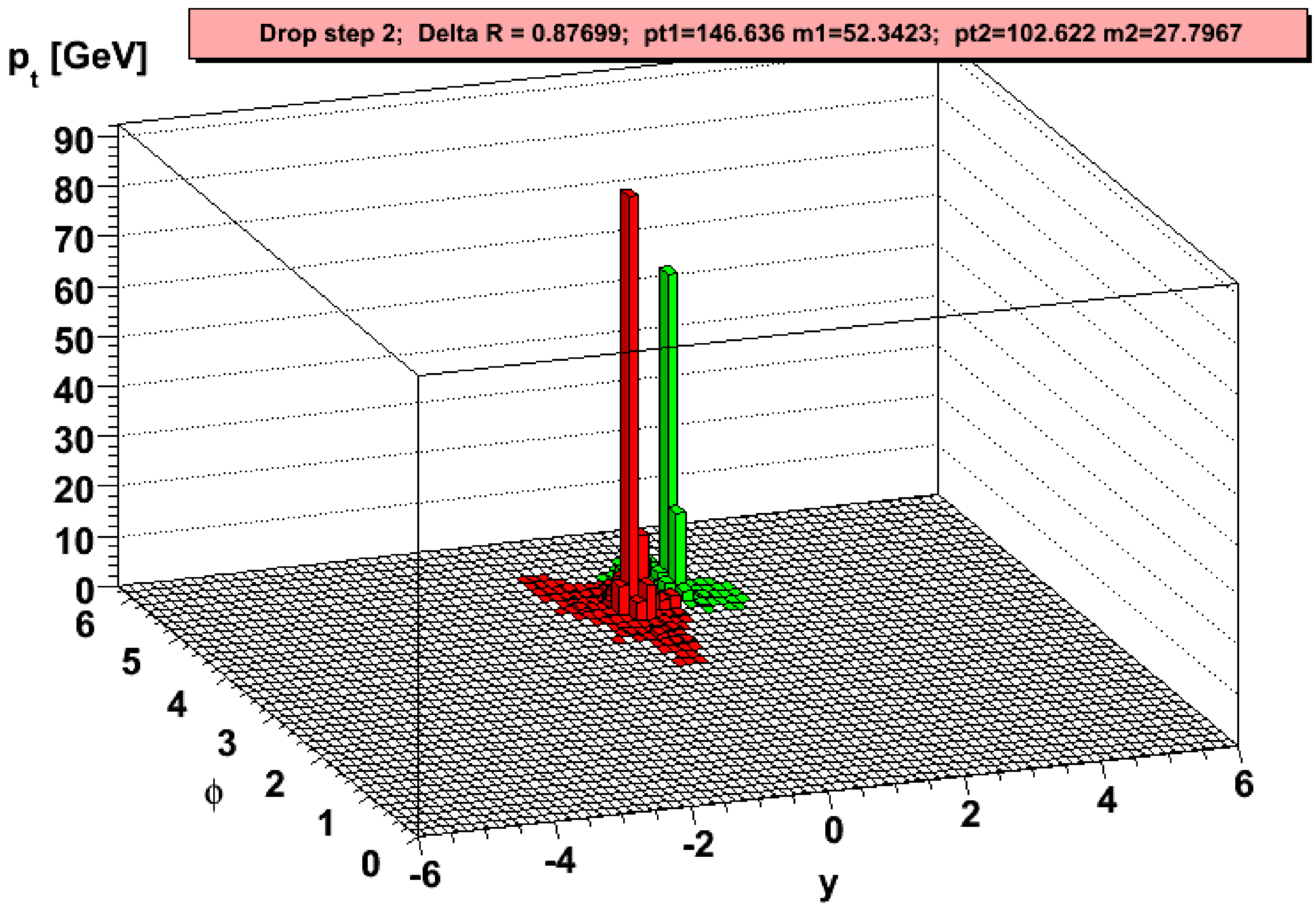

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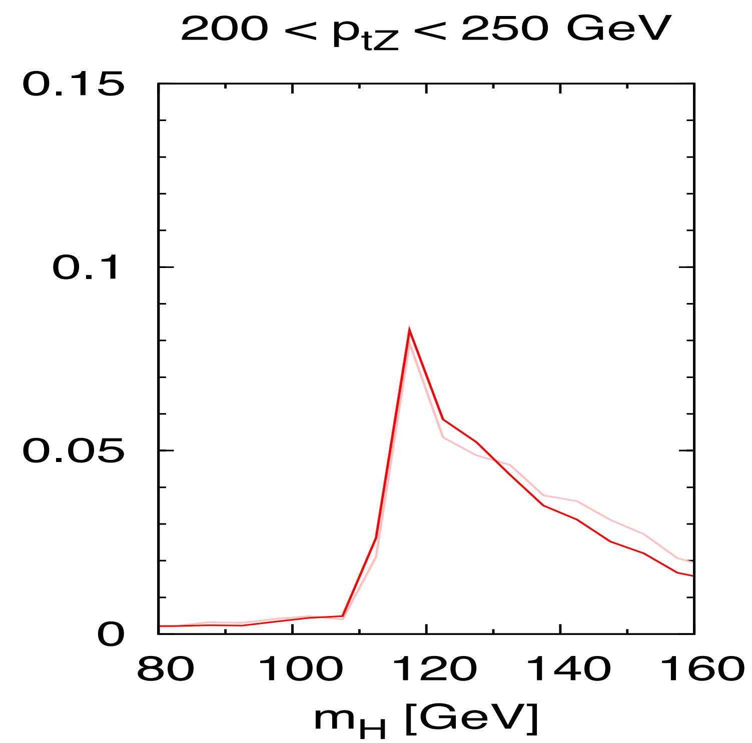

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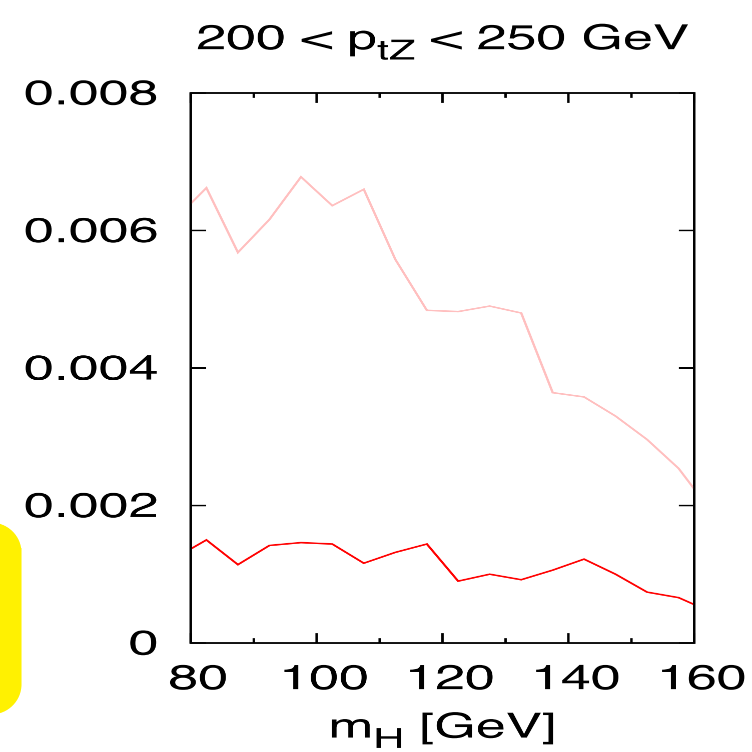


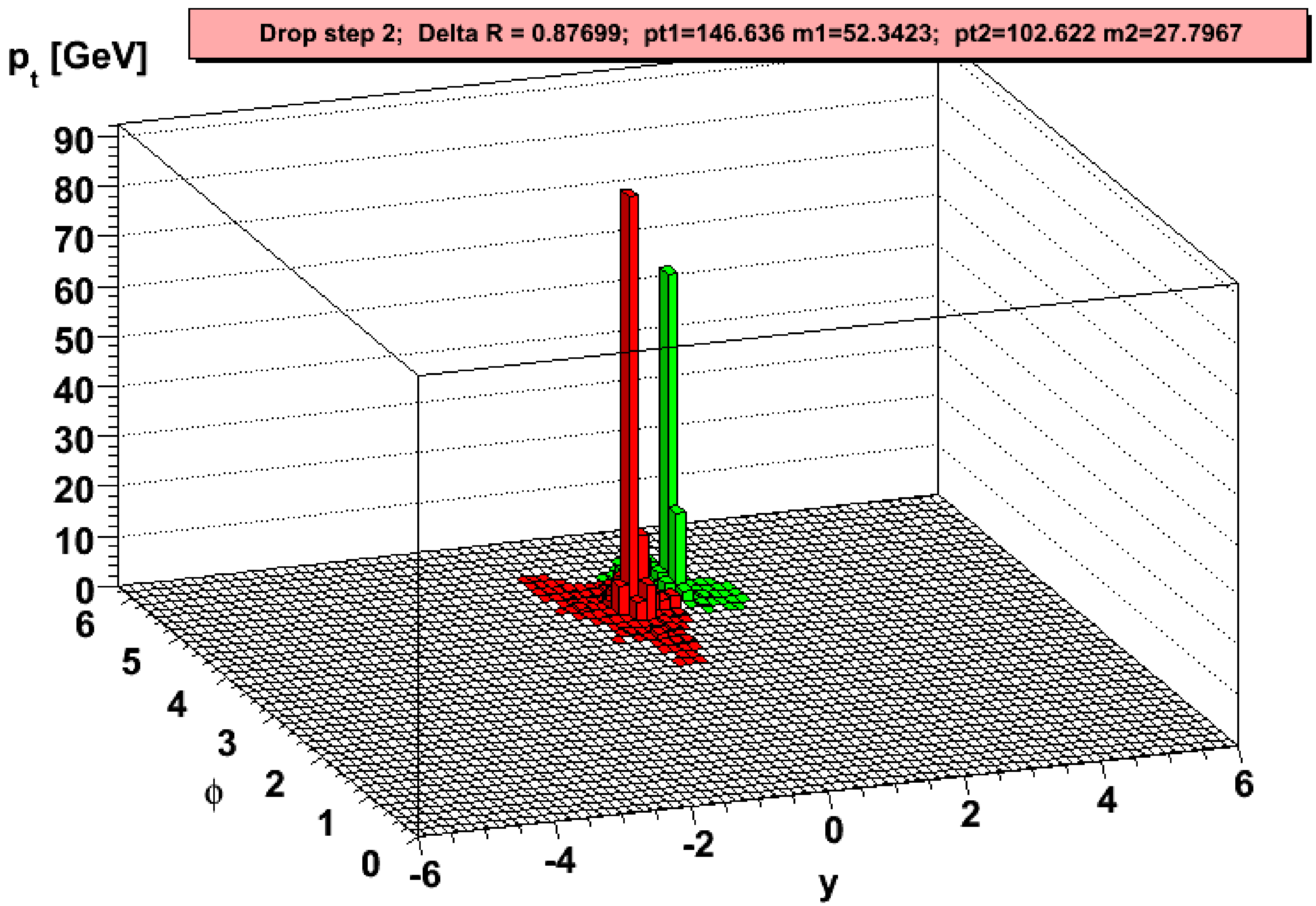
split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

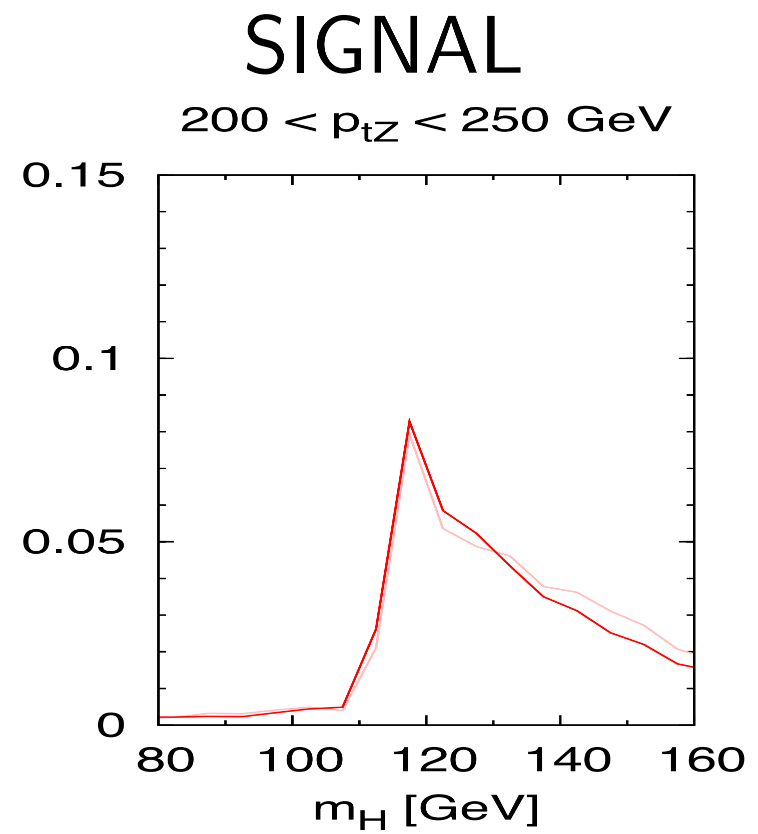
Butterworth, Davison, Rubin & GPS '08

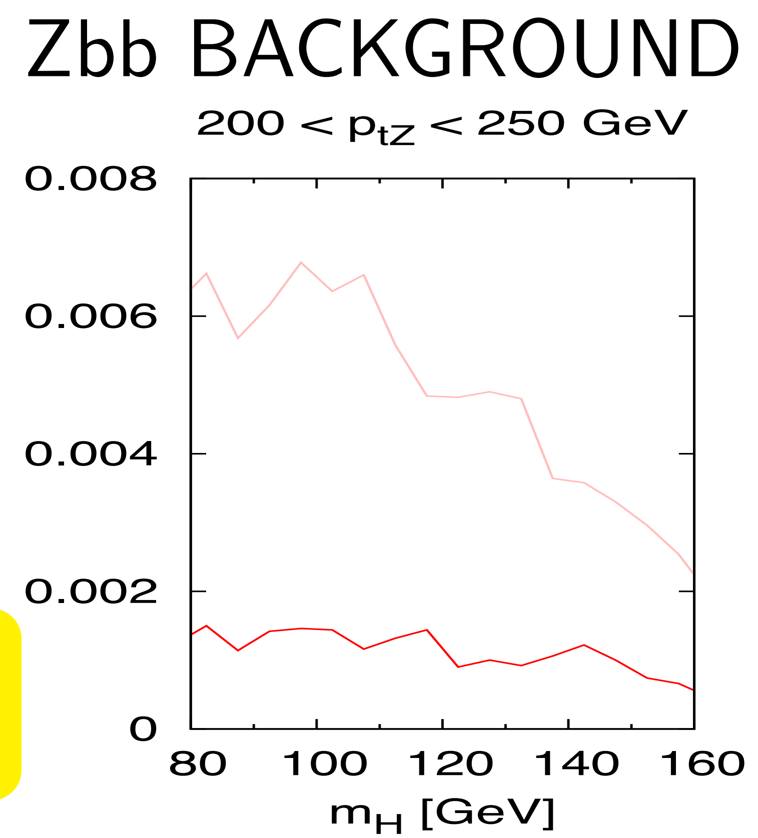
arbitrary norm.

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

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







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.

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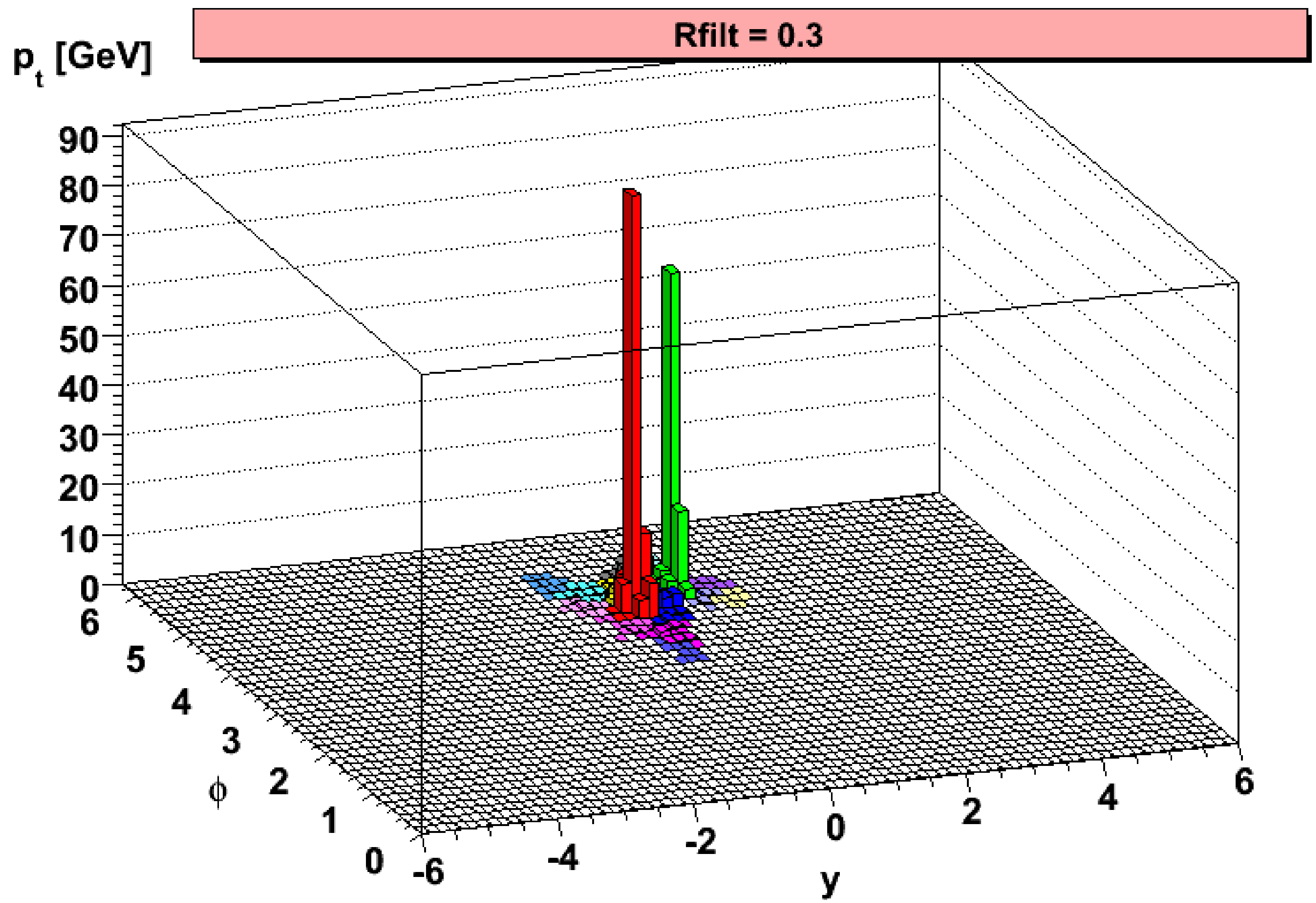

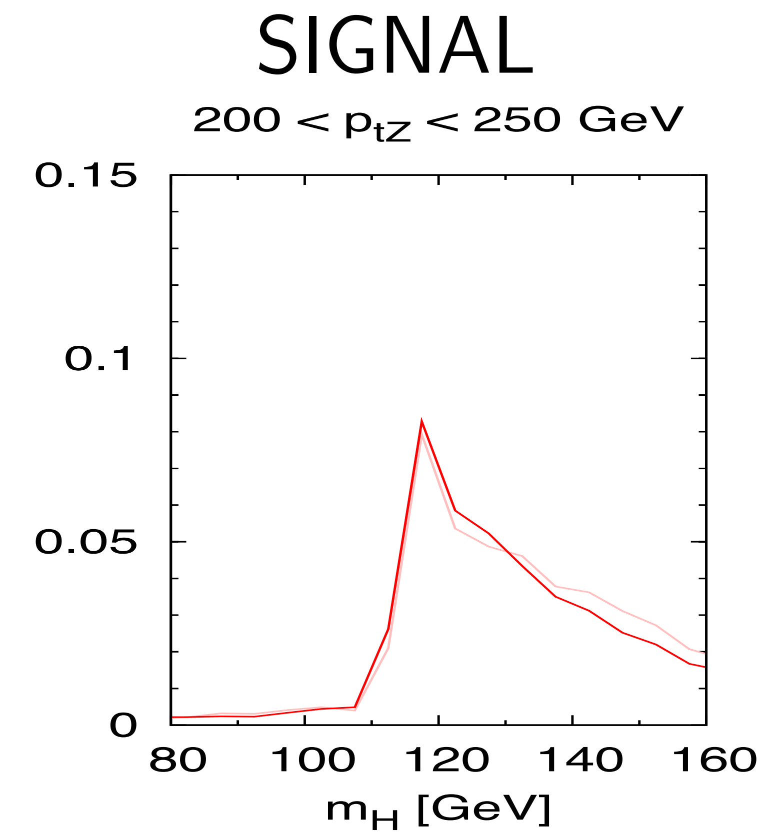

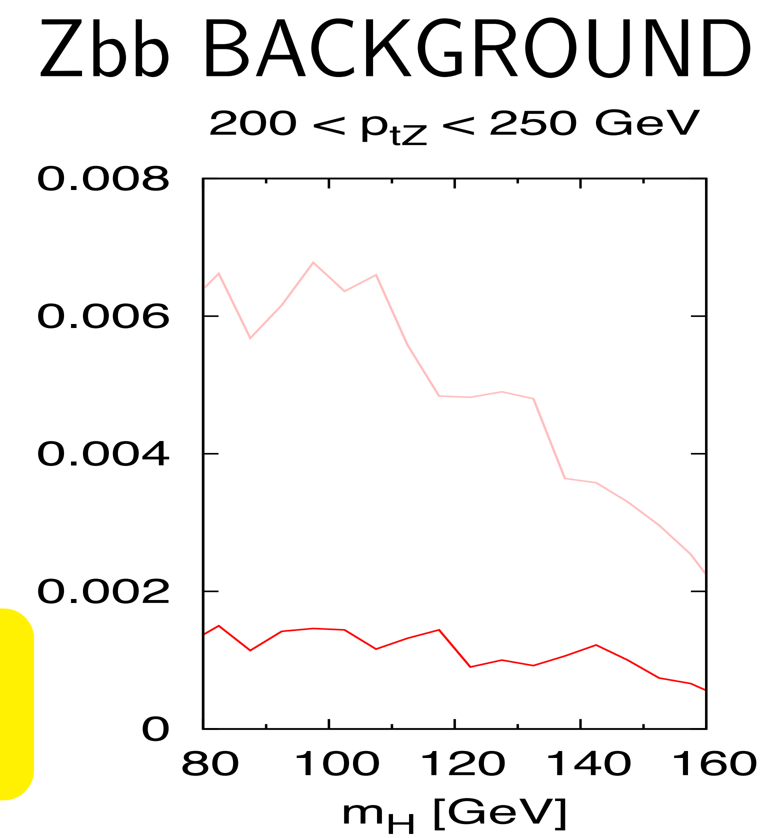

$R_{filt} = 0.3$

Butterworth, Davison, Rubin & GPS '08

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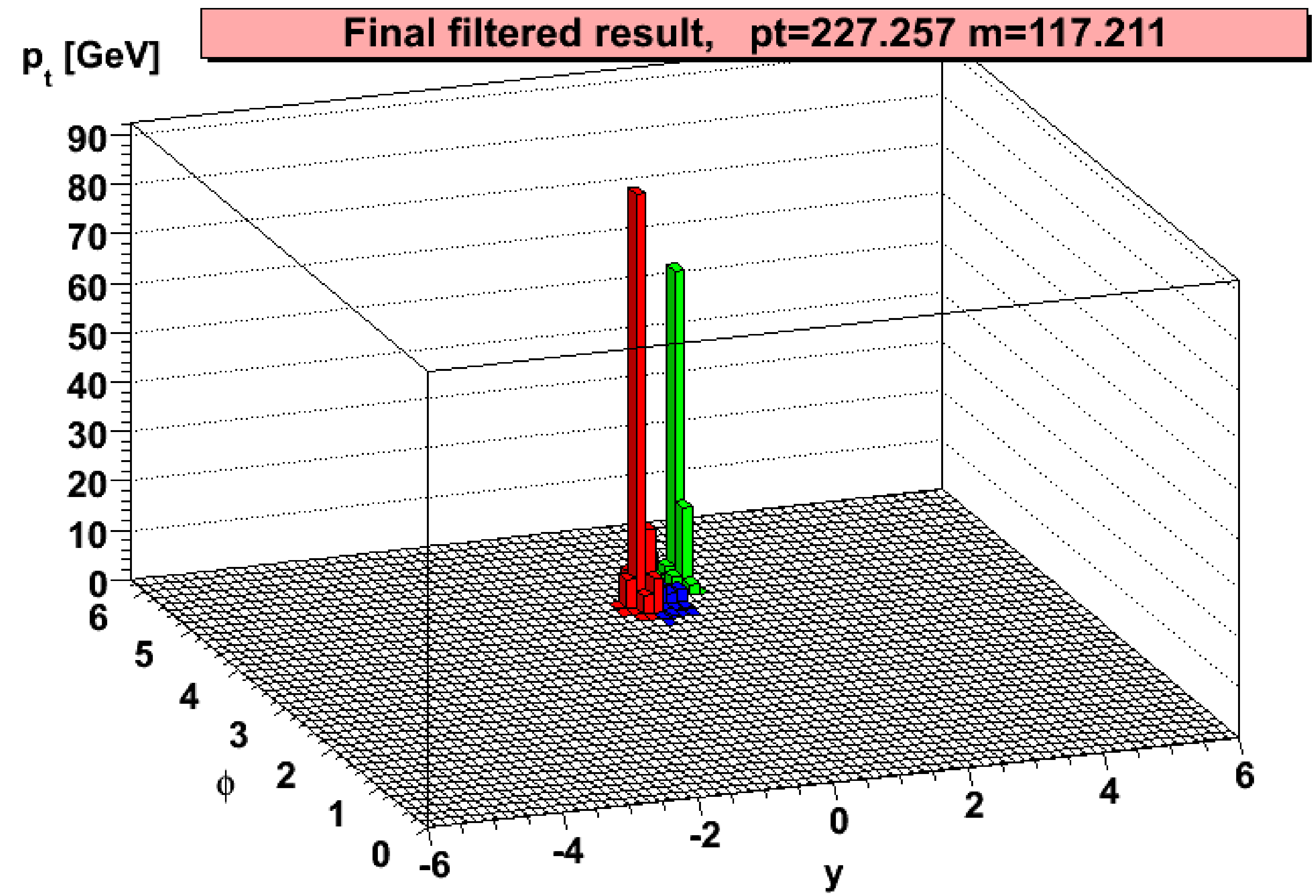
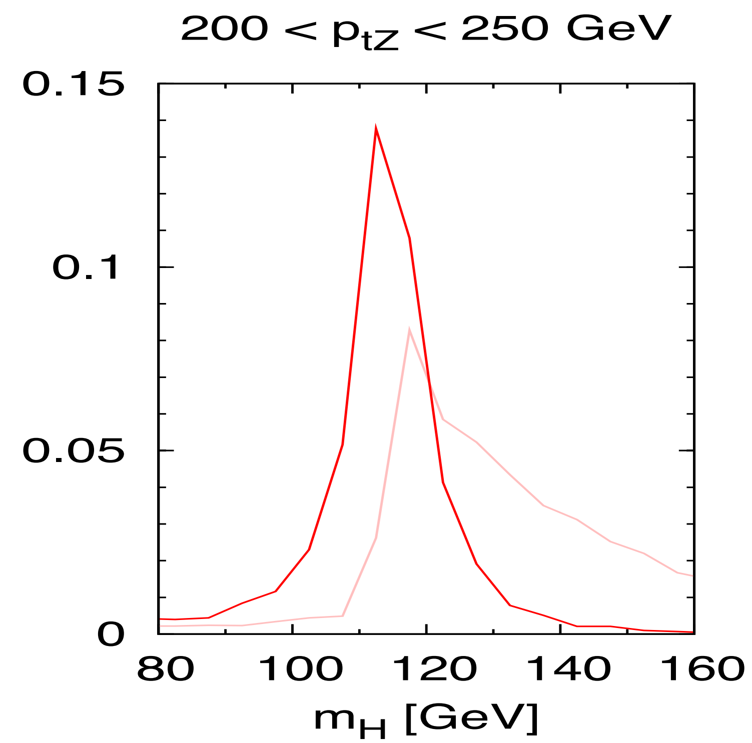
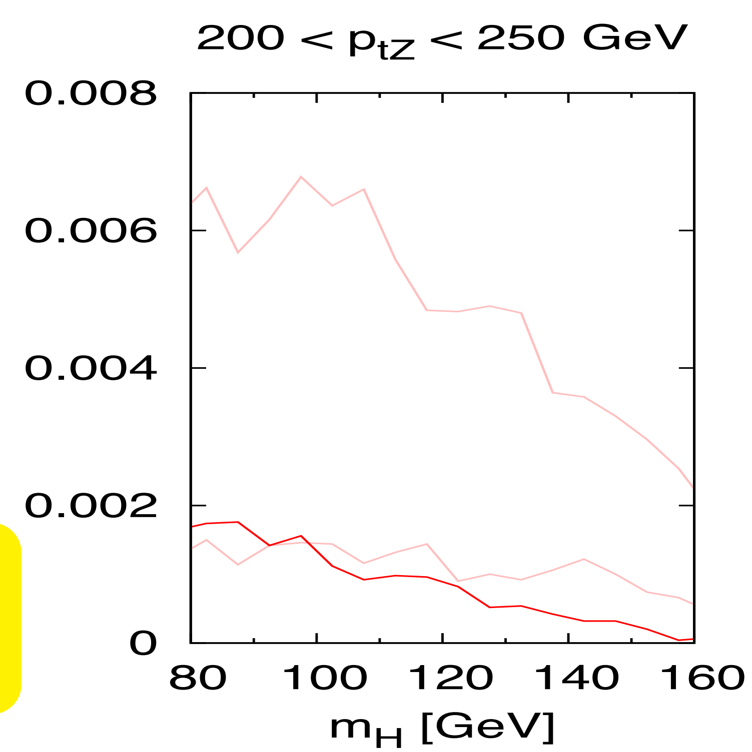


SIGNAL



Zbb BACKGROUND



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

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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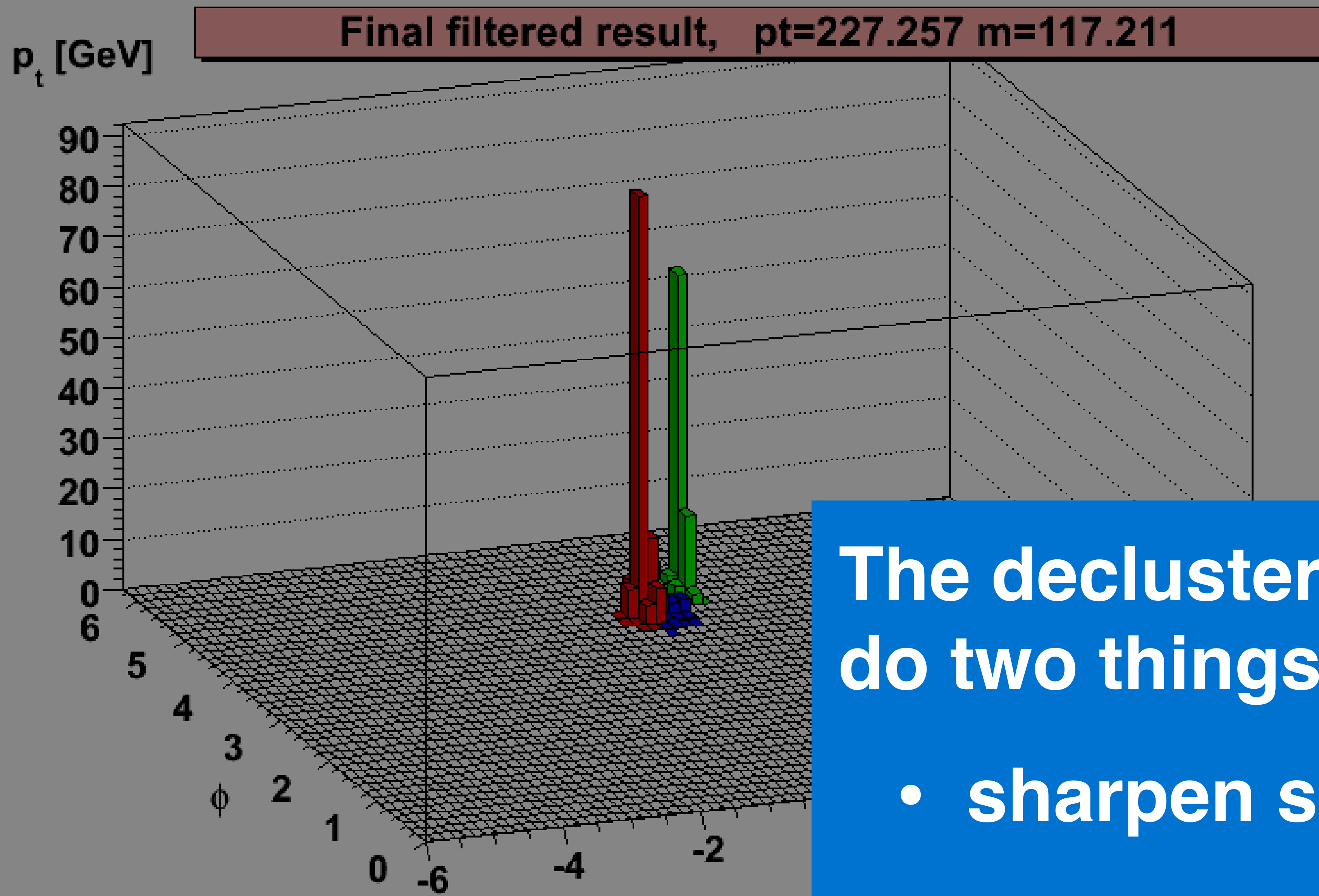
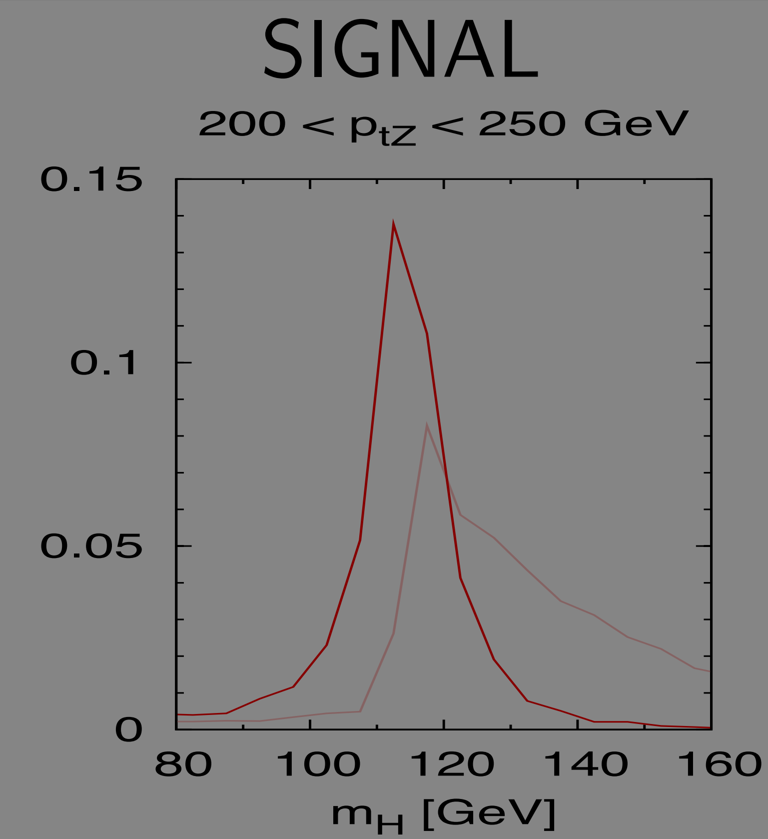
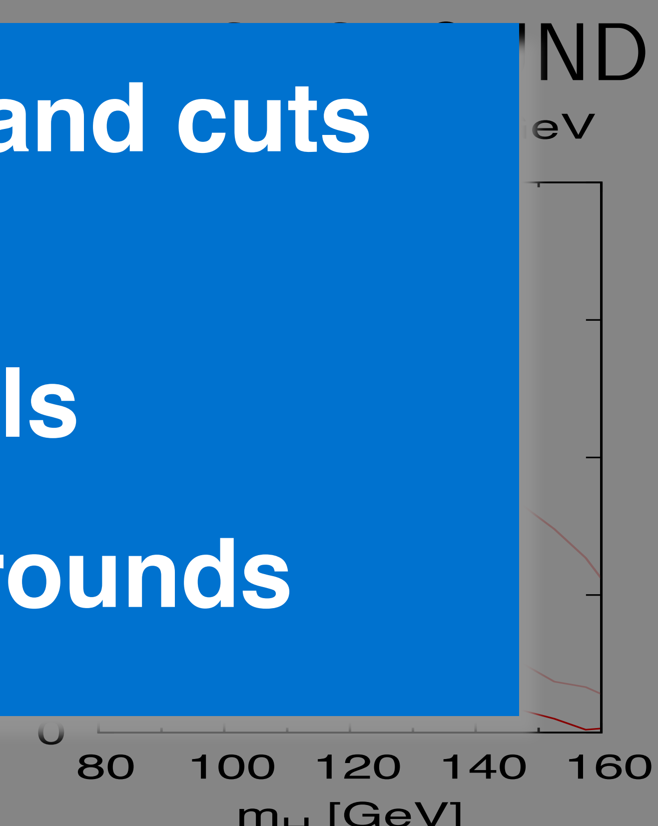
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3







The declustering and cuts do two things

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

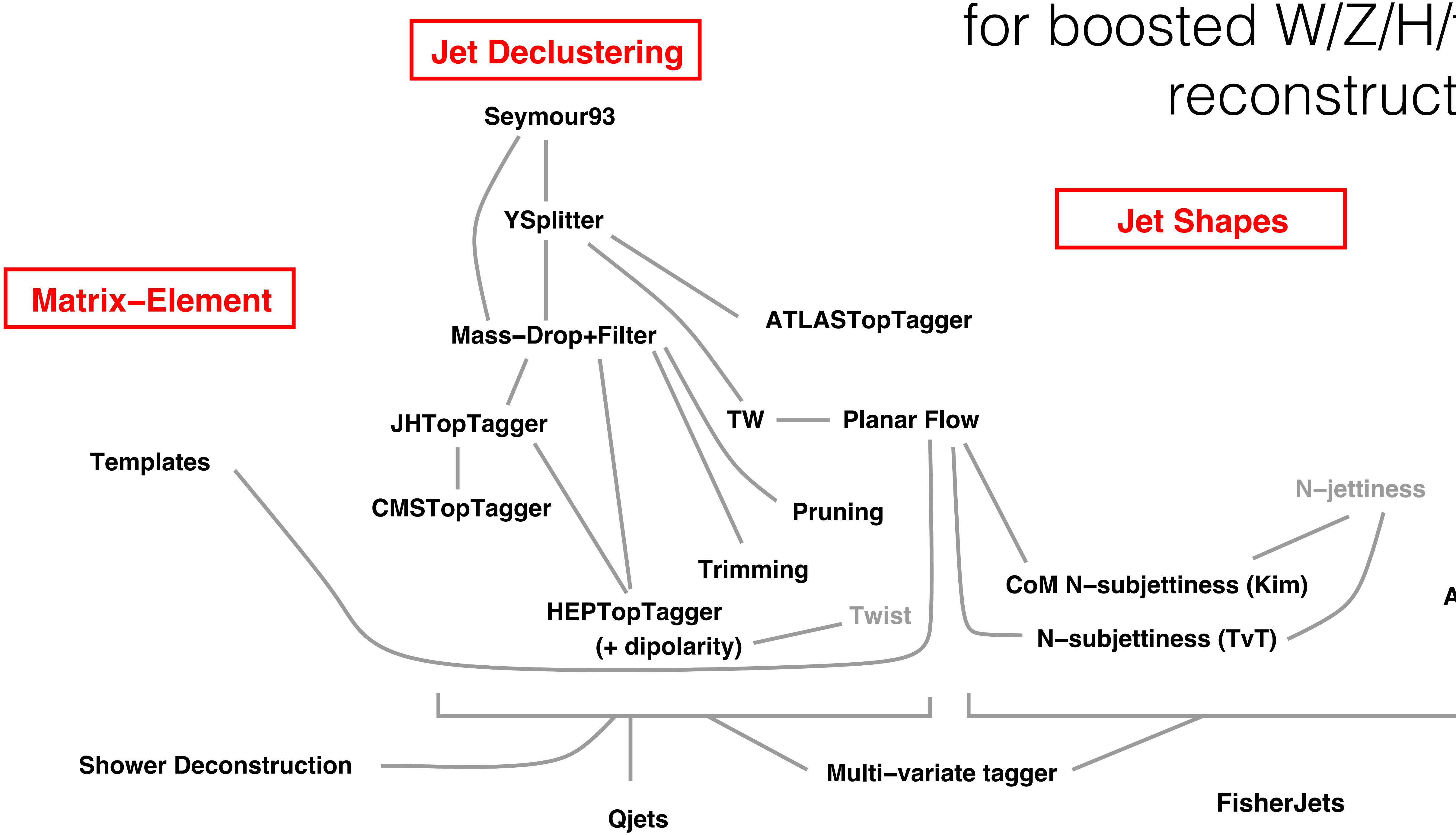
$R_{filt} = 0.3$: take 3 hardest, **m =**

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

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

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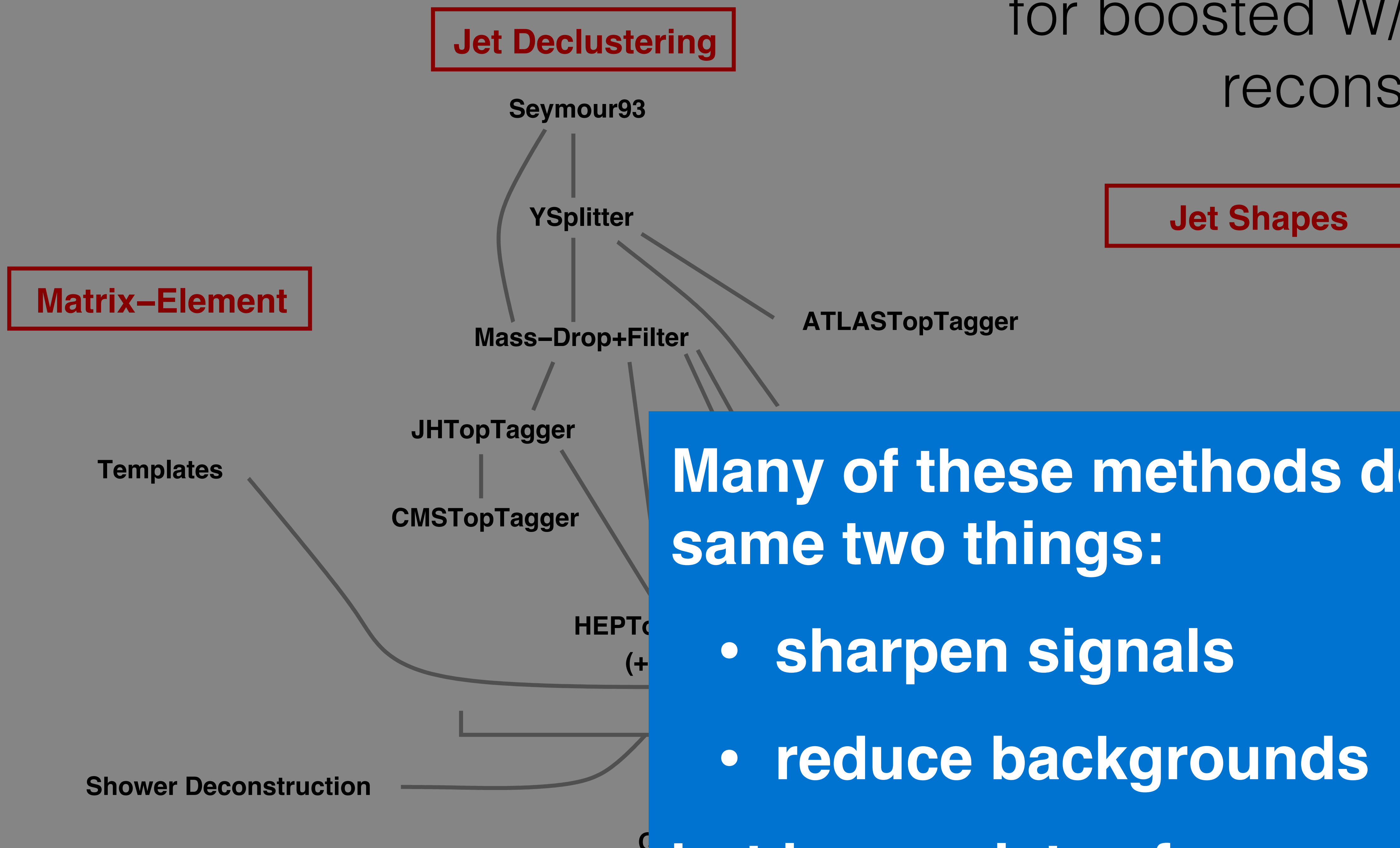


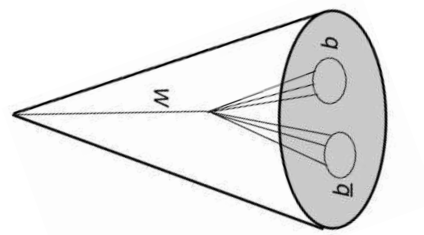
Many of these methods do the same two things:

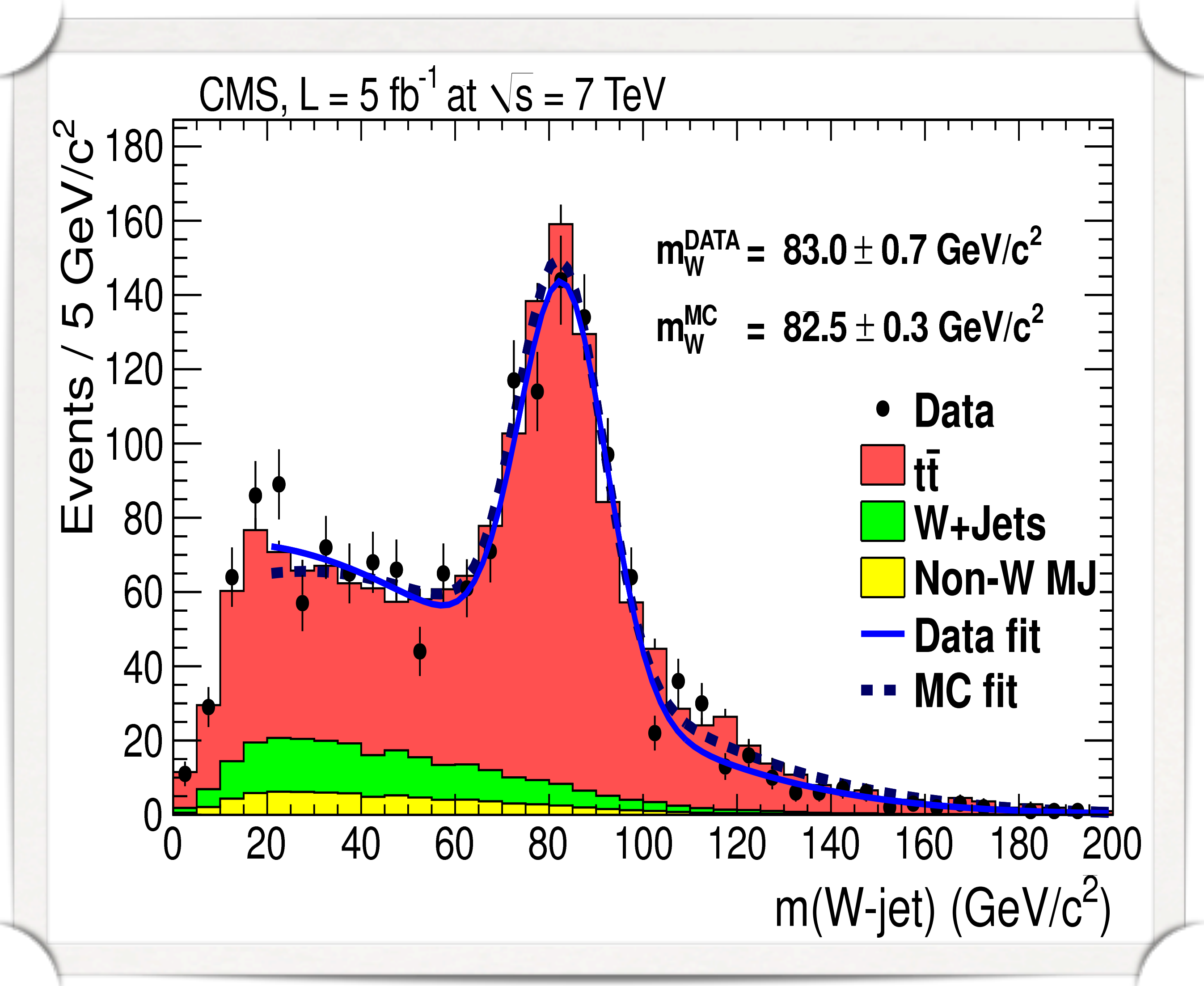
- **sharpen signals**
- **reduce backgrounds**

but in a variety of ways

Seeing hadronic W's and tops in a single jet

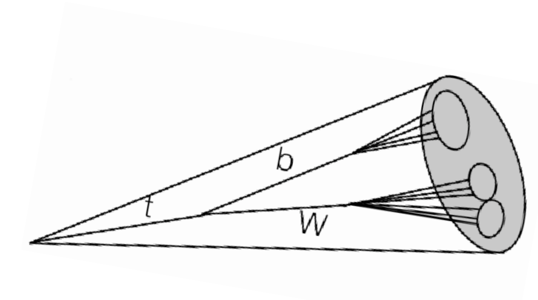
W's in a single jet

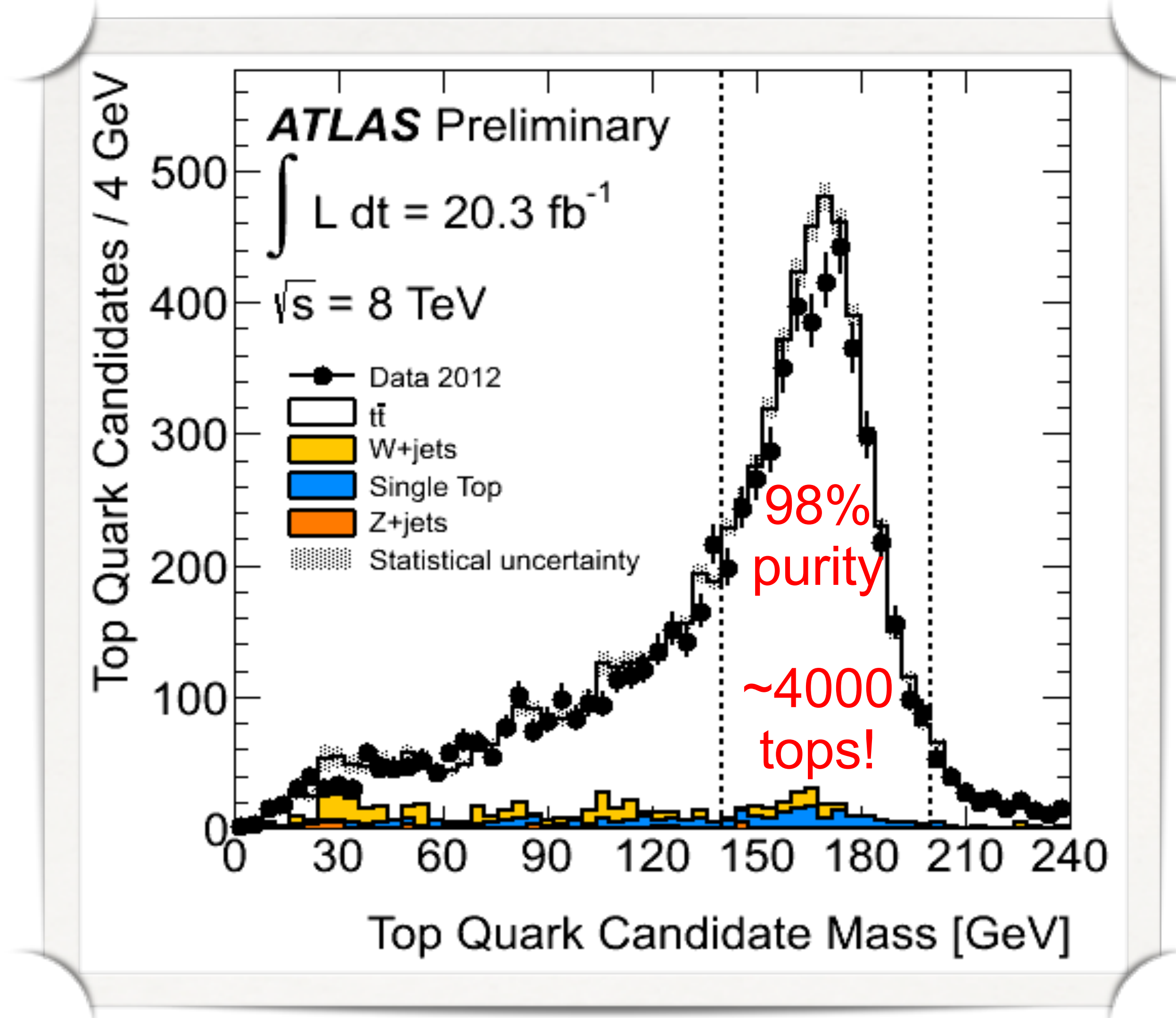




Pruning applied to C/A jets in events that have a W→ l ν and b tags

tops in a single jet





C/A R=1.5 jets with p_T > 200 GeV after W→μν preselection and default HEPTopTagger criteria

Extensive experimental work

Recent ATLAS & CMS preprints citing jet substructure work

Jet Cross-Section Measurements In CMS
CMS Collaboration
Inspire. arXiv:1306.6604 (ps, pdf). Int.J.Mod.Phys. A28 (2013) 1330030.

Performance of jet substructure techniques for large-R jets in proton-proton collisions at $\sqrt{s}$ = 7 TeV using the ATLAS detector
ATLAS Collaboration
Inspire. arXiv:1306.4945 (ps, pdf). JHEP 1309 (2013) 076. 16 cites [co]

Measurement of jet shapes in top pair events at $\sqrt{s}$ = 7 TeV using the ATLAS detector
ATLAS Collaboration
Inspire. arXiv:1307.5749 (ps, pdf).

Searches for New Physics in Multijet Final States
for the CMS Collaboration
Inspire. arXiv:1307.2518 (ps, pdf).

Search for Single and Pair-Production of Dijet Resonances with the CMS Detector
CMS Collaboration
Inspire. arXiv:1307.1400 (ps, pdf). J.Phys.Conf.Ser. 455 (2013) 012034. 1 cites [co]

Search for dark matter in events with a hadronically decaying W or Z boson and missing transverse momentum in pp collisions at $\sqrt{s}$=8 TeV with the ATLAS detector
ATLAS Collaboration
Inspire. arXiv:1309.4017 (ps, pdf). 5 cites [co]

Searches for anomalous ttbar production in pp collisions at $\sqrt{s}$=8 TeV
CMS Collaboration
Inspire. arXiv:1309.2030 (ps, pdf). 6 cites [co]

Search for heavy resonances decaying to top quarks
for the CMS Collaboration
Inspire. arXiv:1310.8183 (ps, pdf).

Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks
CMS Collaboration
Inspire. arXiv:1310.3687 (ps, pdf). 3 cites [co]

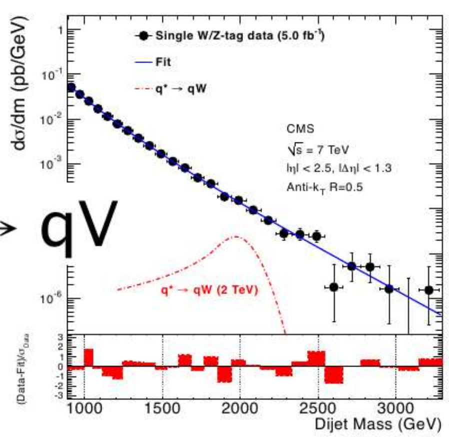
Search for the SM Higgs Boson Produced in Association with a Vector Boson and Decaying to Bottom Quarks
for the CMS Collaboration
Inspire. arXiv:1310.3551 (ps, pdf).

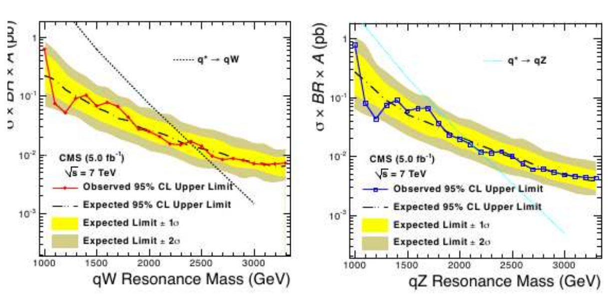
Inclusive search for a vector-like T quark with charge 2/3 in pp collisions at $\sqrt{s}$=8 TeV
CMS Collaboration
Inspire. arXiv:1311.7667 (ps, pdf).

Search for top-quark partners with charge 5/3 in the same-sign dilepton final state
CMS Collaboration
Inspire. arXiv:1312.2391 (ps, pdf).

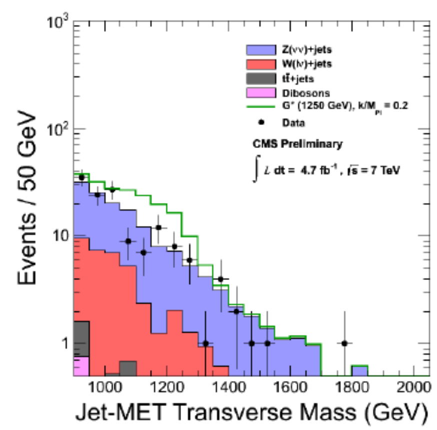
Searches with substructure tools

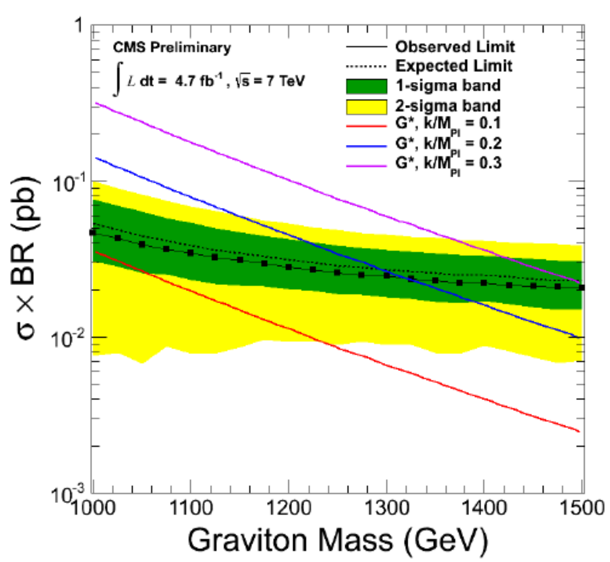
X → qV

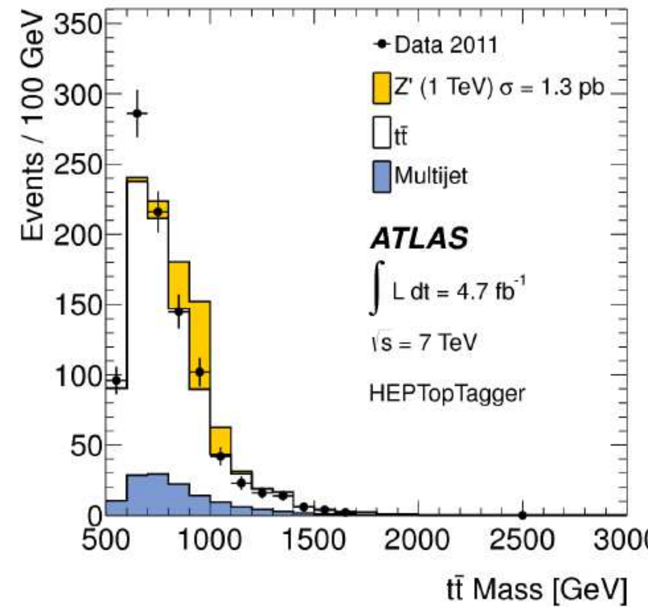


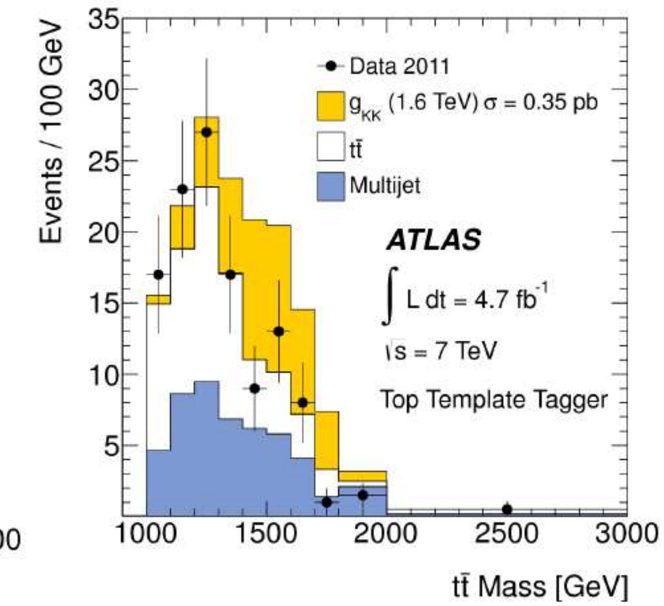


X → ZZ → 2ν2q

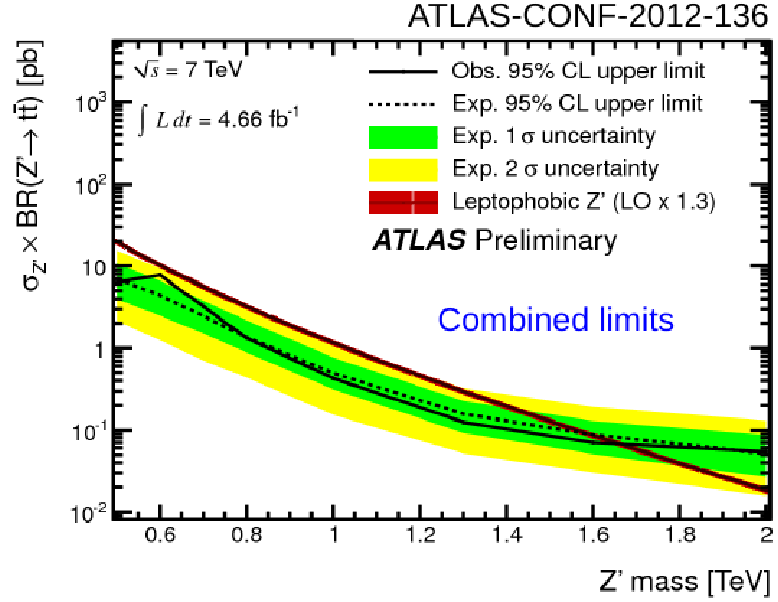








ATLAS-CONF-2012-136



A range of techniques being used for varied BSM scenarios

developing an understanding – “jetography”

What do different tools do the same/differently?

Are they exploiting all relevant physics?

What methods can we reliably use to predict their behaviour?

[These tools will become ever more common at 14 TeV]

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

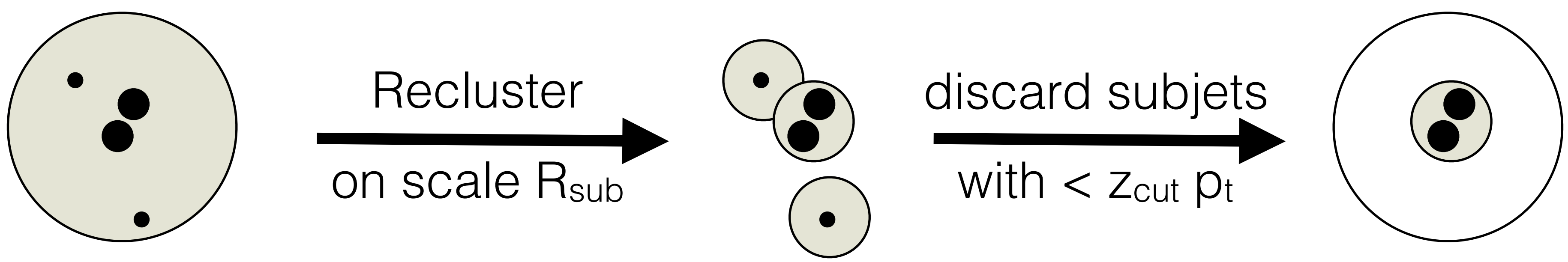
But you need to start somewhere.
We chose the QCD jets because:

(a) they have the richest structure.

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

Cannot possibly study all tools
These 3 are widely used

Trimming



study 3 taggers/groomers

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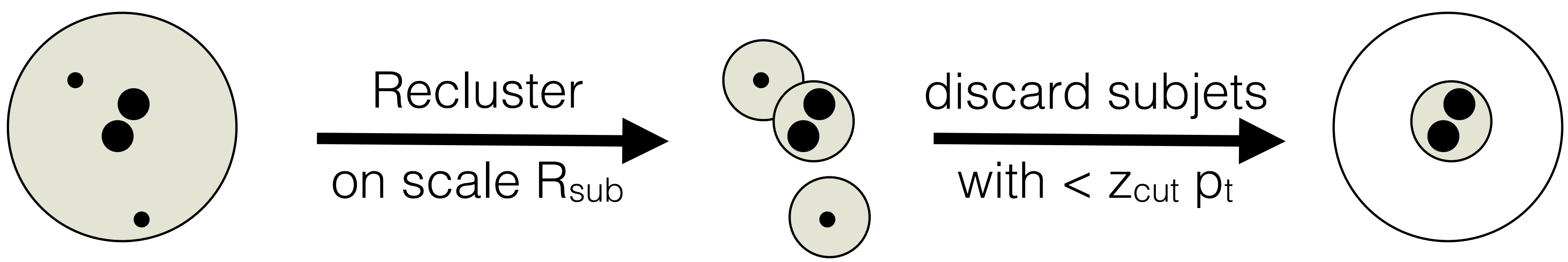
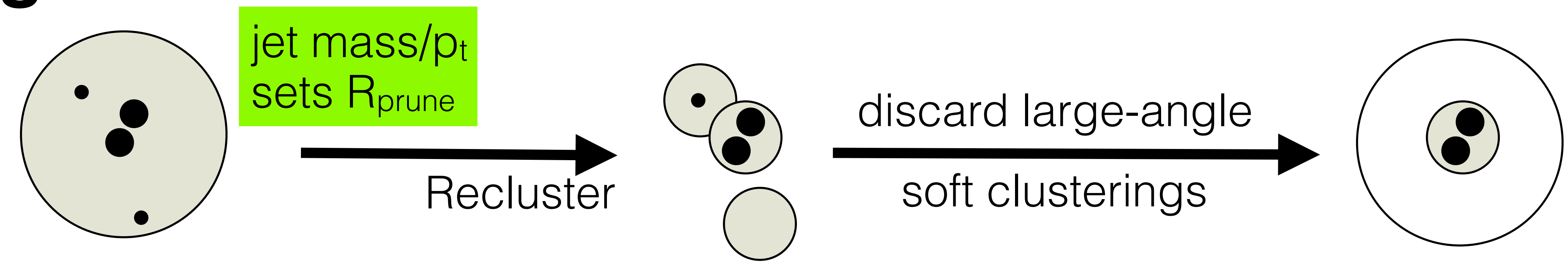


Pruning



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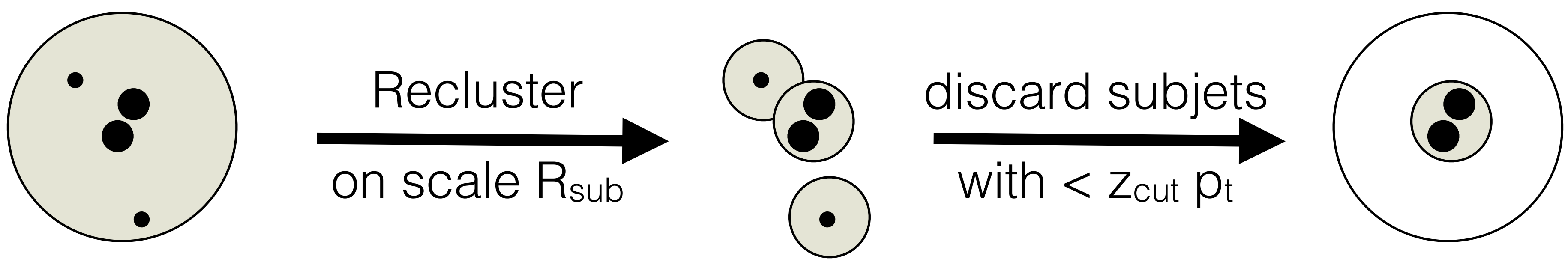

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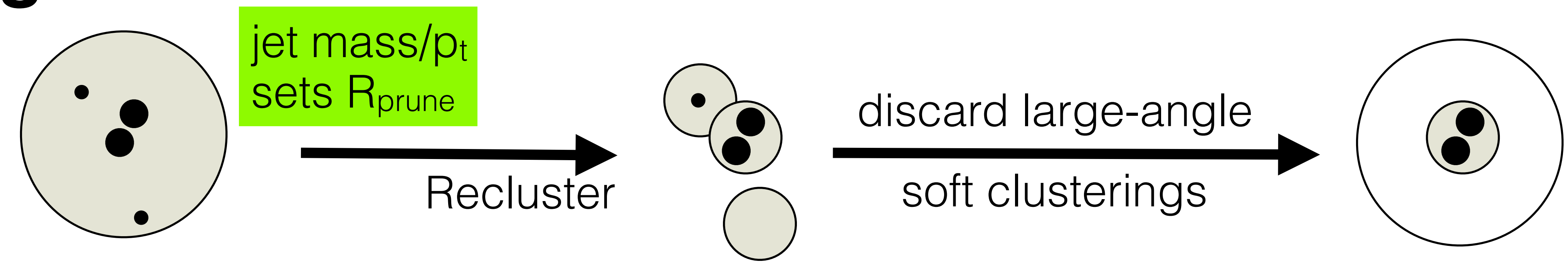
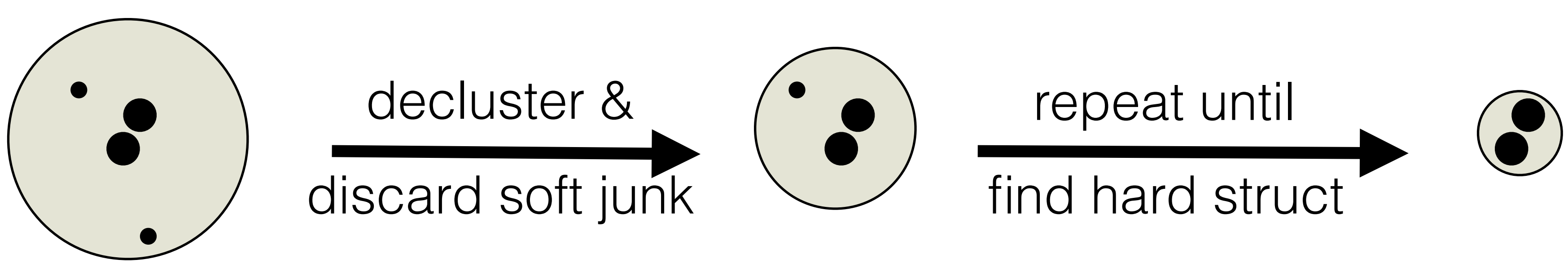


Mass-drop tagger (MDT, aka BDRS)



The key variables

For phenomenology

Jet mass: *m*

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

For QCD calculations

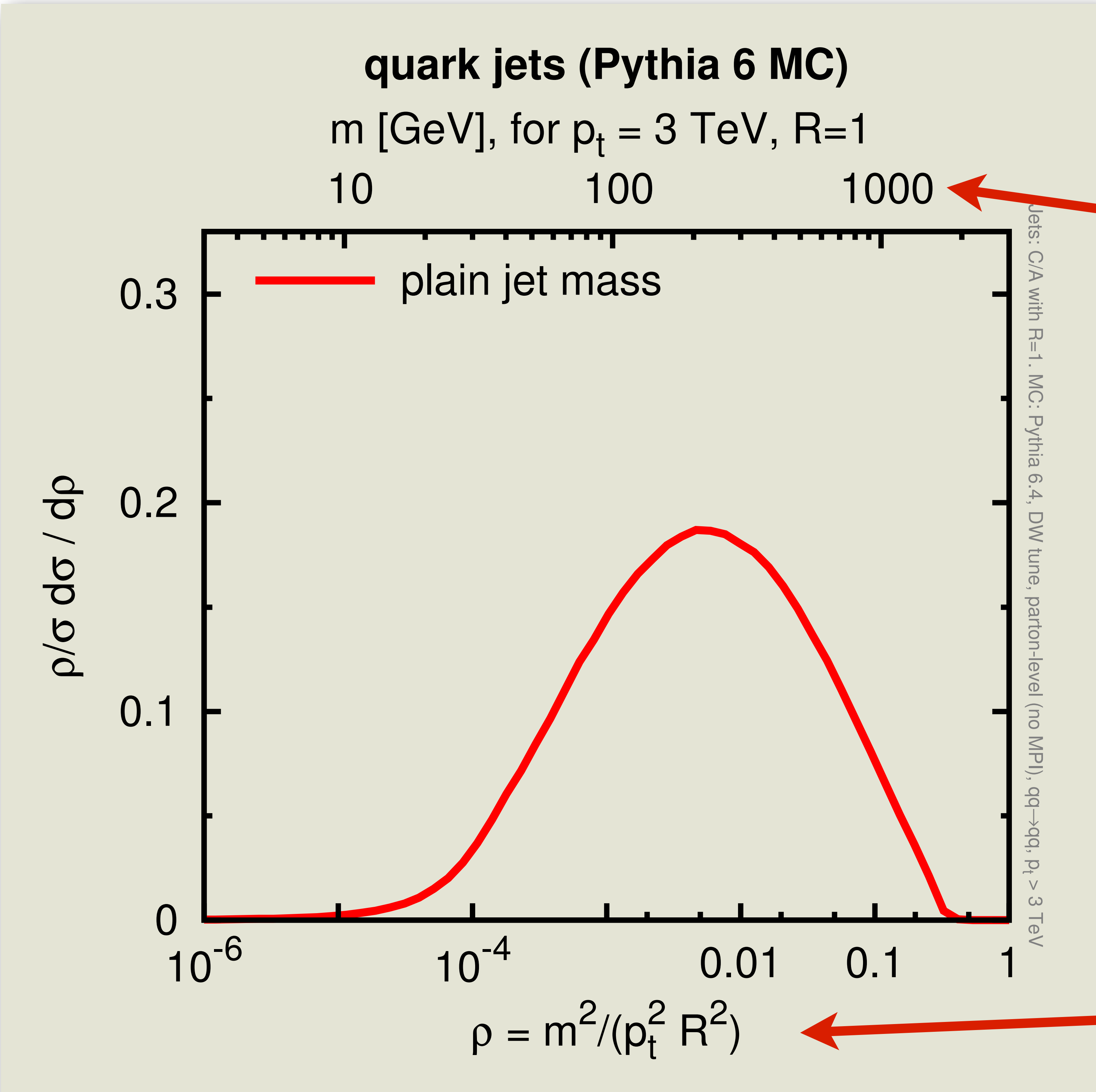
$$\rho = \frac{m^2}{p_t^2 R^2}$$

[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 mass^2

(i.e. the QCD variable)

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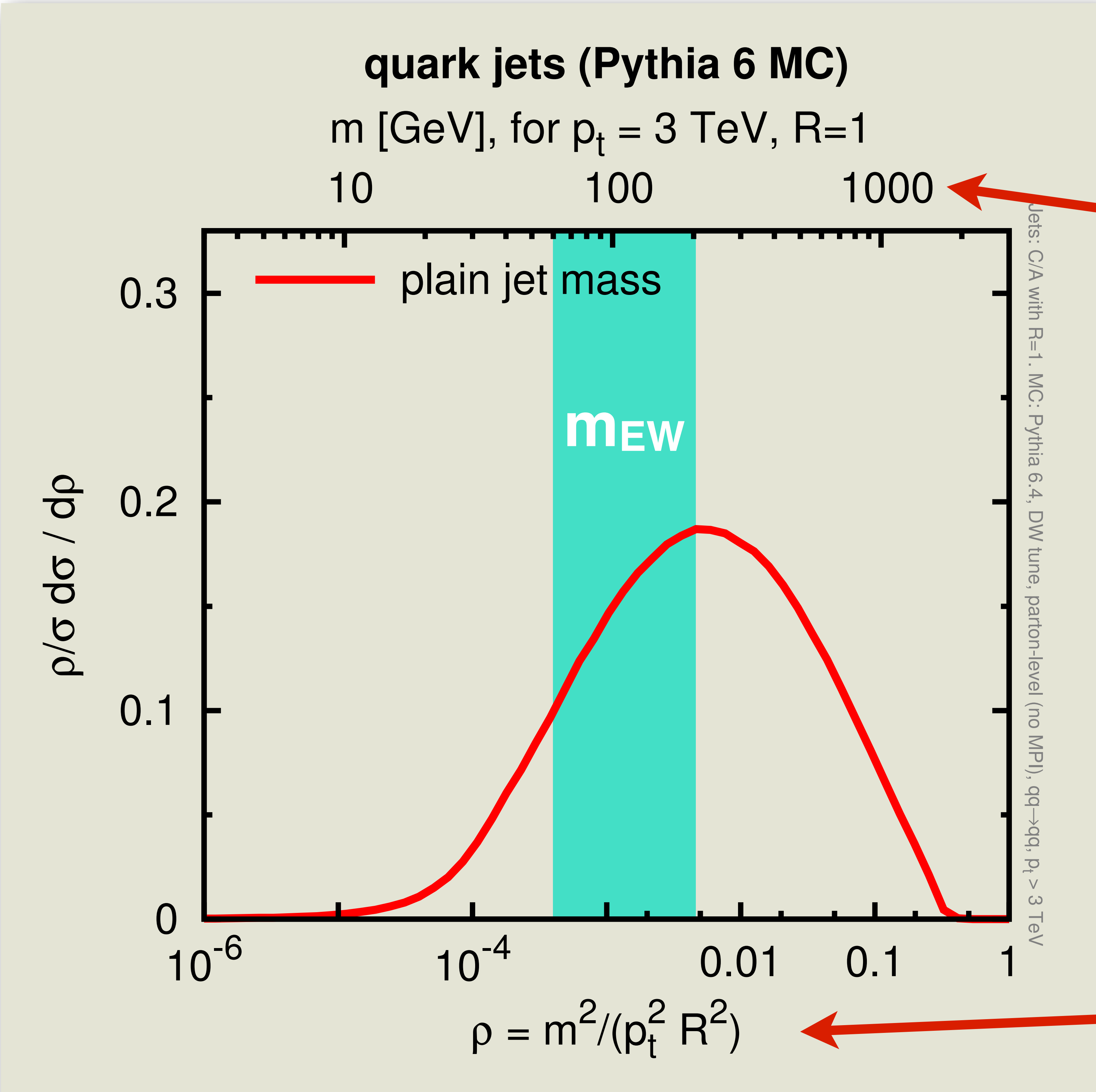

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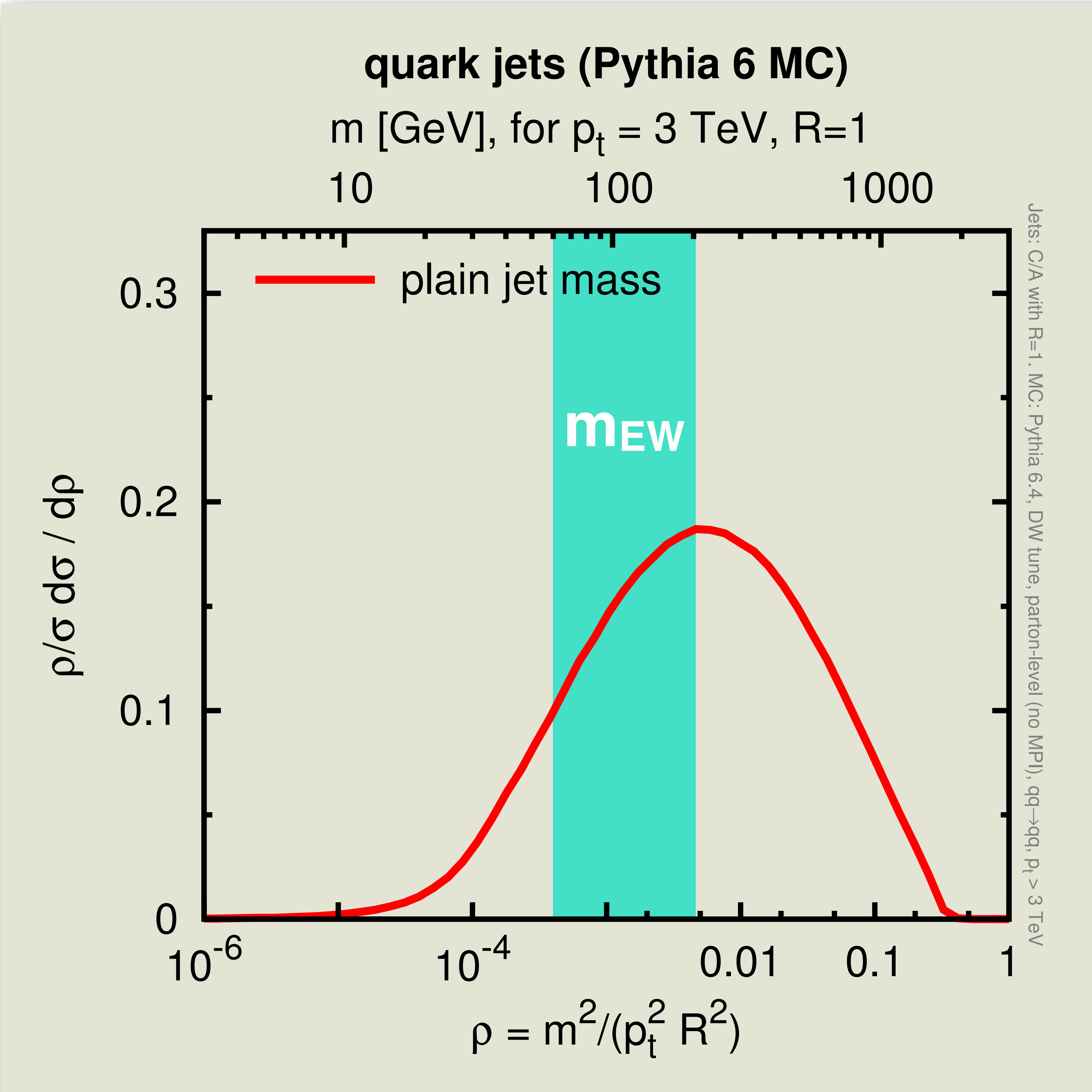

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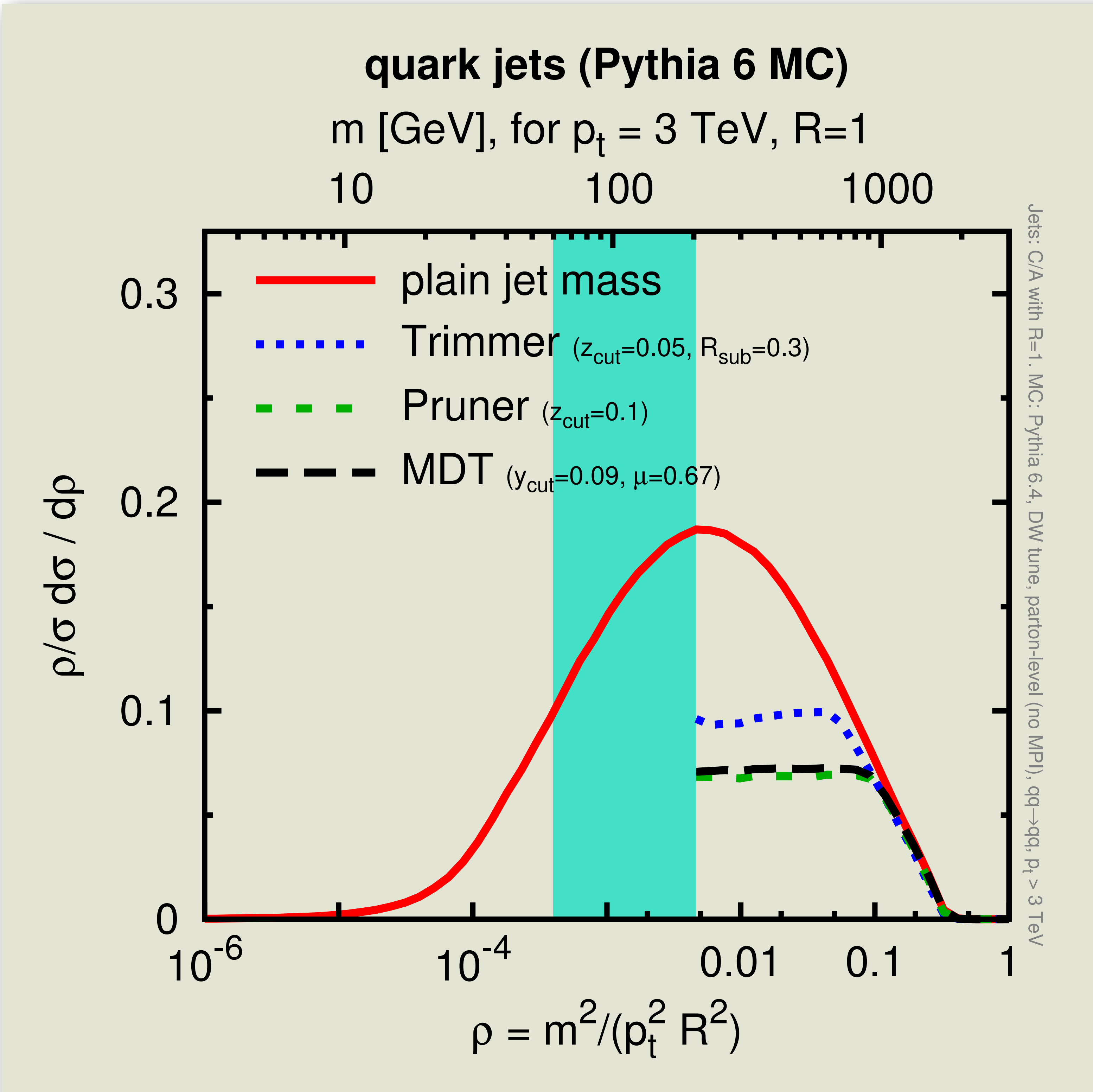
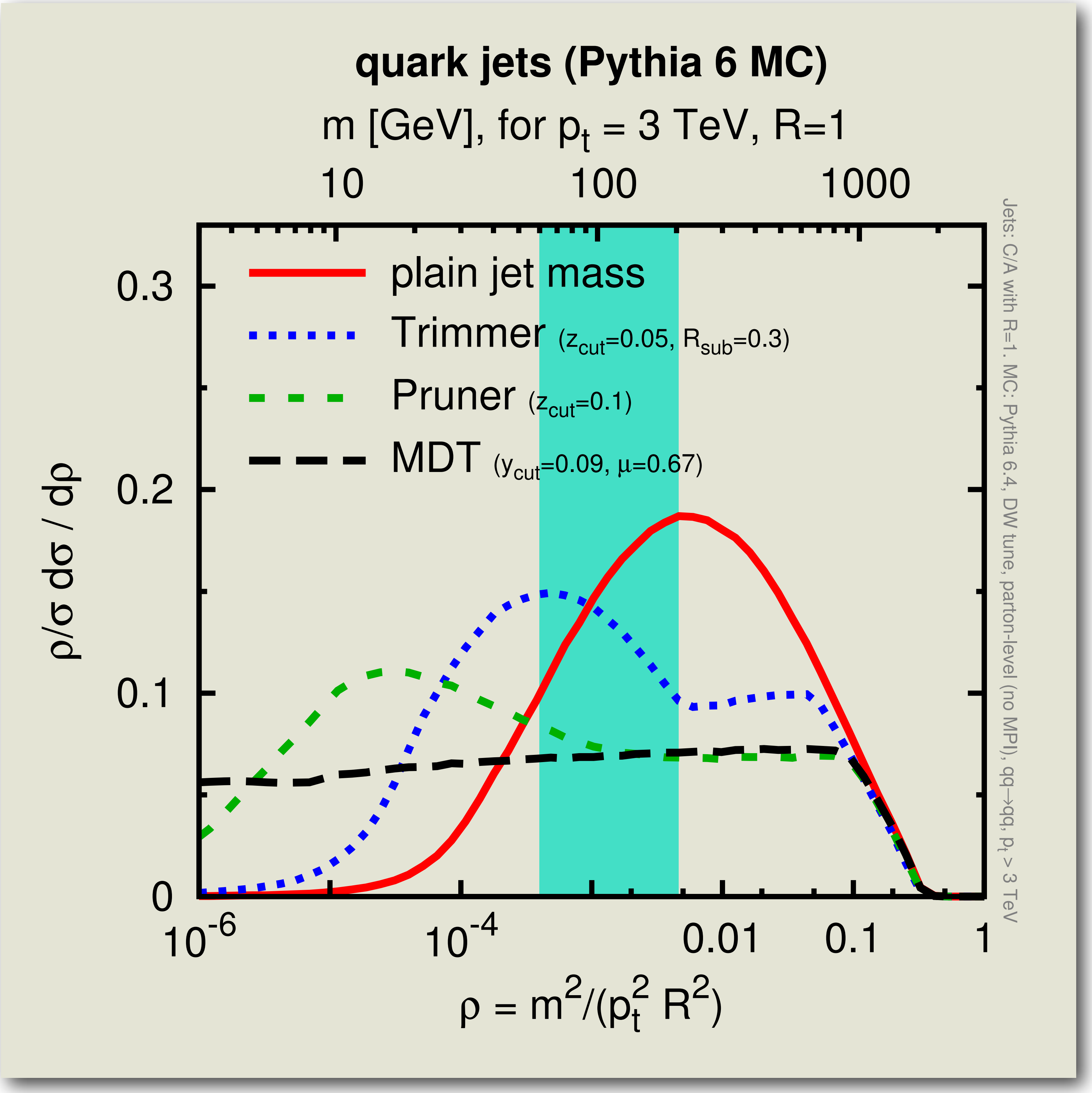


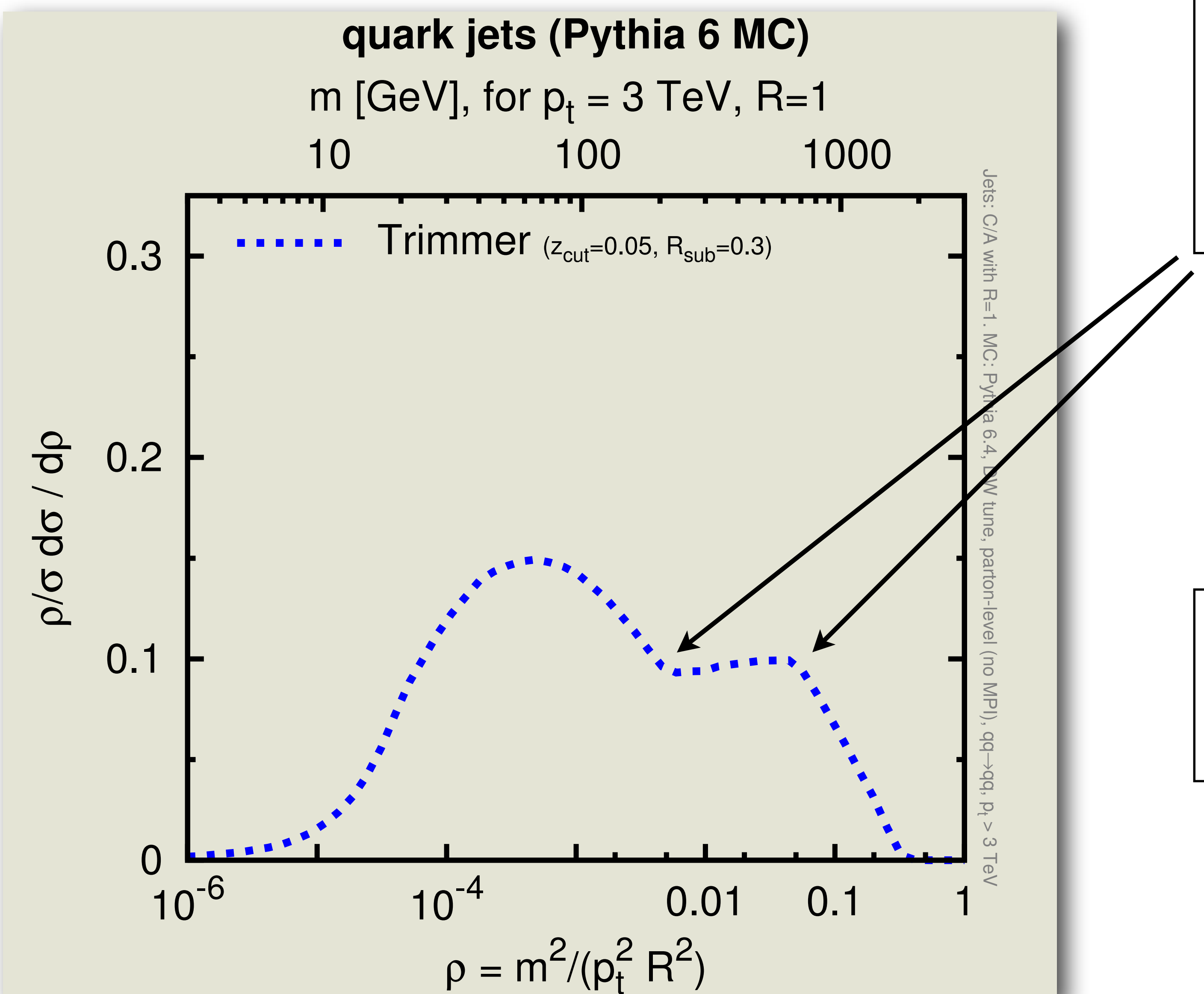
Different taggers can be quite similar

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-driver 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

[Analytic] understanding

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

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**
- 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

$$R_{sub} < R$$

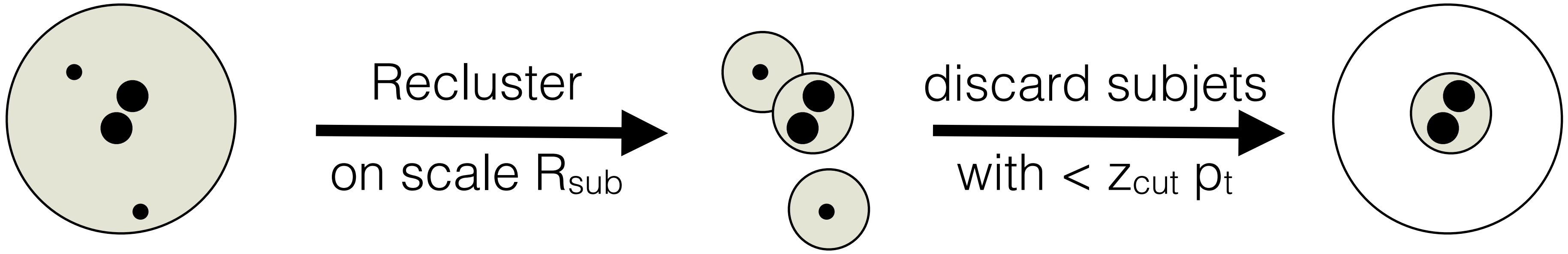
The subjets that satisfy the condition

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

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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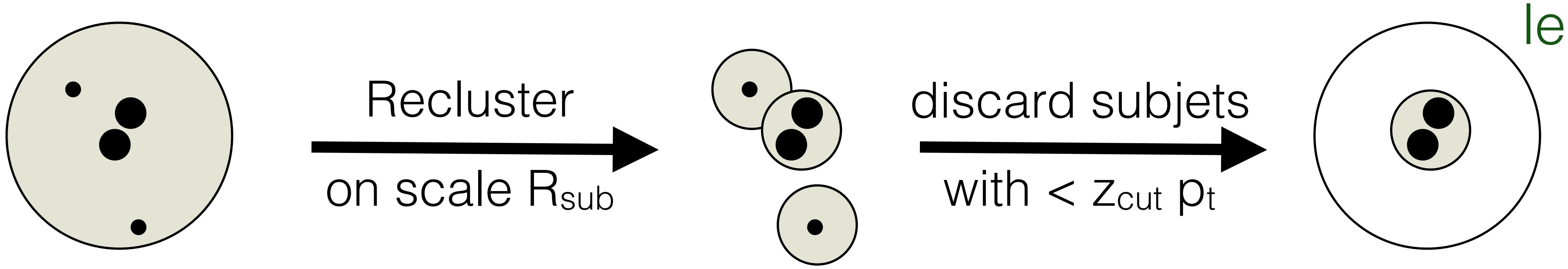


Our approximations

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

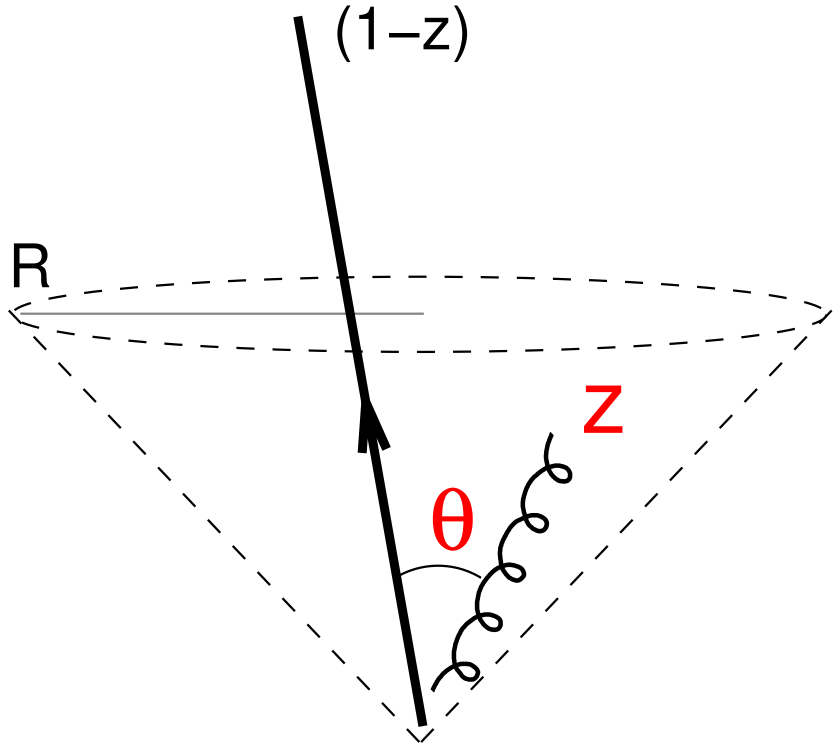
These approximations are not as "wild"as they might sound.

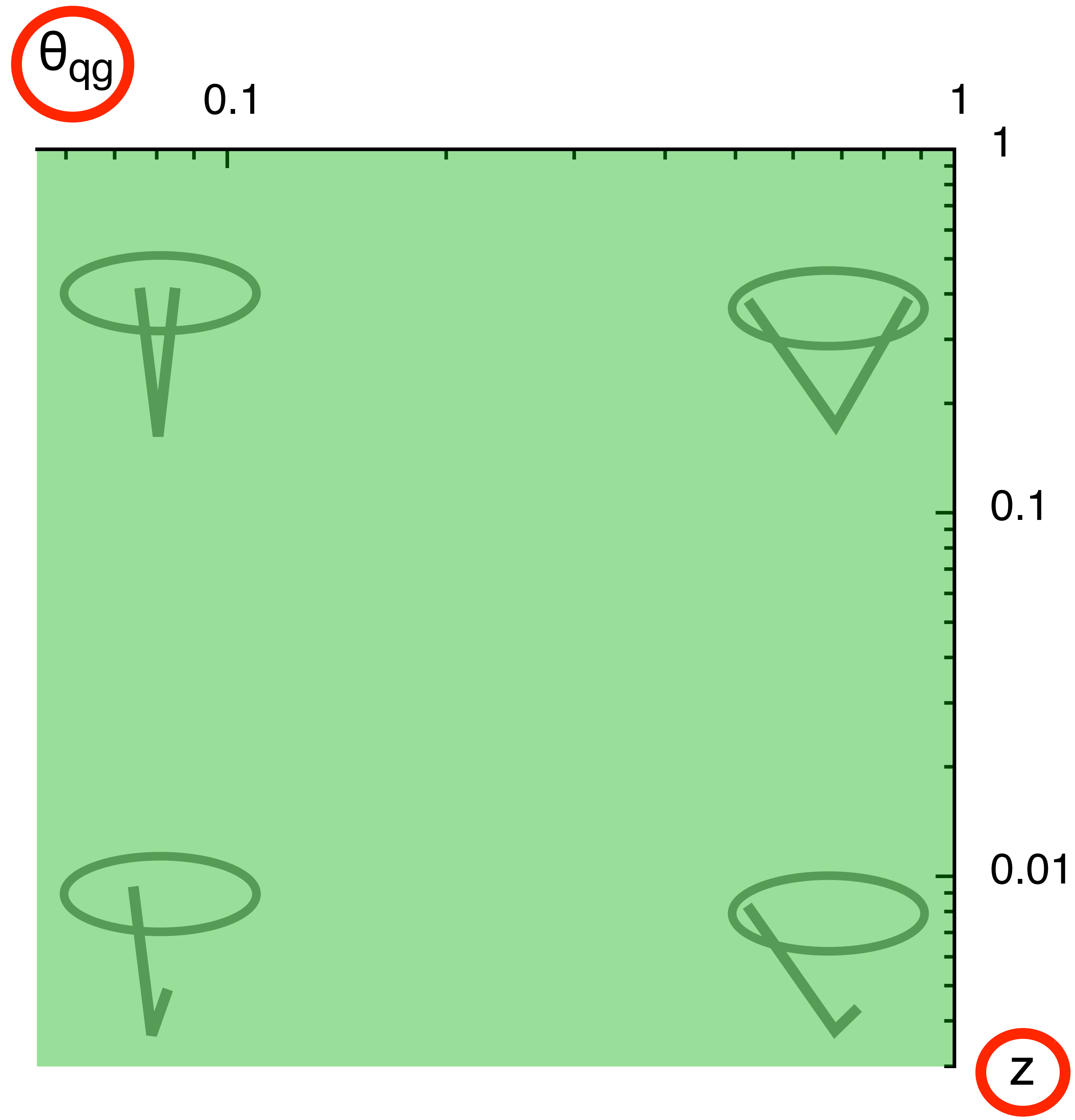
They can also be relaxed.

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

Leading Order — 2-body kinematic plane

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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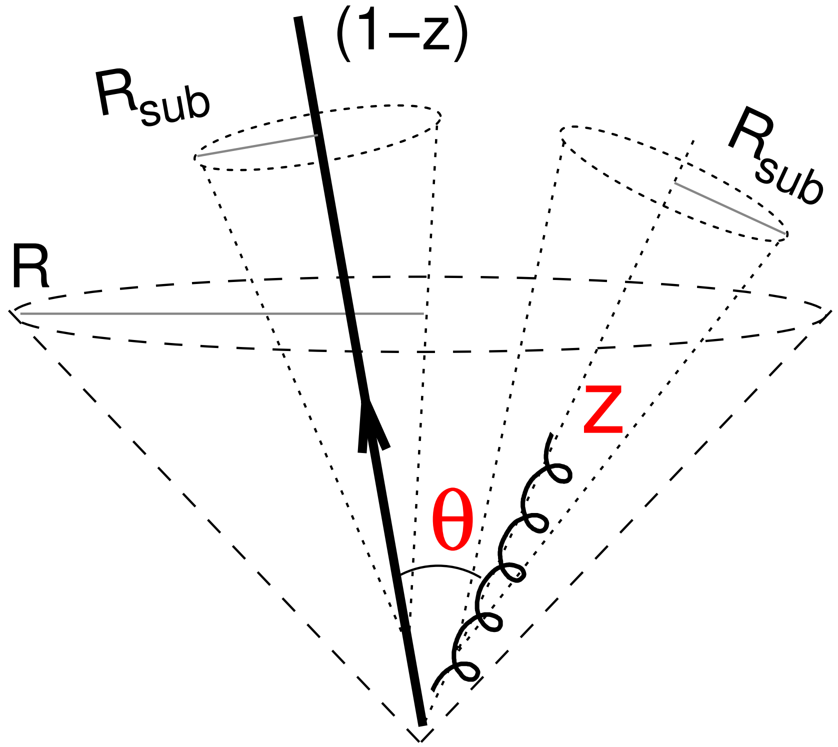

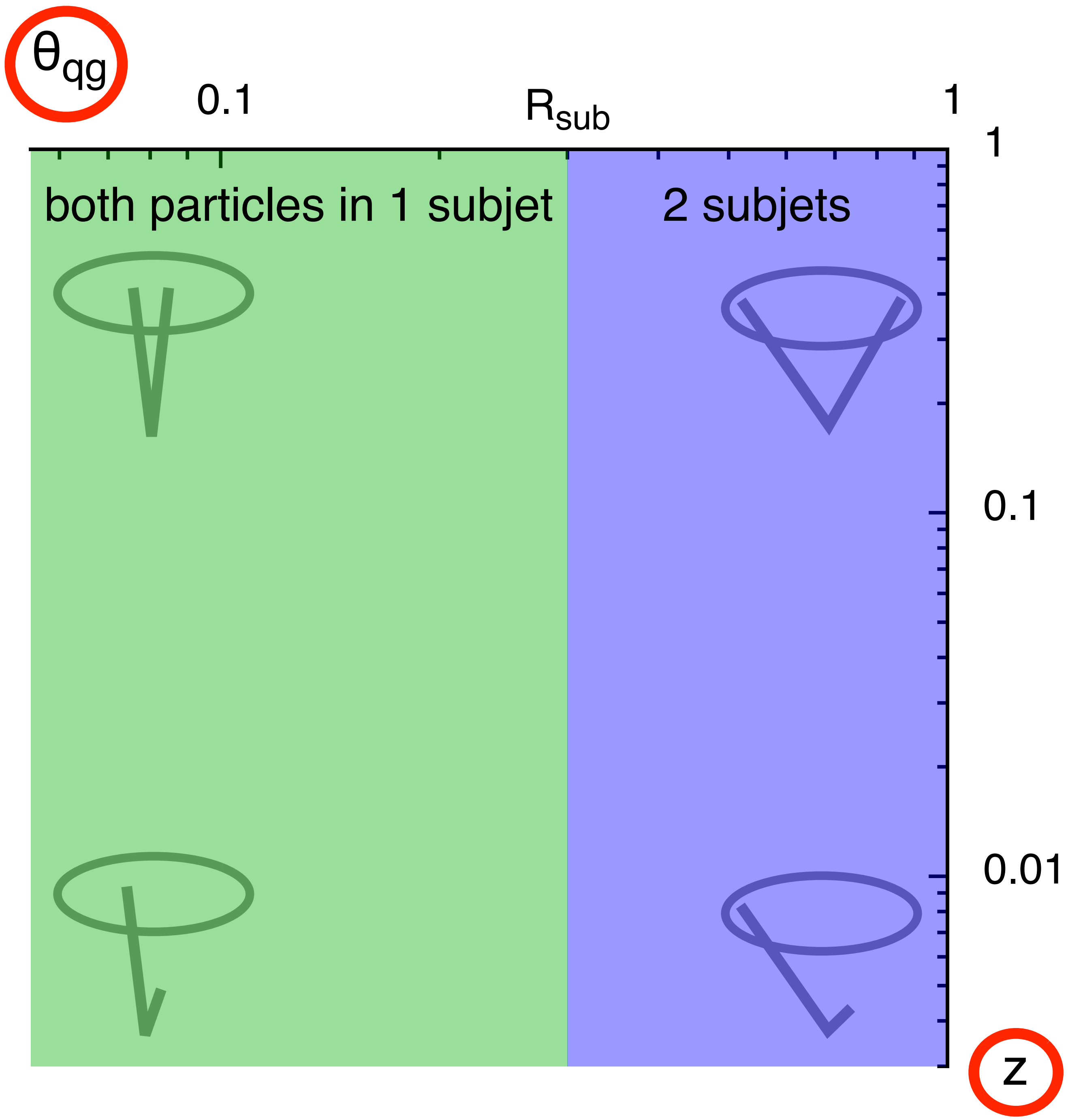

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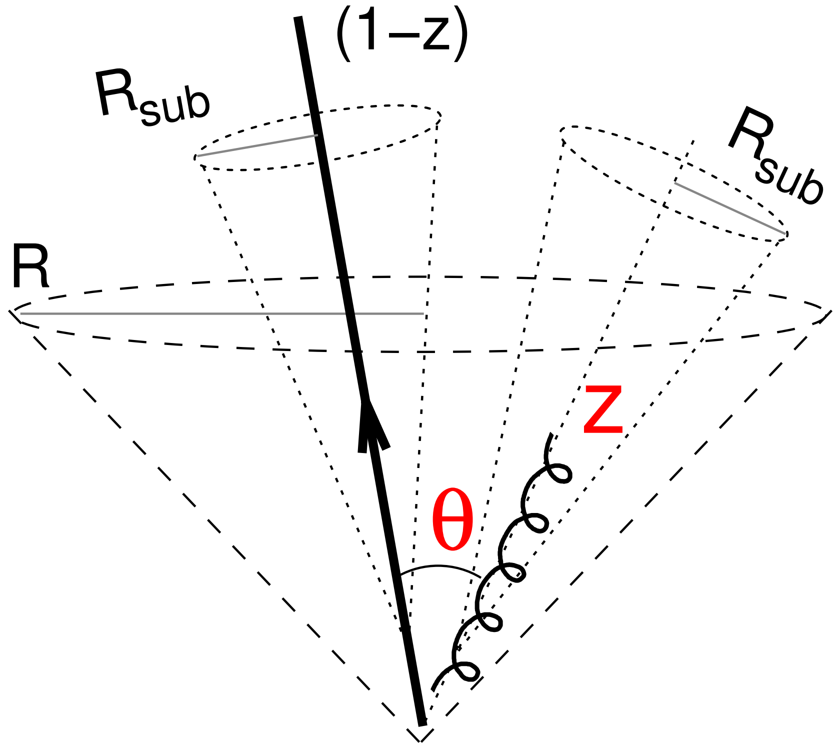
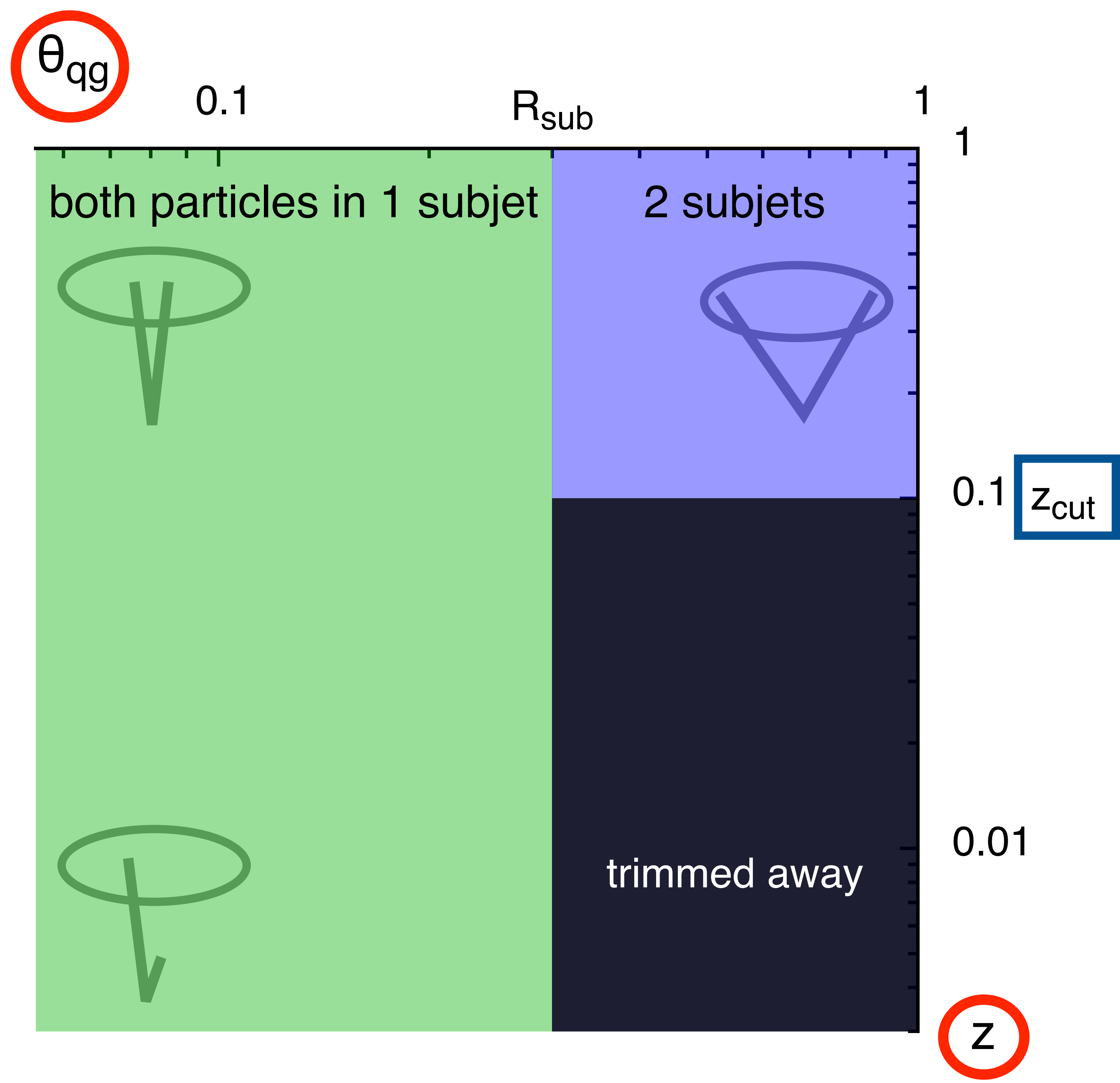
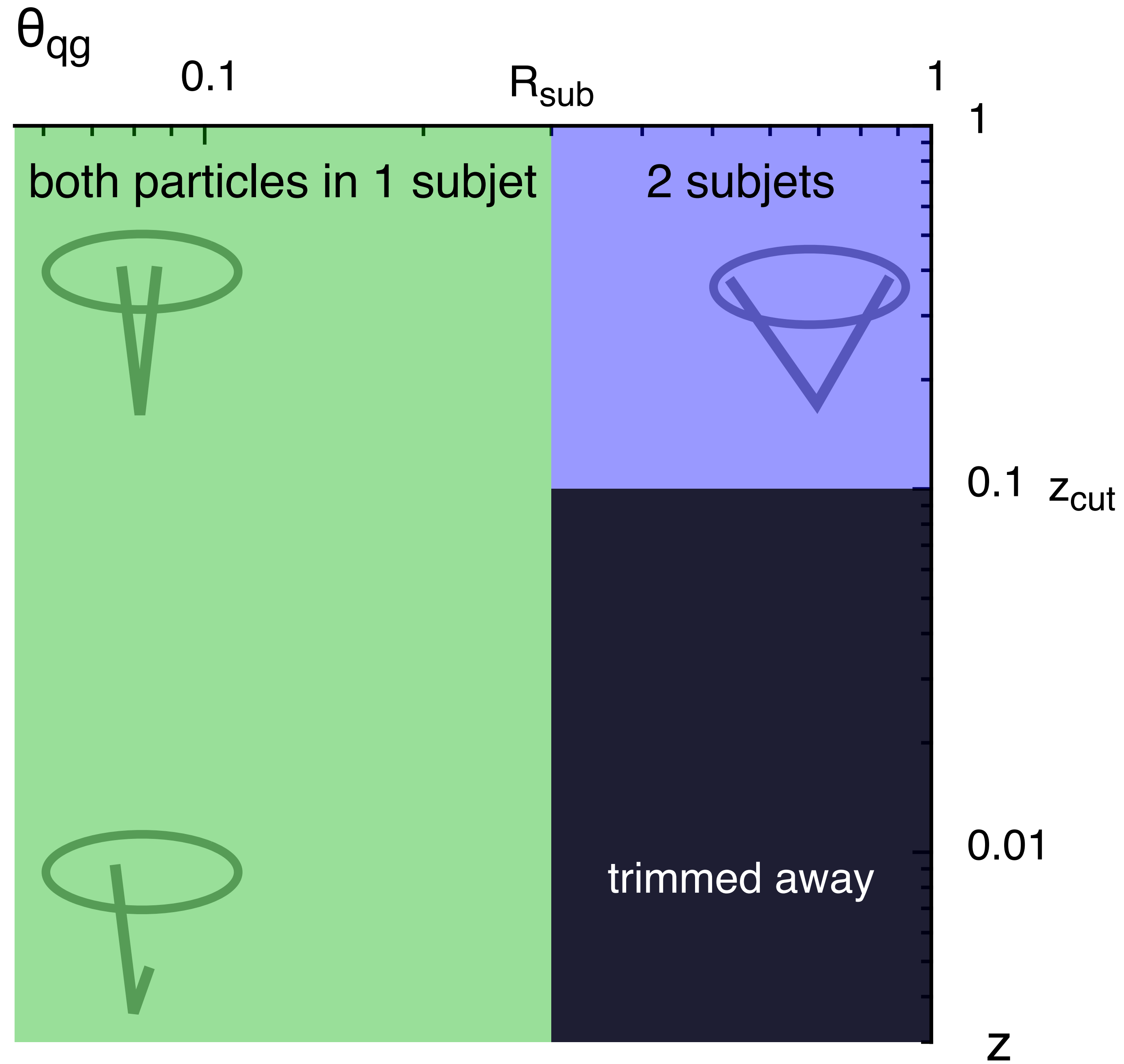




matrix element

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

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

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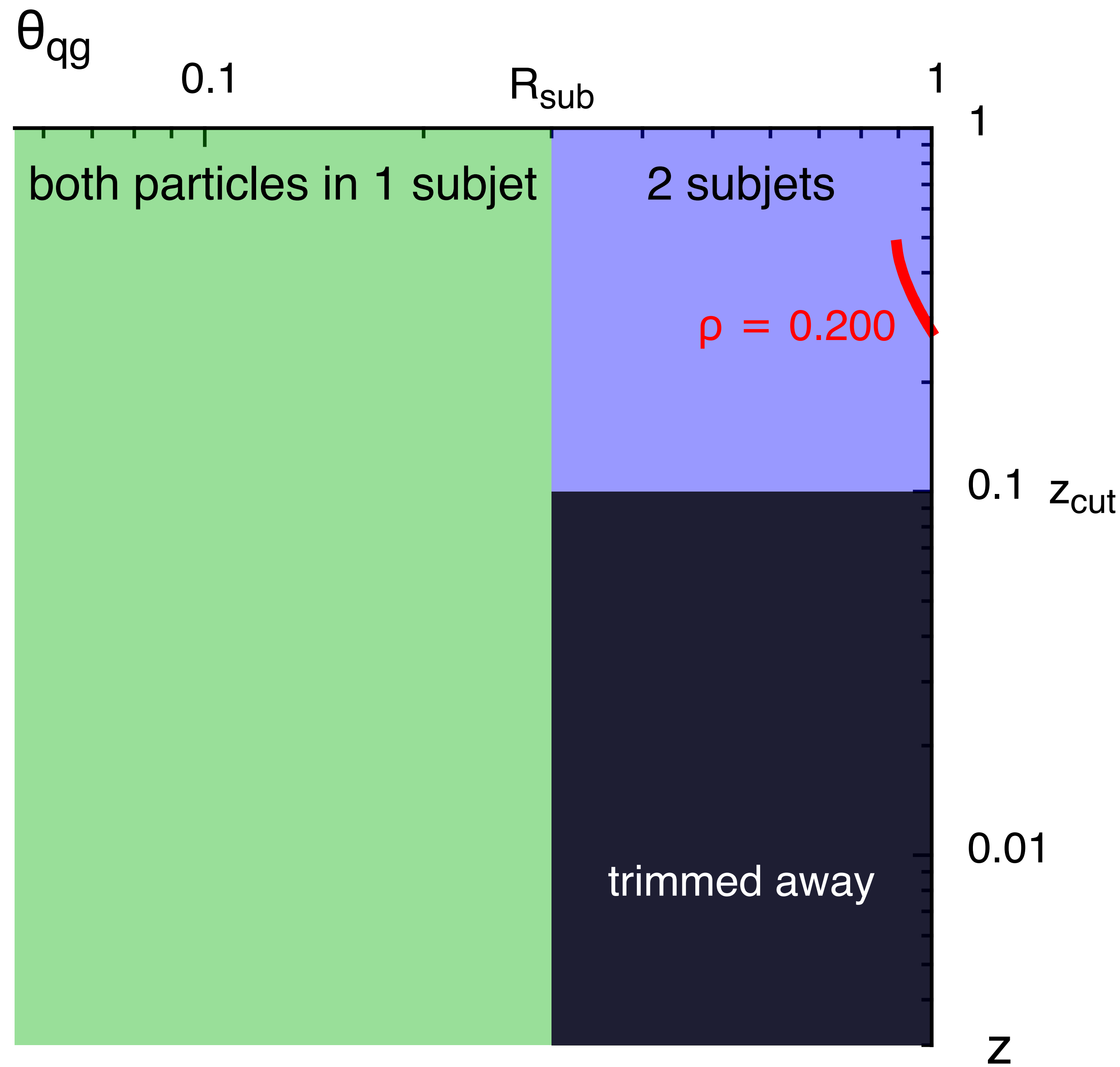

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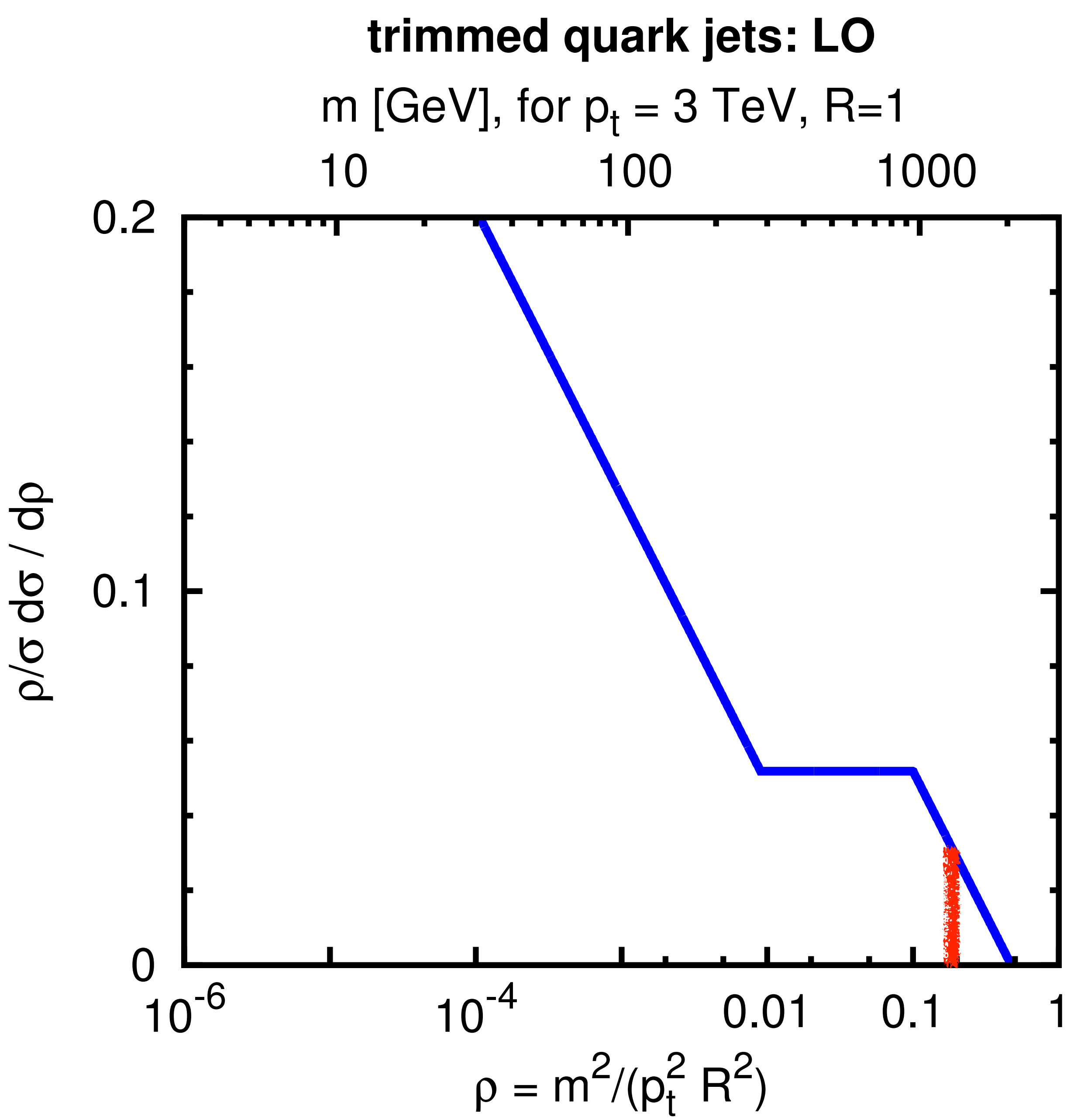

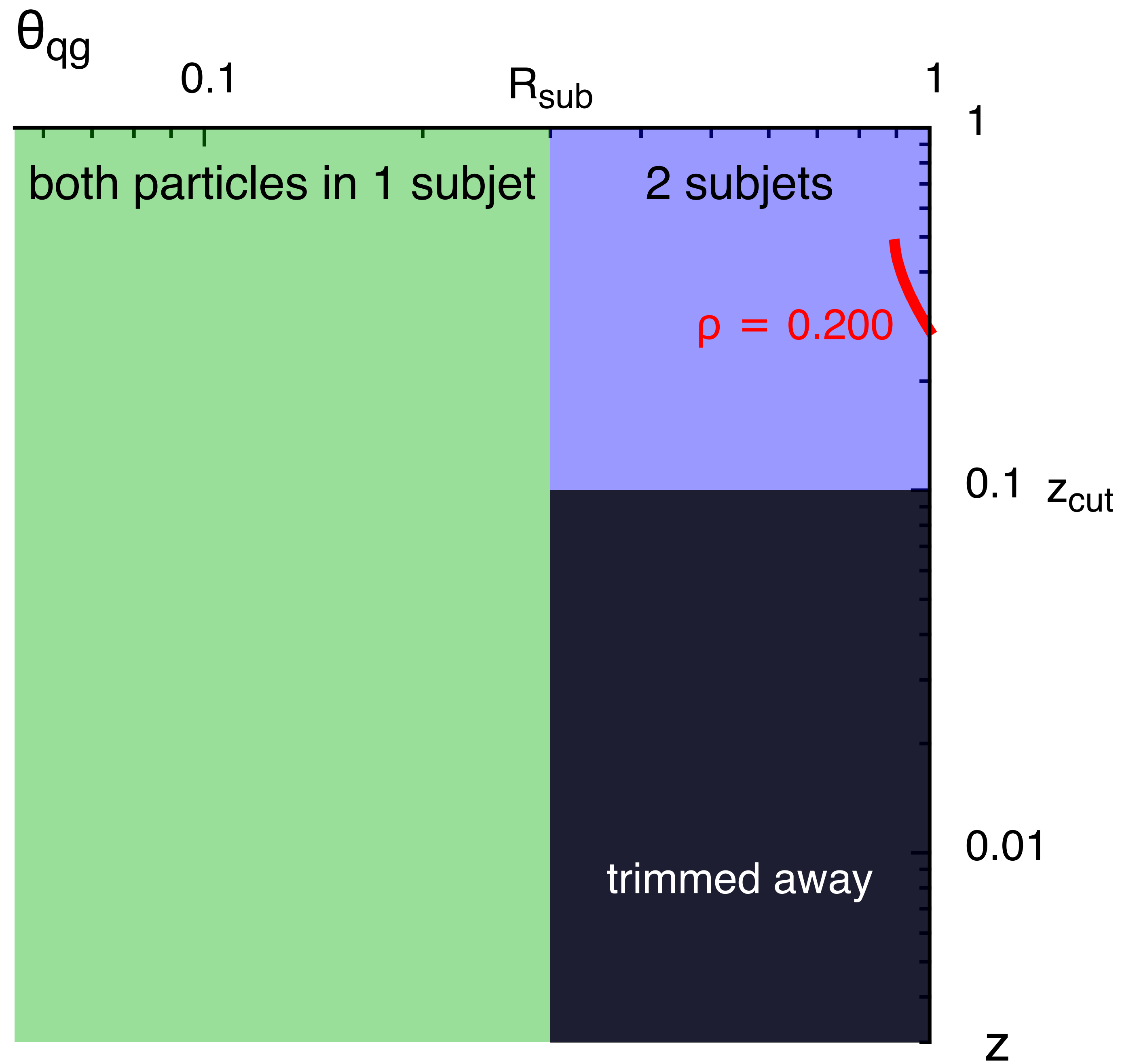

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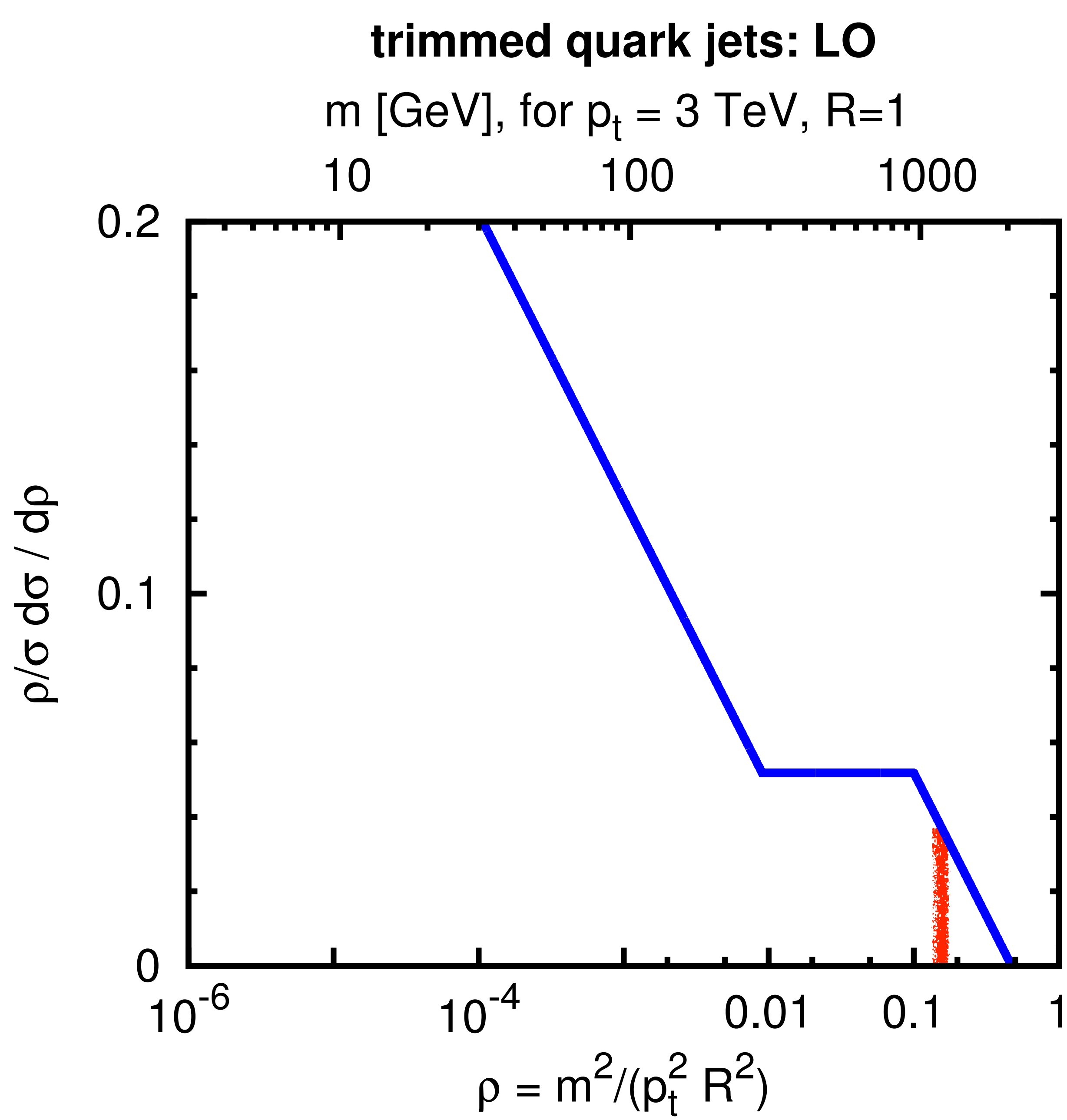

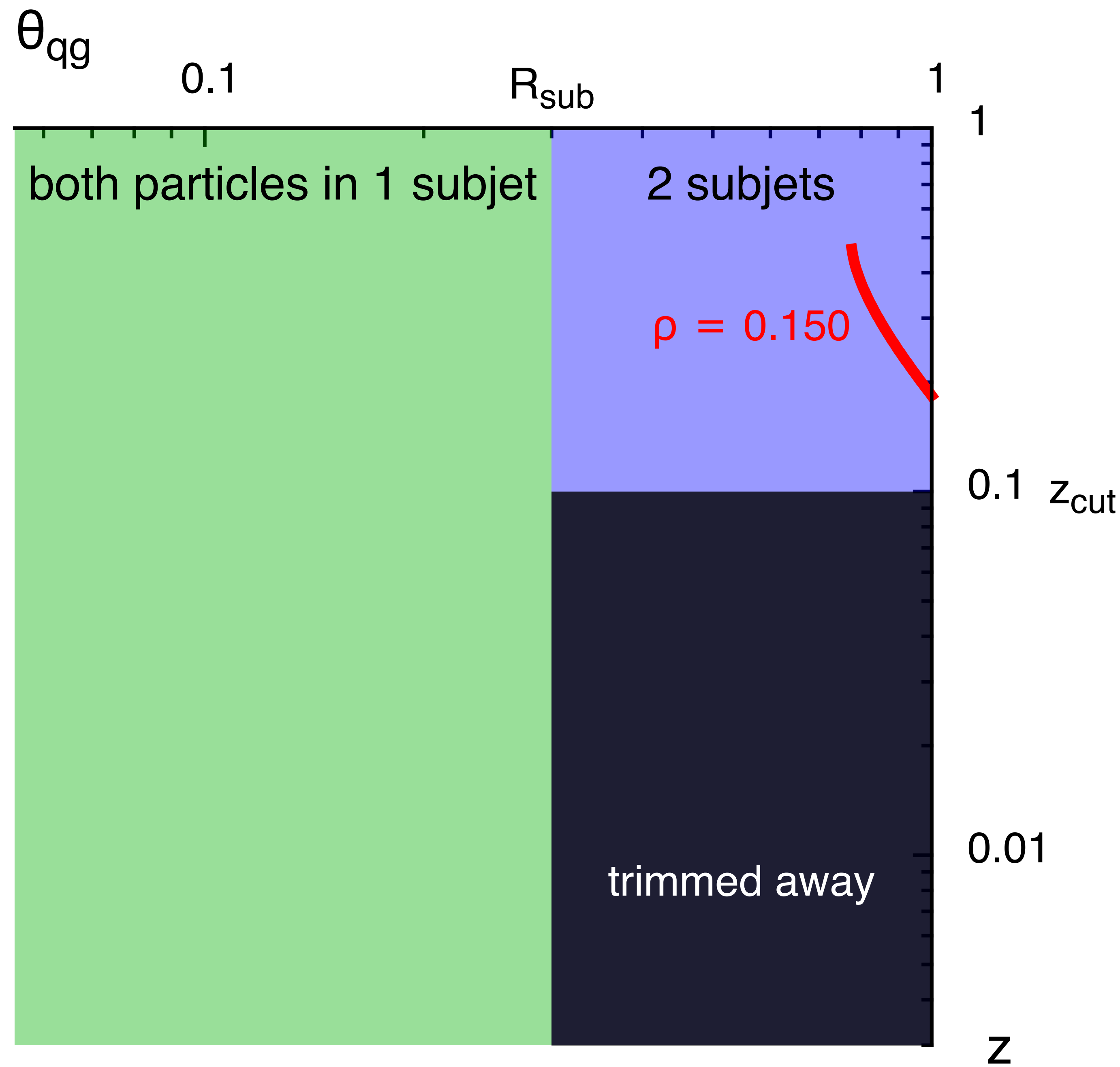

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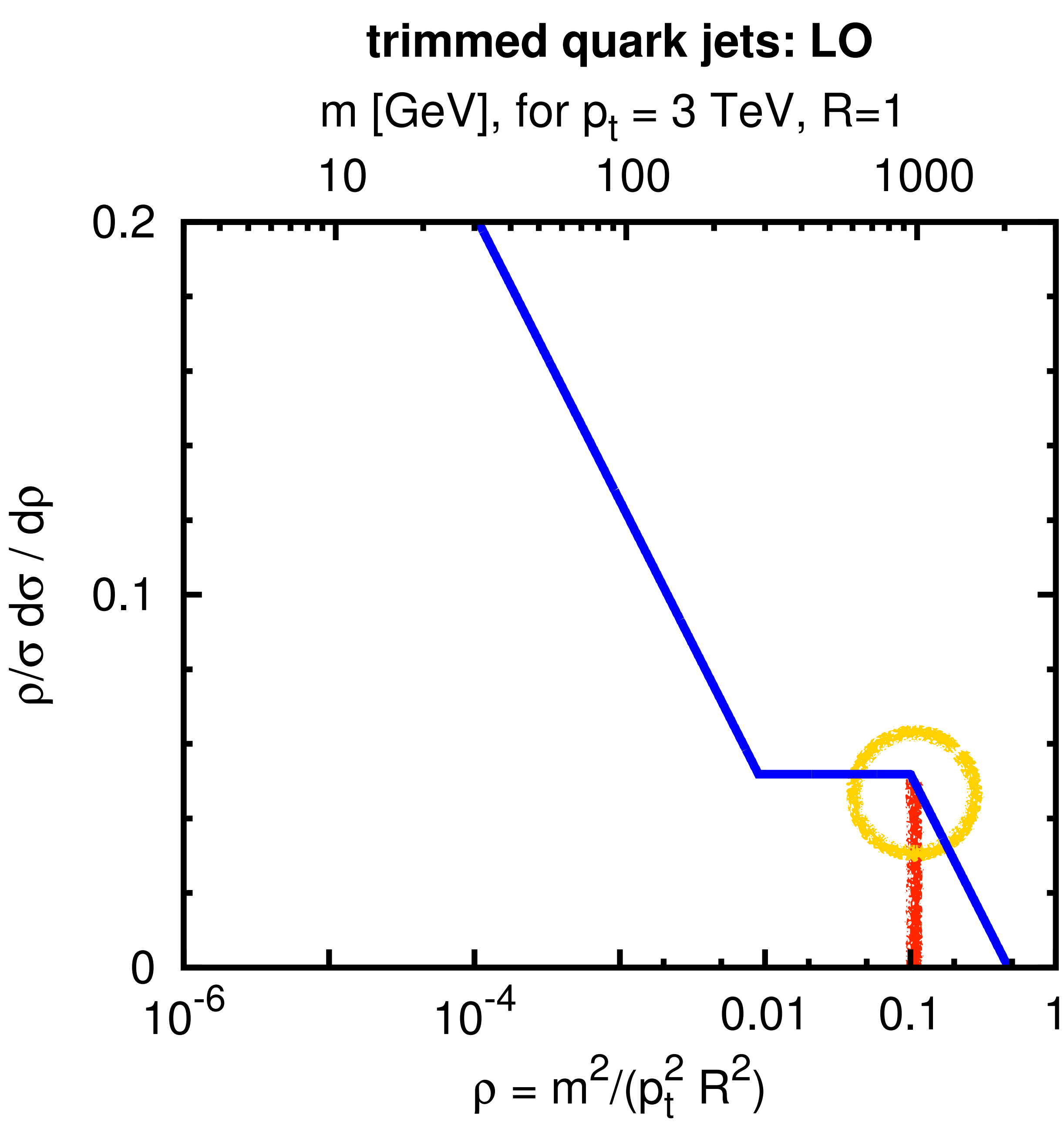

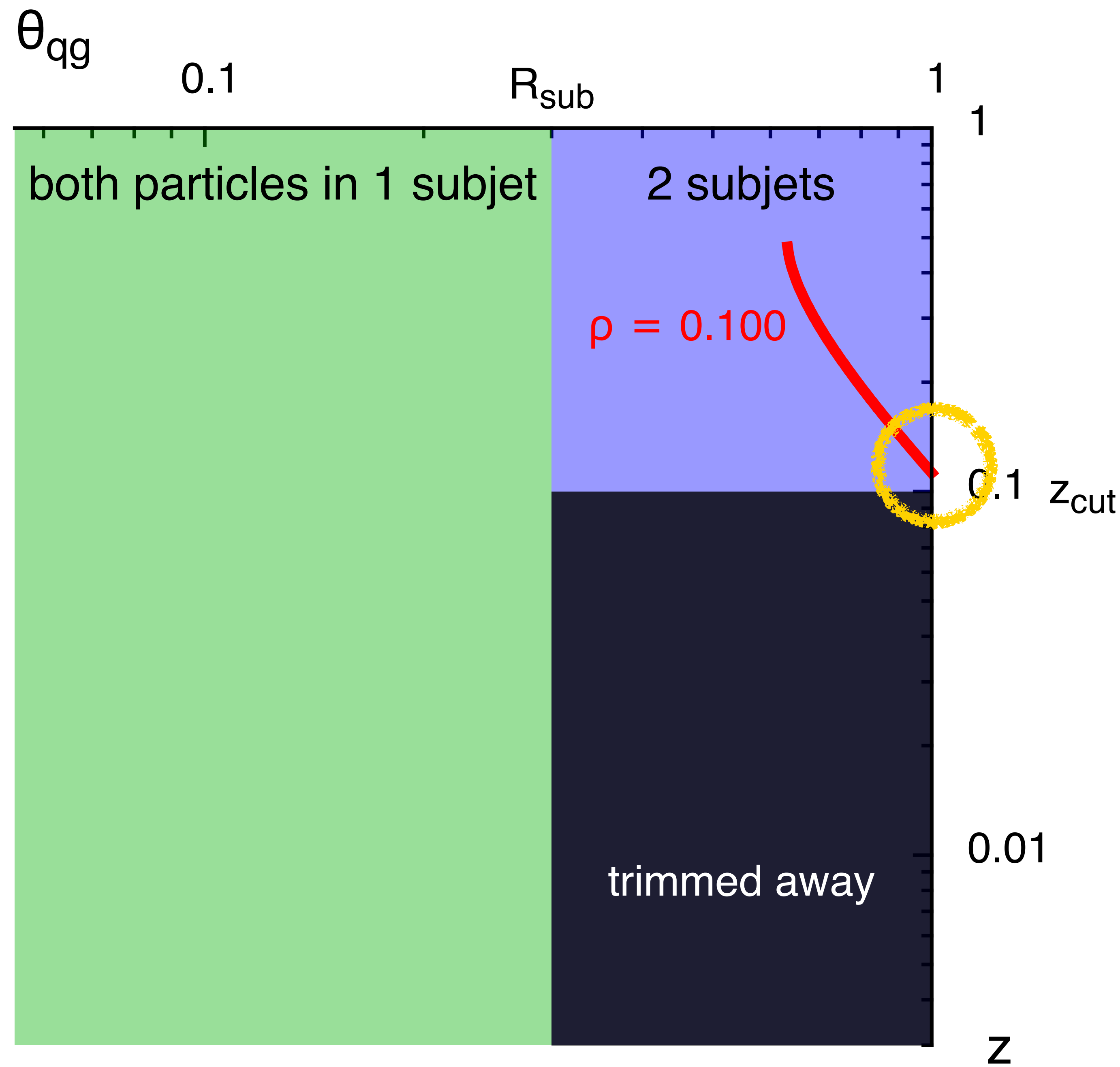

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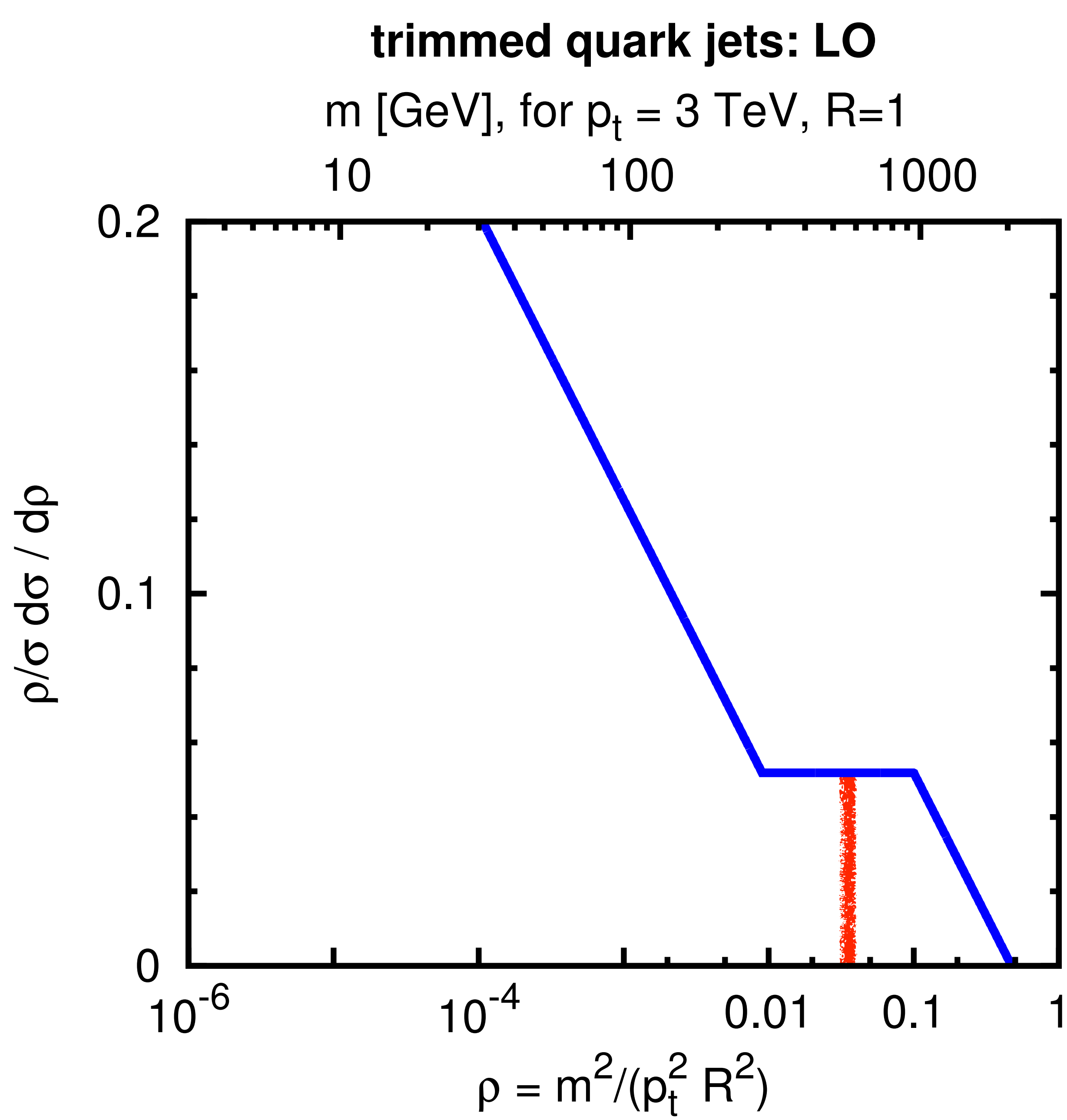

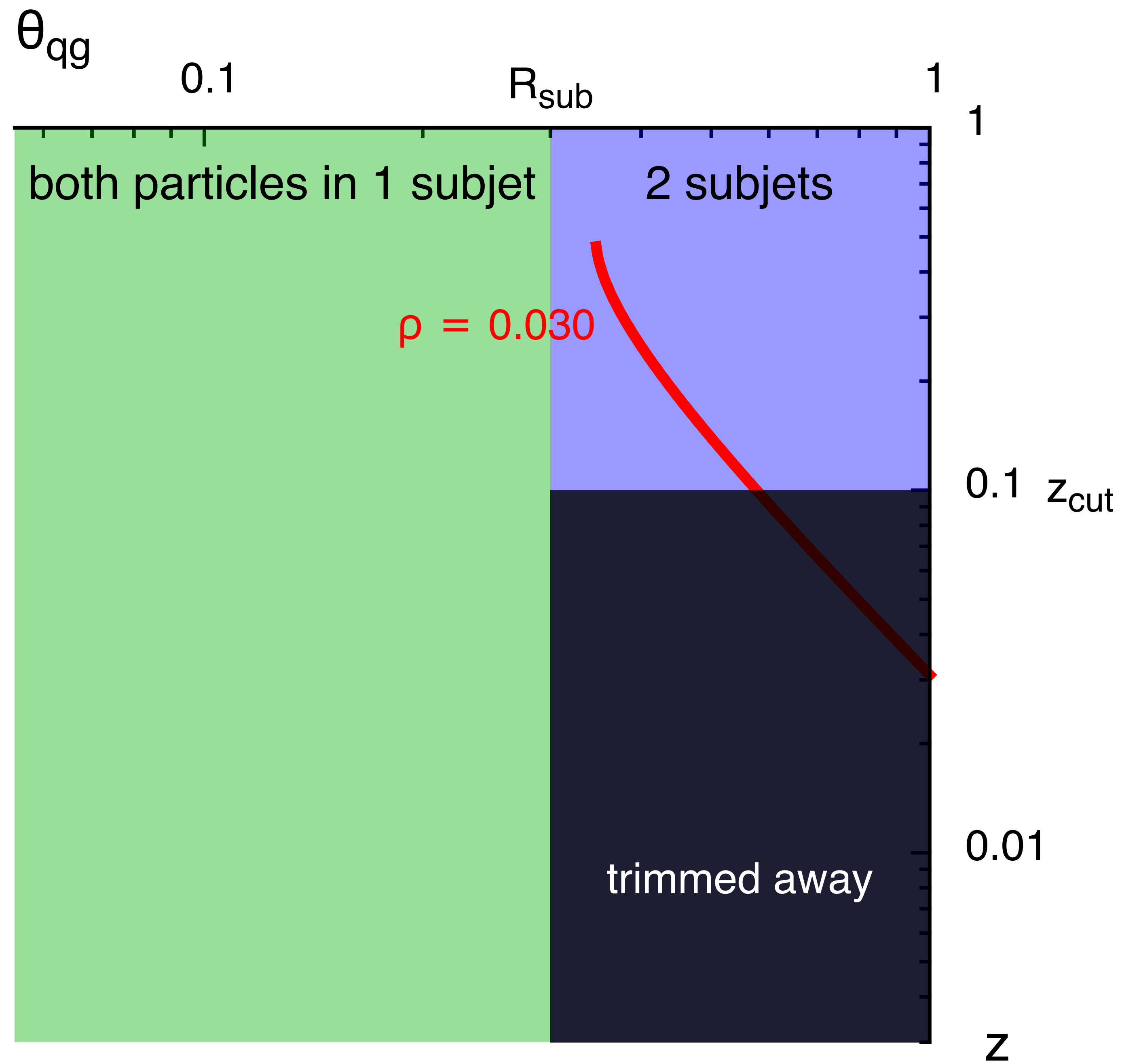

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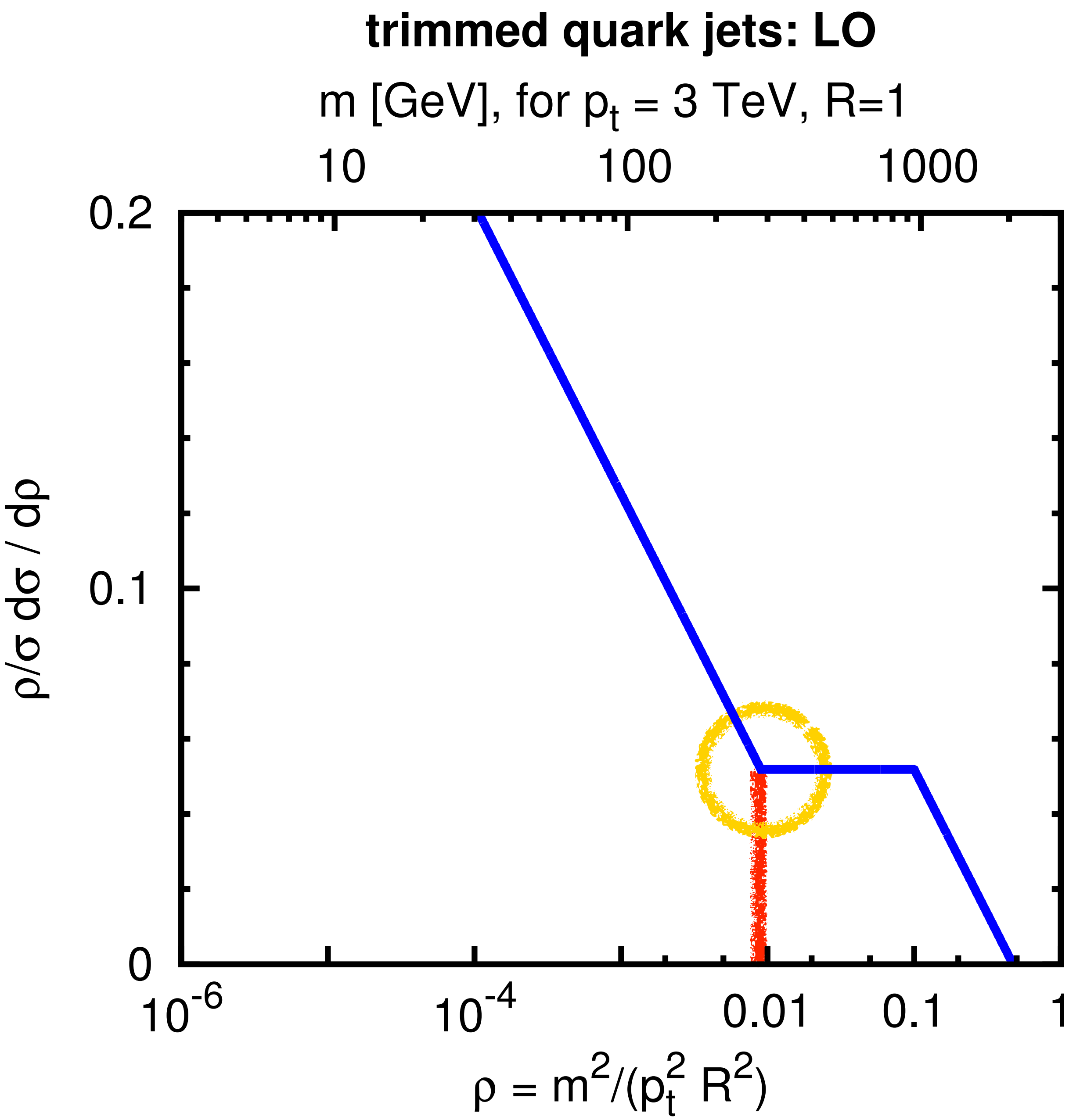

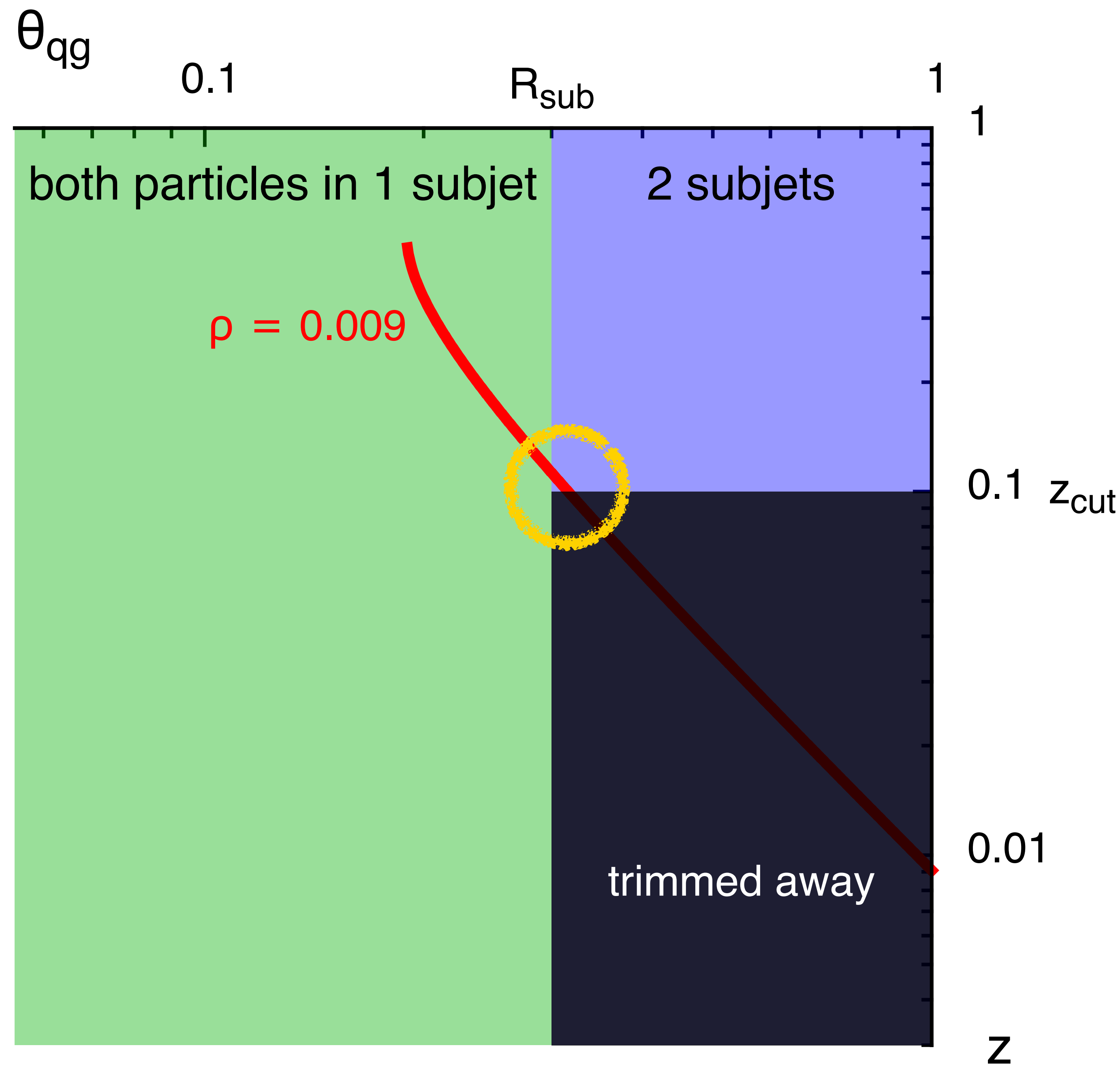

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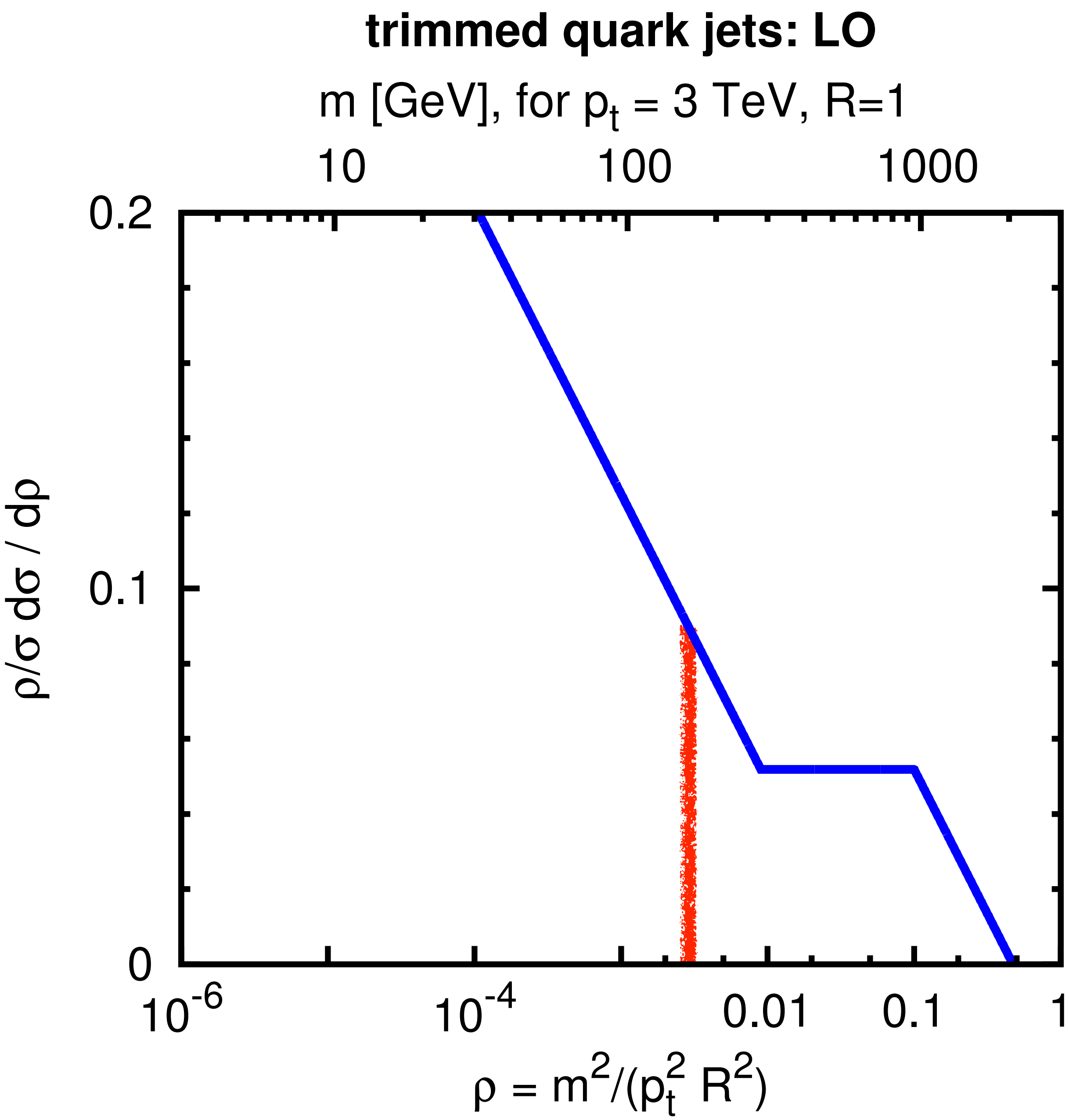

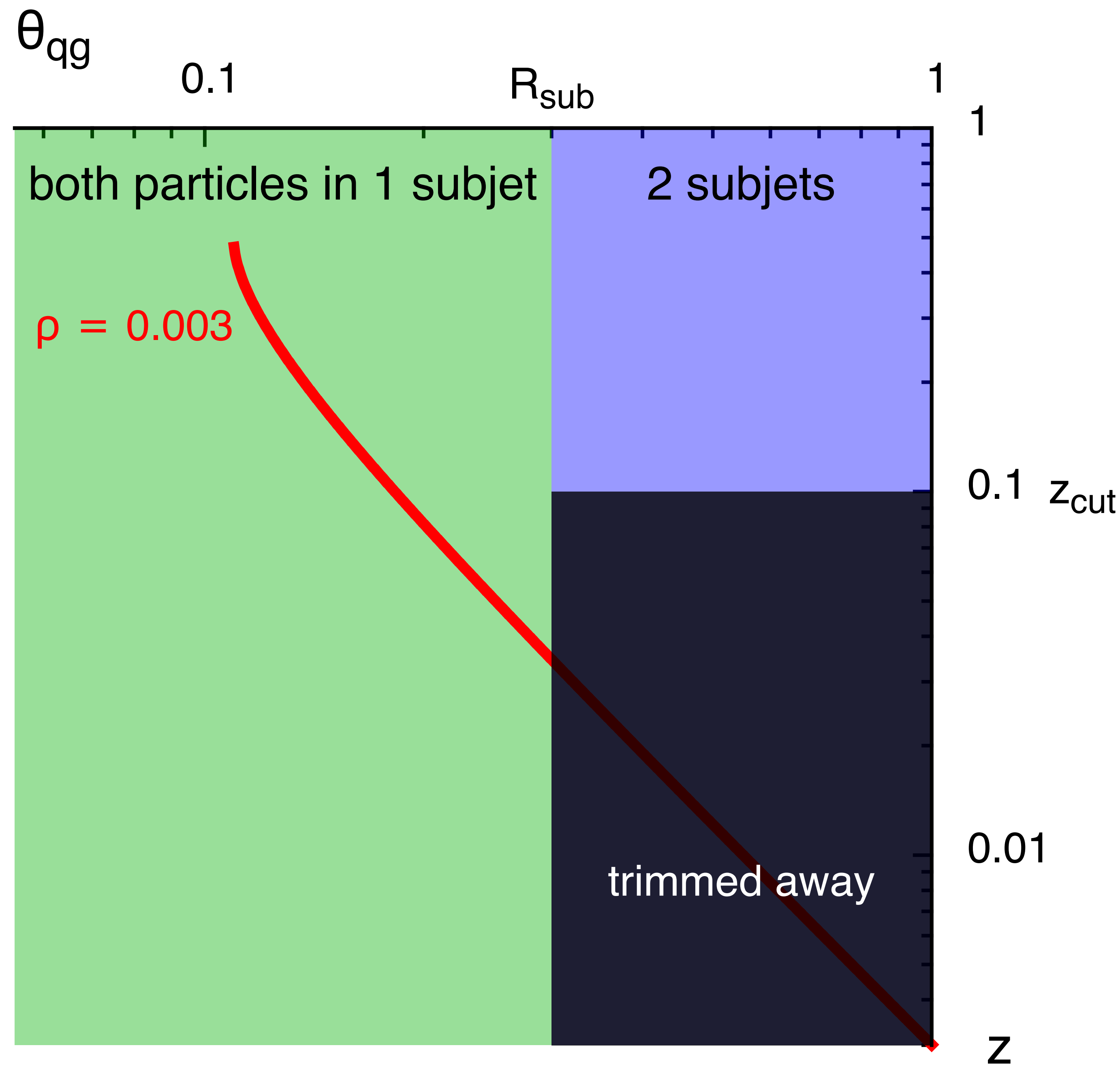

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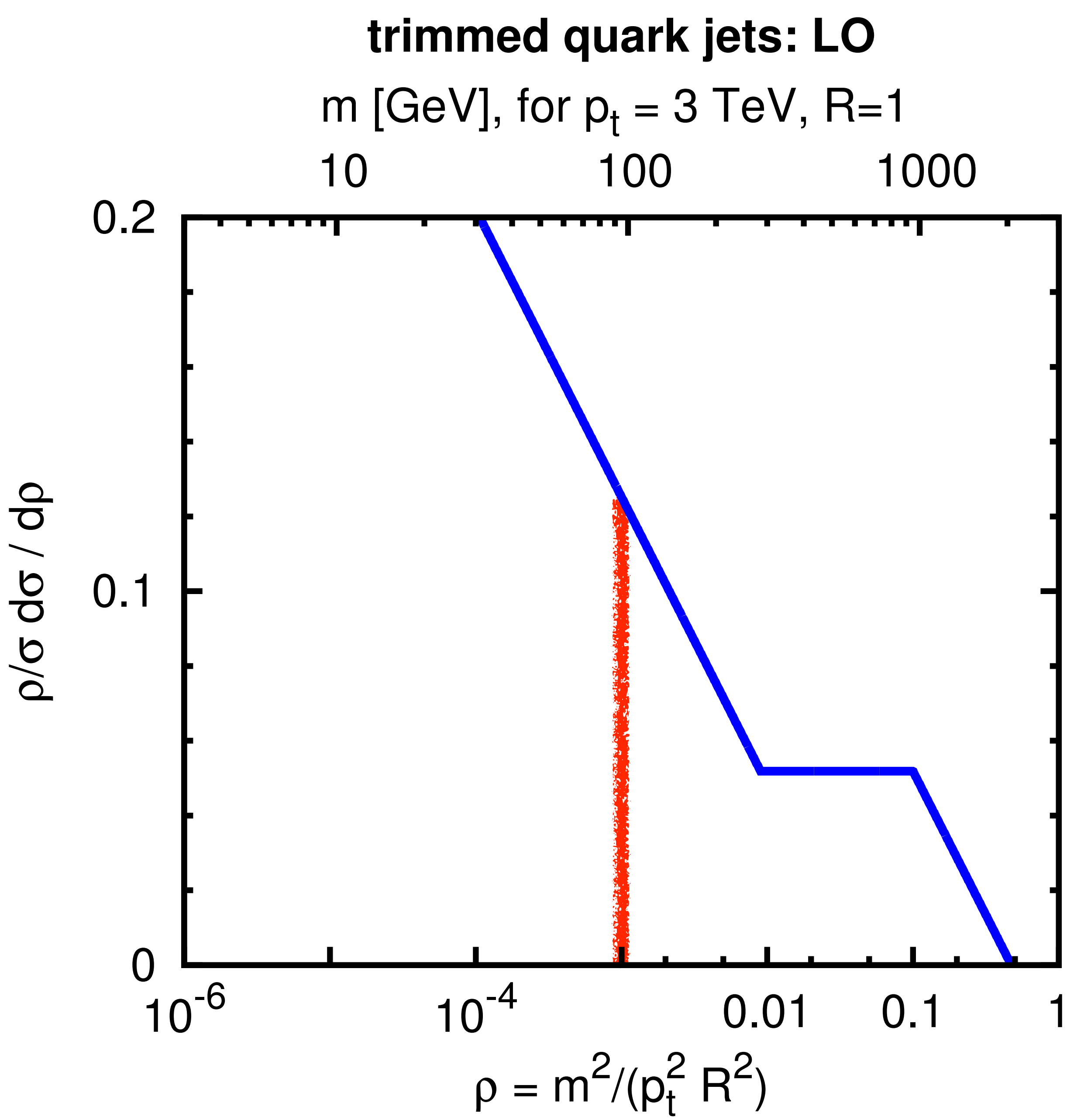
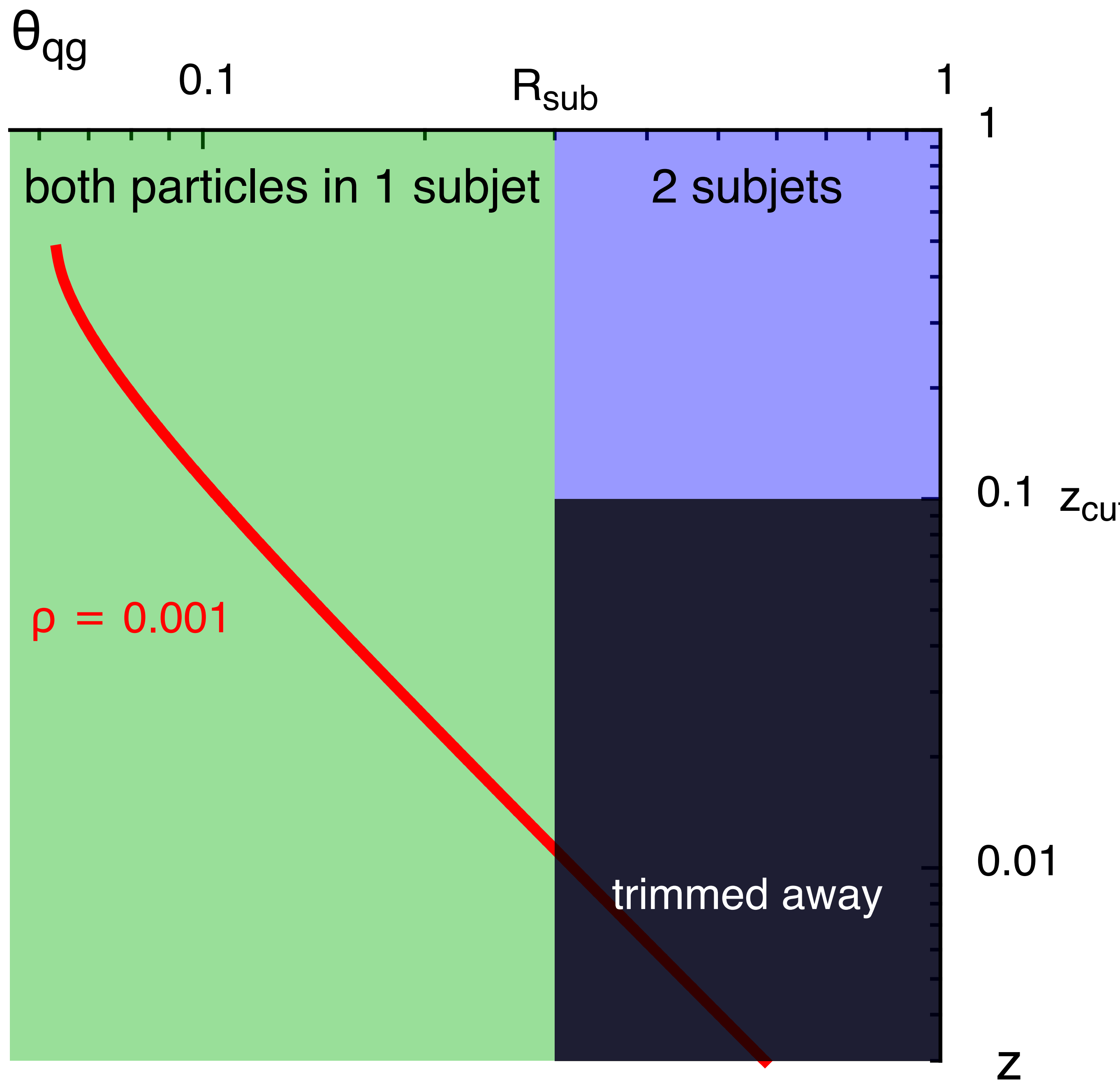
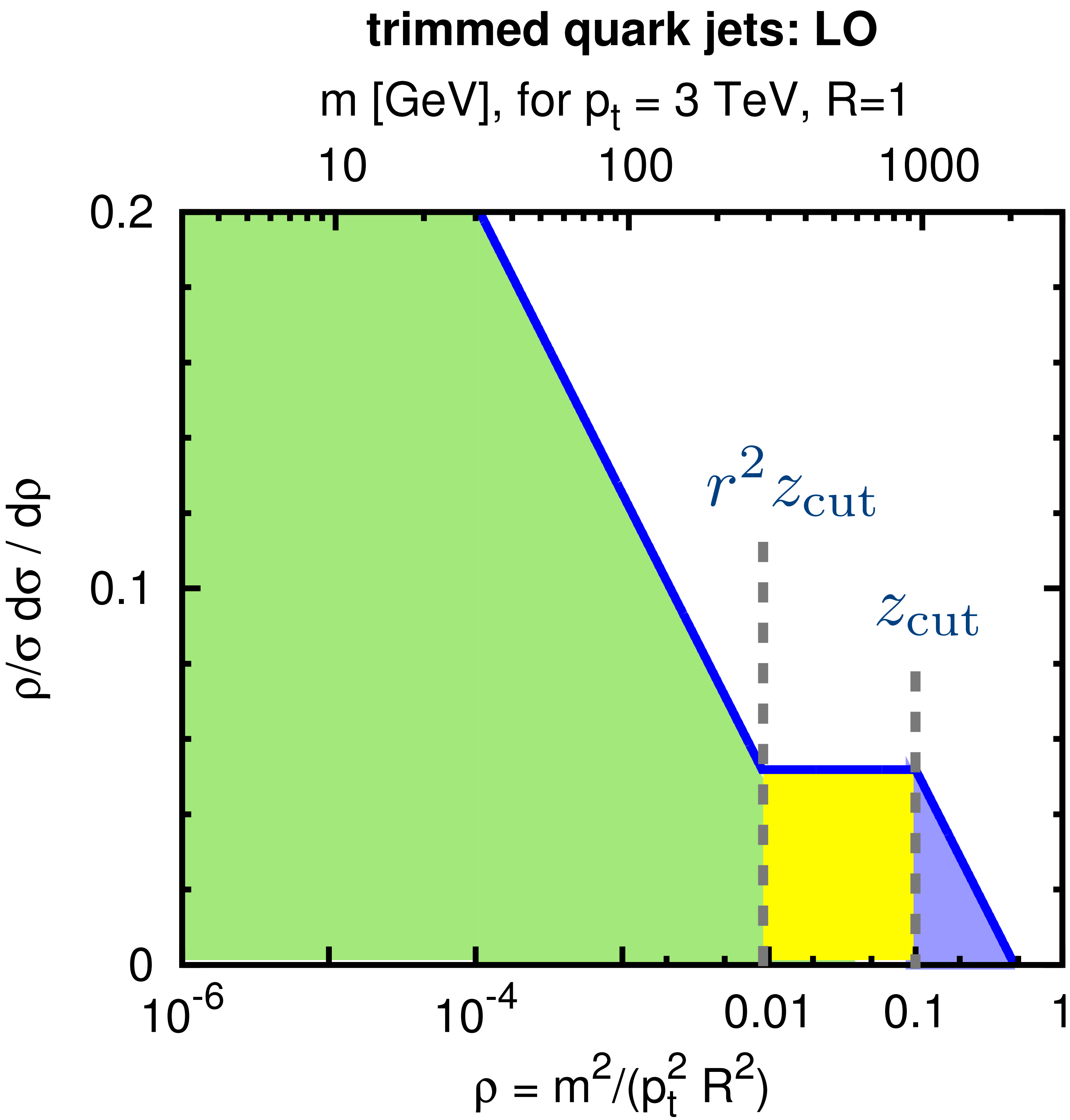




Trimming at LO in α_s



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

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

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

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

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

continue with all-order resummation of terms

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

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 at all orders

Trimming

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

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

Trimmed jet reduces (~) to sum of trimmed emissions

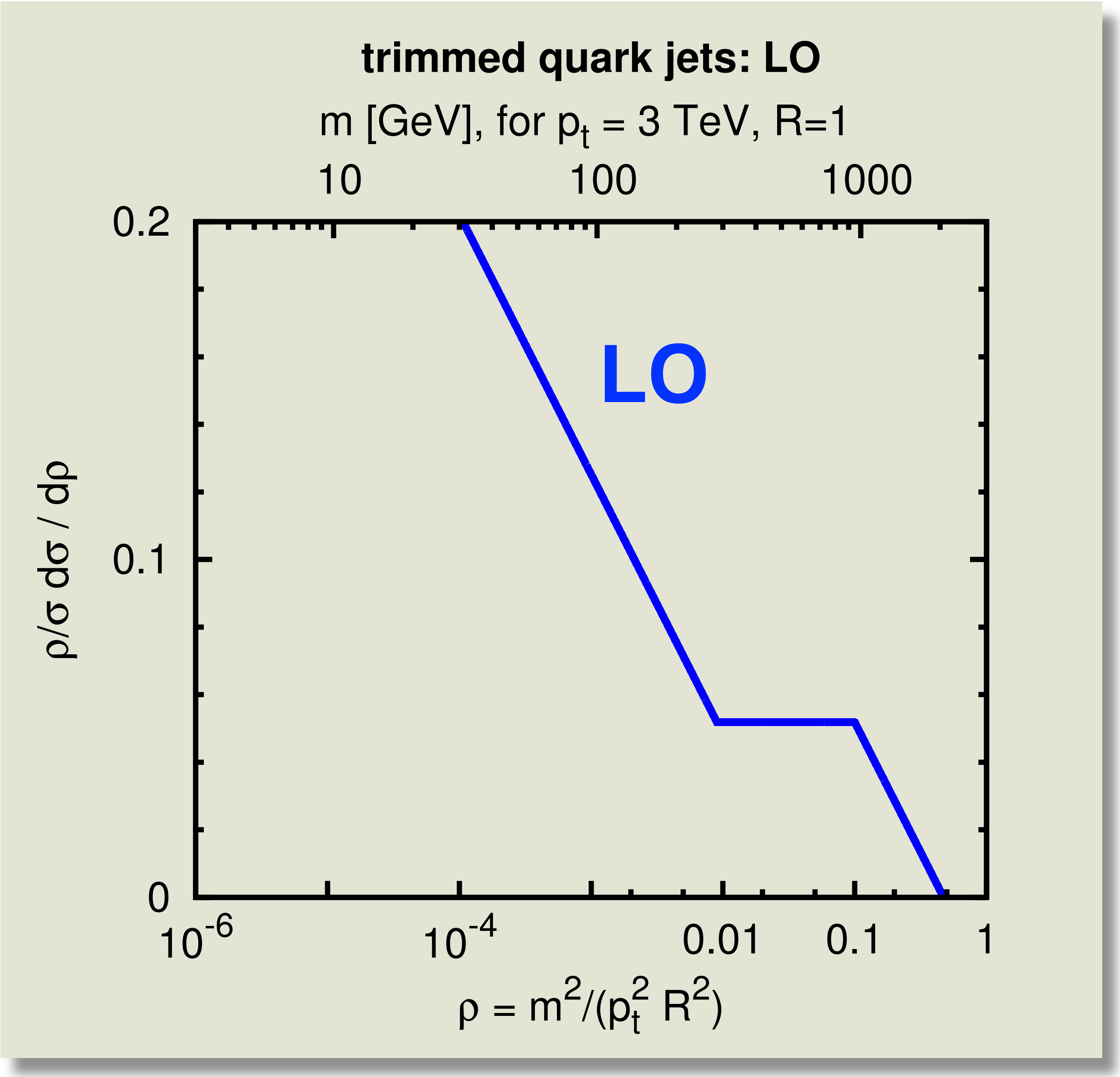
Matrix element

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

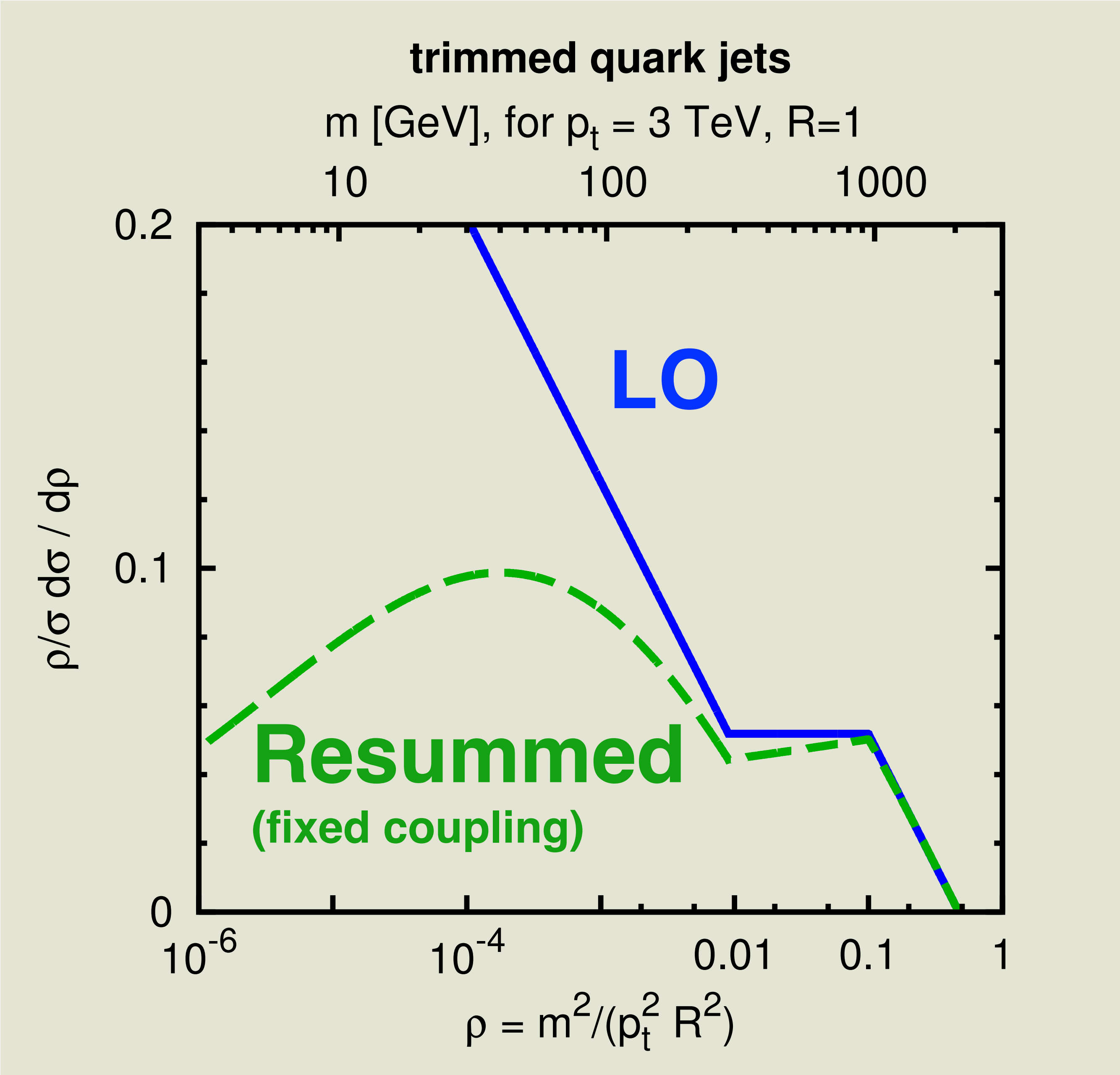
can use QED-like independent emissions, as if gluons don't split

+ virtual corrections, essentially from unitarity

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



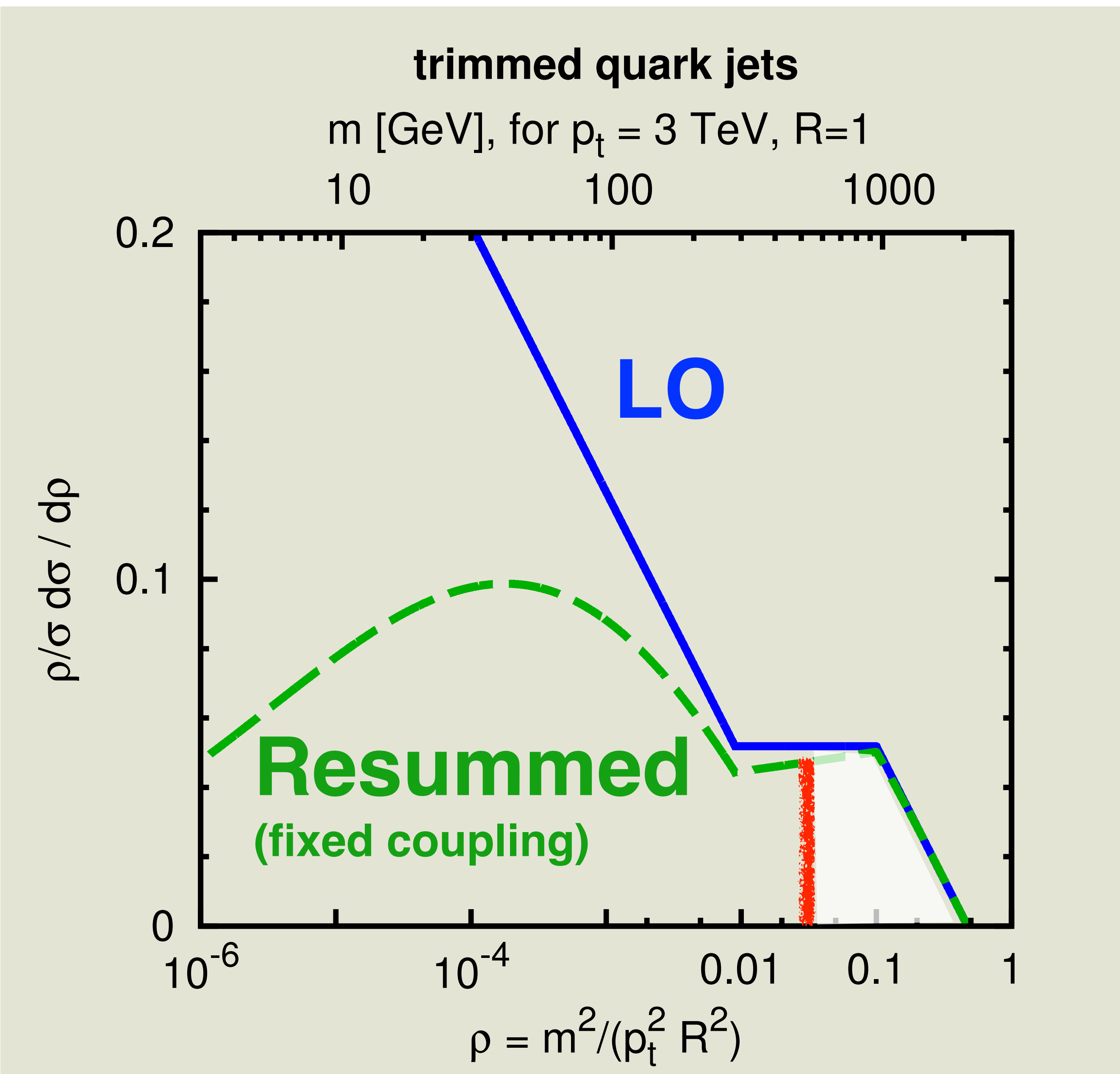
$$\frac{d\sigma^{\text{trim,resum}}}{d\rho} = \frac{d\sigma^{\text{trim,LO}}}{d\rho} \exp\left[-\int_\rho d\rho' \frac{1}{\sigma} \frac{d\sigma^{\text{trim,LO}}}{d\rho'}\right]$$

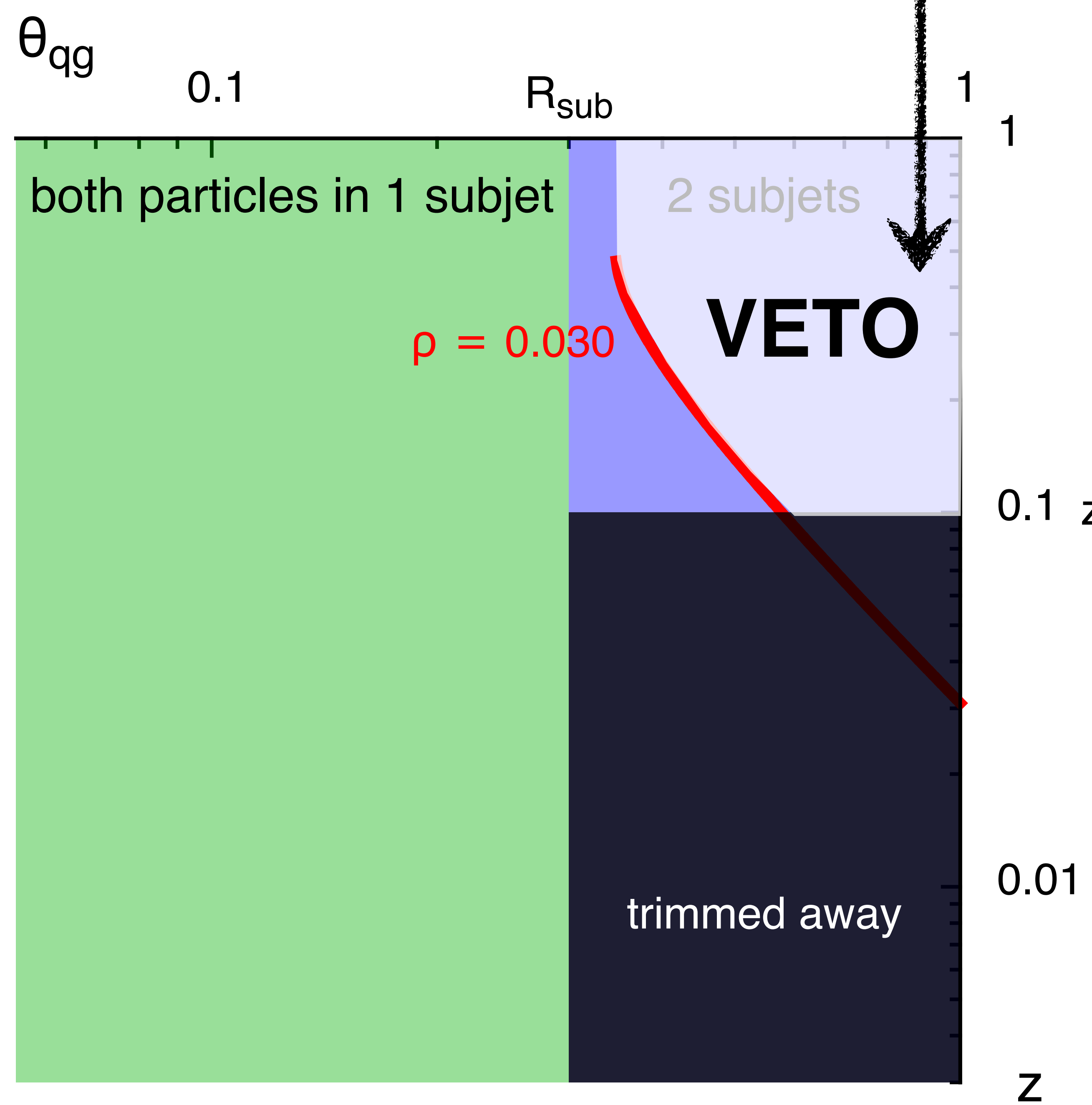


Trimming at all orders

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

Sudakov





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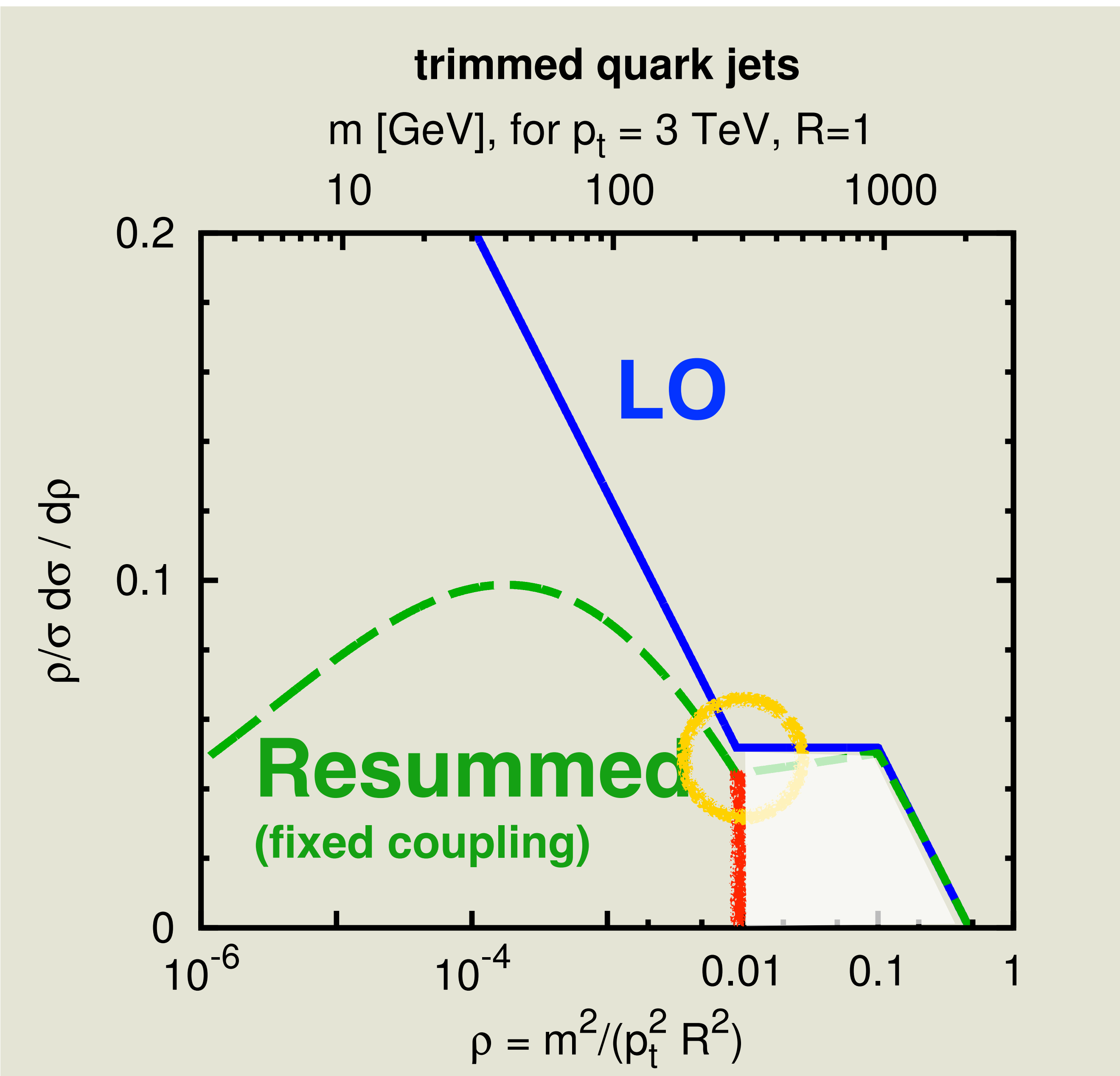

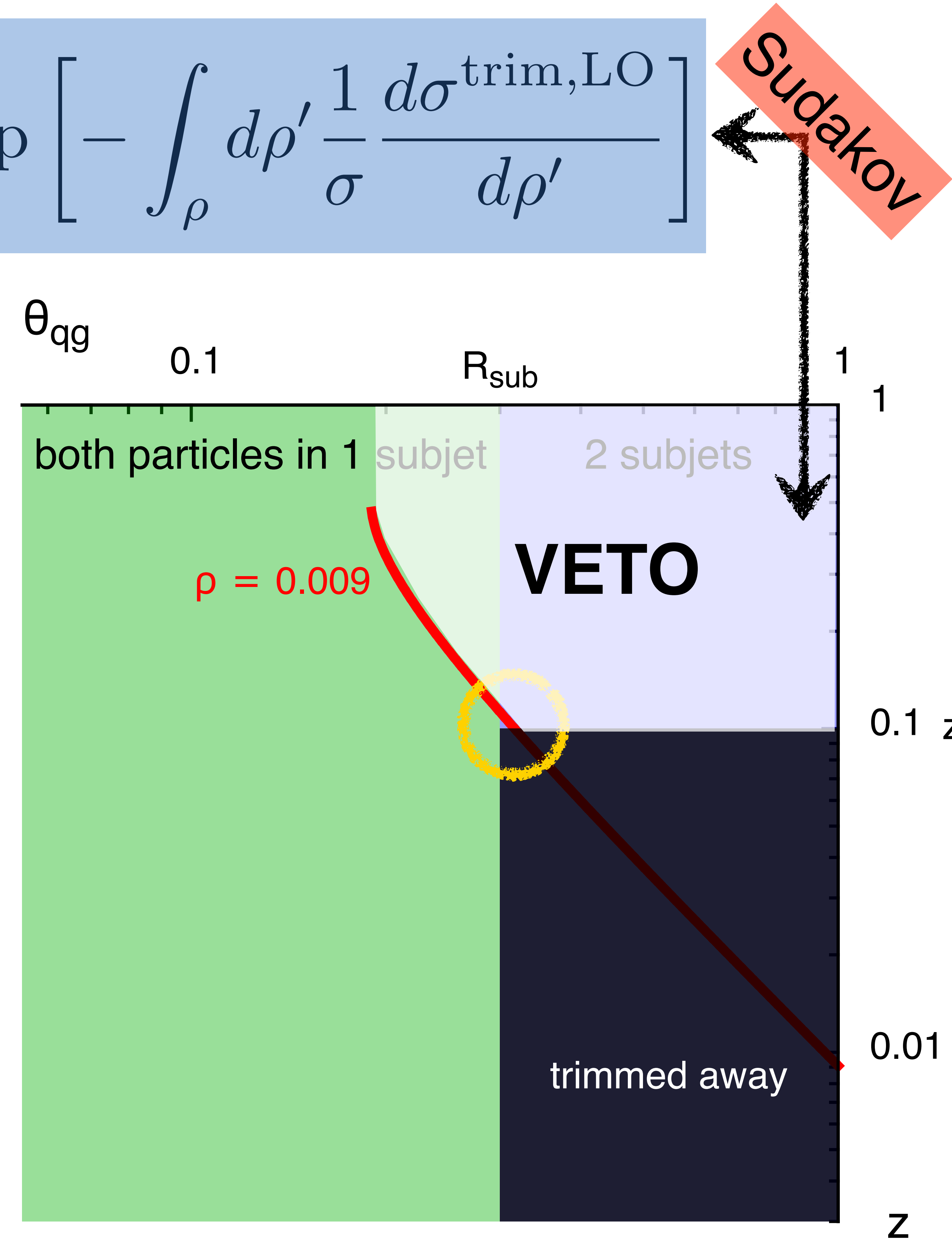

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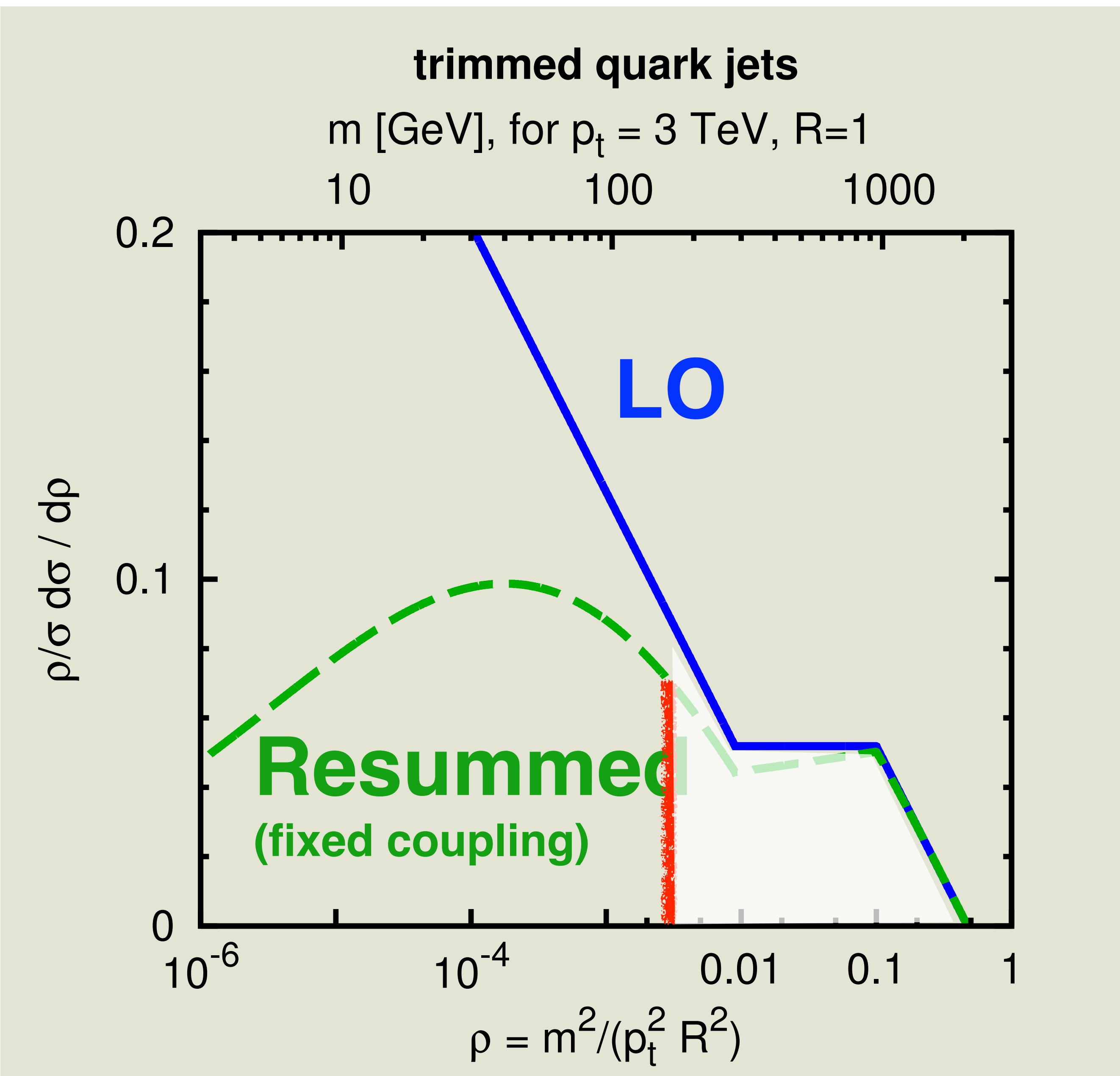

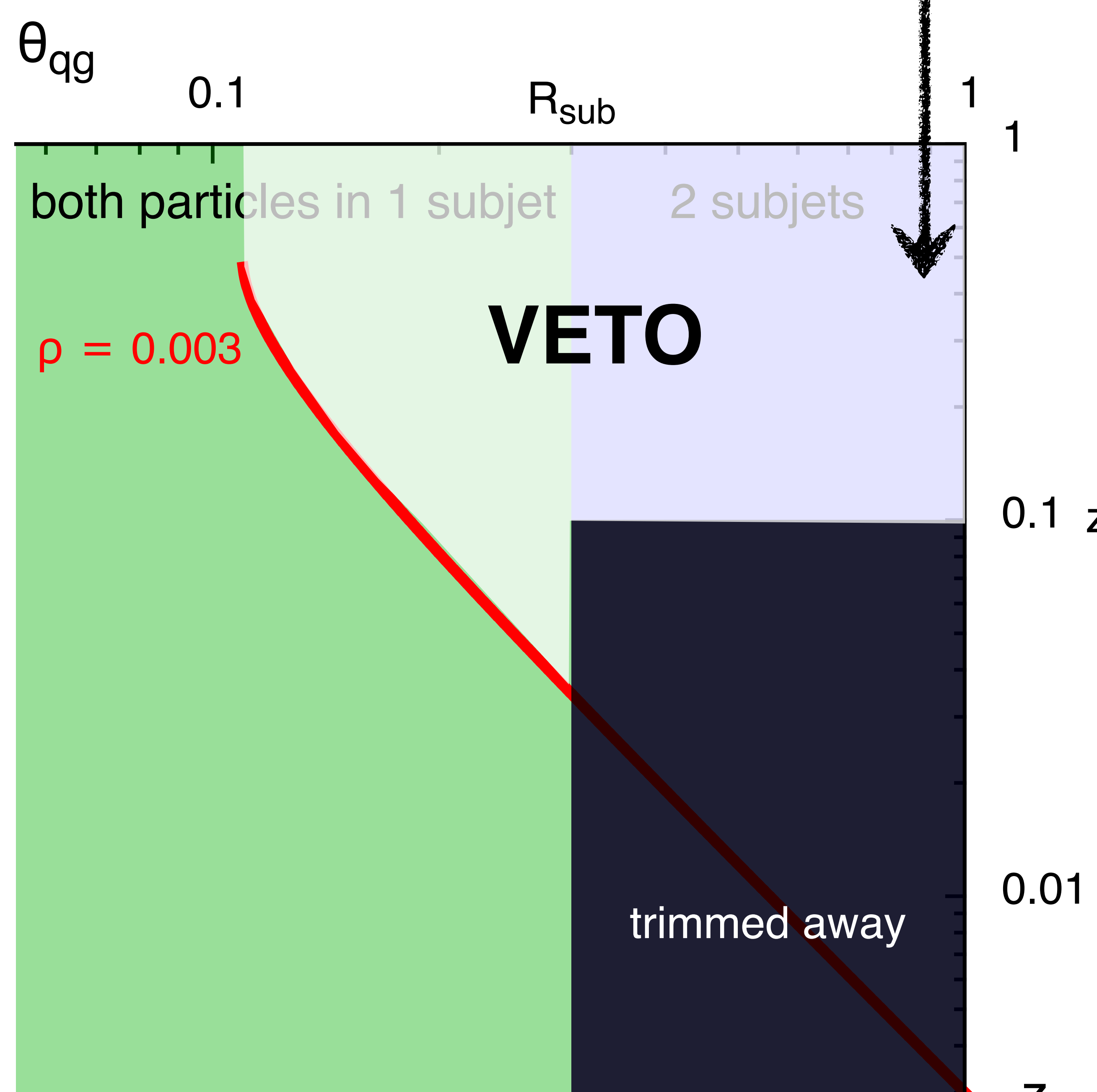

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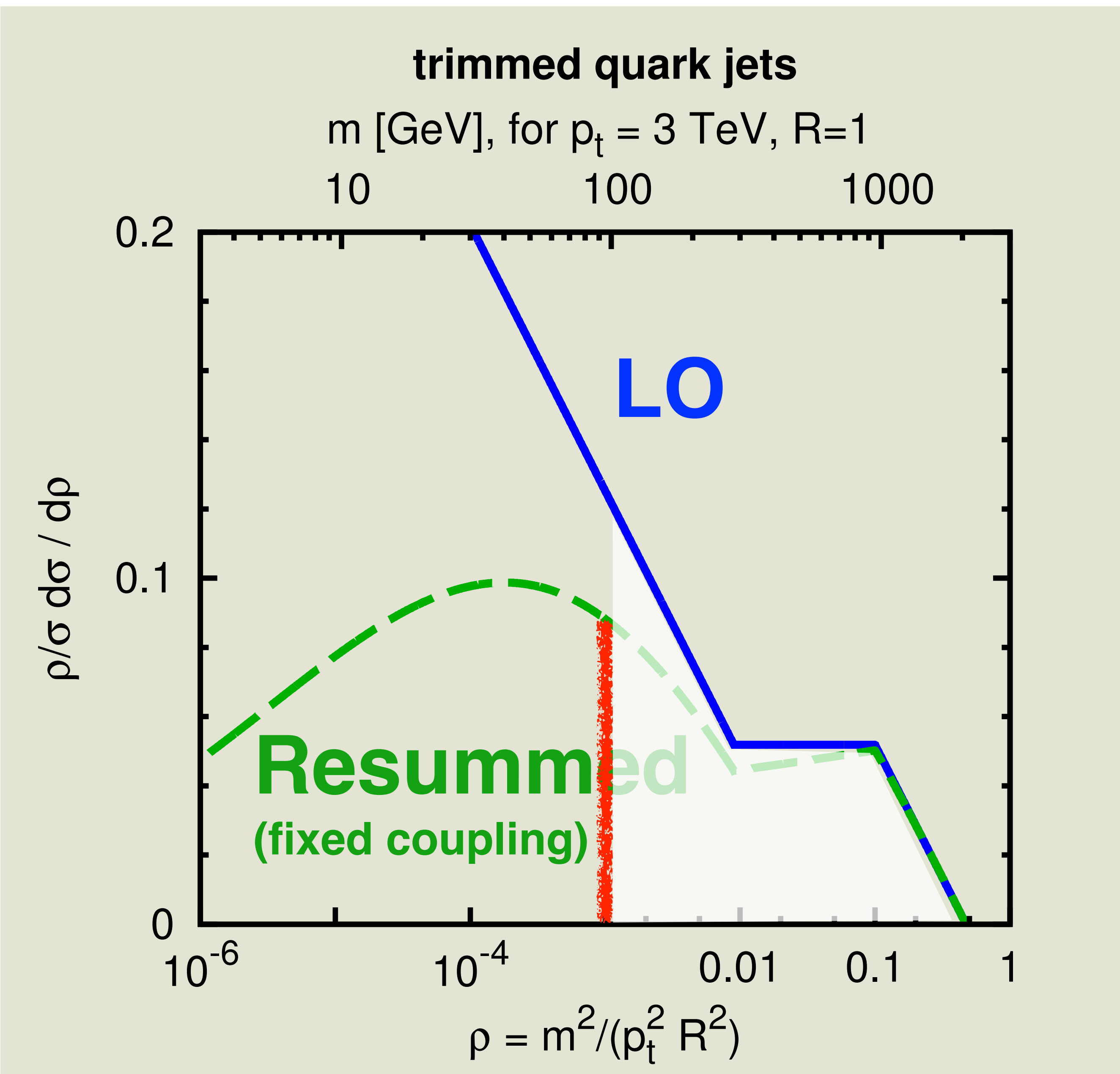

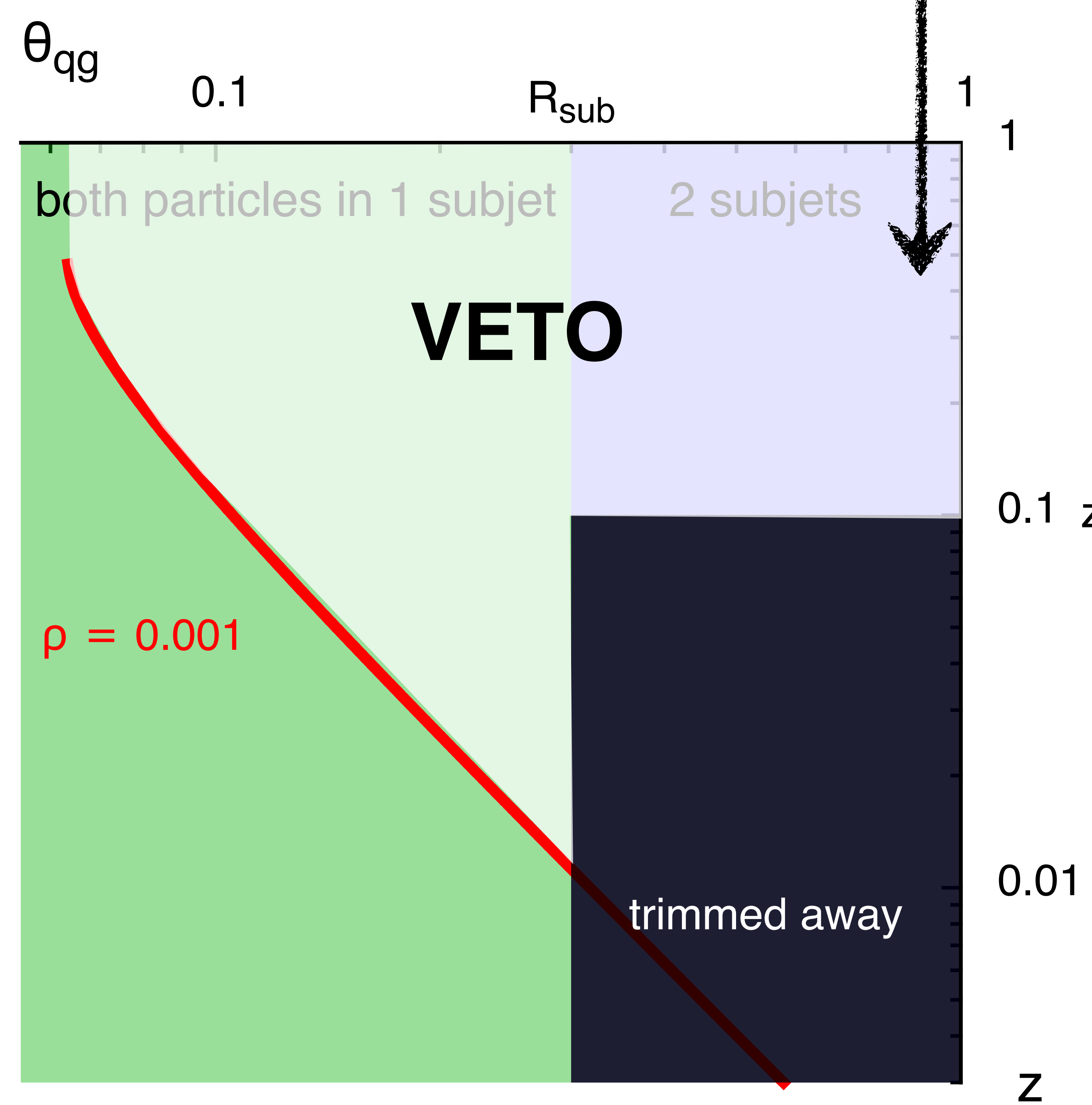

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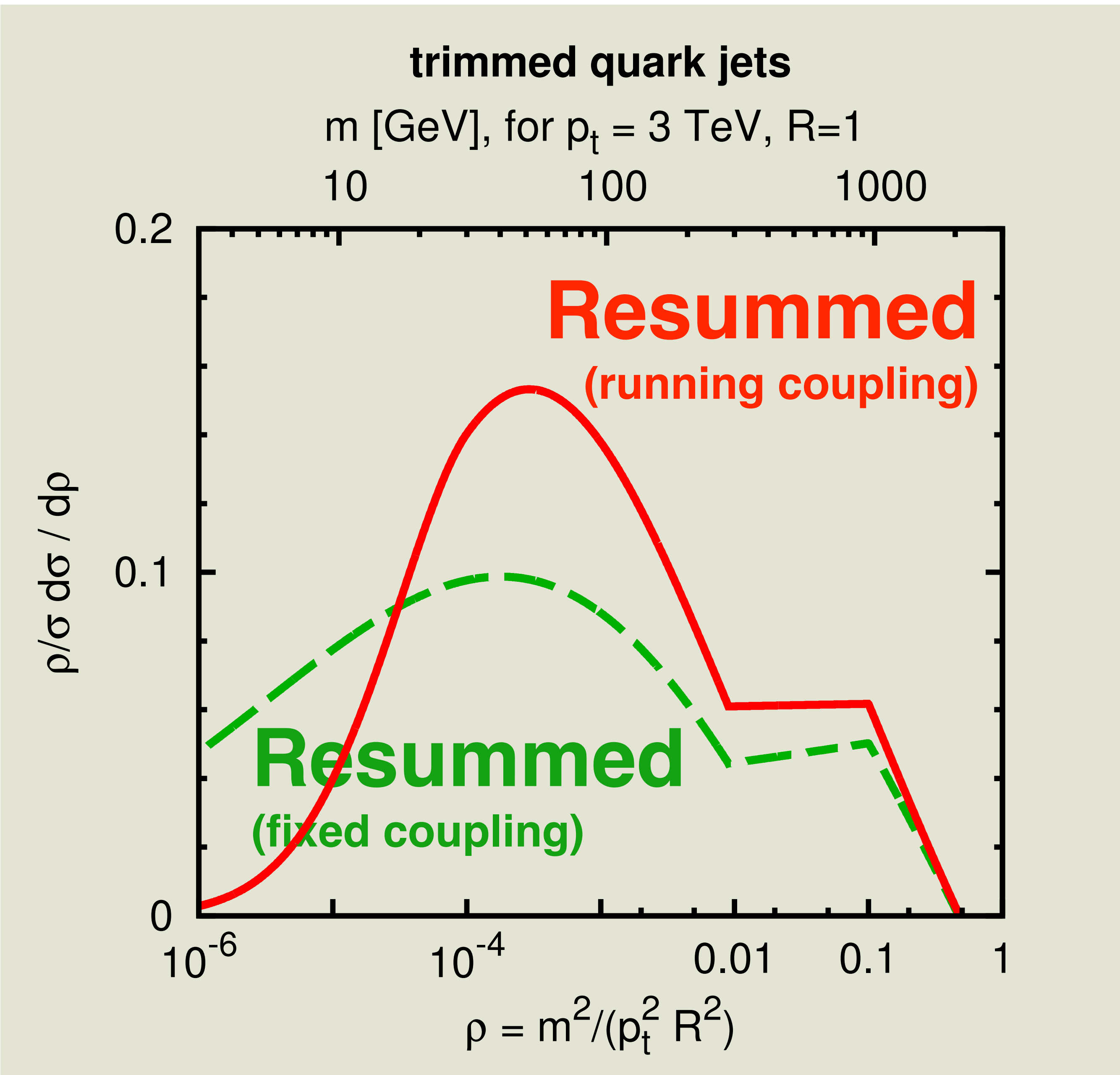

Full resummation also needs treatment of running coupling

What logs, what accuracy?

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

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

Use shorthand L = log 1/**ρ**

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

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

Just like the jet mass

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

What logs, what accuracy?

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Just like the jet mass

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

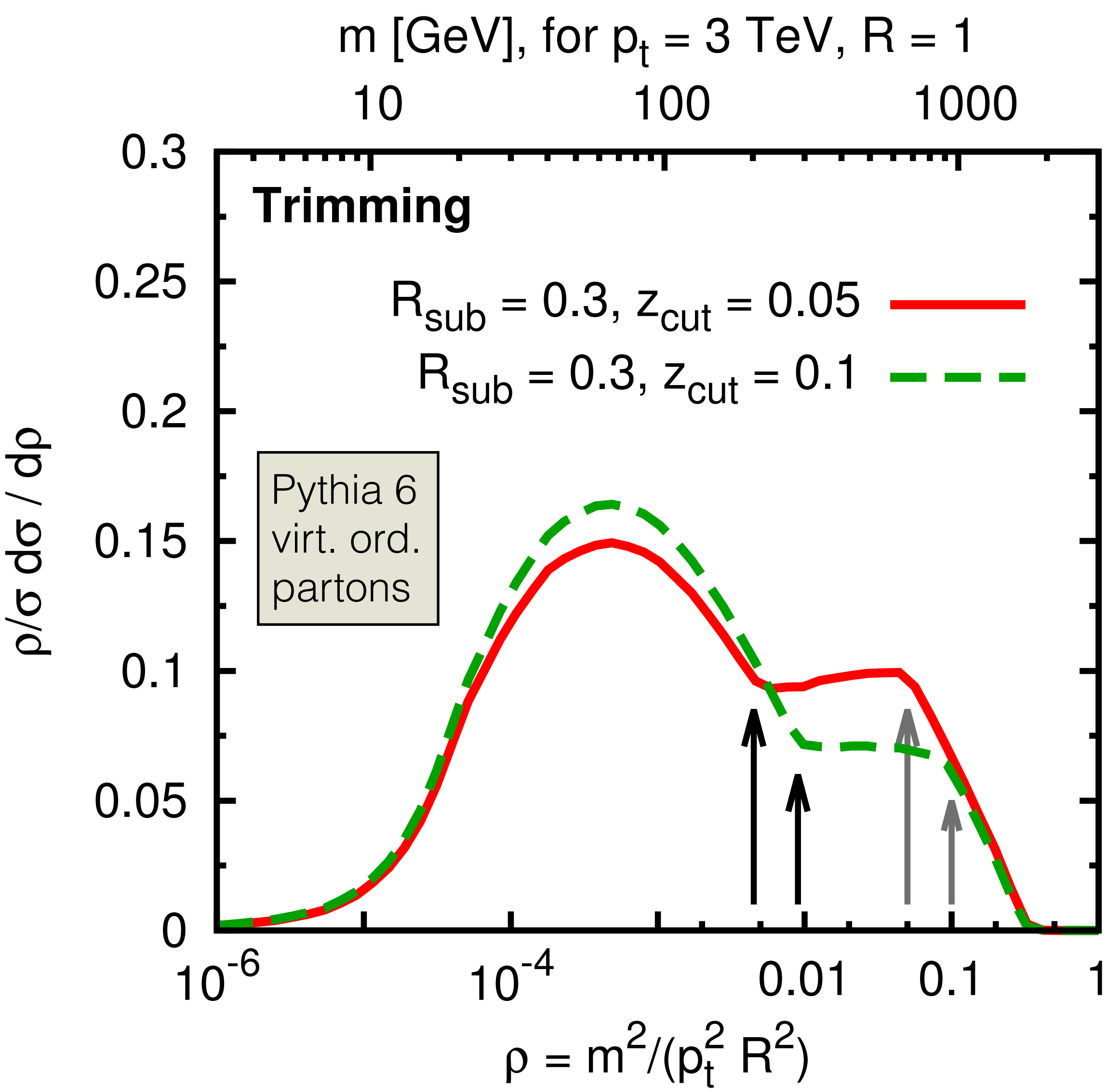
Could we do better? Yes: NLL in ln **Σ**:

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

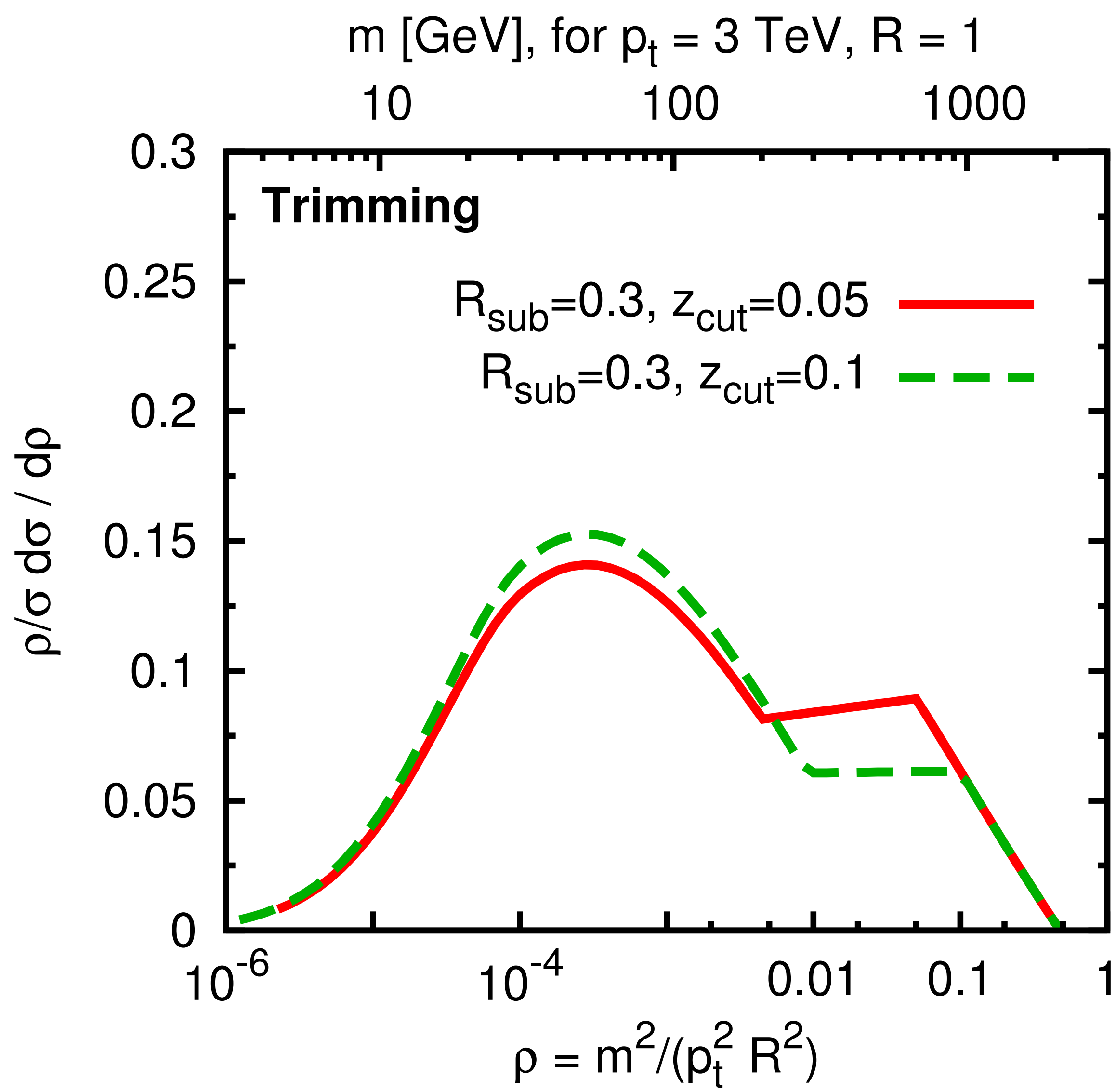
Trimmed mass is like plain jet mass (with R → R_{sub}), and this accuracy involves **non-global logs, clustering logs**

Trimming: MC v. analytics

Monte Carlo



Analytic

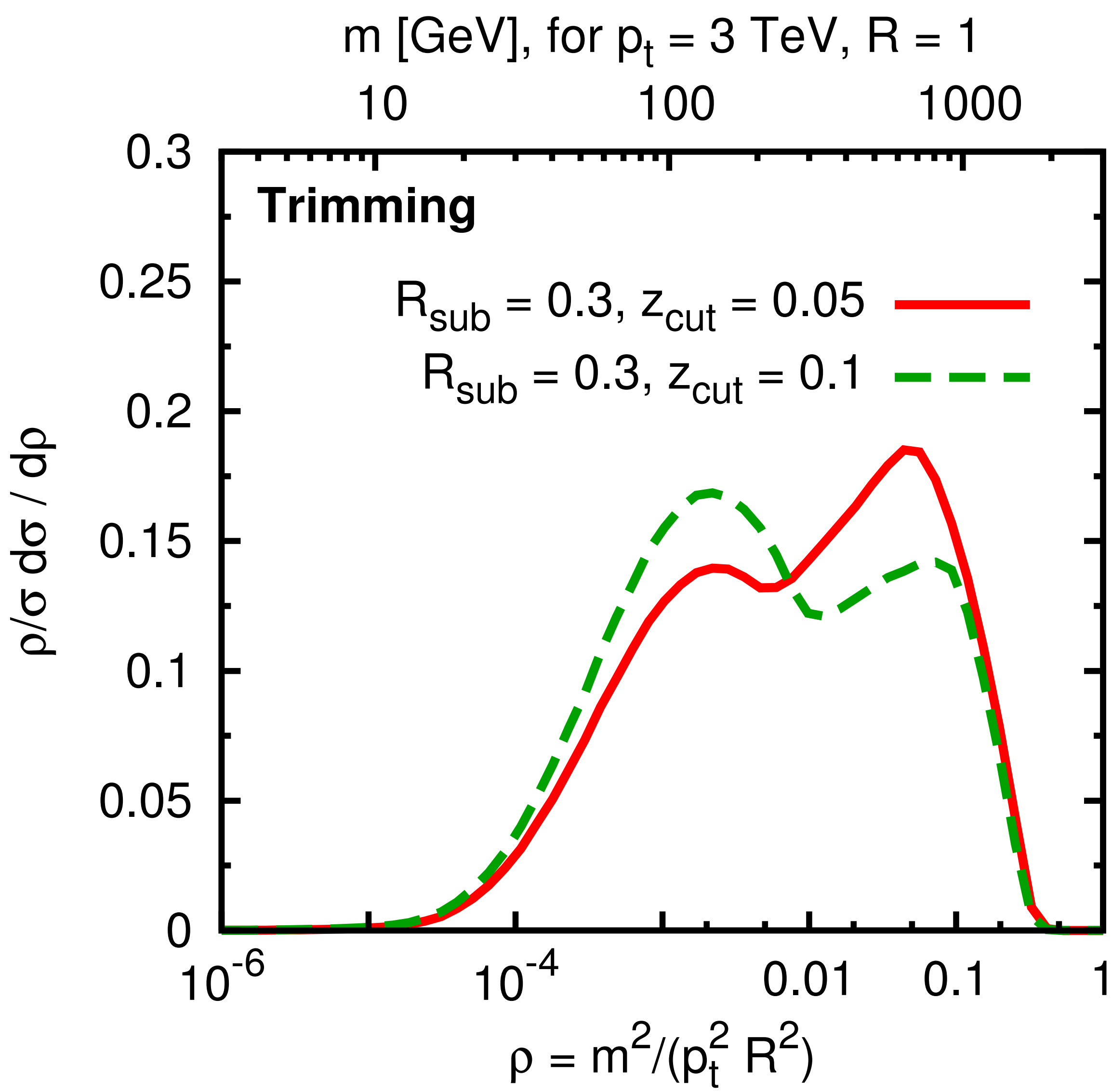


Non-trivial agreement!

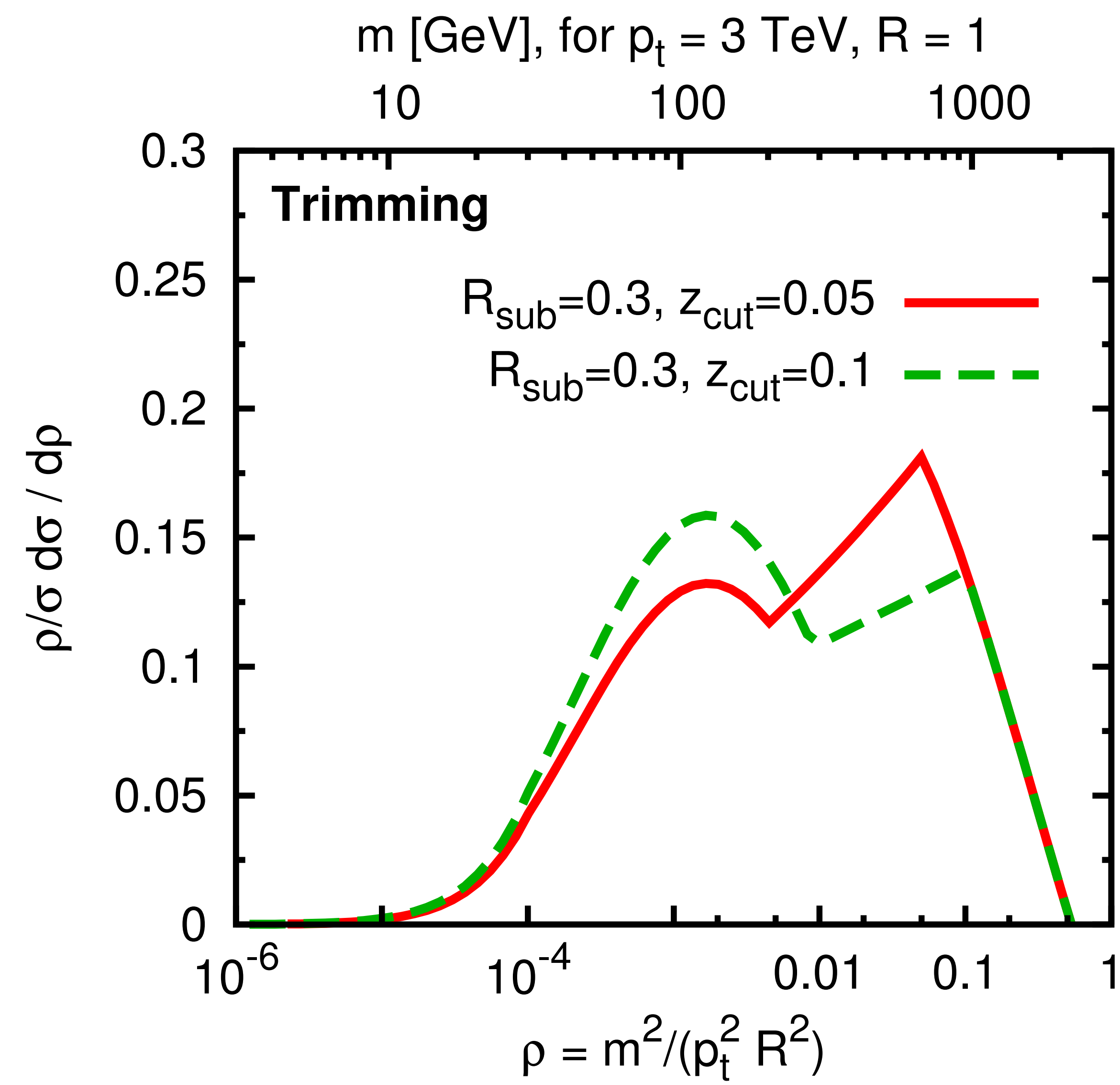
(also for dependence on parameters)

Trimming: MC v. analytics

Monte Carlo



Analytic



Non-trivial agreement!

(also for dependence on parameters)

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

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

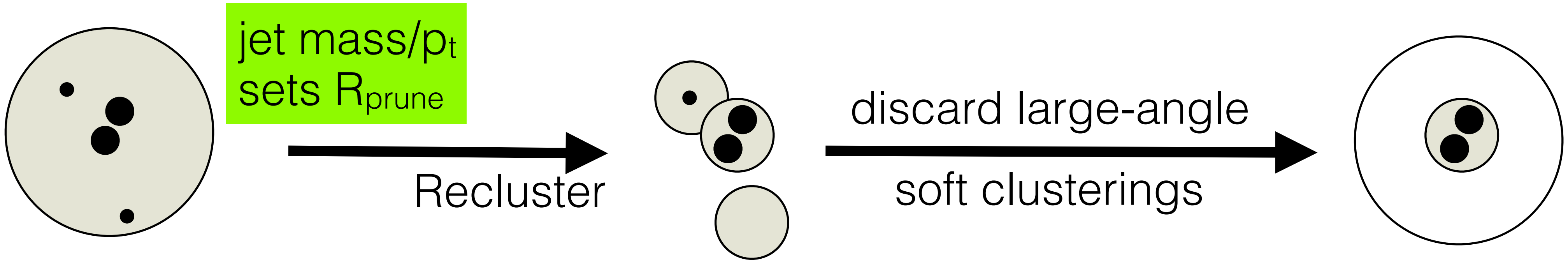
$$\Delta R_{ij} > R_{\text{prune}}$$

discard softer prong.

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

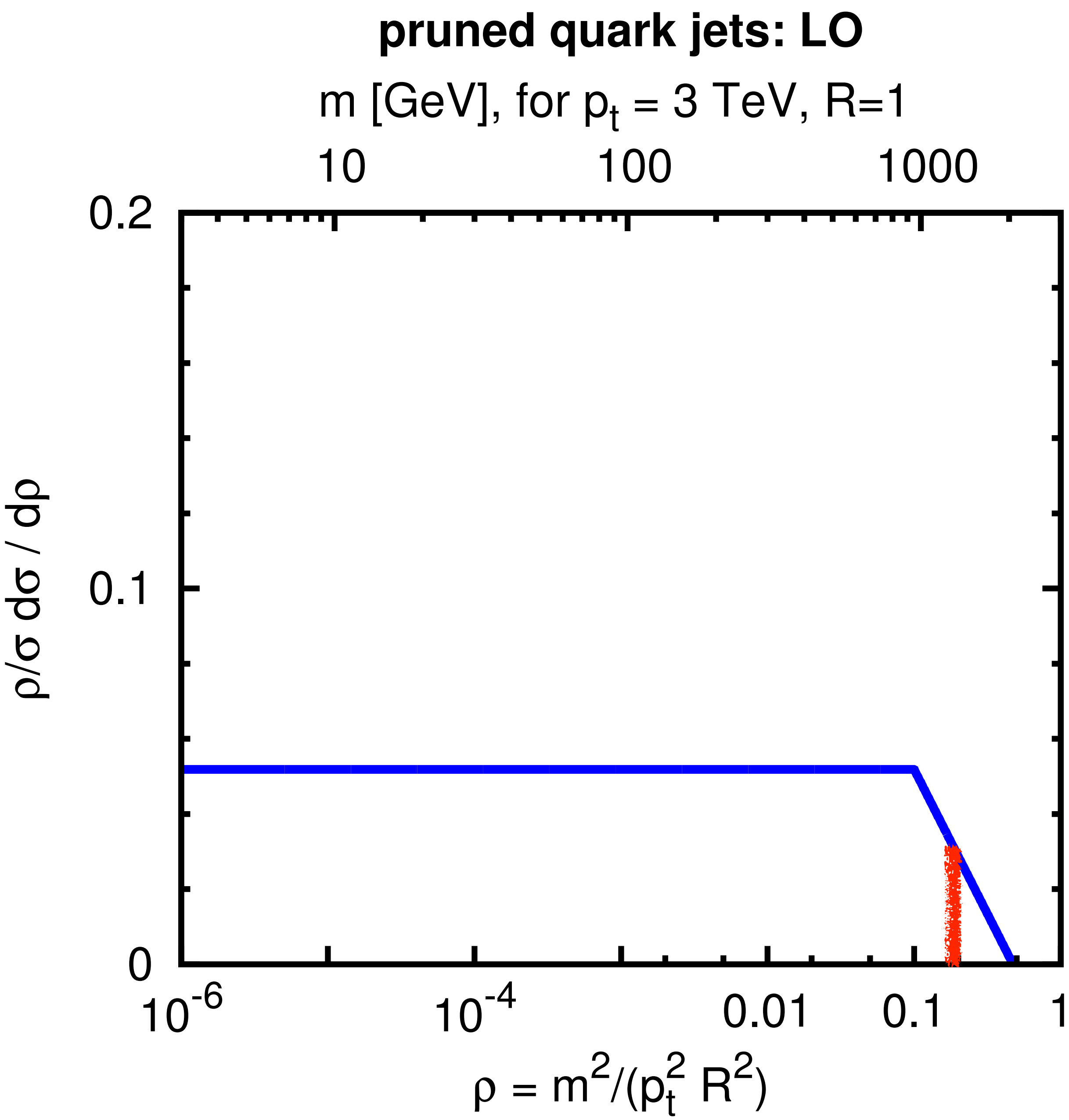
one (main) parameter: z_{cut}

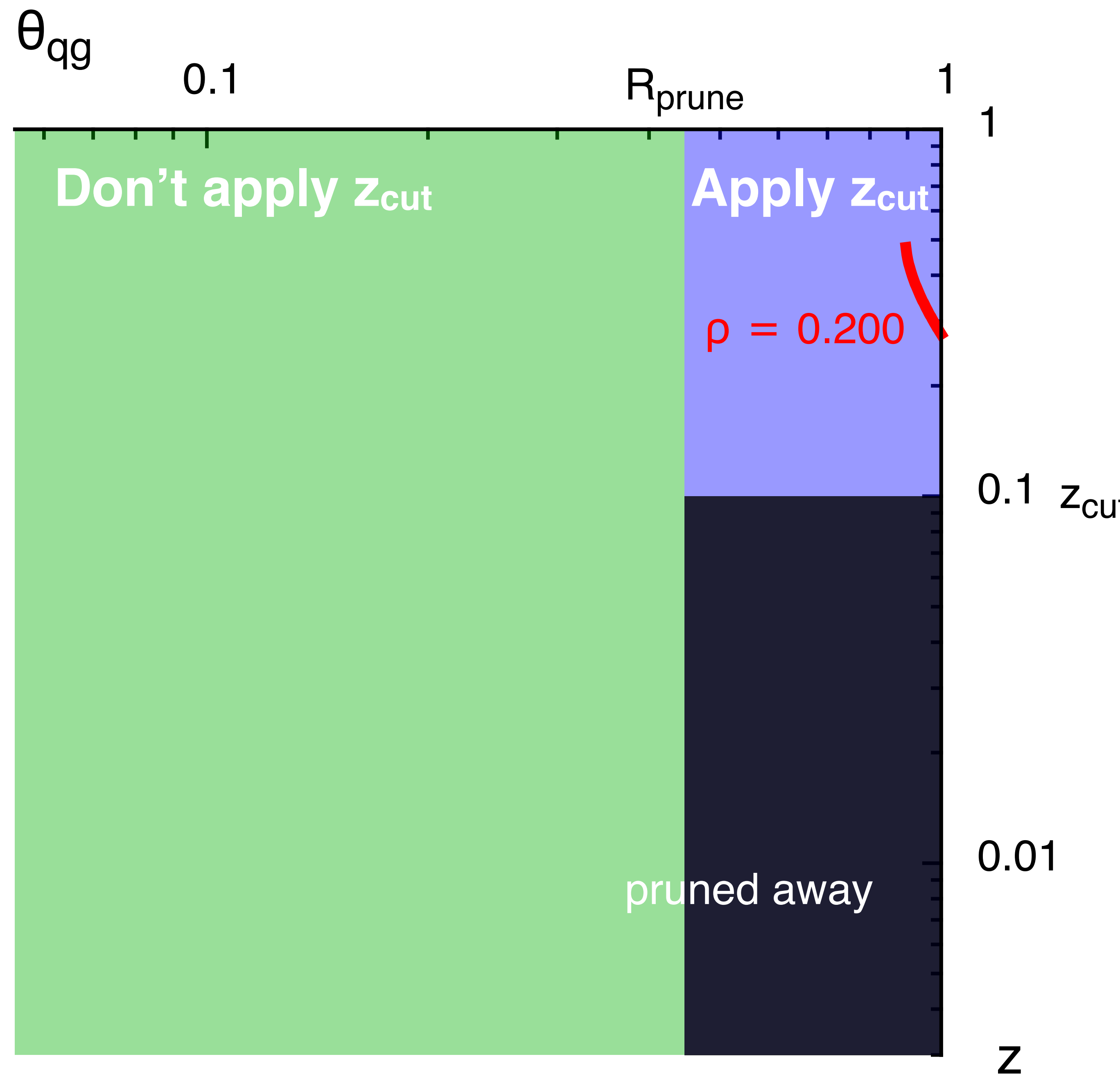
we'll study variant with C/A reclustering



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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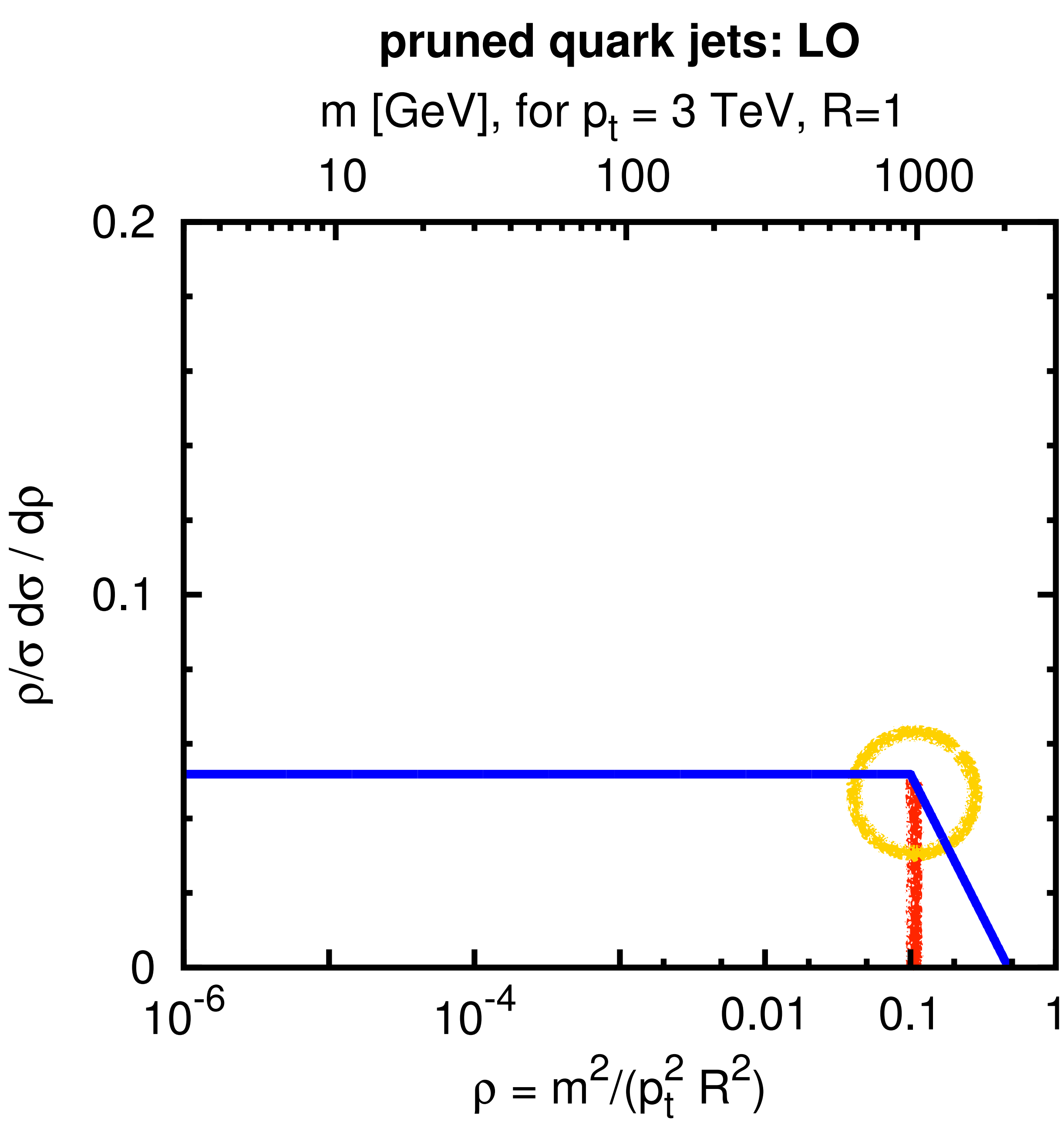

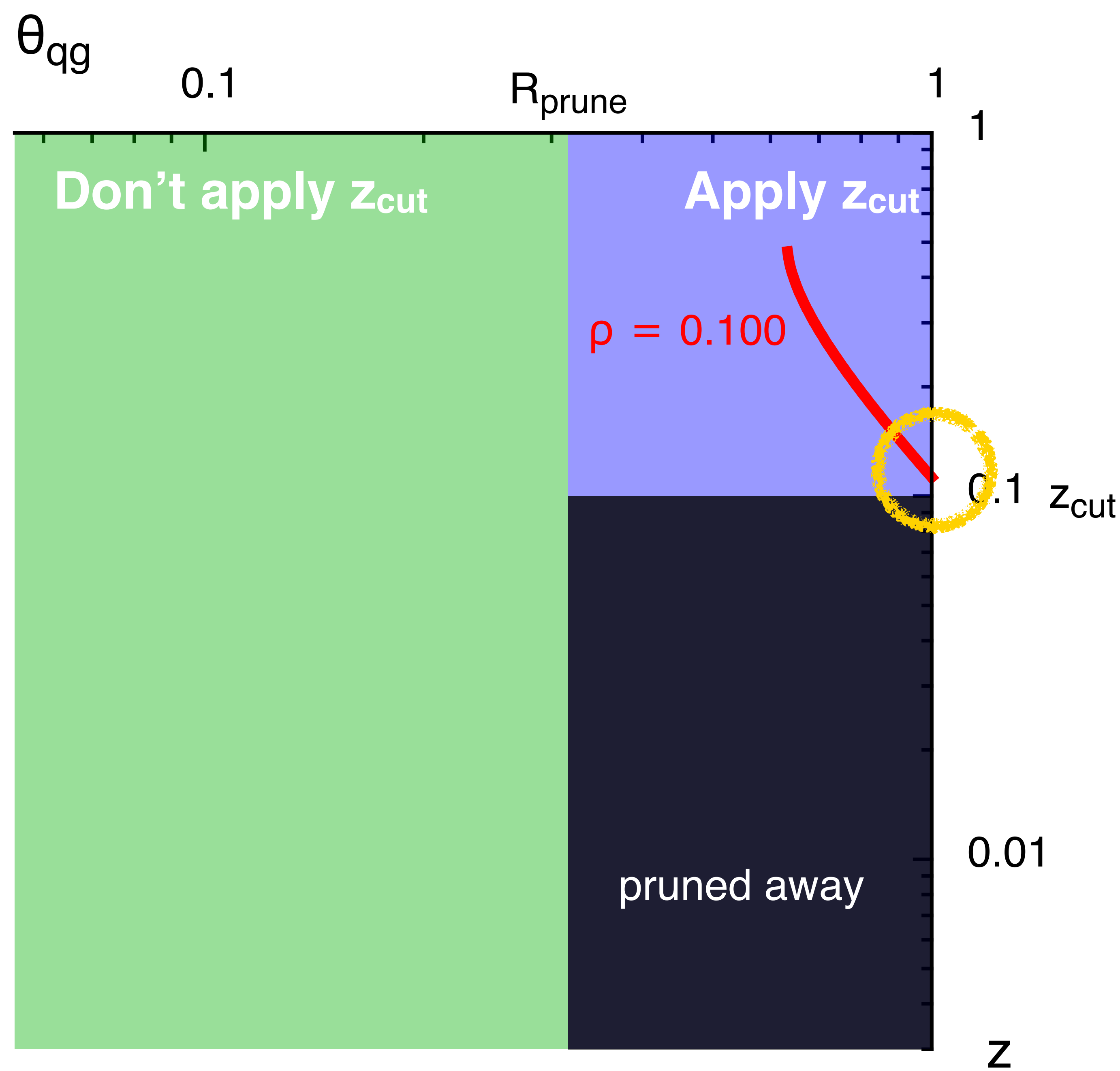

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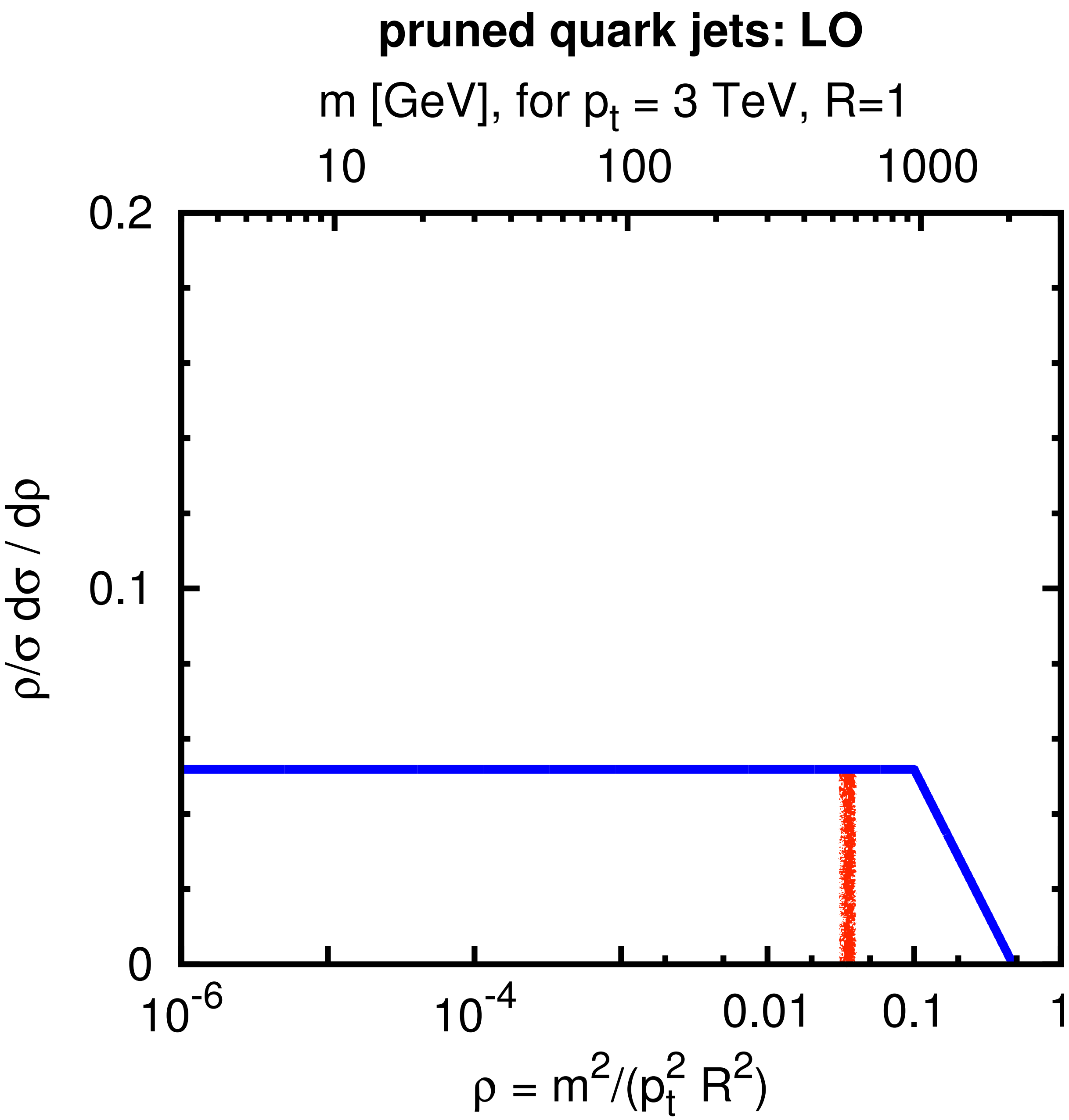

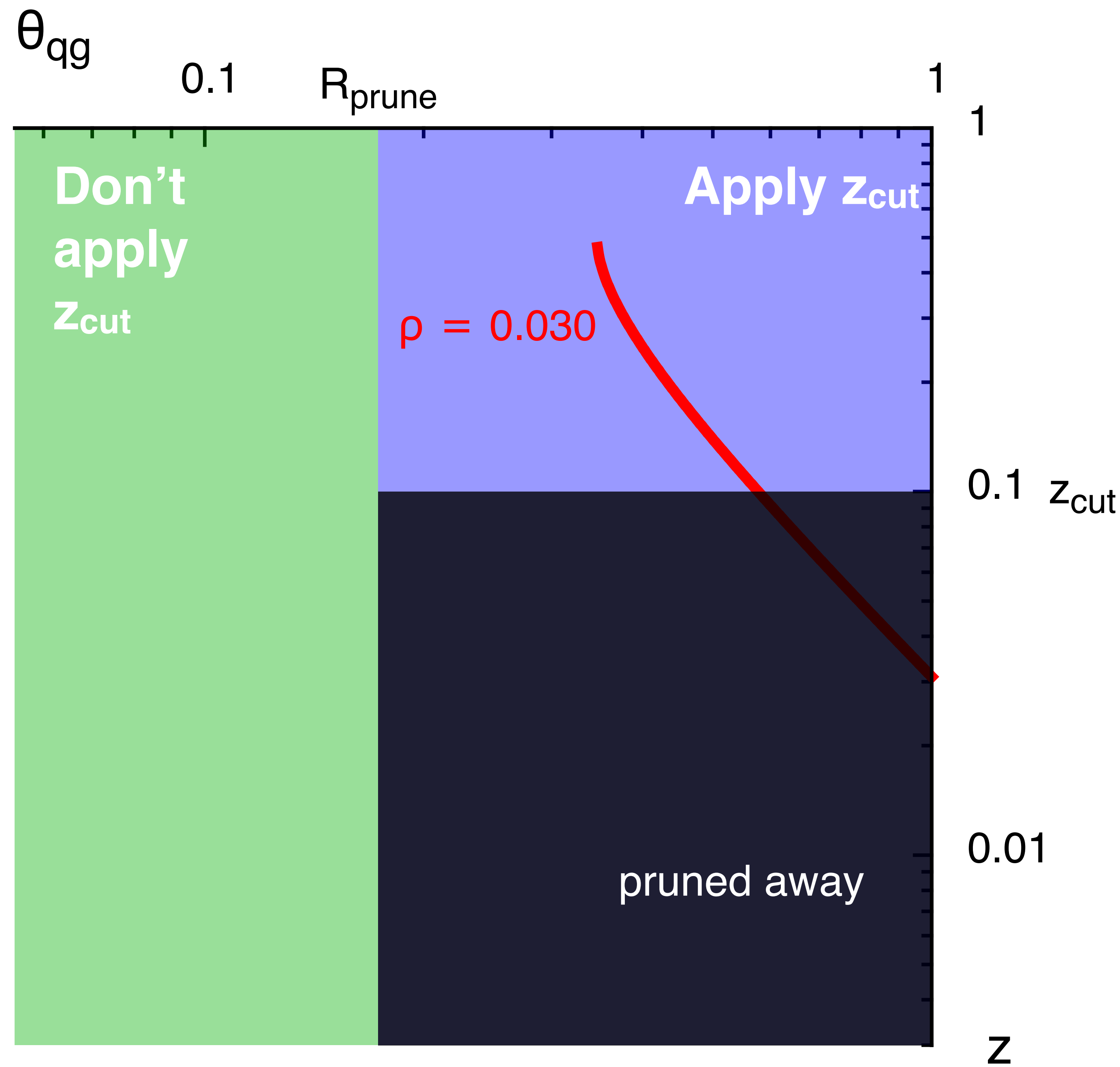

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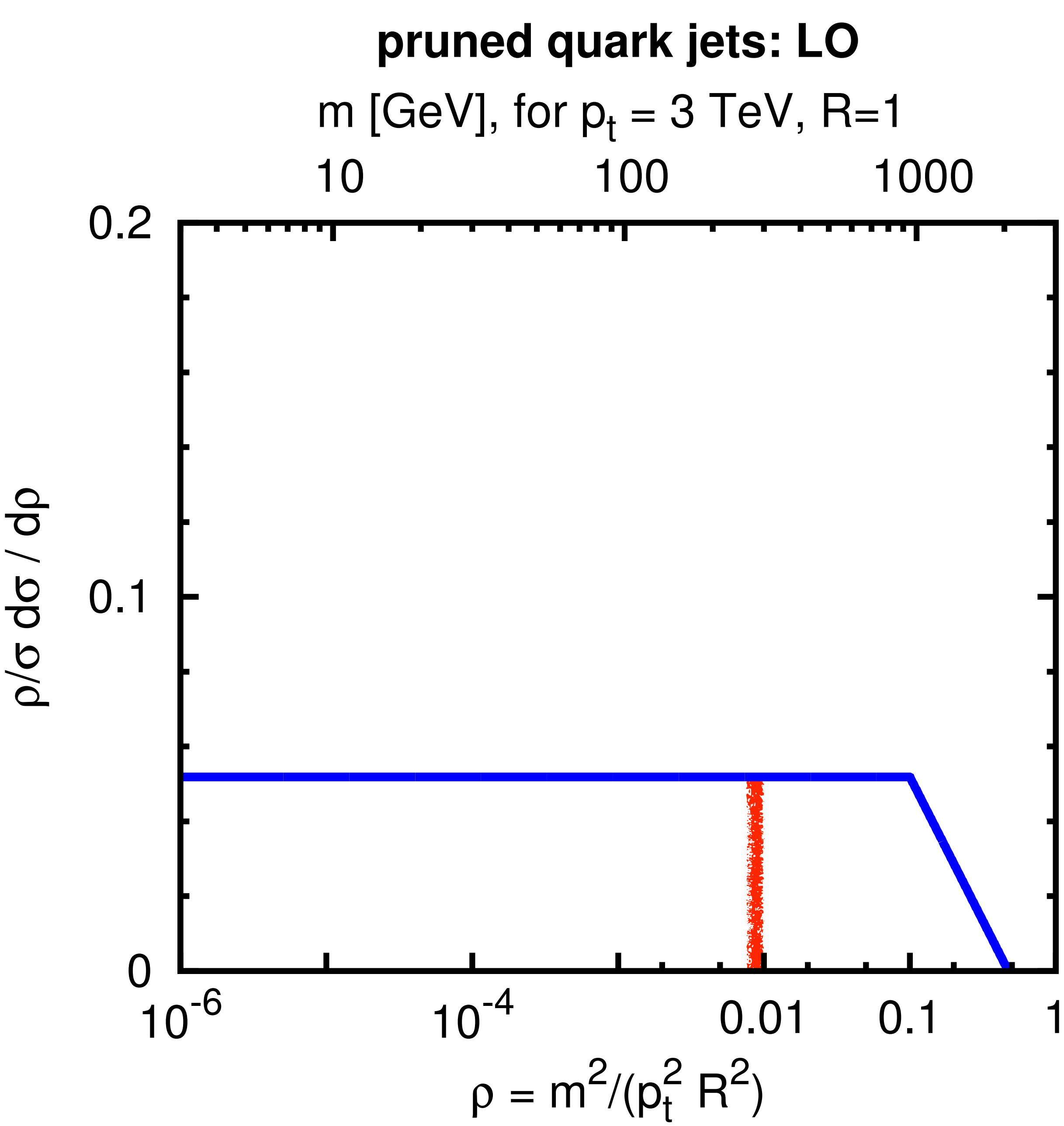

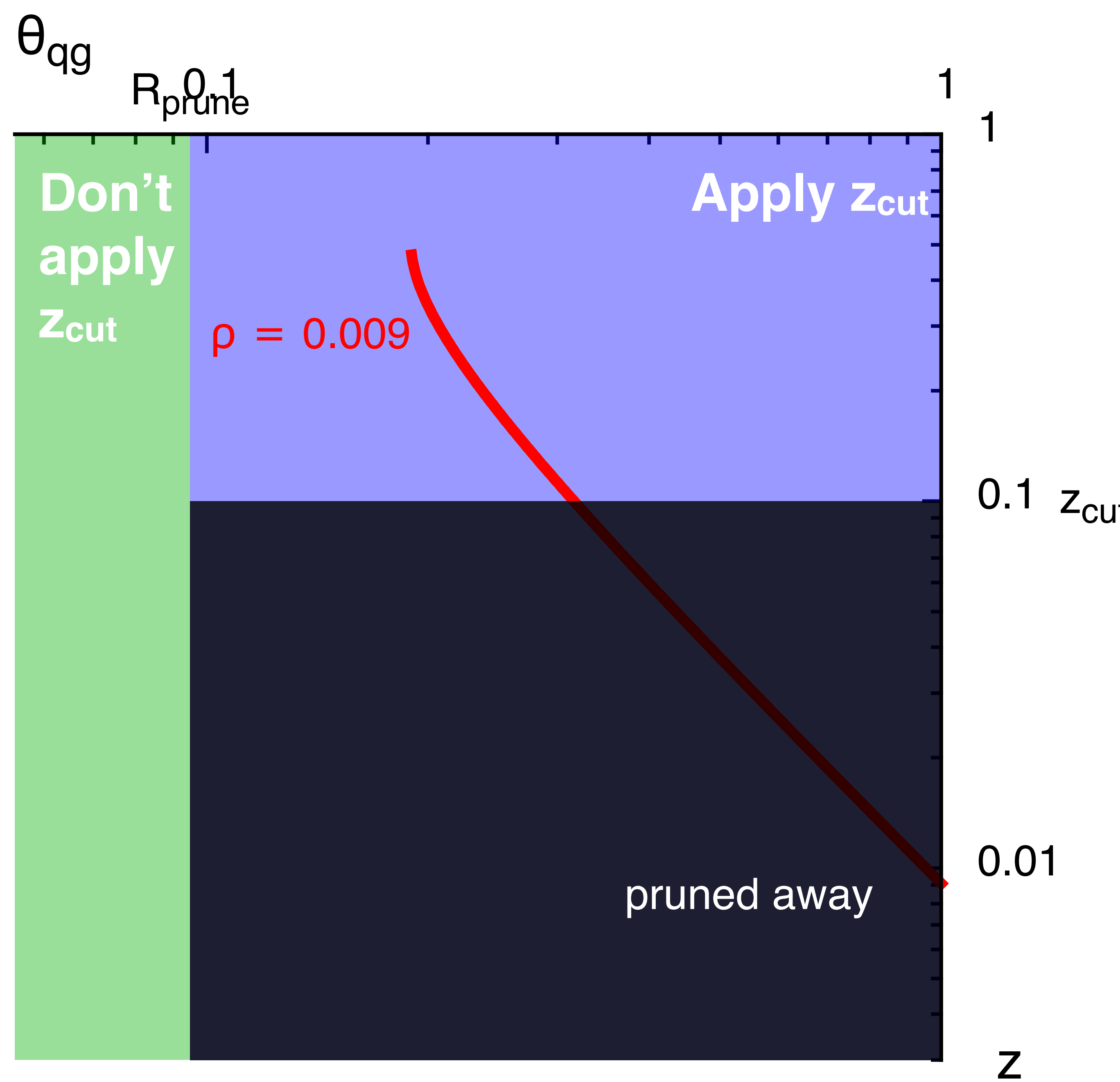

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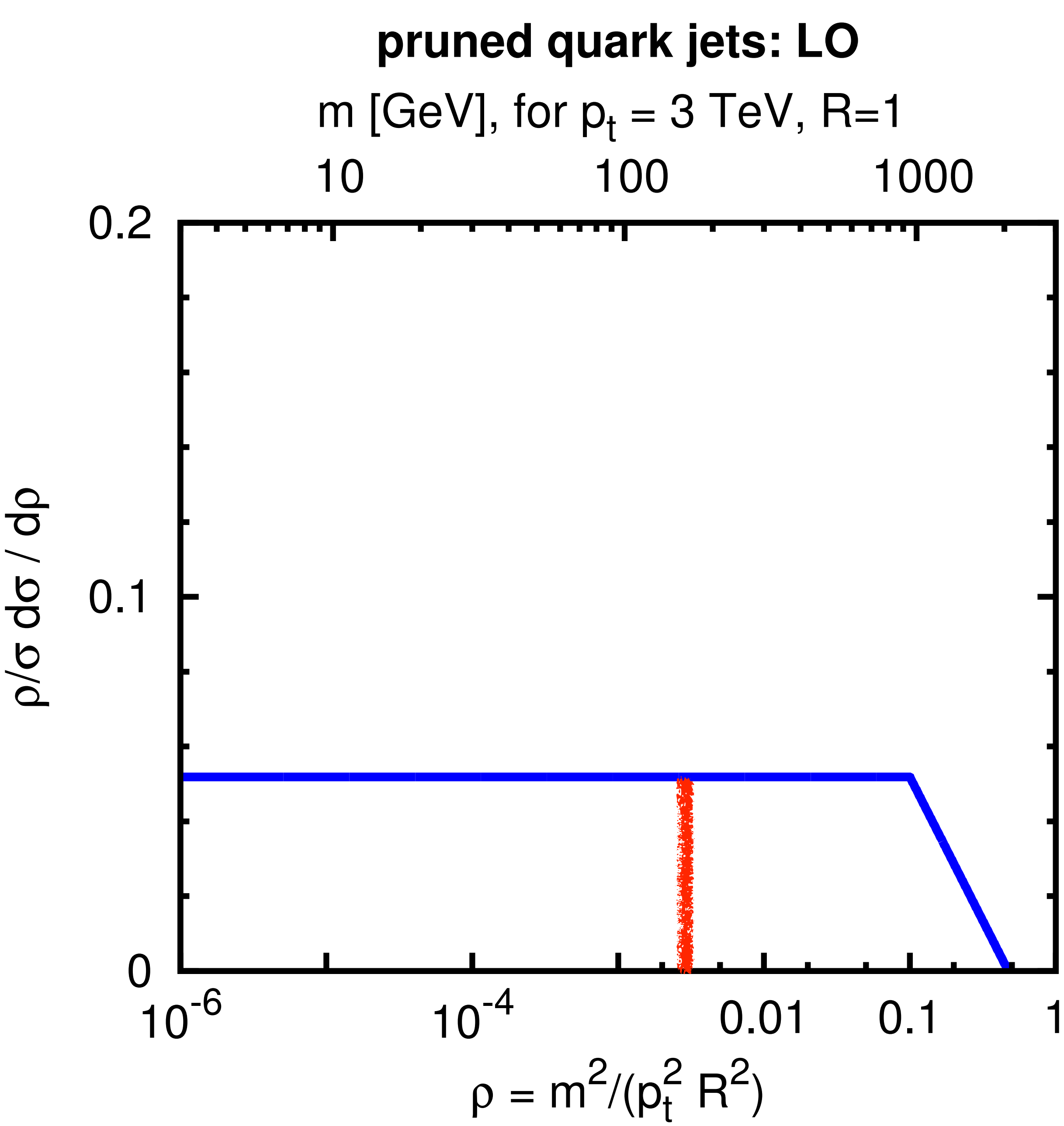

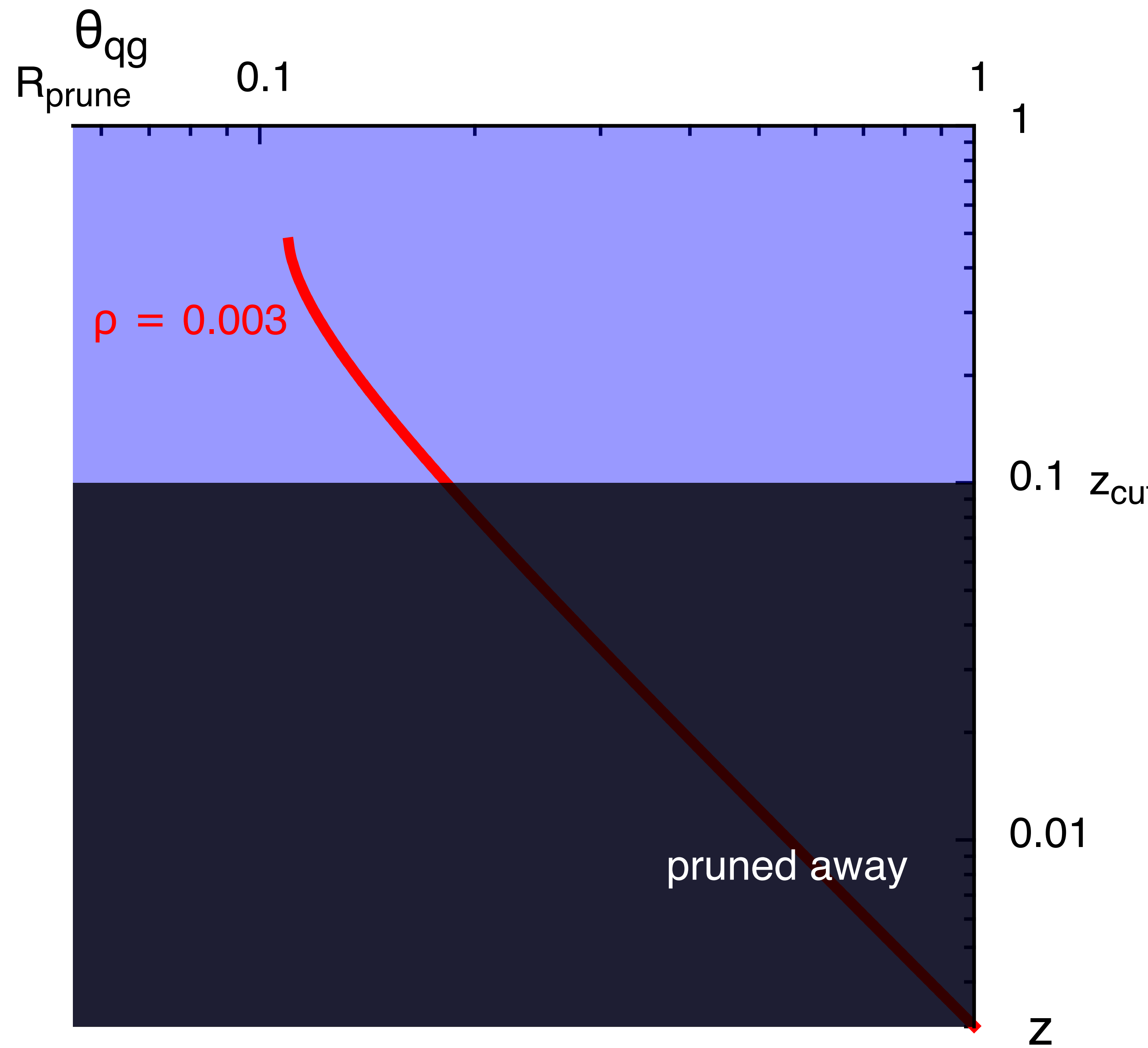

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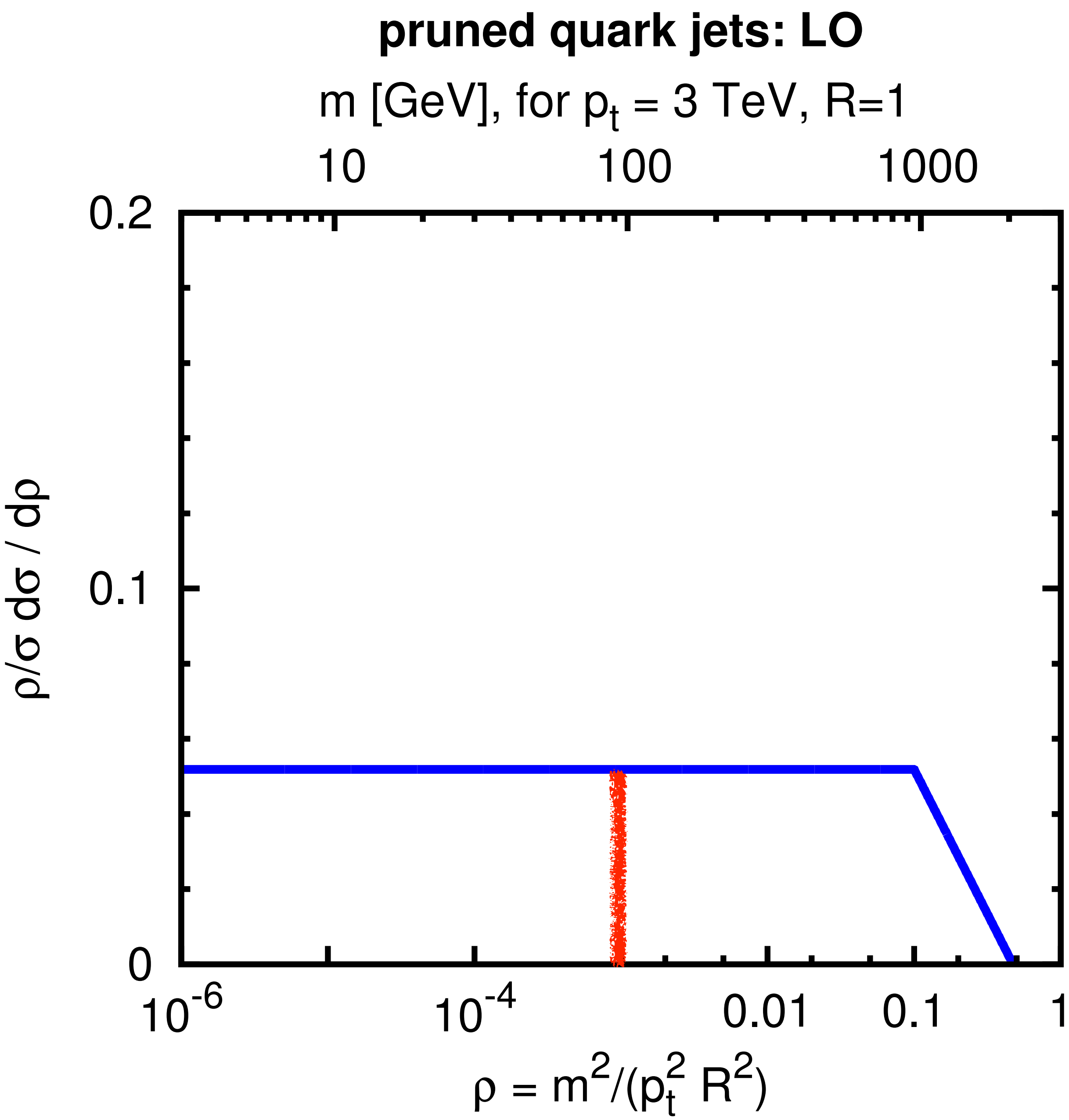
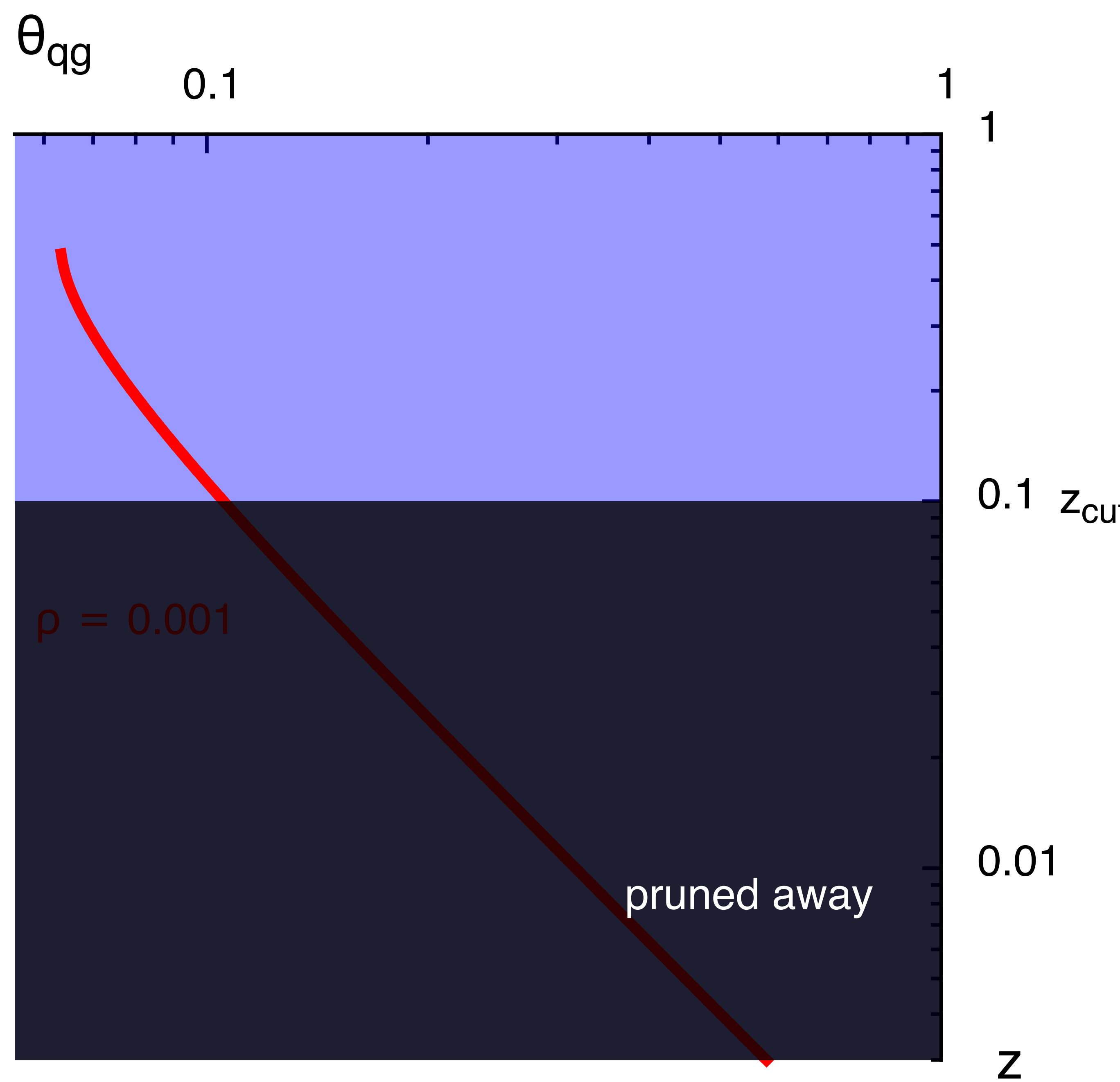
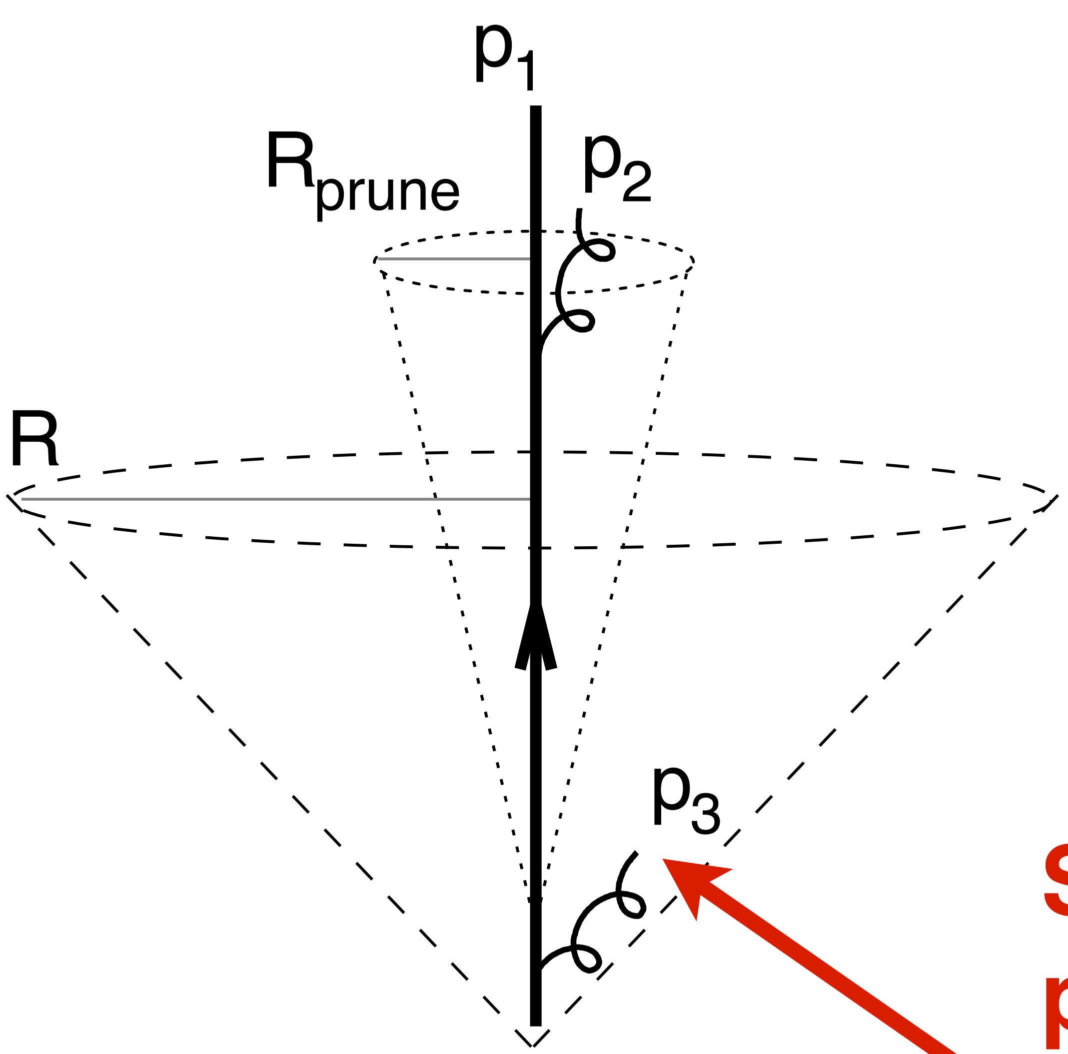




pruning beyond 1st order: consider multiple emissions



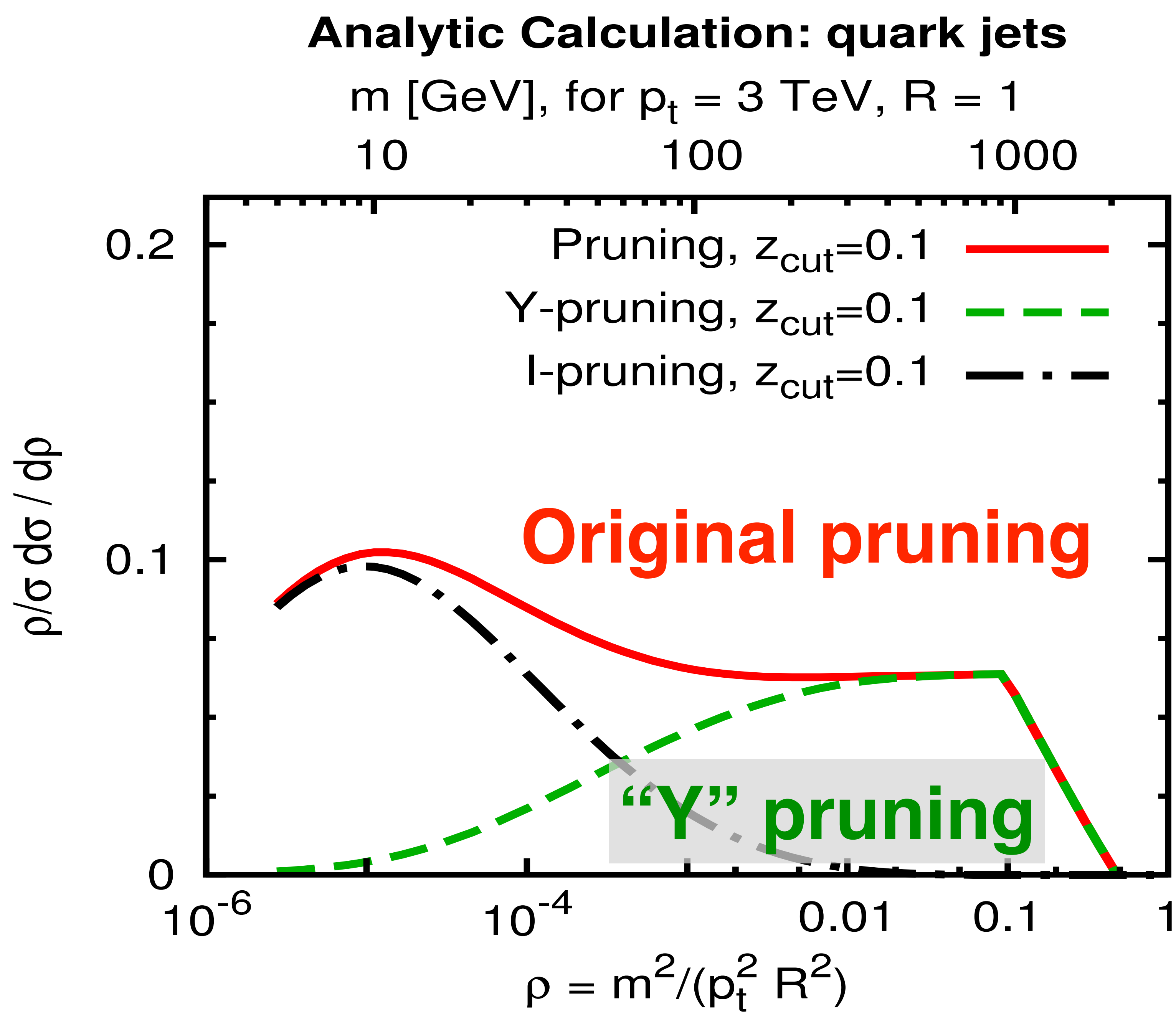
What pruning sometimes does

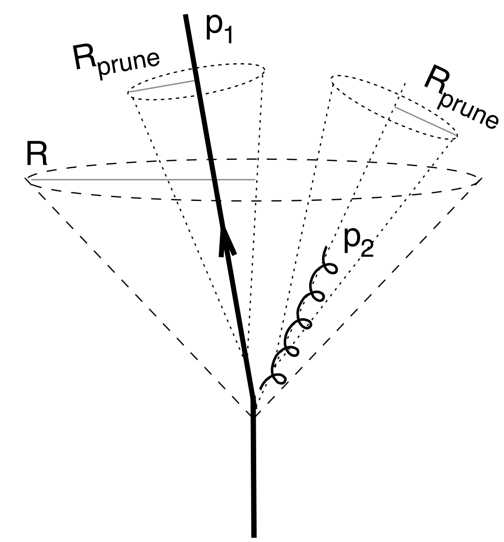
Chooses R_{prune} based on a soft p_3 (dominates total jet mass), and leads to a single narrow subjet whose mass is also dominated by a soft emission (p_2, within R_{prune} of p_1, so not pruned away).

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

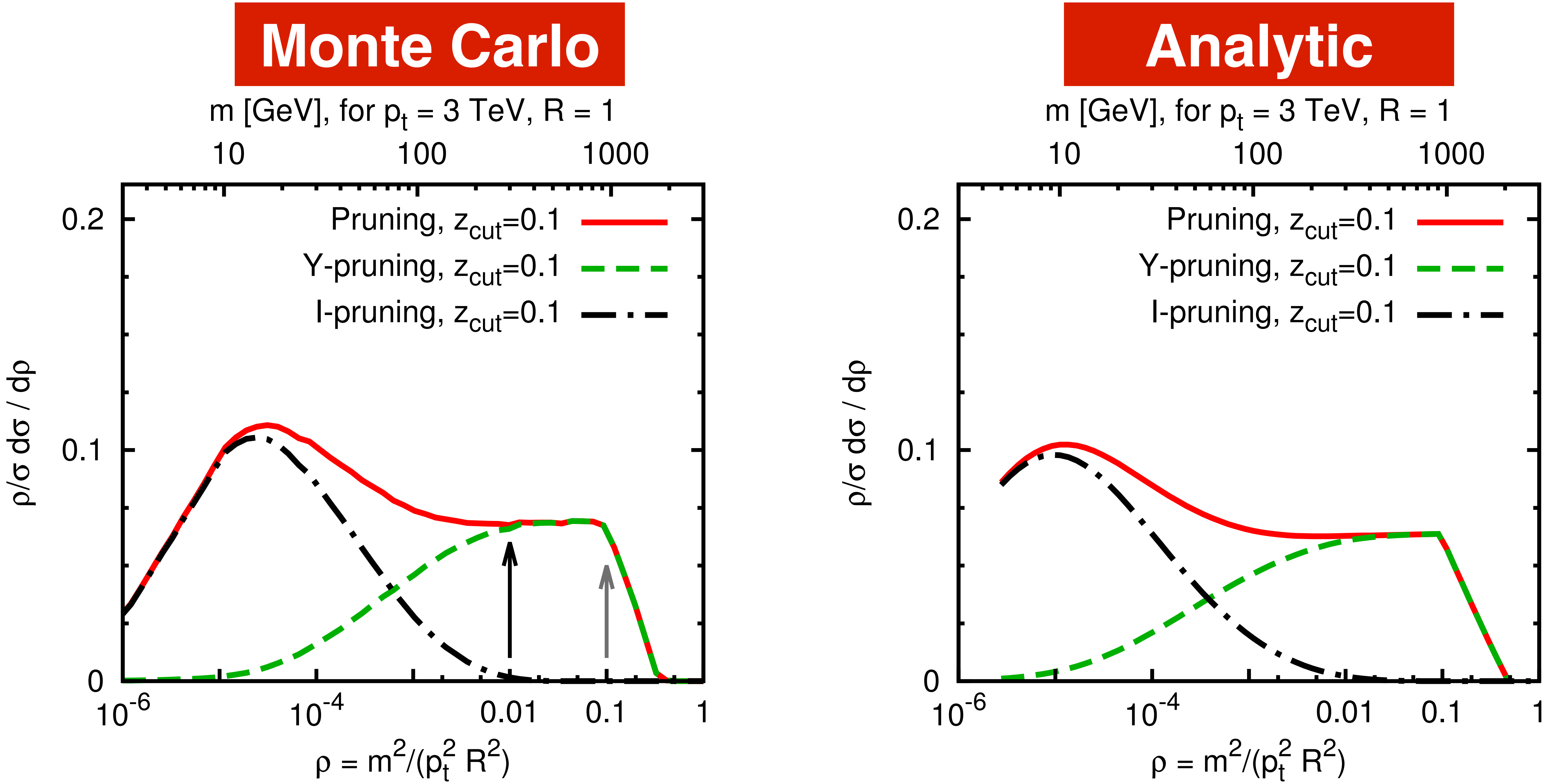
Y-Pruning's leading logs (LL, in Σ) are:

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

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)

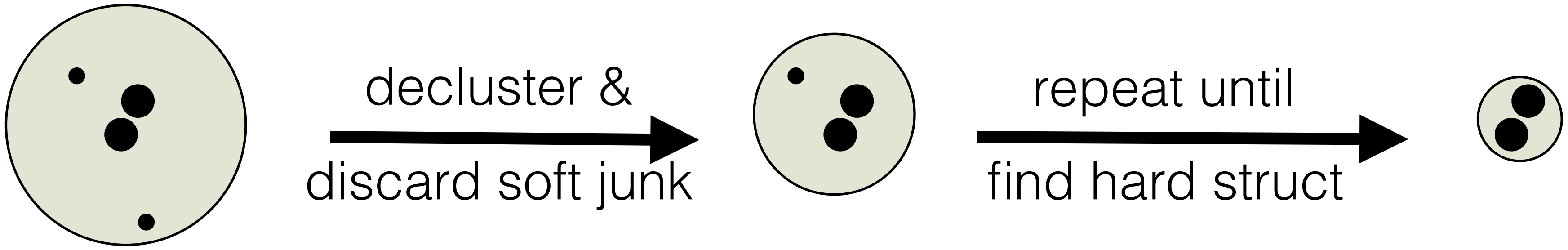
Mass-Drop Tagger

Butterworth, Davison, Rubin & GPS '08

For a jet clustered with C/A:

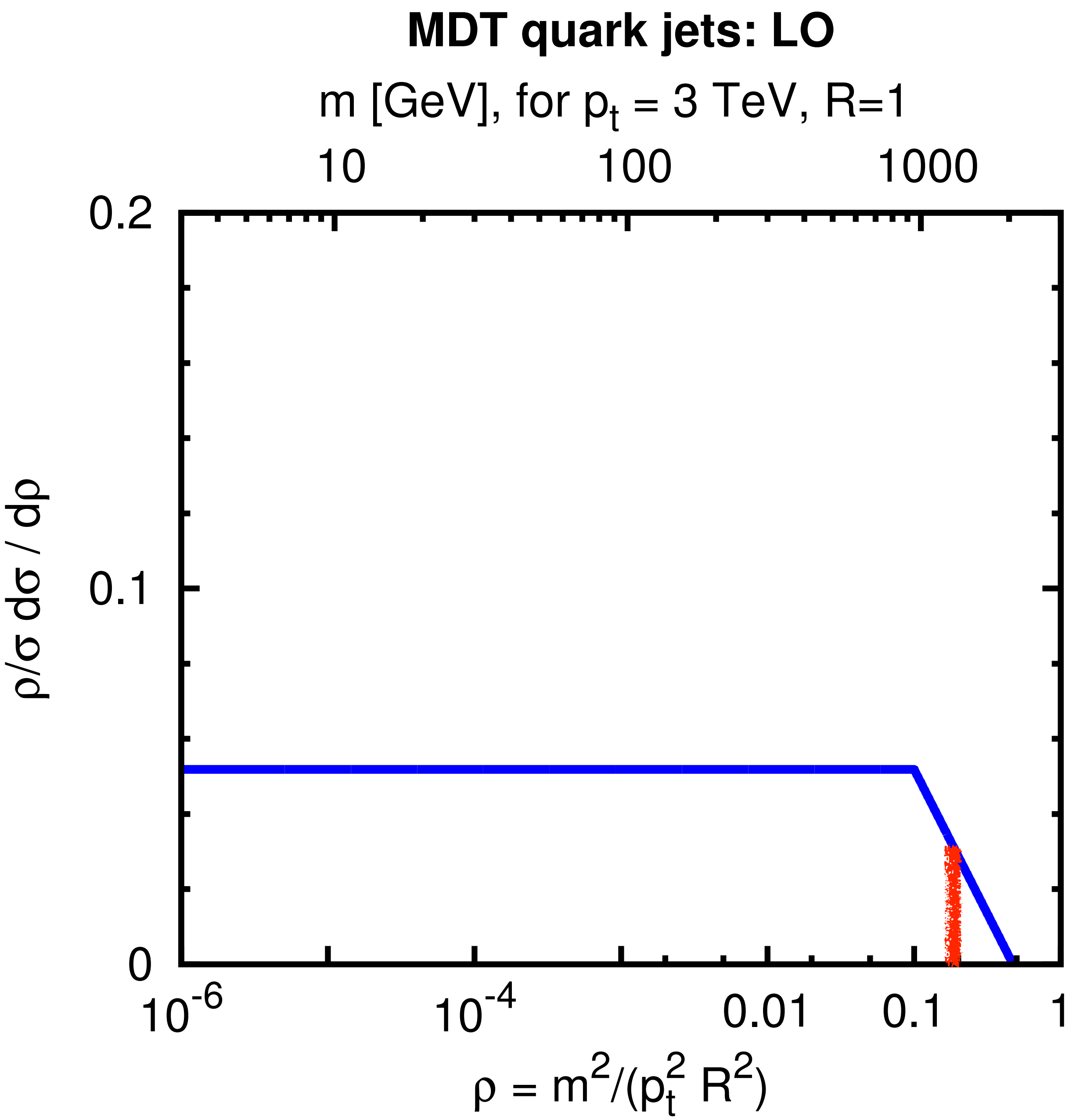
1. undo last clustering step to break jet (mass m) into two subjets with $m_1 > m_2$
2. If significant mass-drop ($m_1 < \mu m$) and subjet energy-sharing not too asymmetric
   $$\min(p_{t1}^2, p_{t2}^2)\Delta R_{12}^2 < y_{\rm cut} m^2$$
   jet is **tagged**.
3. Otherwise discard subjet 2, and go to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

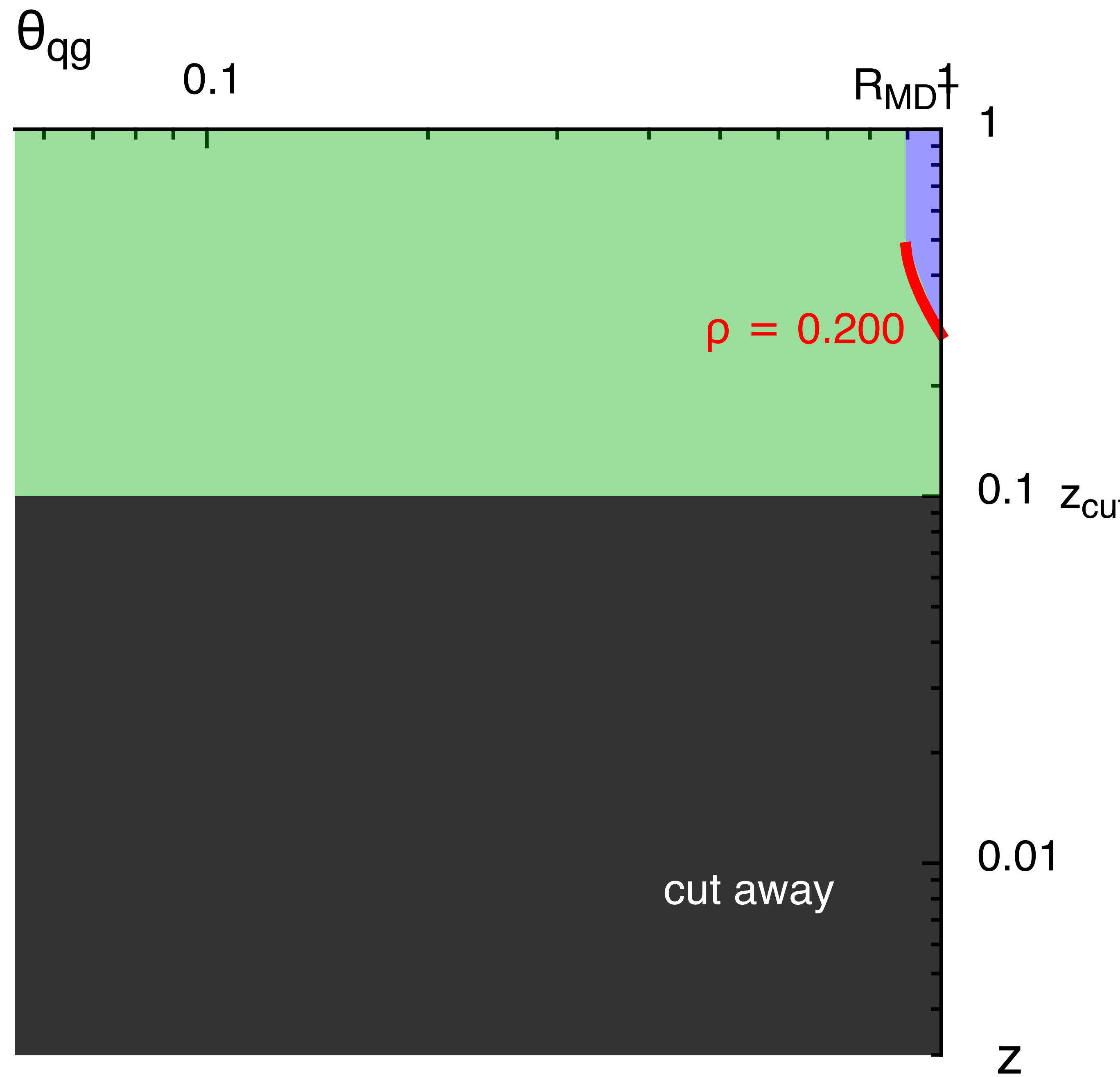
two parameters:
μ and $y_{\rm cut}$ ($\sim z_{\rm cut}$)



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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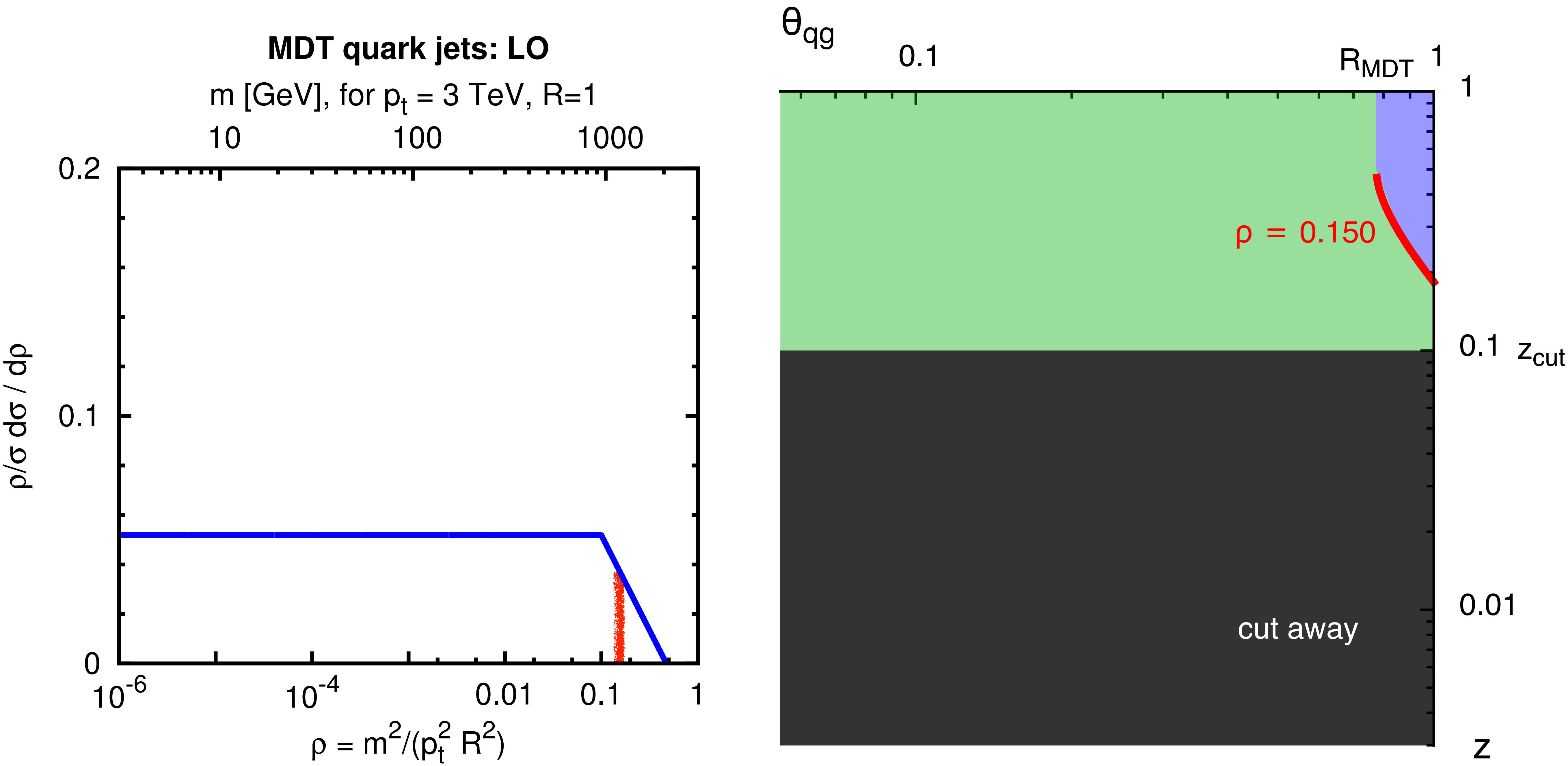

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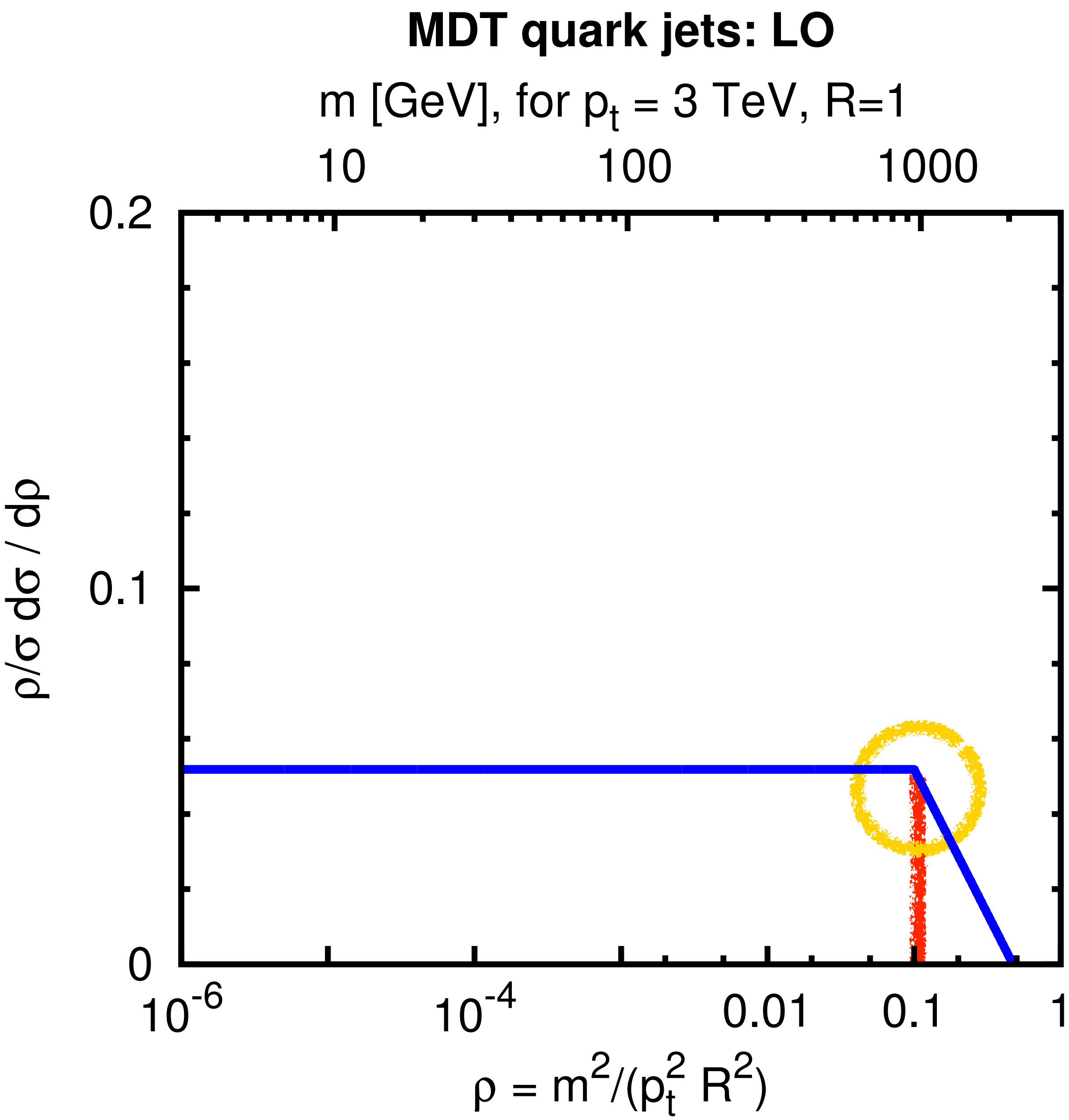

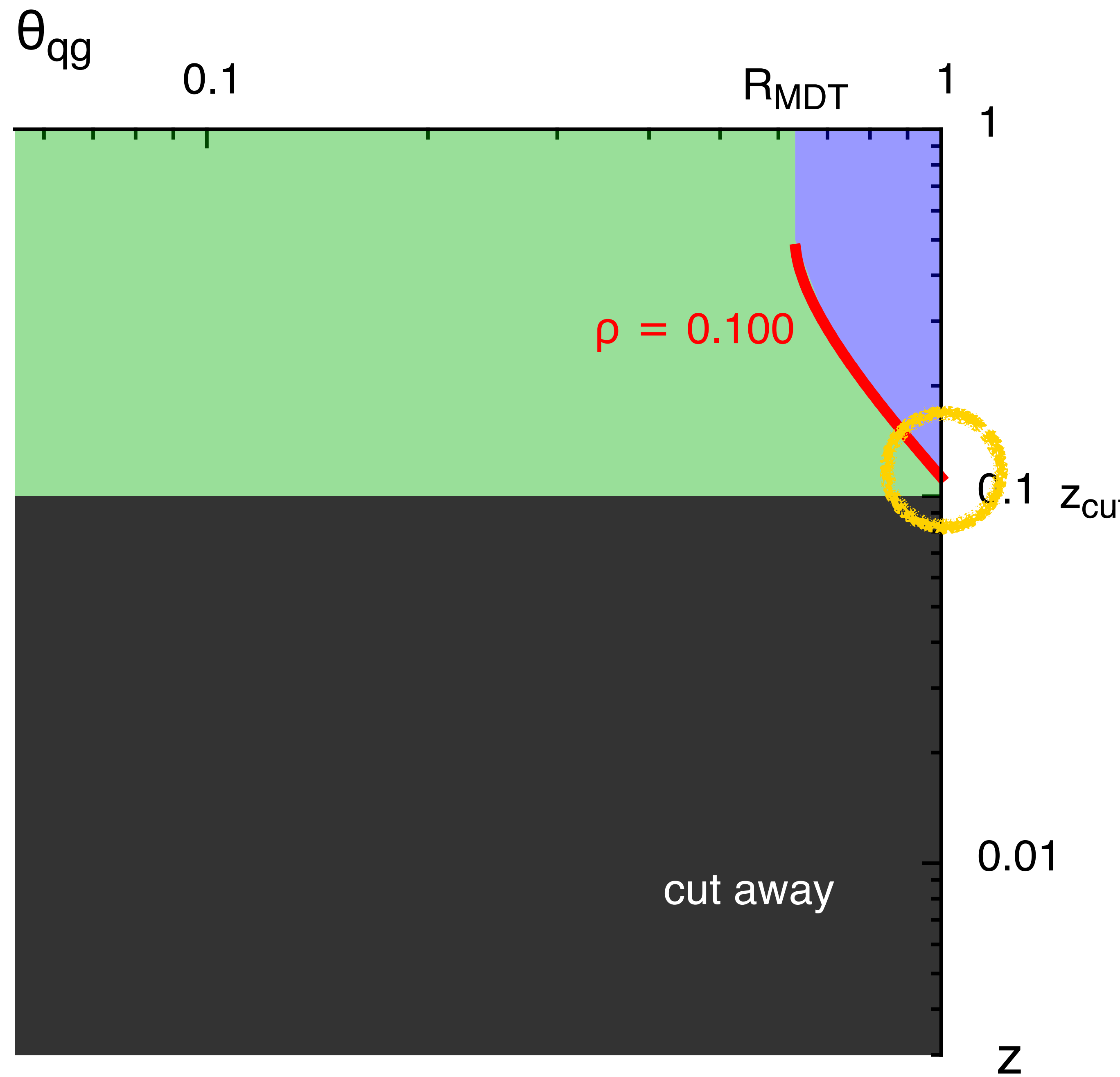

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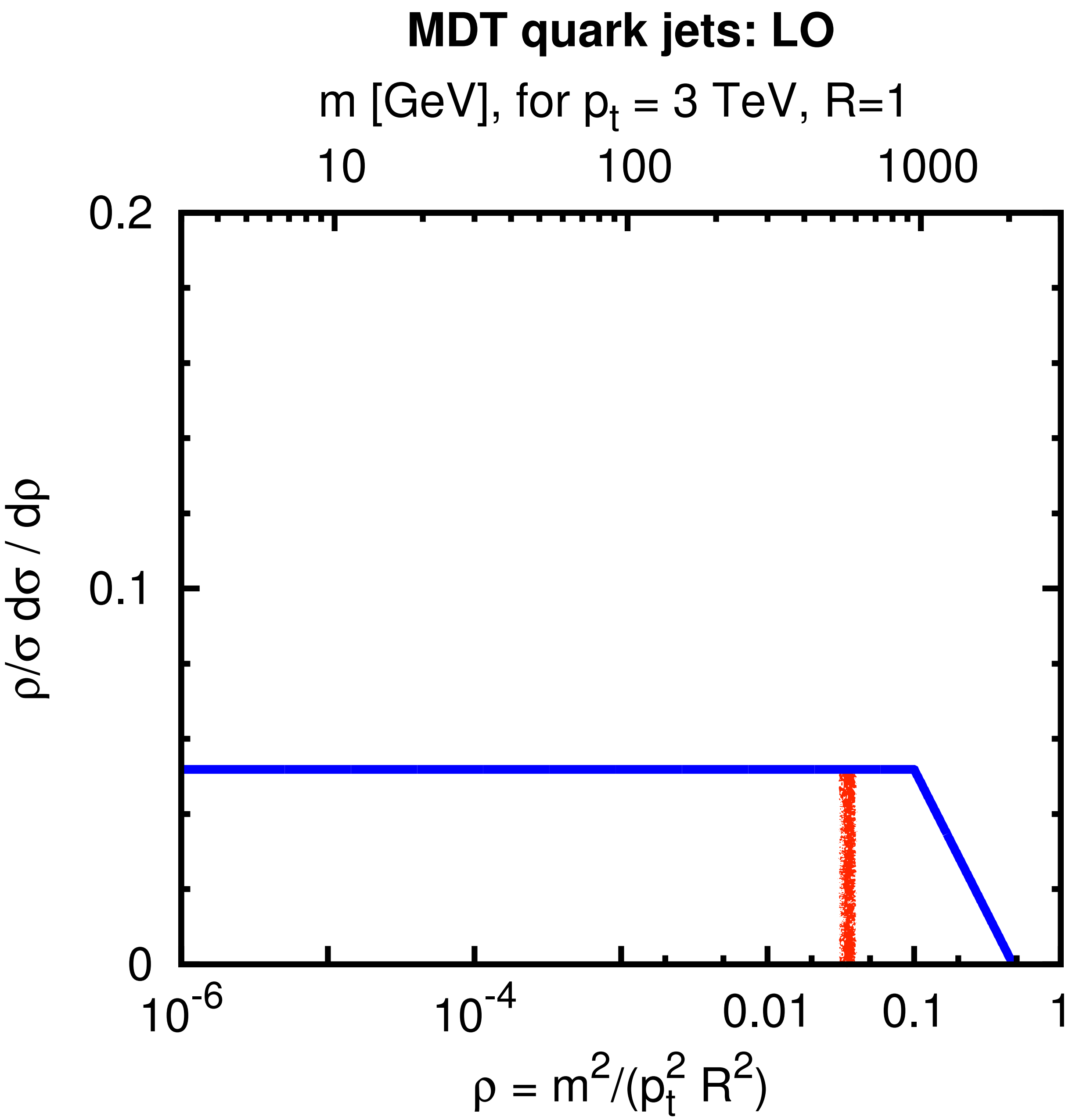

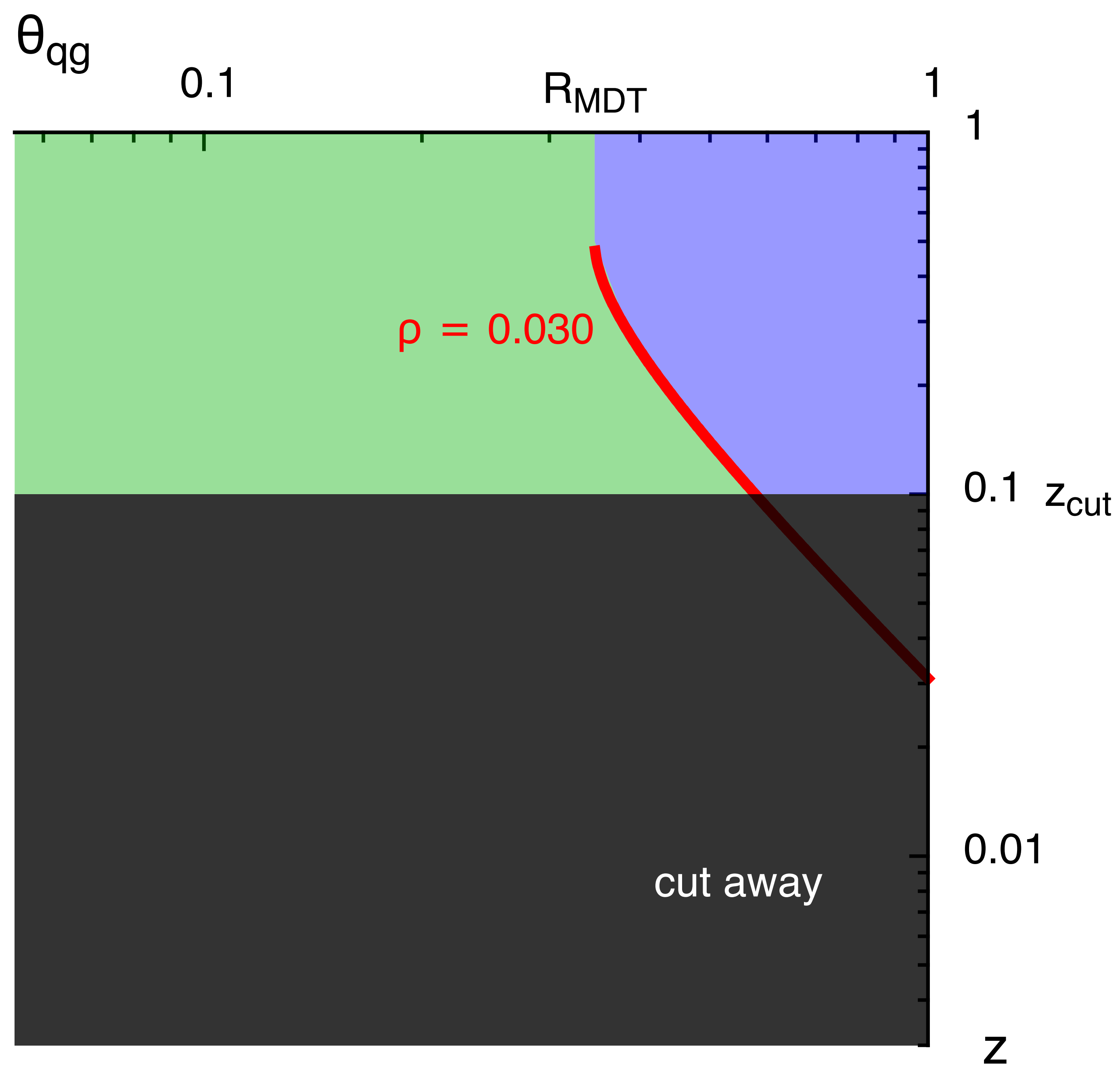

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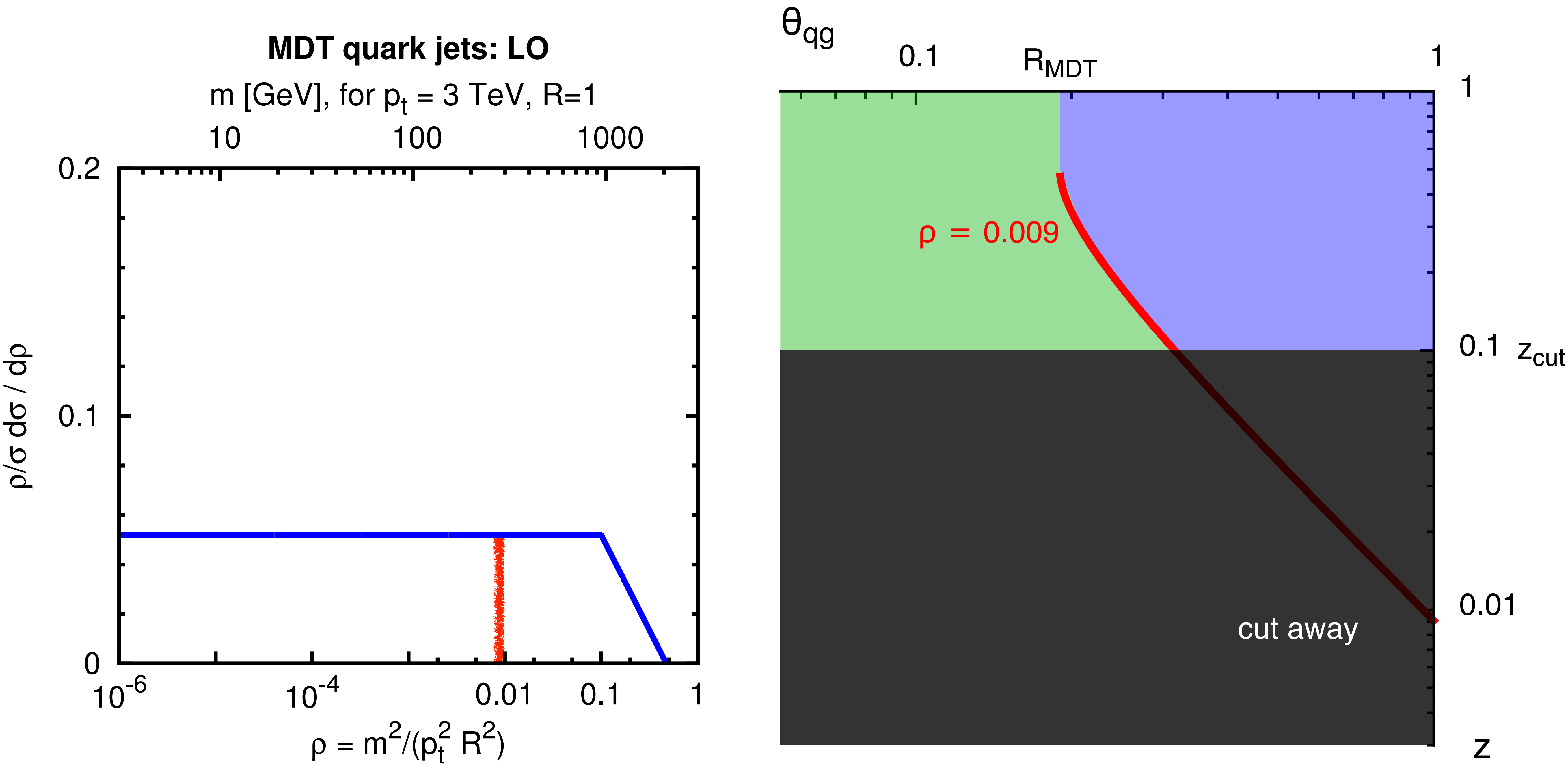

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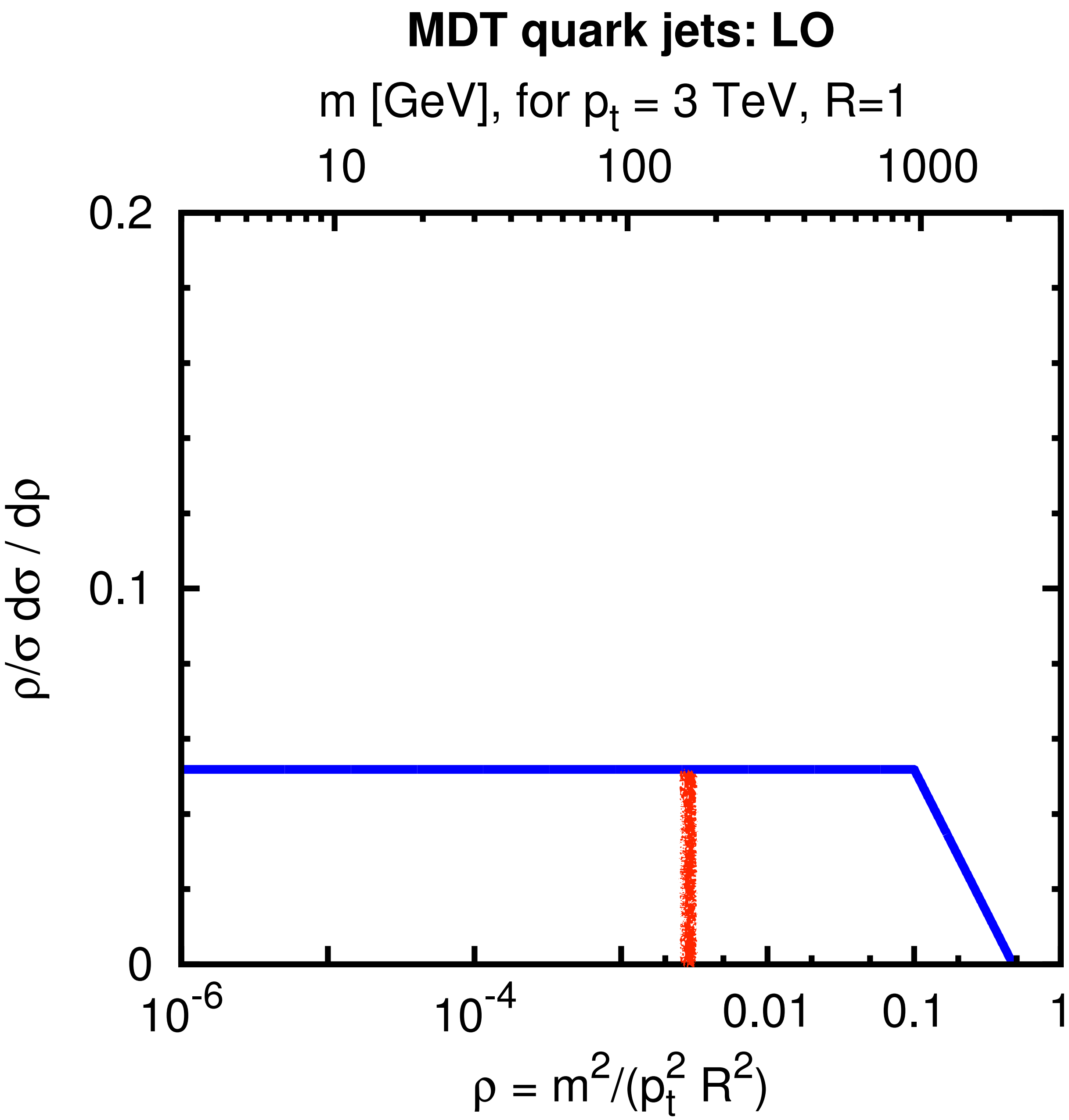

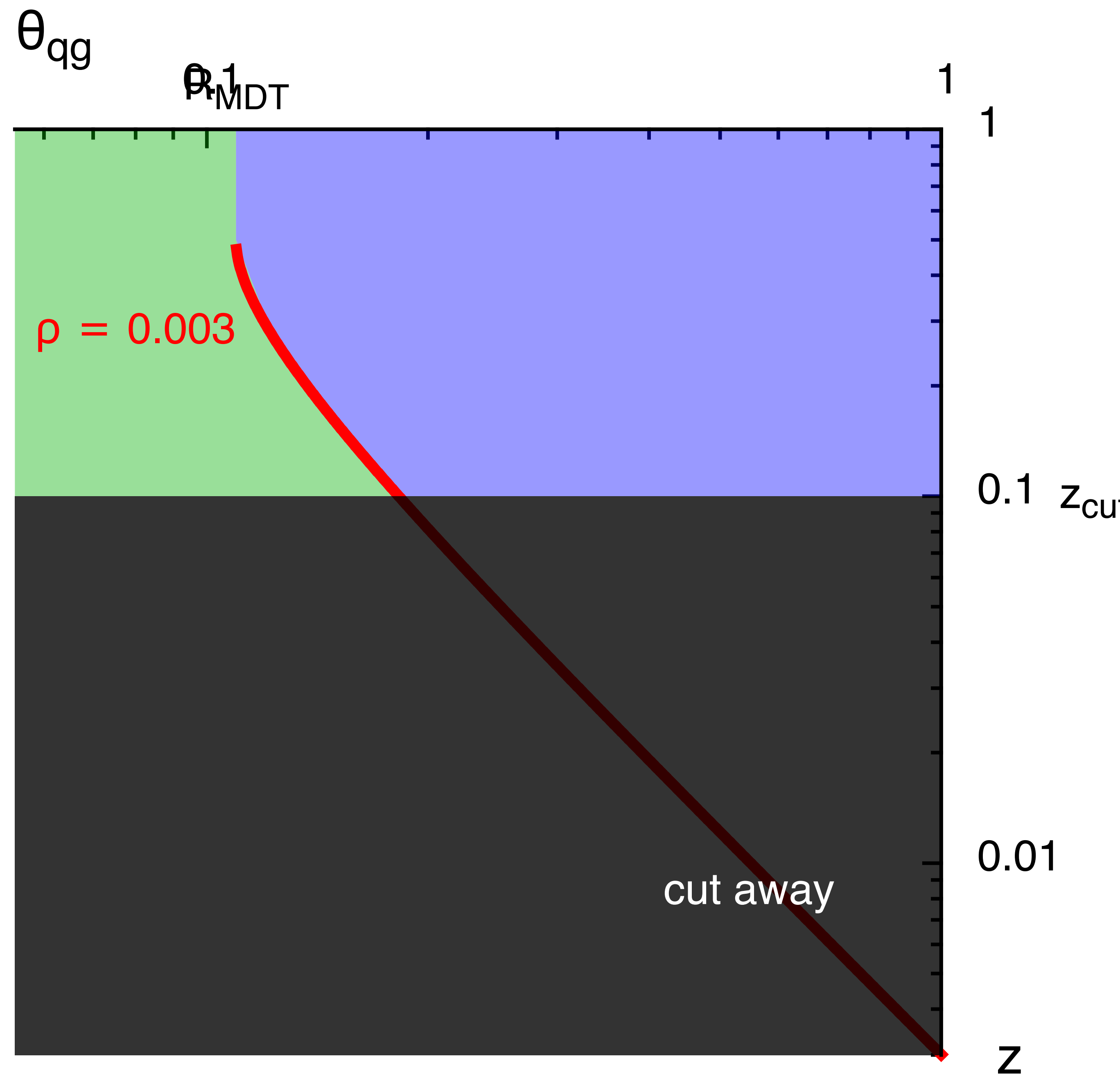

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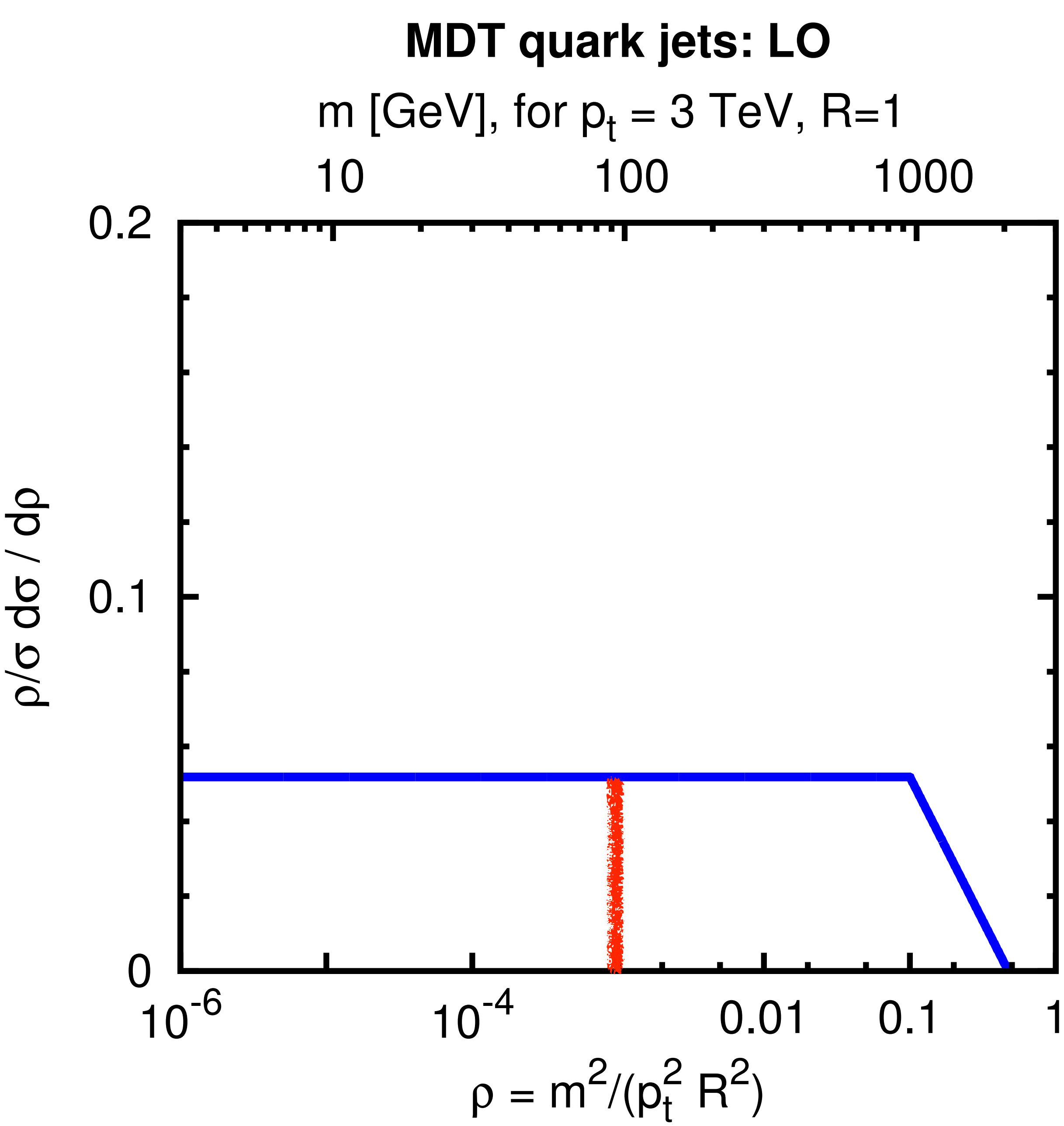
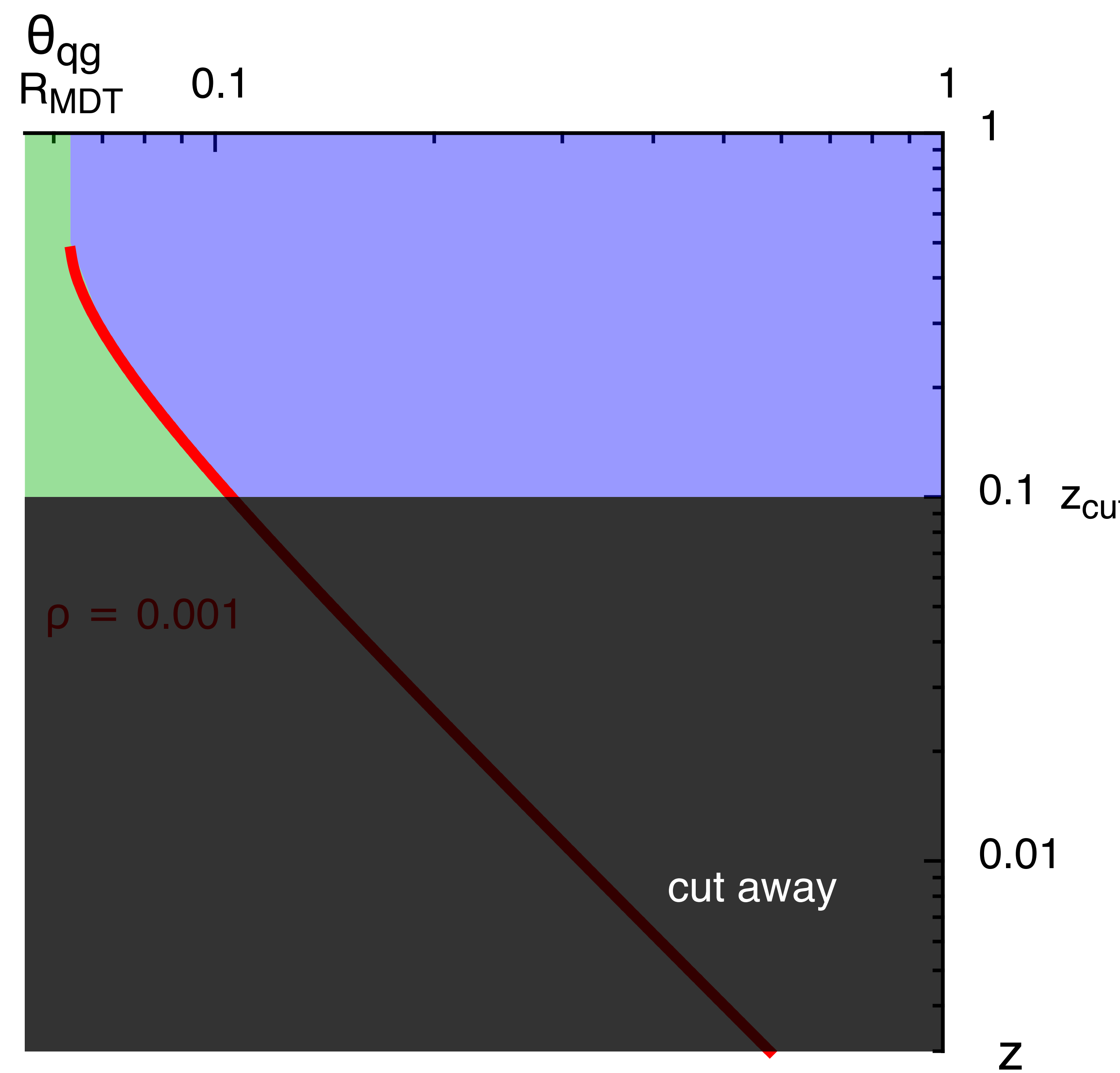
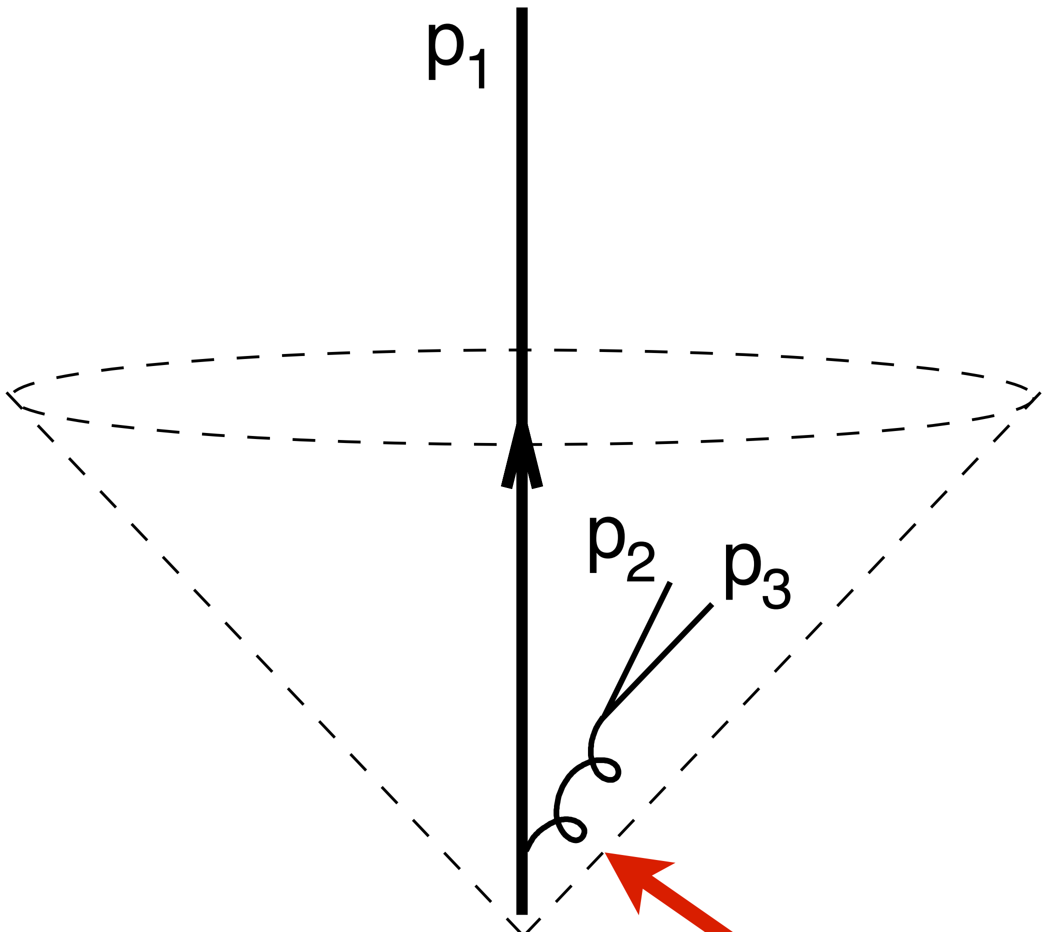






What MDT does wrong beyond LO:

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:

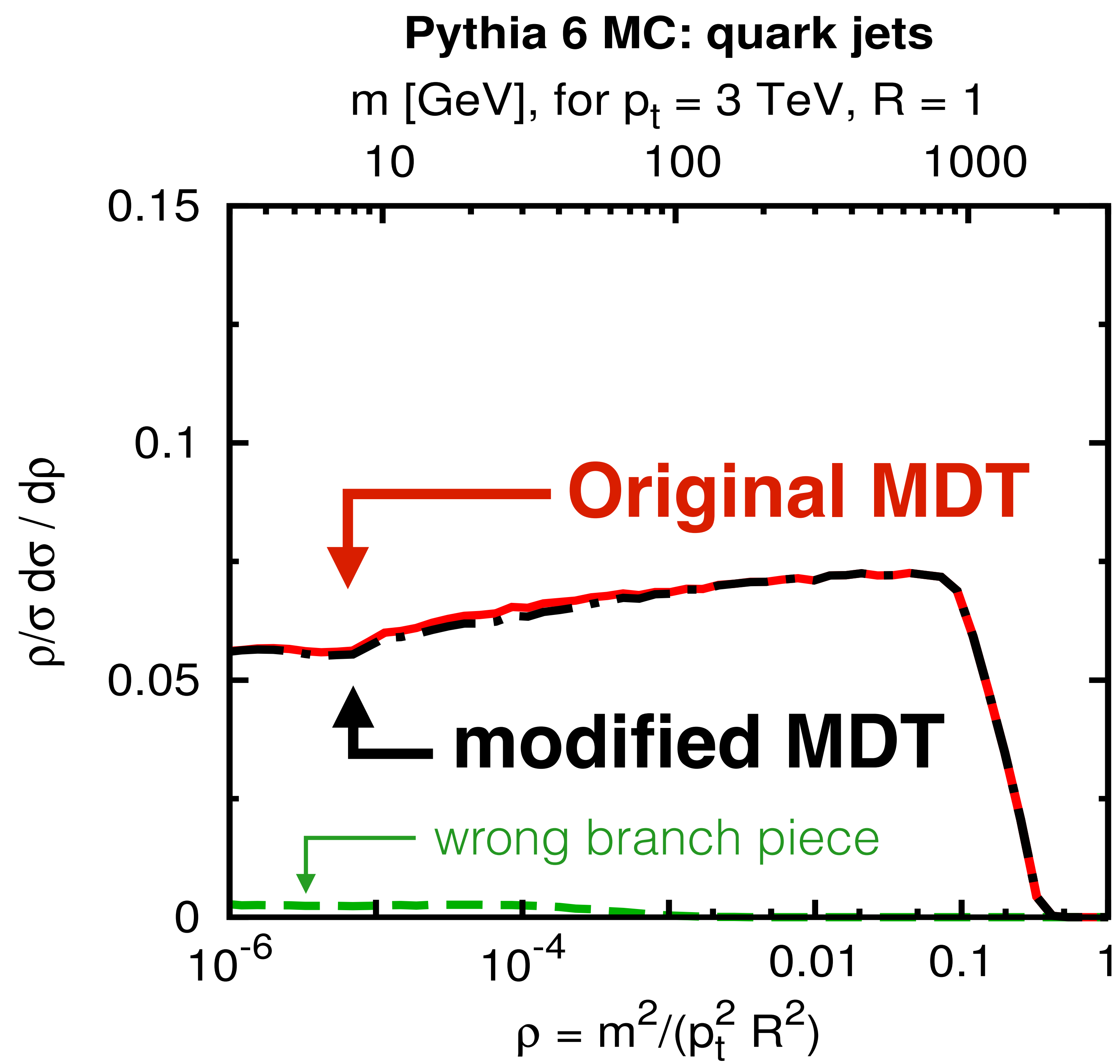
$$\alpha_s L,\ \alpha_s^2 L^3,\ \ldots.\ \text{I.e. } \boldsymbol{\alpha_s^n L^{2n-1}}$$

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

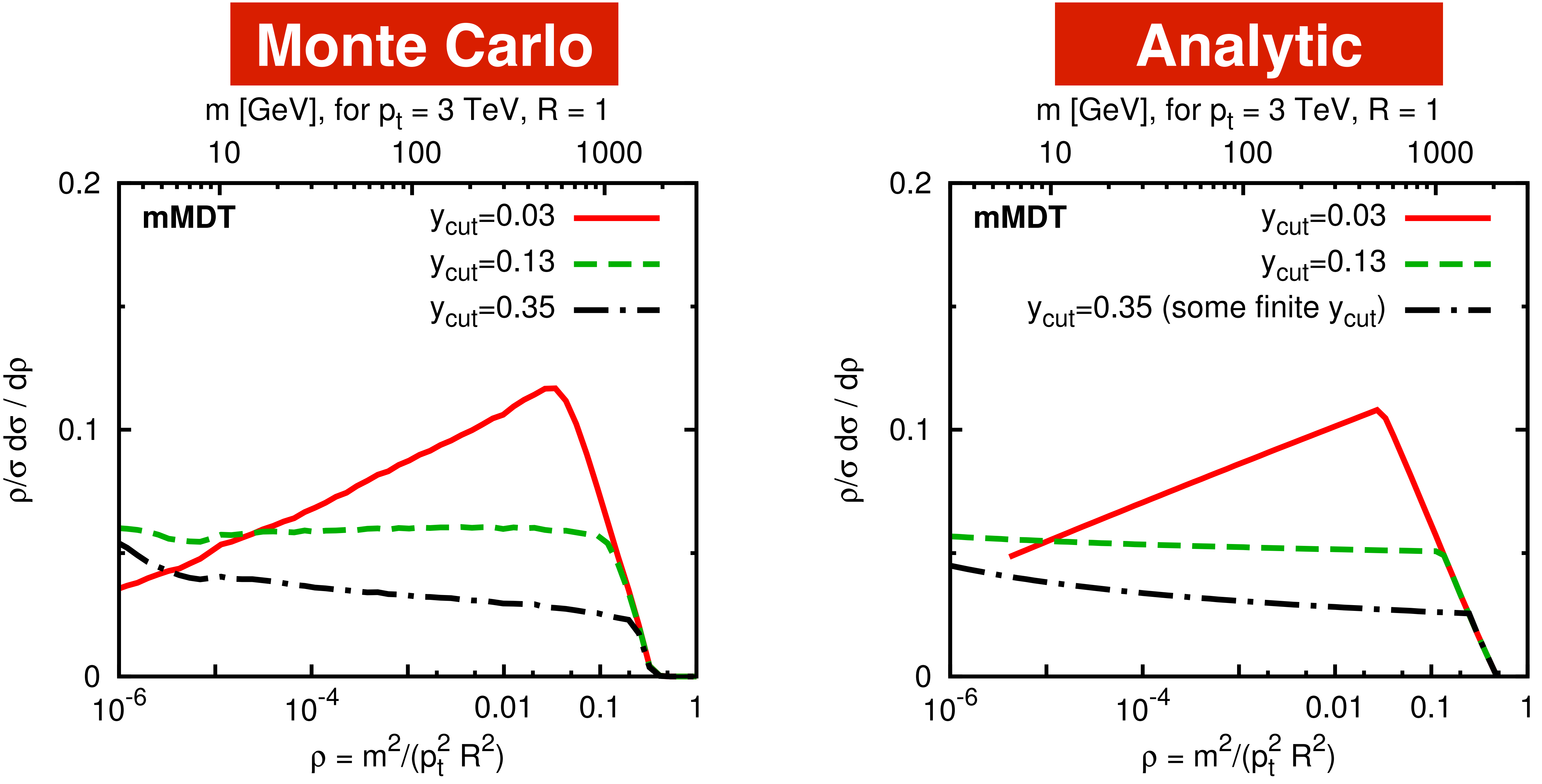
➡ no super-leading (factorization-breaking) logs

First time anything like this has been seen

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

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

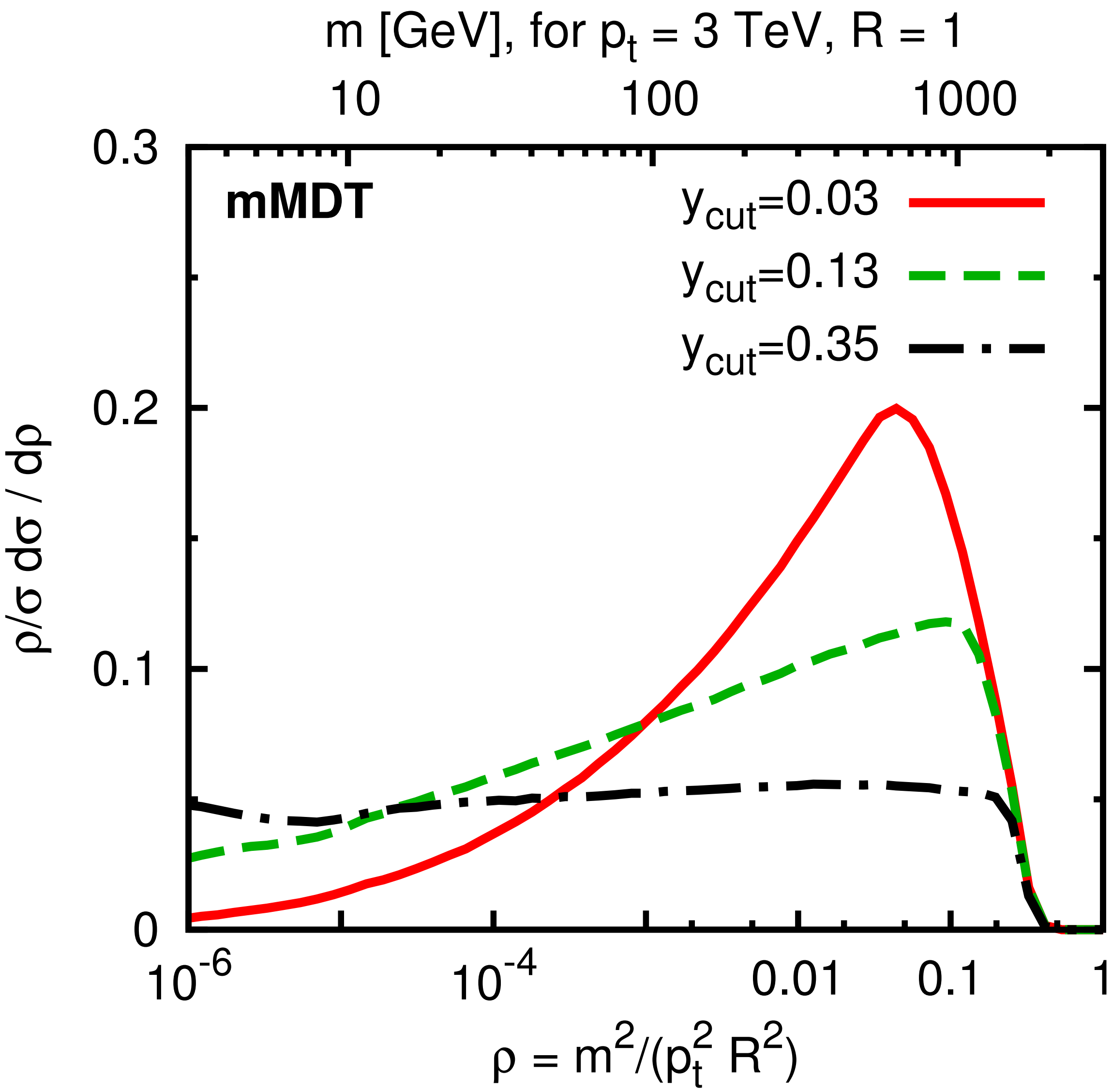
mMDT MC v. Resummation



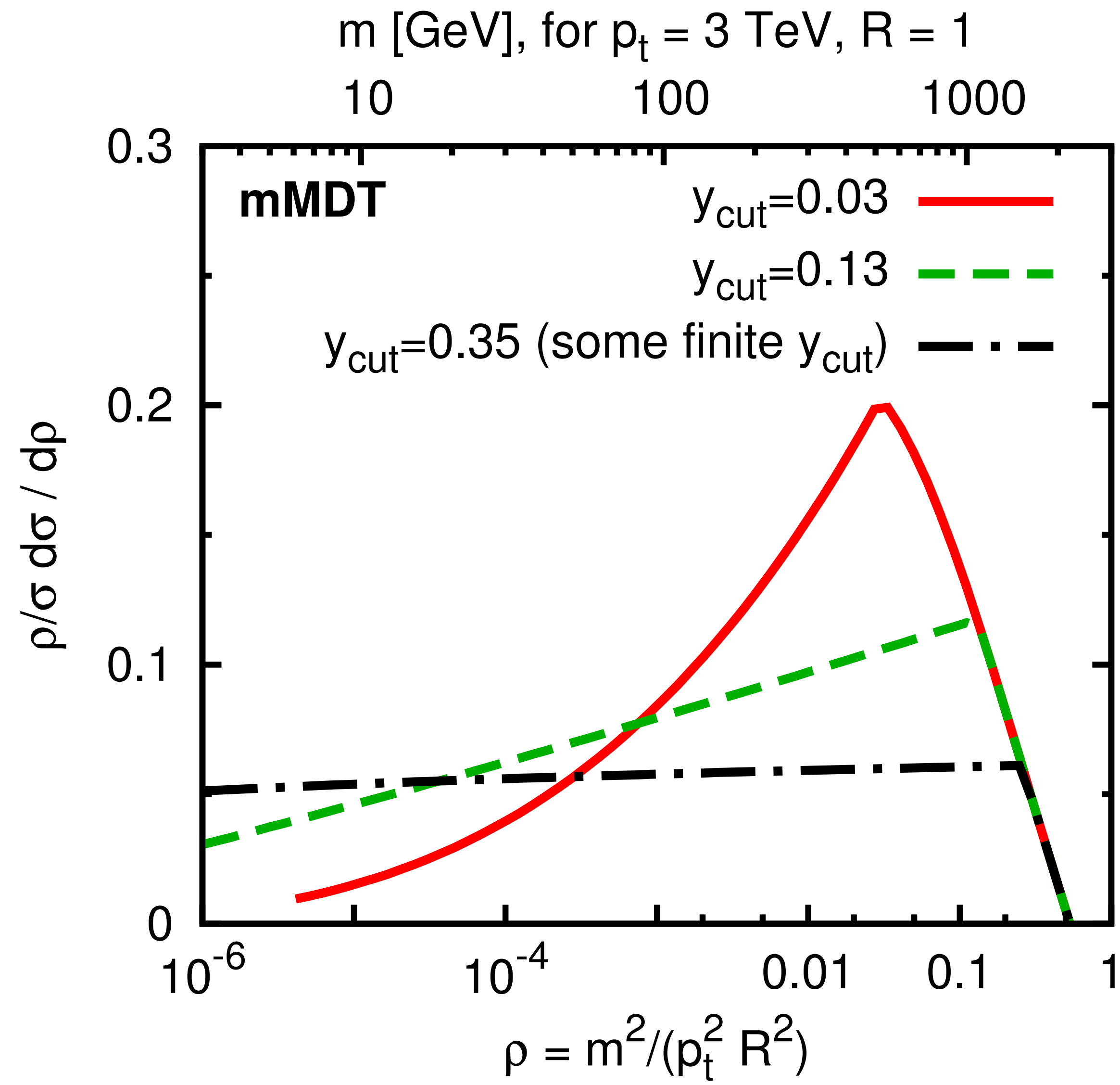
[mMDT is closest we have to a scale-invariant tagger, though exact behaviour depends on q/g fractions]

mMDT MC v. Resummation

Monte Carlo



Analytic



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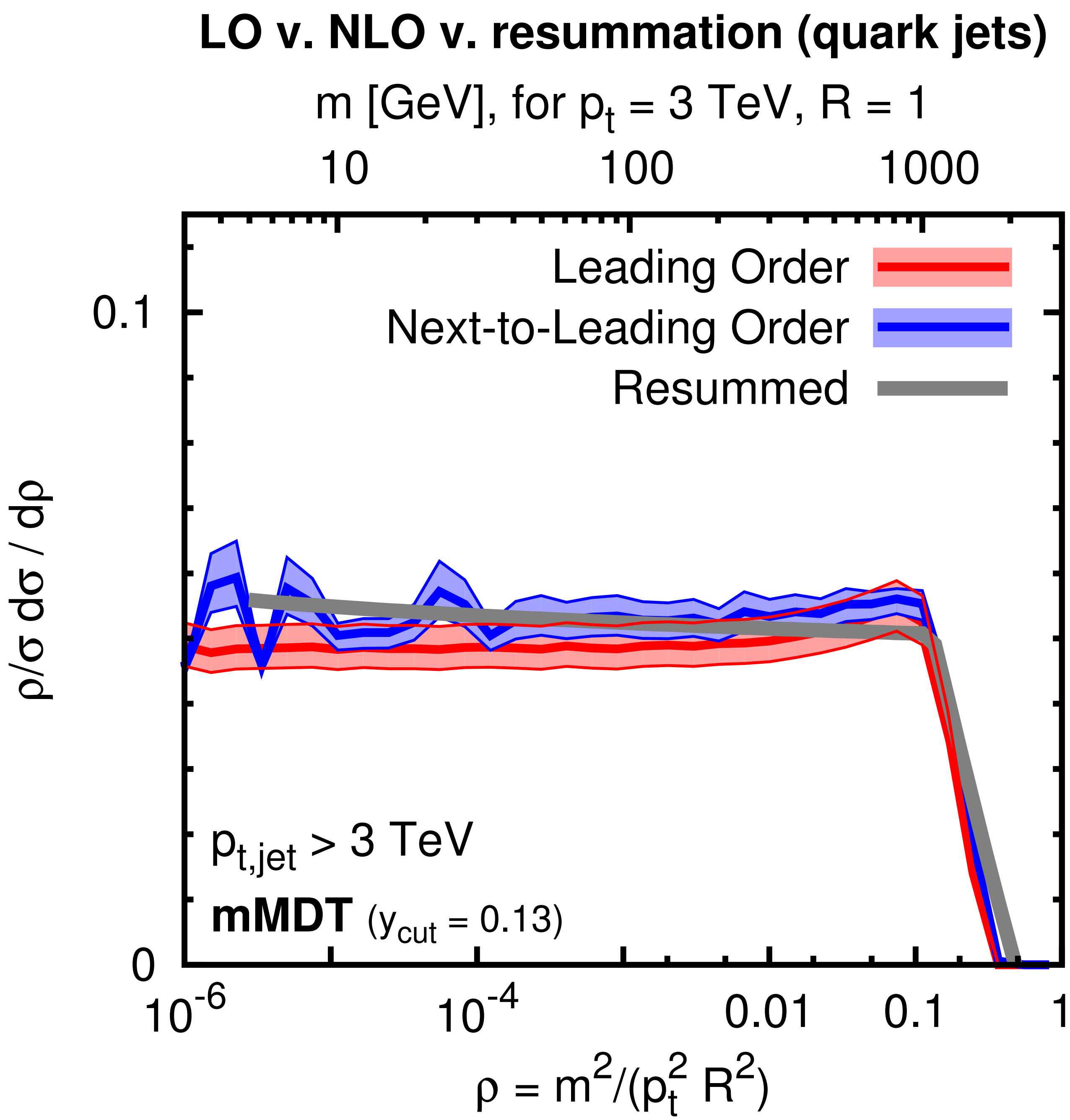
mMDT resummation v. fixed order

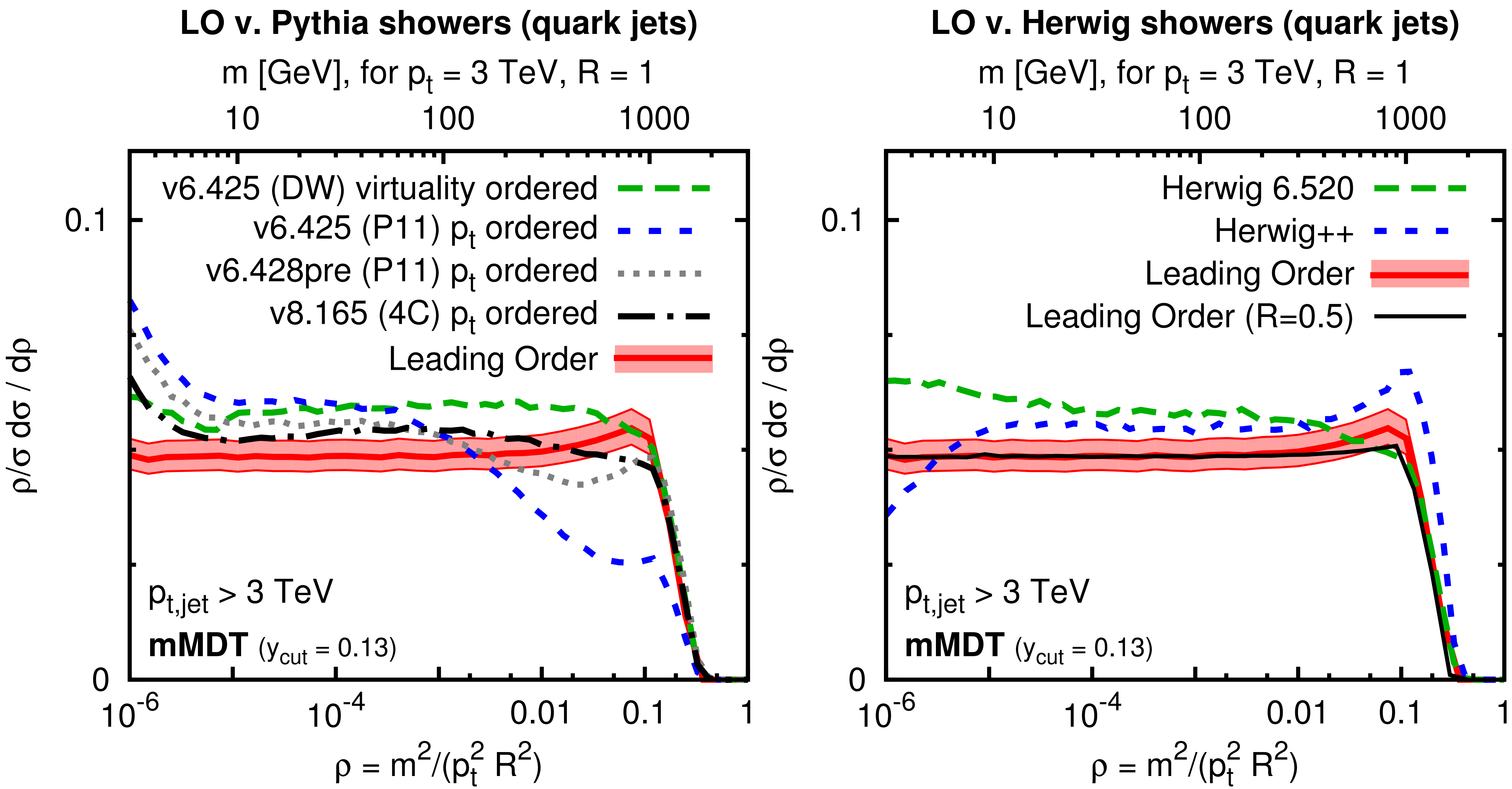


Because we only have single logs, fixed-order is valid over a broader than usual range of scales

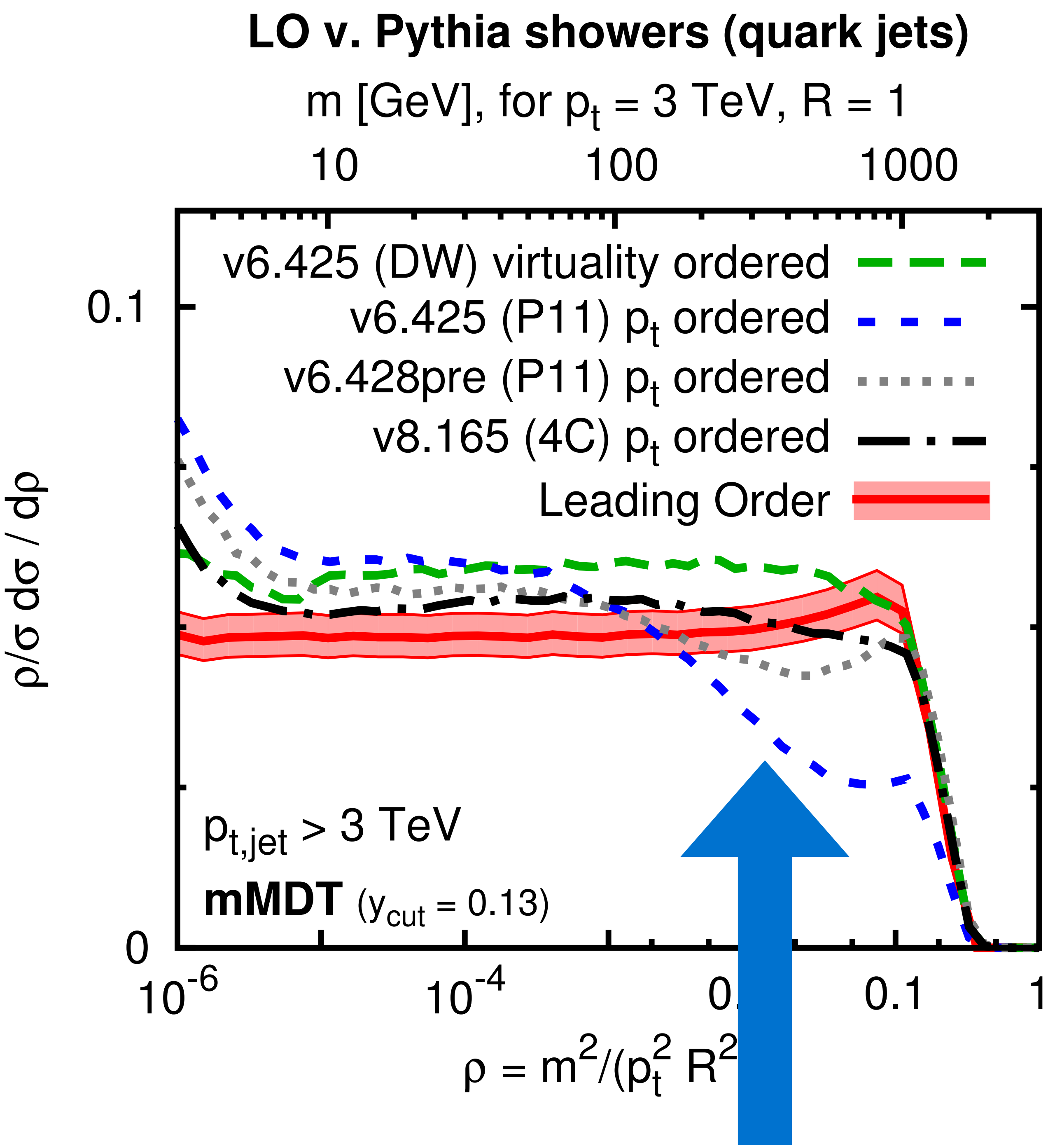
(helped by fortuitous cancellation between running coupling and single-log Sudakov)

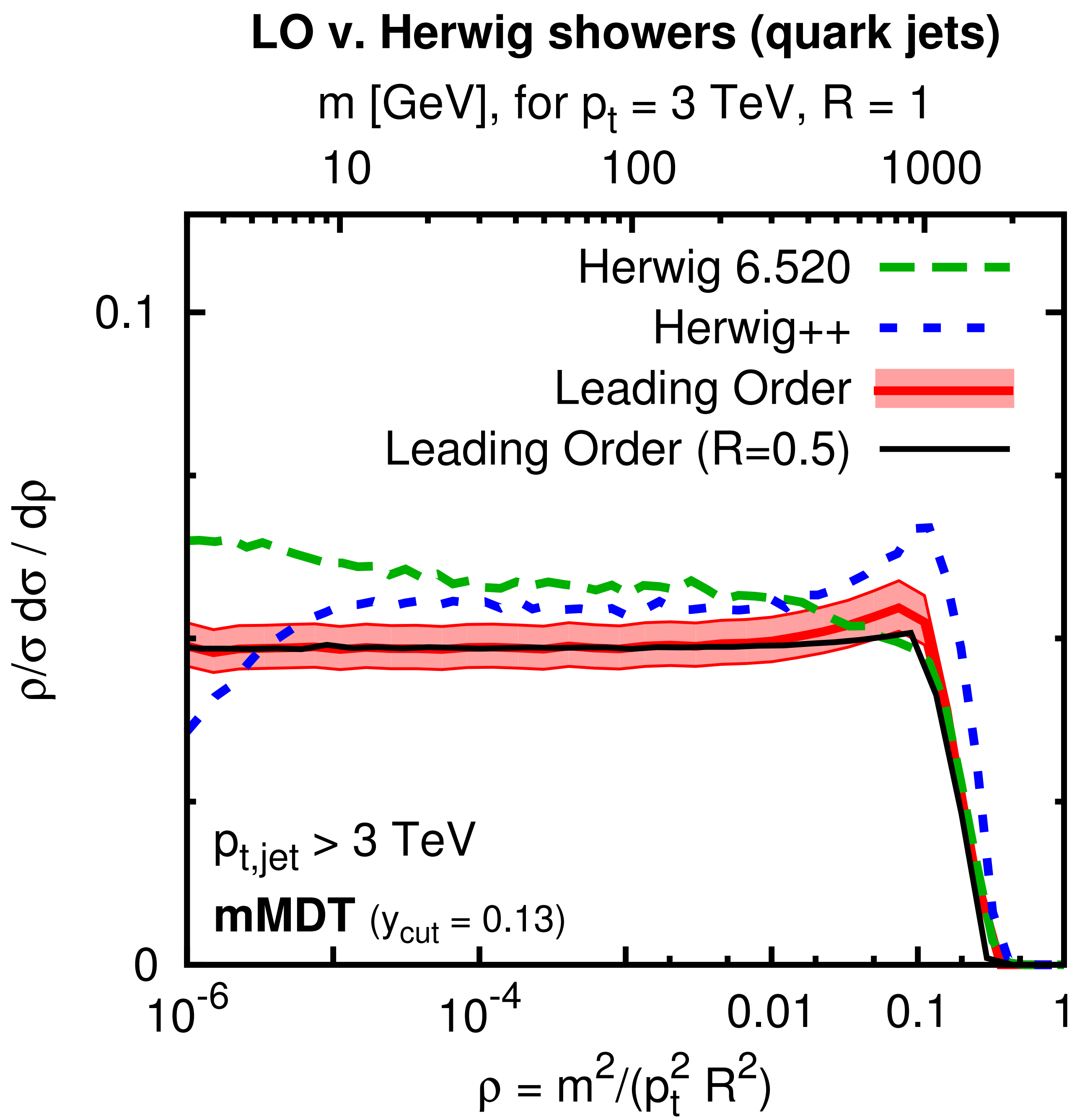
NLO from NLOJet++

mMDT: comparing many showers



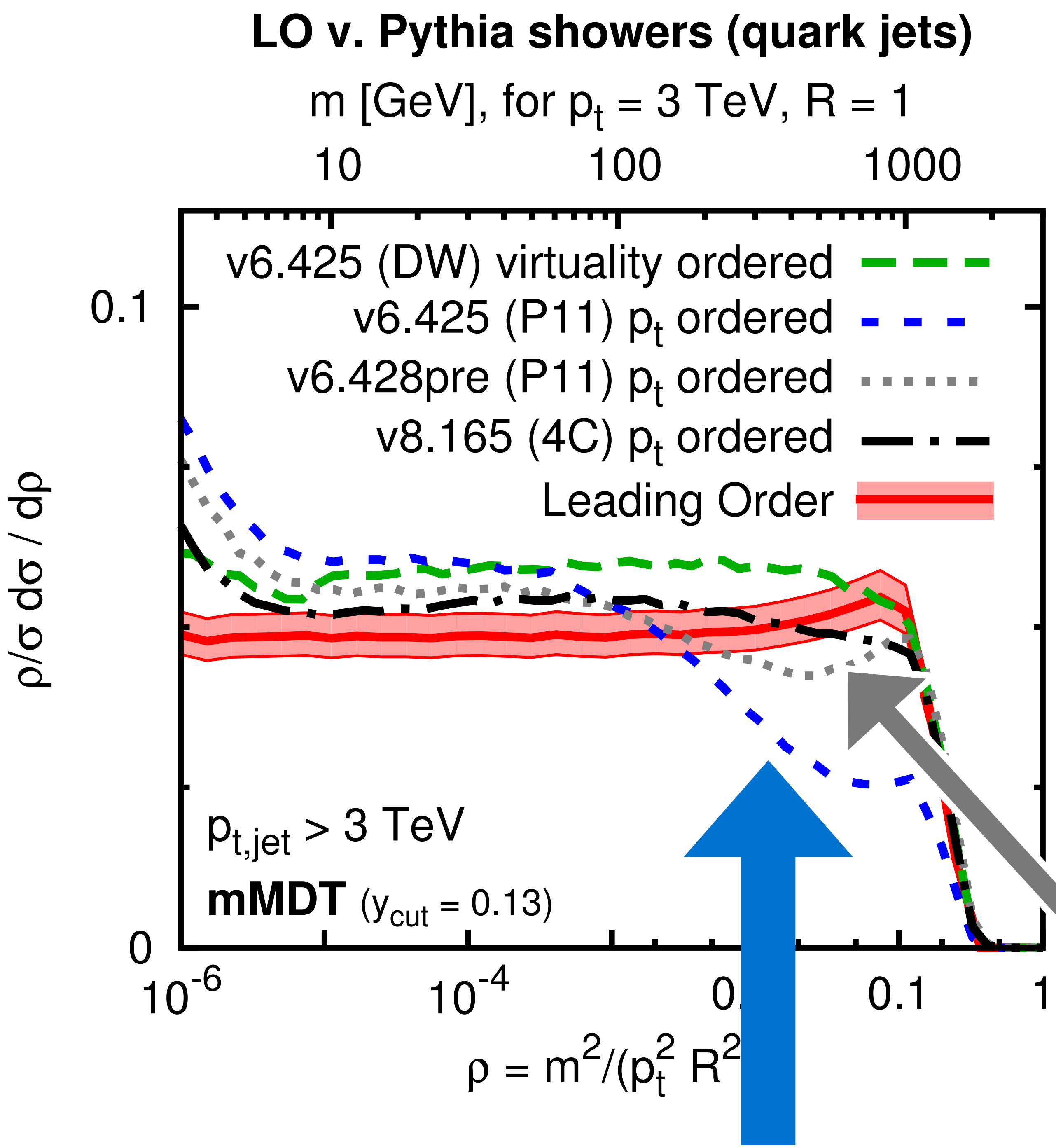
mMDT: comparing many showers

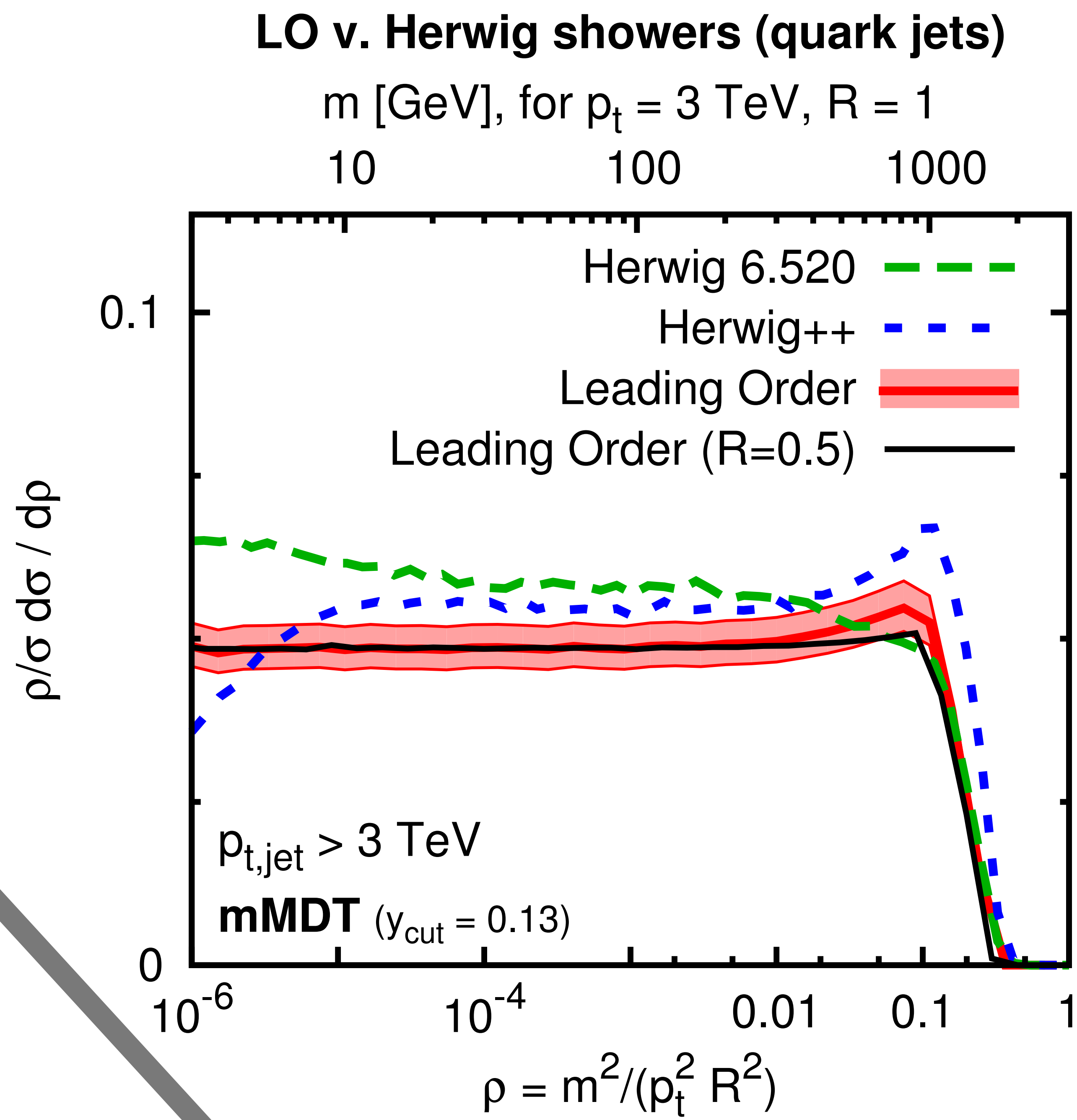




Issue found in Pythia 6 p_t-ordered shower → promptly identified and fixed by Pythia authors!

mMDT: comparing many showers



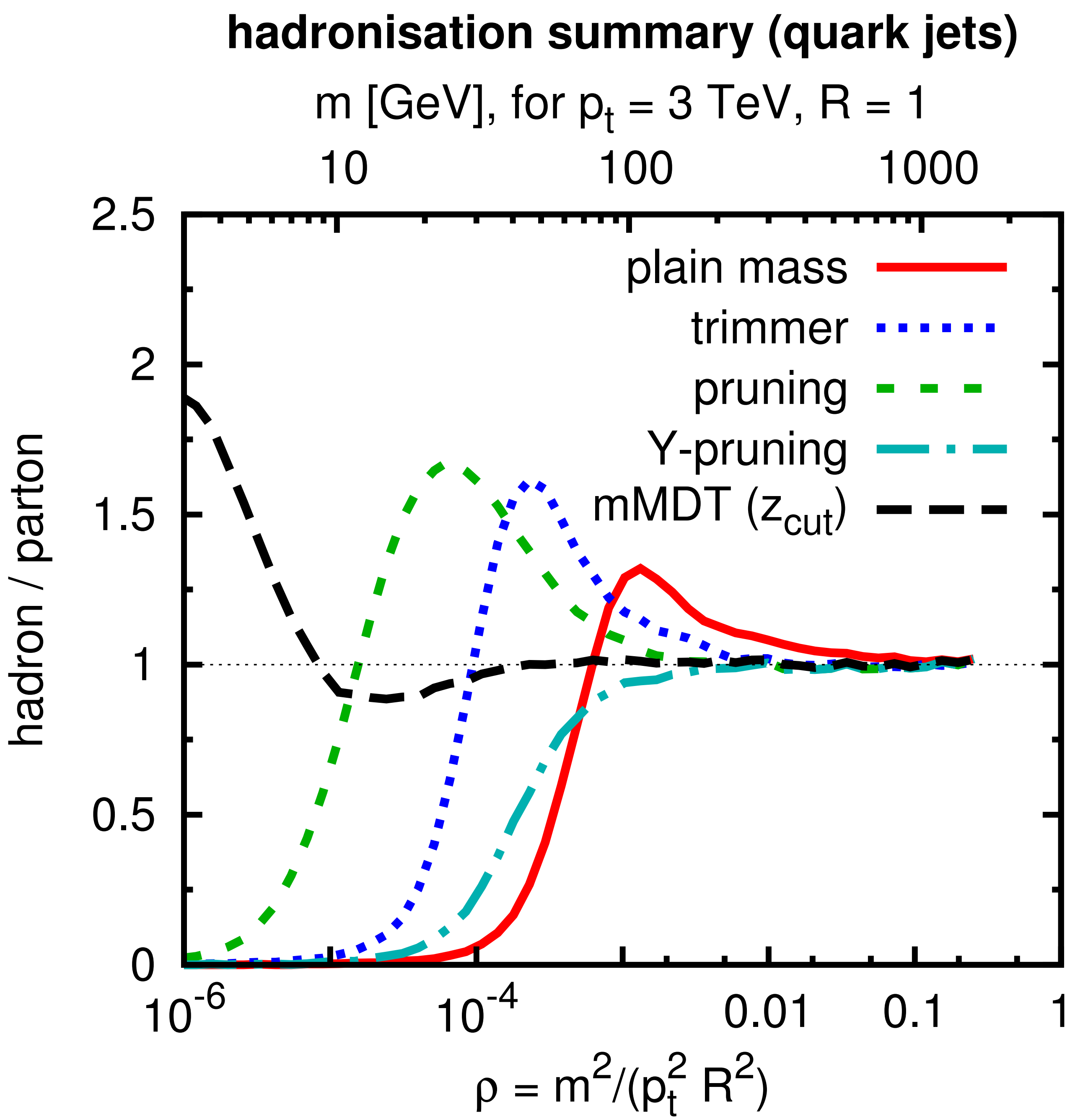


Issue found in Pythia 6 p_t-ordered shower → promptly identified and fixed by Pythia authors!

What about
non-perturbative effects?

[on 3 TeV jets?!]

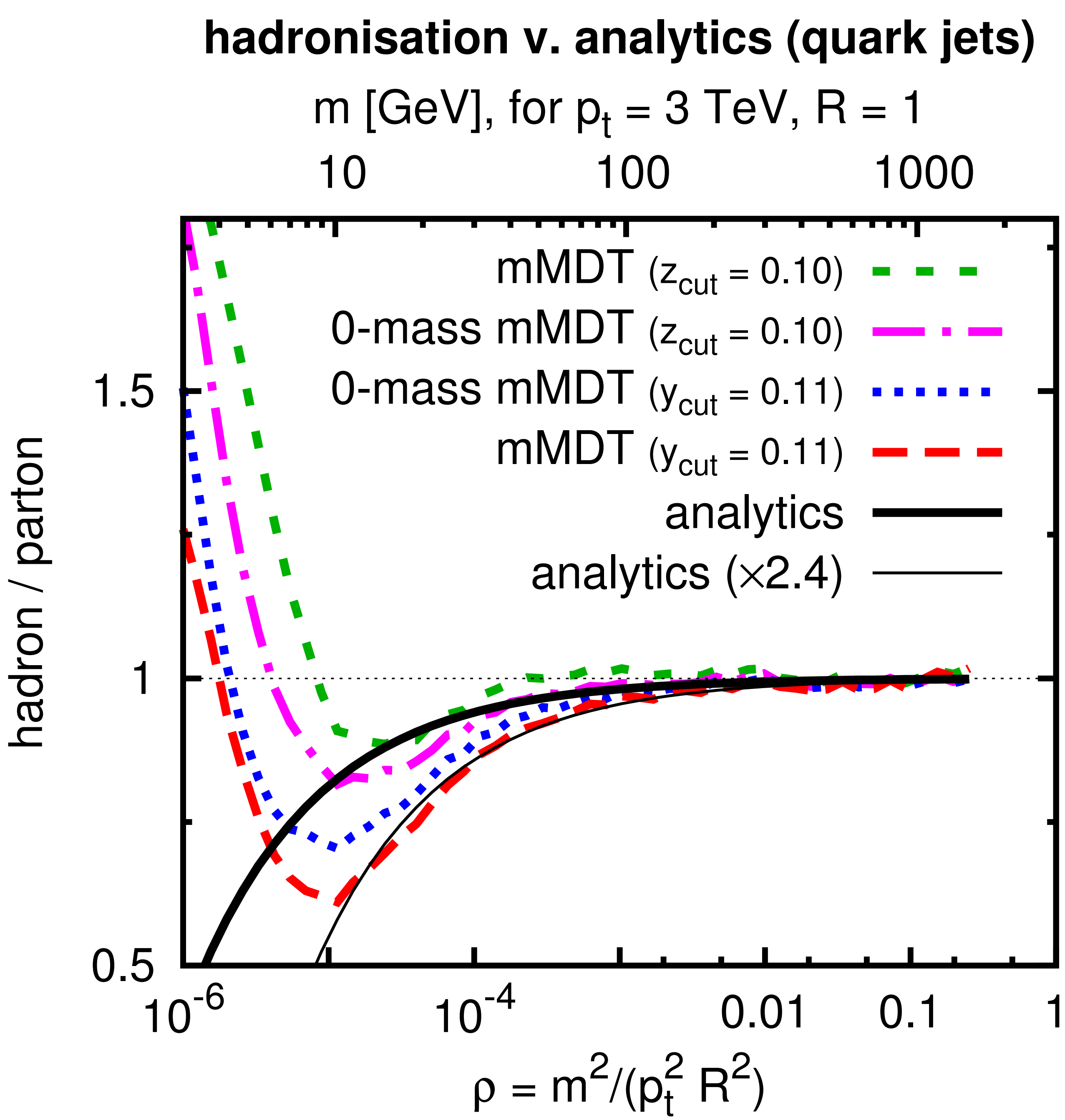
Hadronisation effects



Nearly all taggers have large hadronisation effects:

15 – 60%
for m = 30 – 100 GeV

Hadronisation effects

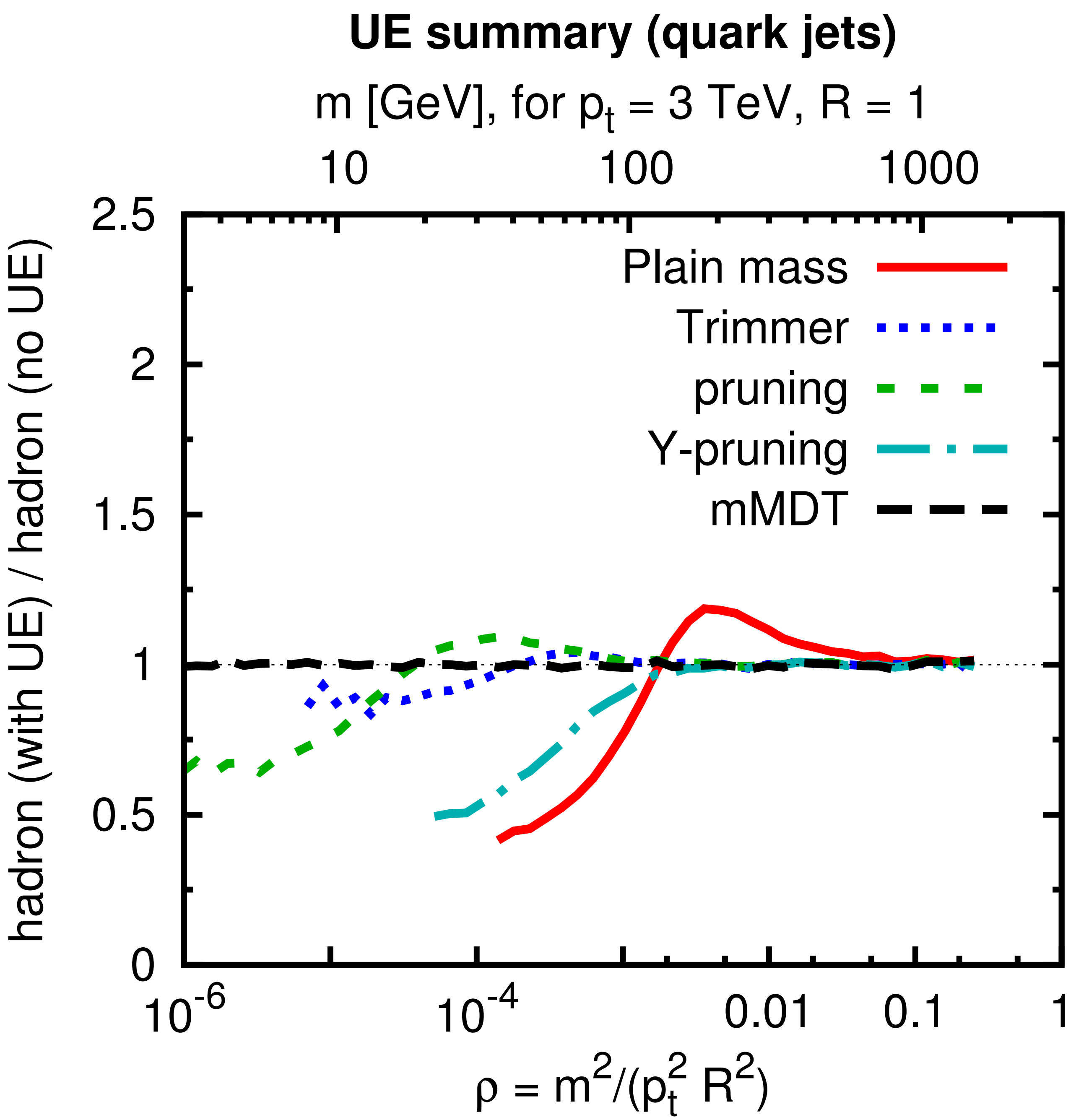


Exception is (m)MDT.

In some cases just few % effect.

m-dependence of hadronisation even understood analytically!

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

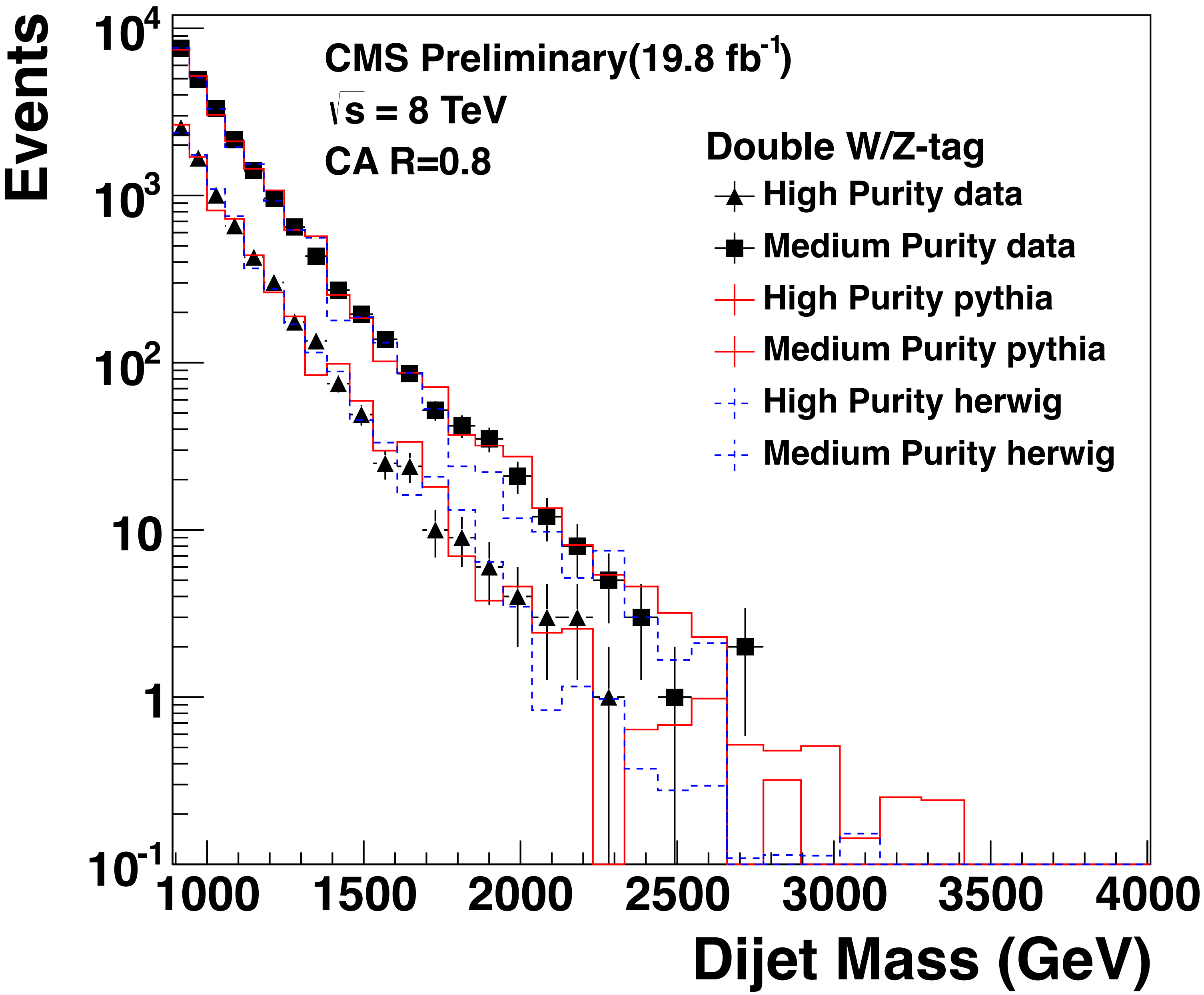


Underlying event impact much reduced relative to jet mass

Almost zero for mMDT (this depends on jet p_t)

Does it matter?

In a way, that's a premature question
Payoff is not intended to be immediate
But let's still look at a couple of examples



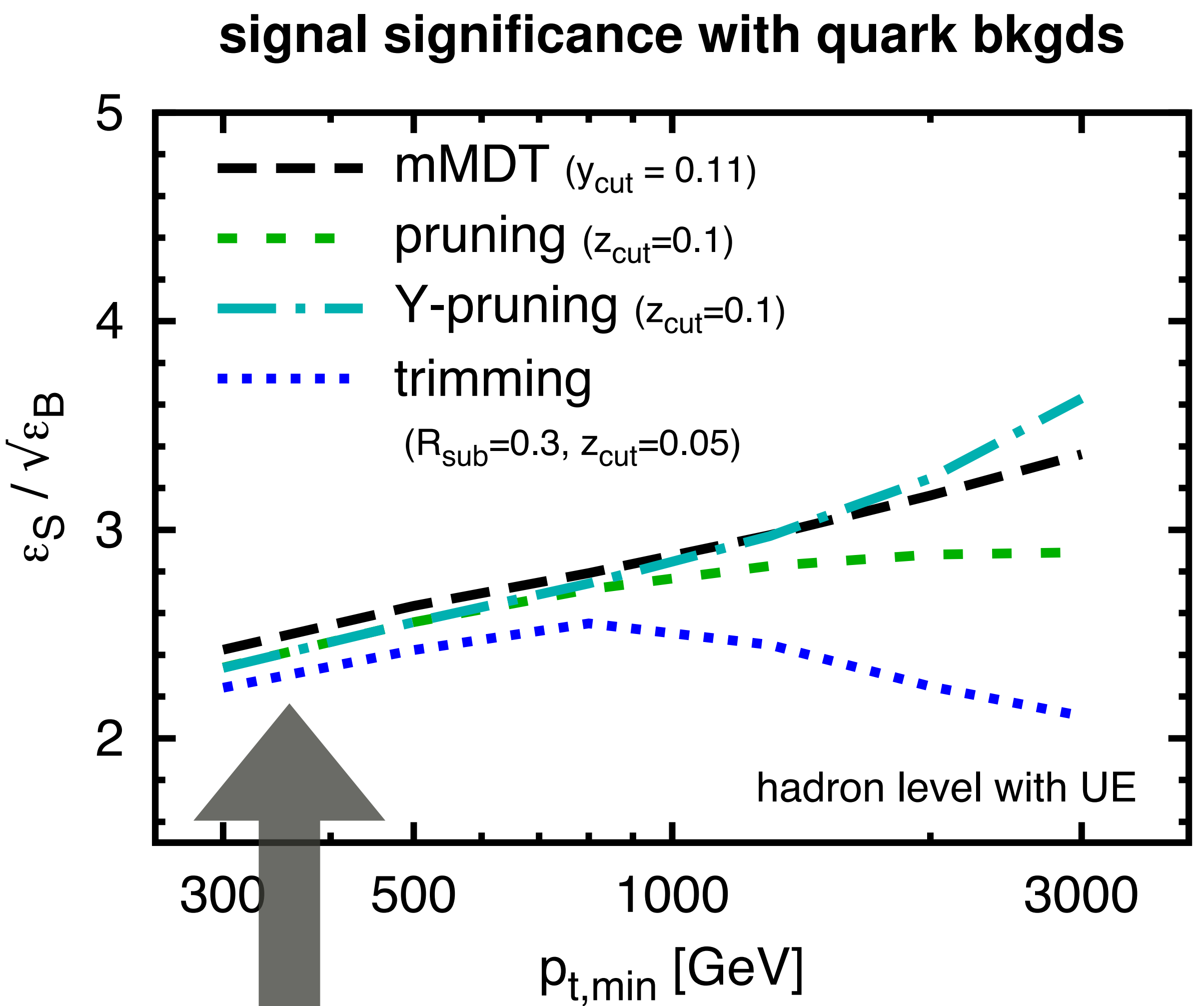
Search for resonances in doubly-tagged dijet events.

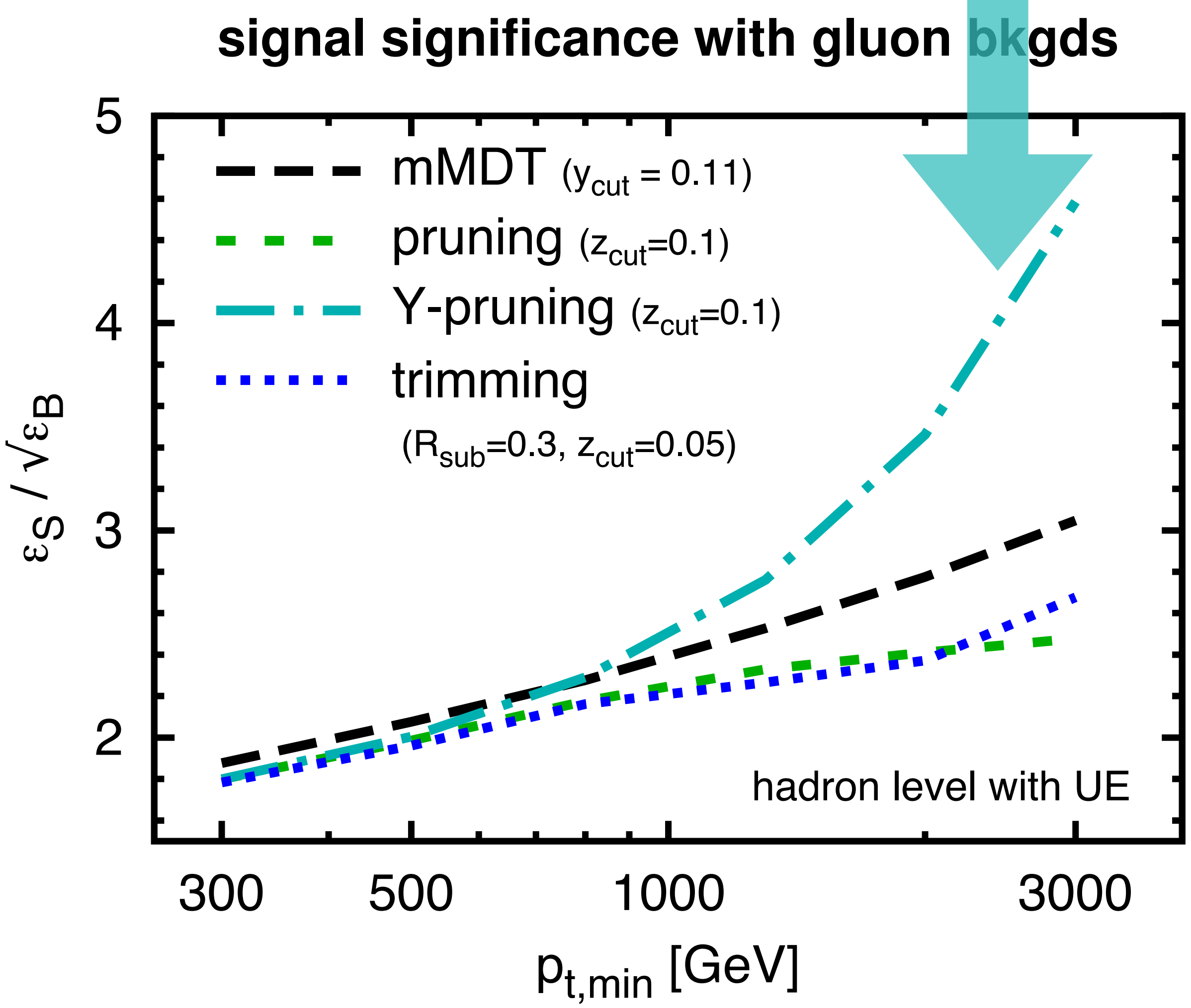
Tagging = pruning + tau21 cut

Note different Herwig++ and Pythia6 shapes

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

Summary

Use of jets beyond the *"jet=parton"* idea is with us today.

That puts a responsibility on theorists to start understanding jet substructure beyond simply running Monte Carlos.

It seems that's feasible, with the potential also to guide development of more powerful and more robust jet tools.

Hopefully, this will help reliably stretch the boundaries of what LHC can do in its searches and measurements!

Bottom line on “understanding”

- 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.
- New “modified” Mass Drop Tagger is especially simple
- New Y-pruning is also interesting – further investigation warranted...

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

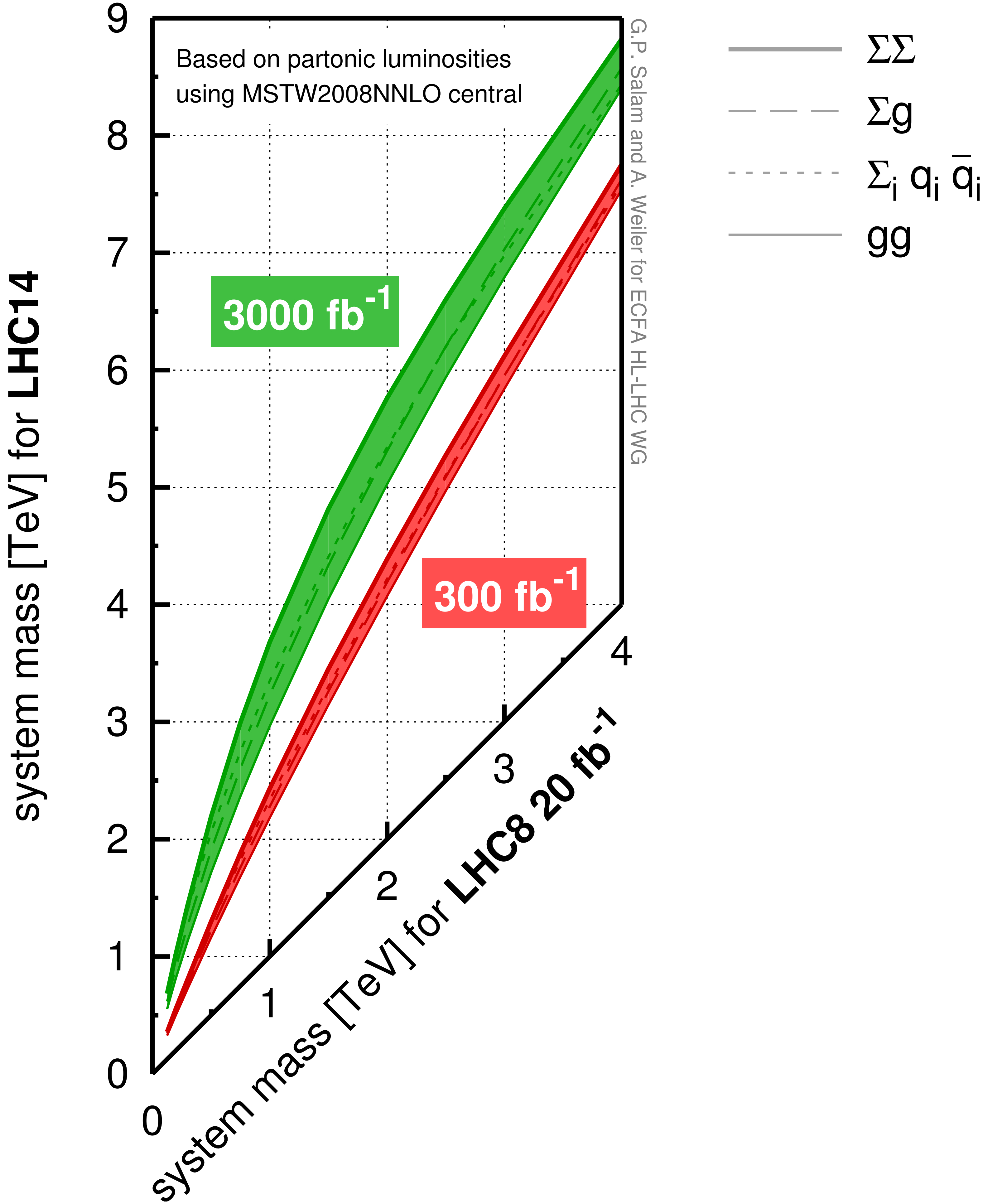
NEW

Special: only single logarithms (L = ln ρ)

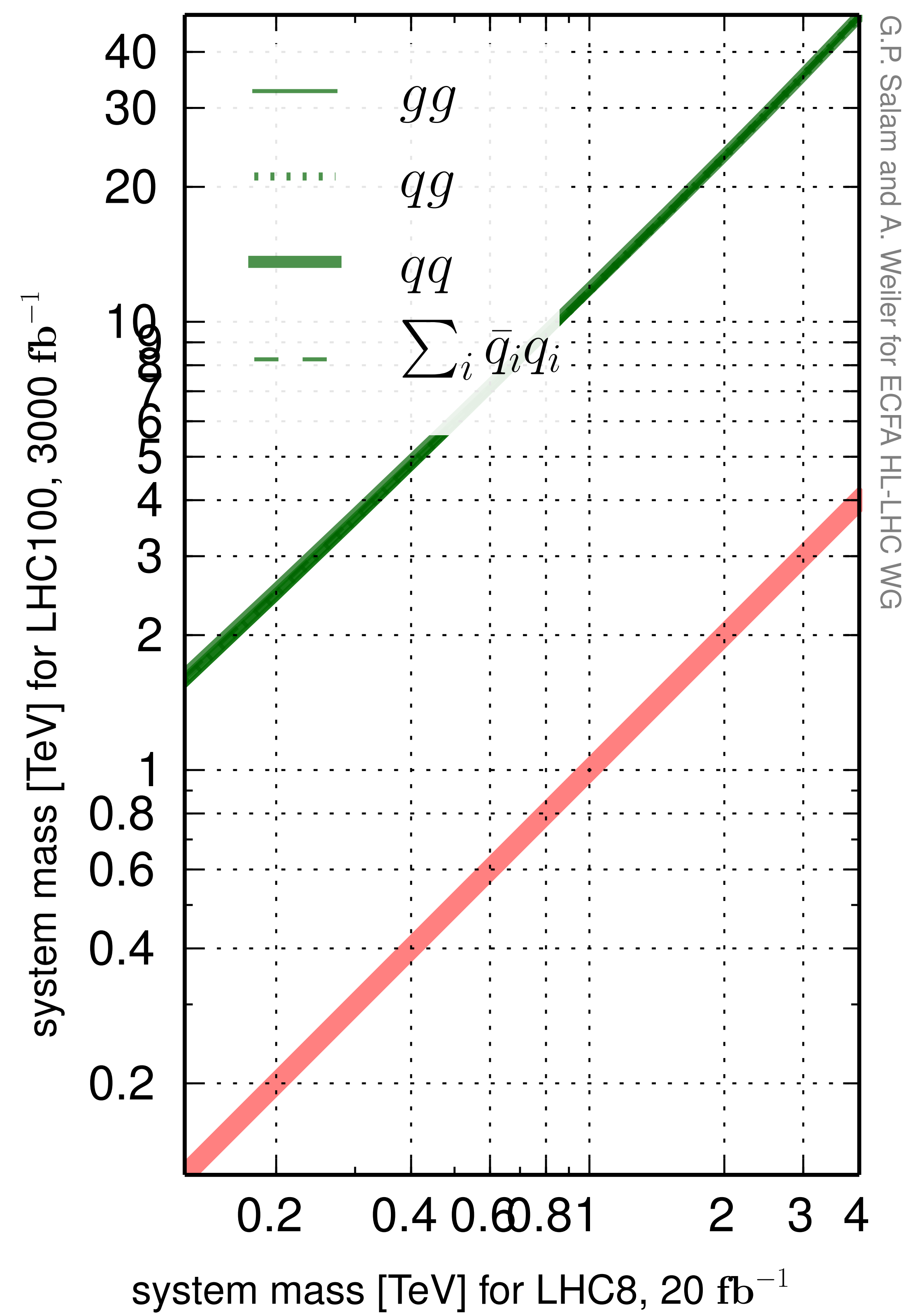
→ more accurately calculable

Special: better exploits signal/bkgd differences

EXTRAS

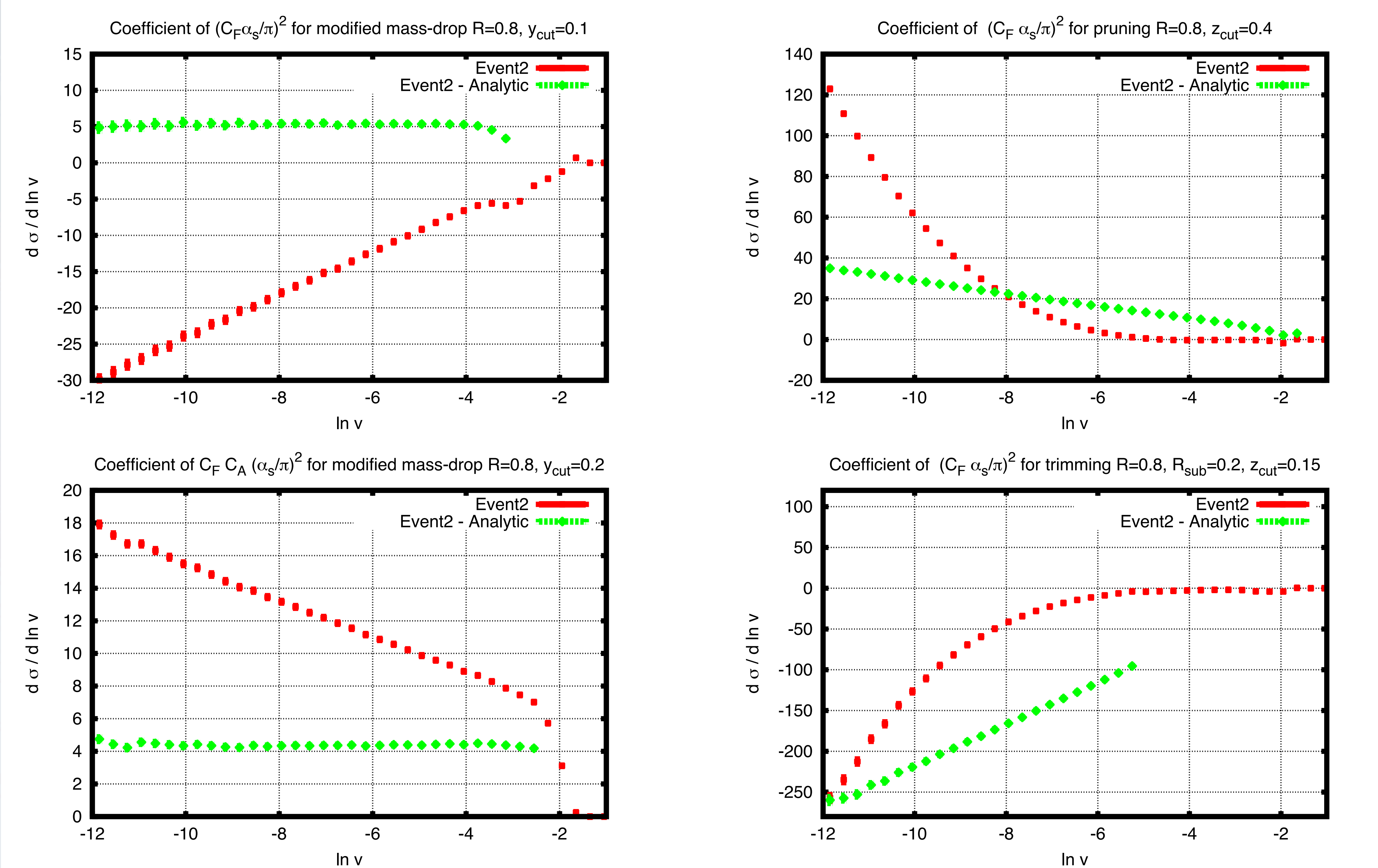


Based on partonic luminosities
using MSTW2008NNLO central
3000 fb-1
300 fb-1
system mass [TeV] for LHC14
system mass [TeV] for LHC8 20 fb-1
G.P. Salam and A. Weiler for ECFA HL-LHC WG
ΣΣ
Σg
Σi qi q̄i
gg



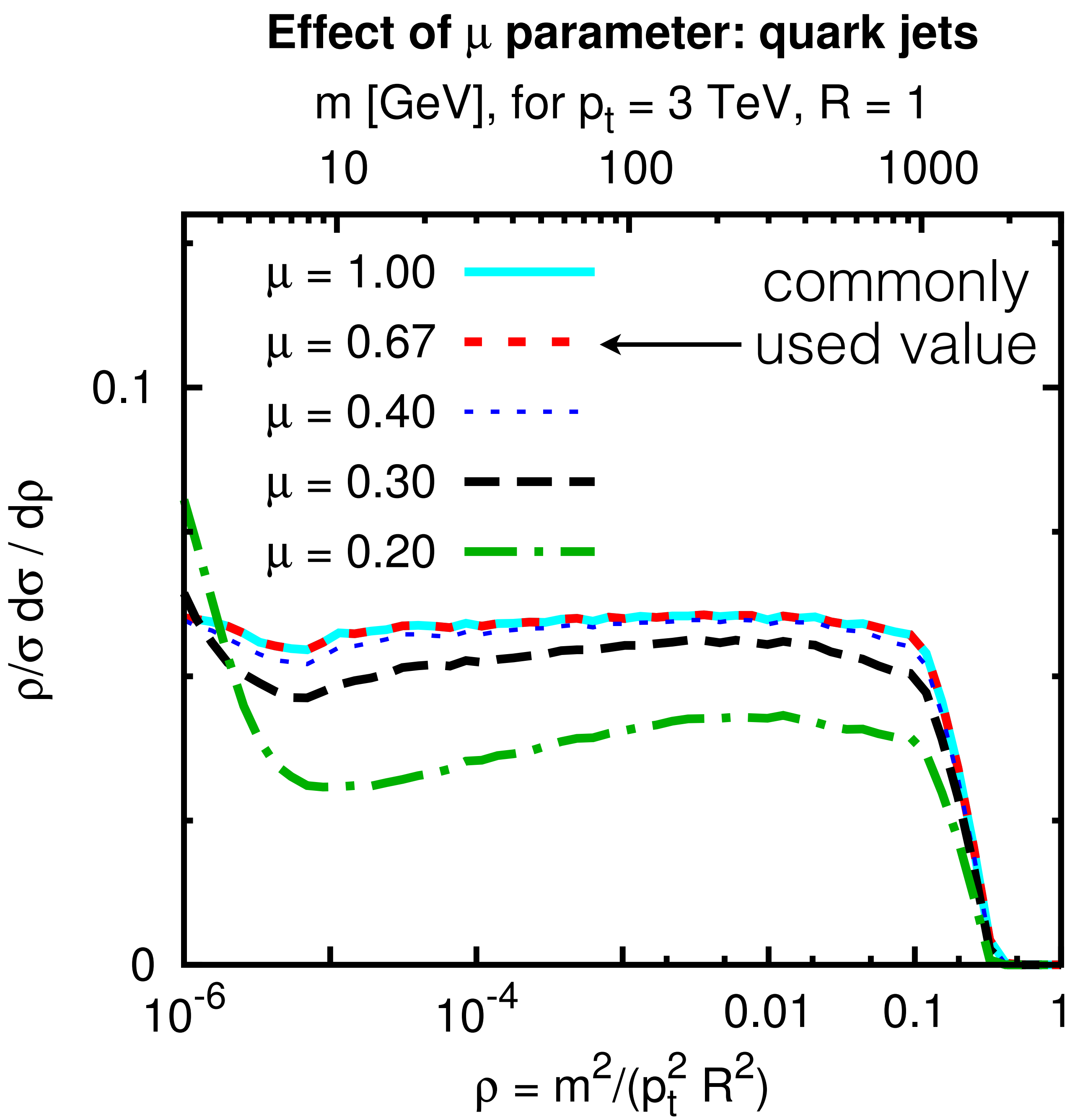
gg
qg
qq
∑i q̄i qi
system mass [TeV] for LHC100, 3000 fb−1
system mass [TeV] for LHC8, 20 fb−1
G.P. Salam and A. Weiler for ECFA HL-LHC WG

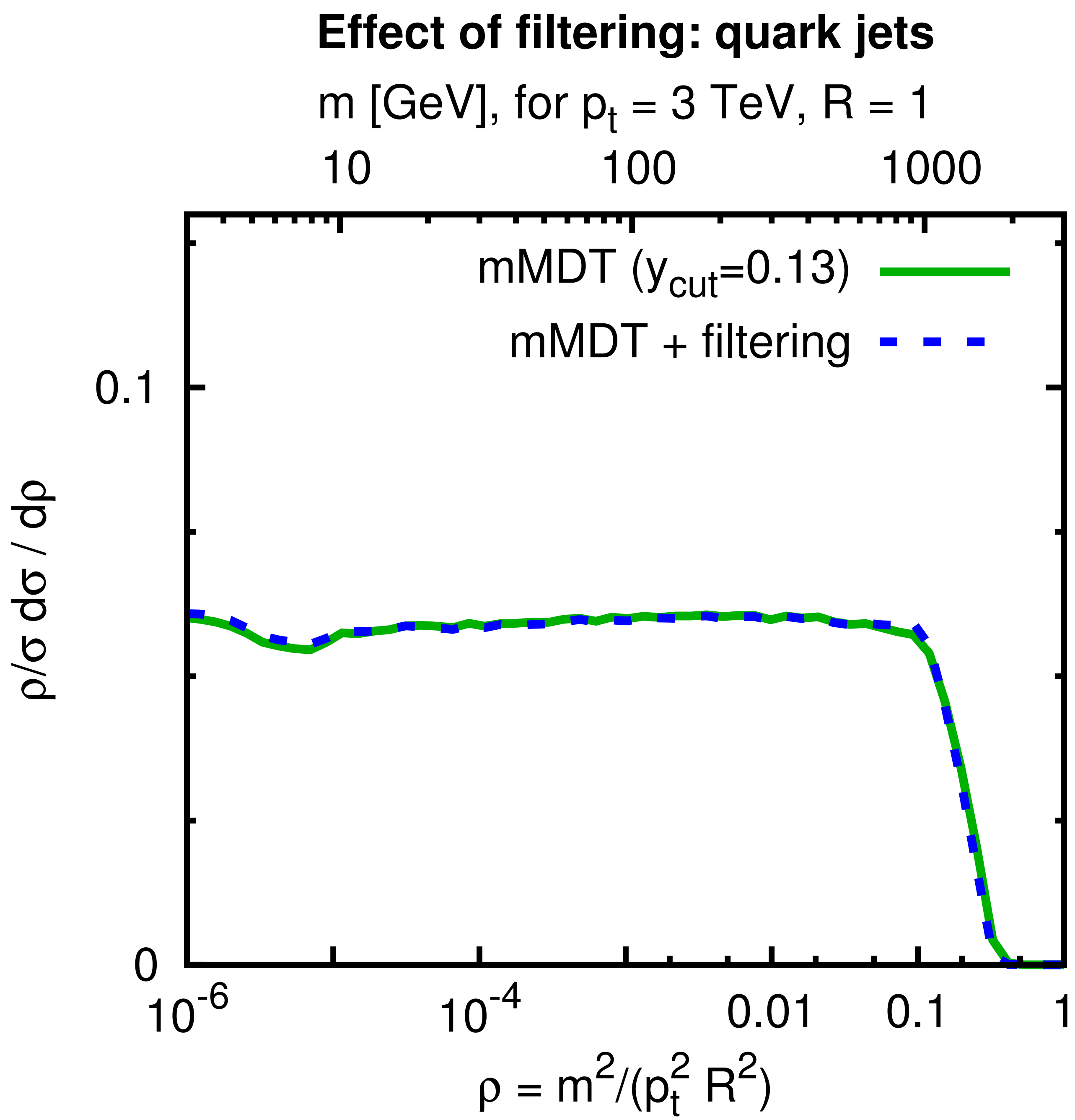
Examples of NLO checks



Dasgupta, Fregoso, Marzani & Powling, 1307.0013

mMDT: impact of μ and of filtering





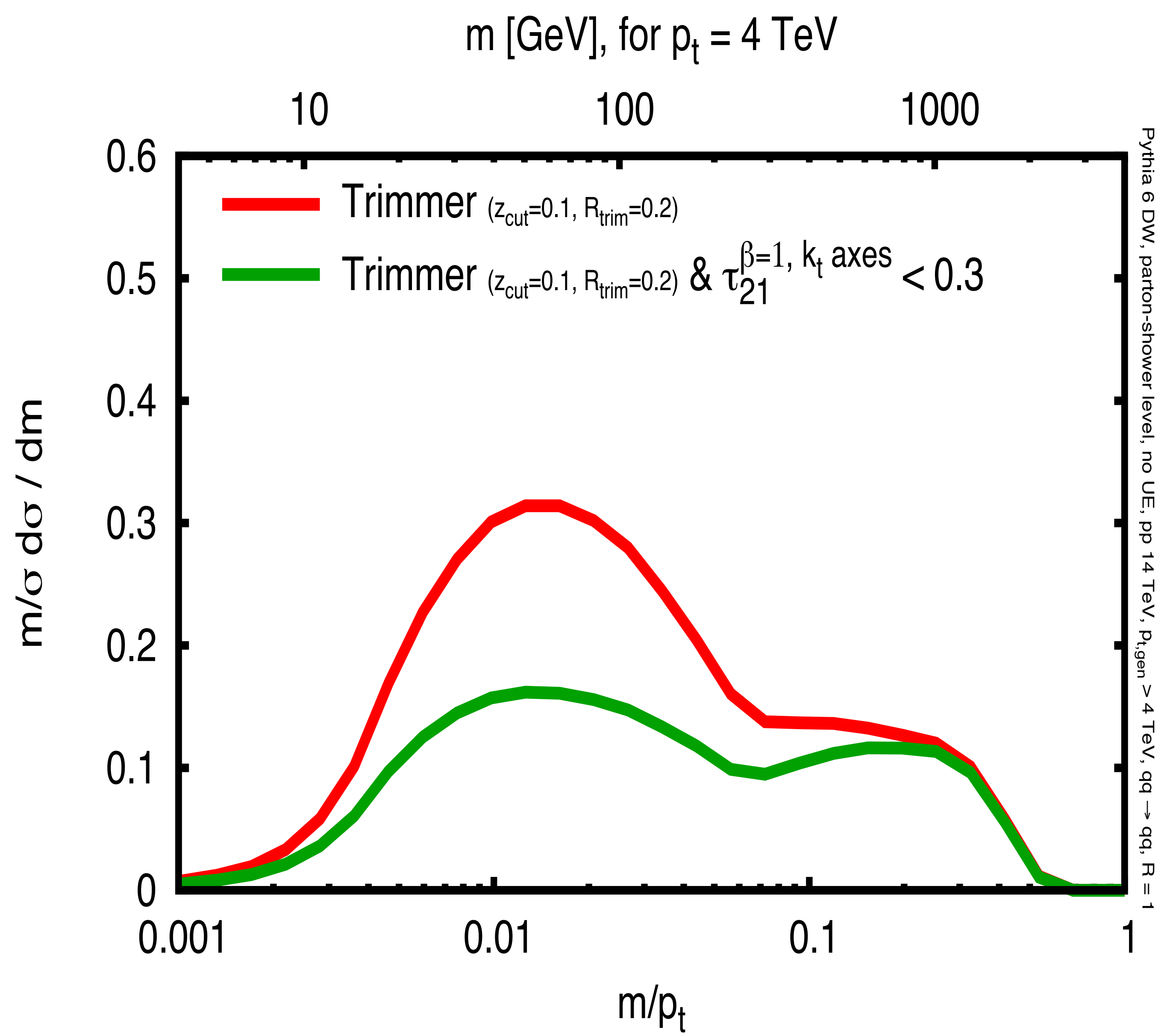
μ parameter basically irrelevant (simpler tagger discards it)

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

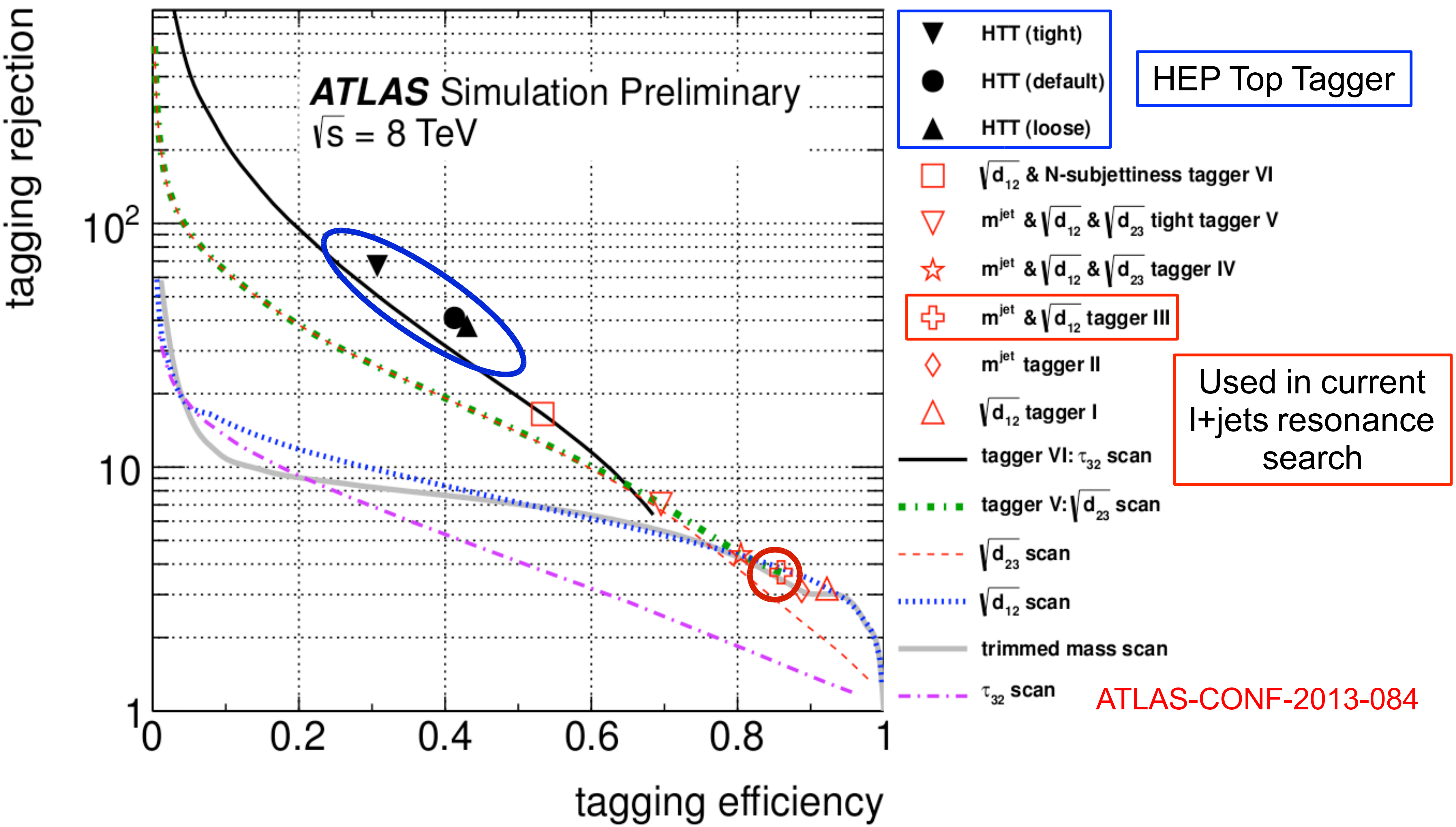
What about cuts on shapes/radiation

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

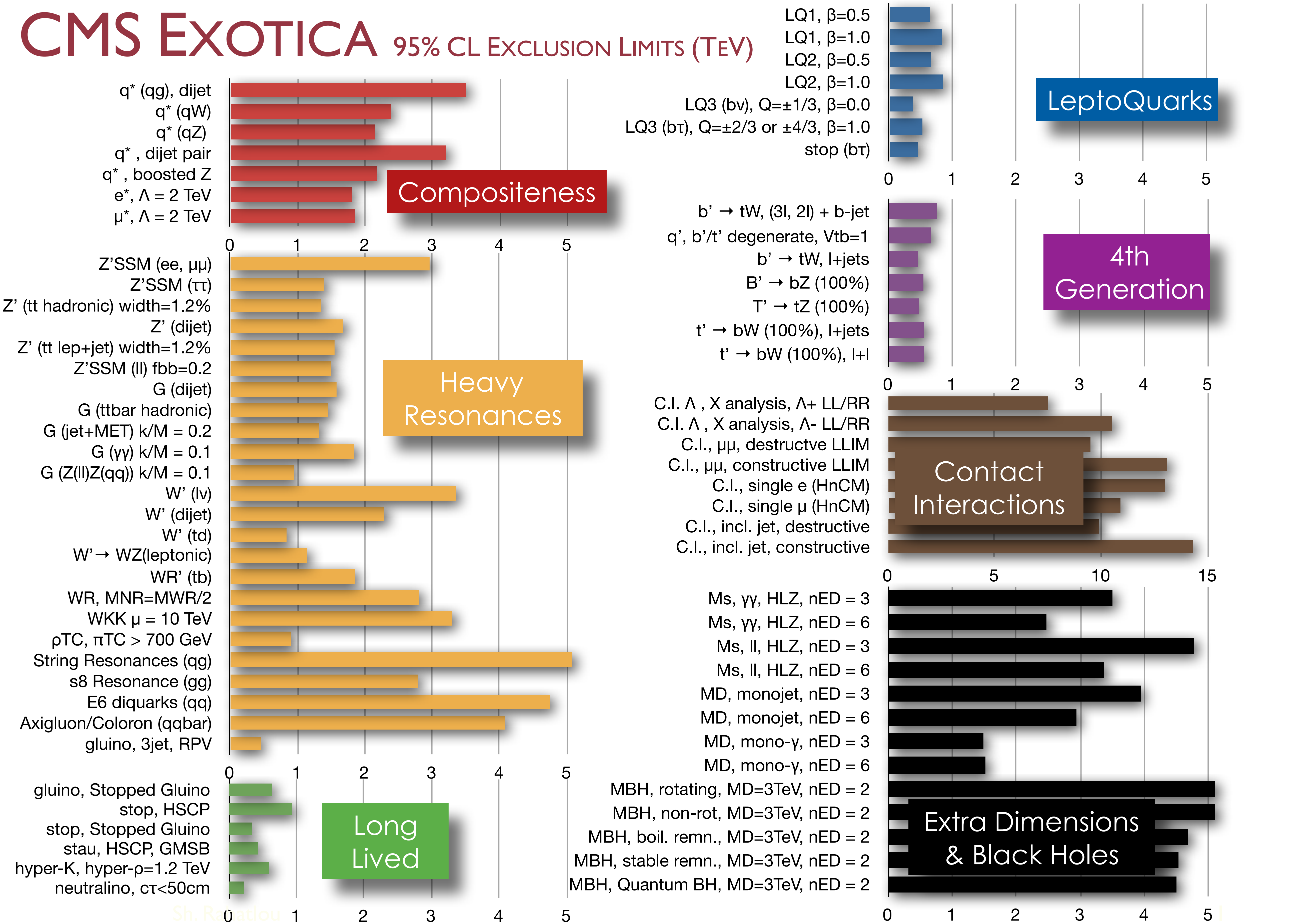
- These cuts are nearly always for a jet whose mass is somehow groomed. All the structure from the grooming persists.
- So tagging & shape must probably be calculated together



Top Tagger Comparison

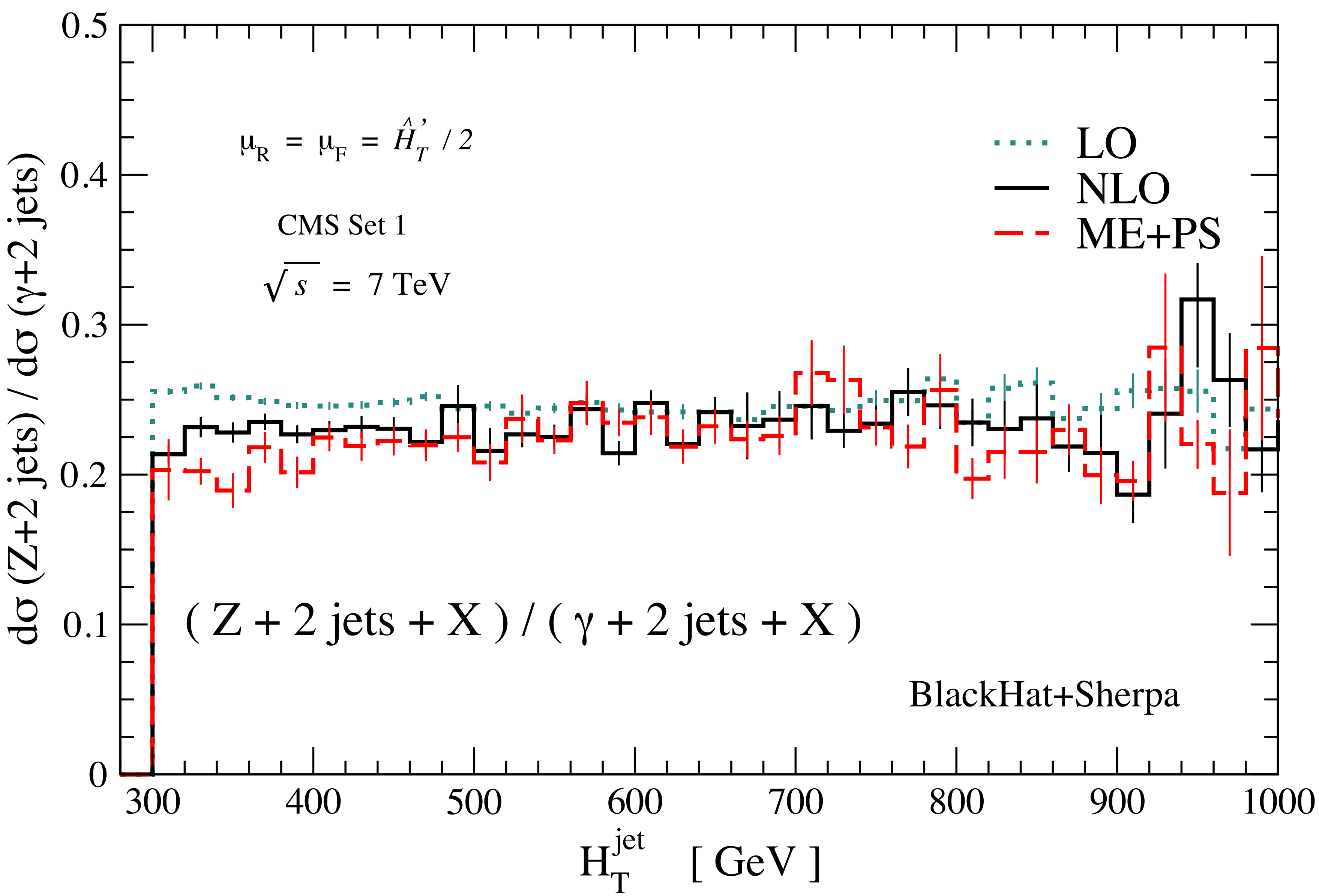


We have a wide variety of taggers available for different analyses!


CMS Exotica 95% CL Exclusion Limits (TeV)
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Heavy Resonances
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lv)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
4th Generation
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
Contact Interactions
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
0 5 10 15
Extra Dimensions & Black Holes
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
0 1 2 3 4 5

Understanding your taggers means you know what tools you can safely use with them

For robustness, you can then choose taggers whose distributions can be predicted in many ways



Just like MET($Z \to \nu\nu$) in multijets is reliably estimated from γ+jets because multiple types of calculations of the ratio agree

What are we comfortable with?

Resolved Analysis

Find one jet/prong

Cut on jet p_t, Δy, ...

What are we comfortable with?

Resolved Analysis | **Fat-jet Analysis**

Find one jet/prong → Find subjets

Cut on jet p_t, Δy, ... → Cut on subjet z, ΔR, ...

[MDT/Prune/Trim/Filt/XYZTopTagger/Template ...]

What are we comfortable with?

Resolved Analysis		Fat-jet Analysis
Find one jet/prong	→	Find subjets
Cut on jet p_t, Δy, ...	→	Cut on subjet z, ΔR, ...
		[MDT/Prune/Trim/Filt/XYZTopTagger/Template ...]
Isolation cut for colourless leptons, γ		
Cut on radiation in jet for q/g discrimination		

What are we comfortable with?

Resolved Analysis		Fat-jet Analysis
Find one jet/prong	→	Find subjets
Cut on jet p_t, Δy, ...	→	Cut on subjet z, ΔR, ... [MDT/Prune/Trim/Filt/XYZTopTagger/Template ...]
Isolation cut for colourless leptons, γ	→	Cut on radiation for colourless W,H,...
Cut on radiation in jet for q/g discrimination	→	Cut on radiation in subjets [τ_{mn}, Qjets, deconstruction...]

What are we comfortable with?

Resolved Analysis		Fat-jet Analysis
Find one jet/prong	→	Find subjets
Cut on jet p_t, Δy, ...	→	Cut on subjet z, ΔR, ...
		[MDT/Prune/Trim/Filt/XYZTopTagger/Template ...]
Isolation cut for colourless leptons, γ	→	Cut on radiation for colourless W,H,...
Cut on radiation in jet for q/g discrimination	→	Cut on radiation in subjets
		[τ_{mn}, Qjets, deconstruction...]

Standard, well understood

Less standard requires case-by-base validation

Different fat-jet tagger types

Prong based

(e.g. HEPTopTagger, Template Tagger)

- Identifies prongs
- Requires prongs be consistent with kinematics of $t \rightarrow Wb \rightarrow$ 3 quarks

Radiation based

(e.g. N-subjettiness = τ_3/τ_2 + mass cut)

- Requires top-mass consistency (maybe with some grooming)
- Exploits weaker radiation from top (3 quarks) than background (1q+2g or 3g)