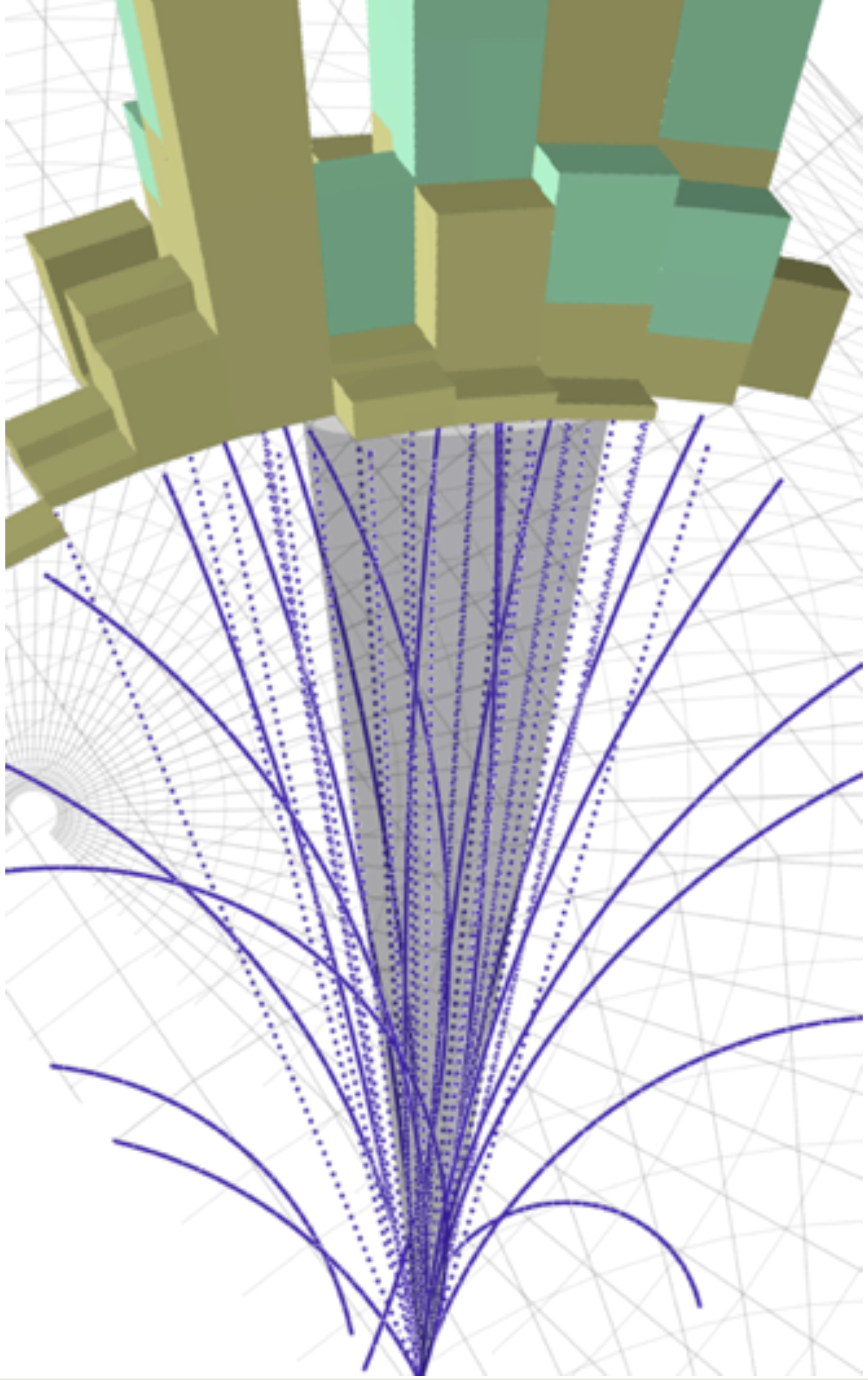


Towards an understanding of jet substructure

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

CERN PH–TH
13 December 2013

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)

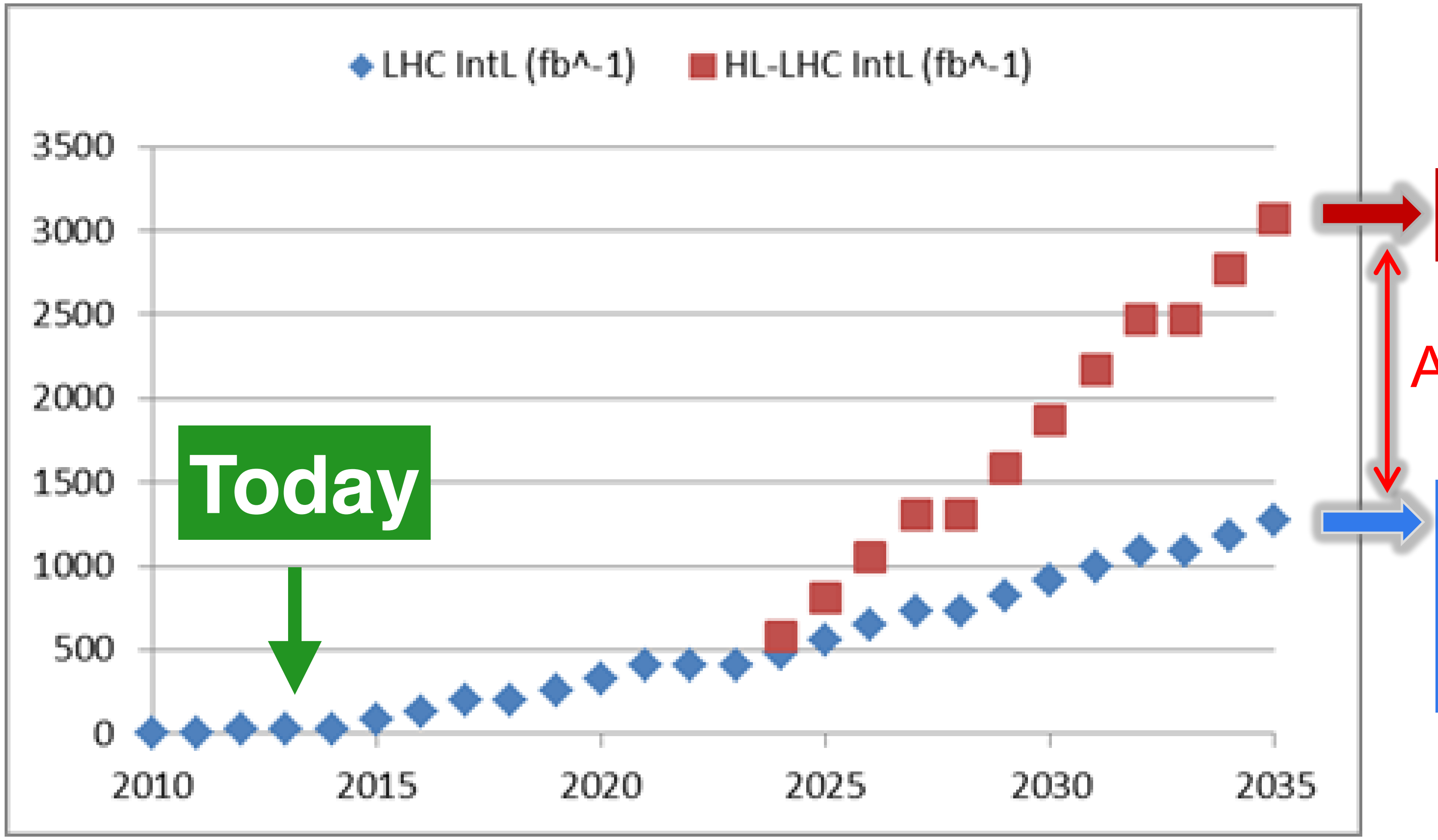
Highly precise Standard Model measurements

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



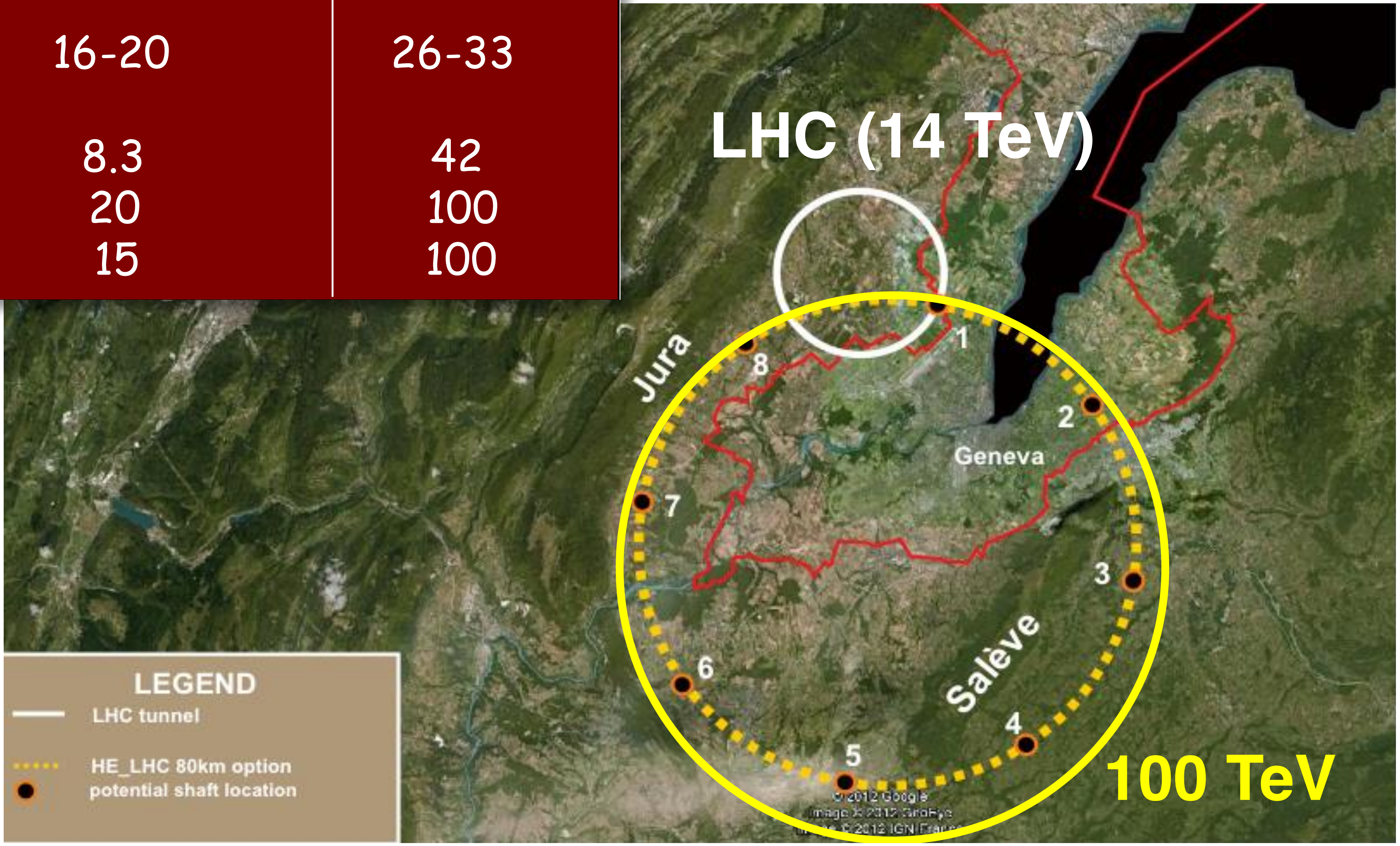
By implementing HL-LHC

Almost a factor 3

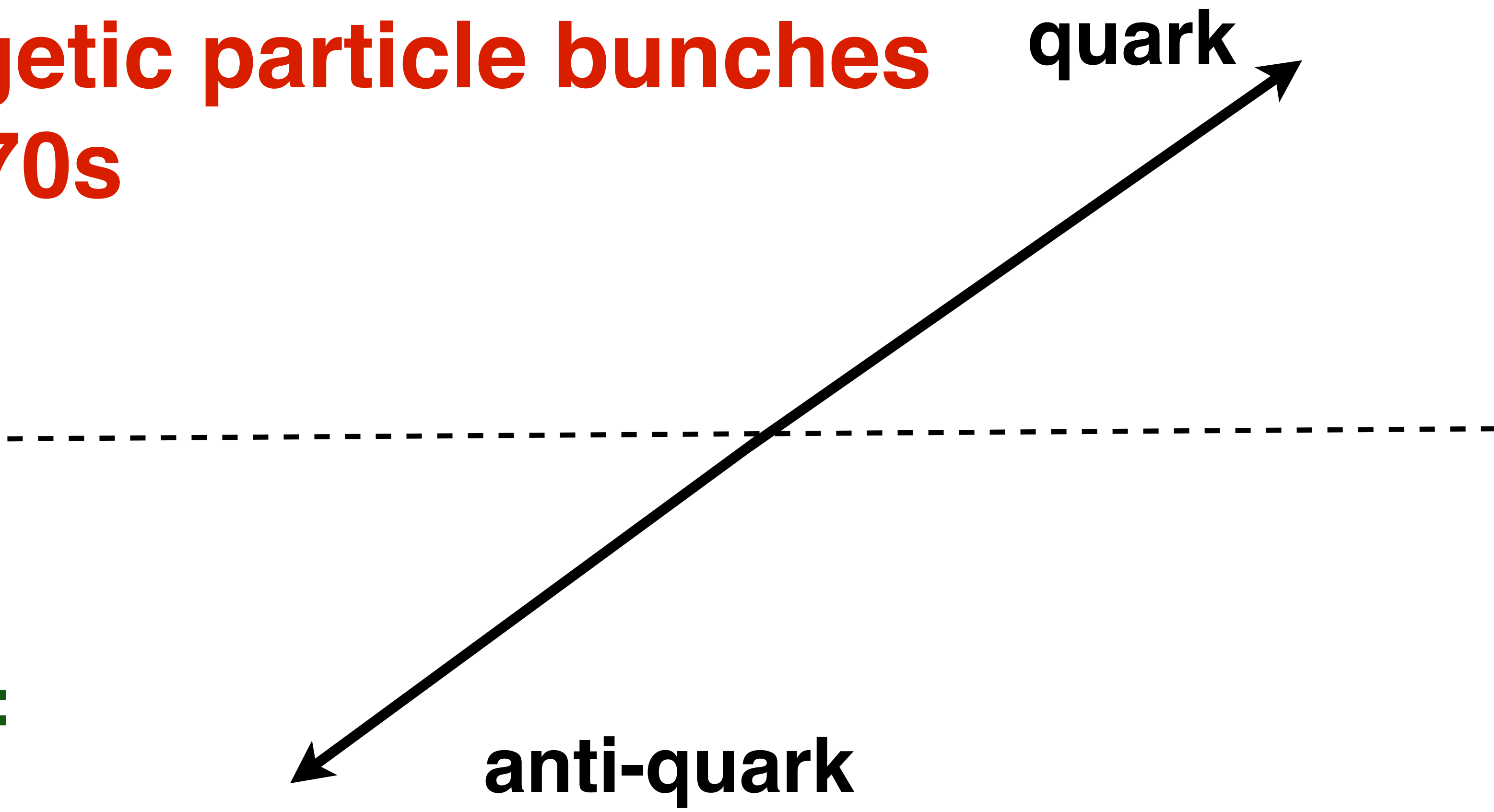
By continuous performance improvement and consolidation

Even longer term – a 100 TeV collider?

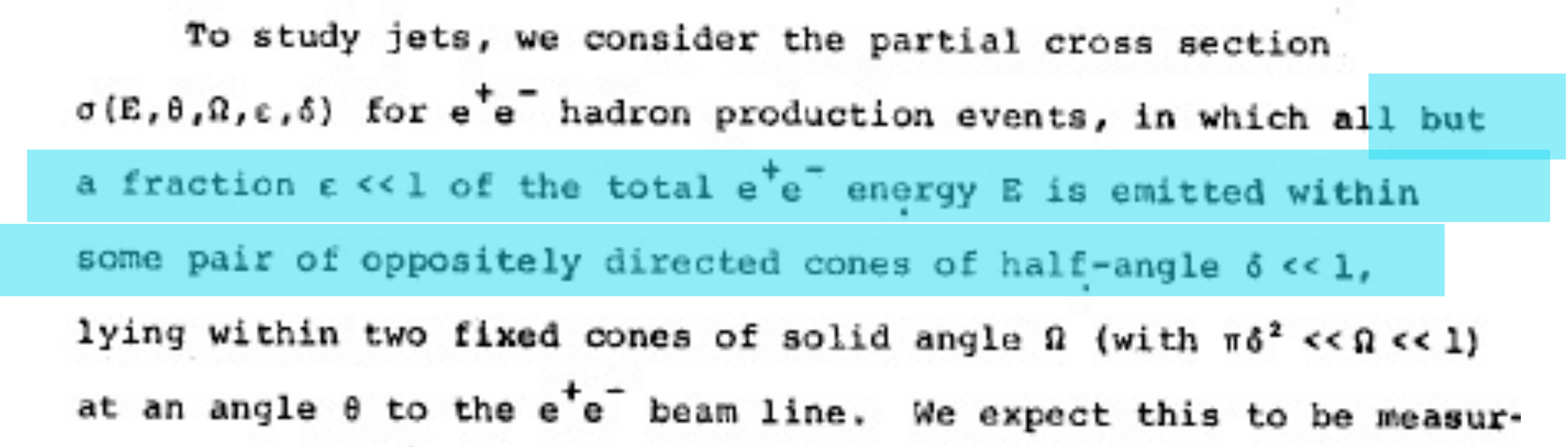
Facility	Ring (km)	Magnets (T)	√s (TeV)
(SSC)	87	6.6	40
LHC	27	8.3	14
HE-LHC	27	16-20	26-33
FHC	80	8.3	42
	80	20	100
	100	15	100


LHC (14 TeV)
Jura
1
2
3
4
5
6
7
8
Geneva
Salève
100 TeV
LEGEND
LHC tunnel
HE_LHC 80km option
● potential shaft location
©2012 Google

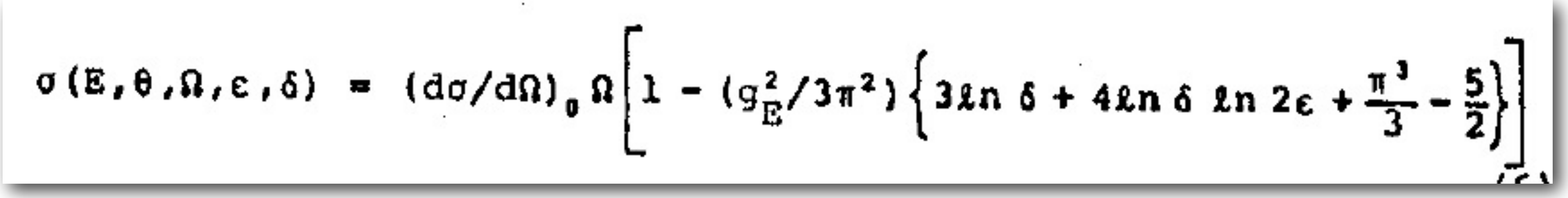
Jets — collimated energetic particle bunches date back to the late 1970s



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

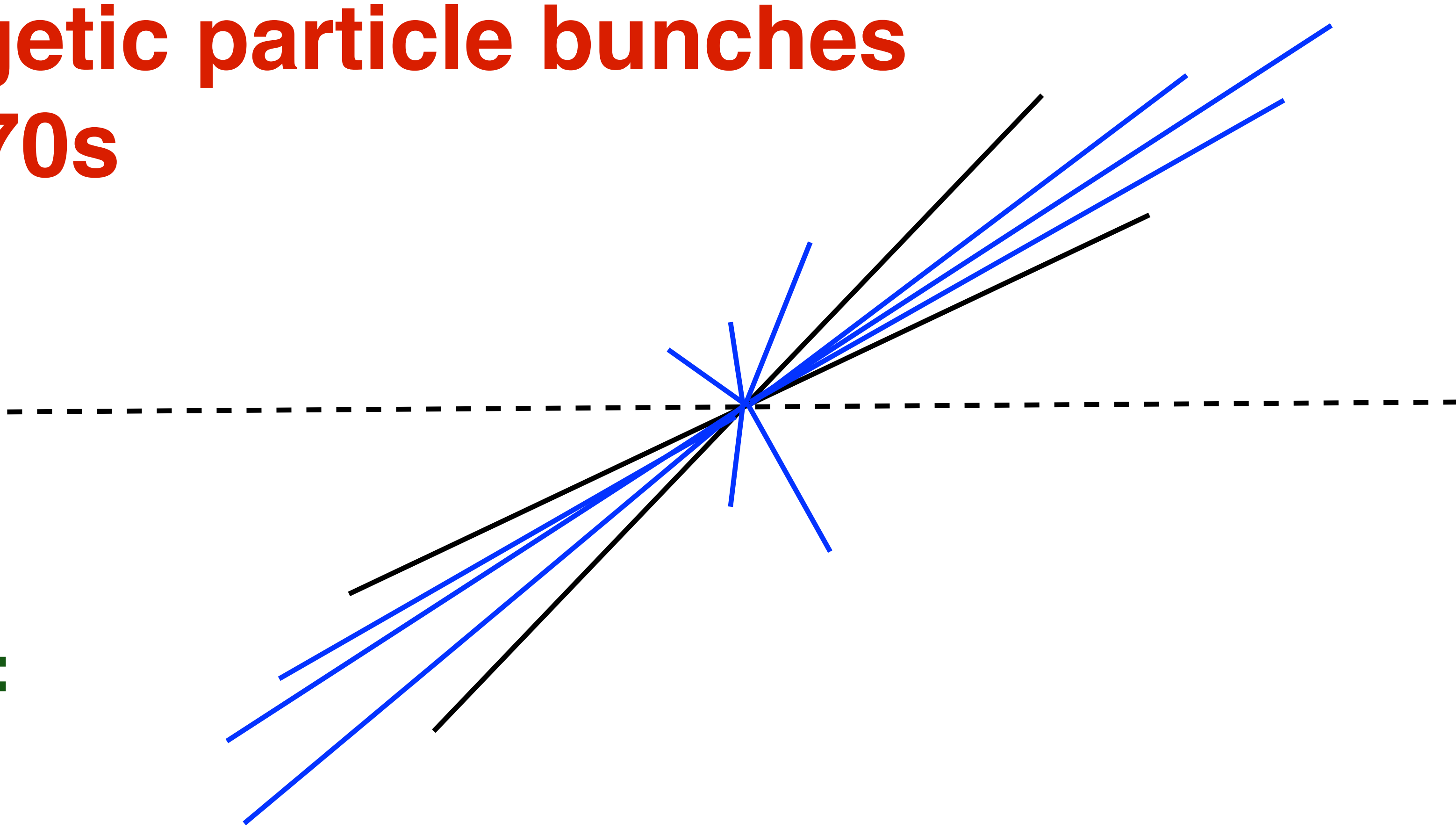


To study jets, we consider the partial cross section $\sigma(E,\theta,\Omega,\varepsilon,\delta)$ for e^+e^- hadron production events, in which all but a fraction $\varepsilon \ll 1$ of the total e^+e^- energy E is emitted within some pair of oppositely directed cones of half-angle $\delta \ll 1$, lying 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-



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

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



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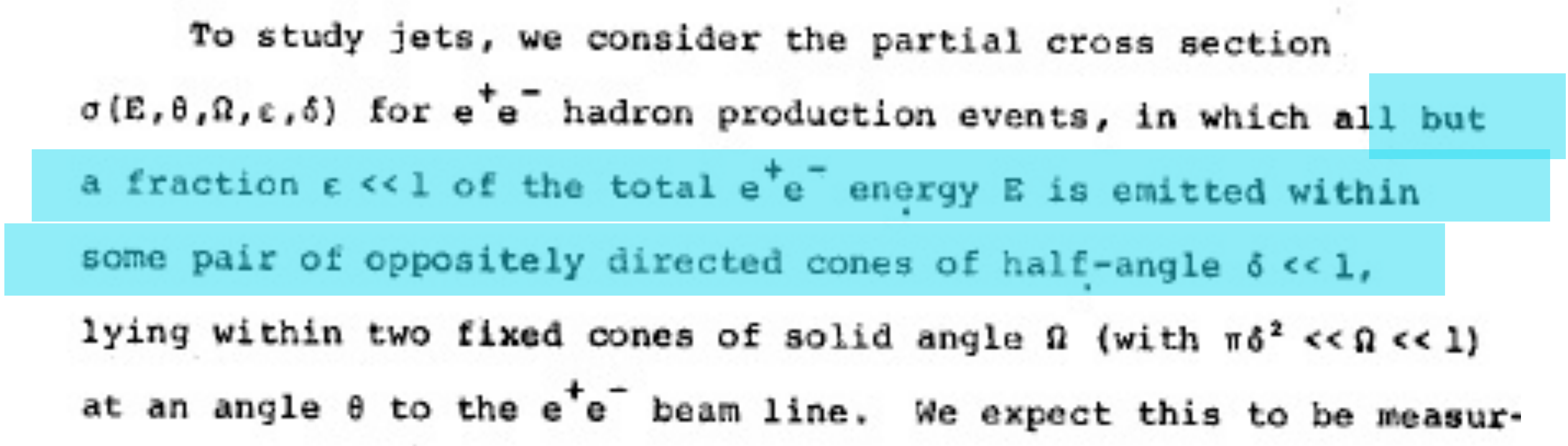

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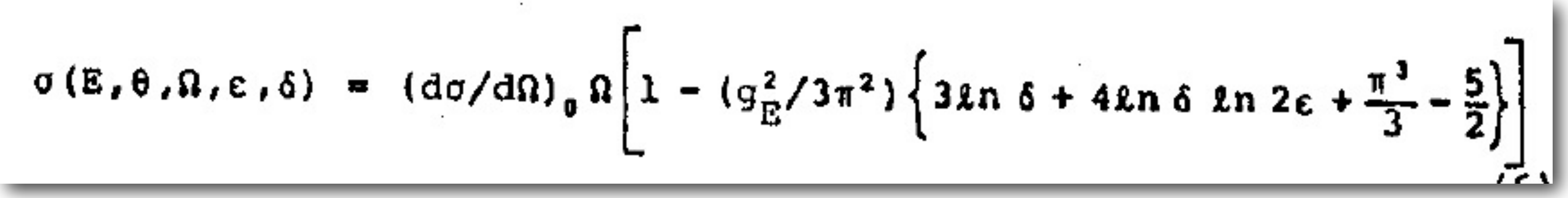

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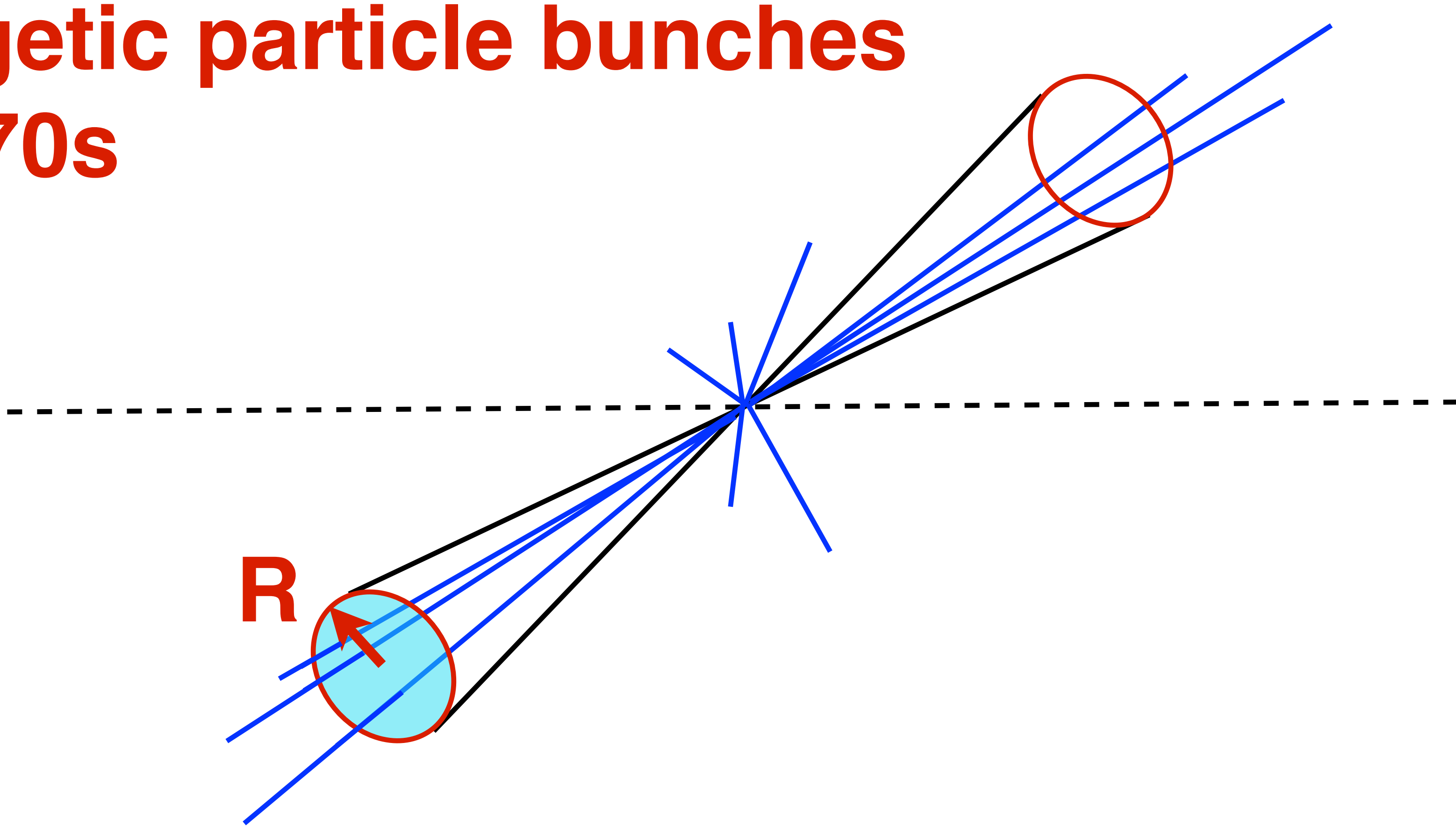
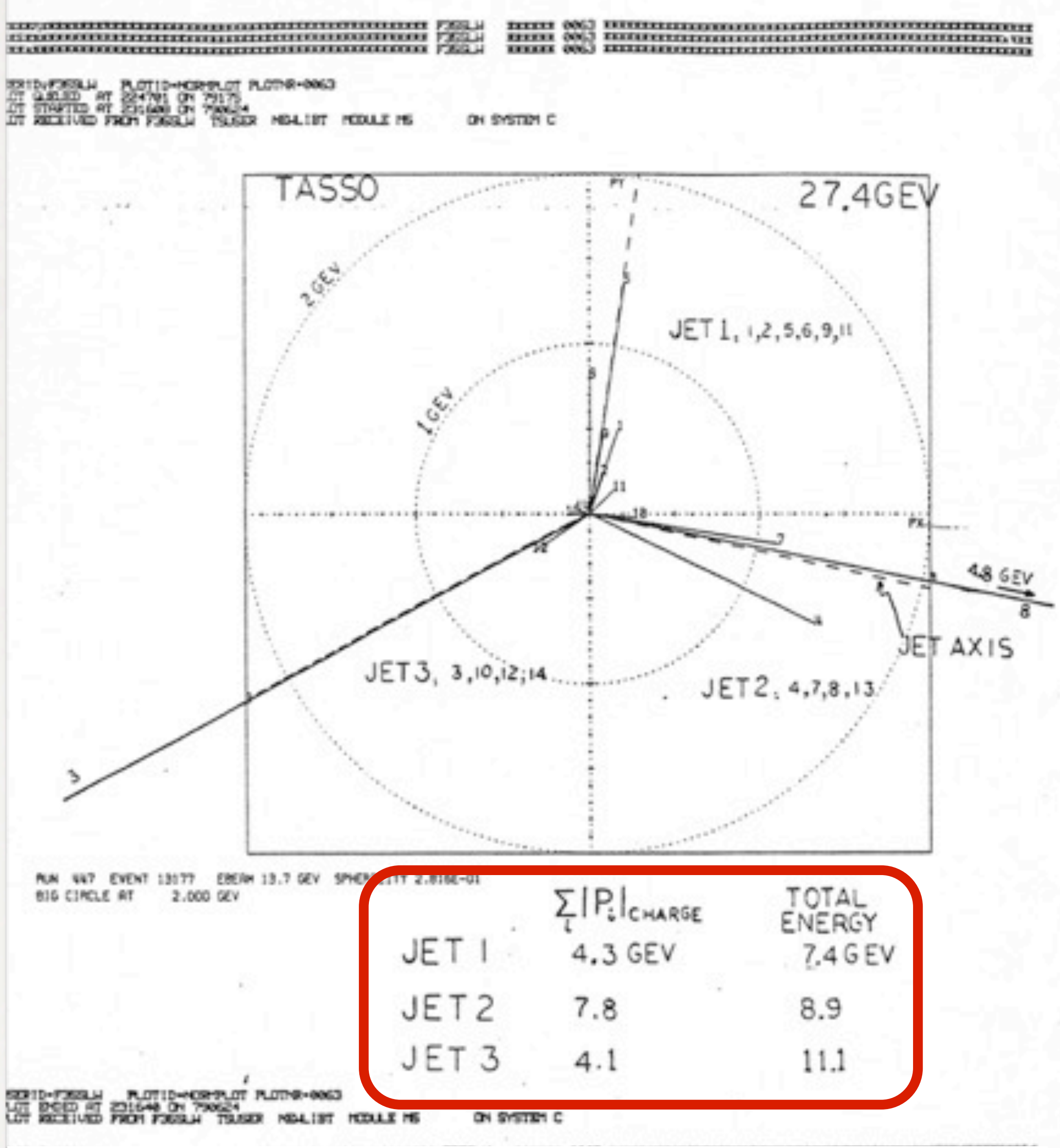
Jets — collimated energetic particle bunches date back to the late 1970s



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

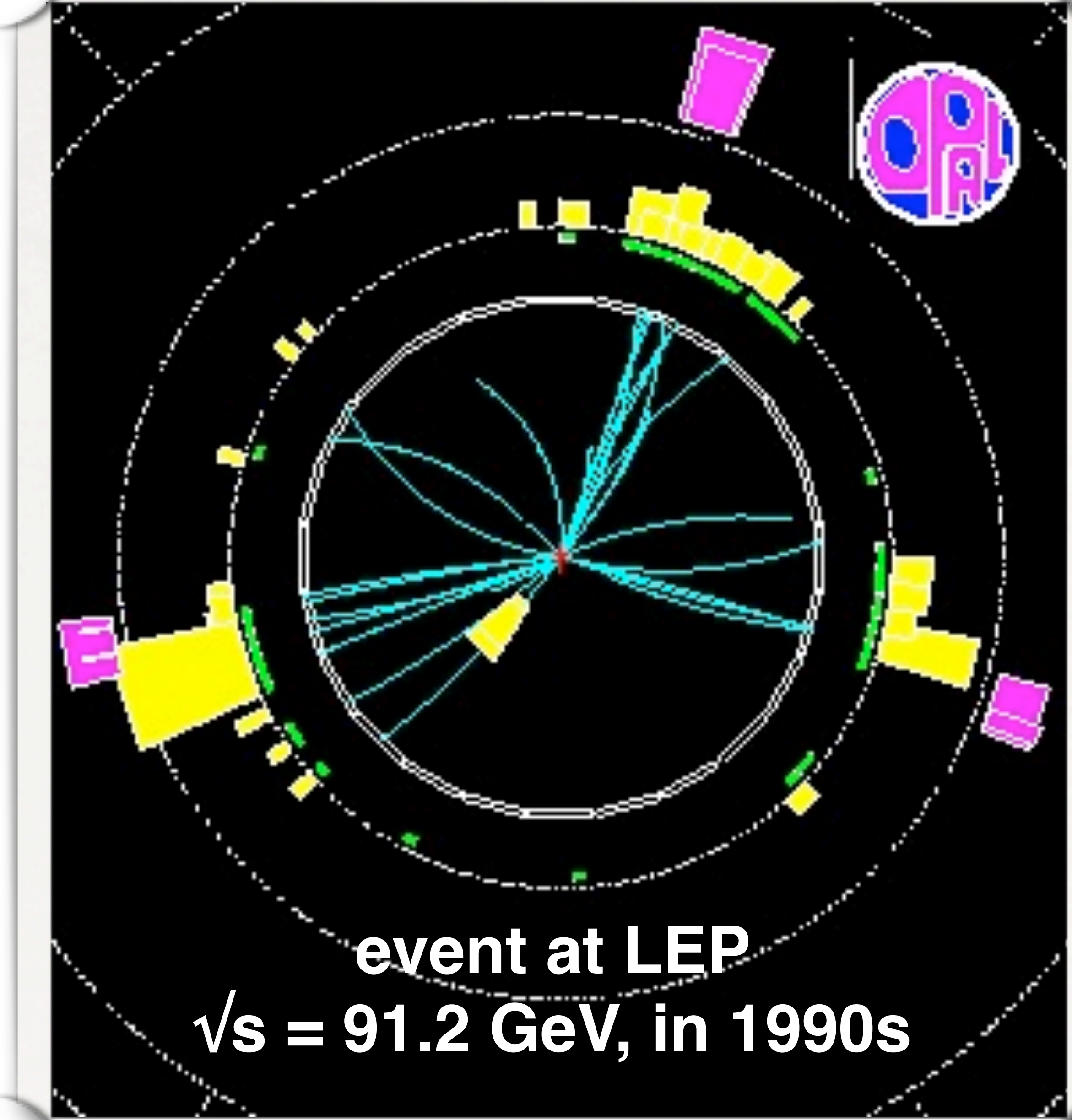
And they’ve been used and studied at every collider since


TASSO
27.4GEV
2 GEV
1 GEV
JET 1, 1,2,5,6,9,11
JET 2, 4,7,8,13
JET 3, 3,10,12,14
48 GEV
JET AXIS

	$\sum_i \lvert P_i \rvert_{\text{CHARGE}}$	TOTAL ENERGY
JET 1	4.3 GEV	7.4 GEV
JET 2	7.8	8.9
JET 3	4.1	11.1

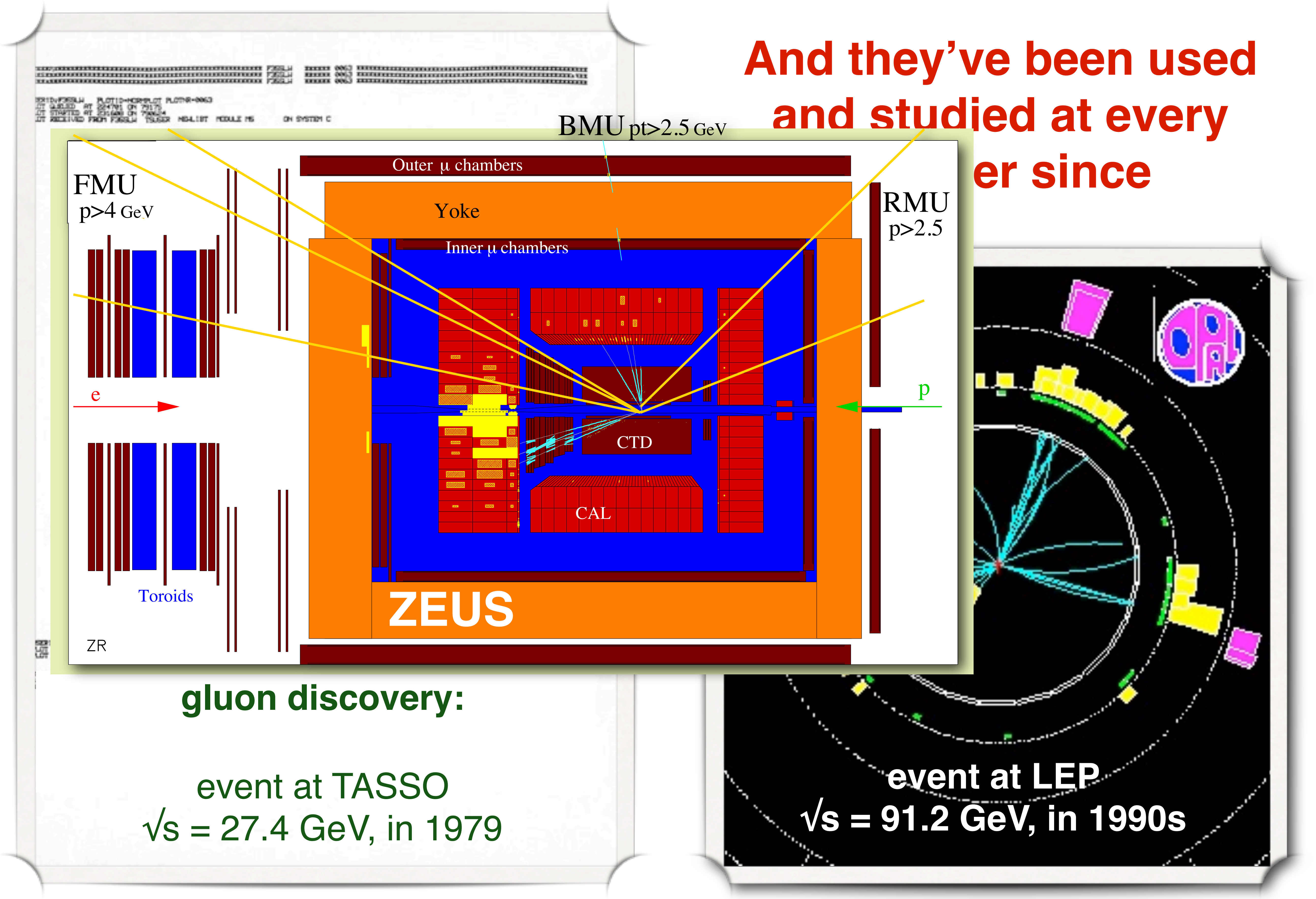
gluon discovery:

event at TASSO
$\sqrt{s}$ = 27.4 GeV, in 1979



event at LEP
$\sqrt{s}$ = 91.2 GeV, in 1990s

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


BMU pt>2.5 GeV
Outer μ chambers
FMU
p>4 GeV
Yoke
Inner μ chambers
RMU
p>2.5
e
p
CTD
CAL
Toroids
ZEUS
ZR

gluon discovery:

event at TASSO
$\sqrt{s} = 27.4$ GeV, in 1979

event at LEP
$\sqrt{s} = 91.2$ GeV, in 1990s

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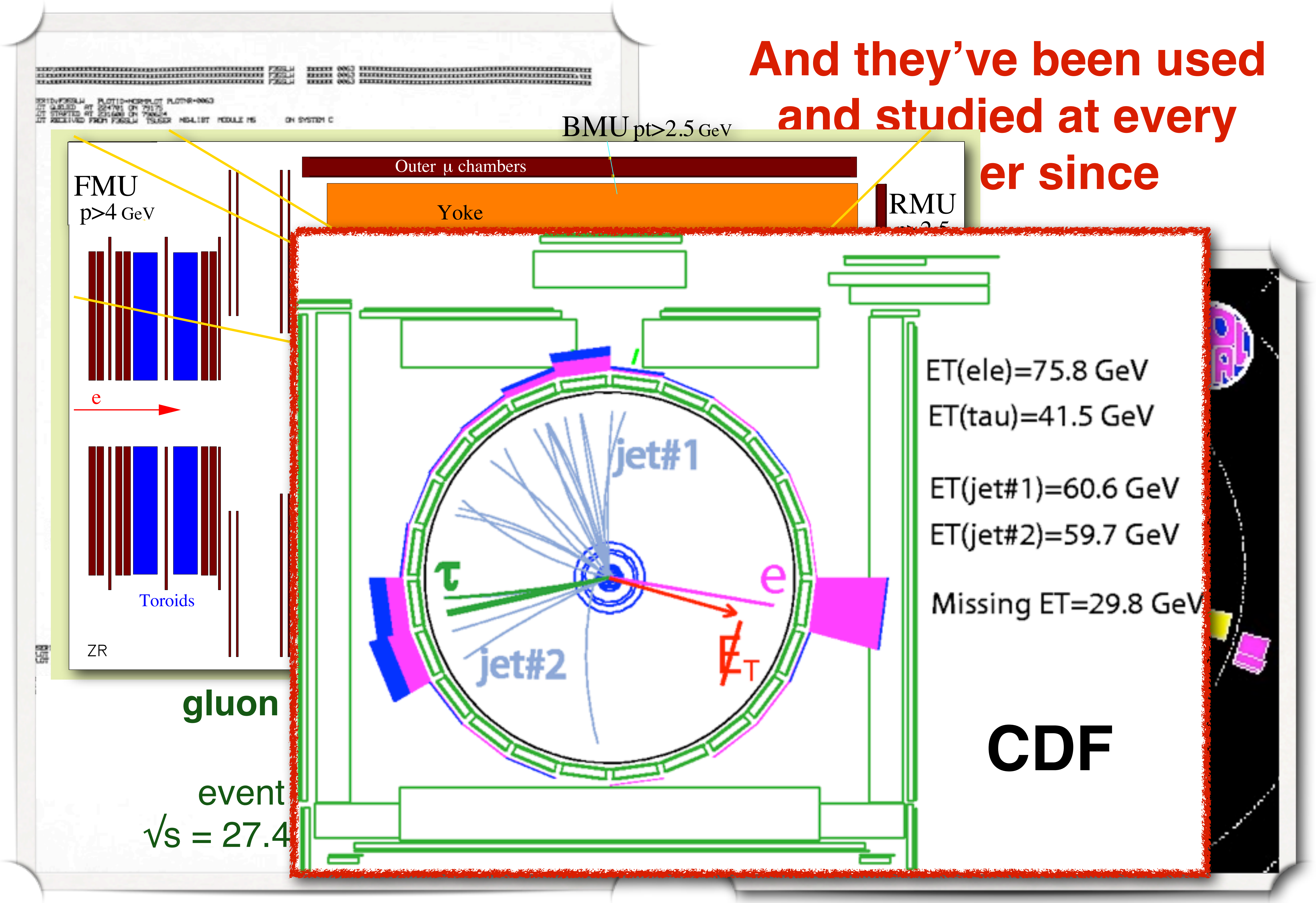
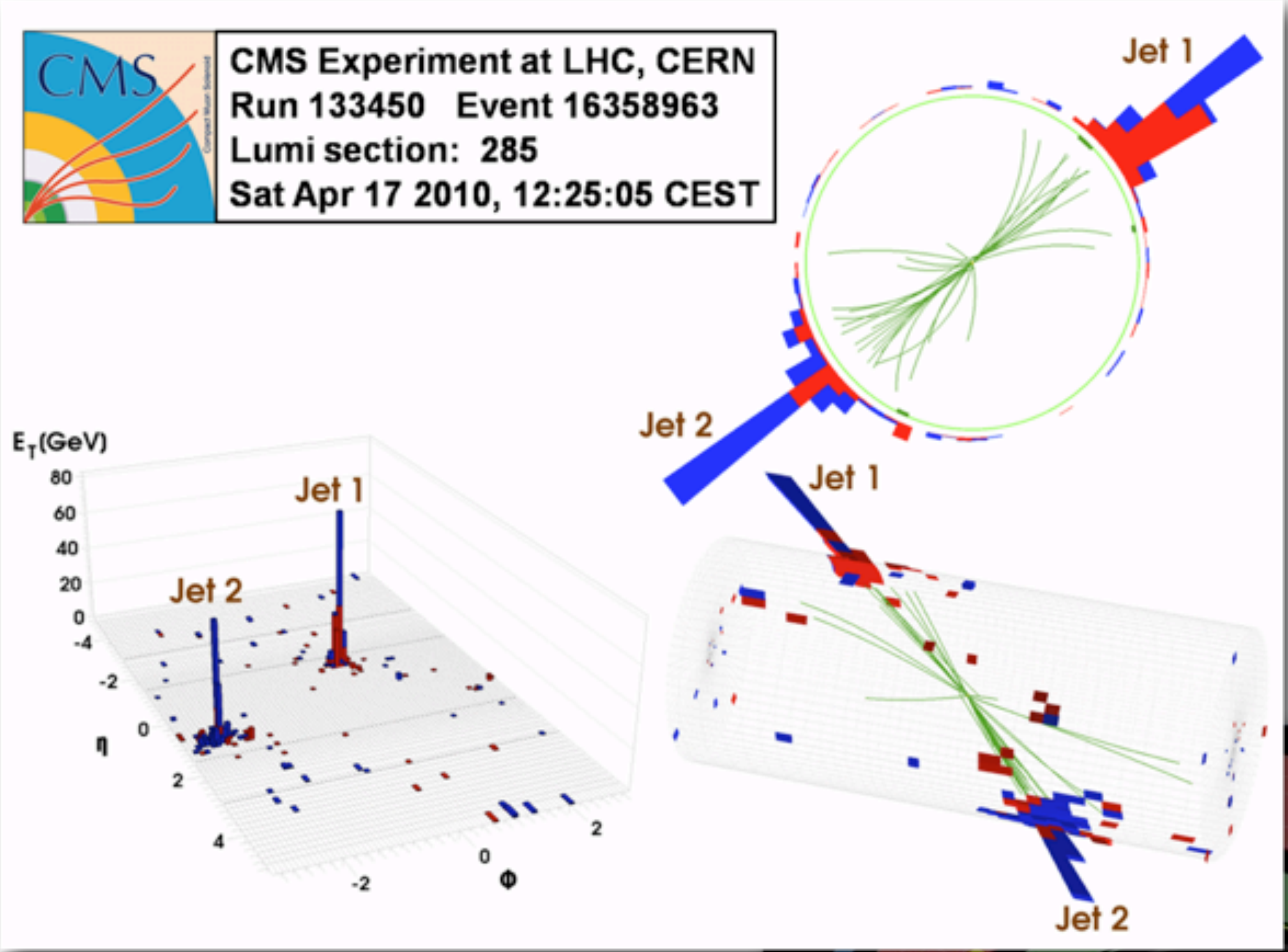
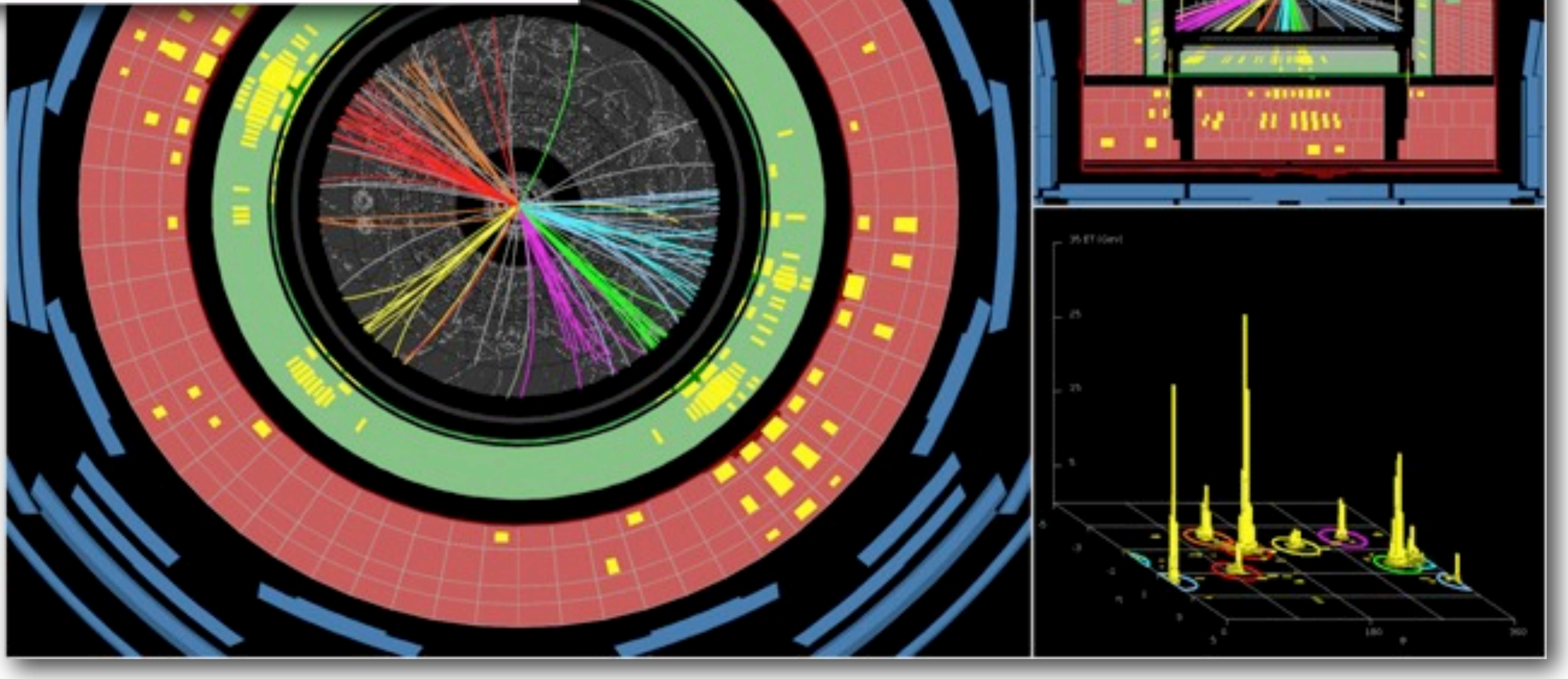

BMU pt>2.5 GeV
Outer μ chambers
Yoke
FMU
p>4 GeV
RMU
e
Toroids
ZR
τ
jet#1
jet#2
e
$\not{E}_T$
ET(ele)=75.8 GeV
ET(tau)=41.5 GeV
ET(jet#1)=60.6 GeV
ET(jet#2)=59.7 GeV
Missing ET=29.8 GeV
CDF

gluon

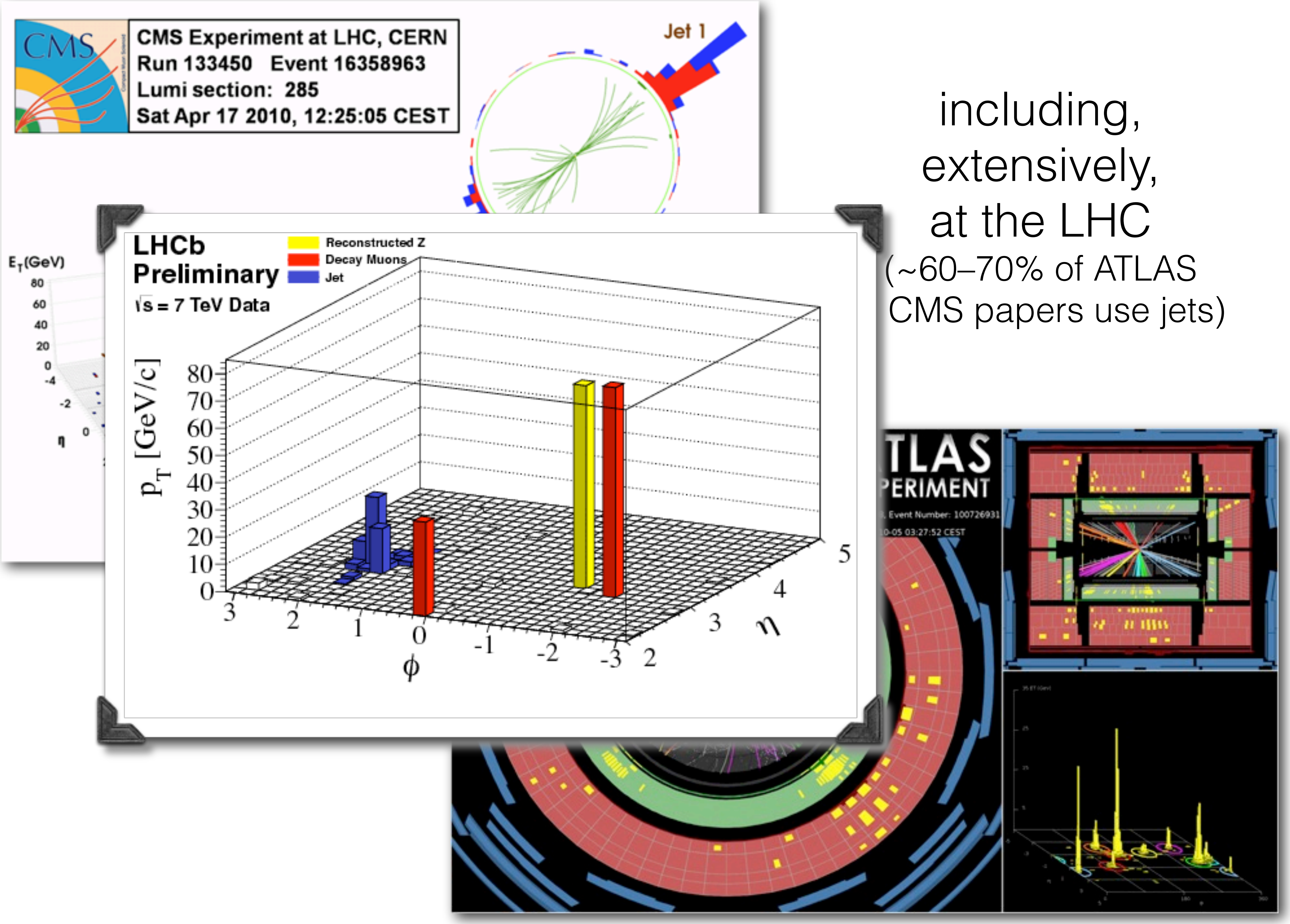
event

√s = 27.4


CMS Experiment at LHC, CERN
Run 133450 Event 16358963
Lumi section: 285
Sat Apr 17 2010, 12:25:05 CEST
Jet 1
Jet 2
Jet 1
Jet 2
E_T(GeV)
80
60
40
20
0
Jet 1
Jet 2
-4
-2
0
2
4
η
-2
0
2
Φ


ATLAS EXPERIMENT
Run Number: 166198, Event Number: 100726931
Date: 2010-10-05 03:27:52 CEST

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



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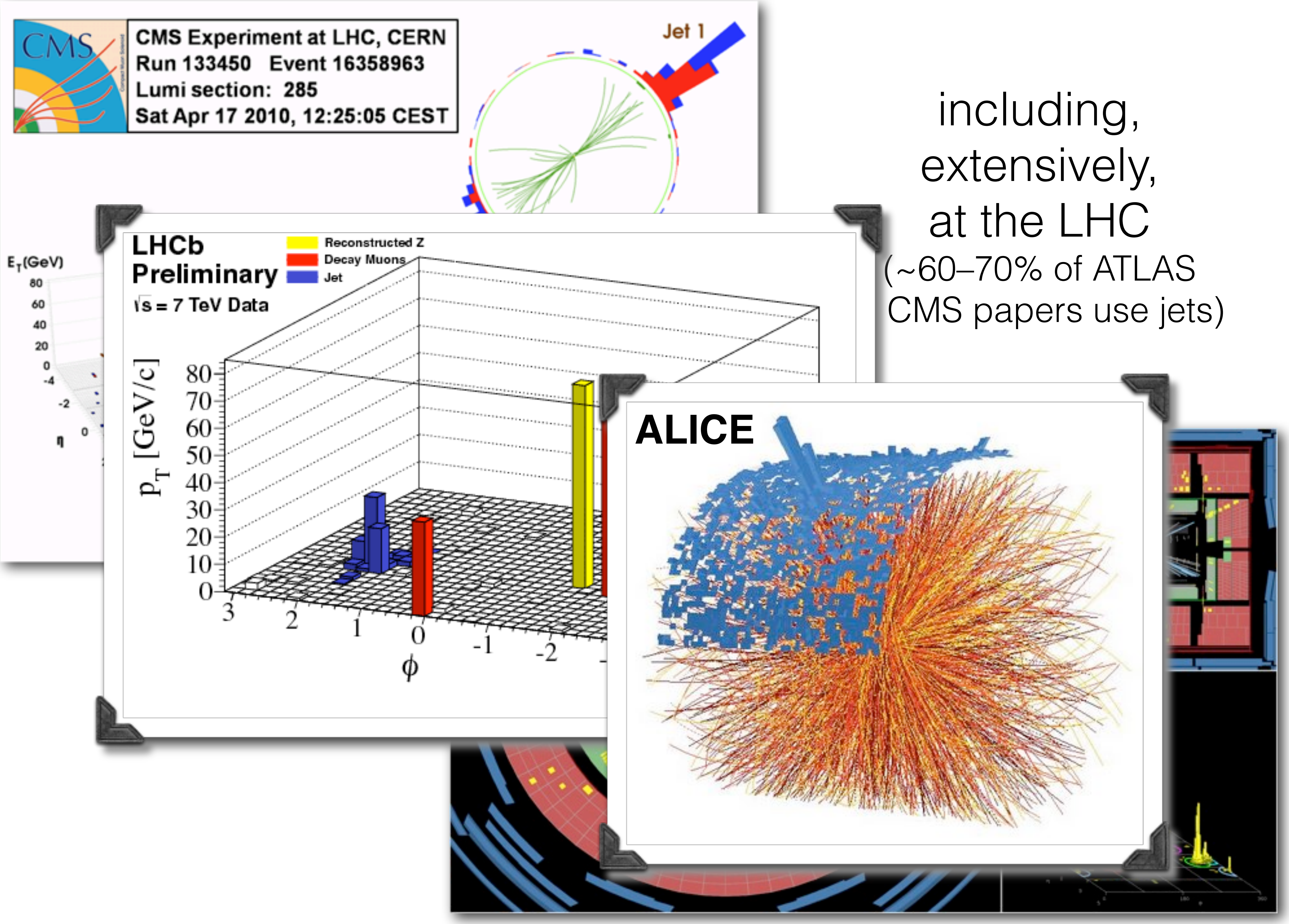
CMS papers use jets)



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

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–'13),
anti-k_t (idem '08), area subtraction of pileup (idem, '06–'12)
and the hard work of **experimental calibration**

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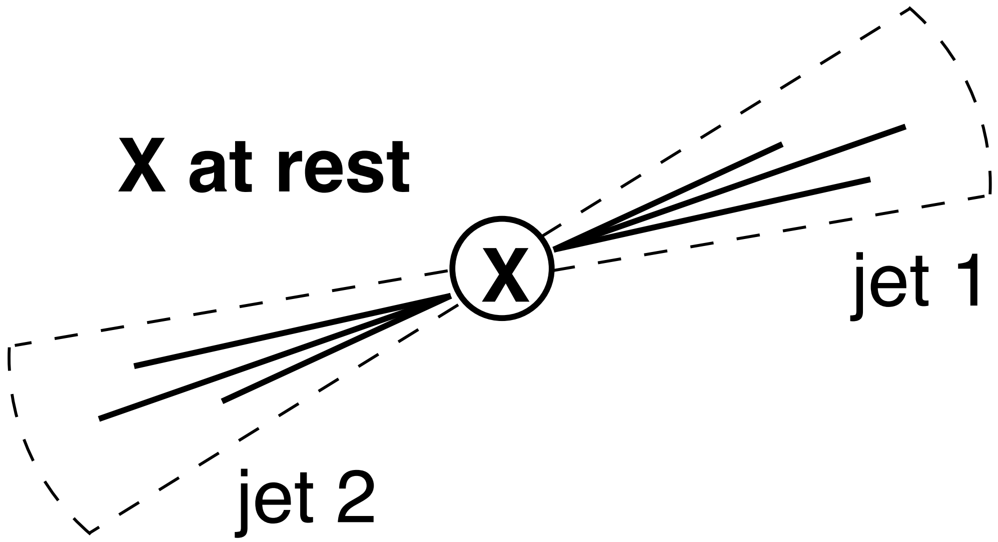
But as LHC moves to search “harder” for new physics, we start to need to push analyses to their boundary, e.g.

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

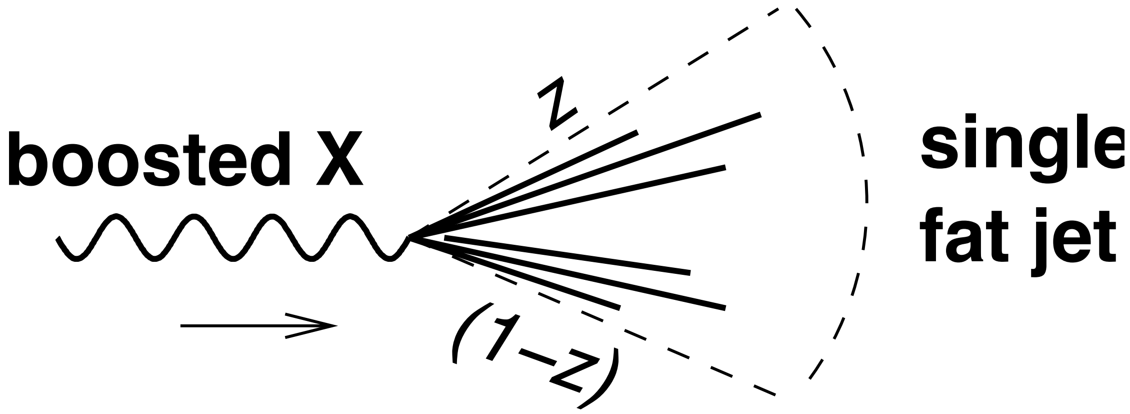
Boosted hadronic decays

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

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


X at rest
X
jet 1
jet 2

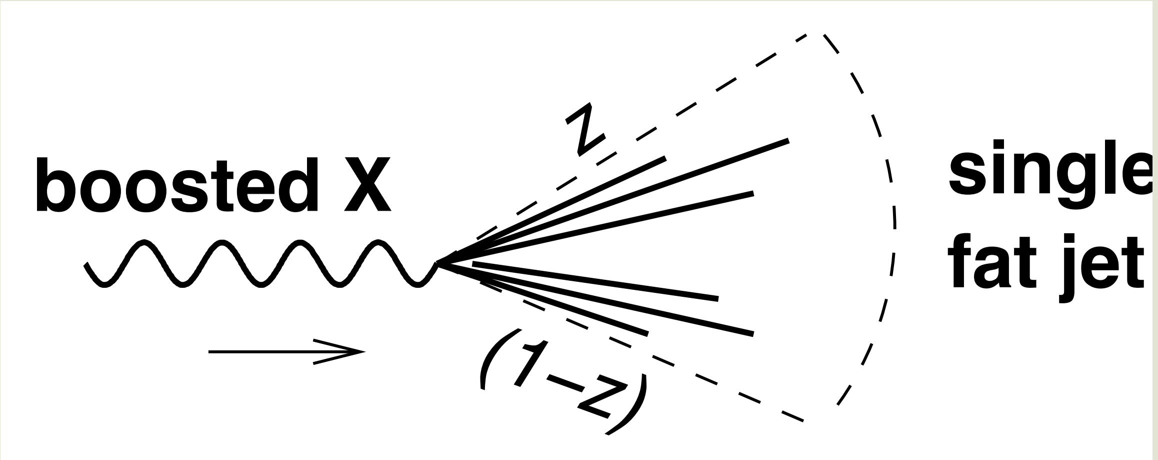
High-p_t regime: EW object X is boosted, decay is collimated, $q\bar{q}$ both in same jet


boosted X
z
(1−z)
single
fat jet

Happens for $p_t \gtrsim 2m/R$

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

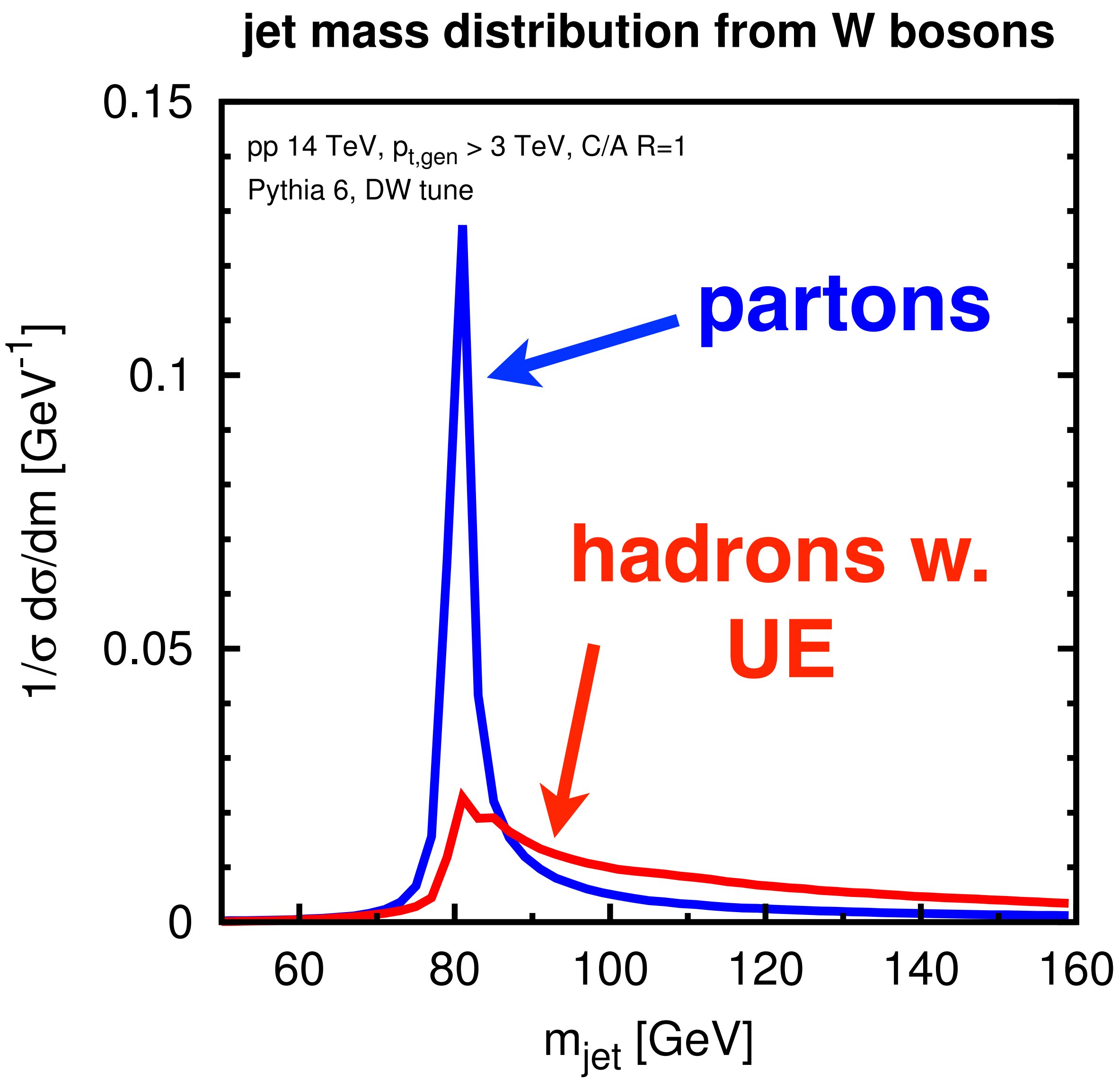
Most obvious way of detecting a boosted decay is through the mass of the jet


boosted X
z
(1−z)
single fat jet

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

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

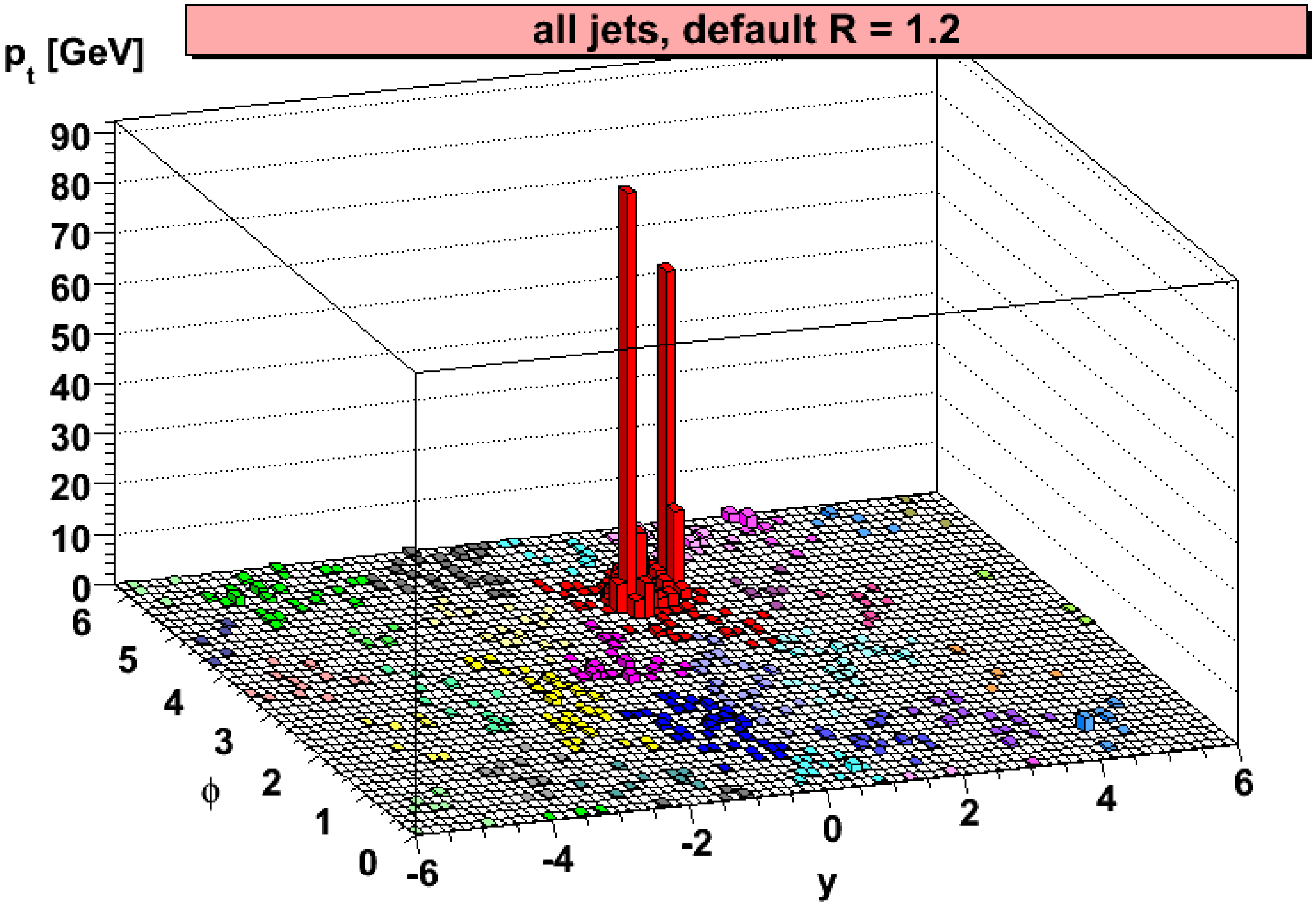
(mainly underlying event/ pileup)



$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @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

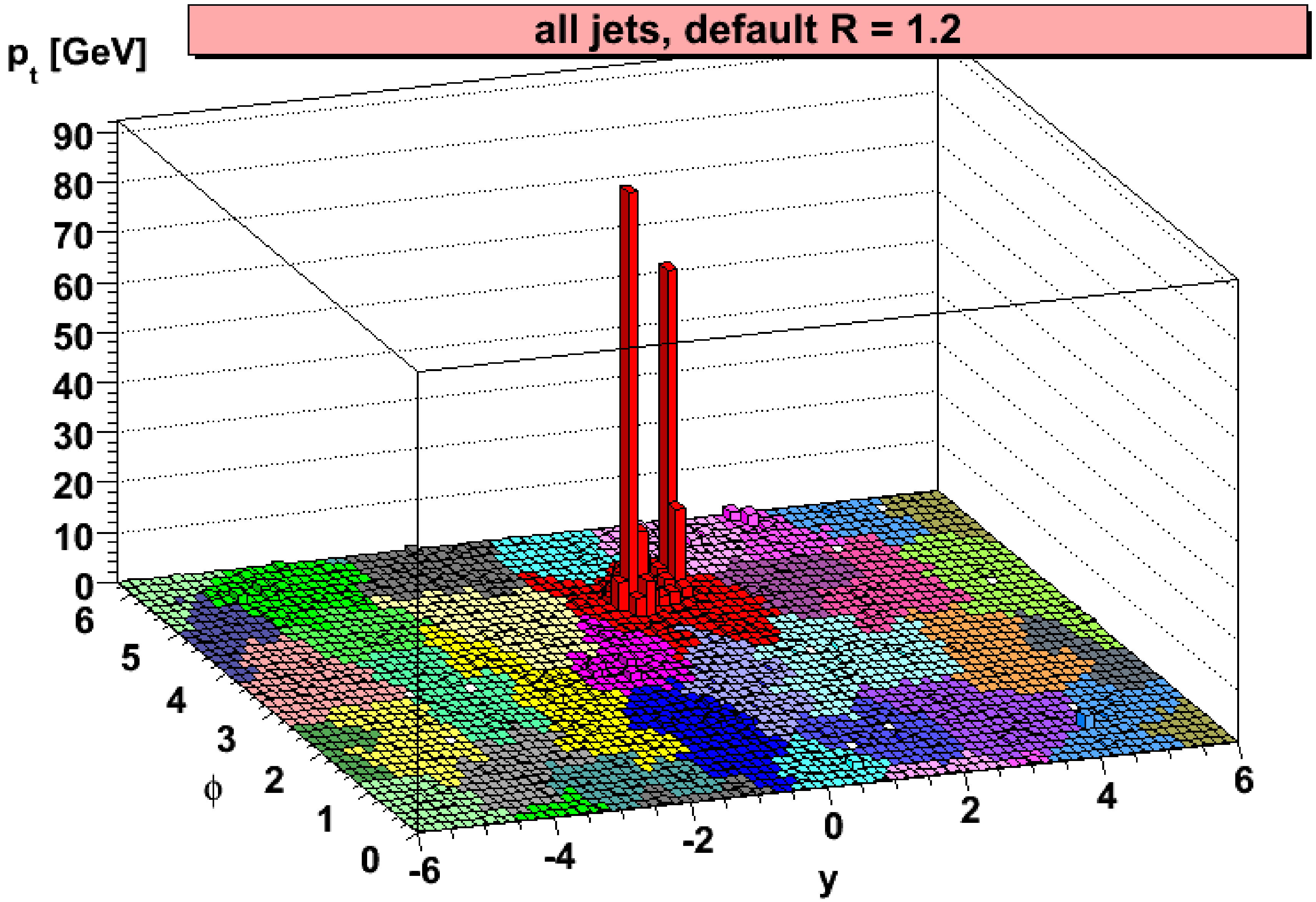
Butterworth, Davison, Rubin & GPS '08

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

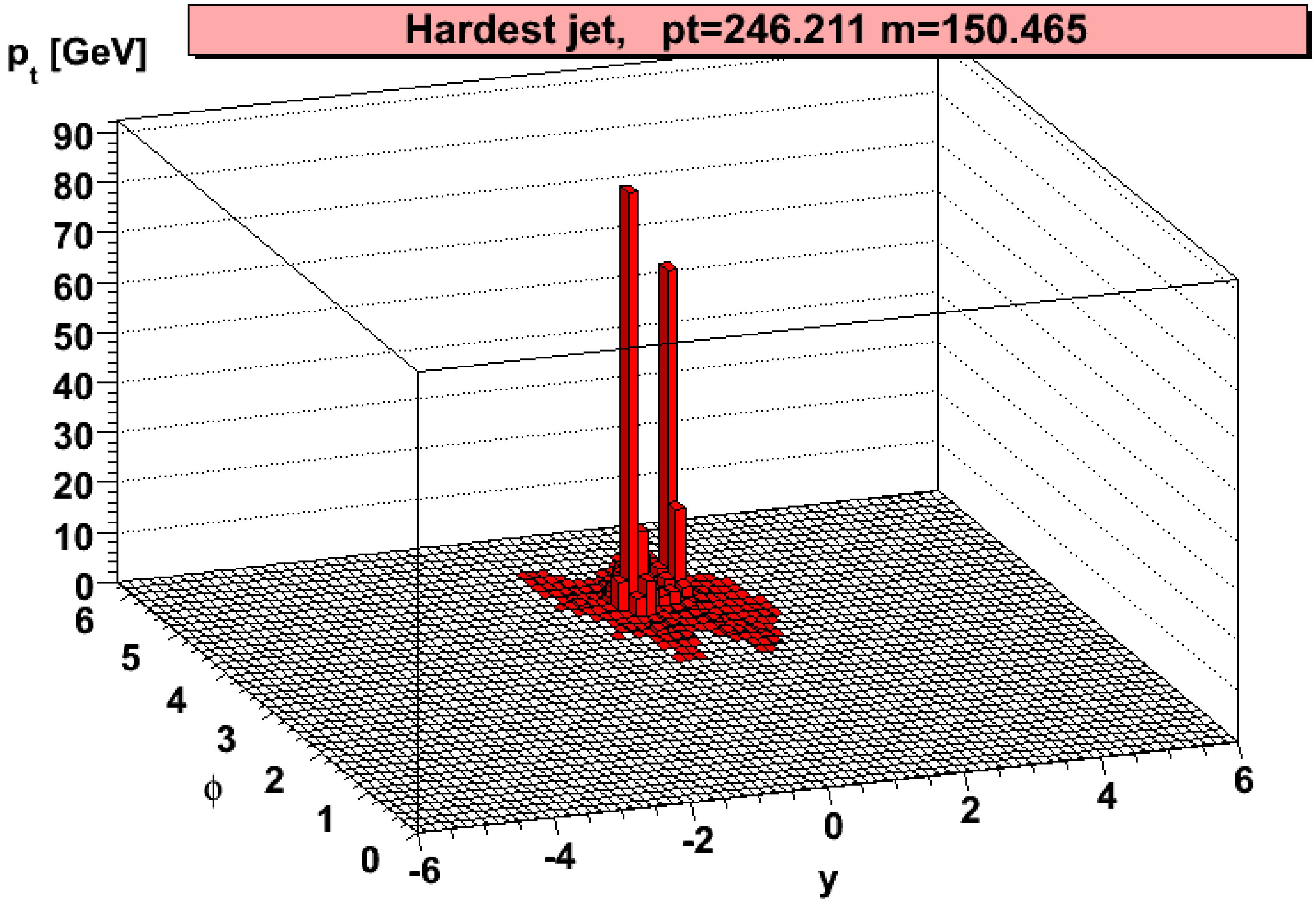
Fill it in, → show jets more clearly

Butterworth, Davison, Rubin & GPS '08

arbitrary norm.

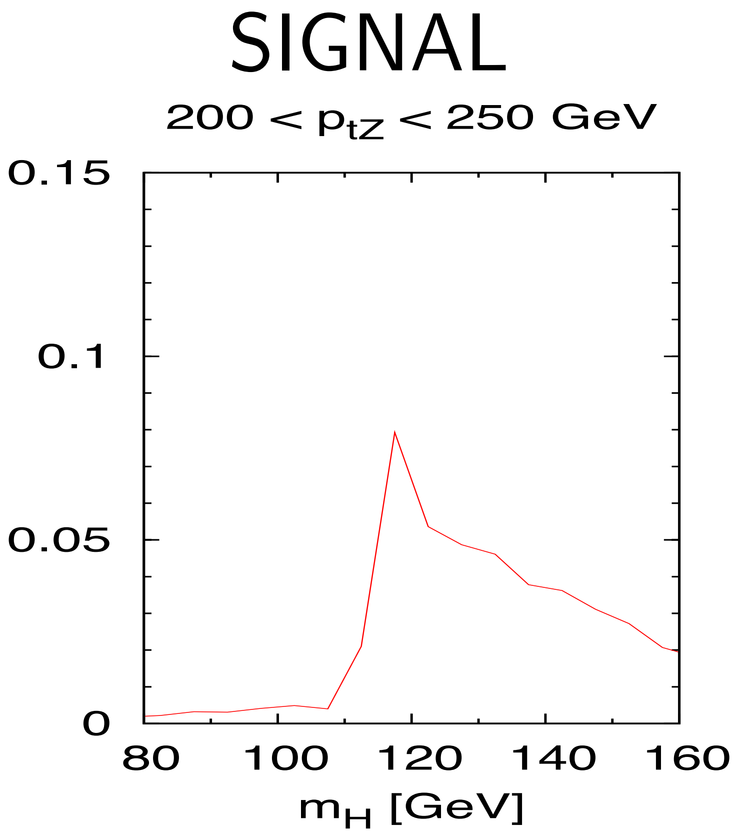
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

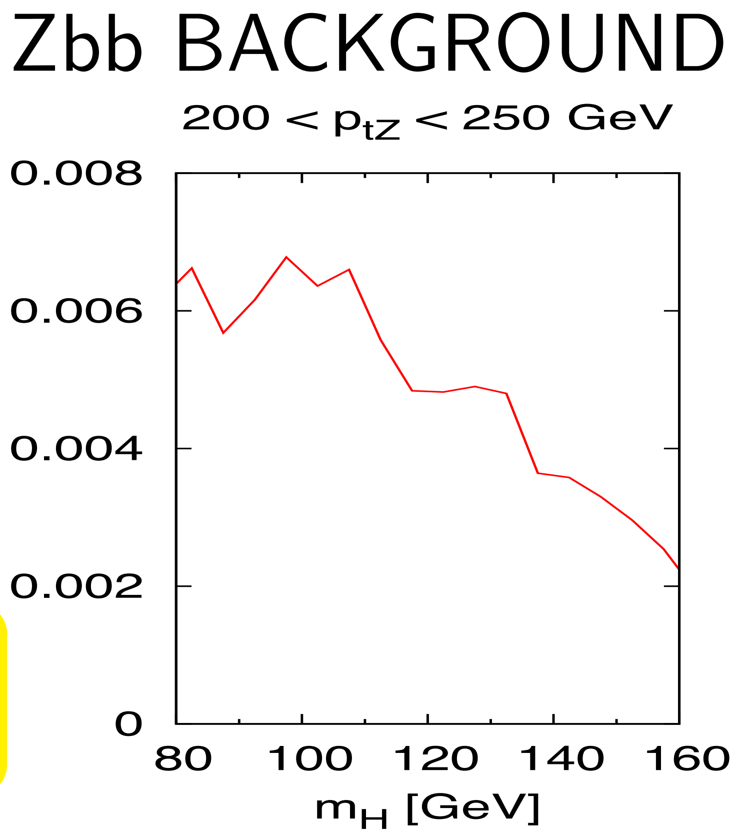
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



Consider hardest jet, $m = 150$ GeV

Butterworth, Davison, Rubin & GPS '08





arbitrary norm.

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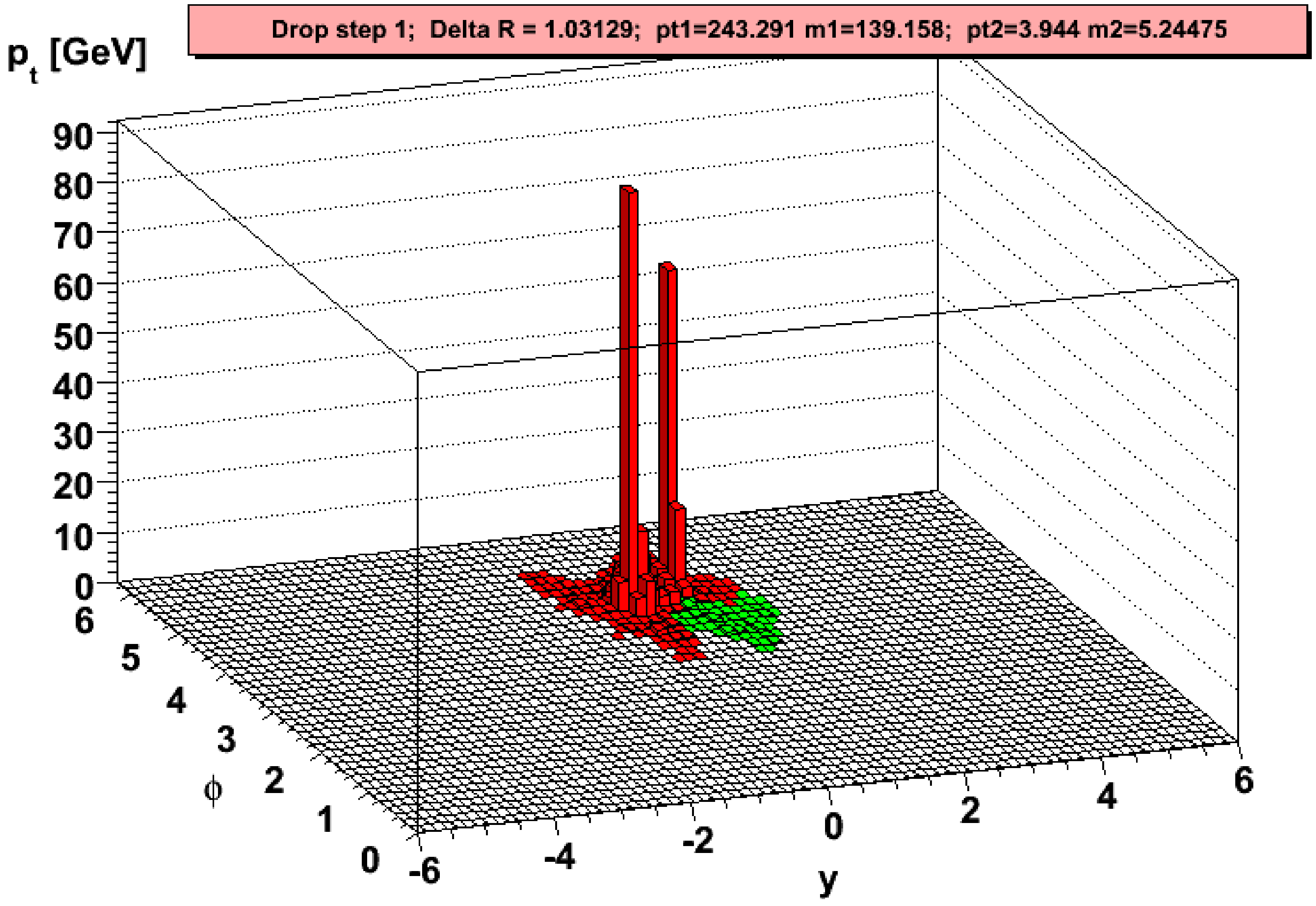
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

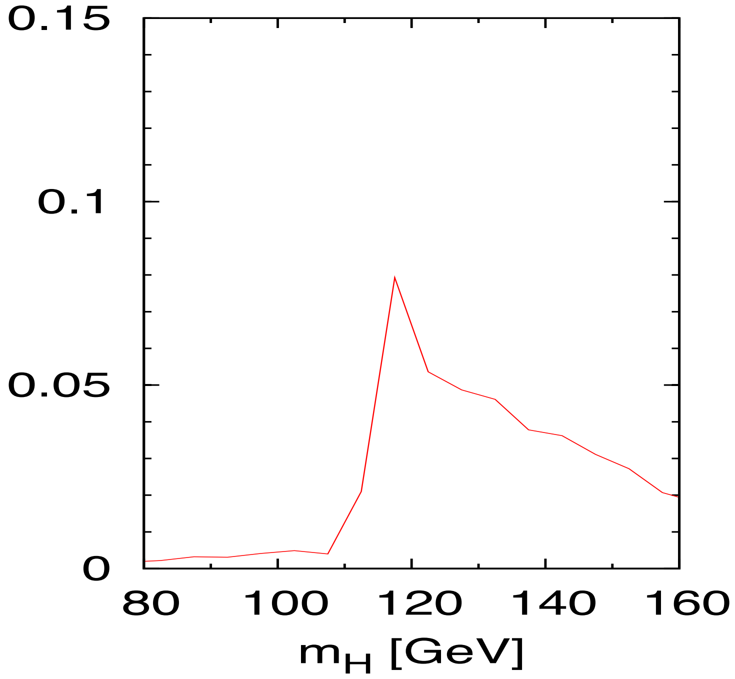


split: $m = 150$ GeV, $\frac{\max(m_1,m2)}{m} = 0.92 \to$ repeat

Butterworth, Davison, Rubin & GPS '08

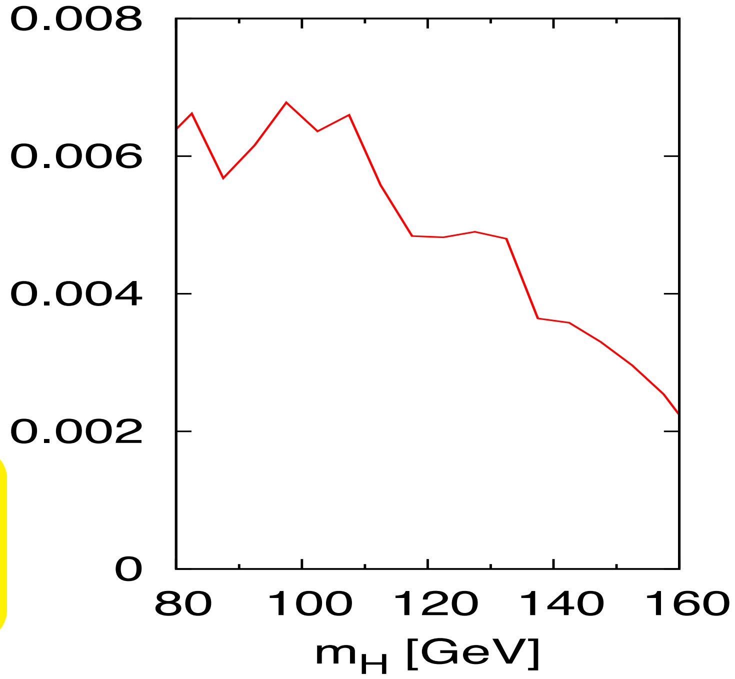
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

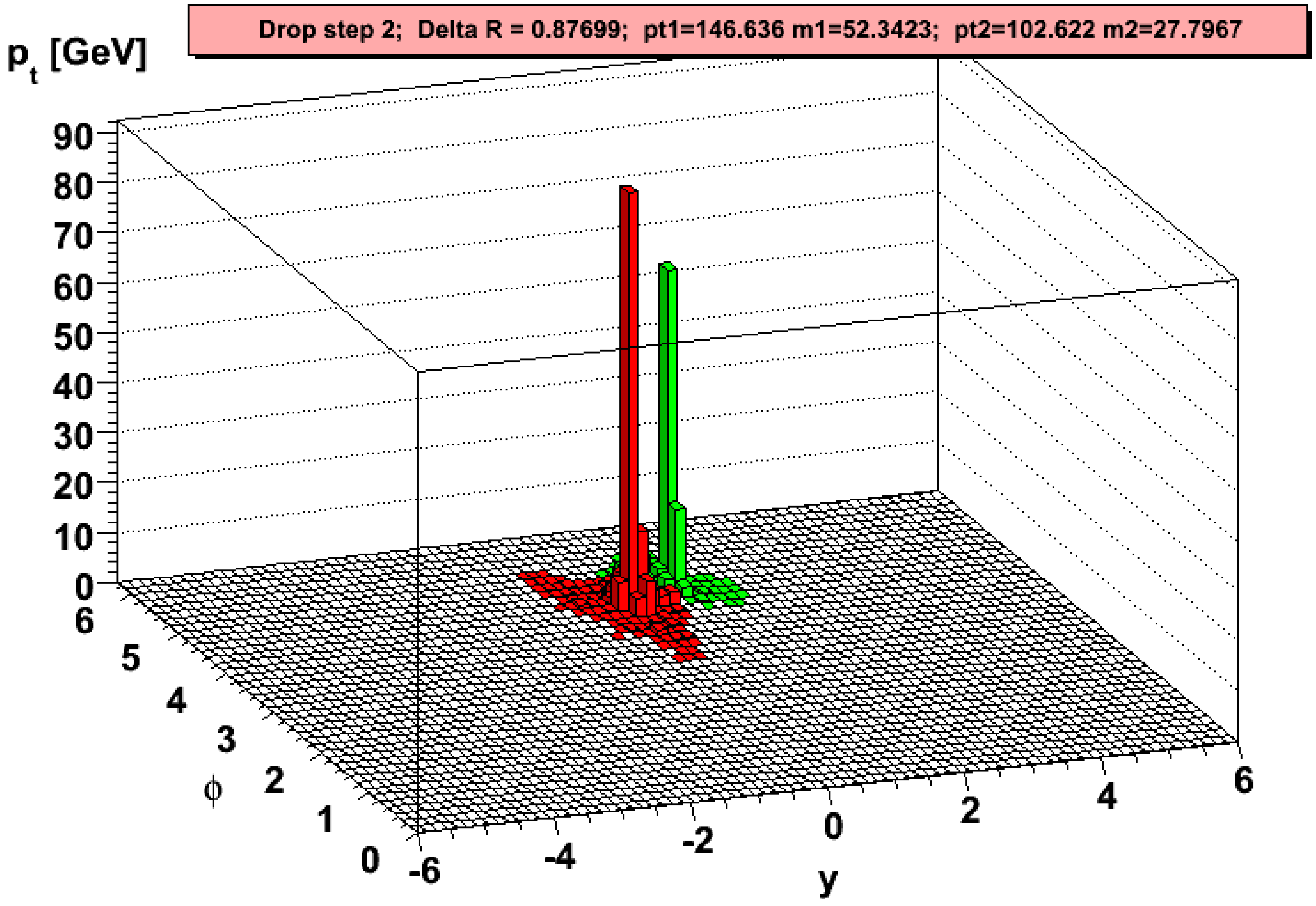
$200 < p_{tZ} < 250$ GeV



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

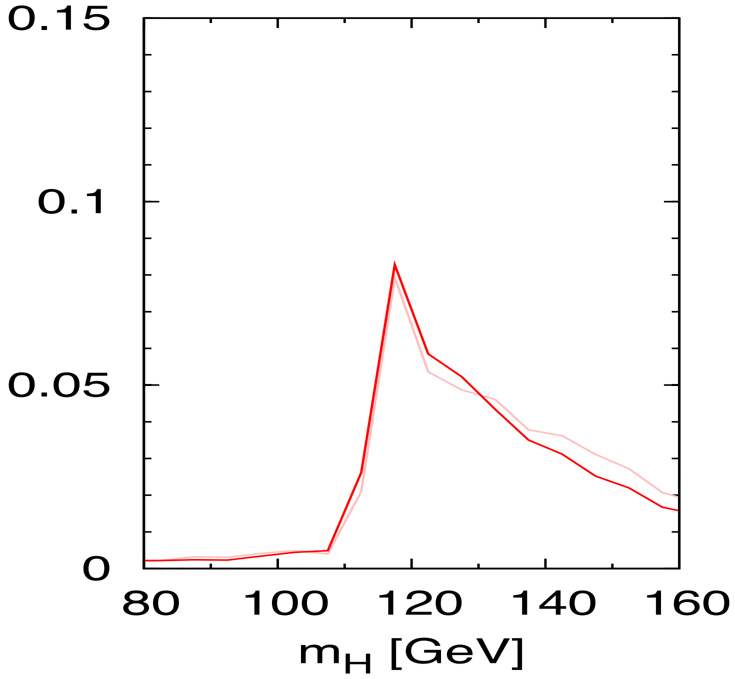


split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

Butterworth, Davison, Rubin & GPS '08

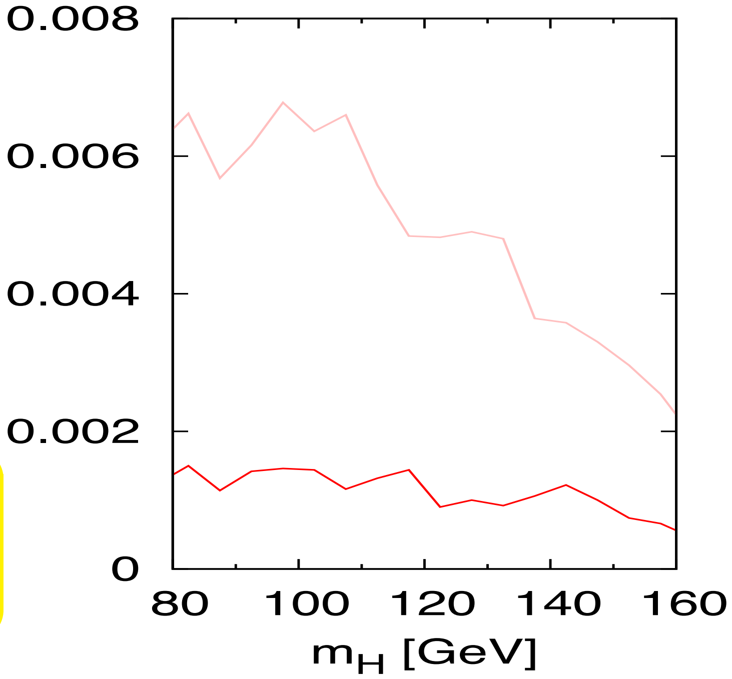
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

$200 < p_{tZ} < 250$ GeV



arbitrary norm.

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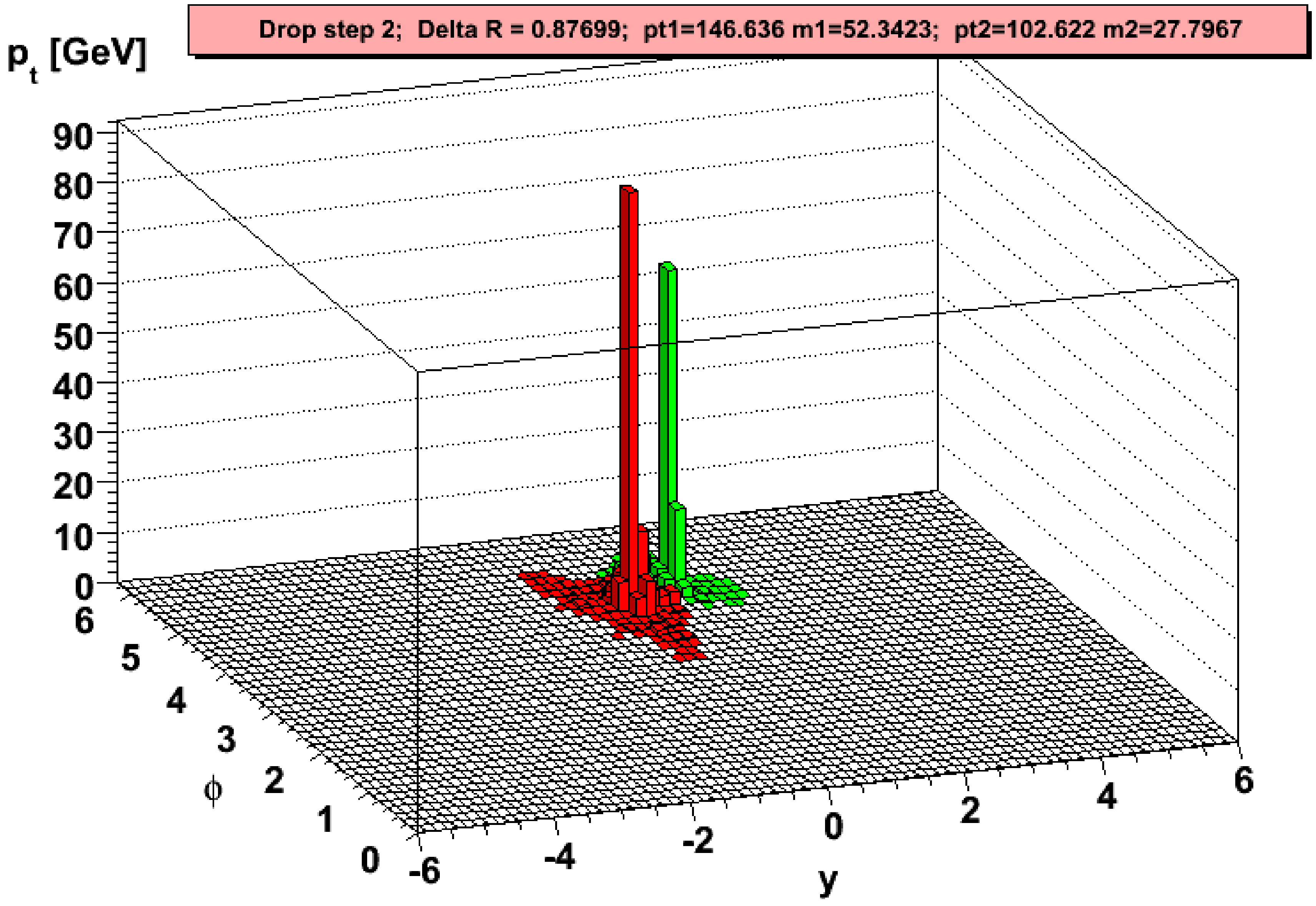
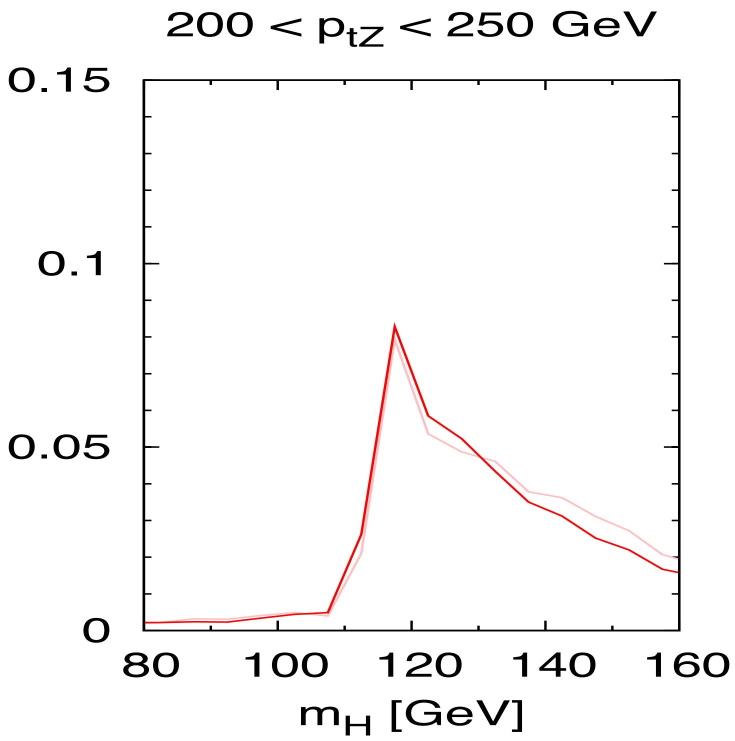
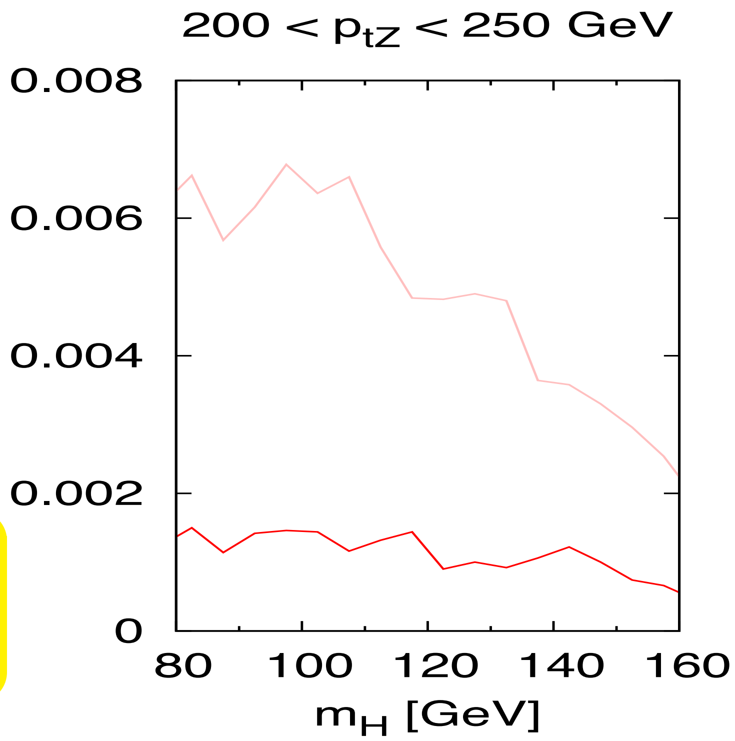


SIGNAL



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.

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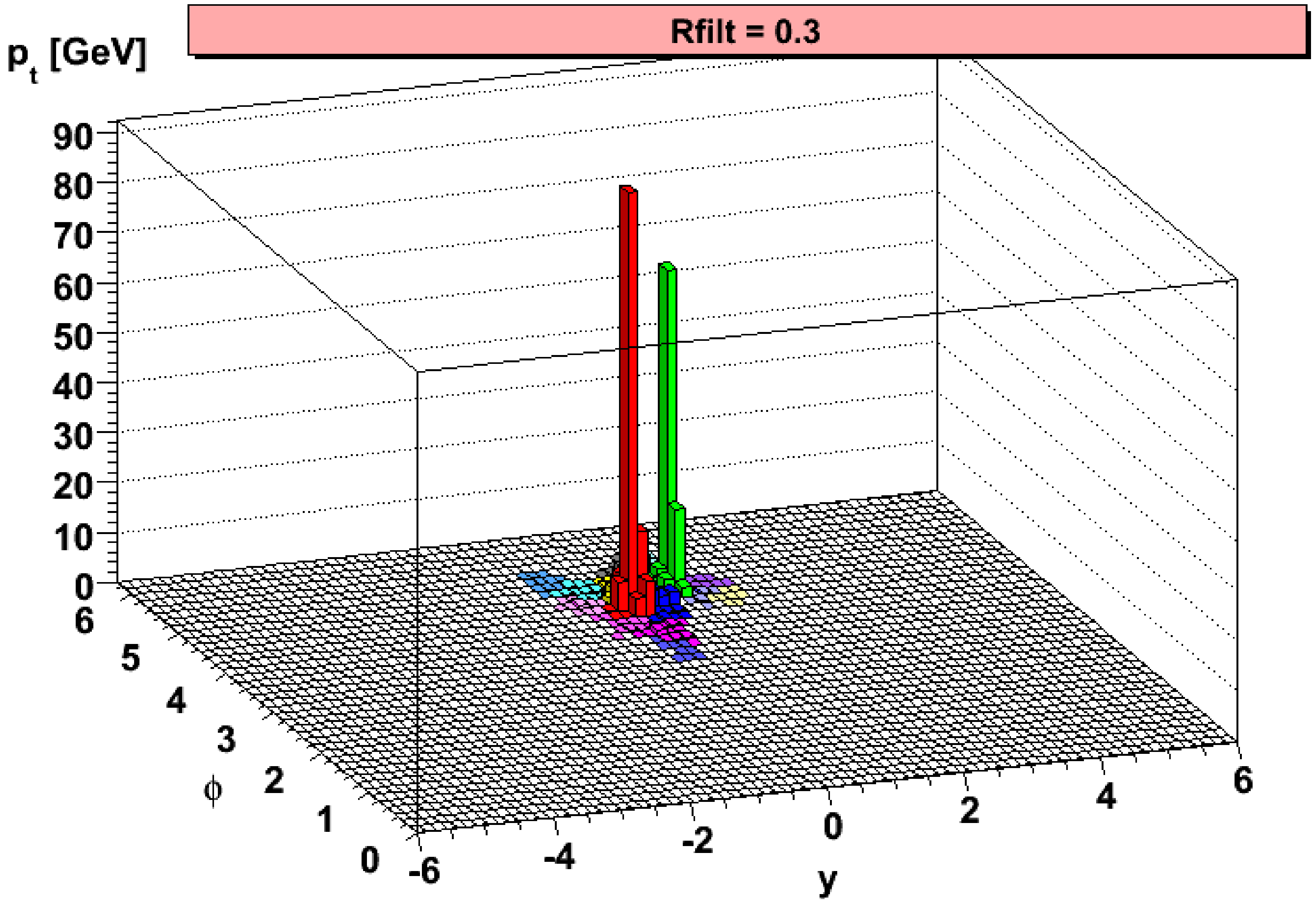
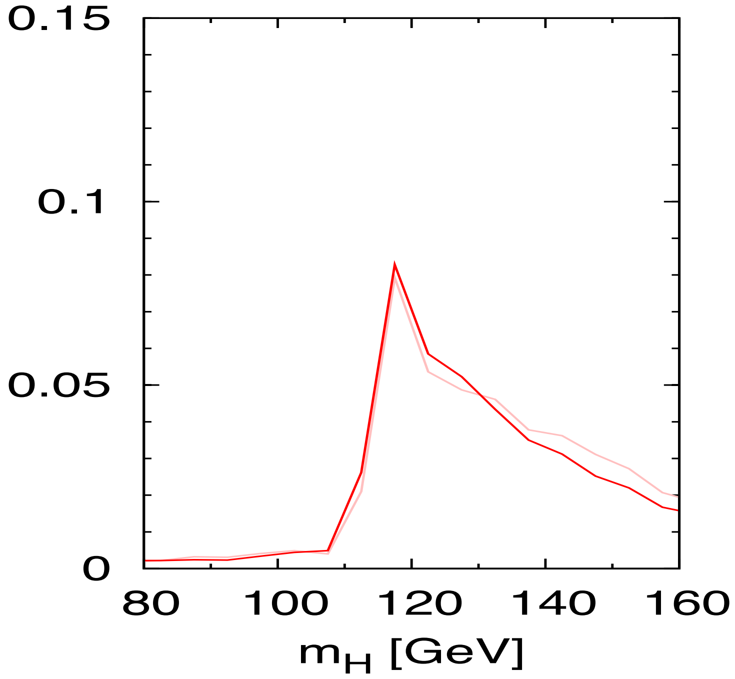
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



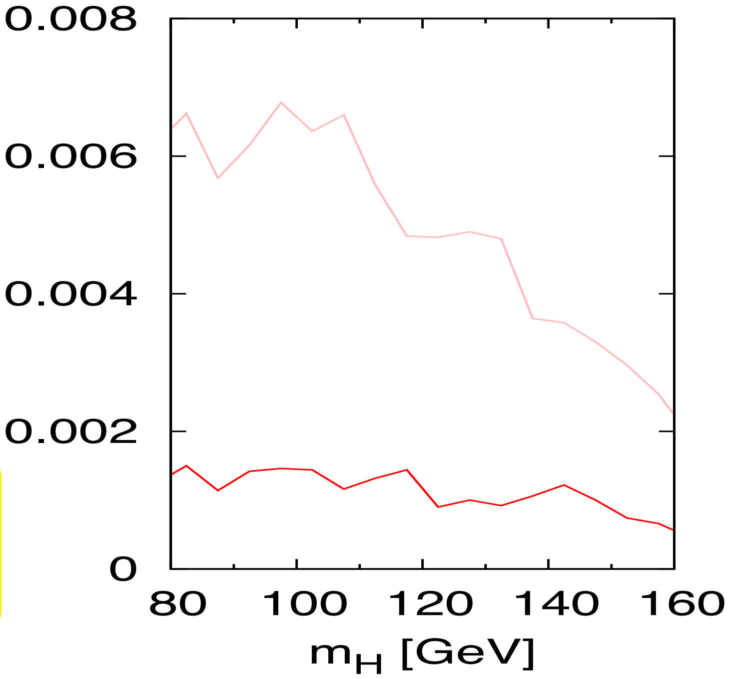
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

$200 < p_{tZ} < 250$ GeV



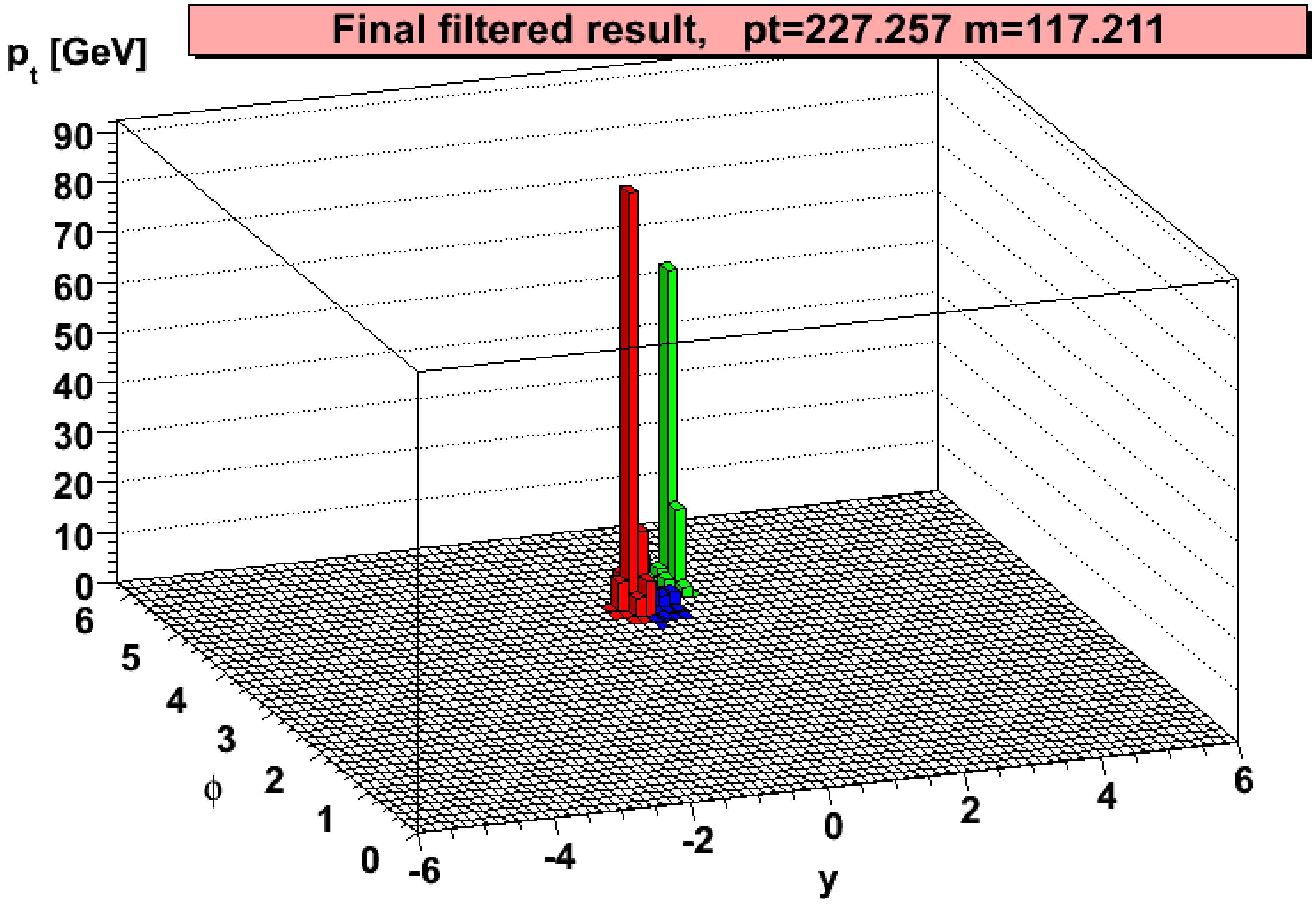
$R_{filt} = 0.3$

Butterworth, Davison, Rubin & GPS '08

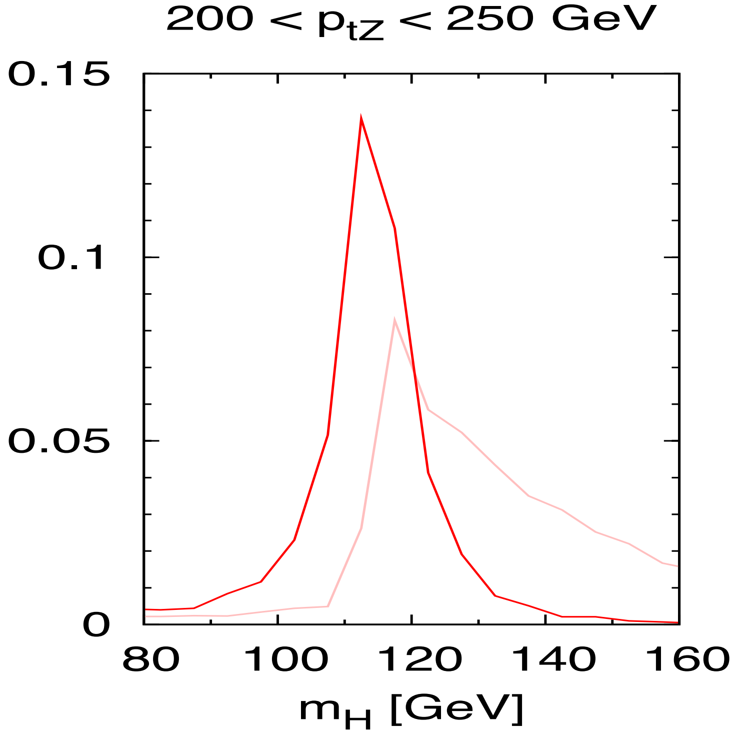
arbitrary norm.

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

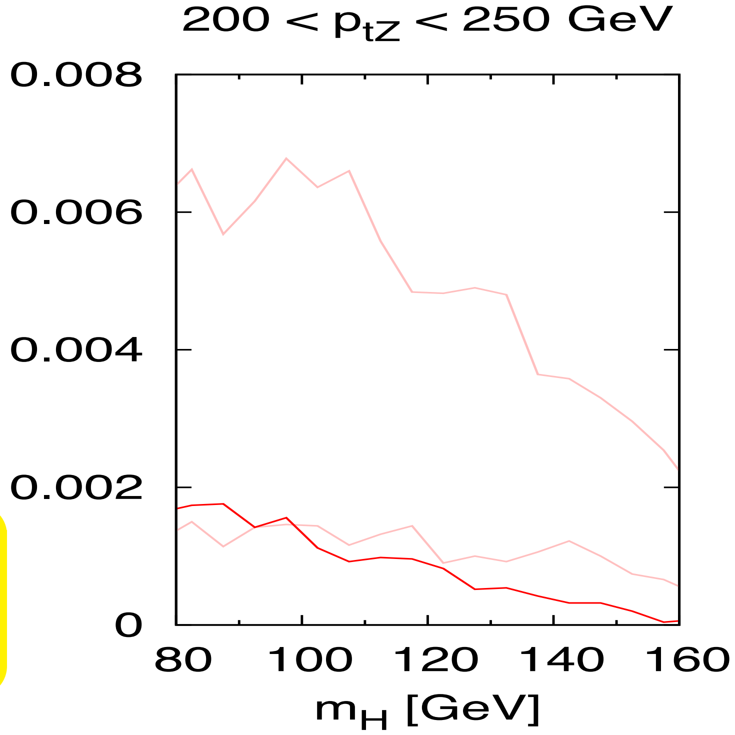
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND



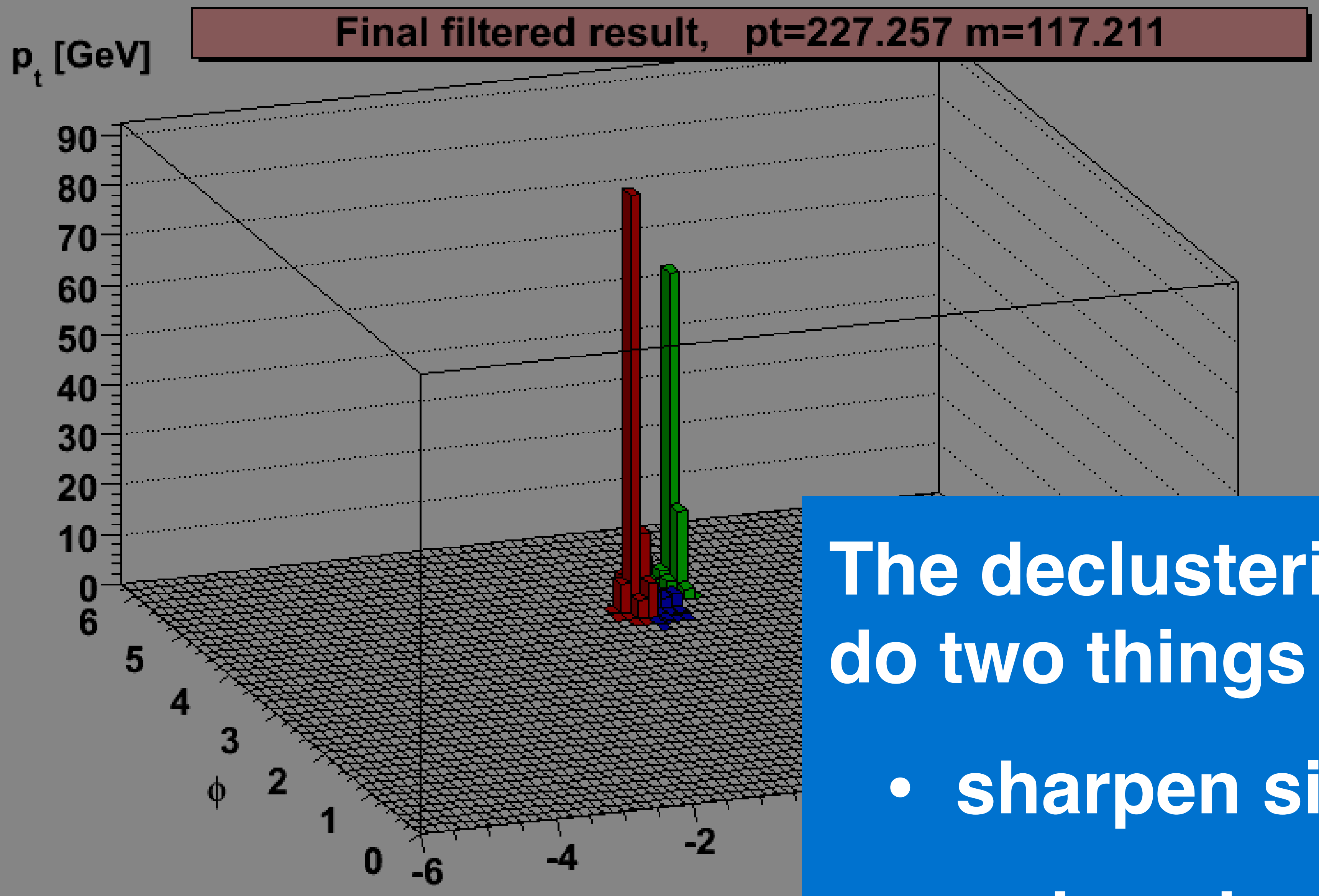
$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

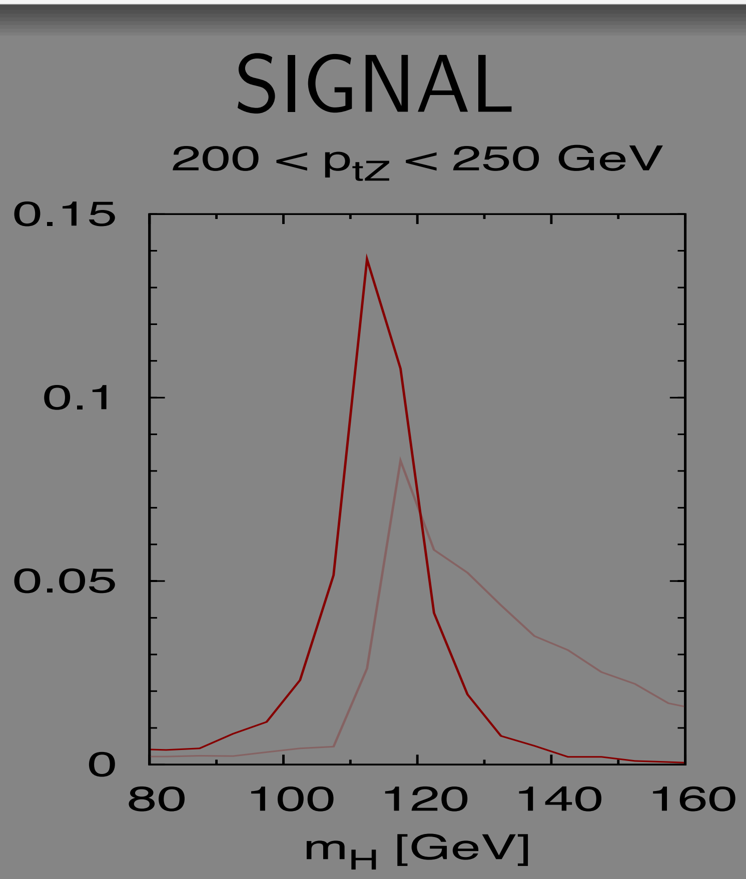
Butterworth, Davison, Rubin & GPS '08

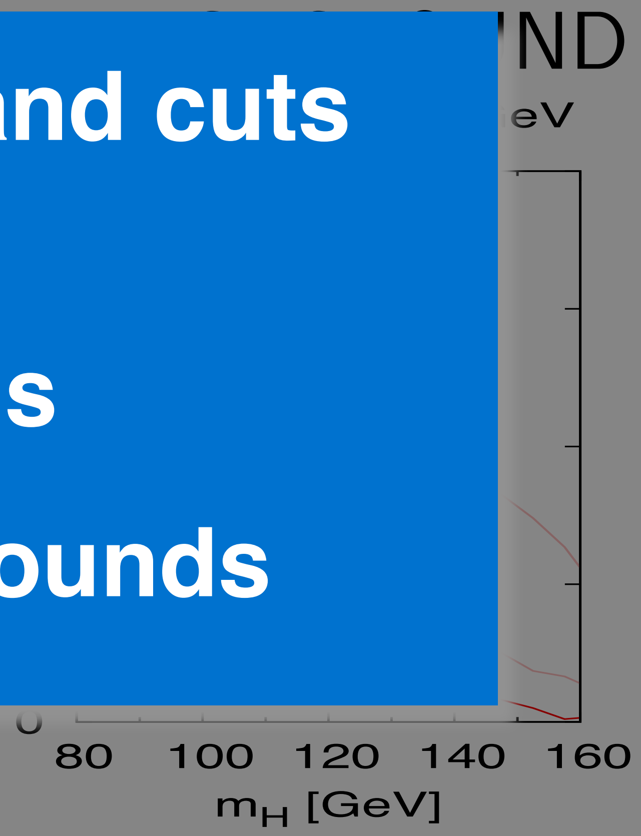
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @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**

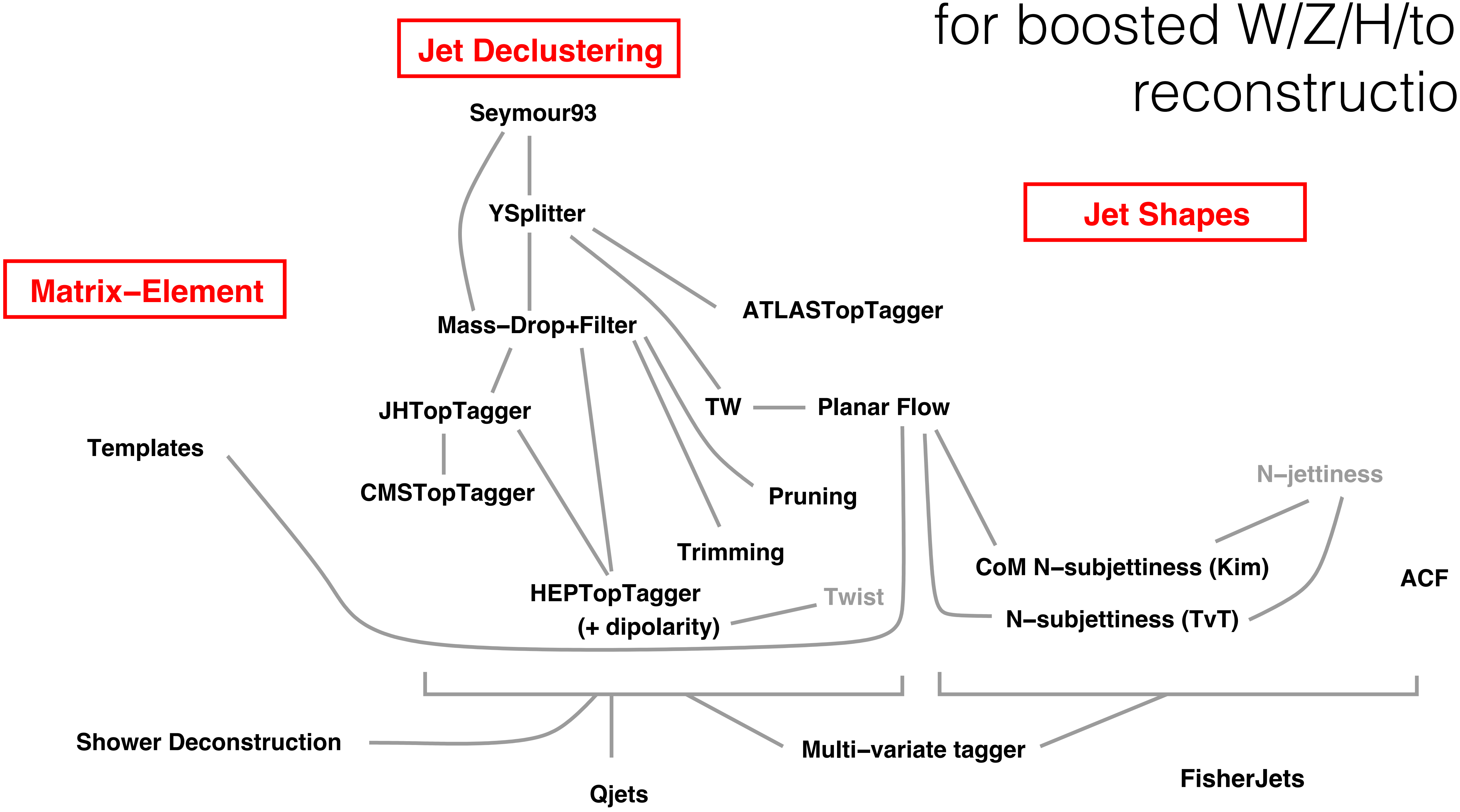
$R_{filt} = 0.3$: take 3 hardest, **m =**

Butterworth, Davison, Rubin & GPS ’08

arbitrary norm.

Very active research field

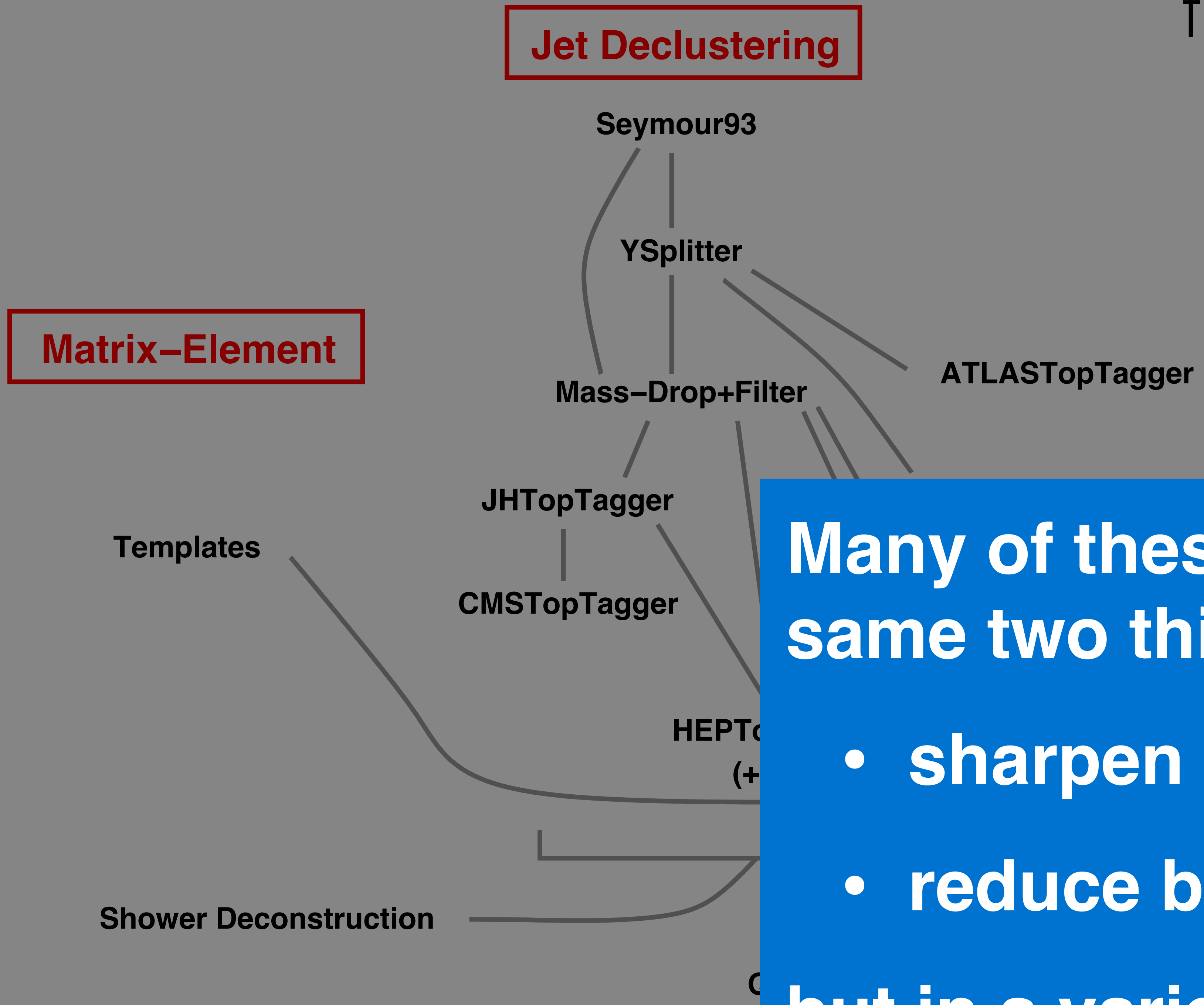
Some of the tools developed
for boosted W/Z/H/top
reconstruction


Jet Declustering
Seymour93
YSplitter
Jet Shapes
Matrix–Element
ATLASTopTagger
Mass–Drop+Filter
JHTopTagger
TW
Planar Flow
Templates
CMSTopTagger
Pruning
N–jettiness
Trimming
CoM N–subjettiness (Kim)
ACF
HEPTopTagger
(+ dipolarity)
Twist
N–subjettiness (TvT)
Shower Deconstruction
Multi–variate tagger
Qjets
FisherJets

apologies for omitted taggers, arguable links, etc.

Very active research field

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



Jet Declustering

Seymour93

YSplitter

ATLASTopTagger

Mass–Drop+Filter

JHTopTagger

CMSTopTagger

HEPT

(+

Matrix–Element

Templates

Shower Deconstruction

C

Jet Shapes

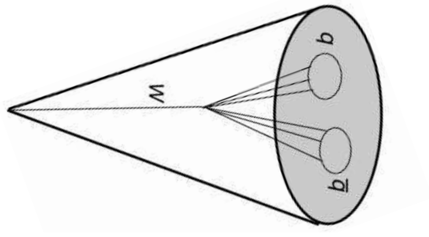
Many of these methods do the same two things:

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

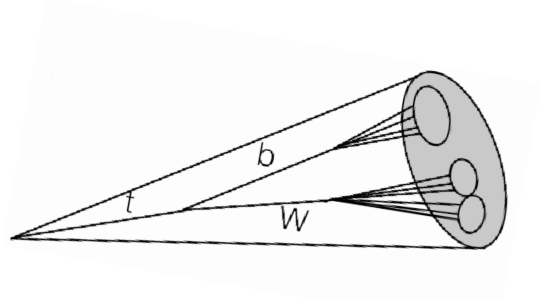
but in a variety of ways

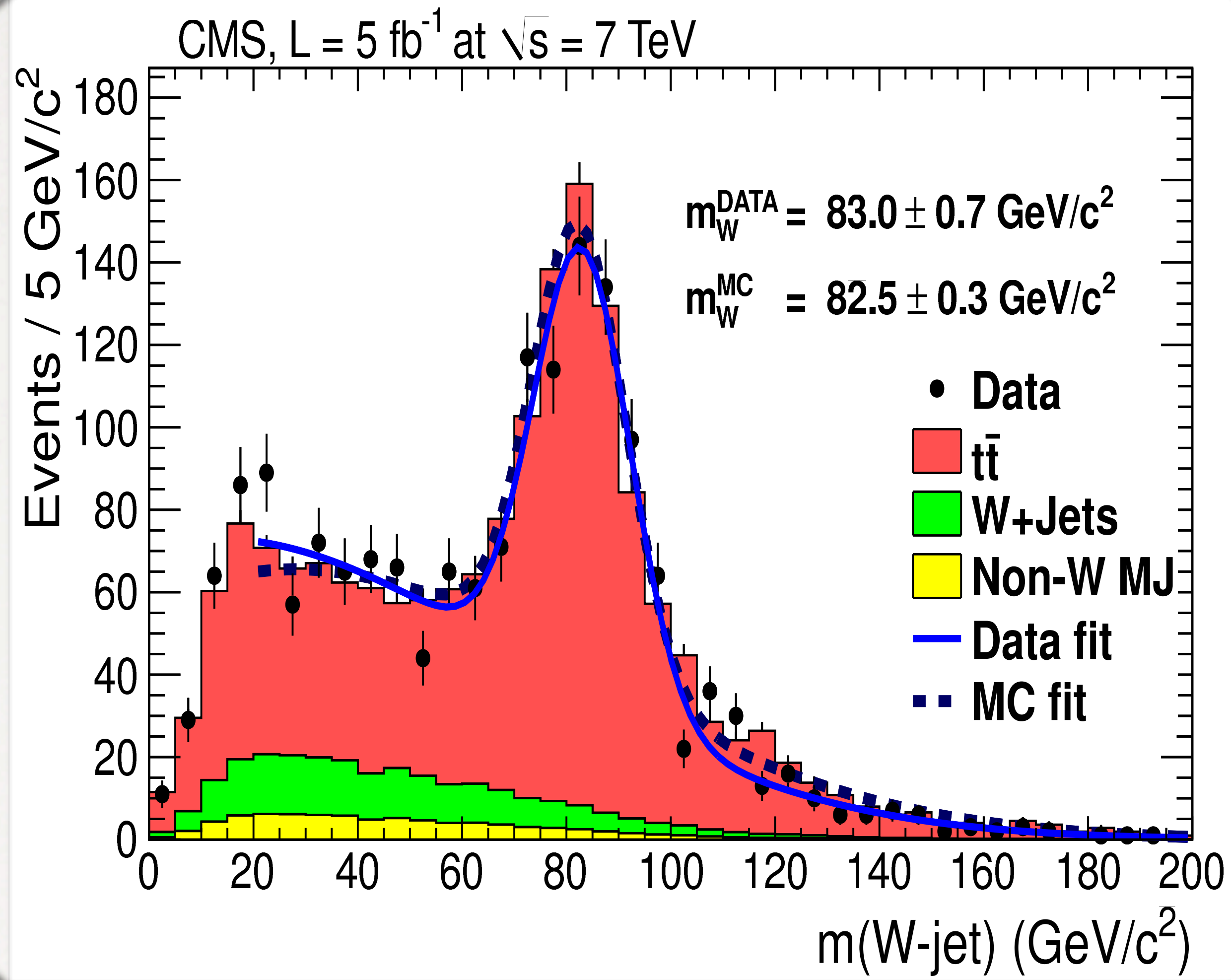
Seeing hadronic W's and tops in a single jet

W's in a single jet

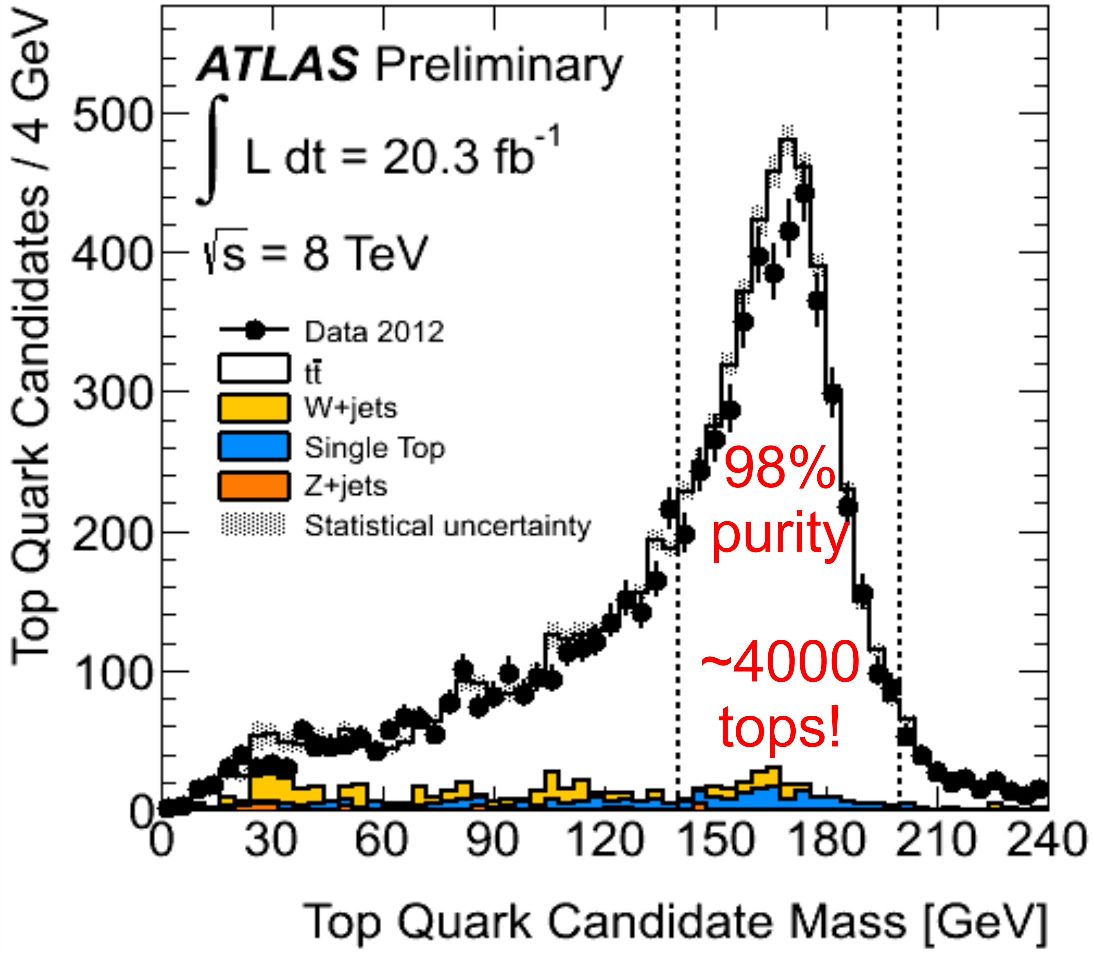


tops in a single jet





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



98% purity

~4000 tops!

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

Extensive experimental work

Last 12 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]

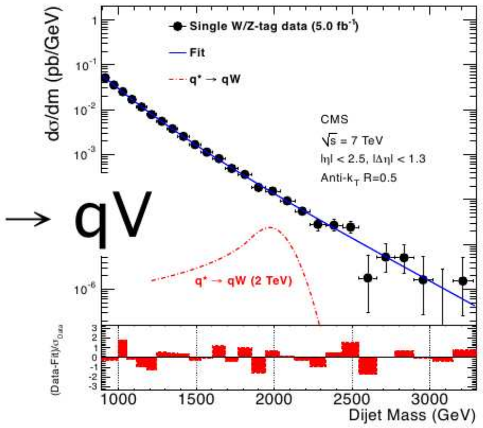
Search for the SM Higgs Boson Produced in Association with a Vector Boson and Decaying to Bottom Quarks
for the CMS Collaboration
Inspire. arXiv:1310.3551 (ps, pdf).

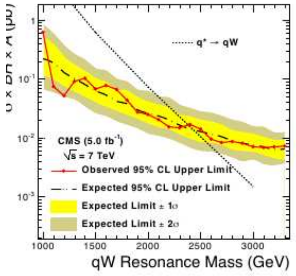
Inclusive search for a vector-like T quark with charge 2/3 in pp collisions at $\sqrt{s}$=8 TeV
CMS Collaboration
Inspire. arXiv:1311.7667 (ps, pdf).

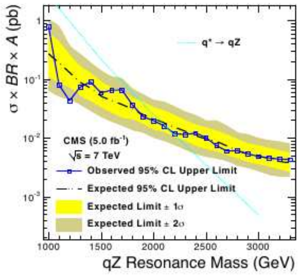
Search for top-quark partners with charge 5/3 in the same-sign dilepton final state
CMS Collaboration
Inspire. arXiv:1312.2391 (ps, pdf).

Searches with substructure tools

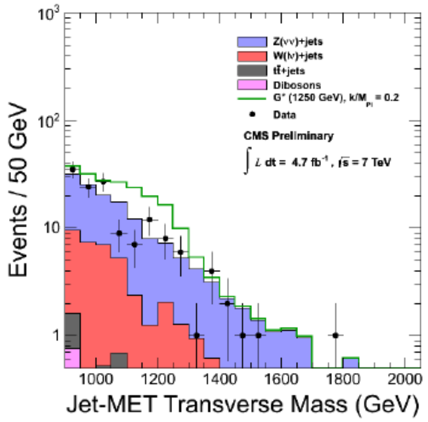
X → qV

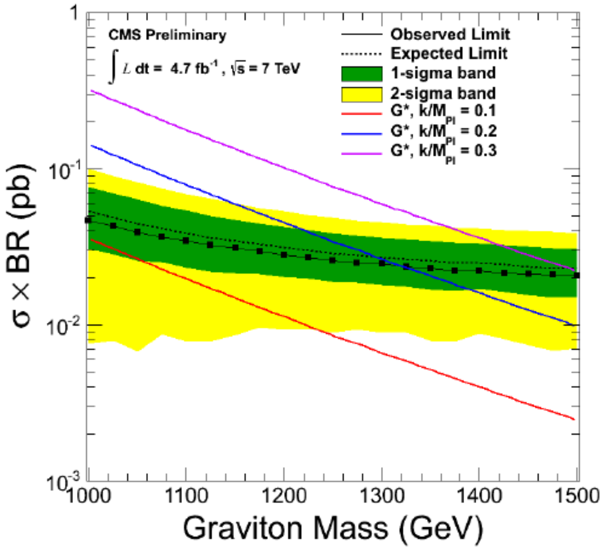


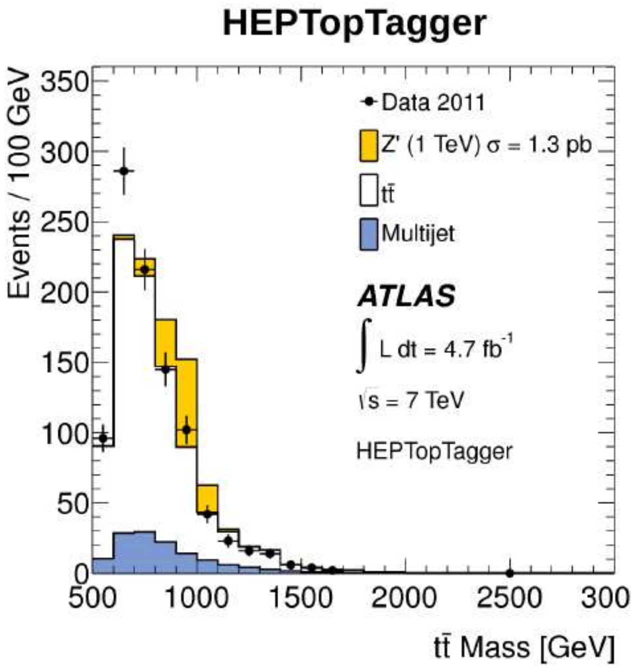


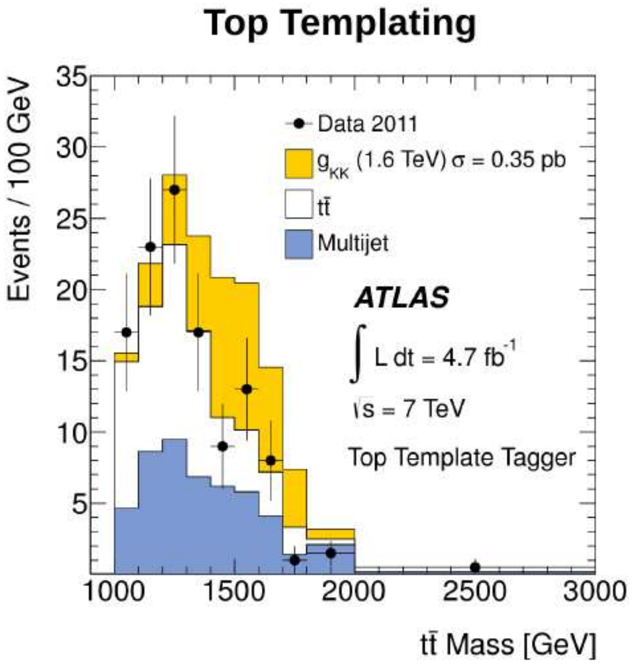


X → ZZ → 2ν2q

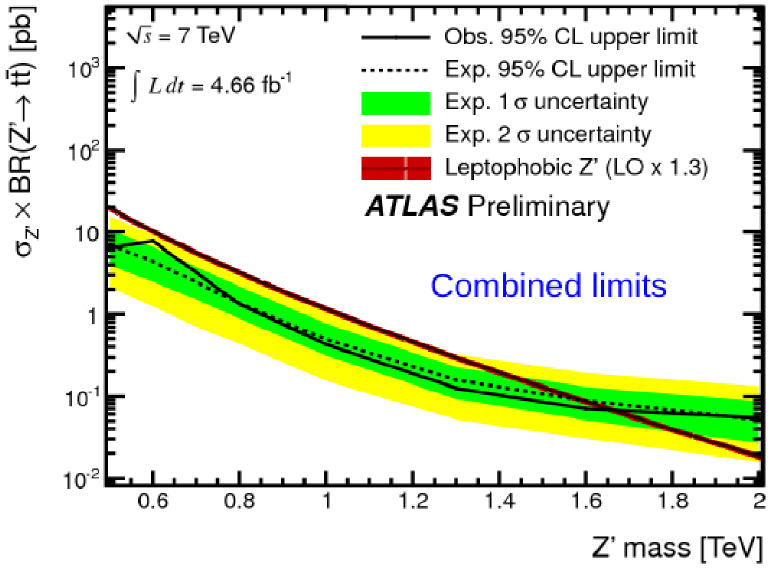








ATLAS-CONF-2012-136



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:

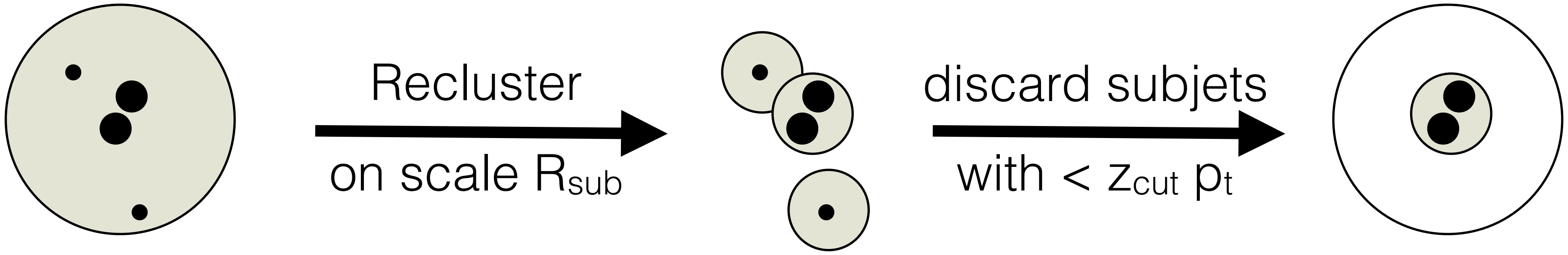
(a) they have the richest structure.

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

study 3 taggers/groomers

Cannot possibly study all tools
These 3 are widely used

Trimming



Recluster

on scale R_{sub}

discard subjets

with < z_{cut} p_t

study 3 taggers/groomers

Cannot possibly study all tools
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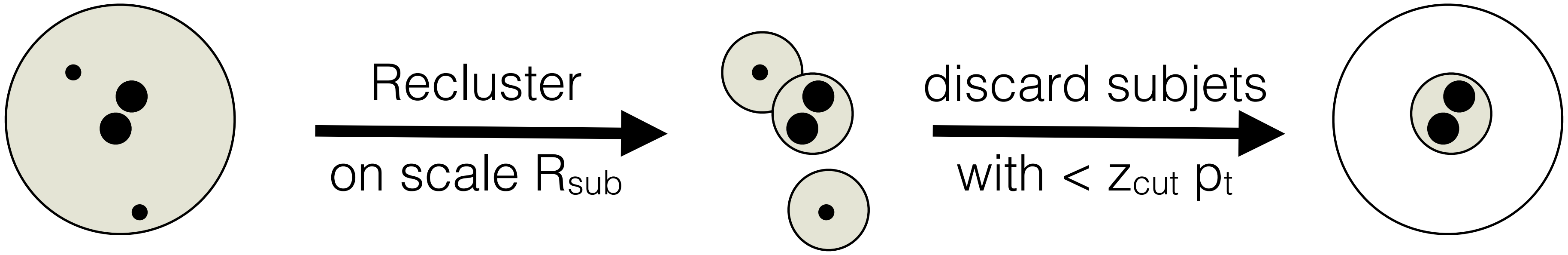
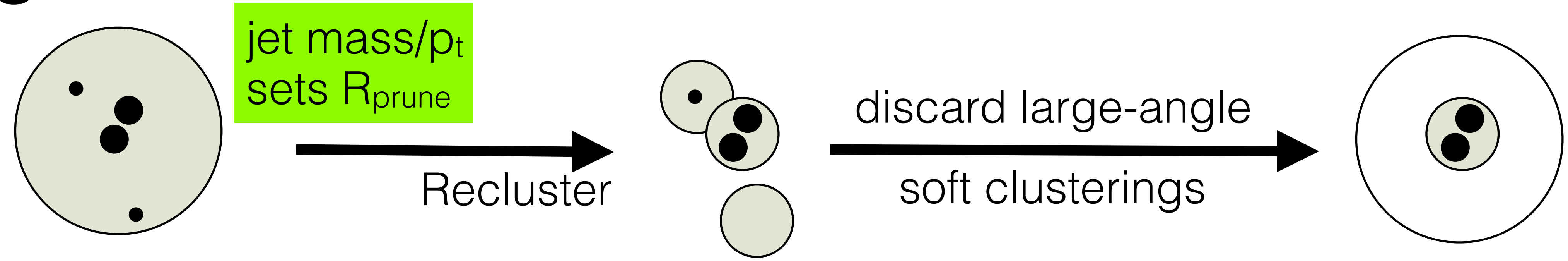
Trimming



Recluster on scale R_{sub}

discard subjets with $< z_{cut}\, p_t$

Pruning



jet mass/p_t sets R_{prune}

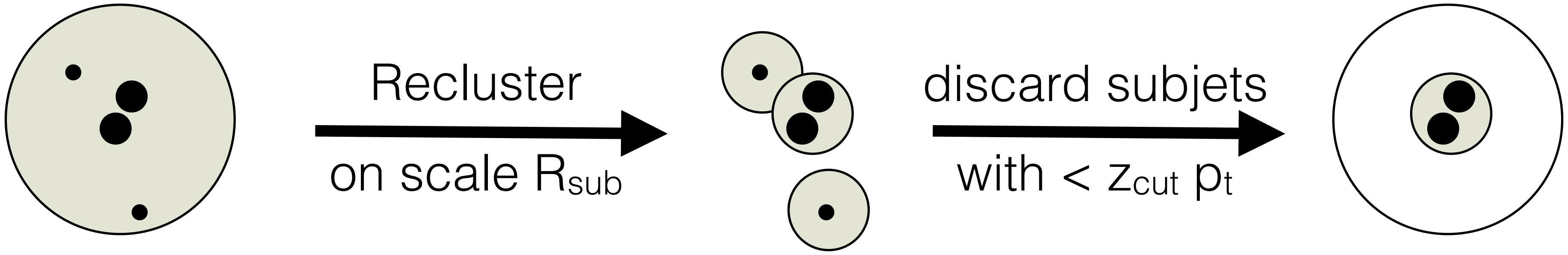
Recluster

discard large-angle soft clusterings

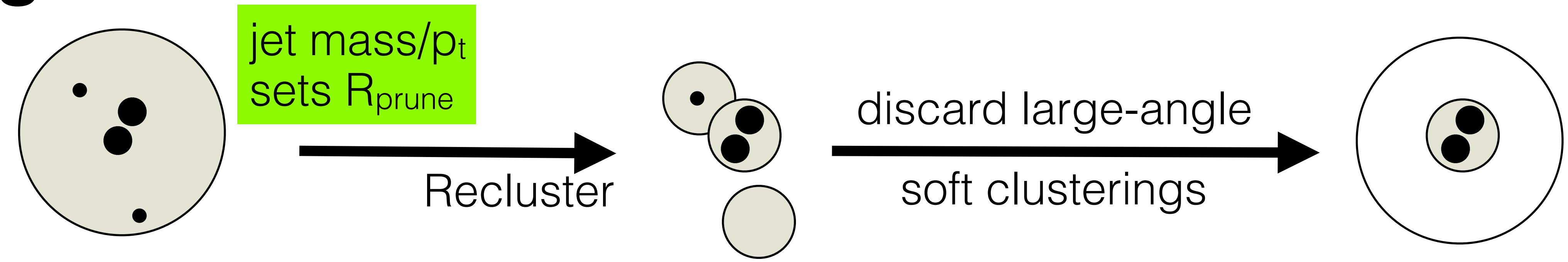
study 3 taggers/groomers

Cannot possibly study all tools
These 3 are widely used

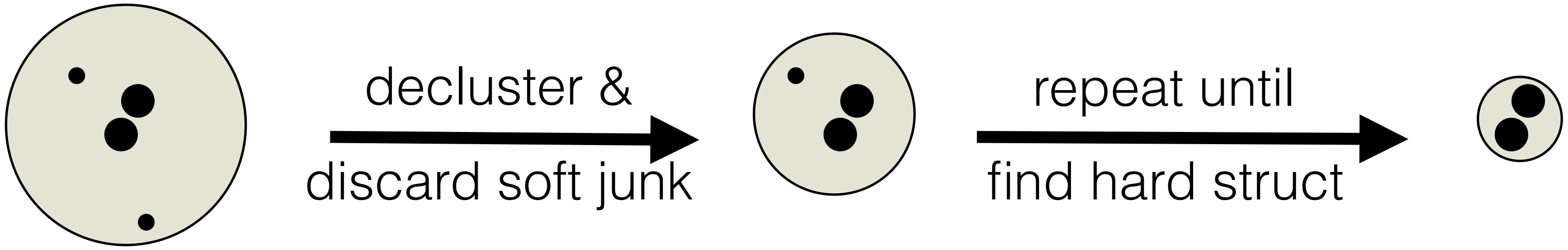
Trimming


Recluster
on scale R_{sub}
discard subjets
with < z_{cut} p_t

Pruning


jet mass/p_t
sets R_{prune}
Recluster
discard large-angle
soft clusterings

Mass-drop tagger (MDT, aka BDRS)


decluster &
discard soft junk
repeat until
find hard struct

The key variables

For phenomenology

Jet mass: *m*

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

For QCD calculations

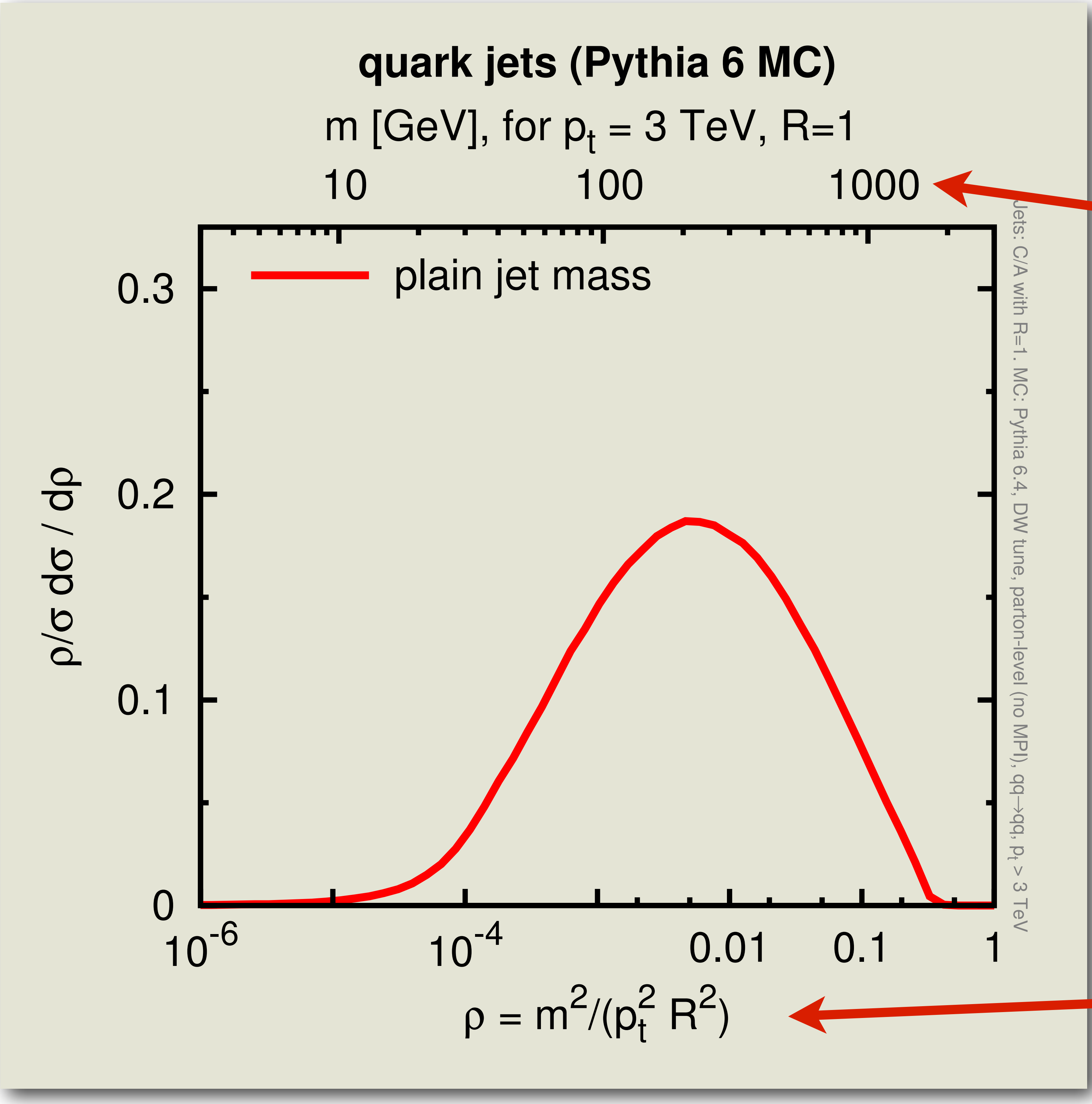
$$\rho = \frac{m^2}{p_t^2 R^2}$$

[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)



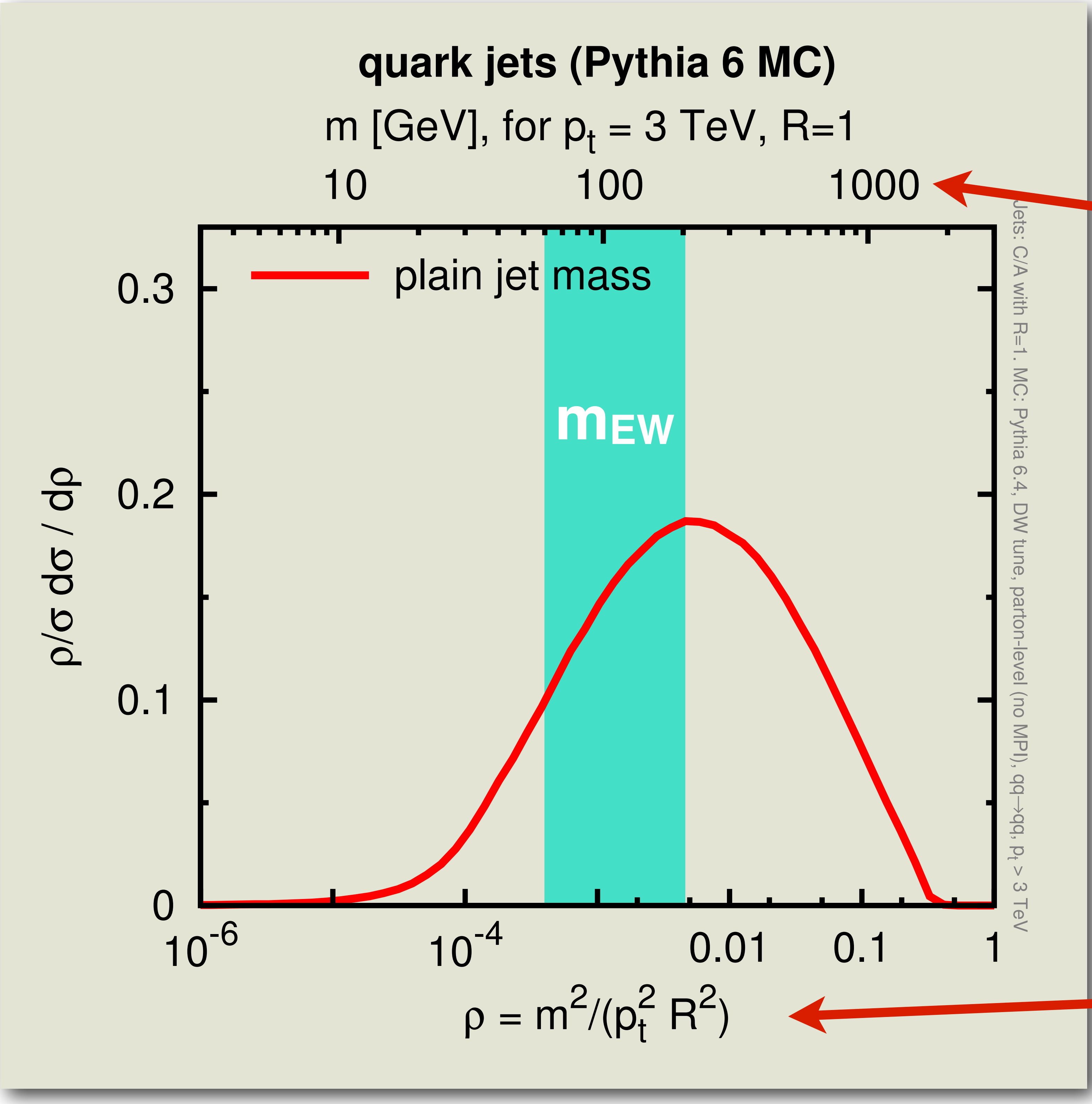
Physical mass for 3 TeV, R=1 jets

ρ ~ Rescaled mass^2

(i.e. the QCD variable)

The “right” MC study can already be instructive

(testing on quark [background] jets)



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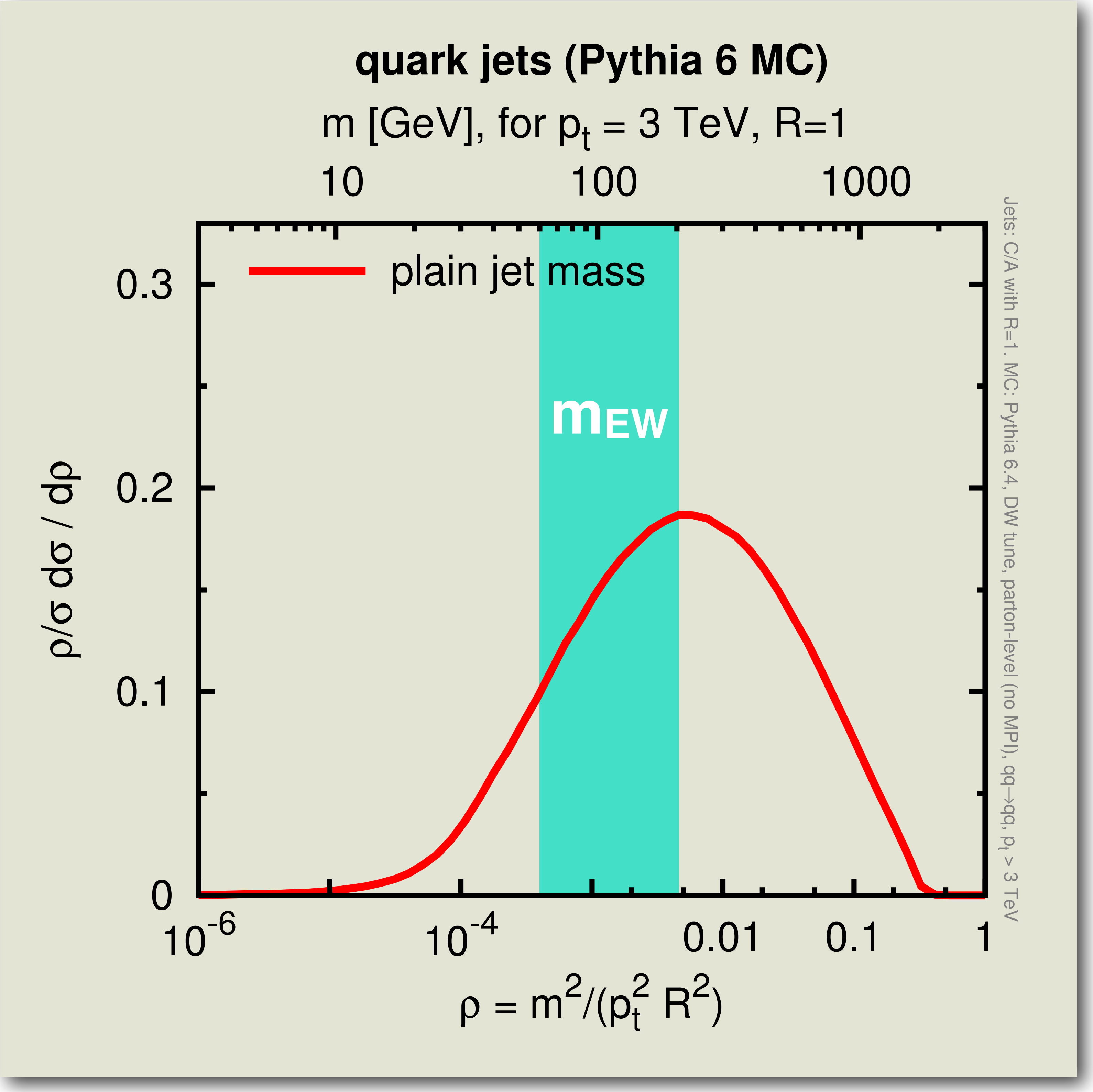
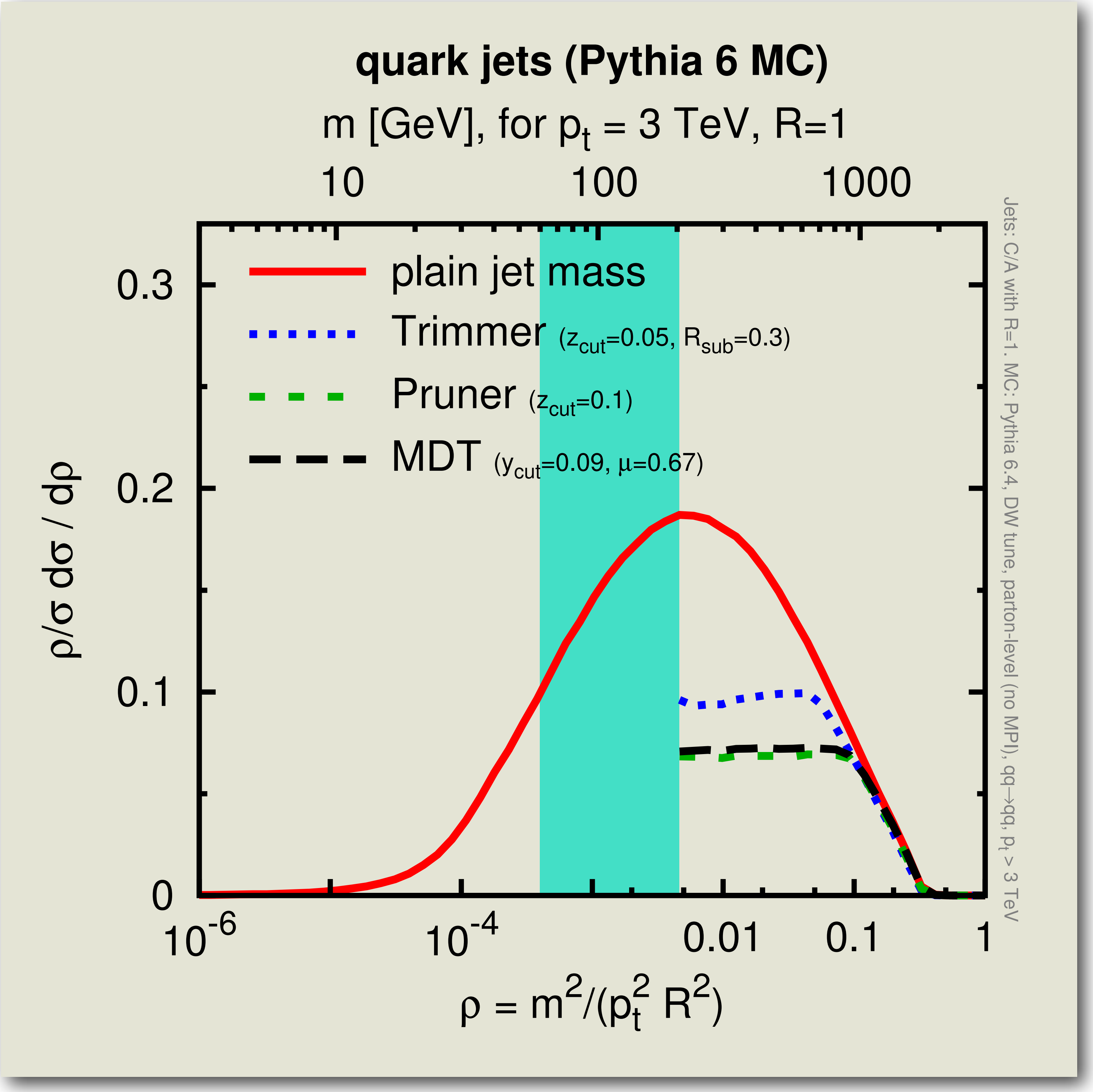


The "right" MC study can already be instructive

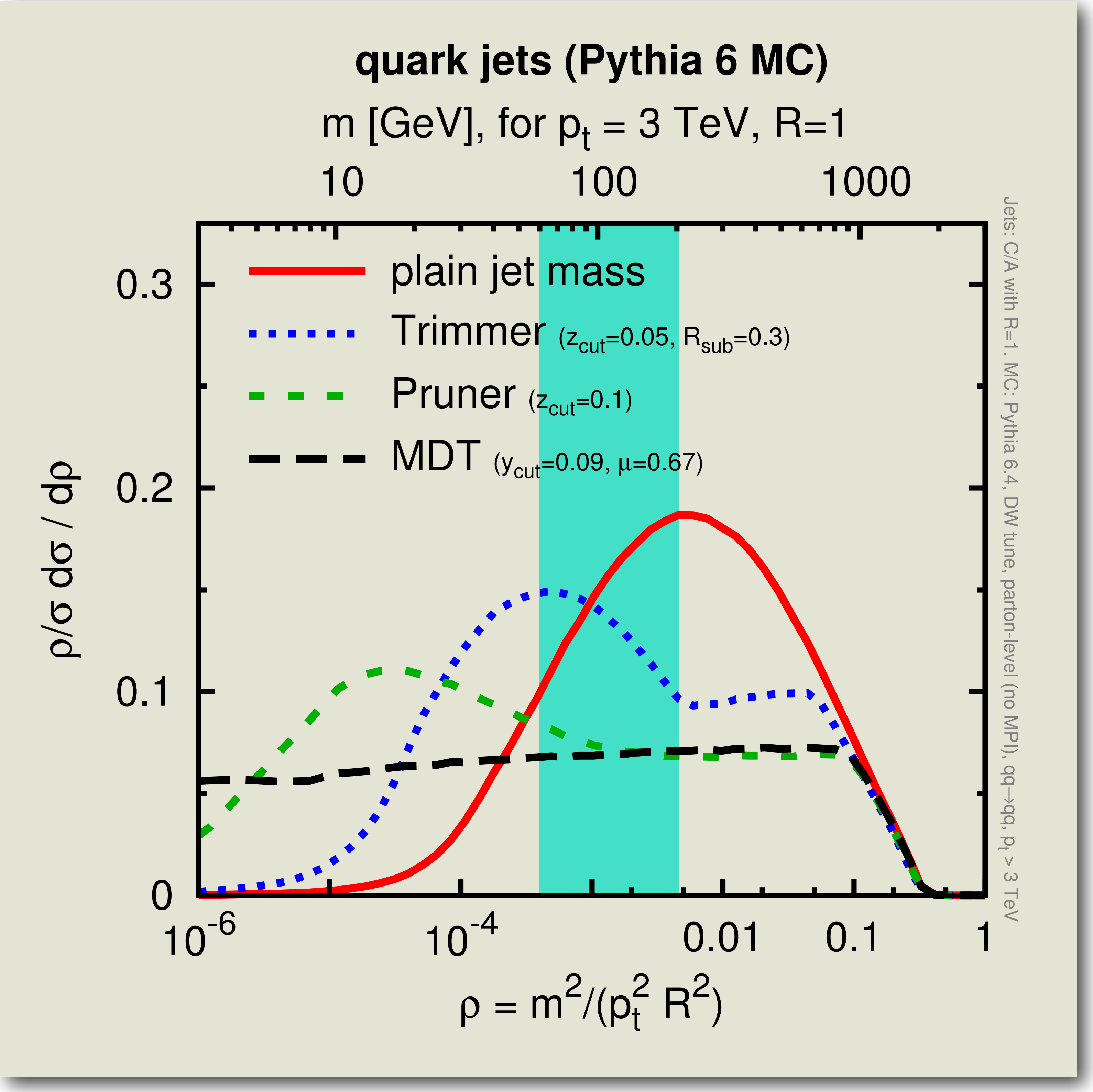
(testing on quark [background] jets)



Different taggers
can be
quite similar

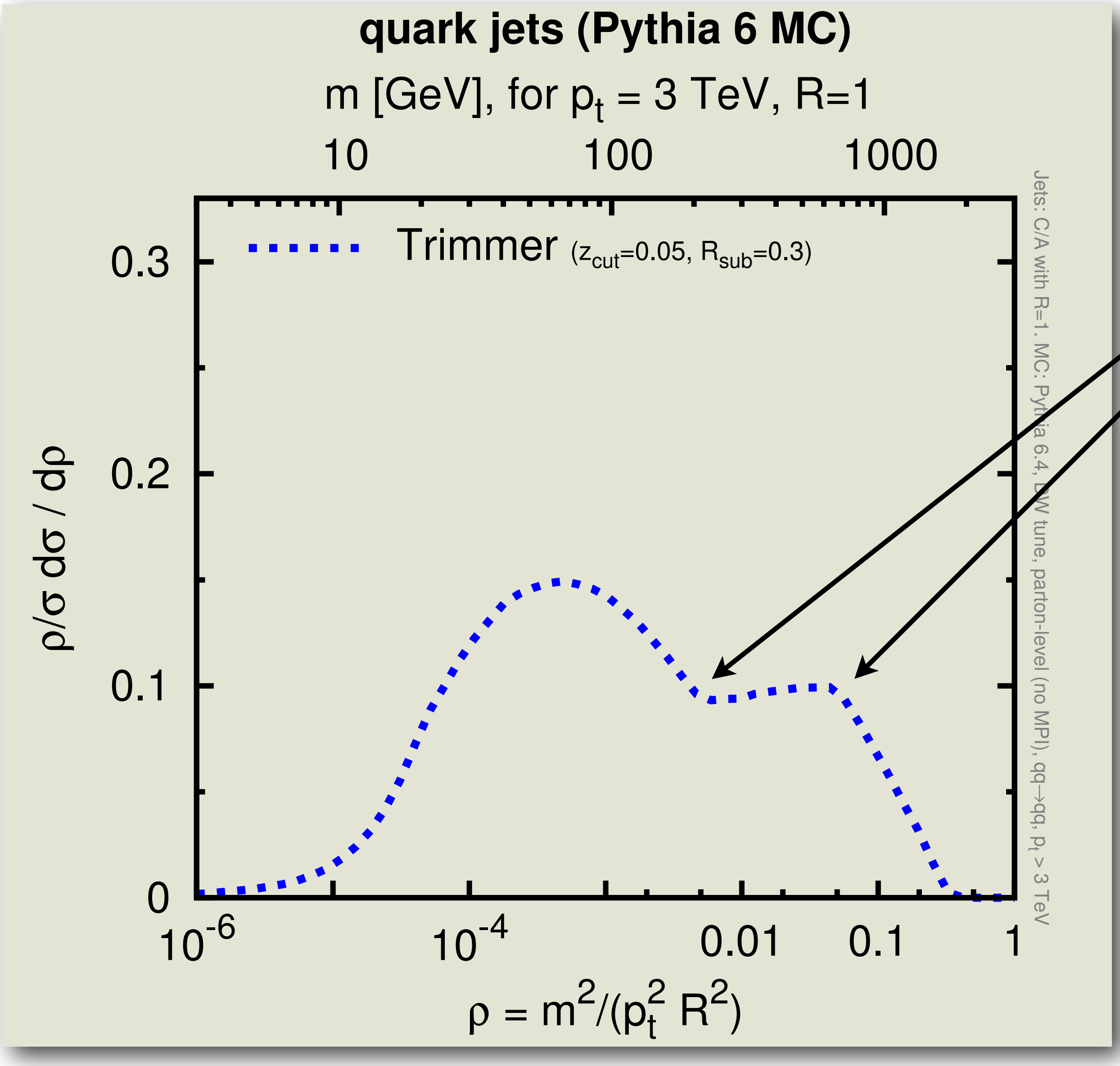
The “right” MC study can already be instructive

(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

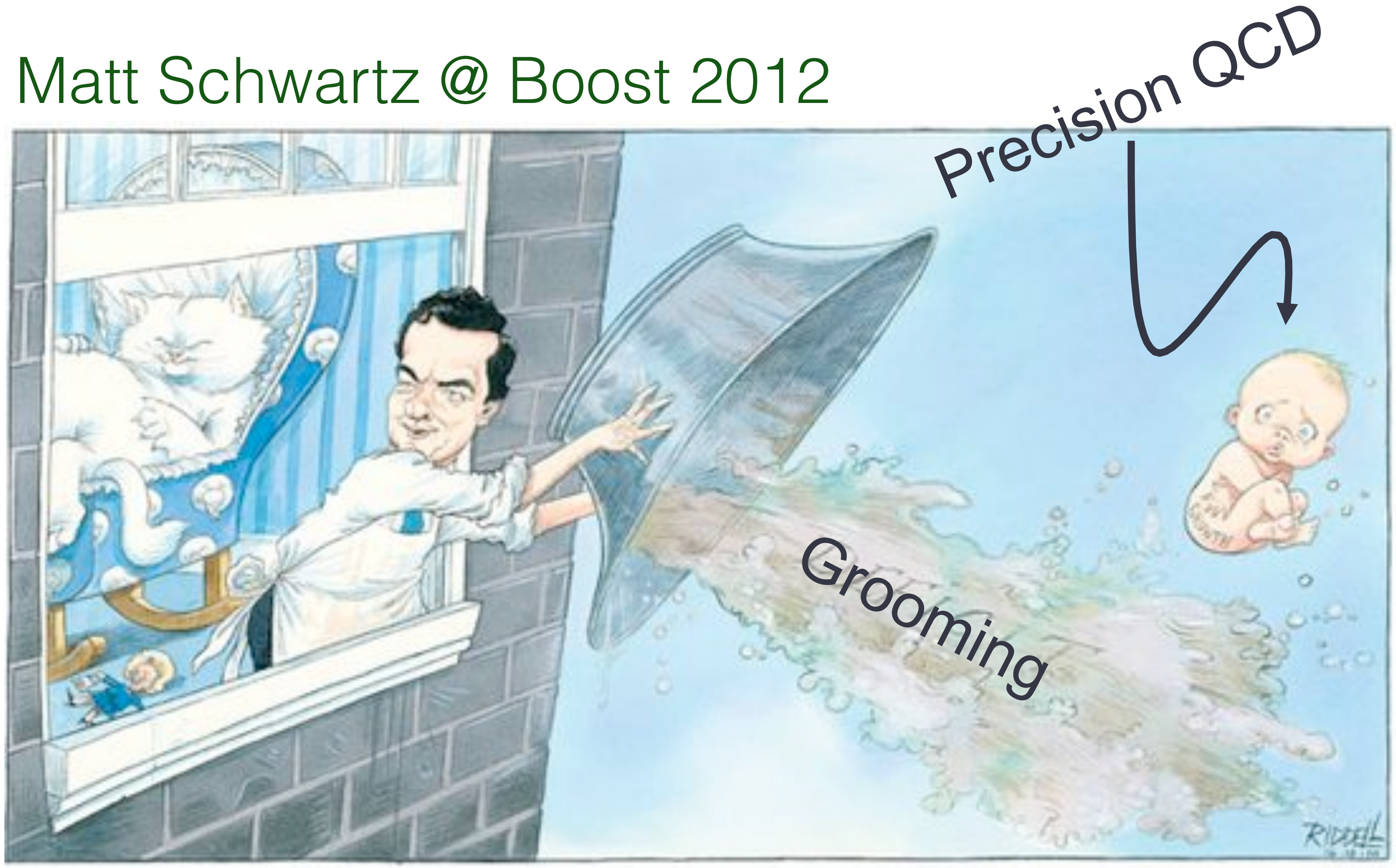
arXiv:1307.0007
Dasgupta, Fregoso, Marzani & GPS
+Dasgupta, Fregoso, Marzani & Powling, 1307.0013

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


Precision QCD
Grooming
RIDDELL

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

$\mathbf{R_{sub}} < R$

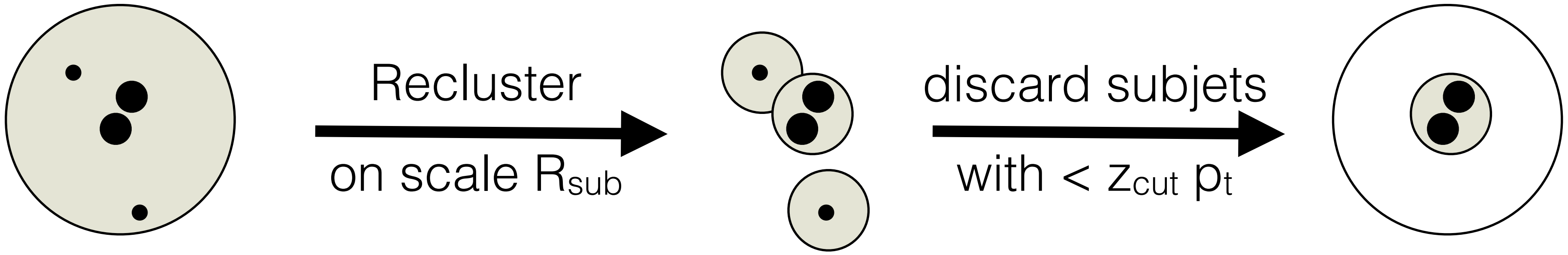
The subjets that satisfy the condition

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

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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on scale R_{sub}

discard subjets

with < z_{cut} p_t

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$\mathbf{R_{sub}} < R$

The subjets that satisfy the condition

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

are kept and merged to form the trimmed jet.

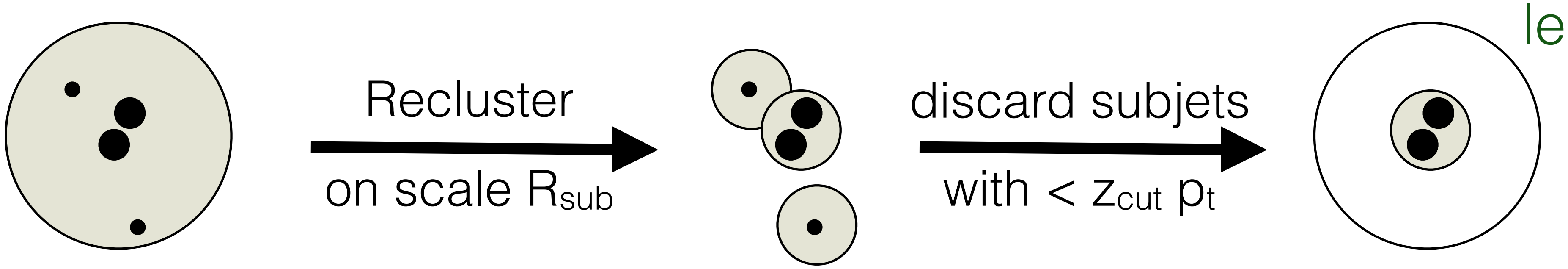
Our approximations

- $\rho \ll 1$
  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.



Recluster

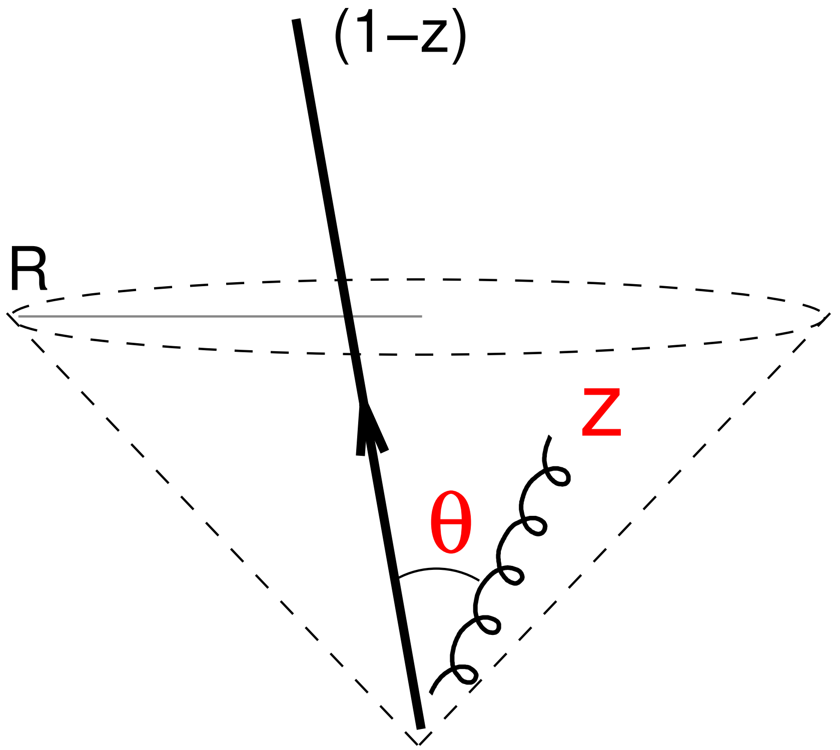
on scale R_{sub}

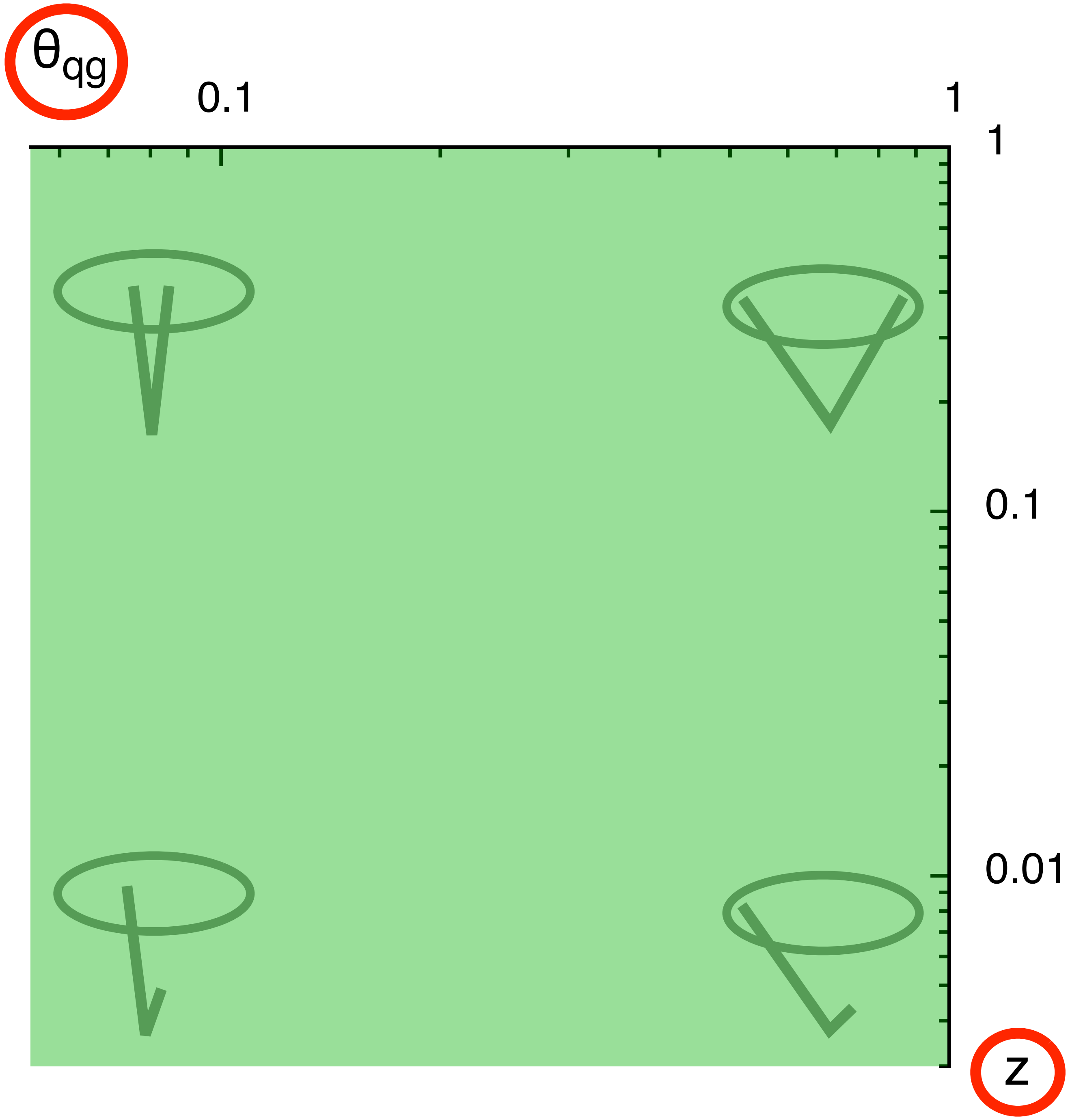
discard subjets

with $< z_{cut}\, p_t$

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**





Leading Order — 2-body kinematic plane

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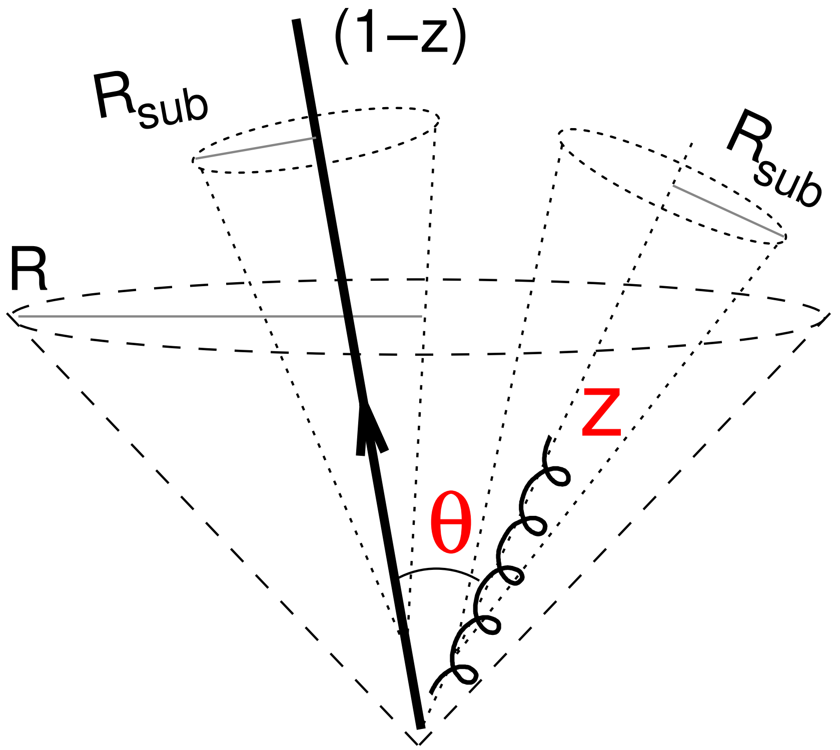

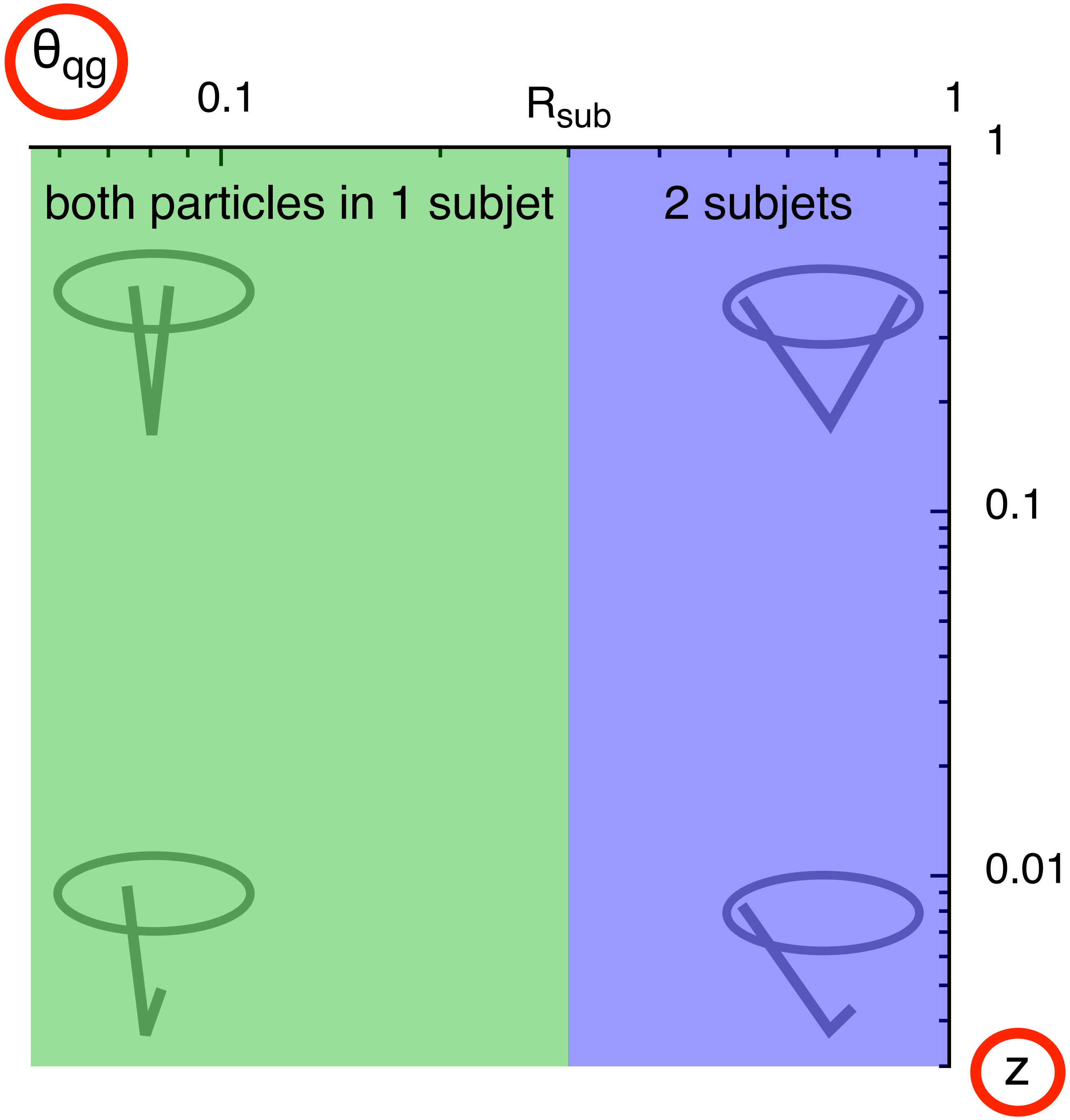

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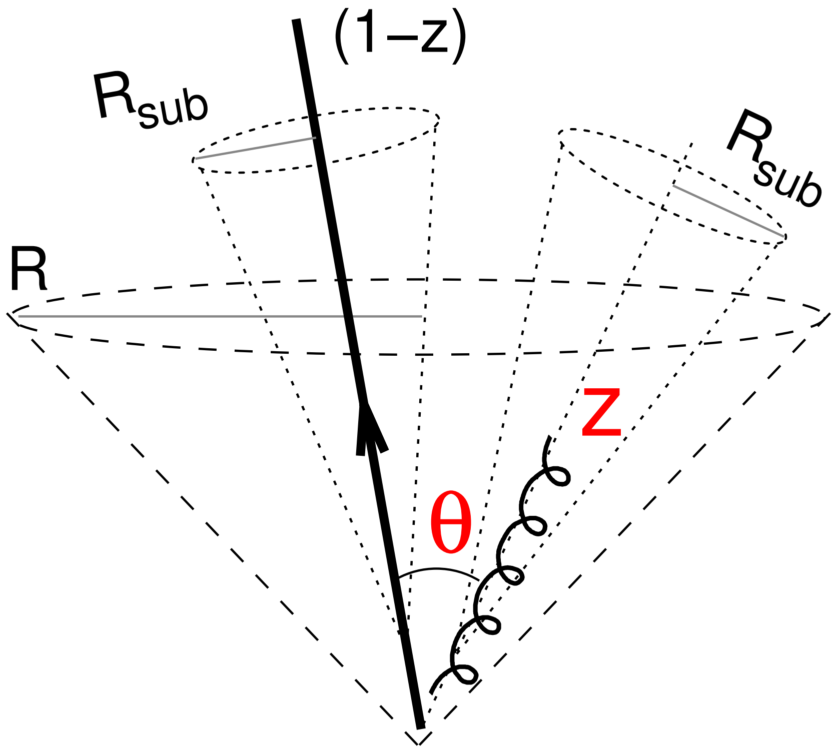
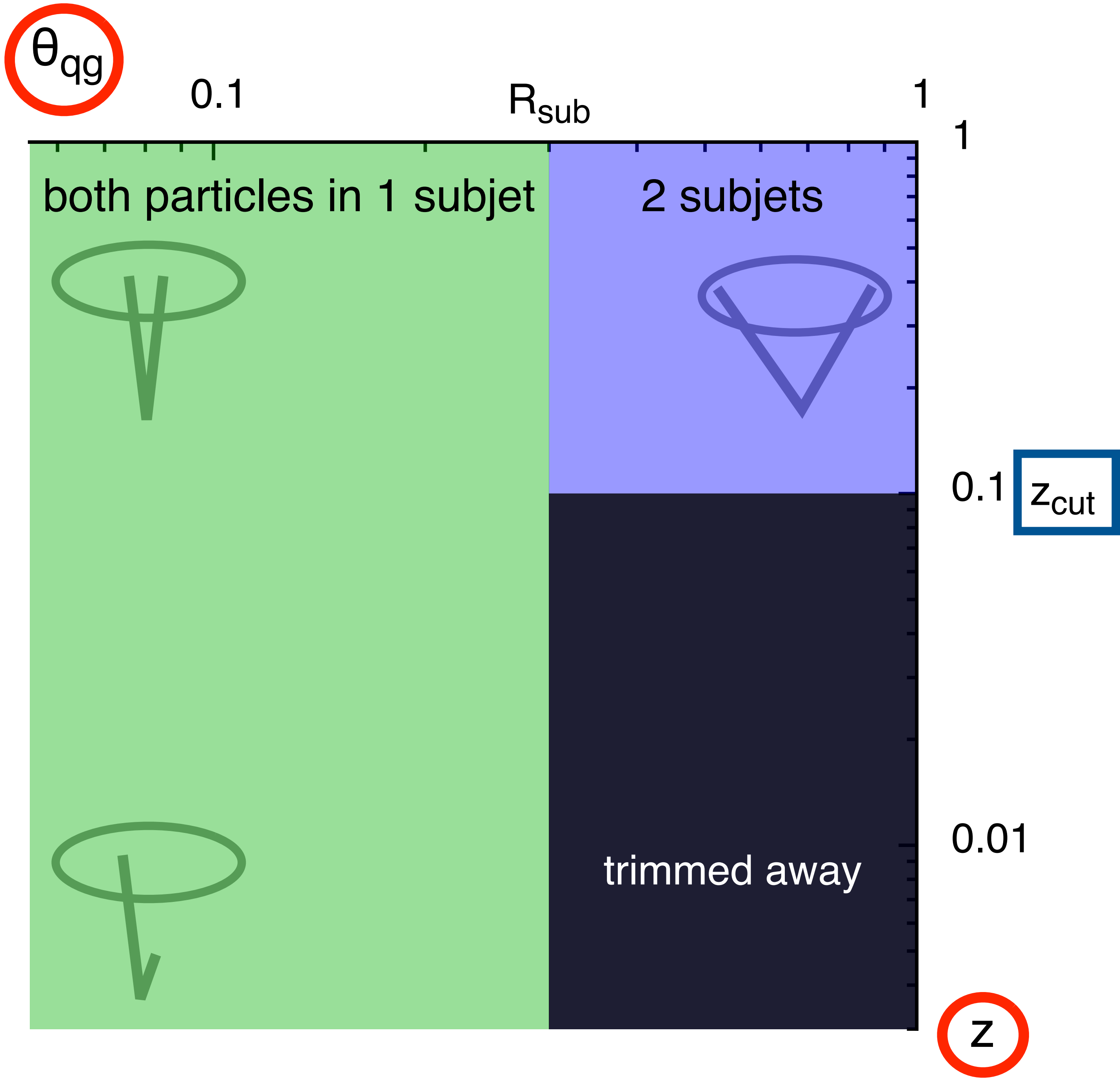
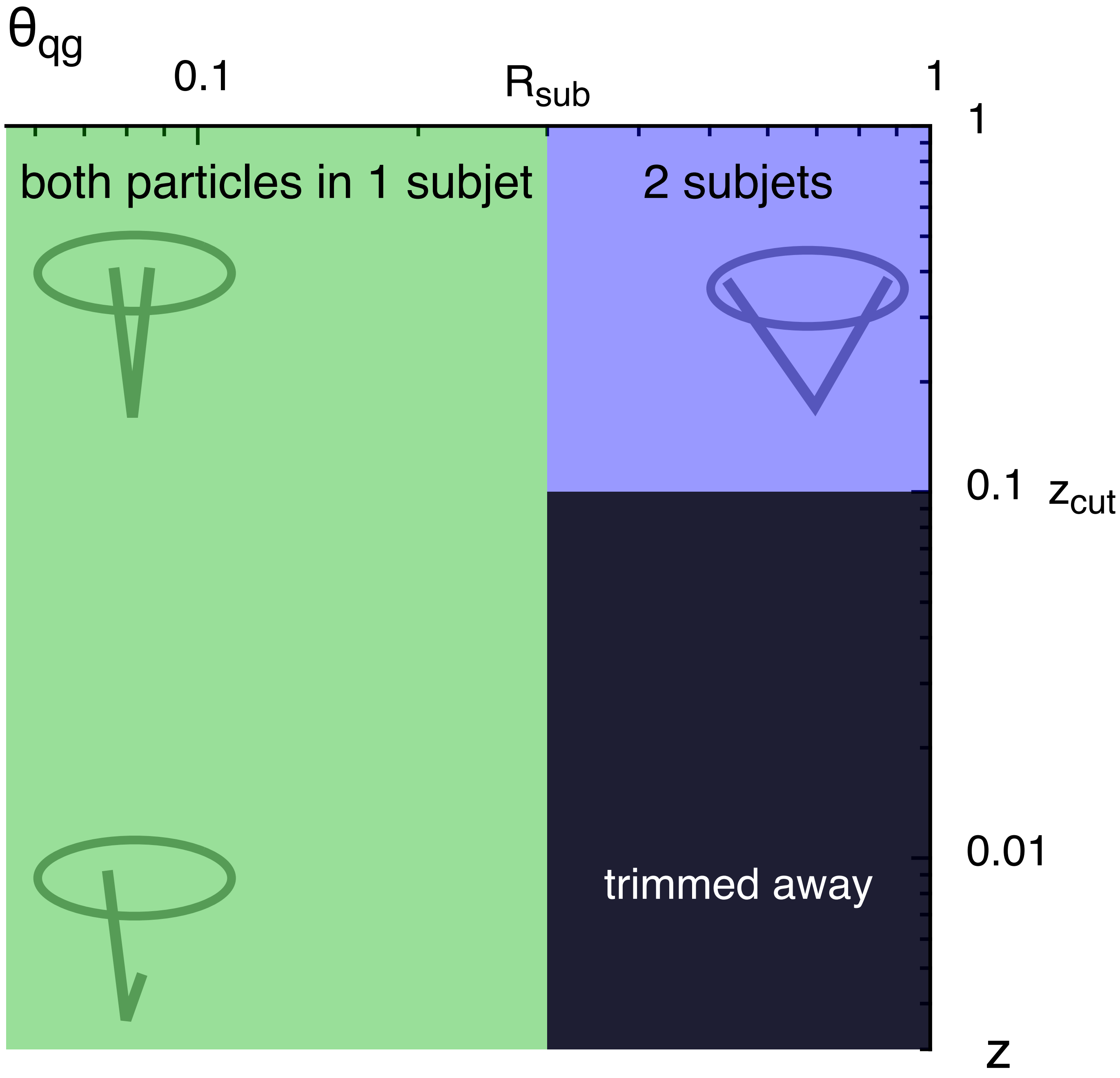




matrix element

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

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


θ_{qg}
0.1
R_{sub}
1
1
both particles in 1 subjet
2 subjets
0.1
z_{cut}
0.01
trimmed away
z

jet mass

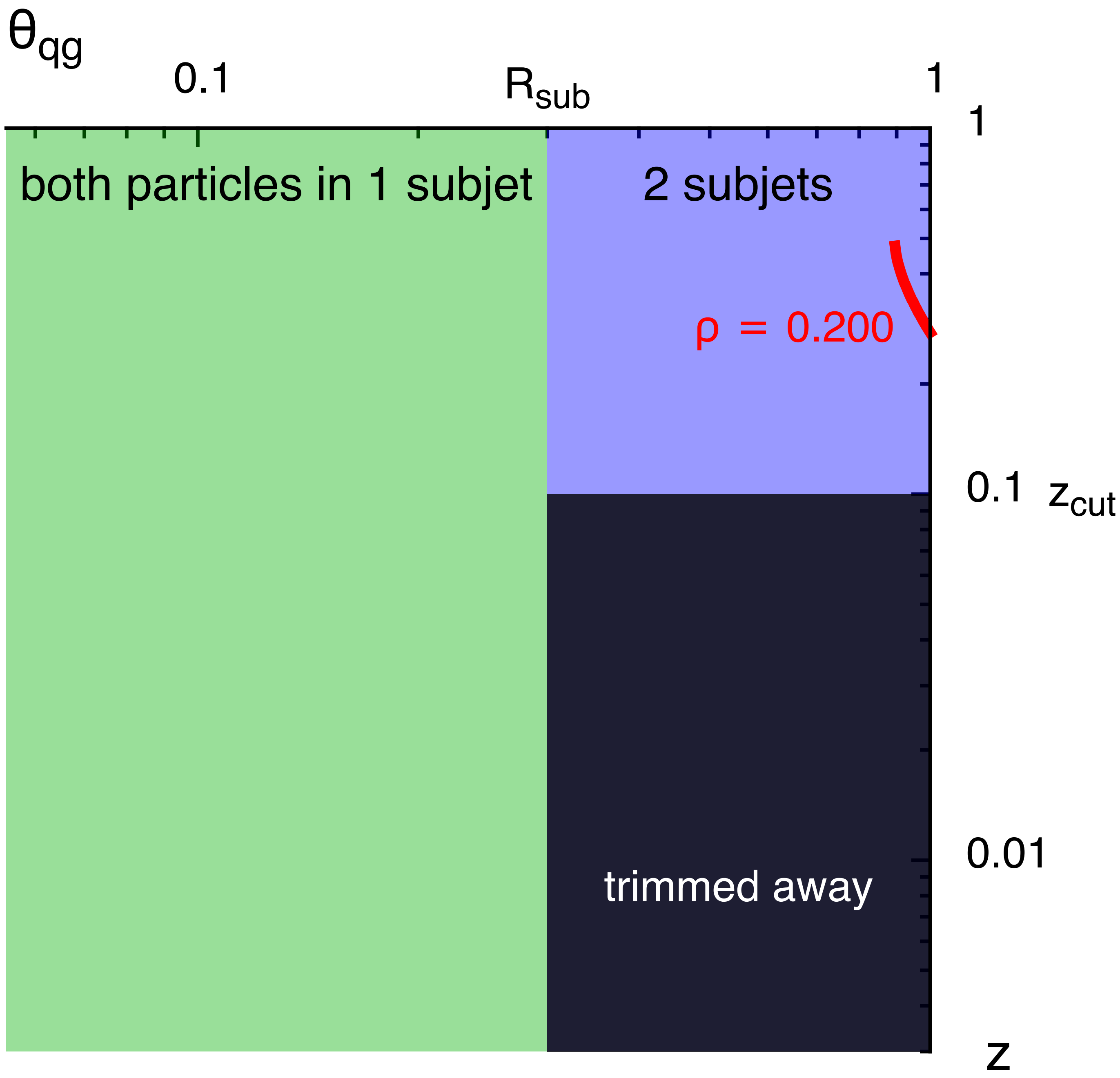
$$\rho = z(1-z)\theta^2$$

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

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



θ_{qg}
0.1
R_{sub}
1
1
both particles in 1 subjet
2 subjets
ρ = 0.200
0.1
z_{cut}
trimmed away
0.01
z

jet mass

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

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

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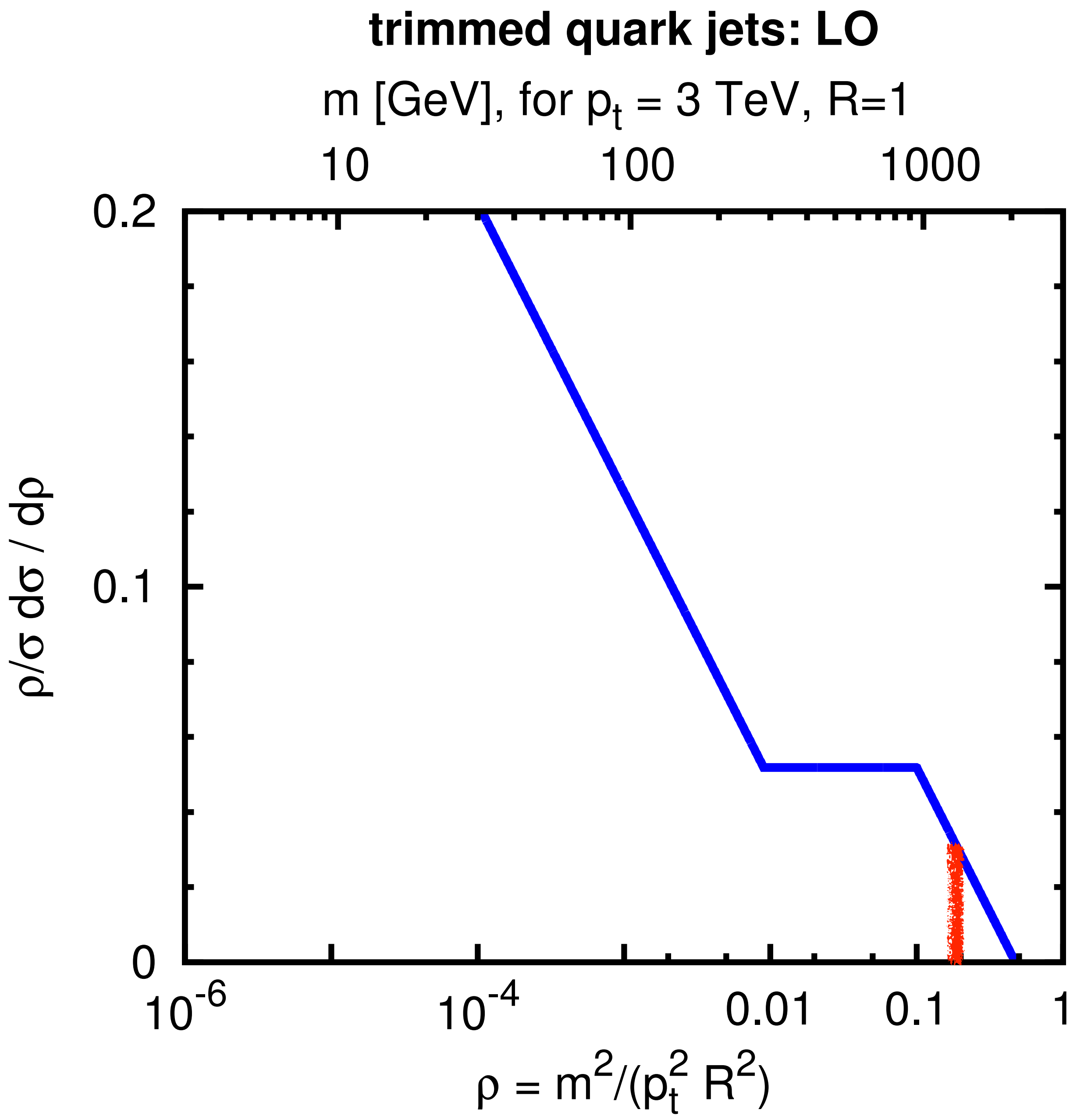

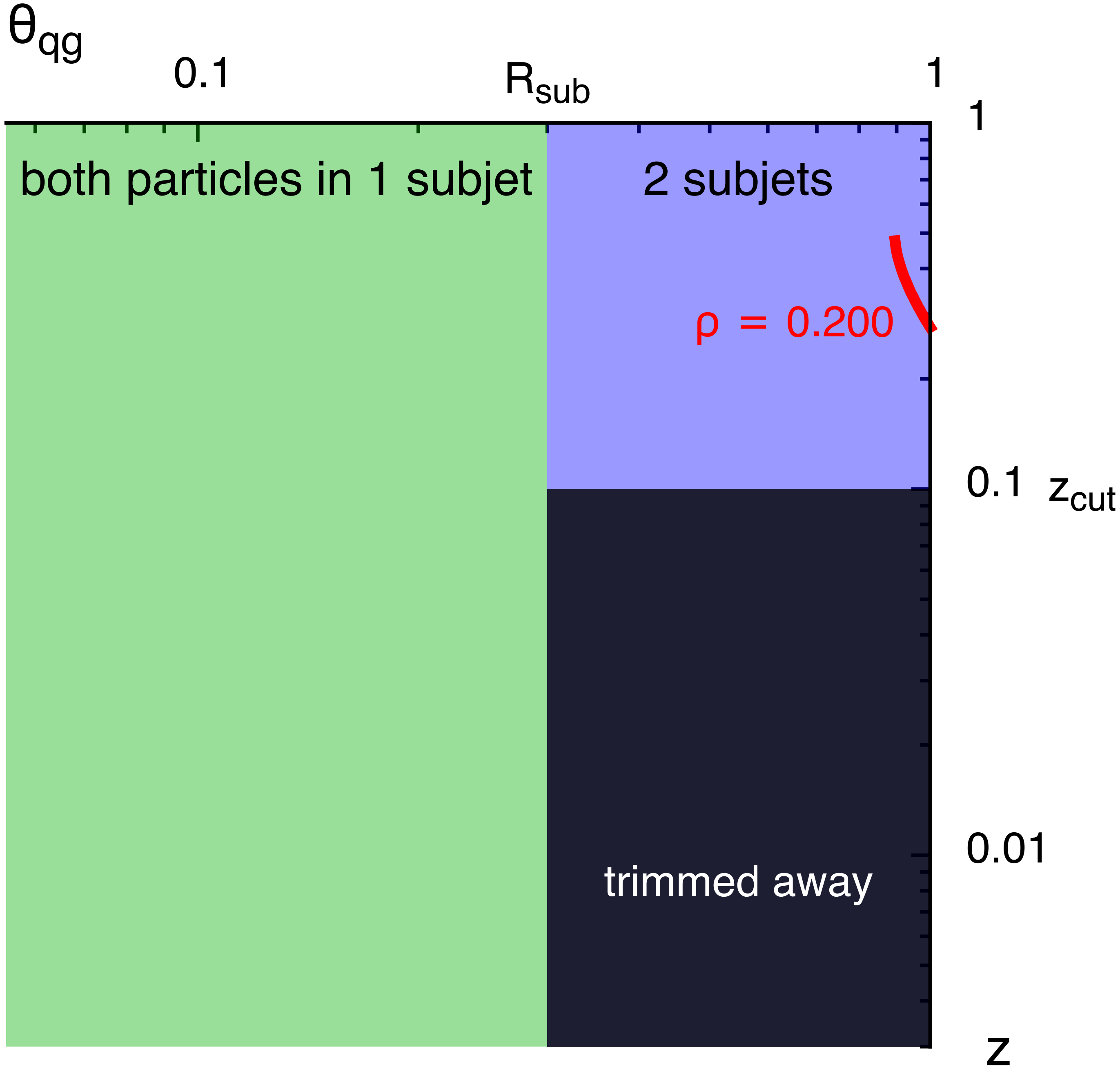
θ_{qg}
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trimmed away
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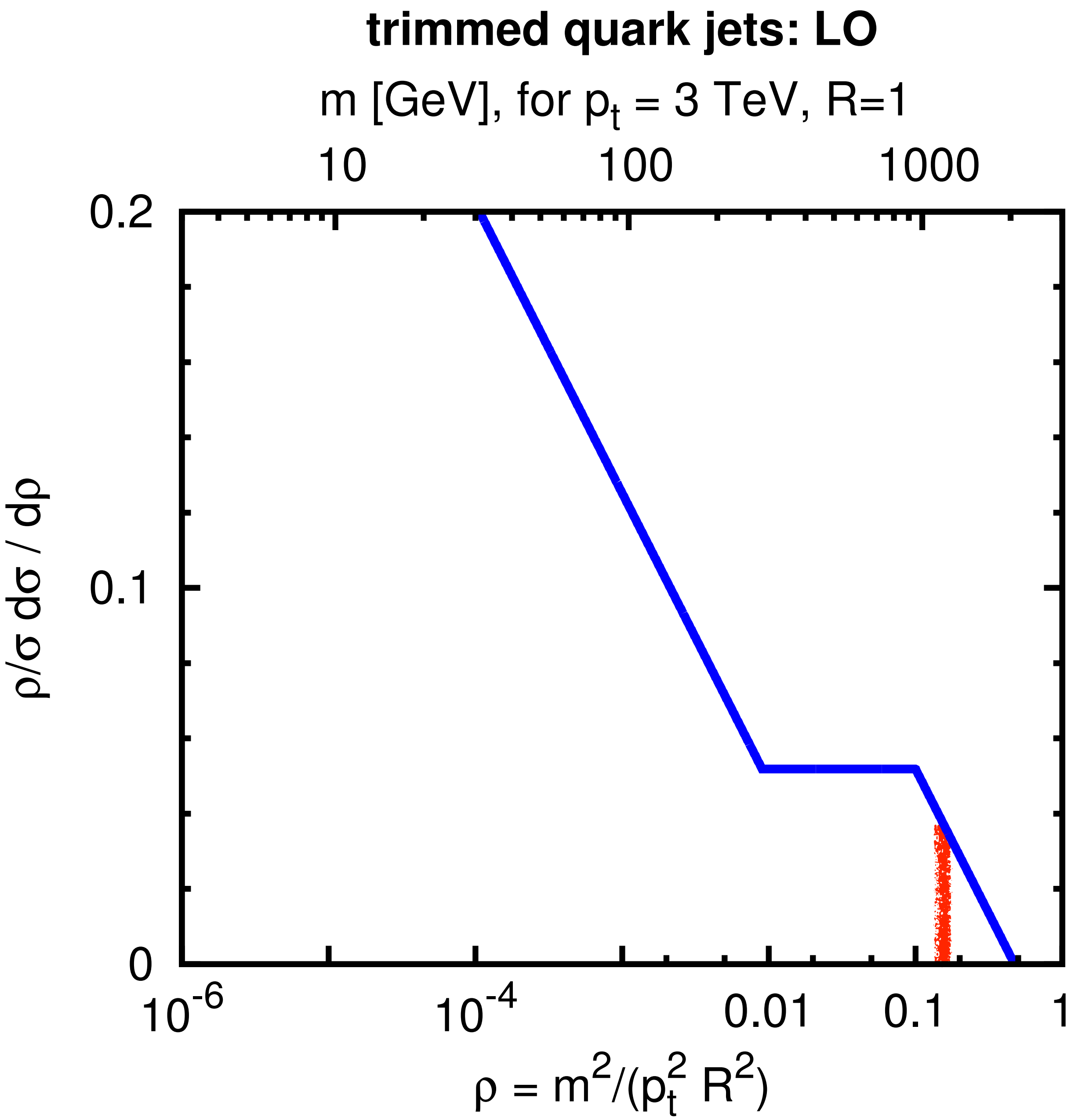
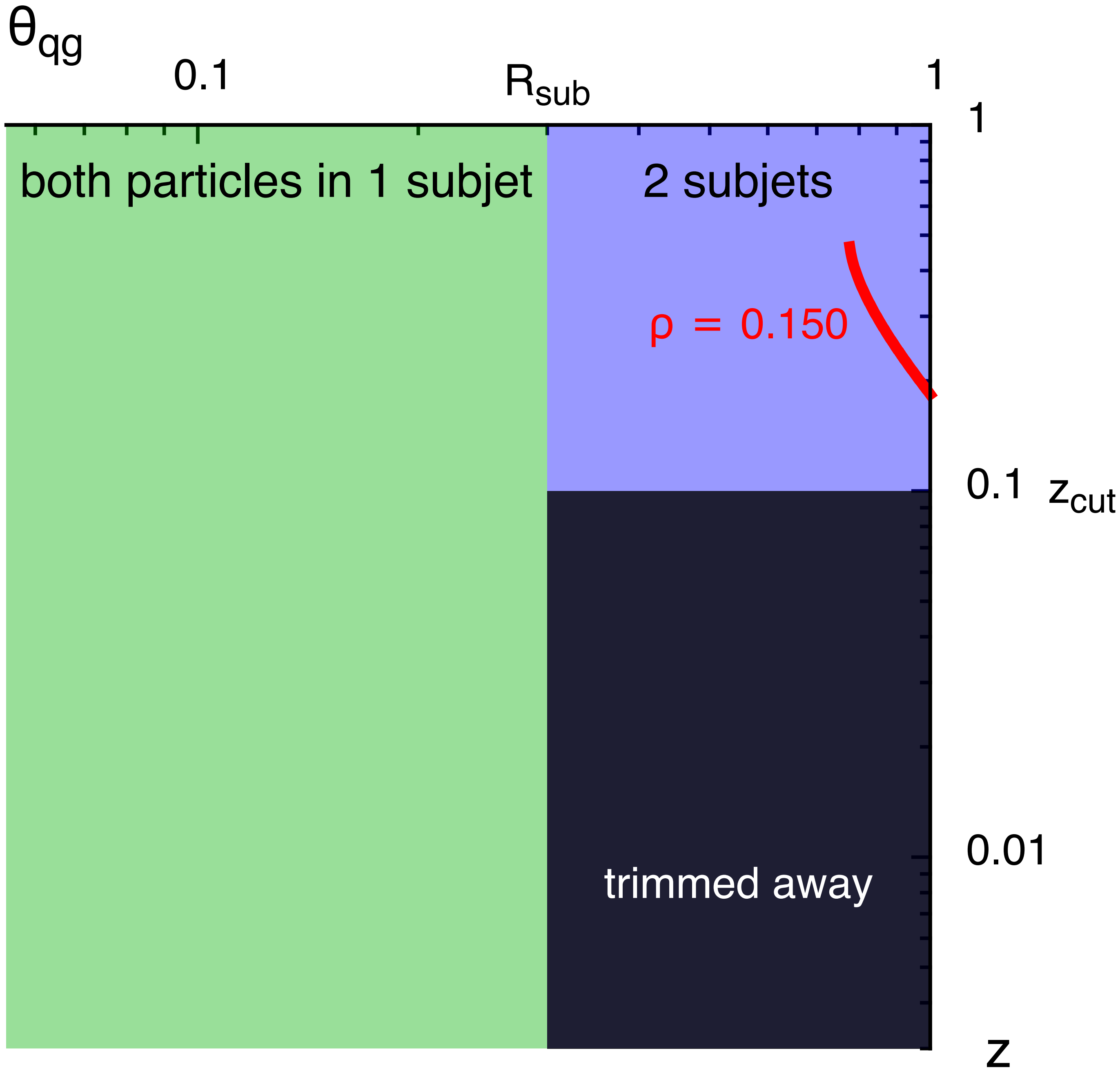




θ_{qg}
0.1
R_{sub}
1
1
both particles in 1 subjet
2 subjets
ρ = 0.150
0.1
z_{cut}
0.01
trimmed away
z

jet mass

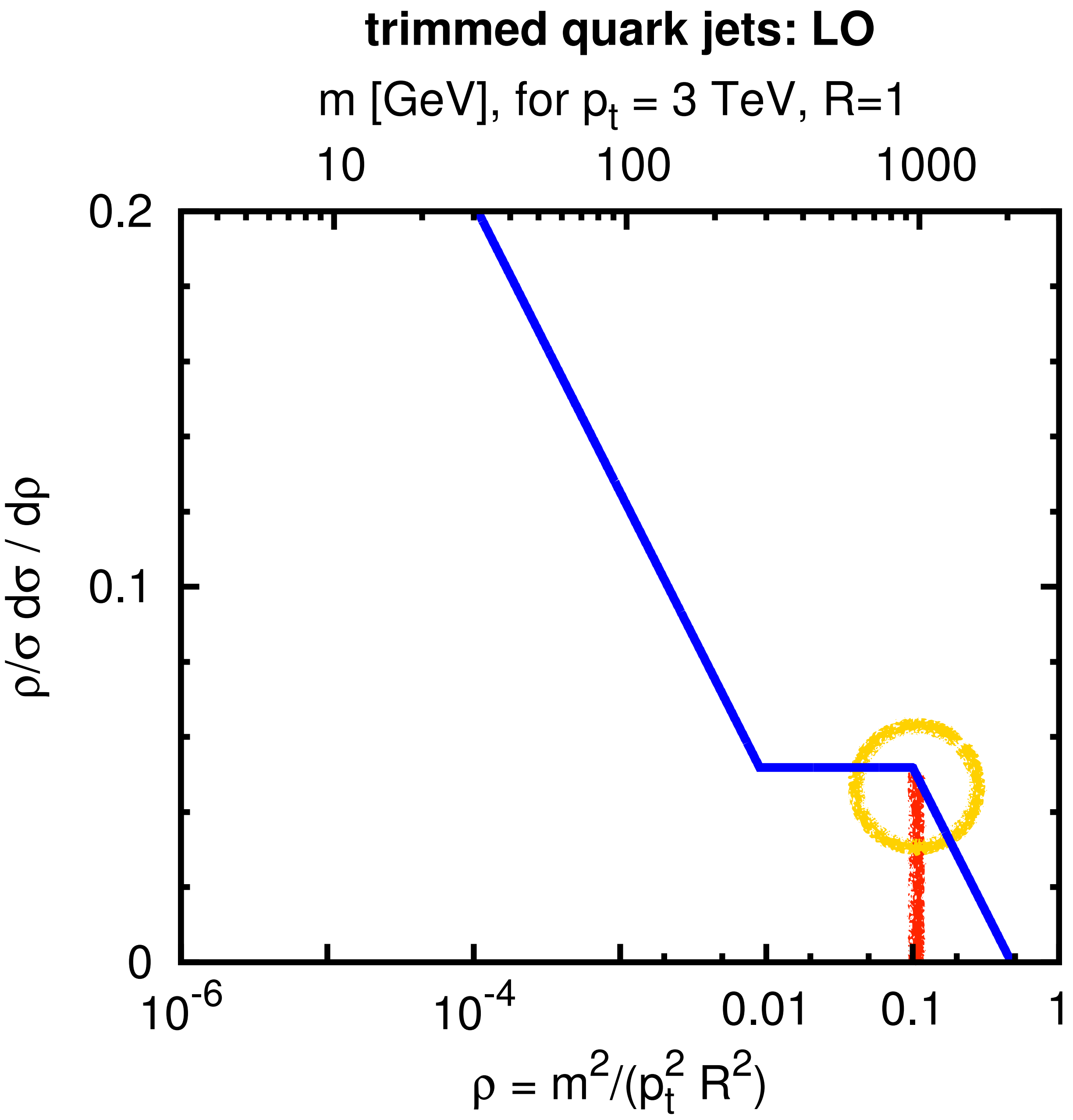
$$\rho = z(1-z)\theta^2$$

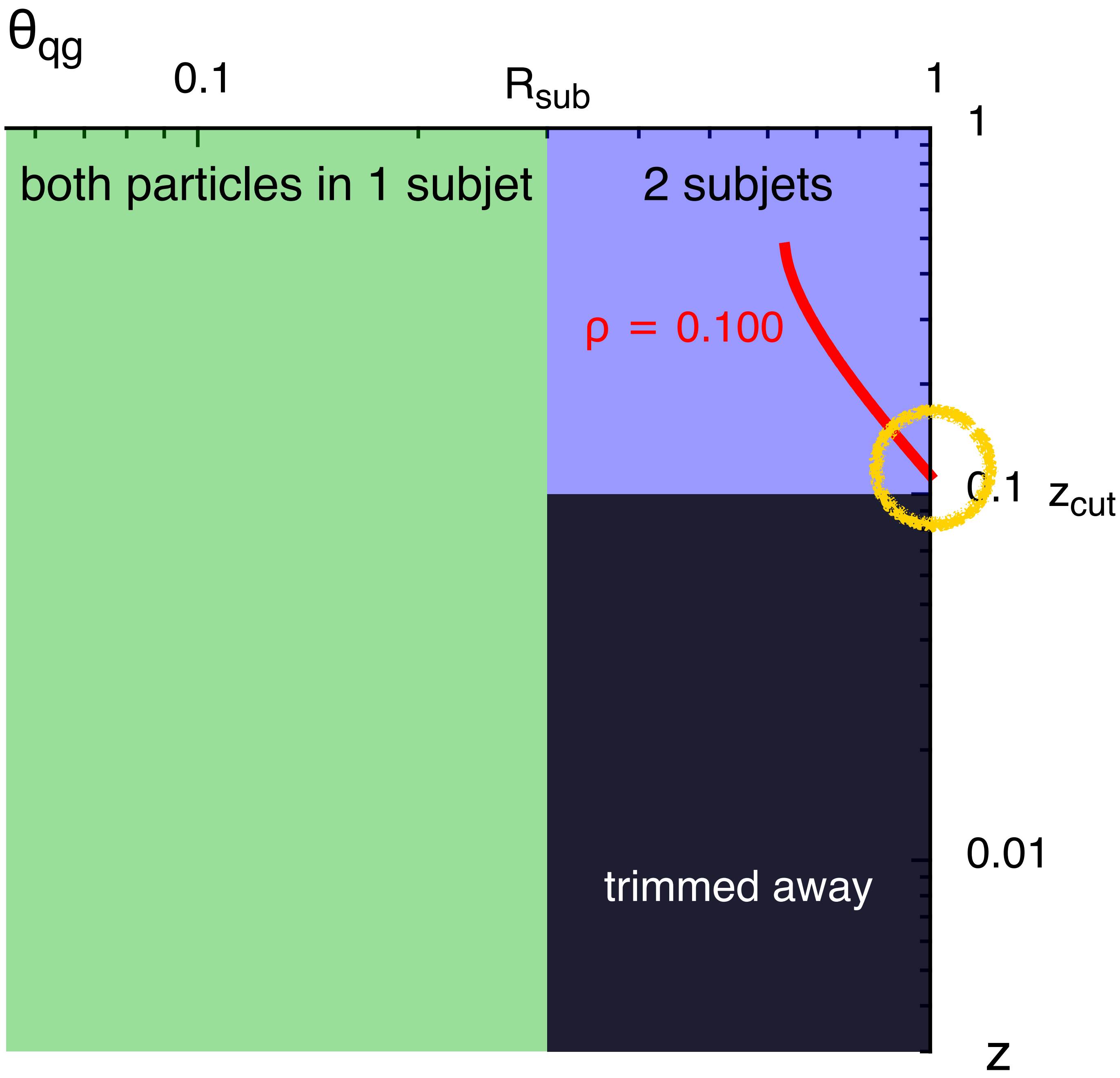
length of **fixed-ρ contour** ~ LO differential cross section

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




θ_{qg}
0.1
R_{sub}
1
1
both particles in 1 subjet
2 subjets
ρ = 0.100
0.1
z_{cut}
0.01
trimmed away
z

jet mass

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

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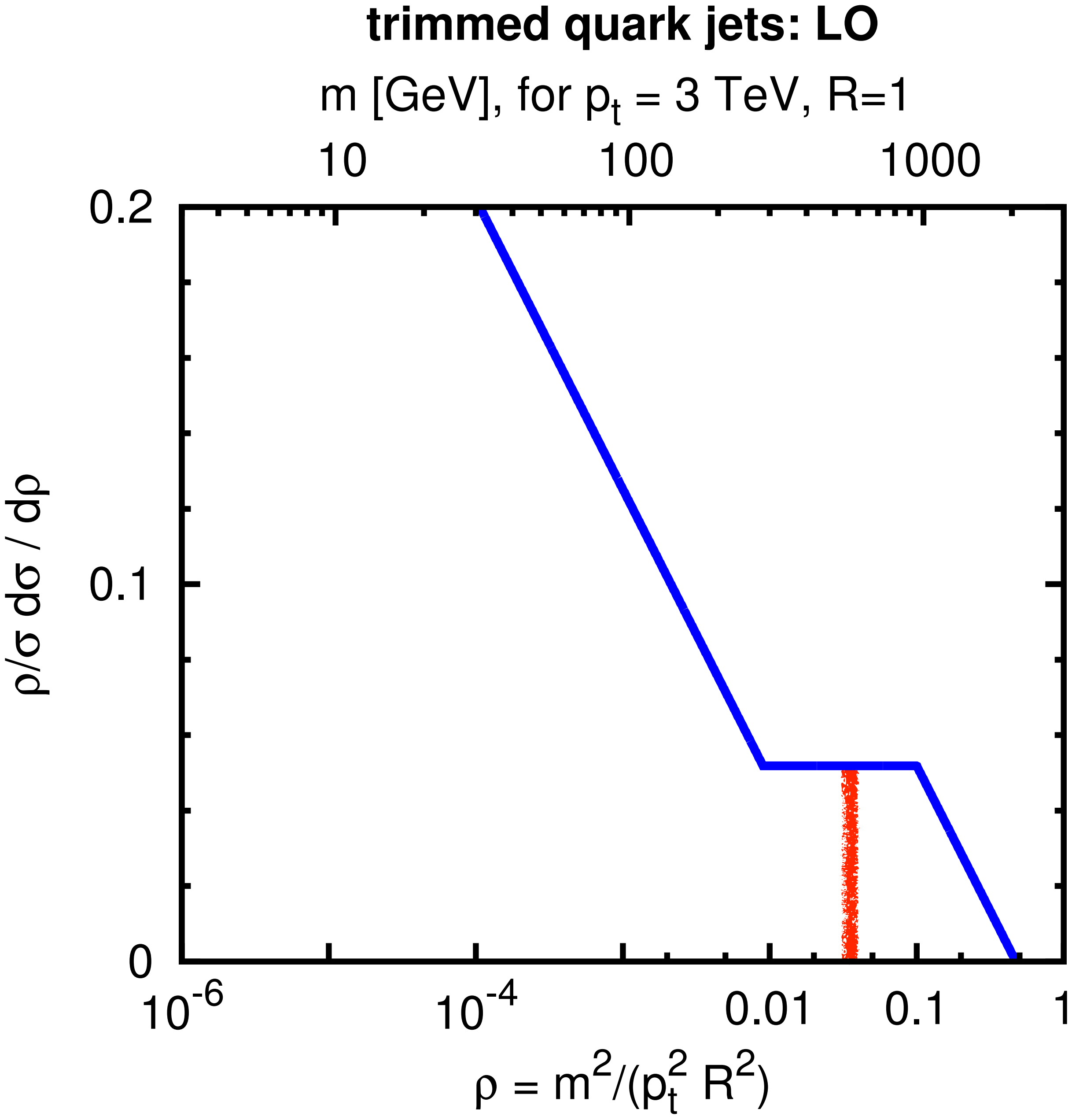
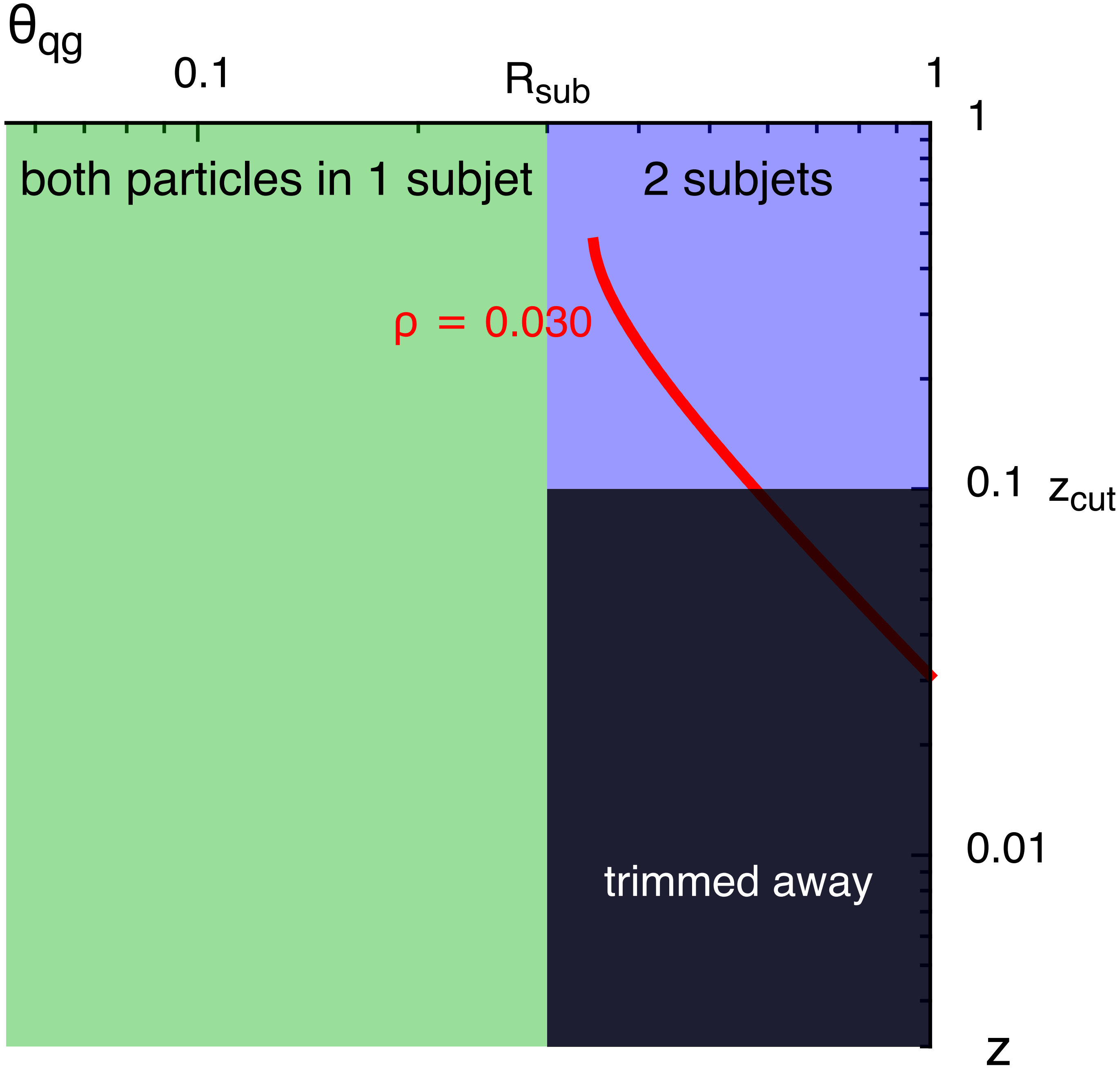
emission probability ~ constant in log θ – log *z* plane




θ_{qg}
0.1
R_{sub}
1
1
both particles in 1 subjet
2 subjets
ρ = 0.030
0.1
z_{cut}
0.01
trimmed away
z

jet mass

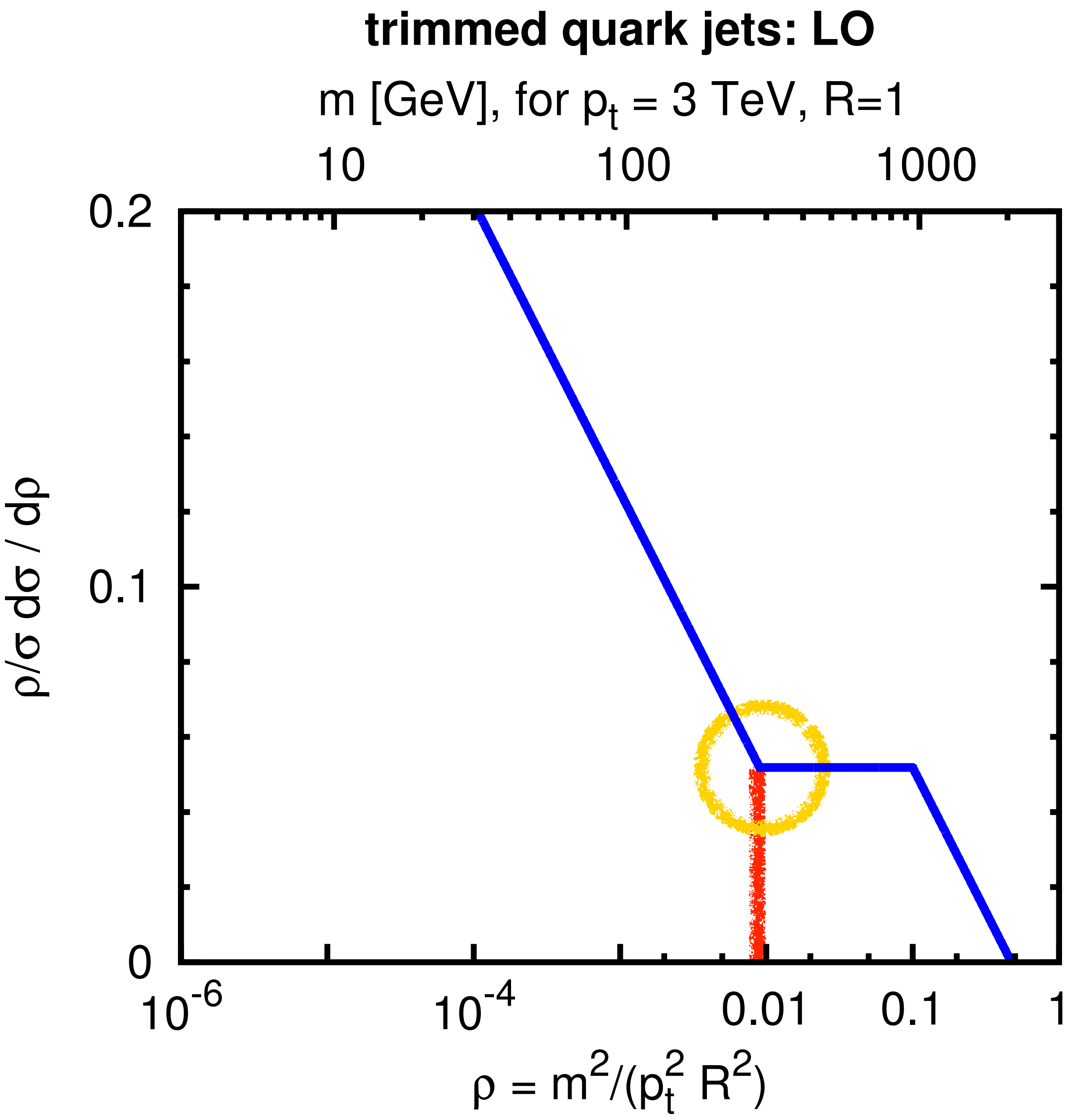
$$\rho = z(1-z)\theta^2$$

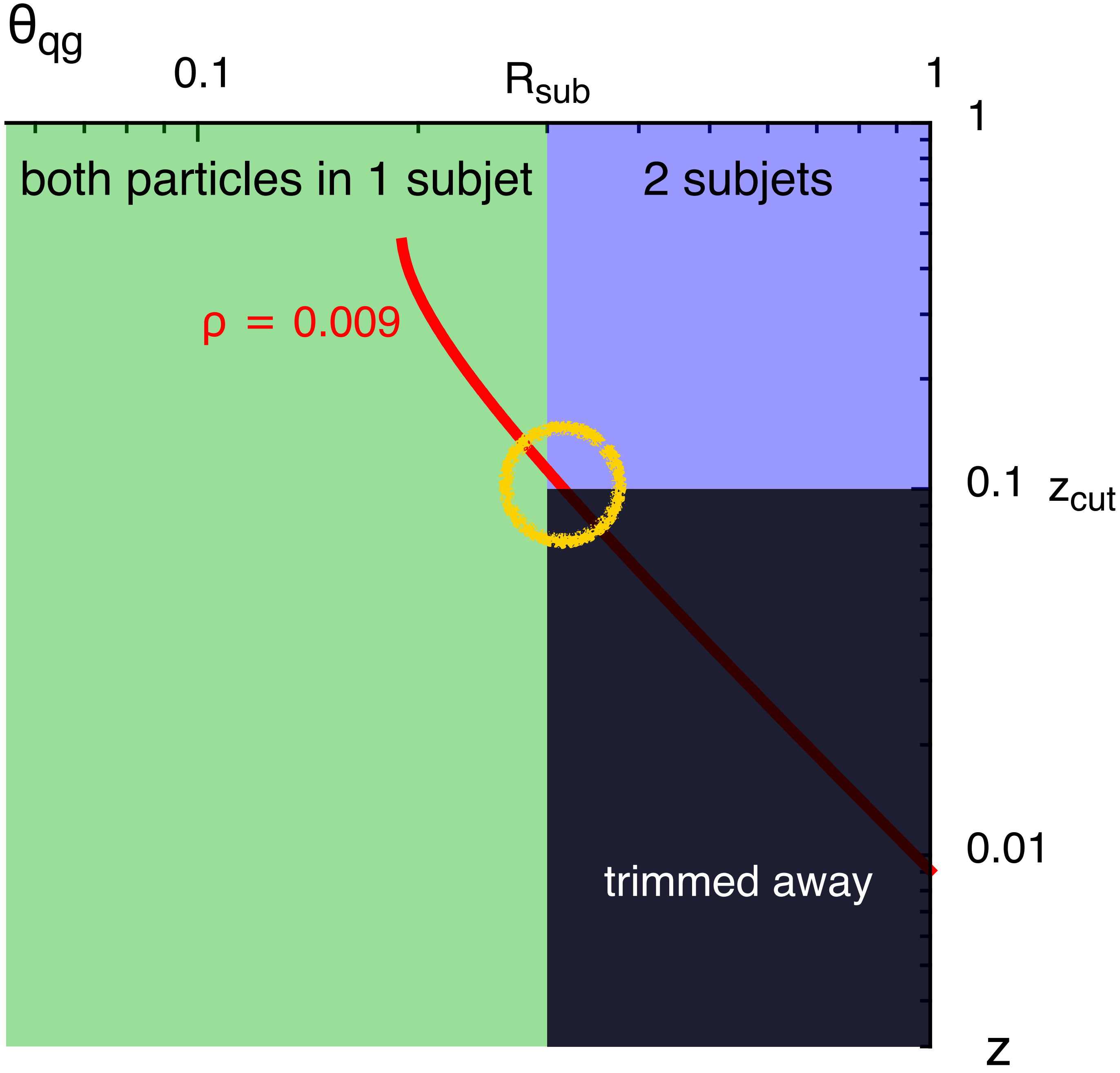
length of **fixed-ρ contour** ~
LO differential cross section

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




θ_{qg}
0.1
R_{sub}
1
1
both particles in 1 subjet
2 subjets
ρ = 0.009
0.1
z_{cut}
0.01
trimmed away
z

jet mass

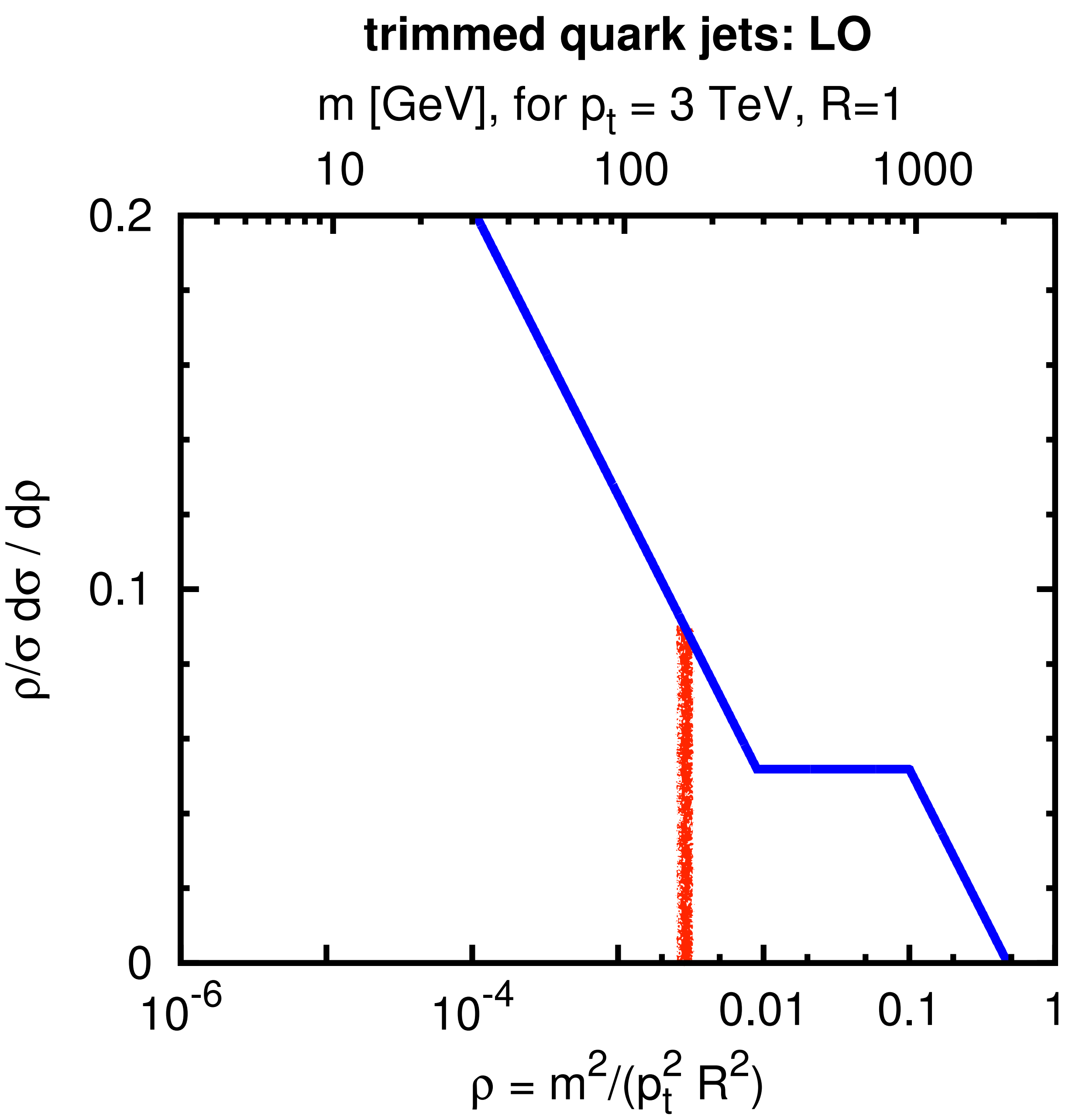
$$\rho = z(1-z)\theta^2$$

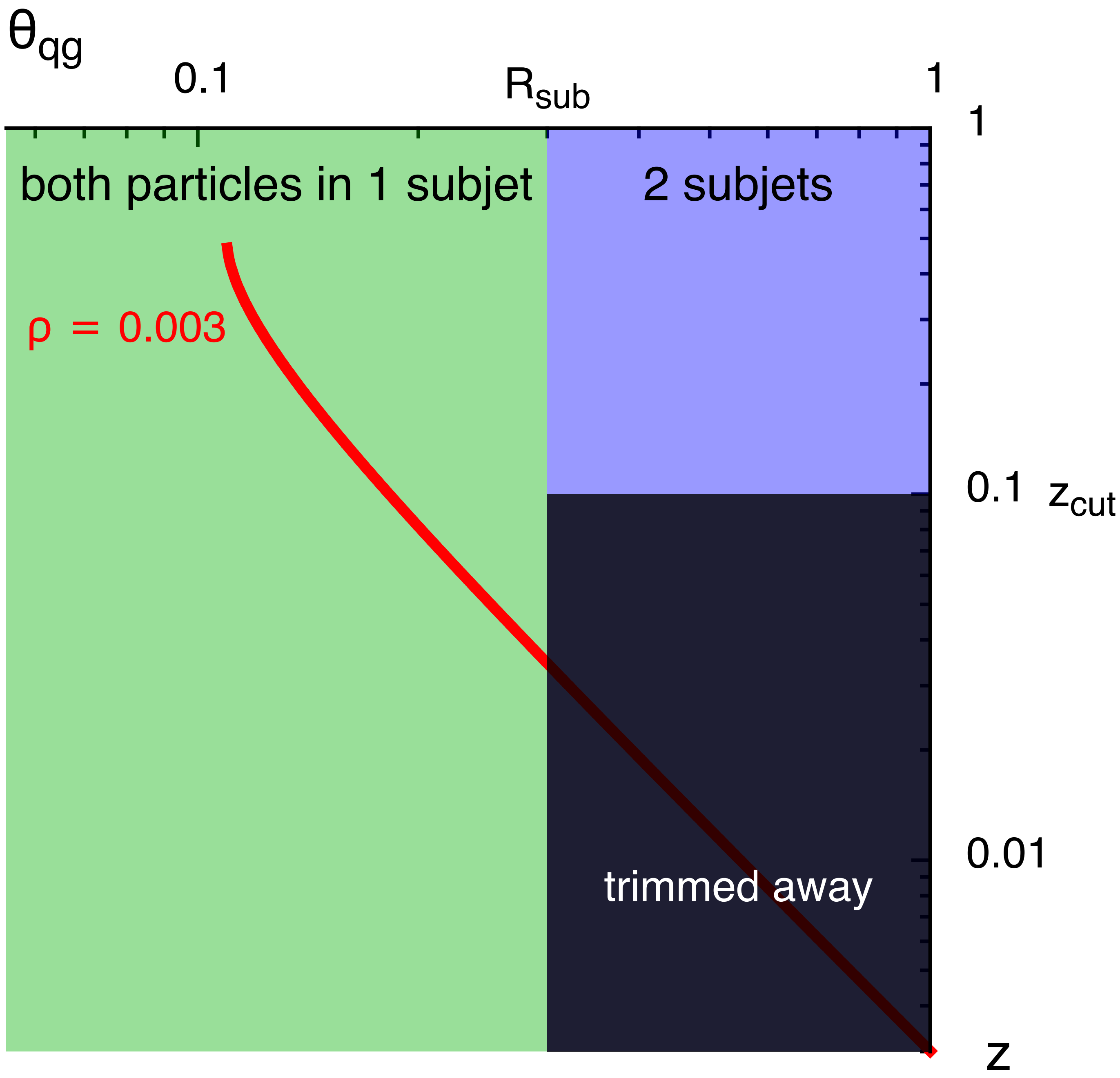
length of **fixed-ρ contour** ~ LO differential cross section

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

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R_{sub}
1
1
both particles in 1 subjet
2 subjets
ρ = 0.003
0.1
z_{cut}
0.01
trimmed away
z

jet mass

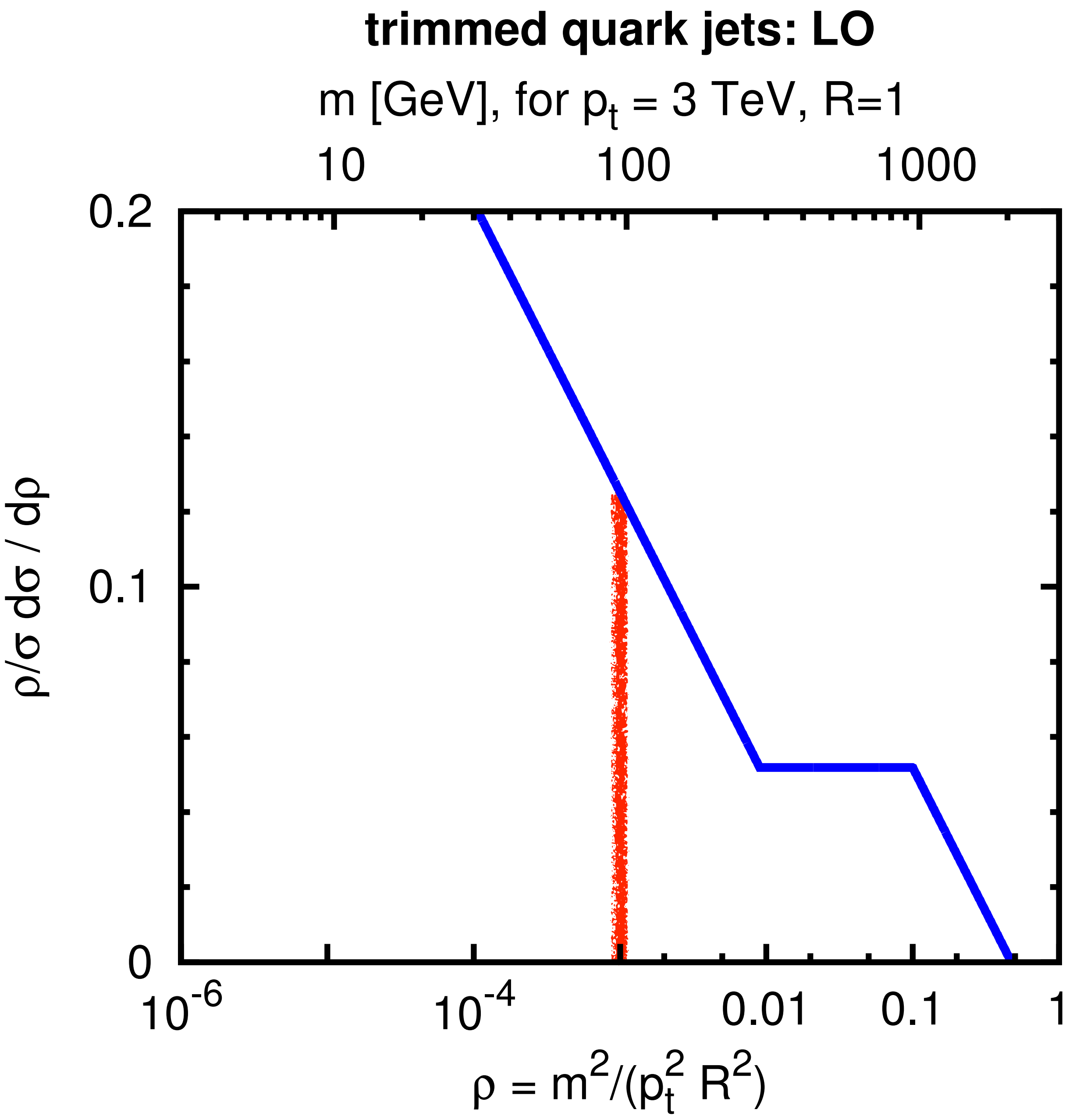
$$\rho = z(1-z)\theta^2$$

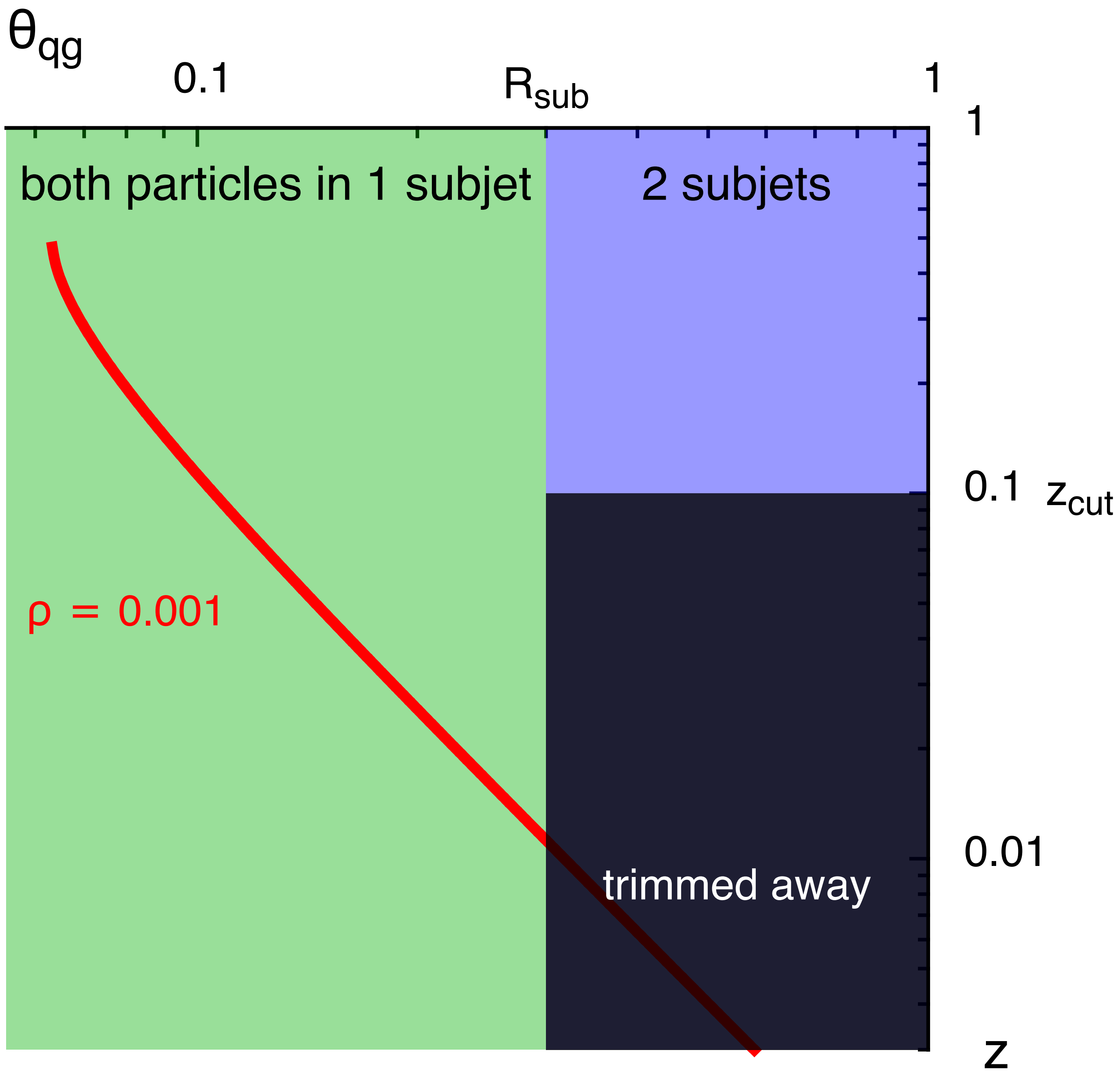
length of **fixed-ρ contour** ~ LO differential cross section

matrix element

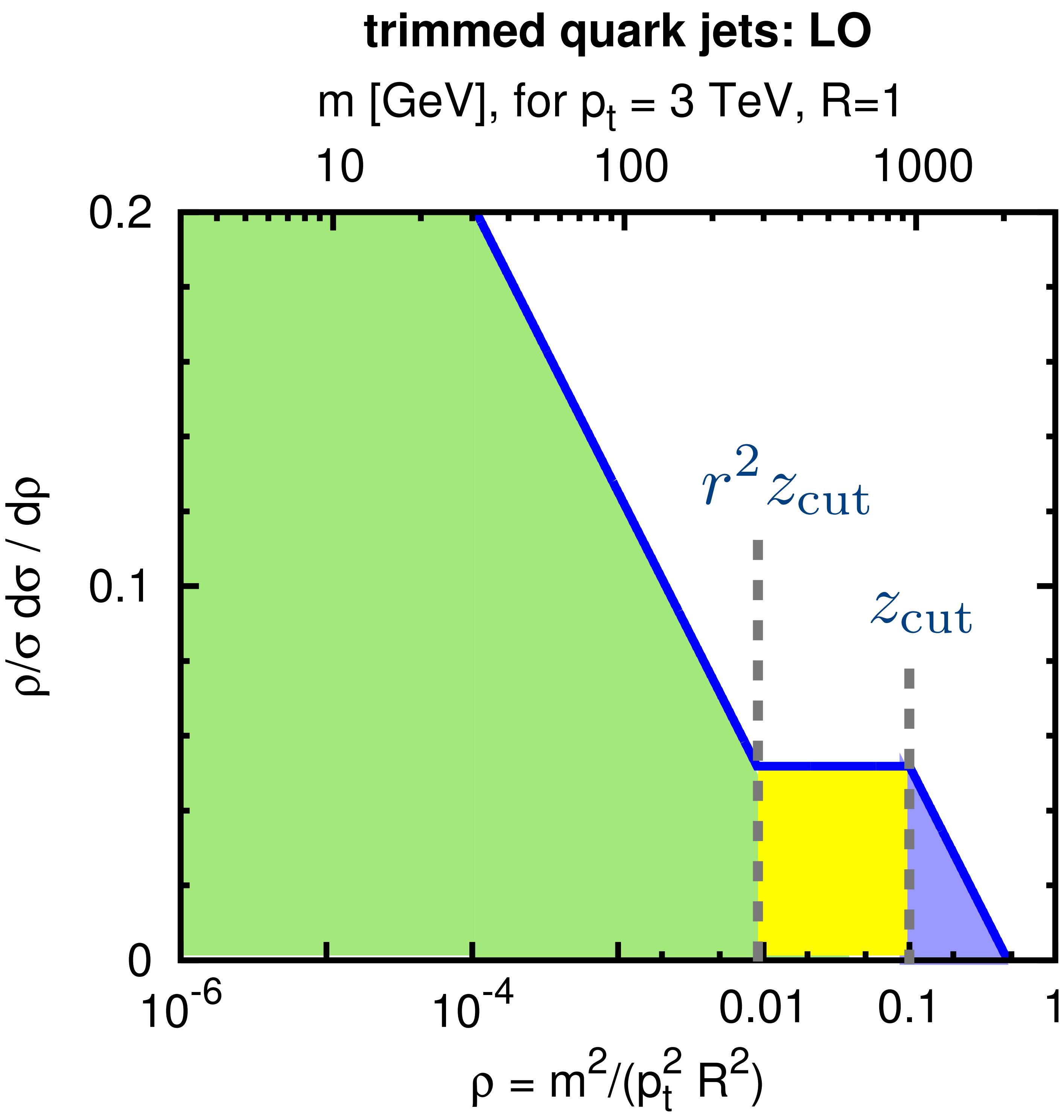
$$\frac{\alpha_s C_F}{\pi}\frac{d\theta^2}{\theta^2}\frac{dz}{z}$$

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




θ_{qg}
0.1
R_{sub}
1
1
both particles in 1 subjet
2 subjets
0.1
z_{cut}
ρ = 0.001
0.01
trimmed away
z

Trimming at LO in α_s



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

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

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

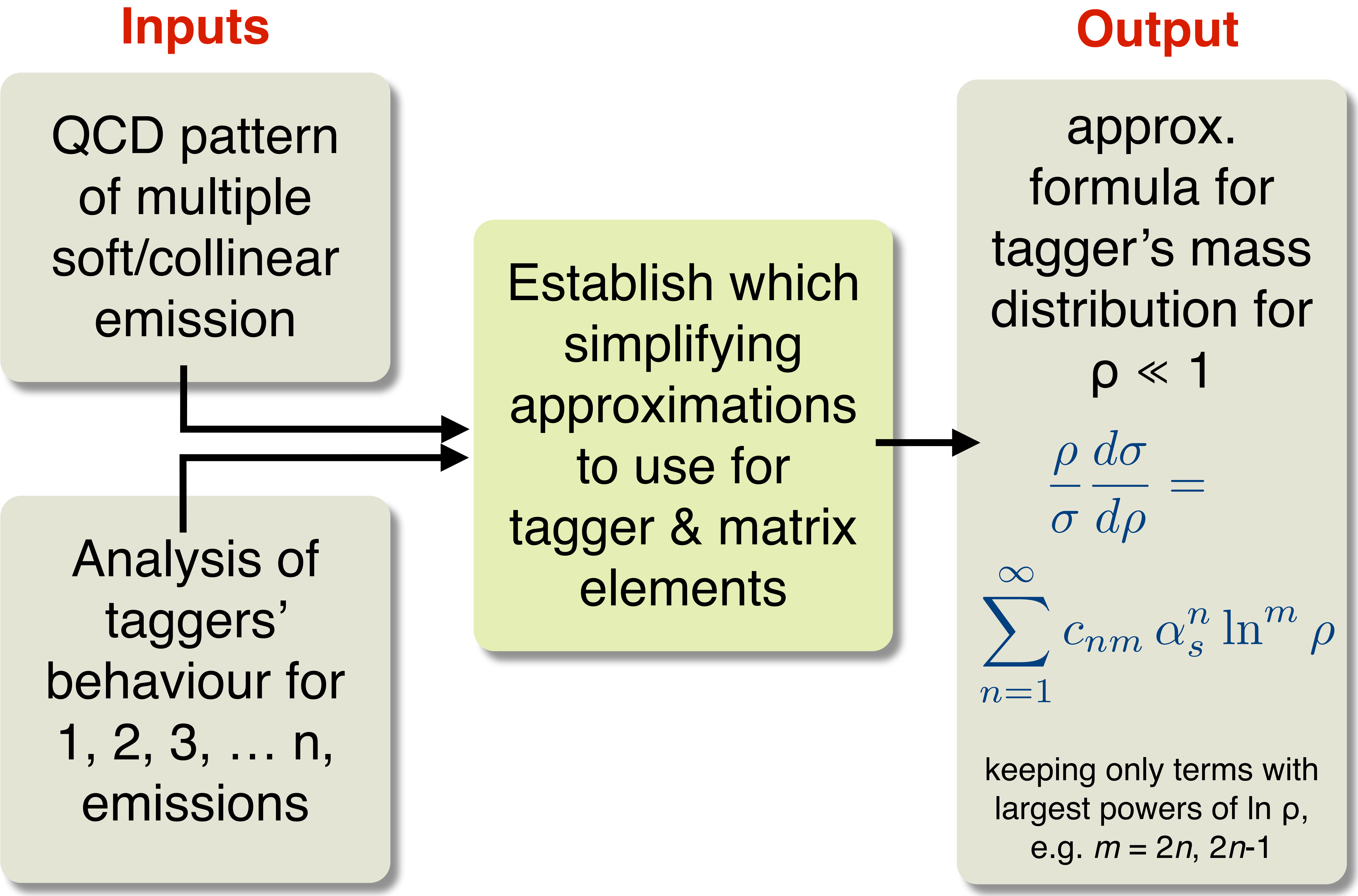
$$\frac{\alpha_s C_F}{\pi}\left(\ln\frac{1}{\rho} - \frac{3}{4}\right)$$

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

continue with all-order resummation of terms

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

→ 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 at all orders

Trimming

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

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

Trimmed jet reduces (~) to sum of trimmed emissions

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

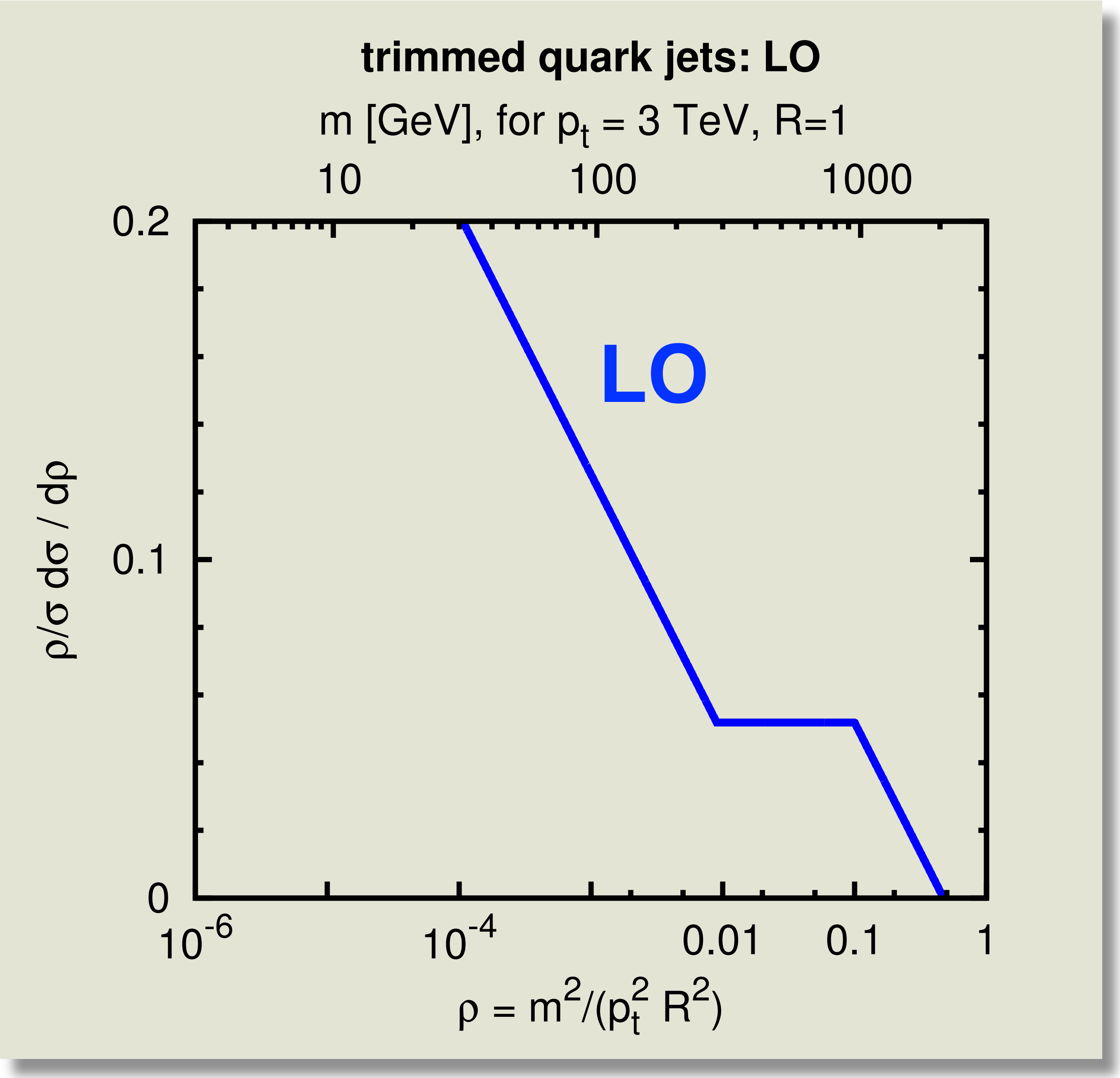
Matrix element

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

+ virtual corrections, essentially from unitarity

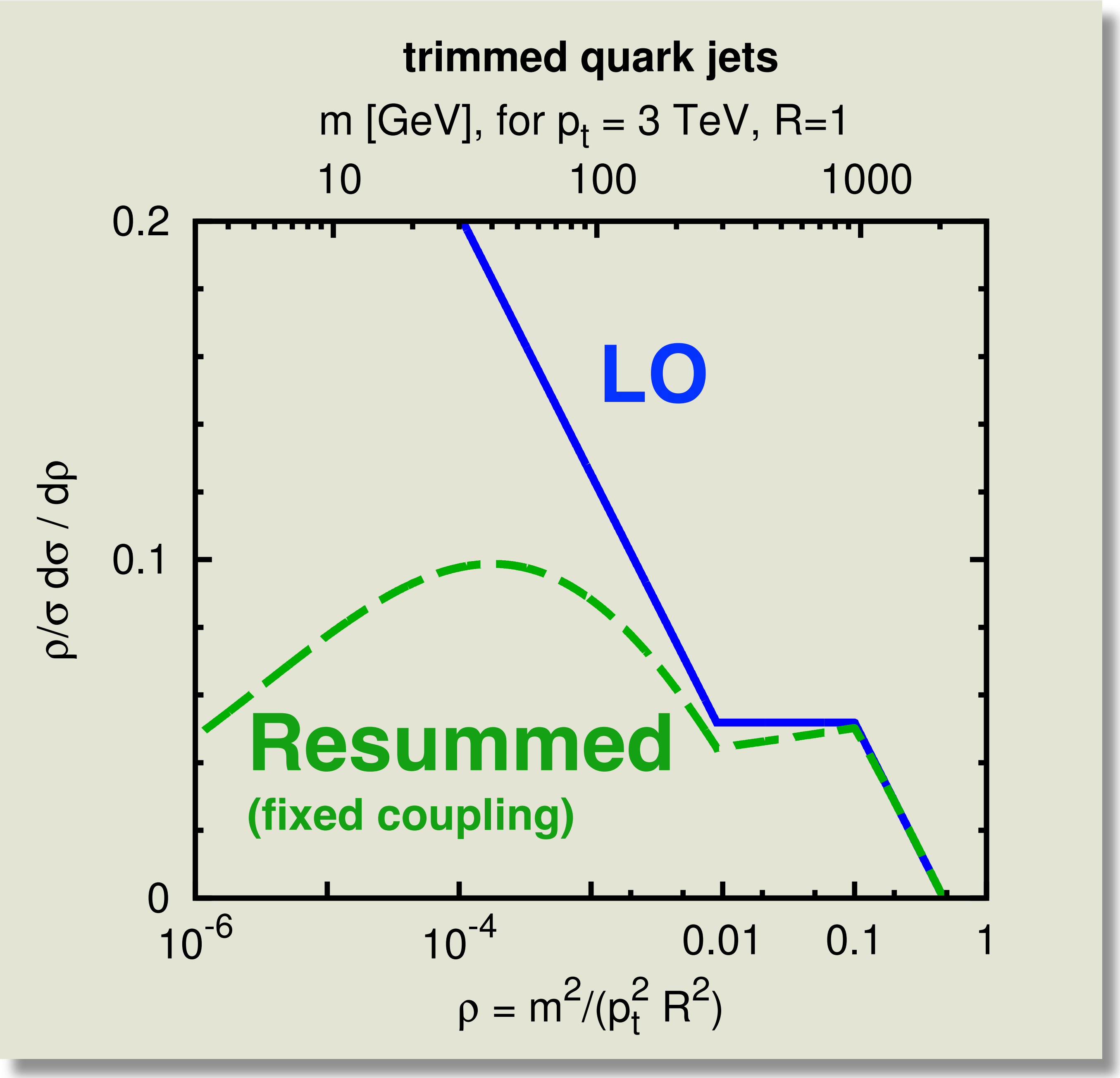
Trimming at all orders

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



Trimming at all orders

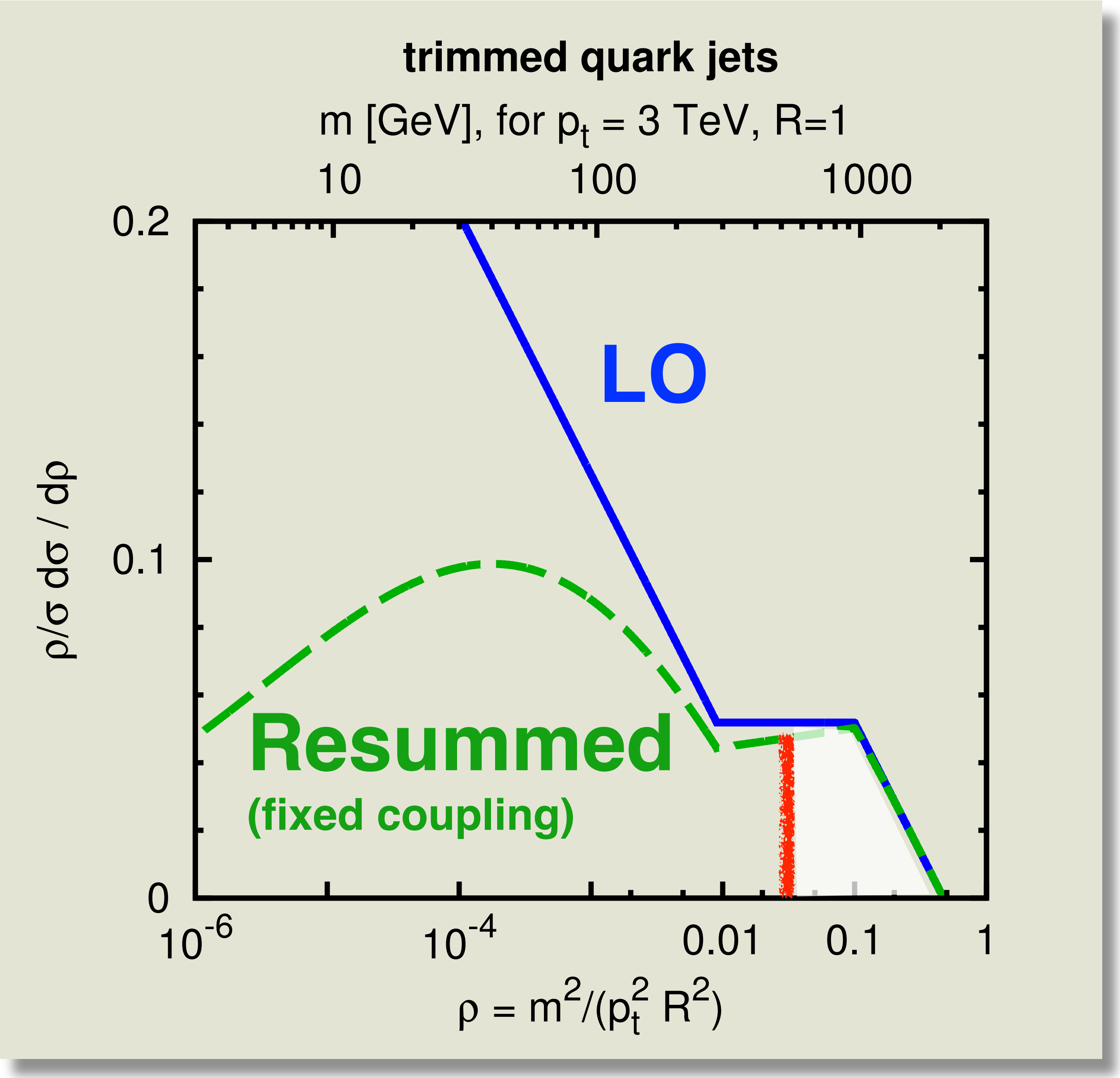
$$\frac{d\sigma^{\text{trim,resum}}}{d\rho} = \frac{d\sigma^{\text{trim,LO}}}{d\rho} \exp\left[-\int_\rho d\rho' \frac{1}{\sigma}\frac{d\sigma^{\text{trim,LO}}}{d\rho'}\right]$$

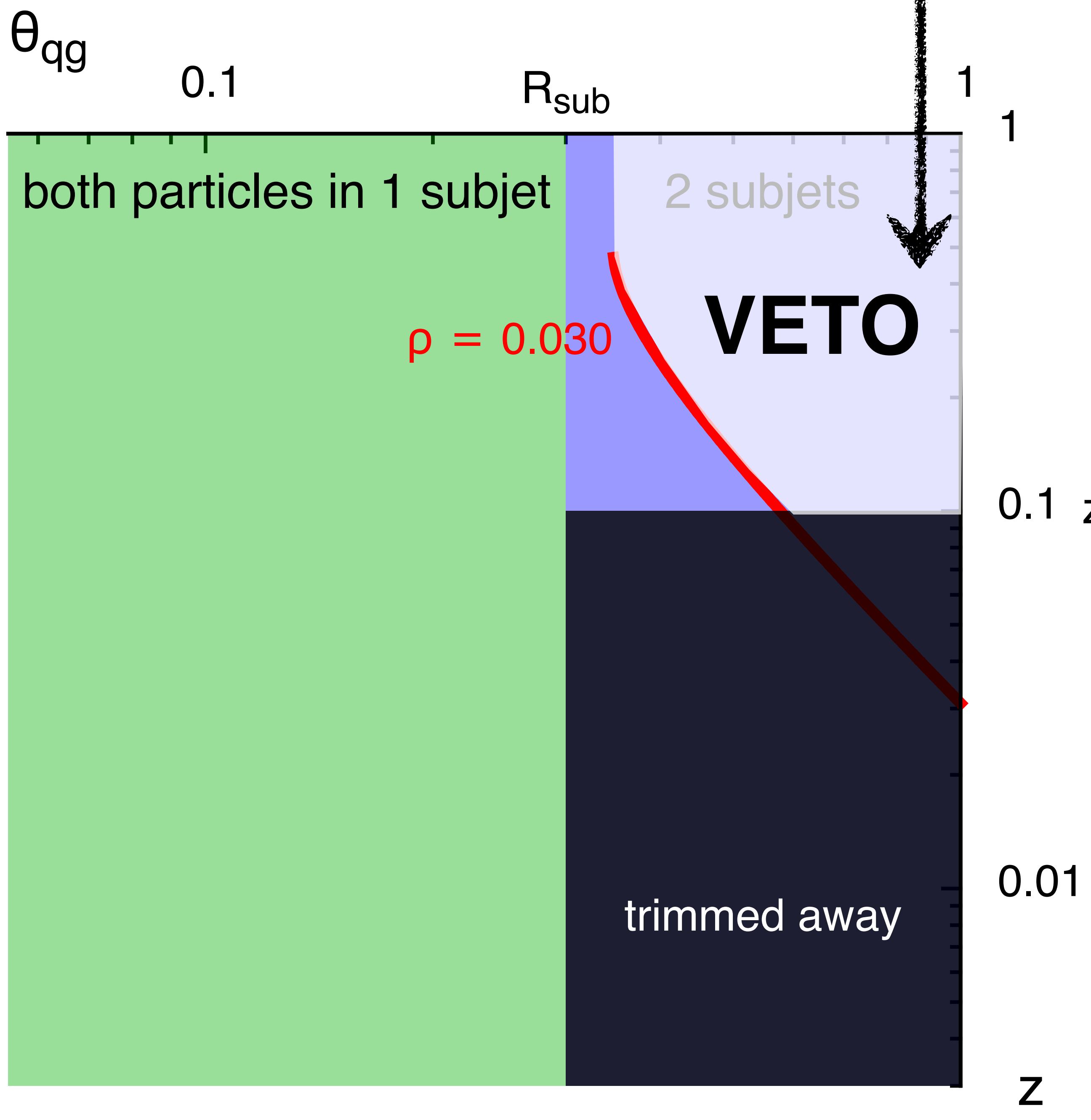


Trimming at all orders

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

Sudakov




θ_{qg}
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R_{sub}
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ρ = 0.030
VETO
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0.01
trimmed away
z

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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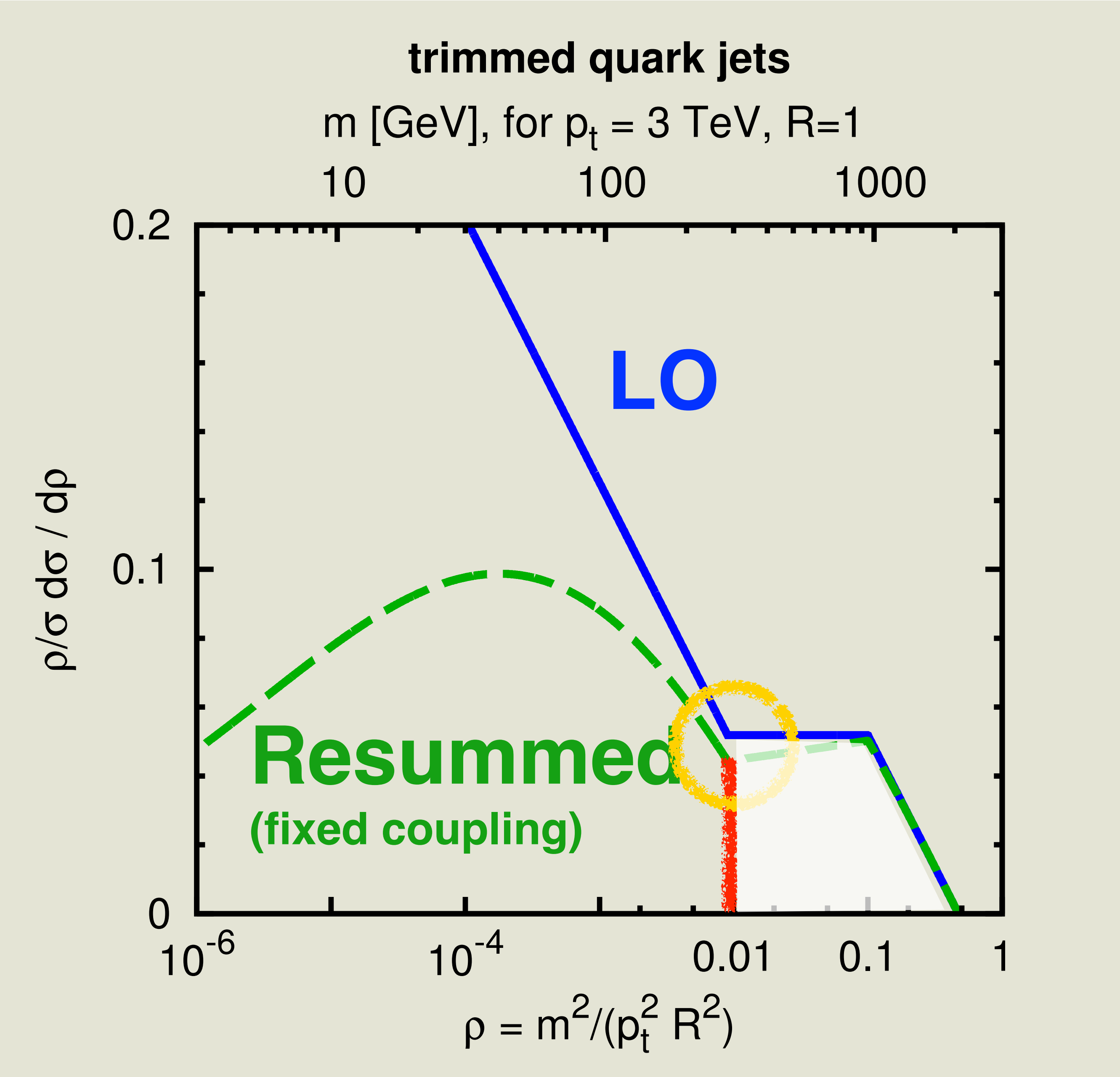

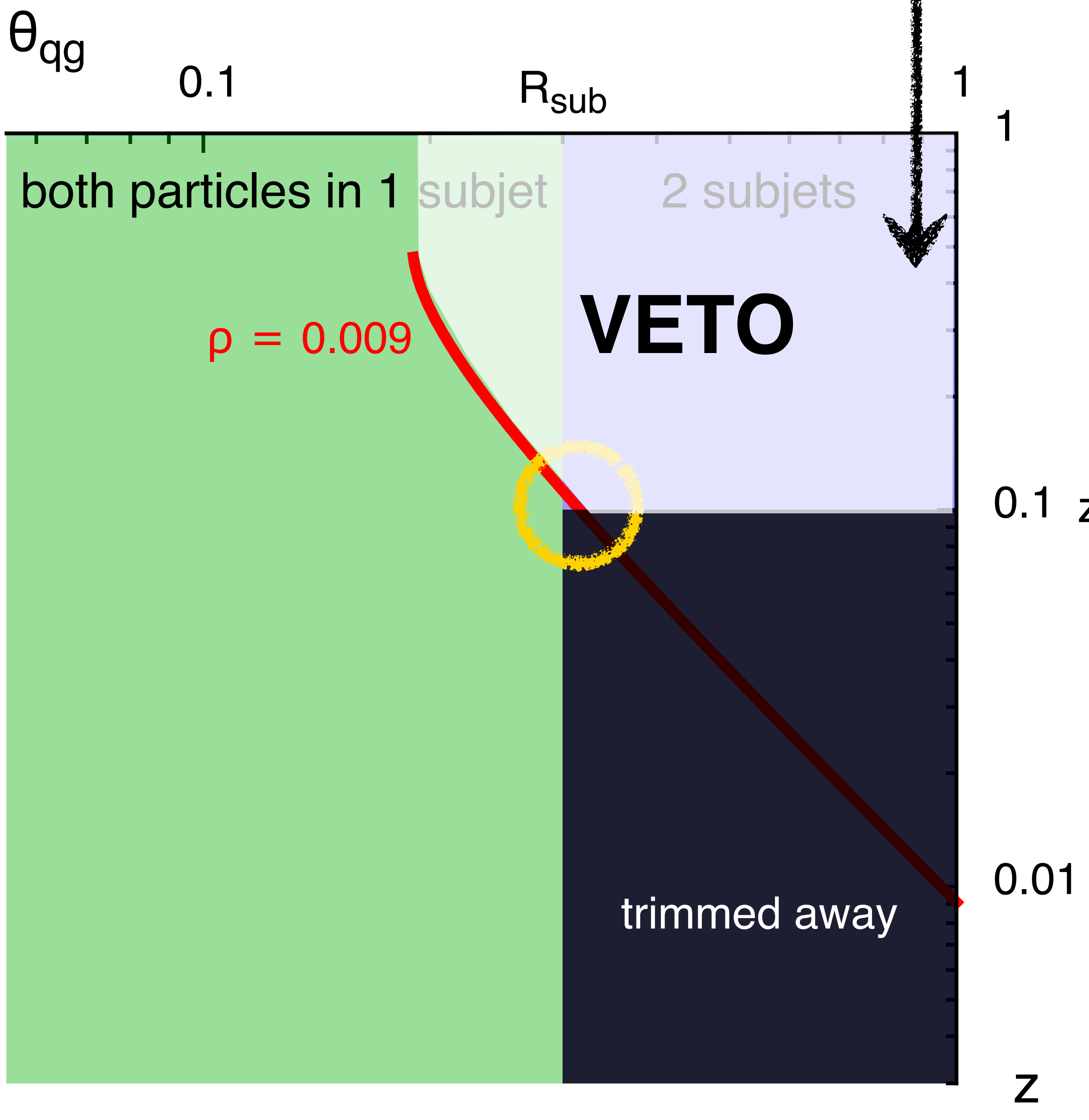
θ_{qg}
0.1
R_{sub}
1
1
both particles in 1 subjet
2 subjets
VETO
ρ = 0.009
0.1
0.01
trimmed away
z

Trimming at all orders

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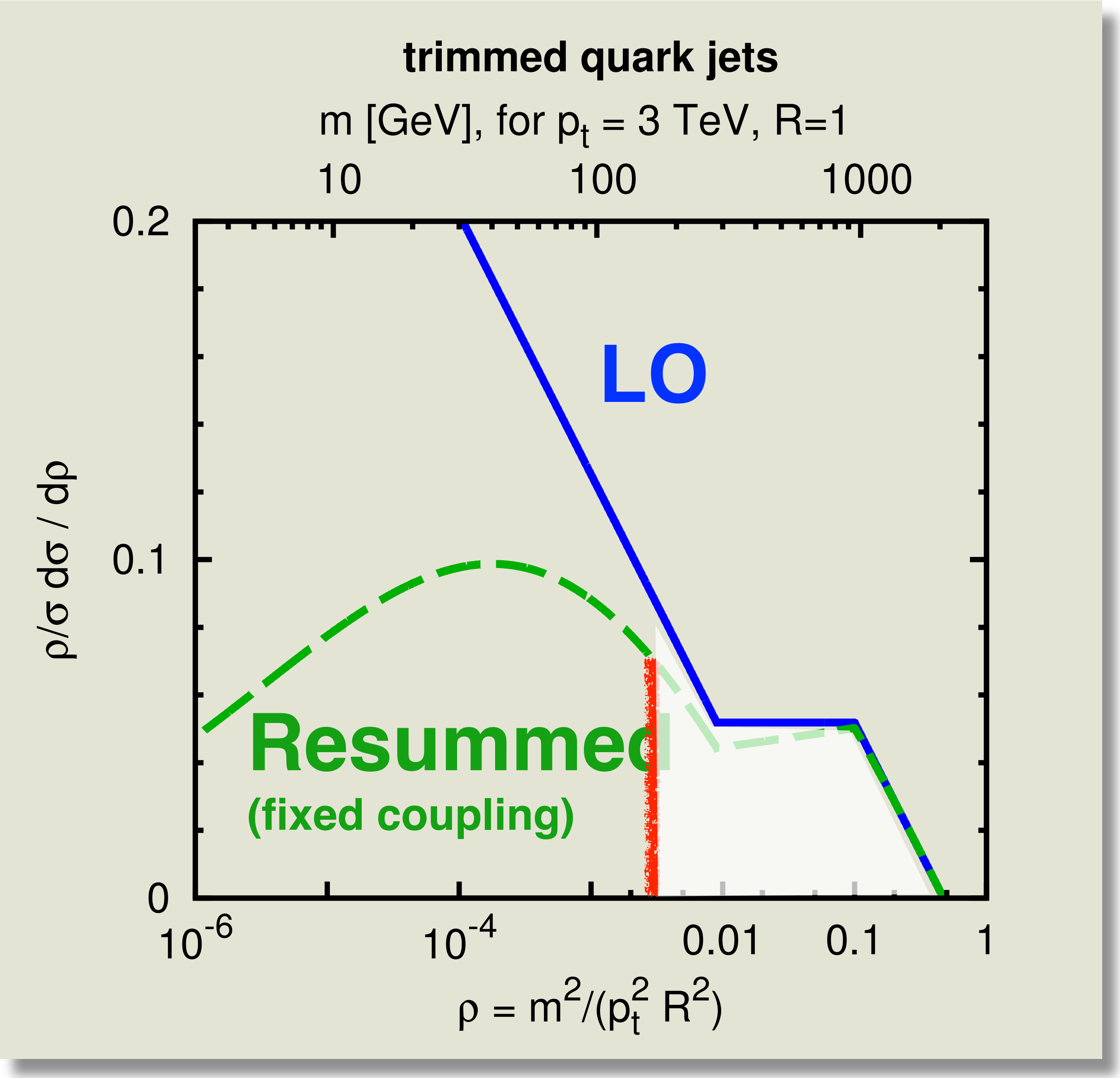
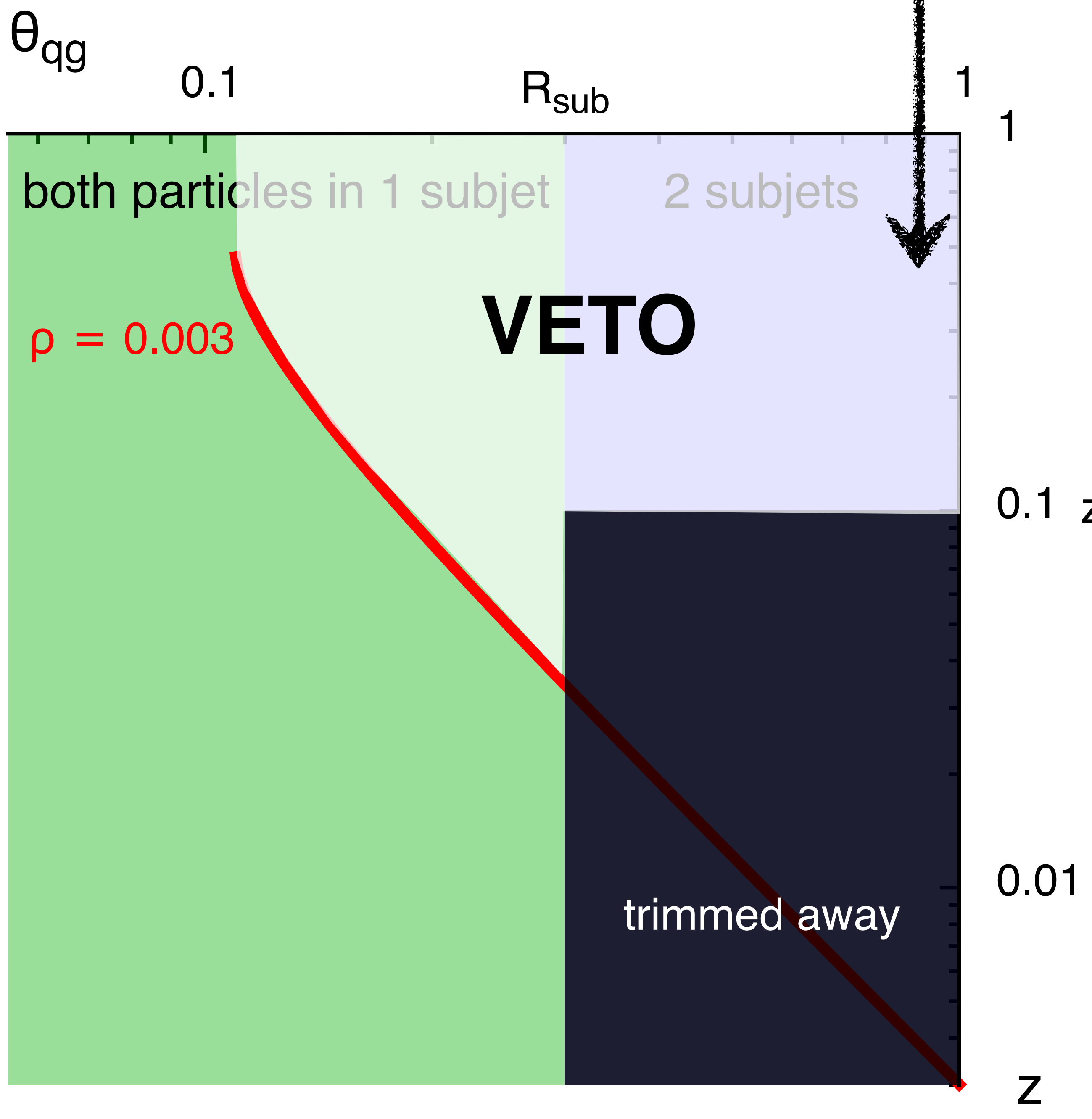
Sudakov

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R_{sub}
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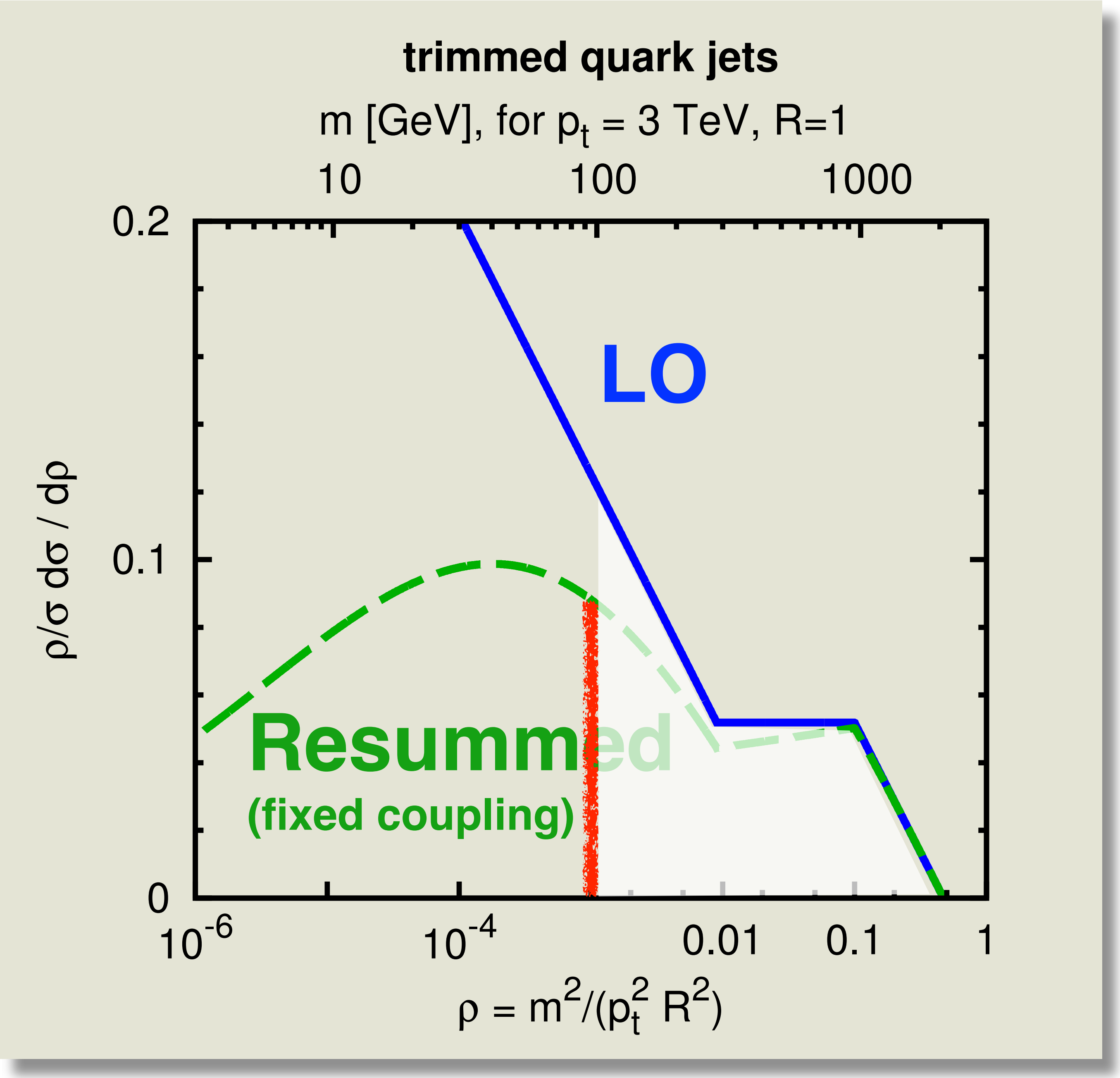
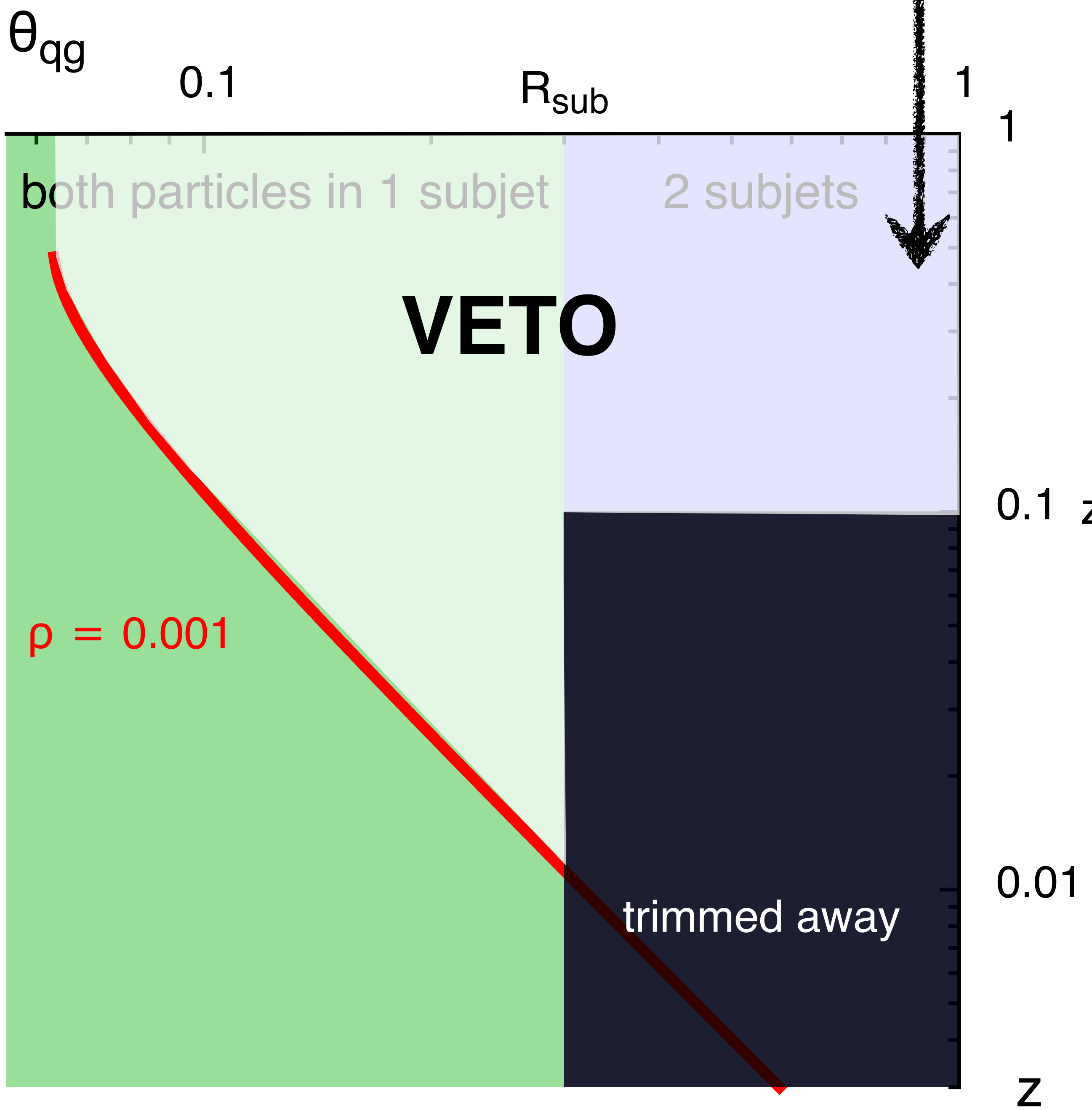
both particles in 1 subjet
2 subjets
ρ = 0.003
VETO
0.1
0.01
trimmed away
z

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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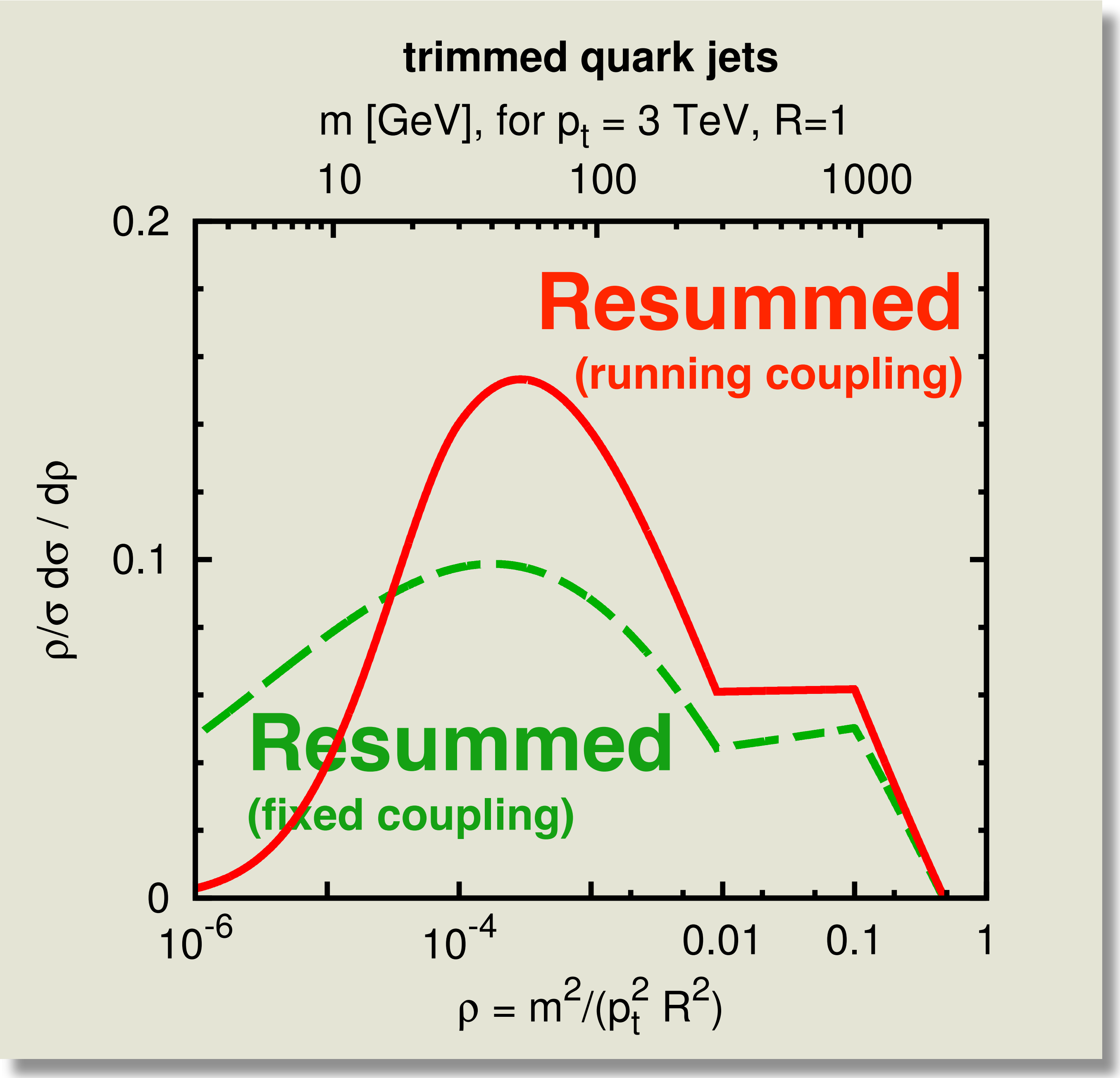
both particles in 1 subjet
2 subjets
VETO
ρ = 0.001
0.1
0.01
trimmed away
z

Trimming at all orders

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



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:

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

Just like the
jet mass

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

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:

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

Just like the jet mass

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

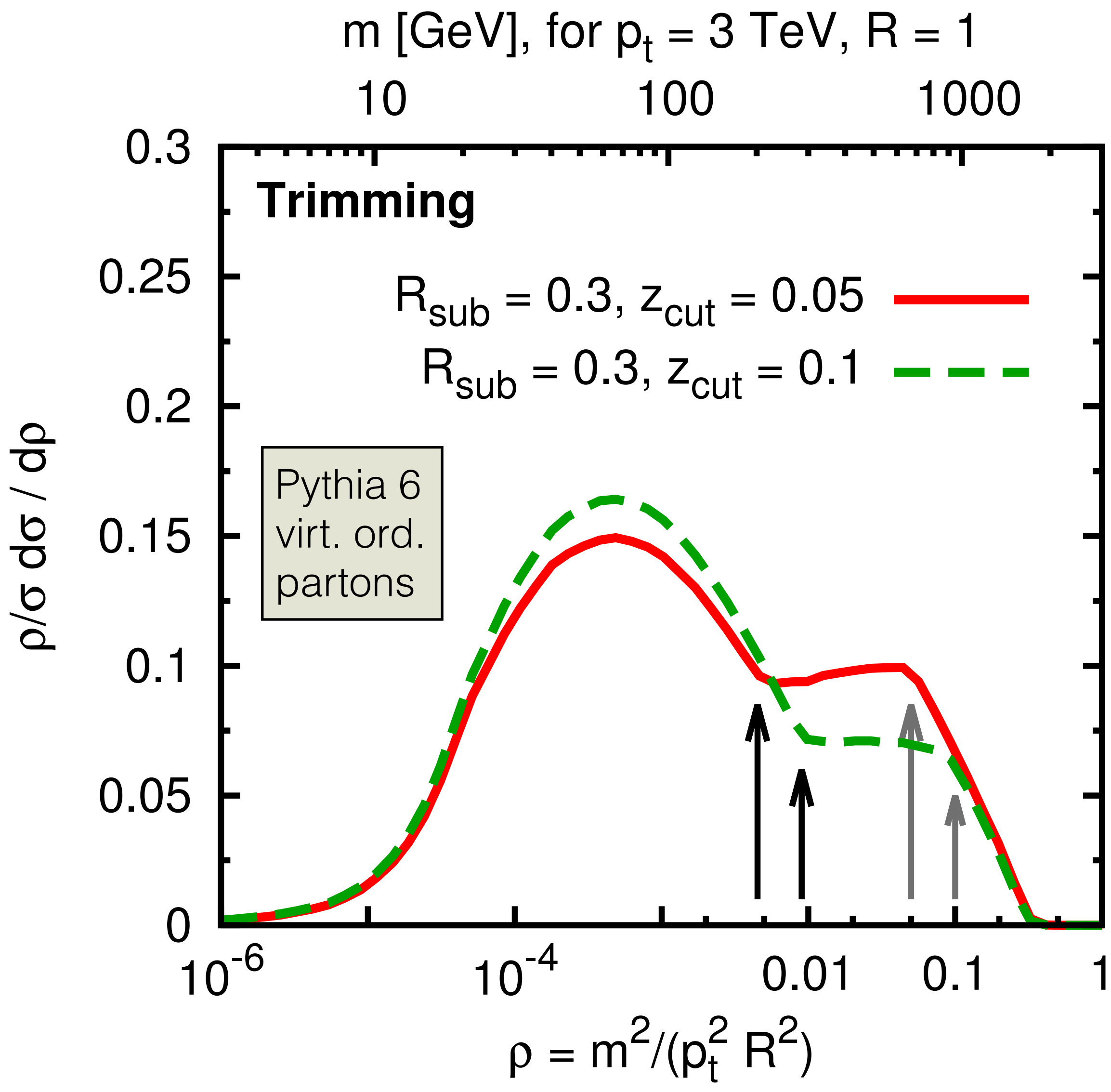
Could we do better? Yes: NLL in ln Σ:

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

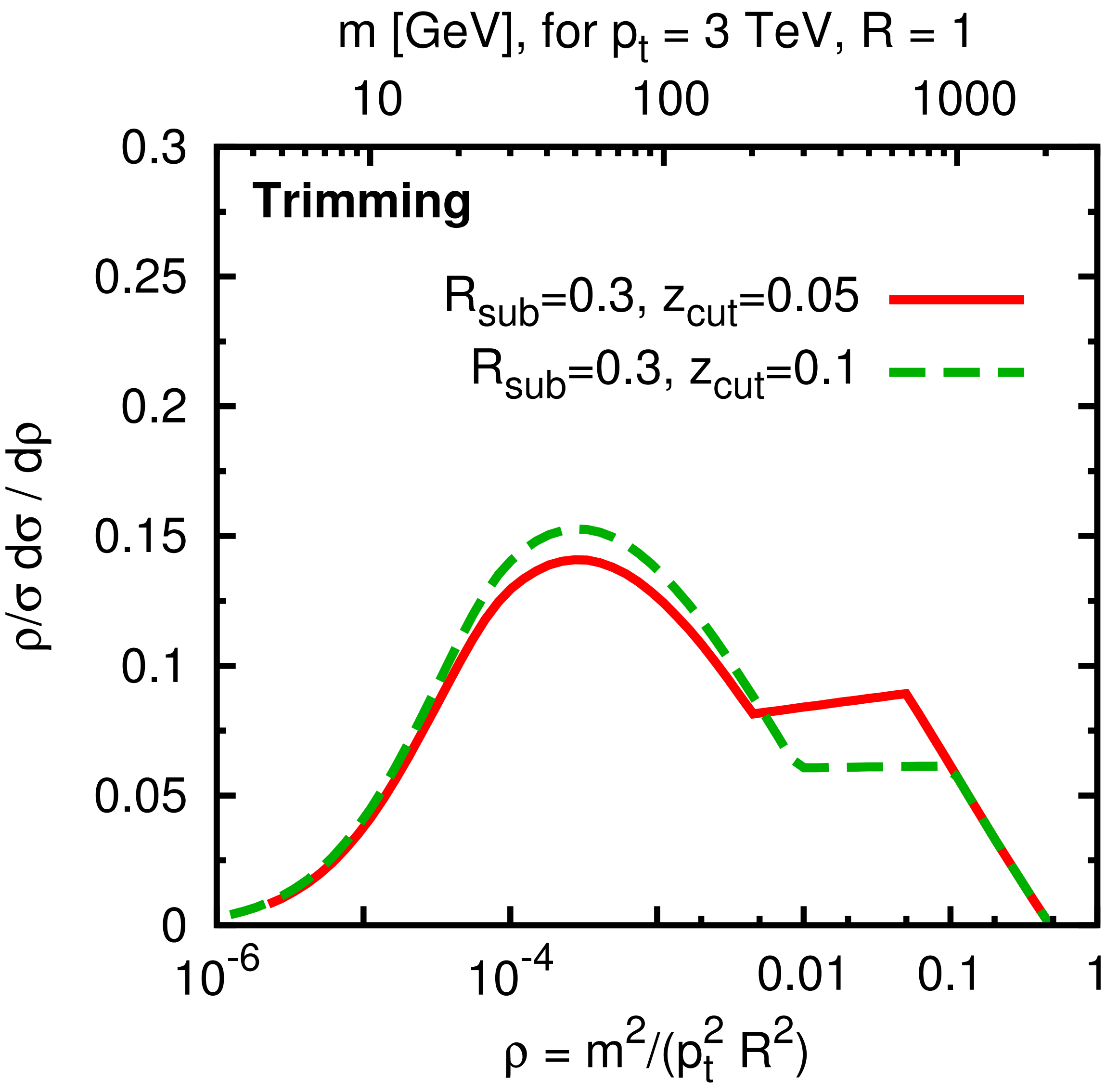
Trimmed mass is like plain jet mass (with R → R_{sub}), and this accuracy involves **non-global logs, clustering logs**

Trimming: MC v. analytics

Monte Carlo



Analytic



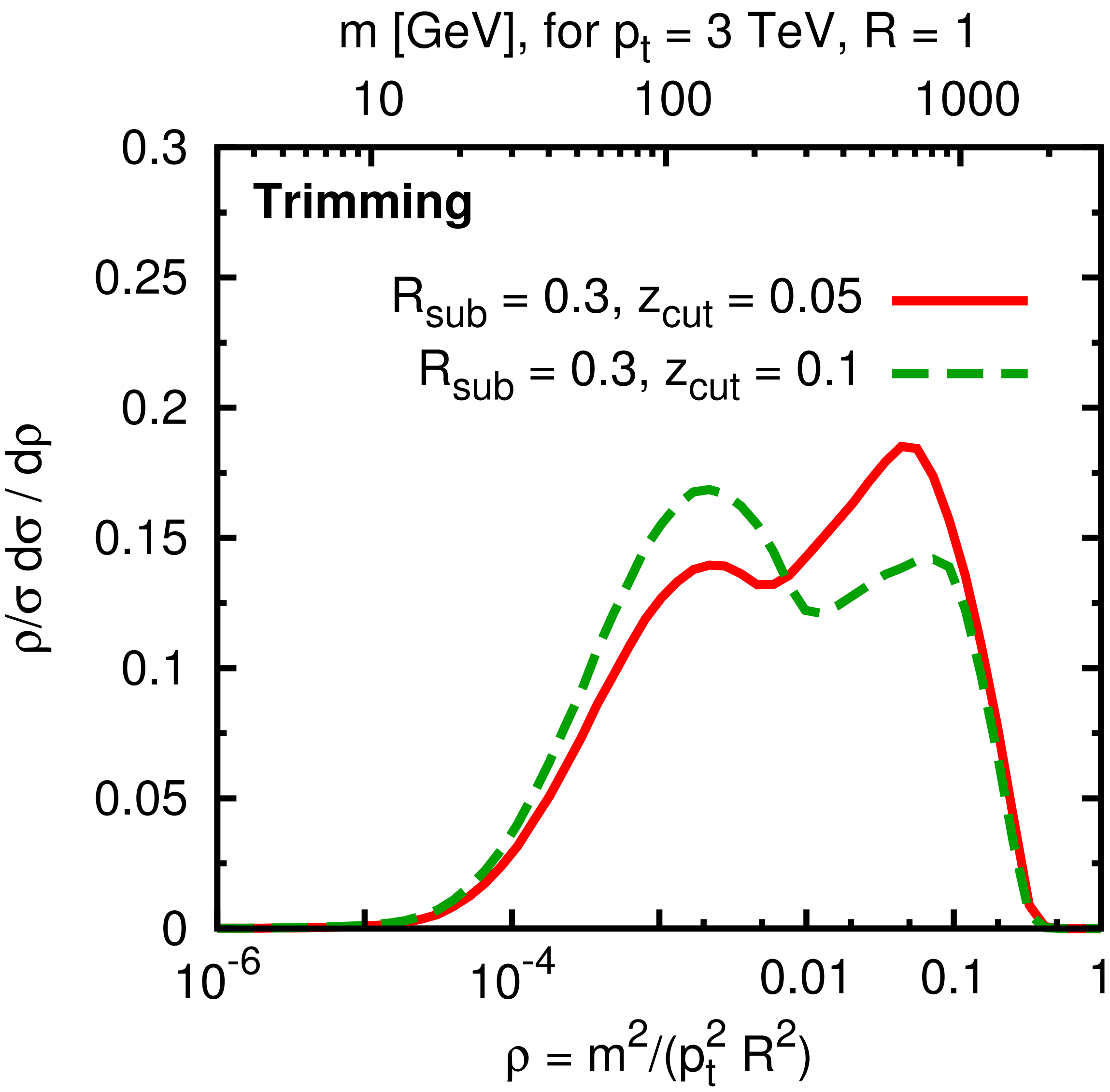
Non-trivial agreement!

(also for dependence on parameters)

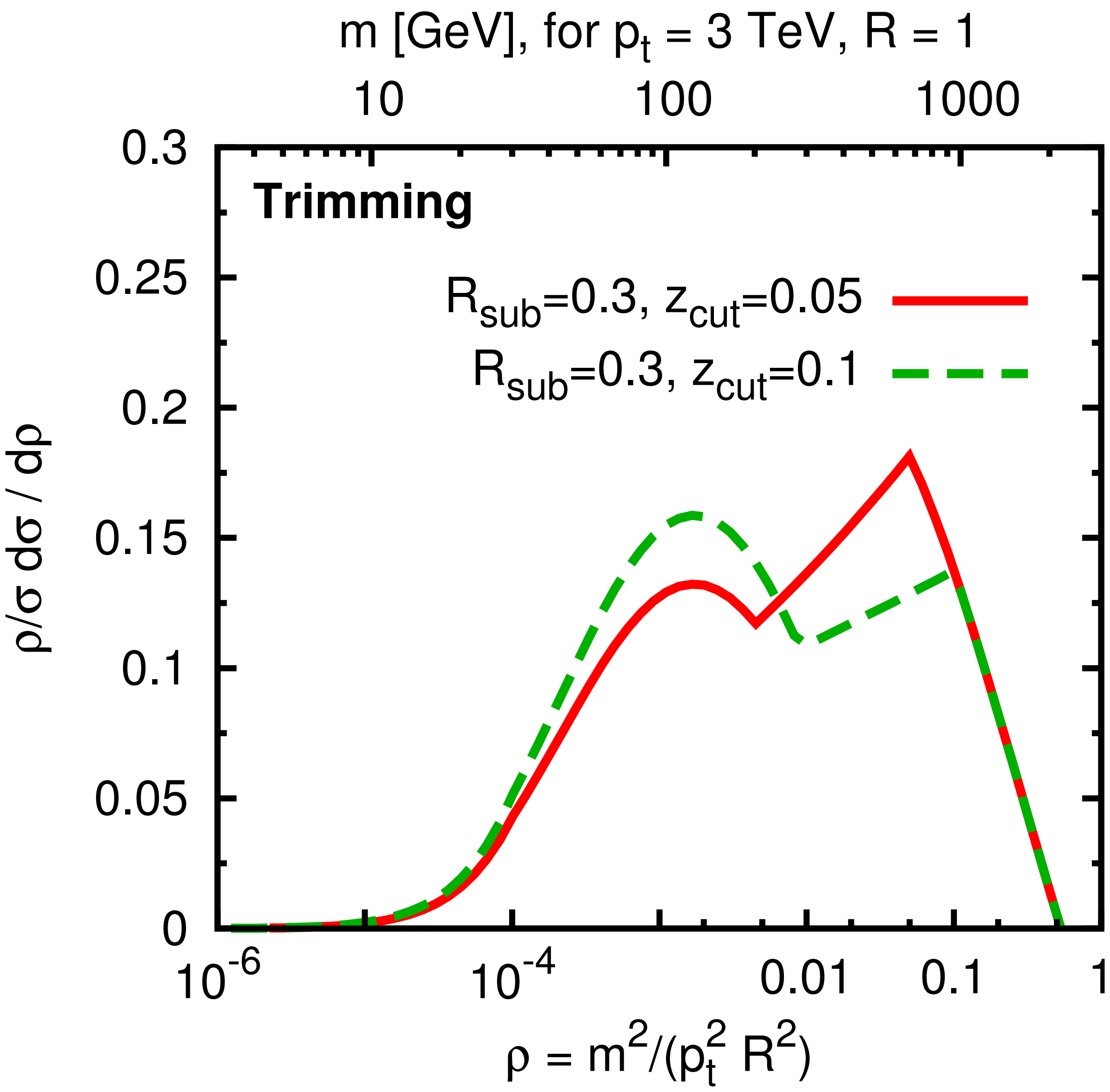
gluon jets

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

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

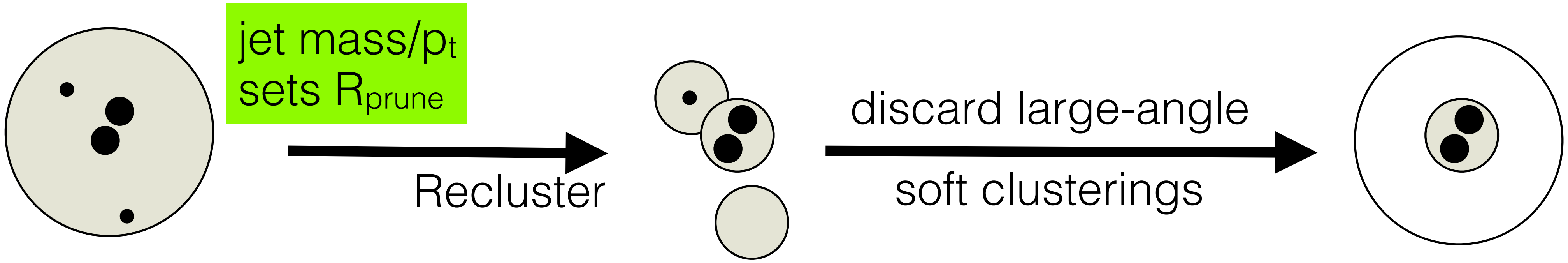
$$\Delta R_{ij} > R_{\text{prune}}$$

discard softer prong.

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

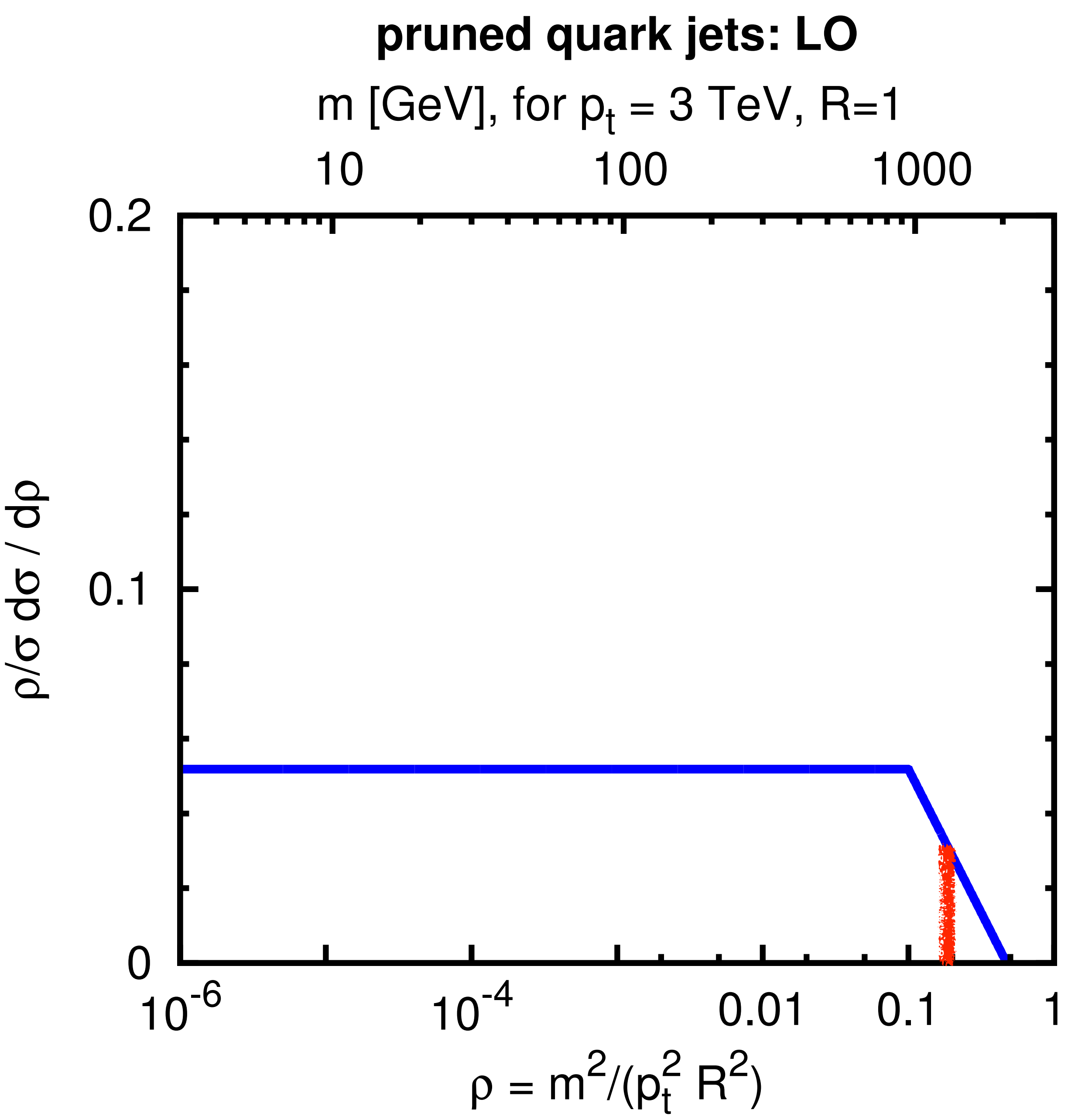
one (main) parameter: z_{cut}

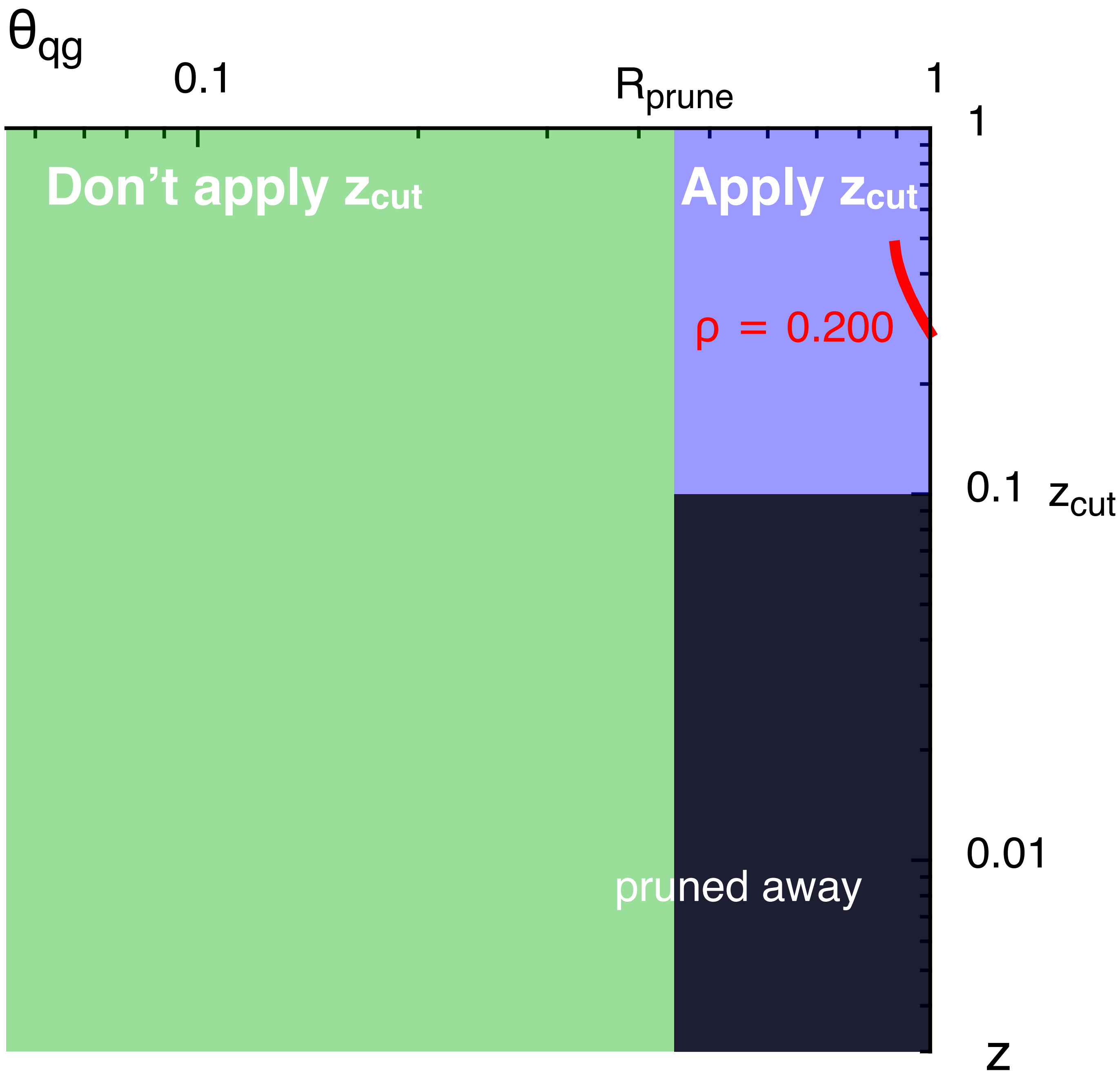
we’ll study variant with C/A reclustering


jet mass/p_t sets R_{prune}
Recluster
discard large-angle
soft clusterings

Pruning at LO

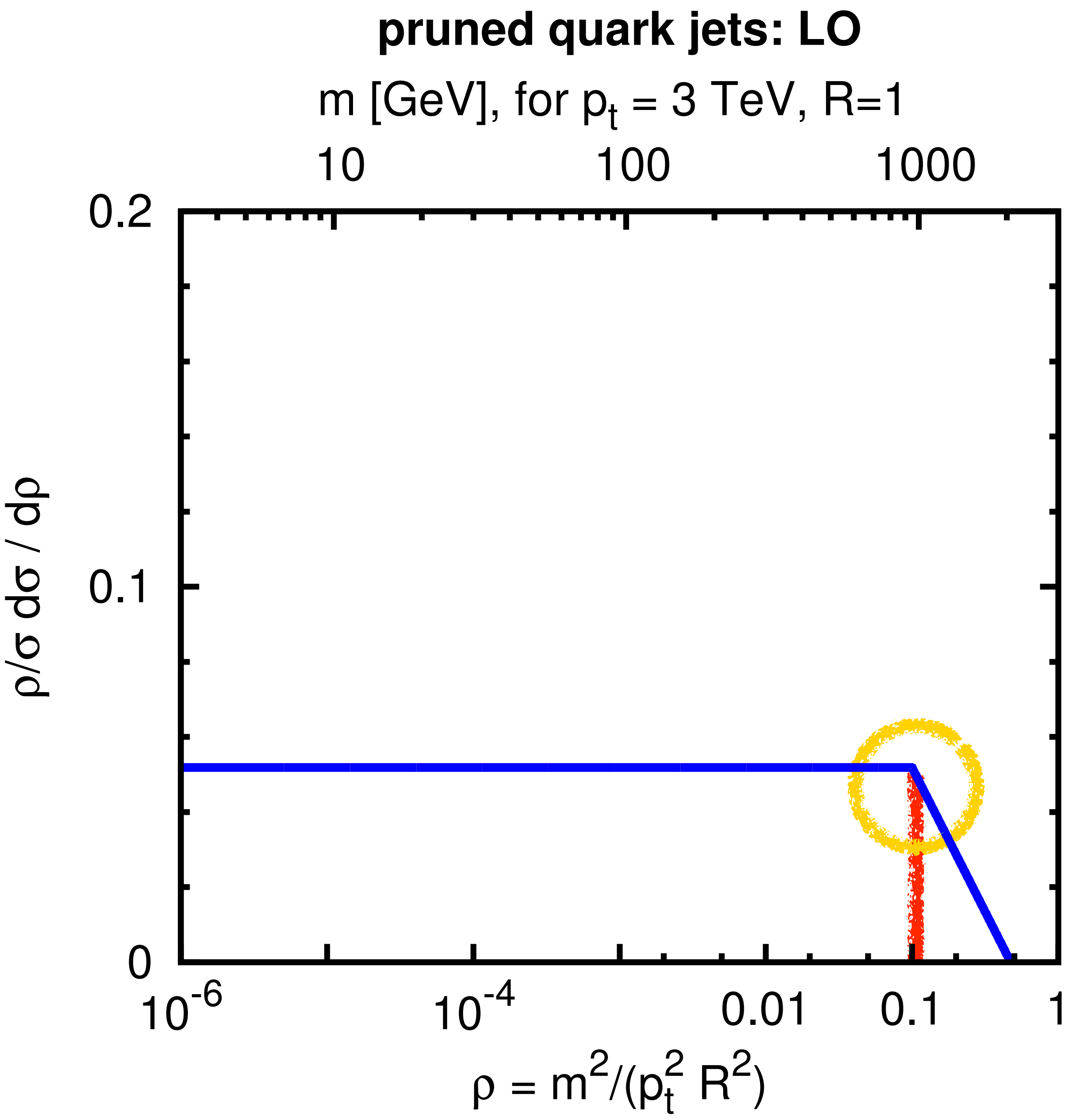
Dynamical choice of R_{prune} means that two prongs are always separated by > R_{prune}. So, unlike trimming, z_{cut} always applied.

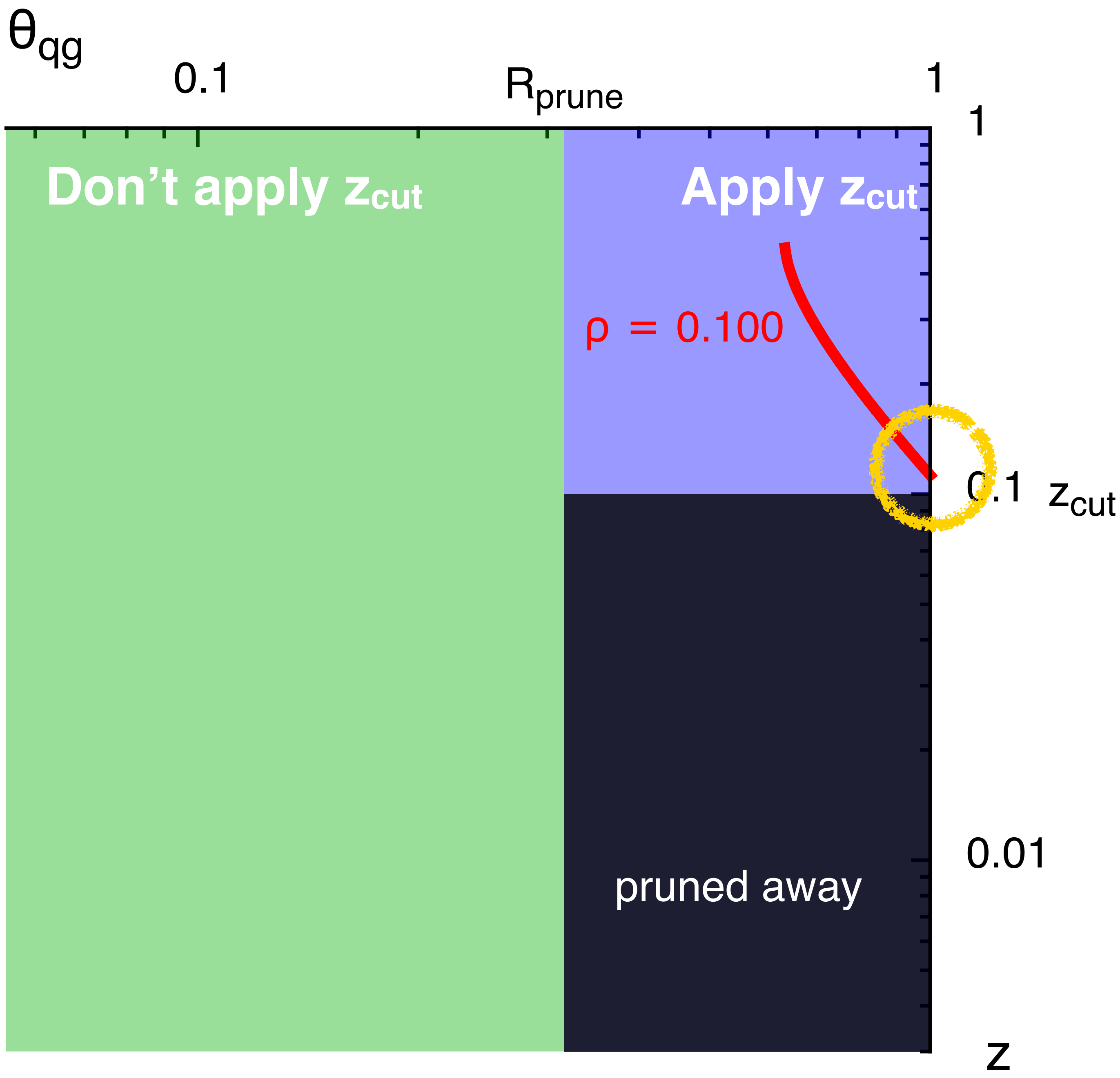



θ_{qg}
0.1
R_{prune}
1
1
Don't apply z_{cut}
Apply z_{cut}
$\rho = 0.200$
0.1
z_{cut}
0.01
pruned away
z

Pruning at LO

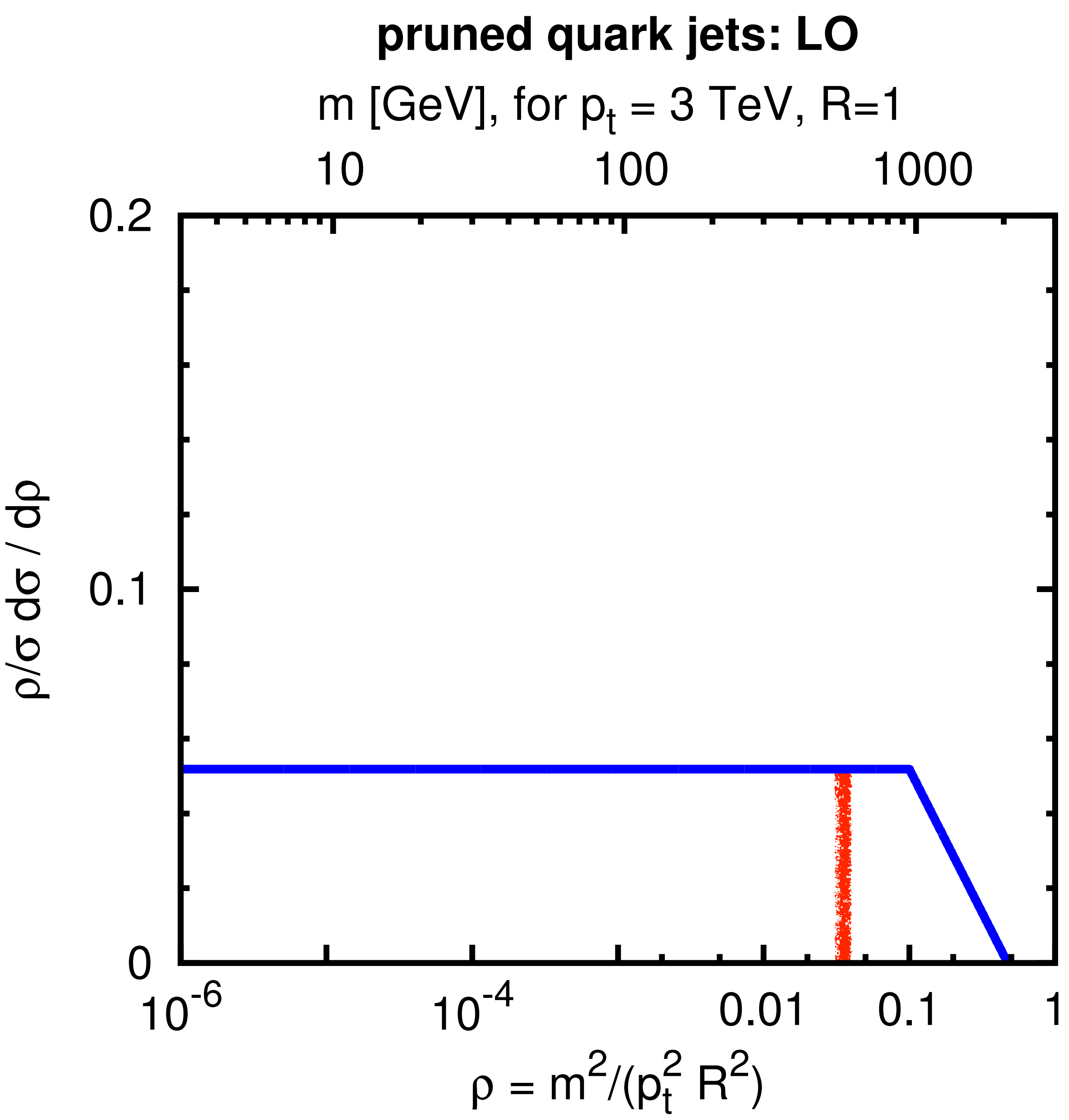
Dynamical choice of R_{prune} means that two prongs are always separated by > R_{prune}. So, unlike trimming, z_{cut} always applied.

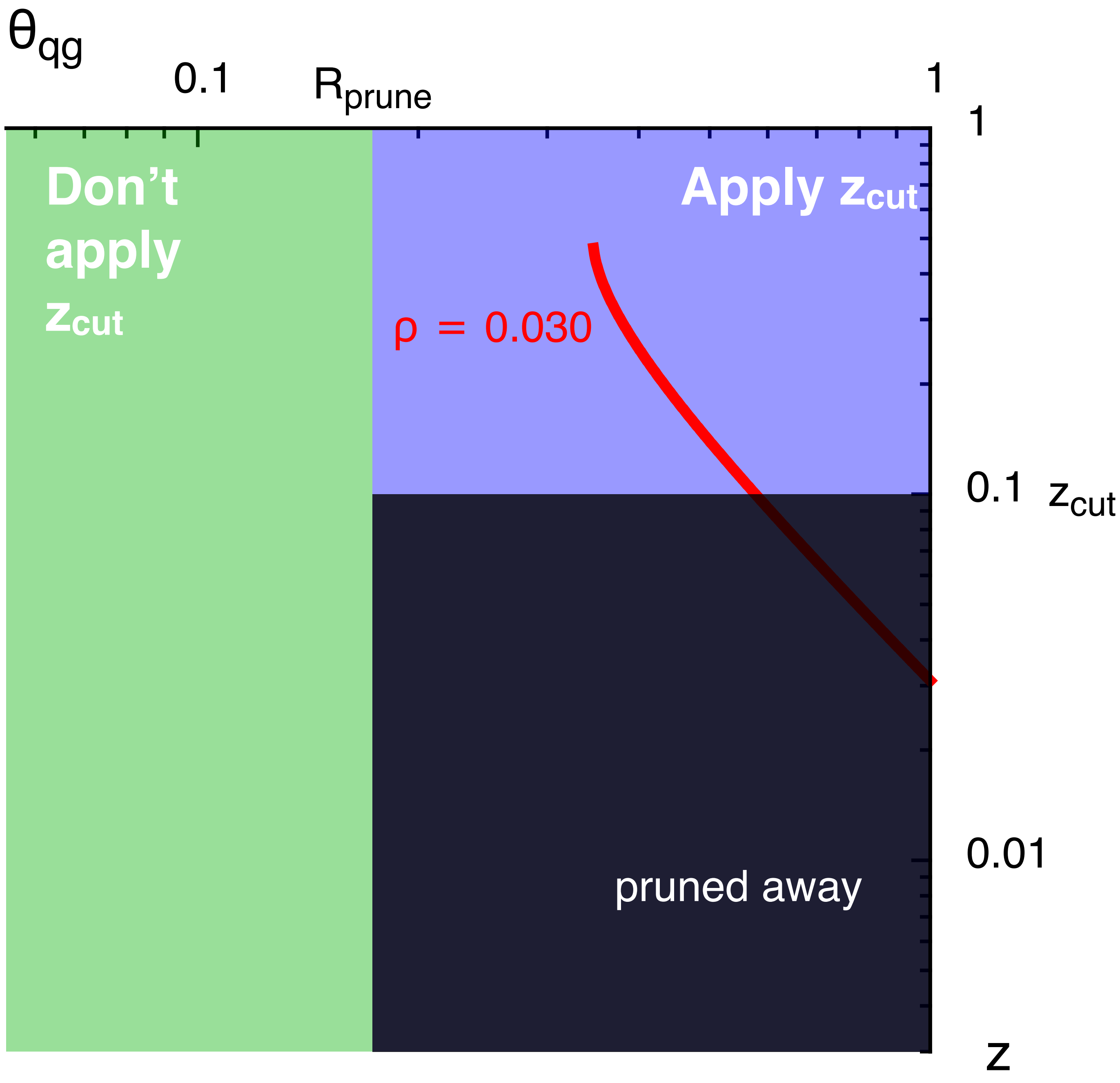



θ_qg
0.1
R_prune
1
1
Don't apply z_cut
Apply z_cut
ρ = 0.100
0.1
z_cut
0.01
pruned away
z

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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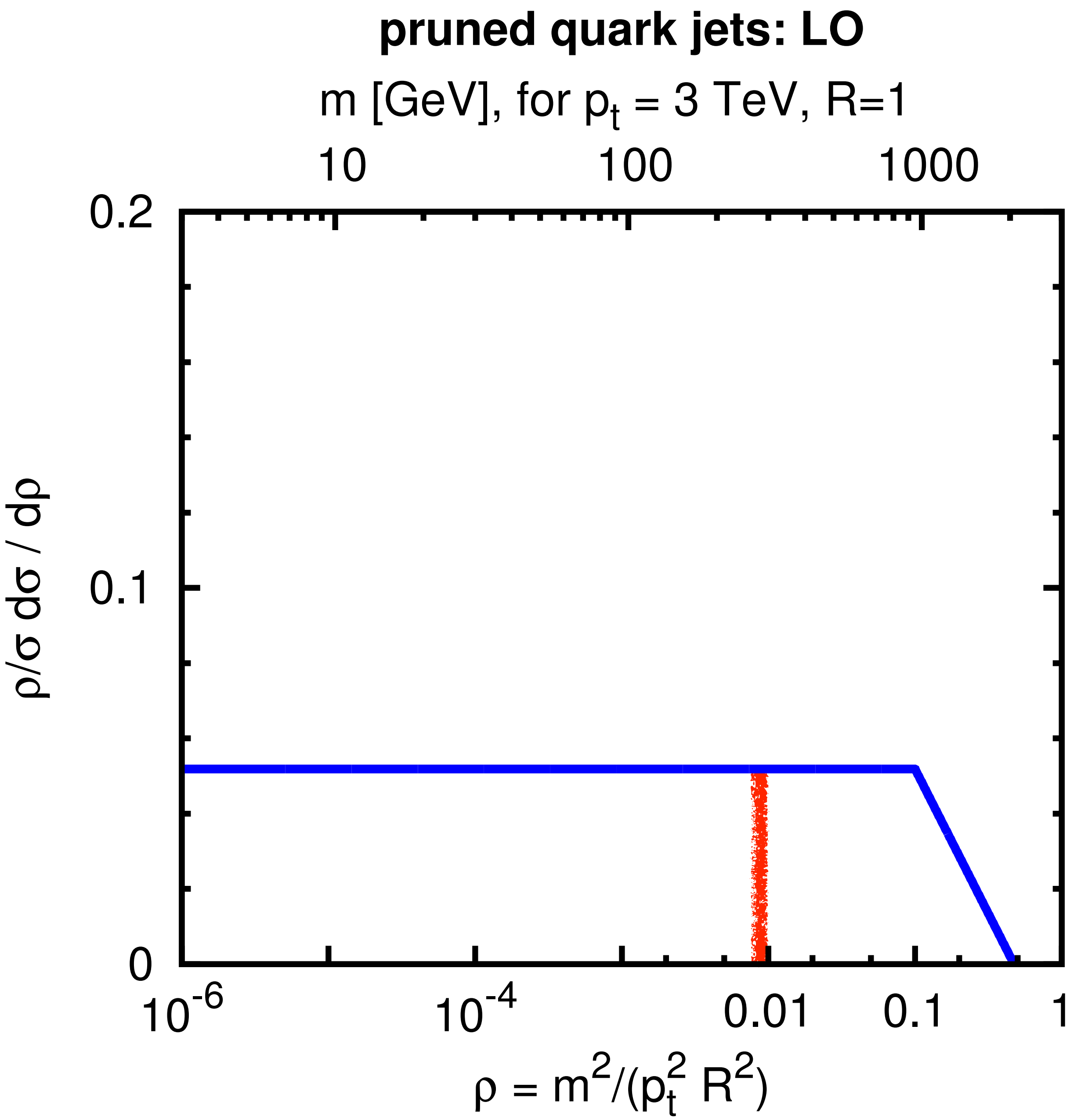

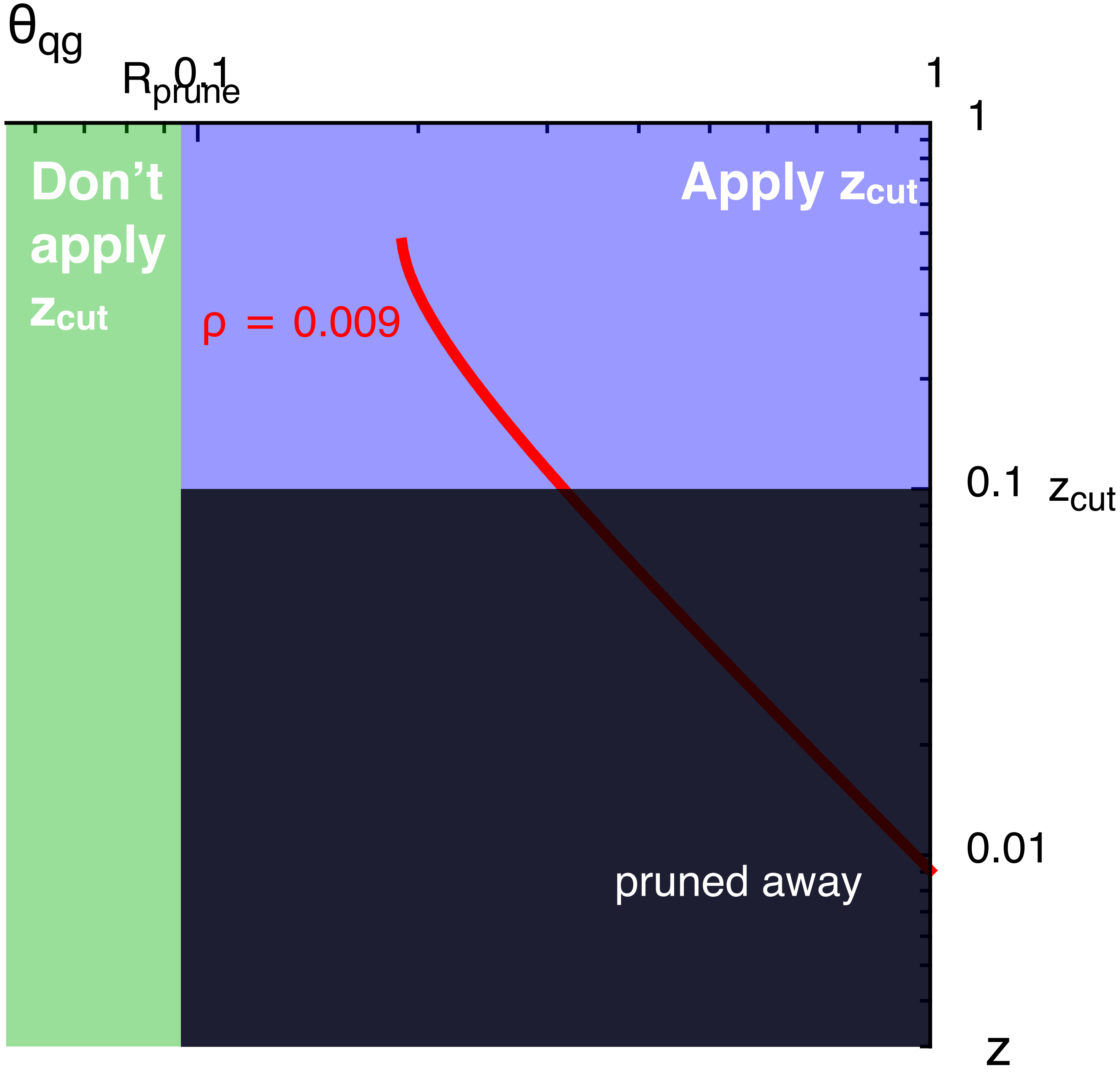
θ$_{qg}$
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0.1
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Don't apply z$_{cut}$
Apply z$_{cut}$
ρ = 0.009
0.1
z$_{cut}$
0.01
pruned away
z

Pruning at LO

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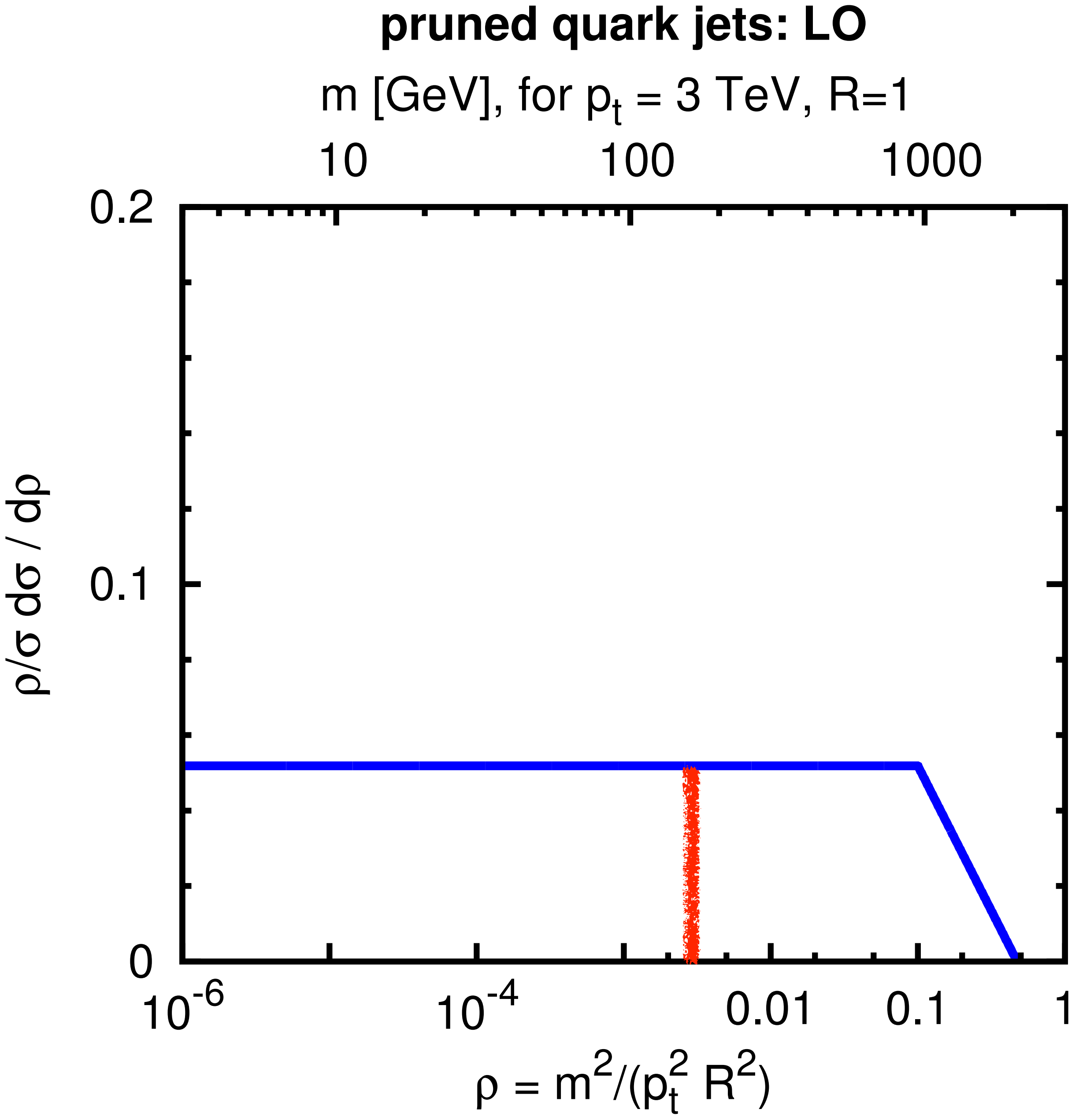

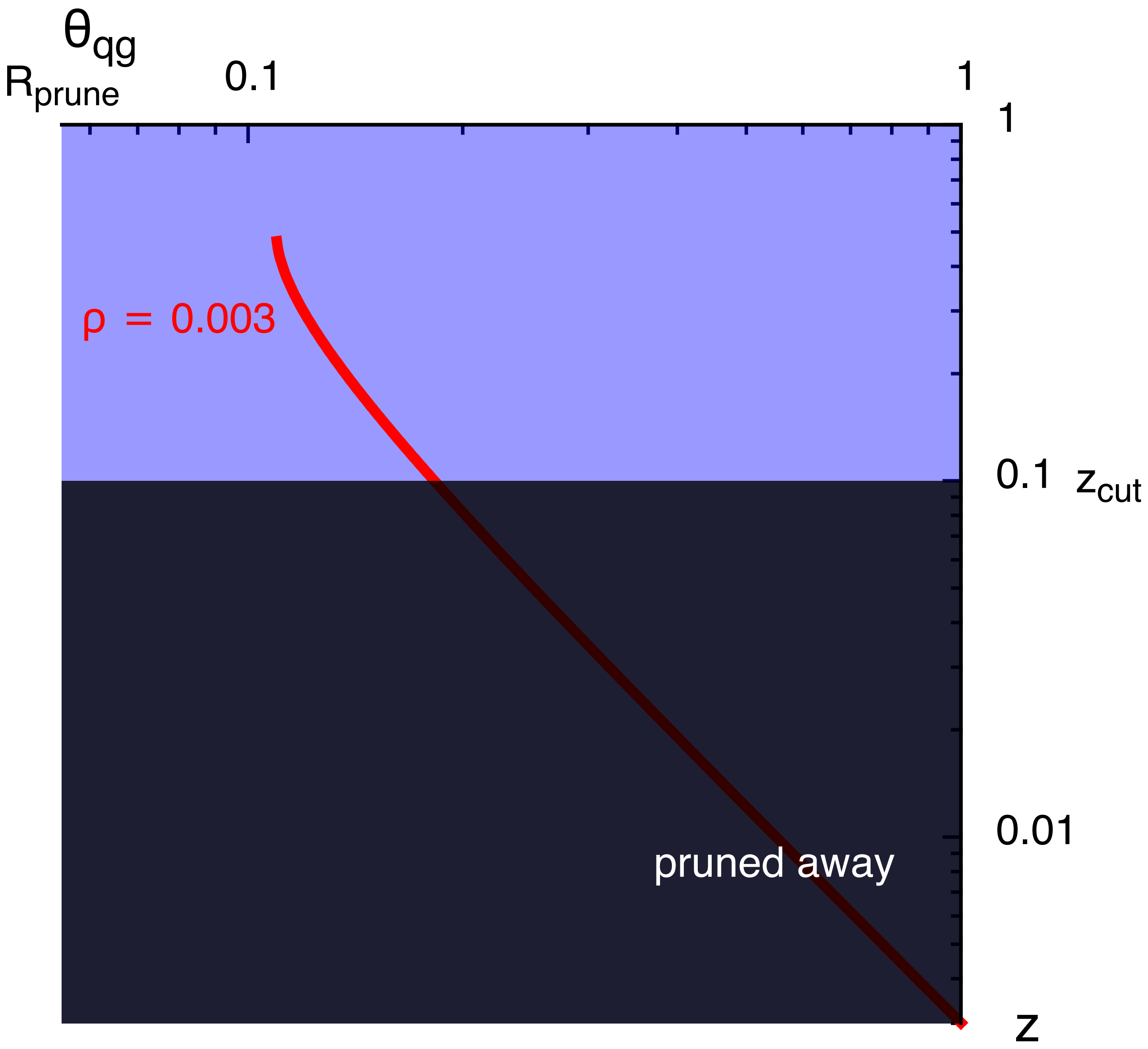

Pruning at LO

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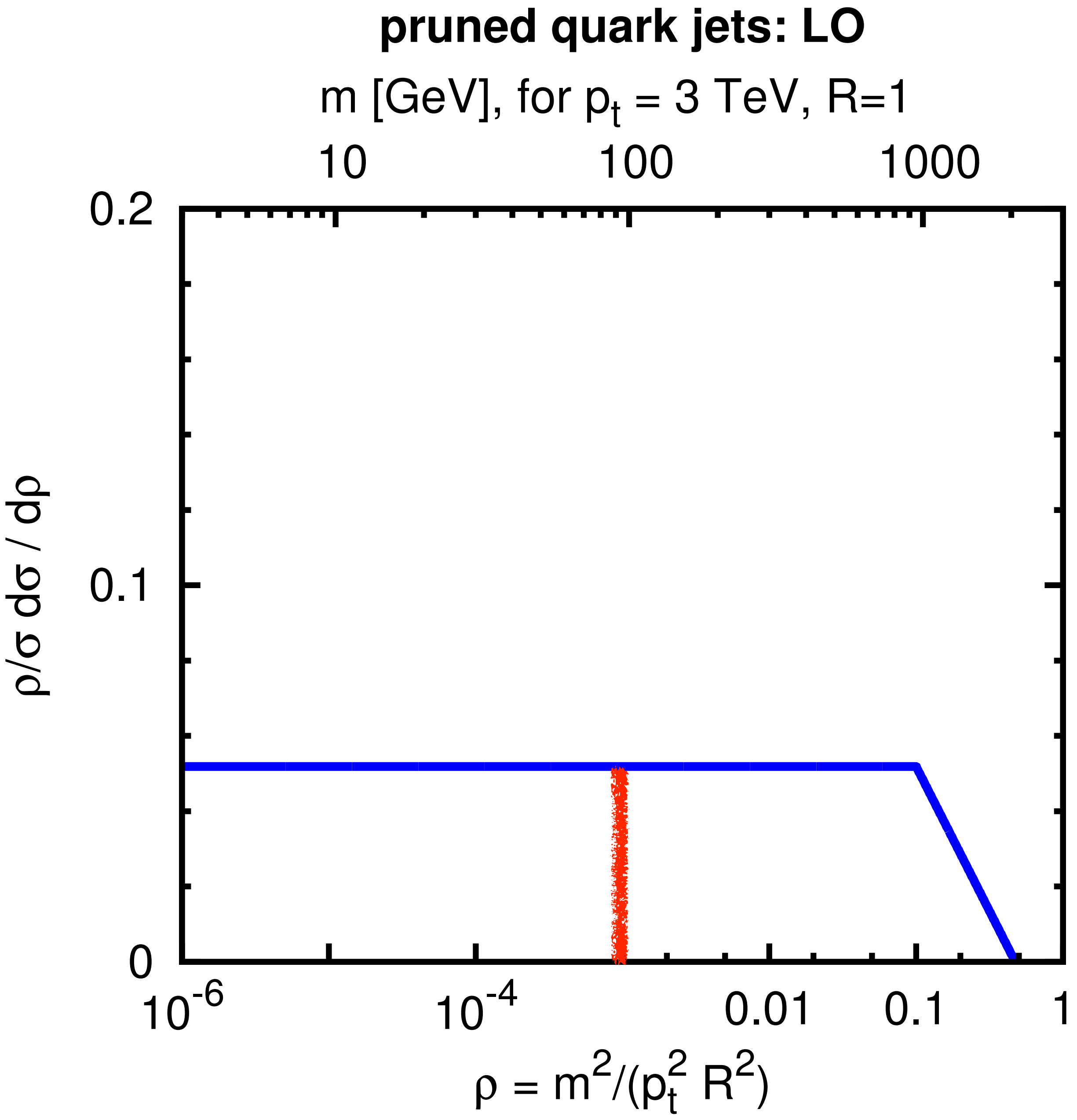
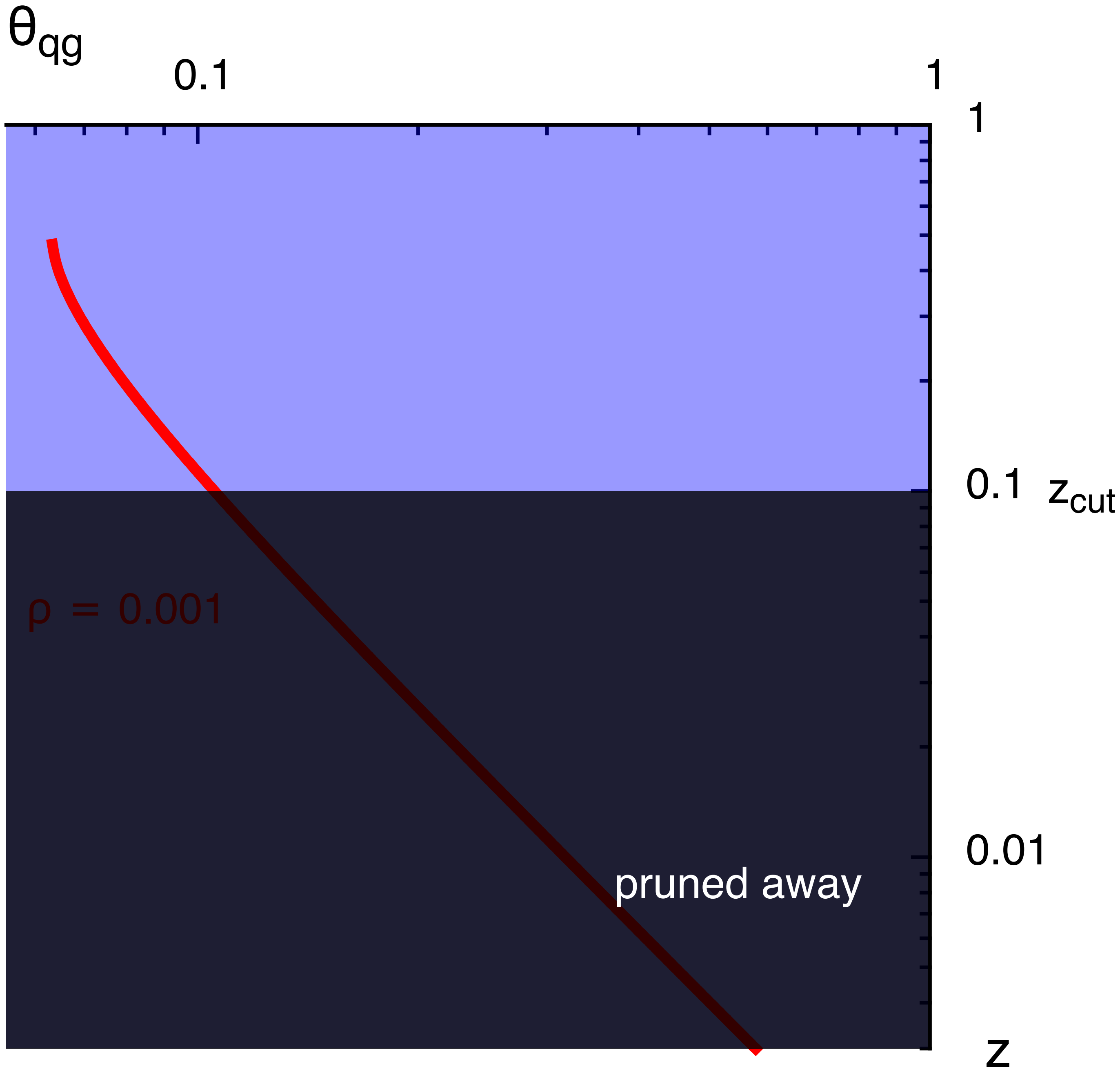
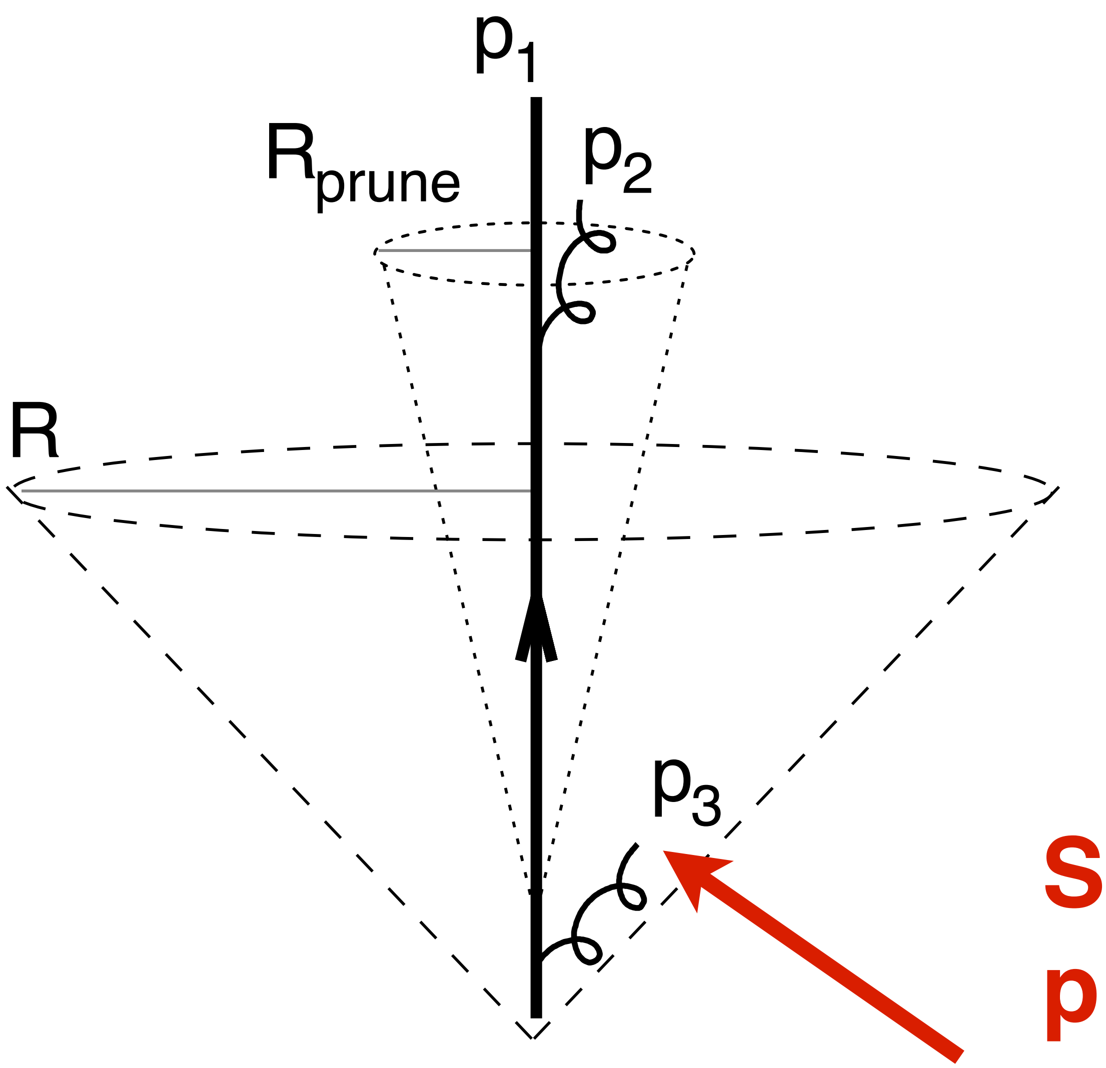




pruning beyond 1st order: consider multiple emissions



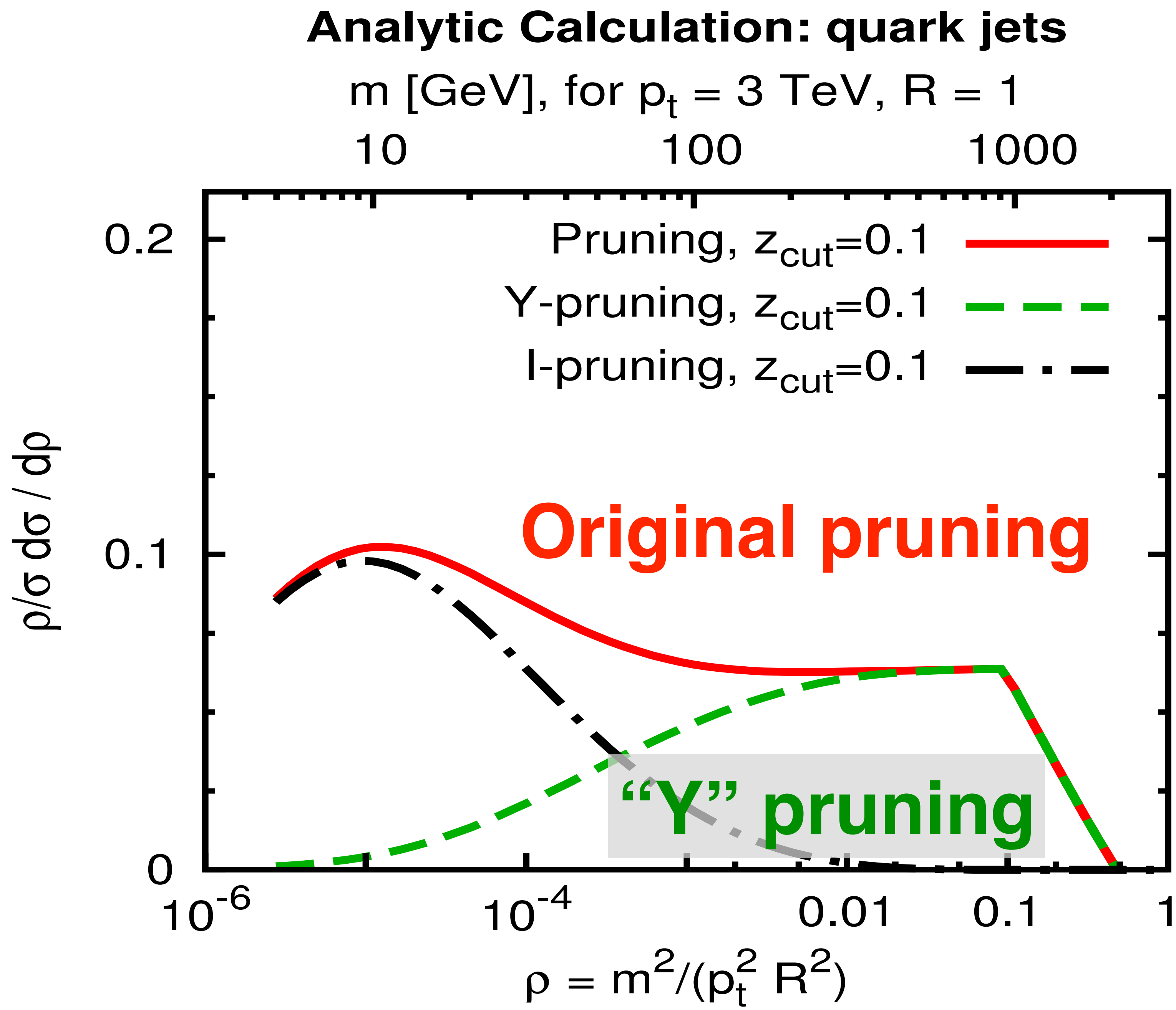
What pruning sometimes does

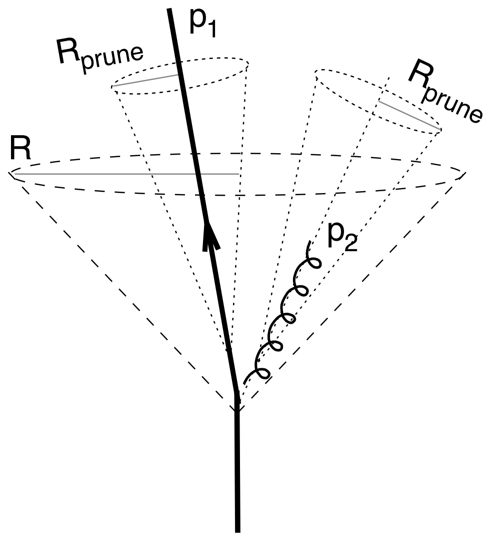
Chooses R_{prune} based on a soft p_3 (dominates total jet mass), and leads to a single narrow subjet whose mass is also dominated by a soft emission (p_2, within R_{prune} of p_1, so not pruned away).

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 $\Delta R > R_{\text{prune}}$ and $z > z_{\text{cut}}$ — forces 2-pronged (“Y”) configurations





R_{prune}
p_1
R_{prune}
R
p_2

“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:

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

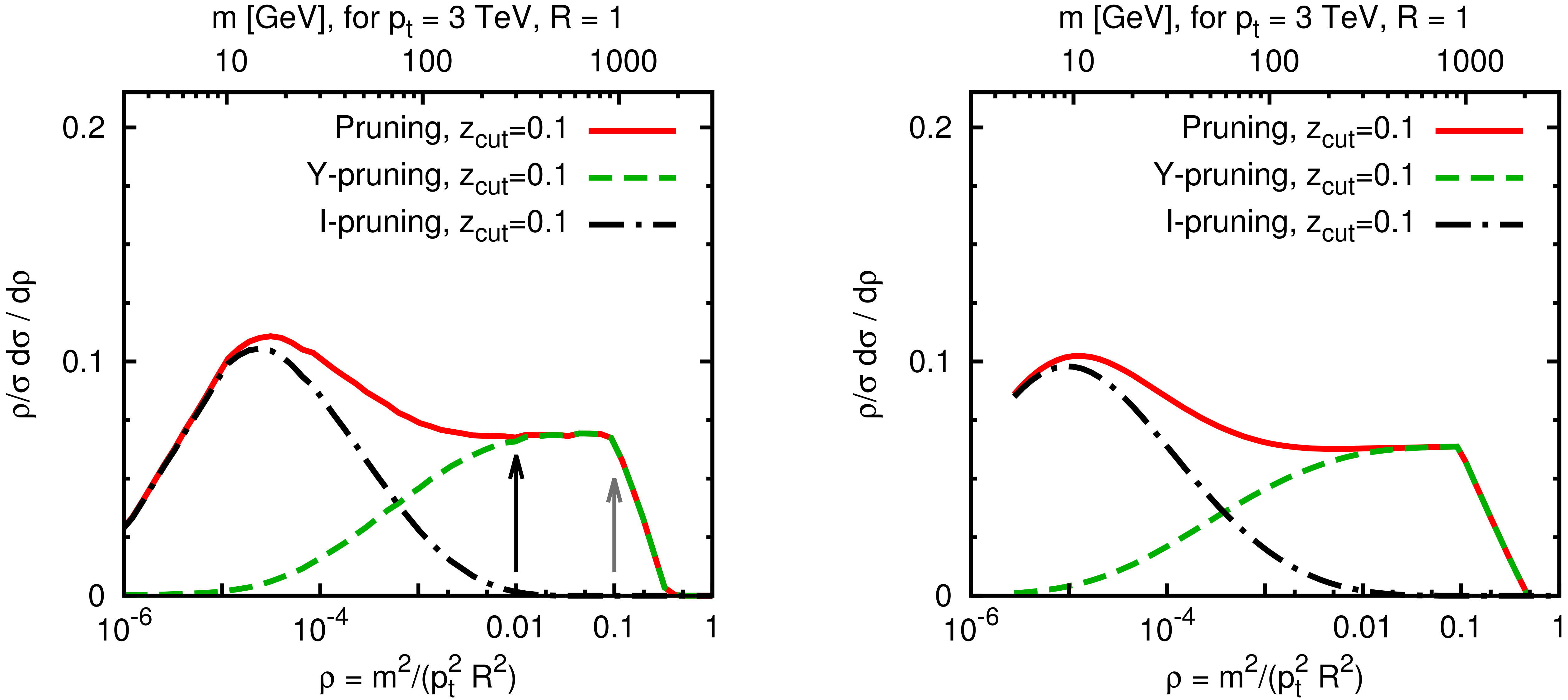
we also have NLL

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

Pruning

Monte Carlo

Analytic



Non-trivial agreement!

(also for dependence on parameters)

Mass-Drop Tagger

Butterworth, Davison, Rubin & GPS '08

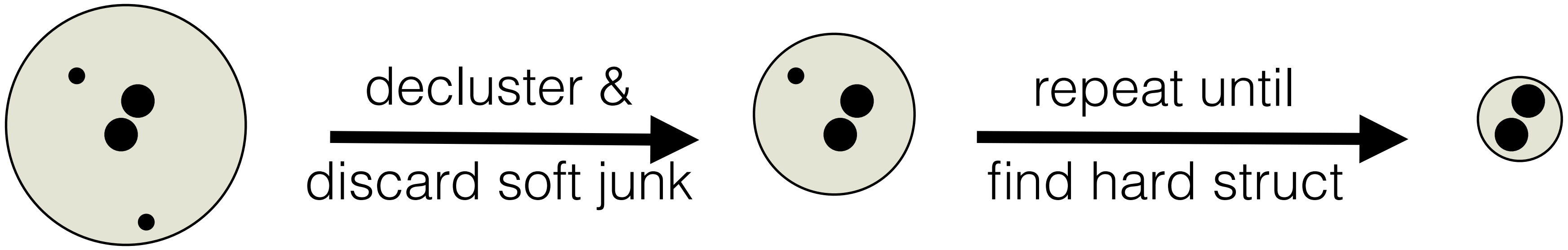
For a jet clustered with C/A:

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

   $$\min(p_{t1}^2, p_{t2}^2)\Delta R_{12}^2 < y_{\text{cut}} m^2$$

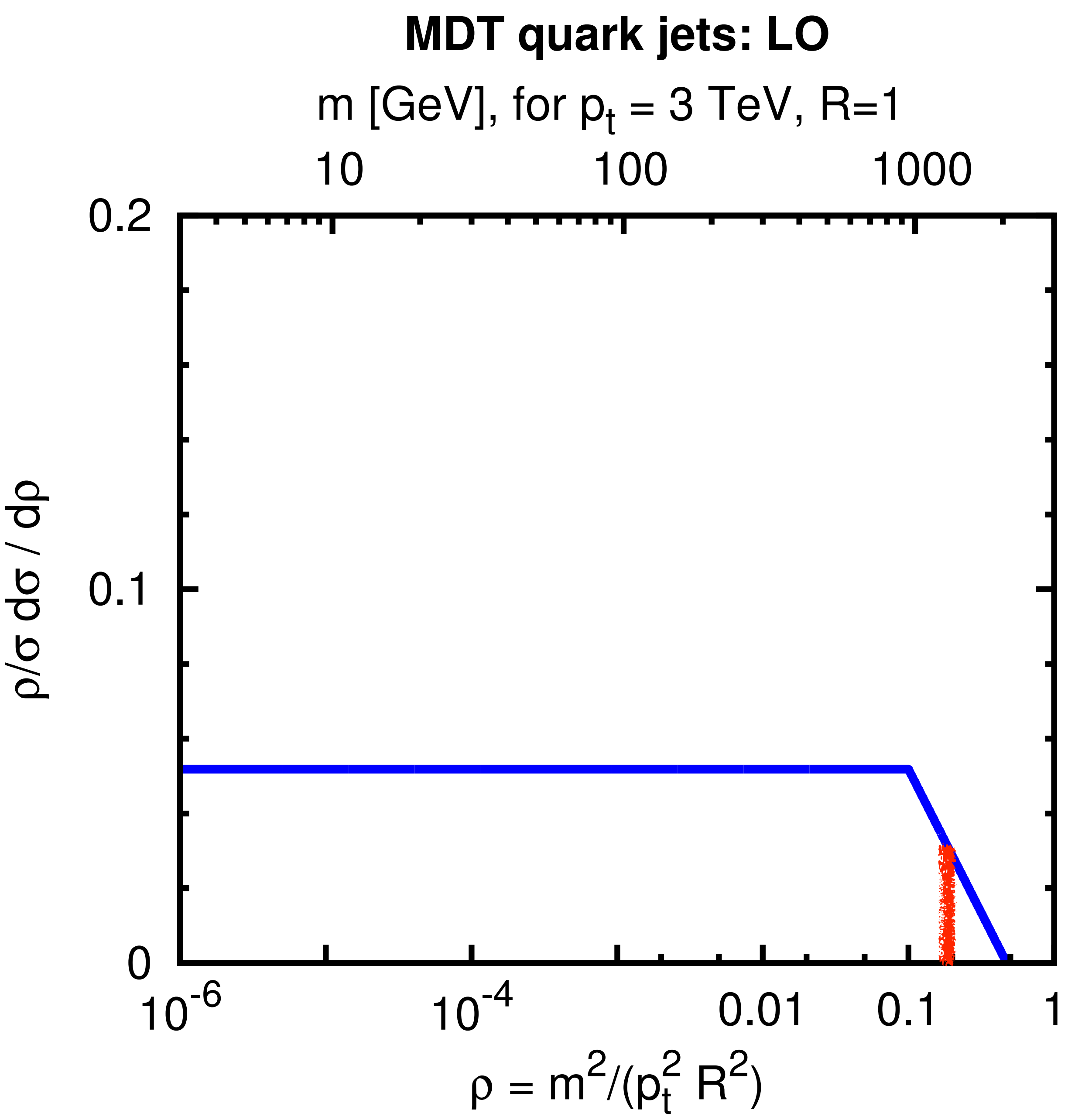
   jet is **tagged**.
3. Otherwise discard subjet 2, and go to step 1 with jet → subjet 1.

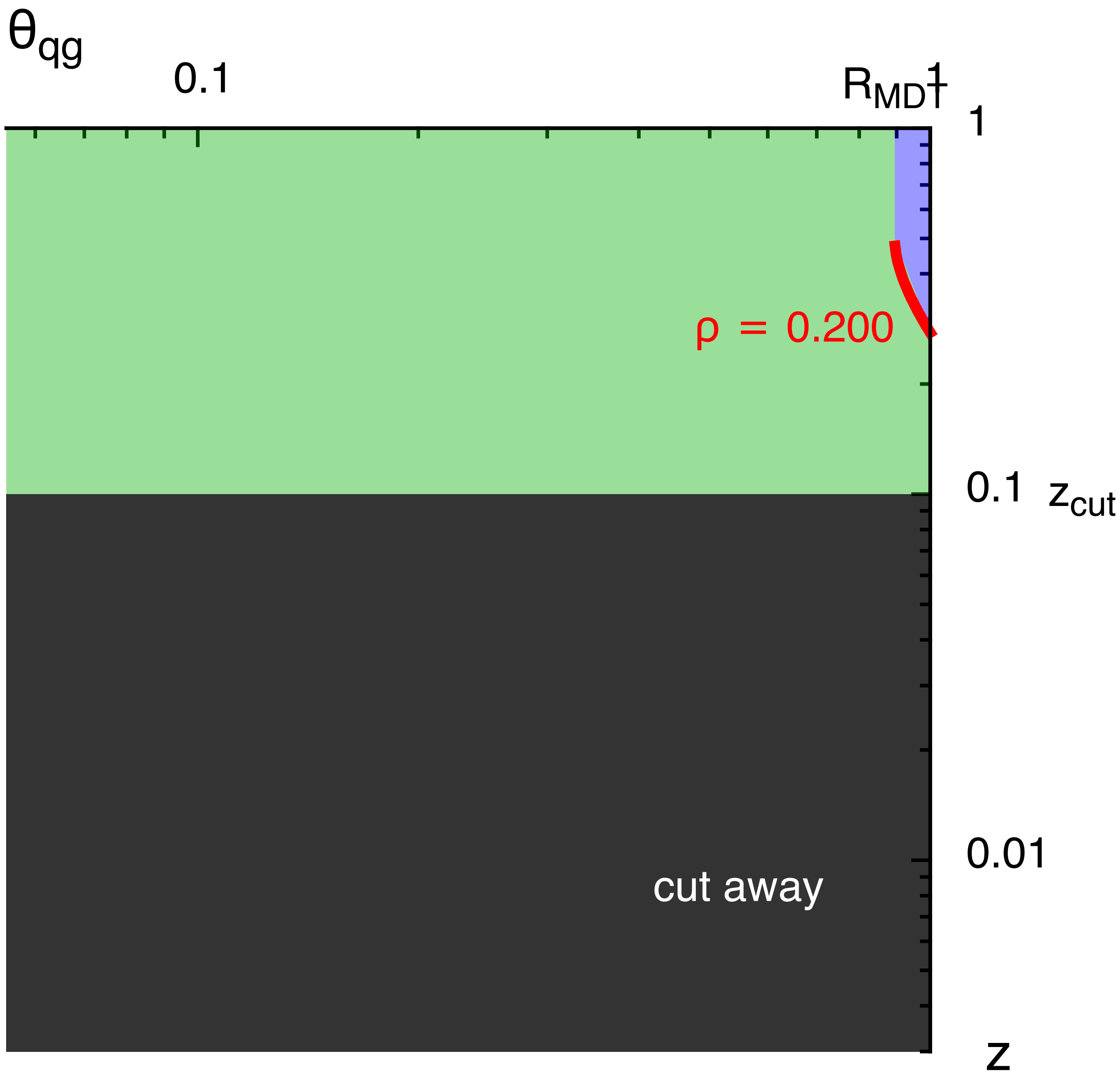
two parameters:
μ and y_{cut} ($\sim z_{\text{cut}}$)


decluster &
discard soft junk
repeat until
find hard struct

Mass-Drop Tagger at LO

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





Mass-Drop Tagger at LO

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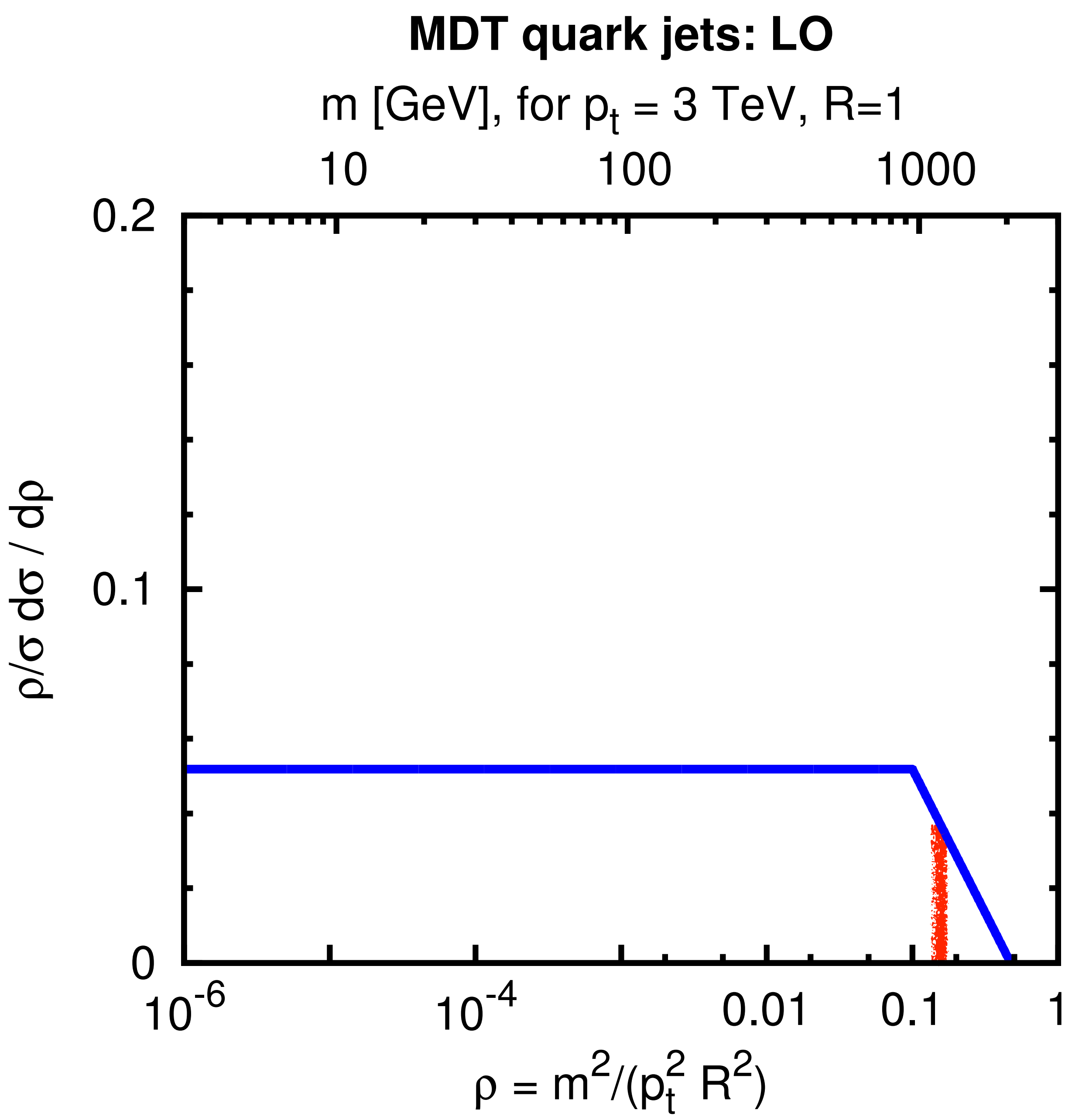

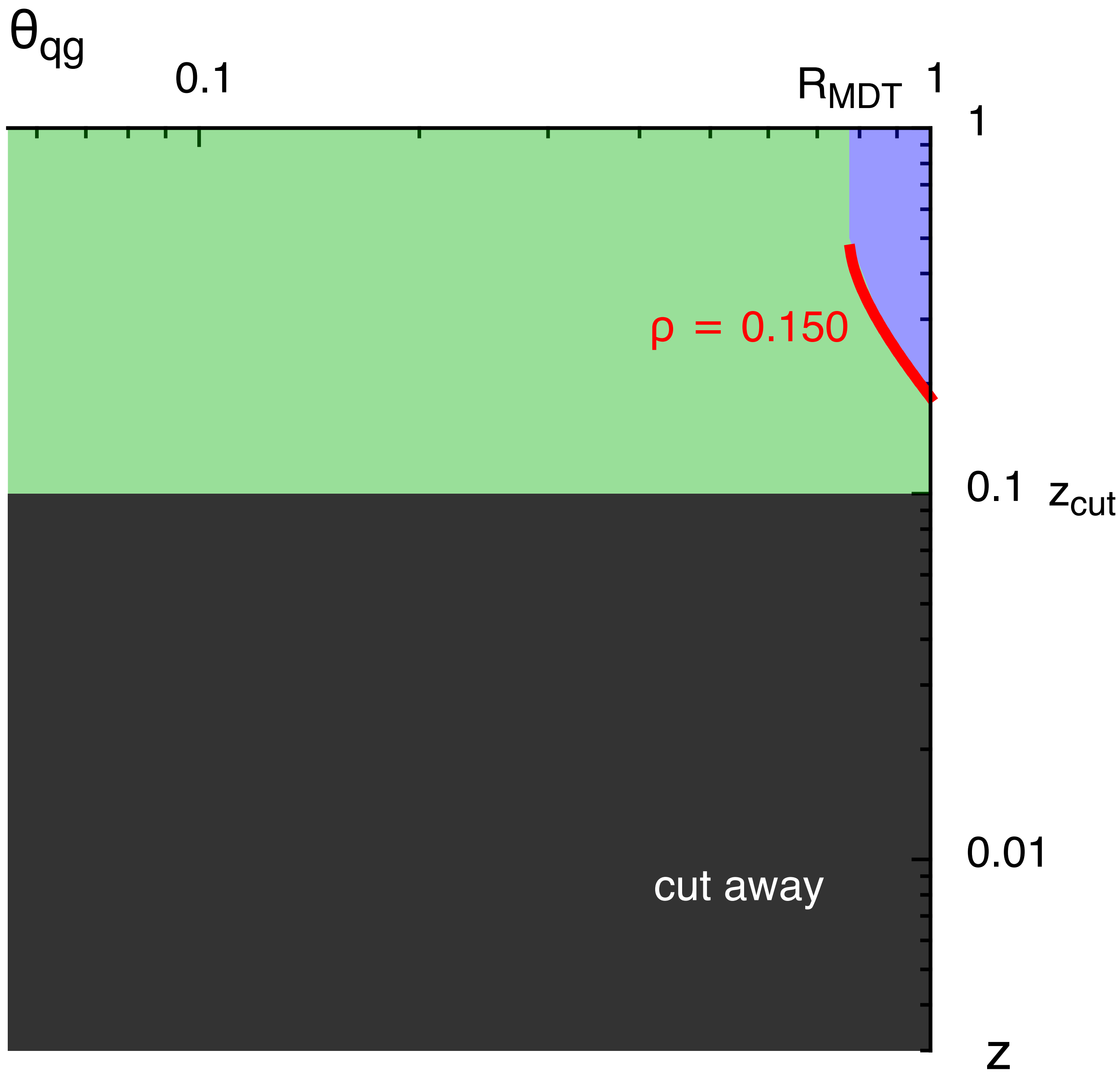

Mass-Drop Tagger at LO

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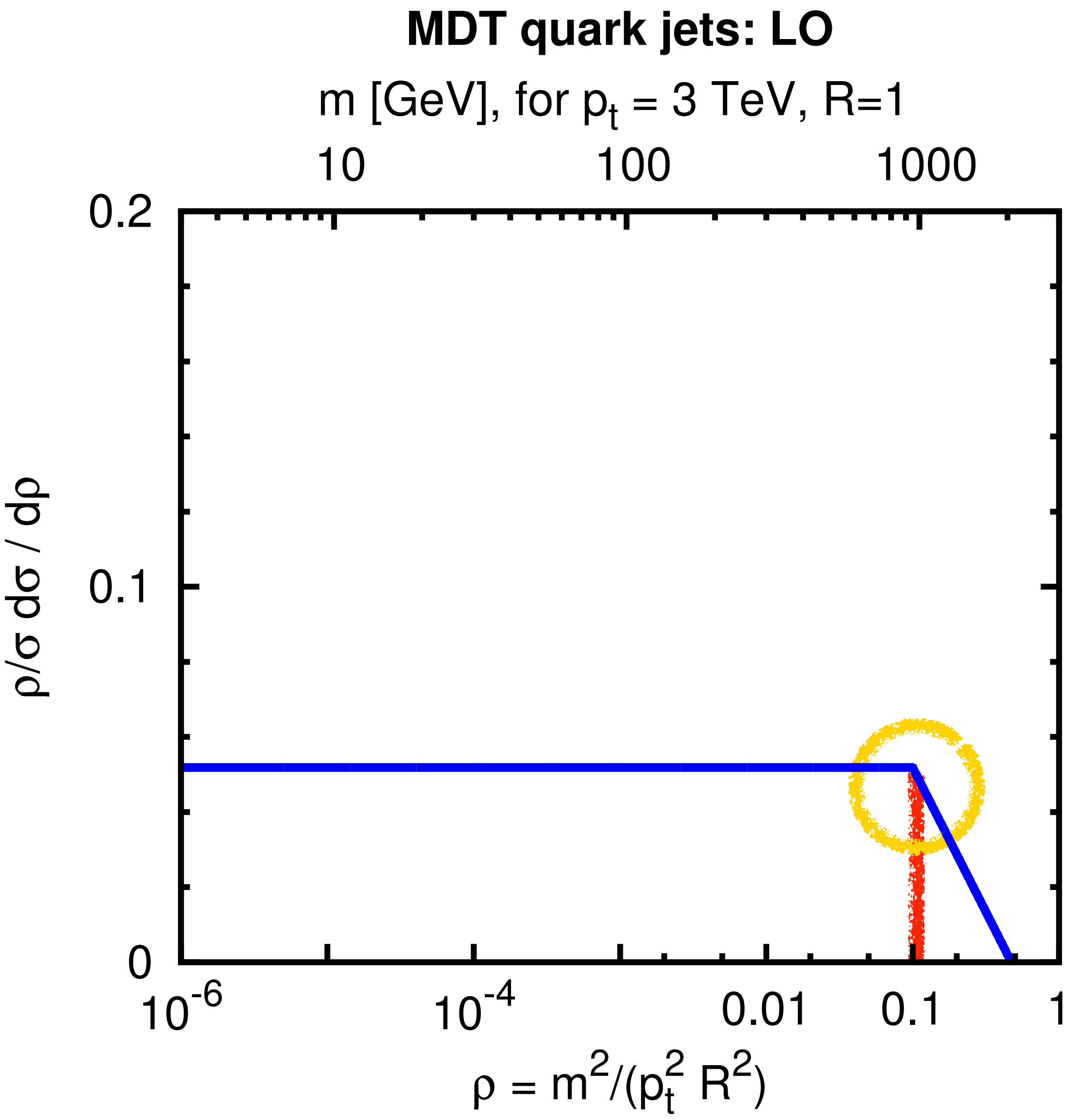

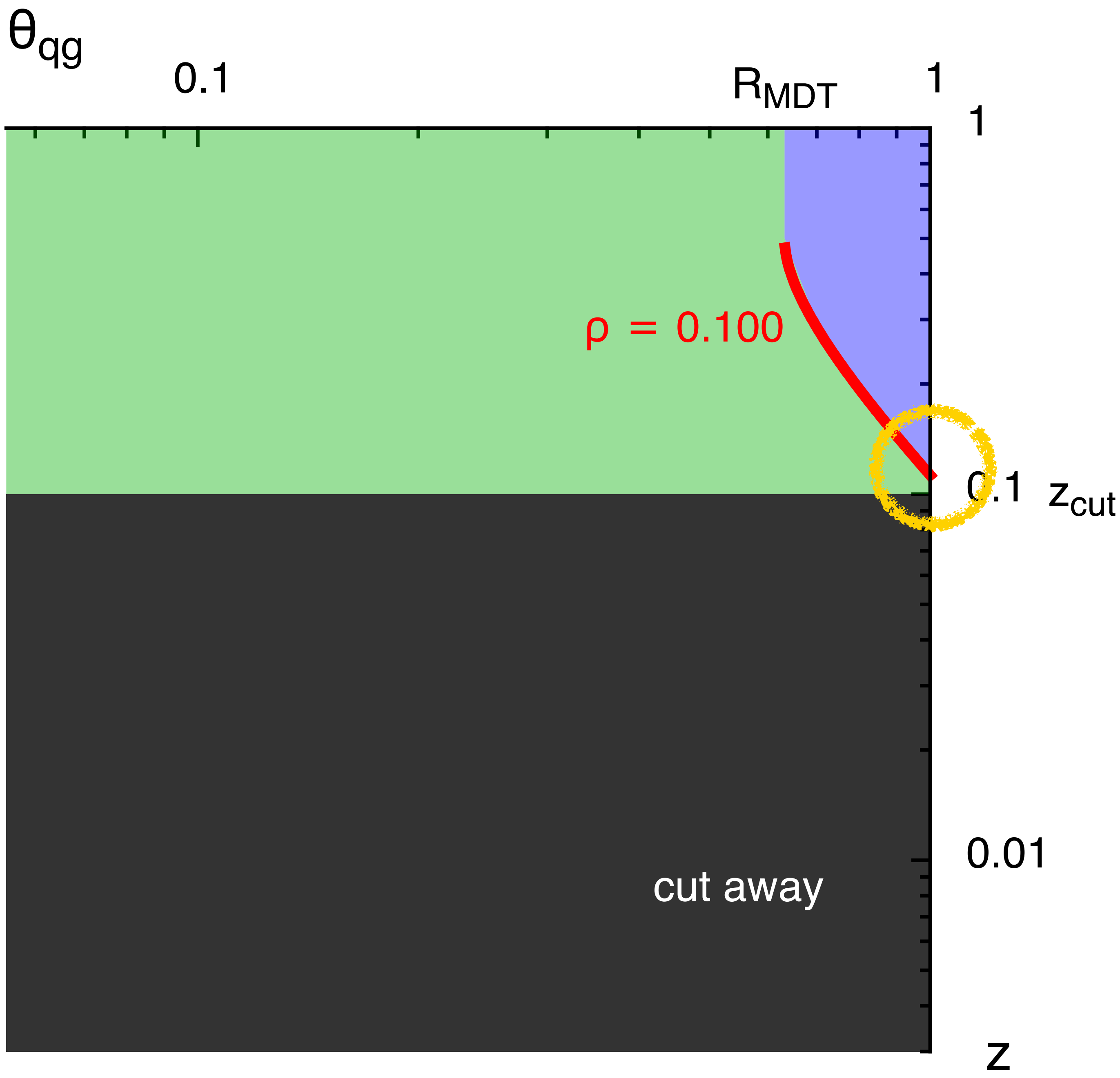

Mass-Drop Tagger at LO

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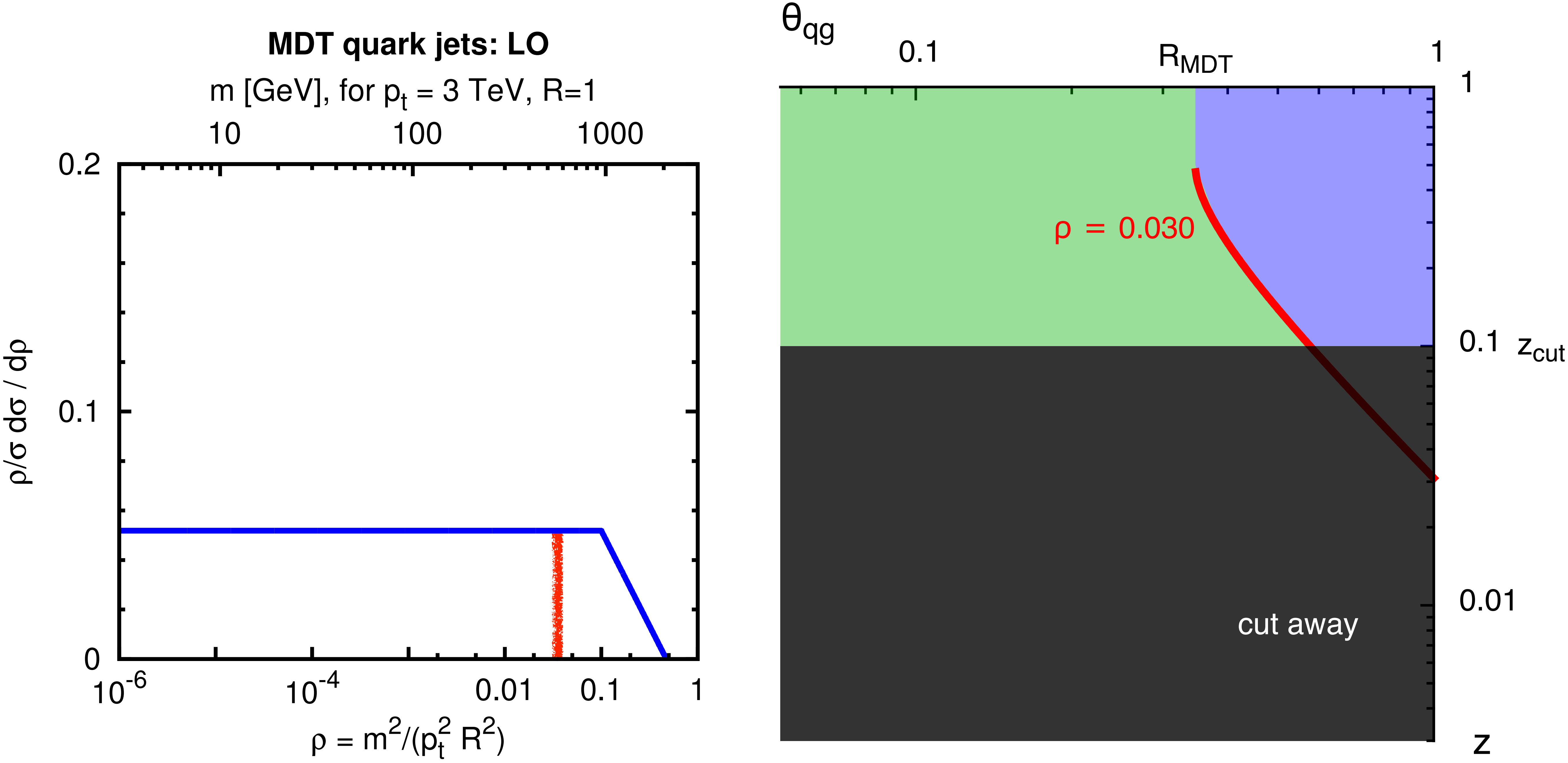

Mass-Drop Tagger at LO

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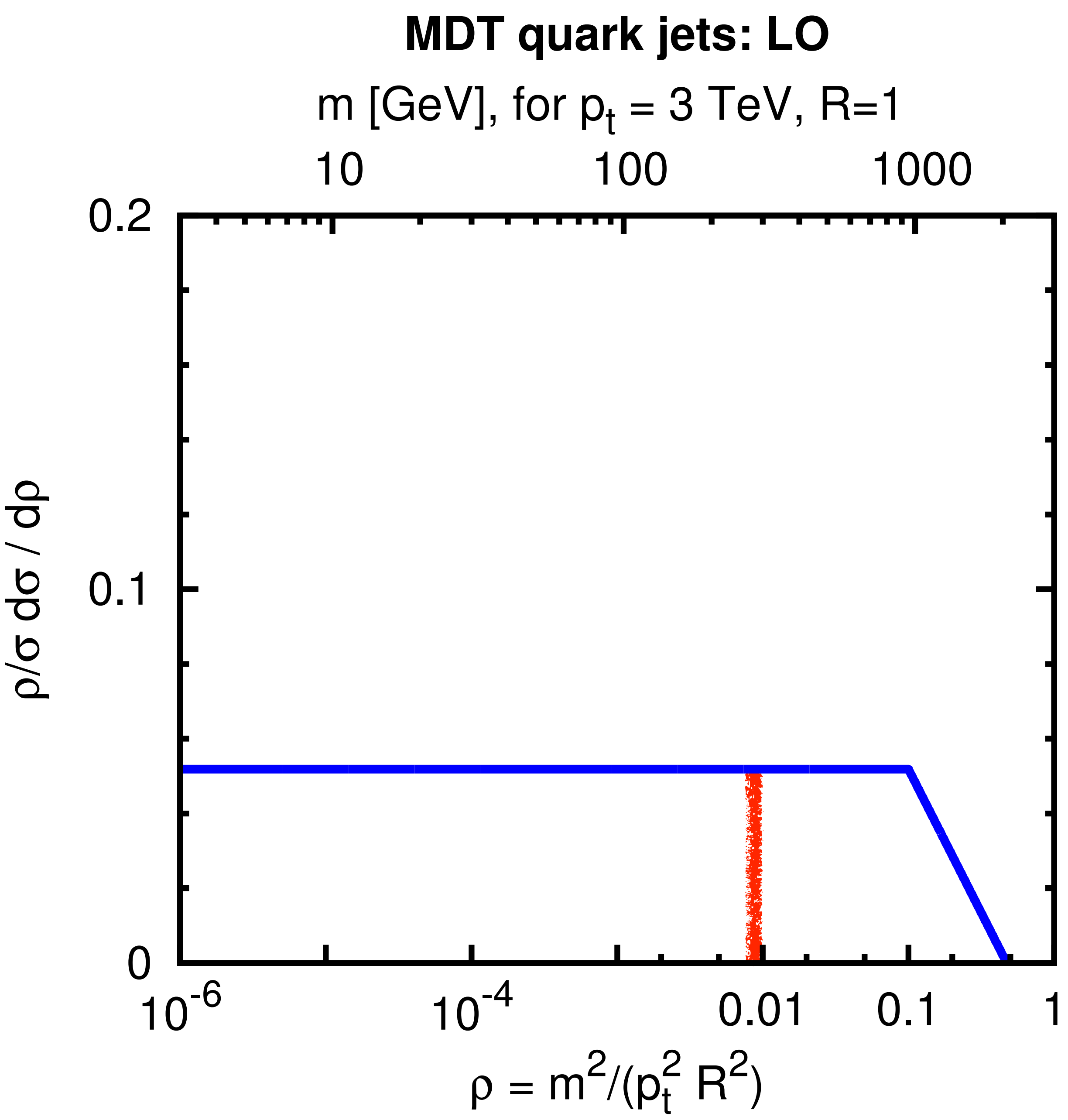

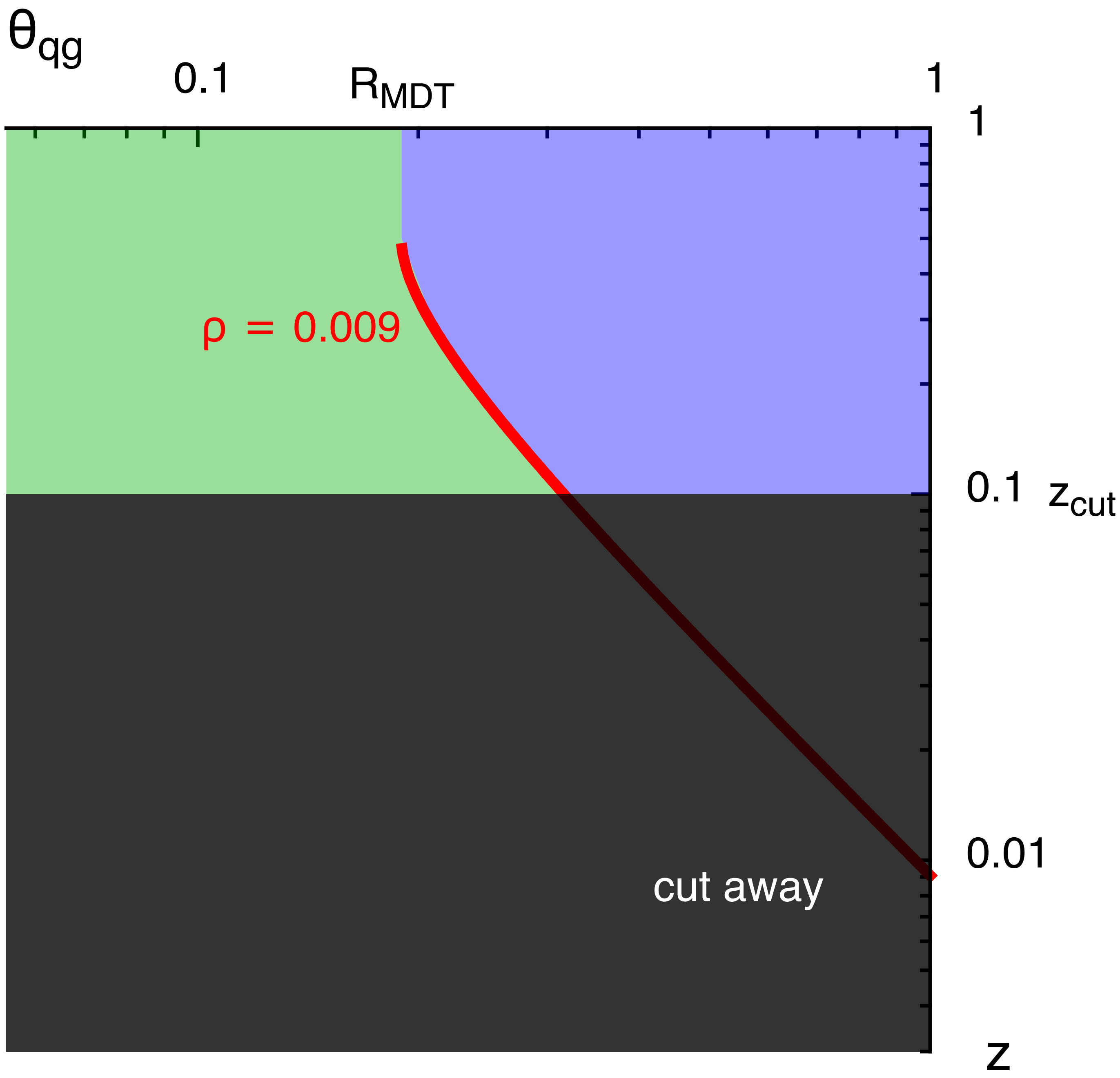

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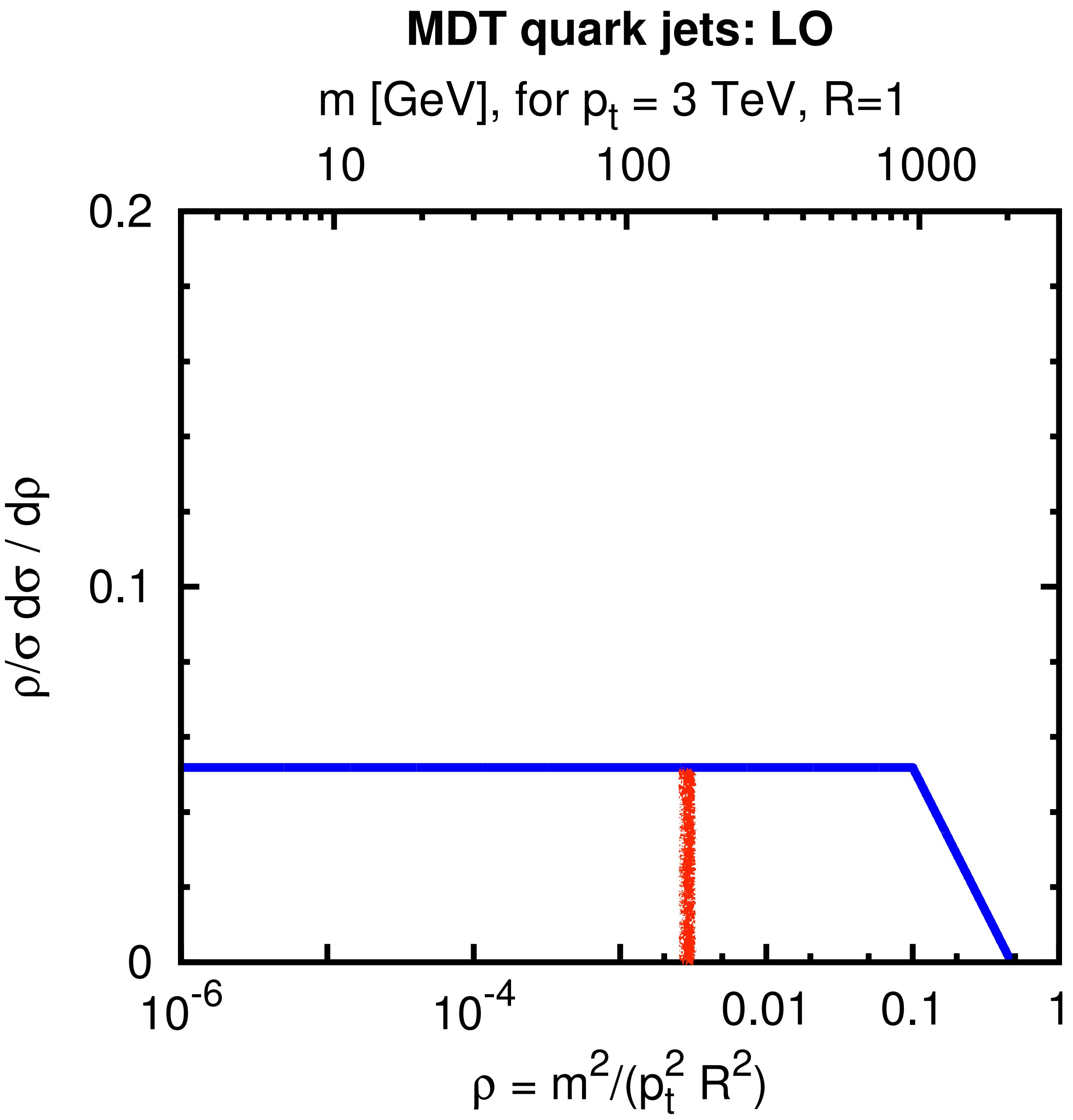

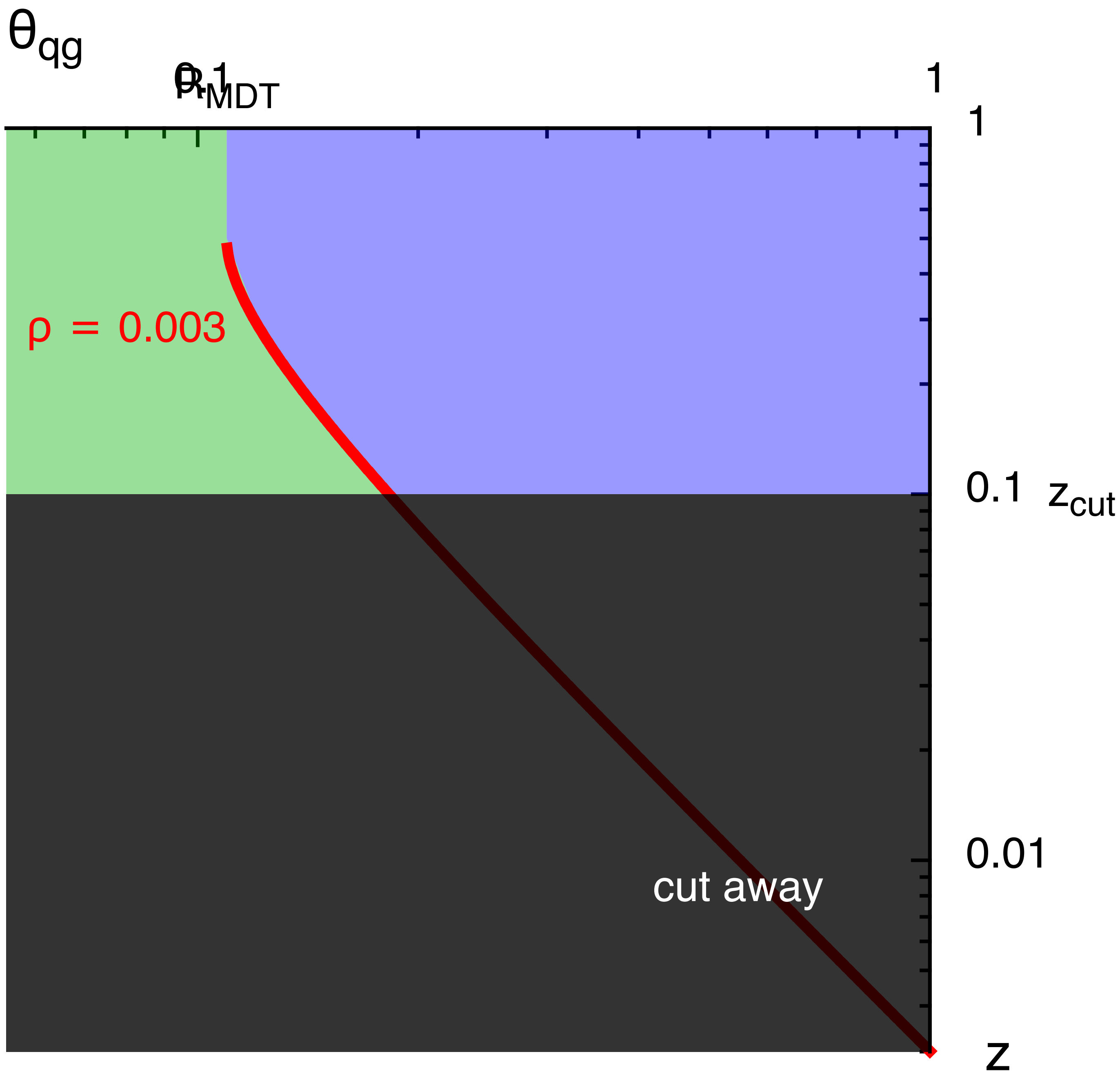

Mass-Drop Tagger at LO

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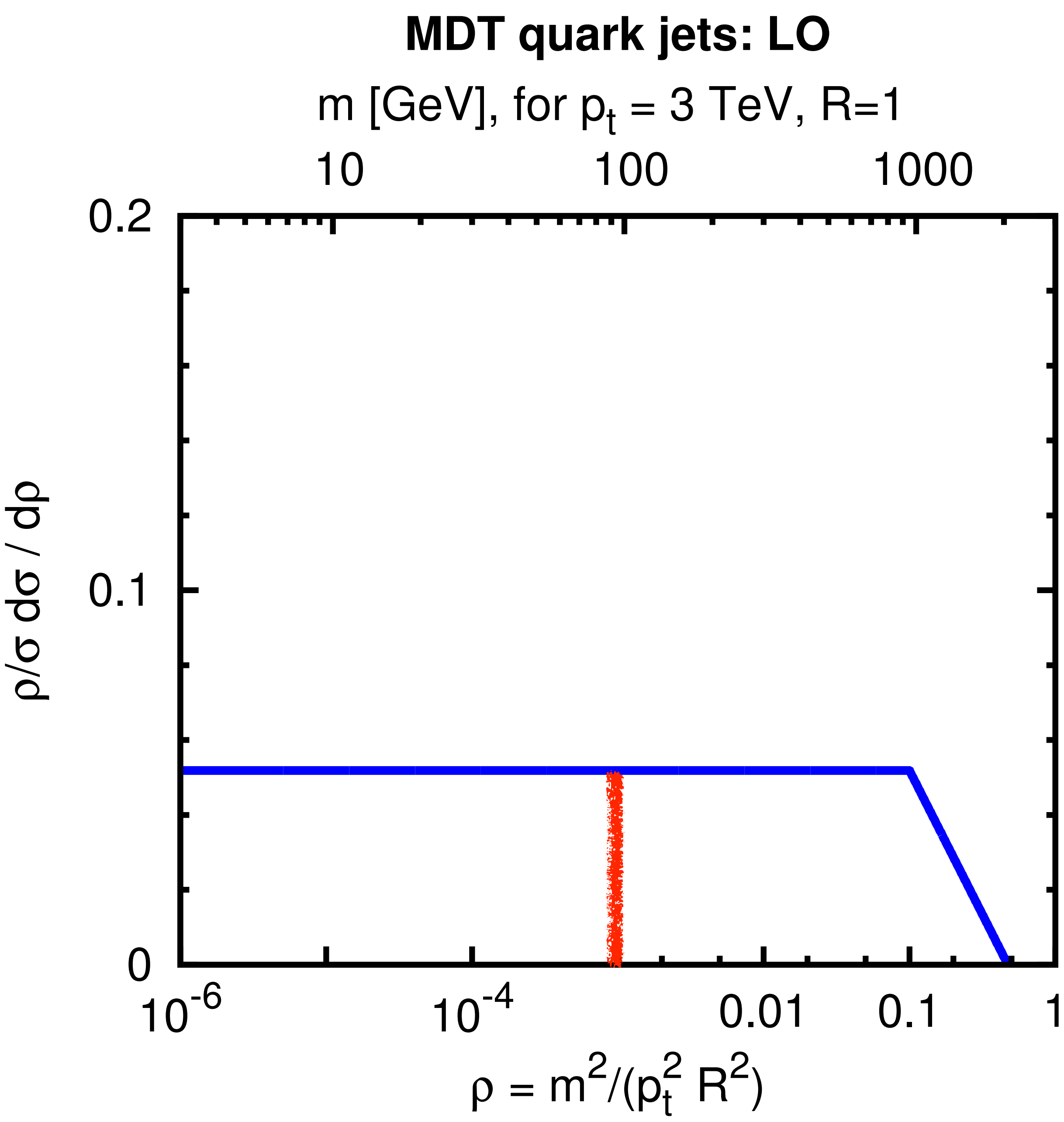
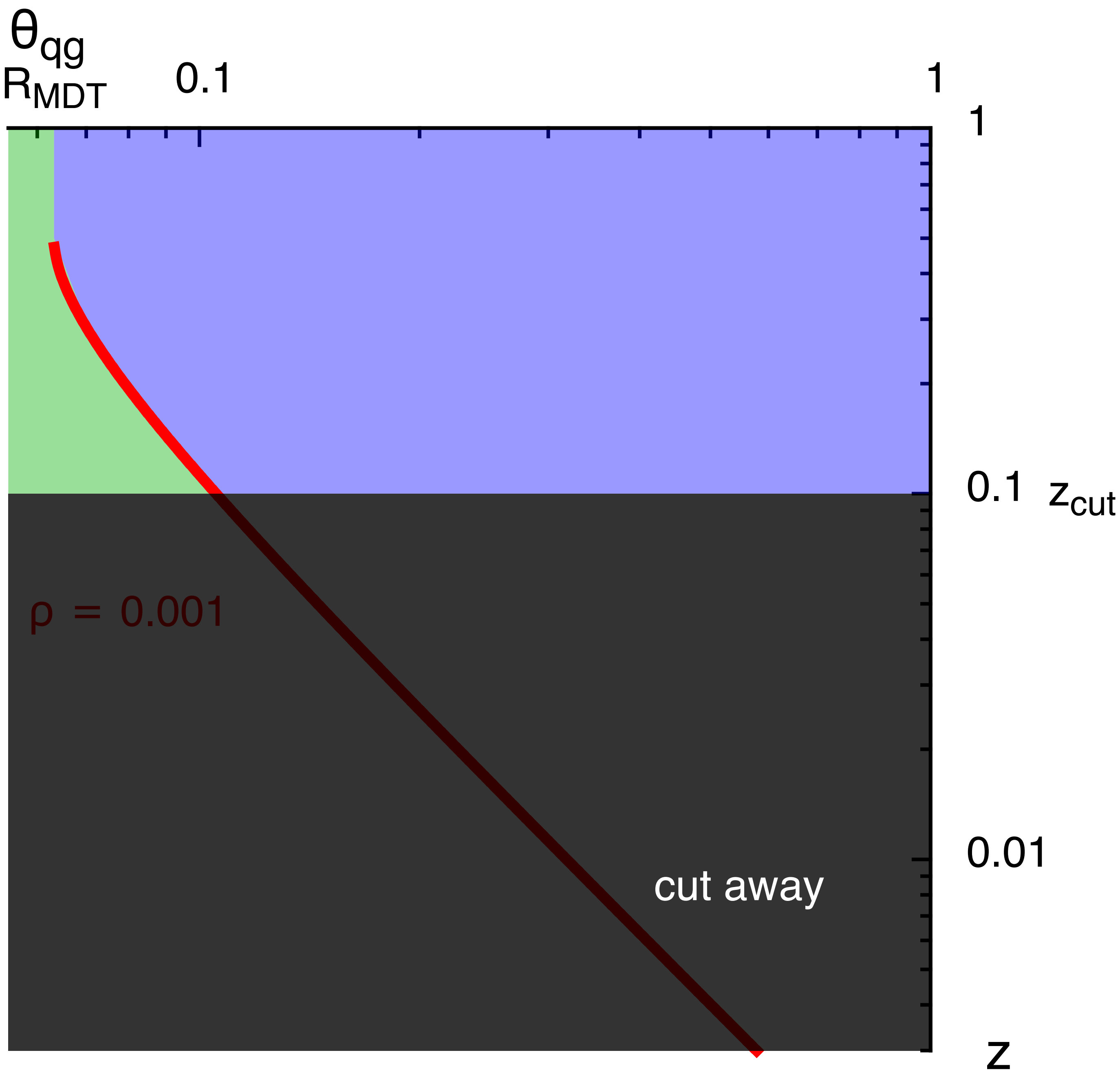
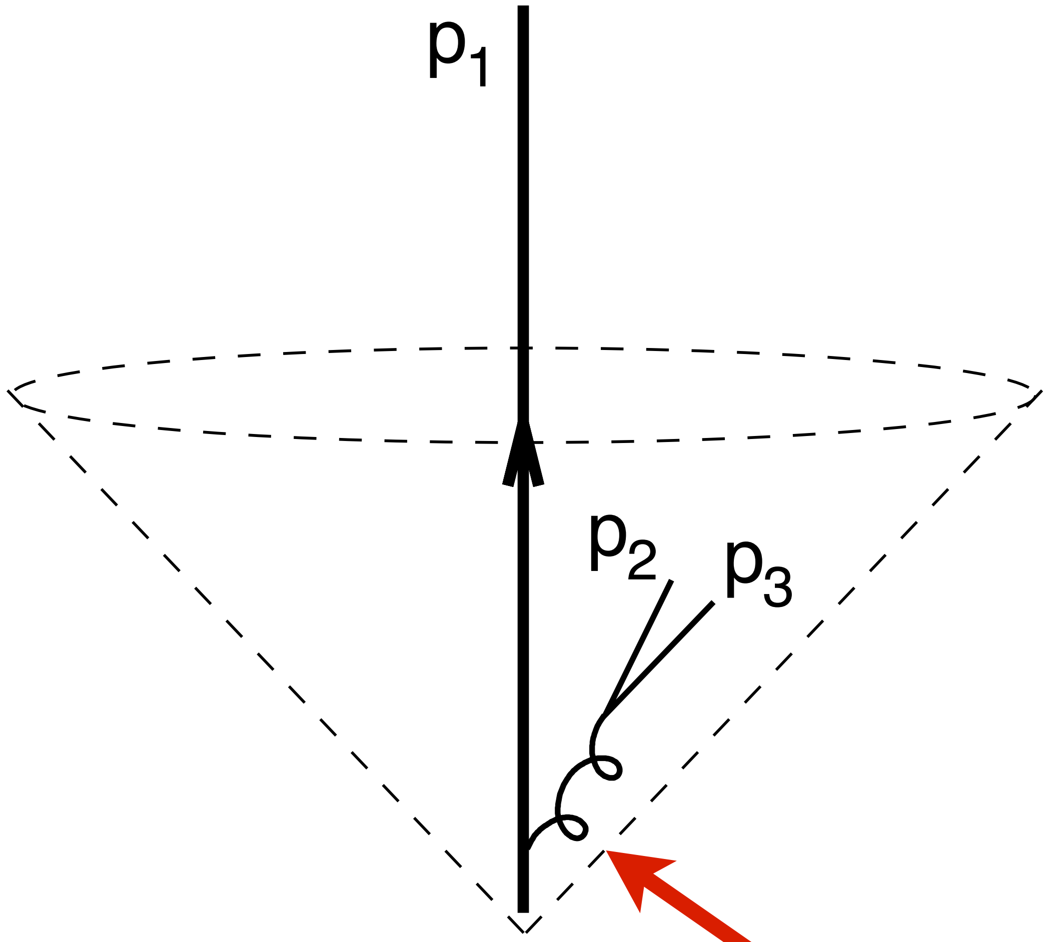






What MDT does wrong beyond LO:

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:

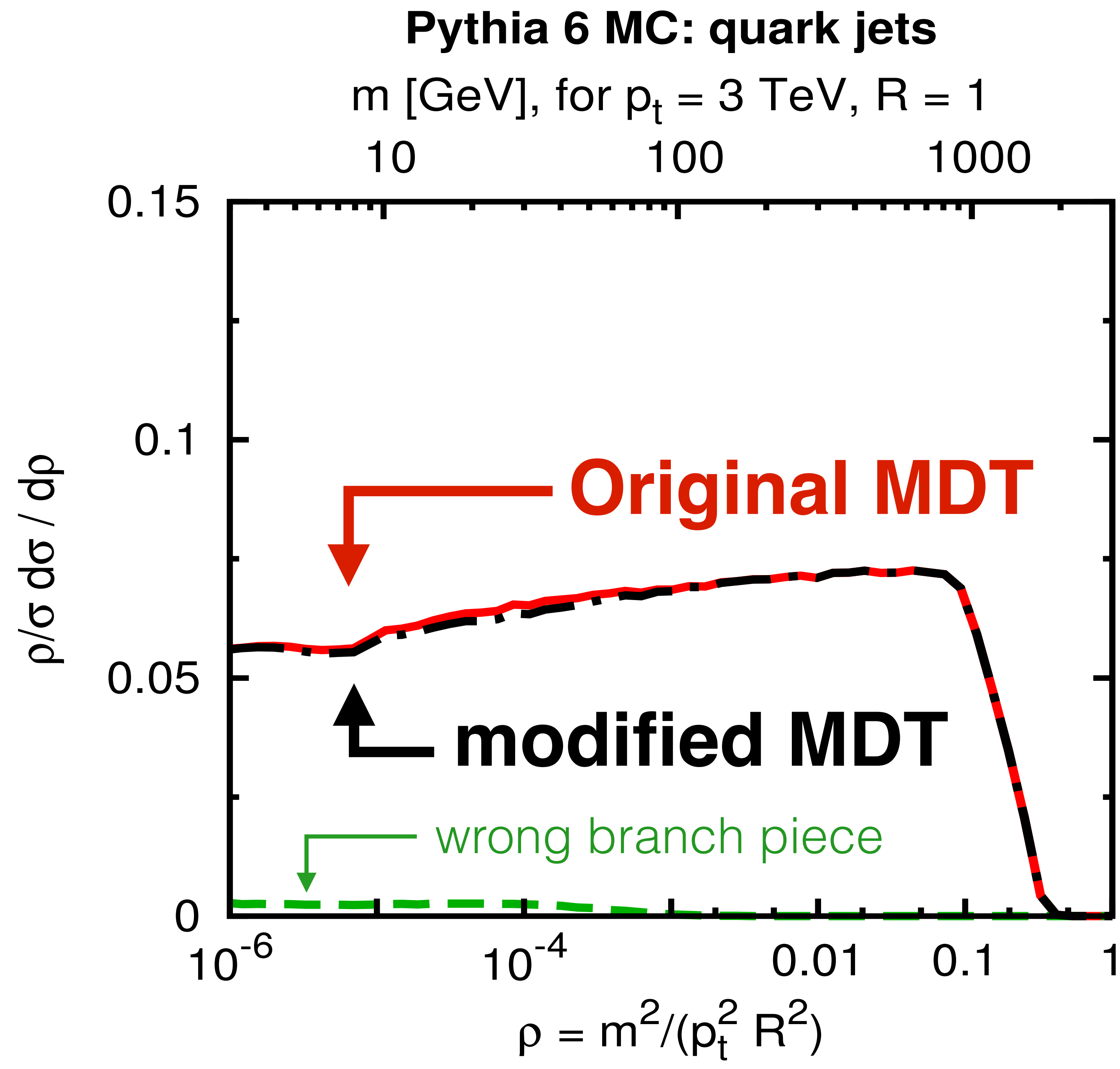
$$\alpha_s L,\ \alpha_s^2 L^3,\ \ldots.\ \text{I.e.}\ \boldsymbol{\alpha_s^n L^{2n-1}}$$

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...

modified Mass Drop Tagger

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

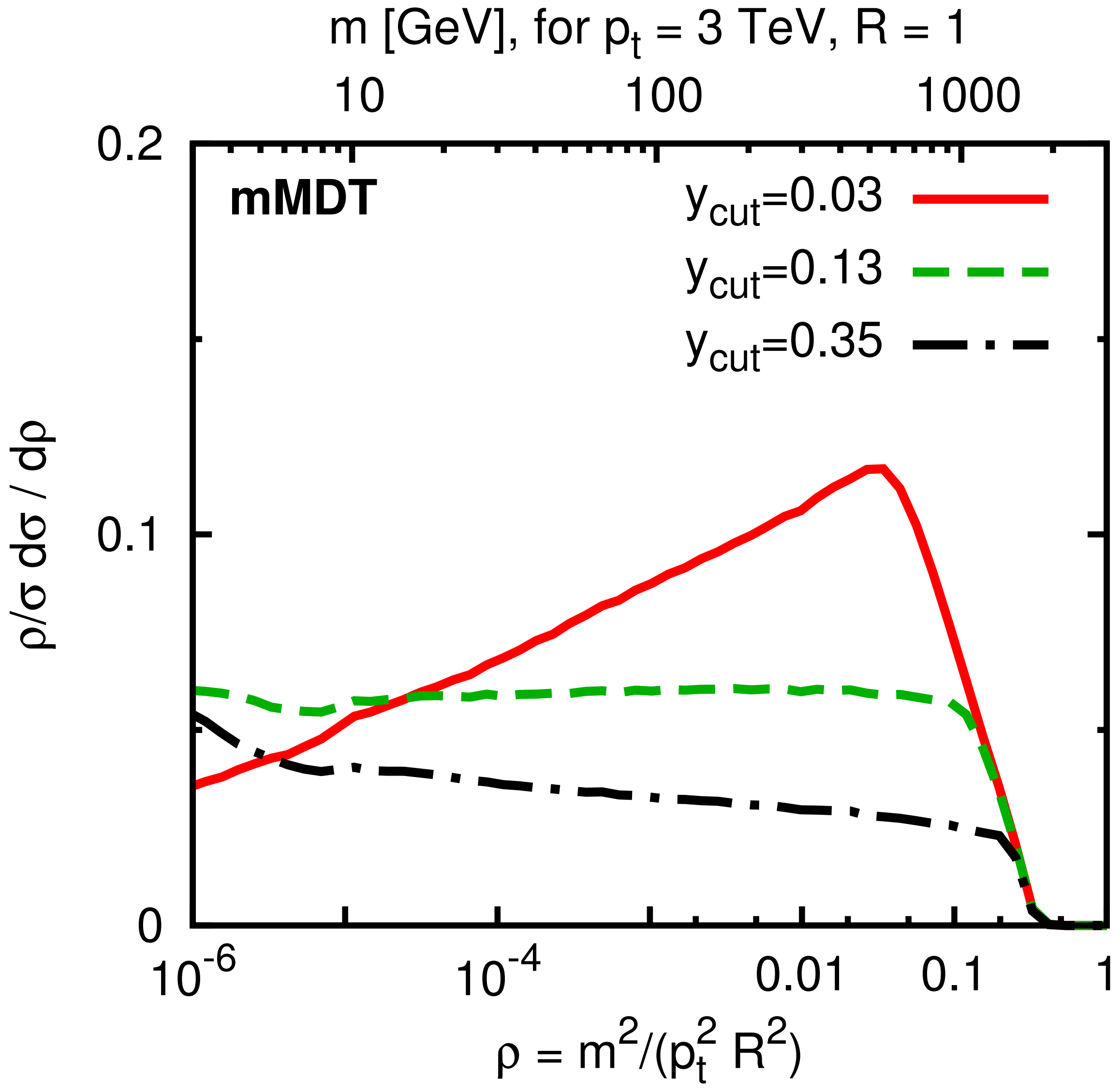
Fairly simple formulae; e.g. [fixed-coupling]

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

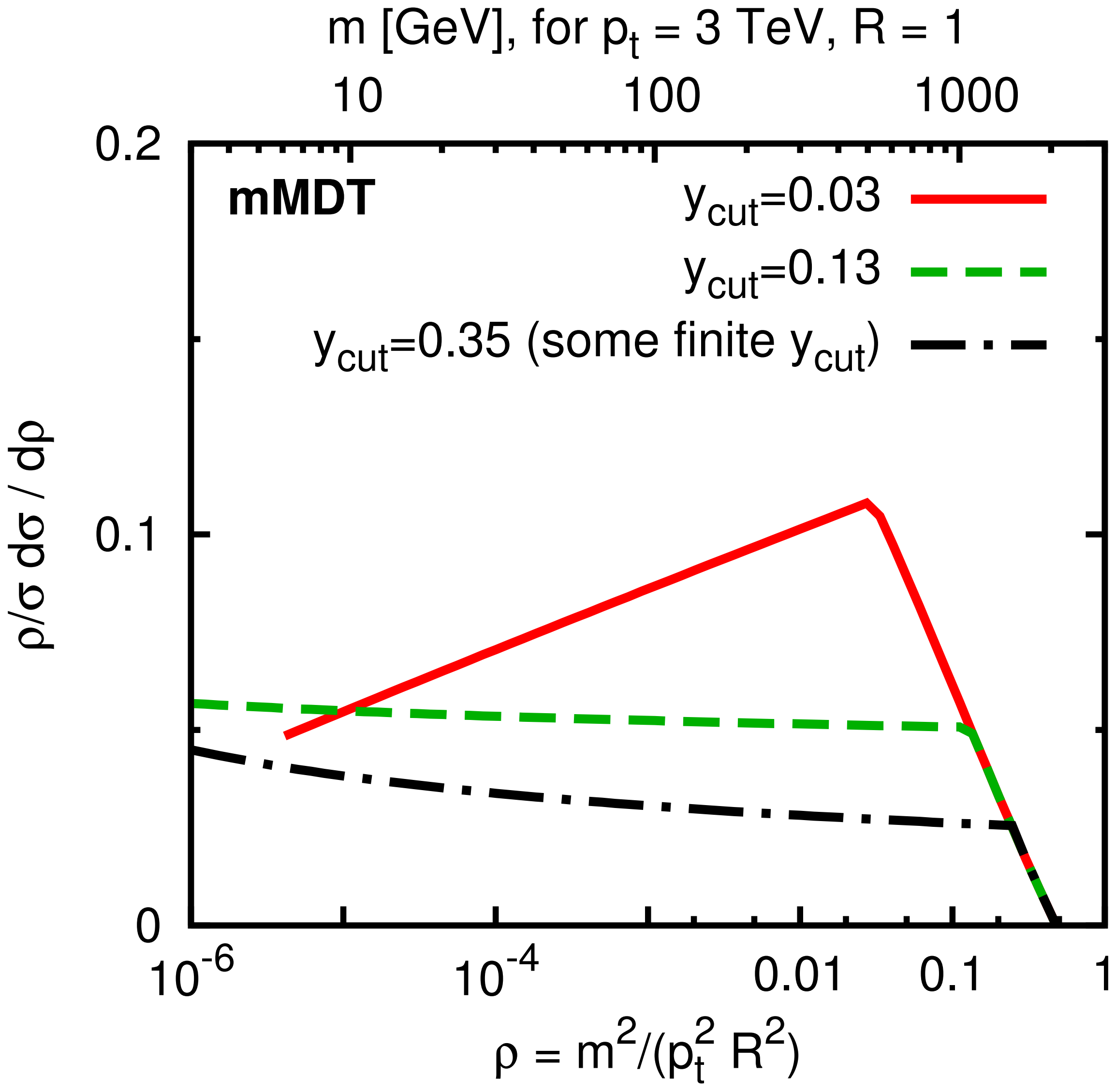
quark jets

mMDT MC v. Resummation

Monte Carlo

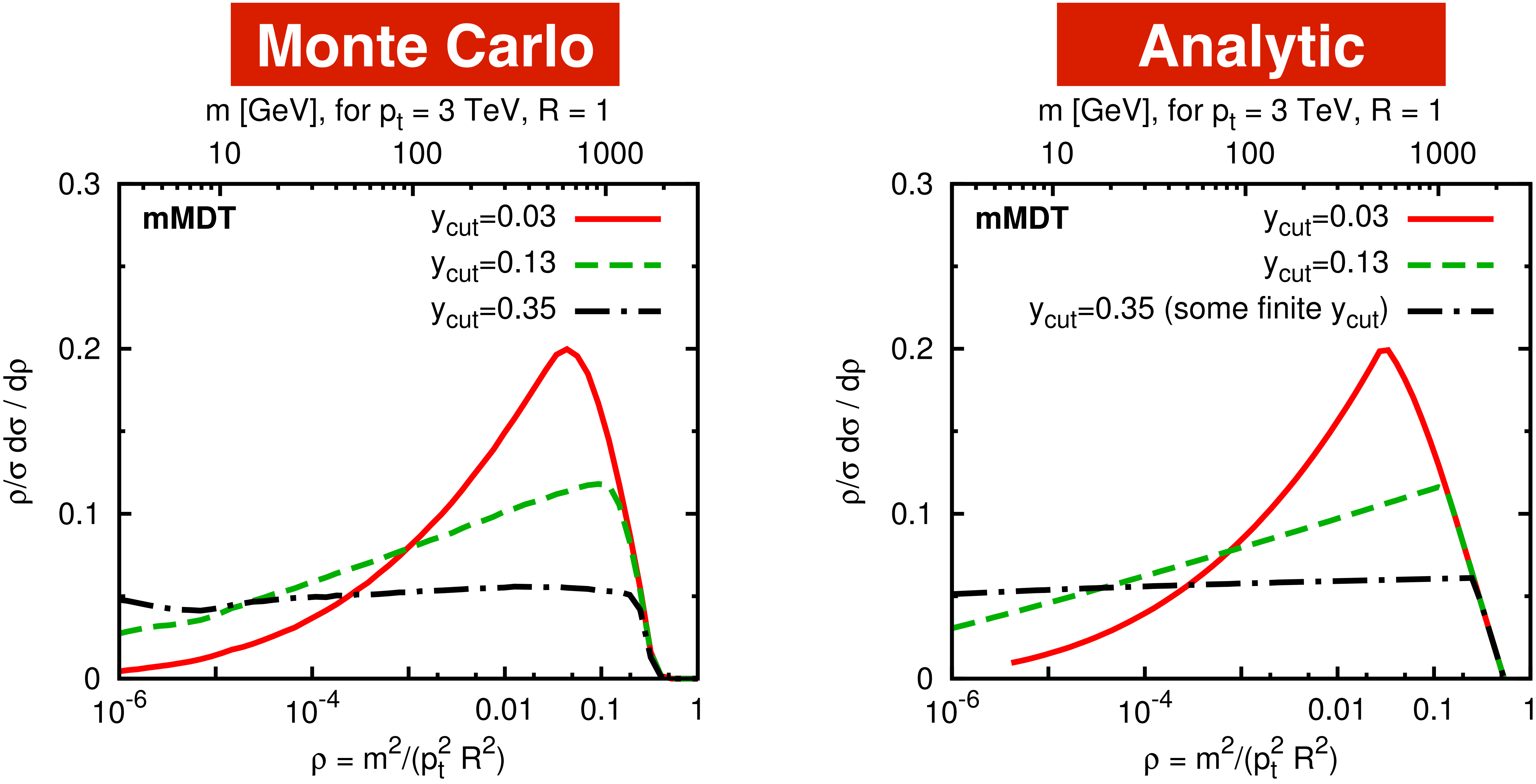


Analytic



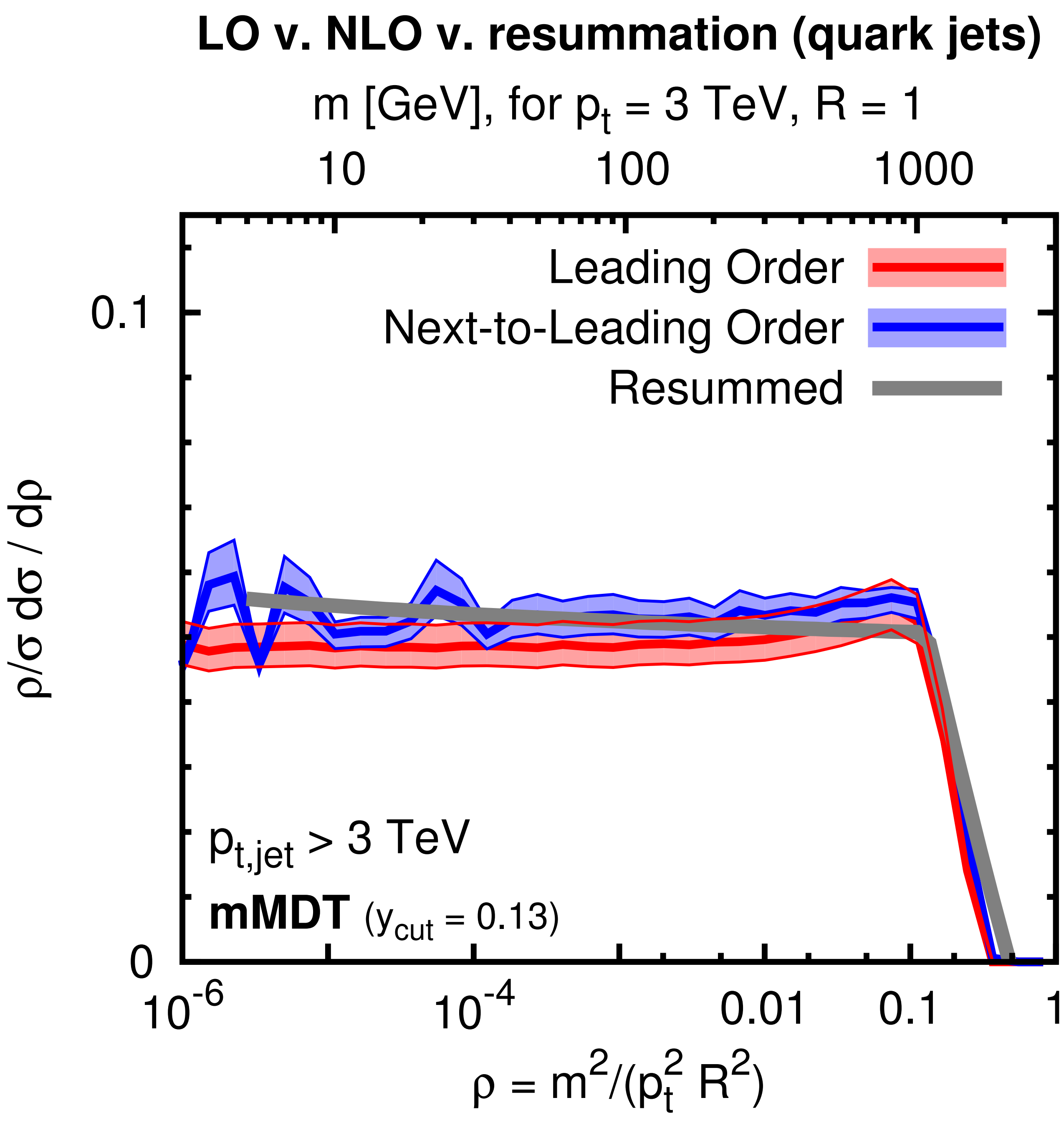
[mMDT is closest we have to a scale-invariant tagger, though exact behaviour depends on q/g fractions]

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

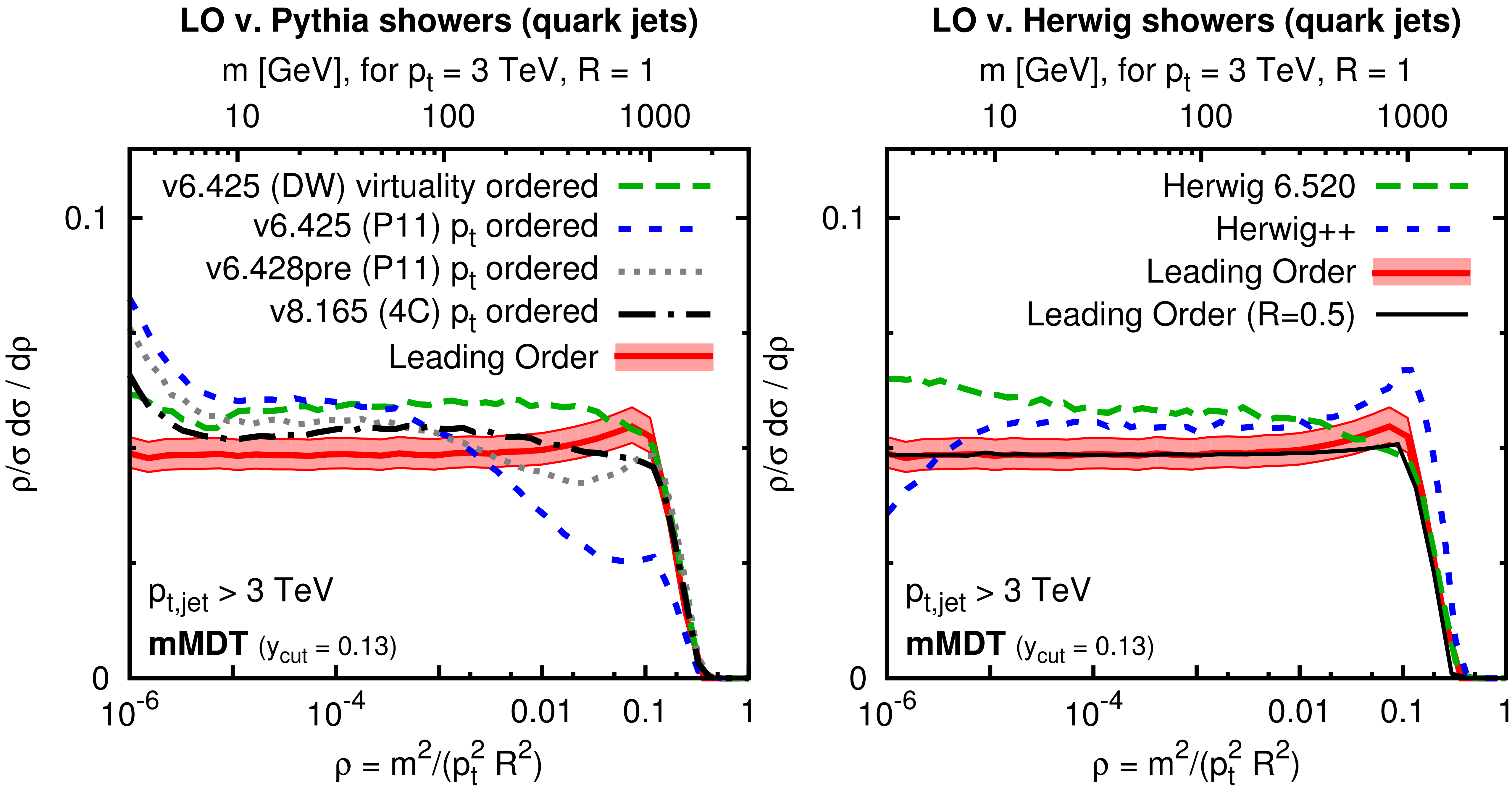


NLO from NLOJet++

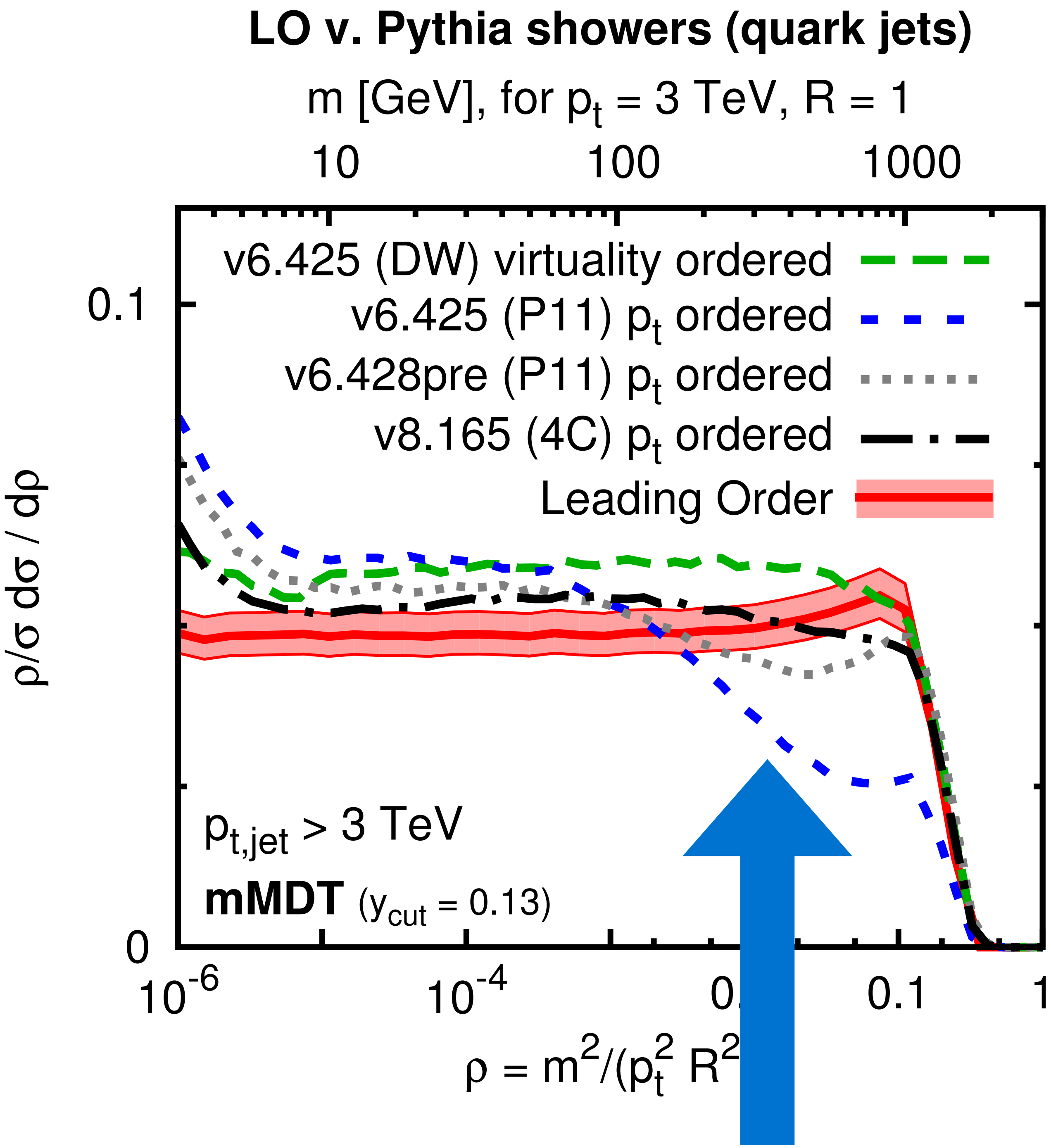
Because we only have single logs, fixed-order is valid over a broader than usual range of scales

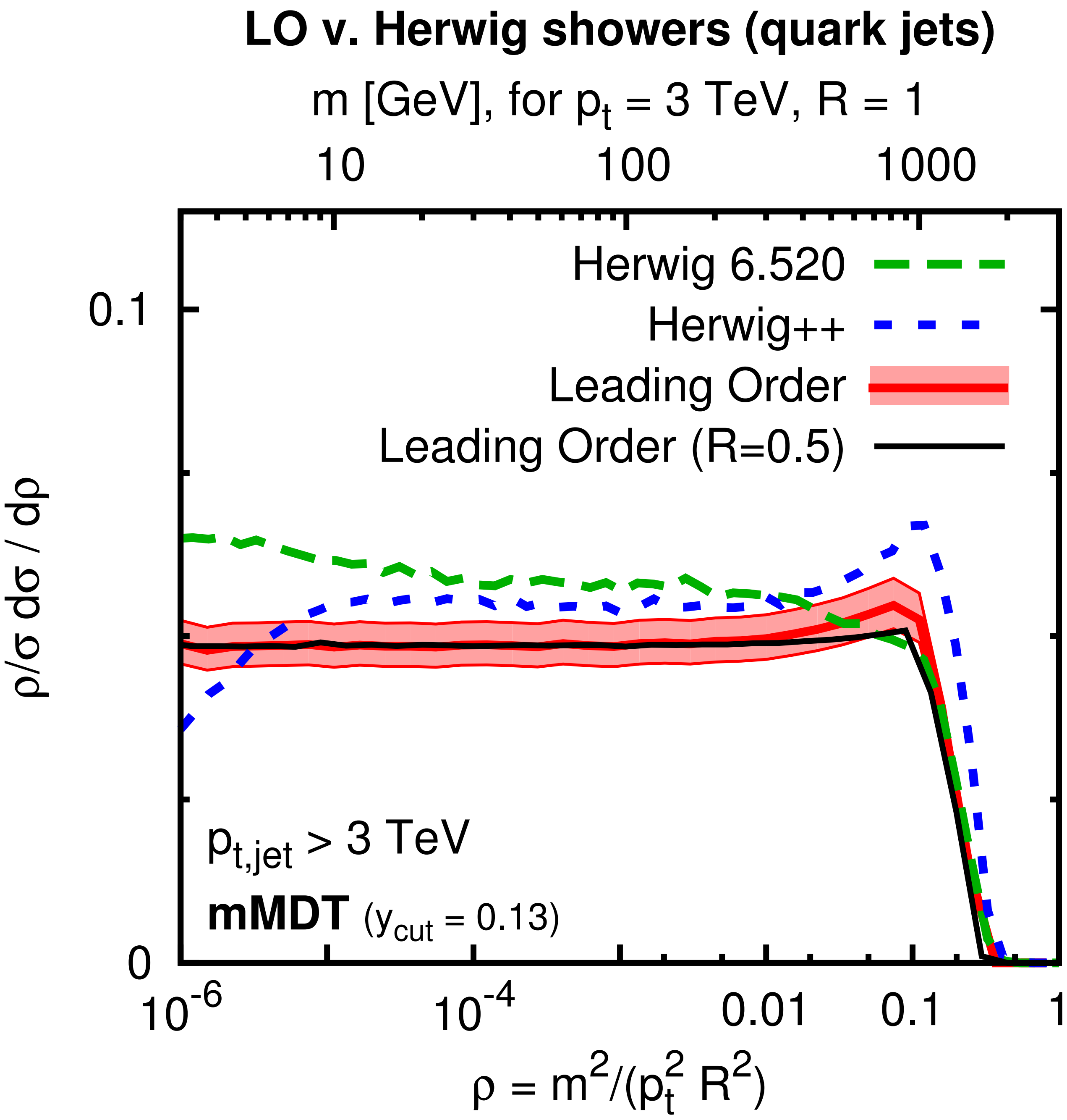
(helped by fortuitous cancellation between running coupling and single-log Sudakov)

mMDT: comparing many showers



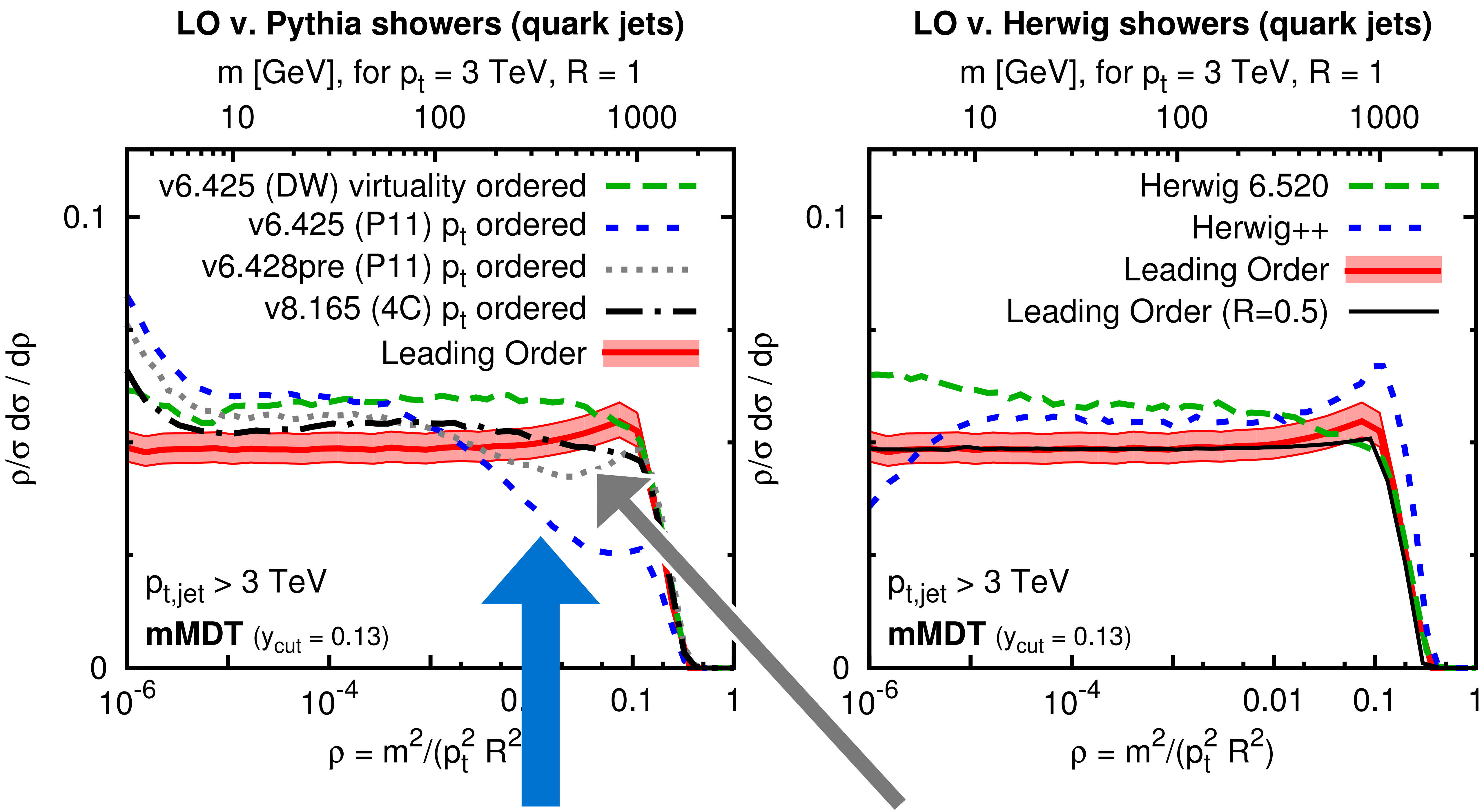
mMDT: comparing many showers


LO v. Pythia showers (quark jets)


LO v. Herwig showers (quark jets)

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

mMDT: comparing many showers

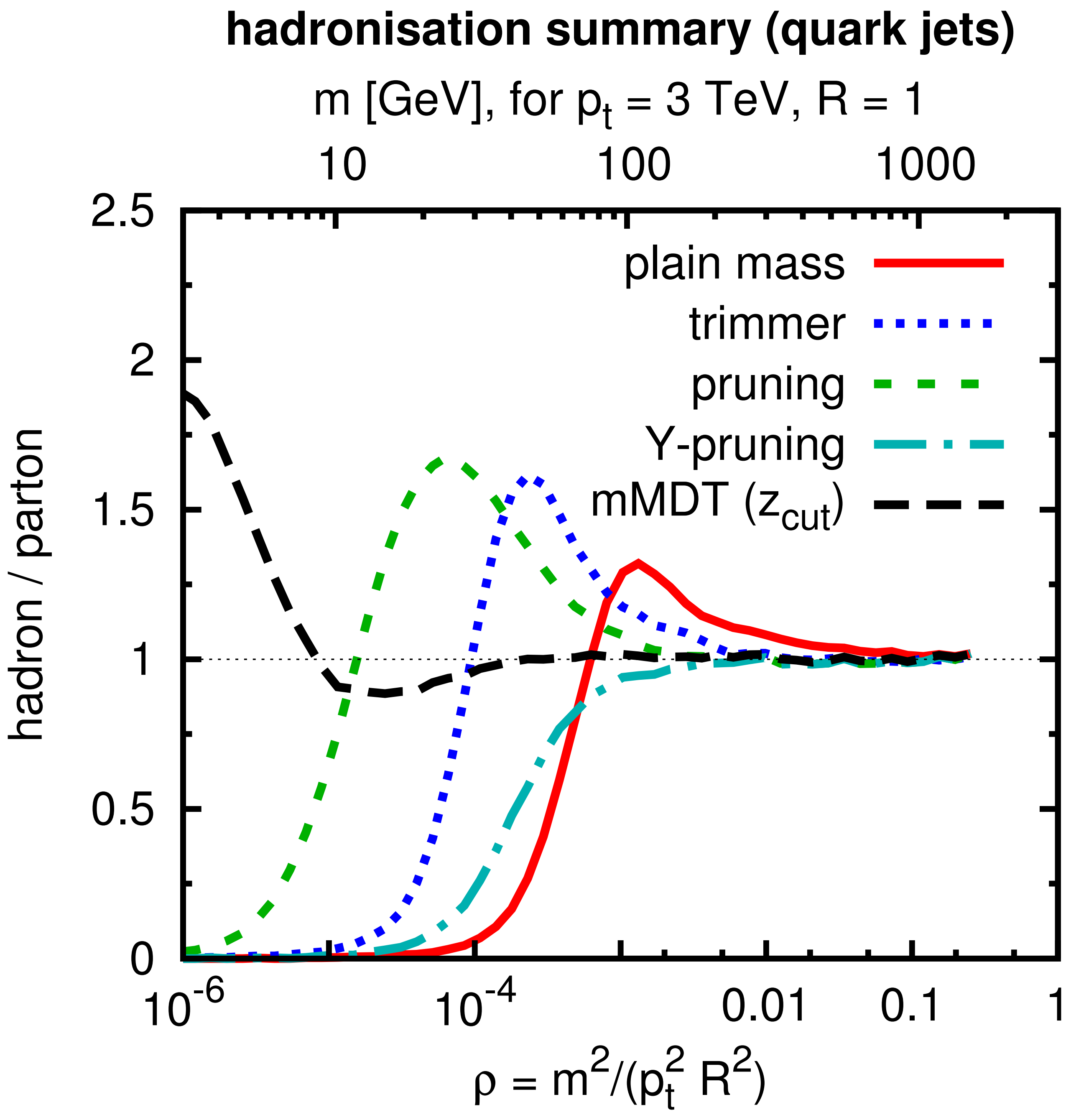


Issue found in Pythia 6 p_t-ordered shower → promptly identified and fixed by Pythia authors!

What about non-perturbative effects?

[on 3 TeV jets?!]

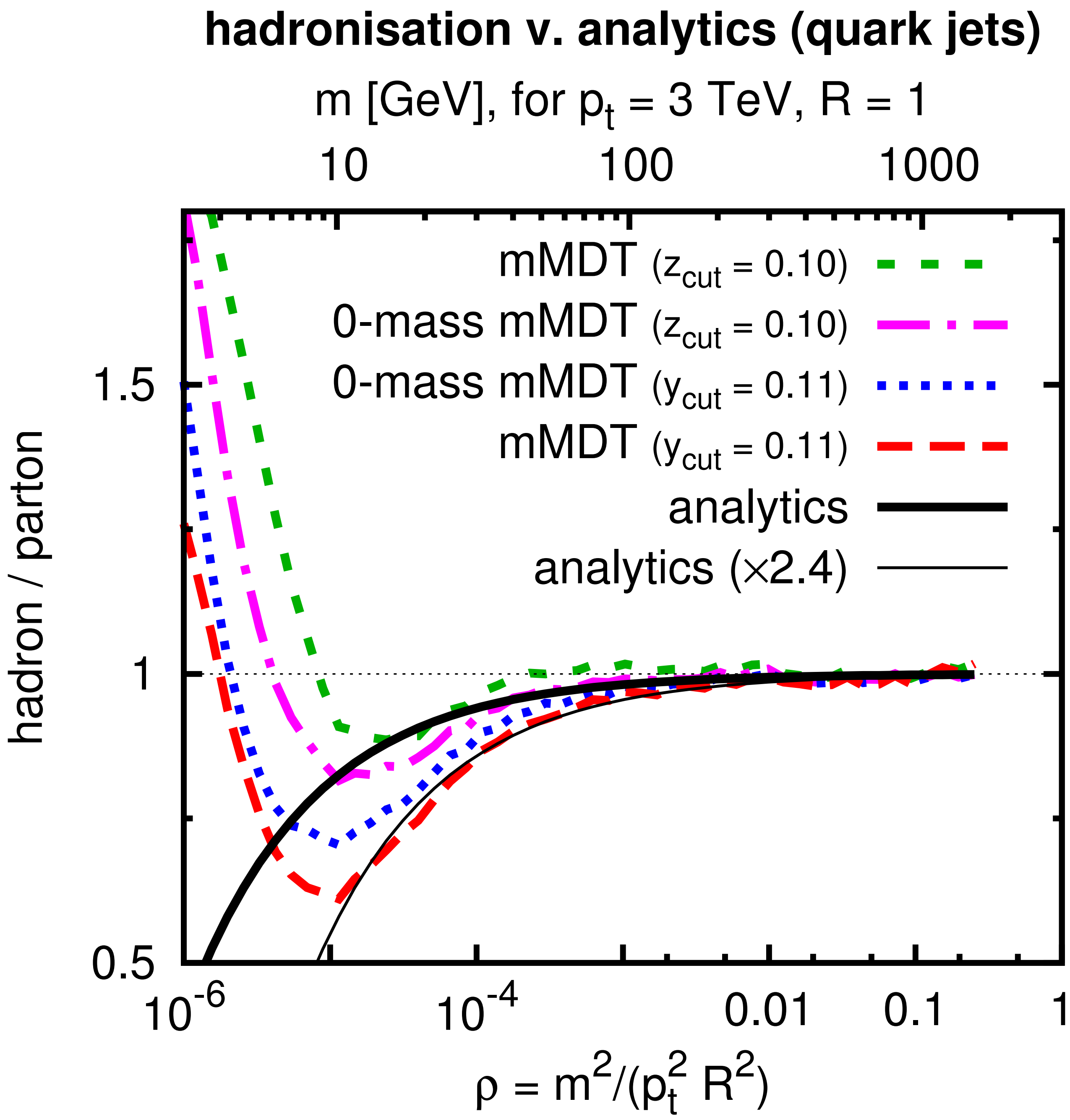
Hadronisation effects



Nearly all taggers have large hadronisation effects:

15 – 60%
for m = 30 – 100 GeV

Hadronisation effects



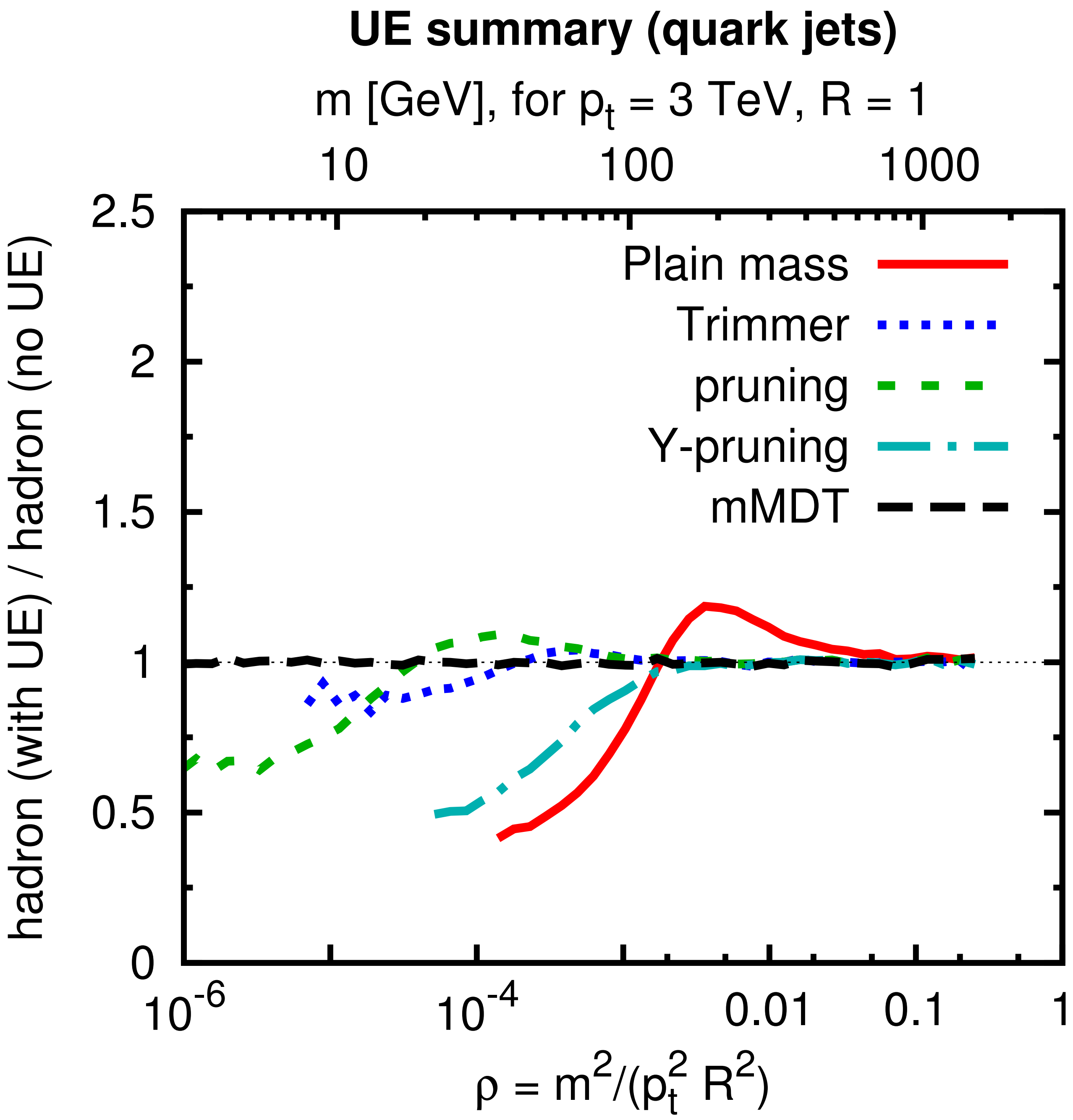
Exception is (m)MDT.

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 (UE)

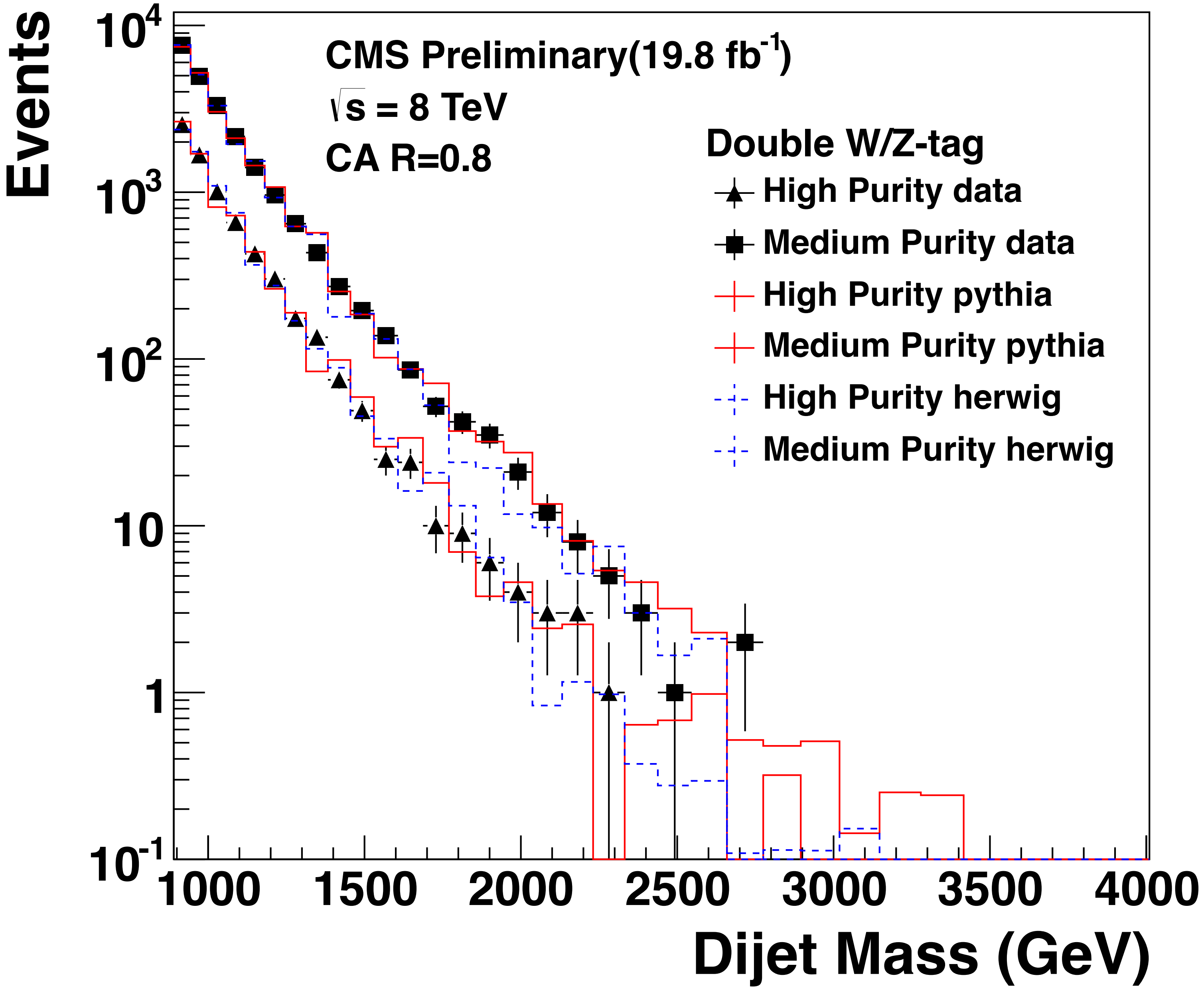


Underlying event impact much reduced relative to jet mass

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



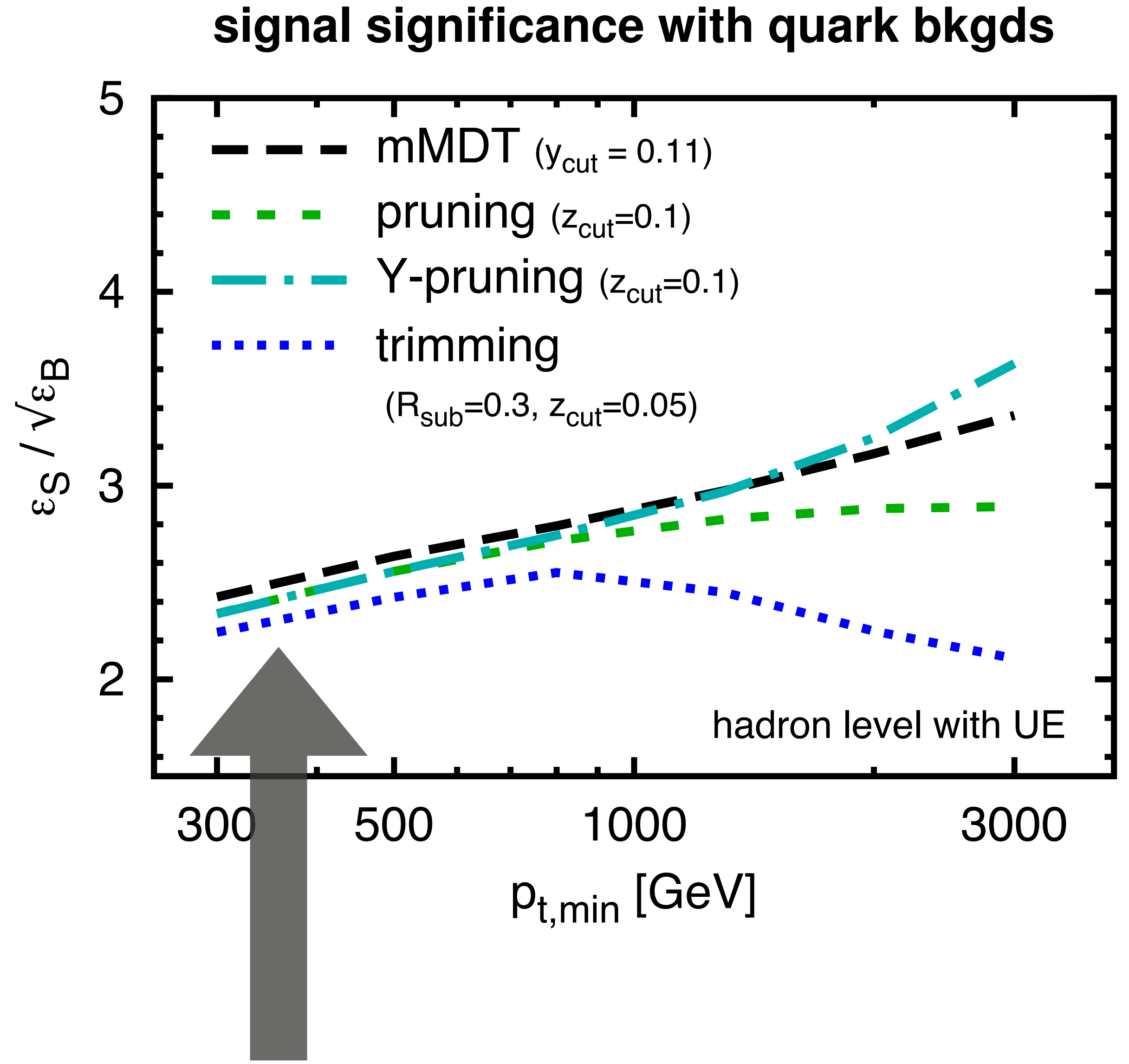
Search for resonances in doubly-tagged dijet events.

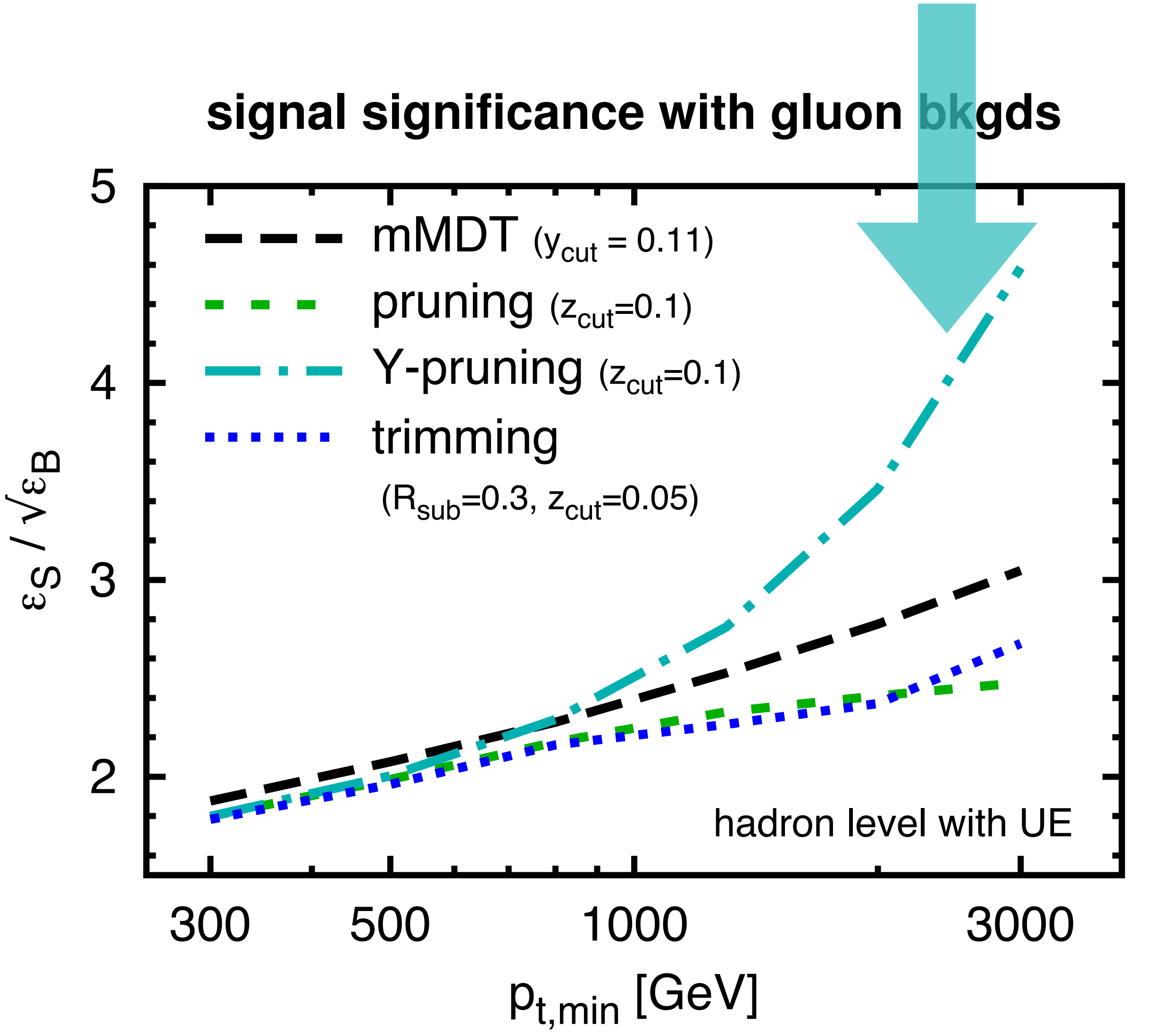
Tagging = pruning + tau21 cut

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)


signal significance with quark bkgds


signal significance with gluon bkgds

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	$\alpha_s^n L^{2n}$	$z_{\rm cut},\ r^2 z_{\rm cut}$	$L \simeq 1/\sqrt{\bar{\alpha}_s} - 2\ln r$	yes
pruning	$\alpha_s^n L^{2n}$	$z_{\rm cut},\ z_{\rm cut}^2$	$L \simeq 2.3/\sqrt{\bar{\alpha}_s}$	yes
MDT	$\alpha_s^n L^{2n-1}$	$y_{\rm cut},\ \frac{1}{4}y_{\rm cut}^2,\ y_{\rm cut}^3$	—	yes
Y-pruning	$\alpha_s^n L^{2n-1}$	$z_{\rm cut}$	(Sudakov tail)	yes
mMDT	$\alpha_s^n L^n$	$y_{\rm cut}$	—	no

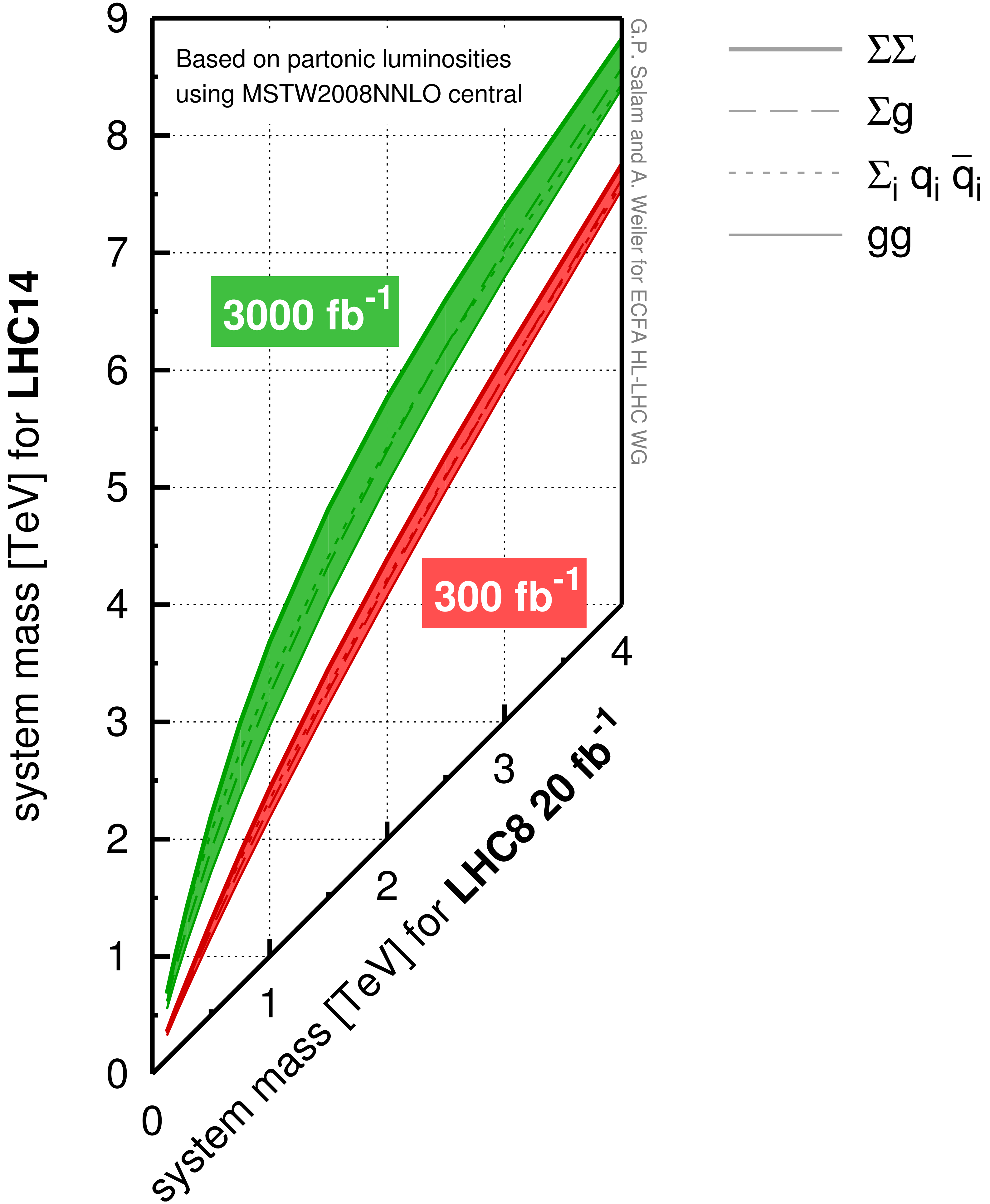
NEW

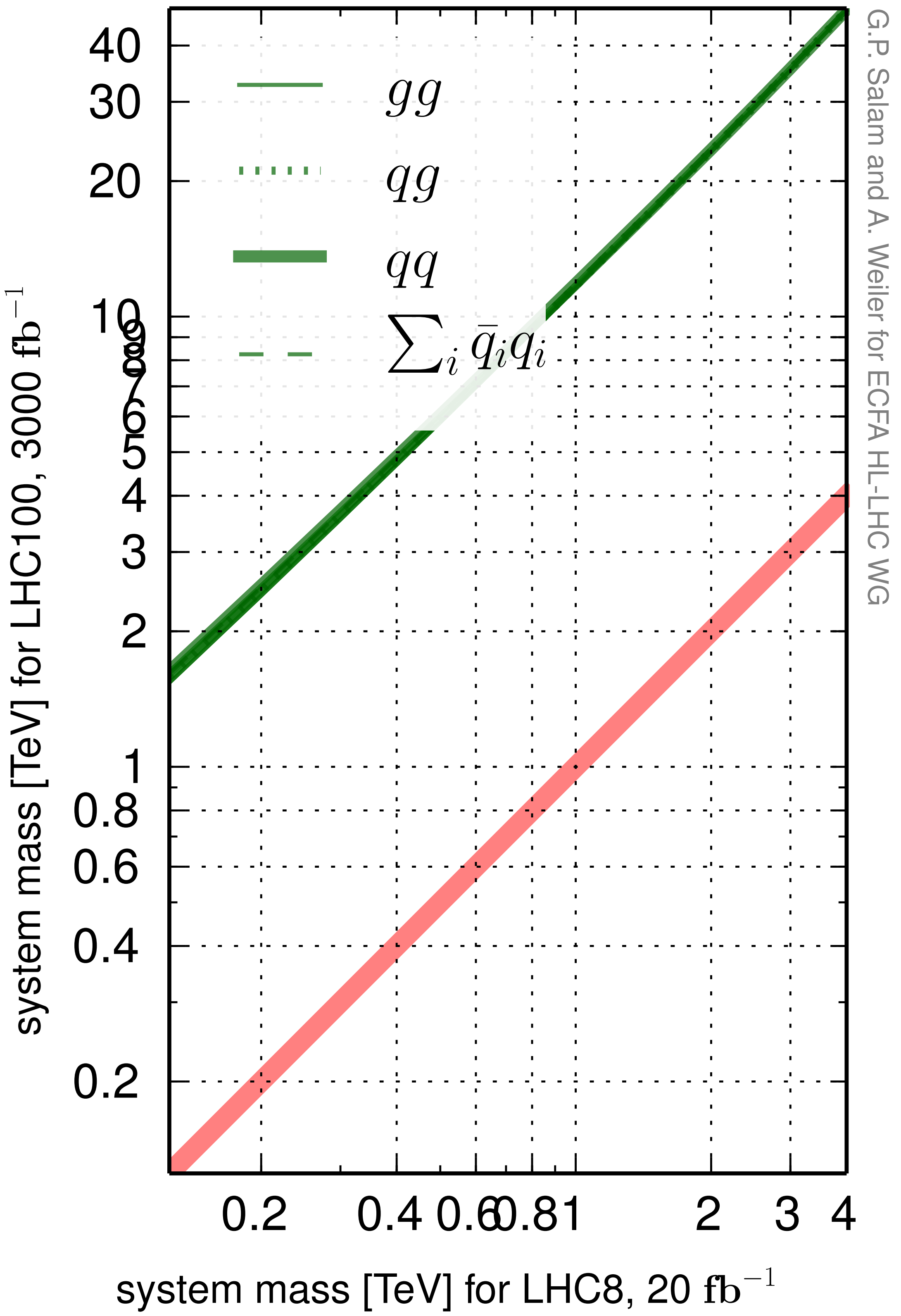
Special: only single logarithms (L = ln ρ)

→ more accurately calculable

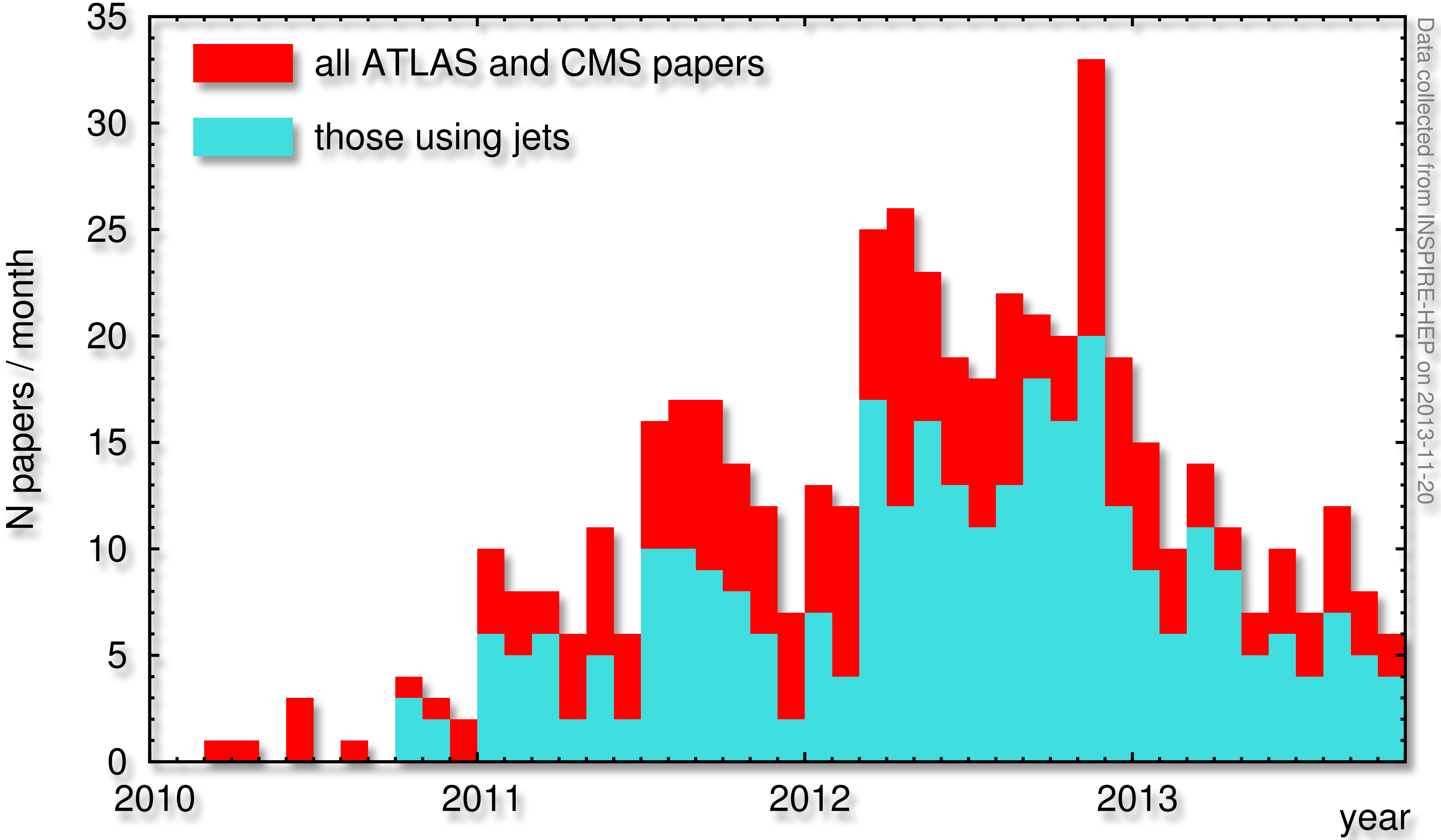
Special: better exploits signal/bkgd differences

EXTRAS

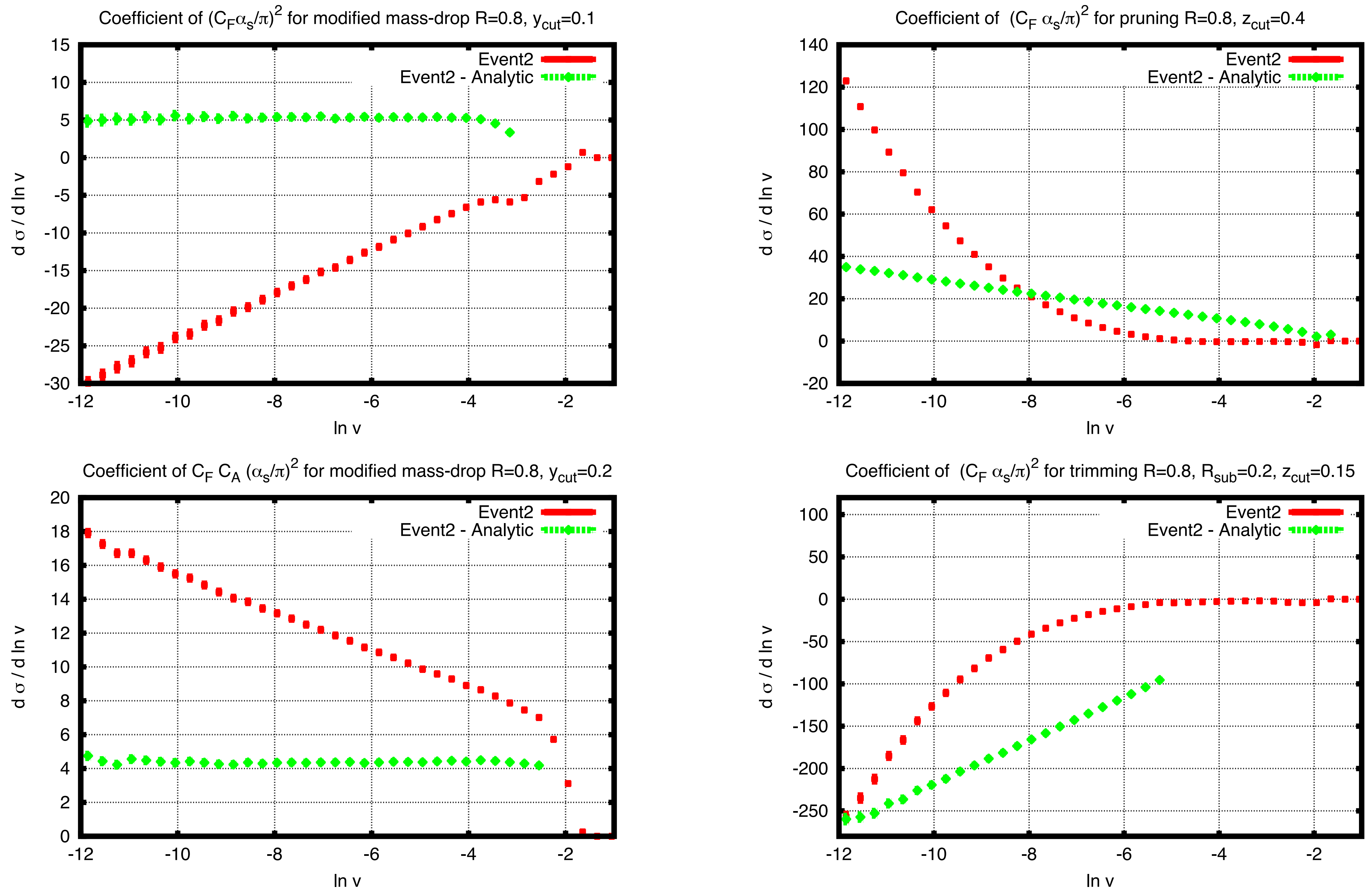

Based on partonic luminosities
using MSTW2008NNLO central
3000 fb^{-1}
300 fb^{-1}
system mass [TeV] for **LHC14**
system mass [TeV] for **LHC8 20 fb^{-1}**
0
1
2
3
4
5
6
7
8
9
G.P. Salam and A. Weiler for ECFA HL-LHC WG
ΣΣ
Σg
Σ_i q_i $\bar{q}_i$
gg


gg
qg
qq
$\sum_i \bar{q}_i q_i$
system mass [TeV] for LHC100, 3000 fb^{-1}
system mass [TeV] for LHC8, 20 fb^{-1}
40
30
20
10
9
8
7
6
5
4
3
2
1
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
1
2
3
4
G.P. Salam and A. Weiler for ECFA HL-LHC WG

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



Examples of NLO checks



Coefficient of $(C_F\alpha_s/\pi)^2$ for modified mass-drop R=0.8, y_{cut}=0.1

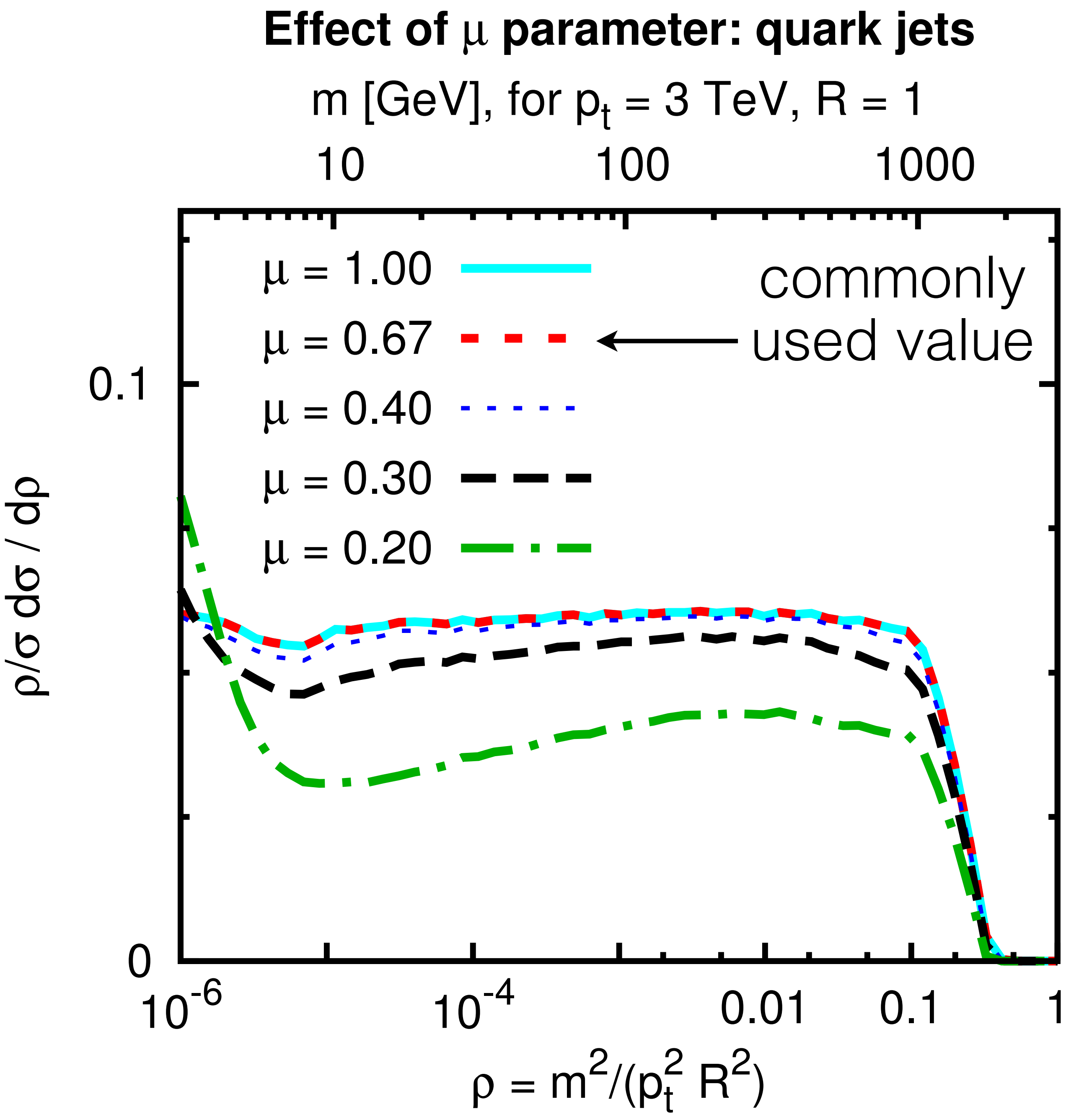
Coefficient of $(C_F\ \alpha_s/\pi)^2$ for pruning R=0.8, z_{cut}=0.4

Coefficient of $C_F\ C_A\ (\alpha_s/\pi)^2$ for modified mass-drop R=0.8, y_{cut}=0.2

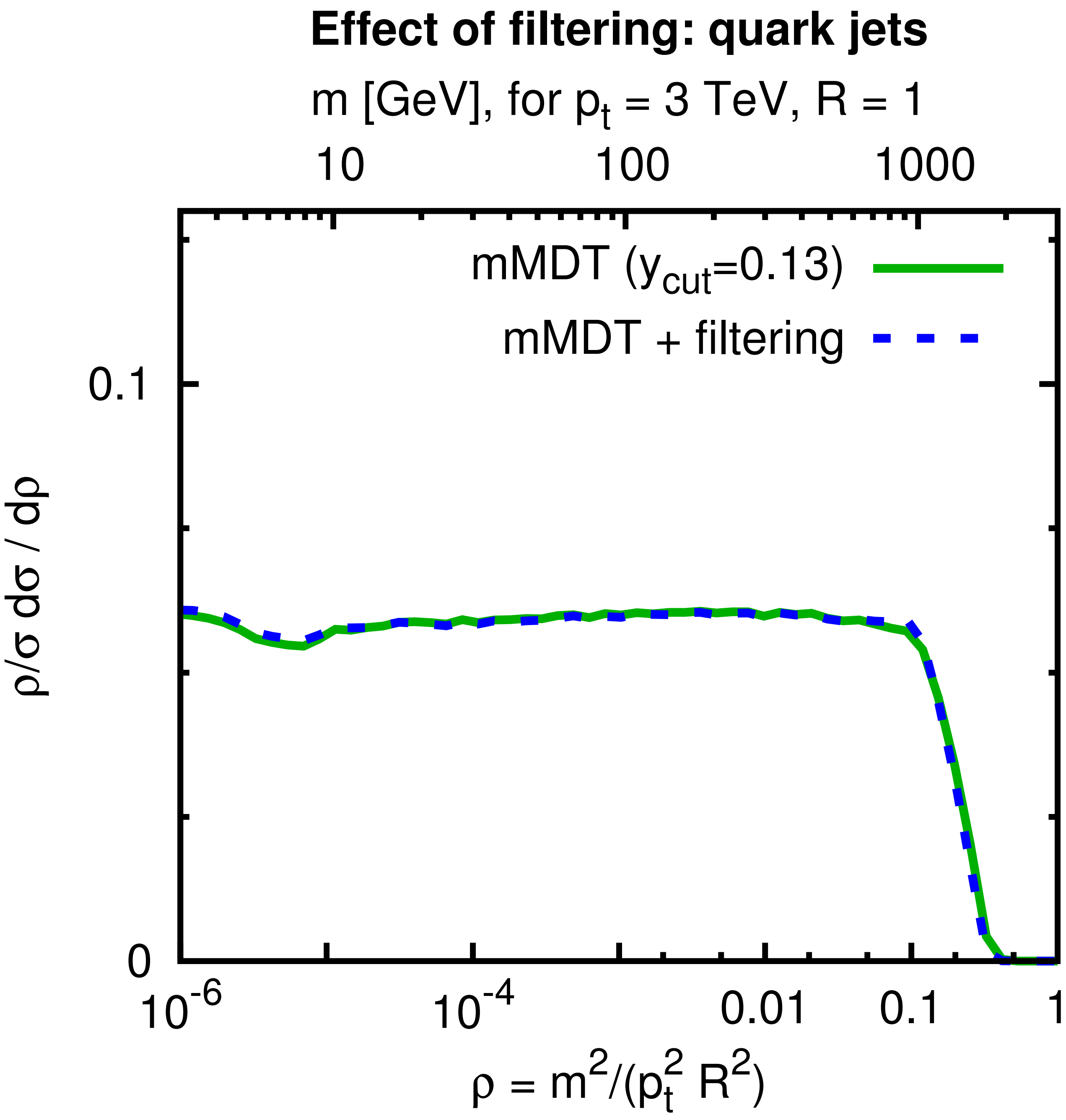
Coefficient of $(C_F\ \alpha_s/\pi)^2$ for trimming R=0.8, R_{sub}=0.2, z_{cut}=0.15

Dasgupta, Fregoso, Marzani & Powling, 1307.0013

mMDT: impact of μ and of filtering



Effect of μ parameter: quark jets



Effect of filtering: quark jets

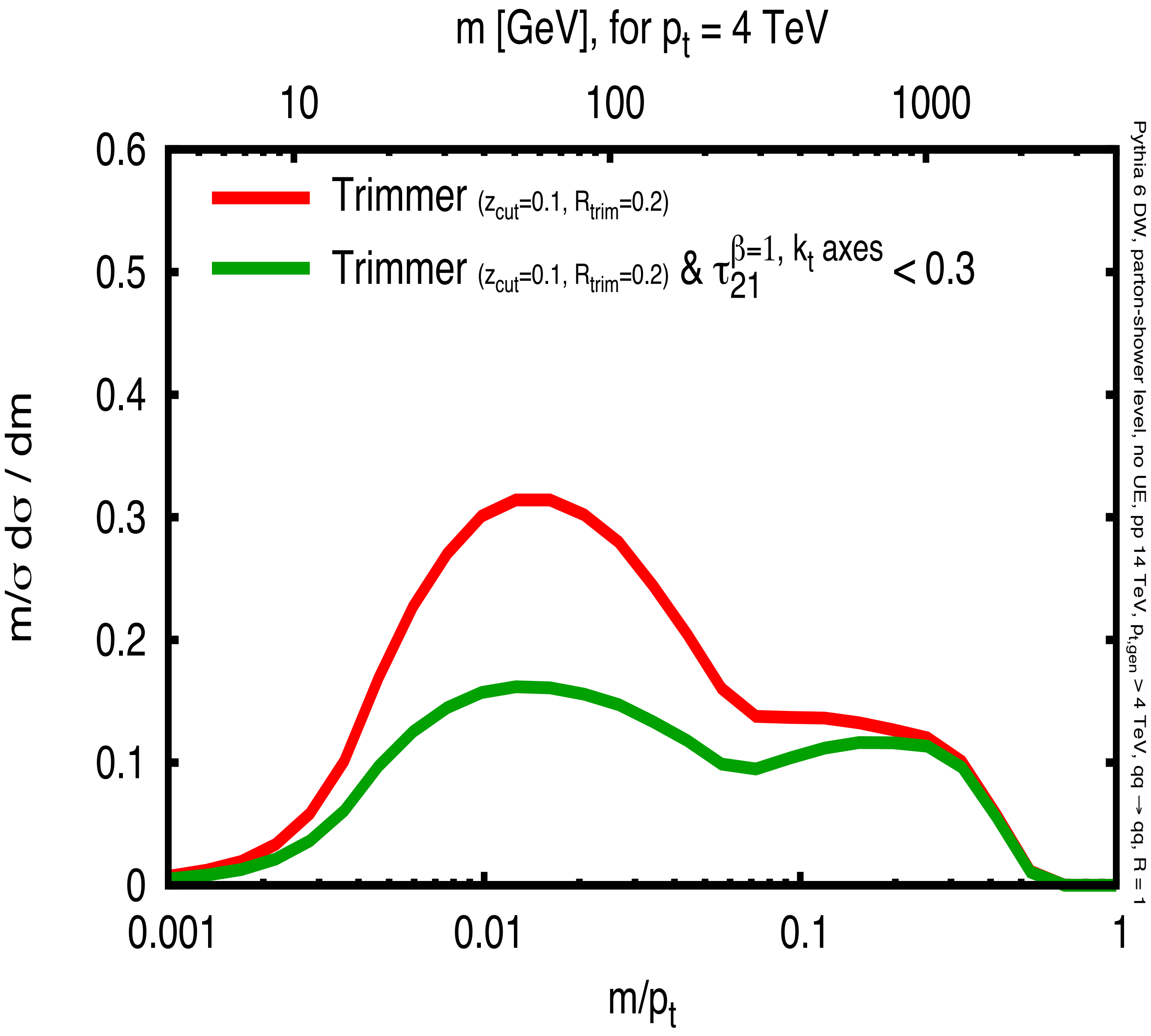
μ parameter basically irrelevant (simpler tagger discards it)

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

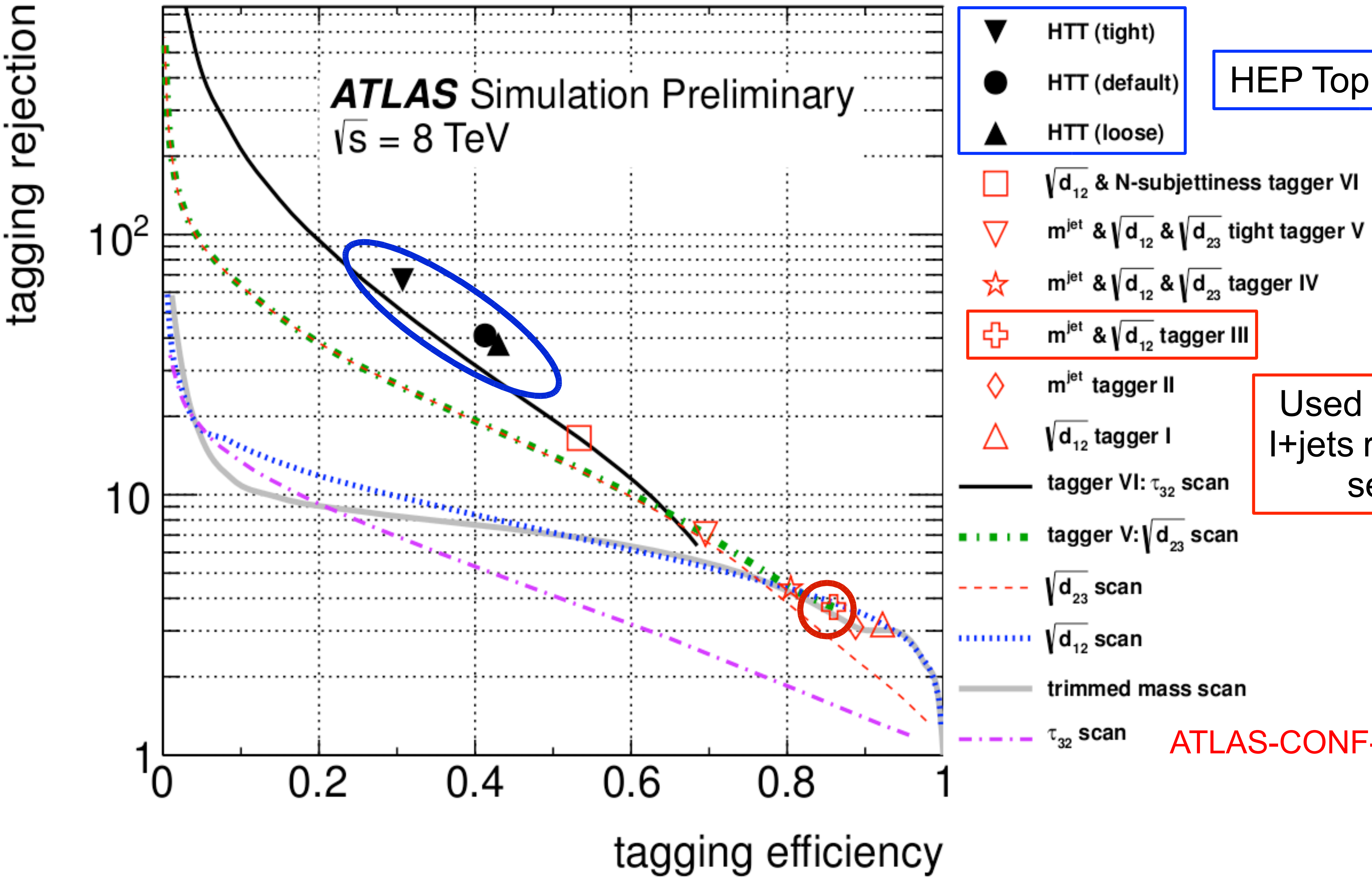
What about cuts on shapes/radiation

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



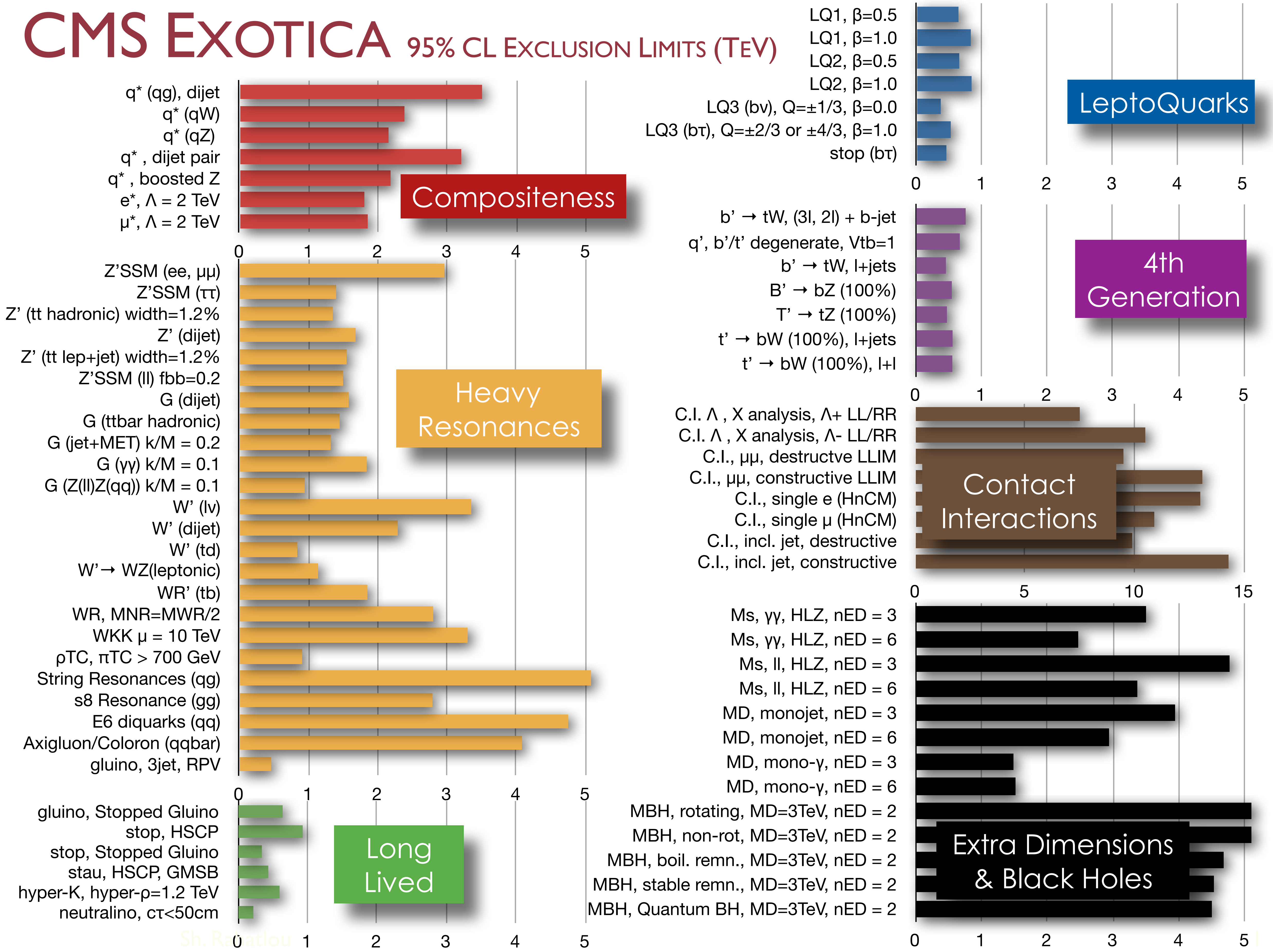
HEP Top Tagger

Used in current l+jets resonance search

ATLAS-CONF-2013-084

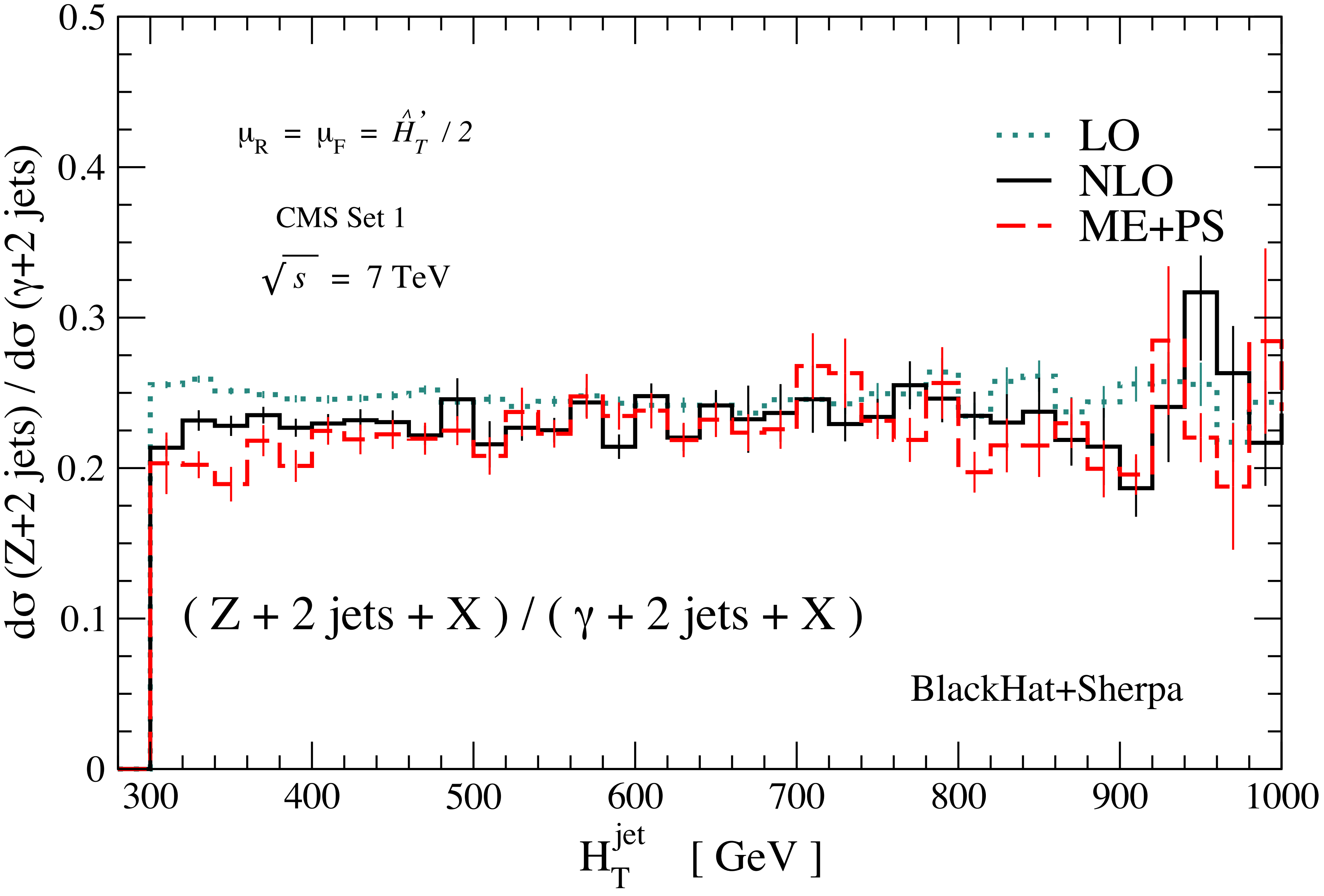
We have a wide variety of taggers available for different analyses!

CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)



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→νν) 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 ...]

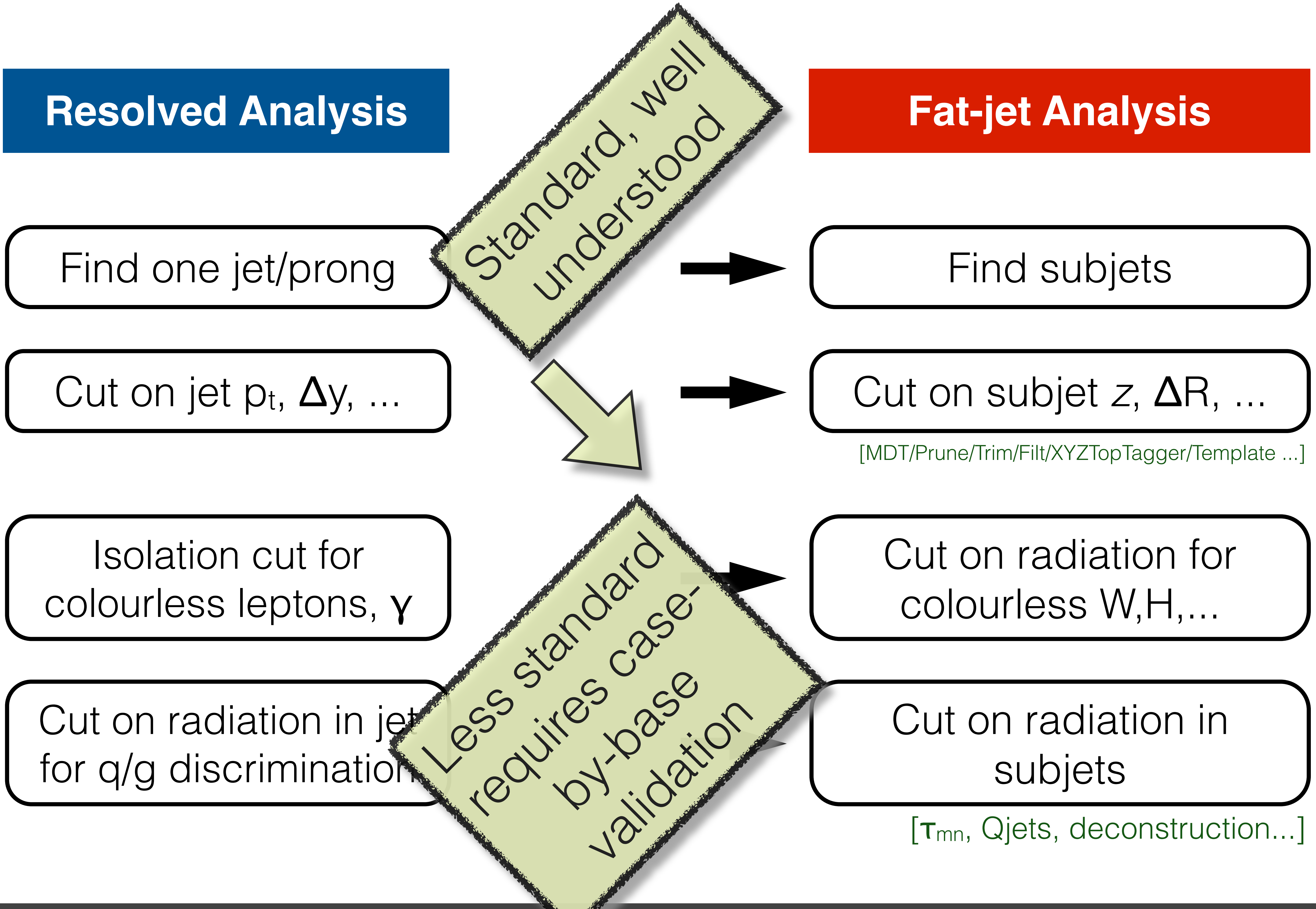
What are we comfortable with?

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→Wb→ 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)