The Accidental Boost

Searches for High Multiplicity New Physics

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3 Talks Today

High Multiplicity Signals @ the LHC

Jet Mass Searches

Subjet Counting Searches

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Last 2 years at the LHC

Searches for BSM physics have been extensive and effective

Searches are less model dependent

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Searches for BSM physics have been extensive and effective

Searches are less model dependent

Still waiting for discovery

Signals could be just out of reach

or

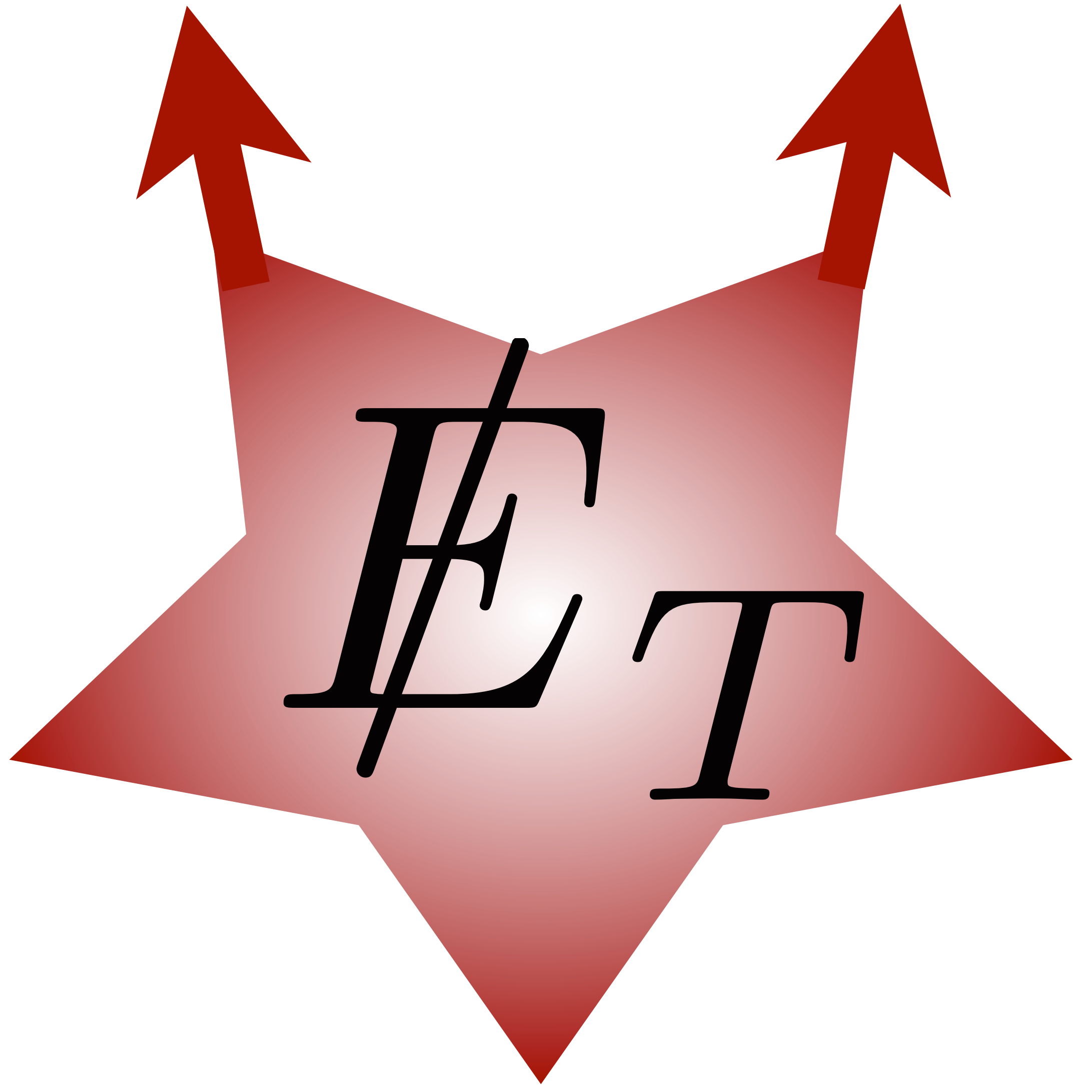
Buried under background

Key Handle to Separate S from B

Key Handle to Separate *S* from *B*

Dramatically reduces
QCD Multijet rate

Key Handle to Separate *S* from *B*



But if signal is not MET-rich

Large classes of signatures are invisible

Work today:

Progress towards low background MET-Less Searches

Will *reduce* the importance of MET

No single solution

Need to be tailored to signal

Boosted Techniques

Leads to new possibilities of
separating signal from backgrounds

Even relatively standard searches can benefit

Boosted techniques can be applied
even when there is no intrinsic boost

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The Accidental Boost

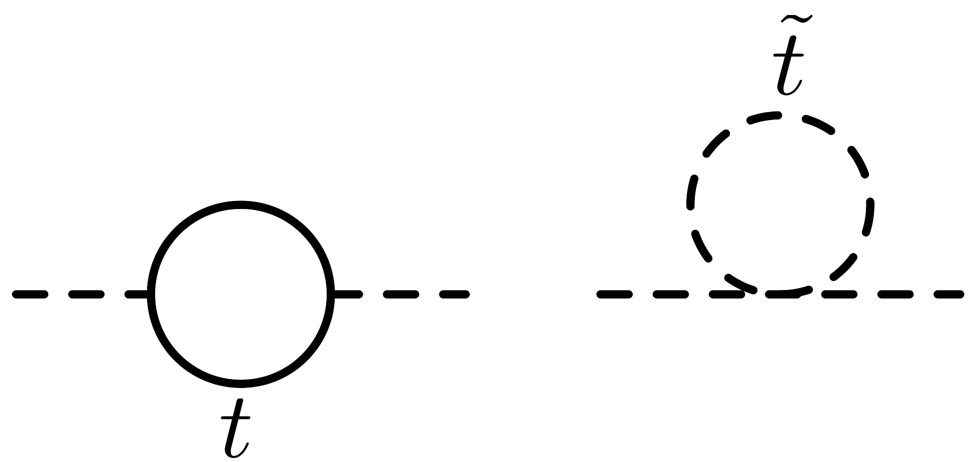
Goal: Eliminate Background & Keep Signal
Not to identify what a hypothetical signal is

One Target: Natural Susy

$m_h^2 \qquad \sim (125 \text{ GeV})^2$

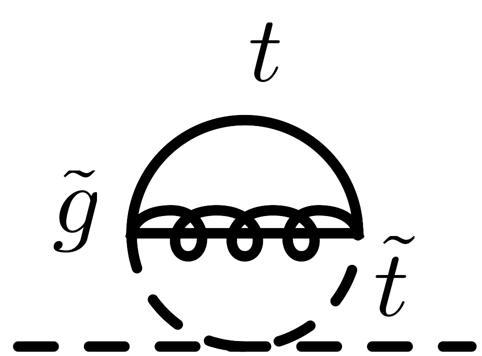
Tree $\qquad \mu^2 \qquad$ Higgsinos ~ 200 GeV

1 loop



Top Squarks ~ 500 GeV

2 loop



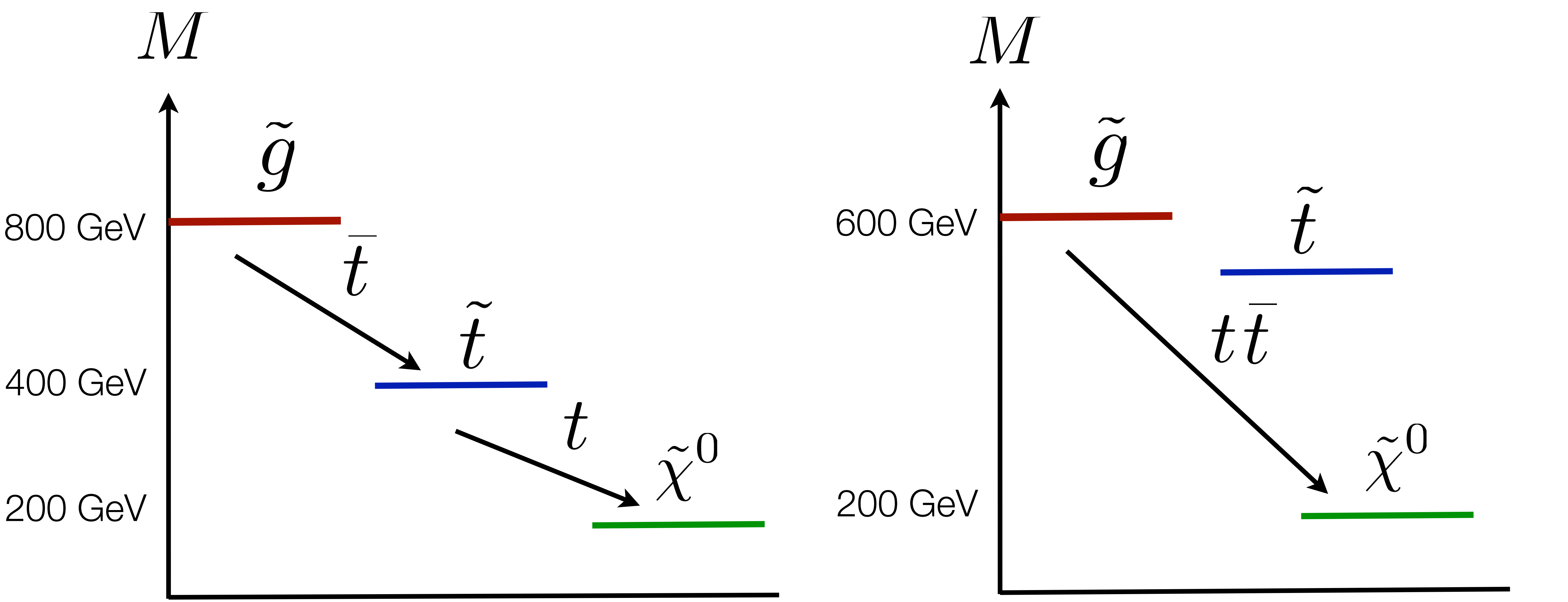
Gluinos ~ 1500 GeV

Famous "Natural Susy"

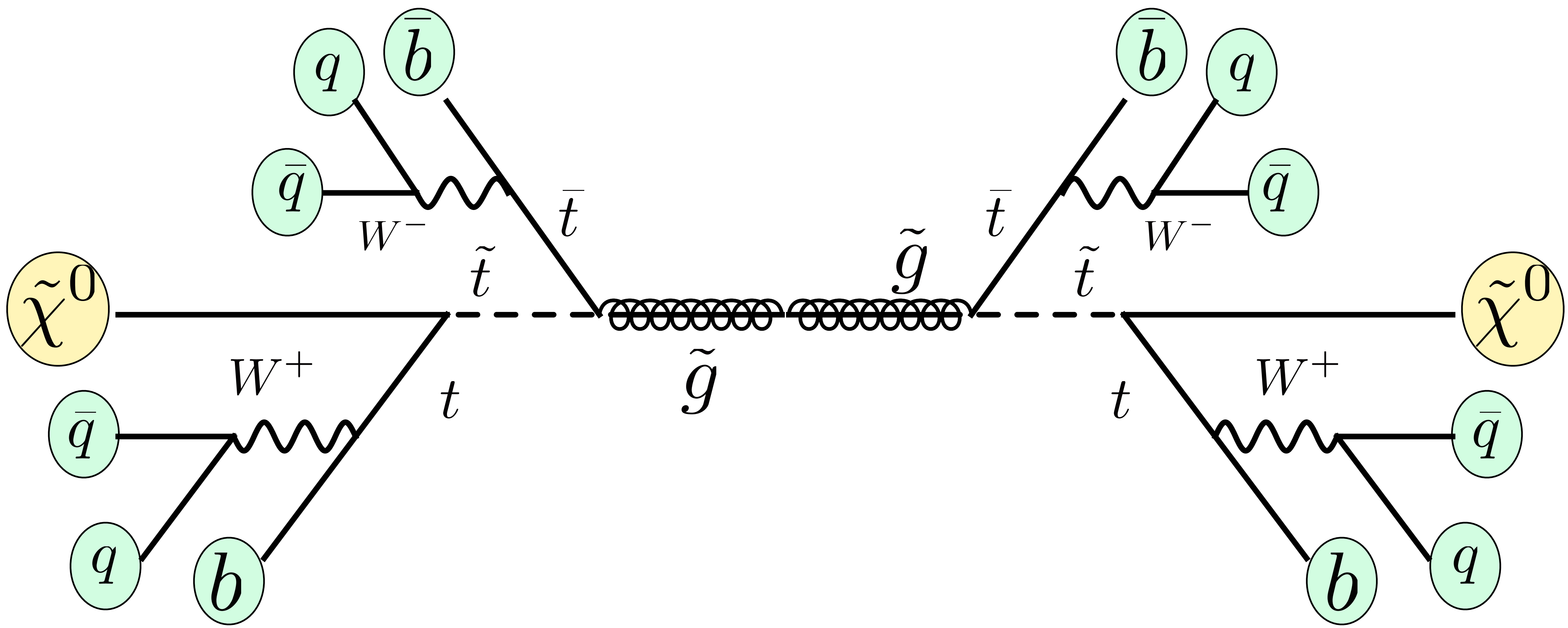
Moderately light gluinos

Light Stops

Light Higgsinos



The Classic Signature



12^+ Jets

Should Be Easy

Shooting Fish in a Barrel!

Should Be Easy

Shooting Fish in a Barrel!

Not completely trivial

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Not completely trivial

High Multiplicity Backgrounds

No NLO

Tree-level is state of the art

Data Driven Extrapolation: $N \to N + 1$

Should Be Easy

Shooting Fish in a Barrel!

Not completely trivial

High Multiplicity Backgrounds

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Data Driven Extrapolation: $N \to N+1$

Heterogenous final states (+ b-tagging)

$4W : (8j, 0\ell) \to (0j, 4\ell)$

Jets can be Merged Together

A variety of final state jet multiplicities

Isolated Jet P_T is Reduced

Easily fall beneath 50 GeV

Baryonic R-Parity Violation

Eviscerates MET

$$\int d^2\theta \;\; \lambda''_{ijk} \, U_i^c D_j^c D_k^c$$

Makes LSP decay

to 3 quarks (most LSPs)

to 2 quarks (squark LSPs)

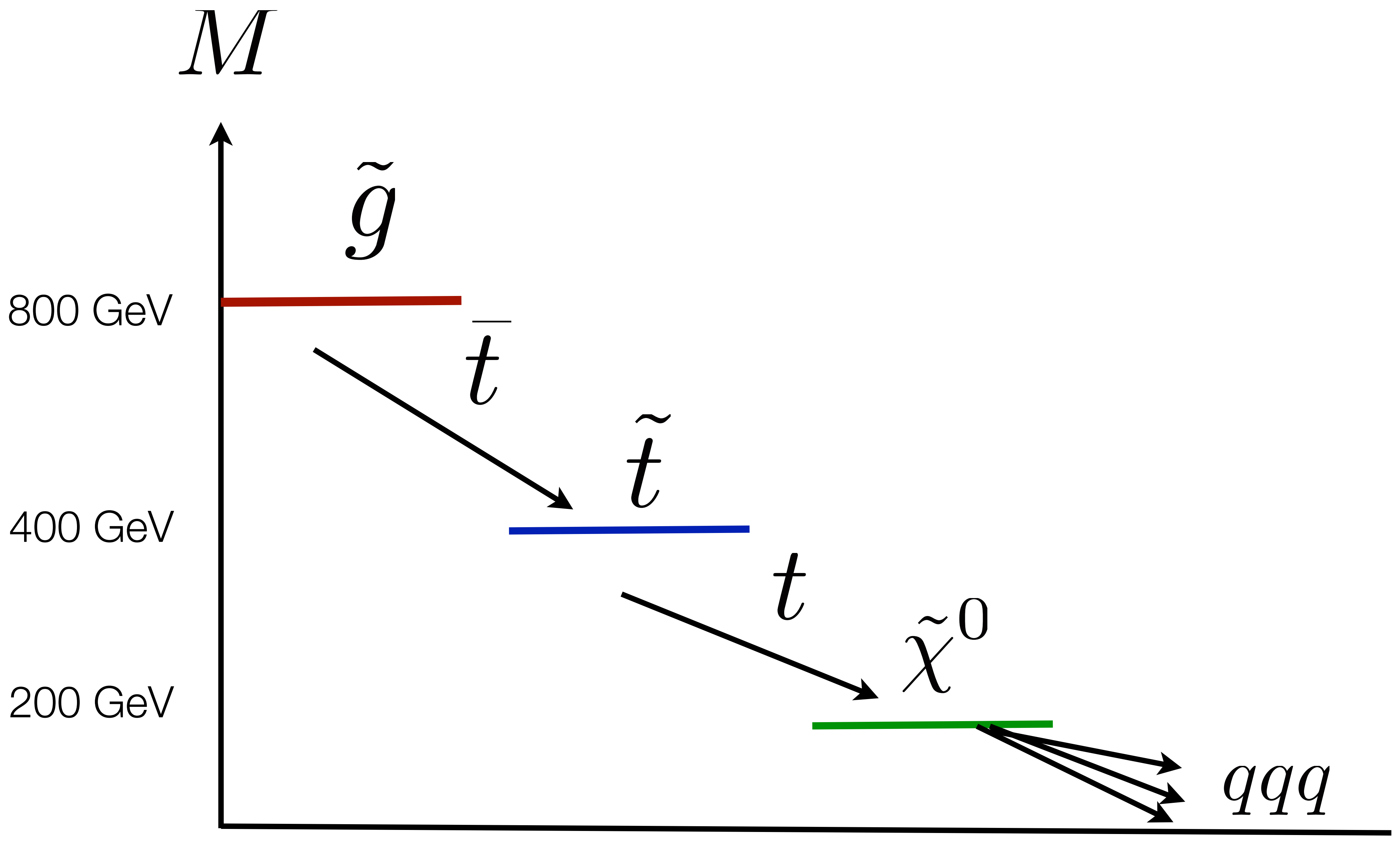
(one quark could be top → +2j)

Increases multiplicity significantly

Natural Susy

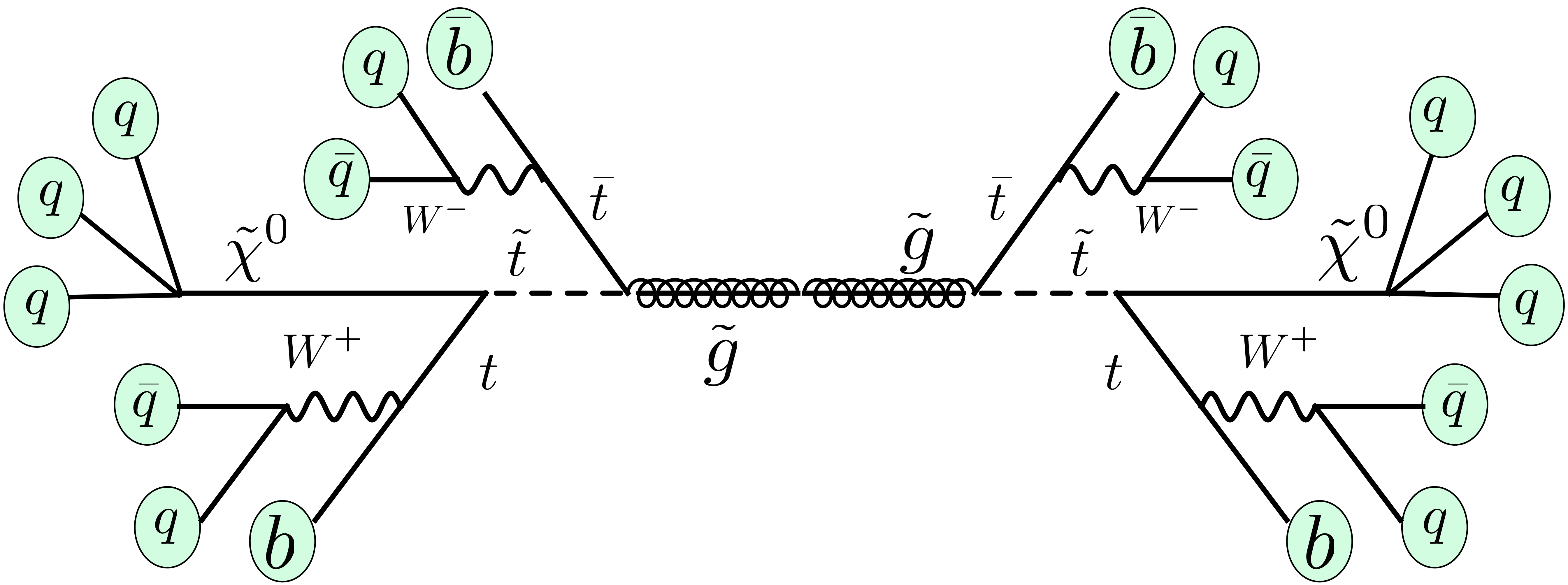
with RPV

Multiplicity explodes



The Less-Classic Natural Susy Signature

18^+ Jets

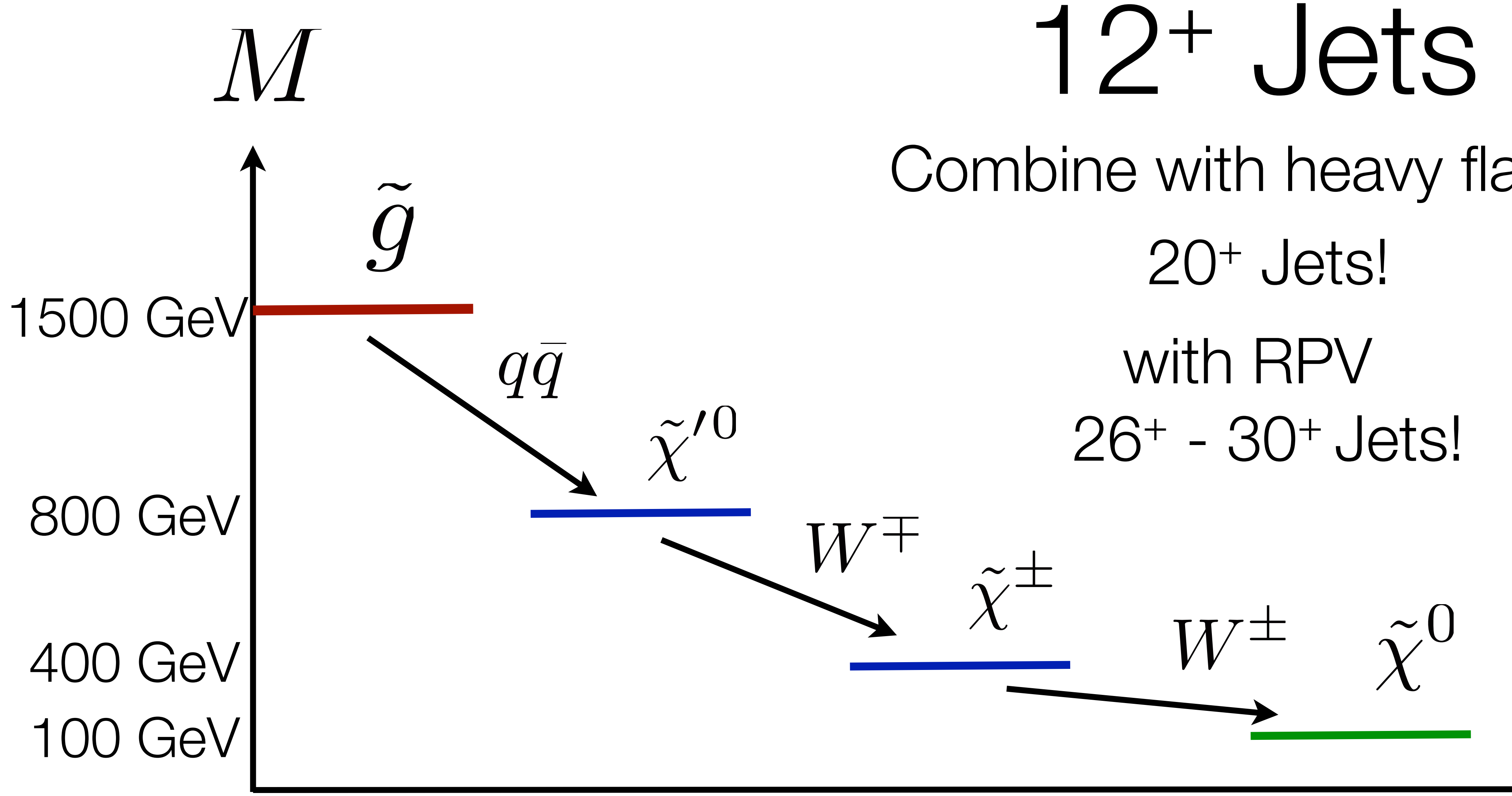


Lots of similar examples in Susy

2 Step Cascade Decay

$$\tilde{g} \longrightarrow \tilde{W} \longrightarrow \tilde{H} \longrightarrow \tilde{B} \quad \text{(light flavor)}$$

$$\tilde{g} \longrightarrow \tilde{H} \longrightarrow \tilde{W} \longrightarrow \tilde{B} \quad \text{(heavy flavor)}$$



12^+ Jets

Combine with heavy flavor

20^+ Jets!

with RPV

26^+ - 30^+ Jets!

Technicolor/Composite Higgs Theories

Frequently have colored vectors and pseudo-Goldstone bosons

Kilic, Okui, Sundrum (2008)

Evans, Luty (2009)

If $\pi_T > 2m_t$

$$\mathrm{Br}(\pi_T \to t\bar{t}) \sim \mathcal{O}(1)$$

Frequently easiest to produce vector resonances

$$pp \to \rho_T \to \pi_T \pi_T \to (t\bar{t})(t\bar{t})$$

$$pp \to \omega_T \to \pi_T \pi_T \pi_T \to (t\bar{t})(t\bar{t})(t\bar{t})$$

$$pp \to \rho_T \rho_T \to (\pi_T \pi_T)(\pi_T \pi_T) \to ((t\bar{t})(t\bar{t}))((t\bar{t})(t\bar{t}))$$

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Inclusive Approach

Gain sensitivity to high multiplicity final states

Requiring N jets requires O(N) cuts

Jets may have small p_T (accidentally forward)

Jets merge together

Get Lost

The more cuts, the less inclusive

Less likely to be the best discovery channel

Typical Susy Searches use

anti-k_T R = 0.4 to 0.6

Lots of room for isolated jets
Can find up to 60

Good at separating high multiplicity
from low multiplicity

Typical Susy Searches use

anti-k_T $R = 0.4$ to 0.6

Lots of room for isolated jets
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Good at separating high multiplicity
from low multiplicity

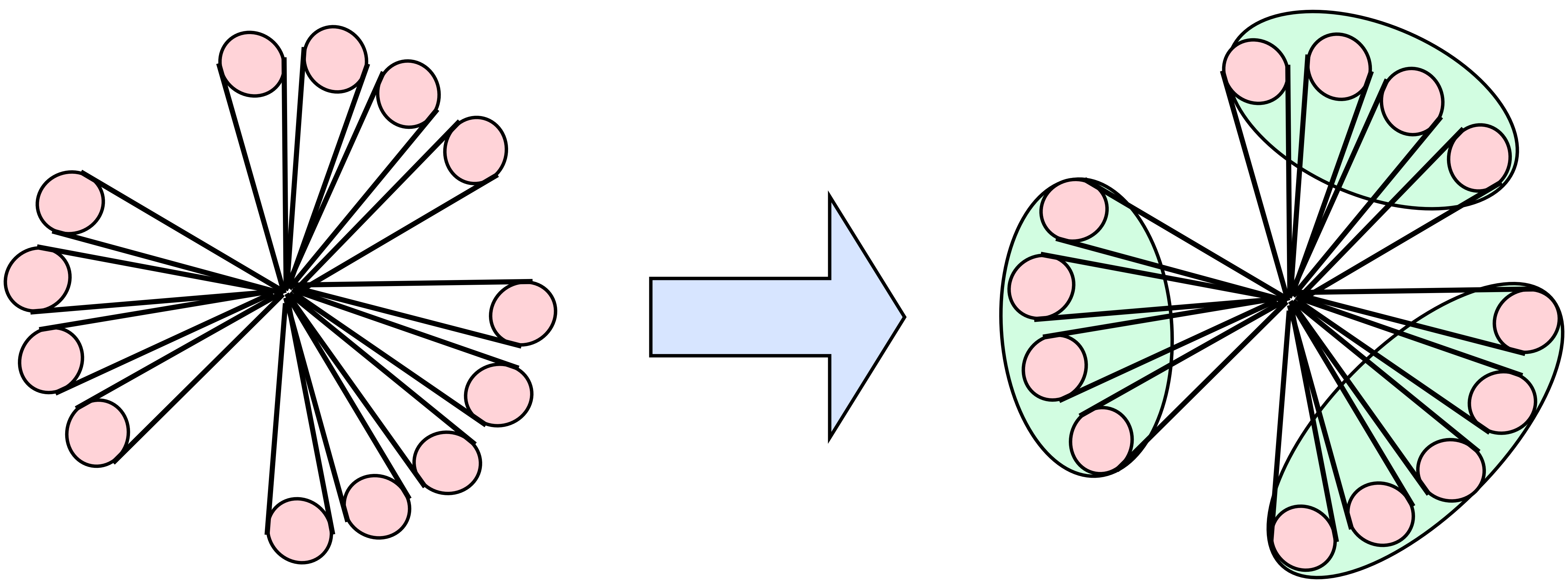
Start by going backwards

anti-k_T $R = 1.2$

No room for isolated jets
Only 4 to 6 jets possible

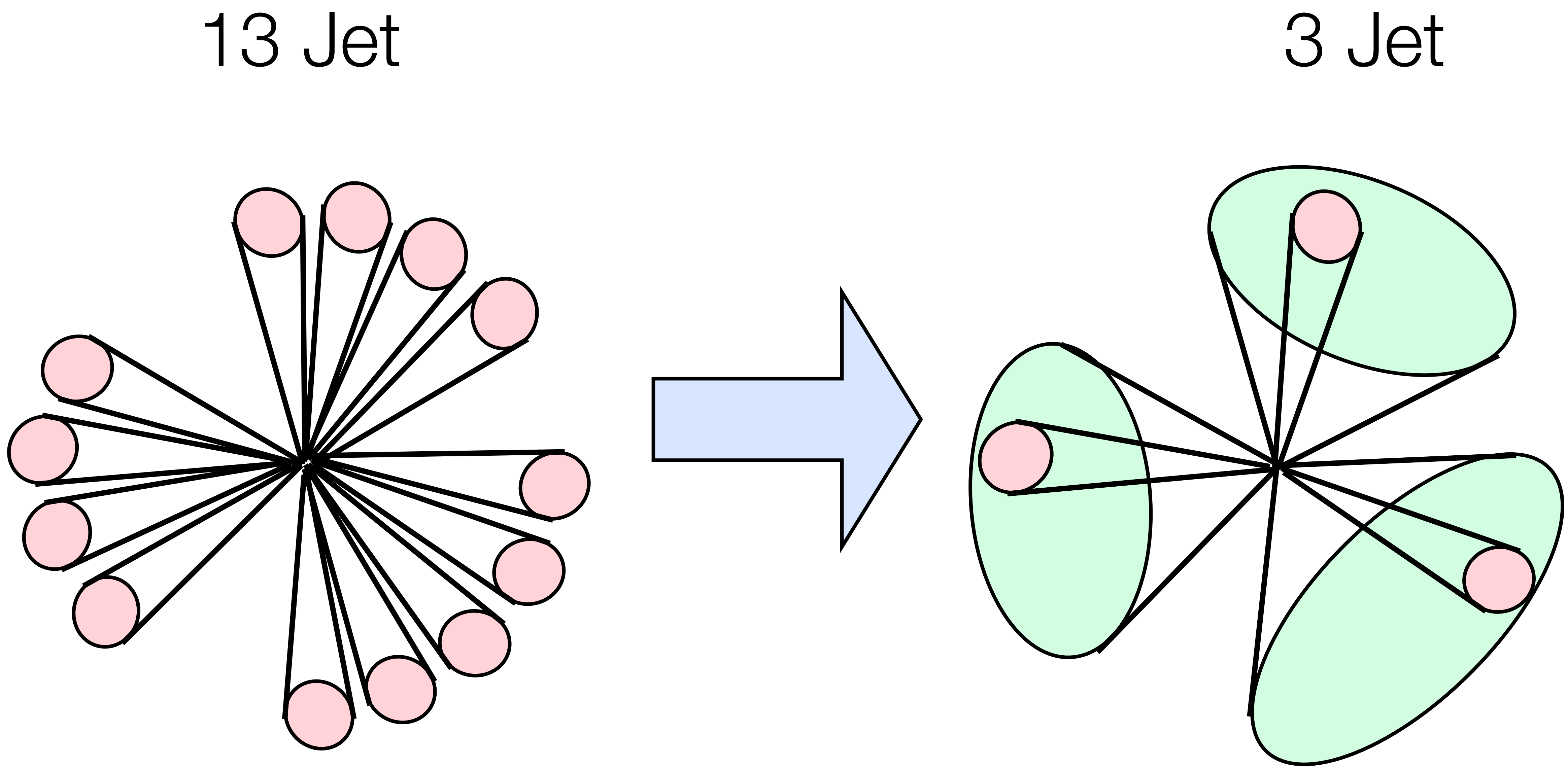
Seem to have lost
the single feature that made
these events special

13 Jet Event 3 Jet Event



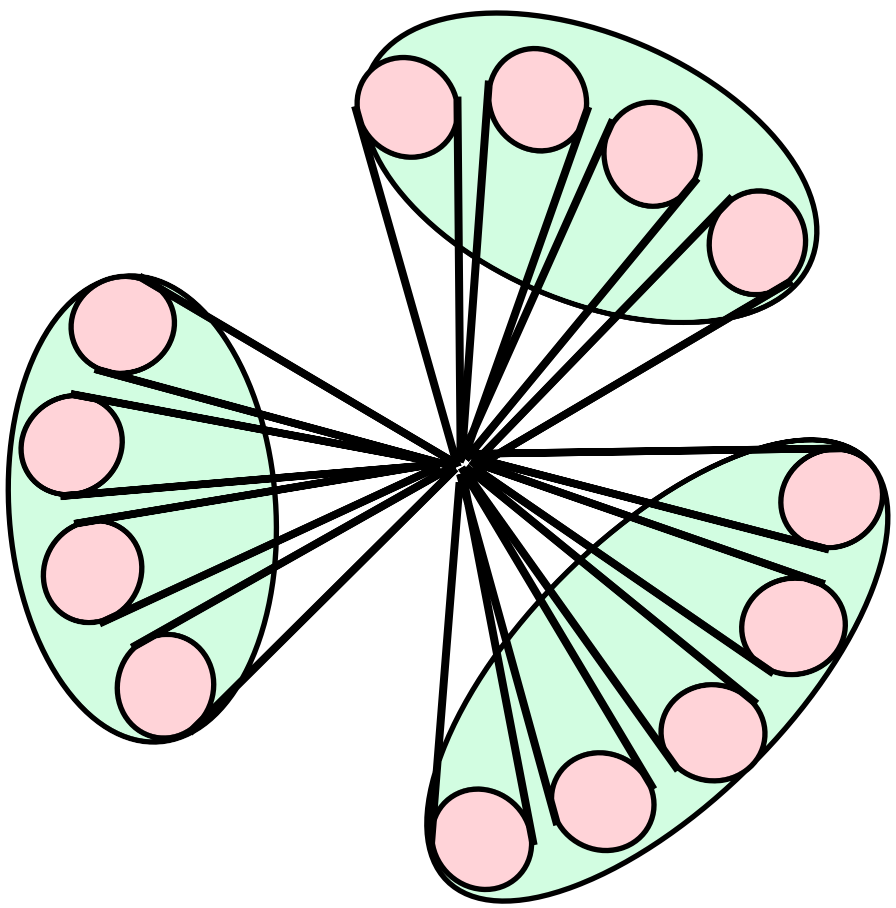
Typical QCD Background

Background rate skyrockets

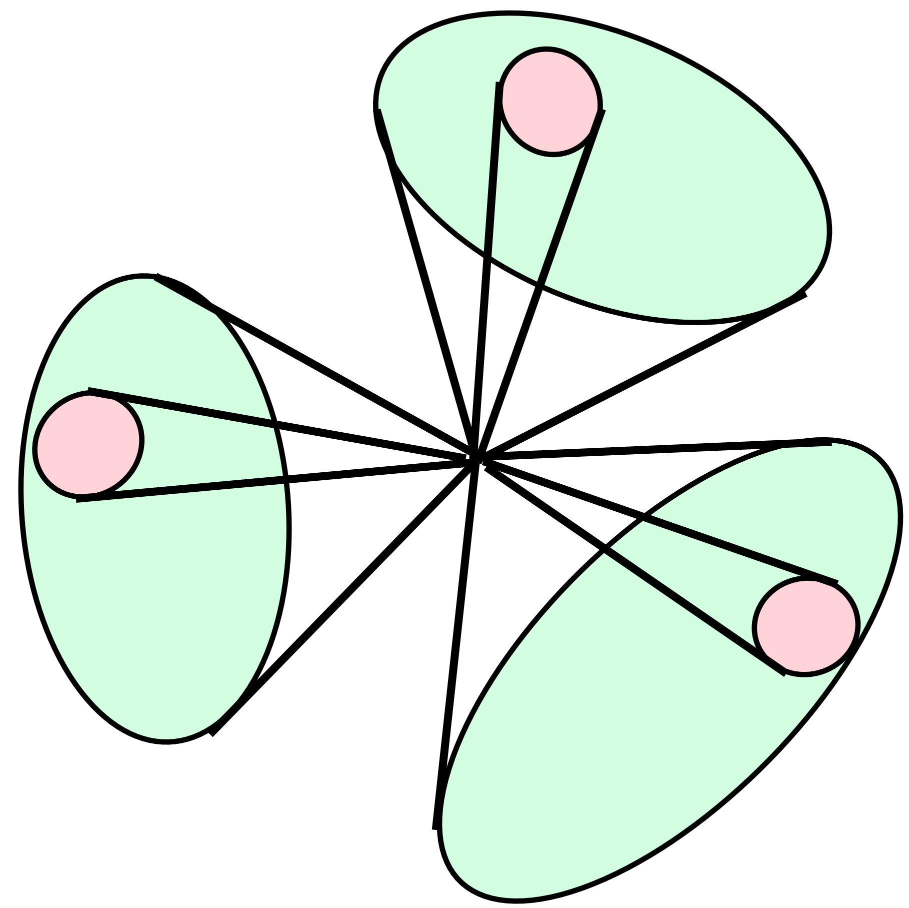


Now need to distinguish

Signal

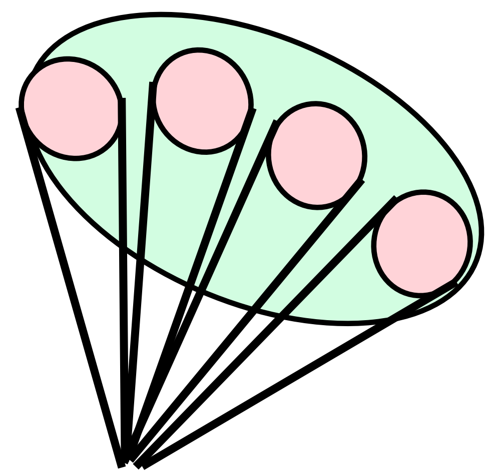


Background



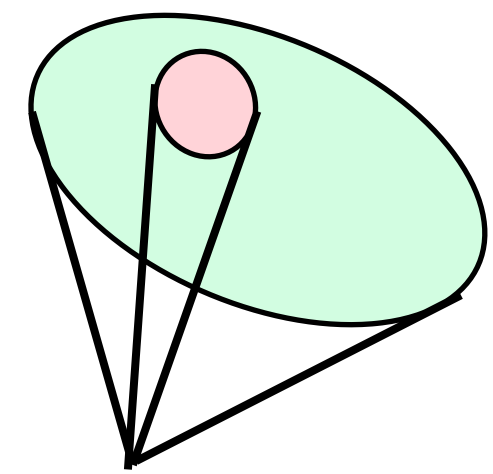
The difference between them is clear

Large Jet Mass



$$\frac{m_j}{p_T} \sim 1$$

Small Jet Mass



$$\frac{m_j}{p_T} \sim 0.3$$

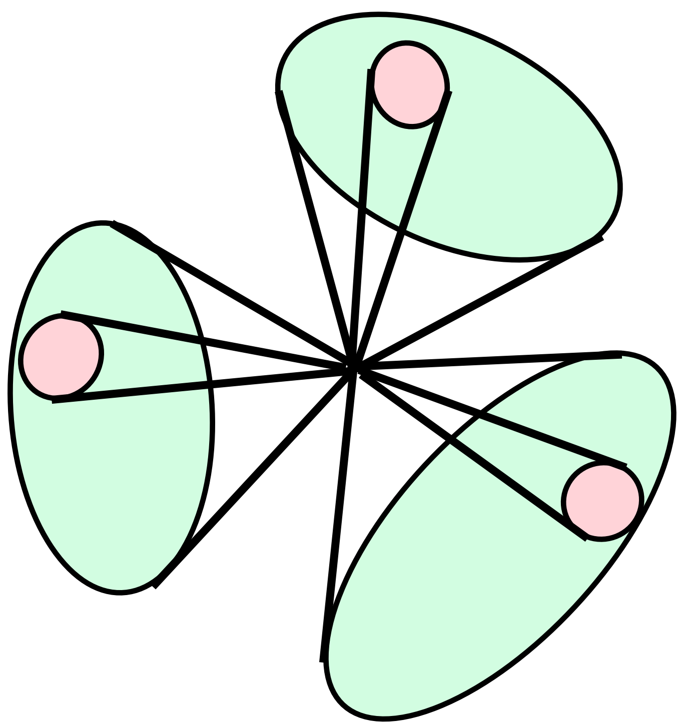
Each jet mass is *approximately* independent for QCD

Getting multiple massive jets rare

Jet mass correlations never studied before

QCD jets only have small correlations

Data driven background predictions possible



$$P_3(x_1, x_2, x_3) \simeq P_1(x_1)P_1(x_2)P_1(x_3)$$

Measure in one sample and extrapolate

Also can use other control regions (MET/leptons/bjets)

Would like a calculation to understand correlations

Should measure in multiple settings (q vs g composition)

Introduce 1 New Variable

Sum of Jet Masses

$$M_J = \sum_{n=1}^{N_J} m_{j_n}$$

QCD jets have most of their mass generated by the parton shower

Top events have their mass capped near 400 GeV

M_J as a replacement for H_T

Signal

$$m_{j_i}^2 \propto p_{T\,i}^2$$

Background

$$m_{j_i}^2 \propto \alpha_s \, p_{T\,i}^2$$

$$m_j \sim \kappa p_T$$

$$H_T = \sum E_{T\,i} \qquad H_T = \sum_i (p_{T\,i}^2 + m_{j_i}^2)^{\frac{1}{2}}$$

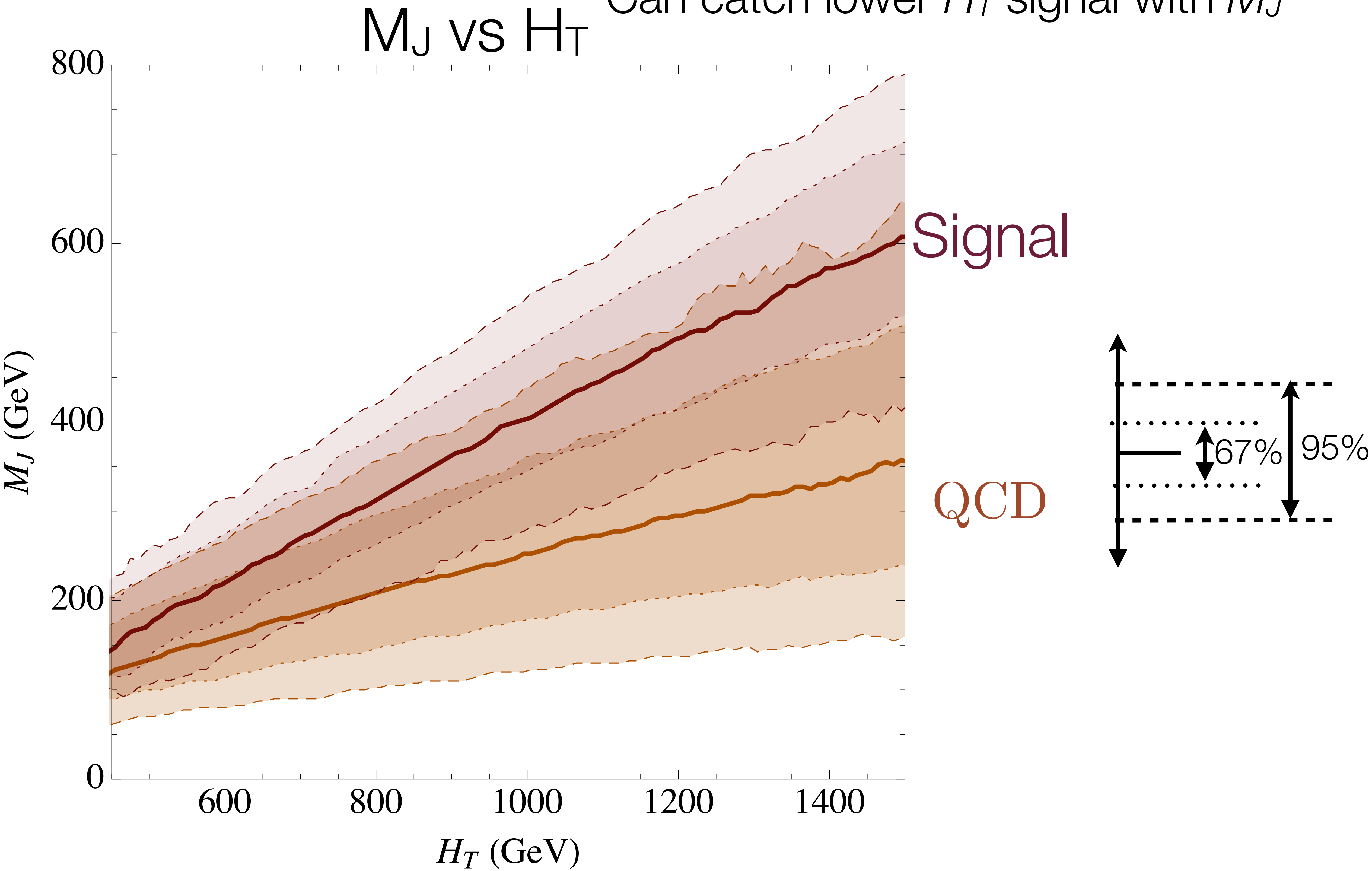
$$H_T \sim \sum_i m_{j_i} (\kappa^{-2} + 1)^{\frac{1}{2}} = M_J (\kappa^{-2} + 1)^{\frac{1}{2}}$$

Signal has higher M_J for fixed H_T

Never does parametrically worse

Signal vs QCD: Steeper than Top

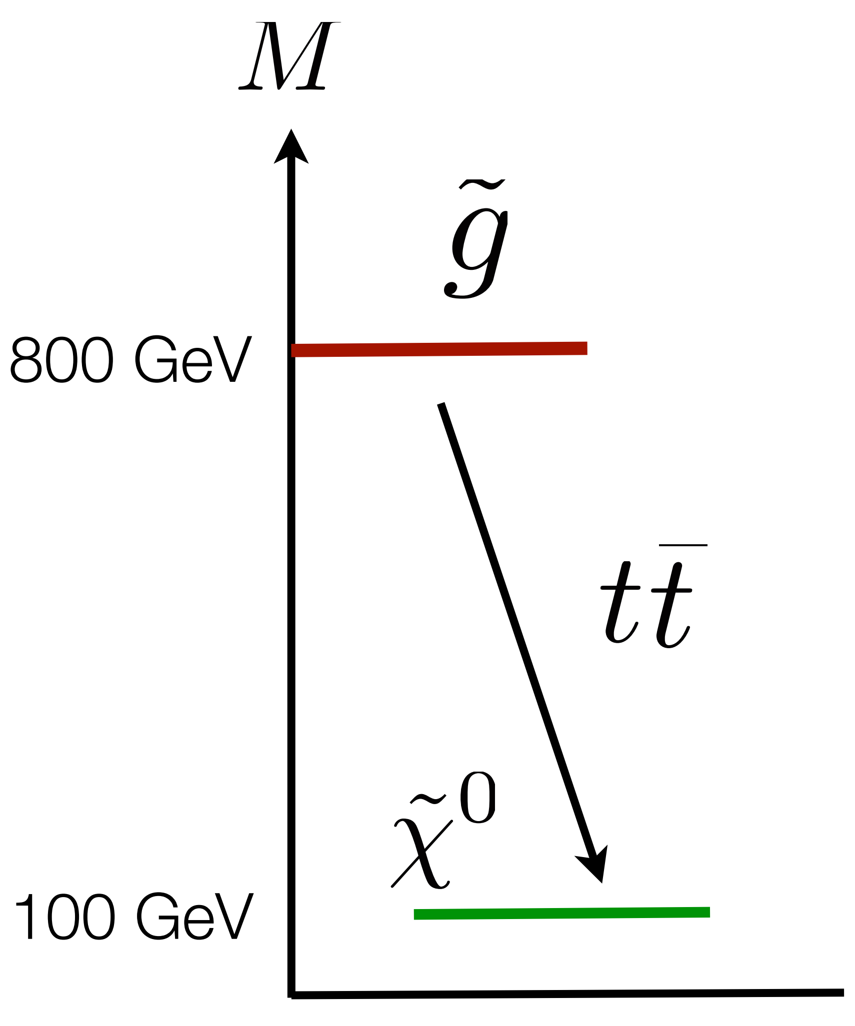
Can catch lower H_T signal with M_J



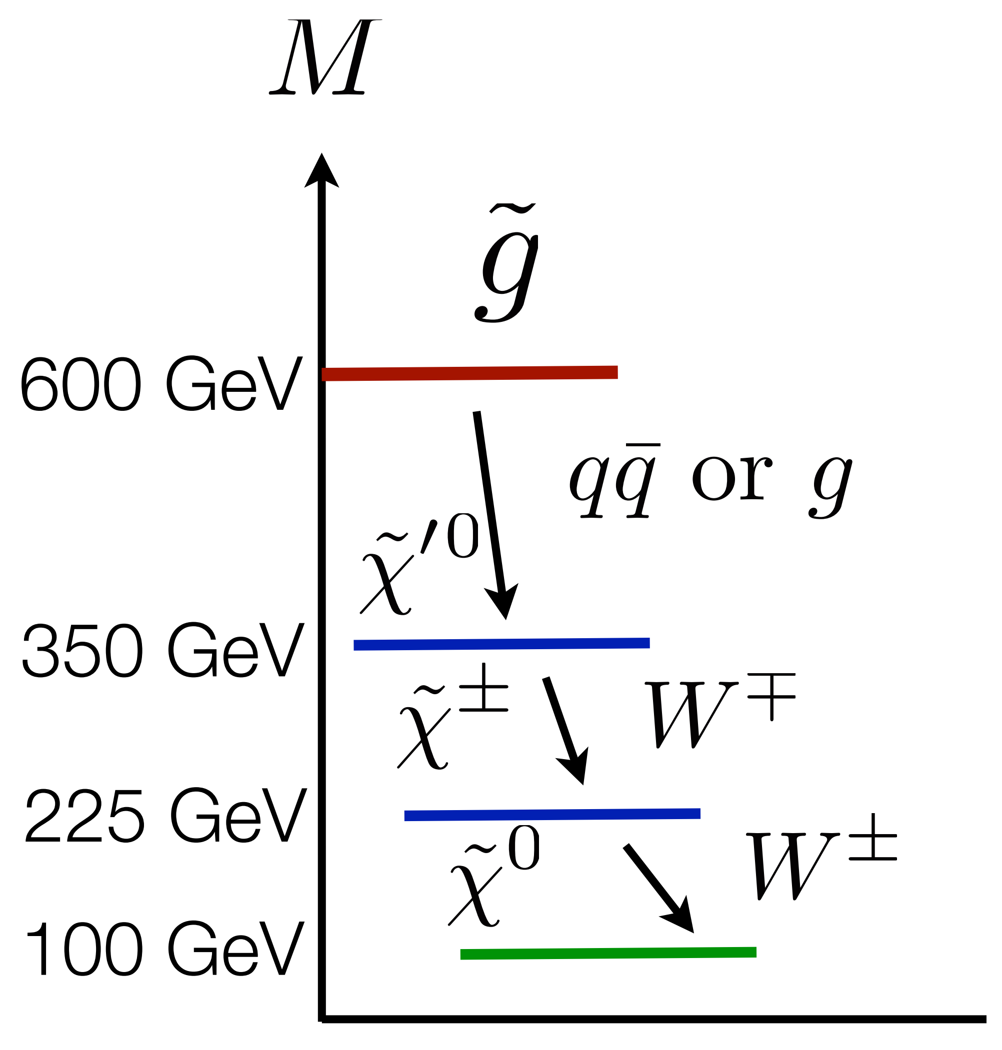
Two Benchmark Models

(1fb^{-1} 7 TeV reference)

4 Top

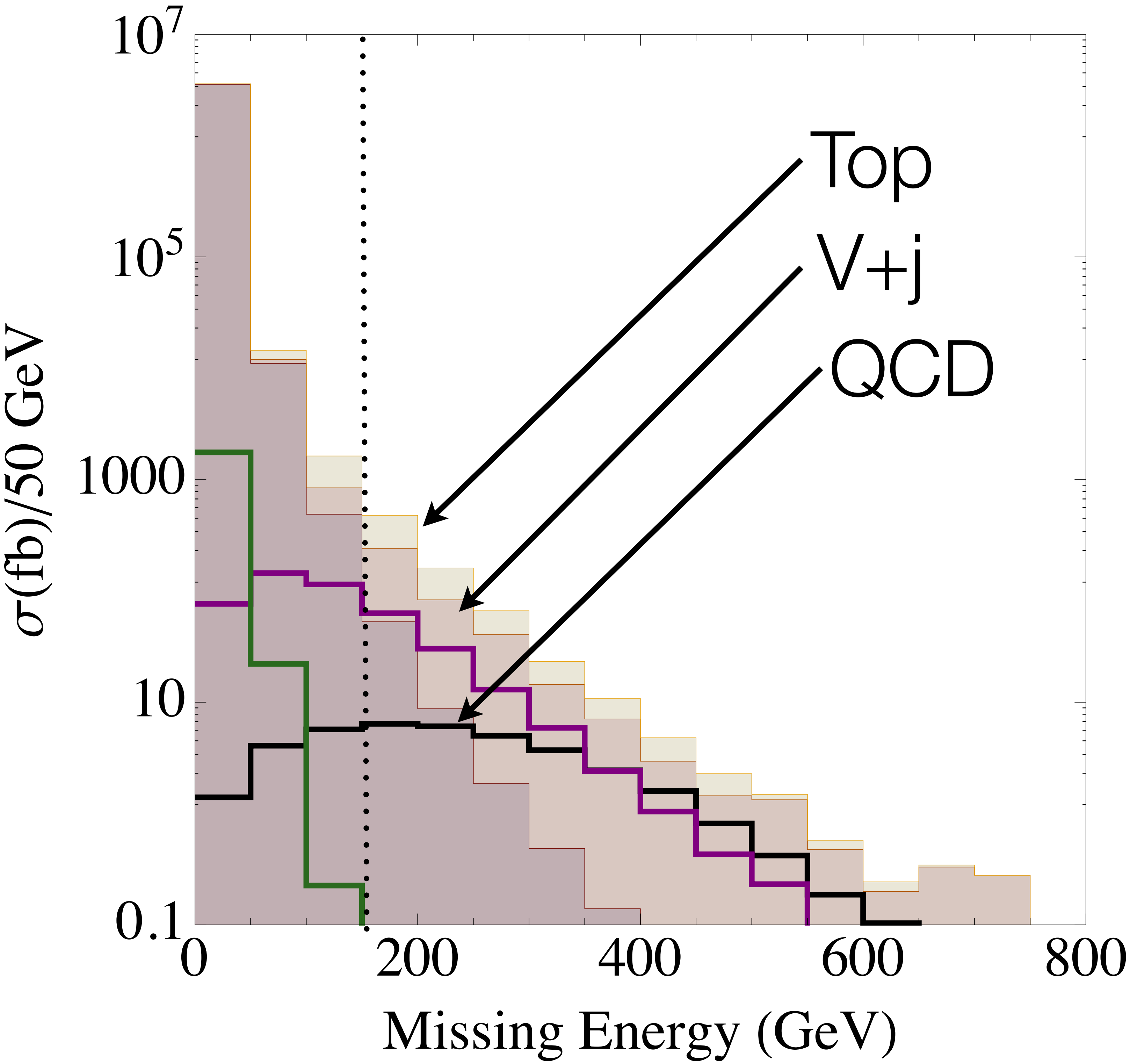


2 Step



Missing Energy Distribution

4j $p_T > 150$ GeV



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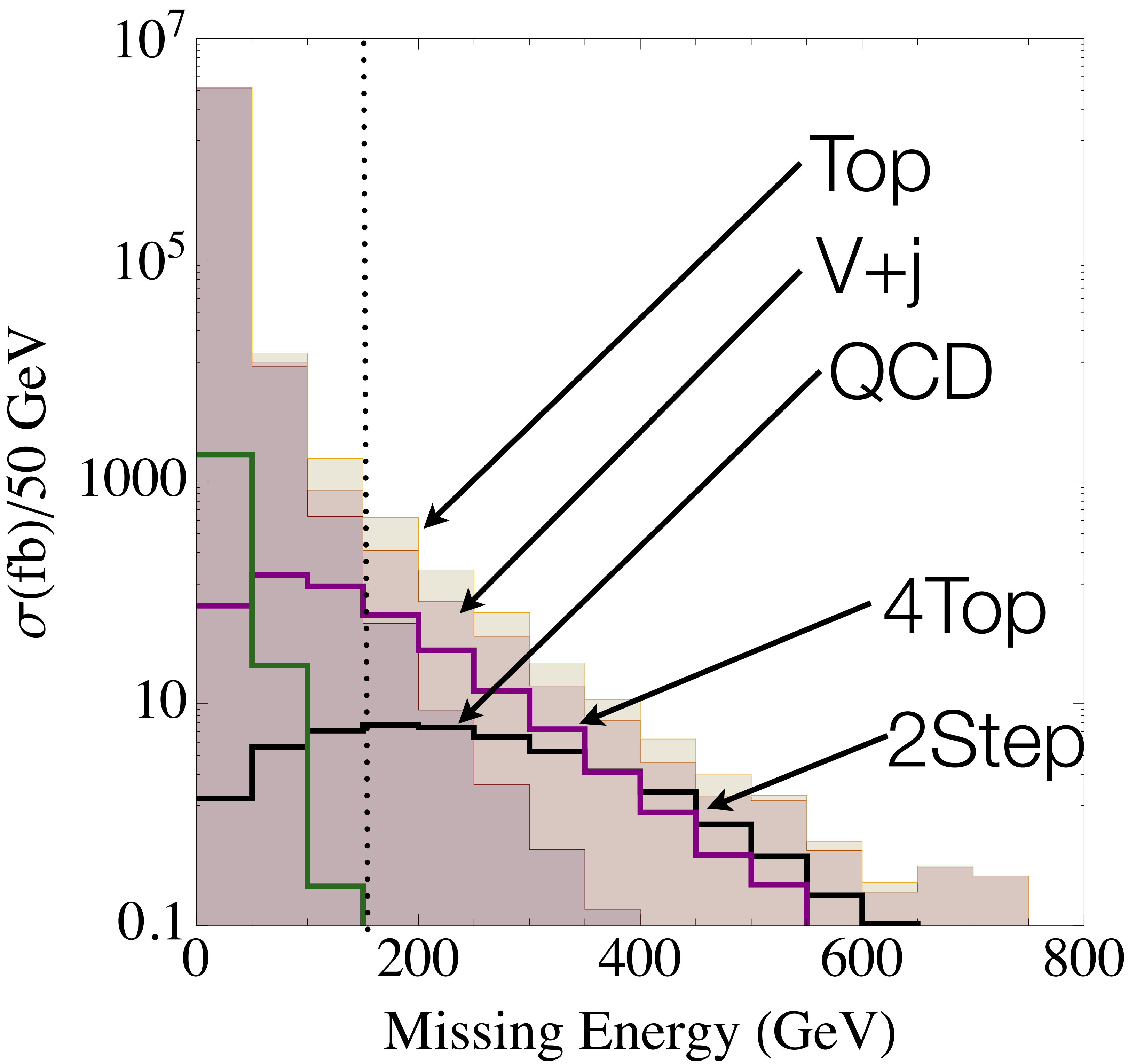
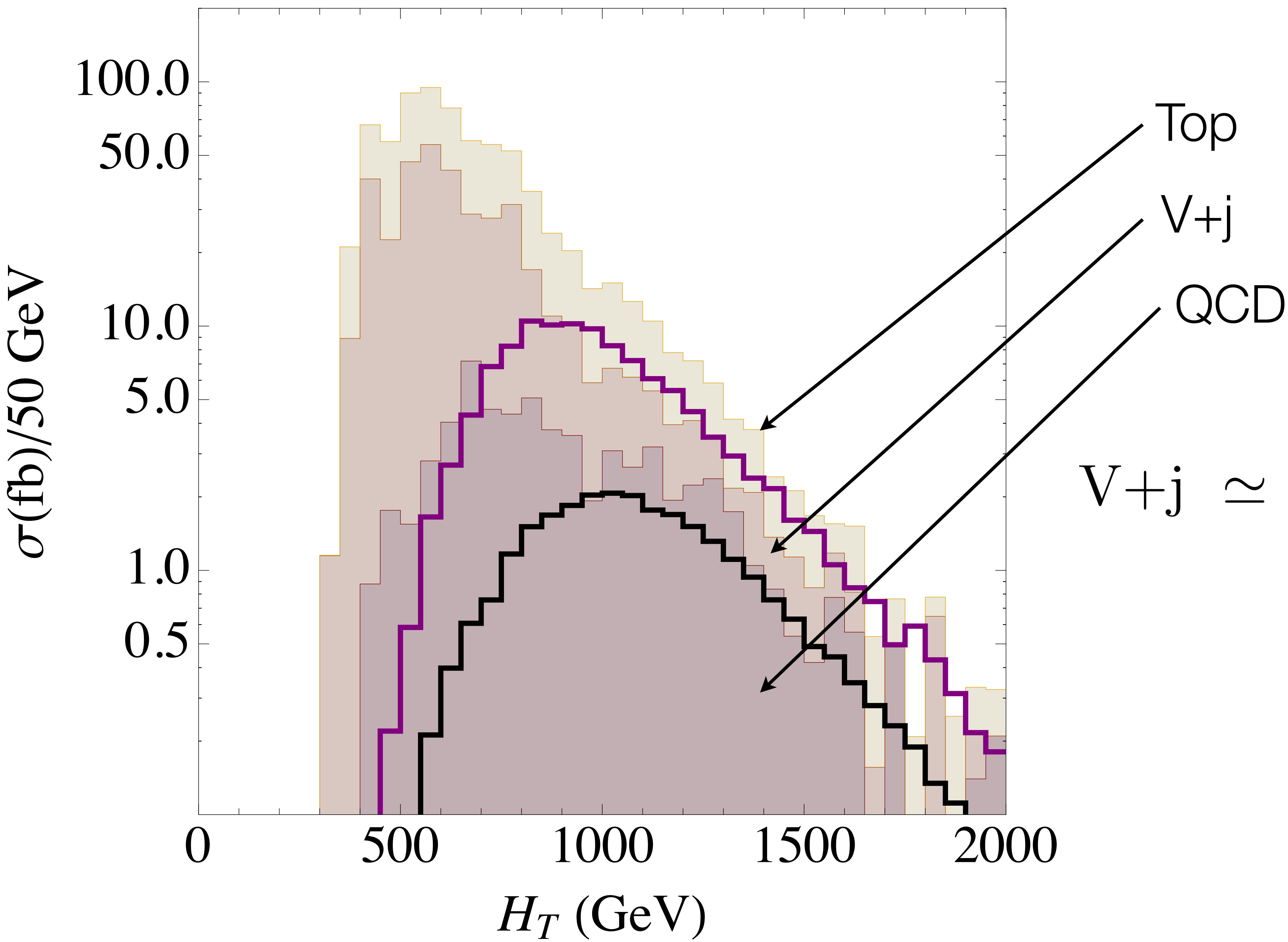


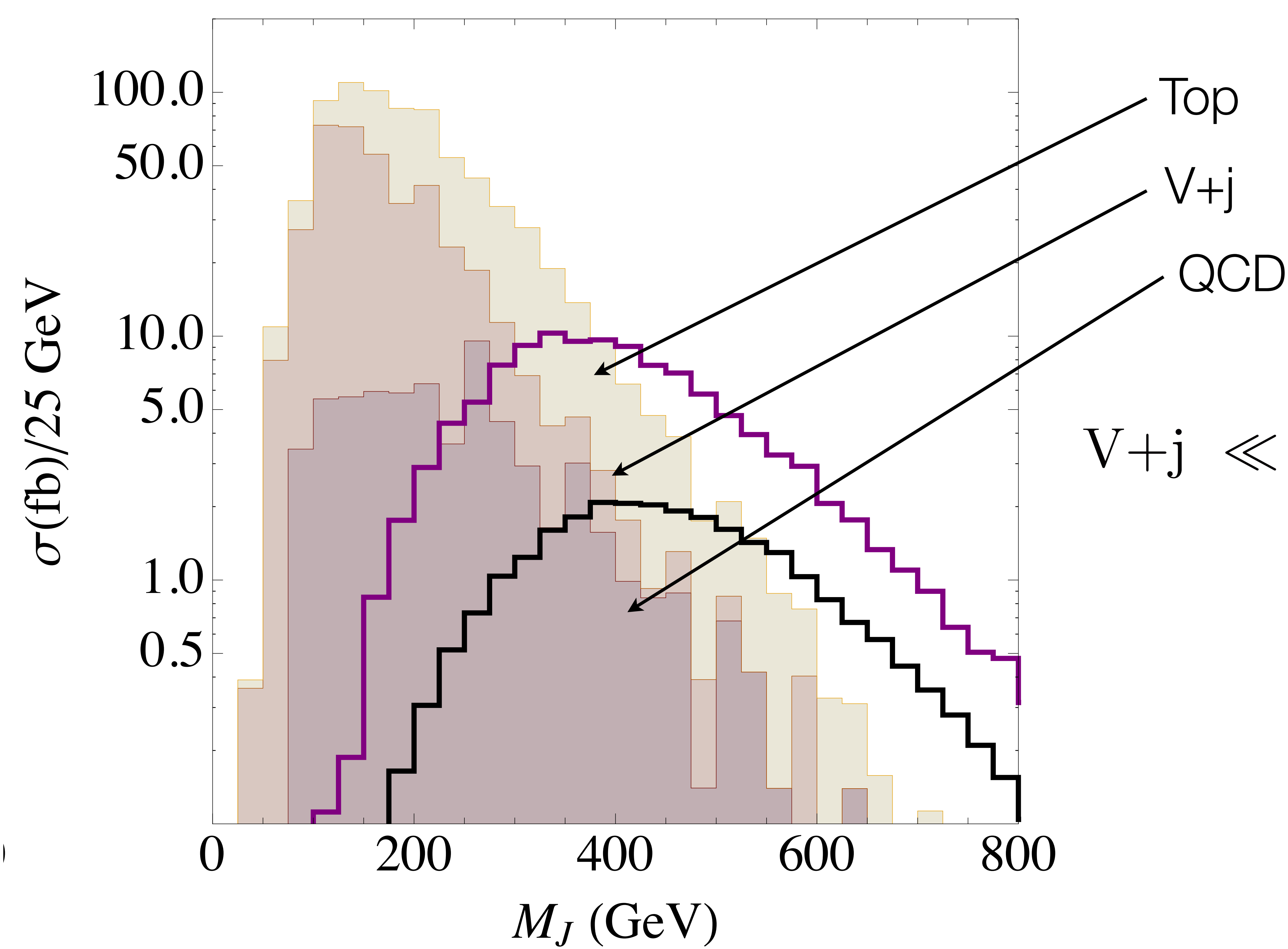
After cut of $\not{E}_T > 150$ GeV

S/B < 1



$\text{V+j} \simeq \text{Top}$

Gain at high M_J



$$V+j \ll \text{Top}$$

Final Search

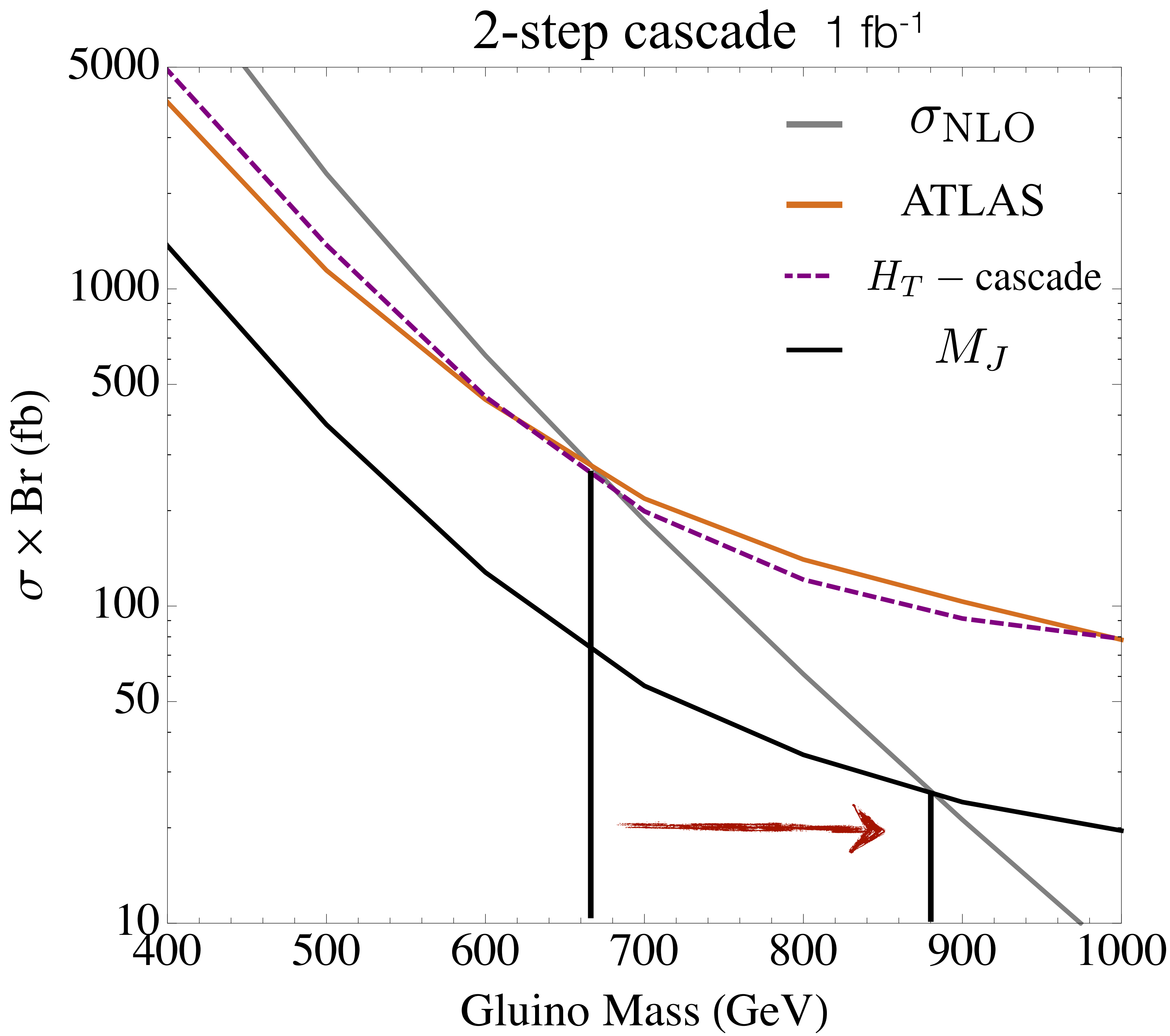
Compare to straw-men

Search	N_j	R	Leptons	N_b	$\not{E}_T$ [GeV]	H_T [GeV]	M_J [GeV]
ATLAS	6-8$^+$	0.4	0	0^+	$3.5\sqrt{H_T}$	$\emptyset$	$\emptyset$
H_T+SSDL-top	3^+	1.2	SSDL	1^+	$\emptyset$	300	$\emptyset$
H_T-top	4^+	1.2	0^+	1^+	250	800	$\emptyset$
H_T-cascade	4^+	1.2	0^+	0^+	150	1000	$\emptyset$
M_J search	4^+	1.2	0^+	0^+	150	$\emptyset$	450

Maximally Inclusive

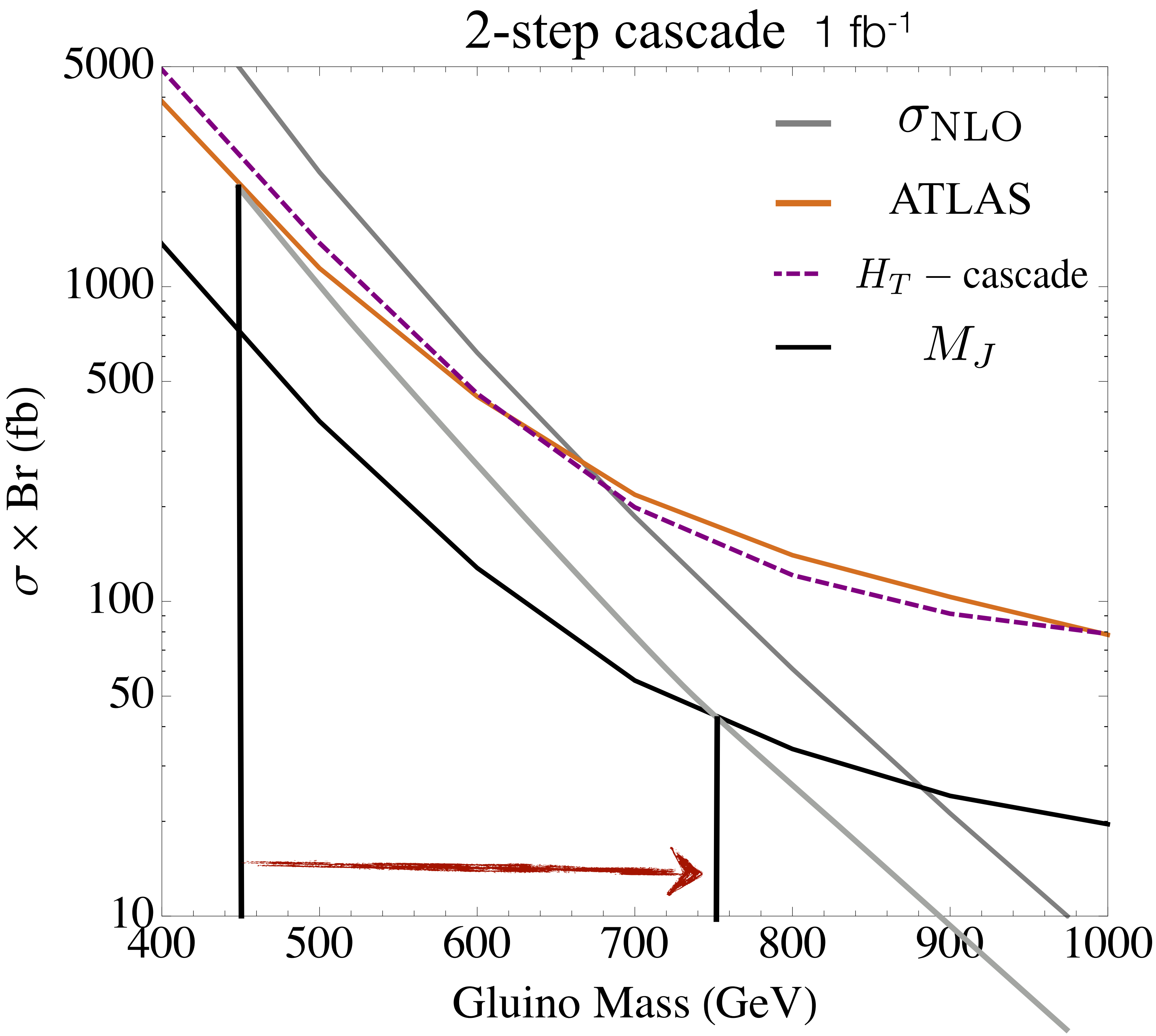
No b-tags, no lepton vetos, low MET

2 Step Expected Sensitivity



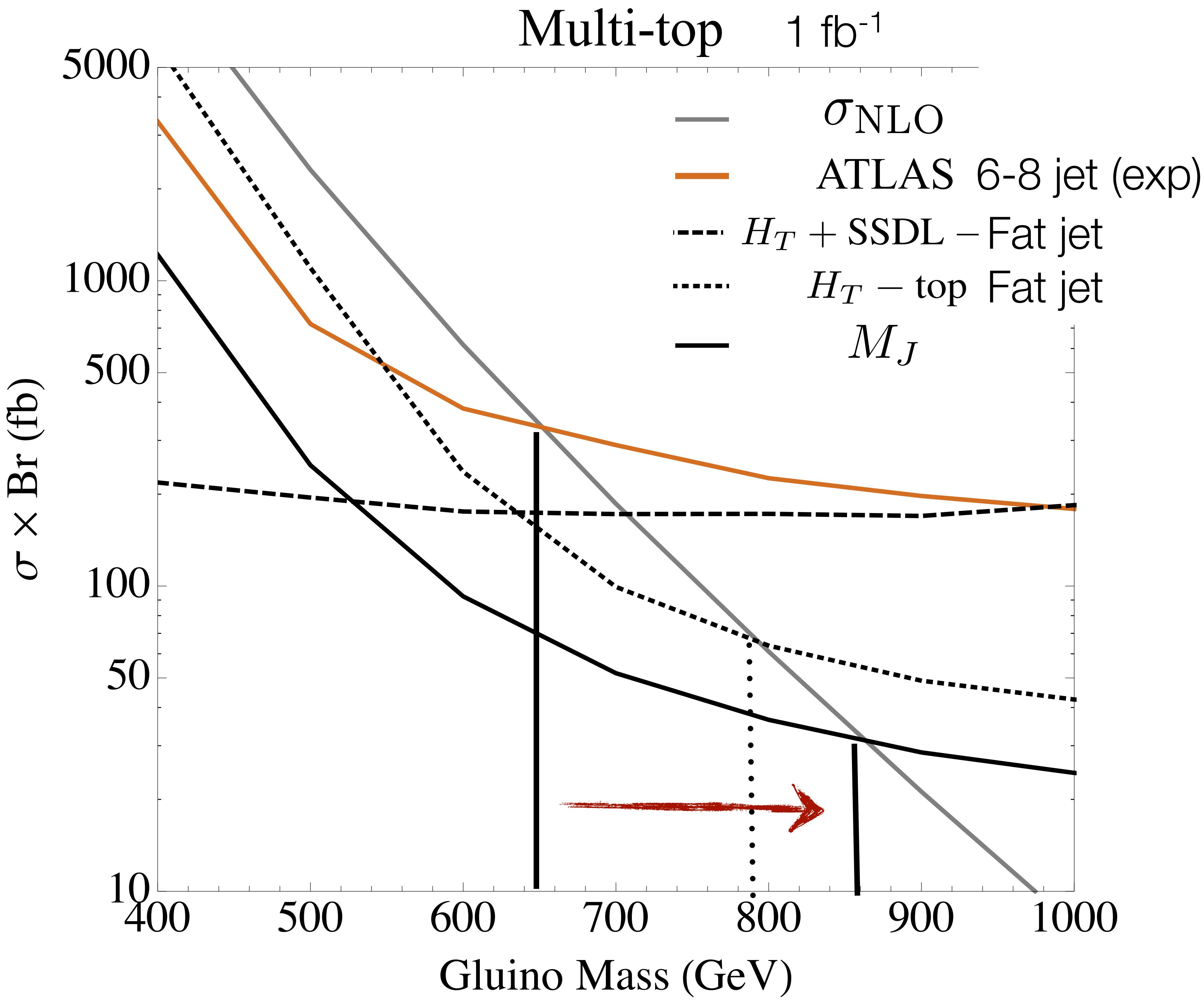
Gain from 660 GeV to 880 GeV

2 Step Expected Sensitivity



@Br=60% Gain from 450 GeV to 750 GeV

4 Top Expected Sensitivity



Gain from 650 GeV to 850 GeV

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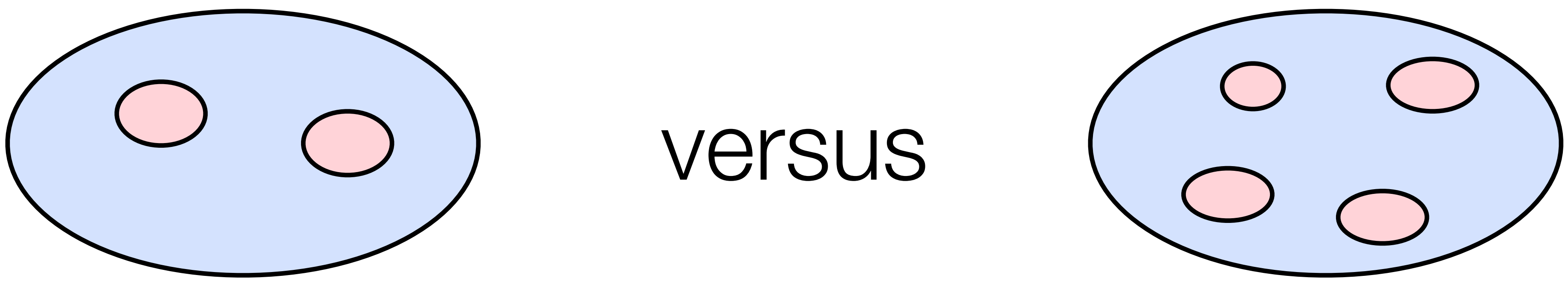
Subjettiness

Jet mass is the coarsest measure of jet substructure

Equal pT and mass jets



Massive QCD jets mostly have 2 subjets

High multiplicity signals are many more subjets

How to count the number of subjets?

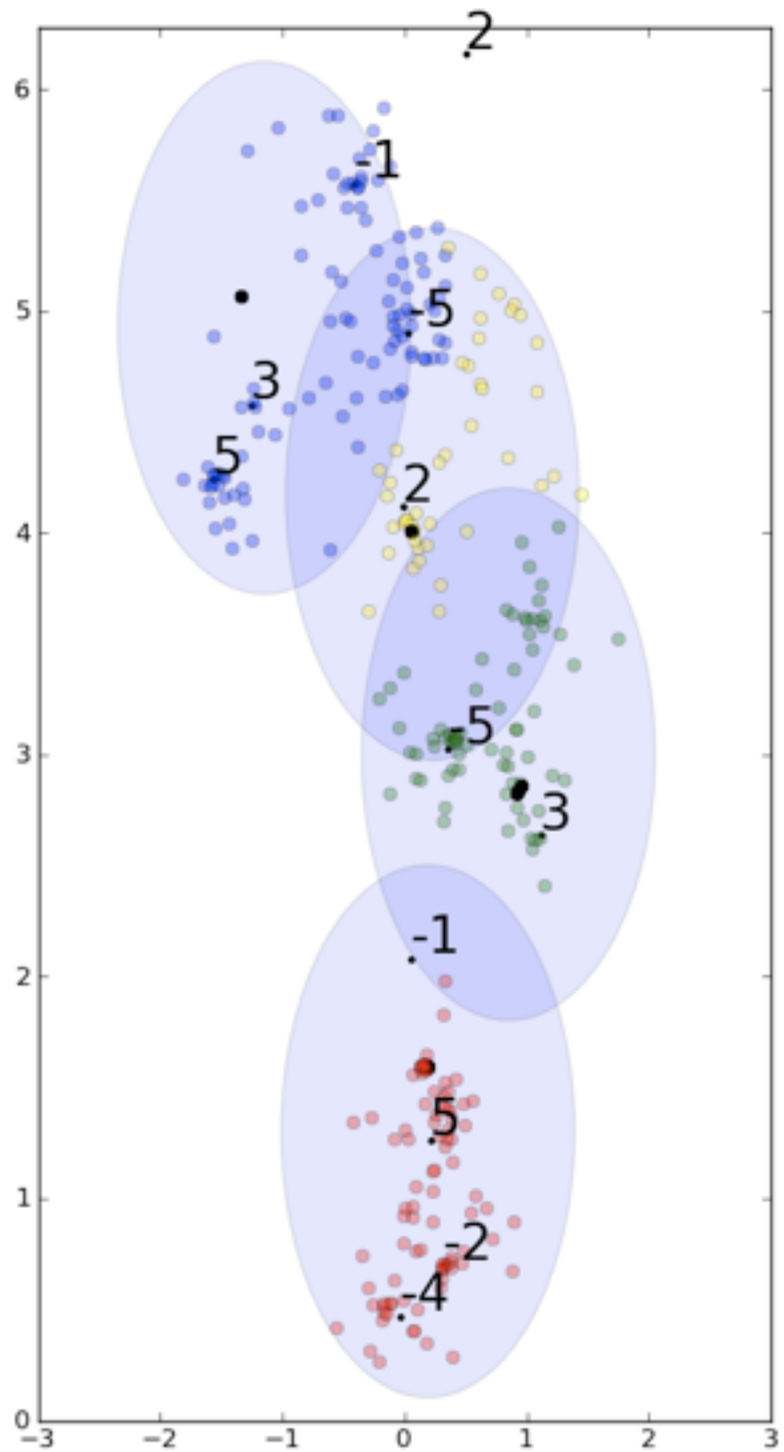
Not a solved problem

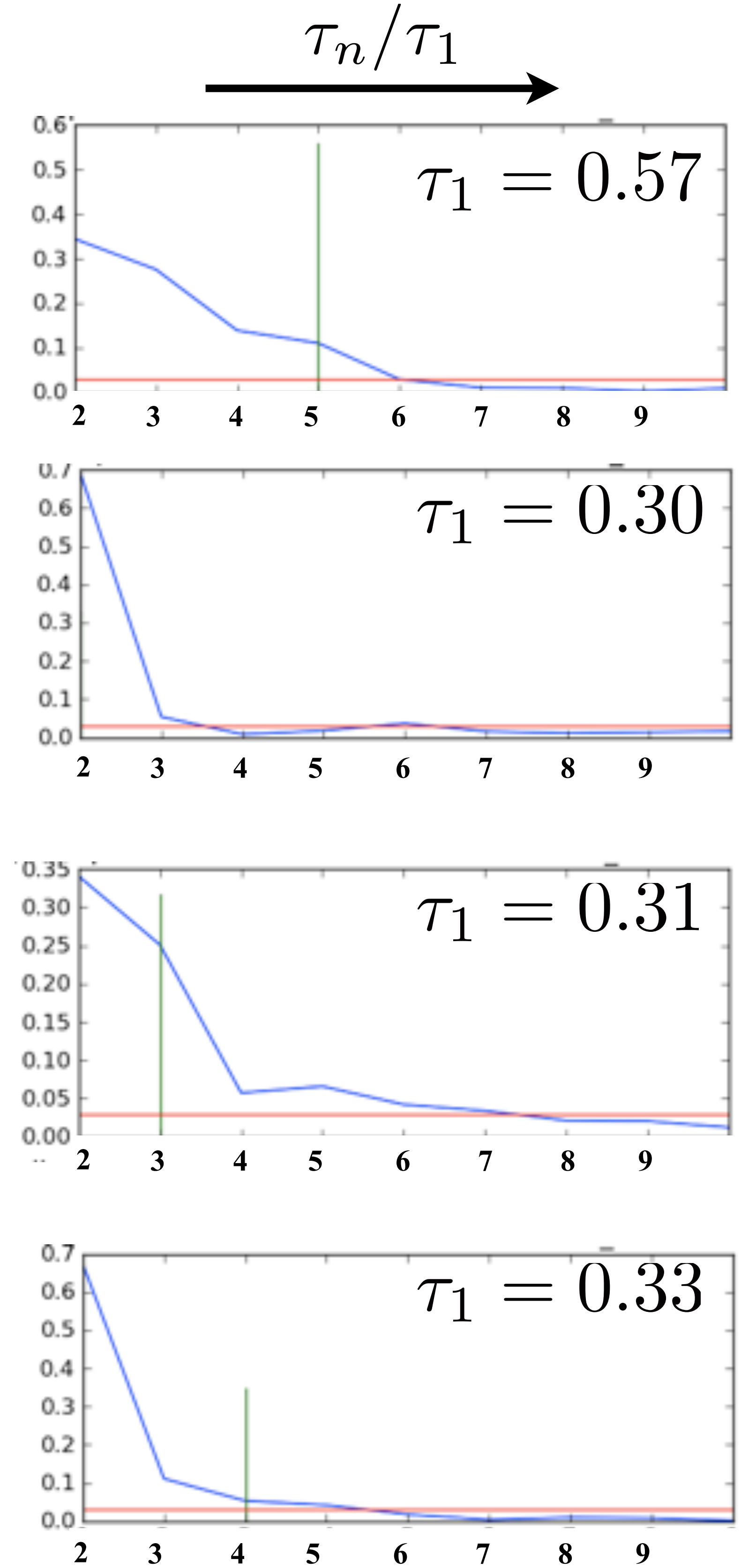
Introduce 2 Techniques

N-Subjettiness

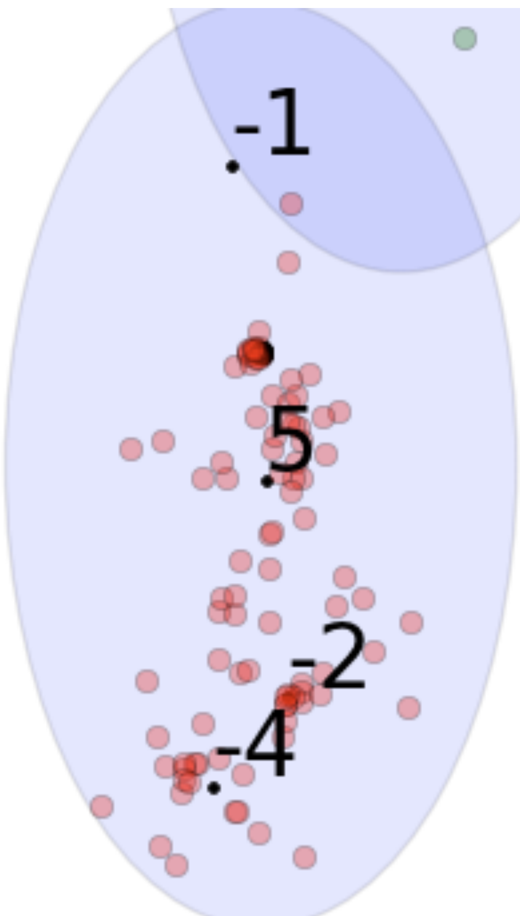
Jet Deconstruction

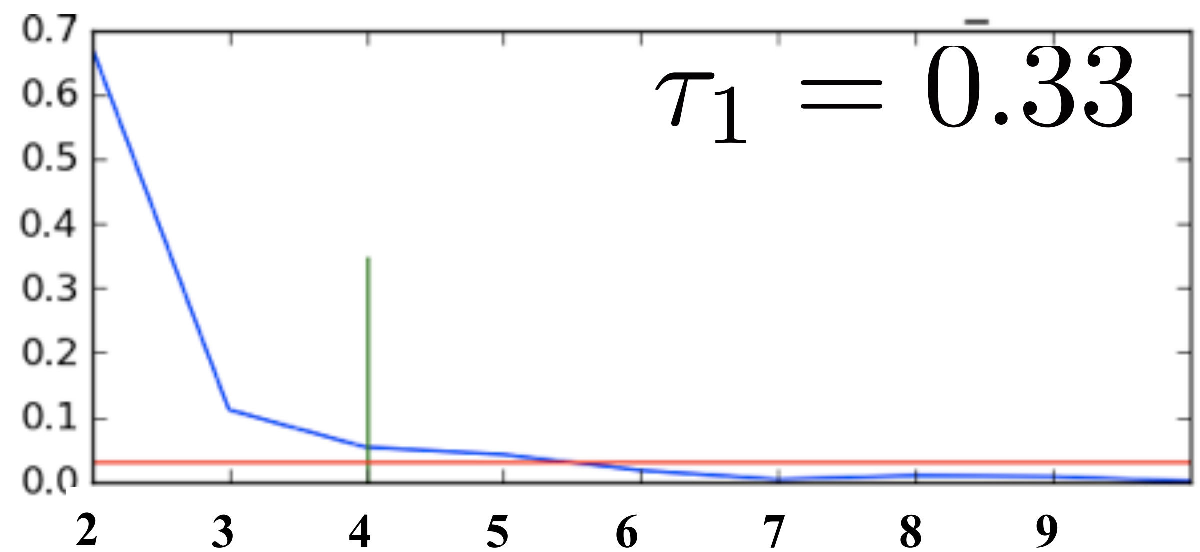
Typical 4 Top event





Hard to pull out the number subjets



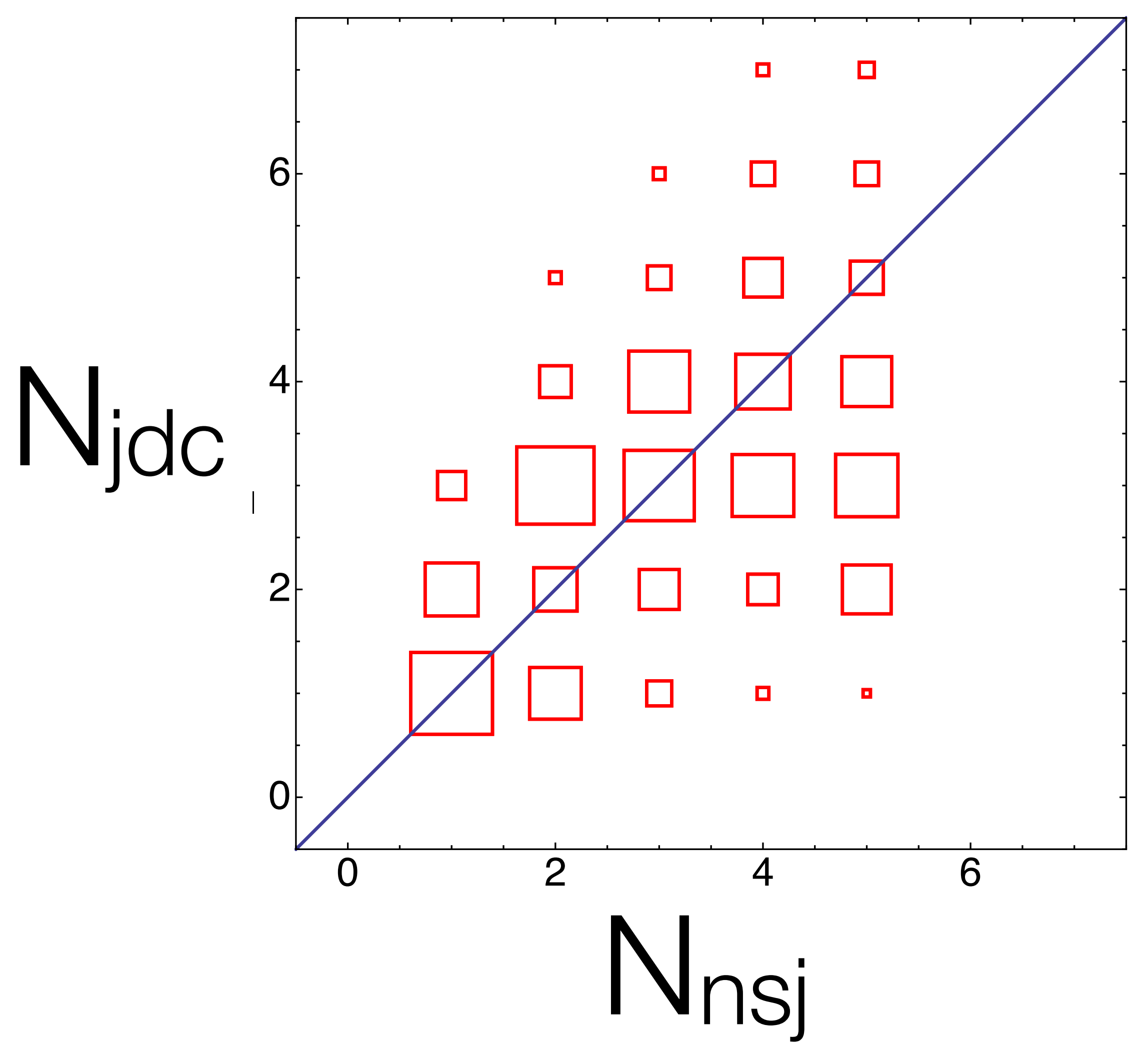


Nevertheless, the information is in the distributions

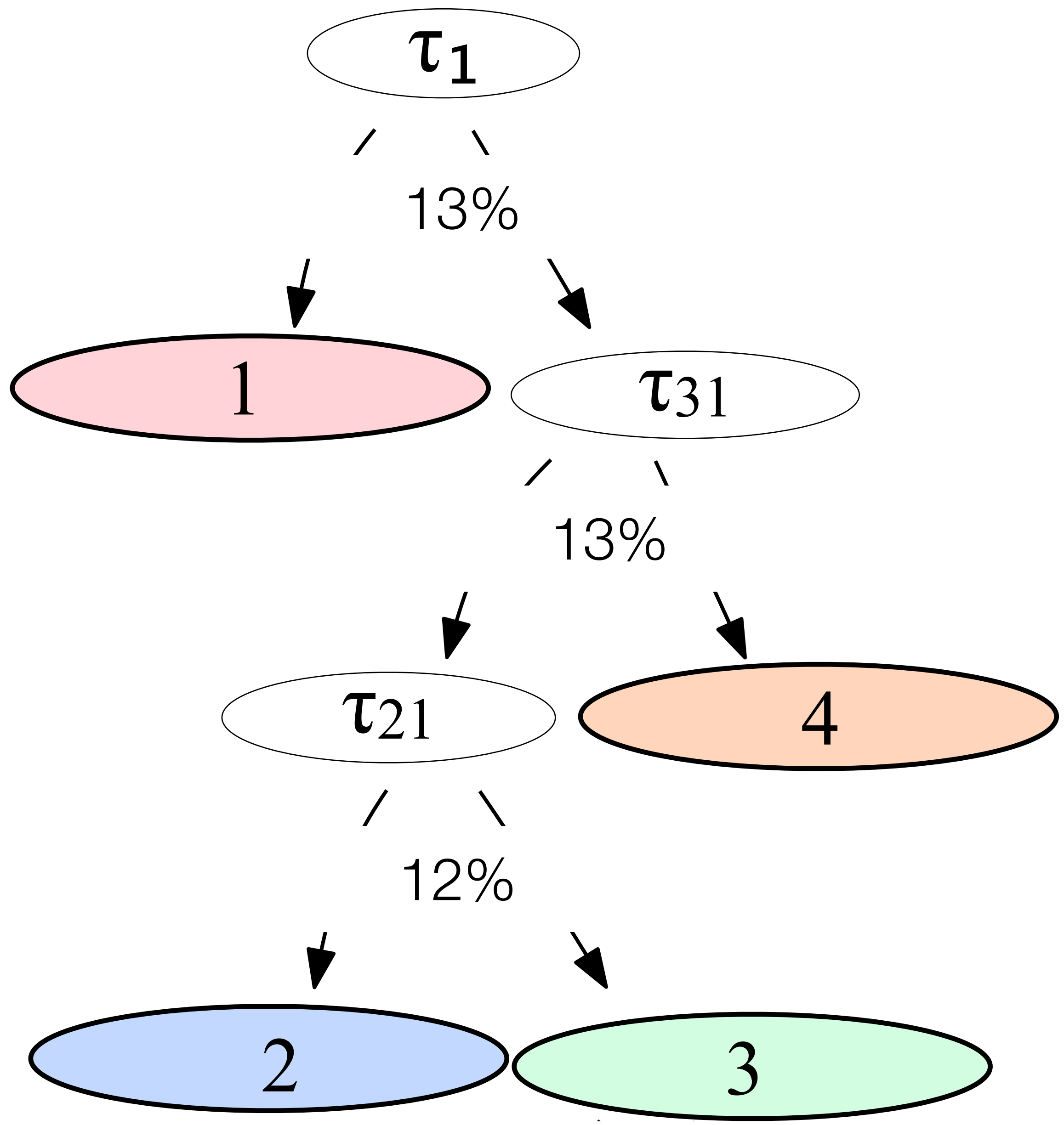
Strong Correlation Between Techniques

Jet Deconstruction

N-Subjettiness

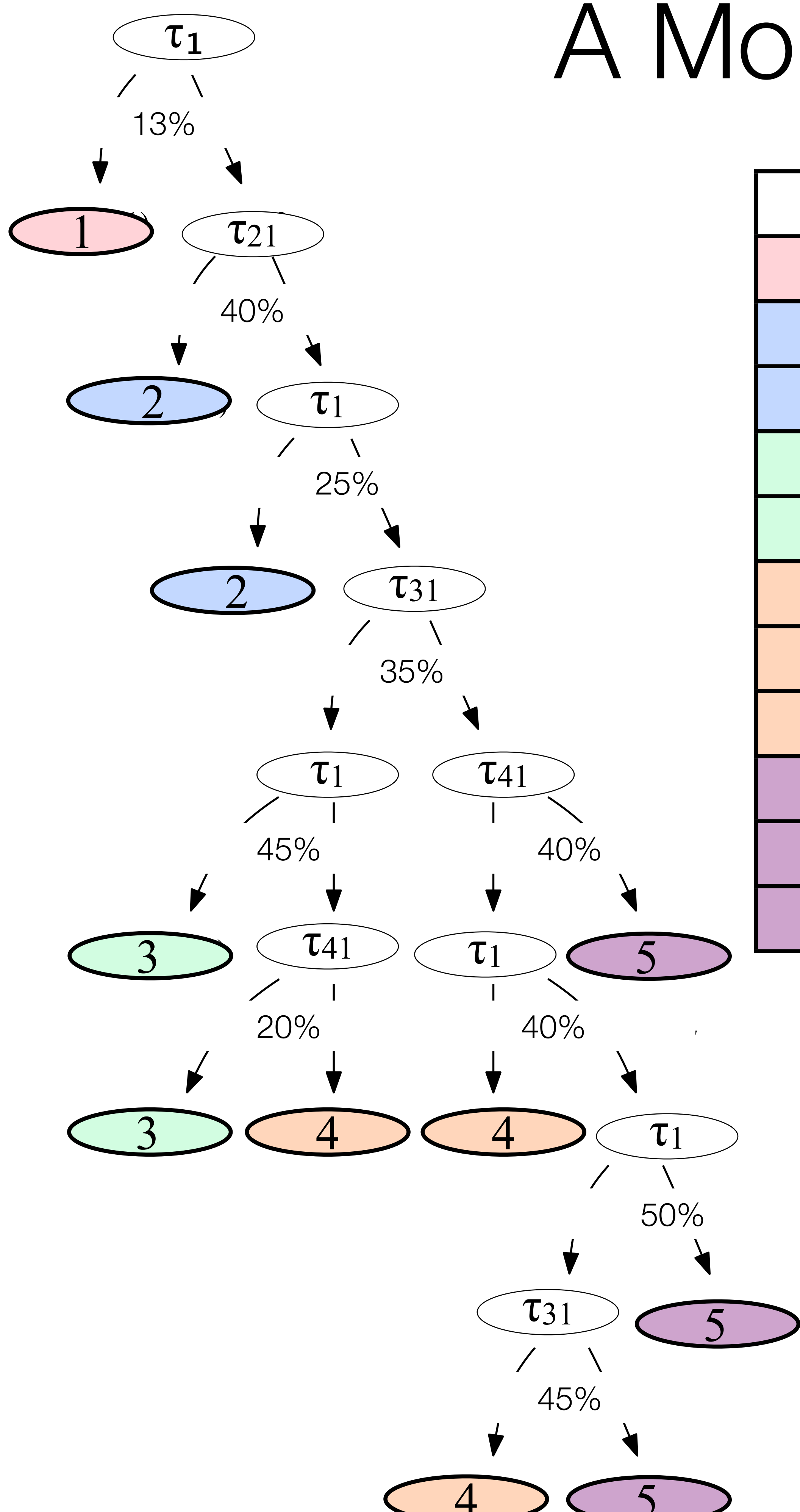


A Sample Classifier



Relatively simple & works so-so

A More Realistic Case



N	τ1	τ21	τ31	τ41
1	<13%			
2	13% - 25%			
2	>25%	<40%		
3	25% - 45%	>40%	<35%	
3	>45%	>40%	<35%	<20%
4	>45%	>40%	<35%	>20%
4	25% - 40%	>40%	>35%	<40%
4	25% - 50%	>40%	35%-45%	<40%
5	>25%	>40%	>35%	>40%
5	25% - 50%	>40%	>45%	<40%
5	>50%	>40%	35%-45%	>40%

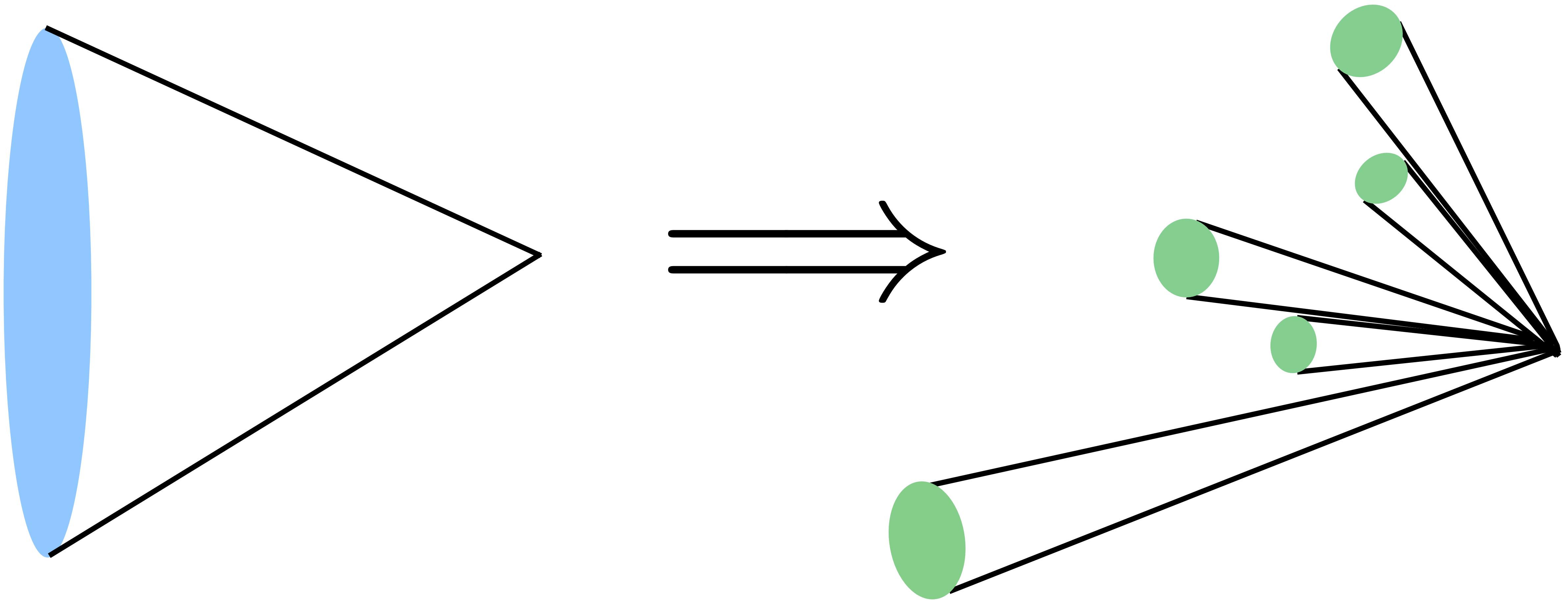
Jet Deconstruction Algorithm

cluster using the CA algorithm

decluster recursively down to a mass scale m_{cut}

(in the spirit of the HEPTopTagger)

the number of identified subjets is n_{rec}



Counting subjets recursively

pseudocode for recursive procedure:

uncluster j into j_1 and j_2 (with j_1 harder)

if $m_j < m_{cut}$ or $dR(j_1, j_2) < R_{min}$
consider j a subjet and exit recursion

throw out j_2 if $p_{T2} < y_{cut} \cdot p_{Ttot}$

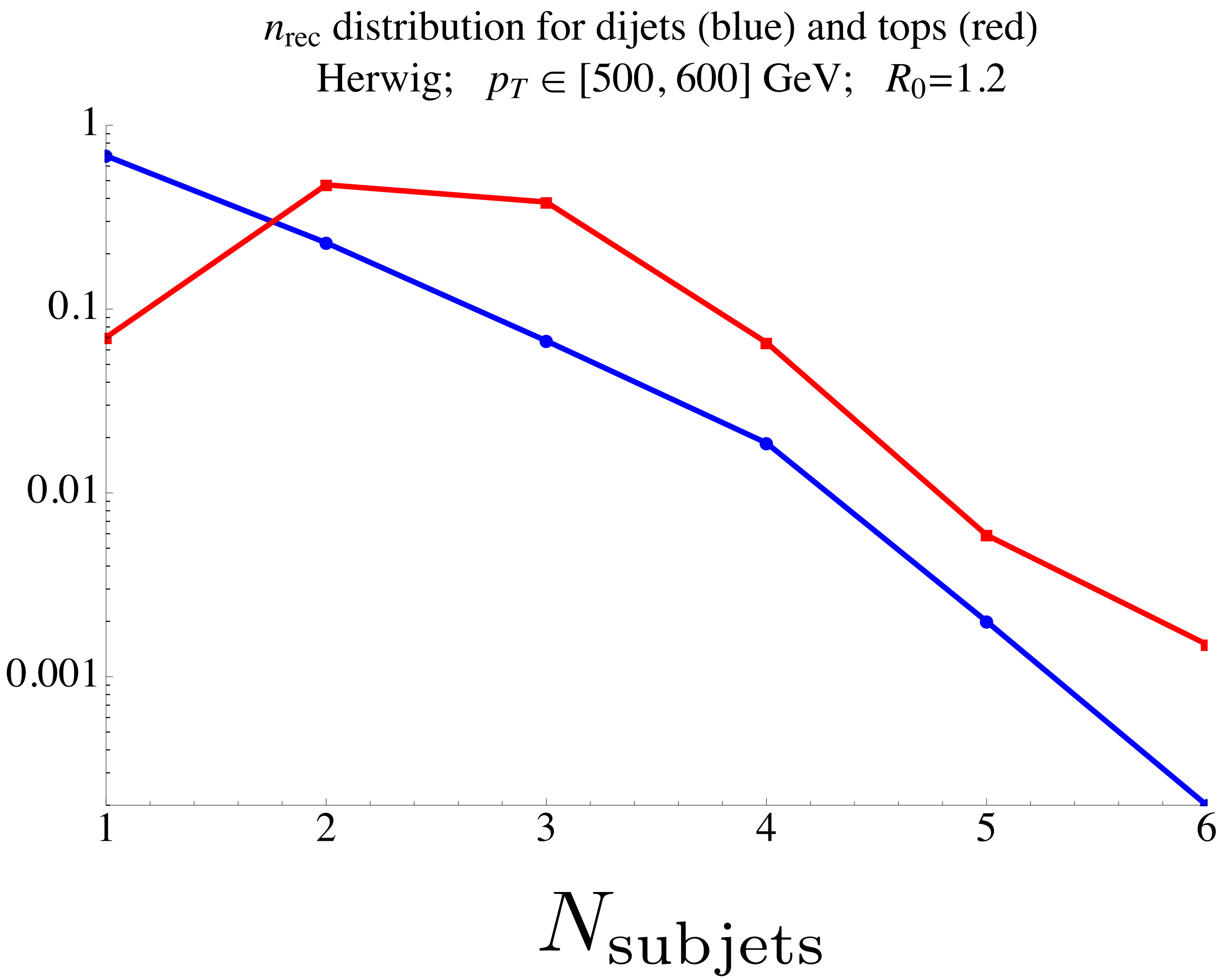
continue recursion on j_1 and j_2 (if retained)

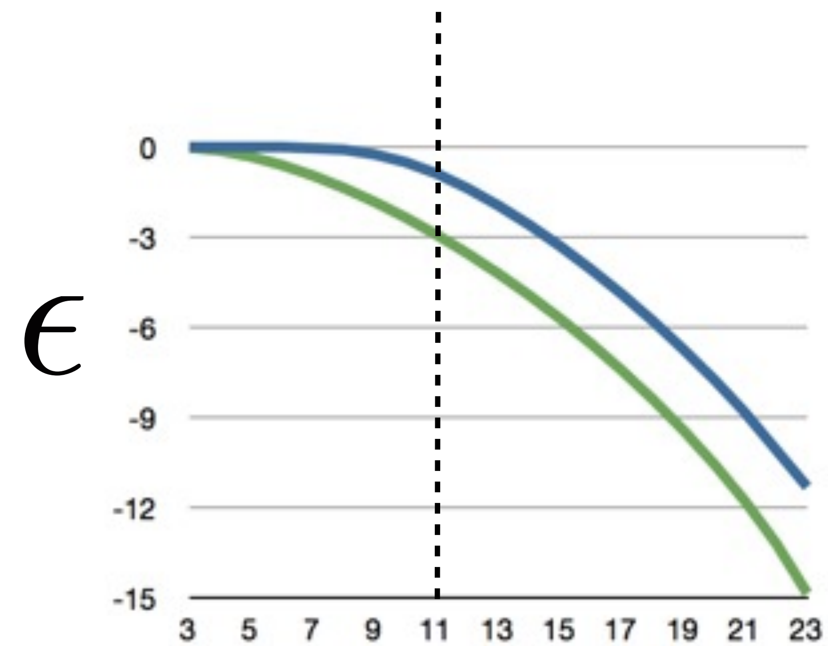
count the number of identified subjets with $p_T > p_{Tcut}$; this is n_{rec}

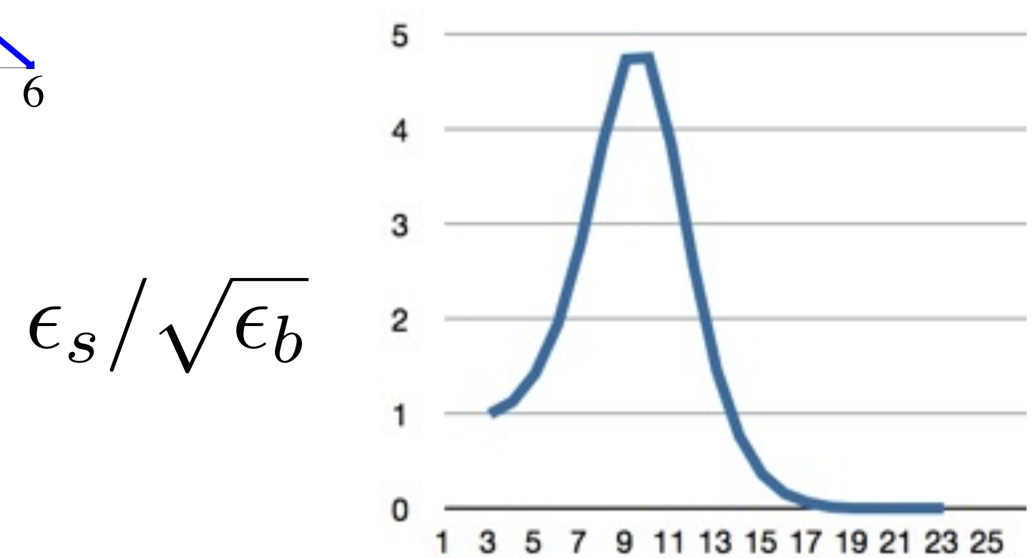
$$\text{Parameters}: m_{cut} = 30\ \text{GeV},\ y_{cut} = 0.15$$

$$p_{Tcut} = 40\ \text{GeV},\ R_{min} = 0.20$$

Calibrating on Dijets can Extrapolate to Multijets







Can beat down QCD by 2^+ orders of magnitude

Preliminary results

on cutting on the number of subjets in entire event

Can reduce reliance on MET further

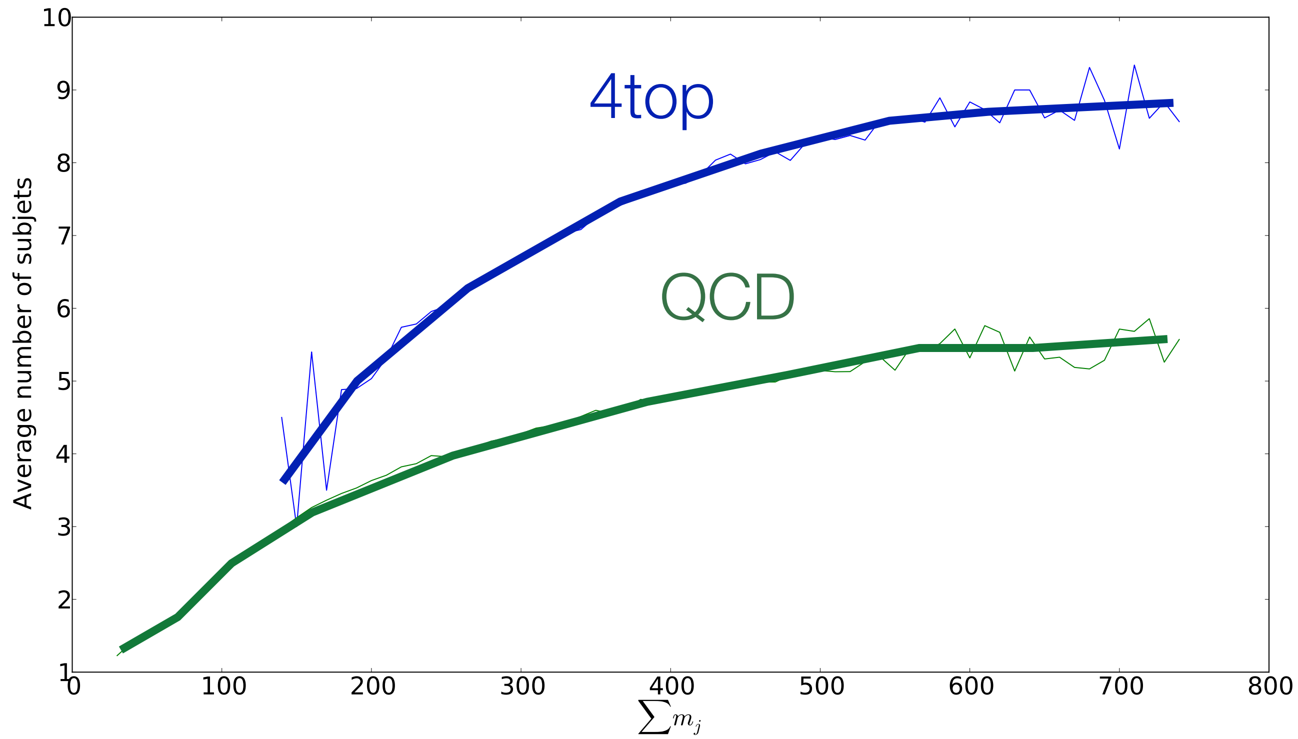
Can use in conjunction with M_J or H_T

would like n-subjets independent of visible energy cut

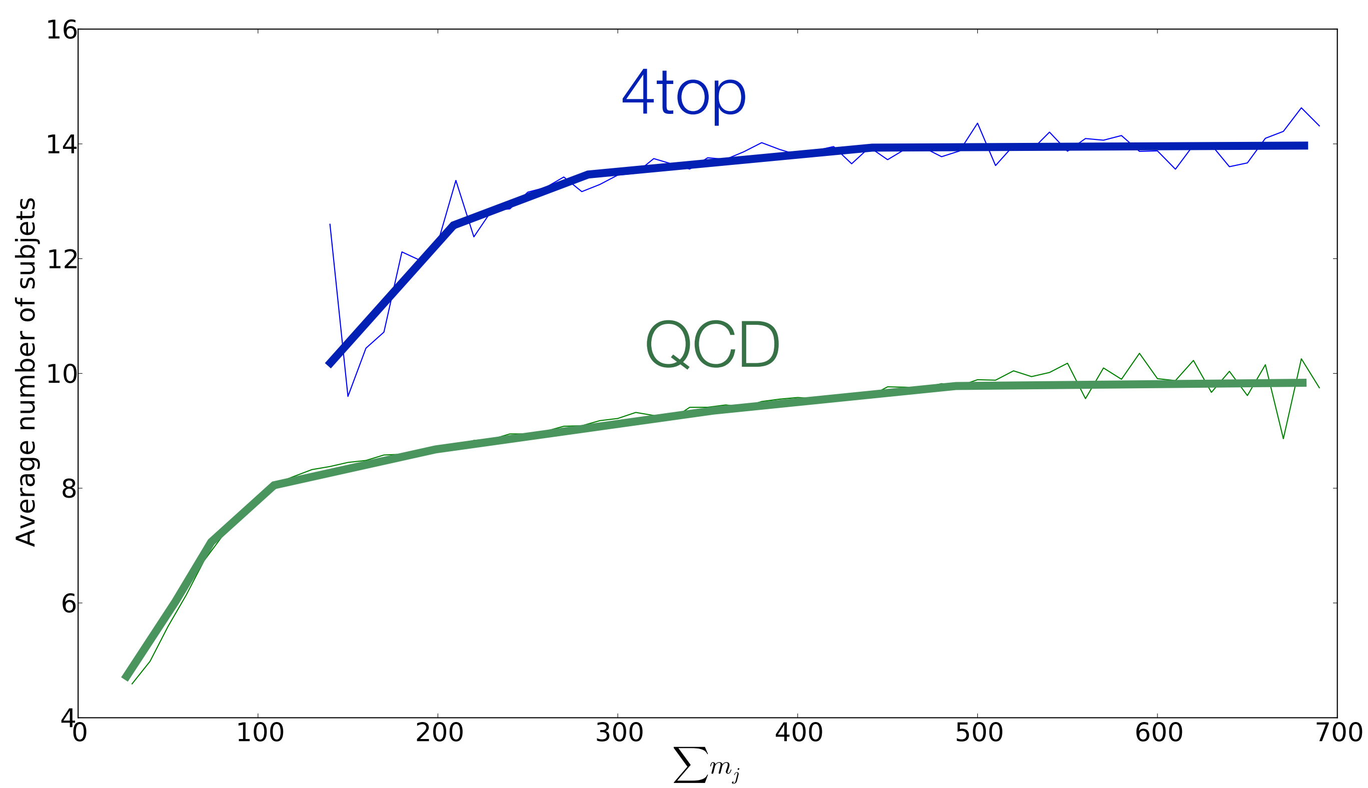
Contains more information about
underlying details of the physics

N_{subjet} and M_J Not Strongly Correlated

JDC



NSJ

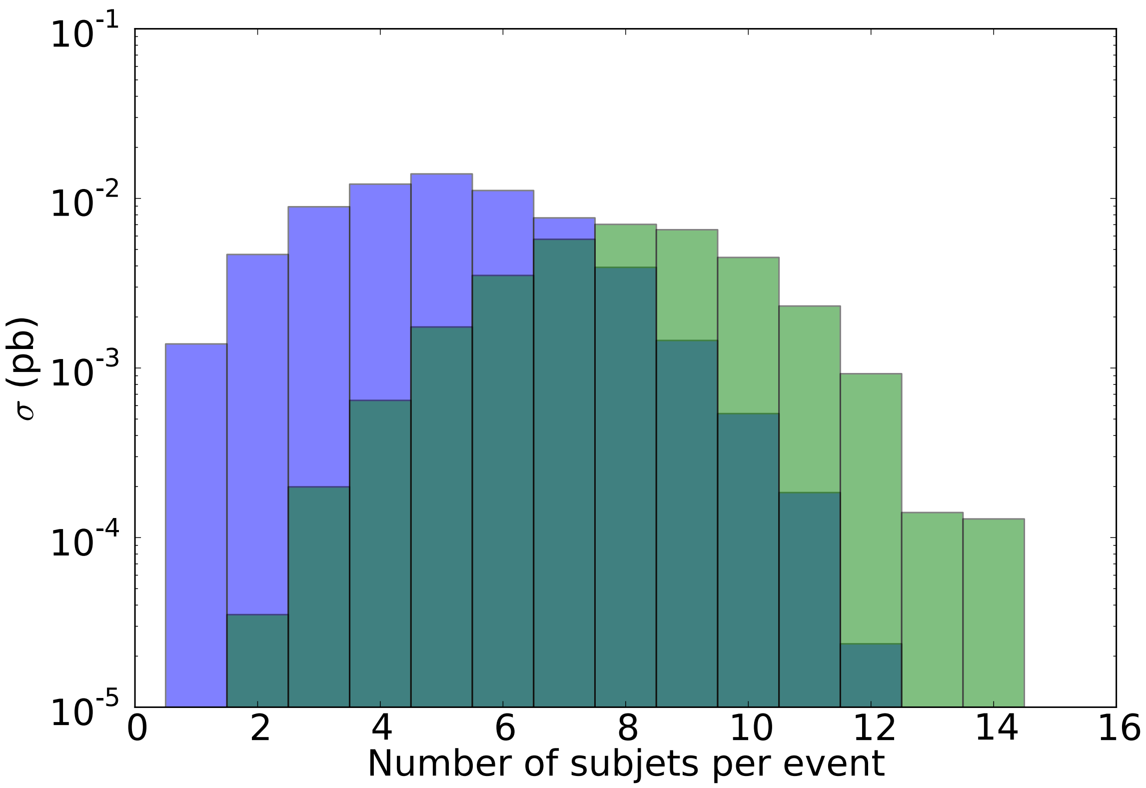


Signal & Background Comparison

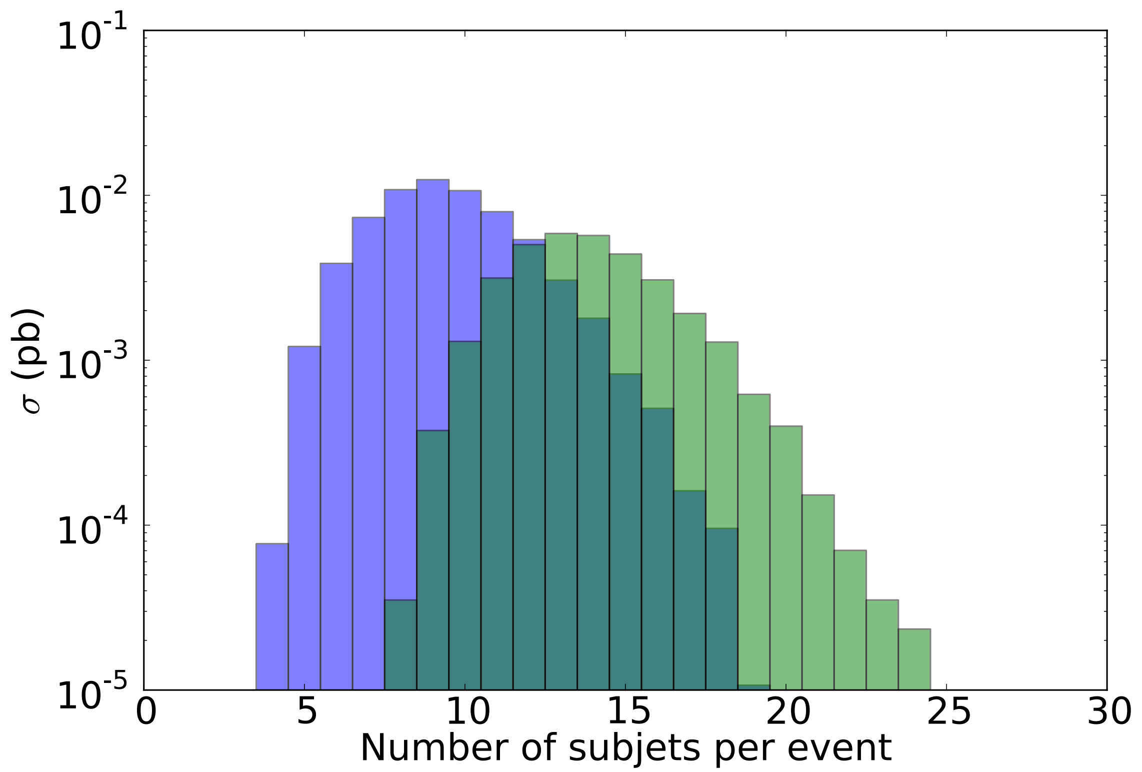
4 Top + MET

After MJ>400 GeV & MET >100 GeV

JDC



NSJ



Improvement over MJ search

4 Top Decay

$\tilde{g} \rightarrow t\bar{t}\chi^0$

MET cut of 100 GeV

$m_{\tilde{g}}$	m_{χ^0}	$\mathrm{Sig}_{\mathrm{subjet}}/\mathrm{Sig}_{\mathrm{mass}}$
600	0	2.6
700	0	3.1
800	0	4.6
900	0	4.4
1000	0	4.4

Sliding MJ> 450 GeV - 650 GeV cut, Nsub > 8

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Outlook

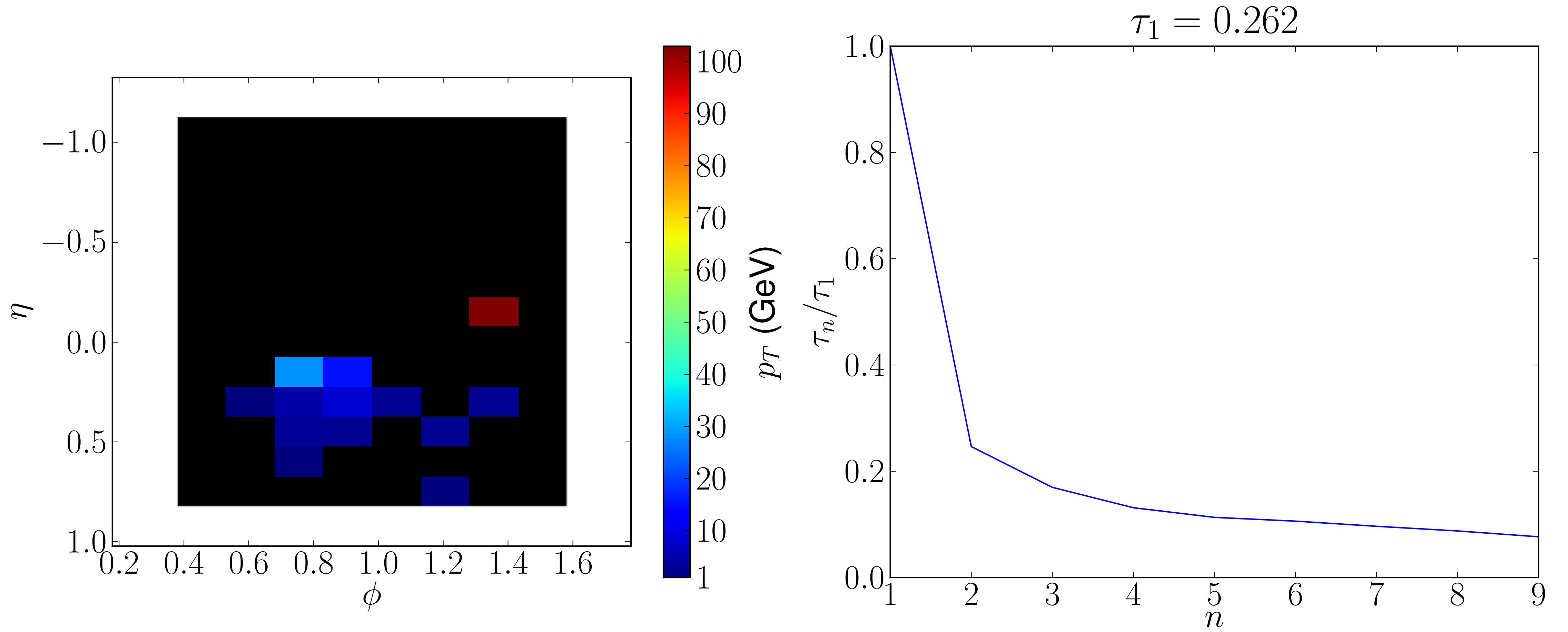
High Multiplicity Signals are Challenging

M_J can be a powerful new tool

Counting the number of subjets is feasible and more powerful

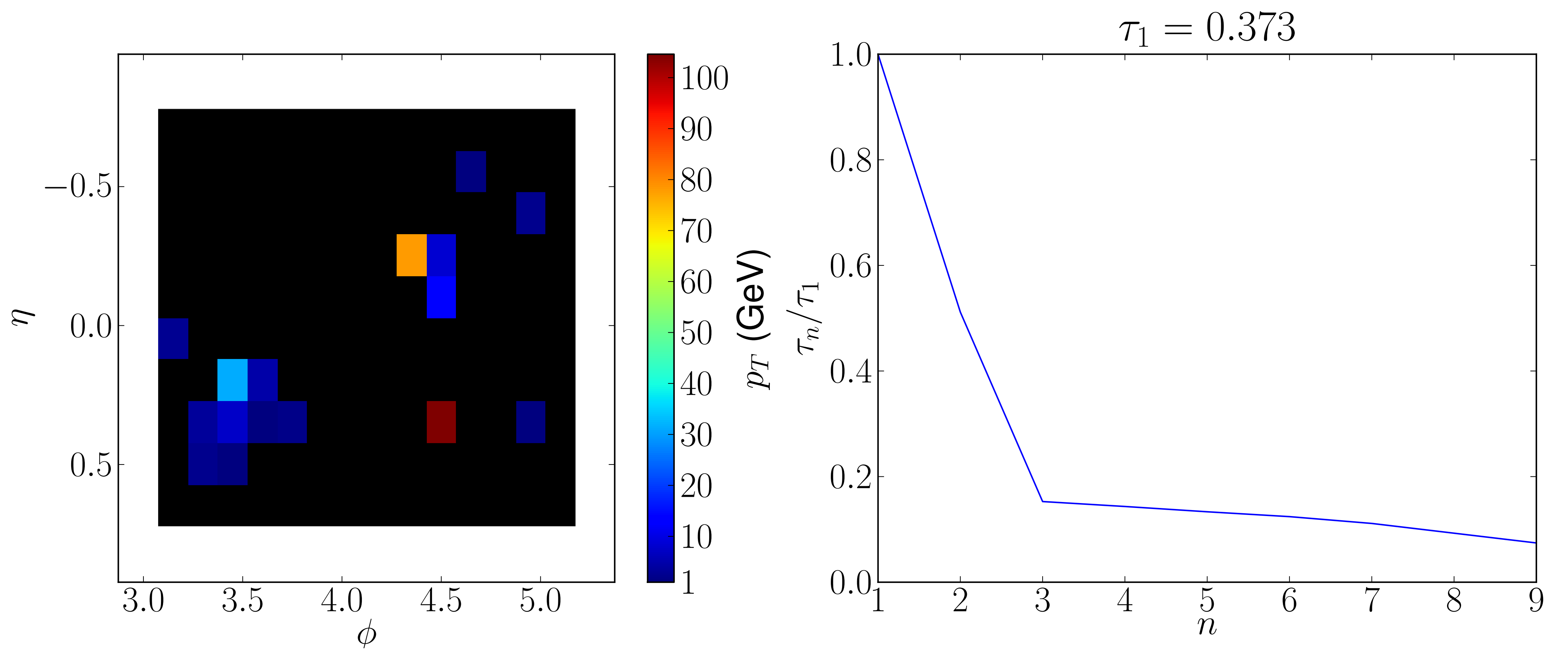
Soon may be able to have low background searches without MET

2 Subjets



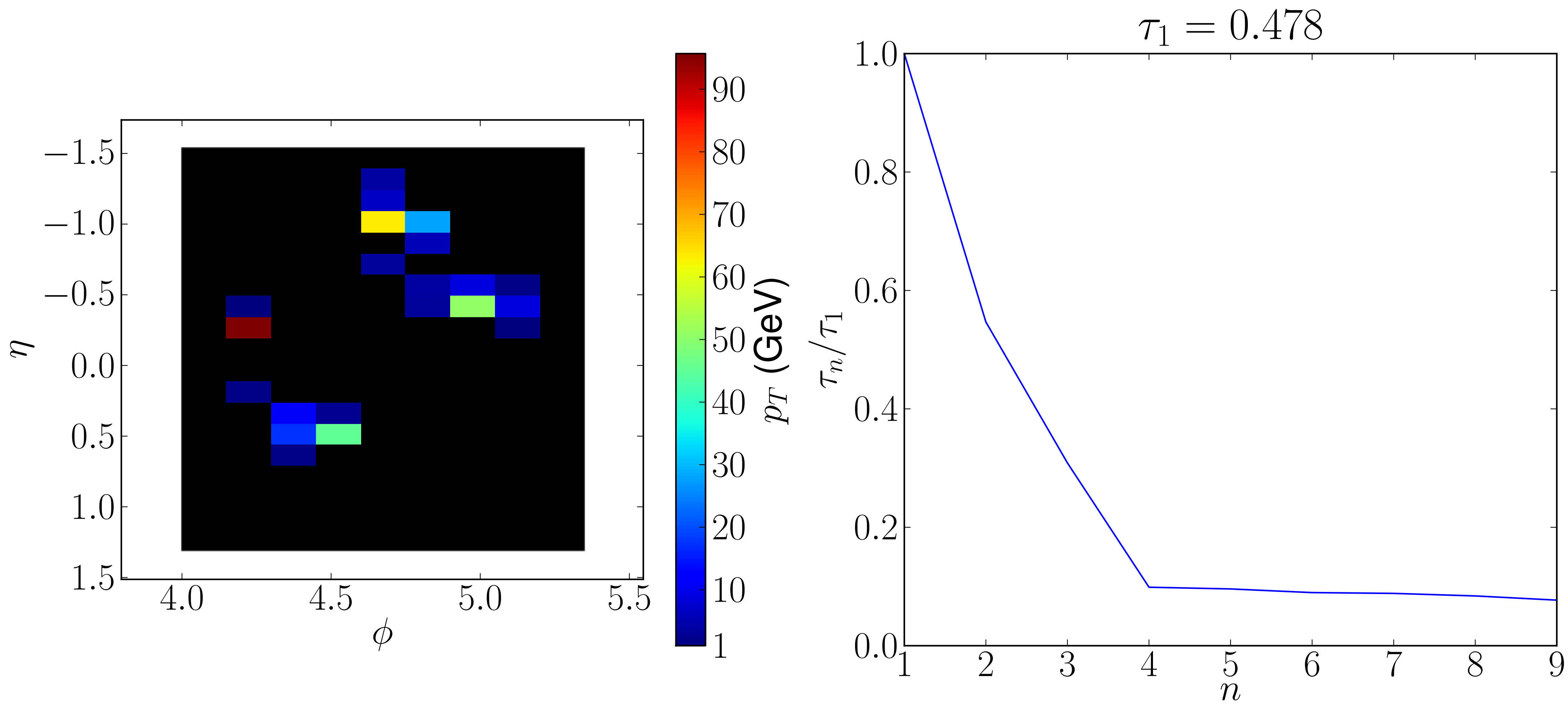
−1.0
−0.5
0.0
0.5
1.0
η
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
ϕ
100
90
80
70
60
50
40
30
20
10
1
p_T (GeV)
$\tau_1 = 0.262$
1.0
0.8
0.6
0.4
0.2
0.0
τ_n/τ_1
1
2
3
4
5
6
7
8
9
n

3 Subjets



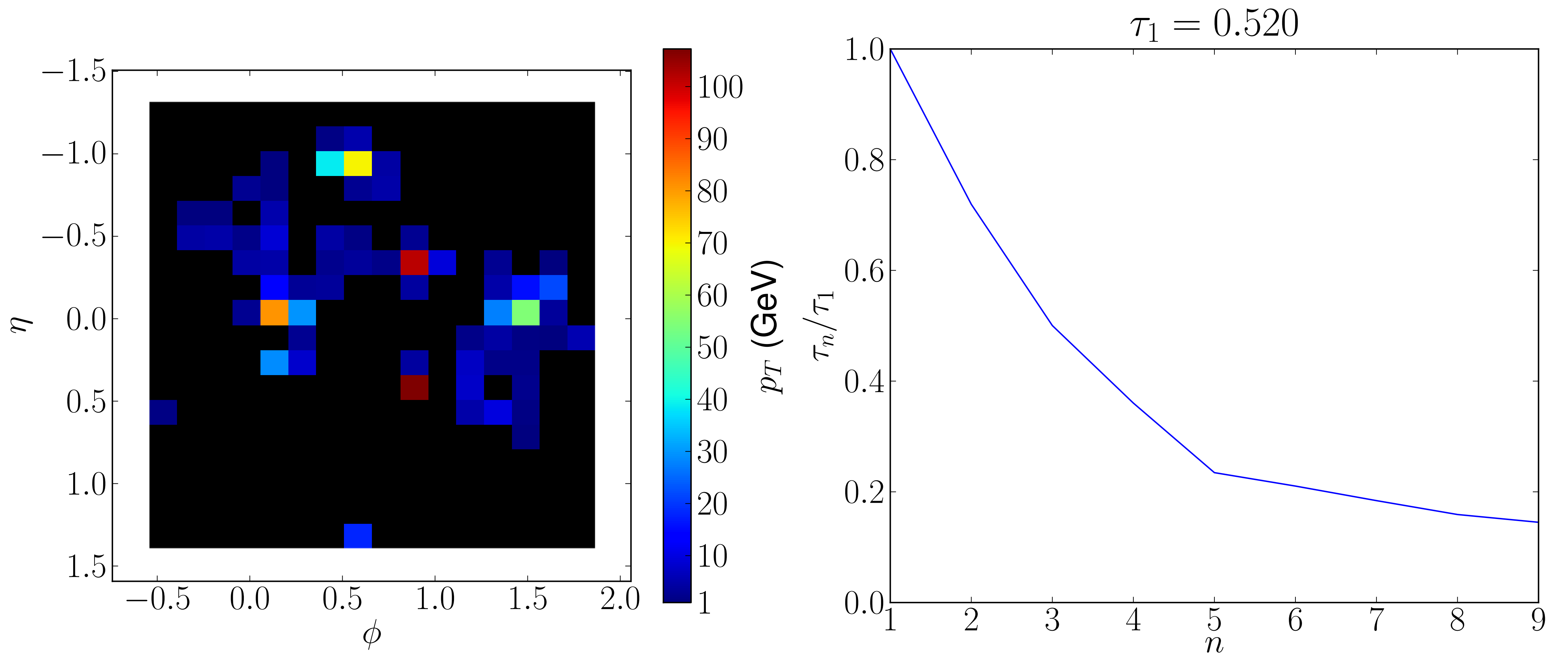
η
-0.5
0.0
0.5
3.0 3.5 4.0 4.5 5.0
ϕ
100 90 80 70 60 50 40 30 20 10 1
p_T (GeV)
$\tau_1 = 0.373$
τ_n/τ_1
1.0 0.8 0.6 0.4 0.2 0.0
1 2 3 4 5 6 7 8 9
n

4 Subjets



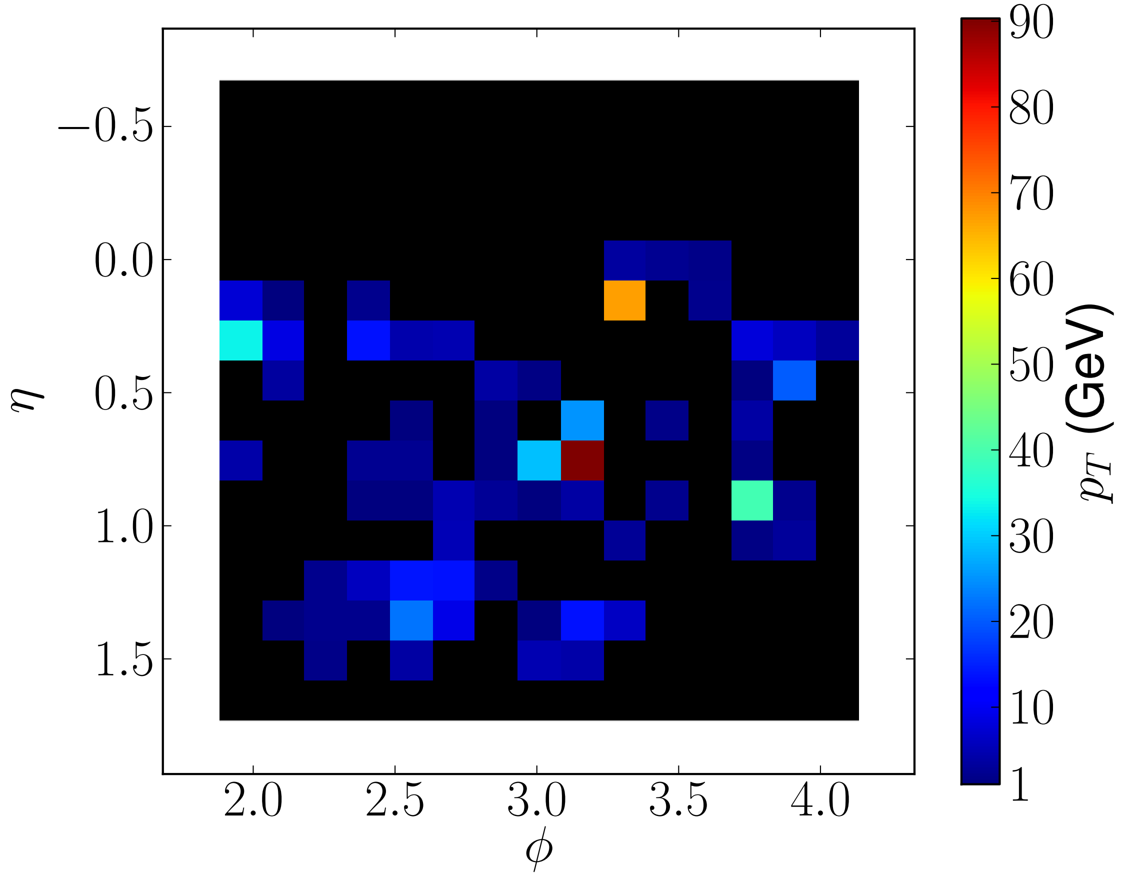
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
η
4.0
4.5
5.0
5.5
ϕ
90
80
70
60
50
40
30
20
10
1
p_T (GeV)
$\tau_1 = 0.478$
1.0
0.8
0.6
0.4
0.2
0.0
τ_n/τ_1
1
2
3
4
5
6
7
8
9
n

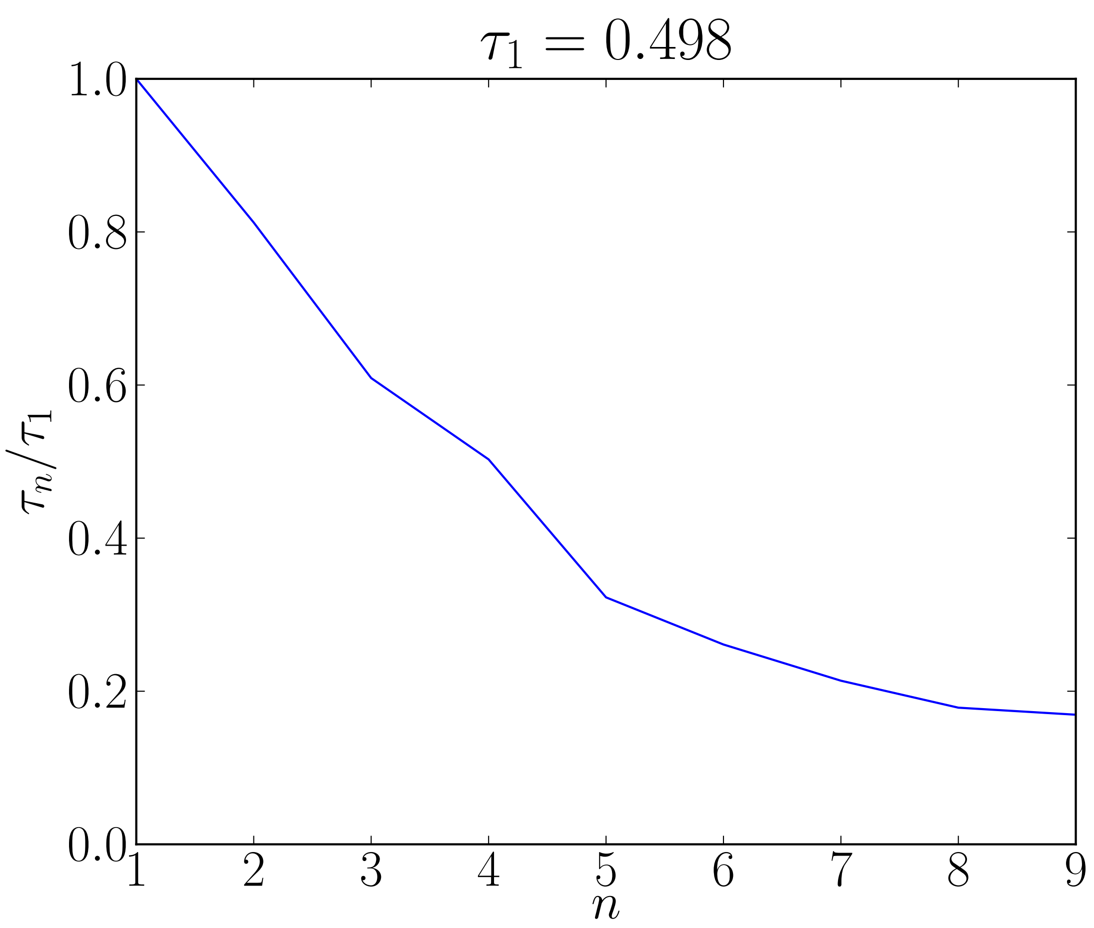
5 Subjets



-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
η
-0.5
0.0
0.5
1.0
1.5
2.0
ϕ
100
90
80
70
60
50
40
30
20
10
1
p_T (GeV)
$\tau_1 = 0.520$
τ_n/τ_1
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6
7
8
9
n

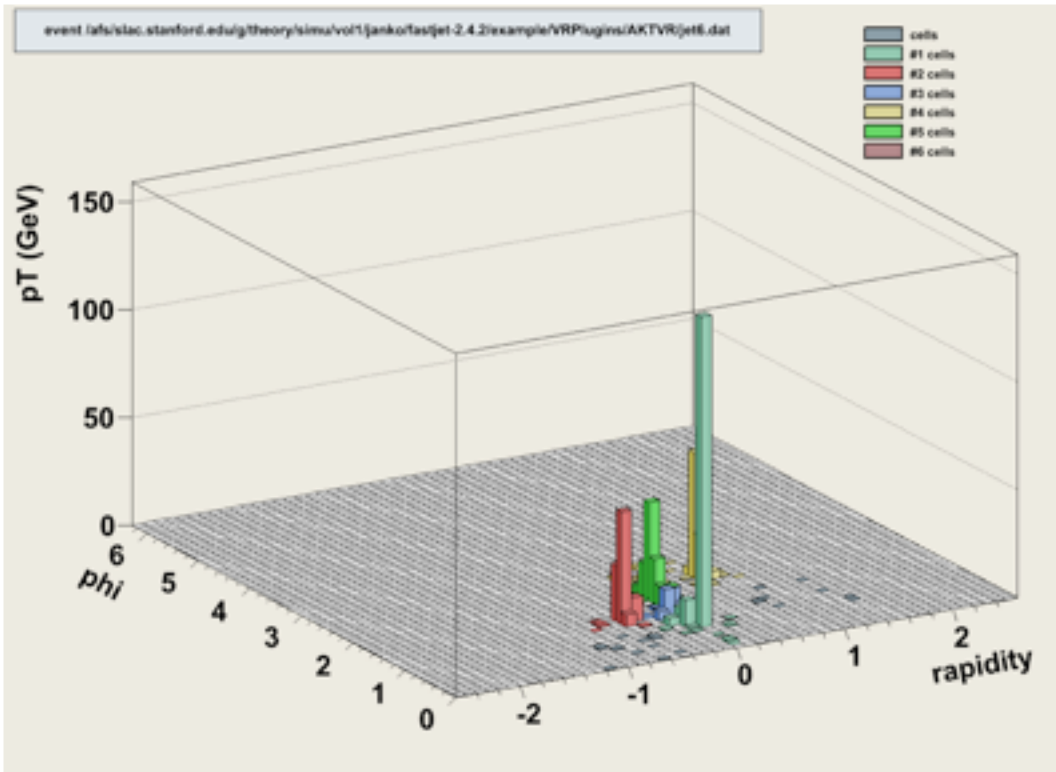
Many Subjets

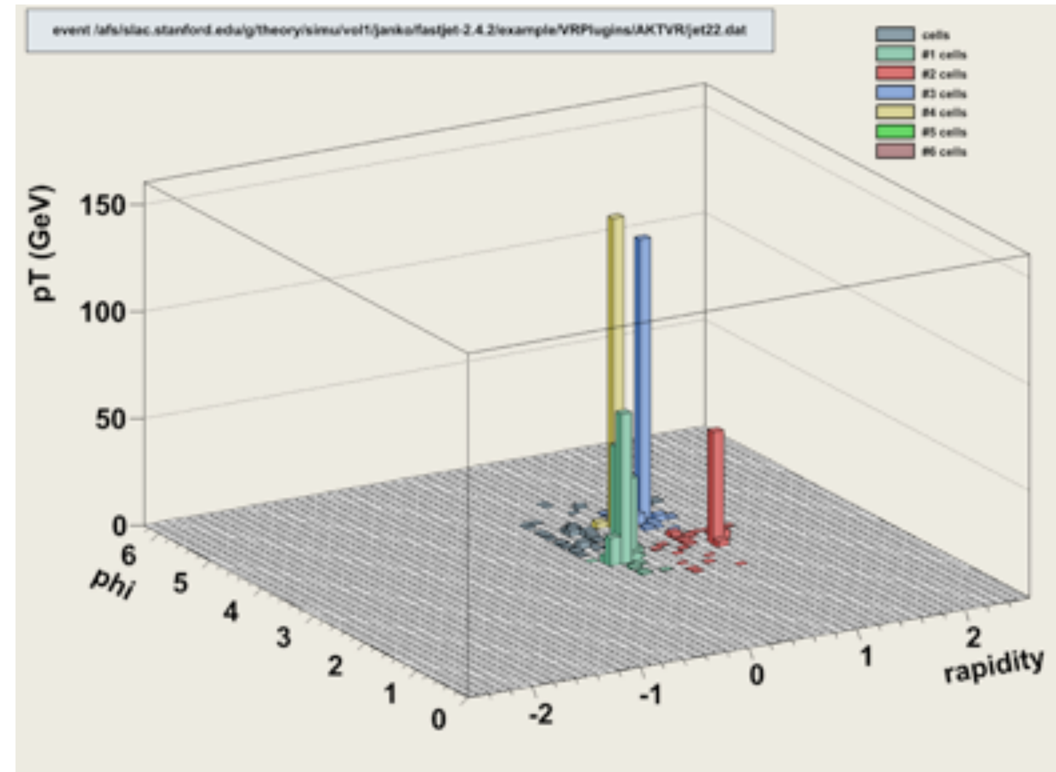




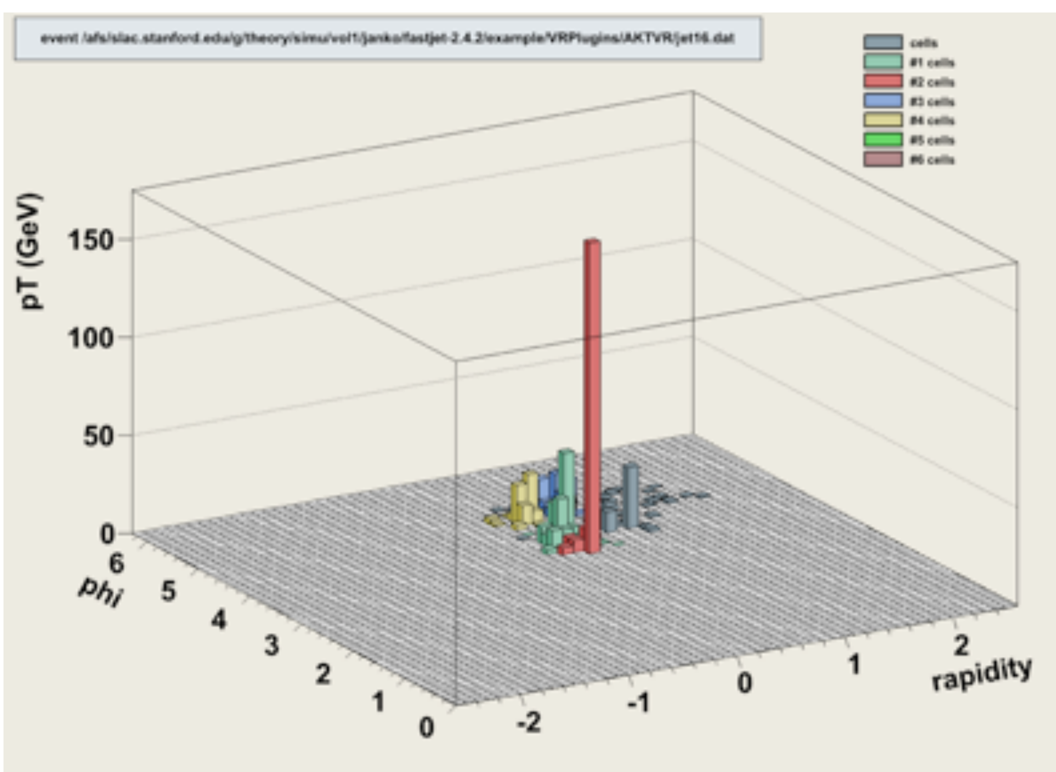
Jet Deconstruction Counting

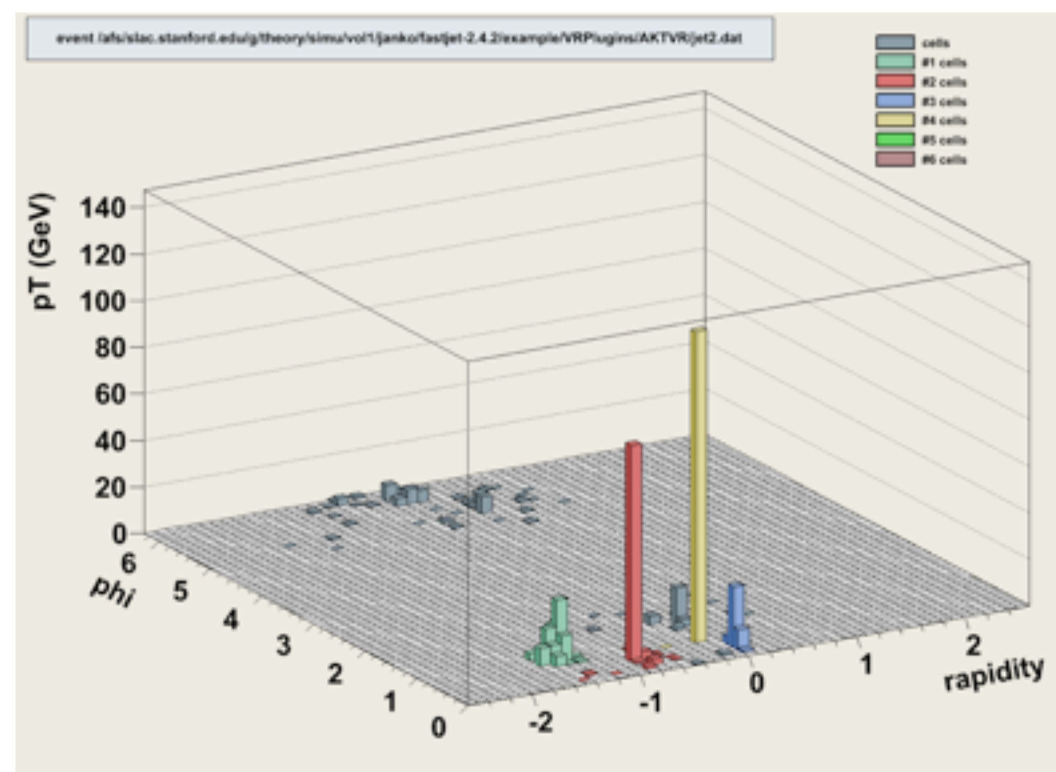
Signal





QCD



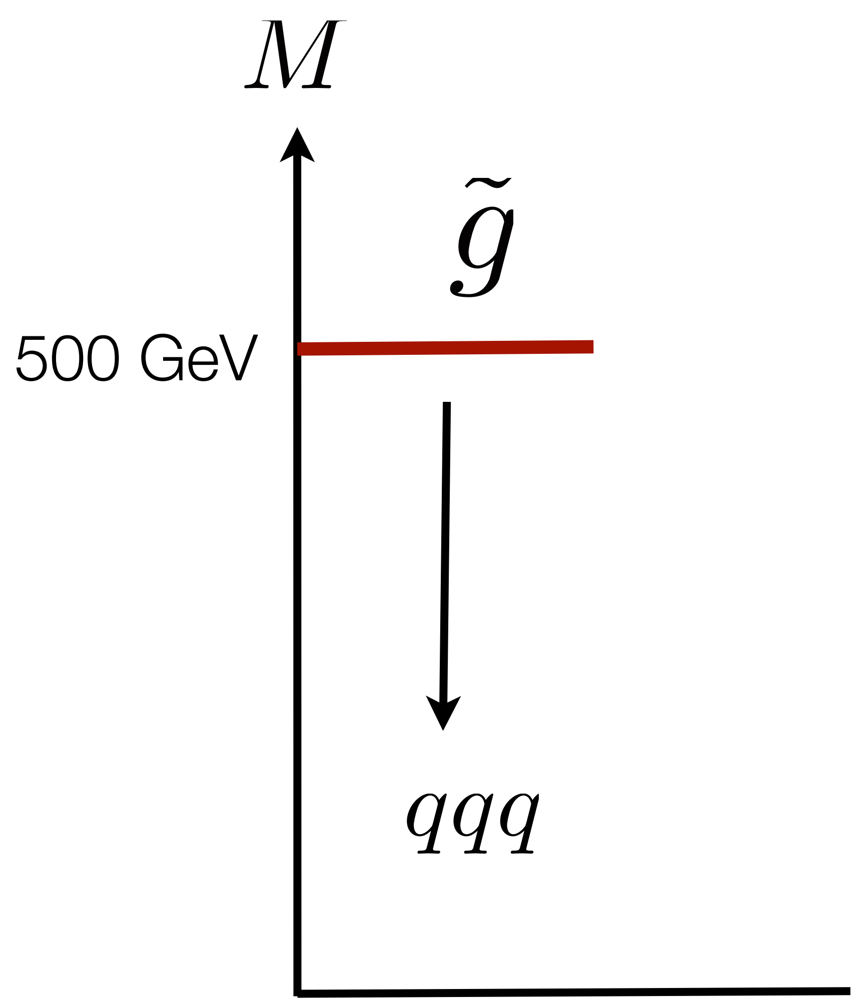


Non-MET Searches

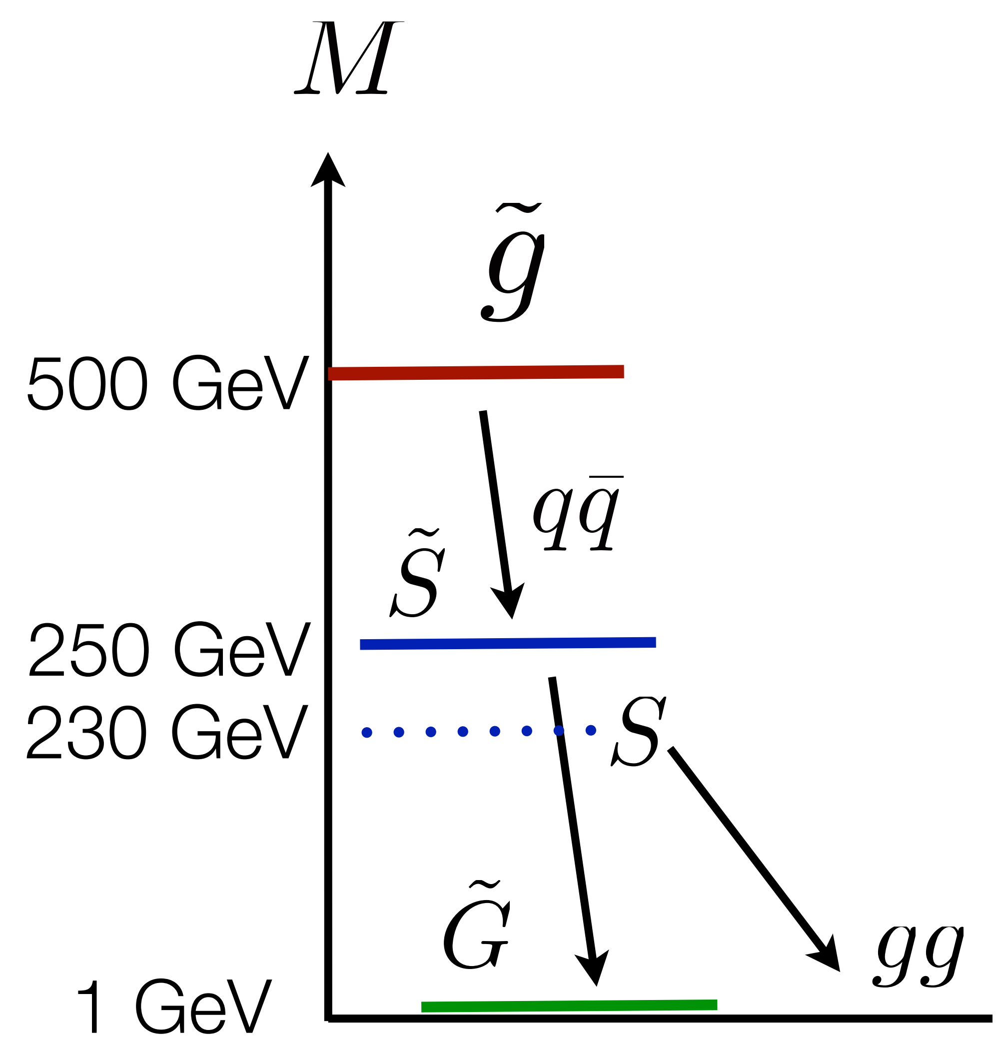
Not all theories have large MET

Two Benchmark Models

Baryonic RPV

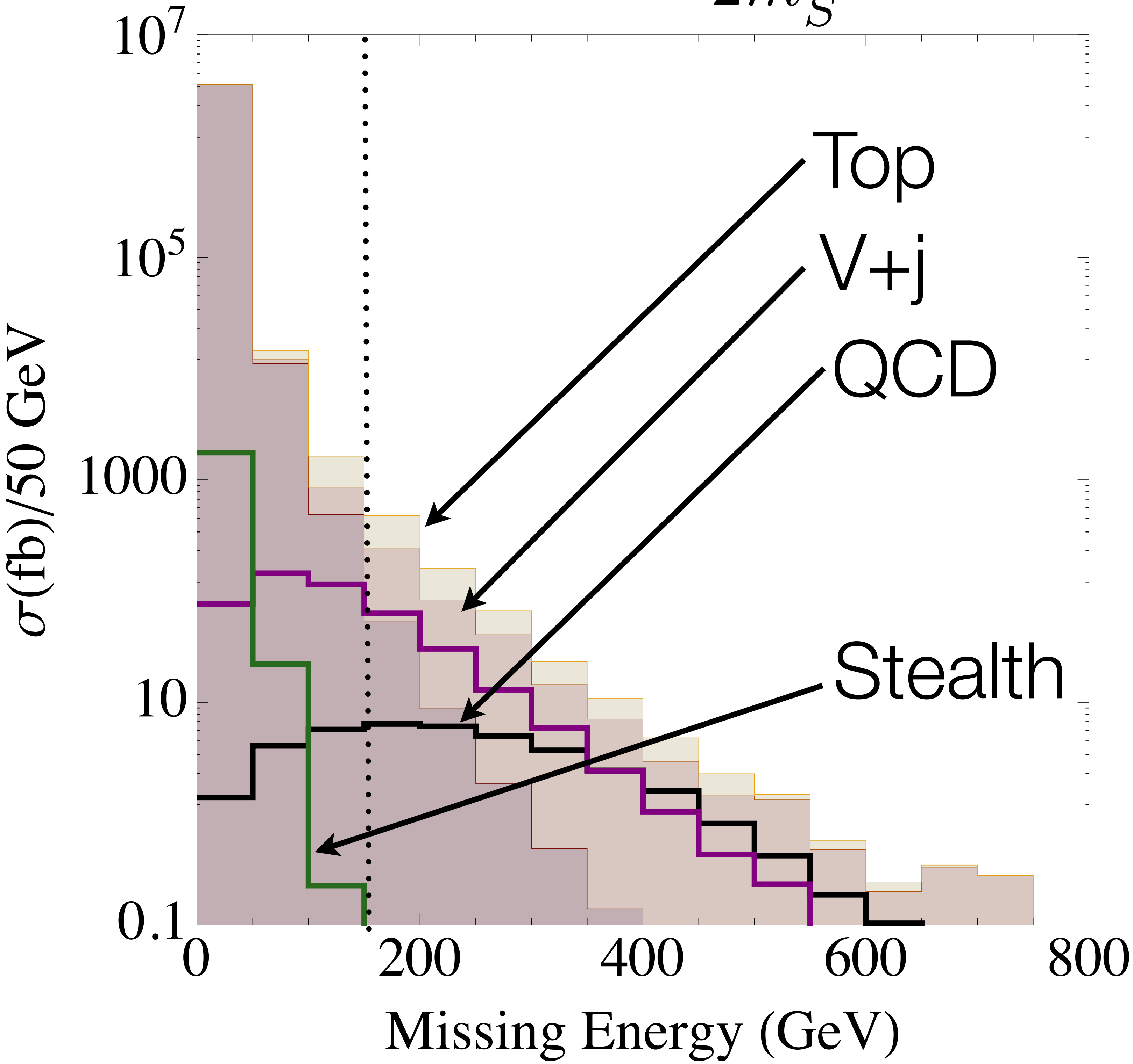


Stealth Susy



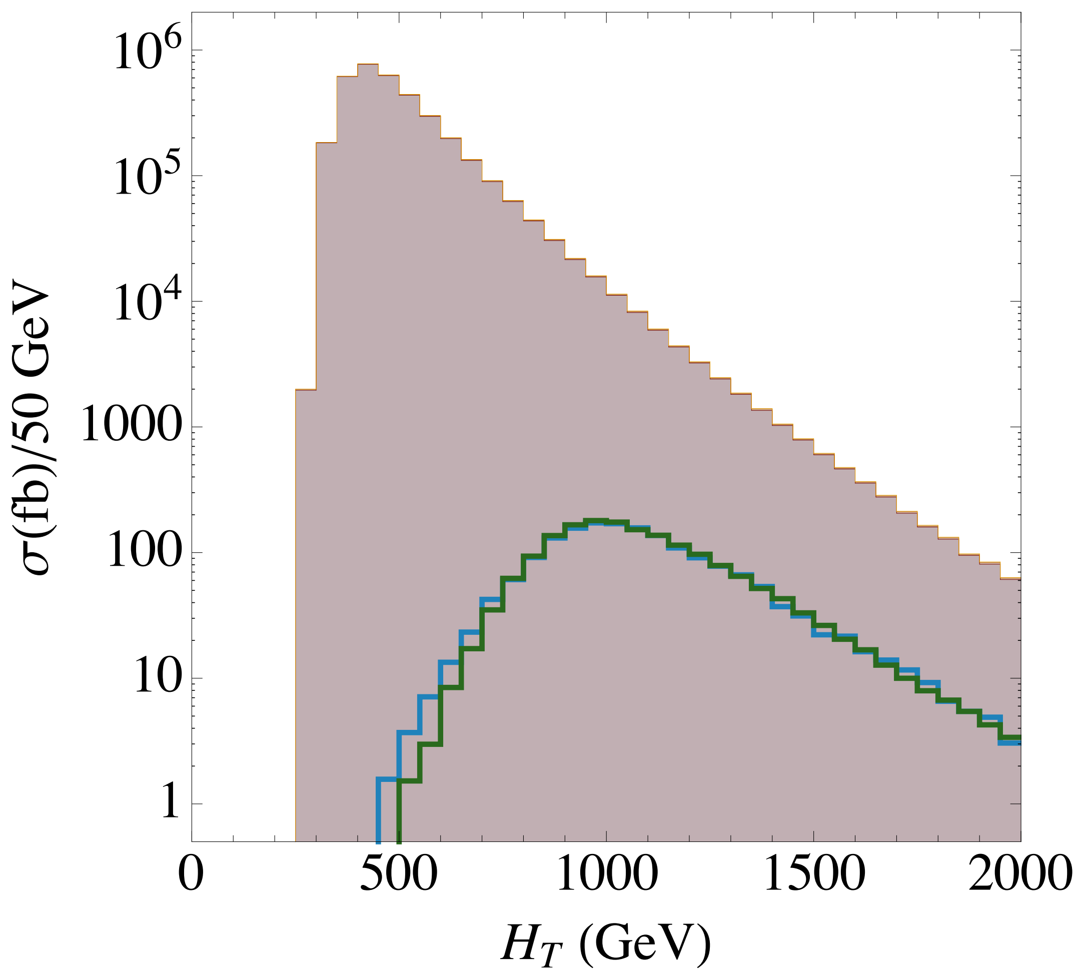
Stealth Susy MET

$$\not{E}_T \sim \frac{m_{\tilde{g}}}{2m_{\tilde{S}}}(m_{\tilde{G}} \oplus \delta m_{S\tilde{S}})$$ ~30 GeV

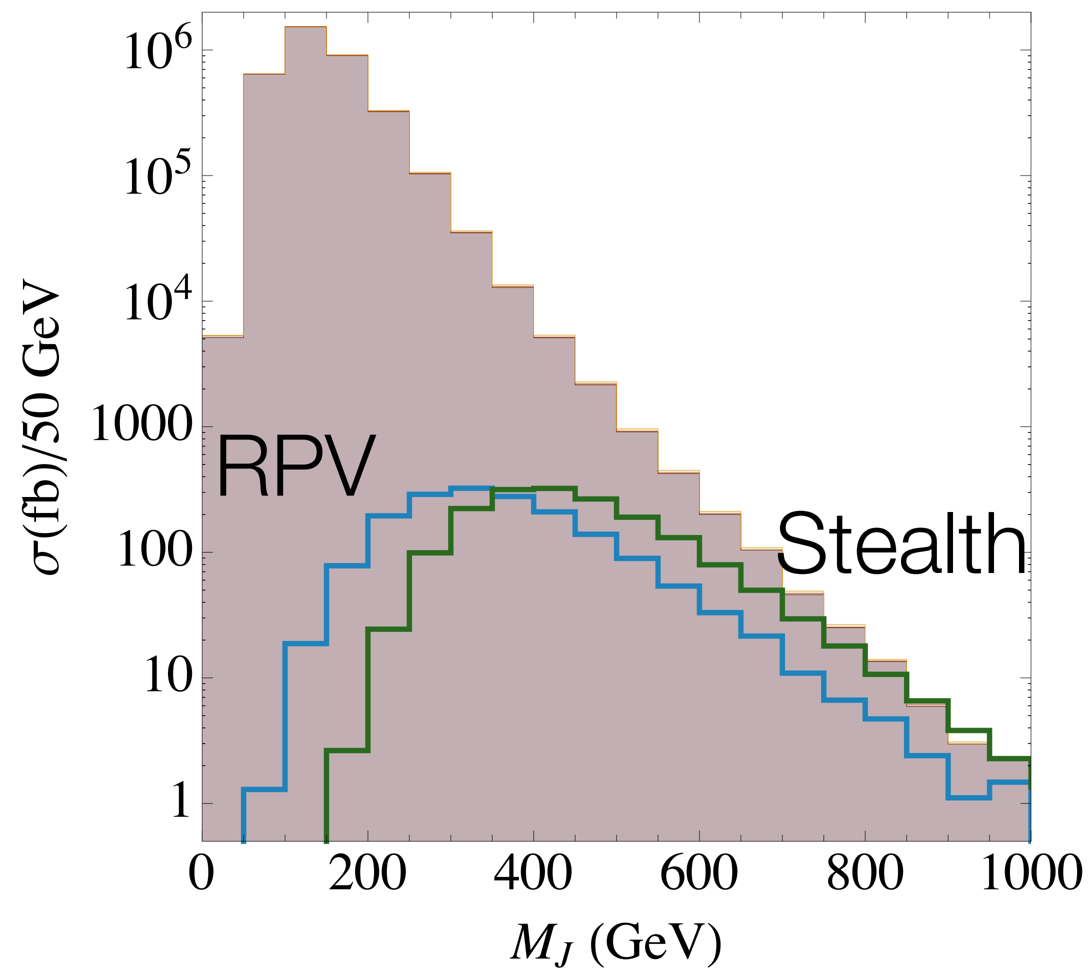


M_J vs H_T

Hopeless



Possible



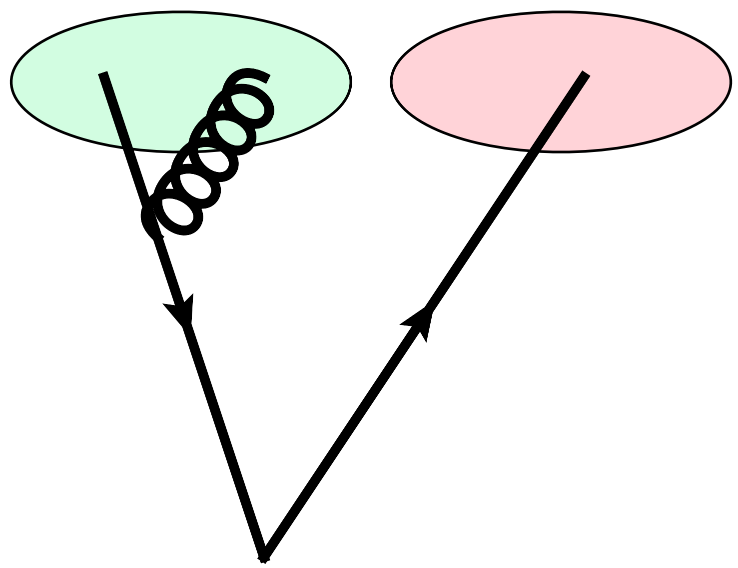
Reach for Stealth ~ 700 GeV

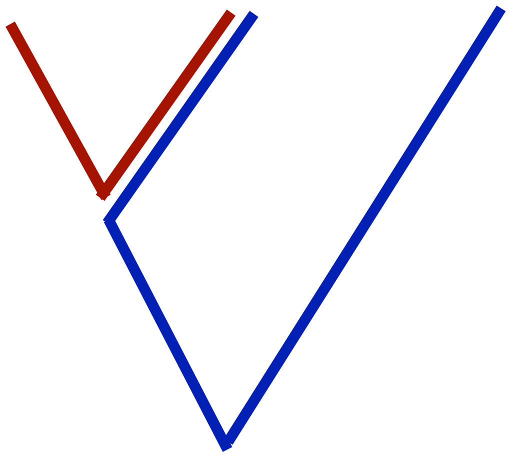
Reach for RPV ~ 400 GeV

Can do better by looking for resonant structures

Color Dipoles Picture

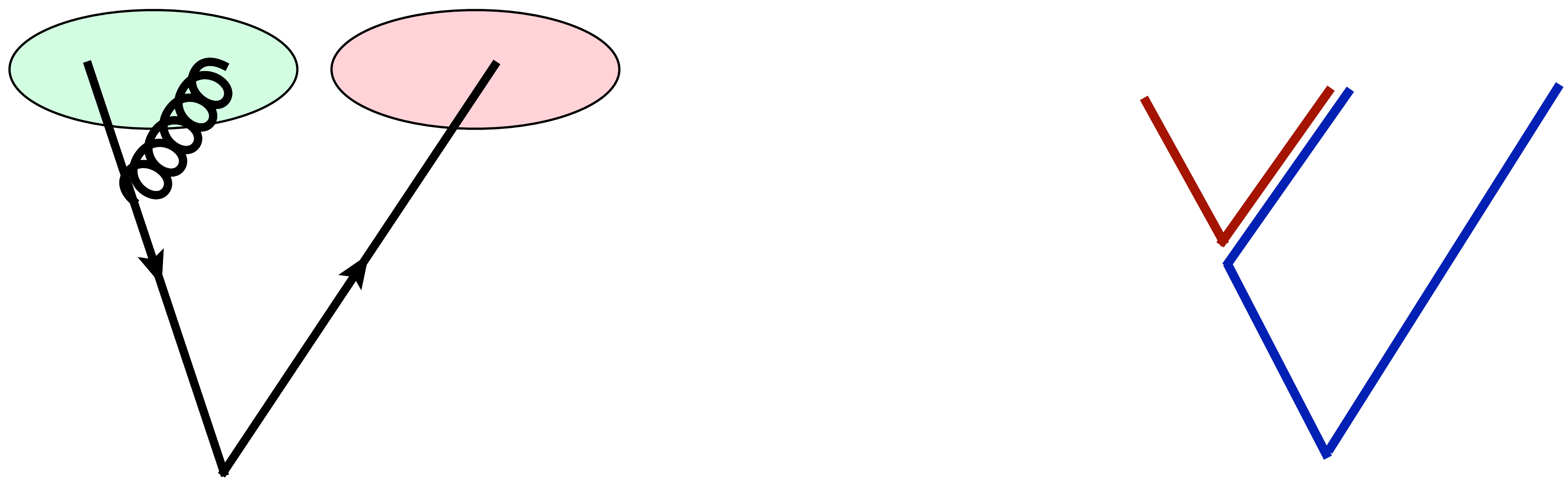
First Radiation Gives Mass





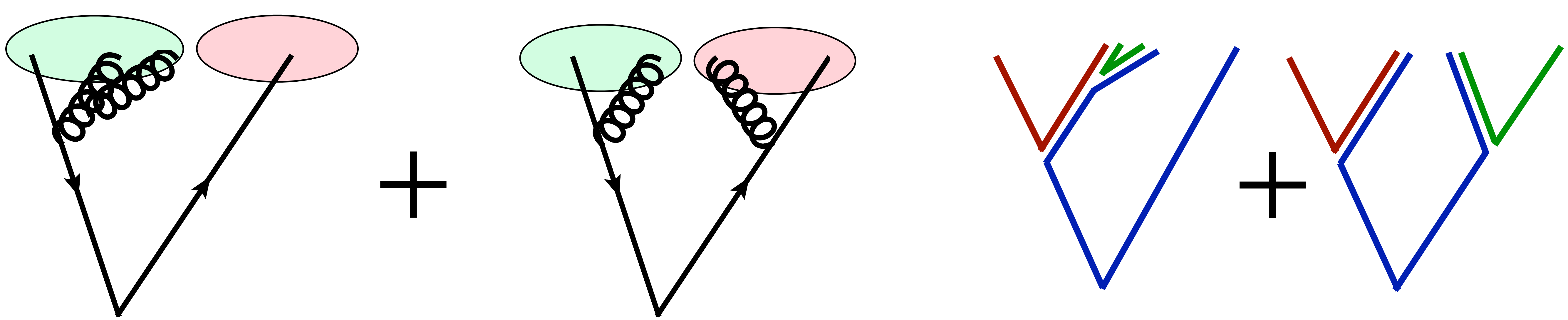
Color Dipoles Picture

First Radiation Gives Mass



Color Connection Causes Pull on Second Jet

Second order effect



If 1st jet has a large mass, will the 2nd jet have a large mass more often?

Consider m_j/p_T of 2 leading jets

$$h(x_1,x_2)$$

$$H(x_1,x_2) = \frac{h(x_1,x_2)\int h(x_1,x_2)dx_1dx_2}{\int h(x_1,x_2)dx_1 \int h(x_1,x_2)dx_2},$$

$$\text{if } h(x_1,x_2) = g_1(x_1)g_2(x_2), \text{ then } H(x_1,x_2) = 1$$

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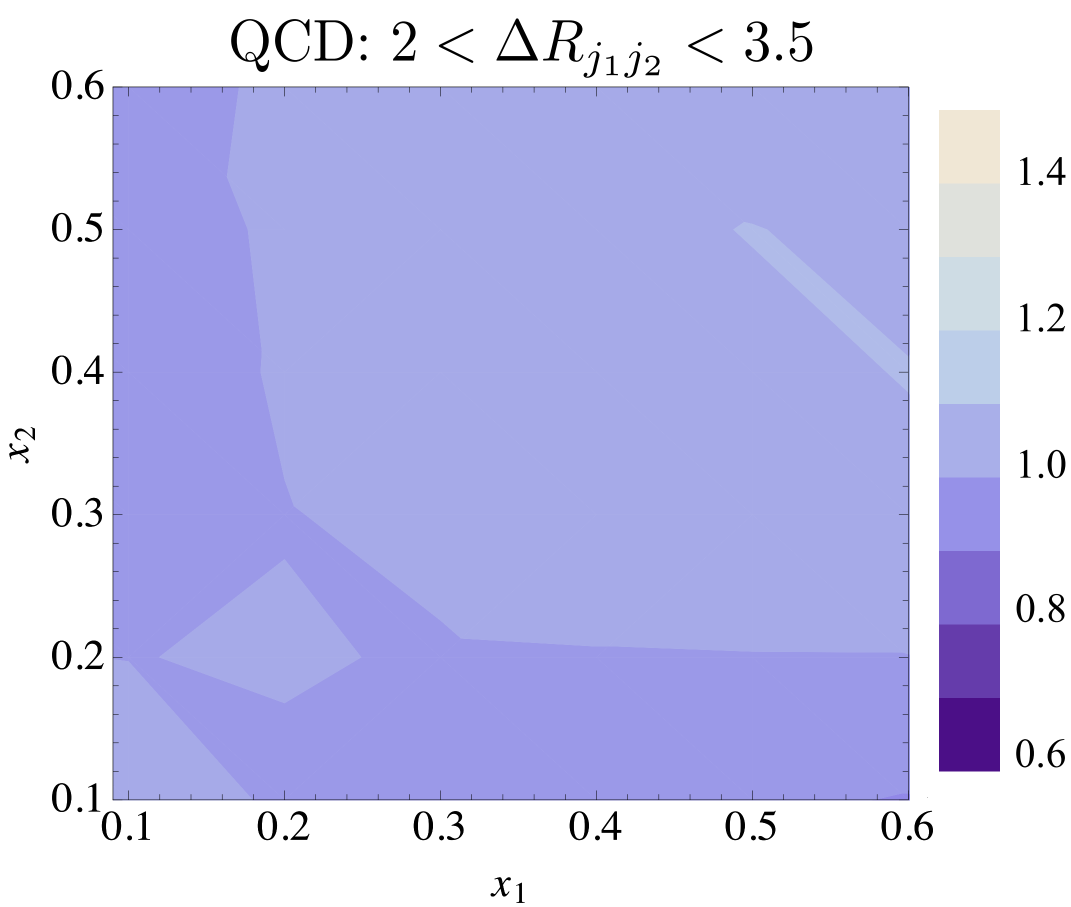
$$\text{if } h(x_1,x_2) = g_1(x_1)g_2(x_2), \text{ then } H(x_1,x_2) = 1$$



Z^0+2^+j with MG4 + Pythia 6.4

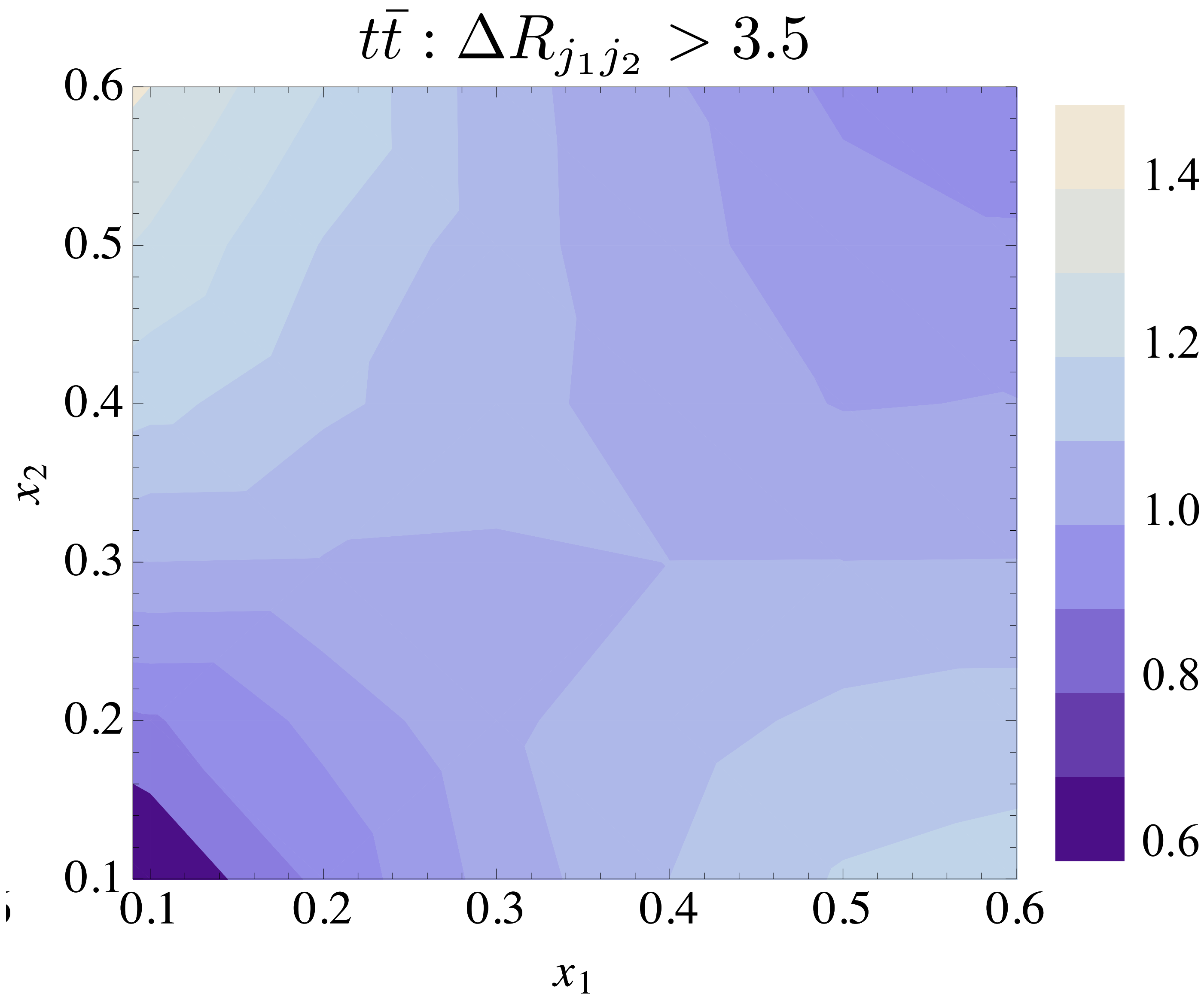
~5% correlations

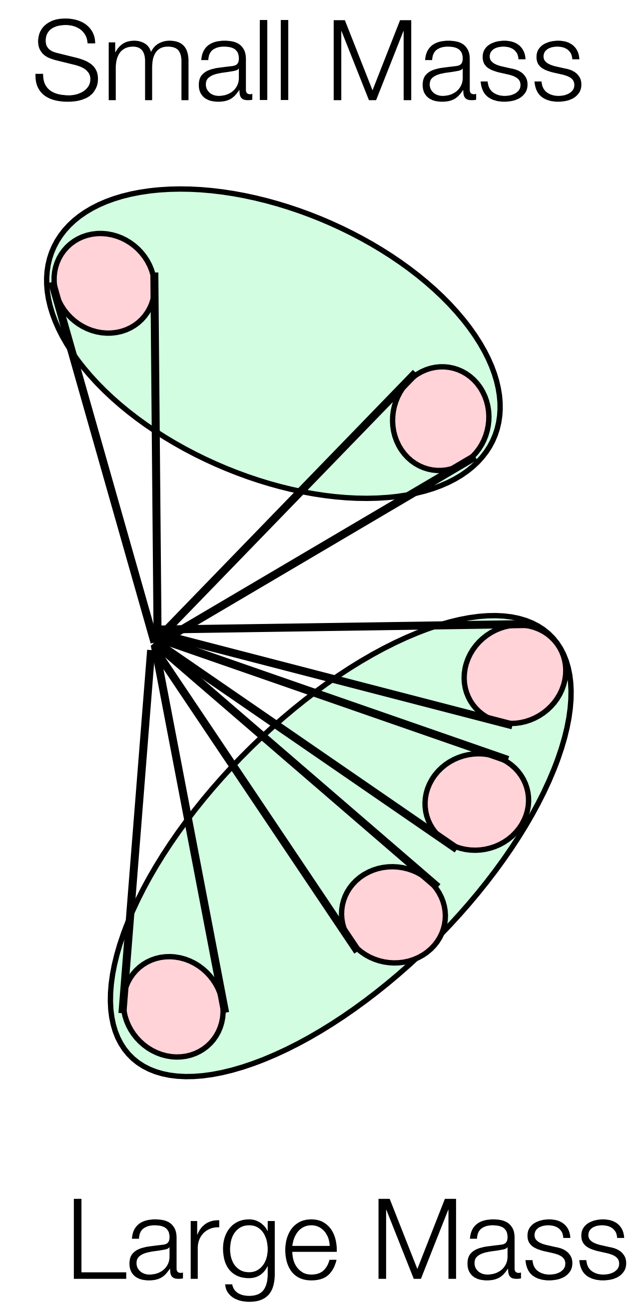
Slightly positive correlation

No calculation to compare to

5% requires 10k events per bin

Contrast to top events





30% Correlations

Negative correlation

If one is massive,
the second is *less* likely to be massive

Fat Jet Masses at ATLAS

Fat jets are calibrated and available for use