Theoretical Perspective on 3rd Generation Searches

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Workshop on Heavy Flavor Production
LBNL
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Outline

- Perspective

High Multiplicity Signals

Fat Jet Techniques

The 7 & 8 TeV Run of the LHC

Adjectives I'd use to describe searches for new physics:

Effective

Well-Designed

Extensive

Thorough

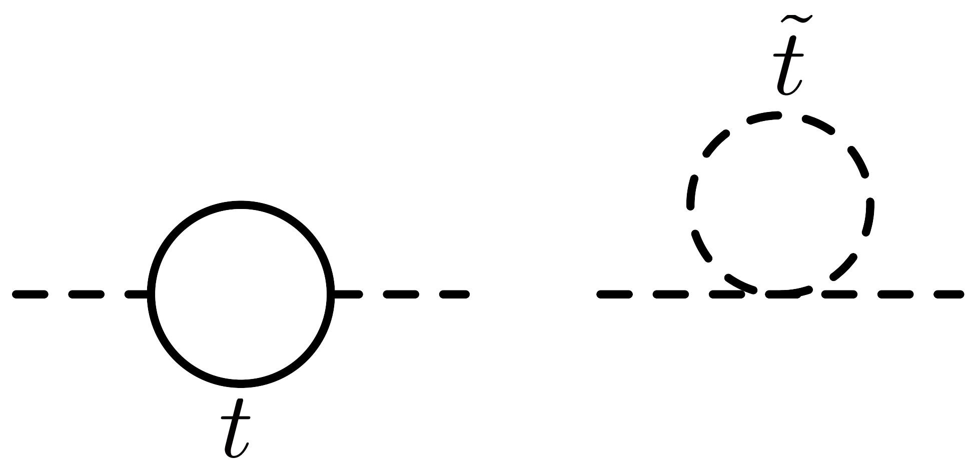
Pragmatic

Natural SUSY

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

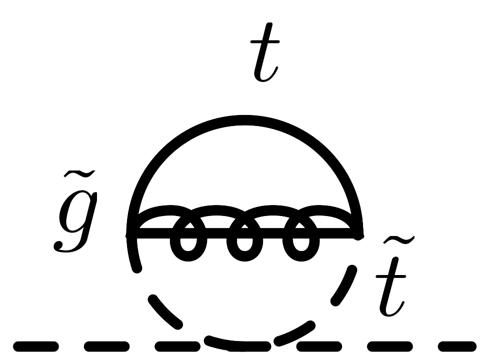
Tree μ^2 Higgsinos $\sim 200\ \mathrm{GeV}$

1 loop



Top Squarks $\sim 500\ \mathrm{GeV}$

2 loop



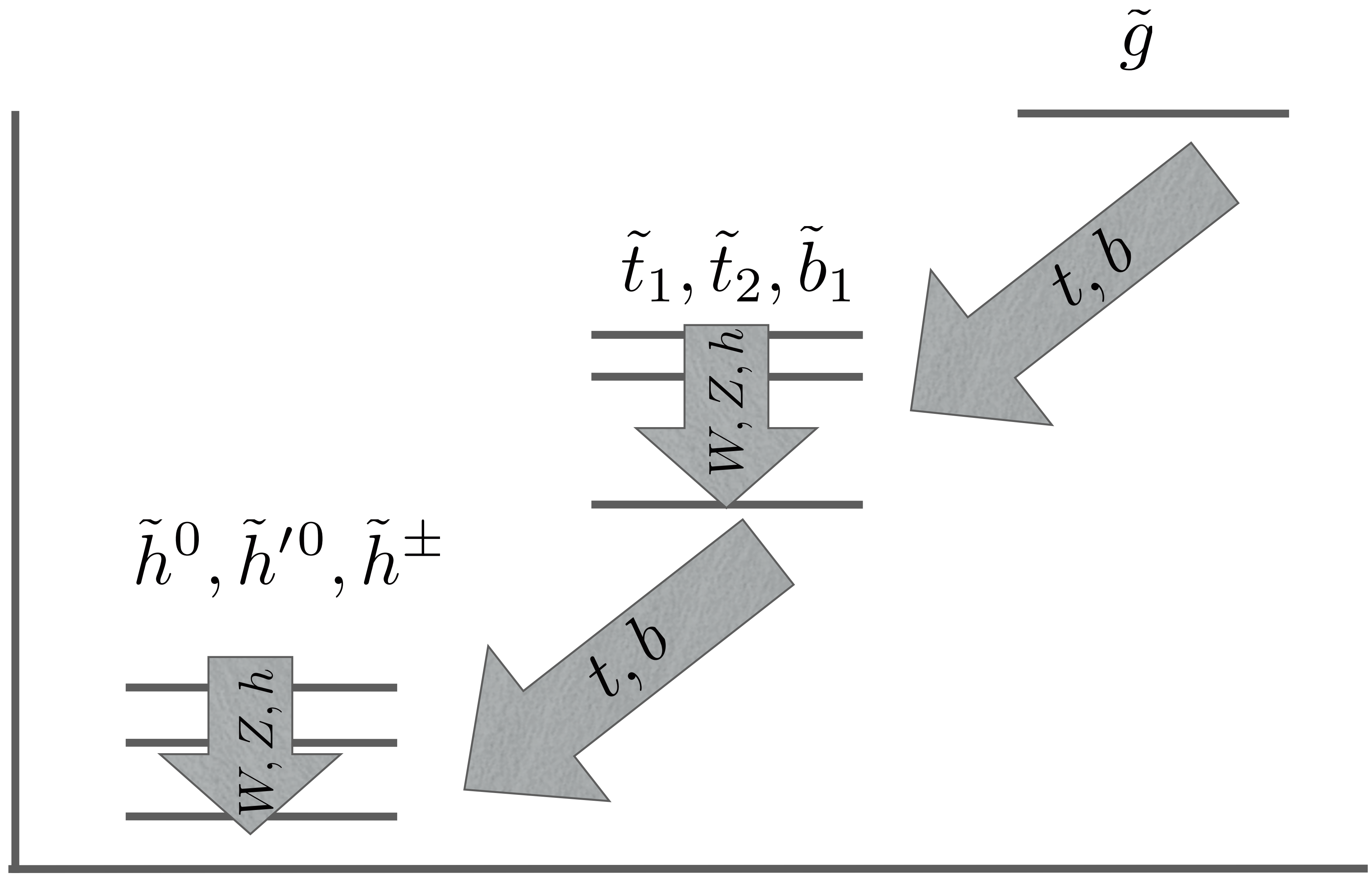
Gluinos $\sim 1500\ \mathrm{GeV}$

NATURAL SUSY TARGETS

HIGGSINOS	$\tilde{h}^0, \tilde{h}'^0, \tilde{h}^\pm$
TOP SQUARKS	$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$
GLUINO	$\tilde{g}$

General Strategy to Search for
Lightest Colored Particle (LCP)
that decays to LSP

The General Setup



Lots of parameter space

Searches for 3rd Generation are typical of these

ATLAS-CONF-2012-145

Search for gluino pair production in final states with missing transverse momentum and at least three b-jets using 12.8 fb-1 of pp collisions at sqrt(s) = 8 TeV with the ATLAS Detector.

The ATLAS collaboration

12 Nov 2012. - mult. p.

ATLAS-CONF-2012-153

Search for Supersymmetry in events with four or more leptons in 13 fb−1 pp collisions at √s = 8 TeV with the ATLAS detector

The ATLAS collaboration

12 Nov 2012. - mult. p.

Detectors and Experimental Techniques

ATLAS-CONF-2012-165

Search for direct sbottom production in event with two b-jets using 12.8 fb-1 of pp collisions at sqrt{s} = 8 TeV with the ATLAS Detector.

The ATLAS collaboration

04 Dec 2012. - mult. p.

ATLAS-CONF-2012-166

Search for direct top squark pair production in final states with one isolated lepton, jets, and missing transverse momentum in sqrt(s) = 8 TeV pp collisions using 13.0 ifb of ATLAS data

The ATLAS collaboration

05 Dec 2012. - 22 p.

ATLAS-CONF-2012-167

Search for a supersymmetric top-quark partner in final states with two leptons in sqrt(s) = 8 TeV pp collisions using 13 ifb of ATLAS data

The ATLAS collaboration

05 Dec 2012. - 17 p.

ATLAS-CONF-2013-001

Search for direct stop production in events with missing transverse momentum and two b-jets using 12.8 fb^{-1} of pp collisions at sqrt{s} = 8 TeV with the ATLAS detector

The ATLAS collaboration

05 Jan 2013. - mult. p.

CMS-PAS-SUS-12-028

Search for supersymmetry in final states with missing transverse energy and 0, 1, 2, 3, or at least 4 b-quark jets in 8 TeV pp collisions using the variable AlphaT

CMS-PAS-SUS-12-017

Search for supersymmetry in events with same-sign dileptons

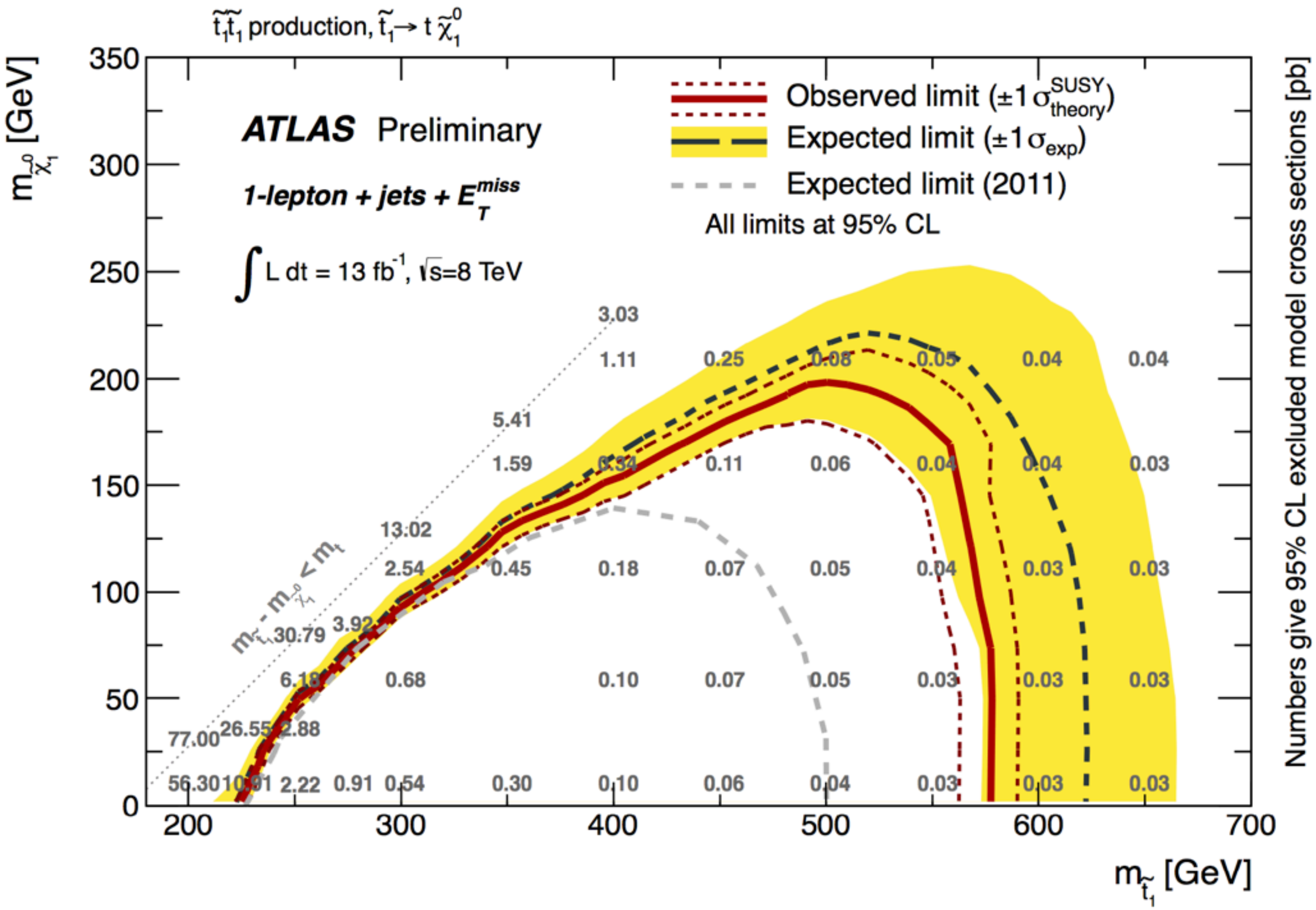
CMS-PAS-SUS-12-029

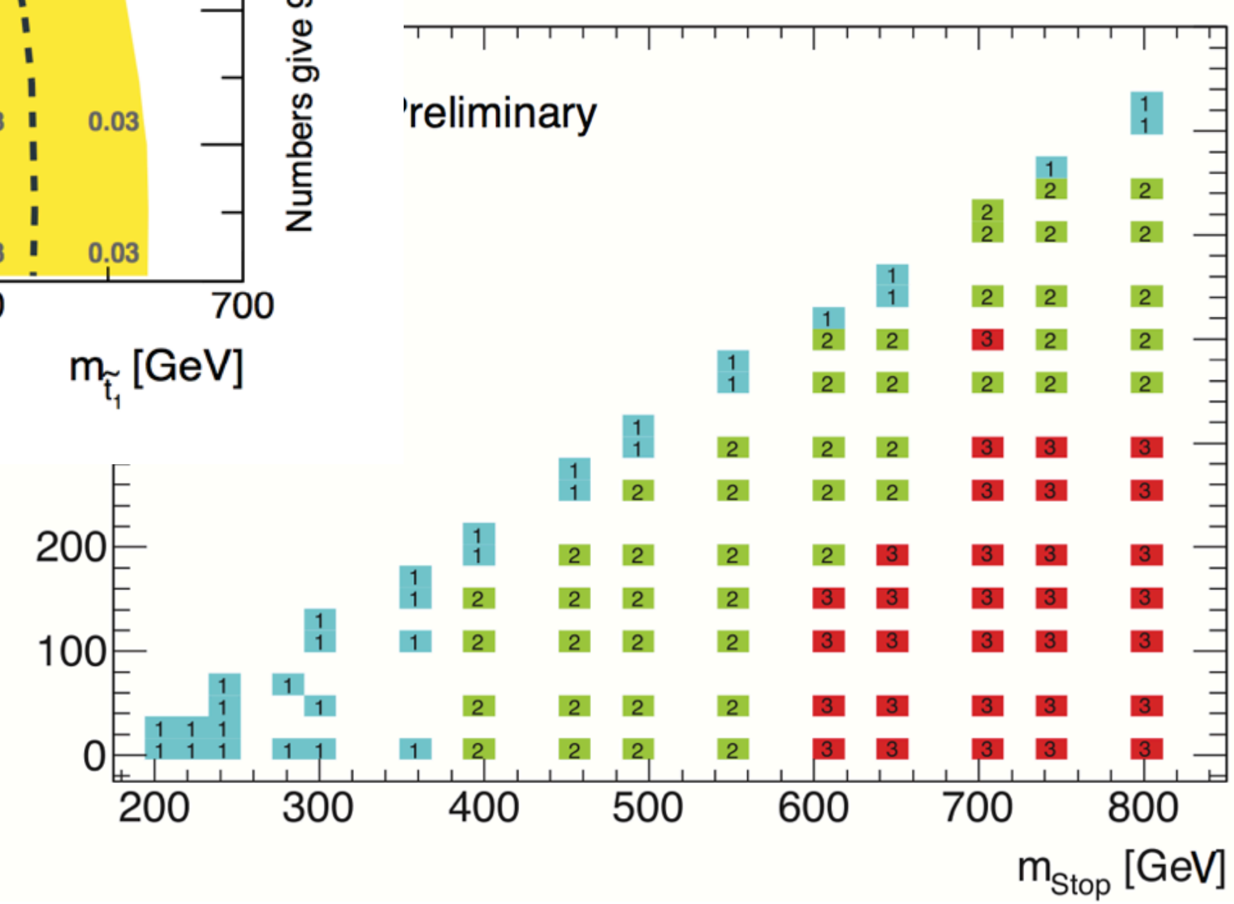
Search for supersymmetry in events with same-sign dileptons and b-tagged jets with 8 TeV data

CMS-PAS-SUS-12-016

Search for supersymmetery in final states with missing transverse momentum and 0, 1, 2, or ≥3 b jets in 8 TeV pp collisions

Search results are useful even when null



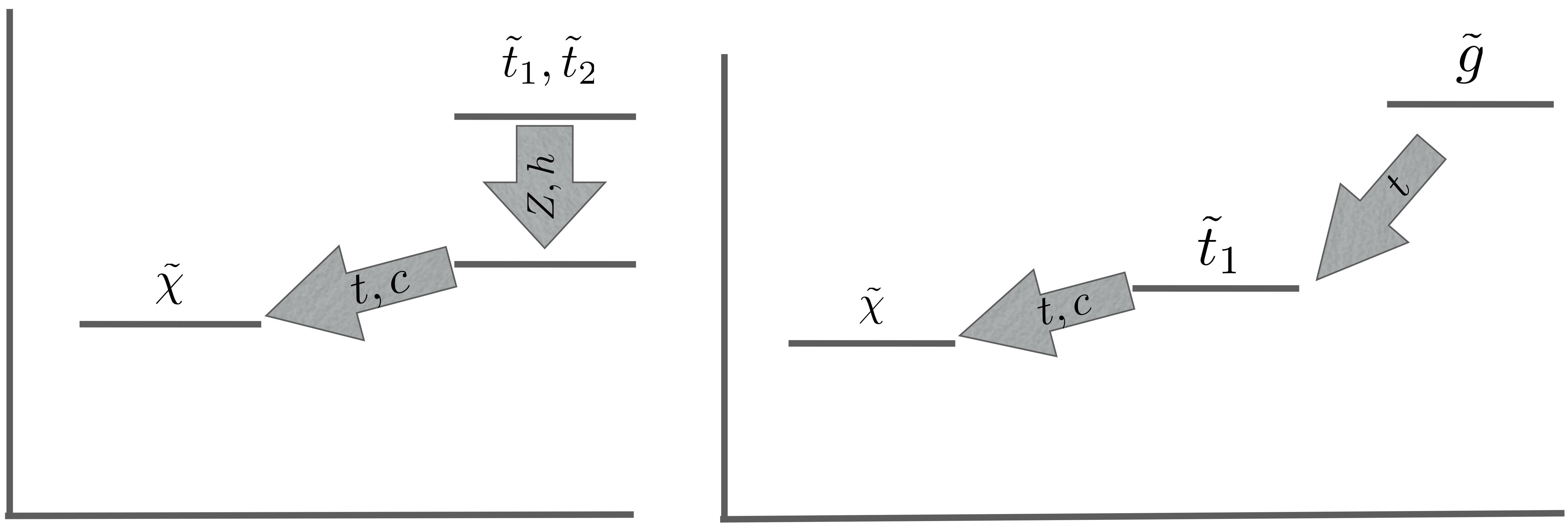


The basic searches are covered

Lower reach with a compressed spectra

Could possibly gain by looking at heavier particles

(Still 2D scans since LSP-LCP mass splitting fixed & small)



Composite Higgs & Little Higgs

Same-Spin Particles called Partners

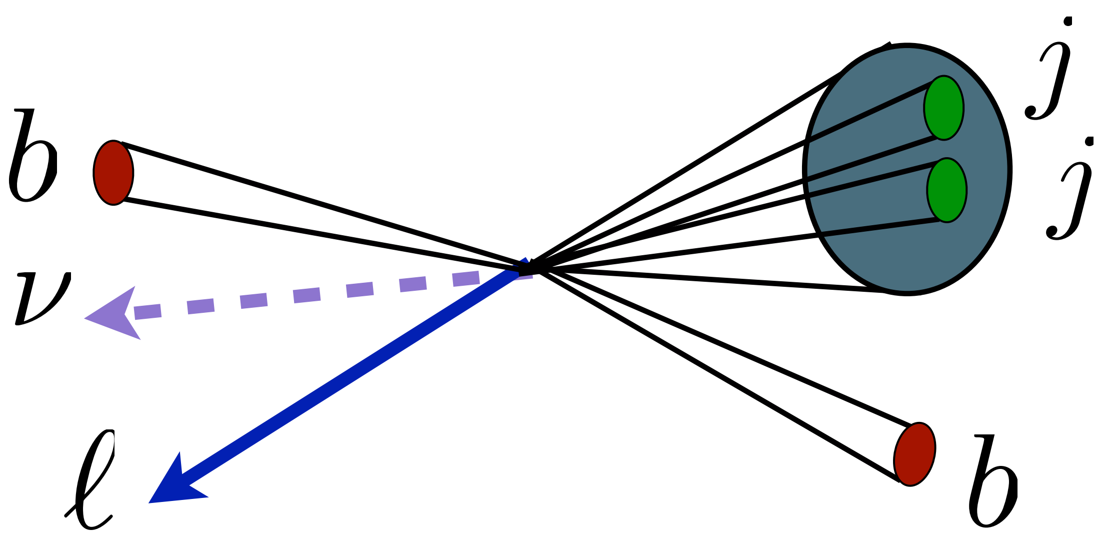
Top Partners $t'_{\frac{2}{3}}, \quad (t'_{\frac{2}{3}}, b'_{-\frac{1}{3}}), \quad (\psi'_{\frac{5}{3}}, t'_{\frac{2}{3}})$

EW Vector Partners $W', \quad Z'$

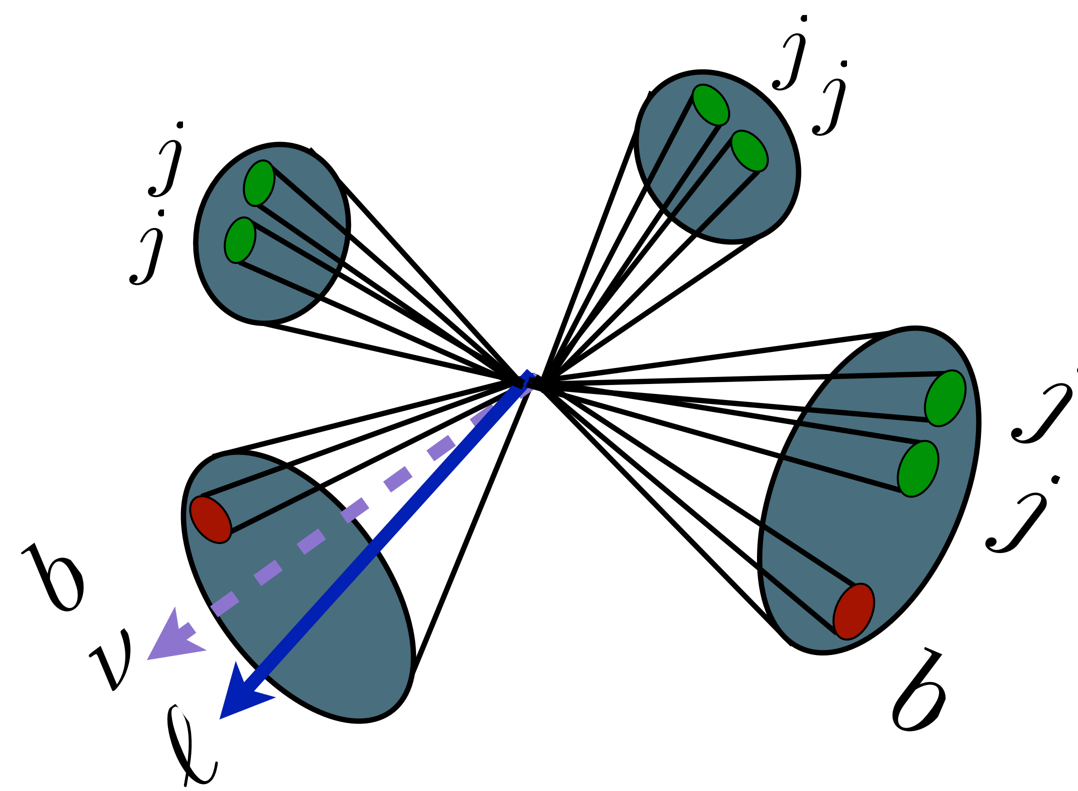
Many Searches Being Done

Pair-produced Top Partners

$$t' \to bW^+$$



$$b' \to tW^-$$



Single production also possible

Composite Higgs Theories

Frequently have colored vectors and pseudo-Goldstone bosons

If $\pi_T > 2m_t$ $\quad \mathrm{Br}(\pi_T \to t\bar{t}) \sim \mathcal{O}(1)$

Frequently easiest to produce vector resonances

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

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

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

Searches aren’t as complete
as SUSY searches

Boosted Techniques developed for
these signals

Still waiting for discovery

Signals could be just out of reach

Is there something that we're missing?

Key Handle to Separate *S* from *B*

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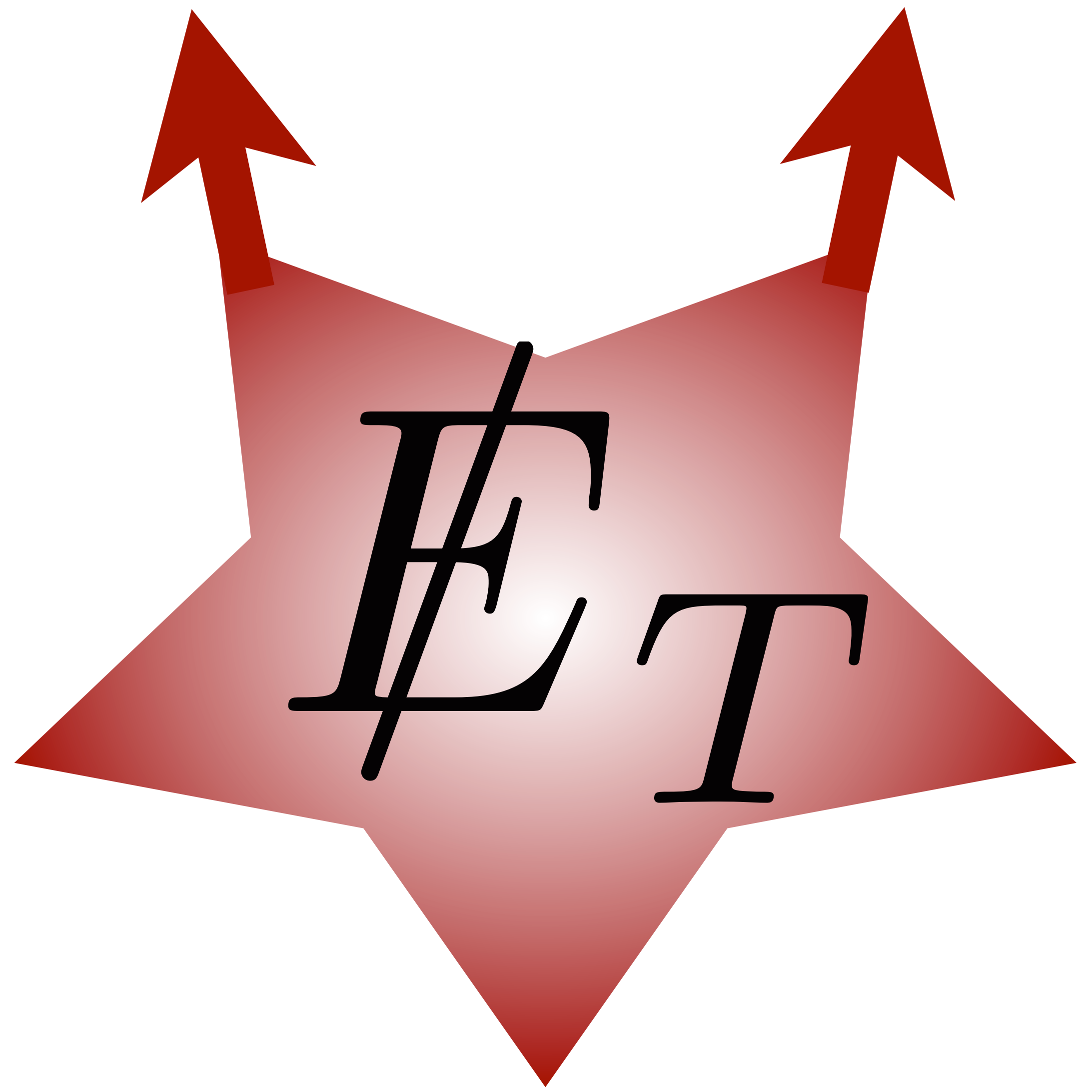
Dramatically reduces
QCD Multijet rate

Key Handle to Separate *S* from *B*



But if signal is not MET-rich

Large classes of signatures are invisible

New Physics Searches

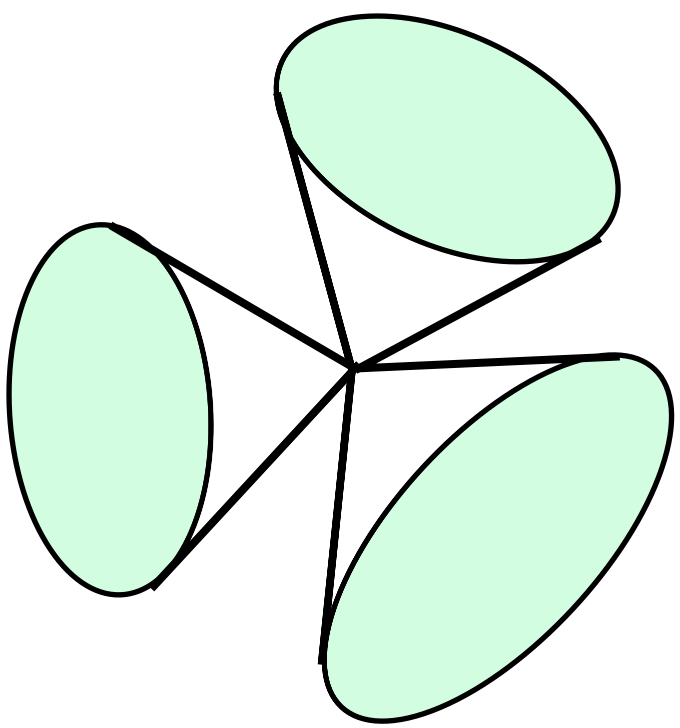
Rely heavily on one object
that QCD doesn’t directly produce

Gives parametric control of QCD background

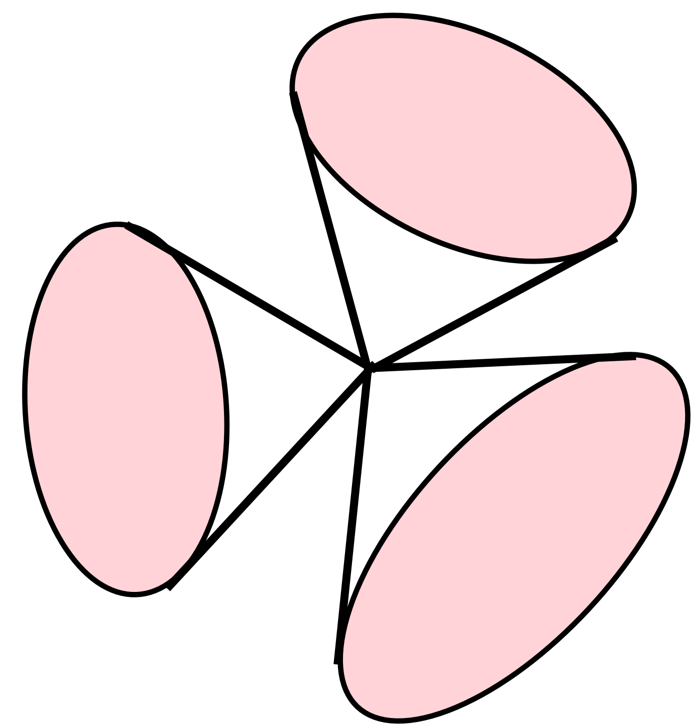
But if the signal doesn’t have it,
we’re eliminating signals

Need a handle to distinguish

Normal QCD Multijet



BSM Multijet



Work today:

Progress towards low background MET-Less Searches

Will *reduce* the importance of MET

No single solution

Need to be tailored to signal

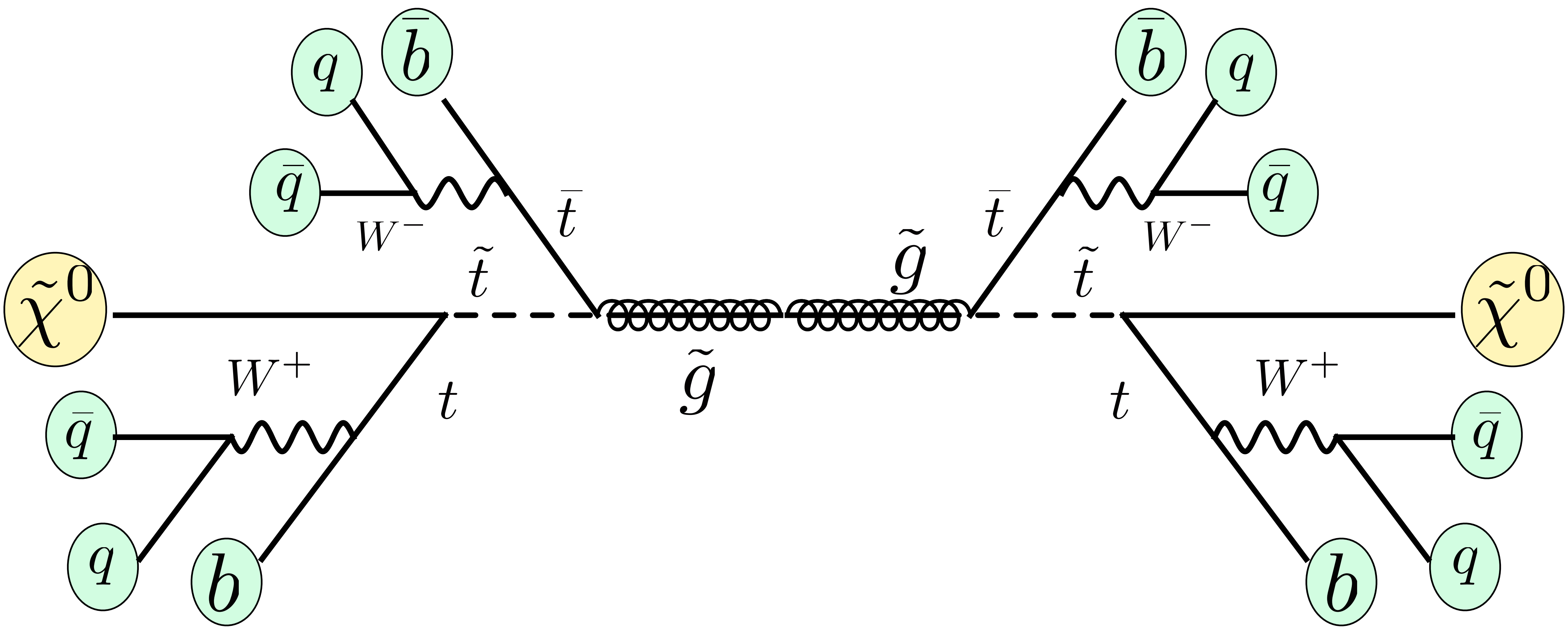
Outline

Perspective

- High Multiplicity Signals

Fat Jet Techniques

The Classic Signature



12^+ Jets

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)

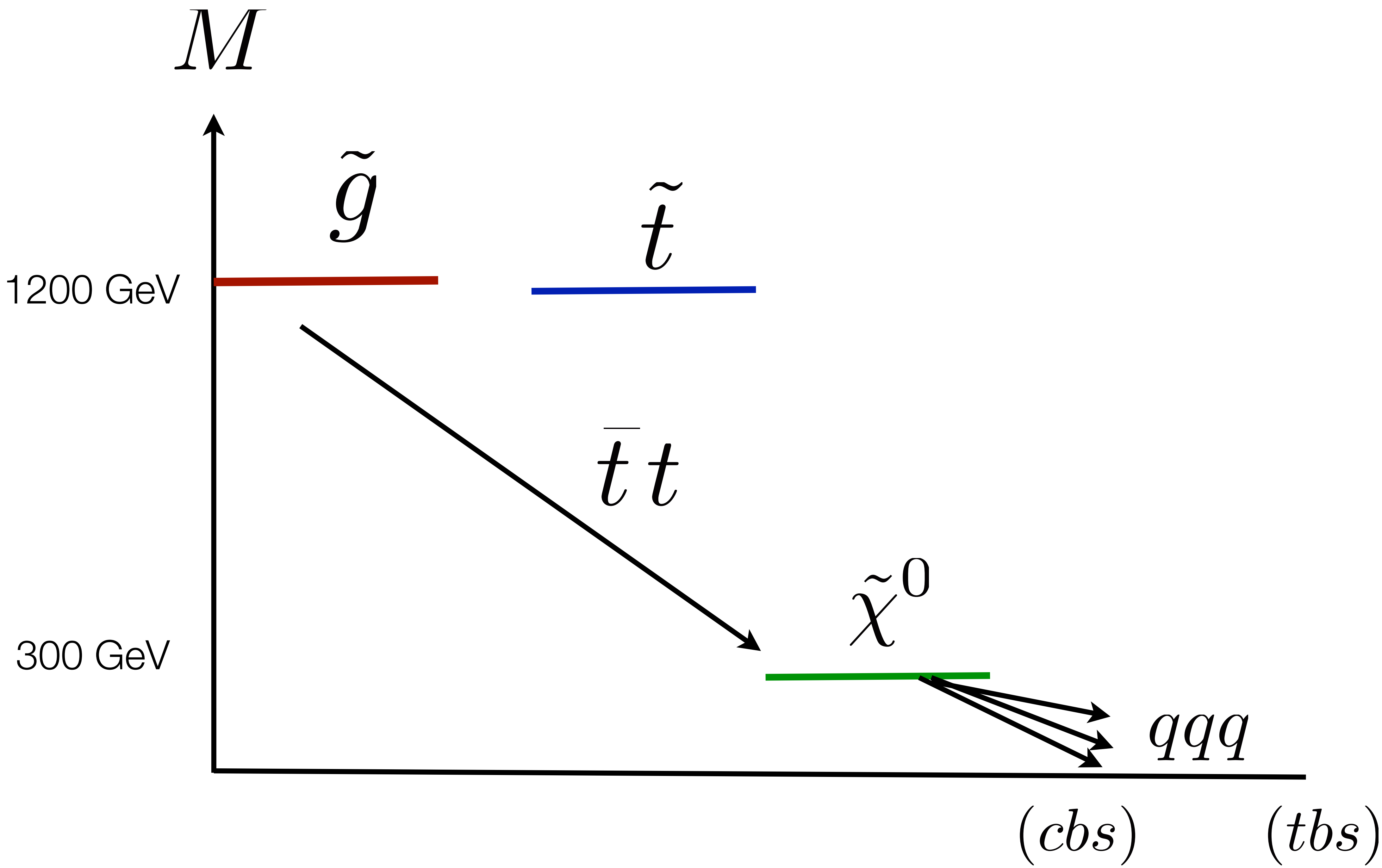
(one quark could be top → +2j)

Increases multiplicity significantly

Natural Susy

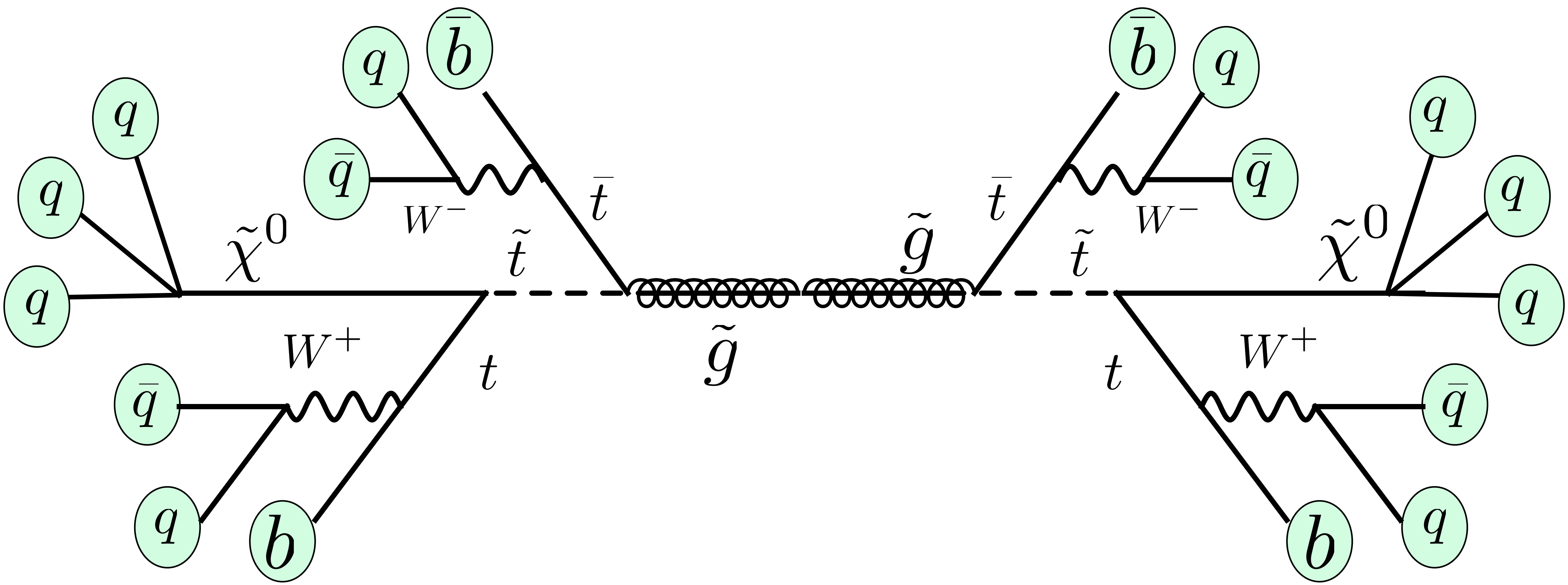
with RPV

Multiplicity explodes



The Less-Classic Natural Susy Signature

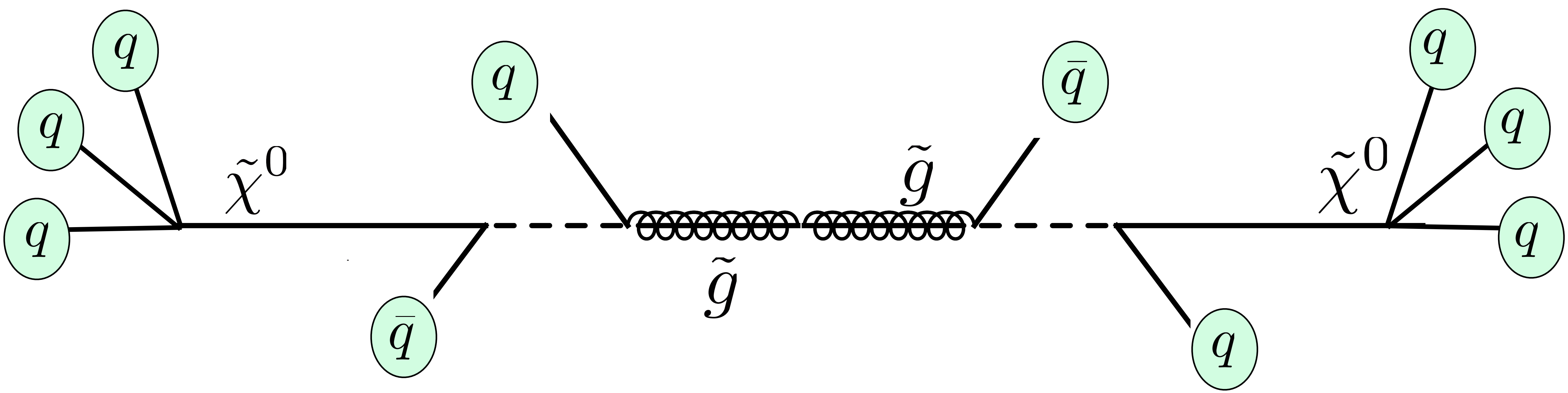
18^{+} Jets



Potentially lots of b-jets

The Less-Classic Natural Susy Signature

10^+ Jets



Potentially lots of b-jets

Punchline:

Many signals of new physics
produce lots of final state quarks

Easy to come up with other signals
with high multiplicity signals

Outline

Perspective

High Multiplicity Signals

- Fat Jet Techniques
  - Jet Mass
  - Subjets

More 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 $R = 0.4$

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 $R = 0.4$

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Can find up to 60

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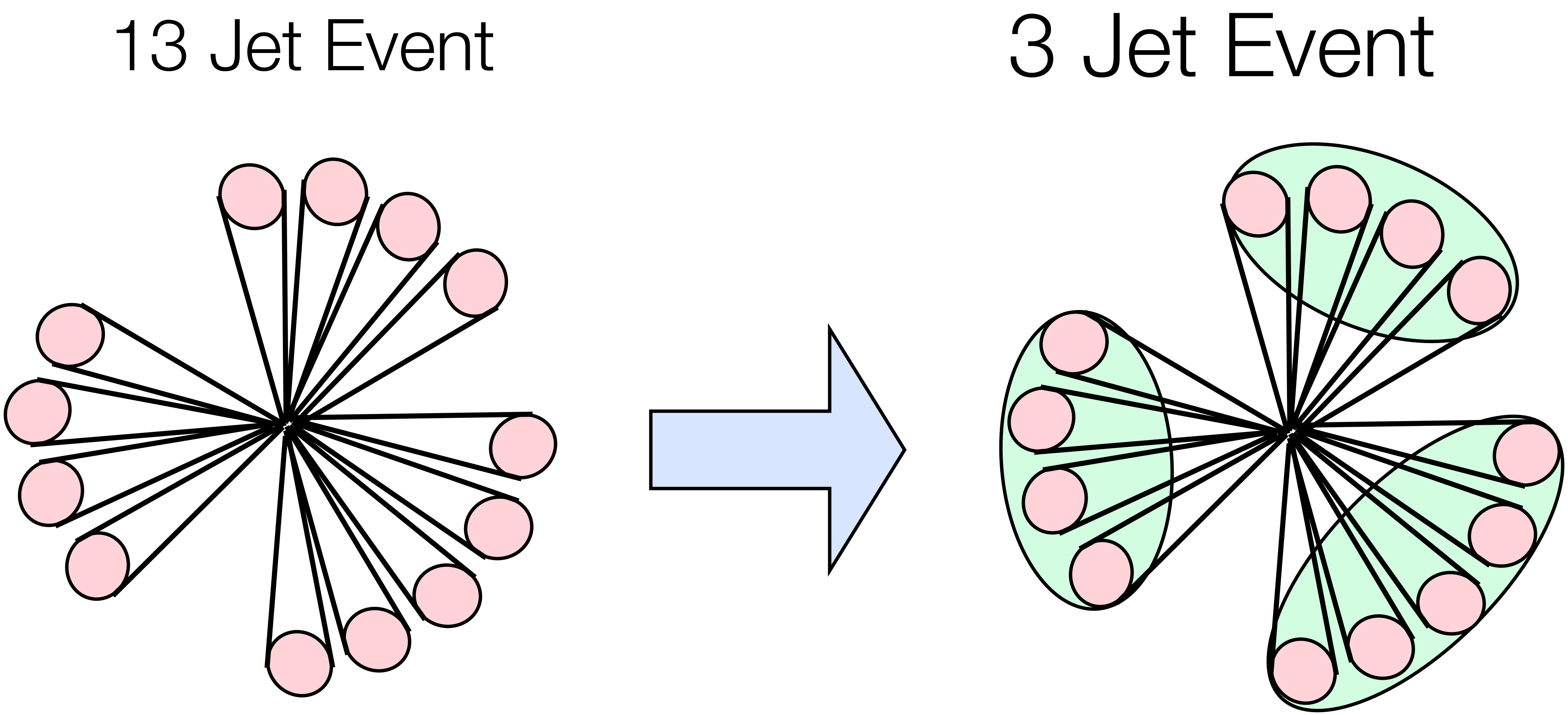
from low multiplicity

Start by going backwards

anti-k_T $R = 1.0$ -1.2

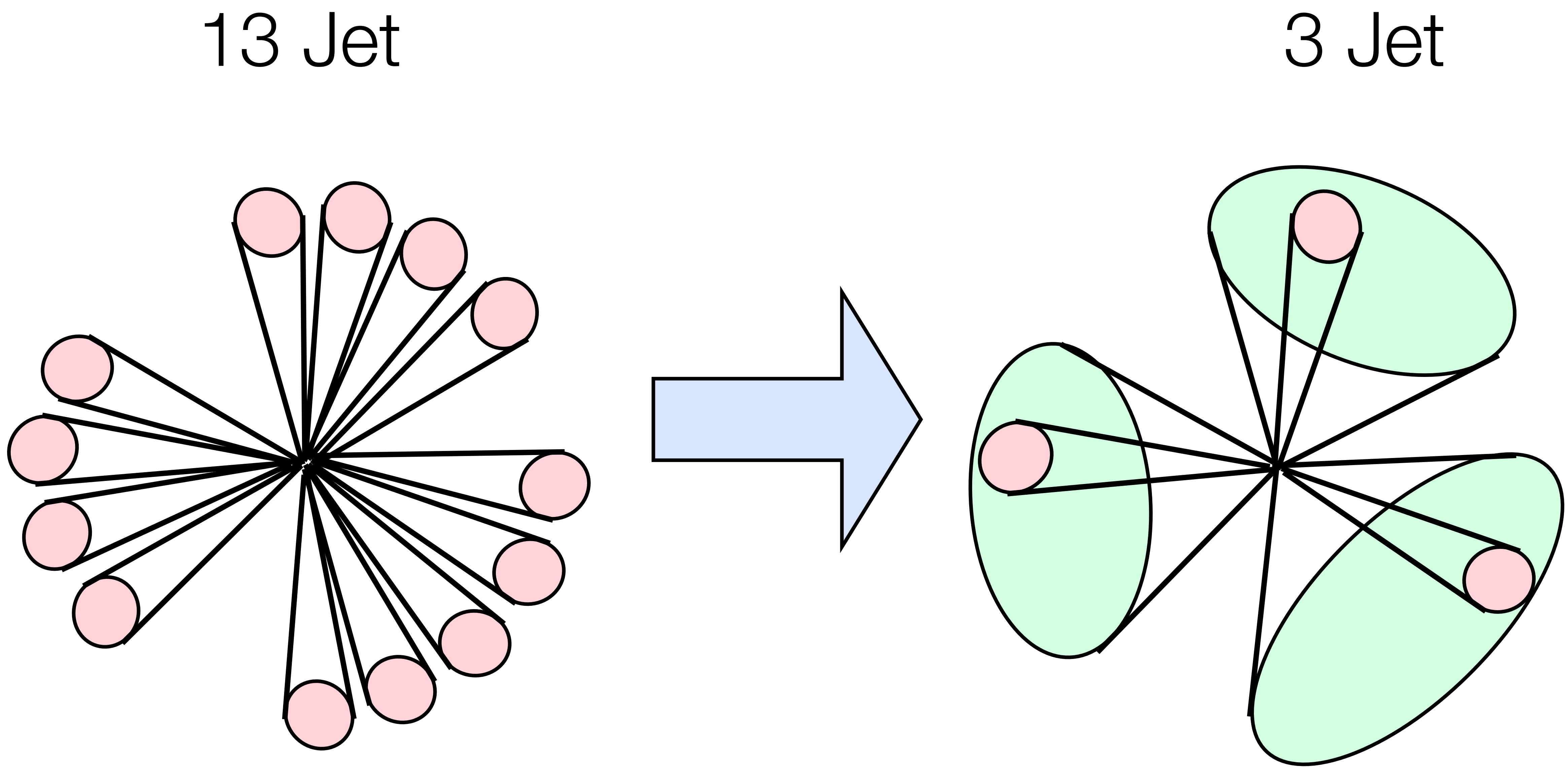
No room for isolated jets
Only 4 to 6 jets possible

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

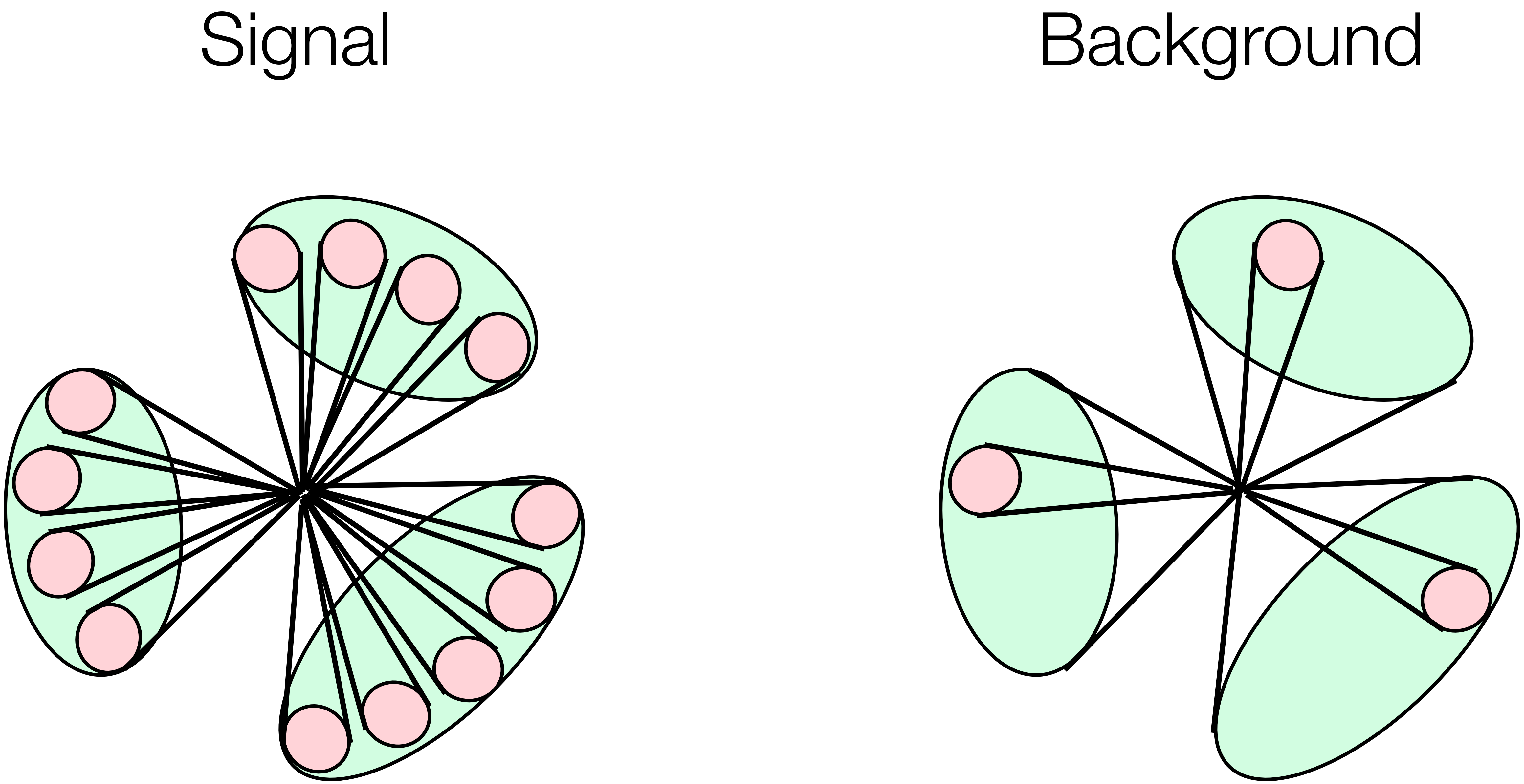


Typical QCD Background

Background rate skyrockets

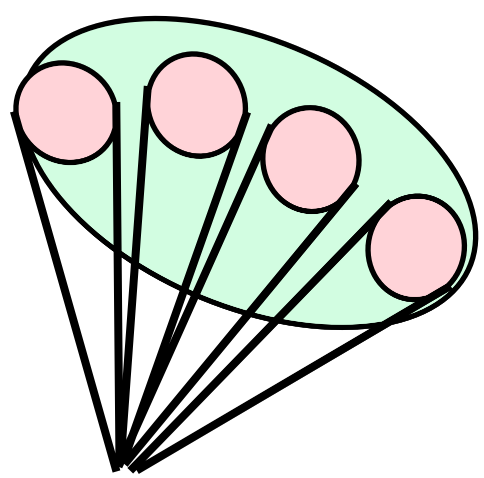


Now need to distinguish



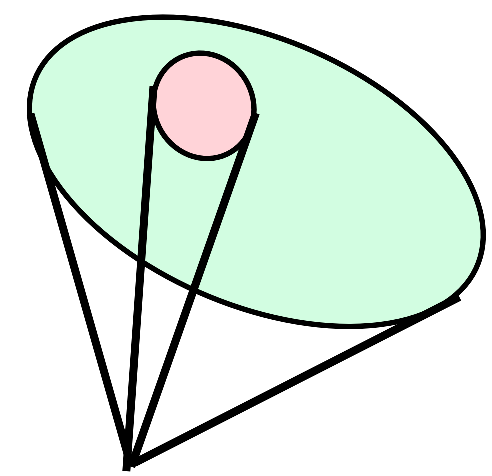
The difference between them is clear

Large Invariant Mass



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

Small Invariant Mass



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

Introduce One 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

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

Signal	Background
$m_j/p_T \sim 1$	$m_j/p_T \lesssim 1$
$H_T \sim M_J$	$H_T \gtrsim M_J$

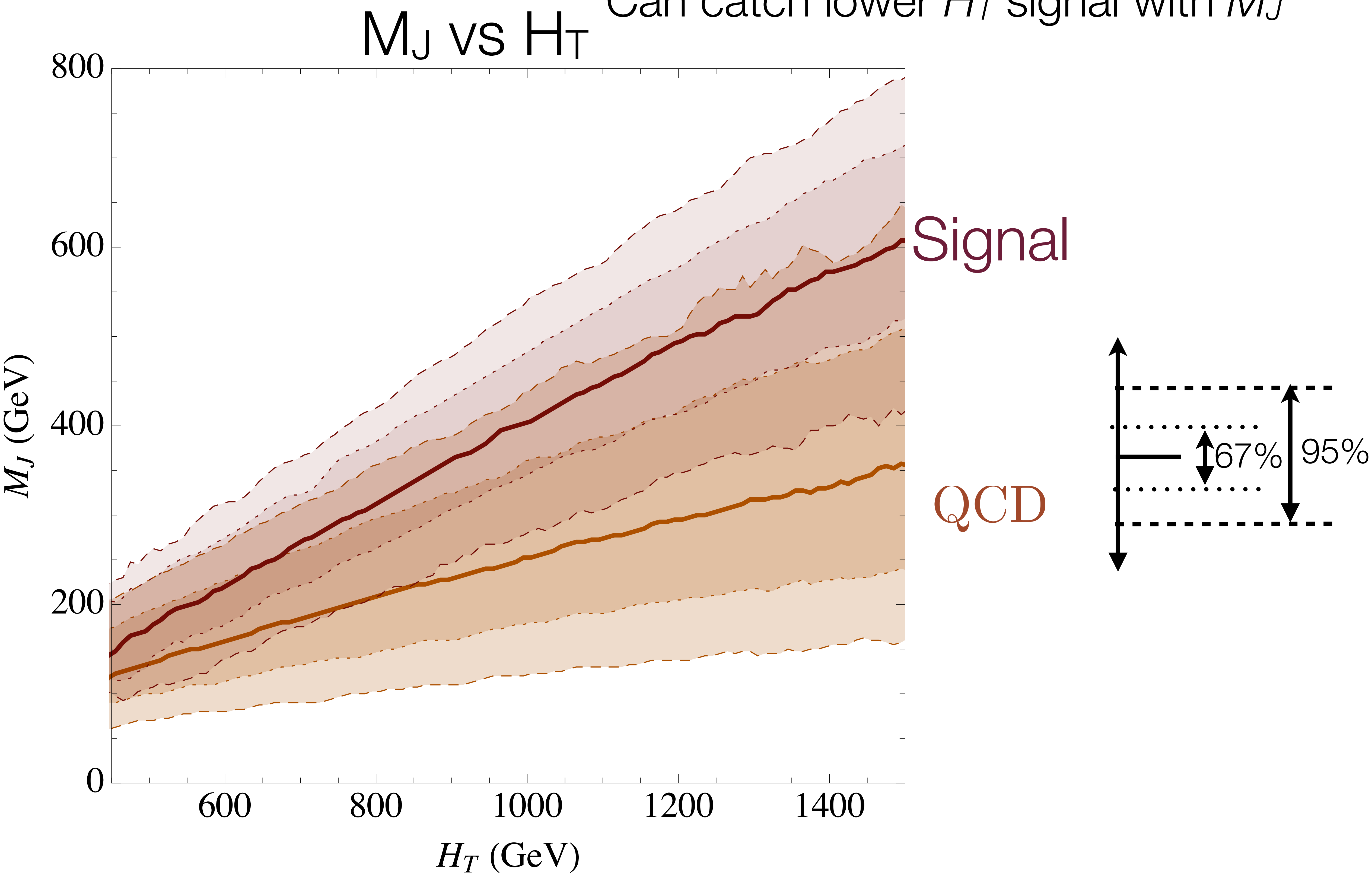
Signal has higher M_J for fixed H_T

Keep less background at same signal efficiency

Never does parametrically worse

Signal vs QCD: Steeper than Top

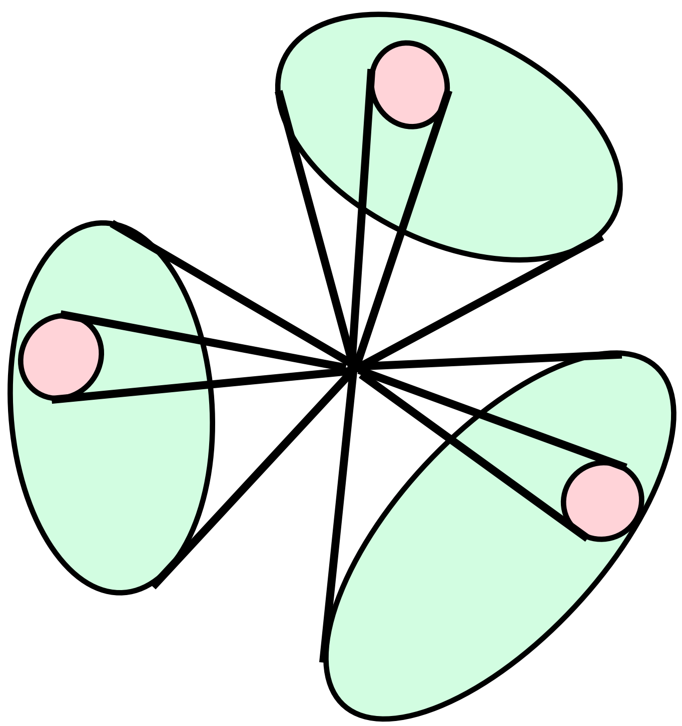
Can catch lower H_T signal with M_J



QCD jets only have small correlations

Data driven background predictions possible

$$x = m_j/p_T$$



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

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)

Natural "Data-Driven" approach to backgrounds

$$P_1(x; p_T)$$

Now use in the multijet sample

Predict event-by-event acceptances

(probability an event passes cut)

$$A(p_{T\,1}, p_{T\,2}, p_{T\,3}) = \int_{M_J > m_{\rm cut}} d^3x \quad P_1(x_1; p_{T\,1}) P_1(x_2; p_{T\,2}) P_1(x_3; p_{T\,3})$$

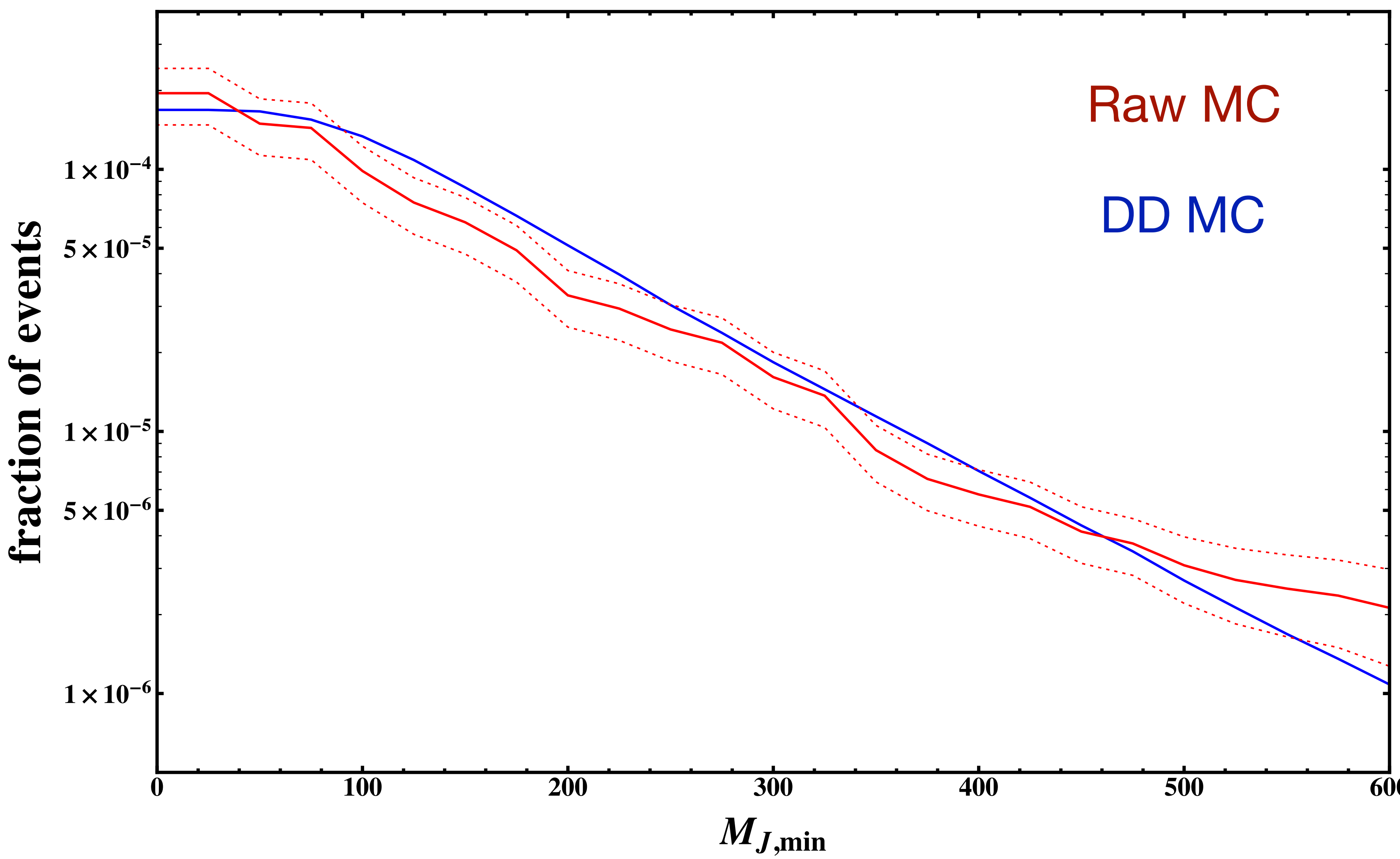
Can make an M_J prediction based upon the events *measured*

Don't need to be able to calculate M_J distribution from first principles

Works well in Monte Carlo

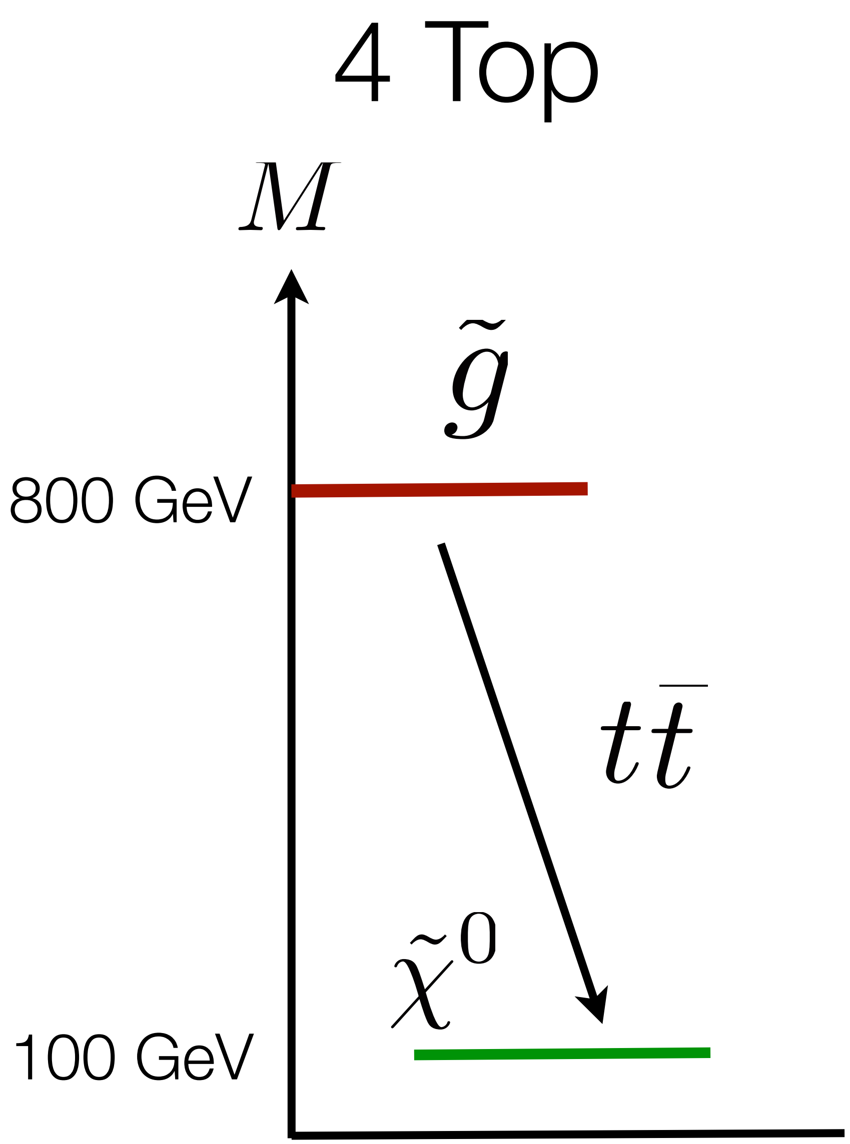
< 20% systematic differences

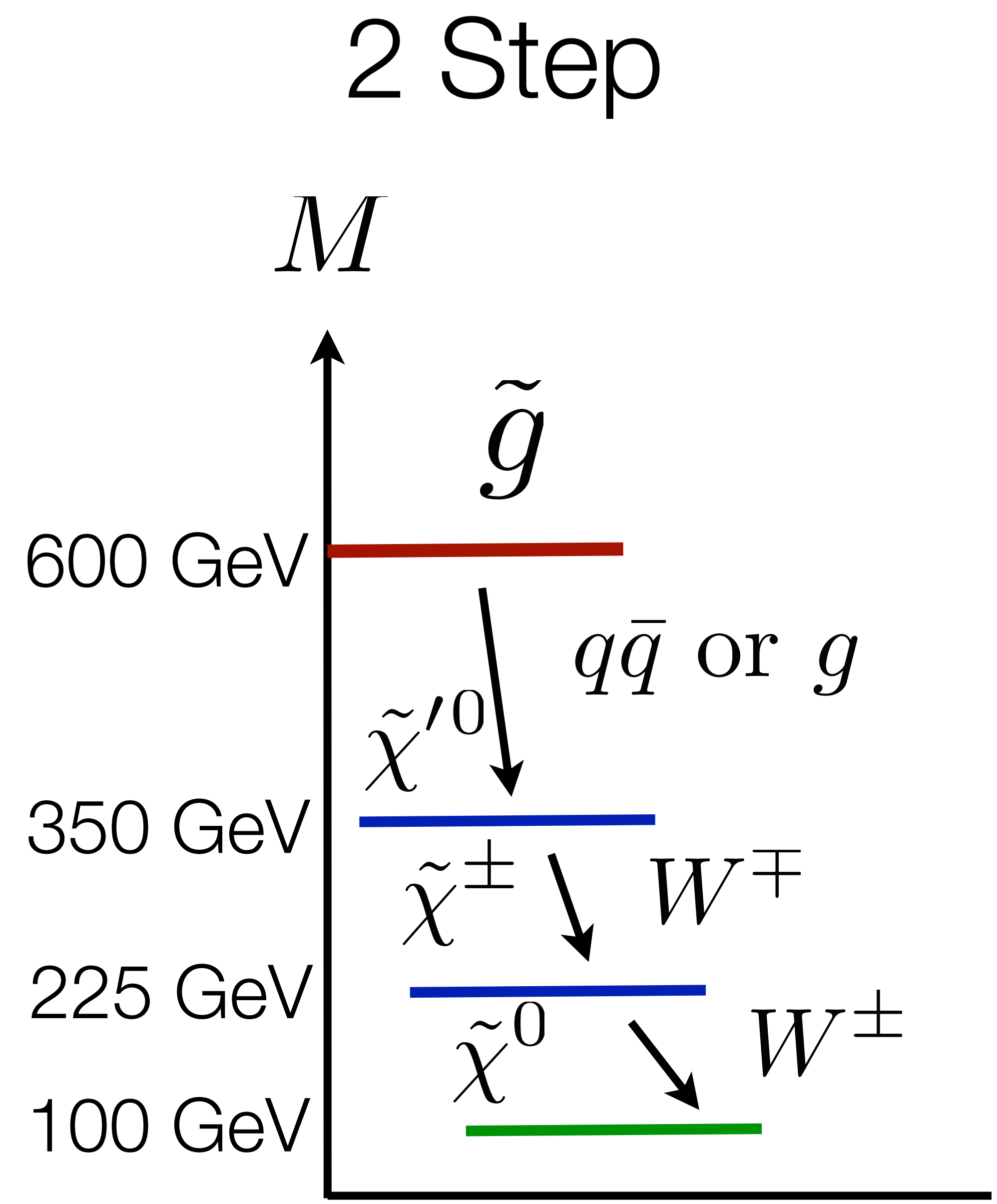
Fraction of QCD events satisfying M_J cut



Two Benchmark Models

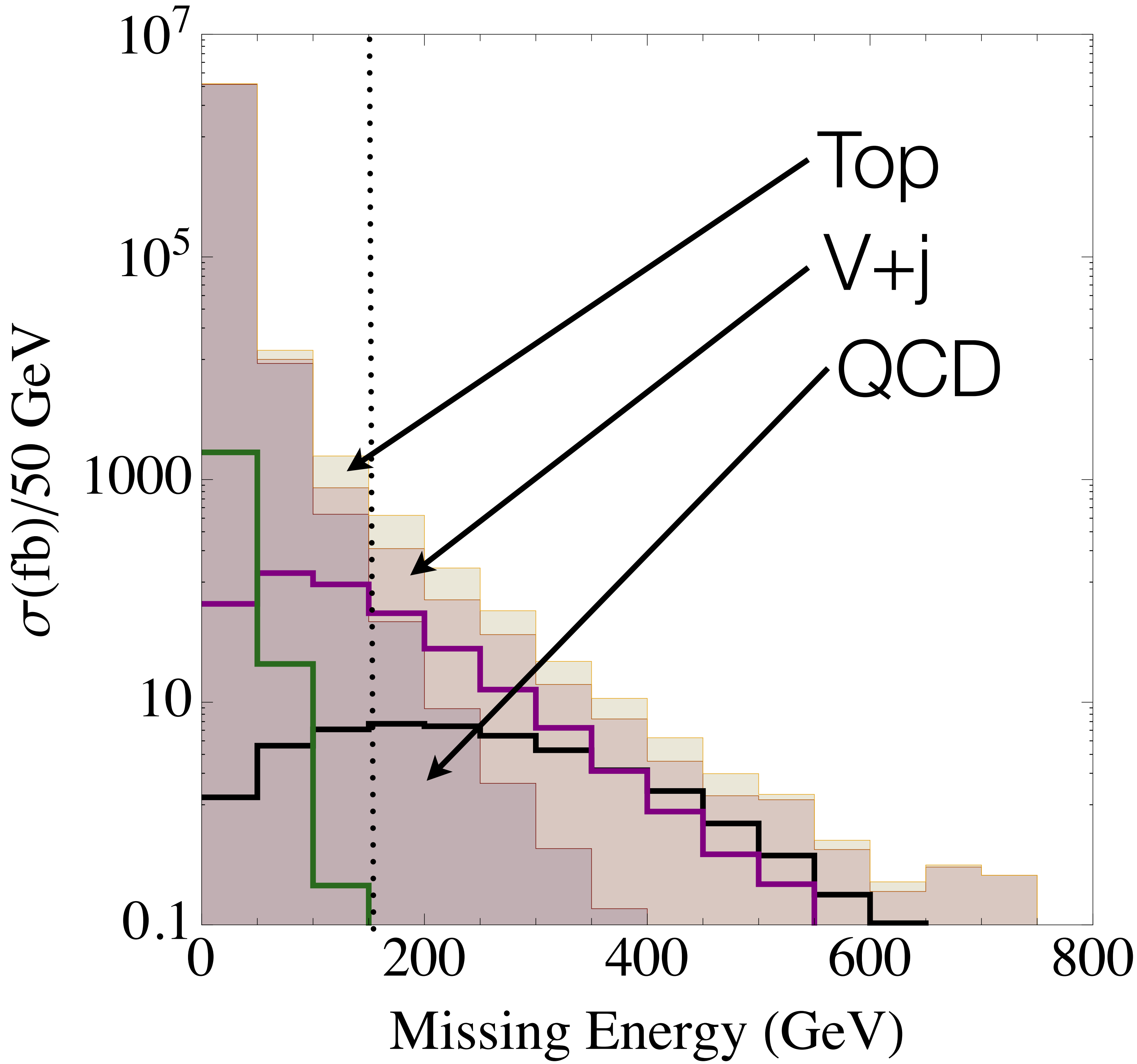
(1fb^{-1} 7 TeV reference)





Missing Energy Distribution

4j $p_T > 150$ GeV



Missing Energy Distribution

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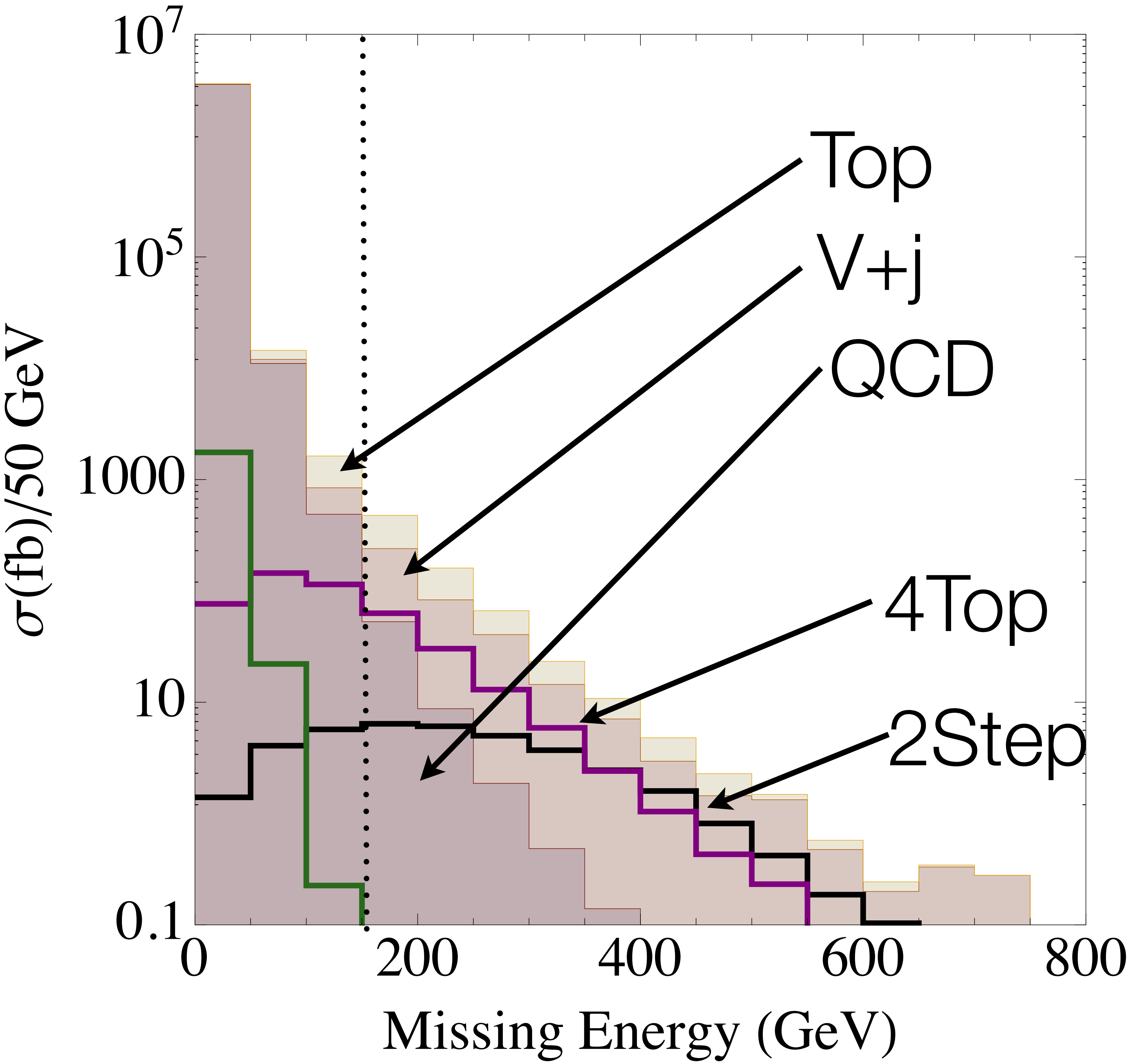
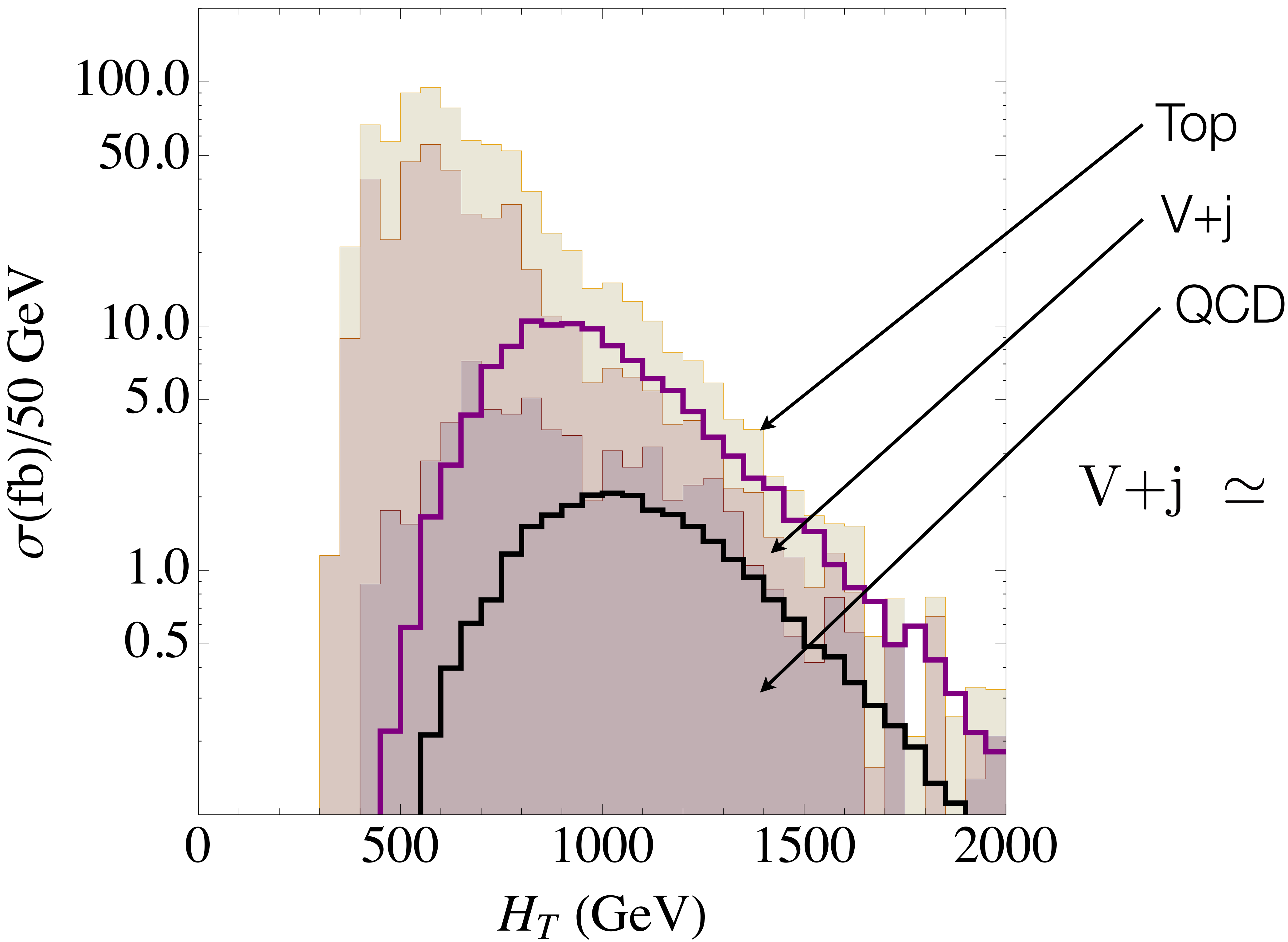


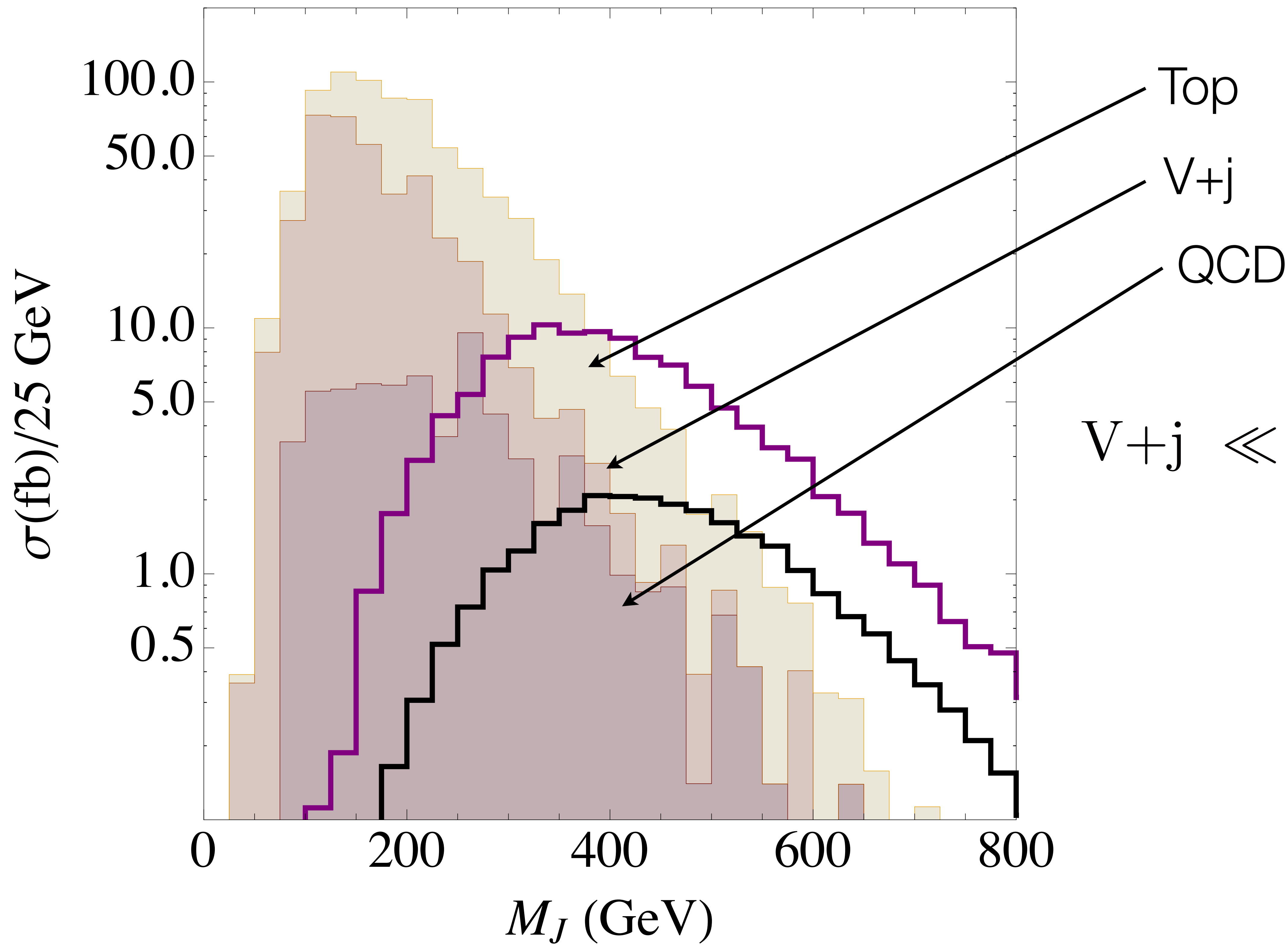
After cut of $\not{E}_T > 150$ GeV

S/B < 1



V+j $\simeq$ Top

Gain at high M_J



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

Final Search

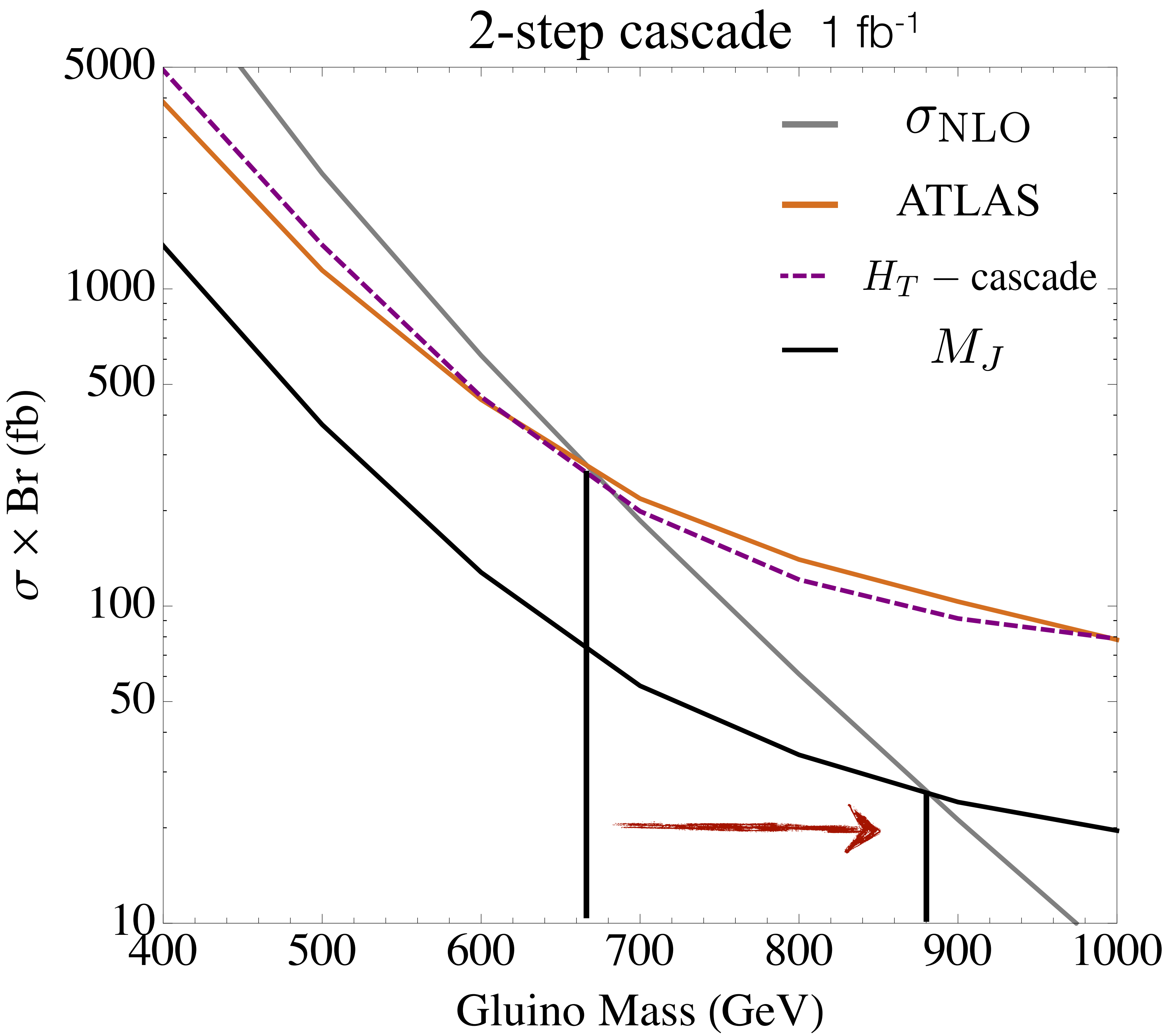
Compare to straw-men

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

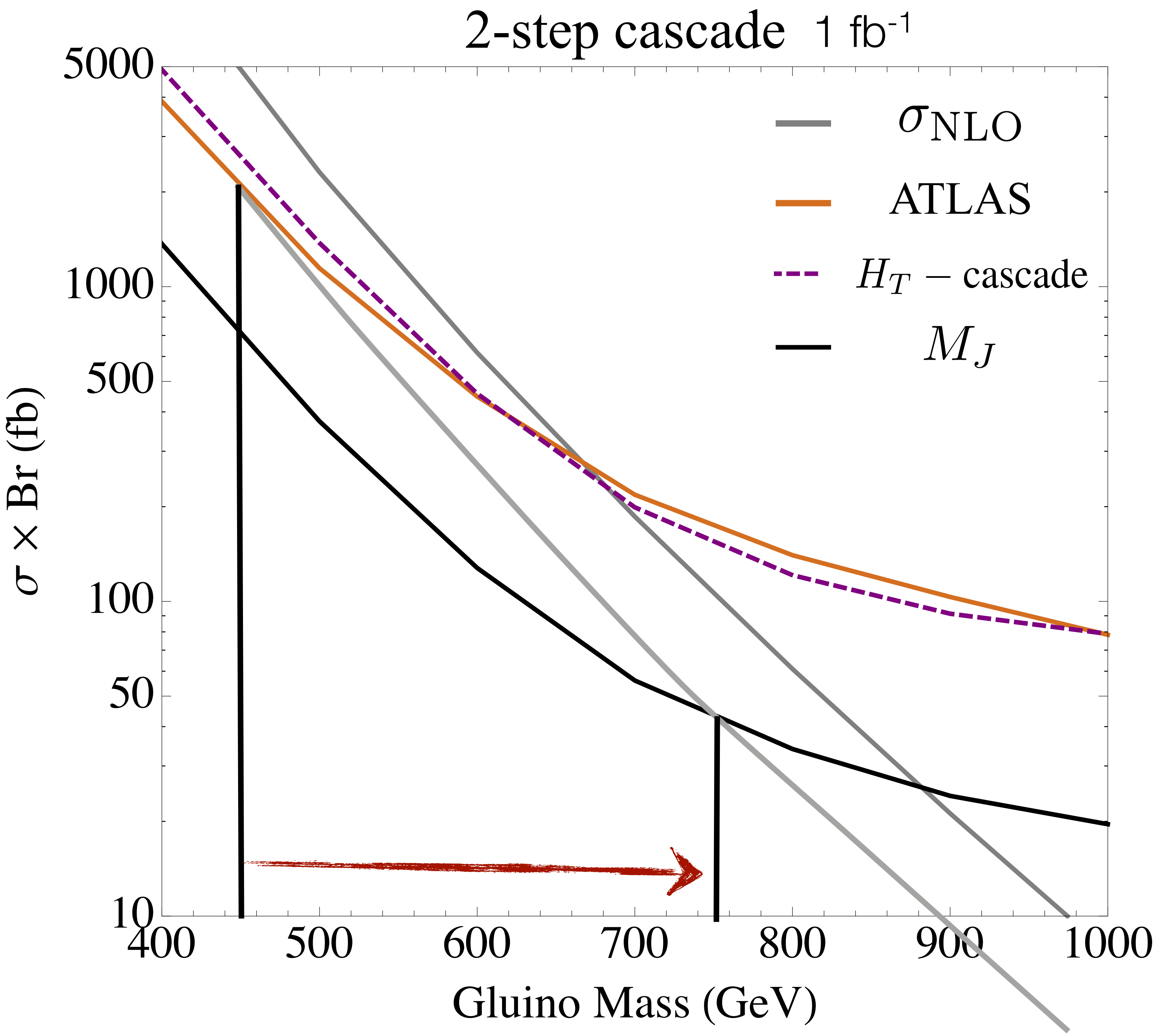
No b-tags, no lepton vetos, low MET

2 Step Expected Sensitivity



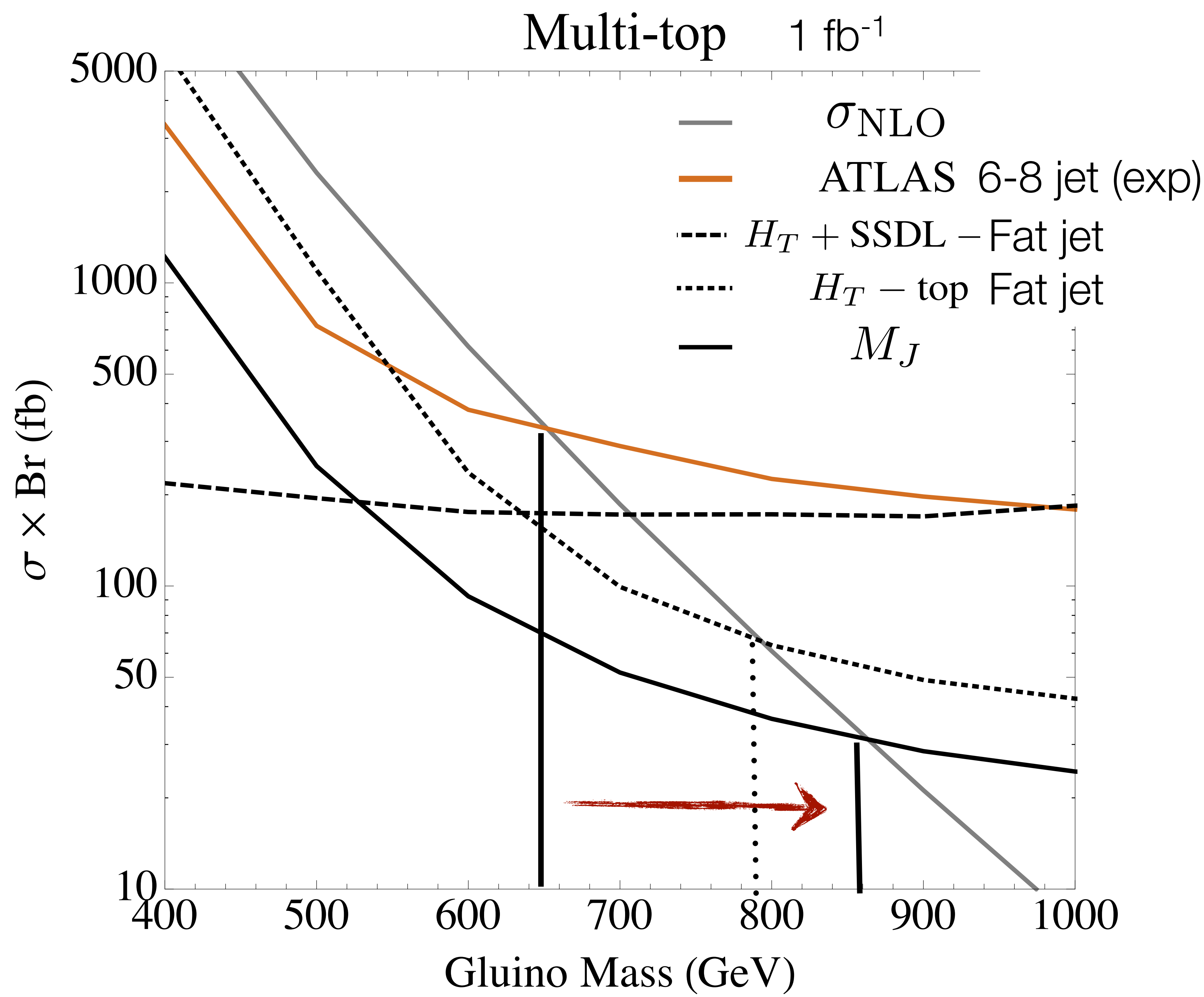
Gain from 660 GeV to 880 GeV

2 Step Expected Sensitivity



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

4 Top Expected Sensitivity



Gain from 650 GeV to 850 GeV

Outline

Perspective

High Multiplicity Signals

Fat Jet Techniques

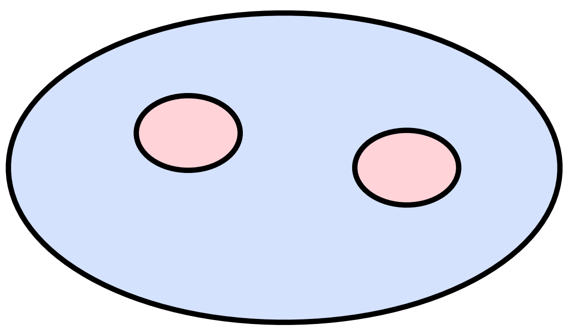
Jet Mass

Subjets

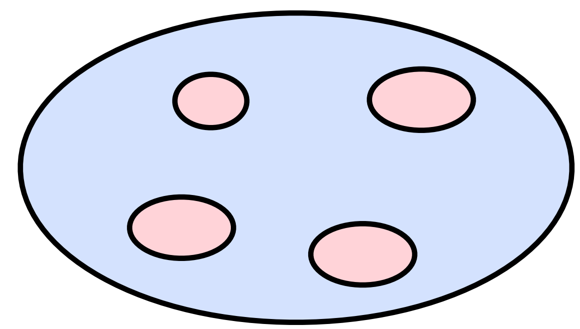
Subjettiness

Jet mass is the coarsest measure of jet substructure

Equal pT and mass jets



versus

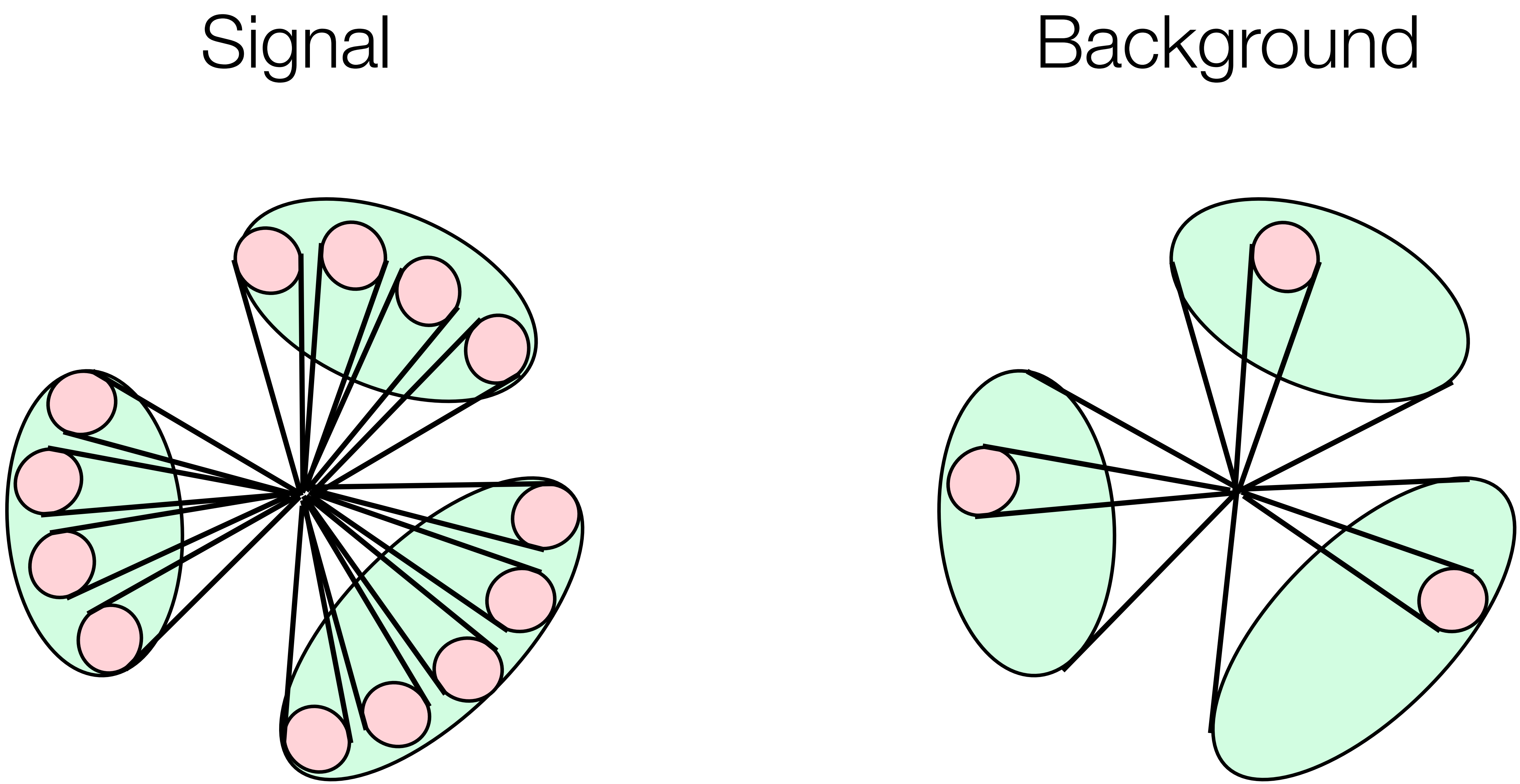


Massive QCD jets mostly have 2 subjets

High multiplicity signals are many more subjets

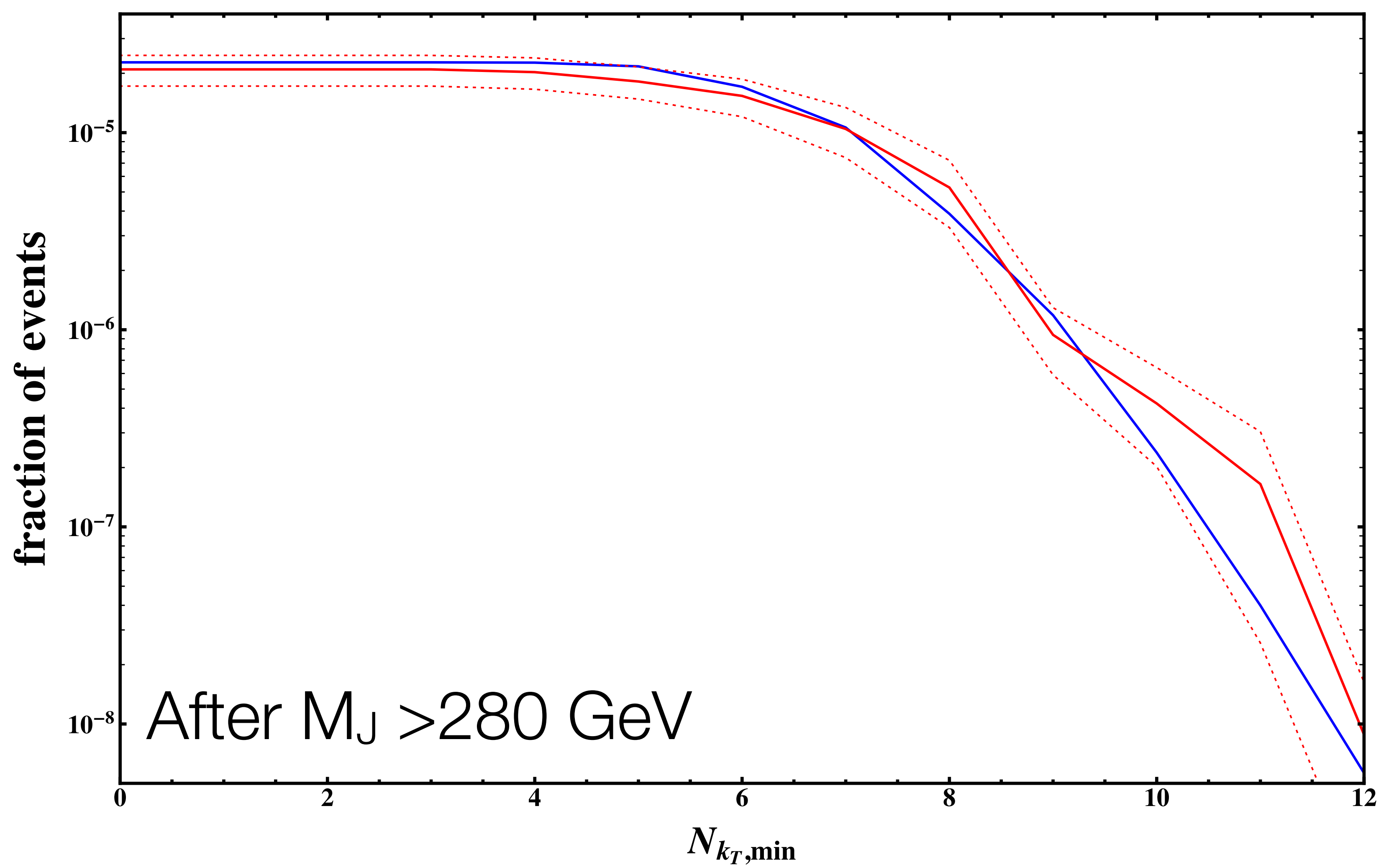
With a way to count subjets

Now can directly distinguish



Can use Data Driven approach to M_J & N_J

QCD Acceptance after NJ cut



Can reduce QCD by 2^+ orders of magnitude

Cutting on the number of subjets in entire event

Can reduce reliance on MET further

Can use in conjunction with M_J

Contains more information about
underlying details of the physics

The Sample Signals

Model	Gluino Decay		EW-ino Decay		LSP Decay		Final State Partons
	$q\bar{q}\chi(+4)$	$t\bar{t}\chi(+12)$	$\chi(+0)$	$VV'\chi(+8)$	$\chi(+0)$	$cbs(+6)$	
$\mathcal{G}_0$	✓		✓		✓		4
$\mathcal{G}_1$		✓	✓		✓		12
$\mathcal{G}_2$	✓			✓	✓		12
$\mathcal{G}_3$		✓		✓	✓		20
$\mathcal{G}_4$	✓		✓			✓	10
$\mathcal{G}_5$		✓	✓			✓	18
$\mathcal{G}_6$	✓			✓		✓	18
$\mathcal{G}_7$		✓		✓		✓	26

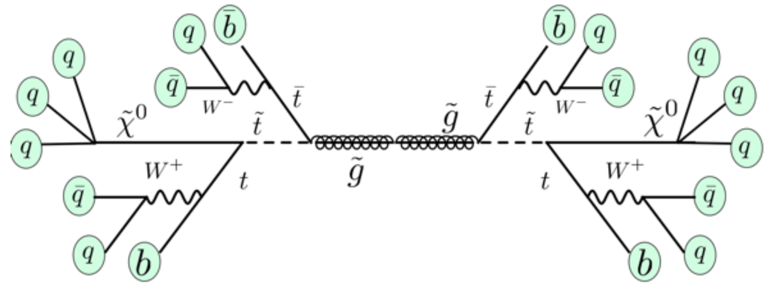
M_J Only

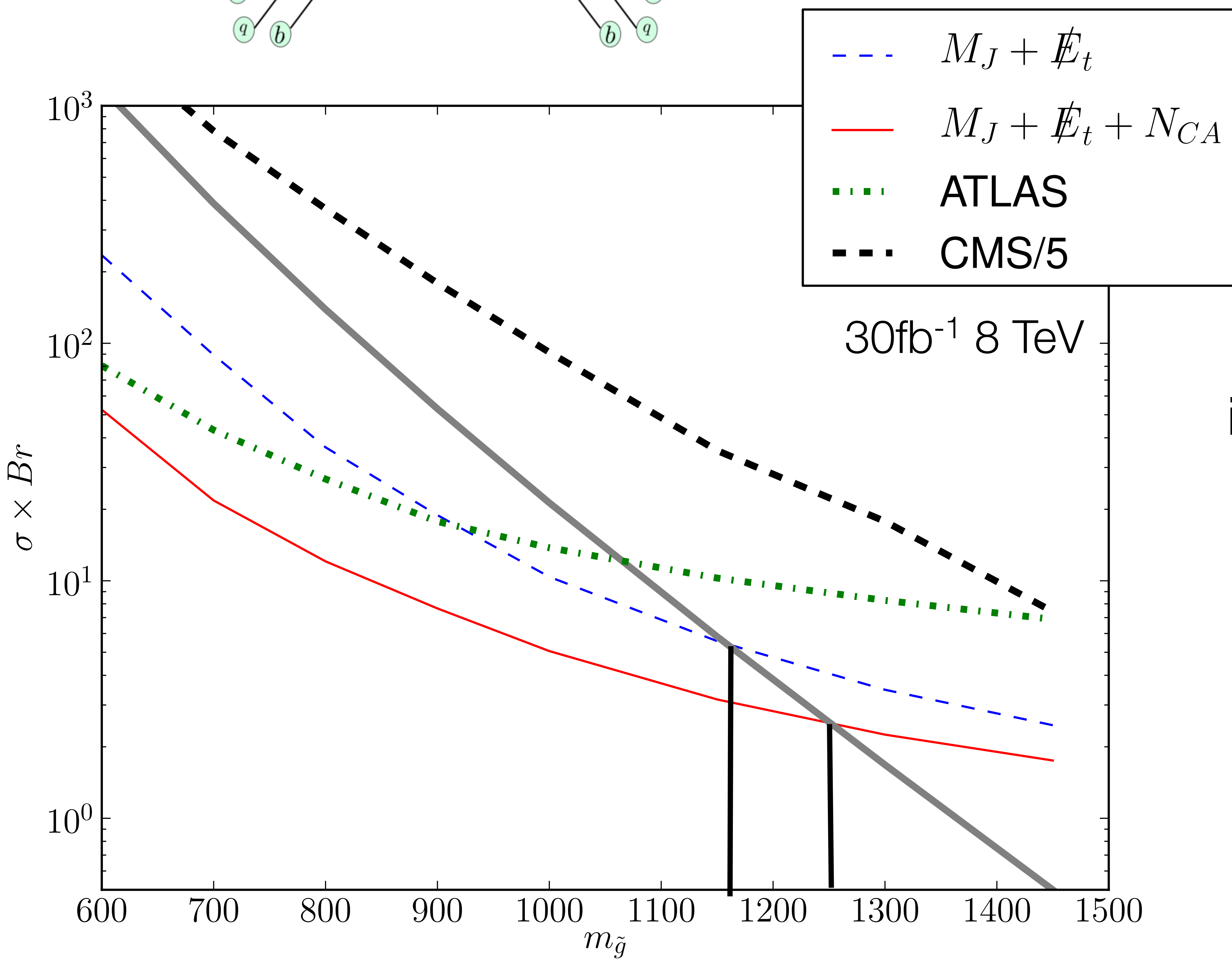
Search Region			Models Covered with $\mathcal{E} < 1.5$		Background (for $30\,\text{fb}^{-1}$)				
Label	M_J	$\not{E}_T$	Class	$m_{\tilde{g}}$	QCD	Top	V+jets	Other	Total
1	1000	0	$\mathcal{G}_4$	$m_{\tilde{g}} \lesssim 1.0\,\text{TeV}$	495.9±61.50	2.38±0.69	6.93±2.73	0.13±0.095	505.33±61.56
2	1350	0	$\mathcal{G}_4$	$m_{\tilde{g}} \gtrsim 1.0\,\text{TeV}$	13.74±1.5	0.0	0.54±0.54	0±0	14.29±1.57
3	400	400	$\mathcal{G}_0$ $\mathcal{G}_1$	$m_{\tilde{g}} \lesssim 1.2\,\text{TeV}$ $750\,\text{GeV} \gtrsim m_{\tilde{g}} \gtrsim 1.1\,\text{TeV}$	0.38±0.04	16.63±1.81	14.30±2.62	4.40±1.52	35.71±3.53
4	500	200	$\mathcal{G}_1$ $\mathcal{G}_{2,3}$	$m_{\tilde{g}} \lesssim 750\,\text{GeV}$ $m_{\tilde{g}} \lesssim 850\,\text{GeV}$	23.94±4.86	54.64±3.29	27.96±5.56	6.26±1.52	112.81±8.22
5	625	425	$\mathcal{G}_0$ $\mathcal{G}_1$ $\mathcal{G}_{2,3}$	$m_{\tilde{g}} \gtrsim 1.2\,\text{TeV}$ $m_{\tilde{g}} \gtrsim 1.1\,\text{TeV}$ $m_{\tilde{g}} \gtrsim 1.3\,\text{TeV}$	0.09±0.02	0.59±0.34	0.73±0.73	0.47±0.29	1.89±0.86
6	725	175	$\mathcal{G}_{2,3}$ $\mathcal{G}_{5,6,7}$	$850\,\text{GeV} \lesssim m_{\tilde{g}} \lesssim 1.3\,\text{TeV}$ all	5.28±0.72	5.34±1.03	2.85±1.08	0.41±0.18	13.87±1.67

N_J and M_J

Search Region				Models Covered with $\mathcal{E} < 1.5$		Background (for $30\,\text{fb}^{-1}$)				
Label	M_J	$\not{E}_T$	$N_{\text{CA,min}}$	Class	$m_{\tilde{g}}$	QCD	Top	V+jets	Other	Total
1	450	450	0	$\mathcal{G}_0$	all	0.18±0.26	8.31±1.28	2.05±1.08	0.64±0.26	11.18±1.70
2	1050	0	13	$\mathcal{G}_4$	all	21.60±3.03	0.0	0.0	0.034±0.014	21.63±3.03
3	475	275	11	$\mathcal{G}_1$ $\mathcal{G}_2$ $\mathcal{G}_3$	all $m_{\tilde{g}} \gtrsim 750\,\text{GeV}$ $m_{\tilde{g}} \gtrsim 850\,\text{GeV}$	0.96±0.46	4.16±0.91	0.78±0.59	0.031±0.009	5.90±1.18
4	525	125	12	$\mathcal{G}_2$ $\mathcal{G}_3$ $\mathcal{G}_{5,6}$	$m_{\tilde{g}} \lesssim 750\,\text{GeV}$ $m_{\tilde{g}} \lesssim 850\,\text{GeV}$ $m_{\tilde{g}} \gtrsim 900\,\text{GeV}$	$7.86^{\pm 1.92}$	7.72±1.24	6.71±4.58	0.33±0.19	22.65±5.11
5	425	125	14	$\mathcal{G}_{5,6}$ $\mathcal{G}_7$	$m_{\tilde{g}} \lesssim 900\,\text{GeV}$ all	1.08±0.32	1.19±0.49	0.0	0.014±0.006	2.26±0.58

Improvements of N_J vs M_J only Search

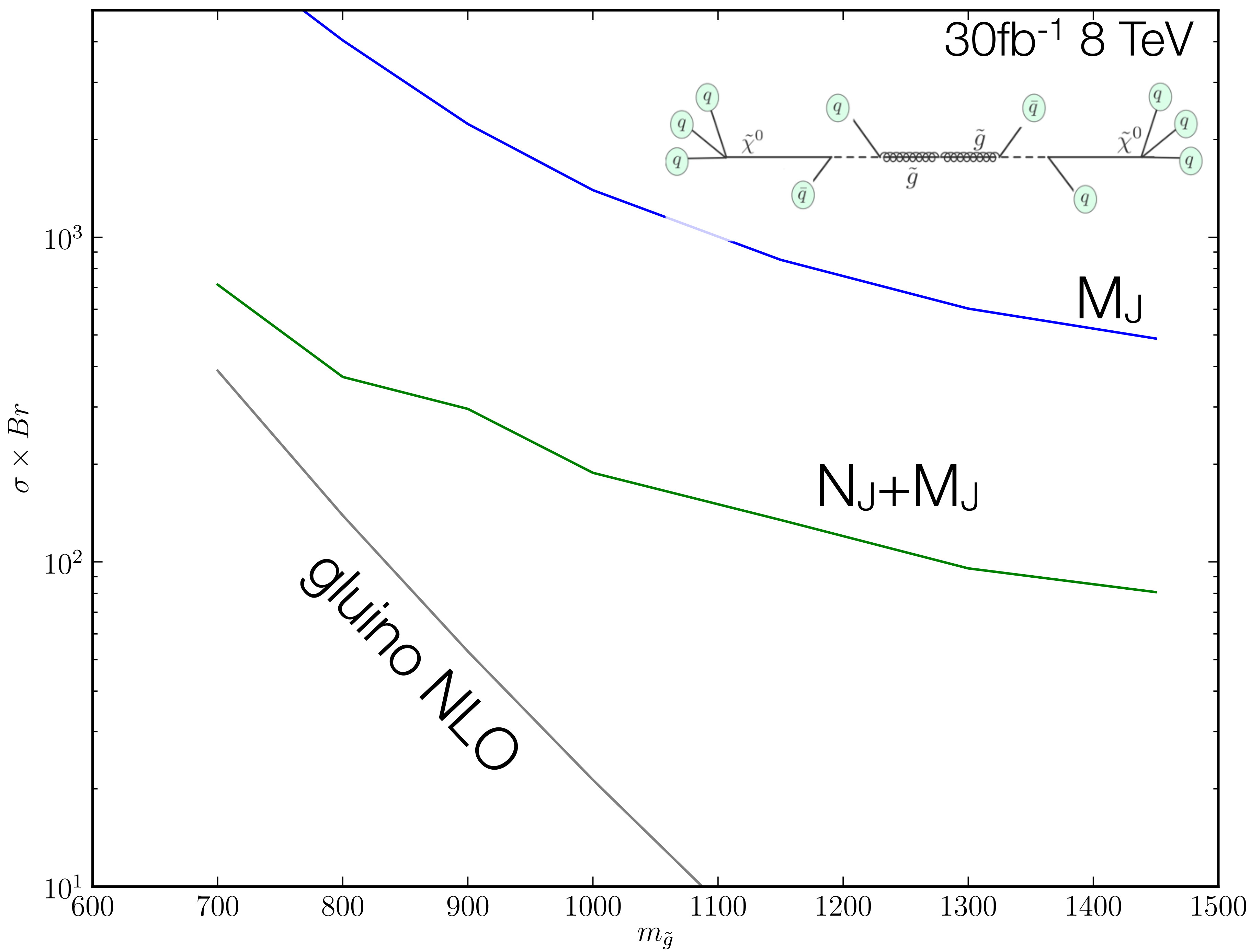




Factor of 2 improvement in cross section, factor of 4 less luminosity

Improvements of N_J vs M_J only Search

(No MET)



Factor of 5 improvement in cross section, requiring 25x less luminosity

b-tagging could help

Haven't Combined With Other Requirements

Can use leptons & b-tags to further reduce reliance on MET

Reduce reliance on dilepton requirements

Conclusion

Existing Heavy Flavor Searches are in good shape

RPC Natural Susy almost closed

Composite Higgs top partner searches need a bit more attention

Need low background MET-less searches

M_J can be a powerful new tool

Counting the number of subjets is better than requiring explicit jets

Many new ideas to try