The LHC: What to Expect When Expecting

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My List - Signposts

- Electroweak symmetry breaking and electroweak precision data
- Naturalness
- Dark Matter
- (Unification)
- ‘Who Ordered That?’

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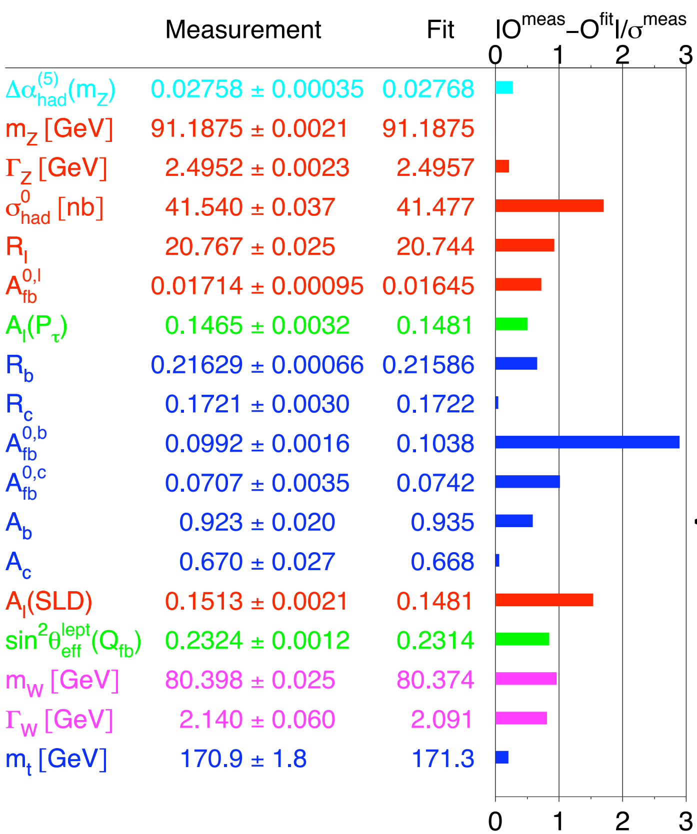
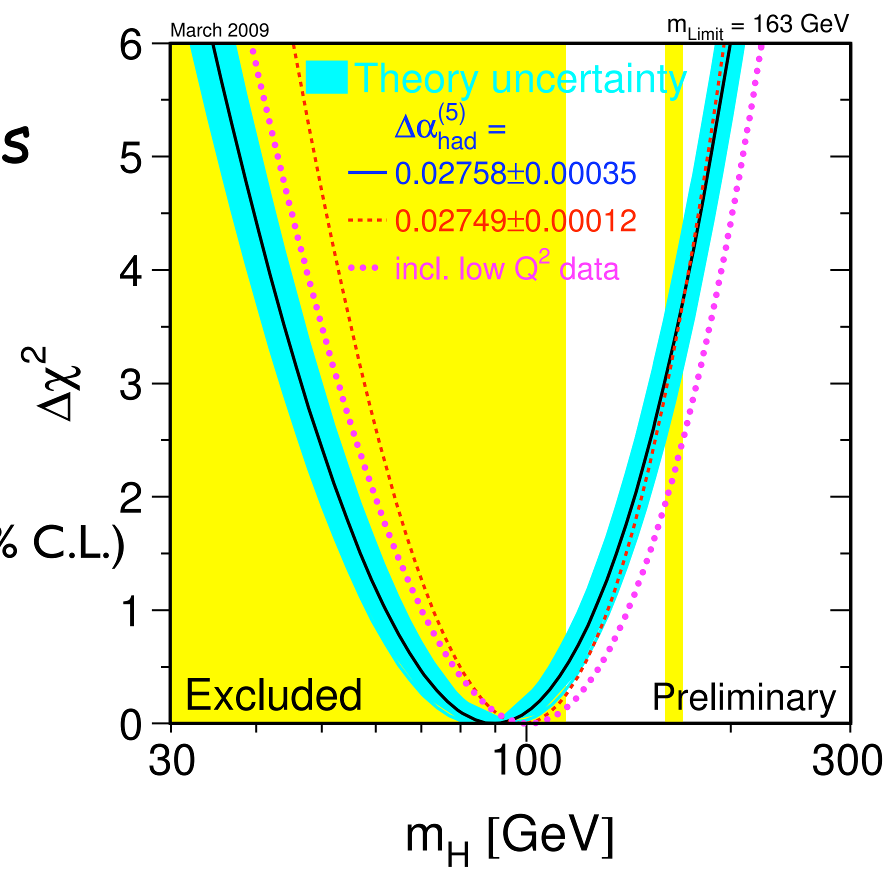
- Electroweak symmetry breaking and electroweak precision data



Higgs Mass fit

90^{+36}_{-27} GeV

< 163 GeV (95% C.L.)



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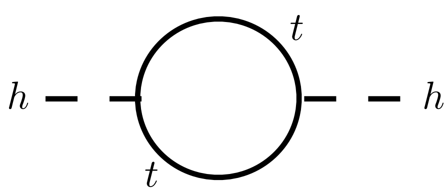
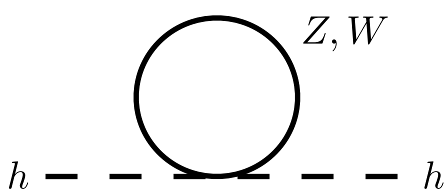
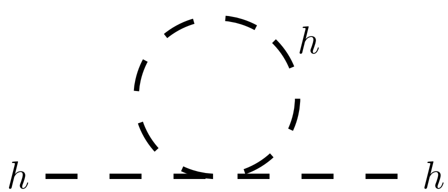


$$\delta m_h^2 \sim -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$



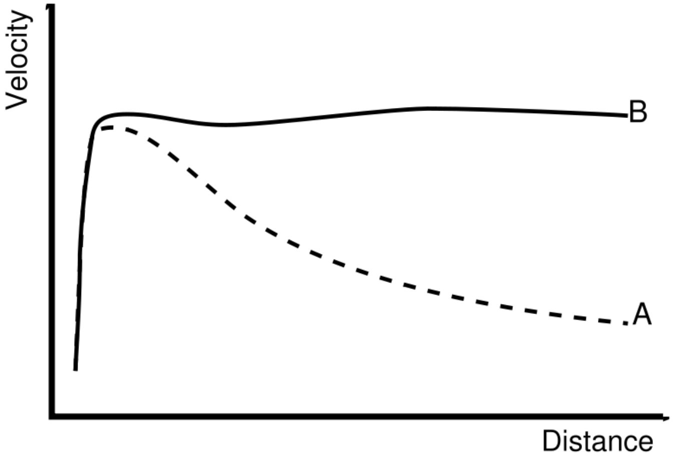
$$\delta m_h^2 \sim \frac{9}{64\pi^2}g^2\Lambda^2$$

most sensitive to the top sector



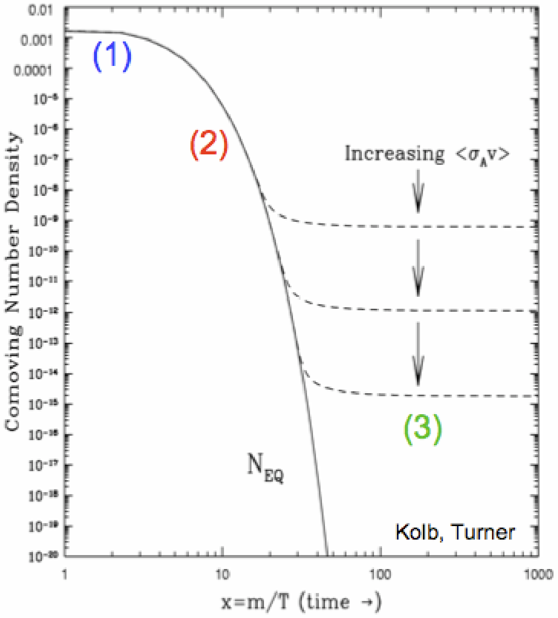
$$\delta m_h^2 \sim \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

My List - Signposts



- Dark Matter

Weak scale (weak coupling) freeze out



My List - Signposts

- (Unification)

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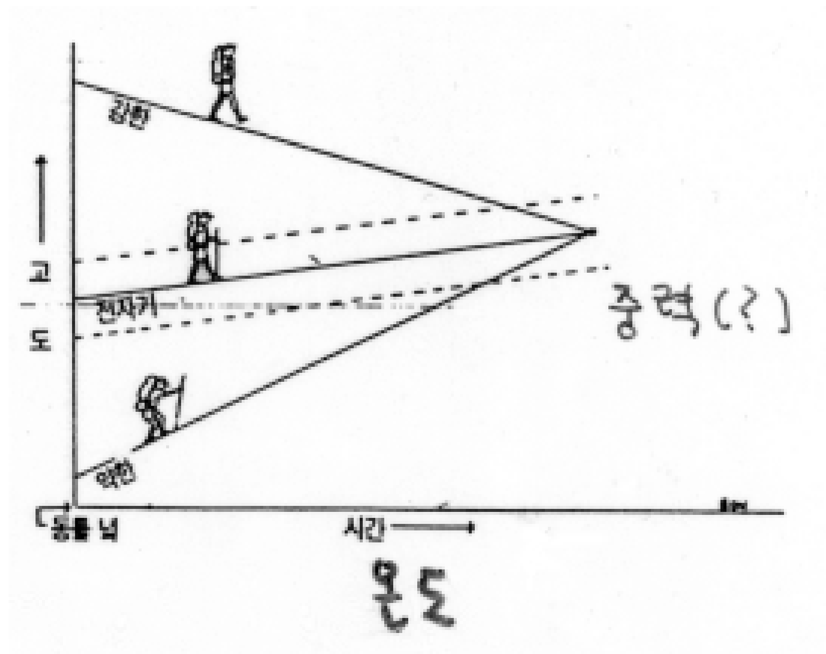

- (Unification)

My List - Signposts

- Naturalness

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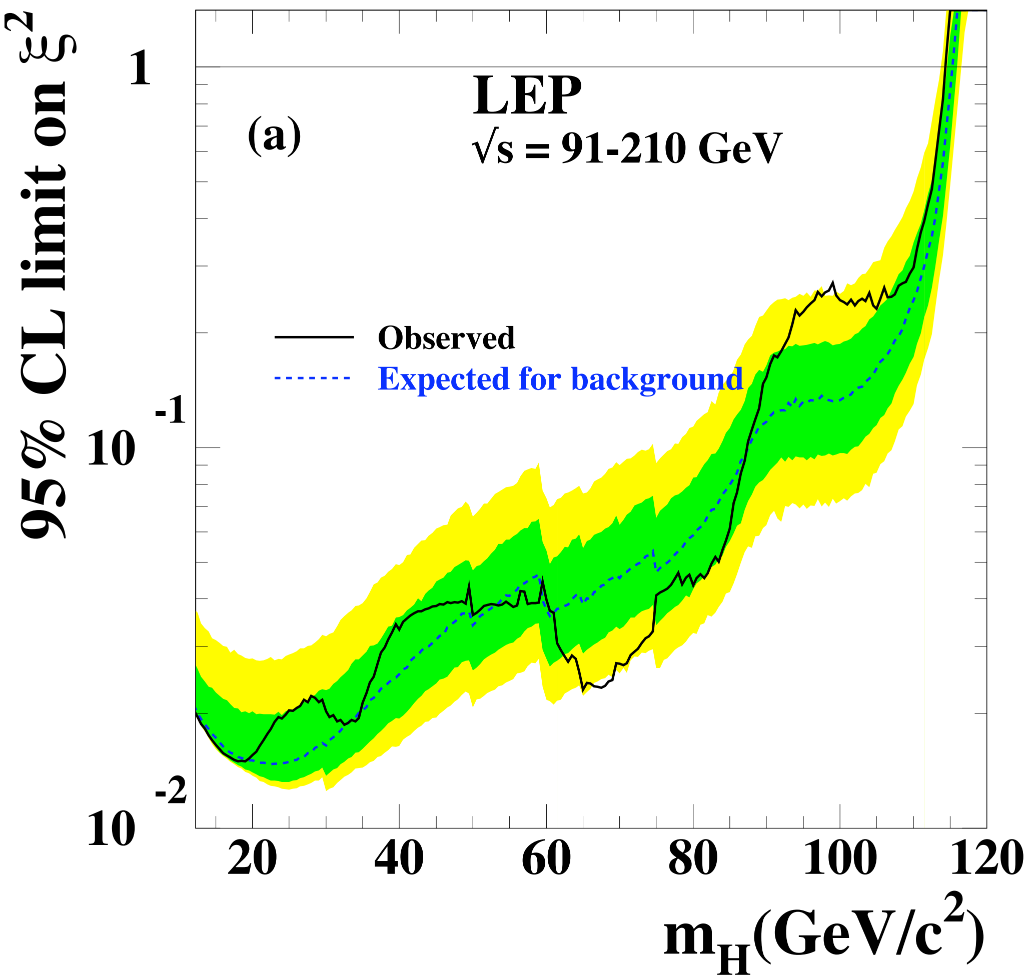
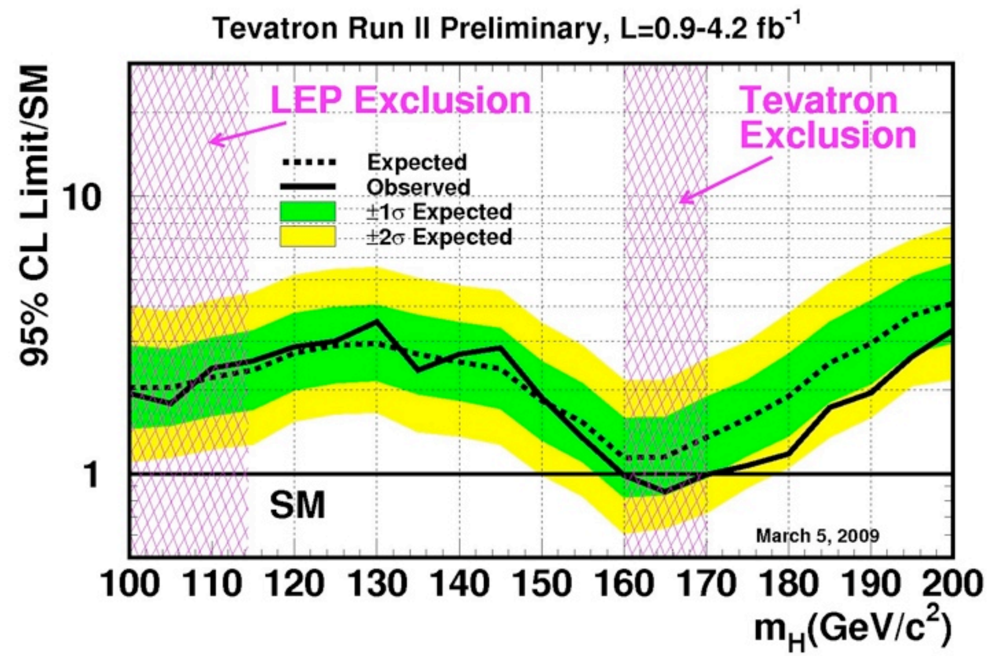
My List - Phenomena

- Higgs, broadly (ewsb)
- New top-quark physics/partners (naturalness)
- Missing E_T (ewp/dm)
- Long-lived particles -- disp. vertices, CHAMPS, out-of-time decays (ew/dm models)
- New Electroweak Bosons (naturalness)
- Weird stuff -- Lepton jets (dm), quirky strings, hidden valleys, unphysics, dragons, ...

Higgs - Collider Bounds



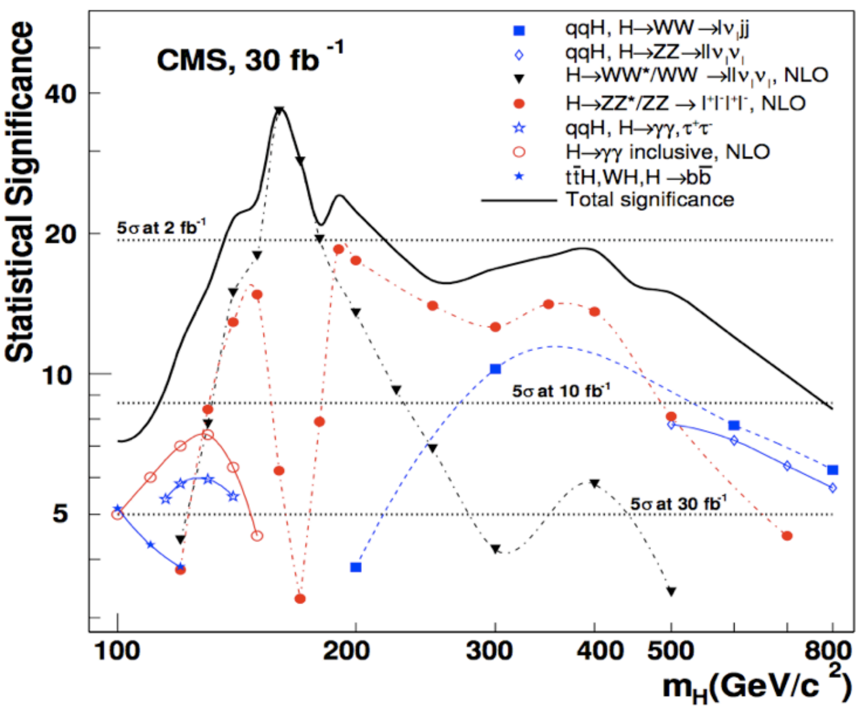


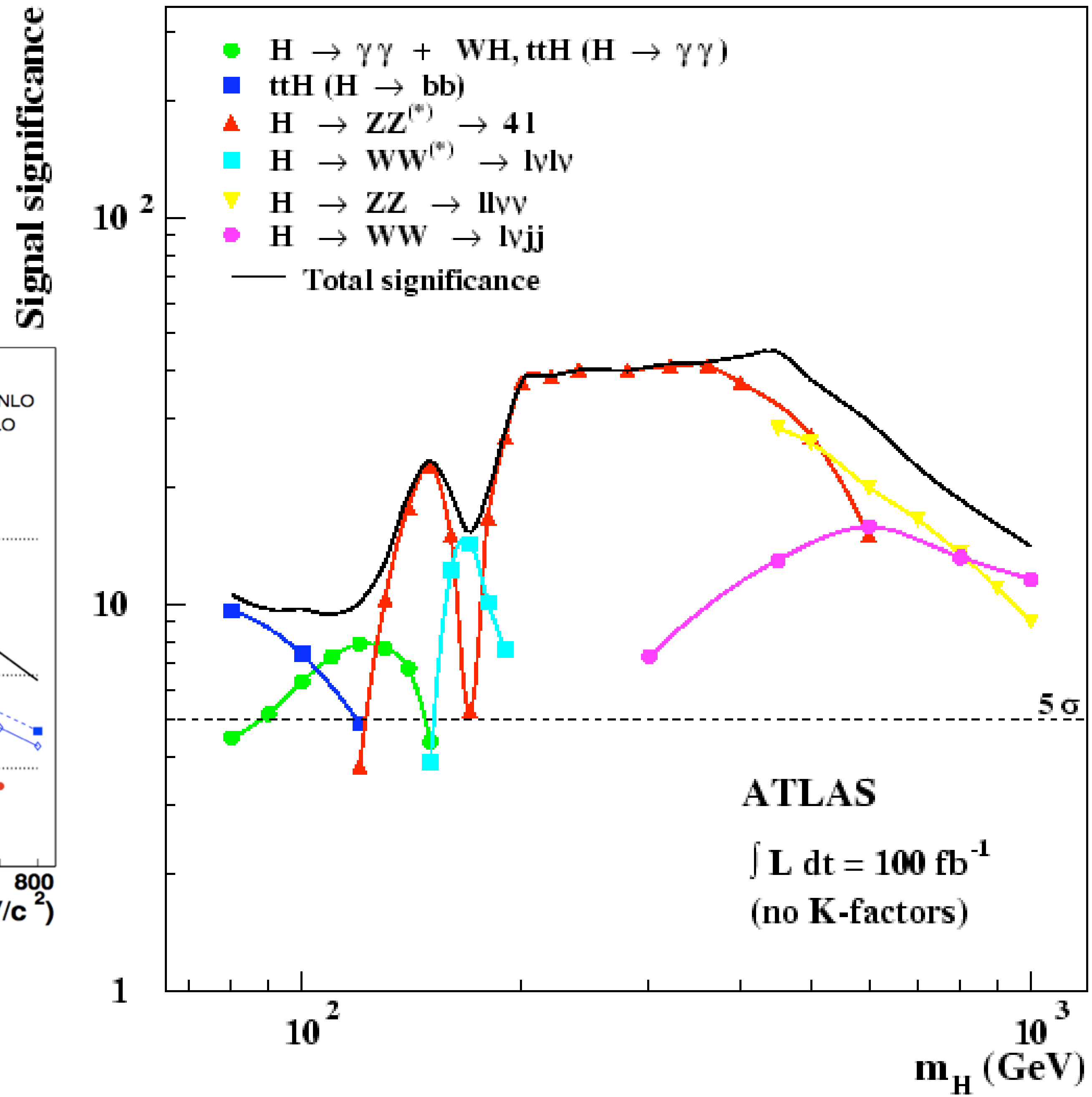
$114.4 < m_h < 160$ GeV

or $m_h > 170$ GeV

Higgs searches

Not an 'early-data' discovery



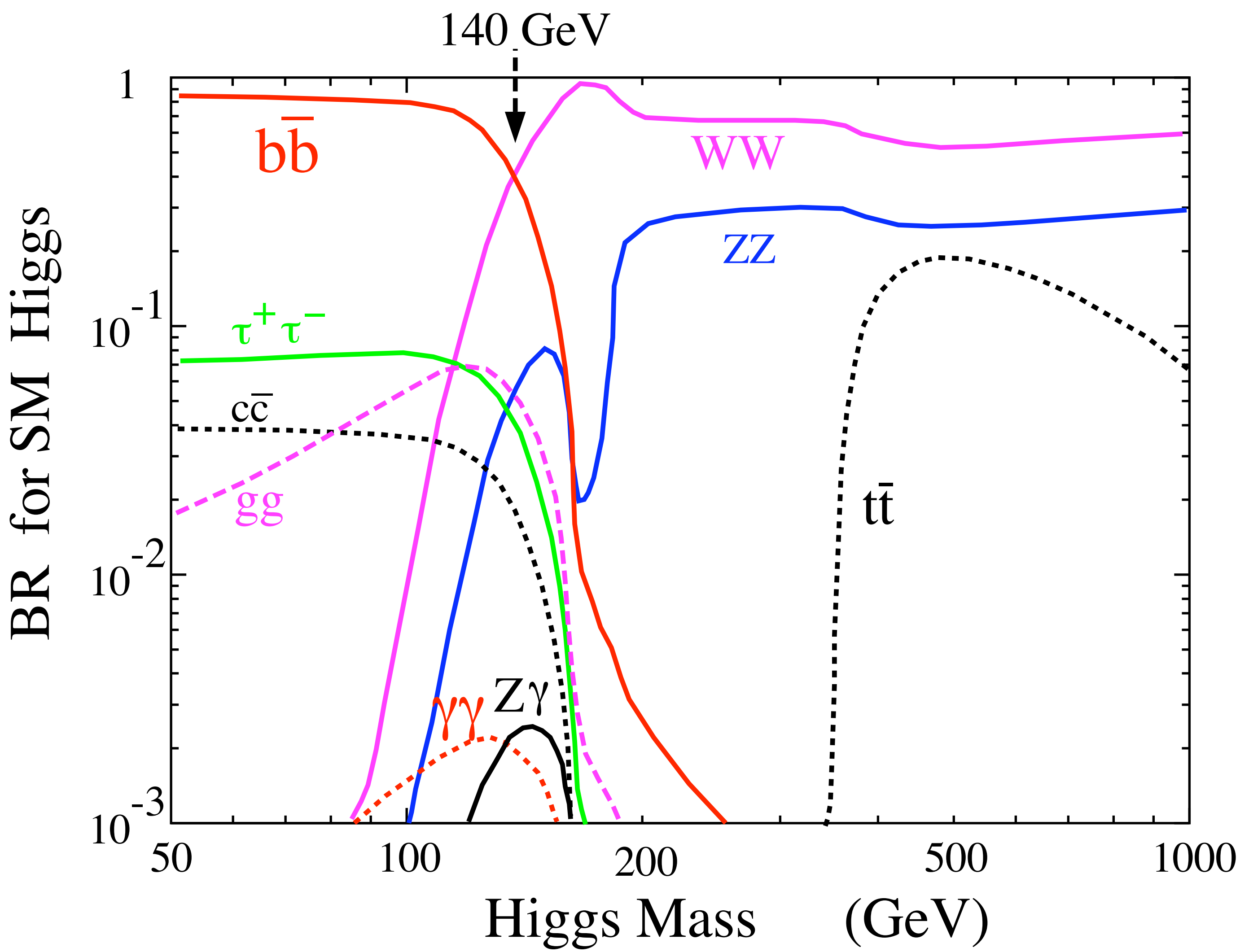


Non-standard Higgs

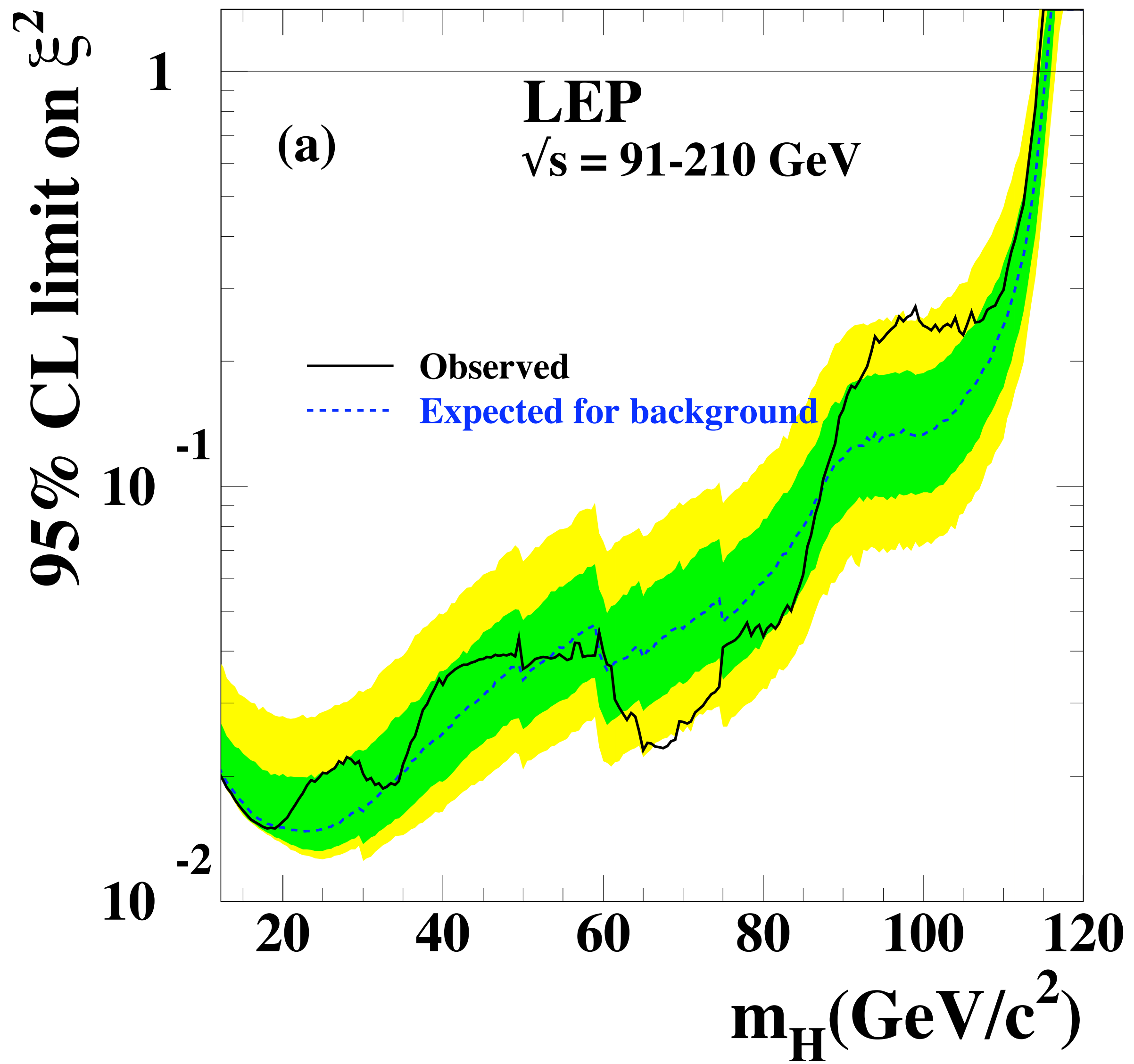
- New Decays
- Variants on Production
- No Higgs

Standard Higgs Decays

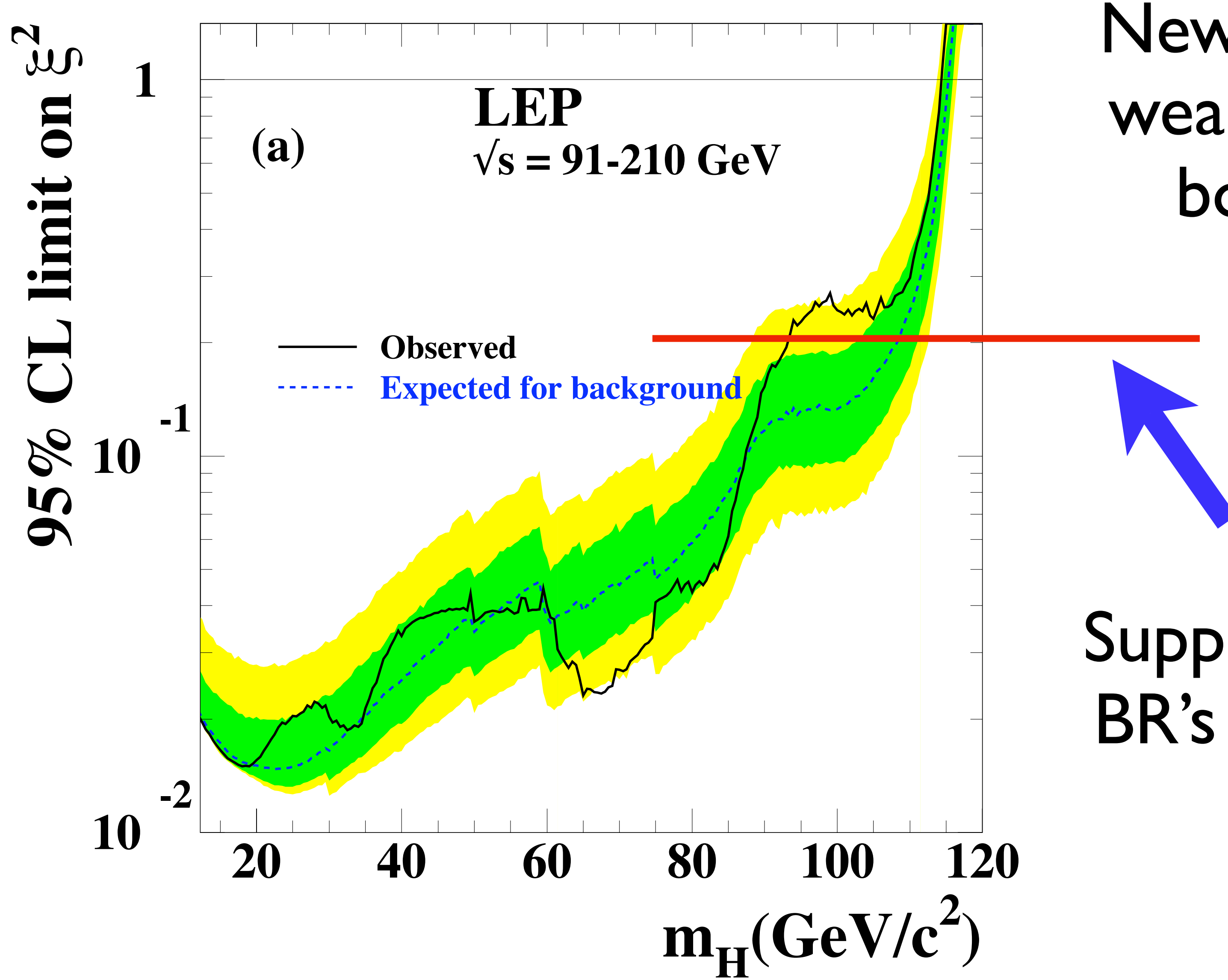
Standard Higgs Decays



Higgs Mass Bound



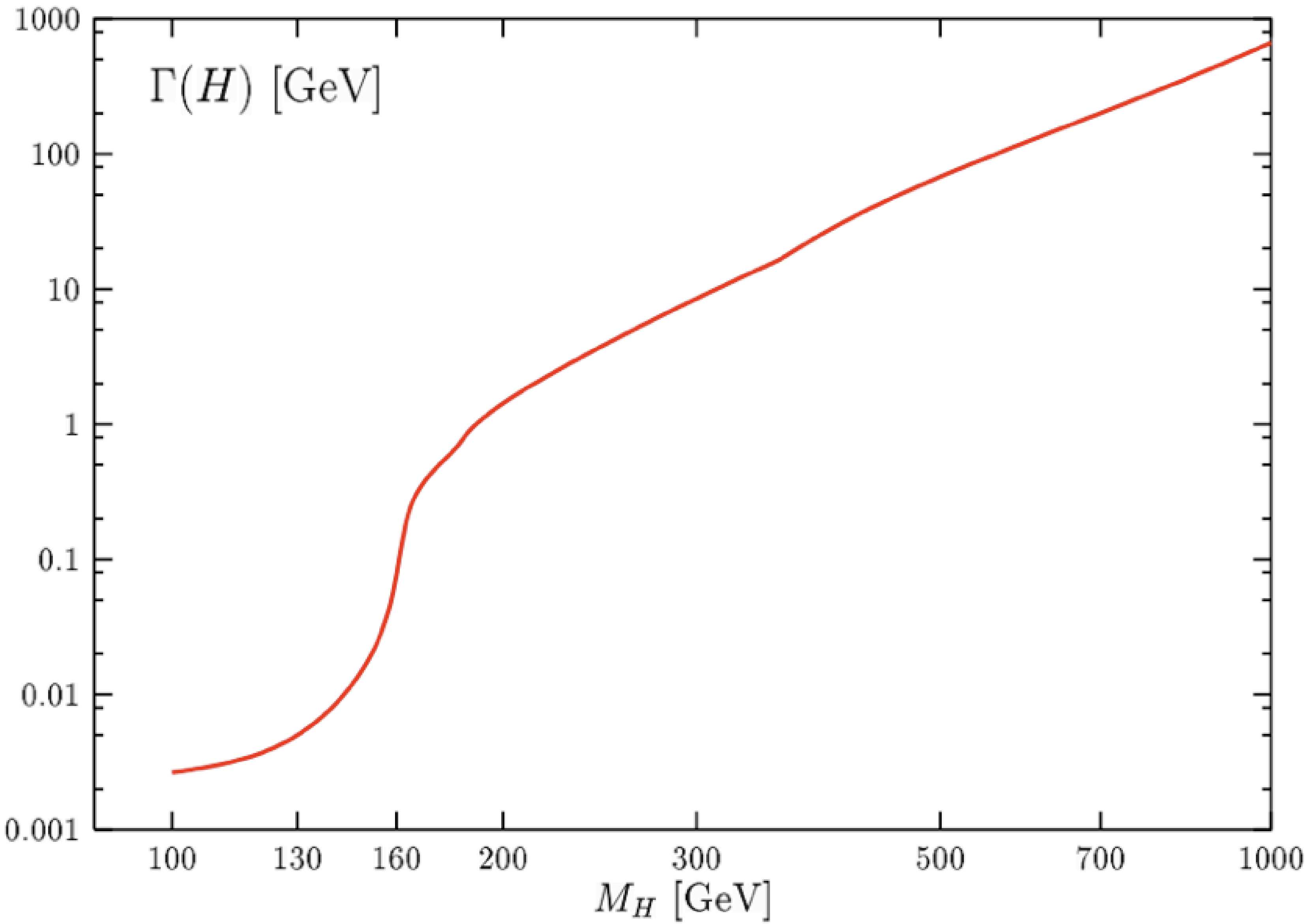
Higgs Mass Bound



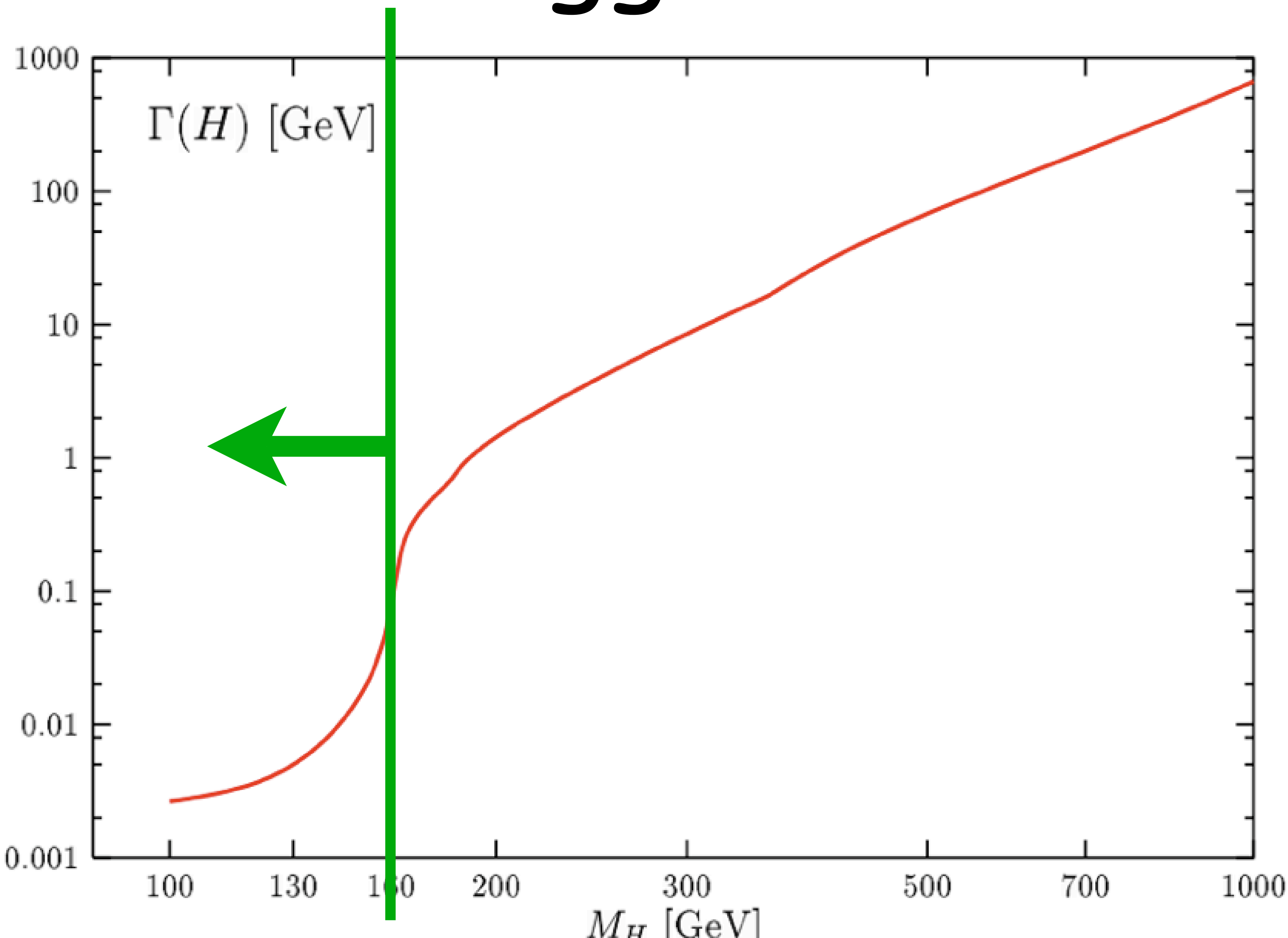
New decays weaken the bound.

Suppress SM BR's to 20%

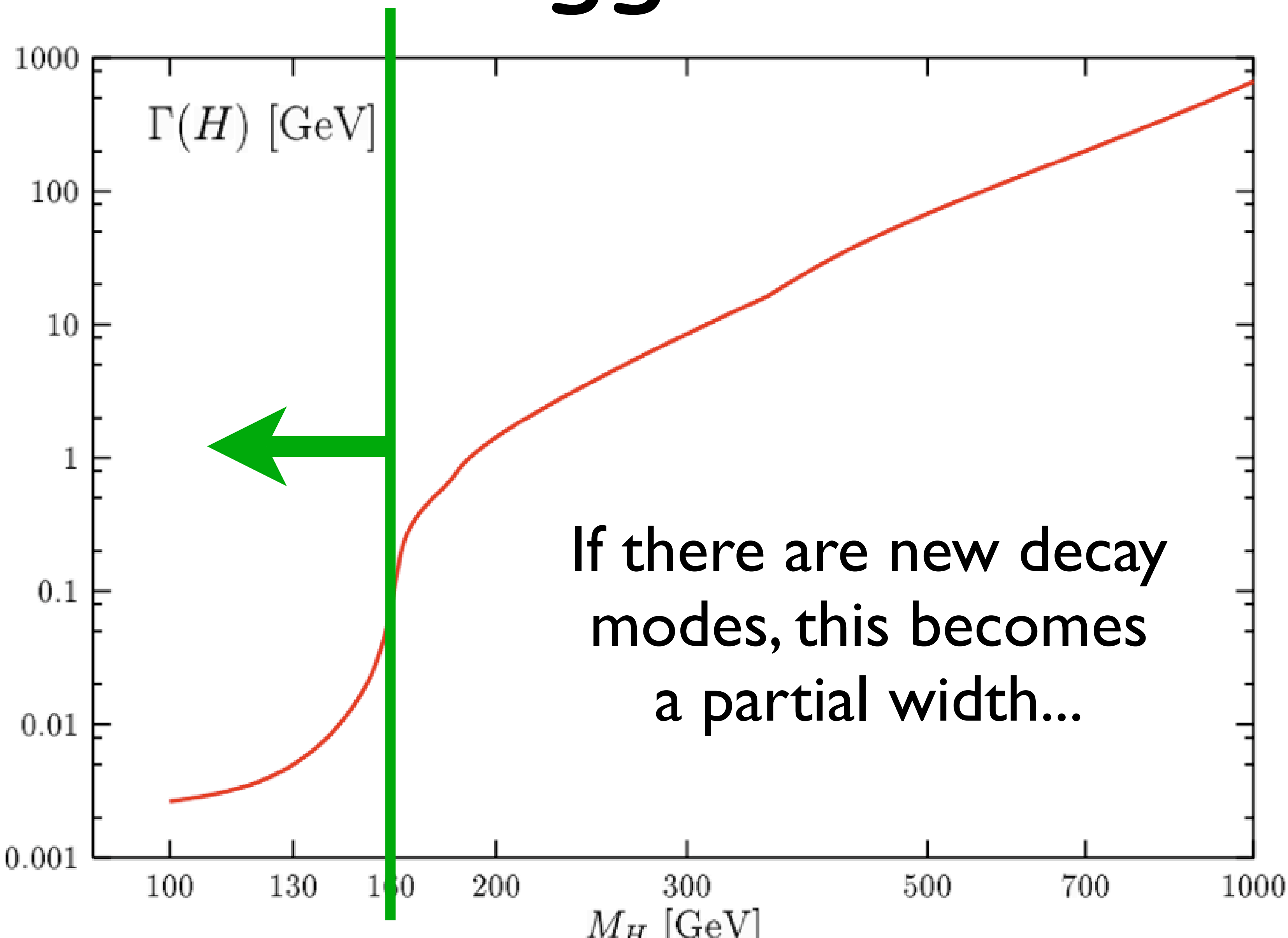
The Higgs Width



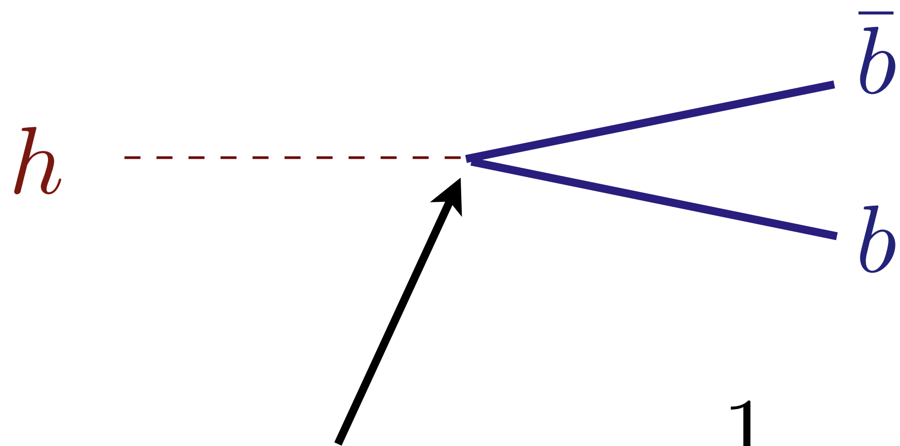
The Higgs Width



The Higgs Width



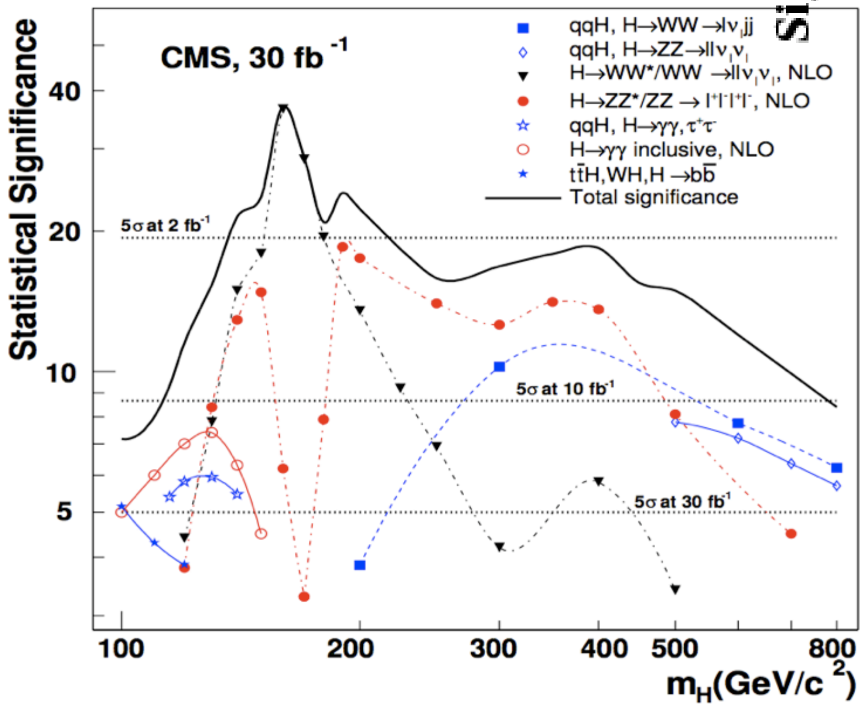
Higgs' Small Width

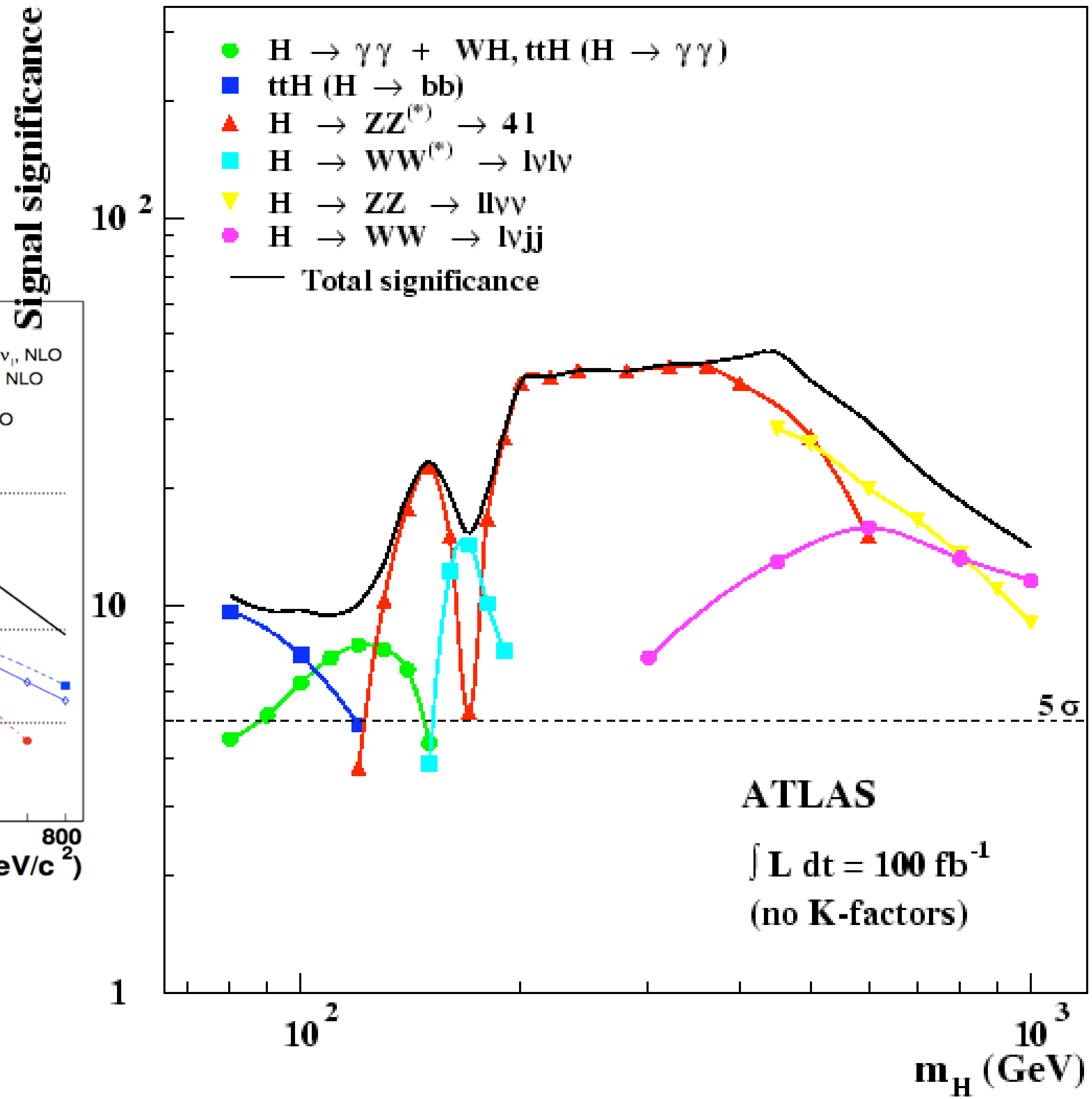


$$y_b(m_h) \sim \frac{1}{60}$$

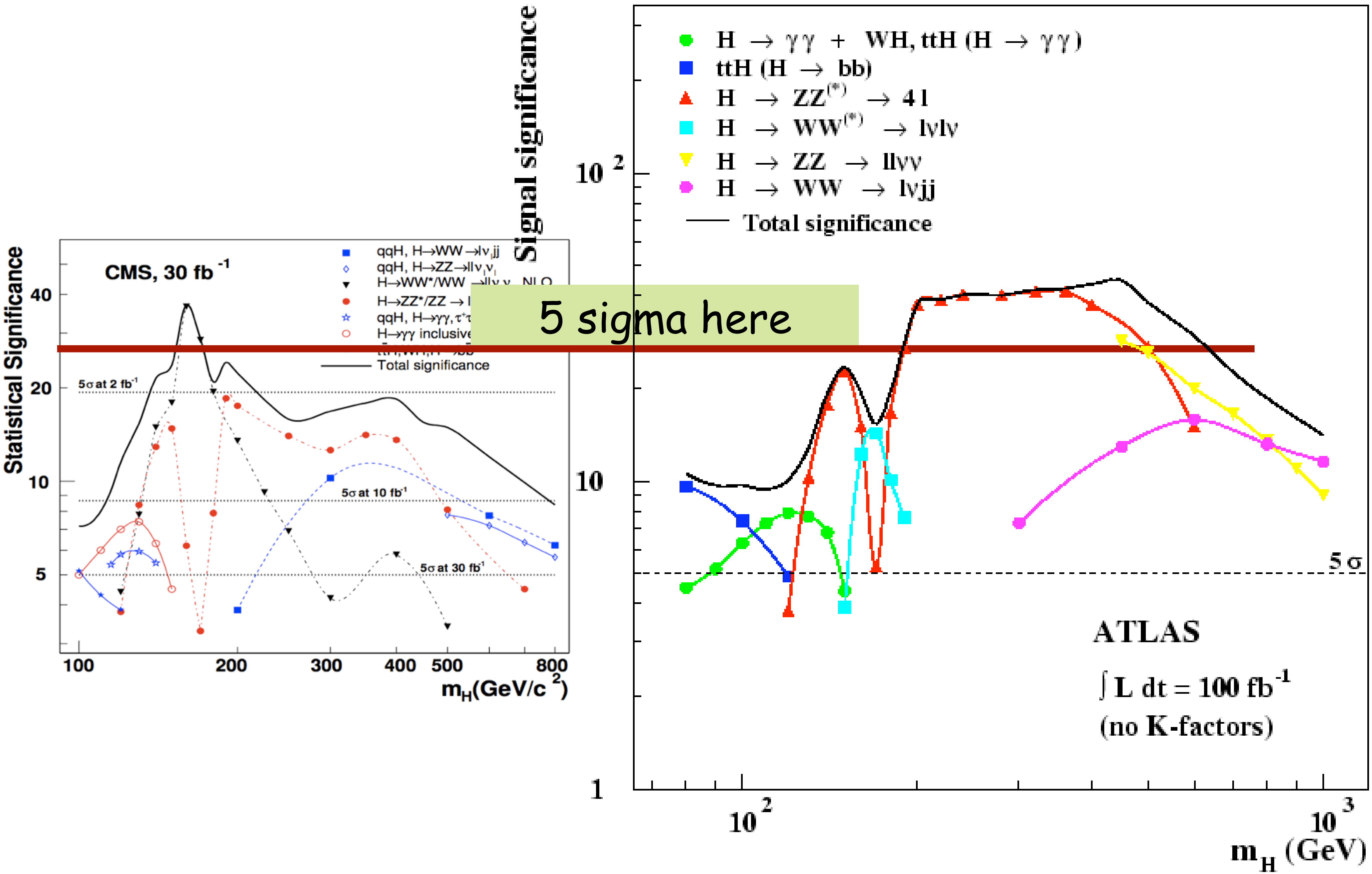
$$\Gamma_{h \to b\bar{b}} \sim y_b^2$$

Higgs searches



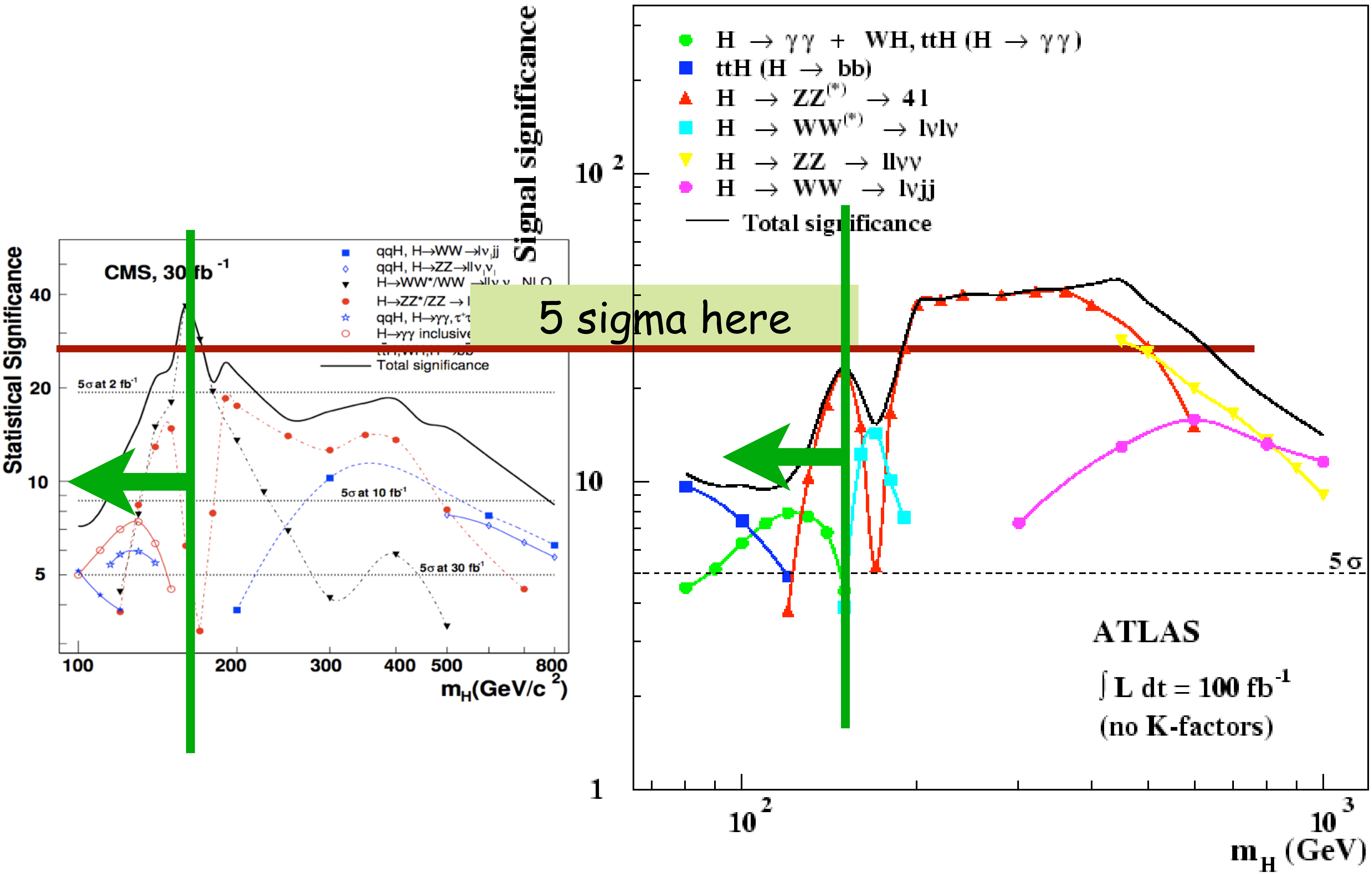


Higgs searches



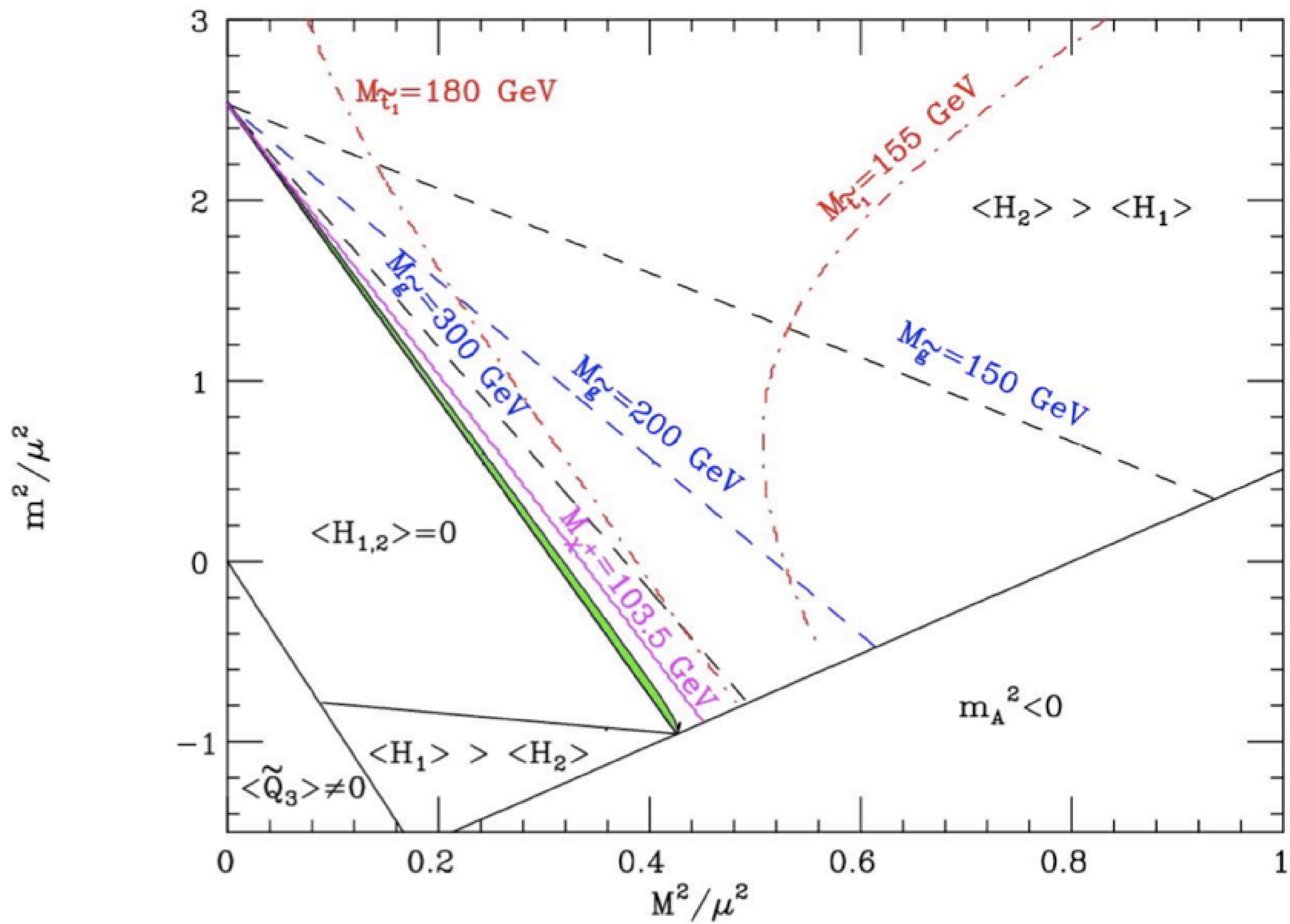
5 sigma here

Higgs searches



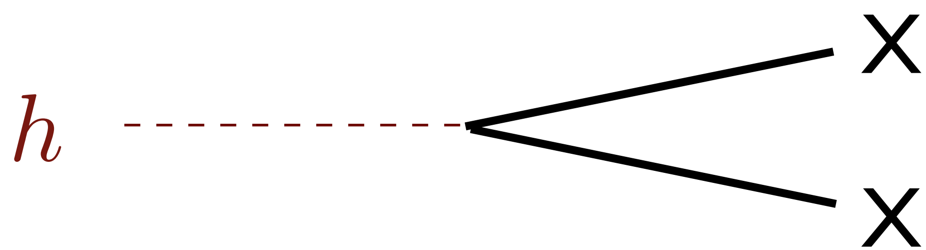
mSUGRA (e.g., SPS1a)

Higgs sector wants to be modified!

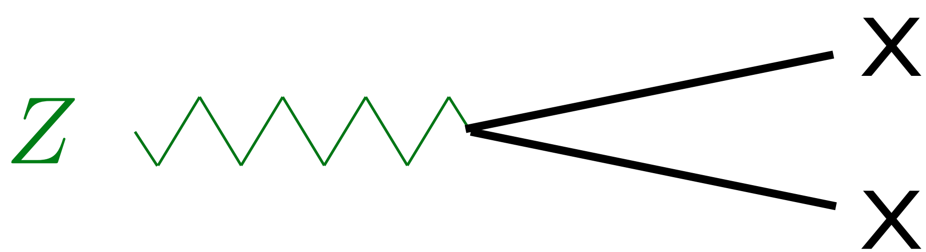


New Particle In Decay

If



then, perhaps



but $\Gamma_Z \simeq 1000 \times \Gamma_h(m_h = 115\ \mathrm{GeV})$

Motivated Models

NMSSM (or MSSM with a singlet)

$$h \to aa \to \bar{b}b\bar{b}b$$
$$h \to aa \to \bar{\tau}\tau\bar{\tau}\tau$$
$$h \to aa \to gggg$$
$$h \to ss \to aaaa \to \bar{b}b\bar{b}b\bar{b}b\bar{b}b$$

New couplings and decays for the Higgs in SUSY can make it naturally heavier and make the LEP bounds weaker.

Motivated Models

Minimal Supersymmetric Standard Model

$$h \to \chi^0 \chi^0$$

invisible

(mSUGRA disfavored)

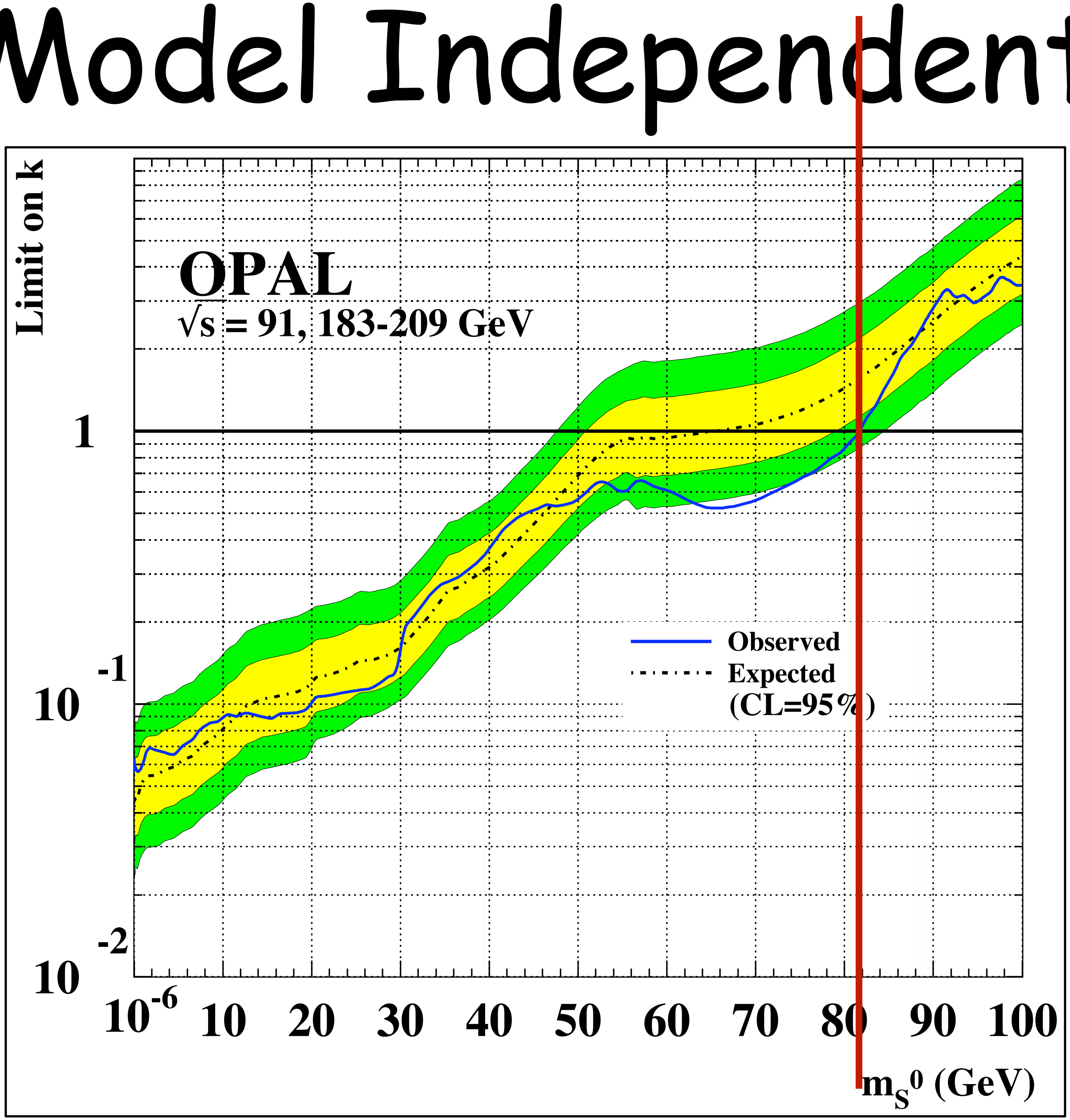
MSSM w/ R-parity violation

$$h \to \chi^0 \chi^0 \to qqqqqq$$

or $\to \ell\ell qqqq$

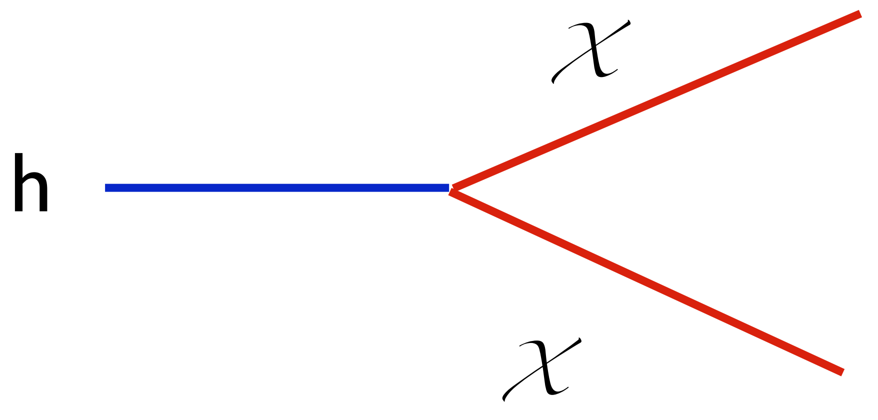
or $\to \ell\ell\ell\ell\nu\nu$

Model Independent

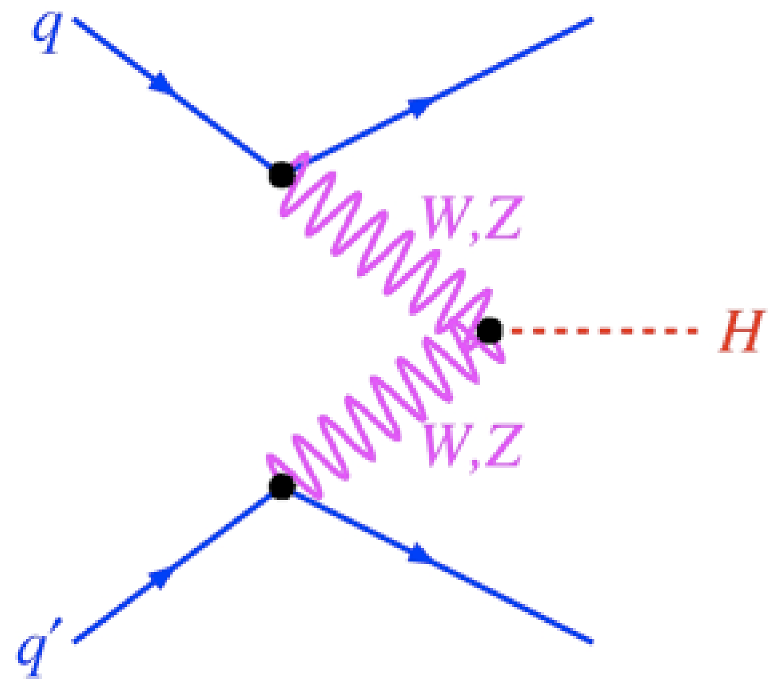


Thus the Higgs could be lighter (and EWP favors it)

The Invisible Higgs



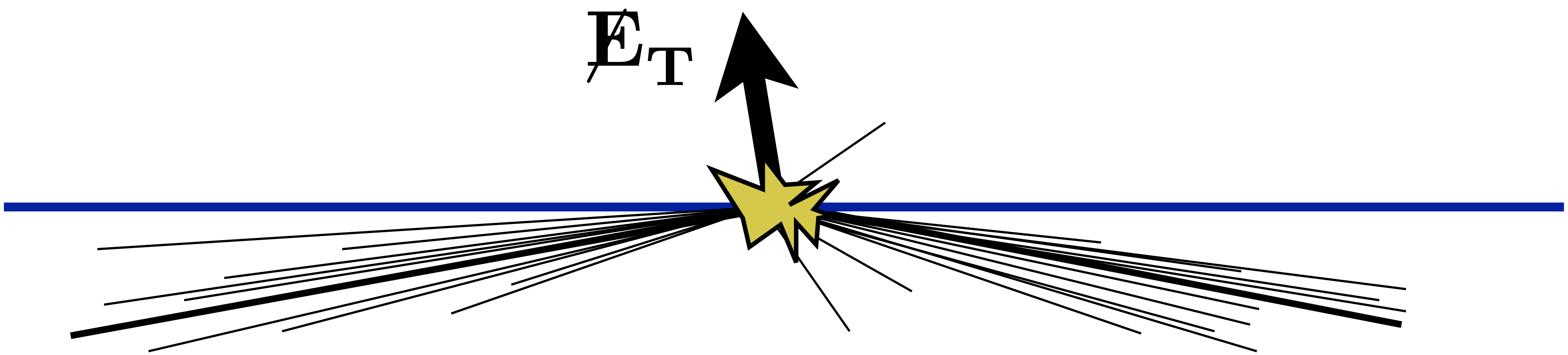
Two forward jets



M_H (GeV)	110	120	130	150	200	300	400
10 fb^{-1}	12.6%	13.0%	13.3%	14.1%	16.3%	22.3%	30.8%
100 fb^{-1}	4.8%	4.9%	5.1%	5.3%	6.2%	8.5%	11.7%

Eboli, Zeppenfeld (2000)

Two forward jets



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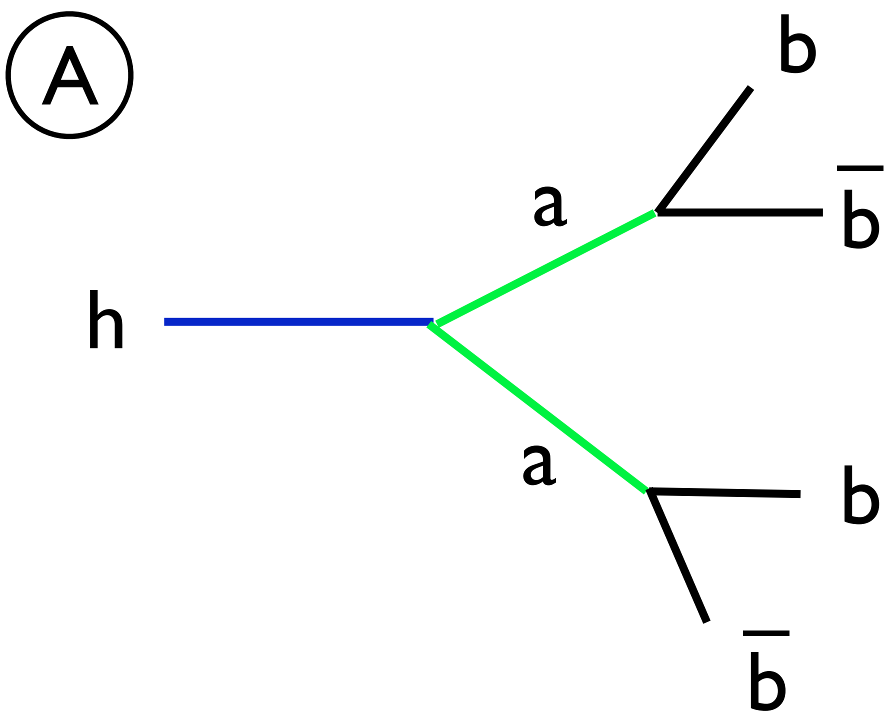
Hadronic decays



P_T cuts help!

Much harder.

Signal:

$\sigma \sim 25\text{pb}$

5×10^4 events

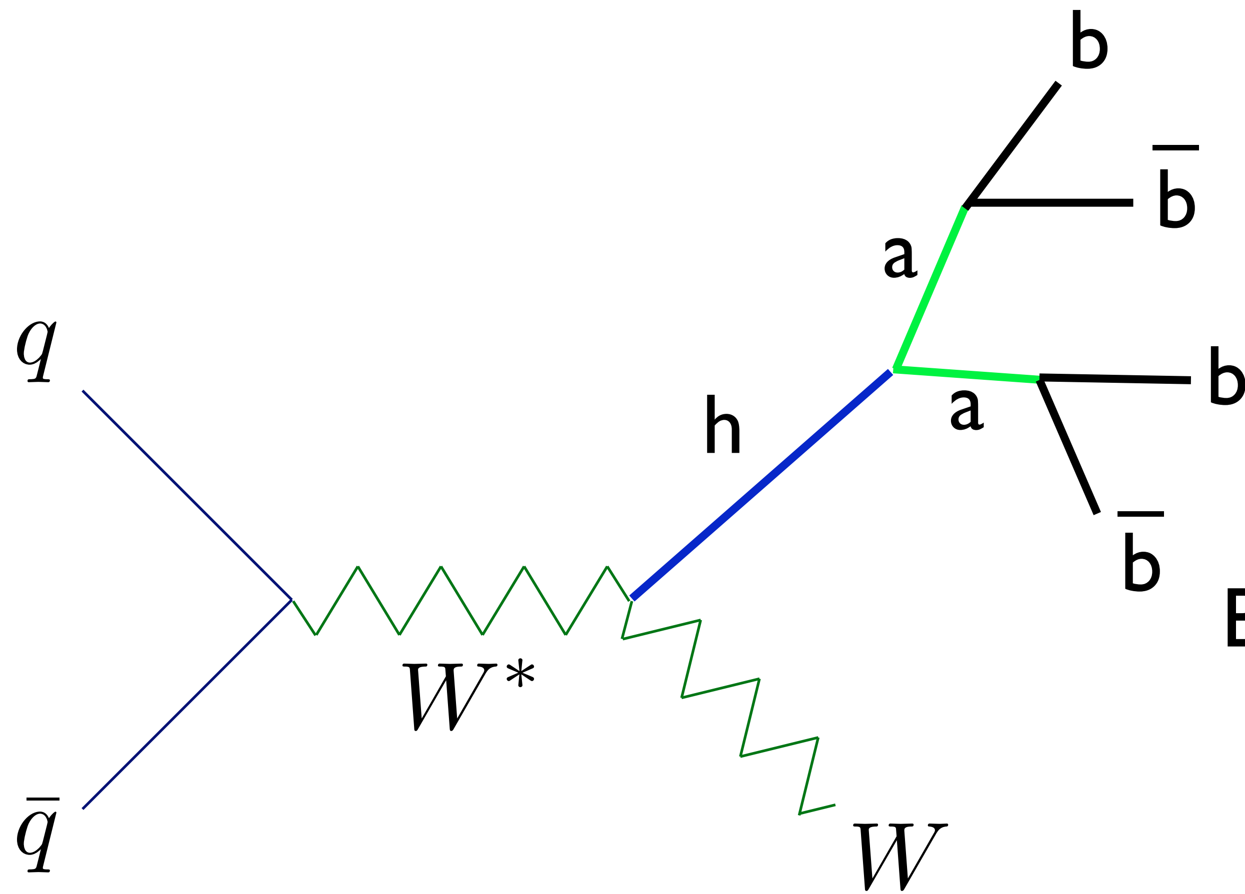
Background:

$\sigma \sim 0.5\mu\text{b}$

$\sim 500,000\text{pb}$

10^9 events

Associated production



(with cuts)

Signal:

$\sigma \sim 1\text{pb}$

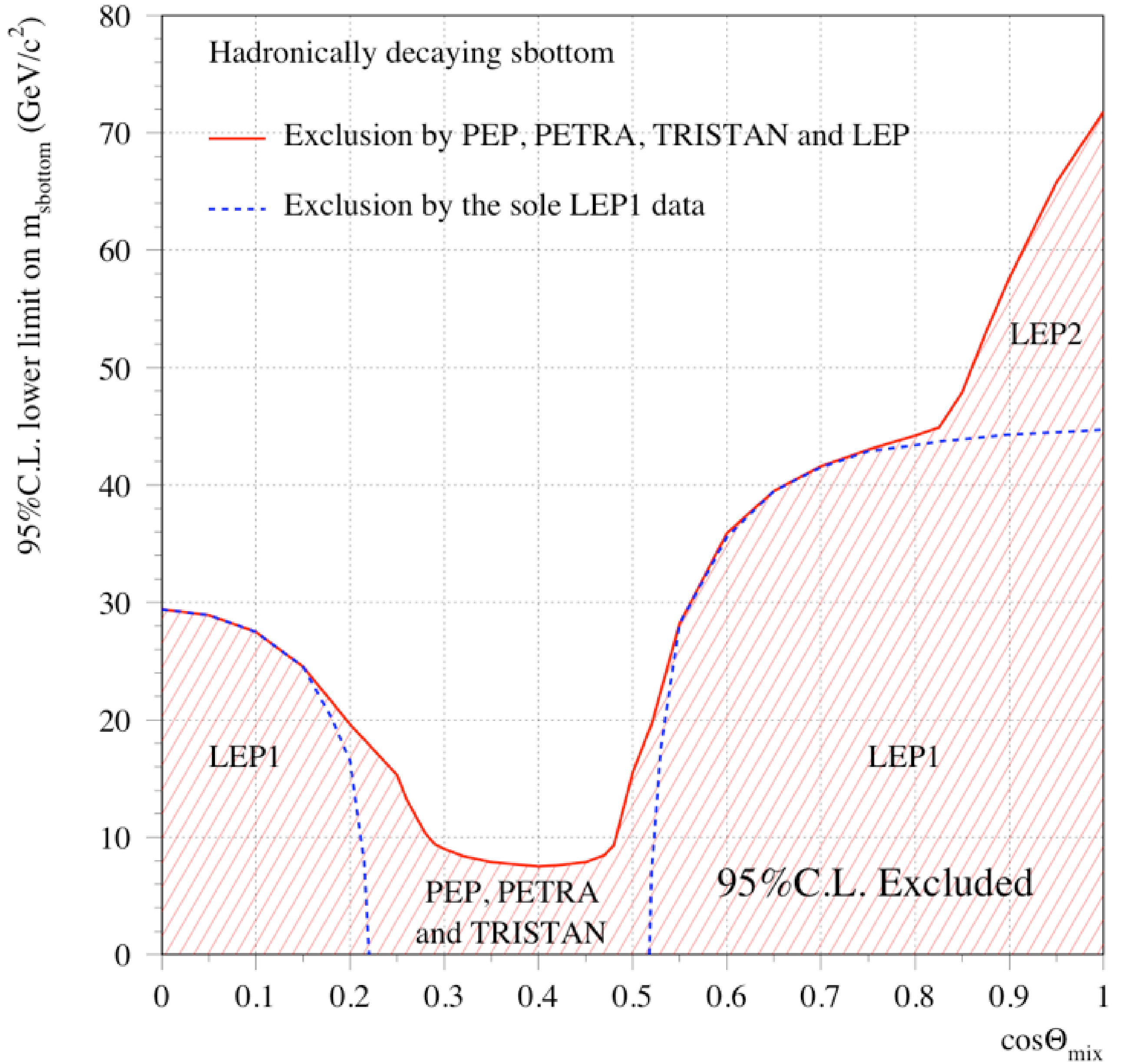
2,000 events

Background:

$\sigma \sim 10\text{pb}$

20,000 events

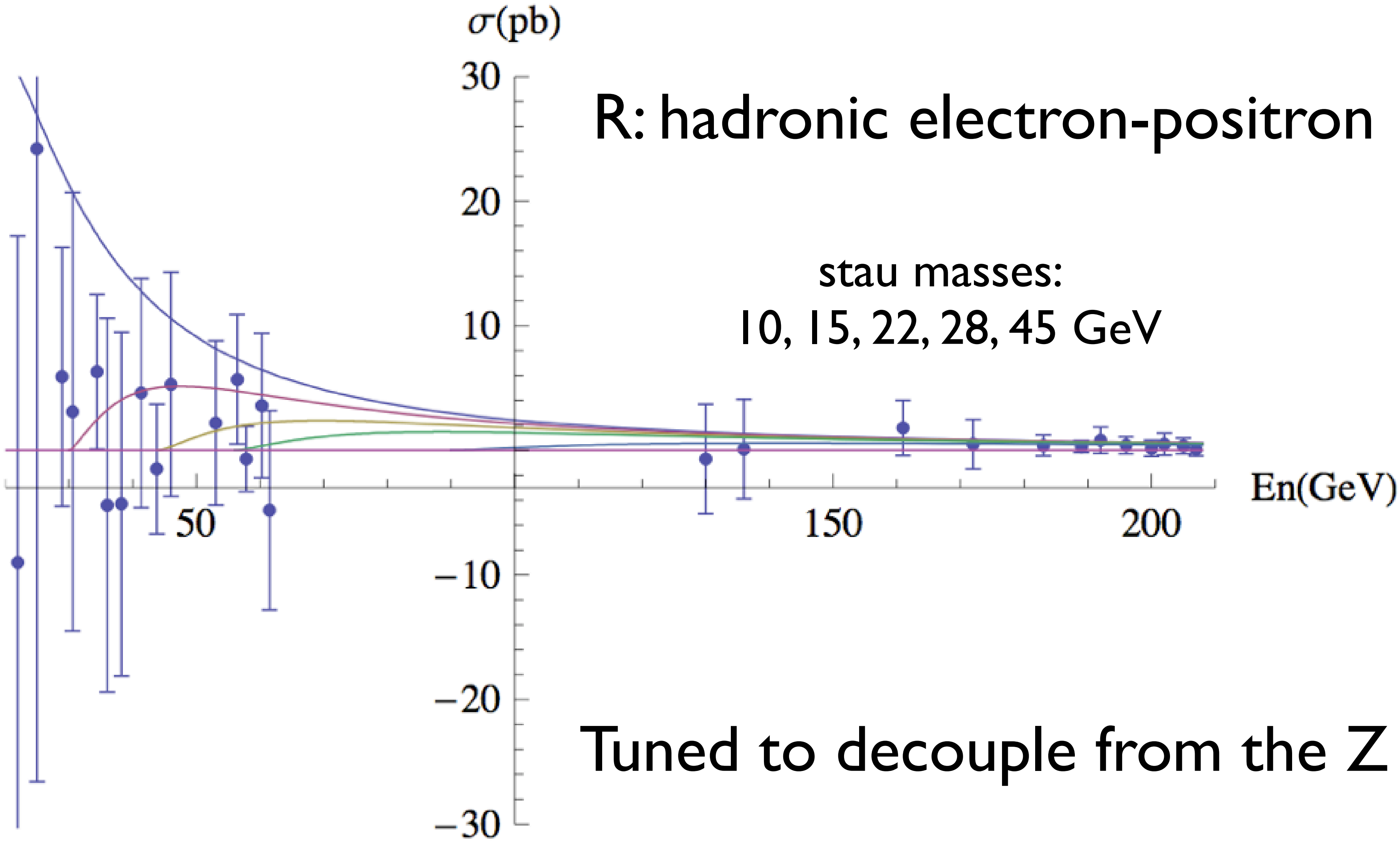
Light Sbottoms



Patrick Janot, 2004

Light Stau?

$$\tilde{\tau}_1 \rightarrow qq'$$



R: hadronic electron-positron

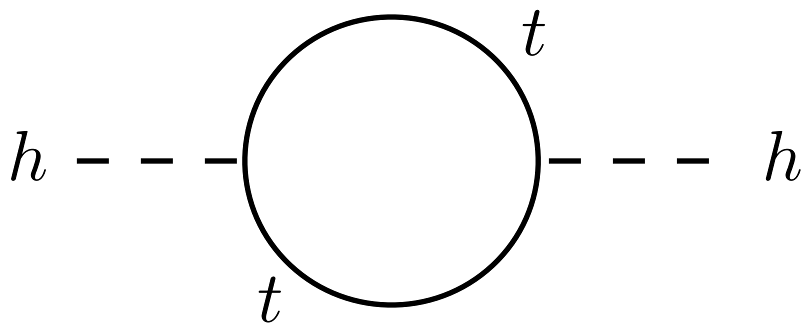
stau masses:
10, 15, 22, 28, 45 GeV

Tuned to decouple from the Z

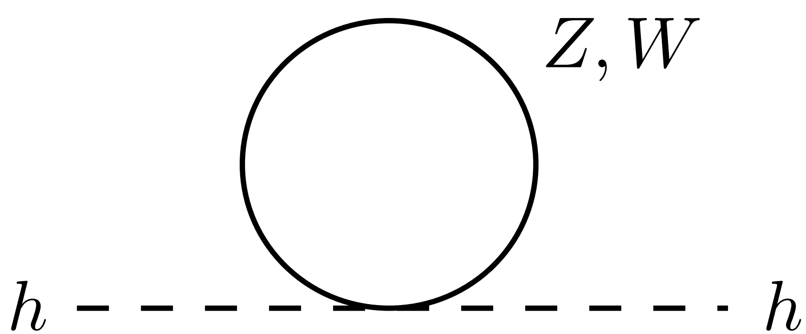
Naturalness

h
h

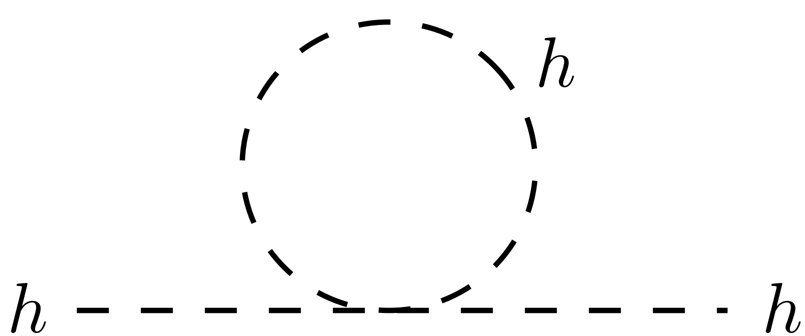
Higgs mass at one loop with cutoff:



$$\delta m_h^2 \sim -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$

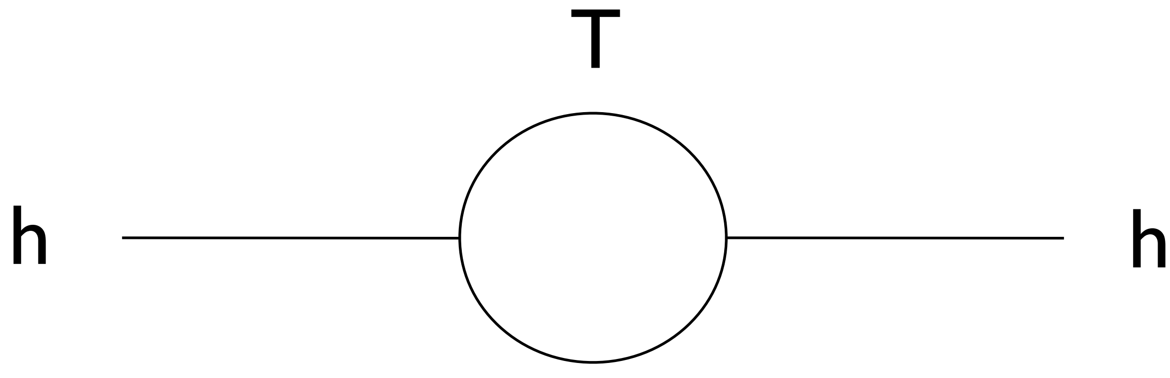


$$\delta m_h^2 \sim \frac{9}{64\pi^2}g^2\Lambda^2$$

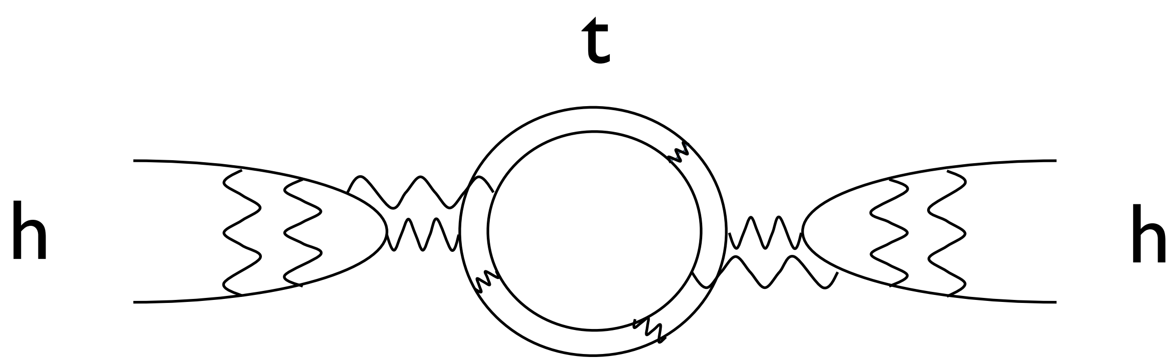


$$\delta m_h^2 \sim \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

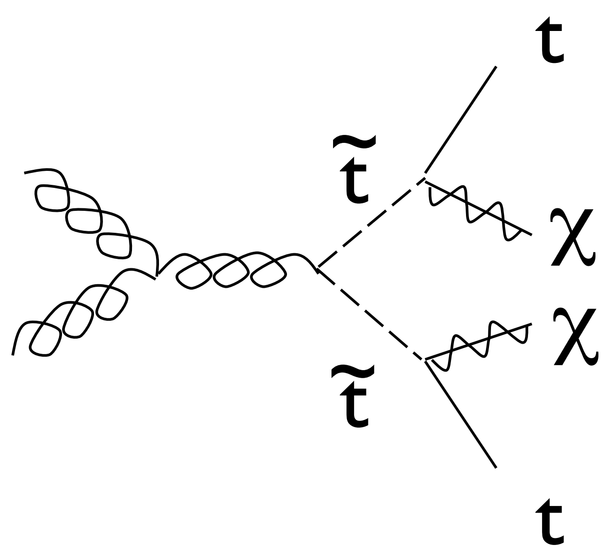
New states (weak)

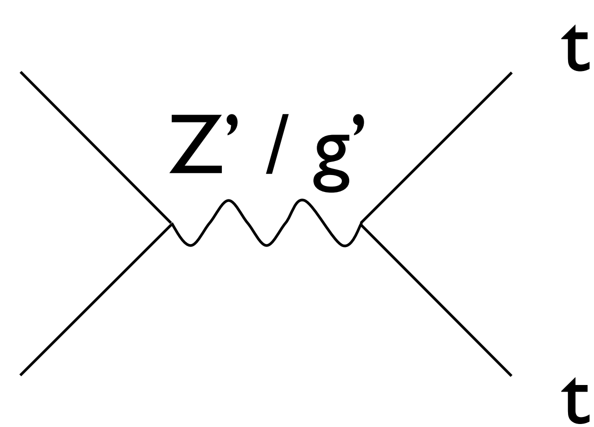


New states (strong)



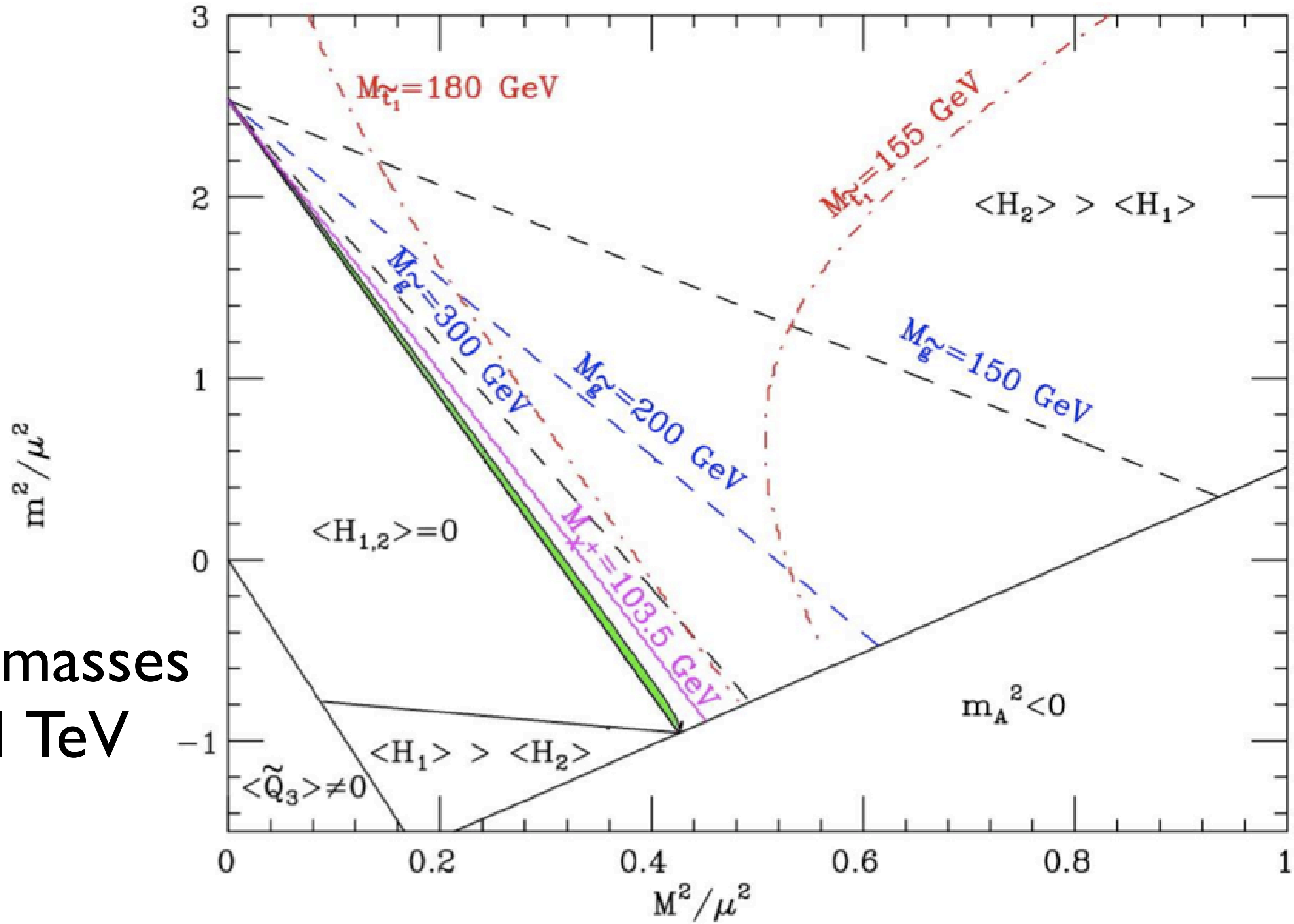
Explicit Examples





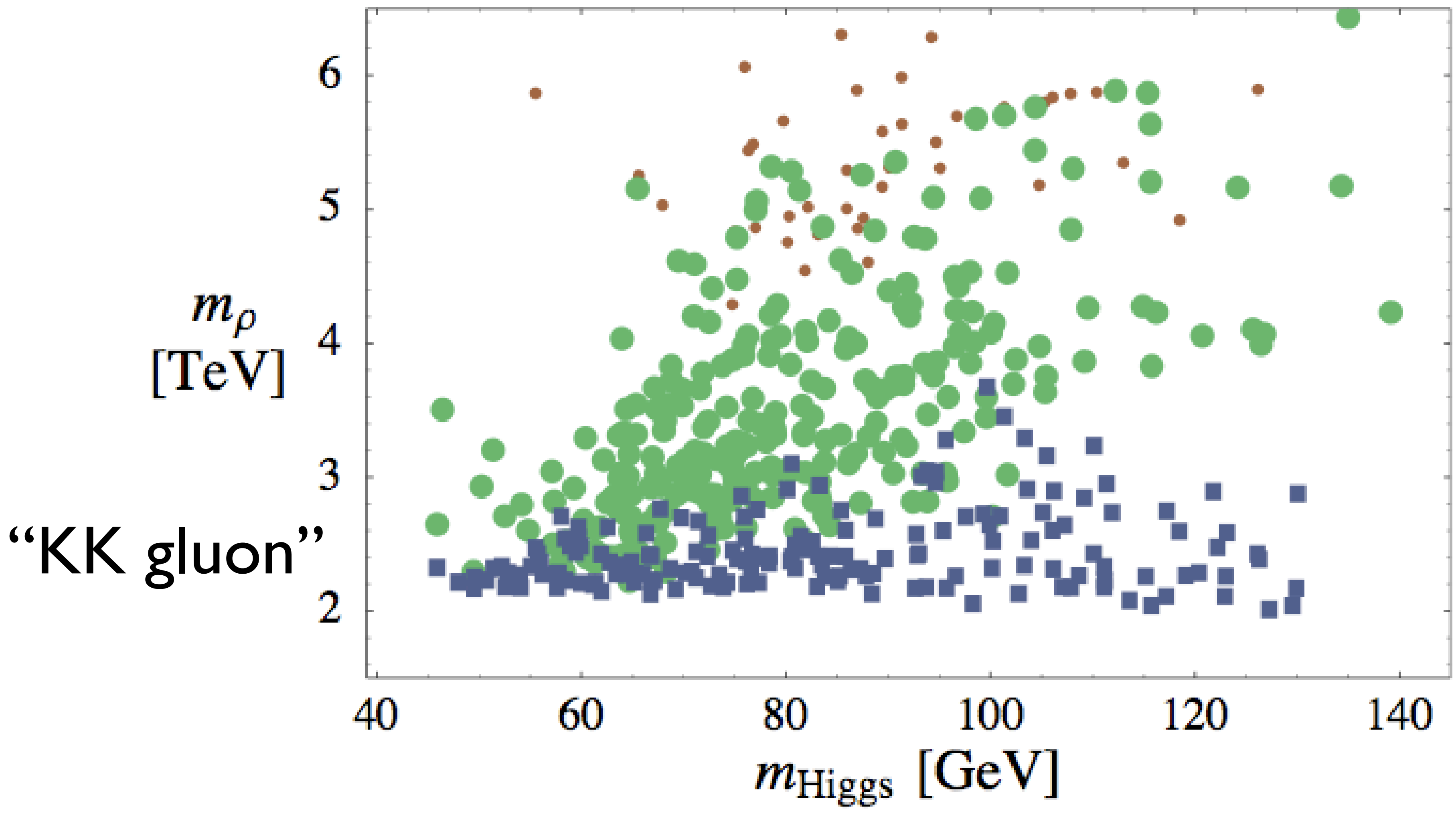
Stops often the lightest squark.
Composite (KK) gauge bosons strongly coupled to tops

mSUGRA (e.g., SPS1a)



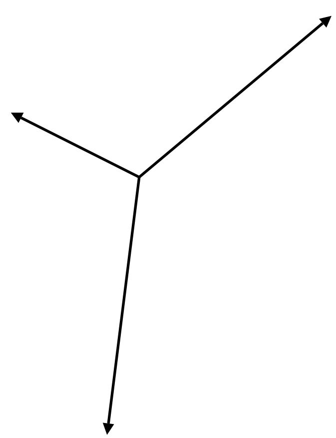
stop masses > 1 TeV

Composite Higgs (RS) scenarios



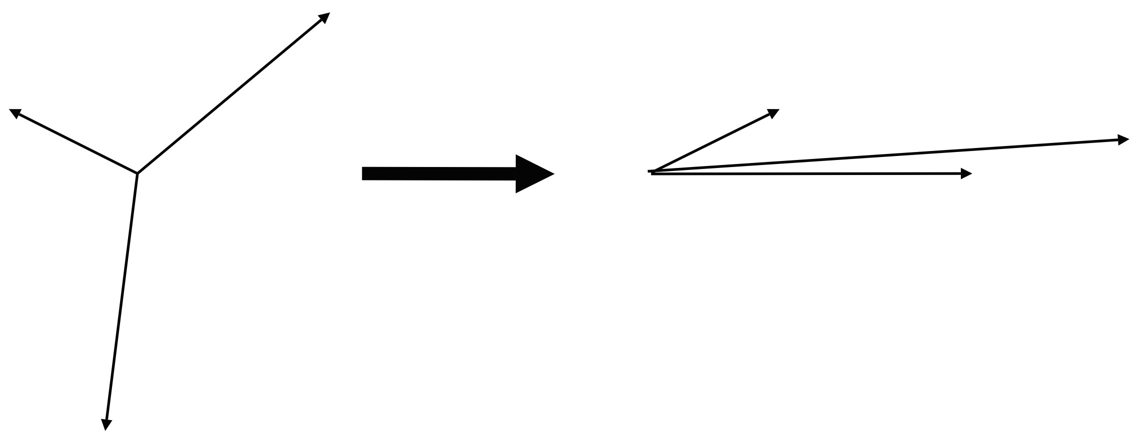
Tagging Tops

$$t \longrightarrow W\,b \begin{cases} l\,\bar{\nu}\,b \\ q\,\bar{q}'\,b \end{cases}$$



- Find 3 hard objects
- ID b-jet using displaced vertices
- Reconstruct top mass and W mass

…At High Pt

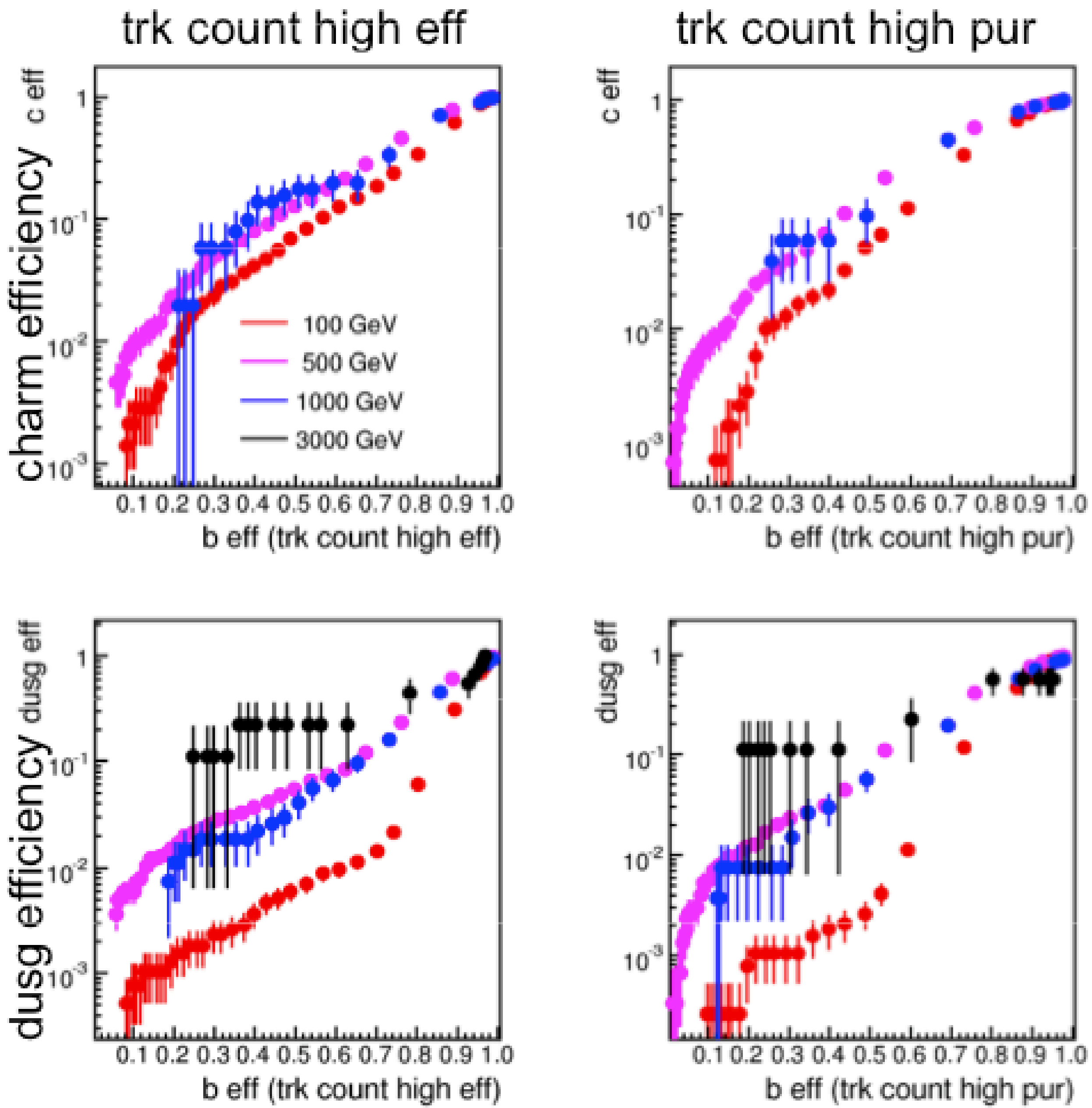


Standard Resonance Search

l+jets

- Cone jets of fixed size
  - Capture variable # of top decay products per jet
  - Lose kinematic info
  - Have to be very careful with the lepton (esp. electrons)
  - Subject to backgrounds you maybe shouldn't be worrying about
- Degraded b-tagging
  - At high Pt, tracks are crowded
  - Fake displaced vertices are a big issue, still under investigation
  - 1 TeV top: 20% b-tag / ~1% udsg mistag
    - Progressively worse at higher Pt
- Total signal efficiency ~ 1%

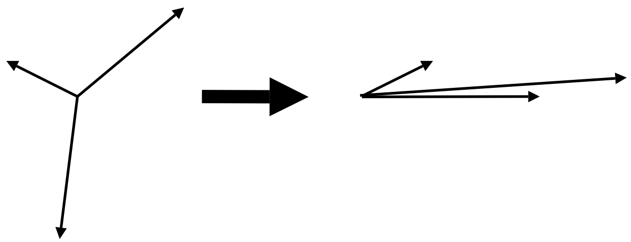
B-mistags for high-pT tops

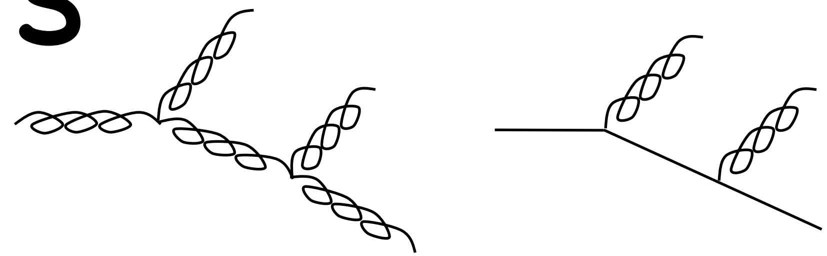


Mission Statement

- We would like some way to look inside these jets and use as much info as possible
- We would also like to free ourselves of reliance on b-tagging

Hadronic Tops vs Light Jets

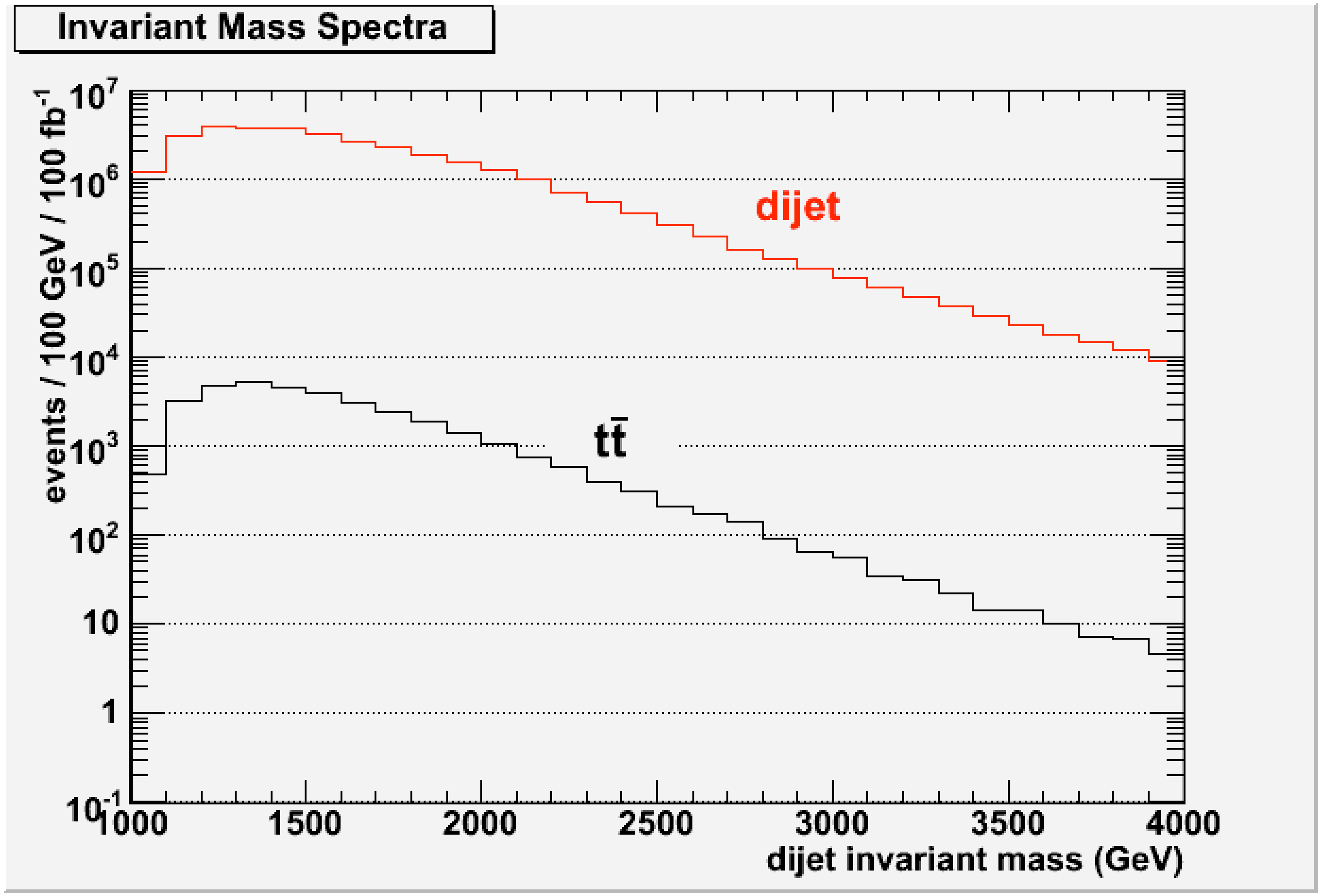




- 3 hard partons
- Mass = m_t
- On-shell W
- ~Isotropic in top frame, comparable energies in lab

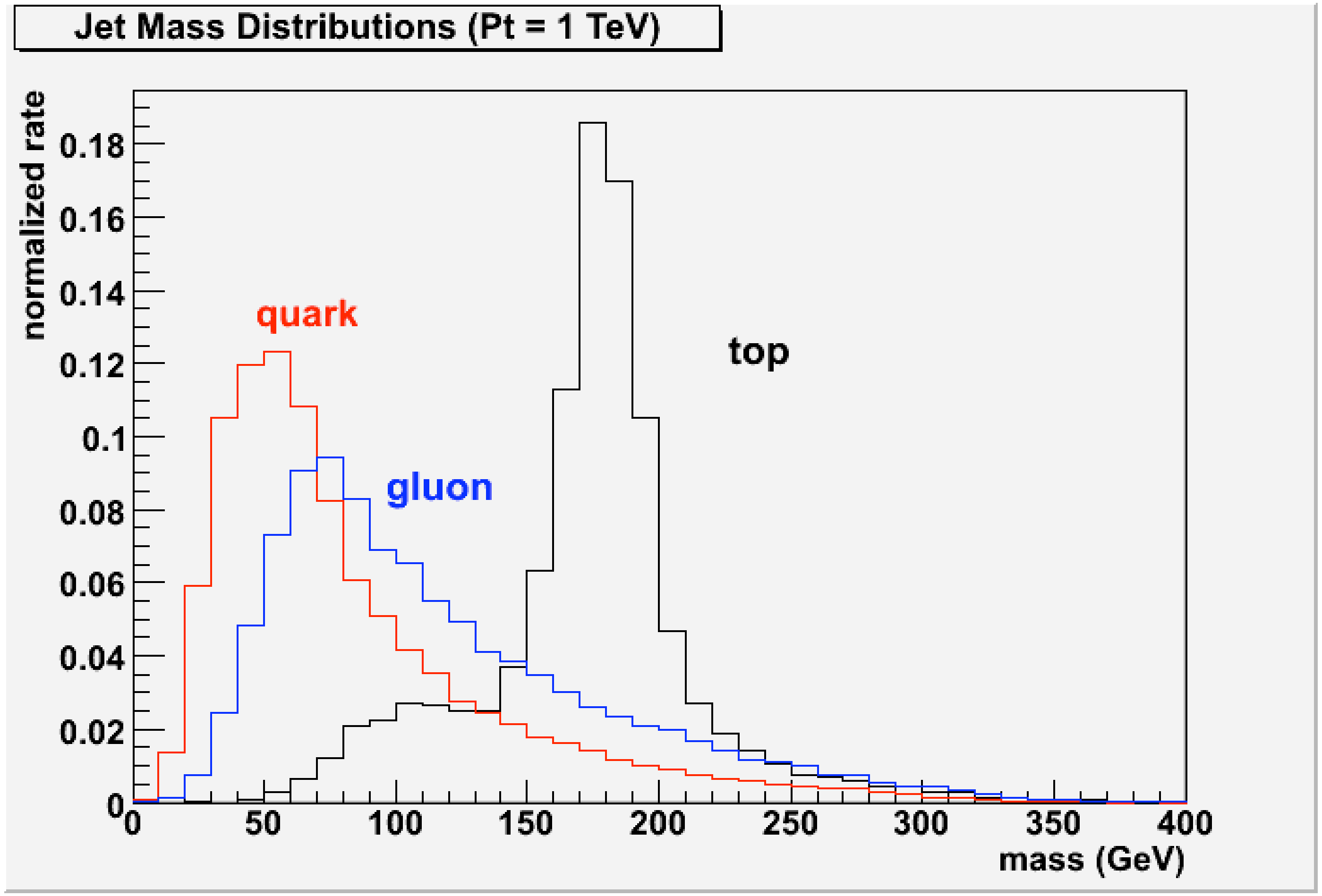
- Variable # hard partons
- Continuum of masses
- Soft/collinear singularities

Dijet Mass Spectrum



- All-hadronic tops
- PYTHIA 6.4 continuum QCD and top pair
- Pt > max(500 GeV, m/4)

First Pass: Mass Cut



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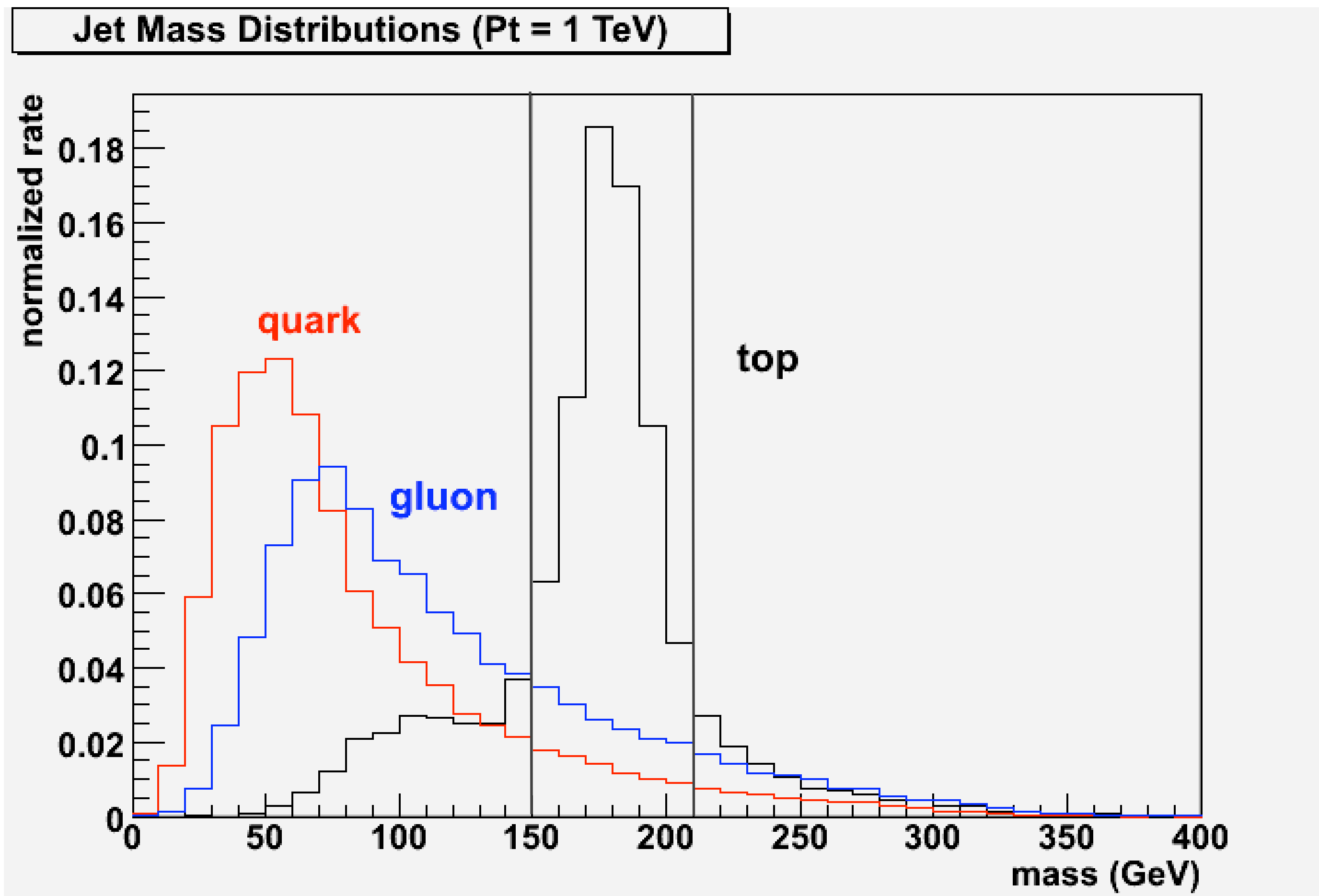
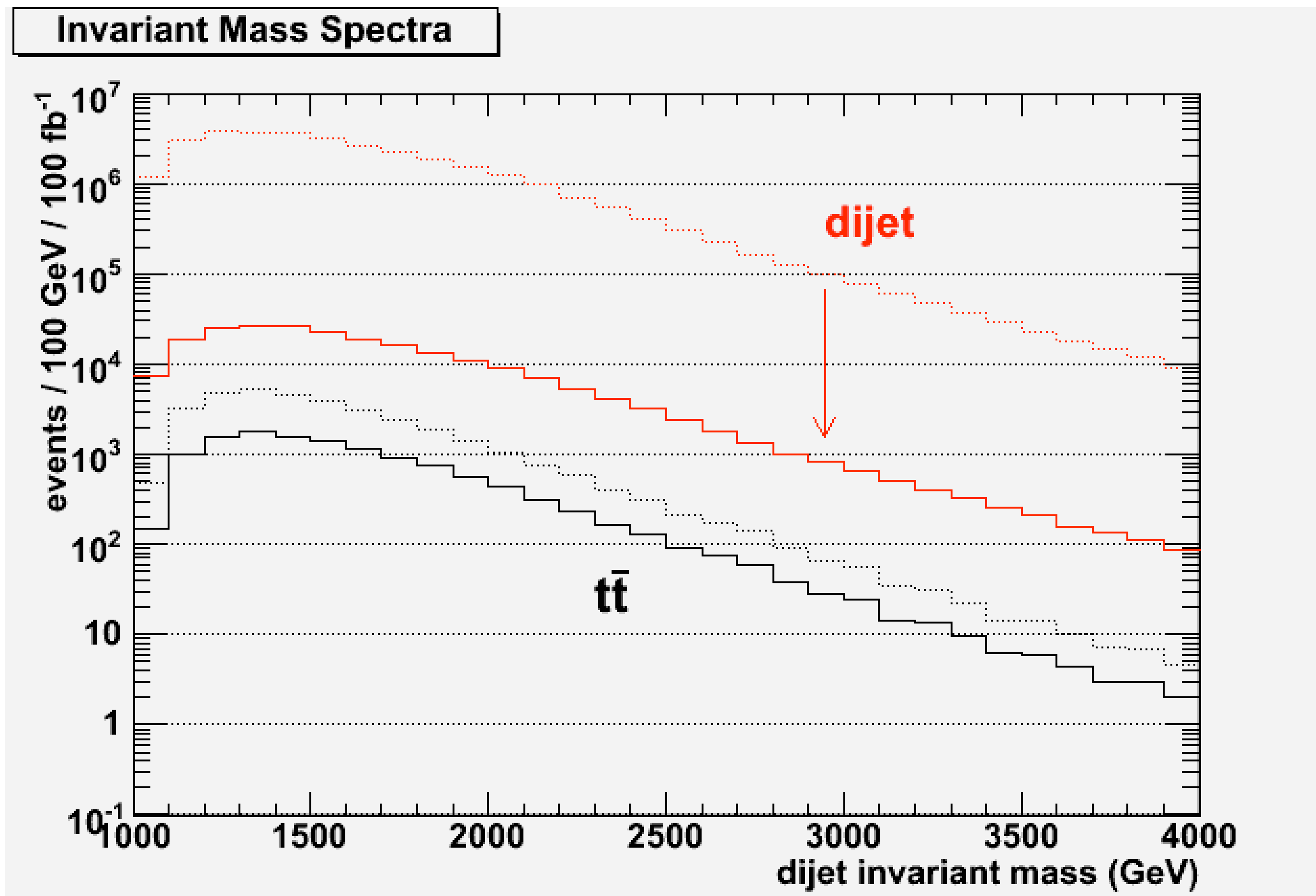
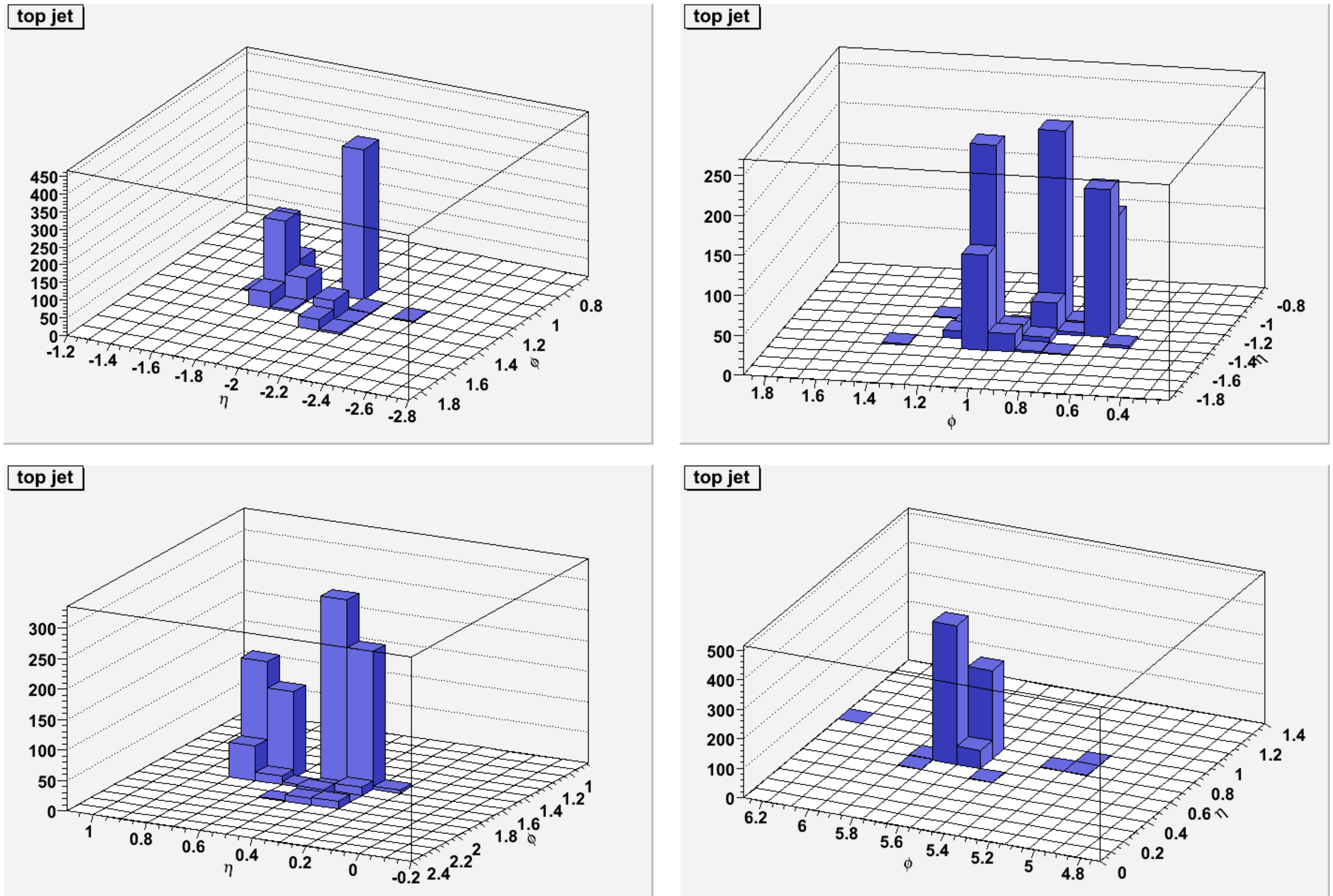


- 68% top
- 8% quark
- 16% gluon

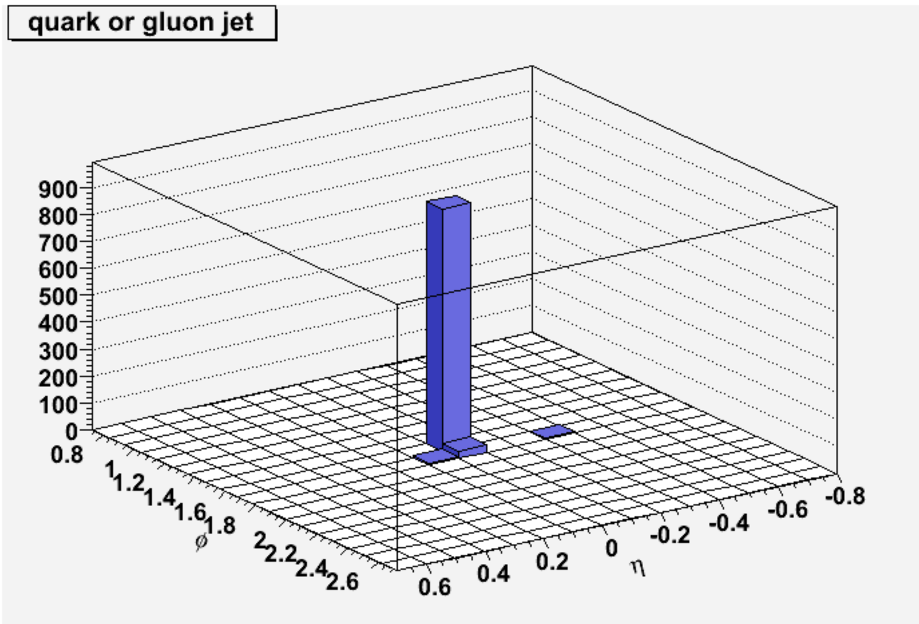
Dijet Mass Spectrum, Again

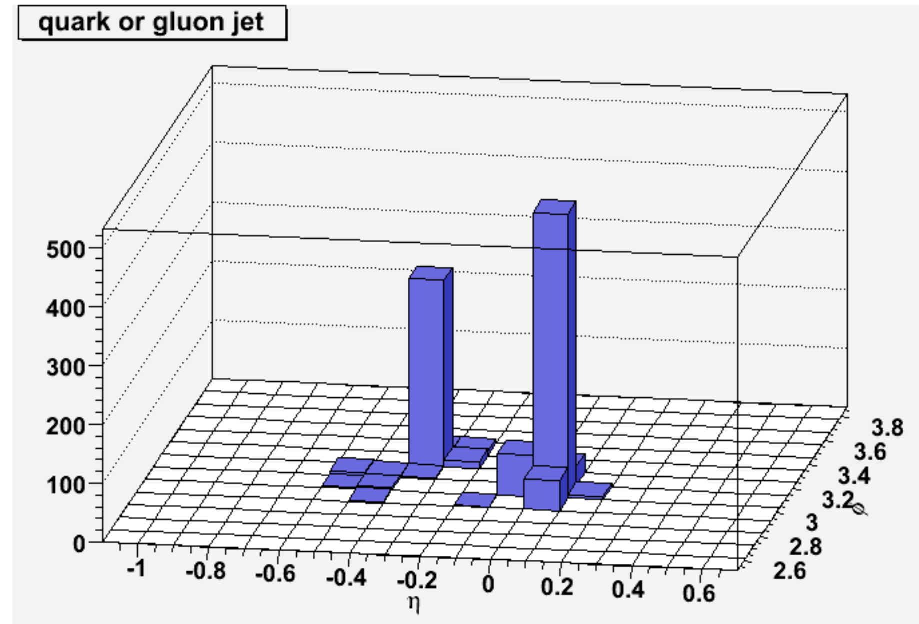


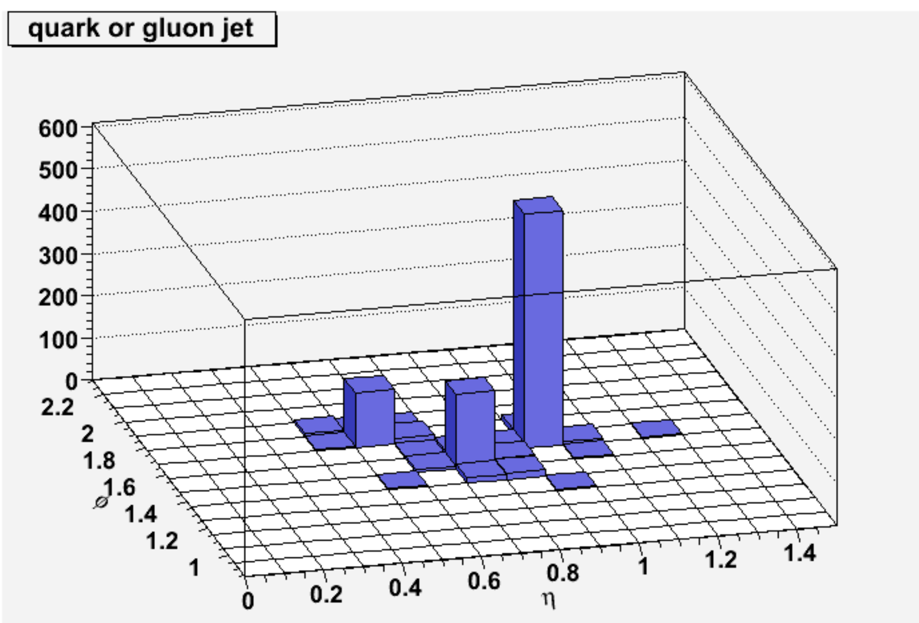
1 TeV Top-Jet Gallery

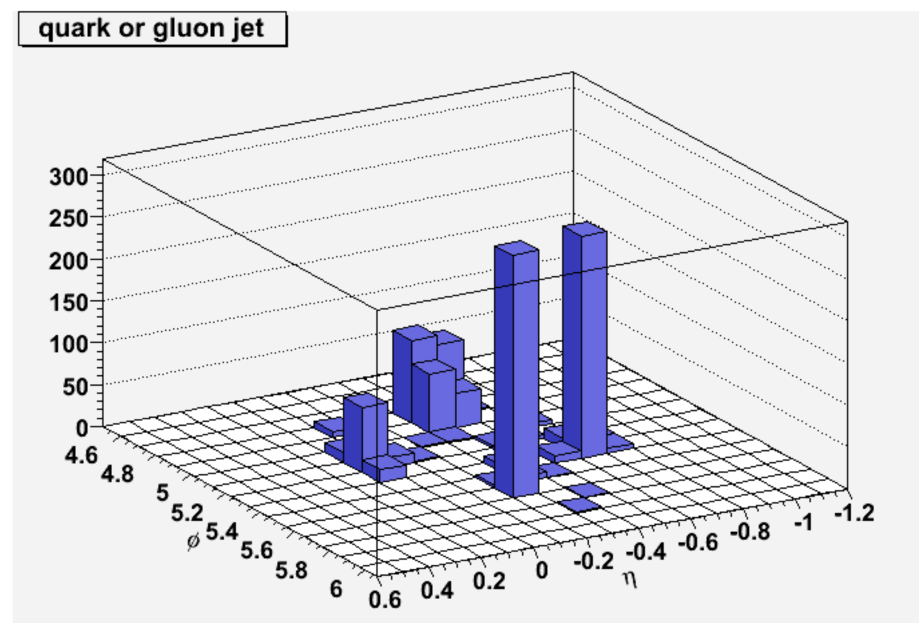


1 TeV Light-Jet Gallery









Our Take on the Problem

- Exploit the excellent calorimeter granularity of CMS and ATLAS to isolate the hard partons at $\Delta R \sim 0.1$
  - If they can be picked out by eye, they can be picked out by a computer program
- Employ both multiplicity and full kinematics as discriminators, as for low Pt
  - But give up on b-tagging
- Give up some conventional notions of what constitutes a “jet”

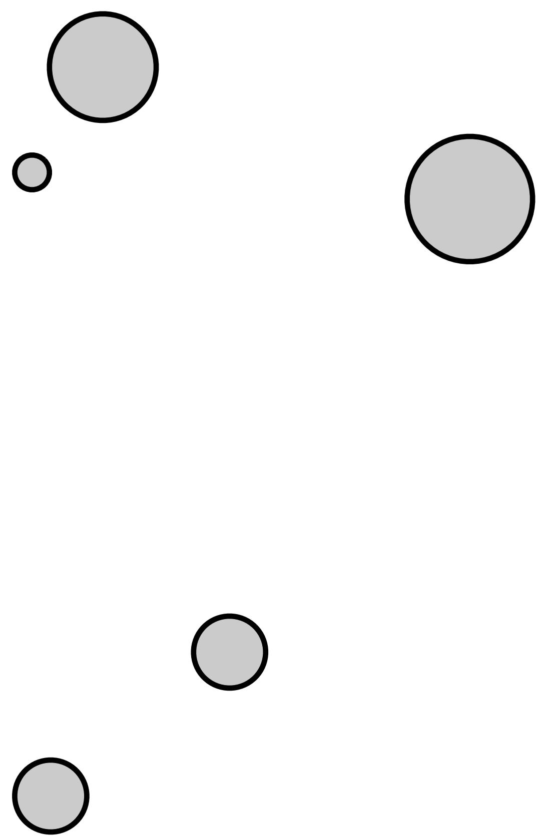
Cambridge/Aachen Algorithm

0. Calorimeter cells = massless 4-vectors

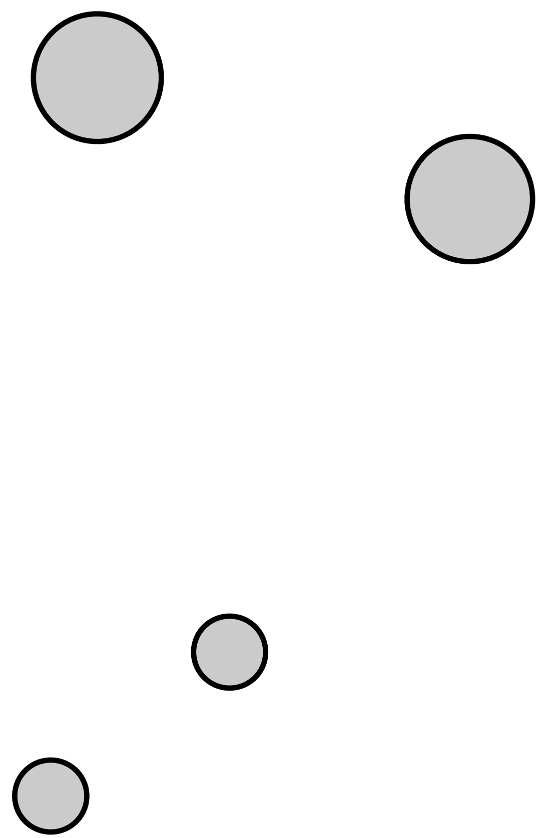
   Calculate distance ΔR_{ij} between all pairs of 4-vectors

   Stop if all $\Delta R_{ij} > R$, otherwise add together the closest pair and go back to Step 1

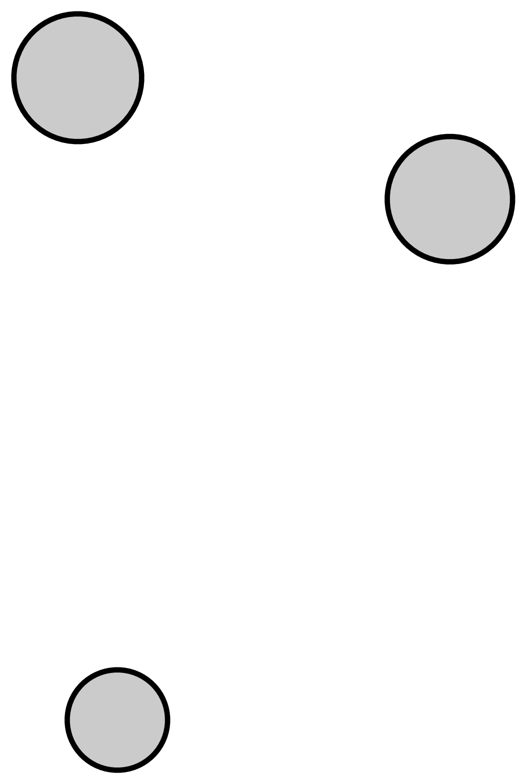
Cambridge/Aachen Algorithm



Cambridge/Aachen Algorithm



Cambridge/Aachen Algorithm



Cambridge/Aachen Algorithm

Cambridge/Aachen Algorithm

Our Algorithm, Part I

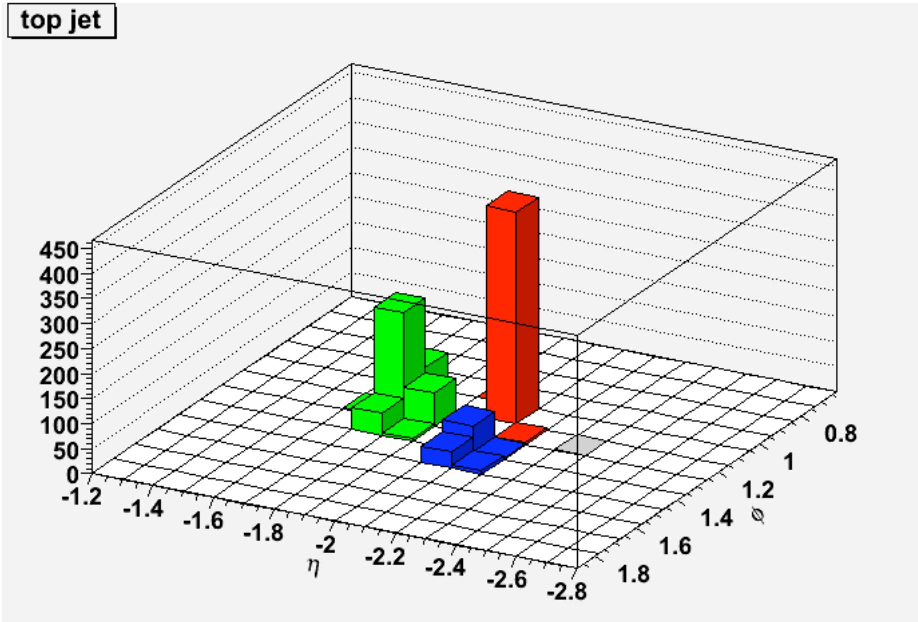
1. Cluster event with C/A and look at individual jets
2. Decluster jet one step. Throw away softer object if its Pt < δ_p and continue declustering.
3. Stop declustering if:
   1. Both objects Pt > δ_p. These are **subjets**.
   2. Both objects Pt < δ_p
   3. Objects are "too close": $|\Delta N_\eta| + |\Delta N_\phi| < \delta_N$
   4. Only one object is left

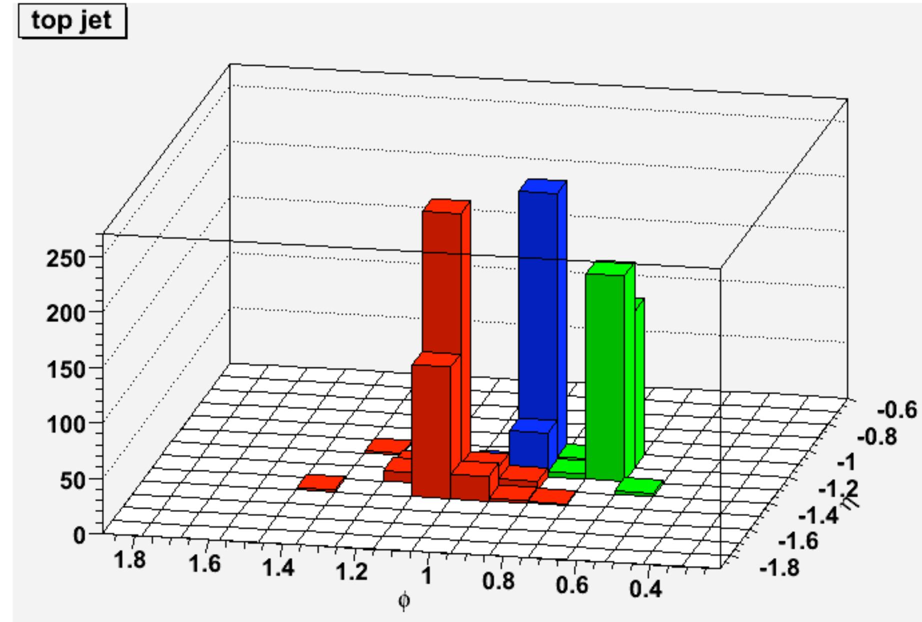
declustering fails, rebuild original jet

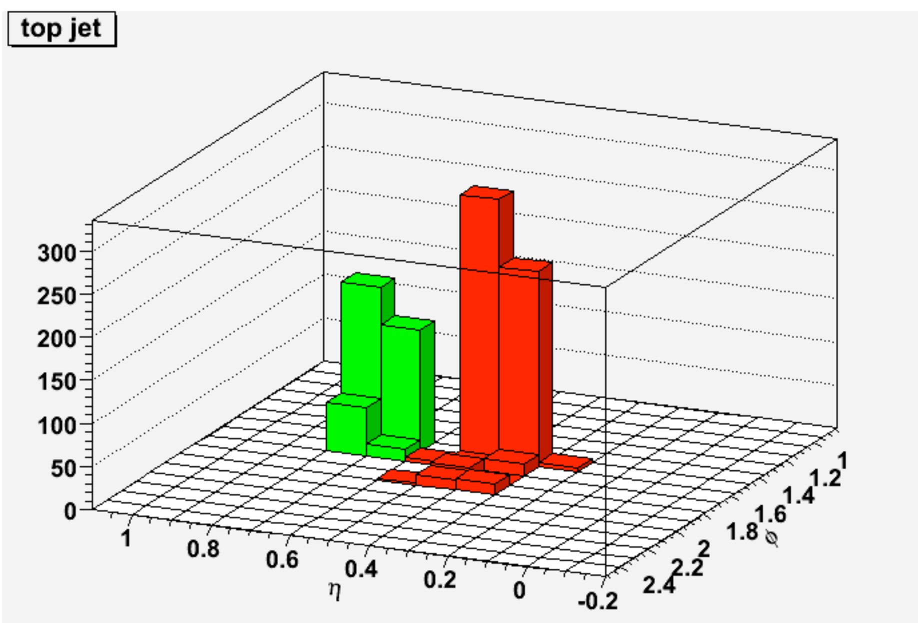
Our Algorithm, Part II

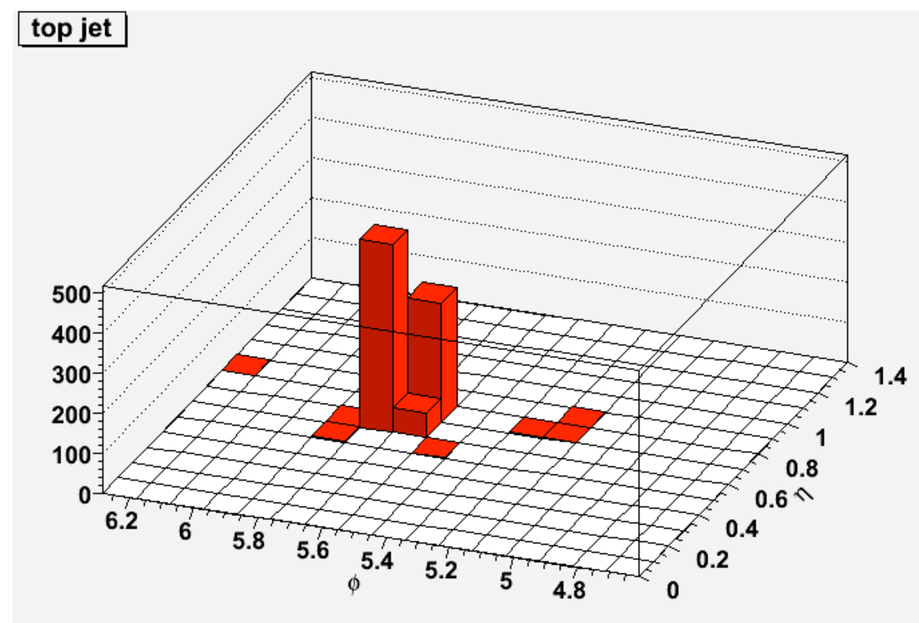
4. If the jet breaks into two subjets, repeat declustering on those subjets
5. Keep cases with 3 or 4 final subjets - 4^{th} is rare, and tends to be very soft
6. Apply kinematic cuts

1 TeV Top-Jet Gallery

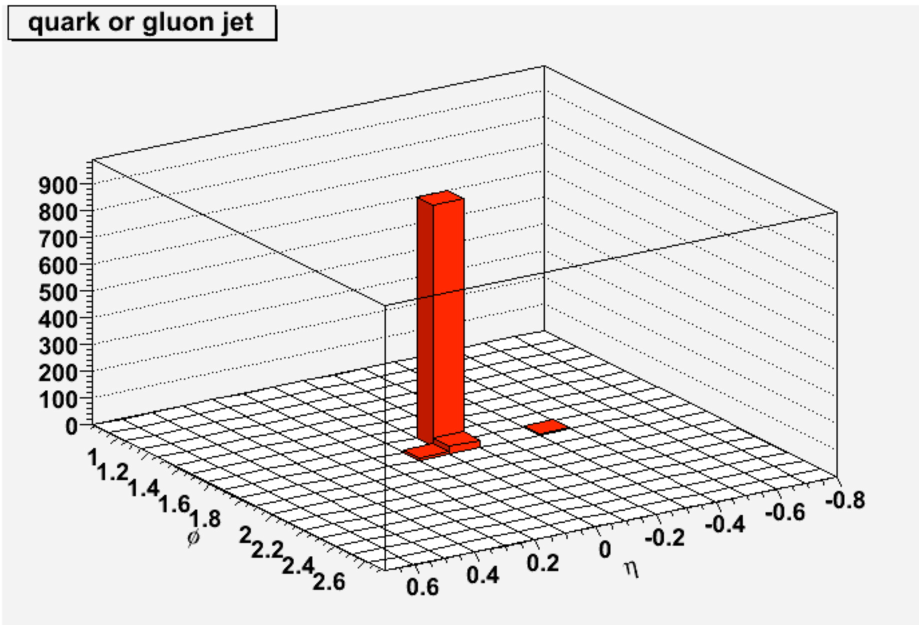


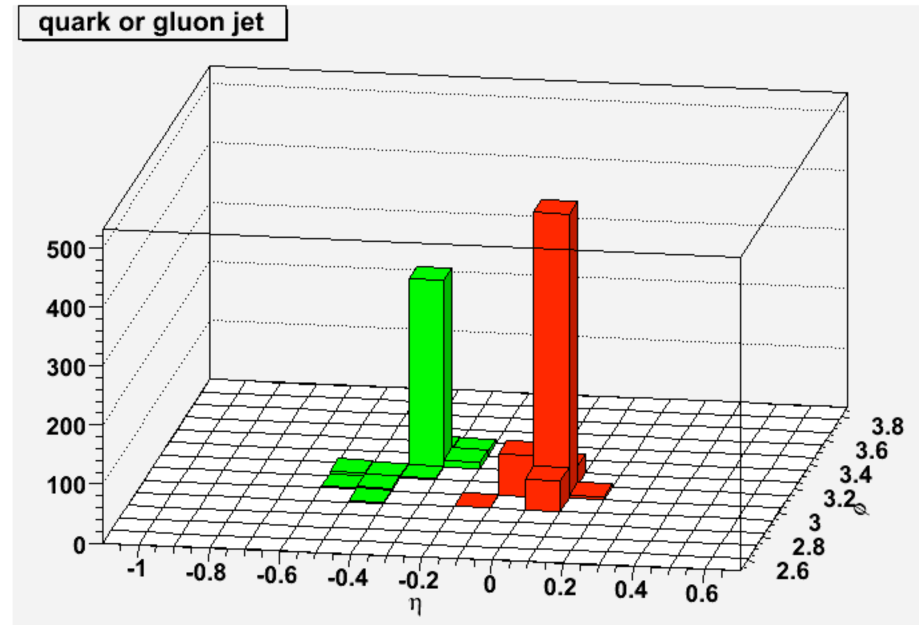


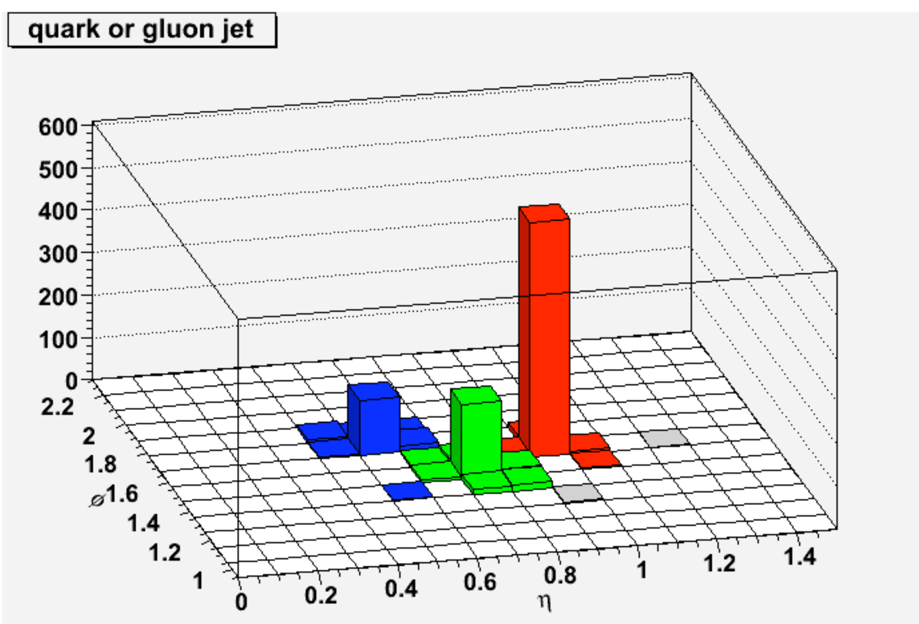


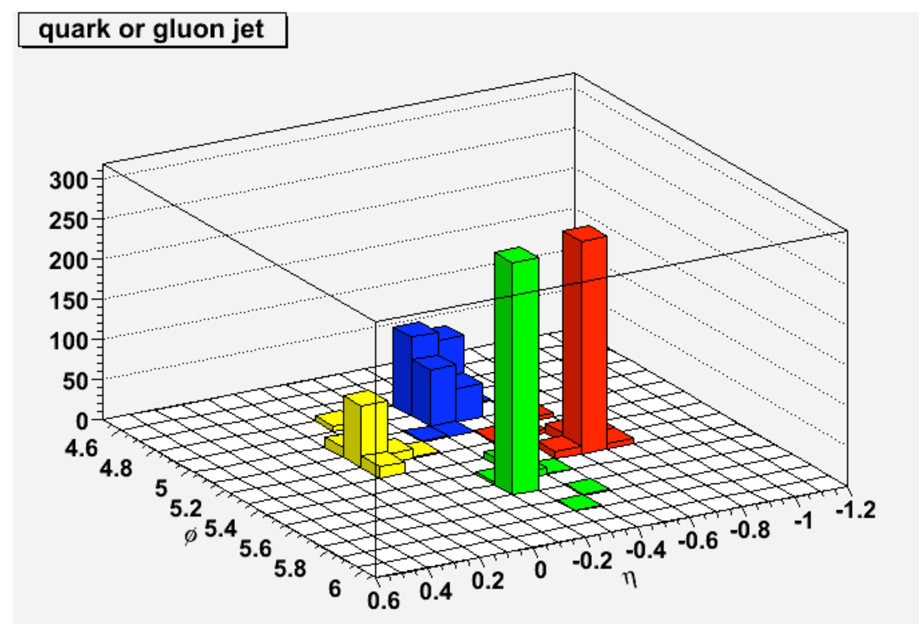


1 TeV Light-Jet Gallery

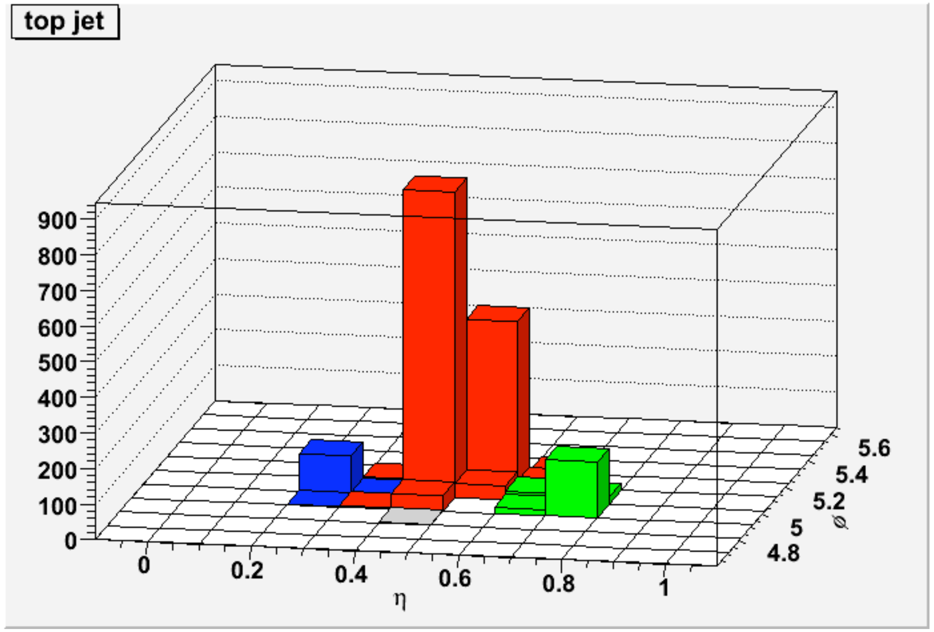


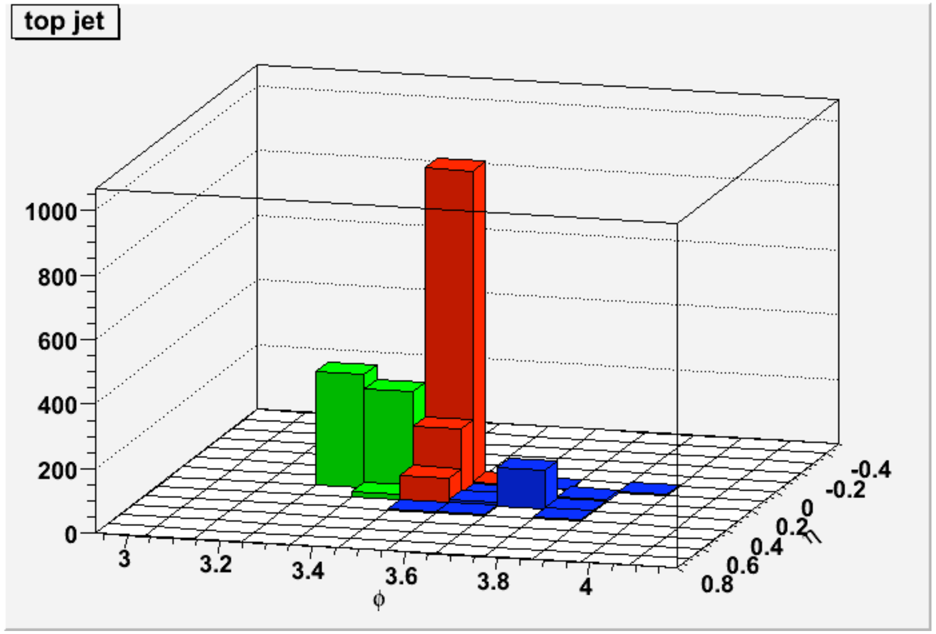




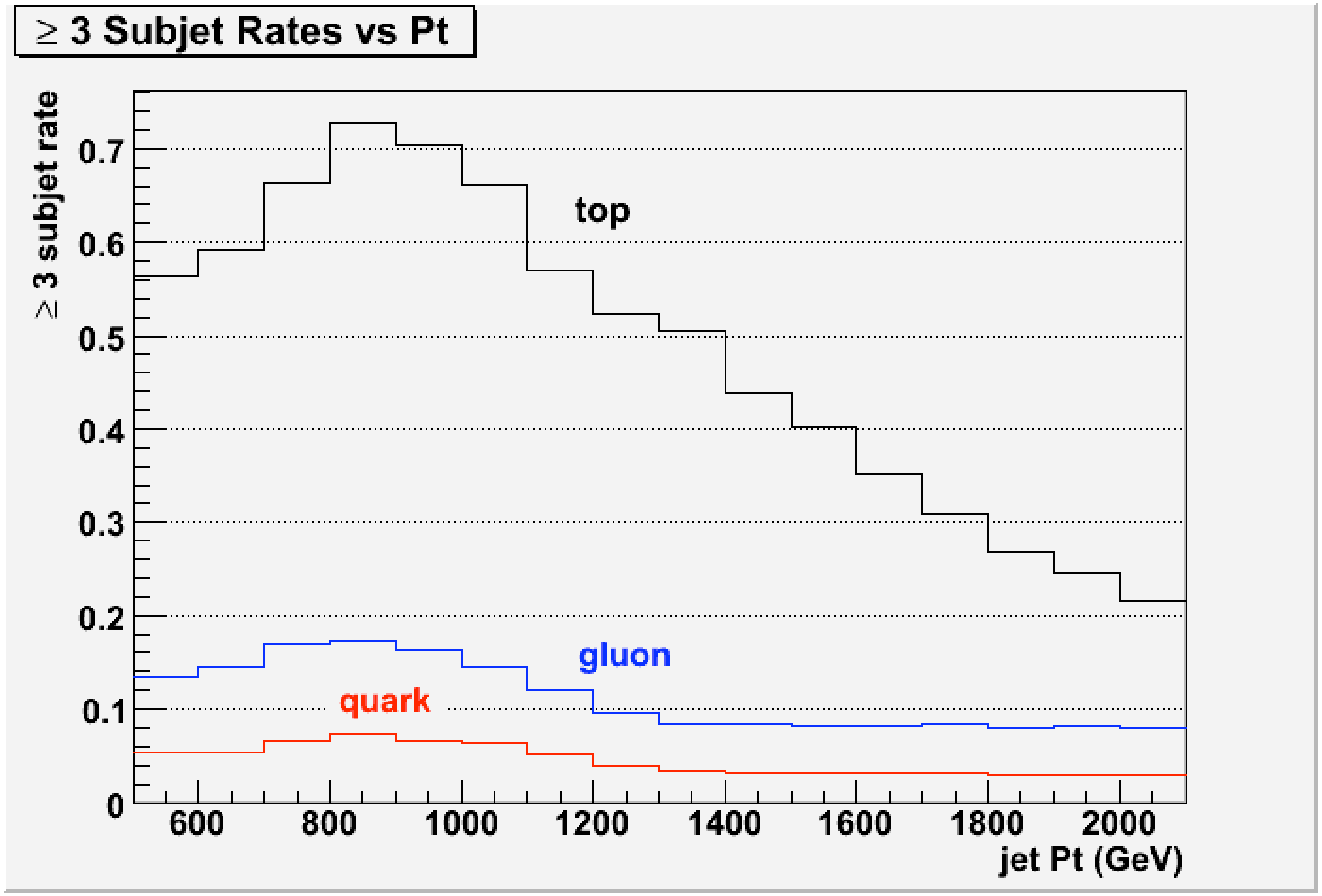


Some 2 TeV Top-Jets





Subjet Rates

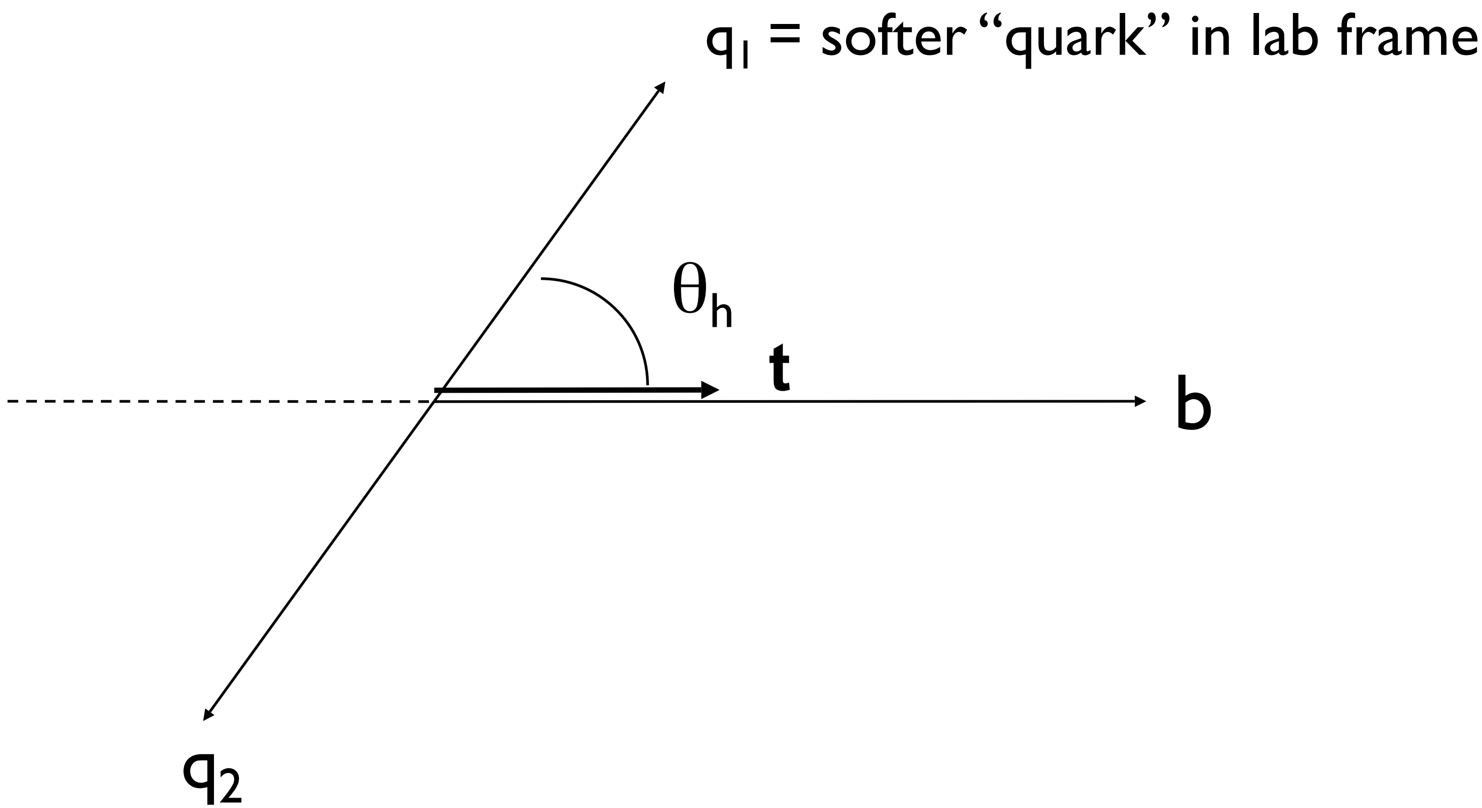


Kinematic Cuts

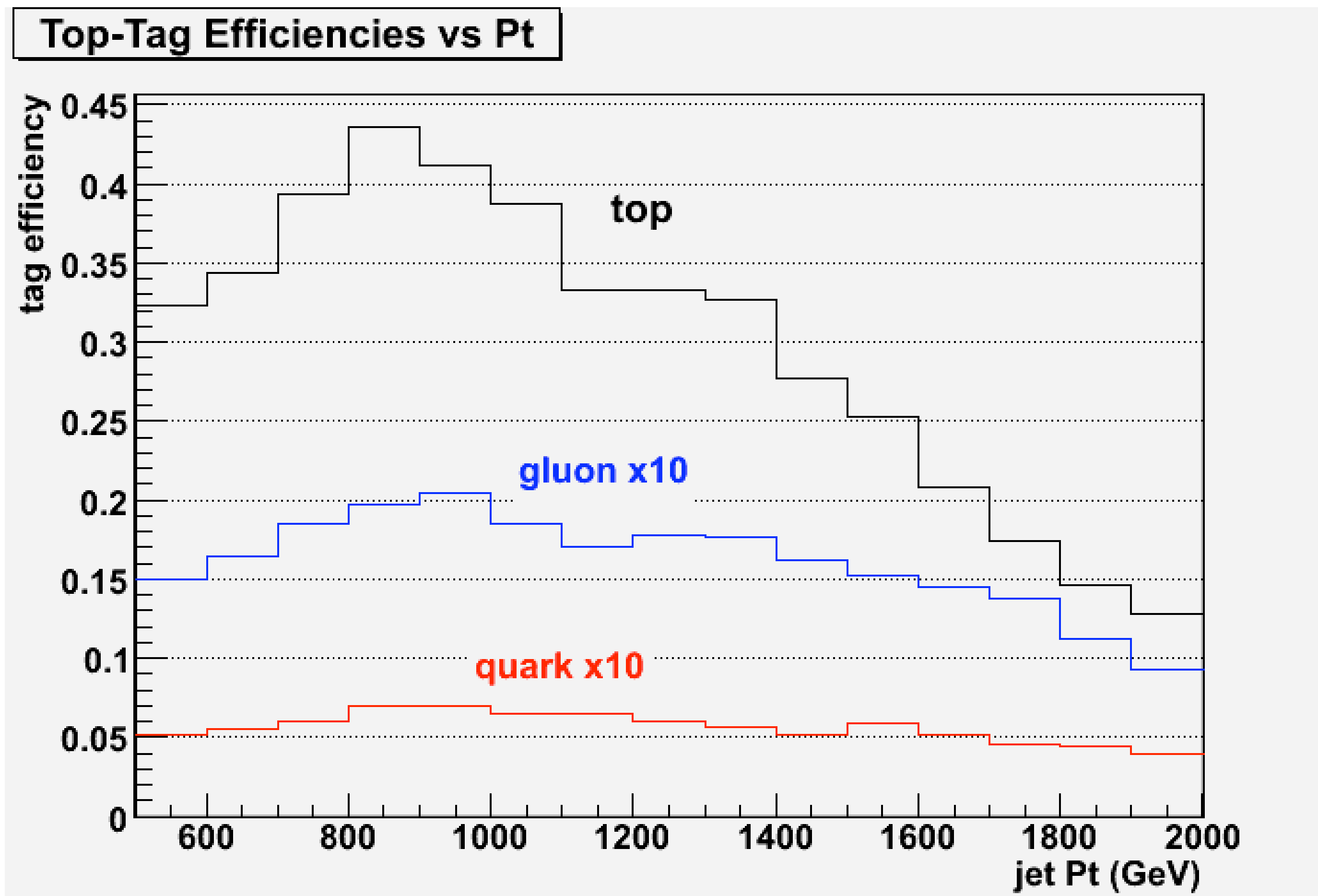
- Top mass
  - Pt < 1 TeV: m_{1234} = [145, 205]
  - Pt > 1 TeV: m_{1234} = [145, Pt/20+155]
- Best-pairing W mass
  - Pt < 1 TeV: m_W = [65, 95]
  - Pt > 1 TeV: m_W = [65, Pt/40+70]
- W helicity angle
  - $\cos\theta_h < 0.7$

W Helicity Angle

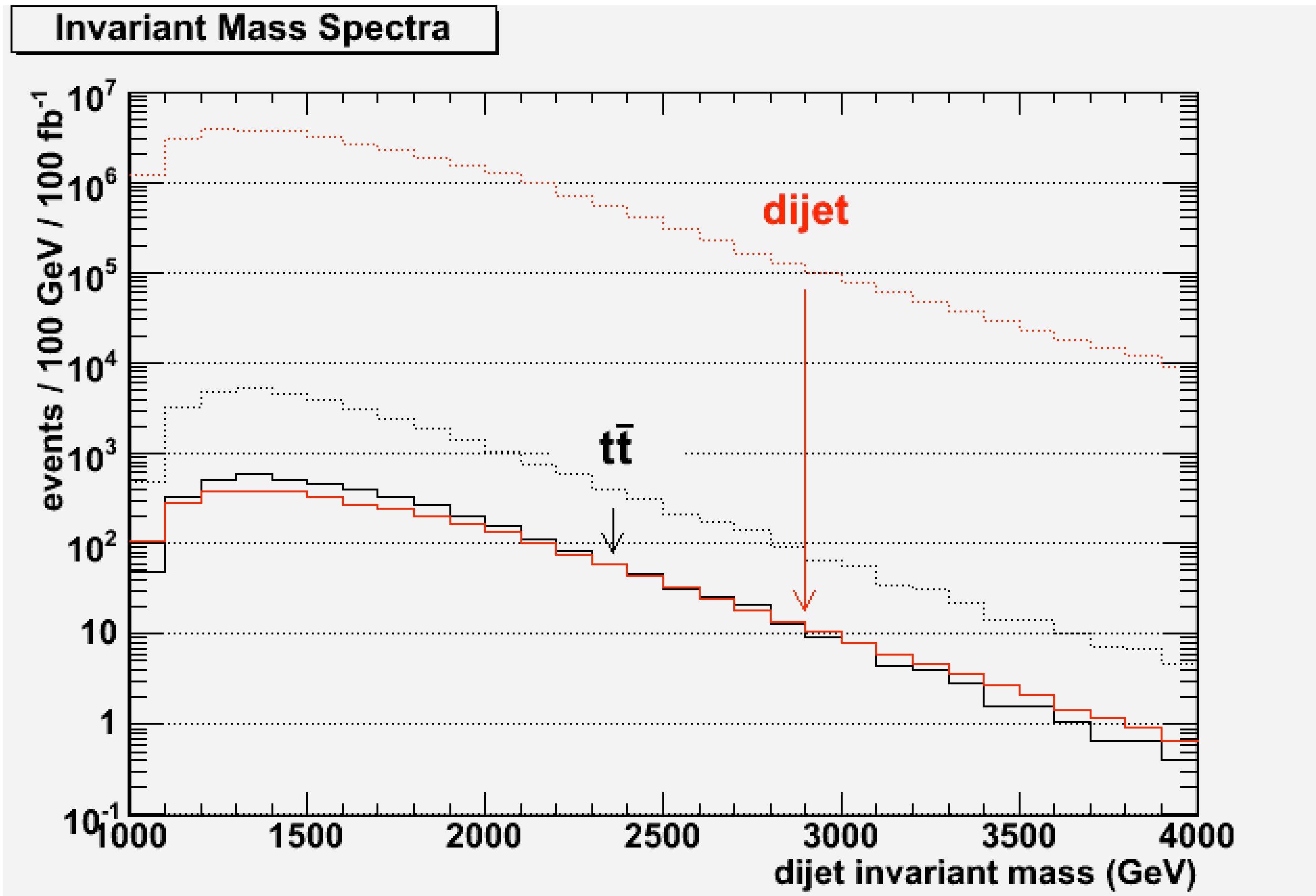
W rest frame



Final Efficiencies



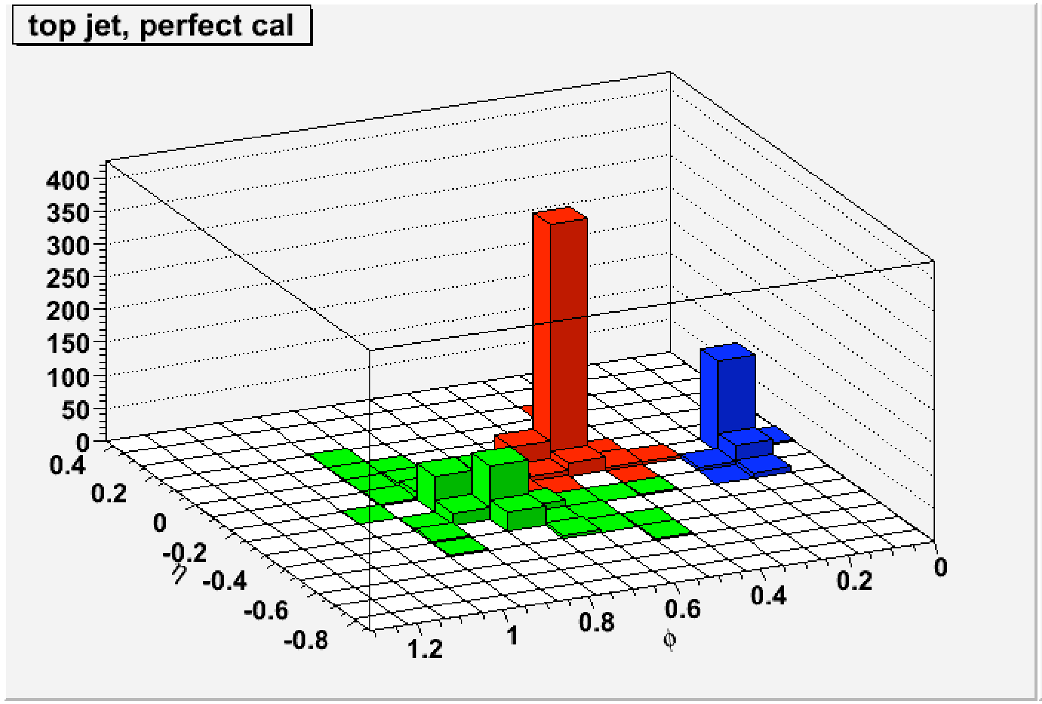
Final Dijet Mass Spectrum



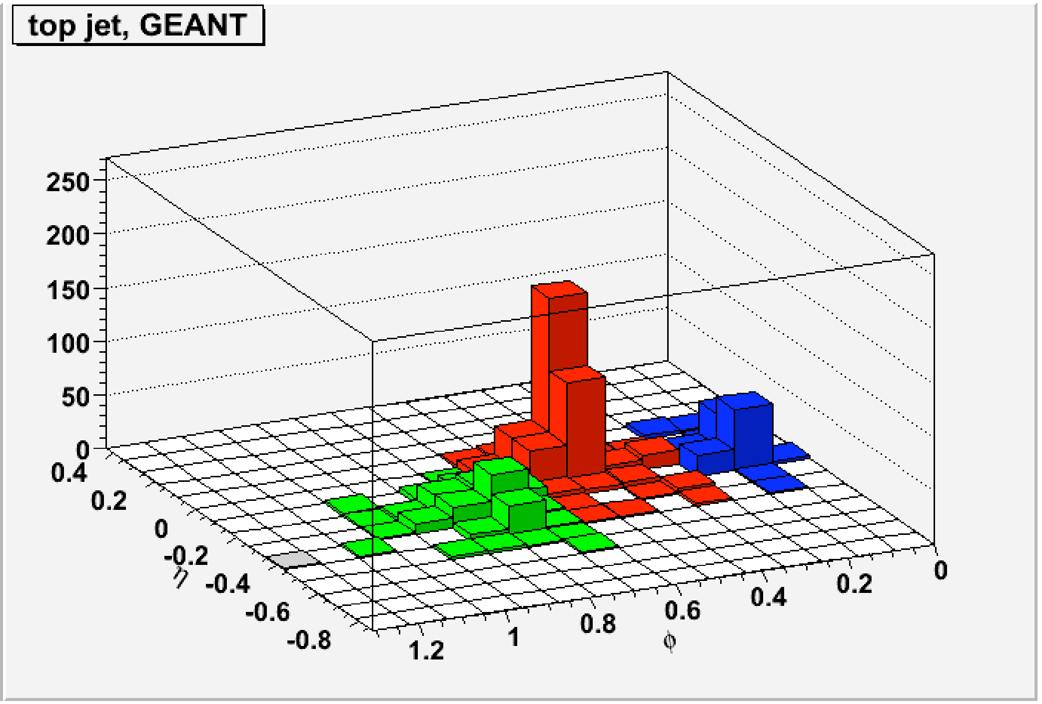
CMS Collaboration

- Sal Rappoccio, Morris Swartz, Petar Maksimovic
- Working on implementation of algorithm in CMS framework
- Proof of concept: 2 TeV *Z*', full detector simulation
  - PYTHIA-based physics
  - Decays to light quarks and tops
  - Pt = 0.5~1 TeV

Us vs Sal

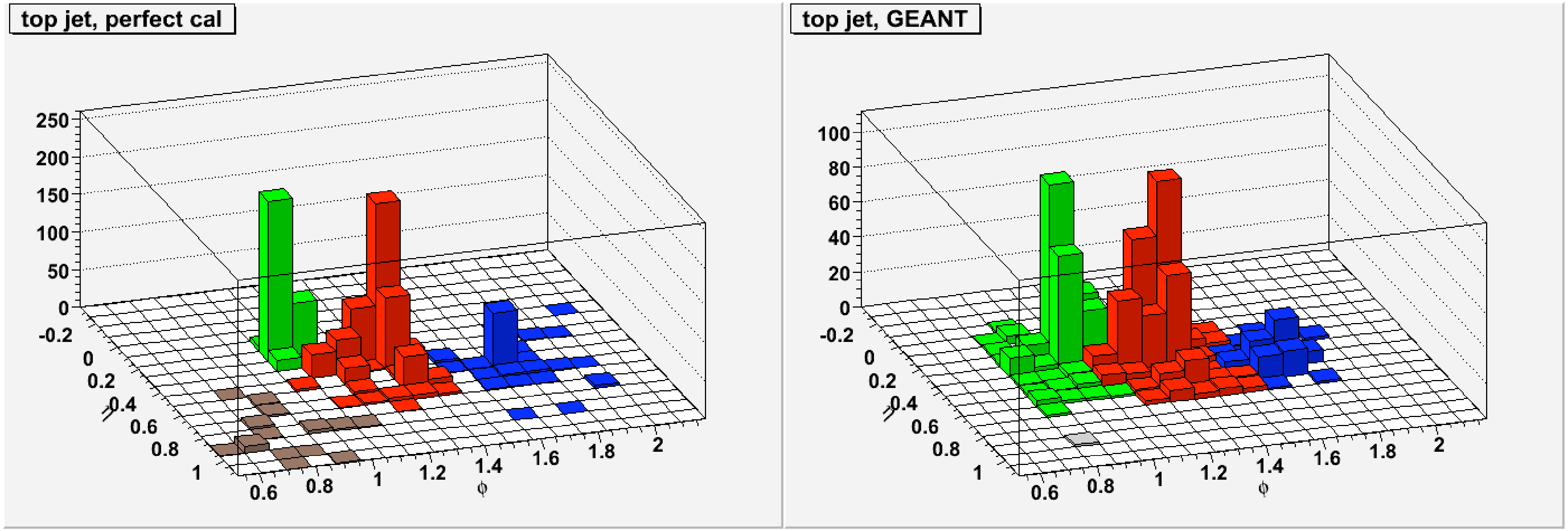


top jet, perfect cal
400
350
300
250
200
150
100
50
0
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
η
1.2
1
0.8
0.6
0.4
0.2
0
φ



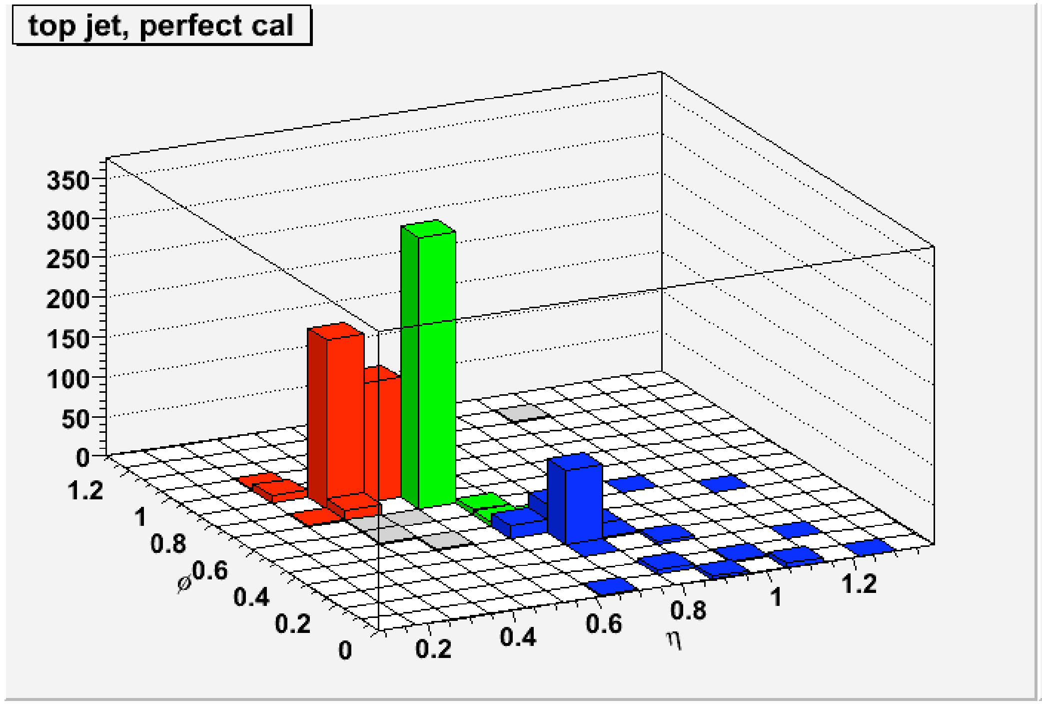
top jet, GEANT
250
200
150
100
50
0
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
η
1.2
1
0.8
0.6
0.4
0.2
0
φ

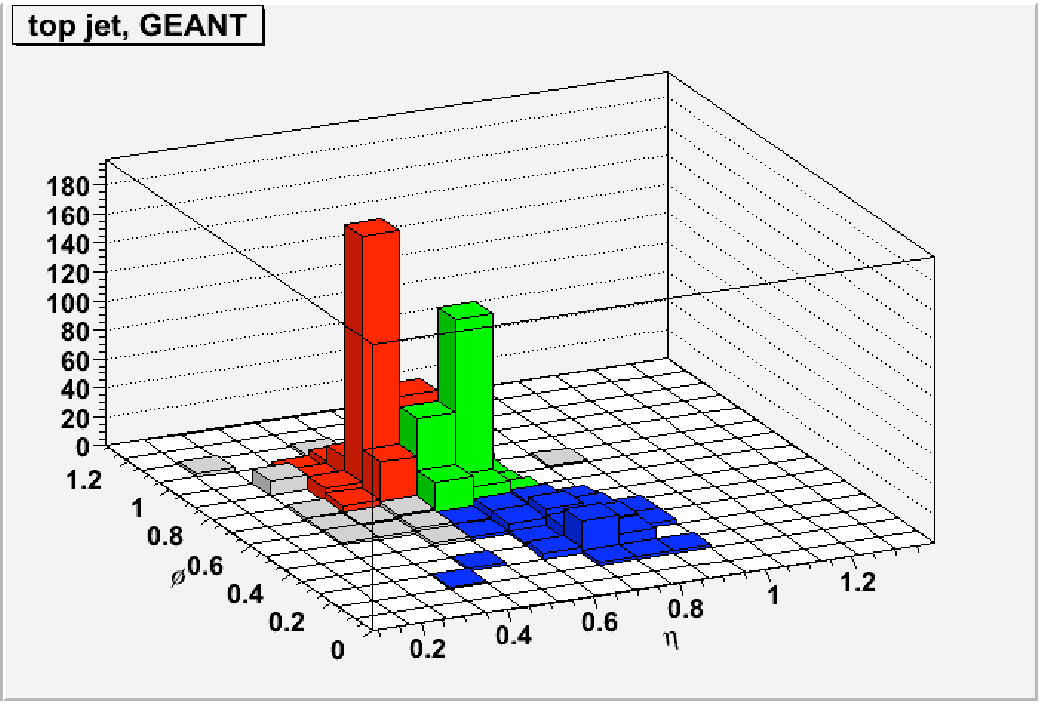
Us vs Sal



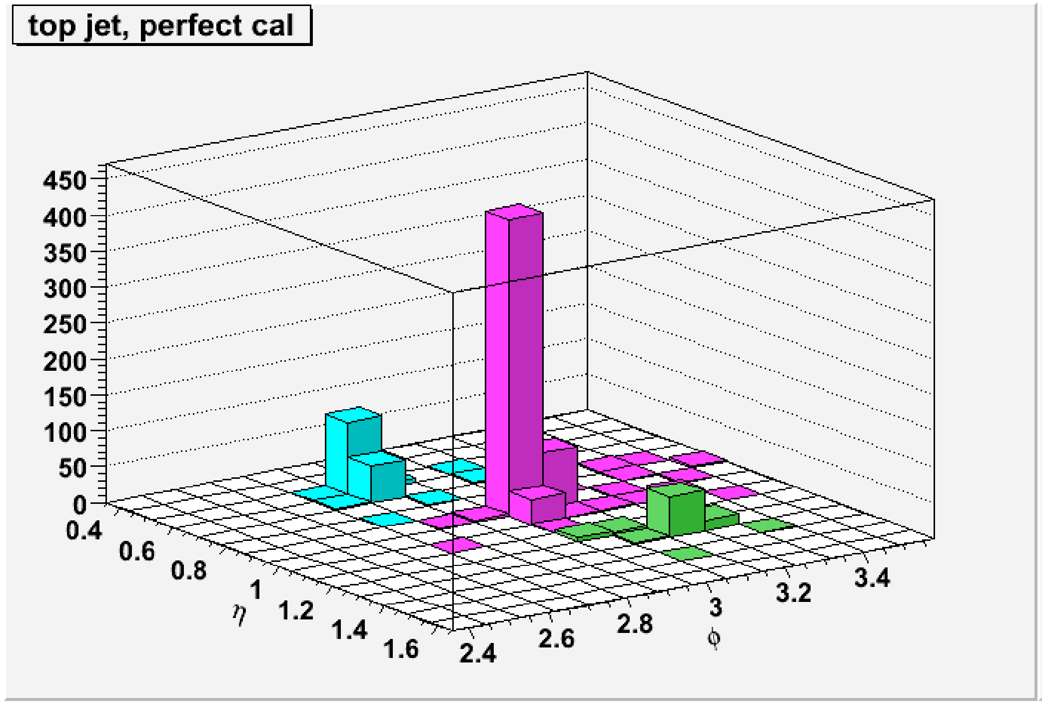
top jet, perfect cal
250
200
150
100
50
0
-0.2
0
0.2
0.4
0.6
0.8
1
0.6
0.8
1
1.2
1.4
1.6
1.8
2
ϕ
top jet, GEANT
100
80
60
40
20
0
-0.2
0
0.2
0.4
0.6
0.8
1
0.6
0.8
1
1.2
1.4
1.6
1.8
2
ϕ

Us vs Sal

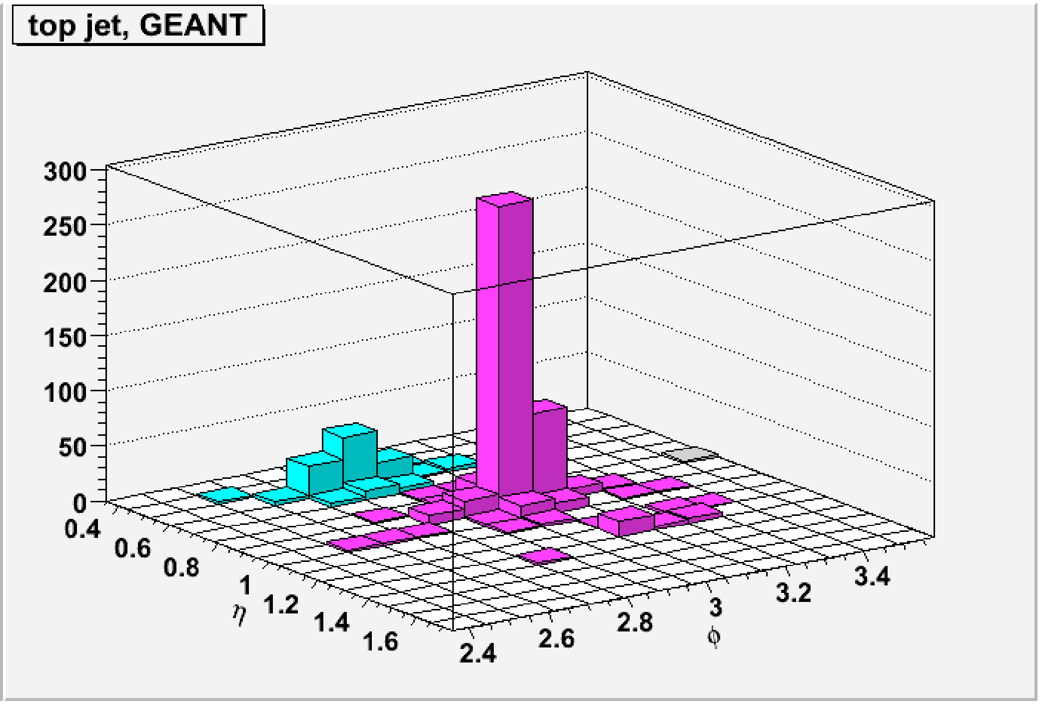

top jet, perfect cal
350
300
250
200
150
100
50
0
1.2
1
0.8
ϕ 0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2
η


top jet, GEANT
180
160
140
120
100
80
60
40
20
0
1.2
1
0.8
ϕ 0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2
η

Us vs Sal



top jet, perfect cal
450
400
350
300
250
200
150
100
50
0
0.4
0.6
0.8
1
1.2
1.4
1.6
η
2.4
2.6
2.8
3
3.2
3.4
φ



top jet, GEANT
300
250
200
150
100
50
0
0.4
0.6
0.8
1
1.2
1.4
1.6
η
2.4
2.6
2.8
3
3.2
3.4
φ

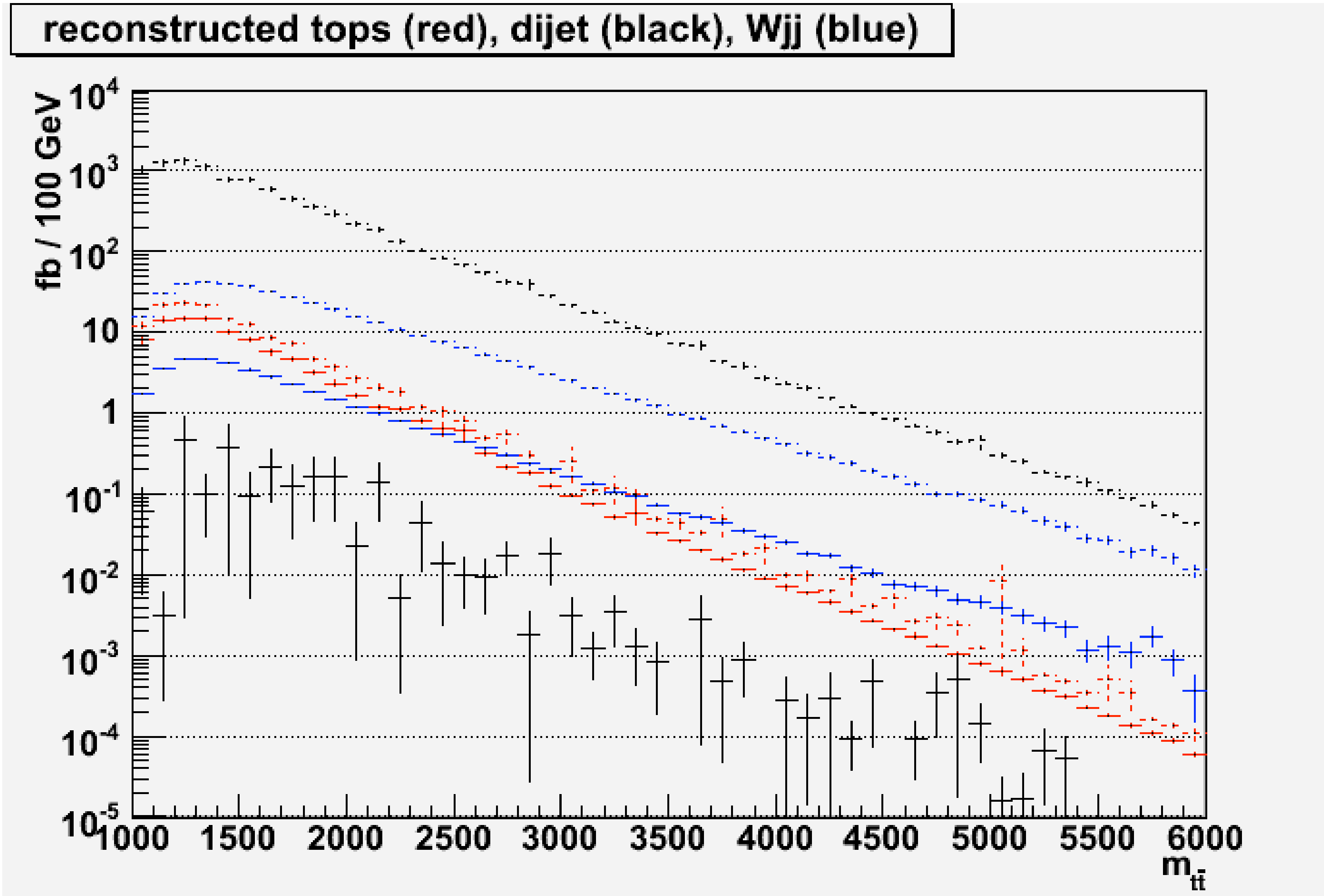
Technology Summary

- Bottomline: it still works
- Final efficiencies for *t* / *q* (2 TeV *Z'*)
  - Us: 36% / 0.7%
  - Sal: 32% / 1.0%
- Most S/B degradation attributable to energy resolution
- Higher stats / masses in the pipeline
  - How fast do efficiencies fall off?

Future Directions

- ECAL
  - Captures ~10% of jet energy
  - 5x better spatial resolution
- Tracker
  - Sees all charged particles
  - Even better resolution
  - Crowded for individual track ID, but maybe not for tracing Et flow

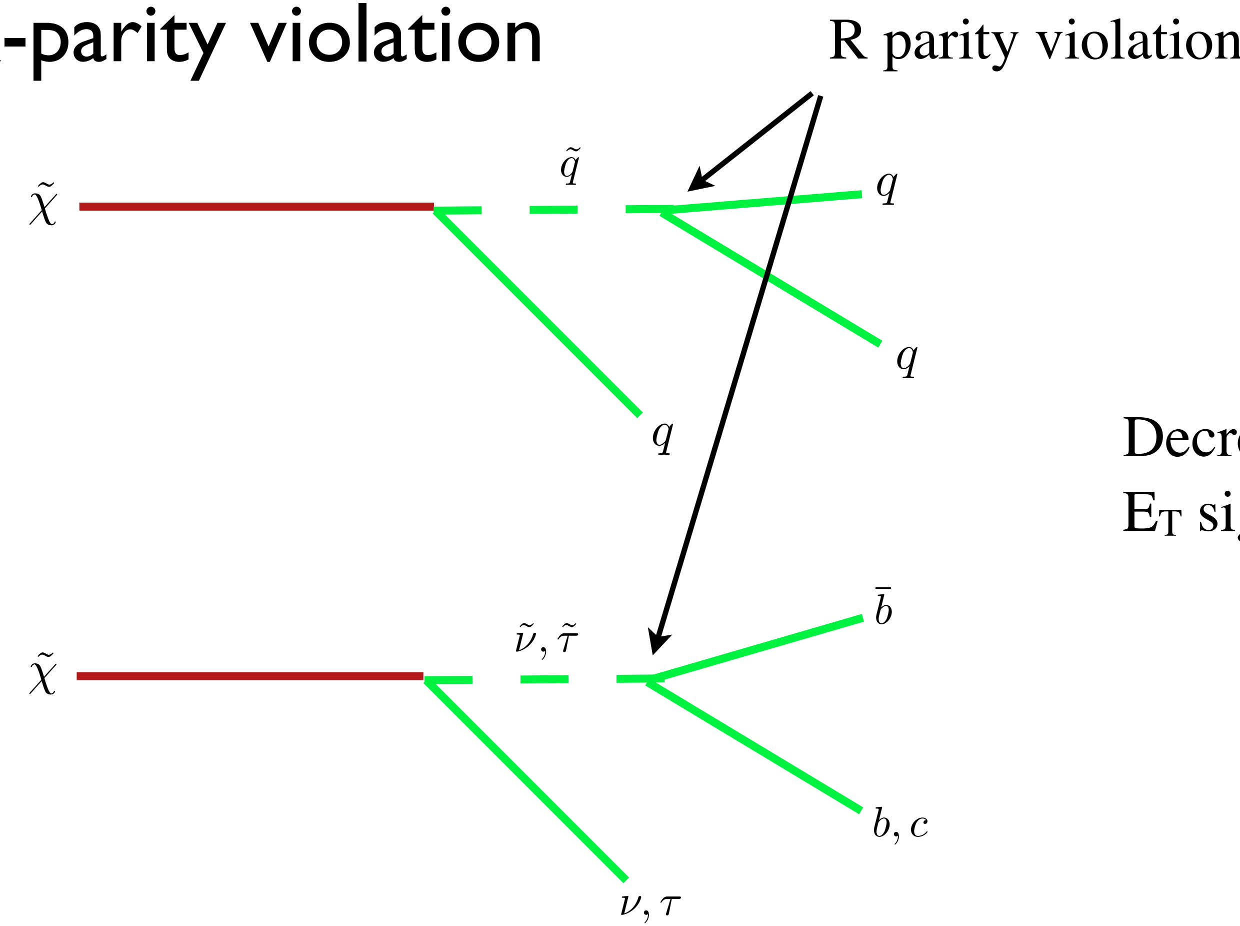
Semi-leptonic



preliminary - Rehermann, Tweedie

Non-standard Searches

Displaced vertices:
e.g., R-parity violation

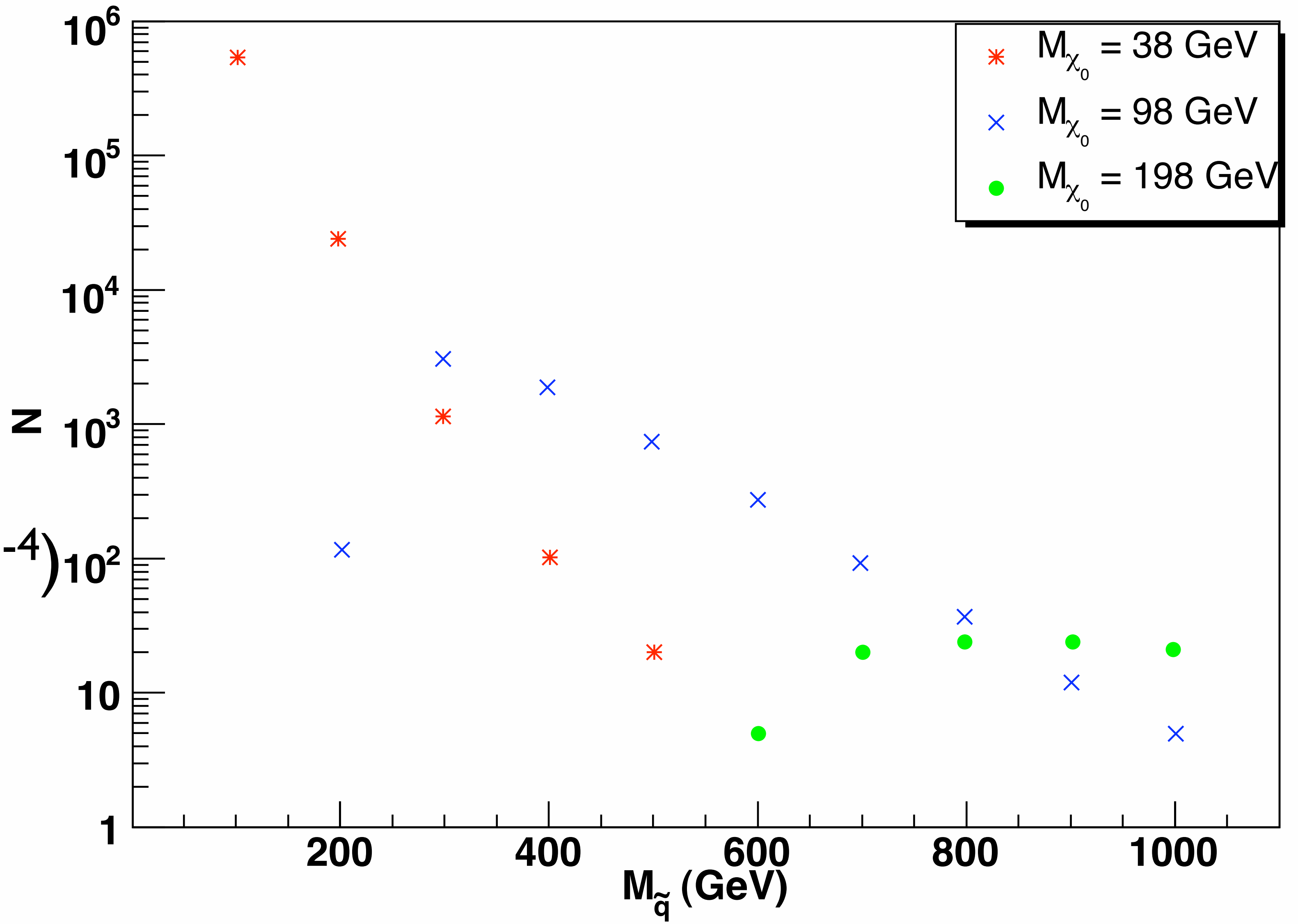


Decreases missing
E_T signal

Squark production at LHCb: One year running

Number of events with at least 5 tracks in the acceptance.

(coupling ~ 10^{-4})

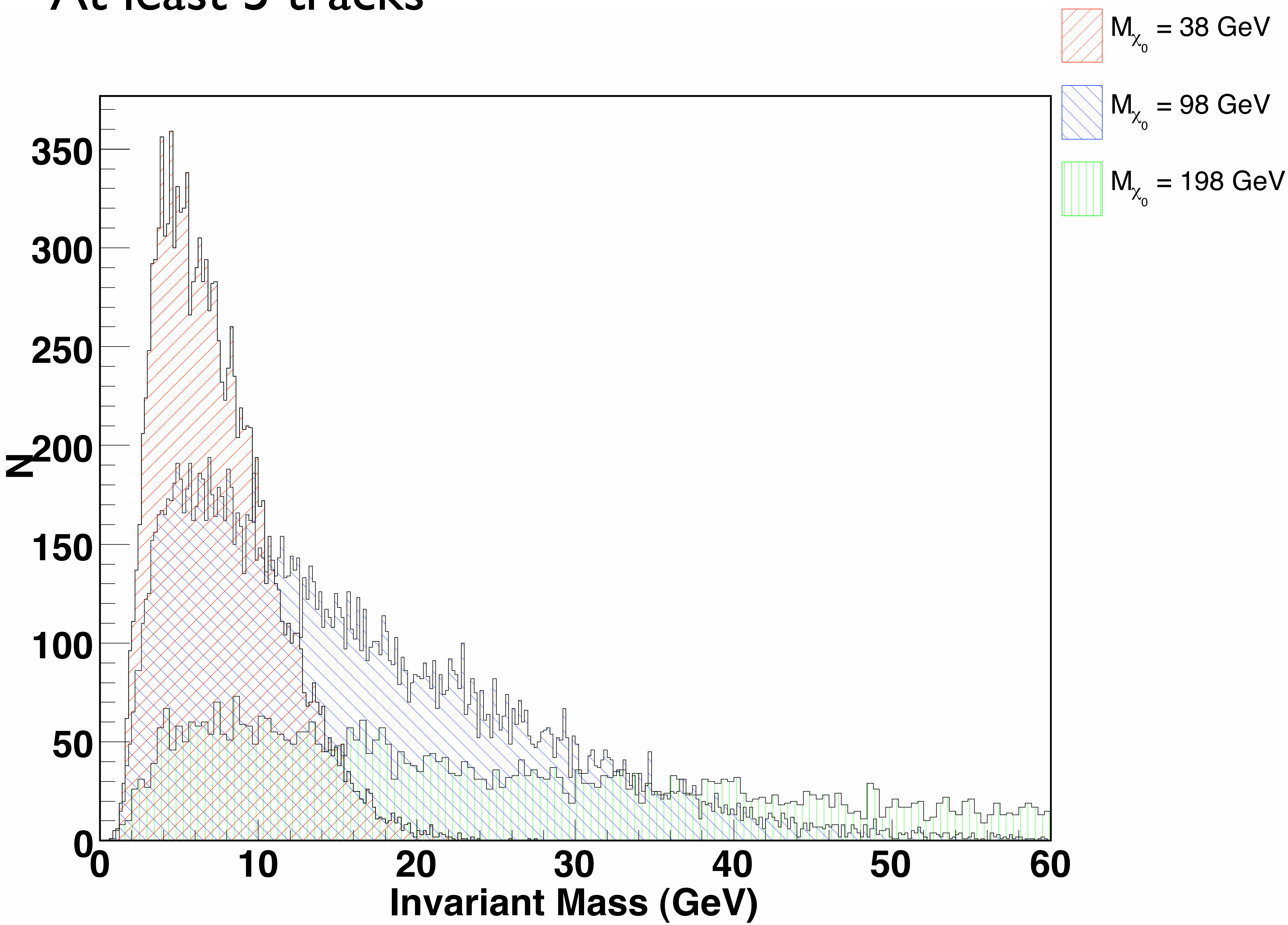


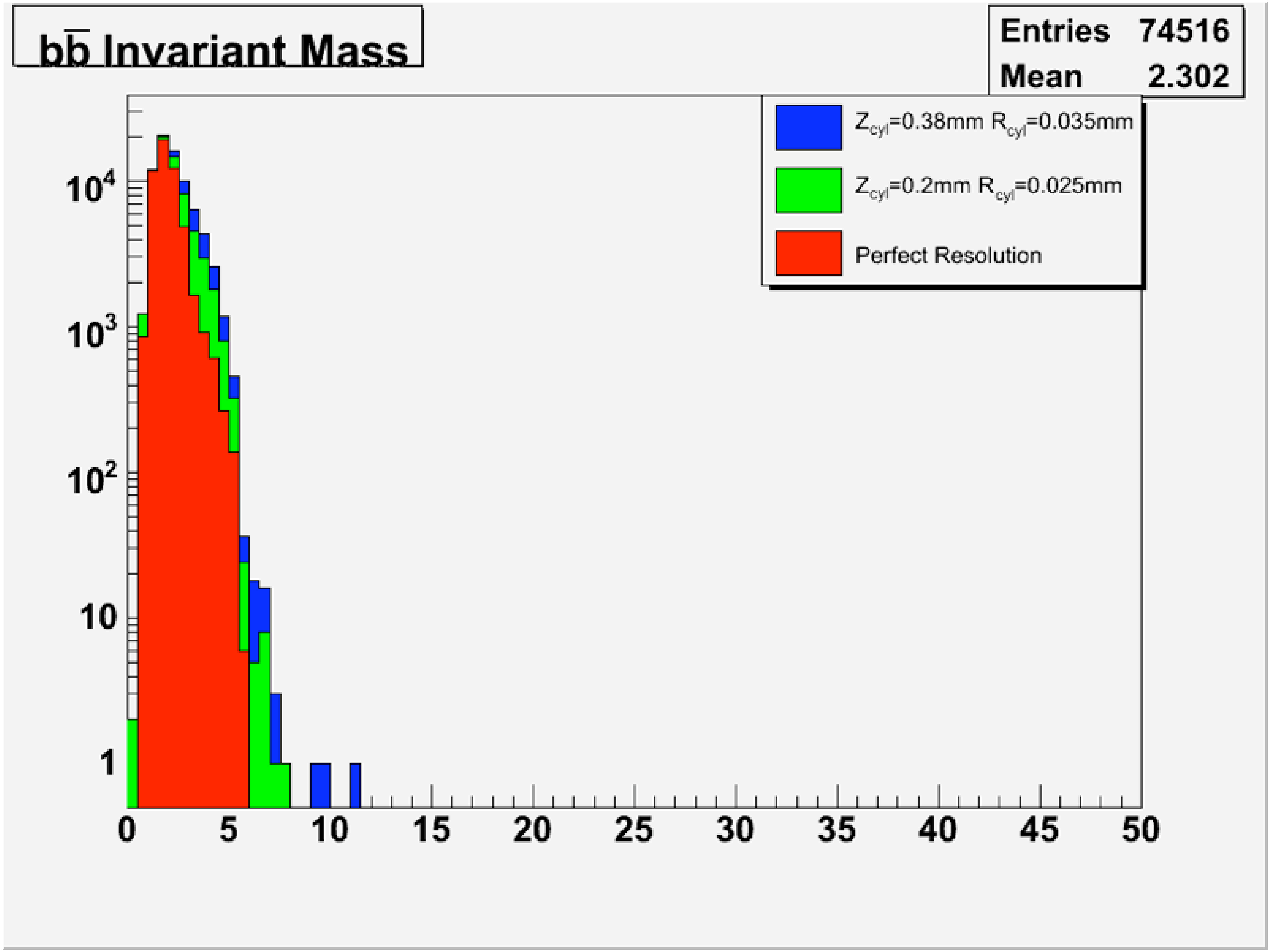
Distinguish from B's

Look at *invariant mass* > 5 GeV
of tracks from displaced vertex.

Look for *large multiplicity* of
tracks from a single vertex.

At least 5 tracks





$b\bar{b}$ Invariant Mass
Entries 74516
Mean 2.302
Z_{cyl}=0.38mm R_{cyl}=0.035mm
Z_{cyl}=0.2mm R_{cyl}=0.025mm
Perfect Resolution
10^4
10^3
10^2
10
1
0
5
10
15
20
25
30
35
40
45
50

Biggest background

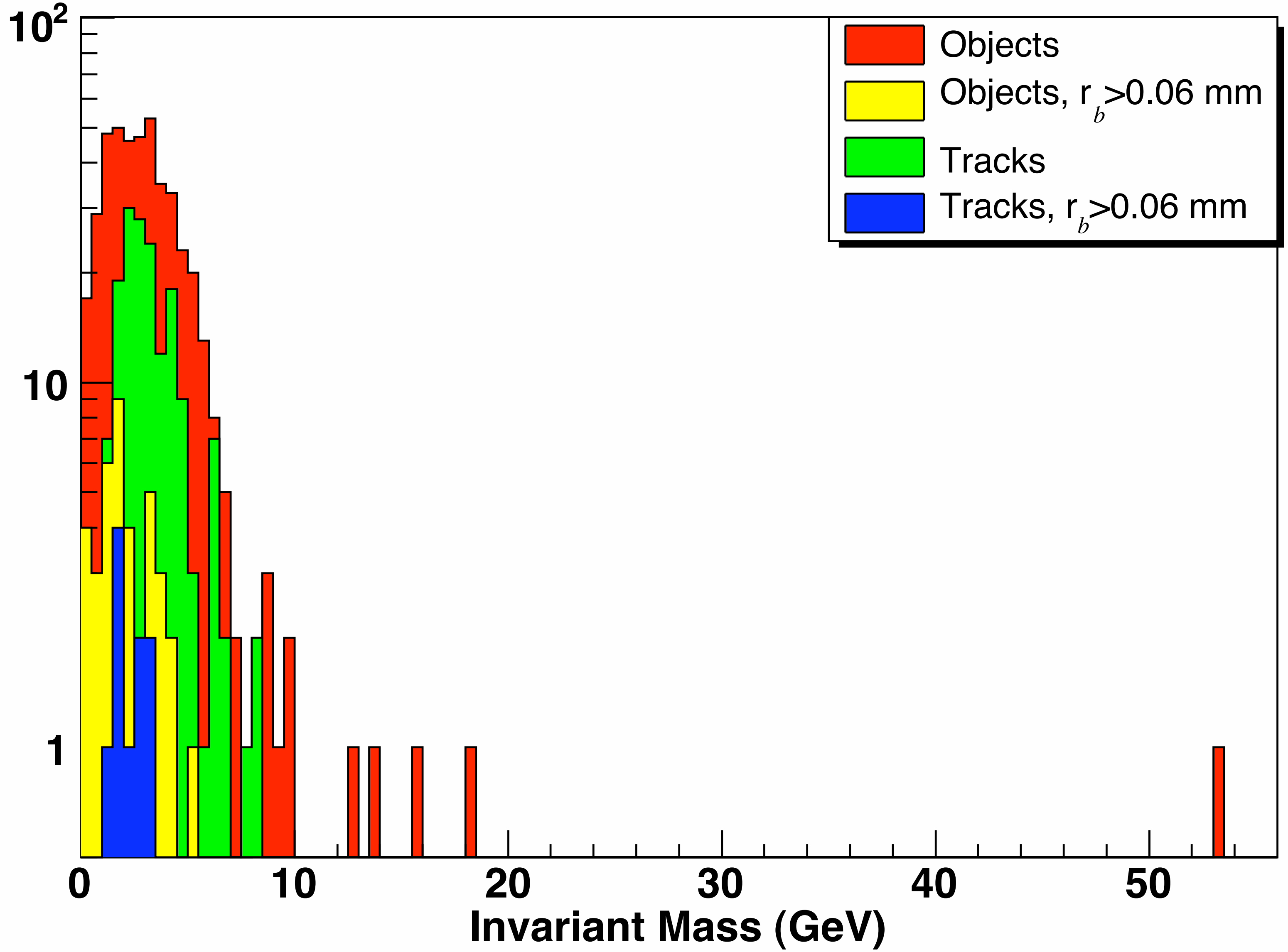
Looked for *b* decays on top of other decays.

Simulated *gg->bb*, *gb->bbb*, *gg->bbbb*, *gg->bbcc*

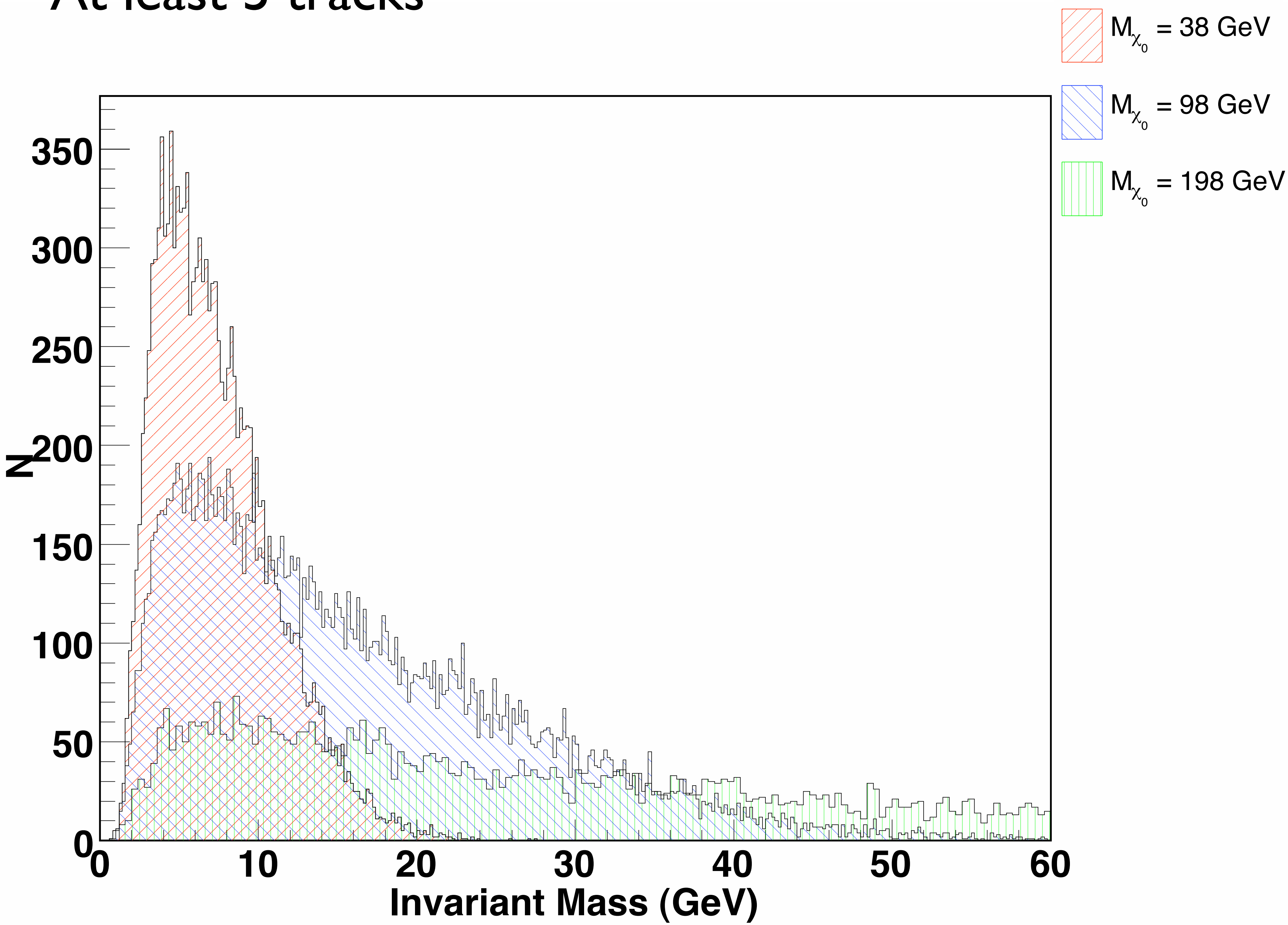
Expect 10^{12} *b*-pairs per year!!!

Had computing time to simulate 10^{-5} years.

Overlapping events

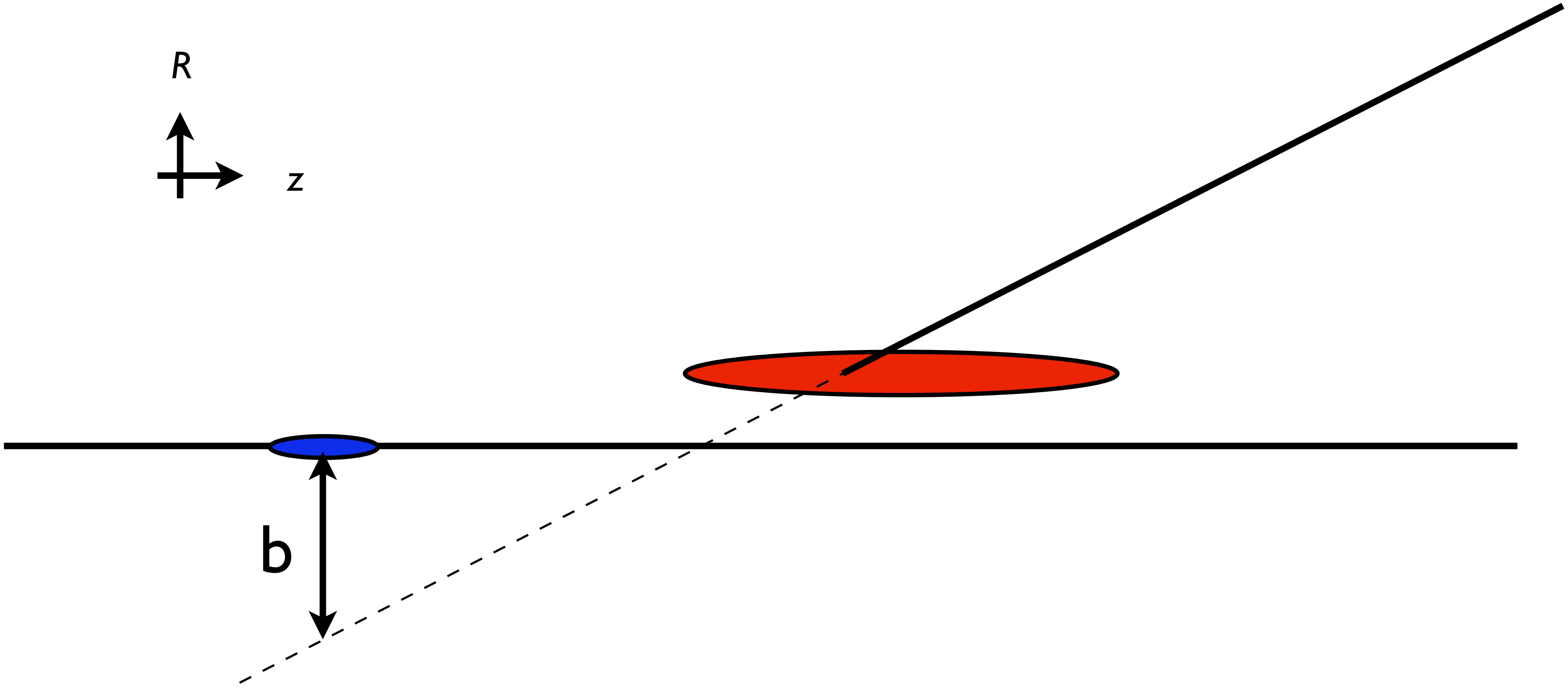


At least 5 tracks

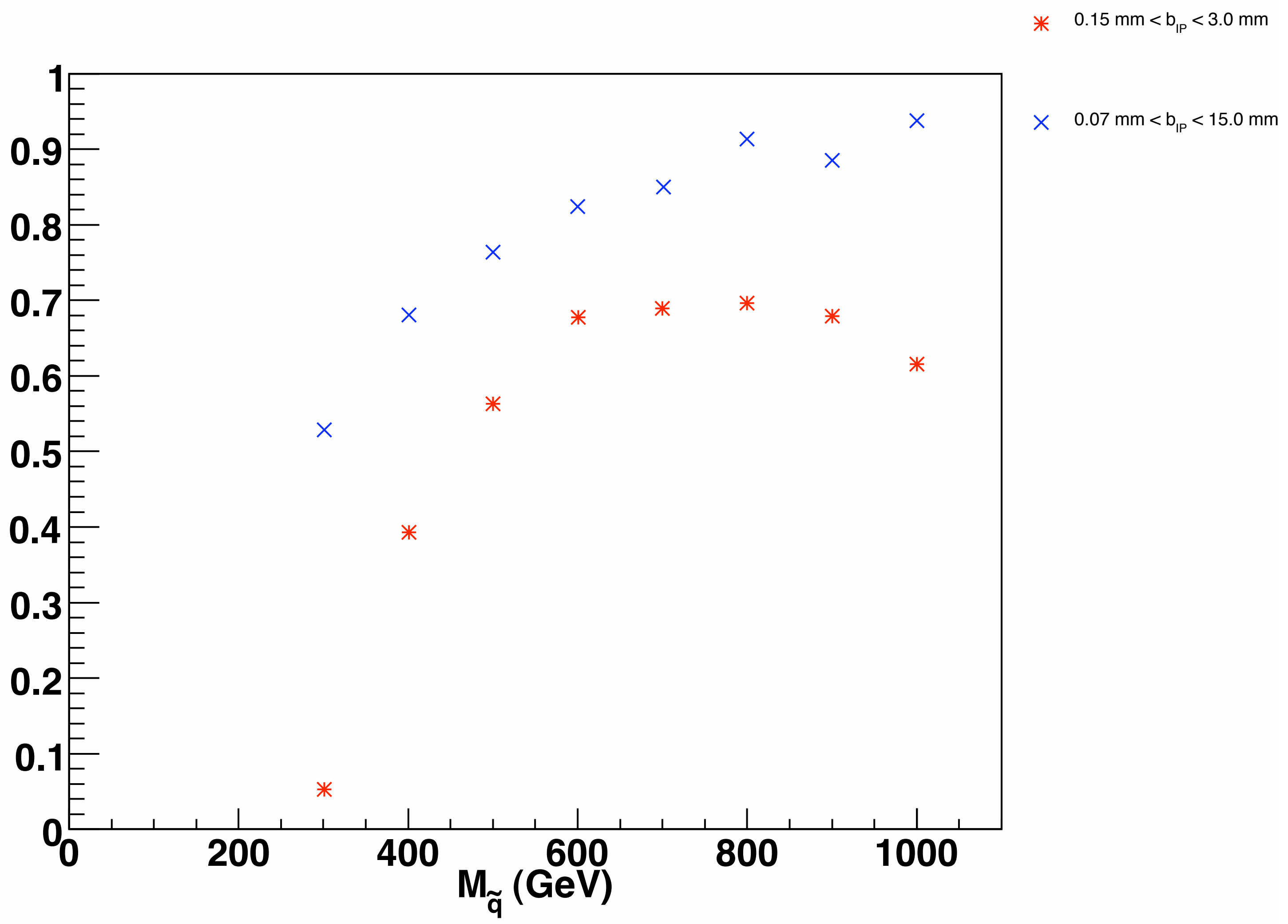


Level 1 Trigger

.15 mm < b < 3 mm



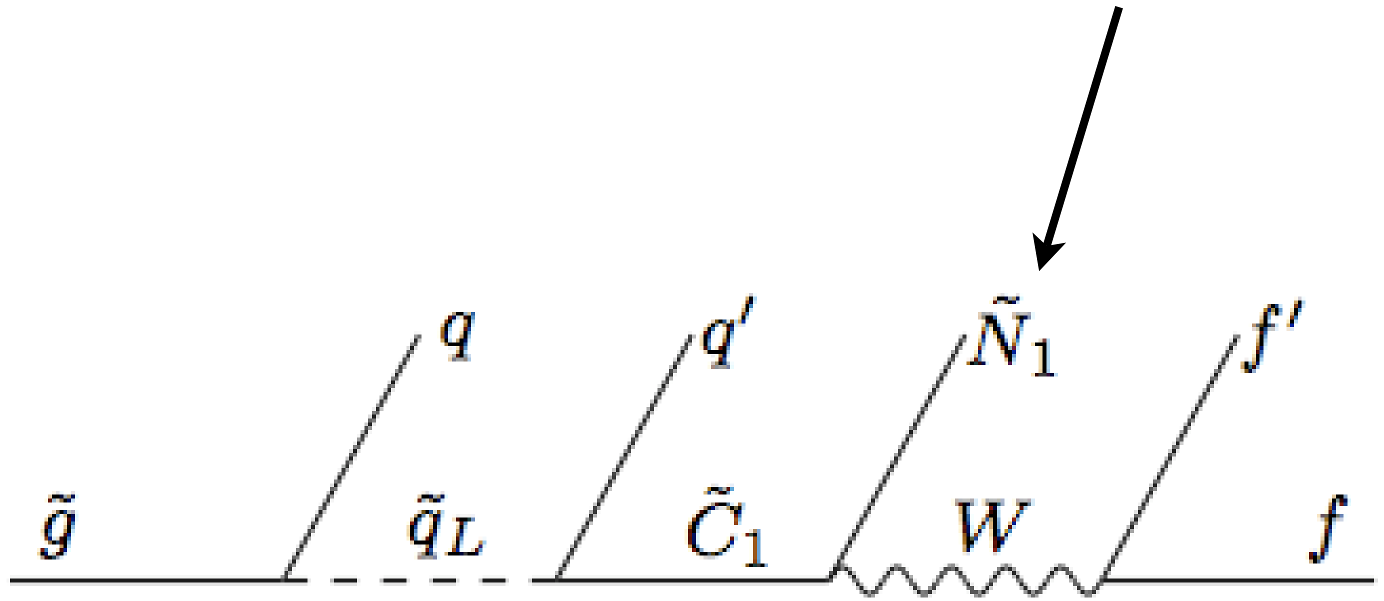
IP cuts and efficiency



Dark Matter

Traditionally, cascades:

stable LSP is DM = missing E_T



Asymmetric DM

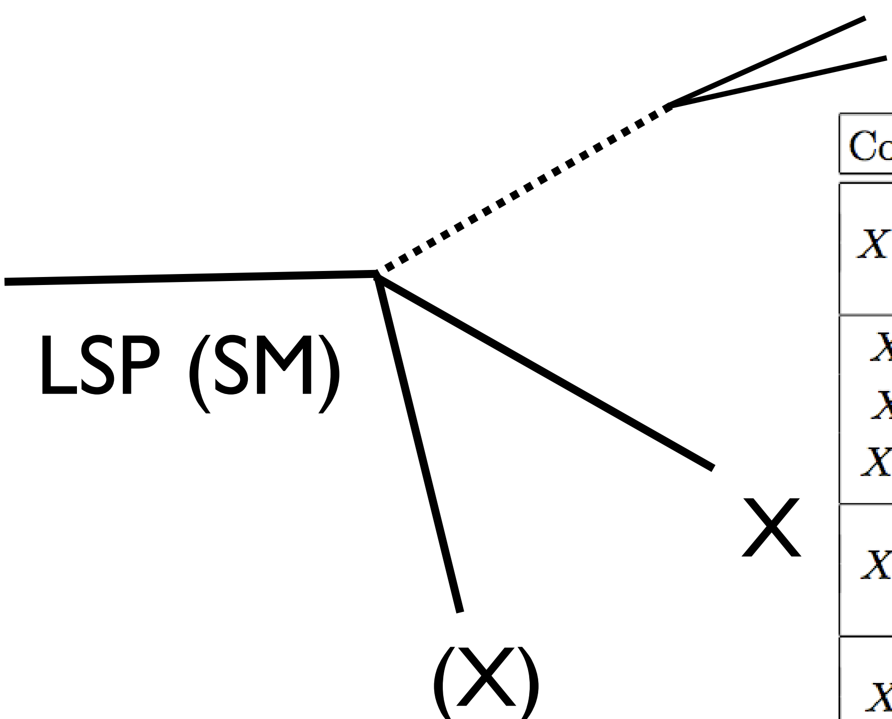
The lepton, or B-L asymmetry is transferred to the dark sector in equilibrium

$$X^2 L H_u$$

$$\frac{\Omega_{DM}}{\Omega_b} \sim \frac{m_{DM}}{m_b}$$

DEK, Luty, Zurek '09; see also DB Kaplan '90; Kitano, Low '05

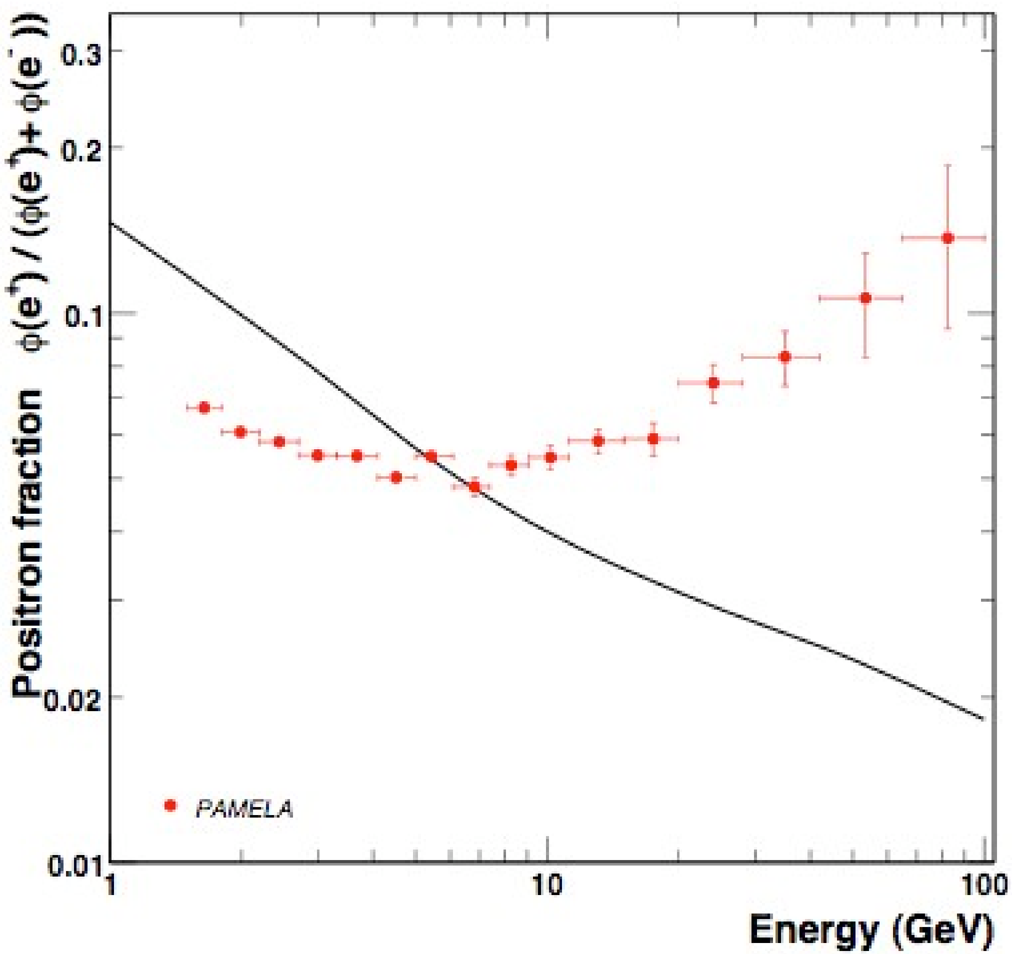
Asymmetric DM



Coupling	NLSP Decay	NLSP Signal
XH_uH_d	$\chi^0 \to X + (h^0, Z)$ $\chi^\pm \to X + (H^\pm, W^\pm)$	vertex $\to (h^0, Z) + \not{E}_T$ track $\to (H^\pm, W^\pm) + \not{E}_T$
XLH_u $XLH_d^\dagger$ $X^\dagger LH_u$	$\chi^\pm \to X + \ell^\pm$ $\tilde{\nu} \to X + (h^0, Z)$ $\tilde{\ell}^\pm \to X + (H^\pm, W^\pm)$	track $\to \ell^\pm + \not{E}_T$ vertex $\to (h^0, Z) + \not{E}_T$ track $\to (H^\pm, W^\pm) + \not{E}_T$
X^2LH_u	$\chi^\pm \to 2X + \ell^\pm$ $\tilde{\ell}^\pm \to 2X + (H^\pm, W^\pm)$	track $\to \ell^\pm + \not{E}_T$ track $\to (H^\pm, W^\pm) + \not{E}_T$
$XLLe^c$	$\tilde{\ell}^\pm \to X + \ell'^\pm$ $\tilde{\nu} \to X + \ell' + \bar{\ell}$	track $\to \ell'^\pm + \not{E}_T$ vertex $\to \ell' + \bar{\ell} + \not{E}_T$
$XQLd^c$	$\tilde{\ell}^\pm \to X + u + \bar{d}$ $\tilde{\nu} \to X + d + \bar{d}$ $\tilde{u} \to X + \ell^+ + d$ $\tilde{d} \to X + \nu + d$	track $\to$ 2 jets $+ \not{E}_T$ vertex $\to$ 2 jets $+ \not{E}_T$ R-hadron $\to \ell^\pm$ + jet $+ \not{E}_T$ R-hadron $\to$ jet $+ \not{E}_T$
$Xu^cd^cd^c$	$\tilde{u} \to X + \bar{d} + \bar{d}'$	R-hadron $\to$ 2 jets $+ \not{E}_T$

DEK, Luty, Zurek ’09;
Chang, Luty ‘09

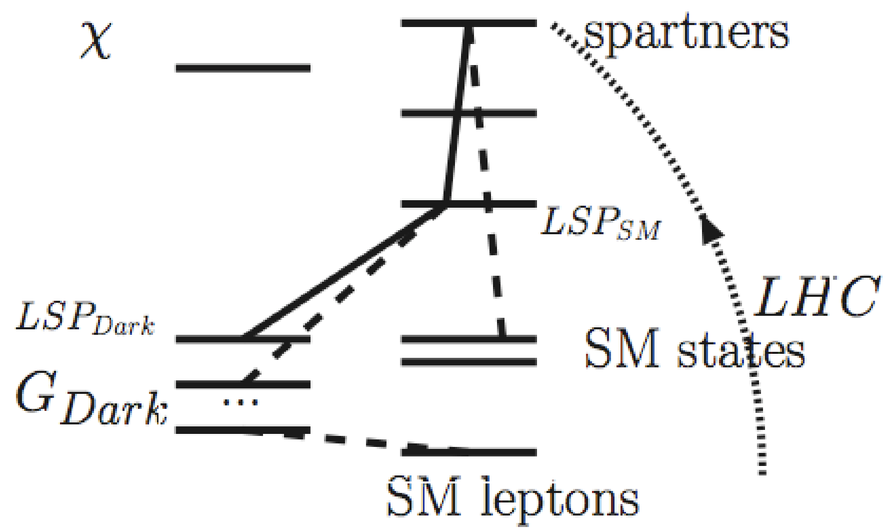
Cosmic Ray Data...

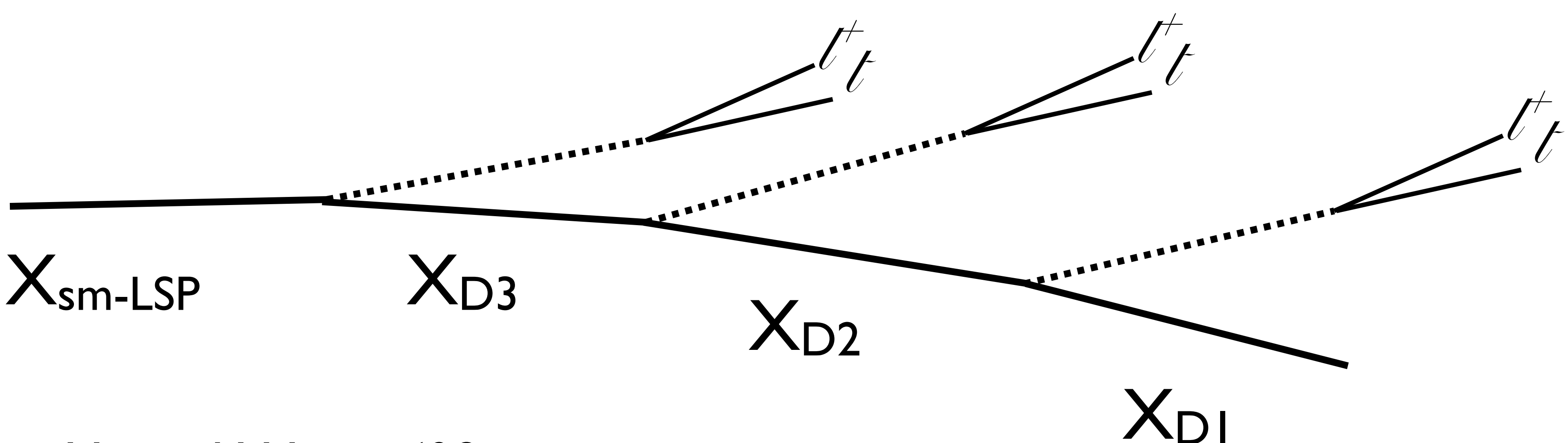


PAMELA satellite

Interpretation: DM annihilation is producing positrons (leptons!)

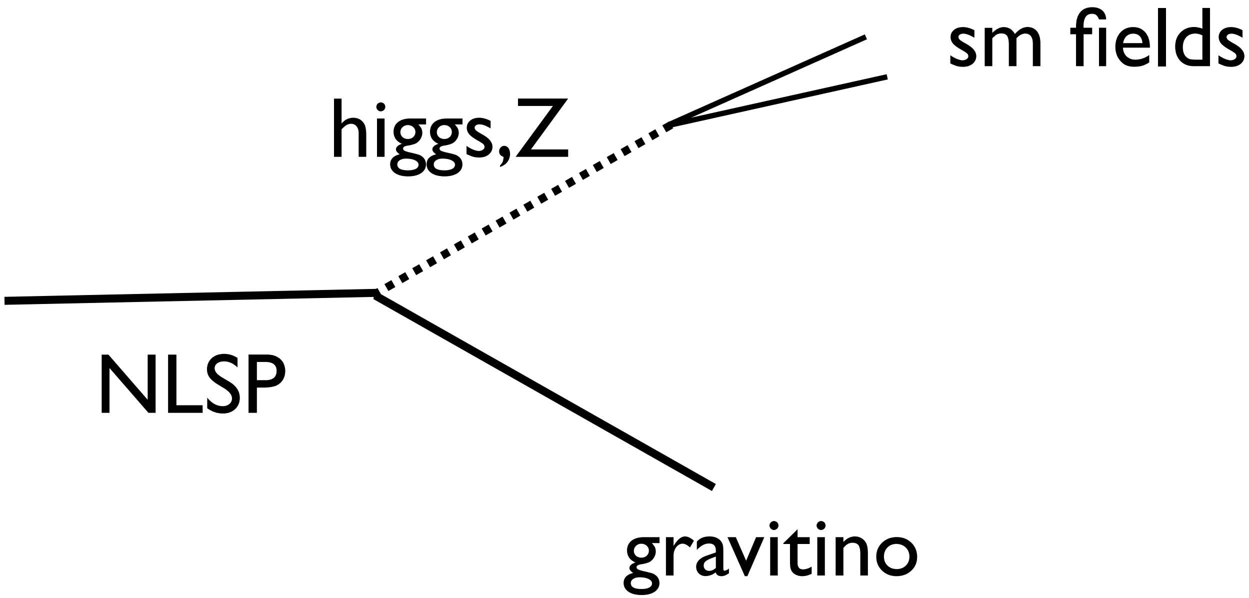
Lepton Jets!





Arkani-Hamed, Weiner '08

Other DVs - GMSB



$$\ell \simeq 100\mu\mathrm{m} \times \left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^5 \left(\frac{M_{mess}}{100\ \mathrm{TeV}}\right)^2 \left(\frac{M_{gluino}}{1\ \mathrm{TeV}}\right)^2$$

Conclusion

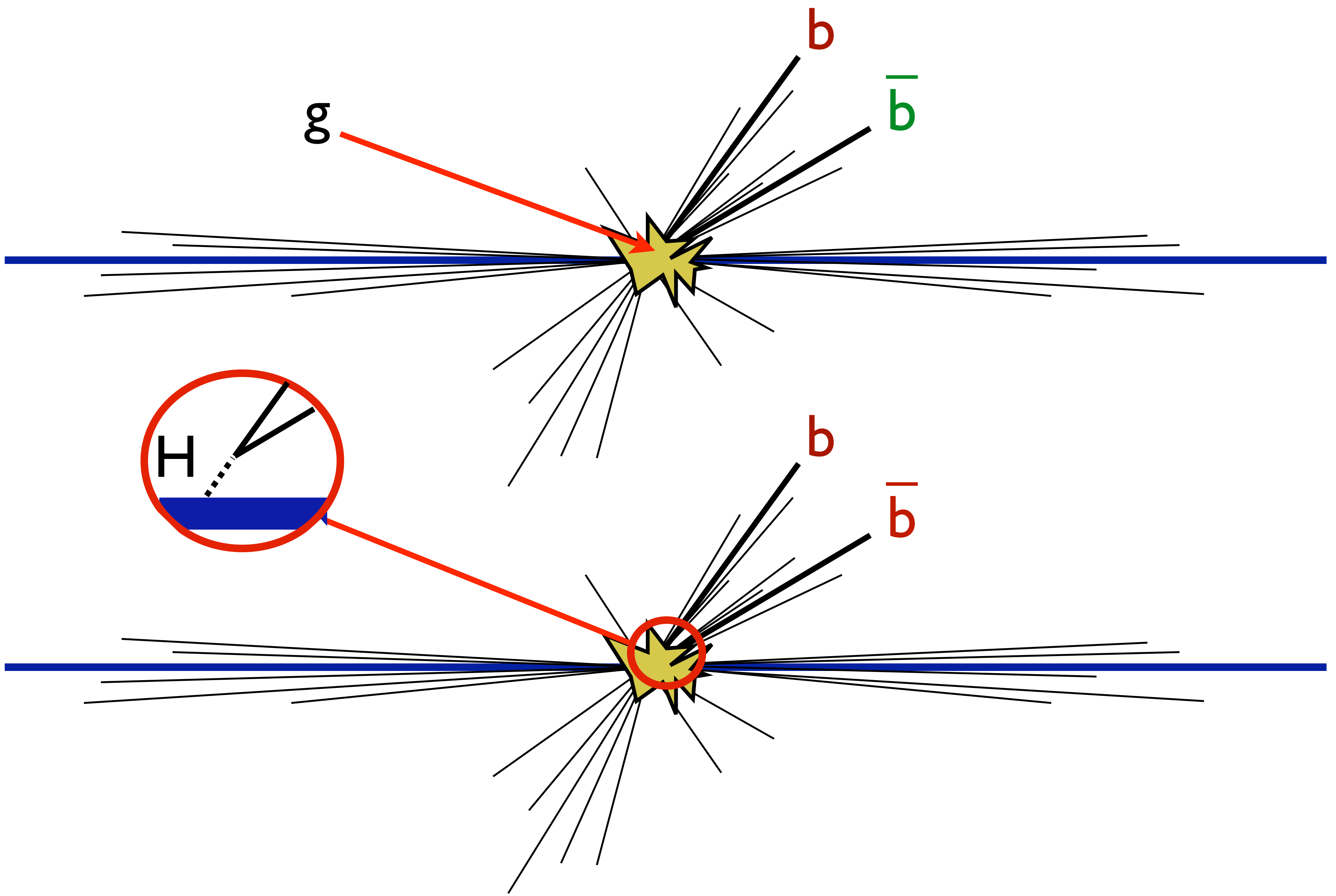
It is hard to model-build these days (emotionally).

Follow principles and signatures.

We are in the middle of a revolution. Work hard and enjoy!

EXTRAS

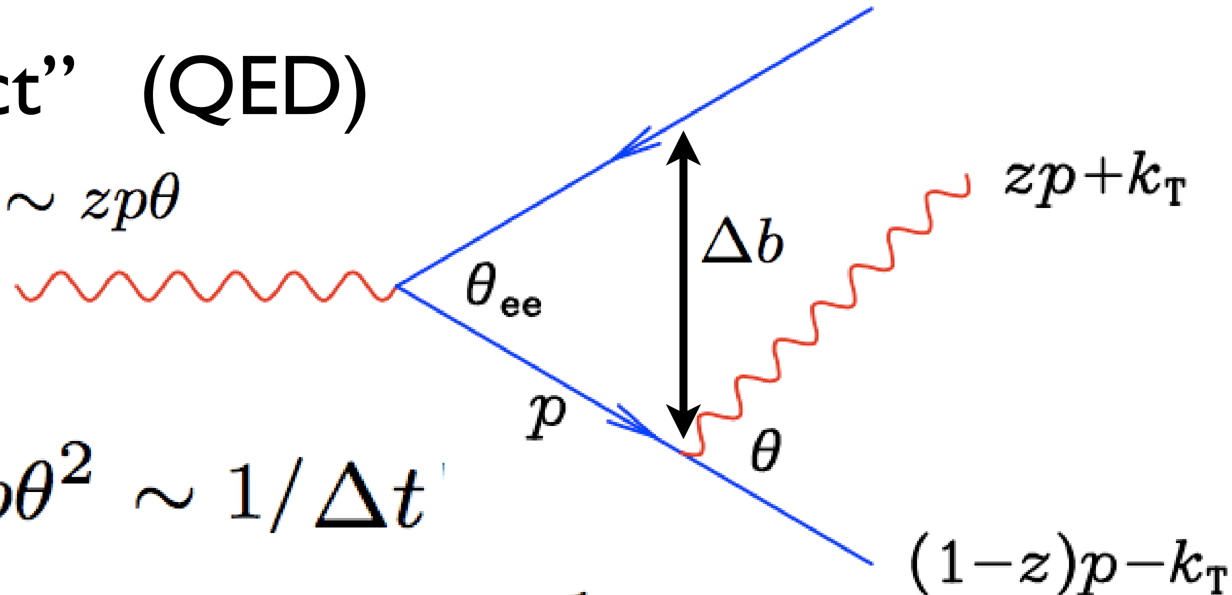
Color flow



Showering differences

The “Chudakov Effect” (QED)

$\theta_{ee}, \theta \ll 1 \longrightarrow k_T \sim zp\theta$



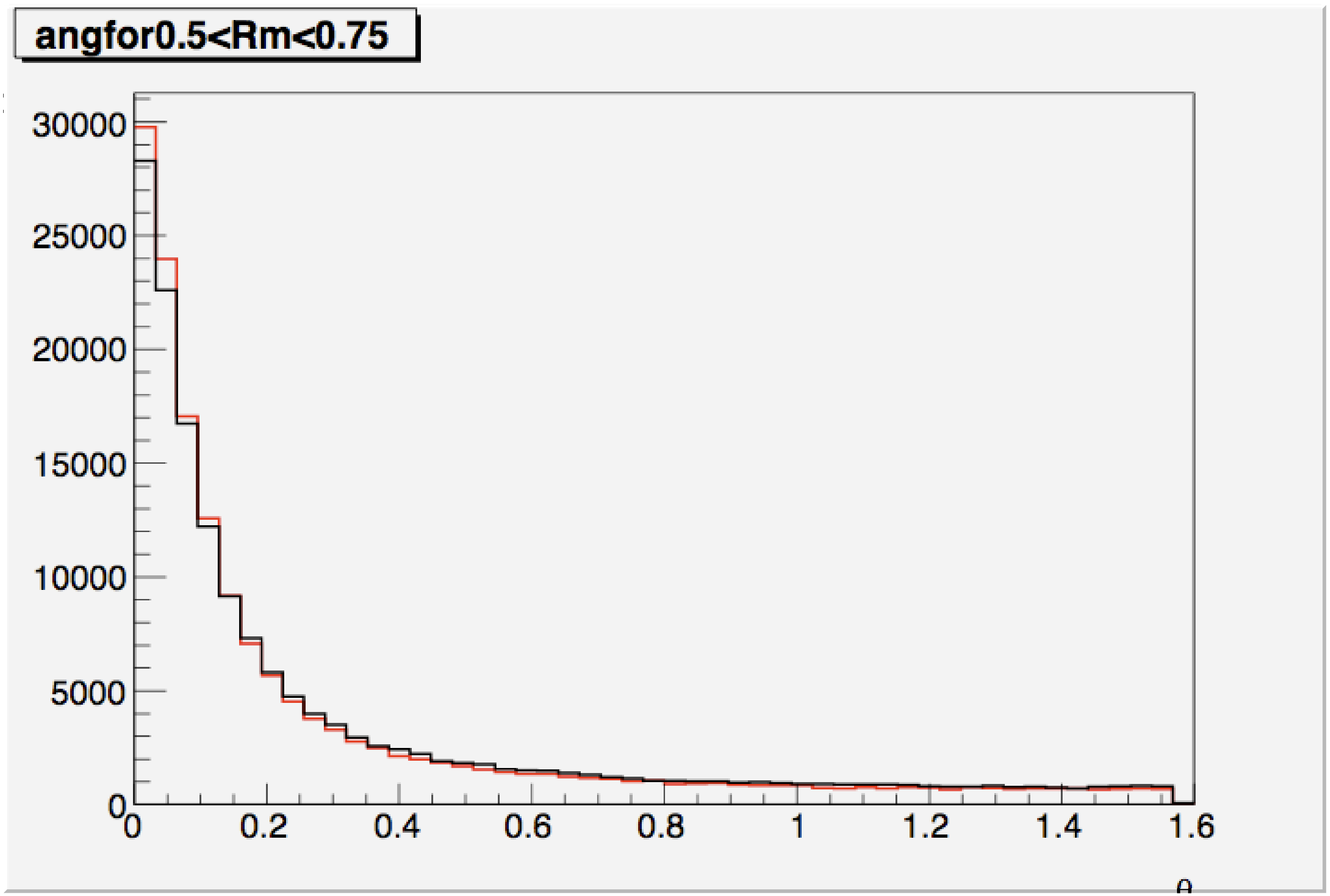
$$\Delta E \sim k_T^2/zp \sim zp\theta^2 \sim 1/\Delta t$$

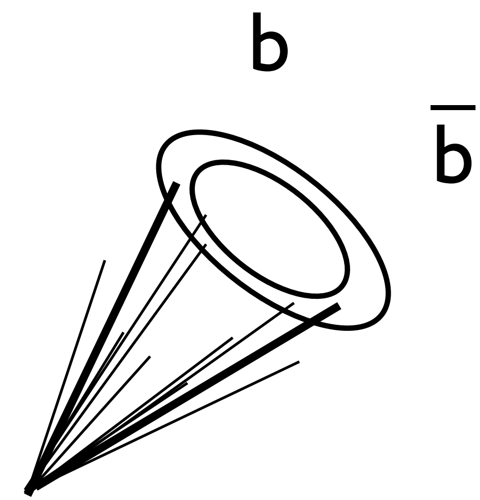
$$\Delta b \sim \theta_{ee}\Delta t > \lambda/\theta \sim (zp\theta)^{-1}$$

$$\theta_{ee}(zp\theta^2)^{-1} > (zp\theta)^{-1} \longrightarrow \theta_{ee} > \theta$$

Preliminary tests

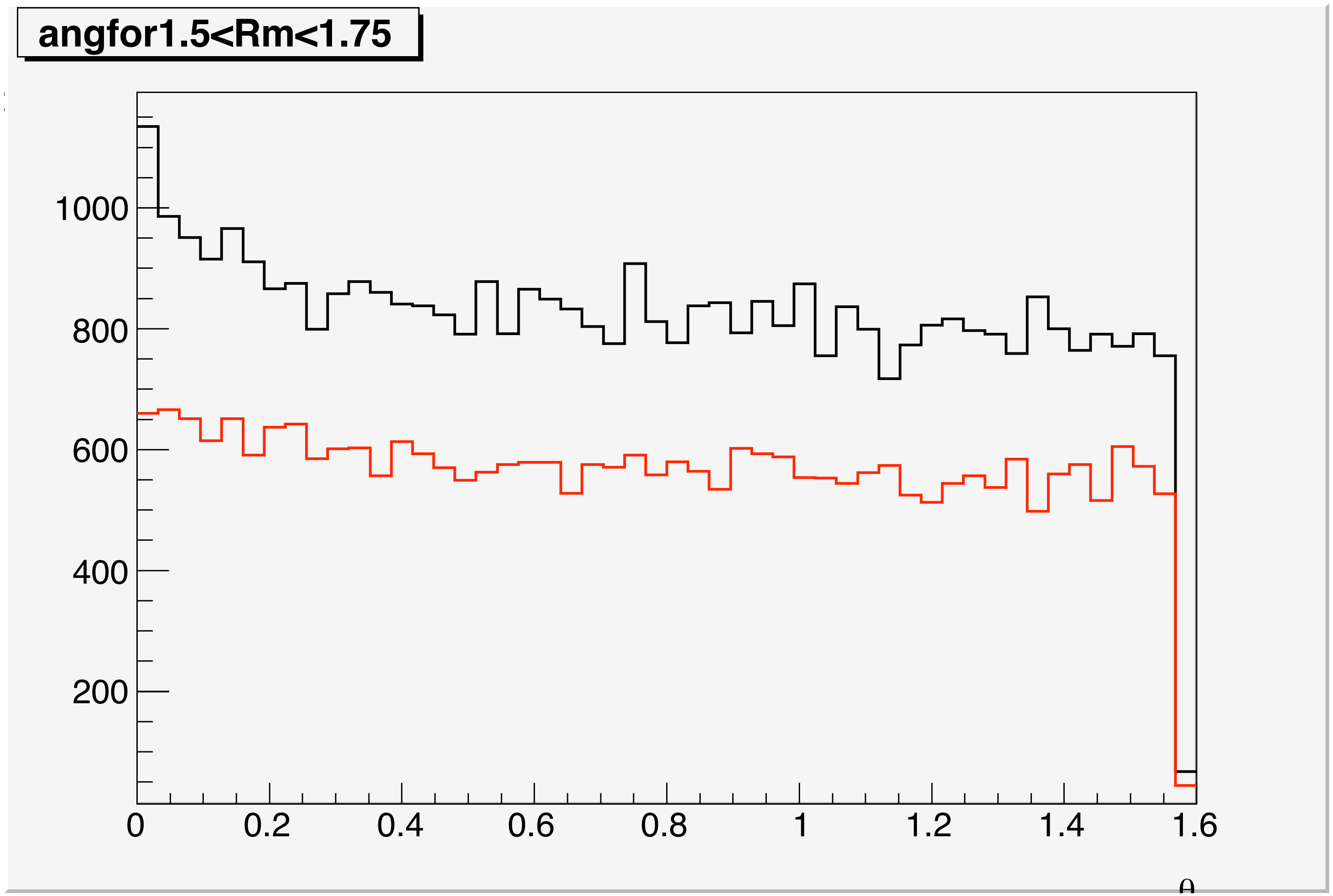
Here is a simulation of Higgs production and QCD production of two b-jets boosted w.r.t. the lab frame.

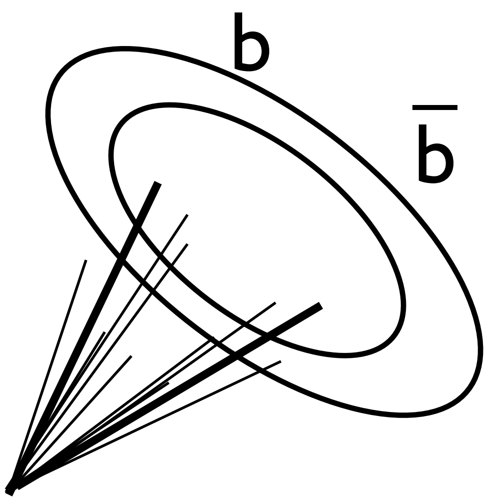




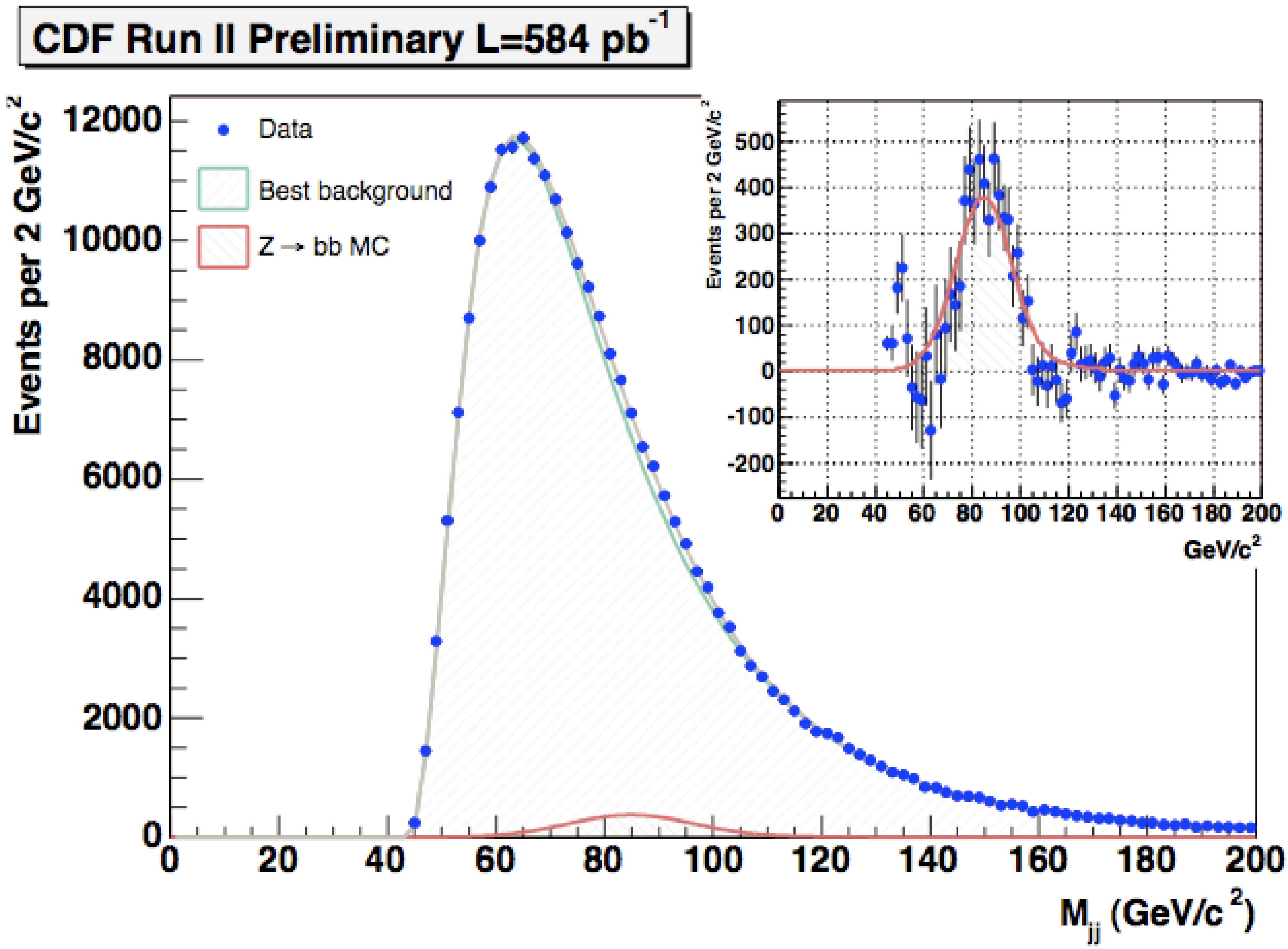
Preliminary tests

Here is a simulation of Higgs production and QCD production of two b-jets boosted w.r.t. the lab frame.





Testing ground



And we could get lucky

“Dude, that can’t be right.”