Discovering the Higgs and Other New Particles at LHCb

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Introduction

Long-lived particles:

- Models with and model-independent motivations for new displaced vertices.

- Variety of phenomena appear in models (diff. lifetimes, track and vertex multiplicities, invariant masses, leptonic content...)

- LHCb's unique position

Why LHCb for New Physics?

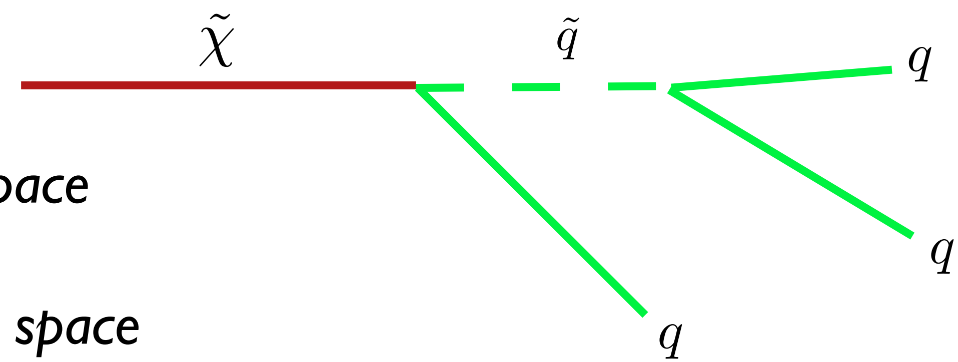
- Luminosity will keep up in the early days
- Smaller coverage (few %) made up for by larger bandwidth (~kHz)
- Very long vertexing and tracking regions
- Lighter resonances will be produced in forward region
- “Softer” physics hard to pick up at hermetic detectors

Sources for displaced vertices

A single new neutral fermion must decay through dimension six operators:

$$\frac{\chi q q q}{M^2}$$

Three-body decays similar to b-decays:



$$\Gamma \sim m_b^5/v^4 \times \text{ \textit{3-body phase space}}$$

$$\Gamma \sim m_\chi^5/M^4 \times \text{ \textit{3-body phase space}}$$

with $M \sim 1 \text{ TeV} \quad m_\chi \sim 30 \text{ GeV}$ and small coupling

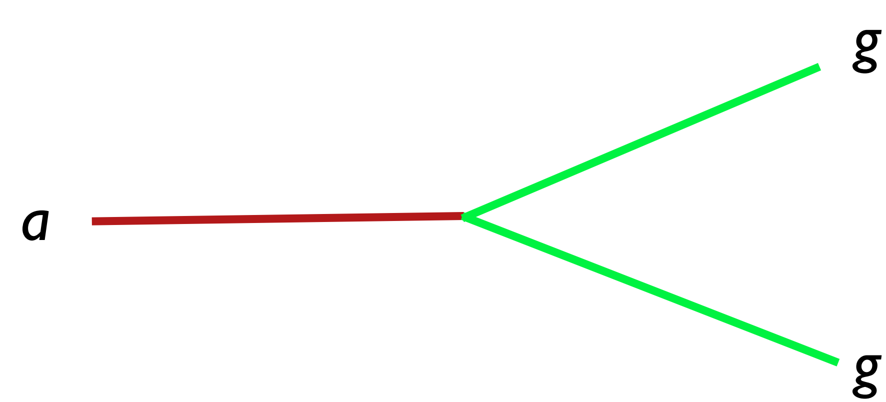
Sources for displaced vertices

A light scalar would naturally be a pseudo-goldstone boson:

$$\frac{a}{f_a} G\tilde{G}$$

Decays suppressed by f_a scale:

$$\Gamma \sim m_a^3 / f_a^2$$



with $f_a \sim 10\ \mathrm{TeV}$ $m_a \sim 1\ \mathrm{GeV}$ and small coupling

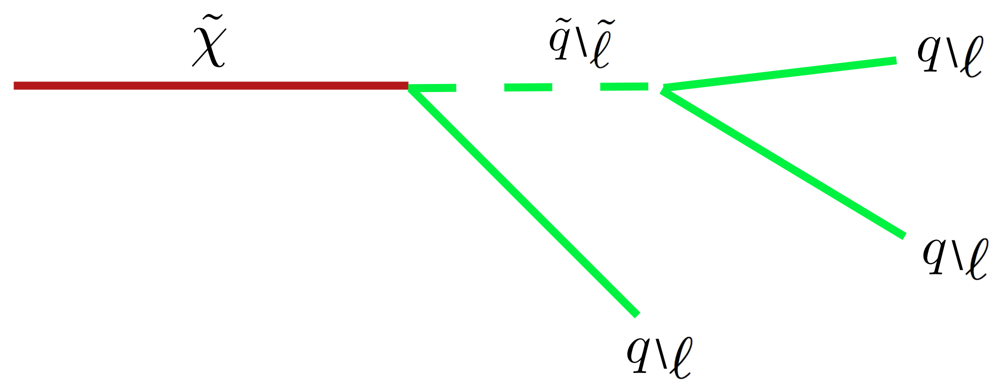
Explicit Models

Supersymmetry with R-parity violation

$$\lambda LLE^c + \lambda' LQD^c$$

or

$$\lambda'' U^c D^c D^c$$



$$c\tau \sim 0.3\ \text{mm} \left(\frac{10^{-3}}{\lambda''}\right)^2 \left(\frac{m_{\tilde{q}}}{100\ \text{GeV}}\right)^4 \left(\frac{30\ \text{GeV}}{m_\chi}\right)^5$$

(pure bino limit)

Bounds on R-parity violation

$$\lambda''_{ijk} U^c_i D^c_j D^c_k$$

$\lambda''_{uds}, \lambda''_{udb} < 10^{-7}, 10^{-4}$ — double nucleon decay, n - $\bar{\text{n}}$ oscillations

$\lambda''_{usb}, \lambda''_{cds}, \lambda''_{cdb}, \lambda''_{csb} < \sim 1$ — unitarity

$(\lambda''_{ijk}\lambda''_{i'j'k'}) < 10^{-2} \sim 10^{-4}$ — hadronic B decays...

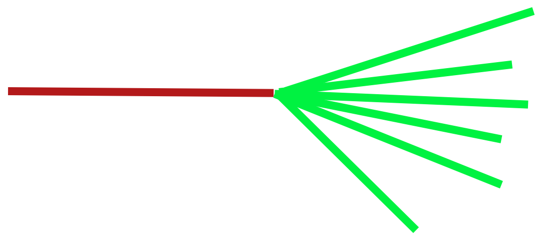
all assuming 100 GeV squarks

easily allows the "spurion mnemonic"
(Hinchliffe and Kaeding, 93)

$$\lambda''_{ijk} \sim \sqrt{m_i m_j m_k / v^3}$$

Warning: Pythia incorrectly uses constituent masses

Specific Phenomena

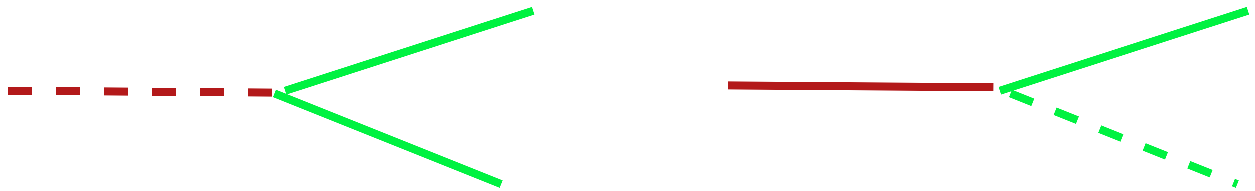


High-multiplicity vertices:

- High invariant mass
- Minimum number of tracks
- DV: short, long (in VELO), very long (outside VELO)
- Muonic/heavy flavor content

- e.g., UDD/LQD r-parity violation, GMSB higgsino NLSP

Specific Phenomena

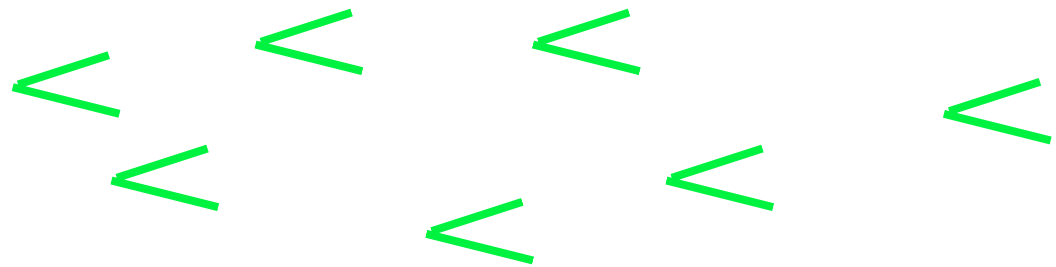


Low-multiplicity vertices:

- High or Low invariant mass
- two tracks or kink
- DV: short, long (in VELO), very long (outside VELO)
- (di-)muon, (di-)hadron

- e.g., LLE r-parity violation, light pseudo scalar in NMSSM

Specific Phenomena

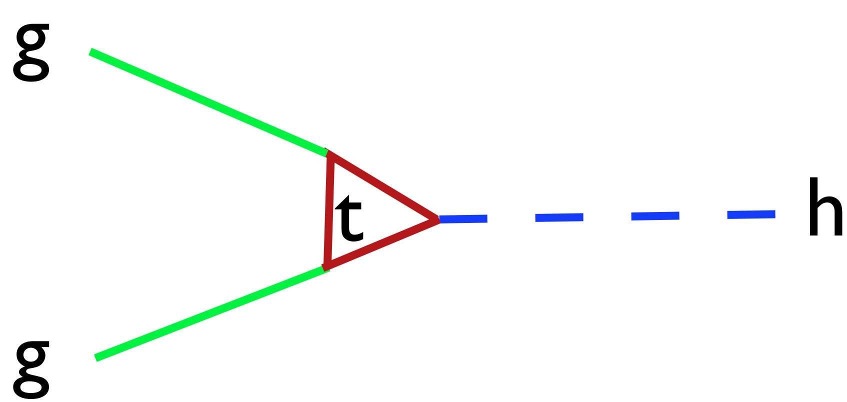


Multiple-vertex events:

- low-ish invariant mass
- two tracks per vertex
- distribution of DVs
- di-muon, di-hadron, etc.

- e.g., hidden valley, lepton jets (see Matt's talk)

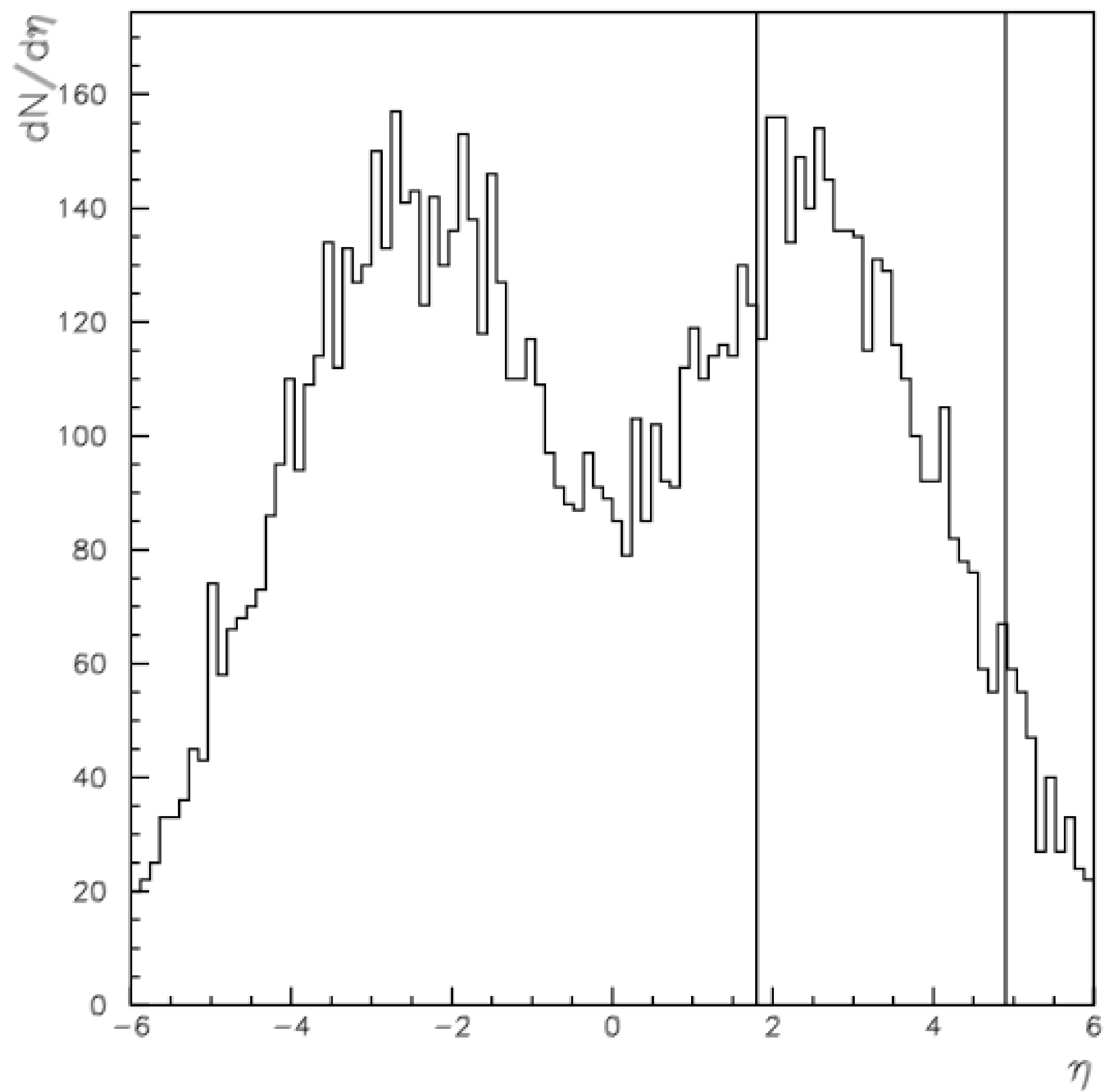
Production: Higgs decays to DVs



So light, it appears in the LHCb detector 30% of the time it is produced

Forward Higgs

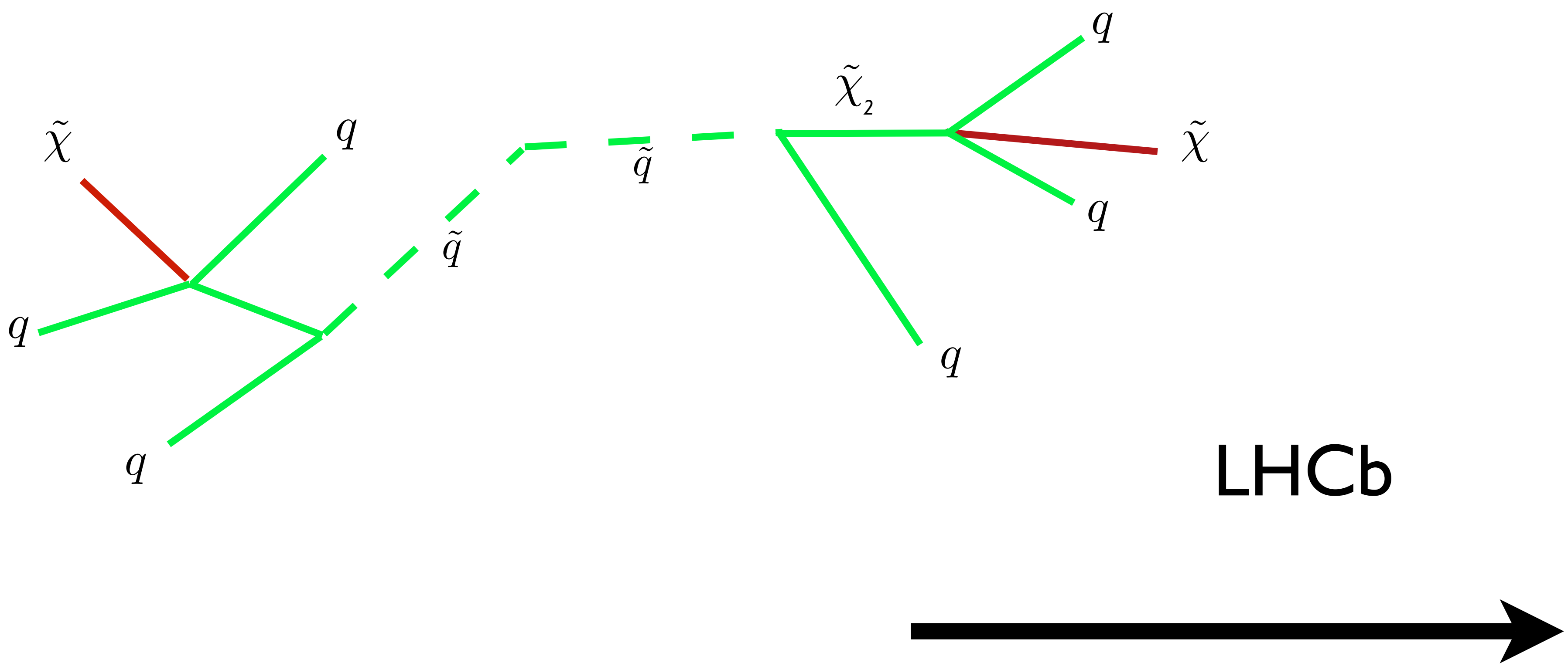
Acceptance cut not as bad as one might think...



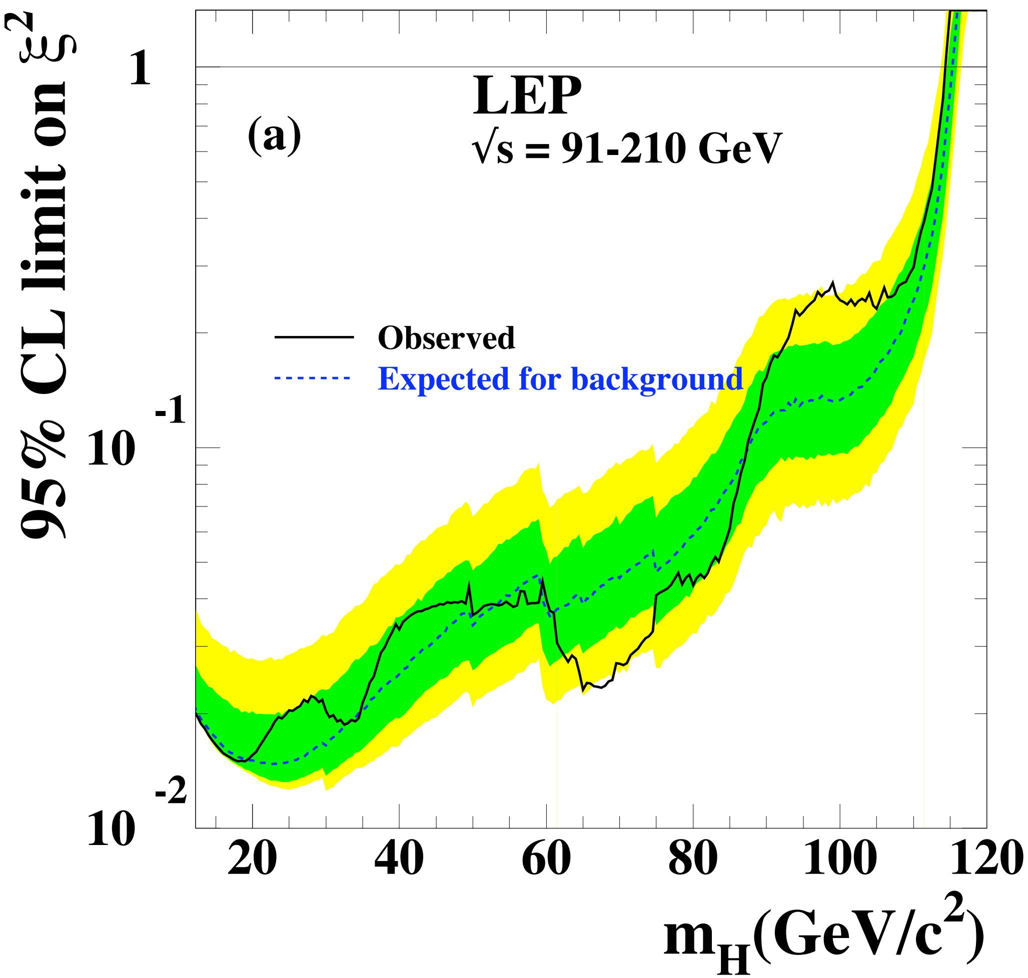
(Neal Gueissaz, 2007)

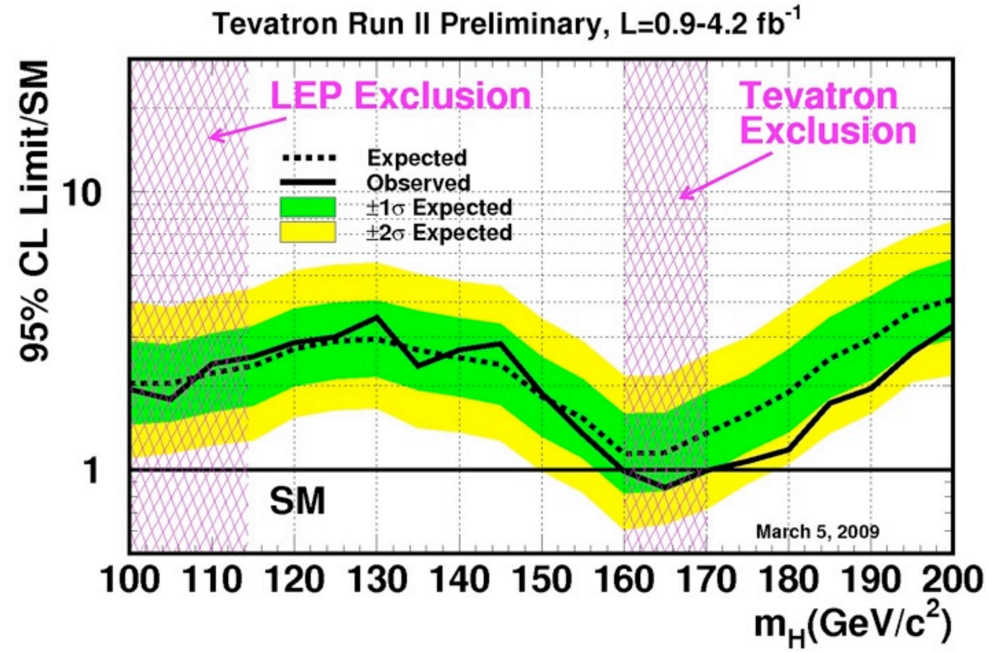
Production: Spherical Cascade

One long-lived particle falls into the acceptance - small boost allows for longer lifetime measurements.



Higgs: Collider Bounds



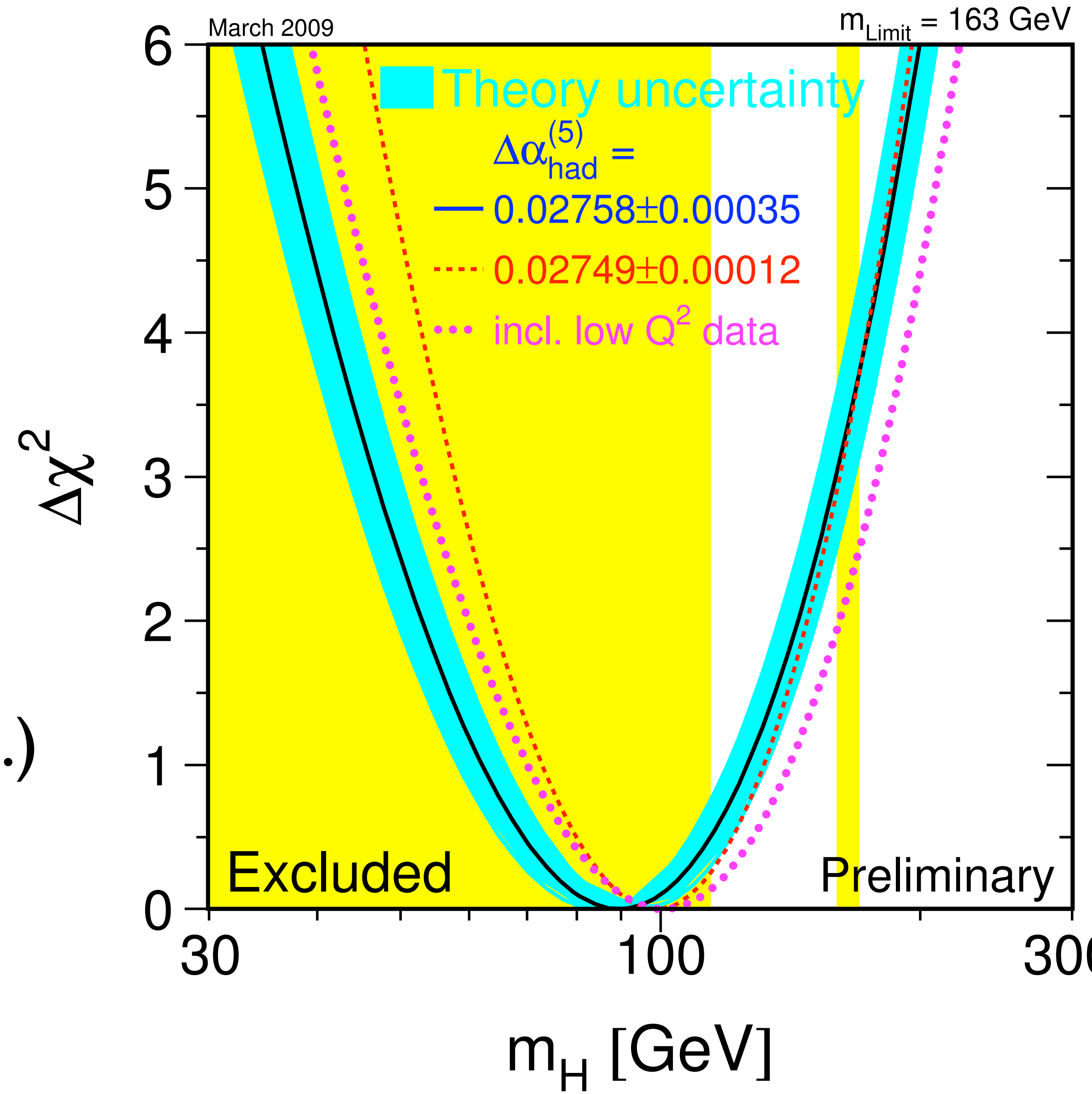


$114.4 < m_h < 160$ GeV
or $m_h > 170$ GeV

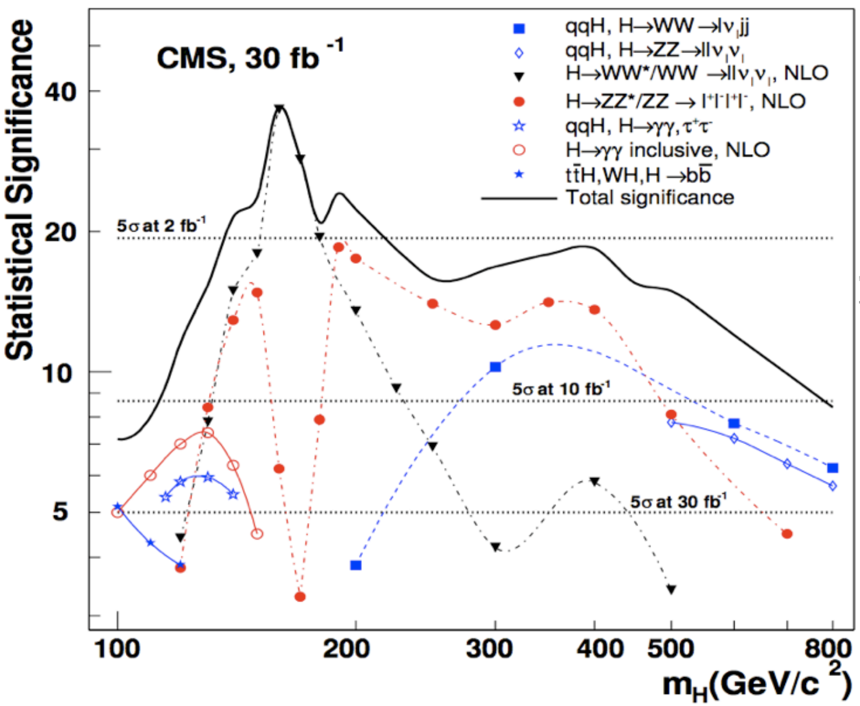
Higgs mass fit

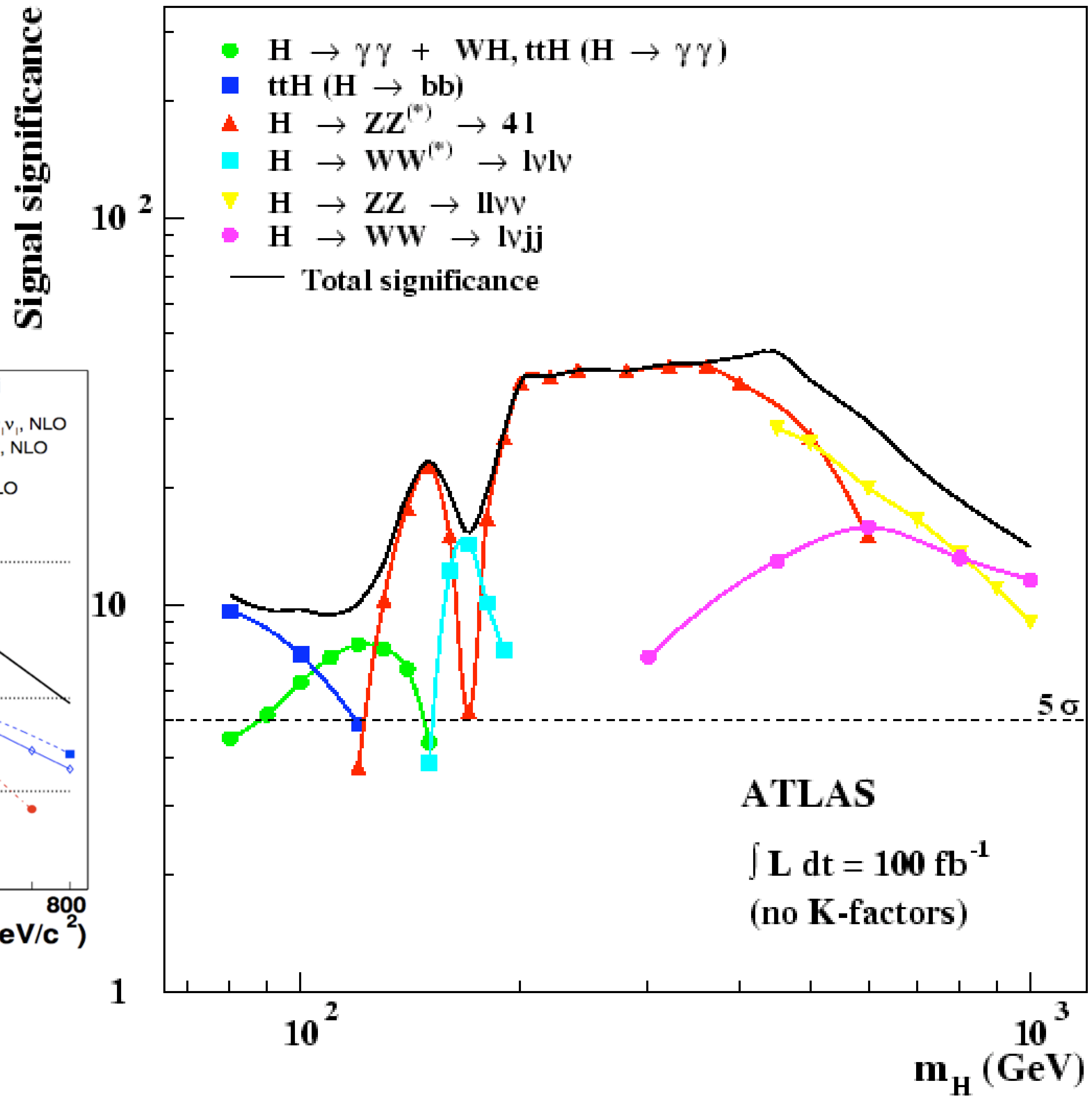
90^{+36}_{-27} GeV

< 163 GeV (95% C.L.)

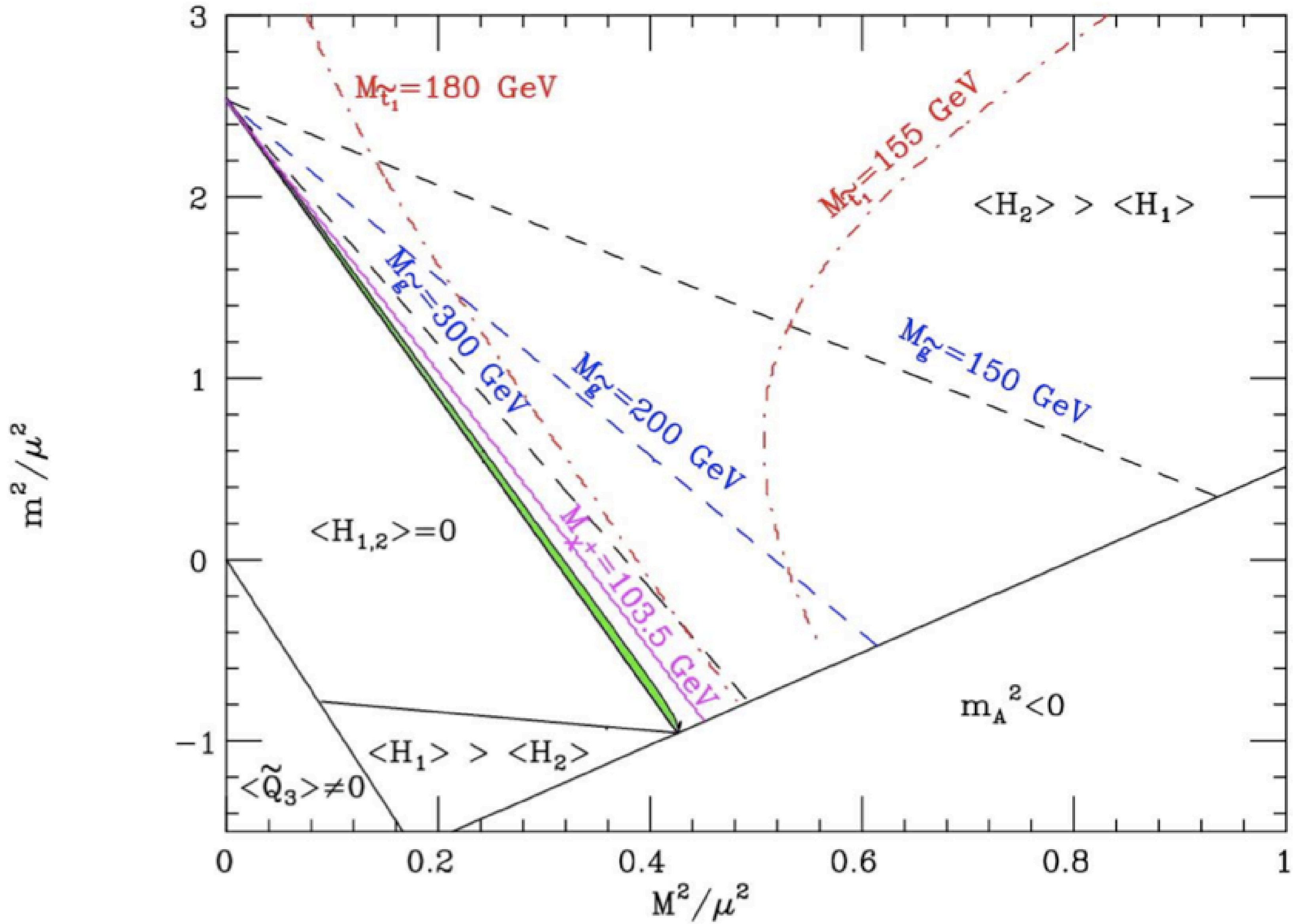


Higgs searches

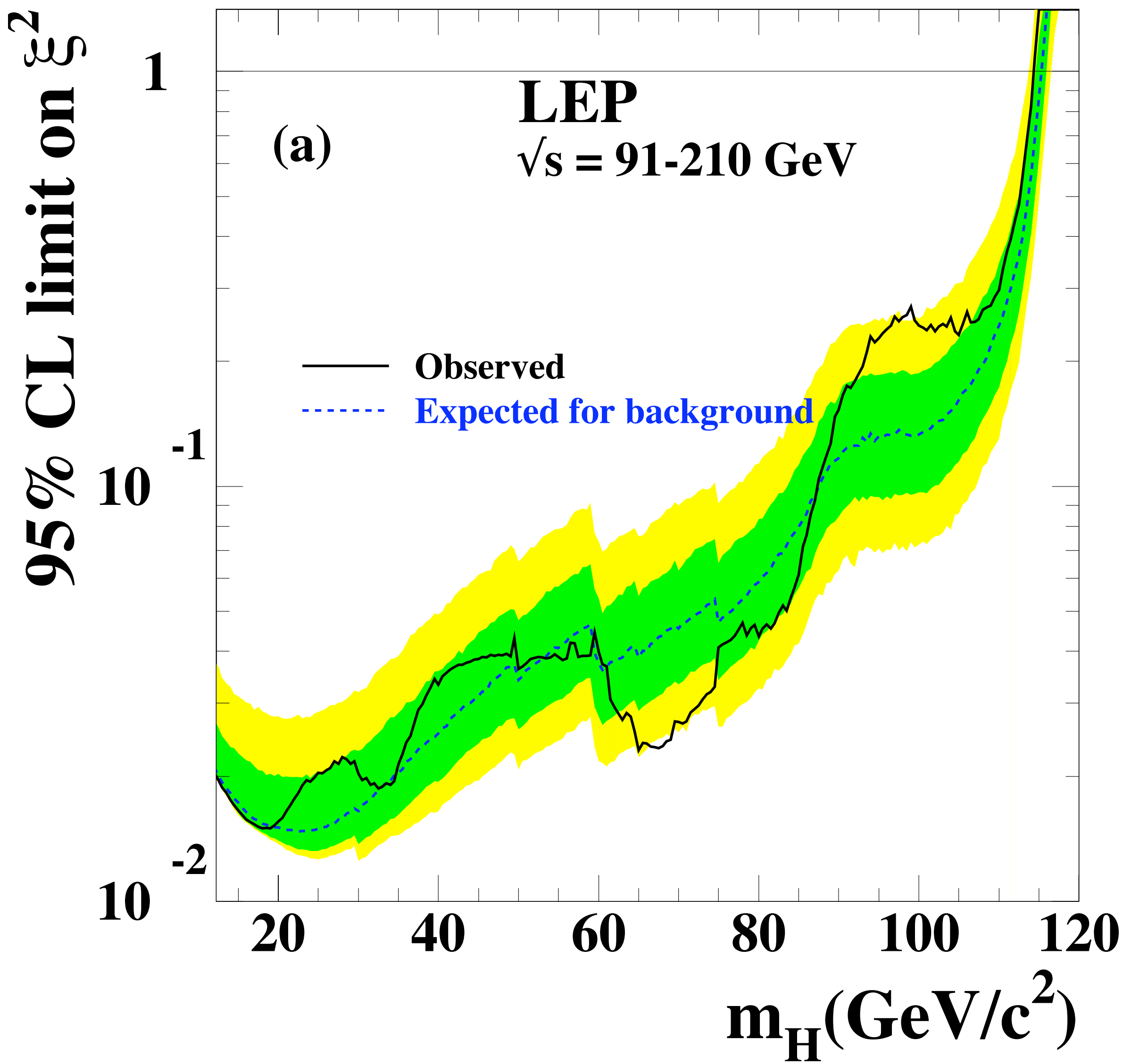




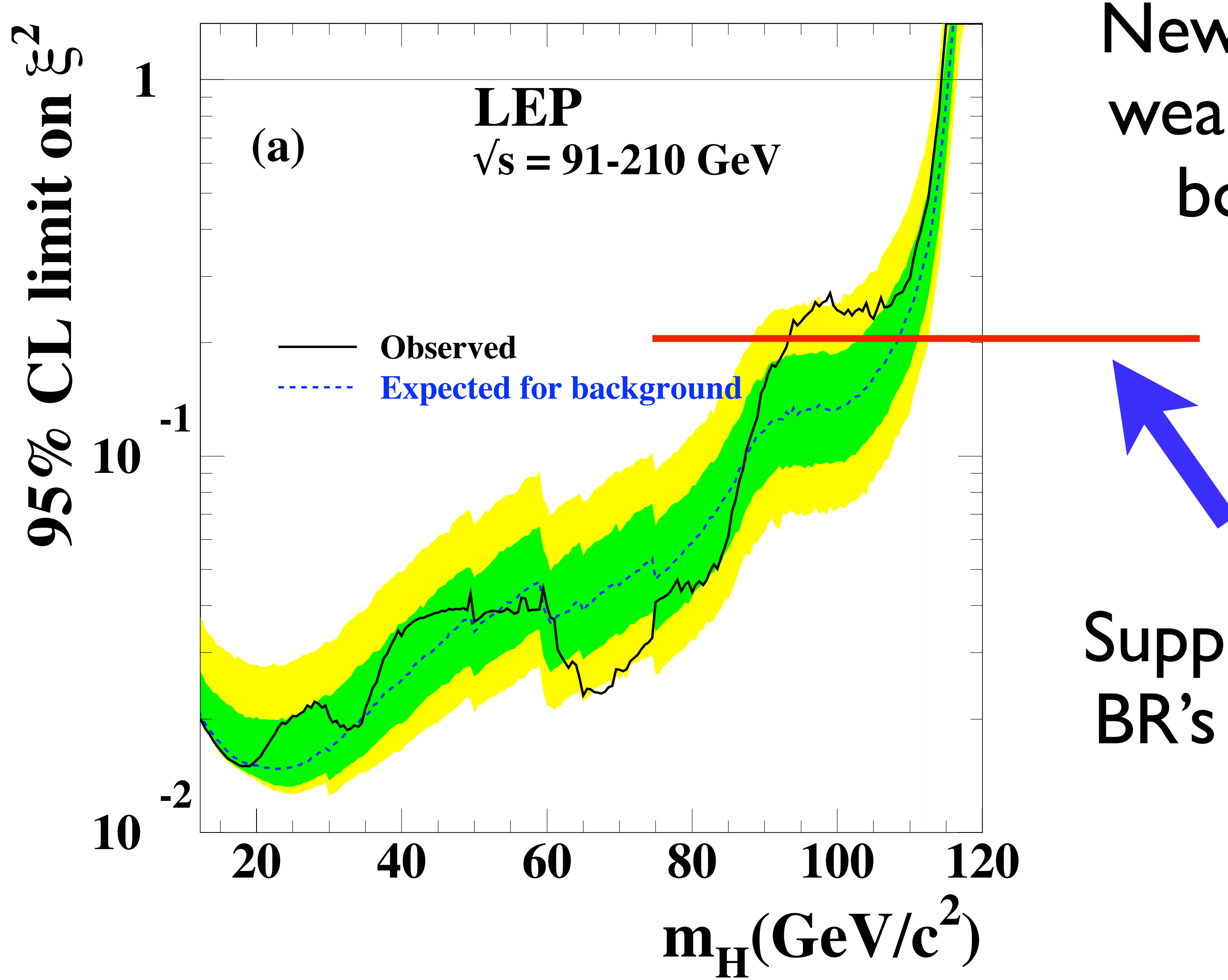
mSUGRA (e.g., SPS1a)



Higgs Mass Bound



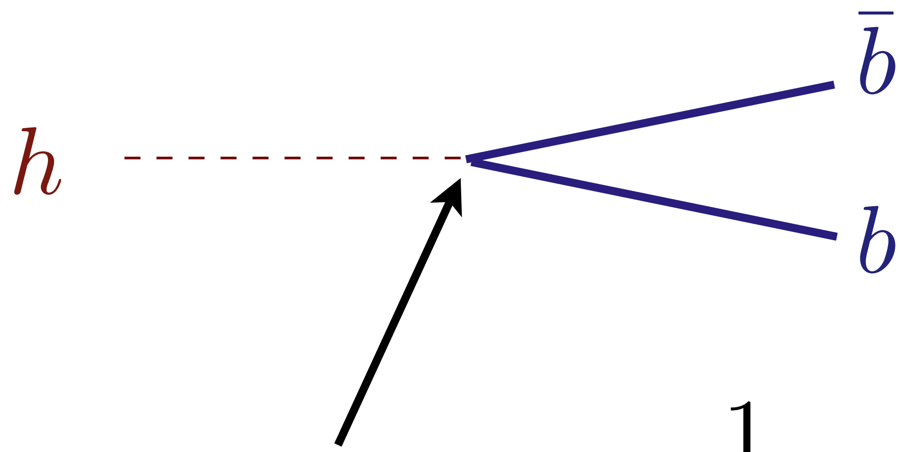
Higgs Mass Bound



New decays weaken the bound.

Suppress SM BR's to 20%

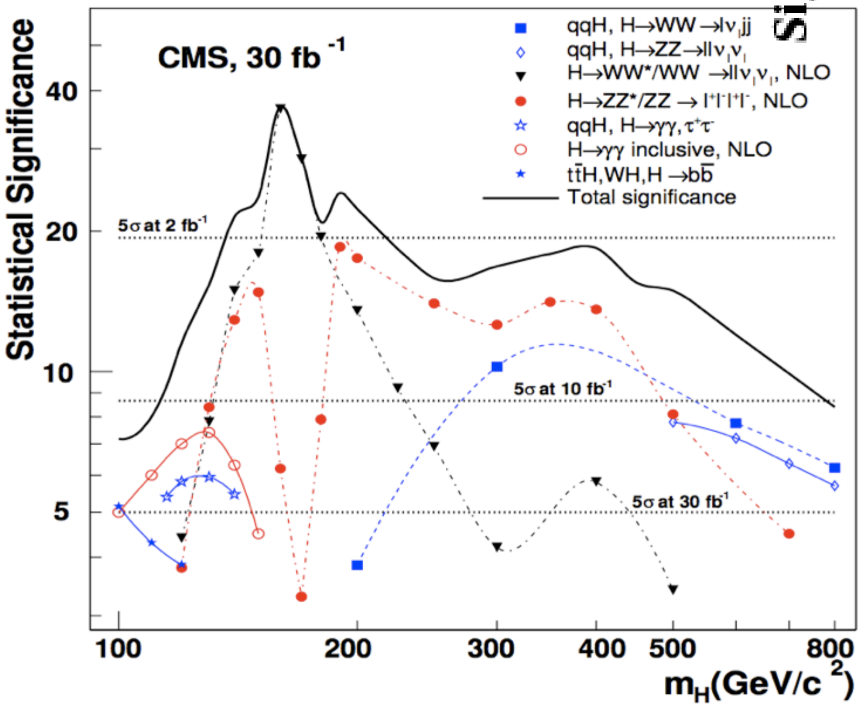
Higgs' Small Width

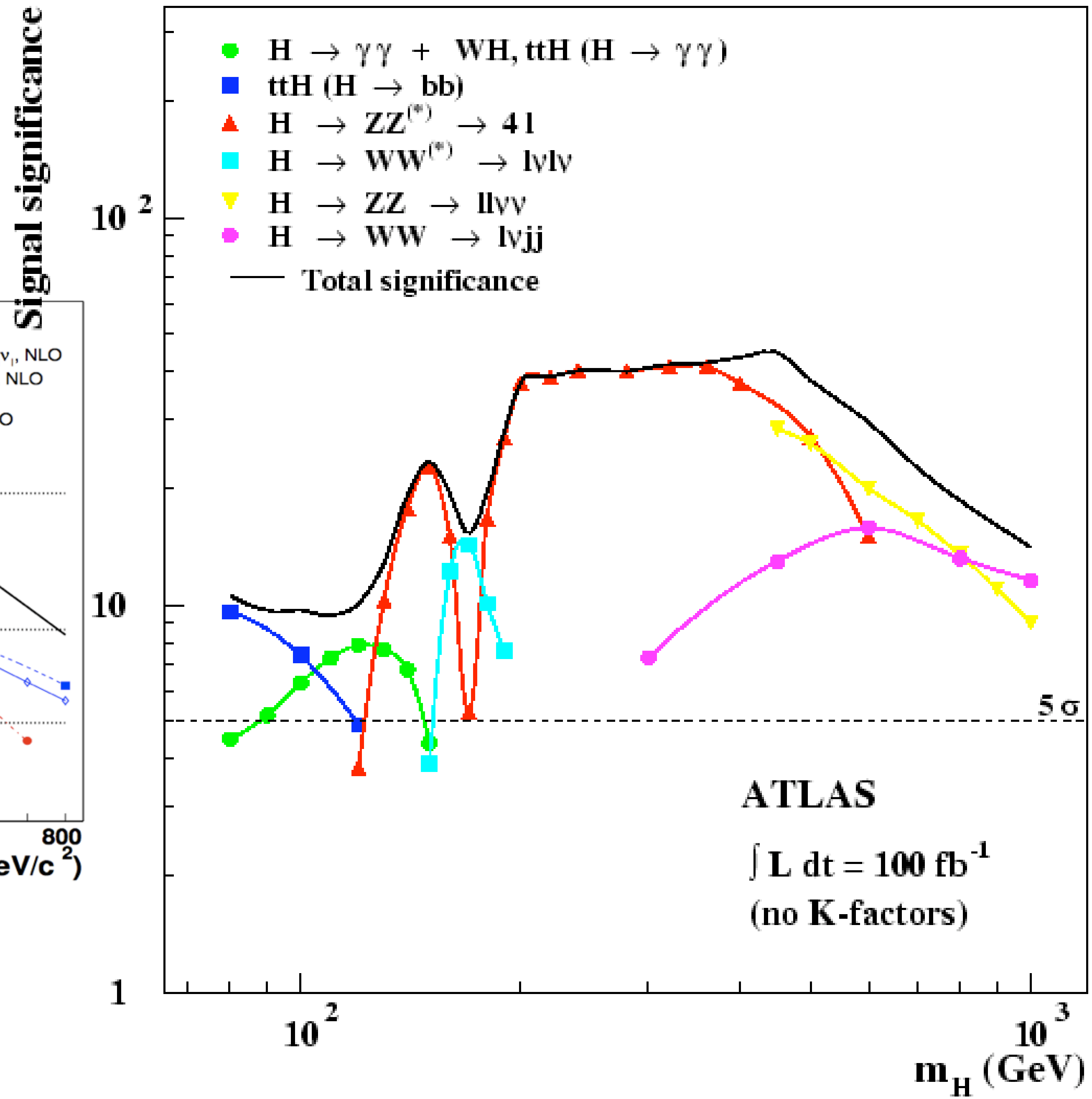


$$y_b(m_h) \sim \frac{1}{60}$$

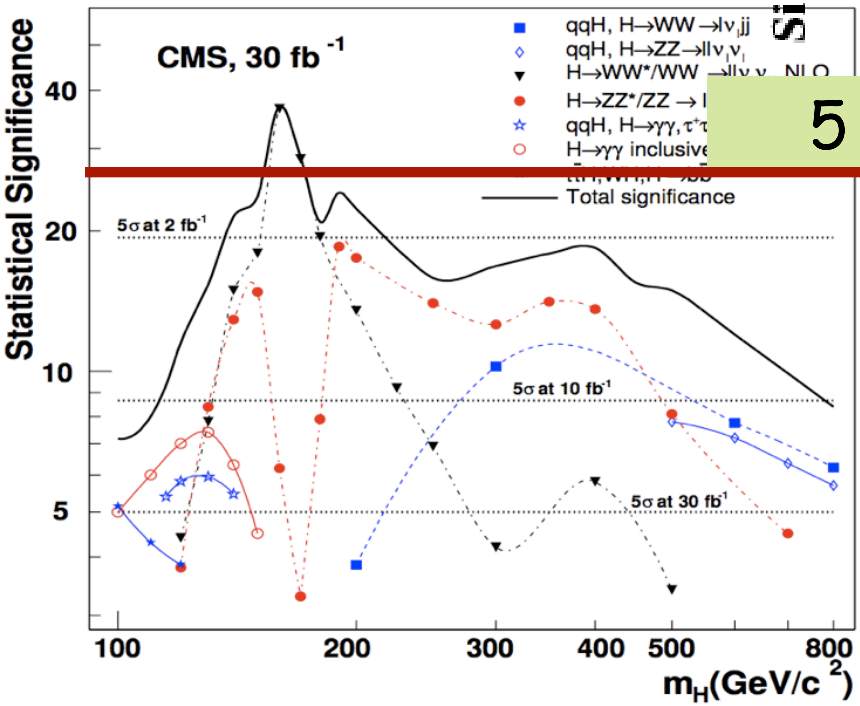
$$\Gamma_{h \to b\bar{b}} \sim y_b^2$$

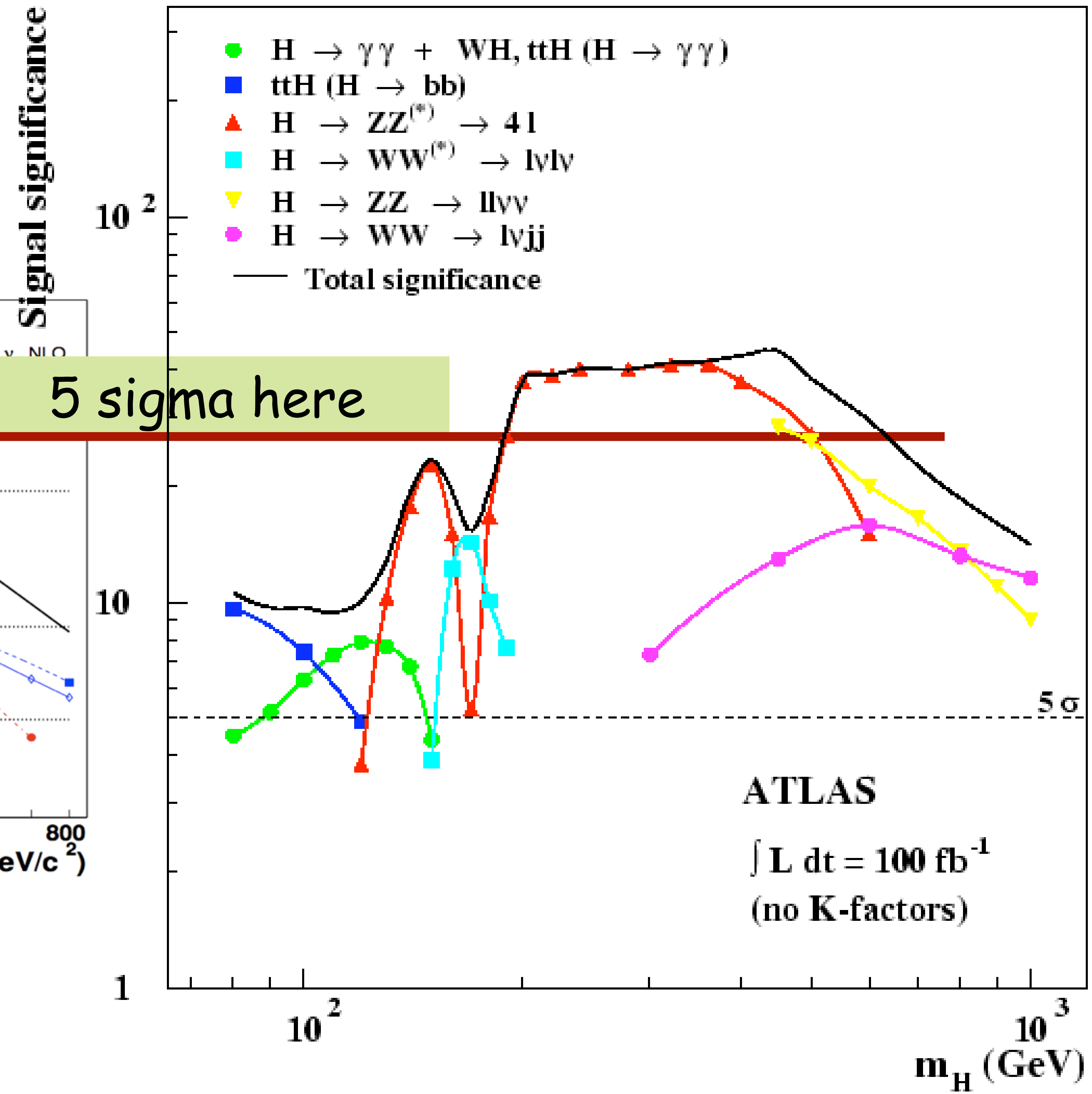
Higgs searches





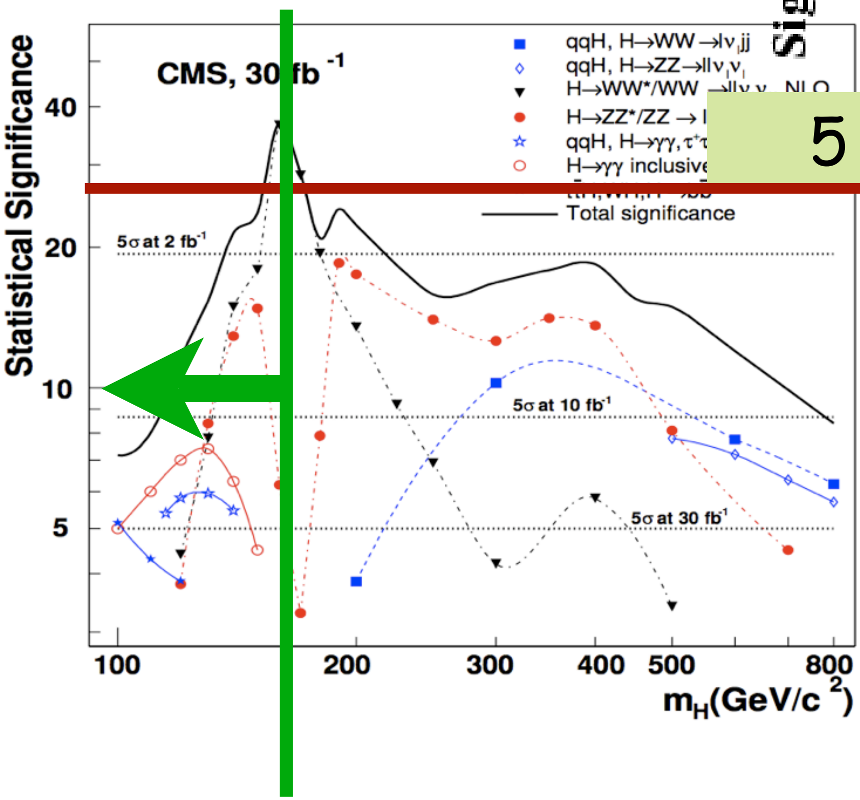
Higgs searches

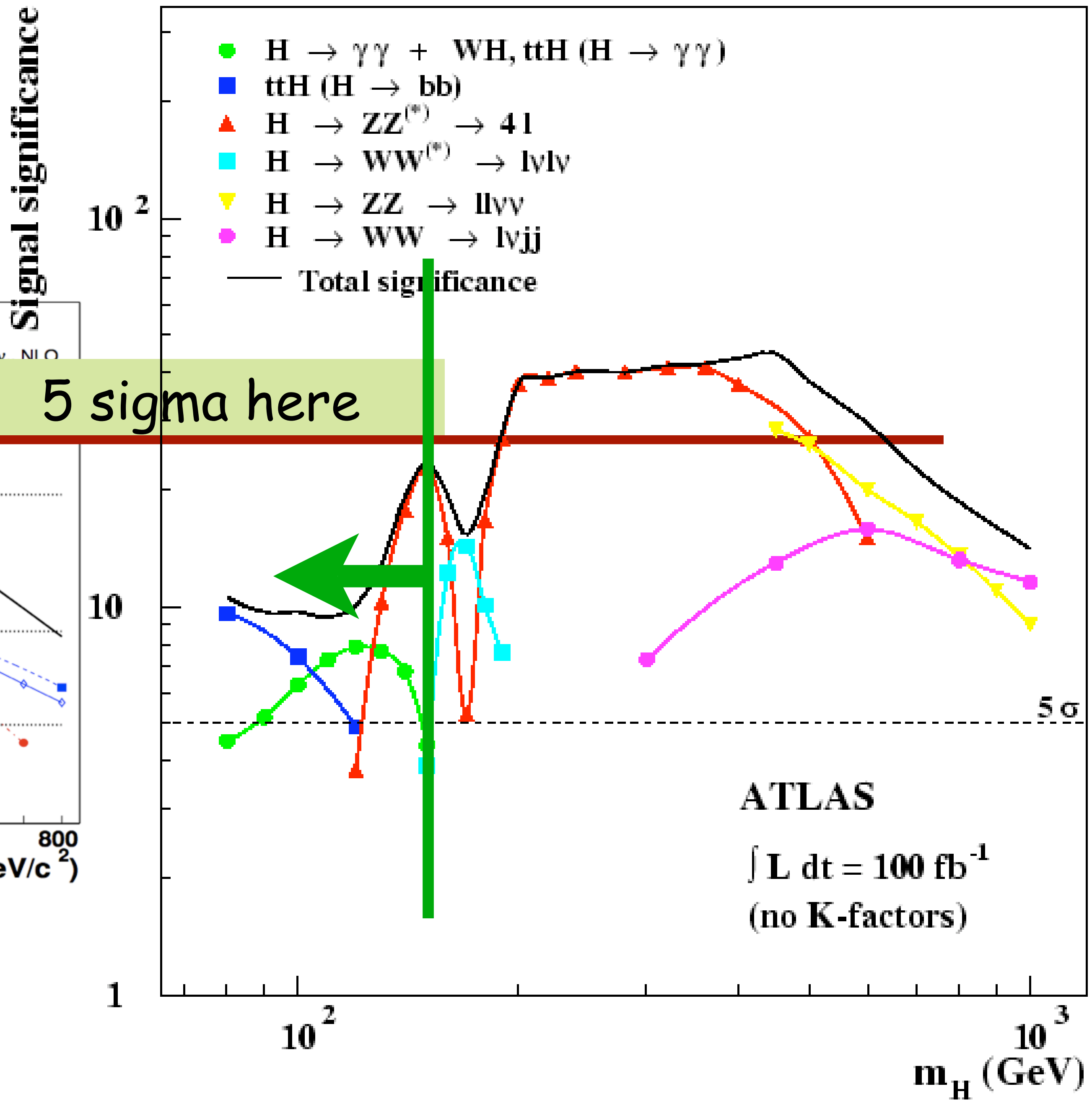




5 sigma here

Higgs searches

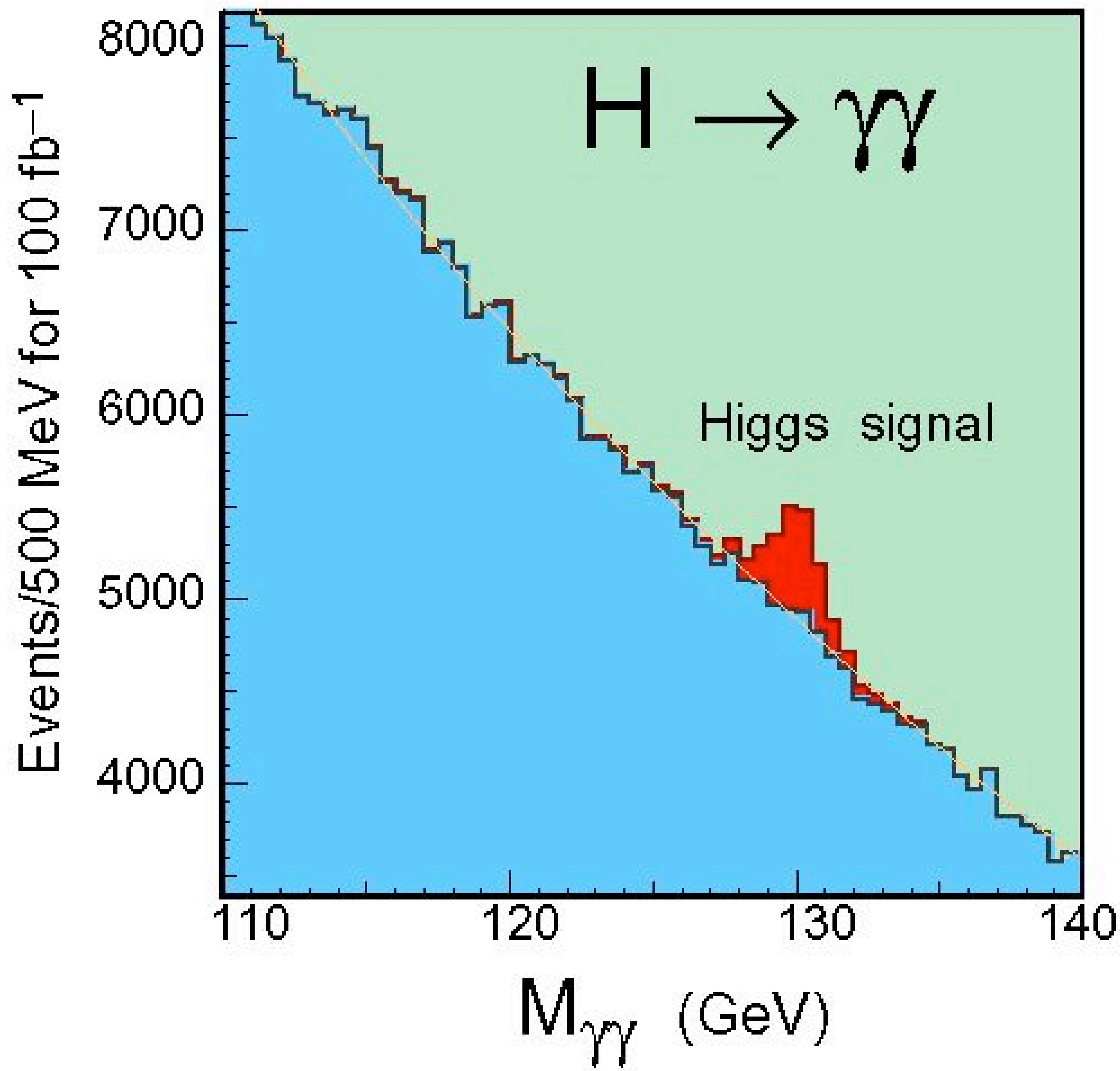




5 sigma here

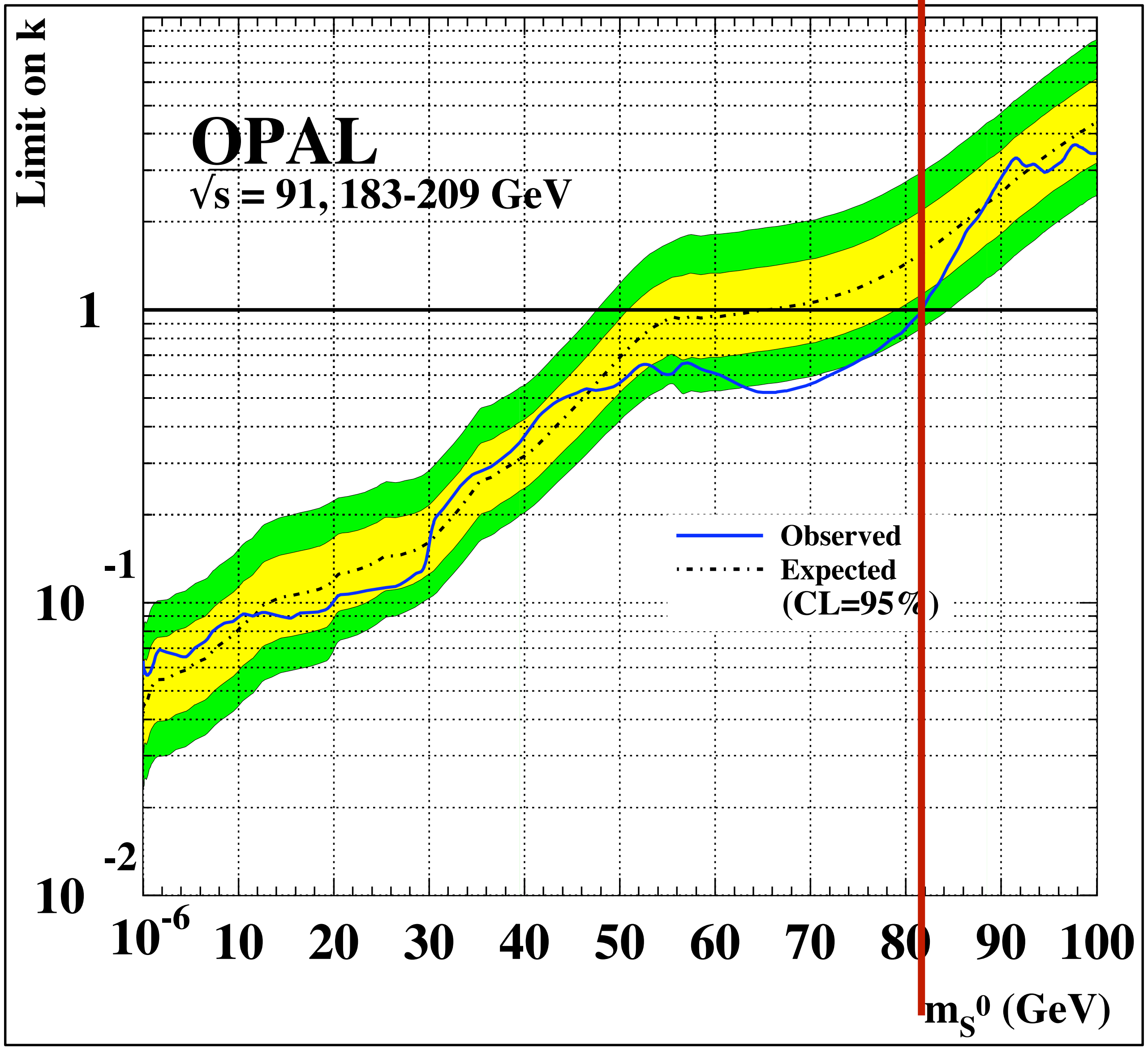
Standard searches

If the rate of Higgs boson decays to multiple jets is, for example, 4 times that into standard model modes, standard searches are dramatically weakened.



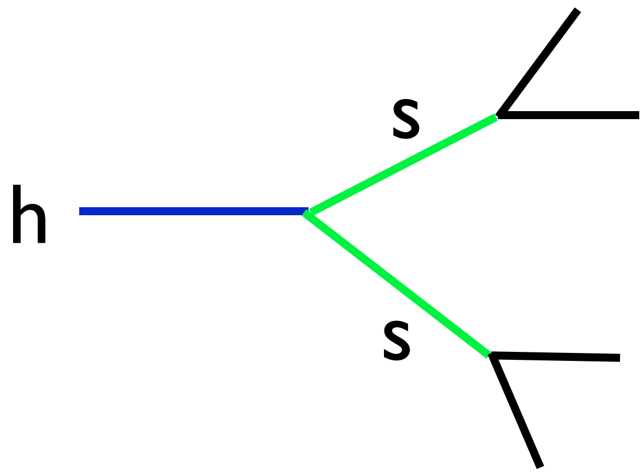
We **must** study the new decay modes.

Model Independent

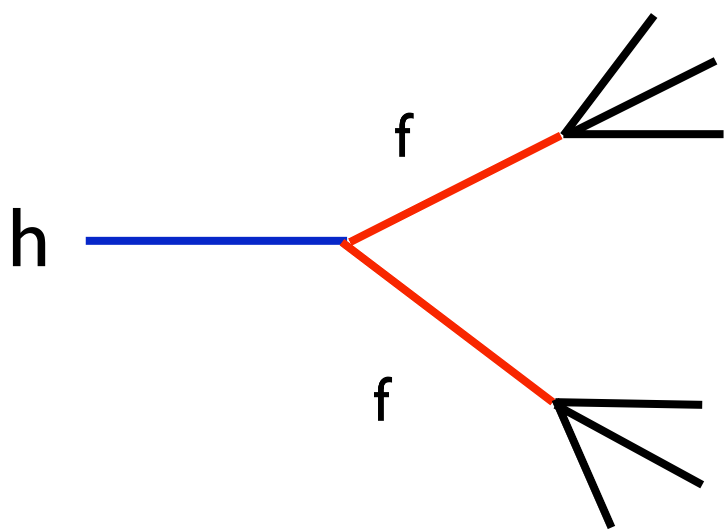


Thus the Higgs could be lighter (and EWP favors it)

Higgs decays



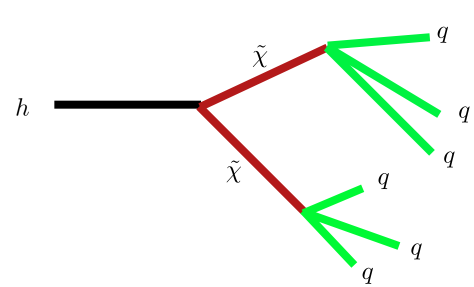
- Di-muons, s.b. easy to trigger if in VELO
- Di-electrons from very light scalars
- e-mu (i.e., from taus)
- di-hadron impossible (strange)?



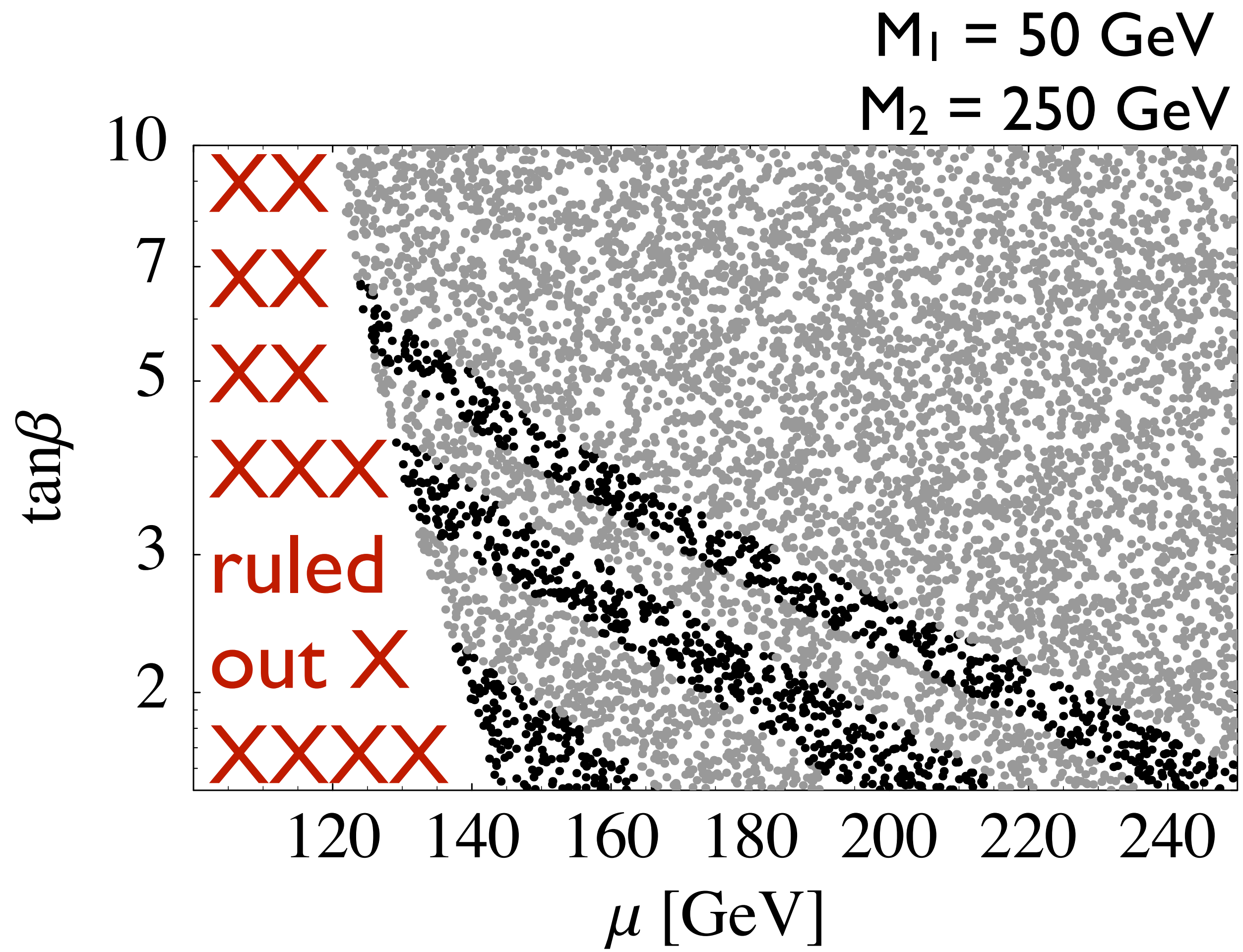
- mu-mu, e-e, e-mu, plus neutrino
- two high multiplicity DVs

MSSM - Higgs decays to neutralinos

Broad regions where this decay is important.



If the neutralinos decay, the Higgs mass could be as low as 90 GeV

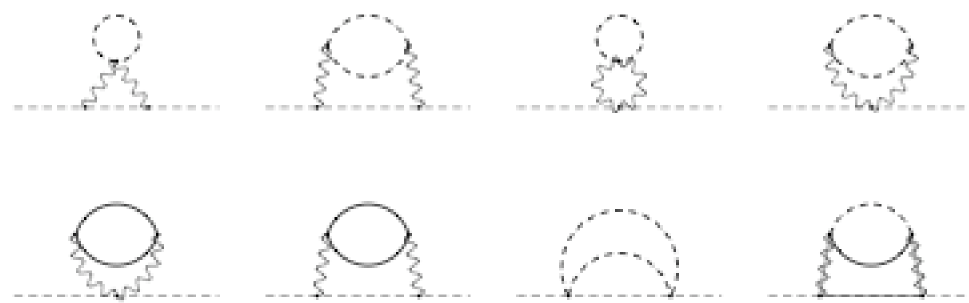


90%,85%,80%,75%,70%

Carpenter, DEK, Rhee (2006)

SUSY: Gauge Mediation

First complete model of supersymmetry-breaking - completely renormalizable and very predictive.



Standard searches for SUSY used plus non-pointing photons.

Gauge Mediation

Gravitino LSP:

$$\langle F \rangle \to \sqrt{3} m_{3/2} M_{\mathrm{P}}$$

The mass is at the weak scale for gravity mediation, but can be as small as .001 eV here.

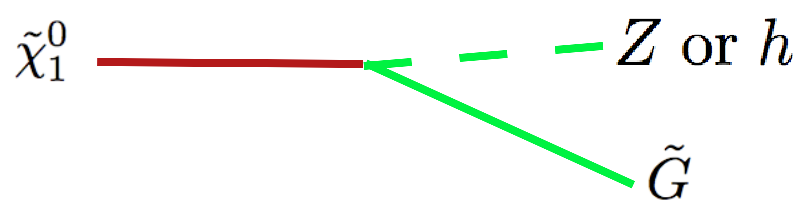
Gauge Mediation

Decays occur at macroscopic distances.

NLSP decays into the gravitino: $$\frac{1}{\Lambda M_{mess}} \tilde{\chi} \partial \tilde{G} \partial (Z \text{ or } h)$$

Result - high multiplicity/high invariant mass vertex.

Pythia ready!



$$d = 9.9 \times 10^{-3} \frac{1}{\kappa_{1\gamma}} (E^2/m^2_{\tilde{N}_1} - 1)^{1/2} \left(\frac{m_{\tilde{N}_1}}{100 \text{ GeV}} \right)^{-5} \left(\frac{\sqrt{\langle F \rangle}}{100 \text{ TeV}} \right)^4 \text{ cm}$$

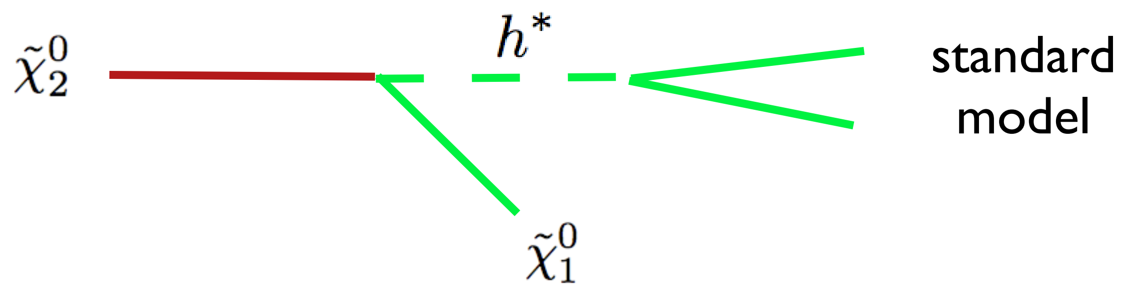
replace with Z/h

Photon or single lepton perhaps too difficult

Extra Fields

NMSSM, or MSSM plus singlet

$$W \supset SH\bar{H} \rightarrow \bar{h}\tilde{s}\tilde{h}$$



Suppressed by m_h and small Yukawa coupling

Pythia ready!

Asymmetric Dark Matter

Dark matter abundance (number density) a result of the baryon/lepton asymmetry.

$$\Delta W_{\rm eff} = \frac{1}{M_i}\bar{X}^2 L_i H_u \qquad \Delta W_{\rm eff} = \frac{1}{M_{ijk}^2}\bar{X}^2 u_i d_j d_k$$

$$c\tau(\chi^0 \to qqq\tilde{X}\tilde{X}) \sim 0.3 \text{ mm} \left(\frac{M}{\text{TeV}}\right)^4 \left(\frac{m}{500 \text{ GeV}}\right)^4 \left(\frac{m_{\chi^0}}{100 \text{ GeV}}\right)^{-9}$$

$$c\tau(\chi^0 \to h^0\nu\bar{X}\bar{X}) \sim \text{mm} \left(\frac{M}{10^6 \text{ GeV}}\right)^2 \left(\frac{m_{\tilde{\nu}}}{200 \text{ GeV}}\right)^4 \left(\frac{m_{\chi^0}}{100 \text{ GeV}}\right)^{-7}$$

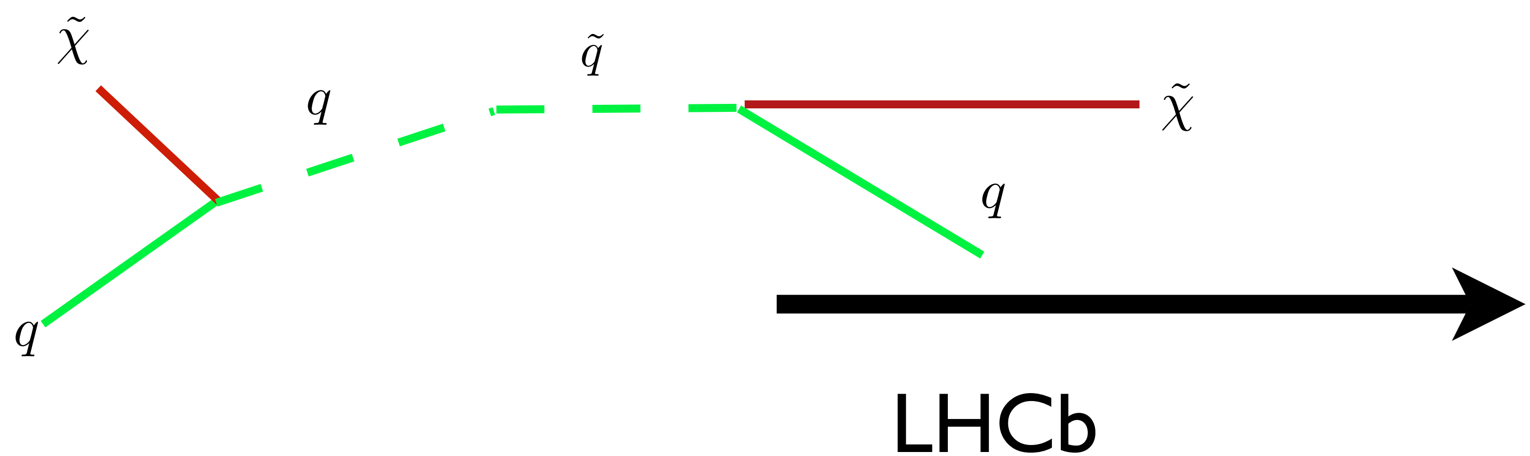
$$c\tau(\tilde{\tau}_R \to \ell\nu\tilde{X}\tilde{X}) \sim \text{cm} \left(\frac{M}{10^7 \text{ GeV}}\right)^2 \left(\frac{m}{200 \text{ GeV}}\right)^2 \left(\frac{m_{\tilde{\tau}}}{100 \text{ GeV}}\right)^{-5}$$

Strange possibilities...

Hidden valleys, quirks, ...

Susy Detection

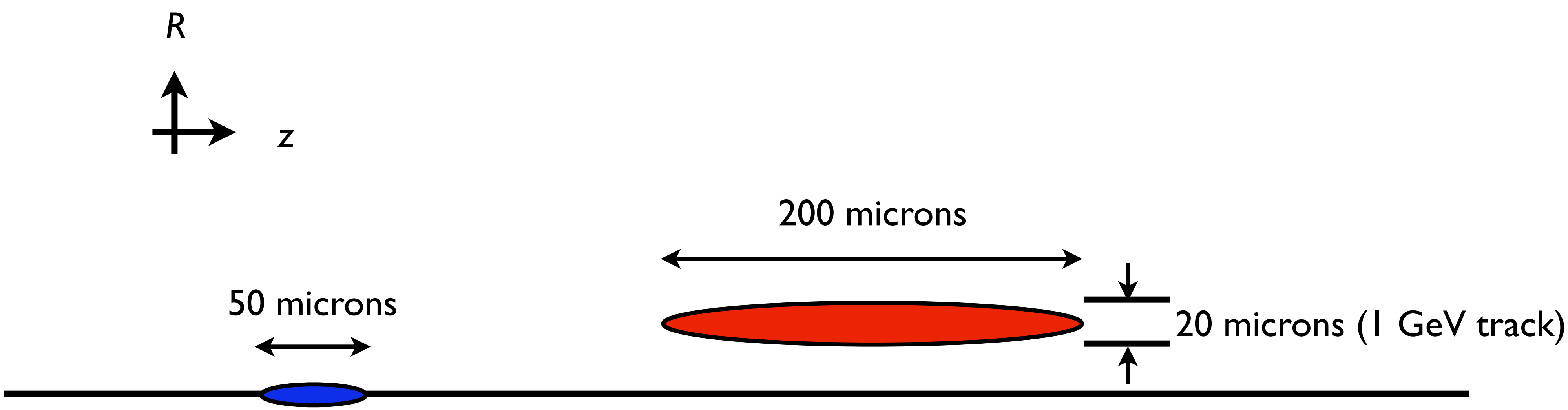
Squarks can be produced and decay such that one neutralino goes into the LHCb detector.



Let's look at R-parity violation.

Off-line resolution used

For typical *b* decays

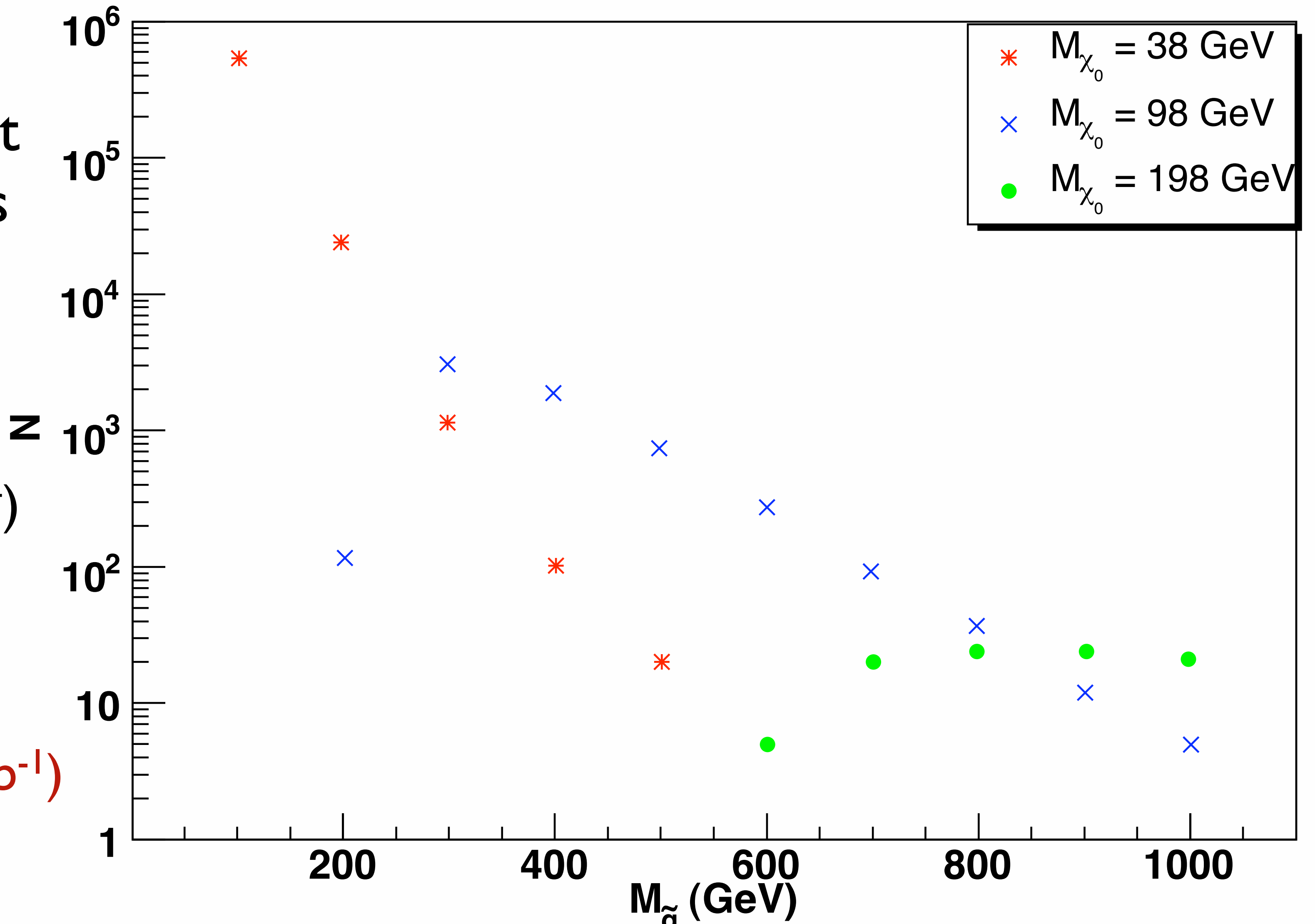


Squark production: One year running

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

(coupling ~ 10^{-4})

(14 TeV and $2\ fb^{-1}$)



Distinguish from Backgrounds

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

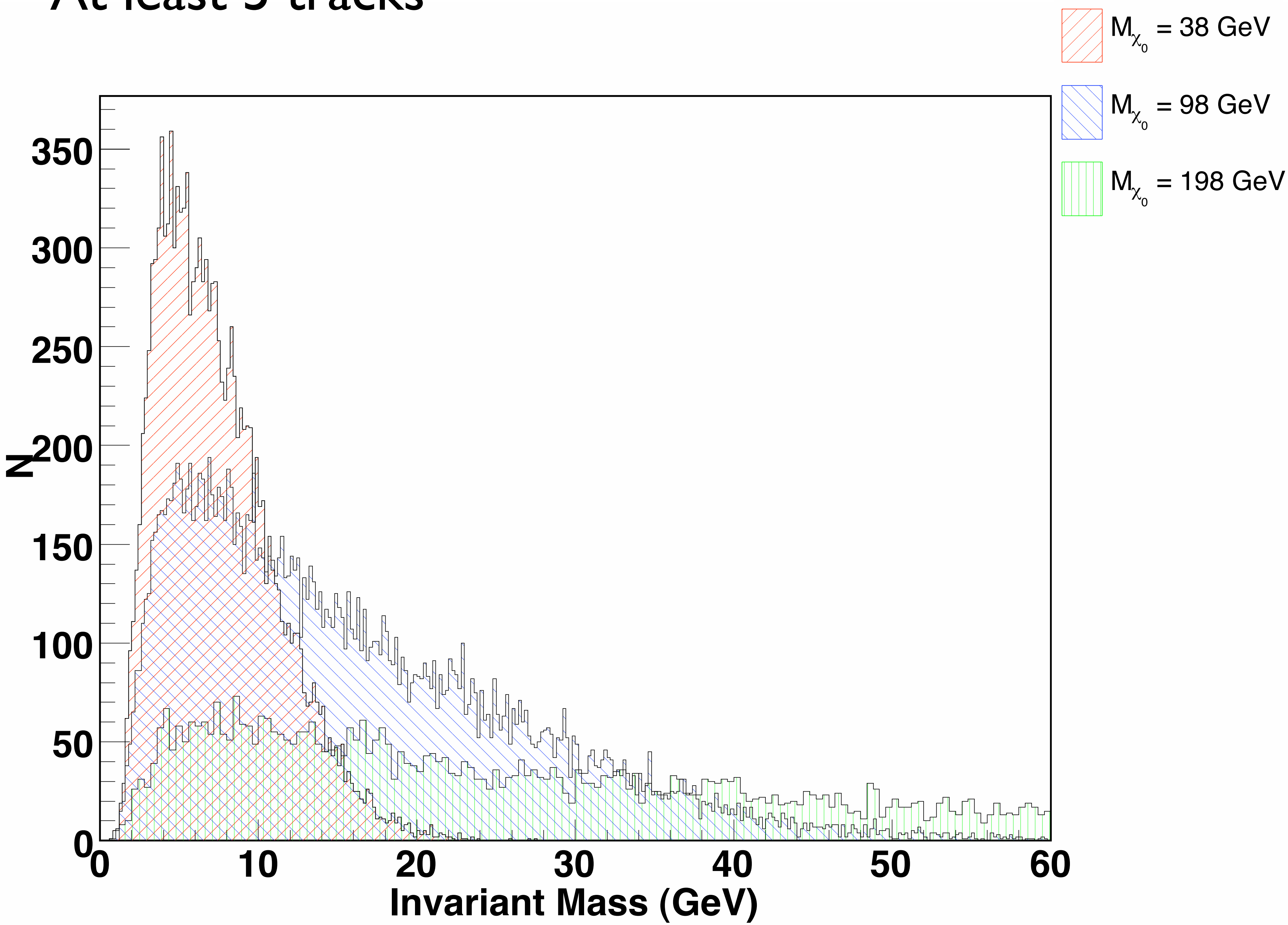
Look for *large multiplicity* of
tracks from a single vertex.

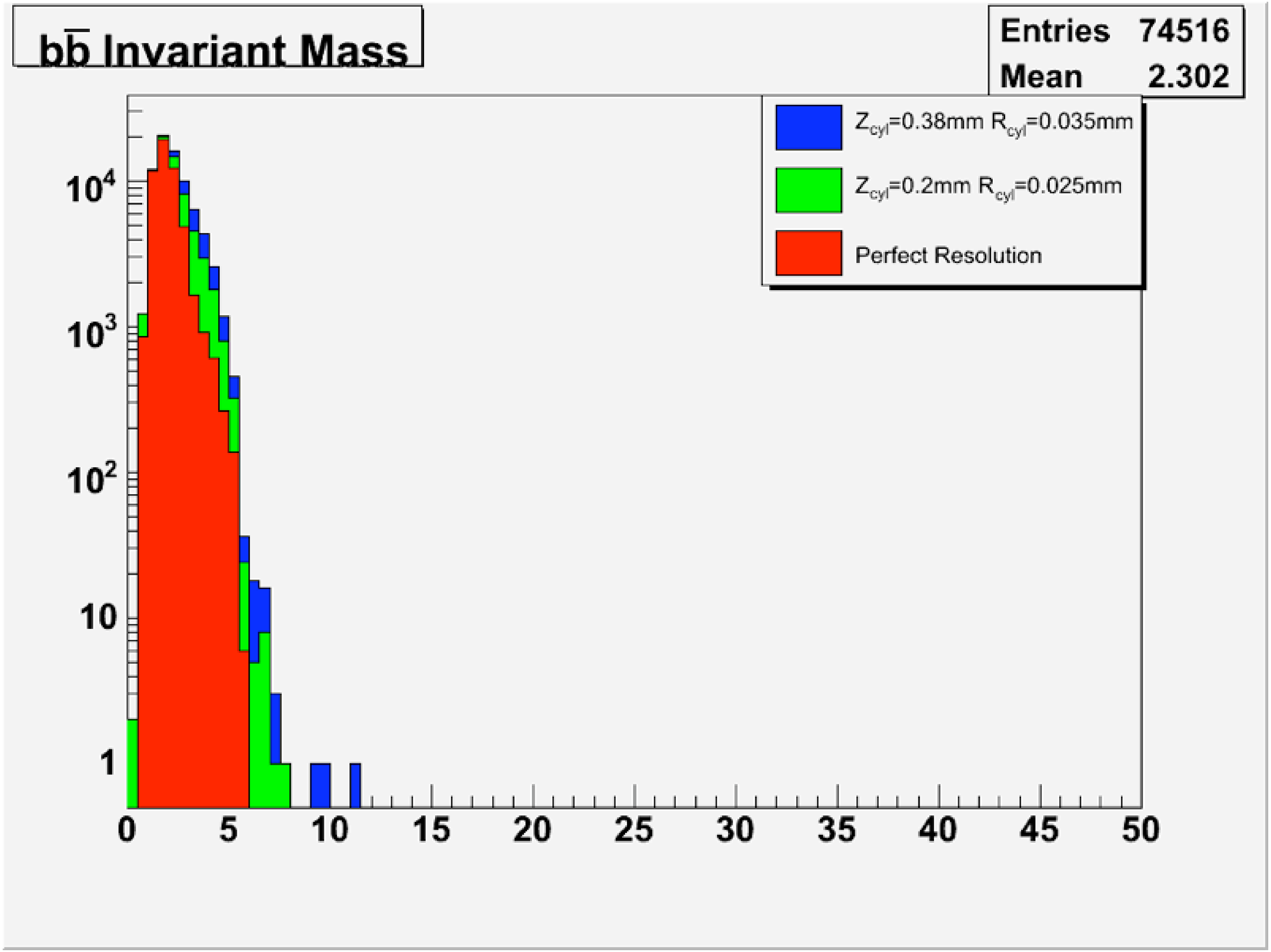
Background concerns:

Overlapping b's or other DVs in the SM.

Material interactions.

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

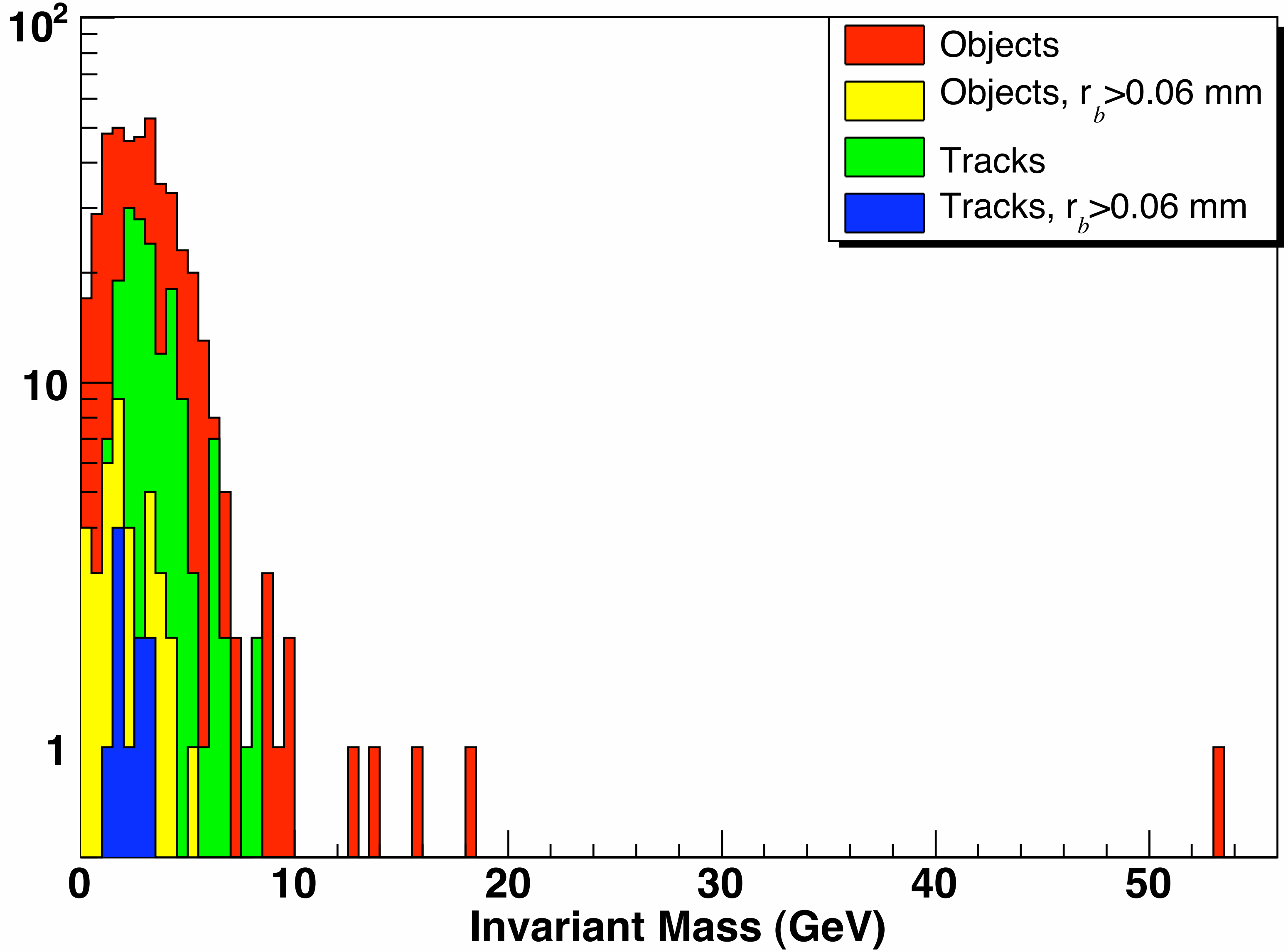
Looked for *b* decays on top of other decays.

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

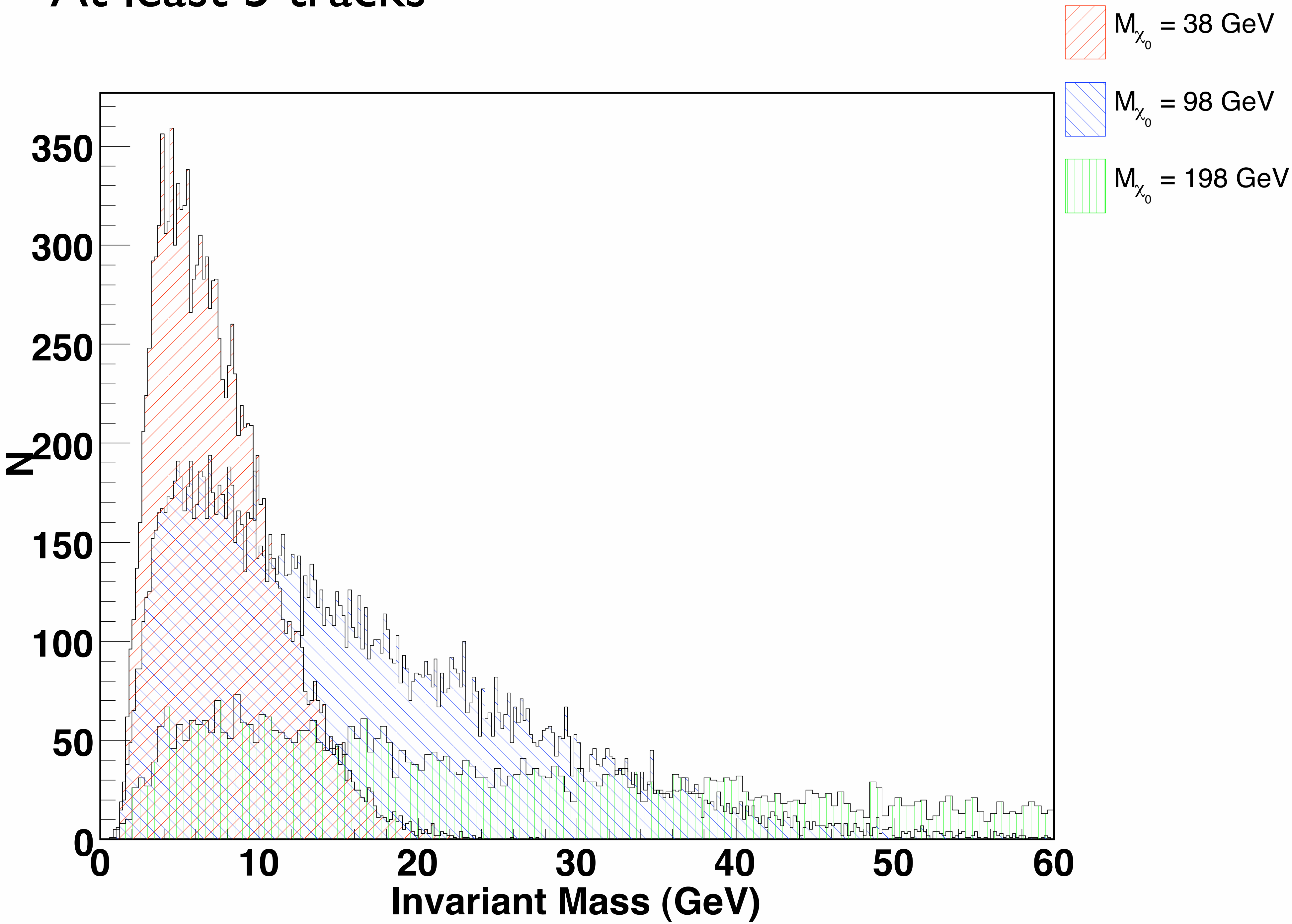
Expect 10^{12} *b*-pairs per year!!!

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

Overlapping events

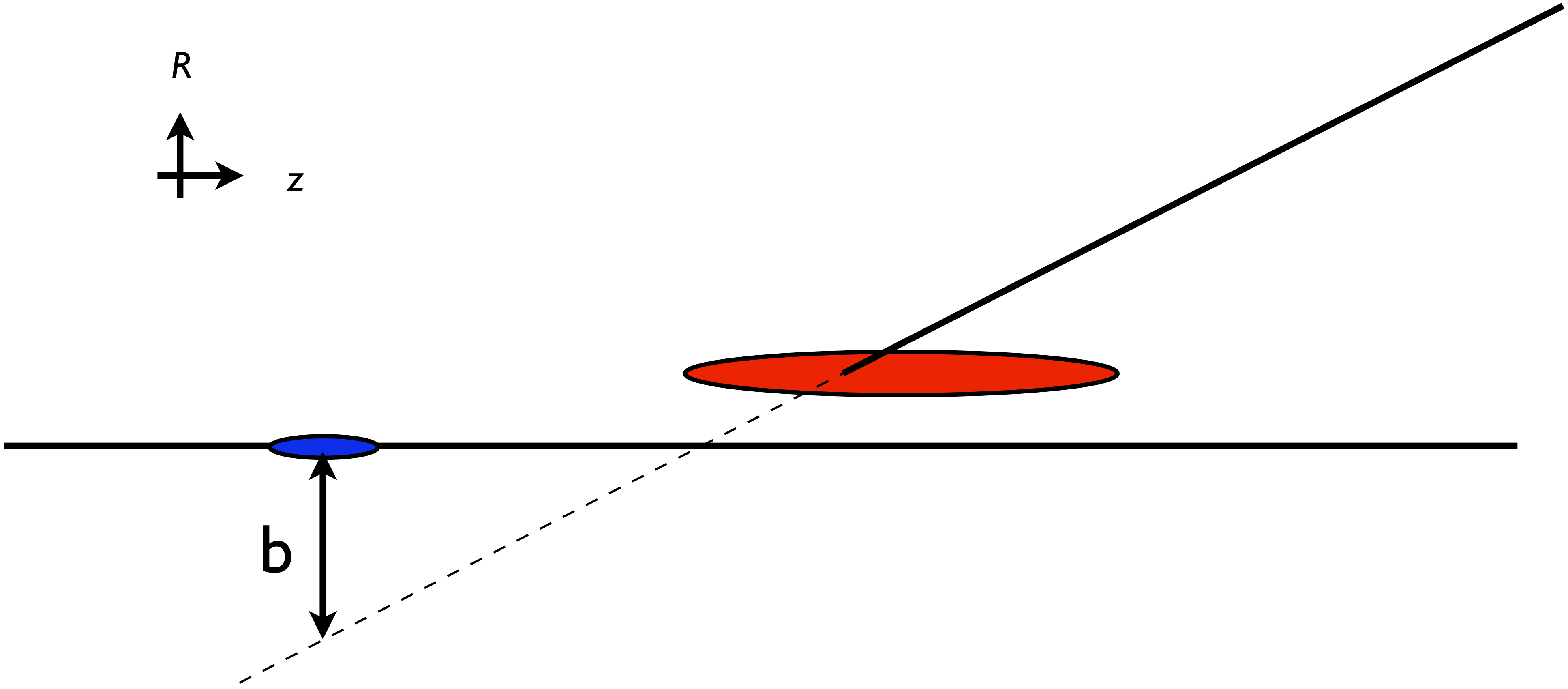


At least 5 tracks

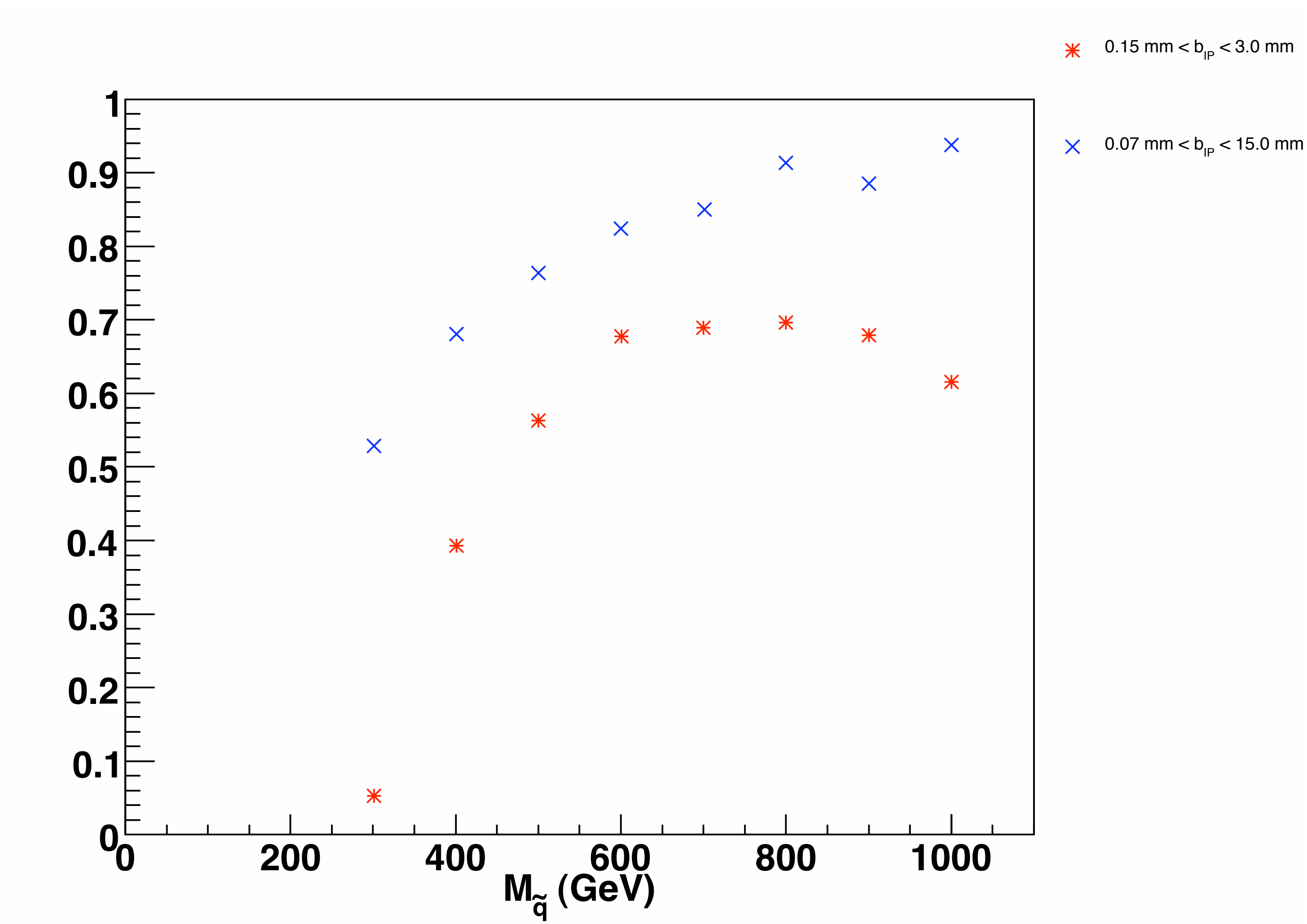


Level 1 Trigger

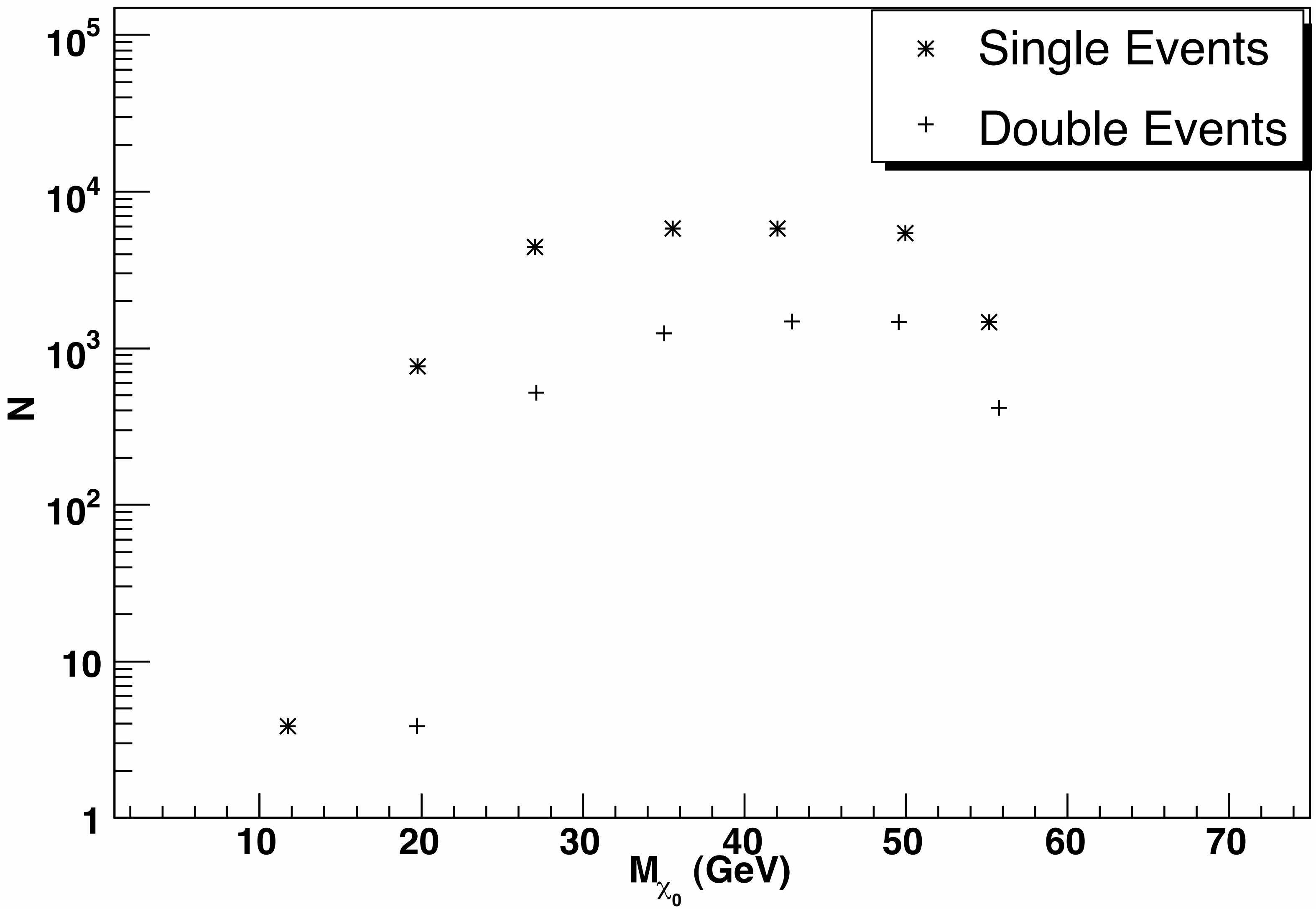
.15 mm < b < 3 mm



Impact Parameter: cuts and efficiency



Higgs in acceptance



Summary

- Supersymmetry and other new physics provide many LHCb-friendly phenomena.

- LHCb complements strengths of the hermetic detectors. Could meet or beat others on Higgs decays.

- Pythia can simulate most current models - high-level triggers NEEDED for these phenomena!

Higgs Potential

$$\lambda |h|^4 \rightarrow \frac{g^2}{8}\left[|H_1|^2 - |H_2|^2\right]^2 \qquad m_h = M_Z|\cos 2\beta|$$

SUSY-breaking loop required - same size as tree.

$$(m_h^2)_{tree} + \delta m_h^2 > (114\,\mathrm{GeV})^2$$ (Big Susy-breaking in top sector)

New tree-level contribution requires new fields:

$$W = ySH_1H_2 \;\rightarrow\; y^2\,|H_1H_2|^2$$

Some decays