Searches for Supersymmetry

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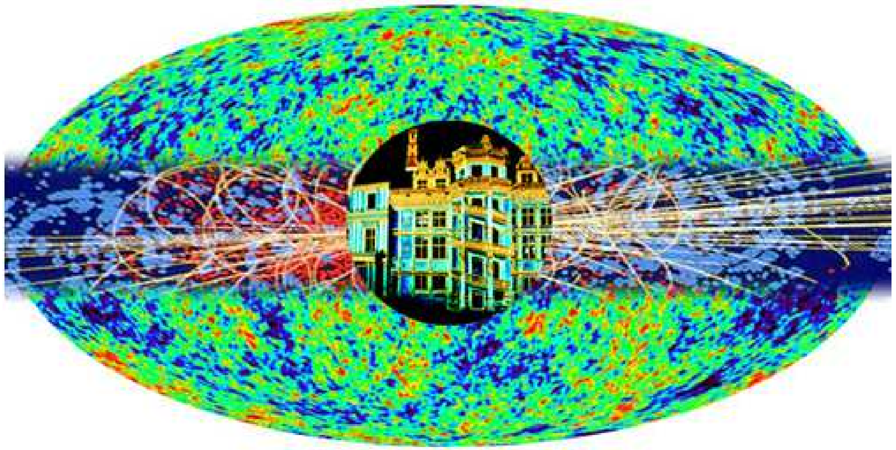


Selection of results from the ALEPH, ATLAS, Babar, CDF, CMS and DØ Collaborations

- The Higgs Sector (see also parallel talks by Cristobal Cuenca, Artur Kalinowski)
- Superpartners (see also parallel talks by John Parsons, Roberto Rossin)

Tevatron: 2 TeV

Proton-Antiproton

In operation since 2001

9 fb^{-1} delivered, expect 12 fb^{-1} by 2011

LHC: 7–14 TeV

Proton-Proton

In operation since 2009

0.2 pb^{-1} delivered, expect 1 fb^{-1} by 2011

Supersymmetry

The idea: particle physics is symmetric under transformation of Fermion $\leftrightarrow$ Boson

$\longrightarrow$ one supersymmetric partner for each SM particle

$\longrightarrow$ stabilizes Higgs mass, unification of coupling constants, dark matter candidate

Superpartners are heavy $\longrightarrow$ SUSY is broken $\longrightarrow$ masses unknown

Prediction:

– Extended Higgs sector: 5 Higgs bosons h,H,A,H$^{\pm}$

– Many new particles: Charginos/Neutralinos/Gluinos, Squarks, Sleptons

Names		spin 0	spin 1/2
squarks, quarks	Q	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$
($\times$3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$
sleptons, leptons	L	$(\widetilde{\nu} \ \ \widetilde{e}_L)$	$(\nu \ \ e_L)$
($\times$3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$
Higgs, higgsinos	H_u	$(H^+_u \ \ H^0_u)$	$(\widetilde{H}^+_u \ \ \widetilde{H}^0_u)$
	H_d	$(H^0_d \ \ H^-_d)$	$(\widetilde{H}^0_d \ \ \widetilde{H}^-_d)$

Names	spin 1/2	spin 1
gluino, gluon	$\widetilde{g}$	g
winos, W bosons	$\widetilde{W}^{\pm} \ \ \widetilde{W}^0$	$W^{\pm} \ \ W^0$
bino, B boson	$\widetilde{B}^0$	B^0

The minimal SUSY Higgs Sector

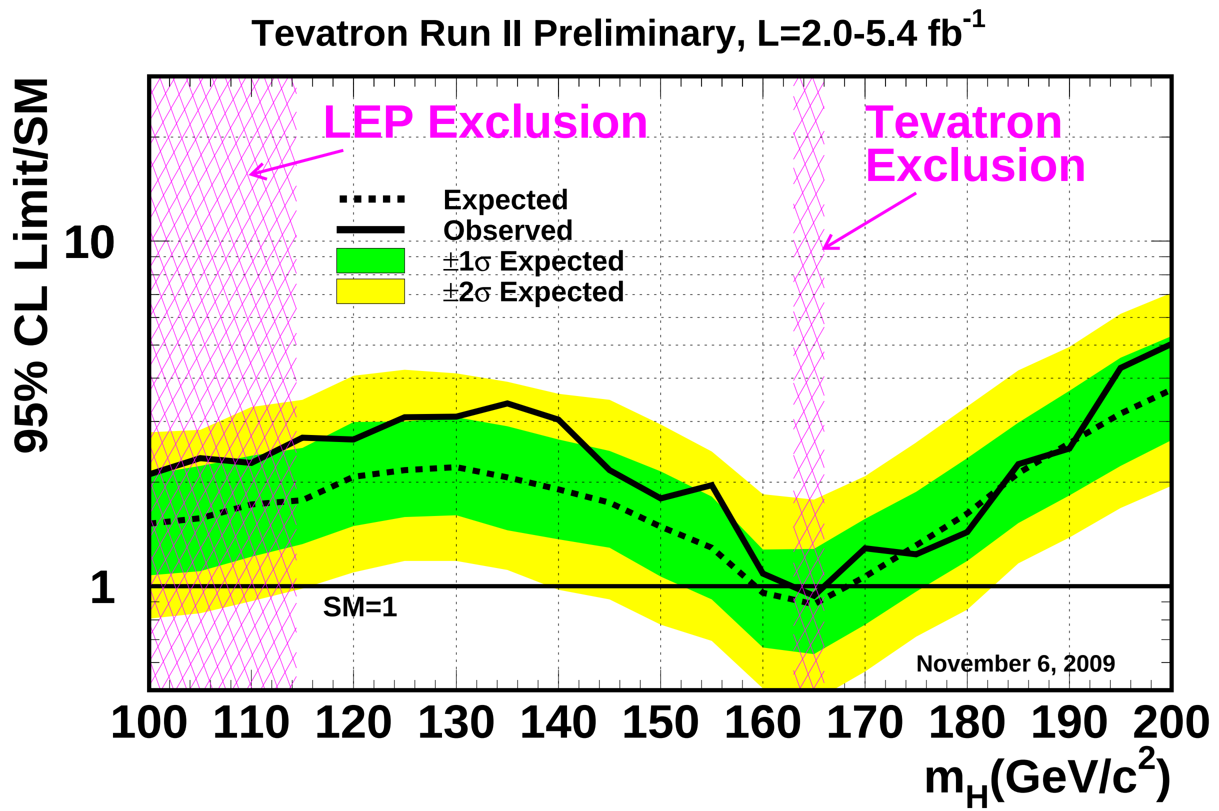
2HDM with only 2 free parameters, typically chosen as m_A and $\tan\beta$

Parameter m_A: regulates masses of heavy Higgs bosons H, A, $H^\pm$

– lightest Higgs h is tied to Z mass and typically behaves SM-like

– decoupling limit $m_A \to \infty$: MSSM$\to$SM

$\to$ SM Higgs searches also relevant to MSSM Higgs sector

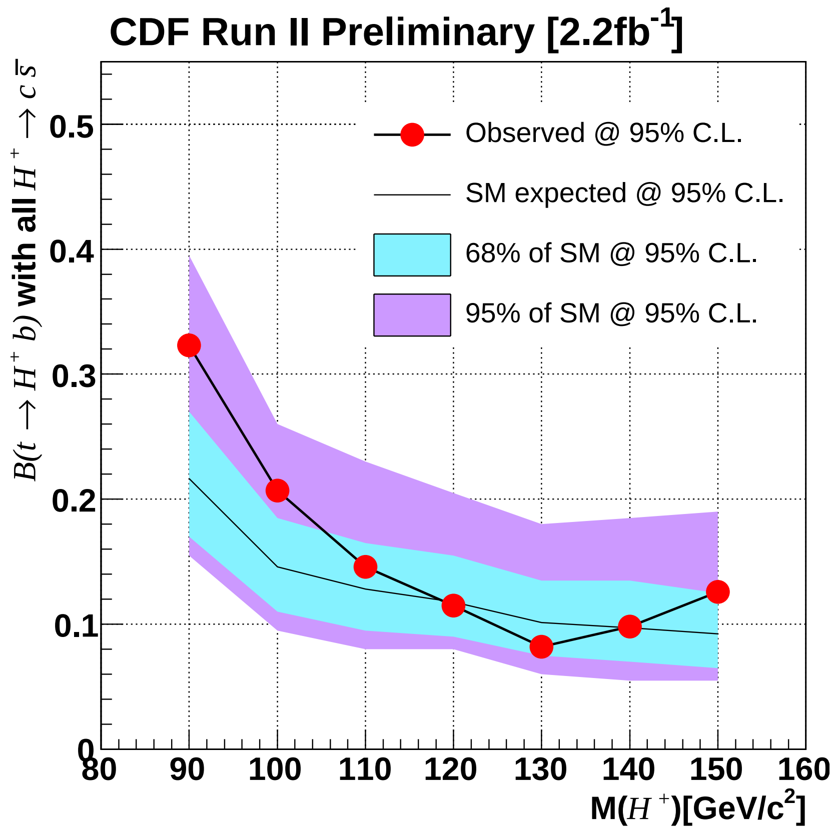


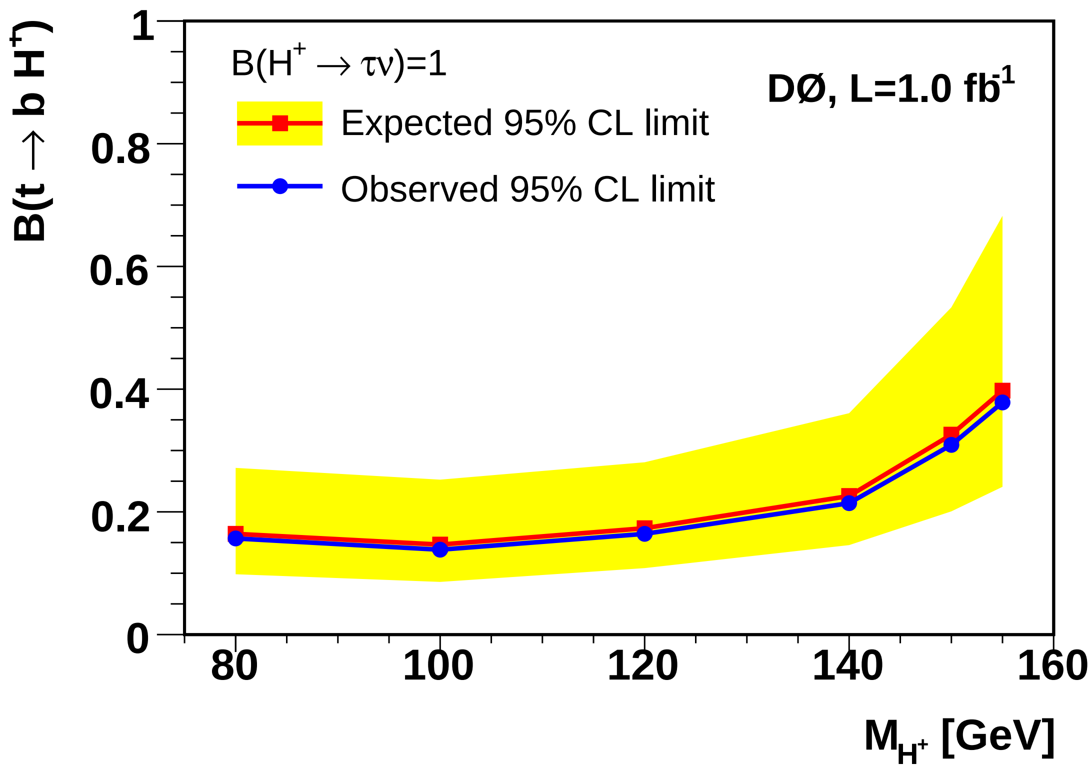
– main difference: couplings to W/Z suppressed

$\to$ will become sensitive only after SM Higgs sensitivity has been reached

The minimal SUSY Higgs Sector: Charged Higgs Bosons

Decay Mode	Production	Method	Experiment	Luminosity
$H^{\pm} \rightarrow \tau\nu$,cs	$e^+e^- \rightarrow H^+H^-$		LEP	2.5 fb^{-1}
$H^{\pm} \rightarrow$ cs	$t \rightarrow H^{\pm}b$	direct	CDF	2.2 fb^{-1}
$H^{\pm} \rightarrow \tau\nu$, qq	$t \rightarrow H^{\pm}b$	direct+indirect	DØ	1.0 fb^{-1}
$H^{\pm} \rightarrow$ tb	$qq \rightarrow H^{\pm}$		DØ	0.9 fb^{-1}
$H^{\pm} \rightarrow \tau\nu$	$t \rightarrow H^{\pm}b$	direct	CDF	0.3 fb^{-1}





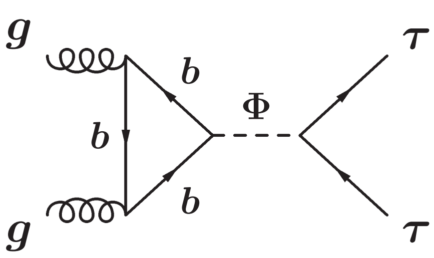
The minimal SUSY Higgs Sector: the high tanβ region

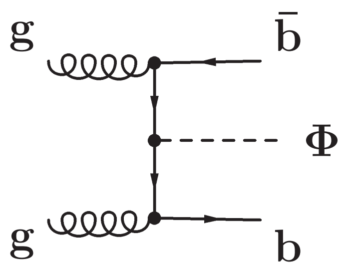
2HDM with only 2 free parameters, typically chosen as m_A and tanβ

Parameter tanβ: regulates Higgs couplings

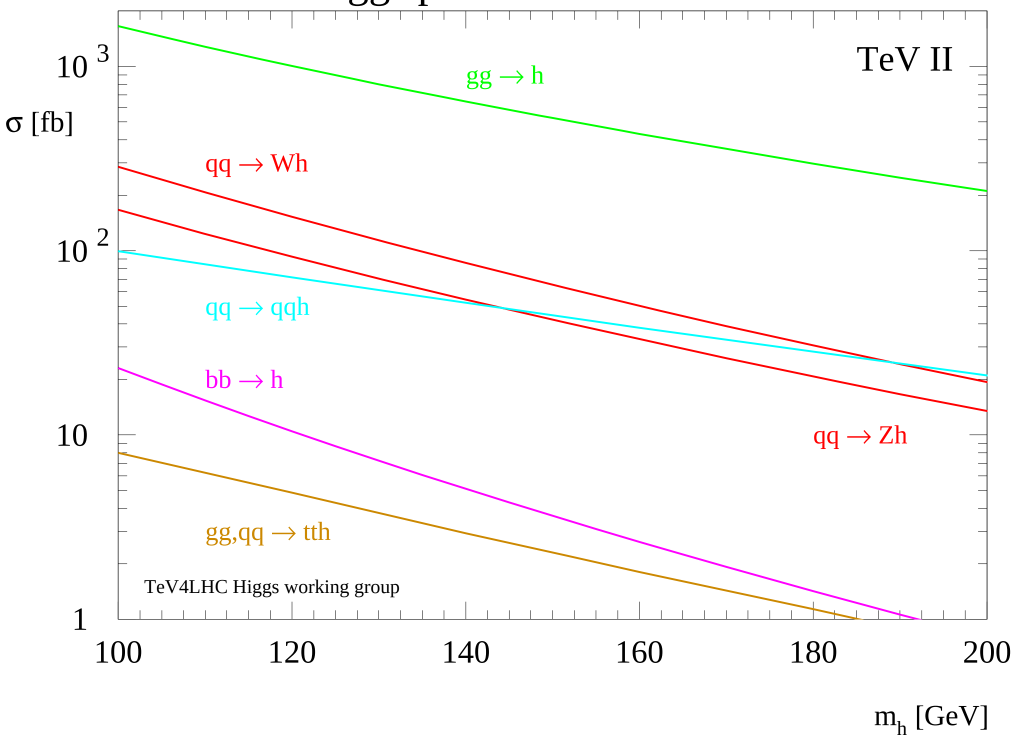
- **most interesting difference to SM: bbΦ coupling proportional to tanβ**

$\rightarrow$ **new search channels with potentially large cross sections**

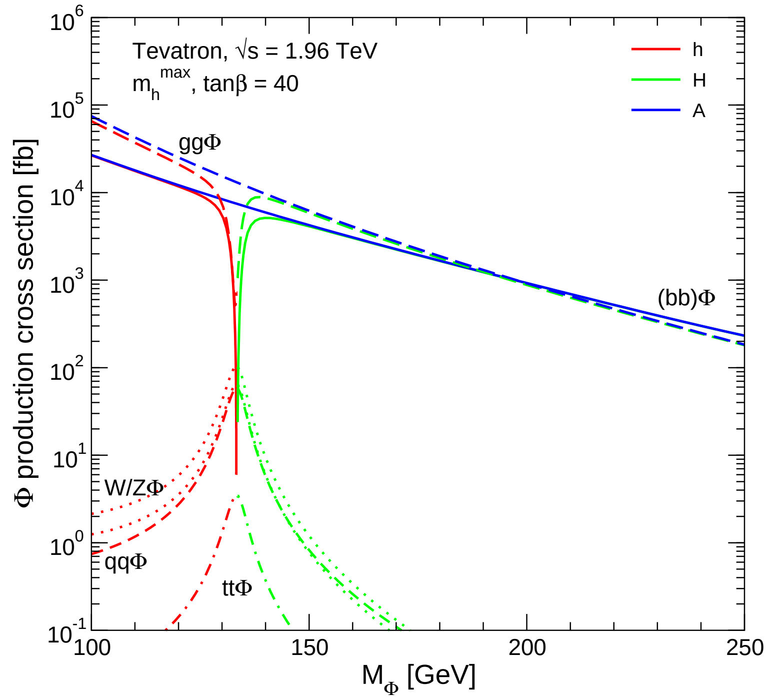




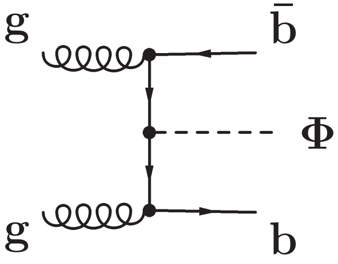
SM Higgs production cross sections



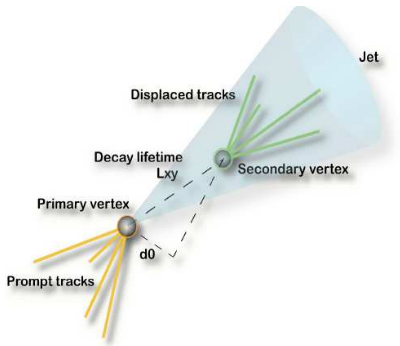
MSSM Higgs Production cross sections

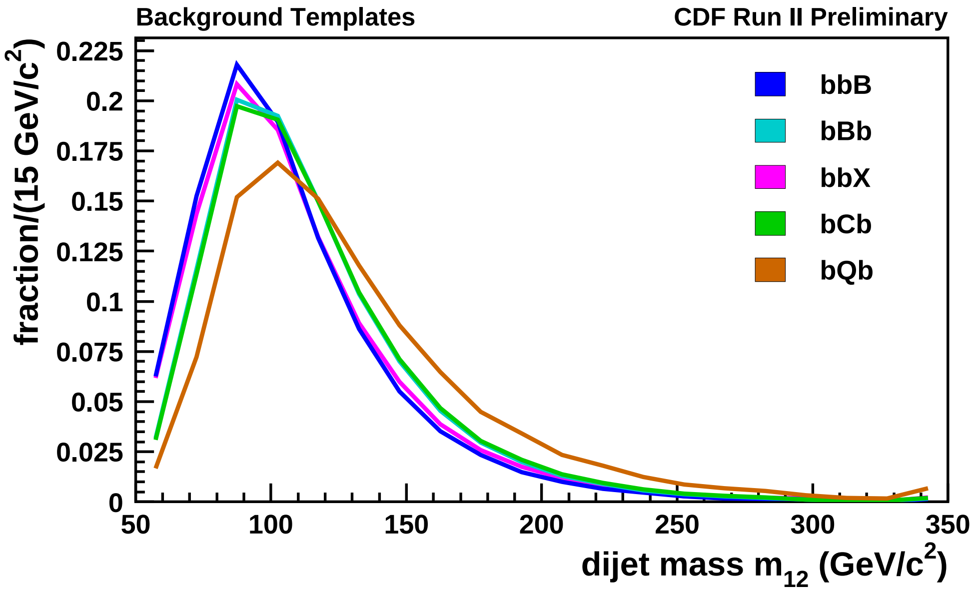


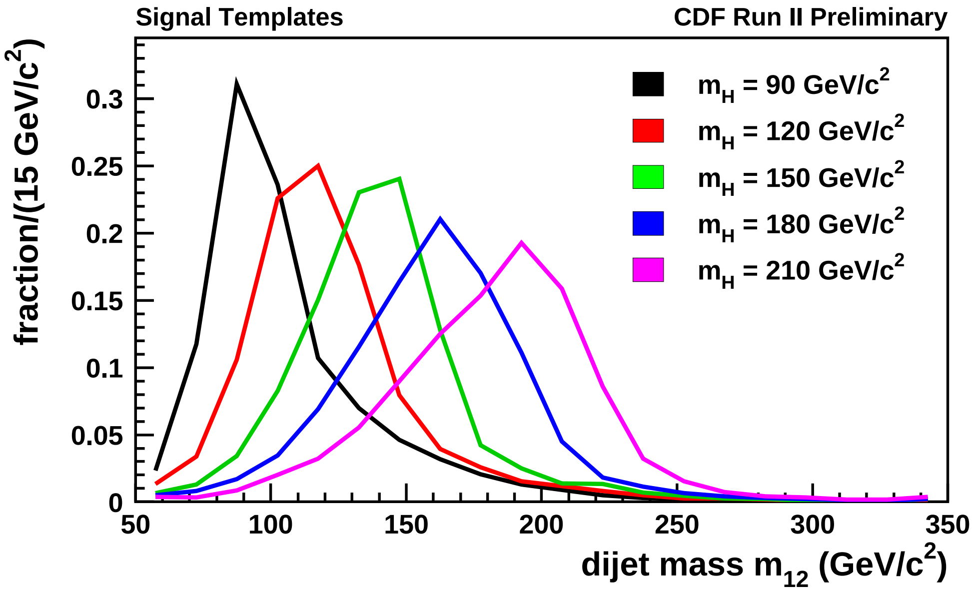
New CDF Result: Search for $\Phi b(b) \rightarrow bbb(b)$



- Selection: at least 3 b-jets
- Backgrounds: multijet production
  - 3 main components: bbb, bbc, bbq
- Reconstruction of Higgs boson mass in $b\bar{b}$ spectrum
- Additional variable: x_{tags}
  - linear combinations of secondary vertex masses in each jet
  - sensitive to flavour composition of the 3 b-tagged jets







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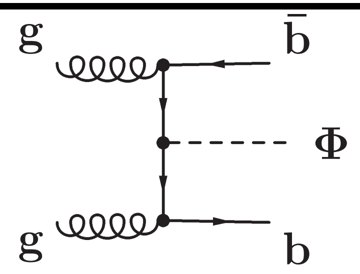
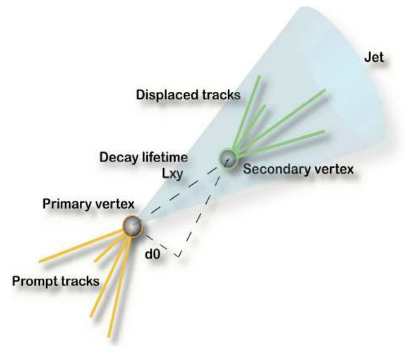
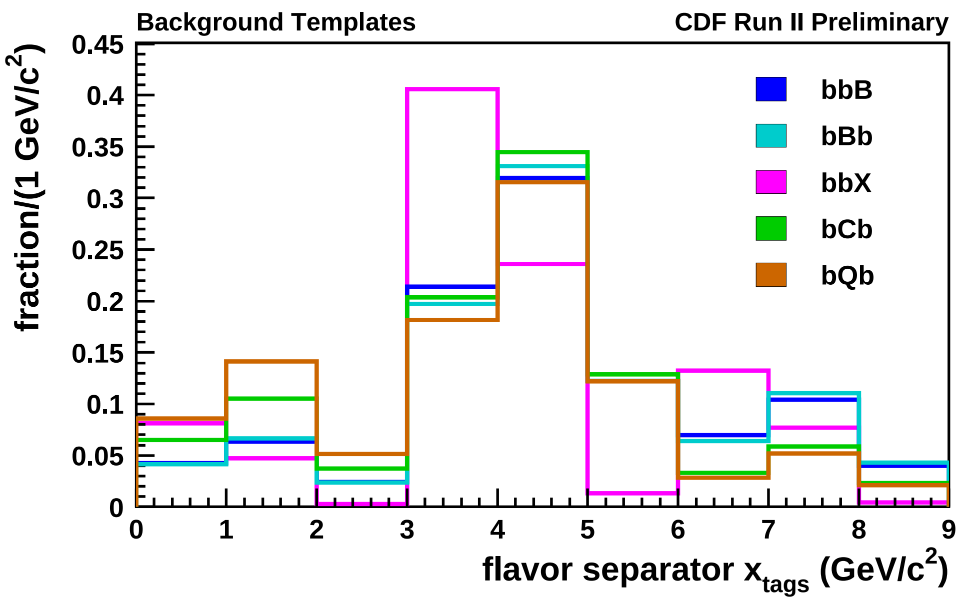
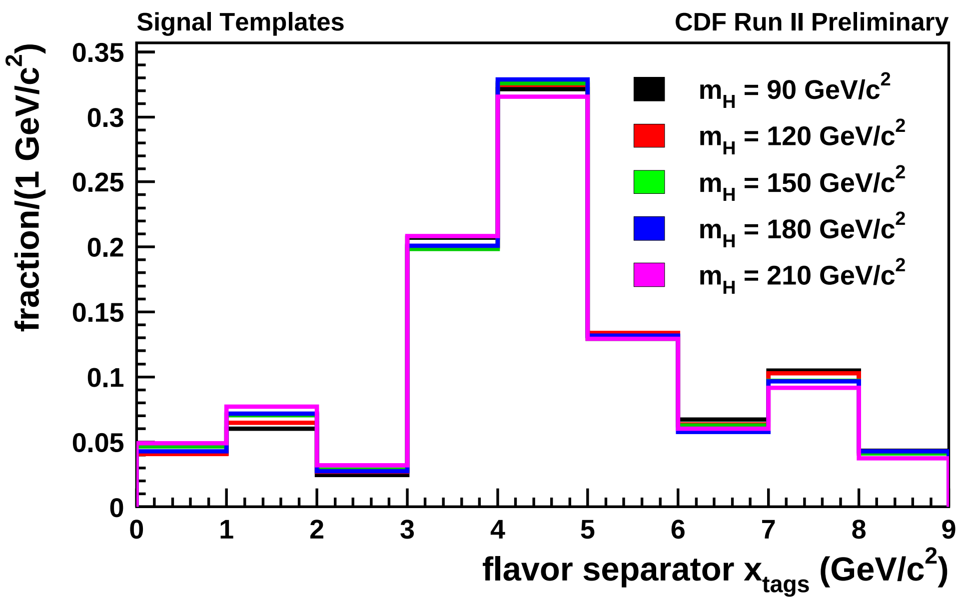








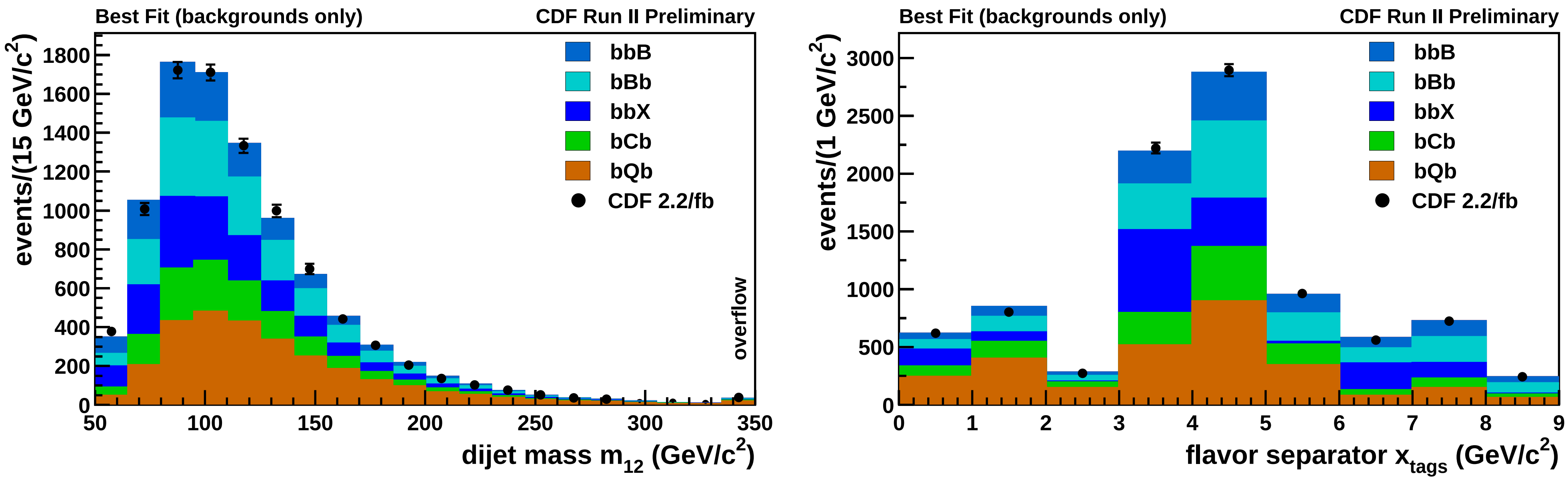
New CDF Result: Search for $\Phi b(b) \to bbb(b)$

Main challenge: construct accurate background model from data

Procedure:

- extract background shapes in dijet mass and x_{tags} from double-tagged sample
- fit normalisation of 2d-templates to triple-tagged sample

Fit results (background only):



- **data consistent with background expectation**

New CDF Result: Search for $\Phi b(b) \to bbb(b)$

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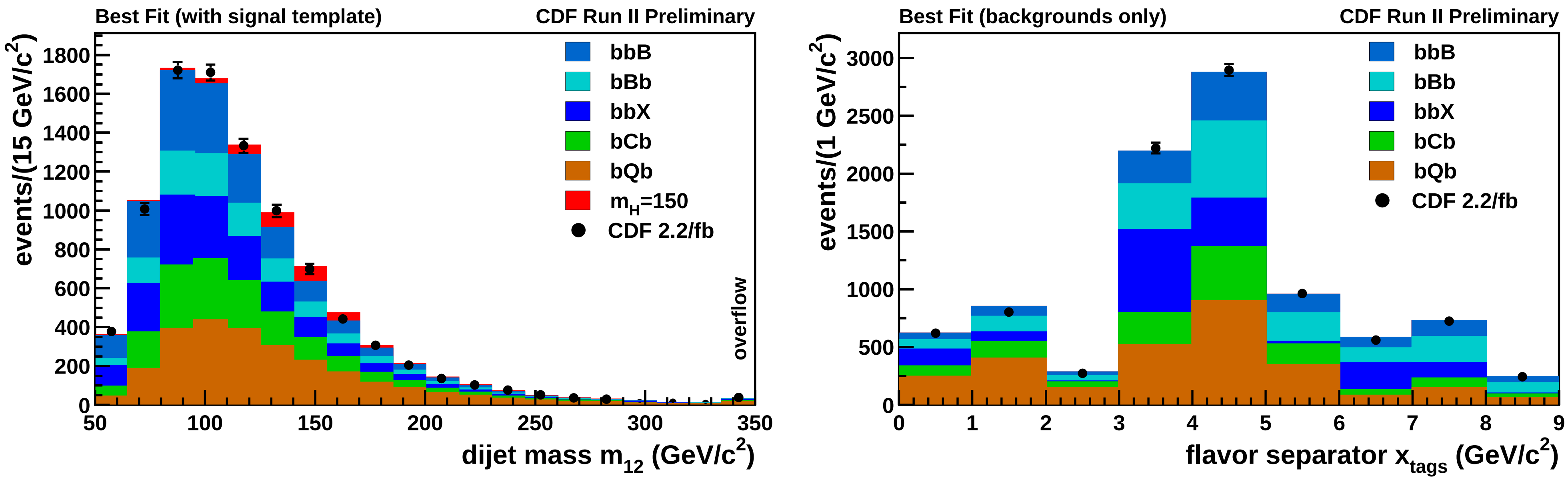
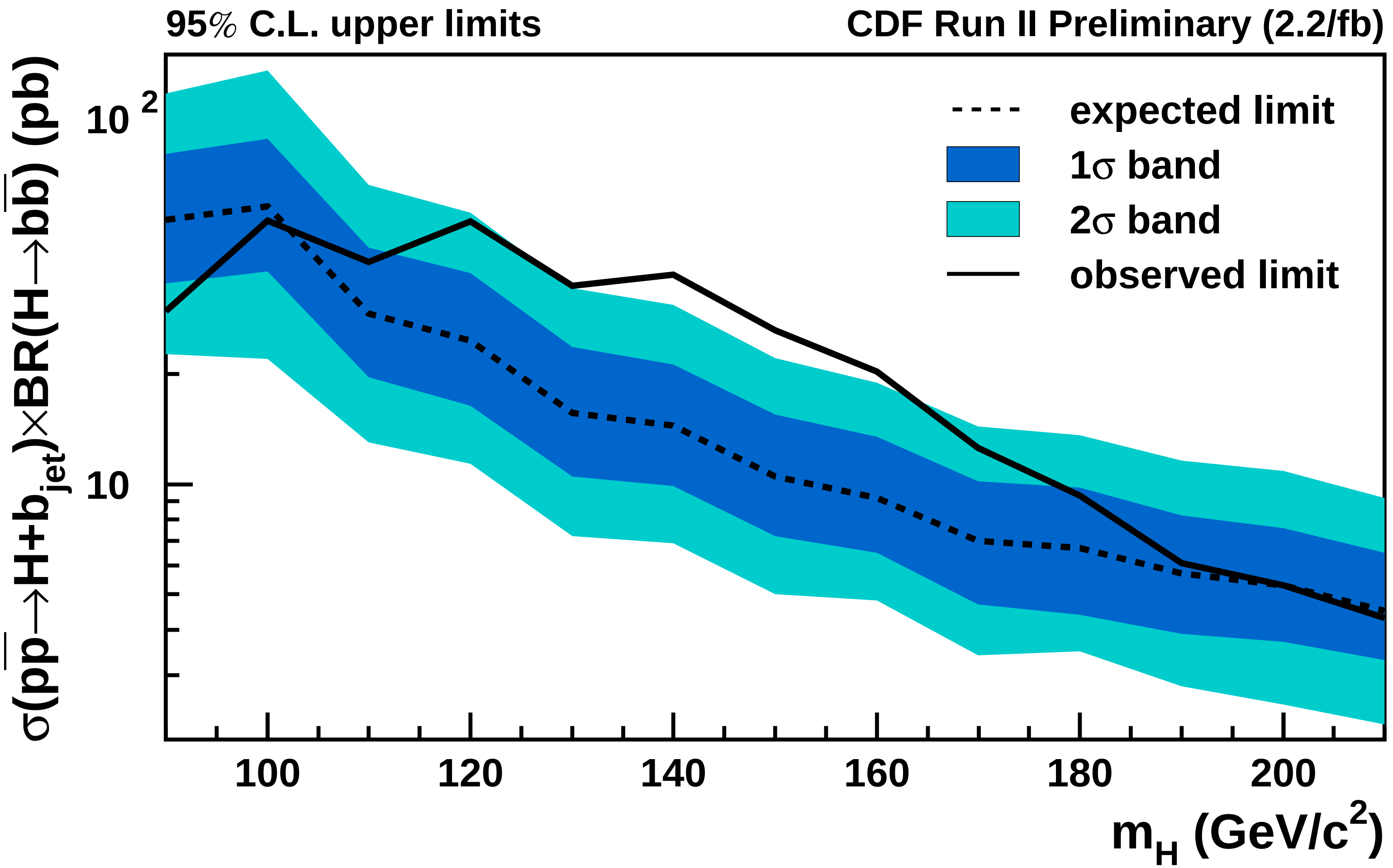


- data consistent with background expectation
- room for signal (in particular for masses around 140 GeV)

New CDF Result: Search for $\Phi b(b) \rightarrow bbb(b)$

Interpretation: upper limit on production cross section

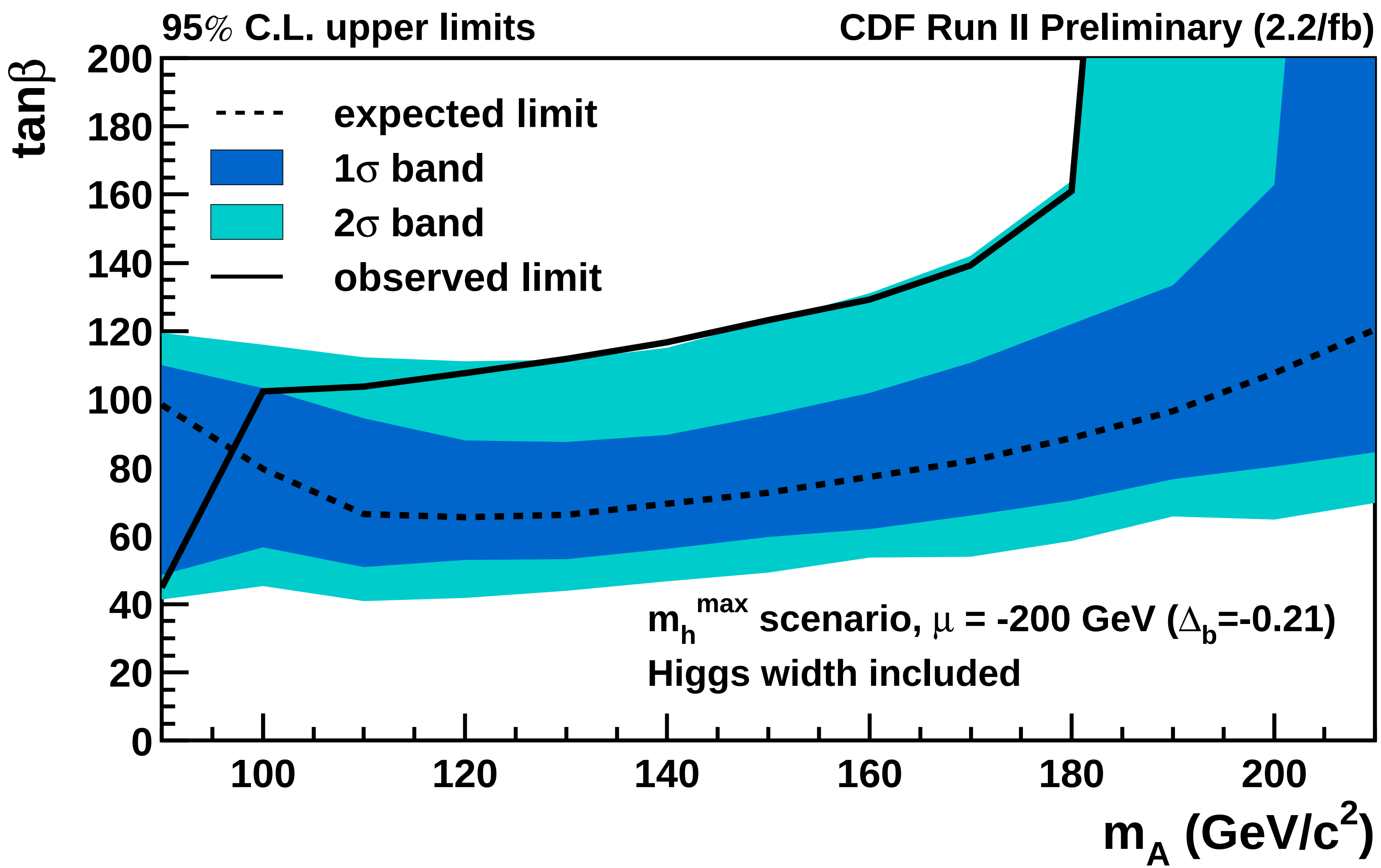


Excess around 140 GeV:

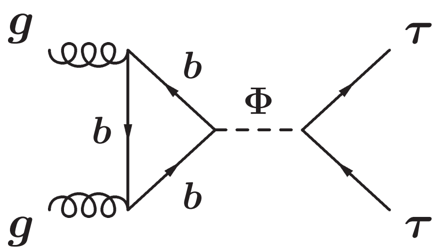
- p-value: 0.9%
- considering trial factor: 5.7%

New CDF Result: Search for $\Phi b(b) \rightarrow bbb(b)$

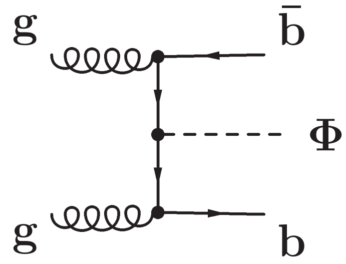
Interpretation: limits on tanβ within m_h^{max} benchmark scenario

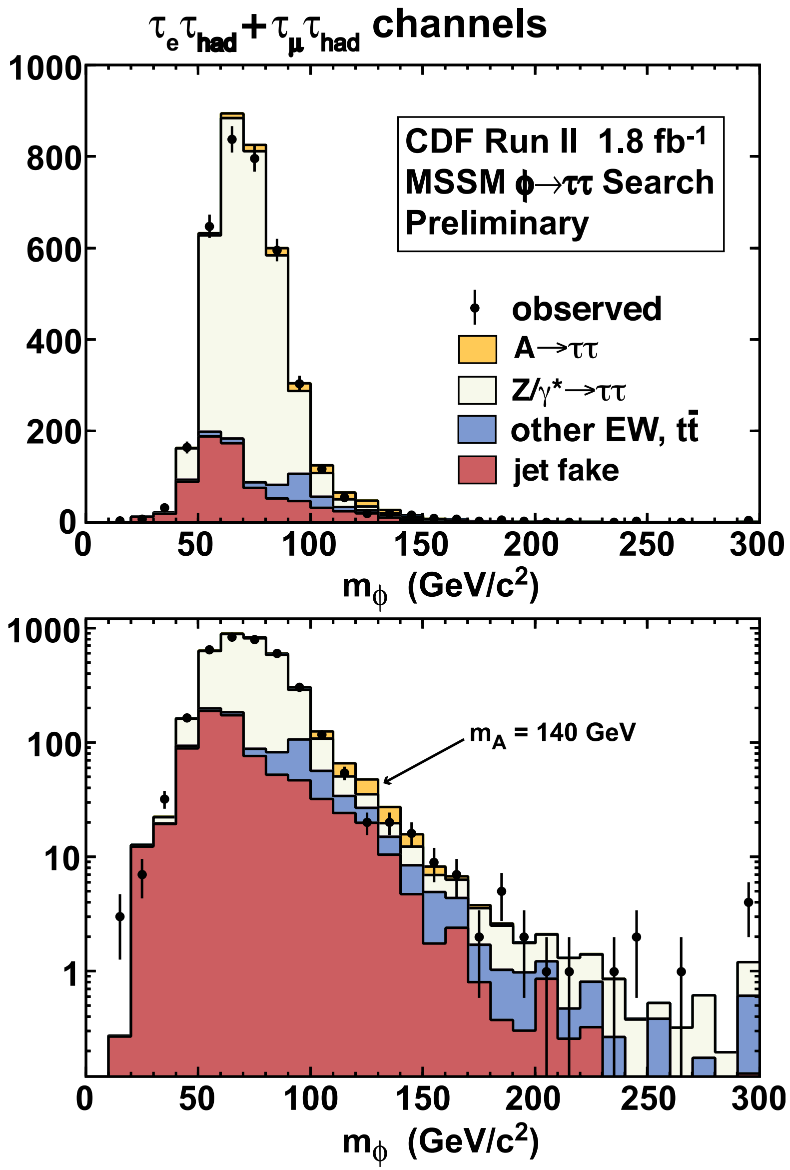


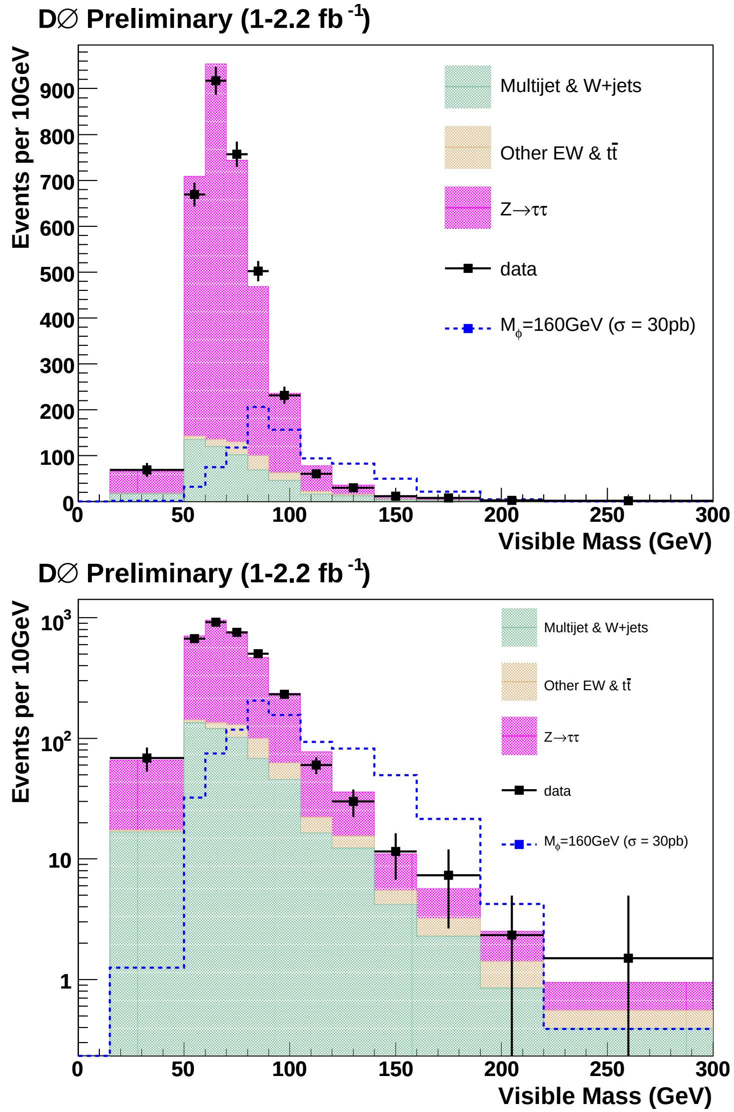
Search for Neutral Higgs Bosons with enhanced coupling to b



Channel	CDF	DØ
$b\Phi \rightarrow bbb$	$2.2\ \text{fb}^{-1}$	$2.6\ \text{fb}^{-1}$
$b\Phi \rightarrow b\tau\tau$	–	$2.7\ \text{fb}^{-1}$
$\Phi \rightarrow \tau\tau$	$1.8\ \text{fb}^{-1}$	$2.2\ \text{fb}^{-1}$





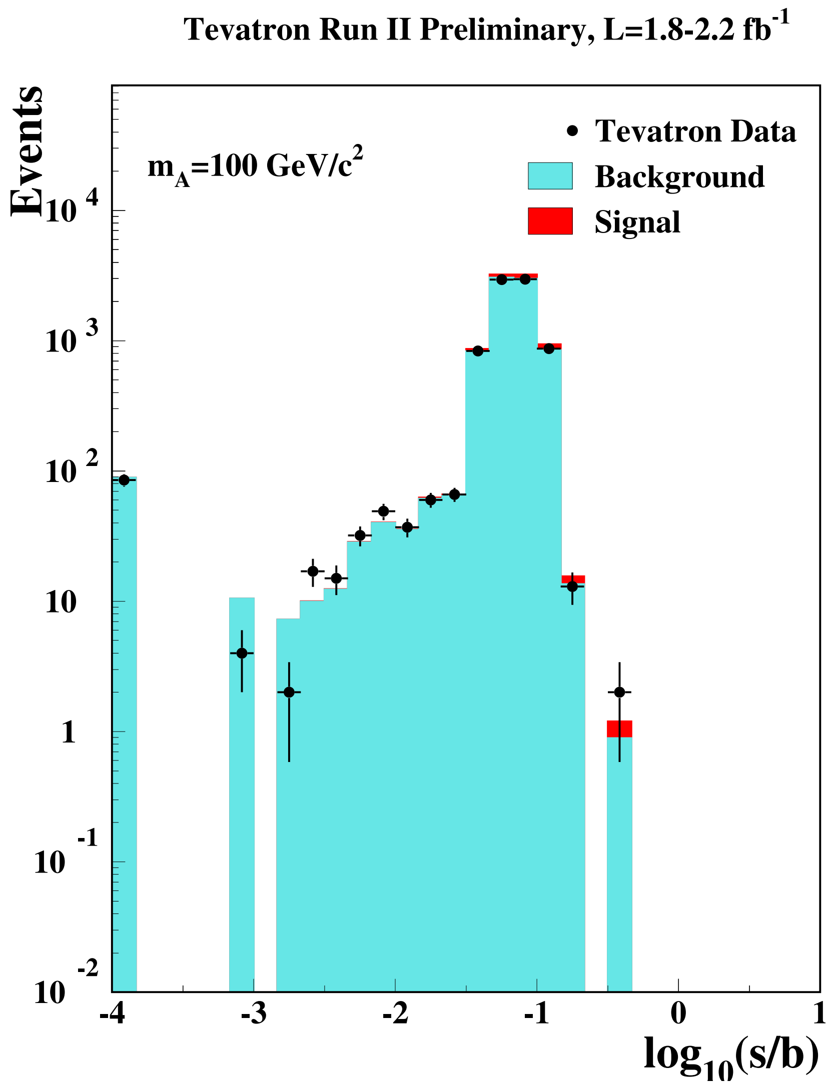


Search for Neutral Higgs Bosons with enhanced coupling to b

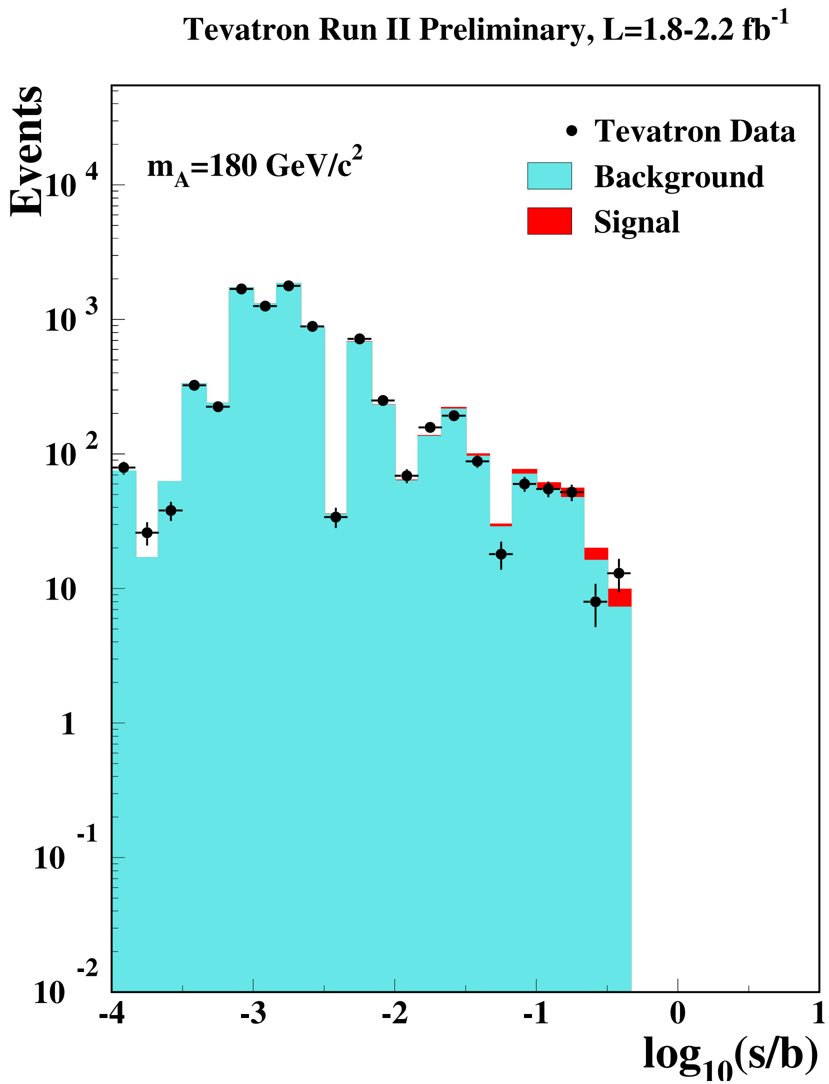
2009: Combined DØ MSSM limits based on $\Phi \rightarrow \tau\tau$, $b\Phi \rightarrow bbb$, $b\Phi \rightarrow b\tau\tau$

NEW: Combined MSSM limits based on CDF and DØ $\Phi \rightarrow \tau\tau$ analyses

– same statistical technique as used for the SM Higgs combination



$M_{\Phi}=100$ GeV, $\sigma \times BR=2$ pb



$M_{\Phi}=180$ GeV, $\sigma \times BR=0.66$ pb

Search for Neutral Higgs Bosons with enhanced coupling to b

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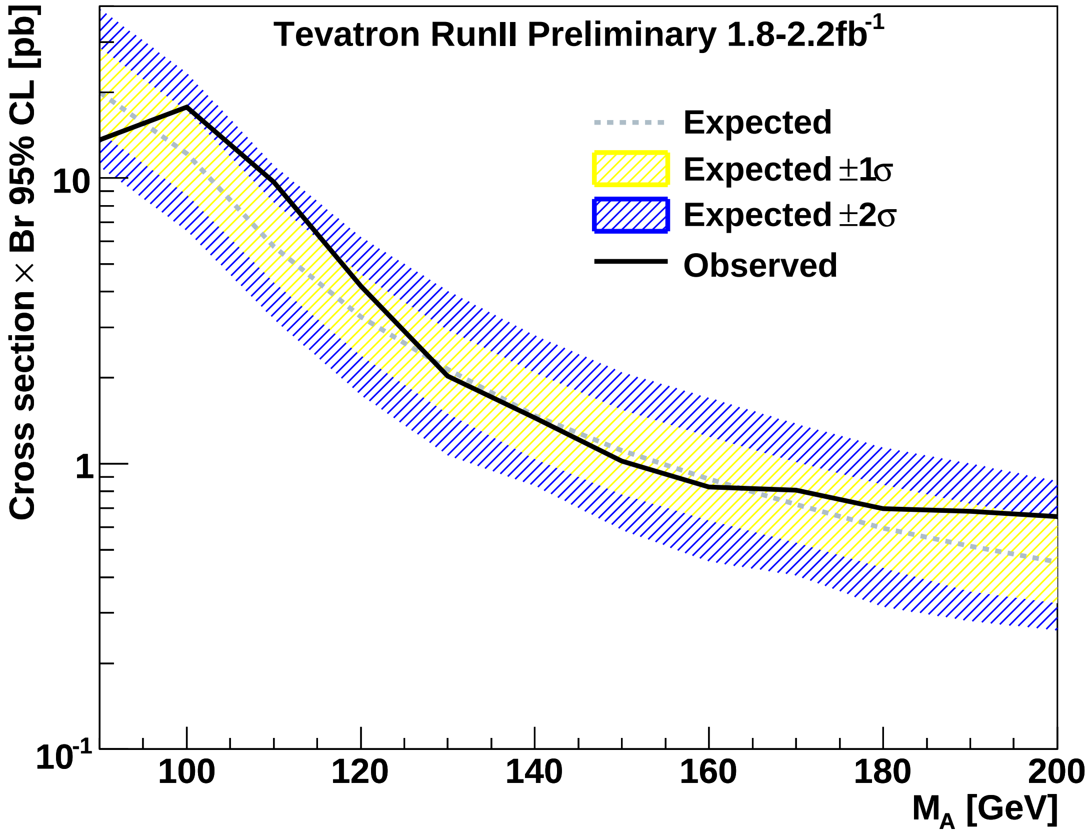

Excess in bbb channel at 140 GeV not confirmed

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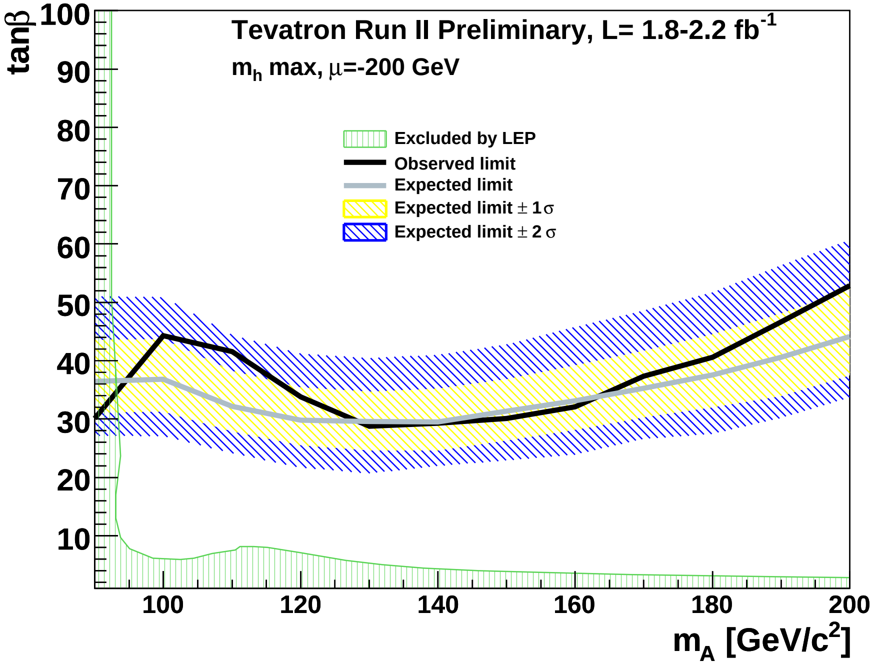
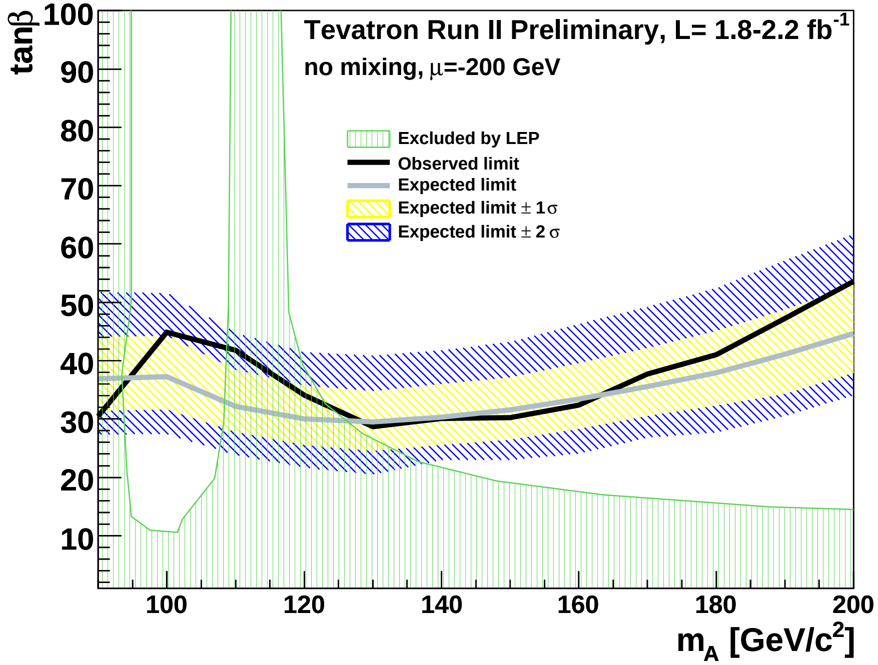


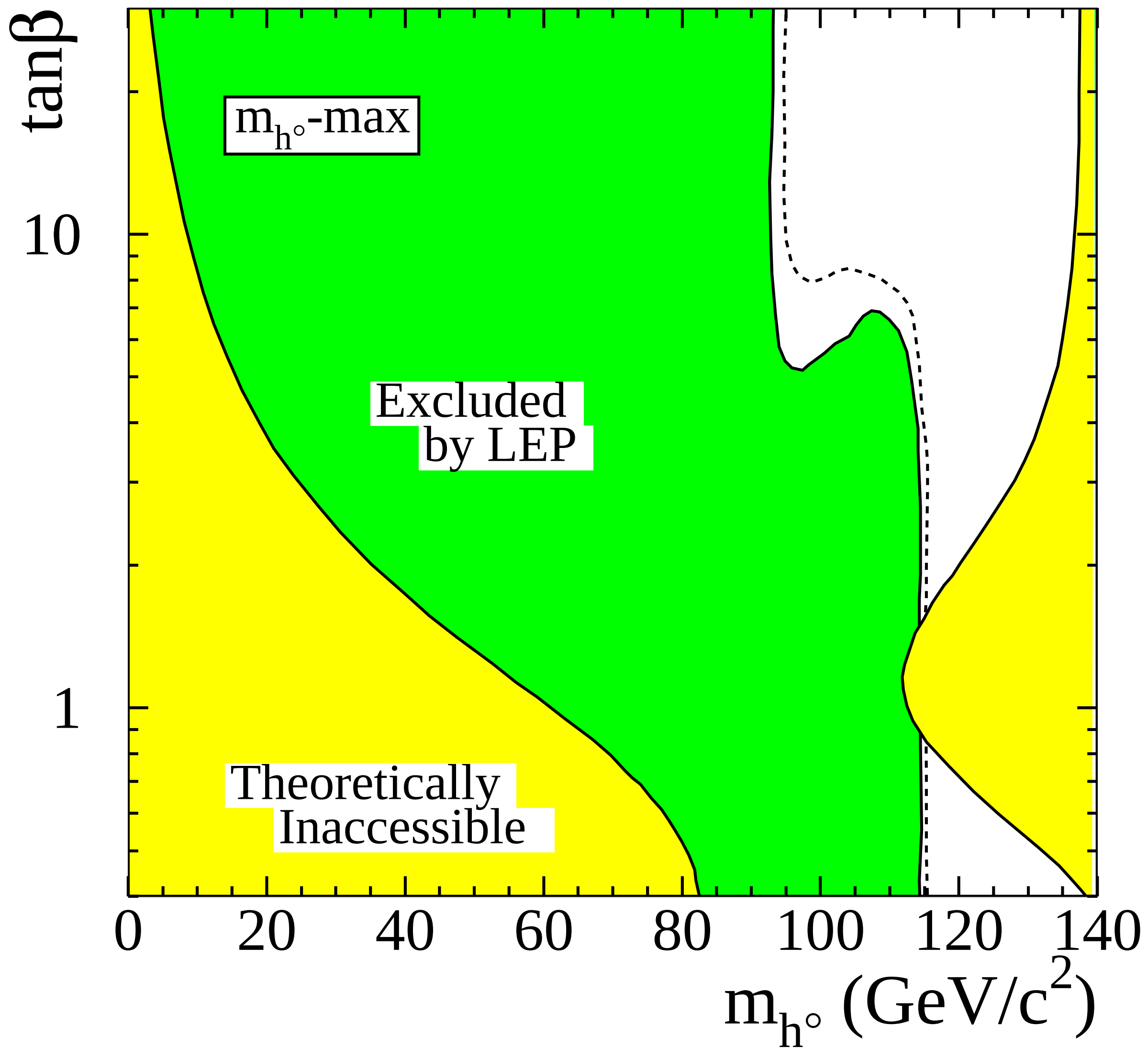


Tevatron now probing down to $\tan\beta = 30$

Next step: include $b\Phi$ channels in the combination

The Art of exclusion plots

LEP 2004: almost full exclusion?



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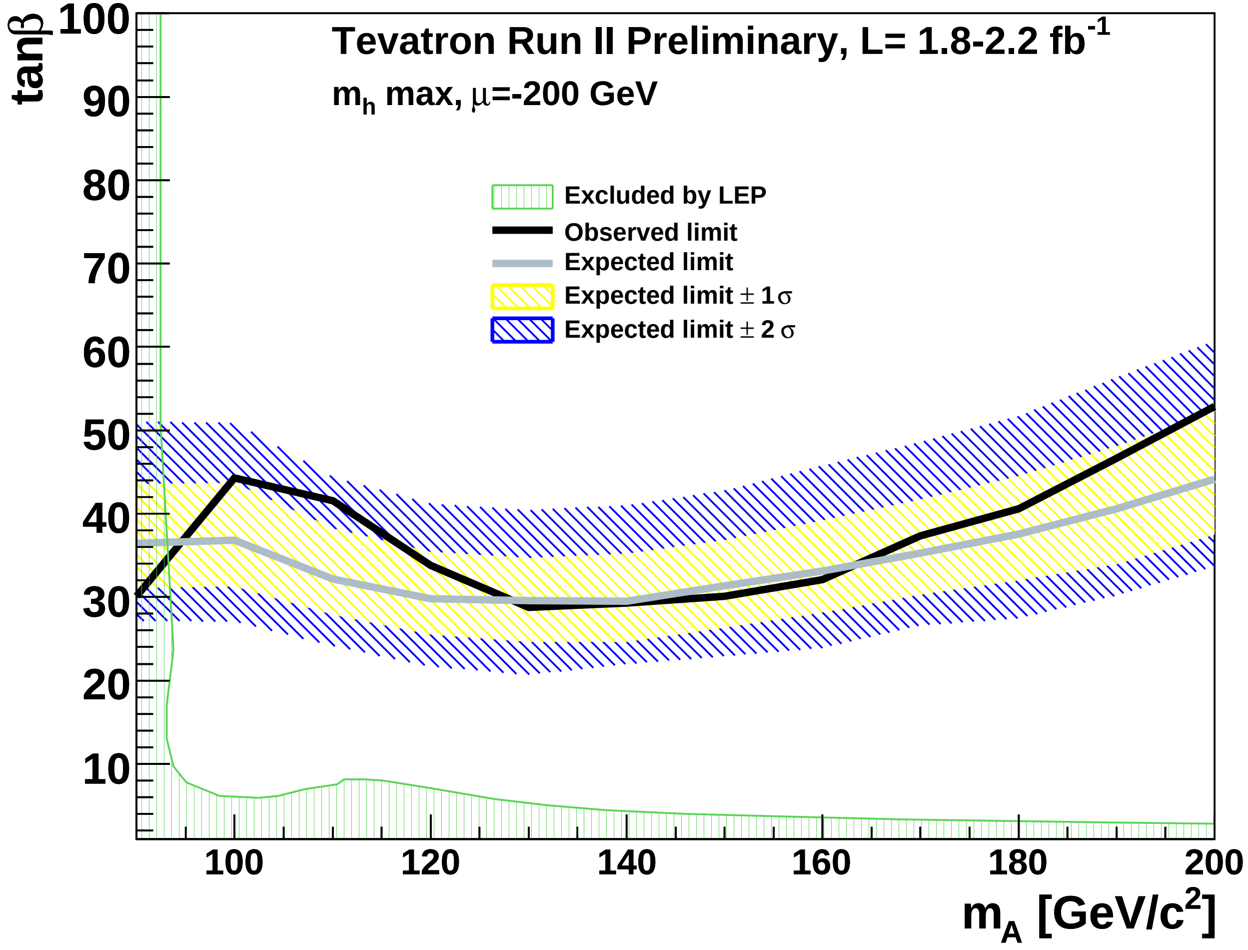

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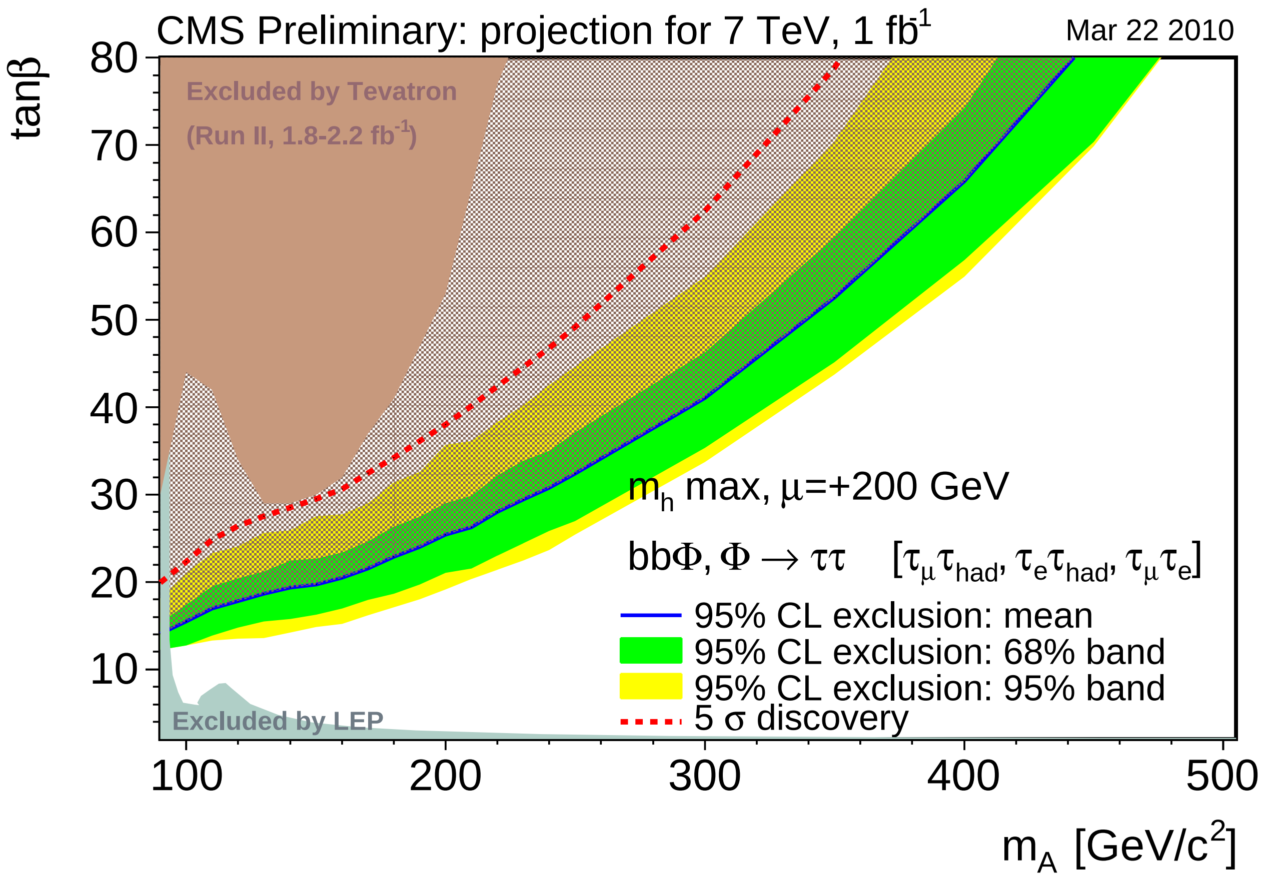


LHC:

- **will start to probe high m_A region with 1 fb^{-1}**
- **full coverage with 30 fb^{-1}**

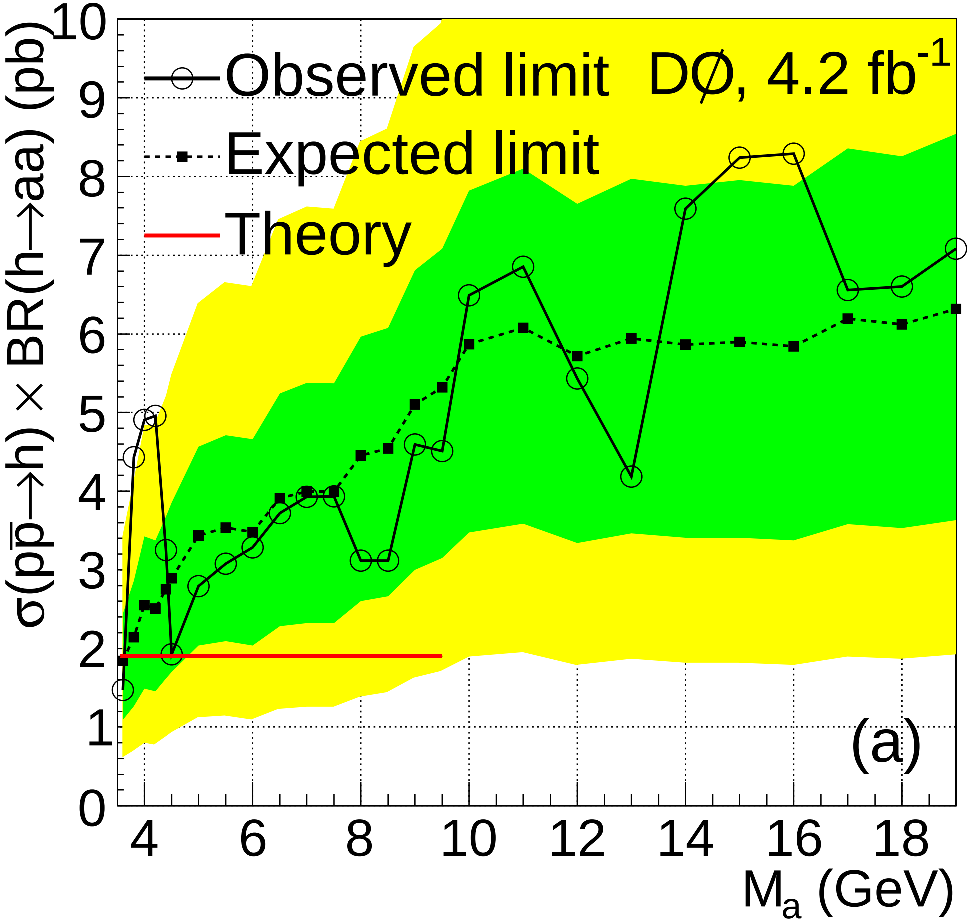
Beyond the MSSM: Higgs light

MSSM LEP Higgs limits can be evaded with light CP-odd Higgs boson a if h⟶aa

Possible within the NMSSM, MSSM with CP-violation in Higgs sector, superstring models

Many recent results:

- **DØ 2009: limits on $p\bar{p} \rightarrow h \rightarrow aa \rightarrow \mu\mu, \tau\tau$**



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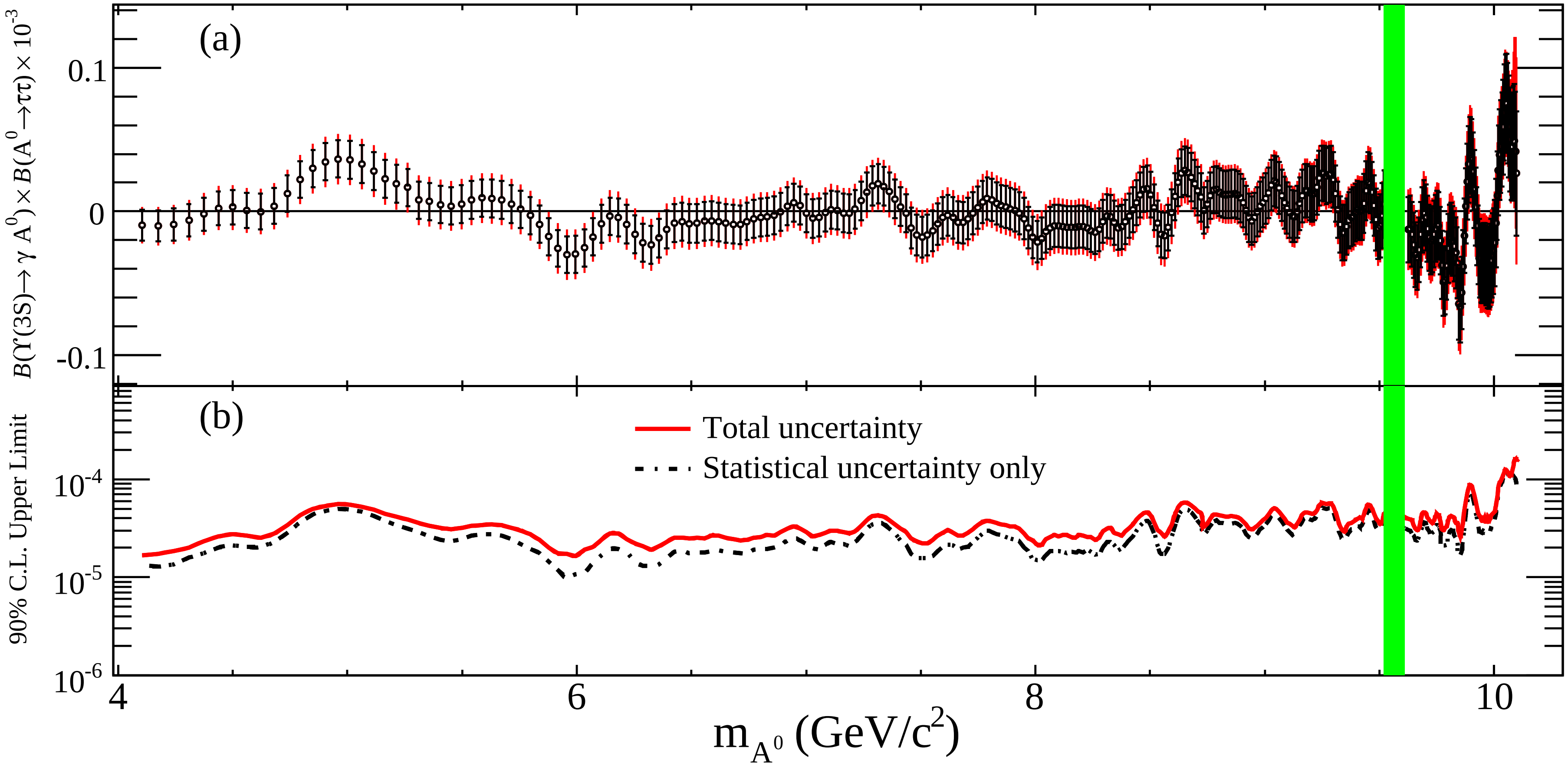
- **Babar 2009: limits on $\Upsilon(3S) \to \gamma a$ with a⟶ $\tau\tau$**



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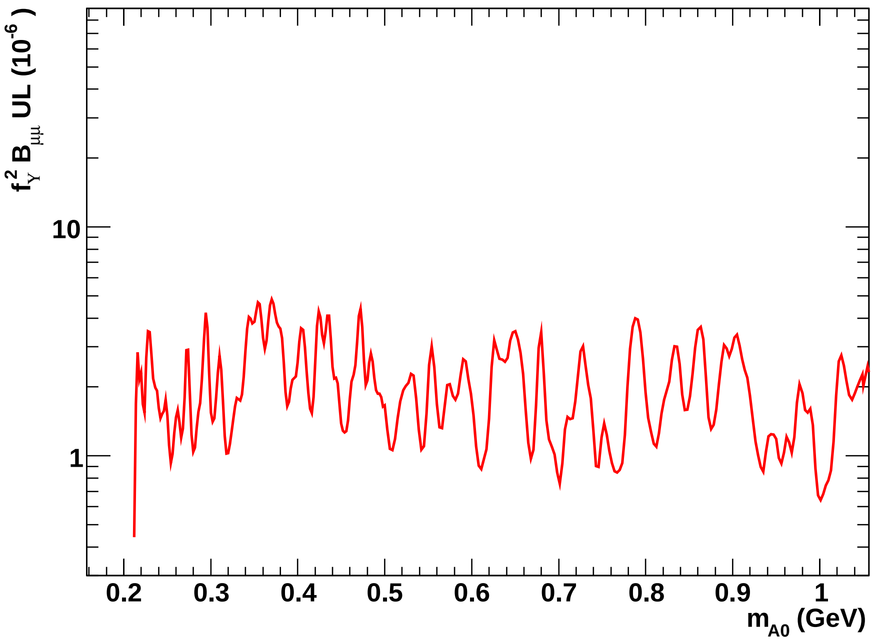
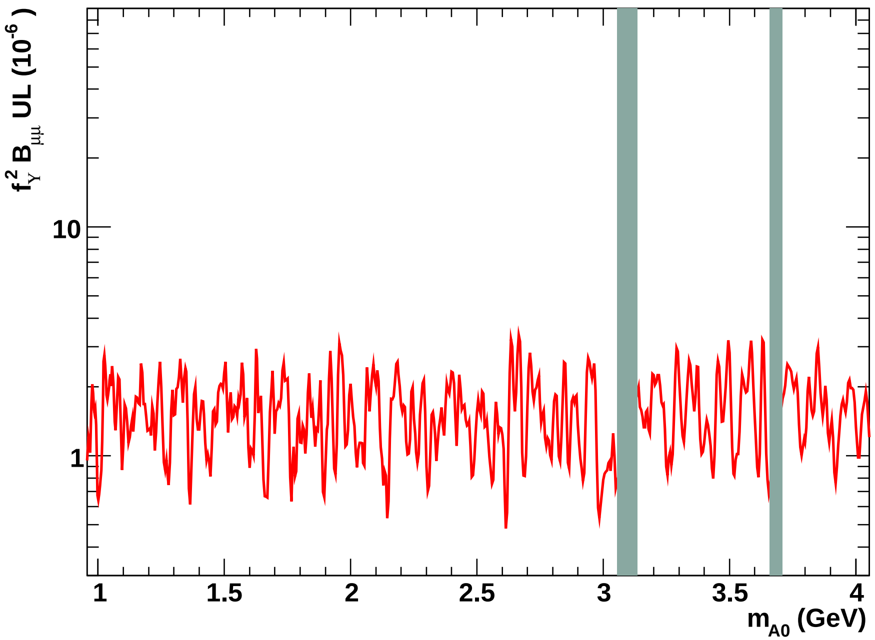
- Babar 2009: limits on $\Upsilon(2S, 3S) \rightarrow \gamma a$ with a→ $\mu\mu$





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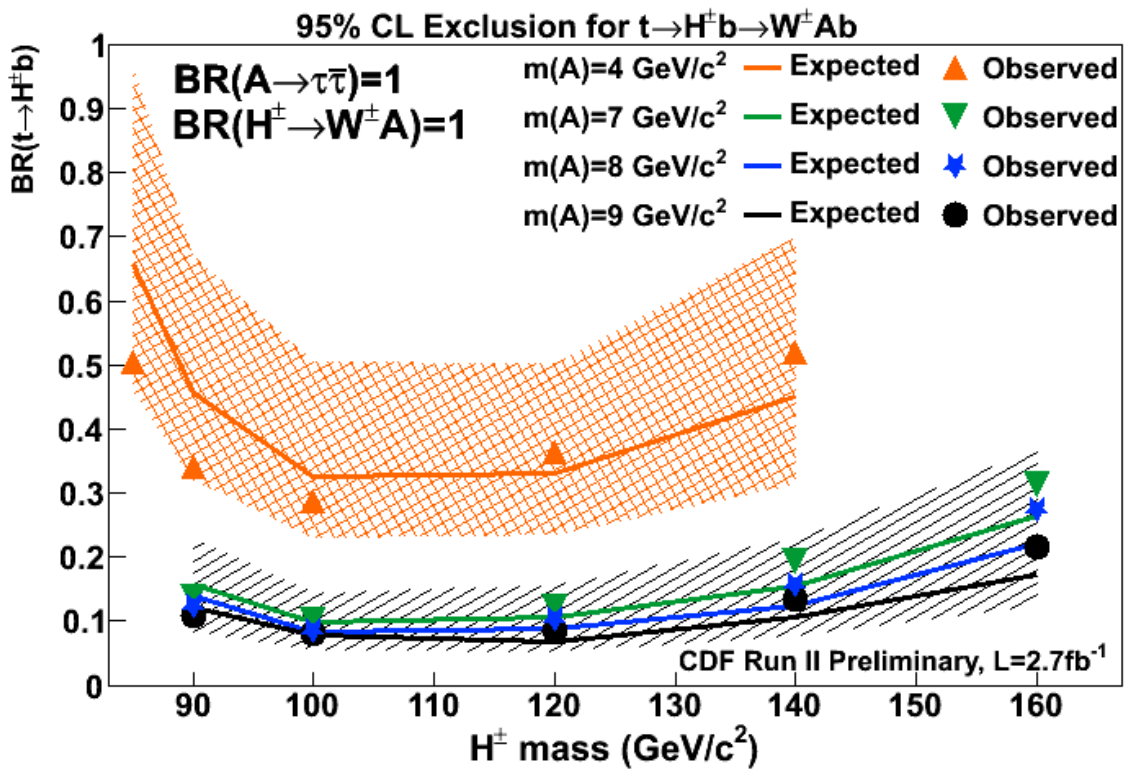
- Babar 2009: limits on $\Upsilon(2S, 3S) \to \gamma a$ with a→ $\mu\mu$
- CDF 2010: limits on BR(t→H$^{\pm}$b) with H$^{\pm}$→Wa and a→ $\tau\tau$



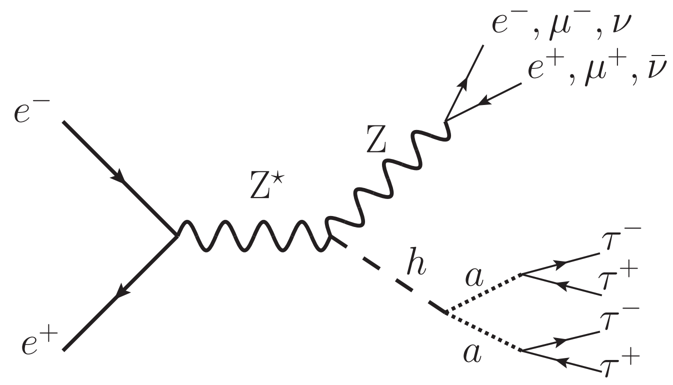
New result from ALEPH: h→aa→4τ

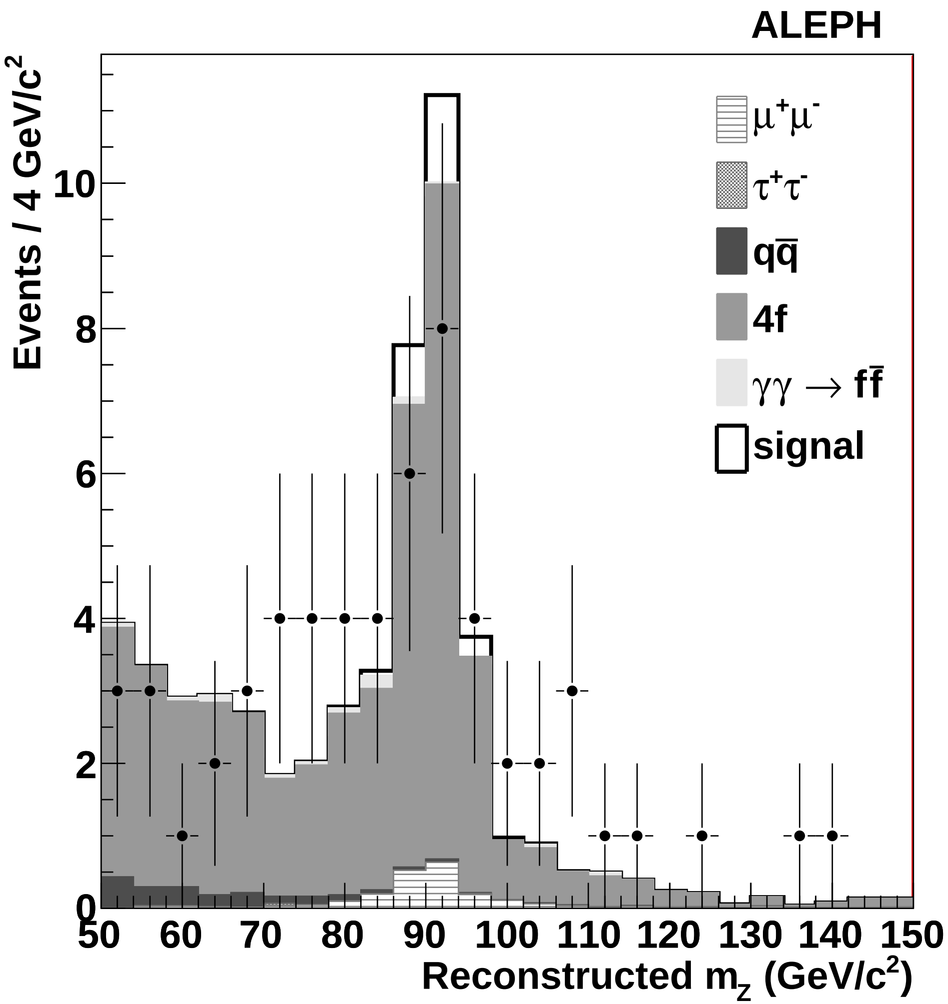
Region of interest: $2m_\tau < m_a < 2m_b$, m_h up to 110 GeV

Signature: 2 jets with 2 collinear τ-decays each

Selection:

Step 1: Z + 2 jets with Z→ $\ell\ell$ or Z→ $\nu\nu$





ALEPH: Search for light h→aa

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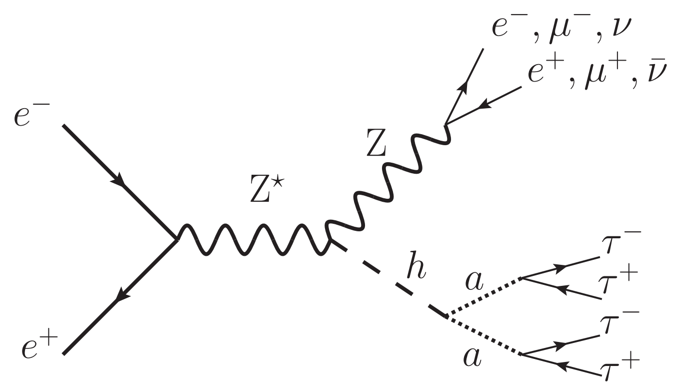
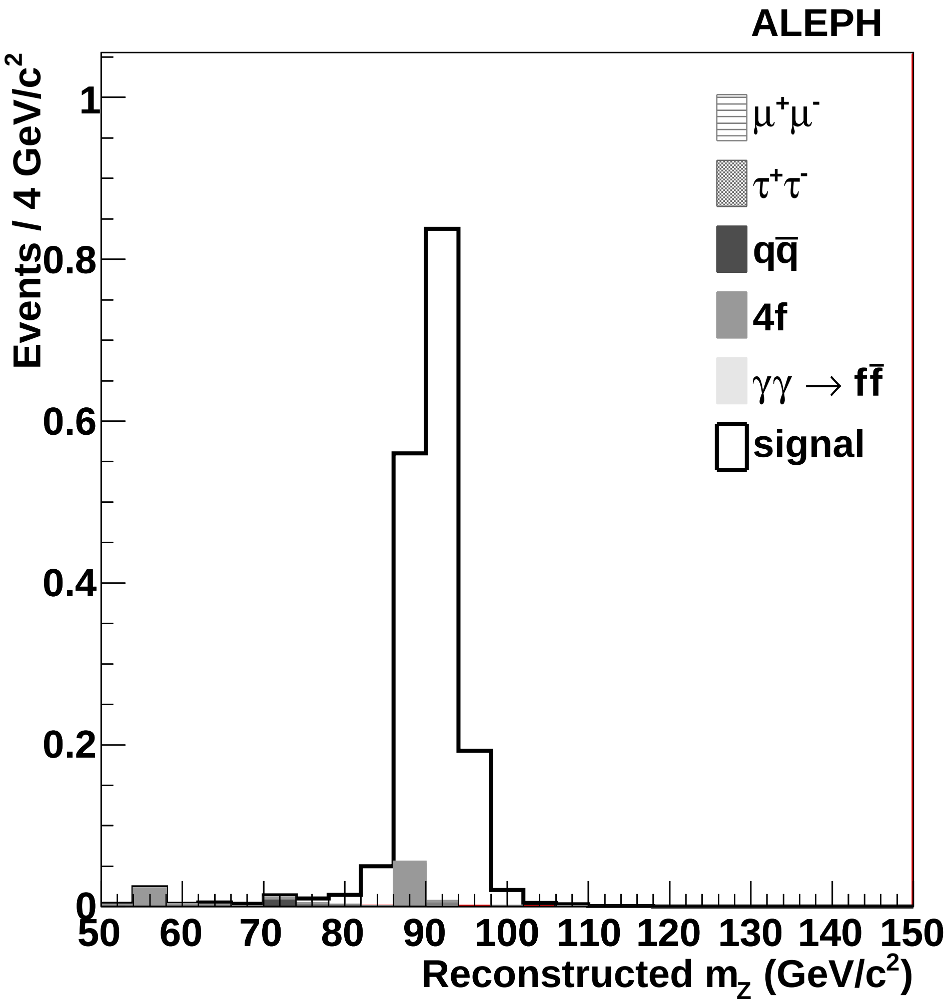
Step 2: require $\not{E}$ and low track multiplicity in jets

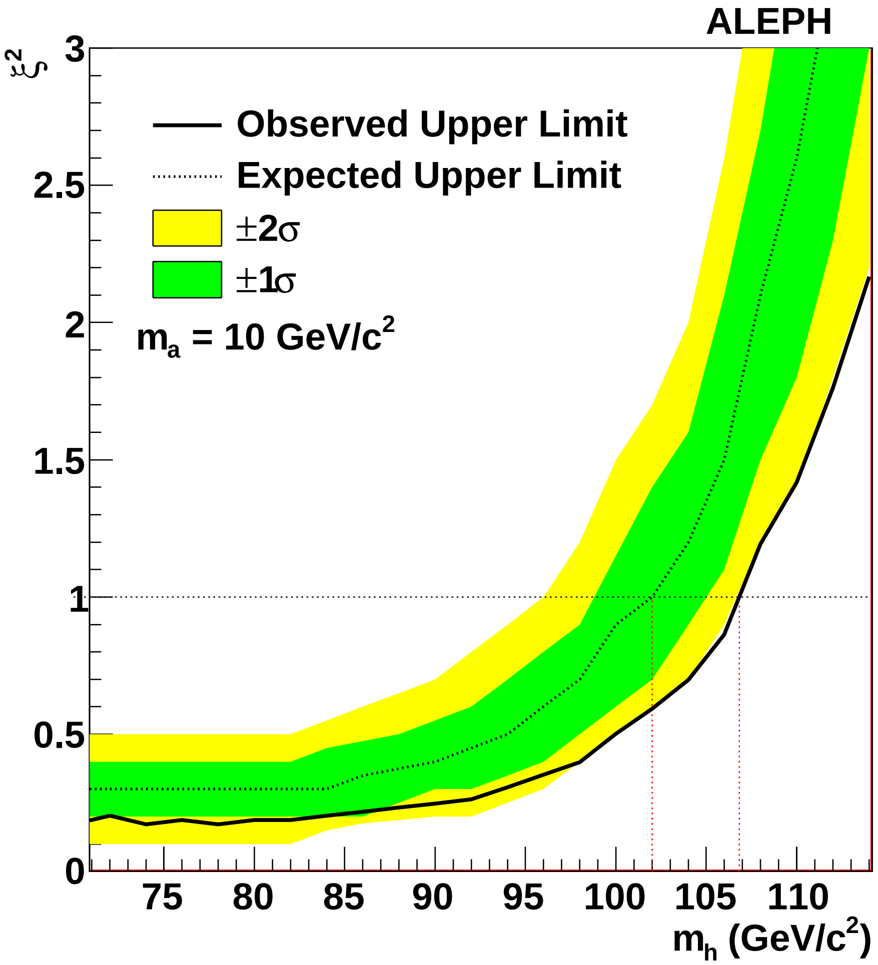


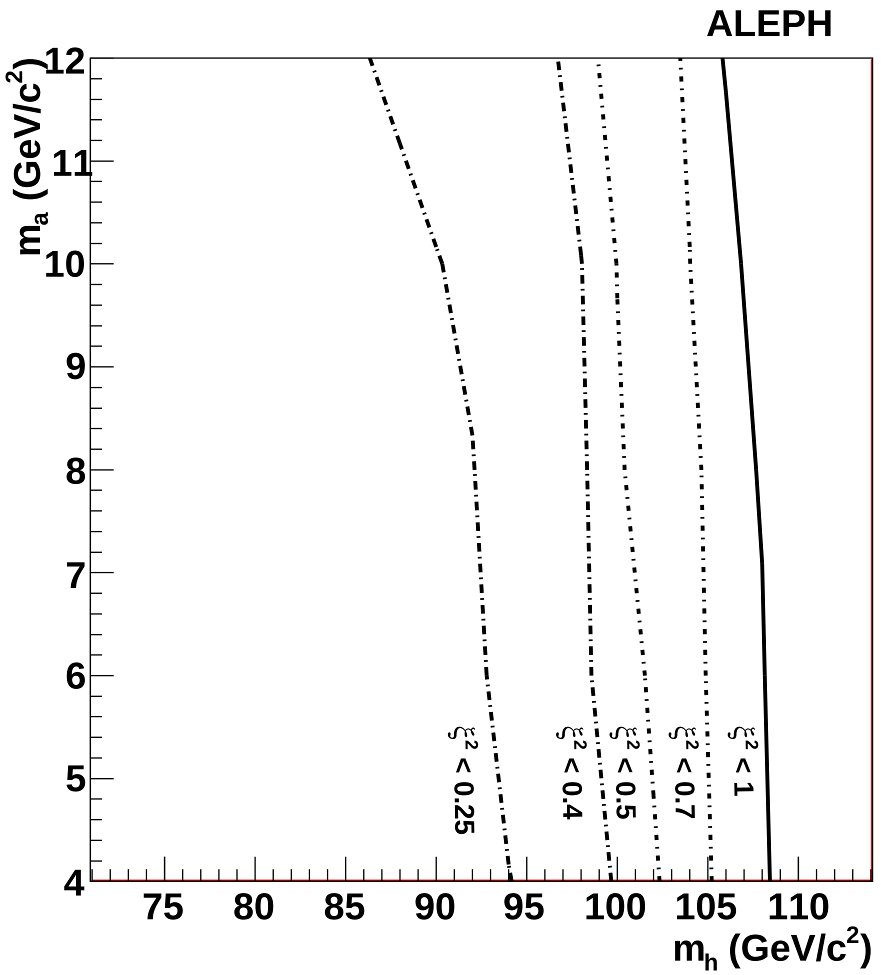


ALEPH: Search for light h→aa

No sign of a signal

$$\rightarrow \textbf{limits on } \xi^2 = \frac{\sigma(e^+e^-\rightarrow Zh)}{\sigma_{SM}(e^+e^-\rightarrow Zh)} \times BR(h \rightarrow aa) \times BR(a \rightarrow \tau\tau)^2$$

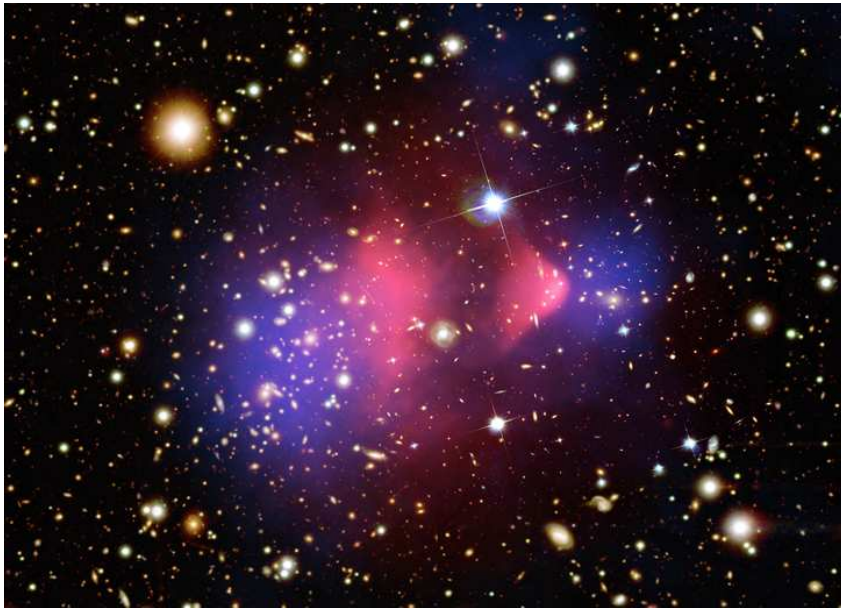




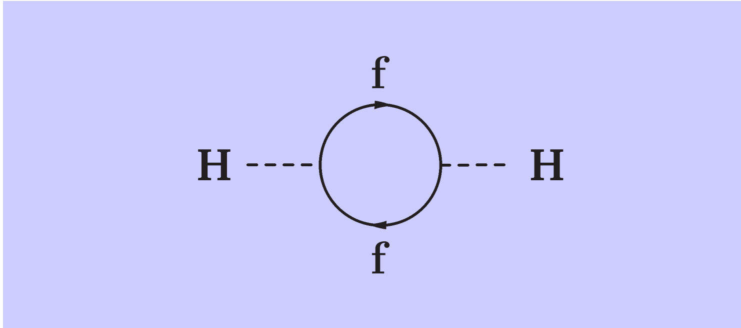
Analysis excludes $\xi^2 > 1$ for $m_h < 170$ GeV and $4 < m_a < 10$ GeV

Superpartners

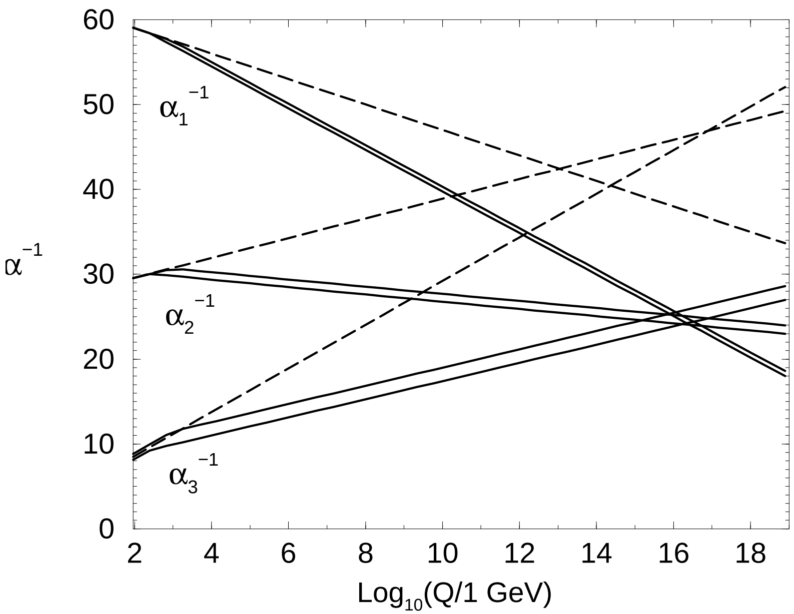
TeV-scale Superpartners?



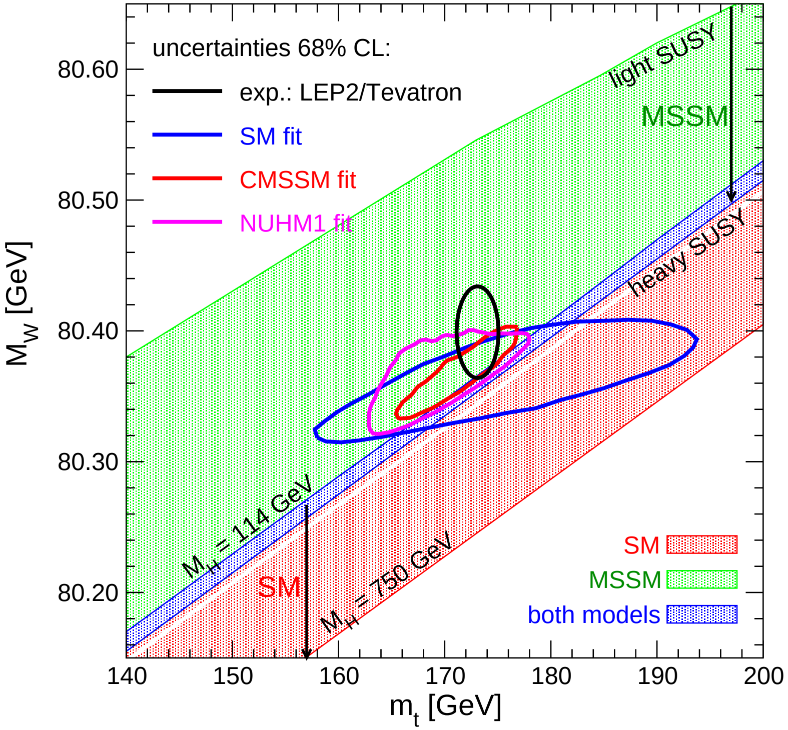
WIMP Dark Matter



Hierarchy Problem

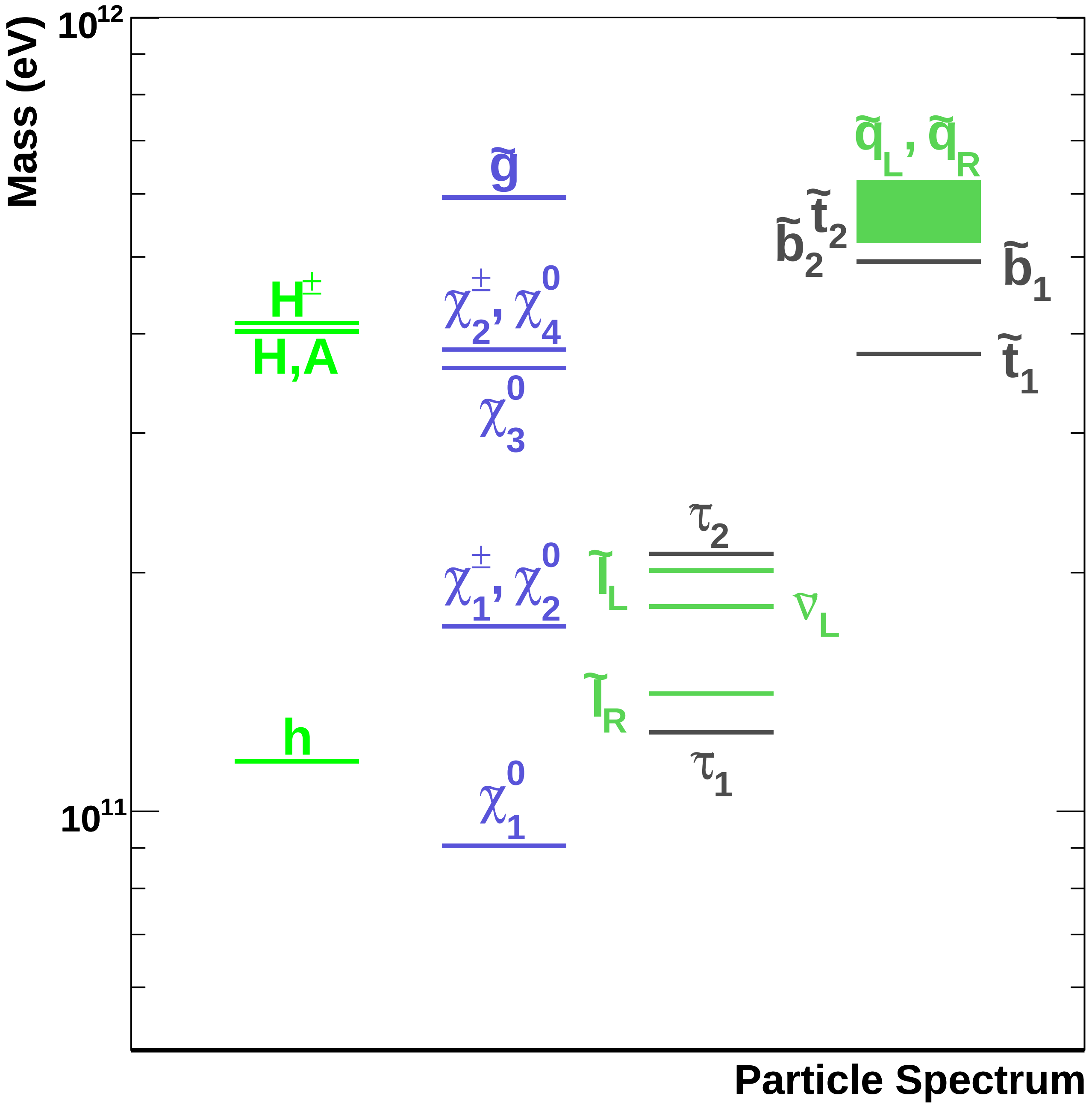


Grand Unification

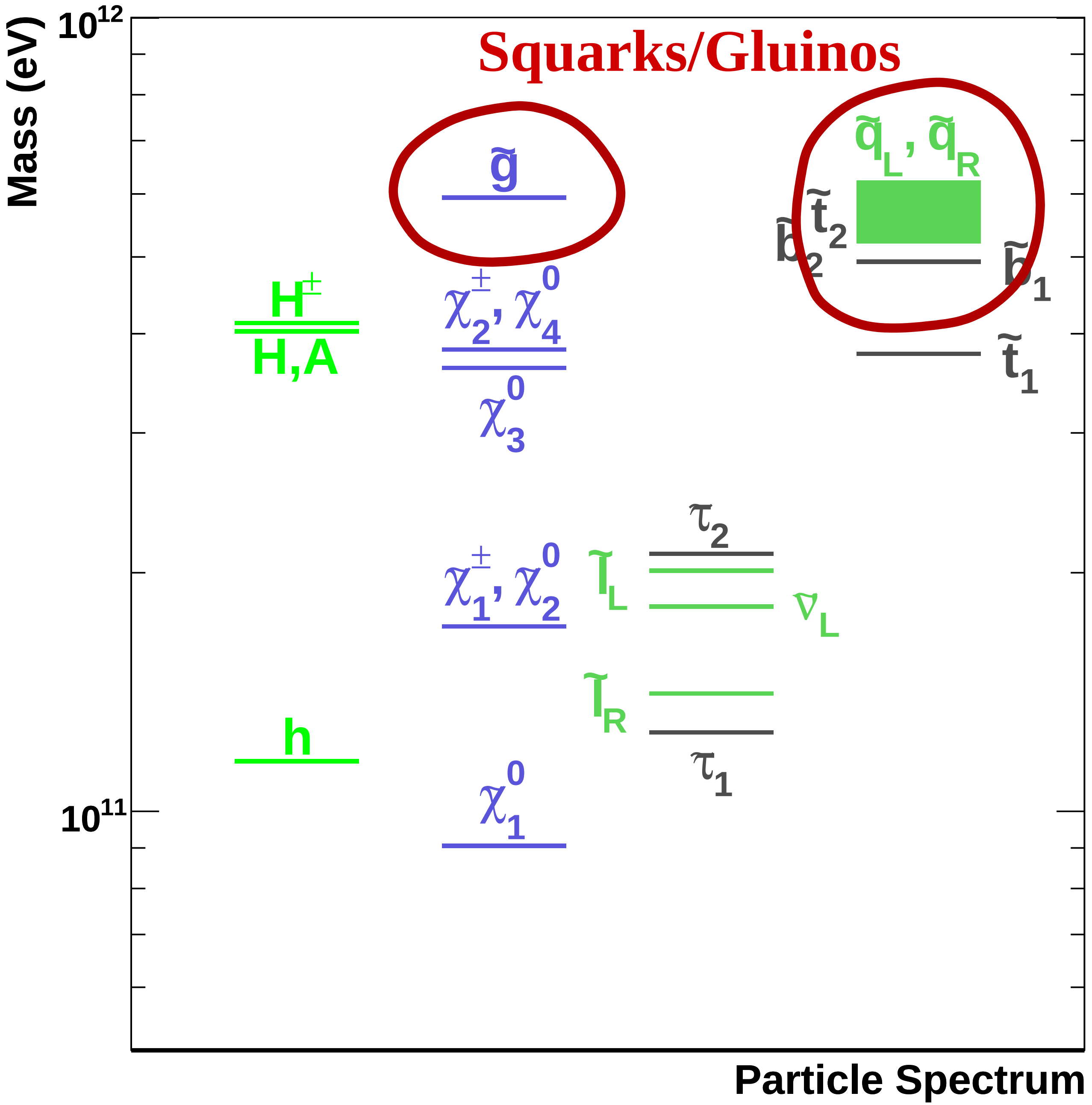


MSSM Fits

A typical Mass Spectrum



A typical Mass Spectrum



Inclusive Search for generic Squarks/Gluinos

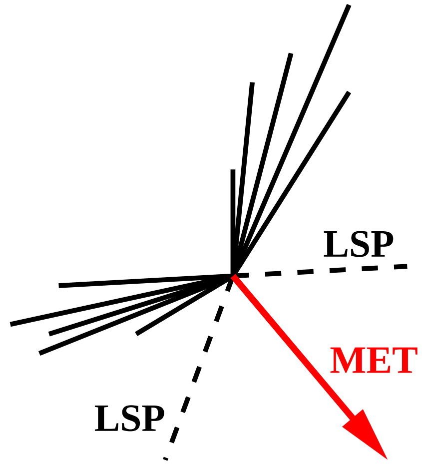
Squarks/Gluinos produced via strong interaction

$\longrightarrow$ large cross sections at hadron colliders

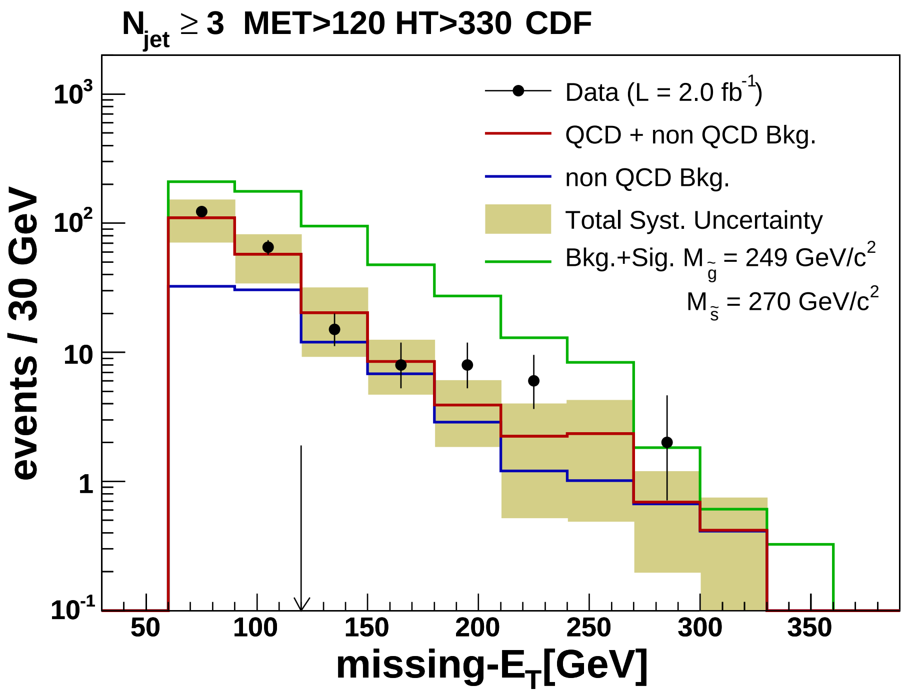
Decays: jets + LSP

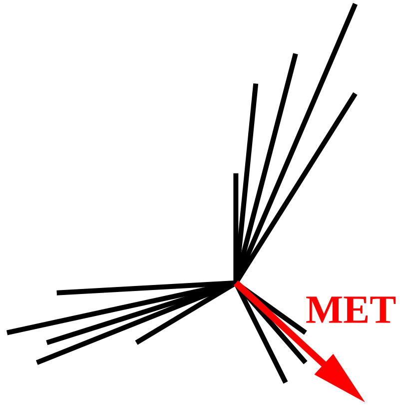
– LSP assumed to be stable (R_p conserved)

$\longrightarrow$ Signature: jets + $\not\!\!E_T$

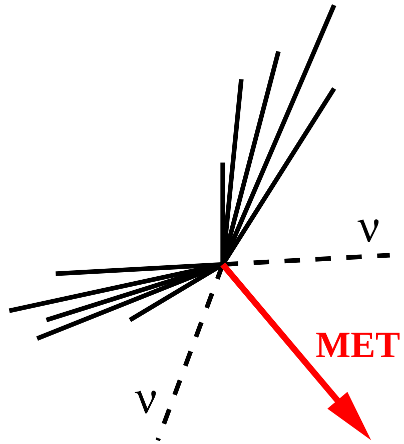


$\tilde{q}\tilde{q} \longrightarrow qq + \not\!\!E_T$





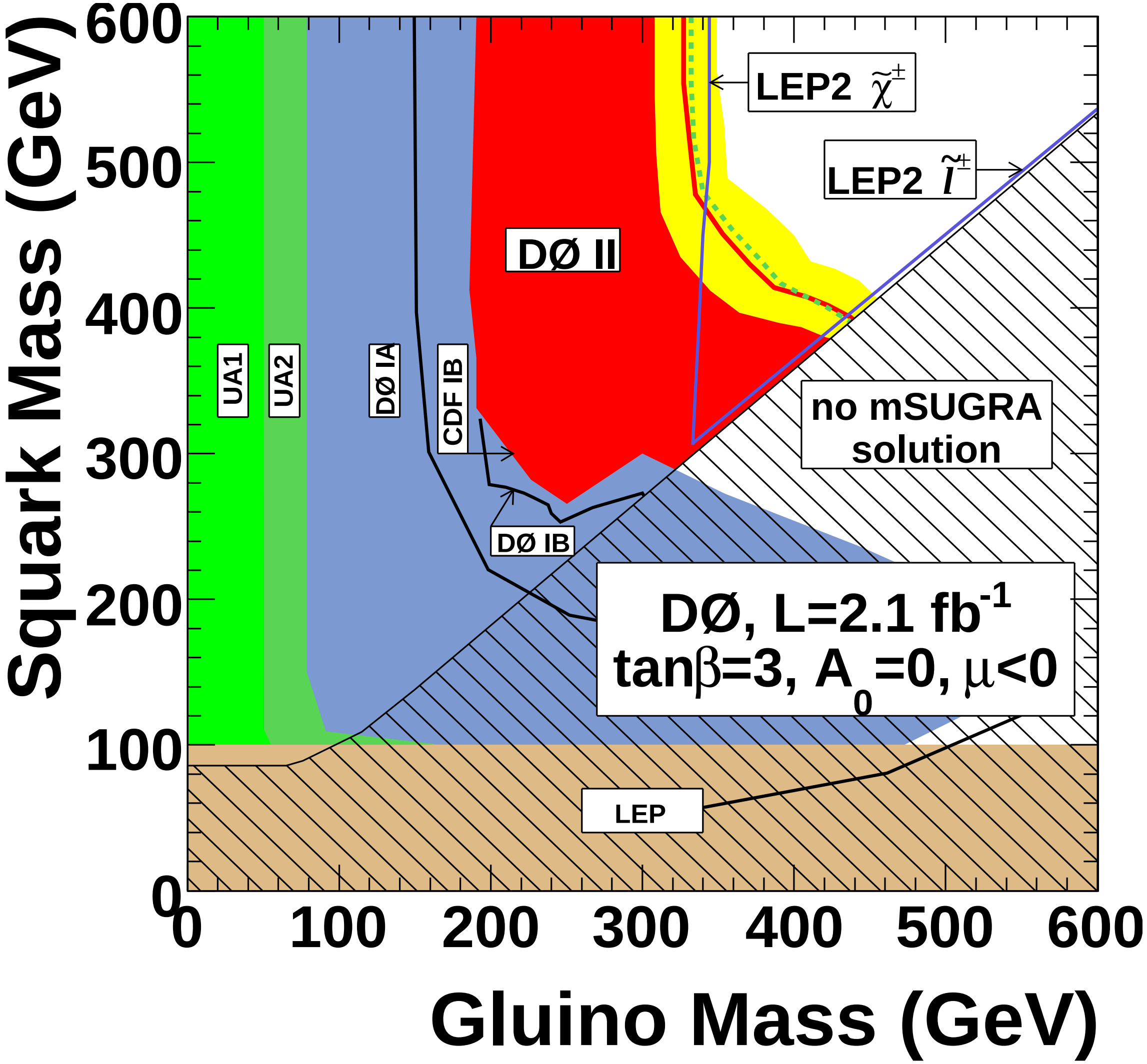
Multijet Background



Background:

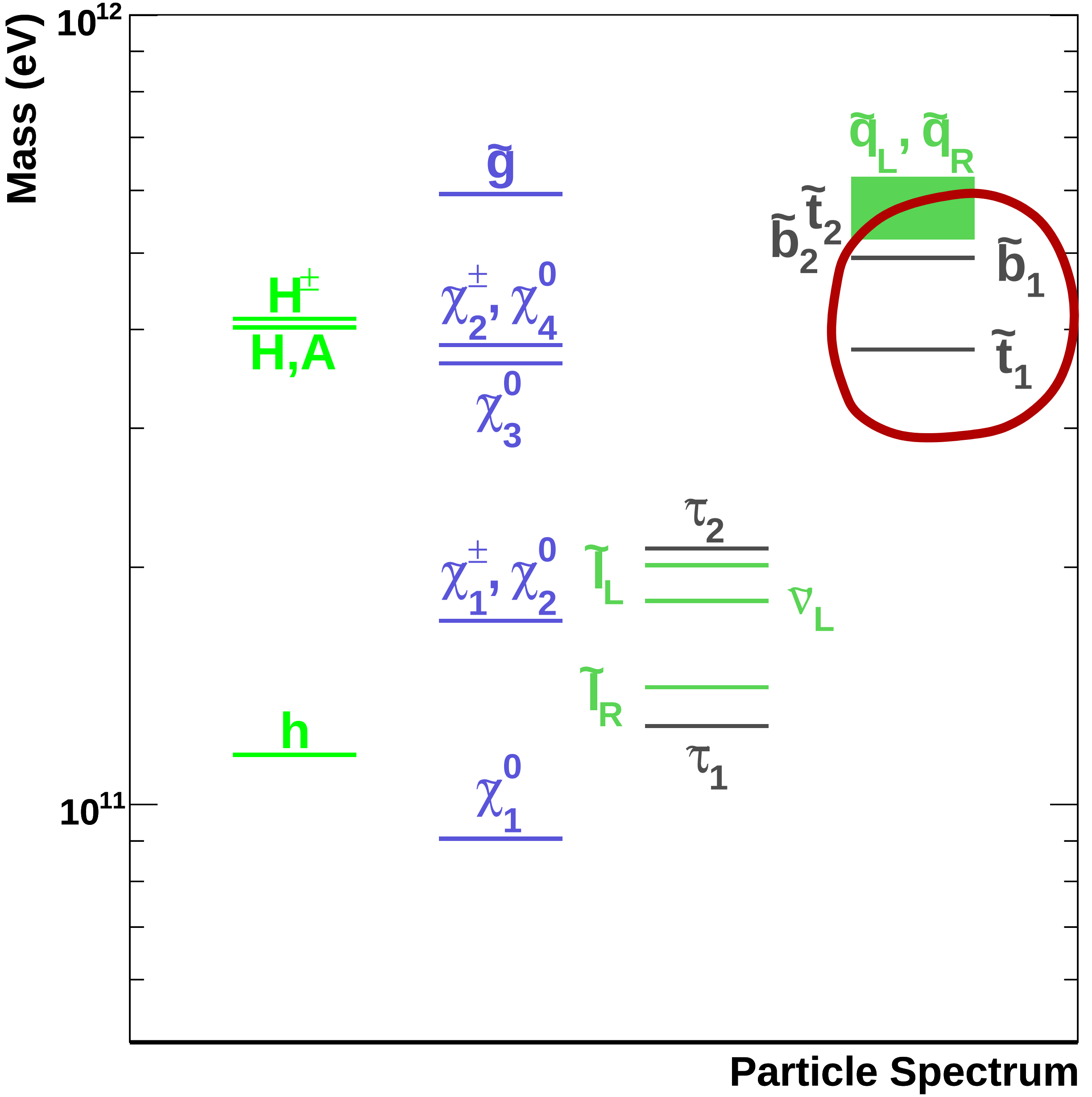
Z$\longrightarrow \nu\nu$+jets

Inclusive Search for generic Squarks/Gluinos



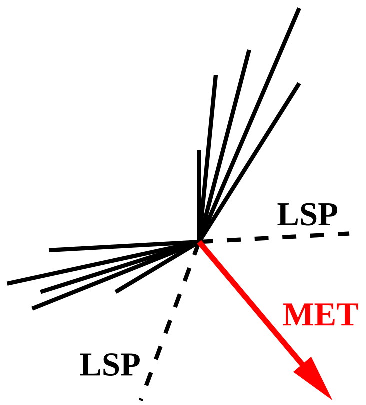
- No evidence for squark/gluino production at the Tevatron
- Limits in squark/gluino mass plane, probing squark/gluino masses up to 400/320 GeV
- starting to be limited by parton luminosities

What SUSY particles to look for?



stop/sbottom
expected to be light

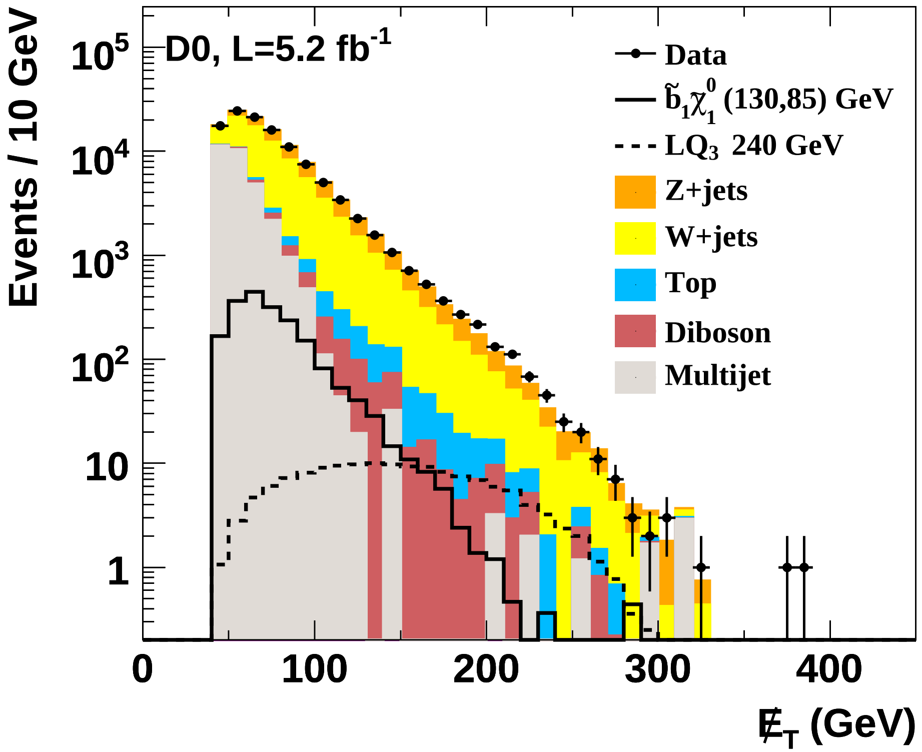
Search for Supersymmetry – Sbottom Quarks



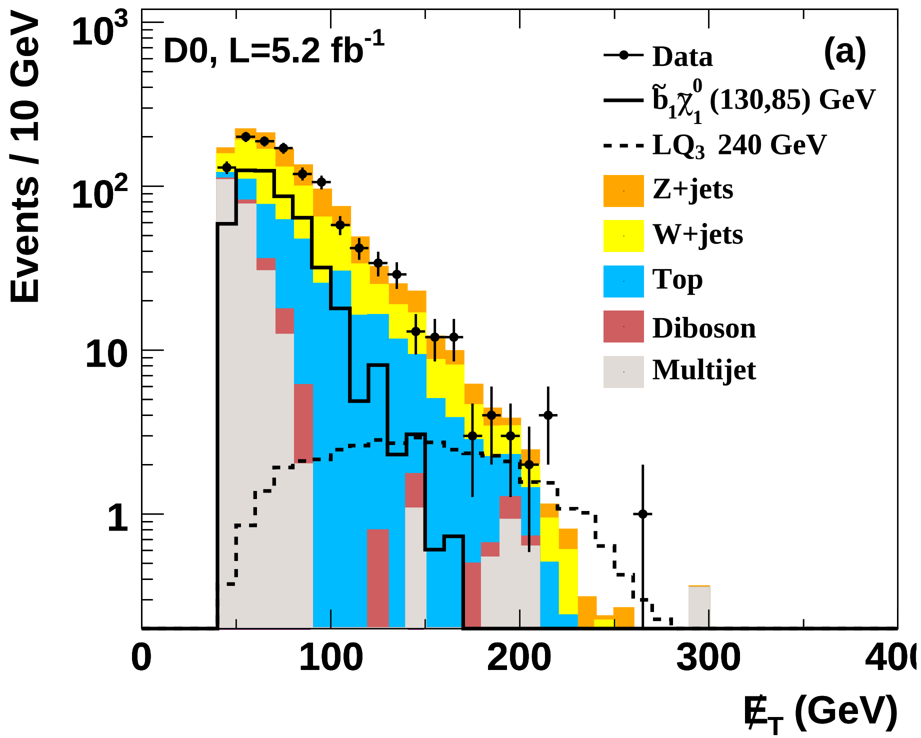
Decay: $\tilde{\mathrm{b}} \longrightarrow b + \tilde{\chi}_1^0$

$\rightarrow$ jets+$\not\!\!E_T$ analysis with b-tagging

New result: DØ, 5.2 fb^{-1}



before b-tagging



after b-tagging

Search for Supersymmetry – Sbottom Quarks

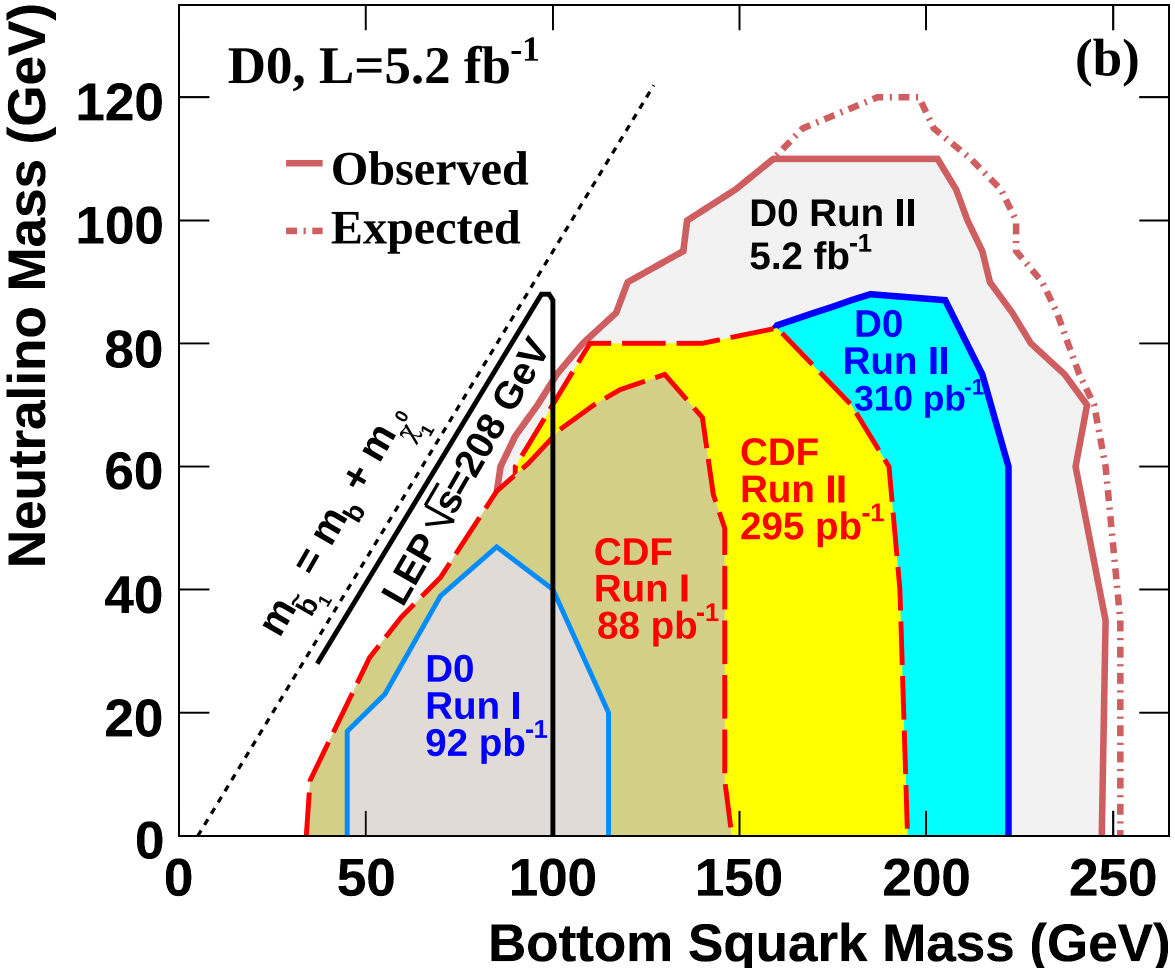
Visible energy in event depends on $\tilde{b}$-$\tilde{\chi}_1^0$ mass difference $\Delta m \rightarrow$ mass-dependent cuts

Example low Δm: 901 events observed, 971$\pm$152 events expected

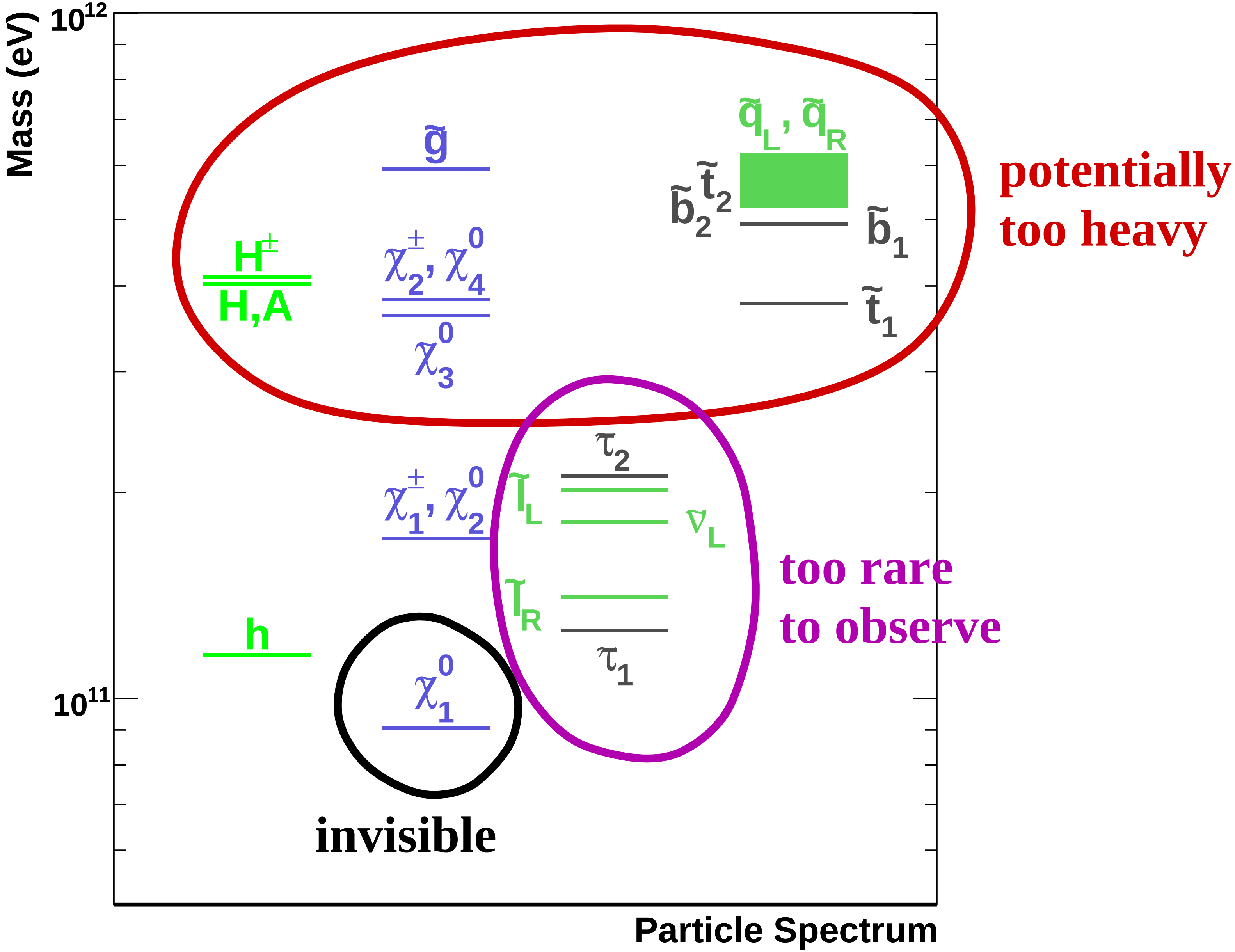
- No reach for $\tilde{b}$-$\tilde{\chi}_1^0$ mass differences below 30 GeV (trigger)

Example high Δm: 7 events observed, 6.9$\pm$1.7 events expected

- Probing sbottom masses up to 250 GeV



What other SUSY particles to look for?

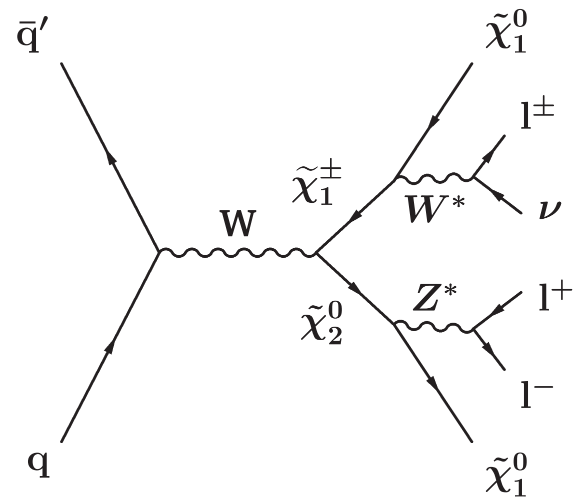


Search for Charginos and Neutralinos

Most sensitive channel: $\tilde{\chi}^{\pm}\tilde{\chi}^0_2 \rightarrow 3\ell + \not{E}_T$

Challenges:

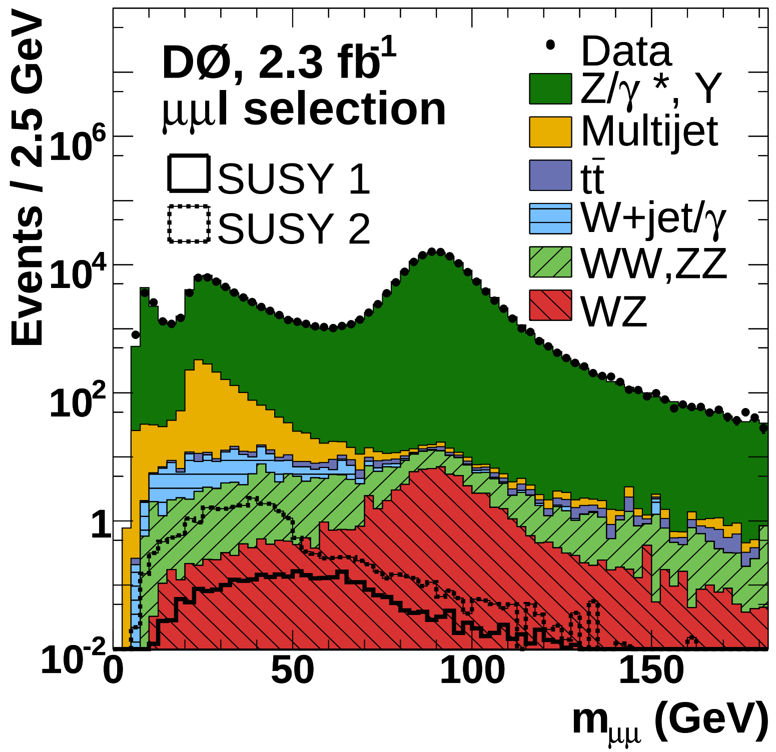
- production cross section (electroweak) relatively small
- low-p_T leptons



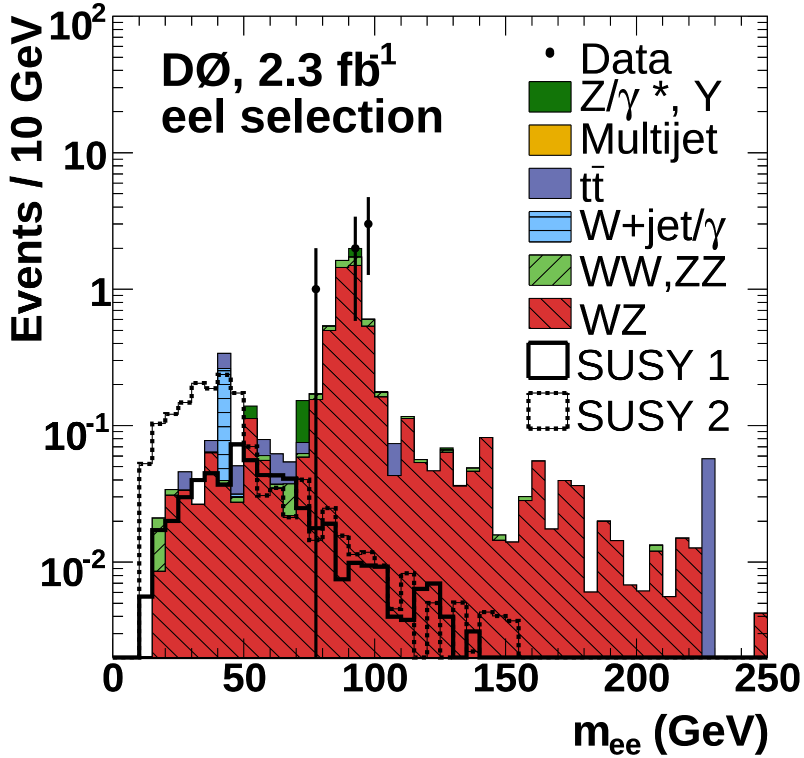
Large number of trilepton and dilepton plus track analyses from CDF and DØ

- pt cuts as low as 3 GeV

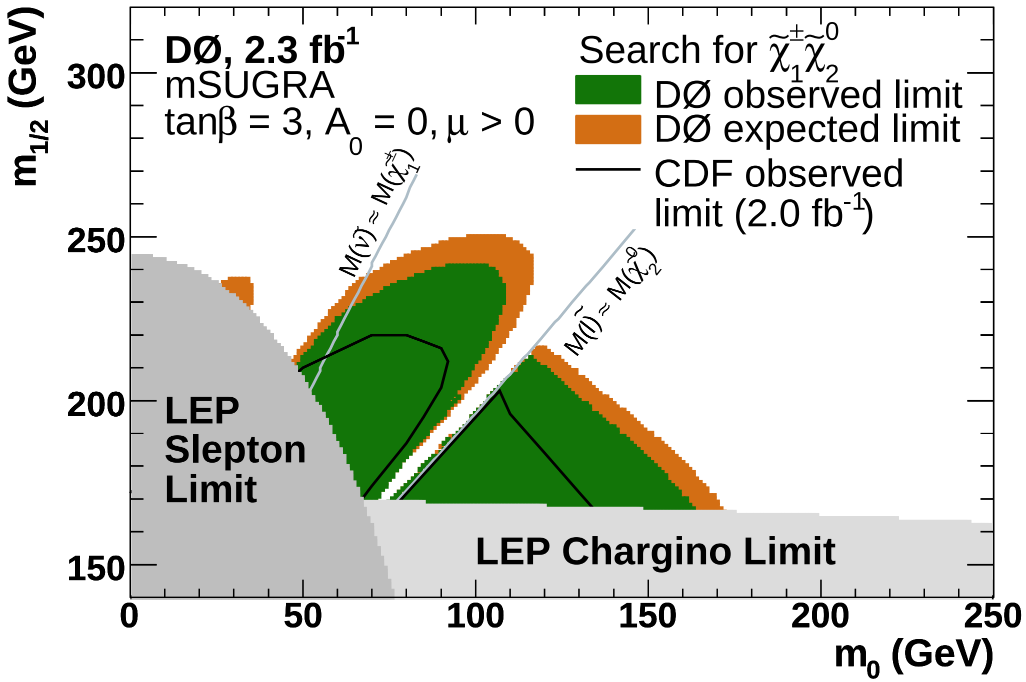
requiring 2 leptons

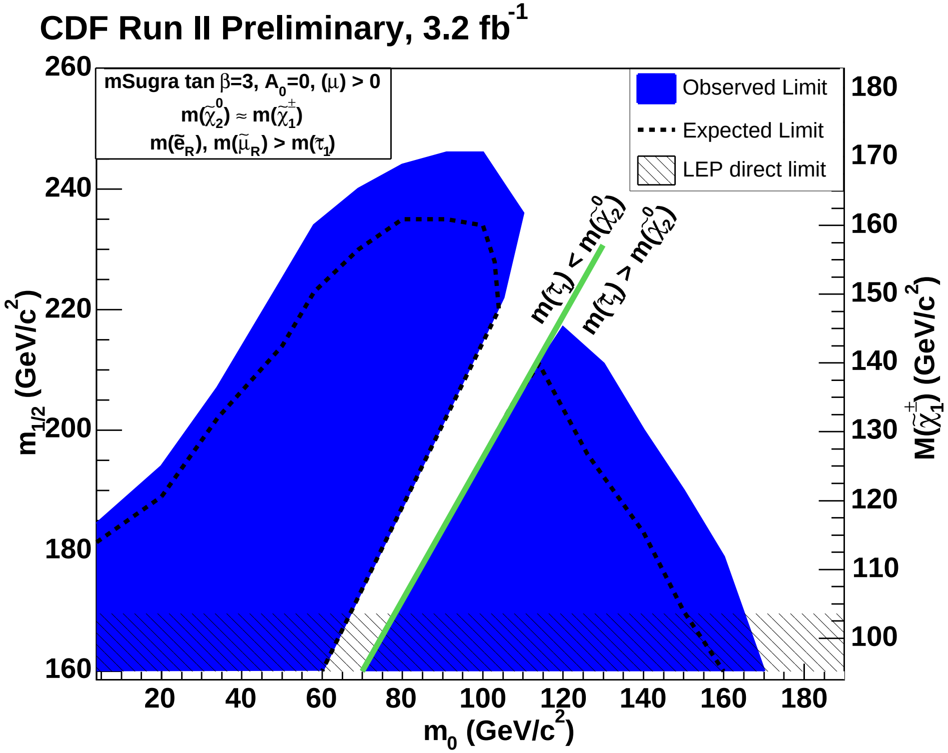


requiring 3 leptons



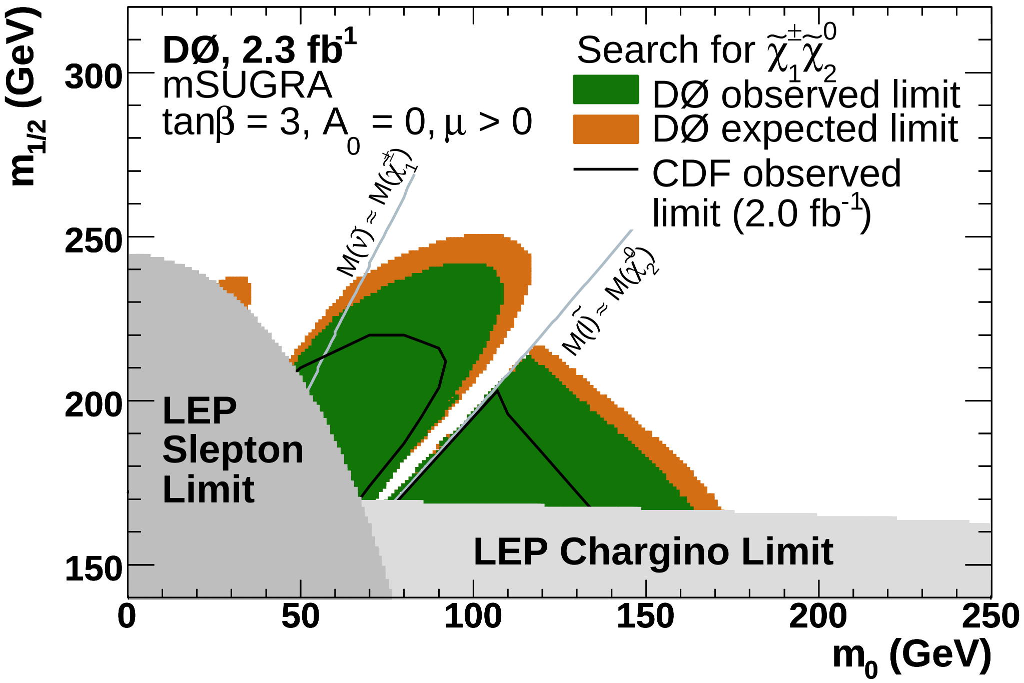
Search for Charginos and Neutralinos: Results

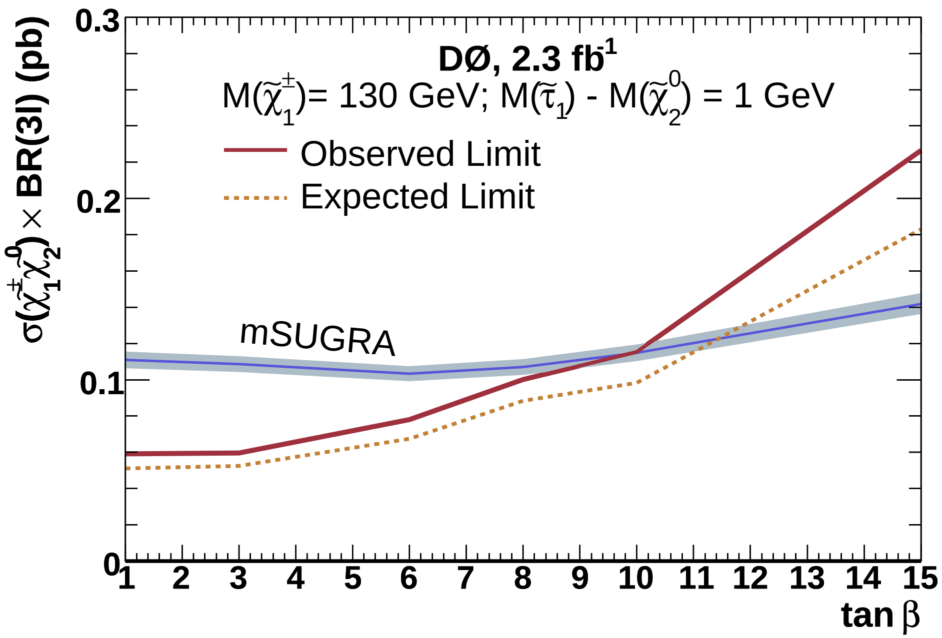




- Analyses probing chargino masses up to 176 GeV
- Reach degrades with increasing tanβ

Search for Charginos and Neutralinos: Results





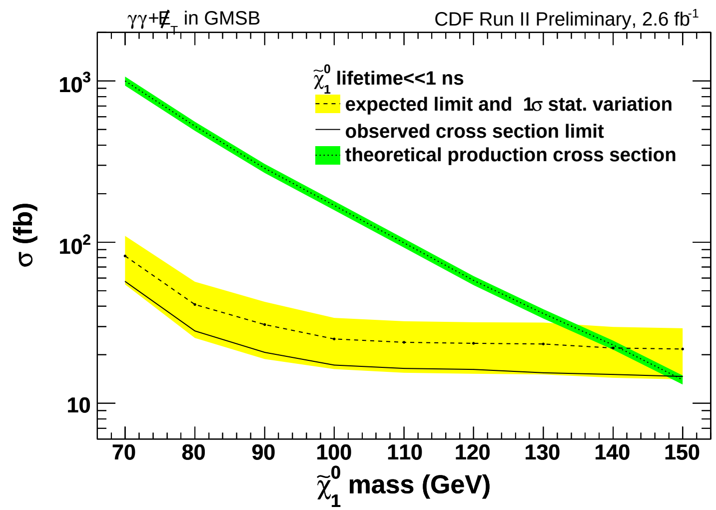
- Analyses probing chargino masses up to 176 GeV
- Reach degrades with increasing tanβ

Beyond mSUGRA

Many other SUSY models on the market $\longrightarrow$ large variety of SUSY searches at the Tevatron

Gauge-Mediated SUSY Breaking

- Inclusive $\gamma\gamma + \not{E}_T$: neutralinos excluded up to 149 GeV (CDF)
- Long-lived neutralinos: limits up to 101 GeV (CDF)



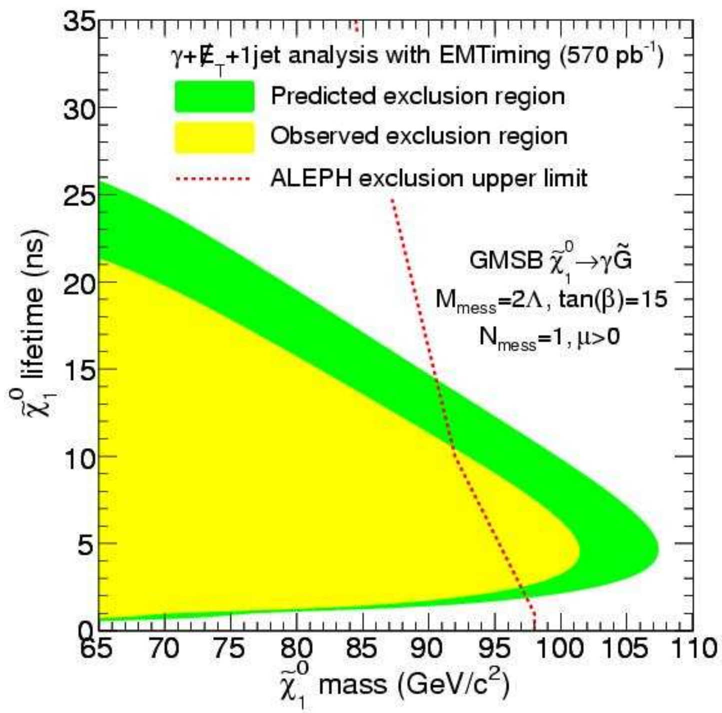
Anomaly-Mediated SUSY Breaking

- Stable charginos: excluded up to 206 GeV (DØ)

Split Supersymmetry

- Long-lived Gluinos $\tilde{g} \longrightarrow g\tilde{\chi}_1^0$:

  limits up to 320 GeV for lifetimes up to 100 hours (DØ)

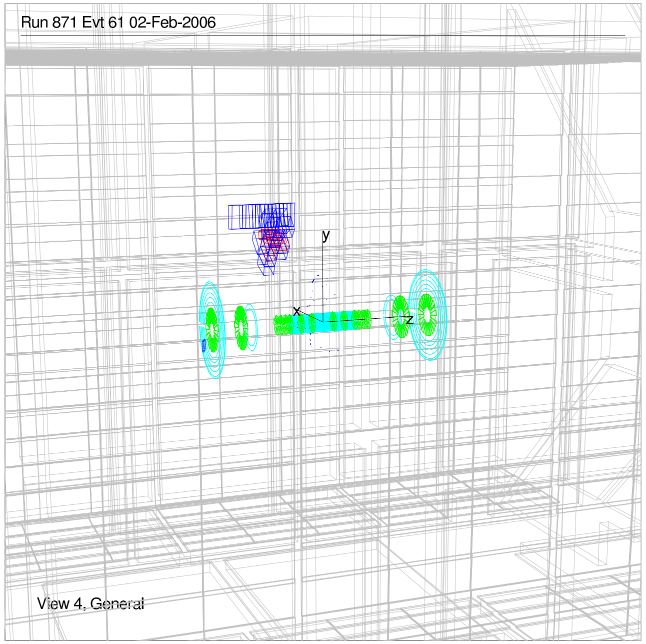


R-Parity Violation

- LLE couplings: limits on charginos up to 234 GeV (DØ)

Beyond mSUGRA

Many other SUSY models on the market → large variety of SUSY searches at the Tevatron



Gauge-Mediated SUSY Breaking

- Inclusive $\gamma\gamma + \not{E}_T$: charginos excluded up to 229 GeV (DØ)
- Long-lived neutralinos: limits up to 101 GeV (CDF)

Anomaly-Mediated SUSY Breaking

- Stable charginos: excluded up to 174 GeV (DØ)

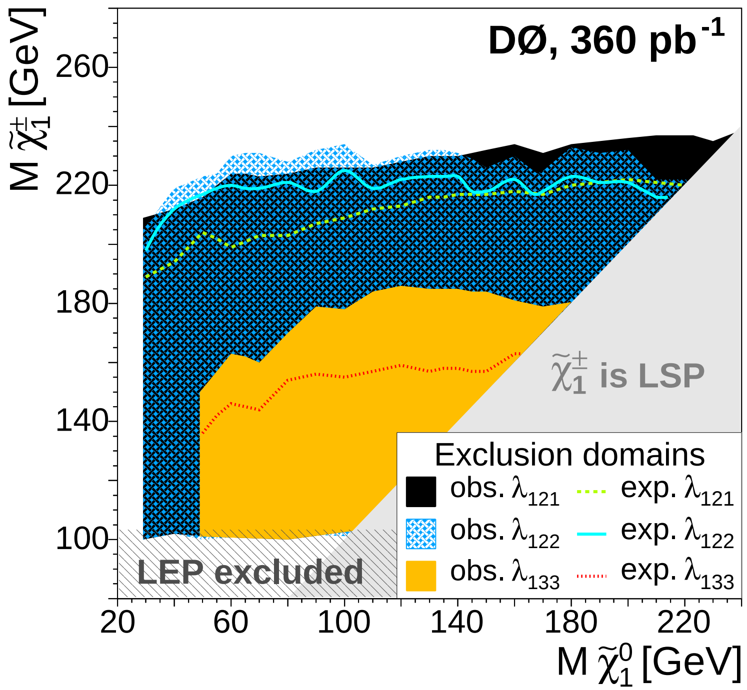
Split Supersymmetry

- Long-lived Gluinos $\tilde{g} \to g\tilde{\chi}_1^0$:

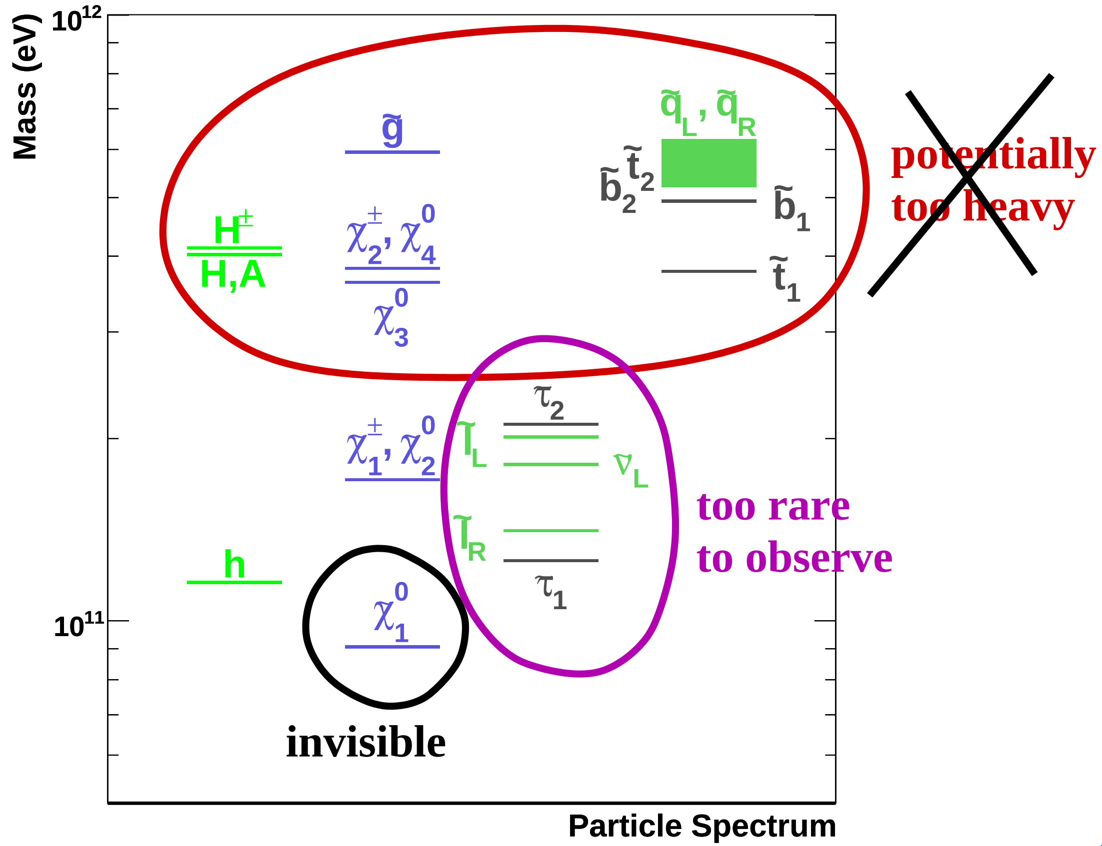
  limits up to 320 GeV for lifetimes up to 100 hours (DØ)

R-Parity Violation

- LLE couplings: limits on charginos up to 234 GeV (DØ)

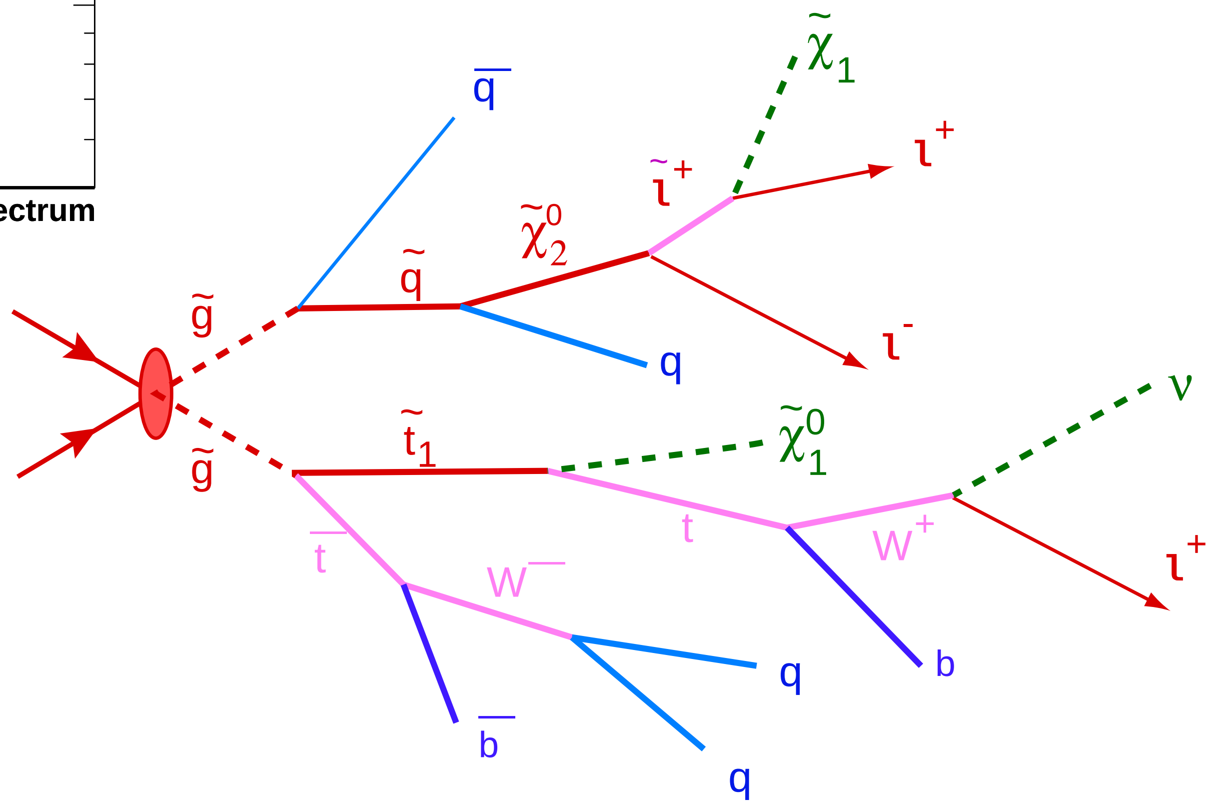


Search for Supersymmetry at the LHC



All particles accessible

- strong production dominates
- potentially long decay cascades

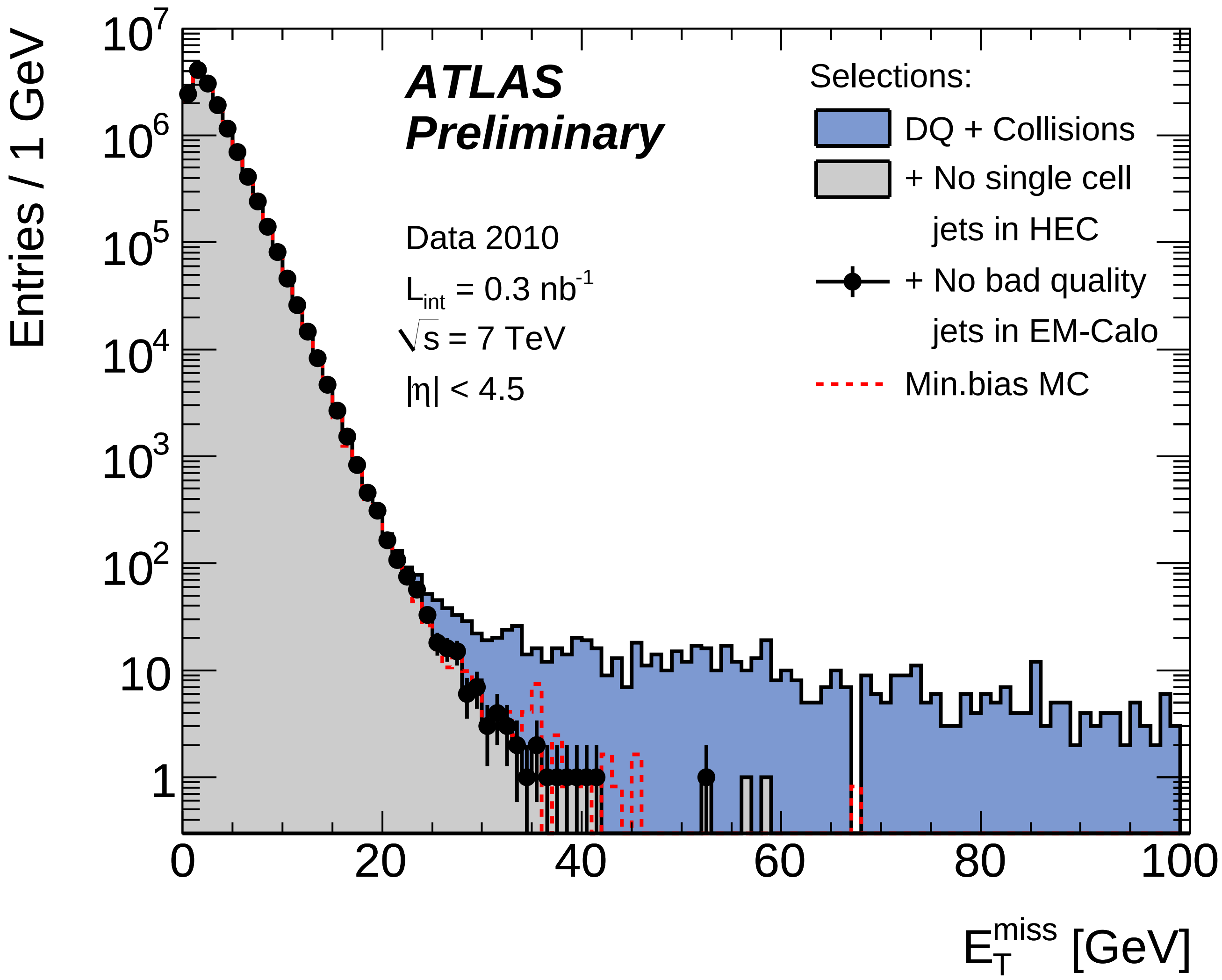


Towards searches for Supersymmetry at the LHC

Key ingredient: missing transverse energy

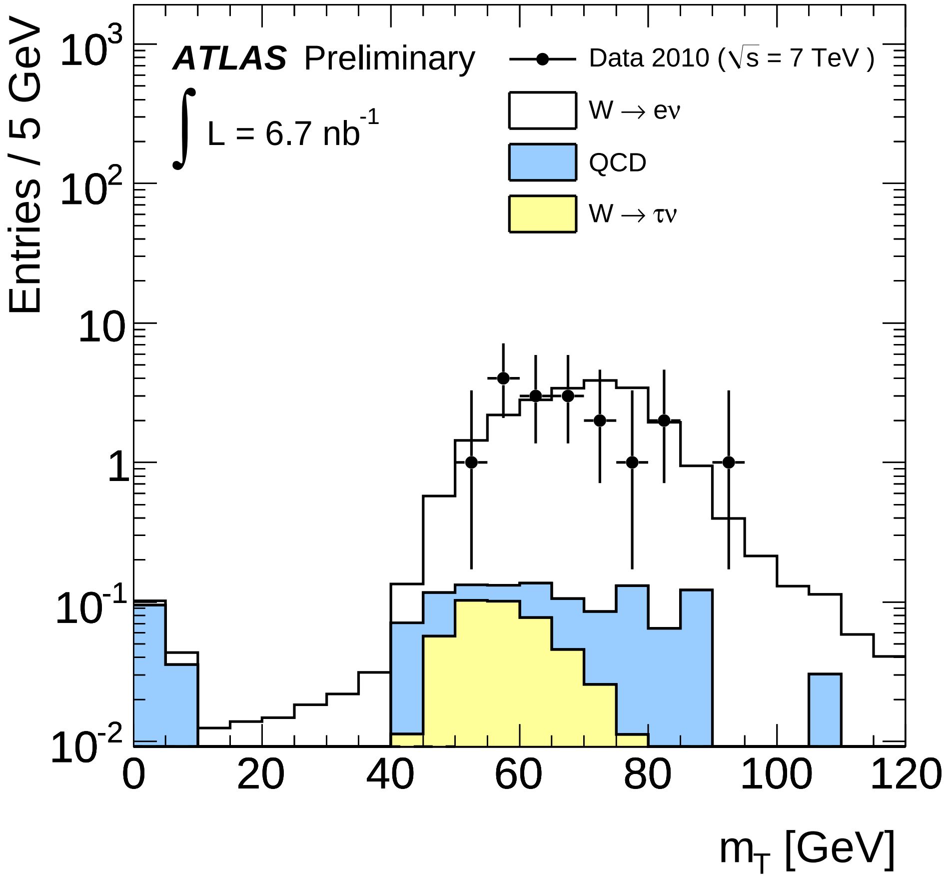
– very sensitive to intermittent, rare detector problems

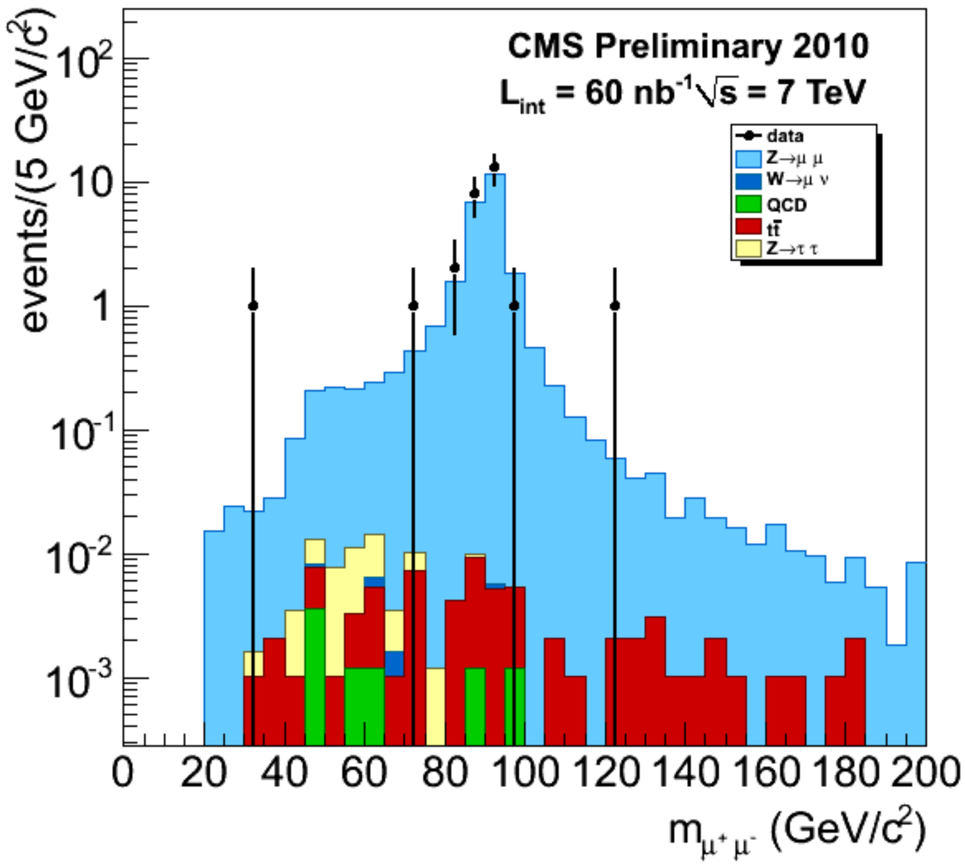
→ extensive cleaning cuts to remove "bad" energy



Key ingredient: leptons

– standard candles W$\rightarrow \ell\nu$ and Z$\rightarrow \ell\ell$ observed



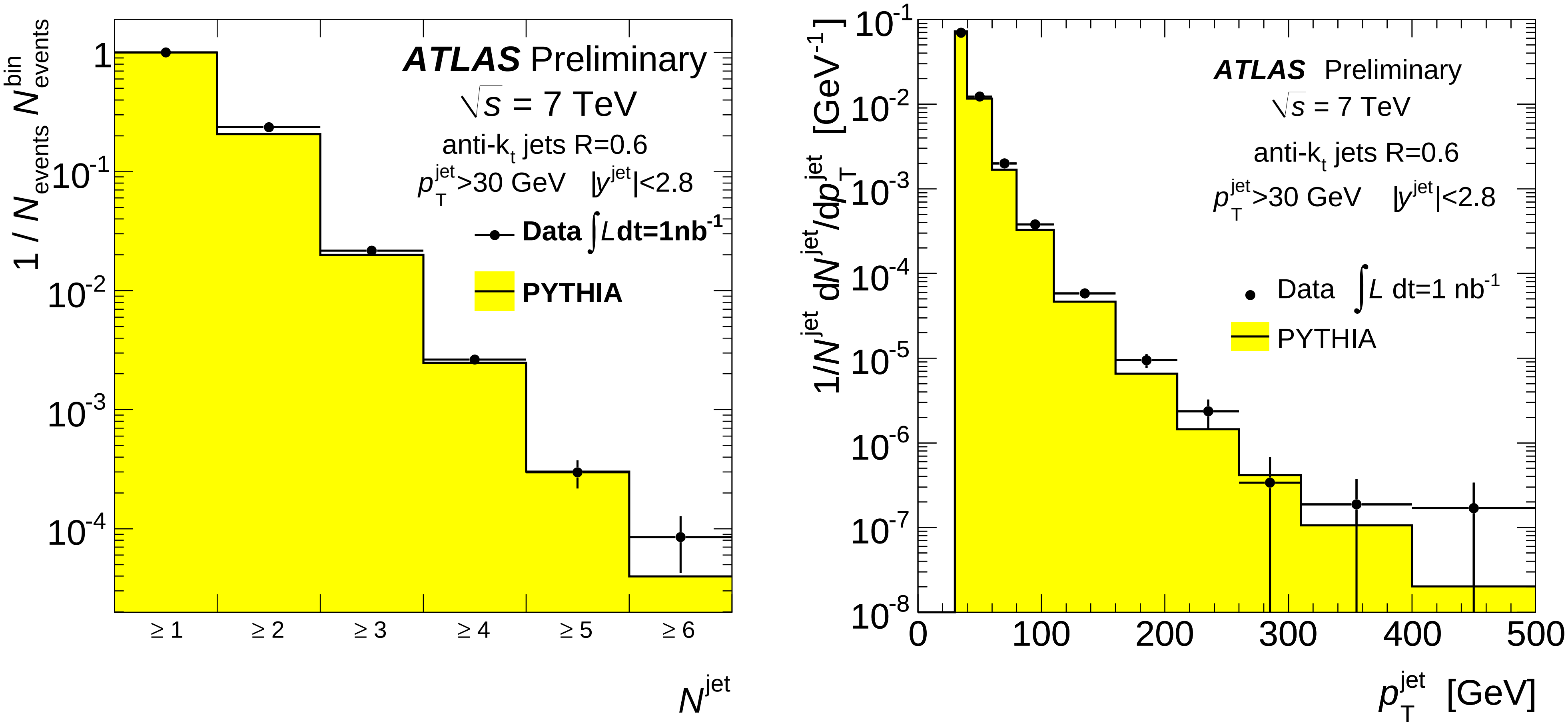


Towards searches for Supersymmetry at the LHC

Key ingredient: jets

- excellent description of data up to 500 GeV
- jet energy calibration:

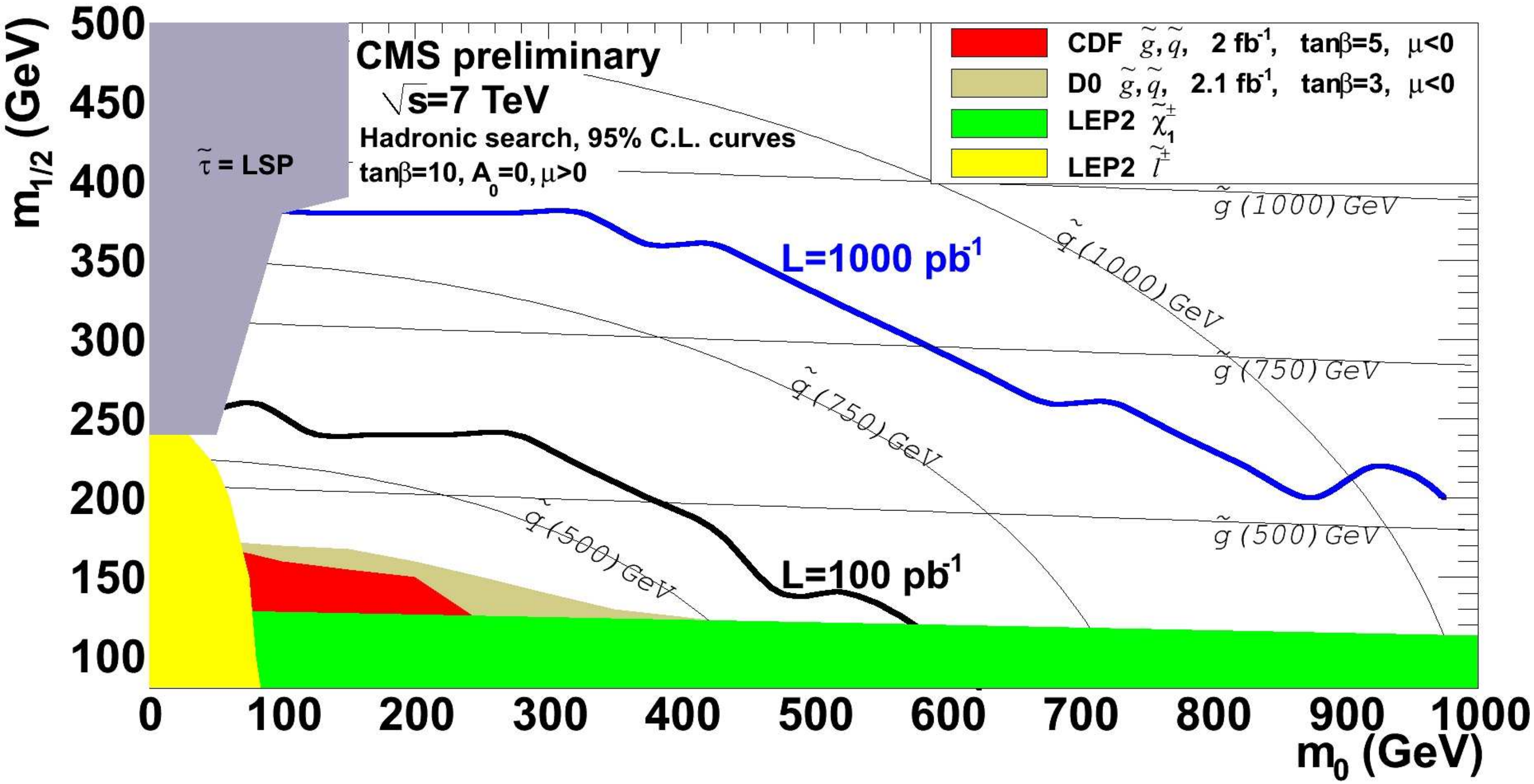
  already achieved a 7% uncertainty (central region, $p_T > 60$ GeV)



Towards searches for Supersymmetry at the LHC

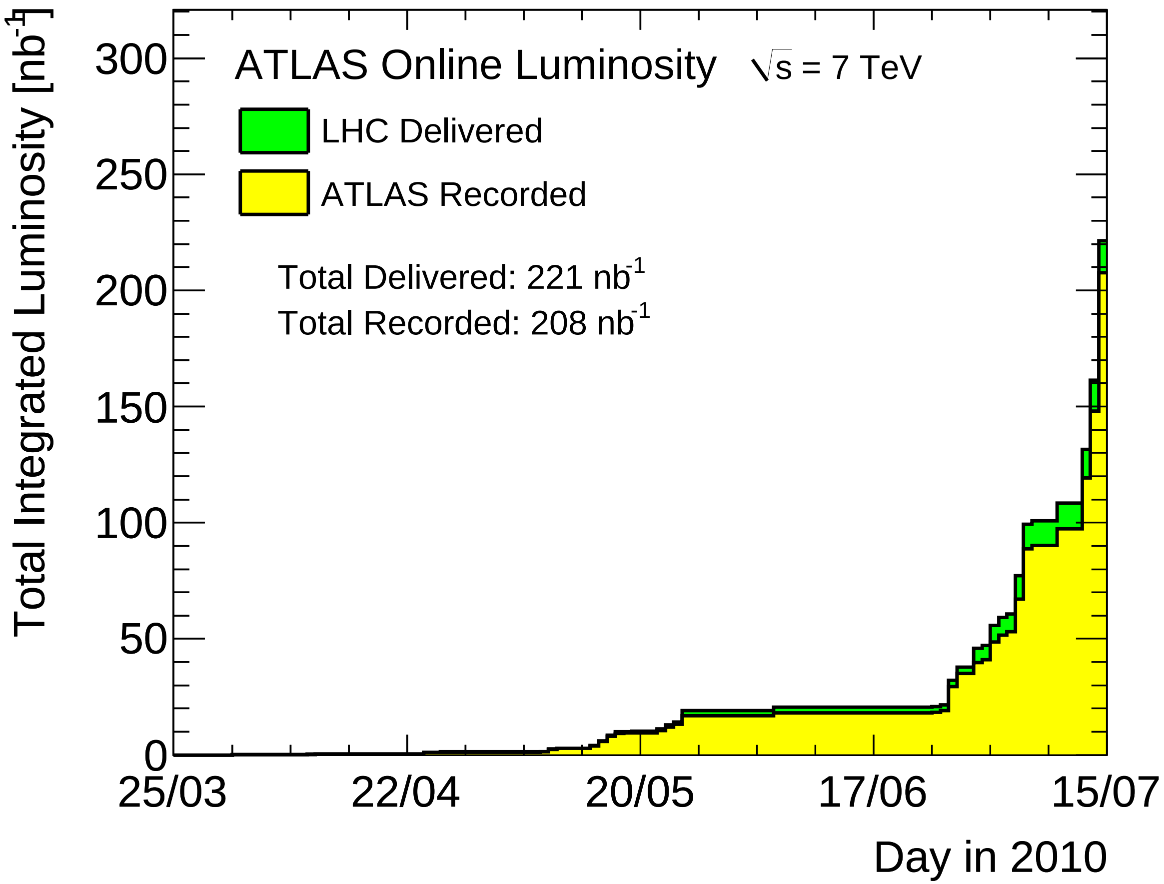
Next in line:

- W/Z+jets (very soon)
- Top-Quark production (1 pb^{-1})
- Supersymmetry! (beyond 10-100 pb^{-1})

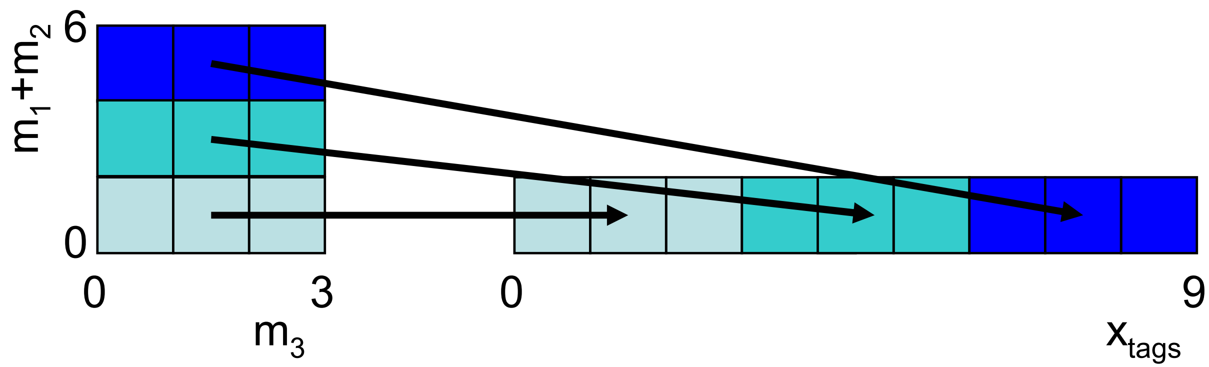


Conclusions

- Broad spectrum of results for SUSY Higgs sector and superpartner searches
- Many results beyond minimal models, but very hard to stay model-independent
- Huge Tevatron dataset: some (not all!) analyses limited by centre-of-mass energy
- ATLAS and CMS catching up very quickly
  - excellent understanding of the detectors
  - rapid increase in peak and integrated LHC luminosity



BACKUP



m1+m2
6
0
0
3
m3
0
9
xtags