Searches for Supersymmetry at CDF

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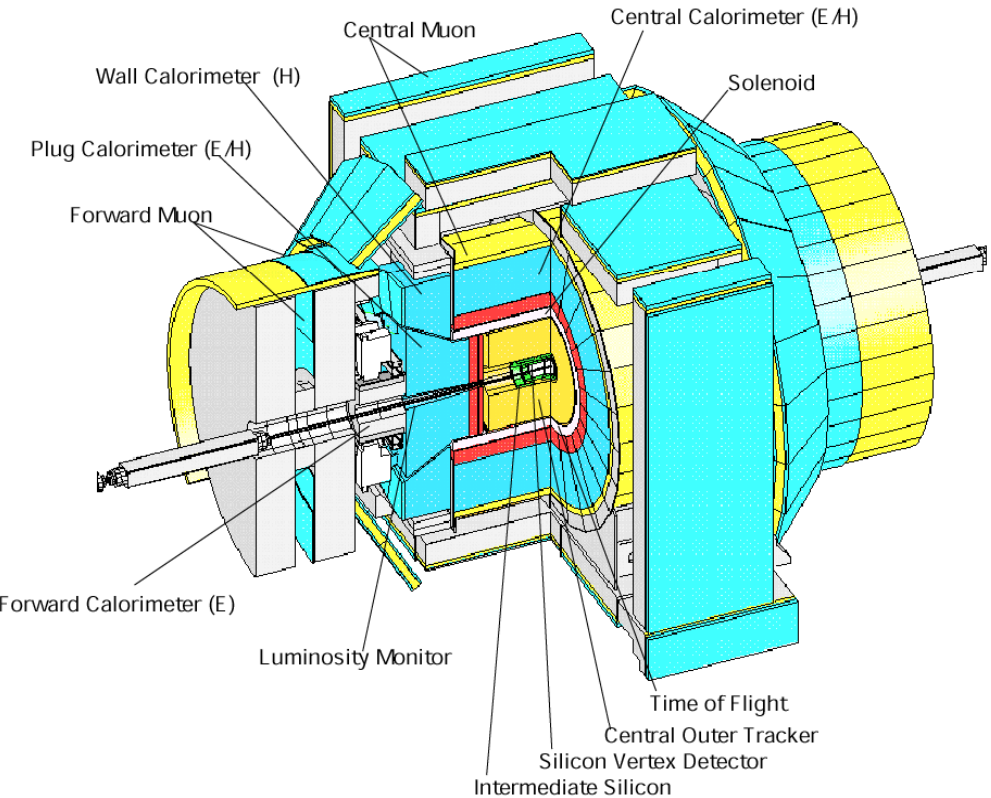
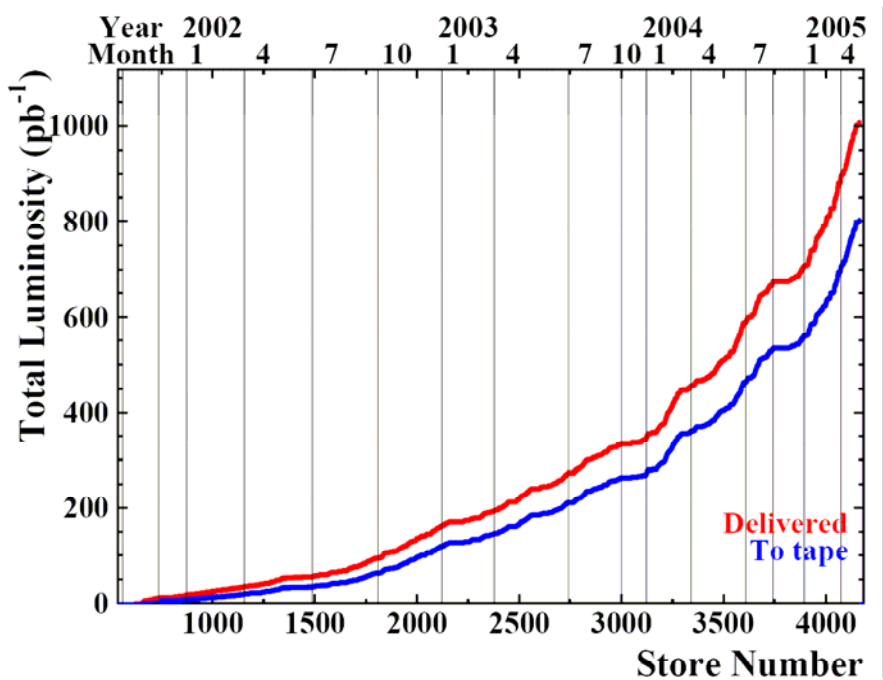
(for CDF Collaboration)

"Wine & Cheese" Seminar, May 27 2005

CDF Today



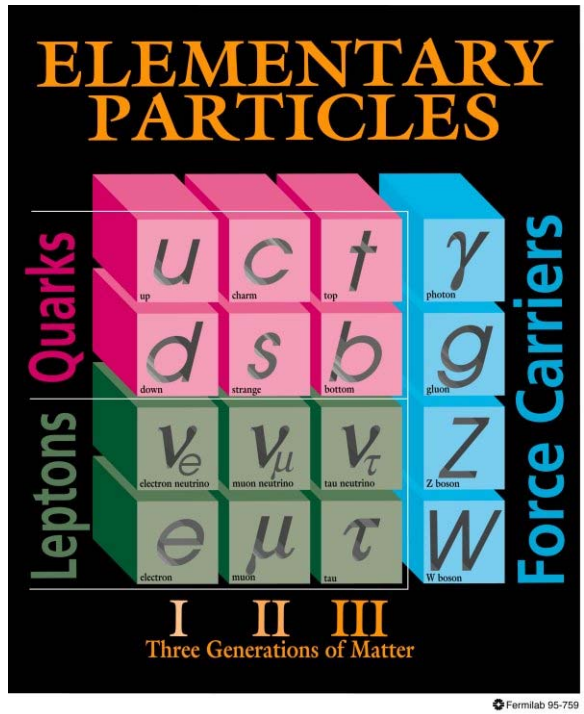
- This week: 1000 pb^{-1}!
  - Many thanks to the Accelerator Division folks!

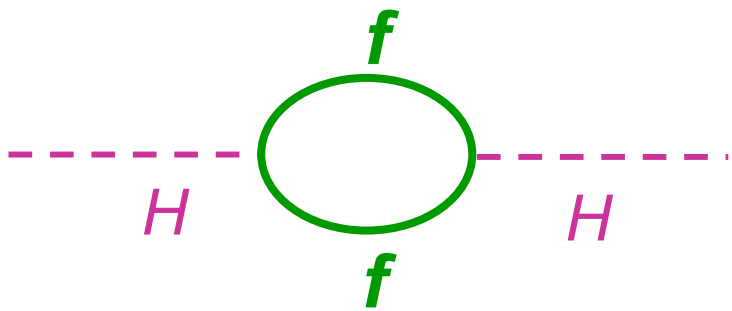


- CDF: stable operating regime
  - All components work well
- 800 pb^{-1} on tape
- Most analyses: 200-350 pb^{-1}

Why Unhappy With SM?

- **Likes:**
  - Standard Model (SM) has been a major success as confirmed by many precision measurements
- **Dislikes:**
  - Not "beautiful" enough:
    - Many input parameters
    - Unification not possible
    - Matter-antimatter asymmetry
    - Scale hierarchy
      - Huge Higgs mass corrections
    - No Dark Matter candidate
  - Can it even work?
    - No Higgs so far
    - Massive neutrinos



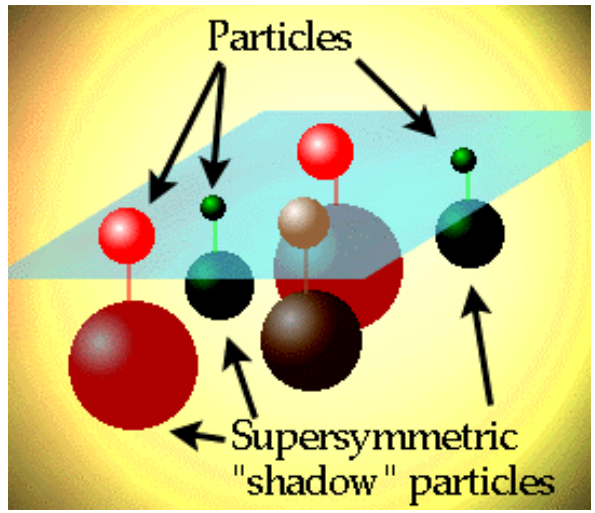


$$\delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}[-2\Lambda_{UV}^2 + \ldots]$$

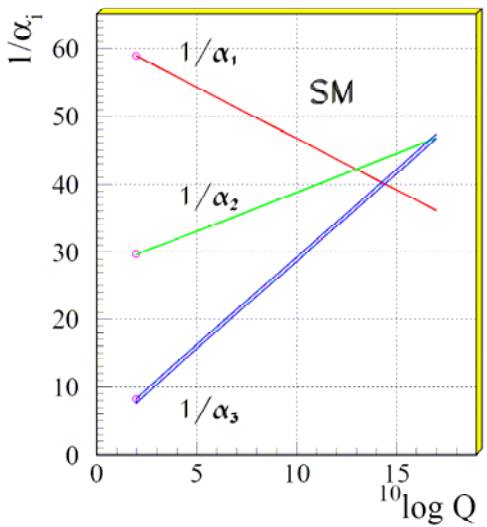
What SUSY Does?

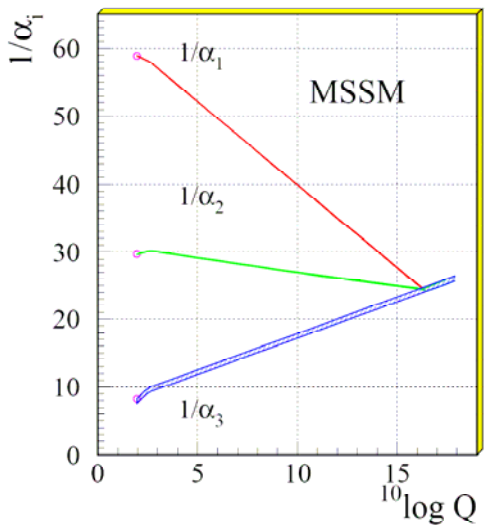
New symmetry: fermions ↔ bosons

$$Q|Boson\rangle = |Fermion\rangle$$
$$Q|Fermion\rangle = |Boson\rangle$$



- Provide cancellation in the Higgs mass corrections
- Practical consequences:
  - Doubled particle spectrum
  - New, not yet seen particles
- SUSY is broken
  - Otherwise $m_p = m_{Sp}$
- Soft breaking $m_S \sim m_{EWK}$:
  - natural *new physics* scale to keep m_H low
- Unification possible
- CDM candidate
- Falls back to SM at low energy





What We Know About SUSY

- Extensive studies of the parameter space by LEP-2
  - Best sensitivity by combining results from all four experiments
    - Many nearly model-independent
  - Stringent limits on slepton and gaugino masses
- Tevatron:
  - Excellent grip on squarks and gluinos
    - Strong production
  - GMSB Gauginos
  - Reach for gauginos via trileptons

Particle	Super-partner
e,ν,u,d	$\tilde{e},\tilde{\nu},\tilde{u},\tilde{d}$
γ,W,Z,h	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^{\pm},$ $\tilde{\chi}_1^0 \ldots \tilde{\chi}_4^0$

Dark Matter Candidate

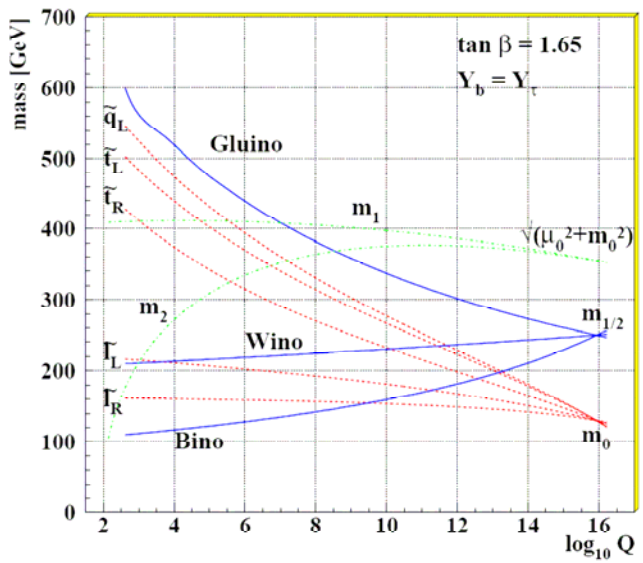
	Mass GeV/c²	
Neutralino $\tilde{\chi}_1^0$	39-46	LEP2
Gaugino $\tilde{\chi}_1^{\pm}$	103	LEP2
GMSB $\tilde{\chi}_1^{\pm}$	150	DØ
Sleptons $\tilde{l}$	80-100	LEP2
$\tilde{g}$ (any $M_{\tilde{q}}$)	195	CDF
$\tilde{q}$ ($M_{\tilde{q}} = M_{\tilde{g}}$)	300	CDF

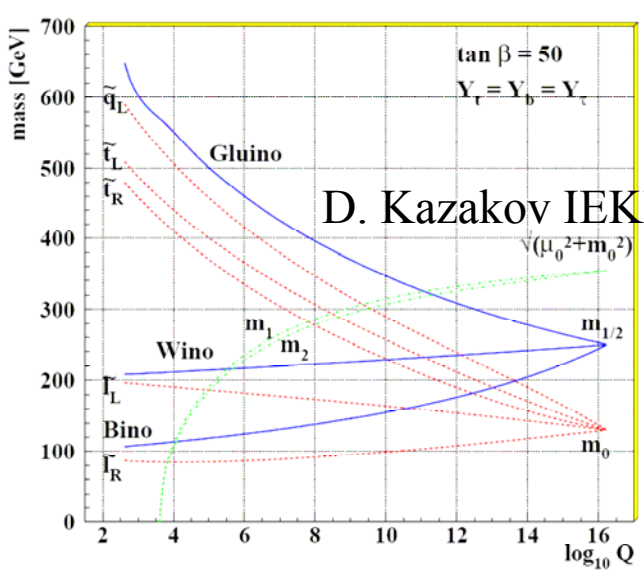
This Talk: Outline

- SUSY:
  - mSUGRA
    - Squarks/gluinos
    - 3rd generation squarks
    - Trileptons
    - High tanβ ($B_s \rightarrow \mu\mu$)
  - GMSB
    - Not included (combined CDF+D0 covered last week)
  - R-parity
    - Sneutrino (production and decay)
    - Stop (decay)
  - Higgs $\rightarrow \tau\tau$

mSUGRA

- One of the best studied SUSY models
- SUSY breaking is transmitted via gravity
- SUSY breaking terms are low-energy "remnants" of SuperGravity models
- Unification of masses at GUT scale (m_0, $m_{1/2}$)



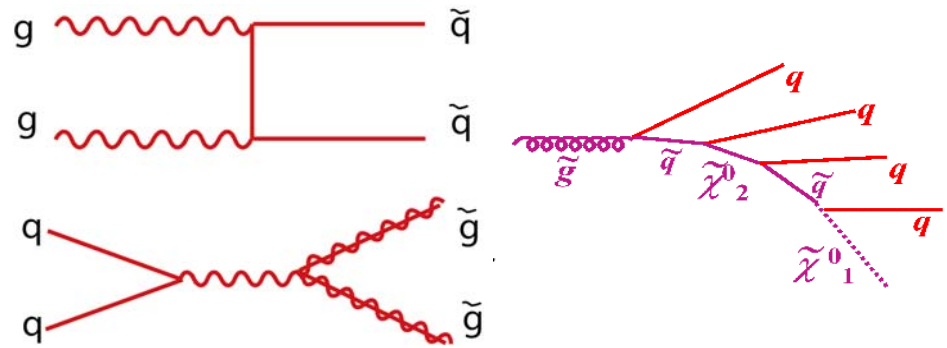


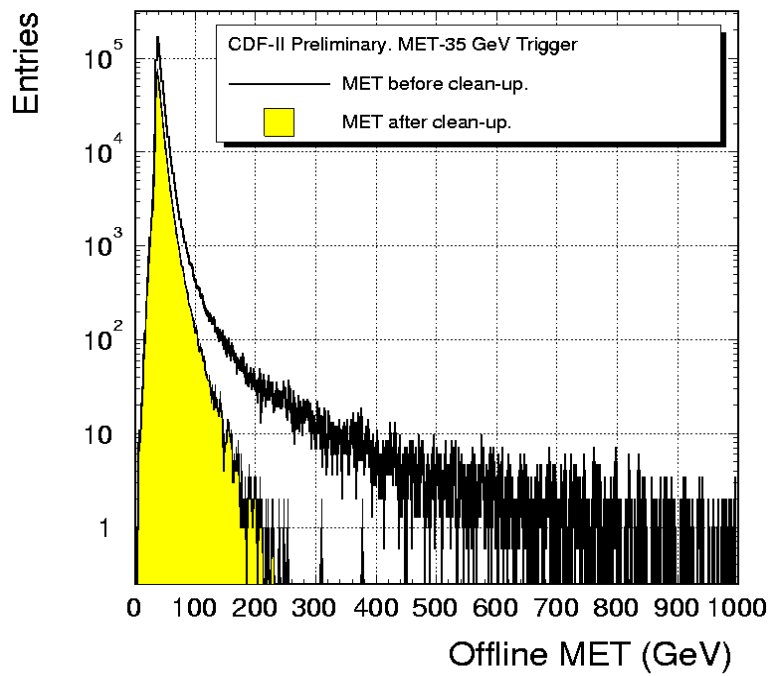
D. Kazakov IEKP-KA/2001-1

- **Bolts and nuts:**
  - LSP – neutralino; NLSP – chargino or 3rd gen squarks/sleptons
  - 3rd gen is usually light
- **Experimental signature:**
  - Cascade decays with large missing energy due to LSP
  - Final states: leptons/jets

Search for Squarks/Gluinos

- mSUGRA: A0=0, sign(μ) = -1, tanβ = 5
- 3rd generation excluded
  - Different decay mode
  - Requires special treatment
- Signature: $\geq$3 jets+missing transverse energy

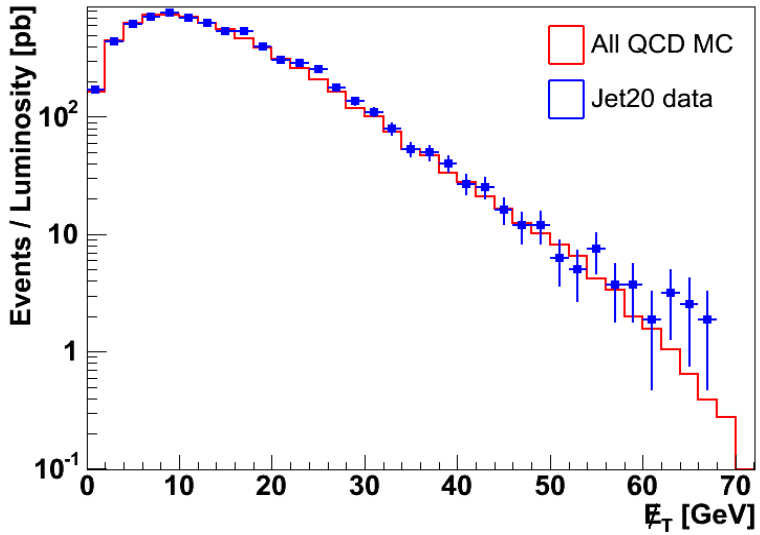




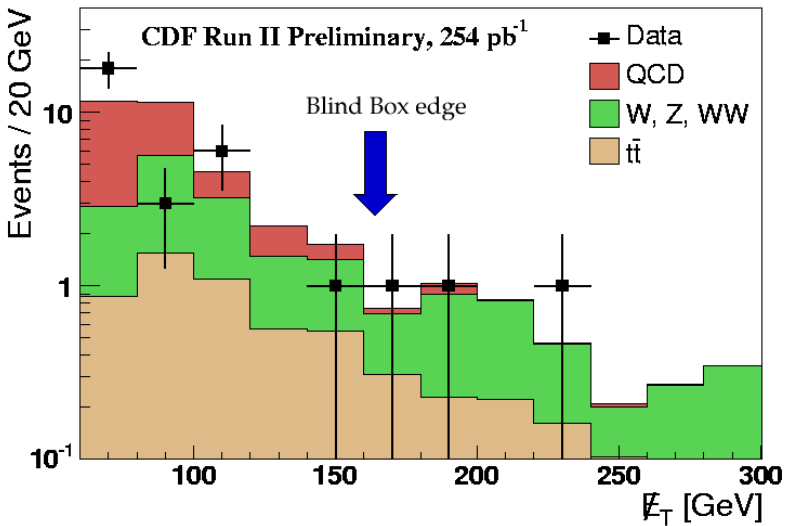
- Trigger: MET35+2jets
- Challenging measurement
  - Signal is buried under enormous QCD background
    - Difficult to control
  - Missing energy mismeasurements
    - Beam Halo, hot towers etc.

Squarks/Gluinos

- Compare QCD and MC shapes and normalizations:
  - Excellent agreement
- Check other control regions
  - Everything ok
- At the end, backgrounds are dominated by EWK



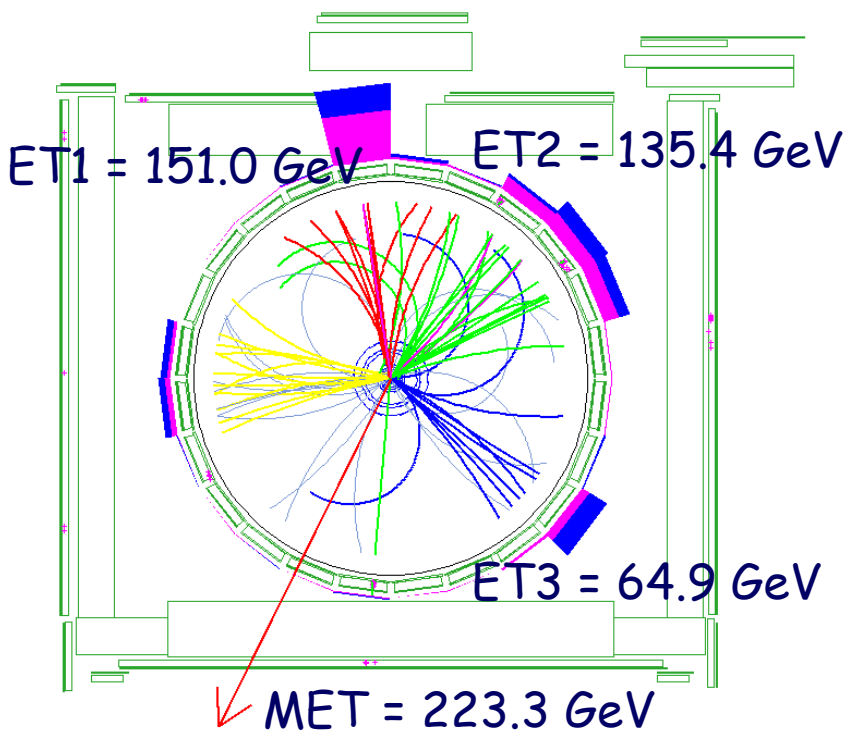
Selections:
E_T(1st jet) > 125 GeV ; E_T(2nd jet) > 75 GeV E_T(3rd jet) > 25 GeV
$\Delta\phi$ angle (MET, jet) > 0.7 for all 3 jets
EMF < 0.9 for all 3 jets (anti-electron)
MET>165 GeV
$H_T \equiv E_{T1}+E_{T2}+E_{T3}$ >350 GeV

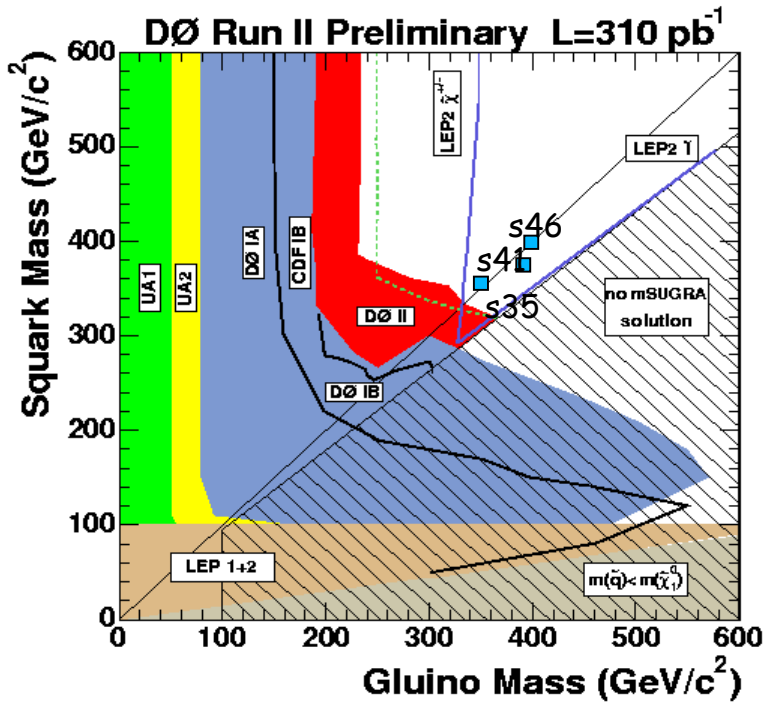


Squarks/Gluinos

Samples	Expected Events ($254pb^{-1}$)	Efficiency (%)	S/sqrt(B)
Signal s35	$4.8 \pm 0.1 \pm 0.7$	$7.2 \pm 0.2 \pm 0.9$	2.3 ± 0.8
Signal s41	$3.6 \pm 0.1 \pm 0.6$	$8.4 \pm 0.2 \pm 1.1$	1.8 ± 0.6
Signal s46	$0.7 \pm 0.0 \pm 0.2$	$9.7 \pm 0.2 \pm 1.3$	0.4 ± 0.1
Background	$4.1 \pm 0.6 \pm 1.4$		

- 3 observed events
- Complete scan in 2D plane to produce final limits

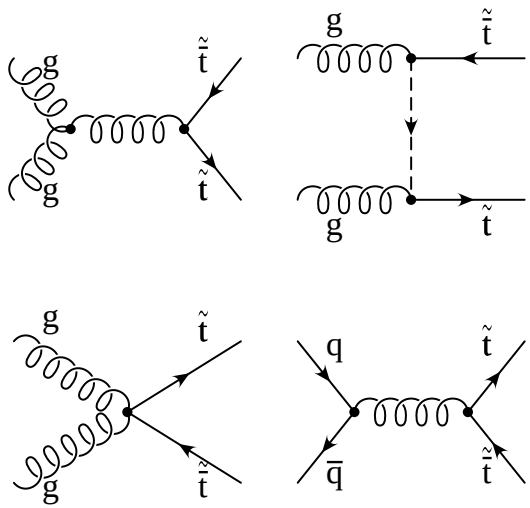




Third Generation Squarks

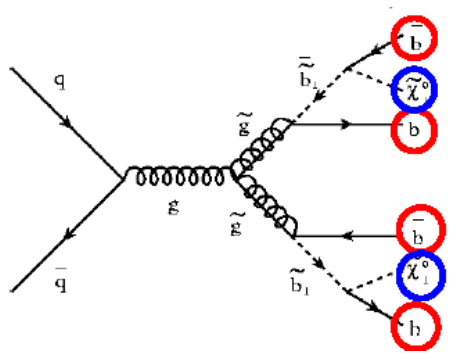
- **One Stop - lightest squark due to large top quark mass**
  - **Decay depends on masses:**

1. $\tilde{t}_1 \to b\tilde{\chi}_1^+ \quad \tilde{\chi}_1^+ \to W^{+(*)}\tilde{\chi}_1^0$
2. $\tilde{t}_1 \to bl\tilde{\nu}$
3. $\tilde{t}_1 \to c\tilde{\chi}_1^0$ **if (1),(2) forbidden**



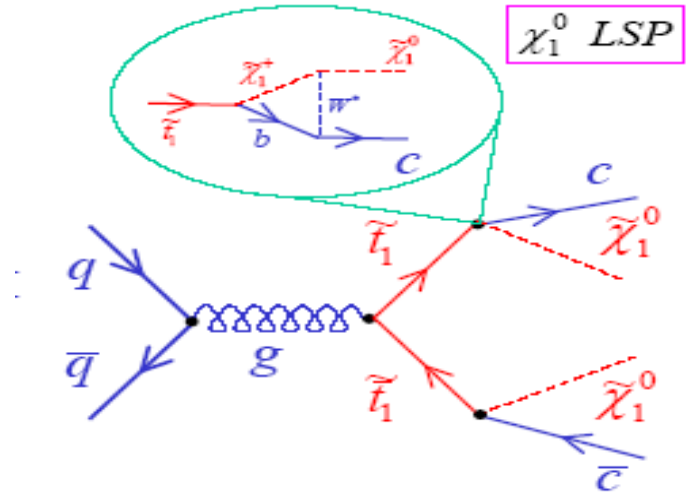
- **One Sbottom - light if tanβ large**
  - **Production modes:**

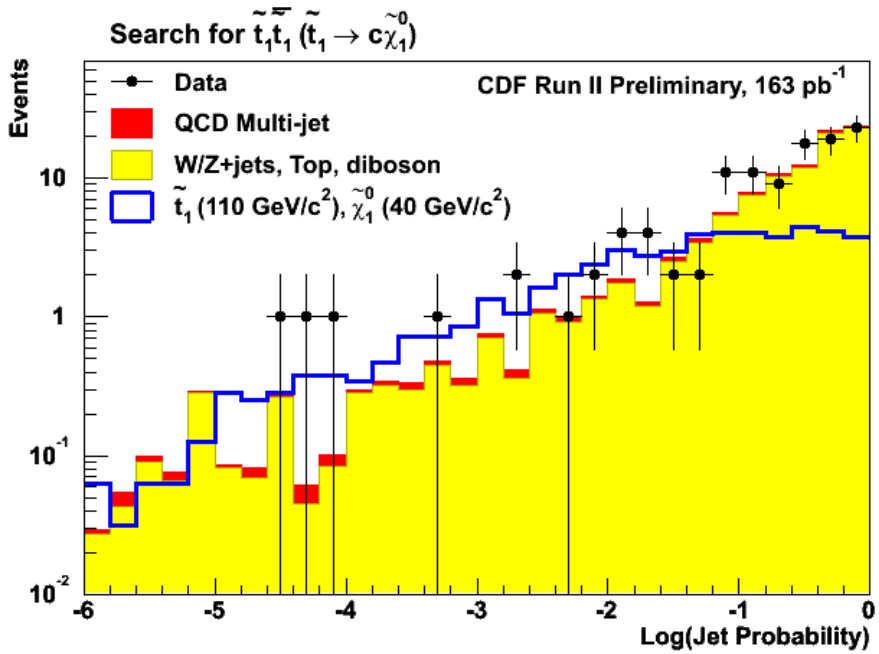
1. $pp \to \tilde{g}\tilde{g} \to b\tilde{b}b\tilde{b} \to bbbb\chi_1^0\chi_1^0$
2. $pp \to \tilde{b}\tilde{b} \to bb\chi_1^0\chi_1^0$

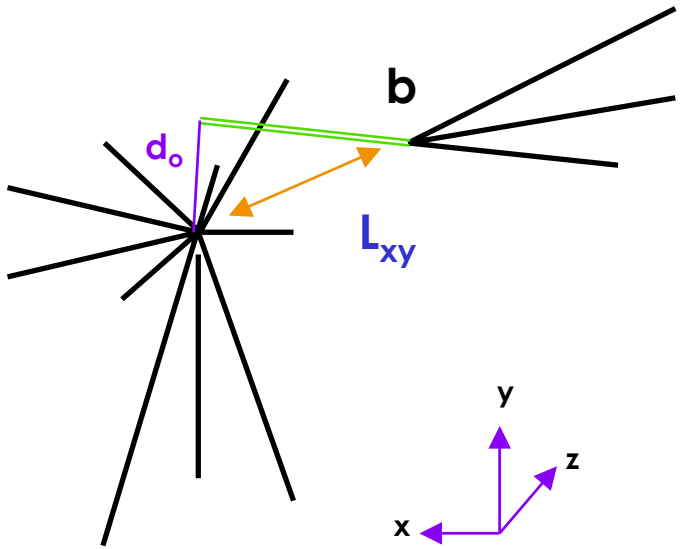


3rd Gen. Squarks: Stop

- **Special case:**
  - Stop is often light
    - No cascade decays leading to multi-jets
- **Signature:**
  - 2 jets, large MET
  - Tag charm using JetProb
- **Trigger: MET45**





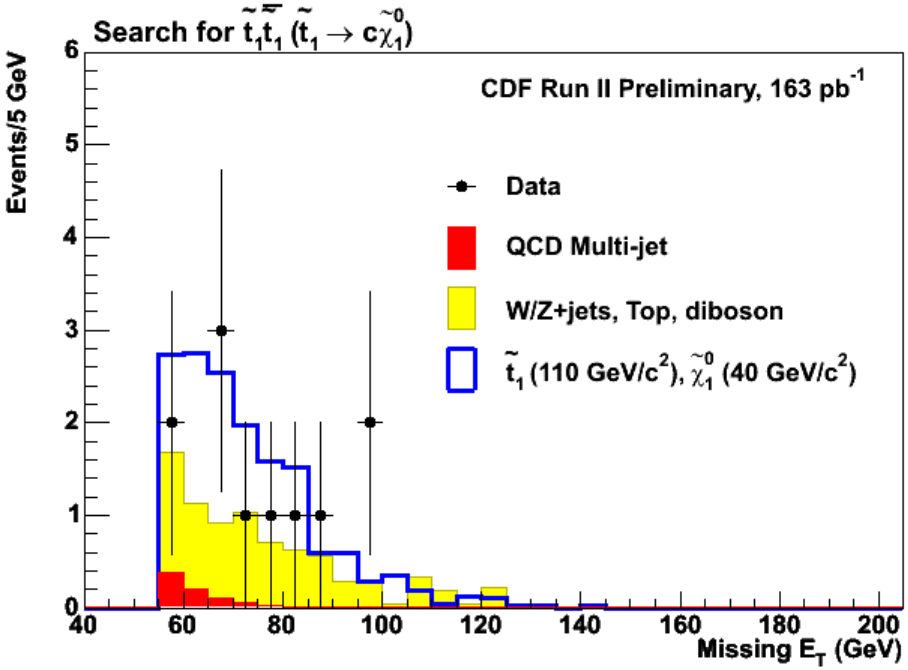


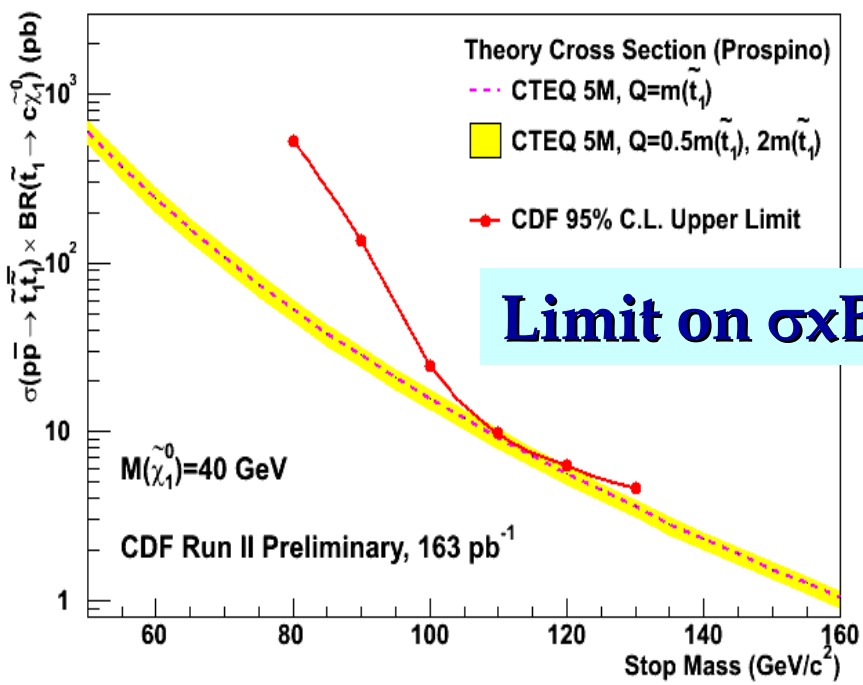
3rd Gen. Squarks: Stop

	Exp.	Obs.
Pre-tag	105 ± 12	119
Tag (silicon)	8.3 ± 2.3	11

- No excess, set limit
- Benchmark assuming

$$BR(\tilde{t}_1 \to c\tilde{\chi}_1^0) \sim 100\%, m_{\chi_1^0} = 40\mathrm{GeV}/c^2$$





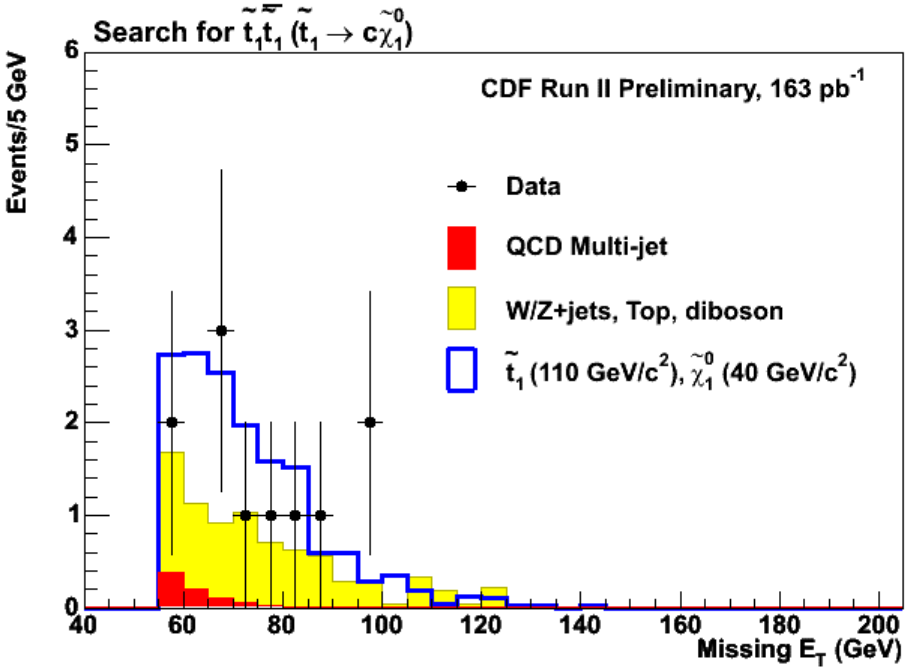
Limit on σxBR

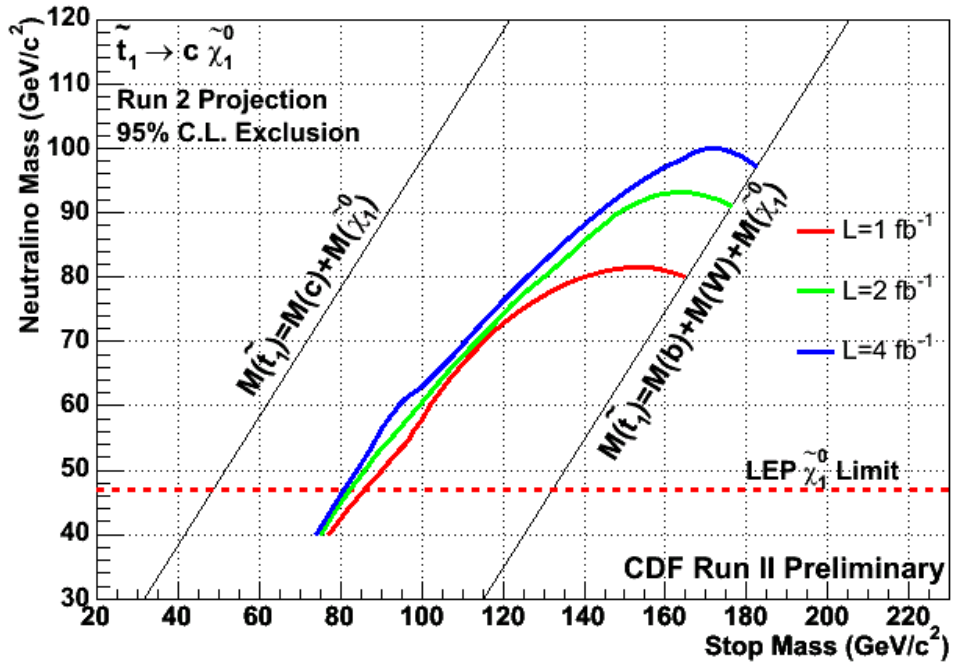
3rd Gen. Squarks: Stop

	Exp.	Obs.
Pre-tag	105 ± 12	119
Tag (silicon)	8.3 ± 2.3	11

- No excess, set limit
- Benchmark assuming

$$BR(\tilde{t}_1 \to c\tilde{\chi}_1^0) \sim 100\%, m_{\chi_1^0} = 40\text{GeV}/c^2$$

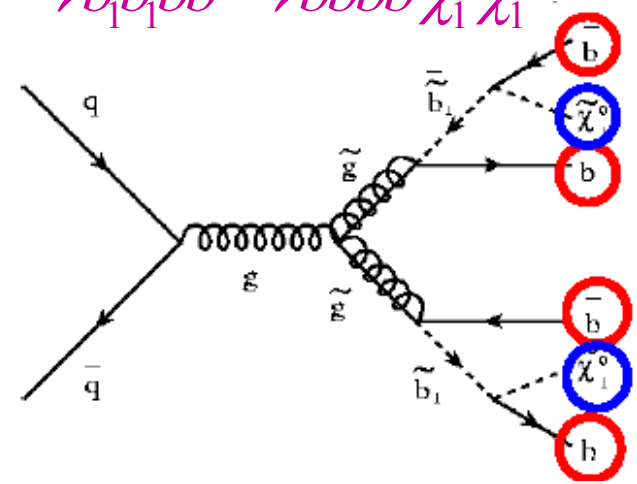


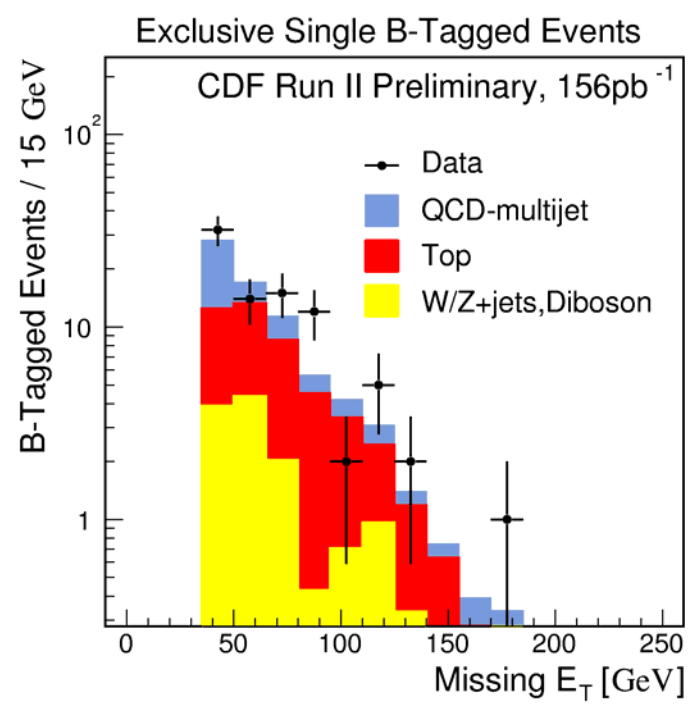


3rd Gen. Squarks: Sbottom

- **Striking signature:**
  - 4 b-jets in the final state
  - Large E_T^{Miss}
- **Selections:**
  - $\geq$3 jets (E_T>15 GeV)
  - MET>80 GeV
  - Lepton veto
  - *b*-tag to reduce QCD backgrounds
    - SECondary VerTeX
- **Control Region:**
  - Reverse lepton veto

$$\tilde{g}\tilde{g} \rightarrow \tilde{b}_1\bar{\tilde{b}}_1 b\bar{b} \rightarrow b\bar{b}b\bar{b}\,\tilde{\chi}_1^0\tilde{\chi}_1^0$$

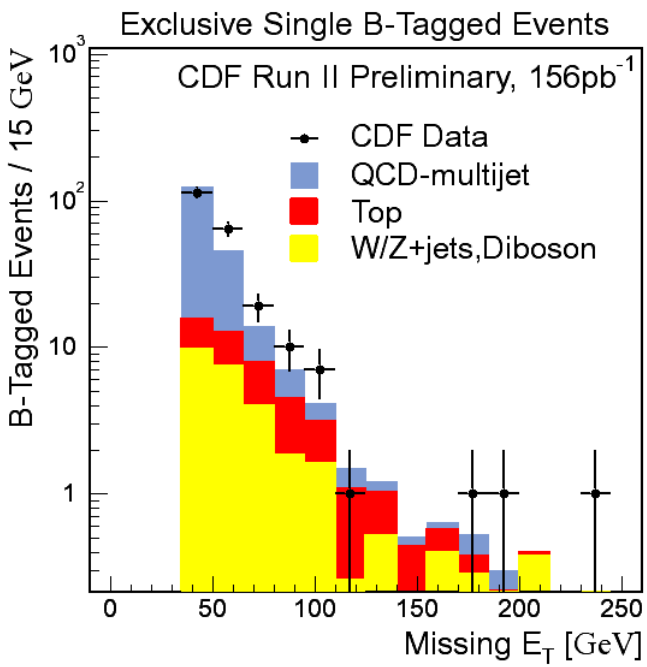


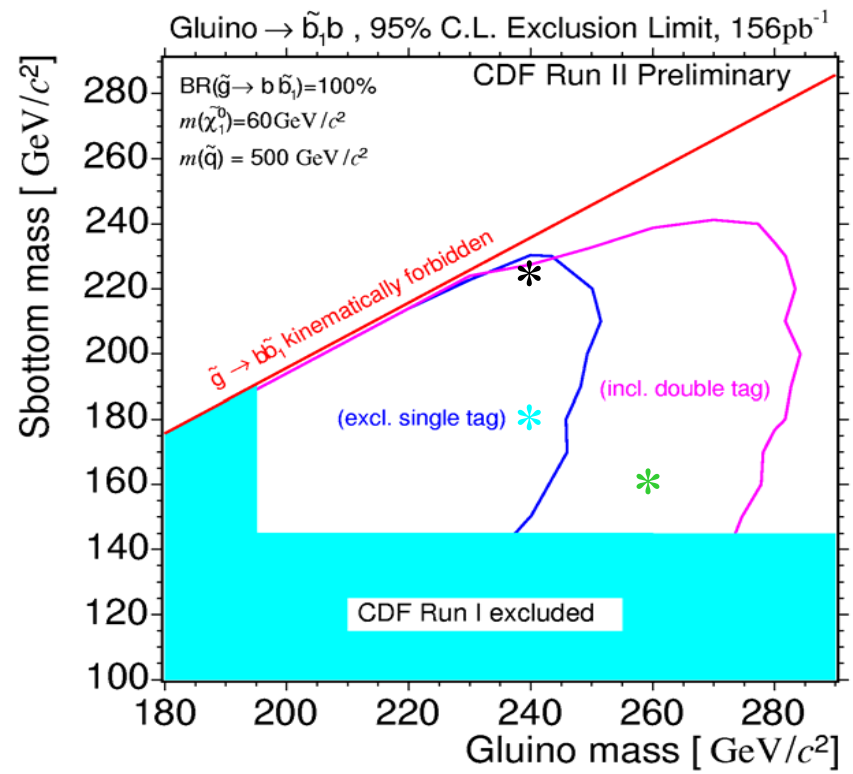


3rd Gen. Squarks: Sbottom

- Two regions:
  1. =1 b-tag
  2. ≥2 b-tags
- Open the box:

n_{tag}	Bkgnd	Obs.
=1	16.4 ± 3.7	21
>=2	2.6 ± 0.7	4





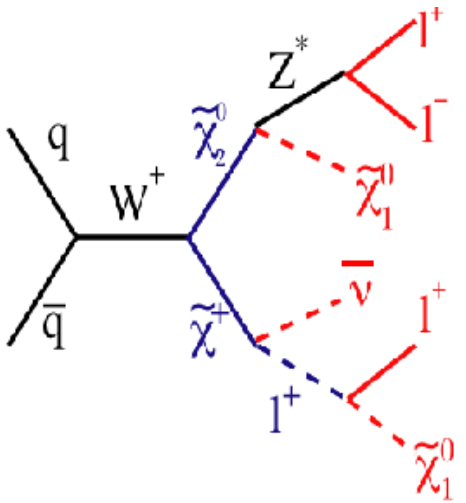
- No excess, set limit
  - 2D: m_{gluino}, $m_{sbottom}$

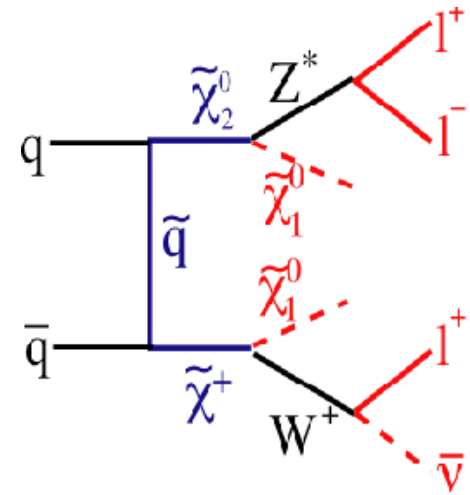
Trileptons

- Tevatron "golden mode" for SUSY
- Final state with 3 leptons, large E_T^{Miss}
  - Striking signature
  - Small SM backgrounds
- So far, completed two channels:

	High Pt	Low Pt
Lepton 1	e: >20 GeV	e: >10 GeV
Lepton 2	e: >8 GeV	e: >5 GeV
Lepton 3	e/μ: >5 GeV	track: >4 GeV

  - Largely complementary
    - Low Pt analysis has more backgrounds, thus tighter cuts



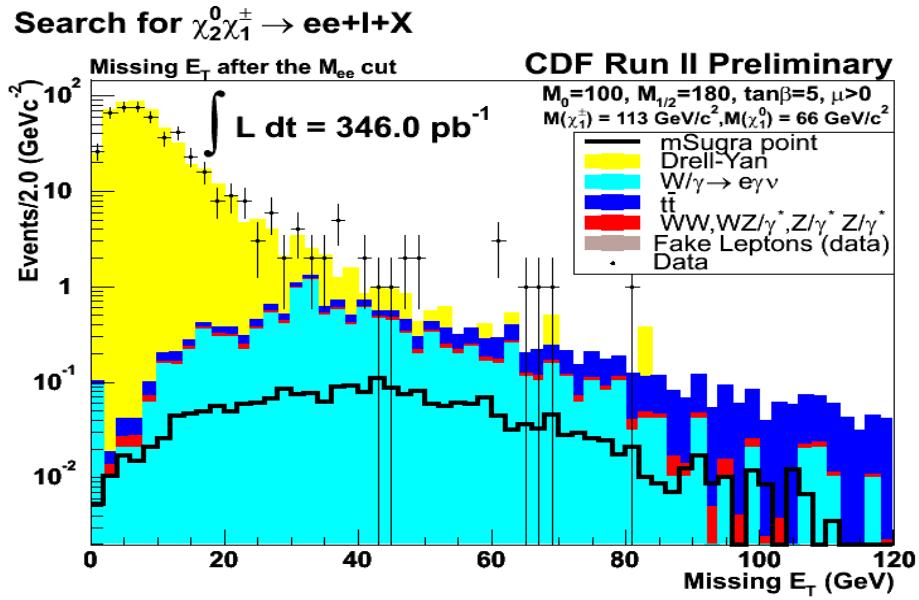


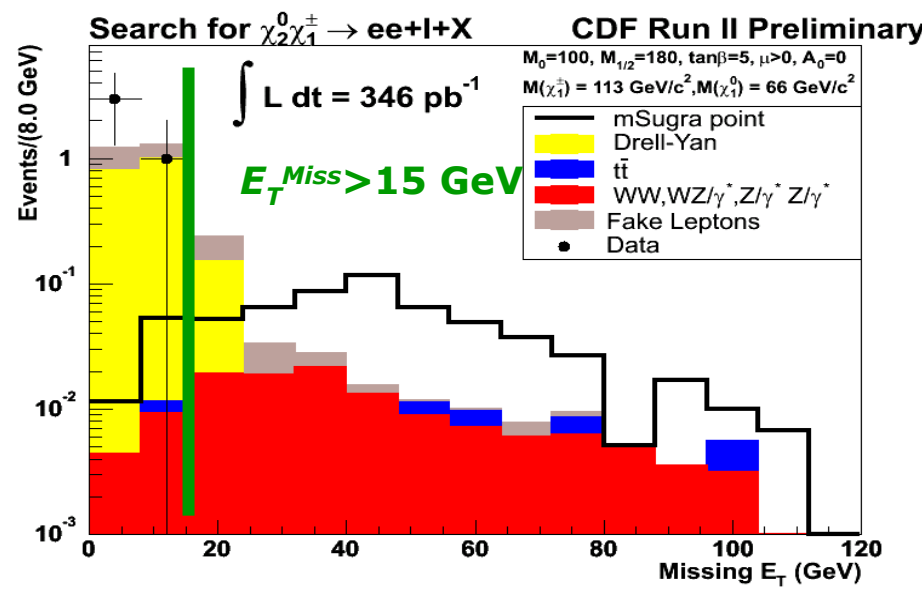
Gaugino, Higgsino content, m(slepton) determines BR's, coupling strengths

Trileptons: "High Pt"

- **Trigger:**
  - inclusive electron E_T>18
- **Selections:**
  - eeℓ (ℓ =e,μ) $|\eta| < 1$
  - E_T^{Miss}>15 GeV/c^2
  - 15<M($\ell\ell$) <76, >106 GeV/c^2
  - $|\Delta\phi(\ell\ell)|$< 160
  - Njets(20 GeV) <2

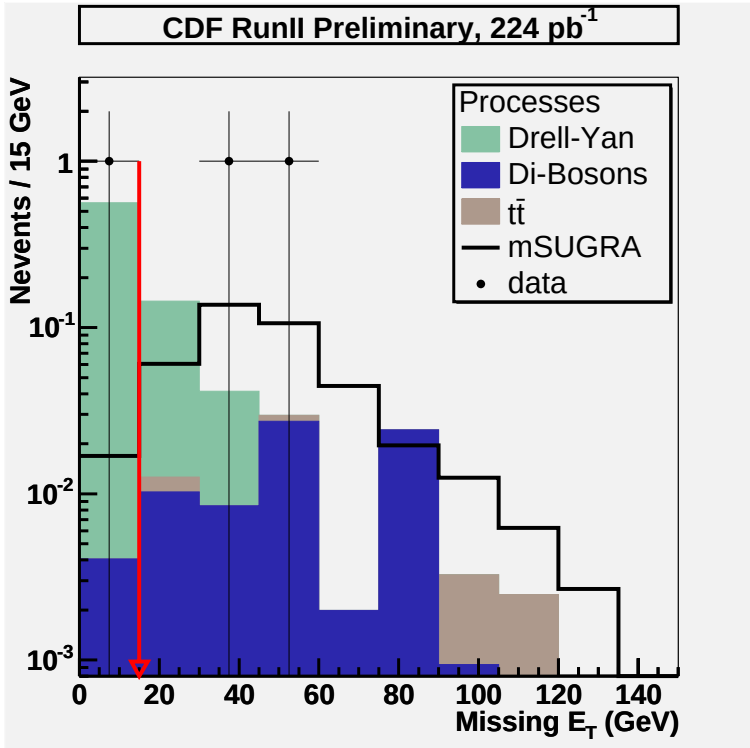
mSugra	0.5
Bkgnd Expected	0.16±0.07
OBSERVED	0





Trileptons: "Low Pt"

- **Trigger:**
  - SUSY di-electron $E_{T1/2}$>4/4 GeV
- **Selections:**
  - ee+track: 10/5/4 GeV $|\eta| < 1$
  - $\Delta\Phi$(ee)<2.9 rad
  - Ht<80 GeV
  - Min(Mt)>10 GeV
  - Mass OS2 < 60 GeV
  - MET>15 GeV
  - M(ee), M(et)>15 GeV
  - 15<M(*ll*) <76, >106 GeV/c^2
  - $|\Delta\phi|$< 160

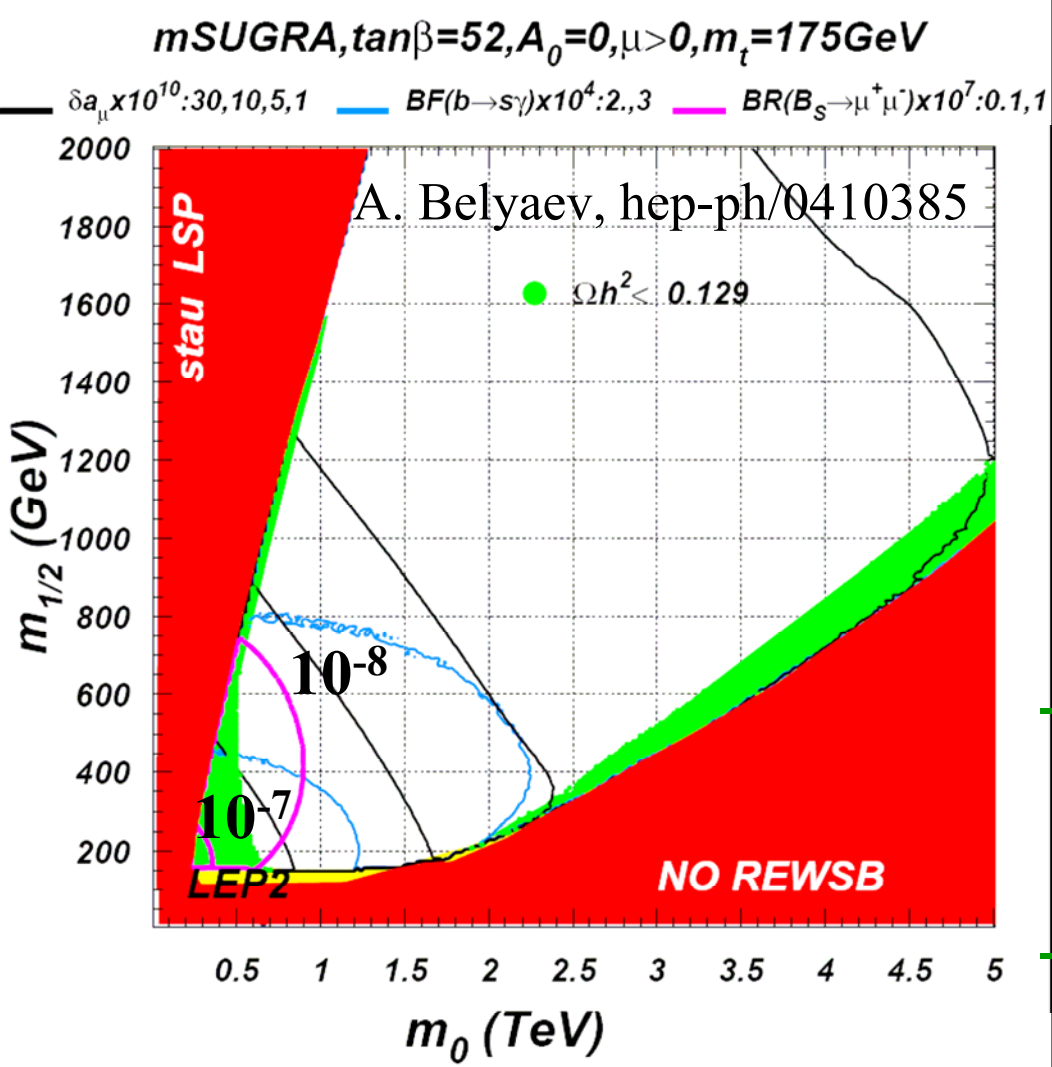


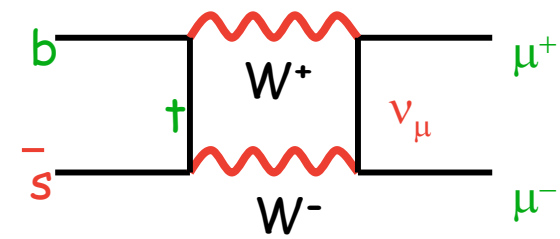
	"High Pt"	"Low Pt"
mSugra	0.5	0.5
Exp. Bkg.	0.16±0.07	0.36±0.27
OBSERVED	0	2

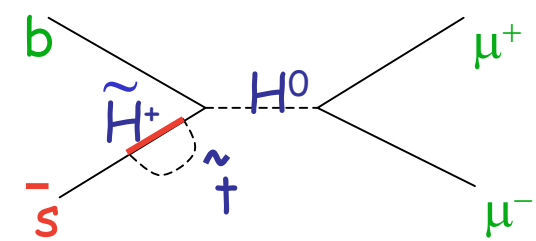
- **Lots to do:**
  - Add muon channels (soon)
  - Forward region (electrons)
  - Optimize for best sensitivity
  - Taus (later)

BR(Bs→μμ)

- Important in several areas
  - Will consider mSUGRA at high tanβ





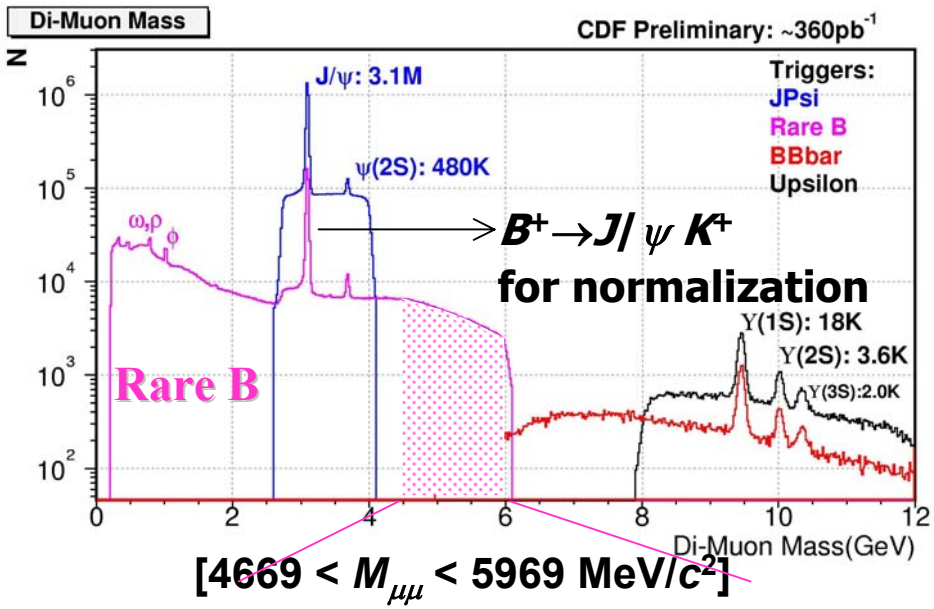


$$BR(SUSY) \propto BR(SM) \cdot \frac{m_b^4 \cdot (\tan\beta)^6}{m_{H^0}^4}$$

- If sensitivity is sufficient, will constrain allowed by WMAP region
- Need BR($Bs \rightarrow \mu\mu$)~10^{-8}

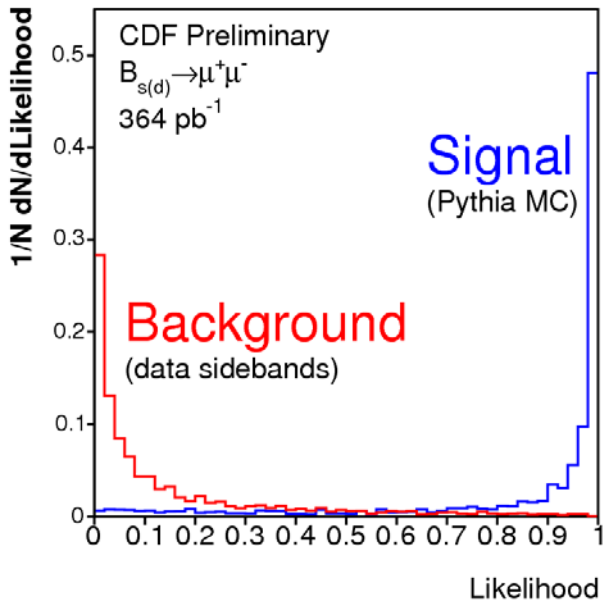
$BR(B_s \rightarrow \mu\mu)$

- New CDF result with many improvements
- Include $0.6 < |\eta| < 1.0$ μ's
- Data from four (!) "Rare B" triggers:
  - CMUP-CMU(X)
  - CMU-CMU(X)-SumPt



[$4669 < M_{\mu\mu} < 5969$ MeV/c^2]

- Employ a multivariate discriminant for better background rejection:
  - LH>0.99
    - Proper decay length (3D)
    - Isolation
    - Pointing (3D)



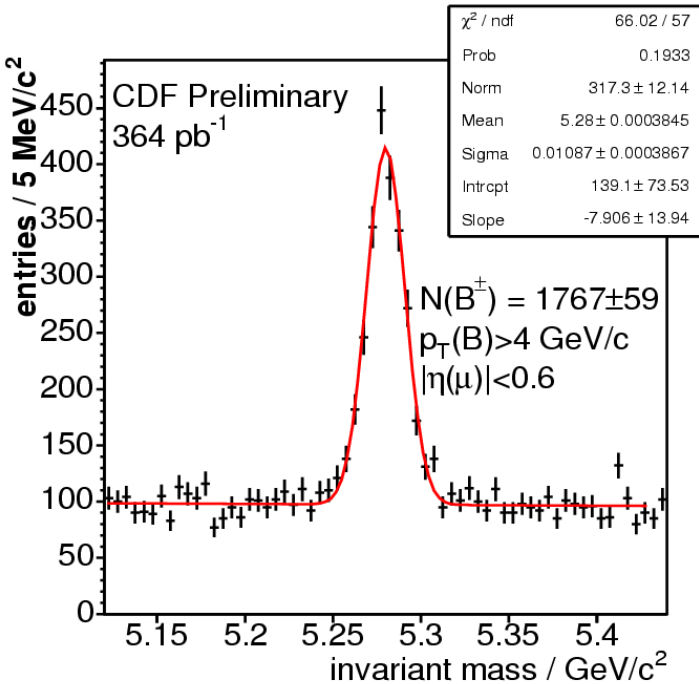
$BR(B_s \rightarrow \mu\mu)$

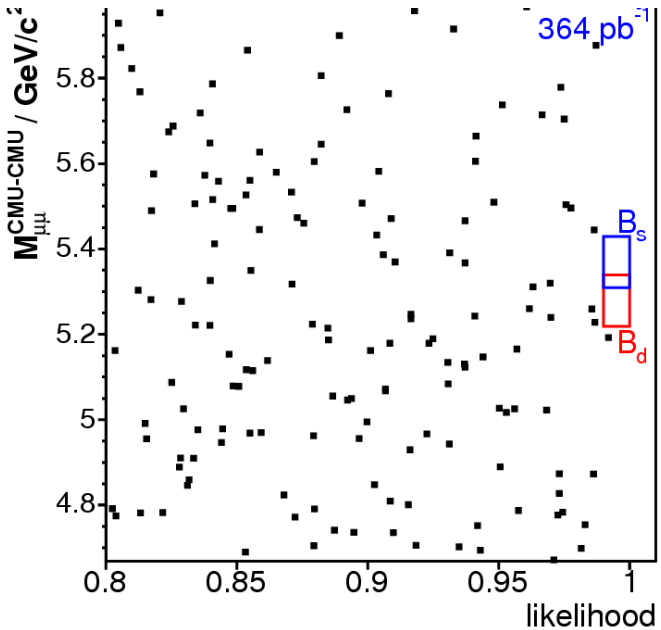
- **Signal normalization directly from data:**
  - **Reconstruct $B^+ \rightarrow J/\psi\ K^+$ events**
- **Open the box:**
  - **Exp. Bkg. = 1.47 ± 0.18**
  - **Obs. = 0**
- **Set new world best limit:**

2x improvement wrt prev. best published result

$$BR(B_d \rightarrow \mu^+\mu^-) < 4.9 \times 10^{-8} \text{ at 95\% CL}$$

$$BR(B_s \rightarrow \mu^+\mu^-) < 2.0 \times 10^{-7} \text{ at 95\% CL}$$





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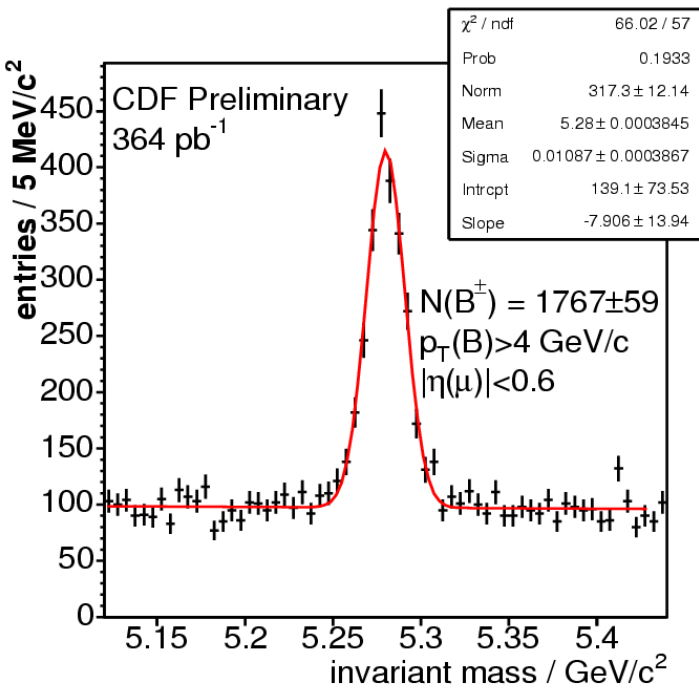
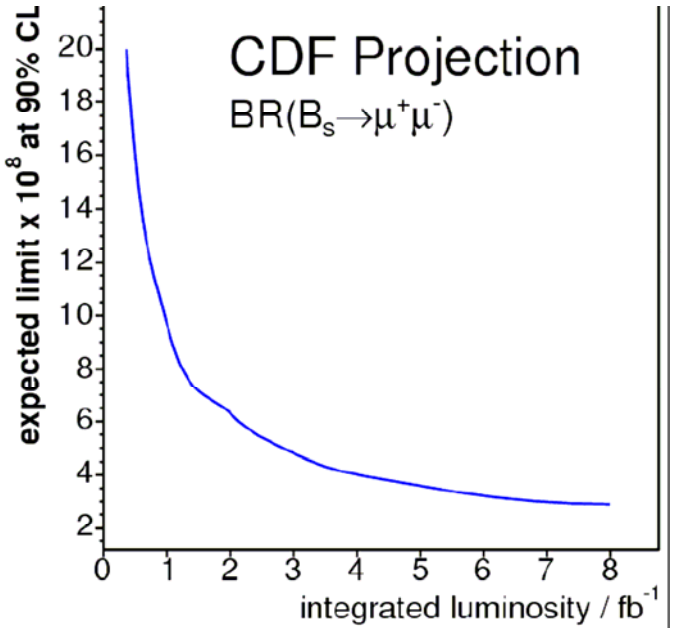


- Expect rapid improvement with luminosity
- Re-optimize after 1 fb^{-1}



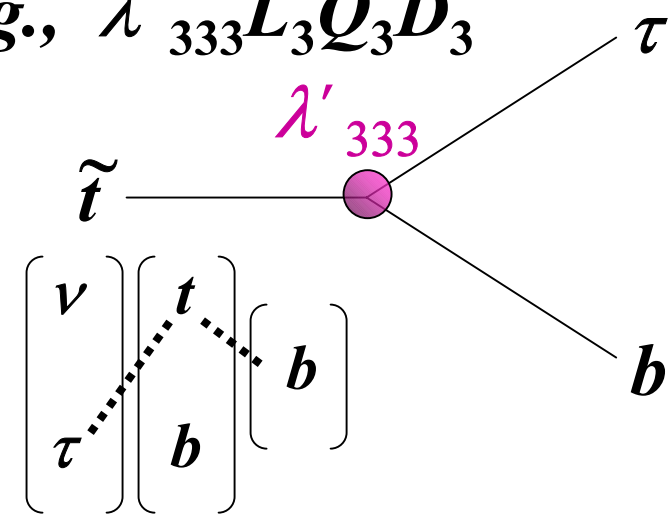
R-Parity in SUSY

- R-parity violation will allow super-partners to couple to SM particles only
- Upside:
  - Could help explain baryon asymmetry and neutrino oscillations (e.g. Ma et al., hep-ph/0008050)
- Downside:
  - No CDM candidate as LSP unstable
    - If very long living, can be ok (e.g. Hirsch et al. JHEP03(2005)062)
- Existing constrains make violating both B and L unlikely
- Particularly interesting case: L violation
- Experimentally:
  - A lot less MET
  - Often LFV and LNV

$$R_P \equiv (-1)^{3(B-L)+2s}$$

$$\underbrace{\lambda_{ijk}, \lambda'_{ijk}}_{\text{Lepton-number violating terms}}, \underbrace{\lambda''_{ijk}}_{\text{Baryon-number violating terms}}$$

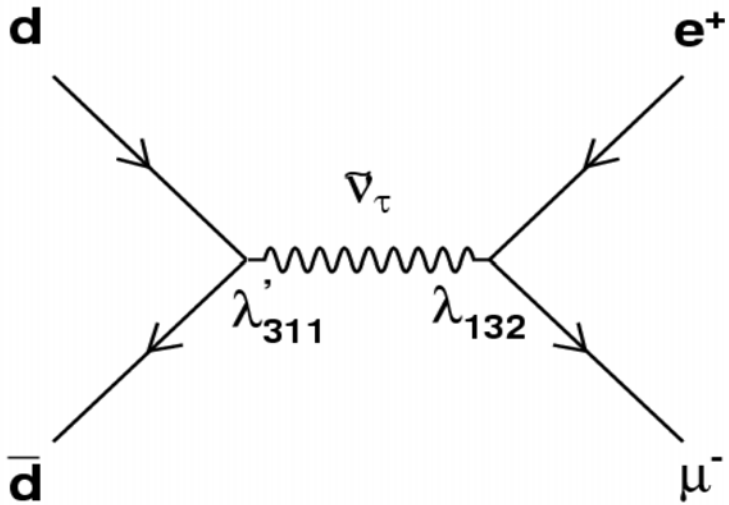
e.g., $\lambda'_{333} L_3 Q_3 D_3$



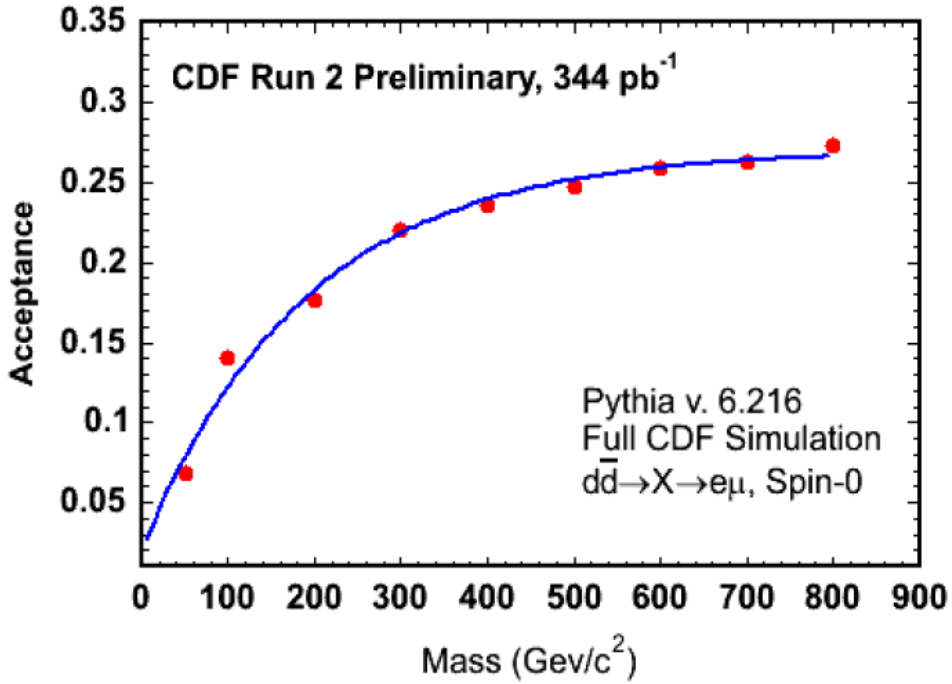
RPV: Scalar Neutrino Search

- Resonance-like production
- Start with e+μ channel
  - Sensitive to both λ and λ'

$$\sigma \propto \lambda'^2_{311}\ \lambda^2_{132}$$



- Selections:
  - Electron E_T>20 GeV
  - Muon P_T>20 GeV
  - OS charge
- High acceptance in the region of interest
- Very clean signature
  - Dominant background is Z→ττ



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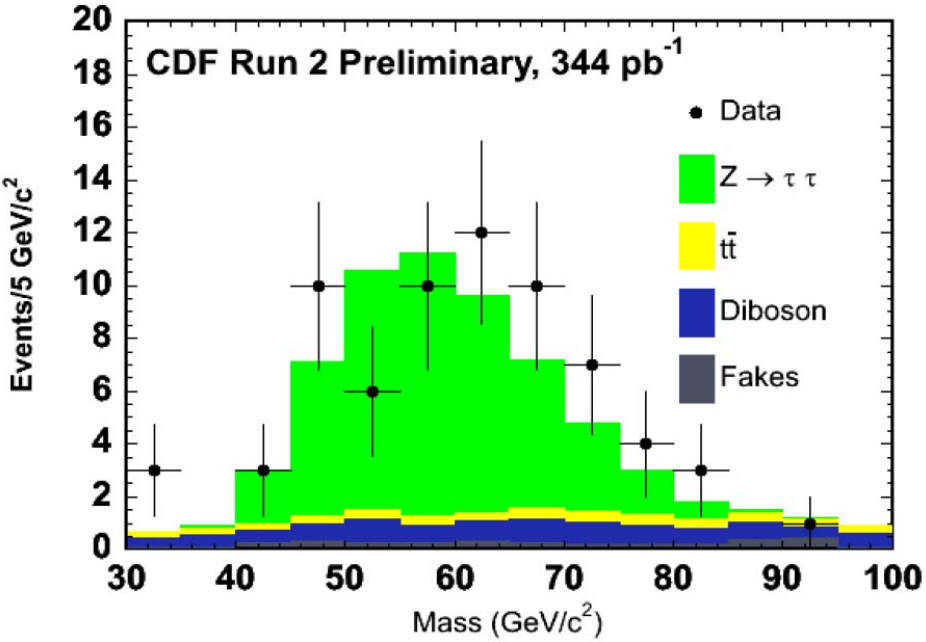
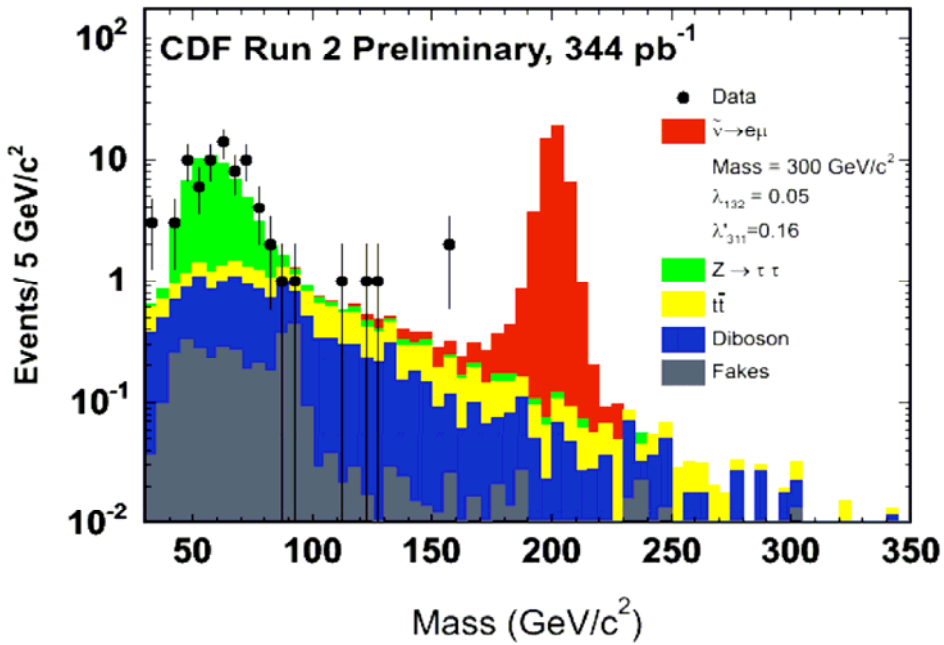
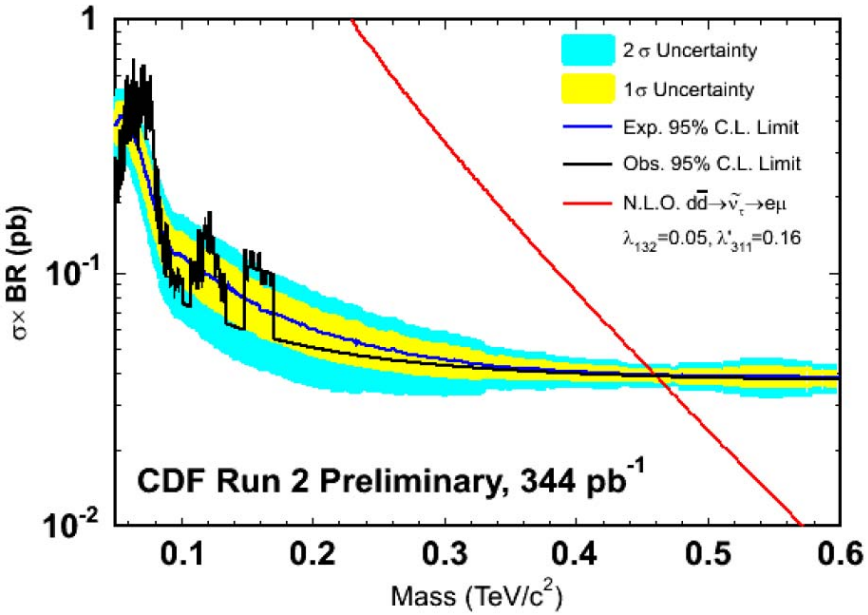


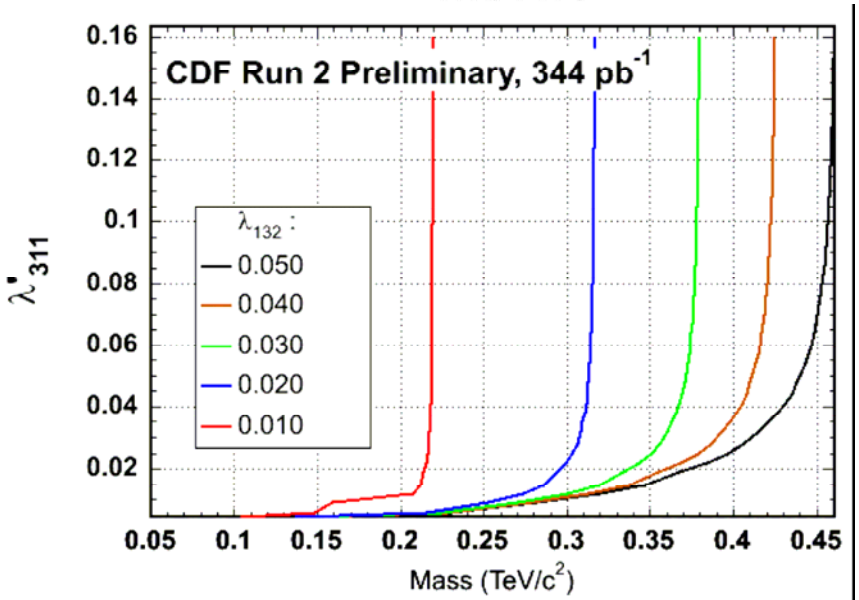
Channel	Exp.
$Z \to \tau\tau$	47.0 ±0.8
tt-bar	7.8 ±0.1
WW	11.4 ±0.3
WZ	0.85 ±0.05
ZZ	0.15 ±0.01
Total:	71.3 ±0.9
Data	74



- Low mass region OK
- Open Signal Box
- No excess, set limit

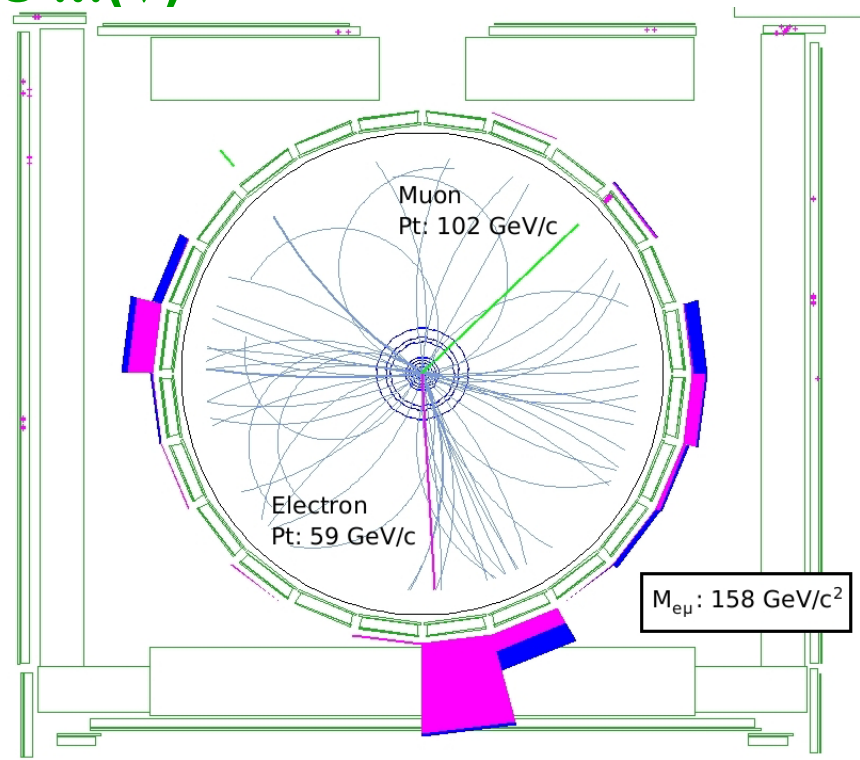
RPV: Scalar Neutrino Search





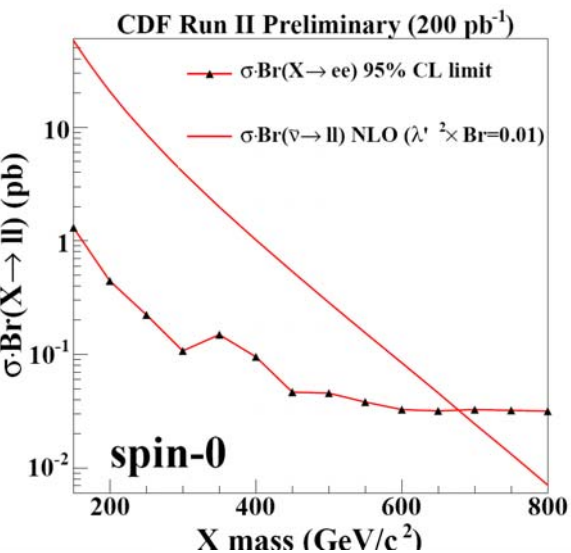
Interpret x-section limit:

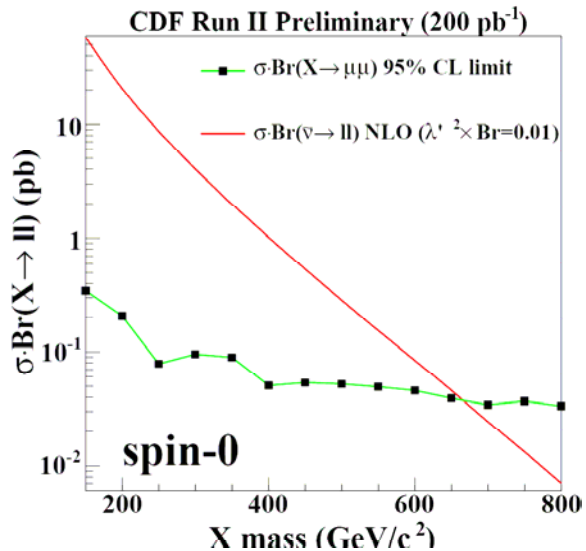
- For λ^{132}=0.05 λ'^{311}=0. 16
  - M>460 GeV
- Can set a limit in 2D λ'^{311} vs M(ν)

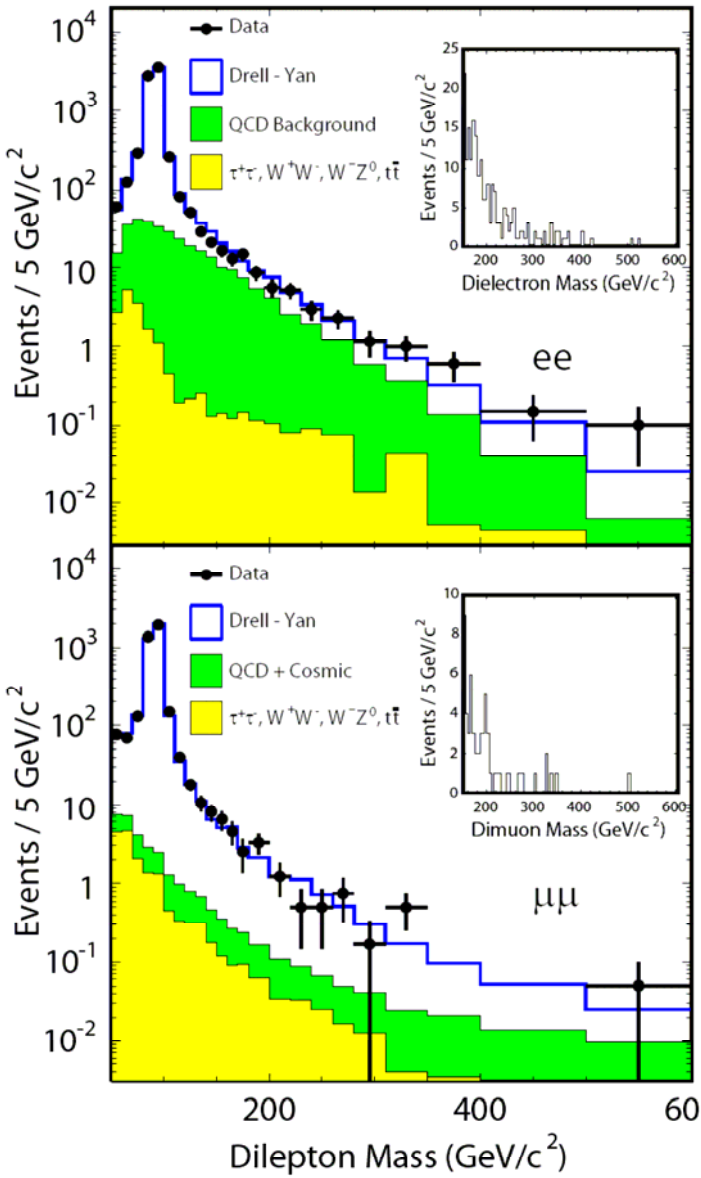


RPV: Scalar Neutrino Search

- Reinterpret CDF Z' results in terms of RPV SUSY
- Limits on diagonal (in leptons) λ-parameters:
  - Z'→ee: $\sigma \propto \lambda'^2_{311}\ \lambda^2_{131}$
  - Z'→μμ: $\sigma \propto \lambda'^2_{311}\ \lambda^2_{232}$

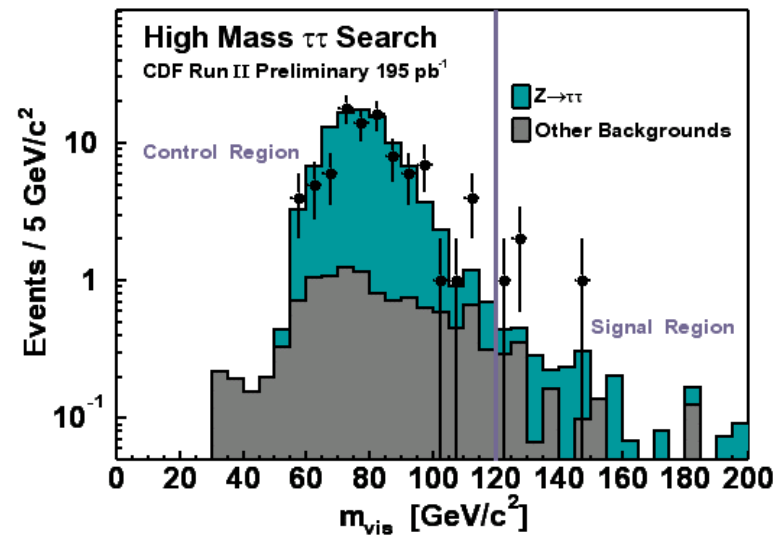




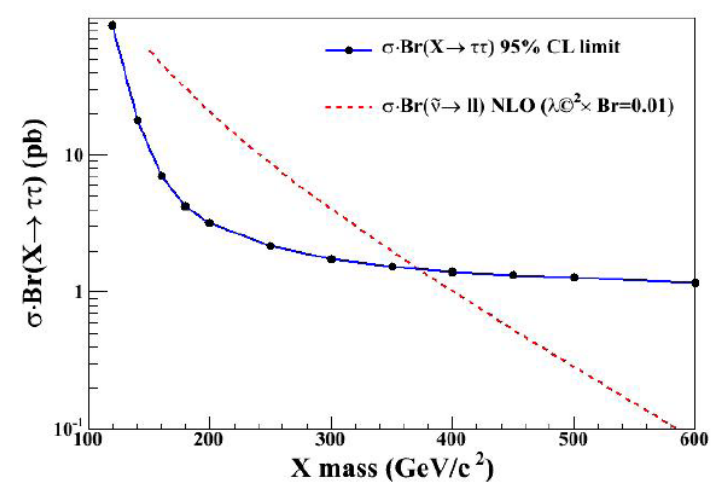


RPV: Scalar Neutrino Summary

- Did we forget something?
- Taus!
  - Z'→ττ: $\sigma \propto \lambda'^2_{311}\ \lambda^2_{333}$
- Summary
  - Mass limits assume
    $\lambda'^2_{311}\ Br(\tilde{\nu}_\tau \to X) = 0.01$

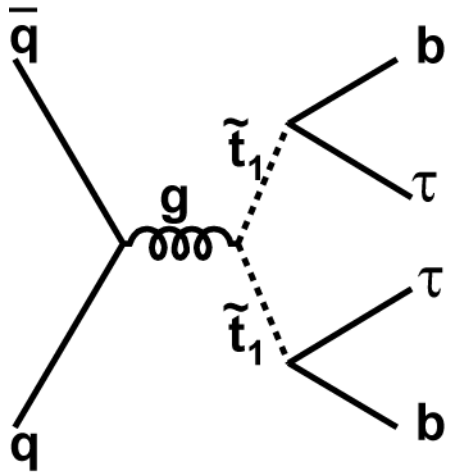


Coupling	Channel	Limit
λ_{131}	ee	M>680
λ_{132}	eμ	M>460
λ_{133}	eτ	-
λ_{232}	μμ	M>665
λ_{233}	μτ	-
λ_{333}	ττ	M>375



Search for RPV Stop

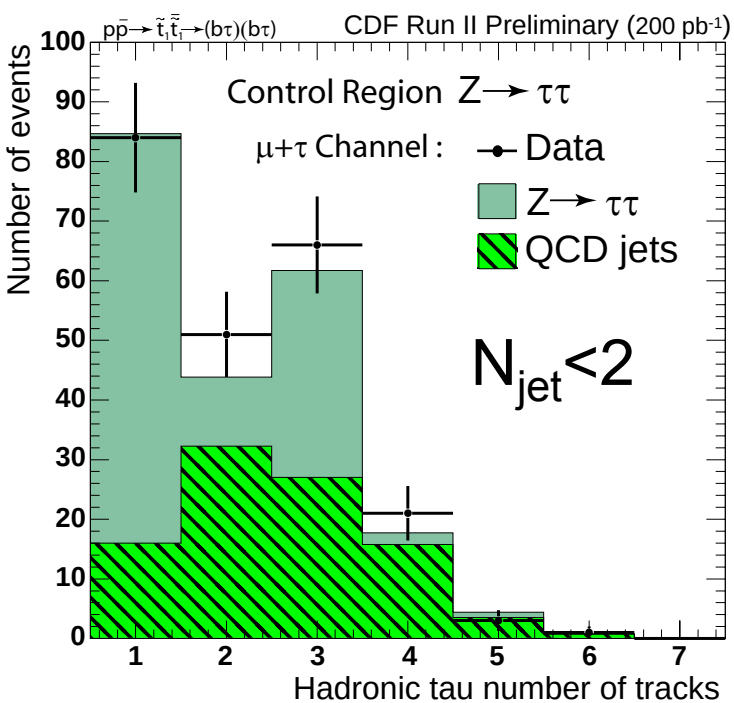
- If exists, pair-production dominates
- Can decay into tau and a b-jet
- Signature: (e or μ) + τ_h + 2 jets
- Selections:
  - Lepton: $p_T(\ell)$>10 GeV
  - Hadronic tau: $p_T(\tau)$>15 GeV
  - $N_{jet} \geq 2$ (in addition to tau and lepton)
  - 2 regions: $M_T(\ell, MET)$ = 0-35 and 35-100 GeV

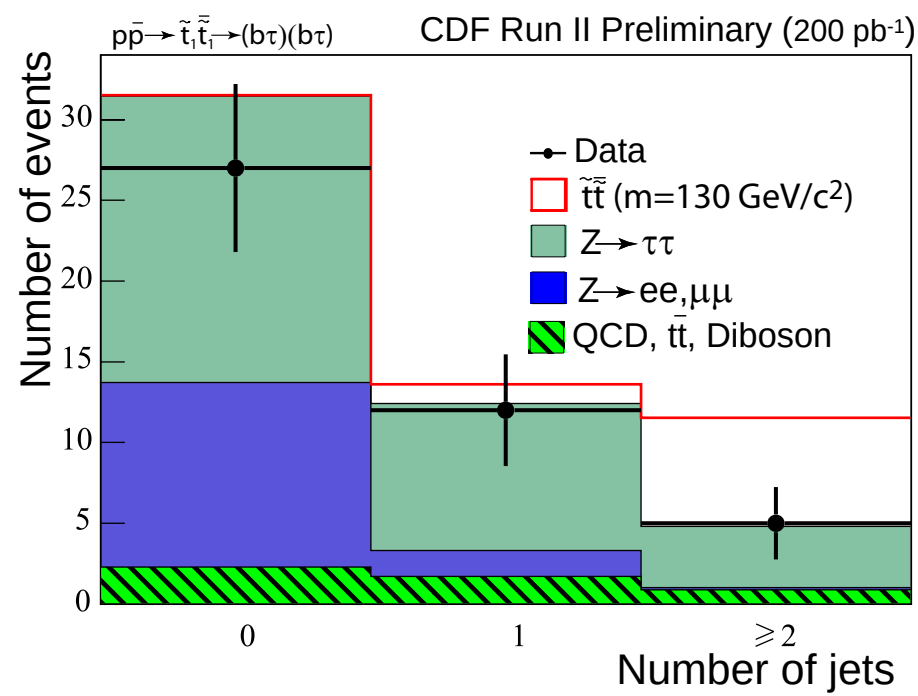


- Note: Identical to the scalar LQ_3 in the limit of high gluino mass
- Existing Limits:
  - LQ_3: m>99 GeV (LEP / CDF Run I)
  - RPV stop: m>122 GeV (CDF Run I)

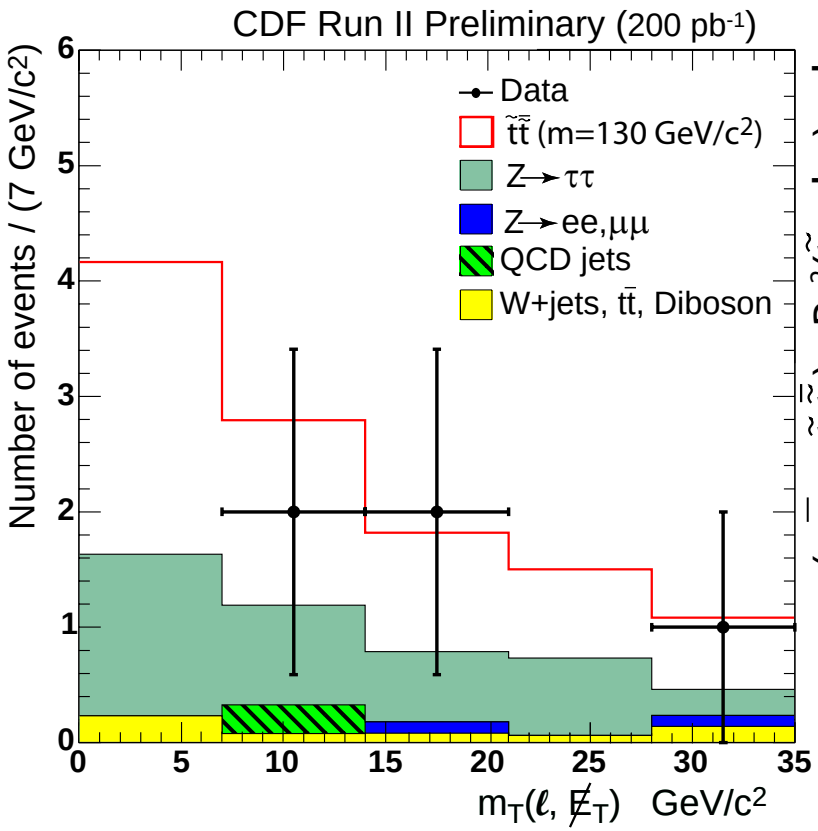
Stop Search: Control Regions

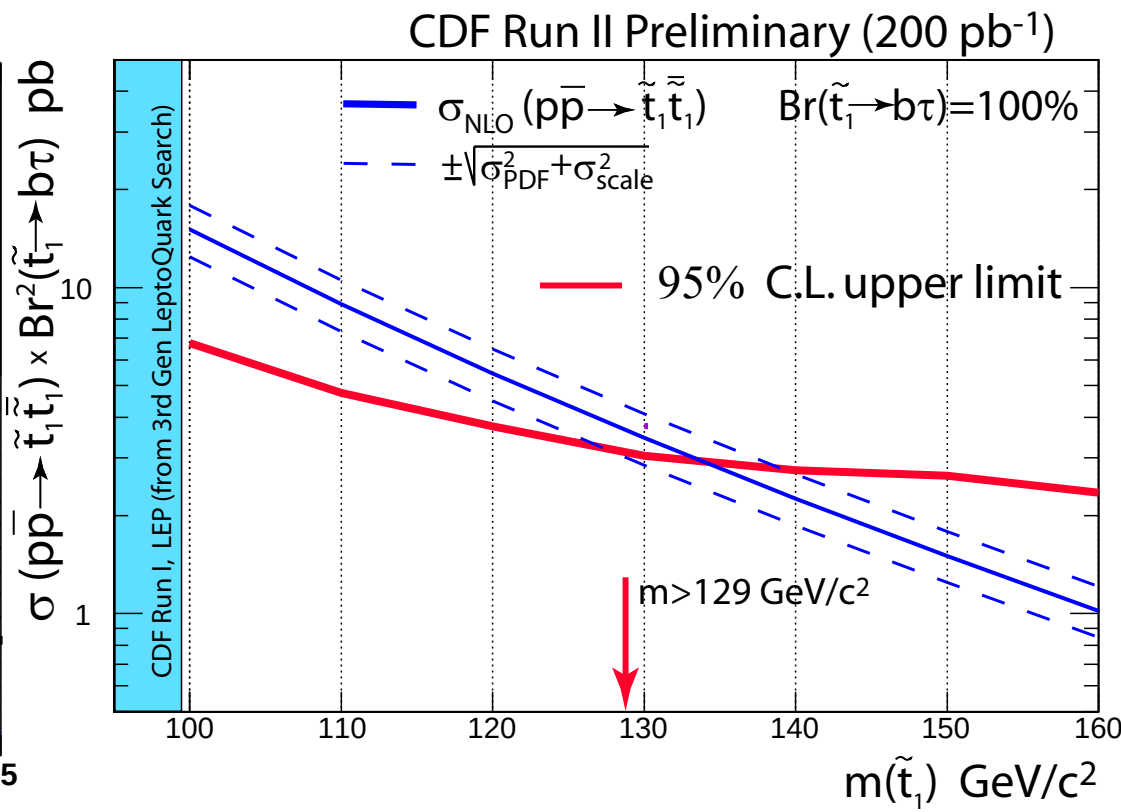
- **With all machinery in place, check control regions:**
  - **Tau ID: $Z \rightarrow \tau\tau$**
  - $\left|\vec{p}_T^{\,l} + \vec{\not{E}}_T\right| > 25\ GeV$
  - **Agreement in Njet=0,1 bins**
  - **$N_{jet} \geq 2$ was looked at later**





Stop Search: In-the-Box





- Observed 5 events vs 4.8 expected
- World best limit on stop mass: m>129 GeV
  - Bi-product: best limit on 3rd Gen. scalar LQ

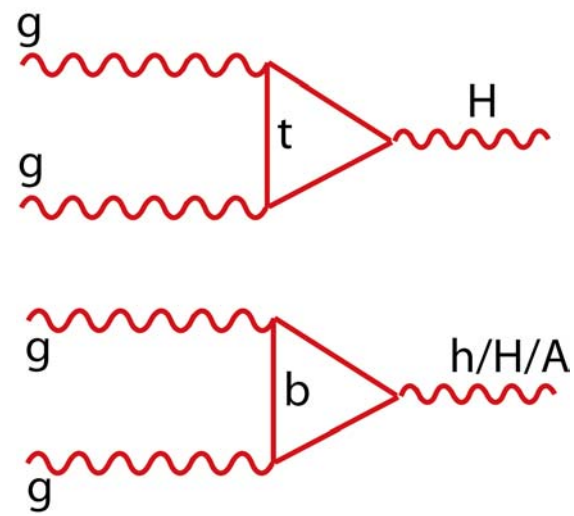
MSSM $H \to \tau\tau$

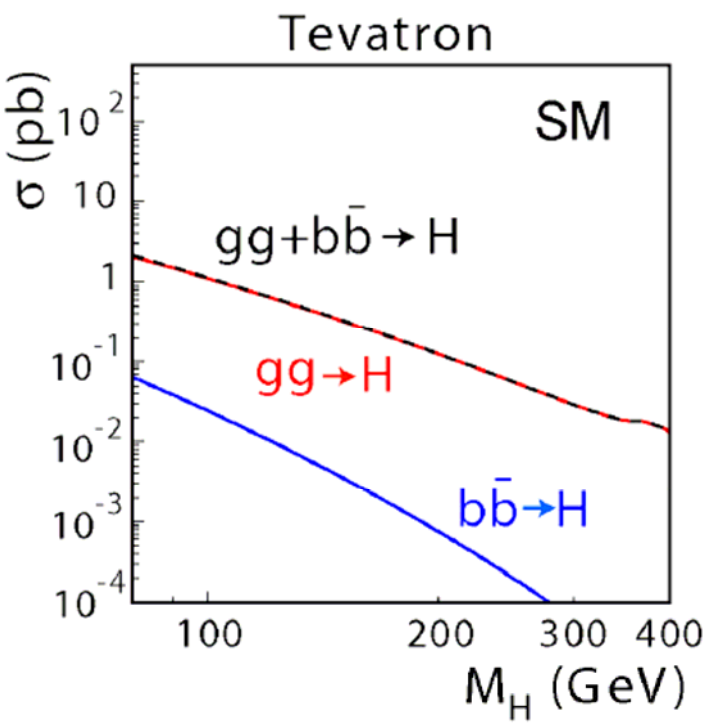
- Higgs production enhanced at large $\tan\beta$

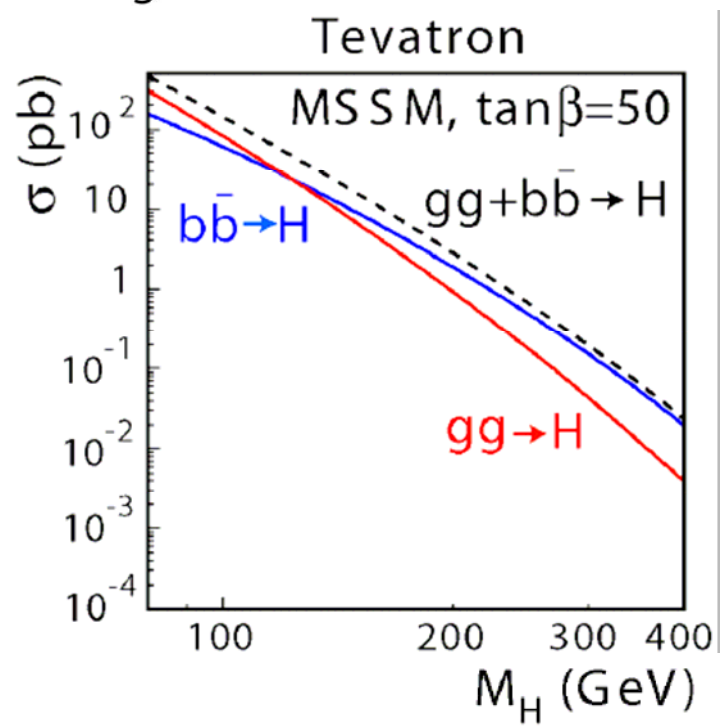
$\sigma(pp \to H/A/h) \propto \tan^2\beta$

- Promising channel at Tevatron

A. Belyaev et al., JHEP 0307:021, 2003

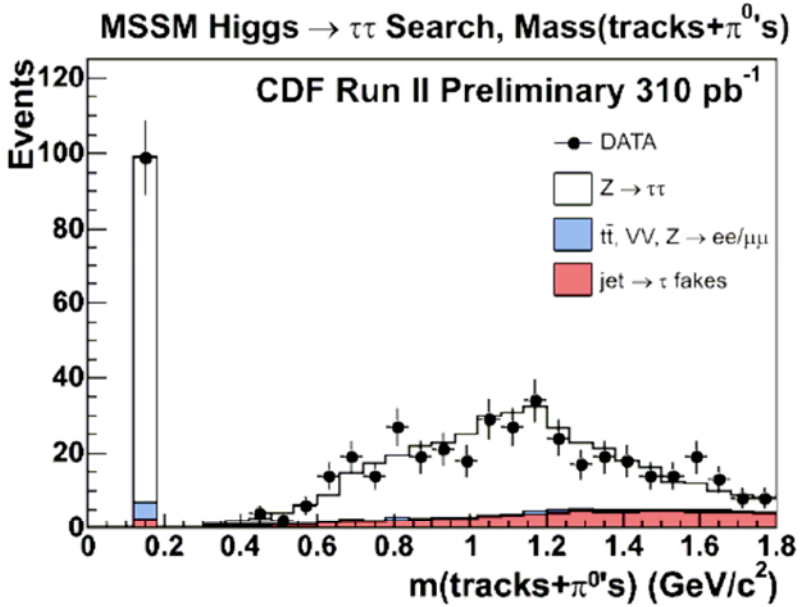


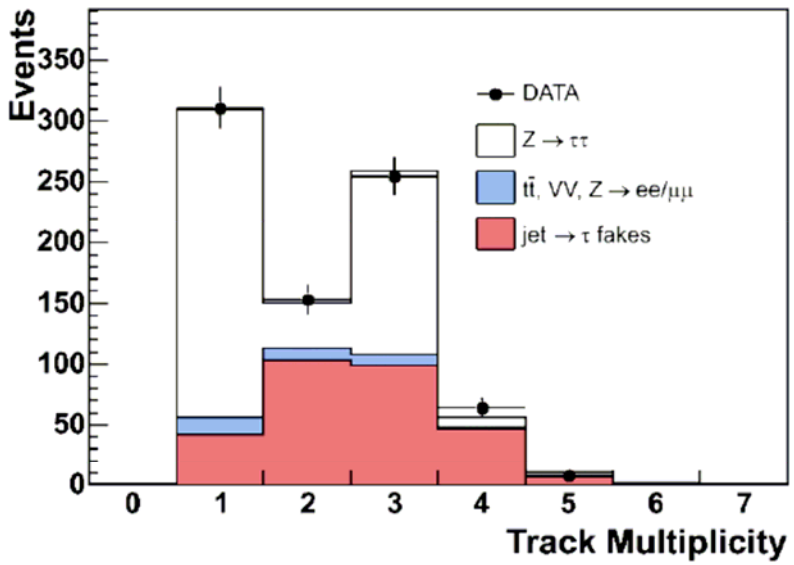




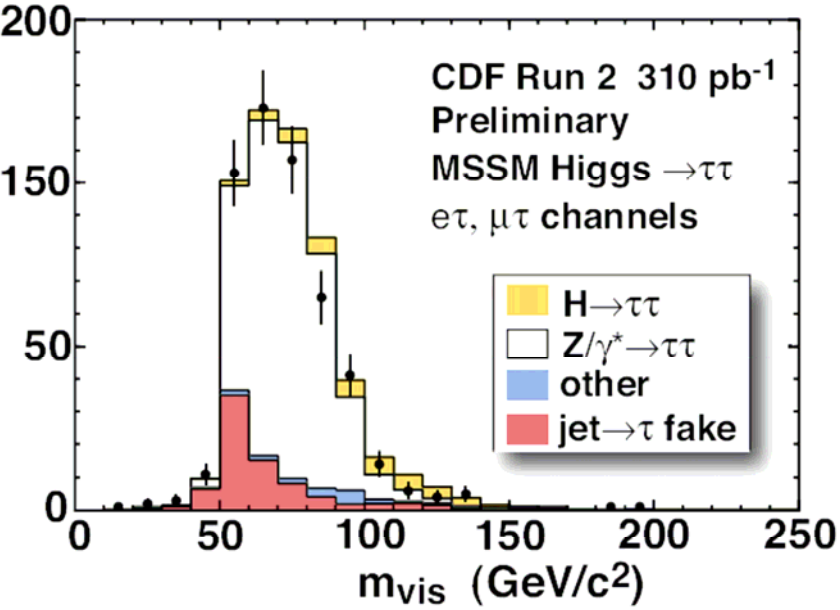
MSSM $H \rightarrow \tau\tau$

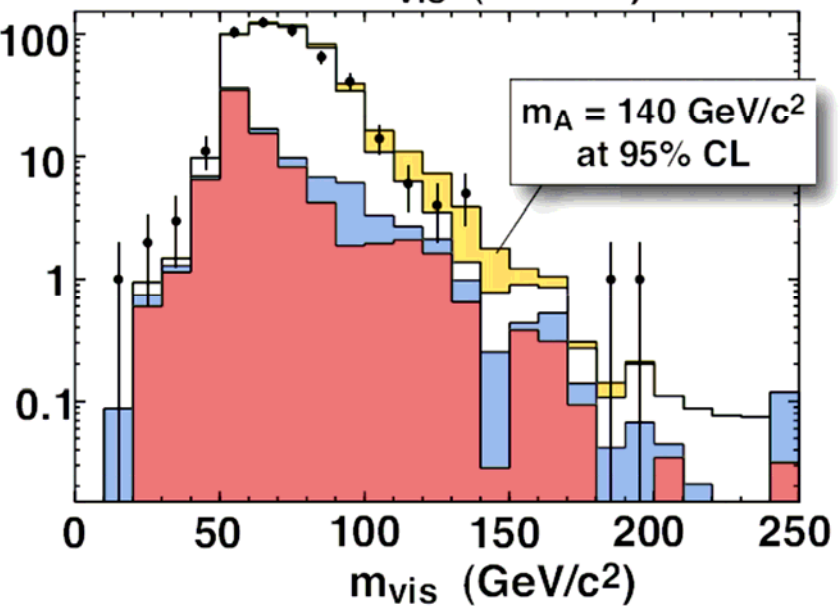
- **Selections:**
  - Lepton (e/μ) p_T>10 GeV
  - Had. Tau p_T>15 GeV
  - H_T>50 GeV
  - Anti-W cut
- **Backgrounds:**
  - $Z \rightarrow \tau\tau$ (understood)
  - W+jets, QCD: fake rate technique
    - Verify on a variety of control samples



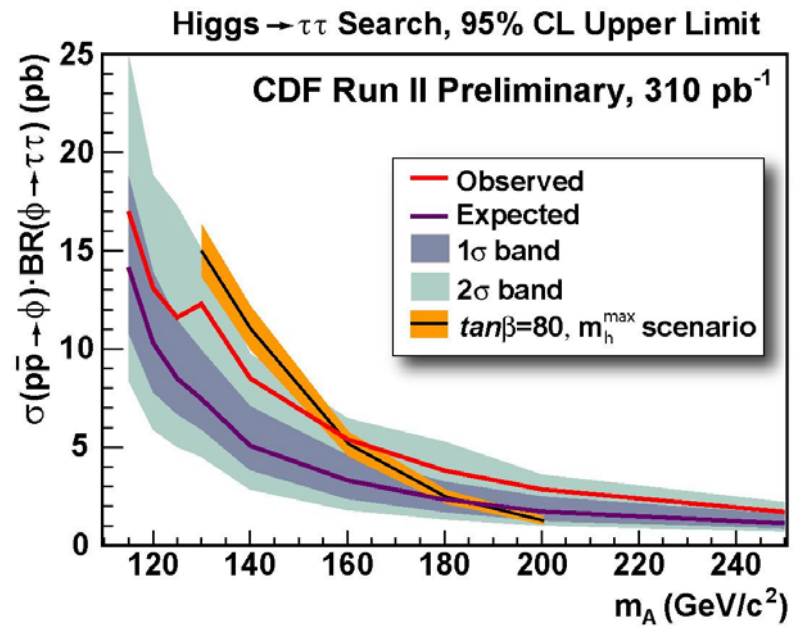


MSSM H→ττ



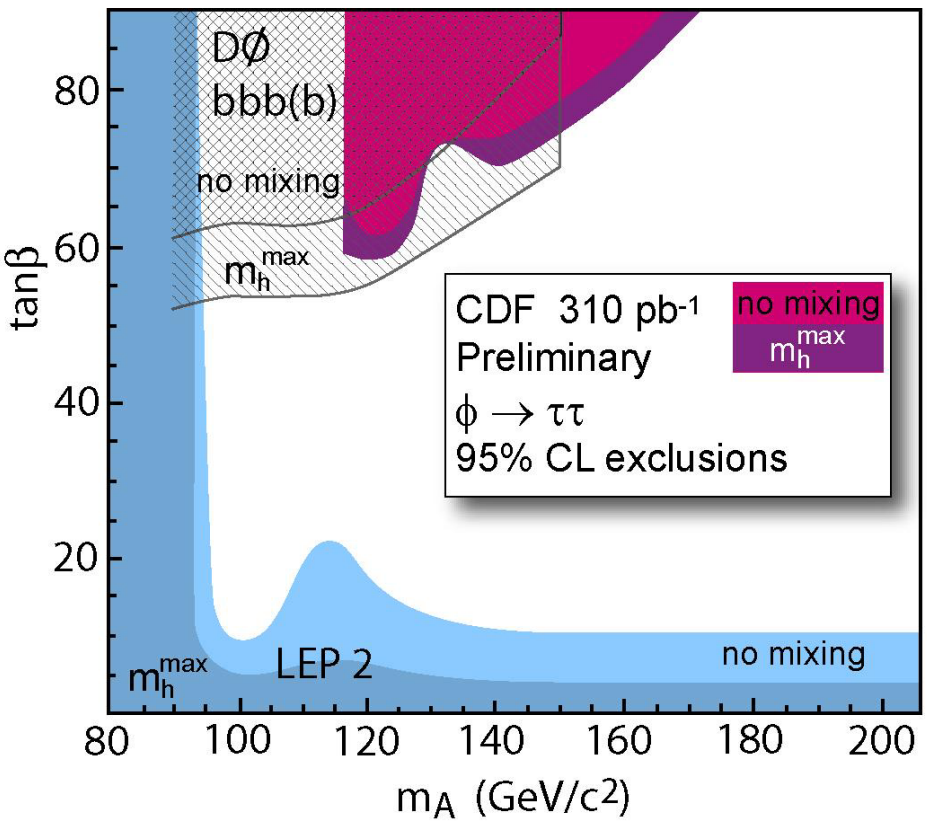


- Good agreement between data and SM expectation in low mass region
- High mass events (m>120):
  - Exp. SM = 8.4 ev, Obs. = 11
- Limit:
  - Fit mass spectrum for (Bkg+Z+h)



MSSM $H \rightarrow \tau\tau$

- Interpret cross-section limit in terms of tanβ and mA:
  - Competitive with "golden" SUSY Higgs bbb(b) mode
- Several improvements in the pipeline for the next round:
  - Will lead to better sensitivity



M. Carena et al., hep-ph/0202167:
m_h^{max}: μ=+200, $A_0=\sqrt{6}M_{SUSY}$ (we use M_{SUSY}=1 TeV)
Min mix: μ=+200, A_0=0

MSSM H→ττ

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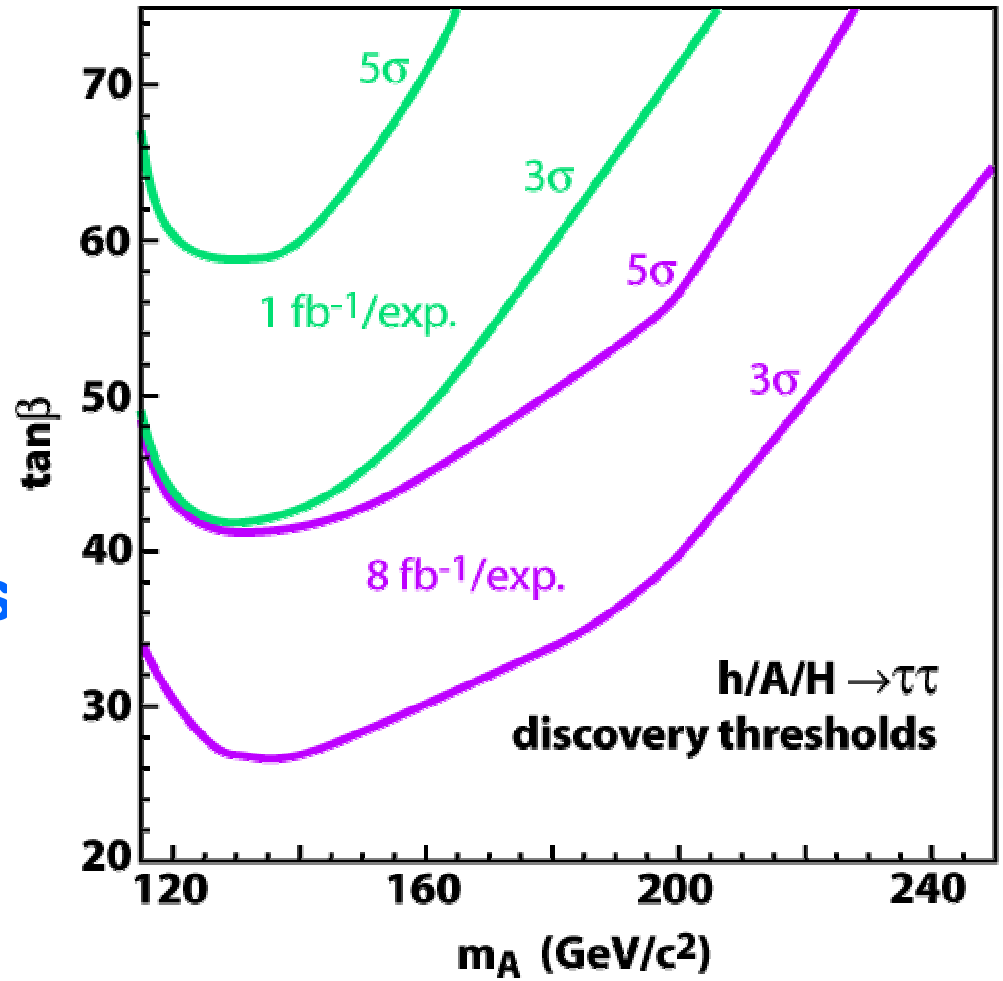

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Summary and Outlook

- No SUSY yet, but we just passed our first femtobarn
- Many results:
  - Several new world best limits
  - More in the pipeline
- Going after SUSY with a wide net:
  - Particles: Squarks, gluinos, gauginos, Higgs
  - Scenarios: mSUGRA, GMSB, RPV
- 7.5 more to come!