Searches for New Phenomena and the Standard Model Higgs Boson at CDF

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Outline

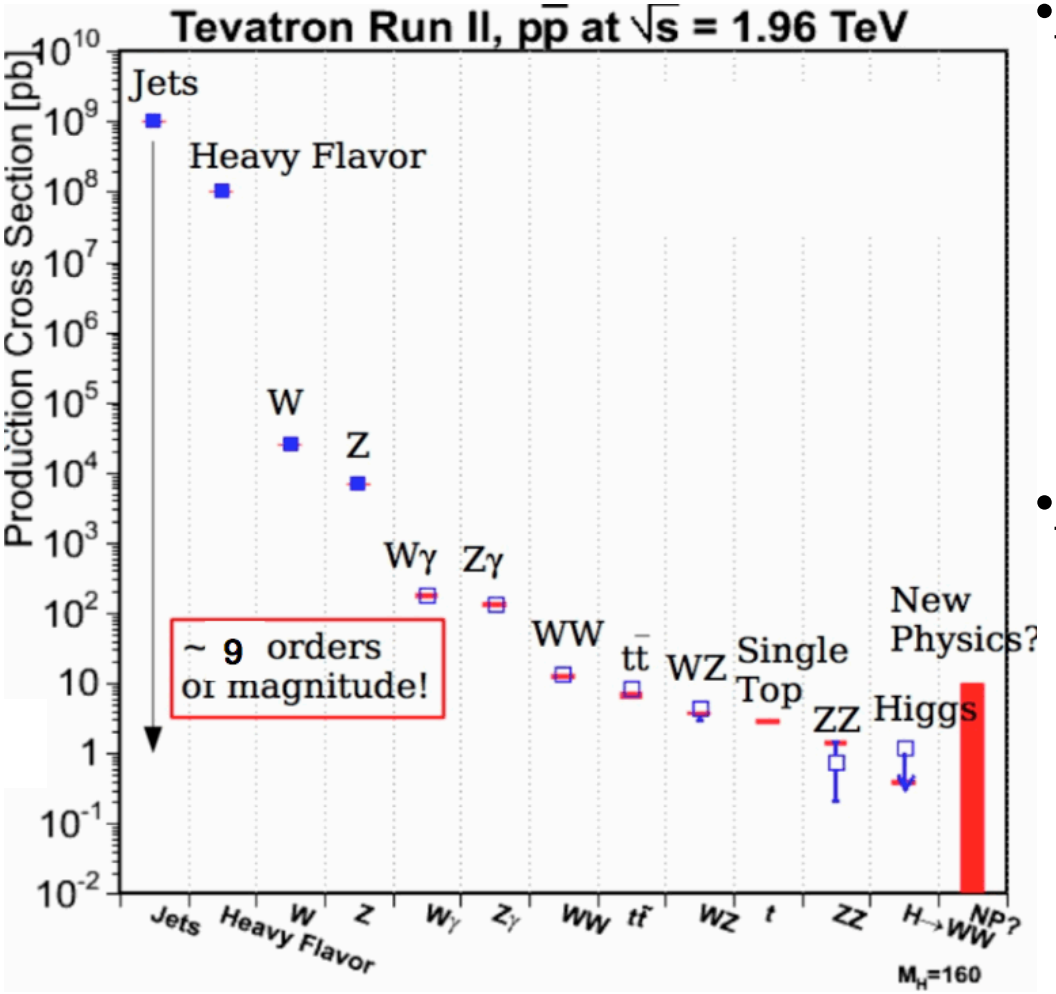
- Introduction
- Results from searches :
  - Supersymmetry
  - Non-Supersymmetry
    - New Heavy Resonances
    - New Fermions
  - Higgs Boson
- Summary

Standard Model is GREAT but ***NOT ENOUGH !***

- SM withstood rigorous experimental tests over past ~30 years
- All predicted particles are discovered except the Higgs boson
- Yet many questions SM does not answer:
  - Large separation between Electroweak and Planck scale
  - No accounting of Gravity
  - Large asymmetry between particles and anti-particles
  - What is the source of dark matter
- Extension or modification of SM is inevitable
- Strong interest in HEP community to search for the last SM predicted particle and signs of physics beyond the SM.

Search Strategies

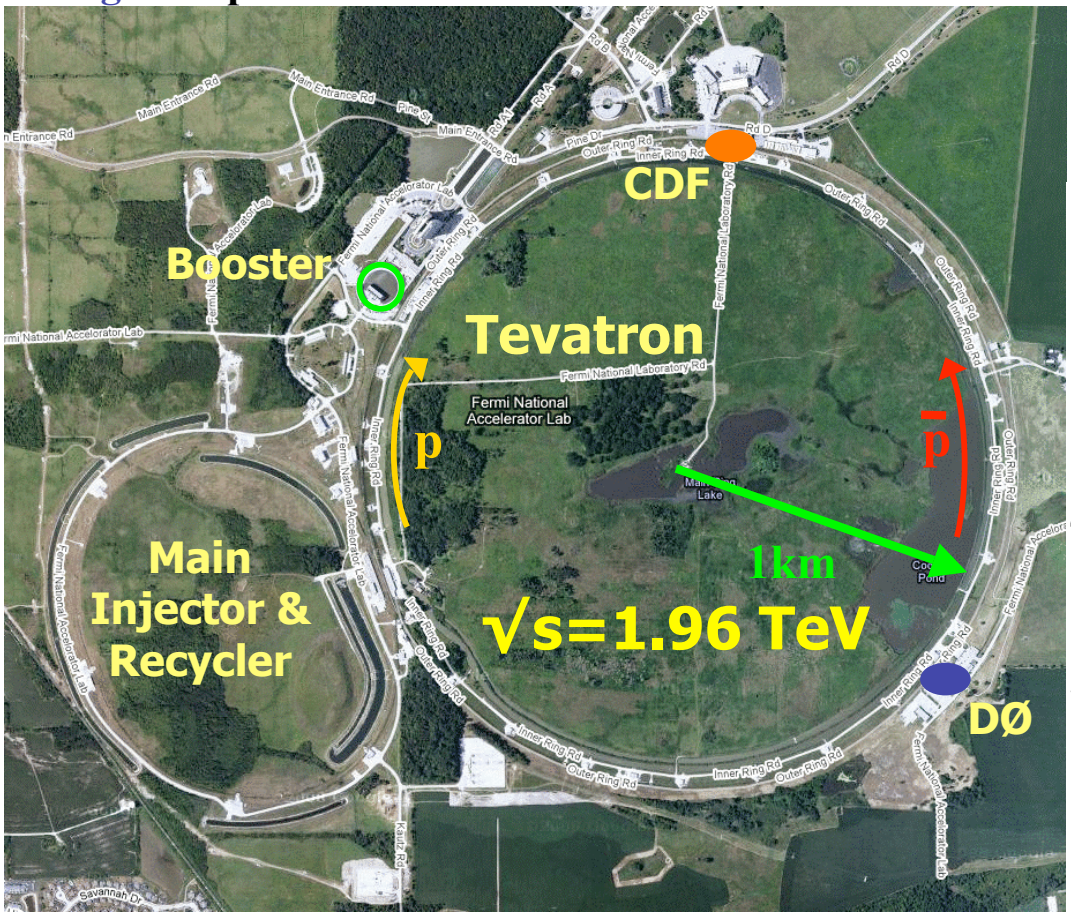
- SM Higgs boson or possible new physics are expected to be produced at very small rate compare to most SM processes
- Need to device strategies to conduct searches :

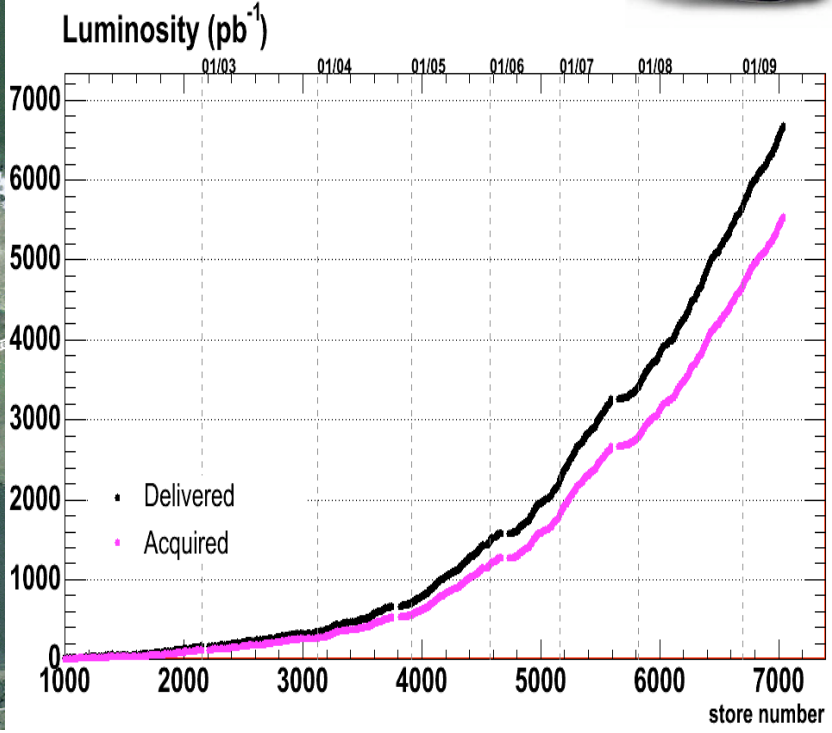


- **<u>Test a particular Model</u>**
  - Optimize analysis to look out for events w/ particular unique signature predicted by the model
  - Either discover or exclude the model or part of a parameter space of the model
- **<u>General Signature search</u>**
  - Not optimized to a particular model, thus not as sensitive as model based search
  - May discover new physics not predicted by any model
  - Be prepared for the **<u>Un-Expected</u>**

Tevatron : *Still Running and Running and…*

Google Maps

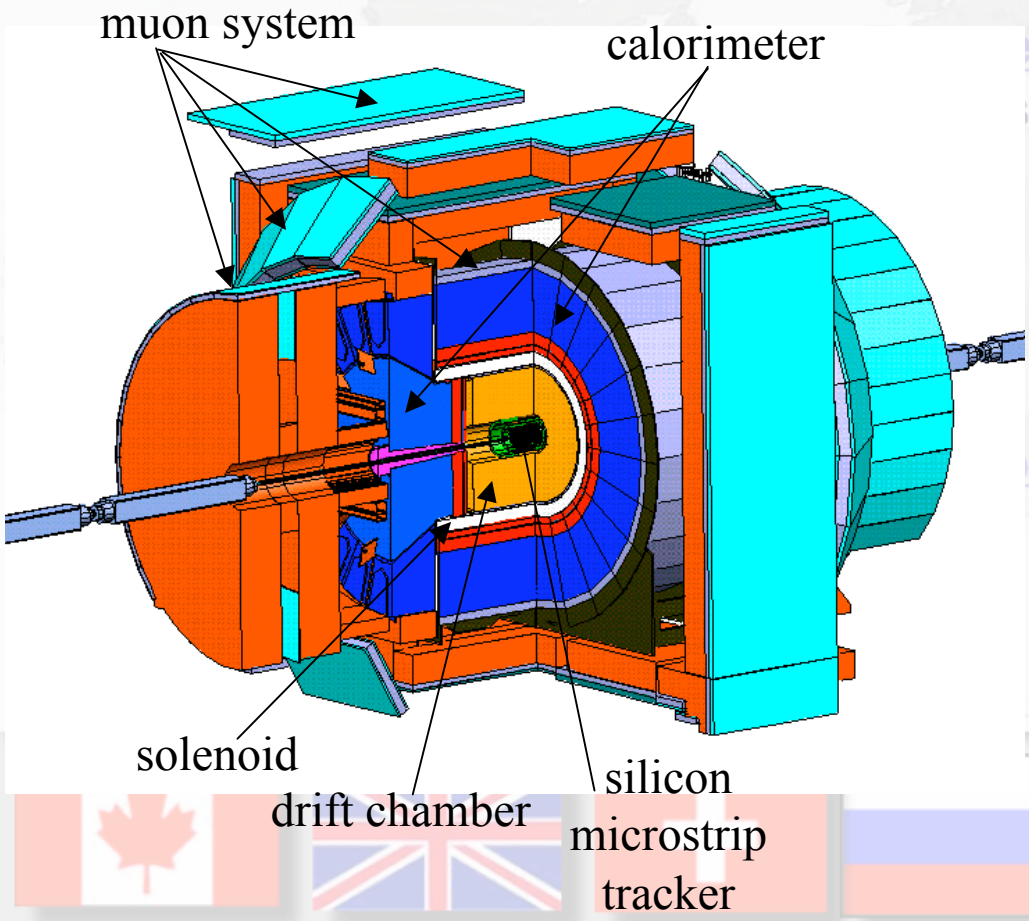




- Delivered ~6.5 fb^{-1} per experiment (~1.8 fb^{-1} in 2008)
  - CDF/D0 : ~5.5 fb^{-1}
- Current rate : 50-60 pb^{-1} per week
- Peak lumi : ~300-350e30 cm^2s^{-1}

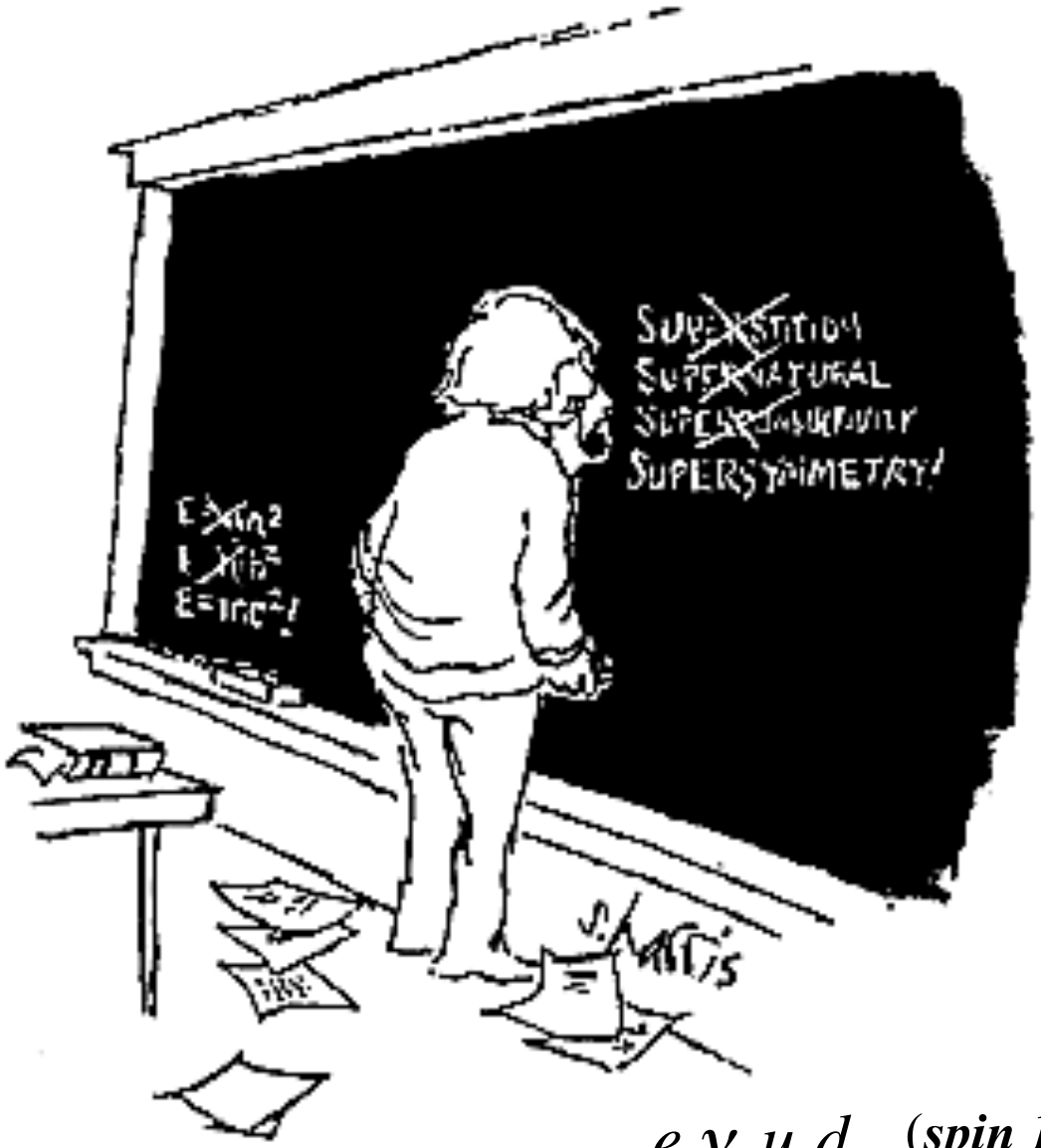
- Present results using data samples with $\int L$= ~2 - 3.6 fb^{-1}

CDF Experiment



- CDF collaboration :
  - ~600 scientists from 14 countries
- CDF detector :
  - A general multi-purpose detector
  - Consists of silicon tracker, central tracker, solenoid, calorimeter, muon chambers
  - Operating well, collecting data at ~80-90% efficiency

Search for Supersymmetry (SUSY)



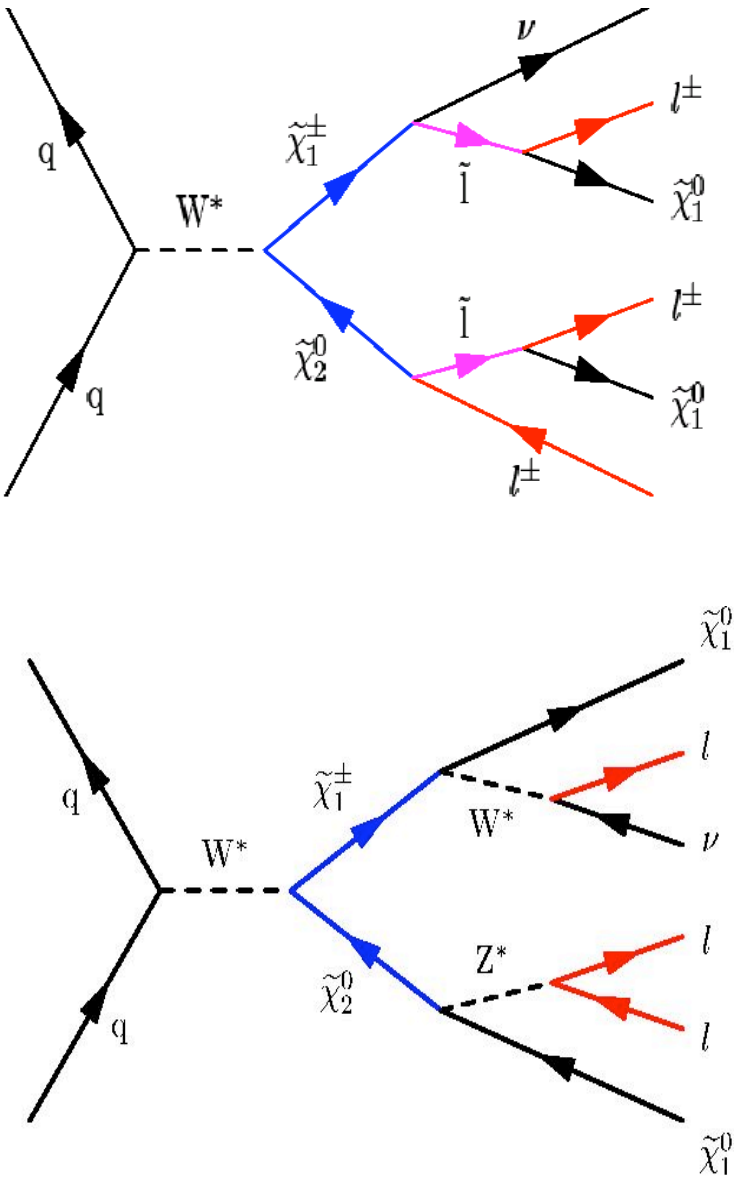
- An extensions to the SM
- Postulate symmetry between boson and fermions
- Every SM particle has a SUSY partner with same quantum numbers except spin (differ by 1/2)

$$e,\nu,u,d,..(\textit{spin 1/2}) \Rightarrow \tilde{e},\tilde{\nu},\tilde{u},\tilde{d},... \quad (\textit{spin 0})$$

$$\gamma,W^{\pm},Z^{0},g,...(\textit{spin 1}) \Rightarrow \tilde{\chi}^{0}_{1,2,3,4}, \tilde{\chi}^{\pm}_{1,2}, \tilde{g} \quad (\textit{spin 1/2})$$

Search for Chargino & Neutralino Production (I)

- $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$ are some of the lightest SUSY particles ⇒ may have relatively large production rate
- Pair production may lead to multiple leptons and large missing transverse energy (MET) in final state (R-parity conservation)
- Search for $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ production in final state with 3 charged leptons and large MET
  - Require 2 isolated leptons (e or μ)
  - Additional isolated e/μ or track
    - Allow acceptance for τ in leptonic decay or single prong hadronic decay



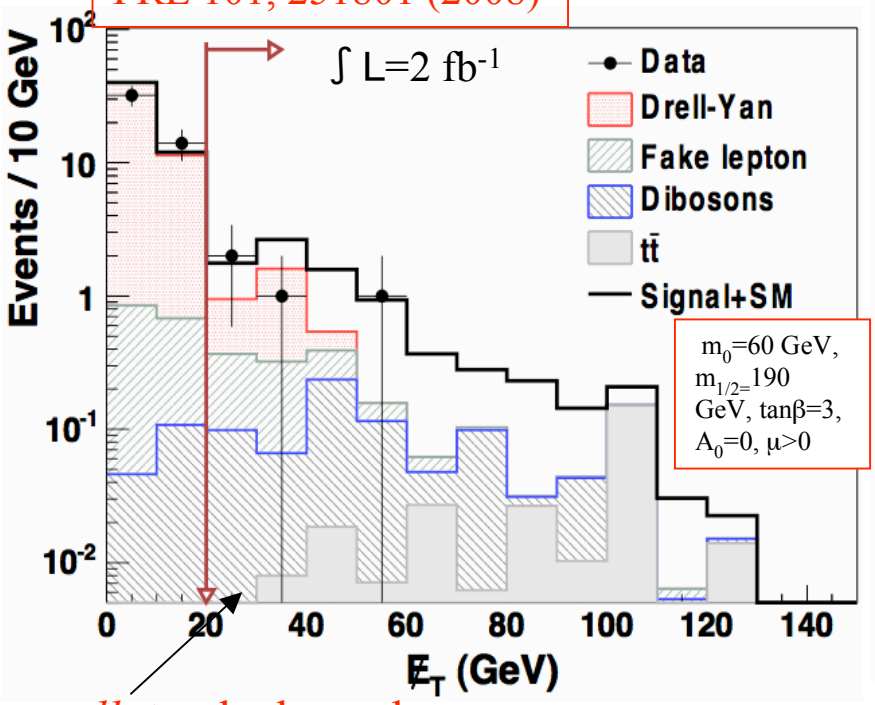
$\tilde{\chi}_1^0$: LSP

Main Background :

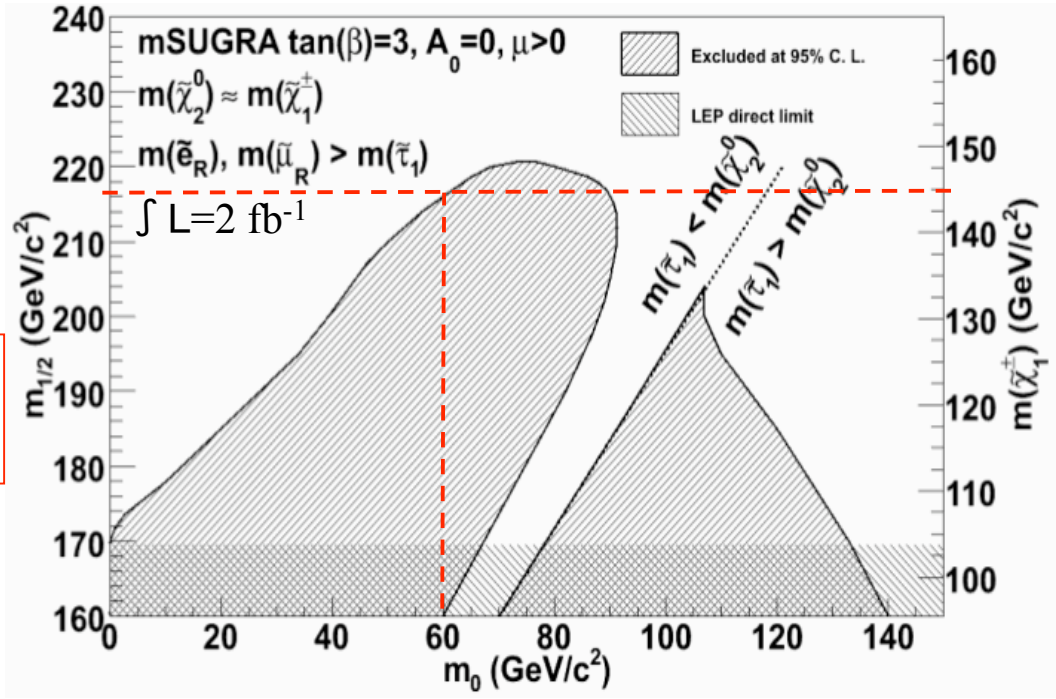
- DY, Di-bosons, jets faking leptons, conversions

Search for Chargino & Neutralino Production (I)

PRL 101, 251801 (2008)



ll+track channel



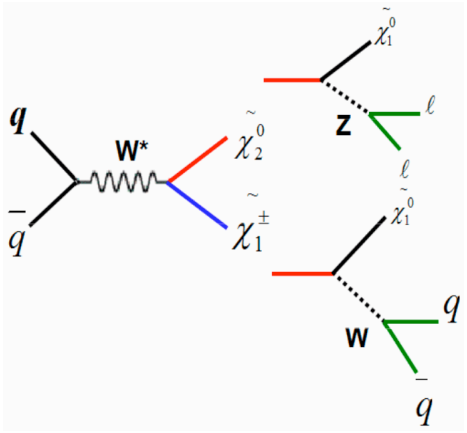
- Data consistent with predicted background
  - Ndata=7
  - Nexpect=6.4

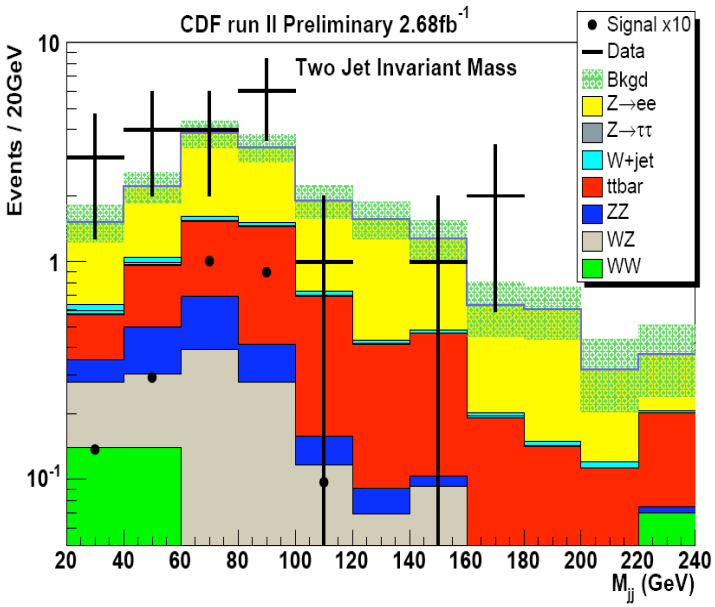
- Set limits in $m_{1/2}$ vs m_0 mSUGRA plane
- Limits depend on relative neutralino-slepton masses
  - $m(\tilde{\chi}_2^0)$>m(slepton) : increases branching ratio to e/μ
  - $m(\tilde{\chi}_2^0)$≈m(slepton) : reduce acceptance to low Pt leptons

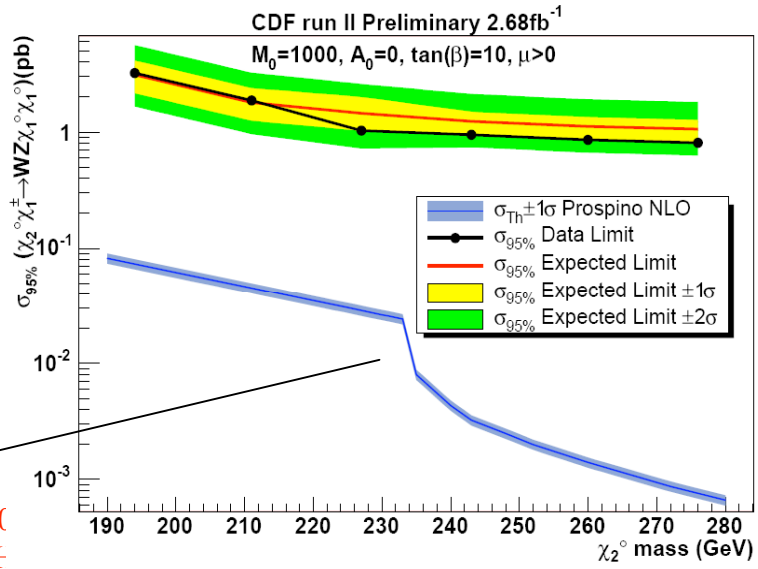
- Exclude chargino mass below 145 GeV for m_0=60 GeV

Search for Chargino & Neutralino Production (II)

- Search in parameter space where:
  - $m(\tilde{\chi}_2^0) > m(Z^0) + m(\tilde{\chi}_1^0)$
  - $m(\tilde{\chi}_1^\pm) > m(W^\pm) + m(\tilde{\chi}_1^0)$
- Assume $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ decay to on shell Z,W
- Consider decay channels:
  - $Z \rightarrow e^+e^-$, $W \rightarrow qq'$
- Final state signature:
  - e^+e^-(from Z) + 2jets + MET
- Set upper limit on $\sigma(\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow WZ\tilde{\chi}_1^0 \tilde{\chi}_1^0)$ at ~1pb



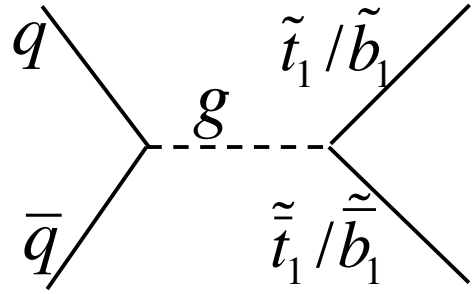




Increase in $B(\tilde{\chi}_2^0 \rightarrow h^0 \tilde{\chi}_1^0)$

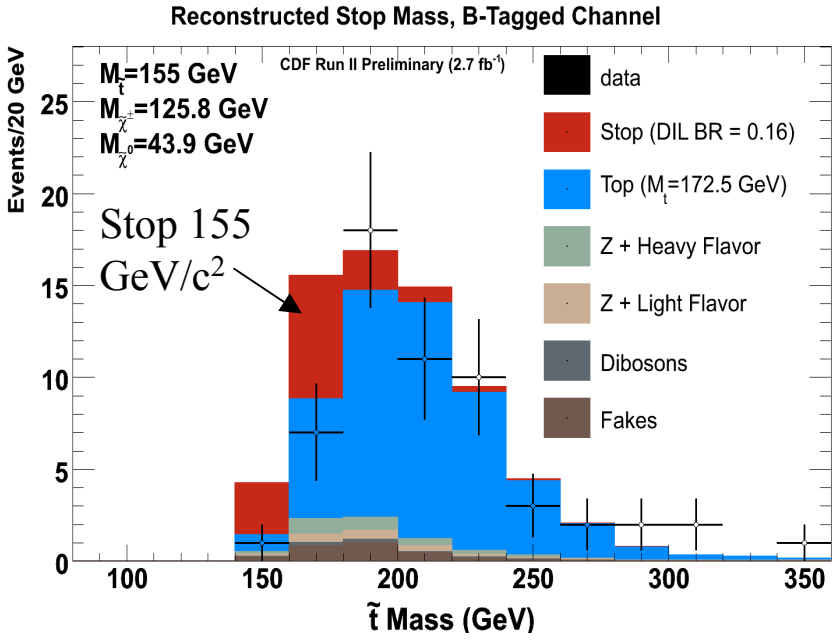
Search for Third Generation Squarks

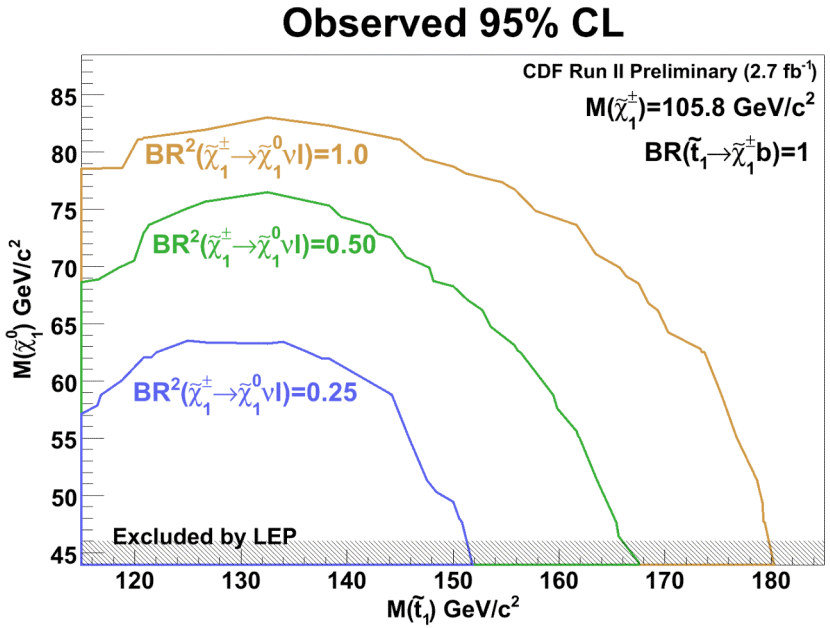
- Large mixing between the L- and R-handed weak eigenstates
  - Stop : due to large top quark mass
  - Sbottom : large mixing occurs at high tanβ
- ⇒ one of the stop and sbottom quarks can be light
- Stop & sbottom can be pair produced at Tevatron
- Or produce from gluino decay:
  - $\tilde{g} \to t\tilde{t}$
    - Rate may be very small at Tevatron, but possible at LHC
  - $\tilde{g} \to b\tilde{b}$



Search for Stop in Top-Like Signal

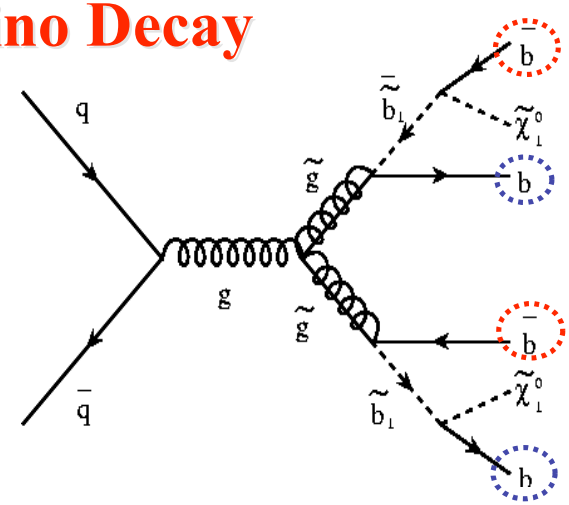
- Search for stop pair produced
- Assume m(stop)<m(t) & **m(stop)>m($\tilde{\chi}_1^{\pm}$)+m(b)**
- Consider decay channel:
  - stop→b $\tilde{\chi}_1^{\pm}$→bl$\nu\tilde{\chi}_1^{0}$
- Final state signature similar to tt-bar production in the di-lepton decay channel : *llbb*+MET
  - Main background is tt-bar production
- Perform search separately with b-tagged & un-tagged events
- Reconstruct stop mass and use to discriminate against background



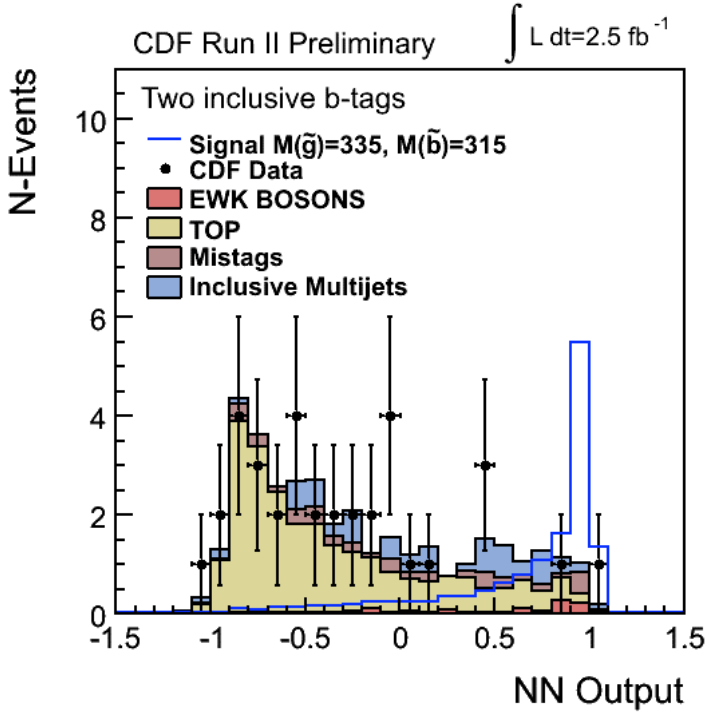


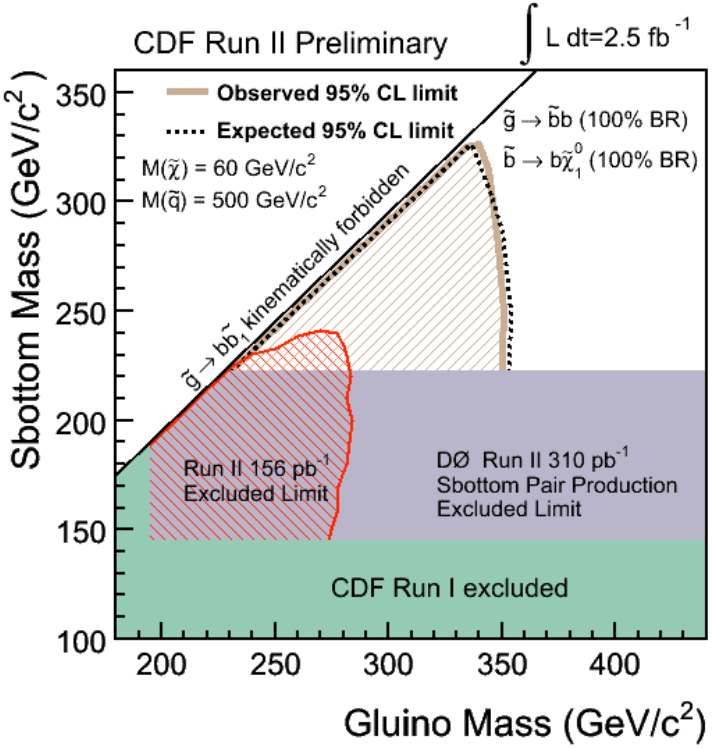
Search for Sbottom from Gluino Decay

- At Tevatron gluino pair production can be large
- $\tilde{g} \to \bar{b}\tilde{b}$ if $m(\tilde{g}) > m(\tilde{b}) + m(b)$
- Assume :
  - $B(\tilde{g} \to \bar{b}\tilde{b}) = 100\%$
  - $B(\tilde{b} \to b\tilde{\chi}_1^0) = 100\%$ ($\tilde{\chi}_1^0$: LSP)
- Select events with large MET and ≥2 b-tagged jets
- 2 Neural-Nets (NN) trained to separate heavy-flavor multi-jet and tt-bar from signal



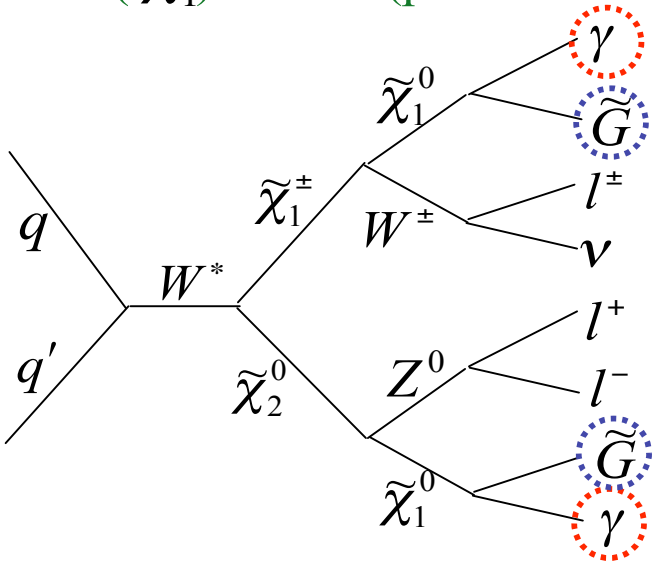
- Separate NN trainings for small/large $\Delta m(\tilde{g},\tilde{b})$



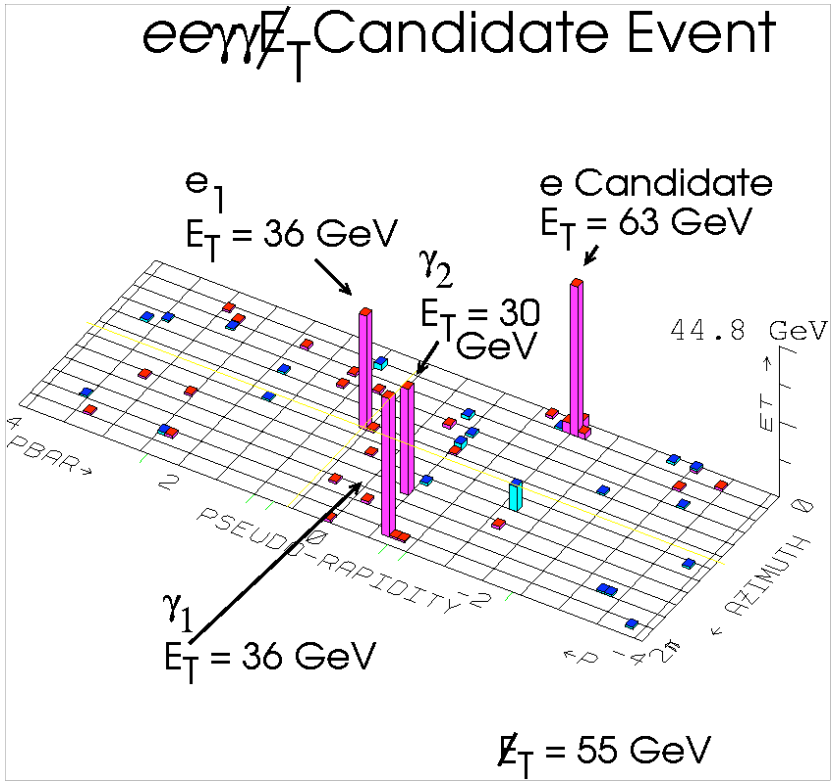


Search for GMSB in Di-Photon+MET

- In Run 1 CDF observed an event with $ee\gamma\gamma$+MET in the final state
- Di-photon+MET signature is rare in SM processes
- Possible SUSY scenario :
  - GMSB (Gauge Mediated Symmetry Breaking)
  - $\tilde{G}$ is LSP, $\tilde{\chi}_1^0$ is NLSP, $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$
  - $\tilde{\chi}_1^0$ can be long-lived
- CDF has searched for GMSB in two cases:
  - $\Gamma(\tilde{\chi}_1^0) > 2$ ns (presented in PPP2007)
  - $\Gamma(\tilde{\chi}_1^0) < 2$ ns (present today)

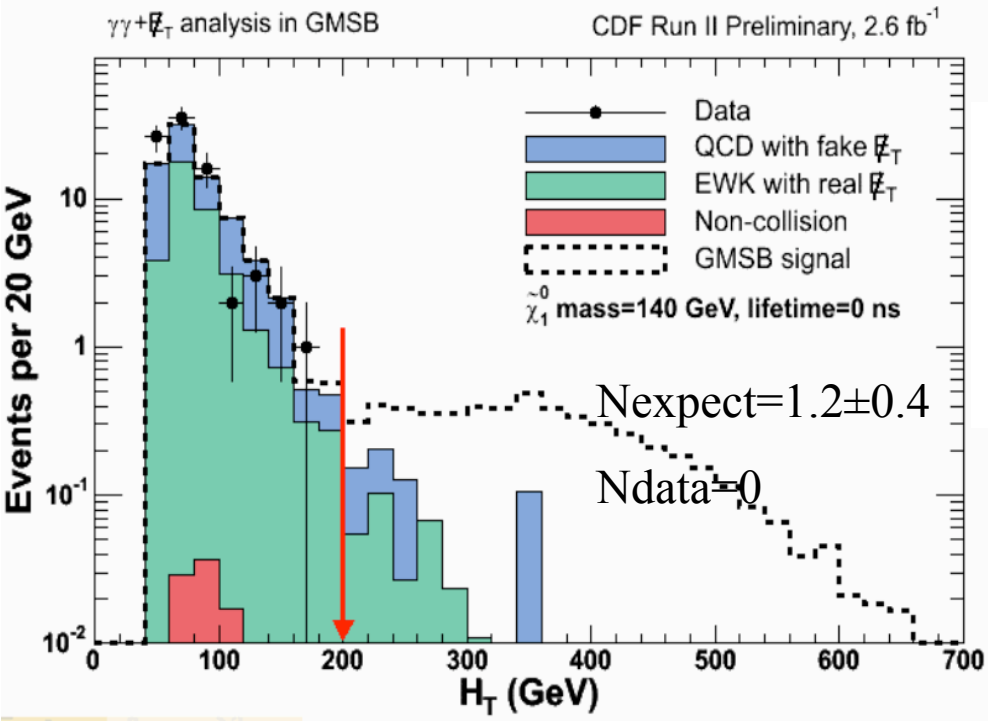


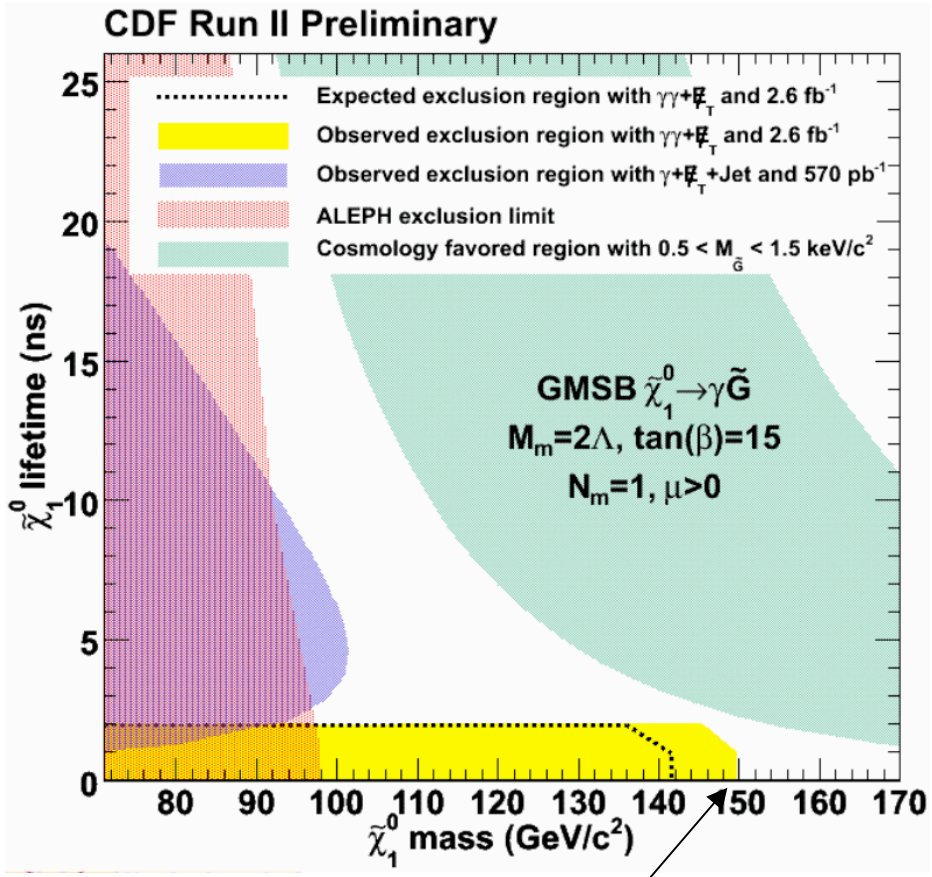
CDF Run1



Search for GMSB in Di-Photon+MET

- Select events with 2 isolated central γ and large MET
- Background:
  - γγ, γ+jet (jet mis-Id as γ)
  - W(→eν)γ (e mis-Id as γ)
  - W(→eν)+jet (e, jet mis-Id as γ)
- Optimize cuts to reduce background
  - High MET significant
  - Large Ht(ΣEt(γ)+MET)
  - γγ : not back-to-back

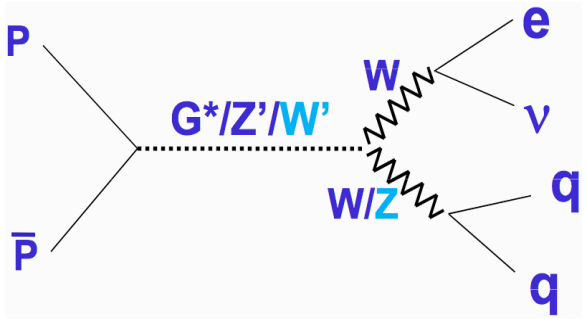


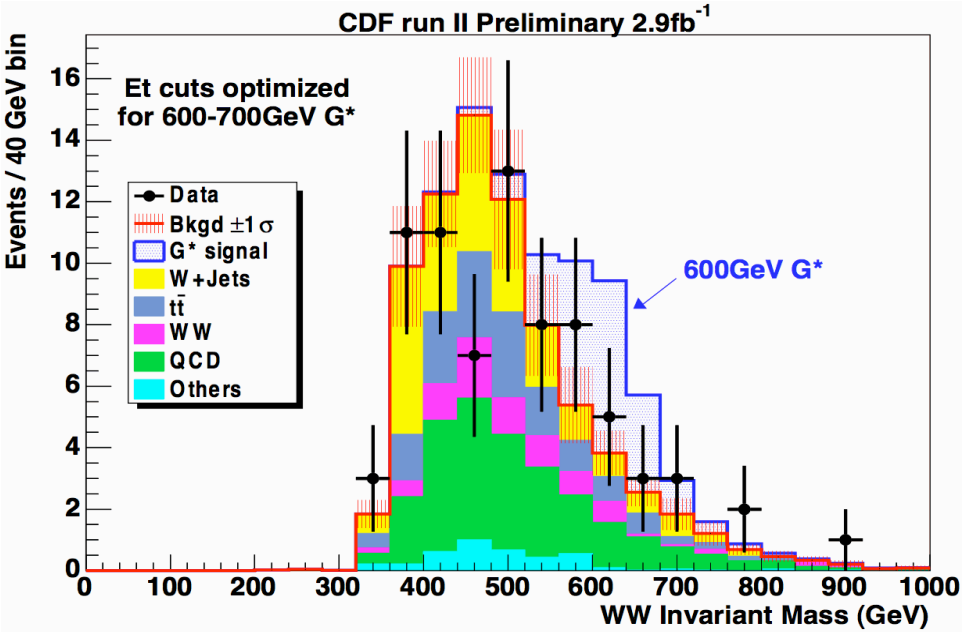


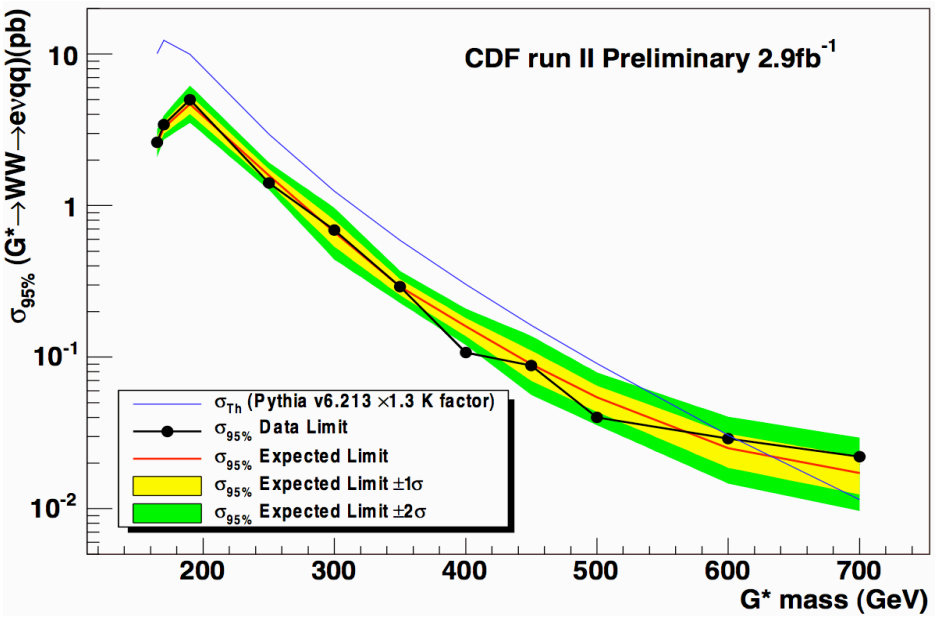
Non-Supersymmetry : New Heavy Resonance

Search for X→WW or WZ

- Look for di-boson resonance in final state : *lqq*+MET
- W/Z hadronic decay has larger branching fraction over leptonic mode, but larger background
  - W+jets, QCD multi-jet, tt-bar, Di-boson
- Selection cuts are separately optimized to search for RS Graviton, Z' and W'







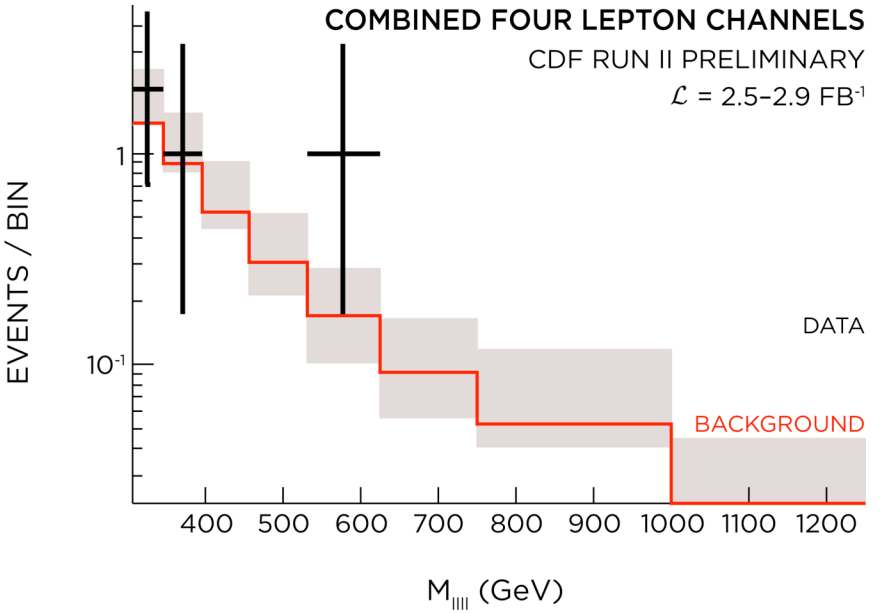
Exclusion:

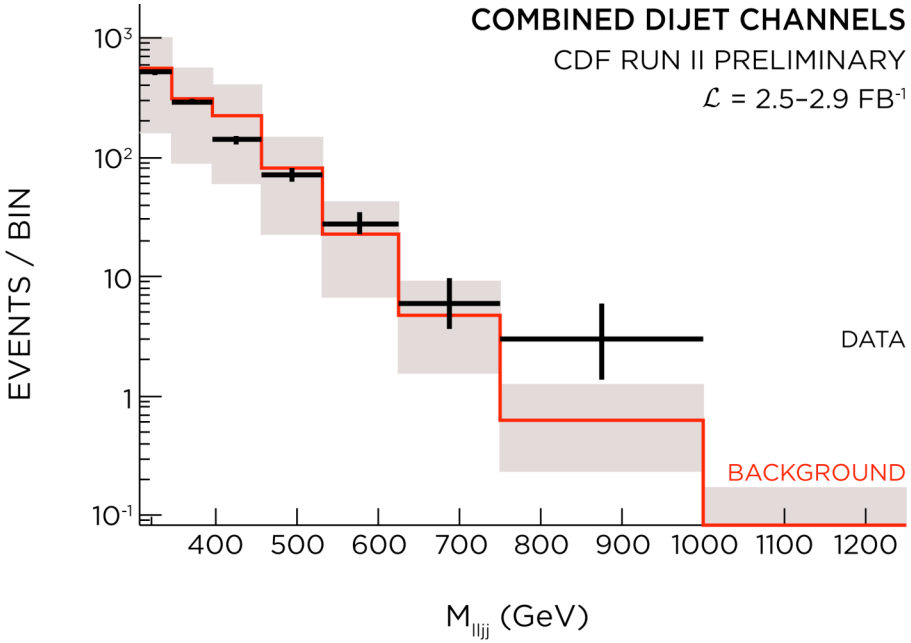
- RS Graviton ($k/M_{Pl}=0.1$) : $m(G^*)<606$ GeV
- Z' : $247<m(Z')<545$ GeV
- W' : $284<m(W')<515$ GeV

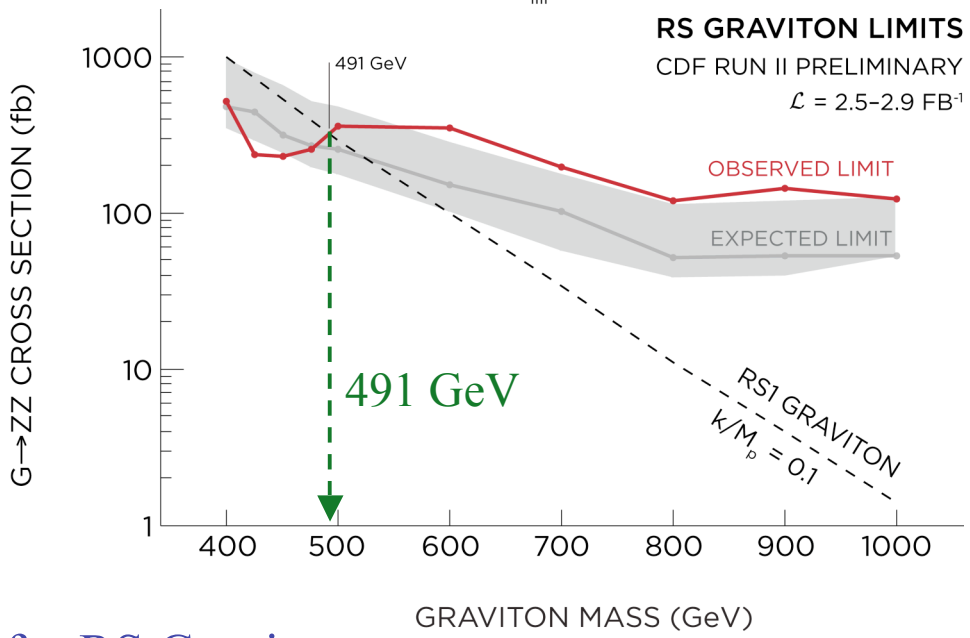
} Assuming SM coupling strength

Search for X→ZZ

- Search for a heavy particle X decaying into two Z bosons
- Perform search in final states : *eeee*, *eeμμ*, *μμμμ*, *ll*+jj (*l*=*e* or *μ*)
- Loosen lepton selection criteria and improve forward tracking to increase signal acceptance
- Search for signal in m(X)>300 GeV







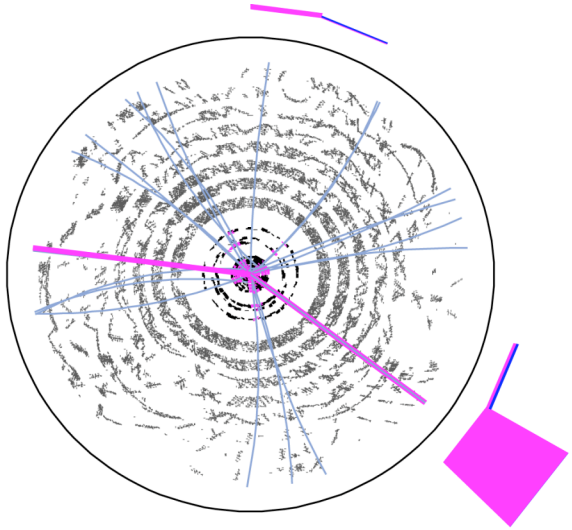
- Interpret results in the search for RS Graviton (k/M_{Pl}=0.1), exclude m(G^*)<491 GeV

Search for X→ZZ

M(ee) = 96.5 +/- 1.3 GeV

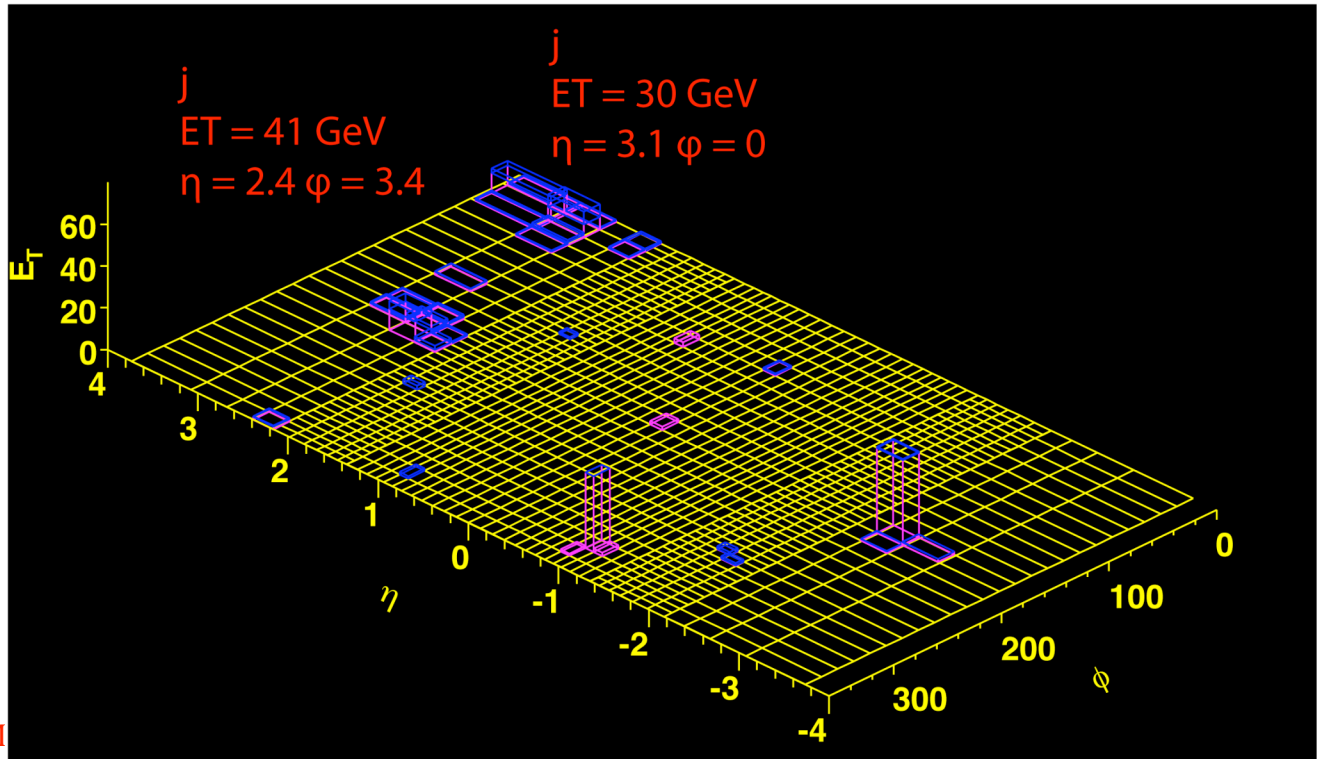
M(jj) = 77.8 +/- 6.5 GeV

e
ET = 26 GeV
η = -2.7 φ = 3.0



e
ET = 35 GeV
η = -1 φ = -0.6

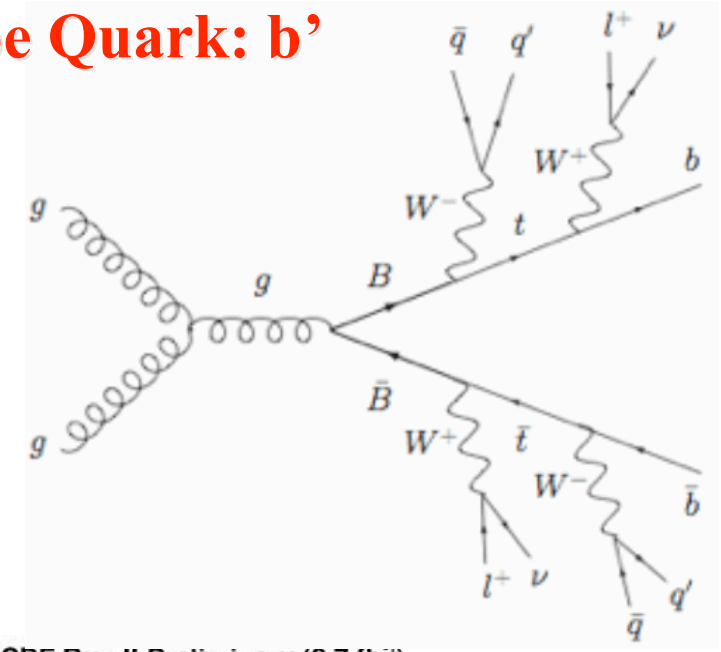
- Highest mass lljj event (868 GeV)



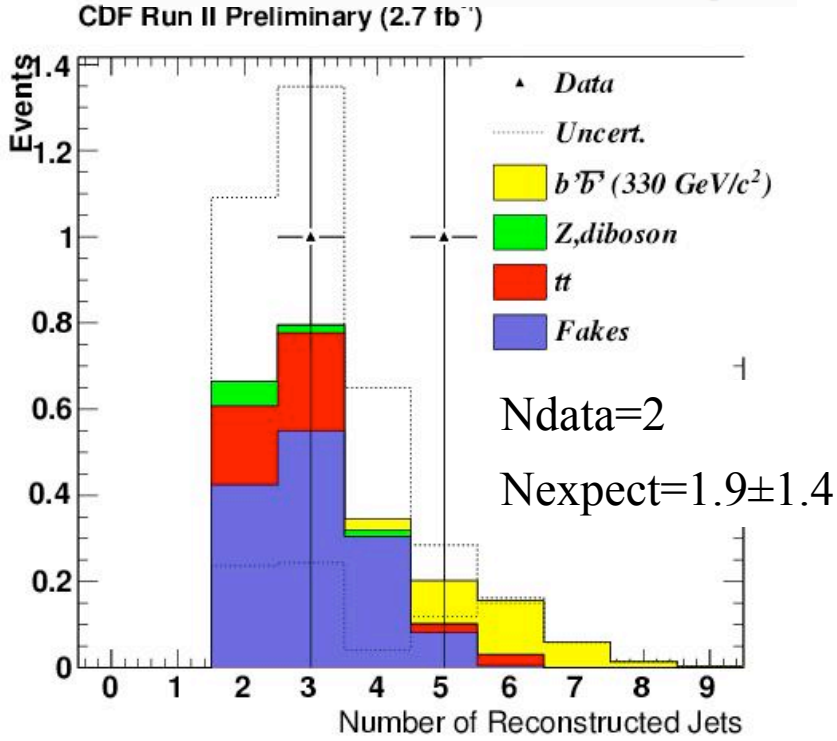
Non-Supersymmetry : New Fermions

4th Generation Down-Type Quark: b'

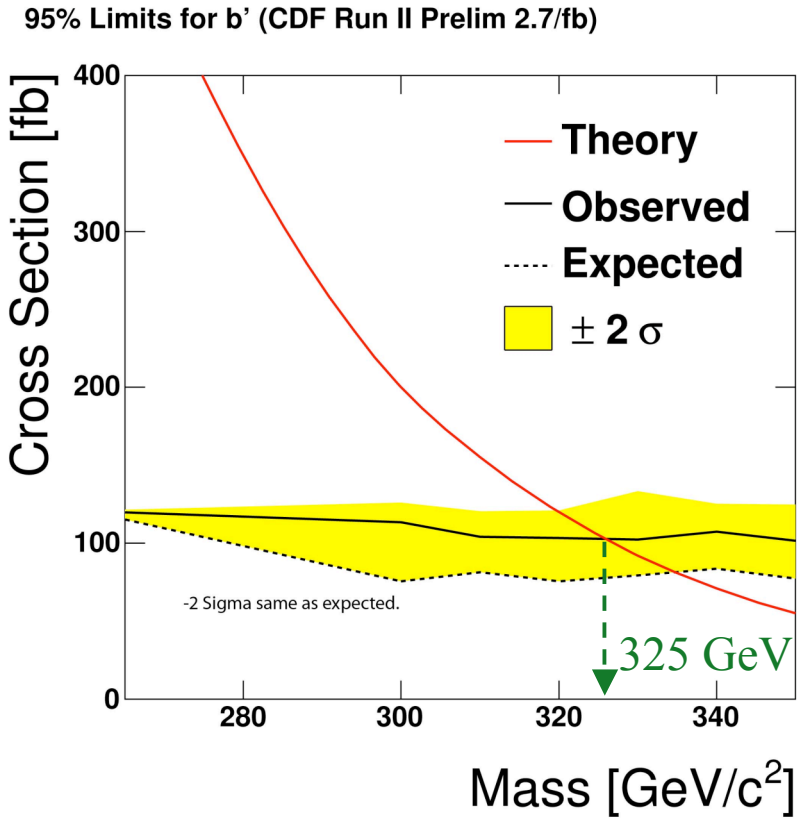
- Search for pair production of generic 4th-gen. down-type quark (b')
- Assume B(b'→Wt)=100%
- With t→Wb, ⇒ leads to WWWWbb final state
- Leptonic W decay can result in a pair of same-sign charge leptons ⇒ provide clean signature for search



- **Event selection:**
  - A pair of same-sign lepton (e,μ)
  - ≥2 jets, ≥1 b-tagged jet
  - Large MET (MET>20 GeV)
- Dominant background:
  - W+jets, tt-bar, DY, Diboson
- Search for signal in jet-multiplicity distribution
  - Expect signal has high jet-multiplicity



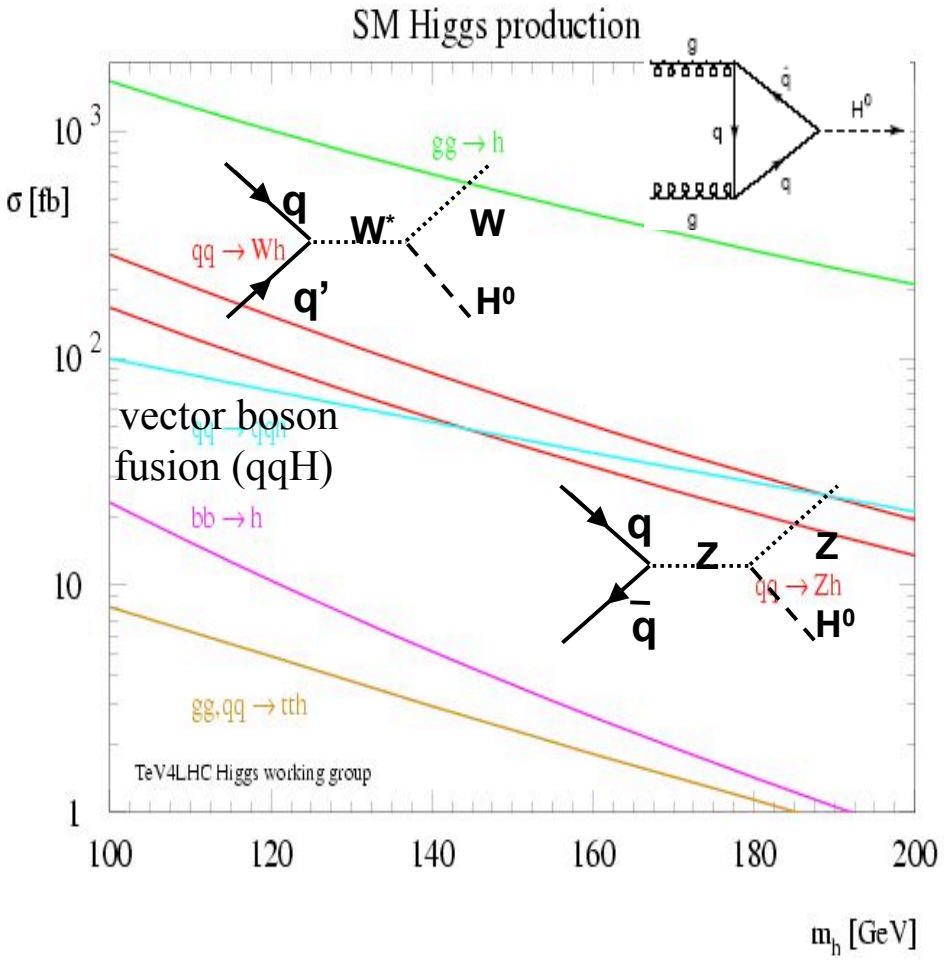
4th Generation Down-Type Quark: b'

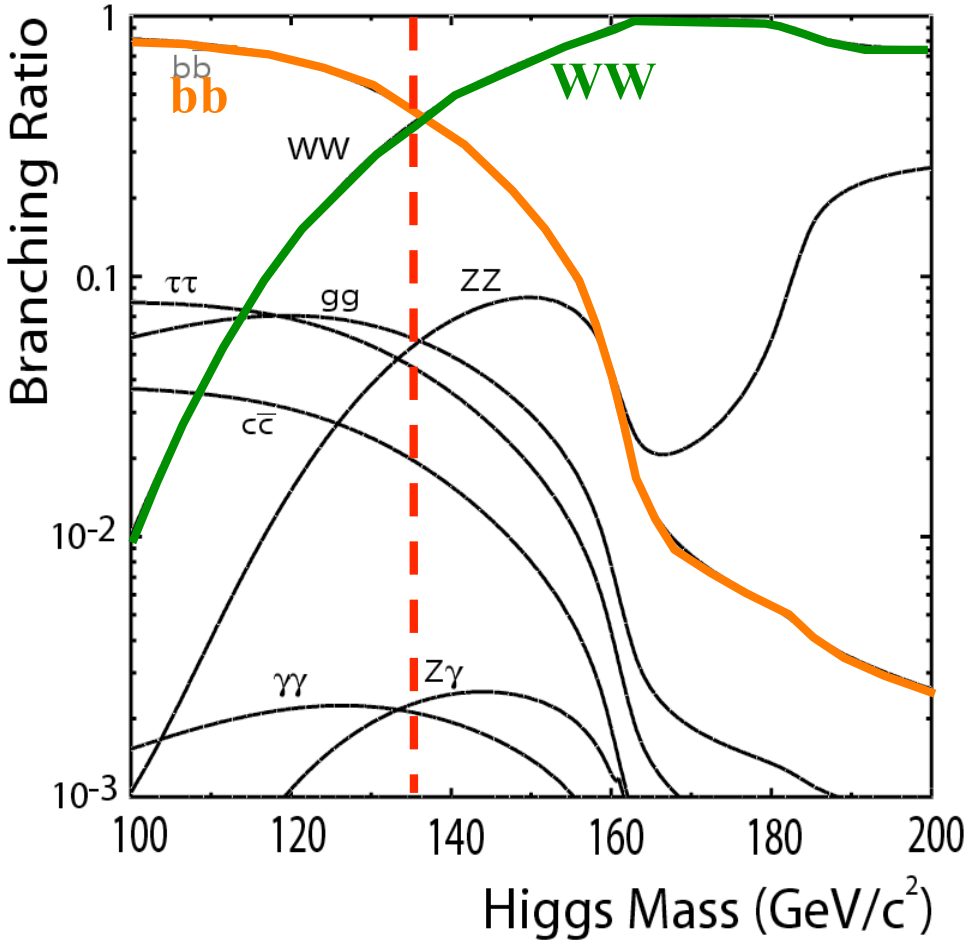


- Set 95% C.L. limit on b' mass to be m(b')>325 GeV
- Also interpret results in the search for exotic top partners (B, $T_{5/3}$) in the context of composite Higgs model (R. Contino, G. Servant, JHEP 0806:026 (2008))
- Set 95% C.L. limit on mass of B and $T_{5/3}$ to be >351 GeV

Searches for the Standard Model Higgs Boson

SM Higgs Boson Productions and Decays





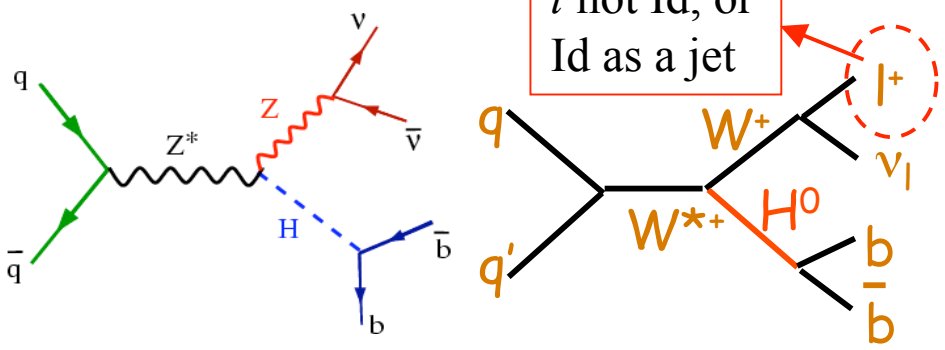
- Higgs decays predominantly :
  - $H \rightarrow b\bar{b}$ (m_H<135 GeV)
  - $H \rightarrow W^+W^-$ (m_H>135 GeV)

SM Higgs Boson Search Channels at CDF

	Production	Higgs Decay	Other Decays	Signature
Light Higgs	gg→H	H→ττ		Di-tau
	qq'→W*→WH	H→bb	W→*l*ν	lep+MET+2b
	qq'→Z*→ZH	H→bb	Z→l^+l^-	*ll* + 2b
	W/Z+H	H→bb	Z→νν, W→*l*ν (*l* not ID)	MET+2b
	W/Z+H	H→bb	W,Z→qq	2q + 2b
	W/Z+H	H→ττ	W,Z→qq	2τ + 2q
	(VBF) qqH	H→ττ		2τ+2q (2 forward jets)
	ttH	H→bb	t→bW	4b
Heavy Higgs	gg→H	H→WW*	W→*l*ν	2*l* + MET
	qq'→W*→WH	H→WW*	W→*l*ν	like-sign lepton pair, or trilepton + MET
	W/Z+H	H→WW*	W,Z all decay channels	2*l*+MET +lepton(s) or jets

Search for Higgs Boson in MET+Jets

- Search for Higgs boson produced in association with a W or Z boson
- Signature : Large MET + *b*-jets

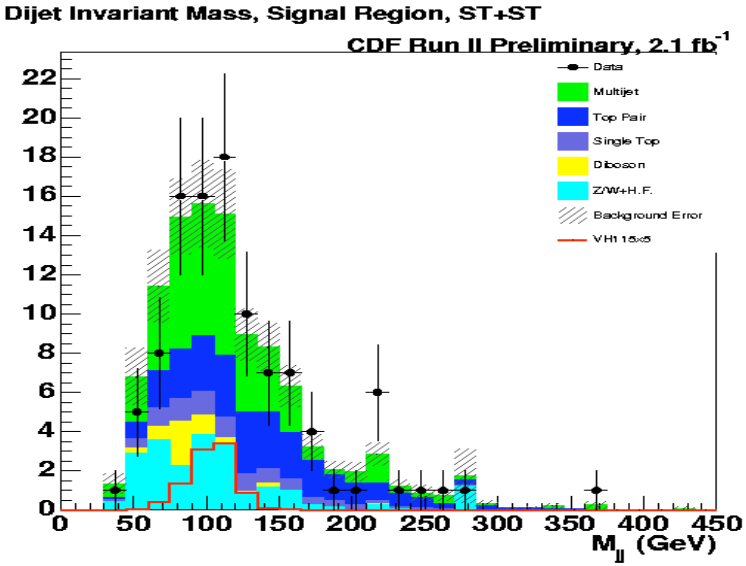


Event Selection:

- No identified *e*, μ
- Large MET
- 2 or 3 jets (3rd jet allows *e*,τ from W$\rightarrow l\nu$)
- ≥1 b-tagged jet

Main Background:

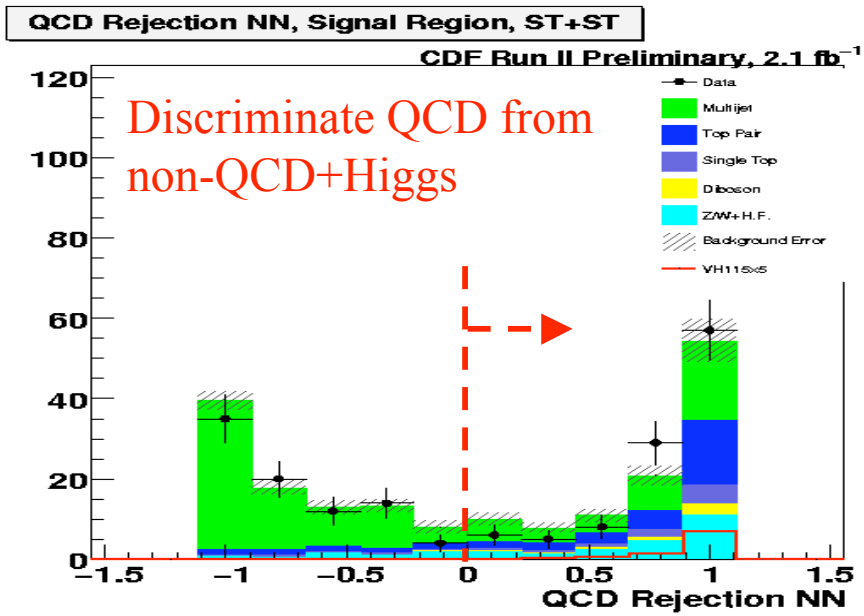
- QCD heavy-flavor, mis-tag
- W/Z + heavy-flavor jets
- tt-bar
- Di-boson

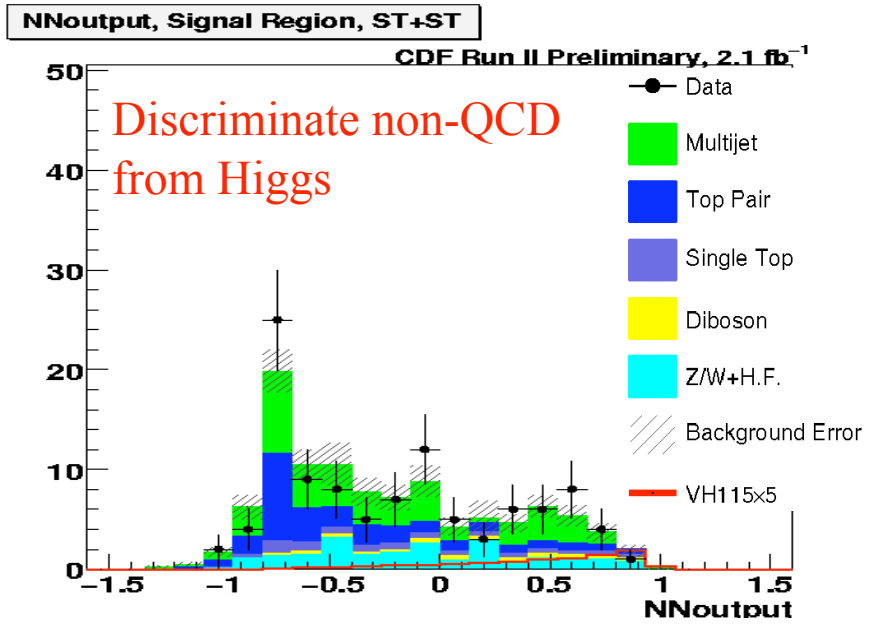


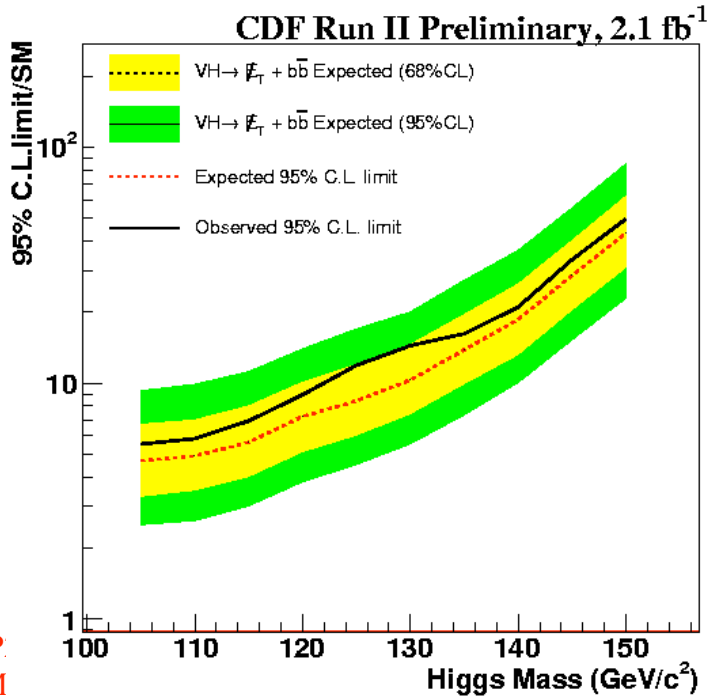
Train separate Neural-Net algorithm:

- Discriminate :
  - QCD from non-QCD+Higgs
  - non-QCD from Higgs

Search for Higgs Boson in MET+Jets







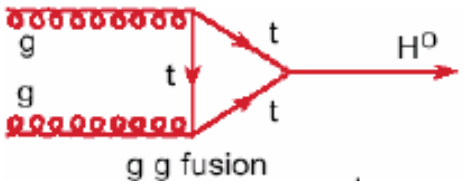
Limits: (@ 95% C.L.)

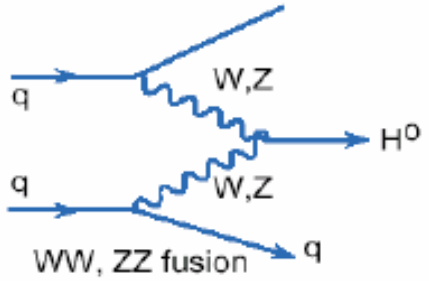
- @ m(H)=115 GeV/c^2
  - Expect : σ < 1.2 pb (5.6x SM)
  - Observe : σ < 1.5 pb (6.9x SM)

Search for Higgs Boson in $H \rightarrow W^+W^-$

- Search for Higgs boson in various production channels and with H→WW
  - gg→H→WW→*lνlν*
  - WH→WWW→*jjlνlν*, *lνlνlν*
  - ZH→ZWW→*ννlνlν*, *jjlνlν*, *lllνlν*
  - ppbar→*qq*H→*qq*WW→*qqlνlν*

Can have same-sign lepton pair

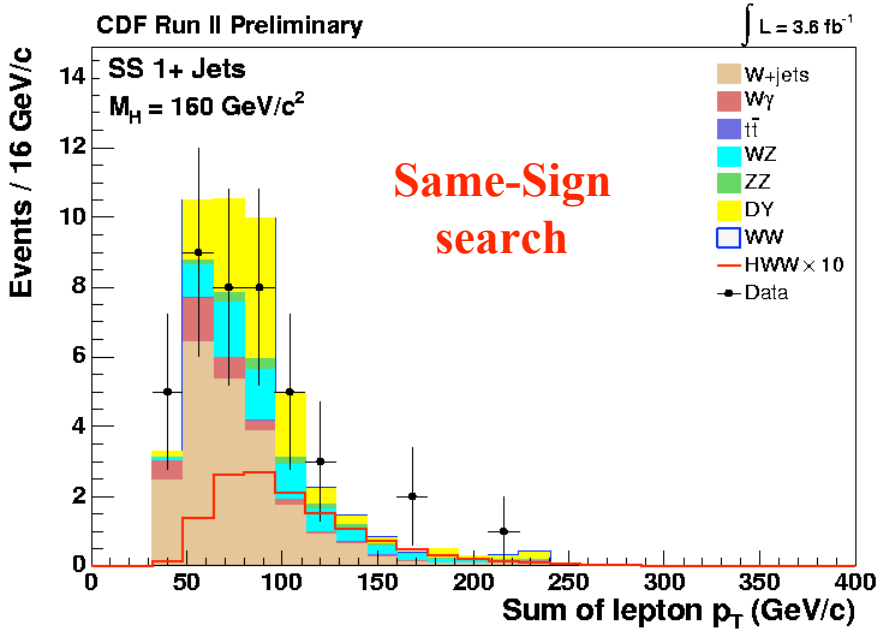




Common Signature: ≥2 high Pt isolated leptons and large MET

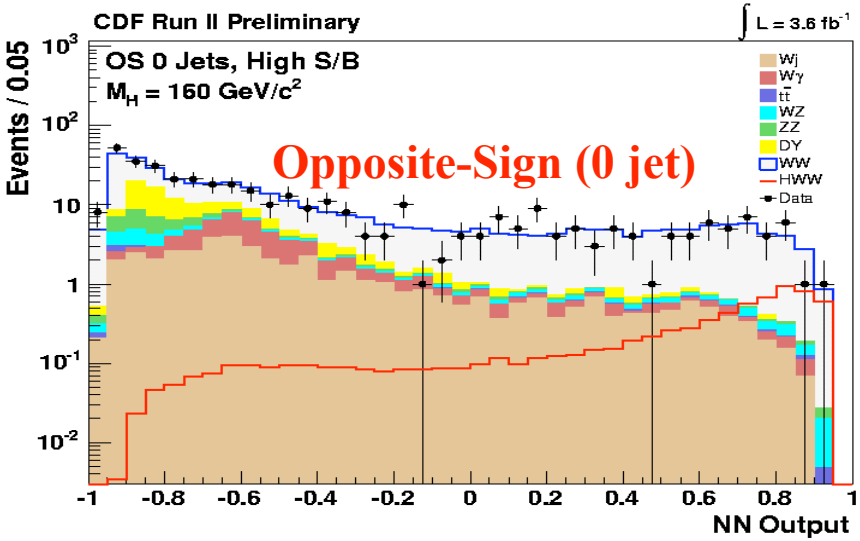
Background:

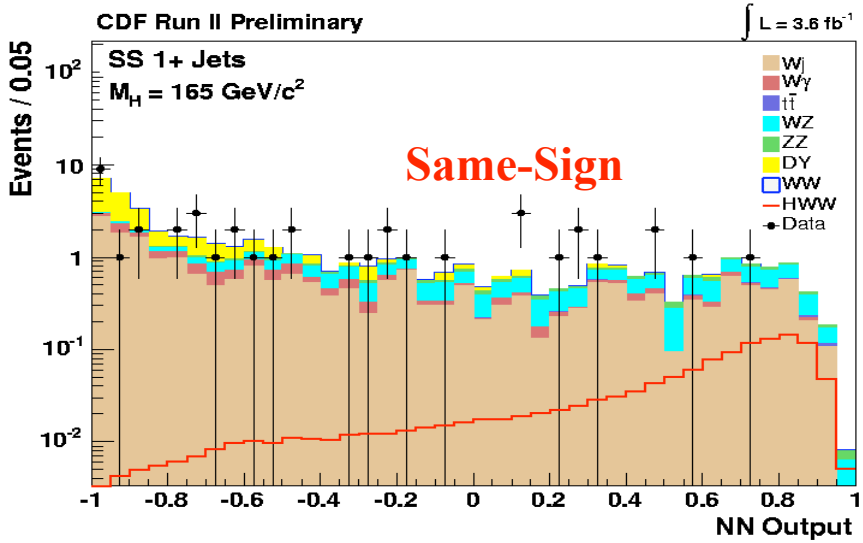
- WW (dominant for opposite-sign search), WZ, ZZ, Wγ
- W+jets (jet fake as a lepton, dominant background for same-sign search)
- tt-bar



Search for Higgs Boson in $H \rightarrow W^+W^-$

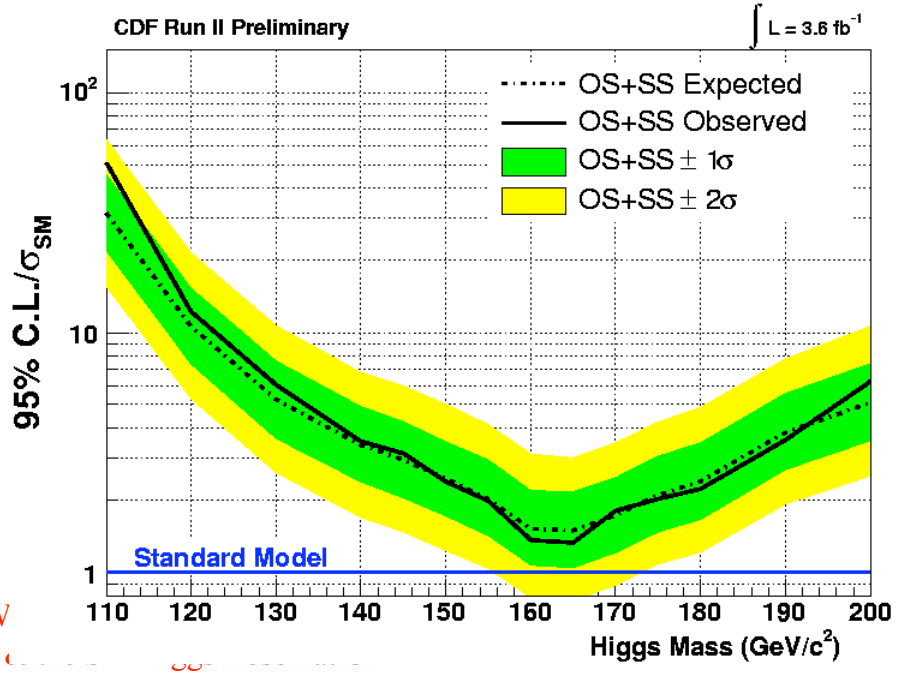
- Use Neural-Net algorithm to separate Higgs signal from background



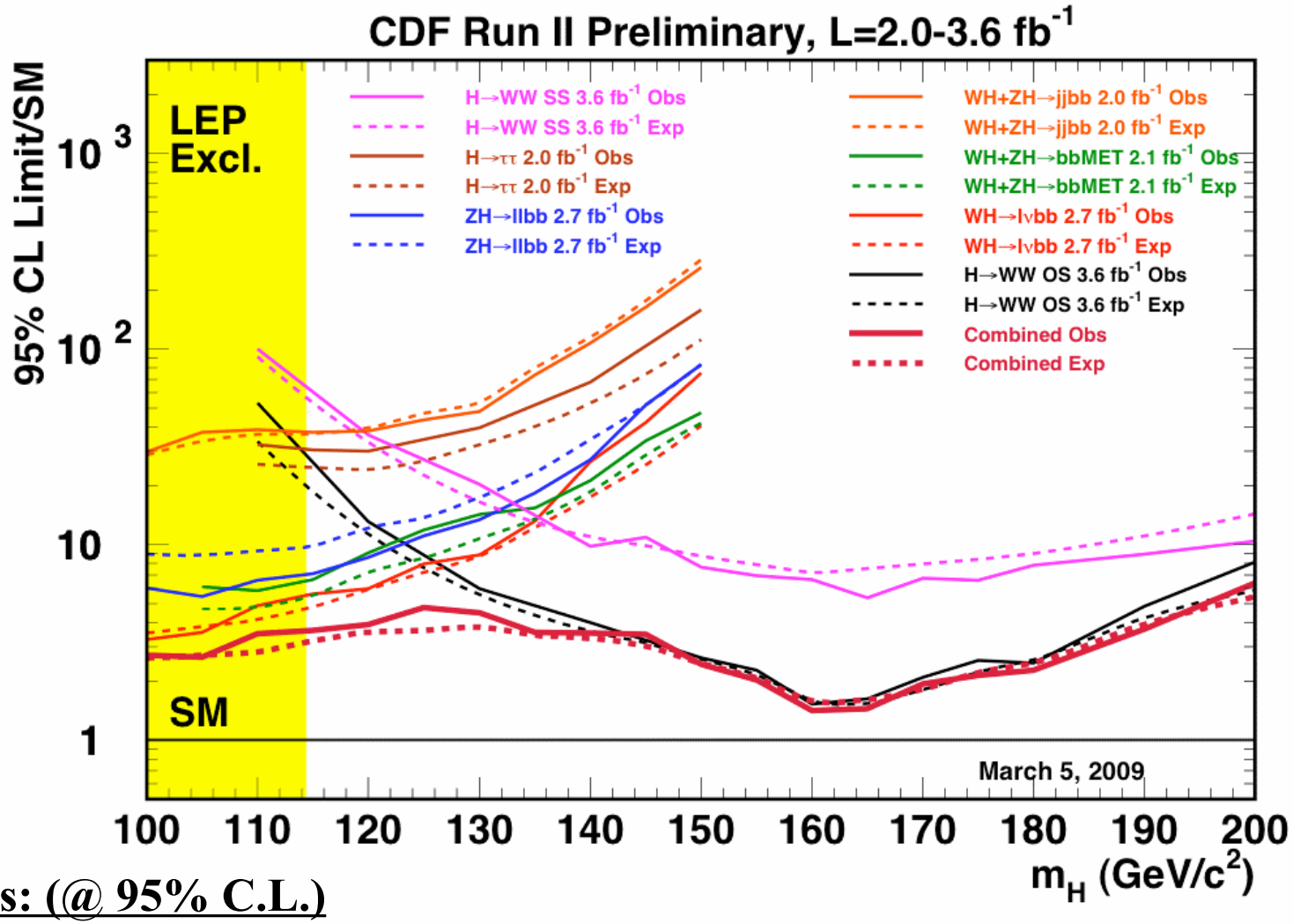


Limits: (@ 95% C.L.)

- @ m(H)=160 GeV/c^2
  - Expect : $\sigma < 1.6 \times SM$
  - Observe : $\sigma < 1.4 \times SM$



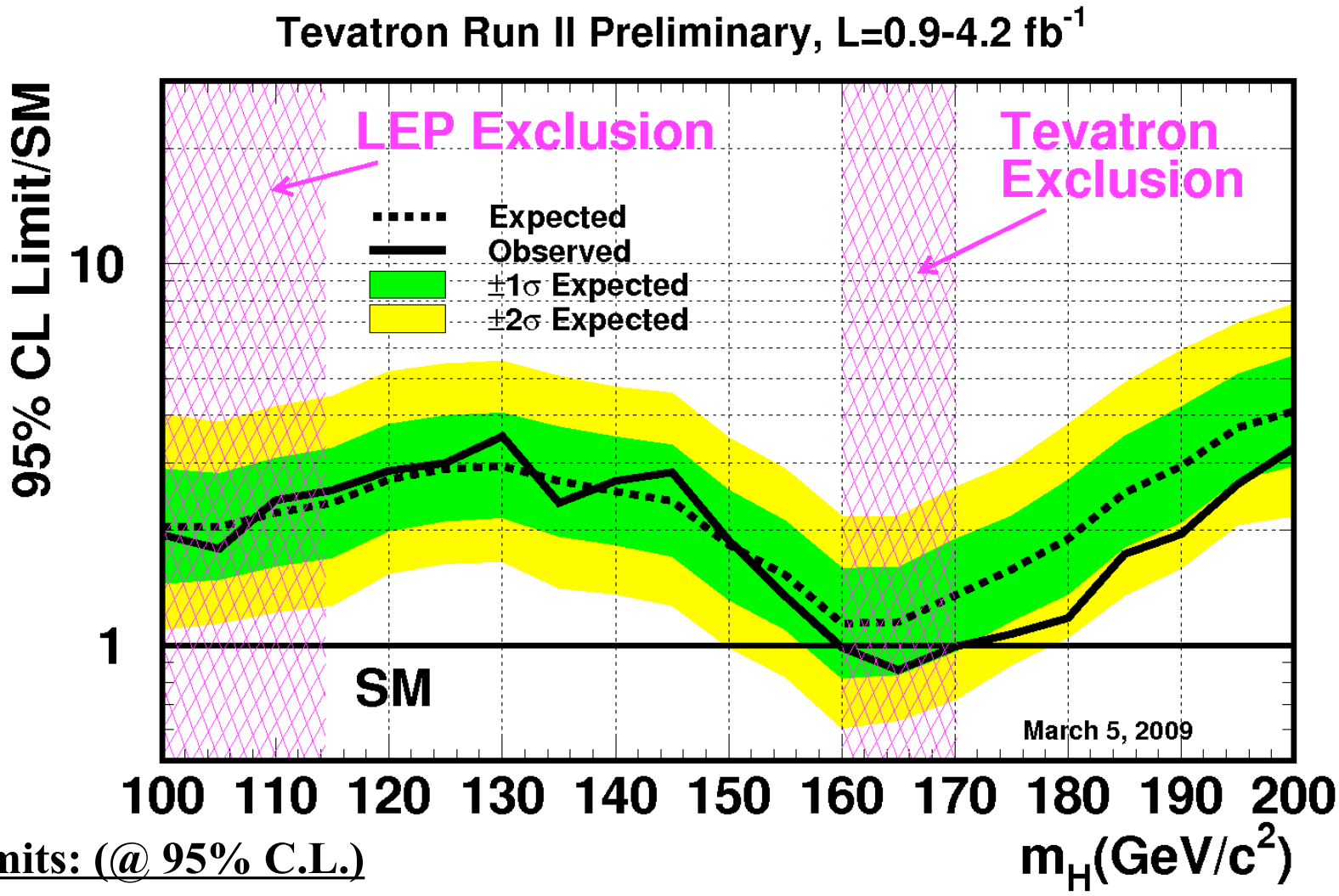
CDF Combined Search Results



Limits: (@ 95% C.L.)

- @ 115 GeV/c^2 : Obs (Expect) = 3.6 (3.2) x SM
- @ 160 GeV/c^2 : Obs (Expect) = 1.4 (1.6) x SM

Tevatron Combined Search Results



Limits: (@ 95% C.L.)

- @ 115 GeV/c^2 : Obs (Expect) = 2.5 (2.4) x SM
- Exclude mass region from 160 to 170 GeV/c^2

Summary

- Presented several search results using data samples up to ~3-4 fb^{-1}
  - Many other results are not covered in this talk, can be found at :
    - http://www-cdf.fnal.gov/physics/exotic/exotic.html
    - http://www-cdf.fnal.gov/physics/new/hdg/hdg.html
- Our searches are now excluding away larger portions of parameter spaces in some new physics models.
- CDF & D0 combined Higgs search exclude Higgs in the mass range 160-170 GeV, with data sample $\leq$ 4 fb^{-1}
- Tevatron will most likely continue to run in 2010, and (rumors) may also run in 2011.
  - May expect another ~2-4 fb^{-1} by end of Run II
- **Will hear more exciting results from the Tevatron and new results from LHC @ PPP2011 !**

Back-Up

Search for High Mass μμ Resonance

- Di-lepton signature can explore many models :
  - Z', SUSY(RPV), RS Graviton,…
  - Look for resonance or enhancement in mass spectrum
- Analyze 2.3 fb^{-1} of data
  - 2 μ with Pt>30 GeV
  - Look for resonance in m(μμ)>100 GeV
  - Dominant background is Drell-Yan production

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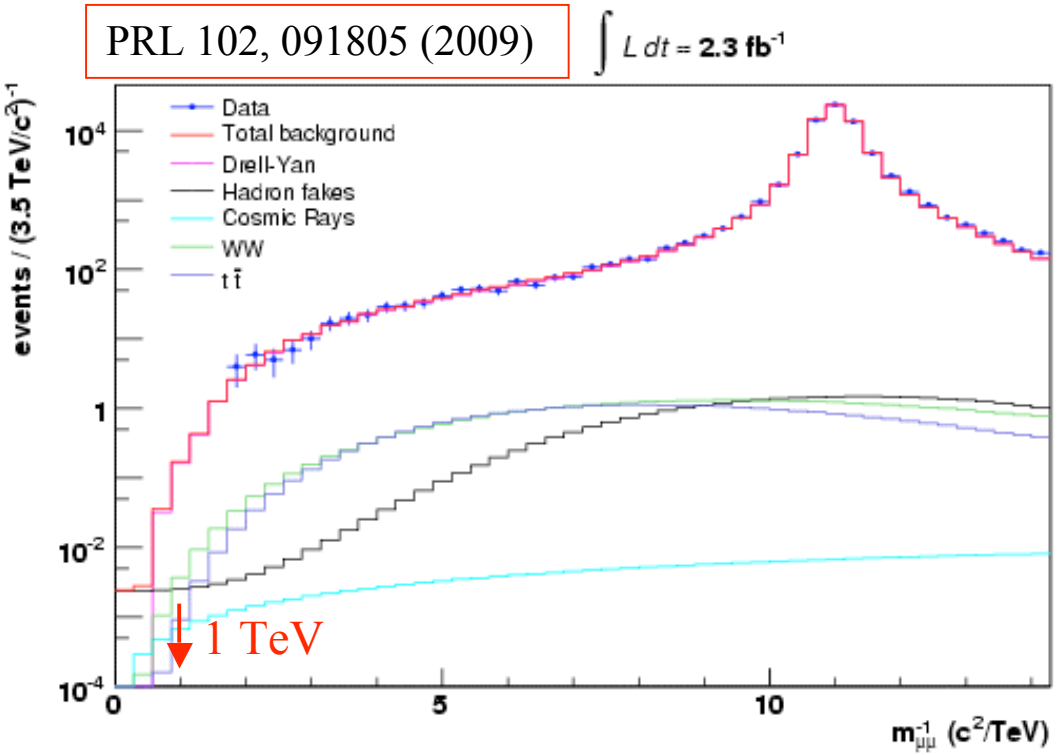
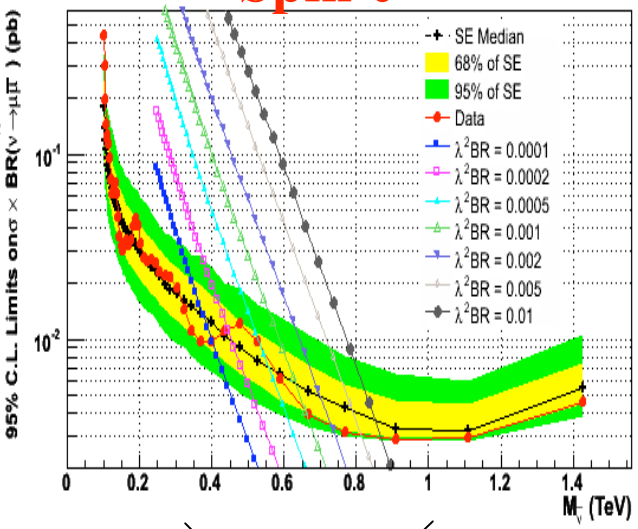
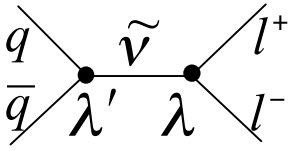


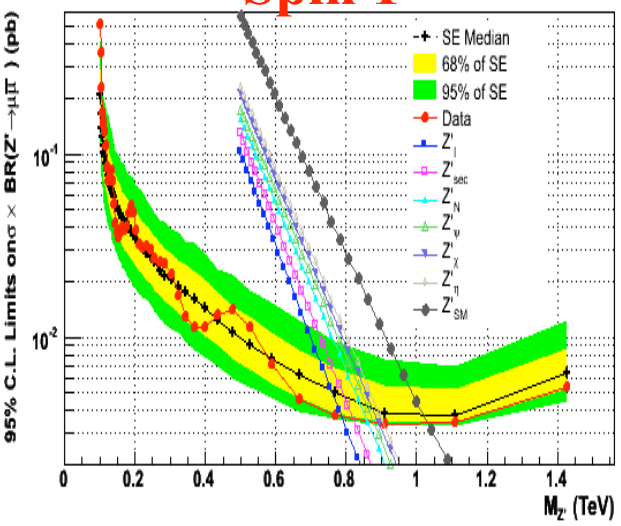
Search for High Mass μμ Resonance

Spin 0

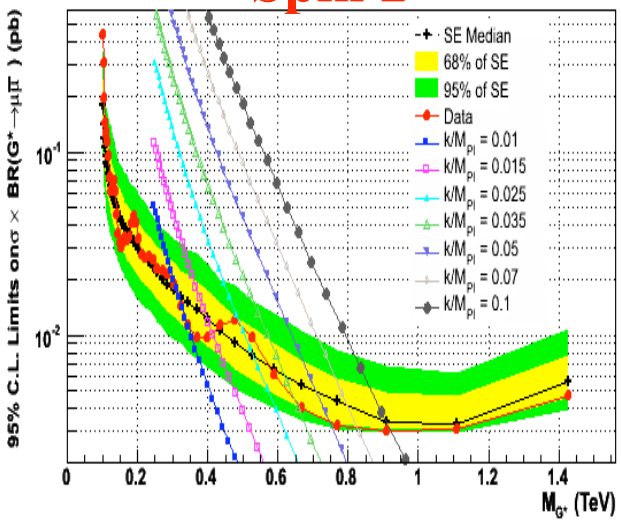




Spin 1



Spin 2



Sneutrino mass limit

CDF II preliminary $L = 2.3\ fb^{-1}$

$\lambda^2 \cdot BR$	Mass Limit, 95% CL (GeV/c^2)
0.01	866
0.005	810
0.002	731
0.001	662
0.0005	541
0.0002	441
0.0001	397

Z' mass limit

CDF II preliminary $L = 2.3\ fb^{-1}$

Model	Mass Limits, 95% CL (GeV/c^2)
Z' (SM)	1030
Z' (η)	904
Z' (χ)	892
Z' (ψ)	878
Z' (N)	861
Z' (sec)	821
Z' (I)	789

Graviton mass limit

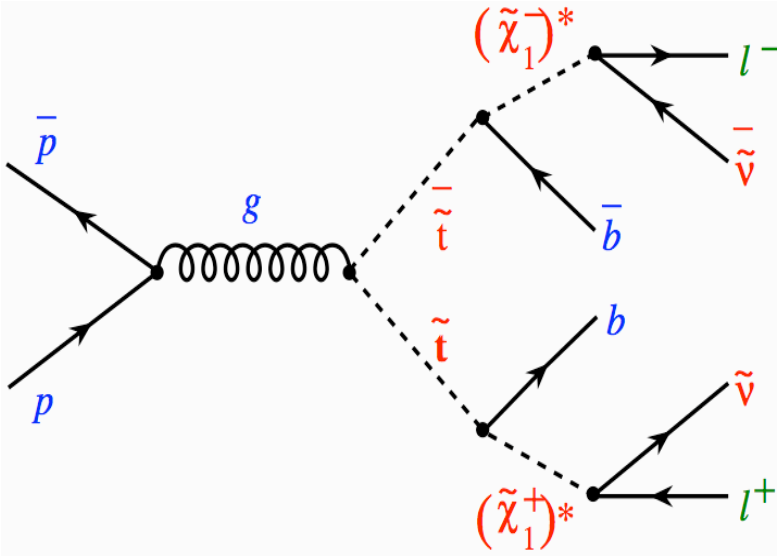
CDF II preliminary $L = 2.3\ fb^{-1}$

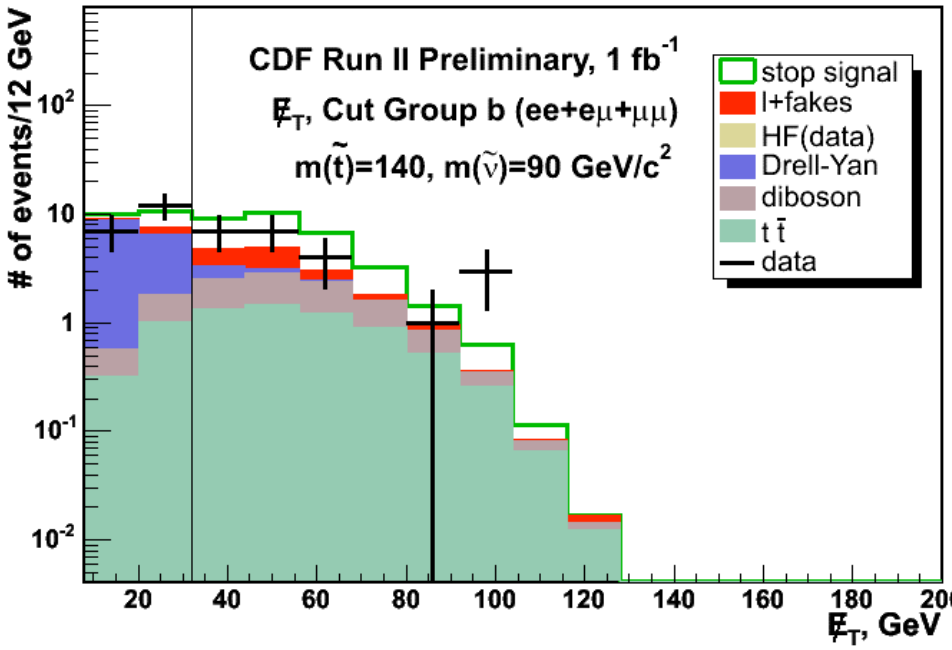
Graviton k/M_{Pl}	Mass Limit, 95% CL (GeV/c^2)
0.1	921
0.07	824
0.05	746
0.035	651
0.025	493
0.015	409
0.01	293

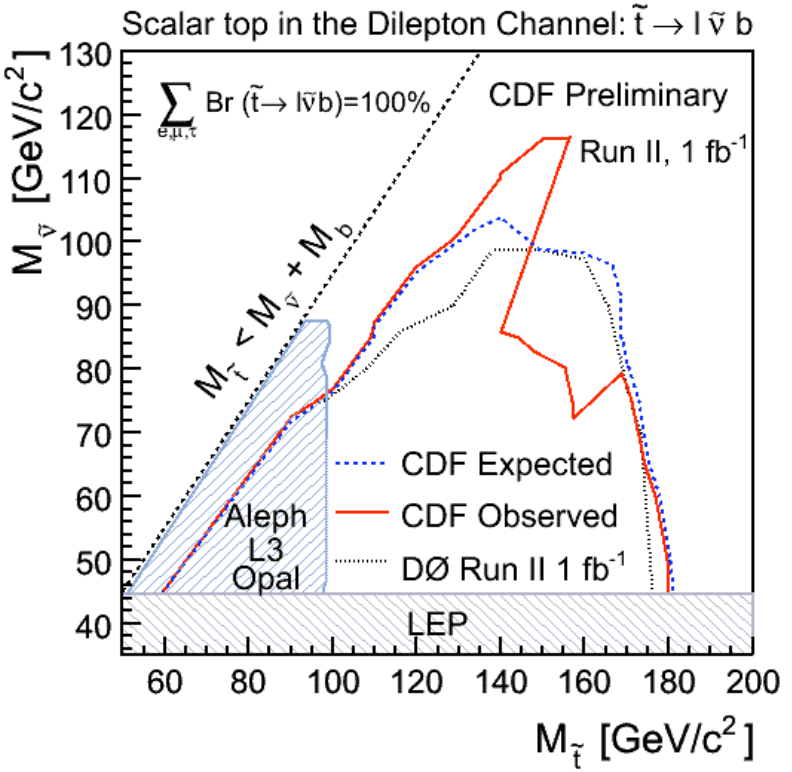
World's tightest constraints !

Search for Stop in Di-lepton Final State

- Assume m(stop)<m(t) & **m(stop)<m($\tilde{\chi}_1^{\pm}$)**
  - Undergo 3 body decay: $\tilde{t} \rightarrow bl\tilde{\nu}$ ($\tilde{\nu}$: LSP)
- Final state also consists of : *llbb*+MET
- Leptons and b-jets are softer compare to previous search
- Search in 3 di-lepton channels (ee,eμ,μμ), no b-tagging required
- Optimize cuts in different $\Delta m(\tilde{t},\tilde{\nu})$ regions

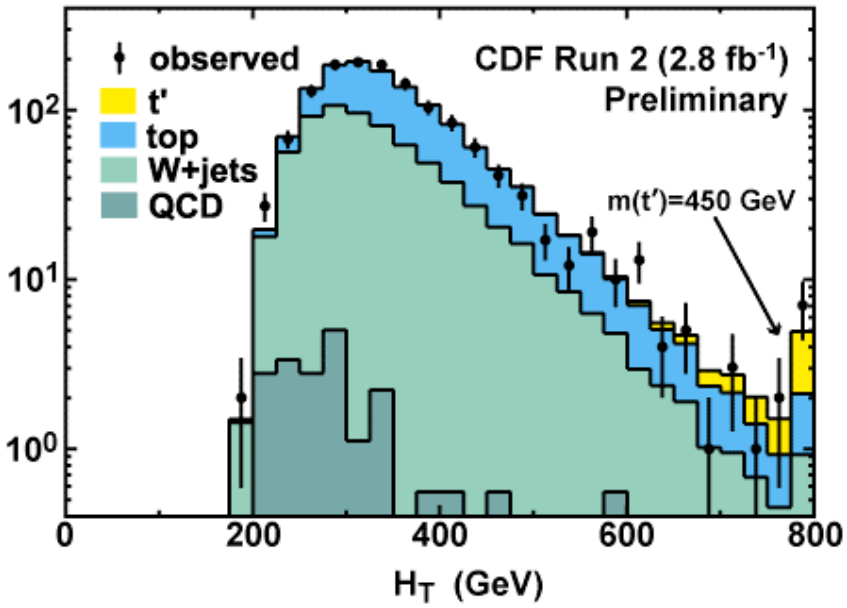




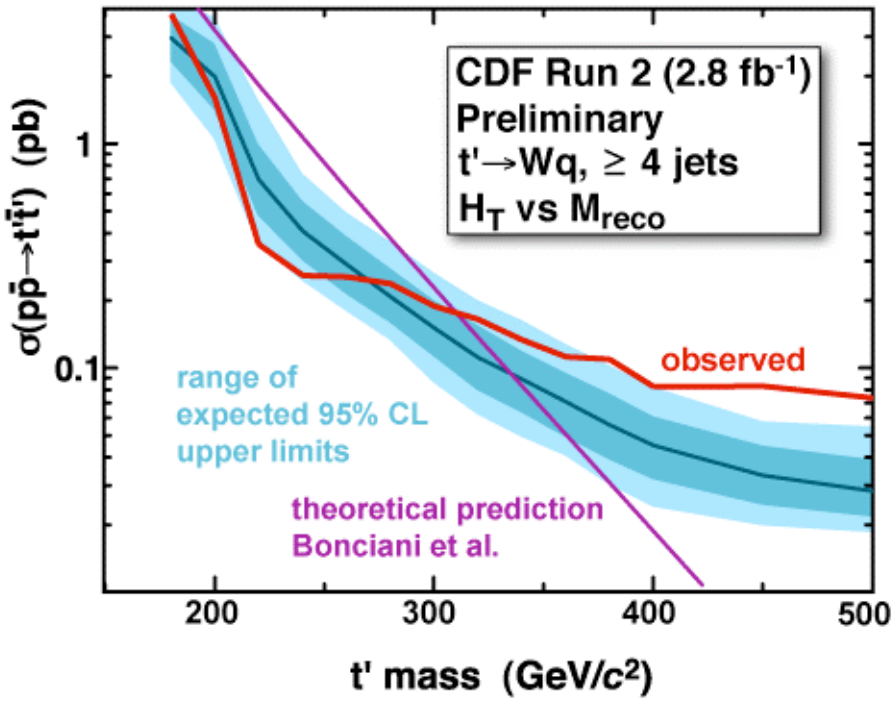


Search for Heavy Top : t'

- Assume:
  - t' can be strongly pair produced at Tevatron
  - m(t')>m(t) and m(t')-m(b')<m(W)
    - ⇒ t'→Wq (q=d,s,b)
- Search in the lepton+jets final state
  - $t'\bar{t}' \rightarrow WqWq \rightarrow l\nu qqqq$

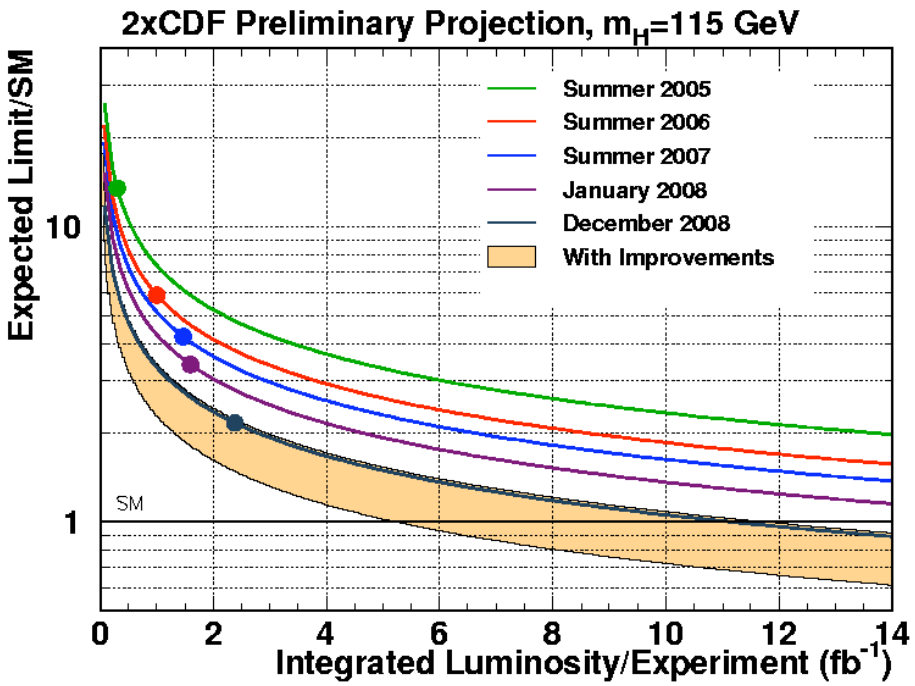


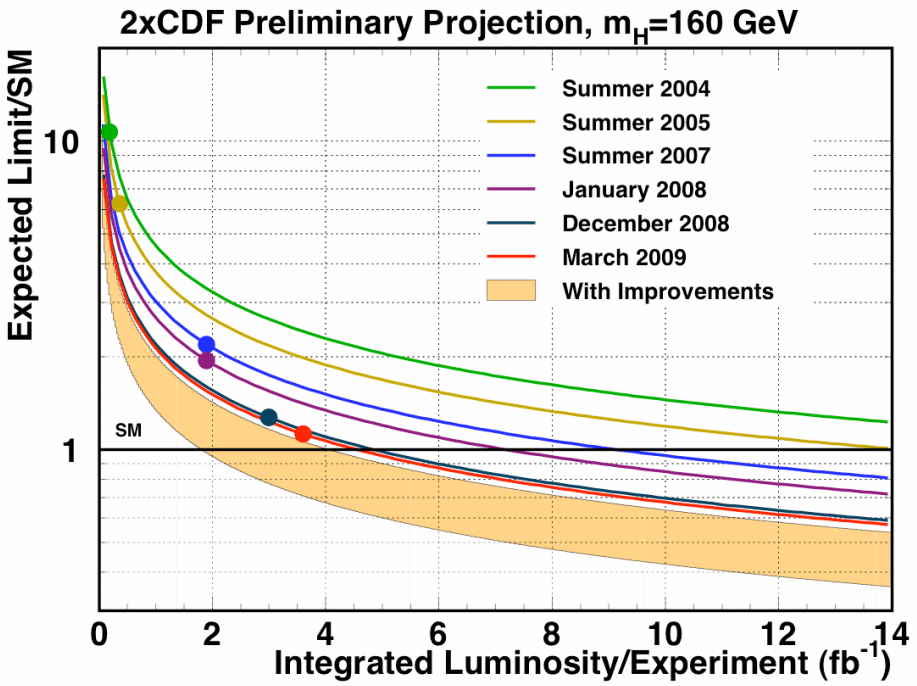
- Reconstruct t' mass (M_{reco}), search for signal in M_{reco} vs H_T
  - $H_T = \Sigma Et(jet) + Et(lep) + MET$



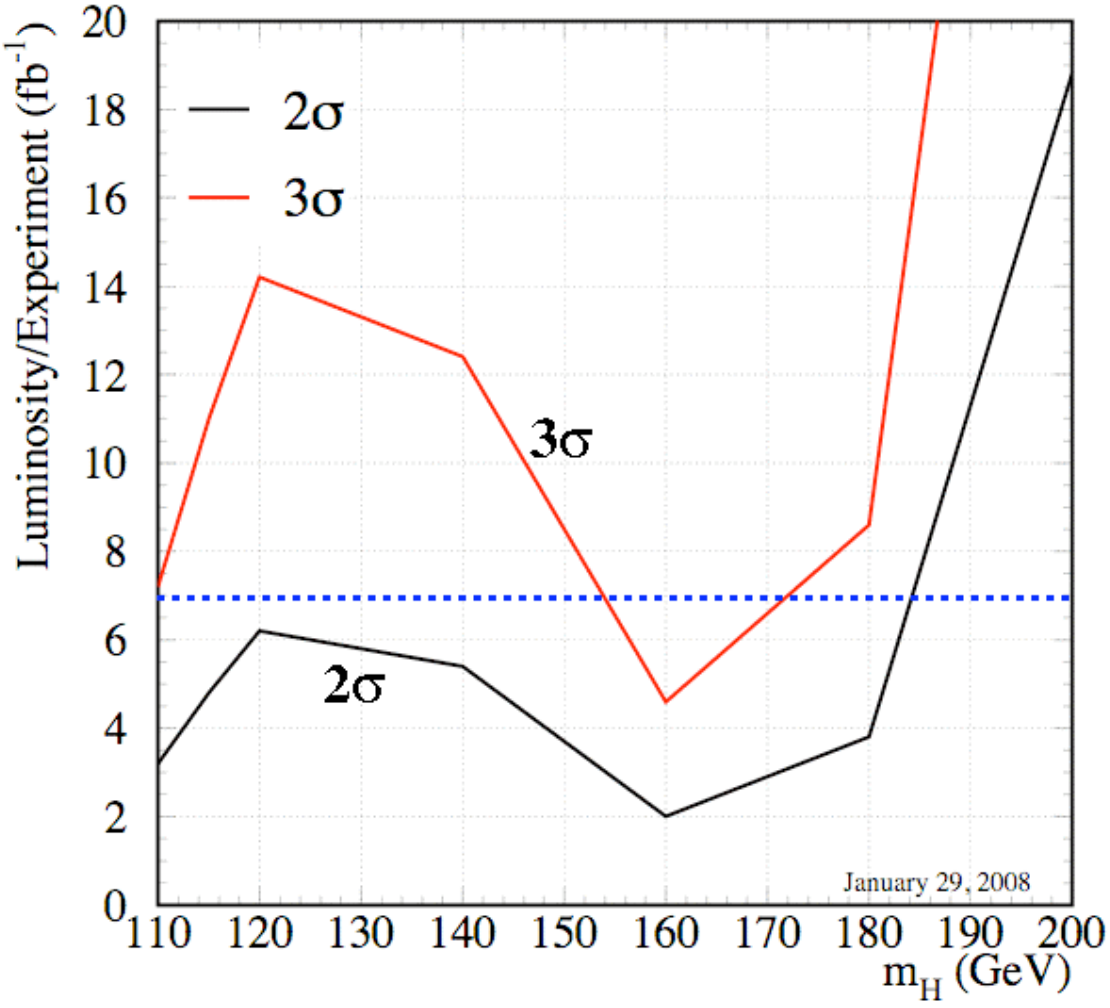
Exclude t' mass below 311 GeV

Higgs Boson Search Projection

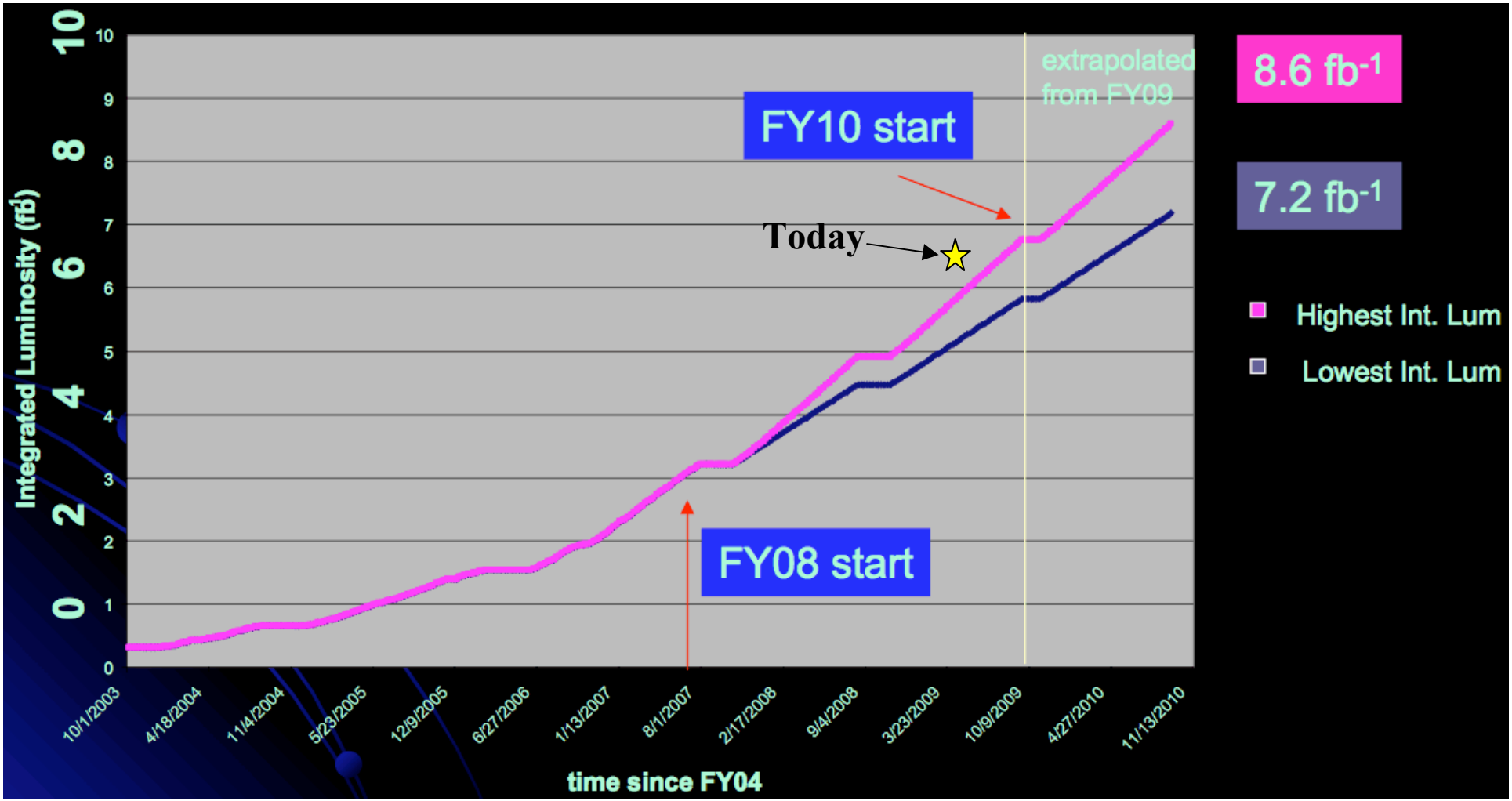




Higgs Boson Search Projection



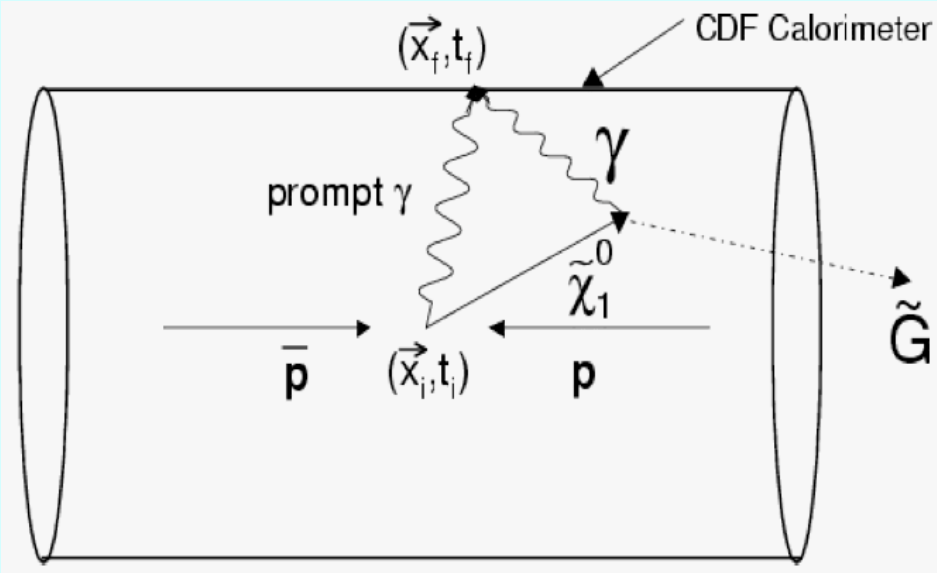
Tevatron Projection



Search for SUSY in Delayed Photon Signature

•CDF search for heavy long lived particle decaying (inside detector) into γ

•Focus on GMSB model where lifetime of $\tilde{\chi}_1^0$ (NLSP) is free parameter

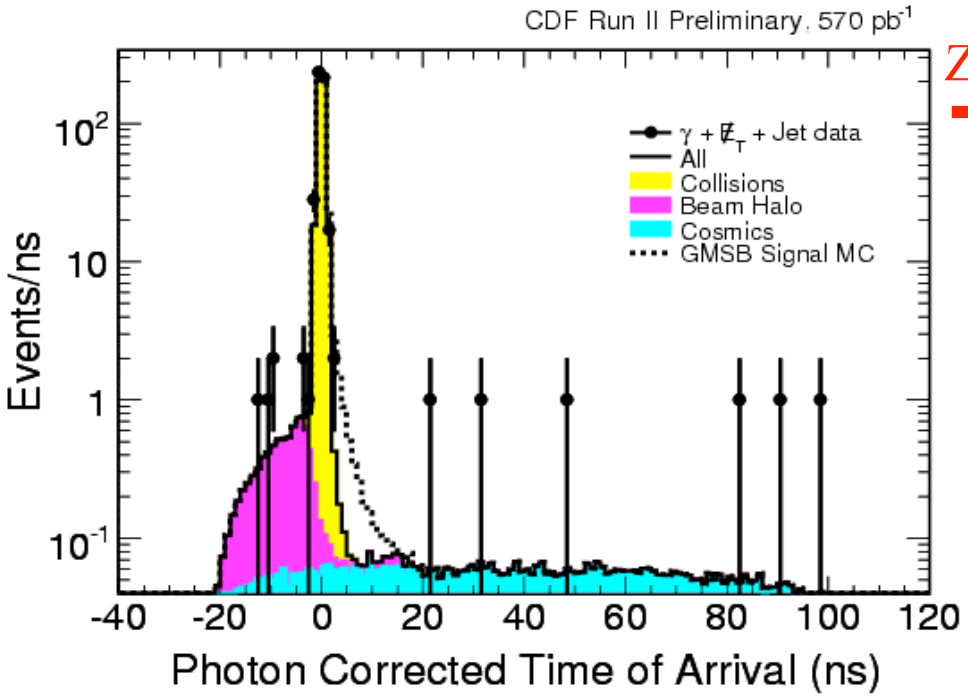


- $\tilde{\chi}_1^0$ is long lived and decays into γ and $\tilde{G}$
- γ from $\tilde{\chi}_1^0$ decay will arrive at face of detector with time delayed relative to promptly produced γ

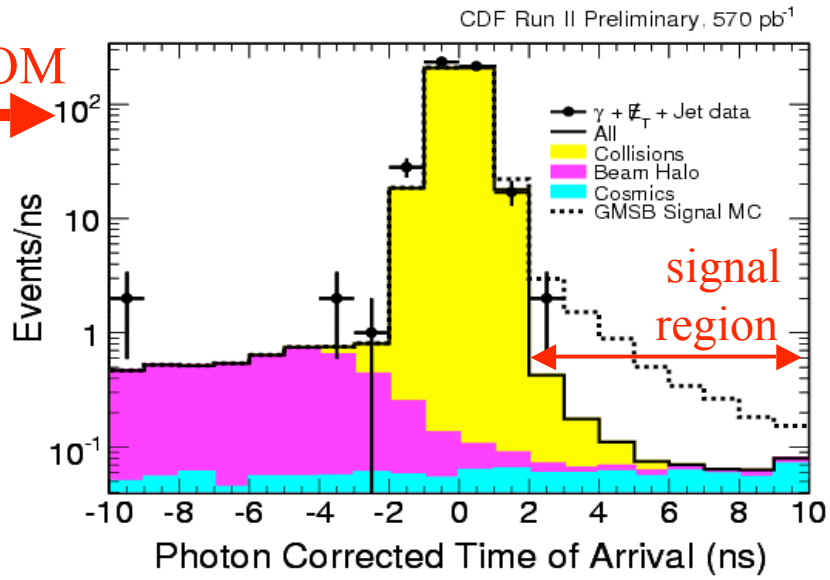
- In GMSB, gravitino $\tilde{G}$ is LSP (escape undetected)
- If $\tilde{\chi}_1^0$ is NLSP, then $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
- Final state consists of γ+Missing E_T+X in SUSY production under GMSB

- Select events with γ+MET+jet signature :
  - Et(γ) > 30 GeV
  - Et(jet) > 35 GeV
  - MET > 40 GeV
- Arrival time of γ is measured by the timing system of the EM calorimeter

Search for SUSY in Delayed Photon Signature



ZOOM



- γ time corrected for TOF assuming coming from interaction point
- Signal window 2-10 ns
- Predict 1.3±0.7 BG events
- Observe 2 events
- Set exclusion in M($\tilde{\chi}_1^0$) and $\tilde{\chi}_1^0$ lifetime plane