From the TeVatron to the LHC: What could lie beyond the SM?

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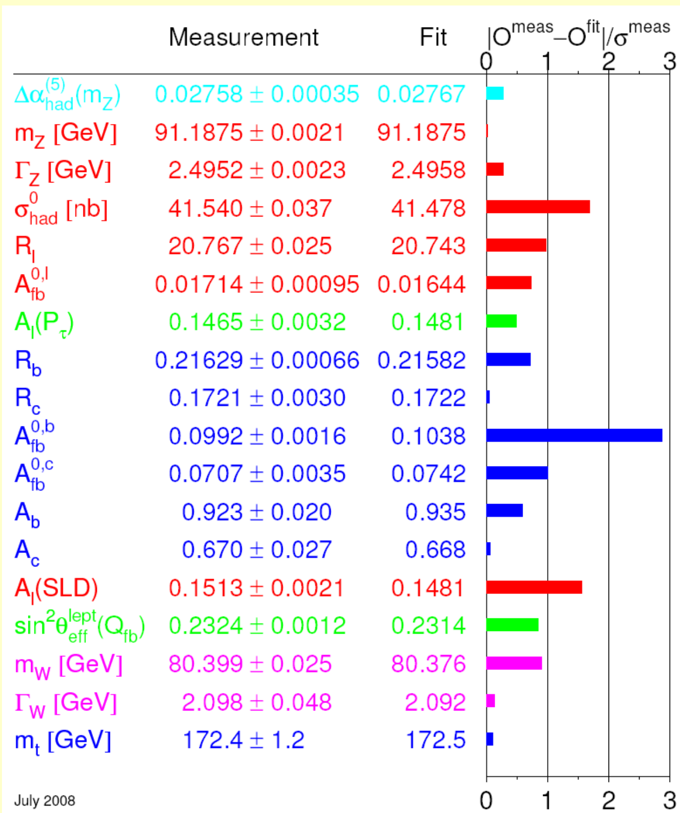
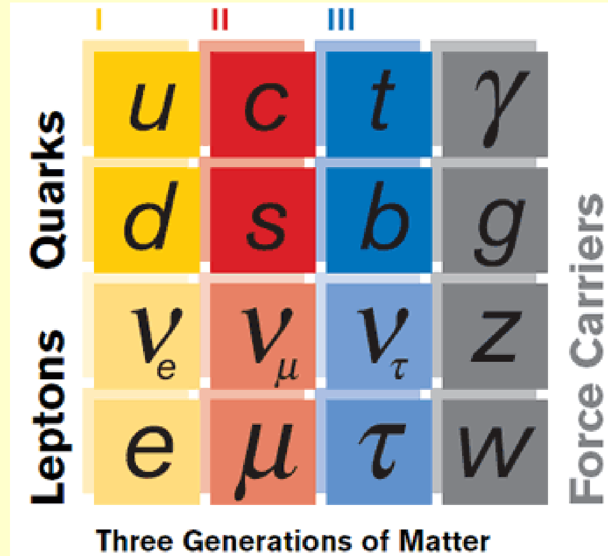
The Standard Model

- Matter is made out of fermions:
  - 3 generations of quarks and leptons
- Forces are carried by Bosons:
  - Electroweak: γ,W,Z
  - Strong: gluons





Remarkably successful description of known phenomena:

- predicted the existence of charm, bottom, top quarks, tau neutrino, W and Z bosons.
- Very good fit to the experimental data so far

but ...

The missing piece: the Higgs

- **What is the origin of masses?**

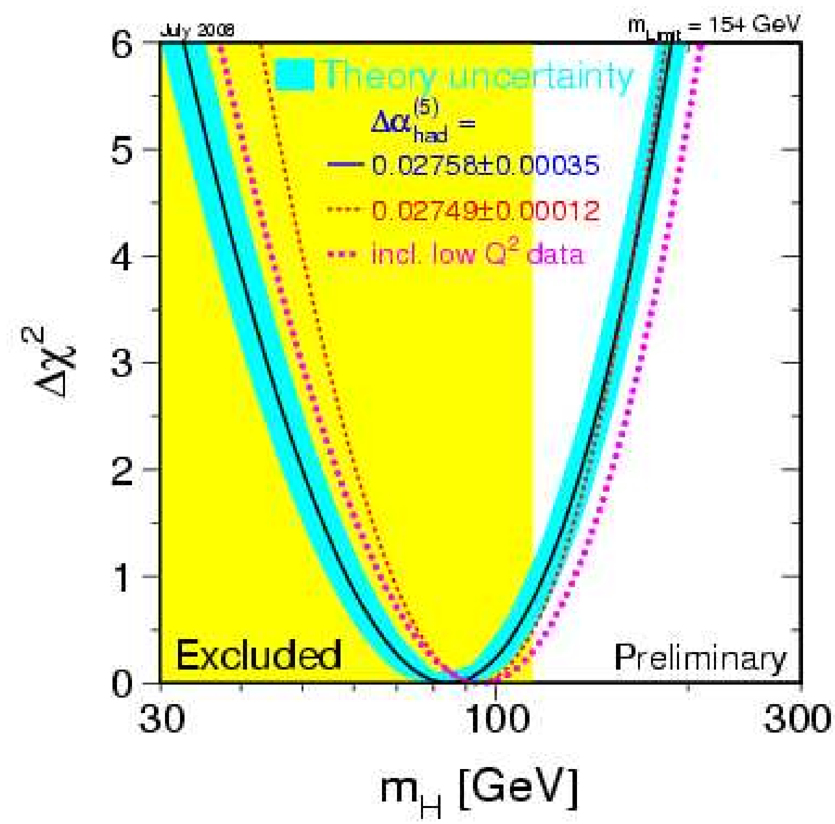
  → Within SM, **Higgs field** gives mass ro Particles (EWK symmetry breaking)
- SM predicts existence of a new massive neutral particle

  Not found yet!
- Theory does not predict its mass
- LEP limit: m_H>114 GeV @ 95% CL
- Indirect limit from EW data:

  - Preferred value: $m_H = 84^{+34}_{-26}$ GeV

  - m_H < 154 GeV @ 95% CL

with $\alpha_S(M_Z) = 0.1185 \pm 0.0026$, $\Delta\alpha_S(5)_{had} = 0.02758 \pm 0.00035$

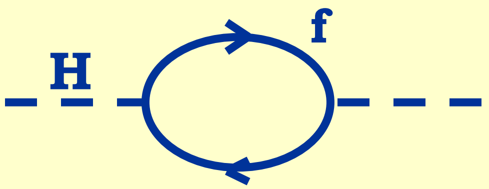


WOULD THE HIGGS DISCOVERY

COMPLETE OUR UNDERSTANDING OF NATURE ?

Beyond SM: the Unknown

The Standard Model is theoretically incomplete

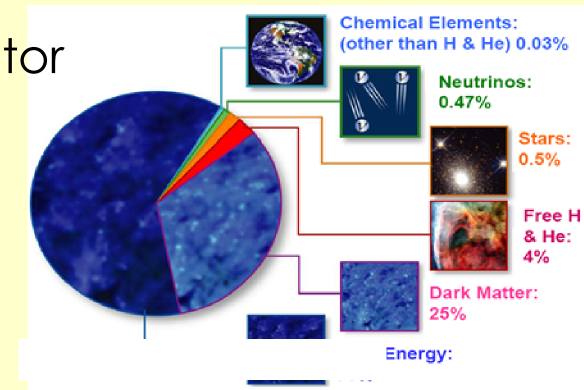


$\Delta m_H^2 \sim \Lambda^2$

$\Lambda = M_{pl}$?

- Mass **hierarchy problem**

→ radiative correction in Higgs sector
- Unification
- Dark Matter
- Matter-antimatter asymmetry



- Many possible new particles and theories
  - SuperSymmetry
  - Extra Dimension
  - New Gauge groups (Z', W')
  - New fermions (e*, t', b' …)
  - …

Can show up in direct searches or as subtle deviations in precision measurements

Outline

- Tevatron and the CDF and DØ experiments
- Tevatron sensitivities: achievements understanding the SM
- The SM Higgs
- Searching for physics beyond SM
  - Supersymmetry
    - mSUGRA-inspired searches:
      - Squark/gluino
      - Third generation squarks
      - Chargino/neutralinos
    - GMSB-inspired searches
      - Searches in Diphoton+Missing E_T
  - Extra-dimension and new gauge bosons:
    - Search for high-mass resonances
- Perspectives for the LHC

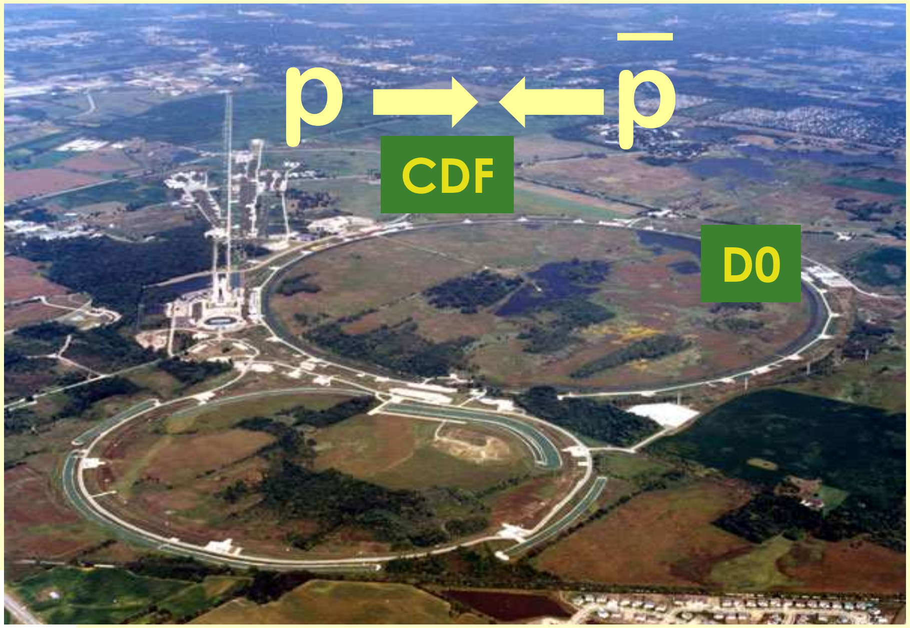
"Particles, particles, particles."

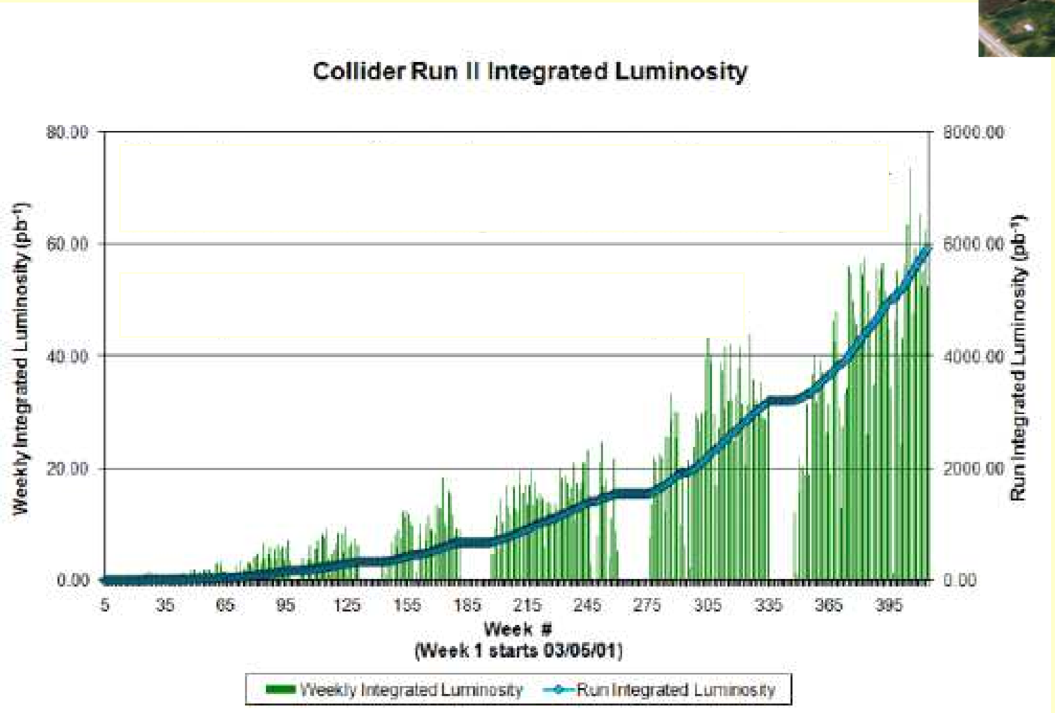
The Tevatron

Highest-energy accelerator currently operational

Peak luminosity → > **3.4 $*10^{32}$ cm^{-2} s^{-1}**

Integrated luminosity/week → **~ 60 pb^{-1}**



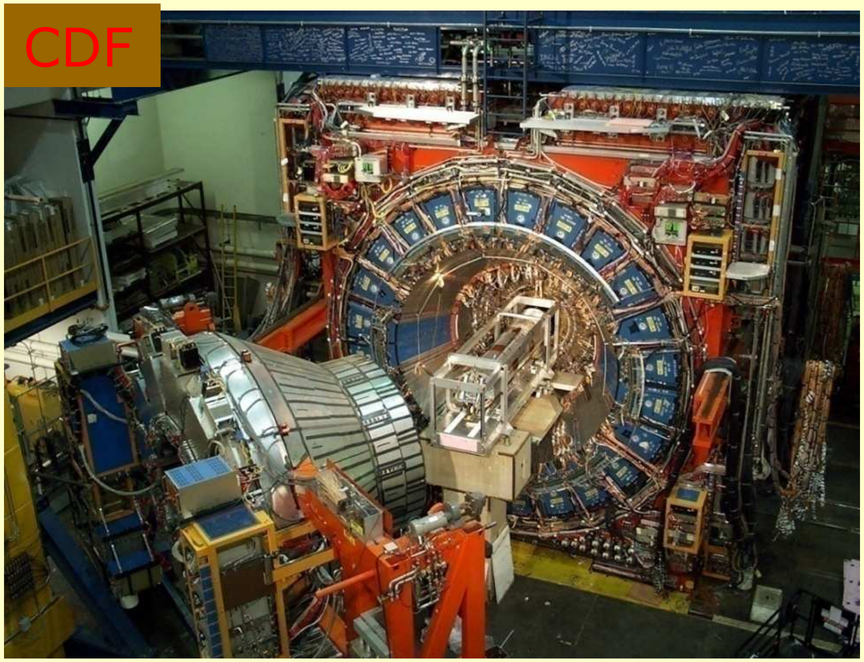


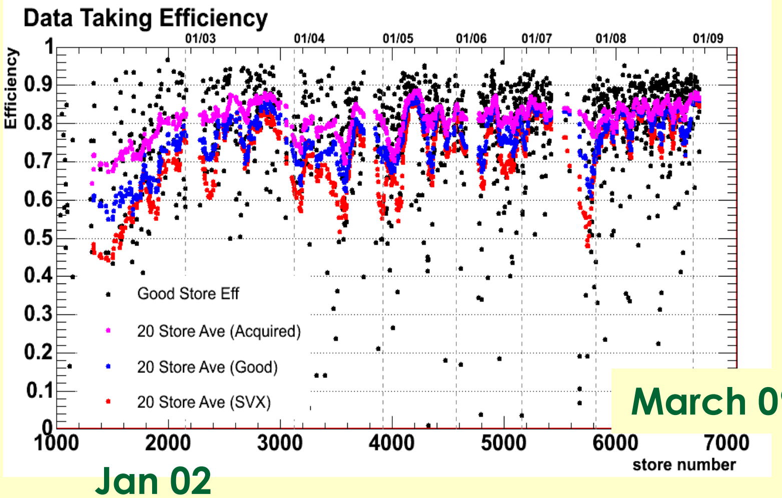
Delivered: 6.1 fb^{-1}

Acquired: 5.1-5.3 fb^{-1}

(CDF/ DØ)

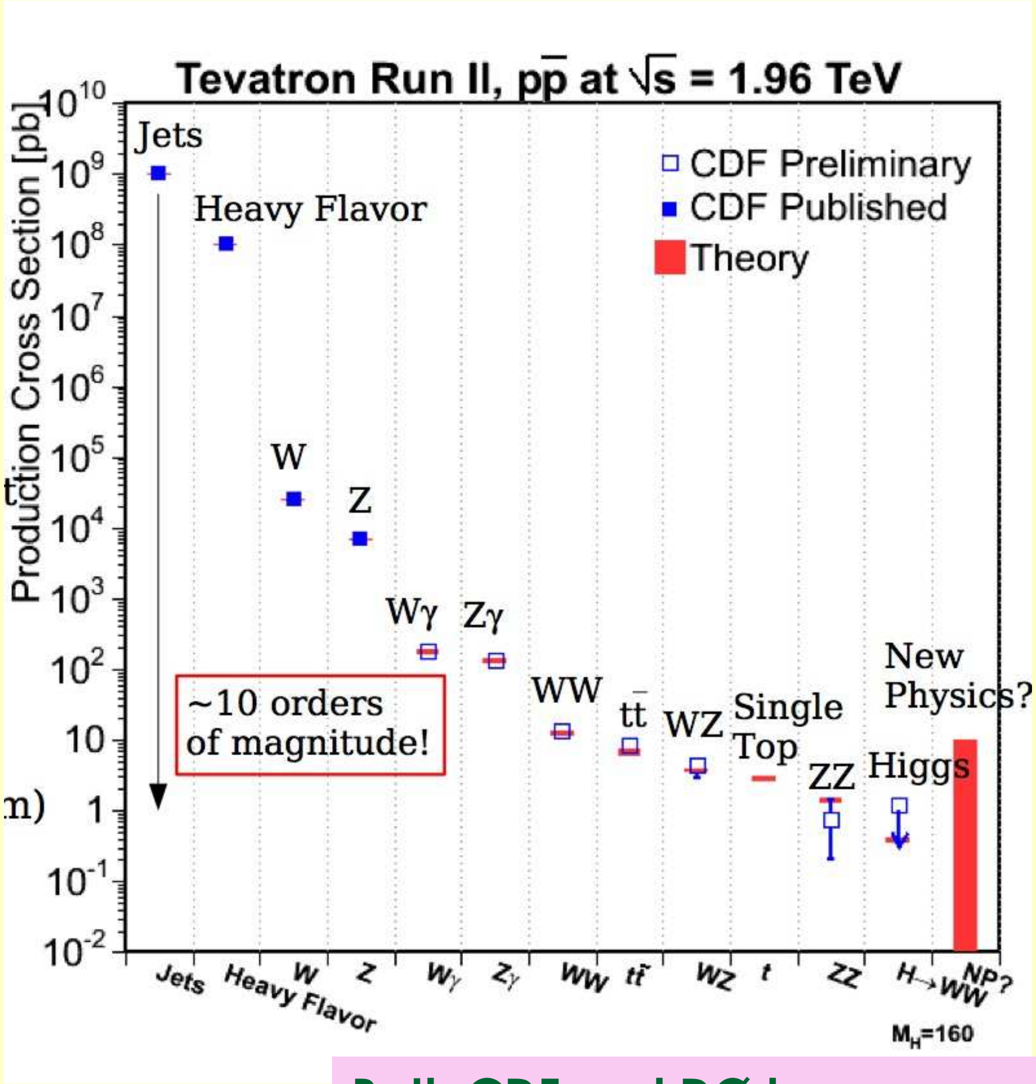
CDF and DØ in RunII





Took >1 years of collisions to get to stable high efficiency

Tevatron Sensitivities



- Jet cross section measurements, heavy flavor physics, inclusive W/Z

⇓

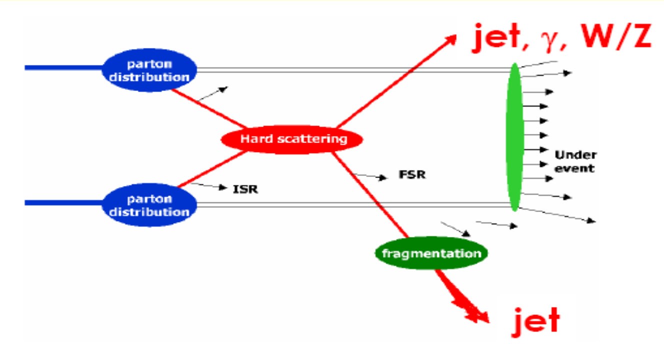
- Precision measurements (Top properties, observation of rare processes...)

⇓

- New Physics searches, looking for 'the' unexpected

Both CDF and DØ have a very rich physics program!

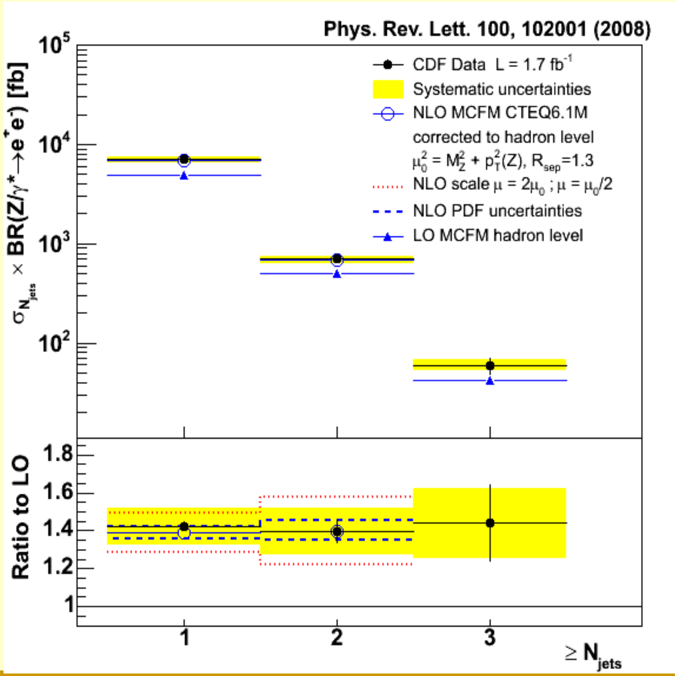
Knowledge of the SM: QCD and EWK



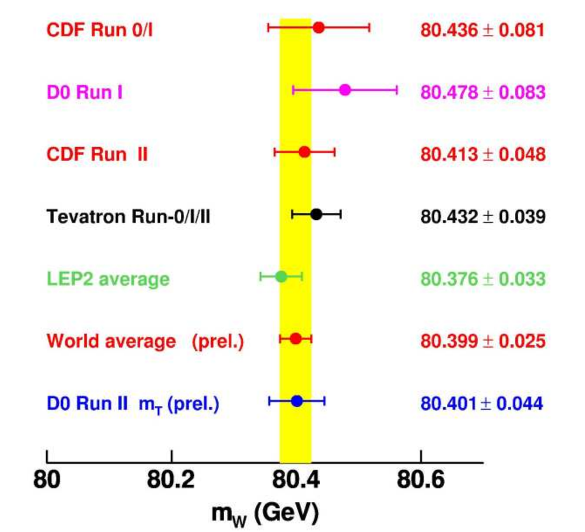
Test of Next-to-Leading Order perturbative QCD

- inclusive jet cross section
  - Probing distances ~10^{-19} m
  - Constrains gluon PDF at high-x

- Z(→e+e-)+jets
  - Clean signature, low background
  - Test ground for Monte Carlo tools



- W Mass and width



M_W = 80413±48 MeV (CDF, 0.3 fb^{-1})

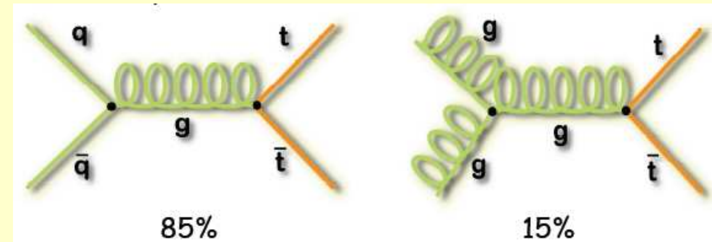
= 80401±44 MeV (DØ, 1 fb^{-1})

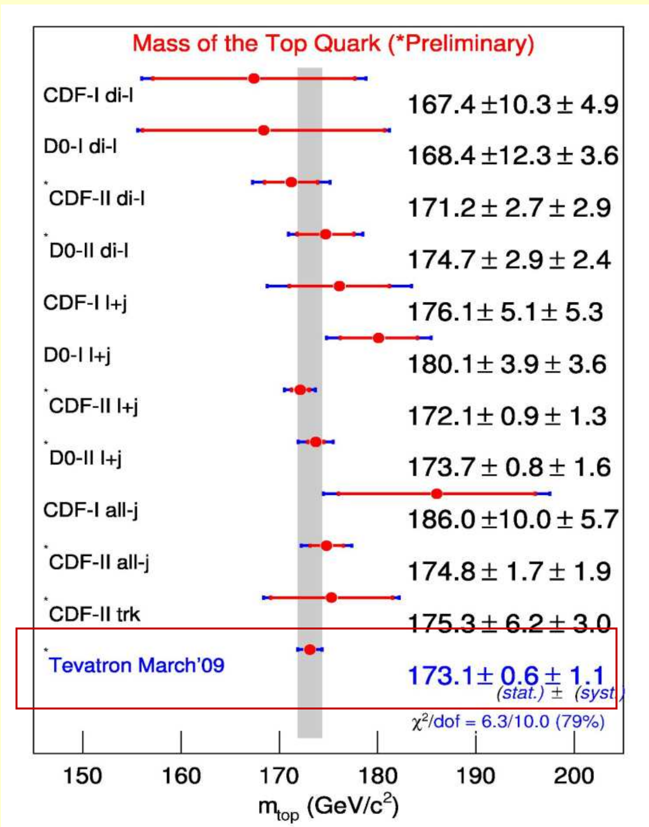
Γ_W = 2032±73 MeV (CDF)

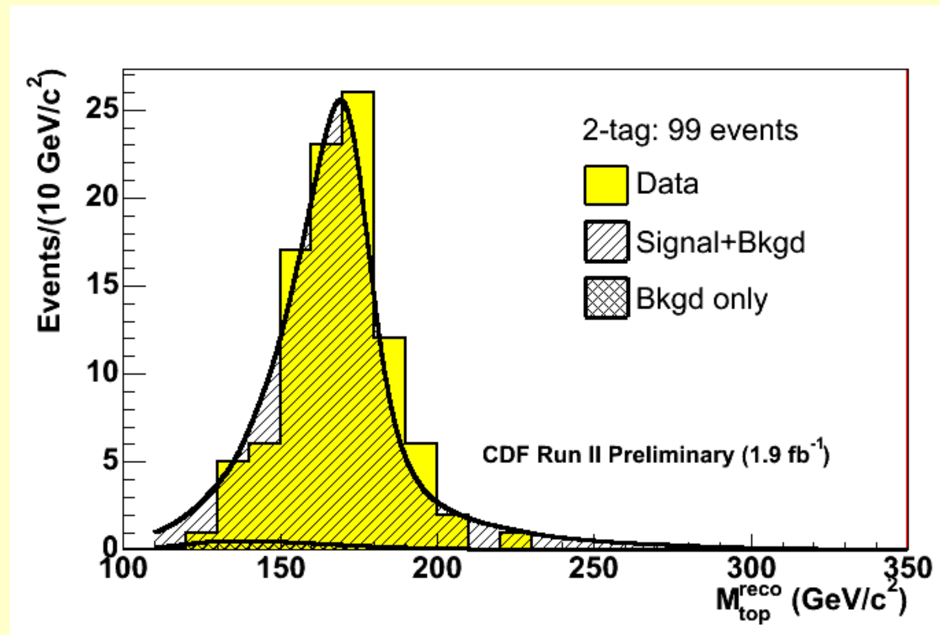
world's most precise single measurements!

Knowledge of SM: top physics

- Top quark discovered at the Tevatron in 1995
- Very extensive program on top physics:
  - Precision measurements of top mass
  - Top cross sections, properties…



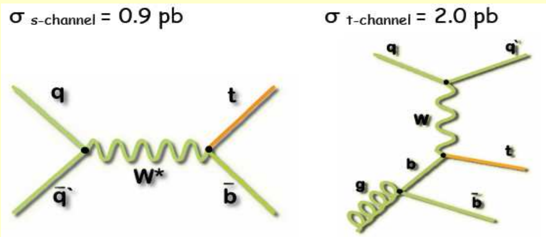




M_{top} = 173.1 ± 0.6 (stat) ± 1.1 (syst) GeV/c^2

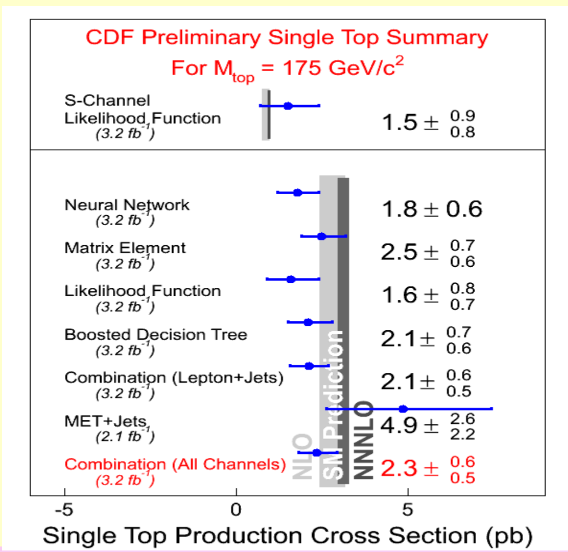
Knowledge of SM: rare processes

- Observation of **Single top** **(CDF/D0 release results on March 9th)**

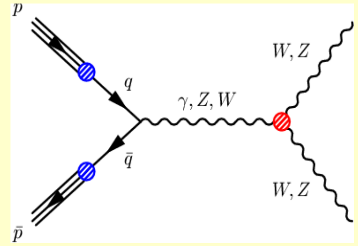


DØ : $\sigma_s + \sigma_t = 3.94 \pm 0.88$ pb

CDF: $\sigma_s + \sigma_t = 2.3{+}0.6{-}0.5$ pb



- **DiBoson** cross sections



Measurements of **W/Zγ**, **WW** and **WZ** cross sections

$$\boxed{\sigma(WW) = 13.6 \pm 2.3(stat) \pm 1.6(syst) \pm 1.2(lum)\, pb}$$

$$\boxed{\sigma(WZ) = 4.4^{+1.3}_{-1.0}(stat) \pm 0.2(syst) \pm 0.3(lum)\, pb}$$

Consistent with NLO calculation

ZZ production → Evidence at CDF
Observation at DØ!!

$$\boxed{\sigma(ZZ) = 1.48 \pm 0.59(stat)^{+0.17}_{-0.19}\, pb}$$

Consistent with NLO calculation: 1.4 ± 0.1 pb

The focus is now to uncover the unknown

Needle in the haystack

- Every measurement we make is an attempt to find New Physics
- When searching for a needle in a haystack, the hay is more important than the needle...
- Many searches are extensions of SM measurements.

→ Model-inspired searches

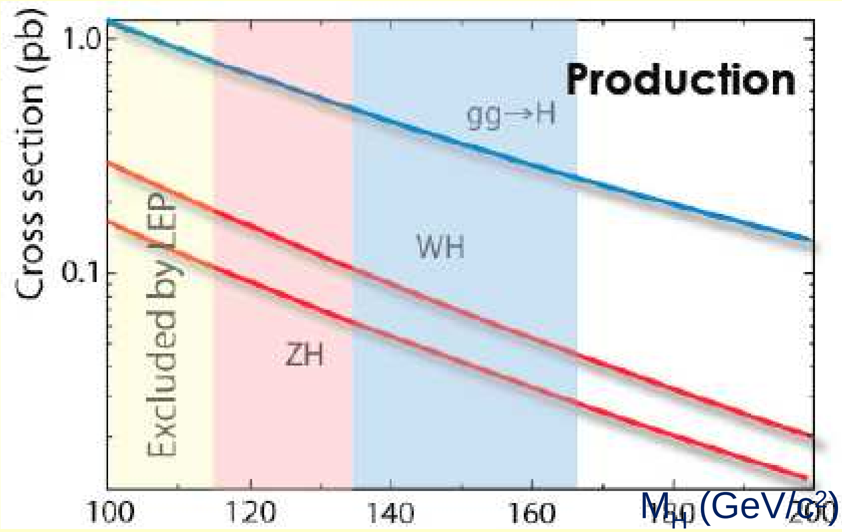
- **Theory driven**
- **Model-dependent optimization of event selection**
- **Set limits on model parameters**

→ Signature-based searches

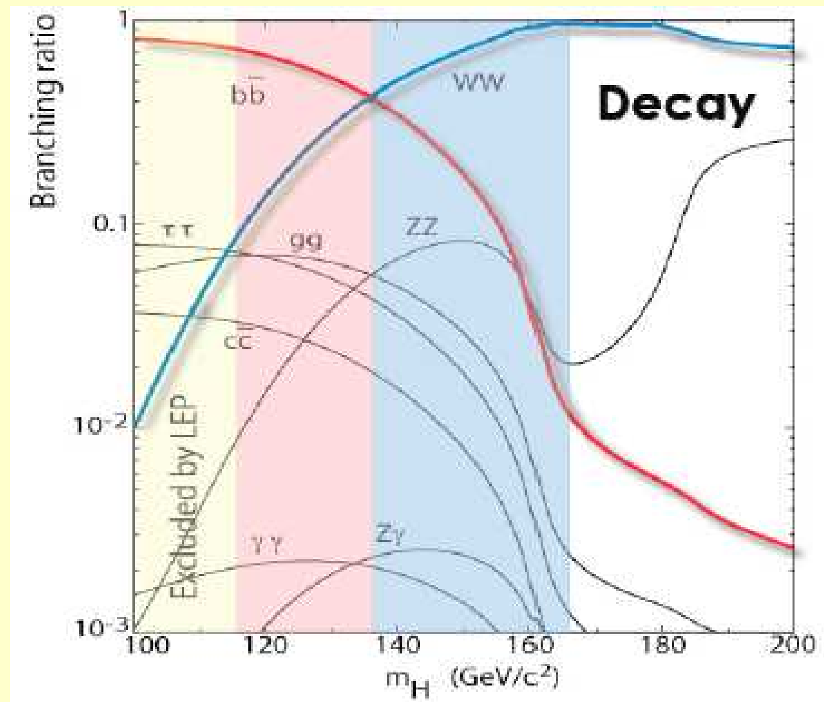
- **Signature driven**
- **Optimize selection to reduce backgrounds**
- **Event count; event kinematics**

The SM Higgs Boson

SM Higgs Production and Decay



- Direct production $gg \rightarrow H$
  - Highest Production rate
  - Largest background
- Associated production ZH/WH
  - Leptonic vector boson decay helps for triggering and signal extraction



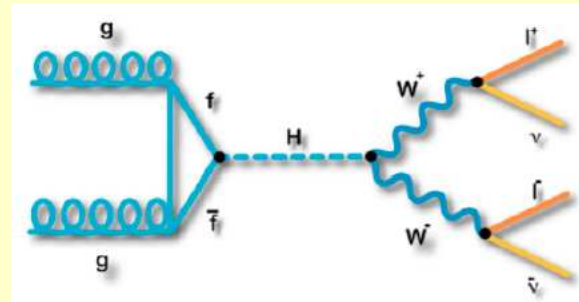
- Low Mass (M_H<135 GeV/c²)
  - $H \rightarrow b\bar{b}$ mode dominates
  - → $WH \rightarrow l\nu b\bar{b}$, $ZH \rightarrow \nu\nu b\bar{b}$, $ZH \rightarrow llb\bar{b}$
    VBF Production, $VH \rightarrow qqb\bar{b}$, $H \rightarrow \tau\tau$(with 2jets), $H \rightarrow \gamma\gamma$, WH->WWW, ttH
- **High Mass (135<M_H<200 GeV/c²)**
  - $H \rightarrow WW$ mode dominates

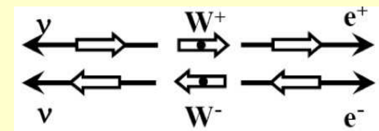
Higgs→WW→lνlν*

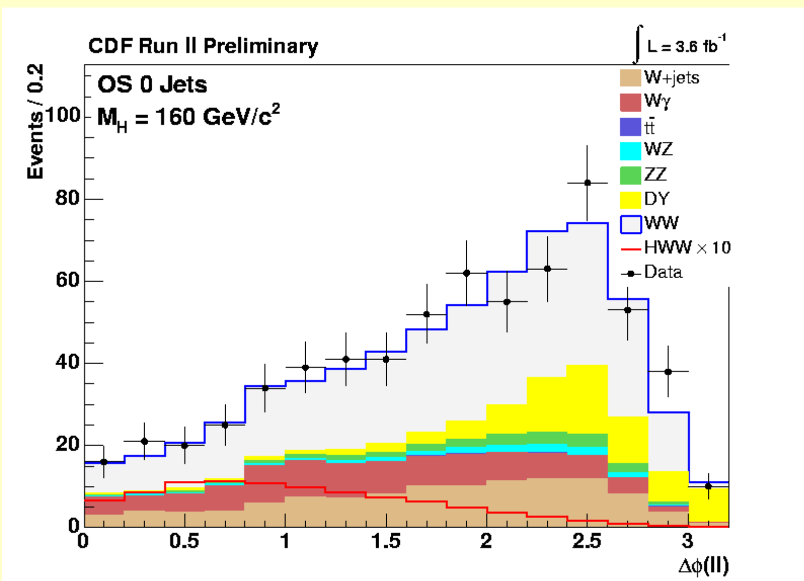
- Most sensitive channel for high mass Higgs
- Unbalanced transverse energy (MET) from ν

$$\not{E}_T = \sum_i E_T^i \vec{n}_i$$

- 2 leptons: e,μ,τ→e,μ (must have opposite signs)
  - *Key issue*: Maximizing lepton acceptance
  - Primary backgrounds: WW (and top in di-lepton decay channel)
    - Higgs is scalar ⇒ leptons travel same direction
    - In t-channel WW, W are polarized along the beam direction







- Use Matrix Element and Neural Network methods

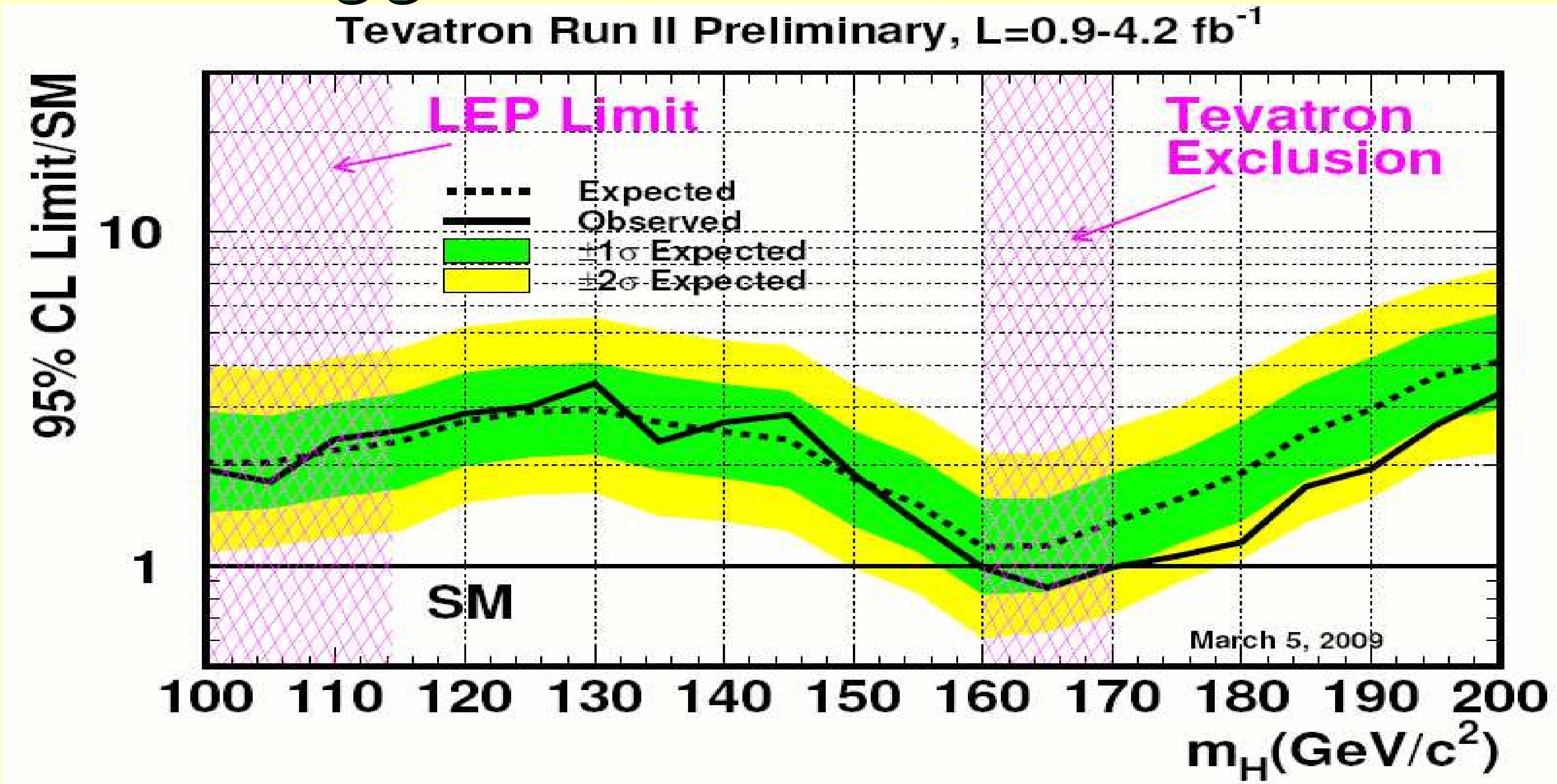
Results at m_H = 160GeV : 95%CL Limits/SM

	L (fb^{-1})	Higgs Events	Exp.	Obs.
CDF	3.6	20.0±2.5	1.5	1.5
DØ	3.0-4.2	23.2±0.1(stat)	1.8	2.7

Both experiments approaching SM sensitivity!

SM Higgs limits

CDF/D0 combination



Expected limits of 1.1 and 1.4 x σ_{SM} @160 and 170 GeV/c^2

Tevatron exclude @95% C.L. the production of SM Higgs in the mass range **160-170 GeV**

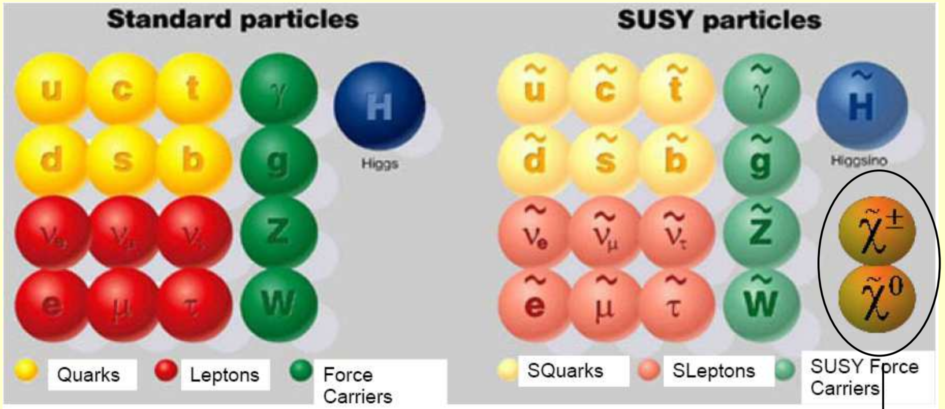
A ~30 GeV window [154:181] excluded @ 90% CL

http://www.fnal.gov/pub/presspass/press_releases/Higgsmass-constraints-20090313.html

Searches Beyond SM

Supersymmetry

Supersymmetry



gaugino/higgsino mixing

- New spin-based symmetry relating fermions and bosons:

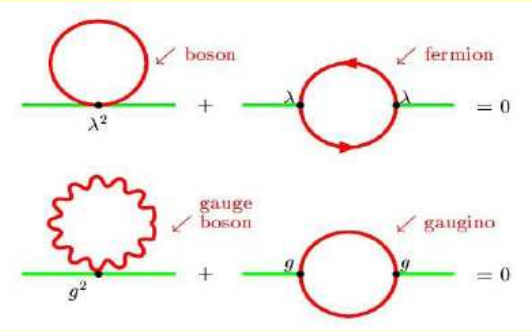
  Q | Boson> = Fermion

  Q | Fermion> = Boson

- Minimal SuperSymmetric SM (MSSM):
  - Mirror spectrum of particles
  - Enlarged Higgs sector: two doublets with 5 physical states

$$\boxed{H_U, H_D \longrightarrow h, H, A, H^{\pm}}$$

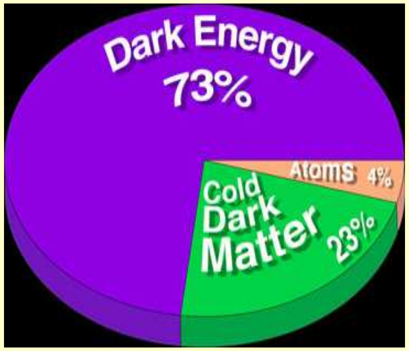
Naturally solve the hierarchy problem



- Define R-parity = $(-1)^{3(B-L)+2s}$
  - R = 1 for SM particles
  - R = -1 for MSSM partners

If conserved, provides Dark Matter Candidate

(Lightest Supersymmetric Particle)



Symmetry breaking

No SUSY particles found yet:

- SUSY must be broken $L = L_{SUSY} + L_{Soft}$
- More than 100 parameters even in minimal (MSSM) models
- Breaking mechanism determines **phenomenology** and **search strategy** at colliders:
  - Direct searches or subtle deviations in precision measurements

choose a model →

mSUGRA,
GMSB,
....

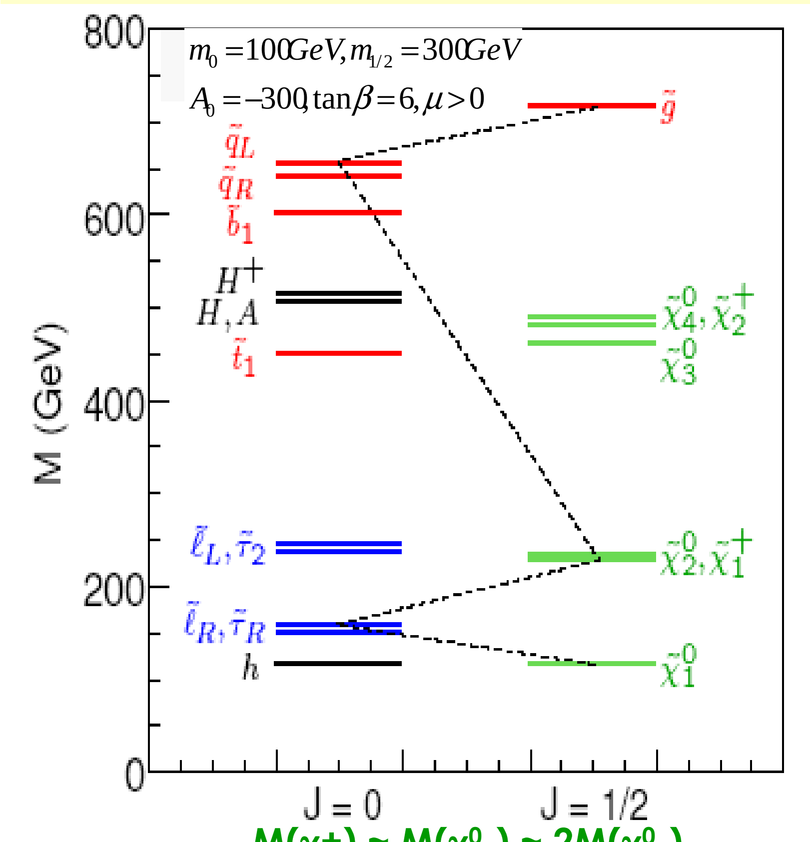
SUSY breaking (hidden sector) $\xrightarrow{\text{gravity}}$ *or* $\xrightarrow[\text{Gauge fields, loop effects....}]{}$ MSSM (visible sector)

Constrained MSSM models used as benchmark

Sparticles mass and cross sections

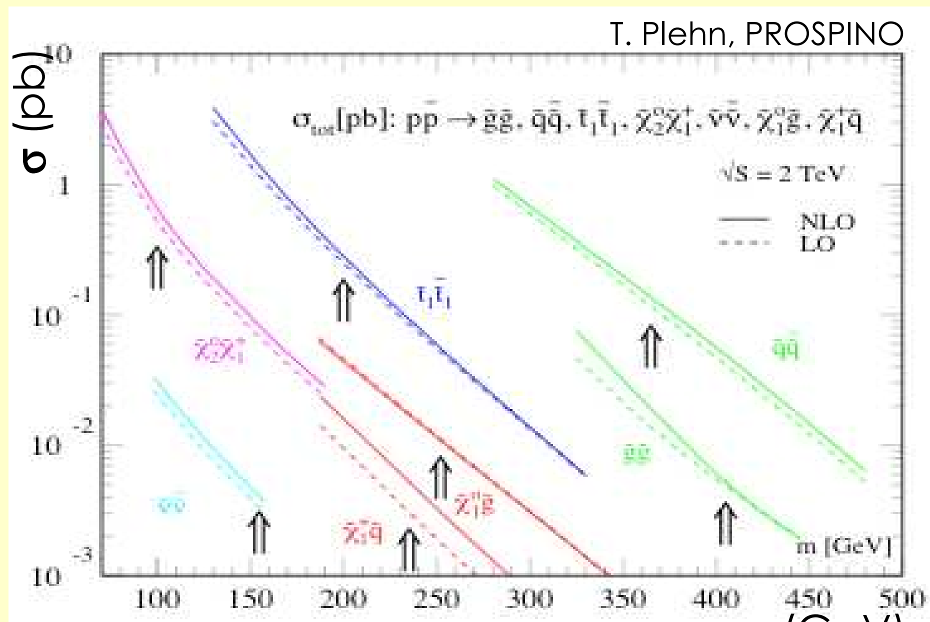
- in **mSUGRA**, new superfields in "hidden" sector
- Interact gravitationally with MSSM
- **5 parameter at GUT scale**

1. Unified gaugino mass $m_{1/2}$
2. Unified scalar mass m_0
3. Ratio of H_1, H_2 vevs $\tan\beta$
4. Trilinear coupling A_0
5. Higgs mass term $sgn(\mu)$



$M(\chi+) \sim M(\chi^0_2) \sim 2M(\chi^0_1)$

$M(\tilde{g}) \sim 3M(\chi+)$

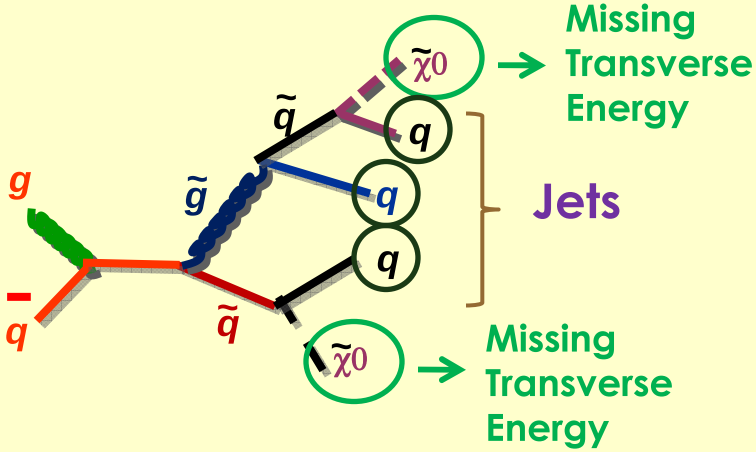


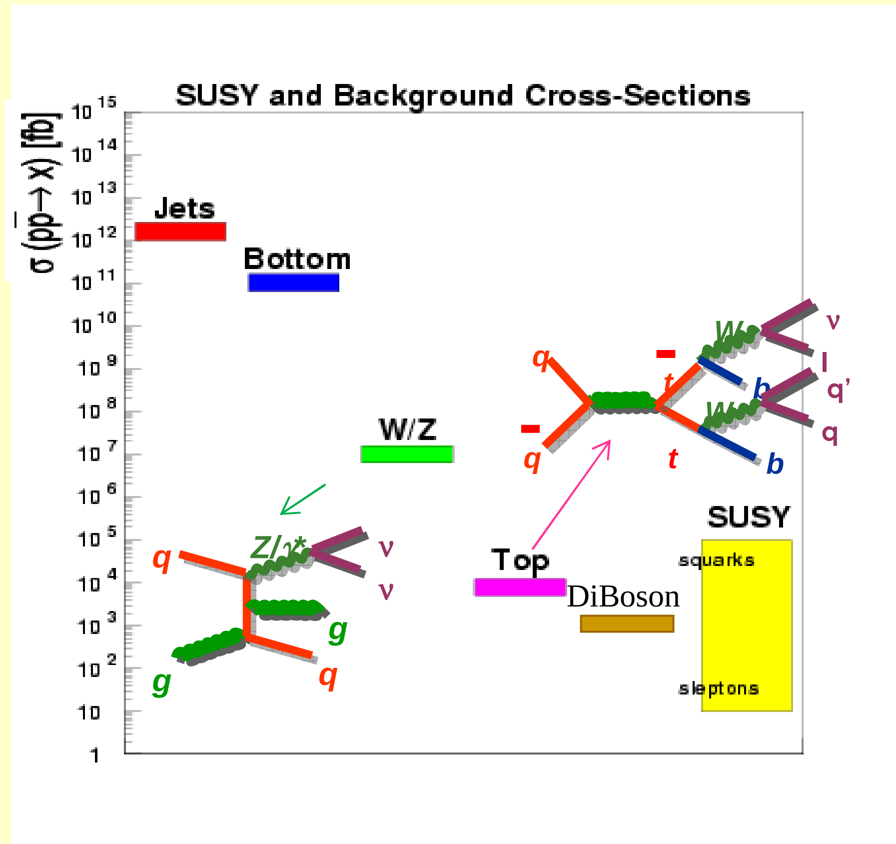
- Squarks and gluinos are heavy
- Sizeable Chargino/neutralino cross sections

In R parity conservation scenario, the LSP is the neutralino (χ^0_1)

Squark/gluino production

- Strongly interacting particles → "large" production cross section
  - For squark/gluino masses ~ 400 GeV
    - Tevatron: ~ 50 events per fb^{-1}
    - LHC: ~ 100K events per fb^{-1}
- Pair produced in R_p conservation scenario





Signature: jets of hadrons and large unbalanced energy (χ^0)

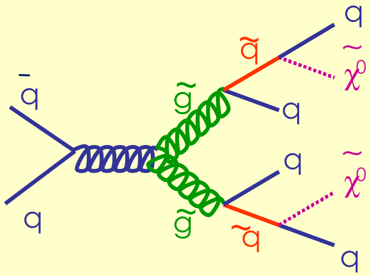
$\sigma(SM)/\sigma(SUSY) \sim O(10^{10})$

- Severe rejection of QCD multi-jets and top needed
- Z->$\nu\nu$+jets irreducible

Search strategy

$A_0 = 0$, $\mu<0$
$M_0 \in [0,500\ \mathrm{GeV/c^2}]$
$m_{1/2} \in [50,200\ \mathrm{GeV/c^2}]$

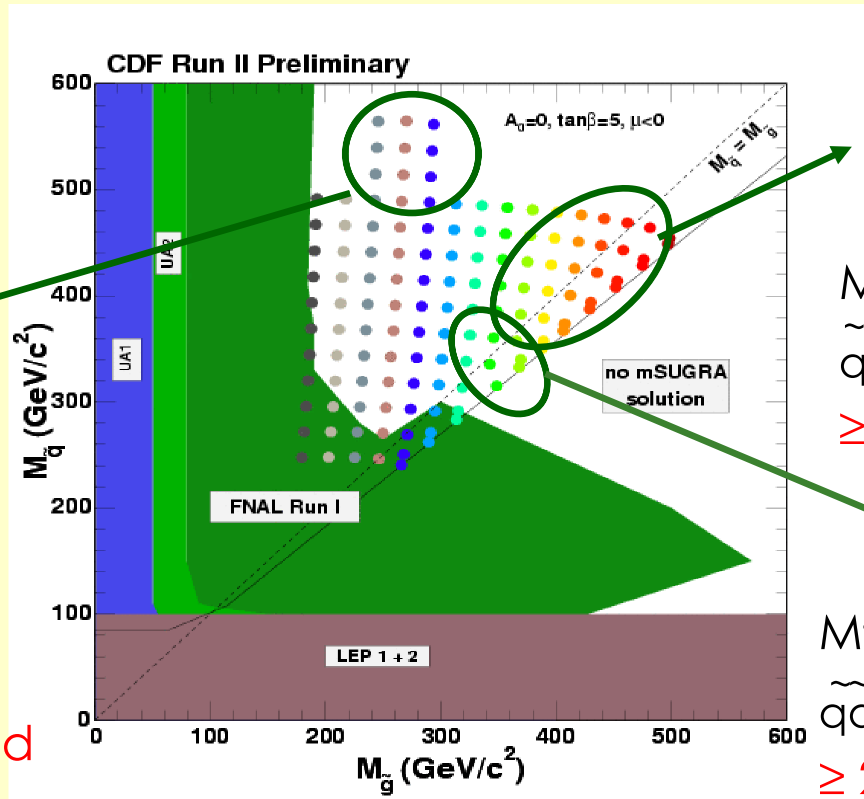
→mSUGRA: Low tan β (=5 CDF, =3 DØ)
→Assume 5-flavors degenerate

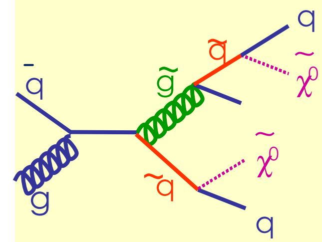


$M_{\tilde{q}} > M_{\tilde{g}}$

$\tilde{g}\tilde{g}$ final state dominates

≥ 4 jets expected

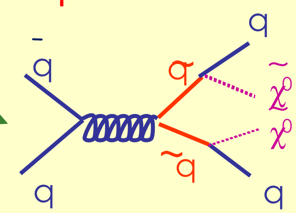




$M_{\tilde{q}} \sim M_{\tilde{g}}$

$\tilde{q}\tilde{g}$ final state dominates

≥ 3 jets expected



$M_{\tilde{q}} < M_{\tilde{g}}$

$\tilde{q}\tilde{q}$ final state dominates

≥ 2 jets expected

3 different analyses carried out with different jet multiplicities

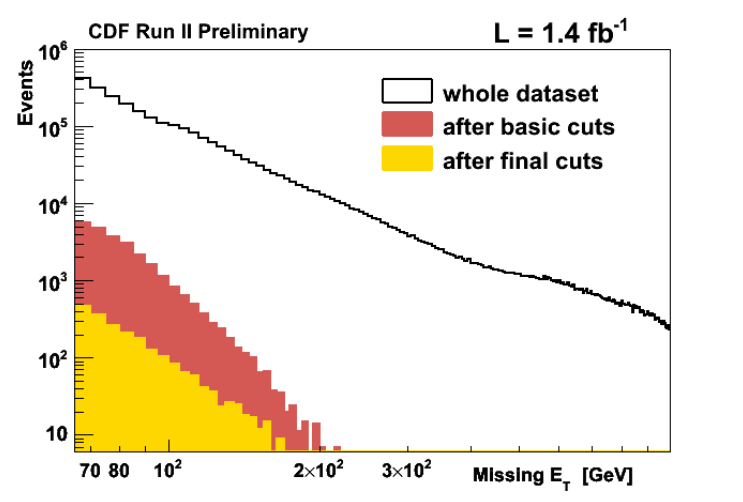
Final selection based on Missing E_T , $H_T = \Sigma$ ($E_T$jets) and E_T jets

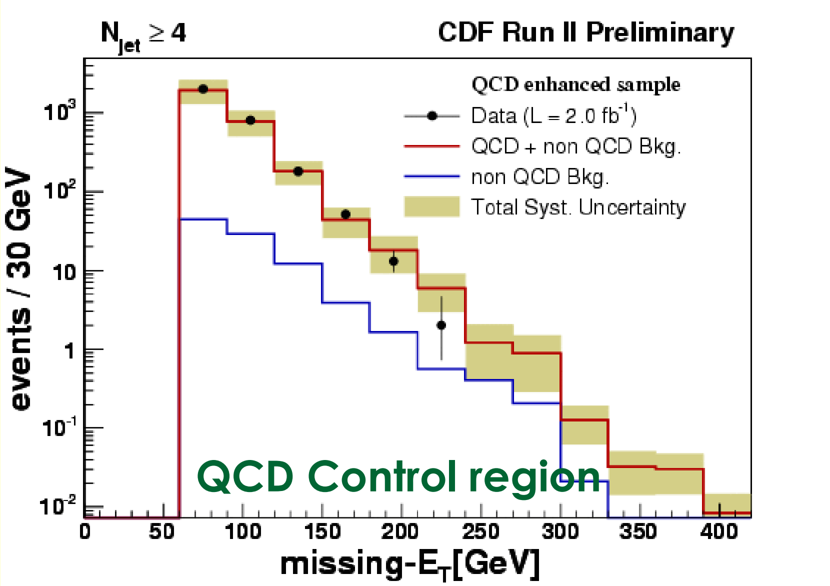
Background rejection

- Clean-up cuts applied to reject cosmics and beam-related bkg

- **QCD multijet rejection:** due to Missing E_T from mis-reconstructed jets
  → Apply cuts on $\Delta\phi$ (missingE_T-jets)

- **Boson+jets, DiBoson and top production rejection:** Genuine Missing E_T in the event
  → Suppressed vetoing events with:
  - jet Electromagnetic fraction > 90%
  - isolated tracks collinear to missing E_T



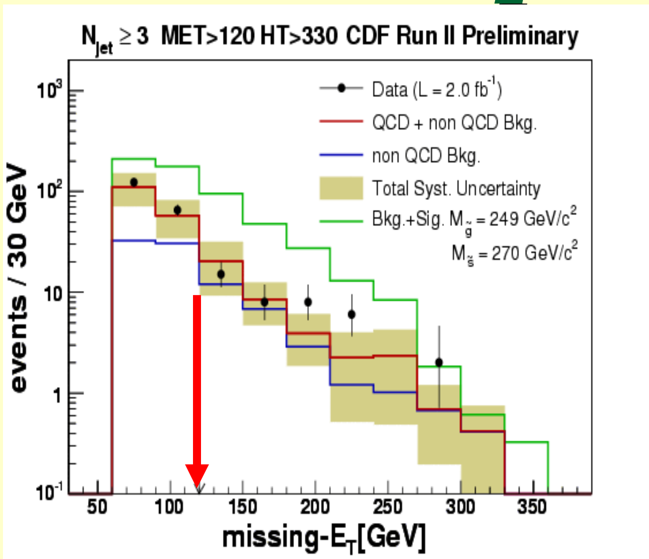


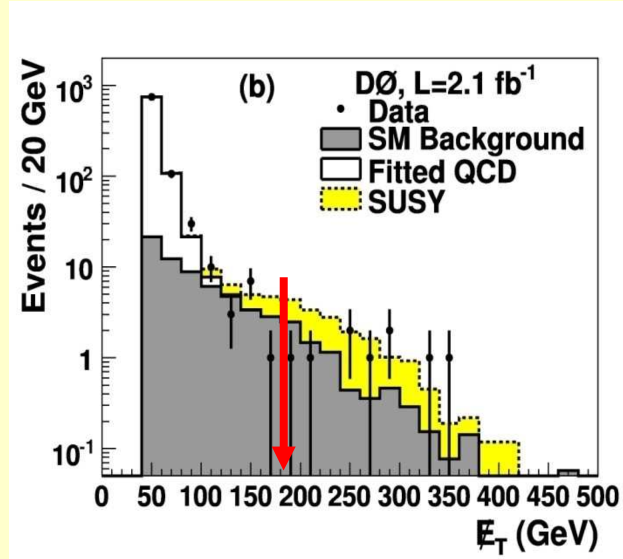
Define **control regions** reversing selections to check predictions for remaining bkgs modeled with MC and normalized to data or NLO

$\Delta\phi$(MET-jets) cut reversed for at least one of the leading jets

DATA vs SM predictions

CDF





DØ

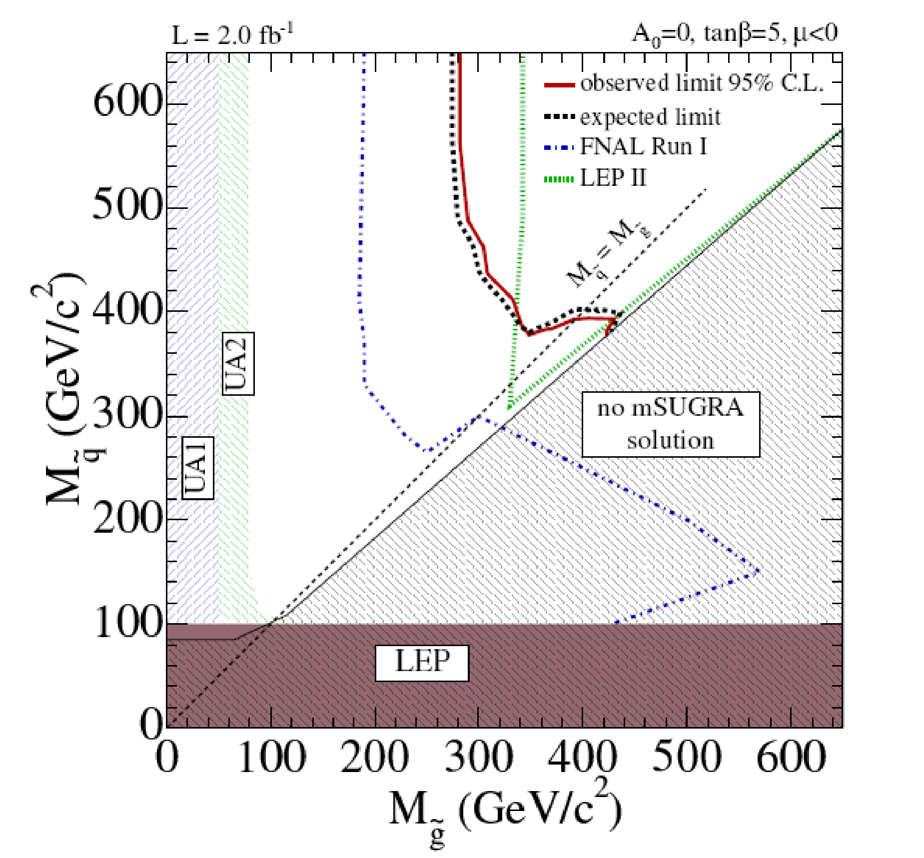
	2 jets	3 jets	4 jets(gluino)
CDF	H_T>330, $\not{E}_T$>180GeV/c^2	H_T>330, $\not{E}_T$>120GeV/c^2	H_T>280, $\not{E}_T$>90GeV/c^2
Data	**18**	**38**	**45**
Expected SM	**16±5**	**37±12**	**47±17**
D0	H_T>330, $\not{E}_T$>225GeV/c^2	H_T>375, $\not{E}_T$>175GeV/c^2	H_T>400,$\not{E}_T$>100GeV/c^2
Data	**11**	**9**	**20**
Expected SM	**11.1±1.2**	**10.7±0.9**	**17.7±1.1**

Good agreement between Observed and Expected events
Systematic uncertainties dominated by Jet Energy scale

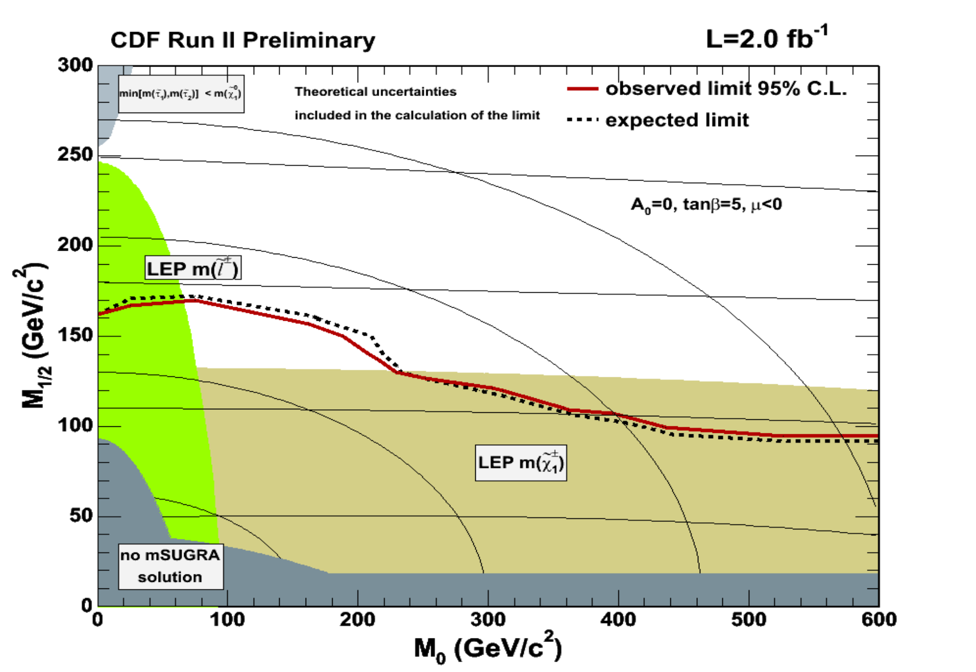
Exclusion limits: $M_{\tilde{g}}$ -$M_{\tilde{q}}$ and M_0-$M_{1/2}$ plane

Similar results for CDF and DØ

95% C.L. Exclusion limit



Results can be interpreted as a function of mSUGRA parameters

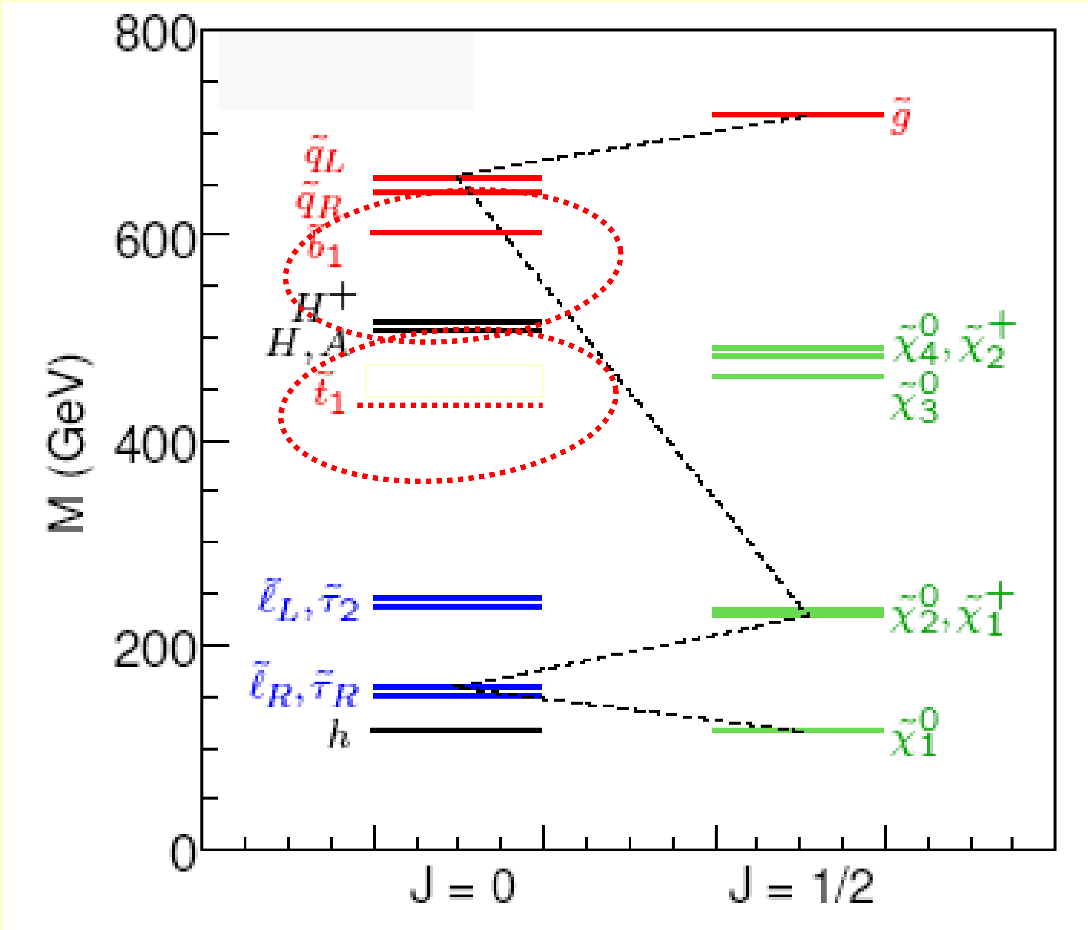


For $M_{\tilde{g}}=M_{\tilde{q}} \rightarrow$ **M > 392** GeV/c²

$M_{\tilde{g}}$> 280 GeV/c² in any case

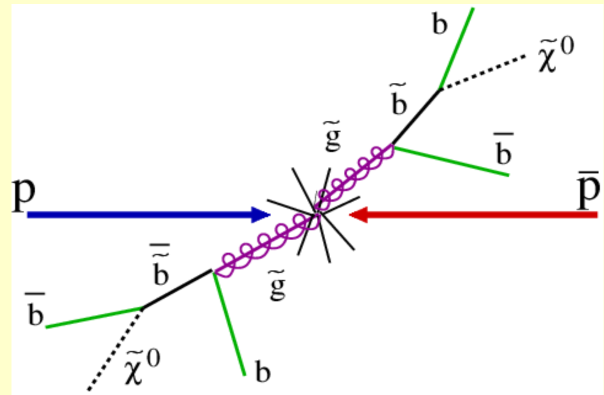
LEP limit improved in the region where **$70<M_0<300$ GeV/c²** and **$130<M_{1/2}<170$ GeV/c²**

Third squarks generation



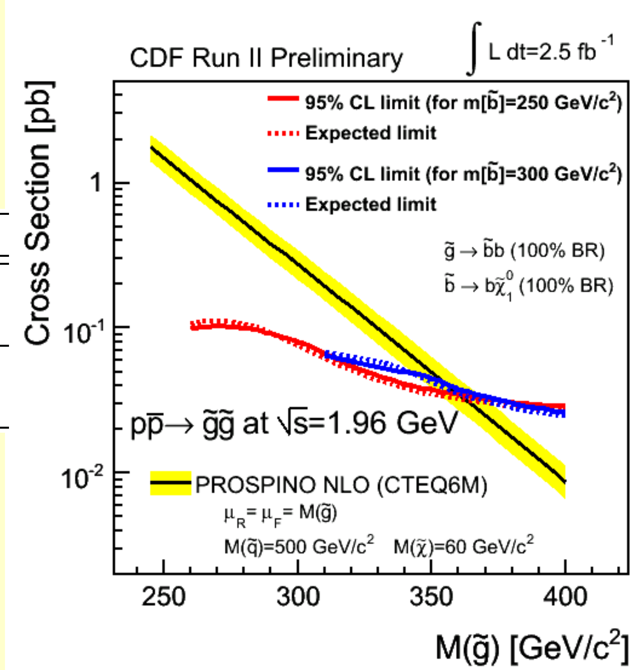
$\tilde{g}$-mediated $\tilde{b}$ production

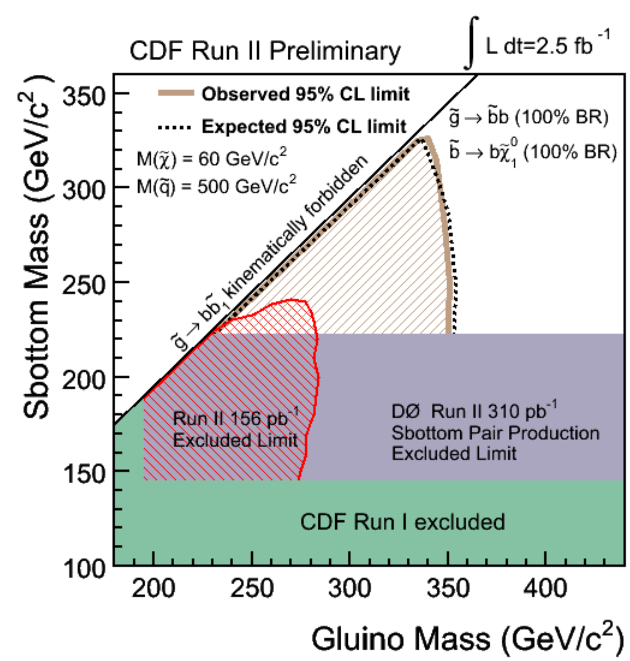
- Light sbottom in large mixing scenarios
- Dedicated searches for $\tilde{b}$ production
- → **If m($\tilde{b}$)<m($\tilde{g}$)** (assuming B.R. ($\tilde{b}$→b $\chi 0$) = 100%) :
  Search for $\tilde{b}$ from gluino decays ($\sigma_{\tilde{g}\tilde{g}}$ ~ 10 $\sigma_{\tilde{b}\tilde{b}}$)
  - **Final state**: $\not{E}_T$ + 4 b-jets
  - Use b-tagging algorithm to identify b-jets and 2 Neural Network to reject background (top and QCD-multijets)



Two optimization regions depending on $\tilde{g}$-$\tilde{b}$ mass

	Large Δm	Small Δm
Exp.	4.5 ± 1.4	2.3 ± 0.8
Obs.	5	2
Sig ($m_{\tilde{g}} = 335$, $m_{\tilde{b}} = 260$)	14.9 ± 5.0	-
Sig ($m_{\tilde{g}} = 335$, $m_{\tilde{b}} = 315$)	-	8.5 ± 2.8

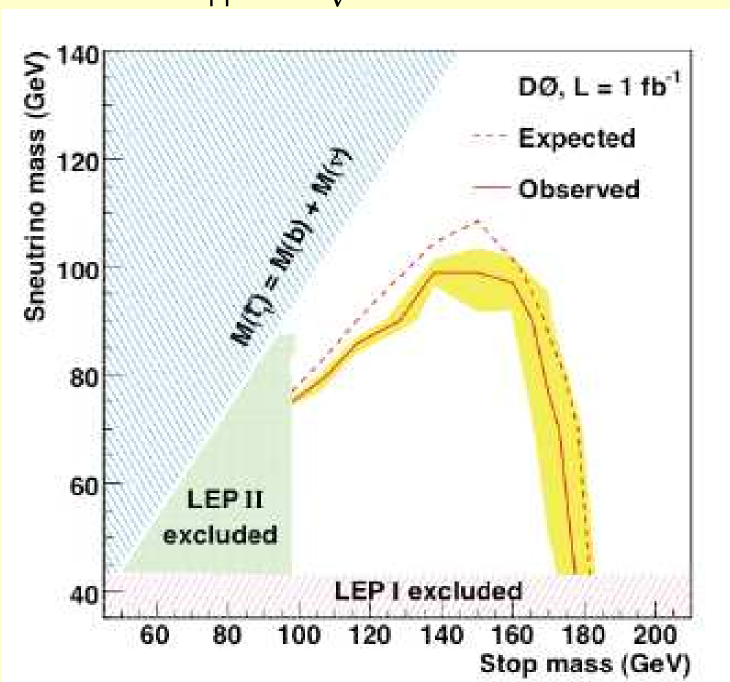




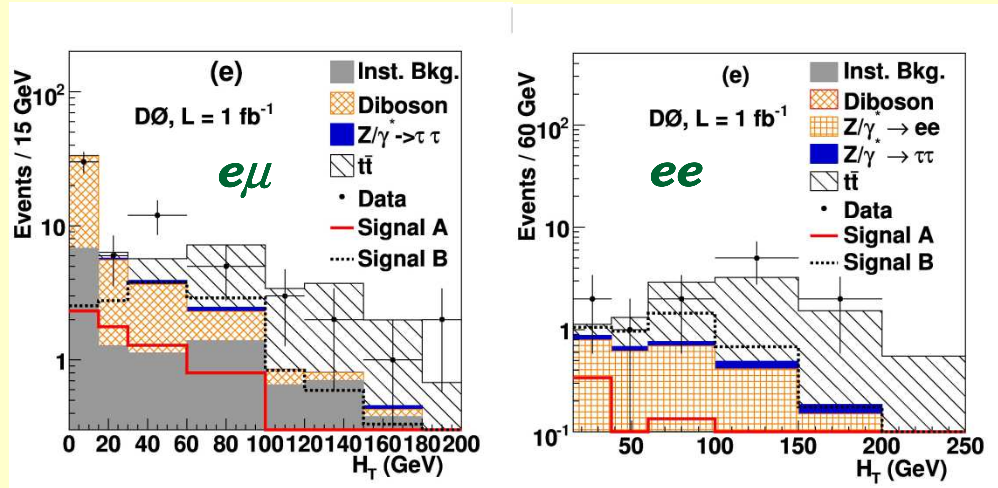
Stop searches

$\tilde{t}_1 \rightarrow bl\,\tilde{\nu}$

- **Signature:** Missing E_T, two opposite-sign leptons (here ee,eμ), 2 b-jets
- Signal topology depends on $\Delta m = m_{\tilde{t}1} - m_{\tilde{\nu}}$



For large Δm: $m_{\tilde{t}1}$ < 175 GeV

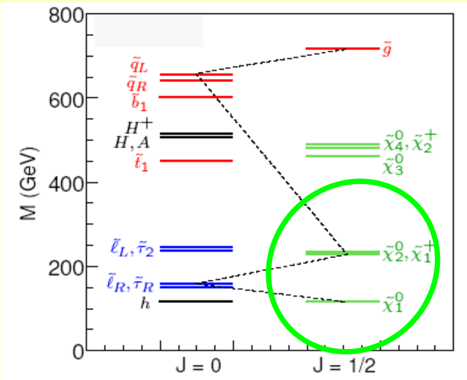


$H_T = \Sigma(p_T\text{jets})$

- Main background processes: WW, top production, Z→ee/ττ
  - Use Monte Carlo samples
  - Normalized to NLO cross section
- Optimization in H_T, H_T+leptonsP_T

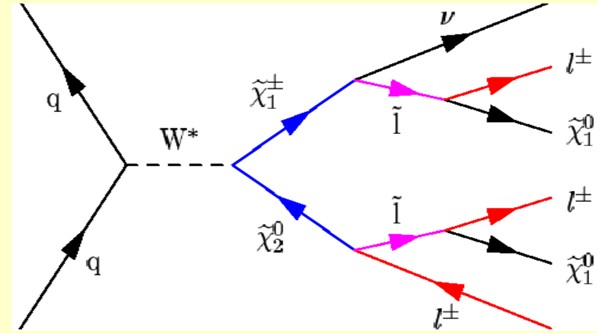
channel	Data	Exp. Bkg.	Sig. A	Sig. B
ee	12	12.2 ± 0.4	0.6	4.6
$e\mu$	61	65 ± 4	6.0	16.1

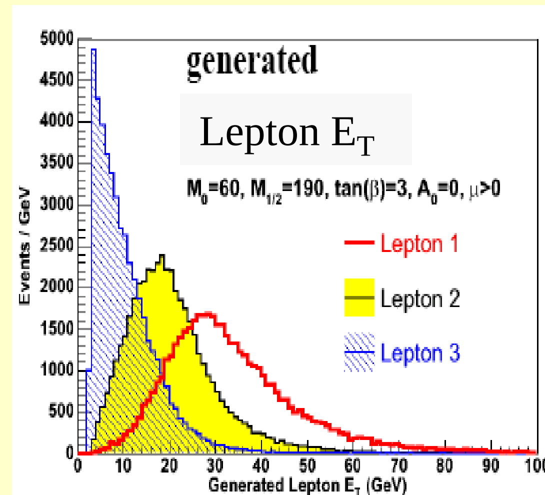
Search for chargino/neutralino



mSUGRA $\chi^0_2\,\chi^\pm_1$ pair production

Signature: three leptons and $\not{E}_T$





- **Small cross sections (~0.1-0.5 pb)**
- **Very low background:**
  - Drell-Yan, Diboson (WW, WZ/γ*, ZZ/γ*, Wγ)
  - Top pair production
  - QCD-multijets, W+jets (misidentified leptons)

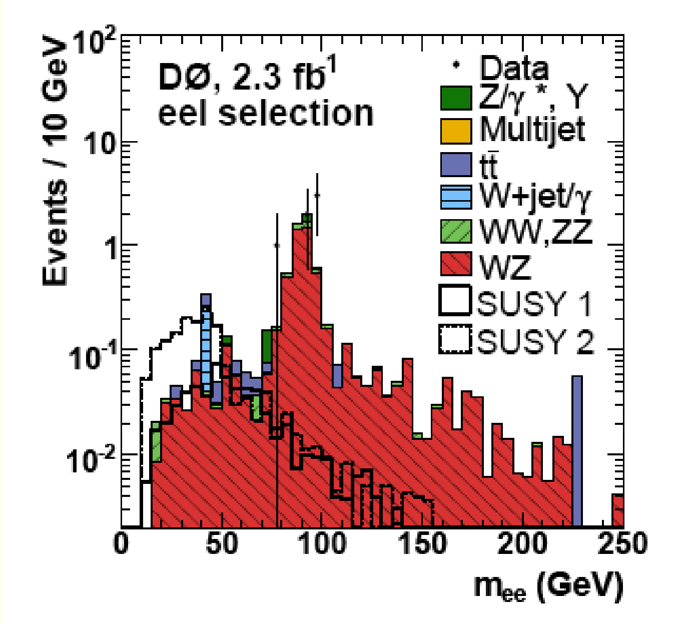
- **CDF (2 fb^{-1}):**
  - 5 exclusive channels
  - combinations of "tight" (t) and "loose" (l) lepton categories
    - 3-leptons (e,μ,τ_{Lept})
    - 2-leptons (e,μ,τ_{Lept}) + iso-track T (τ_{Hadr})

- **DØ (1.0-2.3 fb^{-1}):**
  - 3 channels type
  - 2 identified leptons (e,μ)+IsoTrk
  - μτ+IsoTrk, μτ+τ (τ hadronic decay)
  - "low"-p_T and "high"-p_T search

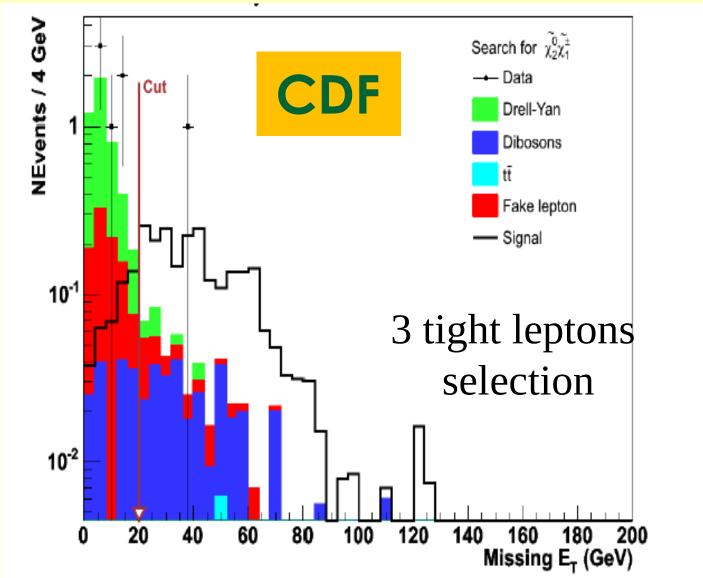
$\chi^0{}_2\,\chi^\pm{}_1$ results

DØ

Background reduction using several kinematic selections:
→ Invariant mass dilepton pairs, N jets, Missing E_T, $\Delta\phi$ between leptons ...



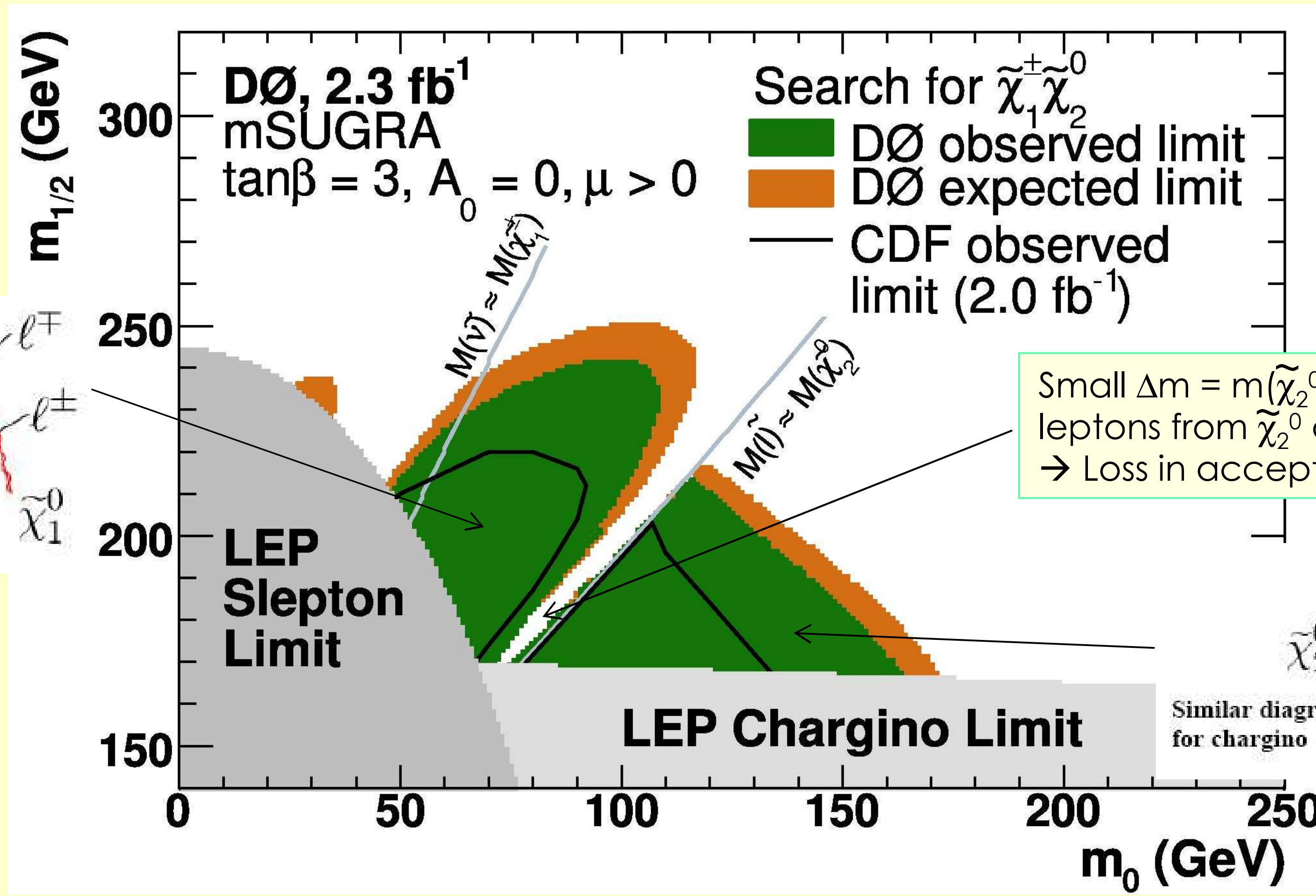
DØ (2.3 fb^{-1})			CDF (2.0 fb^{-1})		
Channel	SM expected	Data	Channel	SM expected	Data
Low p_T	5.4 ± 0.6	9	Trilepton	0.88 ± 0.14	1
High p_T	3.3 ± 0.4	4	Lepton+trk	5.5 ± 1.1	6

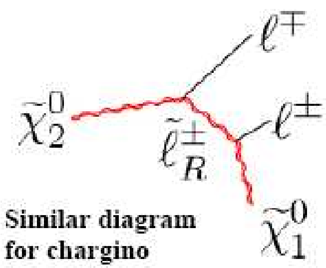


Good agreement between data and SM prediction → set limit

Excluded region in mSUGRA

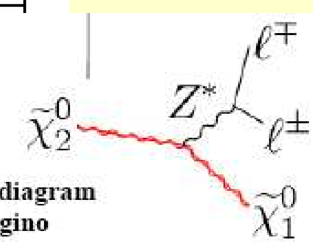
excluded region in mSUGRA m_0-$m_{½}$ space for tan(β)=3, A_0=0, μ>0





Similar diagram for chargino

Small Δm = m($\tilde{\chi}_2^0$)-m($\tilde{l}$), soft leptons from $\tilde{\chi}_2^0$ decay
→ Loss in acceptance



Similar diagram for chargino

CDF | **At m_0 = 60 (100) GeV/c^2**
Exclude $m\chi^{\pm}_1$ < 145 (127) GeV/c^2

DØ | **In "3l"-max scenario:**
Exclude $m\chi^{\pm}_1$ < 138 GeV/c^2

Gauge Mediated Symmetry Breaking

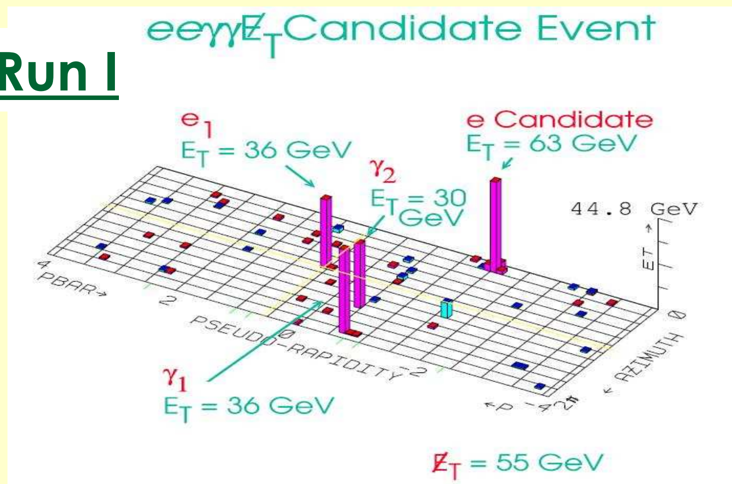
- SUSY breaking at scale Λ (10 -100 TeV). Mediated by Gauge Fields ("messengers")
- Gravitino very light (<< MeV) and LSP
- Neutralino or slepton can be NLSP
- If NLSP is neutralino

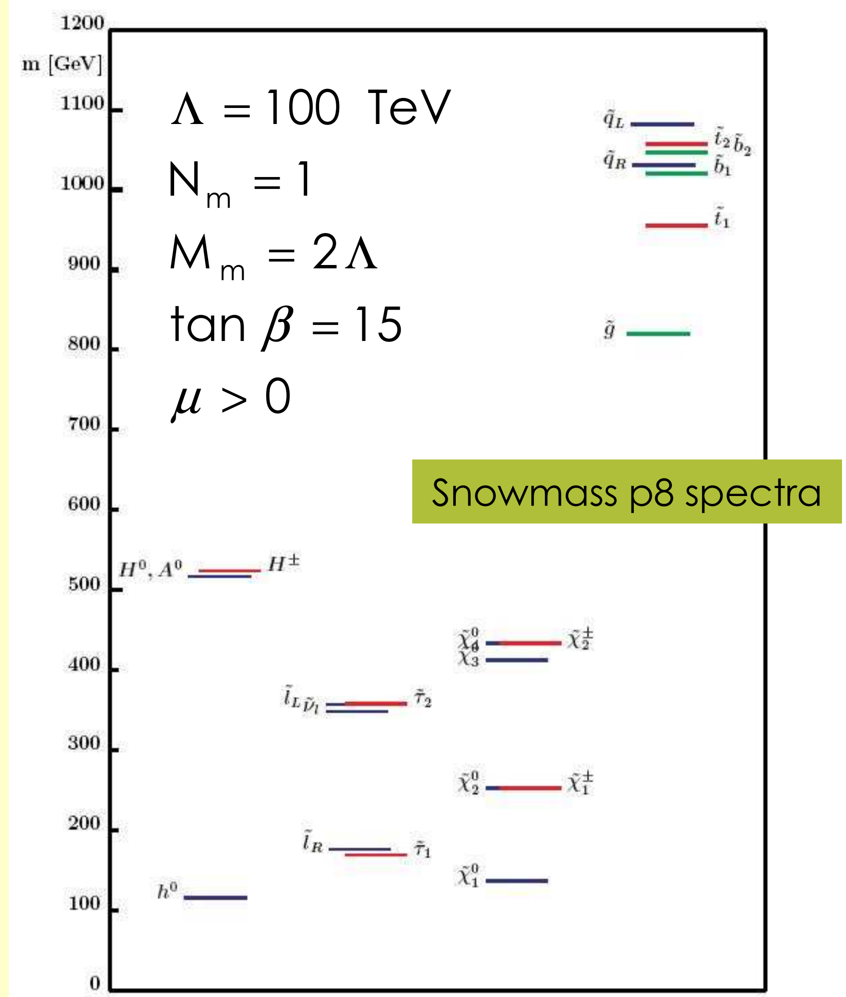
$$\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$$

In R_p conservation scenario:

→ 2 NLSP → 2γ + MET (+X) in final state

CDF Run I

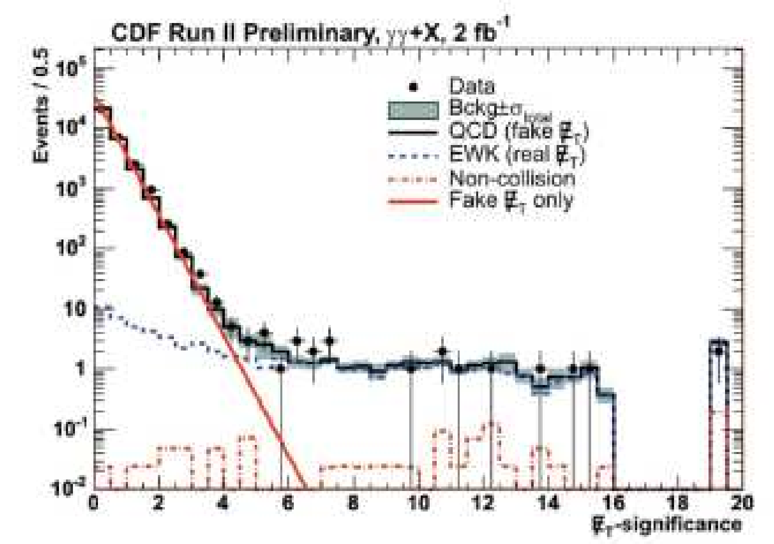




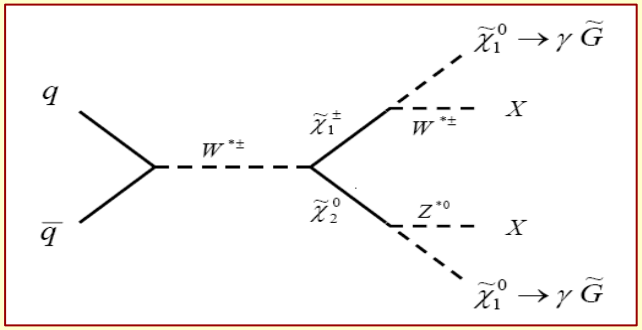
(taken from N. Ghodbane et al., hep-ph/0201233)

$\gamma\gamma$+Missing E_T

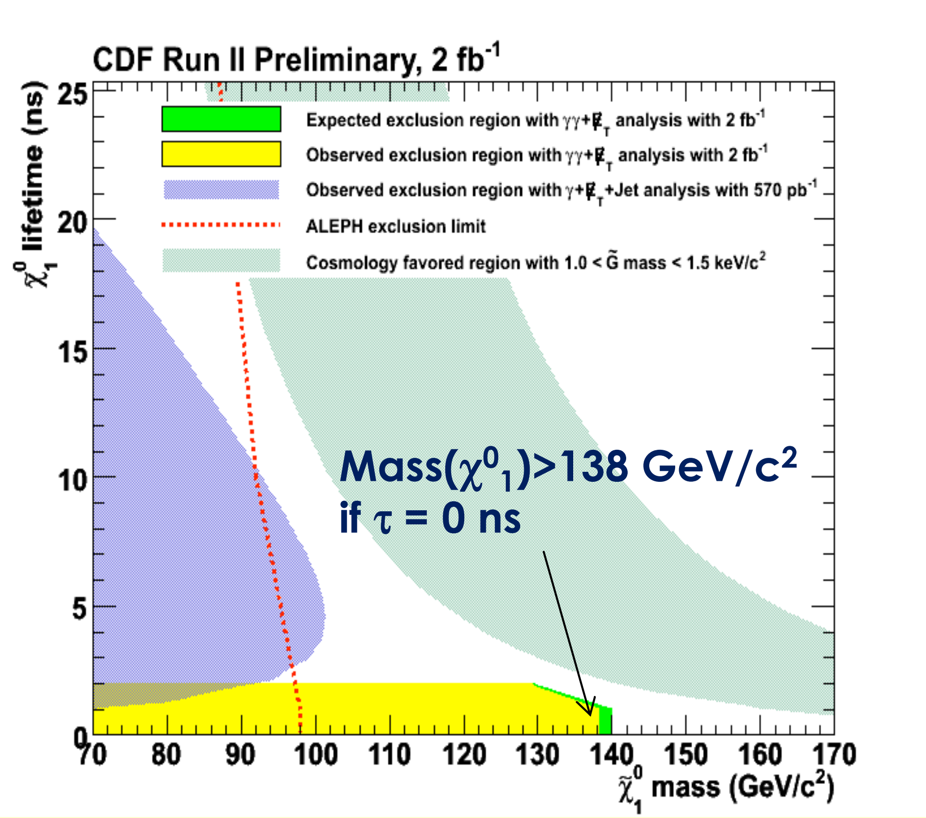
- χ^0_1 (NLSP) short-lived or long-lived
- Very low SM background
  - $Z\gamma\gamma \rightarrow \nu\nu\gamma\gamma$, $W\gamma\gamma \rightarrow l\nu\gamma\gamma$
- Understanding of instrumental background challenging:
  - Mis-measured E_T: use multijet data sample
  - $e \rightarrow \gamma$ misidentification: use $W(\rightarrow e\nu)\gamma$ data



Selection in Missing E_T significance
No excess observed



- Limits on neutralino mass VS lifetime



Searches Beyond SM

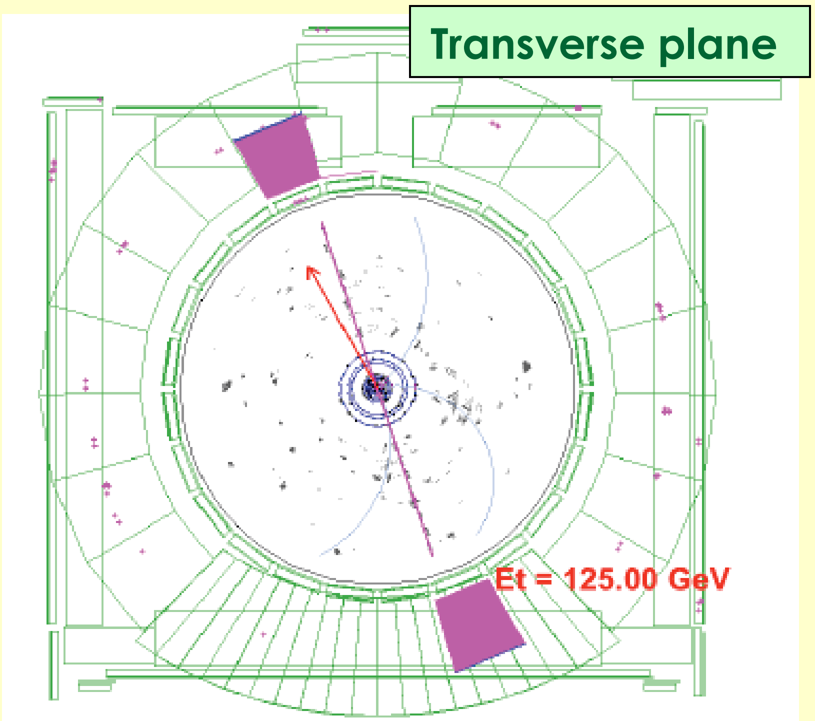
More 'Exotic' models…

- **Extra-Dimensions**
- **New Gauge bosons**

Search for high mass resonances

- ***Di-lepton*** *resonances* have a strong track record for discovery → J/ψ, Y, Z
  - Enlarge the possible final states looking also in ***dijet, ditop or dibosons***!
- Construct the pair invariant mass and look for any excesses in the high mass spectrum

Example of di-lepton events



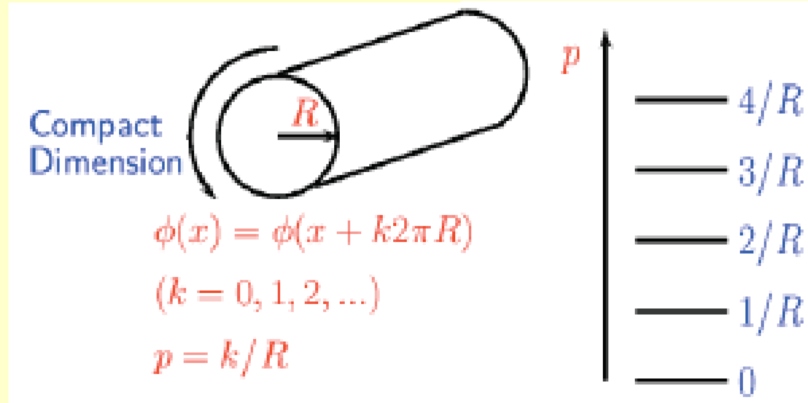
Advantage

Sensitive to many BSM scenarios:
- Extra-Dimensions
- Extended SUSY-GUT groups (SO(10),E6,E8...leading to additional gauge bosons, **Z'** and **W'**)
- R-parity violating SUSY

and more...

Extra-Dimensions

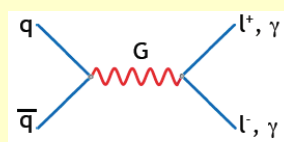
'Solves' the hierarchy problem by postulating that we live in more than 4 dimensions.

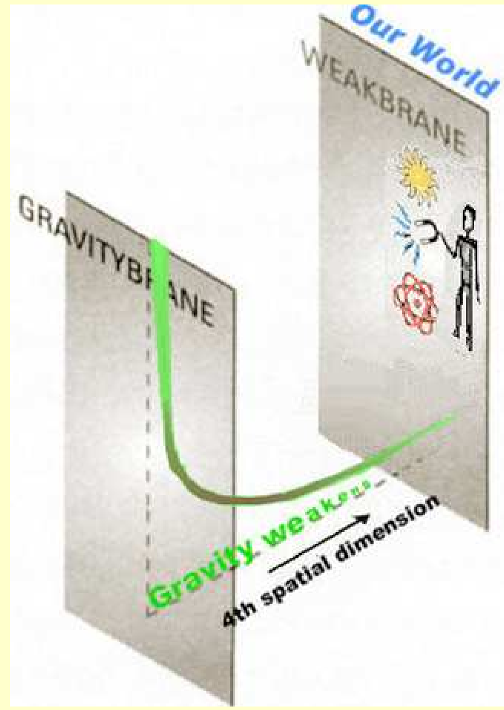


- **Large Extra Dimensions**: Arkani-Hamed, Dimopoulos, Dvali (ADD)
  - Gravity propagate in n_d additional spatial dimensions compactified at radius R
  - Effective Planck scale:

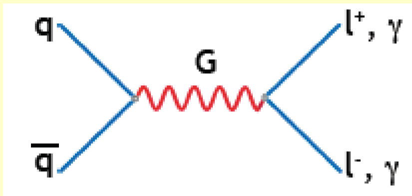
$$M^2_{Planck} \sim R^n (M_D)^{n+2}\ ,\ M_D \sim 1\ TeV$$

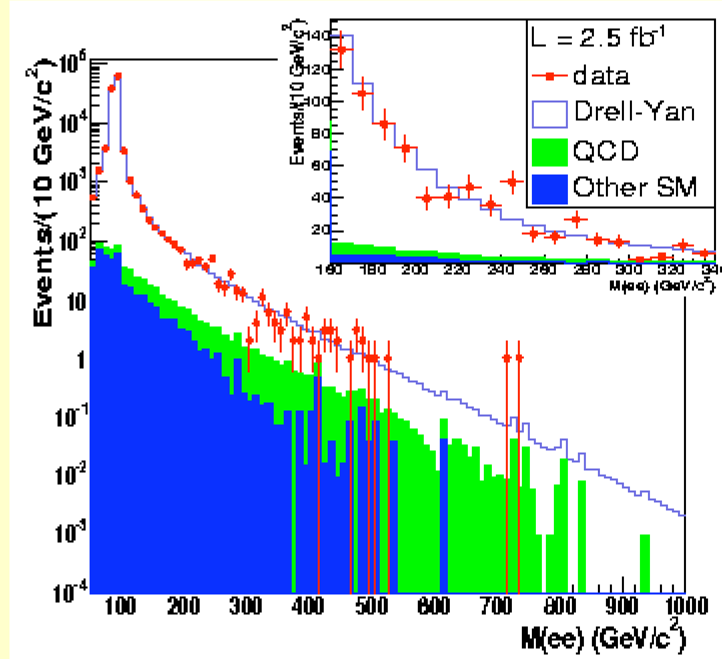
- **Randall-Sundrum model:** Only one extra dimensions (wraped) limited by two 4-dimensional brains.
  - SM particles live in one of the brains.
  - Graviton can travel in all 5 dimensions, appears as Kaluza-Klein towers
  - dimensionless coupling (k/M_{Pl}) free parameter





Search for High Mass e^+e^- / $\gamma\gamma$ Resonance

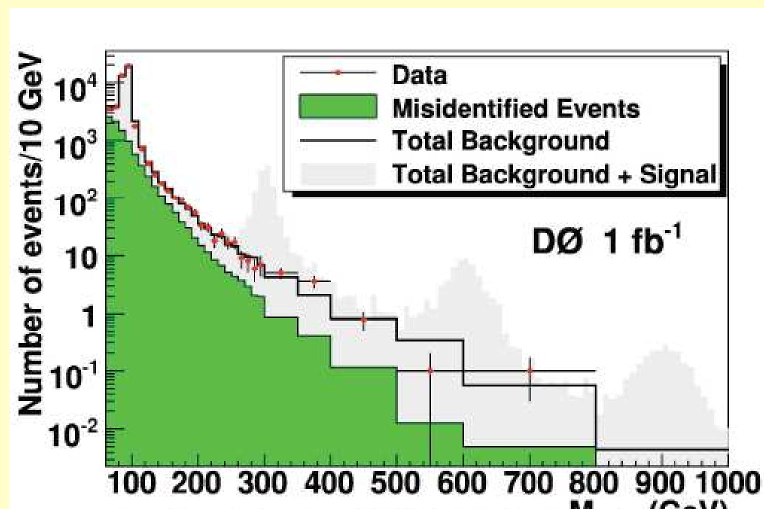




- Central-Central ($|\eta_{1,2}|<1$) or Central-Forward ($|\eta|<2$) e^+e^- pair with $E_T>25$ GeV

Major Backgrounds:

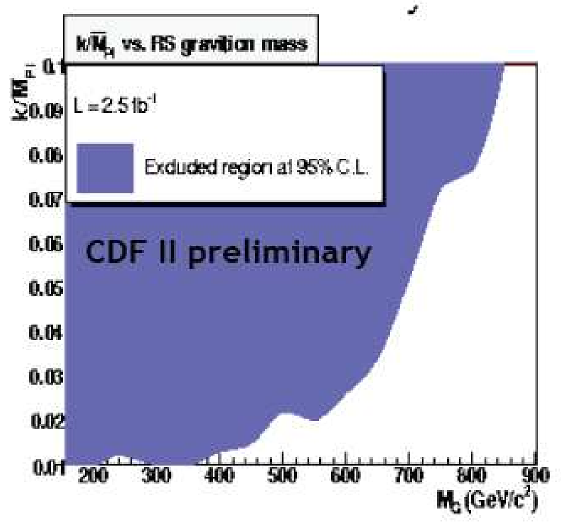
- DrellYan
- QCD (including W+jets)

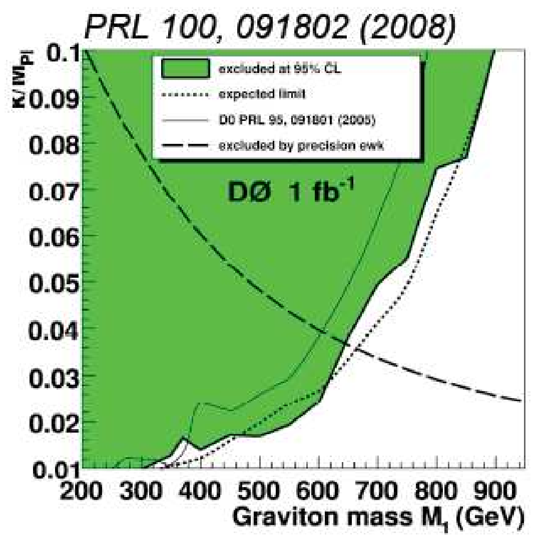


PRL 100, 091802 (2008)

- CDF/D0: Resonance search performed in mass range 150-1000 GeV/c^2
- No evidence for narrow resonances
  → set limits

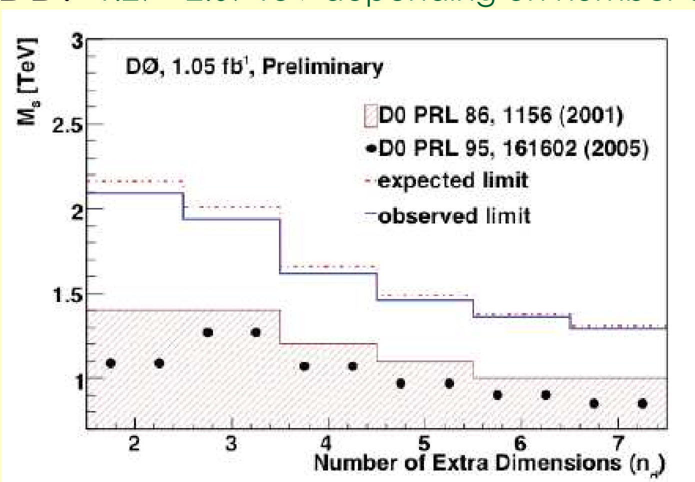
Exclusion limits

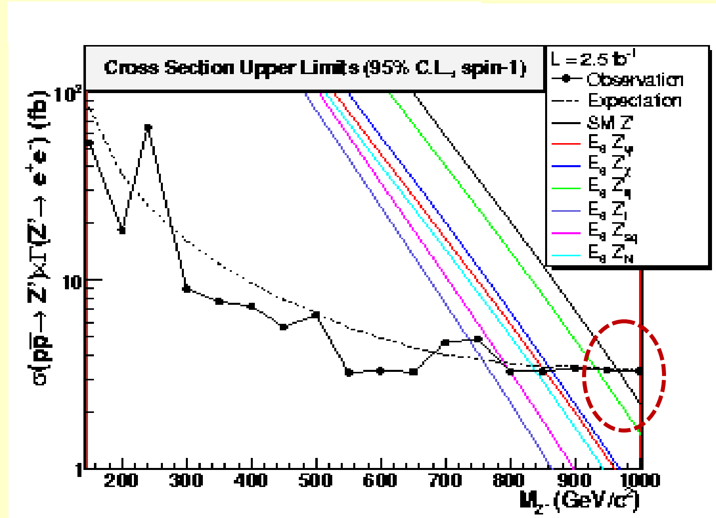




- CDF (DØ) exclude RS graviton with mass below 850 **(900)** GeV/c^2 for k/MPl=0.1

- Limits on effective Planck scale in ADD: 1.29 - 2.09 TeV depending on number of ED

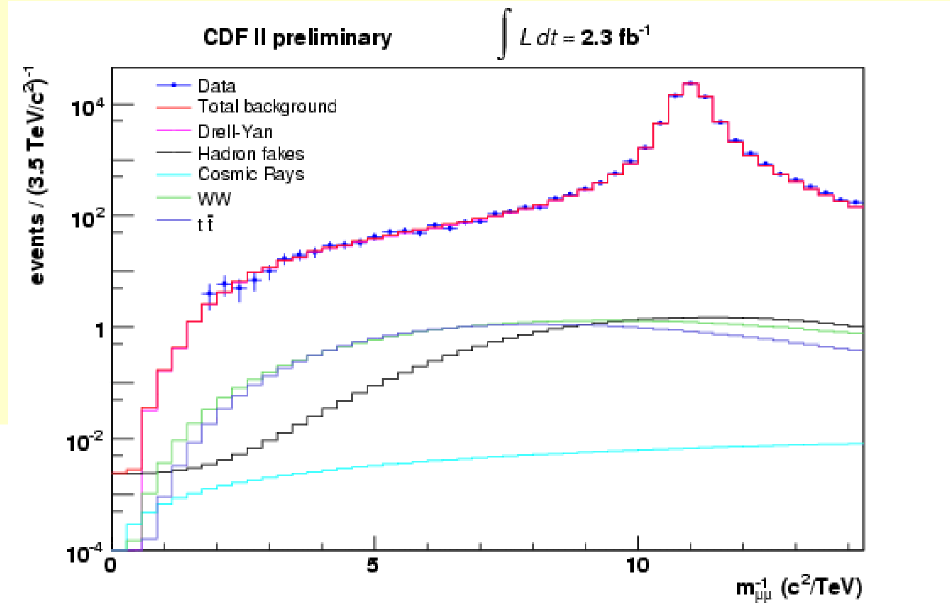




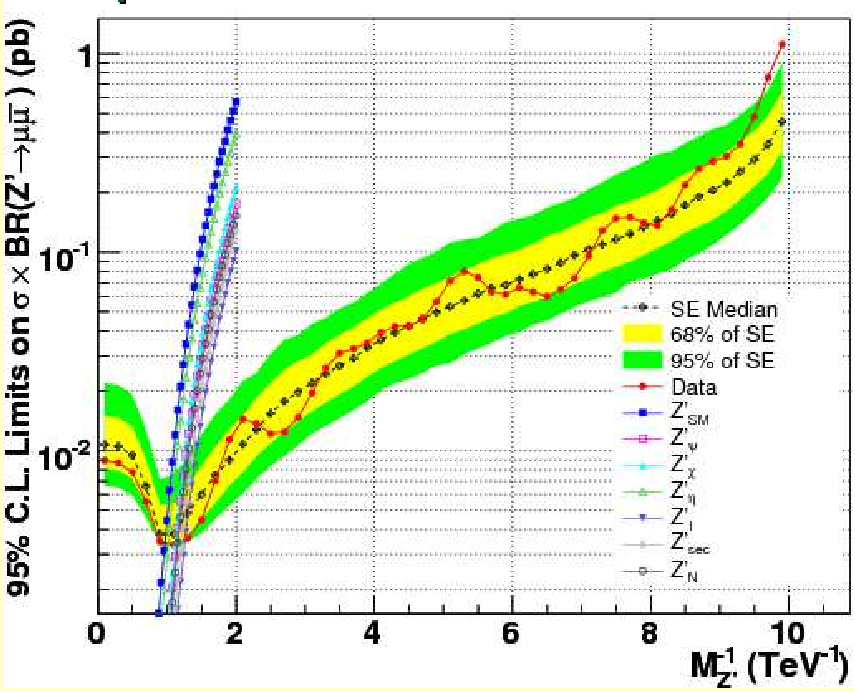
- Limits on several extended gauge groups theories: SM-like Z': **966 GeV/c^2**

Di-muon resonances

- Resonance decaying to dimuon have spin 0, 1 and 2
- Search in $1/m_{\mu\mu}$ in which detector resolution is ~const:
  - → 17% inverse mass resolution at 1 TeV



Spin 1 Z'-like limits



Z' model	Z' mass limit
Z'_I	789
Z'_{sec}	821
Z'_N	861
Z'_ψ	878
Z'_χ	892
Z'_η	982
Z'_{SM}	1030

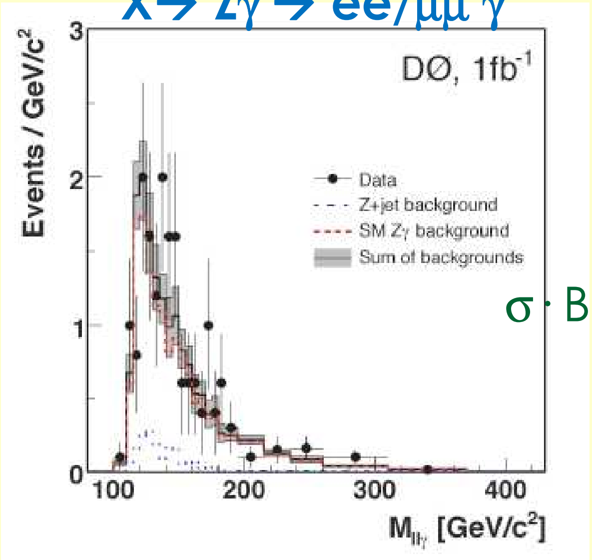
For the first time beyond one TeV for SM-Z'!

DiBoson resonances

DØ

- Investigate same models as before (E6, RS..) and more exotics ones
- DiBosons → clean final states + mass constraints → small backgrounds
- Here shown Zγ, WW, WZ, ZZ

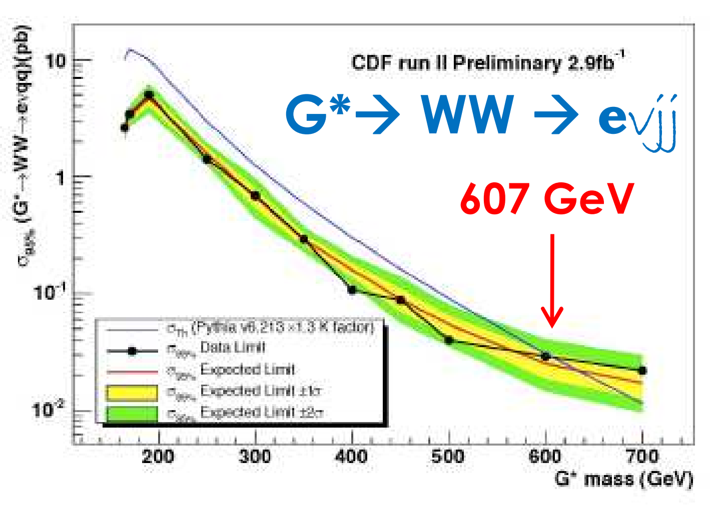
X→ Zγ → ee/μμ γ

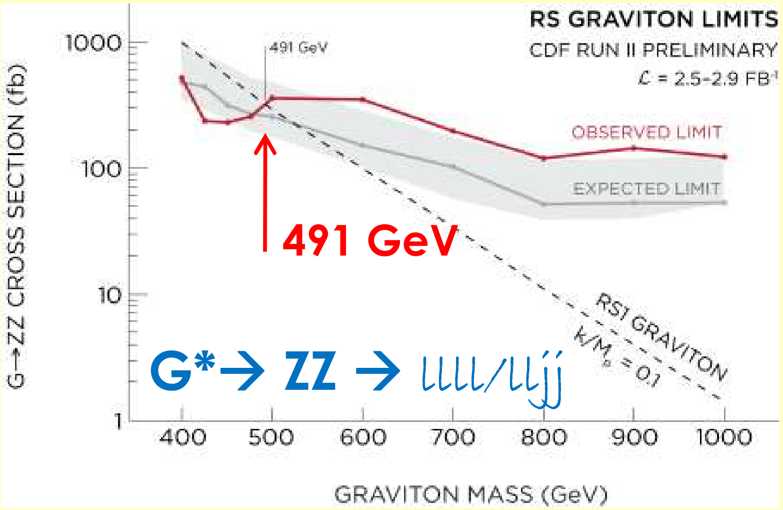


No significant excess

$\sigma \cdot BR(X \rightarrow Z\gamma) < 0.2$ pb
(M_X = 600 GeV)
< 2.5 pb
(M_X = 140 GeV)

CDF



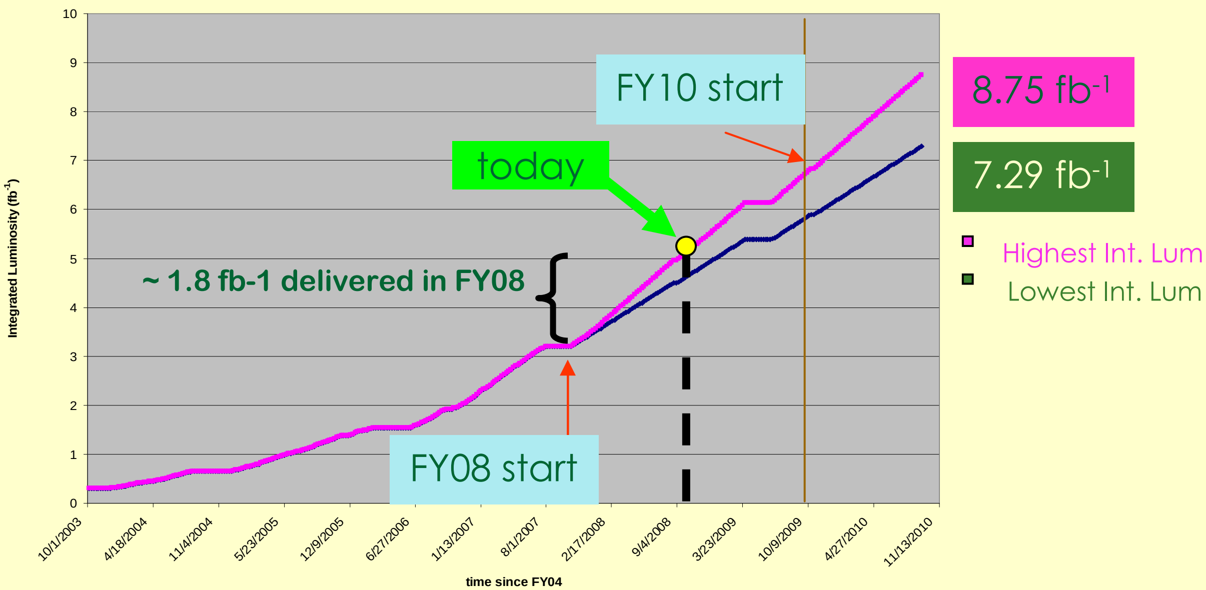


Also: limits on Z’ and W’ (in WZ final states)

Final remarks

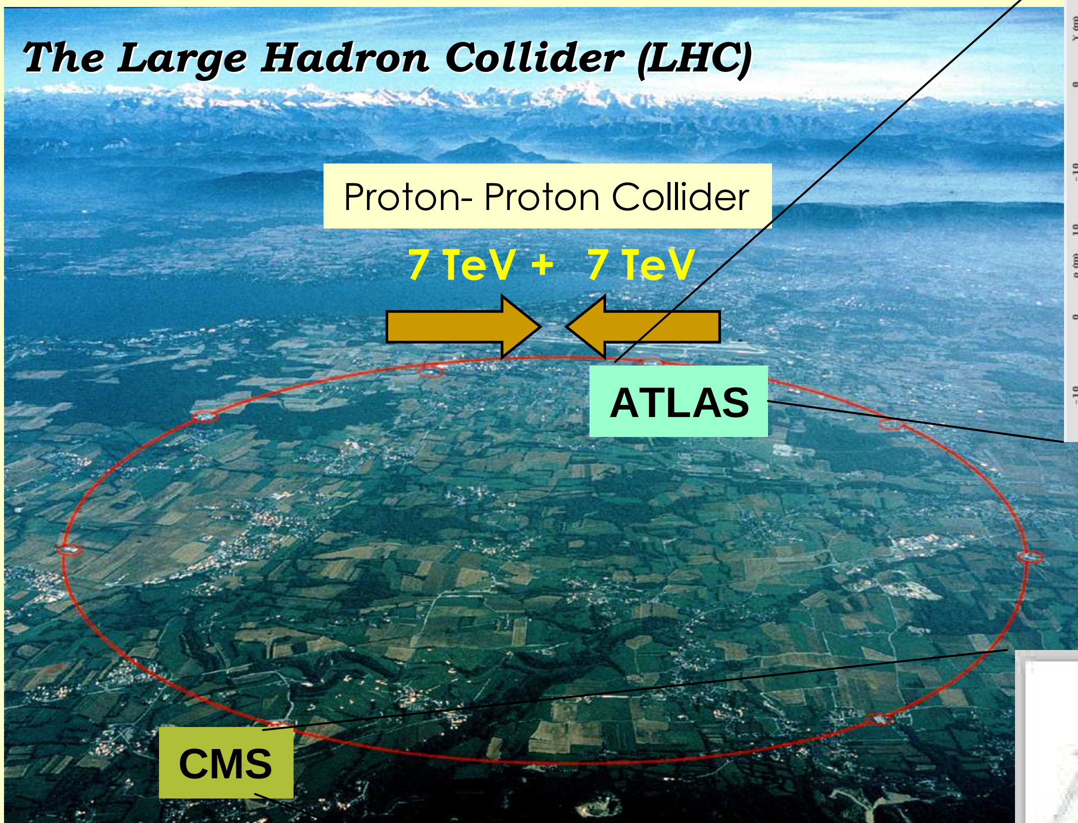
CDF and D0 have a wide and rich program of searches. No evidence of new physics yet, but.. expect to collect and analyze up to 8 fb^{-1} of data in the next years.

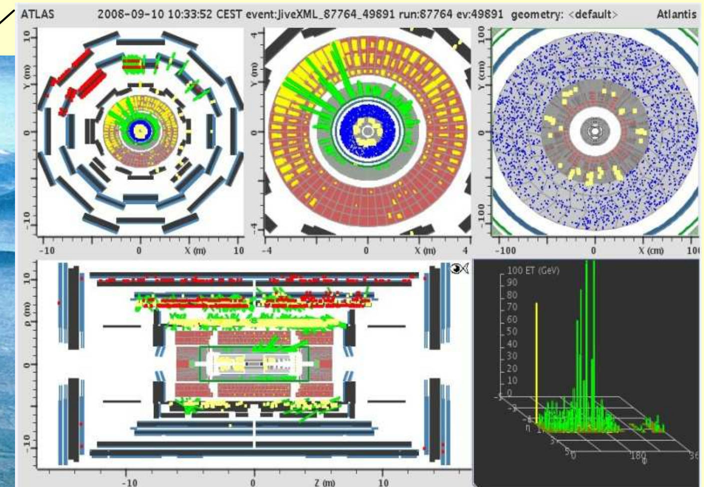
Projection curves

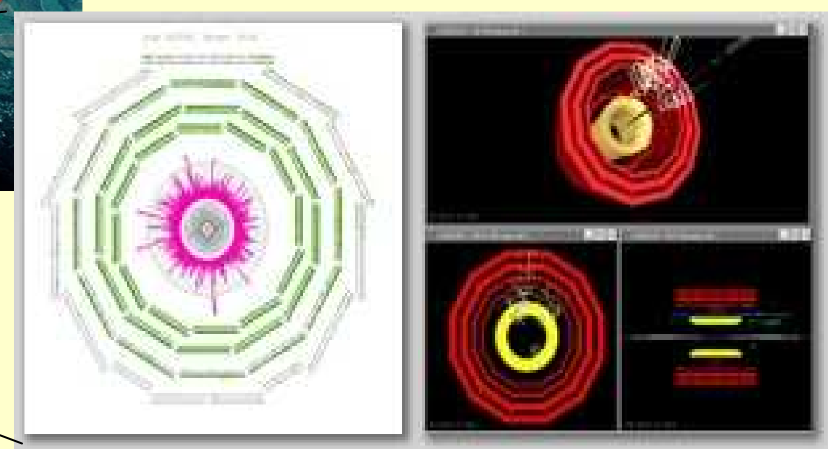


In case we don't find new particles @ Tevatron....

The Future …. now almost present

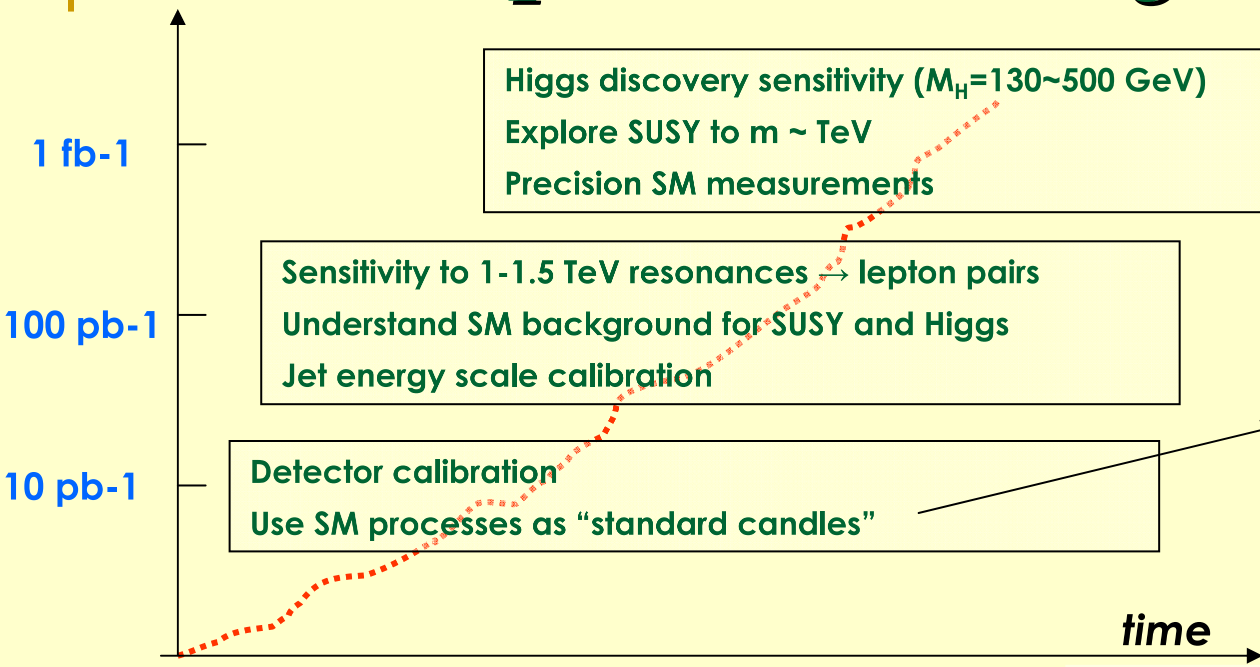


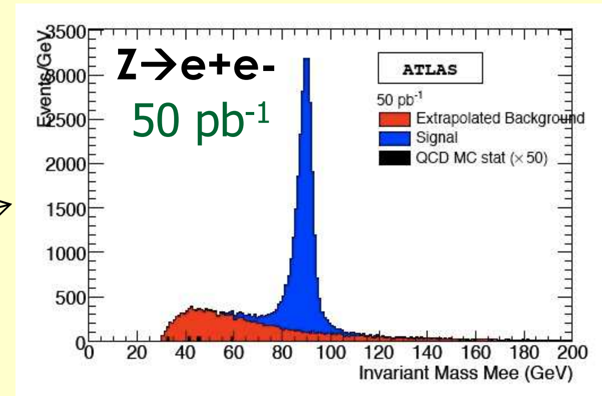




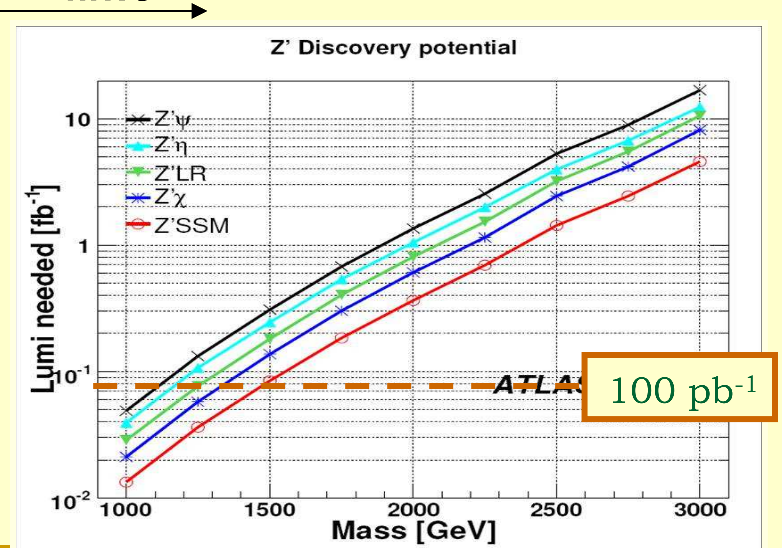
First Event (9/10/2008)!

Roadmap to discovery





- High-p_T lepton resonances may provide the first signal of New Physics:
  - Less sensitive to calorimeter performance
- Z/γ + jets can be used for calibration of jet energy scale

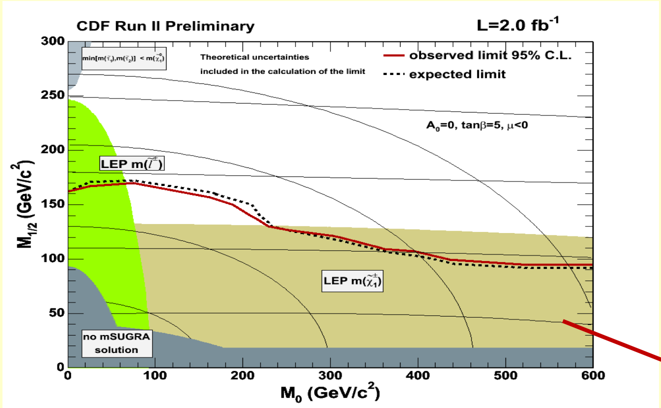


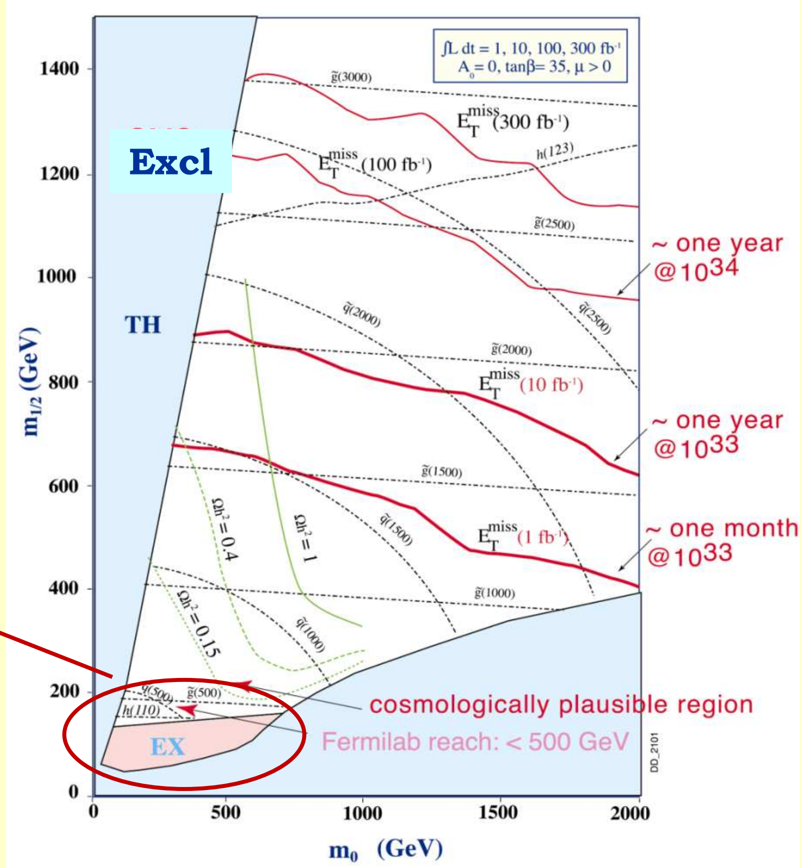
SUSY@LHC

The LHC is built to discover SUSY
If there, we will find it relatively soon

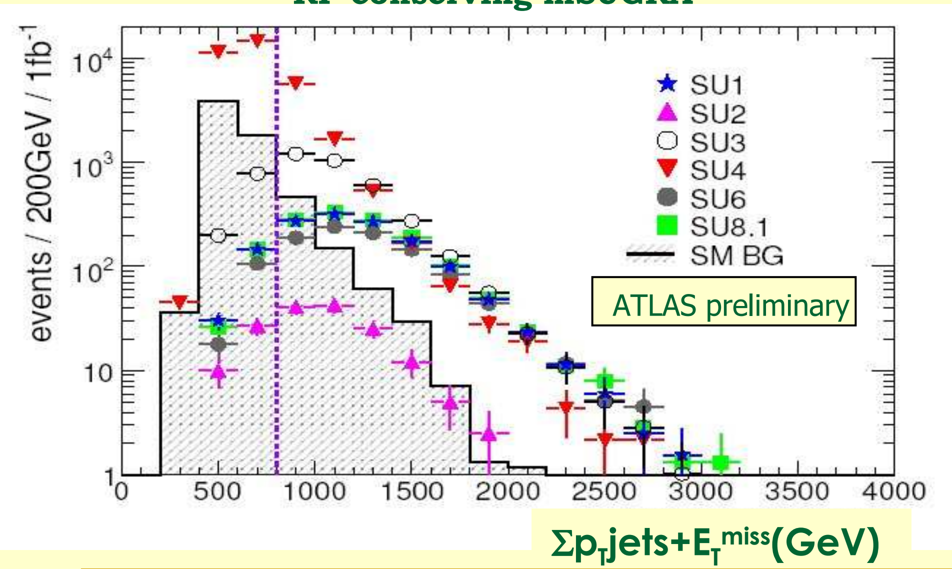
An example:

squark-gluino production





RP-conserving mSUGRA

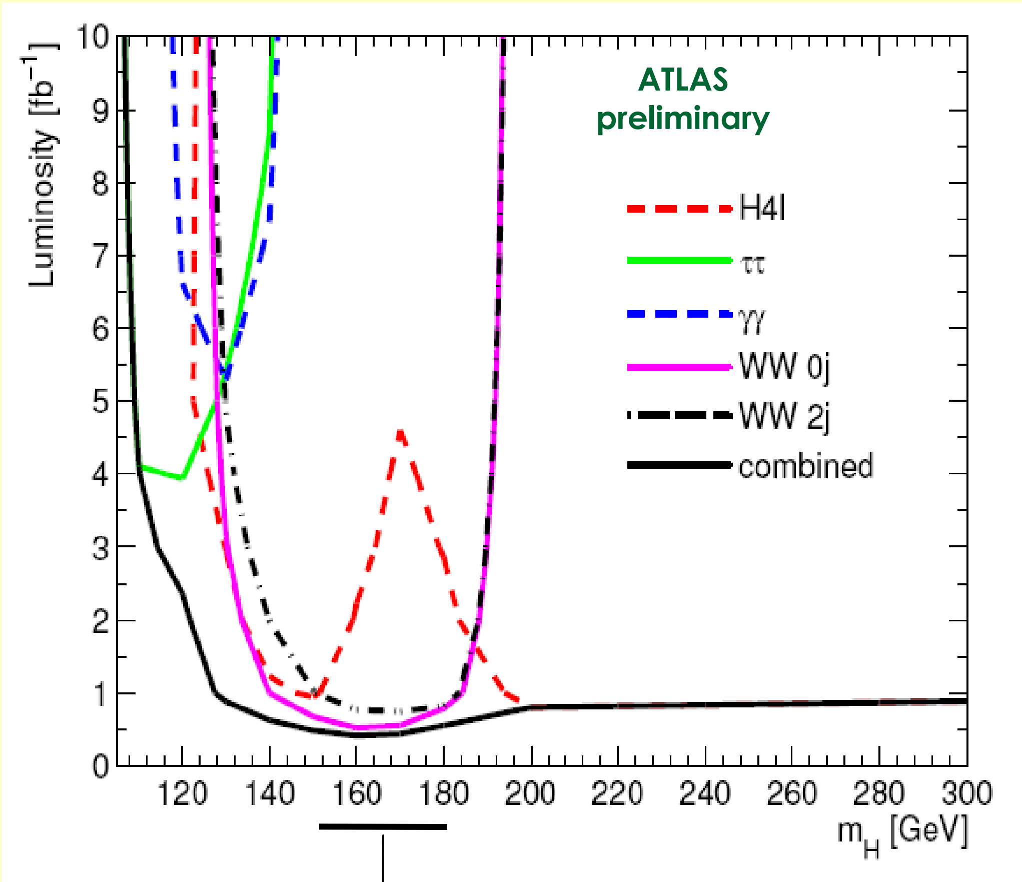


But it will take a bit of time:

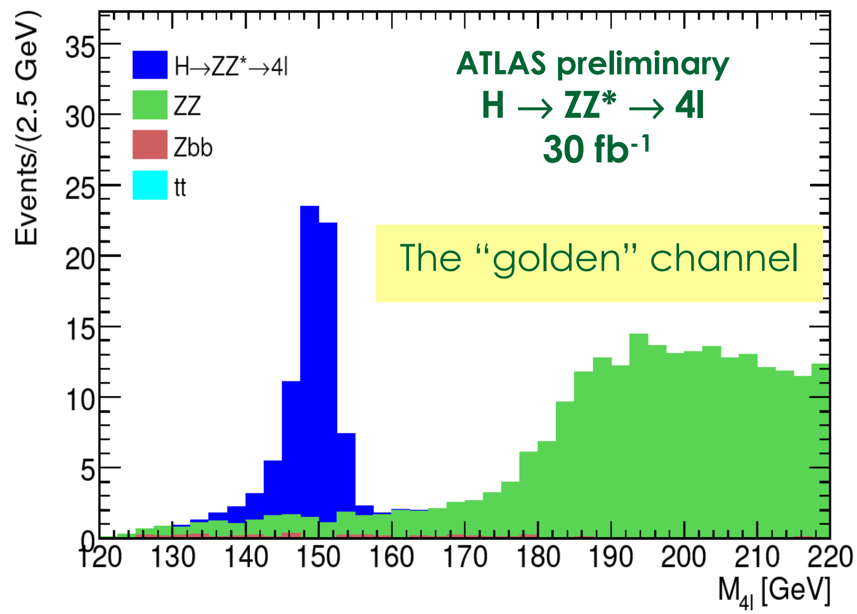
- **commissioning phase to understand detector performance and "re-discover" the SM**

SM Higgs: a challenge!

Required luminosity for 95% C.L. exclusion



For low mass of ~120 GeV need to combine many channels with small S/B or low statistics ($H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$, $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow l\upsilon l\upsilon$)



most promising in the range 150-180 GeV, again with $H \rightarrow WW^* \rightarrow l\upsilon l\upsilon$

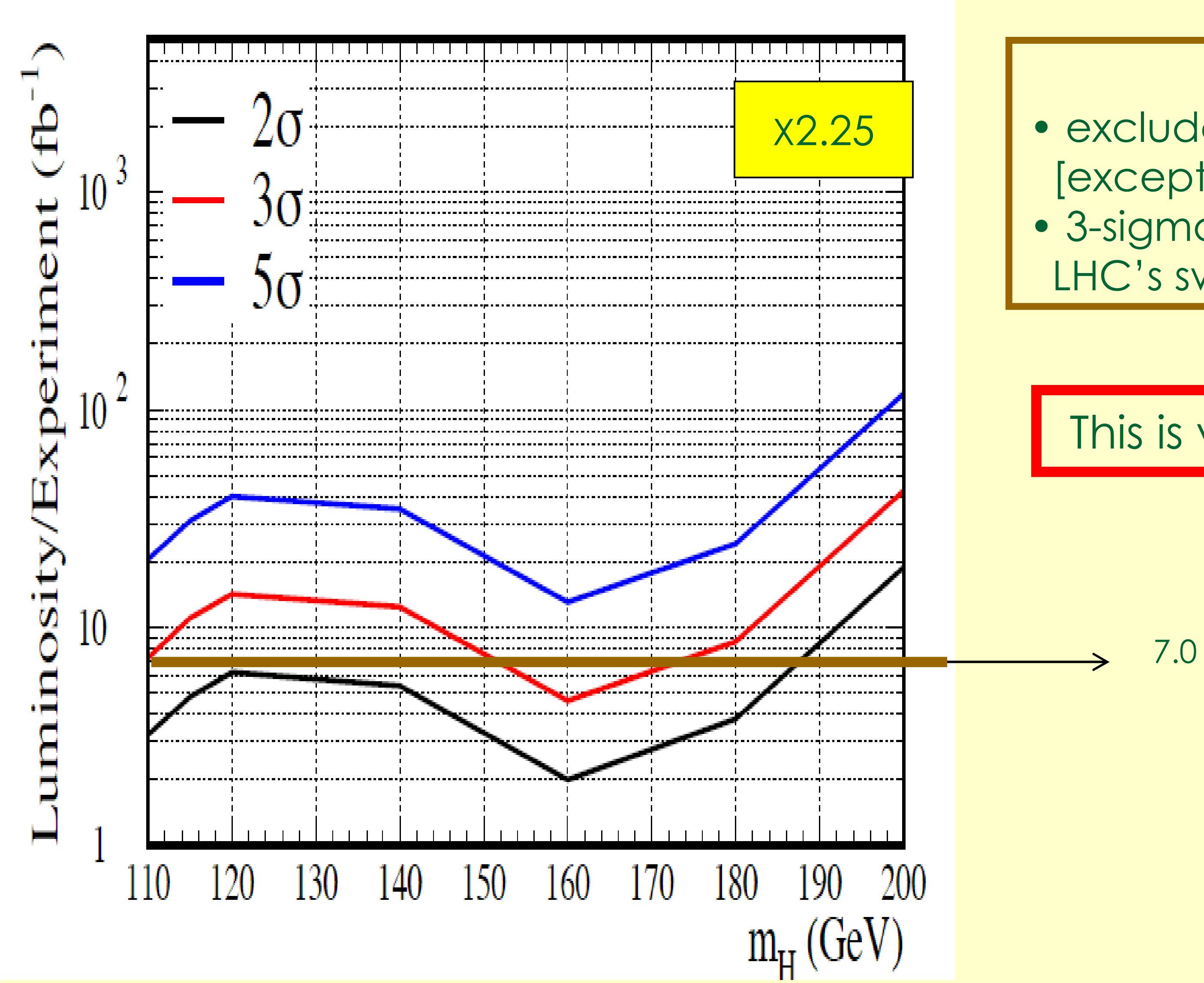
→ almost excluded at the Tevatron!

Conclusions

"Whatever" is beyond the Standard Model, these are exciting times for high energy physics!

Back up

Higgs reach @ Tevatron



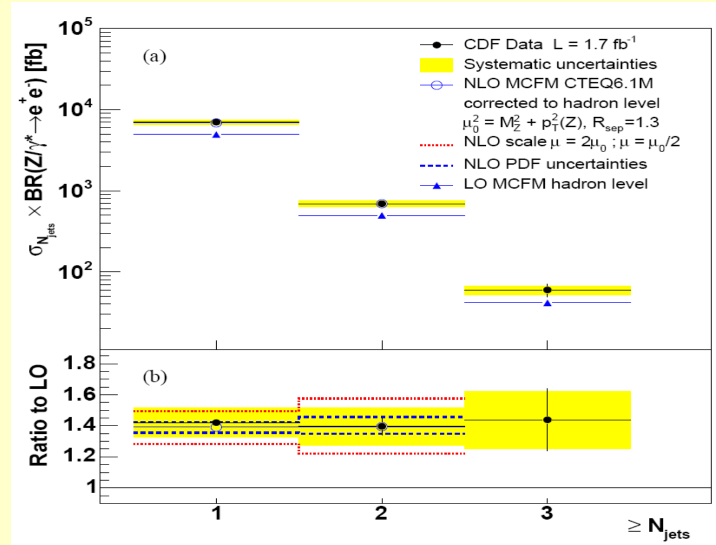
With 7 fb^{-1}

- exclude all masses !!! [except real mass]
- 3-sigma sensitivity 150:170 LHC's sweet spot

This is very compelling

Boson + jets

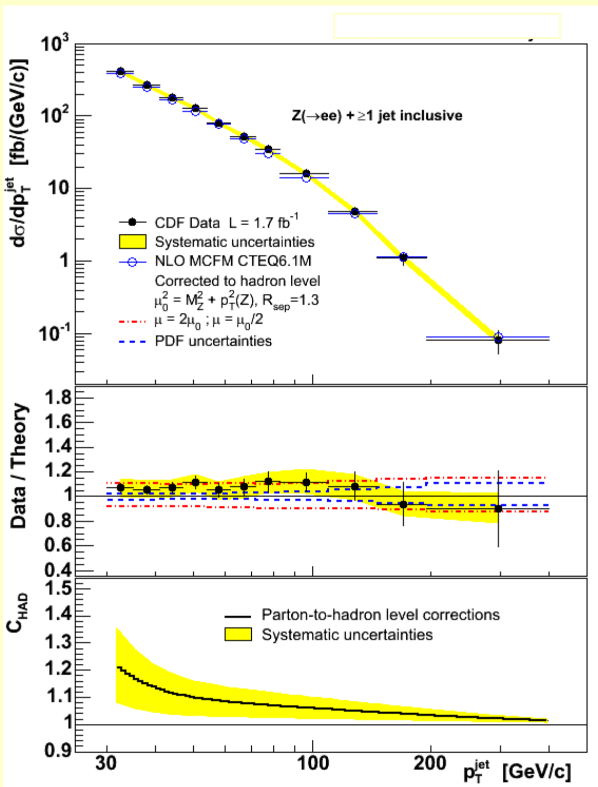
MCFM: NLO, no showering + CTEQ6.1M, hadron-to-parton corrections from PYTHIA TUNE A



Dedicated measurements performed for boson+jets cross sections

Z(→e⁺e⁻)+jets:

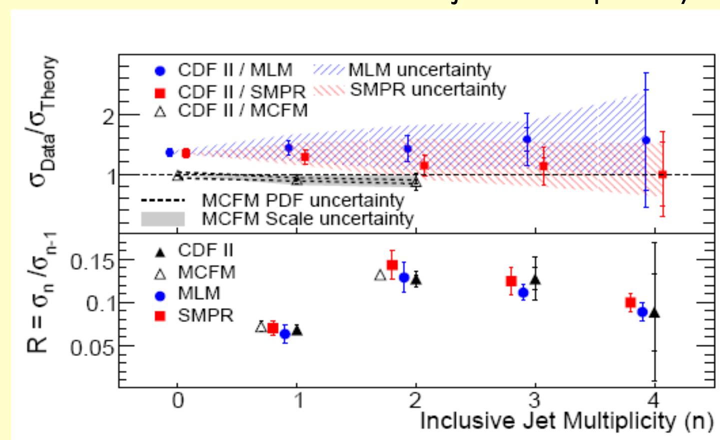
- clean signature, low background
- Does not constitute background for BSM physics involving Missing E_T



- Data in good agreement with MCFM NLO predictions
- Can define a common scale factor for all jet multiplicity

W+jets

- Statistics for high jet multiplicity
- Real MET, signature similar BSM signals



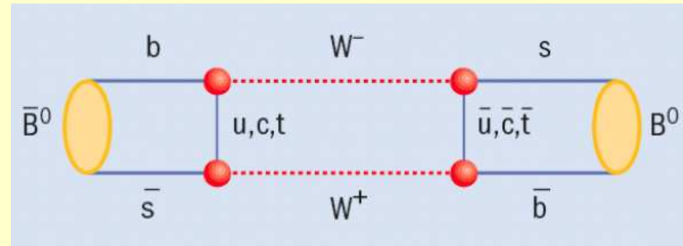
MLM : ALPGEN v2.12 (LO) + Herwig v6.5 + MLM + CTEQ5L
SMPR: MadGraph v4 (LO) + Pythia v6.3 + CKKW + CTEQ6L1
MCFM: NLO, no showering + CTEQ6.1M

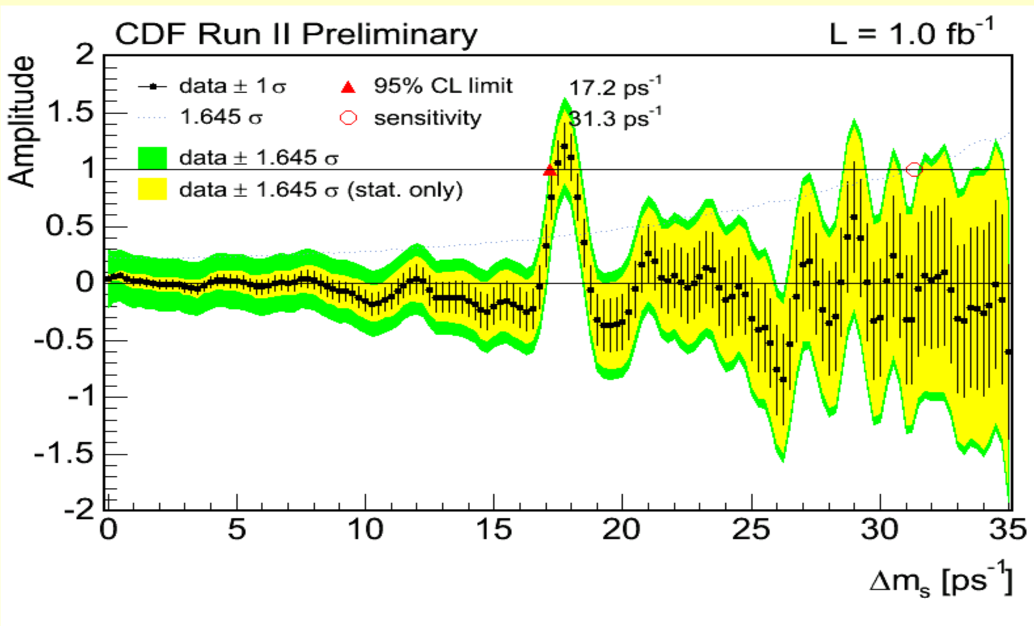
Knowledge of SM: B-physics

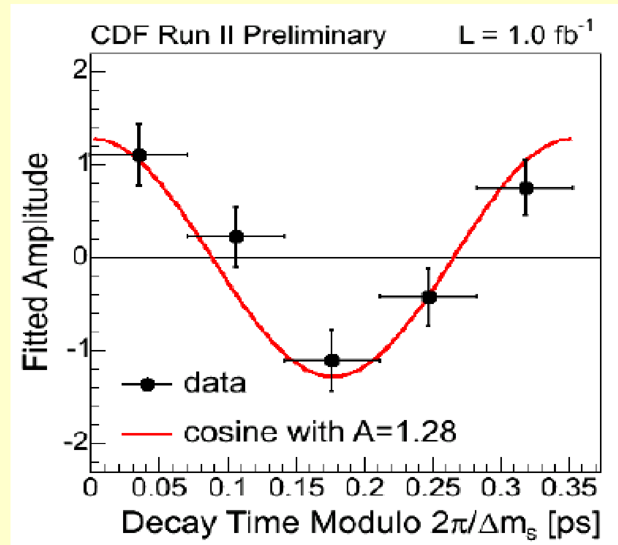
One of the flagship measurements of Run II

→ Observation of B_s - B_s Oscillations

Δm_s = 17.77 ± 0.10 (stat) ± 0.07(sys)

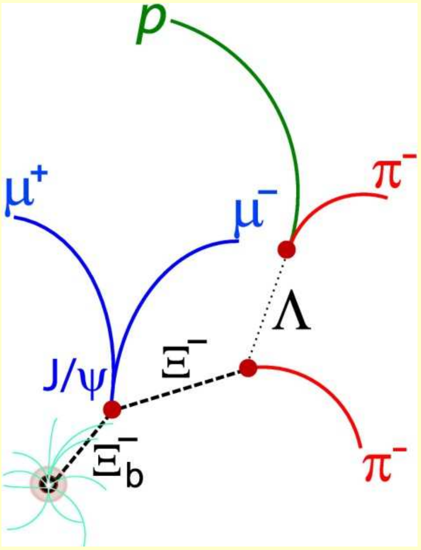




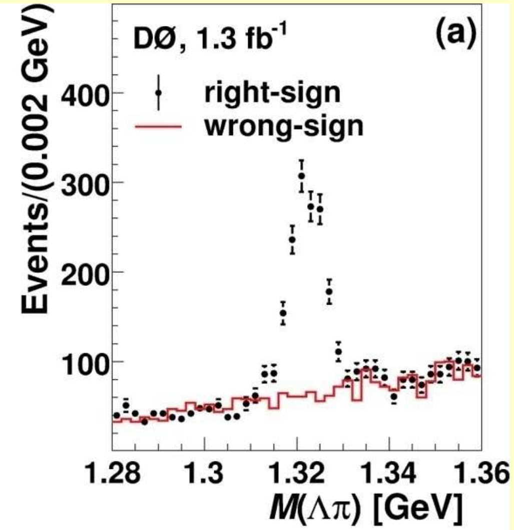


and extract the ratio **$|V_{td}|/|V_{ts}|$ = 0.2060 ± 0.0007 (stat+sys)**
[+0.0081-0.0060] (theo)

Ξ_b^- Direct Observation

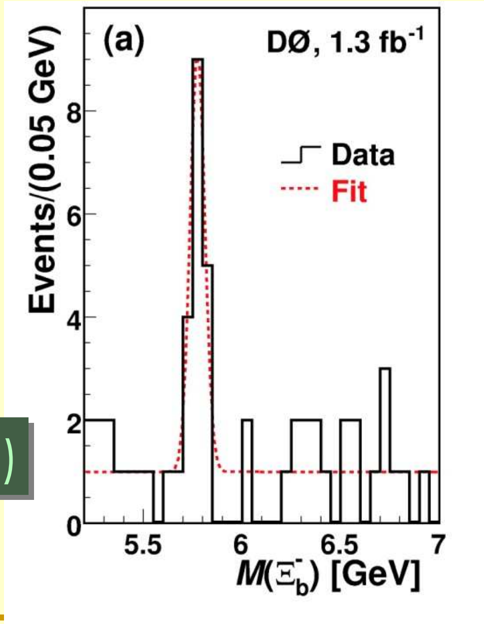


- Many new baryon discoveries this past year
- Ξ_b^-(dsb) one quark from each generation
- Fully reconstruct exclusive decay
  - Sign of charge of tracks
  - Reconstructed displaced vertices
  - Masses and impact parameter resolution of reconstructed vertices
  - Angular separation between tracks
  - Minimum p_T requirements
- Use $\Lambda\pi^+$ for background studies
  - Wrong-sign
- Interpretation of peak as Ξ_b^- using unbinned likelihood



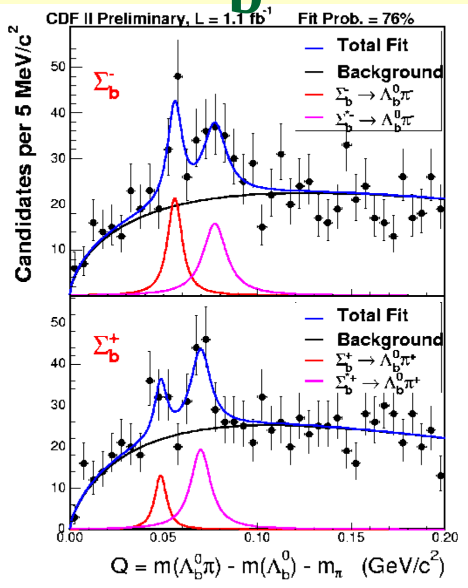
Peak: 5.5σ significance

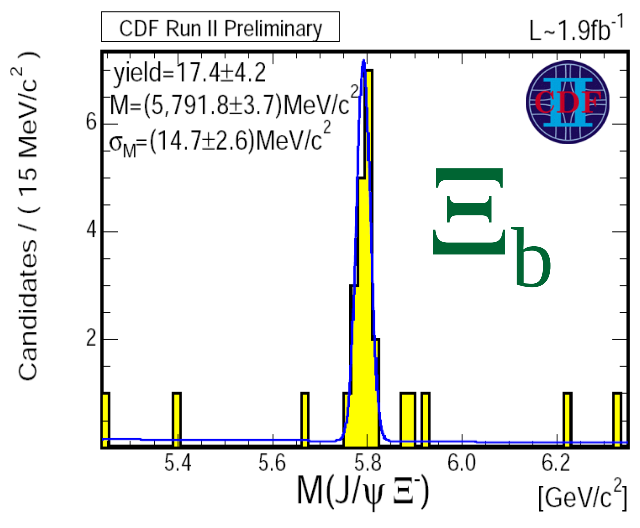
$M(\Xi_b^-) = 5.774 \pm 0.011(\text{stat}) \pm 0.015(\text{syst})$



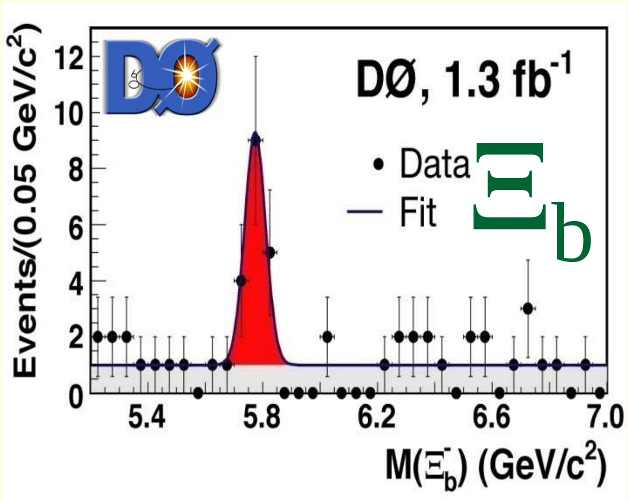
B Baryon Discoveries

Σ_b





Ξ_b



Ξ_b

The Hierarchy problem

The SM requires a non-vanishing VEV for the Higgs at the minimum of the potential ***V***

$$V = m_H^2 |H|^2 + \lambda |H|^4$$

if $m^2_H < 0$, VEV results in: $\langle H \rangle = \sqrt{-m_H^2/2\lambda}$

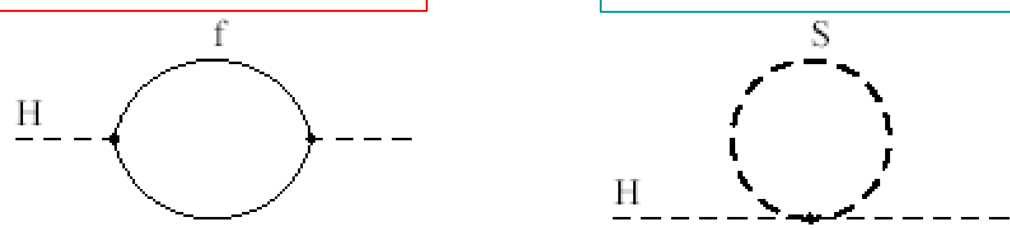
Experimentally, <H> = 174 GeV and $m^2_H \sim -(100\ \mathrm{GeV})^2$
+ quantum corrections from virtual effects of particles coupling to Higgs field

$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{\rm UV}^2 + 6 m_f^2 \ln(\Lambda_{\rm UV}/m_f) + \ldots\right]$$

Fermion loop

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\rm UV}^2 - 2 m_S^2 \ln(\Lambda_{\rm UV}/m_S) + \ldots\right]$$

loop of scalar particles



Λ_{UV} → ultraviolet cutoff

→ Mass of Higgs scalar with quantum corrections is kept small only with fine tuning of the parameters!

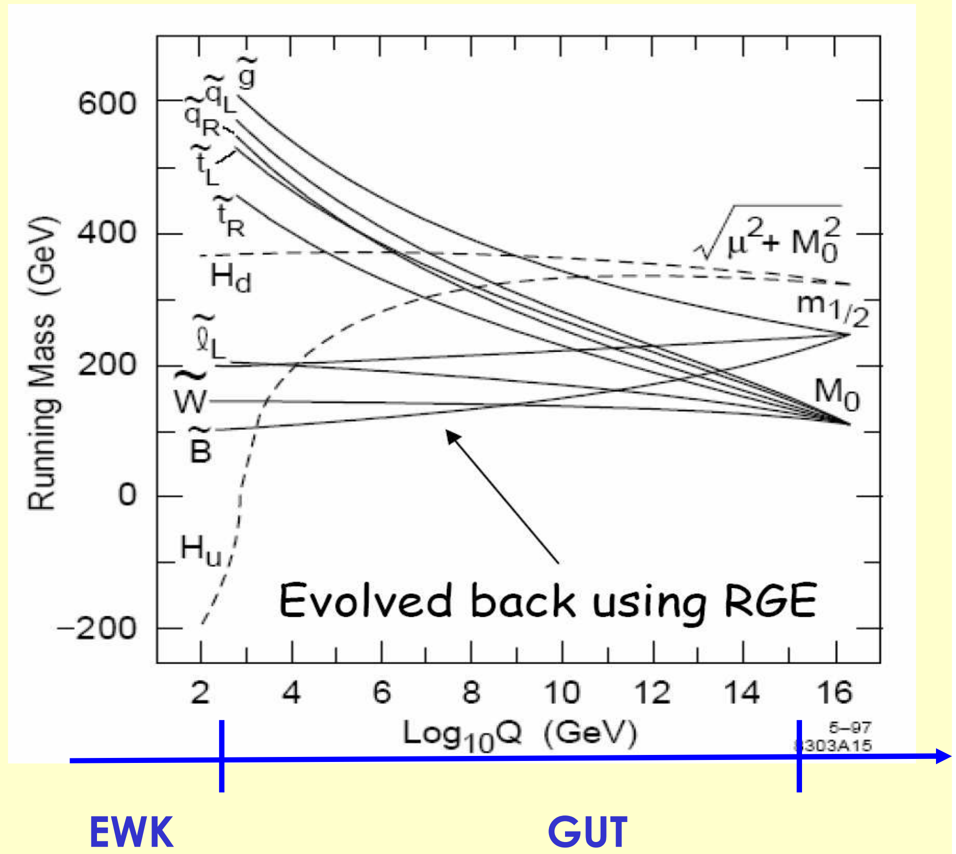
Possible solution: introduce a symmetry to cancel all dangerous contributions

mSUGRA

- New superfields in "hidden" sector
- Interact gravitationally with MSSM
- Soft SUSY breaking

5 parameters at GUT scale

1. Unified gaugino mass $m_{1/2}$
2. Unified scalar mass m_0
3. Ratio of H_1, H_2 vevs $\tan\beta$
4. Trilinear coupling A_0
5. Higgs mass term $\mathrm{sgn}(\mu)$



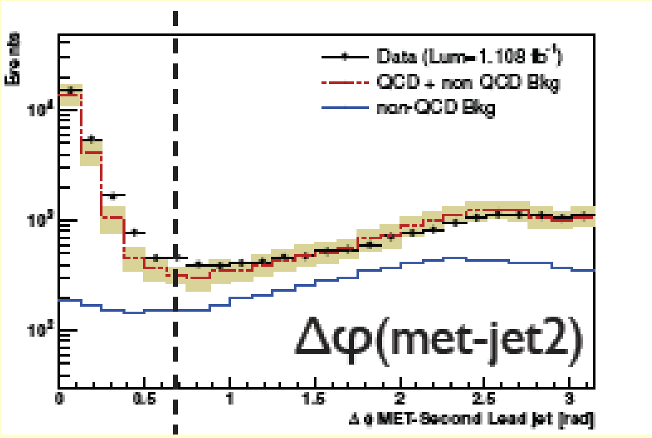
In R parity conservation scenario, the LSP is the neutralino (χ^0_1)

QCD multijet rejection

Missing E_T from mis-reconstructed jets

→ Collinear with one of the leading jets

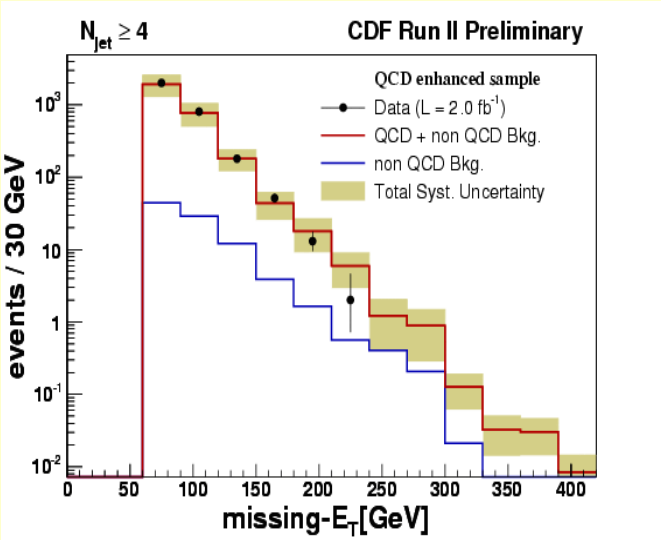
→ Apply cuts on $\Delta\phi$ (missingE_T-jets)



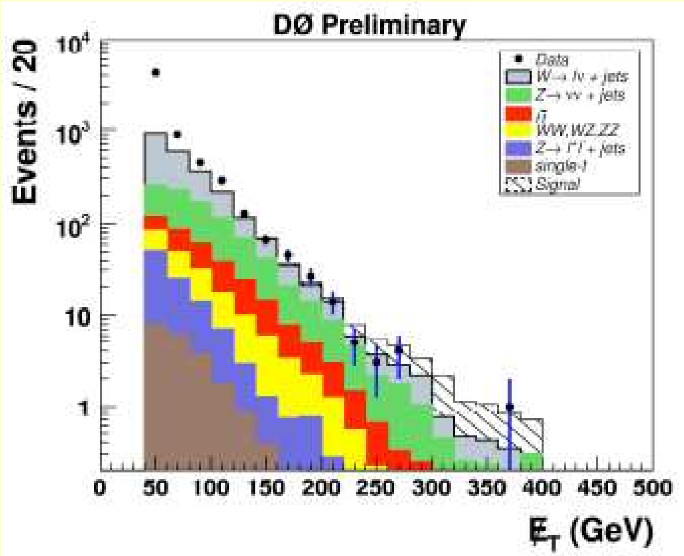
▸**CDF:** remaining QCD-bkg estimatated from Monte Carlo.

▸Control checks in enhanced QCD-sample

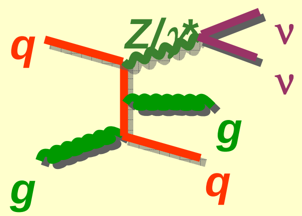
Δφ(MET-jets) cut reversed for at least one of the leading jets

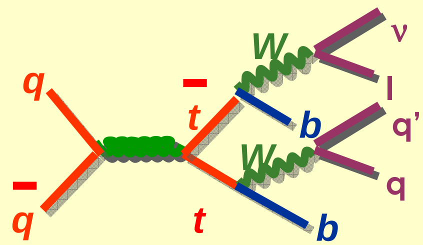


▸**DØ :** QCD-bkg extrapolated in data by exponential fit function

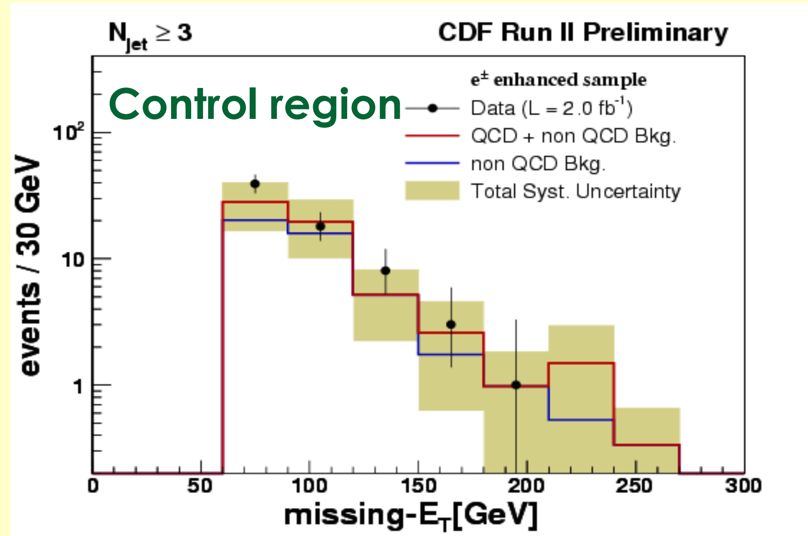


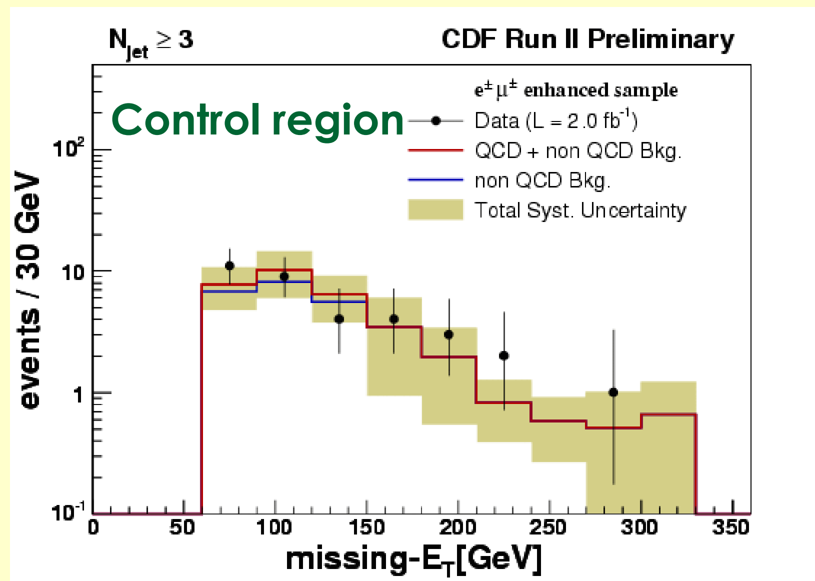
Top and Boson+jets rejection





- Genuine Missing E_T in the event
- Suppressed vetoing events with:
  - jet Electromagnetic fraction > 90%, to reject electrons mis-identified as jets
  - isolated tracks collinear to missing E_T to reject undetected electrons/muons
- Modeled using Monte Carlo
- Normalized to NLO cross section
- Define **control regions** reversing lepton vetoes → checks of background estimations
  - Understanding these processes is fundamental

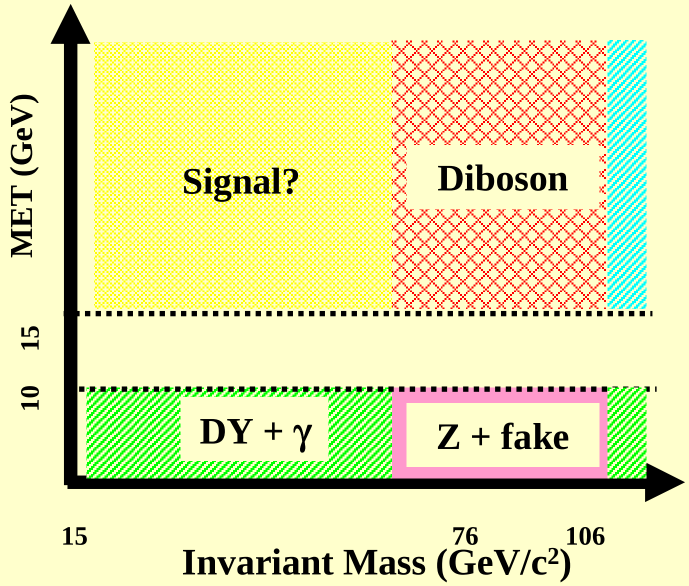


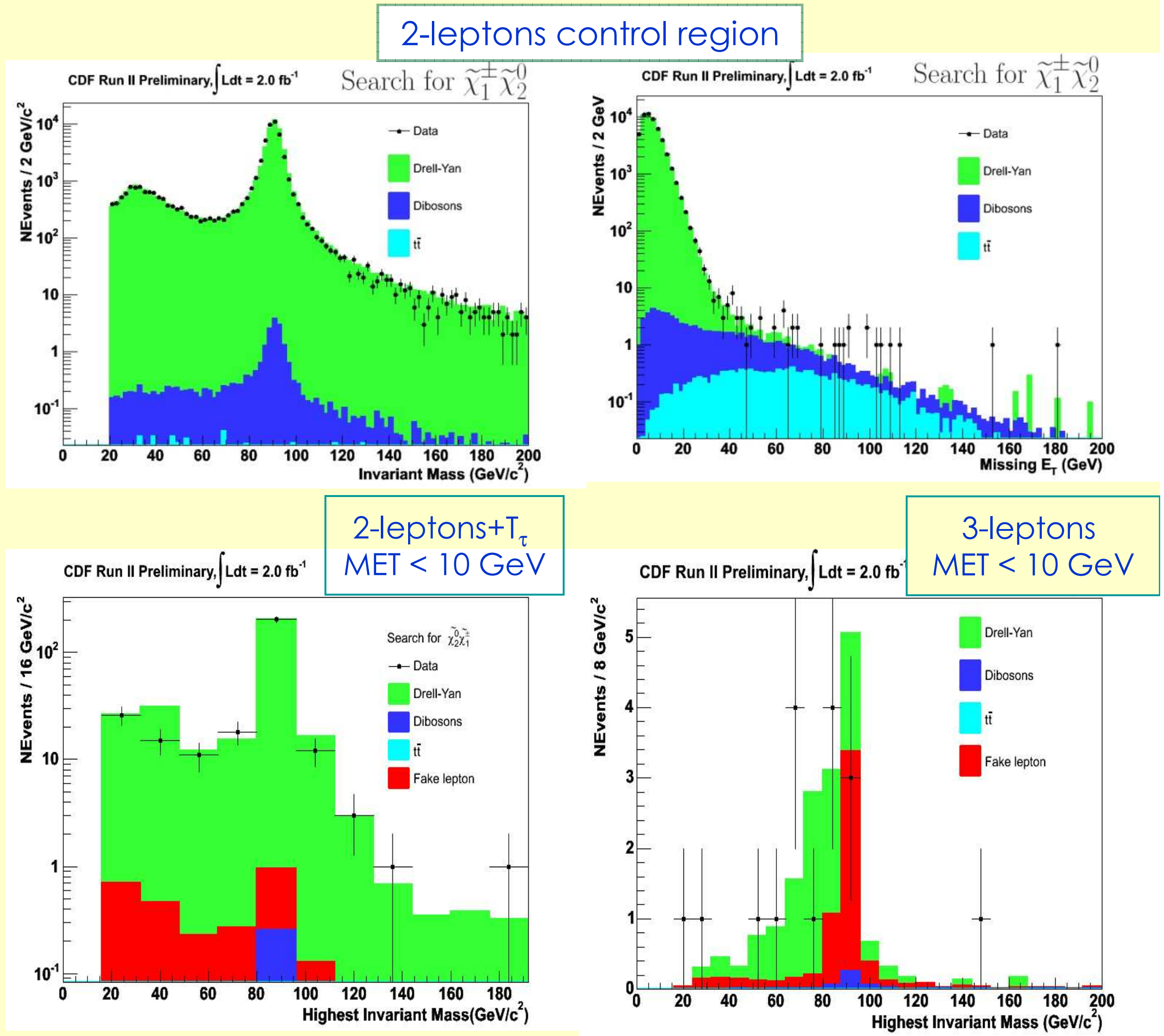


Control regions (CDF)

Dilepton and trilepton control regions defined to test SM predictions:
→ function of $\not{E}_T$ and the invariant mass of the 2 leading leptons

→ 47 in total!

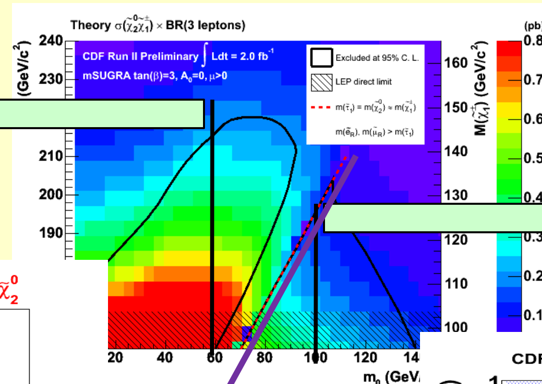


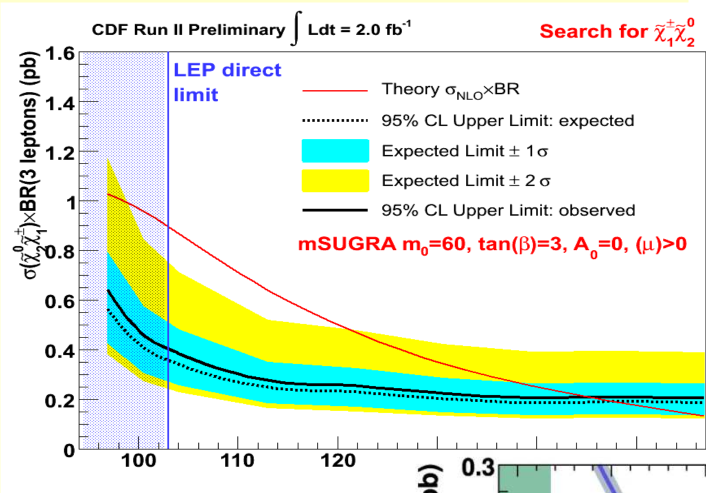


Chargino mass limits in mSUGRA

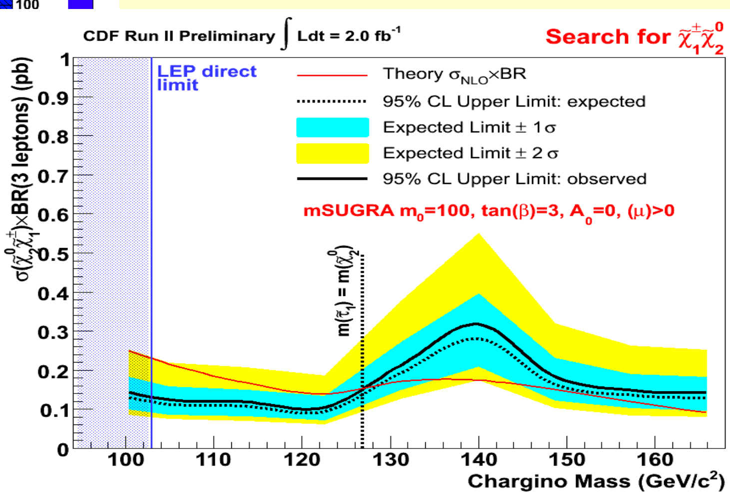
$m_0 = 60$ GeV/c^2
→ Exclude chargino masses **< 145 GeV/c²**

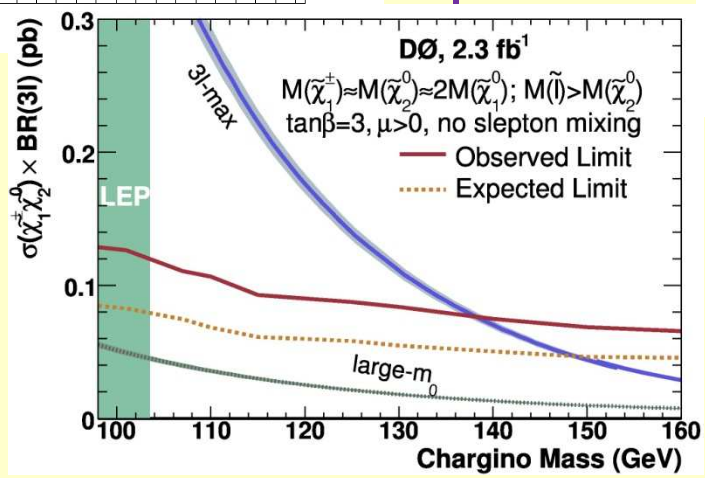
$m_0 = 100$ GeV/c^2
→ Exclude chargino masses **< 127 GeV/c²**





In the direction of a DØ scan

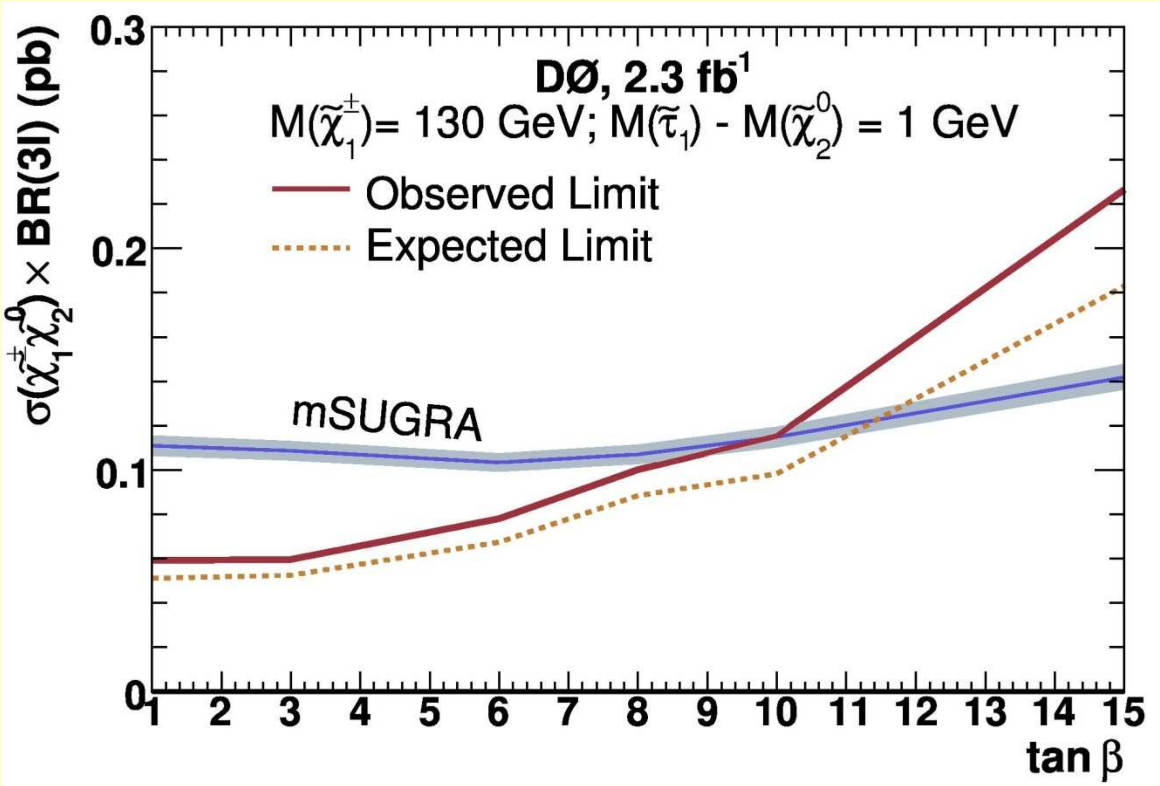




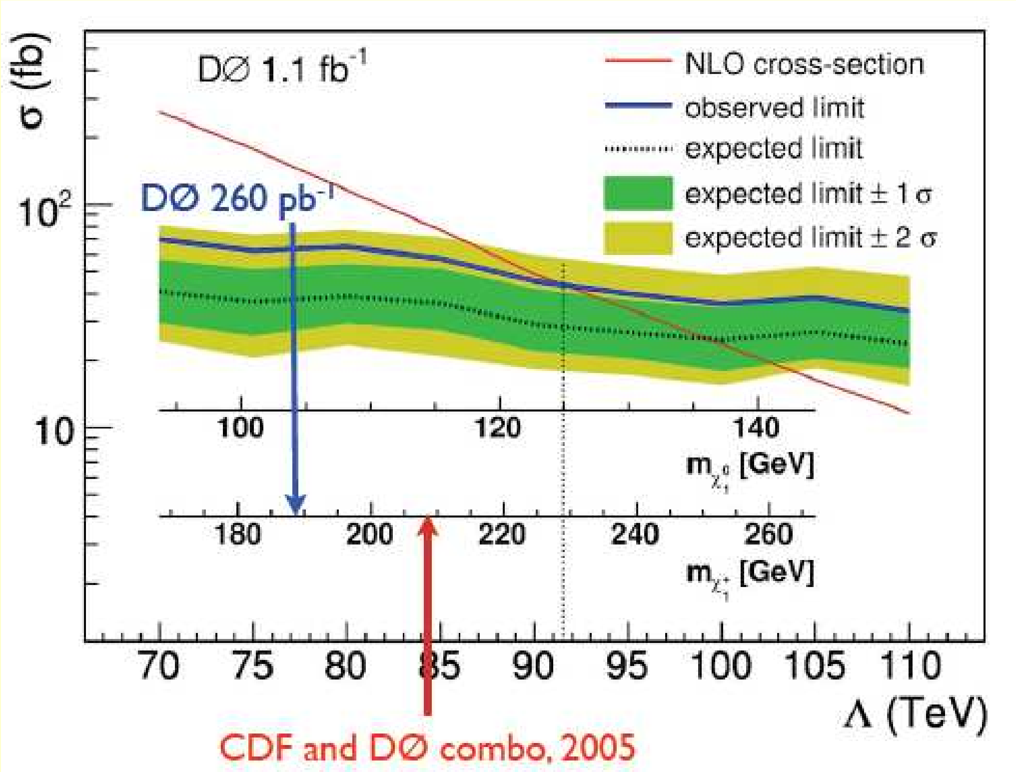
assume no slepton mixing:
excluded chargino mass **<138 GeV**

Chargino limits Vs tanβ

- Dependence with other parameters: eg tanβ
- D∅: Exclude chargino of 130 GeV up to tanβ=9.6



GMSB CDF-D0 combination



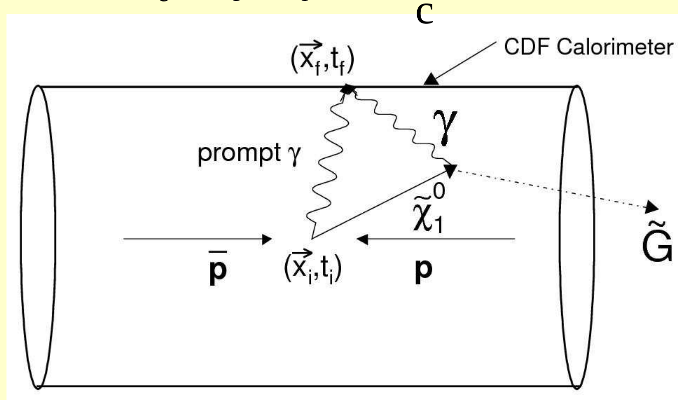
3 events (SM: 1.6±0.4)

$\Lambda > 91.5\,\text{TeV @ 95\% CL}$

$M(\chi_1^0) > 125\,\text{GeV}, M(\chi_1^+) > 229\,\text{GeV}$

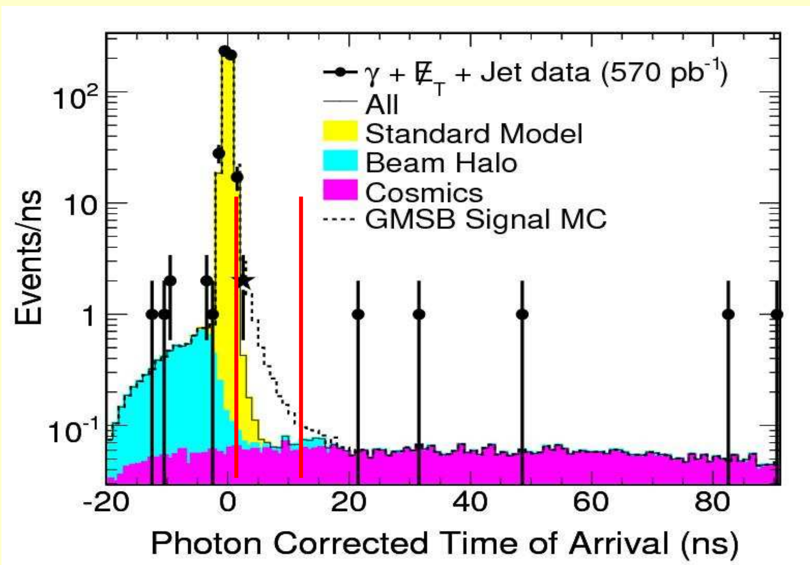
Delayed Photons

$$t_c^{\gamma} \equiv t_f - t_i - \frac{|\vec{x}_f - \vec{x}_i|}{c}$$

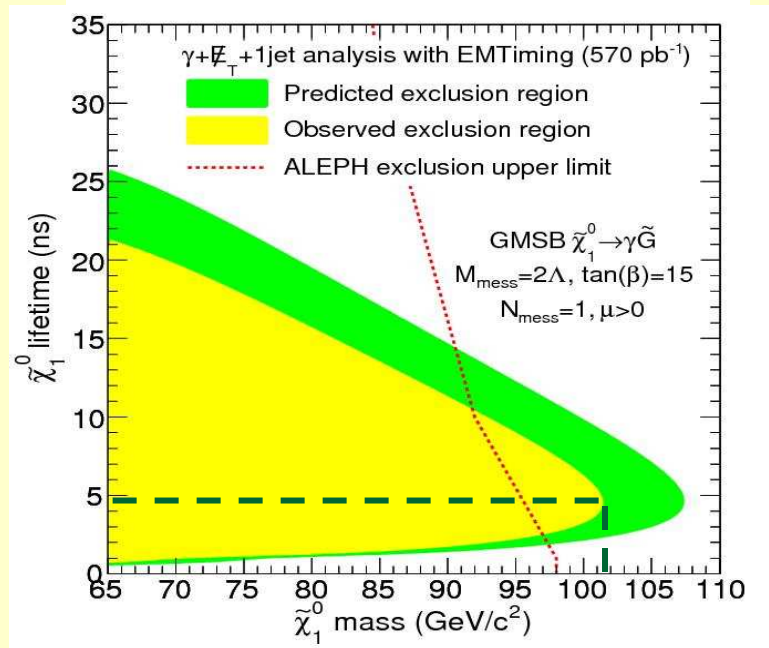


- χ^0_1 life-time undetermined in GMSB → long-lifetime can be in ~ns range
- Final state: **Delayed photon+$\not{E}_T$ +jets**

→ E_T> 40 GeV, p_T^{γ}>25 GeV, E_T^{jet} > 35 GeV
→ $|\eta(\gamma)|$<1.1, $|\eta(jet)|$ < 2.



$t_C(\gamma)$ in [2-10] ns range



Observed 2 events
SM Expect.: 1.3±0.7

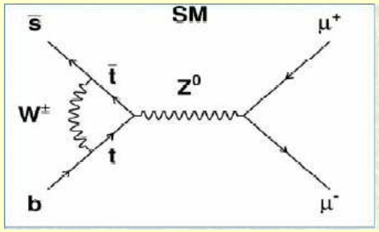
$M(\chi^0_1)$>101 GeV @ 5 ns

Indirect searches: $B_s \rightarrow \mu\mu$

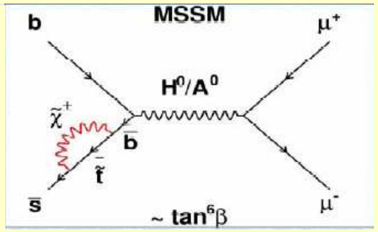
Sensitive to new physics: SUSY particles show up in loops (or direct decays if R_p violation)

- Data sample dominated by random combinatorial background
- Extract signal with Neural Net based discriminant

SM: BR = 3.42×10^{-9}



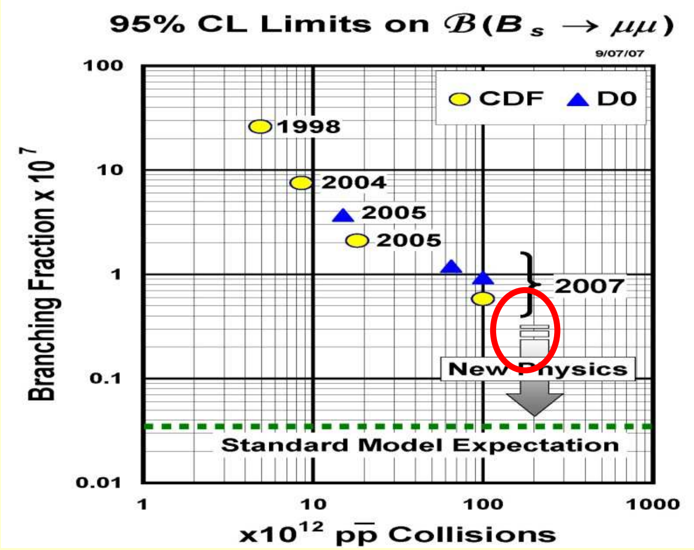
SUSY enhance ~$(\tan\beta)^6$

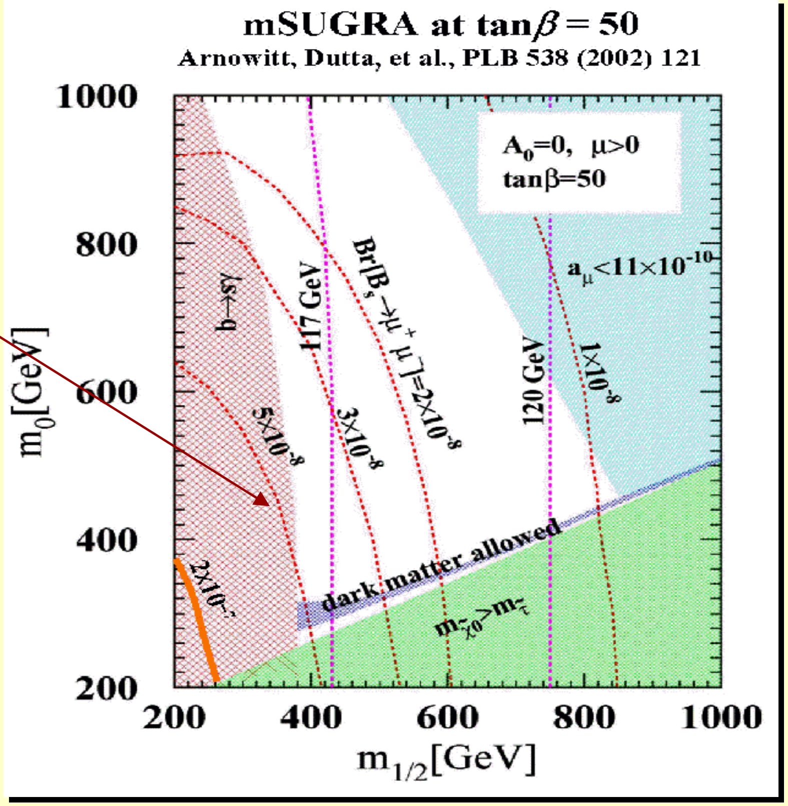


$B_s \rightarrow \mu\mu$ 3 observed events (3.6+/-0.3 exp.bkg.)

$B_d \rightarrow \mu\mu$ 6 observed events (4.3+/-0.3 exp.bkg.)

$Br(B_s \rightarrow \mu\mu) < 5.8 \times 10^{-8}$ @ 95% CL
$Br(B_d \rightarrow \mu\mu) < 1.8 \times 10^{-8}$ @ 95%CL





R-parity violating sneutrino Production

- To solve hierarchy problem, sparticles should have electroweak-scale masses
- Resonant sparticle production requires 'R-parity' violation
  - SM particles: R = 1; sparticles: R = -1
  - Implication: lightest sparticle decays
- *Can still be dark matter candidate if coupling is weak*
- Two terms in Lagrangian relevant for production and decay

$$\mathcal{W}_{\not{R}_p} = \lambda_{ijk} L_i L_j e^c_k + \lambda'_{ijk} L_i Q_j d^c_k$$

Decay

$$\tilde{\nu}_i \to \mu\mu(\lambda_{i22})$$

L_i, Q_i: SU(2) doublet superfields
e^c_k, d^c_k: SU(2) ~ singlet superfields

Production

$$dd^c \to \tilde{\nu}_i(\lambda'_{i11})$$

Z' production (1)

- Z' observable if new gauge symmetry broken ~ TeV
  - Many models predict electroweak-scale U(1) symmetry
  - Useful test model: Superstring-inspired grand unified theory (E8 × E8')
    - *Compactification of extra dimensions breaks E8 to E6 × SU(3)*
    - *E_8' is a hidden sector that breaks supersymmetry*

An example of breaking E_6 to the Standard Model:

$$
\begin{aligned}
E_6 &\rightarrow SO(10)\times U(1) \\
&\rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
&\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y
\end{aligned}
$$

All matter particles in fundamental 27 representation of E_6

Contains 16 (SM fermions), 10 (Higgs doublets) and 1 of SO(10)

$$
(\mathbf{16})_1 = \left(\begin{array}{cccc|cccc} \bar{u} & \bar{u} & \bar{u} & \bar{\nu}_e & u & u & u & \nu_e \\ \bar{d}' & \bar{d}' & \bar{d}' & e^+ & d' & d' & d' & e^- \end{array}\right)_L
$$

Restores parity conservation, allows for seesaw mechanism for small neutrino masses, and requires quantized EM charge

Z’ production (2)

- E6 breaking can result in multiple U(1) symmetries

$$
\begin{aligned}
E_6 &\rightarrow SO(10)\times U(1)_\Psi \\
&\rightarrow SU(5)\times U(1)_\chi \times U(1)_\Psi \\
&\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\Psi \\
&\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)' \\
&\rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y
\end{aligned}
$$

Assume electroweak-scale U(1)’ is a linear combination of $U(1)\chi \times U(1)\psi$

- Mass eigenstate:

$Z'(\theta) = Z'_\psi \cos\theta + Z'_\chi \sin\theta$

- θ: Mixing angle, determines the coupling

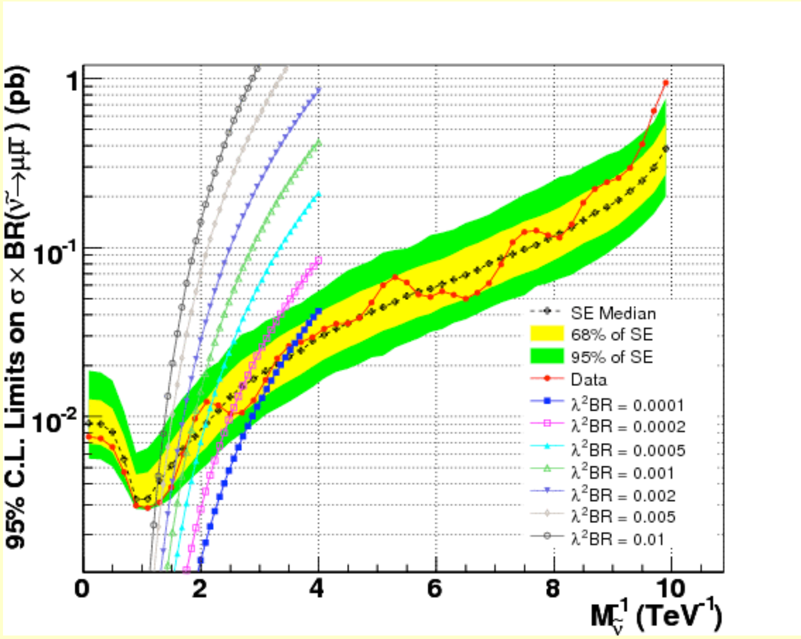
Couplings of Zψ', Zχ' Zη', ZI', ZN', Zsec' determined by group theory and weak charge

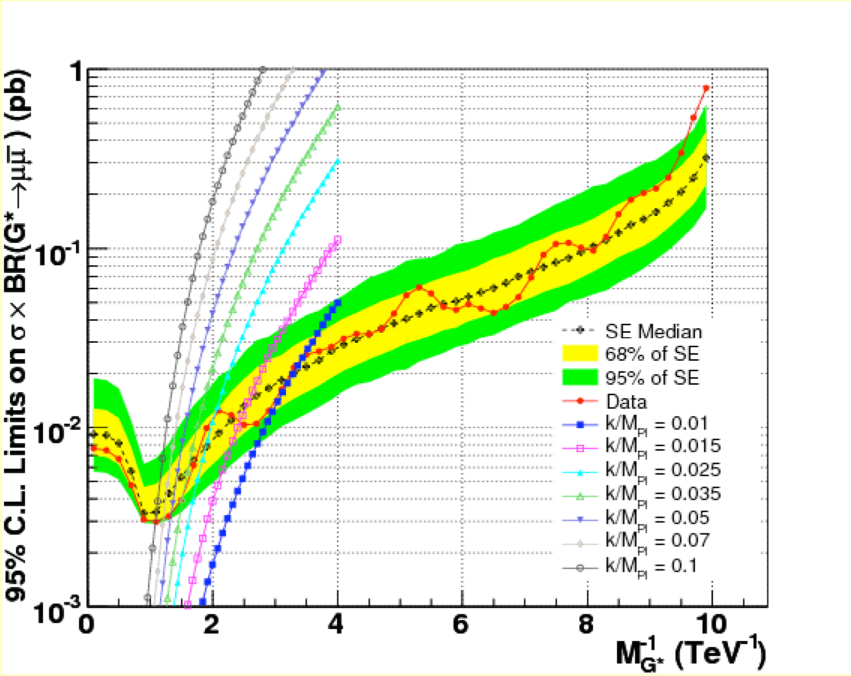
Z' (SM)
Z' (η)
Z' (χ)
Z' (ψ)
Z' (N)
Z' (I)
Z' (sq)

Di-muon results

- Spin 0: **Limits on cross section and sneutrino mass:**
  Choose a variety of $\lambda^2 \times$ BR values (λ: $dd\tilde{\nu}$ coupling ~ at production)

$\tilde{\nu}$ $\lambda^2 \cdot BR$	$\tilde{\nu}$ mass limit
0.0001	278
0.0002	397
0.0005	457
0.001	541
0.002	662
0.005	751
0.01	810





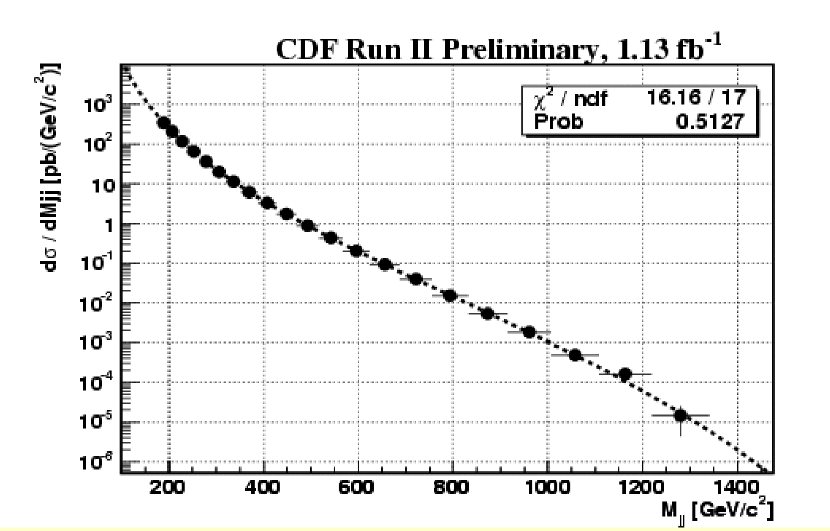
RS graviton k/M_{Planck}	graviton mass limit
0.01	293
0.015	409
0.025	493
0.035	651
0.05	746
0.07	824
0.1	921

Spin 2: **Limits on cross section and mass of first excited R-S graviton:**

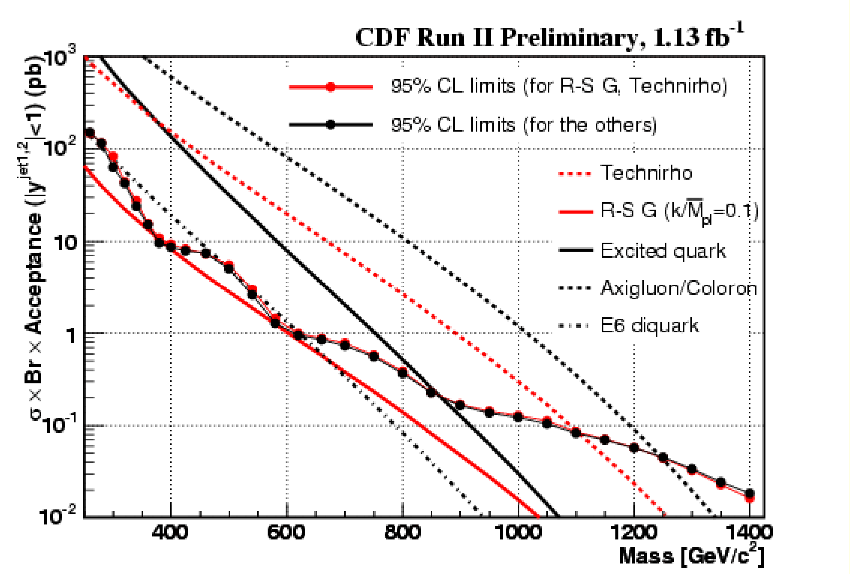
– Choose several couplings (k/MPlanck)

Search for High Mass Di-jet Resonances

- Many Models with new particles decaying into di-jets
  - Axigluons, excited quarks, W'and Z', di-quarks in E_6, RS gravitons, etc.
    - SM couplings for W'/Z'
    - k/Mpl=0.1 for R-S graviton
- Events with $N_{jet} \geq 2$, $|y|<1.0$, $M_{jj}>180$ GeV/c^2

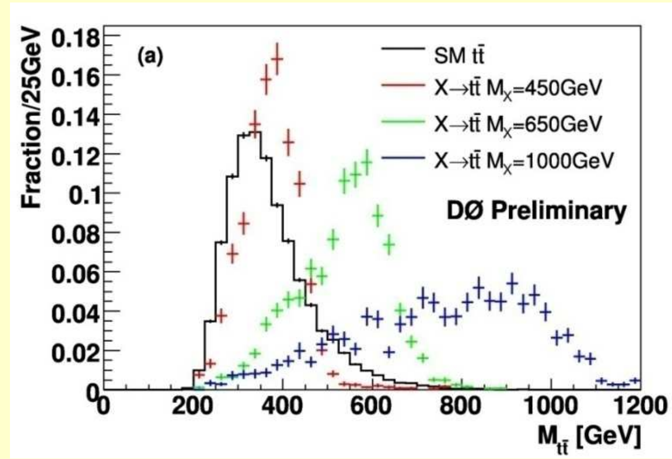


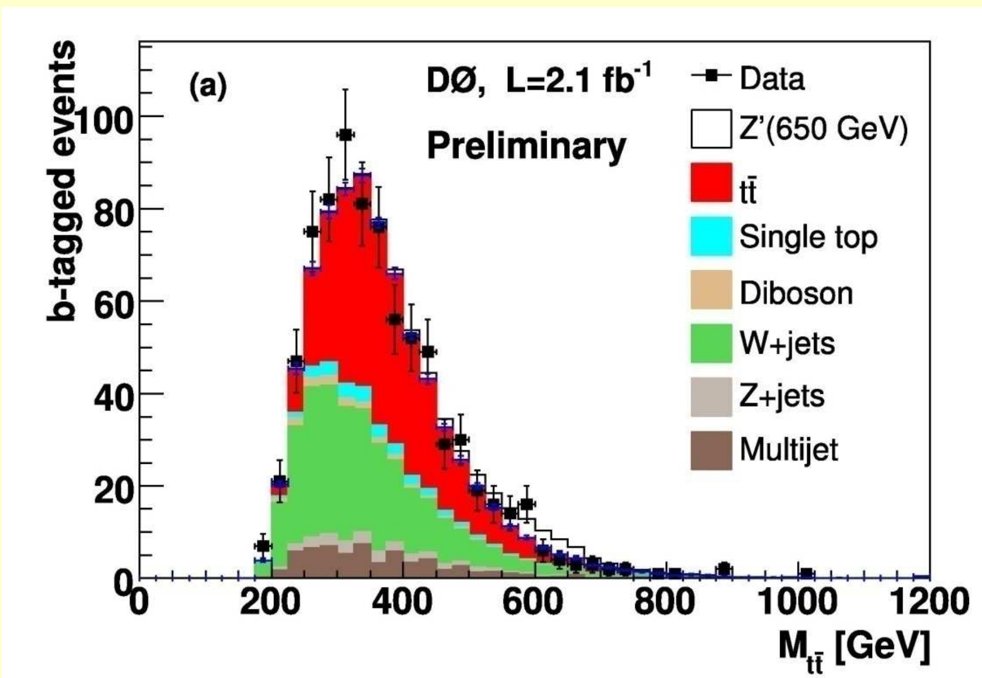
Observed mass exclusion	Model
260-870 GeV/c²	**Excited quark**
260-1110 GeV/c²	**Color-octet technirho**
260-1250 GeV/c²	**Axigluon & coloron**
260-630 GeV/c²	**E6 diquark**
260-840 GeV/c²	**W' (SM couplings)**
260-740 GeV/c²	**Z' (SM couplings)**

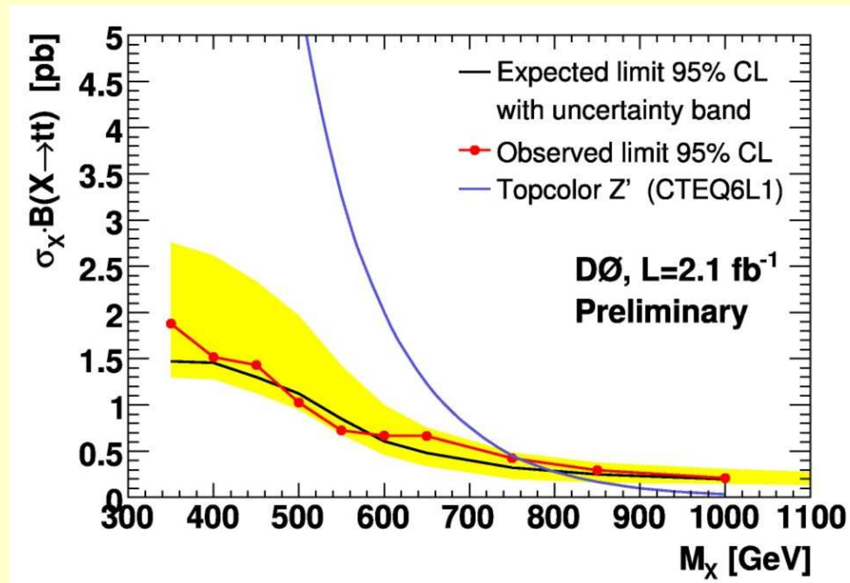


Top pair Resonances

- Resonances of top quarks
  - R-S gravitons couple strongly with quarks
    - Not narrow resonance (Width ~ 0.17M)
  - Leptophobic Z'
- lepton+jets channel using a neural network tagger to identify *b-jets* and the tt invariant mass distribution.
- No evidence of resonant production.

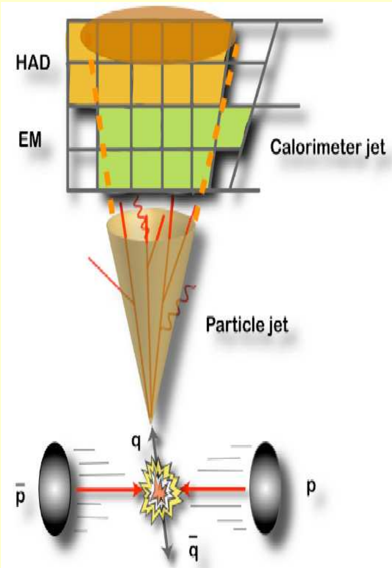






Limits on leptophobic *Z' boson* @ $M_{Z'} < 760$ GeV and $\Gamma_{Z'} = 0.012 M_{Z'}$

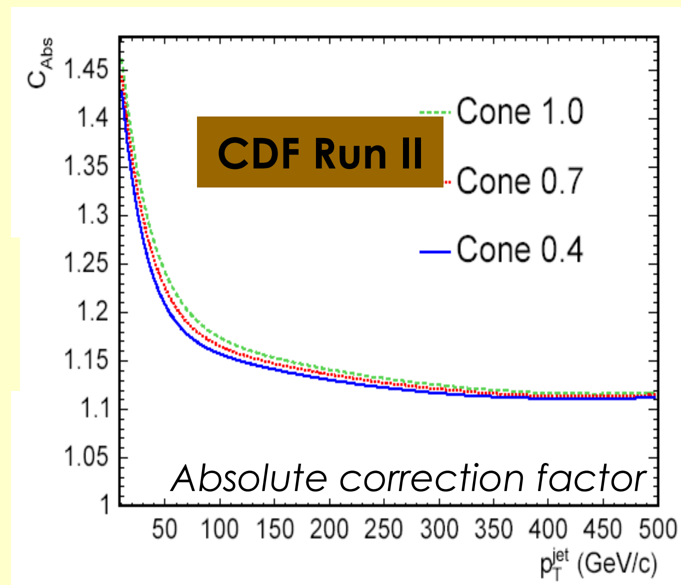
CDF Jet Energy Scale



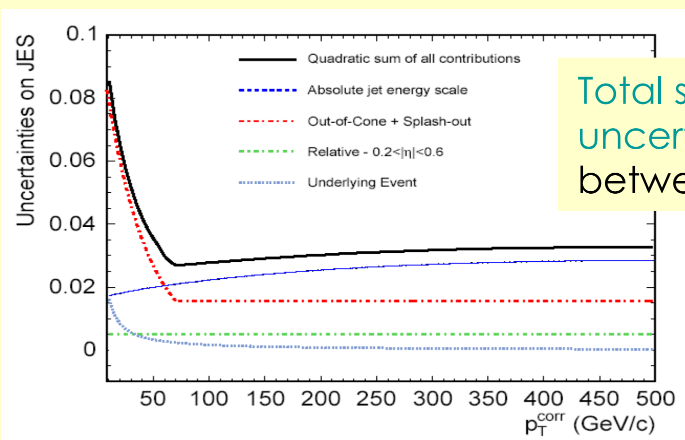
Jets are composite object:
- complex underlying physics
- depends on detector properties

Different correction factors:

- (f_{rel}) Relative Corrections
  - → Make response uniform in η
- (MPI) Multiple Particle Interactions
  - → Energy from different ppbar interaction
- (f_{abs}) Absolute Corrections
  - → Calorimeter non-linear and non-compensating
- (UE) Underlying Event
  - → Energy associated with spectator partons



$$P_{T\,jet}(R) = [\, P_{T\,jet}^{raw}(R) \times f_{rel}(R) - MPI(R)] \times f_{abs}(R) - UE(R)$$



Total systematic uncertainties for JES: between 2% and 3%

MSSM Higgs

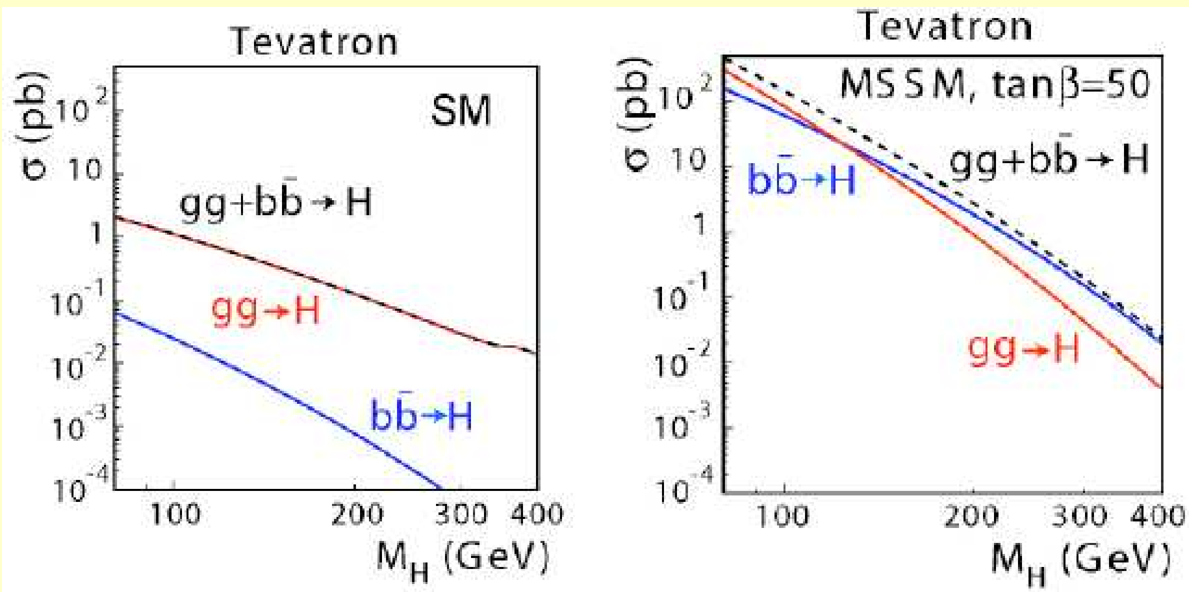
Neutral MSSM Higgs

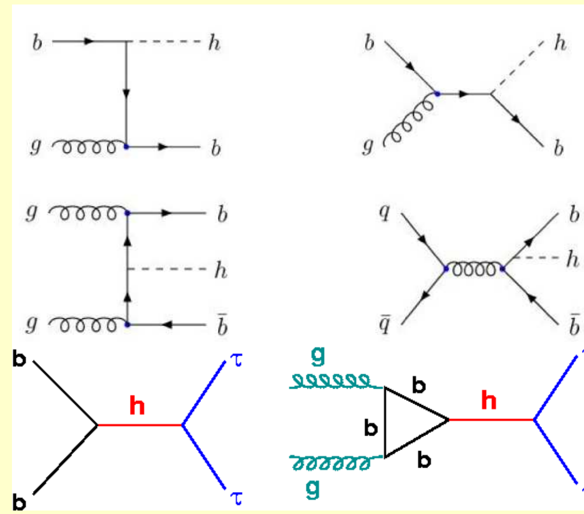
- In MSSM, two Higgs doublets
  - Three neutral (h, H, A), two charged ($H^{\pm}$)
  - Properties of the Higgs sector largely determined by m_A and $\tan\beta$
  - Higher-order effects introduce other SUSY parameters

$$\boxed{H_U, H_D \longrightarrow h, H, A, H^{\pm}}$$

- Large Higgs production cross section at large $\tan\beta$.

$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan\beta^2}{(1+\Delta_b)^2} \times \frac{9}{[9+(1+\Delta_b)^2]}$$





Higgs decays:

BR(bb) : ~90%

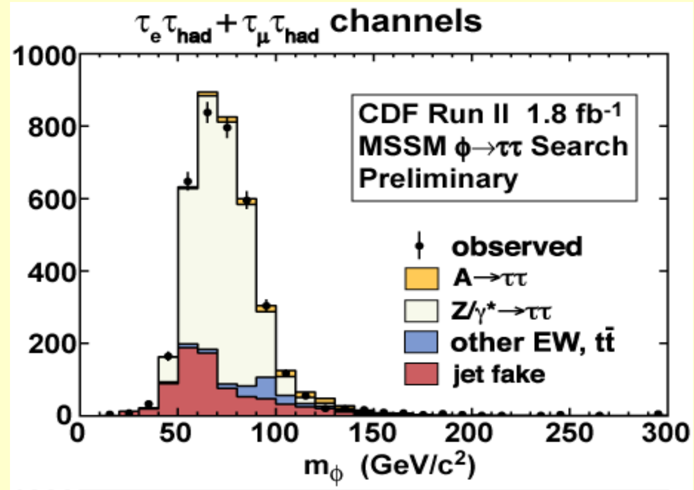
Huge QCD background

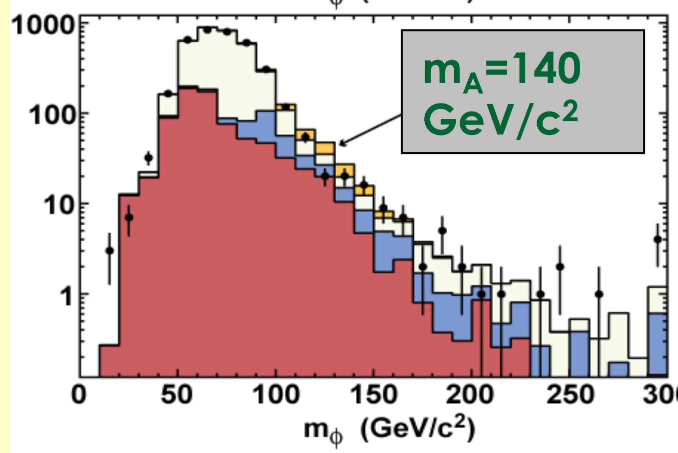
BR(ττ) : ~10%

BSM Higgs: $\phi \rightarrow \tau\tau$

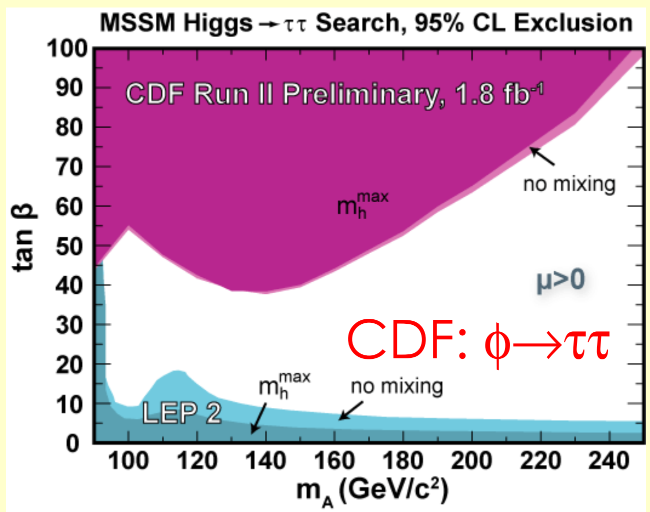
$$m_{vis} = \sqrt{p_{\tau_1}^{vis} + p_{\tau_2}^{vis} + p_T}$$

- CDF and DØ $\phi \rightarrow \tau\tau$ channel
  - $\tau\tau$ pure enough for direct production search
  - DØ adds associated production search: $b\phi \rightarrow b\tau\tau$
- Key issue: understanding τ Id efficiency
  - Large calibration samples: W for Id optimization and Z for confirmation of Id efficiency



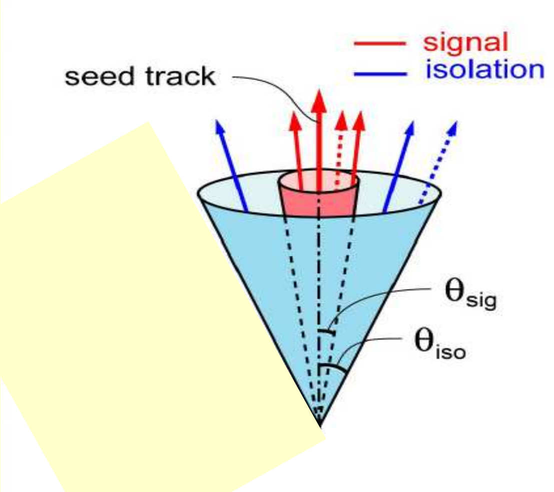


- No Evidence for SUSY Higgs
  - Limits: $\tan\beta$ vs m_A
  - $\phi \rightarrow \tau\tau$ generally sensitive at high $\tan\beta$



τ ID

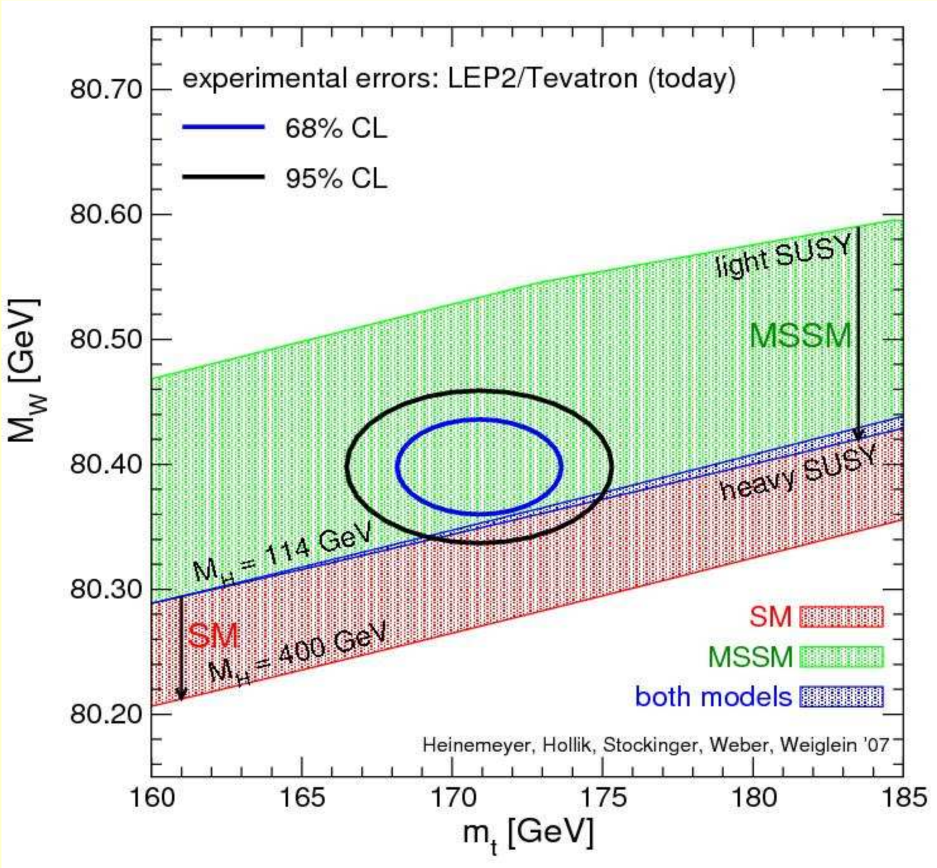
Decay Mode	Final Particles	BR
Leptonic	$e^-\bar{\nu}_e\nu_\tau$	17.8%
	$\mu^-\bar{\nu}_\mu\nu_\tau$	17.4%
Hadronic 1-prong	$\pi^-\nu_\tau$	11.1%
	$\pi^-\pi^0\nu_\tau$	25.4%
	$\pi^-2\pi^0\nu_\tau$	9.2%
	$\pi^-3\pi^0\nu_\tau$	1.1%
	$K^-\nu_\tau$	0.7%
	$K^-\pi^0\nu_\tau$	0.5%
Hadronic 3-prong	$2\pi^-\pi^+\nu_\tau$	9.5%
	$2\pi^-\pi^+\pi^0\nu_\tau$	4.4%



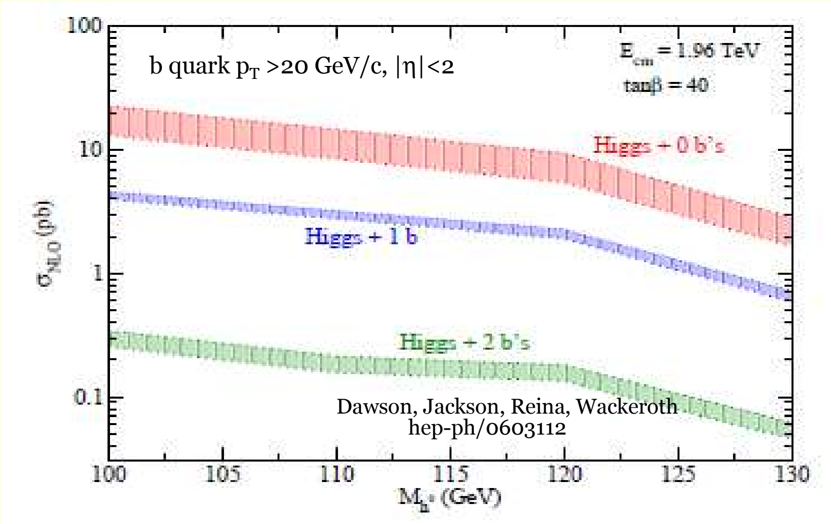
- Signature
  - stiff track pointing to a *narrow* cluster of energy in the calorimeter
- Challenge
  - Discrimination from clusters from generic QCD jets

MSSM Higgs sector

M(W)-M(top)



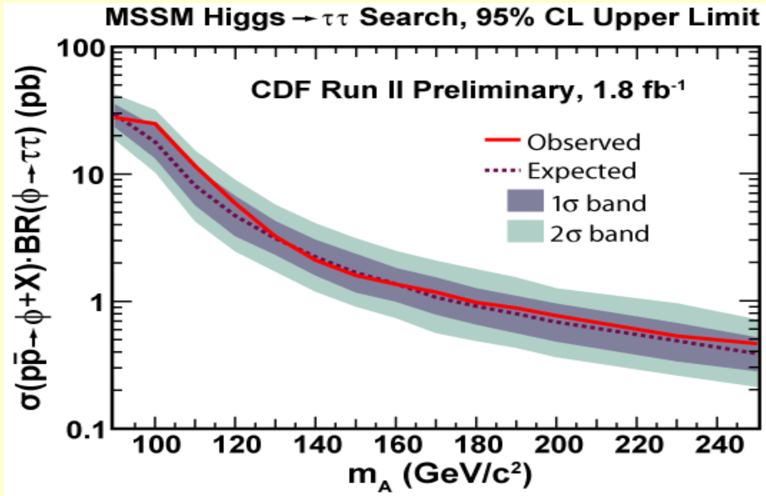
Cross section VS M(H) in Higgs+N-b associated production

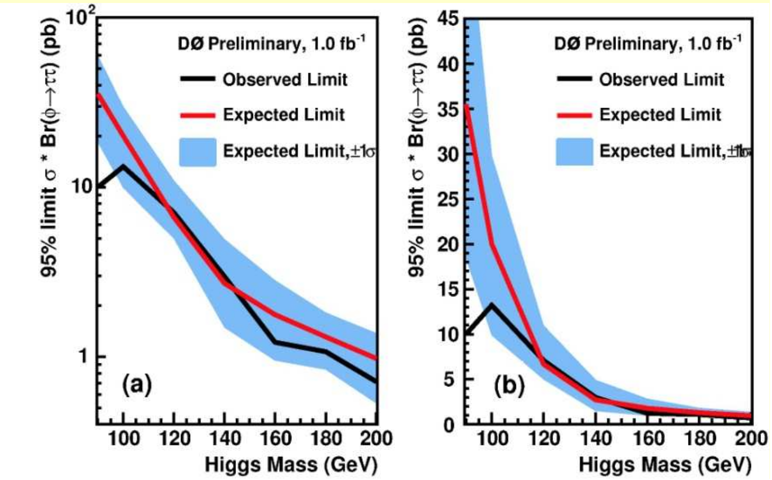


MSSM Higgs Limits

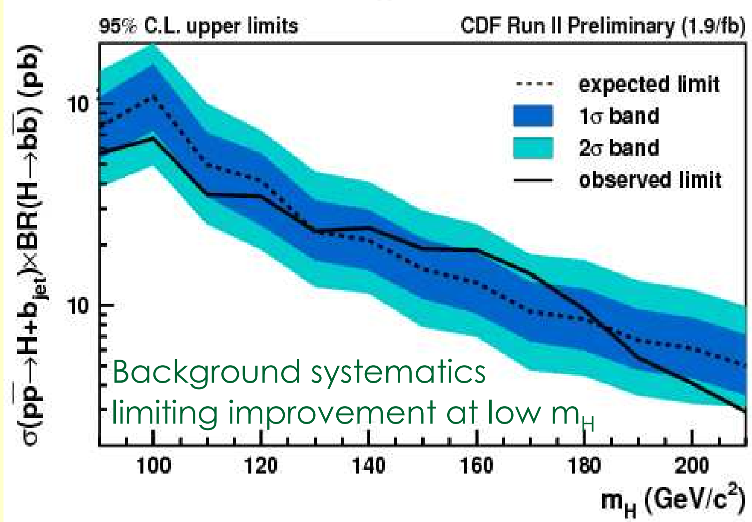
Limits in $\sigma(H)$*BR vs m(H)

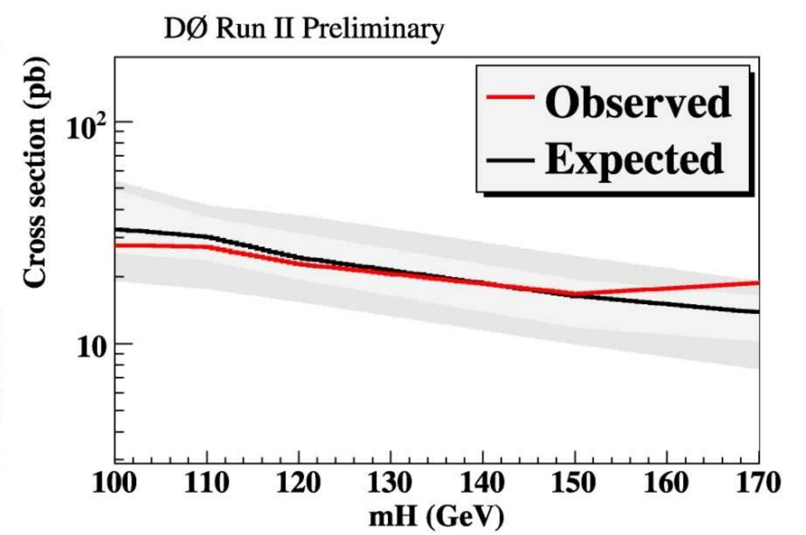
$H \rightarrow \tau\tau$





$H \rightarrow bb$





LHC mSUGRA cross sections

- Strongly interacting particles
- High cross sections for gluinos and squarks production

→ Golden signature!

T. Plehn, PROSPINO

σ (pb)