XXXVIII International Symposium on Multiparticle Dynamics

ISMD 2008

15-20 September 2008, DESY

Topics

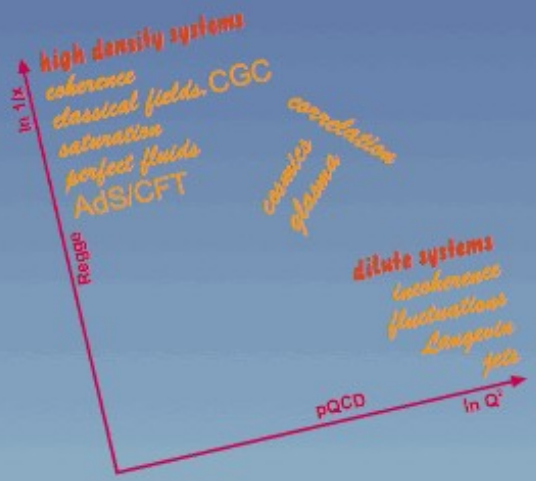
Dilute Systems
- High Q2
- Structure Fcts
- Central Prod.

High density systems
- Saturation
- Hydrodynamics
- CGC
- Perfect fluids

Interpolation region
- Forward production at highest energies
- Diffraction
- Glasma

Strategies and analysis tools
- Correlations
- Heavy Q production
- MC techniques

New physics
- Signals for Higgs, SUSY etc.



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http://ismd08.desy.de **contact: ismd08@desy.de**

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The Physics Landscape

There are many possible models of new physics that could easily produce results in ~1 fb^{-1}.

While supersymmetry may be popular, all that is certain is a high probability for some sort of new physics “just around the corner”:

- Radiative corrections to the Higgs mass
- Gravitation?
- Three generations?
- .....
- If there is one
- Unification of couplings?
- Dark matter?

Searches for New Physics*

Introduction

Compositeness and Leptoquarks

Extra Gauge Bosons

Supersymmetry

- Squarks / Gluinos – Charginos / Neutralinos

Extra Dimensions

Model Independent Searches

Conclusions

* At the Tevatron, for the most part

Arnd Meyer

RWTH Aachen University

September 18, 2008

Searches for New Physics*

Introduction

Compositeness and Leptoquarks

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Conclusions

Recent examples

* At the Tevatron, for the most part

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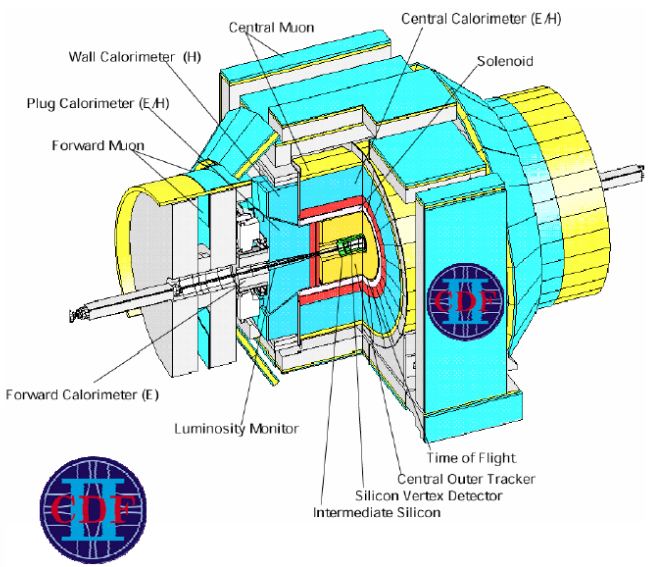
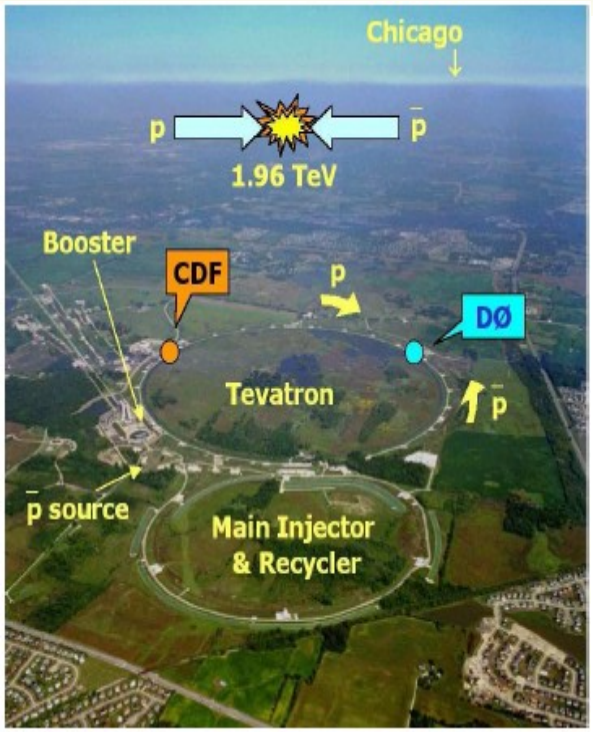
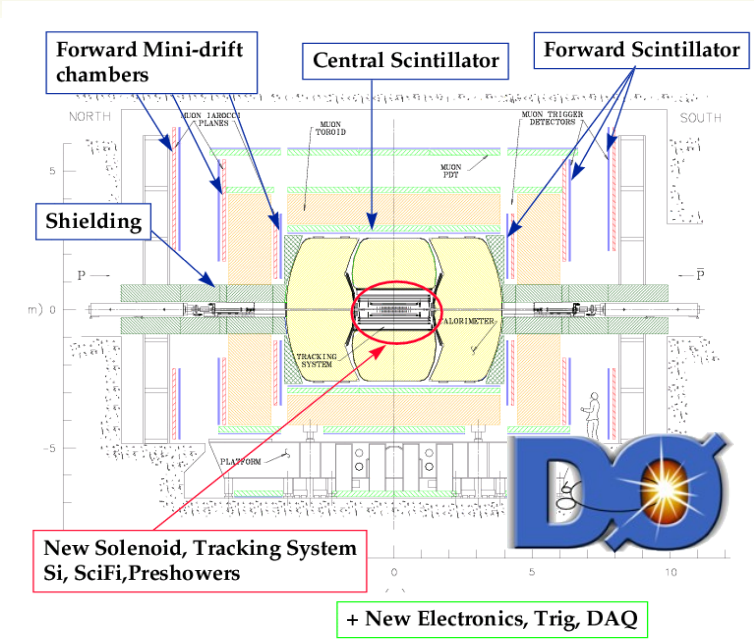
Tevatron: The DØ and CDF Experiments



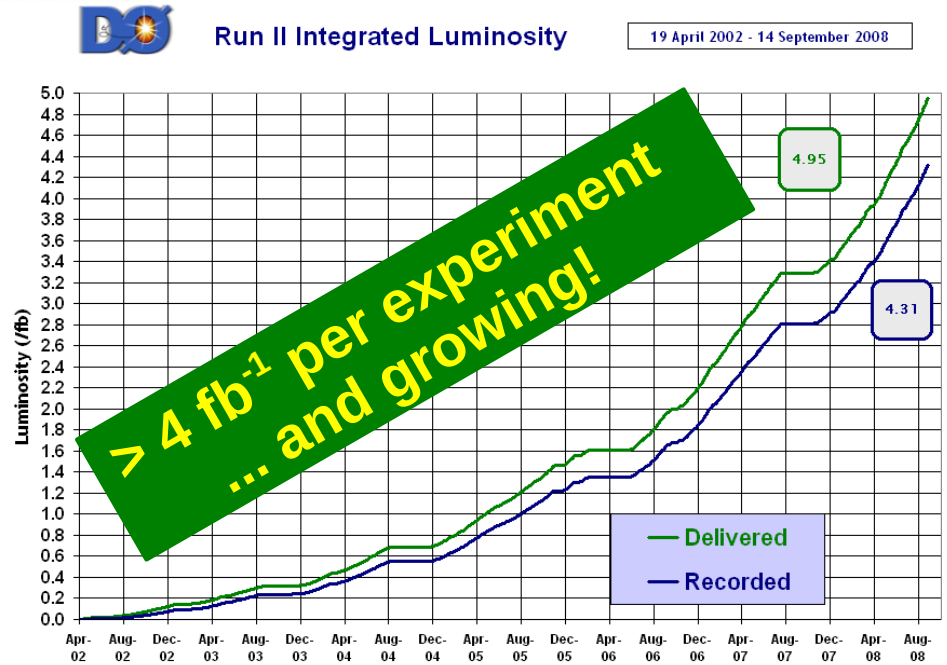




Typically:

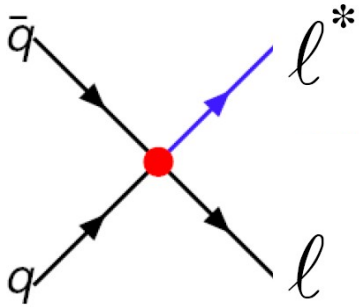
Electron acceptance	$\lvert\eta\rvert < 2.0 - 3.0$
Muon acceptance	$\lvert\eta\rvert < 1.0 - 2.0$
Precision tracking (Si)	$\lvert\eta\rvert < 2.0 - 3.0$

Detectors are well understood and take data with ~80-95% efficiency

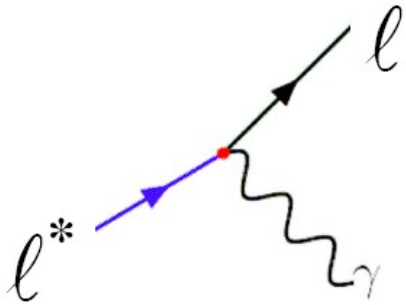


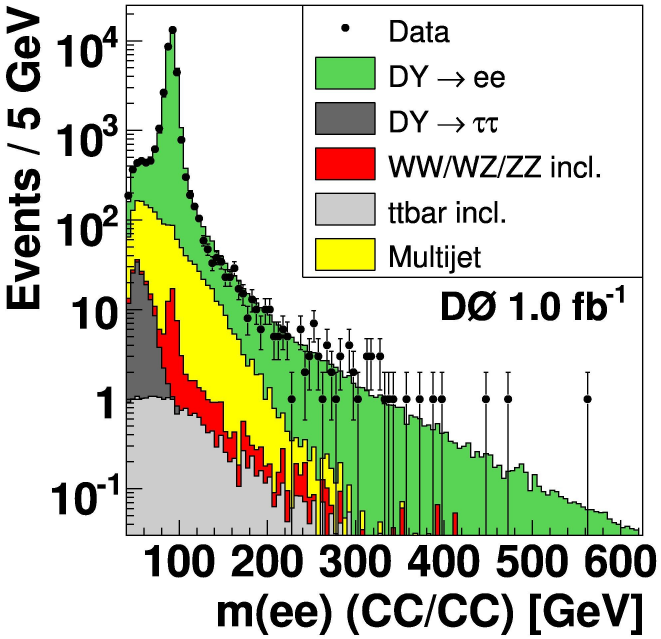
Lepton Compositeness: e*

- Learning from thousands of years of history, quarks and leptons may be made of smaller pieces ("preons")
  - Allows excited states (e^*, μ^*, q^*)
  - Describe as contact interaction (compositeness scale Λ)
  - Decay: gauge interaction ($e^* \to e\,\gamma$, $\nu\,W$, $e\,Z$) or CI ($e^* \to e\,f\,f$)



- Example here: $q\,\bar{q} \to e\,e^* \to e\,e\,\gamma$





Two isolated electrons with

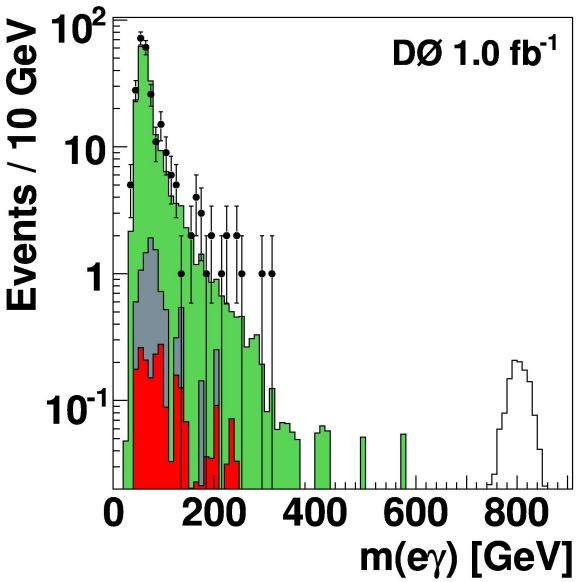
$E_T > 25$ GeV, 15 GeV

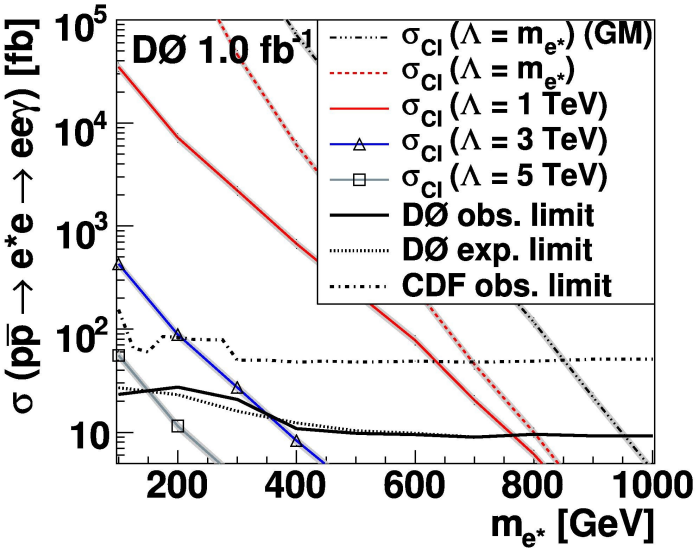
Next: isolated photon with

$E_T > 15$ GeV

Excited Fermions: e*

- Observe **259 events with expectation 239 ± 26 events**
- Search for peak in e+γ invariant mass
- Optimize selection criteria
  - Combination e1+γ or e2+γ
  - Mass window / single sided cut
  - |η| acceptance and separation (for small m(e*))
- Find 0 or 1 event in data for all e* masses, with small expected SM background

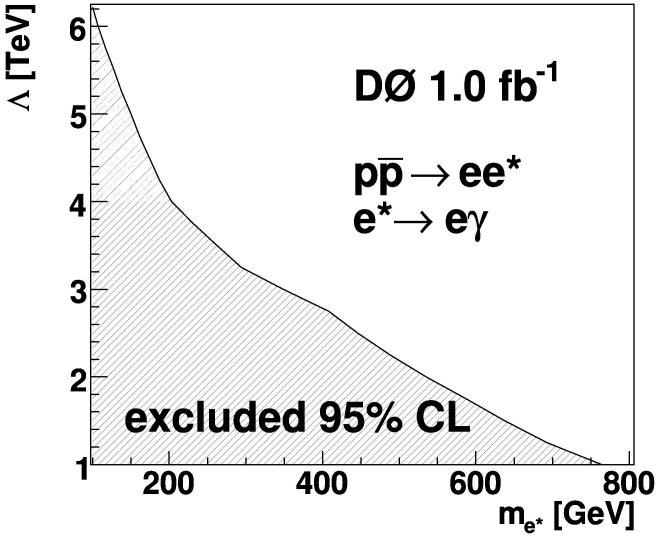




m(e*) > 756 GeV

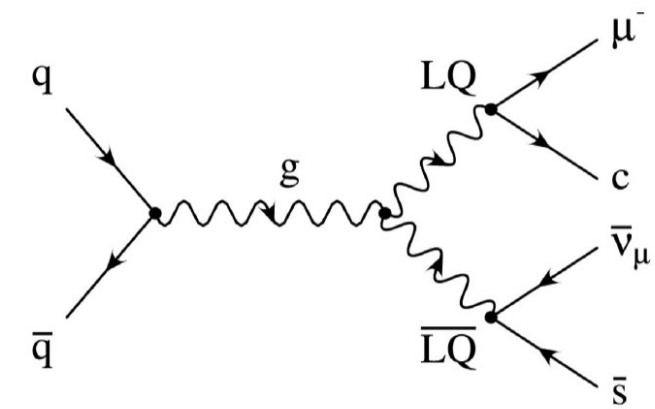
for Λ = 1 TeV

For comparison: m(e*) > 989 GeV when neglecting CI decays, for Λ = m(e*), and using the same theory cross sections as CDF



Leptoquarks

Predicted in GUT's, Extended Technicolor, Compositeness



Properties:

- Couples directly to a quark and a lepton
- Carries both baryon number and lepton number
- Spin-0 or spin-1, charge Q = 1/3, 2/3, 4/3

β := BF(LQ $\rightarrow l$j)

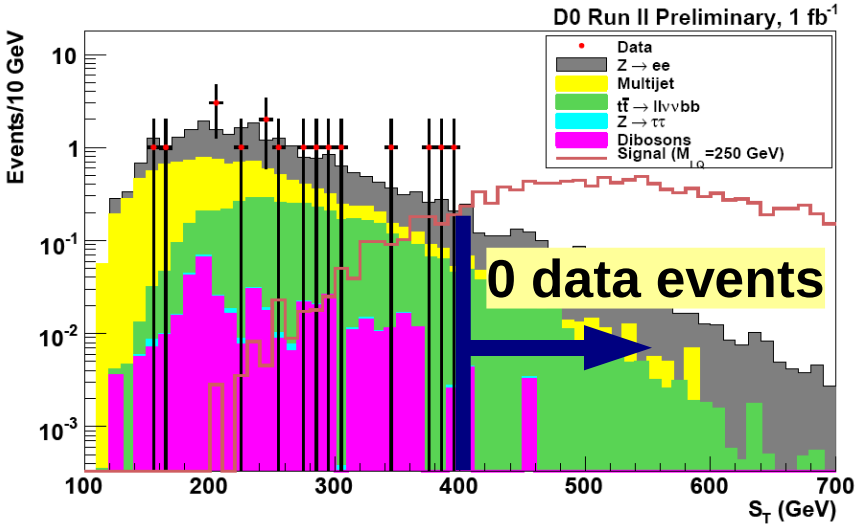
σ x BF($\nu\nu$jj) $\propto (1-\beta)^2$

σ x BF(lljj) $\propto \beta^2$

σ x BF($l\nu$jj) $\propto 2\beta\,(1-\beta)$

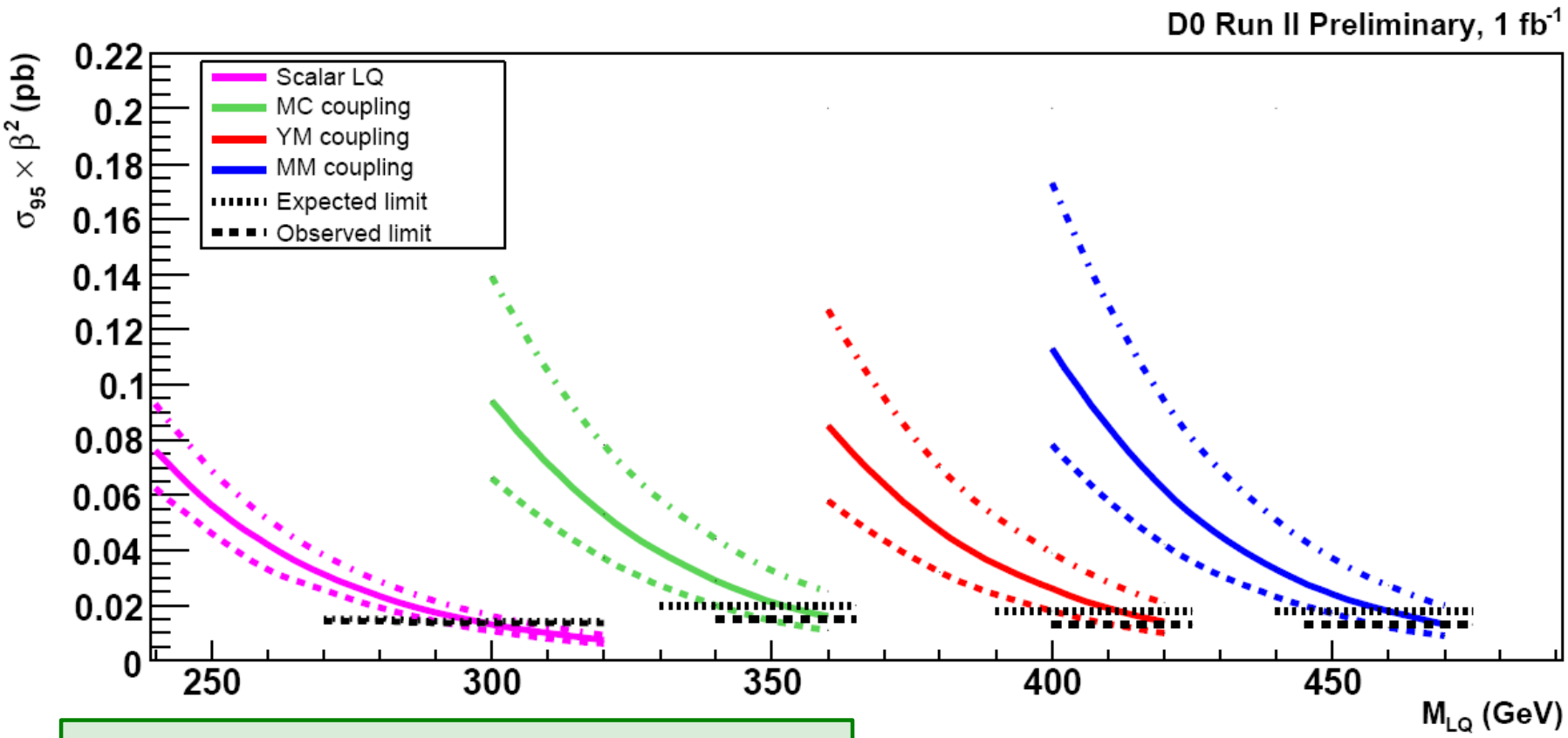
Example: pair production of 1st generation LQ

- At least 2 electrons and 2 jets ($\rightarrow$ sensitive for large β)
- $S_T = E_T(e1) + E_T(e2) + E_T(j1) + E_T(j2)$
- Best expected limits (M(LQ) = 290 GeV) for M(ee) > 110 GeV and S_T > 400 GeV
- Use $\langle M_{ej}\rangle = (M_{ej}1 + M_{ej}2) / 2$ distribution to set limits ($M_{ej}1$ and $M_{ej}2$ chosen such that LQ and LQ difference minimal)



S_T after M(ee) > 110 GeV cut

LQ1 – Results

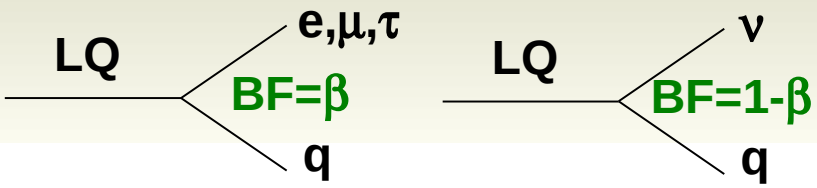


Scalar LQ M(LQ1) > 292 GeV

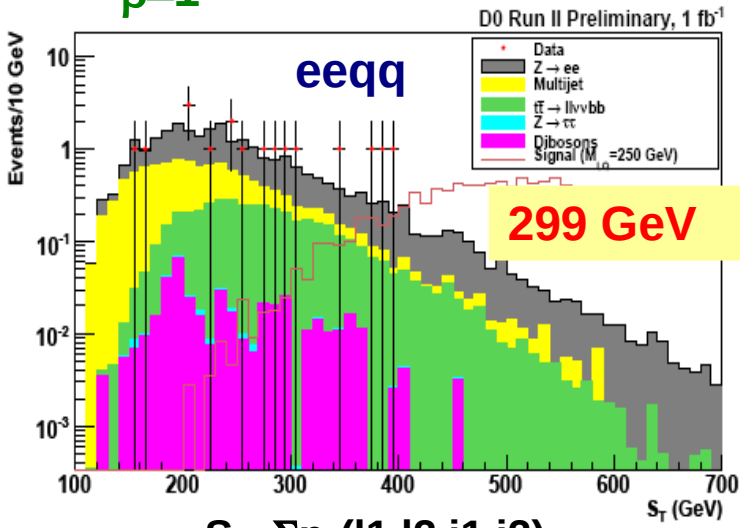
Vector LQ:

M(LQ1) > 350 GeV	($Q=1/3$, $T_3=-1/2$, $\kappa_G=1$, $\lambda_G=0$)
M(LQ1) > 410 GeV	($Q=1/3$, $T_3=-1/2$, $\kappa_G=0$, $\lambda_G=0$)
M(LQ1) > 458 GeV	($Q=1/3$, $T_3=-1/2$, $\kappa_G=-1$, $\lambda_G=-1$)

Scalar Leptoquarks

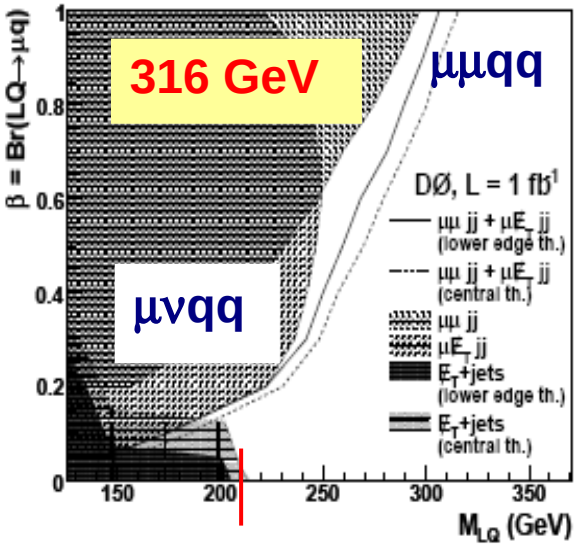


β=1

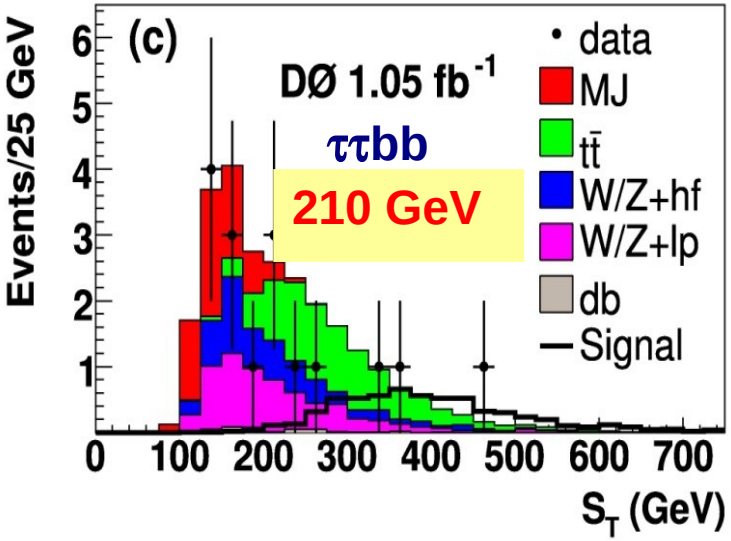


$S_T=\Sigma p_T(l1,l2,j1,j2)$

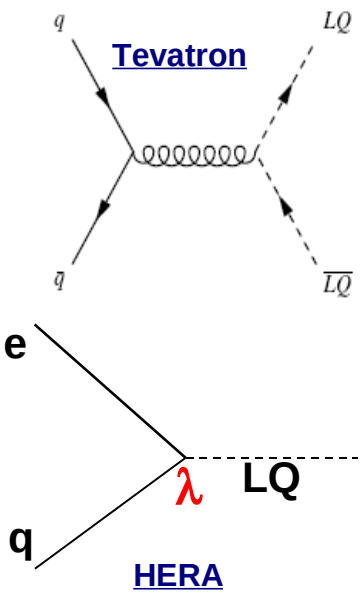
preliminary

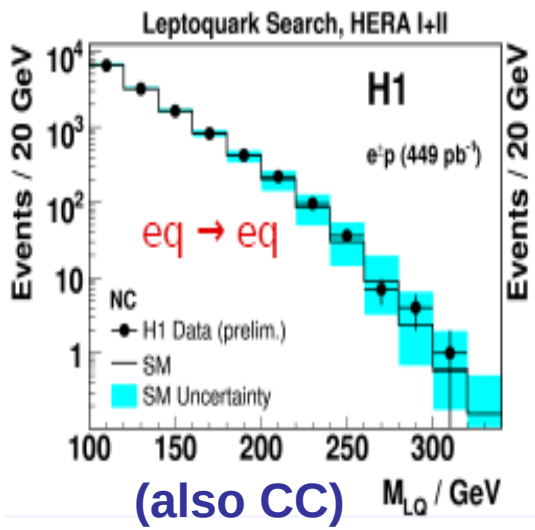


β=1

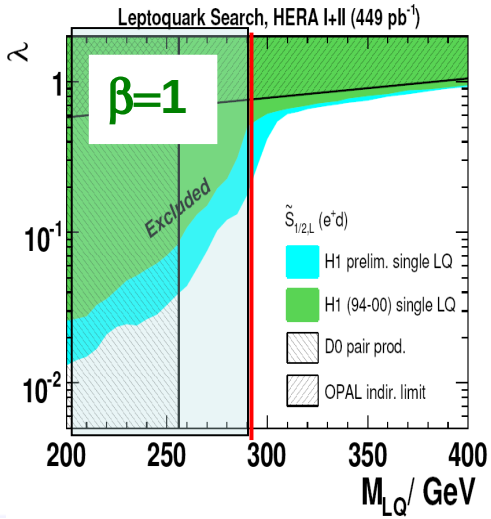


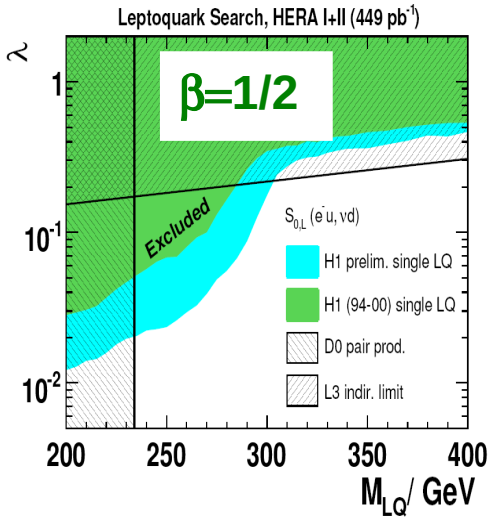
1st & 2nd gen: 214 GeV (β=0 DØ prel. 2.5 fb^{-1})
3rd gen: 229 GeV (β=0 DØ 425 pb^{-1})





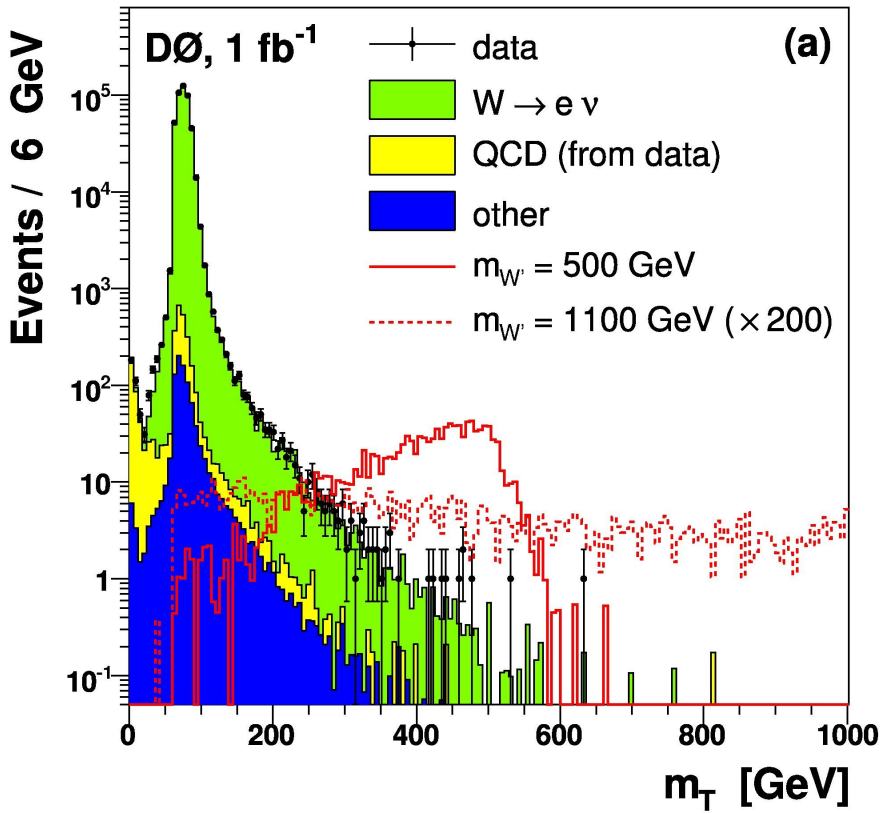
(also CC)

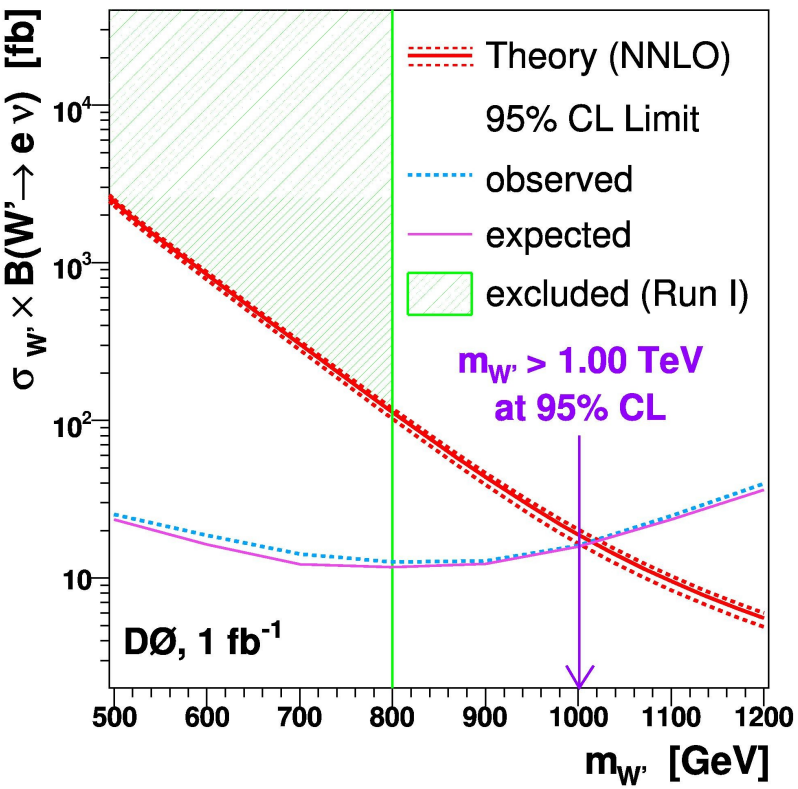




Extra Gauge Bosons: W'

- Predicted in many beyond-SM scenarios
- Data (for M_T > 140 GeV):
  967 events
- Standard Model expectation:
  959 ± 21 (stat) ± 90 (syst) events
- Use M_T distribution to derive limits



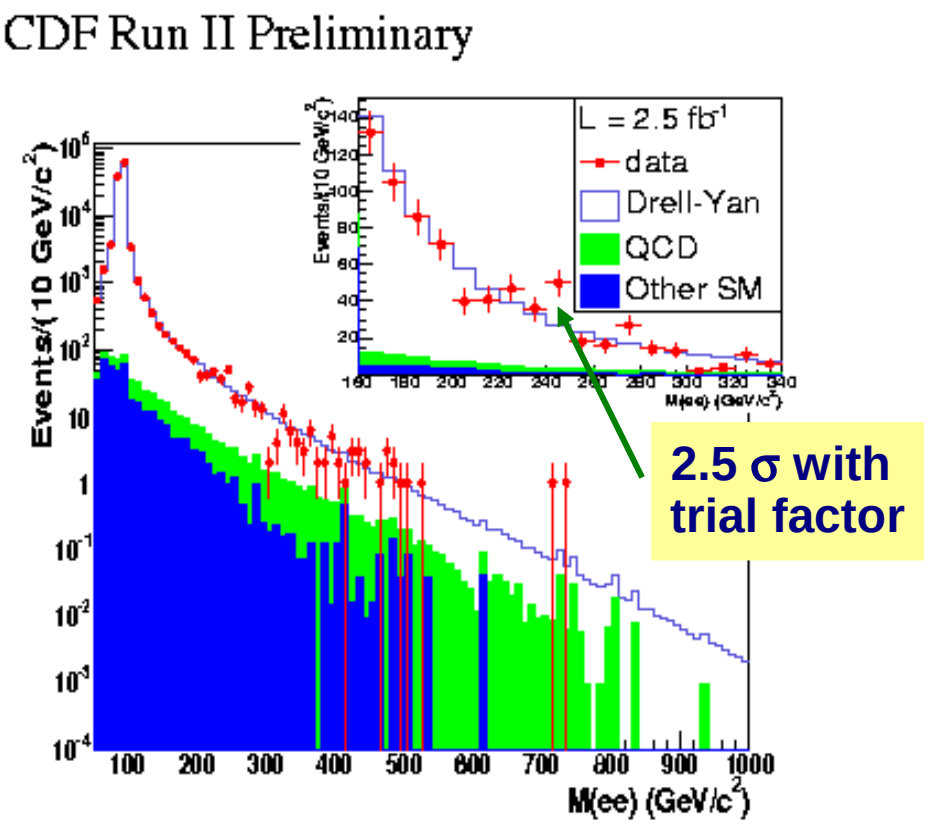


M(W') > 1.00 TeV **(SM-like W')**

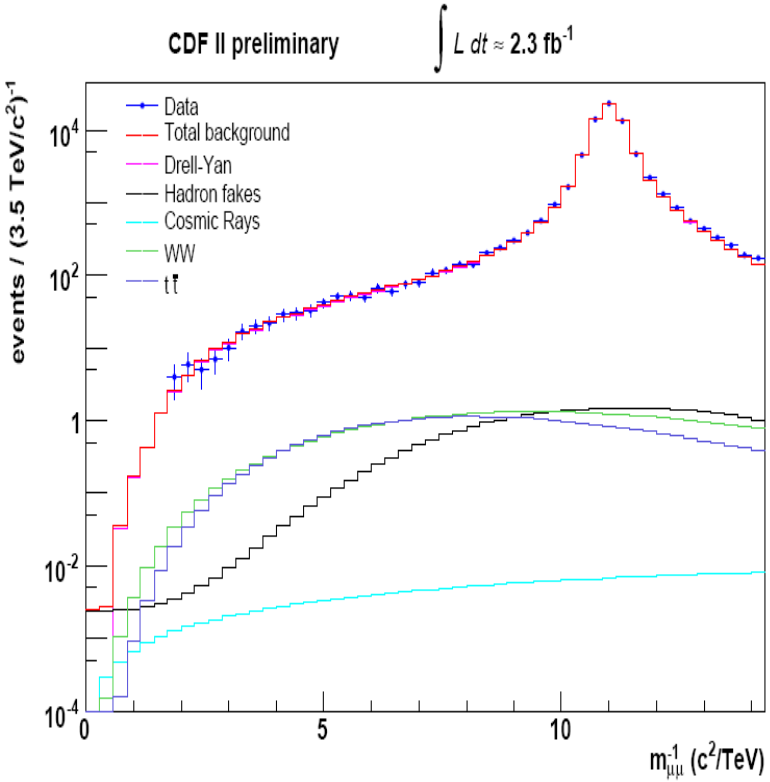
First direct search with sensitivity beyond 1 TeV

Extra Gauge Bosons: Z'

Z' → ee



Z'→μμ



Plot in $1/m_{\mu\mu}$ (consistent with Gaussian resolution in $1/p_T$)

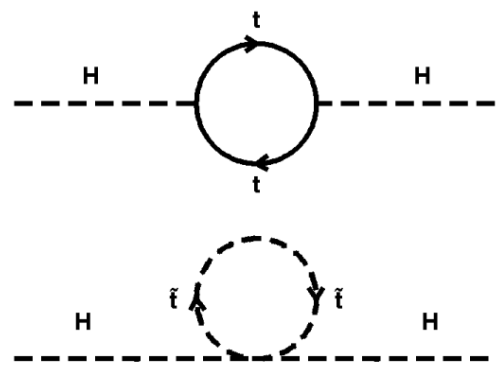
M(Z') > 966 GeV

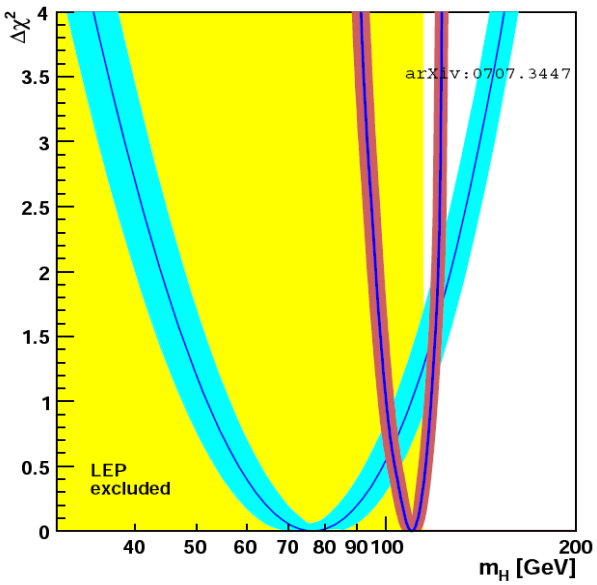
M(Z') > 1030 GeV

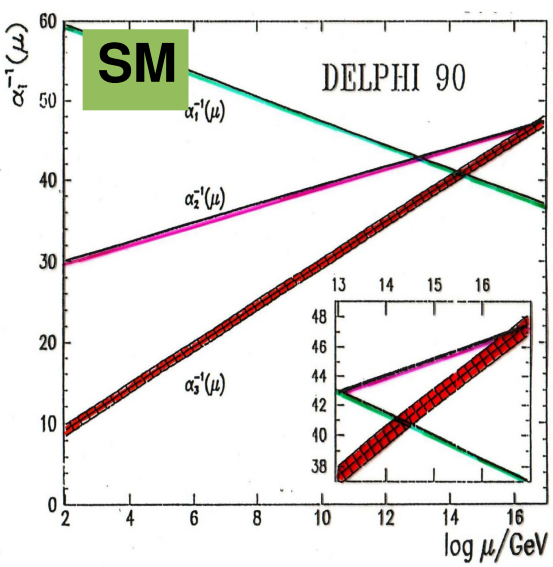
(Sequential Z')

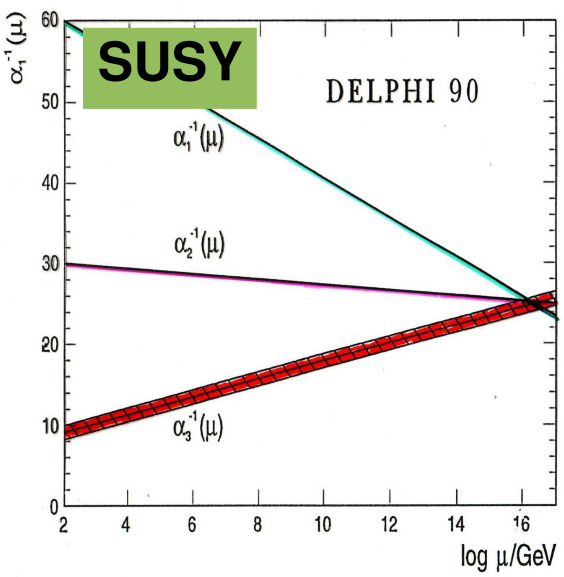
Supersymmetry

- Supersymmetry (SUSY): fundamental symmetry , relating bosons and fermions
- Stabilizing Higgs mass ("fine-tuning")
  - m(Higgs) < 135 GeV (MSSM)
  - In good agreement with expectations from EW fits
- "Running" of couplings is sufficiently modified to allow grand unification at a single scale







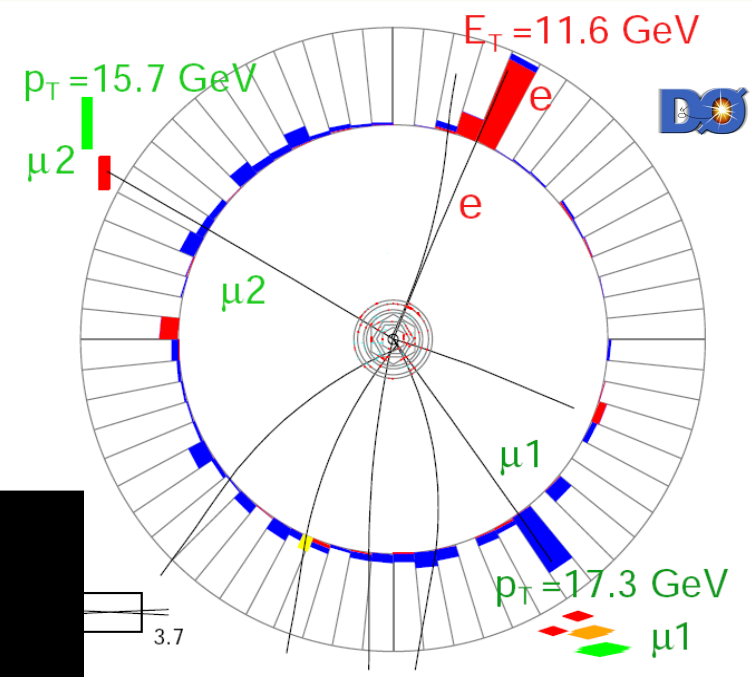


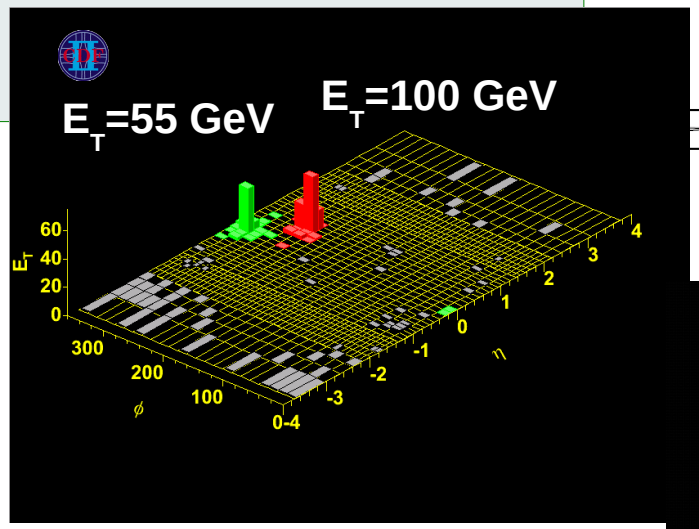
- LSP (Lightest SUSY Particle) is candidate for dark matter

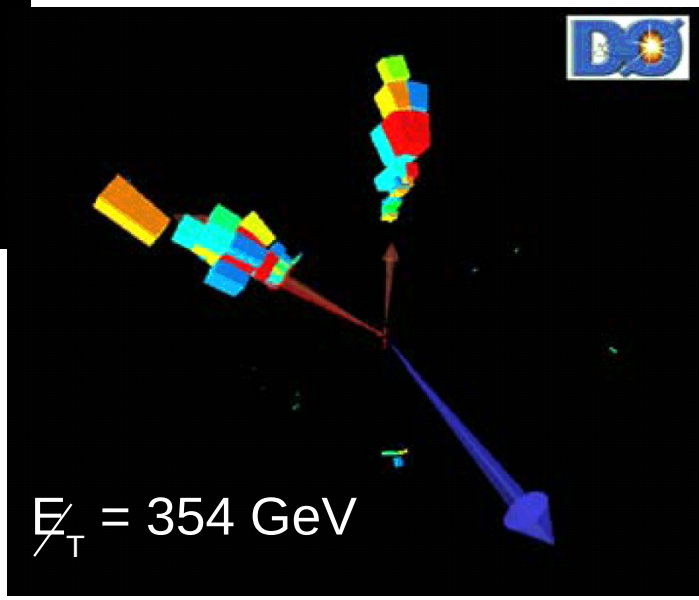
Supersymmetry – Signatures

Studied in great detail is mSUGRA: gravity mediated symmetry breaking, only 4 ½ parameters

- Scalar and gaugino mass at the GUT-scale, **m_0 and $m_{1/2}$**
- Trilinear coupling parameter **A_0**
- **tan β**, ratio of the higgs vacuum expectation values at the electroweak scale
- **sign(μ)**, higgsino mass parameter







Missing transverse energy (LSP)

and/or many jets

and/or many leptons from cascade decays

(but: can be soft)

Supersymmetry – Search Strategies

- Generic sparticle production
  - Probe large regions of parameter space
- Specific sparticle decays / decay chains
- Search for sparticles with unusual properties
  - Small mass differences or couplings, i.e. large lifetimes
  - Also: different SUSY breaking mechanisms
- SUSY Higgs
- Indirect searches
  - Rare decays
- ...
- Global (“model independent”) searches

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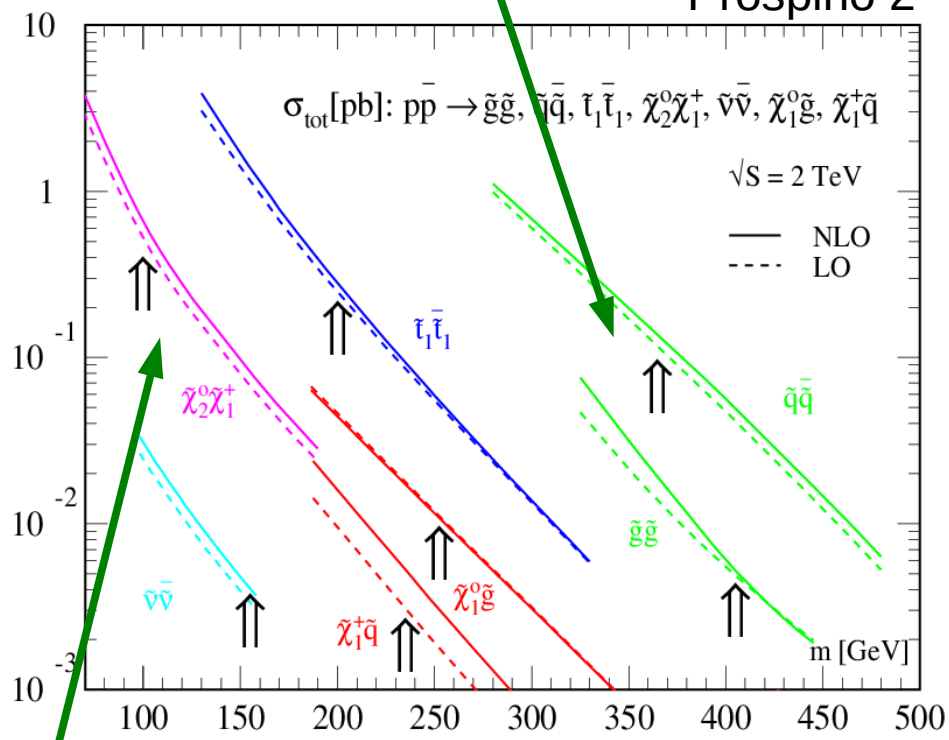
Generic squarks and gluinos
⇒ Multijets + missing E_T

Prospino 2

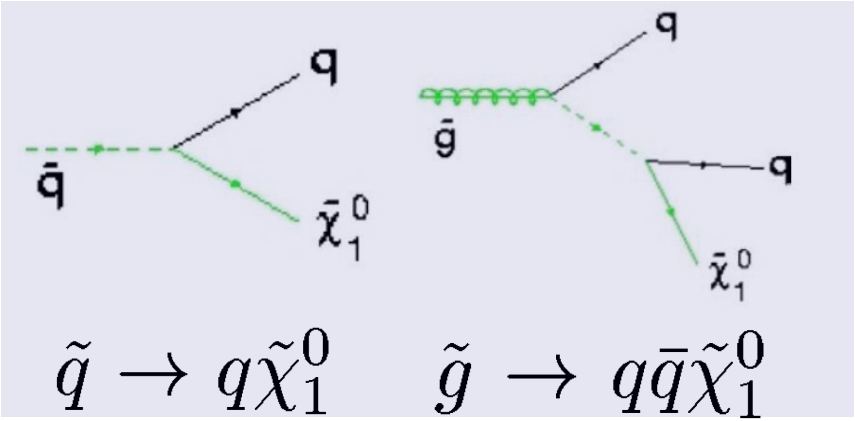


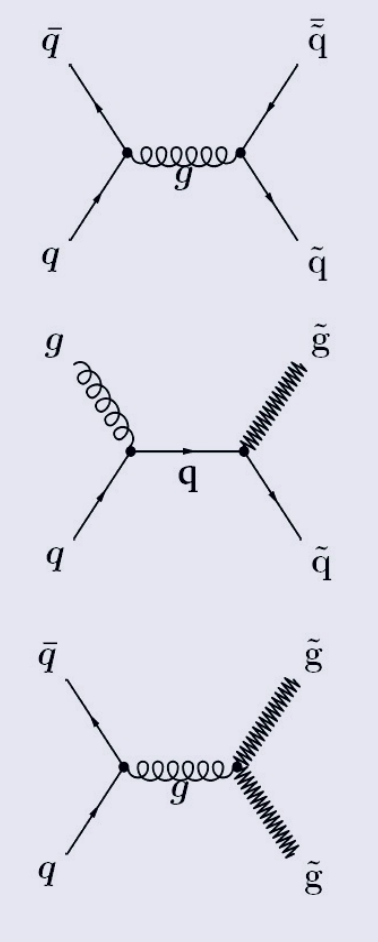
Gauginos with leptonic decays
⇒ Trileptons

Supersymmetry: Squarks and Gluinos

LSP assumed stable (R_p conserved)

→ ≥ 2 jets + $\not{E}_T$ ("MET")





Low m_0, m(squark) < m(gluino)

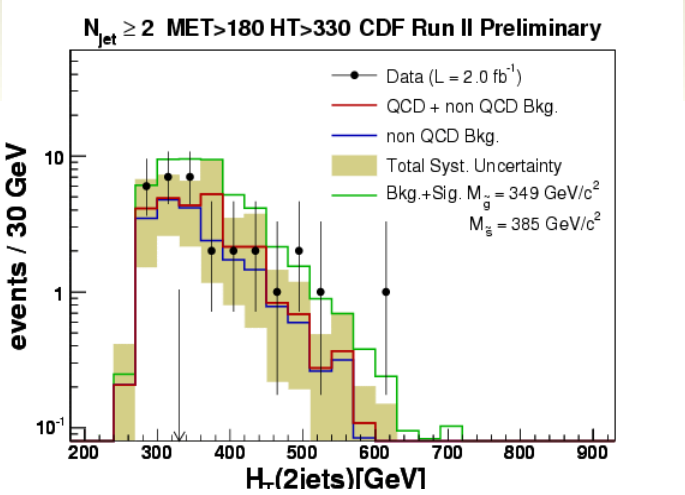
(at least 2 jets)

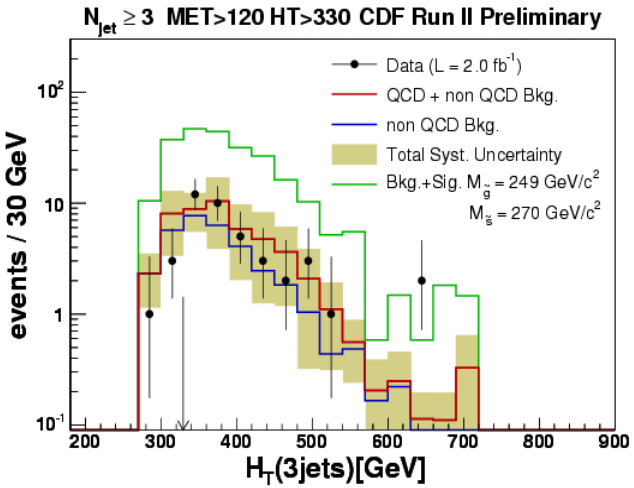
Medium m_0, m(squark) ~ m(gluino)

(at least 3 jets)

High m_0, m(squark) > m(gluino)

(at least 4 jets)





Important backgrounds:

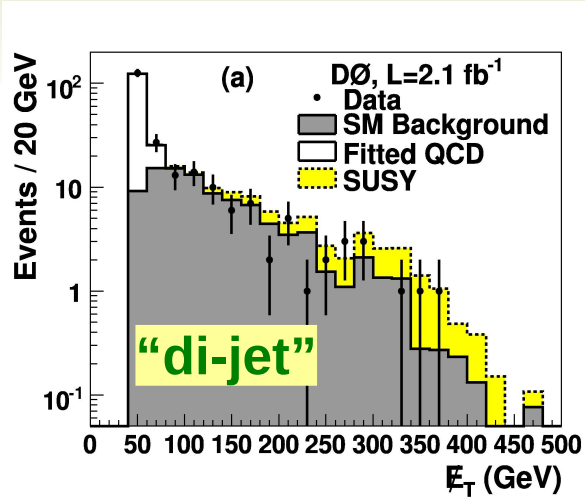
- $Z \rightarrow \nu\nu$ + jets
- Top pairs
- W+jets

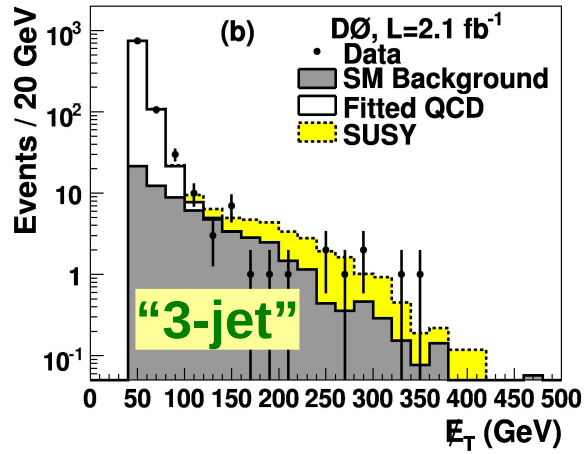
Suppressed using:

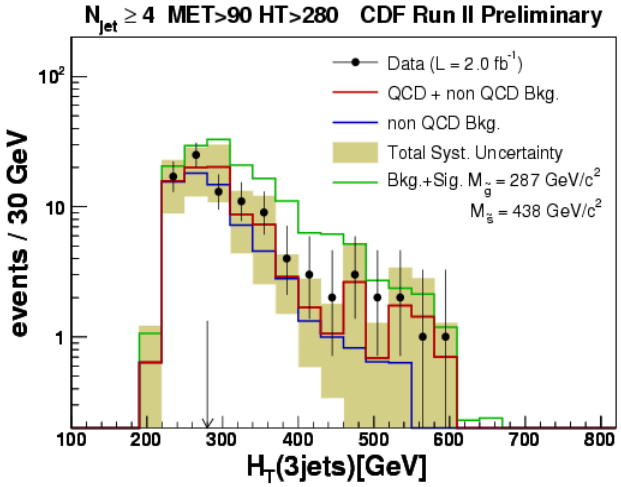
- Jet p_T
- MET
- total energy (H_T)
- angular correlations

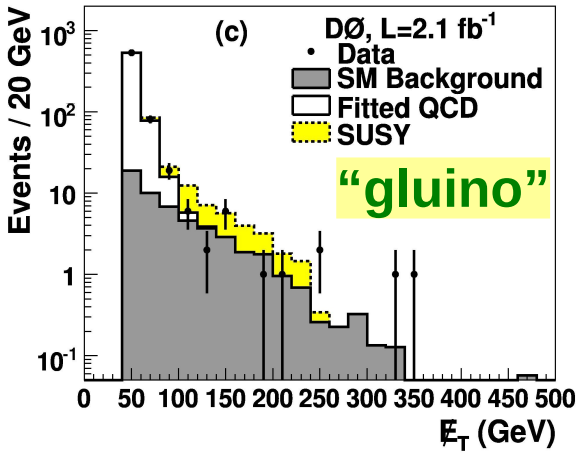
Optimize for multiple SUSY points

No data excess observed

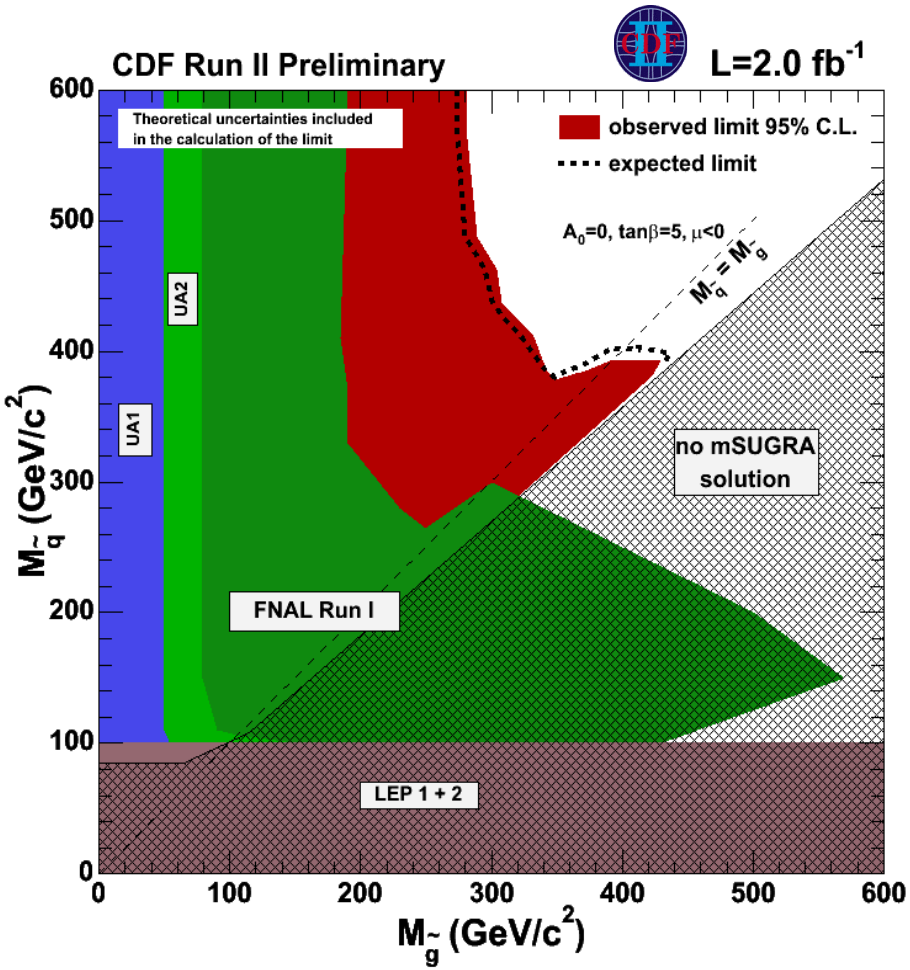


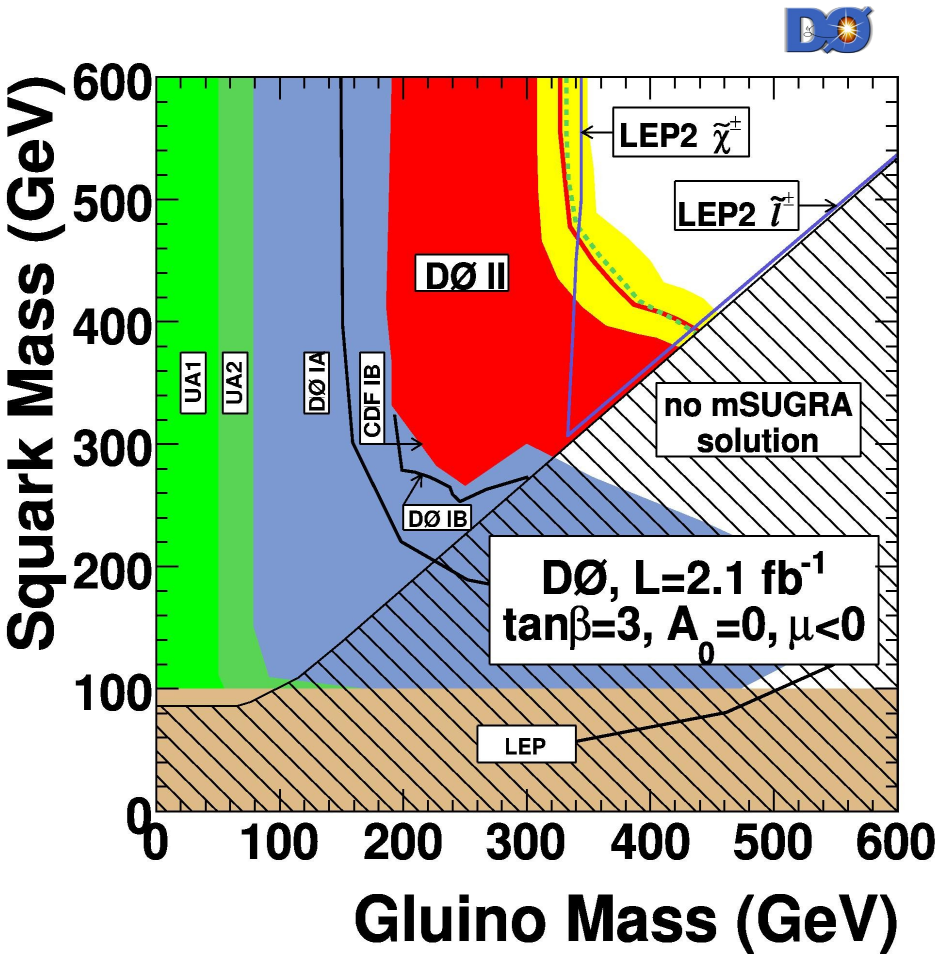






Squarks and Gluinos: Mass Limits

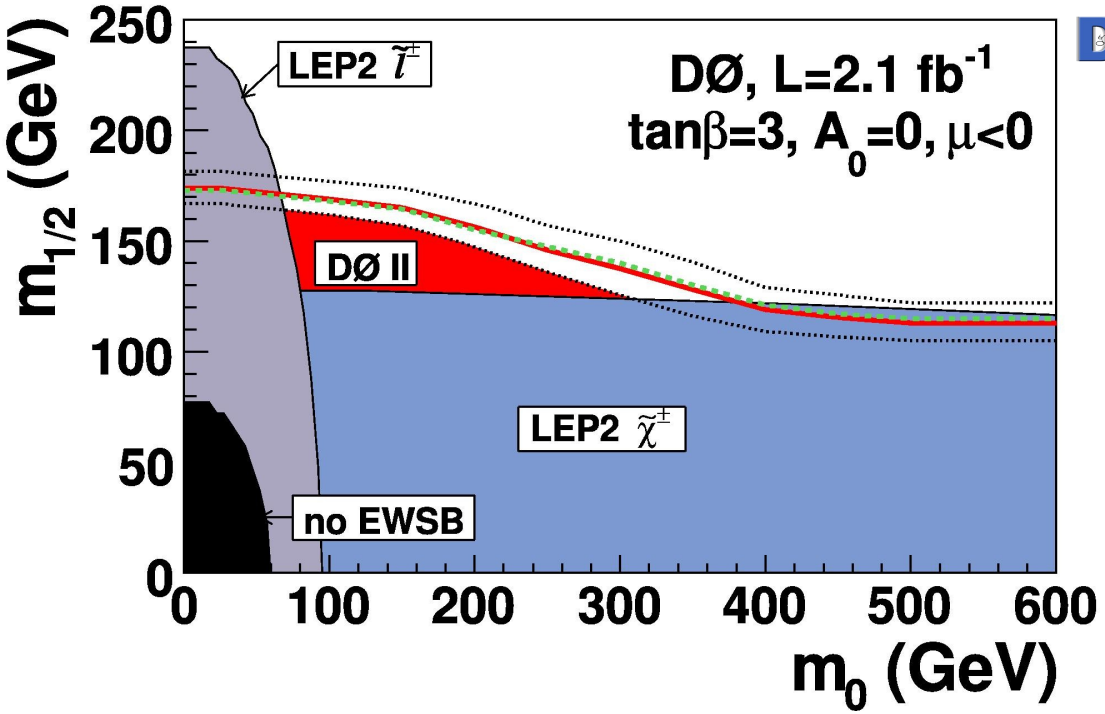


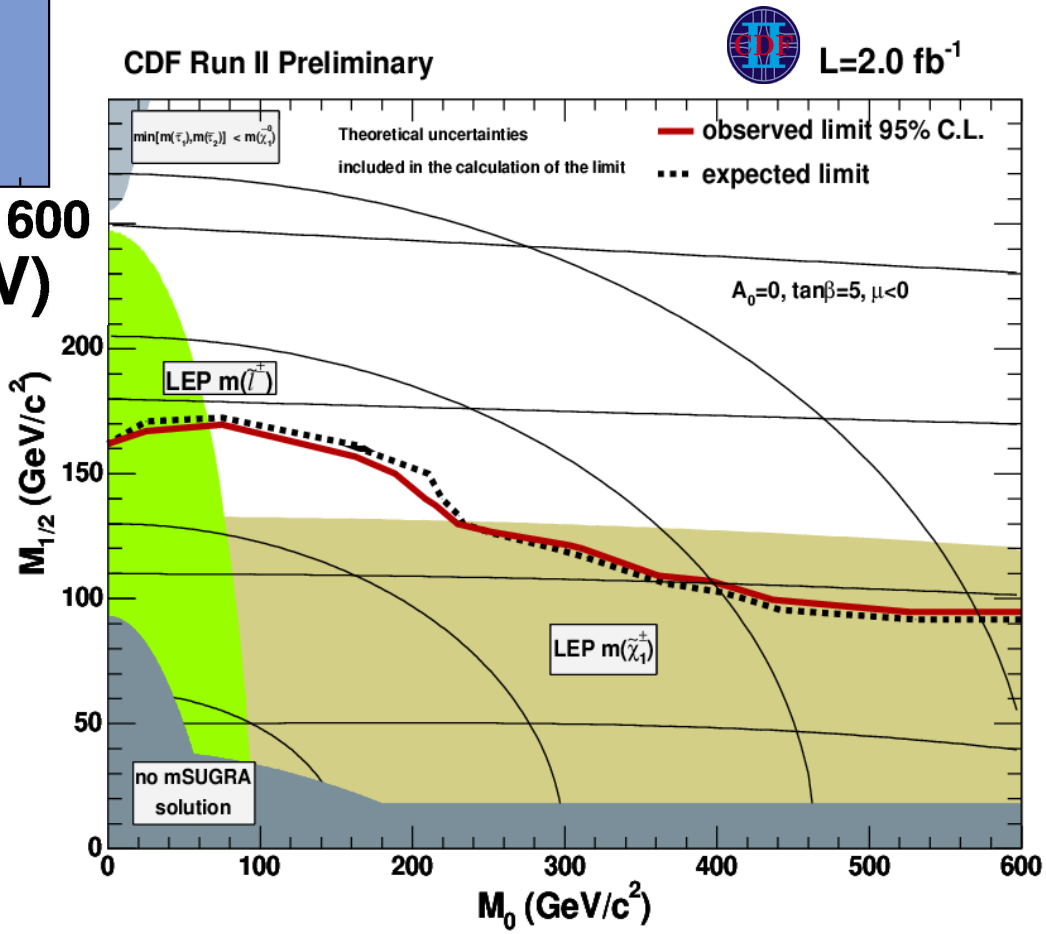


M > 392 GeV [M($\tilde{q}$)=M($\tilde{g}$)]
M($\tilde{g}$) > 280 GeV

M($\tilde{q}$) > 392 GeV
M($\tilde{g}$) > 327 GeV

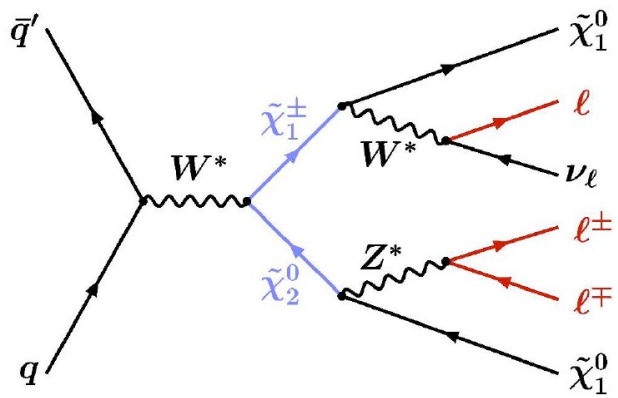
Squarks and Gluinos: Limits in m_0 vs. $m_{1/2}$



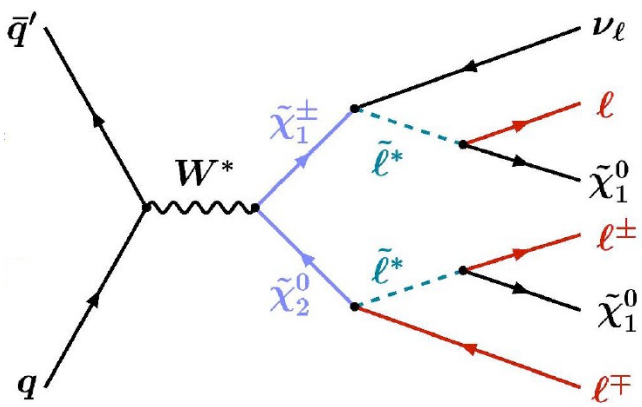


Charginos / Neutralinos: Trilepton Final State

Heavy sleptons:



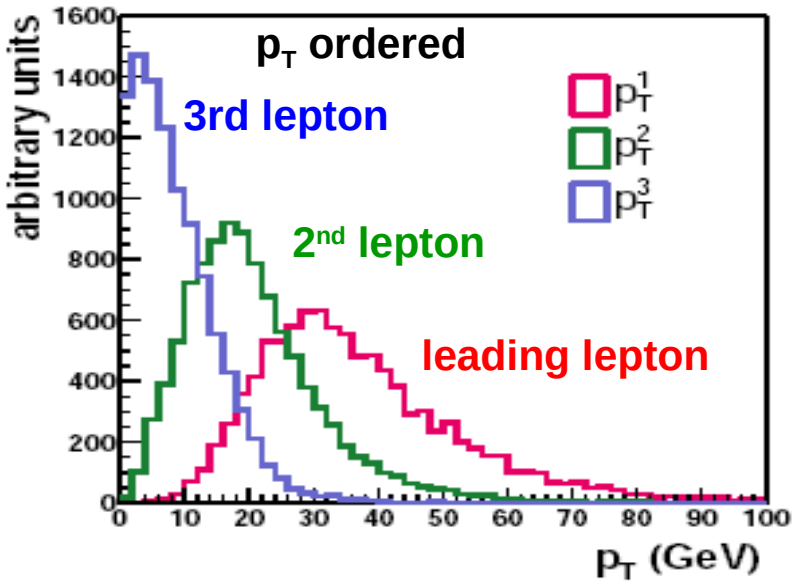
Light sleptons:



- Gaugino pair production via EW interaction
  - Small cross sections, ~0.1 – 0.5 pb
- Charginos and neutralinos decay via gauge bosons or sfermions to LSP and SM particles.
- R-parity conserving models ⇒ LSP stable
- LSP escapes detection in the detector
- SUSY signature
  - 2 electrons or muons
  - Third lepton
  - Large missing E_T

Very clean signature, but small cross sections

Charginos / Neutralinos: Trileptons



- Three search techniques
  - 3 identified leptons (l=e or μ)
  - 2 leptons + isolated track
  - Two same sign leptons
- Allows for some additional acceptance
  - Taus and low p_T leptons

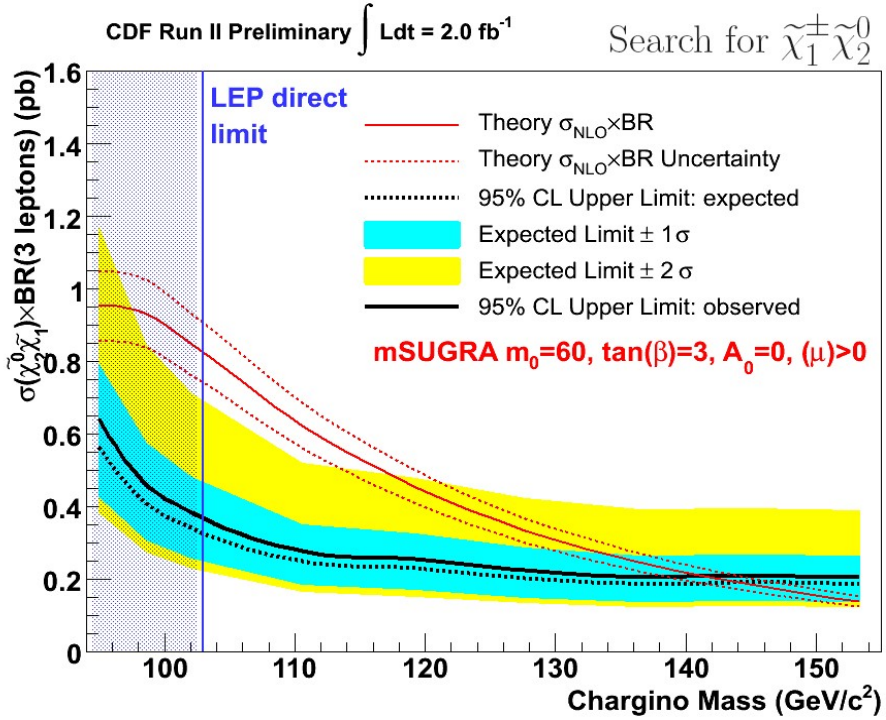
CDF	Background	Data
3 tight	0.49±0.04±0.08	1
2 tight, 1 loose	0.25±0.03±0.03	0
1 tight, 2 loose	0.14±0.02±0.02	0
Total trilepton	0.88±0.05±0.13	1
2 tight, 1 track	3.22±0.48±0.53	4
1 tight, 1 loose, 1 trk	2.28±0.47±0.42	2
Total dilepton+track	5.5±0.7±0.9	6

2.0 fb^{-1}

DØ	Background	Data
ee*l*	1.8±0.8	0
μμ*l*	0.3+1.3-0.3	2
eμ*l*	0.9±0.4	0
$\mu^+\mu^+$	1.1±0.4	1
l = lepton or track		

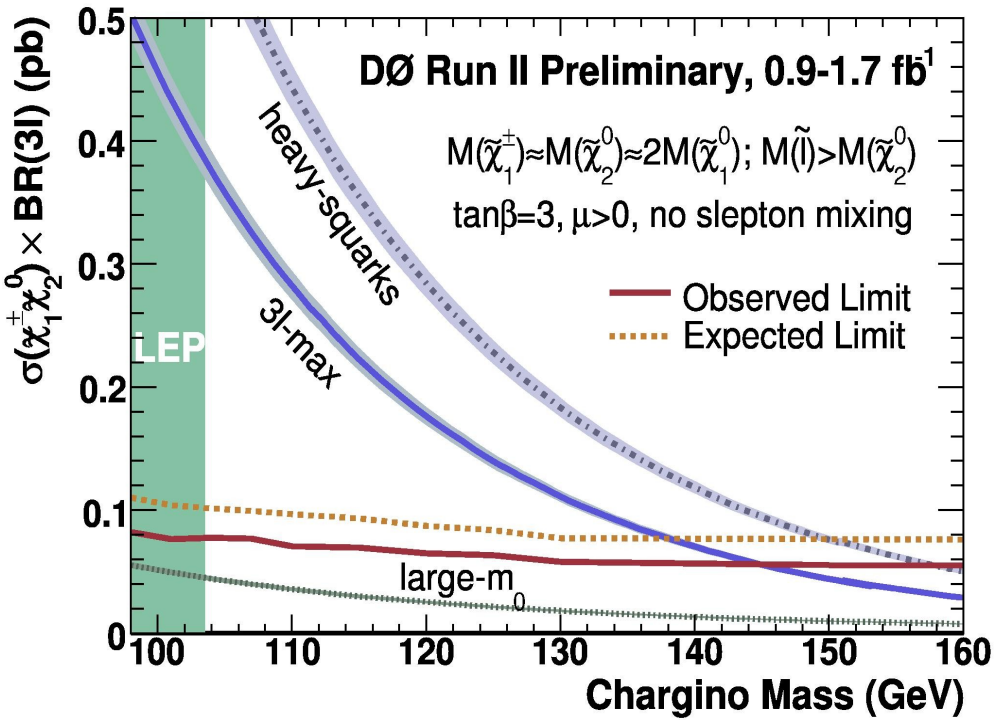
0.9 – 1.7 fb^{-1}

Charginos / Neutralinos: Limits



$M(\tilde{\chi}_1^{\pm}) > 140$ GeV

mSUGRA

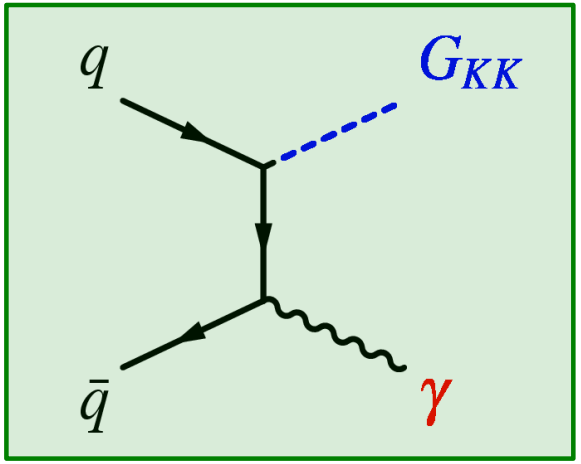


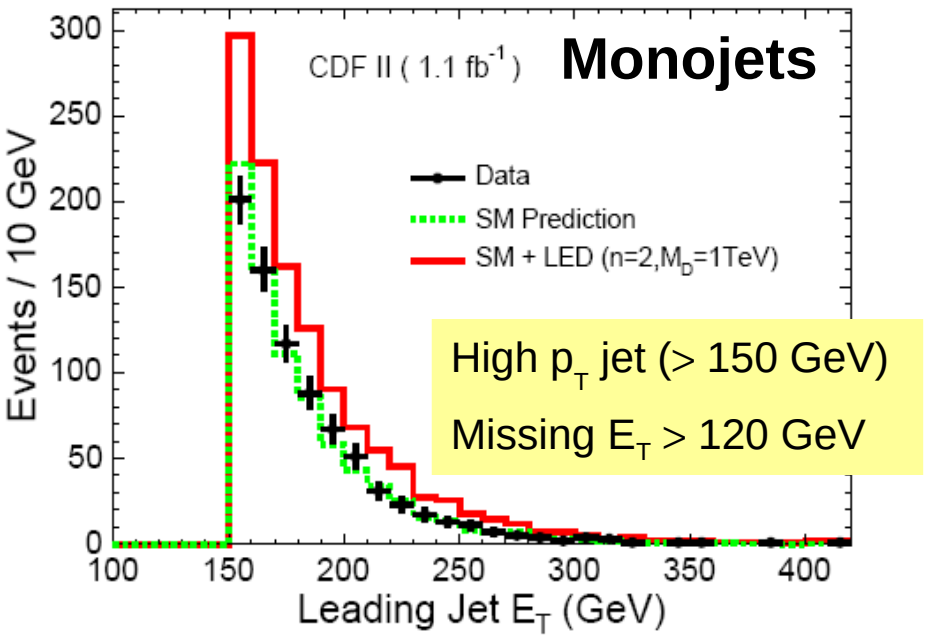
$M(\tilde{\chi}_1^{\pm}) > 145$ GeV

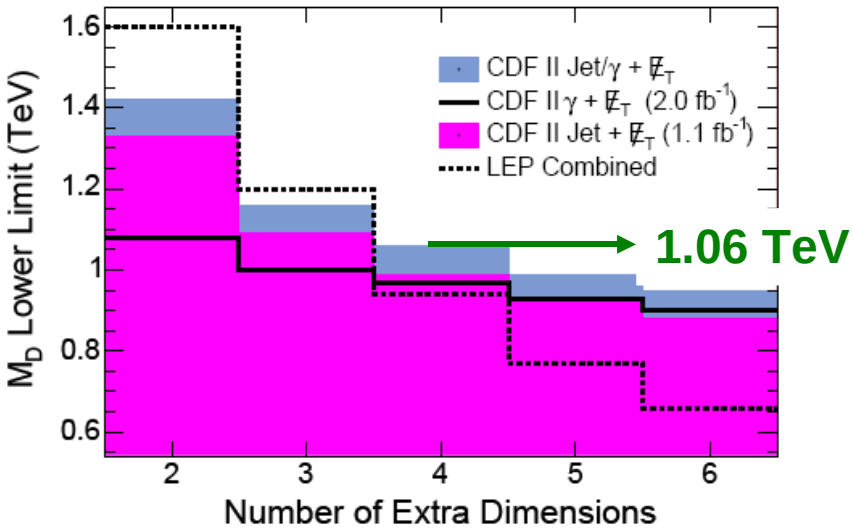
mSUGRA, no slepton mixing

Large Extra Dimensions: γ/jet + MET

- LED can explain why gravity is weak: $1/G \sim M_{Pl}^2 \sim M_D^{n+2} R^n$
- Can solve the hierarchy problem: $M_D \sim M_W$
- Search in **monophoton and monojet** final states







CDF jet & γ combination

Main background: ($Z \rightarrow \nu\nu$) +jet
Calibrated with ($Z \rightarrow ll$ and $W \rightarrow l\nu$) + jet
QCD is negligible

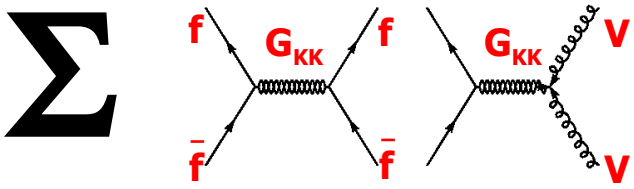
Dielectrons and Diphotons

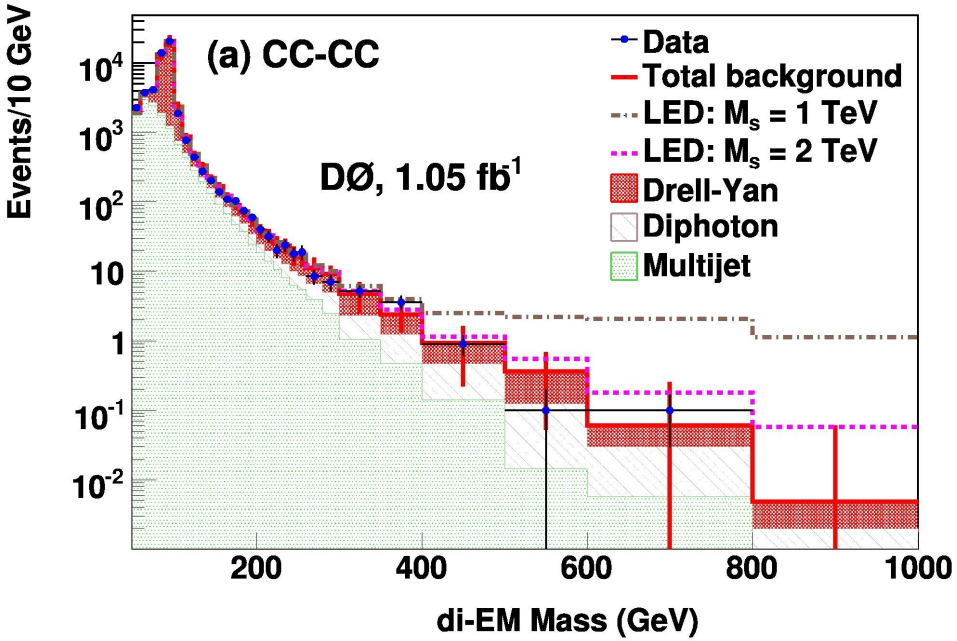
DØ search in 1.1 fb^{-1}:

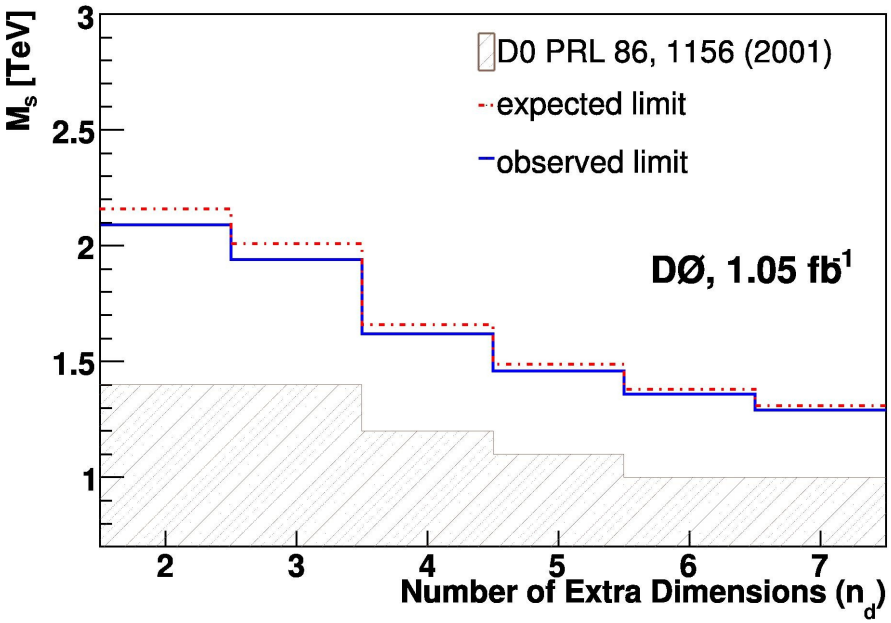
BF(γγ) = 2 BF(ee)

Combine ee and γγ to maximize sensitivity

2D-fit in mass and cos θ*







M_S > 1.62 TeV (GRW)

(HLZ formalism)

Randall-Sundrum Gravitons

Use extra dimensions to address hierarchy problem

RS model:

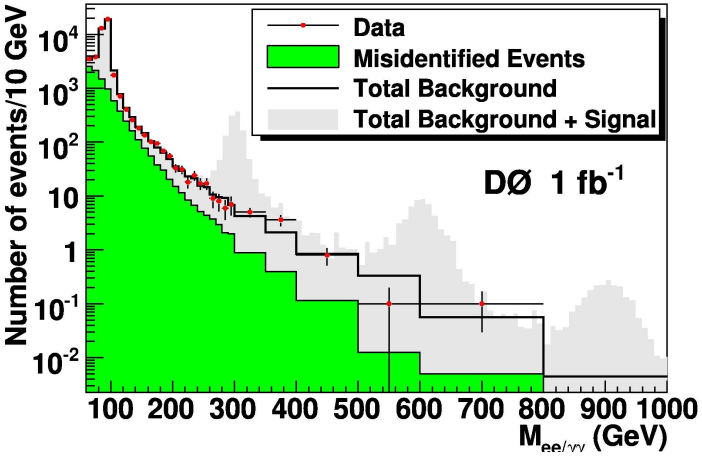
One 5th (infinite) ED with warped geometry

Gravity is localized on a brane other than the SM

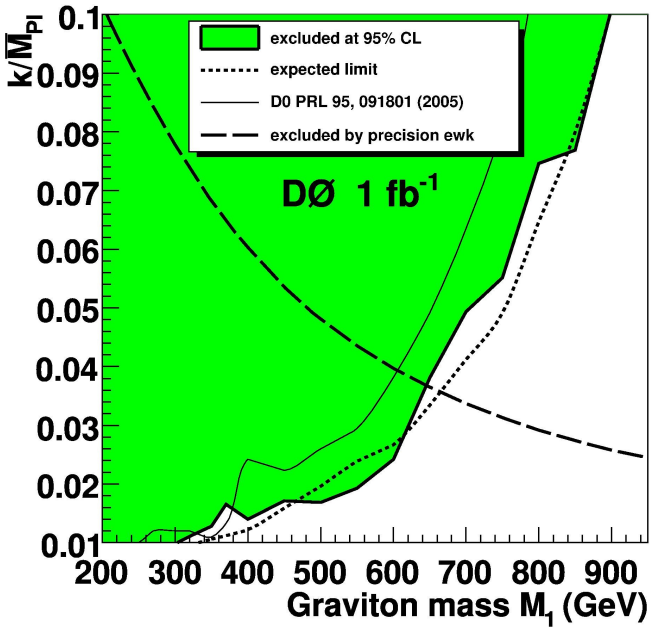
KK excitations have spacings of order TeV

Signature: **narrow, high mass resonances**

Two model parameters: **Mass and coupling (κ/M_{Pl})**



Combined ee + γγ:

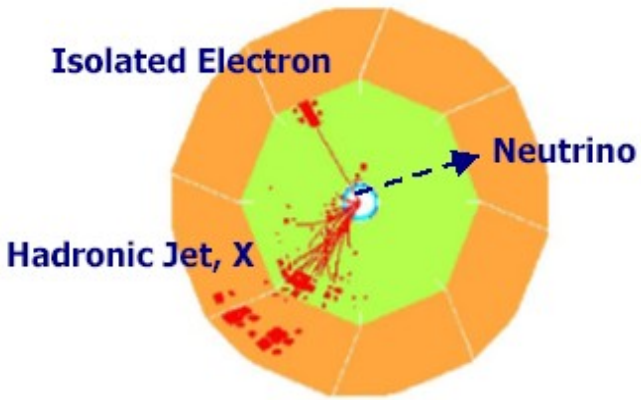


CDF in μμ with 2.3 fb^{-1}:

M > 921 GeV for κ/M_{Pl} = 0.1

For κ/M_{Pl} = 0.1: M > 900 GeV

Isolated Leptons at HERA

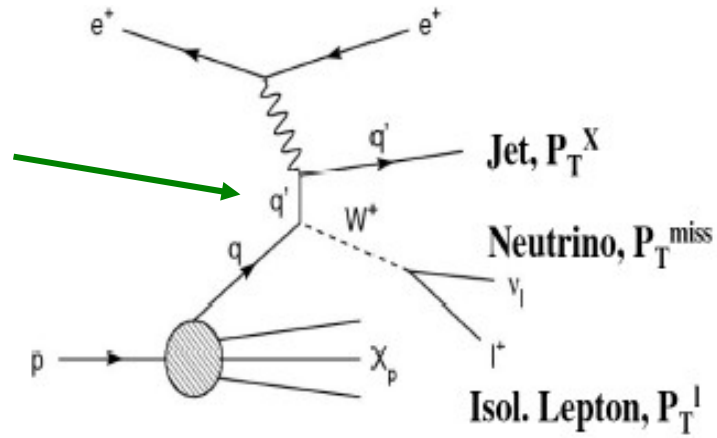


H1 HERA I e + P_T^{miss} event

SM process: W+jet

Excess seen by H1 in HERA-I e^+p data at high p_T^X (> 25 GeV)

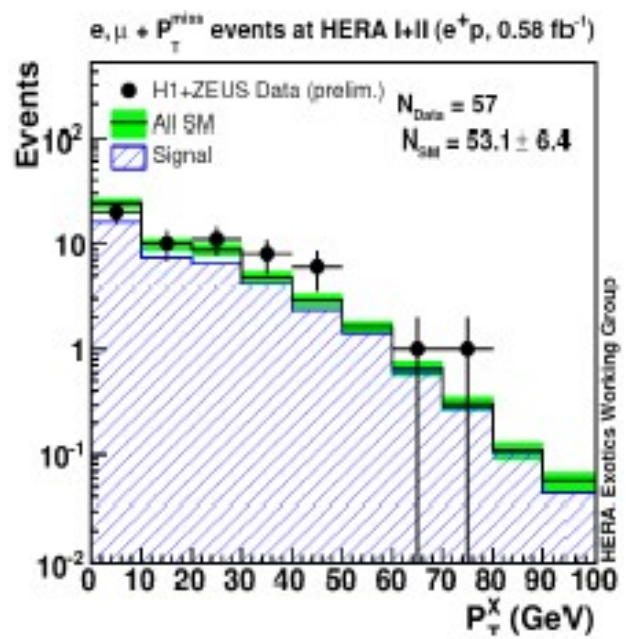
Not seen by ZEUS (≠ selection)



With full HERA I+II statistics and two experiments with identical selections:

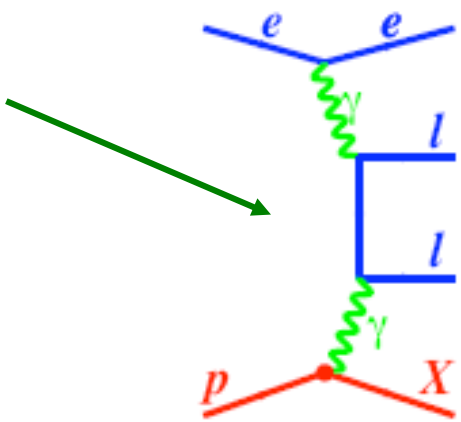
e^+p data	H1	ZEUS	H1+ZEUS
P_T^X>25 GeV	17/7.1±0.9	6/7.5 ±1.1	23/14.6±1.9

H1 – ZEUS consistency: 2σ
Combined significance: 1.8σ



Multi-Leptons at HERA

Expected to be dominated by two-photon interactions



H1: events with 2 or 3 e or μ with $\Sigma p_T > 100$ GeV

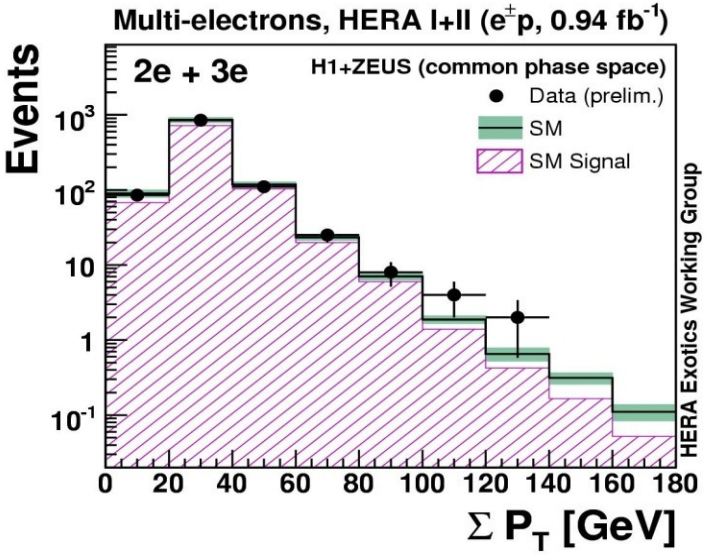
e^+p: 5 events / 0.96±0.12 expected

e^-p: 0 0.64±0.09

H1+ZEUS combination in the 2 or 3 electron channel

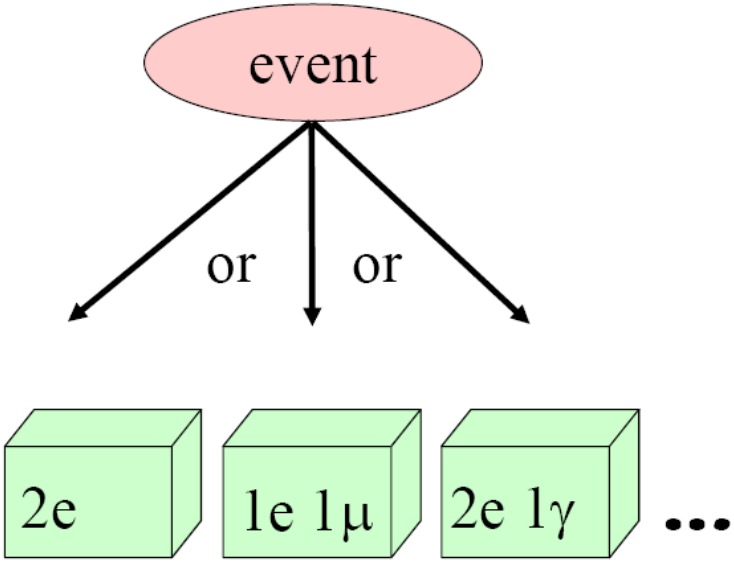
e^+p: 5 evts / 1.82±0.21 expected

e^-p: 1 1.19±0.14



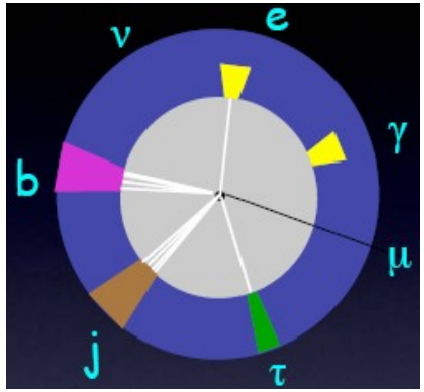
Full combination underway

Global Analysis

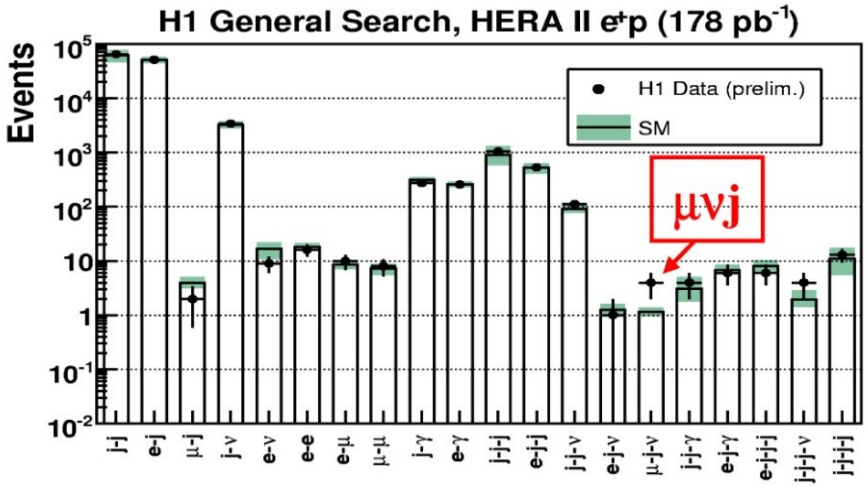


Categorize in terms of (high p_T!) physics objects

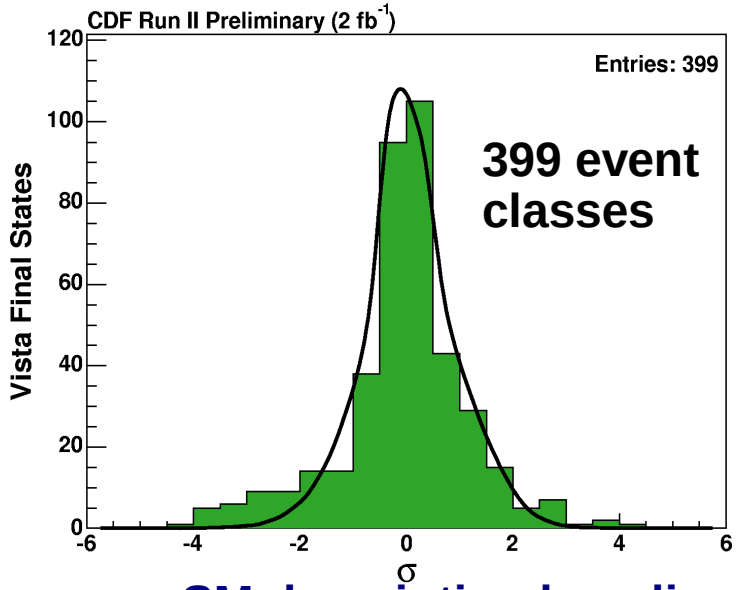
Put events in (e.g.) exclusive boxes
(ej, μjj, γγ+MET, bbj,…)



H1



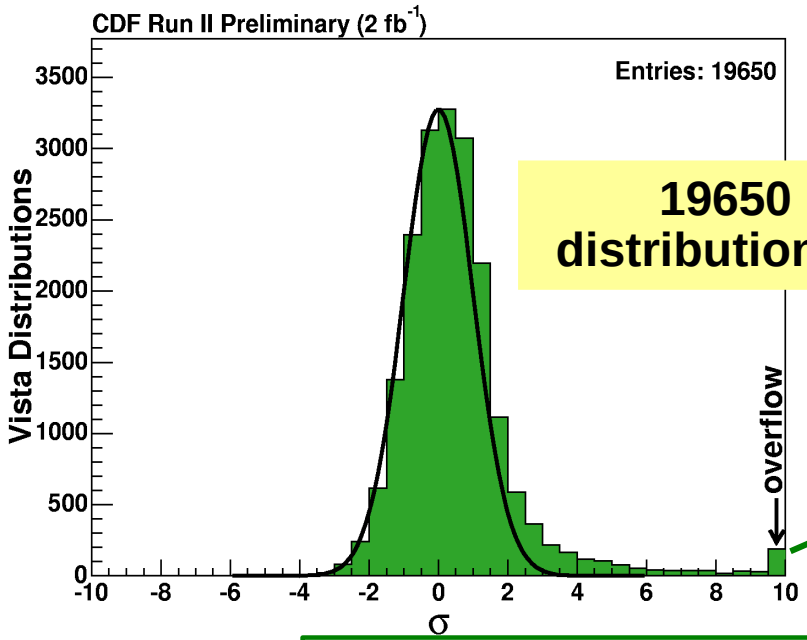
CDF: "Vista"



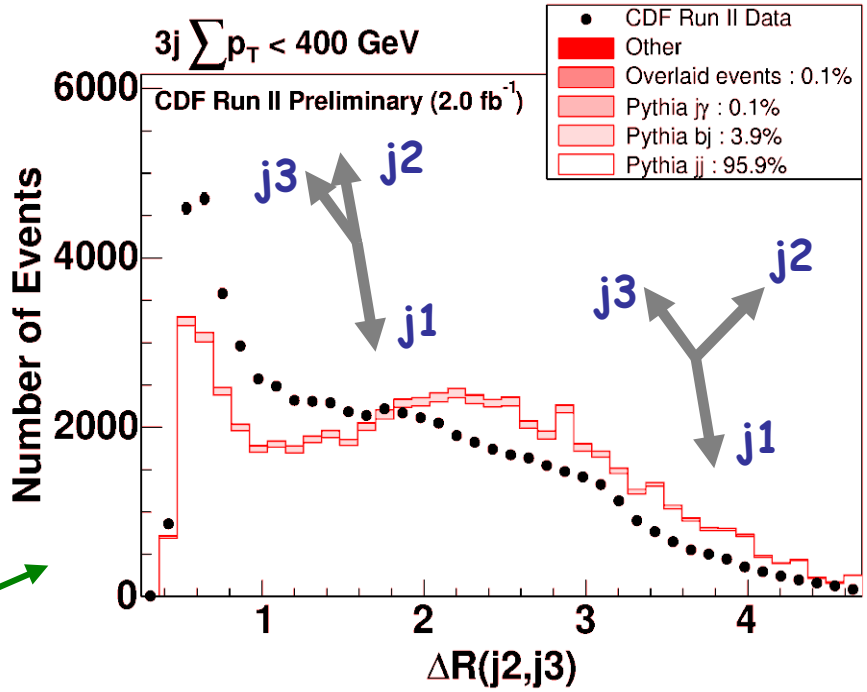
Also: improve SM description by adjusting a number of correction and normalization factors

Global Analysis

Look at a large number of distributions, and perform Kolmogorov-Smirnov tests to find possible discrepancies.



19650 distributions…



Found discrepancies are not suggestive of "new physics", rather of an inadequate modeling of soft QCD

Once the bulk of the distributions is under control, look specifically at the high $\sum p_T$ tails ("Sleuth"), and check for mass bumps

No more deviations than expected from statistics found in 2 fb^{-1}

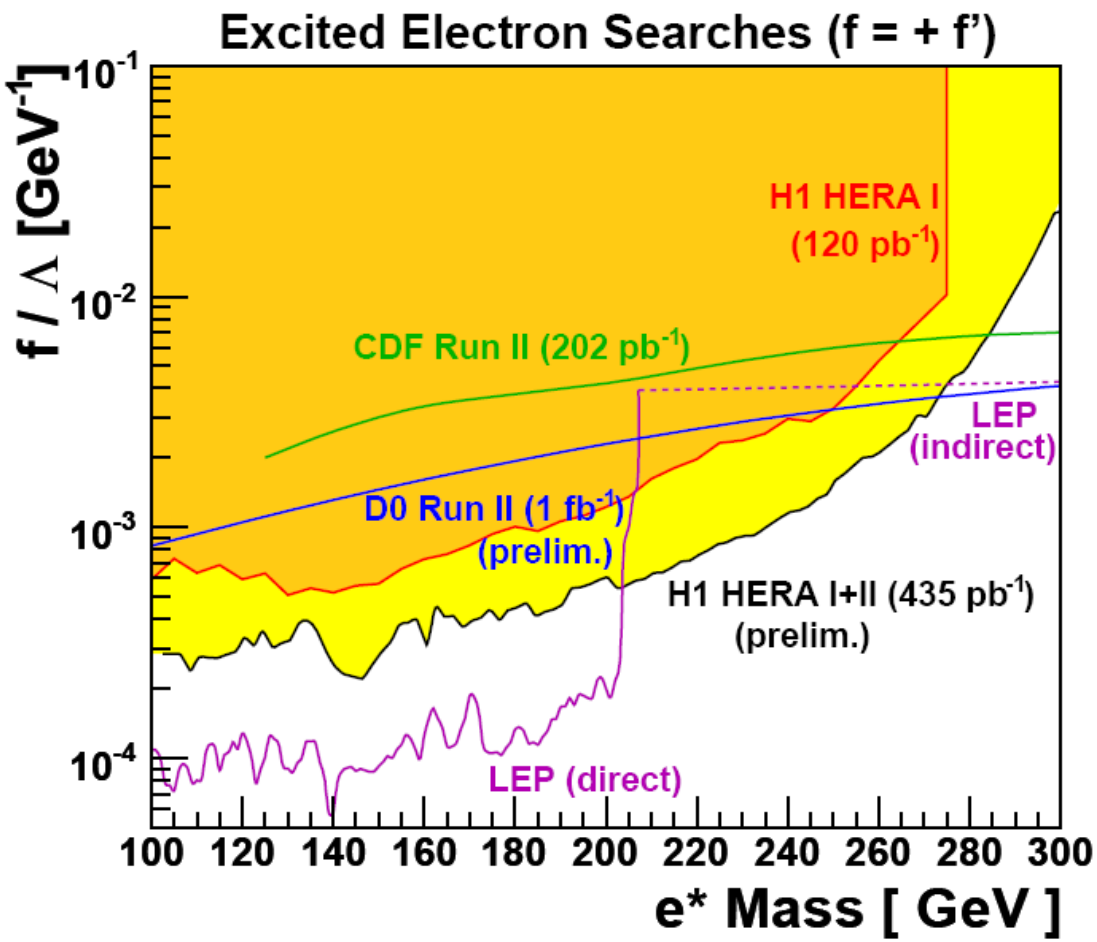
(taking into account the number of trials)

Conclusions

- A vibrant program searching for new phenomena continues – have shown a small selection of new(er) results in selected areas
- With >4 fb^{-1} of integrated luminositycollected at the Tevatron, updates promising
- All Tevatron results and more available at
  http://www-d0.fnal.gov/Run2Physics/WWW/results.htm
  http://www-cdf.fnal.gov/physics/exotic/exotic.html

Backup

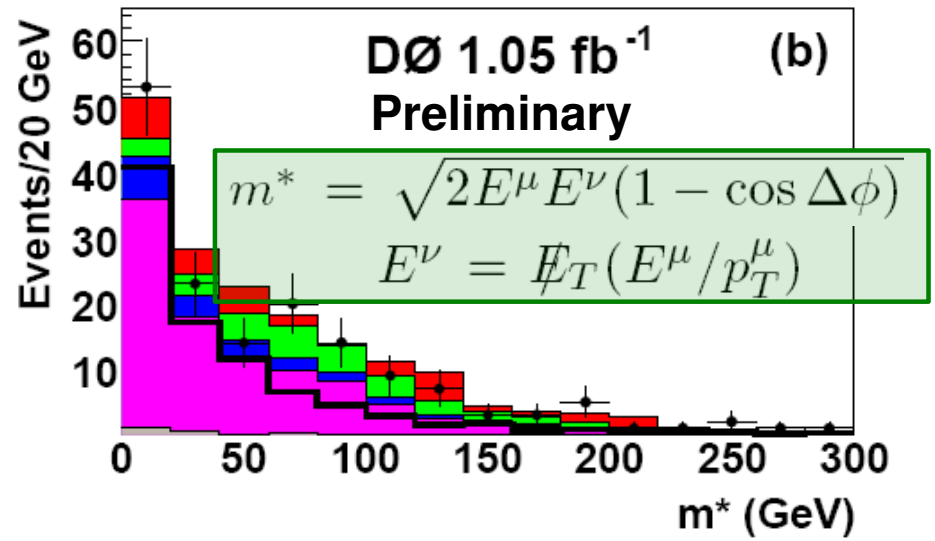
e*

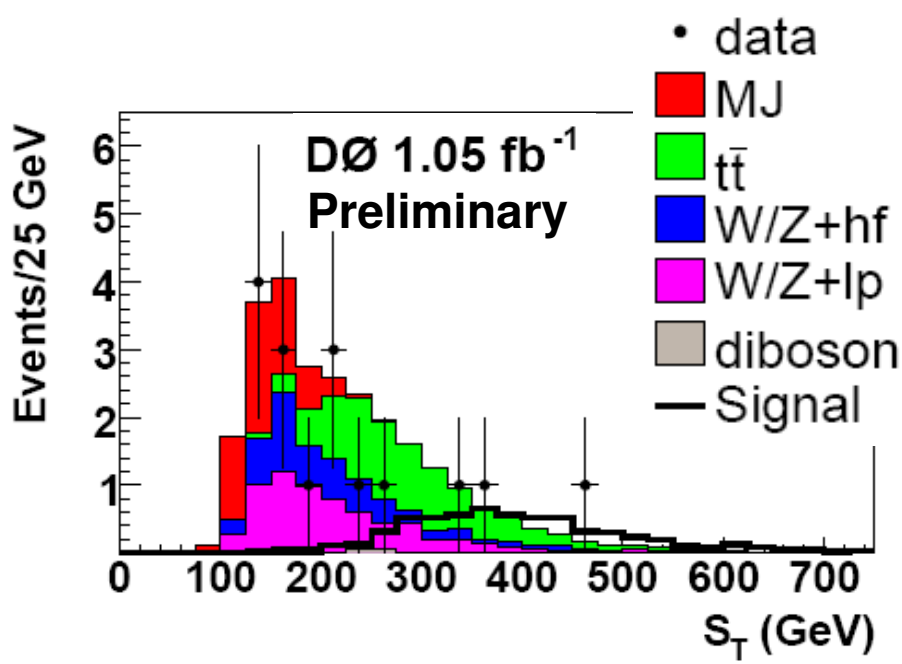

Excited Electron Searches (f = + f')
f / Λ [GeV-1]
10-1
10-2
10-3
10-4
H1 HERA I
(120 pb-1)
CDF Run II (202 pb-1)
LEP
(indirect)
D0 Run II (1 fb-1)
(prelim.)
H1 HERA I+II (435 pb-1)
(prelim.)
LEP (direct)
100 120 140 160 180 200 220 240 260 280 300
e* Mass [GeV]

Leptoquarks: 3rd Generation – $\tau\tau bb$

$$LQ_3\overline{LQ_3} \rightarrow \tau^- b \tau^+ \bar{b}$$
$$\tau_1 \rightarrow \mu\bar{\nu}\nu, \tau_2 \rightarrow \nu + hadrons$$

- Pair production of LQ3
- 2 opposite-sign taus and 2 jets
  - Tau 1: μ p_T> 15 GeV, |η| < 2.0
  - Tau 2: visible p_T> 15 – 20 GeV, identified using NN-algorithm based on tracks and calorimeter information
  - Jets: E_T> 25, 20 GeV, |η| < 2.5
  - m* < 60 GeV
  - Two sub-samples: 1 b-tag or 2 b-tags
  - b-tag based on NN, optimized for sensitivity
- Veto extra muons or electrons



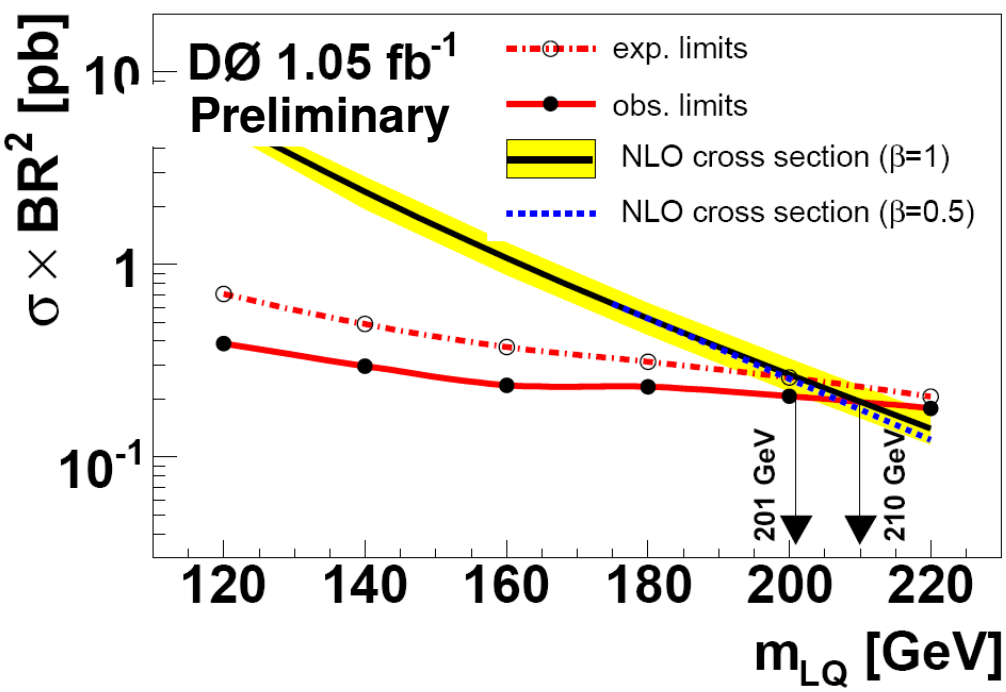


$S_T = p_T(\mu) + p_T(\tau) + p_T(jet1) + p_T(jet2) + MET$

LQ3 – Results

Use S_T distribution and both 1 and $\geq$2 b-tagged samples to obtain limits

- Charge = 4/3, 2/3 LQ, β = 1
- For Q = 2/3, LQ $\rightarrow$ t ν is allowed, only suppressed by phase space
- BF(LQ $\rightarrow$ t ν) = (1 – β) x f_{ps}



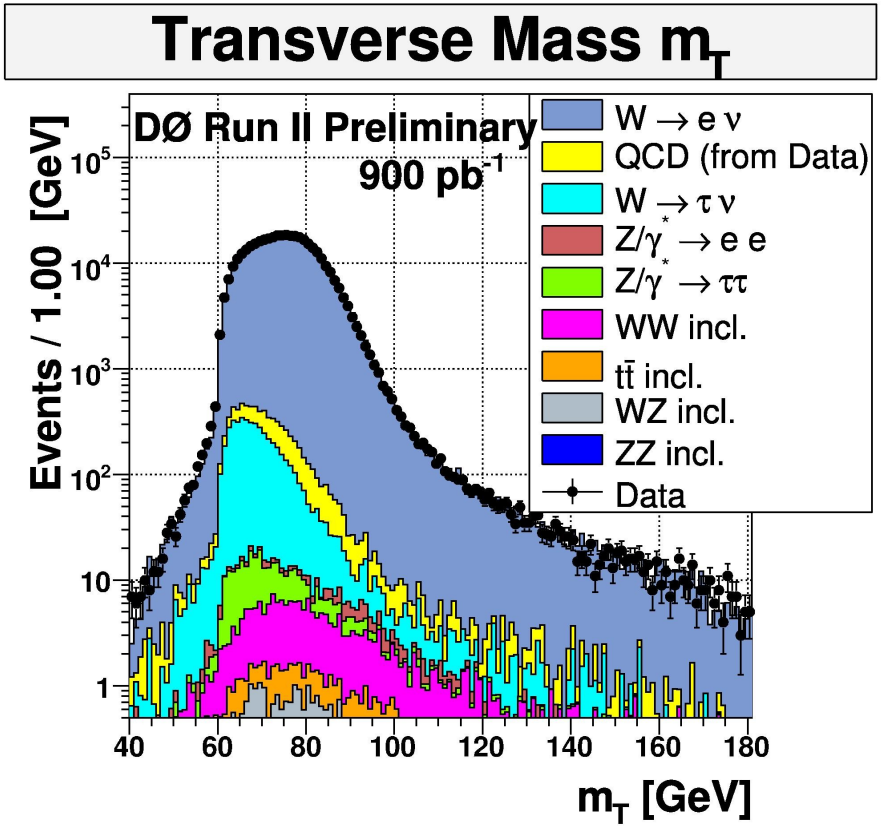
Source	$1b$-tag	$\geq 2b$-tag
$W + \mathrm{lp}$	1.0 ± 0.4	< 0.1
$W + c\bar{c}$	0.4 ± 0.1	< 0.1
$W + b\bar{b}$	0.4 ± 0.1	< 0.1
$Z + \mathrm{lp}$	5.0 ± 0.2	0.1 ± 0.0
$Z + c\bar{c}$	1.7 ± 0.2	0.1 ± 0.1
$Z + b\bar{b}$	1.8 ± 0.1	0.4 ± 0.1
$t\bar{t}$	5.2 ± 0.1	3.1 ± 0.1
Diboson	0.3 ± 0.1	< 0.1
MJ	4.0 ± 2.5	0.8 ± 1.0
Sum Bknd	19.6 ± 2.5	4.8 ± 1.0
Data	15	1
LQ pair signal	3.4 ± 0.1	2.6 ± 0.1

(Uncertainties in Table are statistical only)

m(LQ) > 201 GeV for β = 1

New Gauge Bosons: W' → e ν

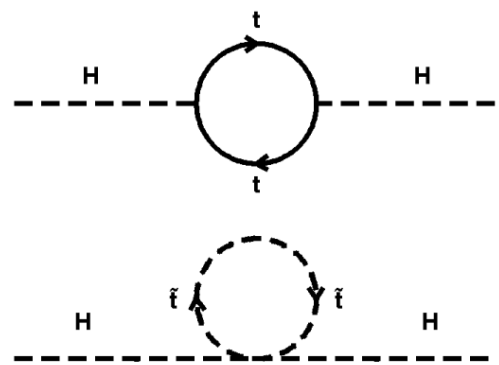
- Predicted in many beyond-SM scenarios, GUT's, e.g. left-right symmetric models ($SU(2)_L \times SU(2)_R$)
- Benchmark: a SM-like W'
- Selection: isolated central electron with E_T>30 GeV
- MET > 30 GeV, M_T > 140 GeV
- Estimate QCD background from low M_T region

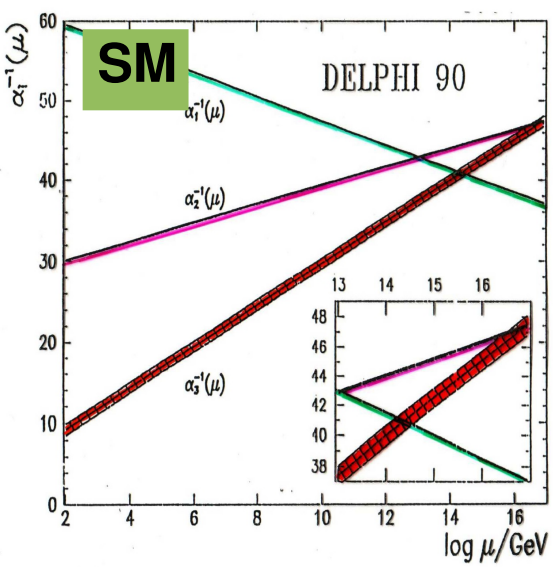


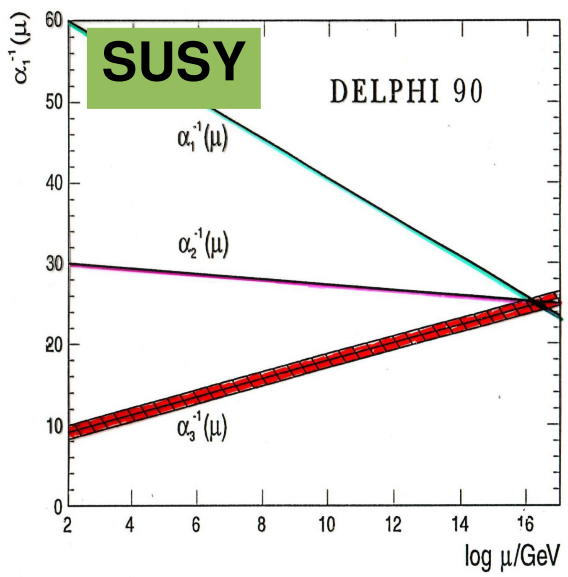
$$M_T = M(p_T(e), MET)$$

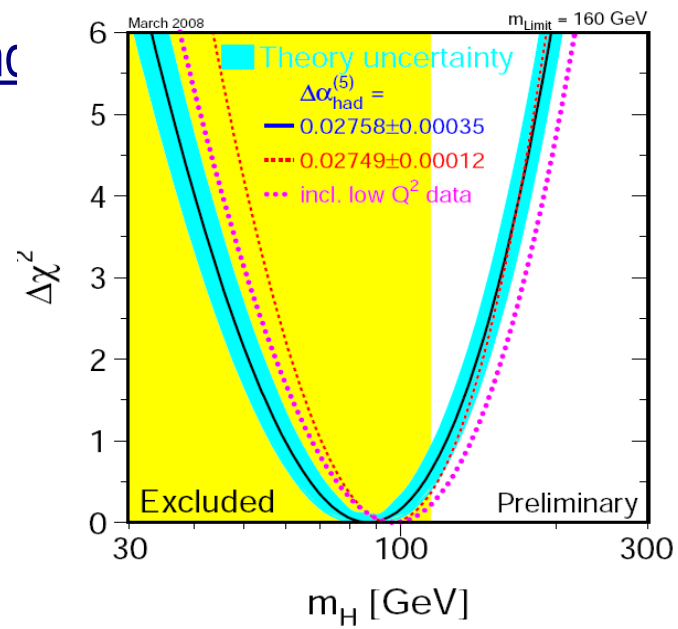
Supersymmetry

- Supersymmetry (SUSY): fundamental symmetry , relating bosons and fermions
- Stabilizing Higgs mass ("fine-tuning")
  - m(Higgs) < 135 GeV (MSSM)
  - In good agreement with expectations from EW fits
- "Running" of couplings is sufficiently modified to allow grand unification at a single scale









http://lepewwg.web.cern.ch/LEPEWWG

- LSP (Lightest SUSY Particle) is candidate for dark matter

Supersymmetry

Spin 0	1/2	1	3/2	2
Higgs $h^0, H^0, A, H^\pm$	Gluino $\tilde{g}$	Gauge	Gravitino $\tilde{G}$	Graviton G
Sleptons $\tilde{l}$	Leptons	bosons		
Squarks $\tilde{q}$	Quarks			
	Gauginos $\tilde{\chi}^\pm, \tilde{\chi}^0$			

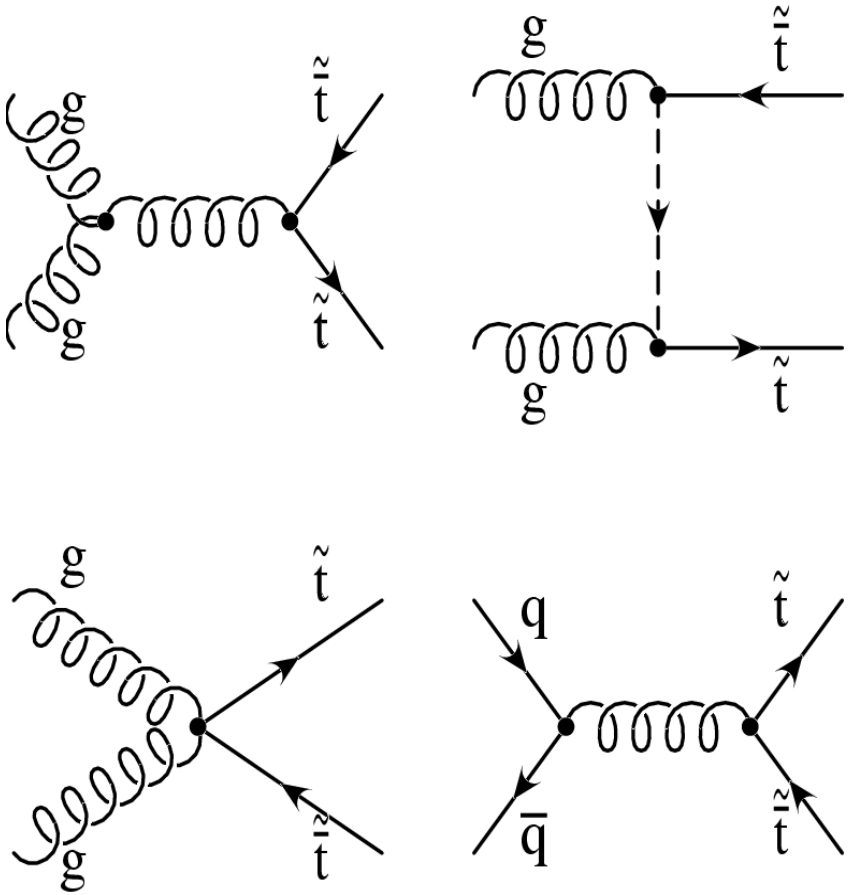
At least 32 new particles

- **Signatures depend on model assumptions** (e.g. MSSM: > 100 parameters)
  - R-parity conservation: $\not{E}_T$ **due to undetected LSP**

    R-Parity $R_p = \begin{matrix} +1 & \text{SM} \\ -1 & \text{SUSY} \end{matrix}$
  - Different models for SUSY breaking mechanism have various phenomenological consequences: **jets, leptons, photons, long-lived particles**
- **Benchmark-Scenarios** allow systematic study of supersymmetric models with realistic effort, simultaneously incorporating experimental and theoretical bounds (e.g. "Snowmass Points and Slopes")
- LEP searches for charginos, sleptons, higgs: $m(\tilde{\chi}^\pm)>103.5$ GeV, $m(\tilde{l})>95$ GeV, $m(h)>114.4$ GeV

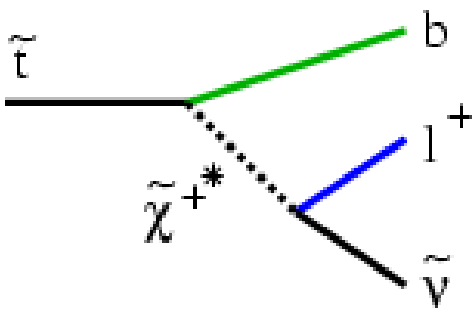
Stop (and Sbottom)

- Third generation "special"
  - Stop could be the lightest squark
- Pair production through strong interaction
- Numerous search channels
- Depend on dominant decay mode



Dileptons	Heavy flavor+MET	Stable, charged particles
ee, eμ, μμ +2b+MET	bb+MET cc+MET	

Stop in eμ + 2b + MET



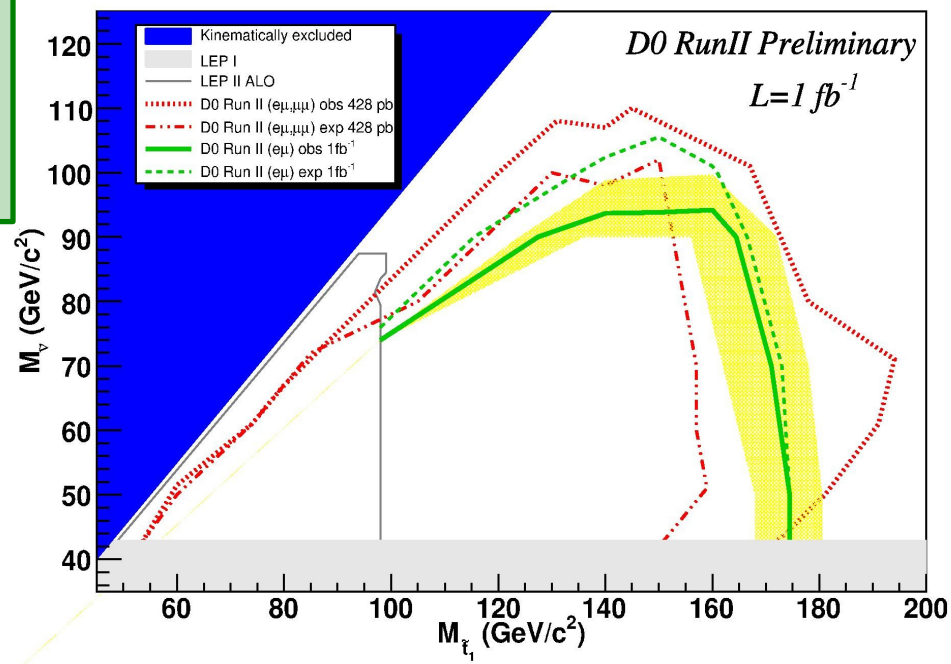
Stop pair production:

Two isolated leptons,

missing E_T,

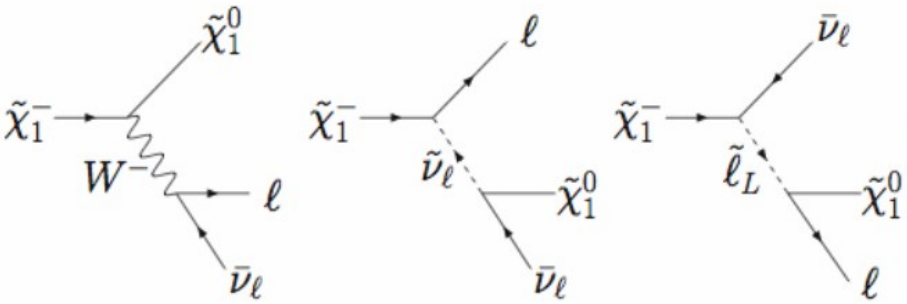
two b-jets (can be soft)

- Decay mode stop → $b\ell\tilde{\nu}$
- Sneutrino is NLSP
- Update in eμ channel
  - Highest dilepton branching fraction
  - Low backgrounds

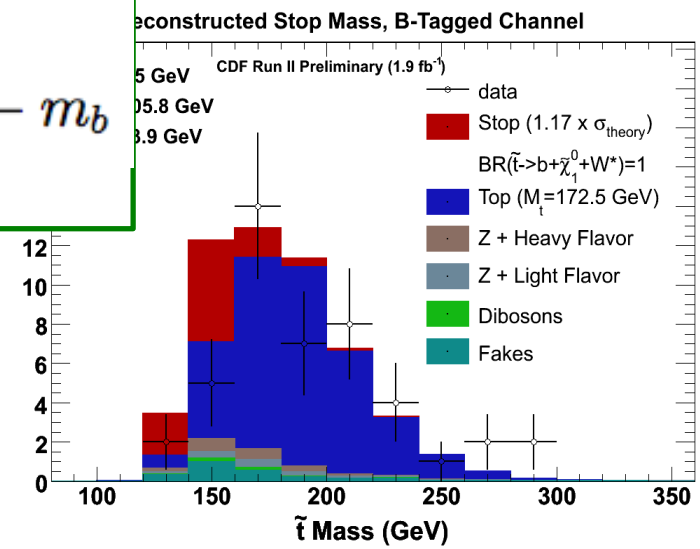


Σp_T (jets) (GeV)	$p_T(\mu) + p_T(e) + MET$ (GeV)					
	0-70		70-120		>120	
	Data	Bkgd	Data	Bkgd	Data	Bkgd
0-15	1	0.3±0.3	15	13±2	12	19±2
15-60	1	0±0	6	4.2±0.9	11	8±1
60-120	0	0±0	1	1.6±0.6	8	9±1
>120	0	0.0±0.0	0	0.9±0.4	6	7±1

Stop → $b\tilde{\chi}_1^{\pm}$ → $b\ell\tilde{\chi}_1^{0}$



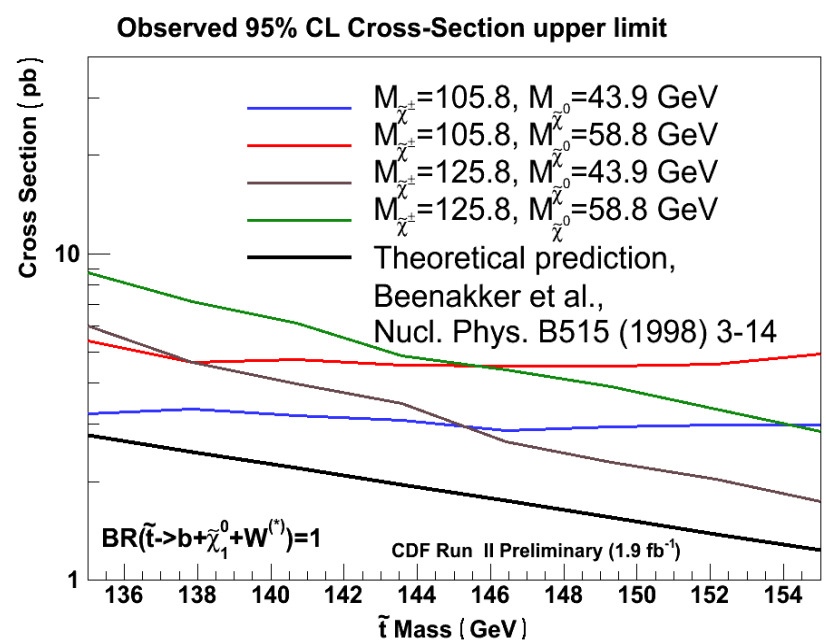
1. $\tilde{\chi}_1^0$ is the LSP
2. $m_{\tilde{t}_1} \lesssim m_t$
3. $m_{\tilde{\chi}_1^+} < m_{\tilde{t}_1} - m_b$



- Stop mass = 135 – 155 GeV
  - several chargino/neutralino mass points

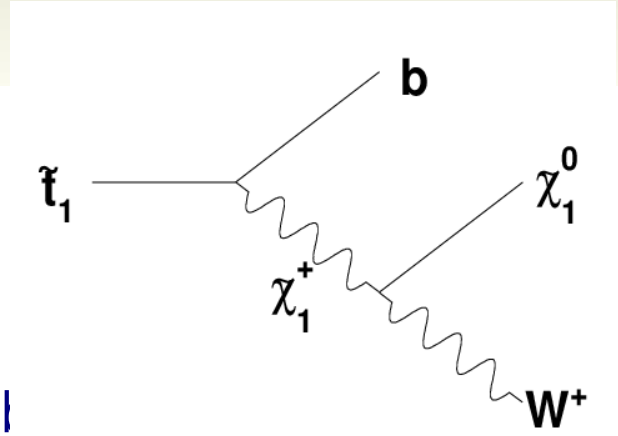
	Background	Data
ee	10.62±1.49	10
μμ	9.46±1.27	11
eμ	22.46±2.88	24
l l	42.53±5.56	45

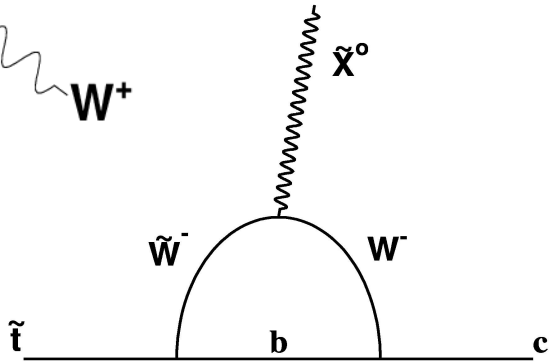
no evidence of stop signal



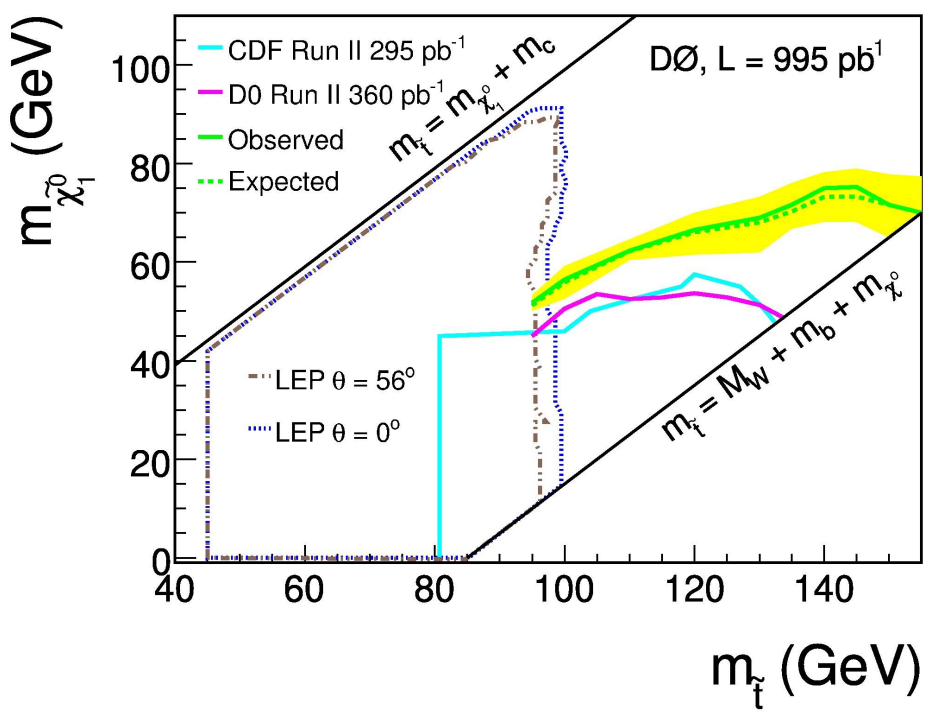
Stop in $c\bar{c}$ + MET

- Decay mode stop → $c + \tilde{\chi}_1^0$
  - $m_{\tilde{t}} < m_b + m_{\tilde{\chi}_1^+}$
  - $m_{\tilde{t}} < m_W + m_b + m_{\tilde{\chi}_1^0}$
- Search for acoplanar charm jets (using l tagging based on lifetime)
- Optimize selection vs. m(stop)

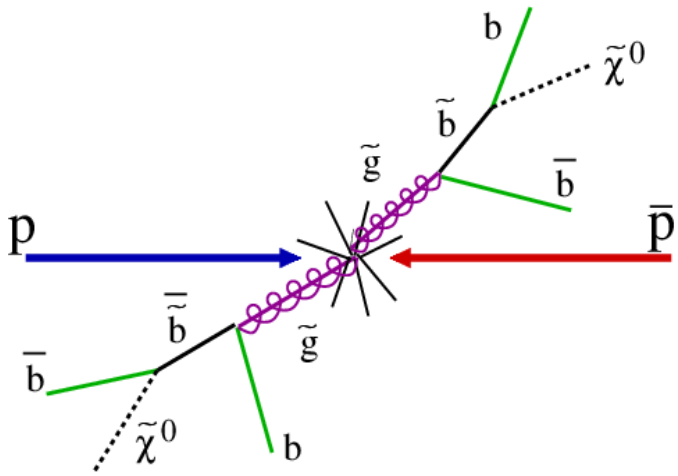




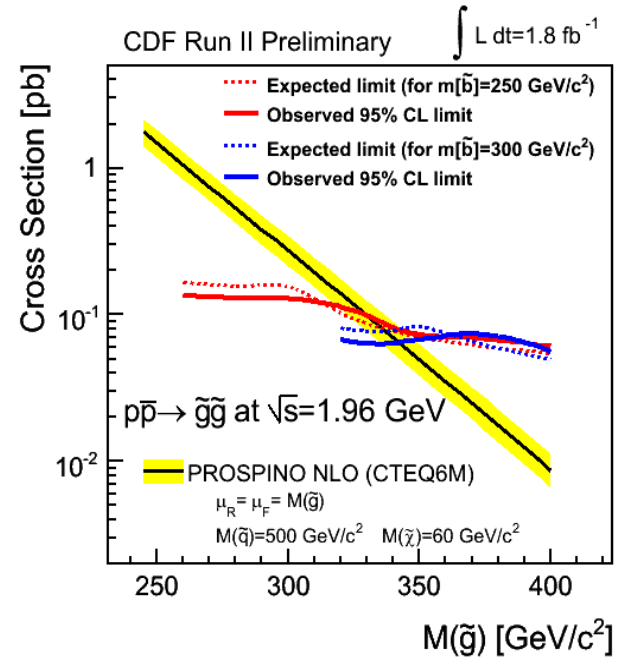
stop mass	background	data
95-130 GeV	85.3±1.8 $^{+12.8}_{-13.0}$	83
135-145 GeV	59.0±1.6 $^{+8.5}_{-8.8}$	57
150-160 GeV	66.6±1.1 $^{+9.6}_{-10.0}$	66



Sbottom in Gluino Production

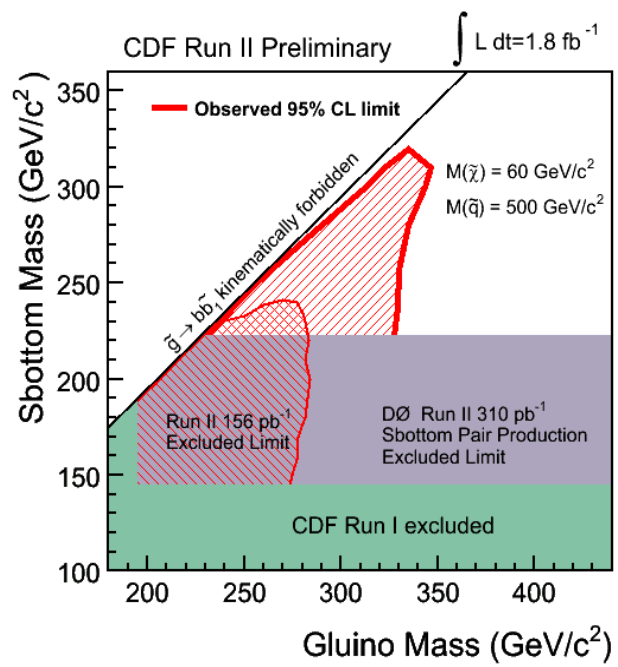


- Pair production of gluinos
- Gluino decays to sbottom + bottom
- Sbottom decays to bottom + neutralino



- Search for events with multiple jets (at least one b-tagged) and MET
- Two regions of $\Delta M = M(\tilde{g}) - M(\tilde{b})$

	Large Δm	Small Δm
Background	22.7 ± 4.6	22.0 ± 3.6
Data	25	19



GMSB in Di-photons

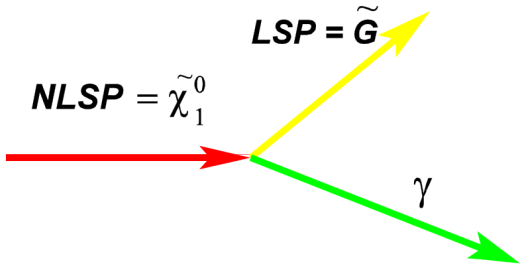
Gauge Mediated SUSY Breaking: Gravitino G is LSP

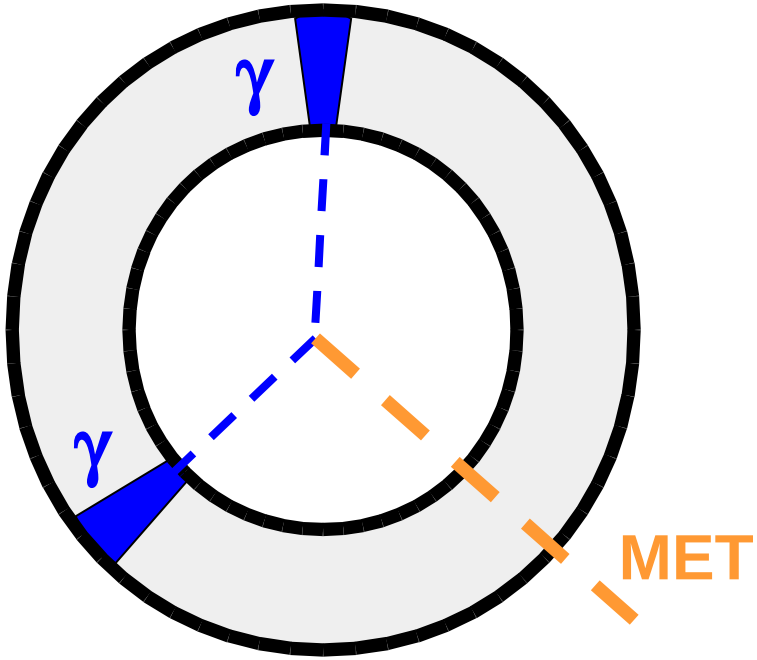
Possible scenario: neutralino NLSP, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$

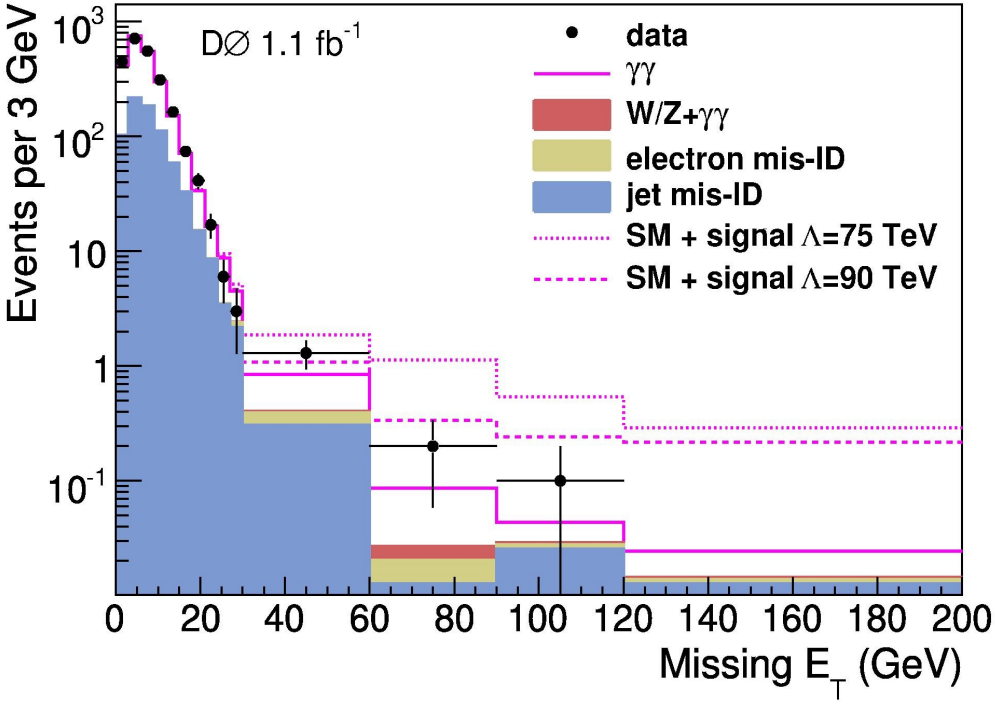
→ Chargino / neutralino production leads to final state $\gamma\gamma + \not{E}_T$

→ Inclusive search for 2 photons plus $\not{E}_T$

Lifetime unknown
Assume here: prompt







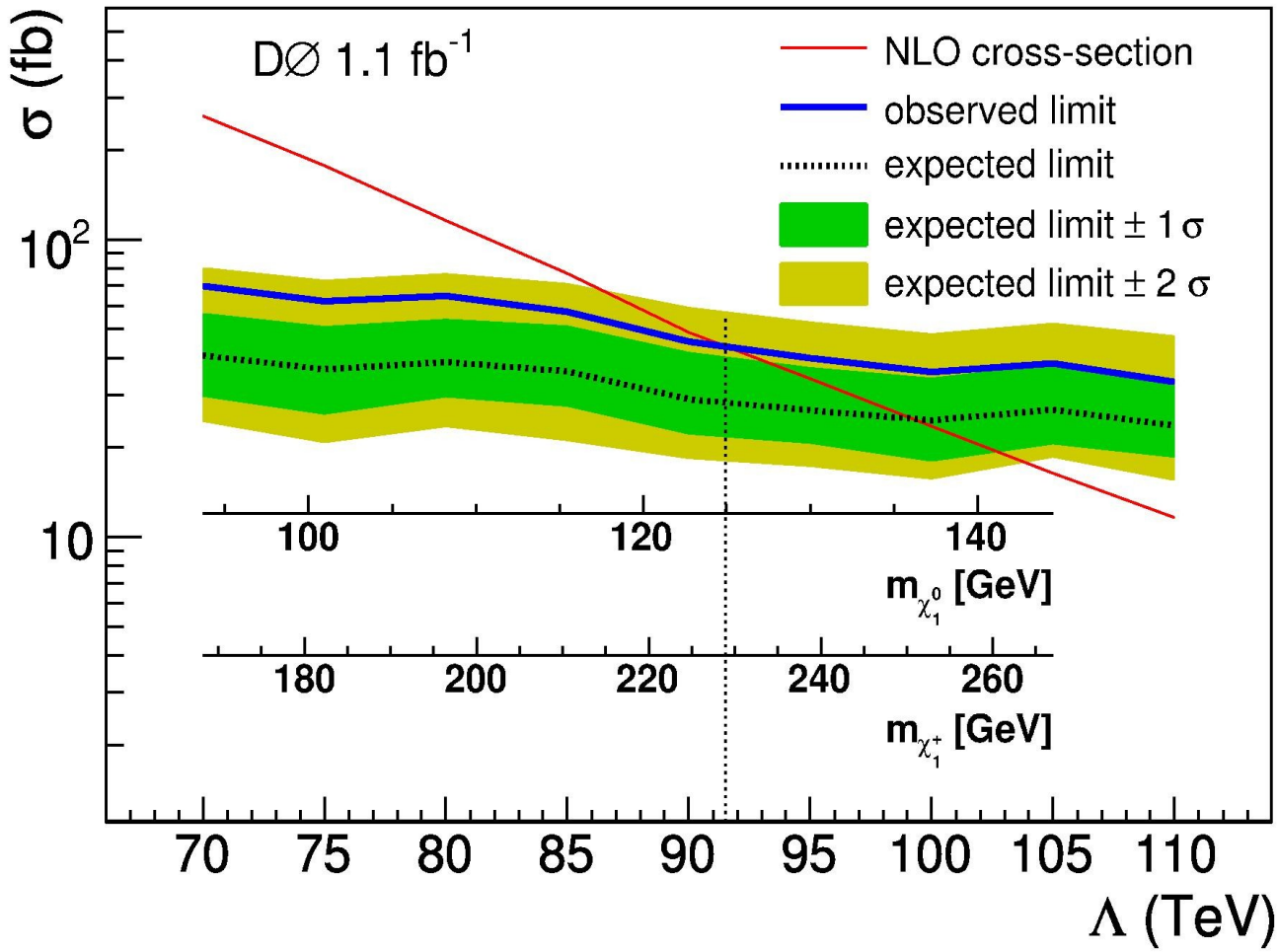
GMSB in Di-photons

$M(\tilde{\chi}_1^0) > 125$ GeV
$M(\tilde{\chi}_1^\pm) > 229$ GeV

Previous CDF and DØ combination:

$M(\tilde{\chi}_1^0) > 114$ GeV
$M(\tilde{\chi}_1^\pm) > 209$ GeV

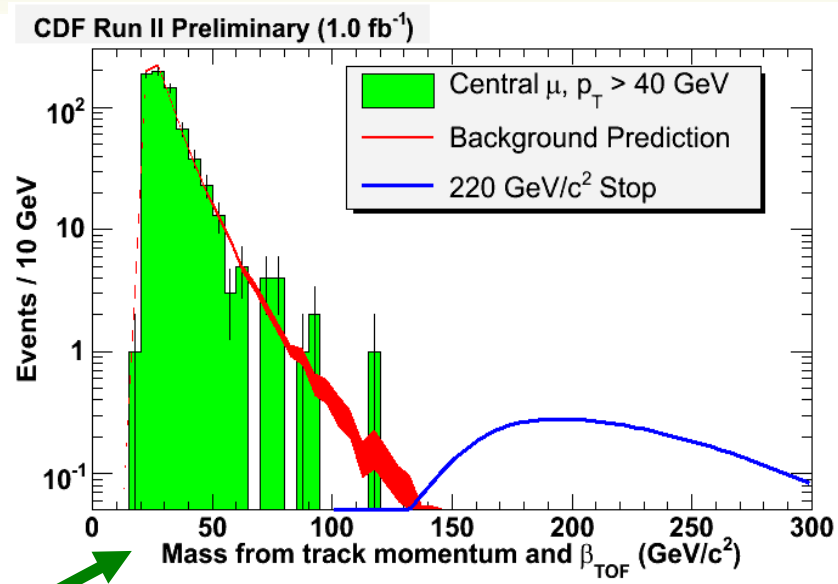
(N_5=1, M_m=2, tanβ=15, μ>0)

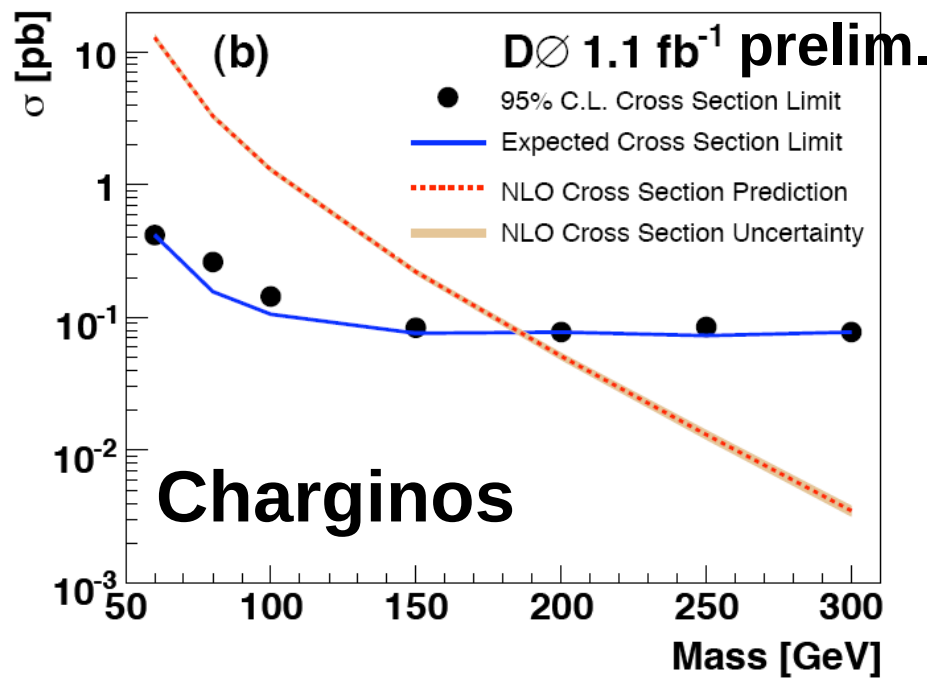


Long-lived Stop / Charginos

- Generic search for CHAMPS – charged, massive, stable particles
- In SUSY for example long-lived stop – escapes detector before decay
- Signature: slow-moving, muon-like particle
  - Measure mass:

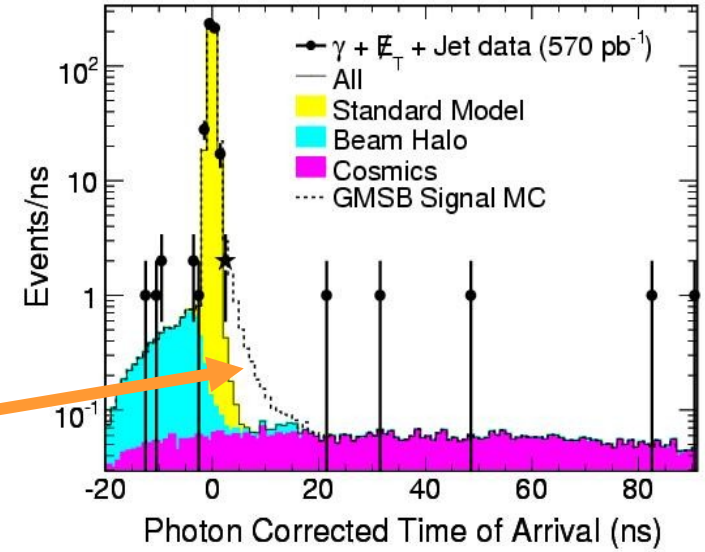
    time of flight → velocity + momentum → mass
- **M(stop) > 250 GeV**
- Long-lived chargino occurs in AMSB models
- **M(chargino) > 185 GeV**

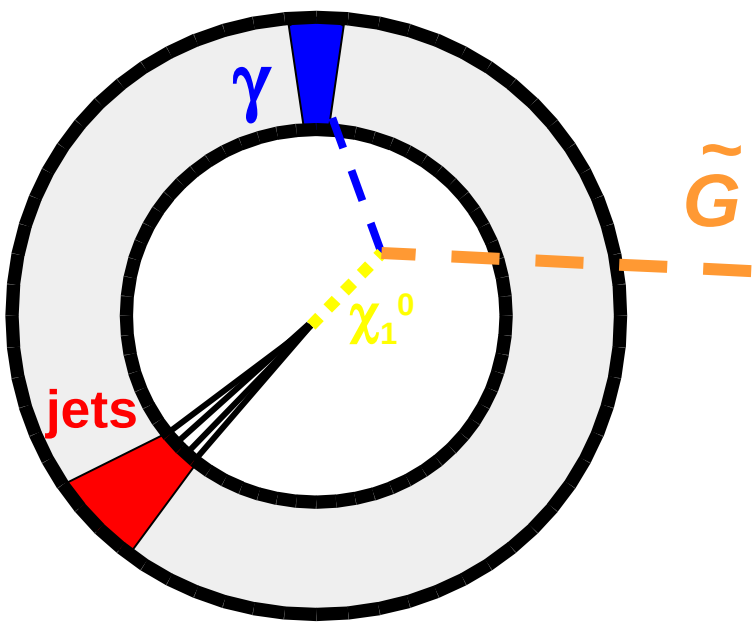




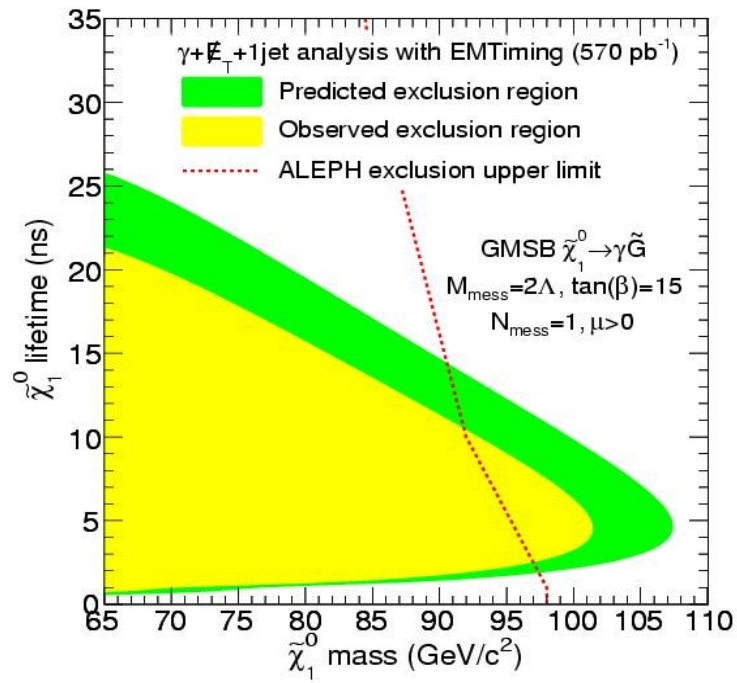
Long-lived Neutralinos

- GMSB SUSY
  - $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$ (same as diphoton)
  - $\tilde{\chi}_1^0$ is long-lived
- Search for γ+jets+MET events
- Measure arrival time of photon
  - Optimize for τ = 5 ns





Data:
2
SM:
1.25 ± 0.66



R-Parity Violation

R-parity: $R_P = (-1)^{3B+L+2S}$

+ 1 SM
– 1 SUSY

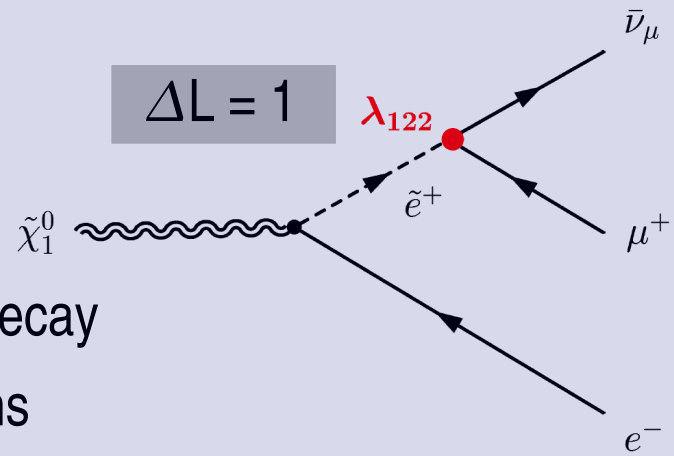
S Spin
B Baryon number
L Lepton number

i,j,k = 1,2,3
Generation indices

Violation of R-parity → **45 additional parameters** (Yukawa couplings)

λ_{ijk} (9)

$\Delta L = 1$



R_P violated in decay

Many leptons

λ''_{ijk} (9) $\Delta B = 1/3$

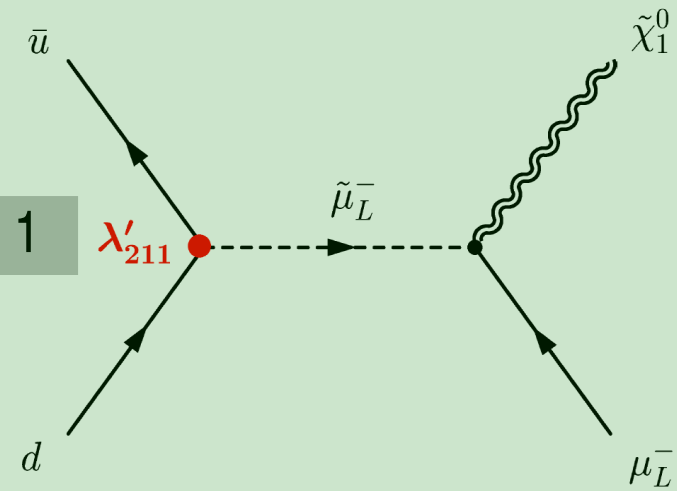
Experimentally and theoretically constrained (p decay etc.)

LSP no candidate for dark matter in RPV models

λ'_{ijk} (27) Resonant production

Leptons and jets

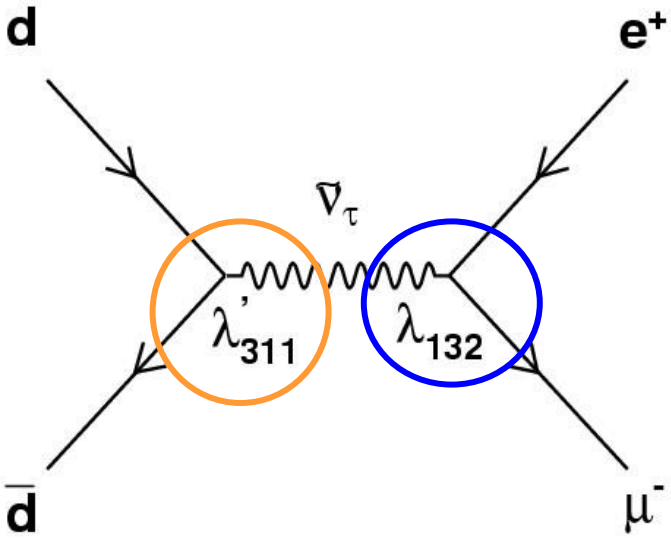
$\Delta L = 1$

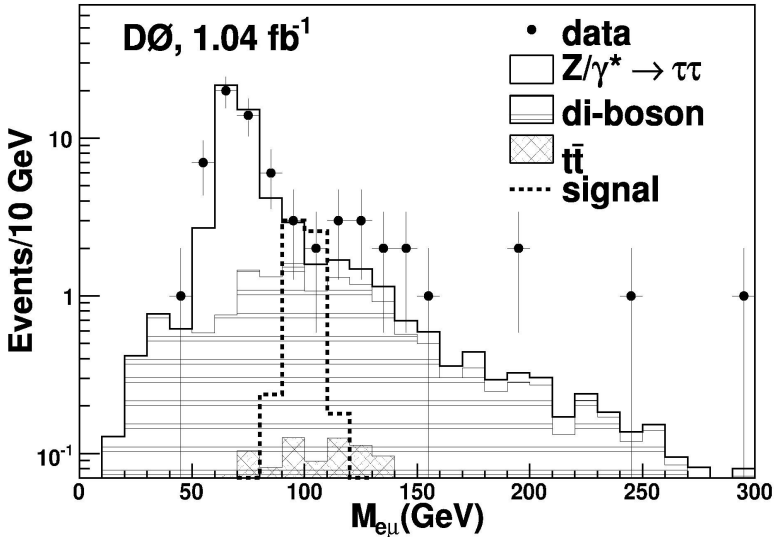


- Can cause small BF or long lifetimes
- Or resonances

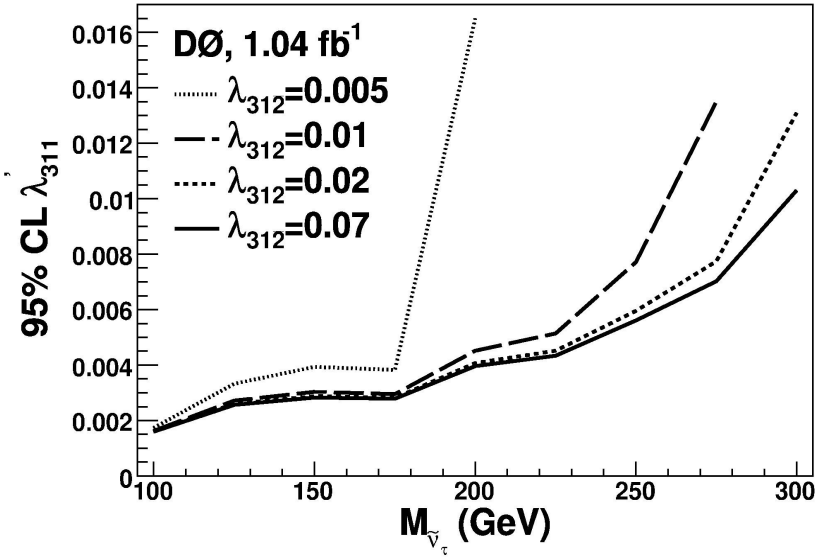
RPV Sneutrinos

- Single sneutrino production
- RPV for production and decay
  - Different couplings λ'_{311} and λ_{132}
- Search for eμ resonance

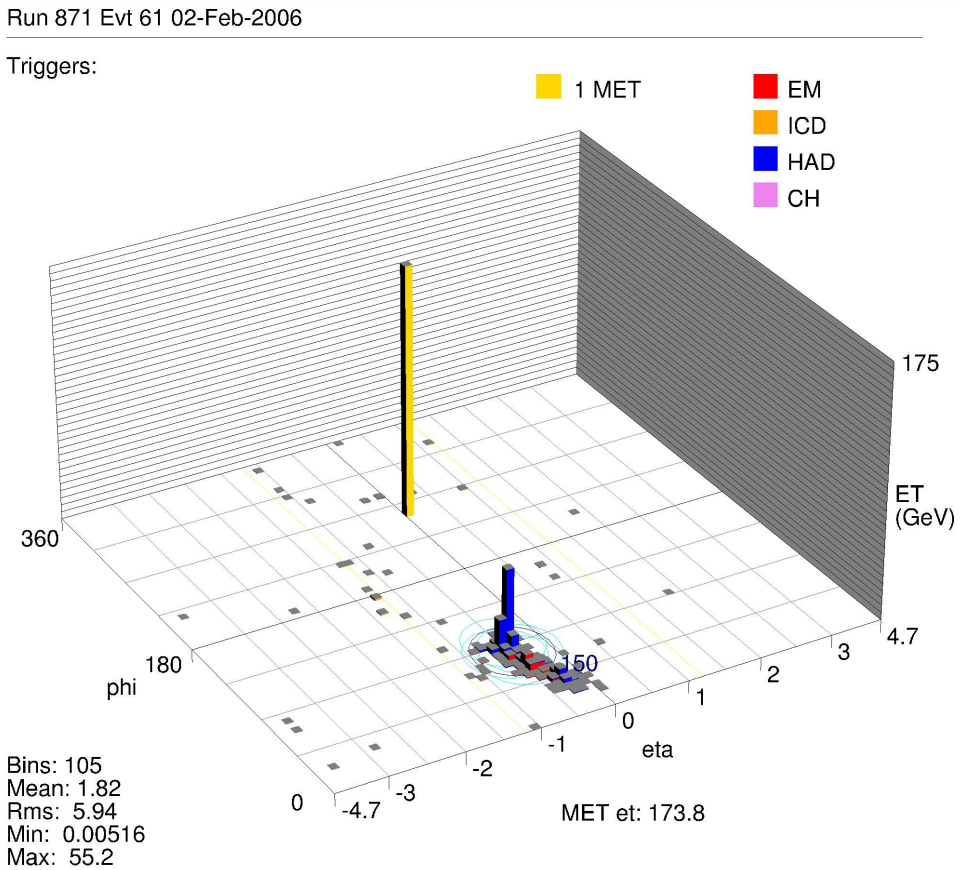


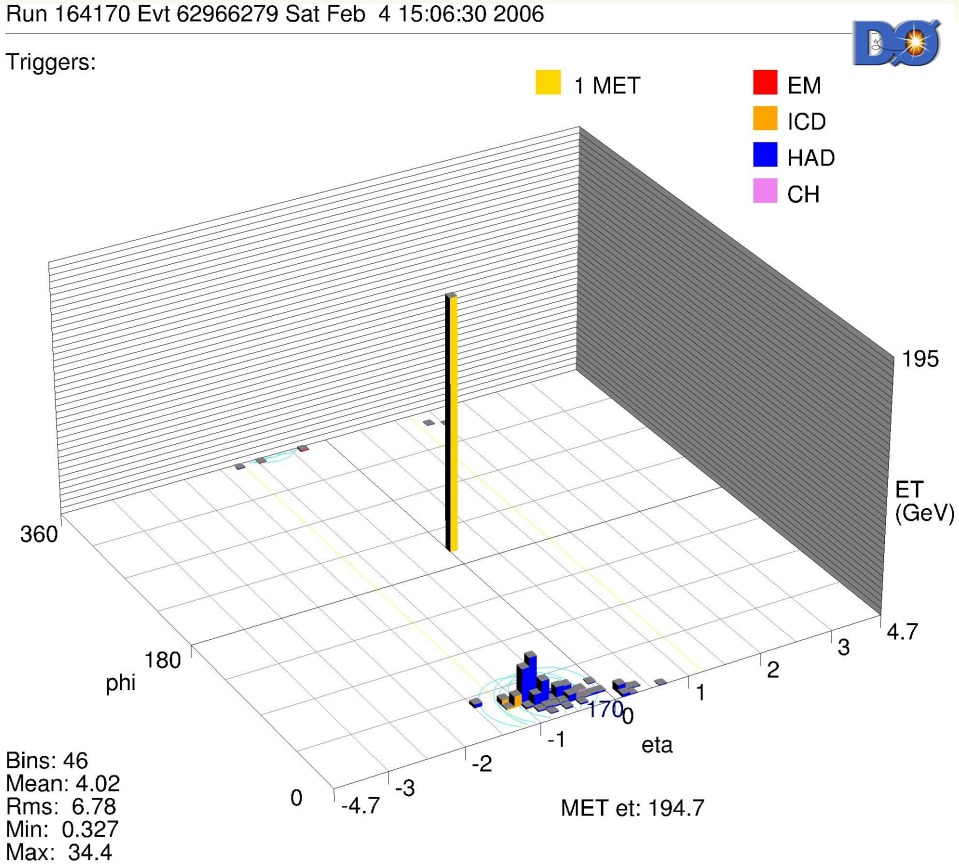


Data:
68
SM:
59.2 ± 5.3

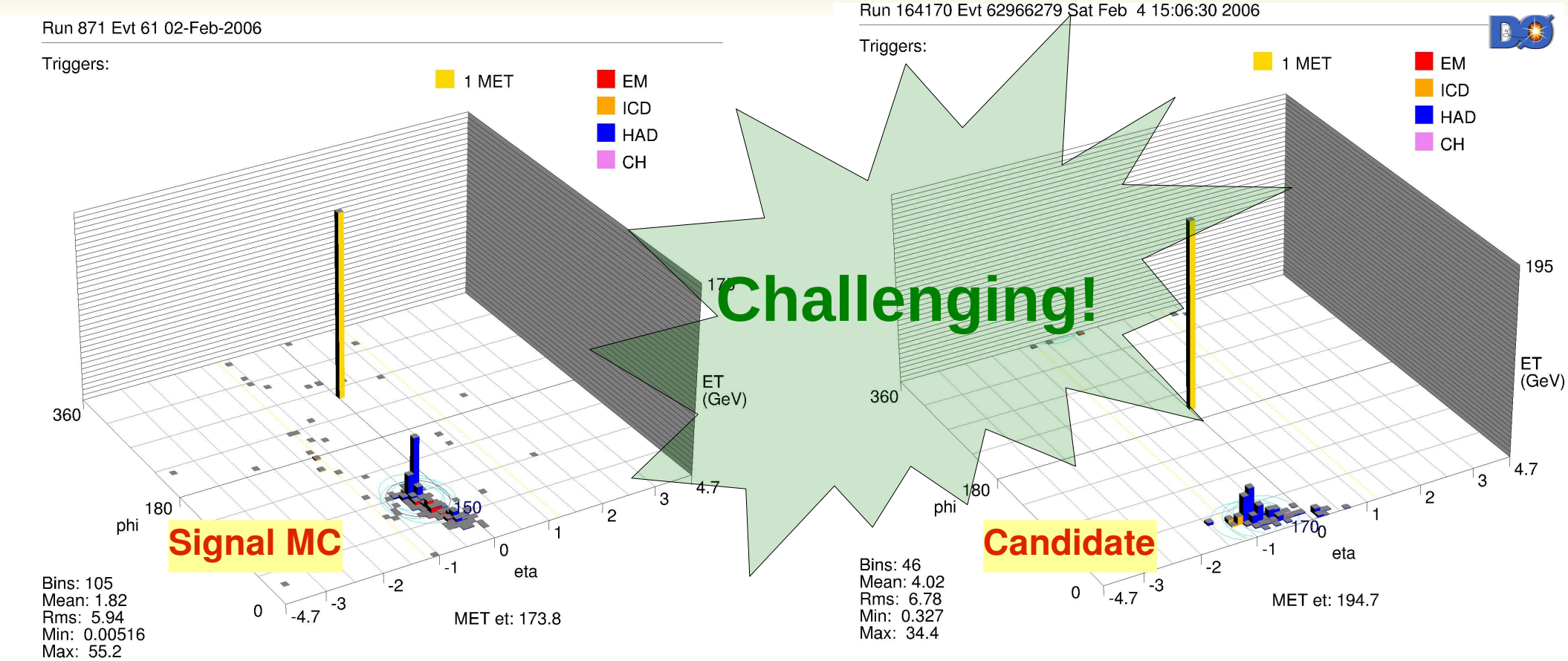


“Stopping Gluinos”





“Stopping Gluinos”



- Gluinos hadronize into *R-hadrons*. Charged R-hadrons can lose all their kinetic energy through ionization and come to rest (“split SUSY” → heavy squarks, light gauginos)
  - **Lifetime between 10 ns and 100 sec,** decay into jets + $\not{E}_T$ (LSP)
  - **~500 “stopped gluinos” in 2 fb^{-1}** for m(gluino) = 300 GeV

"Stopping Gluinos"

Backgrounds (a selection):

– Cosmic muons, beam halo, detector effects, diffractive events, ...
mostly estimated from data

Additional difficulties:

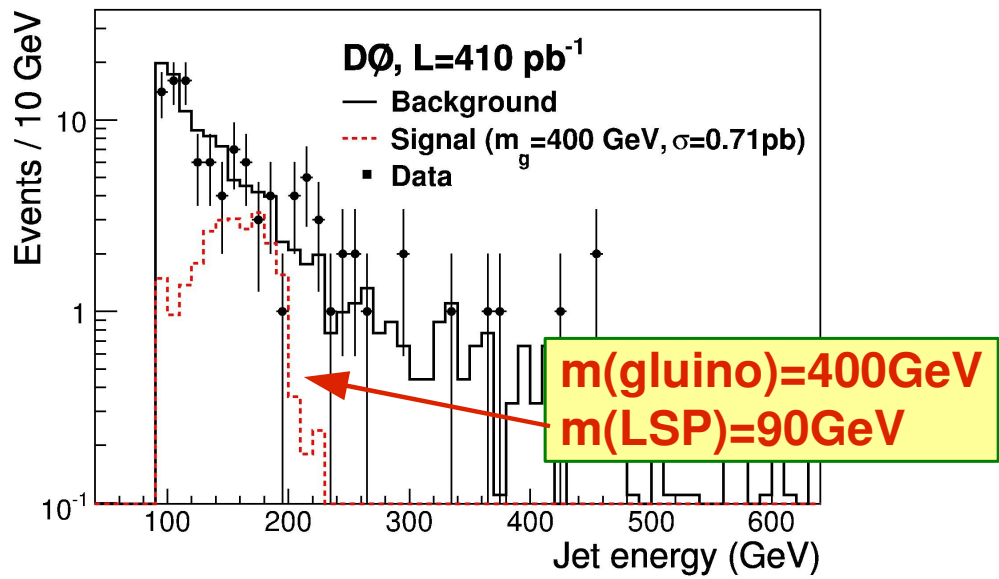
– Energy depositions are out-of-time relative to bunch crossing (→ signal shaping and discrimination)

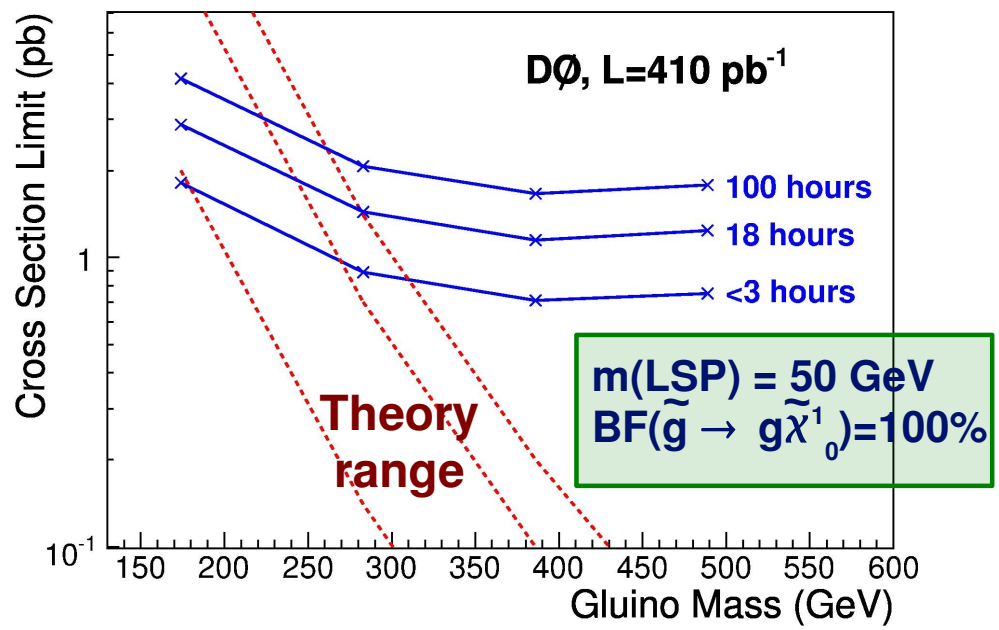
– Trigger

Data compatible with background expectation

Intervals in jet energy translated into gluino mass for a certain LSP mass

$$E = (M_g^2 - M_{LSP}^2)/2M_g$$

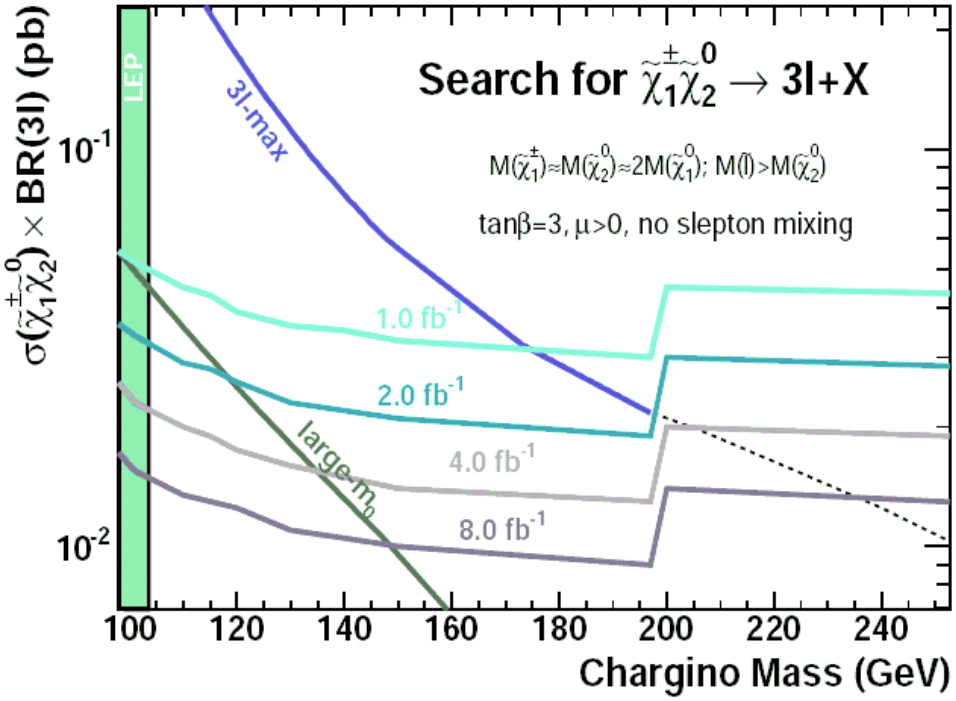




Other SUSY Searches

- Numerous BSM Higgs searches
- B_s (and B_d) into $\mu\mu$
- Squarks in jets+tau+MET
- Stop in b+tau
- Stop admixture to top in lepton + jets
- Long-lived neutralinos decaying to dimuons
- 2nd generation slepton resonances
- RPV SUSY in trileptons
- Long-lived charginos and staus
- Long-lived particles decaying into electron or photon pairs
- ...

Charginos / Neutralinos: Outlook

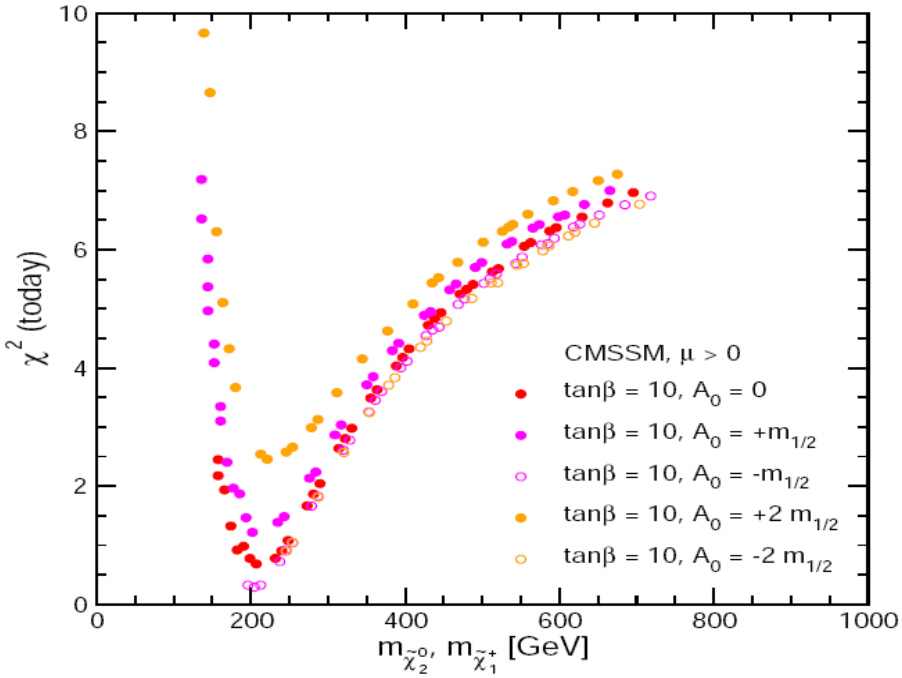


Expected sensitivity (Tevatron combined)

$m(\tilde{\chi}^{\pm}) \simeq 200$ GeV with 2 fb^{-1} in (optimistic) "3l-max"-scenario

Fit of an MSSM to experimental data (CDM, m_W, $(g-2)_\mu$, BF($b \to s\gamma$), $\sin^2\theta_{eff}$)

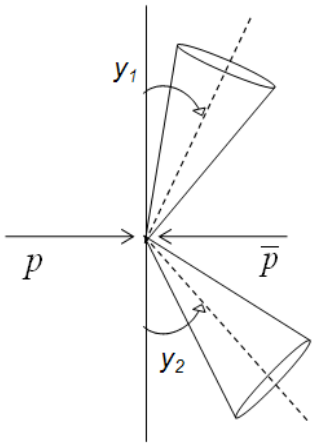
$m(\tilde{\chi}^{\pm}) \simeq 200$ GeV for $\tan\beta = 10$



Ellis, Heinemeyer, Olive, Weiglein

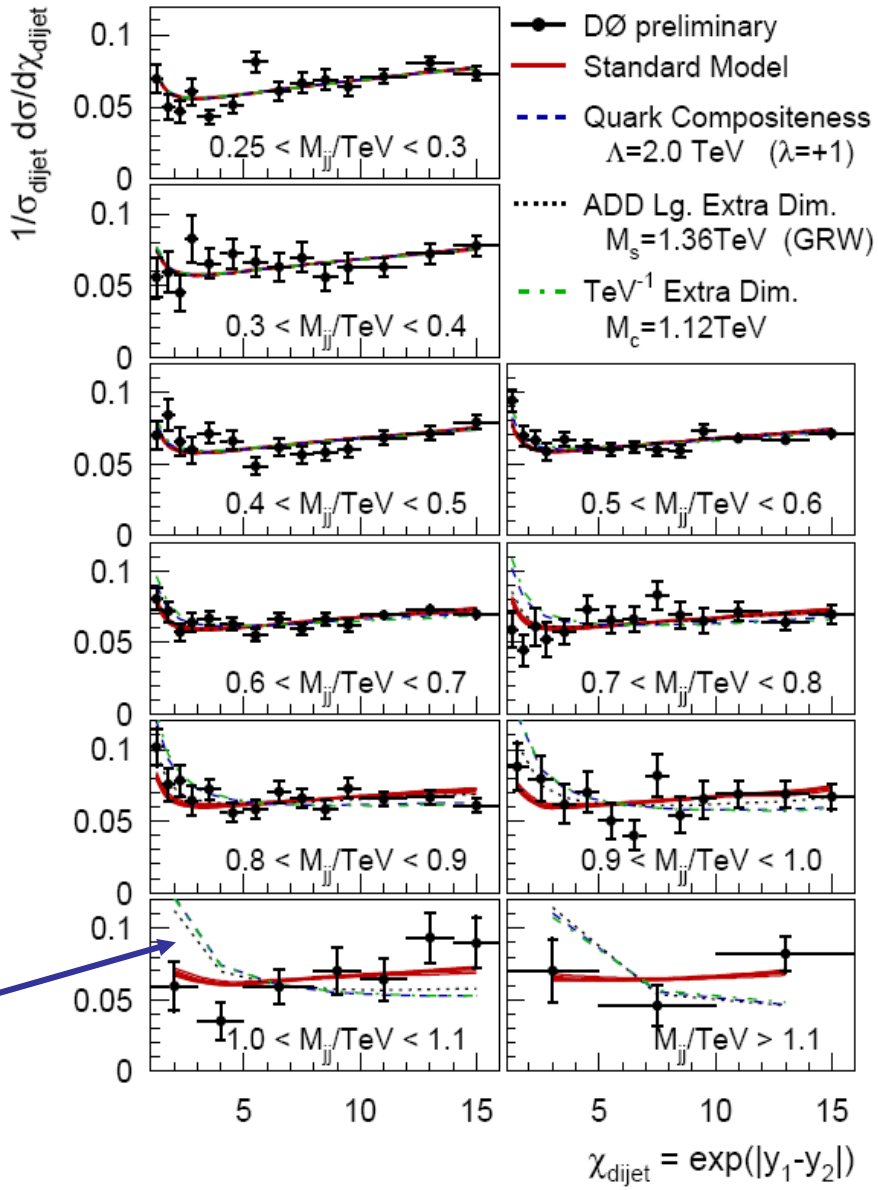
LED in high pT dijets

Dijet angular distribution is sensitive to new physics contributions, but fairly insensitive to theoretical and experimental uncertainties.



$$\chi_{dijet} = \exp(|y_1 - y_2|) \approx \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

Analyzed as a function of the dijet mass in 0.7 fb^{-1} of DØ data



New physics ?

M_S > 1.48 TeV (GRW)