New Phenomena at the Tevatron and HERA

Arnd Meyer – RWTH Aachen

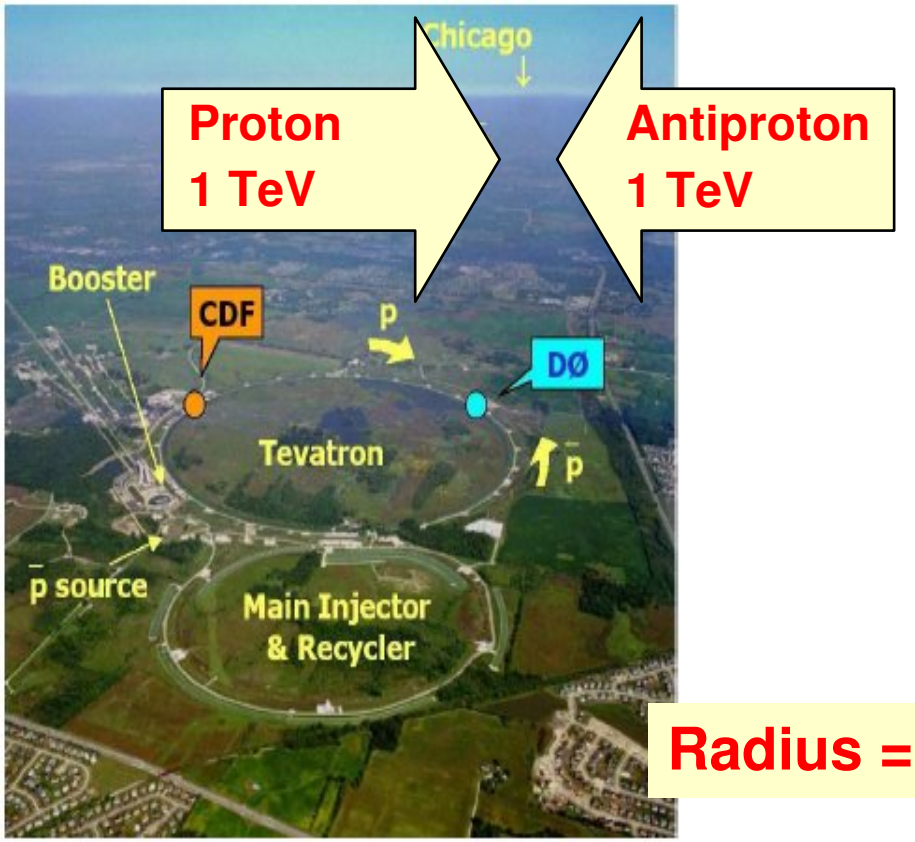
XXVI. Physics in Collision

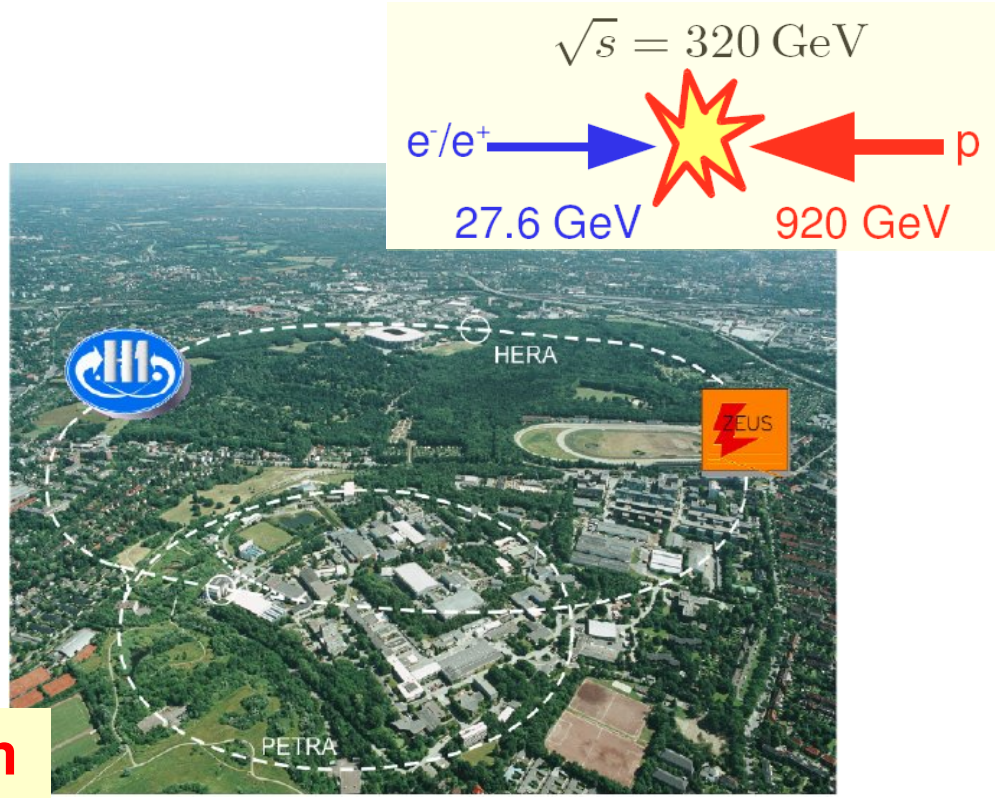
Búzios, 6. July 2006

Outline

Introduction	Searches at the Tevatron and HERA
Signatures	Signature based searches
Higgs	Status of SM Higgs search
Supersymmetry	Squarks and Gluinos
	Charginos and Neutralinos
	R-Parity Violation
	Long-Lived Particles
	Gauge Mediated SUSY Breaking
	SUSY Higgs
Extra Dimensions	Monojets, dileptons and diphotons
(Extra Gauge Bosons	W´, Z´)
(Leptoquarks	1st, 2nd, 3rd Generation)
(Compositeness	Lepton and quark substructure)
Conclusions	

Tools: Accelerators





Radius = 1 km

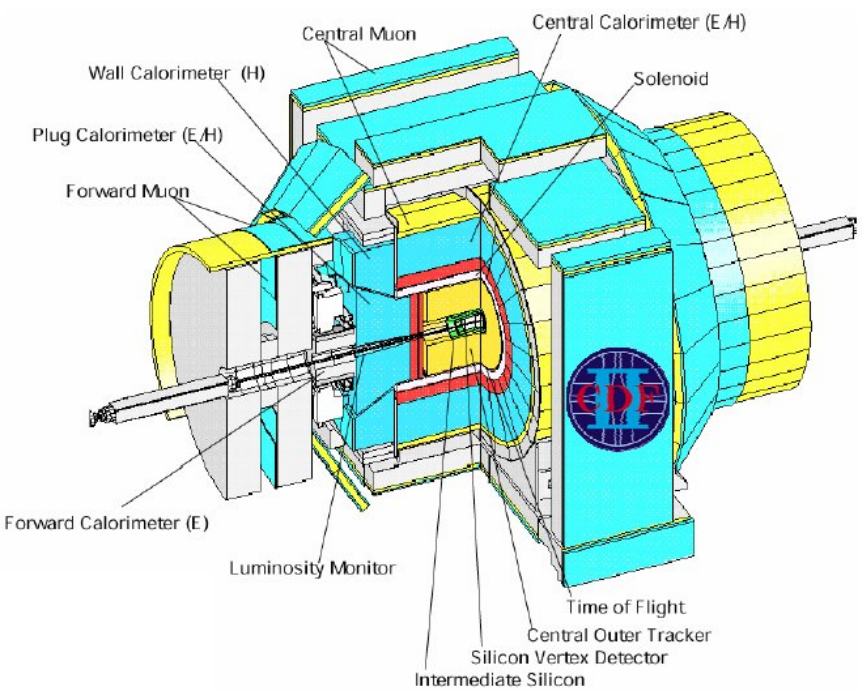
Integrated Luminosity:

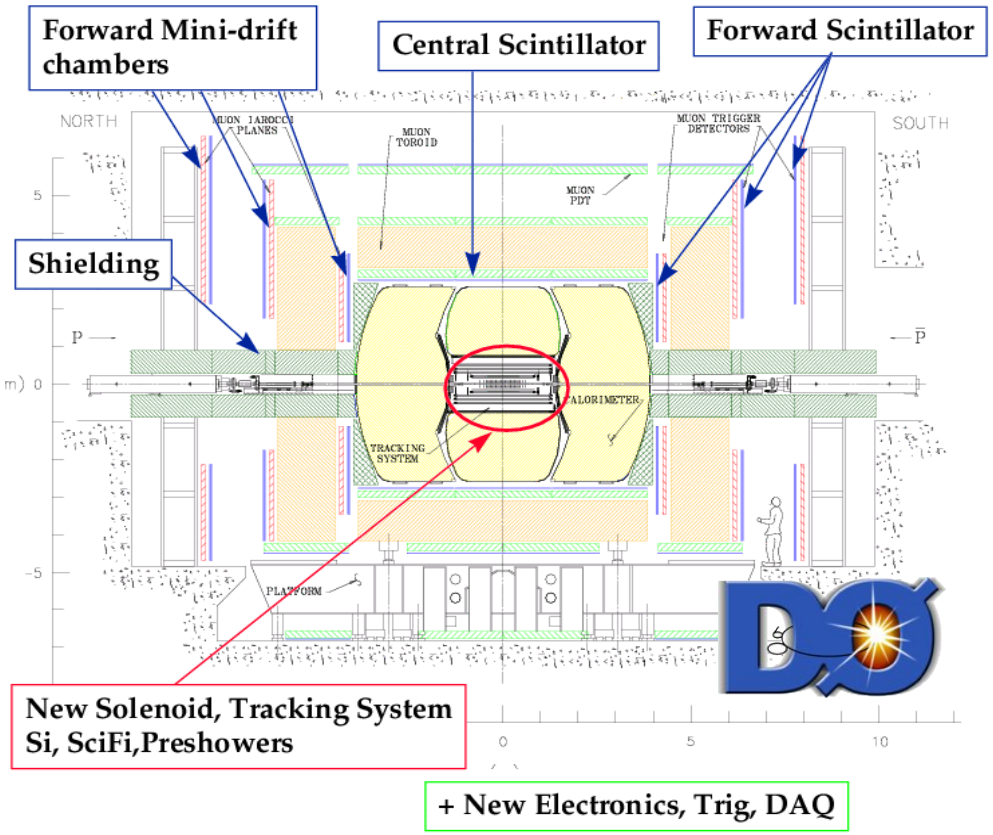
		130 pb^{-1} / exp.	HERA I
		(~85% e^+p)	(1994-2000)
0.1 fb^{-1} / exp.	Run I, 1992-96	350 pb^{-1} / exp.	HERA I+II
1.3 fb^{-1} / exp.	Run IIa, 2002-06	(~50% e^+p)	(+ long. pol. e)
4 – 8 fb^{-1} / exp.	Run IIb, until 2009	600 pb^{-1} / exp.	until Summer 2007

Tevatron: The DØ and CDF Experiments

DØ strengths:
Muon system with large acceptance, hermetic calorimetry

CDF strengths:
large Level 1 trigger bandwidth, central tracking





Typically:

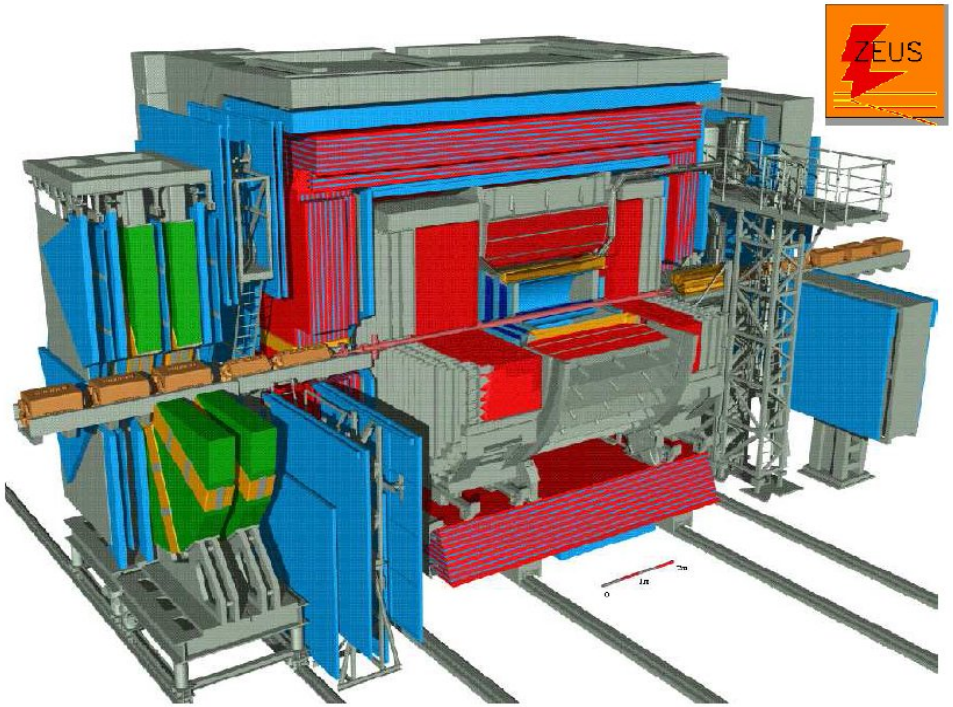
Electron acceptance	$\lvert\eta\rvert < 2.0 - 3.0$
Muon acceptance	$\lvert\eta\rvert < 1.0 - 2.0$
Precision tracking (Si)	$\lvert\eta\rvert < 2.0 - 3.0$

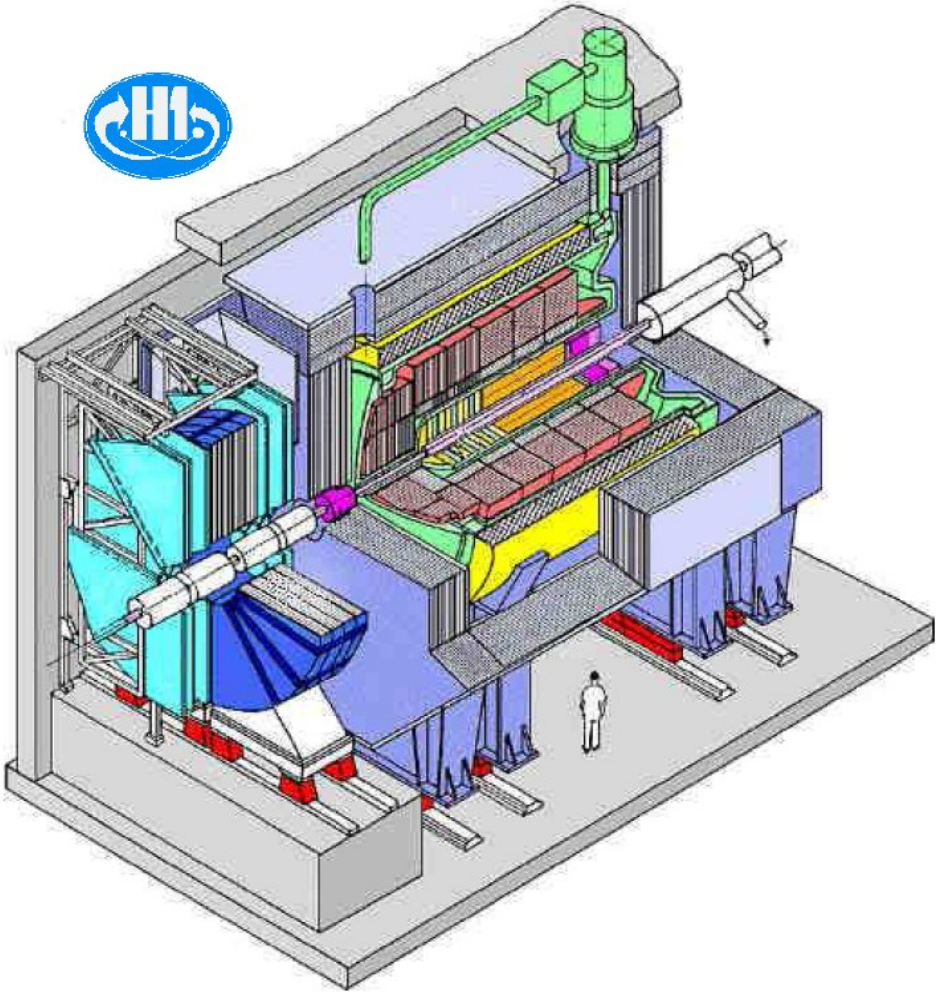
Detectors are well understood and take data with ~80-90% efficiency

HERA: The H1 and ZEUS Experiments

H1:
LAr calorimeter, optimized for scattered lepton

ZEUS:
Compensating Uranium calorimeter, optimited for hadronic final state

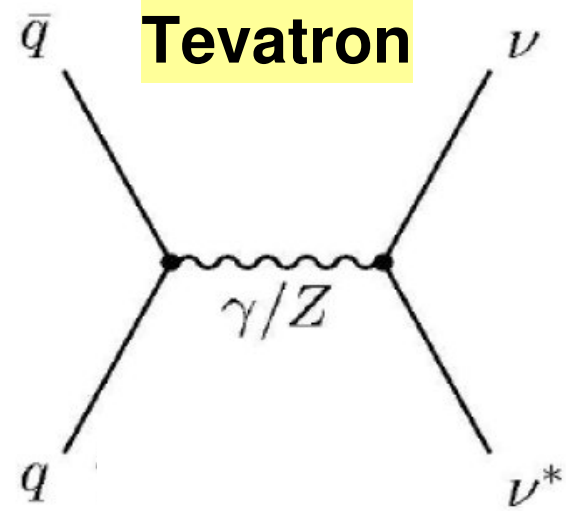




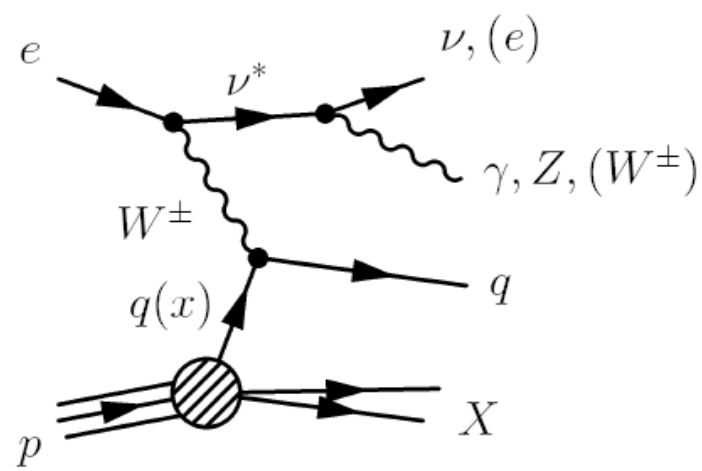
Tevatron vs. HERA

- Tevatron is at the energy frontier, generally with the highest mass reach, although parton-parton cross sections steeply falling
- HERA is not an annihilation machine
  - The cross sections for pair production of new heavy particles are often small
  - Single particle production is usually investigated
  - No absolute mass limits, limits depend on coupling of new particles to SM ones
- "Model independent" searches
  - Pick SM processes with small cross section
  - Investigate all possible final states, and compare data to SM expectation

Tevatron

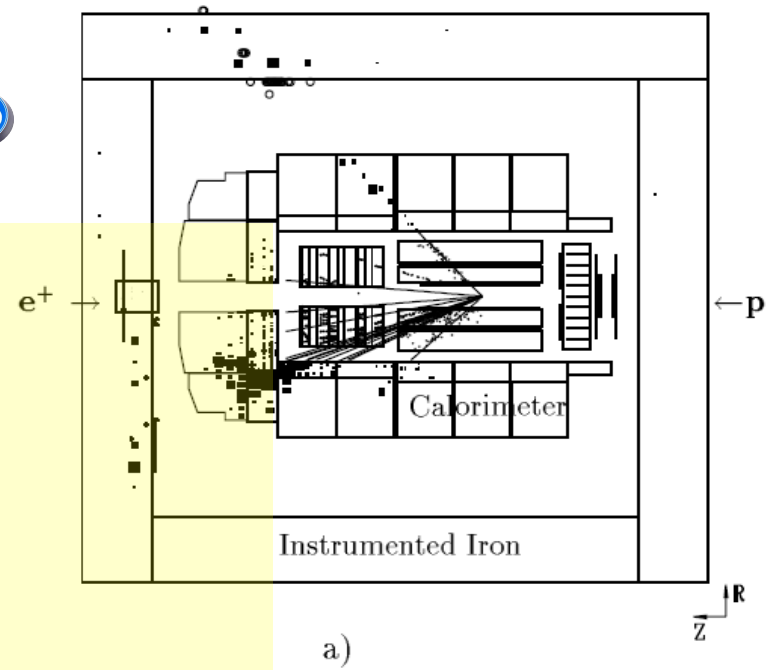


HERA



Isolated Leptons + Large p_T^X

Long, long ago...



DESY 94-248
December 1994

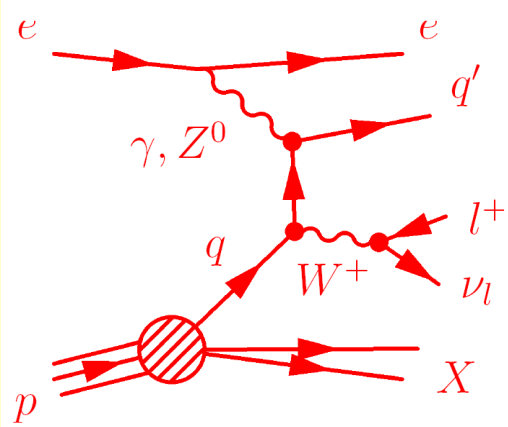
Observation of an $e^+p \to \mu^+X$ Event with High Transverse Momenta at HERA

H1 Collaboration

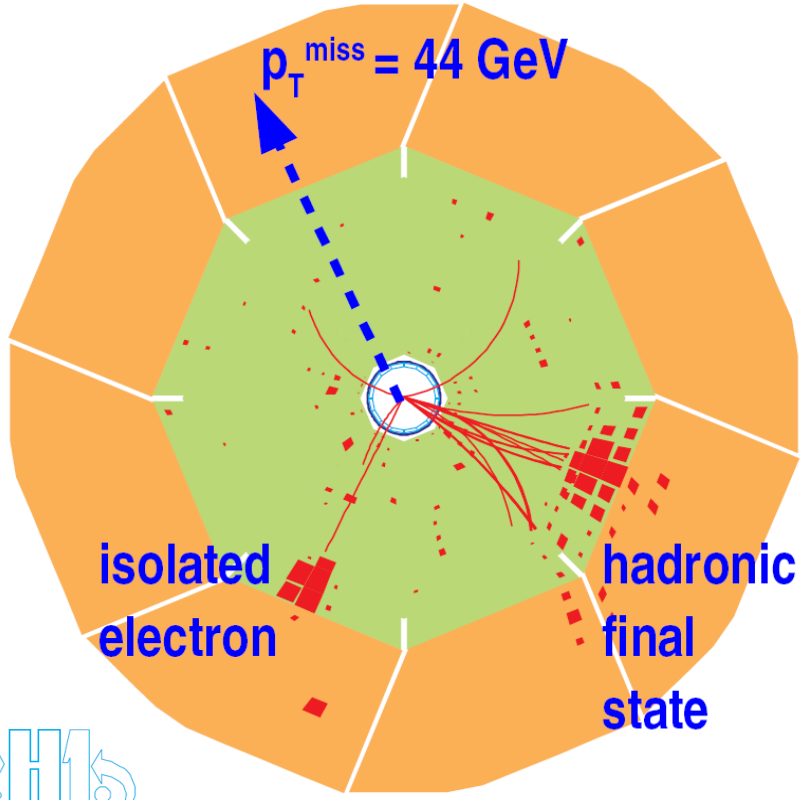
Abstract

At the HERA electron-proton collider an event has been observed in the H1 detector which shows an isolated muon recoiling against a hadronic system, both of high transverse momentum. The event was registered in a total integrated luminosity of $4\,\mathrm{pb}^{-1}$.

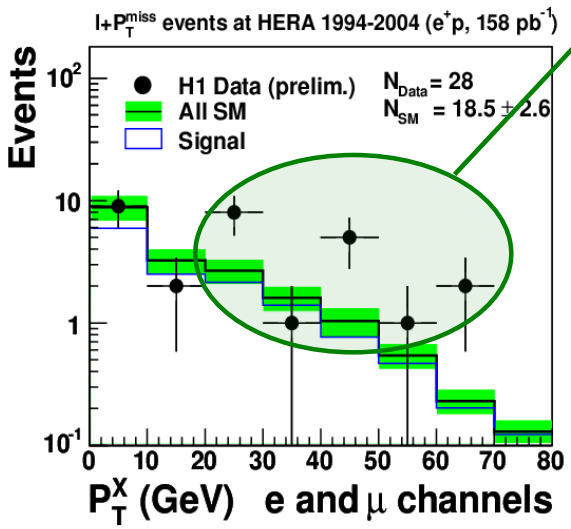
Compatible with W production (expect 0.03 events)

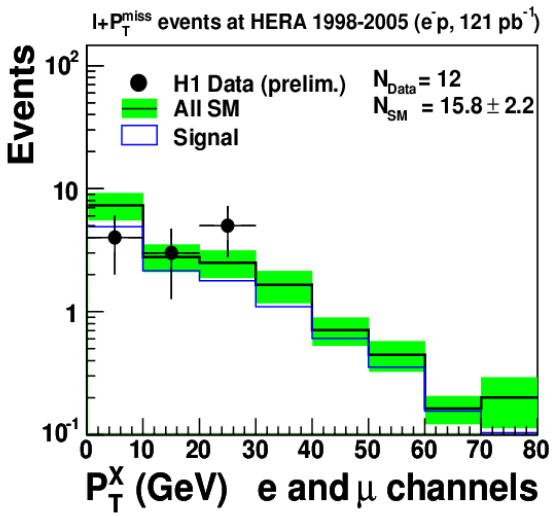


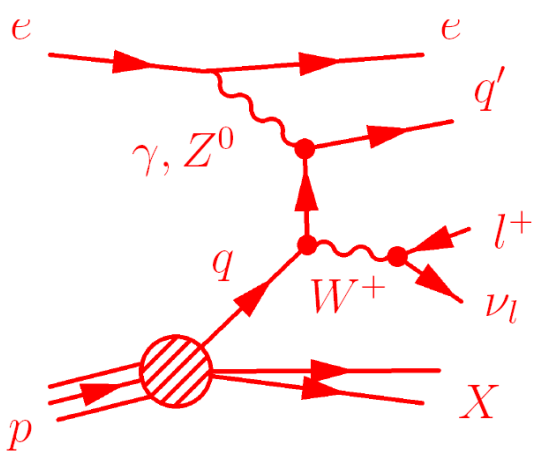
Isolated Leptons + Large p_T^X



H1 (prelim.) 279 pb^{-1}	e channel obs. / exp. (W-cont.)	μ channel obs. / exp. (W-cont.)
Full sample	30 / 27.2 ± 3.8 (68%)	10 / 7.2 ± 1.1 (81%)
p_T^X > 25 GeV	11 / 4.7 ± 0.9 (69%)	6 / 4.3 ± 0.7 (78%)
e^-p (121 pb^{-1})	2 / 2.4 ± 0.5 (62%)	0 / 2.0 ± 0.3 (76%)
e^+p (158 pb^{+1})	9 / 2.3 ± 0.4 (80%)	6 / 2.3 ± 0.4 (78%)







low p_T^X

isol. lepton

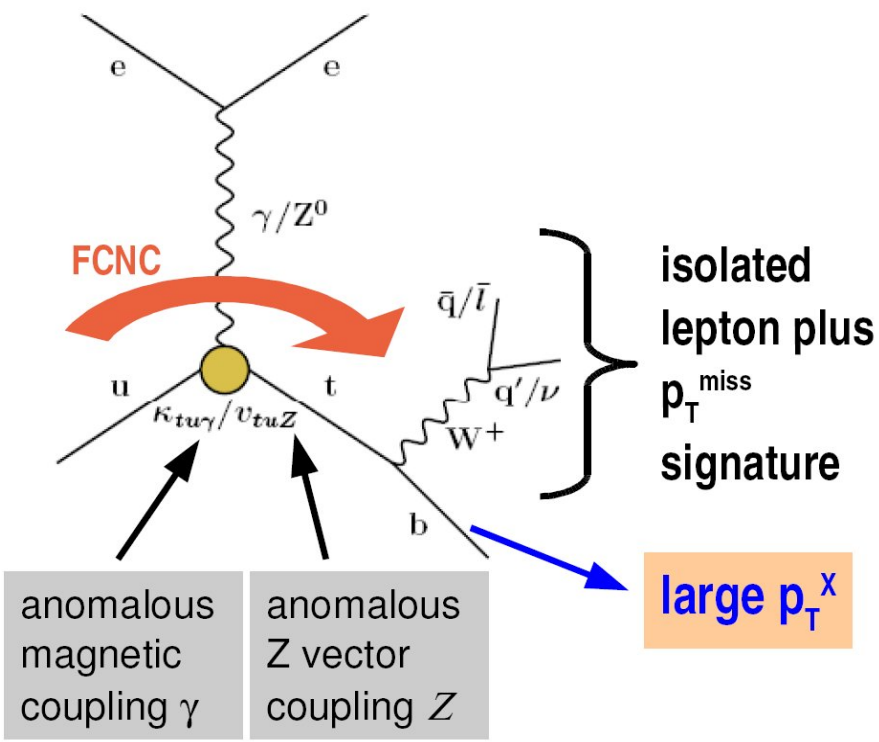
p_T^{miss}

Excess in e^+p data only?!?

Isolated Leptons + Large p_T^X

ZEUS (prelim.)	e channel obs. / exp. (W-cont.)	μ channel obs. / exp. (W-cont.)
12 GeV < p_T^X < 25 GeV	249 pb^{-1}: 5 / 3.5 ± 0.4 (58%)	126 pb^{-1}: 2 / 1.4 ± 0.2 (68%)
p_T^X > 25 GeV	249 pb^{-1}: 4 / 4.4 ± 0.5 (61%)	126 pb^{-1}: 2 / 1.4 ± 0.2 (86%)
e^-p	143 pb^{-1}: 3 / 2.86 ± 0.46 (53%)	126 pb^{-1}: 2 / 1.4 ± 0.2 (86%)
e^+p	106 pb^{-1}: 1 / 1.5 $^{+0.12}_{-0.13}$ (78%)	—

No excess in ZEUS data!



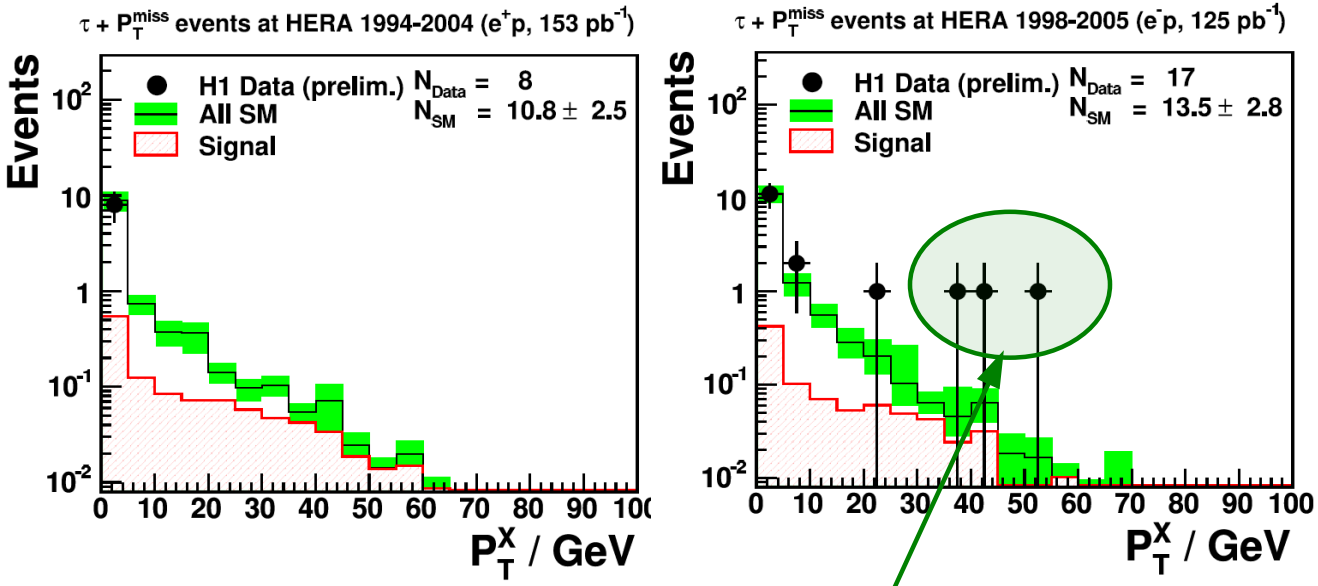
Anomalous top production via FCNC could lead to observed H1 excess, but does not explain:

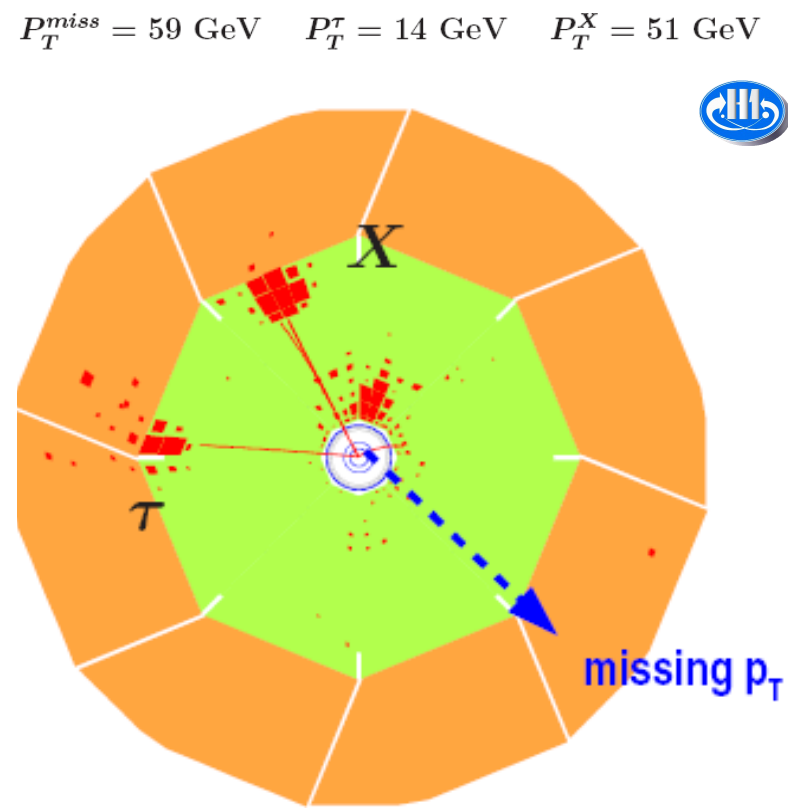
- e^+p / e^-p asymmetry
- H1 / ZEUS asymmetry

(not excluded by Tevatron/LEP)

Isolated tau Leptons + Large p_T^X

Hadronic tau decays identified as jets with low track multiplicity and “pencil-like” shape

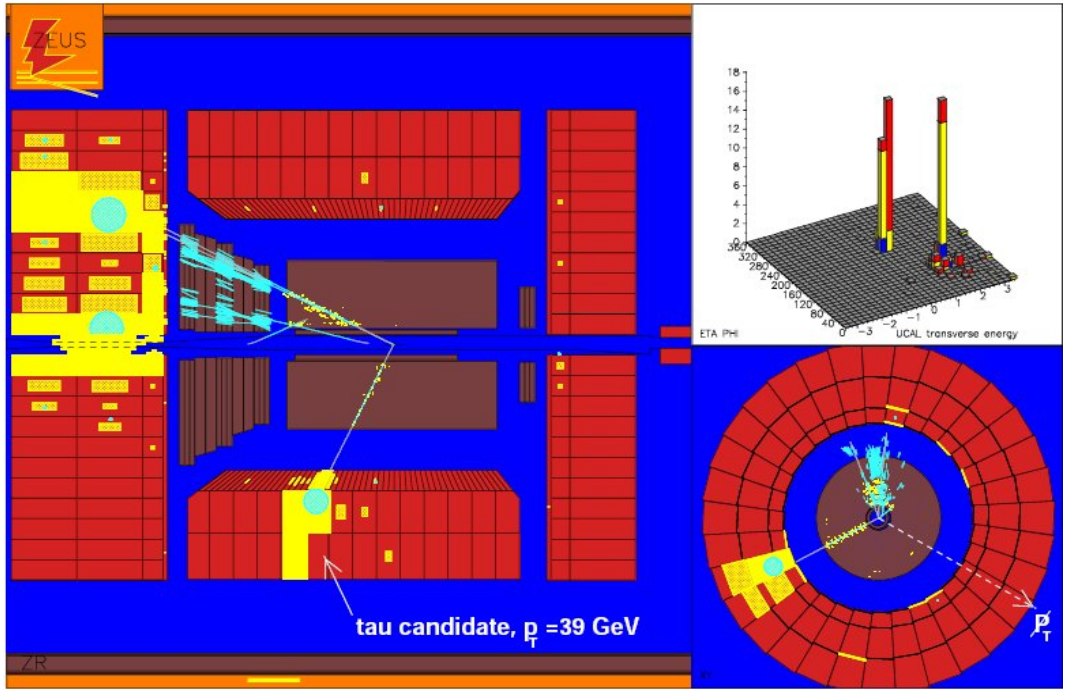




H1 (prelim.) 279 pb^{-1}	$\tau + p_T^{miss}$ obs. / exp.
Total	25 / 24.2 $^{+4.20}_{-5.80}$
p_T^X > 25 GeV	3 / 0.74 $^{+0.19}_{-0.16}$
e^-p (125 pb^{-1})	3 / 0.35 $^{+0.10}_{-0.08}$
e^+p (153 pb^{+1})	0 / 0.40 $^{+0.10}_{-0.10}$

Remarkable events with isolated tau lepton, missing E_T, and large p_T^X, in **e^-p data**

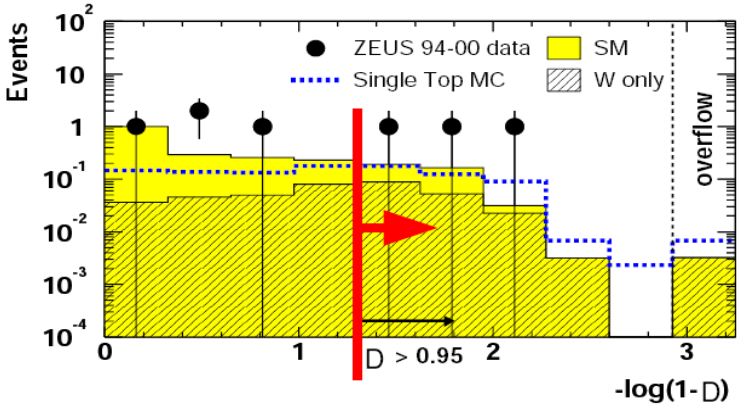
Isolated tau Leptons + Large p_T^X

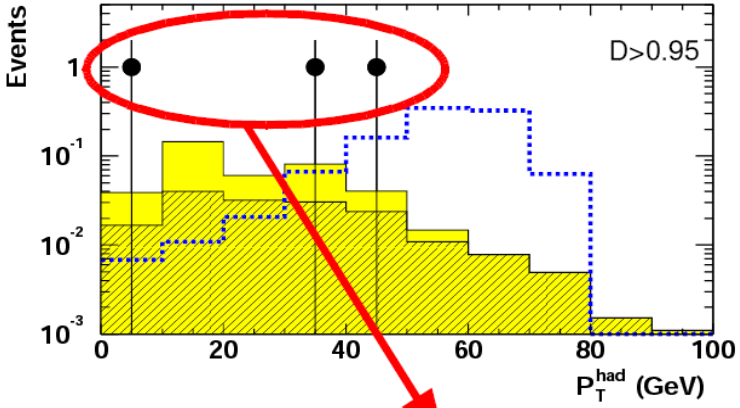


Preselection:	$7 / 2.2^{+0.39}_{-0.58}$
D > 0.95:	$3 / 0.4^{+0.12}_{-0.13}$
$p_T^X > 25$ GeV:	$2 / 0.2^{+0.05}_{-0.05}$
$p_T^X > 40$ GeV:	$1 / 0.07^{+0.39}_{-0.58}$

D: discriminator variable to separate τ-jets from q-jets

HERA I $e^{\pm}p$ data 130 pb^{-1}:





Phys.Lett. B583 (2004) 41-58

Slight excess in the tau channel

HERA I data, so mostly **e^+p data**

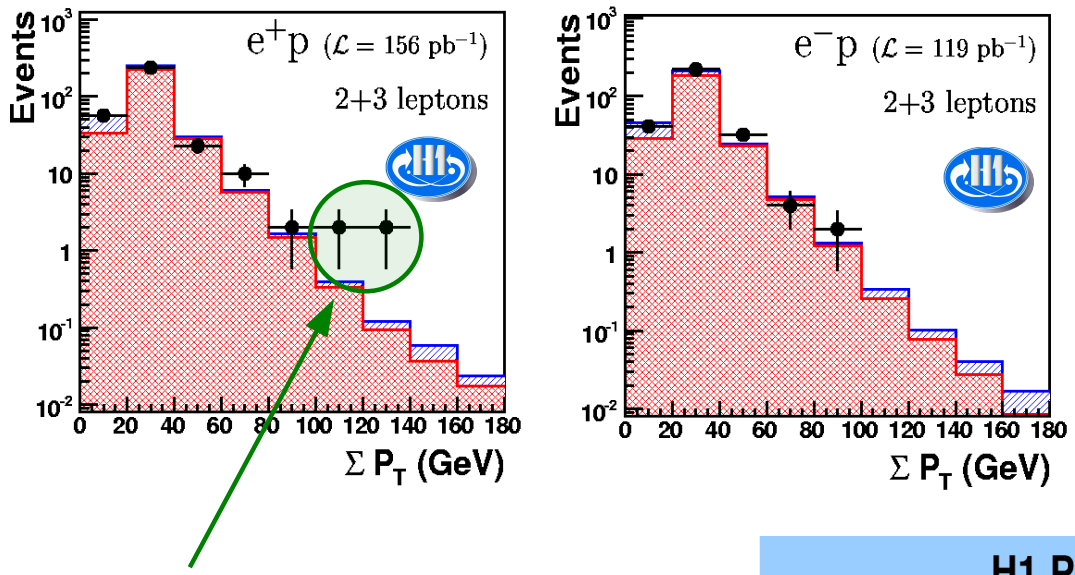
Another x 2 in integrated luminosity is not sufficient to clarify the observed anomalies in isolated leptons

Multileptons

Search for:

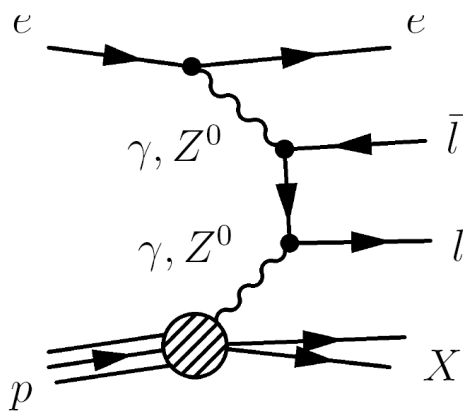
2 leptons: ee, $\mu\mu$, eμ

3 leptons: eee, e$\mu\mu$



H1 Data (prelim.)
DIS+Compton
Pair Production

Dominant SM process is elastic $\gamma\gamma$ scattering



(low p_T, low m_{ll})

Excess at large Σp_T (leptons) is from HERA I data [EJC31 (2003) 17]

H1 Preliminary 275 pb^{-1}		
Σ p_T > 100 GeV	Data	SM
HERA I+II (275 pb^{-1})	4	1.1 ± 0.2
e^+p (156 pb^{-1})	4	0.6 ± 0.1
e^-p (119 pb^{-1})	0	0.5 ± 0.1

ZEUS:

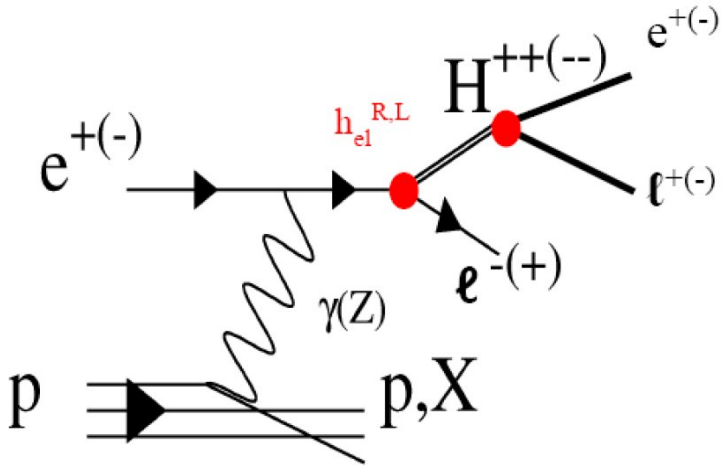
HERA I analysis (130 pb^{-1}) events with two or more electrons:

Type	data	SM
all	217	248.5 ± 3.9
$E_{T,e1}$ > 30 GeV	8	7.1 ± 0.3
M_{12} > 100 GeV	2	1.14 ± 0.09

Compatible with SM expectation

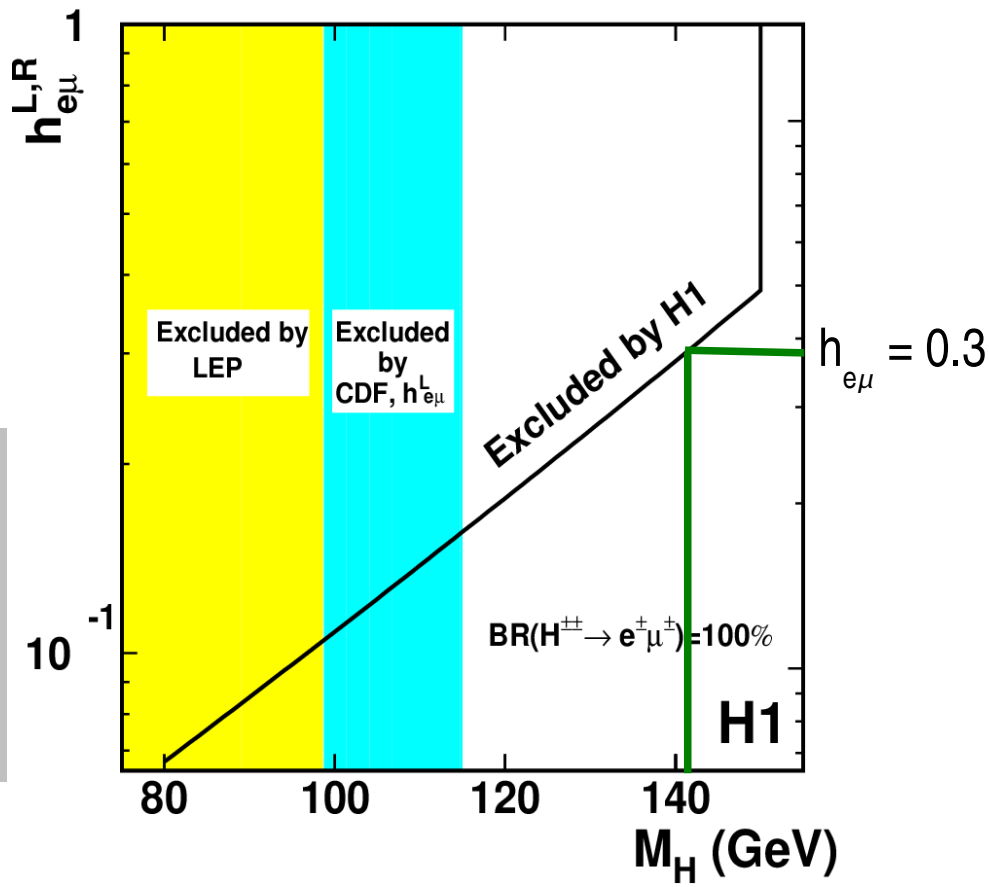
Multileptons / Doubly Charged Higgs

Dedicated search for
ee, eμ or eτ pairs with equally charged leptons (=beam charge)



HERA I analysis (118 pb^{-1}):

	ee:	3 / 2.45 ± 0.11
Results:	eμ:	1 / 4.12 ± 0.44
	eτ:	1 / 2.07 ± 0.54



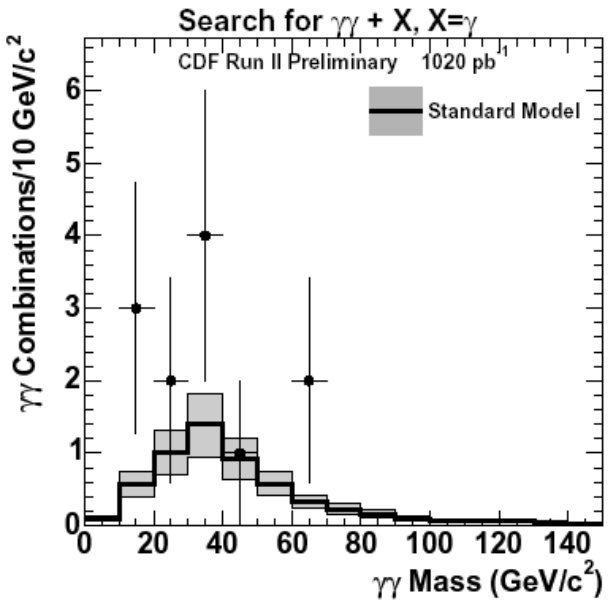
lower limit on mass of H^{++} assuming exclusive coupling $h_{e\mu,e\tau}$=0.3 to eμ (eτ) at 141 GeV (112 GeV)

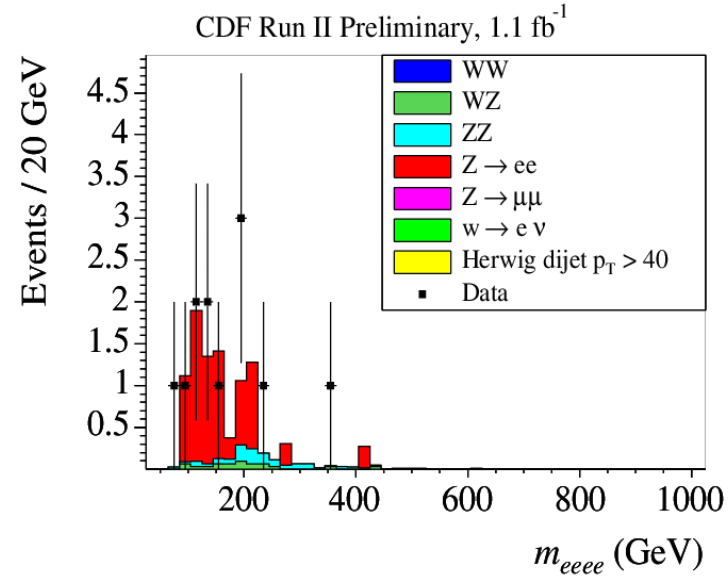
Signature-based Searches at the Tevatron

Run II results just beginning to show up, expect more to come

$\gamma\gamma$ + X in 0.7 to 1 fb^{-1}

X=e	2 vs. 4.5±0.8
X=μ	0 vs. 0.5±0.1
X=γ	4 vs. 1.9±0.6





X → ZZ → eeee in 1.1 fb^{-1}

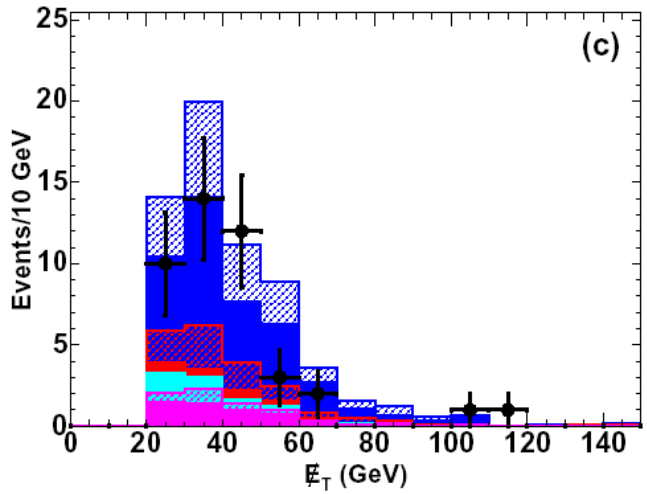
0 events above 400 GeV

l γ + Missing E_T in 0.3 fb^{-1}

l=e	25 vs. 19.8±3.2
l=μ	18 vs. 15.3±2.2

(CDF Run I excess not confirmed)

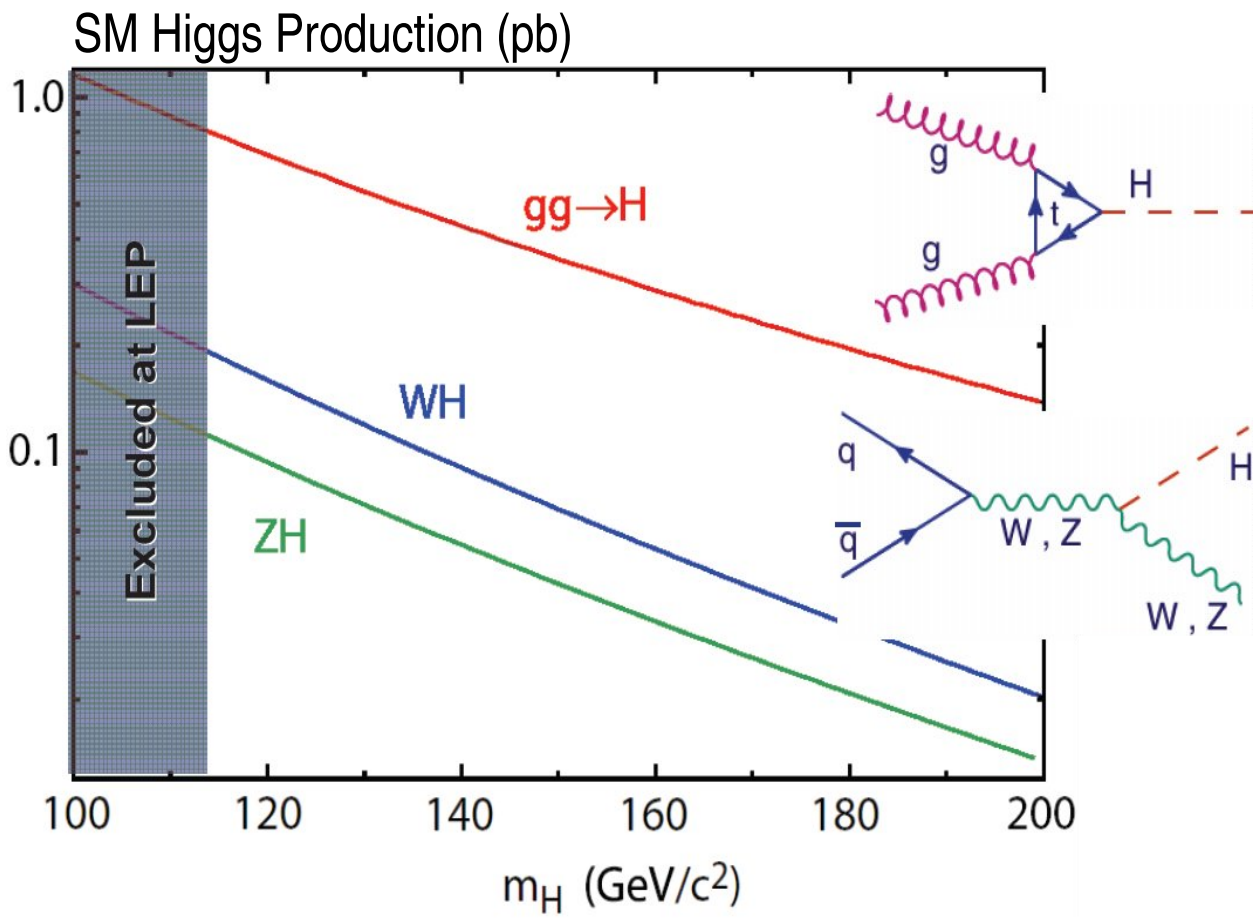
(Also multileptons + photon)



Standard Model Higgs

(Worth a talk on its own)

(SM) Higgs Overview



Experimental challenges: the full program!

(Lepton ID, missing E_T, b-tagging, bbbar mass resolution, angular correlations for WW, ...)

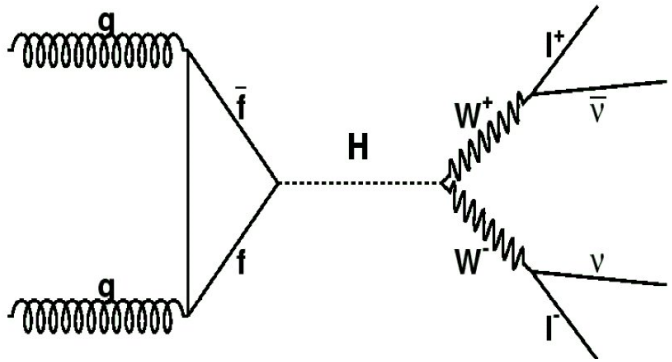
Sensitivity for SM Higgs above LEP limit (m_H > 114.4 GeV) requires ~ 2 fb^{-1} (per experiment)

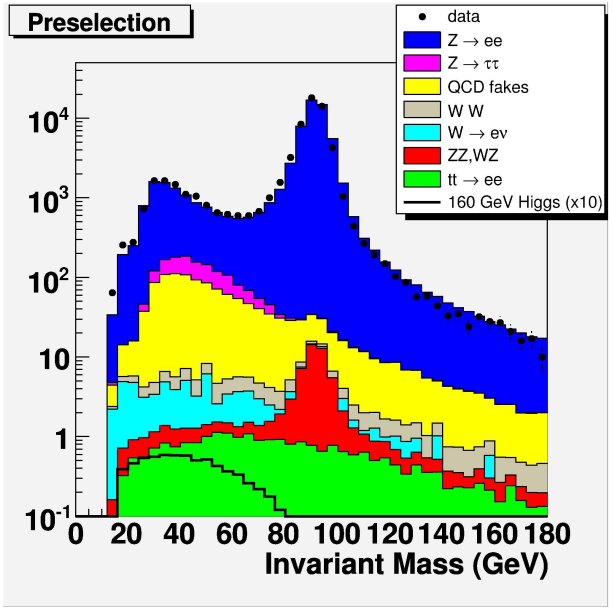
SM Higgs Decay:

< 135 GeV H → bb dominant
> 135 GeV H → WW

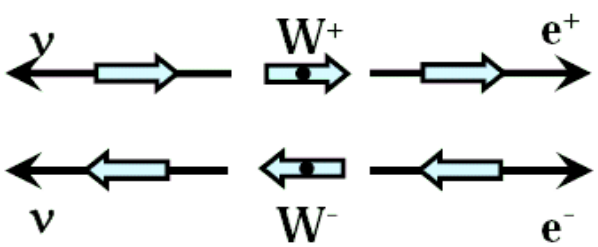
- **H → WW(*)**
- **WH → lν bb**
- WH → WWW(*)
- ZH → νν bb
- ZH → llbb
- Higgs searches with taus
- ttH

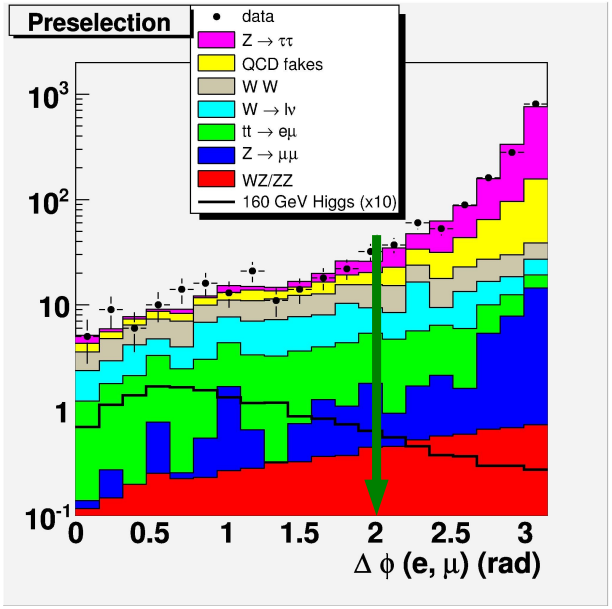
gg → H, H → WW(*)





- Use $\int L\,dt = 950\ pb^{-1}$ of dilepton data:
  2 high p_T isolated leptons with opp. charge: ee, eμ here
  $\not{E}_T > 20$ GeV
- Additional kinematic cuts to suppress physics backgrounds, depending on Higgs mass
- Exploit spin correlation in decay



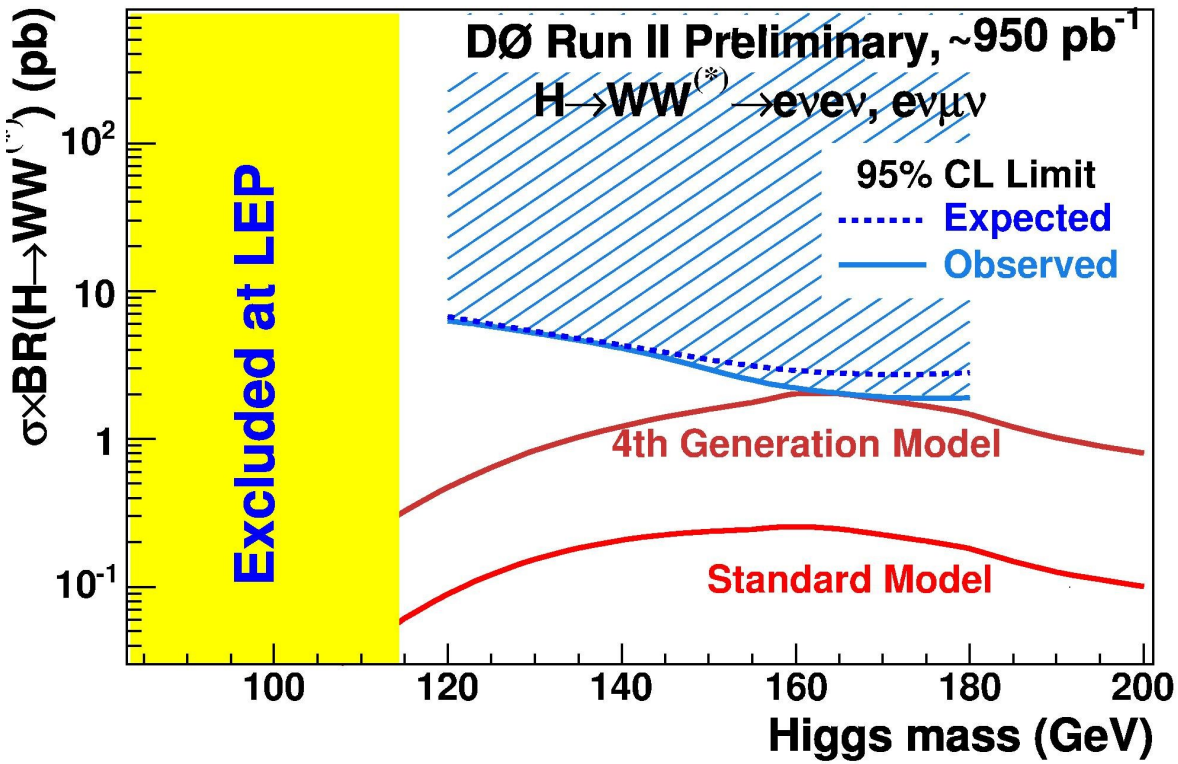


- Remaining backgrounds: Z/DY, Diboson production, W+jet/photon, ttbar

gg → H, H → WW(*)

Example: expected and observed number of events for m_H = 160 GeV

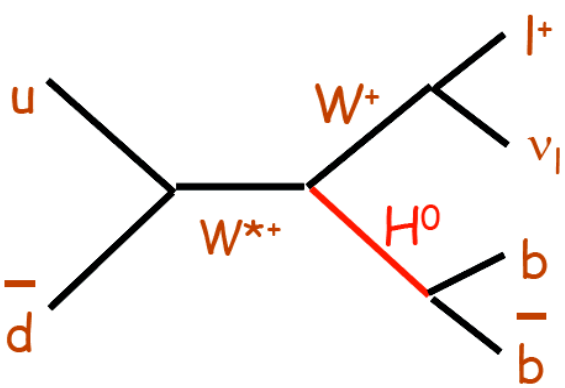
Diboson	W+jet/γ	Z/γ*	tt	Total	Data
24.6±0.2	6.7±1.6	0.02±0.01	3.2±0.1	**34.7±1.7**	**28**



Associated Production: WH, W → l ν, H → bb

Major benchmark channel

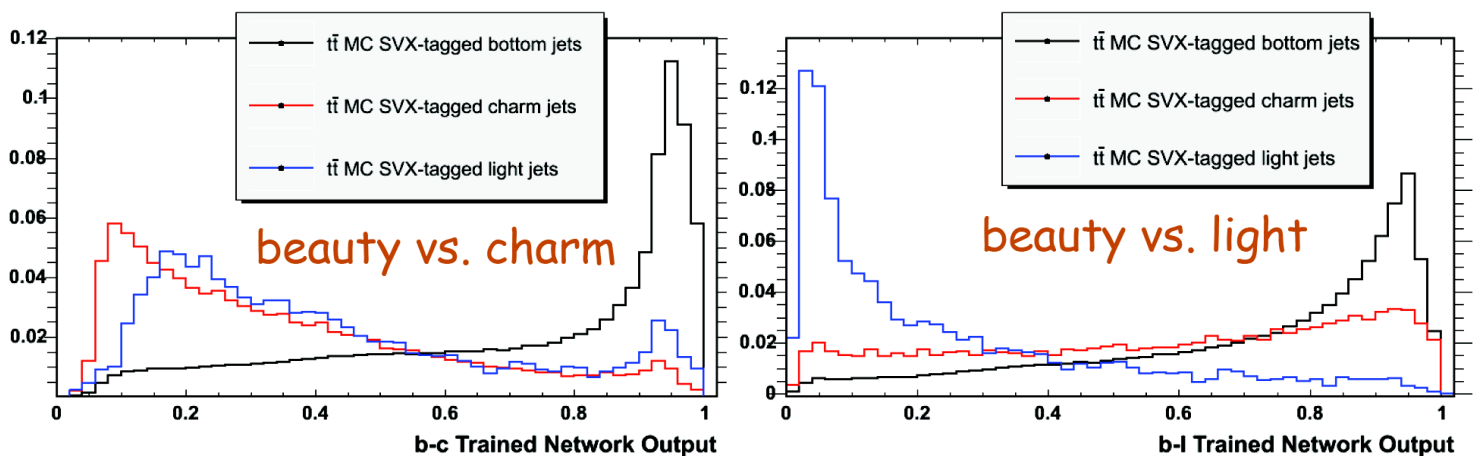
New CDF analysis with doubled data sample and implementing NN b-tagging



- One central isolated lepton with p_T > 20 GeV
- Large Missing E_T (> 20 GeV)
- Two jets (E_T > 15 GeV, $|\eta|$ < 2.0)
- Two jets tagged by Secondary Vertex Tagger
  OR One jet tagged by SecVtx AND NN
- Veto Z and ttbar dilepton events

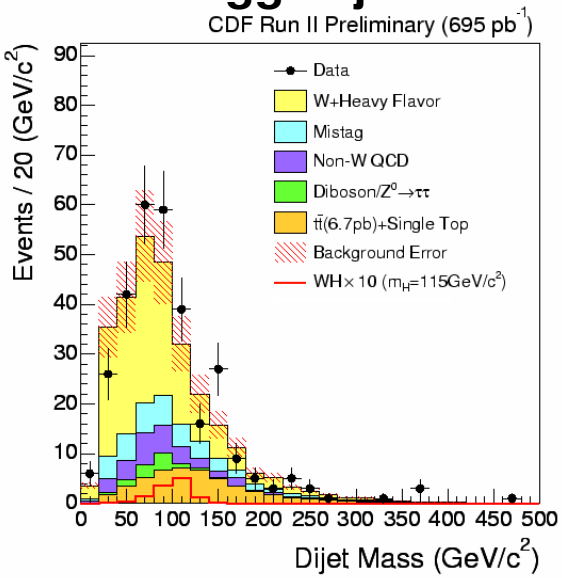
NN trained on jets tagged by Secondary Vertex Tagger

NN b-tag keeps 90% of b jets, and rejects 50% of c jets, 65% of light-flavor jets

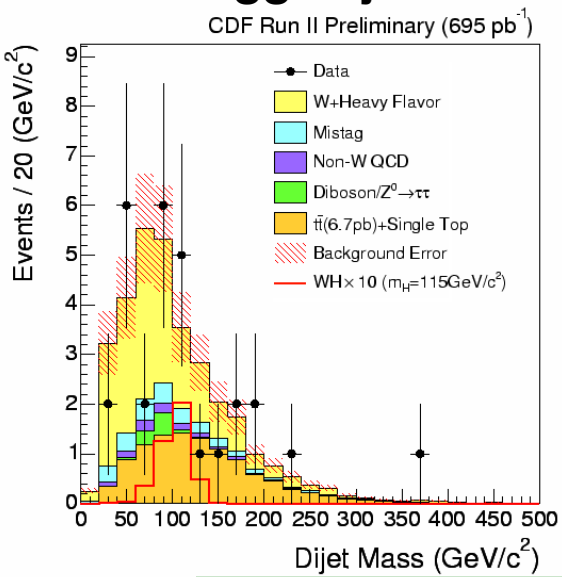


Associated Production: WH, W → l ν, H → bb

= 1 b-tagged jet



= 2 b-tagged jet



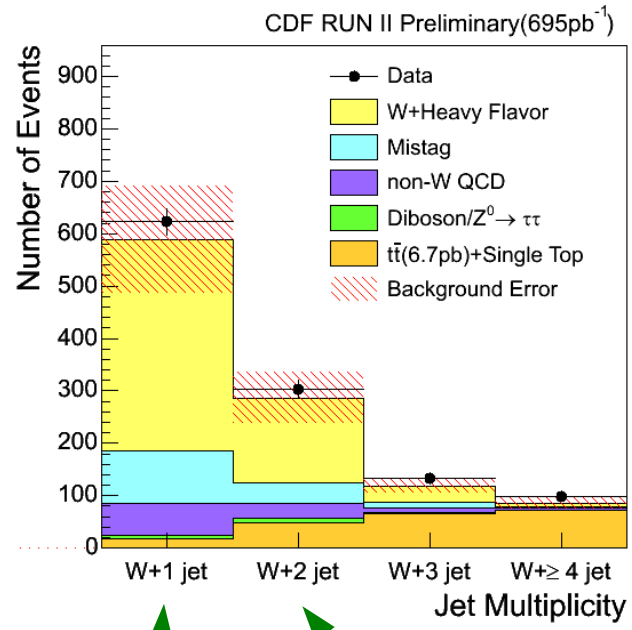
= 1 jet tagged by SecVtx and NN

Jet Multiplicity	w/o NN tag	w/ NN tag
Before b-tagging	10647	10647
Mistag	119.4 ± 19.4	41.8 ± 9.0
$Wb\bar{b}$	130.4 ± 44.6	120.2 ± 41.1
$Wc\bar{c}$	48.9 ± 16.7	33.7 ± 11.5
Wc	47.4 ± 12.4	25.0 ± 6.5
$t\bar{t}$(6.7pb)	43.1 ± 7.3	37.8 ± 6.4
Single Top	22.7 ± 2.4	20.1 ± 2.1
Diboson/$Z^0 \to \tau\tau$	17.0 ± 2.5	10.6 ± 1.7
non-W QCD	44.4 ± 7.7	29.5 ± 5.1
Total Background	473.4 ± 66.9	318.8 ± 54.7
Observed($\geq$1tag)	514	332

= 2 jets tagged by SecVtx

Mistag	3.1 ± 0.5
$Wb\bar{b}$	14.8 ± 5.3
$Wc\bar{c}$	0.2 ± 0.1
Wc	0.0 ± 0.0
$t\bar{t}$(6.7pb)	7.5 ± 1.3
Single Top	3.0 ± 0.3
Diboson/$Z^0 \to \tau\tau$	0.8 ± 0.2
non-W QCD	1.0 ± 0.2
Total Background	30.6 ± 5.6
Observed($\geq$2tag)	29

= 1 b-tagged jet



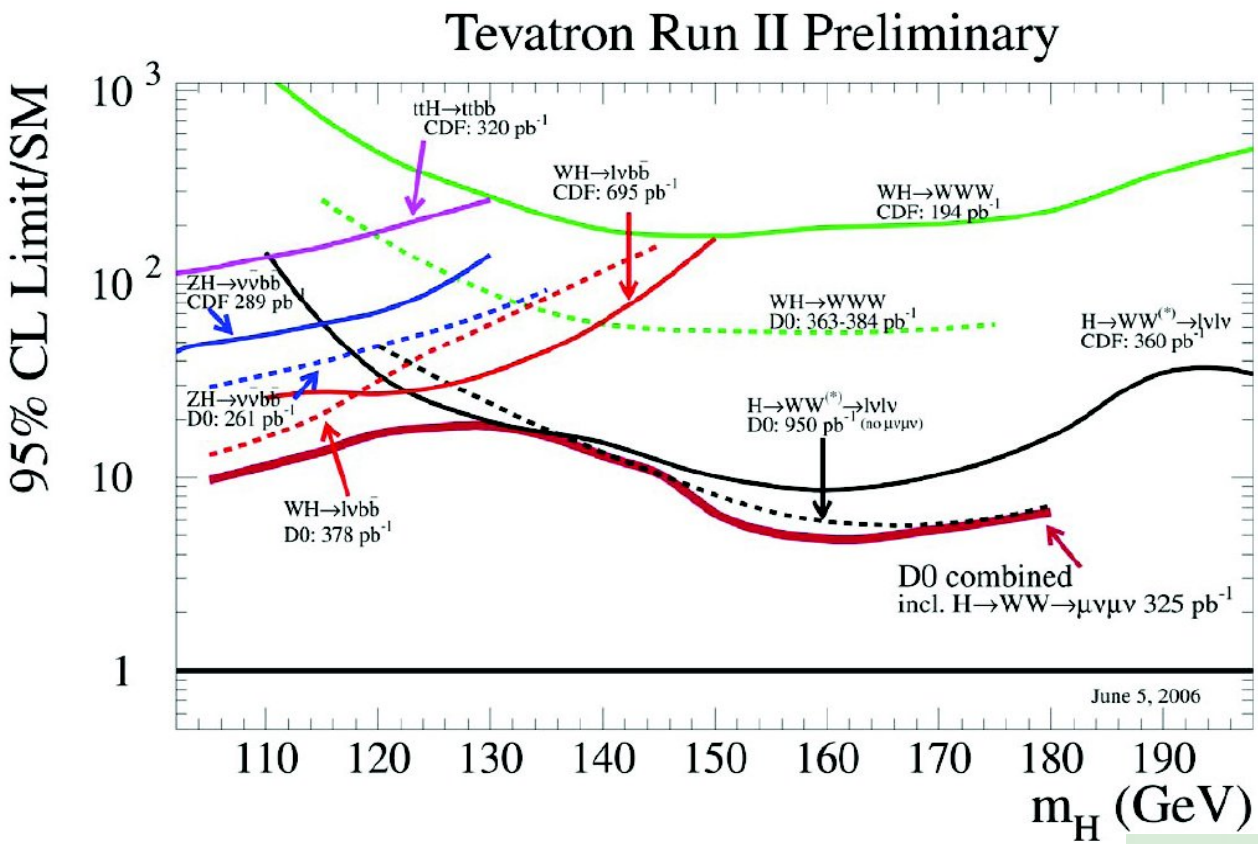
used to normalize HF fraction

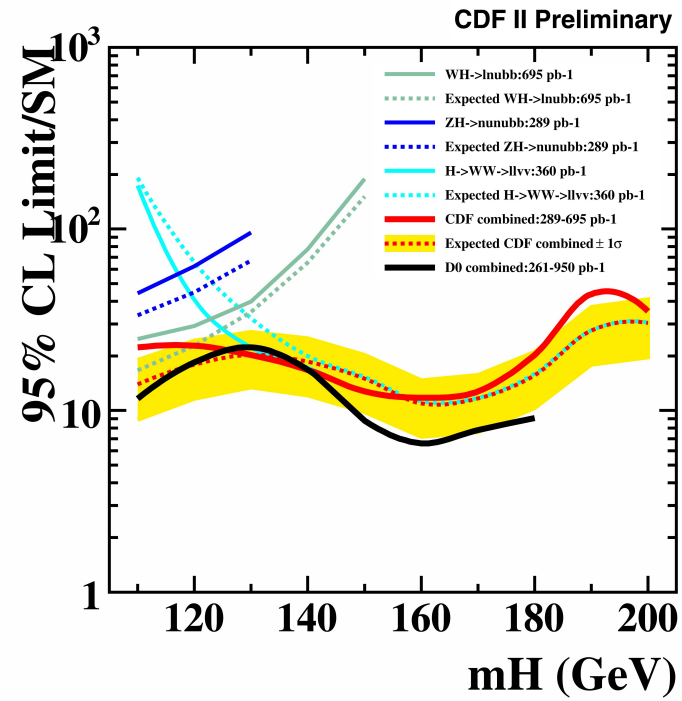
signal region

For $M_H = 115\ \mathrm{GeV}/c^2, \sigma(p\bar{p} \to W^{\pm}H) \times B(H \to b\bar{b}) < 3.6\ \mathrm{pb}$

(20% increased sensitivity by combining 1+2 tagged samples instead of ≥1 tag)

SM Higgs Combination





New: DØ combination of 14 channels, for the first time all major search channels put together

Brand New: CDF combination

Goal: 95% CL for a 115 GeV Higgs with 2 fb^{-1} combining both experiments

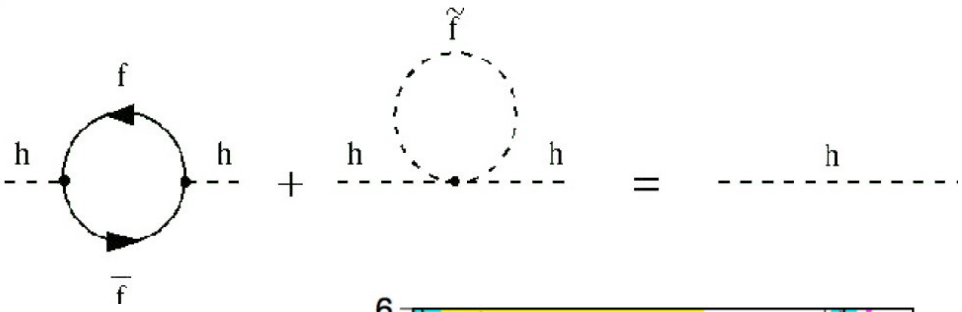
To Do

- Analysis techniques and improved b-tagging (NN)
- Improved calorimeter calibration
- Reduced Jet Energy Scale uncertainty
- More efficient and precise object ID
- Reduced backgrounds (better dijet mass resolution, cal-track-jets)
- More data, combine experiments

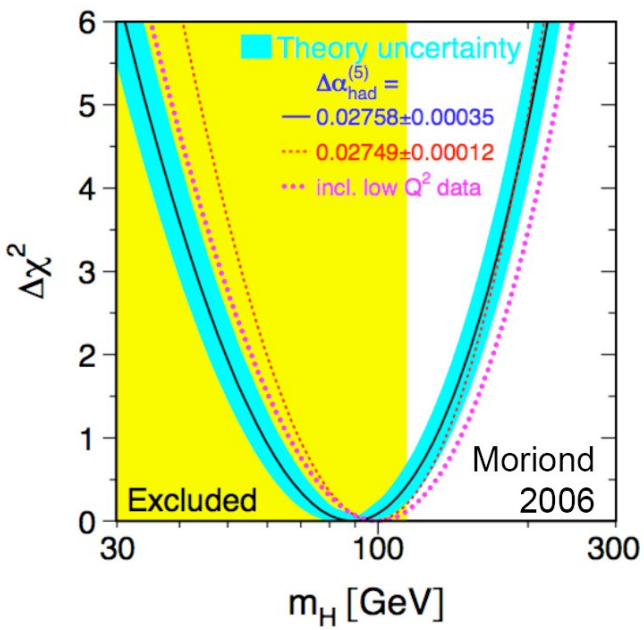
Supersymmetry

Supersymmetry

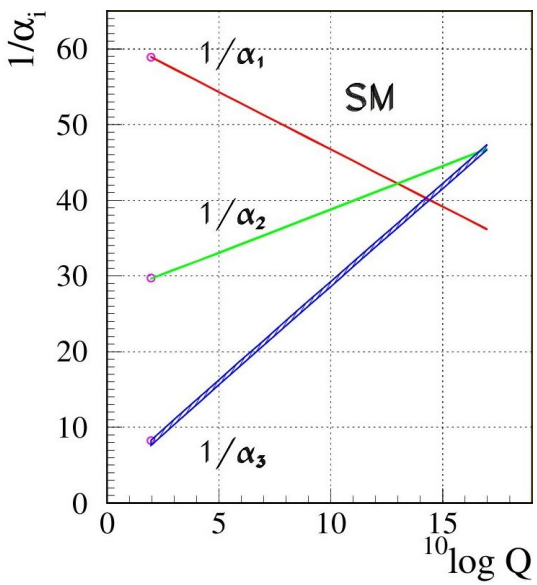
- Supersymmetry (SUSY): fundamental symmetry, relating Bosons and Fermions
- Stabilizing Higgs mass ("fine-tuning")
  - m(Higgs) $\lesssim$ 135 GeV (MSSM)
  - In good agreement with expectations from EW fits

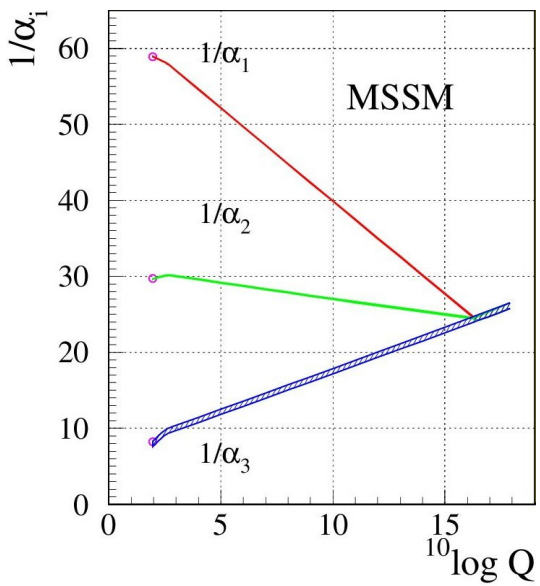


- "Running" of couplings is sufficiently modified to allow Grand Unification at a single scale



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





http://www-ekp.physik.uni-karlsruhe.de/~deboer/

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

Supersymmetry – Signatures

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 $\tilde{\chi}^\pm, \tilde{\chi}^0$			

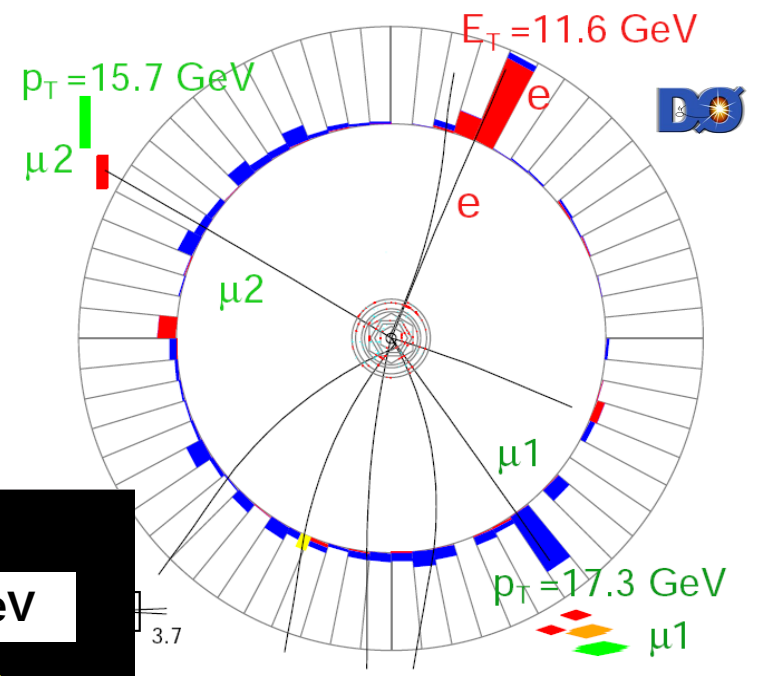
- LEP searches for charginos, sleptons, higgs: $m(\tilde{\chi}^\pm)>103.5$ GeV, $m(\tilde{l})>95$ GeV, $m(h)>114.4$ GeV
- **Signatures depend on model assumptions** (e.g. MSSM: > 100 parameters)
  - R-parity conservation: $\not{E}_T$ **due to undetected LSP**

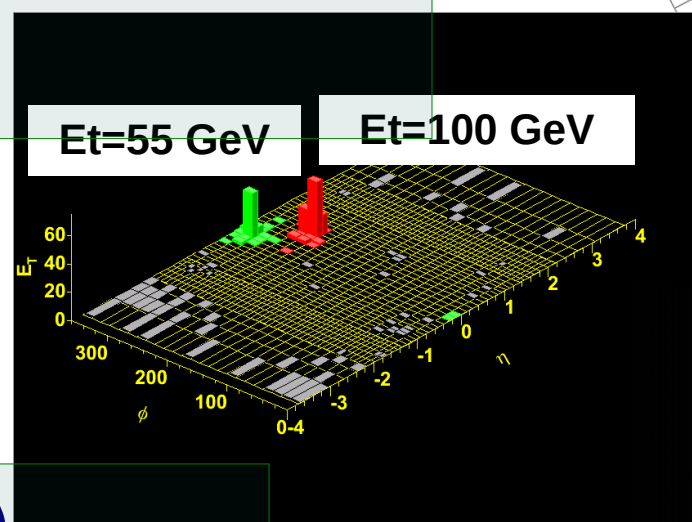
    R-Parity $R_p =$ **+ 1 SM**, **– 1 SUSY**
  - Different models for SUSY breaking mechanism have various phenomenological consequences: **jets, leptons, photons, long-lived particles**
- **Benchmark-Scenarios** allow systematic study of supersymmetric models with realistic effort, simultaneously incorporating experimental and theoretical bounds (e.g. "Snowmass Points and Slopes")

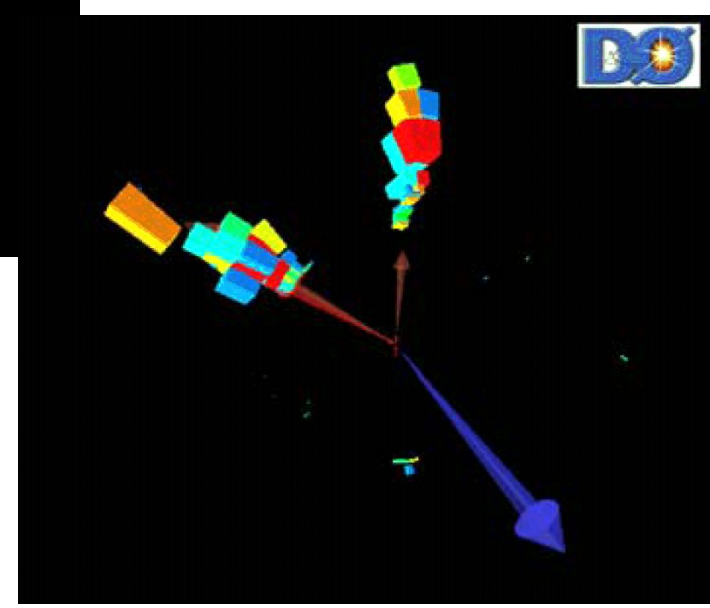
Supersymmetry – Signatures

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

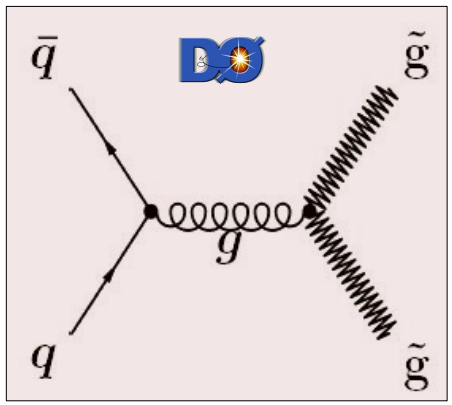
and/or many leptons from cascade decays

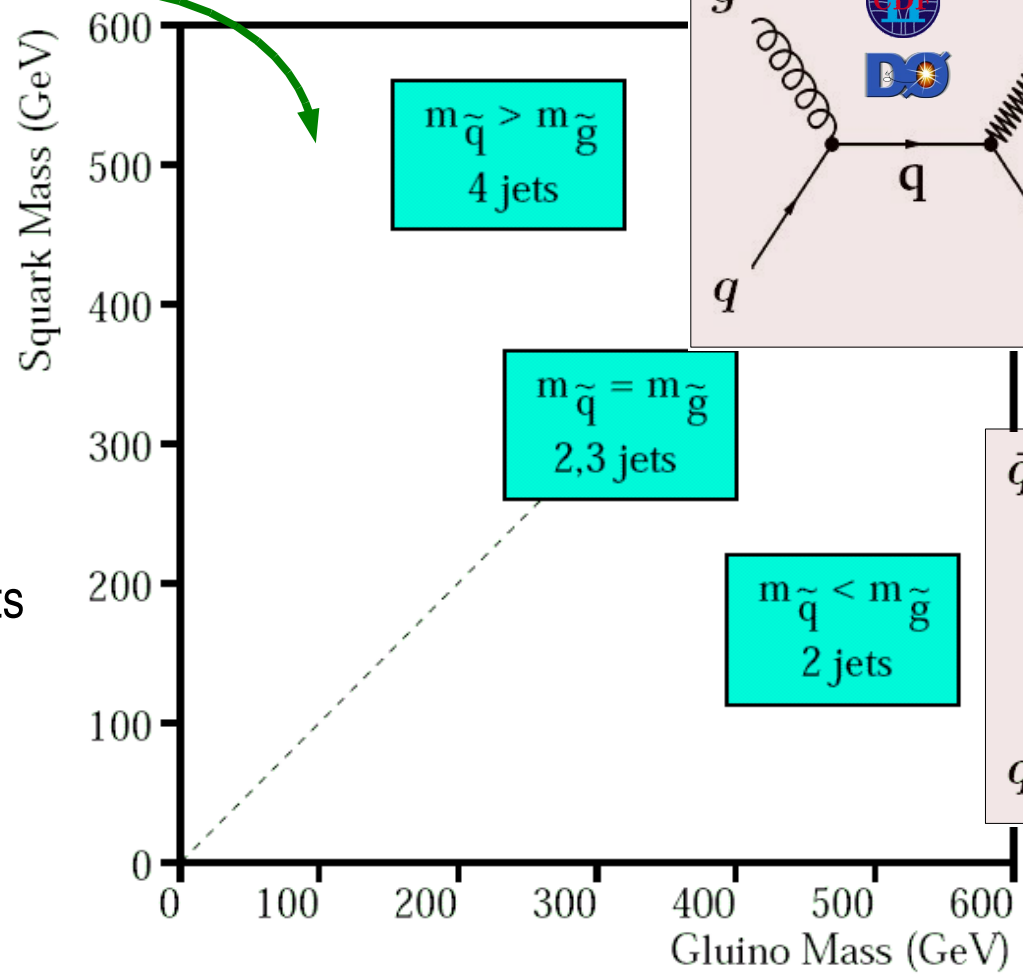
(but: can be soft)

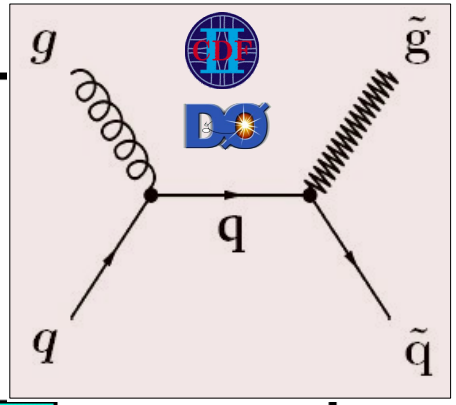
$\not{E}_T$ = 354 GeV

Squarks and Gluinos

- $p\bar{p}$ collider: production of squarks / gluinos through strong interaction → **large cross section**
- LSP assumed stable (R_p conserved) → signature: **Jets + $\not{E}_T$**
- DØ: $\int L\,dt = 310\ pb^{-1}$, CDF: $\int L\,dt = 371\ pb^{-1}$

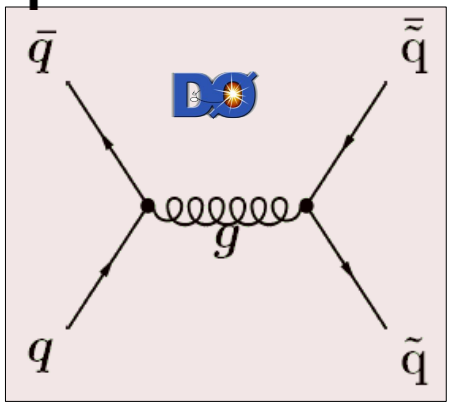






$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$

$\tilde{q} \rightarrow q\tilde{\chi}_1^0$



2 / 3 / 4 jets + large $\not{E}_T$

Separation between $\not{E}_T$ and jets

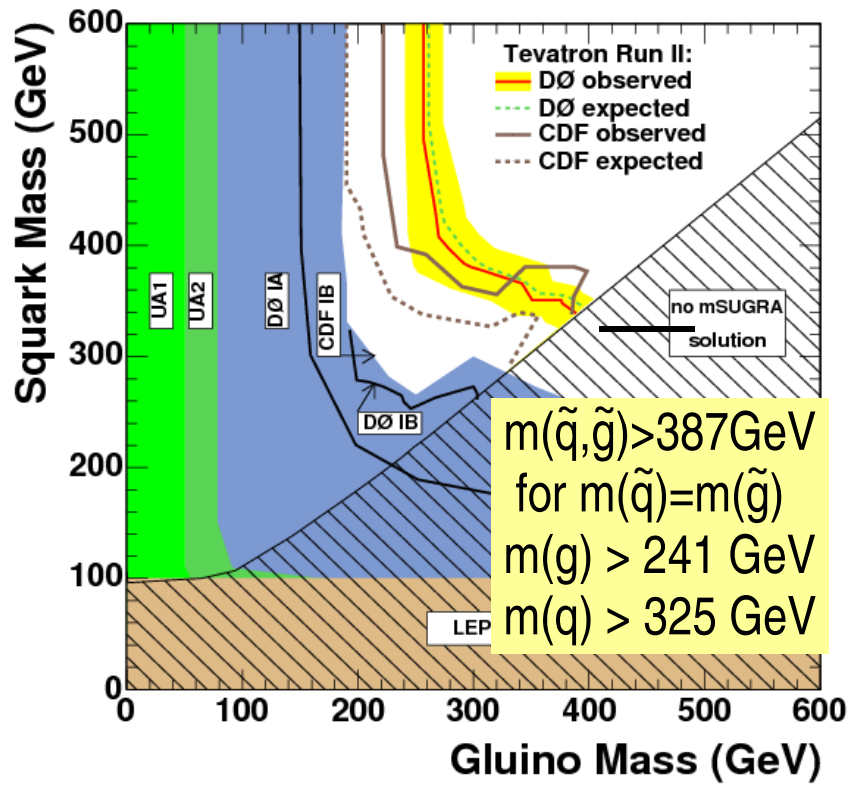
Veto isolated leptons

Missing E_T

H_T = sum of jets p_T

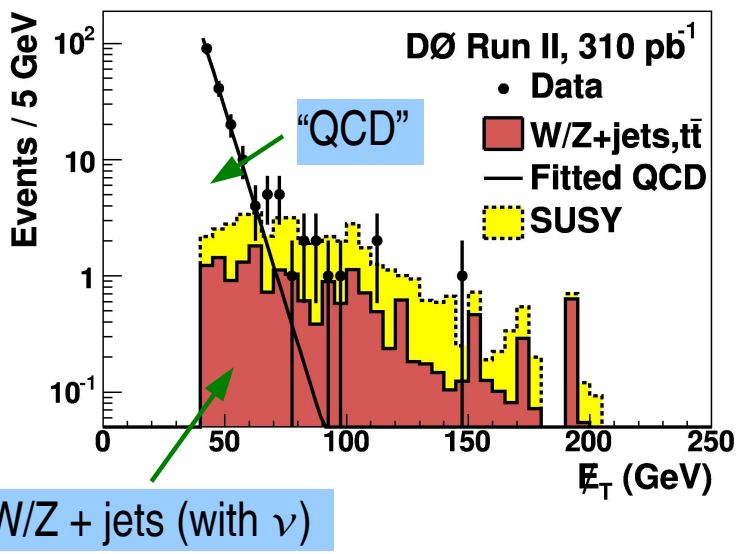
Squarks and Gluinos

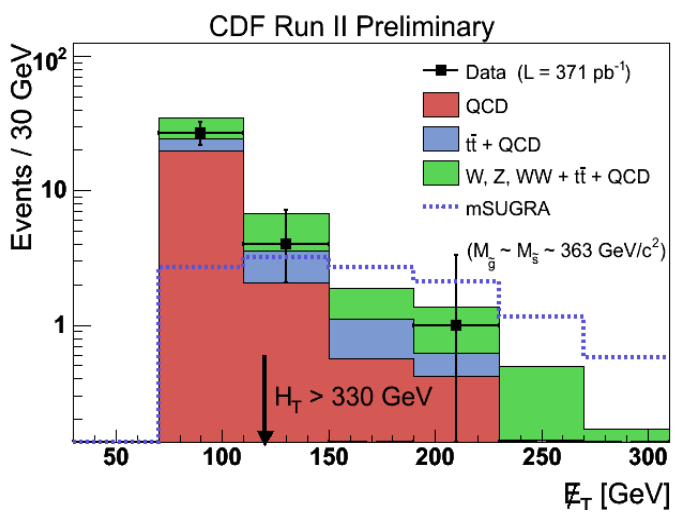
Analyses	Background expected	Events observed
DØ ≥ 2 jets	4.8 ± 4.5	6
DØ ≥ 3 jets	3.9 ± 1.5	4
CDF ≥ 3 jets	8.2 ± 2.9	2
DØ ≥ 4 jets	10.3 ± 2.4	10



mSUGRA: $\tan\beta$=3 (5), A_0=0, μ<0

"Gluino"-analysis before final selection





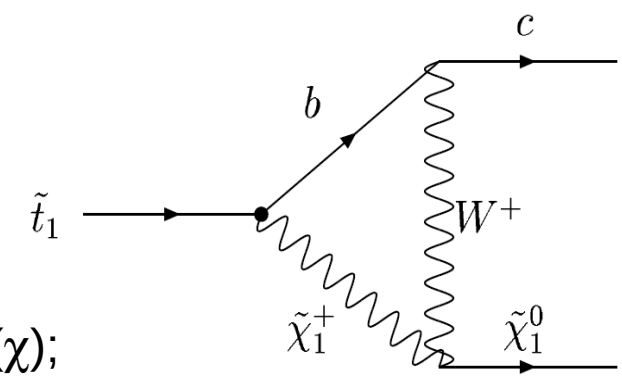
(Note CDF and DØ treat theoretical uncertainties differently)

Stop in charm + Neutralino

- Third generation is "special"
  - Large left-right mixing e.g. ~ m(top)
  - Stop could be the lightest squark
- First scenario:

  stop NLSP and χ LSP with stop $\rightarrow$ c χ

  (relevant as long as m(stop) < m(b) + m(W) + m(χ);
  in SUGRA, needs $M_1 < M_2$ at GUT scale)

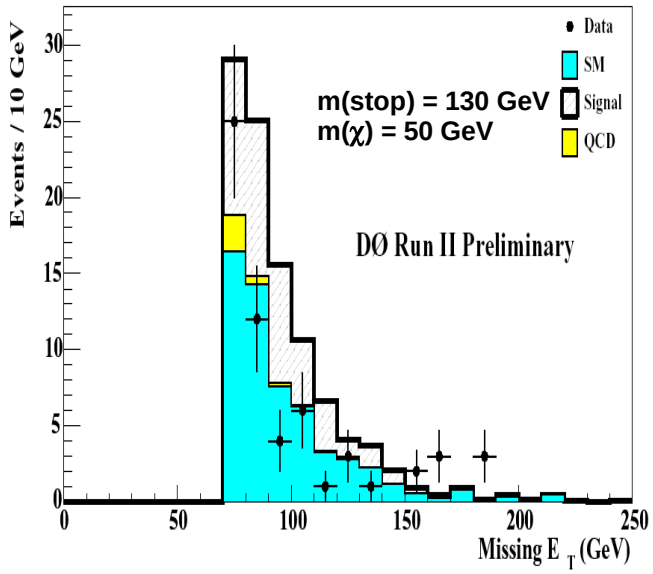


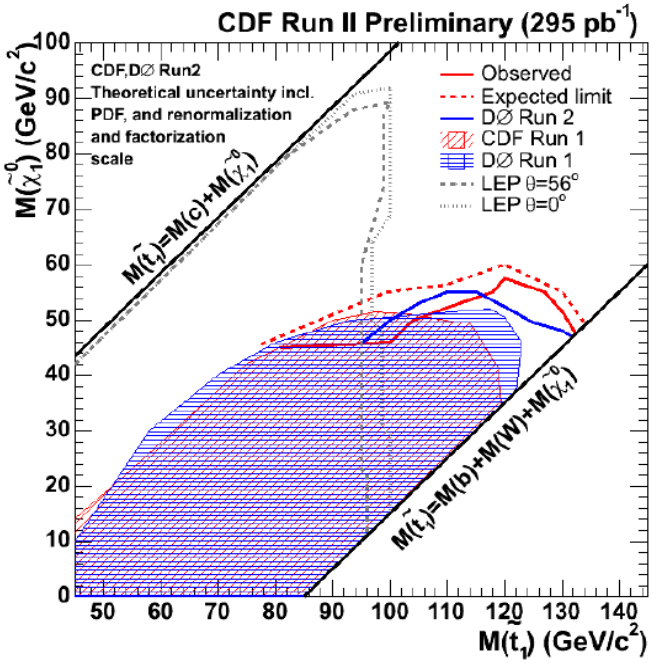
Stop pair production:

- **2 acoplanar jets**
  $\geq$ 1 c-jet (soft tag)
- **Missing E_T**

(cuts optimized for various m(stop),m(χ))

Main backgrounds: **W/Z+jets**

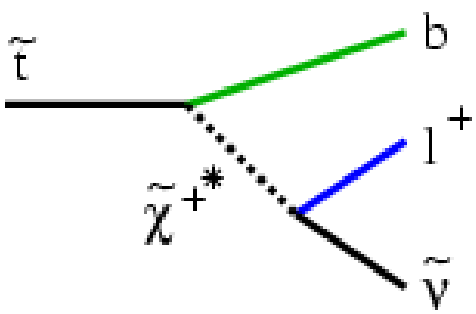




Stop in b $l\,\tilde{\nu}$ ($\mu\mu$+eμ)

For certain parameter choices, most promising decay is

b + lepton + sneutrino



Stop pair production:

Two isolated leptons,

missing E_T,

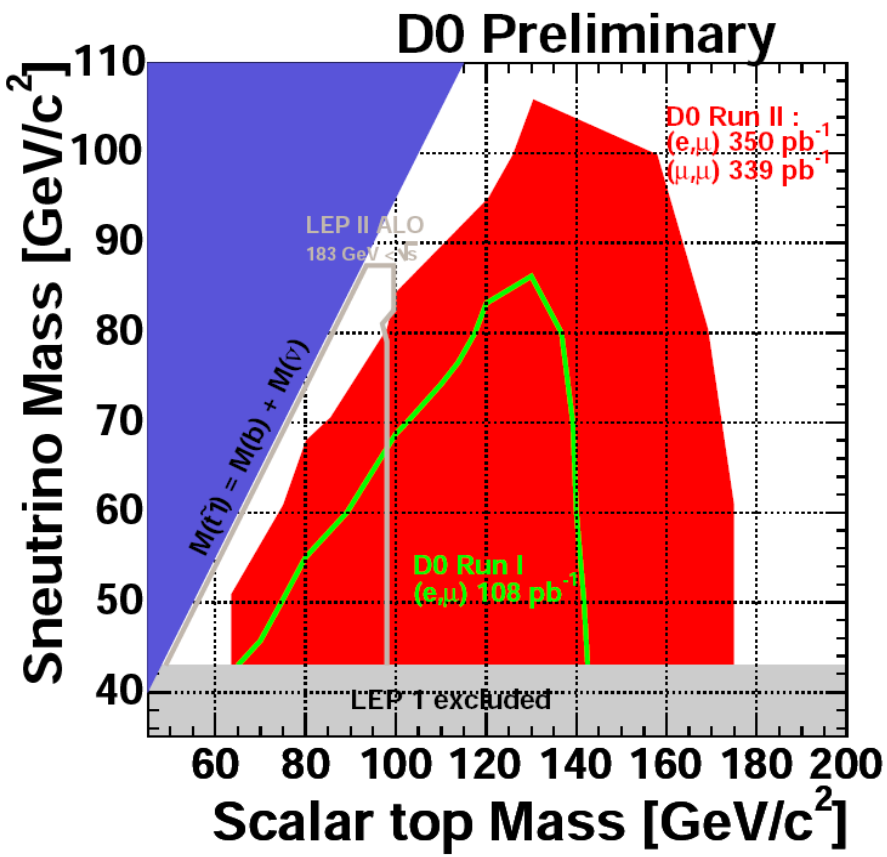
two b-jets (can be soft)

Single loose b-tag ($\mu\mu$)

or number of isolated tracks (eμ) instead of identified b-jets (higher efficiency, reduced systematics)

Optimization depending on $\Delta M = M(\tilde{t}) - M(\tilde{\nu})$

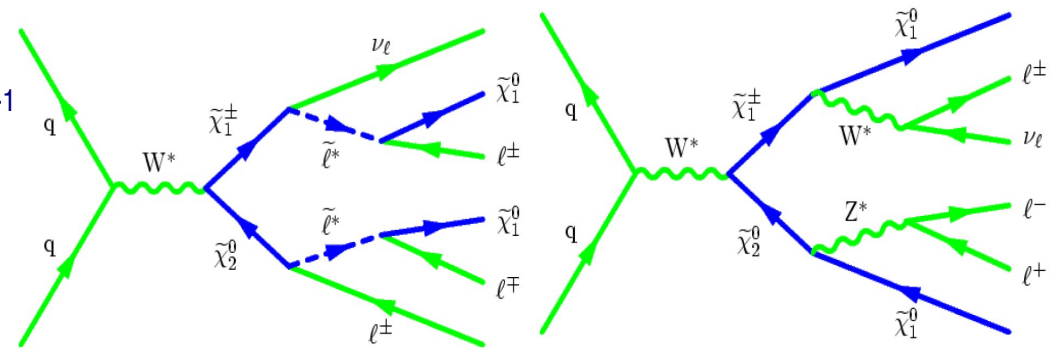
tanβ=20, μ>0



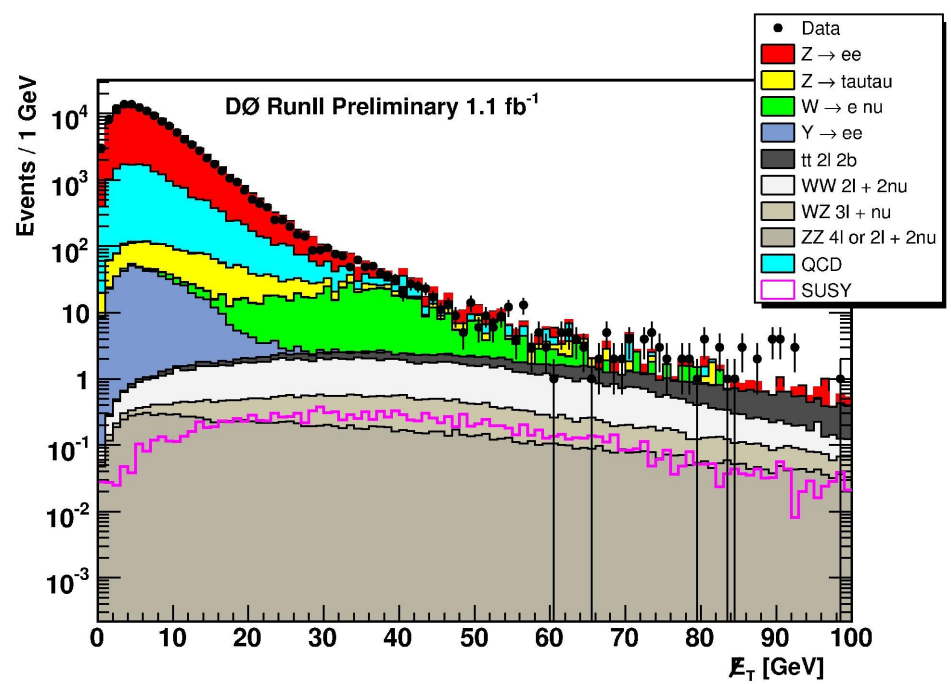
Combination of eμ and $\mu\mu$

Charginos / Neutralinos

- **"Golden channel"**: Cascade decays involving leptons → **three charged leptons + $\not{E}_T$**
- **But:** small event rate (σ x BF < 0.5pb), soft leptons
- **12 analyses (6 / exp.)**, $\int L\,dt \simeq$ 0.3-1.1 fb^{-1}
  - ee, eμ, $\mu\mu$ + 3rd lepton or track
  - LS dileptons
  - eτ + track, $\mu\tau$ + track (interesting at large tan β → light stau → many tau leptons)



- **Selection:**
  - Three leptons (ll + track), p_T > 3 GeV (or higher depending on channel)
  - Missing transverse energy
  - Veto events with Z → ll decays
- Backgrounds
  - Multijet events with misidentified leptons
  - Drell-Yan, Z-production with Z → ll
  - Di-boson

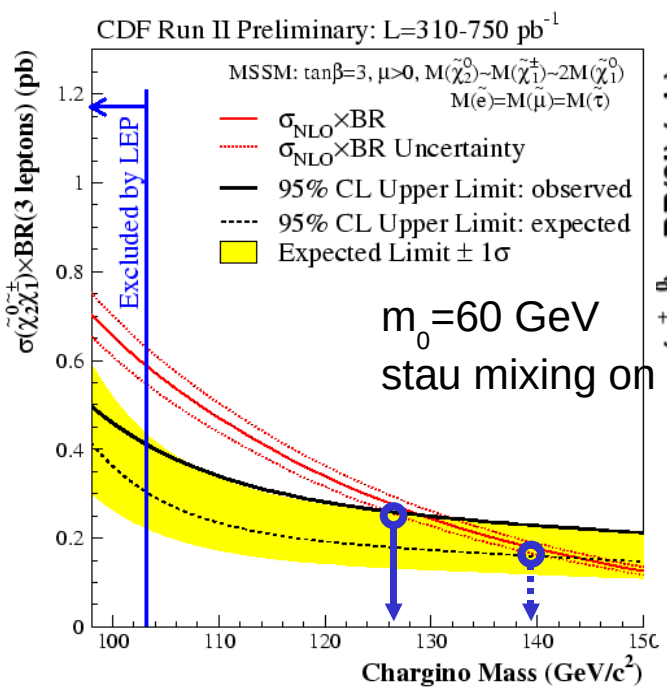


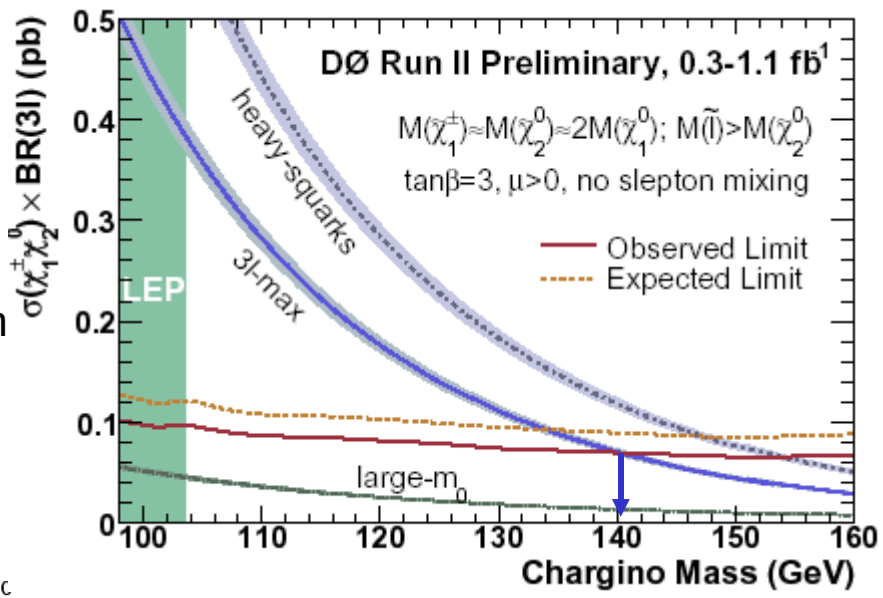
Charginos / Neutralinos: Combination

Tevatron
mSUGRA

CDF Analysis	Lumi (pb^{-1})	Total predicted Background	Observd data
$e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$	710	6.80±1.00	9
μμ +e/μ (low-p_T)	310	0.13±0.03	0
ee+track	610	0.48±0.07	1
ee + e/μ	350	0.17±0.05	0
μμ +e/μ	750	0.64±0.18	1
μe +e/μ	750	0.78±0.15	0

DØ Analysis	Lumi (fb^{-1})	Total predicted Background	Observd data
ee+track	1.1	0.82±0.66	0
μμ+track	0.3	1.75±0.57	2
eμ+track	0.3	0.31±0.13	0
SS μμ	0.9	1.1 ± 0.4	1
eτ+track	0.3	0.58±0.14	0
μτ+track	0.3	0.36±0.13	1



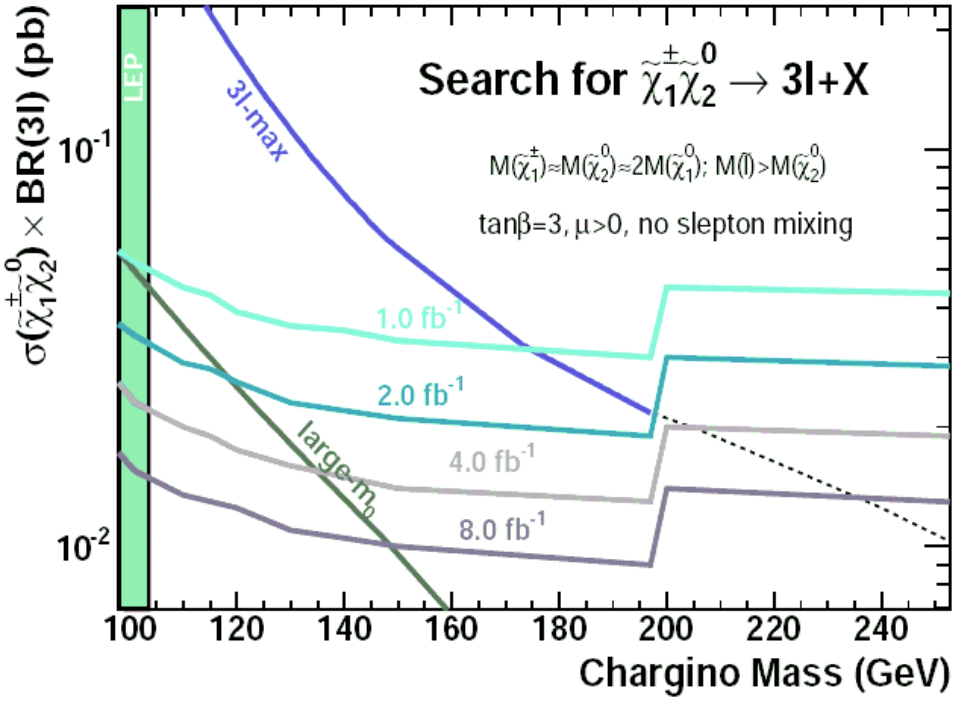


"3*l*-max": large leptonic BF (m(slepton) ≃ m($\tilde{\chi}_2^0$) → sfermion decays dominate)

"Large m_0": Decays via W*/Z* dominate → leptonic BF small

"Heavy squarks" (no mass unification): large cross section

Charginos / Neutralinos Outlook

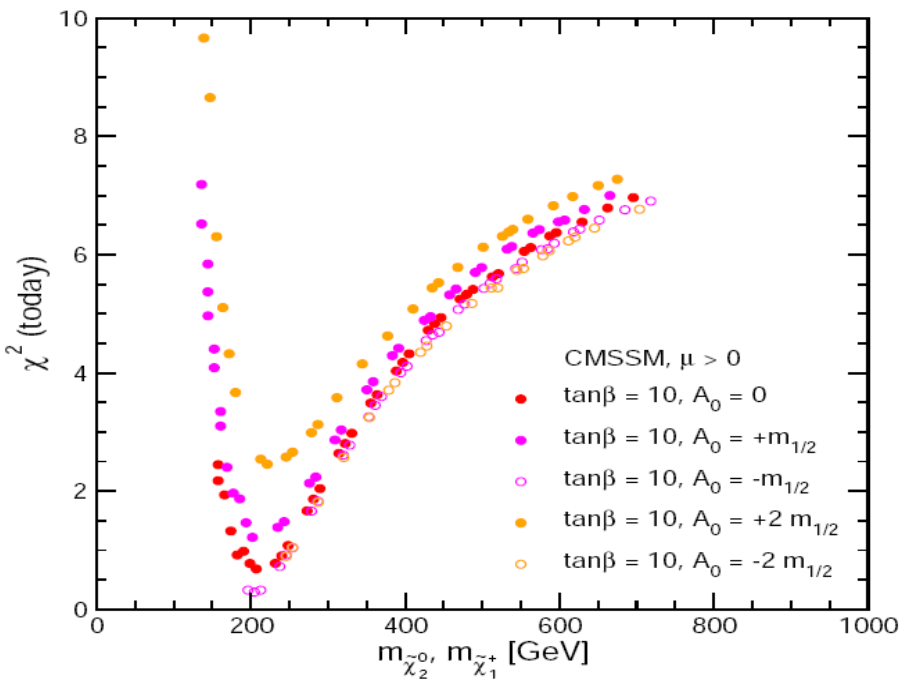


Expected sensitivity (Tevatron combined)

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

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

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



Ellis, Heinemeyer, Olive, Weiglein

R-Parity Violation

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

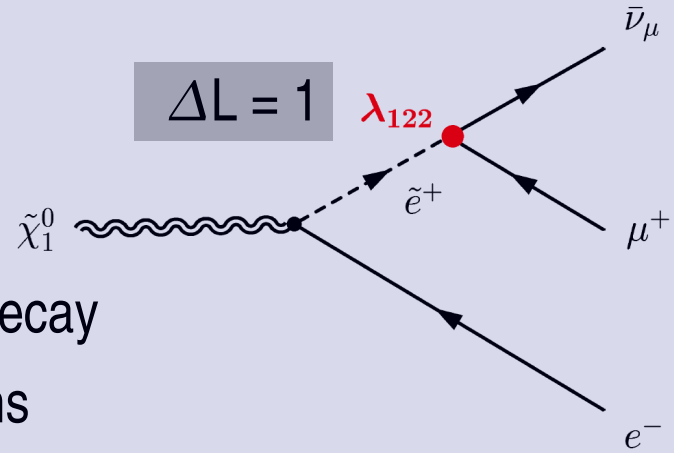
S Spin
B Baryon number
L Lepton number

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

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

λ_{ijk} (9)

$\Delta L = 1$

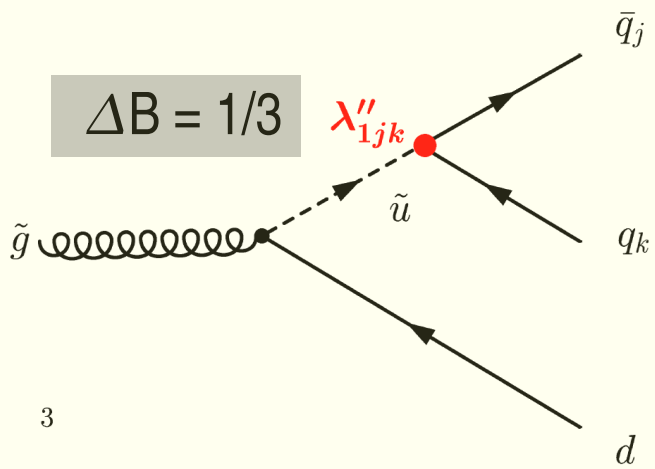


R_P violated in decay

Many leptons

λ''_{ijk} (9)

$\Delta B = 1/3$



Jets
Difficult at a hadron collider

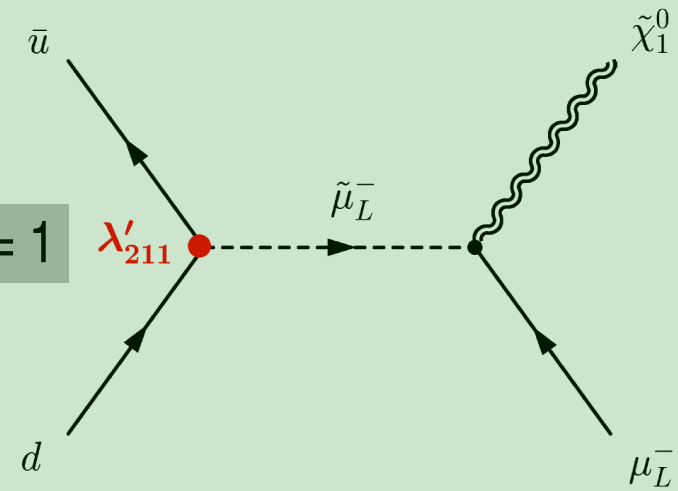
3

Resonant production

λ'_{ijk} (27)

Leptons and jets

$\Delta L = 1$

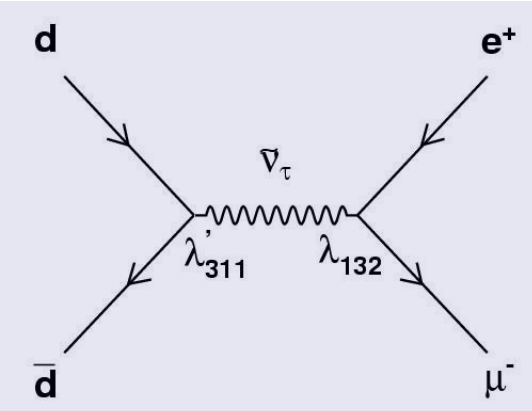


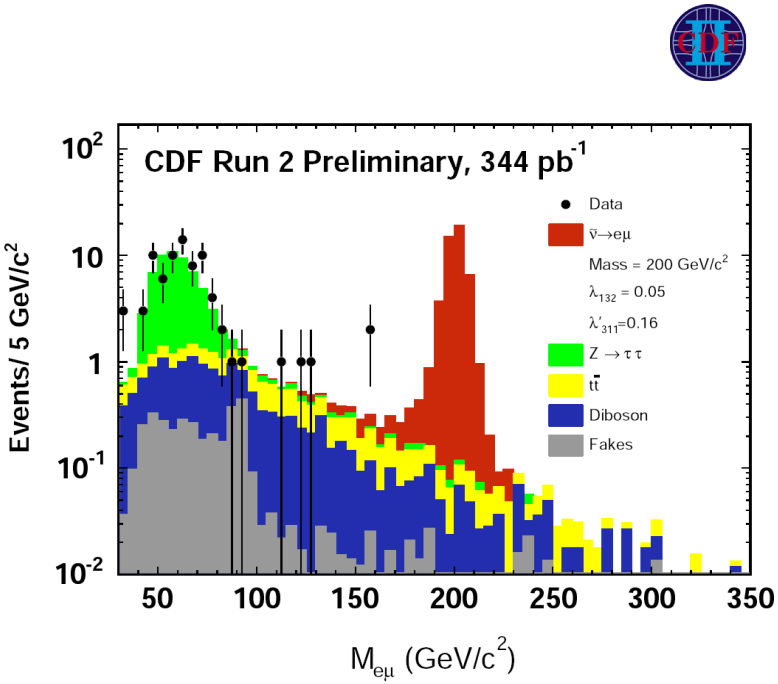
Experimentally and theoretically constrained (p decay etc.)

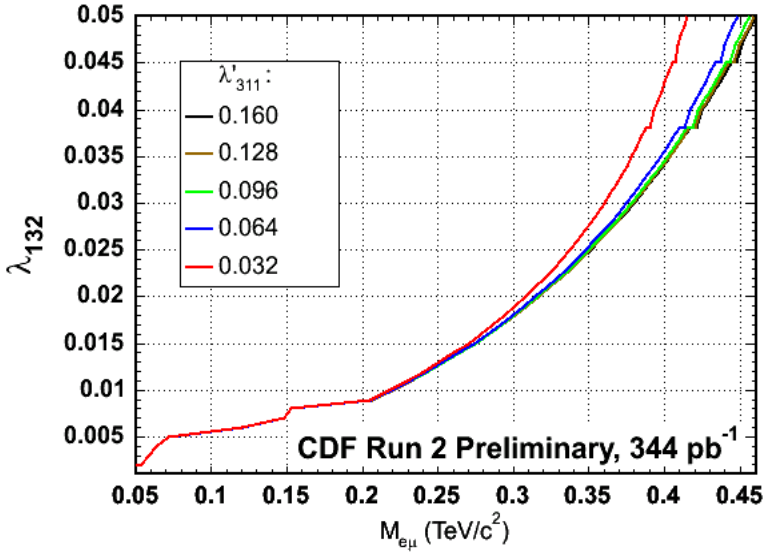
LSP no candidate for dark matter in RPV models

R-Parity Violation

- Analyses in mSUGRA inspired scenarios:
  - λ couplings well studied (final state similar to chargino / neutralino “Trileptons”)
  - λ' couplings: few Tevatron analyses; HERA terrain
- Strong constraints on more than one non-zero coupling, but interesting signatures:



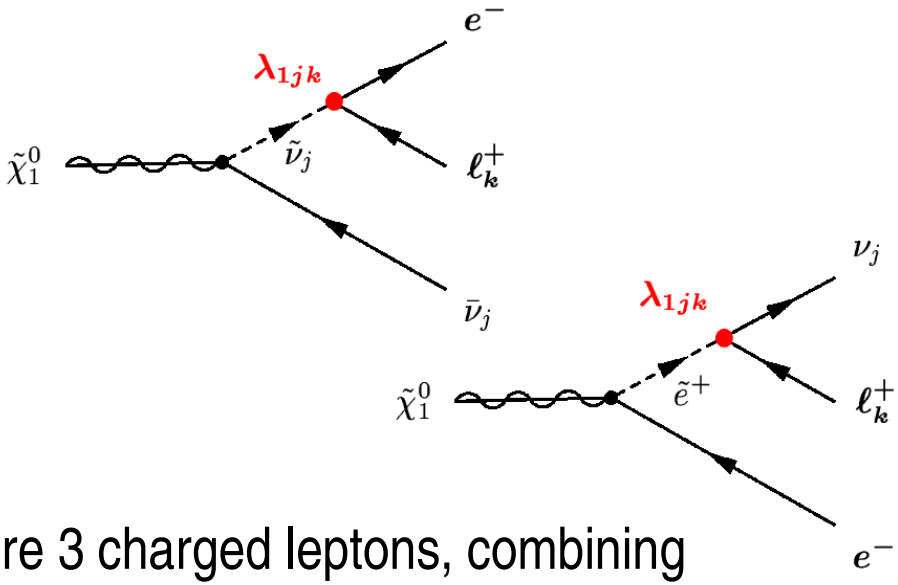


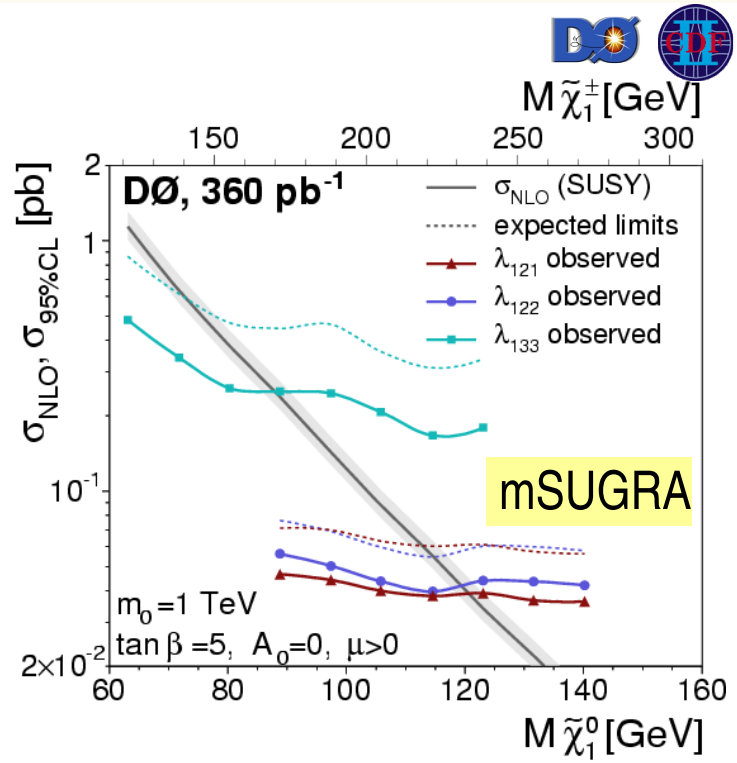


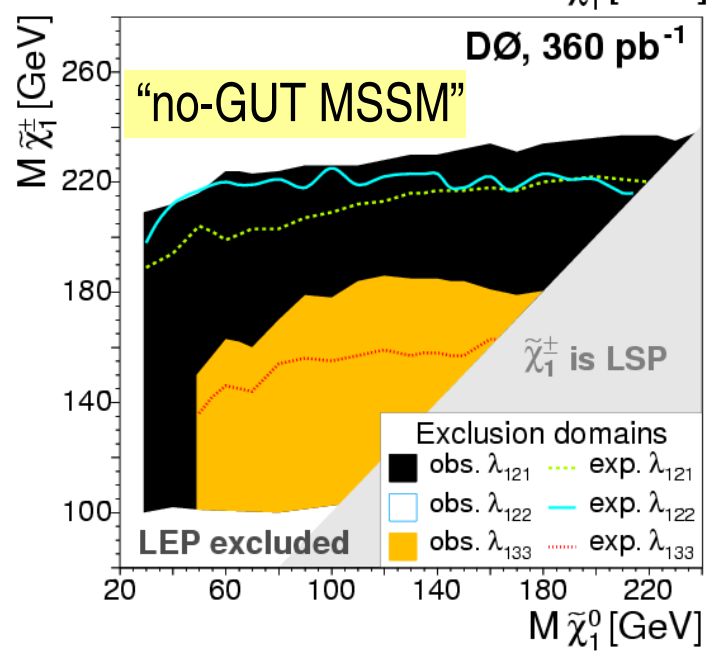
RPV: λ Couplings

RPC production of charginos and neutralinos

RPV in (prompt) **decay** through λ_{1jk} coupling leads to final state with 4 charged leptons







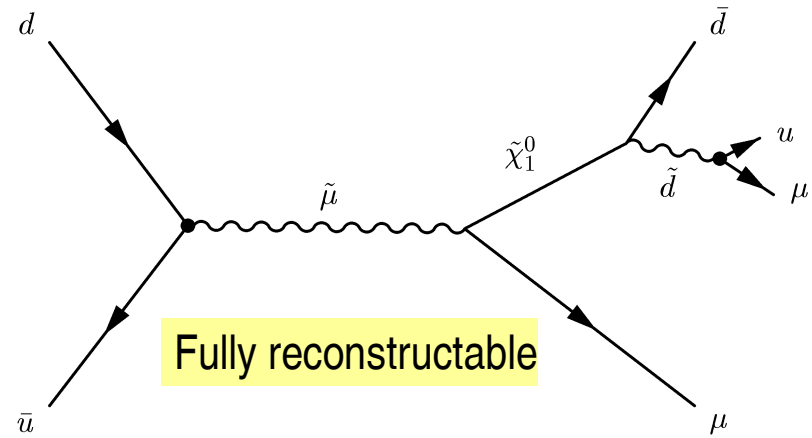
Analyses require 3 charged leptons, combining electrons, muons, taus
→ **sensitive to λ_{121}, λ_{122}, and λ_{133}**

In mSUGRA, exclude up to $m(\tilde{\chi}_1^0)$ = 119 GeV and $m(\tilde{\chi}^\pm)$ = 231 GeV (tan β=5, μ>0, m_0=1TeV, A_0=0)

RPV: λ´ Couplings @ Tevatron

RPV in production and decay

Non-zero λ'_{211} coupling →
resonant production of smuon and muon-sneutrino possible

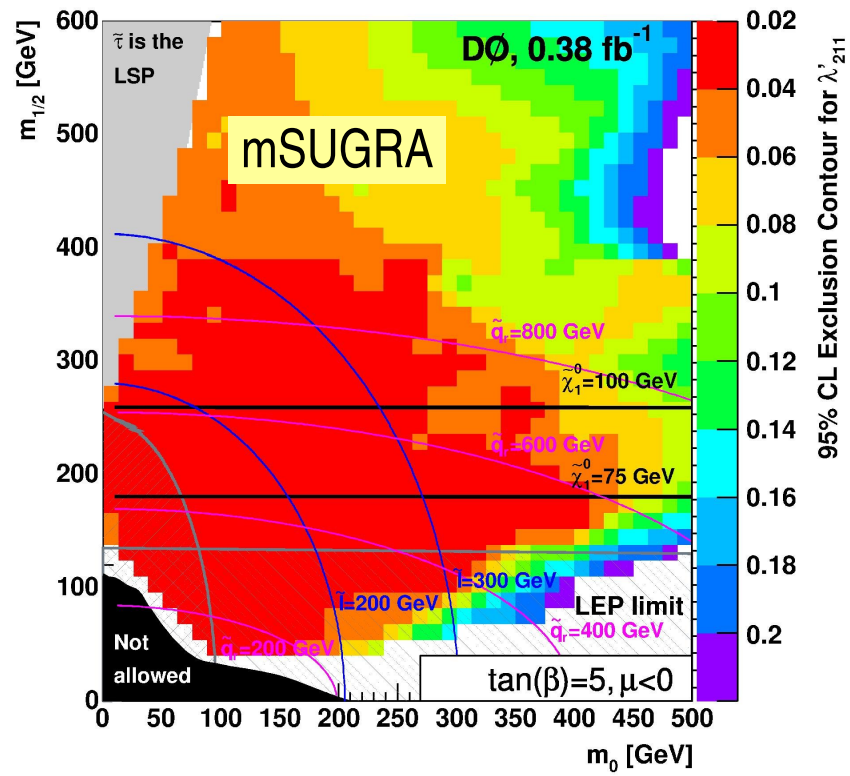


Analyses requires two muons and two jets

Combination of different channels

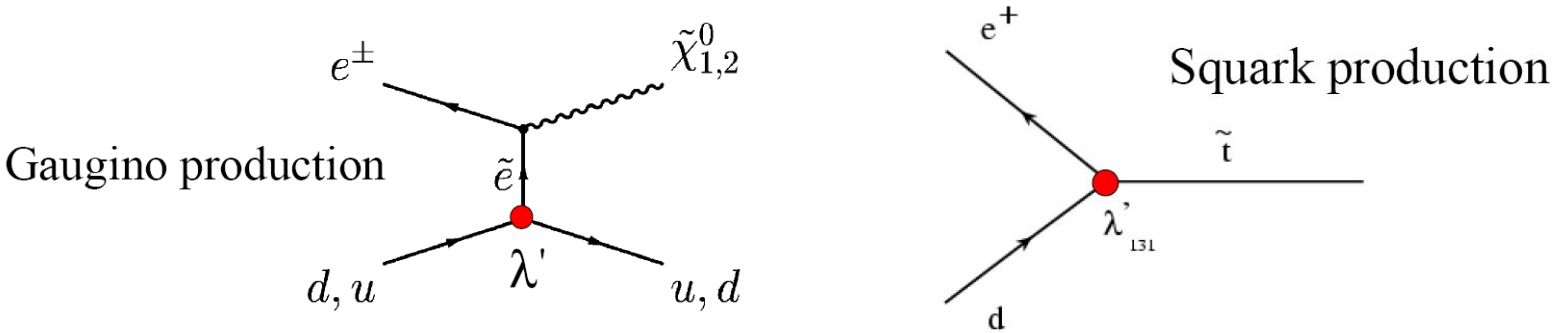
Interpretation within mSUGRA and model-independent cross section limits

Phenomenology becoming complicated...
- For reference point, this analysis excludes $\lambda' > 0.028$ (Run I: 0.09)
- For $\lambda'_{211} > 0.10$, exclude $m(\tilde{l}) < 363$ GeV



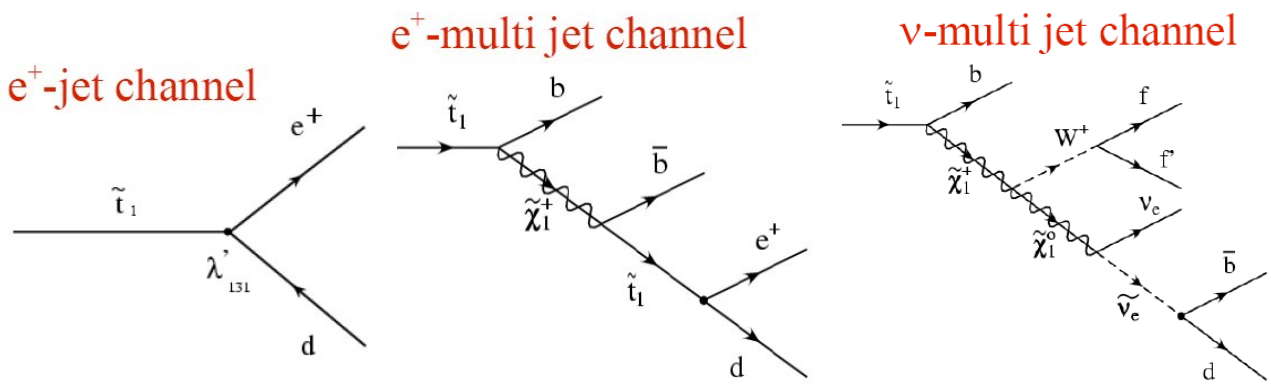
RPV: λ´ Couplings @ HERA

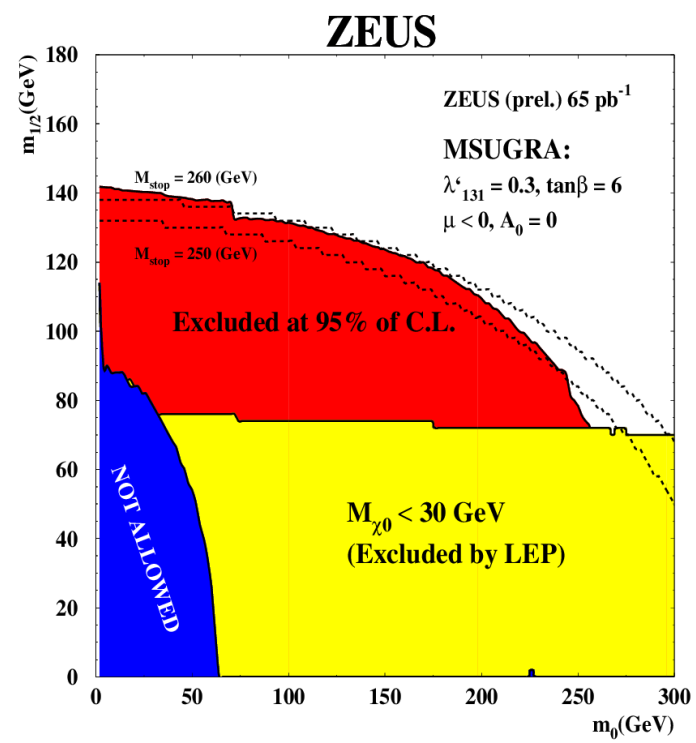
RPV: Single sparticle production



Example: new result with non-zero λ'_{131} coupling → stop production

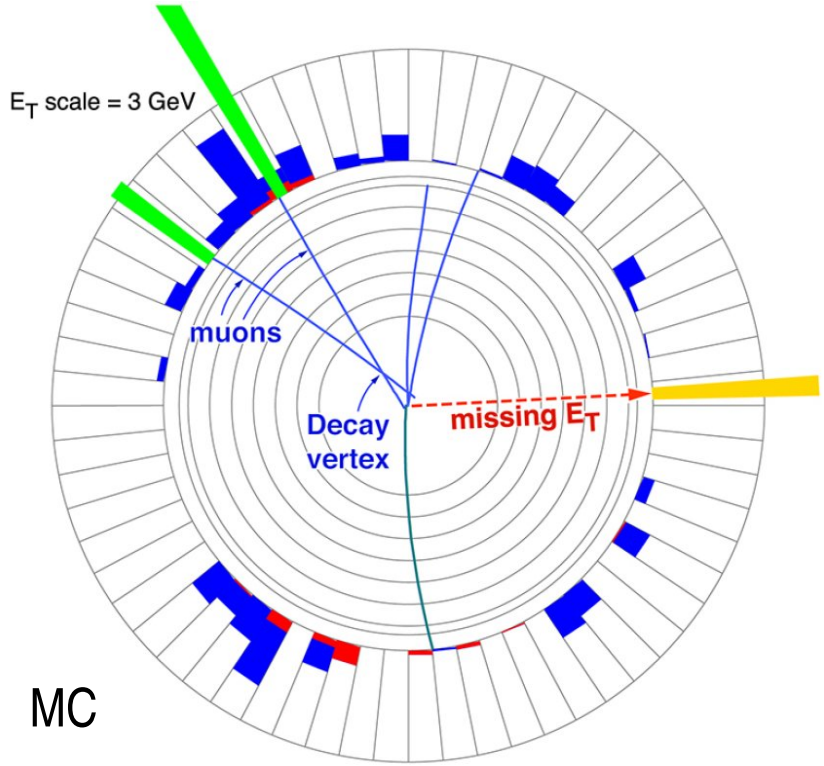
Combination of three channels





mSUGRA interpretation

Neutral Long-Lived Particles

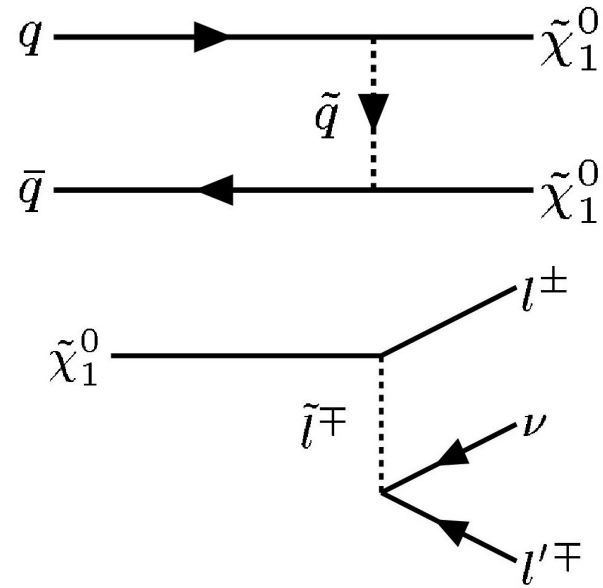


MC

Pair production of heavy neutral particles

Mass O(GeV)
$c\tau$ O(cm)

e.g. MSSM with RPV



M_1= 3,5,8,10 GeV, M_2=200 GeV, M_3=400 GeV
$\tan\beta$=10, μ=-5000
λ_{122}<1.0, $M_{\tilde{b},\tilde{t}}$=1500 GeV, $M_{\tilde{q}}$=300 GeV

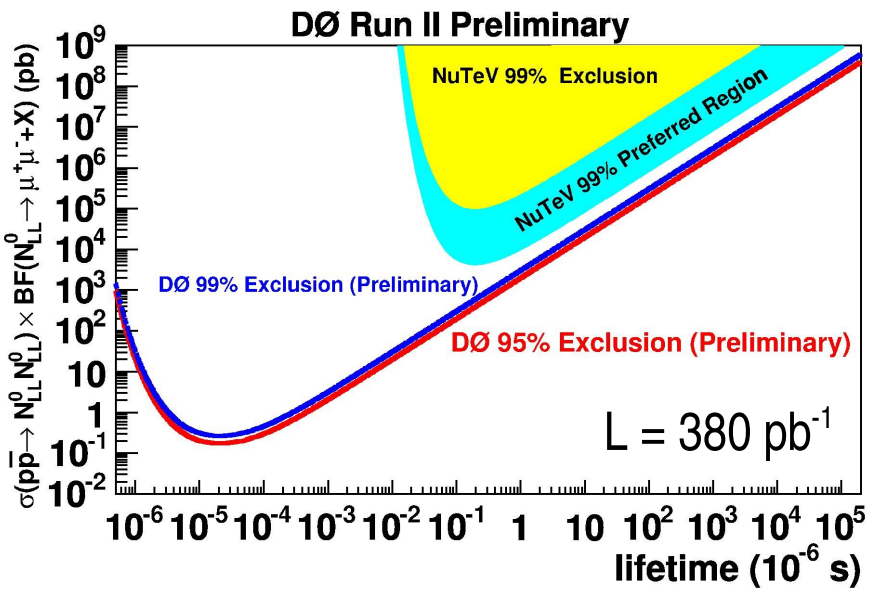
2 isolated muons, p_T > 10 GeV

Vertex with 5 < r < 20 cm

Cuts on dca of muons

N(data) = 0

N(backgr.) = 0.8 ± 1.1 ± 1.1



Inspired by 3 unexpected NuTeV di-muon events

Also: "Hidden Valley" models, NMSSM, ...

Charged Massive Stable Particles

Massive stable particles are predicted in many models

E.g.: **pair production of stable staus** (Gauge-mediated SUSY breaking with stau as NLSP) [Model Line "D" from Snowmass 2001]

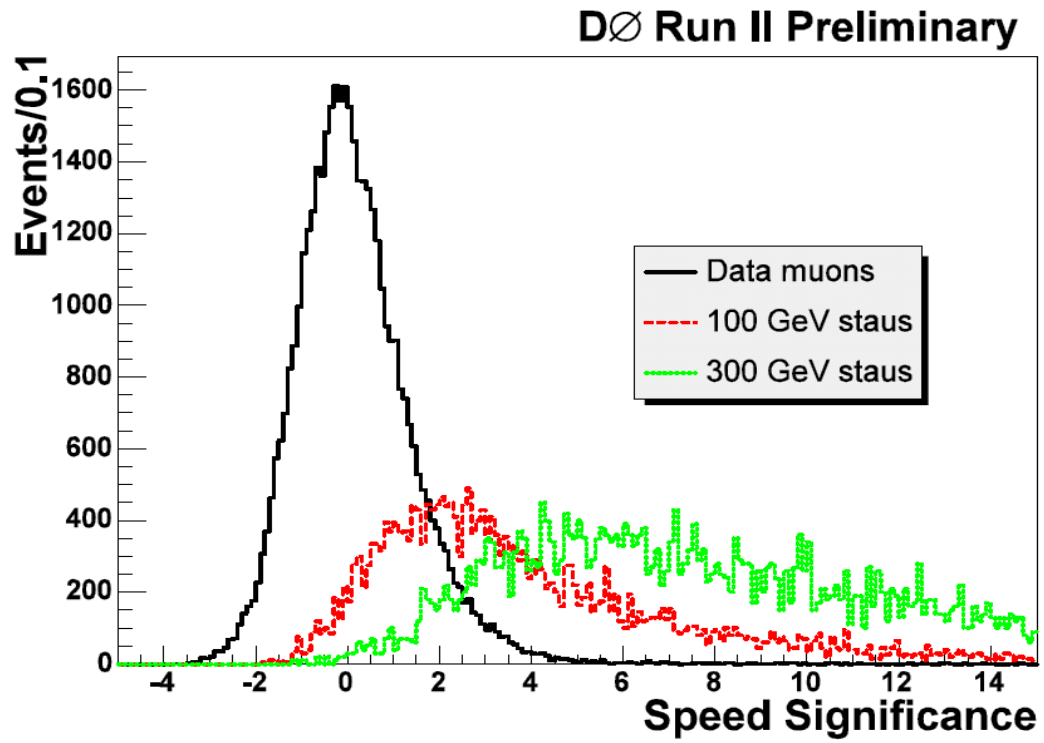
"Stable" = lifetime sufficiently long enough to leave the detector undecayed

Signature: "Muon", but with speed < c and large mass

Selection:

- Di-muon data
- Timing in muon system to identify slow moving particles
- Kinematic cuts against $Z \rightarrow \mu\mu$ with badly reconstructed flight time

Energy loss not (yet) used; CDF: TOF



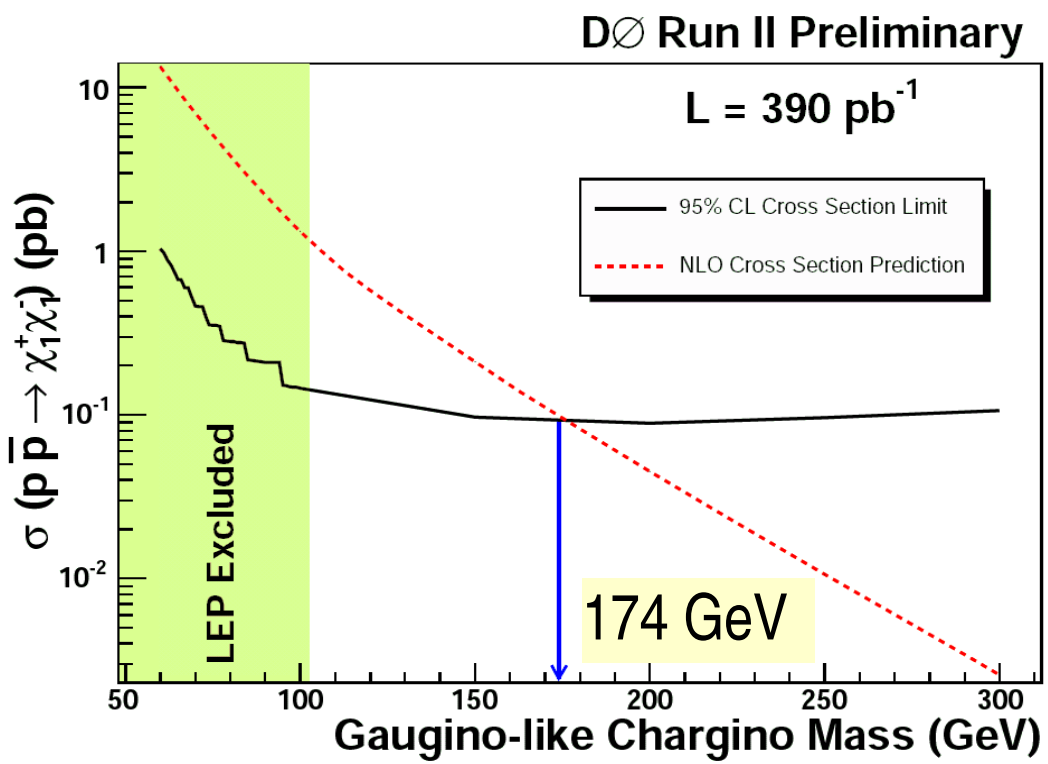
$$\text{speed significance} = \frac{1 - \text{speed}}{\sigma_{\text{speed}}}$$

Charged Massive Stable Particles

No events found in $\int L\,dt = 390\ pb^{-1}$, 0.66 ± 0.06 expected background

Limit for stau production: sensitivity not yet sufficient

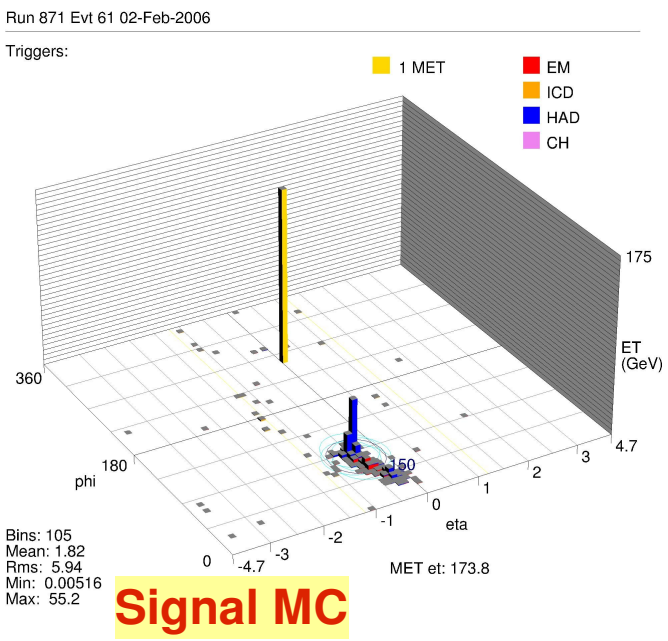
<u>Alternative interpretation:</u>
The lightest chargino can be sufficiently long-lived, if the mass splitting to the lightest neutralino is smaller than ~ 150 MeV (e.g. Anomaly-Mediated SUSY Breaking)

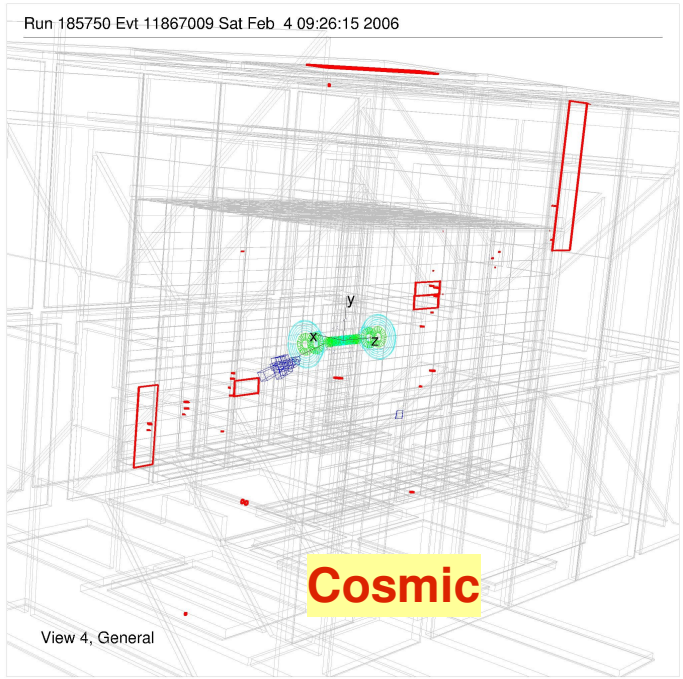


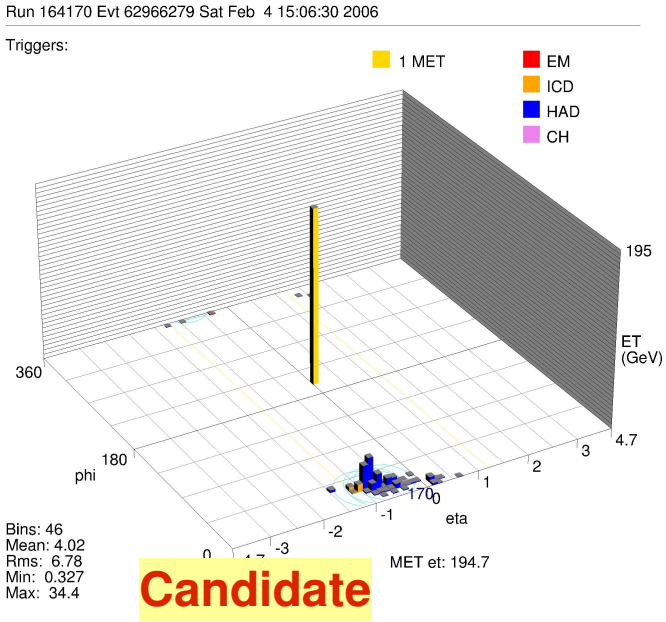
“Stopping Gluinos”

- Gluinos hadronize into *R-hadrons*. Charged R-hadrons can lose all their kinetic energy through ionization and come to rest. See hep-ph/0506242 (“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
- DØ analysis:
  - Exactly one central, “broad” jet with E_T > 90 GeV
  - “Rapidity gap” trigger, as veto against $p\bar{p}$ interaction
  - No primary vertex, veto against muons

Challenging







“Stopping Gluinos”

Backgrounds (a selection):

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

Additional difficulties:

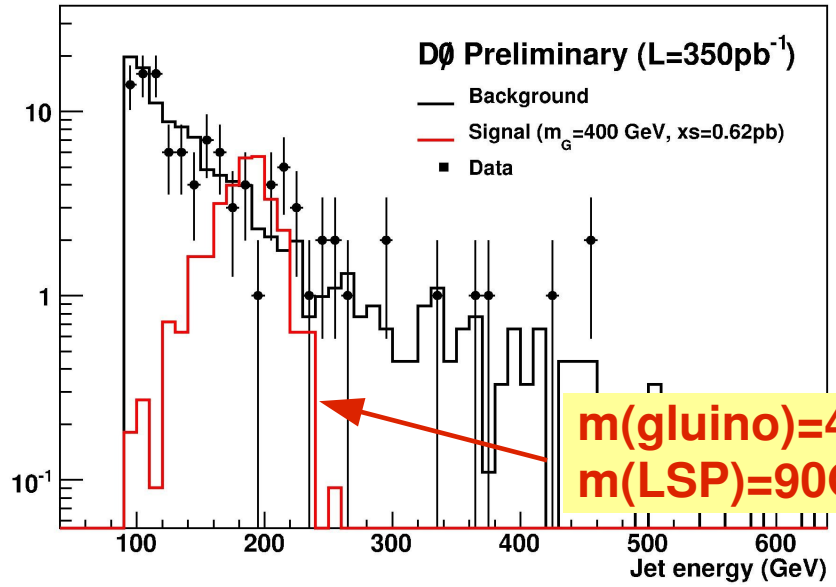
– Energy depositions are out-of-time relative to bunch crossing (→ signal shaping and discrimination)

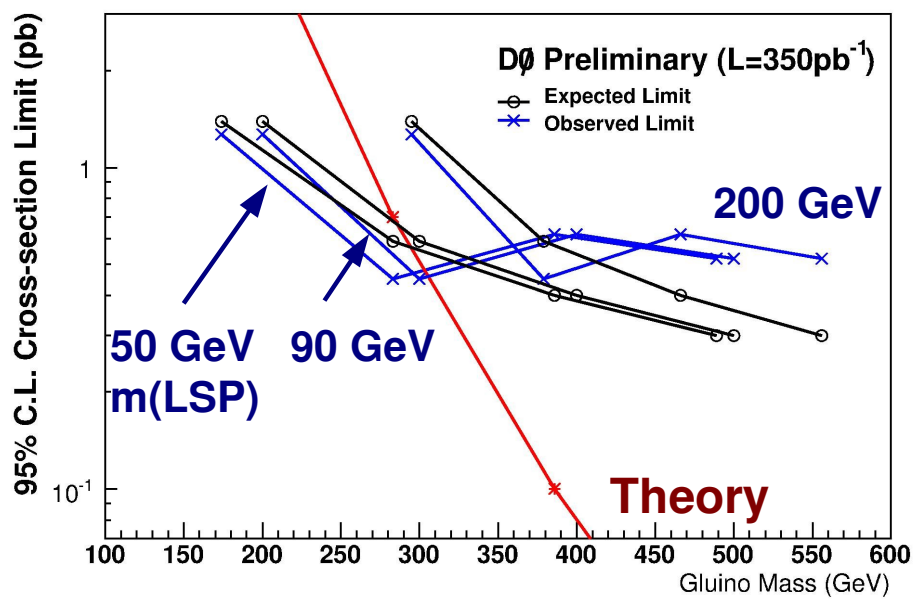
– Trigger

Data compatible with background expectation

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

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





Gauge Mediated SUSY Breaking

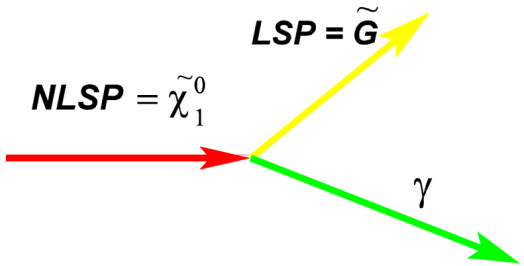
Gauge Mediated SUSY Breaking: Gravitino $\tilde{G}$ is LSP

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

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

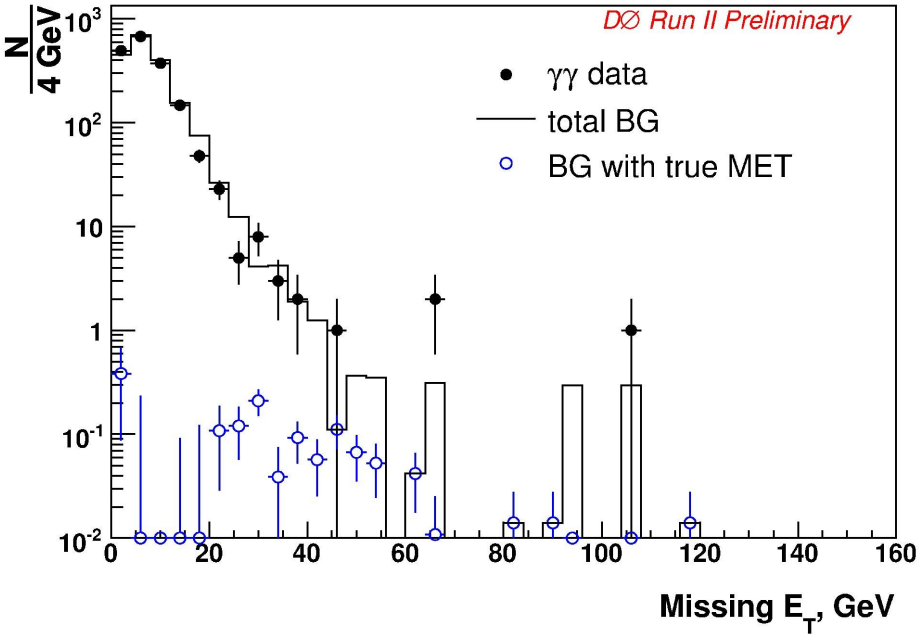
→ Inclusive search for 2 photons plus $\not{E}_T$ ($\int L\,dt = 760\ pb^{-1}$)

Lifetime unknown
Assume here: prompt decay



Selection: Two central photons with E_T > 25 GeV
Optimized cut $\not{E}_T$ > 45 GeV

Data: 4 events, expect 2.1 ± 0.7 events background



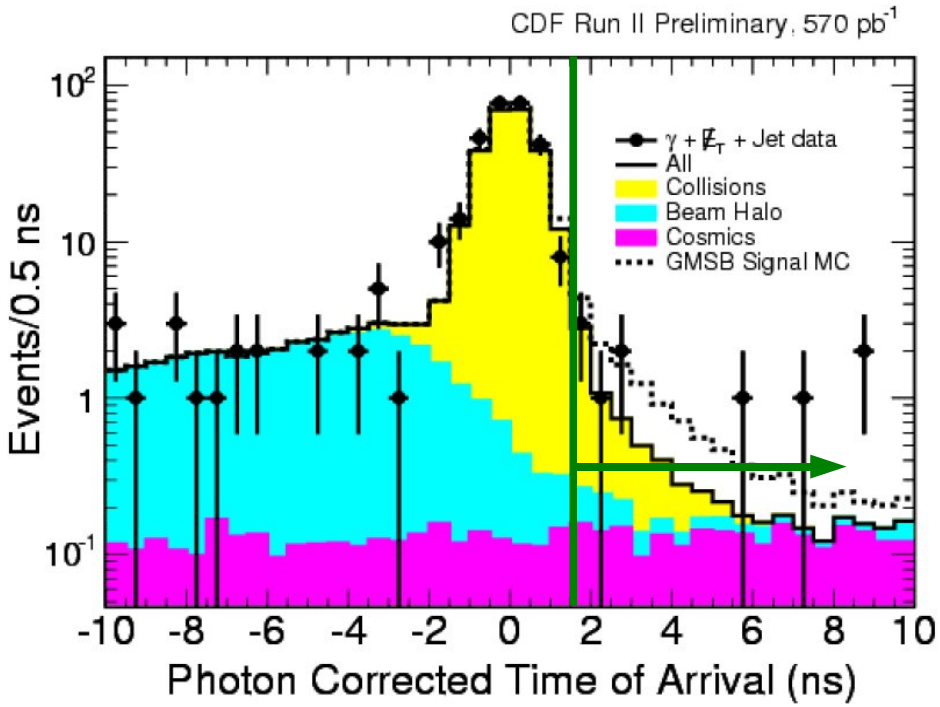
Limits for chargino and neutralino (N_5=1, M_m=2, tanβ=15, μ>0):

$m(\tilde{\chi}_1^0)$ > 120 GeV $\quad$ $m(\tilde{\chi}^{\pm})$ > 220 GeV

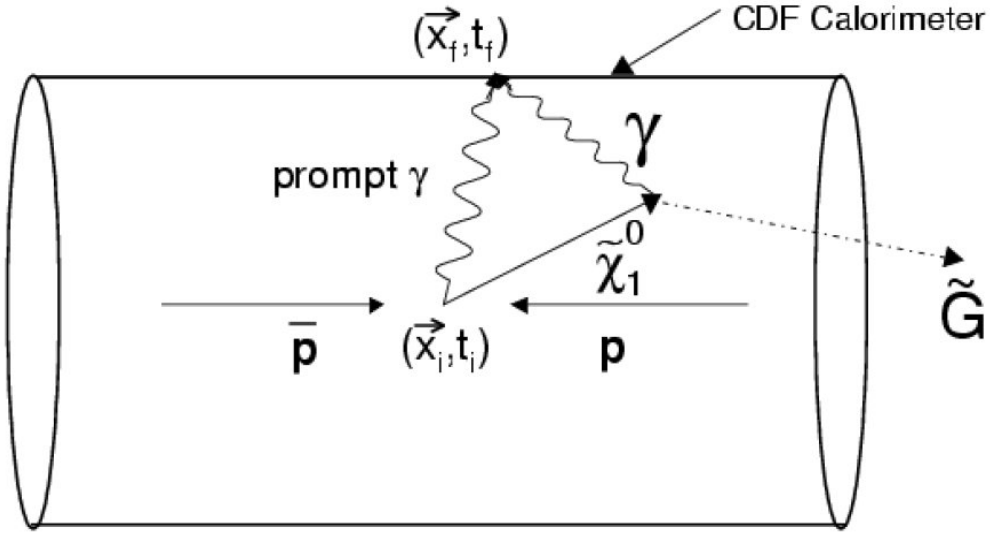
GMSB: Long-Lived Neutralino

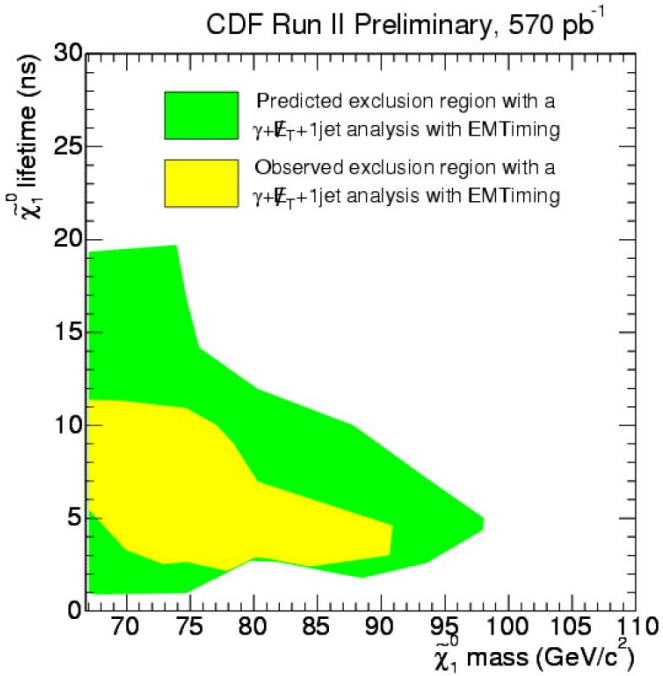
Now allow neutralino with significant lifetime:

- Large Missing E_T > 50 GeV
- Jet with E_T > 30 GeV (other SUSY particle)
- "Late" photon with E_T > 30 GeV



t_0 is the arrival time of prompt particles in the calorimeter
time resolution ~0.6 ns

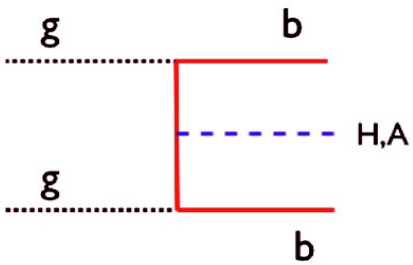




10 events vs. 7.6 ± 1.9 expected background

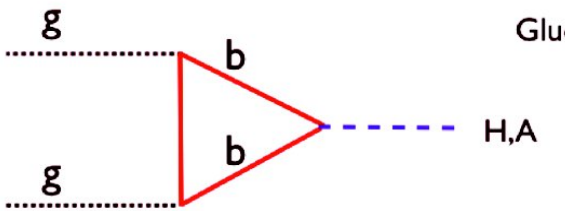
MSSM Higgs

In MSSM, 3 neutral (h, H: CP-even, A: CP-odd) and 2 charged Higgs bosons



Associated Production

Enhanced couplings to b quarks and τ leptons



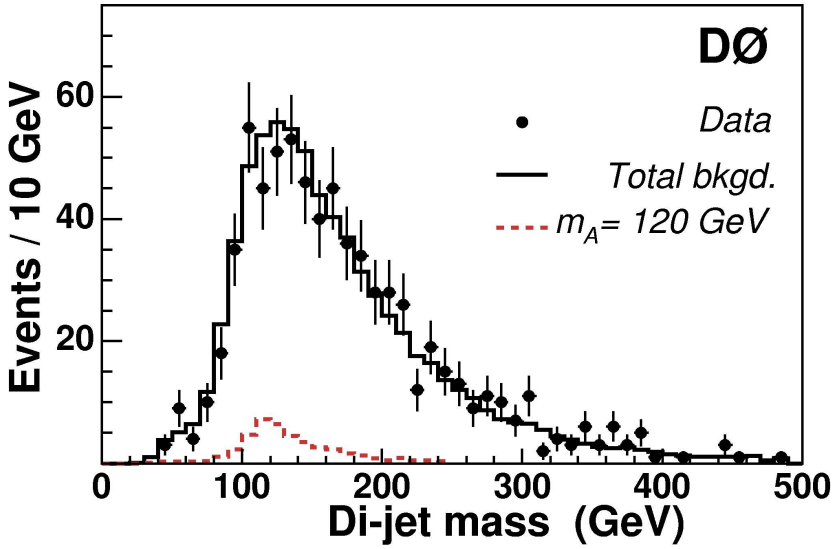
Gluon Fusion

BF(A $\rightarrow$ b b) ~ 90%, BF(A $\rightarrow \tau\tau$) ~ 10%

at high tanβ, σ(h,A+X) $\propto$ tan$^2\beta$

Three analyses so far:

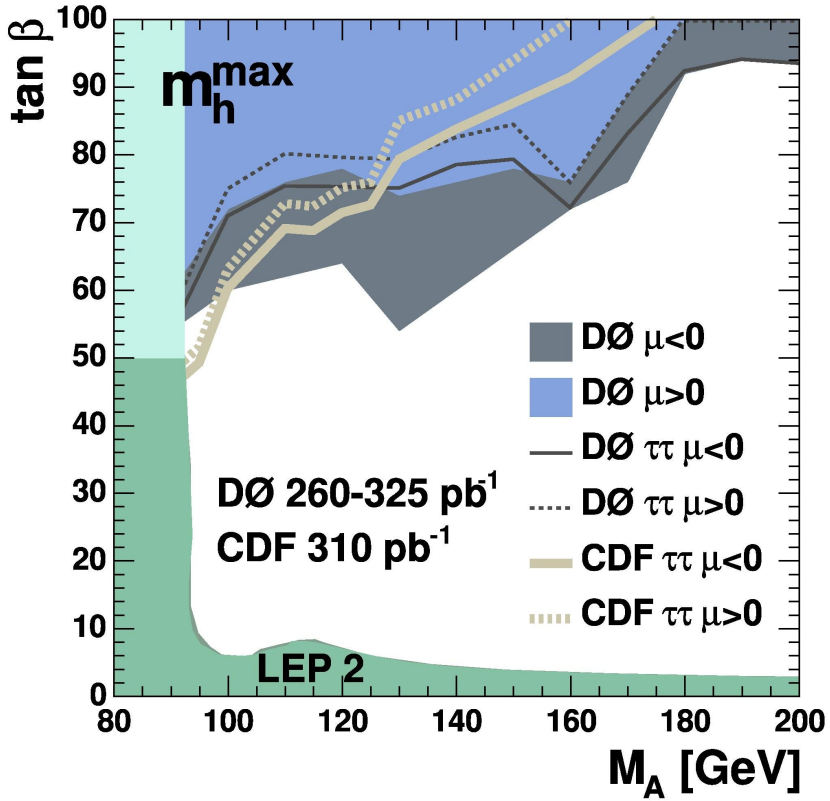
- DØ: b(b)h with at least 3 b-tagged jets (search for excess in di-jet mass)
- DØ, CDF: gg $\rightarrow$ h, A $\rightarrow \tau\tau$ (sophisticated τ-ID, then search for enhancement in visible mass)

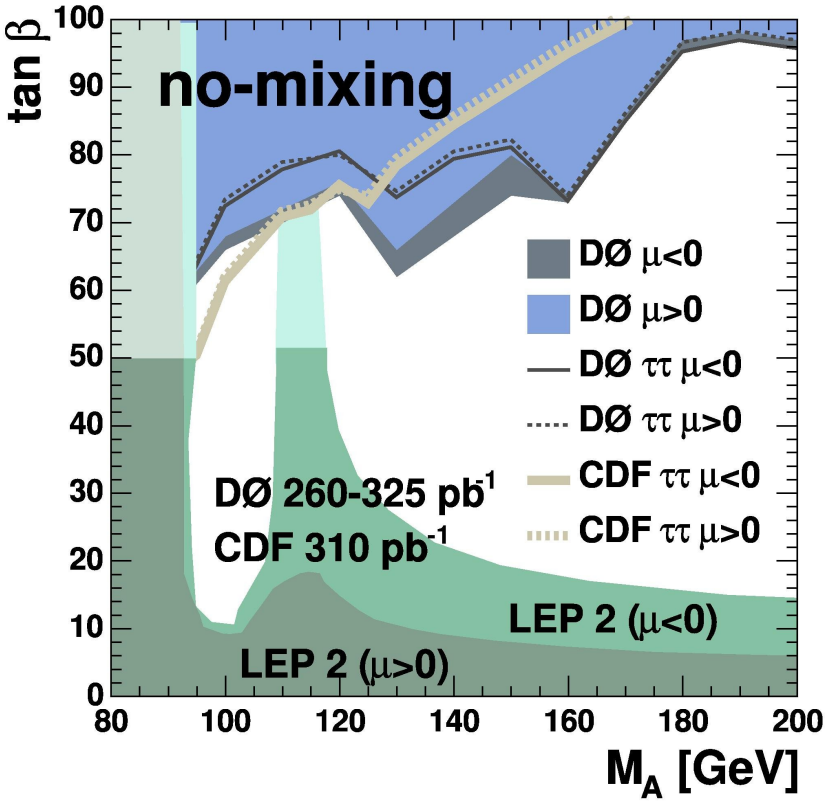


MSSM Higgs

m_h-max: Higgs boson mass m_h close to the maximum possible value for a given tanβ

no-mixing: vanishing mixing in stop sector → small mass for h.





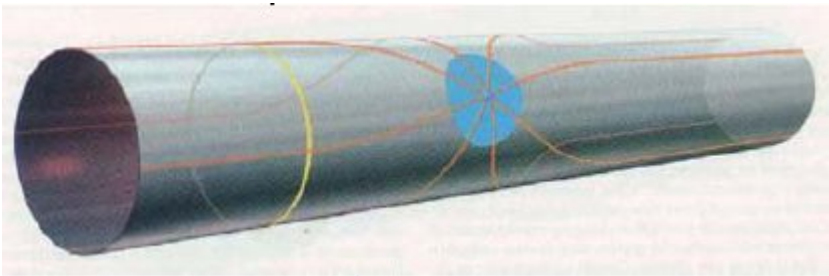
DØ: combination of b(b)h and $\tau\tau$ channels

Extra Dimensions

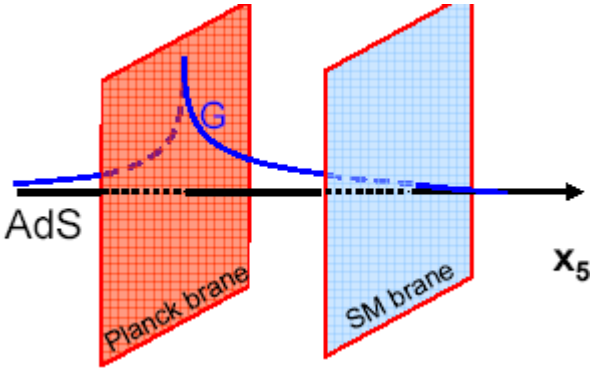
…come in many flavors: LED, TeV^{-1}, UED, RS

Two classes of models considered:

- **ADD**
  - 2 to 7 large (sub mm) EDs
  - gravity propagates freely in the bulk
  - KK excitations cannot be resolved



- **RS**
  - one 5th (infinite) ED with warped geometry
  - gravity is localized on a brane other than the SM
  - KK excitations have spacings of order TeV



Large Extra Dimensions

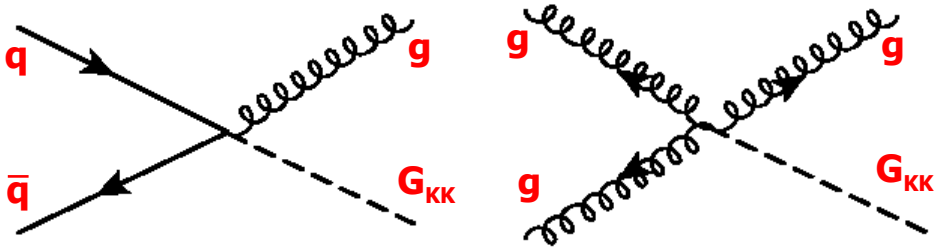
Main search streams at the Tevatron:

Real graviton emission

Apparent energy-momentum non-conservation in 3D-space

⇒ **"Monojets"**

Direct sensitivity to the fundamental Planck scale M_D

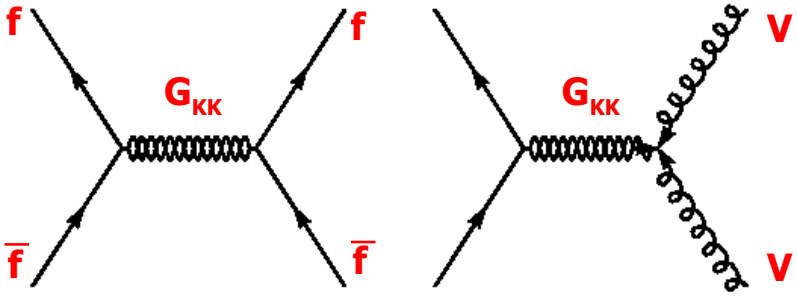


Virtual graviton exchange

Modifies SM cross sections

Sensitivity to the theory cutoff M_S

(M_S expected to be ~ M_D)

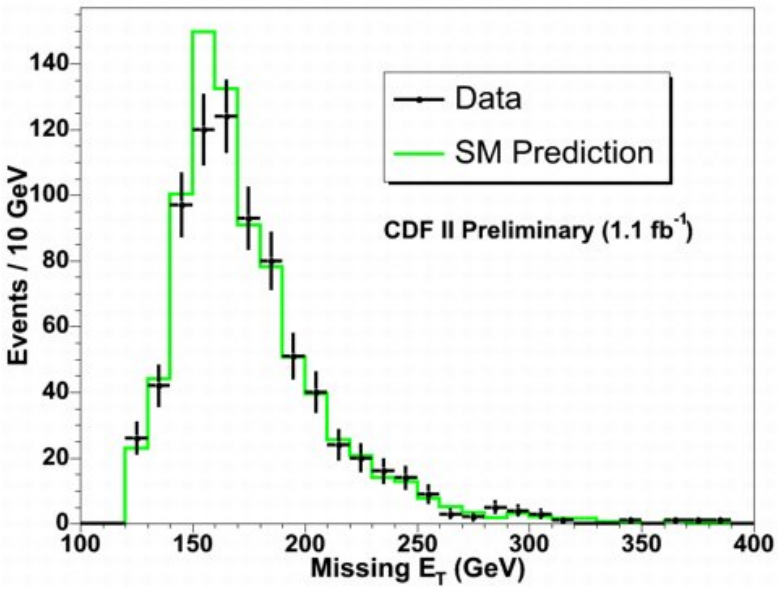


Monojets

Search in 1.1 fb^{-1}:

Main selection cuts:

- one high p_T jet (> 150 GeV)
  (soft jets from ISR are allowed)
- isolated lepton veto
- Missing E_T away from jets
- Missing E_T > 120 GeV

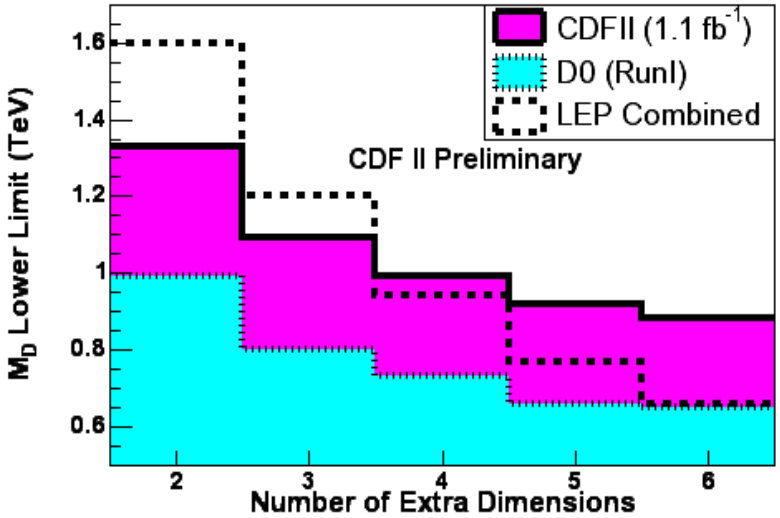


Main background: ($Z \rightarrow \nu\nu$) +jet

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

779 events selected

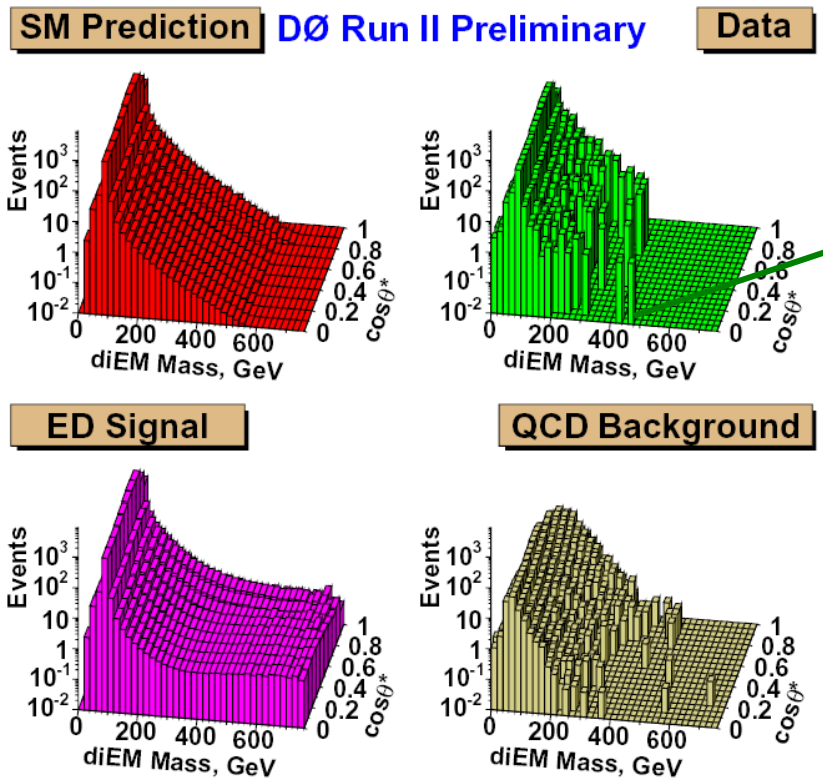
819 ± 71 expected

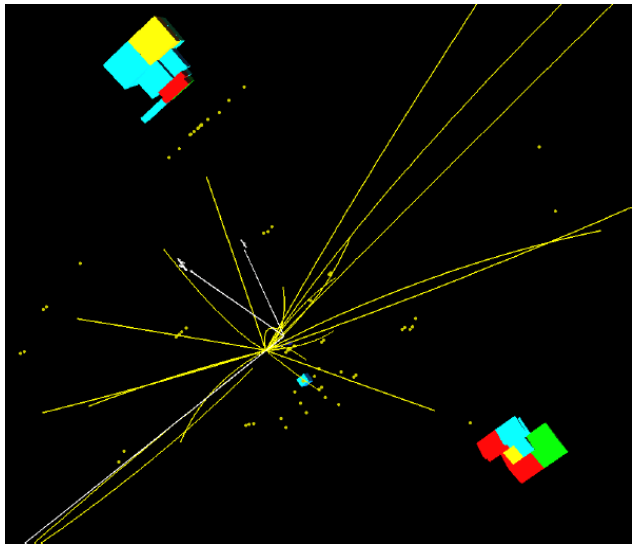


High p_T Dileptons and Diphotons

Search in 200 pb^{-1} **combines ee and γγ to maximize the sensitivity**

Fit of Data to SM+QCD+LED(M_s)





Still world´s tightest limits:

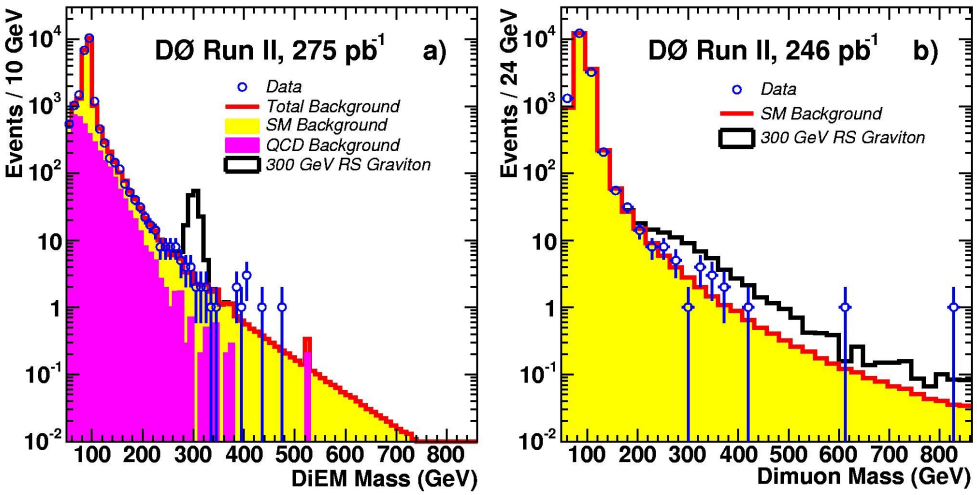
M_s > 1.36 TeV

M_s >1.43 TeV incl. DØ Run I

(GRW formalism)

Randall-Sundrum Gravitons

Here too, **most of the sensitivity is in diphotons** (BR = 2 * ee)



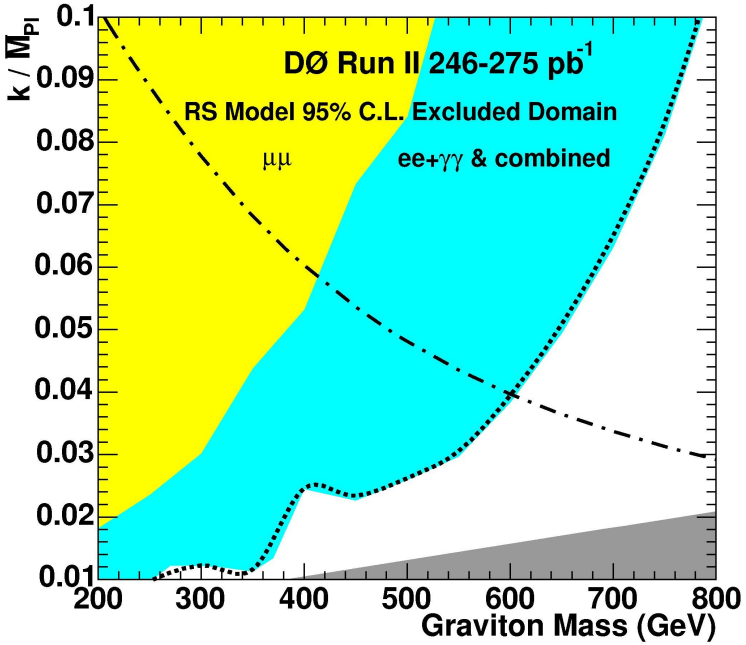
Combined ee + γγ

as for the LED search

μμ doesn't add much

Two model parameters:

Mass and coupling (κ/M_{Pl})

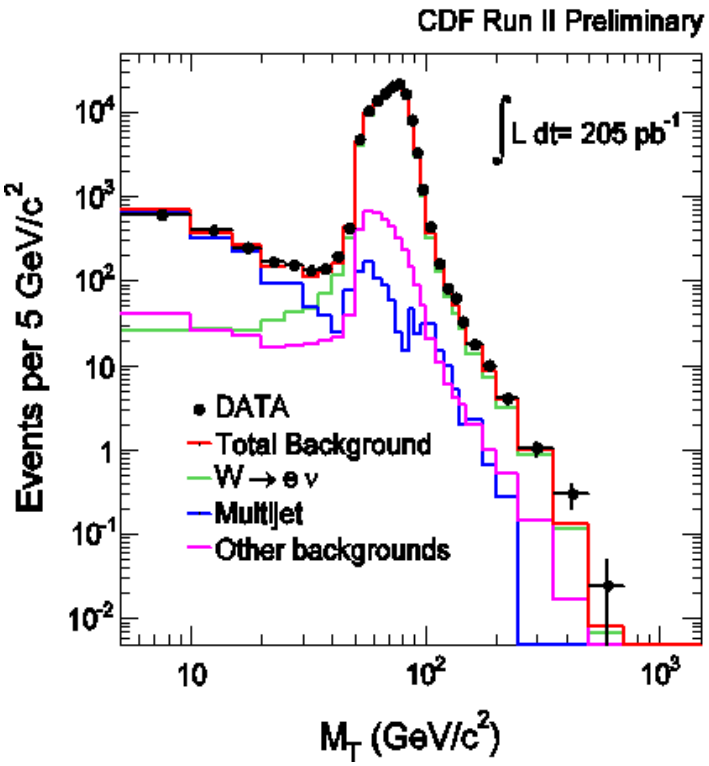


For κ/M_{Pl} = 0.1: M > 785 GeV

Extra Gauge Bosons

Examples:

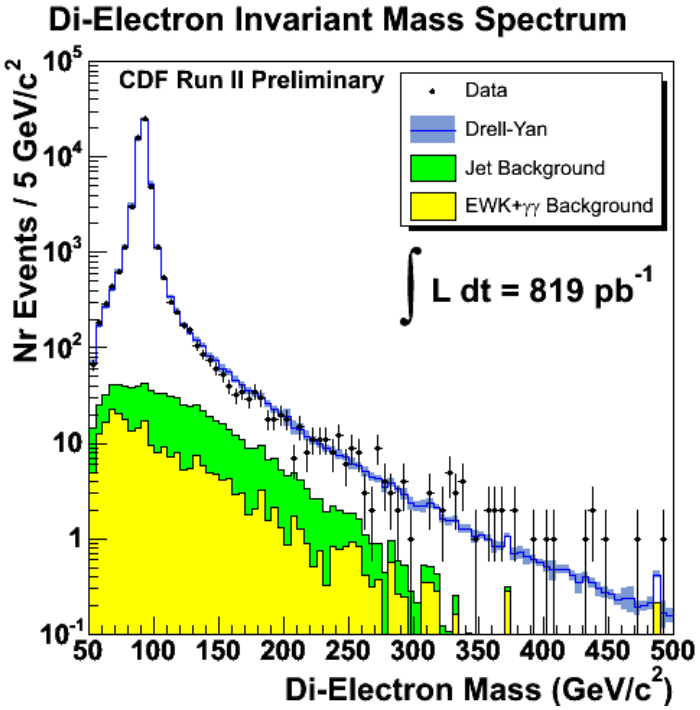
W' in L-R models



M_T = M(electron-p_T,missing-E_T)

M(W'-seq.) > 788 GeV

Z' within E(6) GUTs

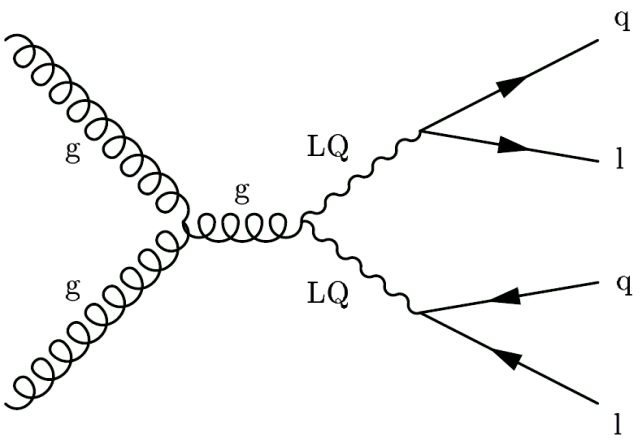


M(Z'-seq.) > 850 GeV

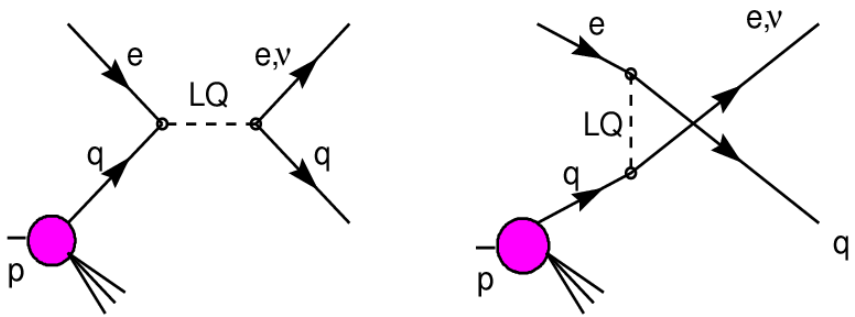
(somewhat lower limits in canonical E(6) models)

Leptoquarks

Leptoquark: – Boson with third-integer charge, carrying lepton and quark quantum numbers
– 3 generations, each coupling to one fermion generation only
(lepton number violation, FCNC)



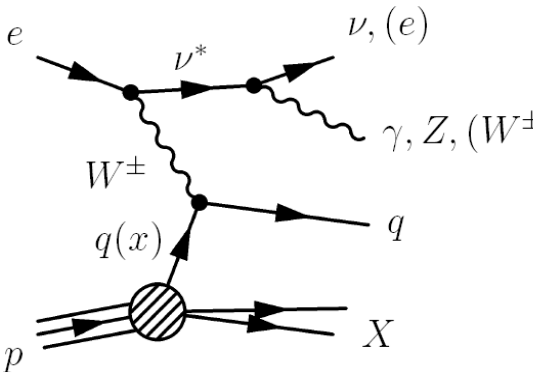
Tevatron: – Searched for all three generations and different decays, with 200-400 pb^{-1}
– Mass limits range from 117 to > 300 GeV



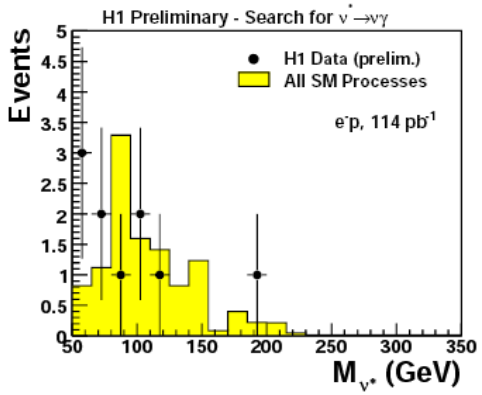
HERA: – Limits depending on coupling to electron and quark

Lepton Compositeness Searches at HERA

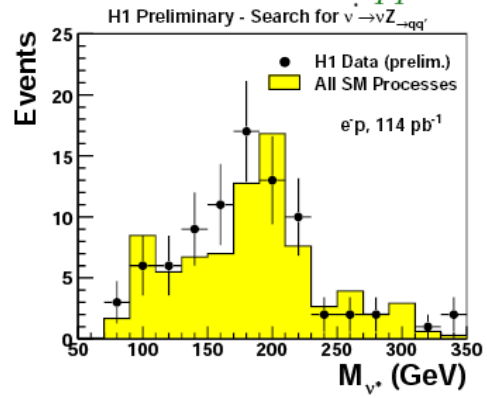
Recent example: Search for excited neutrinos



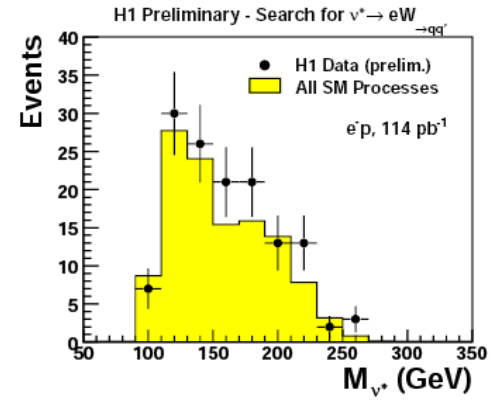
$\nu^* \to \nu\gamma$



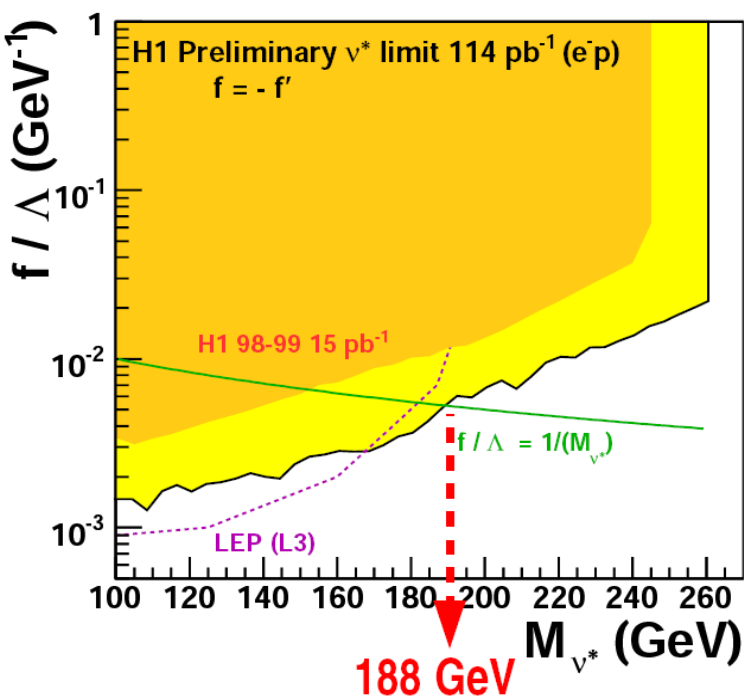
$\nu^* \to \nu Z_{\to qq'}$



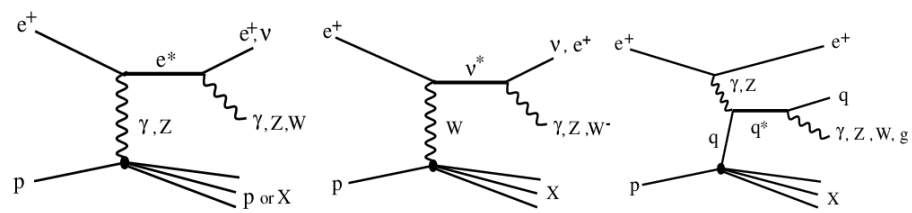
$\nu^* \to eW_{\to qq'}$



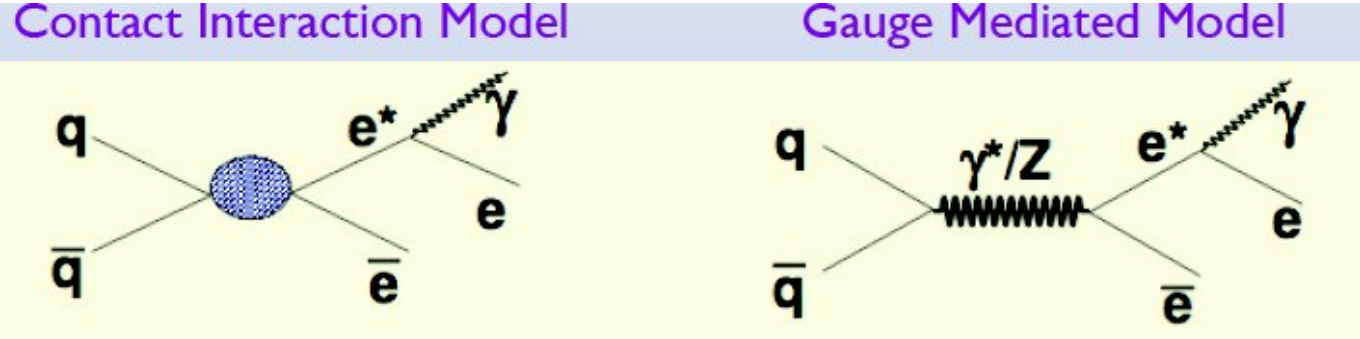
data / SM: $12 \;/\; 11.6 \pm 2.5$ $\quad 88 \;/\; 81 \pm 15$ $\quad 136 \;/\; 118 \pm 22$



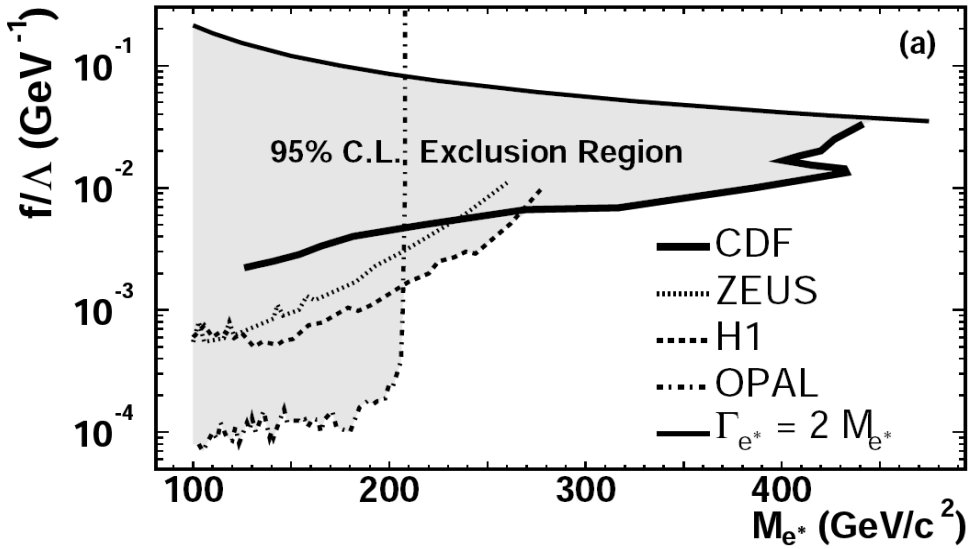
In general at HERA: all first generation excited fermions



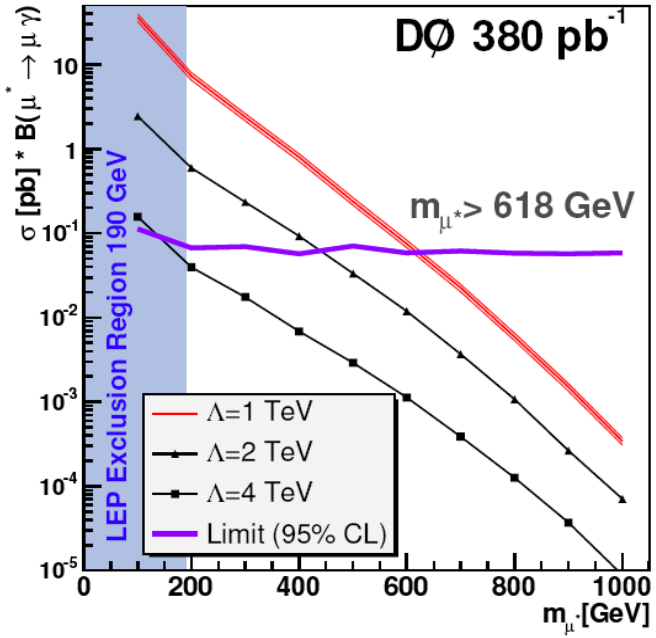
Lepton Compositeness at the Tevatron



e*, gauge mediated model



μ^*, contact interaction model

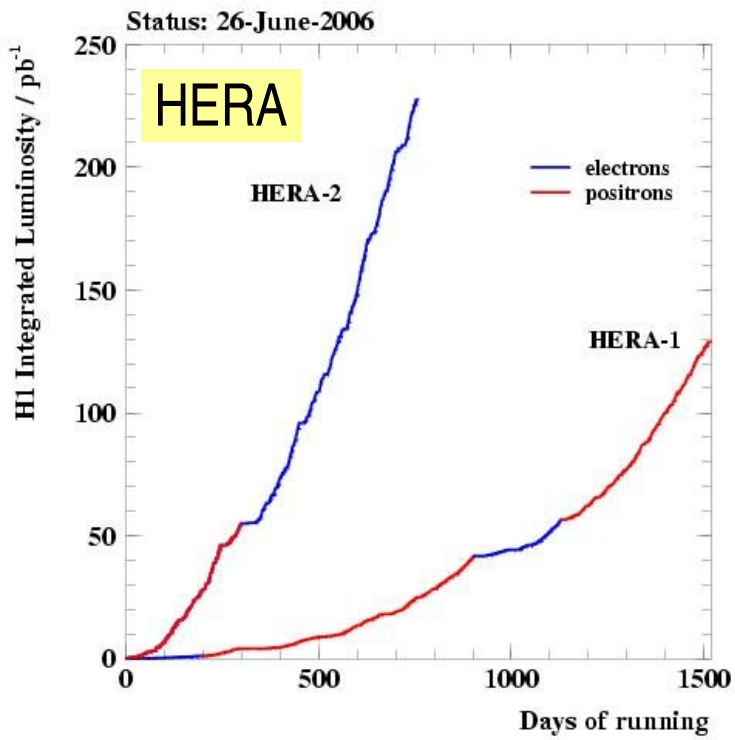


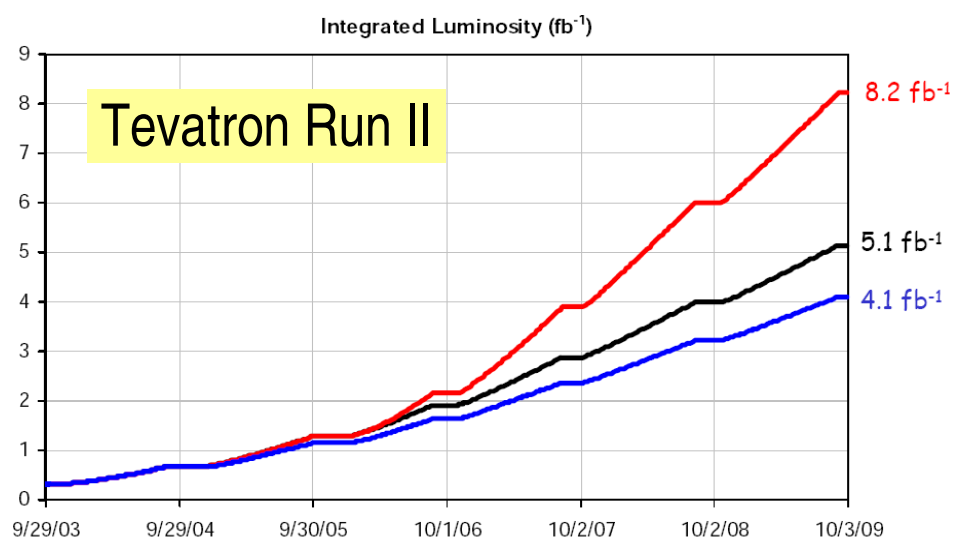
Exclusion up to ~400 GeV (GM) and ~900 GeV (CI)

Also q* in different channels, other compositeness searches – no deviations from SM

Summary

- The Tevatron and HERA experiments are probing an ever increasing territory of possible and impossible models
- Some scenarios lead to unusual and spectacular signatures – e.g. long-lived particles (prepare for the unexpected)
- There´s a large number of results I haven´t touched (leptoquarks, many SUSY signatures, ...) – a very live and active program!
- All hints at new physics in the last 30 (?) years disappeared again – it is about time...





2008 / 9

Observation of Events with Multiple Photons in pp Collisions at $\sqrt{s} = 14$ TeV

We report on the observation of events with five or more photons in pp Collisions at $\sqrt{s} = 14$ TeV, collected with the XXXX detector. In 1 fb^{-1} of data, we find NNN events with at least five photons with transverse energy above 100 GeV, incompatible with the Standard Model expectation. We are not aware of any non Standard Model explanation for the observed excess. Detailed properties of this class of events are given....

Expect the Unexpected...

Murayama, LP 2003 summary

Backup

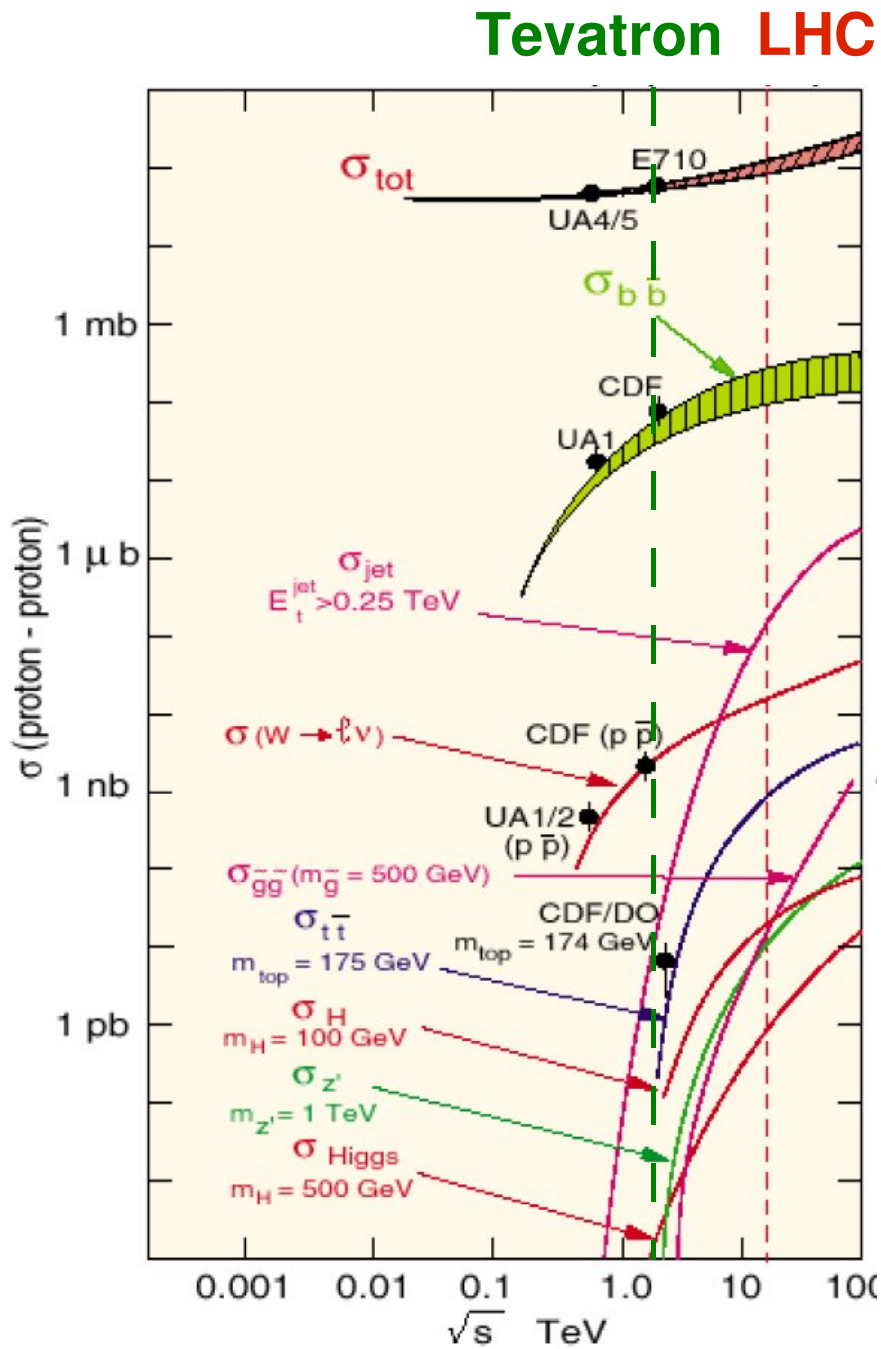
Tevatron vs. LHC

- SUSY cross sections at the Tevatron very small → good understanding of SM backgrounds required (SUSY-free control samples)

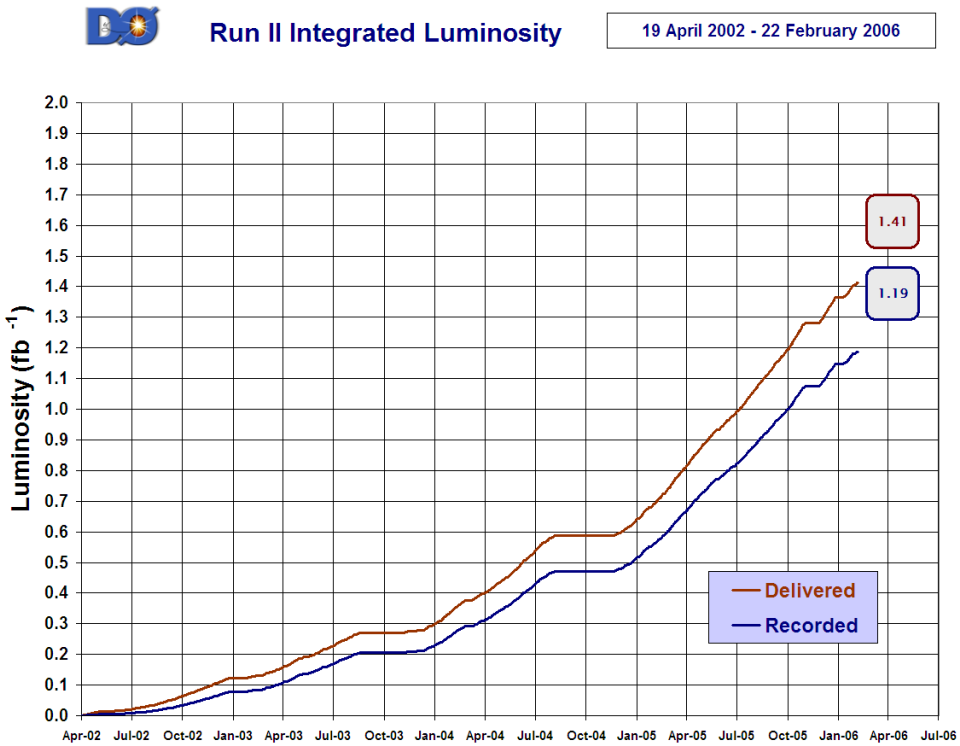
Process	Tev → LHC σ
$\tilde{\chi}^+\tilde{\chi}^-$ (m=200GeV)	x 10
Top pair production	x 100
W+4j (k_t>20GeV)	x 500

(Mrenna, Moriond EWK 2006)

- Tevatron and LHC are "parton-colliders"
- Important: proton structure (→ HERA)
  - Tevatron: often gluon density at large x
  - LHC: also small x
- Uncertainty of theoretical predictions
  - Understanding of proton structure has significant impact on sensitivity (sometimes larger than higher order corrections / scale uncertainties)



Accelerators



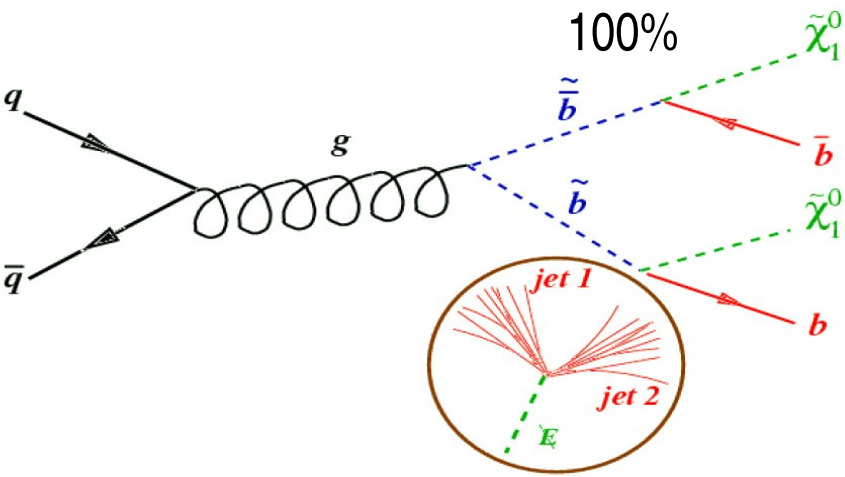
CDF and DØ: 1.2 fb^{-1} per experiment recorded ("Run IIa", 2002 – 2006)

Plan: 4 – 8 fb^{-1} per experiment by 2009 (currently coming out of 3.5 months shutdown)

LHC Start-Up Scenario:

August – October 2007	1 x 1 to 156 x 156 bunches	$\leq 10^{32} cm^{-2} s^{-1}$	0 – 300 pb^{-1}
2008	936 x 936 (75 ns)	$10^{32} – 10^{33} cm^{-2} s^{-1}$	1 ... few fb^{-1}
≥ 2009	2808 x 2808 (25 ns)	... $10^{34} cm^{-2} s^{-1}$	10... 100 fb^{-1} / a

Sbottom



$\int L\,dt = 310\ pb^{-1}$ collected with

acoplanar jet + $\not{E}_T$ trigger

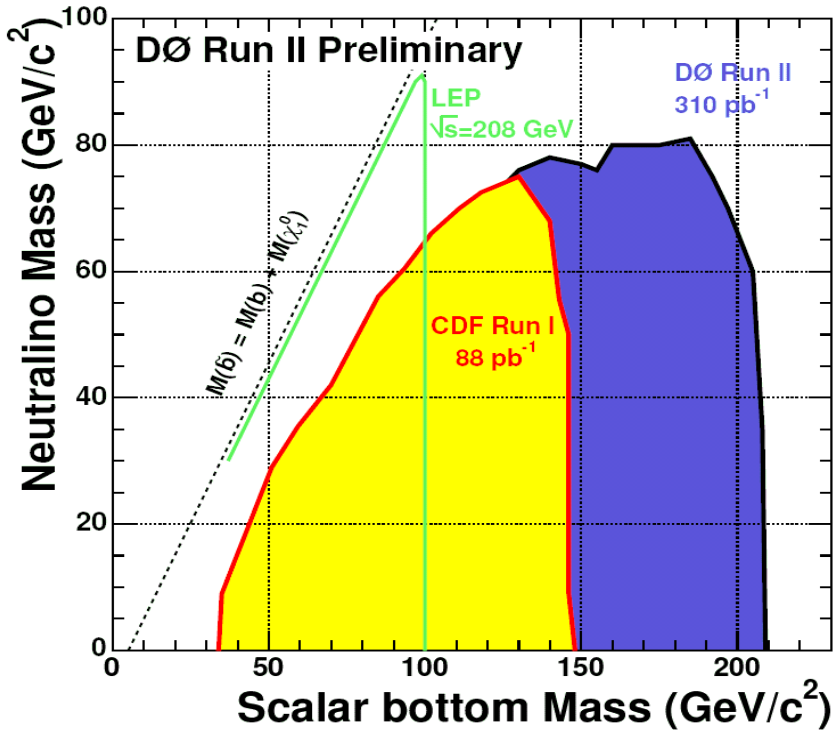
Signal: generic MSSM, varying $m(\tilde{b})$ and $m(\tilde{\chi}_1^0)$

Selection: 2 or 3 Jets, $\not{E}_T$

>= 1 "tight" b-tag

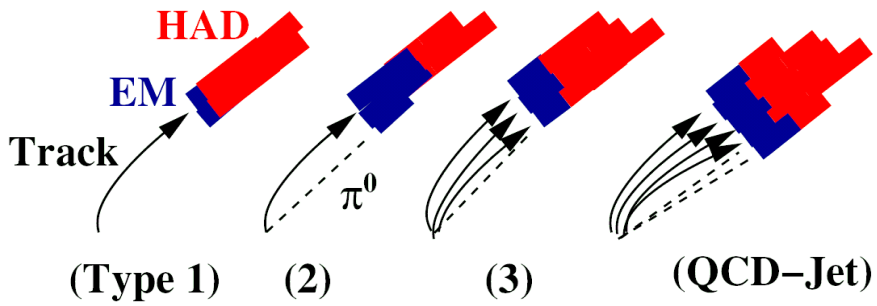
Veto against isolated μ, e, track (p_T > 5 GeV)

Optimization vs. $m(\tilde{b})$



	low $m(\tilde{b})$	medium $m(\tilde{b})$	high $m(\tilde{b})$
SM expectation	38.6 ± 2.8	19.6 ± 1.7	4.4 ± 0.4
Data	36	15	2

Charginos / Neutralinos: τ



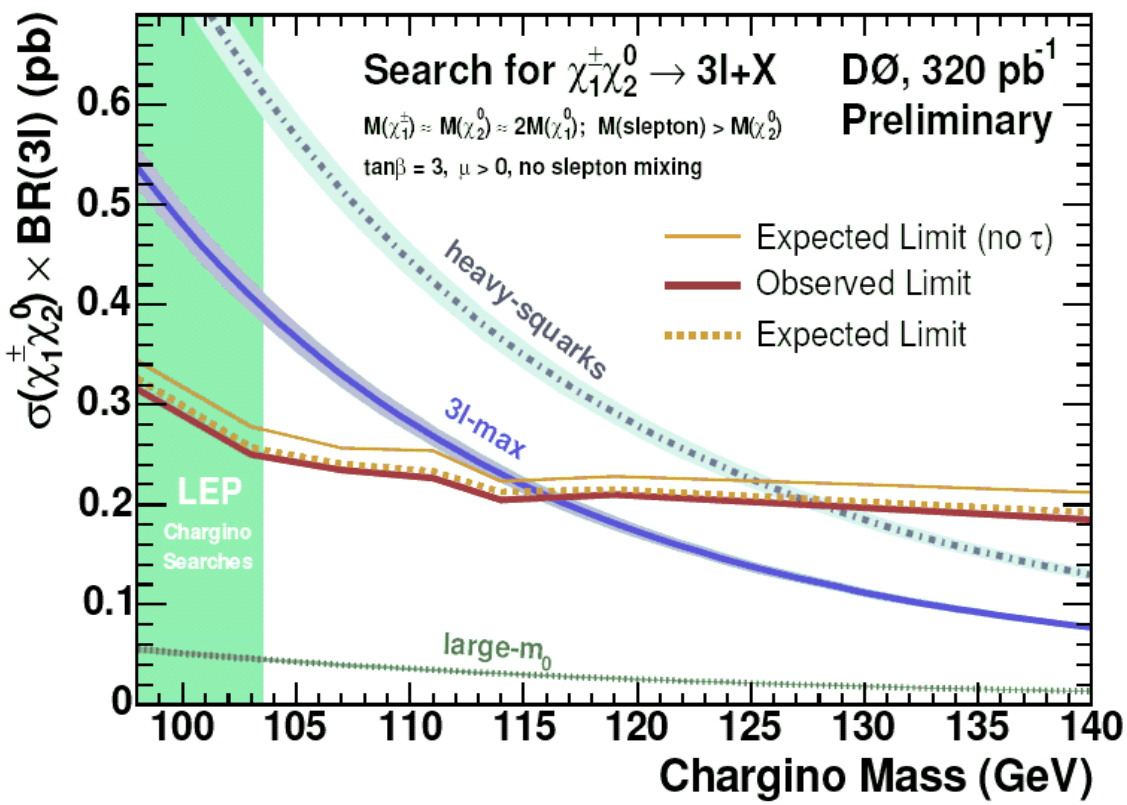
Selection	Expected Background	Observed	Signal ($m_{\tilde{\chi}^\pm}$ = 110 GeV)
$ee\ell$	0.21±0.12	0	1.9±0.2
$e\mu\ell$	0.31±0.13	0	1.6±0.1
$\mu\mu\ell$	1.75±0.57	2	1.3±0.2
ls-$\mu\mu$	0.66±0.37	1	0.7±0.1
$e\tau\ell$	0.58±0.14	0	0.4±0.1
$\mu\tau\ell$	0.36±0.13	1	0.7±0.1
Combined	3.87±0.81	4	6.6±0.3

SUSY with light stau (large tan β) →
Final States with multiple taus

Tau reconstructed as 1 or 3 tracks associated with narrow energy deposition in the calorimeter

Several neural nets, optimized to separate different decay topologies from jets

In existing analysis (tan β = 3), cross section limit is improved by ~10%



R-Parity Violation

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

+ 1 SM
– 1 SUSY

$$W = W_{RPC} + W_{RPV}$$

$$W_{RPV} = \underbrace{\frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\Delta L = 1} + \underbrace{\frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\Delta B = 1}$$

S Spin
B Baryon number
L Lepton number

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

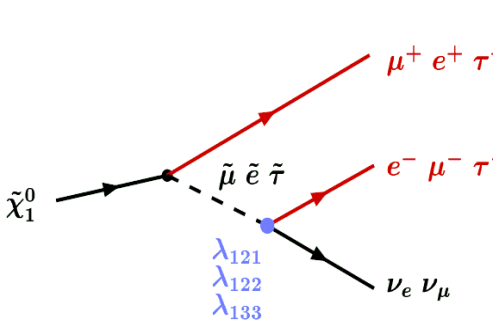
L: Lepton doublet superfield
E: Lepton singlet superfield
Q: Quark doublet superfield
D: Down-type quark singlet superfield

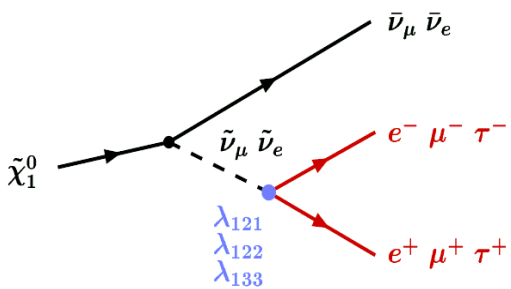
R_P violated in decay
Many leptons

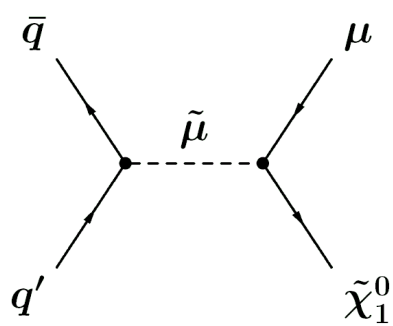
Resonant production
Leptons and jets in the final state

Yukawa couplings λ, λ', λ''
9 + 27 + 9 free parameters
experimentally and theoretically constrained (p decay etc.)

LSP no candidate for dark matter in RPV models

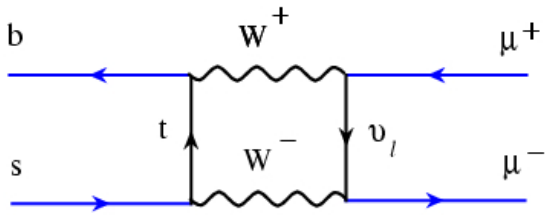


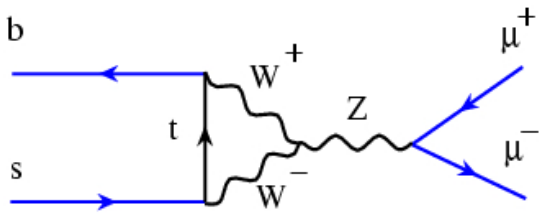




(For non-zero $L_i Q_j \bar{D}_k$-coupling)

$B_s \to \mu\mu$



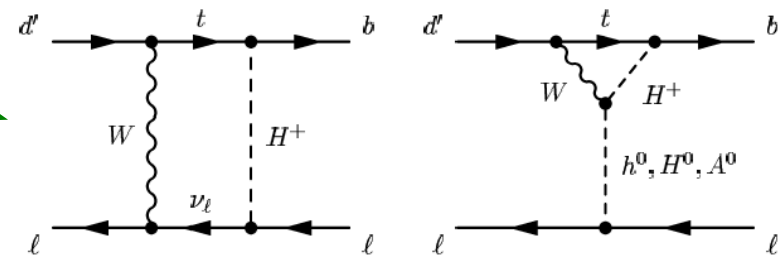


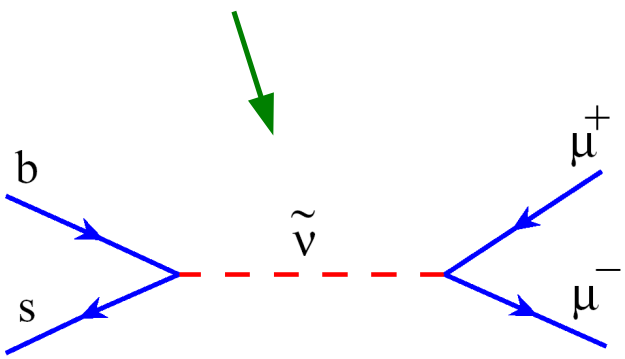
Standard model:

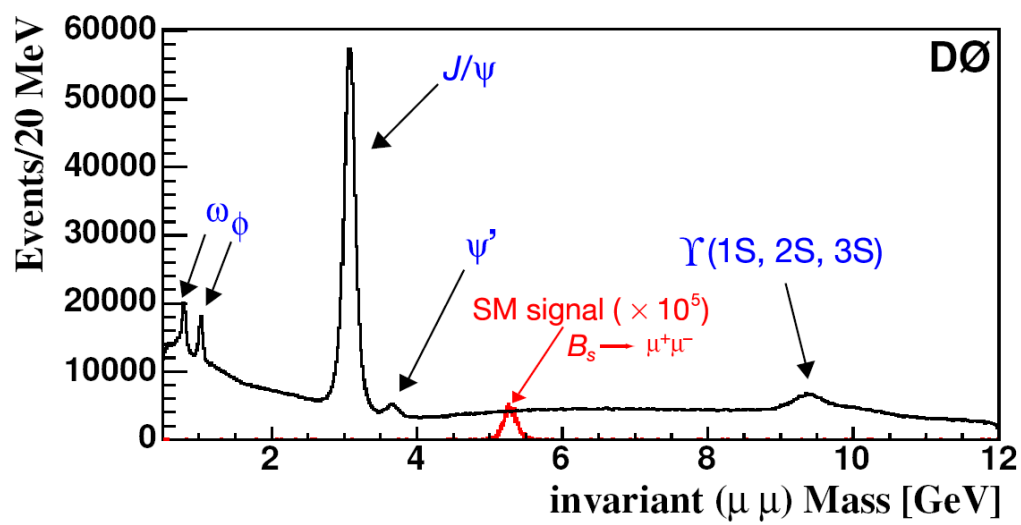
BF ($B_s \to \mu\mu$) $\simeq 3 - 4 \cdot 10^{-9}$

Sensitive to new physics, e.g.:

- Models with extended higgs sector (2HDM)
- e.g. MSSM: BF ~ $\tan^6\beta$
- minimal SO(10) GUT
- R-parity violation

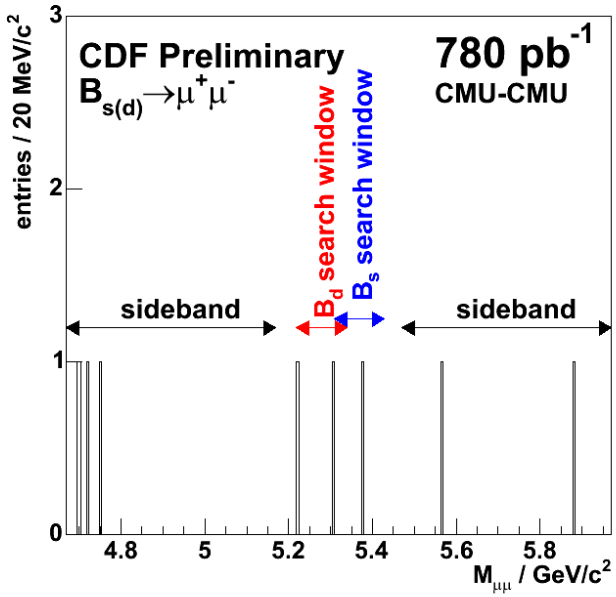


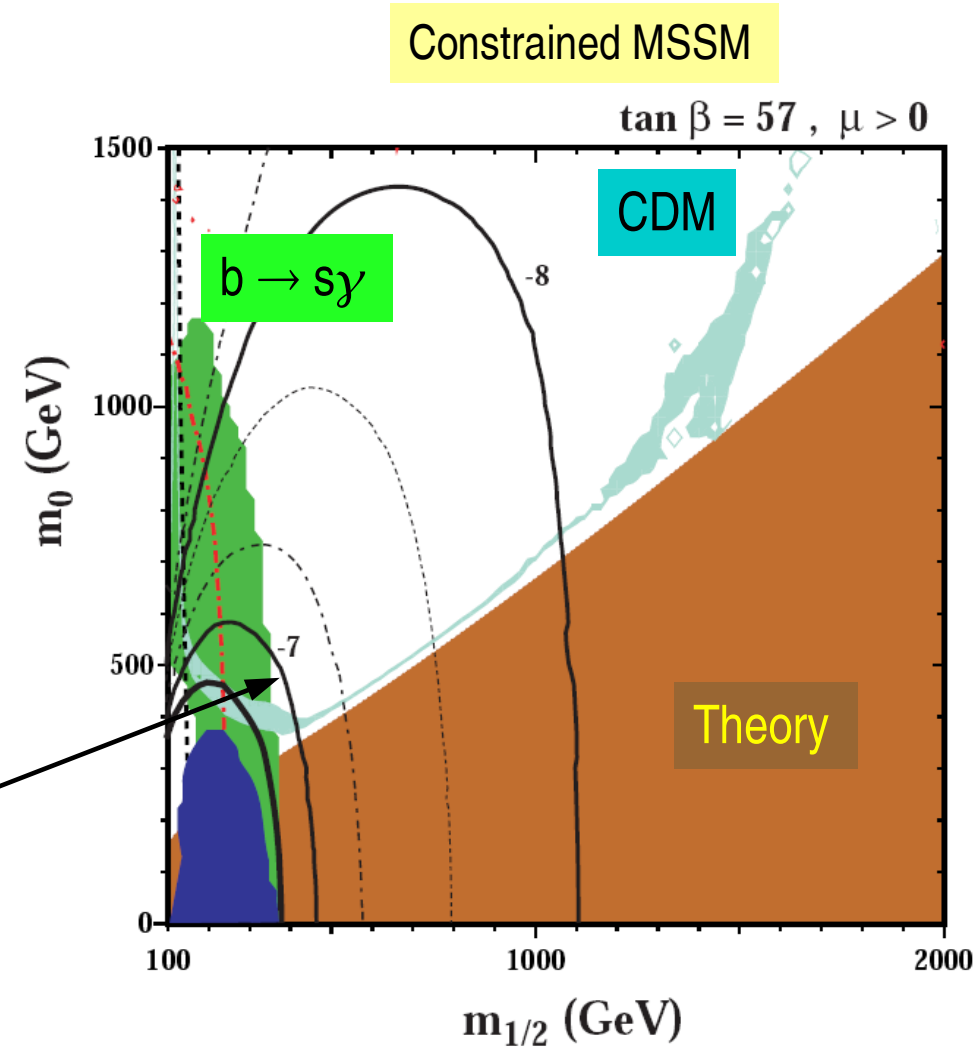




$B_s \to \mu\mu$

After optimized selection (lifetime, isolation):





Ellis, Olive, Spanos

New result from CDF (780 pb^{-1}):

$BF(B_s \to \mu^+ \mu^-) < 1.0 \times 10^{-7}$ (95% C.L.)

"Only" factor 30 above SM expectation

LHC sensitivity expected to reach SM prediction