Searches for New Physics with High Energy Colliders

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The Beyond the SM Landscape

The Standard Model

- $SU(3)_C \times SU(2)_L \times U(1)_Y$
- The Higgs mechanism
- 3 generations of quarks and leptons
- The Poincaré group
- In 4 dimensions

Test Beyond the SM hypotheses

- New substructures ? (compositness)
- quarks ⇔ leptons (Lepto-quarks ?)
- Enlarge the gauge group (Z', W' ?)
- Alternative EWSB mechanisms
- A 4th dimension ?
- Extend Poincaré → Supersymmetry
- (…)

Test the SM

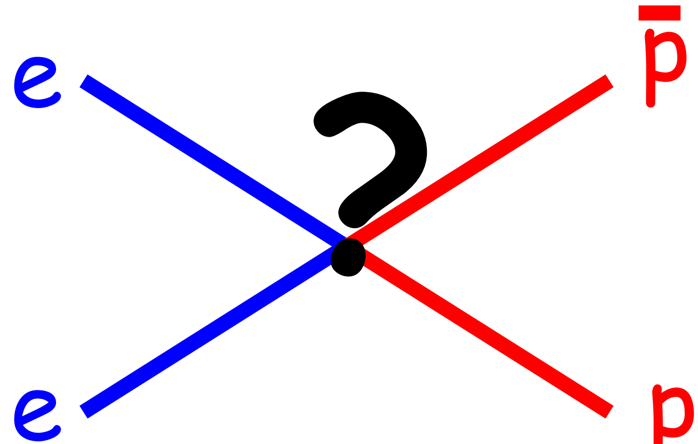
➔ BSM-independent

- New resonances ?
- Topologies with low SM background
- Topologies with specific particle(s)
- General searches

The Experimental Tools

➔ Present and past colliders at the energy frontier

- $\sqrt{s}$ = 210 GeV,
- ~ 0.9 fb^{-1} / exp.
- Results still complementary



- $\sqrt{s}$ = 320 GeV,
- ~ 0.5 fb^{-1} / exp.
- Stopped mid-2007

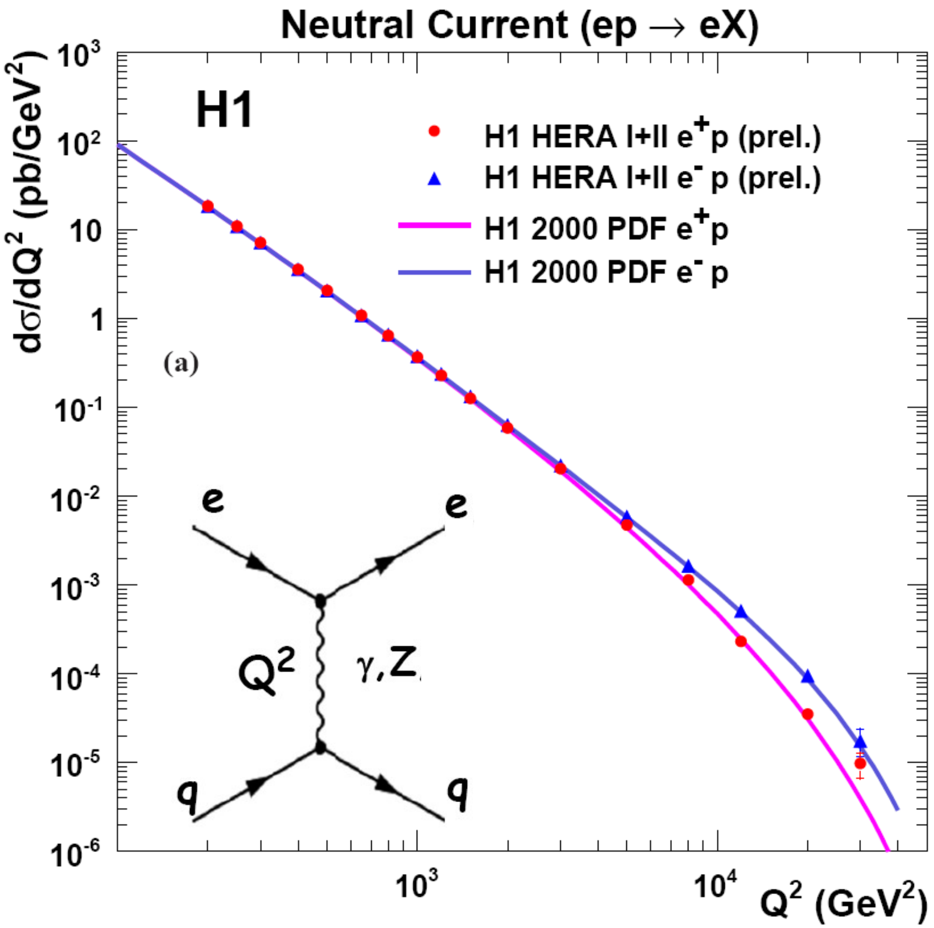
- $\sqrt{s}$ = 1.96 TeV,
- Up to ~ 4 fb^{-1} in analyses
- ~ 6 fb^{-1} on tape

Deeper into Matter Structure

➘ Repeat the history: diffusion of point-like particles on matter

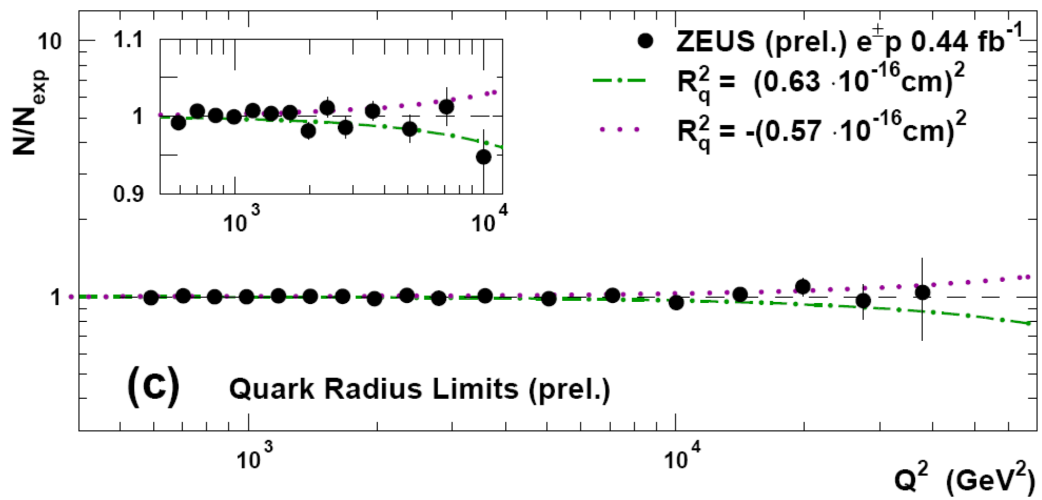
- Atom → Nucleus → Nucleon → Quark (→ ?)

➔ DIS scattering of e on q



➔ A finite size of quarks EW charge distribution

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R_q^2}{6}Q^2\right)^2$$



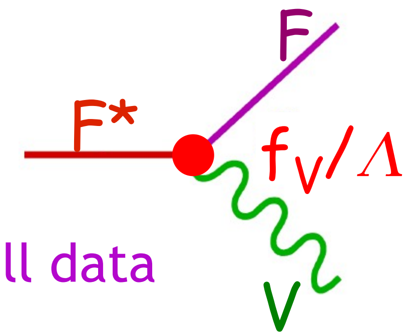
➘ $R_q < 0.63\ 10^{-18}$ m (ZEUS)

➘ $R_q < 0.74\ 10^{-18}$ m (H1)

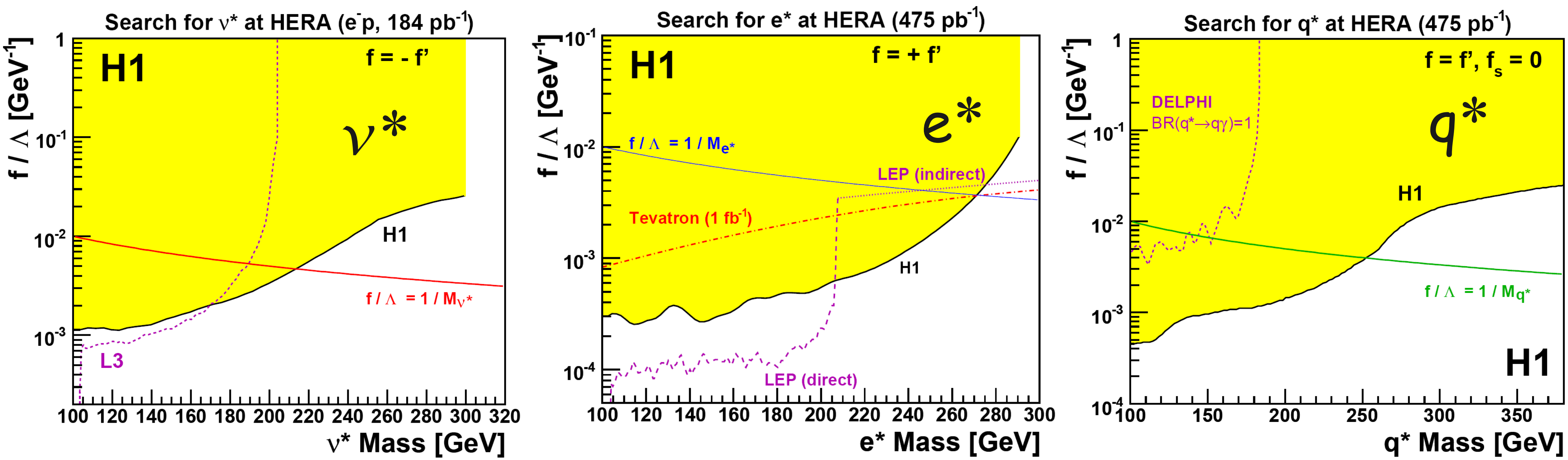
Compositness

[H1, PLB 663 (2008) 382]
[H1, PLB 666 (2008) 131]
[H1, PLB 678 (2008) 335]

- A direct manifestation of new substructures
  - ➔ Existence of fermion excited states
  - ➔ Searches via decays to fermion+ boson



- ep colliders well suited
  - ➔ A complete scan performed by H1 at HERA, using all data
  - ➔ ν*, e* and q* searched for



➘ For l*: HERA has the best sensitivity in $\sqrt{s}_{LEP} = 200 < M_{l^*} < 300$ GeV

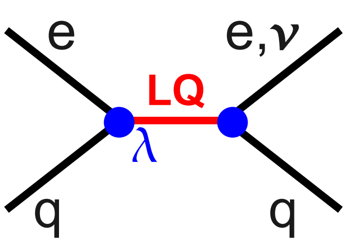
➘ For q*: complementary to Tevatron for small fs

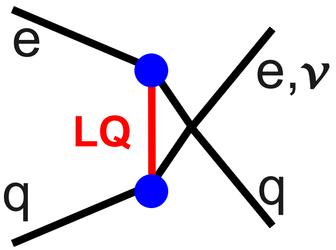
Lepto-quarks

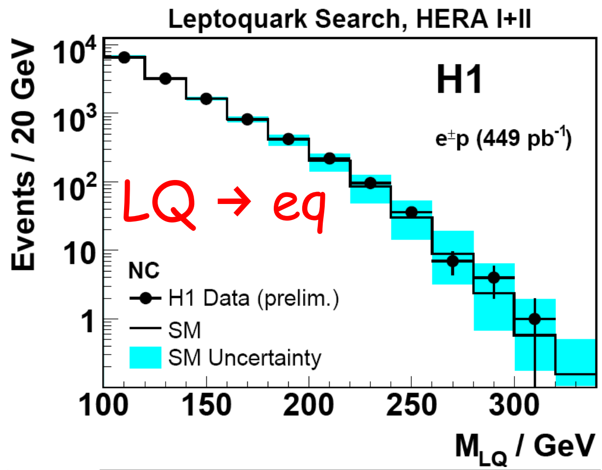
- Leptoquarks: connect lepton and quark sectors

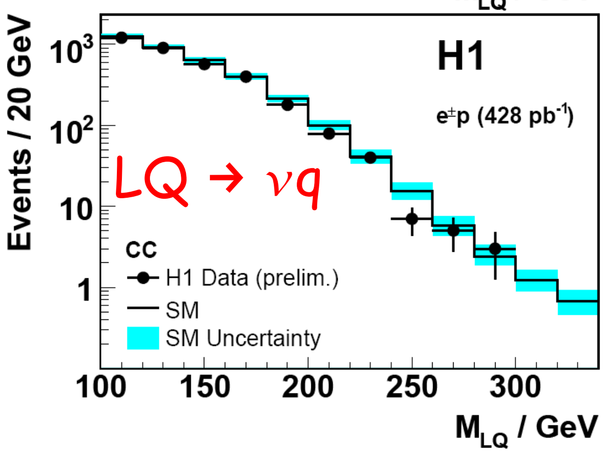
F = L+3B β = BR(LQ→*eq*)

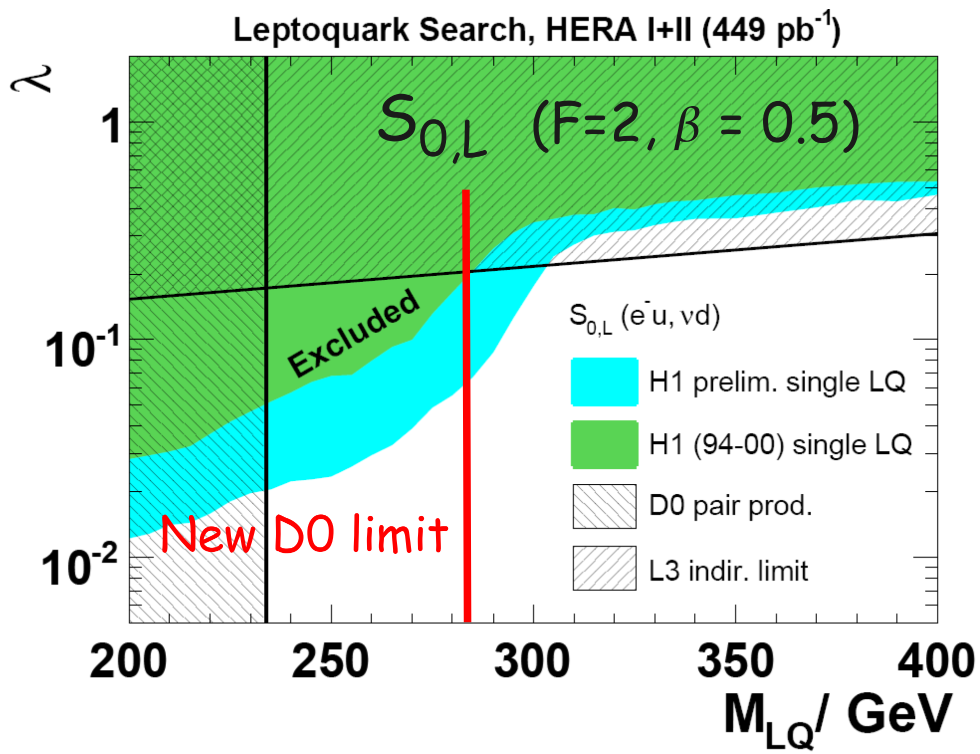
- HERA was ideal to search for 1st generation LQs
  - ➔ Single production possible up to the kinematic limit
  - ➔ Look for lepton-quark resonances in e+jet, ν+jet
  - ➔ Sensitivity via u-channel beyond 320 GeV







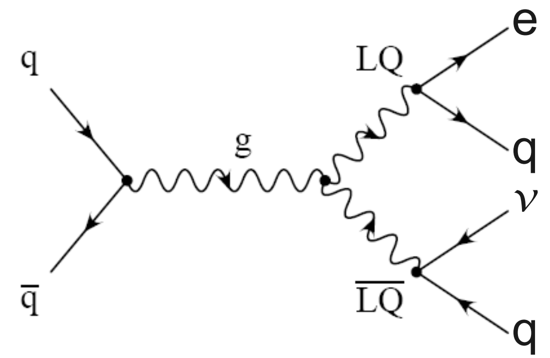


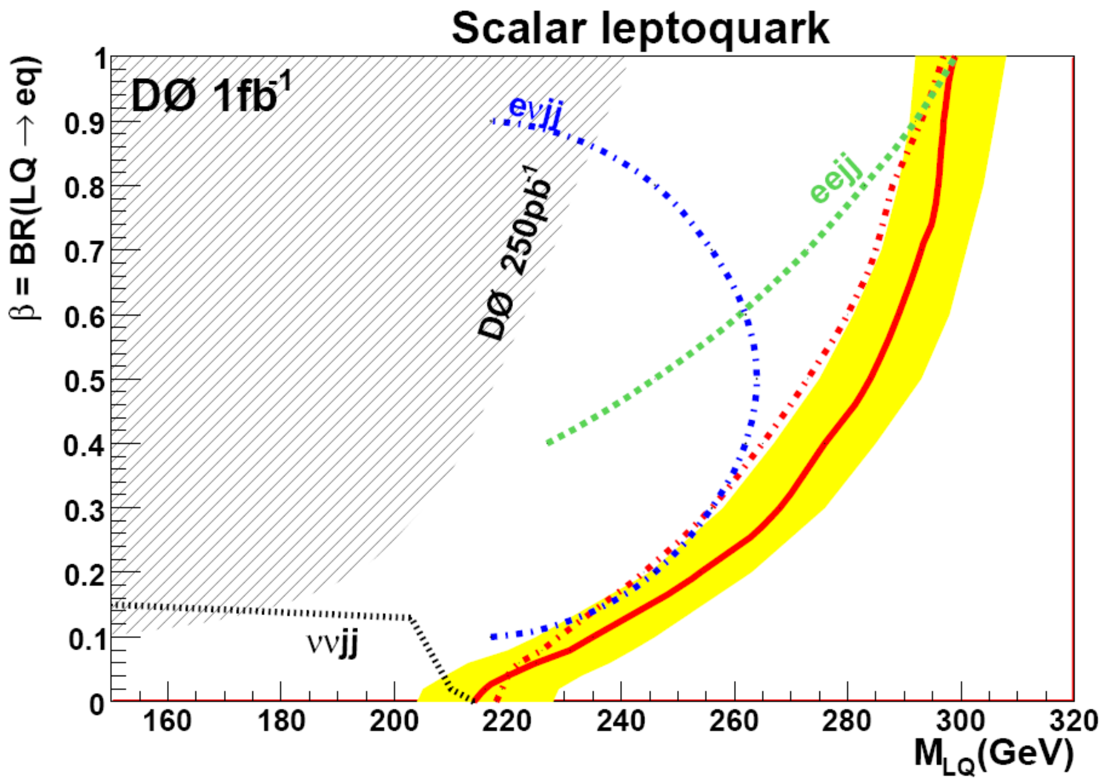


Leptoquarks at the Tevatron

[arXiv:0907.1048]

- Searches for pair production
  - ➔ No sensitivity to λ
- All 3 LQs generations accessible
- Now stringent limits on 1st generation LQs
  - ➔ Searches performed in ej ej and ej MET+j
  - ➔ Lower sensitivity for small β





- Limits for scalar LQs masses (in GeV):

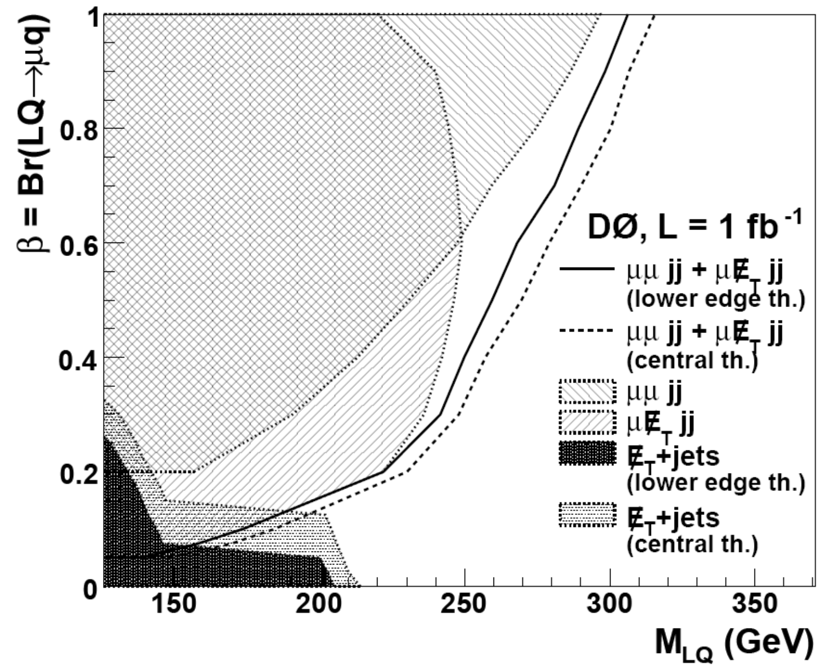
β	scalar
0.1	235
0.5	284
1	299

2^{nd} and 3^{rd} generation Leptoquarks

[D0, PLB 671(2009)224]
[D0, PLB 668(2008)357]

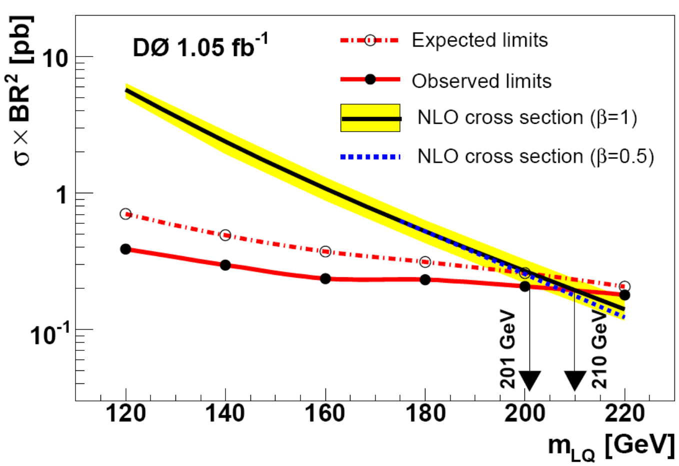
- 2^{nd}: Searches in the μj μj and μj MET (D0)

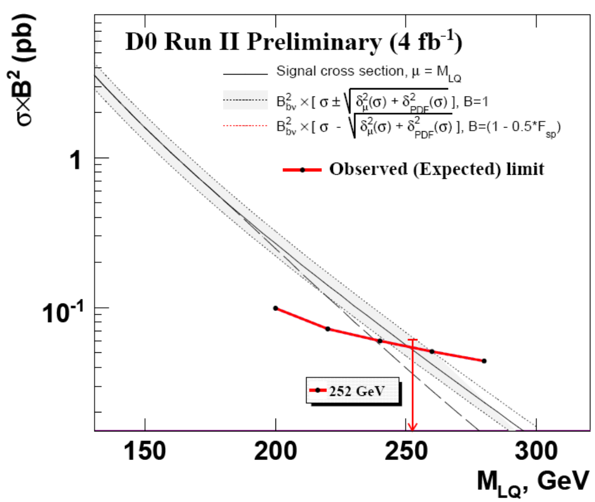
	central theory	
β	M_{LQ}^{obs} (GeV)	M_{LQ}^{exp} (GeV)
0.1	185	181
0.5	270	272
1	316	316



- 2 acoplanar jets +MET (D0)
  - ➔ For β =0: M_{LQ} >214 GeV

- 3^{rd}: Searches in the τb τb and bb + MET





➔ Charge 4/3, $\beta(LQ \to \tau b)$ =1, M_{LQ} > 210 GeV

➔ Charge 1/3, $\beta(LQ \to \nu b)$ =1, M_{LQ} > 252 GeV

SuperSymmetry

- Relates fermion ⇔ bosons ➔ 1 supersymmetric partner for each SM particle
- New quantum number: R-parity, Rp = $(-1)^{3(B-L)+2S}$
- Superpartners should be heavy (not observed) ➔ SUSY is broken
- Minimal field content of the MSSM (Mininal SUSY):

spin 0	spin 1/2	spin 1
squarks: $\tilde{q}_R, \tilde{q}_L$	q	
	gluinos: $\tilde{g}$	g
sleptons: $\tilde{\ell}_R, \tilde{\ell}_L$	ℓ	
h, H, A	neutralinos: $\tilde{\chi}^0_{i=1-4}$	Z^0, γ
$H^\pm$	charginos: $\tilde{\chi}^\pm_{i=1-2}$	$W^\pm$

➔ A priori > 100 parameters

➔ Need to define a specific breaking scheme

Some SUSY models

- mSUGRA: gravity mediated SUSY breaking

  ➔ M_0, $m_{1/2}$, A_0, tan β, sign(μ)

  M_0: common scalar mass at GUT scale
  $M_{1/2}$: common gaugino mass at GUT scale
  A_0: common trilinear coupling at GUT scale
  sign(μ): sign of higgsino mass parameter
  tan β: ratio of Higgs vev's

  - Rp conserved
    - ➔ SUSY particles pair-produced
    - ➔ Cascade decay to the lightest sparticle (LSP)
    - ➔ If LSP = neutralino ➔ Missing transverse energy (MET)
  - Rp not conserved
    - ➔ Single production of sparticles possible

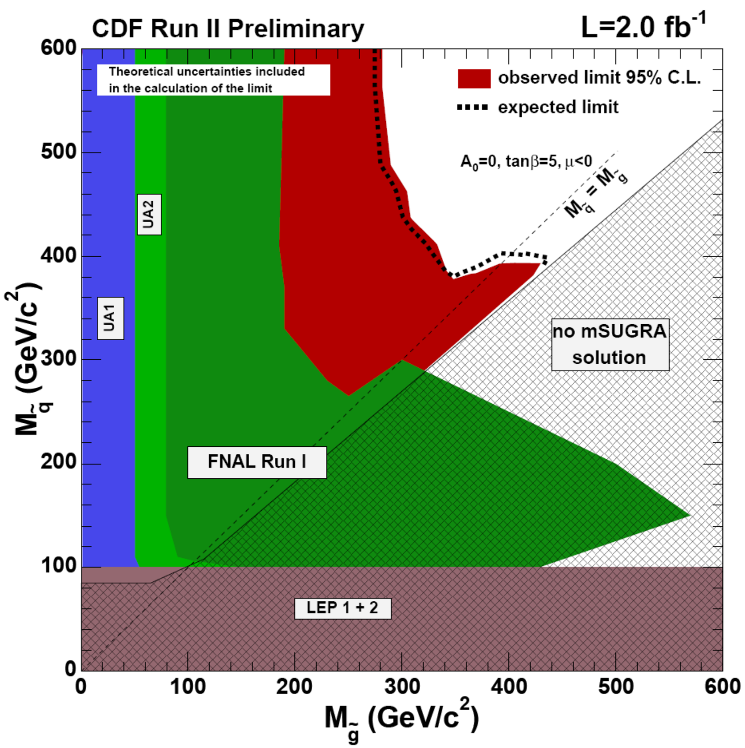
- GMSB: gauge mediated SUSY breaking
  - ➔ The LSP is a light gravitino
  - ➔ The phenomenology depends and the next-to-LSP and its lifetime

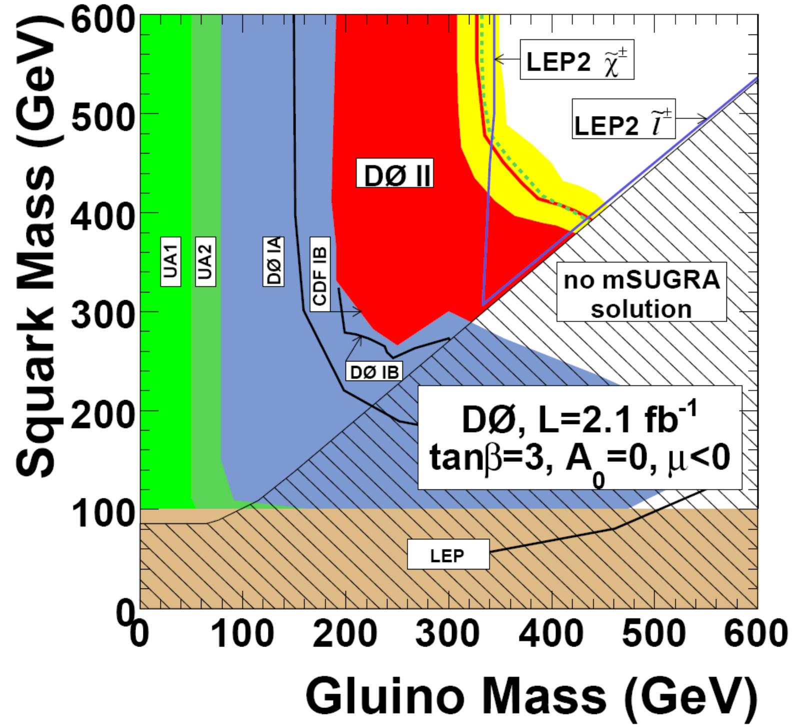
Squarks and gluinos

[D0, PLB 660 (2008) 449]
[CDF, PRL 102 (2009) 121801]

- One of the main stream at the Tevatron: squarks and gluinos produced via strong interaction
  - ➔ Signature: 2-4 jets + MET
  - ➔ Large cross section, large background

$$p\bar{p} \to \tilde{q}\tilde{q} \to q\tilde{\chi}^0 \; q\tilde{\chi}^0 \; X$$
$$p\bar{p} \to \tilde{g}\tilde{q} \to q\bar{q}\tilde{\chi}^0 \; q\tilde{\chi}^0 \; X$$
$$p\bar{p} \to \tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}^0 \; q\bar{q}\tilde{\chi}^0 \; X$$

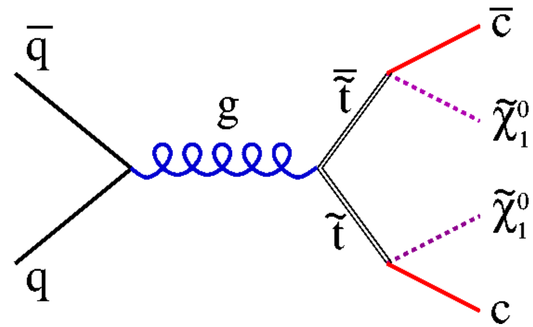




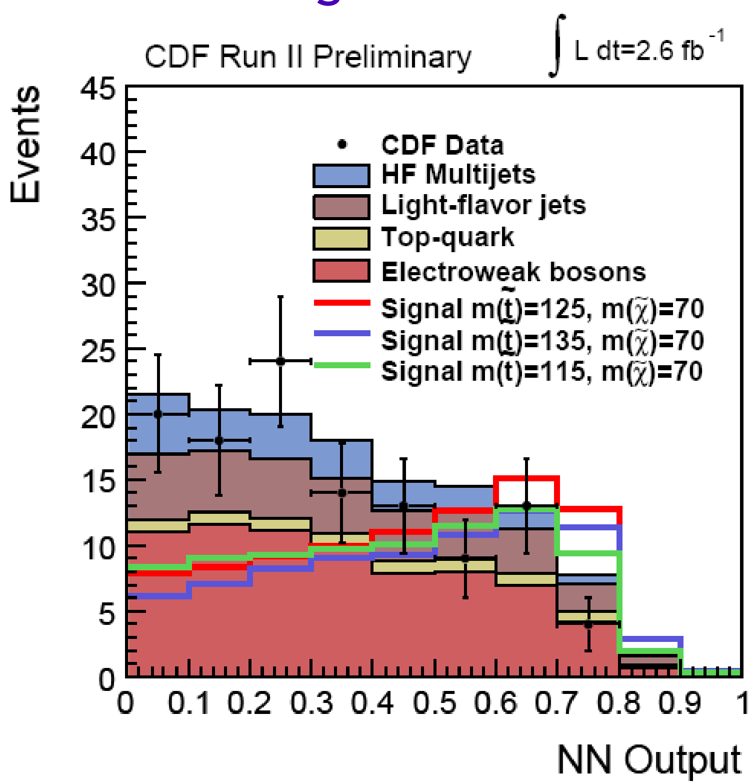
- ➔ gluinos: m > 208 GeV (CDF), 308 Gev (D0) (for all squarks masses)
- ➔ squarks: m >380 GeV (CDF, D0) (for all gluinos mass)
- ➔ In mSUGRA: regions not accessed by LEP excluded

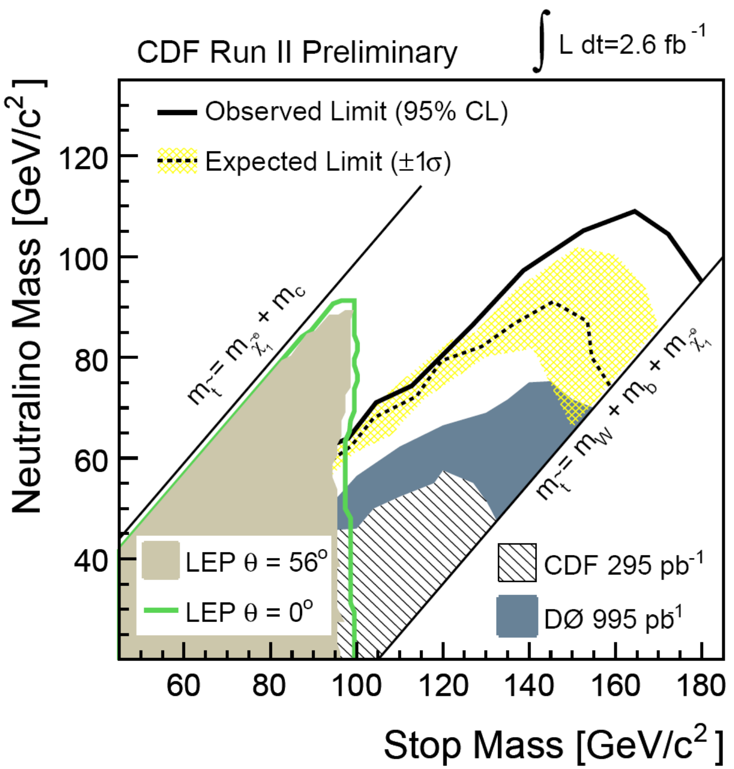
Stop

- Stop and sbottom expected to be light
- For light stop $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ not allowed
  - ➔ Dominant decay mode depends on other SUSY masses
  - ➔ If stop is next-to-LSP: $\tilde{t} \rightarrow c + \tilde{\chi}_1^0$



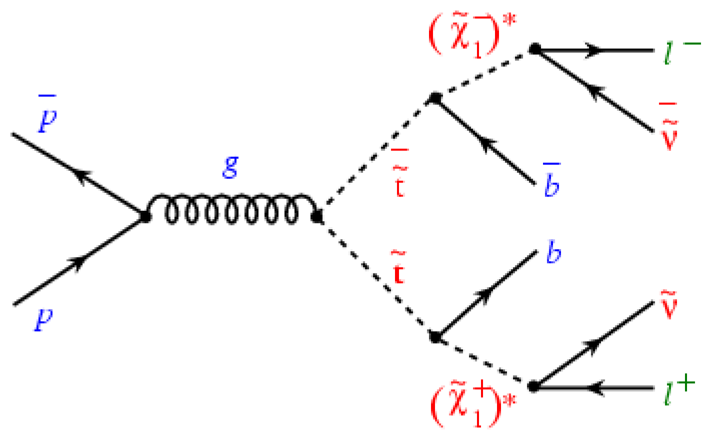
- New CDF analysis exploiting charm tagging (reduces background from bottom jets)

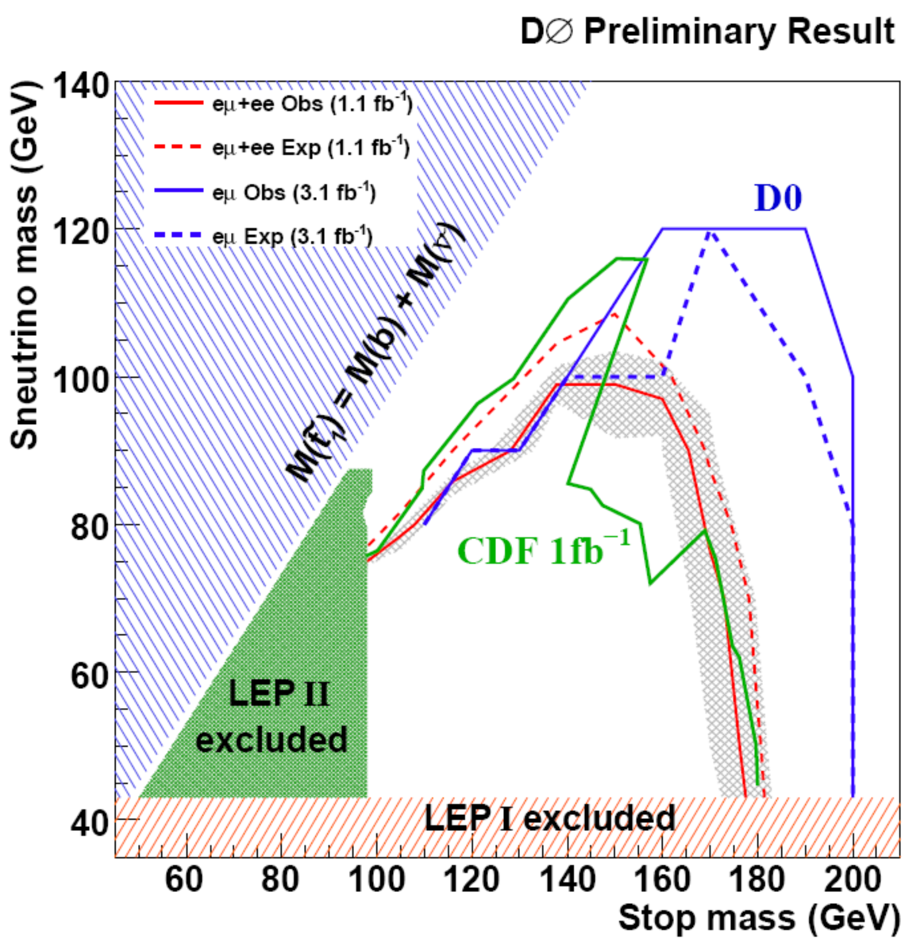




Stop searches in the di-lepton channel

- If sneutrinos lighter than stop: dominant decay $\tilde{t} \to b + \ell + \tilde{\nu}$ with $\tilde{\nu} \to \nu + \tilde{\chi}_1^0$
  - ➔ Signature similar to $t\bar{t}$ di-leptons but with soft leptons and different kinematics
  - ➔ Most sensitive channel: 2b + e + μ + MET





- D0: 3.1 fb^{-1}, eμ channel only
- CDF: 1.1 fb^{-1}, all channels
  - ➔ Difficult backgrounds: QCD multi-jets, lepton+fake, similar topologies (Z ➔ ττ, $t\bar{t}$, WW)
  - ➔ Exlusion limits above top mass: M(stop) > 180 – 200 GeV

Stop searches in top-like events

[D0, PLB 674(2009)4]

- If chargino is lighter than stop: top-like decays dominant

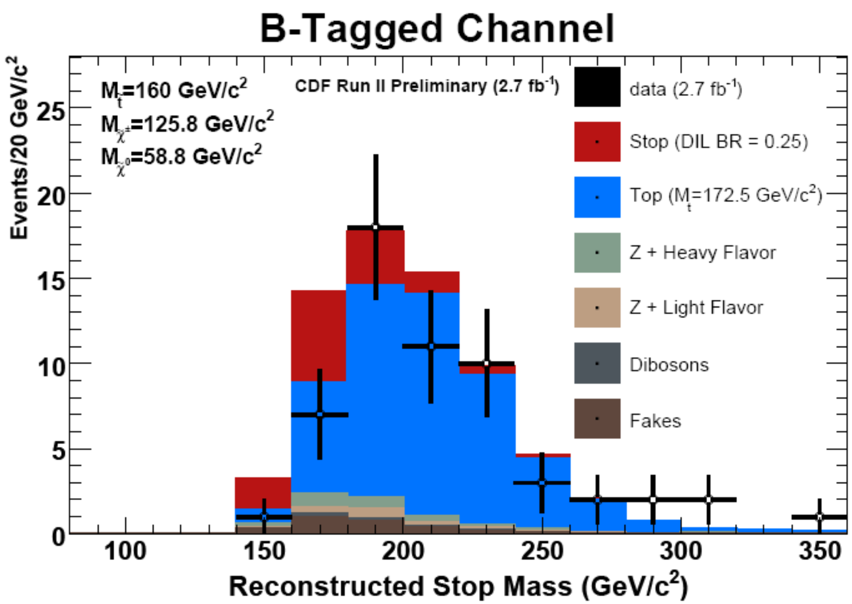
$$\tilde{t} \to b\tilde{\chi}^{+} \to b\ell\nu\tilde{\chi}^{0}$$

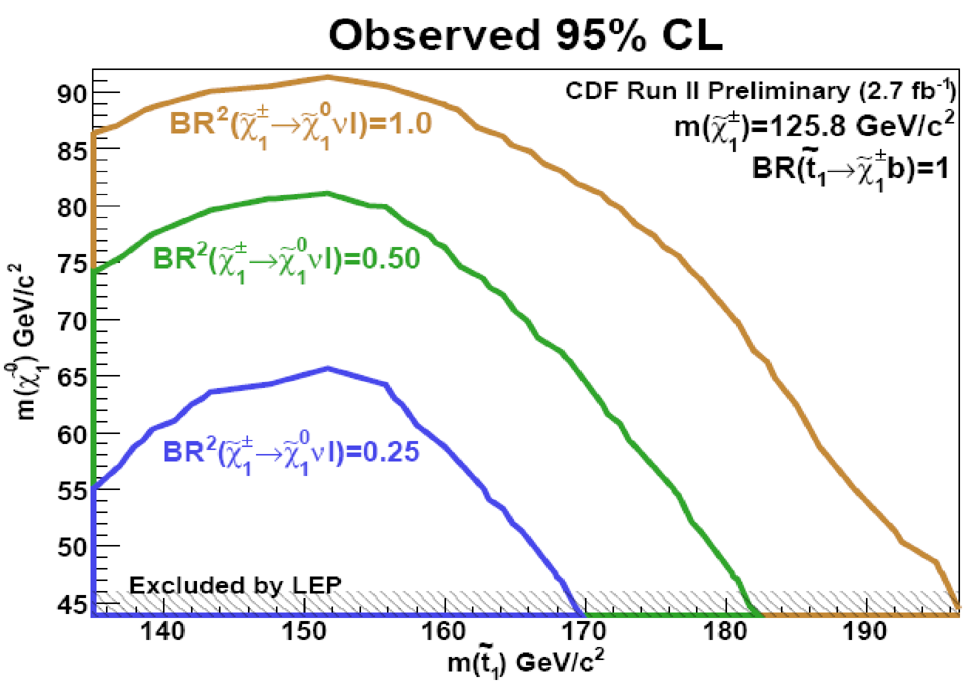
➔ Search stop in lepton+jet top sample (D0)

➔ Search stop in top di-lepton sample (CDF)

➔ Differences in mass distribution of stop and kinematics

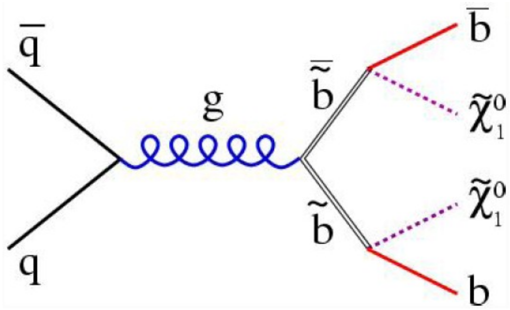
- Extract limits in 3D-space: $m_{\tilde{t}}, m_{\tilde{\chi}_1^{\pm}}, m_{\tilde{\chi}_1^0}$





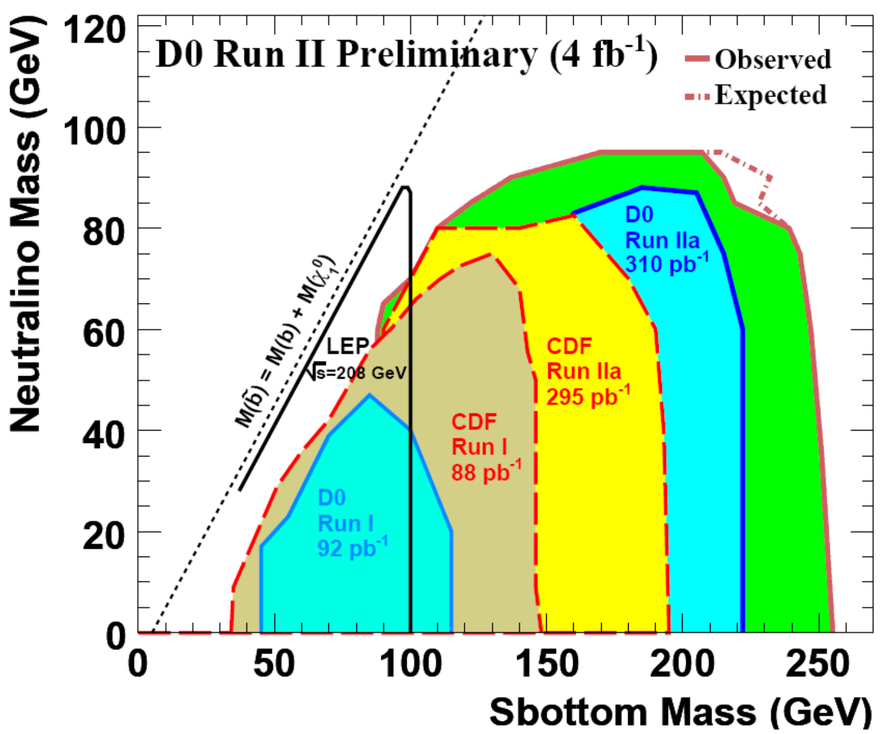
Sbottom

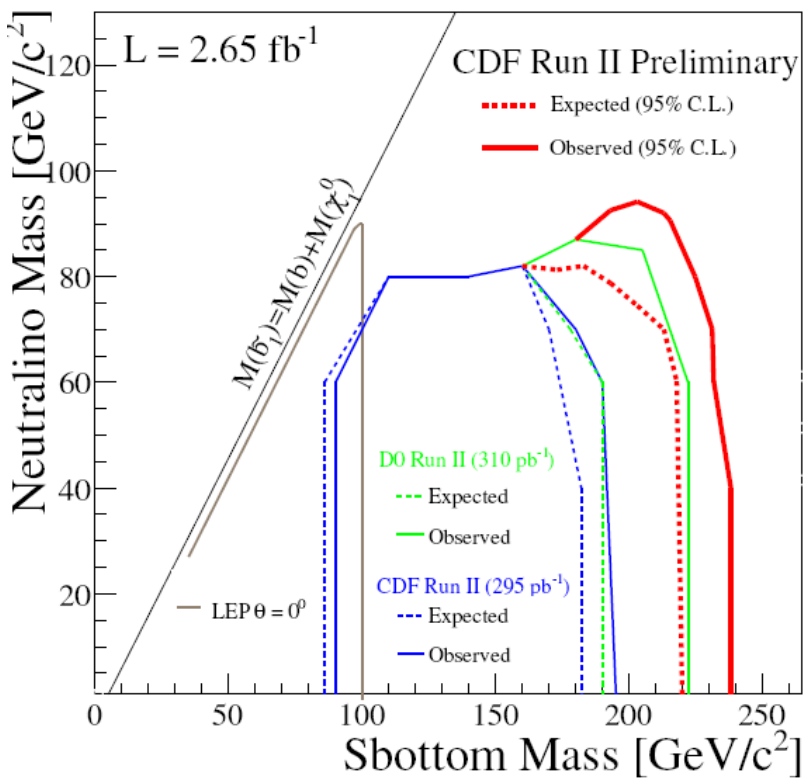
- At large tan β, sbottom may the lightest colored particle
- Decay: $\tilde{b} \to b + \tilde{\chi}_1^0$



➔ 2 b-jets + MET

➔ Visible energy in the event depends on $\tilde{b} - \tilde{\chi}_1^0$ mass difference Δm



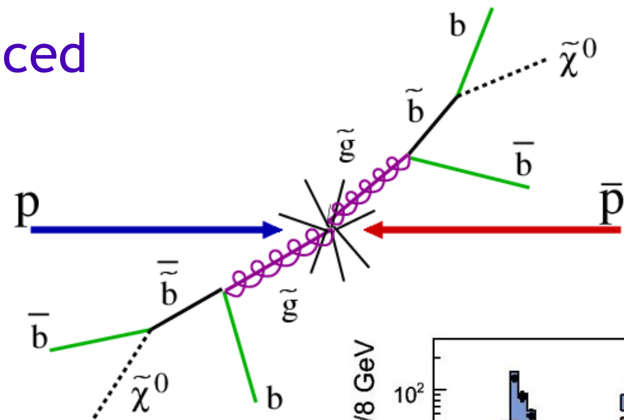


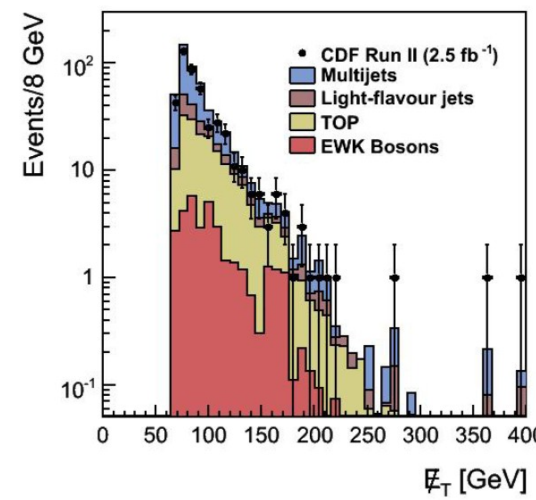
➔ sbottom up to masses ~ 250 GeV are excluded

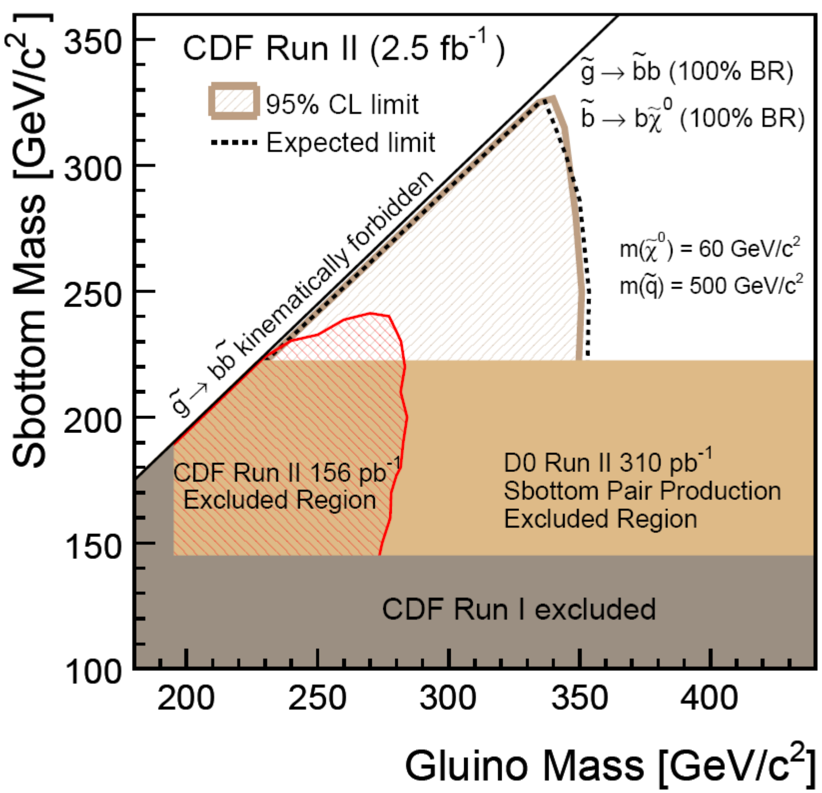
Sbottom: an alternative way

[CDF, PRL 102(2009)221801]

- If sbottom is light enough, it will be produced via gluino decay
- For similar masses gluino cross section is larger than sbottom cross section







➔ 4 b-jets + MET

➔ Low background signature

➔ But large model dependences

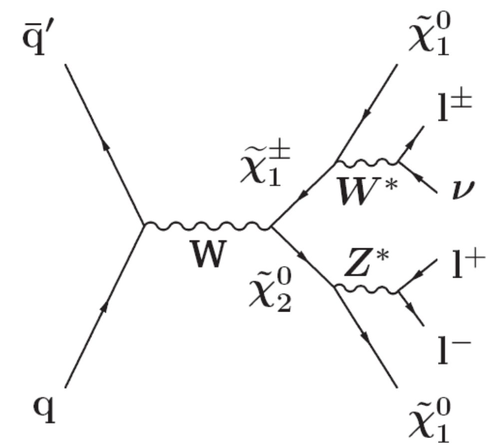
➔ Dependence on gluino mass

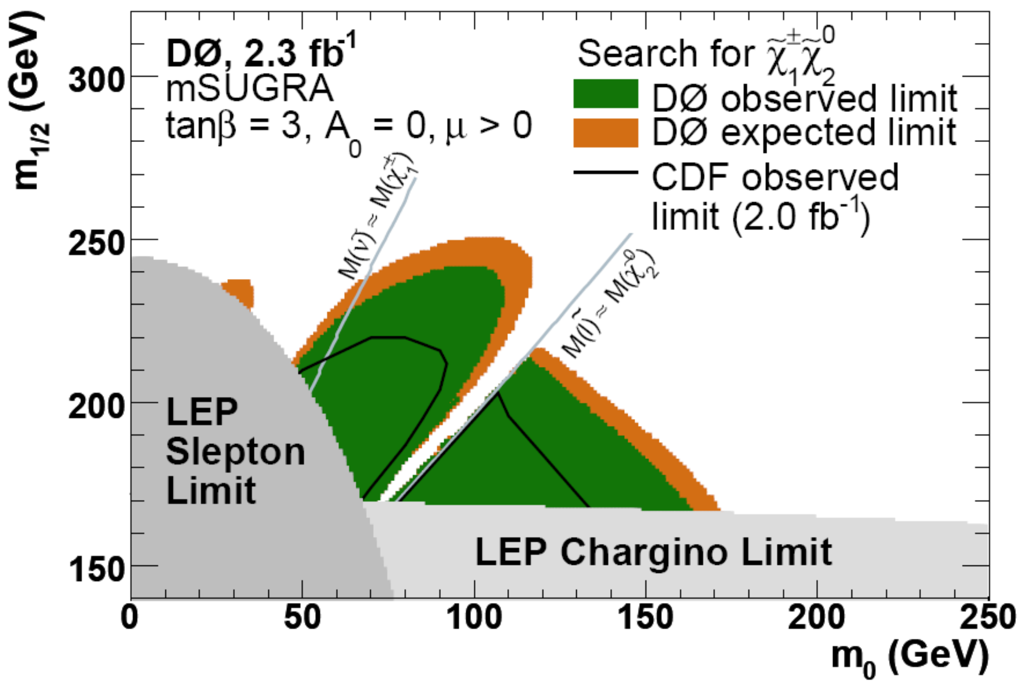
➔ Competitive results for M(gluino) ~ M(sbottom)

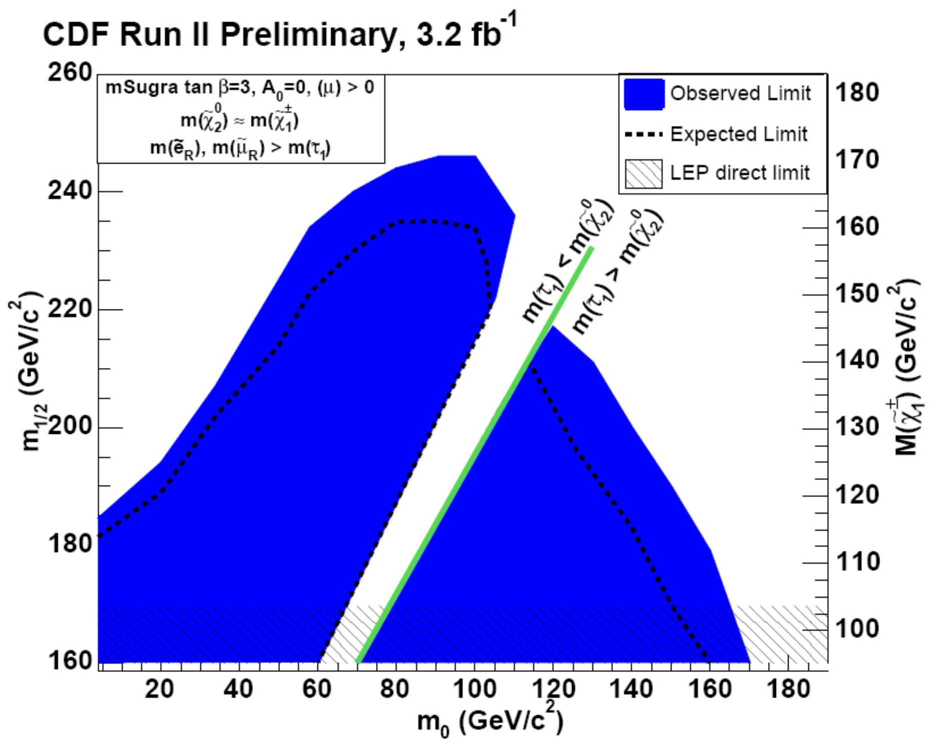
Search for Charginos and Neutralinos

[arXiv:0901.0646]

- One of the golden channel at Tevatron for SUSY: $\tilde{\chi}^{\pm}\,\tilde{\chi}^0_2 \rightarrow 3\ell + MET$
  - ➔ Cross section (EW) relatively small
  - ➔ Low P_T leptons
  - ➔ But clean signature: 3 leptons+ MET



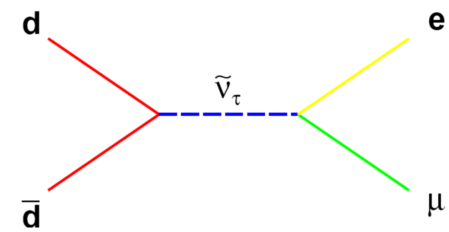


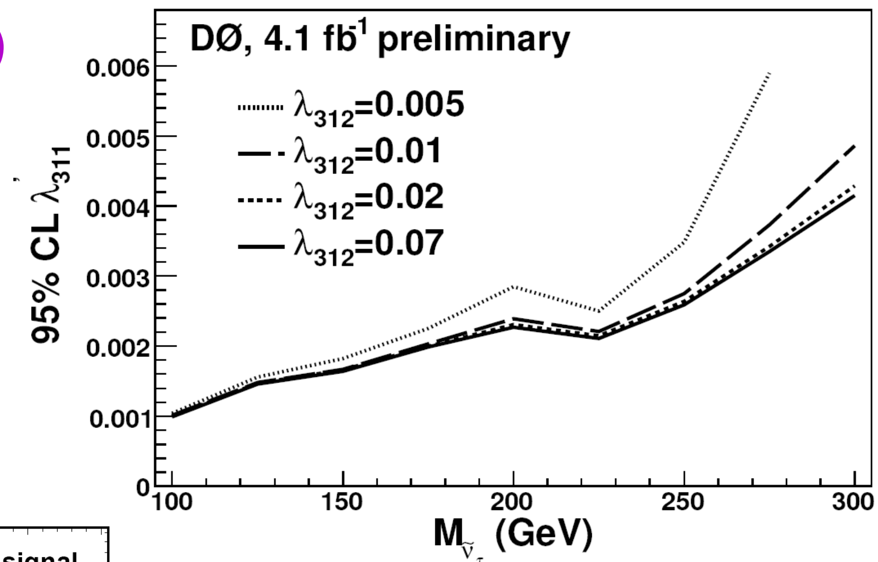


- ➔ Chargino masses up to 176 GeV probed
- ➔ Sensitivity degrades with increasing tan β

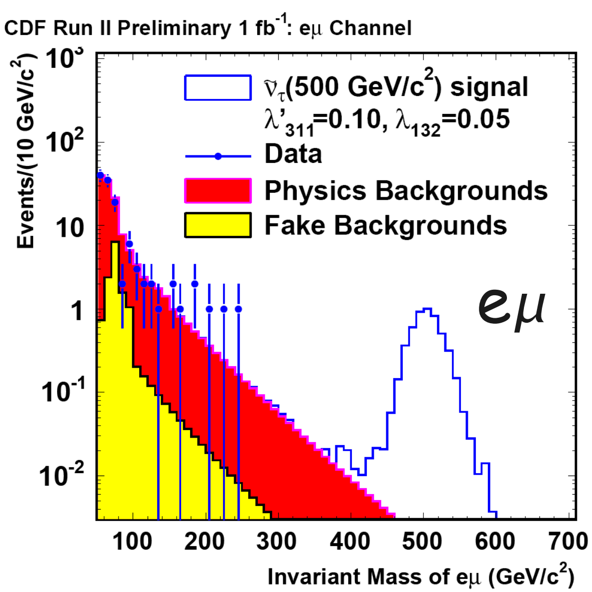
Rp-Violating SUSY at the Tevatron

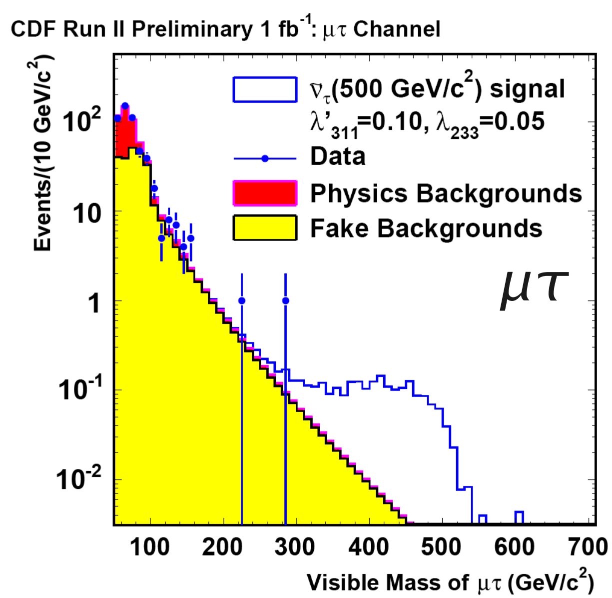
- If RpV, resonant production of sneutrino possible
  - ➔ Very clean topologies: 2 isolated leptons $e\mu$, $e\tau$, $\mu\tau$
  - ➔ Low SM background (WW, $Z/\gamma^* \rightarrow \tau\tau$)
- D0: $e\mu$ channel with 4.1 fb^{-1}
- CDF: 1 fb^{-1} only but $e\tau$ and $\mu\tau$ also investigated

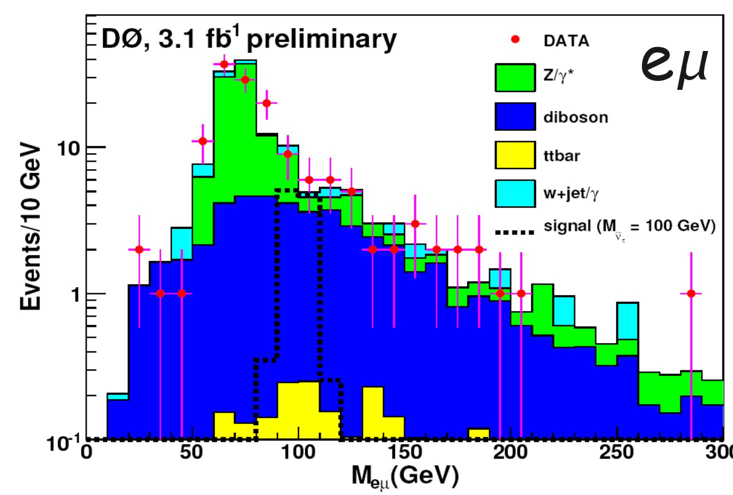




↘ Limits beyond LEP results

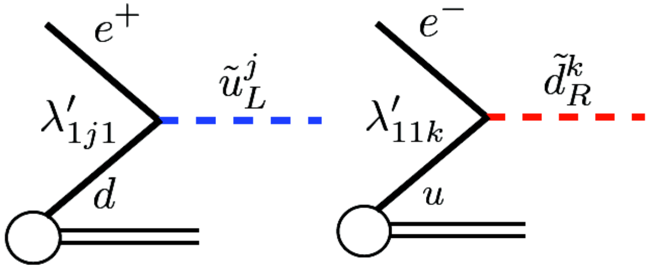






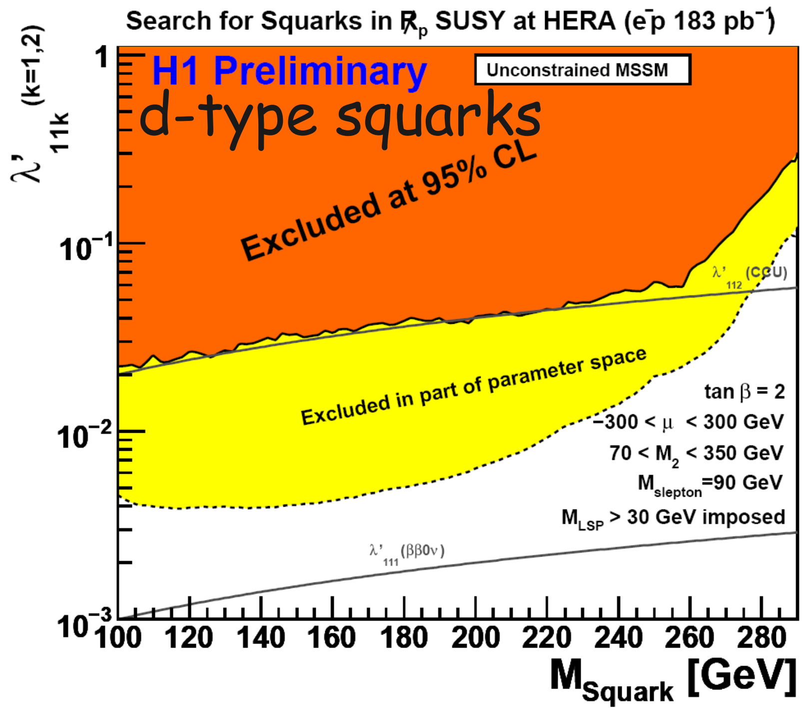
Rp-Violating SUSY at HERA

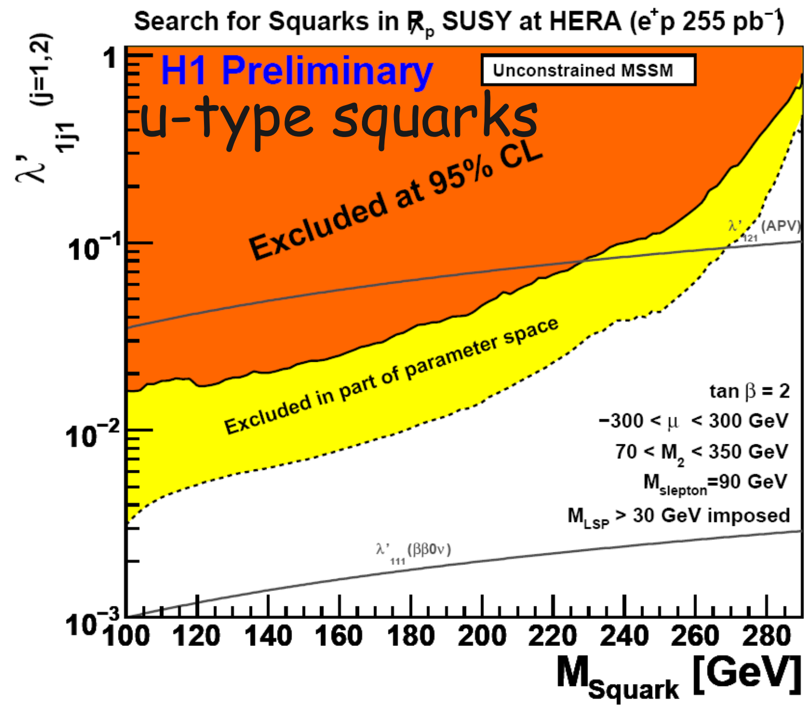
- If RpV, resonant production of squarks possible at HERA



- e-j, ν-j decays and cascade decays via gauginos
  ➔ Many topologies to search for

- Limits derived on squark mass and λ'_{1j1} and λ'_{11k} with j,k=1,2





- For λ' = 0.3 ➔ u-type squarks excluded up to 275 GeV
  ➔ d-type squarks up to 290 GeV

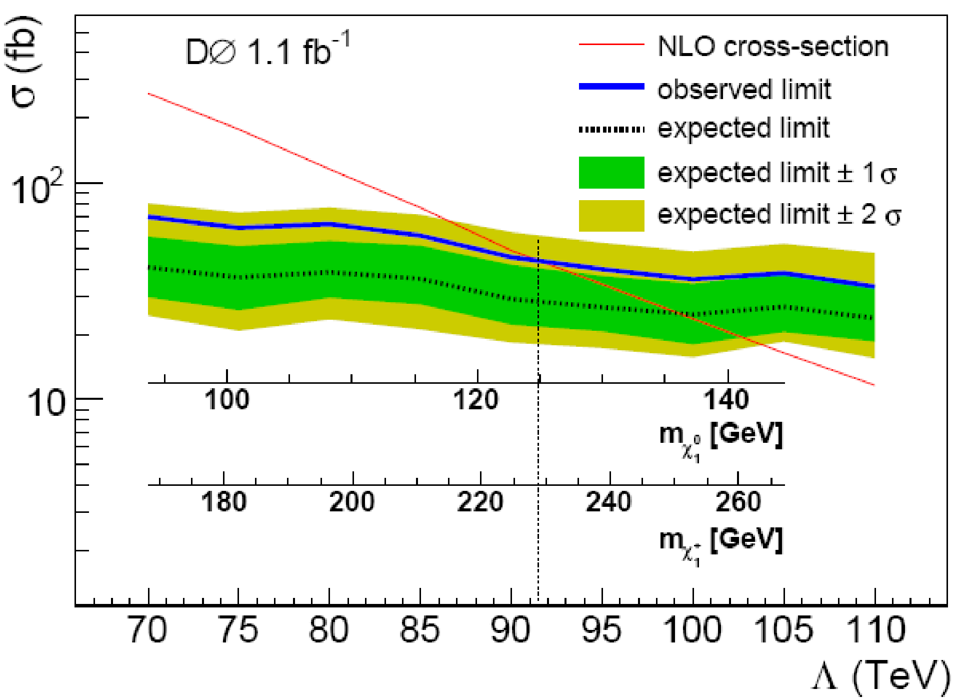
GMSB SUSY: in $\gamma\gamma$ + MET

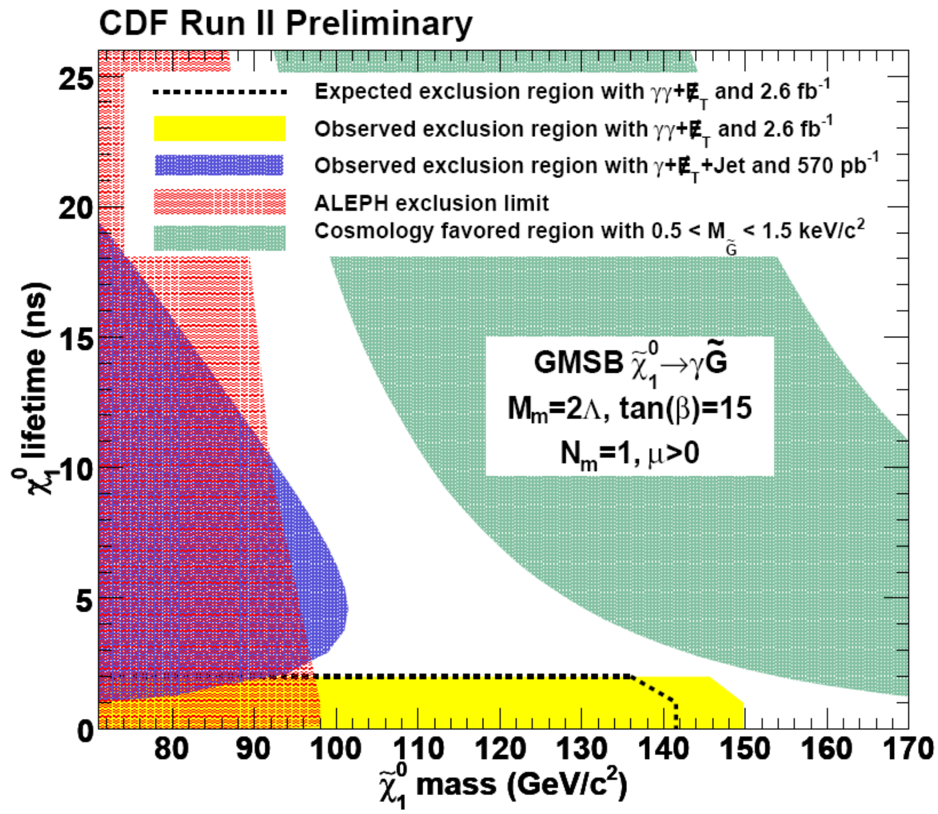
[D0, PLB 659(2008)856]

- In GMSB, usually, allows neutralino decay in a photon and a gravitino (LSP)

$$\tilde{\chi}_1^0 \to \gamma \tilde{G} \qquad (\tau_{\tilde{\chi}_1^0} < 2 \text{ ns})$$

➔ Final states with 2 γ + MET





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

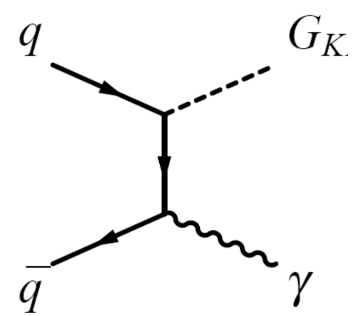
$$m(\tilde{\chi}_1^0) > 149 \text{ GeV} \quad (\tau_{\tilde{\chi}_1^\pm} = 0 \text{ ns})$$

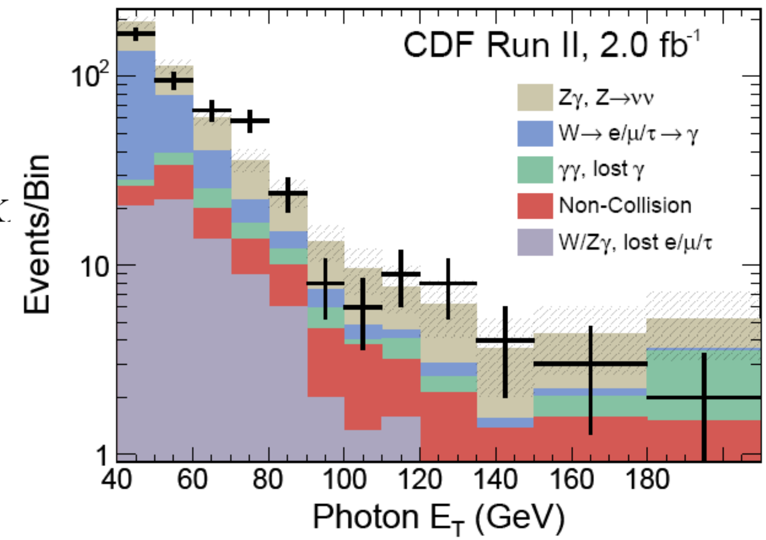
Large Extra Dimensions ?

[CDF, PRL 101(2009)181602]

- If gravity propagates in 4+n dimensions, the fundamental Planck scale M_D could be small

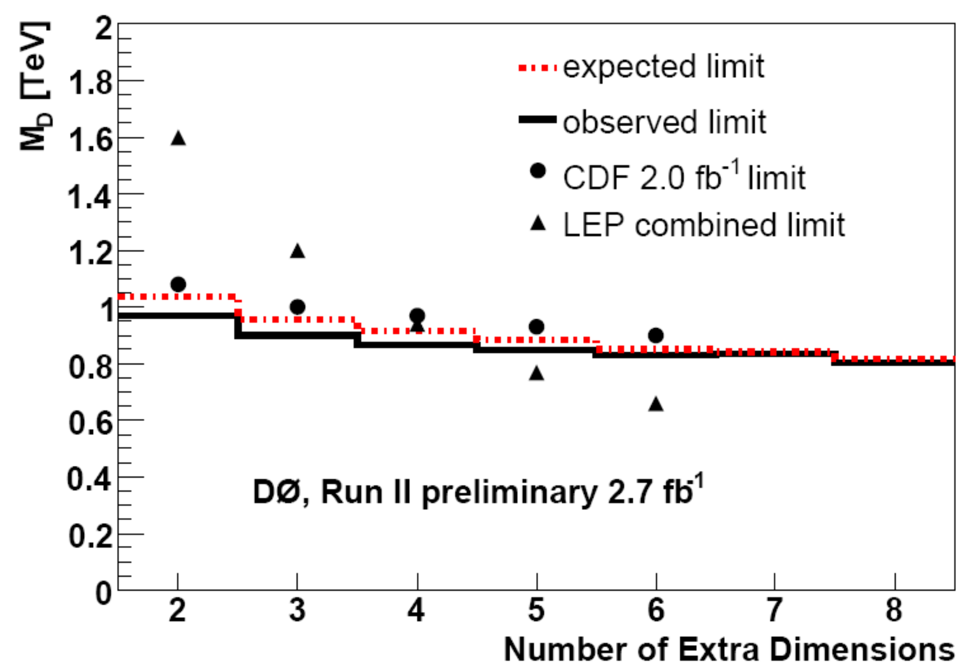
$$M_{Pl}^2 = 8\pi R^n M_D^{n+2}$$





- Real graviton emission the Tevatron:
  - ➔ g + G_{KK} ⇒ mono jet +MET
  - ➔ γ + G_{KK} ⇒ γ + MET
  - ➔ Directly sensitive to M_D
- CDF: combine both, D0 only γ
- Lower limits on M_D in GeV:

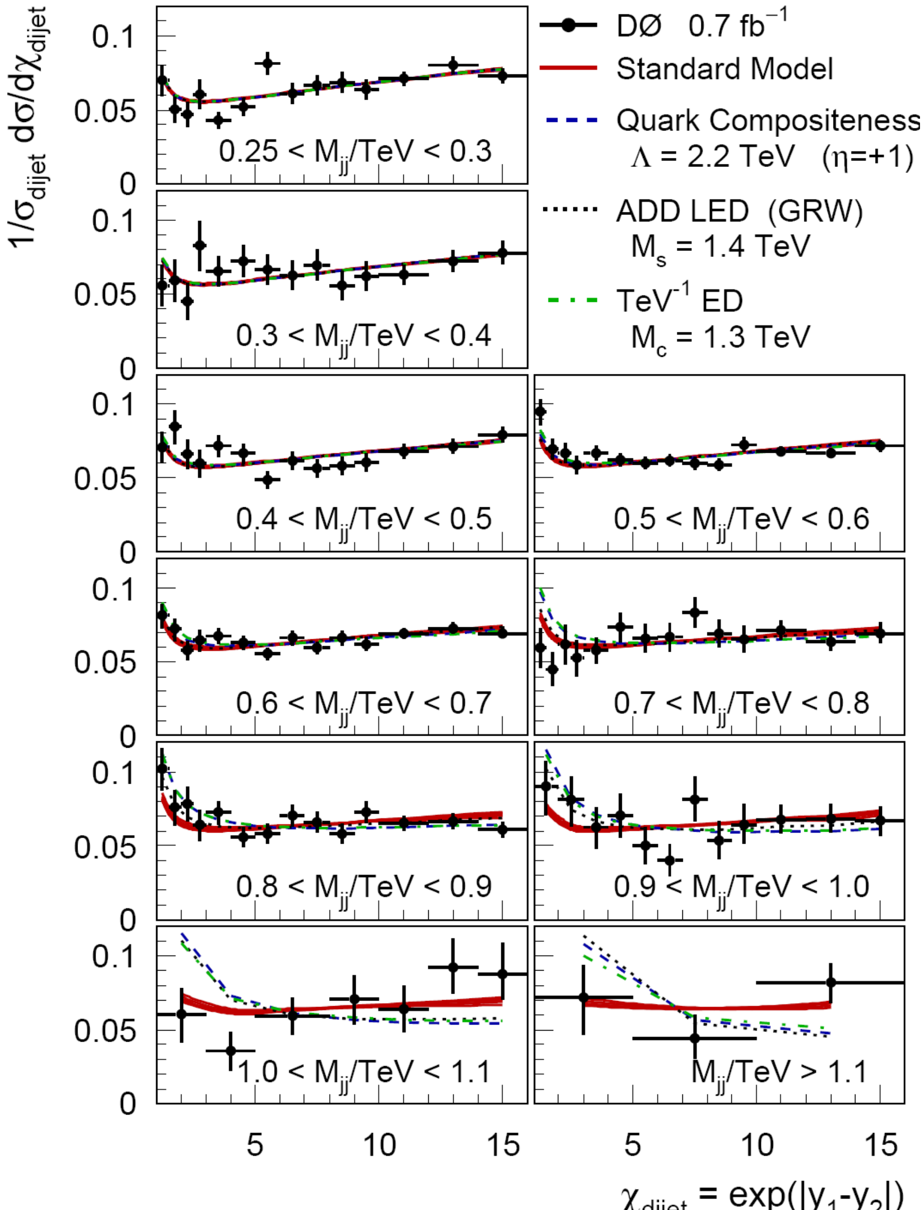
n	CDF	D0
2	1400	970
6	940	831



Indirect LED Searches at the Tevatron

[D0, PRL 102(2009)051601]
[arXiv:0906.4819]

- Virtual KK gravitons exchange
  - ➔ Enhancement of the production of fermion or boson pairs
  - ➔ the Drell-Yann or di-photon cross sections
  - ➔ di-jets
- Sensitivity on the effective Planck scale Ms (ultraviolet cutoff)
  - ➘ D0: combining di-e and di-γ:
    Ms > 1.62 TeV (GRW formalism)
  - ➘ CDF: di-jets:
    Ms > 1.66 TeV (GRW)
    - ➔ Uses jet angular distributions $\chi = \exp(|y_1 - y_2|)$



Indirect LED Searches at HERA

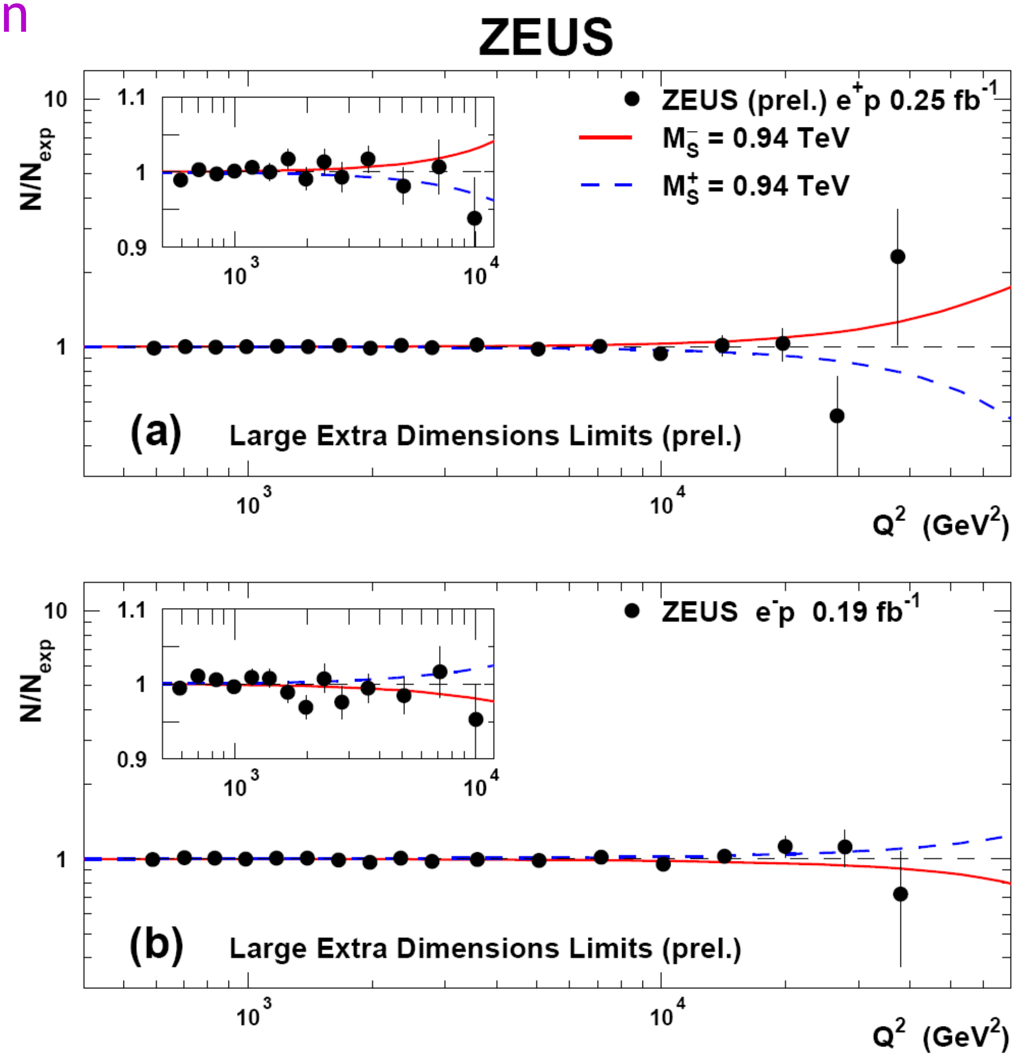
- At HERA: graviton exchange can affect eq → eq scattering

➔ Contact interaction term with an effective coupling:

$$\eta_G = \frac{\pm 1}{M_s^2}$$

➔ Look for deviations in the ep NC DIS cross section

➘ Limit from all ZEUS data: Ms(±1) = 0.94 TeV



Signature Based Searches

- Facing the large variety of BSM models ....

  ➔ Tendency to develop more general signature based searches

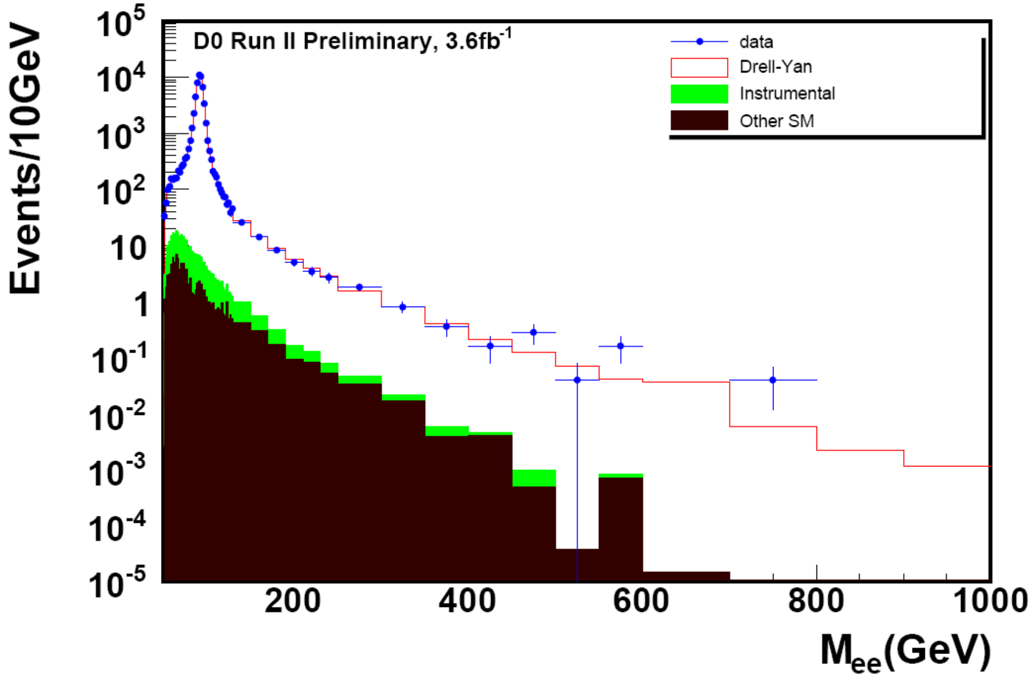
  ➔ Different possible BSM interpretations of a same signal

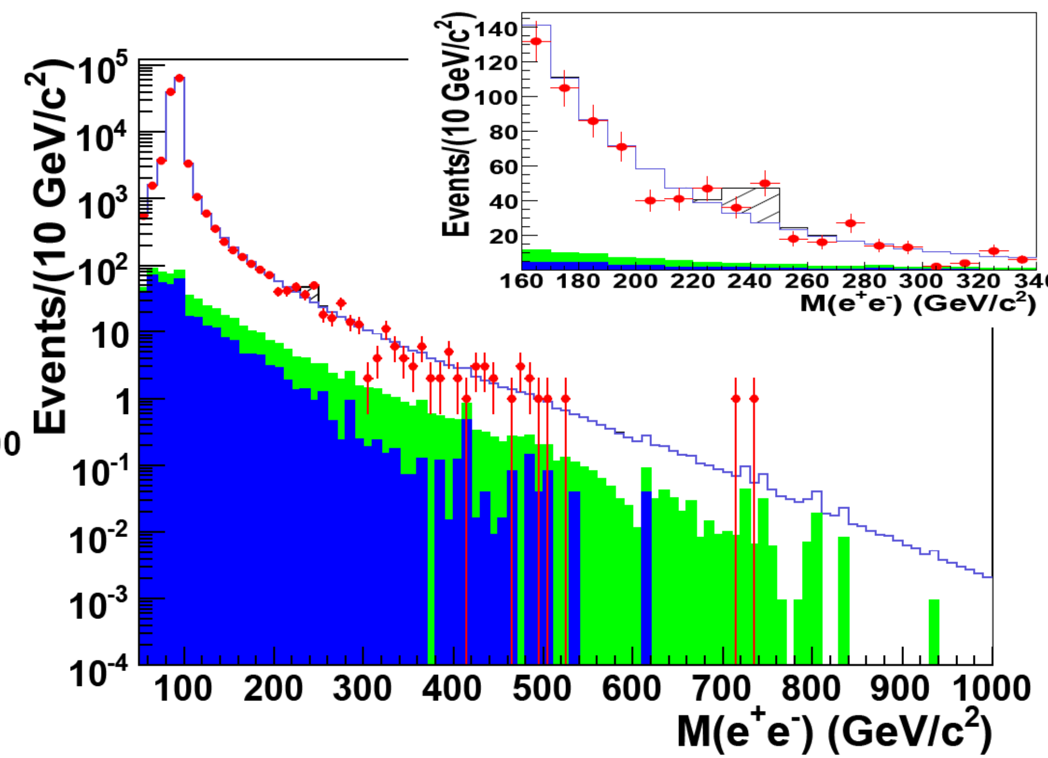
    - Look for new narrow resonances
    - Topologies with low SM expectation
    - Topologies specific particles
    - More general: all possible final states ...

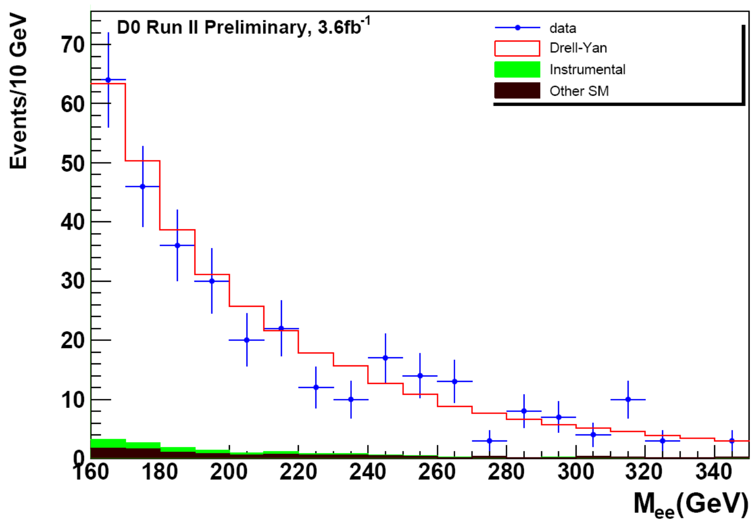
Di-electron Resonances

[CDF, PRL 102(2009)031801]

- ee resonance → new Z' boson ?







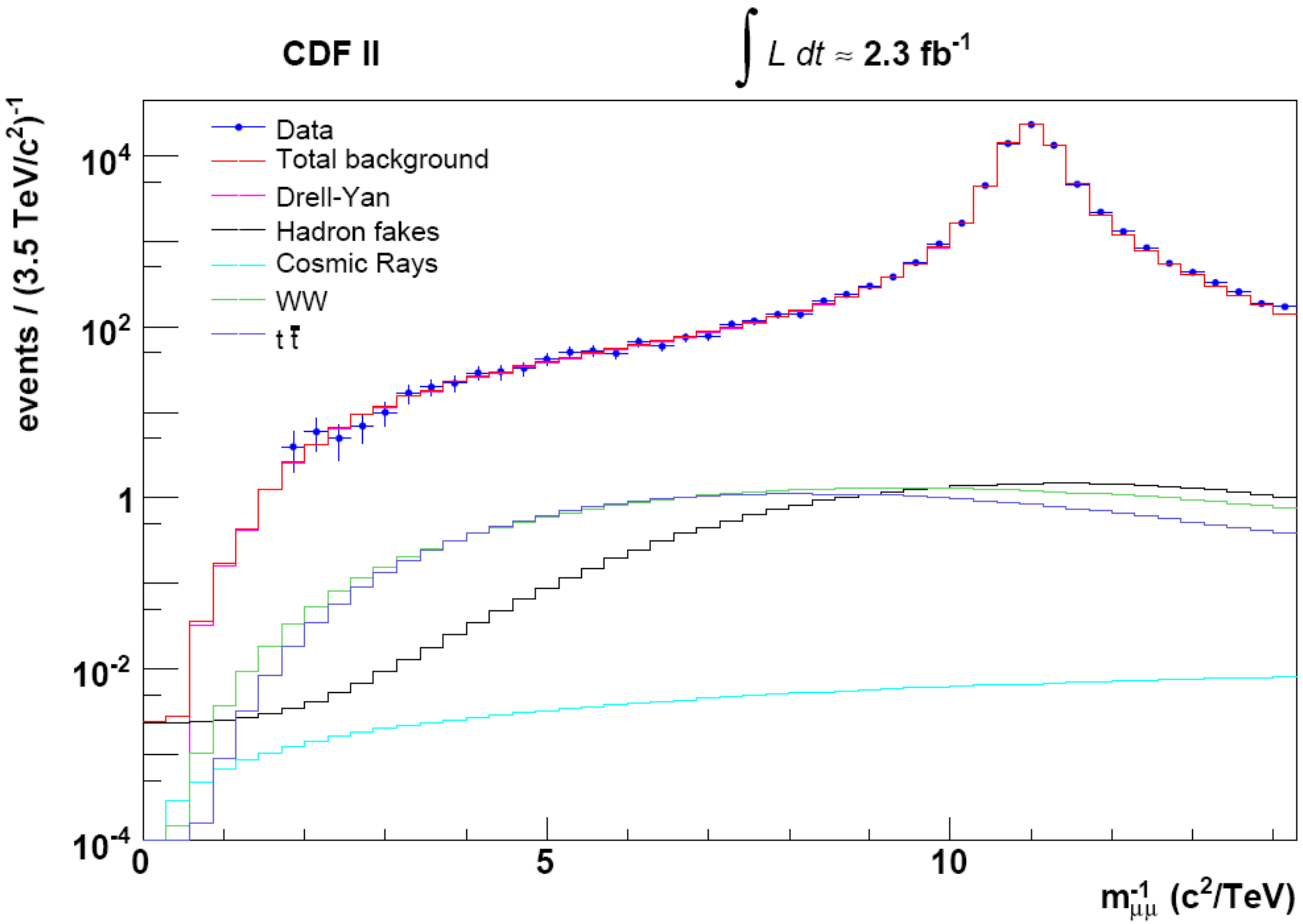
➔ CDF fluctuation at 240 GeV not confirmed by D0

➔ $M_{Z'}$ < 963 GeV excluded.

Di-muon resonances

[CDF, PRL 102(2009)031801]

- Use m^{-1} for a constant resolution



➔ Data well described

➔ Z' excluded up to 1030 GeV

➔ Limits set also on other models

Di-jet resonances

[CDF, PRD 79(2009)112002]

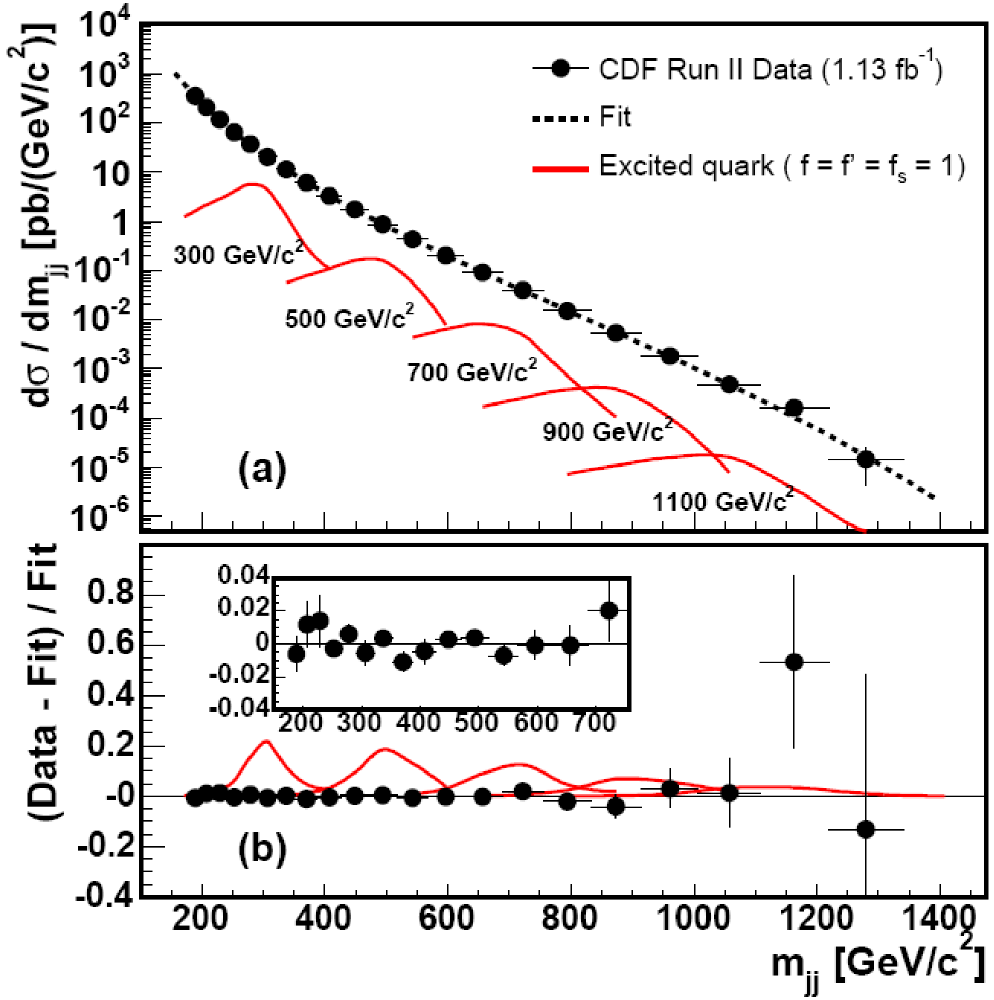
- Investigate the di-jet distribution
- Poorer resolution than for leptons
- Large QCD background

➔ Good agreement with NLO pQCD predictions

➔ Excited quarks excluded up to 870 GeV (f=f'=fs)

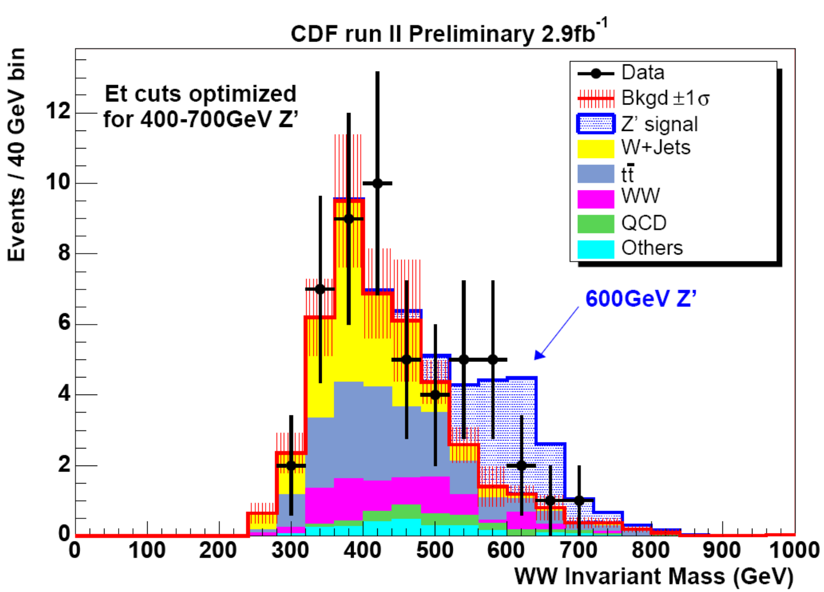
➔ W' up to 840 GeV

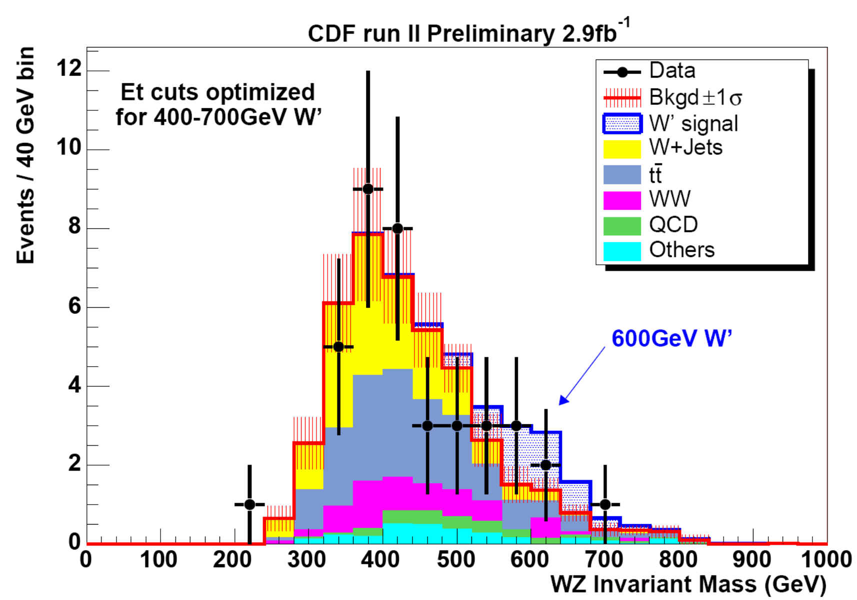
➔ Z' up to 740 GeV



Heavy resonances: $X \to VV$

- Search for $X \to WW/WZ \to (e\nu)(jj)$ by CDF
- Analysis based on SM di-boson production studies
  - ➔ Look for possible excess (e + 2 jets + MET)
- Selection: ➔ $W \to e\nu$ with 2 solutions
  - ➔ di-jets in [65,95] for WW
  - ➔ di-jets in [70,105] for WZ



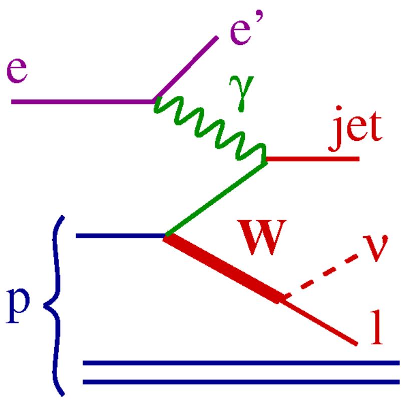


➔ Small fluctuation in WW at ~ 600 GeV

➔ Limit set within different models

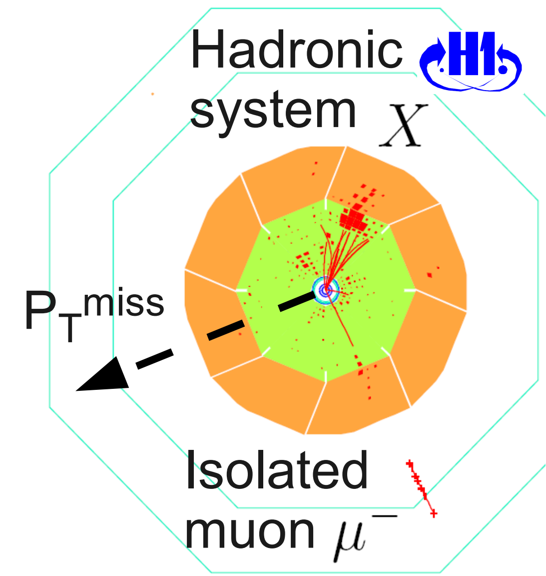
Isolated Leptons at HERA

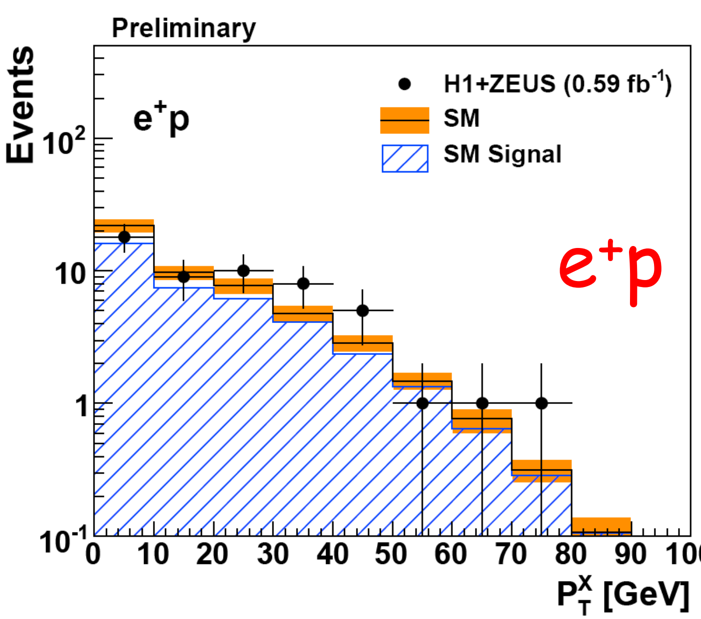
[ZEUS, PLB 672(2009)106]
[arXiv:0901.0488]

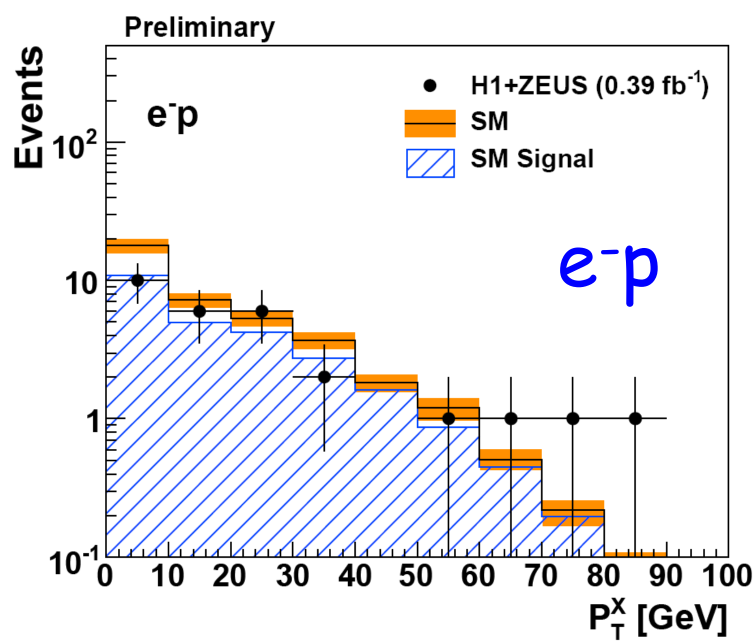


SM W: $\sigma \sim 1.3$ pb

- Events with high P_T e, μ, P_T^{miss} and hadronic system (P_T^X)
  - ➔ H1, for $P_T^X > 25$ GeV, in e+p only an excess of data events (2.4σ)
  - ➔ Not confirmed in ZEUS analysis
- H1+ZEUS combined data: 0.98 fb^{-1}







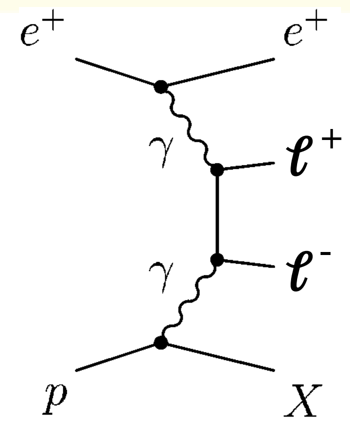
- For $P_T^X > 25$ GeV, in e+p:

  data/SM:
  23 / 14.02 ± 1.94

➘ In e+p: 1.9σ positive fluctuation of data, driven by H1 events

Multi-Leptons at HERA

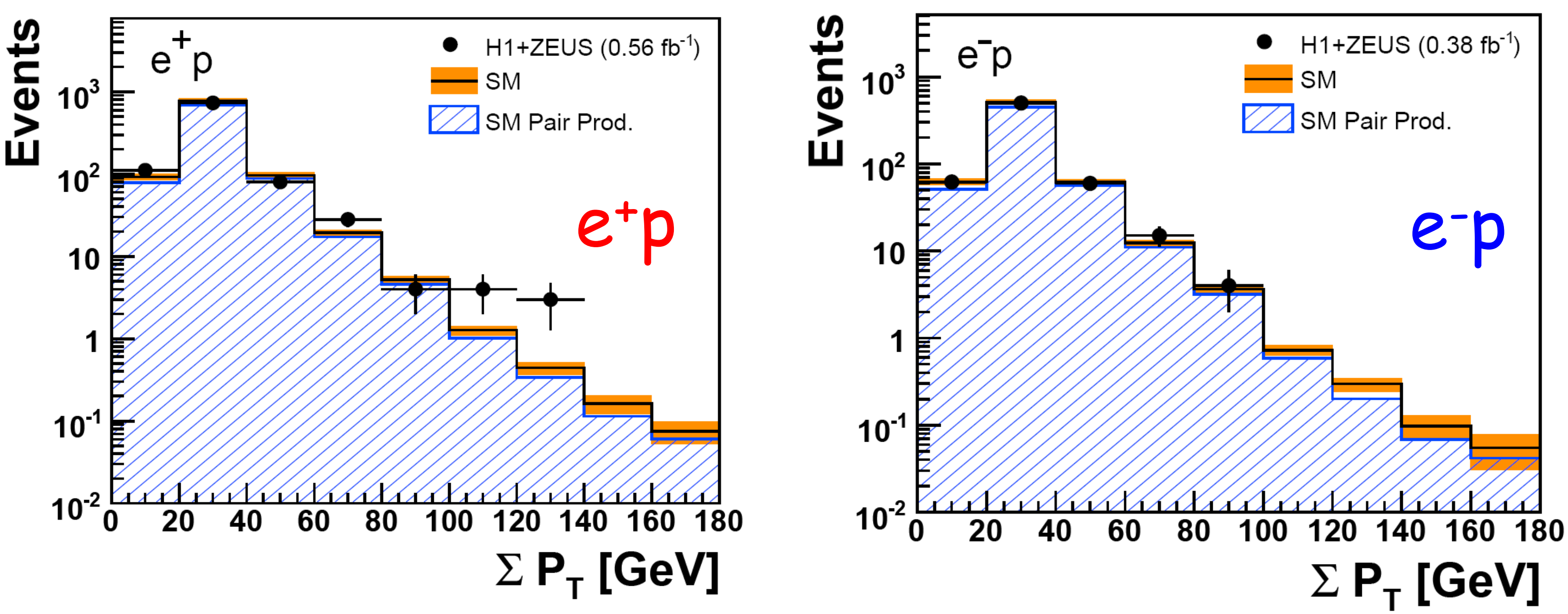
[arXiv:0907.3627]



σ ~ 1 pb (high P_T)

↘ Low and well controlled SM contribution

- Mainly produced via γ-γ in the SM
- Look for events with at least 2 isolated high-P_T leptons (e,μ)
  → ee, eee, eμ, $\mu\mu$, e$\mu\mu$
- H1+ZEUS combined analysis (0.94 fb^{-1})
  → ΣP_T : hardness of the events



→ Striking events observed for ΣP_T > 100 GeV by H1 and ZEUS

→ Only in e+p : 7 / 1.94 ± 0.17

↘ Probability of 0.4% (2.6σ)

Signature Based Searches with Photons

[arXiv:0906.0518]
[arXiv:0905.0231]

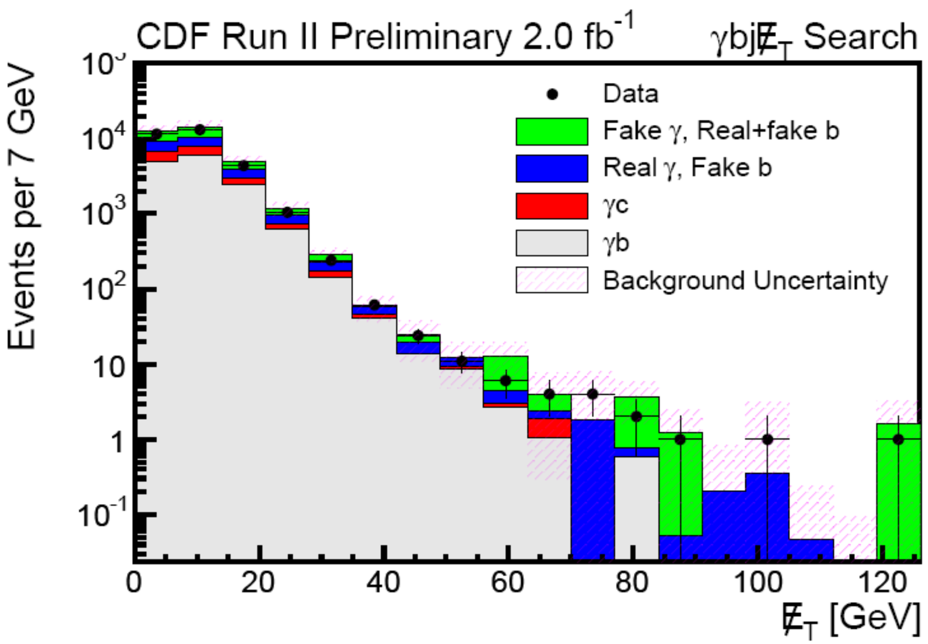
- Various topologies with high P_T photons investigated by CDF
  ➔ Model independent

- $\gamma\gamma$ + X, X = e, μ, τ, γ, MET with up to 2 fb^{-1}

- lepton +γ + b-jet + MET

# events	$e\gamma b\not\!\!E_T$	$\mu\gamma b\not\!\!E_T$	$(e+\mu)\gamma b\not\!\!E_T$
Predicted	18.4 ± 2.4	$12.6\ ^{+1.9}_{-1.6}$	$31.0\ ^{+4.1}_{-3.9}$
Observed	16	12	28

- γ + jet + b-jet + MET
  ➔ 617 (obs.) / 607 ± 114 (exp.)



➘ All consistent with SM expectations

General Searches

➘ The most general signature based search: investigate ALL possible topologies

- Search for deviations to the SM in many (all) final states
- Independent of any BSM assumptions: no specific selections
  - ➔ More general
  - ➔ Lower sensitivity than dedicated searches
- Allow a statistical quantification of observed discrepancies
- Performed by H1, CDF and D0, using different strategies

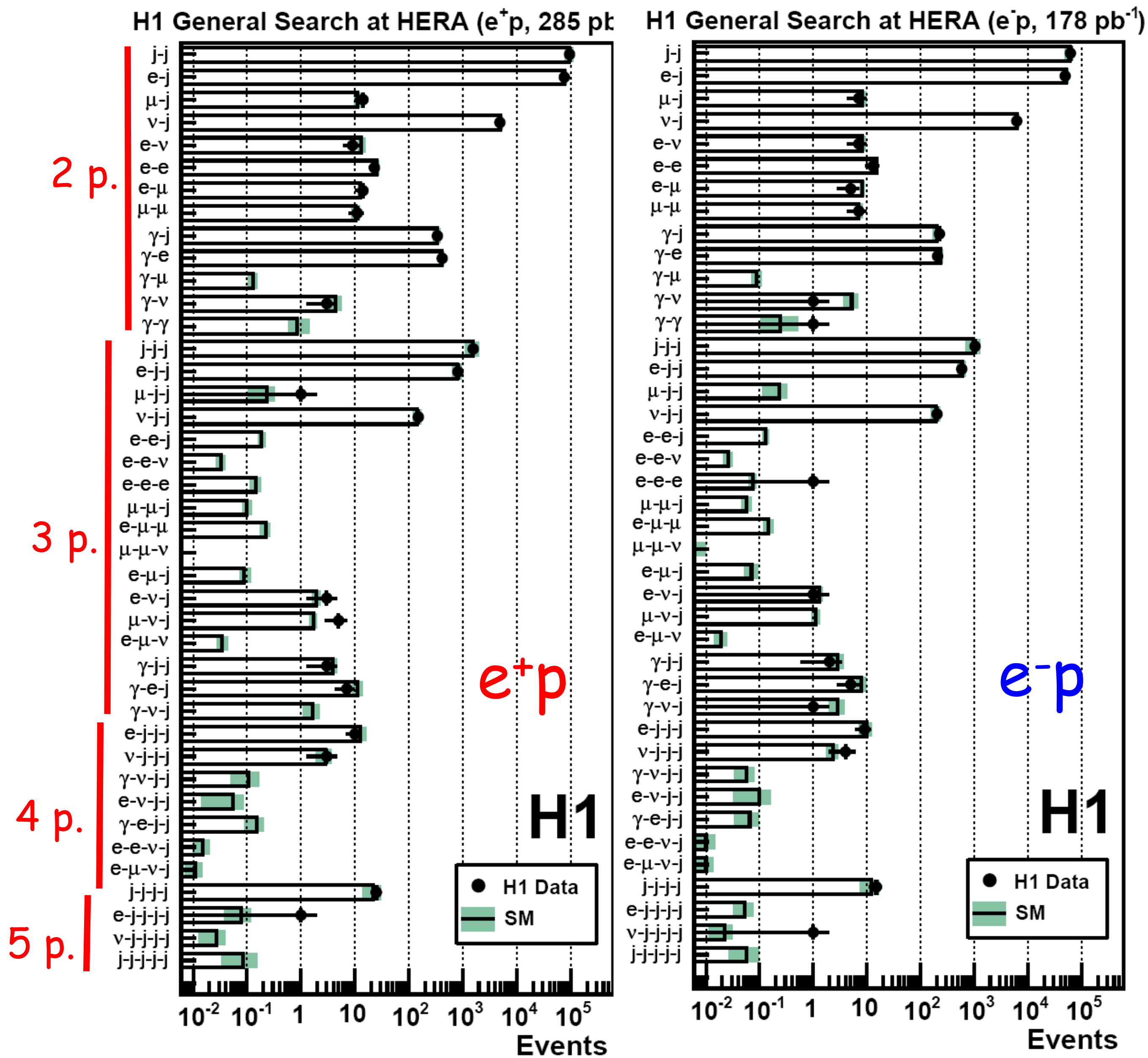
General Search at HERA

[H1, PLB 674(2009)257]

➘ Investigate all high P_T topologies

- Pioneered by H1, full HERA data, 463 pb^{-1}
- Isolated particles
  - ➔ e, γ, μ, jet, ν
- A common phase space
  - ➔ $P_T^{part} > 20$ GeV
  - ➔ $10 < \theta^{part} < 140$ deg.

➔ Good agreement with SM in most classes

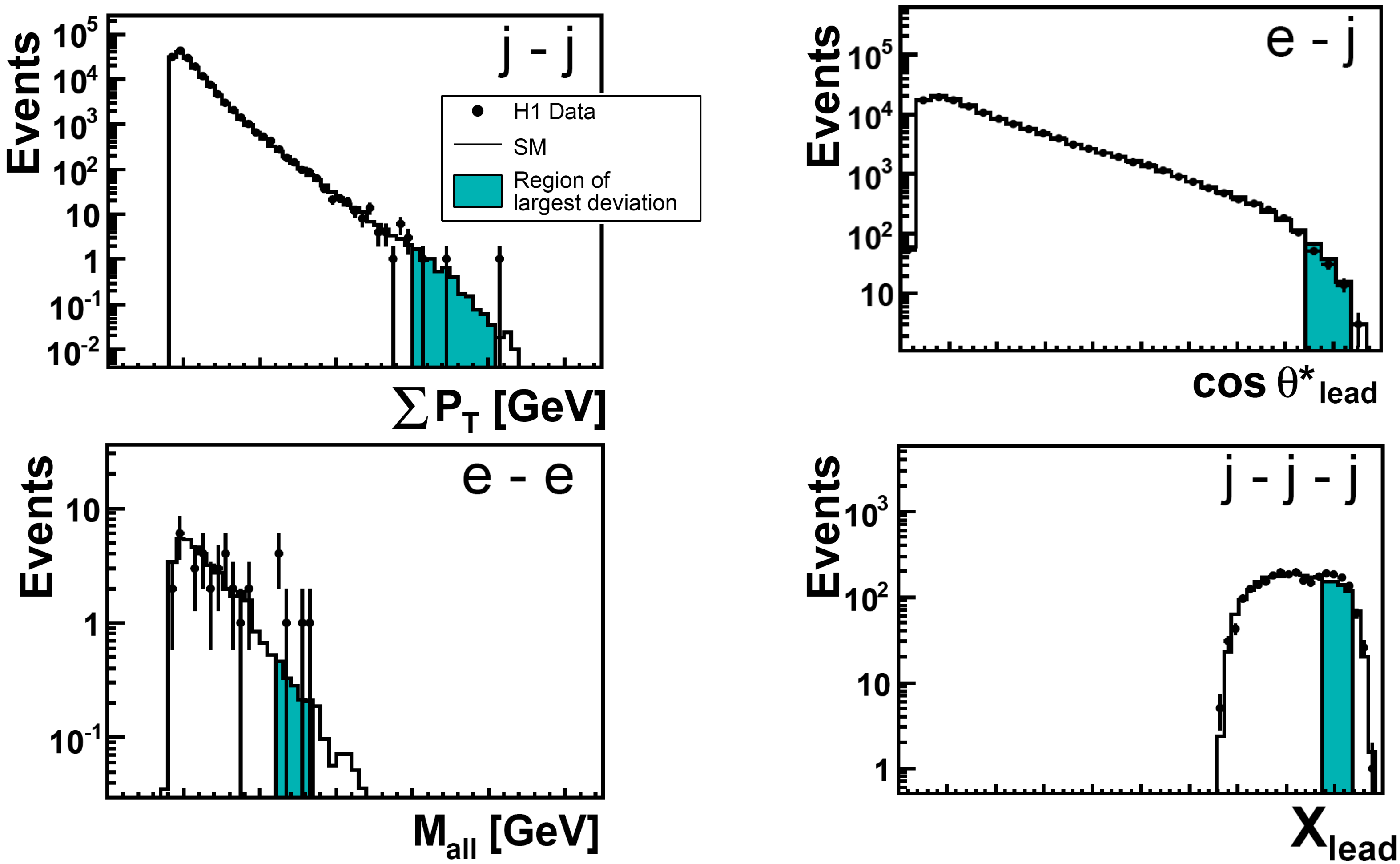


➘ Good understanding of the detector and of SM processes

General Search at HERA -II-

[H1, PLB 674(2009)257]

- Look for regions of data/SM discrepancies in 1D distributions:
  - ➔ ΣP_T, M_{all}
  - ➔ Topological variables: angle and energy sharing



$$X_{\rm lead} = \frac{2E^*_{\rm lead}}{\sum_i E^*_i}$$

➘ Largest deviation observed in e+p, in e-e channel for M_{all} (~2.5σ)

➘ Global probability to observe such deviation in one of the channels: 12%

General Search at the Tevatron

[CDF, PRD 79(2009)011101]

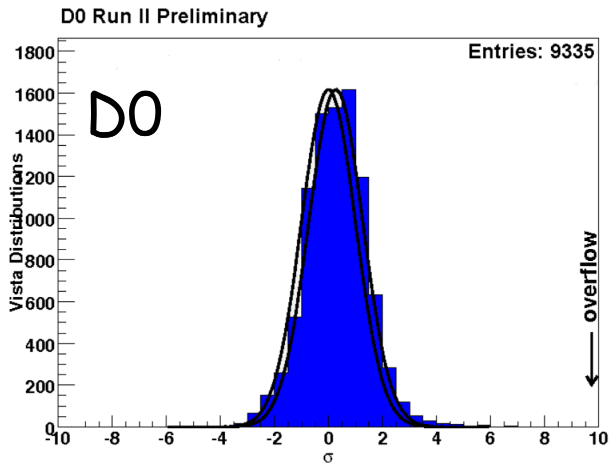
- Also performed by CDF and D0
  - ➔ A common framework used by CDF and D0
  - ➔ CDF: all topologies (399)
  - ➔ D0: only topologies with 1 lepton (180)

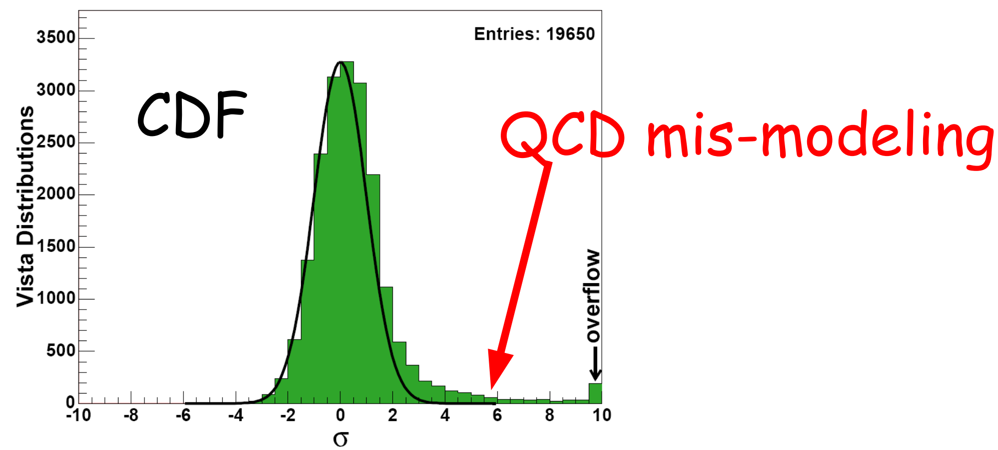
- Adjust the SM simulation to data at low energies
  - ➔ O(40) k-factors used, determined in a dedicated algorithm
  - ➔ Check data/SM discrepancies at high energies

General Search at the Tevatron

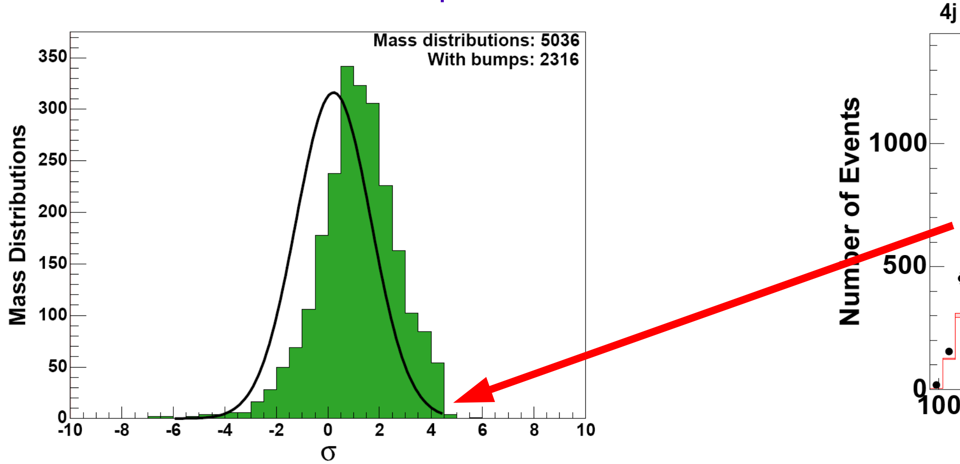
[CDF, PRD 79(2009)011101]

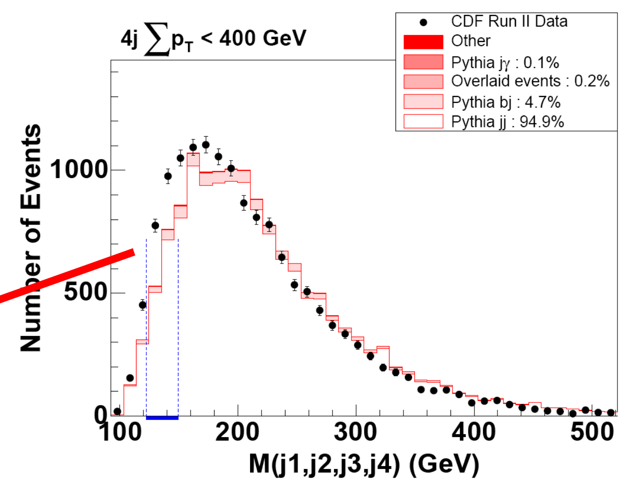
- Check data/SM in rate and shape of distribution





- Look for bumps in ΣP_T distributions





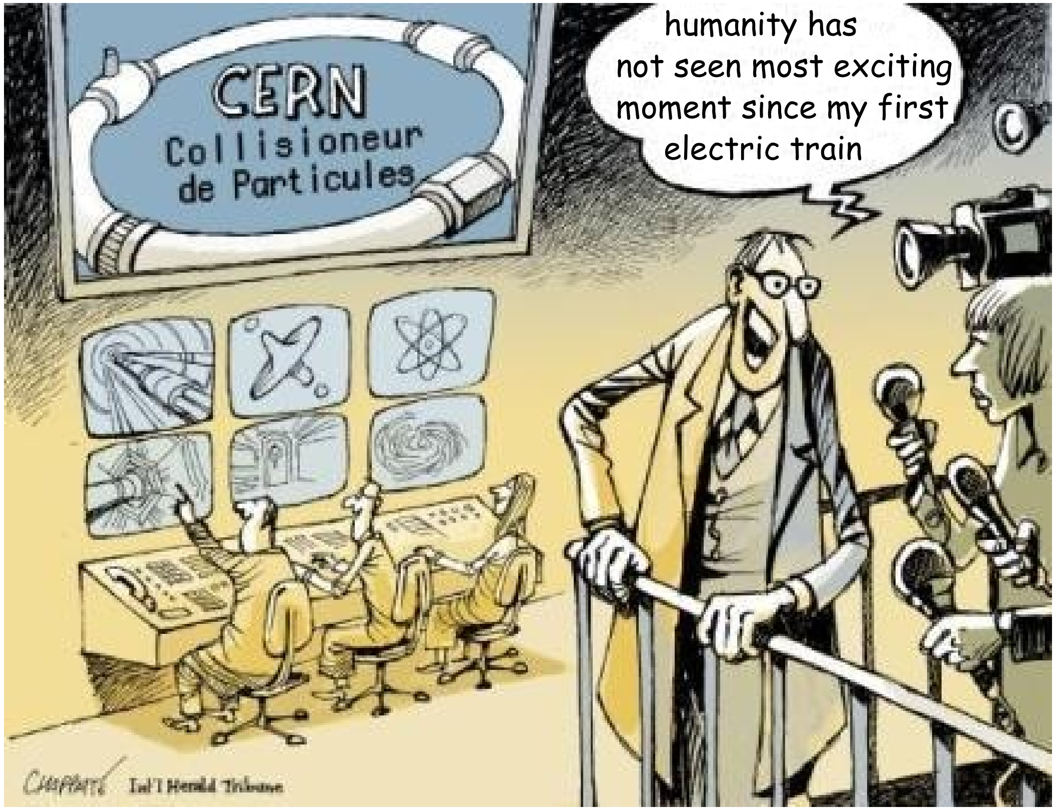
➘ Most significant discrepancies found:
attributed to QCD and detector simulation deficits

Summary

- Beyond the SM: we are searching for the unknown ...
  - ➔ A large variety of possibles searches

- A large domain already explored using high energy colliders
  - ➔ Following model hints
  - ➔ More generic tests of the SM validity

➘ Yet, no evidence for new physics at colliders



- Soon, a new tool for physicists to play with: the LHC
  - ➔ Should open new windows on our universe