

# Beyond the Standard Model Searches at HERA and the Tevatron

Physics in Collision 2008  
Stefan Grünendahl (Fermilab)

# Overview

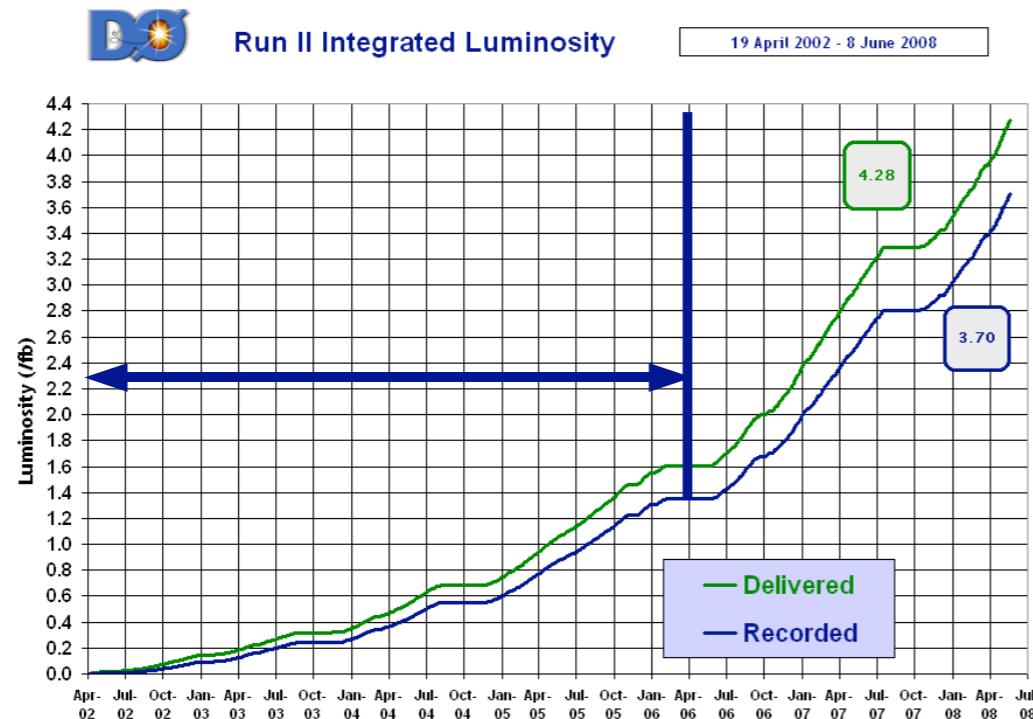
- very fertile field → try to cover subjects updated since last summer
- targeted model specific searches, among them many old stalwarts (LQs, SUSY,W'/Z')
- more recent additions to the non-SM repertoire
- last not least, global/'model-independent' analyses

# Overview

- Leptoquarks (Hera & Tevatron)
- Technicolor (Tevatron)
- SUSY
  - Charginos & Neutralinos  
→ Trileptons (CDF, D0)
  - Squarks & Gluinos →  
Jets + MET (CDF, D0)
  - Stop (CDF, D0)
  - GMSB → 2 Photons
- W'/Z'
- Large Extra Dimensions  
→ Monophotons / Monojets
- 4th Generation
- Maximum Flavour Violation
- Excited Quarks and Leptons
- long-lived particles
- Isolated Leptons (Hera)
- VISTA/Sleuth

# Data Samples

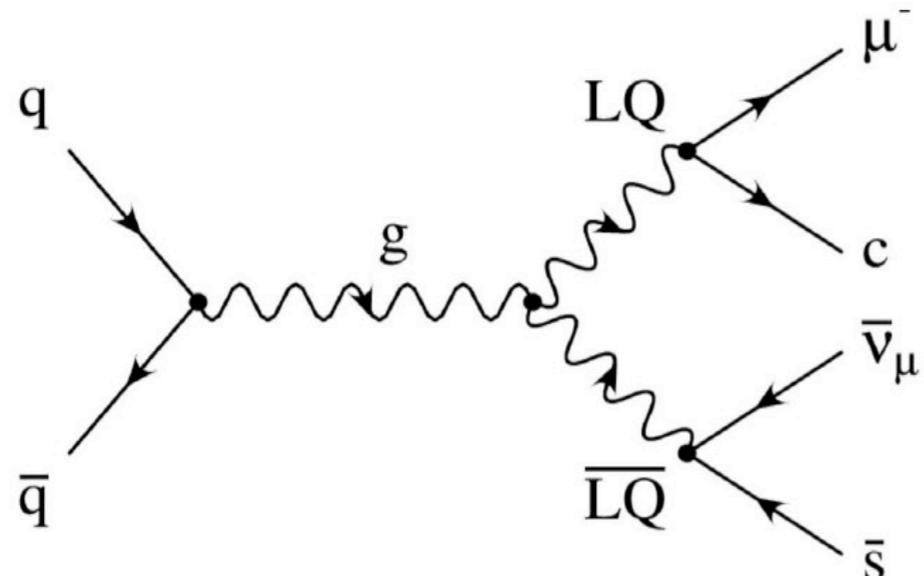
- Tevatron Run II: 4/fb delivered, up to 2/fb analyzed; target of 8/fb/experiment until Fall 2010
- Hera: final (June 2007) sample of 0.5/fb/experiment, distributed over e+/e- and beam polarisations



| Period  | Collisions  | $\sqrt{s}$ | E-beam polarisation | Luminosity           |
|---------|-------------|------------|---------------------|----------------------|
| HERA I  | $e^+p$      | 301 GeV    | 0                   | 37 pb <sup>-1</sup>  |
|         | $e^-p$      | 319 GeV    | 0                   | 14 pb <sup>-1</sup>  |
|         | $e^+p$      | 319 GeV    | 0                   | 64 pb <sup>-1</sup>  |
| HERA II | $e^+p$      | 319 GeV    | +0.31               | 99 pb <sup>-1</sup>  |
|         | $e^+p$      | 319 GeV    | -0.36               | 78 pb <sup>-1</sup>  |
|         | $e^-p$      | 319 GeV    | -0.26               | 104 pb <sup>-1</sup> |
|         | $e^-p$ (NC) | 319 GeV    | +0.32               | 51 pb <sup>-1</sup>  |
|         | $e^-p$ (CC) | 319 GeV    | +0.37               | 30 pb <sup>-1</sup>  |

# Leptoquarks: HERA & Tevatron

- carry both quark and lepton quantum numbers
- appear in GUT's, extended Technicolor, Compositeness
- Tevatron: pair production of all three families (LQ1, LQ2, LQ3)
- Hera: direct production of LQ1
- $\beta = \text{BF} (\text{LQ} \rightarrow \text{lepton} + \text{jet})$

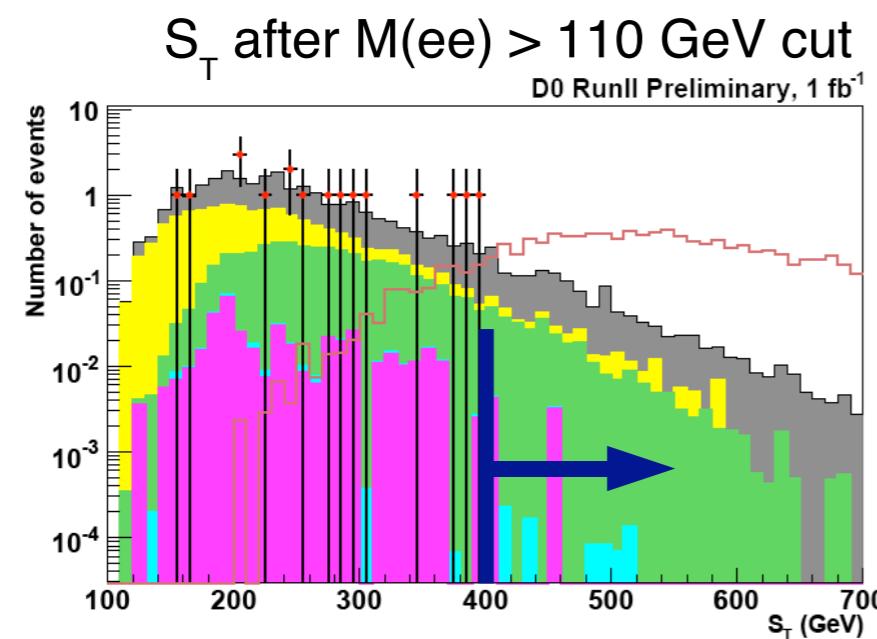
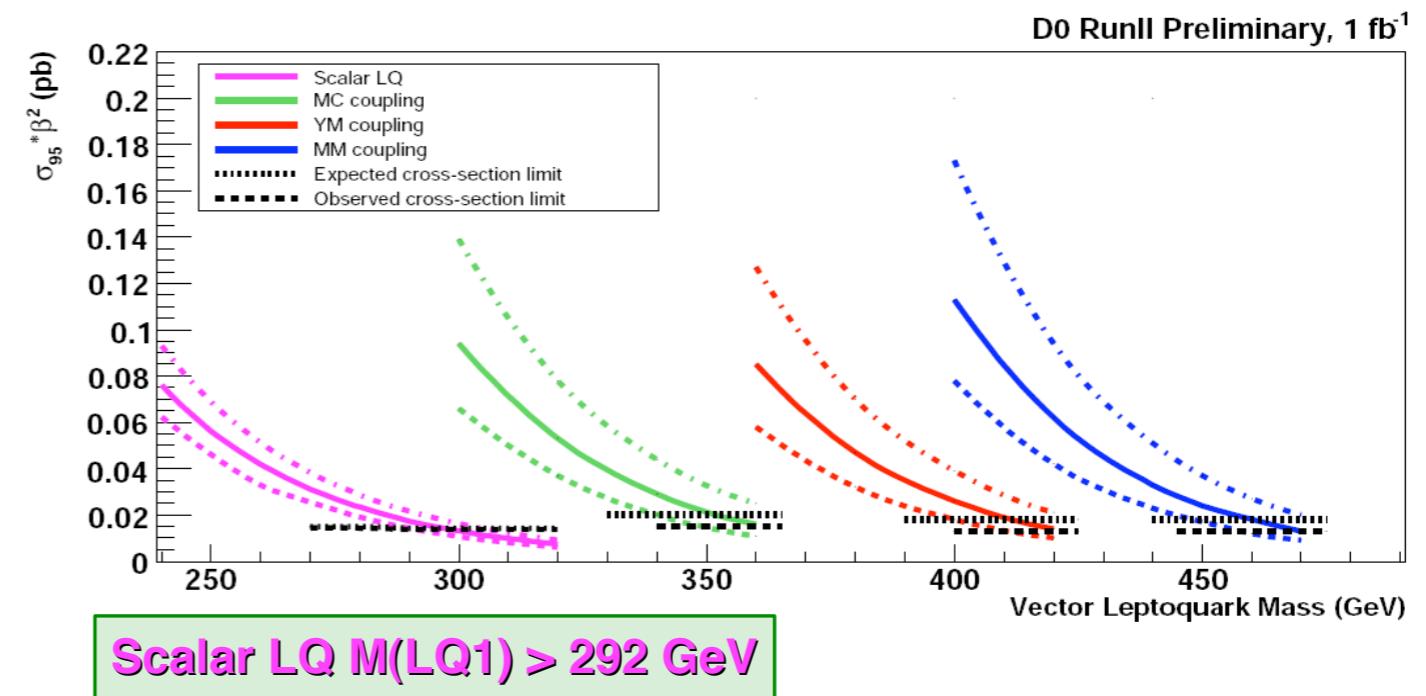
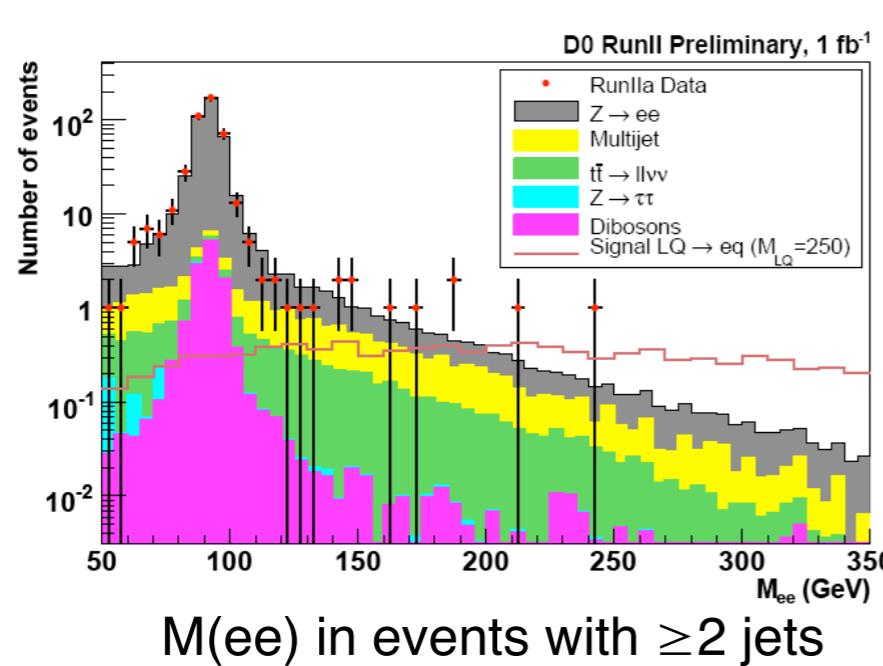


production & decay at Hera  
(within  
Buchmüller-Rückl-Wyler  
model)

| $F = 2$             | Prod./Decay                                                                      | $\beta_e$       | $F = 0$             | Prod./Decay                                                                            | $\beta_e$       |
|---------------------|----------------------------------------------------------------------------------|-----------------|---------------------|----------------------------------------------------------------------------------------|-----------------|
| Scalar Leptoquarks  |                                                                                  |                 |                     |                                                                                        |                 |
| $S_{0,L}$           | $e_L^- u_L \rightarrow e^- u \rightarrow \nu d$                                  | 1/2<br>1/2      | $S_{1/2,L}$         | $e_R^+ u_R \rightarrow e^+ u$                                                          | 1               |
| $S_{0,R}$           | $e_R^- u_R \rightarrow e^- u$                                                    | 1               | $S_{1/2,R}$         | $e_L^+ u_L \rightarrow e^+ u$                                                          | 1               |
| $\tilde{S}_{0,R}$   | $e_R^- d_R \rightarrow e^- d$                                                    | 1               |                     | $e_L^+ d_L \rightarrow e^+ d$                                                          | 1               |
| $S_{1,L}$           | $e_L^- d_L \rightarrow e^- d$<br>$e_L^- u_L \rightarrow e^- u \rightarrow \nu d$ | 1<br>1/2<br>1/2 | $\tilde{S}_{1/2,L}$ | $e_R^+ d_R \rightarrow e^+ d$                                                          | 1               |
| Vector Leptoquarks  |                                                                                  |                 |                     |                                                                                        |                 |
| $V_{1/2,R}$         | $e_R^- d_L \rightarrow e^- d$                                                    | 1               | $V_{0,R}$           | $e_L^+ d_R \rightarrow e^+ d$                                                          | 1               |
|                     | $e_R^- u_L \rightarrow e^- u$                                                    | 1               | $V_{0,L}$           | $e_R^+ d_L \rightarrow e^+ d \rightarrow \bar{\nu} u$                                  | 1/2<br>1/2      |
| $V_{1/2,L}$         | $e_L^- d_R \rightarrow e^- d$                                                    | 1               | $\tilde{V}_{0,R}$   | $e_L^+ u_R \rightarrow e^+ u$                                                          | 1               |
| $\tilde{V}_{1/2,L}$ | $e_L^- u_R \rightarrow e^- u$                                                    | 1               | $V_{1,L}$           | $e_R^+ u_L \rightarrow e^+ u$<br>$e_R^+ d_L \rightarrow e^+ d \rightarrow \bar{\nu} u$ | 1<br>1/2<br>1/2 |

# Leptoquarks: Tevatron

- LQ1: signature 2 electrons + 2 jets



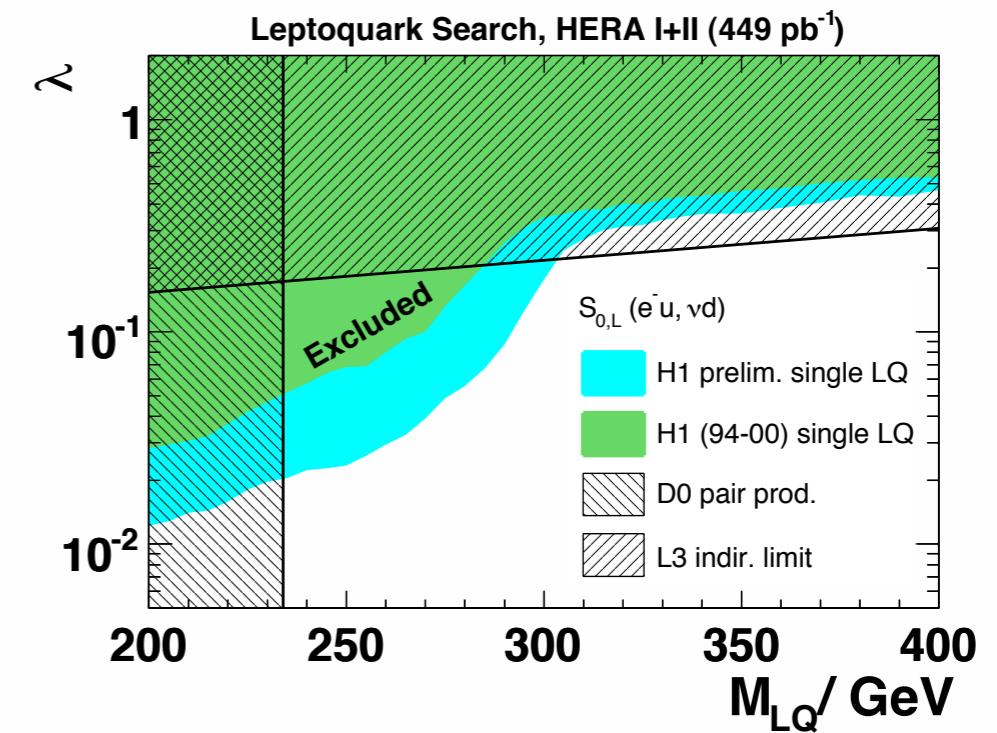
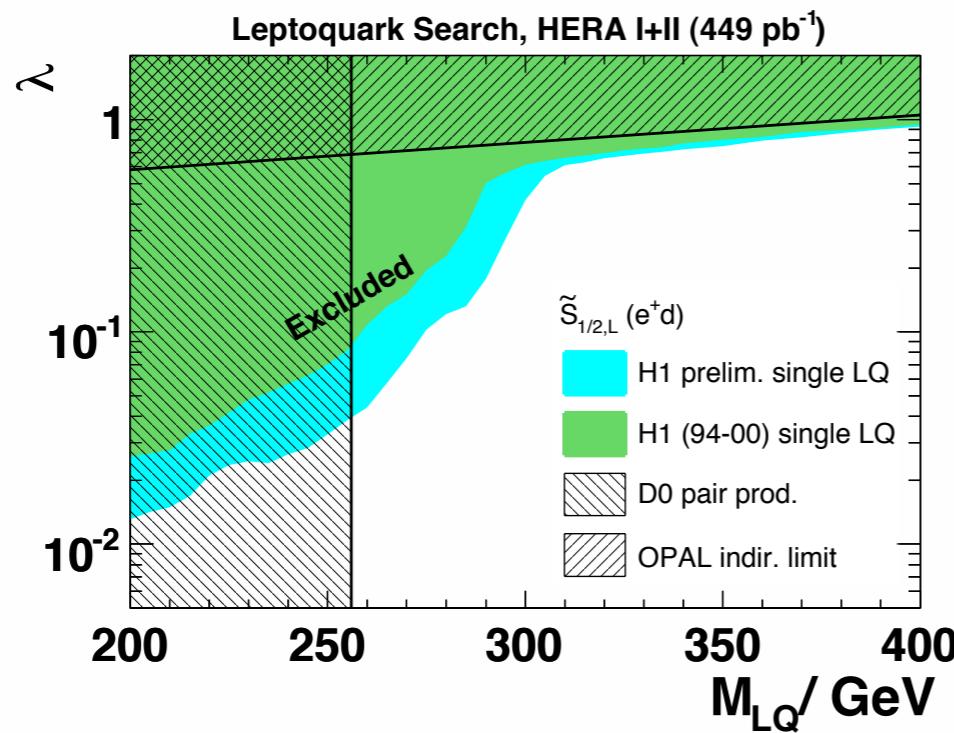
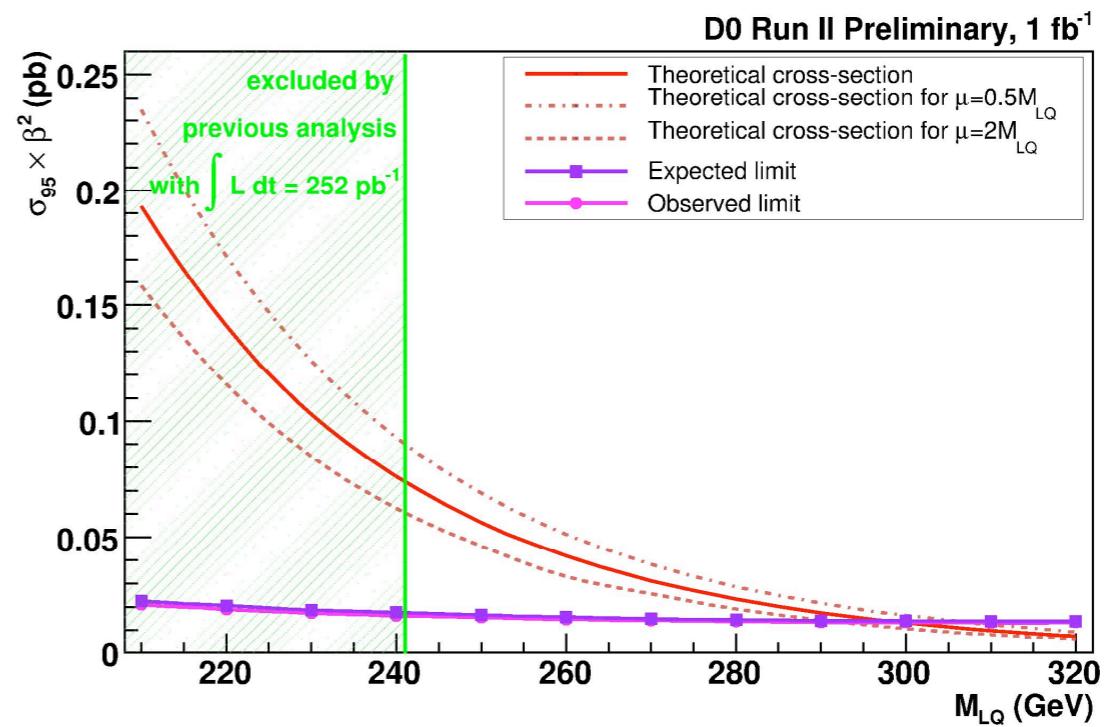
## Vector LQ:

|                  |                                                                        |
|------------------|------------------------------------------------------------------------|
| M(LQ1) > 350 GeV | (Q=1/3, T <sub>3</sub> = -1/2, κ <sub>G</sub> =1, λ <sub>G</sub> =0)   |
| M(LQ1) > 410 GeV | (Q=1/3, T <sub>3</sub> = -1/2, κ <sub>G</sub> =0, λ <sub>G</sub> =0)   |
| M(LQ1) > 458 GeV | (Q=1/3, T <sub>3</sub> = -1/2, κ <sub>G</sub> =-1, λ <sub>G</sub> =-1) |

$$S_T = E_T^{e1} + E_T^{e2} + E_T^{j1} + E_T^{j2}$$

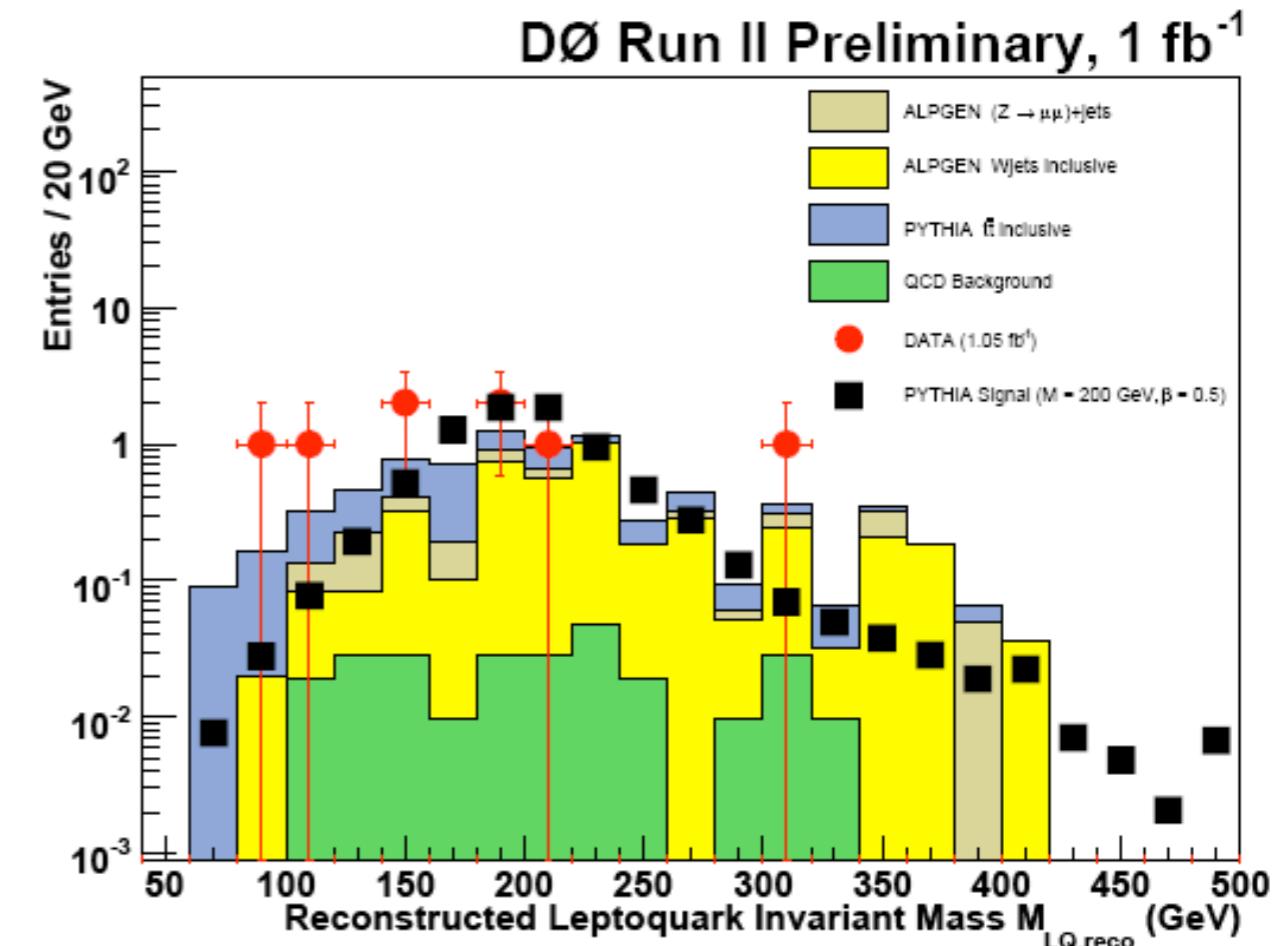
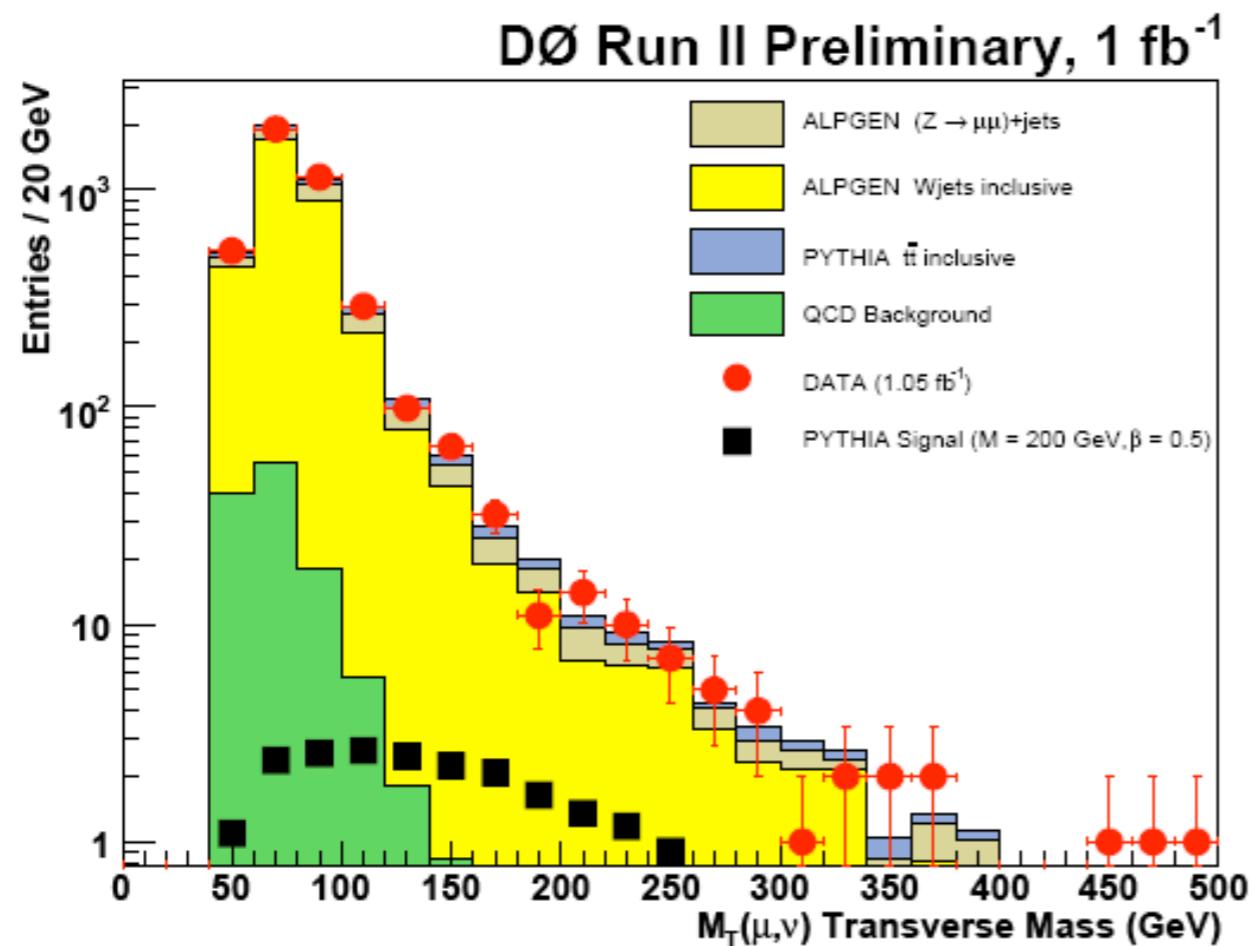
# LQ I:Tevatron & Hera

- comparison to previous D0 limit
- Hera result



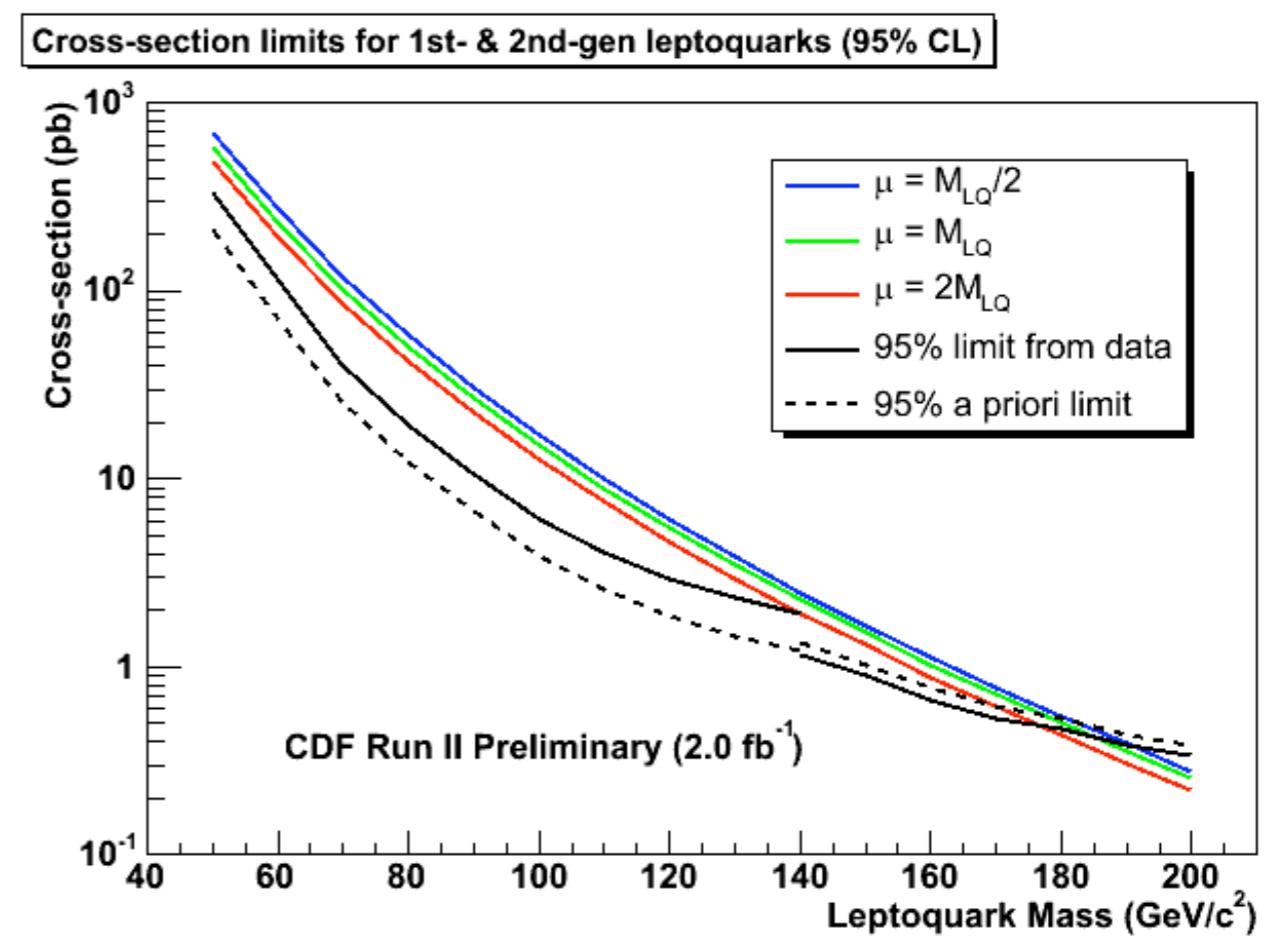
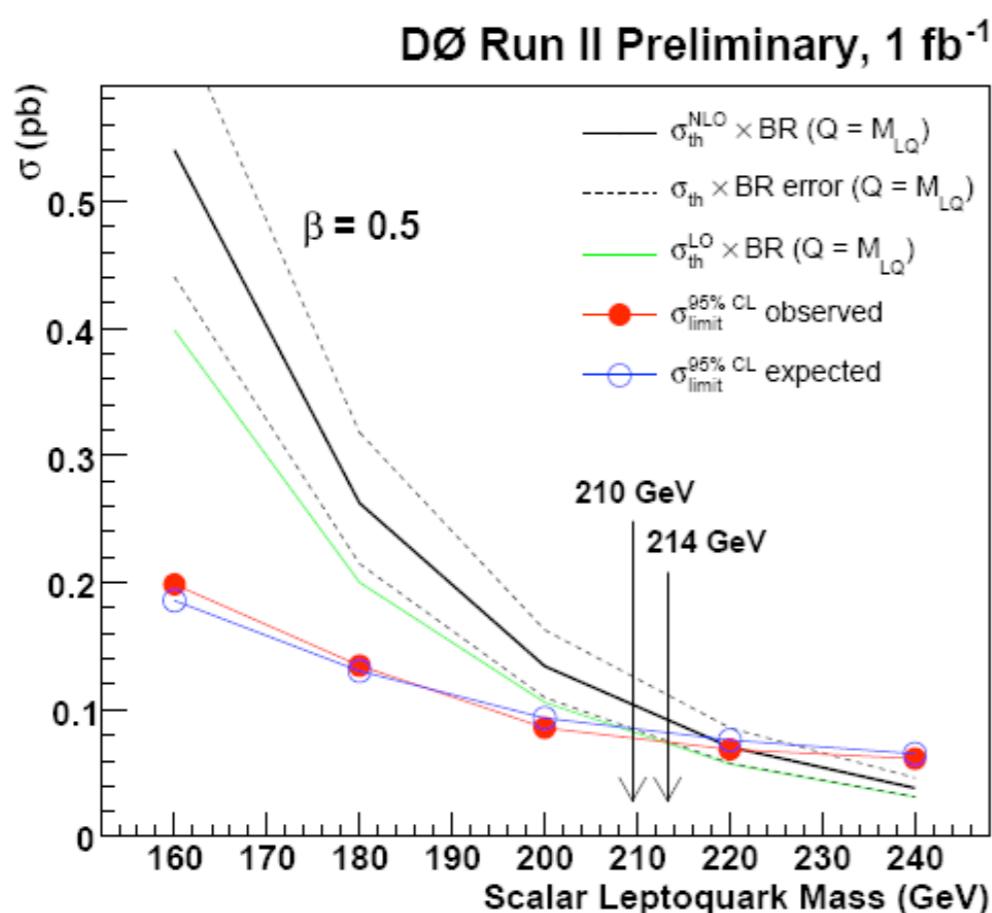
# Leptoquarks: Tevatron: LQ2

- signature: (exactly one) muon + 2 jets + MET



# Leptoquarks: Tevatron

- D0:  $m(LQ2) > 214 \text{ GeV}$   
for  $\beta = 0.5$
- CDF: exclusive dijet + MET analysis



update including  $\mu\mu jj$  channel  
(for publication) underway

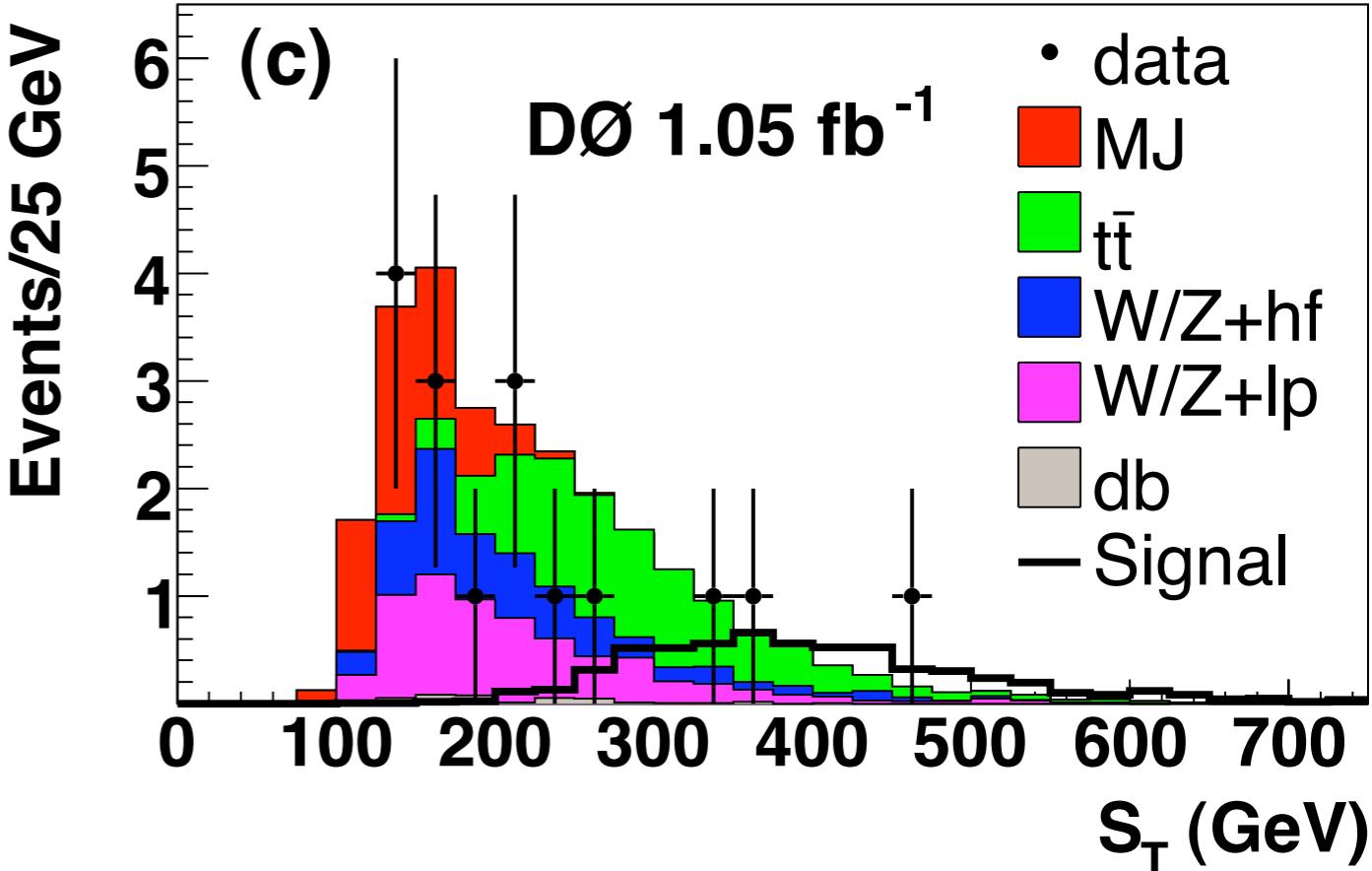
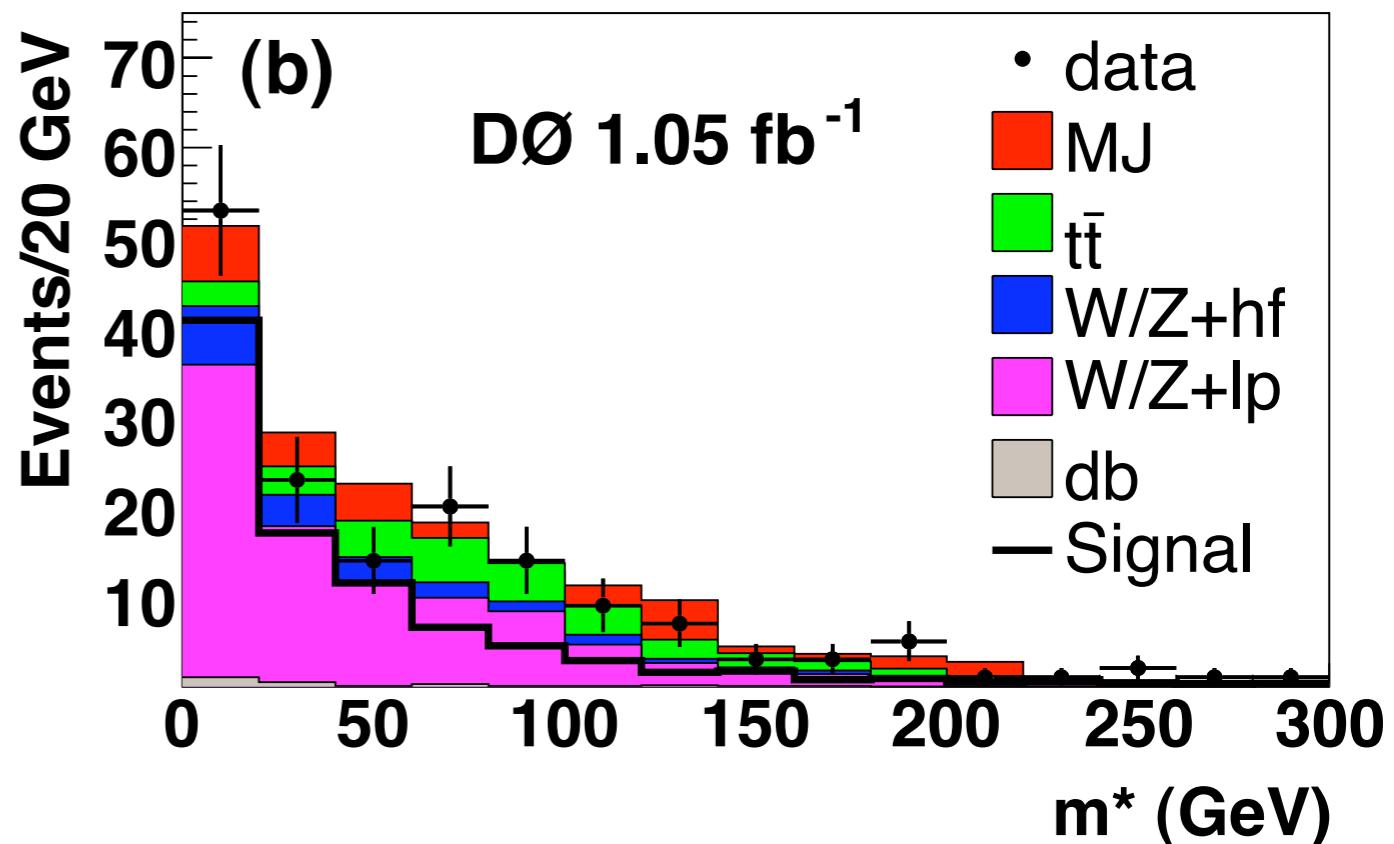
# LQ3:Tevatron

## D0 tau analysis:

submitted to PRL;

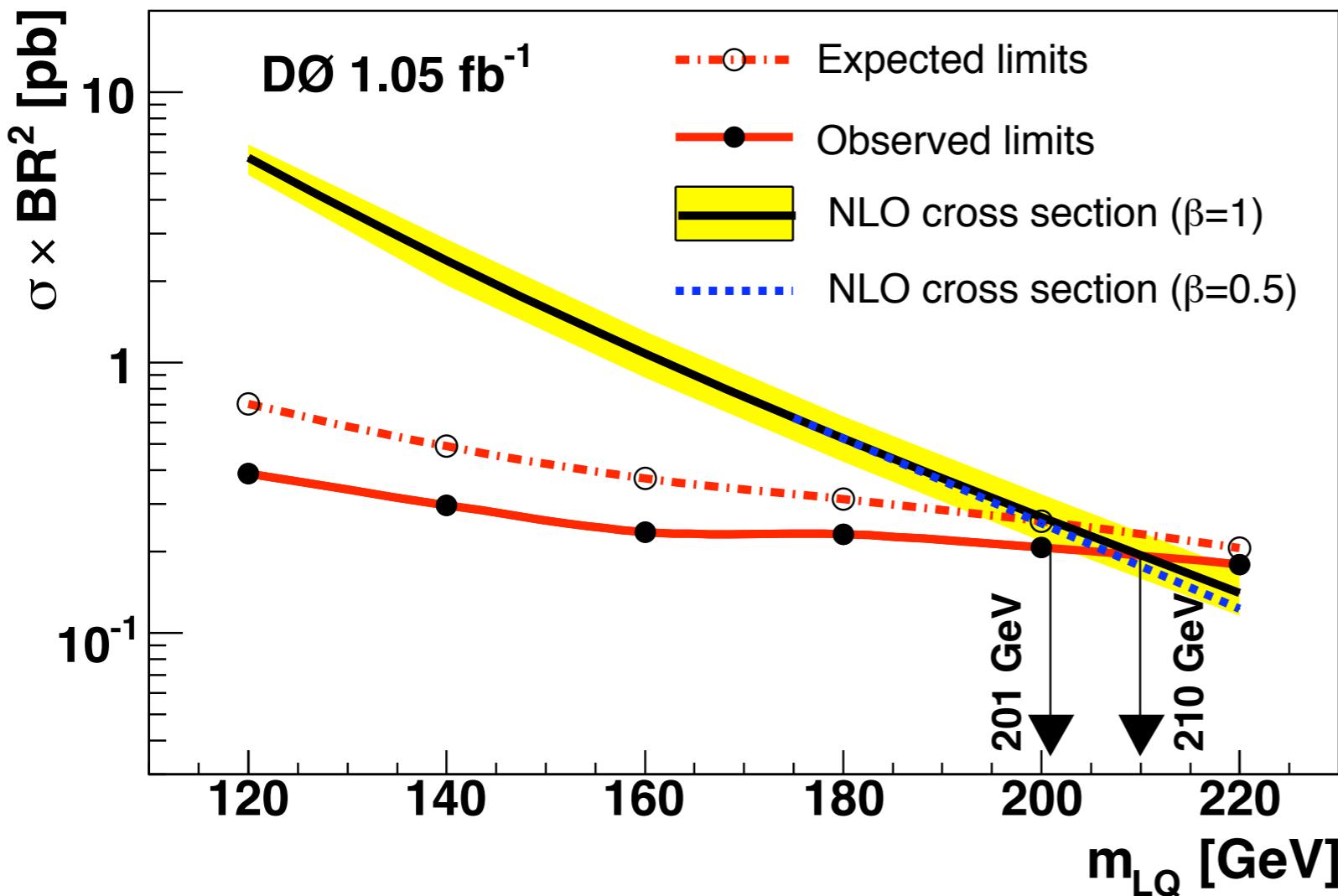
Fermilab-Pub 08-201-E  
arXiv:hep-ex 0806.3527

- LQ3  $\rightarrow \tau b$
- 2 opposite sign taus and 2 jets
- $\tau_1 \rightarrow \mu \nu \nu$
- $\tau_2 \rightarrow \nu + \text{hadrons}$  (neural net)



# LQ3:Tevatron

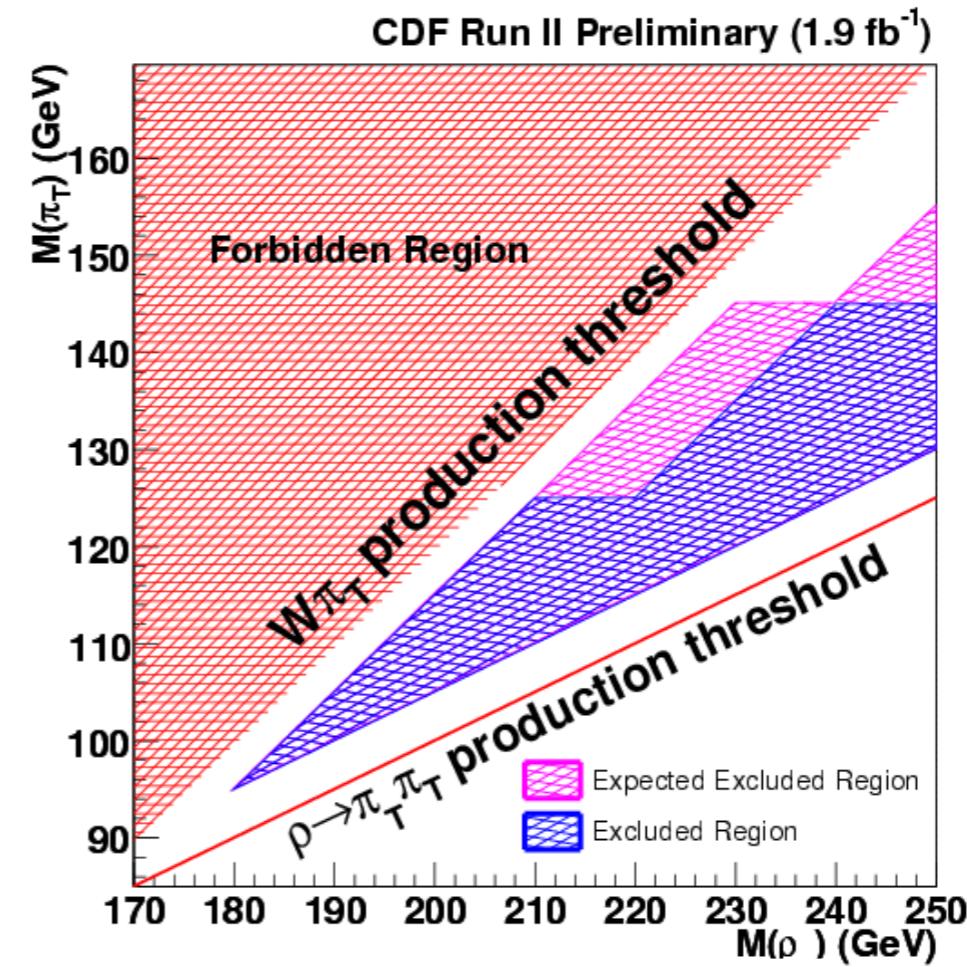
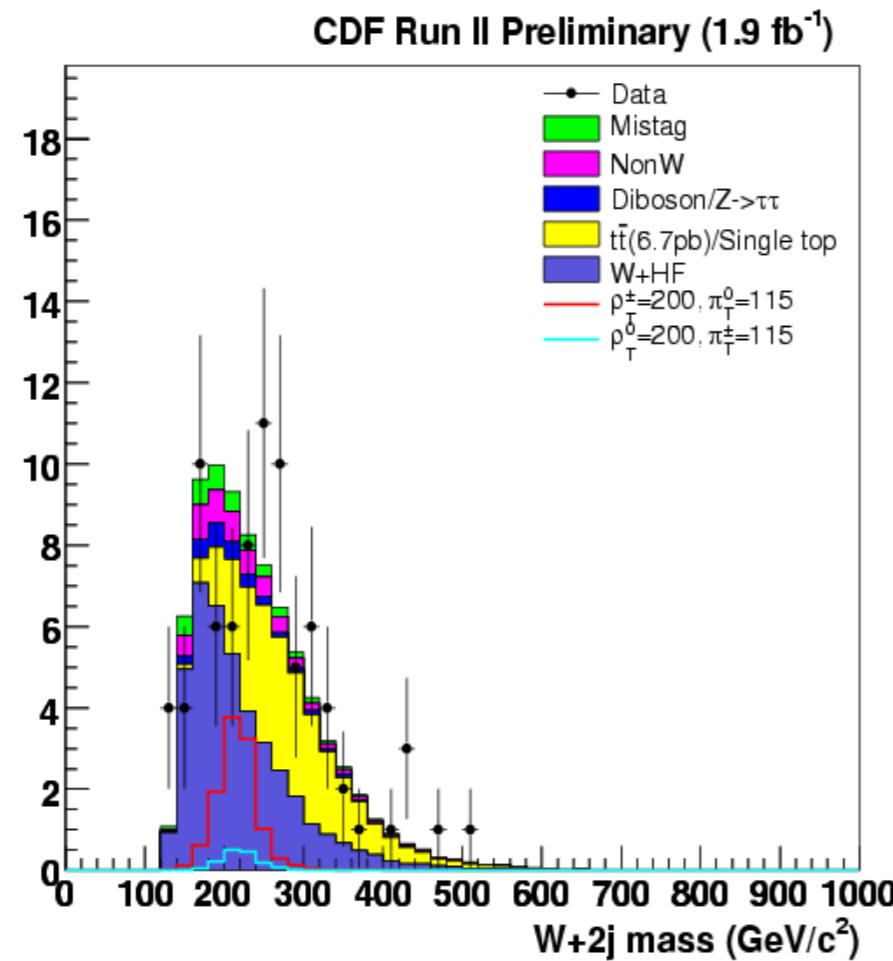
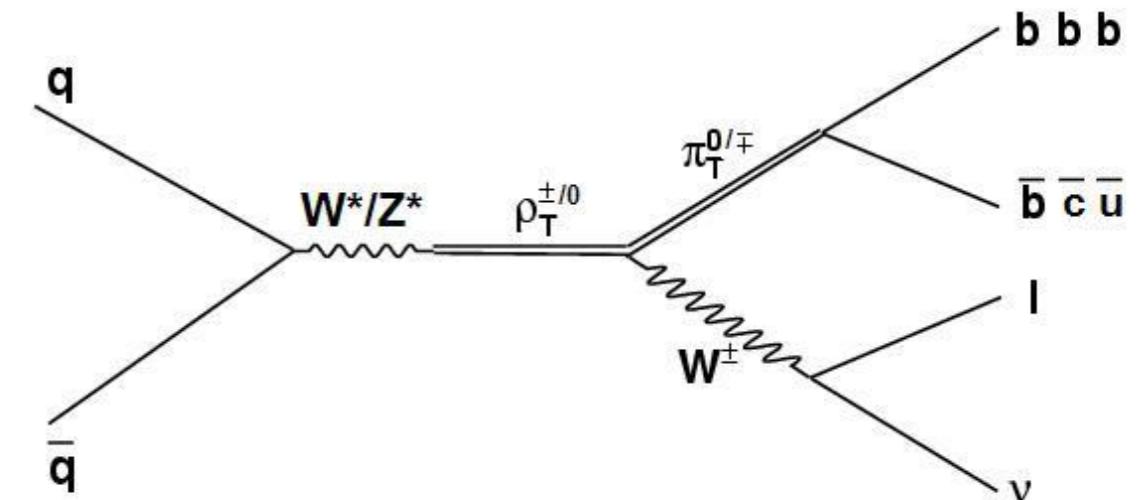
- D0:  $m(LQ3) < 210 \text{ GeV}$  for  $\beta=1$  excluded at 95% CL



- CDF (exclusive dijet analysis):  $m(LQ3) < 167 \text{ GeV}$  excluded at 95% CL

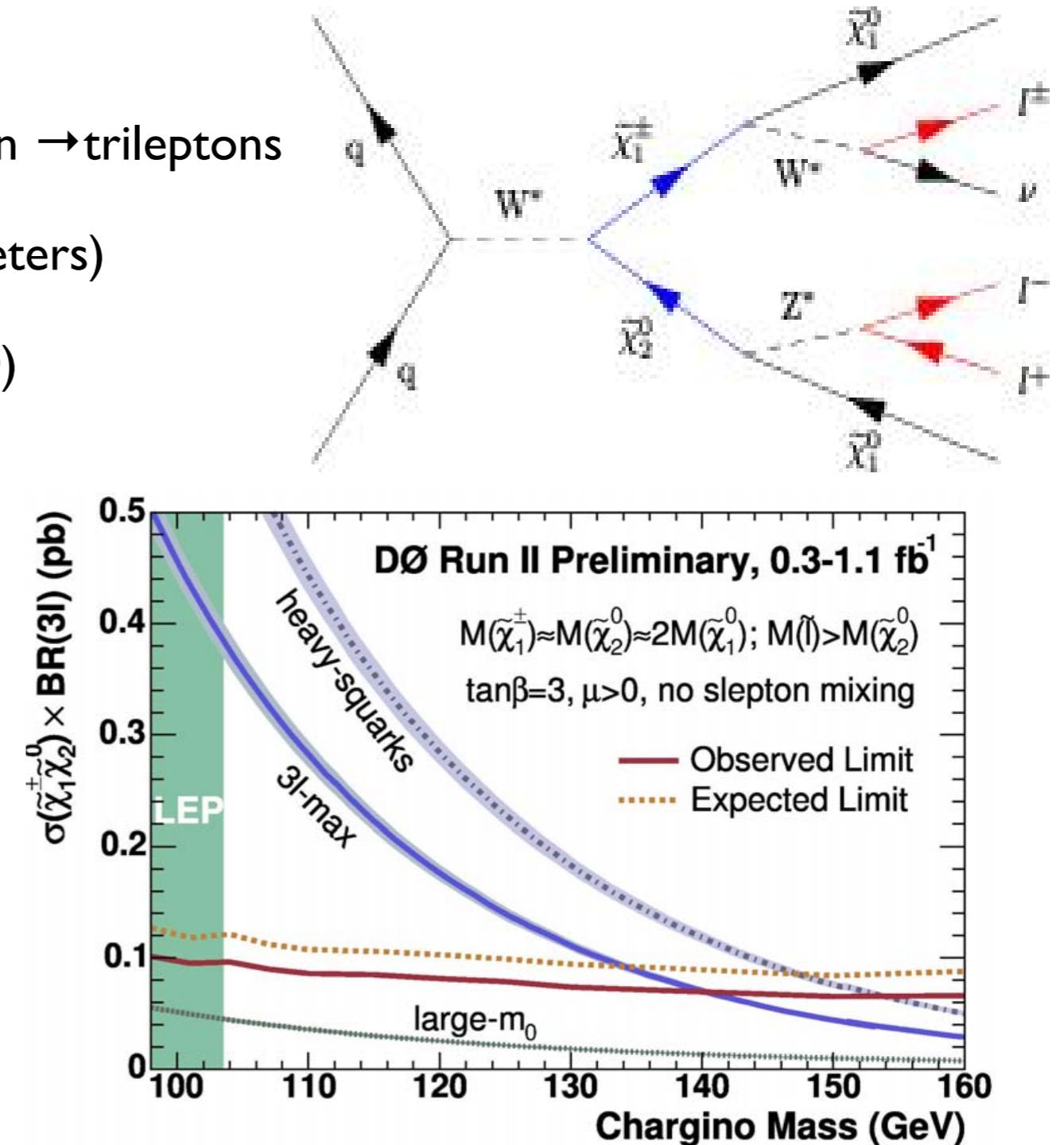
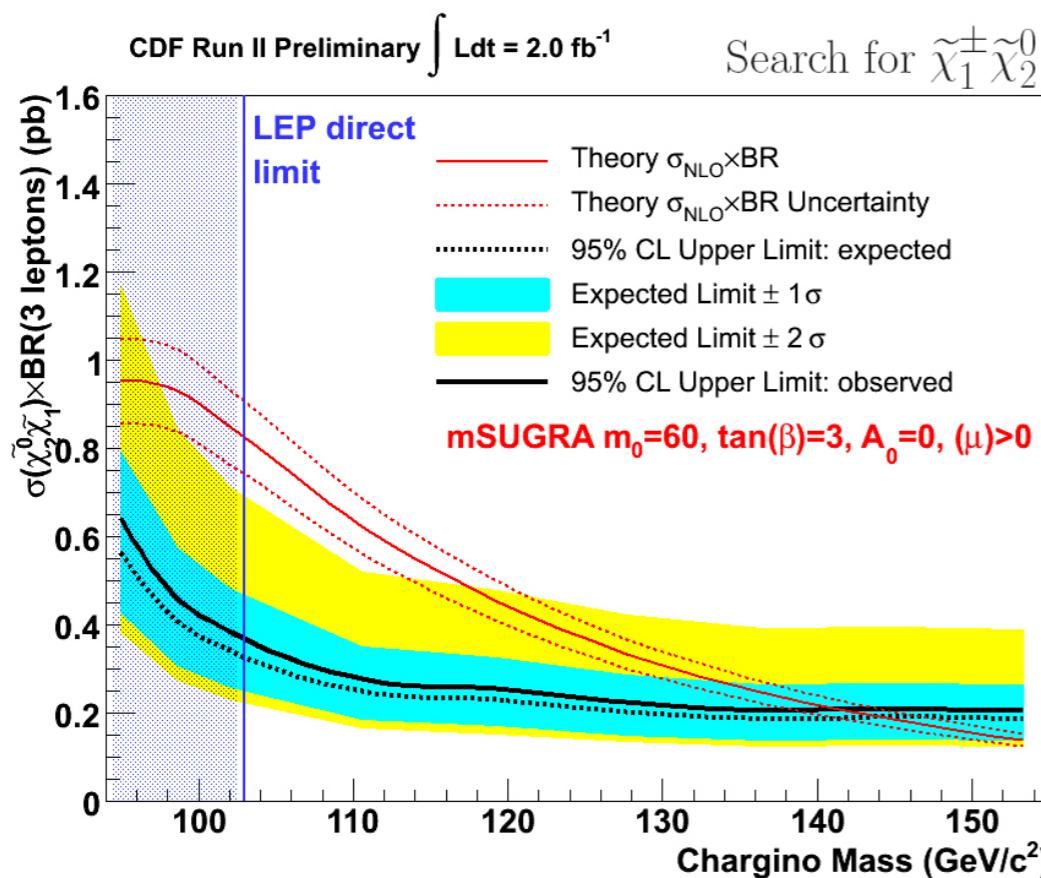
# Technicolor: Tevatron

- alternative (to Higgs) for EWSB
- search for decay techni-rho  $\rightarrow$  techni-pion + W
- signal (W+b-jets) very similar to WH search



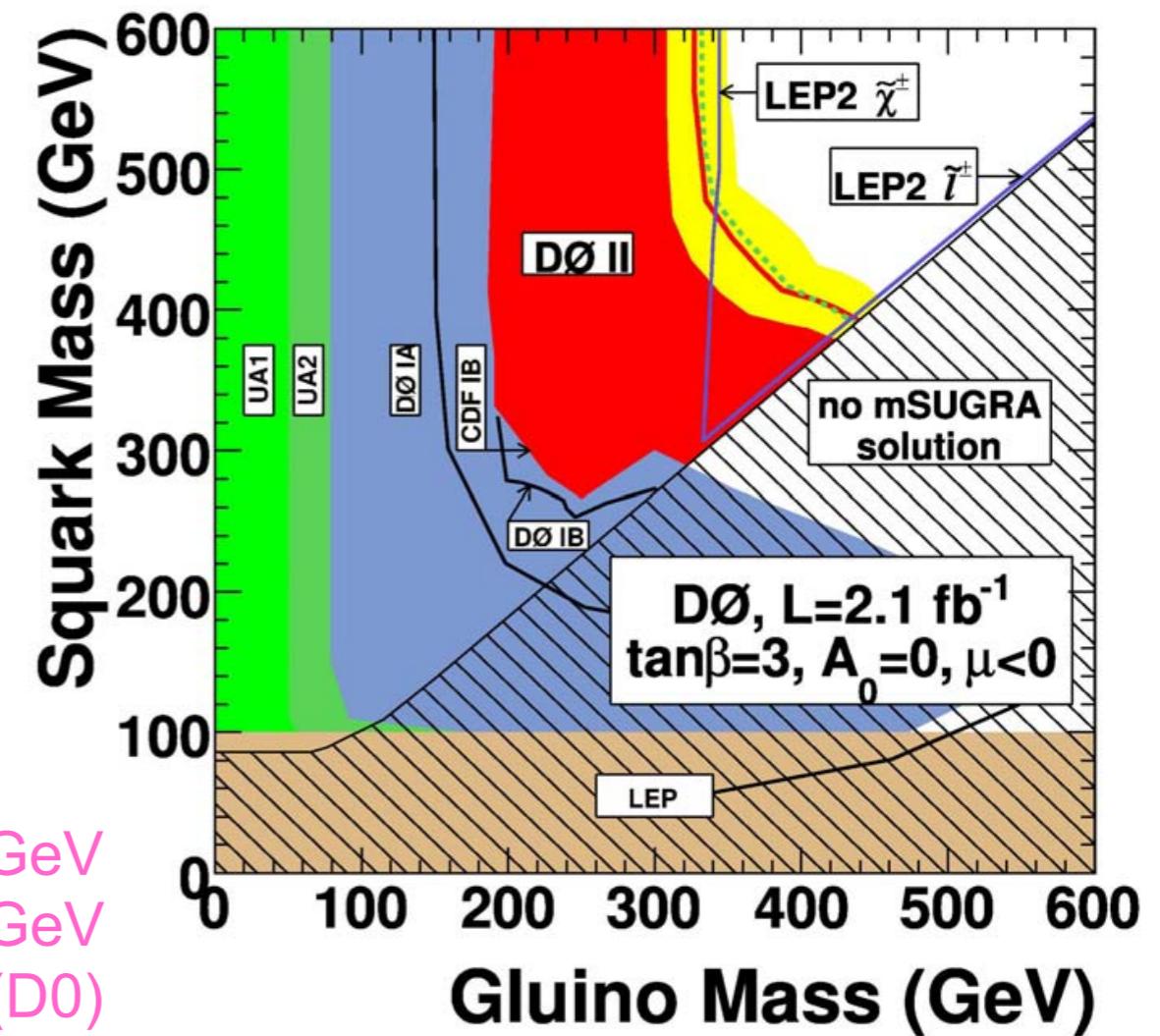
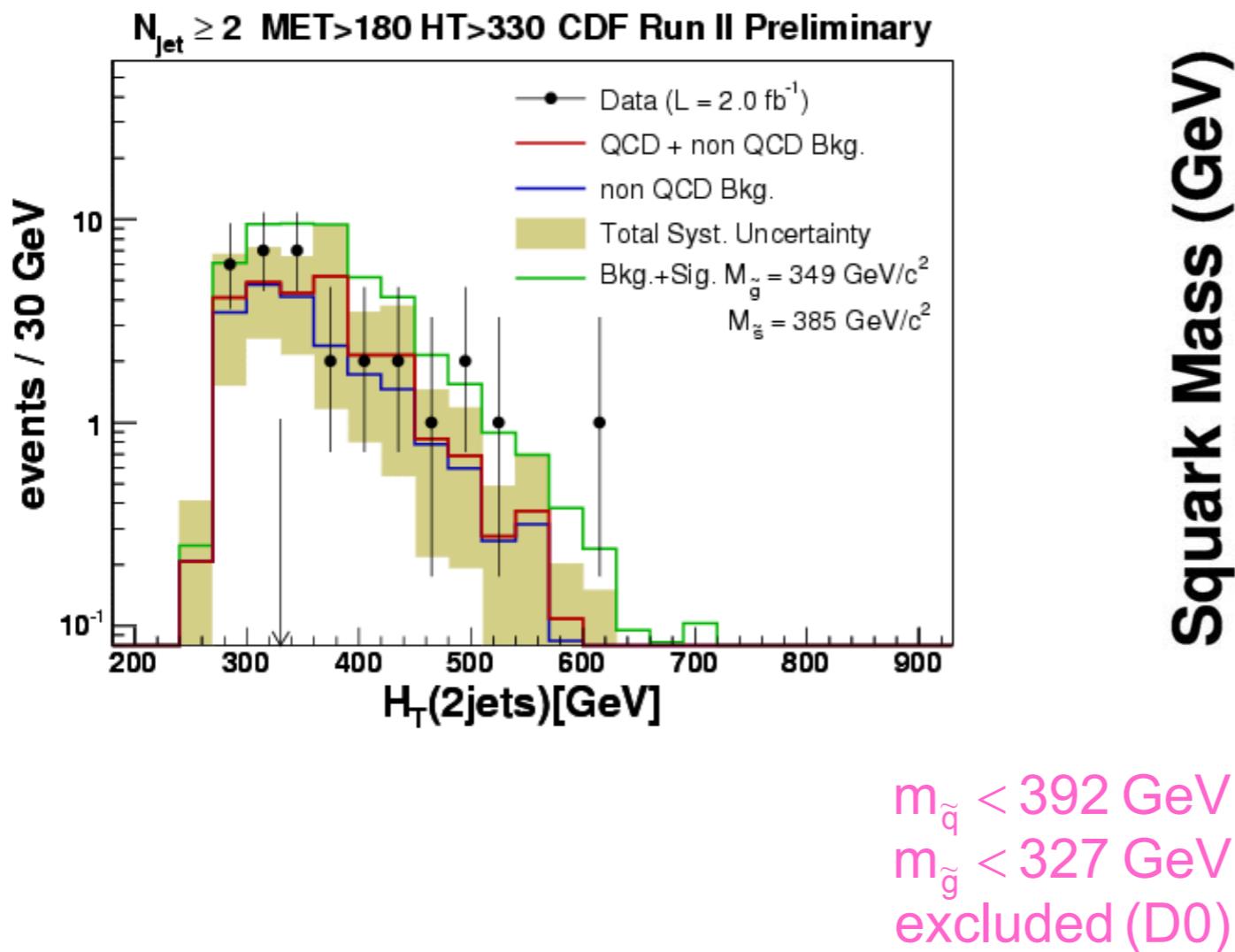
# SUSY:Tevatron

- chargino + neutralino pair production  $\rightarrow$  trileptons
- limits set in mSUGRA (5 free parameters)
- (slightly different choices CDF vs. D0)



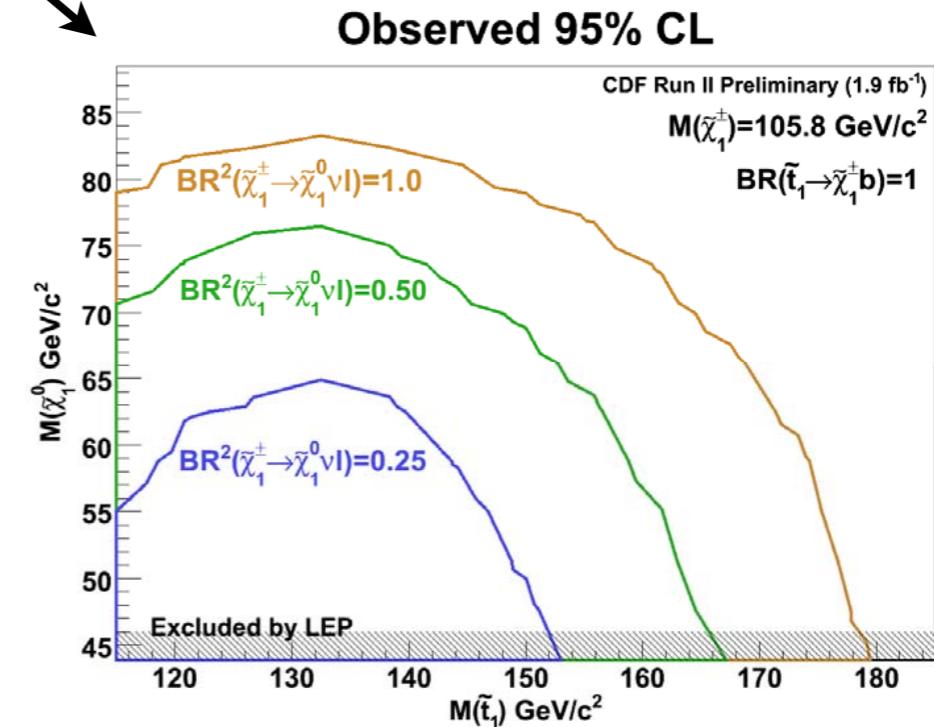
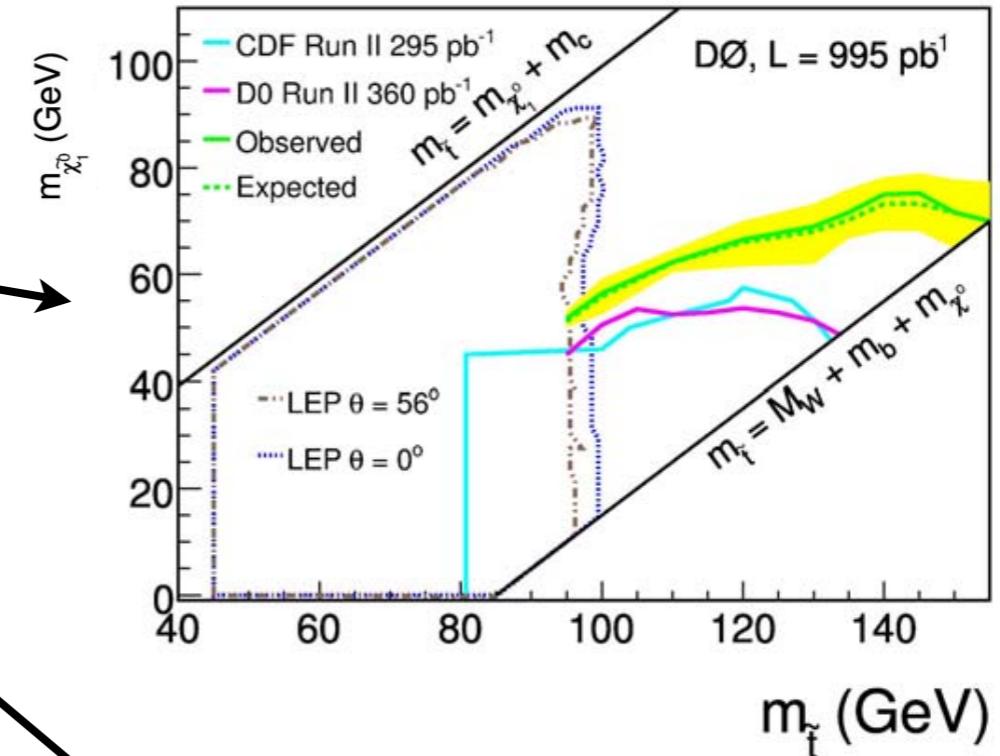
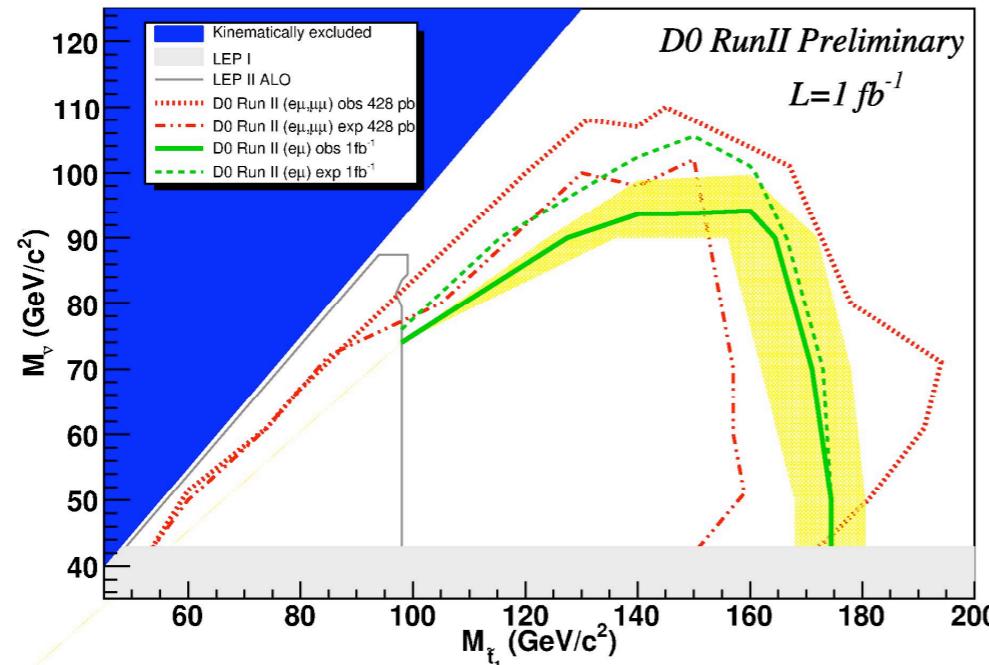
# SUSY: Tevatron

- squarks and gluinos  $\rightarrow$  jets + MET



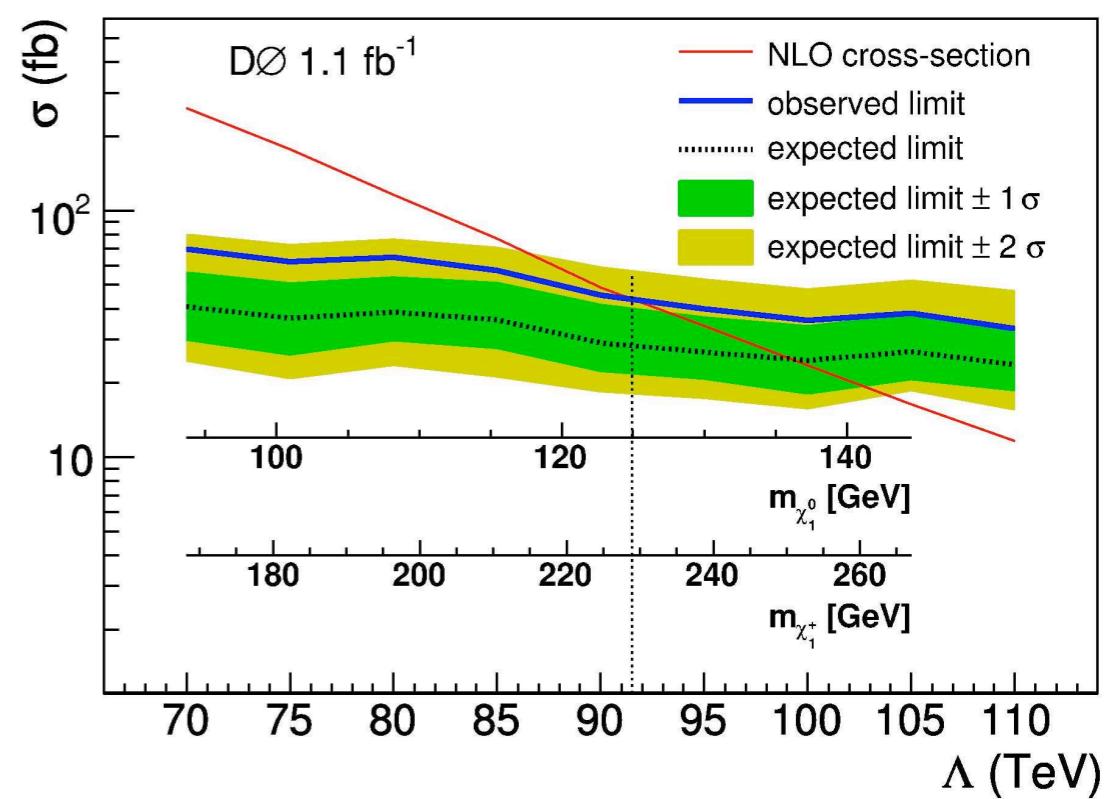
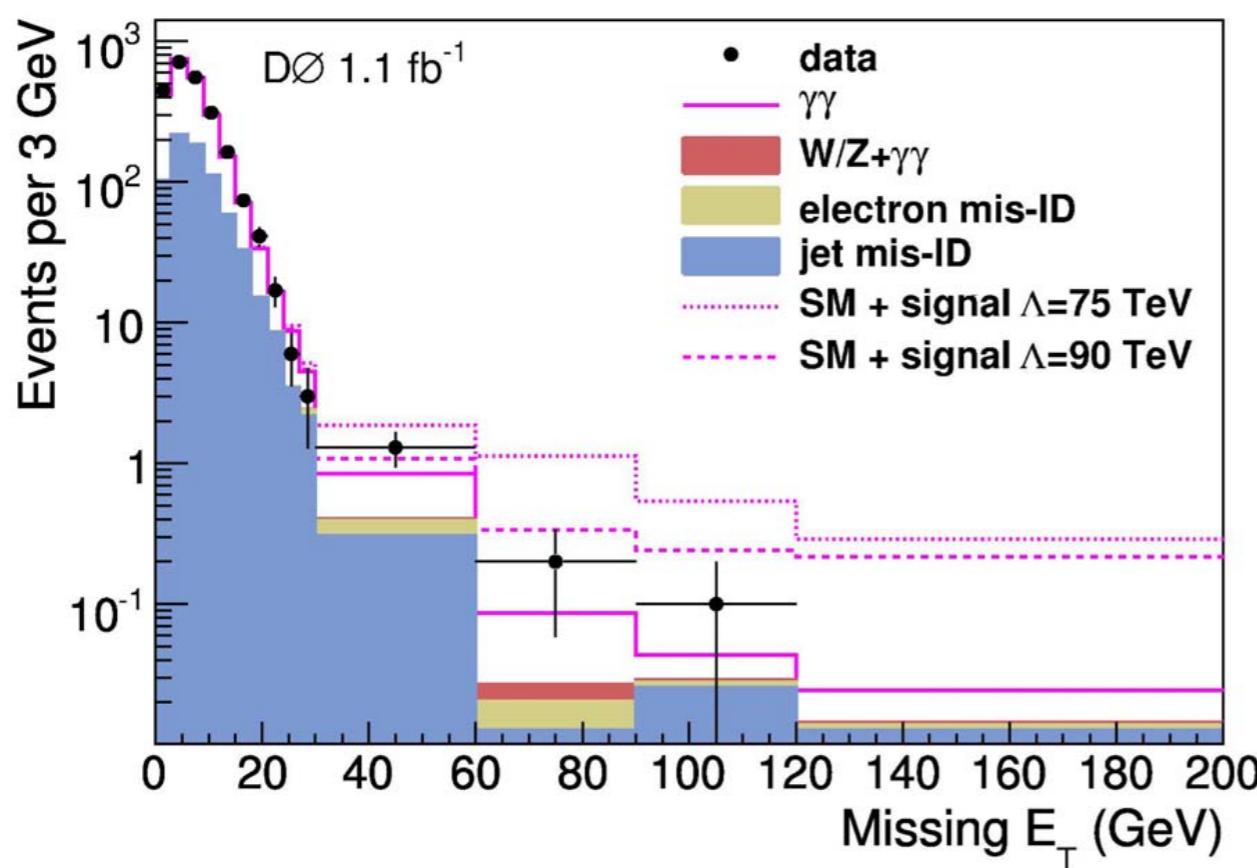
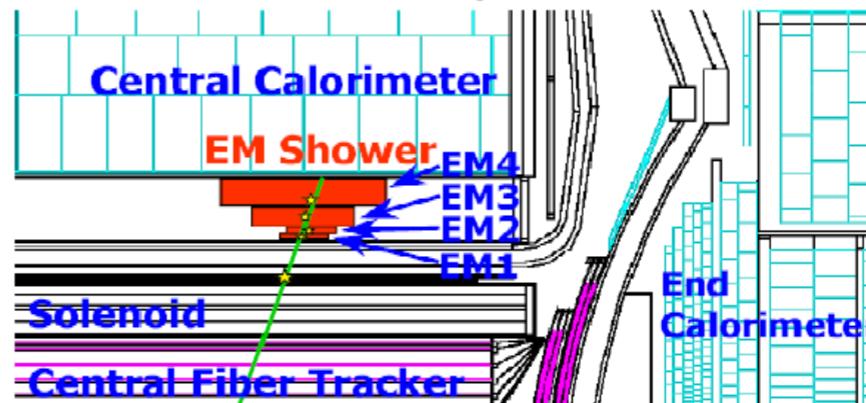
# SUSY: Tevatron: stop

- potentially lightest squark; three decay paths studied:
  - $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$  2 c jets + MET
  - $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow b\tilde{\chi}_1^0 l\nu$   
2 leptons (1 isolated), 2 jets  
(1 btag), MET
  - $\tilde{t}_1 \rightarrow bl\tilde{\nu}$  e+μ+2b+MET



# SUSY:Tevatron: GMSB

- 2 photons + MET
- photon pointing → primary vertex



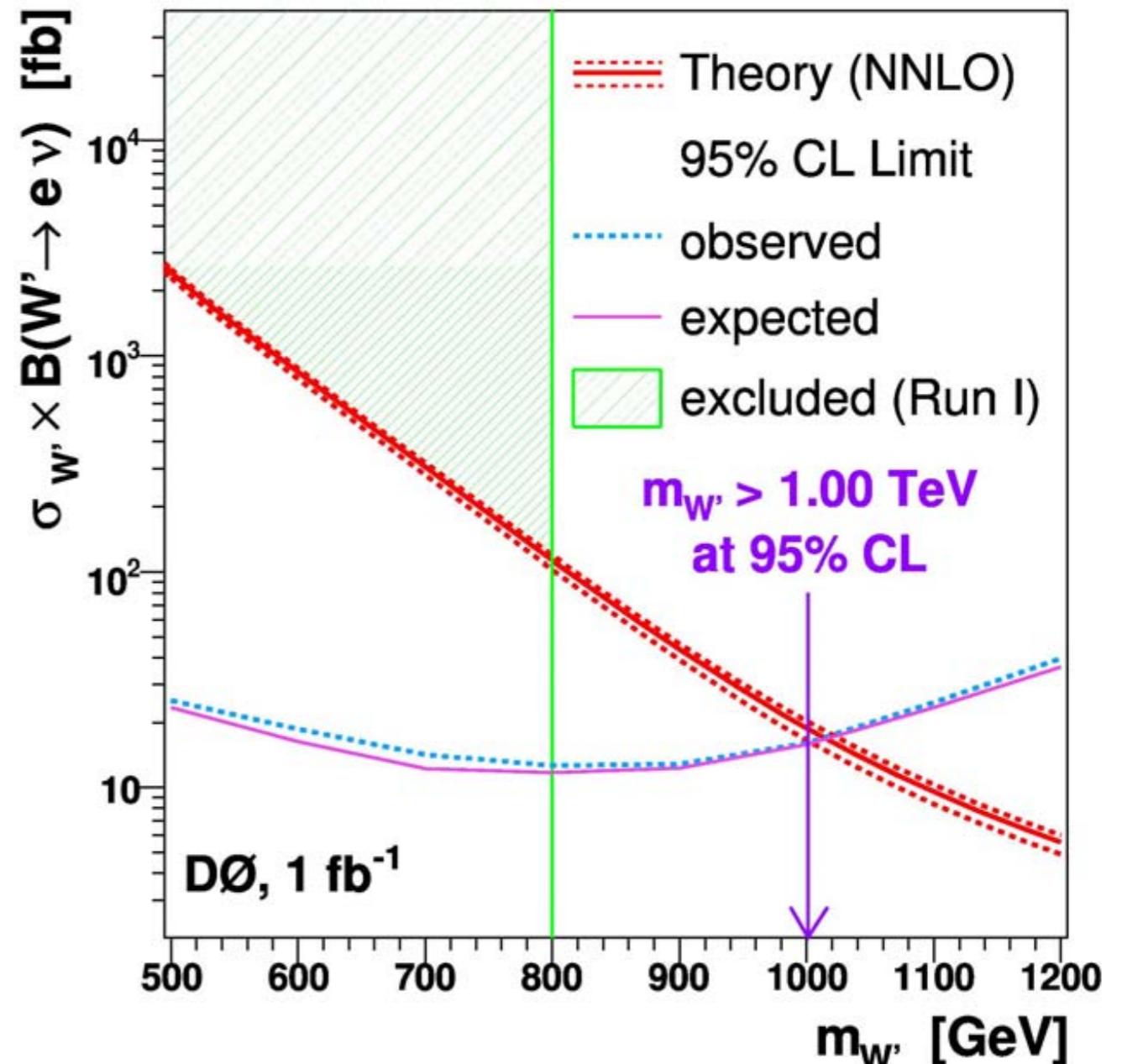
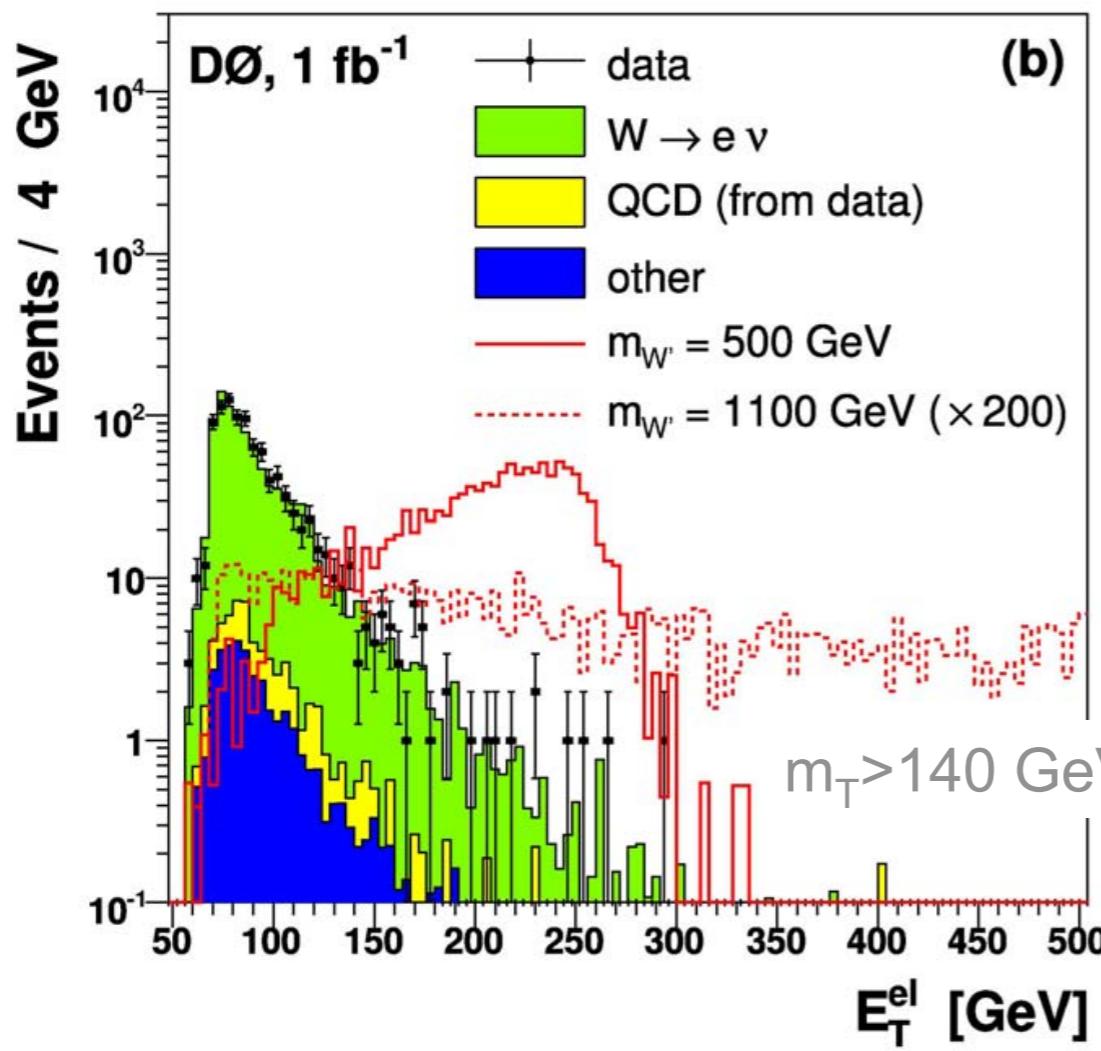
$$m_{\tilde{\chi}_1^\pm} < 229 \text{ GeV}$$

$$m_{\tilde{\chi}_1^0} < 125 \text{ GeV}$$

excluded

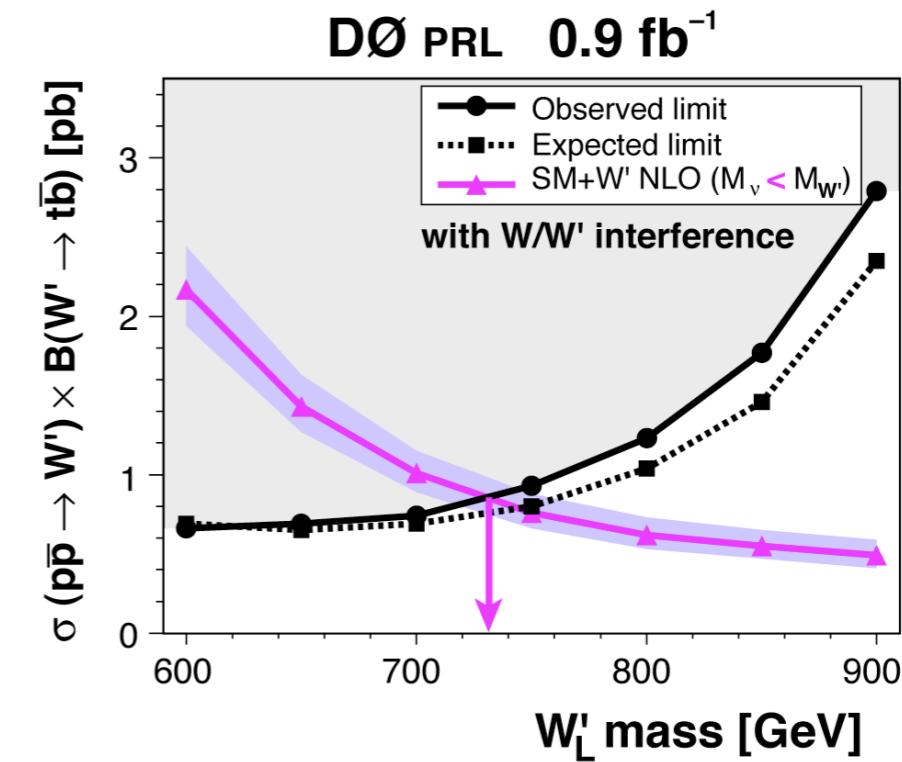
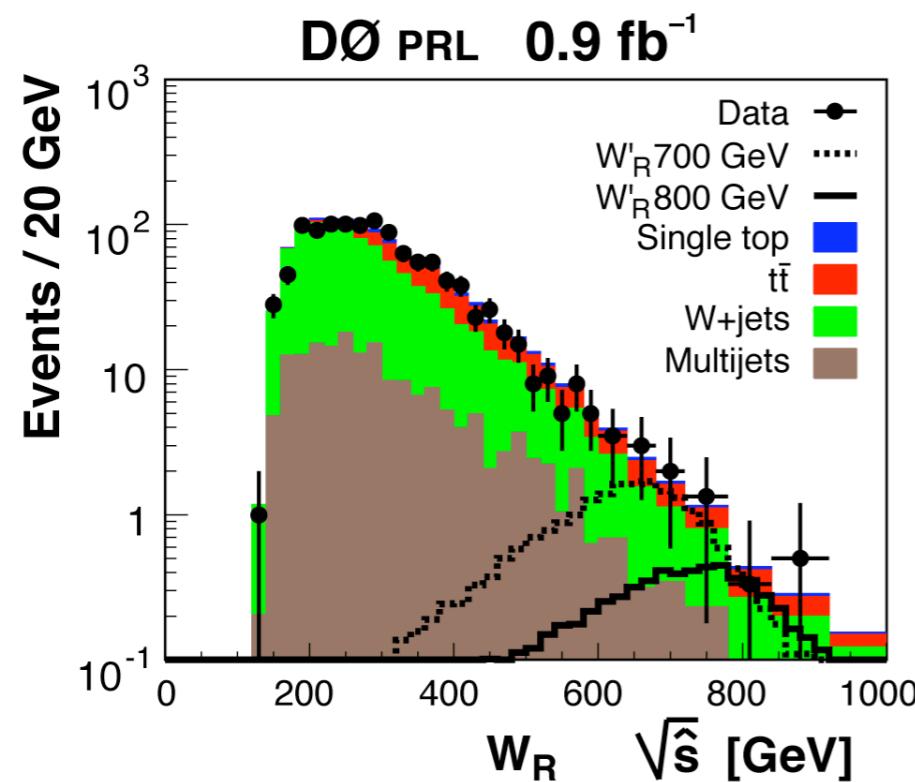
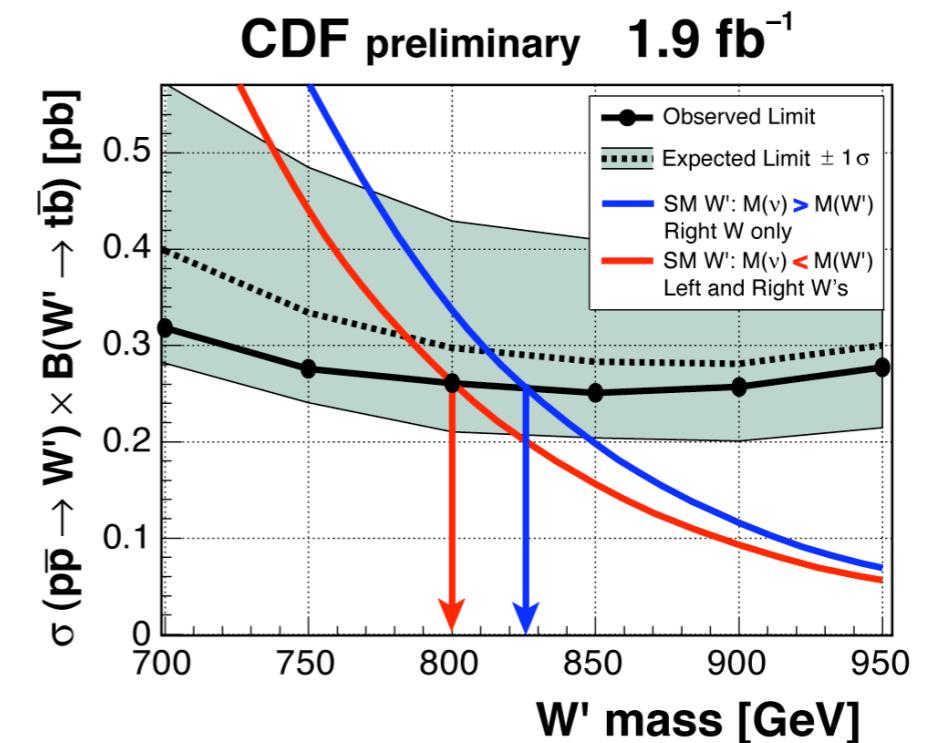
# $W'$ : Tevatron

- $W'_{L,R} \rightarrow e\nu$



# $W' \rightarrow tb$

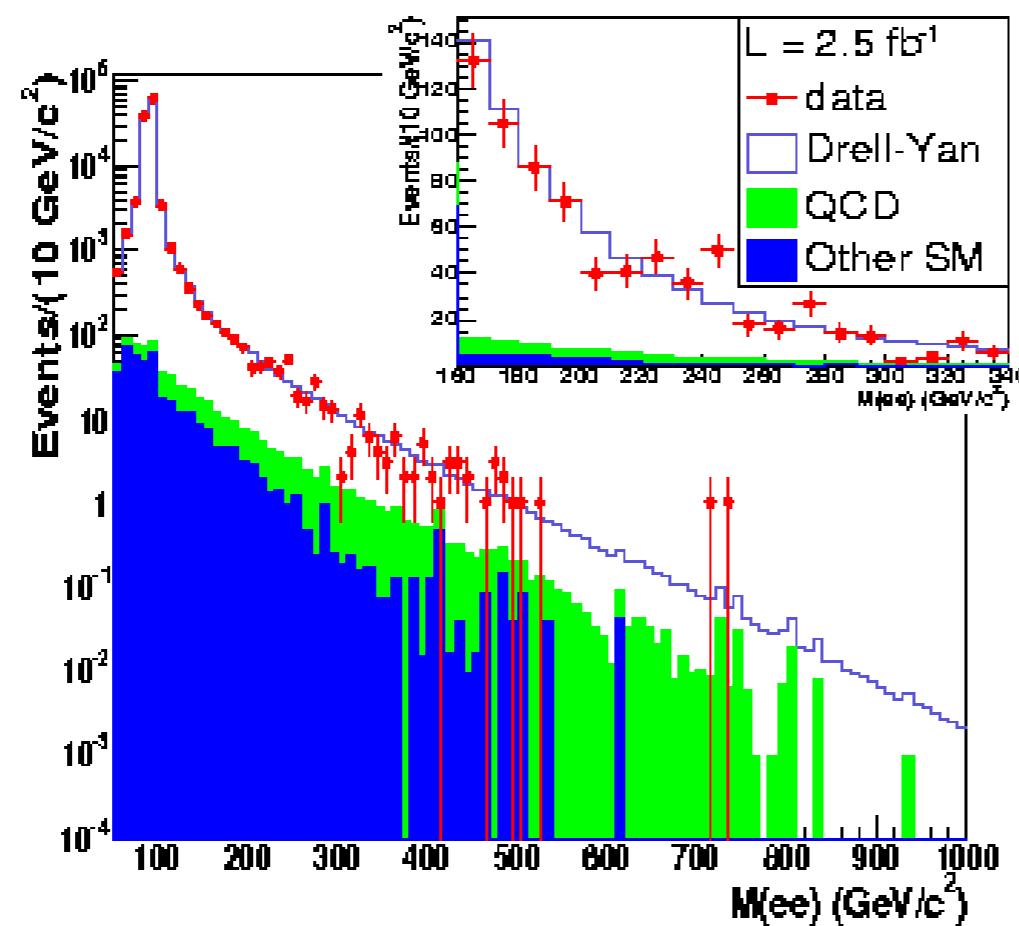
- decay channels depend on mass of right handed neutrino



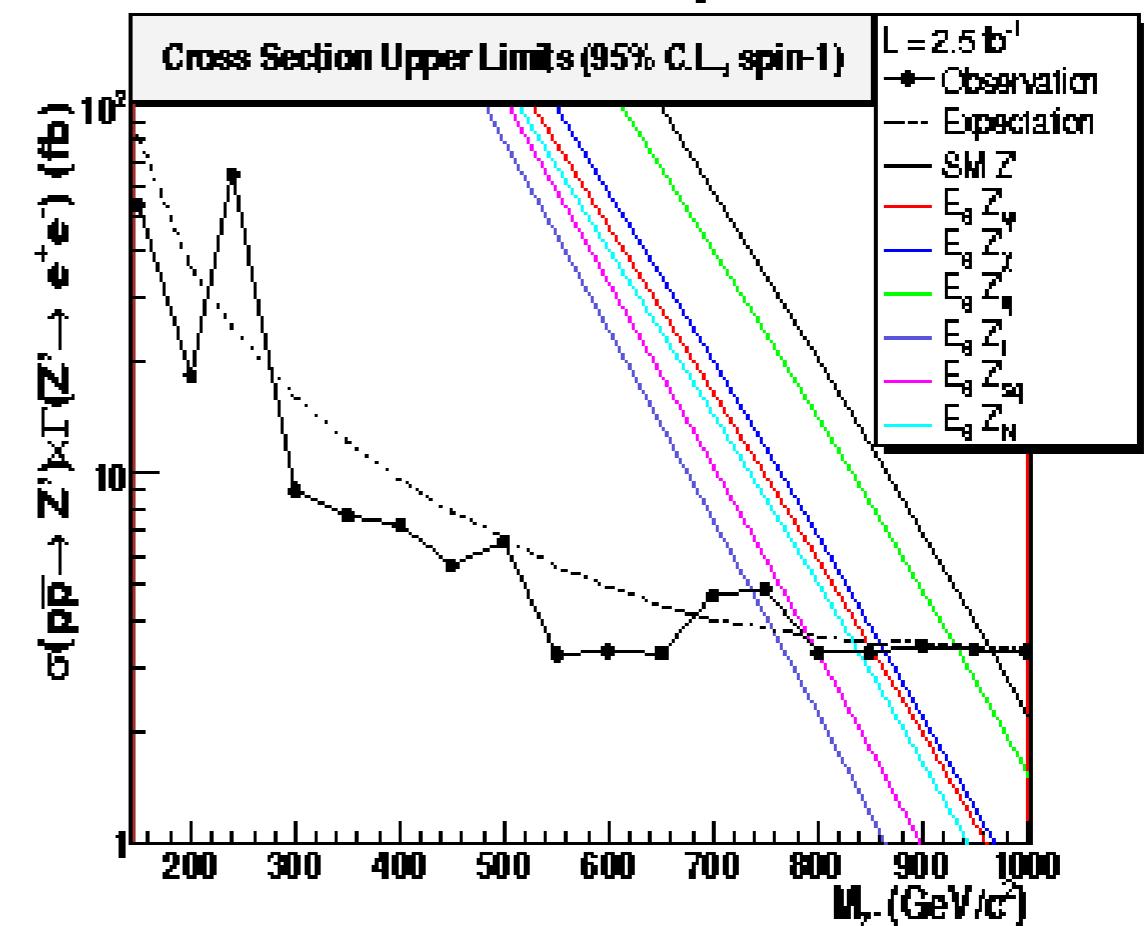
# Z': Tevatron

- scan  $M(ee)$  spectrum in steps of 1 GeV
- largest deviation  $3.8\sigma$

CDF Run II Preliminary

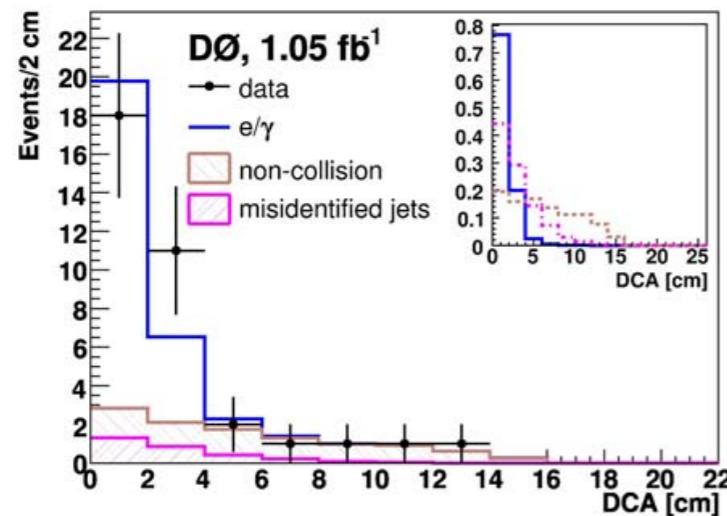


CDF Run II Preliminary

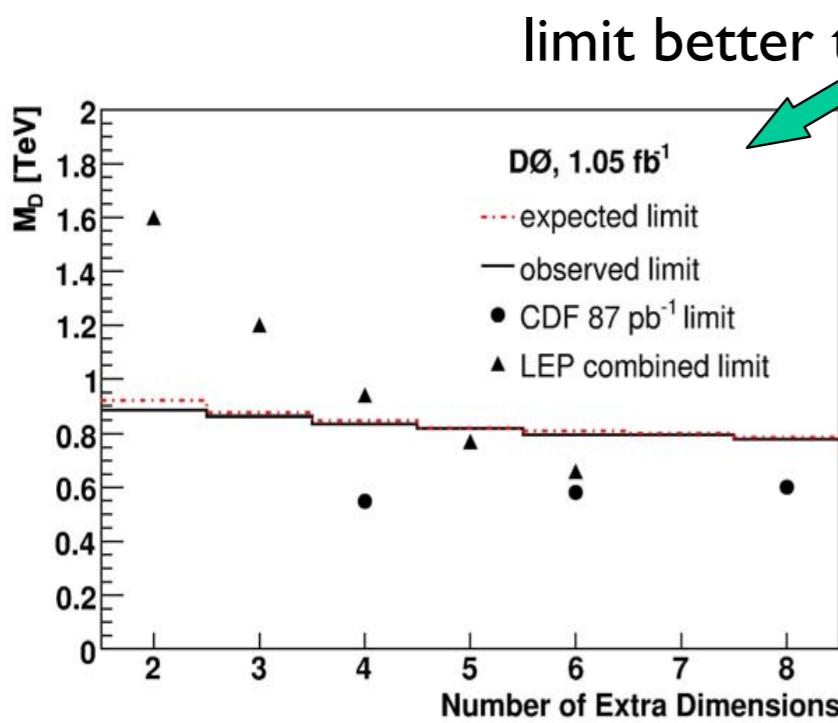
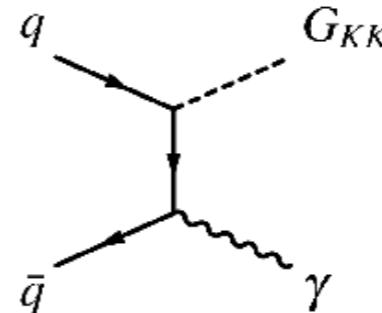


# Large Extra Dimensions: Tevatron

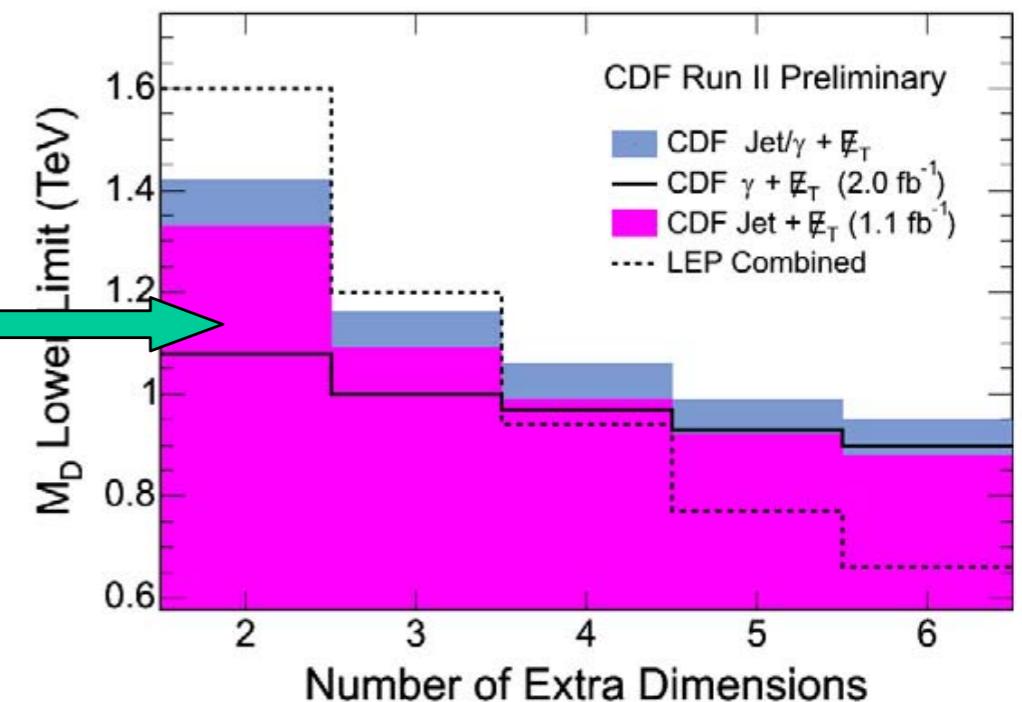
- monophoton and monojet final states



D0: photon pointing

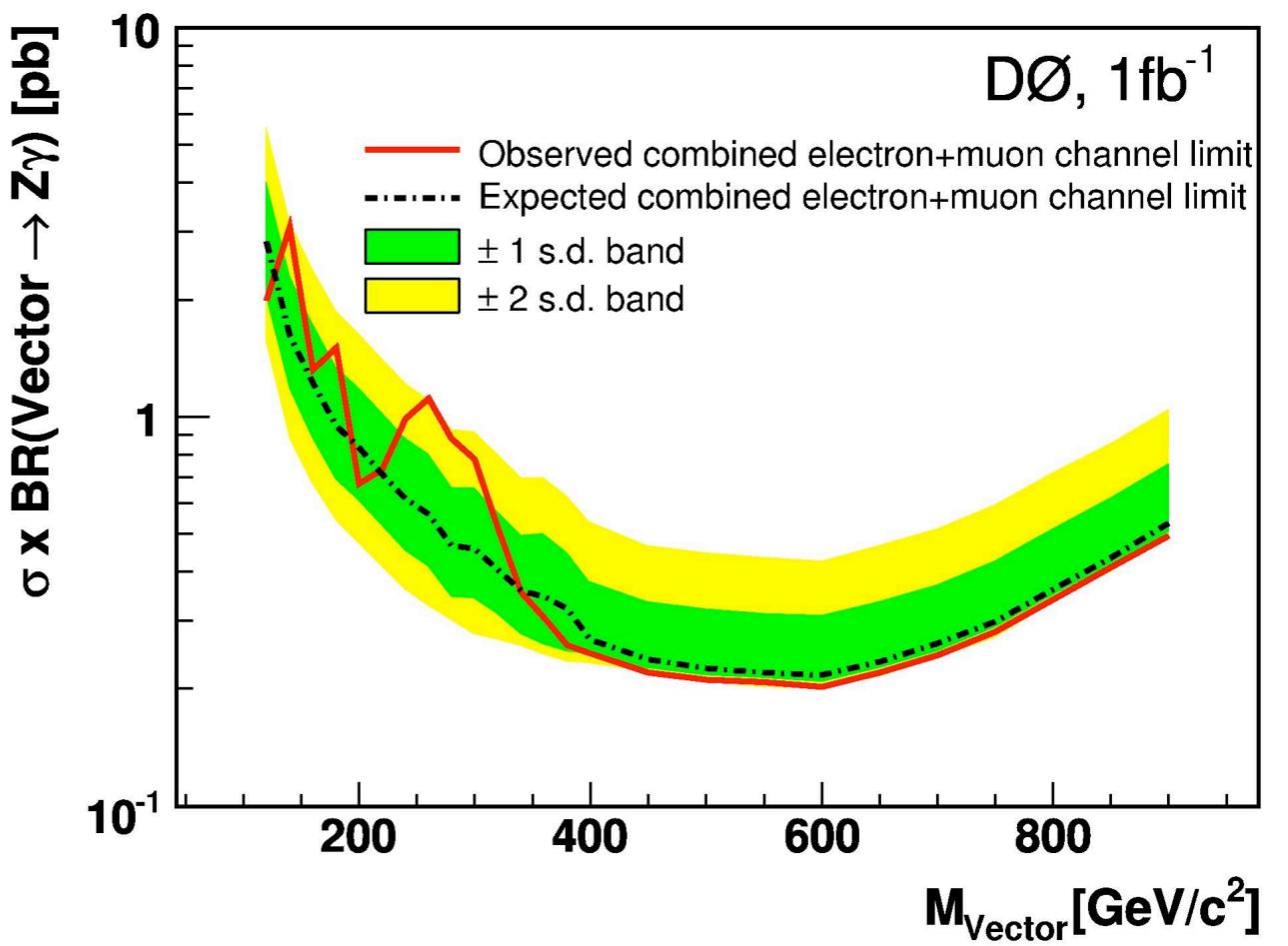
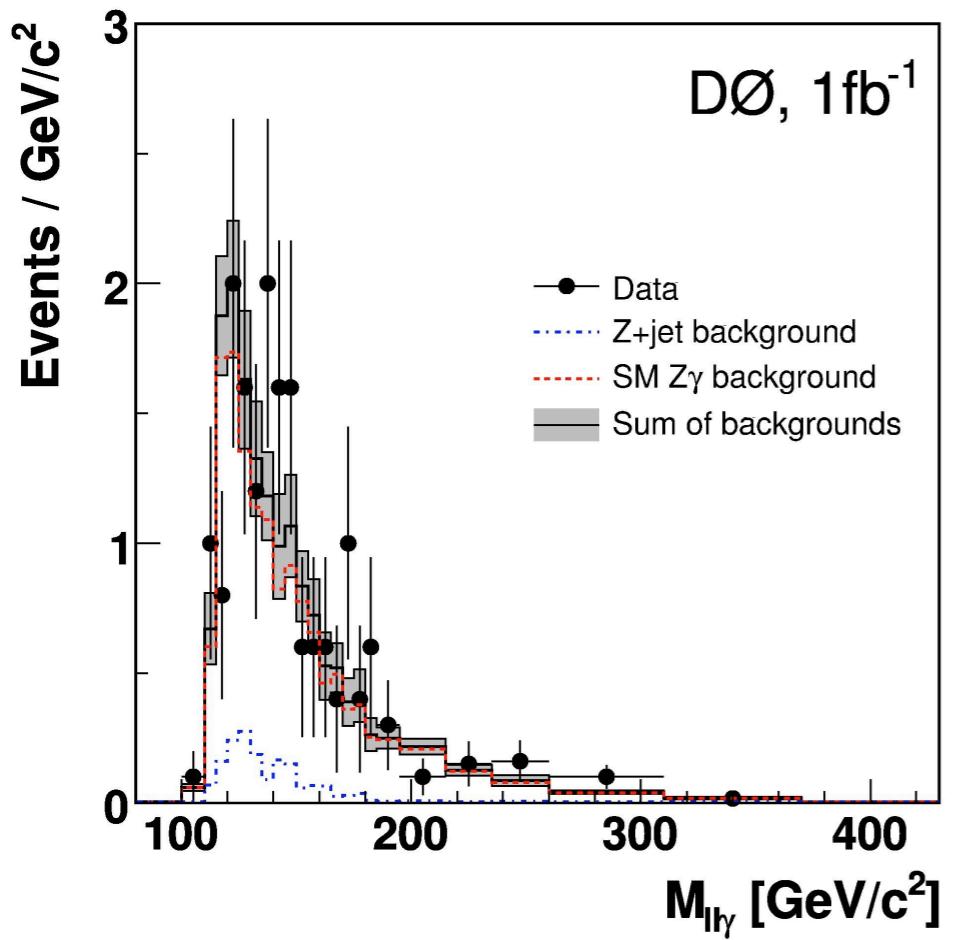


CDF: monophotons & monojets



# Z+ $\gamma$ resonances: Tevatron

- narrow scalar or vector resonance decaying into Z+photon;  $Z \rightarrow ee$  or  $\mu\mu$
- arXiv:0806.0611; sub.to Phys.Lett.B

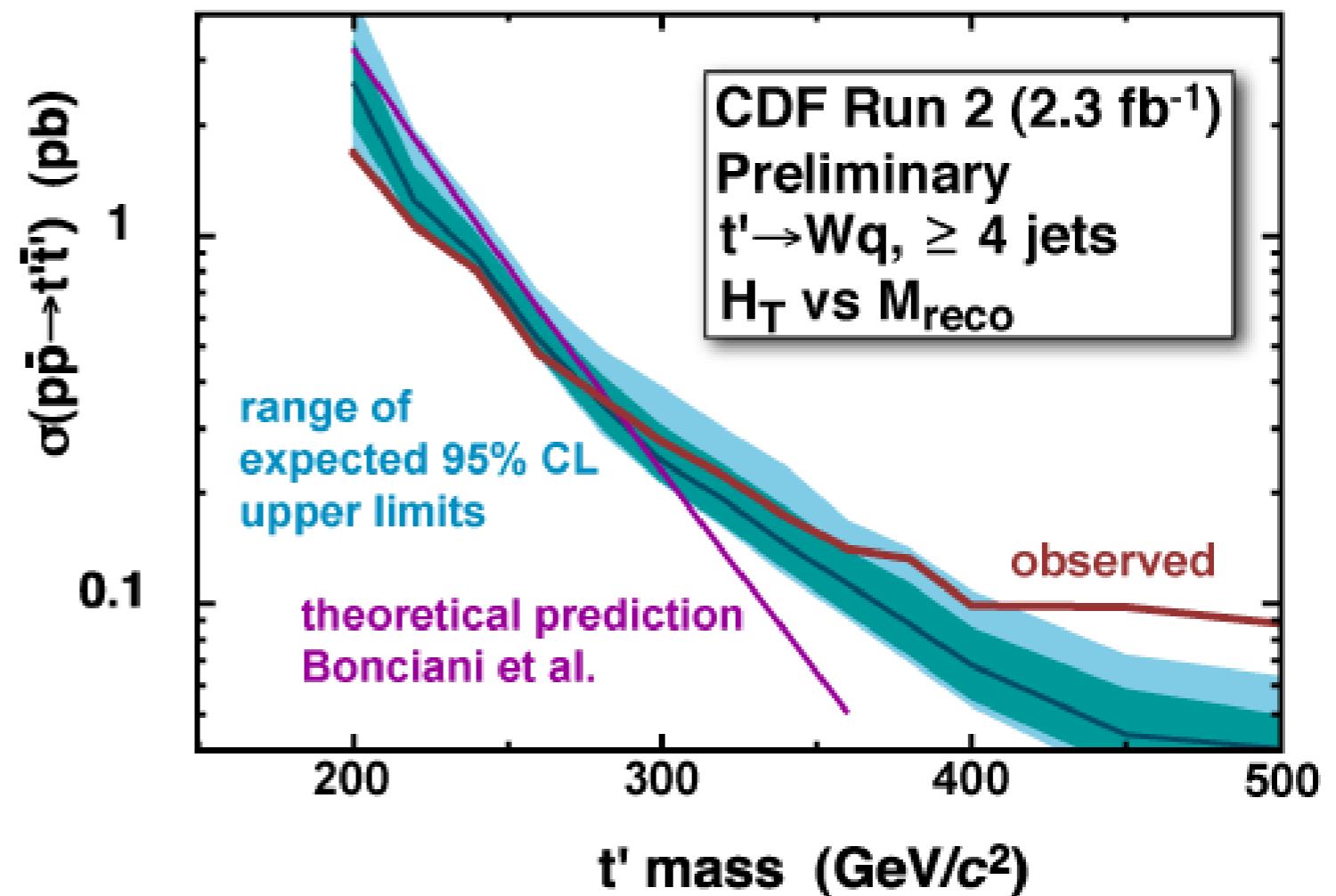
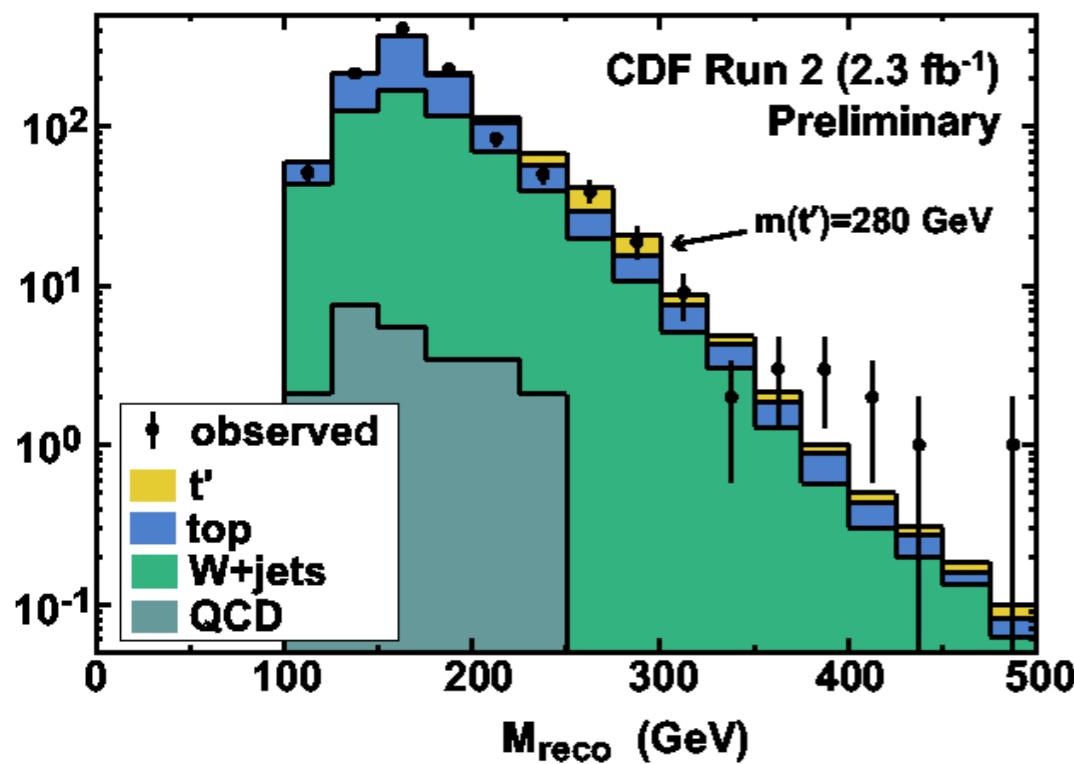


# 4th Generation: Tevatron

- search for  $t't' \rightarrow (Wj)(Wj) \rightarrow (l\nu j)(jjj)$   
(for  $m_t < m_{t'} < m_W + m_{b'}$ )

$$M_{\text{reco}} = M_{\text{jjj}} = M_{l\nu} \text{ (lowest } \chi^2 \text{ match)}$$

$$H_T = \sum_{\text{jets}, l, \text{MET}} E_T$$



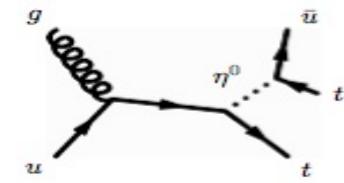
# Maximal Flavour Violation: Tevatron

- same sign top quarks

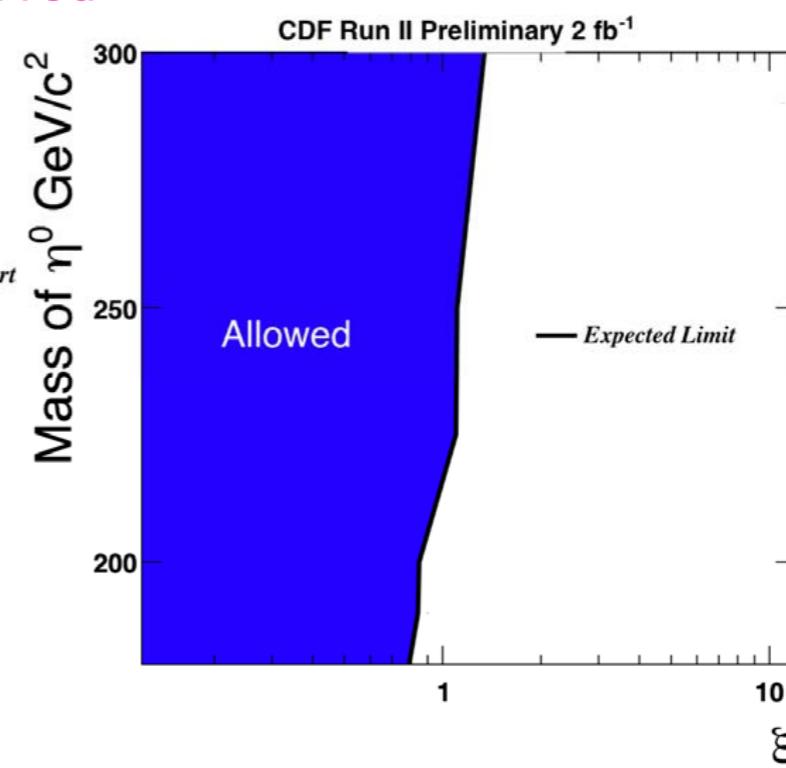
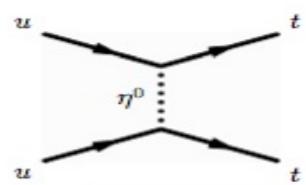
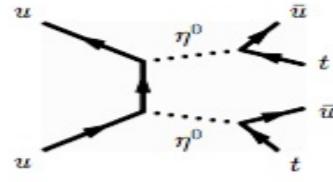
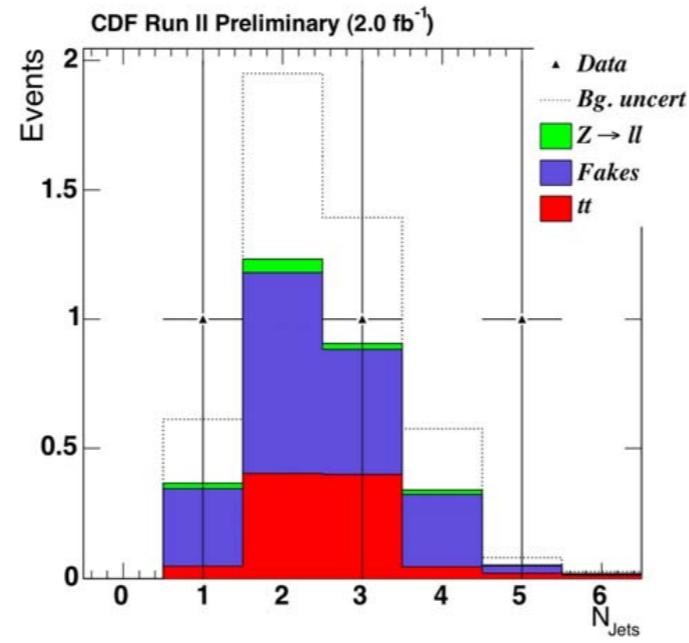
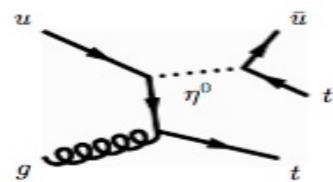
New scalar doublet  $\Phi_{\text{FV}}(\eta^0, \eta^+)$  is proposed with mass in the  $\sim 100 \text{ GeV}$  range and with off-diagonal coupling  $\xi$  to fermion generations ( $i=1,3$ ) :  $\xi_{ii} \sim 0$

only  $\xi_{3i}$  and  $\xi_{i3}$  are non-zero ( max FV contrarily to  $V_{\text{CKM}} \sim \text{diagonal}$ ).  
No contradiction with LE data ( $K^0, B^0, D^0$  oscillations, rare K,B decays).

Predicts new exotic final states, e.g. pair of LS top quarks



2.7-14.9 signal events  
 $2.9 \pm 1.8$  SM bg expected  
 2 data events observed

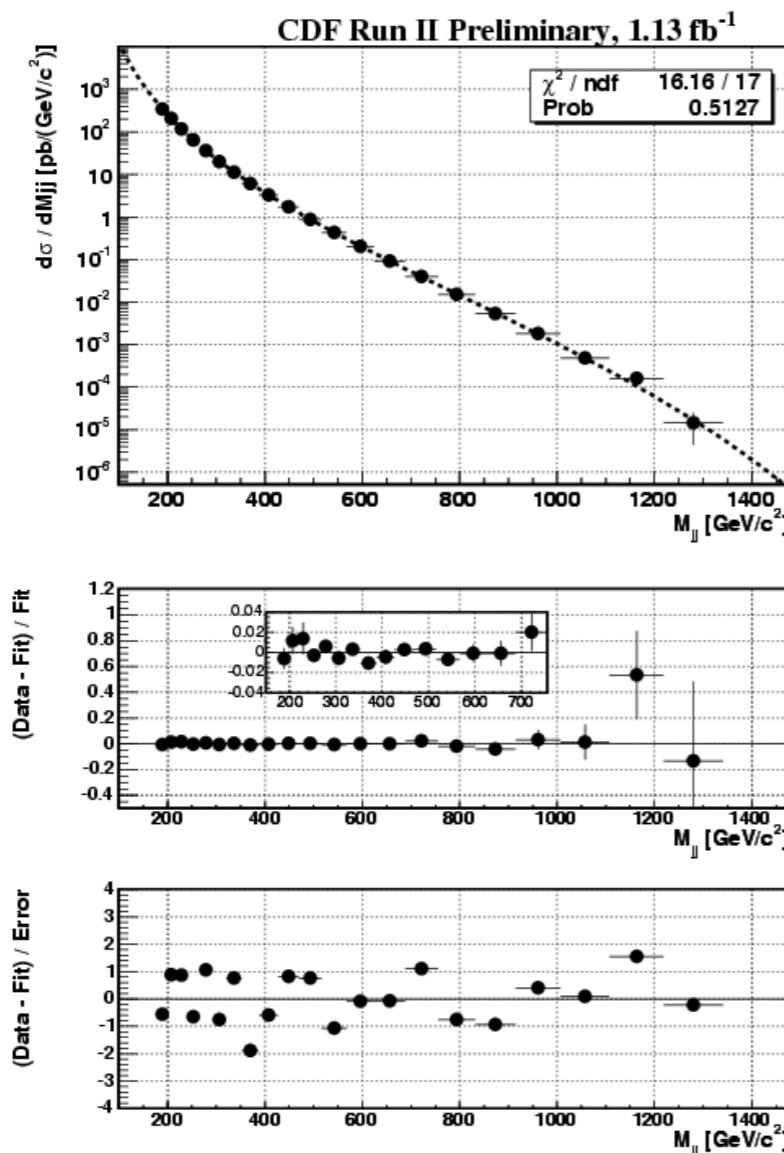


# Global/model-independent Searches

- excited electrons & quarks
- (isolated leptons at Hera: covered on Thursday)
- long-lived particles decaying to diphotons or dielectrons at the Tevatron
- global spectra analysis and bump hunt at the Tevatron

# Quark & Lepton Substructure: Tevatron

- excited quarks → bump in 2 jet mass spectrum

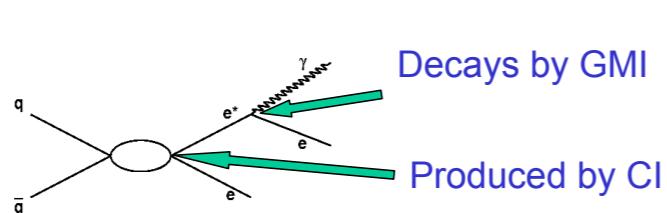


limit:

$$260 \text{ GeV} < M_{q^*} < 870 \text{ GeV}$$

# Quark & Lepton Substructure: Tevatron

- excited electrons
- arXiv:0801.0877 ; Phys.Rev.D77,091102 (2008)



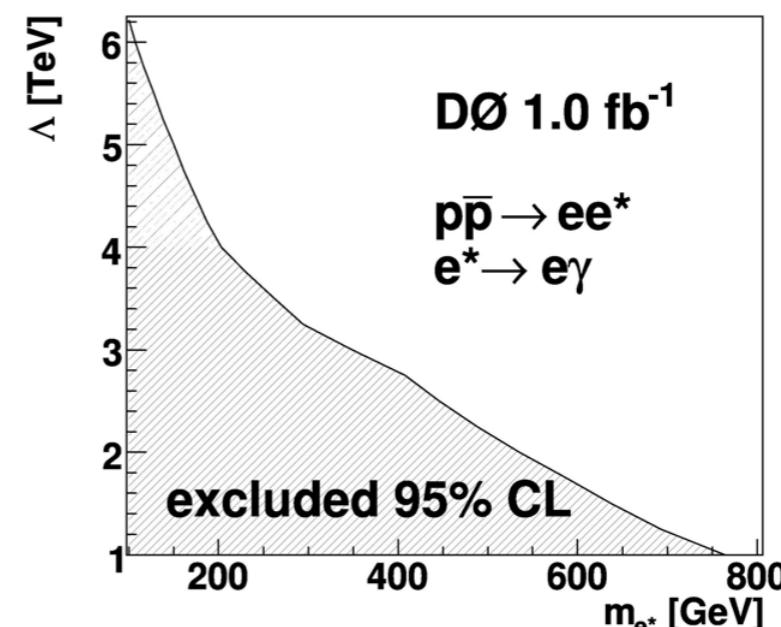
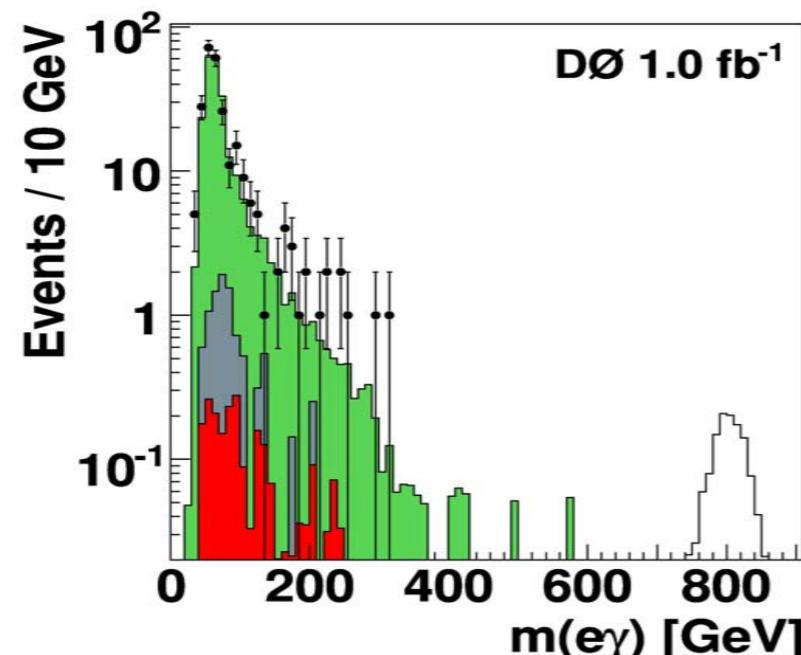
$$L_{GMI} = \frac{1}{2\Lambda} j^{\mu\nu} G_{\mu\nu}$$

$$L_{CI} = \frac{g^2}{2\Lambda^2} j^\mu j_\mu$$

Compositeness  
scale:  $\Lambda$

Signal: 2 high  $p_T$  electron + 1 high ET photon  
Bg: mainly DY+j/γ

$M_{e^*} < 756$  GeV excluded for  $\Lambda = 1$  TeV



# Excited Electrons at Hera

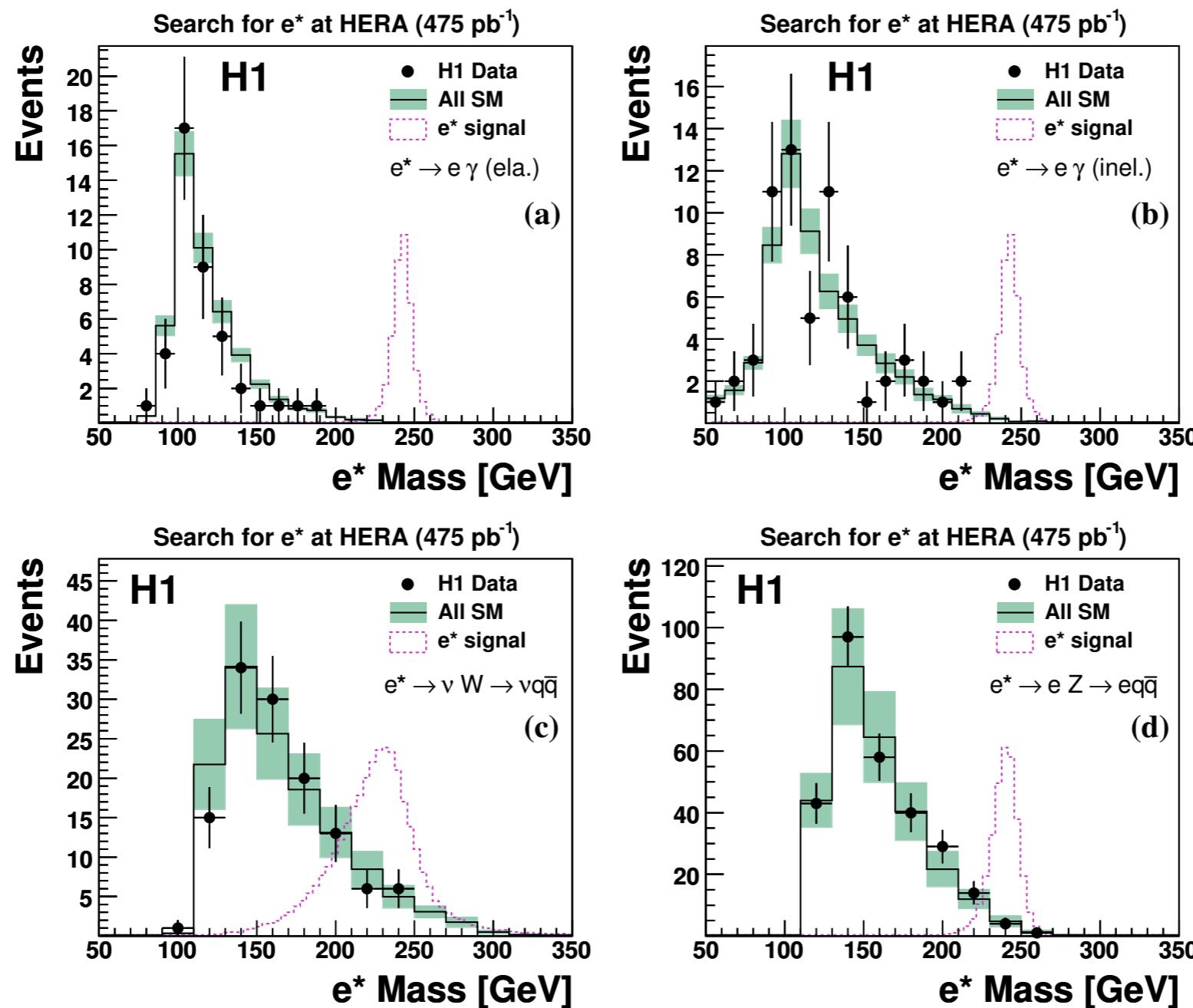
- Search for  $e^*$  in  $e\gamma$ ,  $eZ$  and neutrino  $W$

**Search for  $e^*$  at HERA ( $475 \text{ pb}^{-1}$ )**

| Channel                                          | Data | SM              | Signal Efficiency [%] |
|--------------------------------------------------|------|-----------------|-----------------------|
| $e^* \rightarrow e\gamma$ (ela.)                 | 42   | $48 \pm 4$      | 60–70                 |
| $e^* \rightarrow e\gamma$ (inel.)                | 65   | $65 \pm 8$      | 60–70                 |
| $e^* \rightarrow \nu W \rightarrow \nu q\bar{q}$ | 129  | $133 \pm 32$    | 20–55                 |
| $e^* \rightarrow \nu W \rightarrow \nu e\nu$     | 4    | $4.5 \pm 0.7$   | 60                    |
| $e^* \rightarrow eZ \rightarrow e\nu\nu$         |      |                 | 35                    |
| $e^* \rightarrow eZ \rightarrow eq\bar{q}$       | 286  | $277 \pm 62$    | 20–55                 |
| $e^* \rightarrow eZ \rightarrow eee$             | 0    | $0.72 \pm 0.06$ | 60                    |
| $e^* \rightarrow eZ \rightarrow e\mu\mu$         | 0    | $0.52 \pm 0.05$ | 40–15                 |

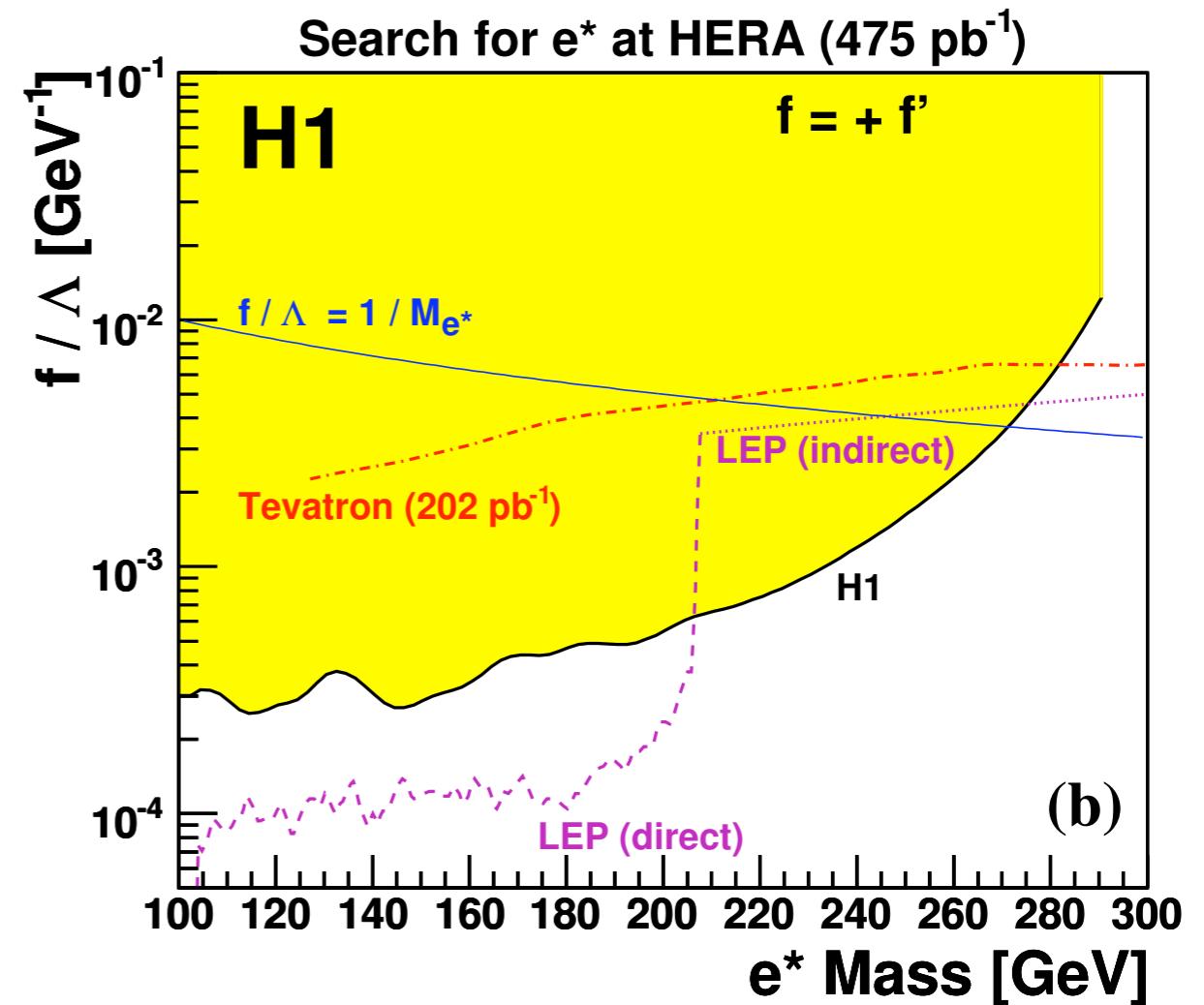
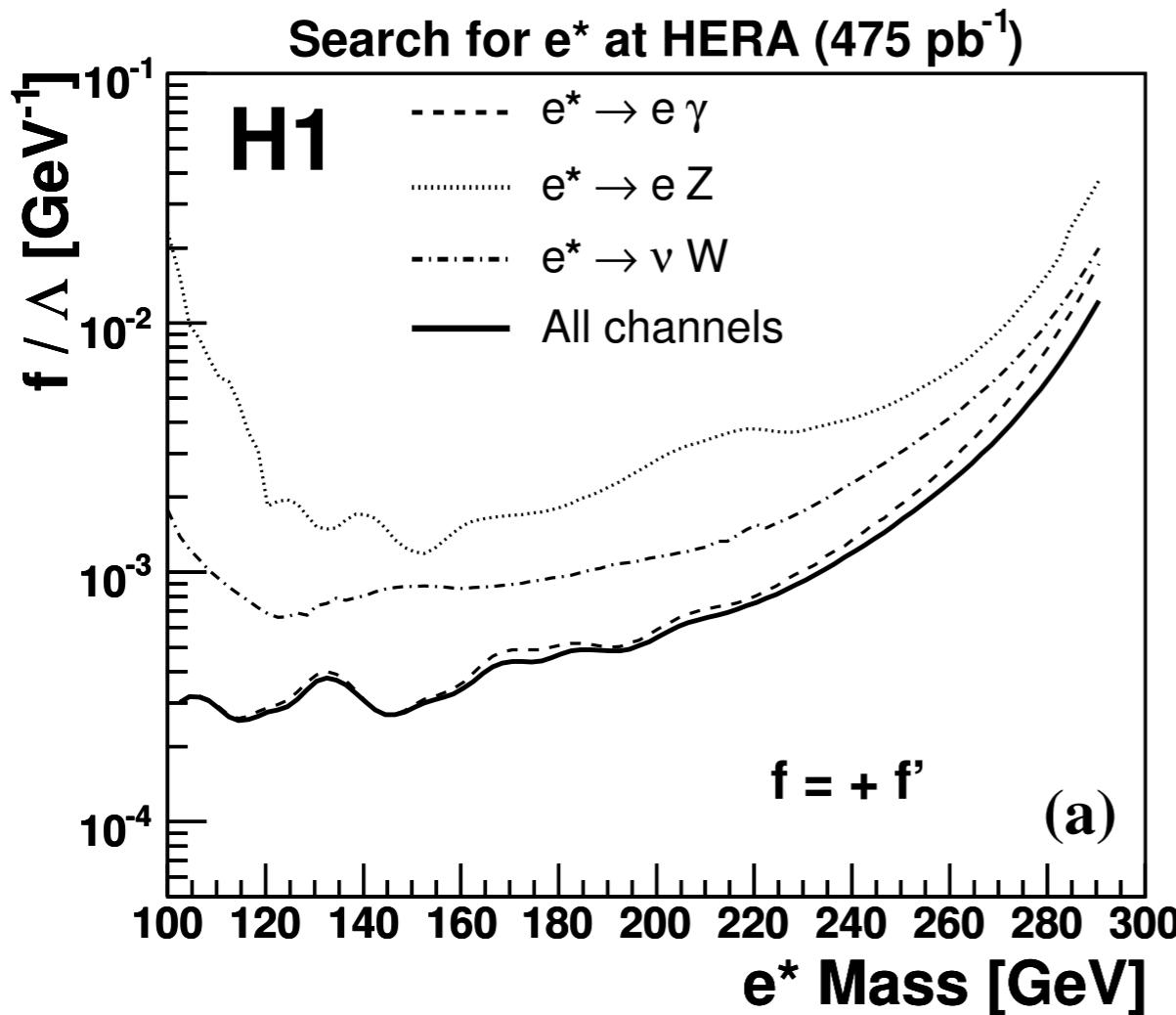
# Excited Electrons at Hera

- $e^*$  mass spectra  $e + \text{photon}$ ,  $\text{neutrino} + \text{jet}$  jet and  $e + \text{jet}$  jet channels



# Excited Electrons at Hera

- Exclusion limits from H1 [DESY 08-052]



# Excited Neutrinos at Hera

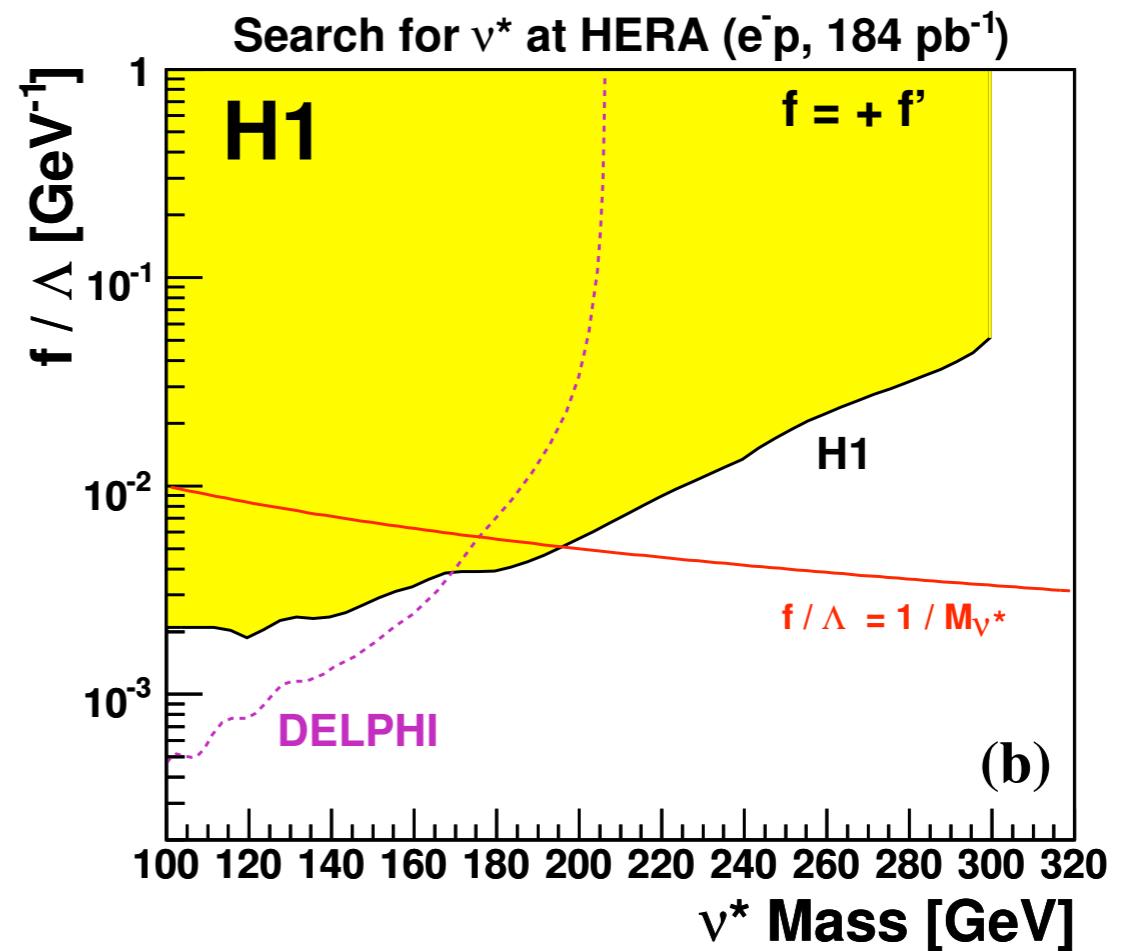
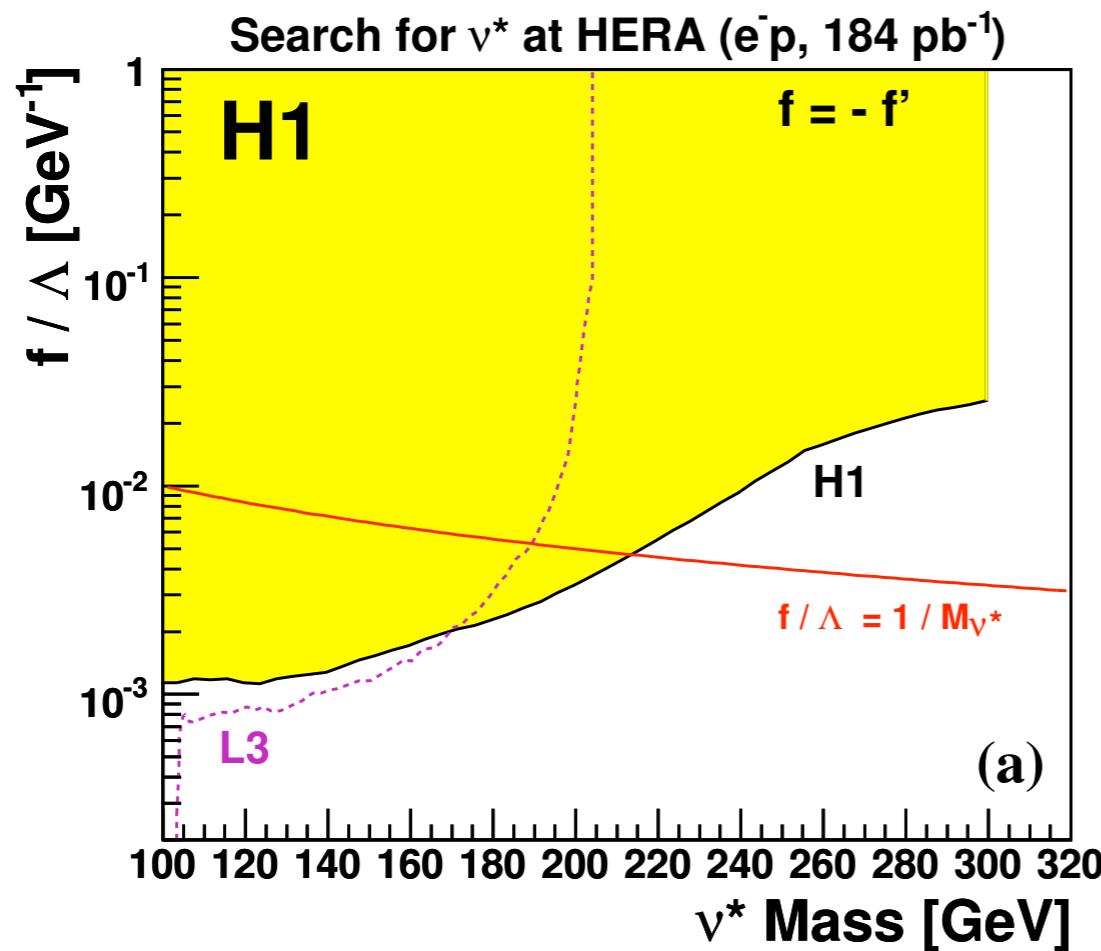
- Search for  $\nu^*$  in  $\nu \gamma$ ,  $\nu Z$  and  $e W$

**Search for  $\nu^*$  at HERA ( $e^- p, 184 \text{ pb}^{-1}$ )**

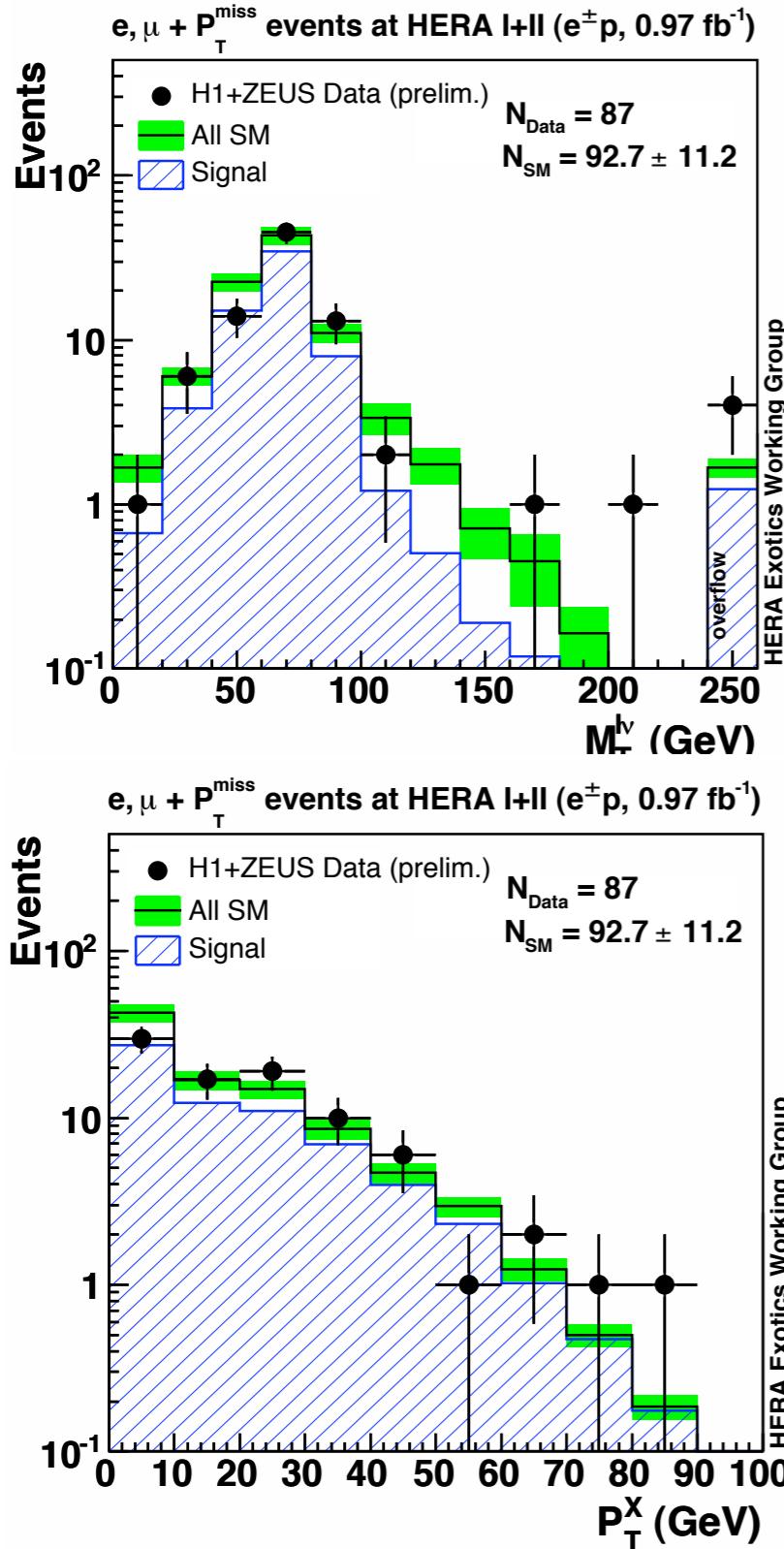
| Channel                                            | Data | SM              | Signal Efficiency [%] |
|----------------------------------------------------|------|-----------------|-----------------------|
| $\nu^* \rightarrow \nu \gamma$                     | 7    | $12.3 \pm 3.0$  | 50–55                 |
| $\nu^* \rightarrow eW \rightarrow eq\bar{q}$       | 220  | $223 \pm 47$    | 40–65                 |
| $\nu^* \rightarrow eW \rightarrow e\nu\mu$         | 0    | $0.40 \pm 0.05$ | 35                    |
| $\nu^* \rightarrow eW \rightarrow e\nu e$          | 0    | $0.7 \pm 0.1$   | 45                    |
| $\nu^* \rightarrow \nu Z \rightarrow \nu q\bar{q}$ | 89   | $95 \pm 21$     | 25–55                 |
| $\nu^* \rightarrow \nu Z \rightarrow \nu ee$       | 0    | $0.19 \pm 0.05$ | 45                    |

# Excited Neutrinos at Hera

- Exclusion contours



# Isolated Leptons at HERA



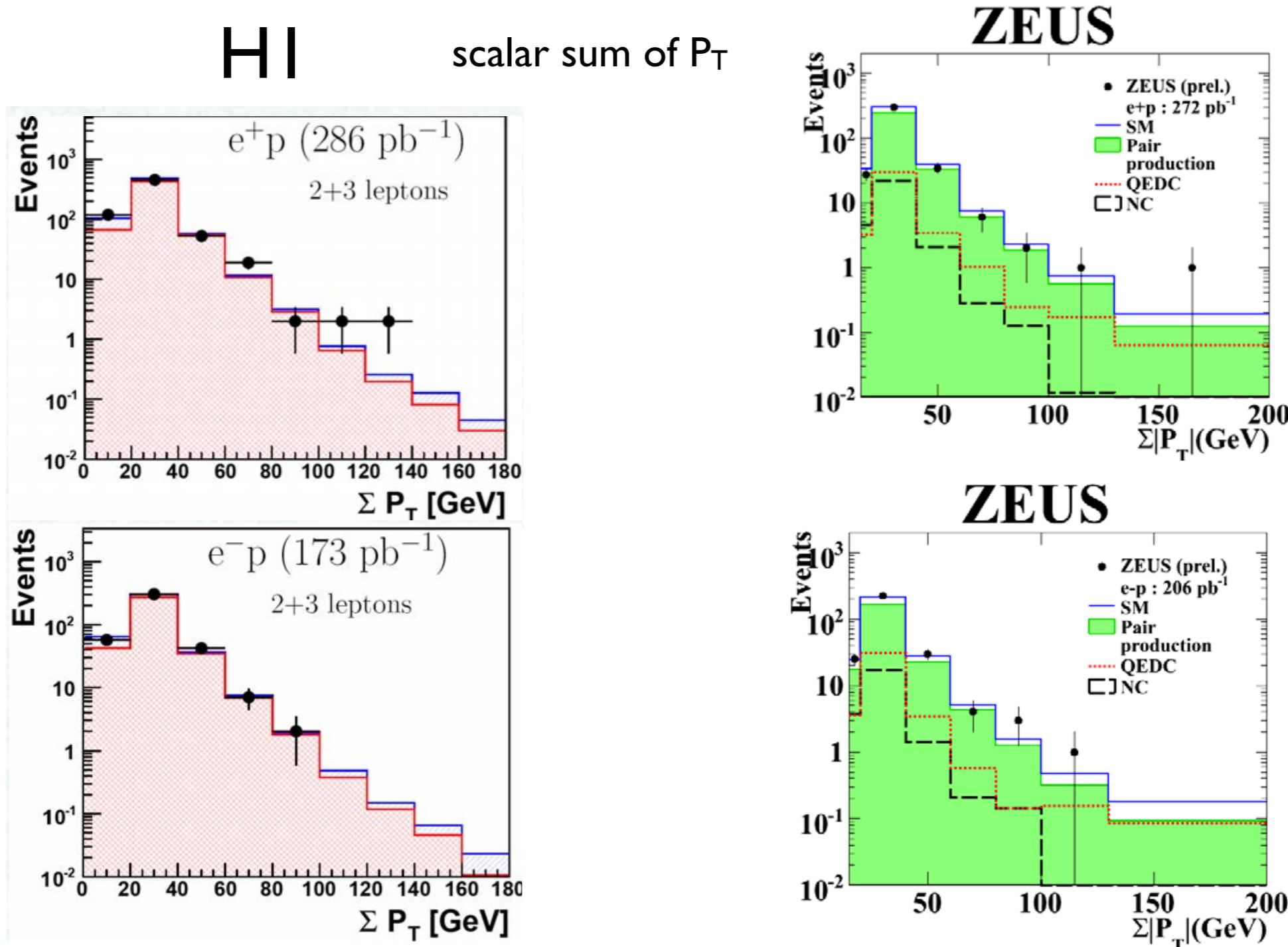
- 3 sigma excess reported by H1
- combined Zeus+H1 analysis on full HERA I + HERA II samples
- final Zeus analysis available

Zeus final numbers (ZEUS-pub-08-005)

| Isolated Lepton Candidates    | $P_T^X < 12 \text{ GeV}$         | $12 < P_T^X < 25 \text{ GeV}$    | $P_T^X > 25 \text{ GeV}$         |
|-------------------------------|----------------------------------|----------------------------------|----------------------------------|
| $e^- p 208 \text{ pb}^{-1}$   | $9/11.3 \pm 1.5 \text{ (54\%)}$  | $6/5.1 \pm 0.7 \text{ (67\%)}$   | $5/5.5 \pm 0.8 \text{ (75\%)}$   |
| $e^+ p 296 \text{ pb}^{-1}$   | $7/12.6 \pm 1.7 \text{ (68\%)}$  | $7/6.2 \pm 0.9 \text{ (75\%)}$   | $6/7.4 \pm 1.0 \text{ (79\%)}$   |
| $e^\pm p 504 \text{ pb}^{-1}$ | $16/23.9 \pm 3.1 \text{ (61\%)}$ | $13/11.2 \pm 1.5 \text{ (71\%)}$ | $11/12.9 \pm 1.7 \text{ (77\%)}$ |

# Multileptons: Hera

- background: well understood QED processes



# Multileptons: Hera

- event yields for sum  $P_T > 100 \text{ GeV}$

| Data sample    | Data | SM            | Pair Production | NCDIS + Compton |
|----------------|------|---------------|-----------------|-----------------|
| e+p<br>L=286pb | 4    | $1.2 \pm 0.2$ | $1.0 \pm 0.2$   | $0.2 \pm 0.1$   |
| e-p<br>L=173pb | 0    | $0.8 \pm 0.2$ | $0.6 \pm 0.2$   | $0.2 \pm 0.1$   |
| All<br>L=459pb | 4    | $1.9 \pm 0.4$ | $1.5 \pm 0.3$   | $0.4 \pm 0.1$   |

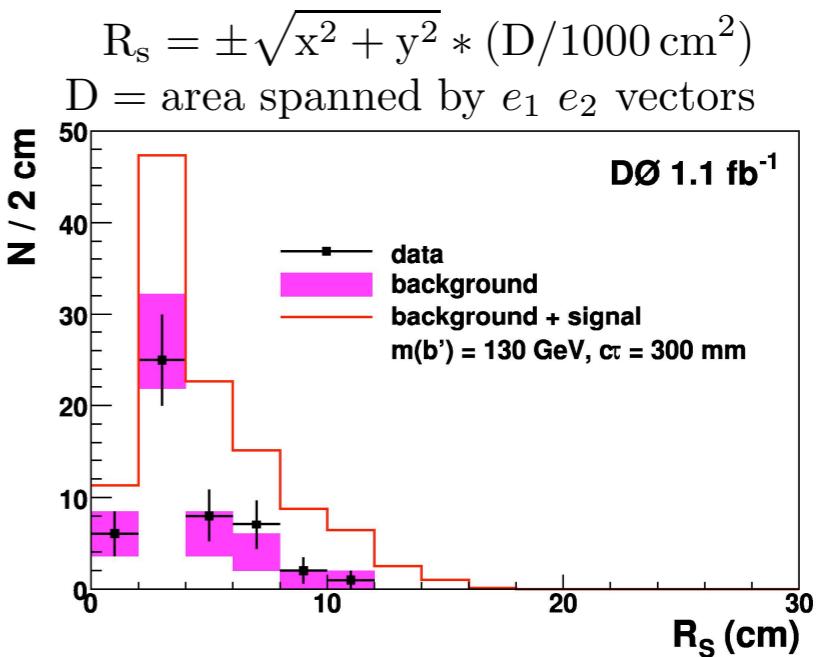
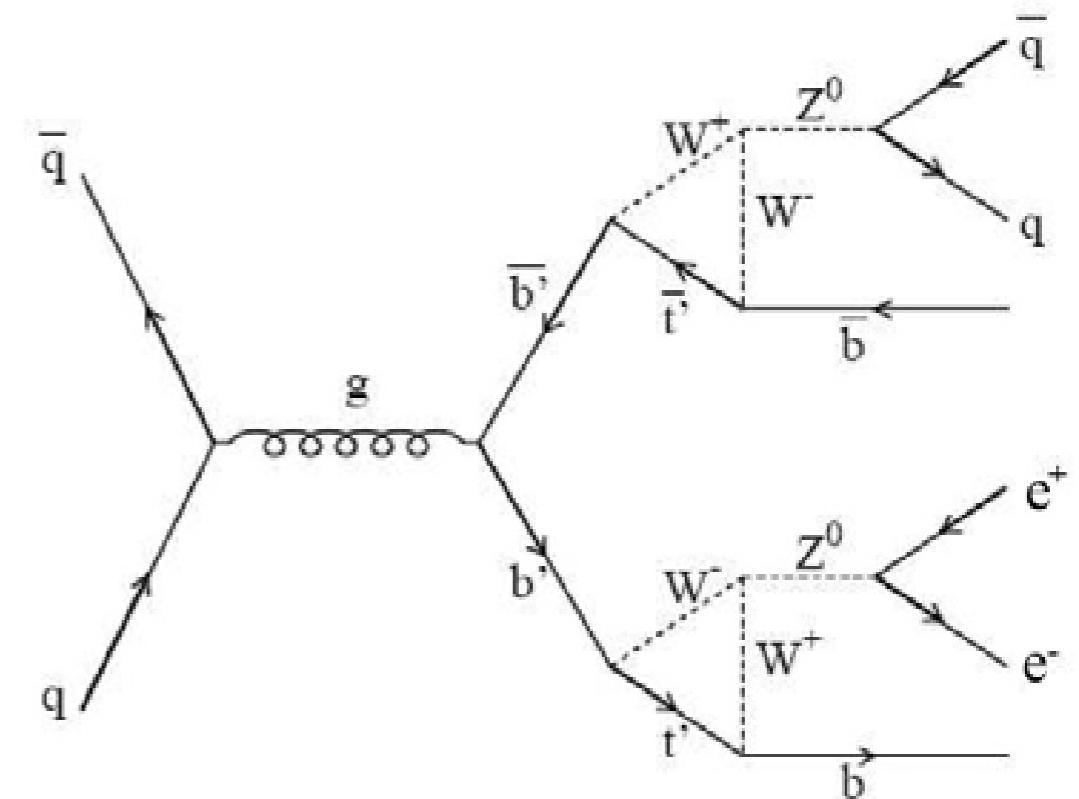
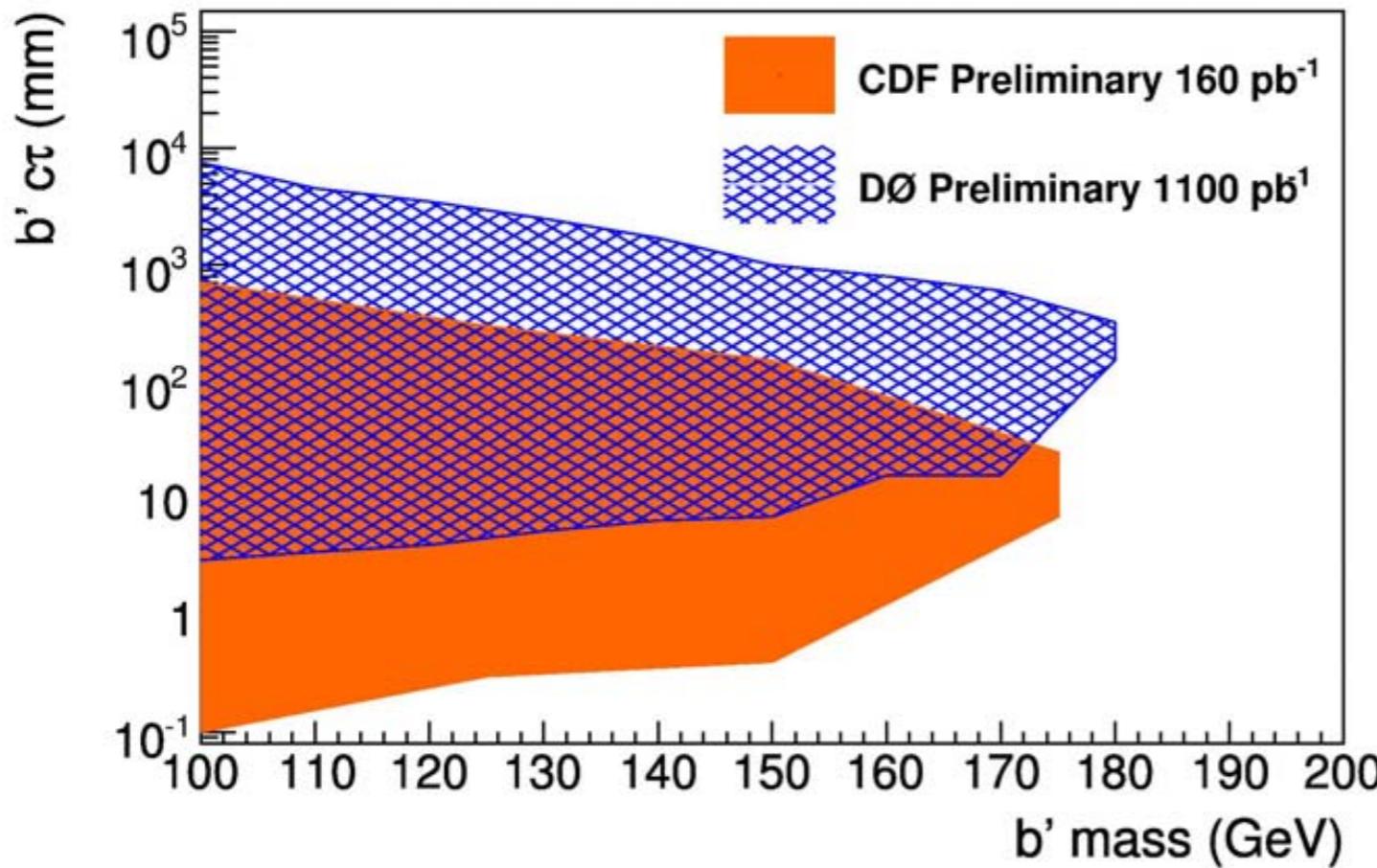
H1 459 pb<sup>-1</sup>

| Data sample    | Data | SM                     | Pair Production | Compton                | NC DIS          |
|----------------|------|------------------------|-----------------|------------------------|-----------------|
| e+p<br>L=272pb | 2    | $0.93^{+0.10}_{-0.09}$ | $0.67 \pm 0.07$ | $0.23^{+0.07}_{-0.06}$ | $0.02 \pm 0.01$ |
| e-p<br>L=206pb | 1    | $0.65^{+0.08}_{-0.07}$ | $0.41 \pm 0.04$ | $0.24^{+0.07}_{-0.06}$ | $0.01 \pm 0.01$ |
| All<br>L=478pb | 3    | $1.58^{+0.16}_{-0.12}$ | $1.08 \pm 0.11$ | $0.47^{+0.15}_{-0.11}$ | $0.03 \pm 0.01$ |

Zeus 478 pb<sup>-1</sup>

# long-lived particles: Tevatron

- search for displaced di-em vertices; example: long-lived  $b'$
- for  $m(b') < m(t)$   $c\tau \sim \text{meters}$
- $b'$  decay (di-em) vertex reconstructed in tracker (CDF)
  - or in central preshower + calorimeter (D0) **(no track required)**

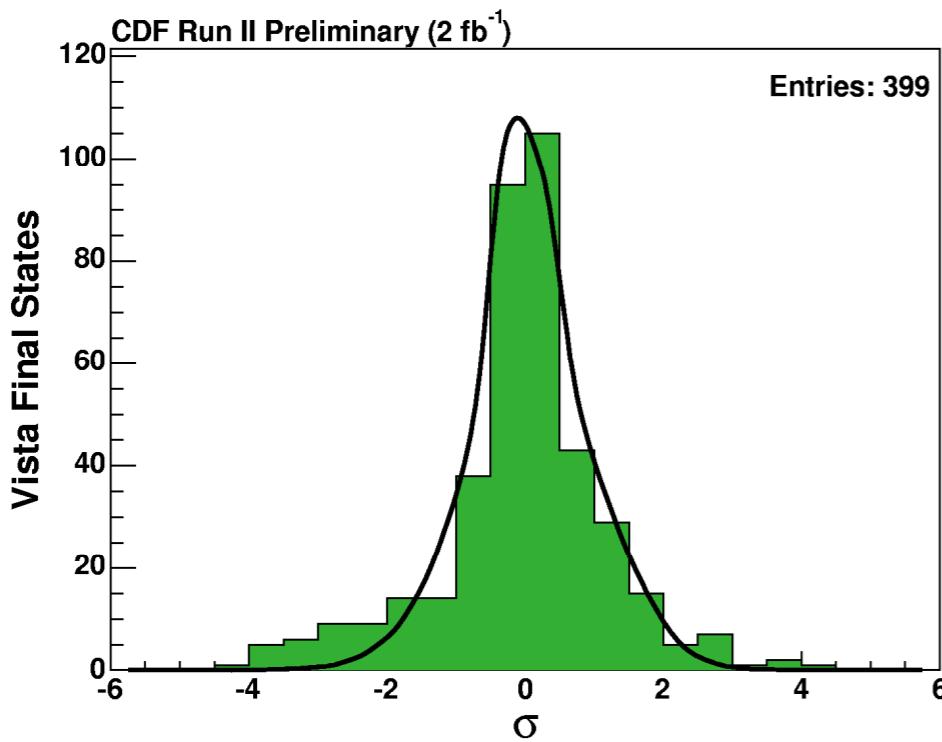


# Global Searches: Tevatron

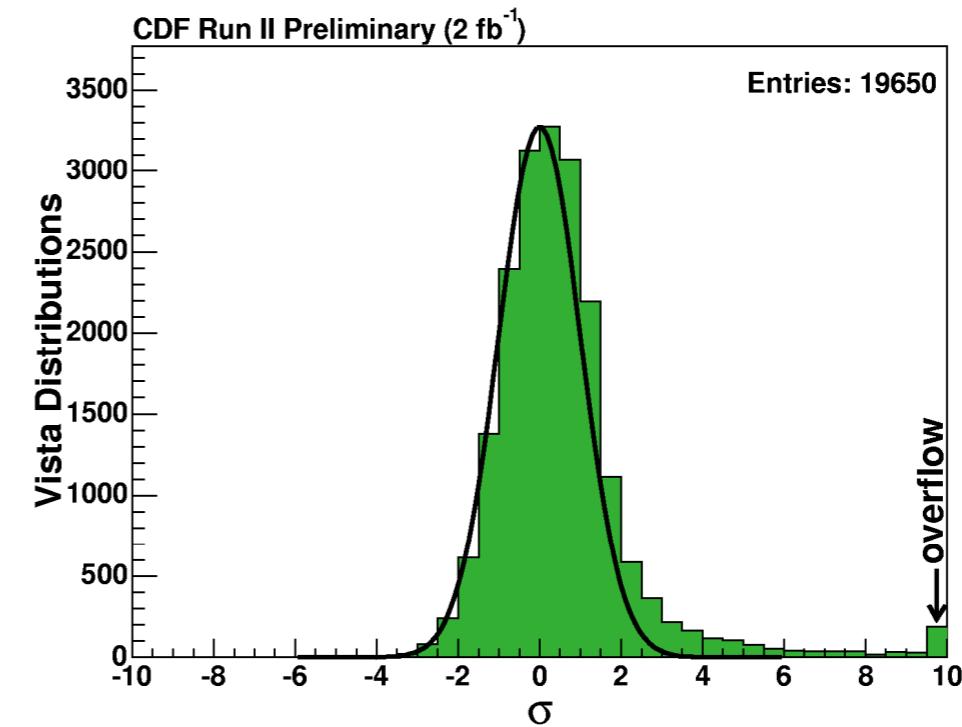
- VISTA:
  - select all data with well-reconstructed objects ( $pT > 17 \text{ GeV}/c$ )  
→ 4 Mio events from 2/fb
  - 400 exclusive final states, 20000 distributions, 5000 mass spectra
  - compare/fit to standard model prediction

# VISTA

- look for outliers (distributions with large deviation from SM prediction)
- dist. of events over final states ok; outliers among kinematic distributions all due to imperfect modeling of 3-jet final states



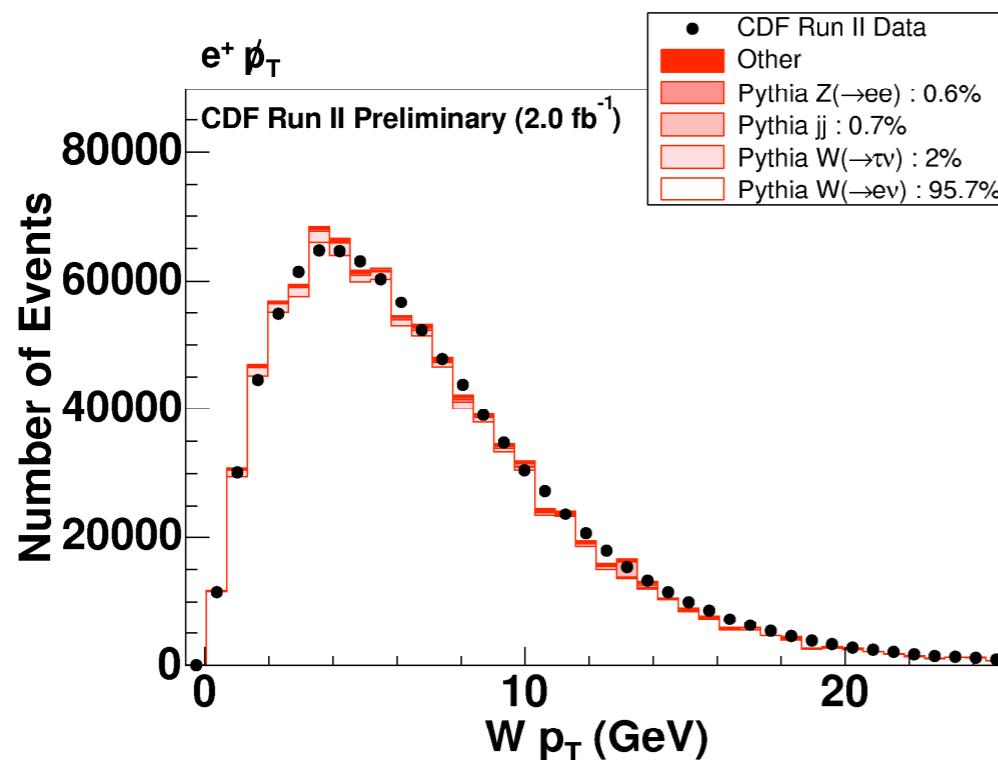
final state population



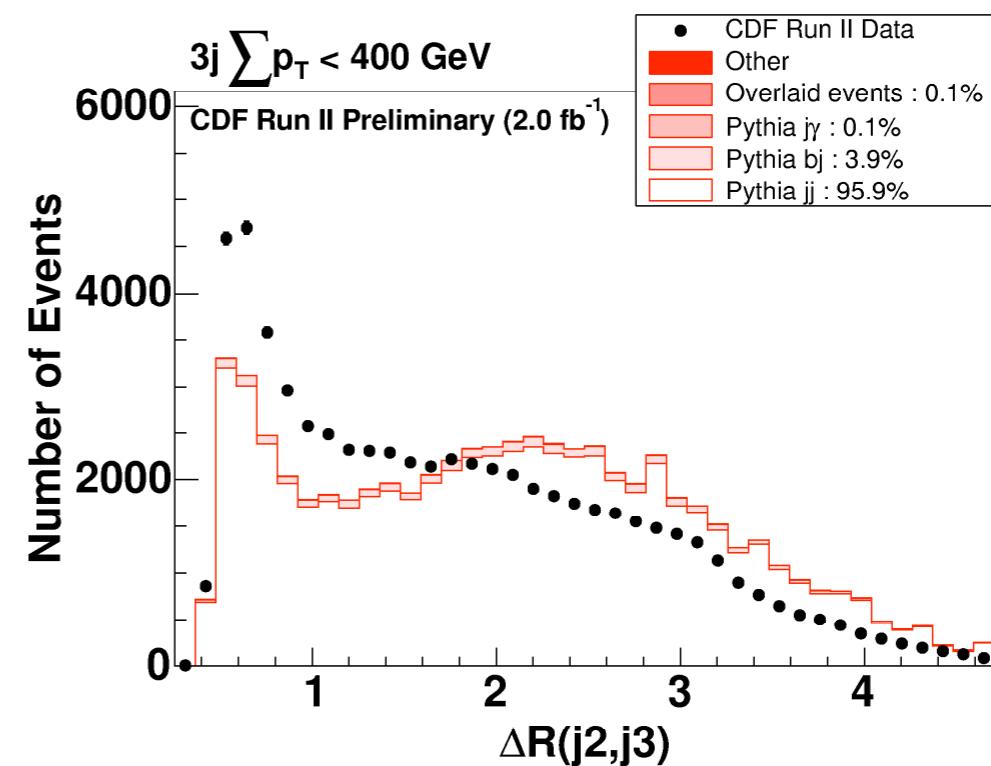
kinematic distributions

# VISTA

- sample distributions



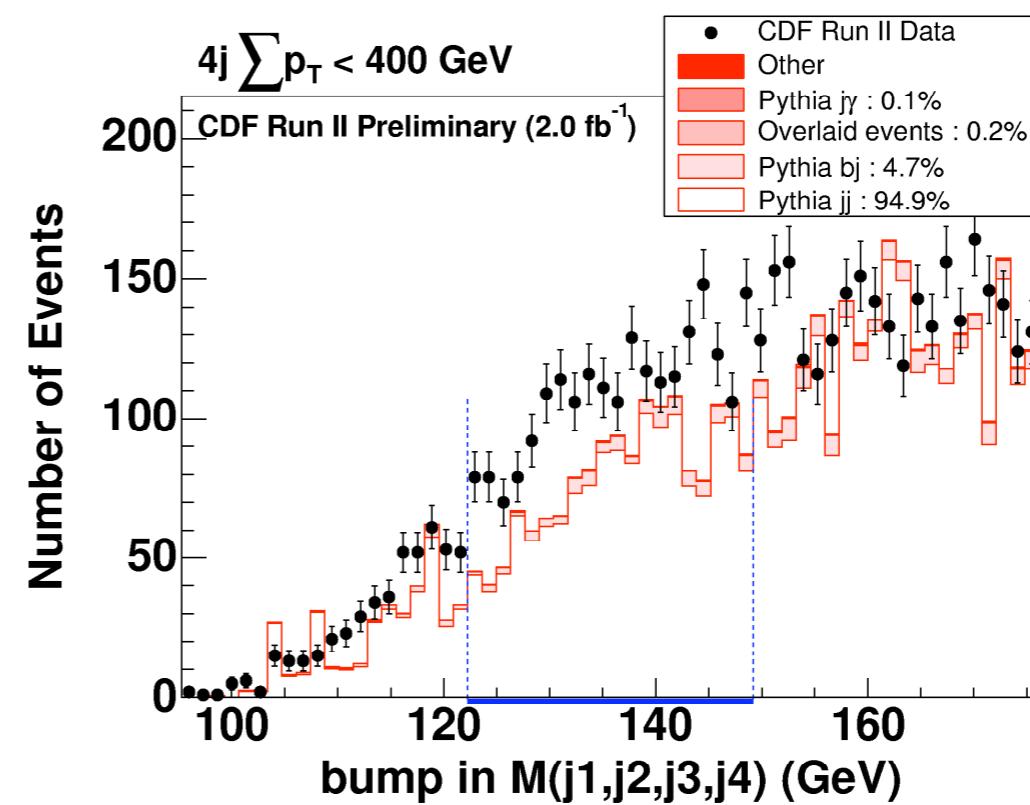
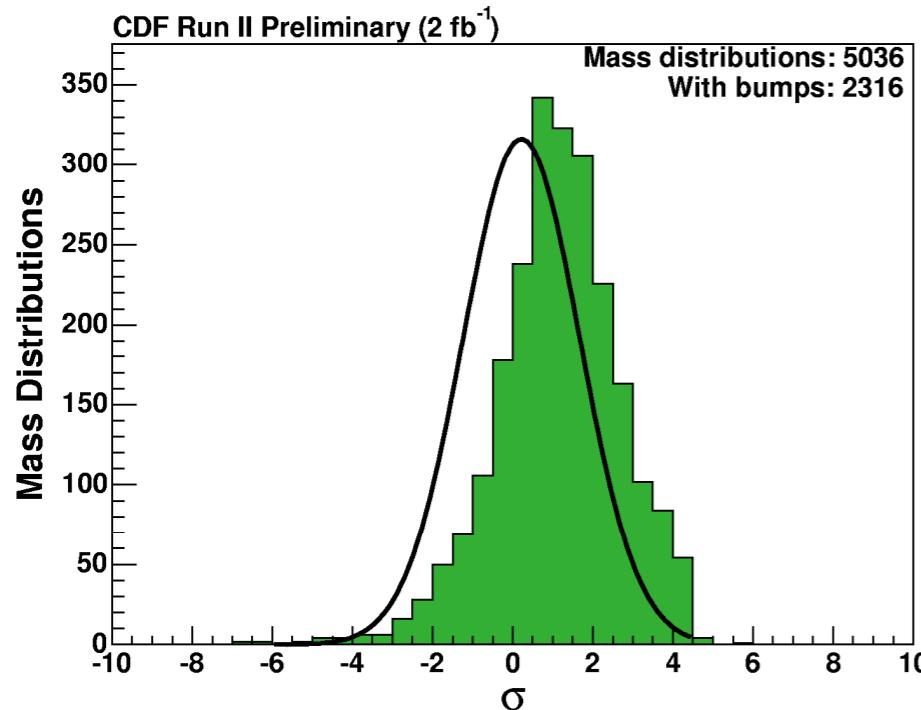
well described



not so well described

# Global Searches: Tevatron:VISTA

- mass bump search



plot variable: probability converted to ‘sigma’ for each of the 2316 mass distributions with a bump passing bump quality cuts; gaussian above 4.5 sigma.  
 $P(5 \text{ sigma}) * 5000 \text{ trials} = P(3 \text{ sigma})$

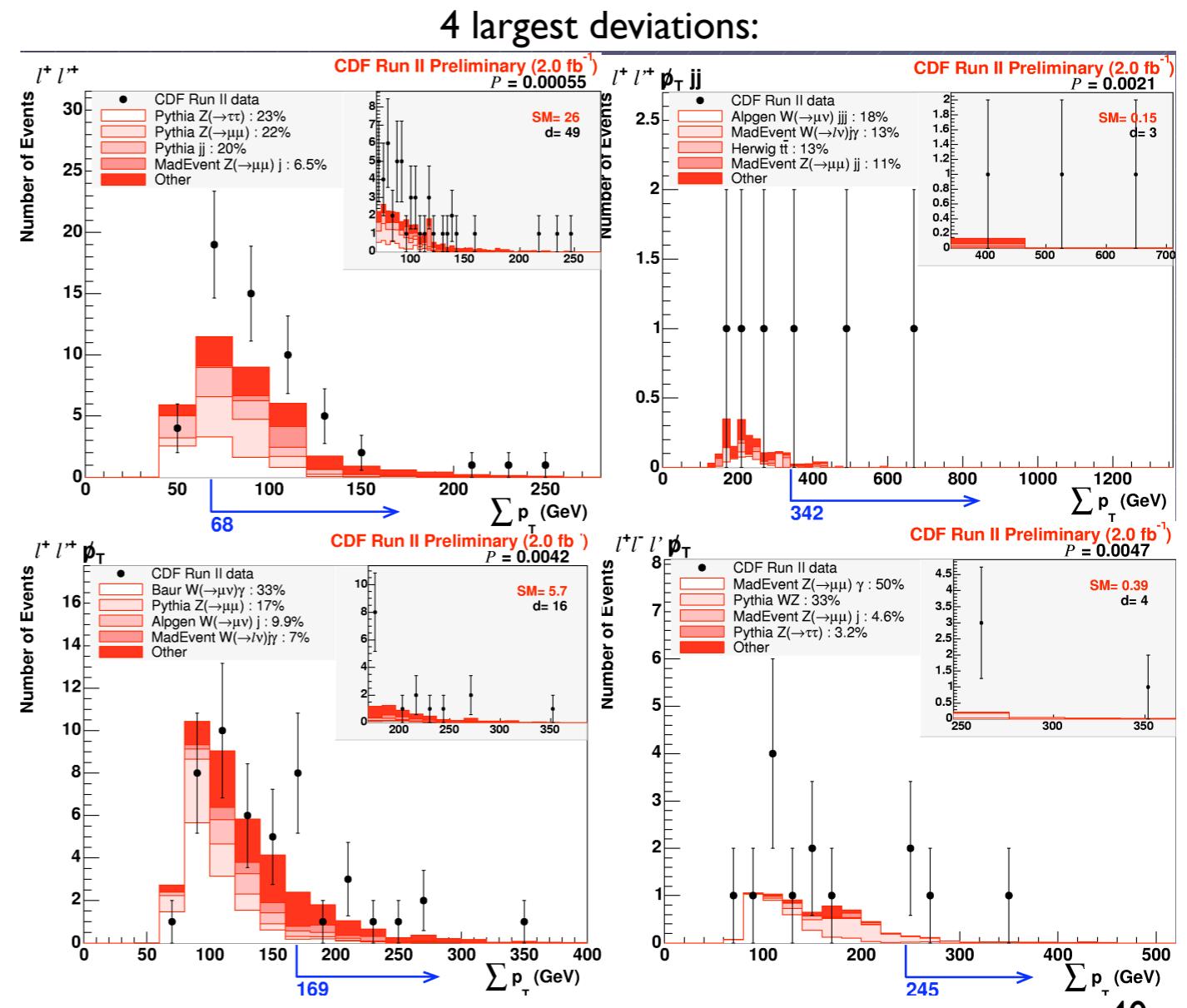
the sole outlier, with a probability (corrected for the trials factor) of 4.1 sigma. Unfortunately also consistent with bad modeling of soft gluon radiation in Pythia...

# Global Search: Tevatron: Sleuth

- examine high pT tails of 87 distributions
- probability to observe the smallest observed FSP in MC experiment: 8%

smallest final state probabilities:

| CDF Run II Preliminary ( $2.0 \text{ fb}^{-1}$ )<br>SLEUTH Final State $\mathcal{P}$ |         |
|--------------------------------------------------------------------------------------|---------|
| $\ell^+ \ell' +$                                                                     | 0.00055 |
| $\ell^+ \ell' + p_{jj}$                                                              | 0.0021  |
| $\ell^+ \ell' + p$                                                                   | 0.0042  |
| $\ell^+ \ell^- \ell' p$                                                              | 0.0047  |
| $\ell^+ \tau^+ p$                                                                    | 0.0065  |



# Analysis Web pages

- <http://www-cdf.fnal.gov/physics/exotic/exotic.html>
- <http://www-d0.fnal.gov/Run2Physics/np/>
- [http://www-h1.desy.de/publications/H1publication.short\\_list.html](http://www-h1.desy.de/publications/H1publication.short_list.html)
- [http://www-zeus.desy.de/public\\_results/publicsearch.html](http://www-zeus.desy.de/public_results/publicsearch.html)
- [http://www-zeus.desy.de/physics/exo/ZEUS\\_PUBLIC/exo\\_public.html](http://www-zeus.desy.de/physics/exo/ZEUS_PUBLIC/exo_public.html)

# Summary

very vibrant and diverse program

HERA final results based on 500/pb per experiment starting to arrive

Tevatron updates based on 1-2/fb; 4/fb delivered; goal of 8/fb by 2010

steady improvements in all areas

new techniques:

- em-cluster pointing replaces tracking to expand coverage for long-lived particles
- massive global searches (10,000s of distributions scoured) for any deviation from Standard Model

**the bulk of the Tevatron data is still to come!**