# Searches Beyond the Standard Model

## Experimental Summary of the results from the B-factories, HERA, Tevatron, LHC, and Super-Kamiokande

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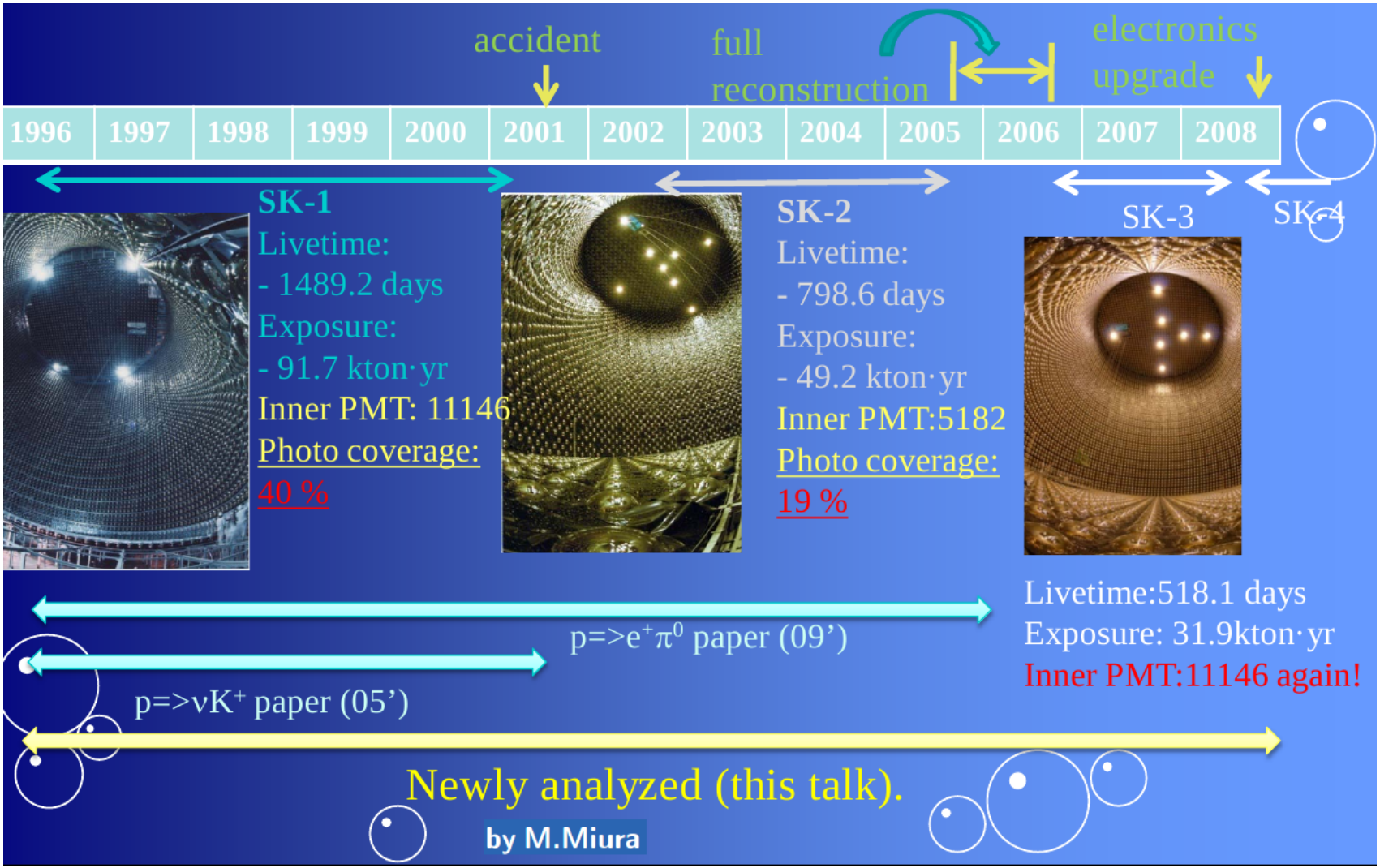
## BSM: Searching for New Symmetries

- even if particle content of the SM was complete, we'd know that there is something beyond
- understanding of the elementary particles interactions has been based on understanding their symmetries
- search for new particles = search for the new symmetries
- searches from the Tevatron use datasets up to 6.3 $fb^{-1}$
- HERA experiments continue to finalize their results
- results from the B-factories
- Super-Kamiokande analysed full dataset of 173 kton·yrs
- first searches at LHC used up to $\sim 300$ $nb^{-1}$!

# Outline

# Super-Kamiokande: probing the Grand Unification scale

- if measured, the proton lifetime may tell about the Grand Unification scale



# Summary of the Super-Kamiokande Results

- SK1-SK3 data : 173 kton·yrs
- no evidence for proton decay found

proton lifetime limits (90% CL):

- $p \to e^+\pi^0$: $T_p > 1.0 \times 10^{34}$ yrs
- $p \to \bar{\nu}K^+$: $T_p > 3.3 \times 10^{33}$ yrs
- other modes:
  - SK1-SK2, 141 kton·yrs
  - $T_p > (6.6 - 0.04) \times 10^{33}$ yrs

| | SK-1 | SK-2 | SK-3 |
|---|---|---|---|
| Eff.(%) | 44.6±8.5 | 43.5±8.3 | 45.2±8.6 |
| BKG | 0.20 evts /1489days | 0.11 evnts /799days | 0.06 evnts /518days |
| Obs | 0 | 0 | 0 |

Lifetime limit (90% C.L):
$> 1.0 \times 10^{34}$ yrs@172.8kton·year

-Super-Kamiokande has reached to $10^{34}$ years !

-Total BKG is 0.37 events (still low enough).

- SK-2 has almost same efficiency even though with a half PMT density.

1 Super-Kamiokande

2 BSM Searches at the Tevatron, HERA, B-factories

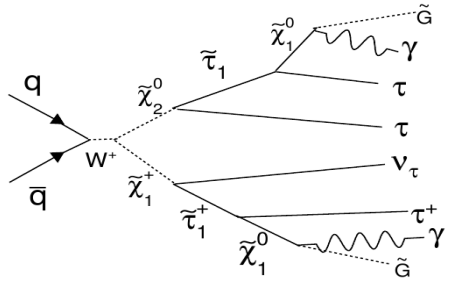
3 First Results from the LHC

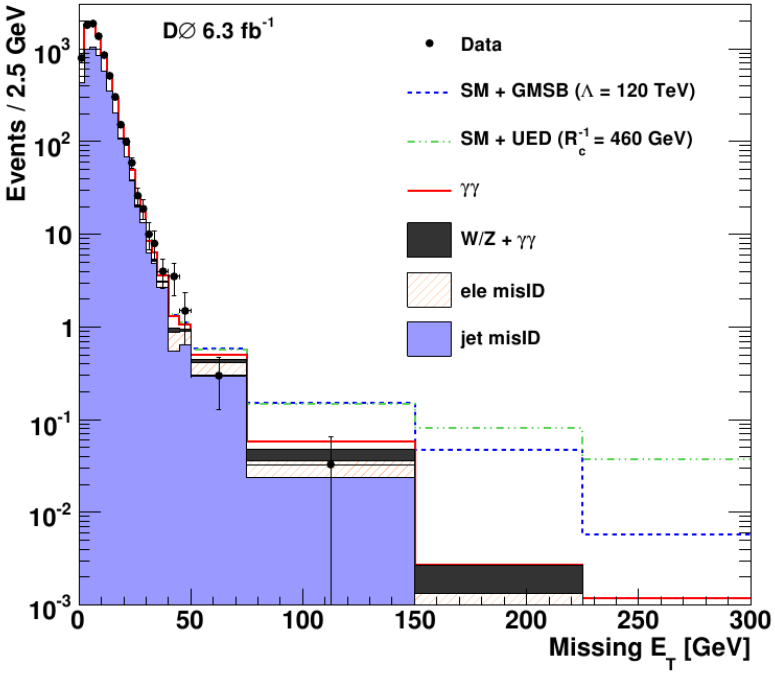
# SUSY

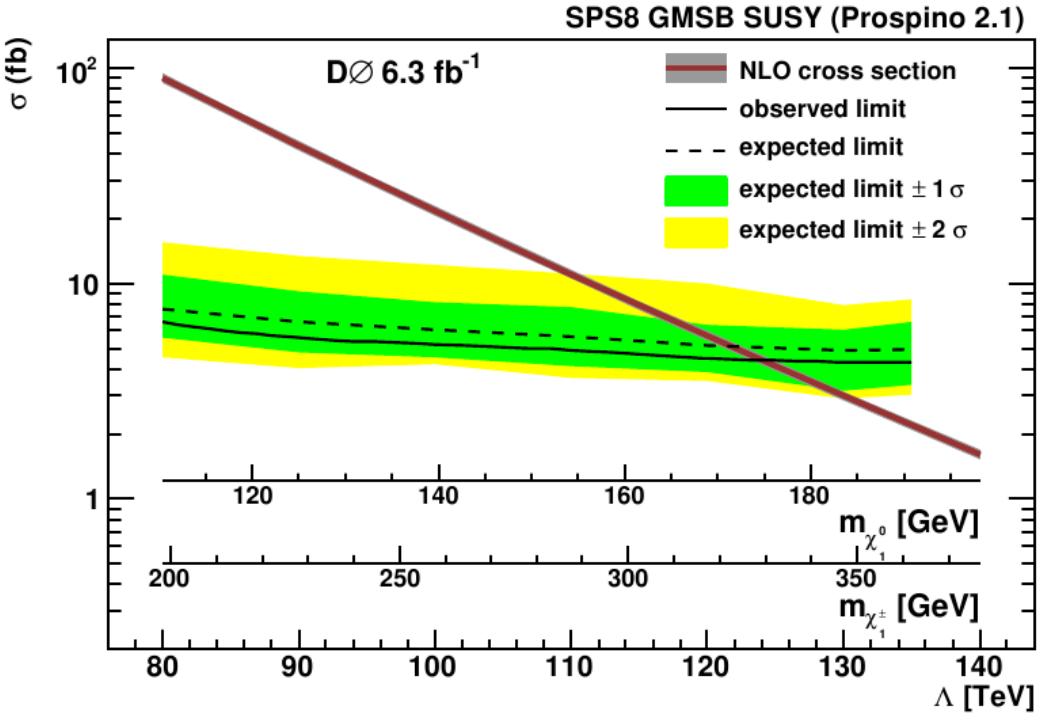
- a symmetry between fermions and bosons
- one of the most motivated symmetries
- introduces framework for multiple models
- a broken symmetry, different symmetry breaking mechanisms (GMSB, mSUGRA, AMSB)
- rich new particle contents and many choices
- R-parity assumed to be conserved in most scenarios
- searched for very extensively over the last decades

# Search for GMSB SUSY: $\gamma\gamma + \not{E}_T$

- in GMSB, the LSP is the gravitino $\tilde{G}$, $M_{\tilde{G}}$ in a KeV range.
- If NLSP is $\tilde{\chi}_1^0$, gaugino / stau pair production can cascade to $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma\gamma\tilde{G}\tilde{G}$
- SM background ($W/Z + \gamma\gamma$) very low



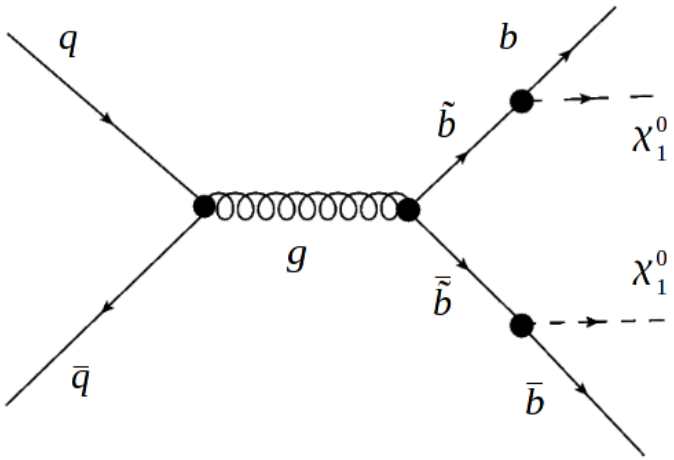



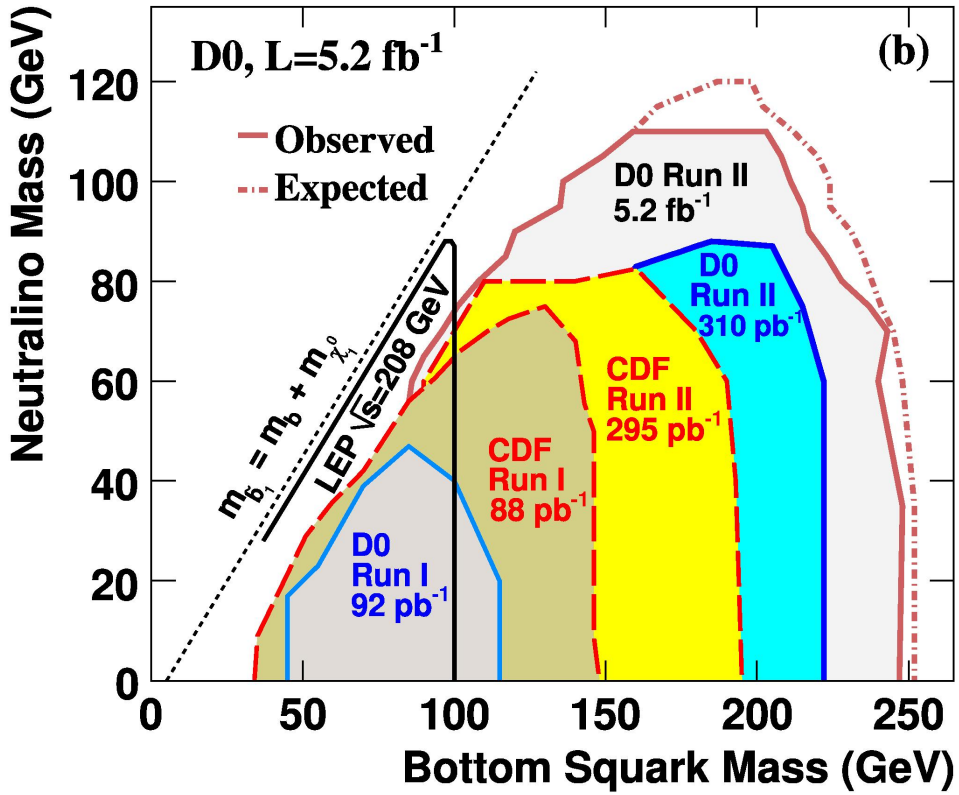




- assuming $t_{\tilde{\chi}_1^0} = 0$, $M(\tilde{\chi}_1^0) > 175 GeV$ at 95% CL (D0, $6.3 fb^{-1}$, Jul'2010)
- for a long-lived $\tilde{\chi}_1^0$, $M(\tilde{\chi}_1^0) > 101 GeV$ for $t_{\tilde{\chi}_1^0} = 5 ns$ at 95% CL (CDF, PRD 78, 032015 (2008))

# Searches for $\tilde{b}$ quarks

- due to mixing, 3rd generation squark, $\tilde{b}_1$, can be light
- direct $\tilde{b}\bar{\tilde{b}}$ pair production (assuming R-parity conservation): $p\bar{p} \rightarrow \tilde{b}\bar{\tilde{b}}$
- mSUGRA, B($\tilde{b} \rightarrow b\tilde{\chi_1}^0$)=100% : 2 b-jets and $\not\!\!E_T$

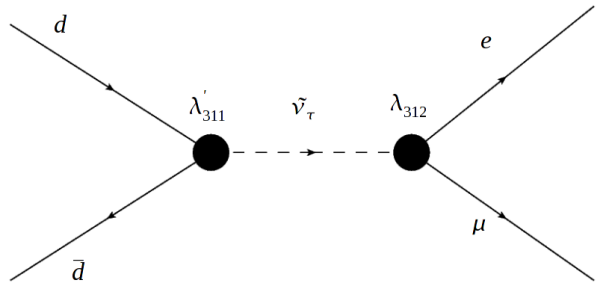


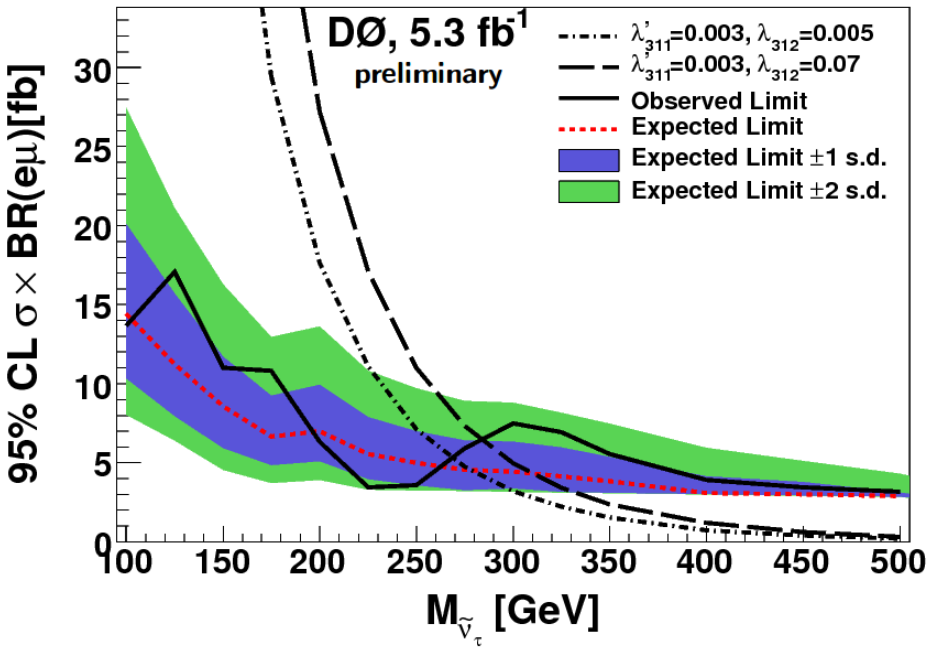

- M($\tilde{b}$) $> 247$ GeV for $M_{\tilde{\chi_1}^0} = 0$ (D0, $5.2 fb^{-1}$, arXiv:1005.2222 [hep-ex])
- previous limit: M($\tilde{b}$) $> 230$ GeV (CDF, $2.65 fb^{-1}$, arXiv:1005.3600 [hep-ex])

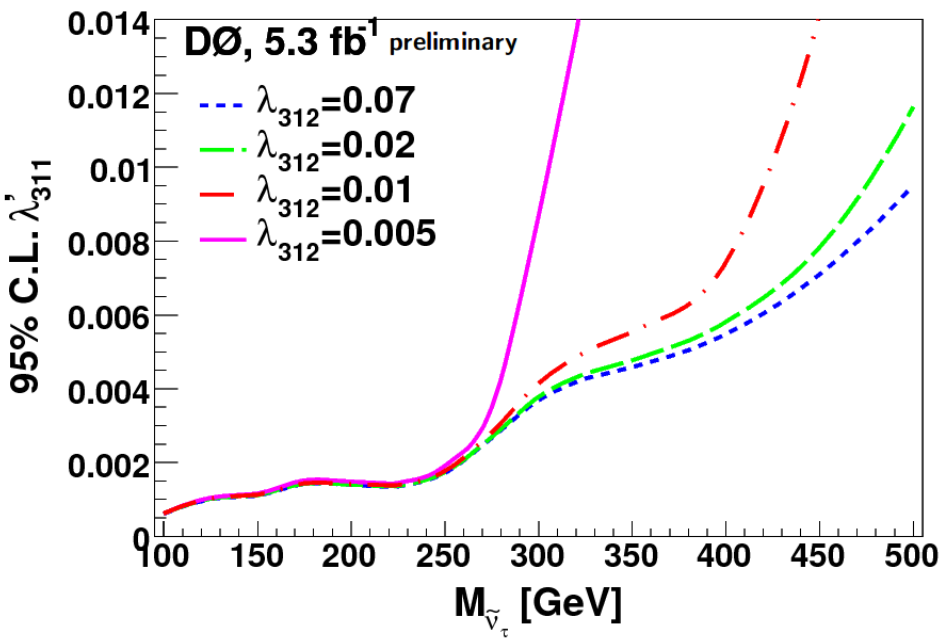
# Searches for Broken Symmetries: R-parity violation

- RPV models: single resonant production of sparticles
- assume only $\lambda'_{311}$ and $\lambda_{312}$ non-zero
- D0'2010 search for $\tilde{\nu} \longrightarrow e\mu$



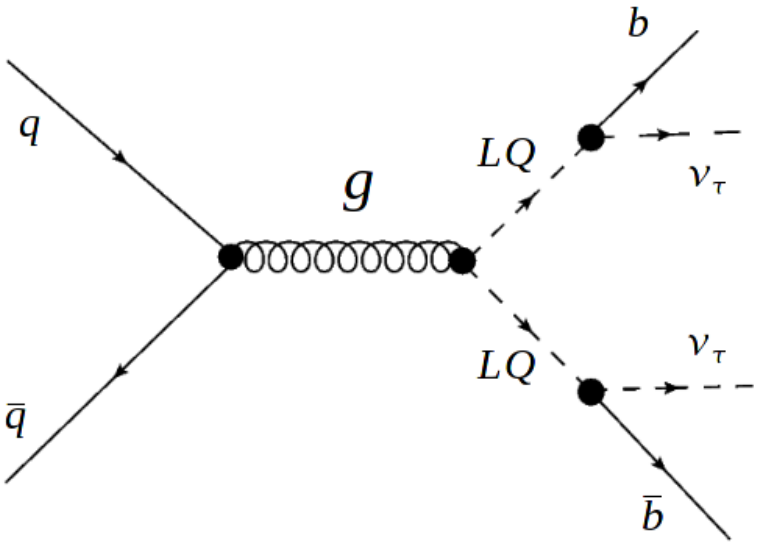

$$B(\tilde{\nu}_\tau \longrightarrow e\mu) = 2\lambda^2_{312}/(3\lambda'^2_{311} + 2\lambda^2_{312})$$

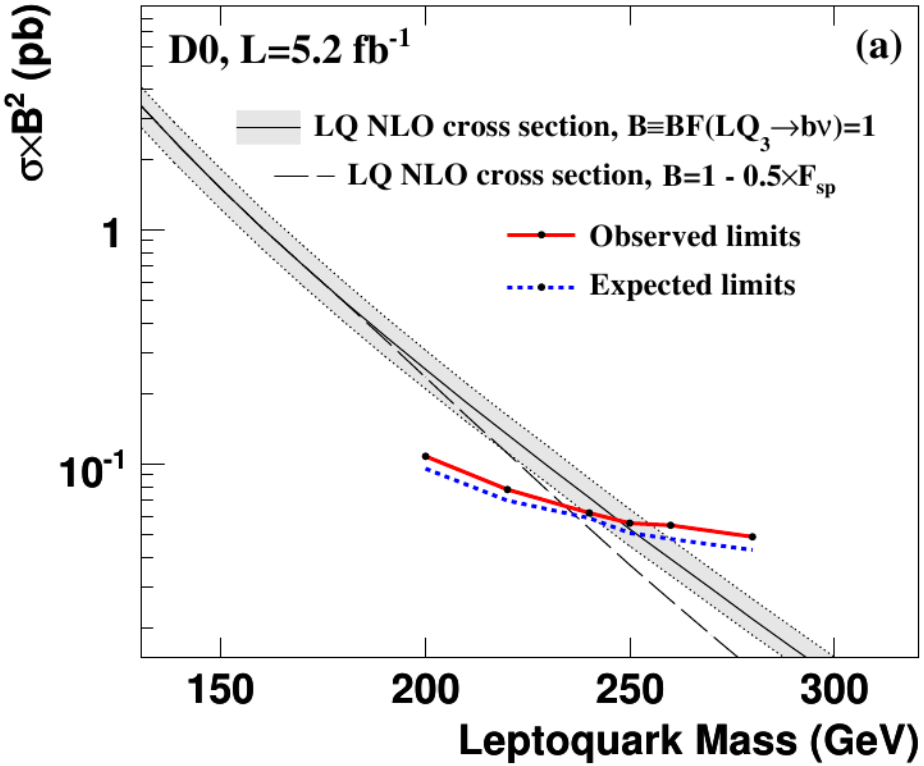


# Searches for Leptoquarks

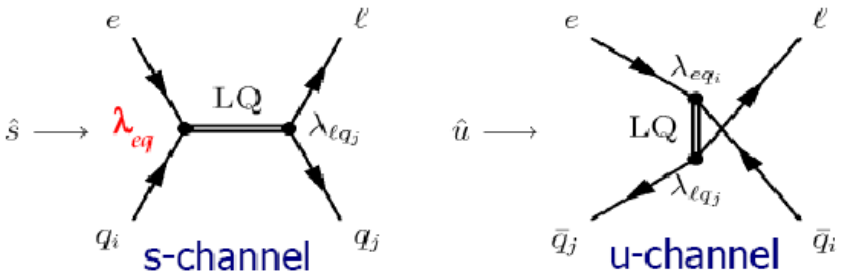
- N(lepton generations) = N(quark generations) - a coincidence or an additional symmetry?
- leptoquarks naturally appear in GUTs, RPV SUSY, ..

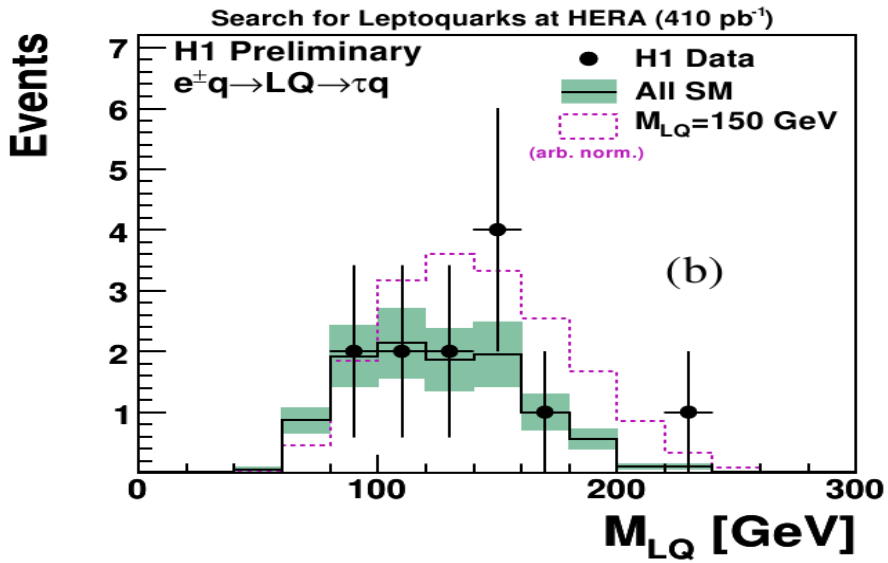



- D0'2010 ($5.2 fb^{-1}$): exclude scalar $LQ_3$ M($LQ_3$) $>$ 247 GeV @ 95%CL (arXiv.org:1005.2222)

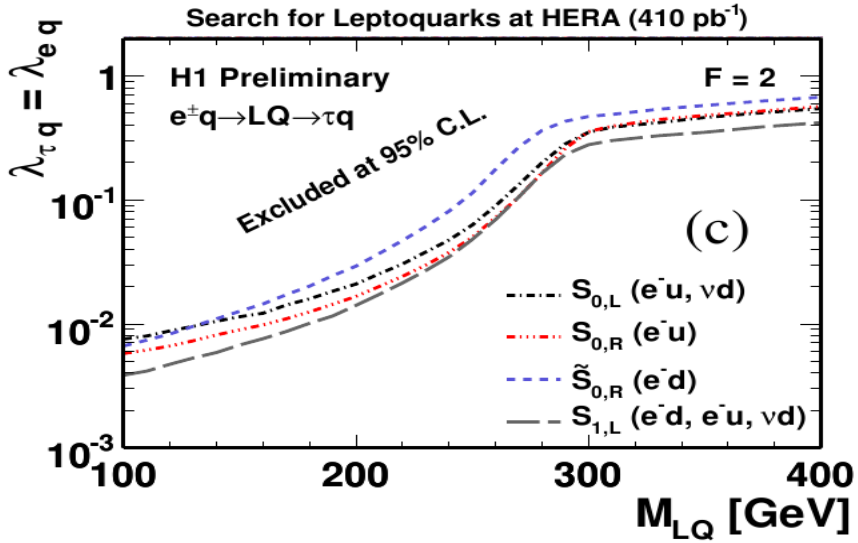
# Search for the Lepton Flavor Violating Scalar Leptoquarks



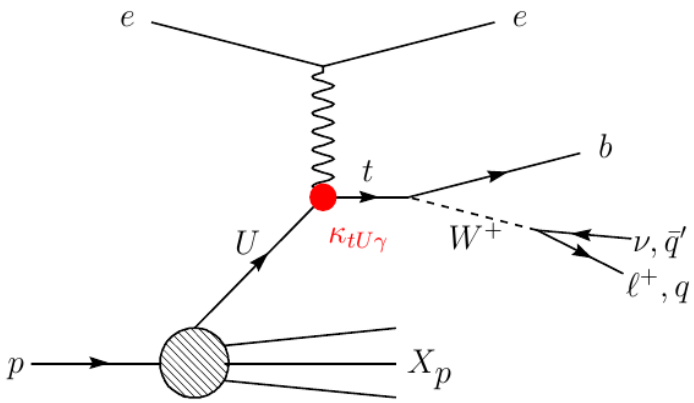



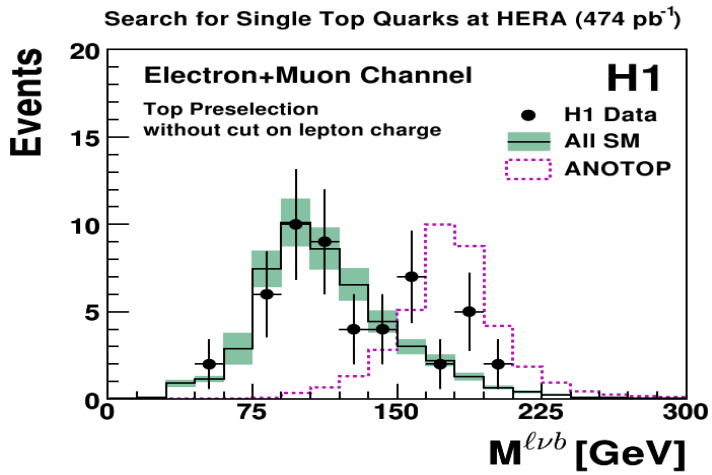

for $\lambda = 0.3$, excluded at 95% CL are:

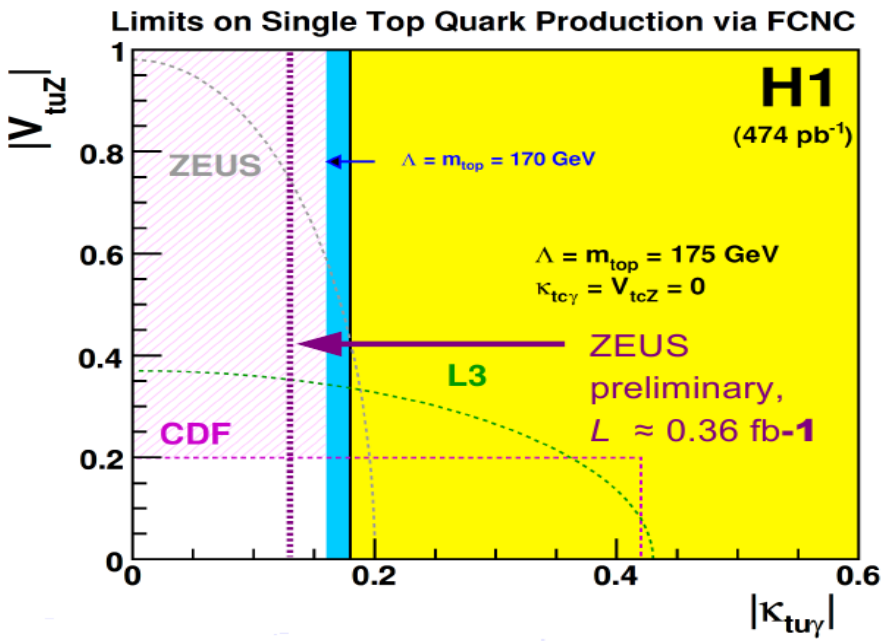
- $eq \rightarrow LQ \rightarrow \mu q$ :
  - $M_{LQ}$ in [304 GeV, 530 GeV]
- $eq \rightarrow LQ \rightarrow \tau q$ :
  - $M_{LQ}$ in [272 GeV, 450 GeV]
- complementary to the Tevatron results



# Search for Anomalous Single Top Production at HERA vis FCNC




analysed channels: $t \to bl\nu$ and $t \to bq\bar{q}$

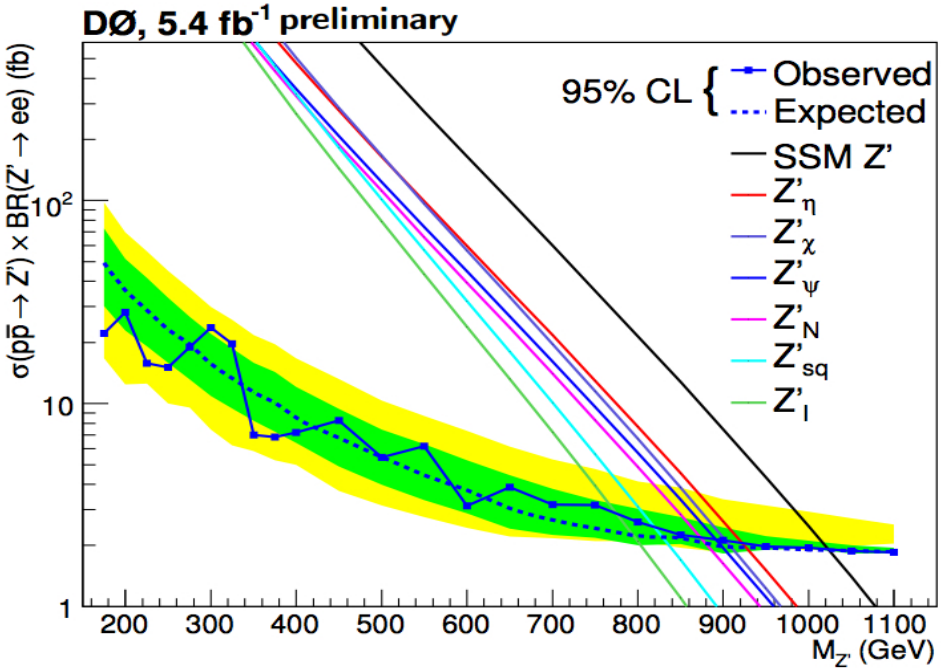
95% CL limits:

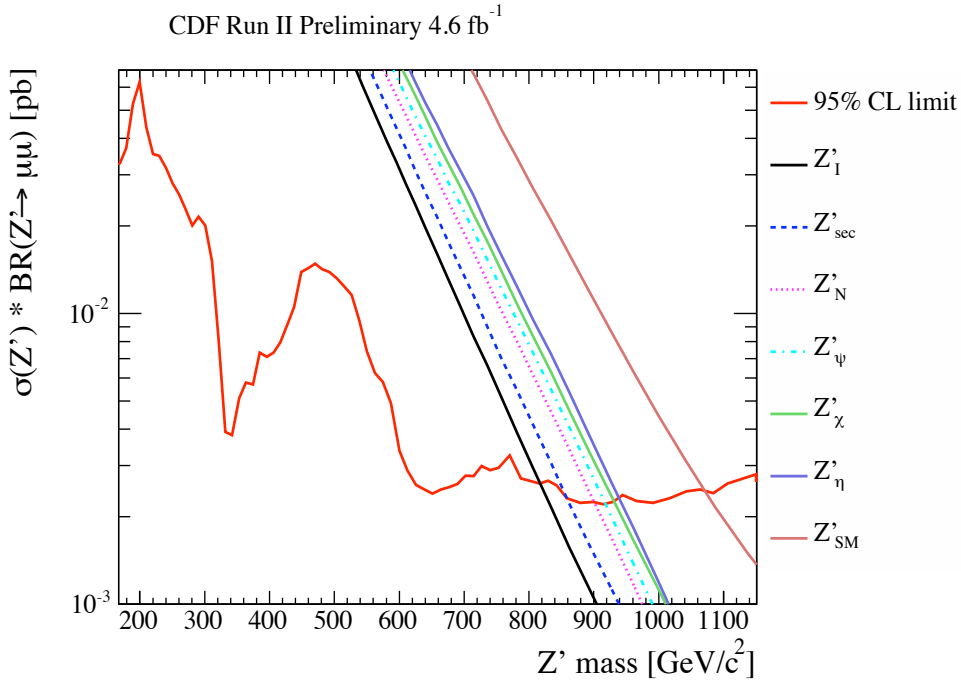
- $\sigma(ep \to etX) < 0.25pb$
- $K_{tu\gamma} < 0.18$

HERA limit on $K_{tu\gamma}$ complementary to the Tevatron

# Search for additional symmetries

- introducing an additional U(1) leads to a new neutral vector boson (Z')

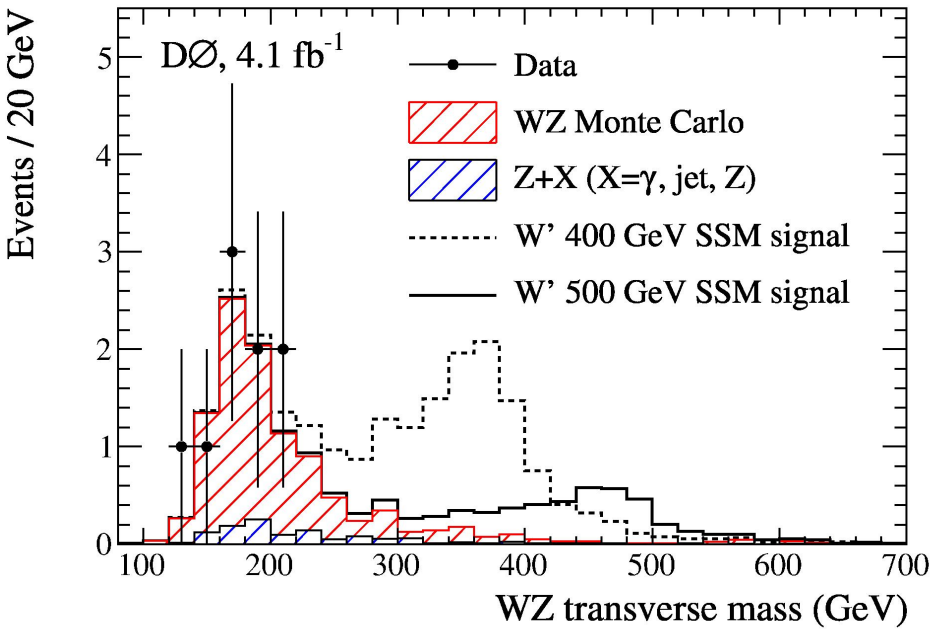


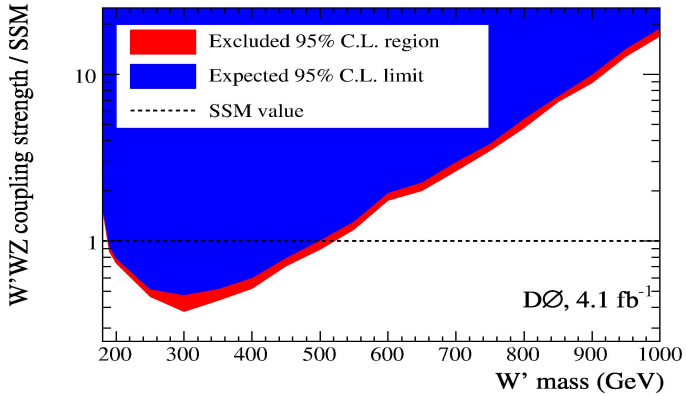



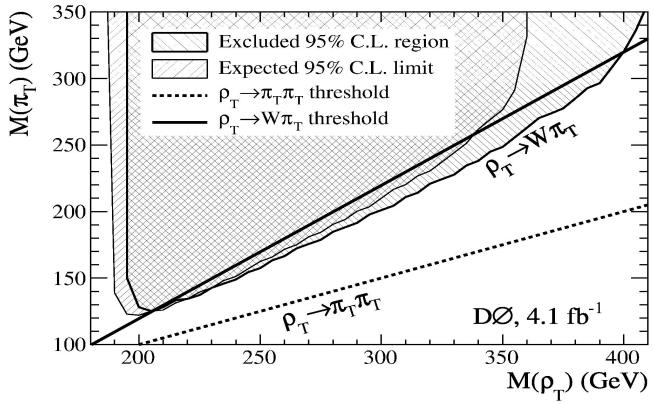

- $Z' \rightarrow ee$ : $M(Z'_{SM})$ >1023 GeV @ 95% CL (D0'2010)
- $Z' \rightarrow \mu\mu$ : $M(Z'_{SM})$ >1071 GeV @ 95% CL (CDF'2010)

# Searches for Heavy Vector Bosons: W'

- $SU(2)_L \times SU(2)_R$, KK excitations of the W in UED: new charged vector bosons (W')
- D0 search for $W'$ in $W' \rightarrow WZ \rightarrow 3l + \nu$ channel (PRL 104, 061801 (2010))



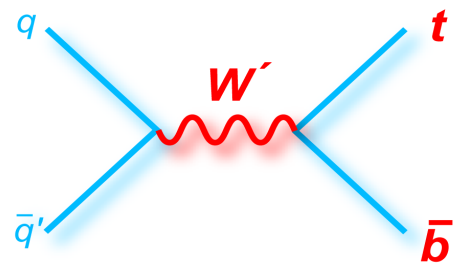



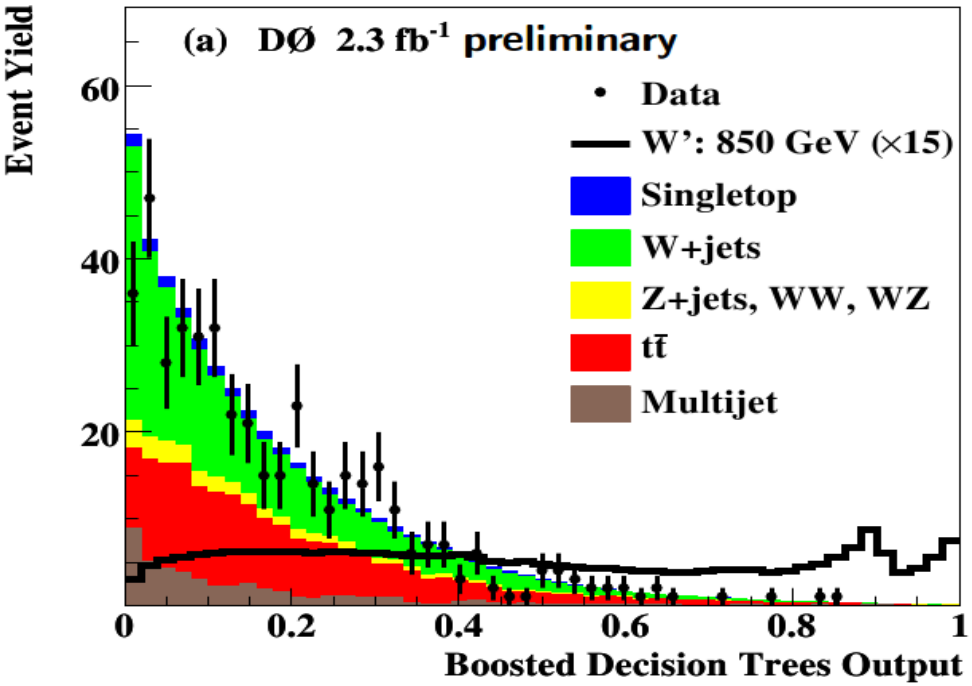



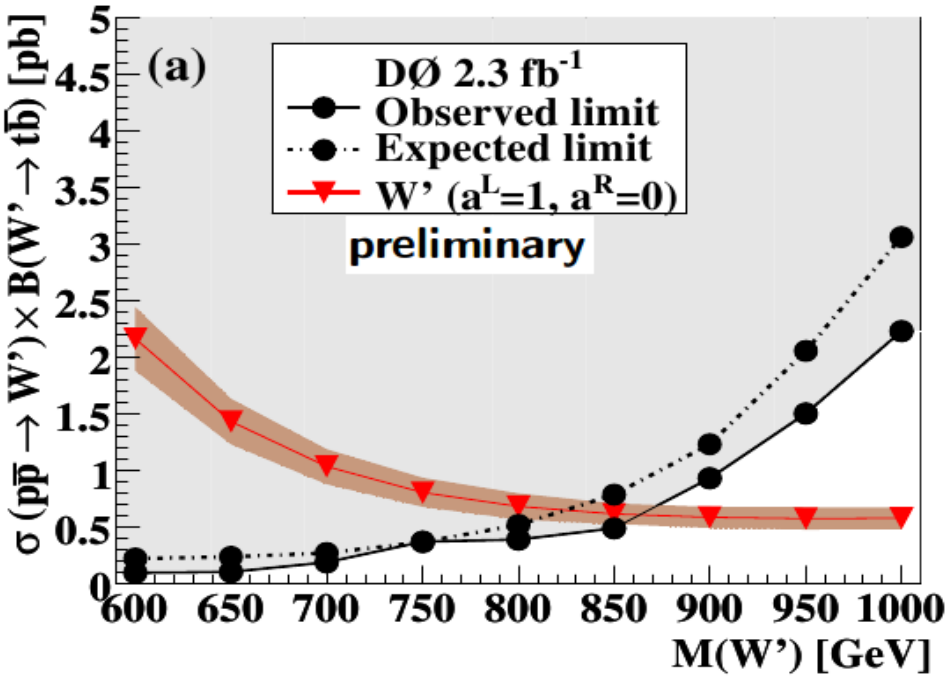

- $W'$ mass range [188 GeV, 520 GeV] is excluded @ 95% CL, assuming SM couplings
- technicolor $\rho_T \rightarrow WZ$ : $M_{\rho_T}$ in [208 GeV, 408 GeV] excluded at 95% CL
- comparable sensitivity to W' in $W' \rightarrow WZ \rightarrow l\nu q\bar{q}$ channel:
  - excluded at 95% CL mass range [285 GeV, 516 GeV] (CDF, PRL 104, 241801 2010)

# Search for Heavy Vector Bosons: $W' \to tb$

- D0'2010: $p\bar{p} \to W' \to tb$ $(2.3 fb^{-1})$



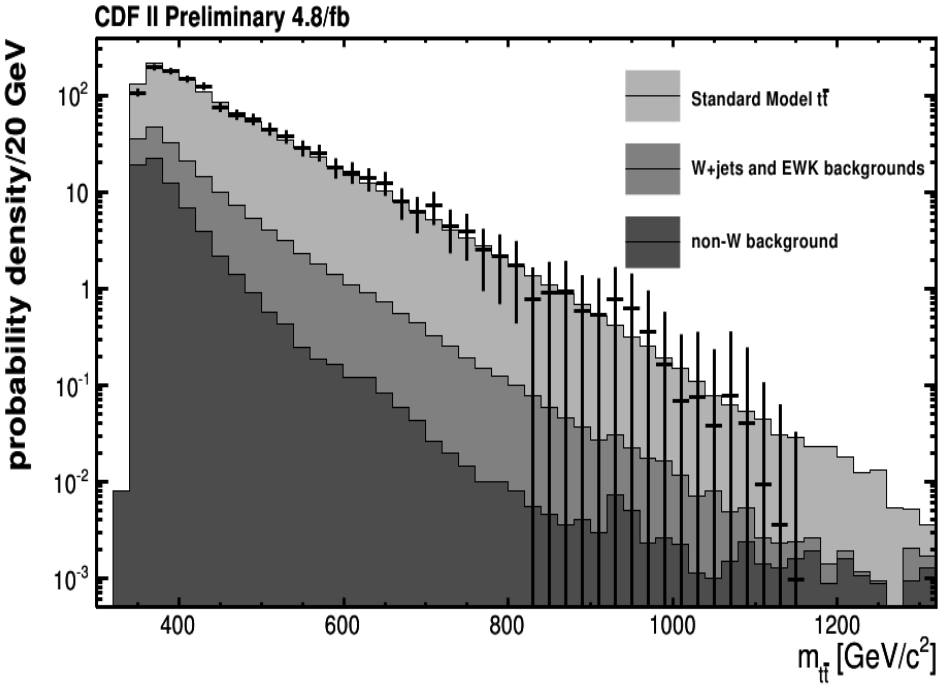



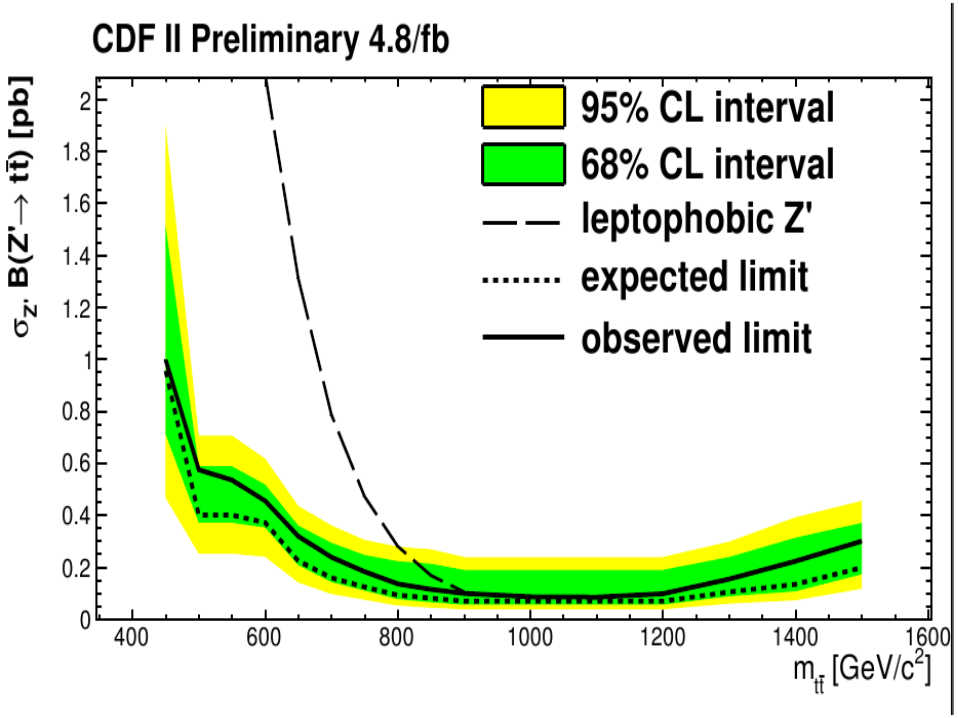




- 95% CL exclusions:
  - M(W') $> 863$ GeV, $a^L = 1,\ a^R = 0$
  - M(W') $> 885$ GeV, $a^L = 0,\ a^R = 1, M(W') < m(\nu_R)$
  - M(W') $> 890$ GeV, $a^L = 0,\ a^R = 1, M(W') > m(\nu_R)$
  - M(W') $> 916$ GeV, $a^L = 1,\ a^R = 1$

# Search for $t\bar{t}$ resonances

- CDF'2010 : search for $R \rightarrow t\bar{t}$ in lepton + jets+$\not\!\!E_T$ channel ($4.8 fb^{-1}$)
- additional U(1): topcolor-assisted Z' (hep-ph/9911288)

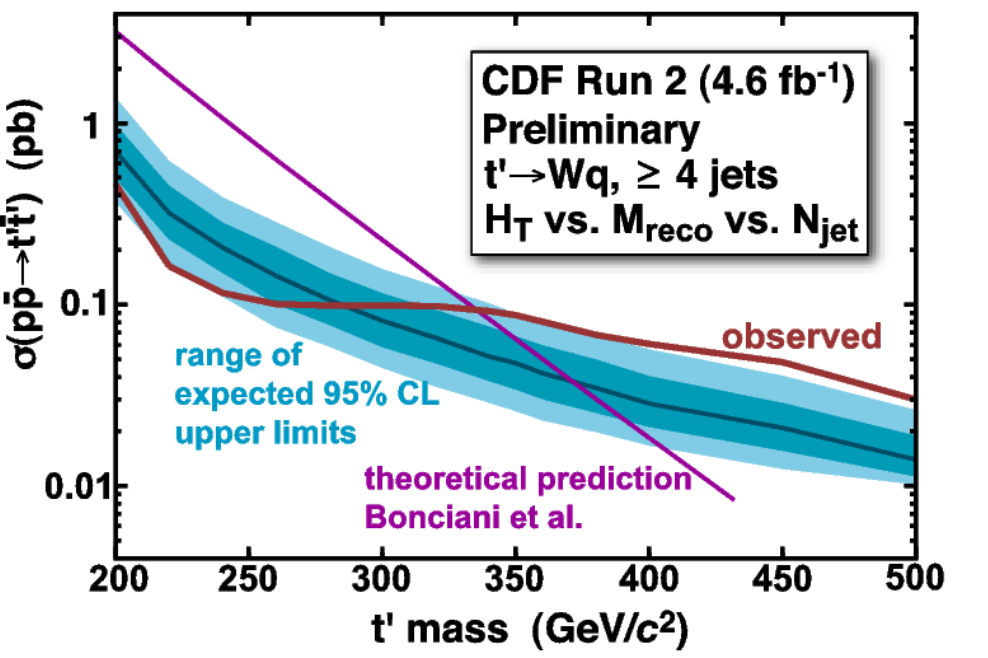


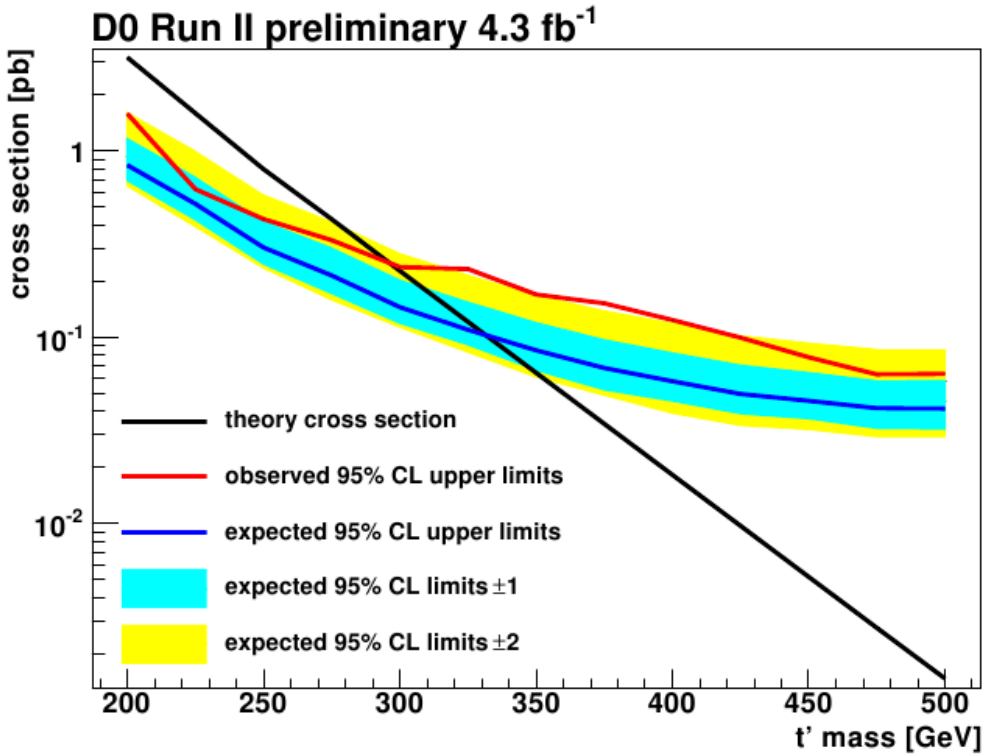




- 95% CL exclusion: $M_{Z'} > 900 GeV, \Gamma_{Z'} = 0.012 M_{Z'}$
- previous 95% CL limit: $M_{Z'} > 820 GeV$ , D0'2009

# 4-th Generation Quarks: Search for Heavy t'

- 4th generation of fermions arises in a set of models
- if mass splitting is small, $M(t') - M(b') < M(W)$, $B(t' \to Wq) = 100\%$
- search for a pair-produced heavy top-like quark



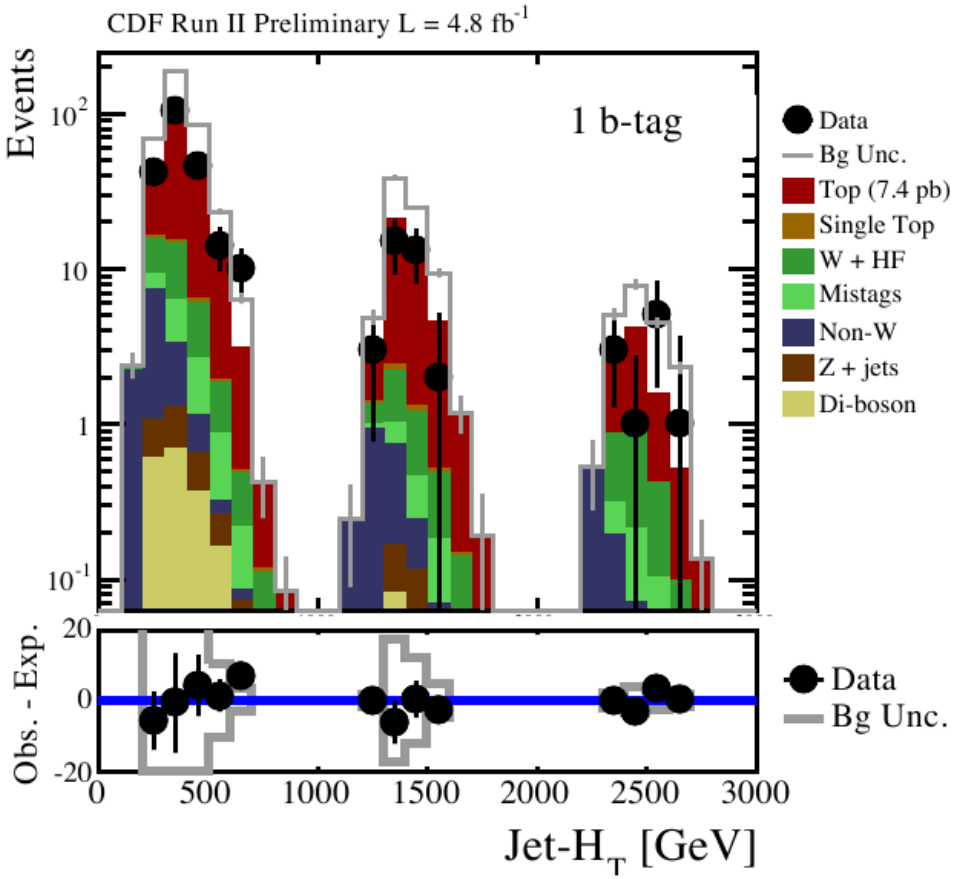



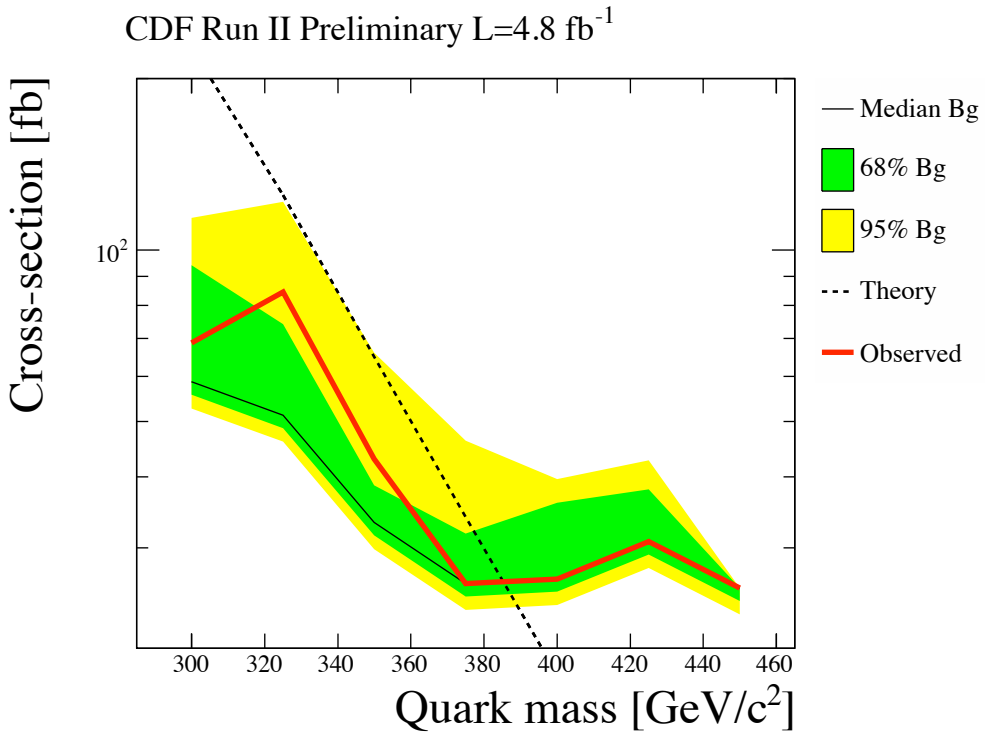

- excluded at 95% CL: $M_{t'} < 335 GeV$ (CDF'2010) , $M_{t'} < 296 GeV$ (D0'2010)

# 4th Generation Quarks: Search for Heavy b'

- search for a pair-produced heavy b': $p\bar{p} \rightarrow b'\bar{b}' \rightarrow WWt\bar{t} \rightarrow WWWWb\bar{b} \rightarrow l + \not{E}_T + jets$
- final states with multiple (5,6,7) jets, very large $H_T = \Sigma E_T + \not{E}_T$

5 jets 6jets 7jets

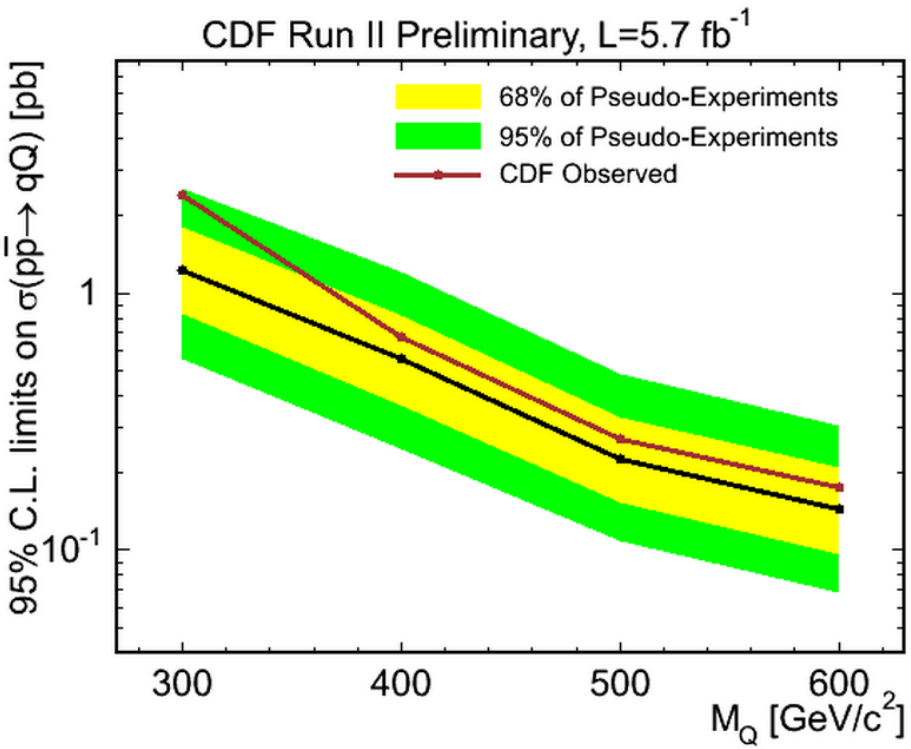


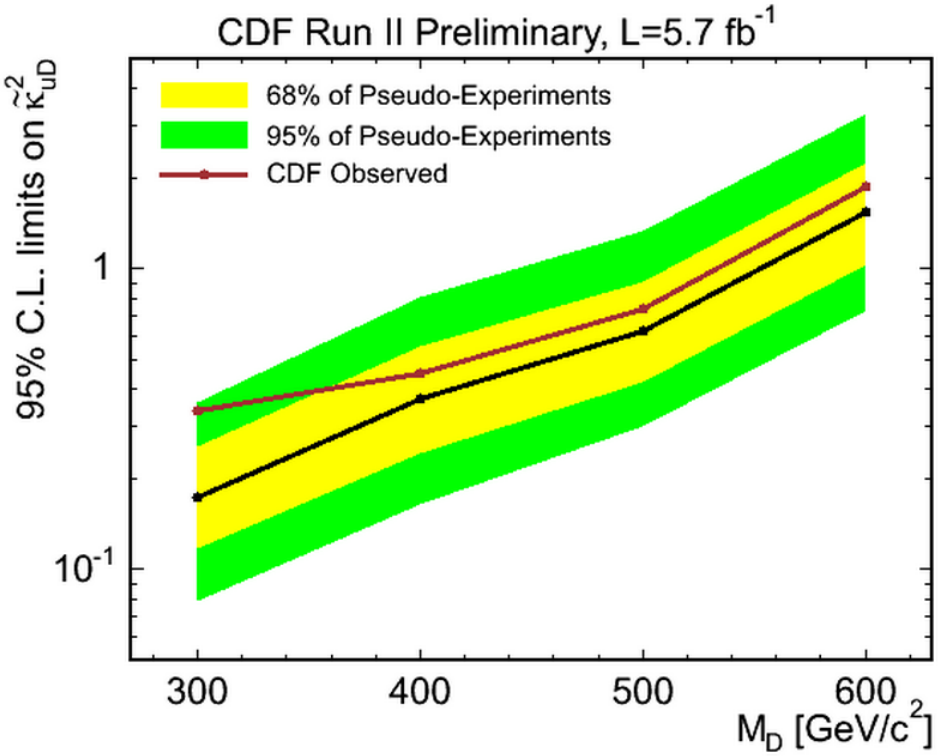




- $M_{b'} < 385 GeV/c^2$ excluded at 95% CL (CDF'2010)

# Search for Single Production of Heavy Vector-like Quarks

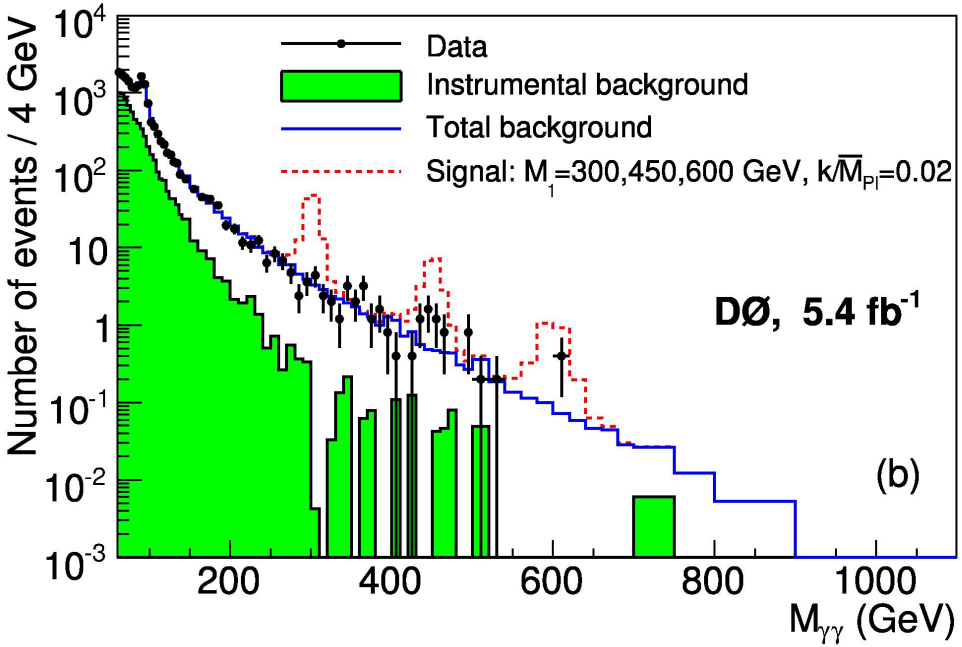
- for $M_Q$ approaching $\sqrt{s}$, $\sigma(qq' \to Qq)$ could be significantly larger than $\sigma(qq', gg \to Q\bar{Q})$
- assume gauge interactions with the 1st generation SM quarks
- parameterization of the couplings: $\sigma(qq' \to Qq') = k^2_{qQ}\sigma_{SM}(qq' \to qQ)$
- CDF'2010 search for $qq' \to Qq$:

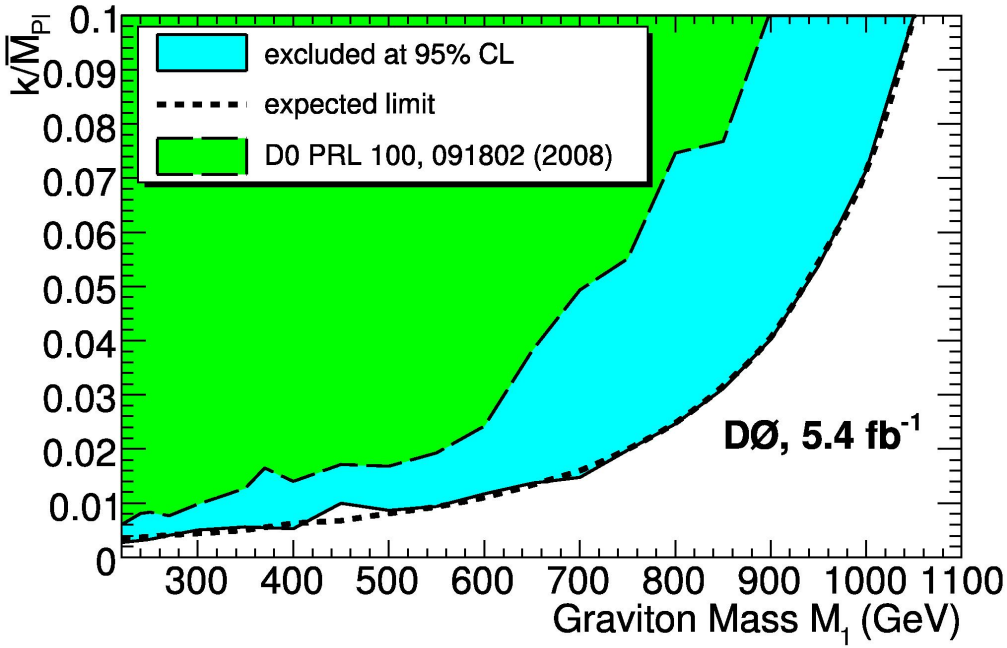


# Extra Dimensions

- a solution to a hierarchy problem (Arkani-Hamed,Dimopulous,Dvali'99)
- warped extra dimensions (Randall, Sundrum'99) :
  - Kaluza-Klein excitations of a graviton, $G^*$, are coupled to SM particles and narrow
  - $B(G^* \to \gamma\gamma) \approx 2B(G^* \to l^+l^-)$

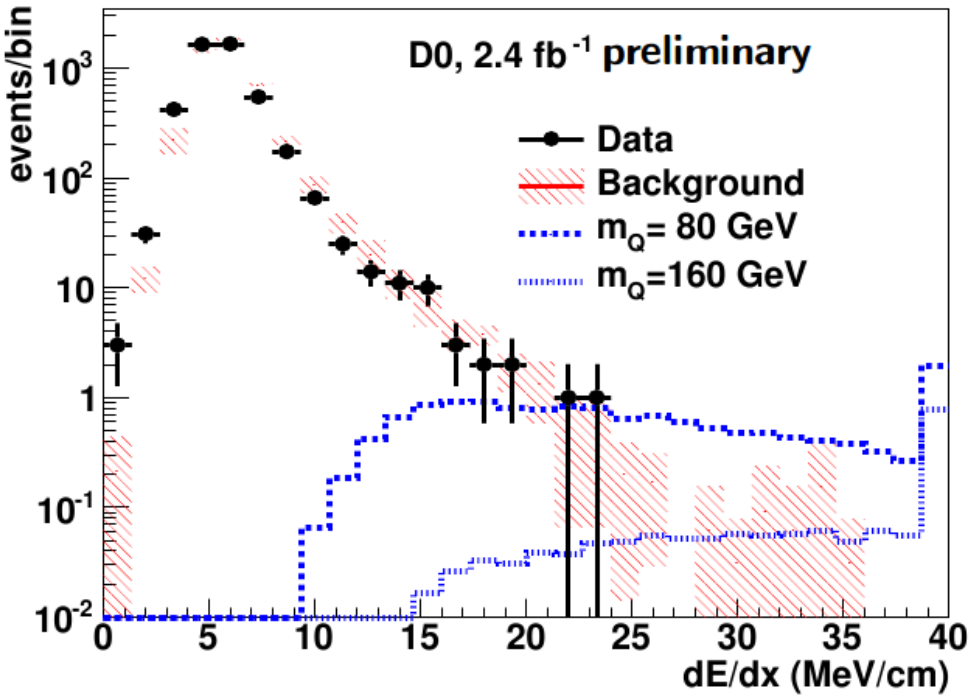


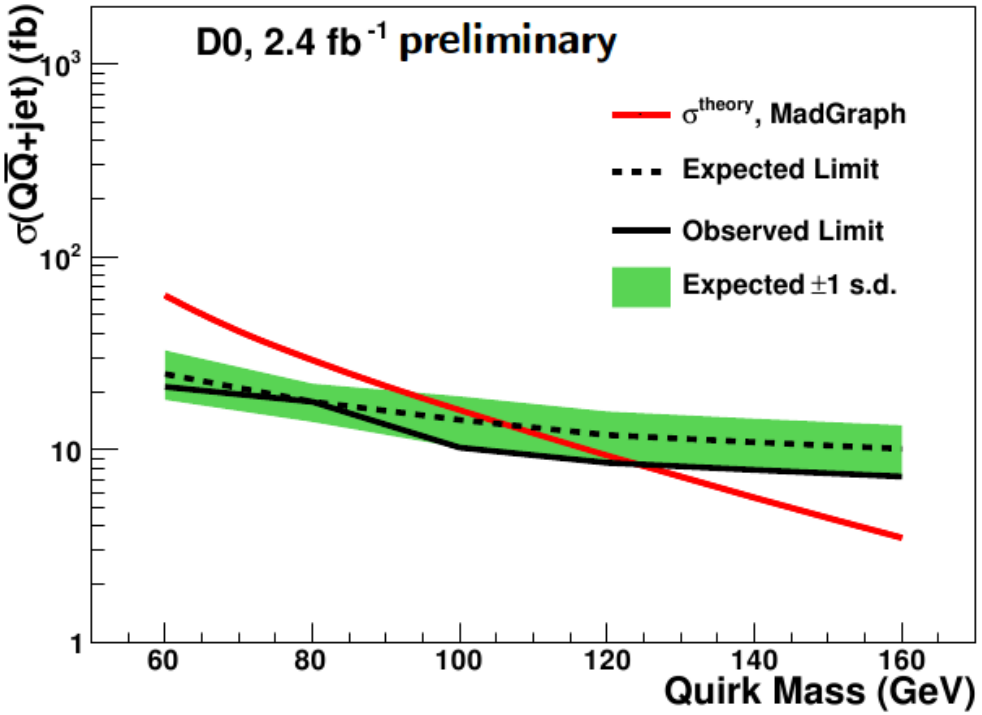




- excluded at 95% CL for $k/M_{Pl} = 0.1$:
  - D0'2010: $G^* \to \gamma\gamma, e^+e^-$: $M_{G^*} < 1050$ GeV PRL 104, 241802
  - CDF'2010: $G^* \to \gamma\gamma$: $M_{G^*} < 976$ GeV arXiv:0910.5170 [hep-ex]

# Search for Heavy Quarks: Quirks

- additional strong SU(N) with $M_Q >> \Lambda$
  - large non-perturbative effects in strong dynamics (Okun,1979)
  - heavy quark and antiquark can form a macroscopic "molecule", $L \sim M_Q/\Lambda^2$
  - an example: "electric dipole" with a size of $\sim$ 10-100 microns
- D0'2010: search for events with highly-ionizing tracks with very large $p_T$

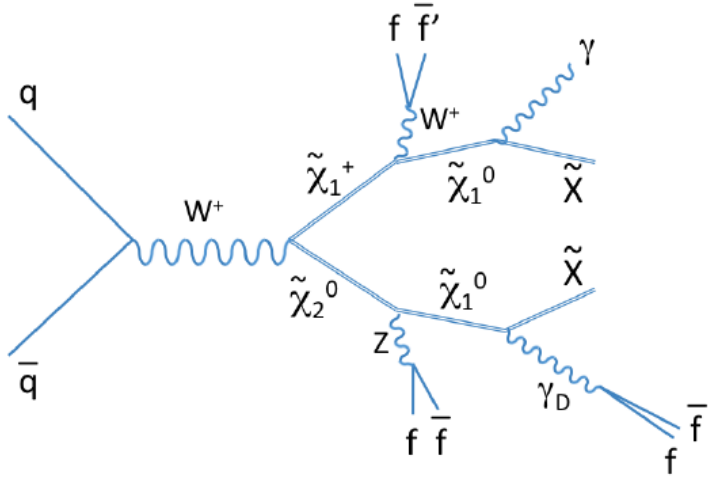


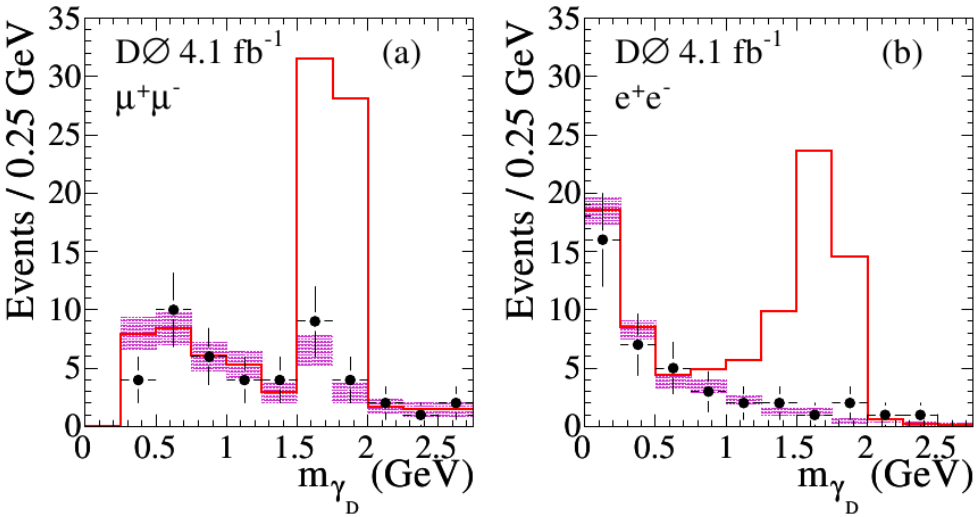



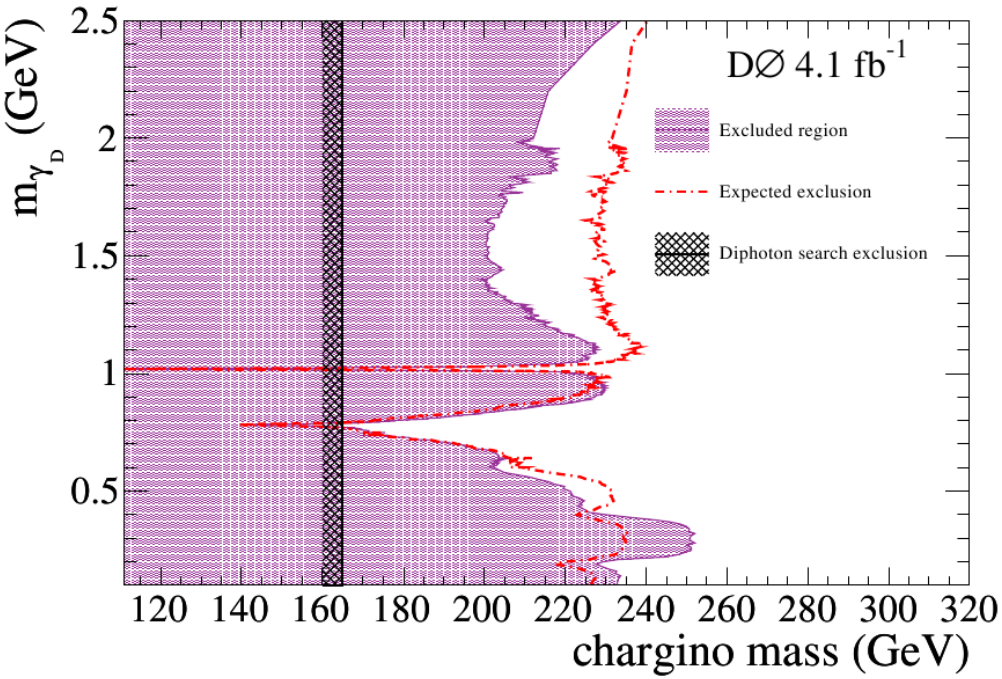

- $M_Q > 124$ GeV for $10KeV < \Lambda < 1MeV$ (95%CL)

# Search for Hidden Symmetries: "Hidden Valley" Models

- "hidden valley" SUSY models (Strassler,Zurek 2007):
  - weakly coupled sector with low mass particles
  - $\gamma_D$, a force carrier, is light and decays predominantly into SM fermions
  - $B(\tilde{\chi} \to \tilde{X}\gamma_D)$ is a free parameter
- D0'2010: search for final states with a photon, 2 close leptons and $\not\!\!E_T$
- assume $B(\tilde{\chi} \to \tilde{X}\gamma_D) = 0.5$

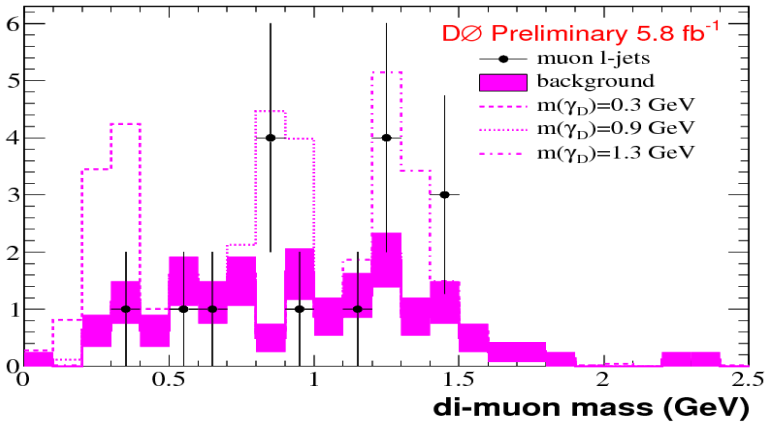


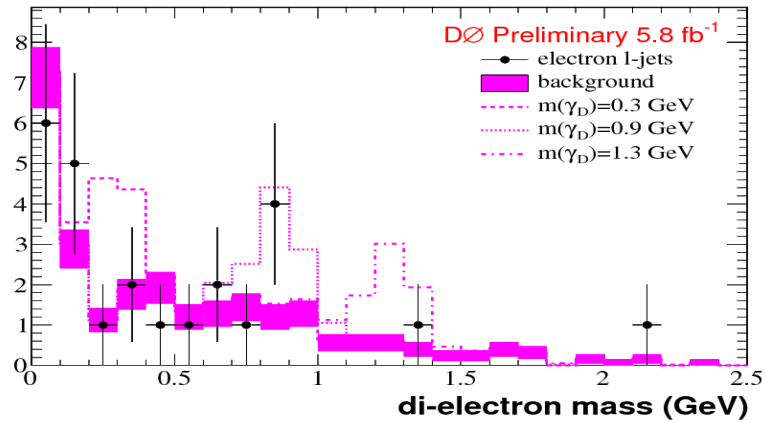



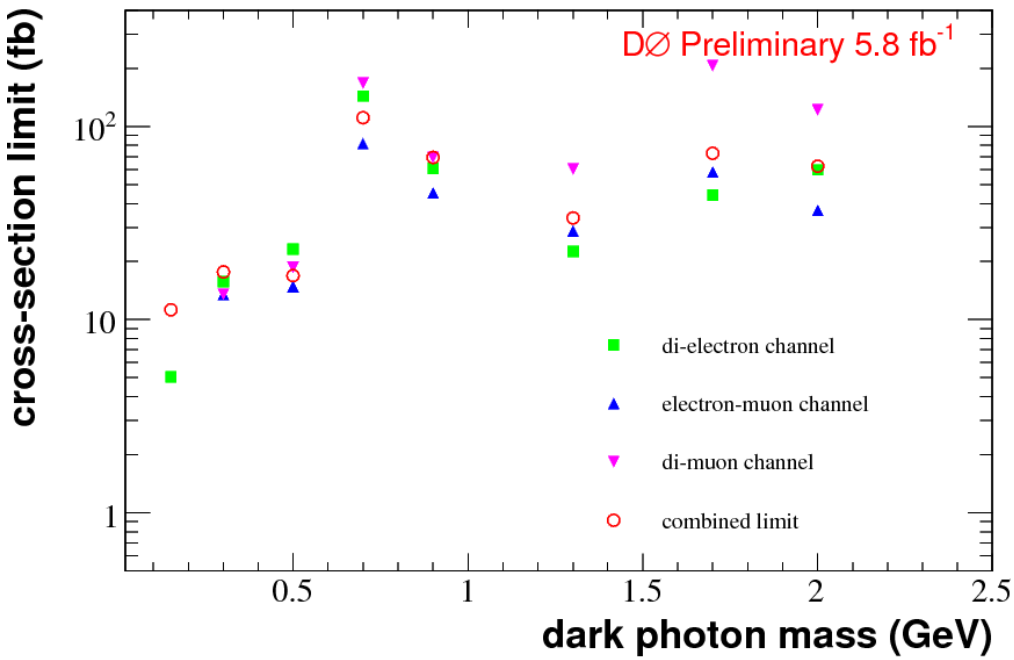



# Constraining Hidden Symmetries: Lepton Jets

- if $B(\tilde{\chi} \to \tilde{X}\gamma_D)$ is large, both SM LSP's decay into this channel
- D0'2010: search for final states with 2 pairs of close leptons and $\not\!\!E_T$ from $\tilde{X}$'s



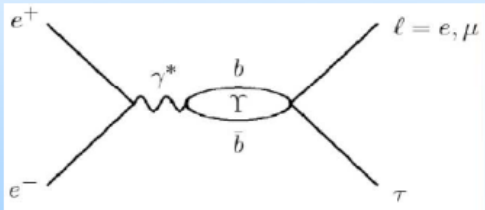




- for $M_{\gamma_D} < 2.5\ GeV\ \sigma(p\bar{p} \to \gamma_D\gamma_D\tilde{X}\tilde{X} + X) < \sim 200$ fb,

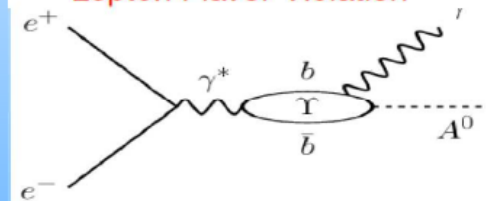
# B-factories

- Charged Lepton Flavor Violation:
  - $\tau \rightarrow l\gamma$ (l=e,μ)
  - $\tau \rightarrow 3l$ (l=e,μ)
  - $Y(2S,3S) \rightarrow l\tau$ (l=e,μ)
- Light Higgs ($A^0$) decays:
  - $Y(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$
  - $Y(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$
  - $Y(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible
  - $Y(2S) \rightarrow \pi^+\pi^- Y(1S)$, $Y(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible
- Lepton Non-Universality:
  - $Y(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow l^+l^-$
- Invisible Bottomonium decays:
  - $Y(3S) \rightarrow \pi^+\pi^- Y(1S)$, $Y(1S) \rightarrow$ invisible
- Dark Sector Gauge Boson mediated decays:
  - $e^+e^- \rightarrow W_D^+ W_D^- \rightarrow l^+l^-l^+l^-$

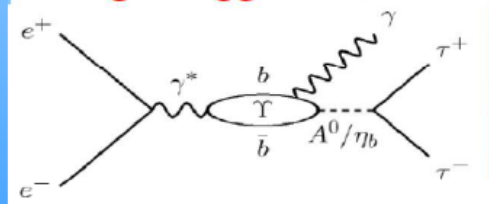
Some Illustrations:



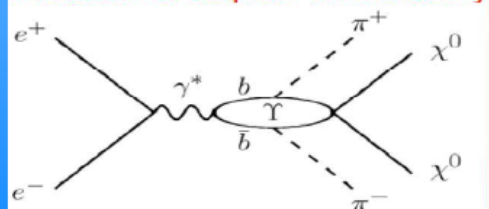

Lepton Flavor Violation




Light Higgs Production



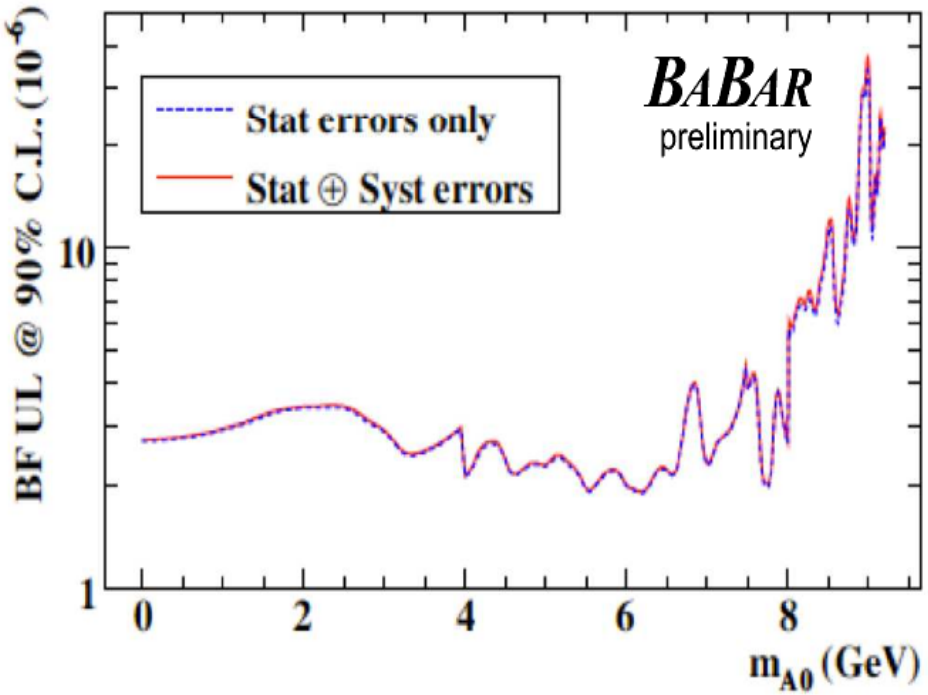

Violation of Lepton Universality

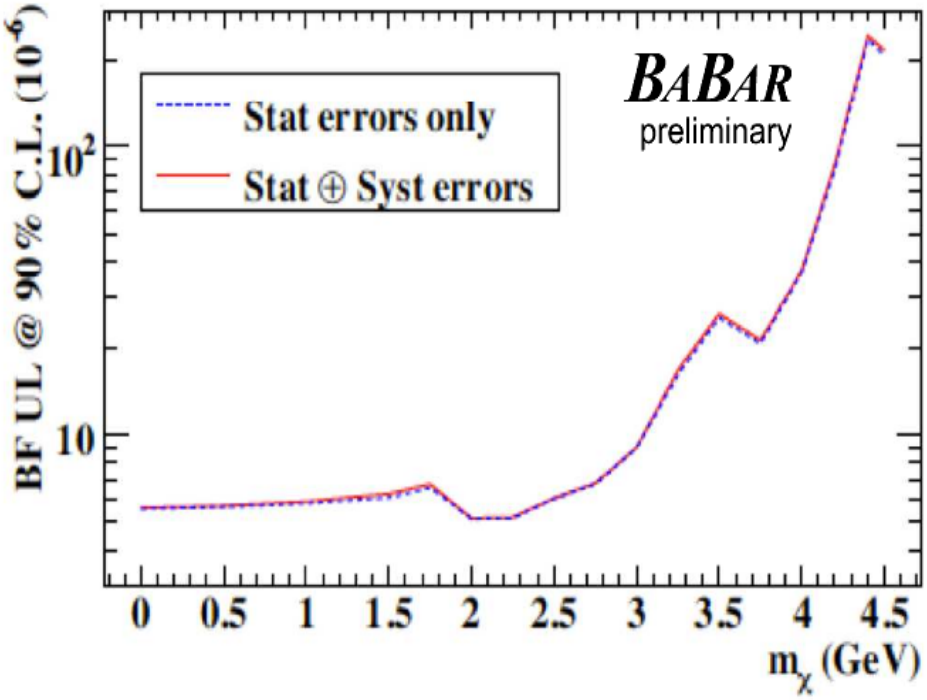



Light Dark Matter Production

# Search for invisible decays of $\Upsilon(1S)$

- $\Upsilon(1S)$ can potentially decay into the dark sector
  - via an intermediate scalar : $\Upsilon(1S) \to \gamma A^0, \quad A^0 \to \textit{invisible}$
  - or via 3-body decay : $\Upsilon(1S) \to \gamma\chi\bar{\chi}$




New 90% CL limits, BaBar'2010

- $B(\Upsilon(1S) \to \gamma A^0) \cdot B(A^0 \to \textit{invisible}) \; < \; (1.9 - 37) \cdot 10^{-6}$
- $B(\Upsilon(1S) \to \gamma\chi\bar{\chi}) \; < \; (0.5 - 24) \cdot 10^{-5}$

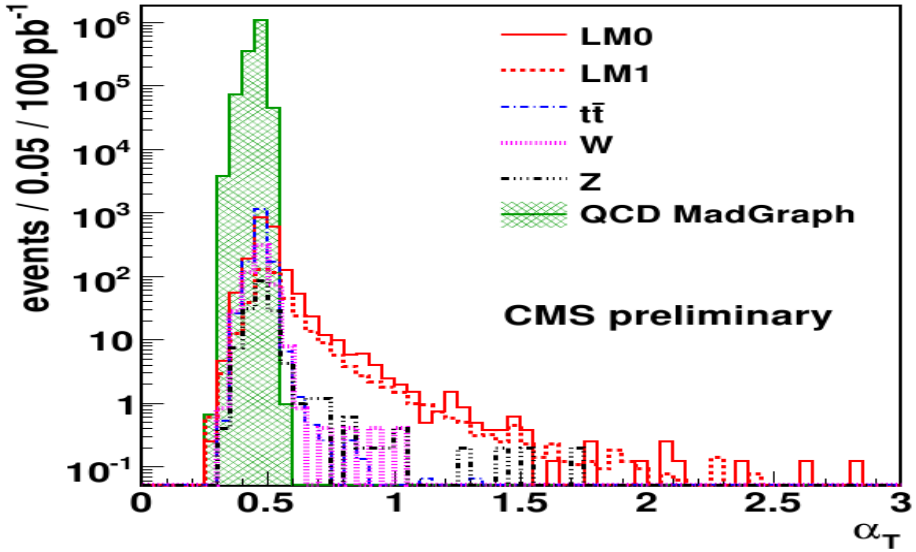
1 Super-Kamiokande

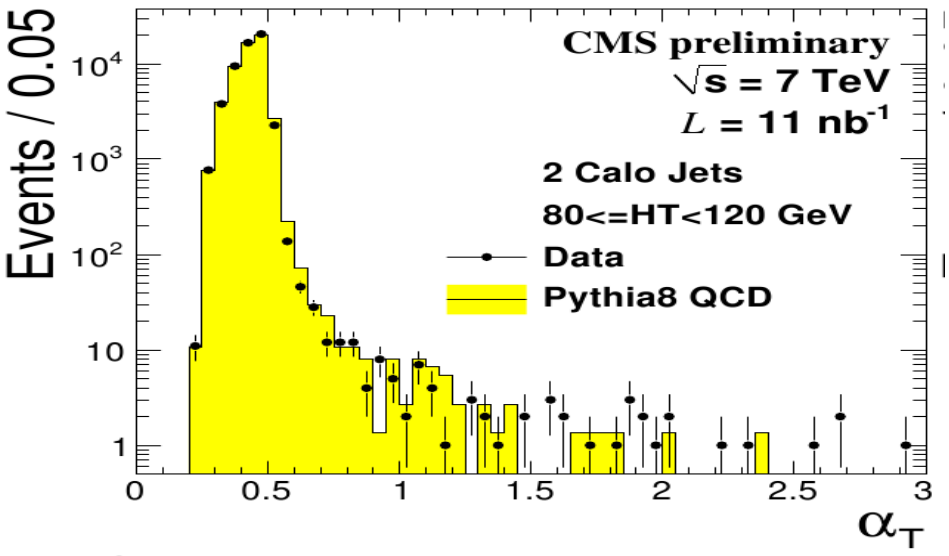
2 BSM Searches at the Tevatron, HERA, B-factories

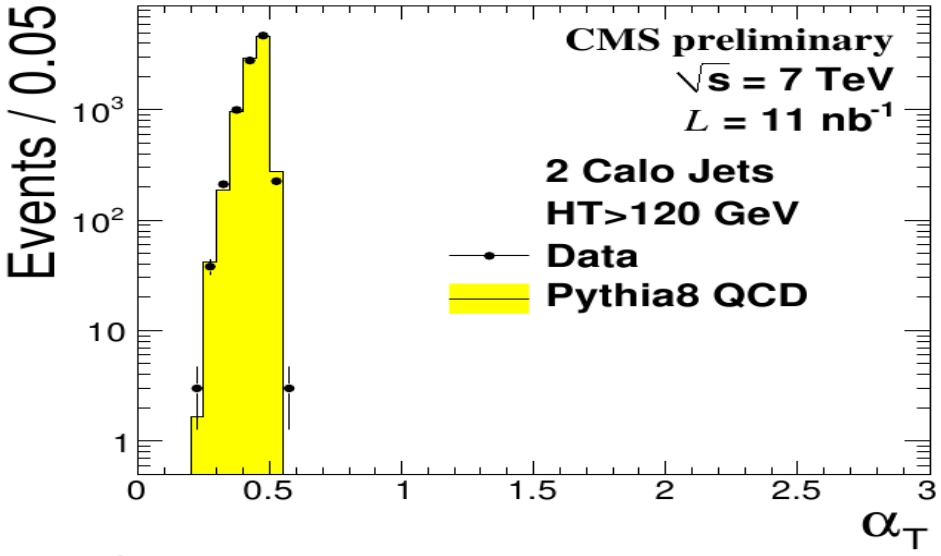
3 First Results from the LHC

# LHC: Getting ready for the first SUSY searches

- largest cross section SUSY channels: (2+) jets + $\not\!\!E_T$
- understanding of backgrounds at large $\not\!\!E_T$ critical
- focus on simple and robust experimental techniques
- event with 2 jets: $\alpha_T = \frac{P_{T_2}}{M_{T_{12}}} = \sqrt{\frac{p_{T2}}{2p_{t_1}(1-cos\Delta\phi_{12})}}$
- for QCD events at large $H_T$ expect $\alpha_T \leq 0.5$

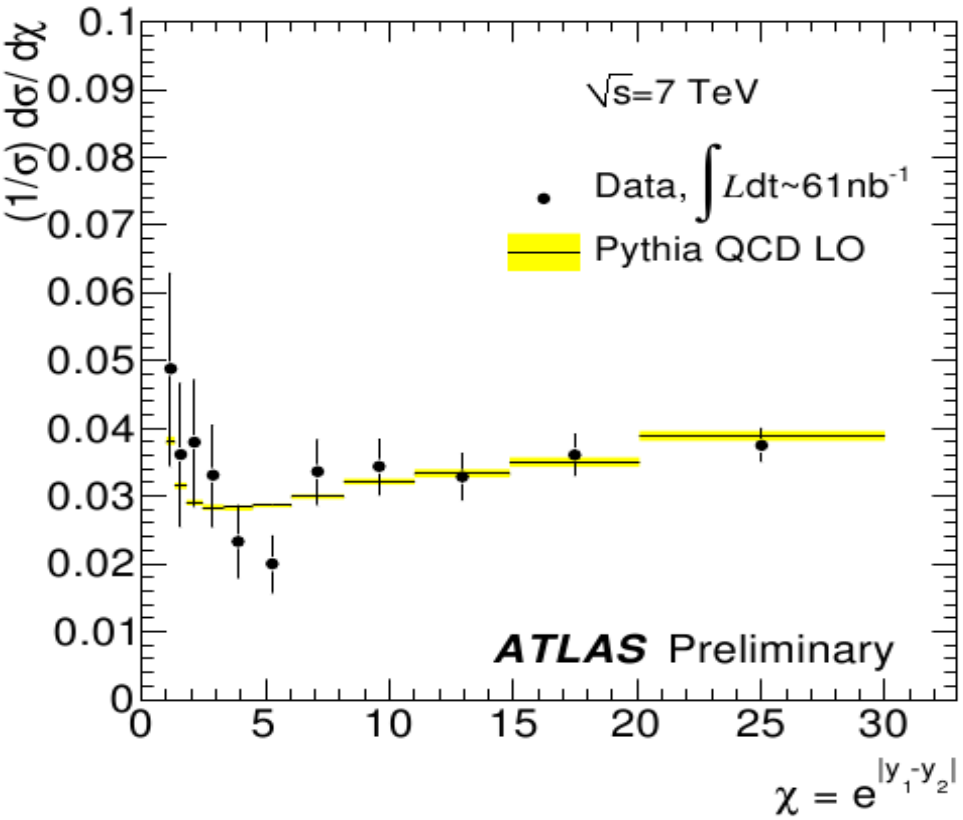


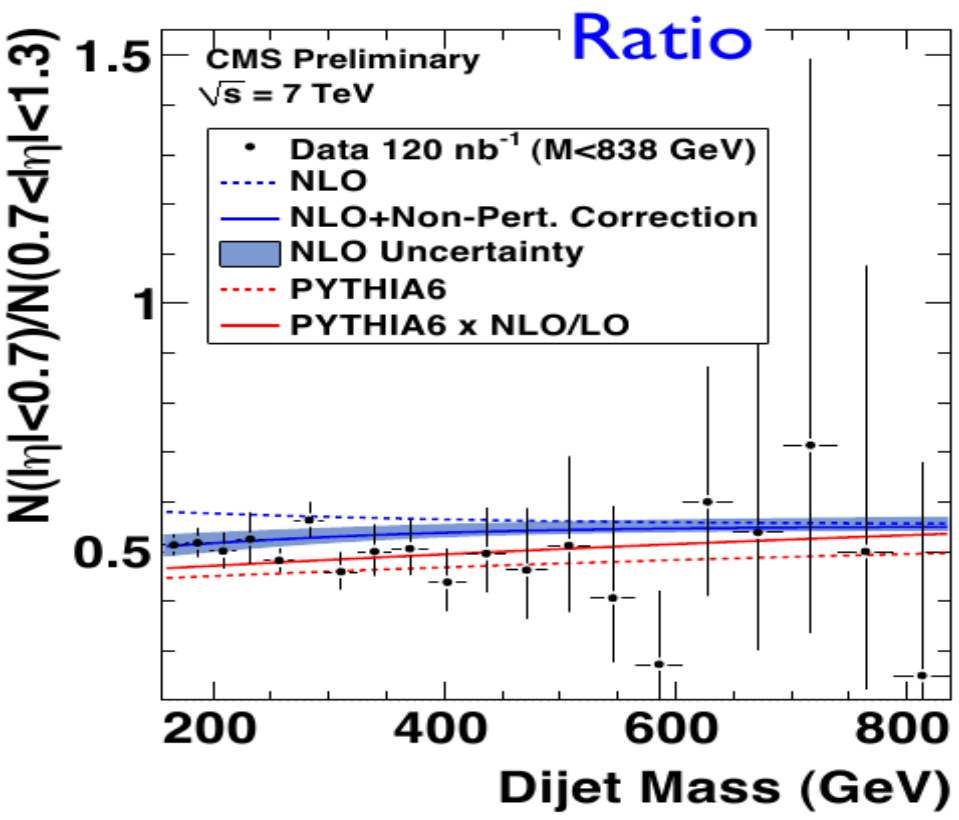




- successfully tested at the level of $10^{-3}$, few more orders of magnitude to go!

# Dijet angular distributions at LHC

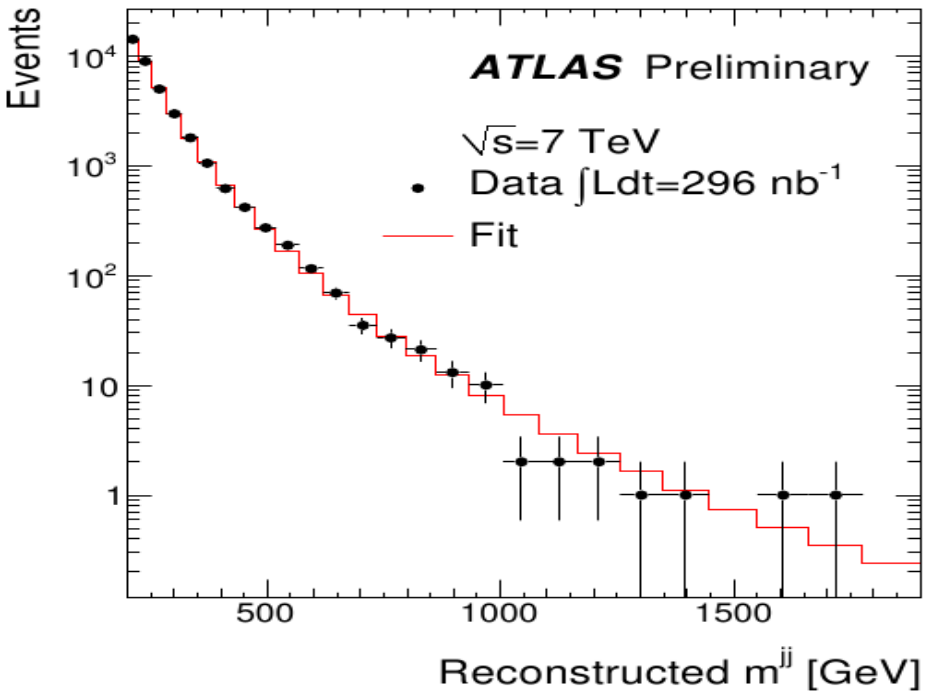


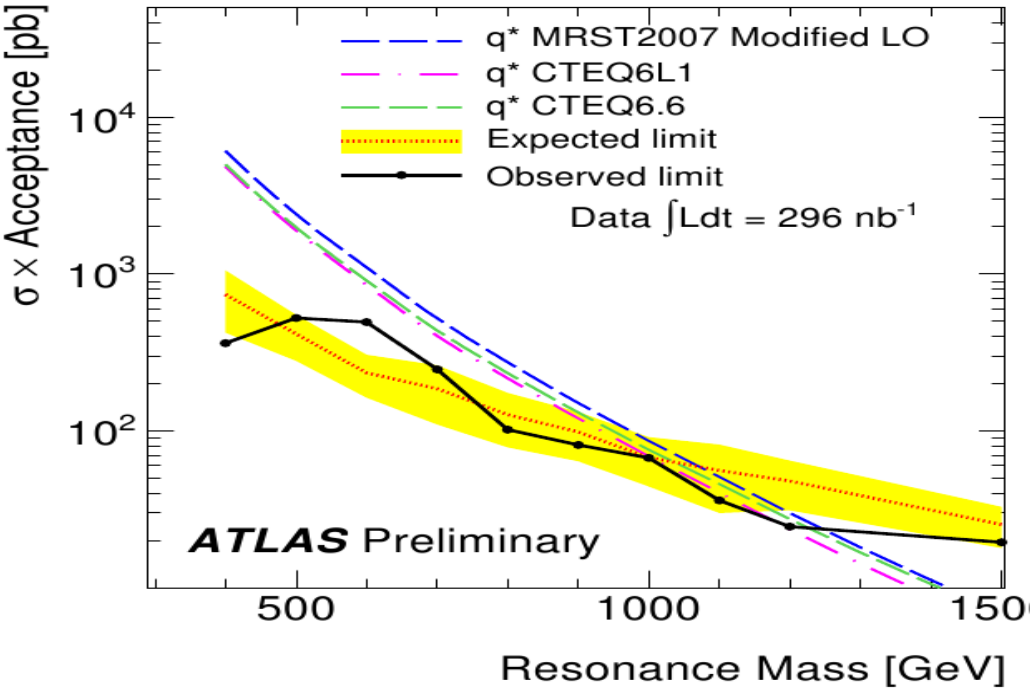




- first 95% CL results on compositness: ATLAS: $\Lambda > 875$ *GeV* , CMS: $\Lambda > 1900$ *GeV*
- Best published limit: $\Lambda > 2800$ *GeV* (D0, PRL 103,191803)
- all the tools needed to deal with higher luminosities are in place!

# First Search for Excited Quarks

- select event with 2 or more jets
- require $|\Delta\eta_{12}| < 1.3$ to improve sensitivity to the high-mass signal

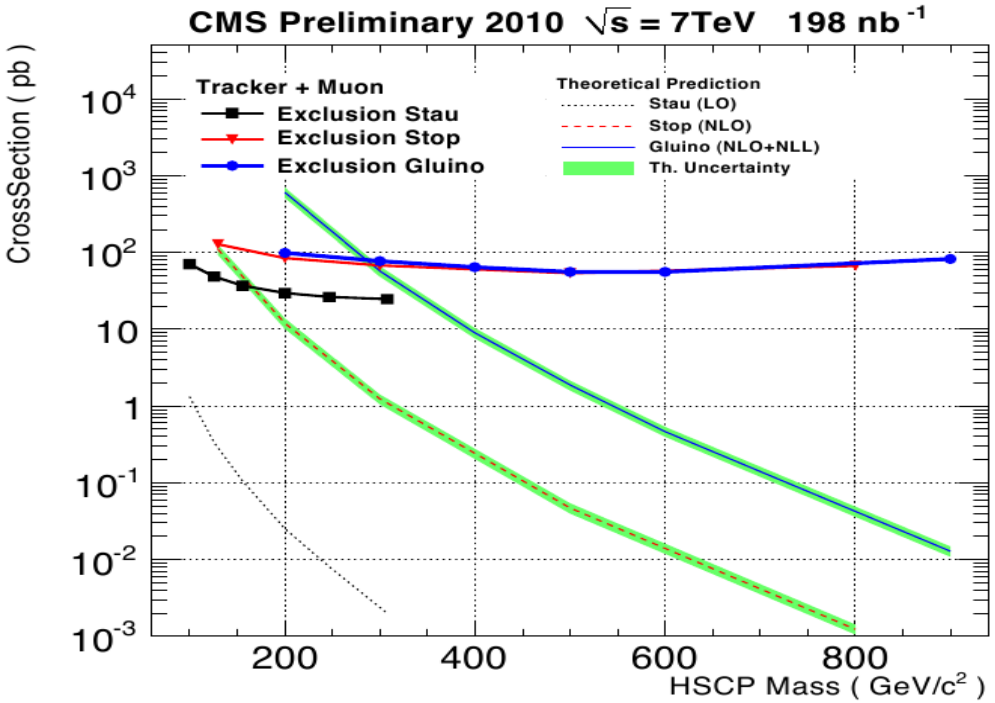


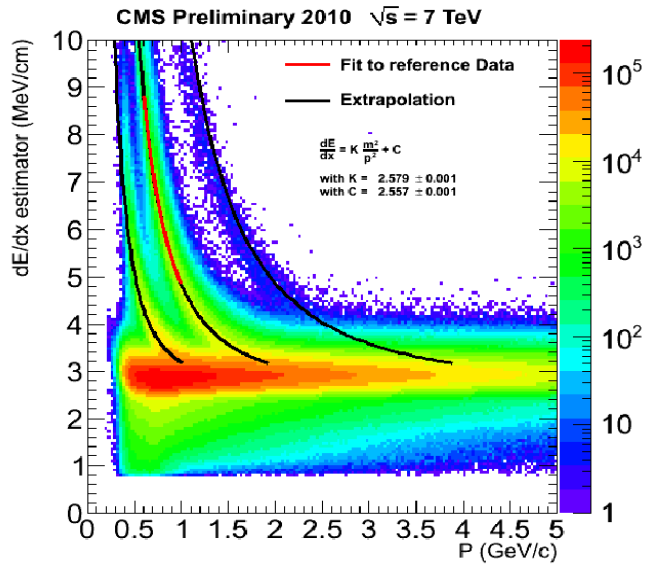



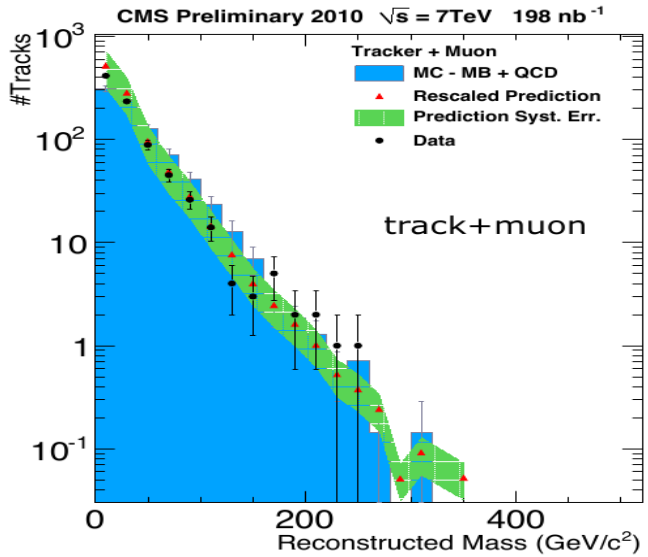

- ATLAS'2010 excluded @ 95% CL
  - $M_{Q^*}$ in [400 GeV, 1180 GeV] with CTEQ6 L1 PDF's
  - $M_{Q^*}$ in [400 GeV, 1290 GeV] with MRST'2007 PDF's

improving best published limit $M_{Q^*} > 870 GeV$ (CDF,1.1$fb^{-1}$, PRD79(2009)112002)

# Search for Heavy Stable Charged Particles (HSCP) by CMS

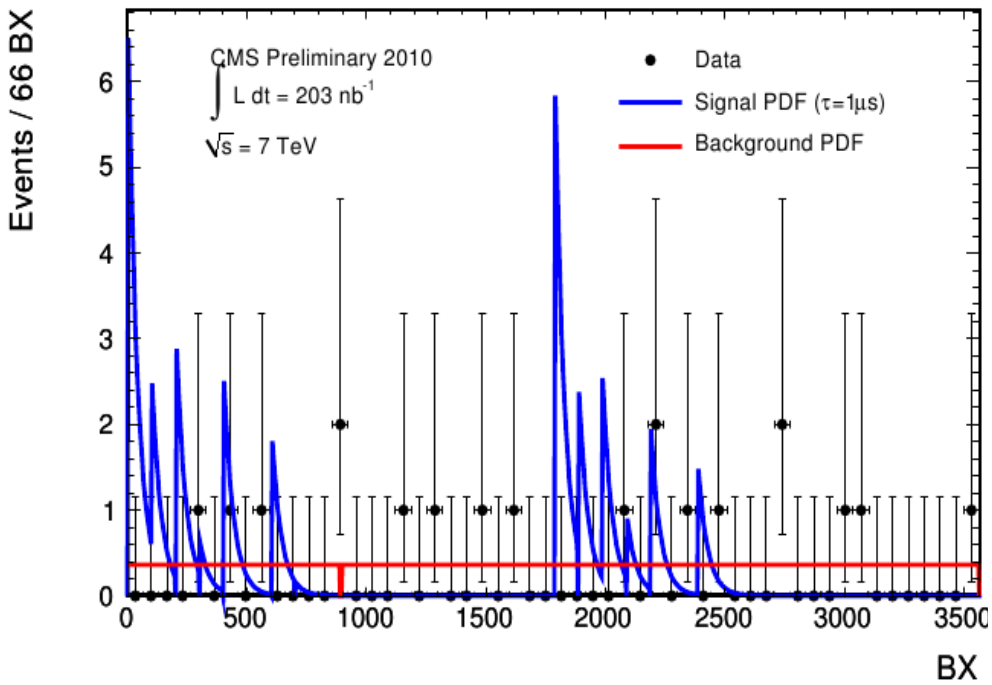


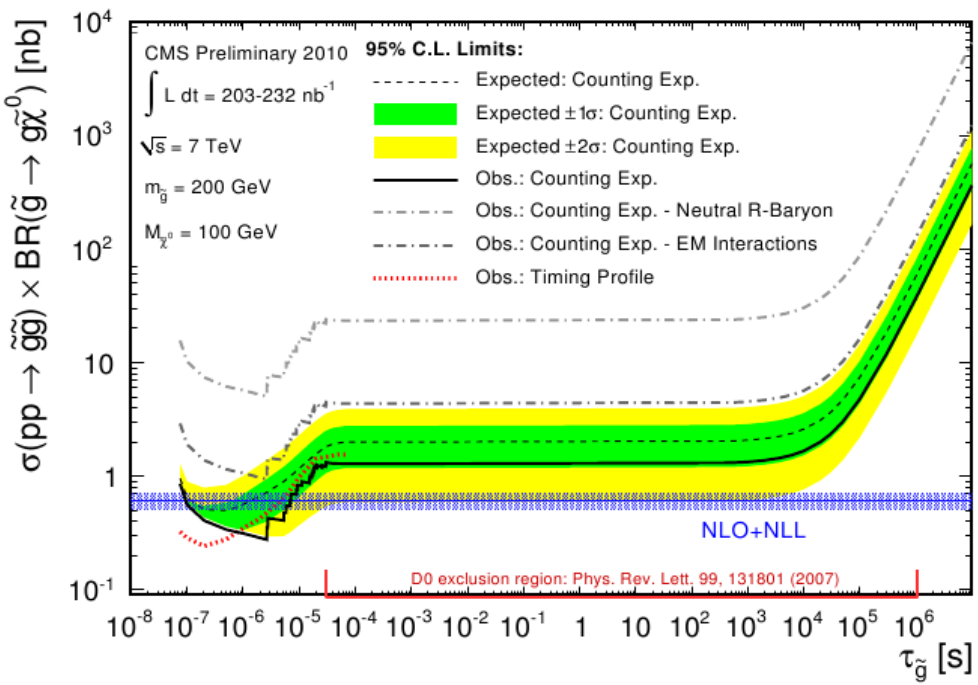




- seach for heavy gluino, hadronizing into a charged R-hadron
- reconstruct R-hadron mass based on measured dE/dX
- CMS'2010 95% CL exclusion:
  - $M_{\tilde{g}} < 271(284)\ GeV/c^2$ for track (muon)

# Searches for Stopped Gluino




- gluino, hadronized into a charged R-hadron, can stop and decay in the calorimeter
- trigger on large “out-of-collision” energy depositions
- sensitive to the large lifetimes
- assume $BR(\tilde{g} \rightarrow g\tilde{\chi}^0) = 100\%,\ M_{\tilde{g}} - M_{\tilde{\chi}^0} > 100\ GeV$
- CMS’2010 95% CL limits on gluino lifetime $\tau_{\tilde{g}}$ :
  - counting experiment excludes $\tau_{\tilde{g}}$ within [120ns, 6$\mu s$]
  - time profile analysis improves low limit down to 75$ns$

## Summary

- extensive searches for physics beyond the SM
- multiple new constraints on the new physics from the Tevatron, HERA, B-factories
- maturity and breadth of the ongoing program
- first search results from the LHC - impressive!
- expect searches at the Tevatron and LHC to complement each other in the future
- anticipate the new results

## Summary

- extensive searches for physics beyond the SM
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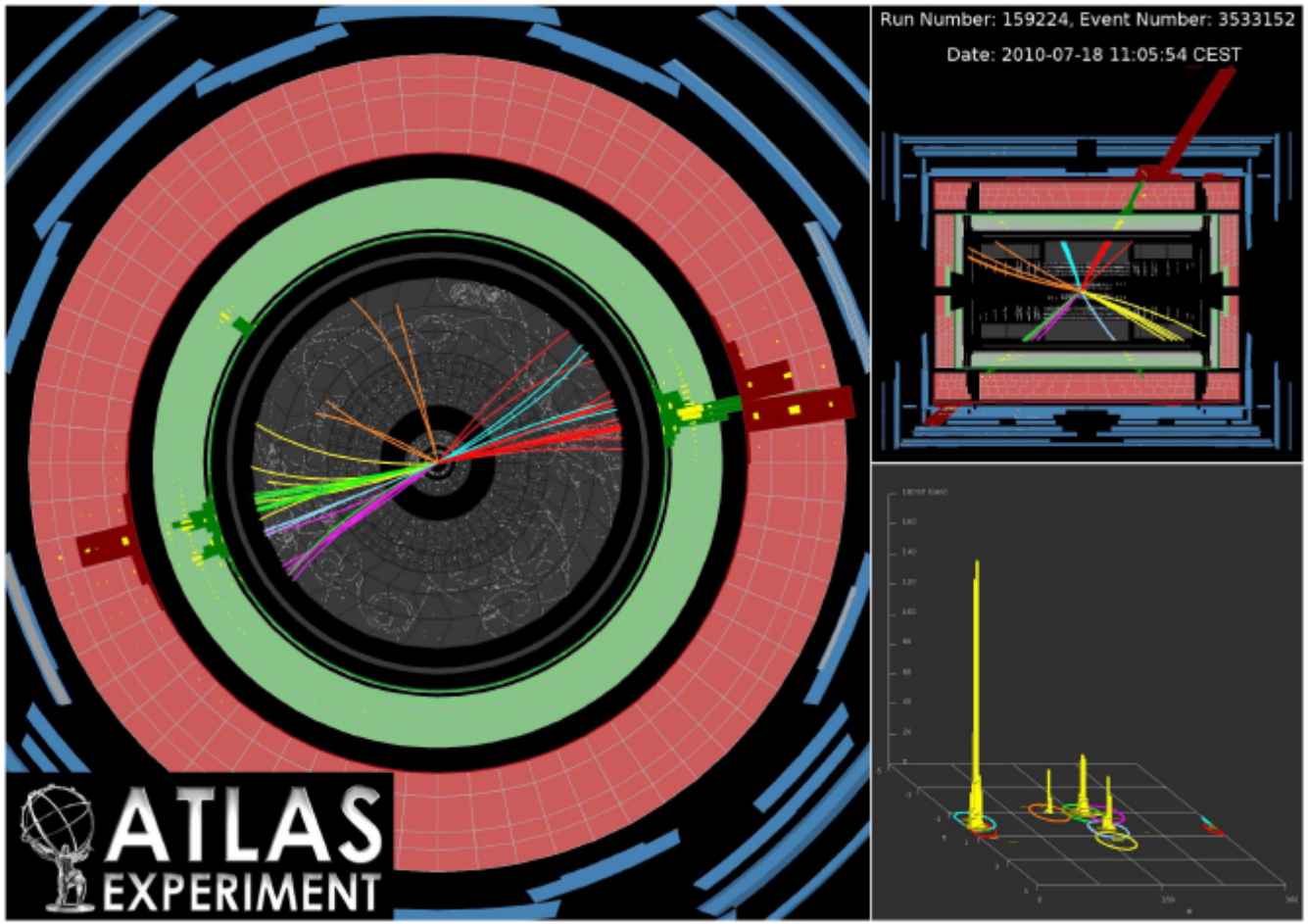
- first search results from the LHC - impressive!
- expect searches at the Tevatron and LHC to complement each other in the future
- anticipate the new results **beyond the 95%CL !**

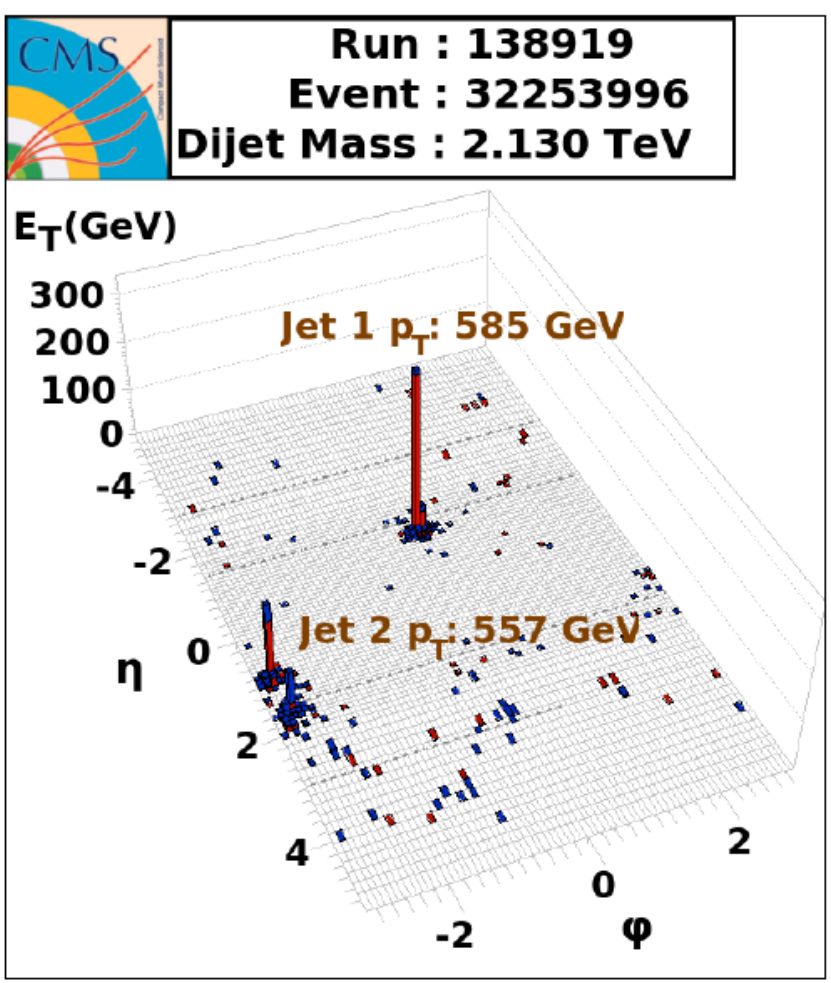
# ATLAS: The highest $E_T$ jet

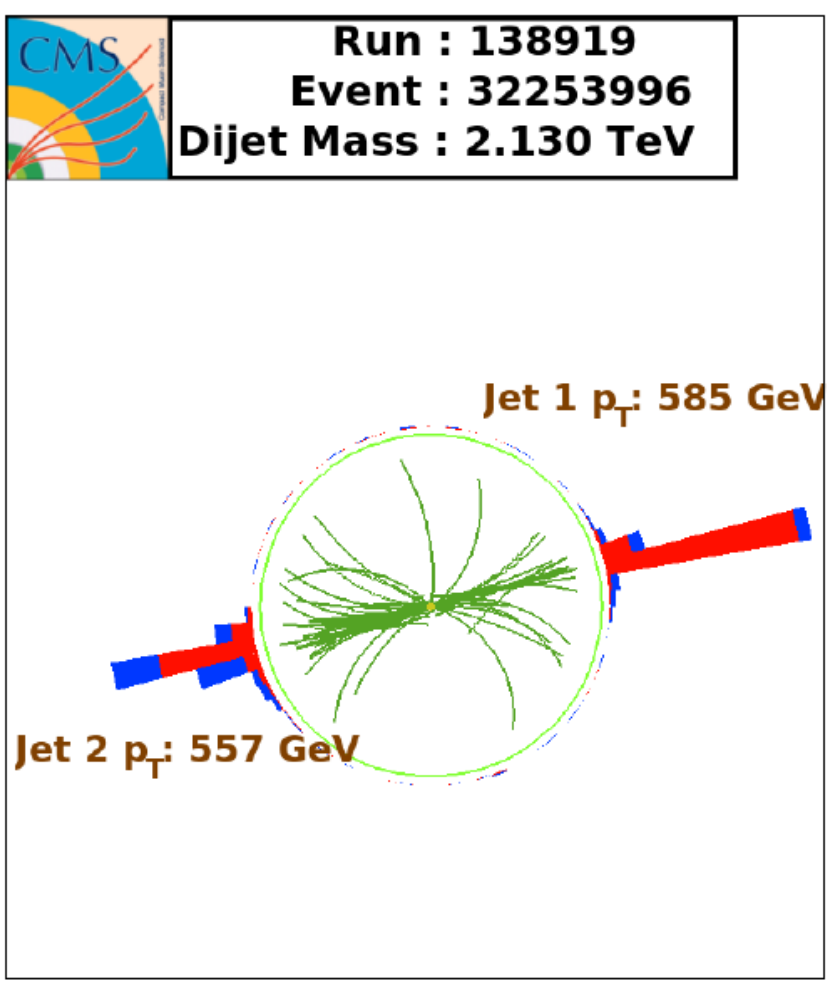
## The highest-$m^{jj}$ central event observed

$m^{jj} = 1.77$ TeV. $p_T^{j1} = 1.1$ TeV. $p_T^{j2} = 480$ GeV, partly in calorimeter gap.



# CMS : the highest dijet mass event



# CMS: early searches with dijets