Searches for New Phenomena at the Tevatron

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Outline of the talk

1. Short introduction
2. Search for unstable particles
3. Search for Dark Matter
4. Search for Extra Dimensions
5. Signature-based searches
6. Conclusion

Any Hope for New Phenomena?

- Why are we interesting in looking for new phenomena?
  - The Standard Model (SM) can't address some fundamental questions
    - Unification, hierarchy problem, number of families, etc
  - We have models which can address some of these problems by extending the SM lagrangian

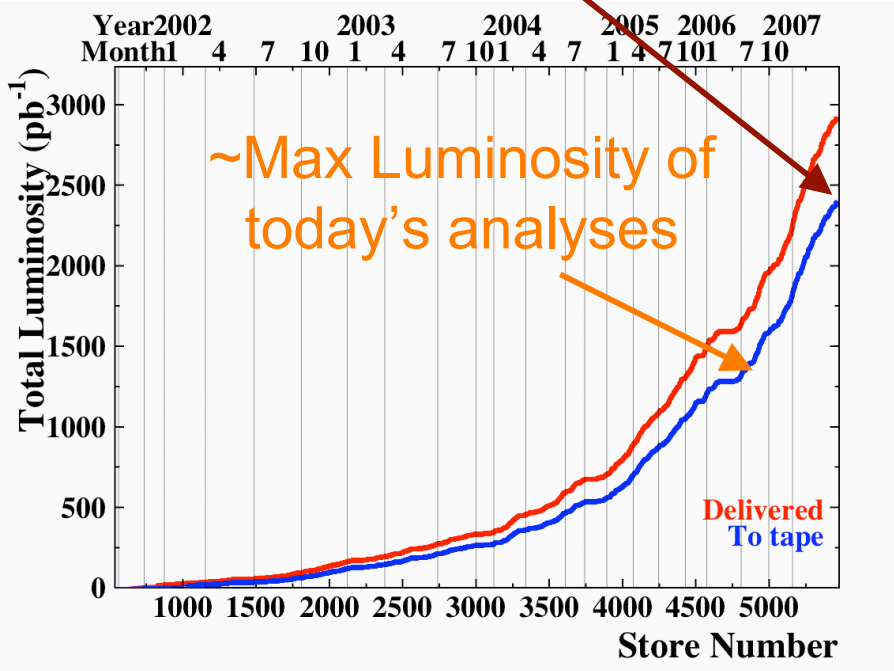
    ⇒ **We have predictions for new phenomena**
  - Observation of Dark Matter cannot be explained in the SM

    ⇒ **Dark Matter = indication for new physics!**

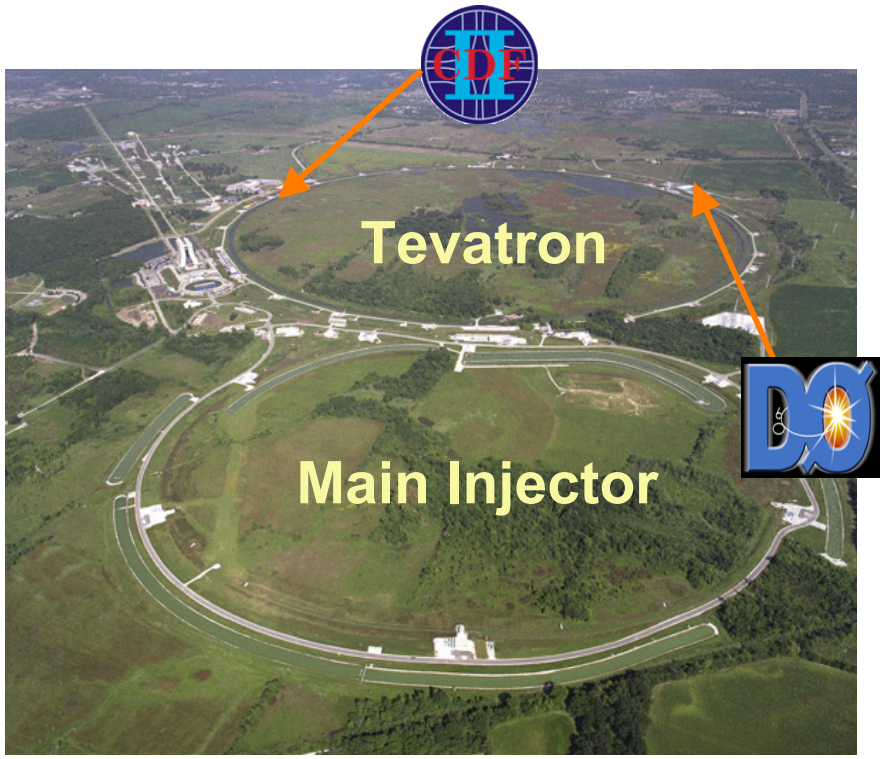
- Why looking for new phenomena at the Tevatron?
  - Some new particles should manifest at the 0.1-1.0 TeV range:
    - Scale of the electroweak symmetry breaking
    - Favored scale for the mass of Cold Dark Matter candidates (WIMP)
  - The Tevatron have enough energy to probe the sub-TeV range.

Tevatron: the energy frontier

A lot more data are ready to be investigated!



pp collision at $\sqrt{s}$ = 1.96 TeV



CDF: http://www-cdf.fnal.gov/physics/exotic/exotic.html

D0: http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm

Search For Unstable Massive Particles

Search for new particles

- Following analyses concentrate on direct searches for the existence of new particles, ie:

  select observables reconstructed from familiar physics objects and look for excess over SM expectations.

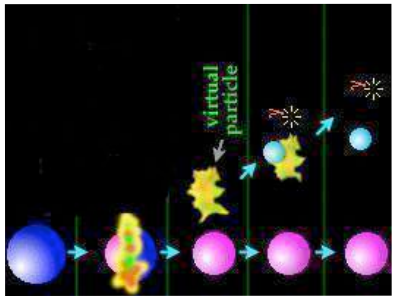
- Different scenarios ⇒ different final state topologies:

  - New bosons:
    - Ex: Z', W'
    - Ex: leptoquark
    - Ex: MSSM Higgs

  ← Unstable particles coupling to pair of SM particles (resonances)

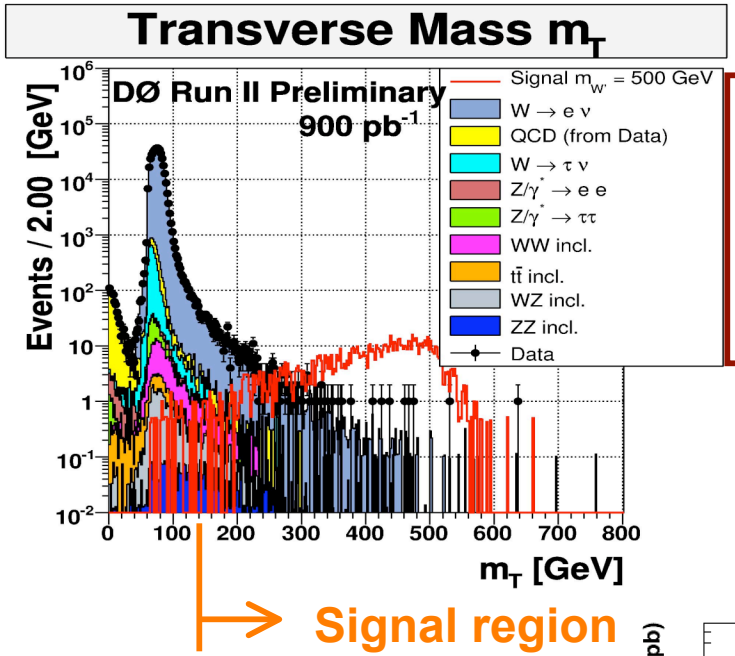
  - New fermions:
    - Ex: b'
    - Ex: excited electron

  ← Unstable particles coupling to a SM gauge boson and a fermion



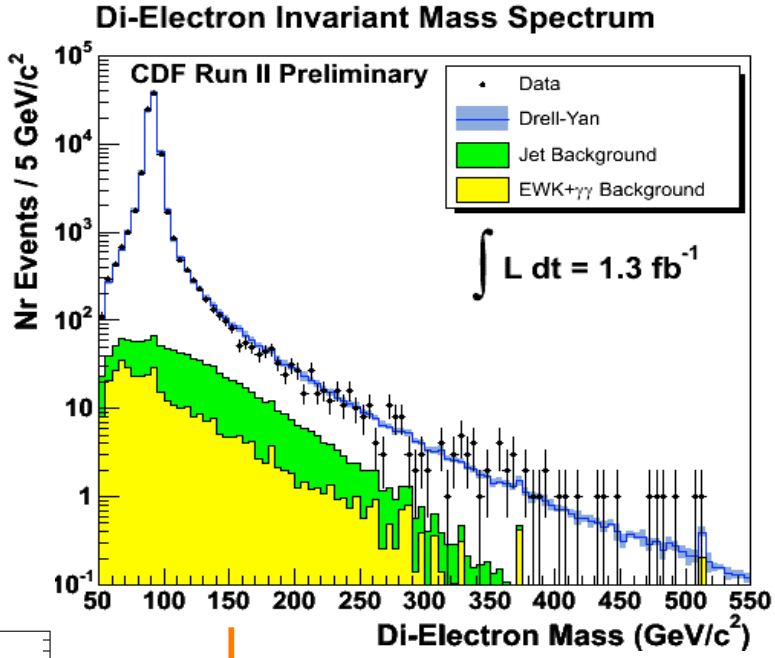
New Gauge bosons: Z', W'

- Massive spin-1 bosons are expected from GUT models



Signal region

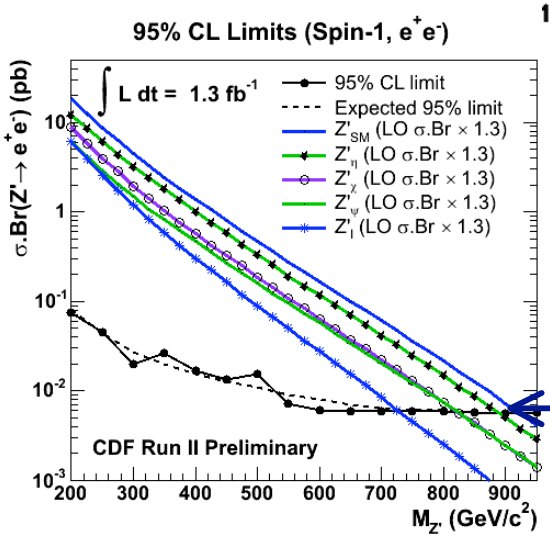
Results from both searches are consistent with SM



Signal region

Example of D0 limit on W':

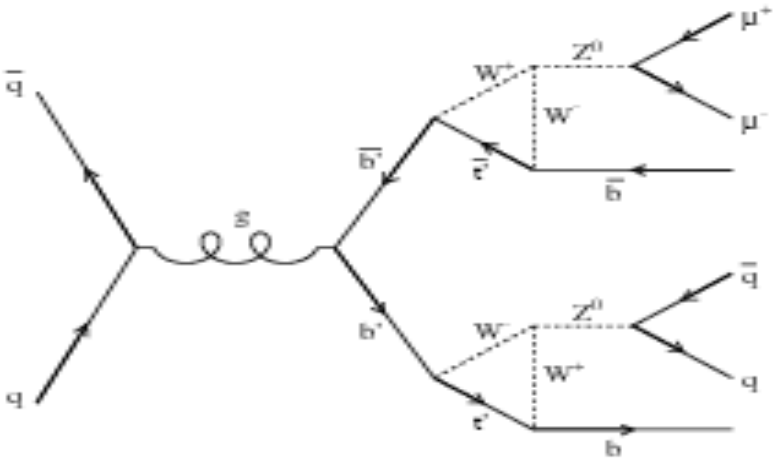
965 GeV/c²



Example of CDF limit on Z':

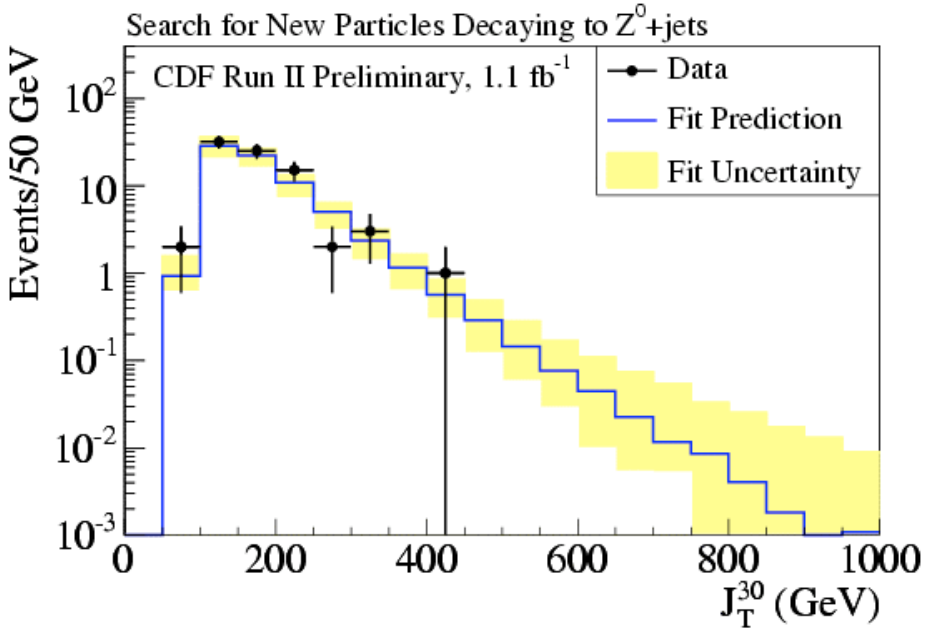
923 GeV/c²

New fermions: b'



- SM doesn't explain why 3 families:
  → Search for a 4th generation
- b' may have large BR to bZ^0 via loop diagrams.

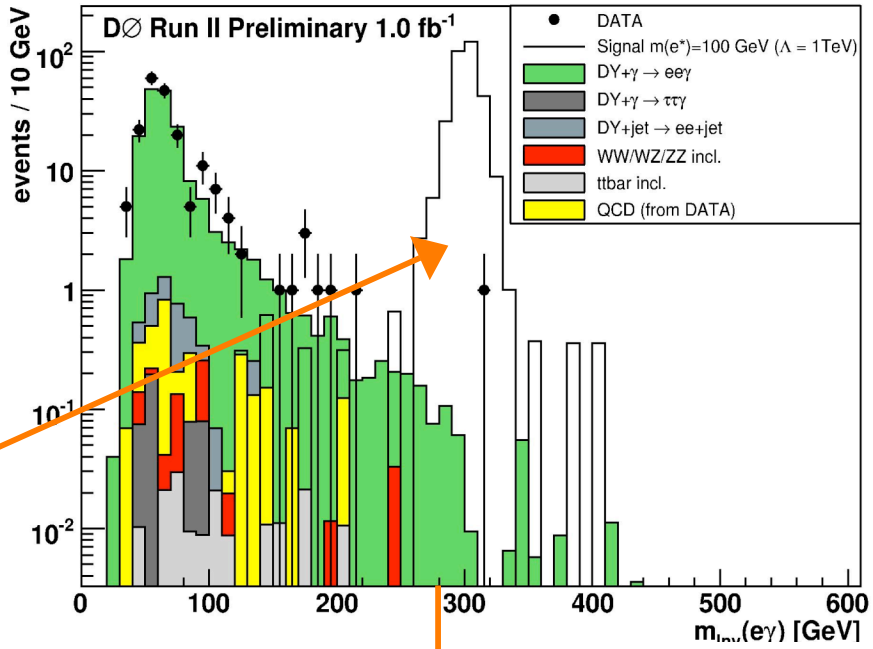
- Perform a model-independent search for excess of Z+jets.
- Z+jets background estimated solely from data.



No significant excess:
$\Rightarrow m_{b'} > 270$ GeV

New lepton: excited electron

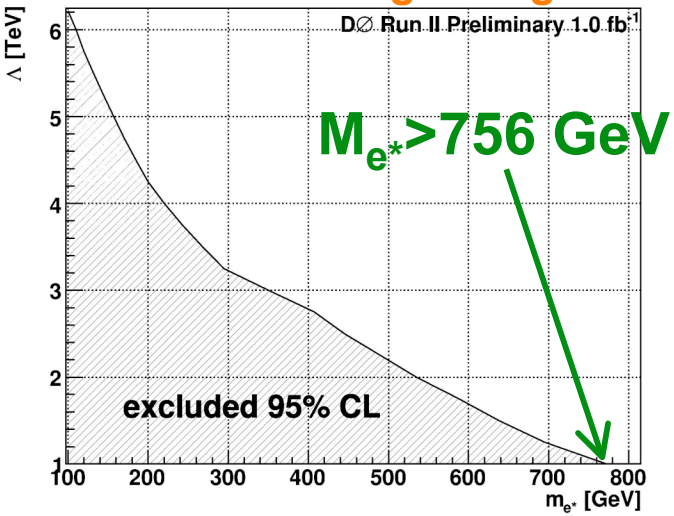
- **Compositeness**: elementary particles bounded by new strong interaction underlies quarks and leptons substructure:
- Similar than QCD hadrons.



ex: m_{e^*}=300 GeV

Signal region

- Look for pp→ee*→eeγ process
- Decay e*→eγ would be observed in a resonance.

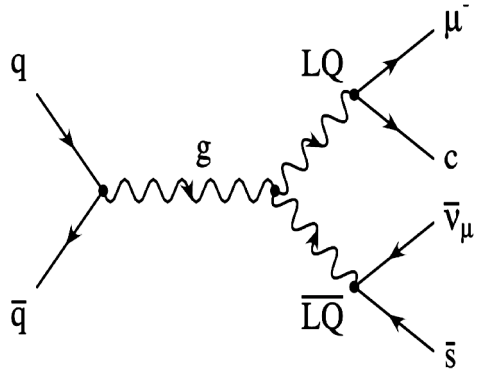


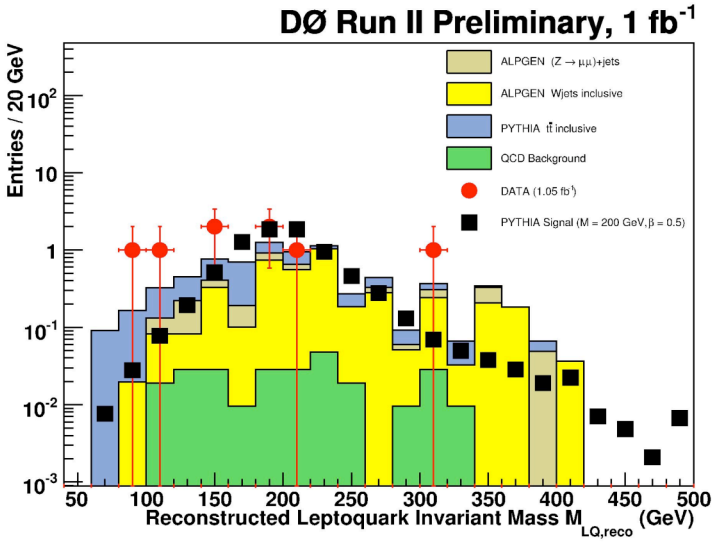
2nd generation Leptoquark

- Leptoquarks: color-triplet bosons carrying lepton and baryon numbers.
- Couple only to one family: constrain from FCNC and proton decay.
- Search for spin=0, Q_{em} = -1/3, 2nd generation leptoquark (LQ $\rightarrow \mu q, \nu q$).

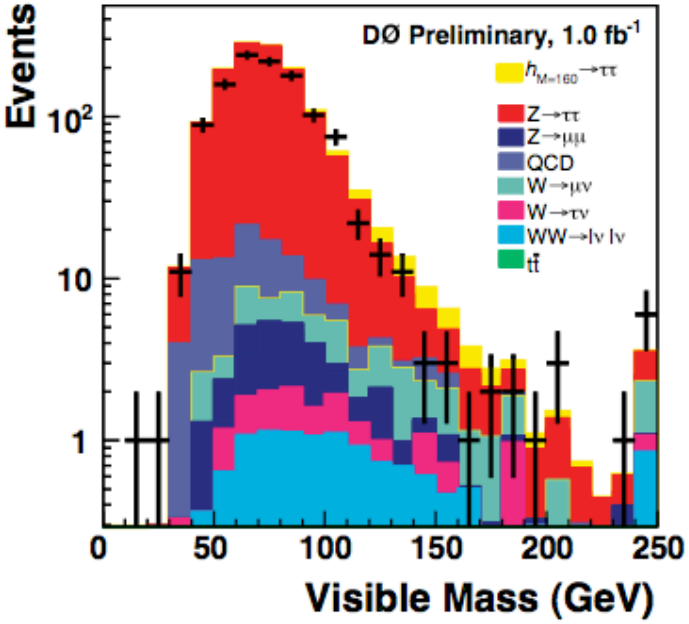
- Final state: LQLQ$\rightarrow \mu\nu qq$
  - Leptoquarks transverse mass:
- Results for M_{LQ}=200 GeV:
  - Prediction: 6.4 ± 0.7 ± 0.8
  - Observed: 6

Limit: M_{LQ}>214 GeV



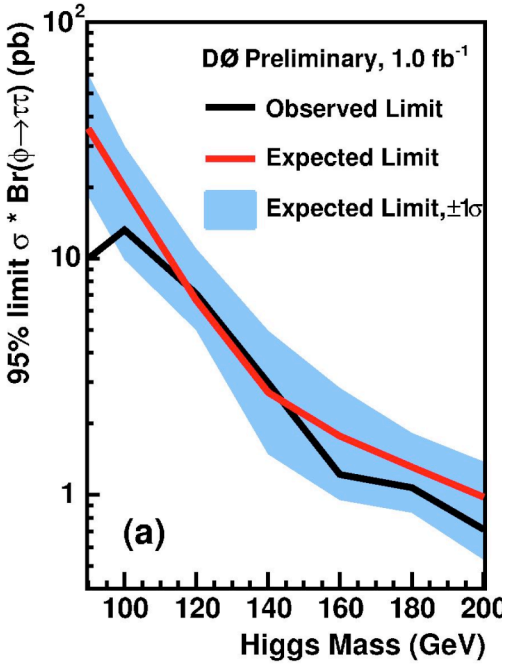


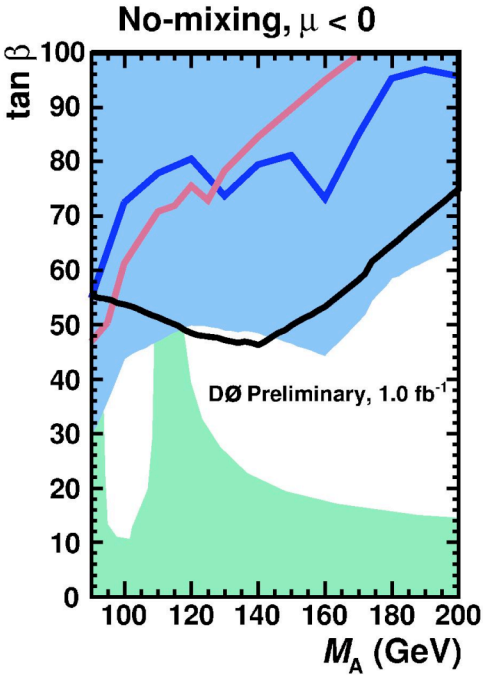
D0: MSSM Higgs



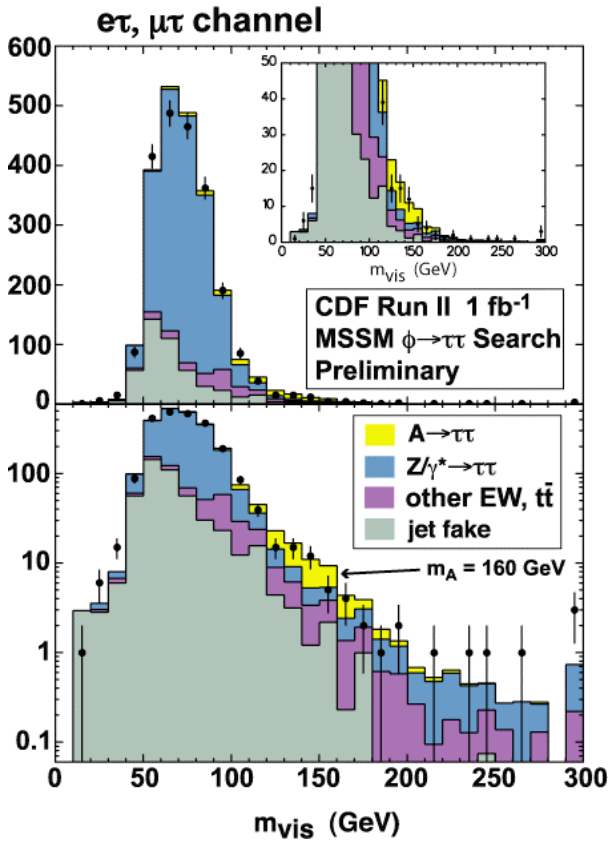
- MSSM predicts 3 neutral higgs: ϕ = h, H, A
- MSSM Higgs sector described by 2 parameters: m_A and tanβ
- Search for $\phi \rightarrow \tau_{\rightarrow\mu}\tau_{\rightarrow had}$

Data are consistent with SM expectations



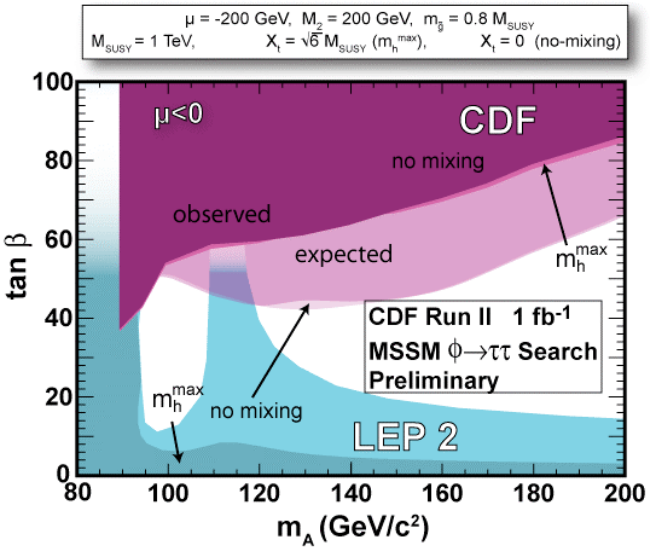


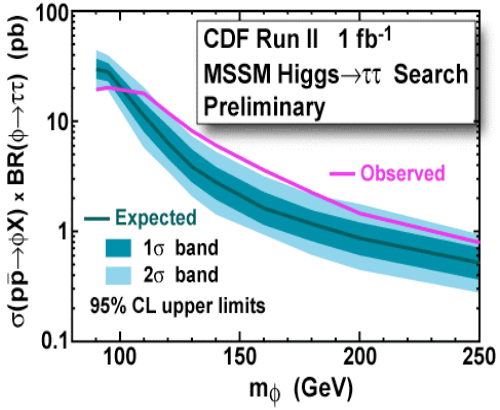
CDF: MSSM Higgs



- Search similar as the D0 one: inclusive $\phi \rightarrow \tau\tau$
- Look at 3 different final states: $\tau_{\rightarrow e}\tau_{\rightarrow had}$, $\tau_{\rightarrow \mu}\tau_{\rightarrow had}$ and $\tau_{\rightarrow e}\tau_{\rightarrow \mu}$

No significant excess is observed





Dark Matter Searches

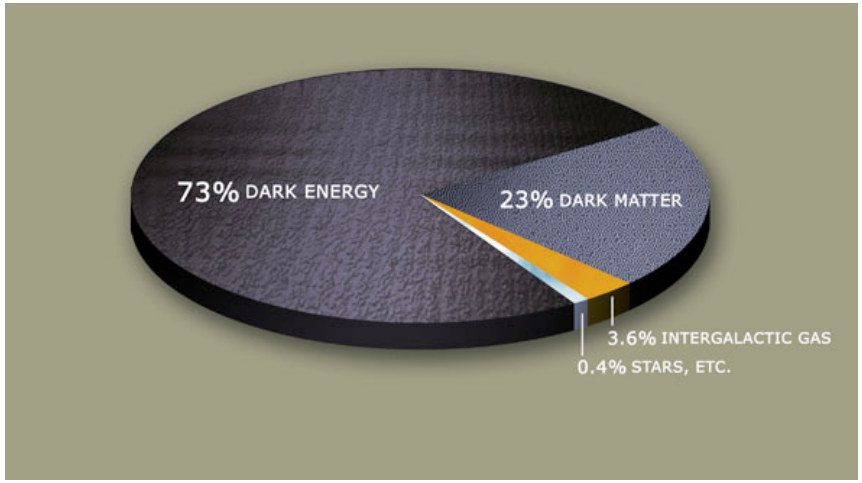
Dark Matter

Observation: $\Omega_{DM}h^2=0.105 \pm 0.004$ (WMAP, SDSS)

$\Rightarrow$ **Best evidence for new physics**

- Weakly Interacting Massive Particles (WIMP) are potential candidates for Dark Matter
- General SUSY models with R-parity conservation provide Dark Matter candidate:
  - Neutralinos are WIMPs

$\Rightarrow$ **Focus on SUSY processes for which neutralinos are produced in the final state.**



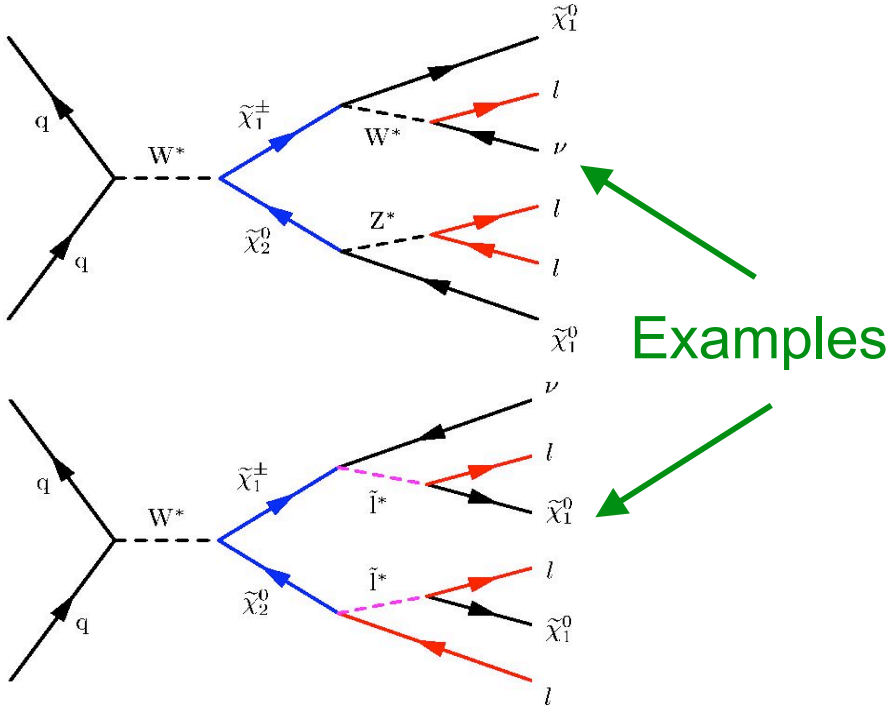
Two main signatures:

- Trileptons+$\not{E}_T$
- Jets+$\not{E}_T$

Missing Transverse Energy ($\not{E}T$) $\Rightarrow$ WIMP signature

Trileptons (I)

- The associated production of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^{0}$ is the dominant SUSY production mechanism at the Tevatron:
  - Experimental limits on squark and gluino constrain their production
- Concentrate in trileptons + $\not{E}_T$ final states:
  - contain 2 lightest neutralino $\tilde{\chi}_1^{0}$ (LSP)
  - have a low SM contamination



Examples

Many SUSY models predict trileptons + $\not{E}_T$

⇒ We present limits for mSugra inspired benchmark scenarios with no slepton mixing

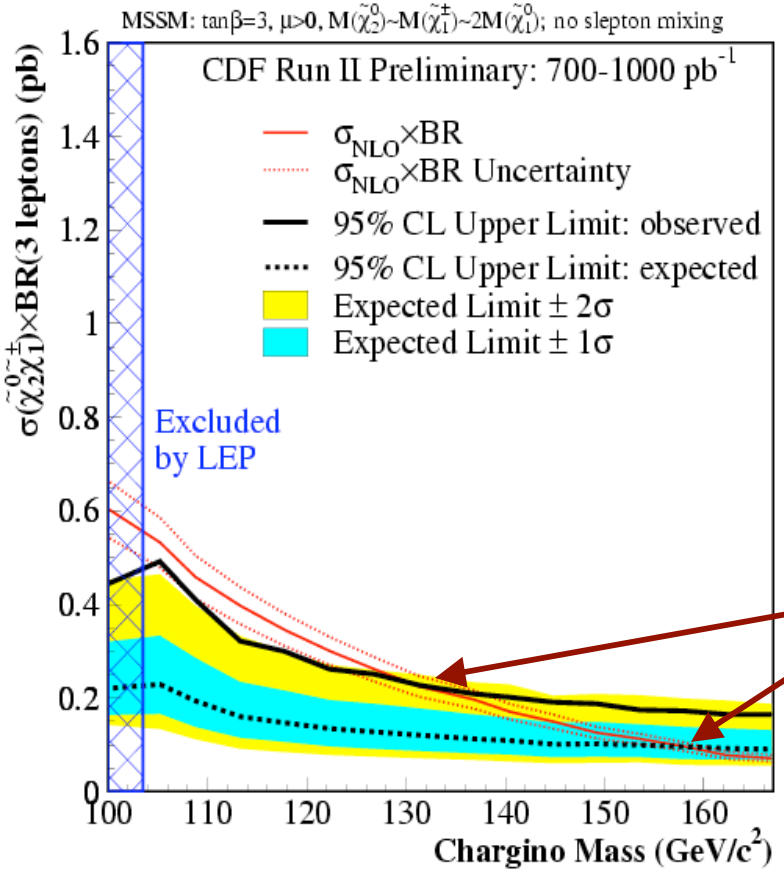
CDF: Trileptons (II)

- Combine 14 different analyses:
  - 3rd lepton is: e, μ or track;
  - inclusive 2 like-sign leptons.
- Dominant backgrounds:

  Drell-Yan and dibosons

  ⇒ **no significant excess**

Also assumes M_0 = 60 GeV



Benchmark:

– **Sensitivity:** $M_{\tilde{\chi}^\pm} > 160$ GeV

– **Limit:** $M_{\tilde{\chi}^\pm} > 130$ GeV

This benchmark assumes:

$$M_{\tilde{\chi}^\pm} \approx 2\, M_{\tilde{\chi}^0_1}$$

⇒ Can be used to estimate limit on the mass of $\tilde{\chi}^0_1$ (WIMP candidate)

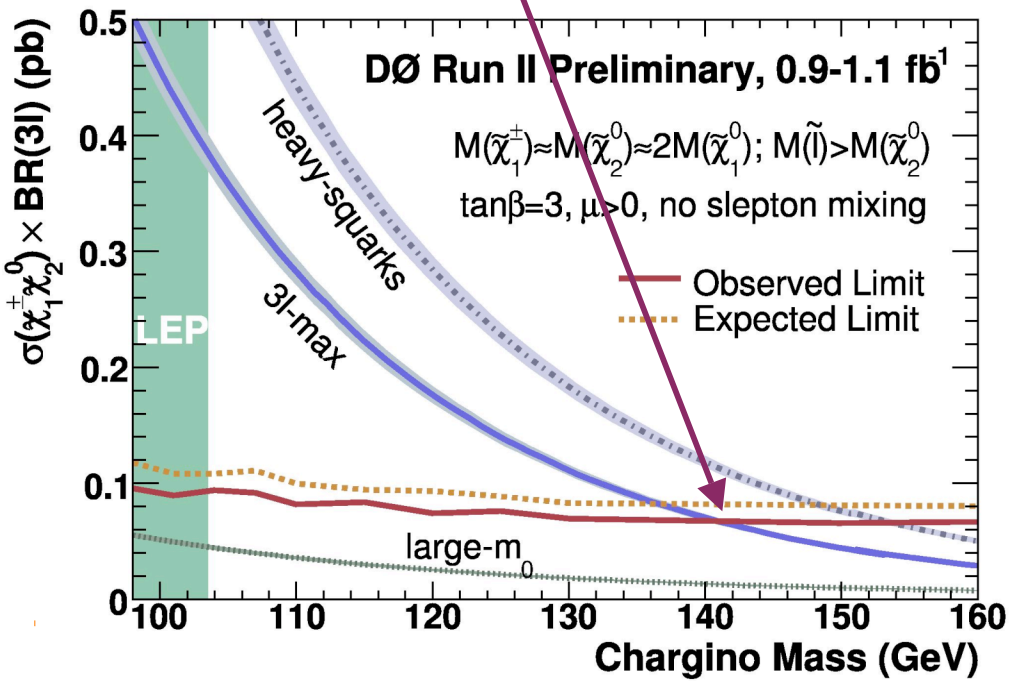
D0: Trileptons (III)

- Combine 4 different analyses:
  - eeℓ, e$\mu\ell$, $\mu\mu\ell$ and $\mu\mu$ like-sign
    (here: ℓ is an isolated track)
- Cut on similar observables:
  - $\not\!\!E_T$, $M_T(\ell_i\ell_j)$, $M_T(\ell_i,\not\!\!E_T)$, etc

topologies	predicted	observed
eeℓ	0.76±0.67	0
e$\mu\ell$	$0.94^{+0.40}_{-0.13}$	0
$\mu\mu\ell$	$0.32^{+0.73}_{-0.03}$	2
$\mu\mu$ (LS)	1.1±0.4	1

No excess

Benchmark limit: $M_{\tilde{\chi}}$>141 GeV



Also assumes $m_{\tilde{\ell}} = m_{\tilde{\chi}_2^0} + \varepsilon$

Jets + $\not{E}_T$ (I)

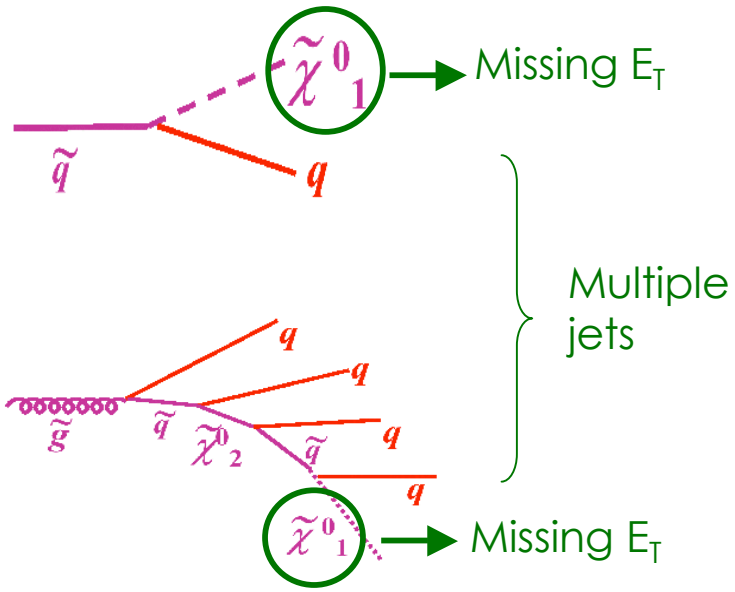
From mSugra, squark and gluino pair production is expected to be important at the Tevatron, if masses are sufficiently light:

- In generic models, 5 lightest squarks have similar masses;
- Stop production will be ignored.

3 production scenarios:

- gluino heavier than squark (low m_0):
  - squarks pair production dominates
    ⇒ **≥2-jets + met topology**
- squarks heavier than gluino (high m_0):
  - gluino pair production dominates
    ⇒ **≥4-jets + met topology**
- similar squarks and gluino masses:
  - mixed squark-gluino final state
    ⇒ **≥3-jets + met topology**

Decays:

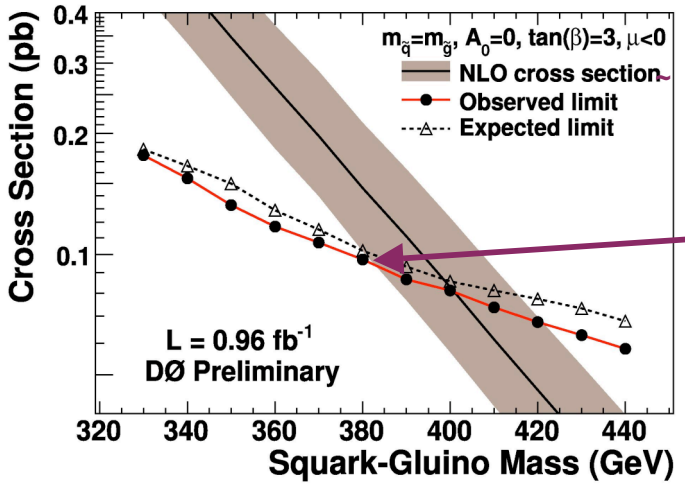


D0: Jets + $\not\!\!E_T$ (II)

3 different analyses:

- Dijet, 3-jets, 4-jets;
- Backgrounds: $Z\rightarrow\nu\nu$+jets, $W\rightarrow\ell\nu$+jets and $t\bar{t}$
- The 3 analyses overlap:

$\Rightarrow$ results are combined from 7 exclusive combinations:



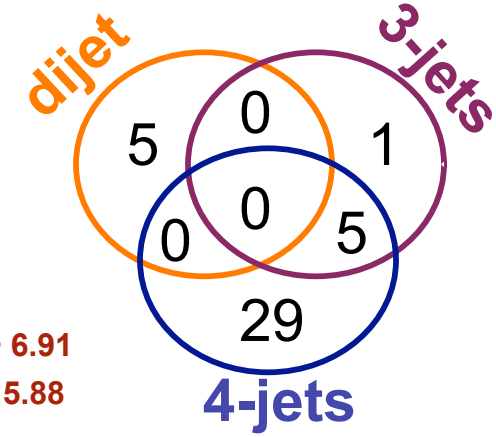
3-jets: $m_{\tilde{q}}=m_{\tilde{g}}$

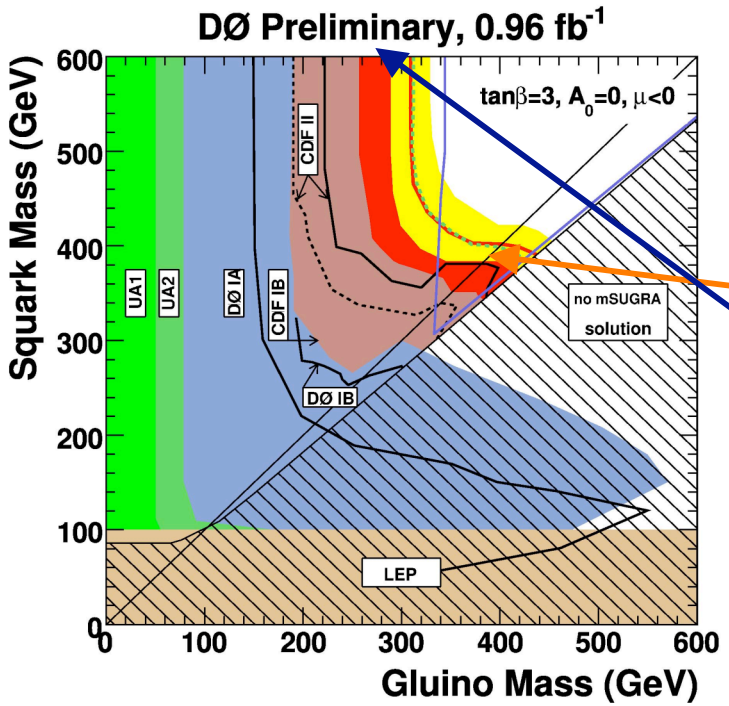
For σ_{min}: 383 GeV

Total data observed: 40

predictions:

$40.76 \pm 1.33^{+6.91}_{-5.88}$



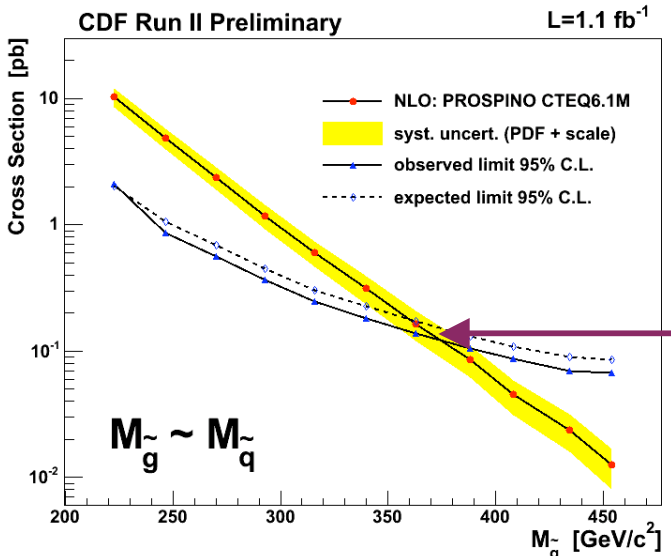


dijet: 375 GeV (for σ_{min})

4-jets: 289 GeV (for σ_{min})

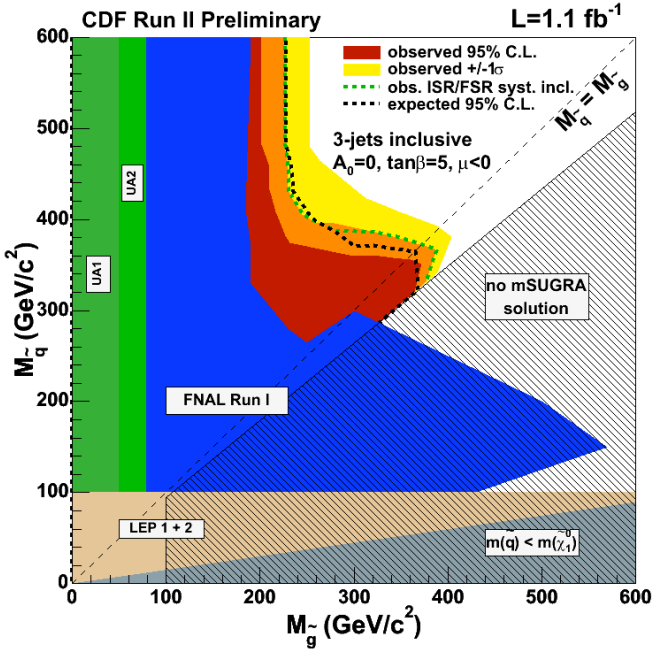
CDF: Jets + $\not\!\!E_T$ (III)

- Same topology for the different scenarios:
  ⇒ **≥3-jets + $\not\!\!E_T$**
- 3 kinematic zones increase sensitivity to the different scenarios:
  - A: 150<$M_{\tilde{g}}$<265 GeV
  - B: 265<$M_{\tilde{g}}$<330 GeV
  - C: $M_{\tilde{g}}$>330 GeV
  ⇒ Different selections on $E_T(j1)$, $E_T(j2)$, H_T and $\not\!\!E_T$



3-jets:
(from σ_{nom}):
380 GeV

Results are Similar to D0 ones

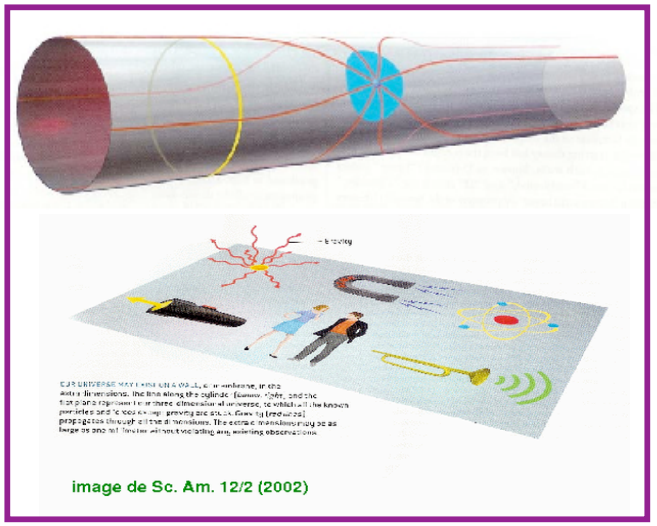


events in 1.1 fb^{-1}	DATA	SM Expected
Type A	494	486 ± 17 (stat.) ± 101 (syst.)
Type B	136	129 ± 8 (stat.) ± 31 (syst.)
Type C	17	20 ± 2 (stat.) ± 5 (syst.)

Searches for Extra Dimensions of space

Extra Dimensions (ED)

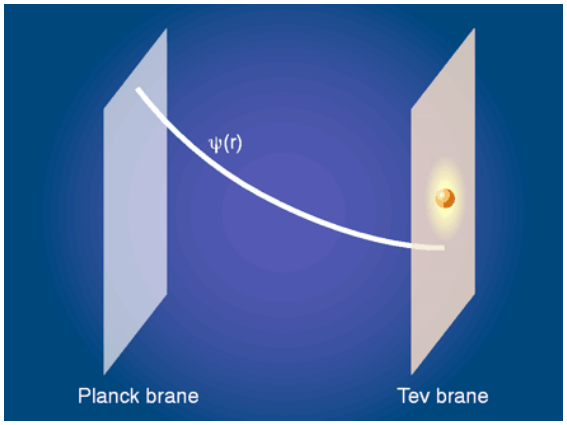
- Universe can have more than 4 dimensions of space-time
  - Extra dimensions must be "confined"



Scenario 1: Large Extra Dimension (LED)

- Extra dimensions can be big (~10μm)
- Gravity couples as $M_D^{-(1+n/2)}$ in 4+n D
- Gravity gets diluted in ED: $G_{eff} \sim M_{pl}^{-2}$
- Signature: 1-jet + $\not{E}_T$

M_D~ 1 TeV



Scenario 2: Randall-Sundrum (RS)

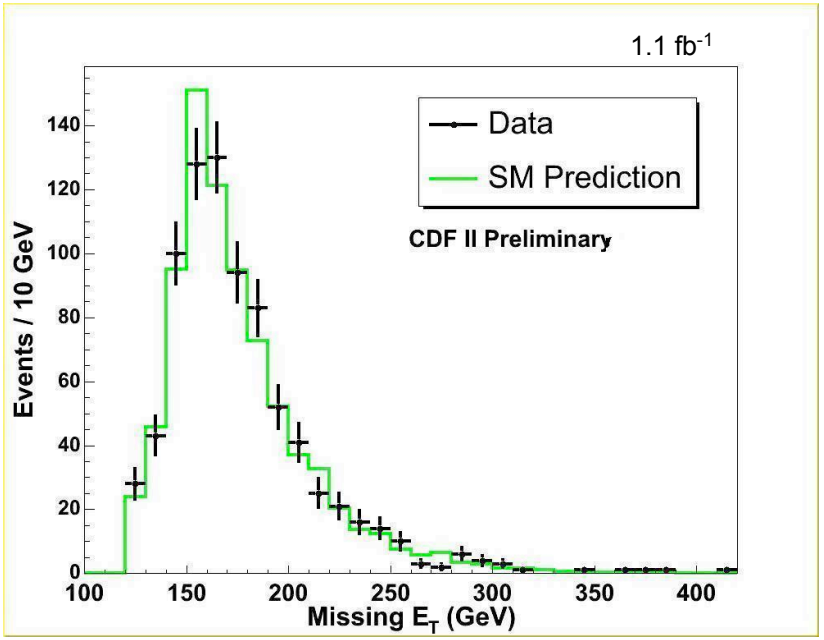
- Small ED with warp factor on metric
- Graviton 0^{th} mode localized on a different brane then SM interactions
- Expect graviton resonance of M_G~1 TeV

LED Search: Monojets

Parton level processses:
$qq \rightarrow gG$, $gq \rightarrow qG$, $gg \rightarrow gG$

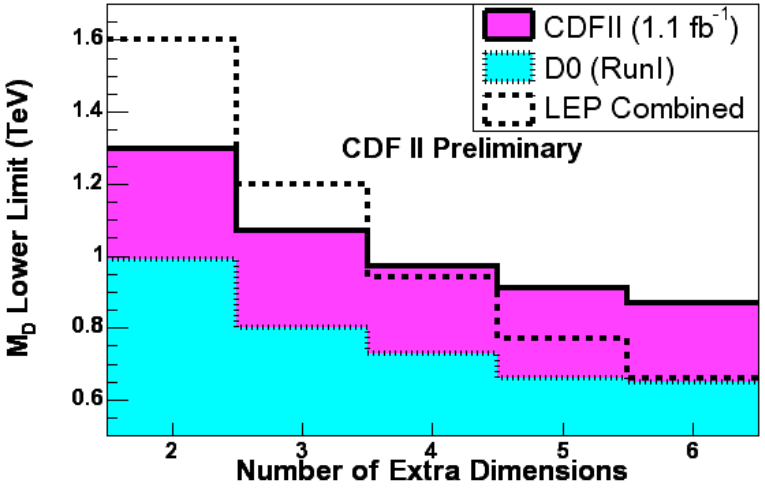
$\Rightarrow$ signature: 1-jet+$\not\!\!E_T$

- Model-independent search with data-driven backgrounds estimate
- cover a wide range of kinematic regime in (jet E_T, $\not\!\!E_T$)



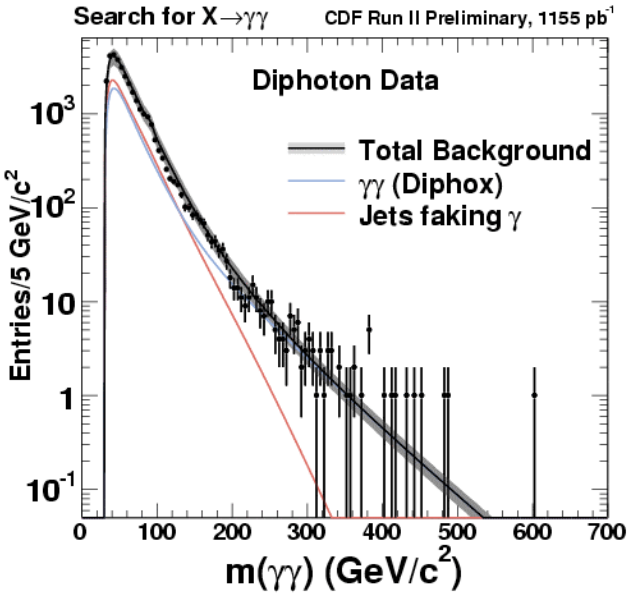
Bkg.	(80,80)	(150,120)	(180,150)
Total predicted	8663 ± 332	808 ± 62	277 ± 30
Data observed	8449	809	319

Limit on M_D

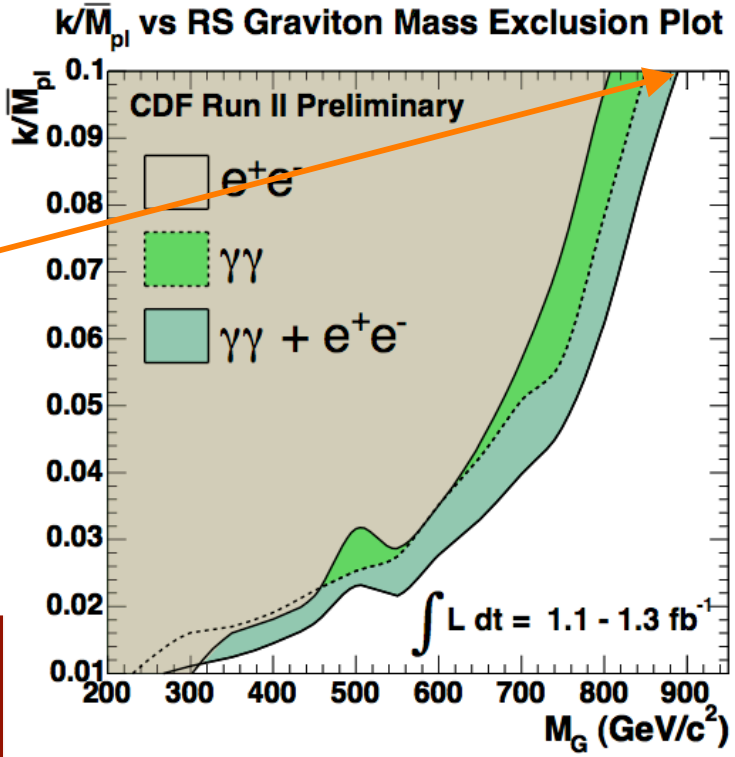


Randall-Sundrum Graviton

- Use diphoton final states.
- Can give sensitivity to fermiophobic resonance.
- Twice the G→ee branching ratio



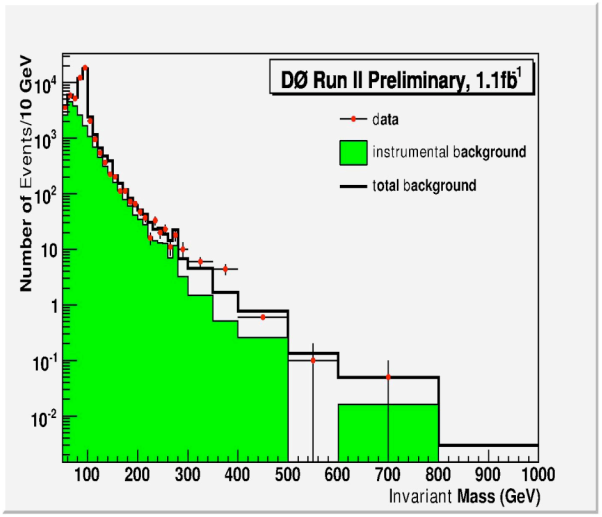
889 GeV

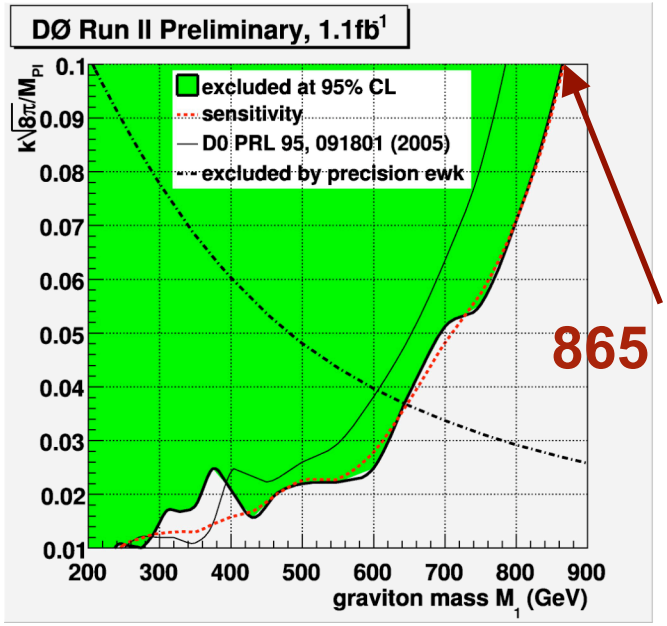


The previous di-electron resonance search can be combined with this γγ search to get better limits on M_G

Randall-Sundrum Graviton

- Inclusive $\gamma\gamma$ and ee analysis:
  $\Rightarrow$ no track requirement
- Drell-Yan, $\gamma\gamma$ and instrumental backgrounds are fitted to data in the invariant mass region [60,140] GeV.





Signature-based searches for deviations from SM

Signature-based searches

- Searches for strongly motivated and compelling models are often optimized in order to get a better sensitivity.

- However, new phenomena can take less understood form or may be hiding where we are not looking

  $\Rightarrow$ motivation for signature-based model-independent searches.

- Many of the previous searches are signature-based searches, looking at final states supported by strong theoretical motivations.

- The following searches rather cast a wider net for new phenomena with no intention of specific interpretations.

Global search: Vista…

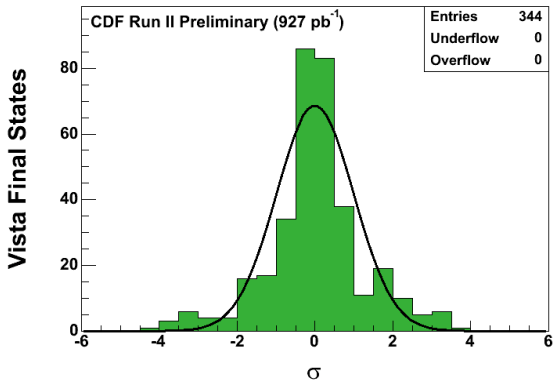
Vista is a model-independent framework which considers gross feature of data to obtain a panoramic view of the bulk of high-p_T data.

- The Vista algorithm:
  - Identify the different "objects" of each event:
    e, μ, τ, γ, jet, b-tagged jet, $\not\!\!E_T$
  - Partition data and MC events into exclusive final states according to their objects content.
  - Estimate the SM contribution to each of the different final states.
  - Develop "correction model" for known deficiency in simulations and cross section calculations.

Data are compared to SM predictions for 16486 kinematic distributions in 344 different final states!

Probability of observing the most discrepant excess = 8%

Need to account for trial factor

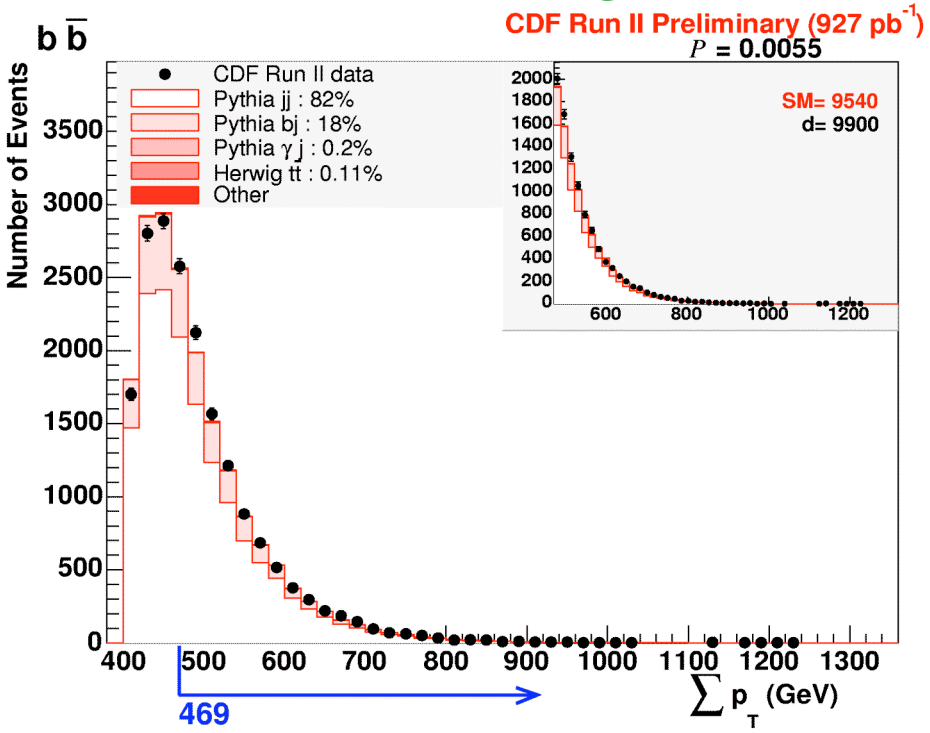


… and Sleuth

Sleuth is a quasi-model-independent framework for new physics searches, emphazing on high tail region of sum-p_T distributions.

- The Sleuth algorithm:
  - Form final states by merging some of the Vista final states to increase statistical significance;
  - Find the most interesting region in each high sum-p_T tails and compute the interestingness of the corresponding final state;
  - Perform trial factor calculations

Sleuth most interesting final state



The probability of observing a final state more interesting in a hypothetical similar CDF experiment is 46%

Conclusion

- The Tevatron currently offers a unique opportunity to search for new phenomena at the energy frontier.
  - A wide range of possible extension of the SM have been covered, including effects from:
    - Unification theory, compositeness, quark-lepton symmetry spectrum, new family
- Studies at the Tevatron are intimately related to fundamental questions of cosmology:
  - Dark Matter
  - Structure of space-time (extra dimensions)
- So far, the SM has been able to withstand the tests of the Tevatron.

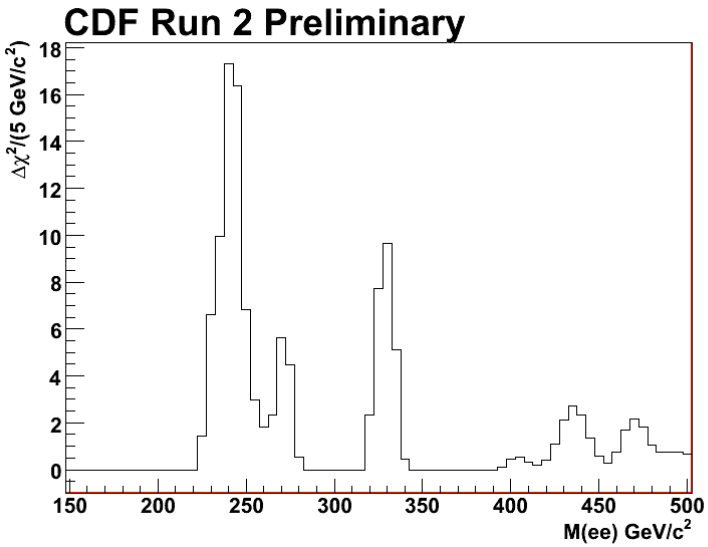
But…

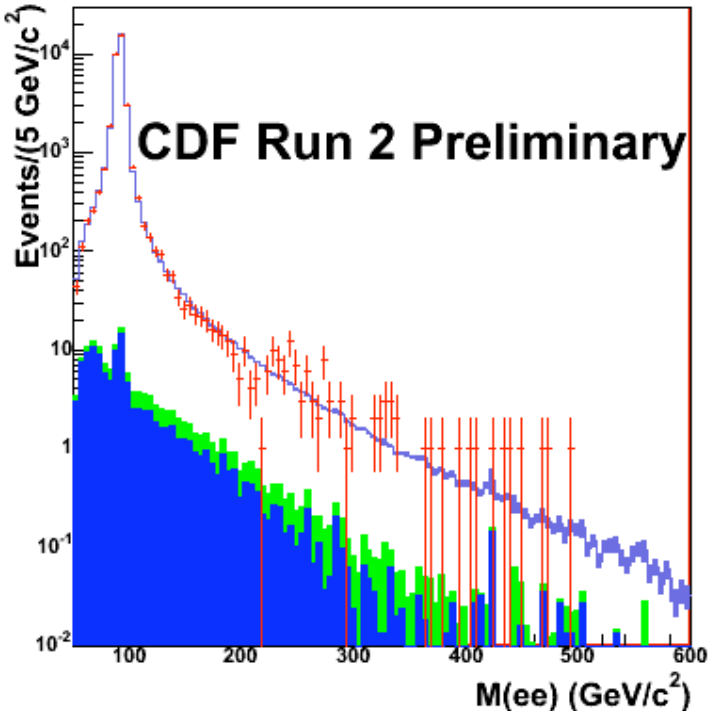
With more than 1fb^{-1} not yet analyzed and even more data to come, the SM may still fall…

BACK-UP SLIDES

Another dielectron search

- The most significant excess occurs for a dielectron mass of about 240 GeV
- The probability of observing an excess as significant or more is 1.7%.
- The two dielectron analyses are statistically consistent with each other at the 5% level.





Plan:

Increased data by a factor of ~1.5, do the same procedure and report.

CDF-Trileptons (II)

TRILEPTON ANALYSES

	$ee(CEM)+\ell$	$ee(PLUG)+\ell$	$e\mu+\ell$	$\mu\mu+\ell$ (high-p_T)	$\mu e(CEM)+\ell$	$\mu e(PLUG)+\ell$	$ee+track$	$\mu\mu+\ell$ (low-p_T)
Luminosity	1034 pb^{-1}	954 pb^{-1}	1034 pb^{-1}	745 pb^{-1}	745 pb^{-1}	680 pb^{-1}	1013 pb^{-1}	976 pb^{-1}
Expected number of signal events	1.15± 0.19	0.32± 0.07	0.84± 0.14	1.60± 0.22	0.83± 0.12	0.20± 0.03	1.98± 0.13	0.57± 0.11
Expected number of SM background events	0.44± 0.08	0.34± 0.10	0.28± 0.09	0.64± 0.18	0.42± 0.08	0.36± 0.07	0.97± 0.28	0.42± 0.12
Number of observed events	0	0	0	1	0	0	3	1

LS-DILEPTON ANALYSES

	ee LS	$e_{si}e$ LS	$e_{si}e_{si}$ LS	$e_{si}\mu$ LS	$e\mu$ LS	$\mu\mu$ LS
Luminosity	993 pb^{-1}	993 pb^{-1}	993 pb^{-1}	971 pb^{-1}	971 pb^{-1}	1087 pb^{-1}
Expected number of signal events	0.040± 0.004	0.070± 0.007	0.510± 0.051	1.540± 0.154	0.200± 0.020	0.950± 0.095
Expected number of SM background events	0.10± 0.10	1.50± 0.30	1.30± 0.30	1.70± 0.20	2.30± 0.50	0.90± 0.10
Number of observed events	1	2	1	4	4	1

Inclusive search: ℓ+γ+X

- In run I: 10^{-6} ee$\gamma\gamma$+$\not\!\!E_T$ were expected, 1 was observed!
- They searched for "cousins" in the inclusive signature $\ell\gamma$+X: 7.6±0.7 events where expected, 16 where found (2.7σ)

- Repeat of the analysis with 929pb^{-1} of data

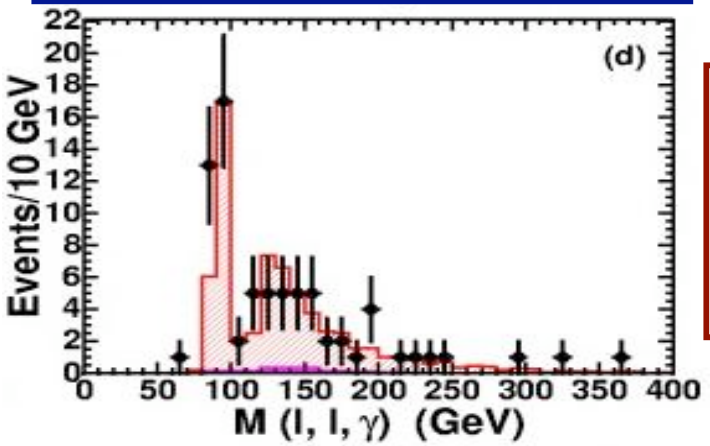
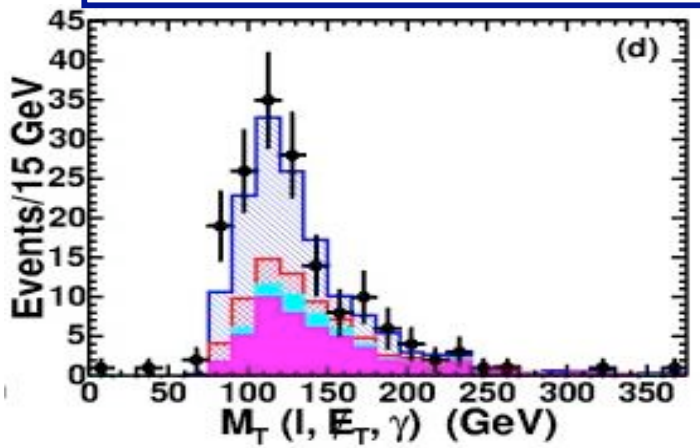
Nothing: control sample

γ: Expected: 0.62±0.15 Observed: 0

X

ℓ: Expected: 65.1±7.7 Observed: 74

$\not\!\!E_T$: Expected: 65.1±7.7 Observed: 74



The Run I excess is gone!