Search for New Physics at the Tevatron

Simona Rolli
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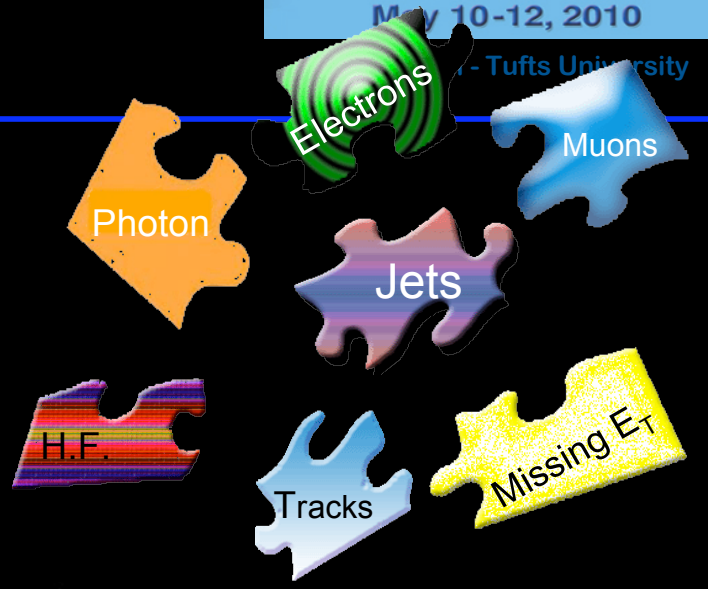
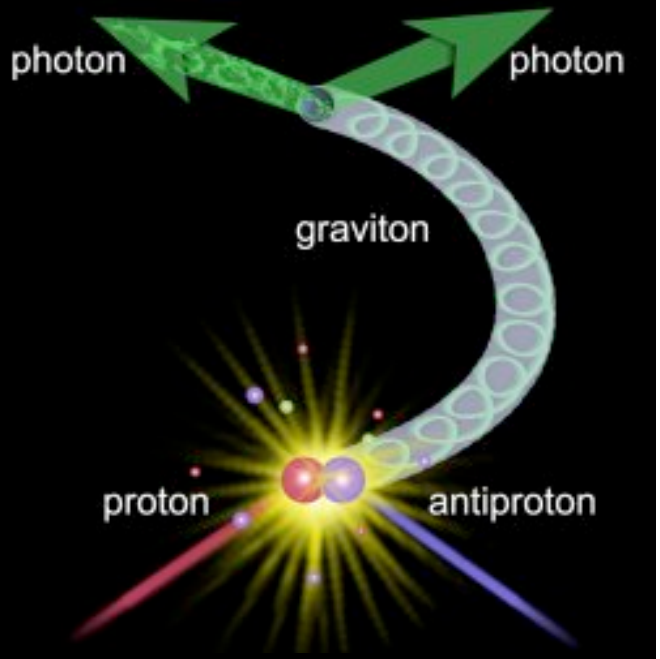
(on behalf of the CDF and D0 Collaborations)

Outline of the talk

PHENO 2010 SYMPOSIUM
University of Wisconsin-Madison
May 10-12, 2010
- Tufts University

- TeVatron status
- Signature-based searches
  - Dilepton/diphotons
  - Dibosons resonances
  - Complex final states (MET, jets, h.f.)
    - Leptoquarks
- Search for SUSY
- Final remarks and conclusions

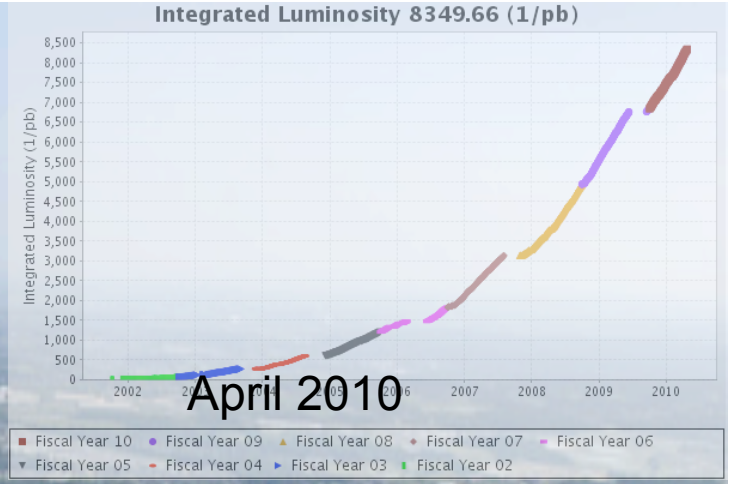




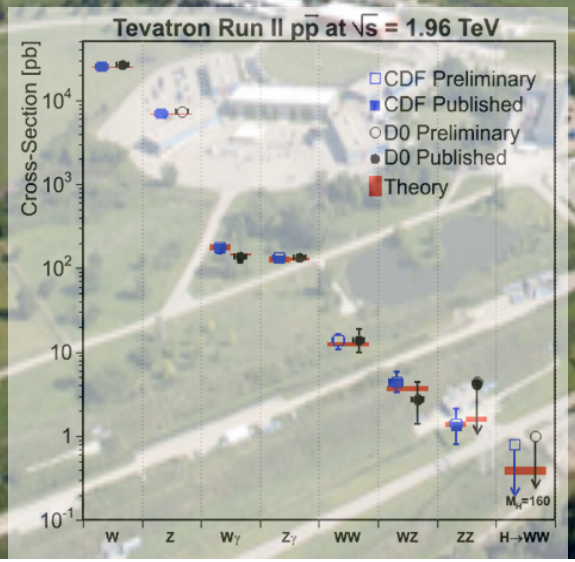
Tevatron Status

The TeVatron is doing very well!

- Data are continuously recorded with very high efficiency (85-90%)
- The machine and the detectors (CDF and D0) are performing very well
  - Both experiments have collected already more than 6 fb^{-1} on tape



April 2010



Today up to 5.4fb^{-1}

Measurements are becoming very precise
- Top quark mass known with precision < 2%

New analyses are now looking for the needle in the hay stack
- low cross section phenomena

Signatures and Physics Objects

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Many processes: several signatures

- Leptons-only final states
  - e/μ identification well understood
  - τ id a little more complex
  - Straightforward and highly efficient approach to search for anomalies
- ... + Missing Energy and Photons
  - Wealth of models and exotic processes
  - Need accurate understanding of detector effects
- ... + Jets and heavy flavors
  - More complex signatures
  - Maintaining high $S/\sqrt{B}$

When a signature-based approach is advocated, final results are generally interpreted in terms of specific models (typical case dilepton searches, MET + jets)

When the analysis is model driven and results are presented as testing of a specific model, there is always a check on control regions, defined in terms of the process signature (blind analyses)

The two approaches are usually pursued in a balanced and complementary way

Signature-based searches

Open searches, final states are analyzed for anomalies when compared with the SM

- Mass bumps searches
- Multi-objects final state (low background)
- Global Searches

Identification efficiency, detector effects and systematic uncertainties need to be very well understood.

The analysis might not be optimized for the latest theory model available but it might be general enough to exclude several other models.

Dilepton final states

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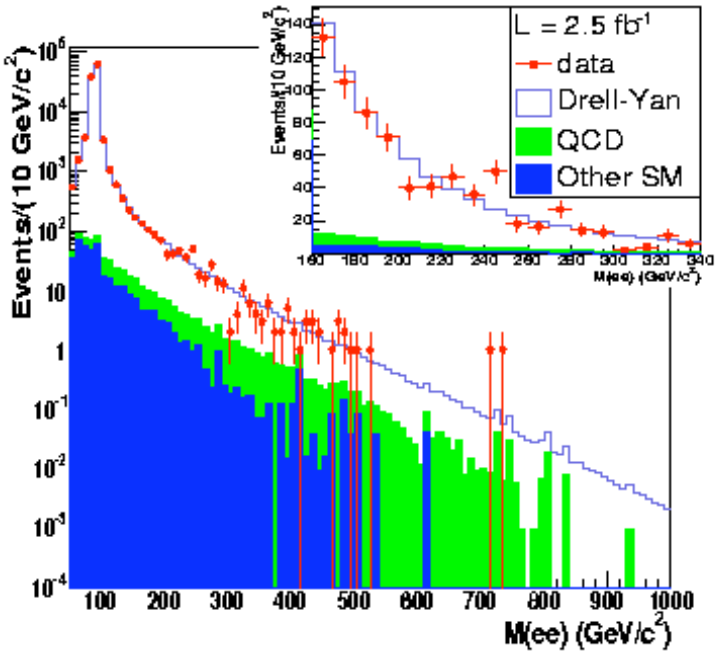
Old-fashioned mass bump hunt..

-Z production and decay into ee/μμ precisely measured
-Lepton ID/Reco and Trigger efficiencies high and very well understood
-Background low and easily determined (QCD fakes)
-Clean events

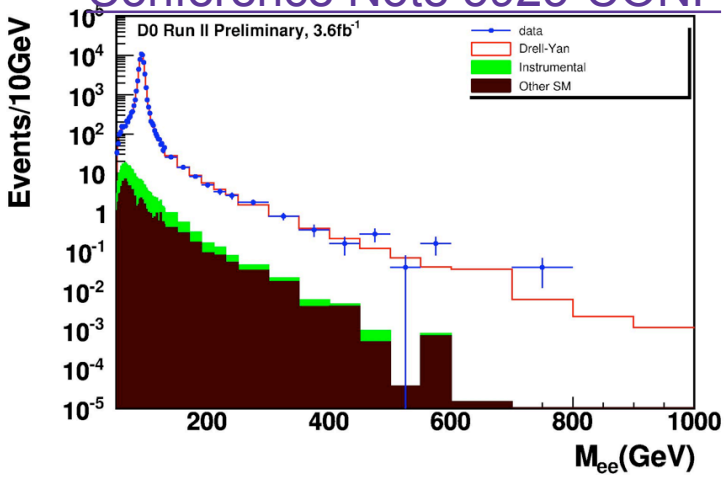
CDF: 2.5fb^{-1}
D0: 3.6fb^{-1}

PRL 102, 031801 (2009)



The most significant region of excess for an e^+e^- invariant mass window of 240 GeV/c^2 (CDF)
2.5 standard deviations above the SM prediction
D0 does not see any deviation from SM in ee channel

Conference Note 5923-CONF



Testing different models

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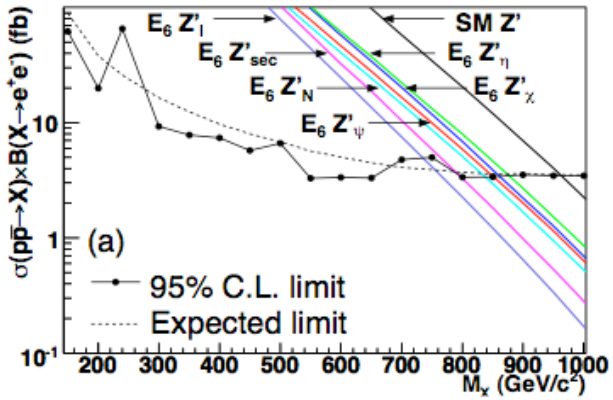
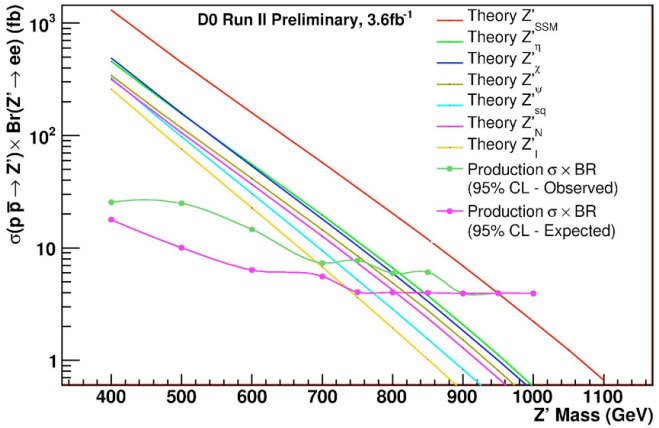
Once the data spectrum is well understood in terms of SM background, from MC, the acceptances for resonant states for different spin particles are derived (Z', RS Graviton) and the expected number of BSM events is calculated.
In the absence of an excess of data, 95% CL limits on production cross-sections and mass of the particles are set.

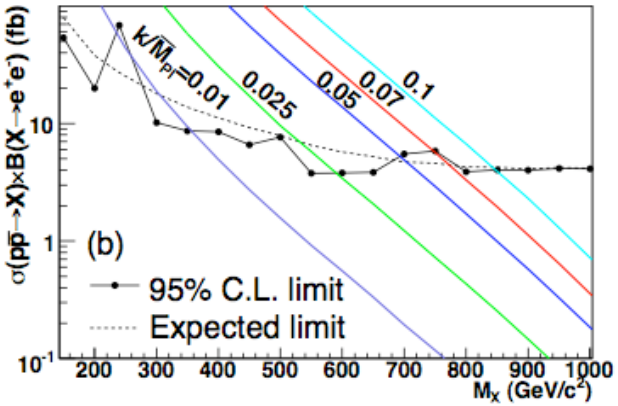


CDF 2.5fb^{-1}

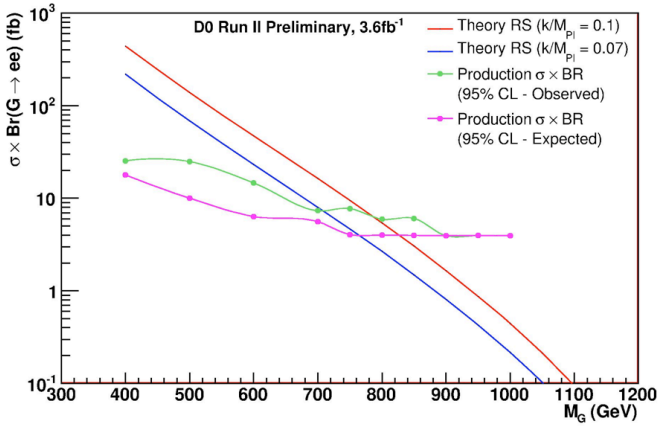
$m_{Z'} > 966$ GeV (SM couplings)
$m_{RSG} > 850$ GeV ($k/M_{Pl} = 0.1$)



D0:3.6fb^{-1}



$m_{Z'} > 950$ GeV (SM couplings)
$m_{RSG} > 786$ GeV ($k/M_{Pl} = 0.1$)



Dimuons final state

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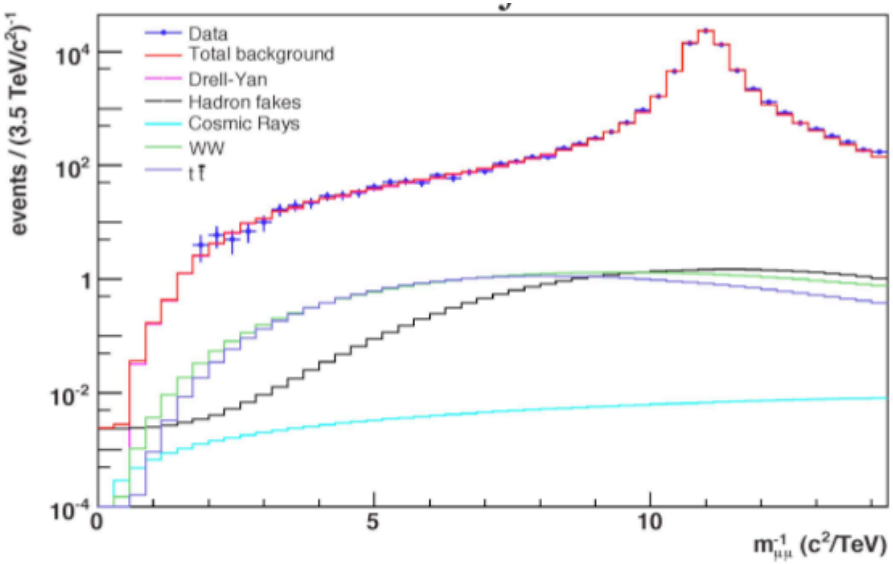
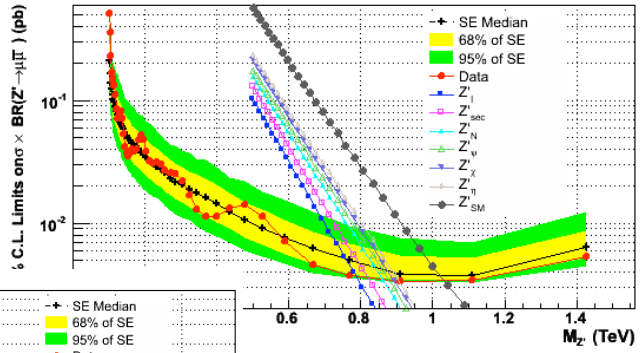
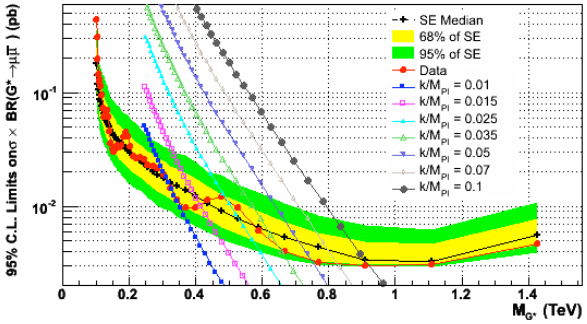
CDF has looked for bumps in the X→μμ final state: no excess is observed.



CDF:2.3fb^{-1}



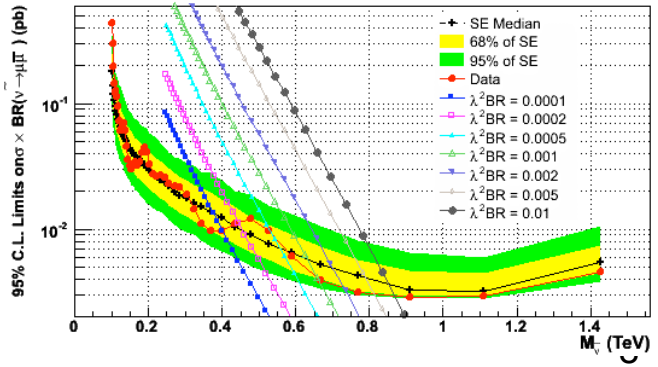


Limits are derived for several scenarios

Sneutrino: up to 866 GeV/c^2 (λ^2BR = 0.01),

Z': up to 1030 GeV/c^2 (SSM Z')

RS graviton: up to 921 GeV/c^2 (K/M$_{PL}$ = 0.1)



PRL 102, 091805 (2009)

Diphotons final states

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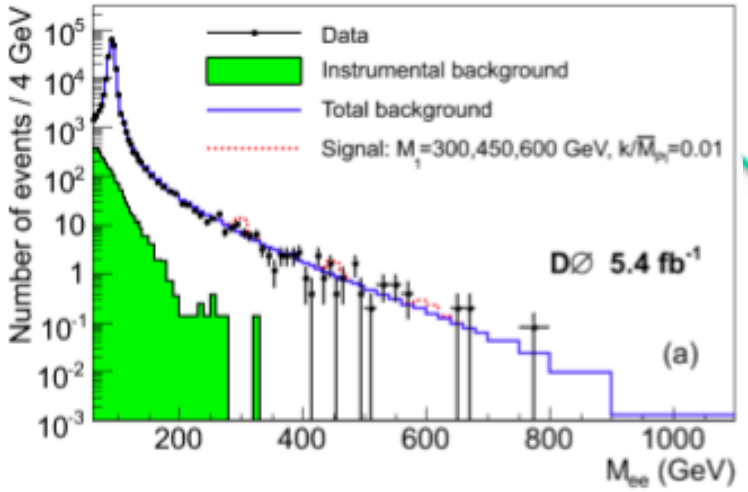
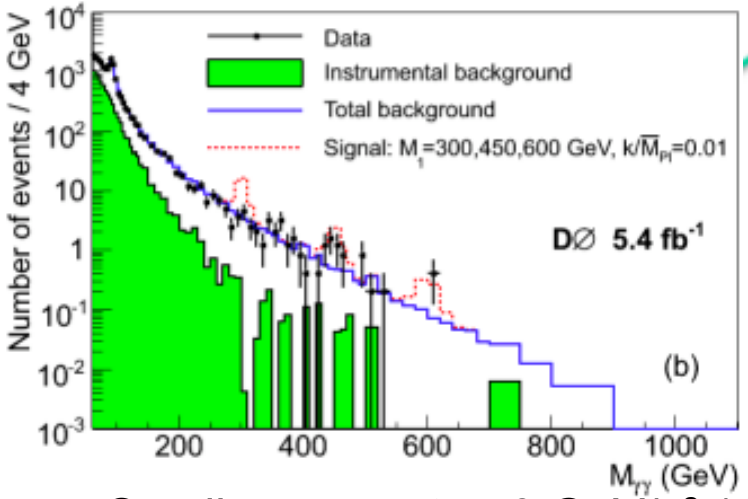
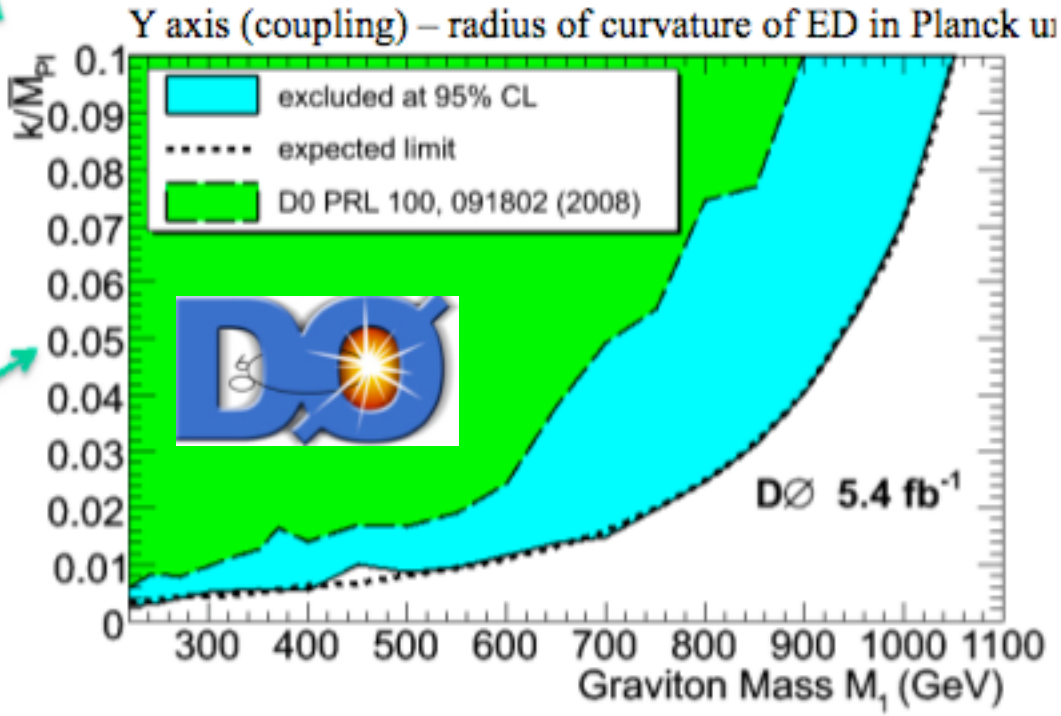




Graviton KK excitation mass limits:
560 - 1040 GeV for 0.01 ≤ k/MPl ≤ 0.1



arXiv.org:1004.1826

Small excess at 450 GeV/c^2 (diphoton)
2.3σ significance - CDF does not observes it..

Diphotons

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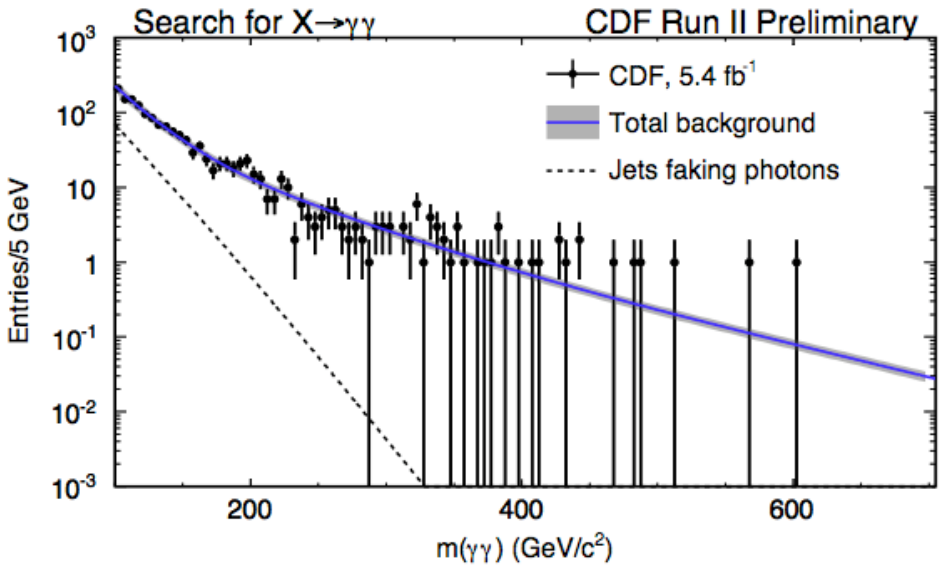
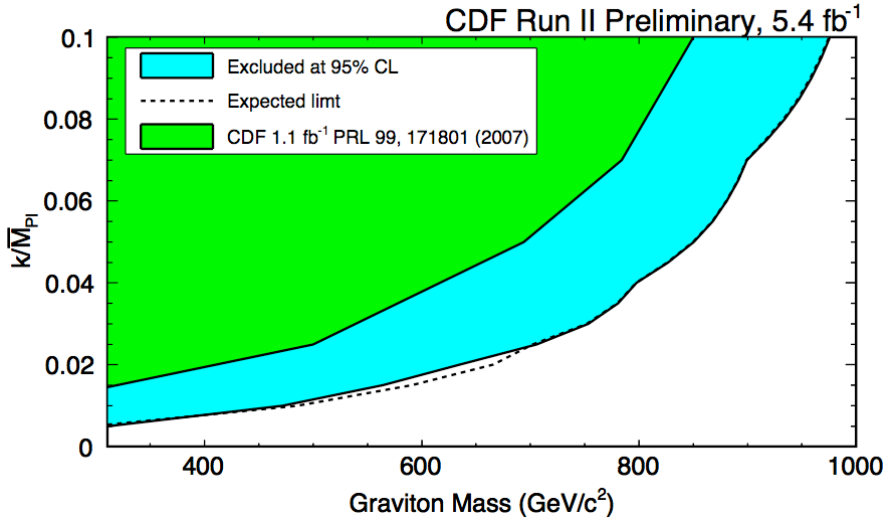


CDF:5.4fb^{-1}

New!

More from Tingjun Yang
In parallel session !



Dijet Mass Spectrum

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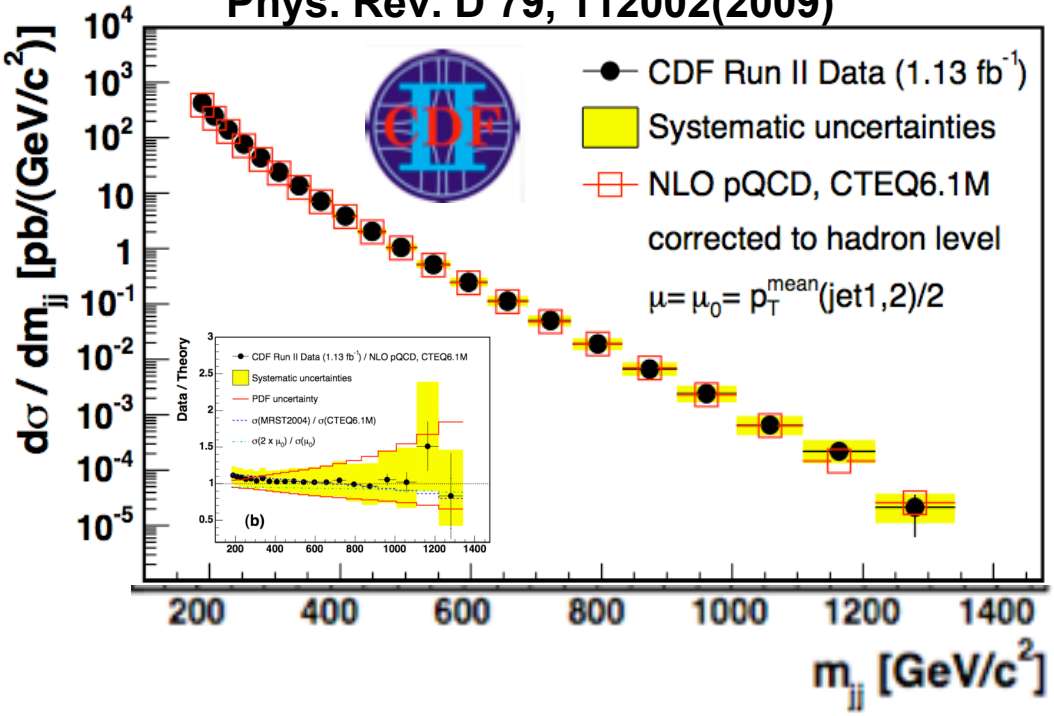
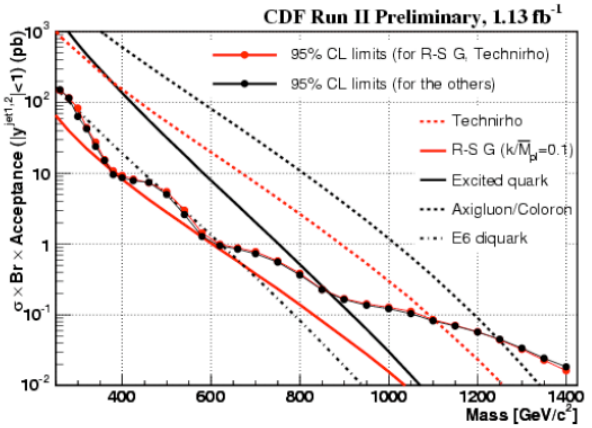
Old fashion mass bump hunt…

- Choose events with two high-p_T jets with rapidity less than 1.0. Look for an excess in the dijet mass spectrum for masses above 180 GeV
- Possible signals include excited quarks, W', Z', and Randall-Sundrum gravitons
- Find functional form of of dijet spectrum in pythia and herwig, fit to data. Look for "bumps" in the data minus fit plot

Phys. Rev. D 79, 112002(2009)



- No significant resonant structure is observed, so limits are set on various models
- Excludes (at 95% CL) excited quarks from 260-870 GeV, W' from 280-840 GeV, and Z' from 320-740 GeV



D0 has also a new result out (arxiv: 1002.4594)

Dijets Angular Distribution

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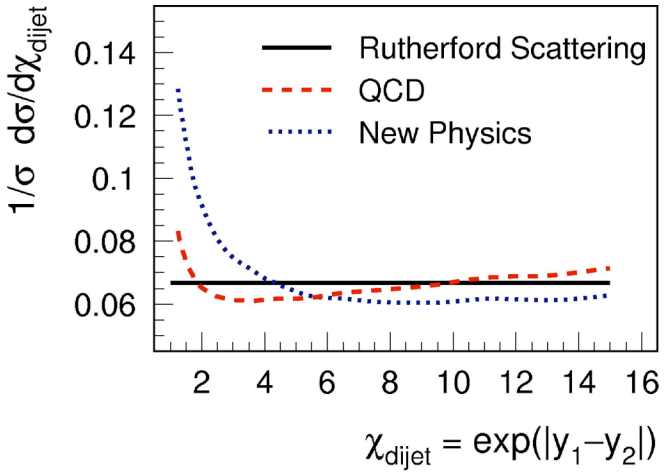
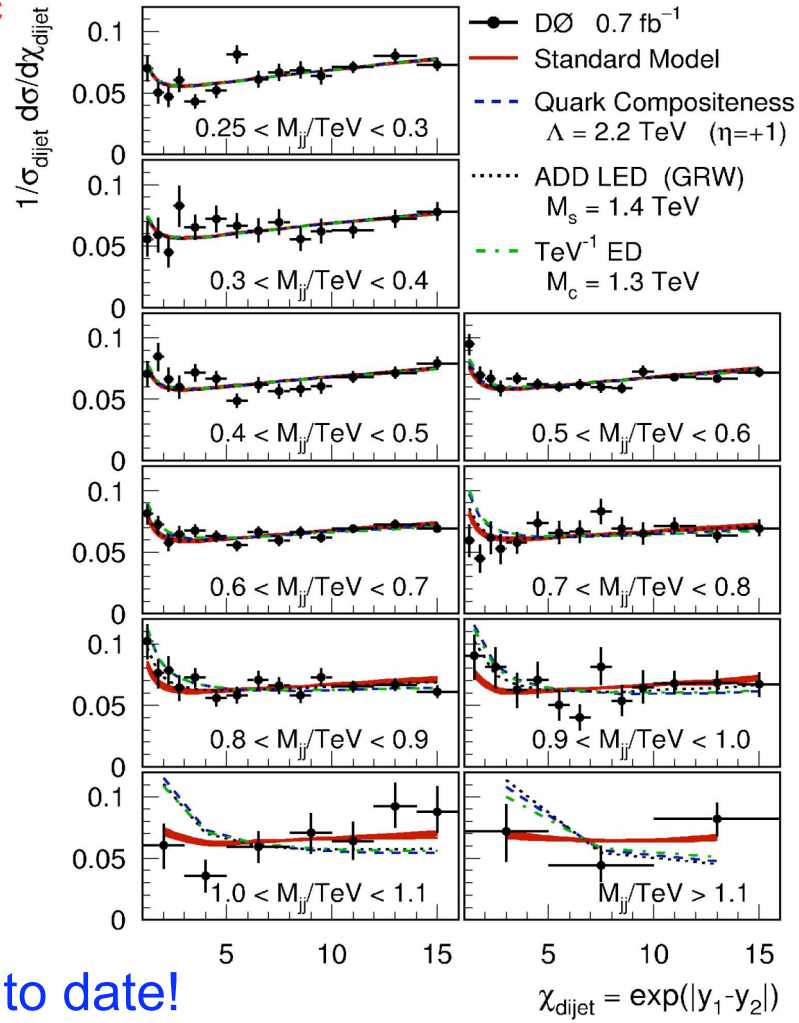
Dijet angular distributions is measured in bins of dijet mass:

- First differential cross section measurement at partonic energies >1 TeV!
- Small experimental and theoretical uncertainties.
- Sensitive to New Physics (95% CL limits)



Consistent with NLO pQCD

Phys. Rev. Lett. **103**, 191803 (2009)



Limits on Compositeness & LED

- Quark Compositeness Λ > 2.9TeV
- ADD LED (GRW) Ms > 1.6 TeV
- TeV-1 ED Mc > 1.6 TeV

Most stringent limits to date!

Diboson resonance searches: $Z\gamma$

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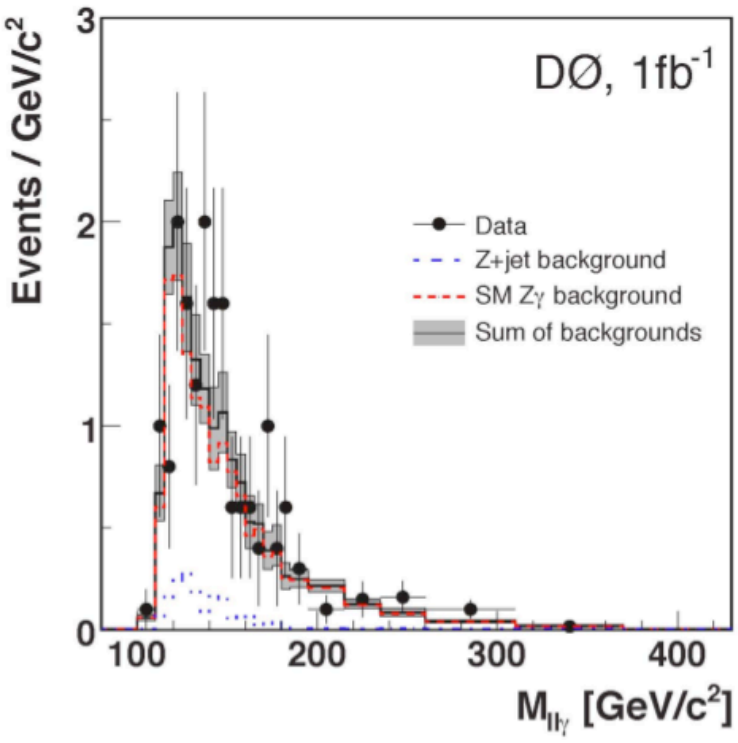
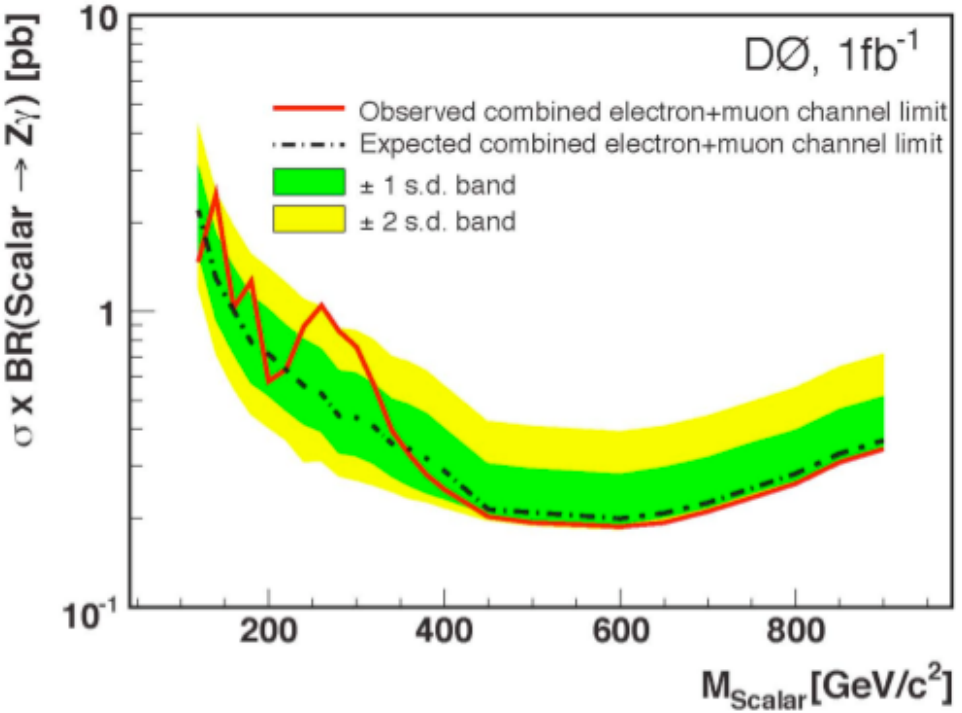
DØ ($X \rightarrow Z\gamma \rightarrow ee/\mu\mu\ \gamma$): no significant excess

Scalar [Vector] X

$\sigma \cdot Br(X \rightarrow Z\gamma) < 0.19[0.20]$ pb (M_X = 600 GeV) $< 2.5[3.1]$ pb (M_X = 140 GeV)





Phys. Lett. B 671 , 349 (2009)

Diboson resonance searches: WW/WZ

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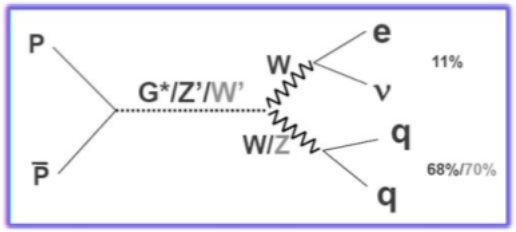
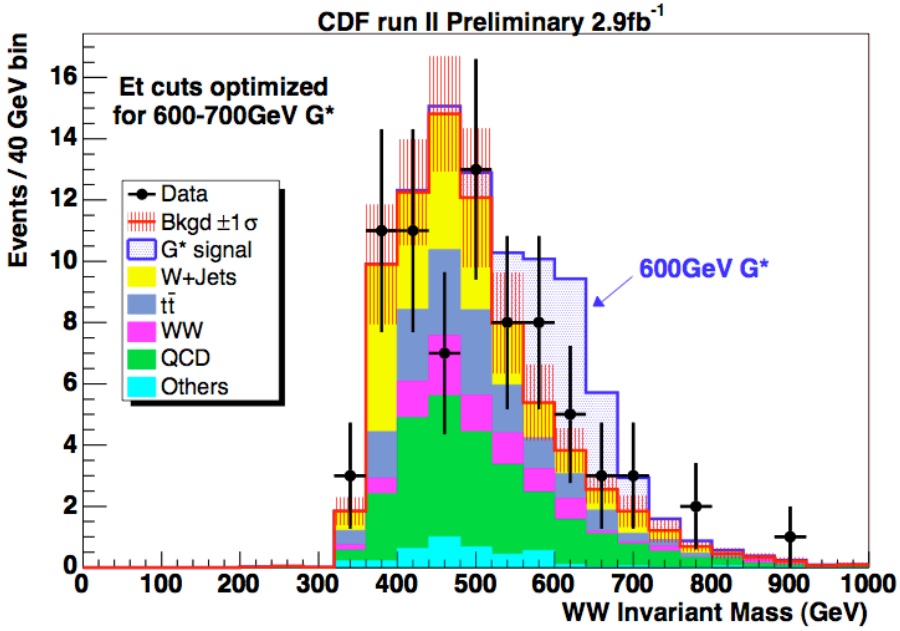
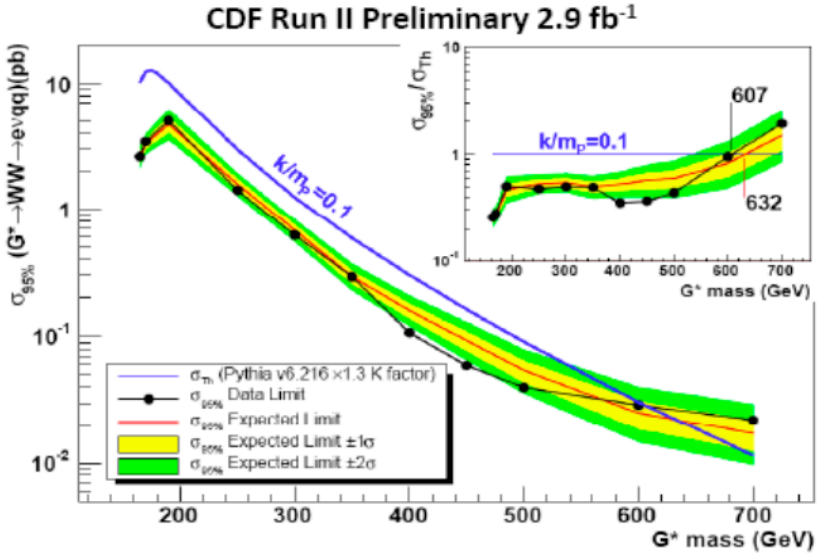
CDF (X→WW/WZ→evjj): no significant excess
⇒ set limits on W′, Z′, RS graviton



$M_{W'} \notin (284,515)$ GeV $M_{Z'} \notin (247,545)$ GeV $M_G > 607$ GeV ($k/M_p = 0.1$)





CDF PUB note 9730

Diboson resonances:WZ

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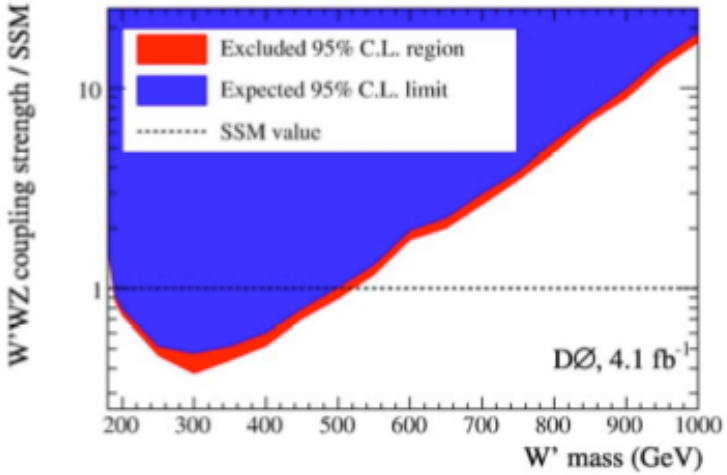
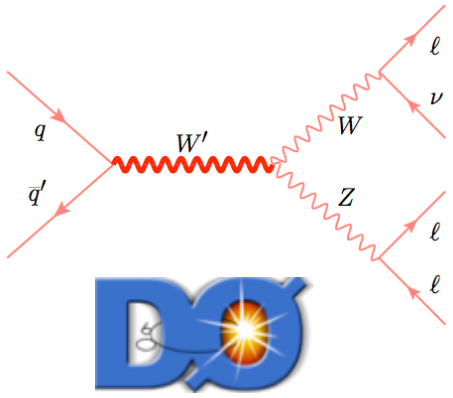
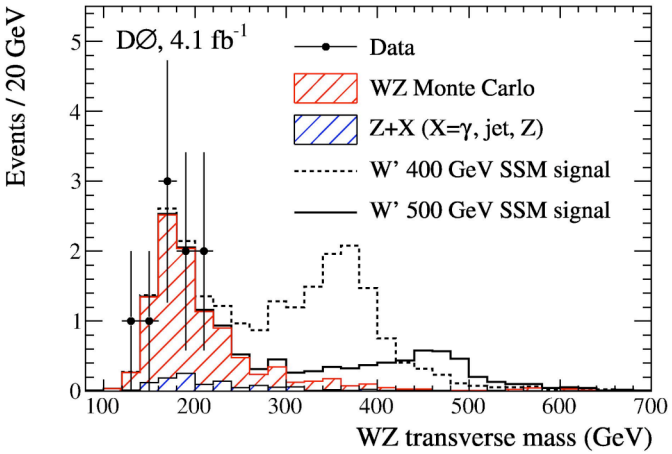
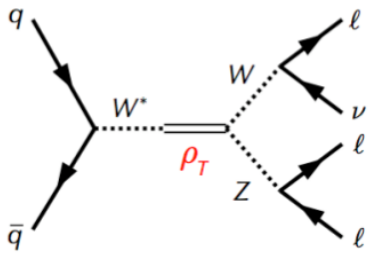
W' → WZ → lνll



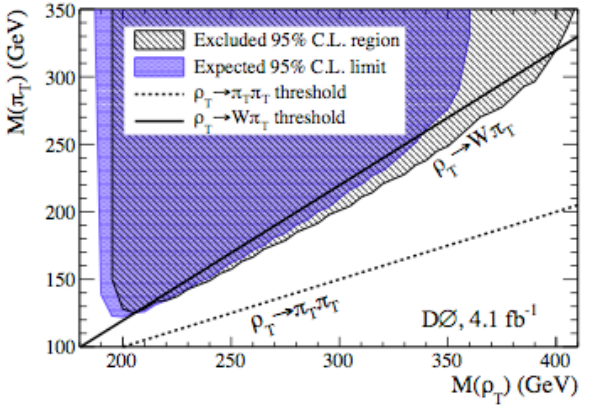




W' excluded between 188 and 502 GeV/c^2, assuming SM coupling scaling with mass (Sequential SM)



Technicolor scenario with $m(\rho_T) < m(\pi_T) + M(W)$
Excluded mass 208-408 GeV/c^2 @ 95% CL



Phys. Rev. Lett. **104**, 061801 (2010)

Diboson resonance searches: ZZ

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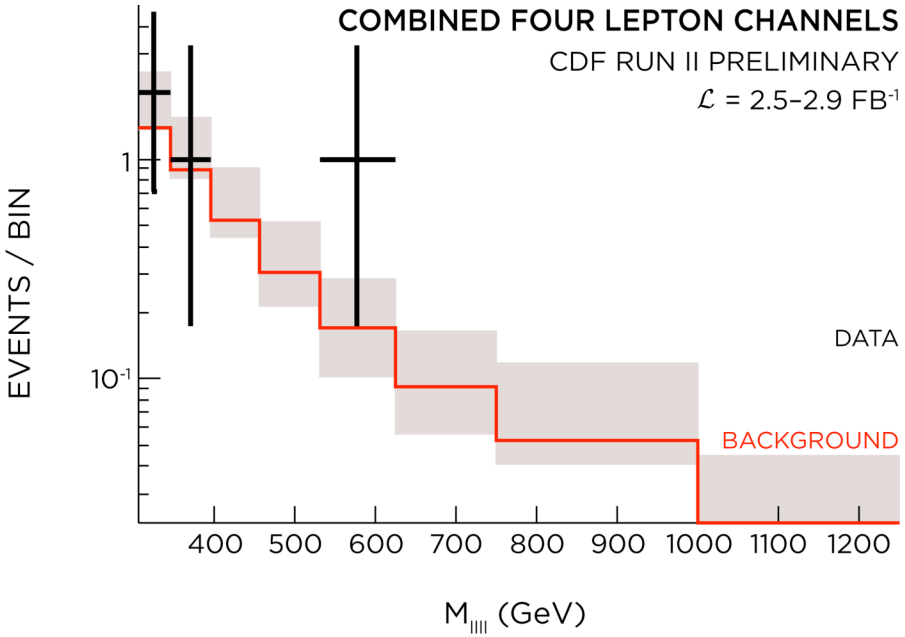
CDF ($X \to ZZ \to llll, lljj$; $l = e, \mu$):

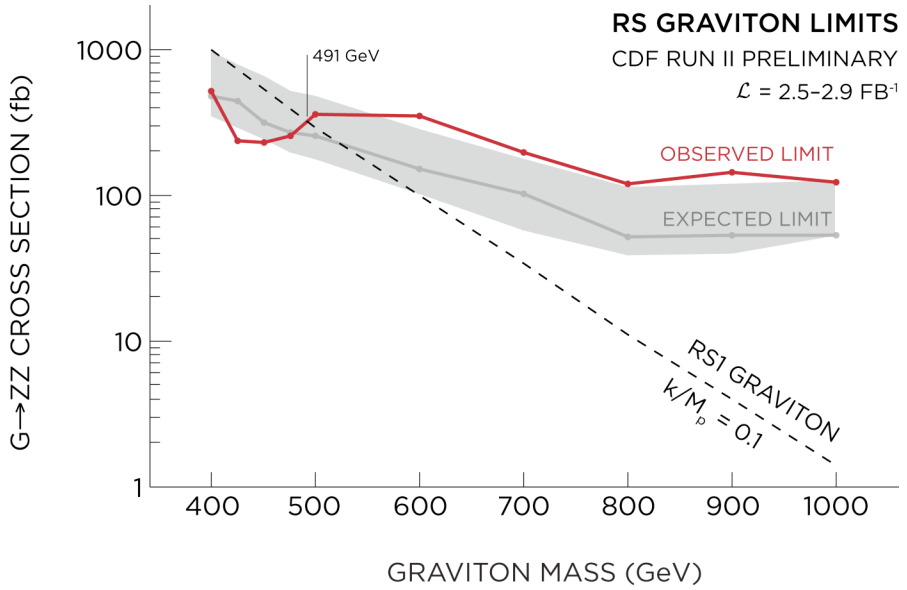
newly-improved forward track reconstruction

more efficient muon identification

no significant excess

10% increase





RS (spin 2) G→ZZ

M>491 GeV (2.5–2.9 fb^{-1}, $k/M_p = 0.1$)

CDF PUB note 9640

Jets+MET final state:Leptoquarks

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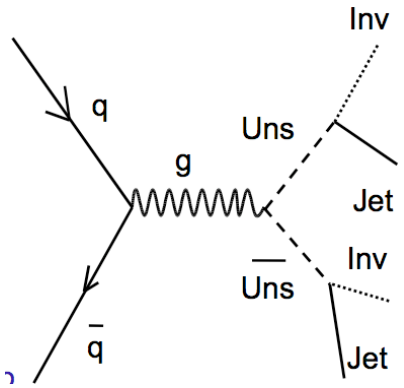
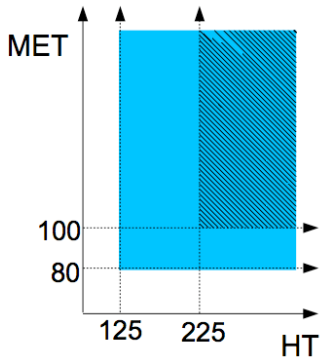


The analysis is a counting experiment examining two different kinematic regions (each region being more sensitive to different models) defined by HT and MET cuts.

Cuts are not optimized for a specific model.

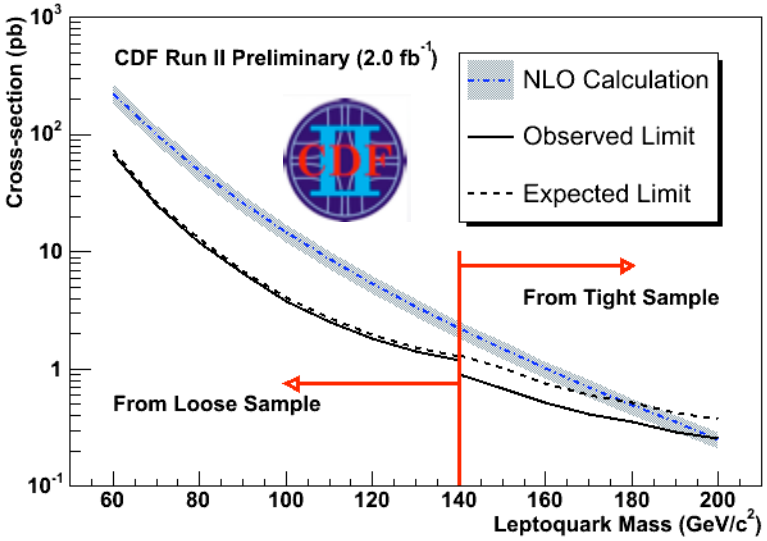


Main backgrounds:

- $Z \rightarrow \nu\nu$ + jets (irreducible background)
- $W \rightarrow l\nu$ + jets (with charged lepton lost)
- Residual QCD and non-collision backgrounds.

arXiv:0912.4691

Data driven prediction



Background	Number of Events
Z -> ν ν	888 +/- 54
W -> τ ν	669 +/- 42
W -> μ ν	399 +/- 25
W -> e ν	256 +/- 16
Z -> l l	29 +/- 4
Top Production	74 +/- 9
Diboson Production	90 +/- 7
QCD	49 +/- 30
Gamma plus Jet	75 +/- 11
Non-Collision	4 +/- 4
Total Predicted	2533 +/- 151
Data Observed	2506

Background	Number of Events
Z -> ν ν	86.4 +/- 12.7
W -> τ ν	50.6 +/- 8.0
W -> μ ν	32.9 +/- 5.2
W -> e ν	14.0 +/- 2.2
Z -> l l	1.7 +/- 0.2
Top Production	10.8 +/- 1.7
Diboson Production	4.9 +/- 0.4
QCD	9.0 +/- 9.0
Gamma plus Jet	4.8 +/- 1.1
Non-Collision	1.0 +/- 1.0
Total Predicted	216.1 +/- 29.8
Data Observed	186

Other Leptoquarks Results

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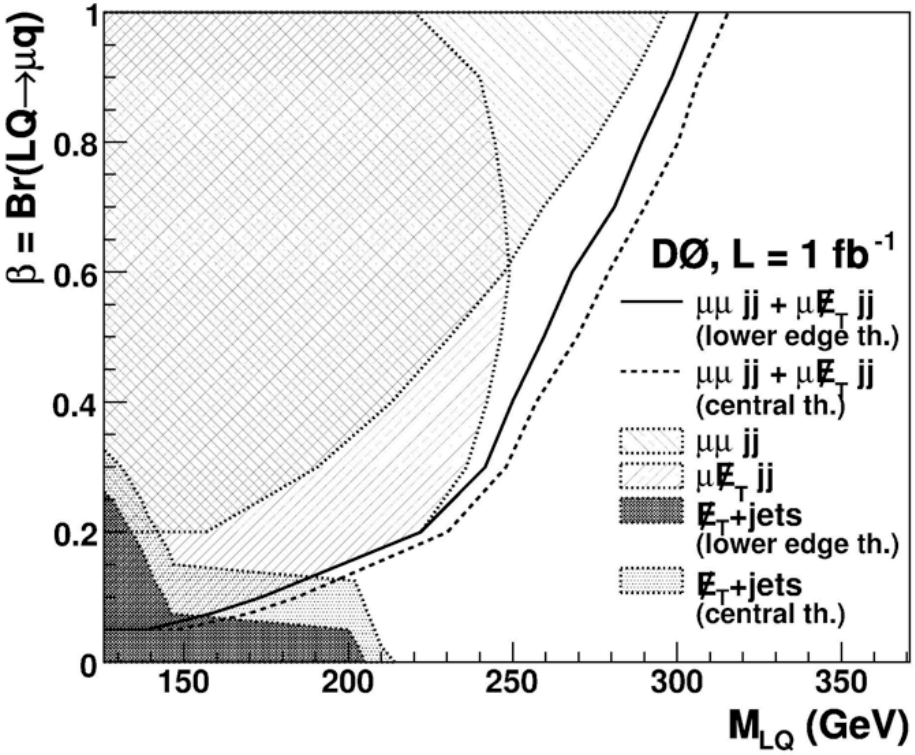
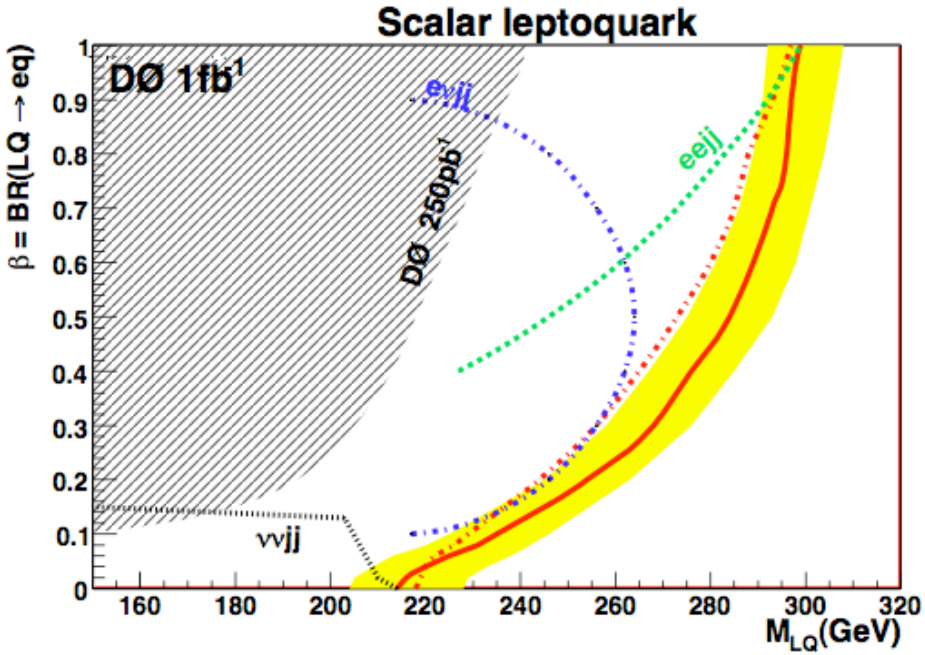
1st Generation	2nd Generation
LQ $\overline{LQ}\rightarrow e^-e^+ q\bar{q}$	LQ $\overline{LQ}\rightarrow \mu^+\mu^- q\bar{q}$
LQ $\overline{LQ}\rightarrow e^{\pm}\nu_e q_i q_j$	LQ $\overline{LQ}\rightarrow \mu^{\pm}\nu_\mu q_i q_j$
LQ $\overline{LQ}\rightarrow \nu_e\nu_e q\bar{q}$	LQ $\overline{LQ}\rightarrow \nu_\mu\nu_\mu q\bar{q}$

Phys. Lett. B **671**, 224 (2009)





Phys. Lett. B **681**, 224 (2009)

Leptoquarks in MET + b-jets

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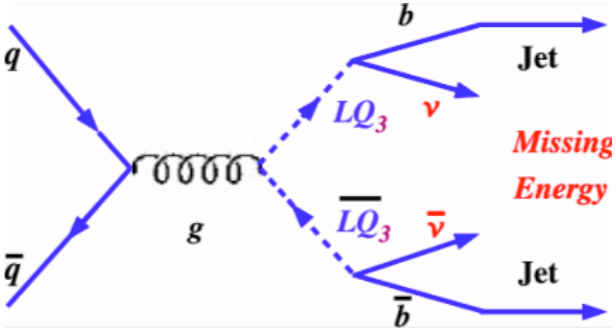
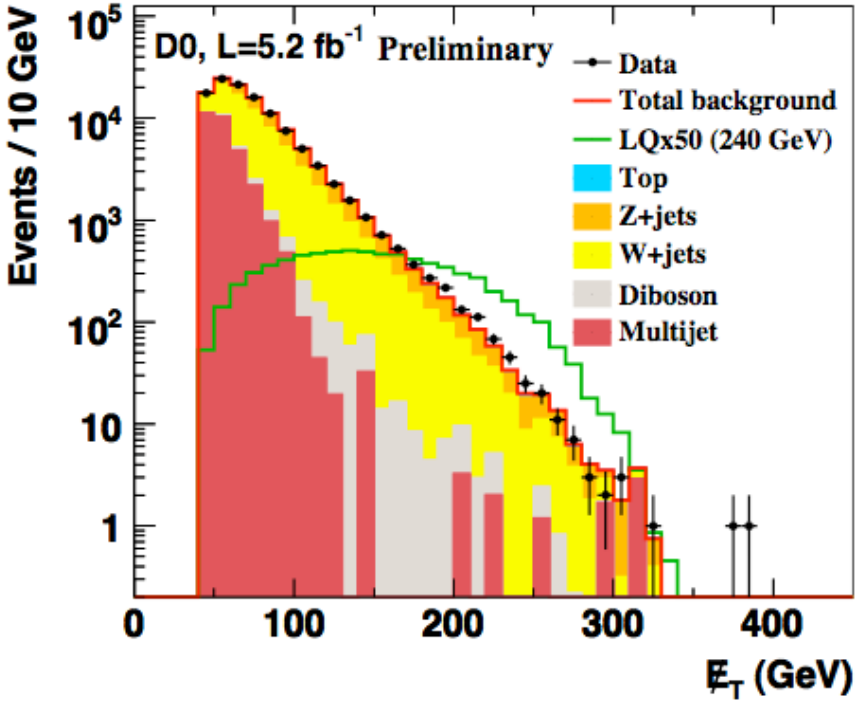
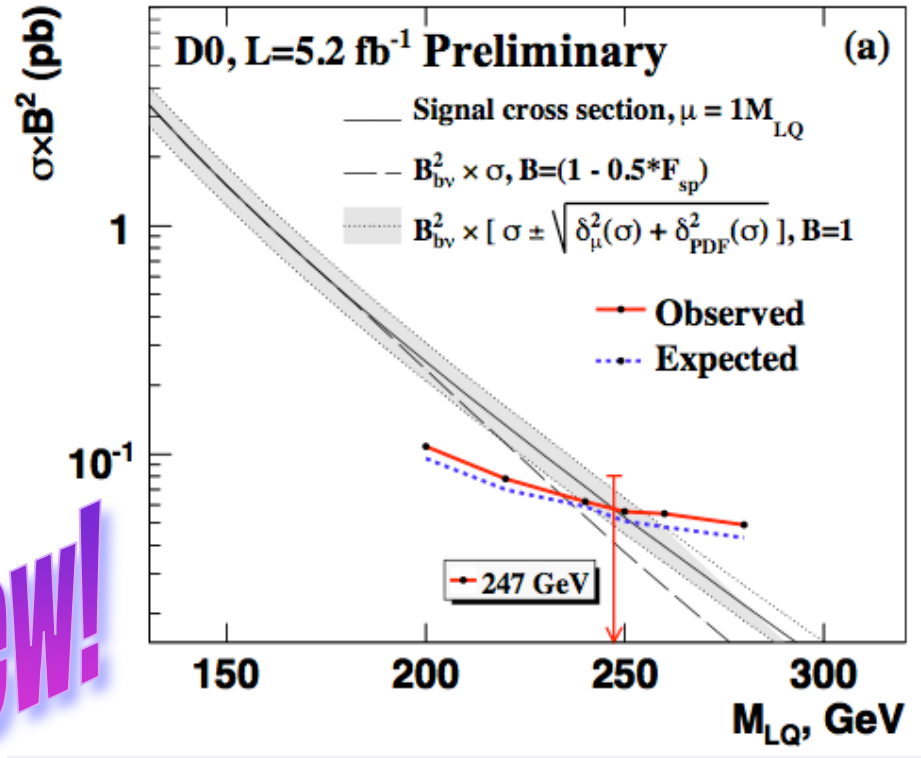




New!



Conference Note 5931-CONF

Search for Supersymmetry

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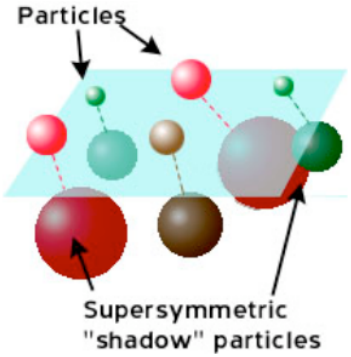
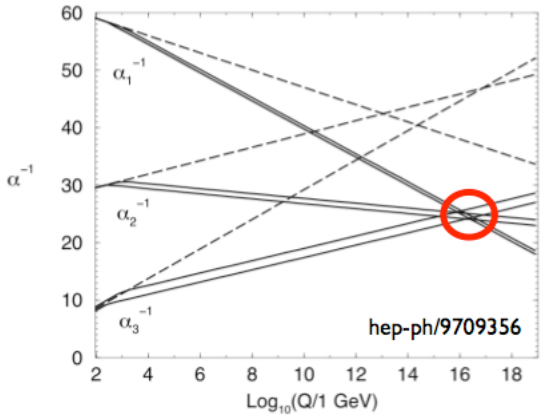
- SUSY is a very popular extension of the SM…
  - It solves several open issues and provide an elegant description of bosons and fermions





•On the other hand…
  –Full set of new particles with constraints on their masses (TeV scale)

•Various signatures with access to a wide phase space
  –Multileptons final states
  –Jets and MET
  –MET and γ
  –Heavy flavors

Names	spin	R_P	Gauge eigenstates	Mass eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	-1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$ $\tilde{c}_L\ \tilde{c}_R\ \tilde{s}_L\ \tilde{s}_R$ $\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	same same $\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	-1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$ $\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$ $\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	same same $\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	-1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\chi_1^0\ \chi_2^0\ \chi_3^0\ \chi_4^0$
charginos	1/2	-1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\chi_1^\pm\ \chi_2^\pm$
gluino	1/2	-1	$\tilde{g}$	same
goldstino	1/2	-1	$\tilde{G}$	same

MSSM particle spectrum

SUSY in Trileptons

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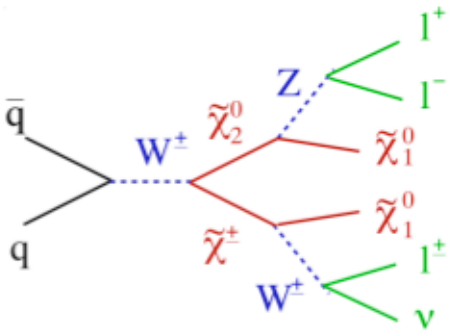
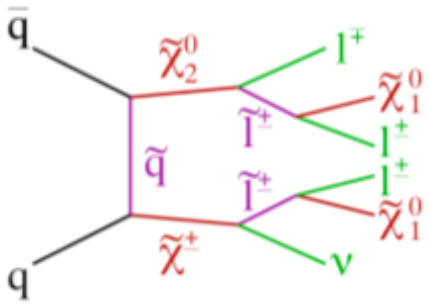
Very clean signature:

- 3 isolated leptons
- $\not\!\!E_T$ due to undetected $\tilde{\chi}_1^0$ and ν





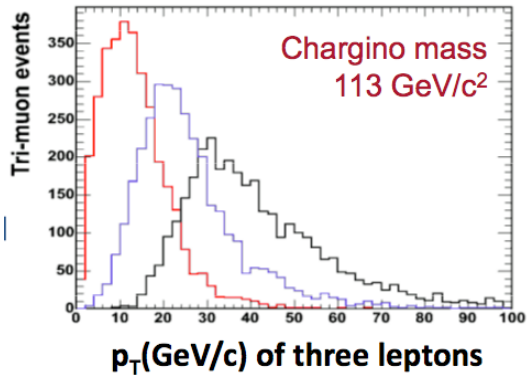
Challenge:

- low cross section:
  $\sigma \times \mathcal{B}r < 0.5$ pb
- very soft 3rd lepton p_T

Search Strategies

CDF: 2.0 fb^{-1}
- 3 identified leptons (e, μ)
- 2 identified leptons + track (ℓ)

DØ: 2.3 fb^{-1}
- 2 identified leptons (e, μ) + ℓ
- μτ + ℓ and μτ + τ (τ had decay)
- "low"-pT vs "high"-pT search



Background is reduced with several set of kinematical cuts: inv-mass cut, lepton (track) p_T cut, $\not\!\!E_T$, M_T, $\Delta\Phi$ between leptons, number of jets...

diboson (WW,WZ)
Drell-Yan $W \rightarrow l\nu$, $t\bar{t}$

SUSY in Trileptons (cont'd)

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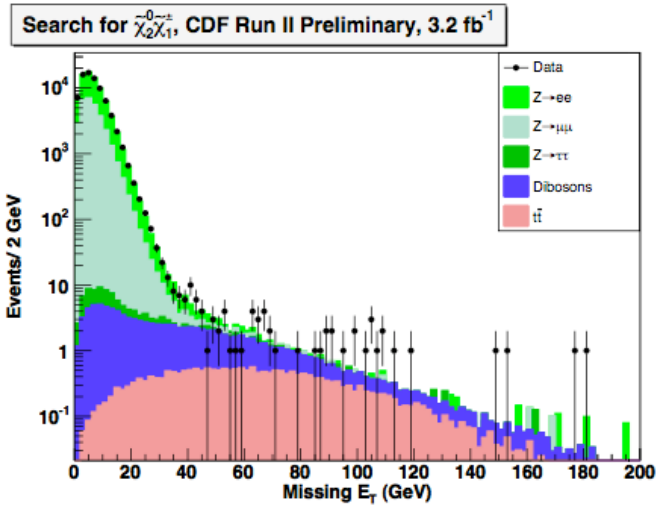


- Good agreement with SM background

DØ $\int \mathcal{L}dt = 2.3$ fb^{-1}	Background	Data	CDF $\int \mathcal{L}dt = 2.0$ fb^{-1}	Background	Data
low p_T	5.4±0.6	9	Trilepton	1.47± 0.21	1
high p_T	3.3±0.4	4	Lepton+track	9.38±1.44	6

Data compatible with SM

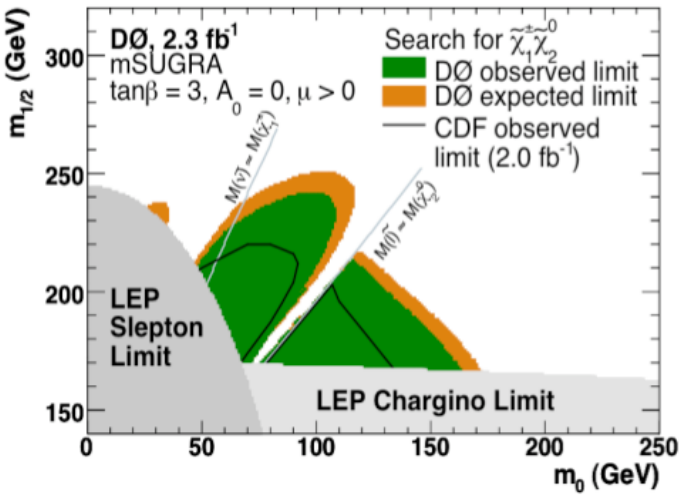
Set limits in the mSUGRA model

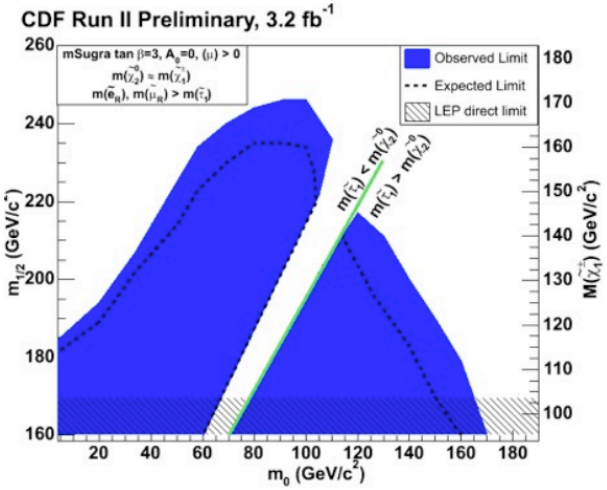
Benchmark scenario:
$A^0=0$, $\tan\beta=3$, $\mu > 0$

Control regions in MET vs $M_{\ell\ell}$ phase-space

- Signal region is investigated only after validating backgrounds in control regions (a blind analysis)

Phys. Lett. B **680**, 34 (2009)





PRL 101, 251801 (2008) and update

Sneutrinos in e+μ/τ final states

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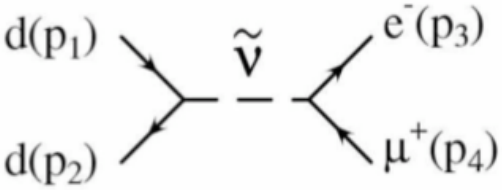
R-parity: $R_P = (-1)^{2S}(-1)^{3(B-L)}$

R-parity violation: single sparticles can be produced



arxiv:1004.3042

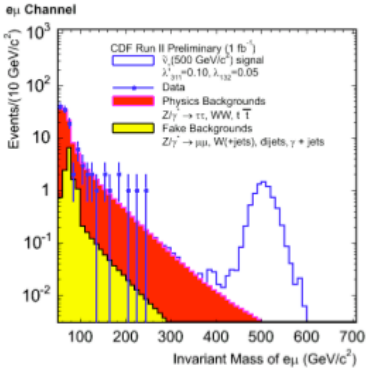
Very clean signature:

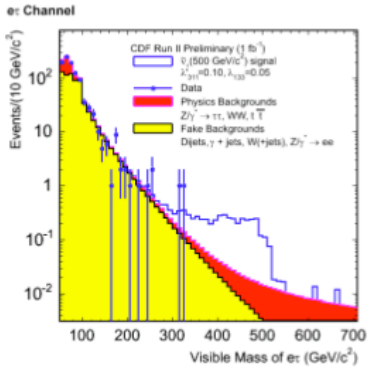
- 2 hard isolated leptons
- typical signal acceptance: 5 to 15%

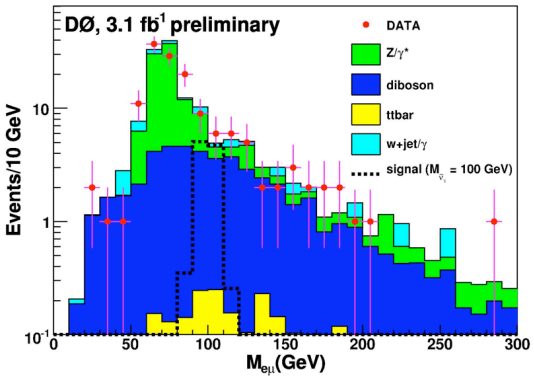
Search Strategies

CDF:
- 1.0 fb^{-1}
- 3 channels: eμ; μτ; eτ

DØ:
- 4.1 fb^{-1}
- only one channel: eμ

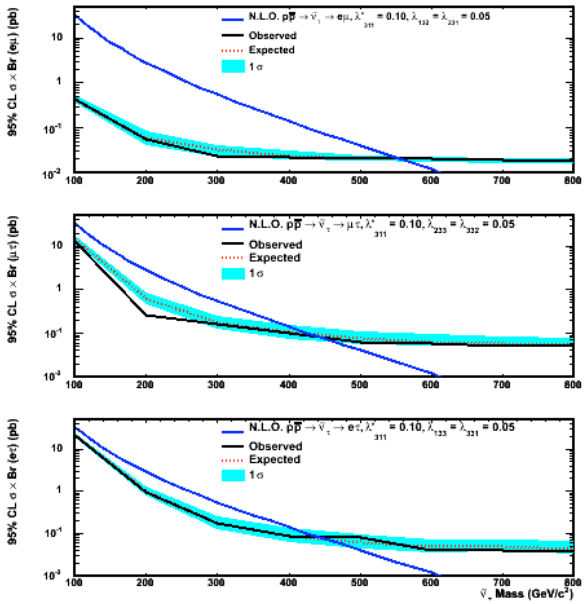






Conference Note 5894-CONF

DØ places limits on λ'_{311} for several values of λ_{321} depending on the stau mass.



GMSB SUSY

Simona Rolli - Tufts University

In gauge mediated SUSY breaking models, SUSY is broken in a hidden sector. The breaking is communicated to (s)quarks, (s)leptons and Higgs(ino) via gauge bosons and gaugino interactions.
Special features:

- gravitino is the LSP
- NLSP is a neutralino or a slepton

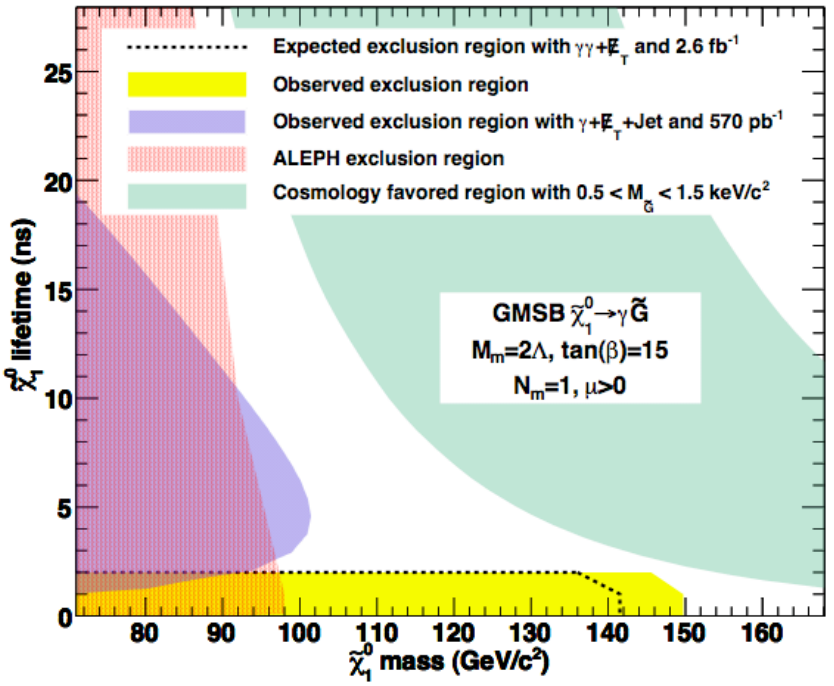
$p\bar{p} \rightarrow (X \rightarrow) \chi^0_1 \chi^0_1 \Rightarrow 2\gamma + \not{E}_T$

- **NLSP can decay early enough to occur in the detector volume**

-**If NLSP = neutralino, one has**: $\tilde{\chi}^0_1 \rightarrow \tilde{G}\gamma$

CDF

2.6 fb^{-1}



PRL 104, 011801 (2010)

γ+MET+ll

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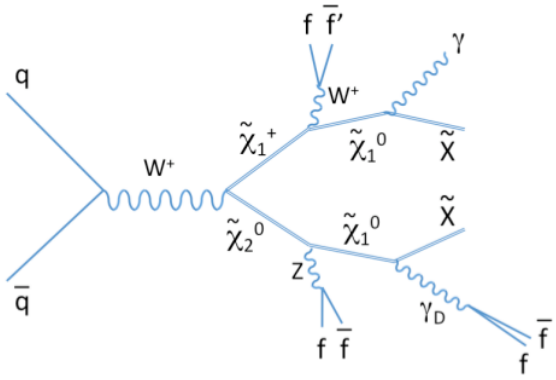
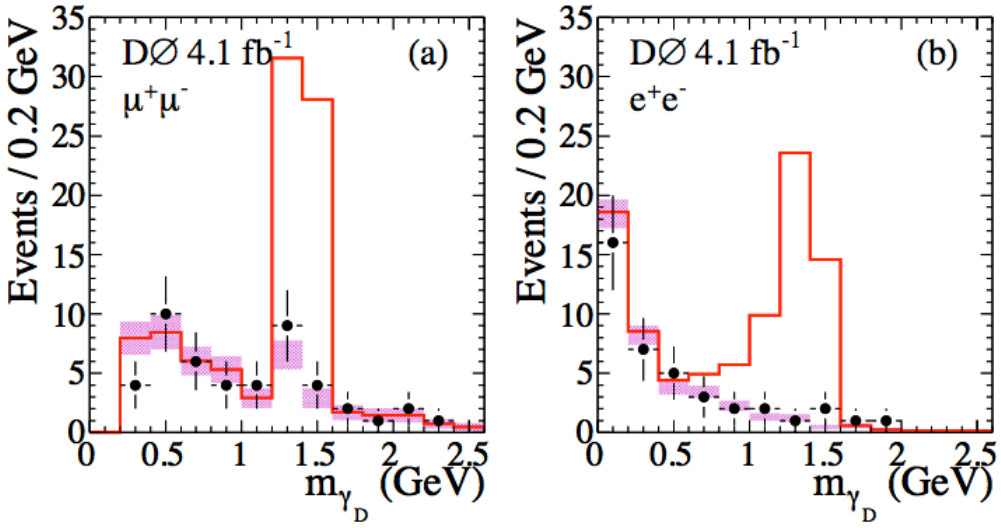
- Very exotic SUSY models :
  - hidden valley dark photons..
  - Axions decaying into muons
  - Hidden-state Y cascading to dark photons

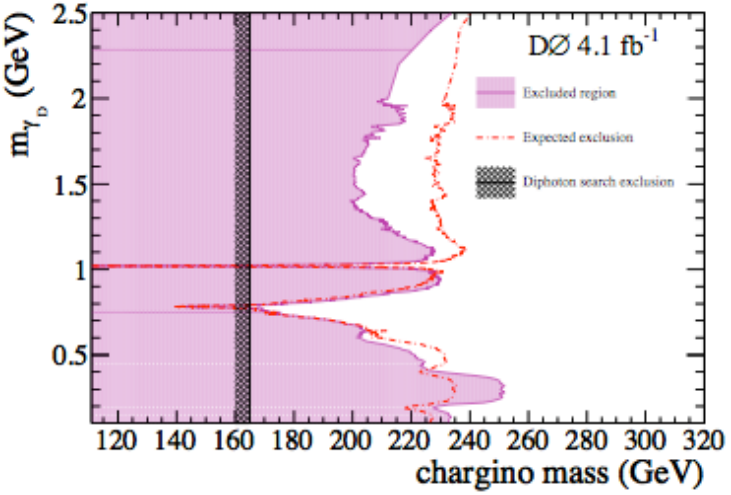


- Signature:Two spatially close leptons (no Iso), MET and γ

Phys. Rev. Lett. **103**, 081802 (2009)

4.1 fb^{-1}





Squarks and gluinos: jets +MET

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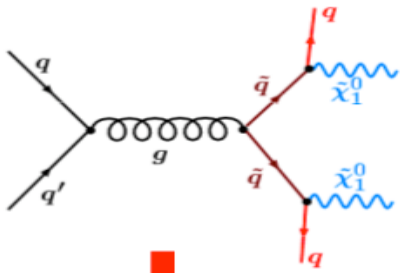
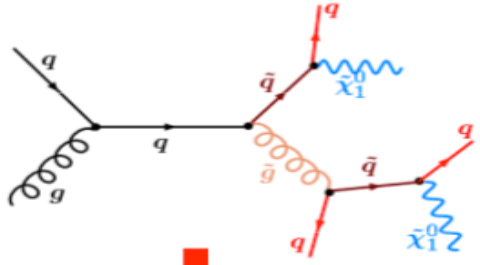
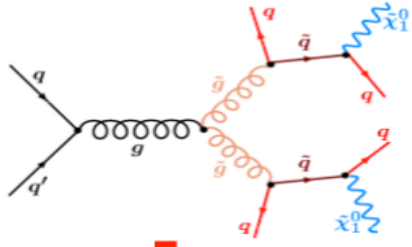


Result: 2 jets and MET

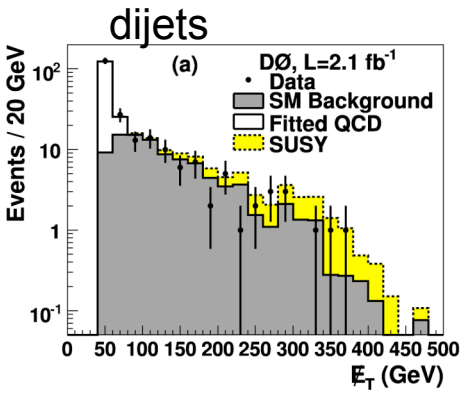


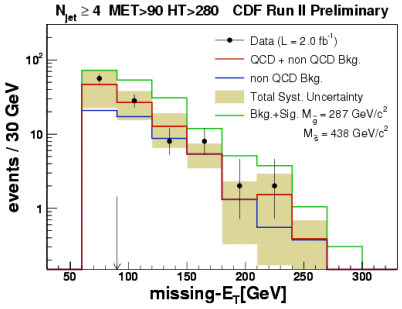
Result: 3 jets and MET



Result: 4 jets and MET

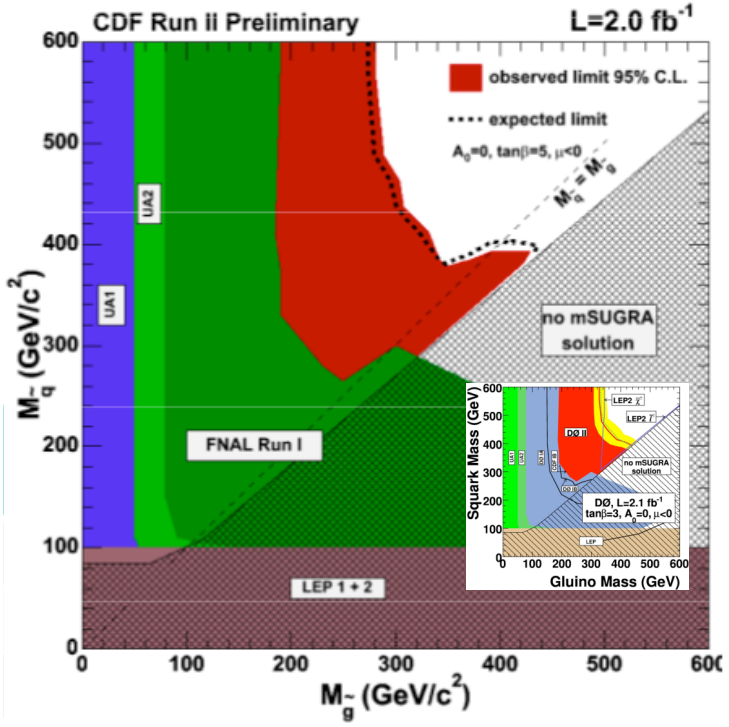
- Although the production is strong, the analyses are challenging due to QCD-multijet and W/Z+jet backgrounds
  - Solution: break-down analyses in jet-multiplicity bins and optimize separately (using MET and HT ← Sum of jet E_T)





CDF,PRL 660, 102 (2009), $\mathcal{L}$=2.0fb^{-1}

D0,PLB 660, 449 (2008), $\mathcal{L}$=2.1fb^{-1}



Search for sbottom in MET + b-jets

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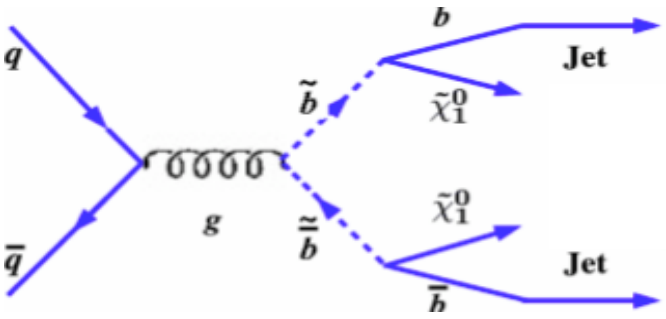
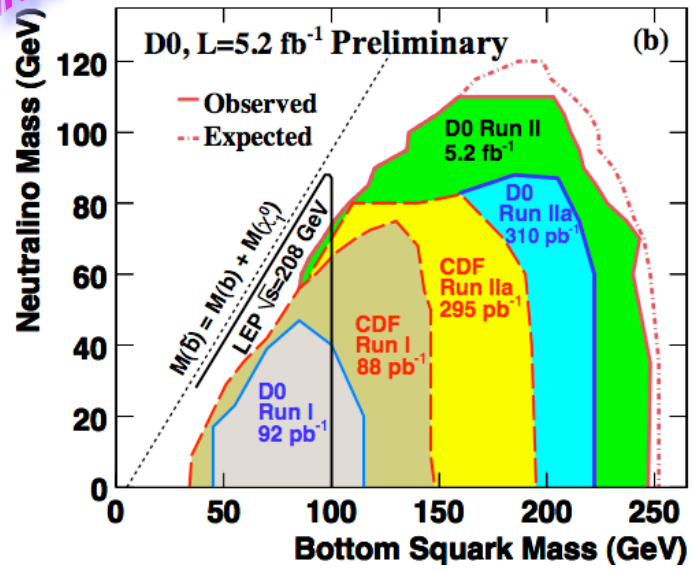


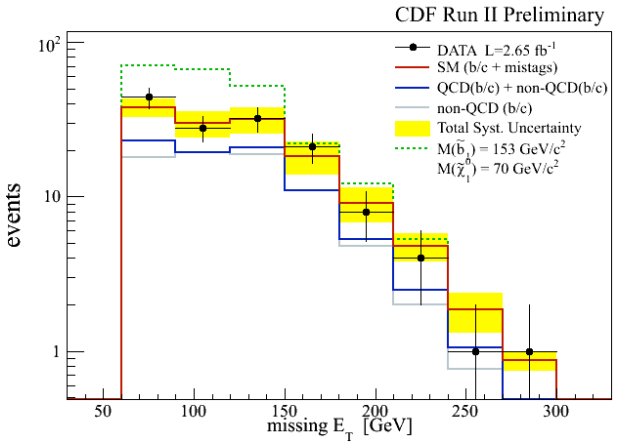
5.2fb^{-1}

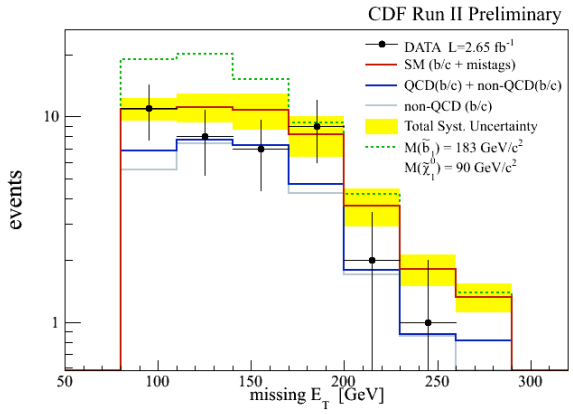
New!

Conference Note 5931-CONF



Both CDF and D0 use b-tagging and different optimization of cuts for different regions on the $\tilde{b}_1$ - $\tilde{\chi}_1^0$ mass plane





Mass limit approaching 250 GeV/c^2

CDF Public Note 9969

Stop Searches

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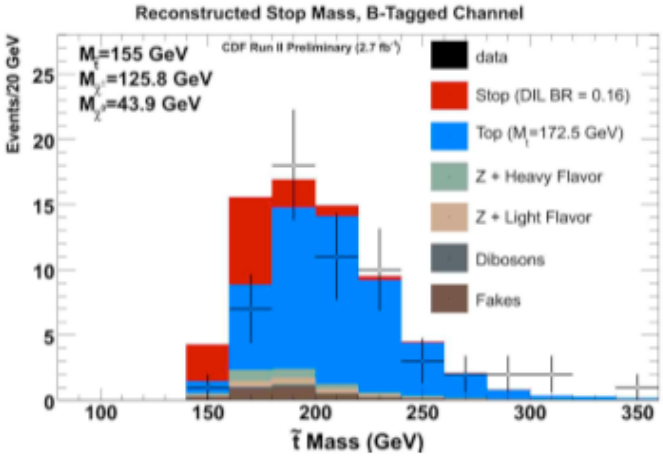
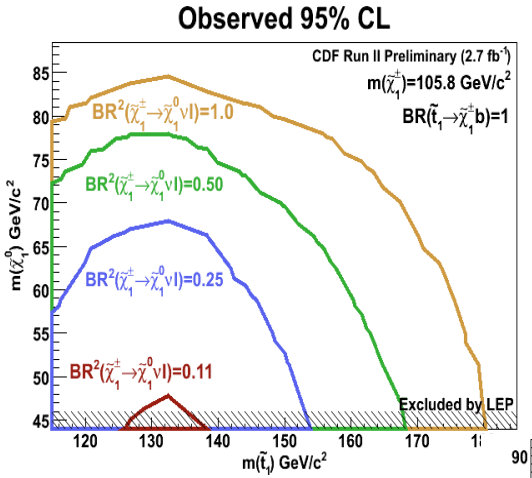
If stop light enough, $m[\tilde{t}] < m[t]$, several interesting decays, depending on the sparticles spectrum:

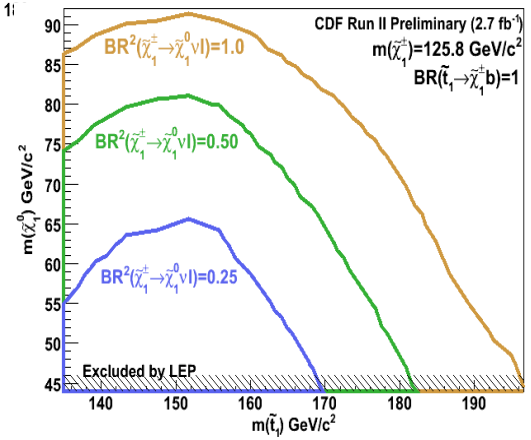
1. $\tilde{t} \to b\tilde{\chi}_1^+ \to b\,l\,\nu\tilde{\chi}_1^0 \quad (m_{\tilde{\chi}_1^+} < m_{\tilde{t}})$
2. $\tilde{t} \to b\tilde{\nu}\,l \quad (m_{\tilde{\chi}_1^+} > m_{\tilde{t}})$
3. $\tilde{t} \to c\tilde{\chi}_1^0$

$$\tilde{t}_1\bar{\tilde{t}}_1 \to b\,b\,l\,l'\,\nu\,\bar{\nu}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

CDF 2.7 fb^{-1}: dileptons (e/μ) with one isolated lepton, $\not\!\!E_T$, high p_T jets, b-tagging. reconstruct the stop mass with a kinematic fit.







arXiv:0912.1308

Stop Searches (cont'd)

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$$\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow b\,b\,l\,l'\,\tilde{\nu}\,\bar{\tilde{\nu}}$$

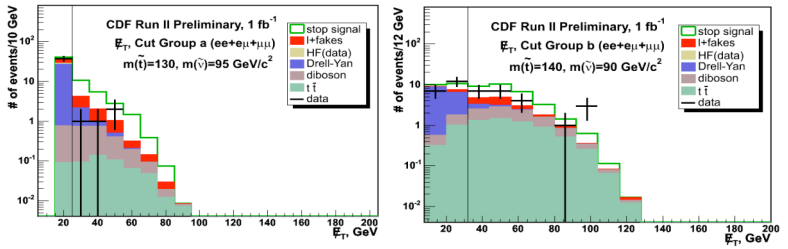
CDF 1.0fb^{-1} : ee, μμ,eμ

Analysis cuts depend dominantly on Δm (stop - sneutrino mass difference). Taking this into account, the signal region is divided into 4 regions. For each region cuts are tuned to get the best expected exclusion limit using all three dilepton channels (ee, eμ, μμ).

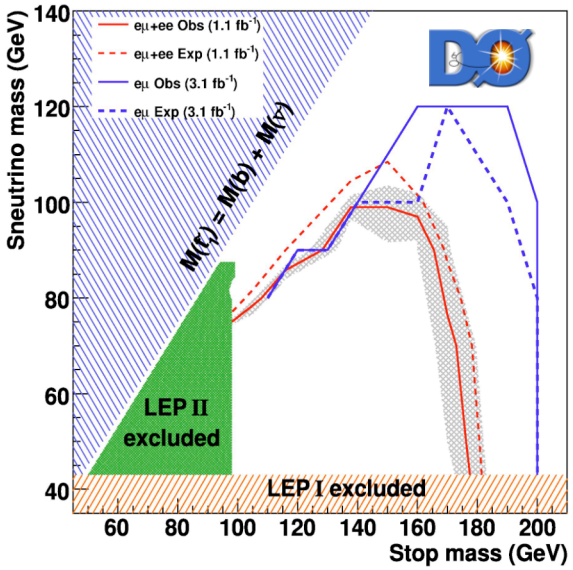
D0 3.2 fb^{-1} : ee,eμ

require hight p_T isolated leptons, $\not\!\!E_T$, use kinematics and b-tagging (for ee) to disentangle signal from background.
Signal efficiency ranges from 0.1 to 10% depending on $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\nu}}$

CDF PUB note 9775



DØ Preliminary Result



Conf Note 5937-CONF

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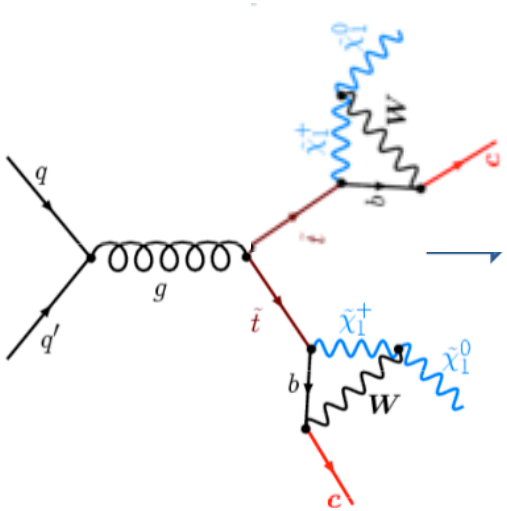
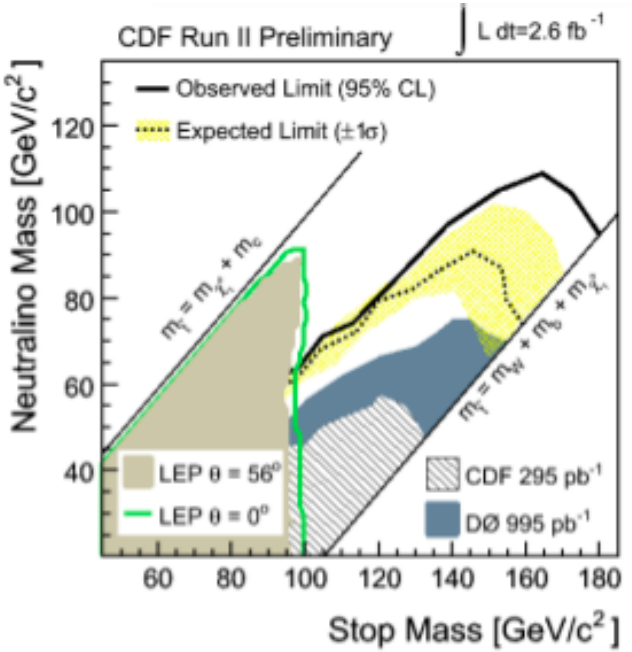
Stop searches (cont'd)

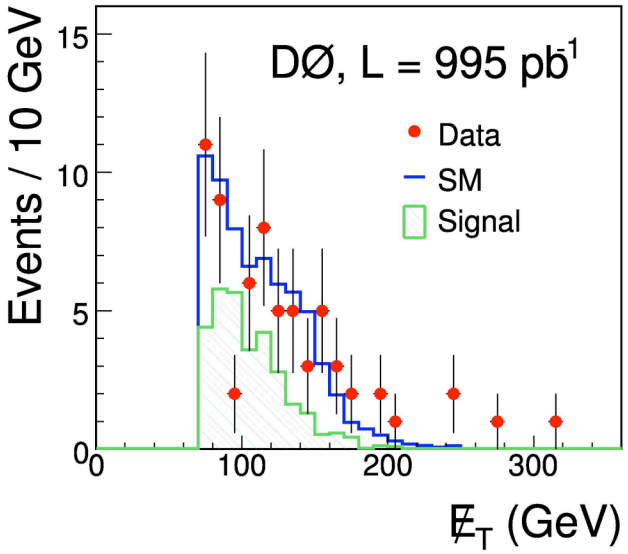


Stop to charm

$$\tilde{t} \rightarrow c\tilde{\chi}_1^0$$

- Charm-tagging to reduce b-jet background.
- Neural Networks





CDF Conf Note 9834

Phys. Lett. B 665 , 1 (2008)

Kinematic Exclusion (up to 180 GeV/c²)

Conclusions

CDF and D0 continue to probe the large, high quality Run II dataset in search of new physics!

Today we have seen several results using > 4 fb^{-1} data

The search for physics beyond the SM is carried on through a careful analysis of various final states using model driven as well as signature based approaches

No evidence for new physics yet, but … expect to collect up to 10 fb^{-1} (or more!) by the end of Run II with very promising expectations

References

- http://www-cdf.fnal.gov/physics/exotic/exotic.html
- http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm

Backup

Diphoton+X

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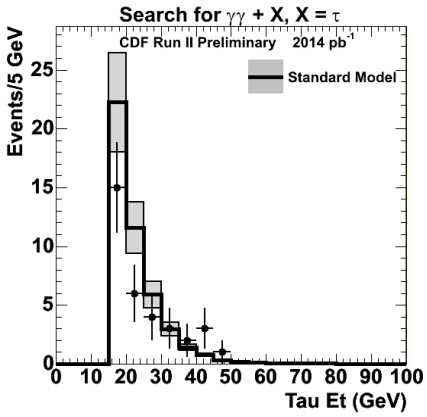
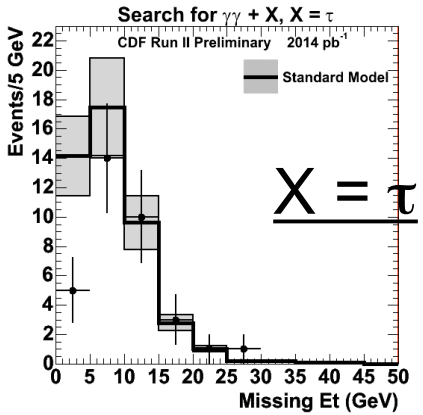
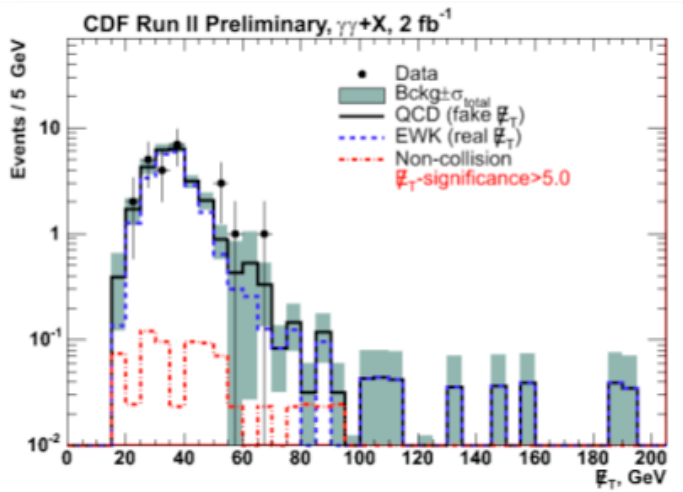
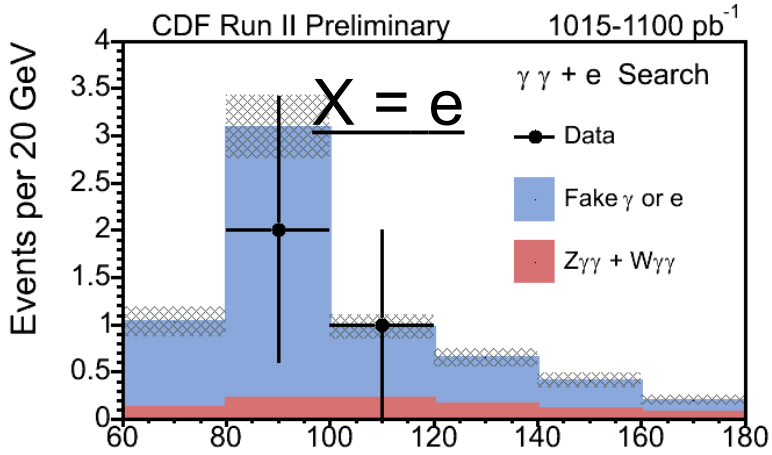
Nominal high E_T object identification and kinematic selections are used.
The observed event counts is reported as well as SM prediction for various kinematic distributions

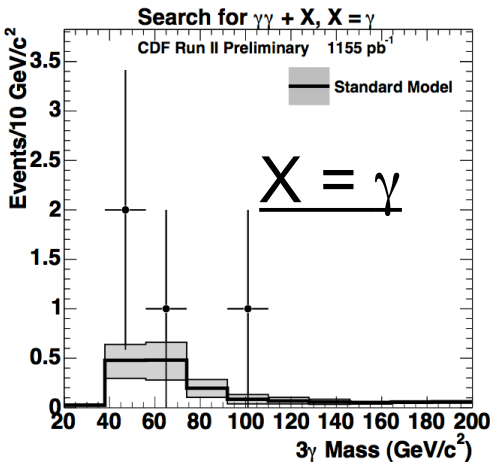




X=MET







Good agreement between data and SM predictions

Squarks into taus

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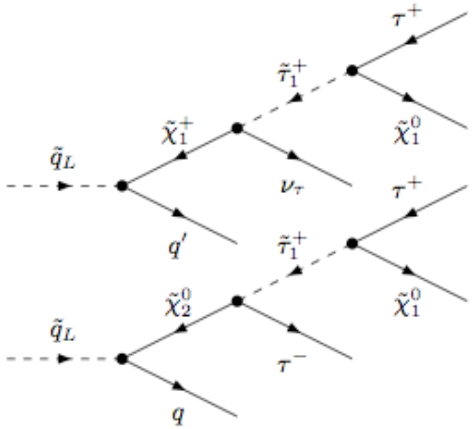
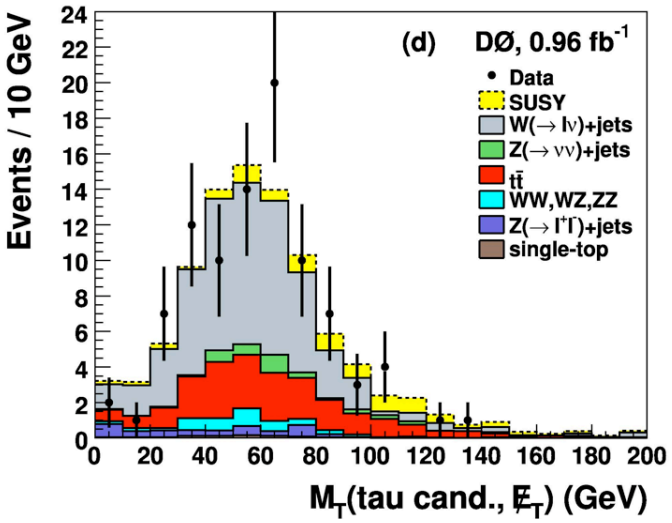


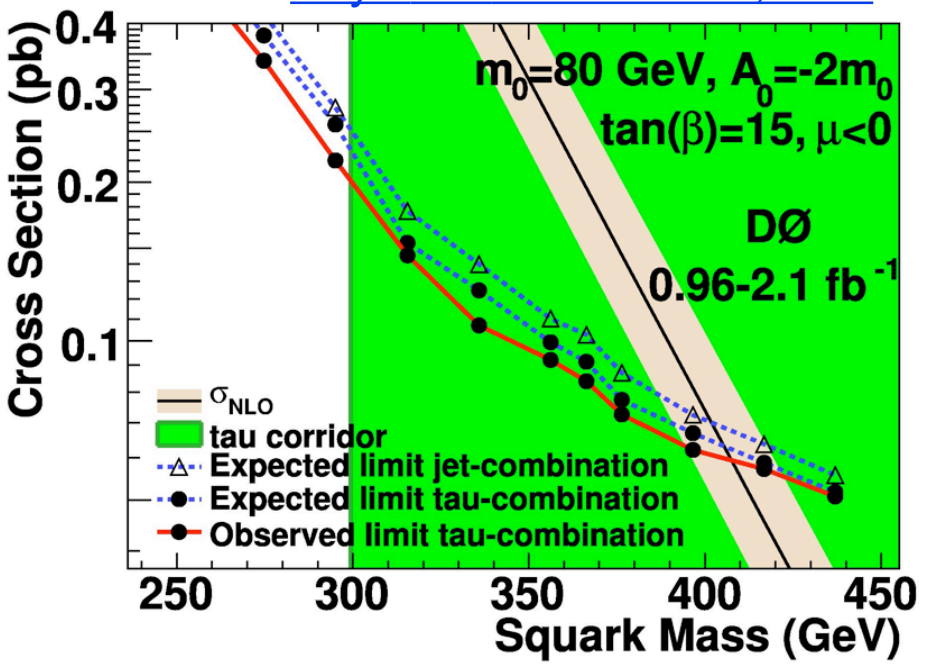
-In some regions of the space parameters squarks and gluinos decay into final state with leptons
-Tau corridor: the stau is the lightest slepton and lighter than chargino/neutralino
-Signature: ≥2jets, large MET and at least 1 τ
-Combined with MET + jets analysis

First time such channel is used

$m_0, m_{1/2}$ (100,150)



Phys.Lett.B680:24-33,2009



Tevatron vs LHC

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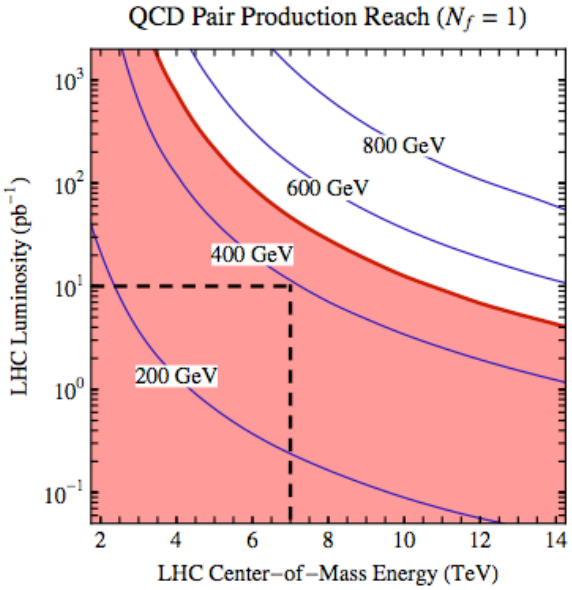
2010-2013: TeVatron 10(-20) fb^{-1} @ 1.96 TeV
LHC 10pb^{-1} -1fb^{-1} @ 7 TeV

For the LHC to be competitive in new particles discovery:



1. Large enough LHC cross section to produce at least 10 signal events[1] with 10 pb^{-1} of data;
2. Small enough Tevatron cross section to evade the projected 2010 Tevatron sensitivity with 10 fb^{-1};
3. Large enough branching fraction to an "easy" final state with essentially no backgrounds;
4. Consistency with other existing bounds.

No QCD pair production
Yes: certain resonances

arXiv:0909.5213v2 [hep-ph] 18 Oct 2009

(C.W.Bauer,Z.Ligeti,M.Schmaltz, J.Thaler and D.G.E.Walker)

Tevatron vs LHC

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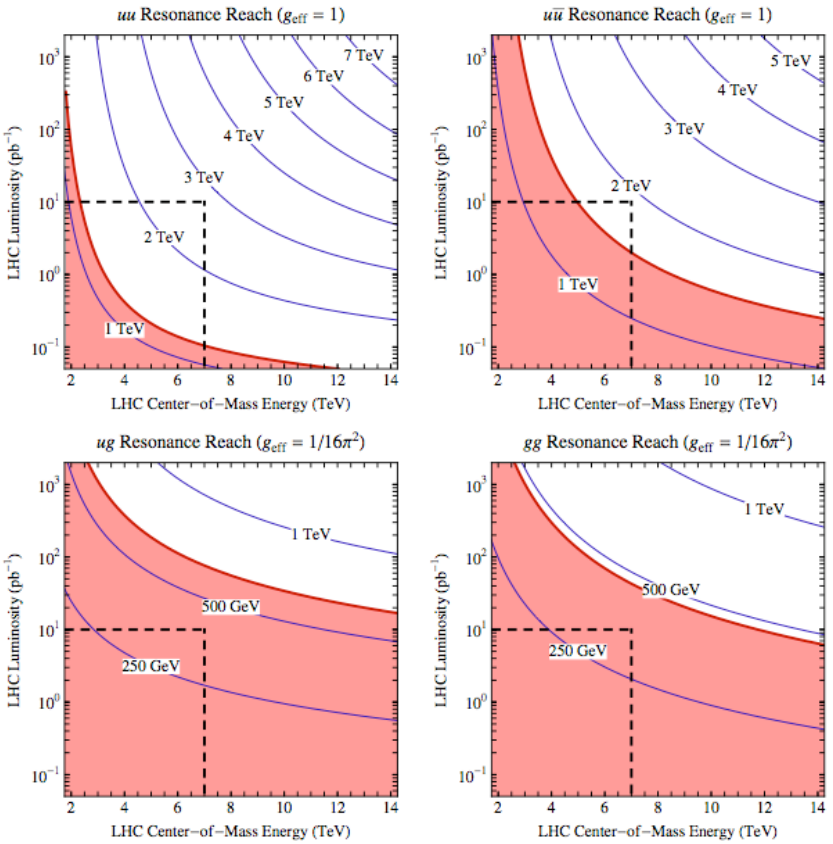
Resonance Production:
qqbar and qq



arXiv:0909.5213v2 [hep-ph] 18 Oct 2009

Data Taking Efficiency

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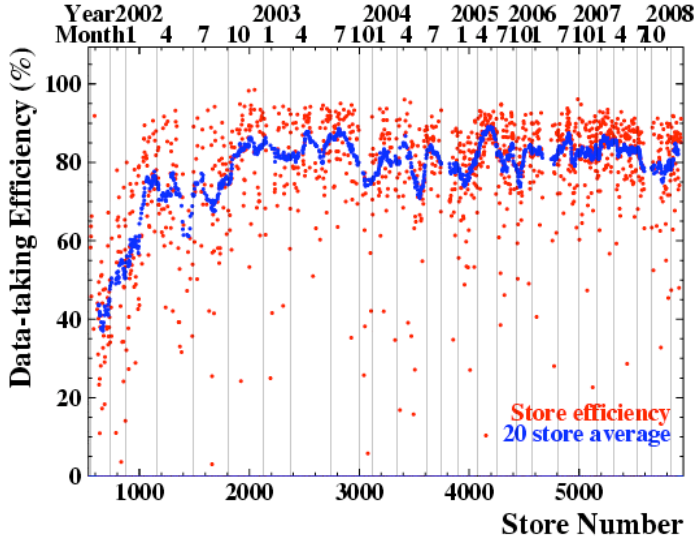

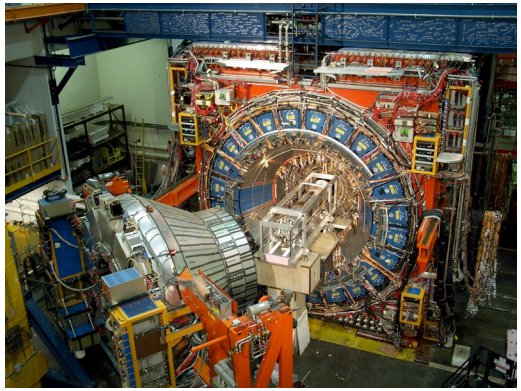

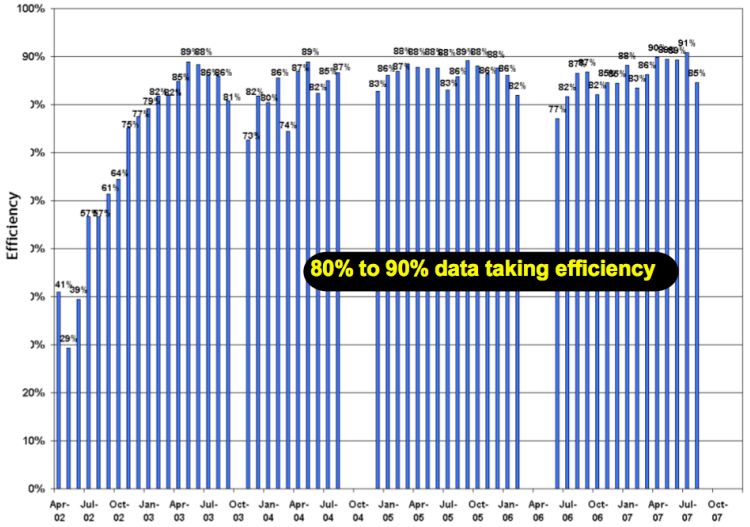

Lepton Efficiencies

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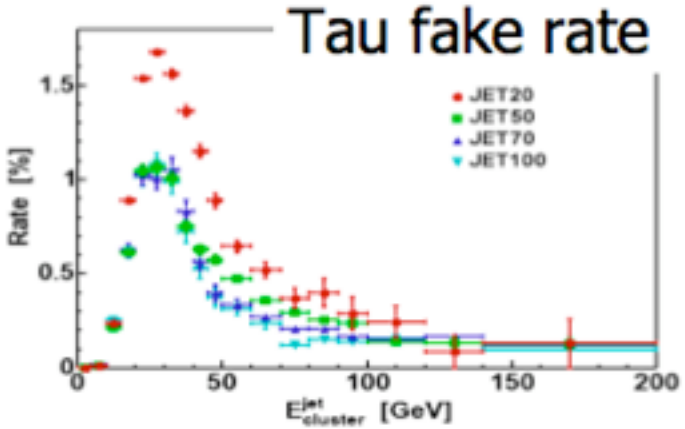
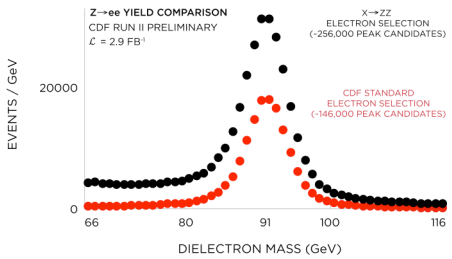
- Compare "typical" high-pt (>20 GeV) isolated lepton efficiency and fake rates

Lepton	Efficiency	Fake Rate
electron	~80%	~0.01%
muon	~85%	~0.01%
tau (box cuts)	~45%	~1-0.1%
tau (neural net)	~80%	~5-1%





Jets and Heavy Flavor

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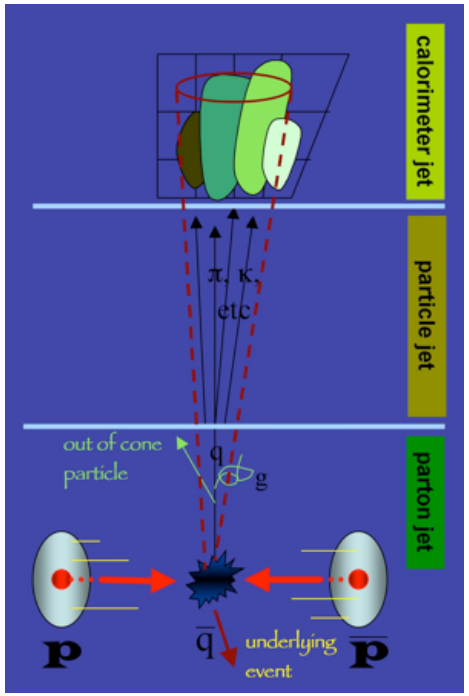
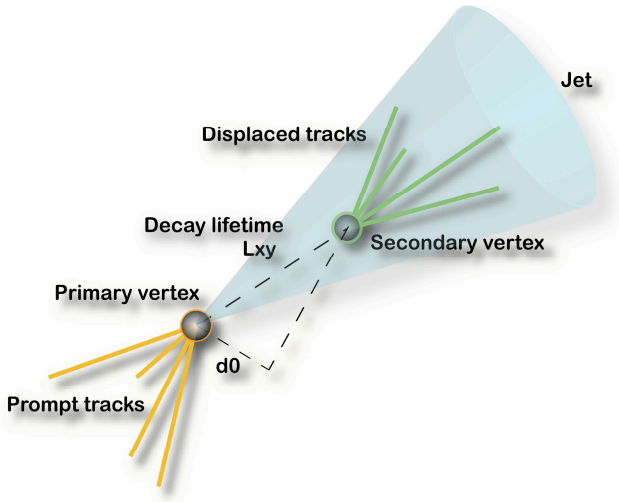
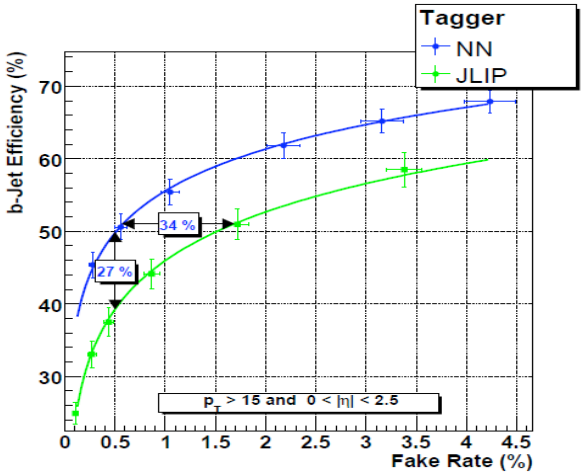
Hadronic jets are reconstructed using several algorithms: Cone,Midpoint, KT etc..
Measured jet energies are corrected to scale them back to the final state particle level jet . Additionally there are corrections to associate the measured jet energy to the parent parton energy, so that direct comparison to the theory can be made. Currently the jet energy scale is the major source of uncertainty in the measurement of the top quark mass and inclusive jet cross section

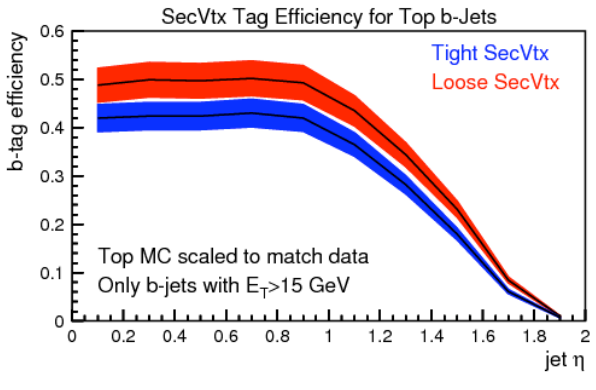


B-jet identification is implemented via:

- -displaced vertices with L_{xy}/σ cut (CDF)
- -Vertex mass separation (CDF)
- -combining vertex properties and displaced track info with NN (D0)
  - -Tag to η beyond 2







Btagging Mistag Rate (CDF)

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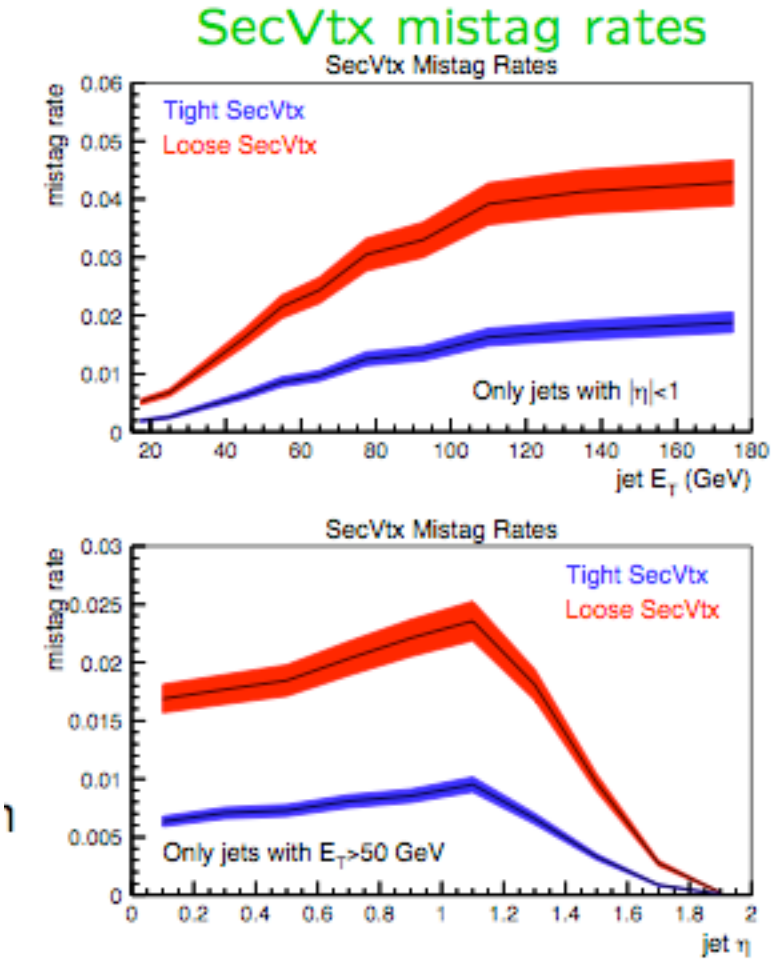

D0 btagging

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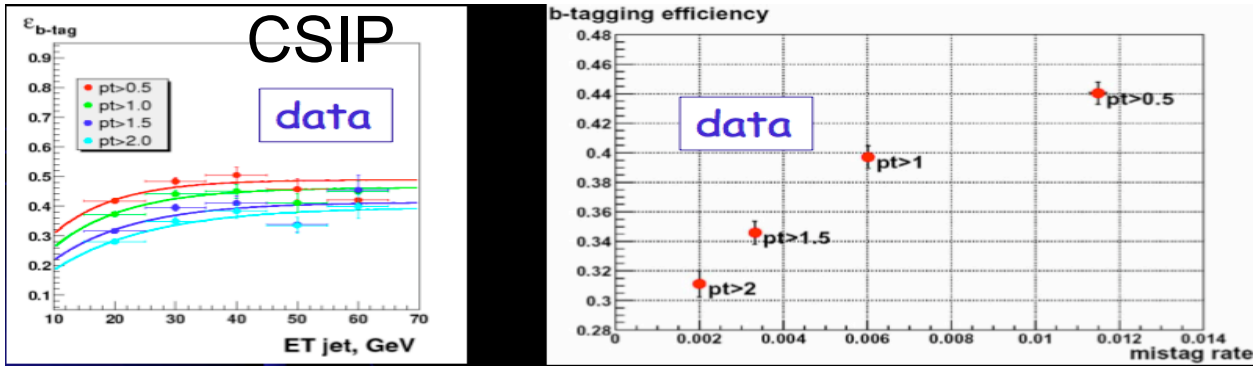

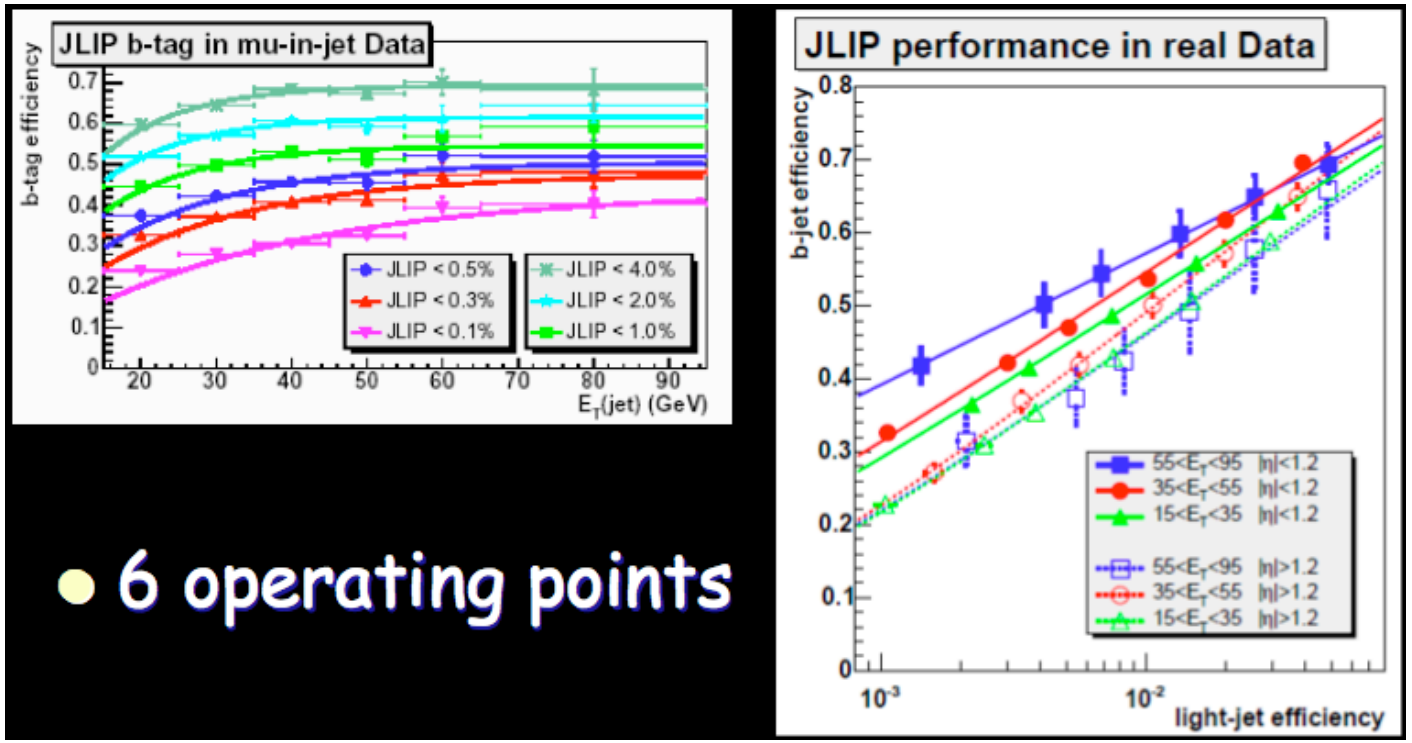

- 6 operating points

$B_s \rightarrow \mu\mu$

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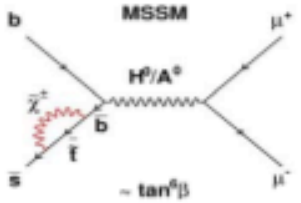
Sensitive to new physics: if no observation, it can strongly constraint SUSY models



SM prediction:
BR = 3.42×10^{-9}

SUSY enhancement
$\sim(\tan\beta)^6$

- Data sample dominated by random combinatorial background
- Extract signal with Neural Net based discrimina

B_s and B_d considered separately:

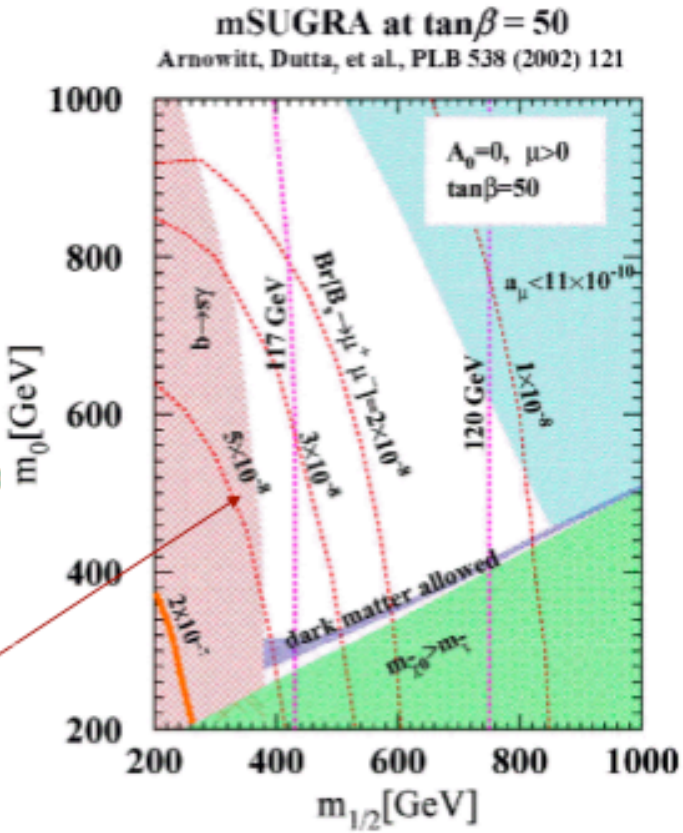
$Bs \rightarrow \mu\mu$ 3 observed events (3.6+/-0.3 exp.bkg.)

$Bd \rightarrow \mu\mu$ 6 observed events (4.3+/-0.3 exp.bkg.)

No significant excess → exclusion limit

$Br(B_s \rightarrow \mu\mu) < 5.8 \times 10^{-8}$ @ 95% CL
$Br(B_d \rightarrow \mu\mu) < 1.8 \times 10^{-8}$ @ 95%CL

Comb CDF/D0



BR($B_s \rightarrow \mu\mu$) < 1.5×10^{-7} @95% CL

hep-ex/0508058

Global Searches at CDF

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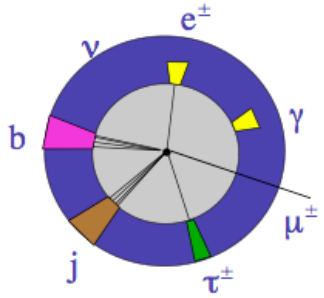
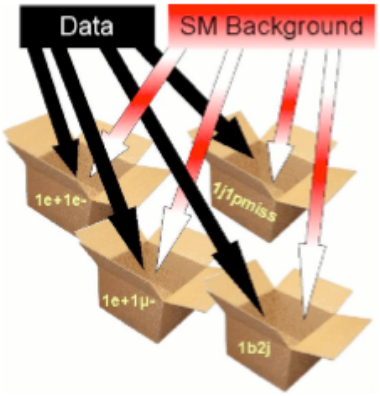
The goal is to perform a model-independent global search of high P_T data:

-study bulk features of high P_T data;
-search for resonances invariant mass distributions
-search for significant excesses at high sum-p_T



Physics objects are categorized and events selected and partitioned into ~400 exclusive final states



The whole high P_T region is monitored at once

Pythia and MadEvent are used to implement the SM theoretical prediction (CdfSim emulates the detector response)
Many correction factors are used to obtain the *true* SM predictions (shouldn't a global search work globally?)

theory k-factors etc
experimental efficiencies and Scale Factors, fake rates etc

Currently observed discrepancies are explained in terms of incorrect MC modeling

Global Searches at D0

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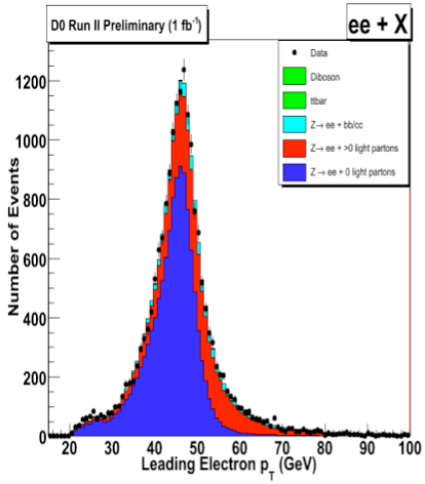
- DØ also uses common MC
  - PYTHIA and ALPGEN
  - Multijets background from data
- Apply common collaboration-wide scale factors
  - Can be bin-by-bin or several parameter functions
  - Use phase space dominated by SM processes
- Then fit for normalization factors
  - Trigger efficiencies, k-factors, etc
  - 7 inclusive final states
  - Exclude high-p_T tails



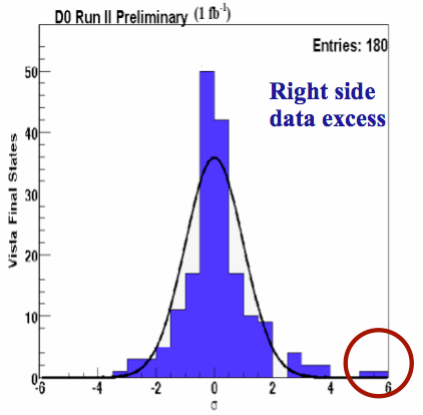
Search limited to final states with leptons

3 basic modeling issues

η-dependent trigger efficiency in μ + jets + MET

Muon resolution in μμ + MET

Jets misidentified as photons in γ states



All of the given discrepancies point to modeling difficulties