Searches for New Physics Beyond the Standard Model at the Tevatron

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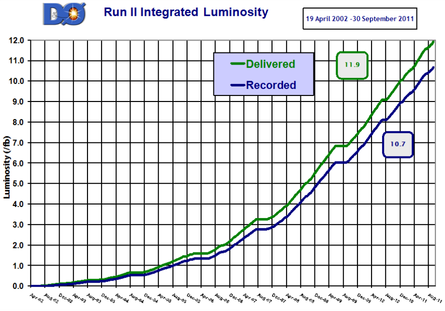
On behalf of the CDF and D0 collaborations

Outline

Tevatron Run II



$p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV

Over 10 years, more than 10 fb^{-1} recorded per experiment

Timeline

For past 10 years, the Tevatron was essentially the only running high energy collider capable of directly exploring high energy phenomena. Now it has been decided that only the LHC should have this privilege in the near future.

Tevatron-LHC Comparison

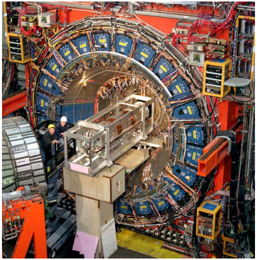
Now LHC has essentially surpassed Tevatron in raw statistics as well as $\sqrt{s}$.

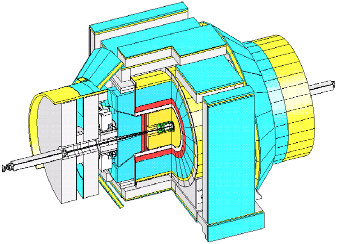
	Tevatron	LHC	
Collision Type	$\mathrm{p\bar{p}}$	pp	
$\sqrt{s}$ (TeV)	1.96	7	(soon 8)
$\int \mathcal{L}\, dt$ (fb^{-1})	10	5	
Design $\mathcal{L}$ (nb^{-1} s^{-1})	0.1	10	
$\mathcal{L}_{\mathrm{max}}$ (nb^{-1} s^{-1})	0.4	5	
σ_{inel} (mb)	60	90	
BX Δt (ns)	396	50	
μ typical	5	20	
$2\sigma_{\mathrm{W}} B_{\ell}$ (nb)	5	20	
Trigger Rate (Hz)	200	200	
Trigger Cross-section (nb)	500	40	

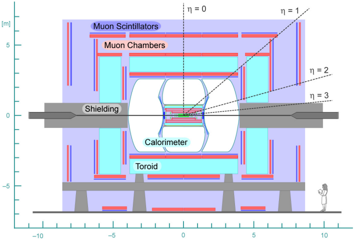
Most Tevatron new physics searches are superseded by LHC in terms of high energy scale reach. For some topics $\mathrm{p\bar{p}}$ is very complementary: m_{W}, low mass Higgs, measurements exploiting particle / anti-particle beam.

It is also an important part of the scientific method to have *complementary* and *independent* measurements - especially in an era where new phenomena are elucidated.

Tevatron Detectors







CDF B=1.4T, R = 1.4m

D0 B=1.9T, R = 0.5m

Technically - could have kept going for 3 more years

What am I going to talk about?

This talk is *not* about SM Higgs (C. Group), *not* about top and electroweak (R. Kehoe) and *not* about rare B-decays (L. Ristori). However the results in these sub-fields do inform us on allowed directions for BSM physics.

I will review selected results on

- Searches for new phenomena
- Hints of new physics in B-physics
- BSM Higgs

Searches rely on *actually searching the data* for potential signals of new physics. Tevatron searches fall into two main types:

- Pseudo model-independent – targeting specific experimental signatures
- Model driven – emphasizing constraints on model parameters

This talk will be fairly SUSY light:

- LHC is now the main player for channels accessible at a hadron collider
- First real test of a predictive consequence/motivation for SUSY is in progress (light Higgs).

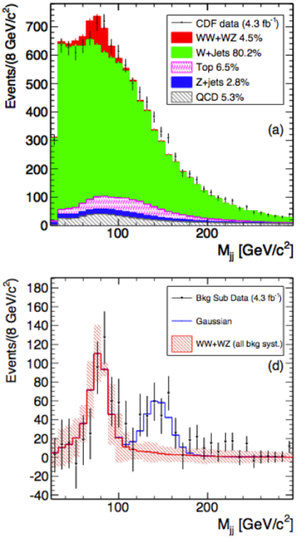
W + jets bump

Claim

- In Spring 2011, CDF reported a 3.2σ excess around 145 GeV in the di-jet mass spectrum in events produced in association with a W (WX with $\mathrm{X} \rightarrow jj$).
- PRL 106 (2011) 171801.
- Putative cross-section 4 pb.
- CDF preliminary analysis with more data, (7.3 fb^{-1}), increases significance to 4.1 σ

Independent Test of Claim

What does D0 see ?

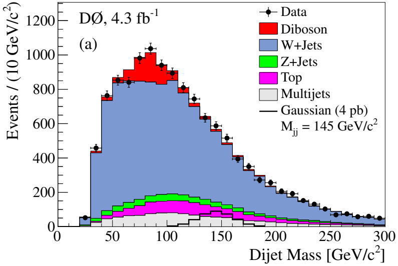


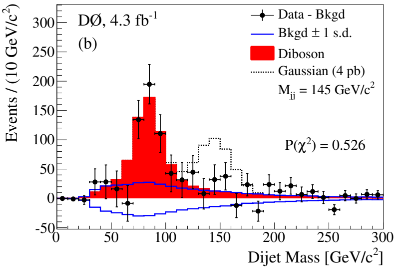
CDF

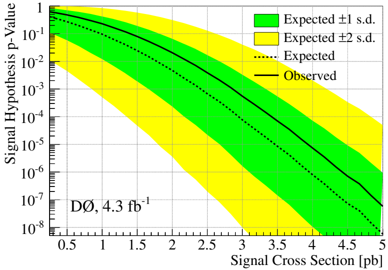
D0 results on claimed W+jets bump

D0 Analysis

- Repeat essentially same analysis as CDF
- Published in PRL 107 (2011) 011804







D0 Results

- See no excess
- Exclude $\sigma = 4$ pb at 99.9992% CL
- Exclude $\sigma > 1.9$ pb at 95% CL

D0 like-sign di-muon charge asymmetry measurement

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

$$A^b_{\rm sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

Synopsis

- D0 published in 2010 a measurement of the charge asymmetry of like-sign dimuons
- Updated, improved and published last fall, PRD 84 (2011) 052007
- Based on 6×10^6 $\mu\mu$
- New 9 fb^{-1} result for $A^b_{\rm sl}$ differs from SM value of $-0.028 \pm 0.006\%$ by 3.9 σ

Semi-leptonic B-decay model

Like-sign di-muon events can arise from $b\overline{b}$ events with semi-leptonic B-hadron decay if one of the hadrons is a B^0_d or B^0_s meson that oscillates. A charge asymmetry can result from CP violation.

$$A^b_{\rm sl} \equiv C_d a^d_{sl} + C_s a^s_{sl}$$

$$a^q_{sl} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

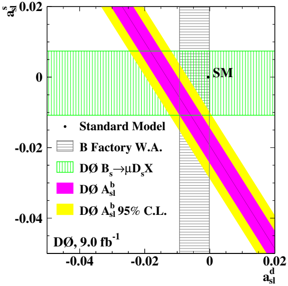
where C_d and C_s depend on mean mixing probabilities and production fractions, ΔM_q, $\Delta\Gamma_q$ are mass and width differences and ϕ_q is a CP-violating phase.

D0 like-sign di-muon charge asymmetry measurement

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}$$

Experimental Method

- Measure di-muon asymmetry, A, and single-muon asymmetry, a, in 6 bins in p_T
- Detector asymmetries controlled by alternating polarities of both the solenoid and muon-toroid
- Estimate backgrounds
- Dominant background is kaon decay. $\sigma(K^+N) < \sigma(K^-N)$, so K^+ has more time to decay
- Systematics partly cancel by using $A' \equiv A - \alpha a$ with appropriate α



Updated Result

Improved methods, higher statistics, lower systematics.

$$A^b_{\rm sl} = -0.787 \pm 0.172 \pm 0.093\% \ (3.9\sigma)$$

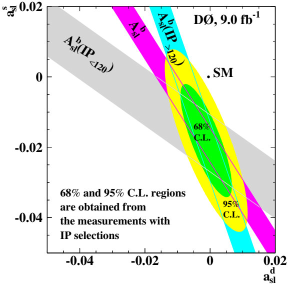
$$A_{\rm res} = -0.246 \pm 0.052 \pm 0.021\% \ (4.2\sigma)$$

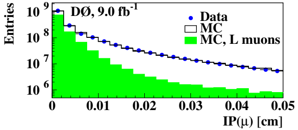
D0 like-sign di-muon charge asymmetry measurement

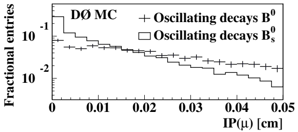
Impact Parameter Study

Use muon impact parameter to separate various contributions. Use separation cut of 120μm.

1. Inclusive Muons. Green is decay-in-flight type background
2. Oscillating B^0 and B_s^0





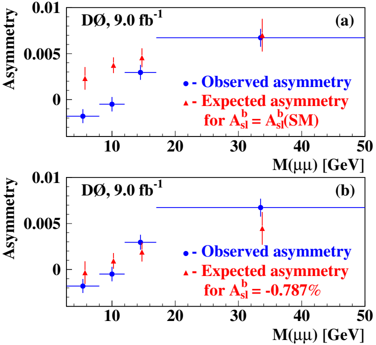


With impact parameter information, measure $a_{sl}^d = -0.12 \pm 0.52\%$ and $a_{sl}^s = -1.81 \pm 1.06\%$. Correlation, $\rho = -0.80$.

D0 like-sign di-muon charge asymmetry measurement

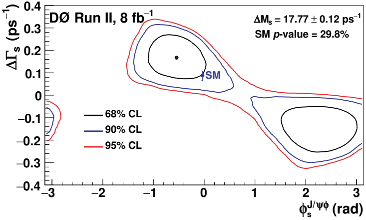
Conclusions

- Robust evidence for CP violation in the B^0/B^0_s system.
- Currently unable to definitively conclude that B^0_s dominates the asymmetry.
- A unique measurement which is not so easy to directly confirm/refute.
  - $\mathrm{p\overline{p}}$ is a CP-even initial state. (pp is not).
  - Very helpful to be able to switch magnet polarities....
- Expect updated and improved results from D0 with flavor-specific asymmetries and improved measurements in the near future.

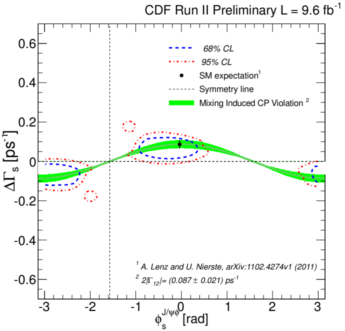


CP Violating Phase Measurements in $B_s^0 \to J/\psi\ \phi$

See talk by L. Ristori for more details



PRD 85 (2012) 032006



These used to be quite discrepant with SM prediction. Now SM p-values are 30% (D0) and 54% (CDF). So now quite consistent with SM.

D0: Observation of a new state decaying to $\Upsilon(1S) + \gamma$

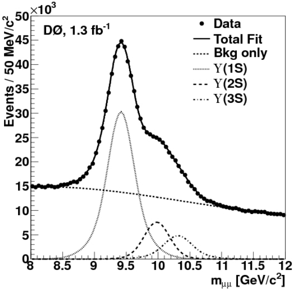
Motivation

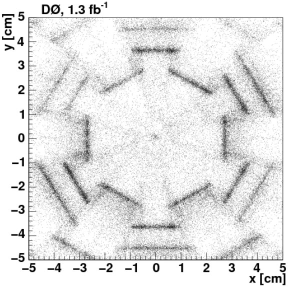
Search for new quarkonium state below $B\overline{B}$ threshold decaying to $\Upsilon(1S) + \gamma$. Decay mode is shared with $\chi_b(1P)$ and $\chi_b(2P)$.

Event Selection

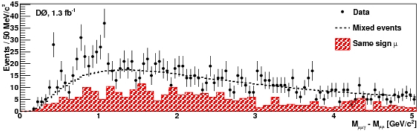
Use $\Upsilon(1S) \to \mu^+\mu^-$ decay. Single muon and di-muon triggers. Require $9.1 < m_{\mu\mu} < 9.7$ GeV. Use photon conversion candidates ($\gamma \to \mathrm{e}^+\mathrm{e}^-$ in the detector material).

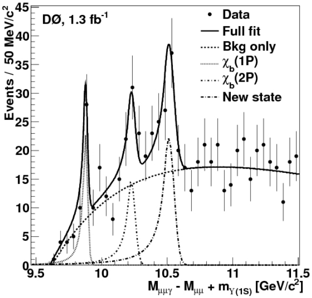
arXiv:1203.6034





D0: Observation of a new state decaying to $\Upsilon(1S) + \gamma$





Method

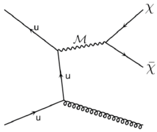
- Use the measured mass difference, $\Delta M \equiv M_{\mu\mu\gamma} - M_{\mu\mu}$ which is measured with high resolution.
- Model the combinatoric background by combining $\Upsilon(1S)$ and photon candidates from different events.
- Fit distribution of $\Delta M + m_{\Upsilon(1S)}$ with 3 signal peaks.
- Find peak widths consistent with resolution.

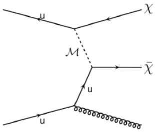
Results

- Measure 65 ± 11 events above background for the new state.
- 5.6 σ significance (10.38-10.63 GeV)
- $M = 10.551 \pm 0.014 \pm 0.017$ GeV

Mass is consistent with recent ATLAS observation ($10.530 \pm 0.005 \pm 0.009$ GeV)

CDF Mono-Jet





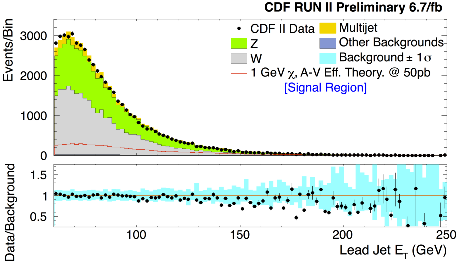
Motivation

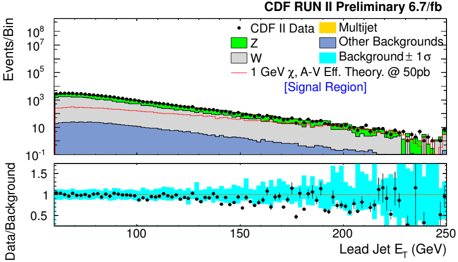
Search for dark matter production in the mono-jet channel. Constrain dark-matter nucleon cross-section.

Method

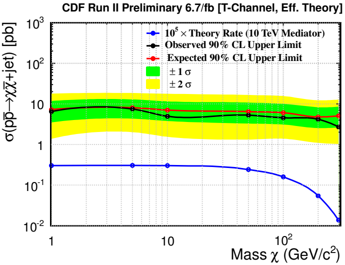
Select events with $\not\!\!E_T > 60$ GeV. Observe 52633 events. Expect 53904 ± 6022 from SM. So set cross-section limits and limits on SI and SD cross-sections following co-authors Fox, Harnik and Bai.

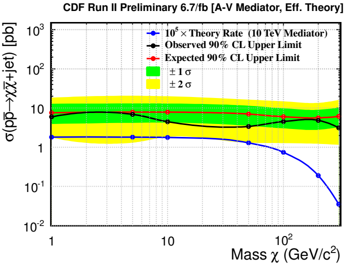
CDF Note 10709

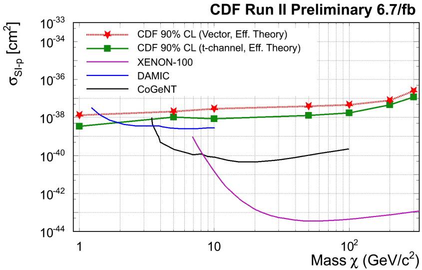


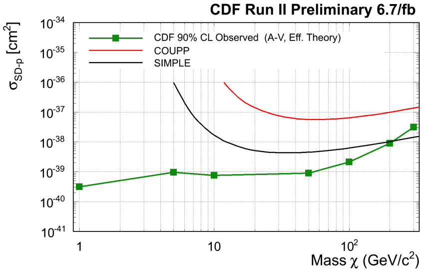


CDF Mono-Jet (Effective Theory (Heavy Mediator) Limits)

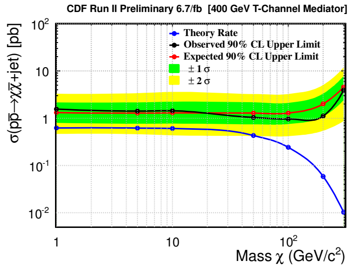


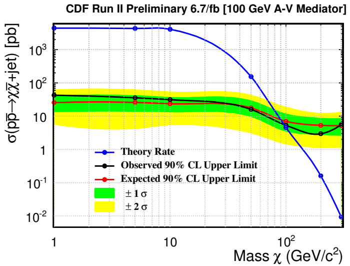


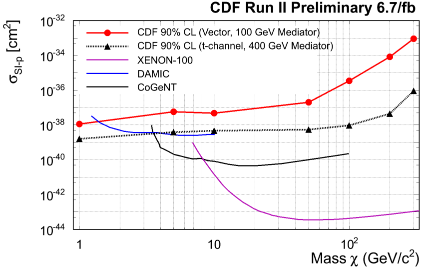


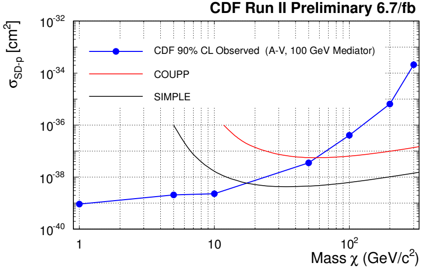


CDF Mono-Jet (Light Mediator Limits)



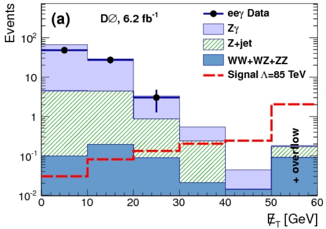


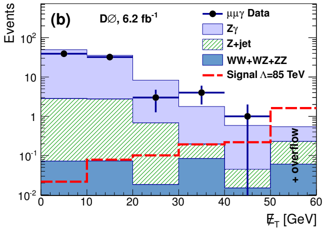




Competitive collider limits relevant to direct dark matter detection

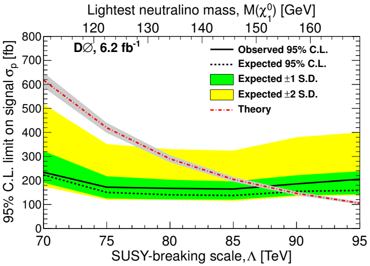
D0: $Z\ \gamma + \not{E}_T$





Results (arXiv:1203.5311)

- Search for $Z\gamma\ \not{E}_T$ in ee and $\mu\mu$ channels
- Potential signature of $\tilde{\chi}_1^0\ \tilde{\chi}_1^0$ in GMSB with $\tilde{\chi}_1^0 \to Z\tilde{G}$ and $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ decay
- Cut-based ($\not{E}_T > 40$ GeV) and BDT based
- Find 1 candidate (1.2 expected from SM).
- Set σ upper limits and exclude $\Lambda < 87$ TeV ($m_{\tilde{\chi}_1^0} < 151$ GeV)



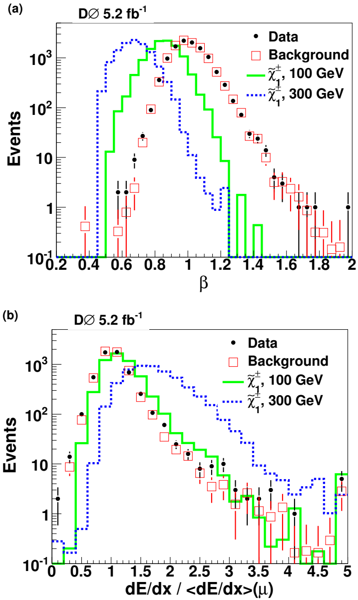
D0 Charged Massive Long-Lived Particle Search

Motivation

Search for charged massive long-lived particles. Quasi-stable particles can arise in many new physics models.

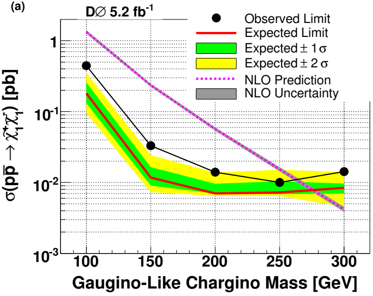
Method (PRL 108 (2012) 121802)

Search for events with ≥ 1 particle reconstructed as a muon with $p_T > 60$ GeV, but with the muon-system scintillator speed estimate, β, and ionization energy loss measurement in the silicon tracker, dE/dx, inconsistent with beam collision muons.
Use control region dominated by mis-measured muons from W decay with low M_T to control the background.

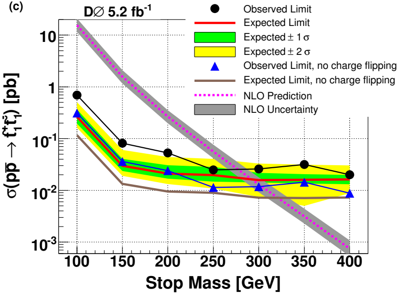


D0 CMLLP Limits

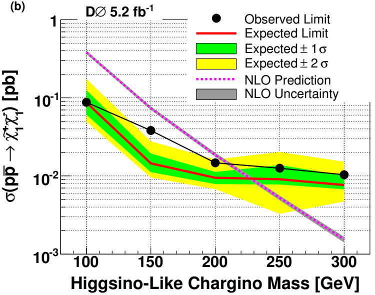
(a)



(c)



(b)



Limits

95%CL Cross-section limits are set on charginos of gaugino (higgsino) nature and on long-lived stops at $\mathcal{O}(0.01)$ pb. These limits exclude gaugino-like charginos below 267 GeV, higgsino-like charginos below 217 GeV and long-lived stops below 285 GeV.

D0 Model-Independent Search

Motivation

Many different channels are relevant to searches for new physics. Specific searches for signatures of (not so credible) models may not be the best way to make scientific progress.

Method

Examine many different channels and distributions associated with well measured reconstructed objects. Based on the 7 main inclusive final states, look at 117 different final states: For example: $\mathrm{e}^+\mathrm{e}^+$ + 3 jets, μ + 4 jets + $\not{E}_T$. Examine 5543 1-d distributions. Use various statistical methods to quantify consistency (VISTA / SLEUTH).

Select 7 non-overlapping inclusive final states (example: $\mathrm{e}\tau + X$).

Final State	Object	$p_T^{\min}$ (GeV)	$\lvert\eta\rvert^{\max}$
e + jets + X^a	e	35	1.1
	jet	20	2.5
	$\not{E}_T$	20	-
μ + jets + X^b	μ	25	1.5
	jet	20	2.5
	$\not{E}_T$	20	-
$ee + X^c$	e	20	1.1
$\mu\mu + X^d$	μ	15	1.5
$\mu e + X^e$	μ	15	1.5
	e	15	1.1
$e\tau + X^f$	e	15	1.1
	τ	15	1.1
$\mu\tau + X^g$	μ	15	1.5
	τ	15	1.1

arXiv:1108.5362

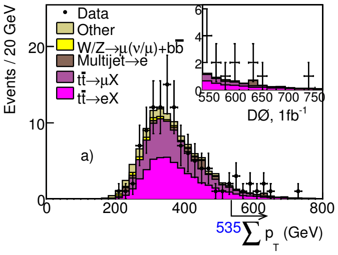
D0 Model-Independent Search

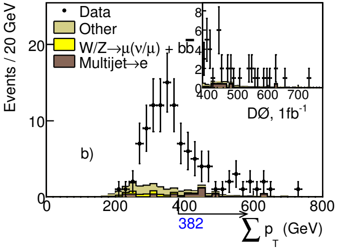
SLEUTH

SLEUTH algorithm is designed to find high-p_T phenomena by scanning a scalar p_T cut to maximize discrepancy between data and MC.
Define a significant output as one with a trials-factor corrected probability, $\overline{P}$ of < 0.001.

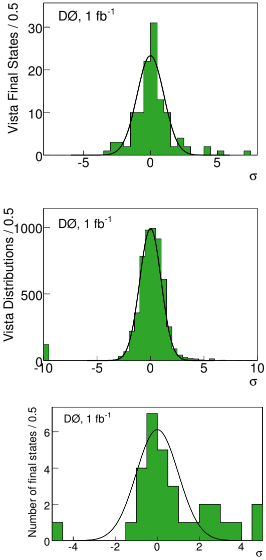
Sensitivity Test

Test with $\ell jjb\overline{b}\,\not{E}_T$. Should be sensitive to the presence or absence of $t\overline{t}$.
$\overline{P} = 0.98$ with $t\overline{t}$.
$\overline{P} < 1.1 \times 10^{-5}$ with no $t\overline{t}$.





D0 Model-Independent Search Results



Bottom-Line

- Global study of D0 high p_T data with 117 final states and 5543 kinematic distributions with 1 fb^{-1} of data.
- 115 of 117 exclusive final states show no statistically significant discrepancy
- Only two exclusive final states show a statistically significant discrepancy ($\mu^+\mu^- \not\!\!E_T$ and $\mu\, j\, j\, \not\!\!E_T$). There are known modeling difficulties in both final states (forward-jet modeling and muon momentum modeling).
- No compelling evidence for new physics from this global study.

D0 stop pair production search in final states with $\mu\,\tau_h$

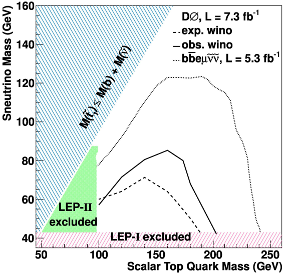
Model

$\tilde{t}_1$ may be the lightest $\tilde{q}$, and may decay by $\tilde{t}_1 \to b\ell\tilde{\nu}$ through a virtual chargino. $\tilde{\nu}$ is either the LSP or decays invisibly.

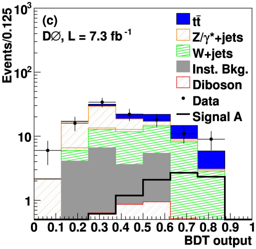
Search

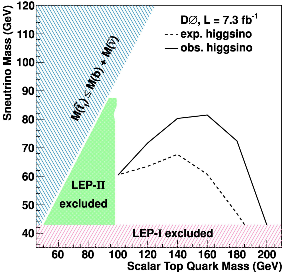
Search for events consistent with $bb\mu\tau\tilde{\nu}\tilde{\nu}$ and $bb\tau\tau\tilde{\nu}\tilde{\nu}$ by looking for $\mu\,\tau_h$. Tau BR can be enhanced if the chargino is Higgsino-like.

arXiv:1202.1978



Example:
njets=2
116 (119.4)
$m(\tilde{t}_1) = 180$
$m(\tilde{\nu}) = 60$
Higgsino





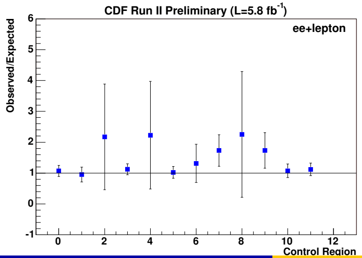
CDF: Searches for New Physics with Trileptons

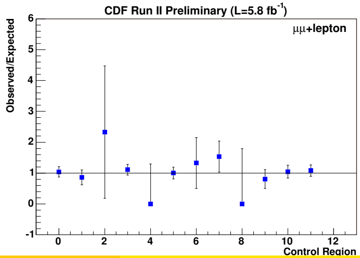
Motivation (CDF Note 10636)

- 3 leptons and $\not{E}_T$ events $\rightarrow$ promising discovery channel in $p\bar{p}$
- General search by CDF in regions of di-lepton mass, $\not{E}_T$ and jet multiplicity.
- Include di-lepton + track events.
- Extend pT acceptance to 5 GeV, and to forward region.

Definition of Control and Signal Regions

Region	$M_{\ell\ell}$ cut (Gev/c^2)	($\not{E}_T$) cut (GeV)	N_{jet} cut
Region0	$M_{\ell\ell} > 20$	$\not{E}_T < 10$	–
Region1	$76 < M_{\ell\ell} < 106$	$\not{E}_T > 15$	$N_{jet} \leq 1$
Region2	$76 < M_{\ell\ell} < 106$	$\not{E}_T > 15$	$N_{jet} \geq 2$
Region3	$20 < M_{\ell\ell} < 76$ or $M_{\ell\ell} > 106$	$\not{E}_T < 10$	$N_{jet} \leq 1$
Region4	$20 < M_{\ell\ell} < 76$ or $M_{\ell\ell} > 106$	$\not{E}_T < 10$	$N_{jet} \geq 2$
Region5	$76 < M_{\ell\ell} < 106$	$\not{E}_T < 10$	$N_{jet} \leq 1$
Region6	$76 < M_{\ell\ell} < 106$	$\not{E}_T < 10$	$N_{jet} \geq 2$
Region7	$20 < M_{\ell\ell} < 76$ or $M_{\ell\ell} > 106$	$\not{E}_T > 15$	$N_{jet} \leq 1$
Region8	$20 < M_{\ell\ell} < 76$ or $M_{\ell\ell} > 106$	$\not{E}_T > 15$	$N_{jet} \geq 2$
Region9	$20 < M_{\ell\ell} < 76$ or $M_{\ell\ell} > 106$	$\not{E}_T > 20$	$N_{jet} \leq 1$
Region10	$76 < M_{\ell\ell} < 106$	–	–
Region11	$M_{\ell\ell} > 20$	–	–





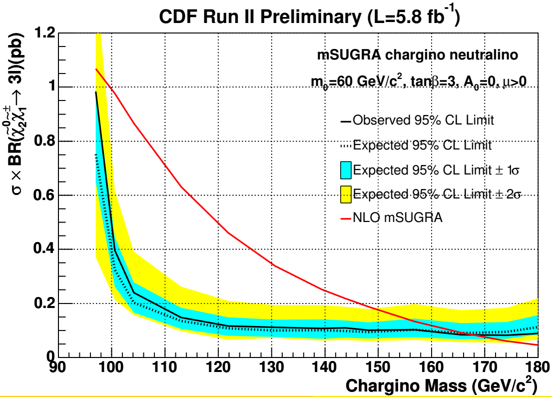
CDF Chargino-Neutralino Limits

SUSY trileptons

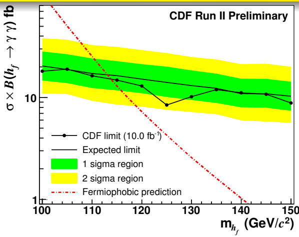
One potential signature of supersymmetry is $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production with leptonic decays of $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$. Production occurs through s-channel W and potentially t-channel squarks. Leptonic decays can be enhanced over expectations from W and Z leptonic branching ratios if sleptons are light.

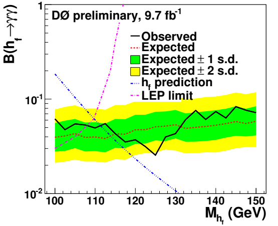
CDF result

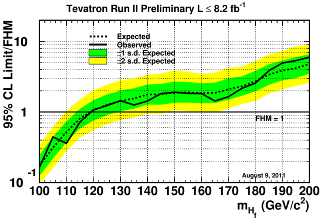
Use $\not{E}_T > 15\text{GeV}$, $N_{\text{jet}} \leq 1$ and Z-mass veto region. Apply kinematic cuts consistent with each mSUGRA hypothesis. Exclude $97 < m(\tilde{\chi}_1^{\pm}) < 168$ GeV for this light sfermion model line.



Fermio-phobic Higgs







CDF and D0 Results

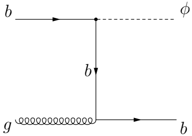
- Higgs may have much suppressed or no coupling to fermions
- If so, gluon-fusion production suppressed and $\gamma\gamma$ (low mass) and WW BRs enhanced
- CDF and D0 have updated $\gamma\gamma$ results
- Now exclude significantly beyond LEP2 limit of 108 GeV

Mass Limits	Obs. (Exp.) (GeV)
CDF ($\gamma\gamma$)	114 (113)
D0 ($\gamma\gamma$)	111.4 (114)
Tevatron (All)*	119 (119)

D0 MSSM Higgs

Motivation

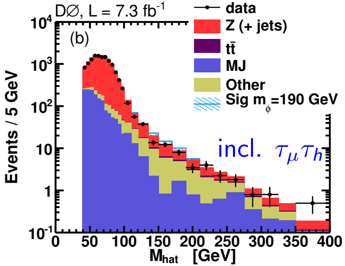
In MSSM, the neutral Higgs particles, h,H,A (denoted ϕ) decay mainly to $b\bar{b}$, $\tau^+\tau^-$. So look for $\phi \to \tau^+\tau^-$ and associated production $b\phi$.

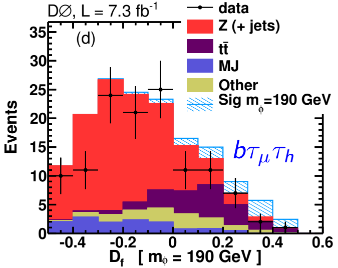


D0 Search

Search for $\phi \to \tau_\mu \tau_h$, $b\phi \to b\tau_\mu\tau_h$, and $b\phi \to bb\bar{b}$.

Signal shown: $m_h^{\max}$ scenario, $\tan\beta = 40$, $\mu = +200$ GeV

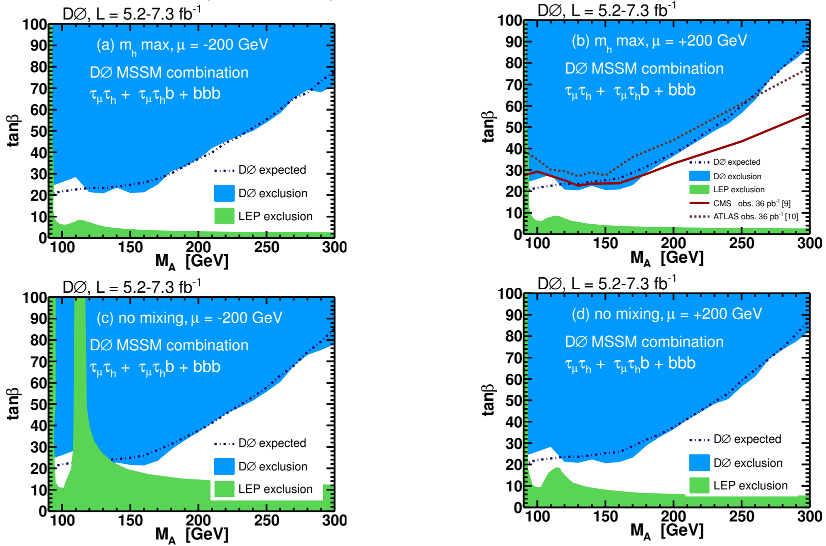




D0 MSSM Higgs Limits

Main channels are $\tau_\mu\tau_h$ and $b\tau_\mu\tau_h$

arXiv:1112.5431



Very competitive with published LHC results from 2011

Concluding Remarks

Concluding Remarks

- The RunII era of the Tevatron experiments' data-taking is over
- Spotlight for collider-based new phenomena searches is now with the LHC
- The Tevatron experiments have finalized many search results
- Hints of new physics? D0's like-sign di-muon asymmetry is still very intriguing. Not clear the field will have any direct independent answers any time soon. Looks like a CP violation measurement that merits investigation
- Hadron collider searches are setting limits on the same dark-matter nucleon cross-sections that are probed in direct dark matter detection experiments
- Overall, the Tevatron has been a facility which has led to about 1000 papers on a wide variety of physics subjects
- The scientific breadth we have seen from facilities like LEP, PEP2 and the Tevatron, and of course now the LHC, should also be factored into decisions on future projects in our field

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