Searches for New Phenomena

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- Introduction
- Searches at the Tevatron
  - B_s->$\mu\mu$
  - trileptons
  - Squarks and Gluinos
  - diphotons
- Summary

Yeti'05, January 2005, Durham

Beyond the Standard Model

- Many things to be discovered?
  - SUSY particles
  - Non-SM Higgs bosons
  - Large Extra Dimensions
  - New Gauge bosons (Z′, W′)
  - Leptoquarks
  - Technicolor particles
  - Others?
- Experiments need to be open and cover any possible signature (as manpower allows)!

Cover "all" signatures…

- New Physics Models are good for:
  - Benchmarking and comparing to other experiments
  - helping theorists to further develop models
  - Gudiance on experimental signature, choice of cuts etc.
- But, should not be too biased towards them
  - Experimentally we should try to find anything, independently of whether predicted or not
  - Who knows what may be out there!
  - Trying to cover ALL experimental signatures (usually you can always find a model that fits it):
    - Not trivial, large combinatorics with e,μ,τ,,ν,j,b,c and e.g. 6-object final states!
    - Manpower limited

SUSY: mSugra inspired

sparticle	Decay Mode				
squark	jjχχ				
stop	ccχχ	lvlvbb	lvjjbbχχ	jjjjbbχχ	stable
sbottom	bbχχ	bbbbχχ			
stau	stable	τν			
$\chi^0_2\chi^+$	lllχ (l=e.μ)	τττχ			
gluino	bbbbχχ	Jets+χχ	LS ll		
indirect	B_s->μμ				

Yellow: Covered in this talk

White: Ongoing in CDF

Over 60 searches ongoing at both CDF and D0!

How to Search for New Physics

- Find favourite model/signature: make MC
- Try to define "control regions" to get confidence in background estimates
- Optimise cuts to maximise sensitivity
  - maximise parameter space
  - choose simple/intuitive cuts as much as possible
- Compare data to SM prediction
- Derive limit on cross section x BR
- Interpret data in your model, best close to what you are searching for: e.g. not M_0, $M_{1/2}$ but rather m(squark)

How to do a Search? (example)

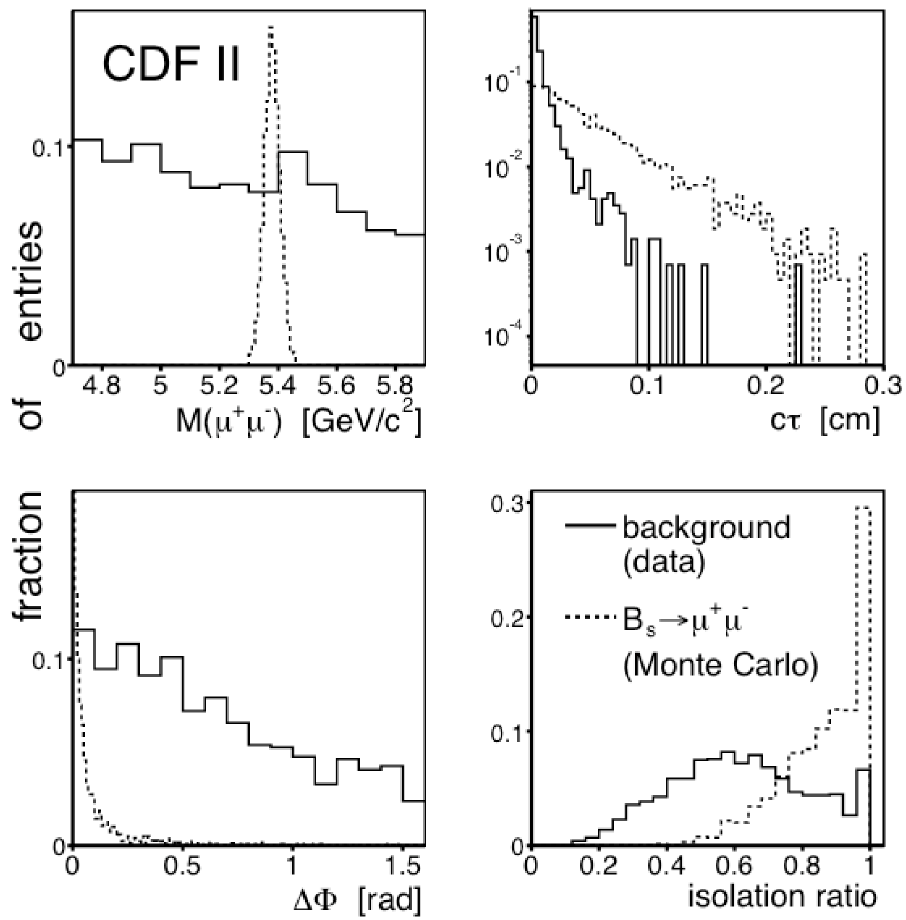
- Example: BR(B_s->$\mu\mu$)
- Need to:
  - Know the background: Bgd
  - Know the acceptance and efficiency: α and ε
  - Know the B_s production cross section σ_{Bs}
  - Know uncertainties on those

$$\langle BR(B_s \rightarrow \mu\mu)\rangle = \frac{(N_{candidates} - Bgd)}{\alpha \cdot \varepsilon_{total} \cdot \sigma_{Bs} \cdot \int Ldt}$$

- This case: "blind"
  - Signal/Blind region: |m($\mu\mu$)-m(B_s)|<100 MeV,cτ>0
  - "Side band" region: |m($\mu\mu$)-m(B_s)|>100 MeV,cτ<0
  - Understand background from side bands
  - Understand signal from MC
  - Don't look at data until the end=> "blind"

Cut Optimisation

- Select ≈3000 events with
  - 2 muons with p_t>2 GeV
  - $P_t(\mu\mu)$>6 GeV
  - 4.669<M(μμ)<5.969 GeV
- Discriminant variables:
  - Dimuon mass
  - Lifetime: ct
  - Δϕ between muons
  - Isolation of B_s
- Cuts optimised to yield maximal Signal/√Bgd



Background Prediction

- Background:
  - Random muons from cc and bb
  - QCD jets -> pion/kaon->mu+X
  - Cannot estimate using MC => use "side bands"
- Define control regions
  - Same sign muons
  - Lifetime<0 (due to misreconstruction)
- Get confidence in background prediction!

- Compare N(expected) vs N(observed) for three different sets of cuts
  - A : ($c\tau$,$\Delta\Phi$,Iso) = (>100μm, <0.20 rad, >0.60)
  - B : ($c\tau$,$\Delta\Phi$,Iso) = (>150μm, <0.20 rad, >0.70)
  - C : ($c\tau$,$\Delta\Phi$,Iso) = (>200μm, <0.10 rad, >0.80)

	Sample	N(expctd)	N(obsrvd)	P(>=obs|exp)
A	OS-	10.43 +/- 1.89	16	4%
	SS+	5.80 +/- 0.98	4	83%
	SS-	6.72 +/- 1.10	7	51%
	Sum	22.94 +/- 3.14	27	
B	OS-	3.69 +/- 0.80	6	17%
	SS+	1.83 +/- 0.35	1	84%
	SS-	2.32 +/- 0.42	4	20%
	Sum	7.84 +/- 1.19	11	
C	OS-	0.64 +/- 0.22	1	47%
	SS+	0.29 +/- 0.08	0	75%
	SS-	0.27 +/- 0.08	1	24%
	Sum	1.21 +/- 0.27	2	

Signal Acceptance

- Does MC reproduce cut variables?
- Use $B^+ \to J/\psi + K^+$ as control sample
  - E.g. test isolation cut of Iso>0.65
  - MC reproduces J/Psi data well
- Assign 5% syst. Error on MC modelling

		Data	MC	(Data/MC)
	Iso > 0.6	(95 +/- 2)%	(97 +/- 1)%	0.98 +/- 0.02
	Iso > 0.7	(88 +/- 2)%	(92 +/- 1)%	0.96 +/- 0.03
	Iso > 0.8	(68 +/- 2)%	(79 +/- 2)%	0.87 +/- 0.04
$c\tau>100\mu m$	$\Delta\Phi < 0.2$	(98 +/- 2)%	(97 +/- 1)%	1.00 +/- 0.02
$c\tau>100\mu m$	$\Delta\Phi < 0.1$	(89 +/- 3)%	(89 +/- 1)%	0.99 +/- 0.03
$c\tau>150\mu m$	$\Delta\Phi < 0.2$	(99 +/- 1)%	(99 +/- 1)%	1.00 +/- 0.01
$c\tau>150\mu m$	$\Delta\Phi < 0.1$	(92 +/- 2)%	(93 +/- 1)%	0.99 +/- 0.02

Final upshot:

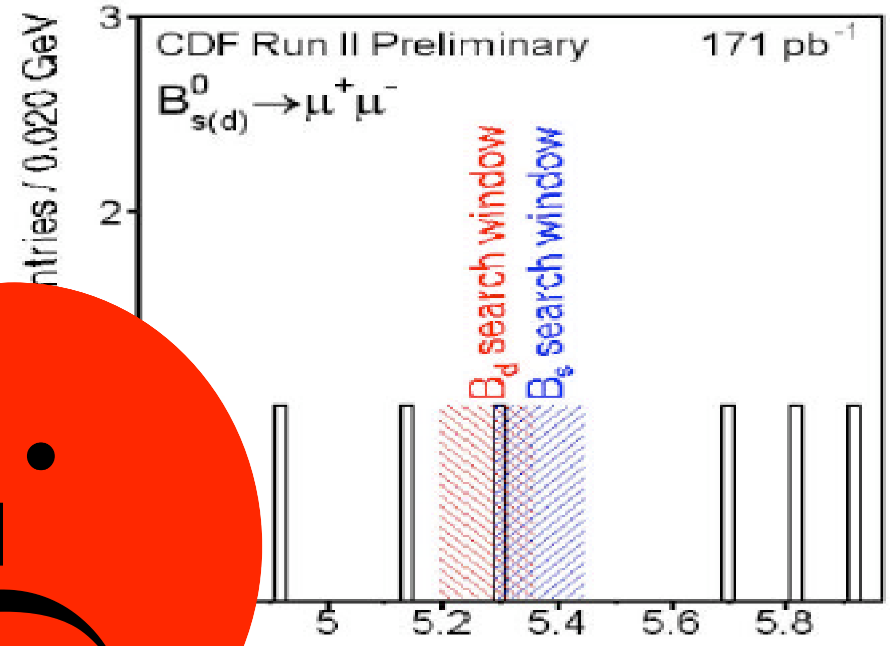
$\alpha^*\varepsilon$(total) = (2.03 +/- 0.21)%

Bgd: 1.1+/-0.3 events

=> Let's open the blind box!

Opening the "Box": Bs->$\mu\mu$

	D0	CDF
expected	3.7±1.1	1.1±0.3
observed	4	1
BR@90% C.L.	<5.0x10^{-7}	<7.[illegible]



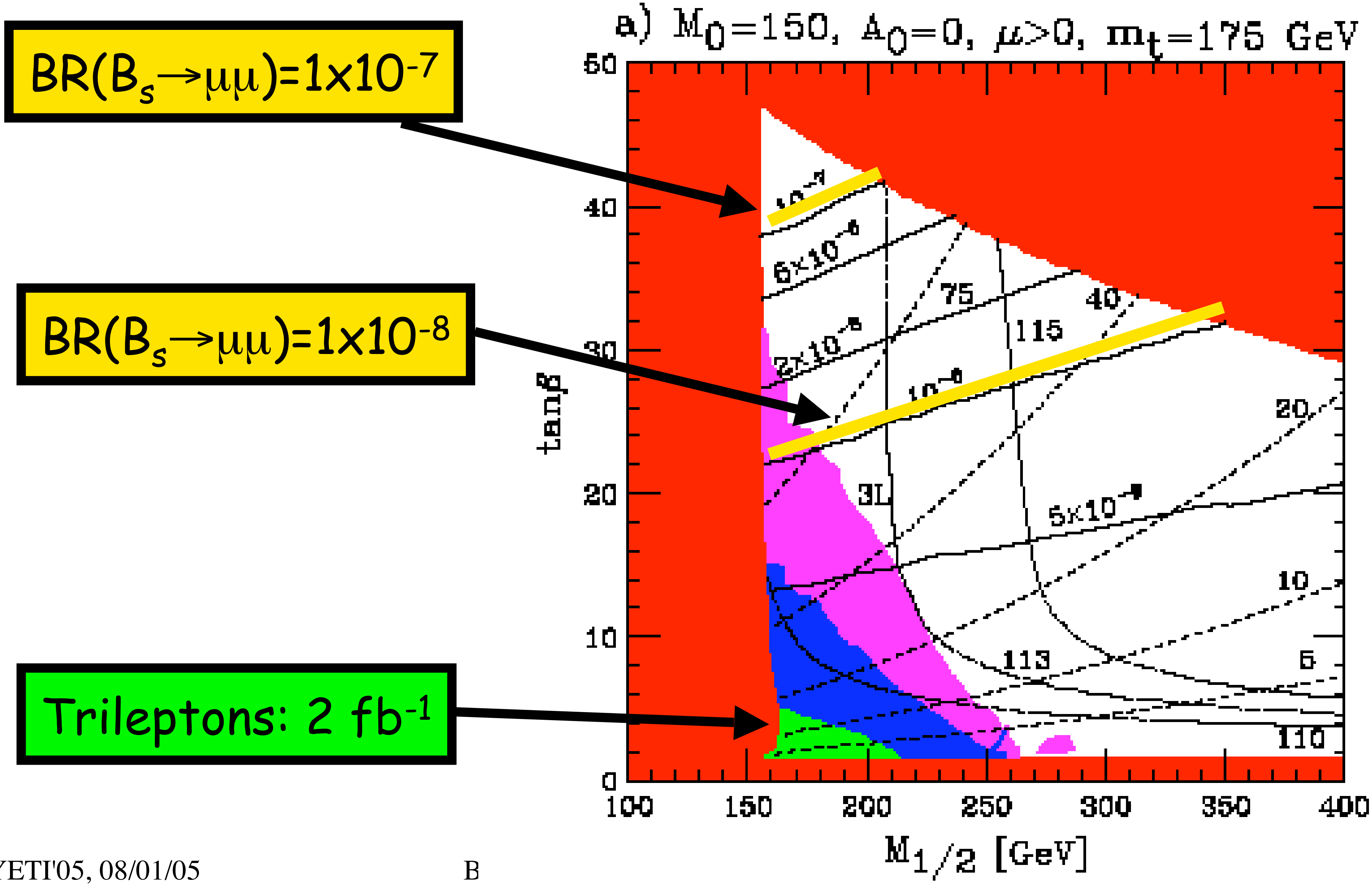
Too bad! But nevermind, I can constrain new physics then!

Calculating a limit

- Different methods:
  - Bayes
  - Frequentist
  - …
- Source of big arguments amongst statisticians:
  - Different method mean different things
  - Say what YOU have done
  - There is no “right” way
- Treatment of syst. Errors somewhat tricky
- But basically:
  - Calculate probability that data consistent with bgd+new physics:
    - $P=e^{-\mu}\mu^N/N!$
    - N = observed events
    - μ is $N_{BG} + N_{new}$
    - P=5% => 95% CL upper limit on N and thus σxBR=N/(αL)
- E.g.:
  - 0 events observed means <2.7 events at 95%C.L.

Trileptons vs B_s->μμ

A. Dedes, H. Dreiner, U. Nierste, P. Richardson , hep-ph/0207026)

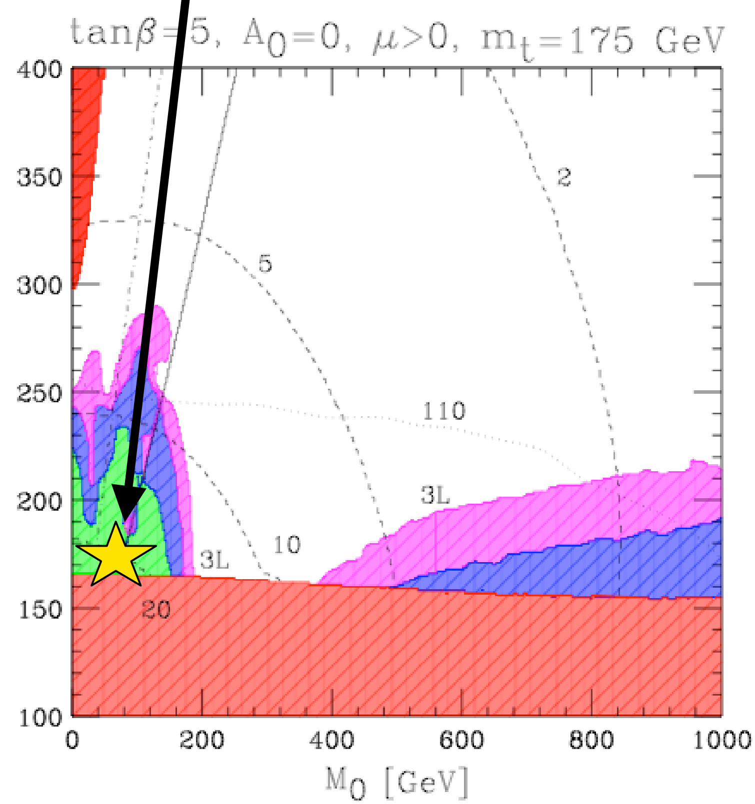


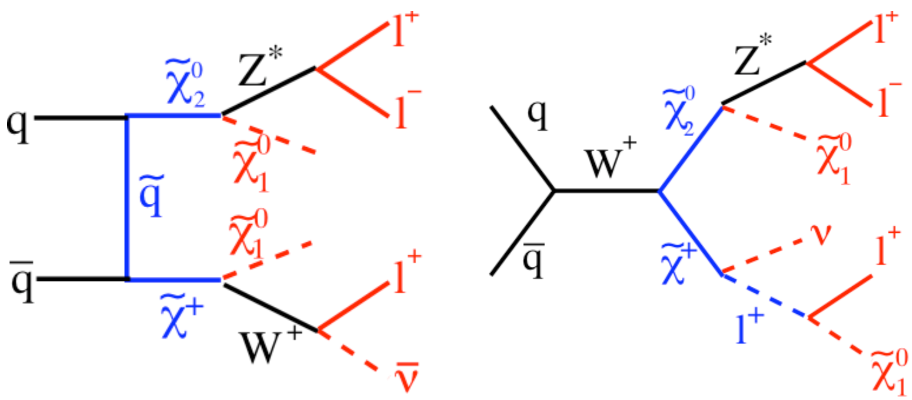
Trileptons

- Trileptons (e.g. $pp \to e^+e^-\mu^+\nu_\mu$):
  - Result from chargino and neutralino decays
  - Sensitive to low $\tan\beta$ (else τ's dominate which are harder)
  - Negative interference between t-channel and s-channel diagrams
  - Two competing effects:
    - *Cross section largest of squark mass large*
    - *BR to leptons largest if slepton mass low*

Current analysis:

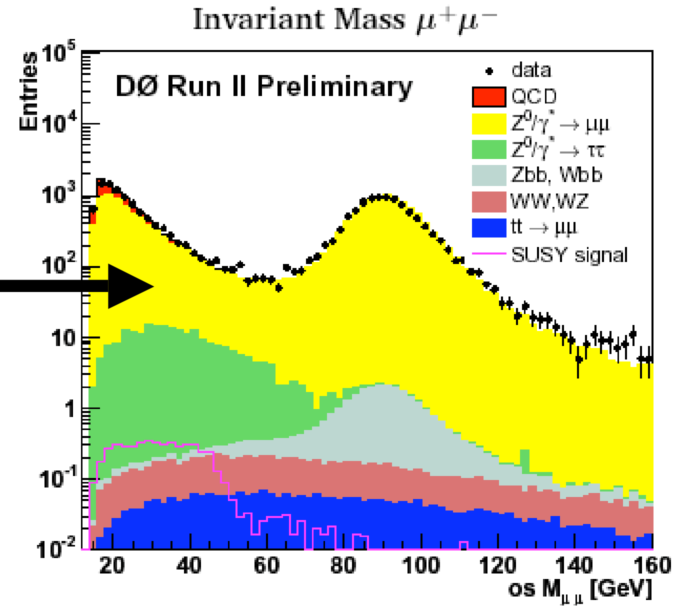
M_0=75 GeV, M_{12}=175 GeV





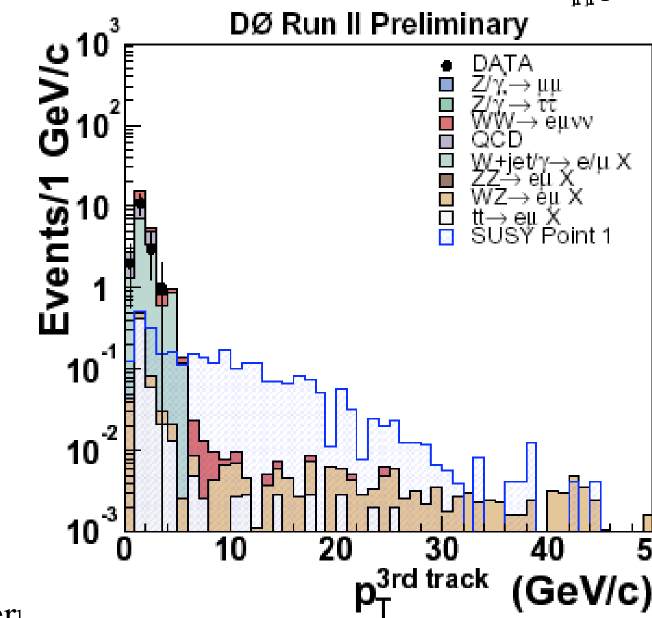
3 leptons + $\not{E}_T$

- Challenge:
  - σxBR low (<0.5 pb)
  - Backgrounds large



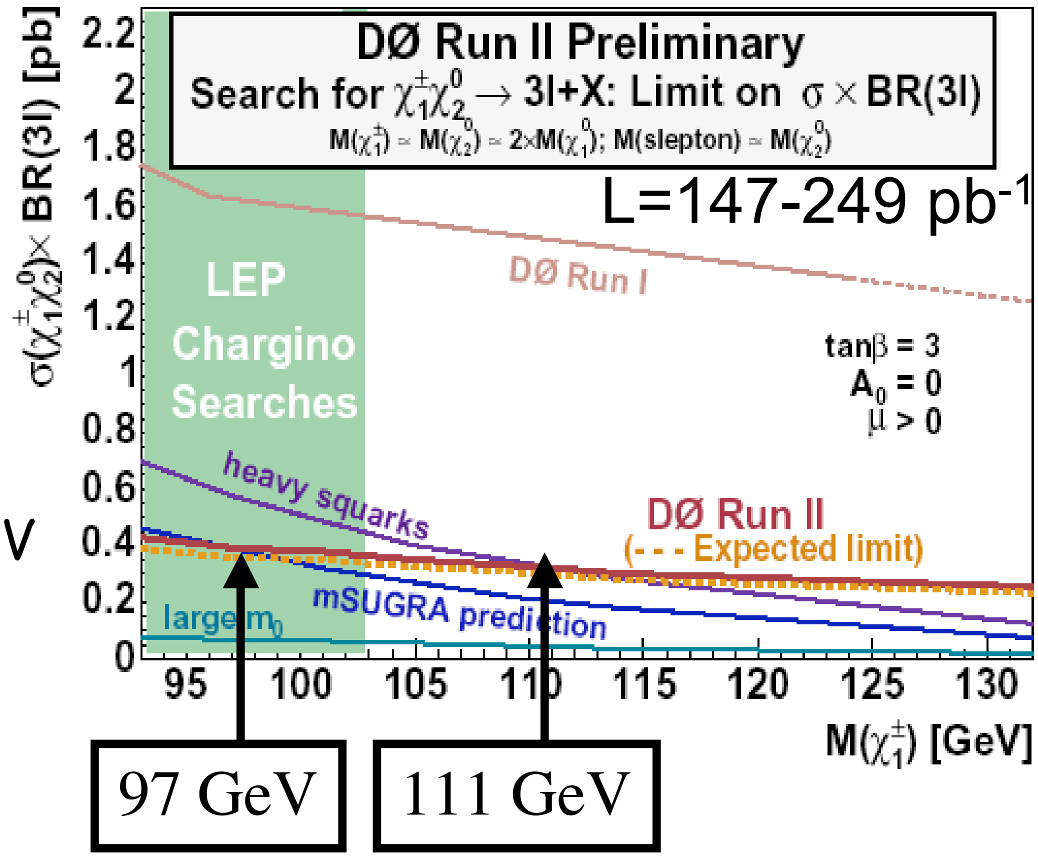
- Selection
  - eel, μμl, eμl (l=isol. track)
  - Significant $\not{E}_T$
  - Topological cuts

selection	background	observed
eel	0.7±0.5	1
eμl	0.3±0.3	0
μμl	1.8±0.4	1



3-lepton result

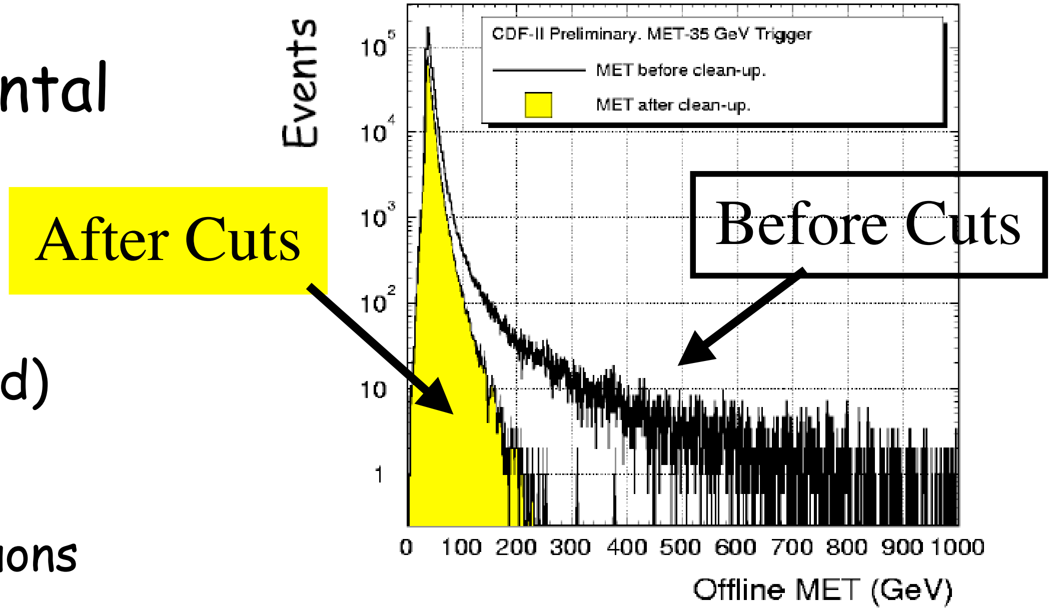
- Combined result:
  - $\sigma \times BR < 0.3$-0.4 pb
- Theory comparison
  - mSugra: $m(\chi^{\pm}) > 97$ GeV
    - $\tan\beta = 3$, $A_0 = 0$, $\mu > 0$
    - $M(\chi^{\pm}) \approx M(\chi^0_2) \approx 2M(\chi^0_1)$
  - Heavy squarks: $m(\chi^{\pm}) > 111$ GeV
    - Reduce destructive interference
  - Large m_0:
    - Sleptons heavy
    - Very difficult



Will extend sensitivity to mSUGRA beyond LEP with just 25% more data: Factor two more already on tape!

Missing Et

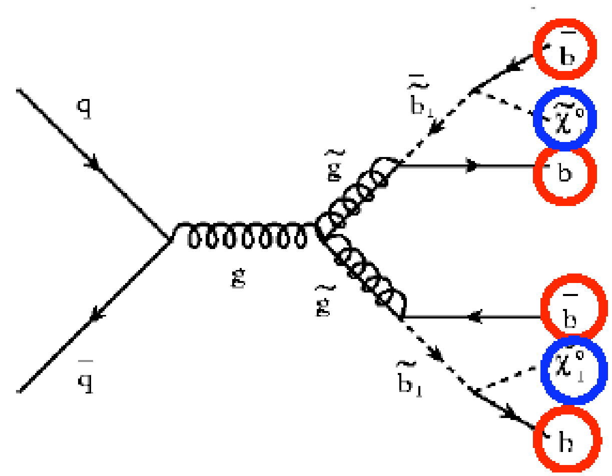
- Most difficult experimental quantity!
- Sources:
  - Genuine due to ν,χ (wanted)
  - Instrumental (unwanted):
    - Cosmic and beam halo muons showering in calorimeter
    - Noise
    - Beam splashes into detector
    - Mismeasured jets
    - Uninstrumented parts (cracks) in detector



- At high Et mostly junk!
- Removed by cuts, e.g.
  - Track towards jet
  - Beam halo filters
  - Cosmic filters, timing cuts
  - etc.

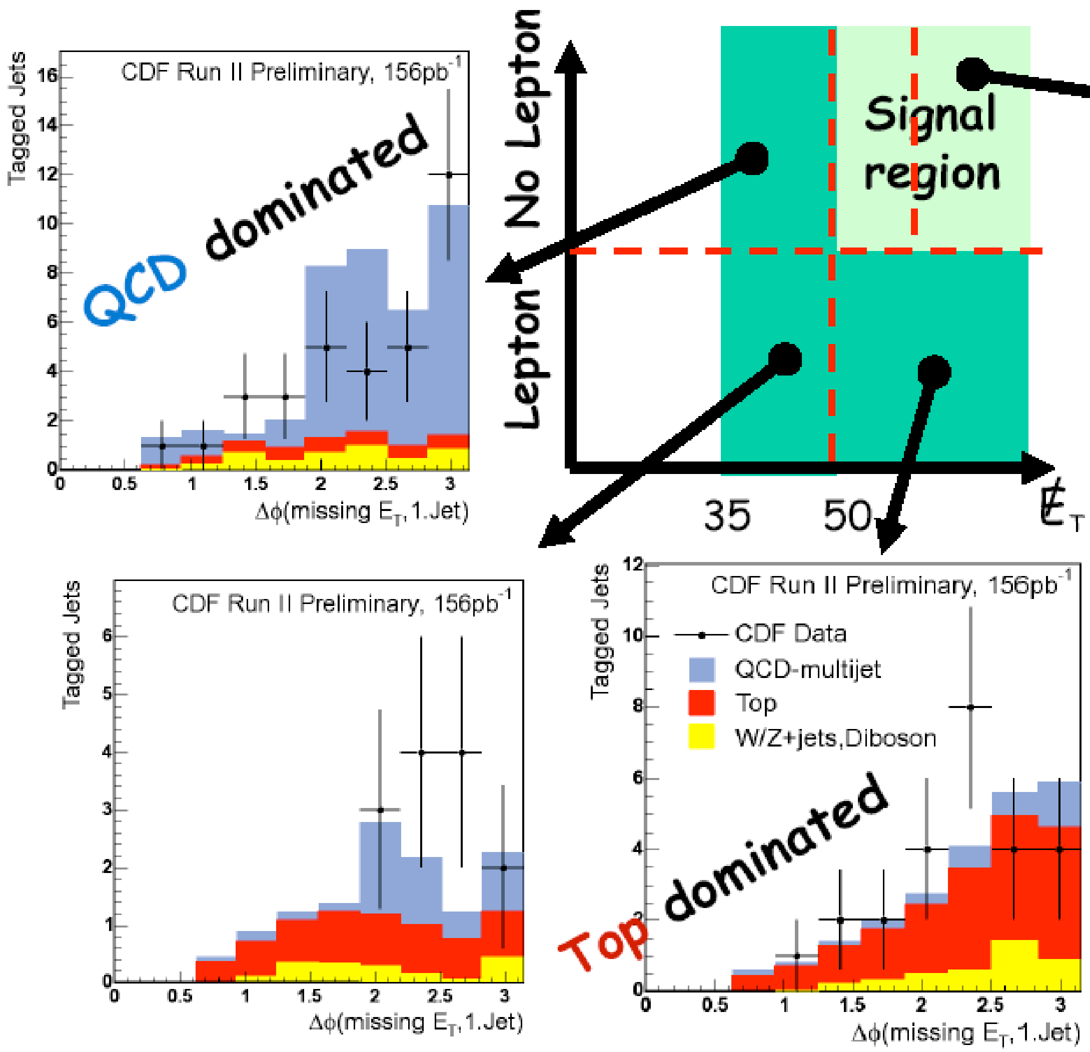
Bottom Squarks

- High tanβ scenario:
  - Sbottom could be "light"
- This analysis:
  - Gluino rather light: 200-300 GeV
  - BR($\tilde{g}\to b\tilde{b}$)~100% assumed
- Spectacular signature:
  - 4 b-quarks + $\not{E}_t$
- Require b-jets and $\not{E}_t$>80 GeV
- Again "blind" analysis
  - define control regiosn to check backgrounds



- Backgrounds:
  - QCD bb + fake E_t
  - EWK backgrounds:
    - Wbb->lνbb (l=e,μ,τ)
    - Zbb->ννbb
  - Top background:
    - tt->lνjjbb
    - tt->jjjjbb

Control of Backgrounds

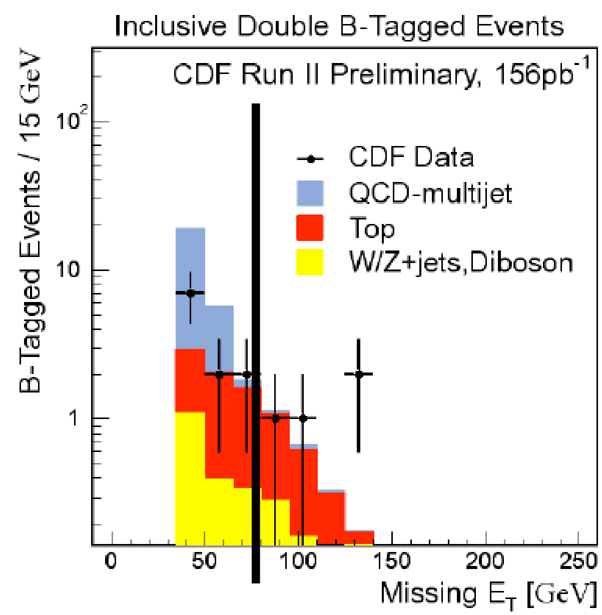


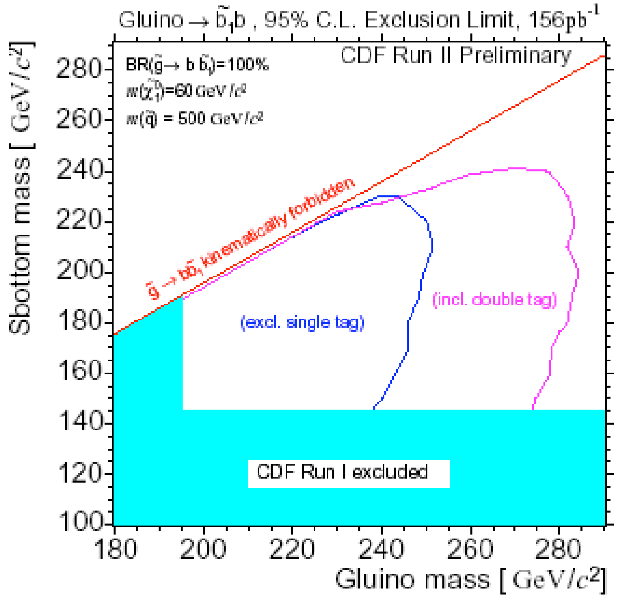
Define three control regions, based on $\not\!\!E_T$ and lepton requirement to provide cross-check for background predictions.

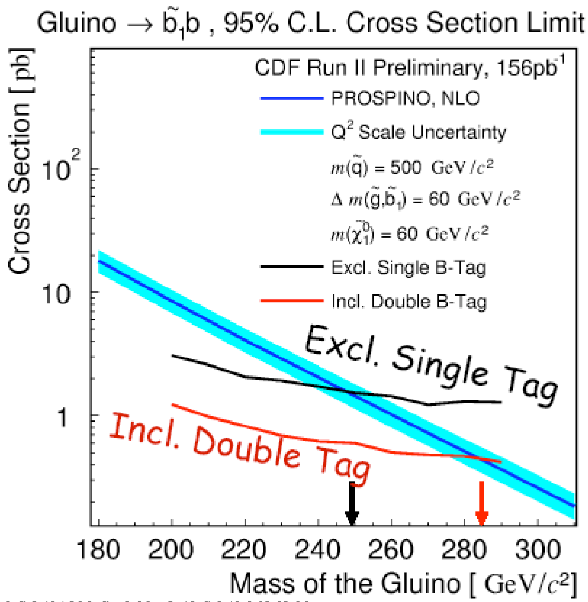
Control regions in agreement with SM predictions

Bottom Squarks

- Result for 2 b-jets:
  - Expect 2.6 +- 0.7 events
  - Observe: 4 events
- Data consistent with expectation
  - Derive limit on cross sectionxBR
  - Derive limit on sbottom and gluino masses

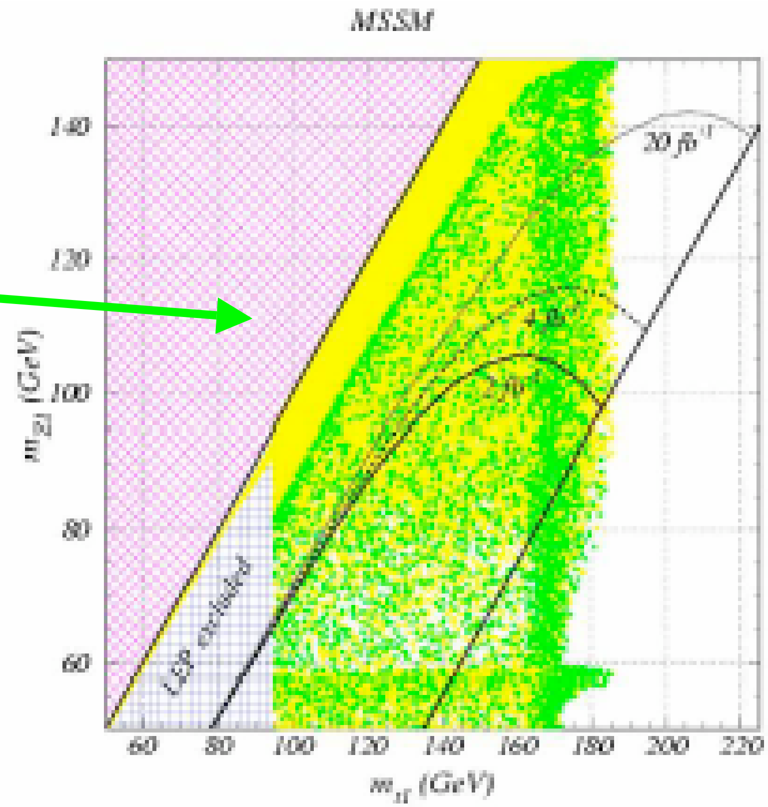






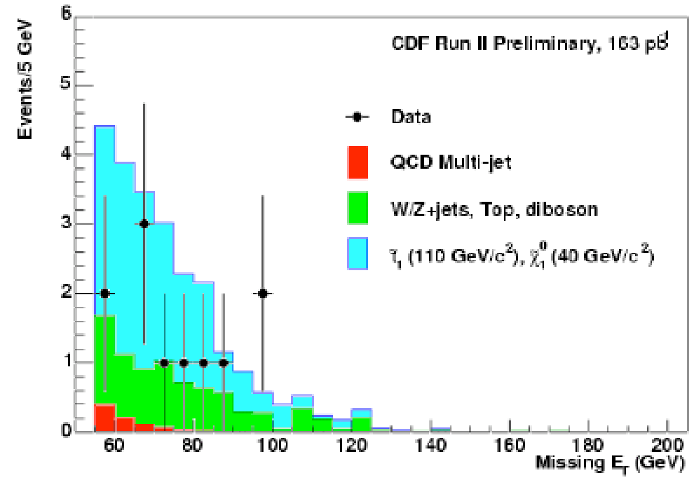
Light Stop-Quark: Motivation

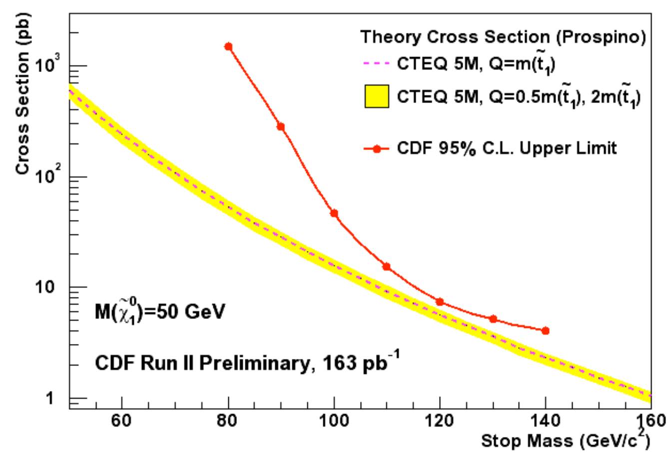
- If stop is light: decay only via $t \to c\chi_1^0$
- E.g. consistent with relic density from WMAP data
  - hep-ph/0403224 (Balazs, Carena, Wagner)
  - Ω_{CDM}=0.11+−0.02
  - $M(t)-M(\chi_1^0) \approx 15$-30 GeV
- Search for 2 charm-jets and large $\not{E}_t$:
  - E_t(jet)>35, 25 GeV
  - $\not{E}_t$>55 GeV



Light Stop-Quark: Result

- Data consistent with background estimate
  - Observed: 11
  - Expected: $8.3^{+2.3}_{-1.7}$
- Main background:
  - Z+ jj -> ννjj
  - W+jj -> τνjj
- Systematic error large: ≈30%
  - ISR/FSR: 23%
  - Stop cross section: 16%
- Not quite yet sensitive to cross section

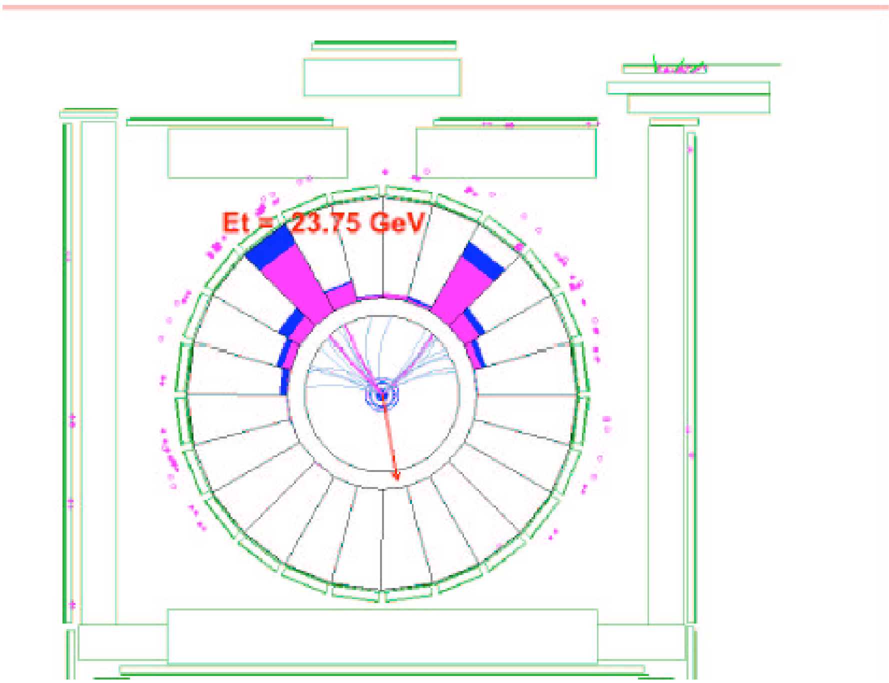


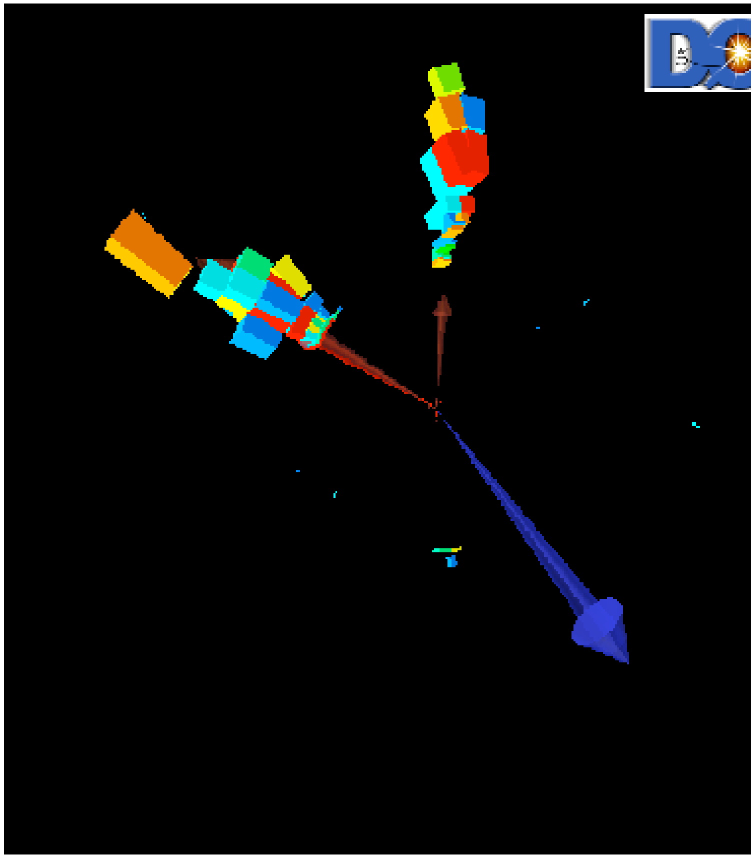


Candidate Events

CDF stop cand.:
$\not{E}_t$=53 GeV, 2 charm-jets

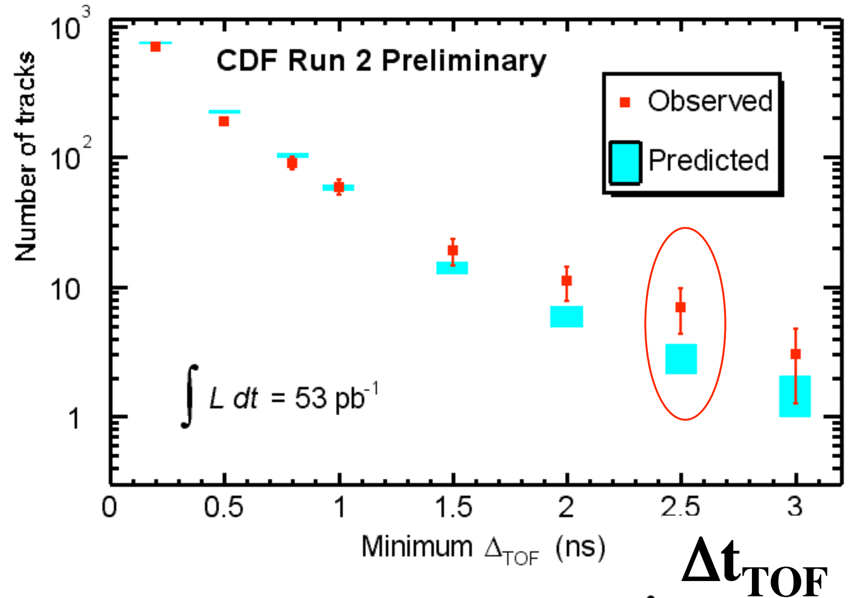
D0 squark/gluino cand.:
$\not{E}_t$=375 GeV!!!

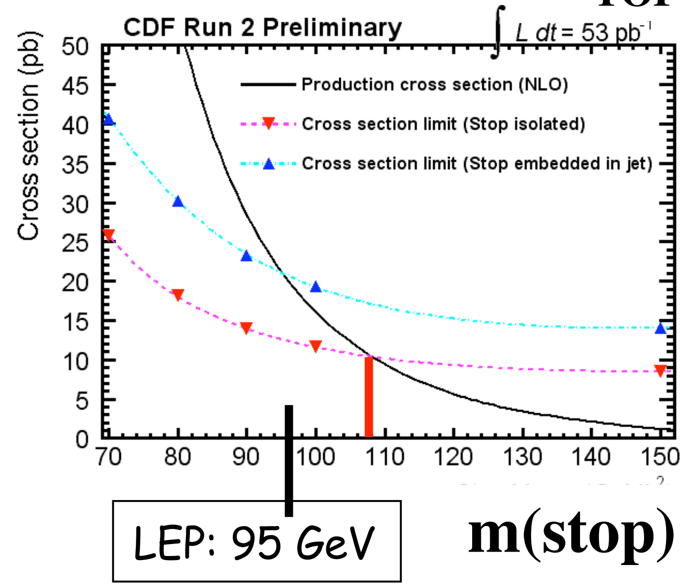




Quasi-stable Stop Quarks

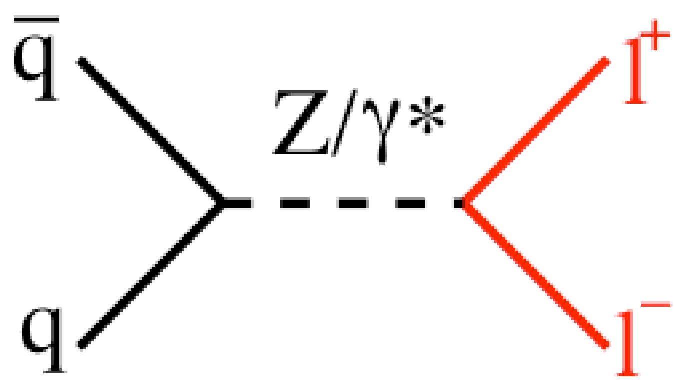
- Model:
  - any charged massive particle (e.g. stop, stau) with long lifetime: "quasi-stable"
  - Assume: fragments like b-quark
- Signature
  - Use Time-Of-Flight Detector:
    - $R_{TOF} \approx 140$cm
    - Resolution: 100ps
  - Heavy particle=> v<<c
  - $\Delta t_{TOF} = t_{track} - t_{event}$ = 2-3 ns
- Result for Δt_{TOF} >2.5 ns:
  - expect 2.9±3.2, observe 7
- σ<10-20pb at m=100 GeV
- $M(\tilde{t})$>97-107 GeV @ 95%C.L.

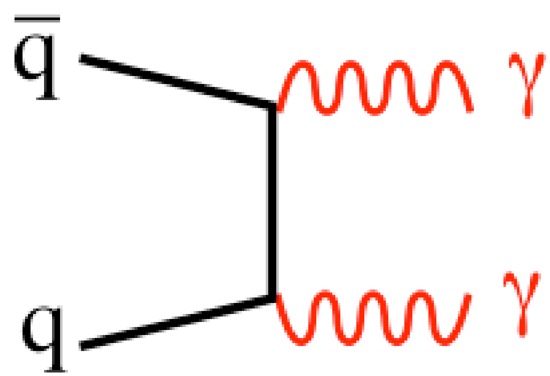




High Mass Dileptons and Diphotons

Standard Model high mass production:



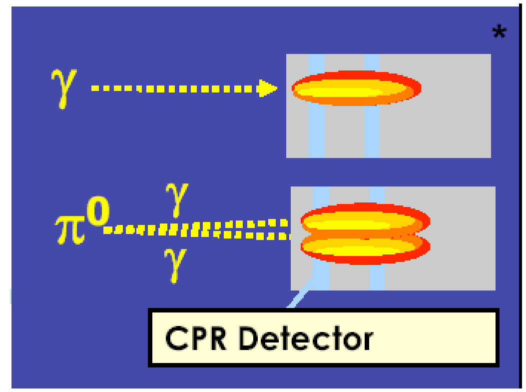


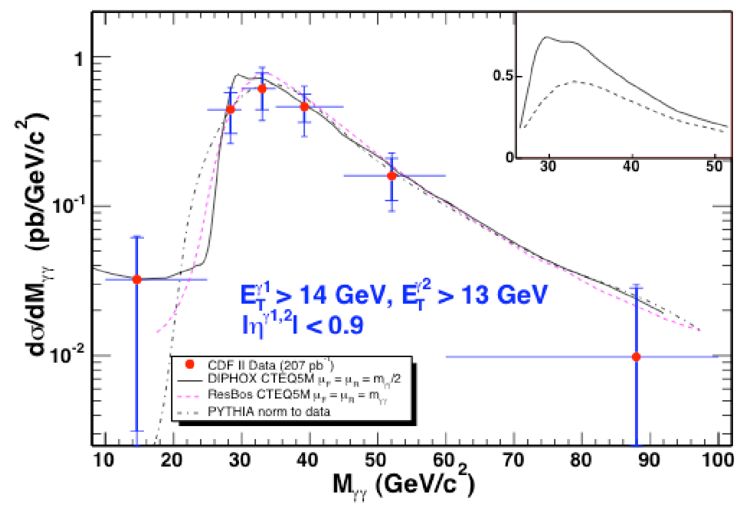
New physics at high mass:

- Resonance signature:
  - Spin-1: Z′
  - Spin-2: Randall-Sundrum (RS) Graviton
  - Spin-0: Higgs
- Tail enhancement:
  - Large Extra Dimensions: Arkani-Hamed, Dimopoulos, Dvali (ADD)
  - Contact interaction

Di-Photon Cross Section

- Select 2 photons with E_T>13 (14) GeV
- Statistical subtraction of BG (mostly $\pi^0 \rightarrow \gamma\gamma$):
  - Hard to control
  - MC cannot be trusted
  - Measure in data
- Data agree well with NLO (DIPHOX, RESBOS)
- PYTHIA describes shape (but normalisation off by factor 2)





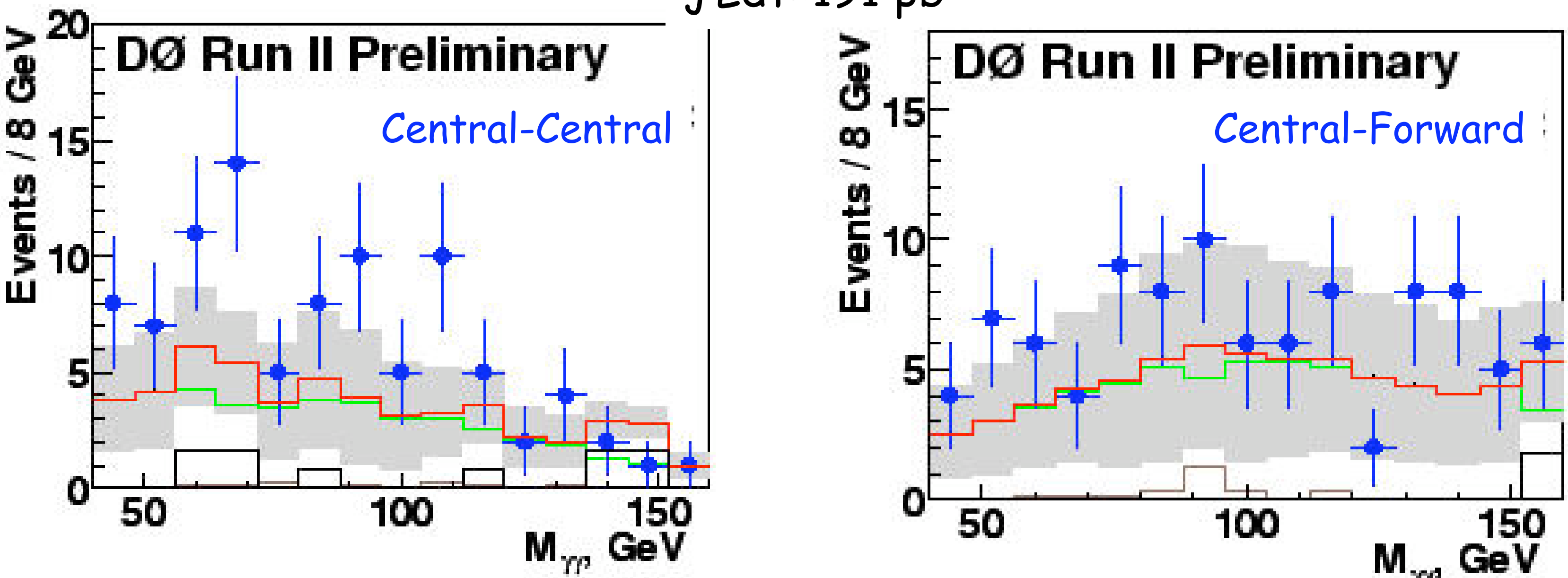
$M_{\gamma\gamma}$ (GeV)

Non-SM Light H→γγ

- Some extensions of SM contain Higgs w/ large B(H→γγ)
  - Fermiophobic Higgs : does not couple to fermions
  - Topcolor Higgs : couples to only to top (i.e. no other fermions)
- Important discovery channel at LHC

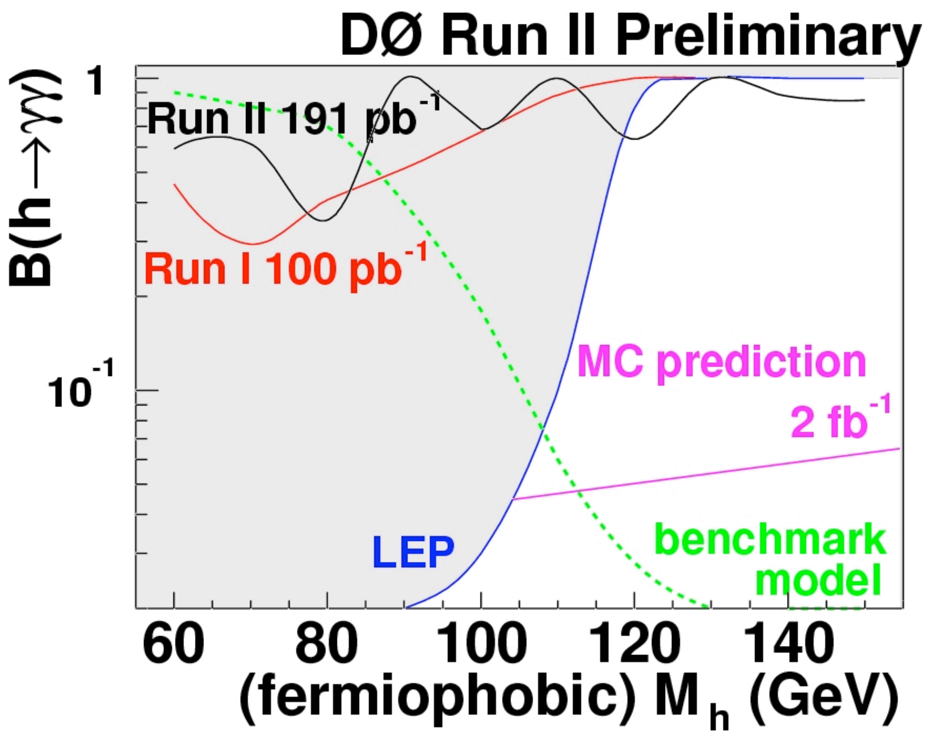
- Event selection
  - 2 Isolated γ's with
    - pT > 25 GeV
    - |η|<1.05 (CC) or 1.5<|η|<2.4 (EC)
  - p_T (γγ) > 35 GeV (optimised)
- BG: mostly jets faking photons
  - Syst. error about 30% per photon!
  - Estimated from Data

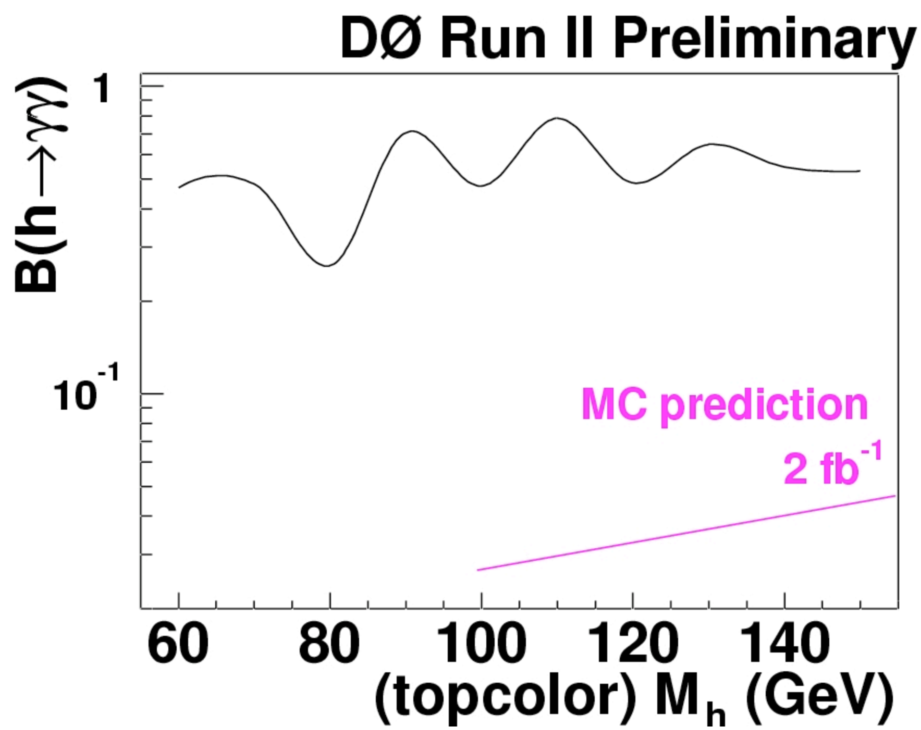
$\int Ldt = 191\ pb^{-1}$



Non-SM Light Higgs H→γγ

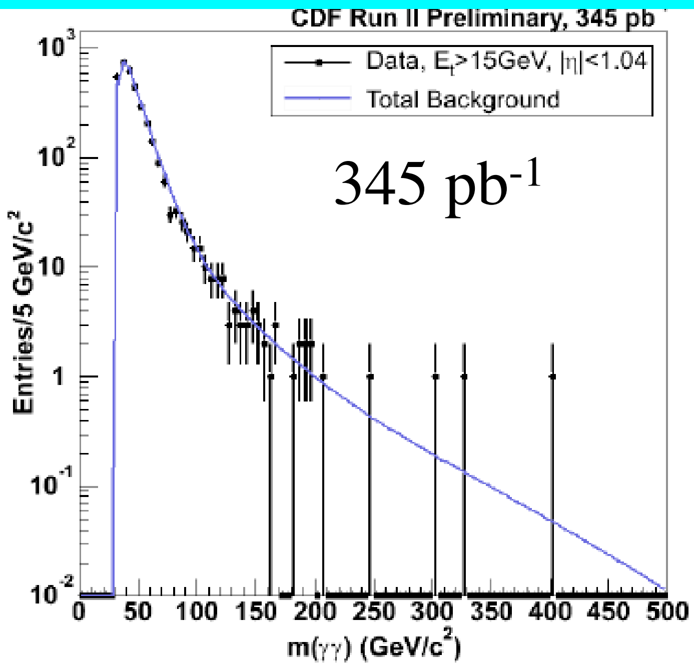
Perform counting experiments on optimized sliding mass window to set limit on B(H→γγ) as function of M(H)

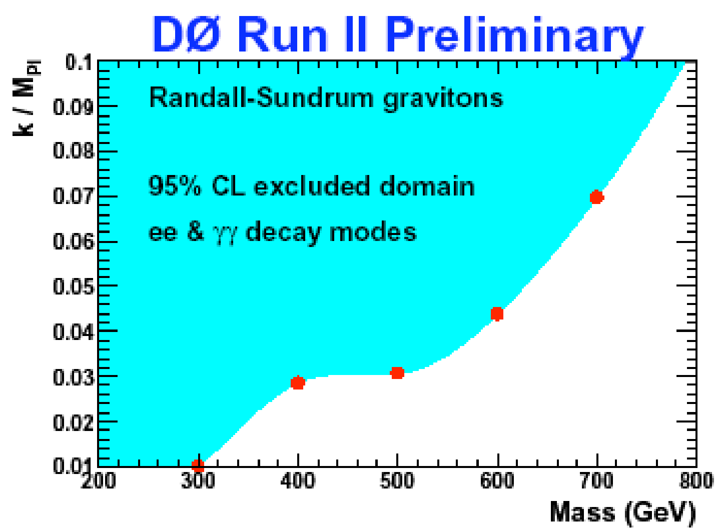




Randall-Sundrum Graviton

- Analysis:
  - D0: combined ee and $\gamma\gamma$
  - CDF: separate ee, $\mu\mu$ and $\gamma\gamma$
- Data consistent with background
- Relevant parameters:
  - Coupling: k/M_{Pl}
  - Mass of 1st KK-mode
- World's best limit from D0:
  - M>785 GeV for k/M_{Pl}=0.1





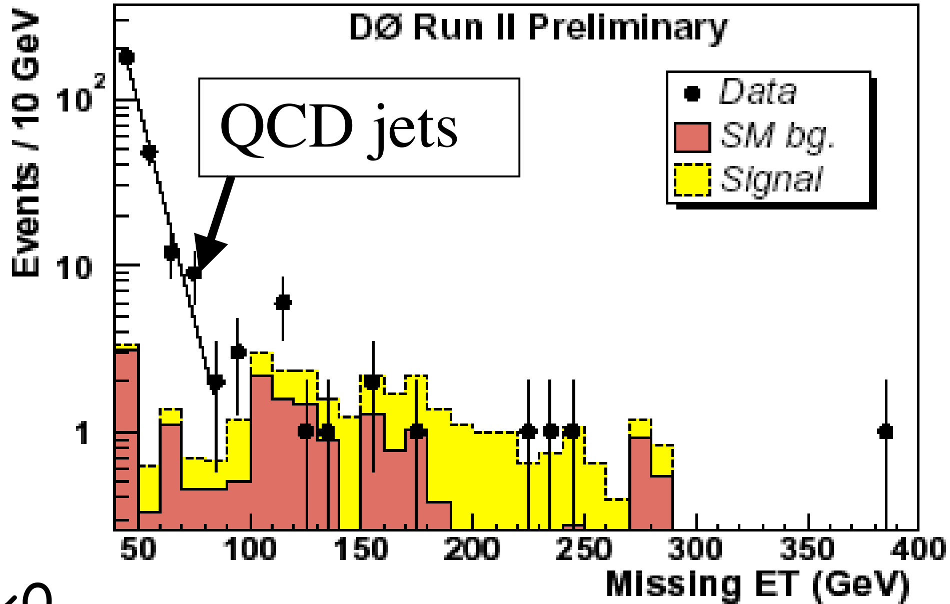
Summary

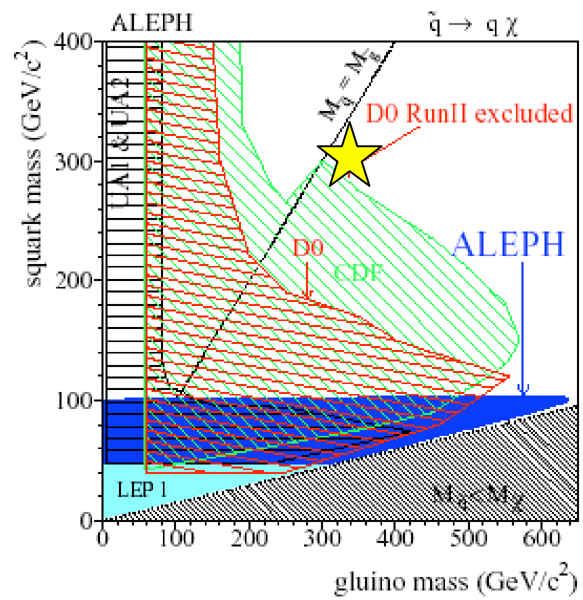
- Search for New Physics is tricky:
  - Backgrounds: estimate from data and MC
  - Acceptance: find calibration channels
  - Control both wherever you can
  - Beware of BG cross section (NLO, NNLO corrections)
  - Publish cross section limit (not just exclusion plane)
- Illustrated just a few results at Tevatron:
  - Many more existing (www-cdf.fnal.gov and www-d0.fnal.gov)
  - Many results from HERA, LEP, BaBar/Belle, etc.
- Use models for benchmarking but don't take them as "truth"
- Not found anything yet BUT
  - it's a lot of fun
  - prospects are good!

Backup Slides

Generic Squarks and Gluinos

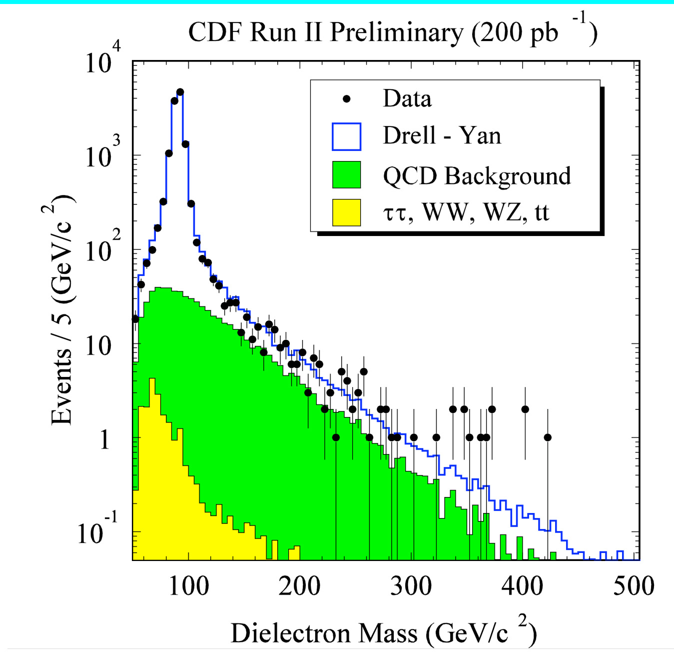
- Signature: $\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0 q\tilde{\chi}_1^0$
  - 2 jets and $\not{E}_t$
  - $\sum P_t^{jet} > 275$ GeV
  - $\not{E}_t > 175$ GeV
- Observe: 4, Expect: 2.7±1.0
- mSugra
  - Fix: m_0=25 GeV, $\tan\beta$=3, A_0=0, μ<0
  - Exclude: $m(\tilde{q}/\tilde{g})$ < 292/333 GeV
- Improves Run I limits:
  - Include more data
  - Scan parameter space

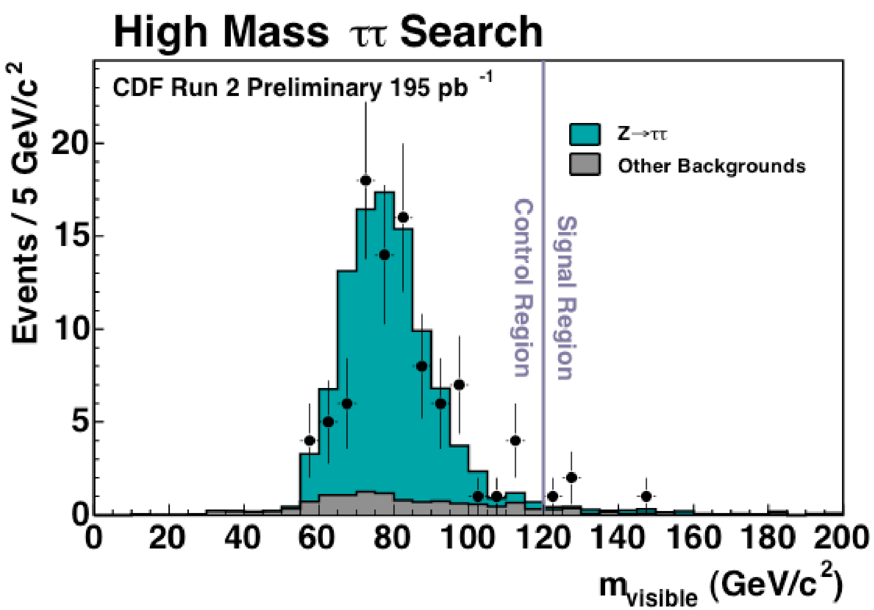


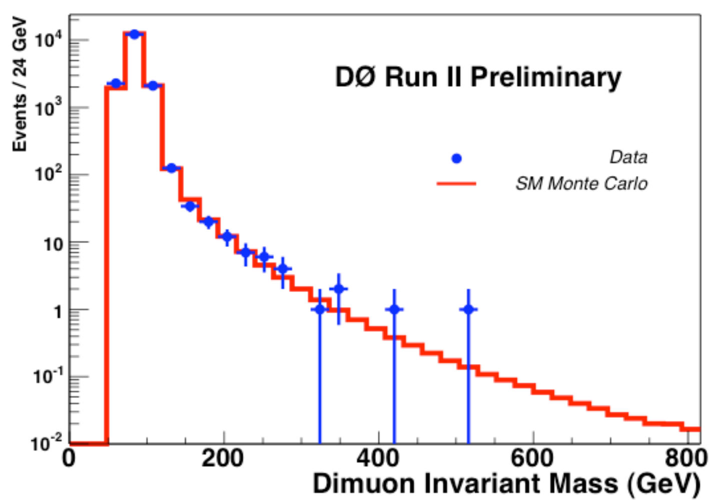


Neutral Spin-1 Bosons: Z′

- 2 high-Pt electrons, muons, taus
- Data agree with BG (Drell-Yan)
- Interpret in Z′ models:
  - E6-models: ψ, η, χ, I
  - SM-like couplings (toy model)



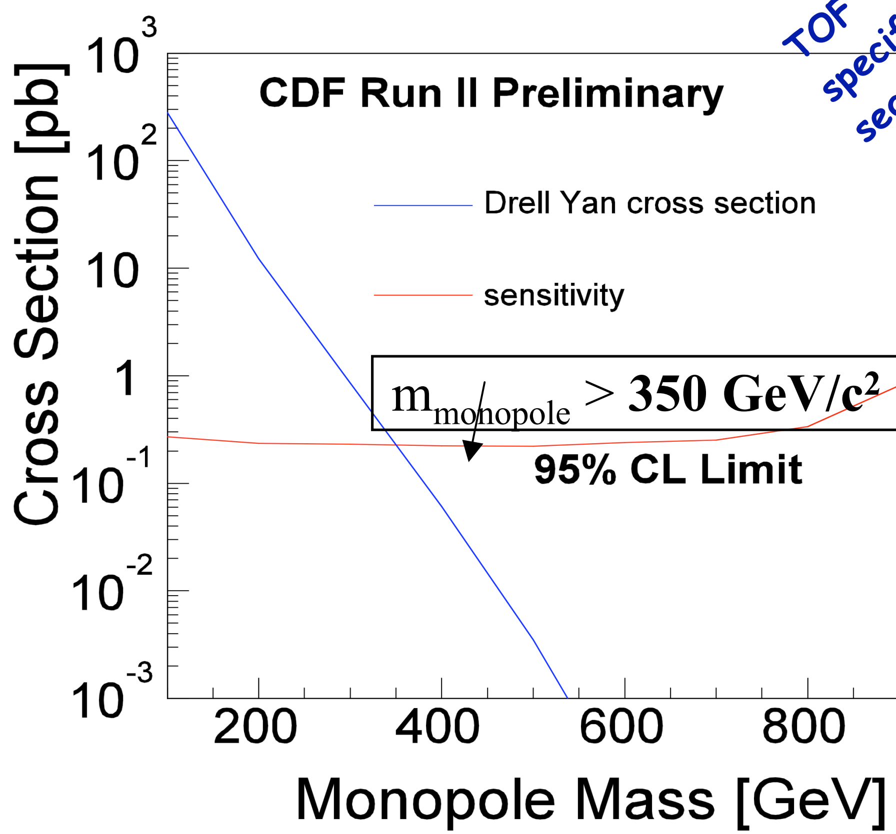


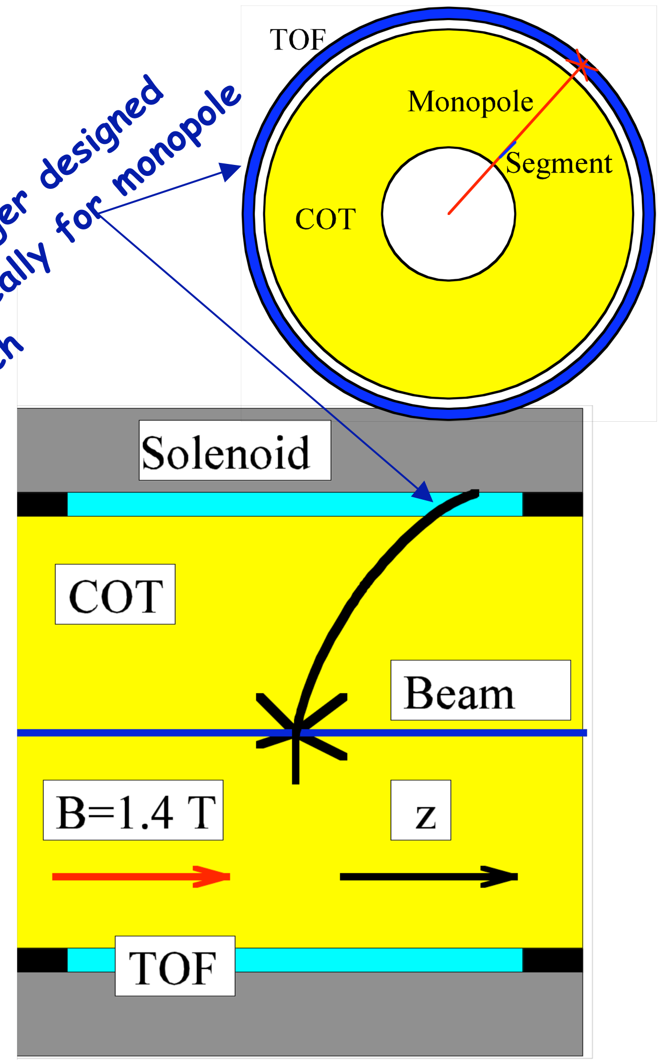


Dirac Magnetic Monopole

- Bends in the ***wrong*** plane (→ high pt)
- Large ionization in scint **(>500 Mips!)**
- Large dE/dx in drift chamber

TOF trigger designed specifically for monopole search

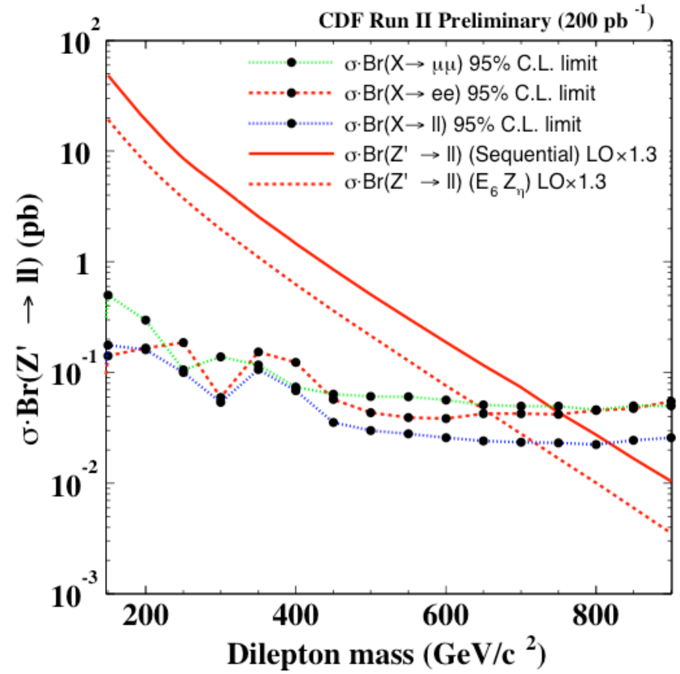


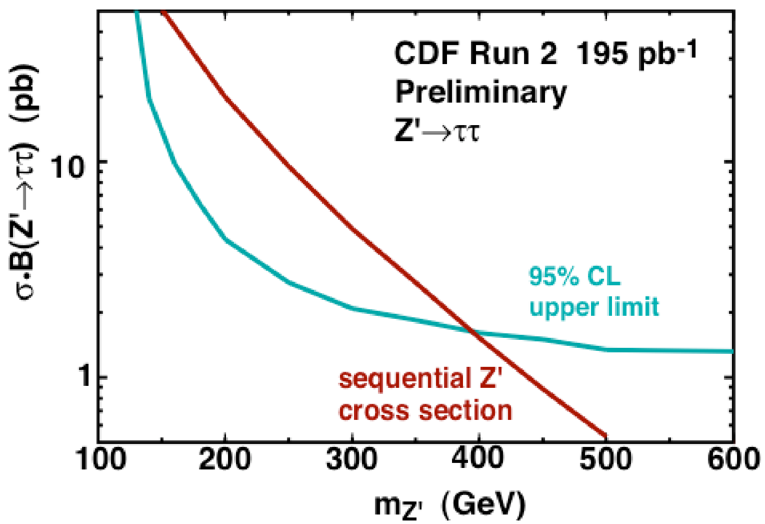


Neutral Spin-1 Bosons: Z'

- 95% C.L. Limits for SM-like Z' (in GeV):

	ee	μμ	ττ
CDF	>750	>735	>395
D0	>780	>680	-

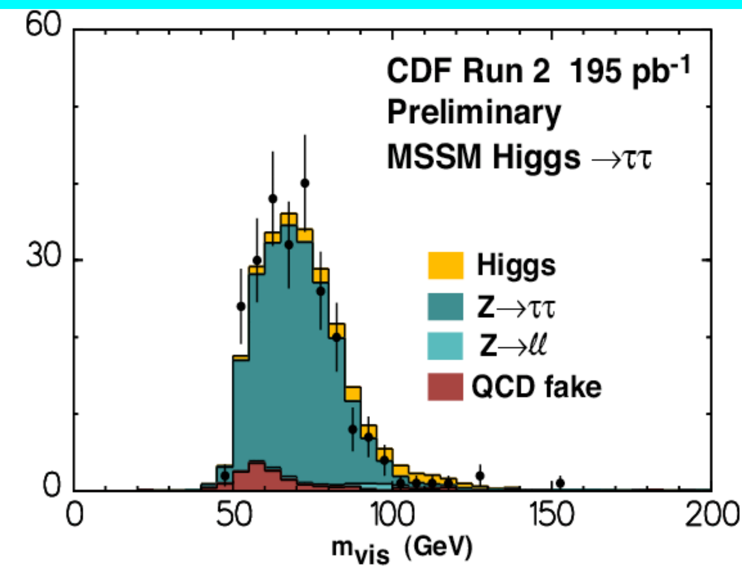


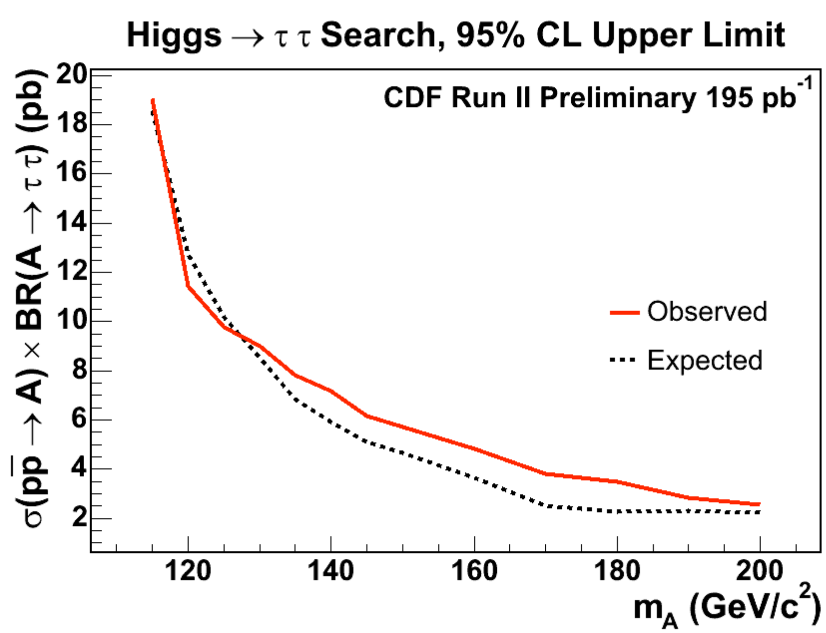


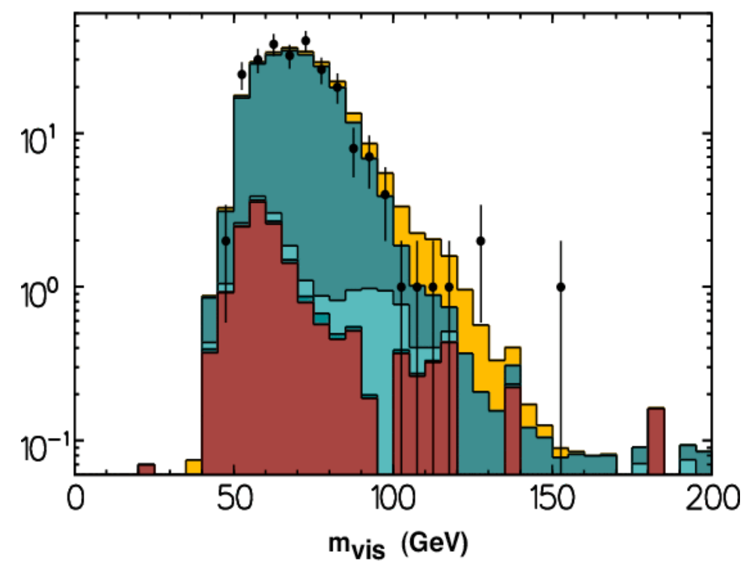
Combined CDF limit:
$M(Z')>815$ GeV/c^2

MSSM Higgs A-> $\tau\tau$

- Fit "visible" mass: from leptons, tau's and $\not{E}_T$
- Limit on σxBR≈10-2 pb
- Interpretation soon in $\tan\beta$ vs m_A plane: also sensitive to $bb\phi$ process

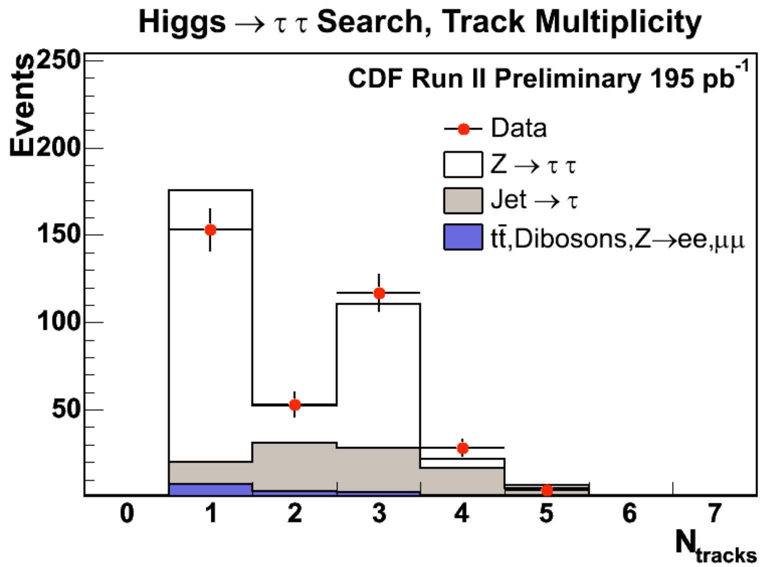


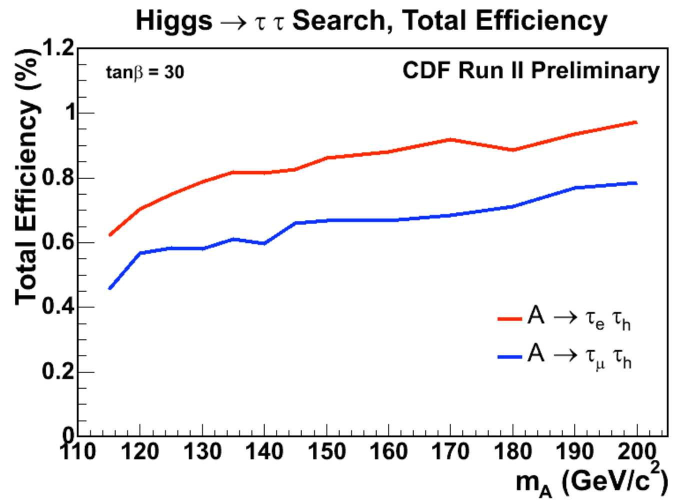




MSSM Higgs: A -> ττ

- τ's are tough!
- Select di-τ events:
  - 1 lepton from $\tau \rightarrow l\nu\nu$
  - 1 hadronic τ-decay (narrow jet)
- Efficiency ≈1%
- Background: mostly Z->ττ

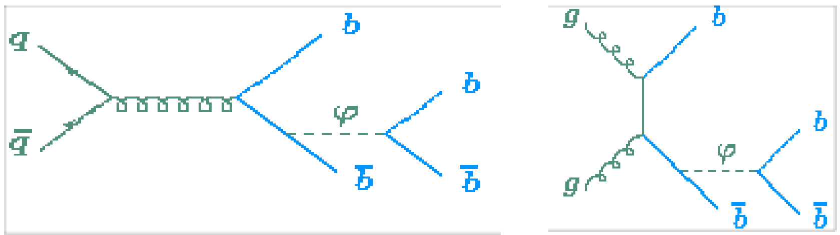




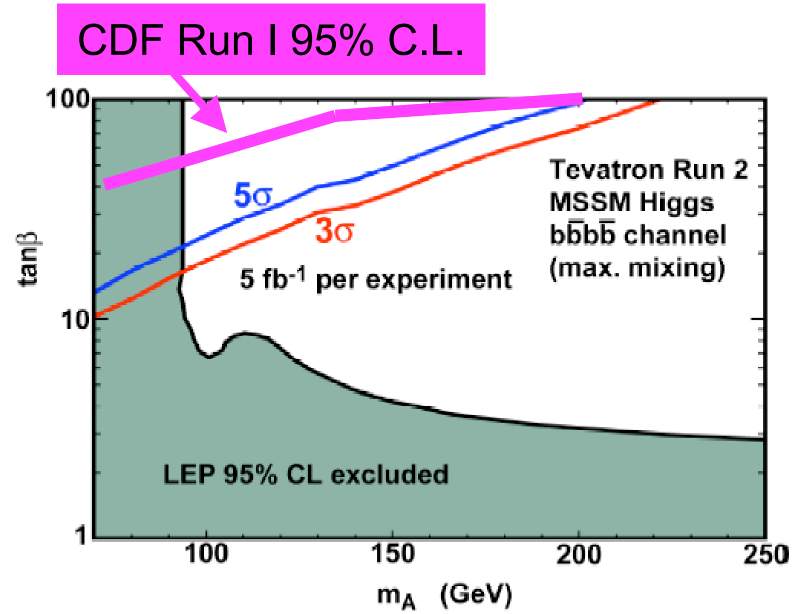
MSSM Higgs

- Standard Model:
  - σ(bbH) =1-10 fb: 100 x smaller than WH
- In MSSM the bbΦ (Φ=A,H) Yukawa coupling grows like tanβ:
  - Larger cross sections
  - Better discovery potential than SM
- Search for final states:
  - Φ+b+X->bbb+X
  - Φ+X–>ττ+X
- E.g. for M(A)=120 GeV:
  - 5σ discovery for tanβ>30
  - 3σ evidence for tanβ>20

$$gg, qq \rightarrow \phi + b\bar{b} \rightarrow b\bar{b}b\bar{b}$$

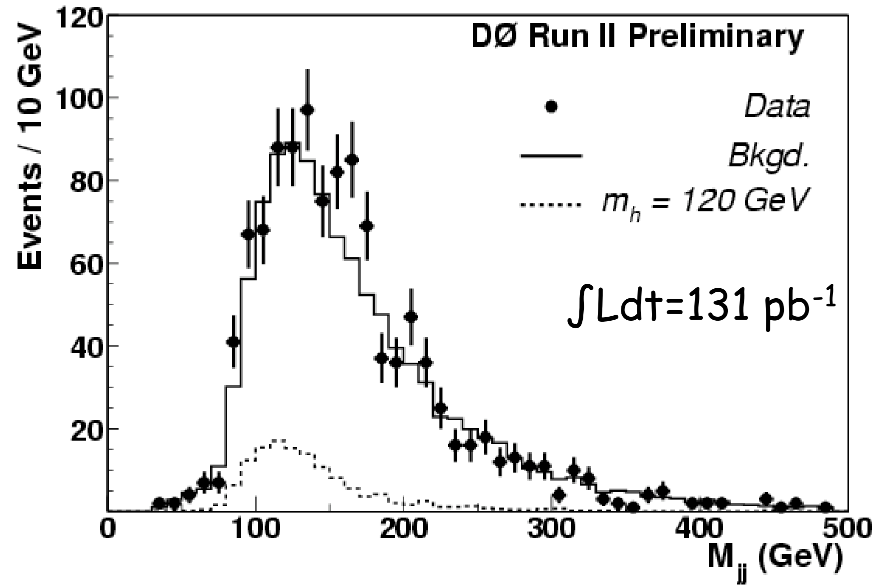


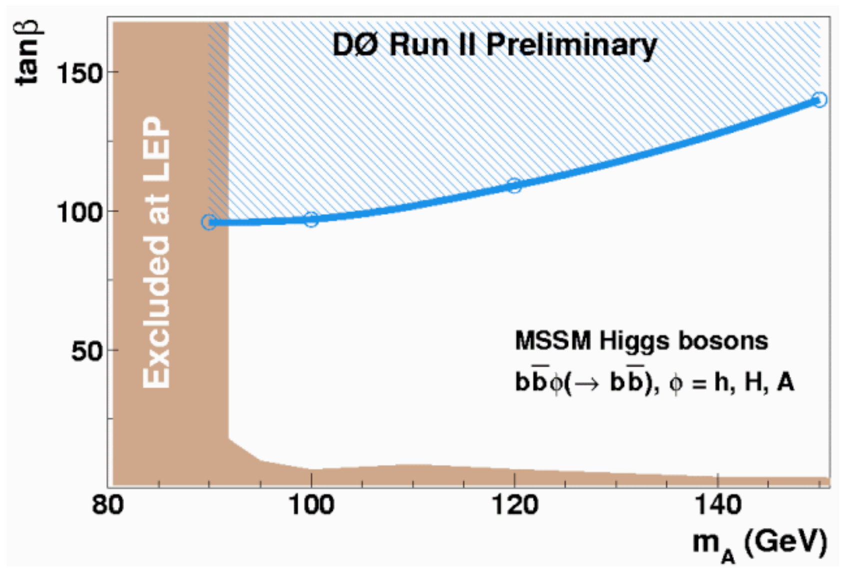
S. Willenbrock



D0: Neutral Higgs at High Tanβ

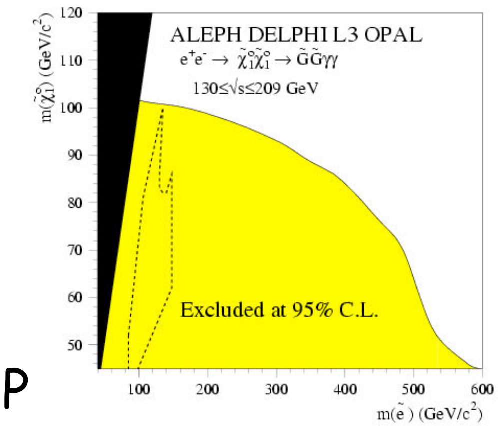
- Event Selection:
  - At least 3 jets:
    E_T cuts on jets optimized for different Higgs mass values
  - B-tagging for each jet
- Main Background:
  - QCD multi b-production
  - Difficult for LO MC: determined from data and/or ALPGEN 1.2
- Signal acceptance about 0.2-1.5% depending on Mass
- Result much worse than CDF Run 1!?!
  - Thought to be due to pdf's: CTEQ3 vs CTEQ5

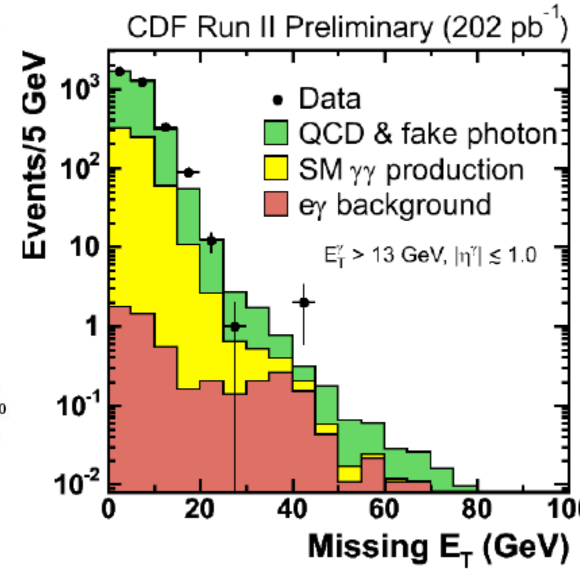


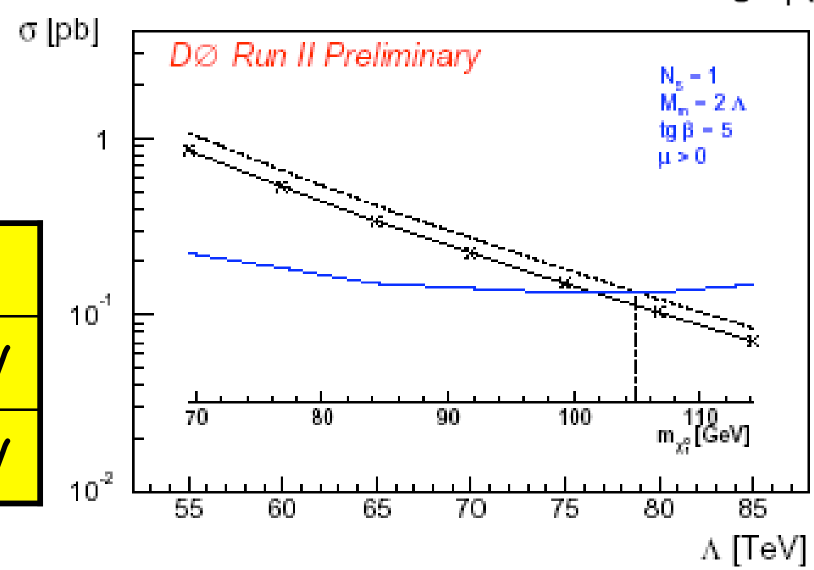


GMSB: $\gamma\gamma+\not{E}_T$

- Assume χ^0_1 is NLSP:
  - Decay to $\tilde{G}+\gamma$
  - $\tilde{G}$ light M~O(1 keV)
  - Inspired by CDF $ee\gamma\gamma+\not{E}_T$ event: now ruled out by LEP
- D0 (CDF) Inclusive search:
  - 2 photons: E_T > 20 (13) GeV
  - $\not{E}_T$ > 40 (45) GeV

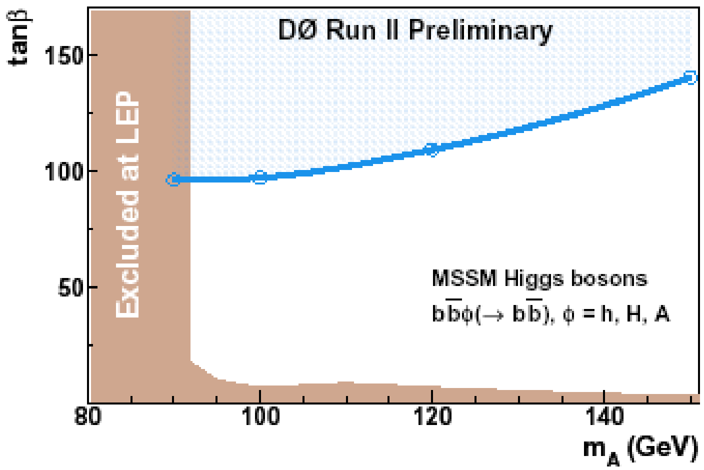






	Exp.	Obs.	$M(\chi^+_1)$
D0	2.5±0.5	1	>192 GeV
CDF	0.3±0.1	0	>168 GeV

$p\bar{p}$-> bbA ->bbbb

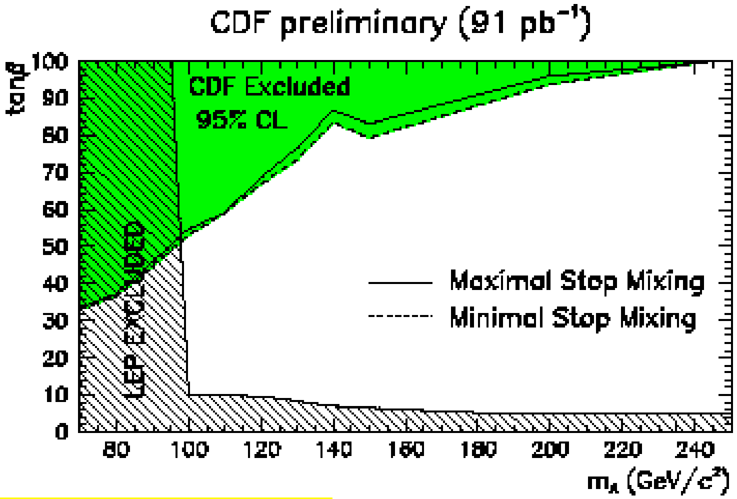


DZero Run II Limit; March 2004

Using 130 pb^{-1}

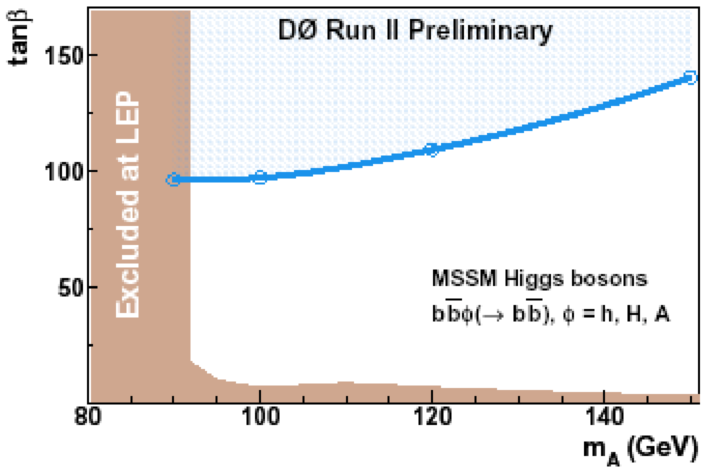
CDF Run I Limit; October 2000

Using 91 pb^{-1}



Why D0 so much worse with more data???

$p\bar{p}$-> bbA ->bbbb



DZero Run II Limit; March 2004

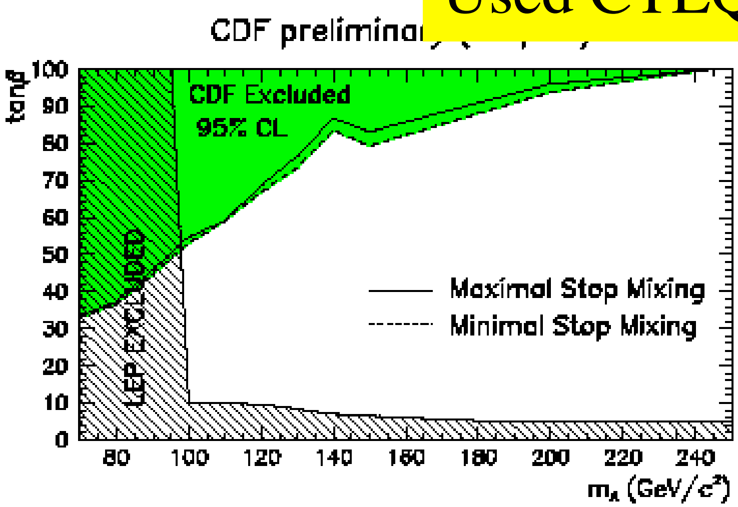
Using 130 pb^{-1}

Used CTEQ5L

Used CTEQ3L

CDF Run I Limit; October 2000

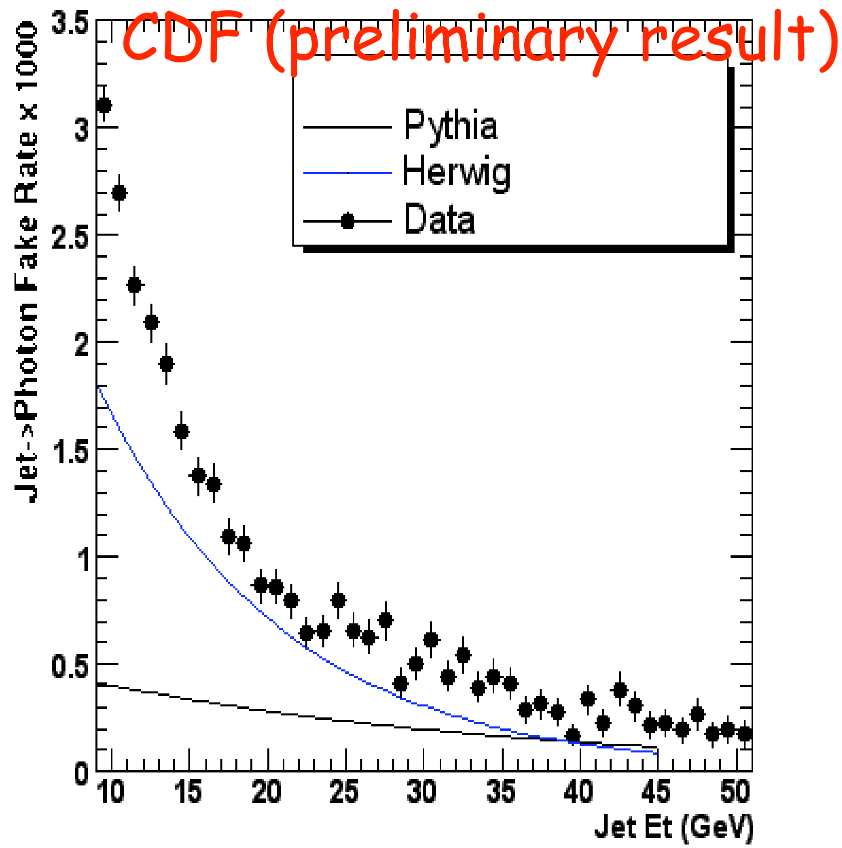
Using 91 pb^{-1}



CTEQ3L 3 times larger acceptance x cross section!

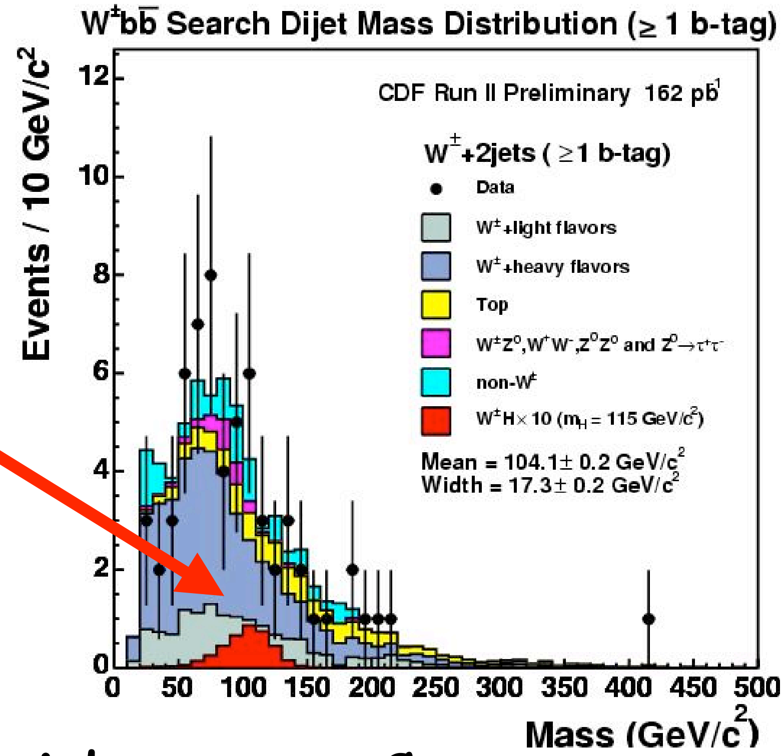
Photon Fake Rate

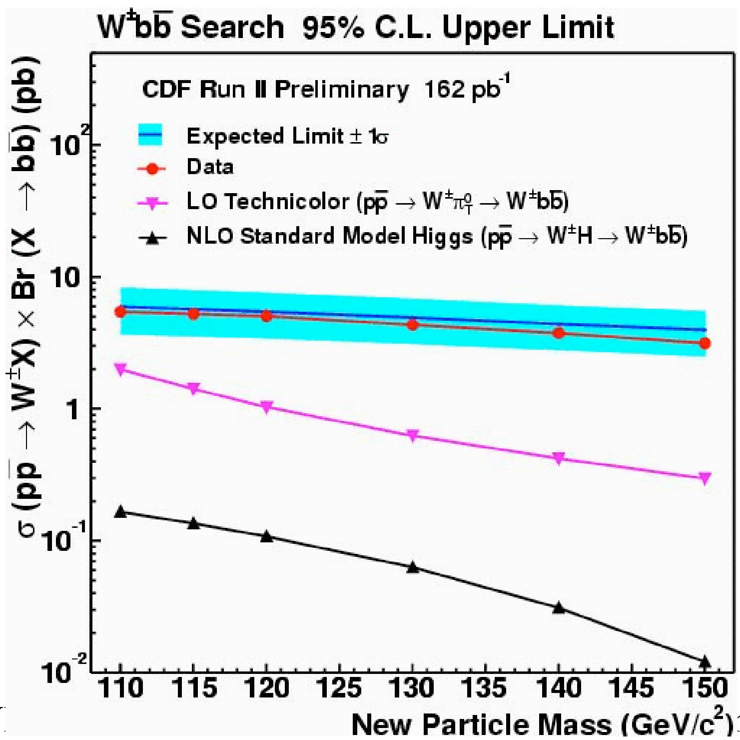
- Rate of jets with leading meson (pi0, eta) which cannot be distinguished from prompt photons: Depends on
  - detector capabilities, e.g. granularity of calorimeter
  - Cuts!
- Systematic error about 30-80% depending on Et
- Data higher than Pythia and Herwig
- Pythia describes data better than Herwig



Wh Production: Run 2 data

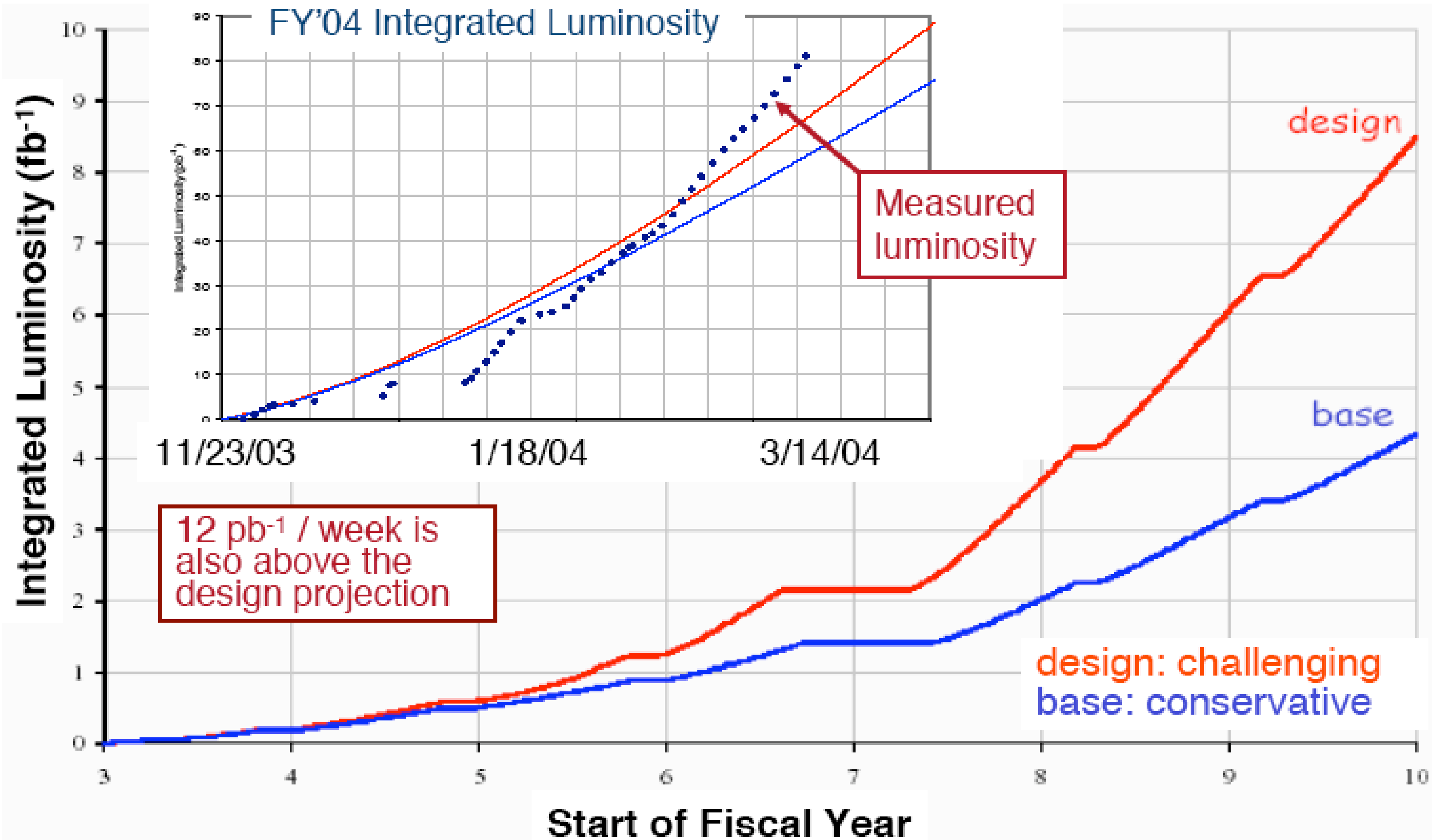
- Selection:
  - W(→μν or eν)
  - 2 jets: 1 b-tagged
- Search for peak in dijet invariant mass distribution





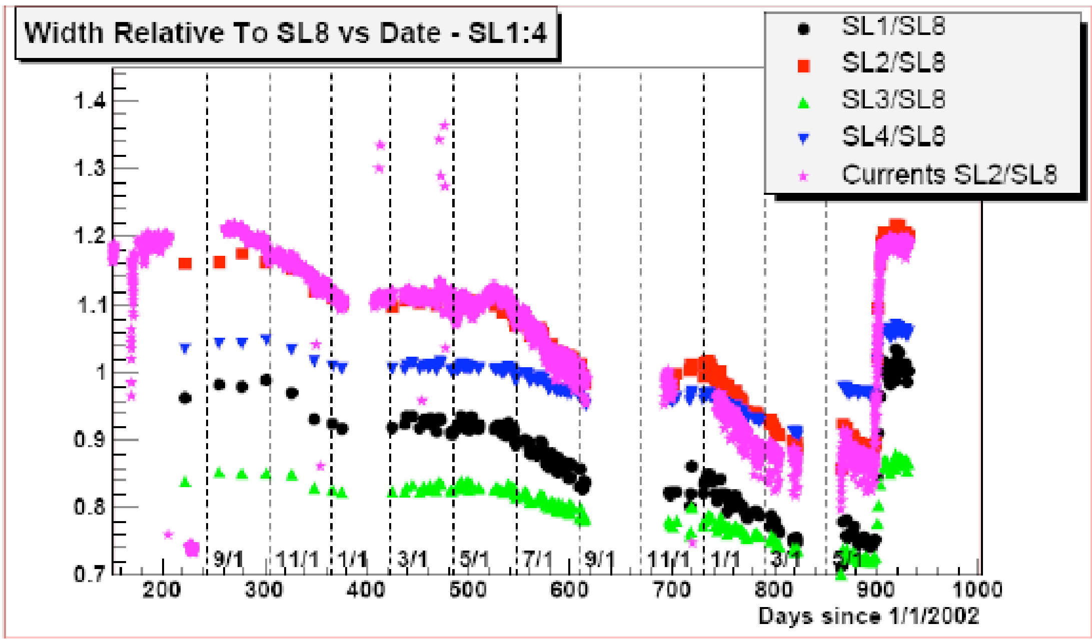
- No evidence => Cross section limit on
  - Wh->Wbb production
  - Techni-ρ ->Techni-π +W

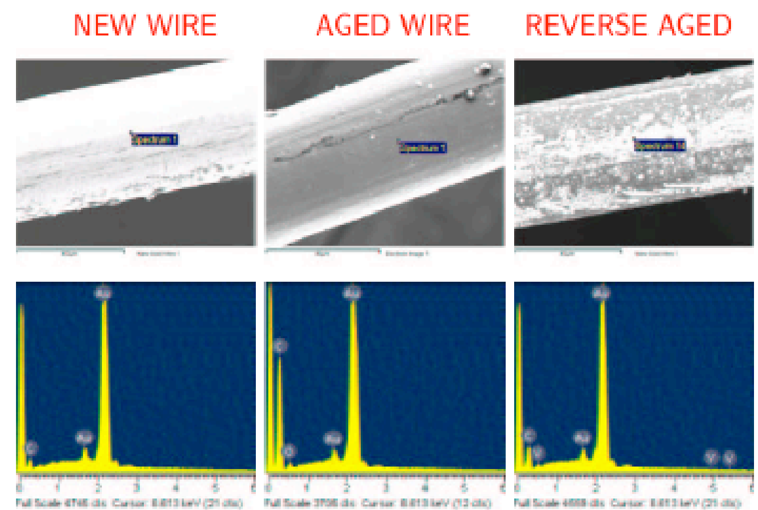
Luminosity Perspectives



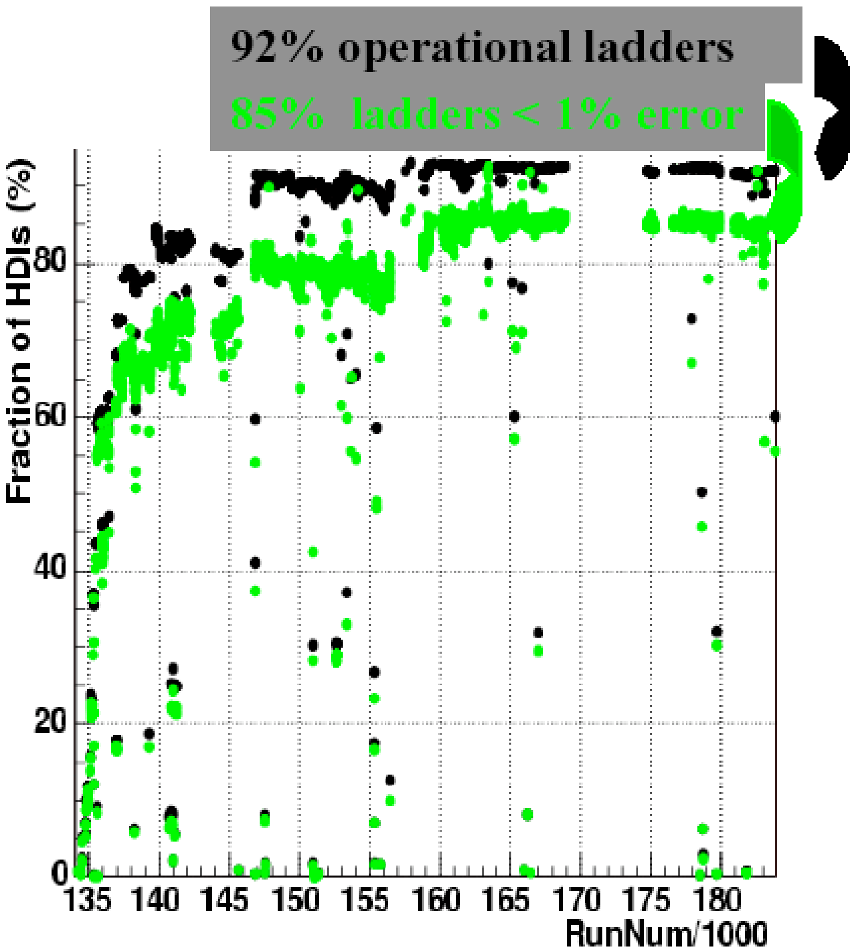
CDF: COT Aging Problem Solved!

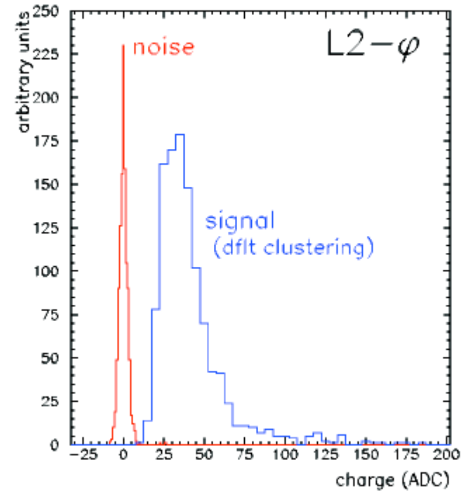
- Gaseous tracking chamber COT: wire aging problem seen in 2003-2004
- hydrocarbon residue detected on sense wires where gain had been falling
- addition of air (probably the oxygen) reverses the aging
- Chamber gains back go pre-aged status
- Voltages reduced on inner superlayers from February to May 2004

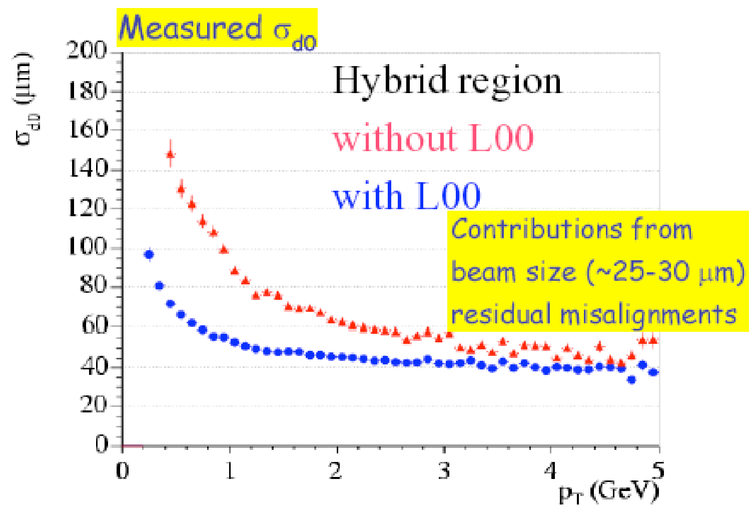




Silicon Performance



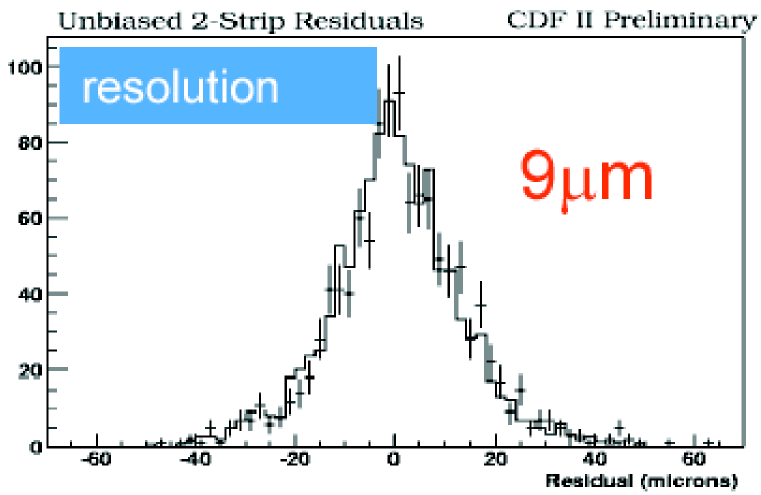


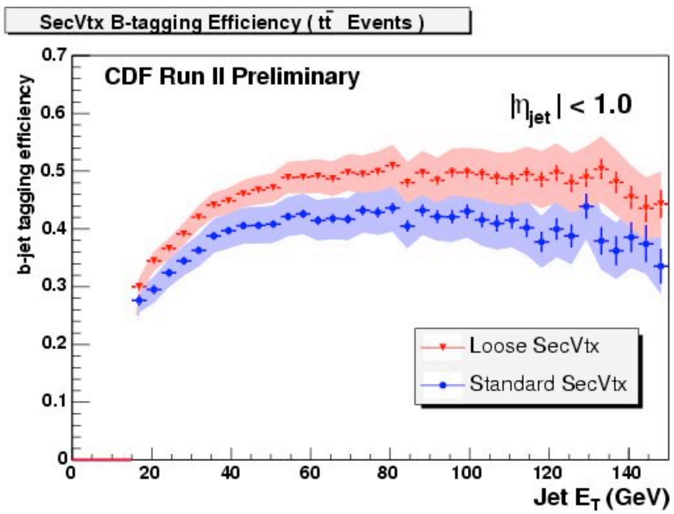


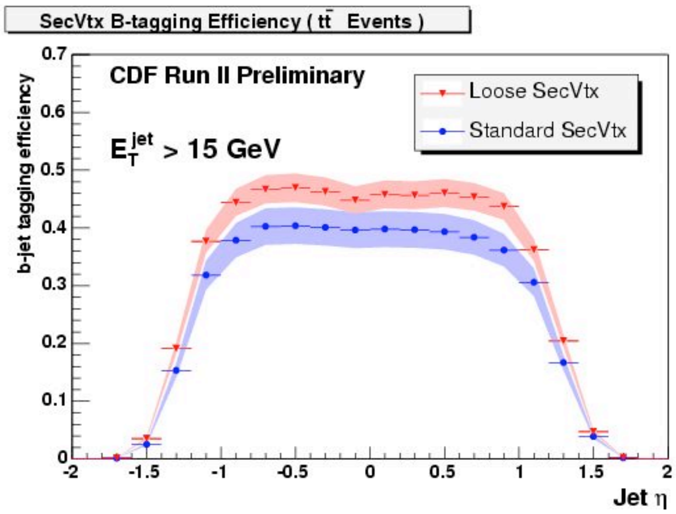
See talk by R. Wallny

CDF: B-tagging and tracking

Requirement	Efficiency	Requirement	Efficiency
$N_{r\phi} \geq 3$	94%	$N_z \geq 3$	80%
$N_{r\phi} \geq 4$	90%	$N_z \geq 4$	61%
$N_{r\phi} = 5$	46%	$N_z = 5$	26%



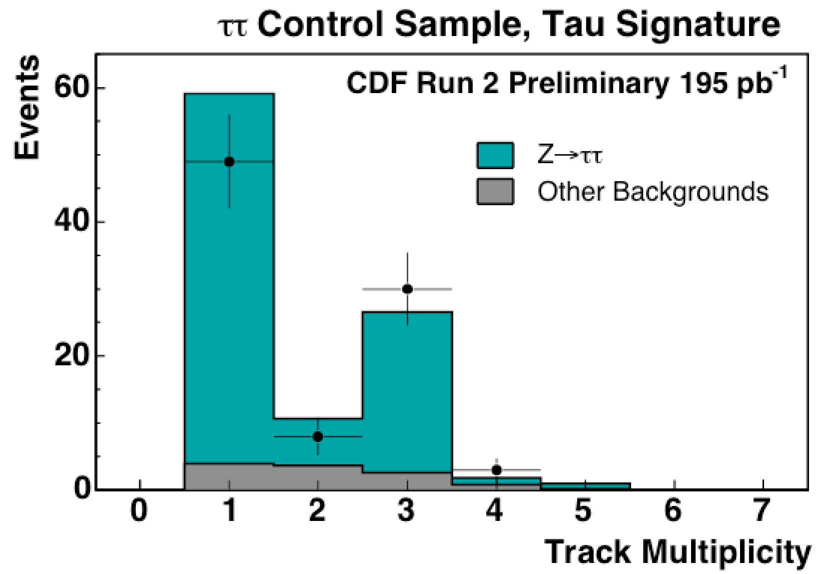


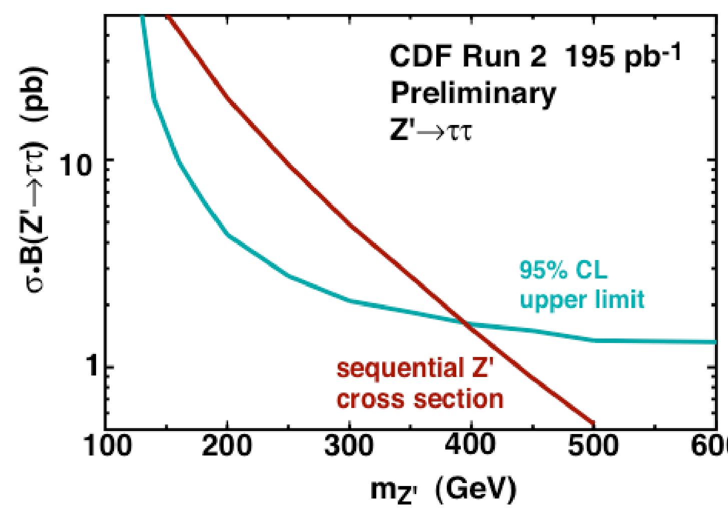


See talk by R. Wallny

Z' -> ττ

- τ's challenging at hadron colliders:
- τ signals established by CDF & D0: W->τν, Z->ττ
  - 1- and 3-prong seen
- Result for m_{vis}>120 GeV:
  - Observe: 4 events
  - Expect: 2.8±0.5
- M(Z')>395 GeV
- Ruled out by ee and μμ channel for SM Z' => explore other models with enhanced τ couplings

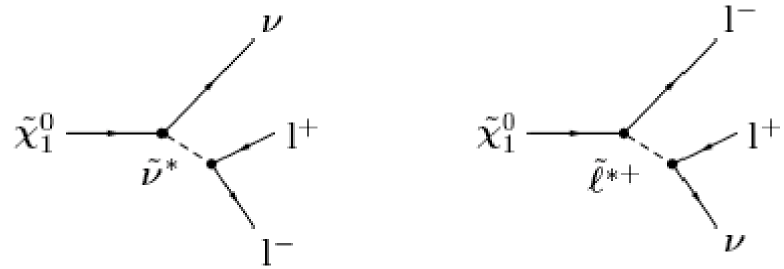




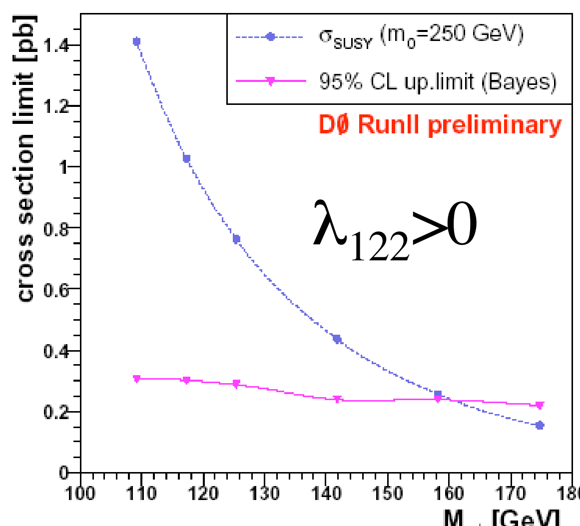
RPV Neutralino Decay

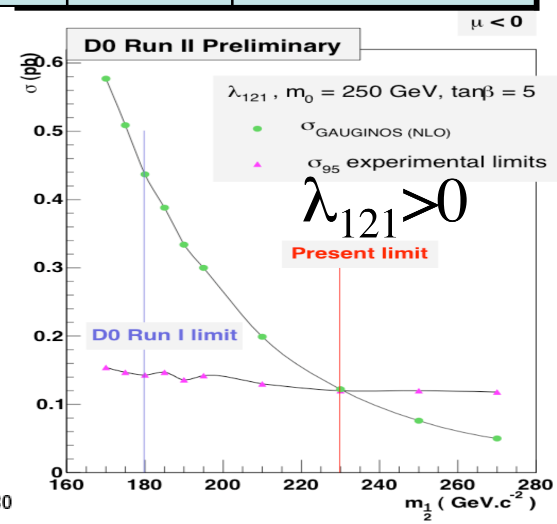
- Model:
  - R-parity conserving production => two neutralinos
  - R-parity violating decay into leptons
  - One RPV couplings non-0: λ_{122} , λ_{121}
- Final state: 4 leptons $+\not{E}_t$
  - eee, eeμ, μμe, μμμ
  - 3rd lepton P_t>3 GeV
  - Largest Background: $b\bar{b}$
- Interpret:
  - M_0=250 GeV, tanβ=5

~



	Obs.	Exp.
eel (l=e,μ)	0	0.5±0.4
μμl (l=e,μ)	2	0.6+1.9-0.6





$m(\tilde{\chi}^+_1)$ >160 GeV

$m(\tilde{\chi}^+_1)$ >183 GeV