Searches for New and Exotic Physics at CDF

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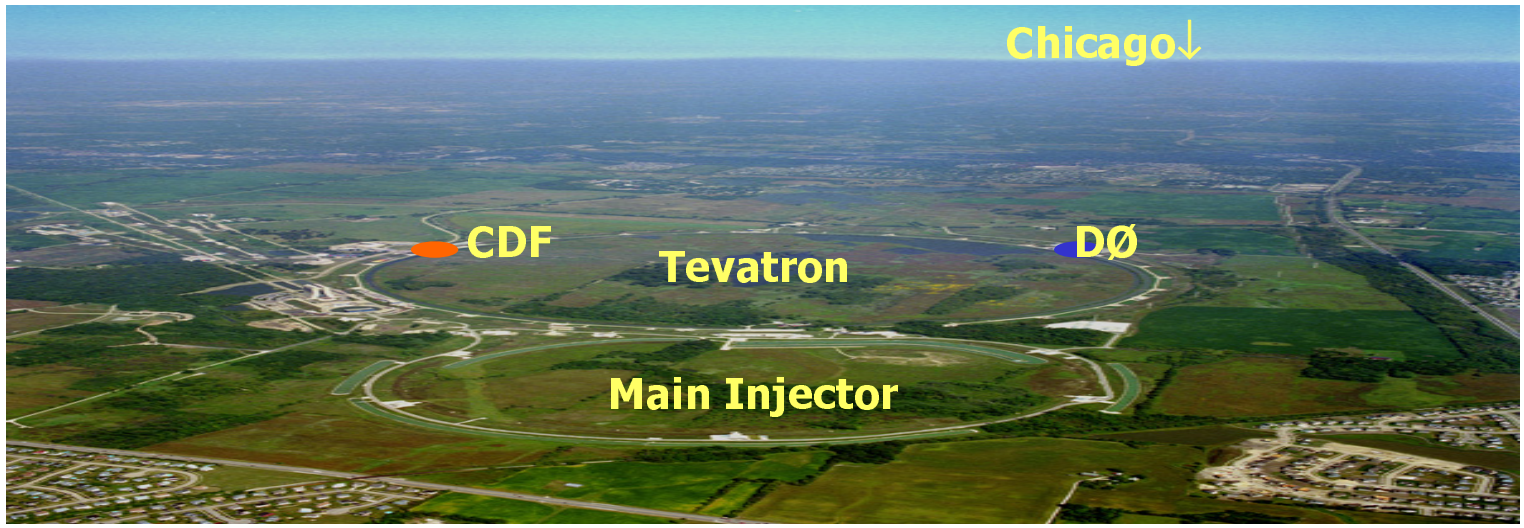
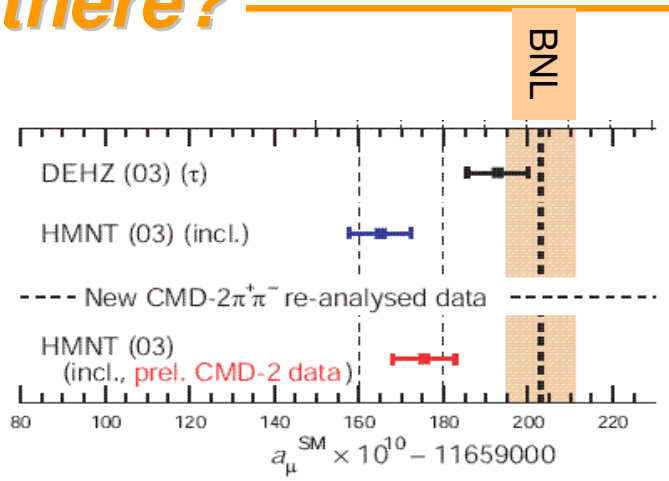


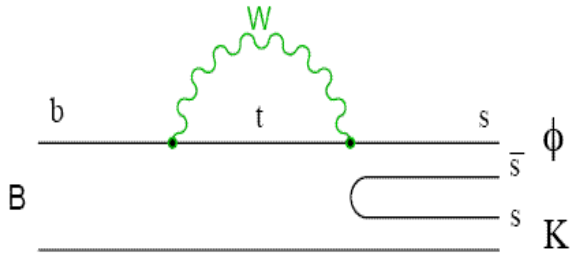
Outline

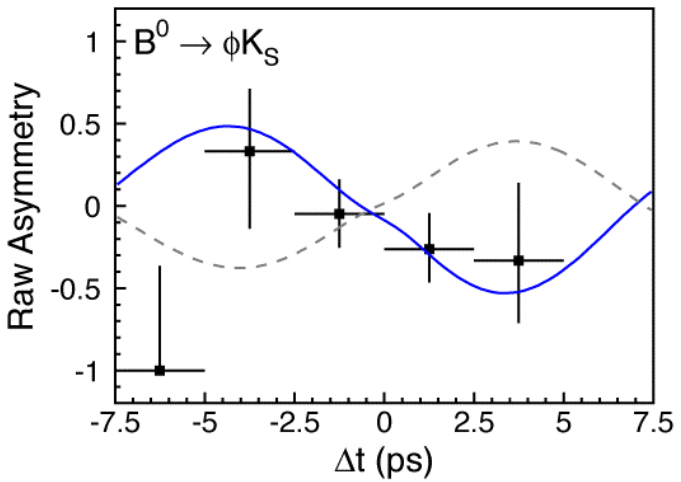
- Hints of physics beyond the Standard Model, and how CDF fits in…
- Status of CDF, Tevatron
- Physics results
  - Dijet resonances: E6 diquarks, RS graviton LED, excited quarks, W´…
  - Dilepton resonances: Z´, RS graviton
  - Champs: long lived charged particles
  - 1st Generation Leptoquarks: eejj and $\nu\nu$jj channels
  - Excited electrons: ee* eeγ
  - Photon-rich signatures: γMET, $\gamma\gamma$, $\gamma\gamma\ell$ and $\gamma\ell$,more
  - Doubly-charged particles: $H^{\pm\pm}$ $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $\mu^{\pm}e^{\pm}$
  - Stop, sbottom, gluinos: search results and prospects
  - Rare decays: B_s $\mu\mu$
- Prospects for finding the SM Higgs
- Status of the Run II Silicon
- Concluding remarks

Any New Physics out there?

- Neutrinos oscillate…
- Dark matter…
- $(g\text{-}2)_\mu$
  - a ≈2.5σ effect?
- Atomic Parity Violation
  - Parity non-conserving amplitudes measured in Cs
  - was >2σ effect, but now agrees…(hep-ph/0305053)
- $\sin^2\theta_W$ at NuTeV
  - a ≈3σ effect, or is it due to theoretical uncertainty?
- B ϕK_s (vs. B $J/\psi K_s$) at Belle
  - $\sin(2\varphi_1)$ = 0.96±0.50 from B ϕK_s penguin
  - $\sin(2\varphi_1)$ = 0.731±0.056 expected (tree level)
  - A ≈3.5σ effect, but disagrees with BaBar
- TeVatron (Run I) has hints of new physics too…
  - bb cross section excess
  - Photon+lepton events
  - Multi-tagged jets
  - Dijet excess

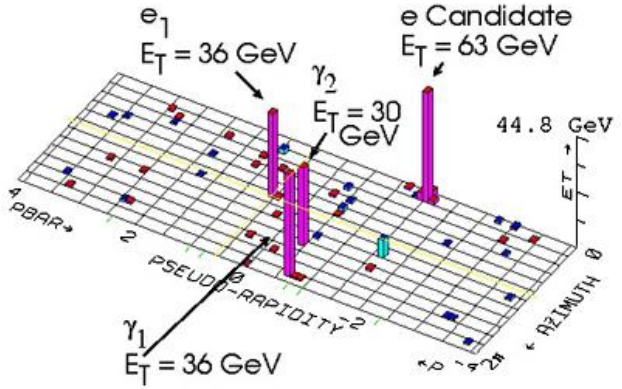






Hints of new physics at the TeVatron?

- $b\bar{b}$ production cross section excess?
  - x2 excess in $\sigma(b\bar{b})$, less after theory changes
- Anomalous photonic events from Run I?
  - ee$\gamma\gamma$MET event EM timing
  - Excess in lepton+photon channel?

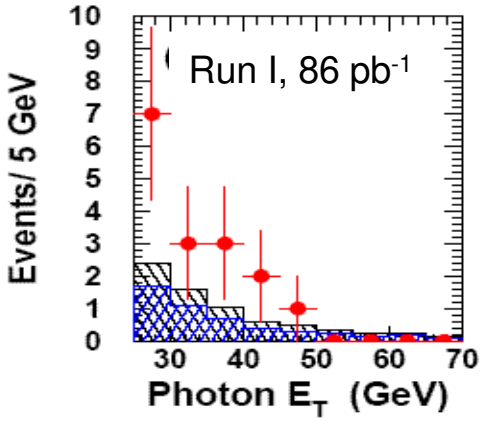


$\not\!\!E_T$ = 55 GeV

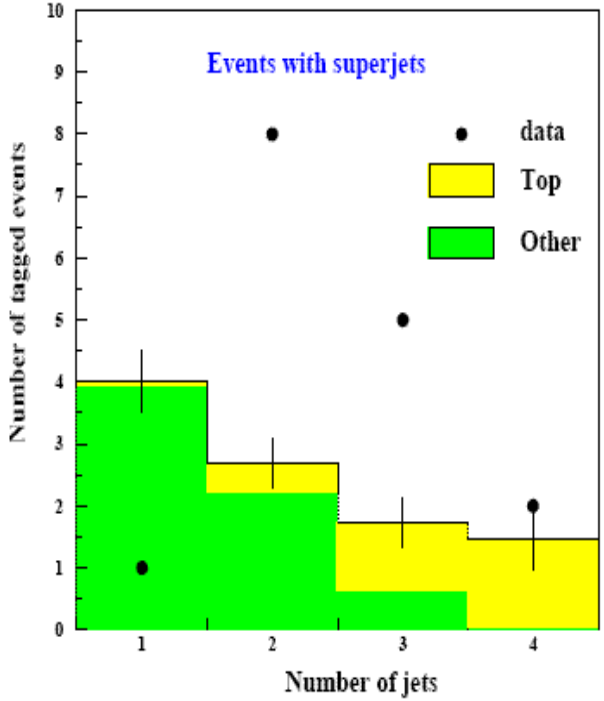
	γ + e/μ
Obs.	16
Exp.	7.6±0.7

(excess mainly in μ channel)

CDF, PRD 66, 012004 (02)

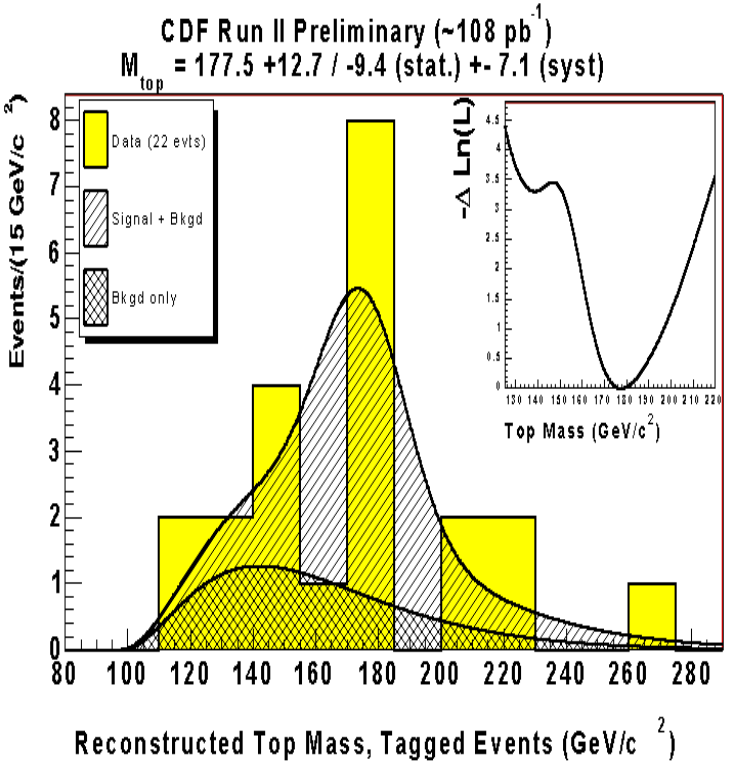


- Anomalous W+jet events from Run I?
  - Study of correlations in soft lepton and displaced vertex tags gives odd result
  - 4.4±0.6 exp, 13 observed in N_{jet} =2,3 bins
  - Many crosschecks
  - Odd kinematics (PRD65(2002)052007)



How is CDF doing?

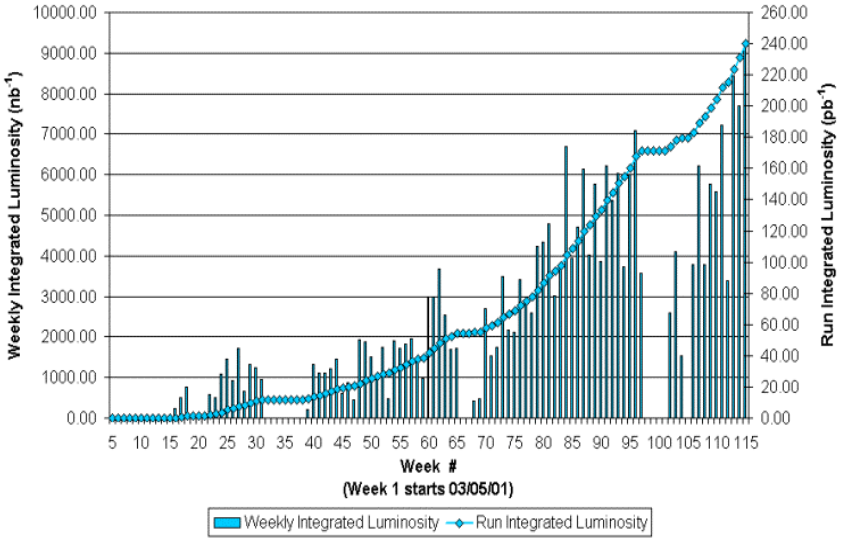
- Commissioning the detector (now mostly done)
  - >2 years of effort already
  - Some pieces still under study
- Re-establish baseline physics program
  - W, Z
  - QCD
- More elaborate tools and techniques now re-established: same capabilities as Run I
  - Precision tracking and B-tagging
  - Missing Energy
  - Top mass (re)measurement good indicator
- Searches for new physics underway!



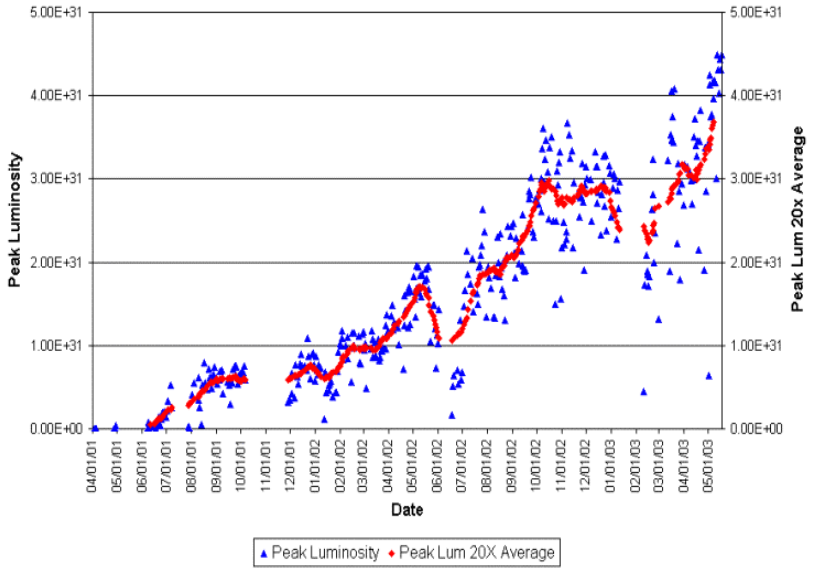
How is the Tevatron doing?

- Accelerator has been running much more reliably
- Records levels achieved, but not maintained
  - One week Luminosity: >9 pb-1
  - a new Inst. luminosity record of 4.5e31
  - record number protons to pbar target, pbar stacking rates, etc.
- Slowly ramping up… Run II is definitely going!
- Long term luminosity projections recently reviewed… will discuss later

Integrated Luminosity



Peak Luminosity



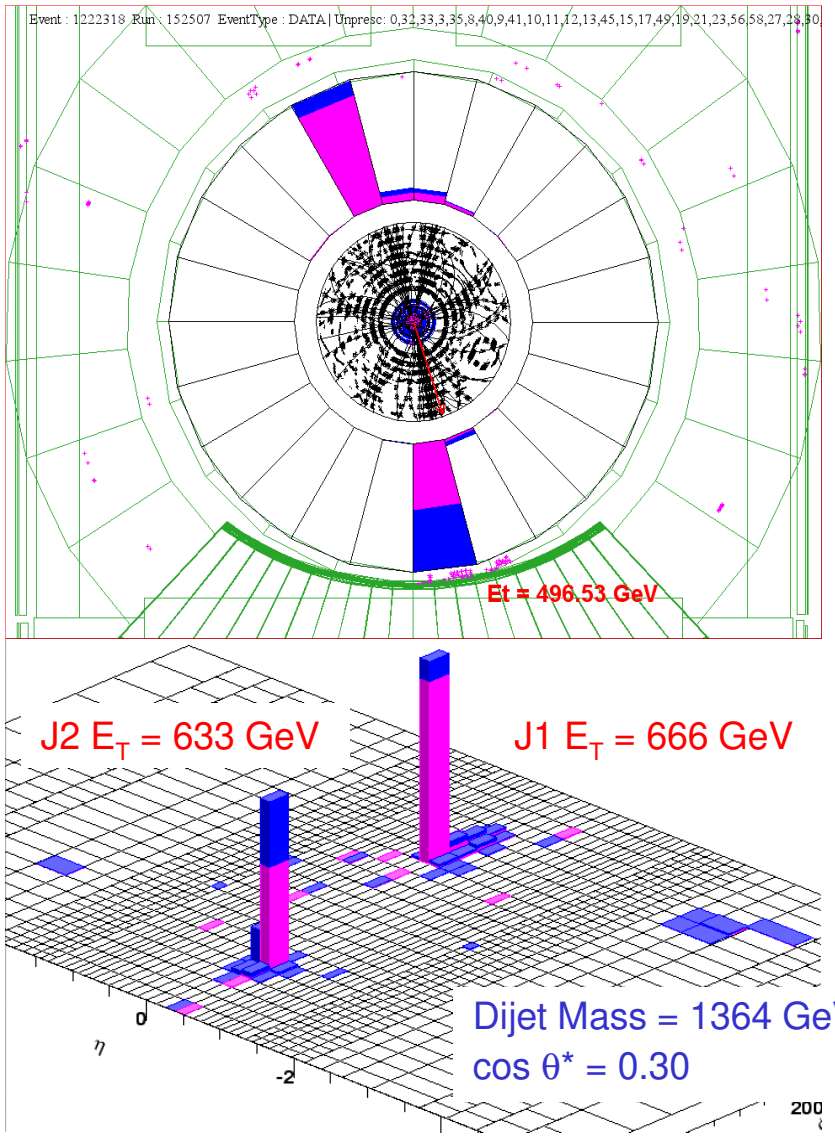
CDF Searches; Run I vs. Run II

- Better coverage for leptons and silicon tracking
  - Muon coverage greatly increased
  - Electron covers out to $\eta < 2.4$
  - Silicon acceptance (hence B-tagging) increased by almost x2.0

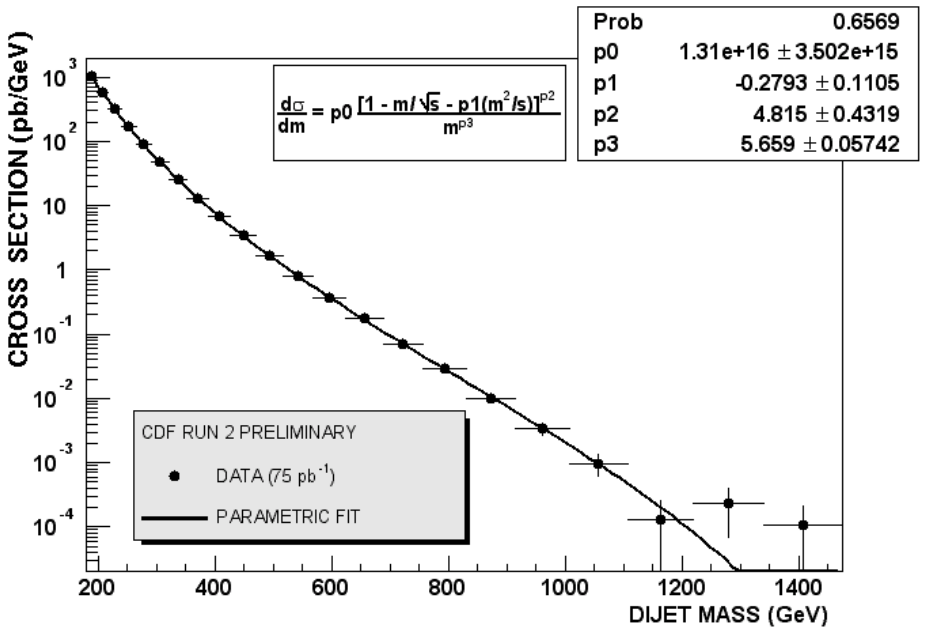
	e	μ	τ	j	b	c
CDF $\|\eta\|$ range	2.4	2.0	2.0	3.0	2.0	2.0

- Missing Transverse Energy (MET) well understood
- B tagging and displaced track triggers
  - Displaced track triggers working well
  - 2D b-tag available and working as expected
- Tau finding and reconstruction
  - Improvements are important for high tanβ regions
  - Reduced fake rate compared to Run I
- CDF running as advertised (!)

High Mass Dijet Events

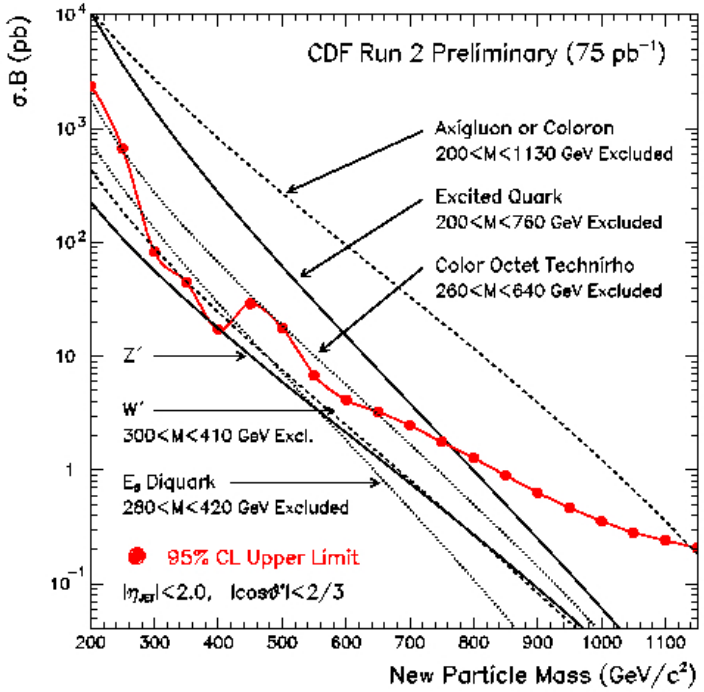


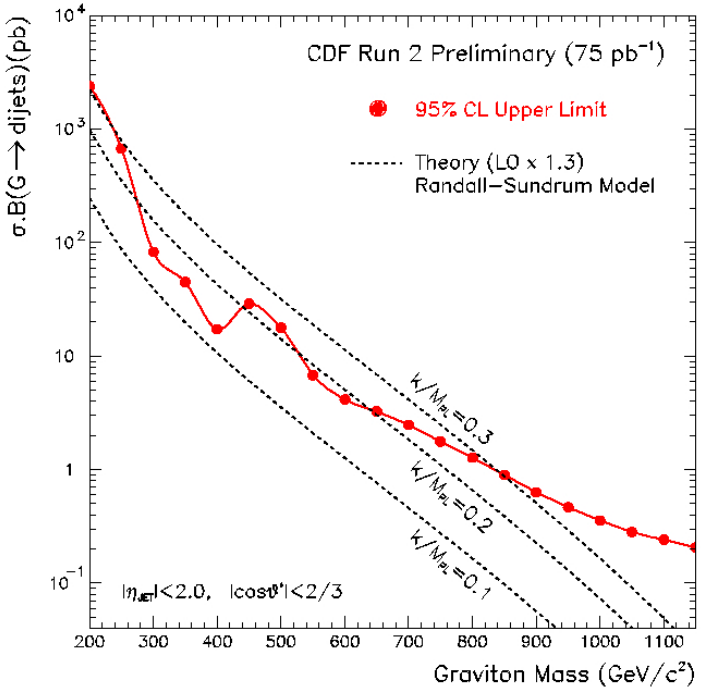
- Highest mass event so far (at left)
- We search for resonances in dijets
  - Assume a narrow width
  - Cleanup includes requirement of MET/sqrt(MET) < 6
  - Simple parameterization (not theory)
- Limits set on a variety of models



New Particles decaying to Dijets

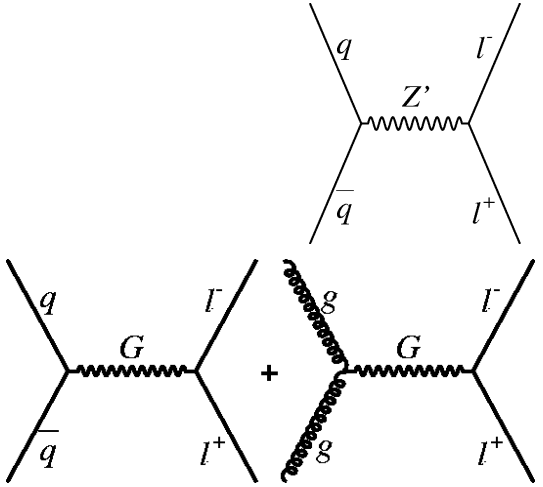
- Axigluons or flavor universal colorons
  200 < m < 1130 GeV/c^2
- Excited quarks
  200 < m < and 760 GeV/c^2
- Color octet techni-rho
  260 < m < 640 GeV/c^2
- E6 Diquarks
  280 < m < 420 GeV/c^2
- W'
  300 < m < 410 GeV/c^2
- RS Graviton (k/M_{pl}=0.3)
  220 < m < 840 GeV

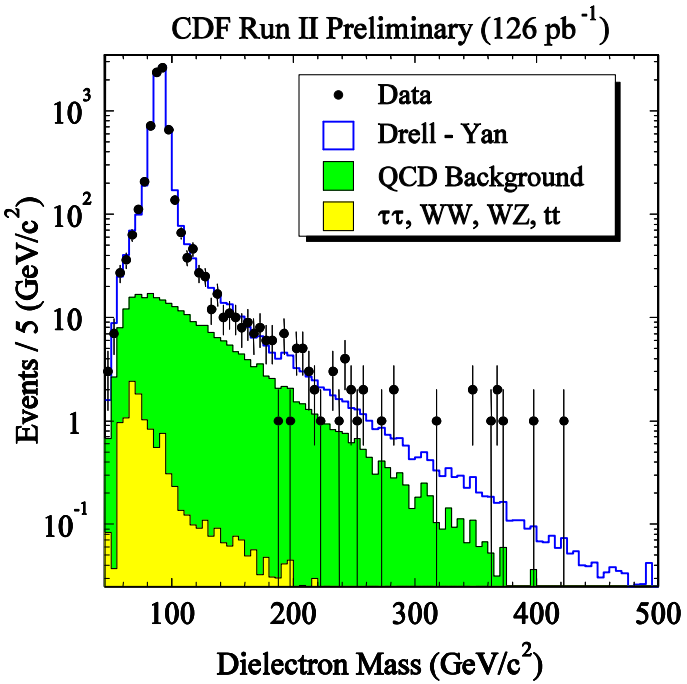


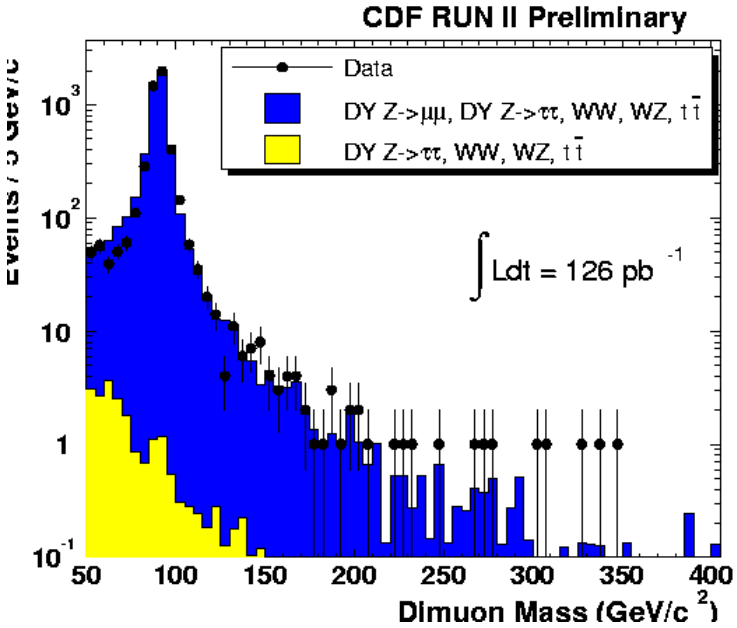


High-Mass Drell-Yan $\mu^+\mu^-$, e^+e^-

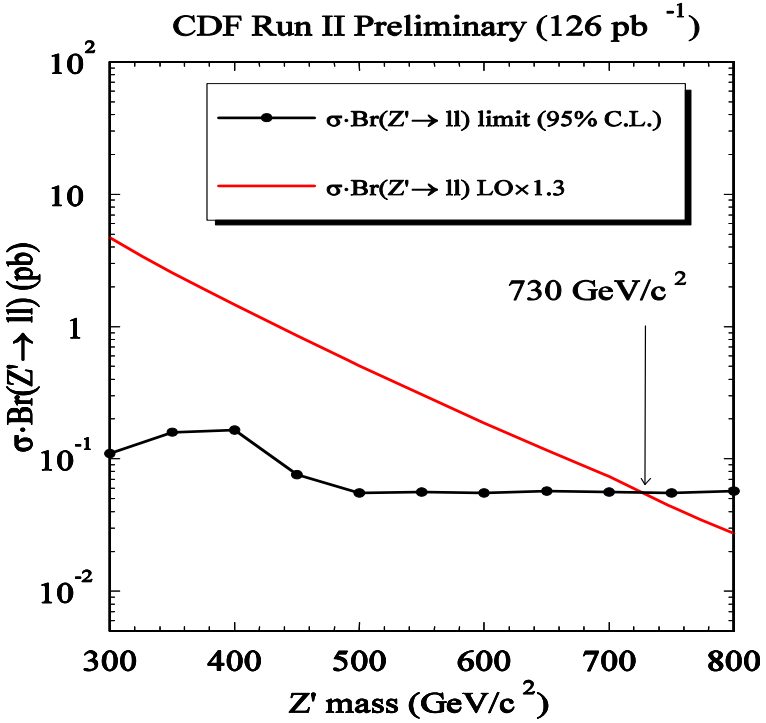
- Search in high-mass region for Z´ (or G_{RS}) $\mu^+\mu^-$, e^+e^-
  - Assume a narrow resonance
  - Muon $p_T > 25$ GeV/c, electron $E_T > 25$ GeV
- Backgrounds include
  - Drell-Yan, QCD, diboson, tt, bb
  - Cosmic ray backgrounds significant but controllable

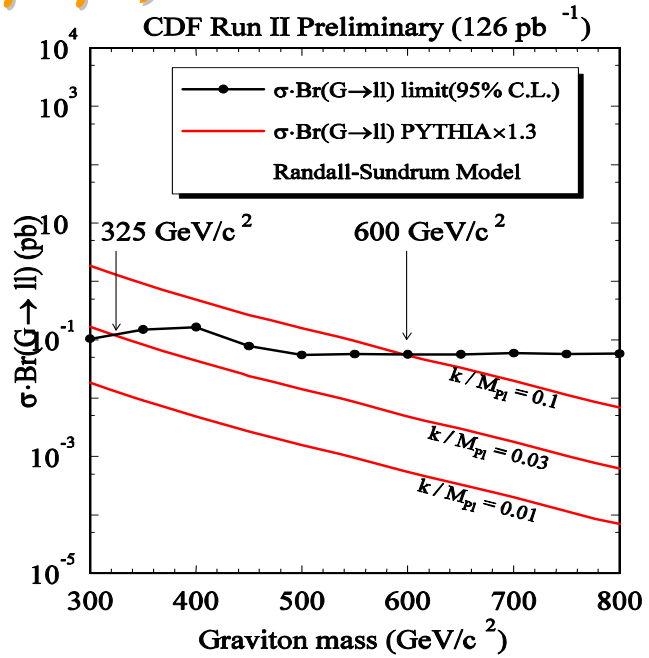


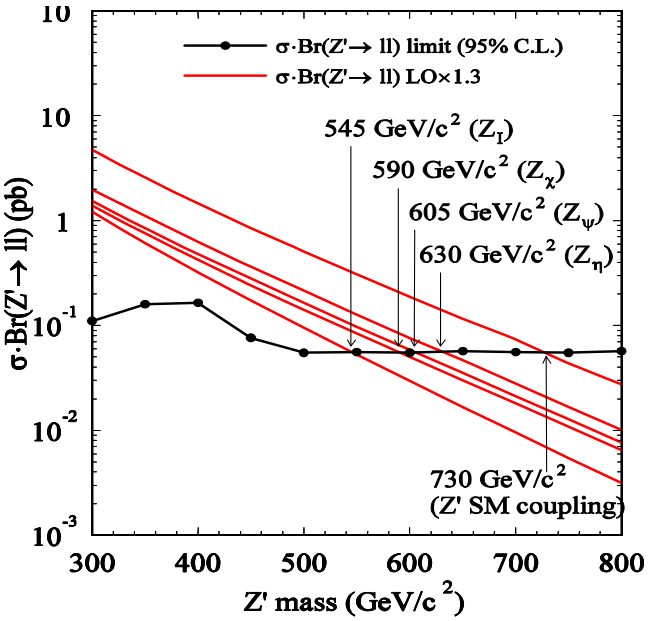




High-Mass Drell-Yan $\mu^+\mu^-$, e^+e^-







- Limits have been placed on
  - 'Standard Model' Z´
  - Randall-Sundrum graviton for $k/M_{PC} > 0.025$
  - Z´ from E6
- Results now exceed Run I limits

"Physics Commissioning" Scorecard

Basic tracking

Basic calorimetry

Basic lepton ID (high p_T)

- New detectors fully commissioned
- Complete coverage for calorimetry
- Missing Energy understood
- Photons
- Precision silicon tracking
- Tau and b jets algorithms
- Low pT lepton ID, fake rates
- Forward tracking and calorimetry
- (Find SUSY! Find the Higgs!)

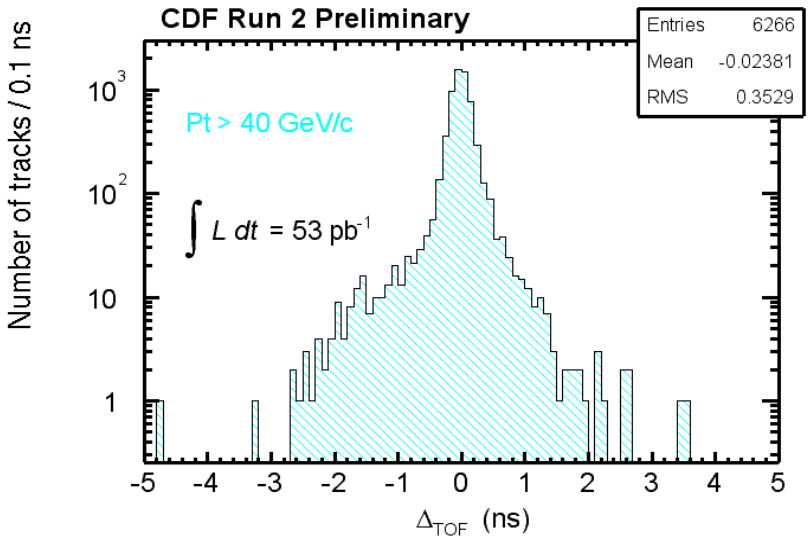
Basic "bump hunts" in jet or lepton channels make use of these

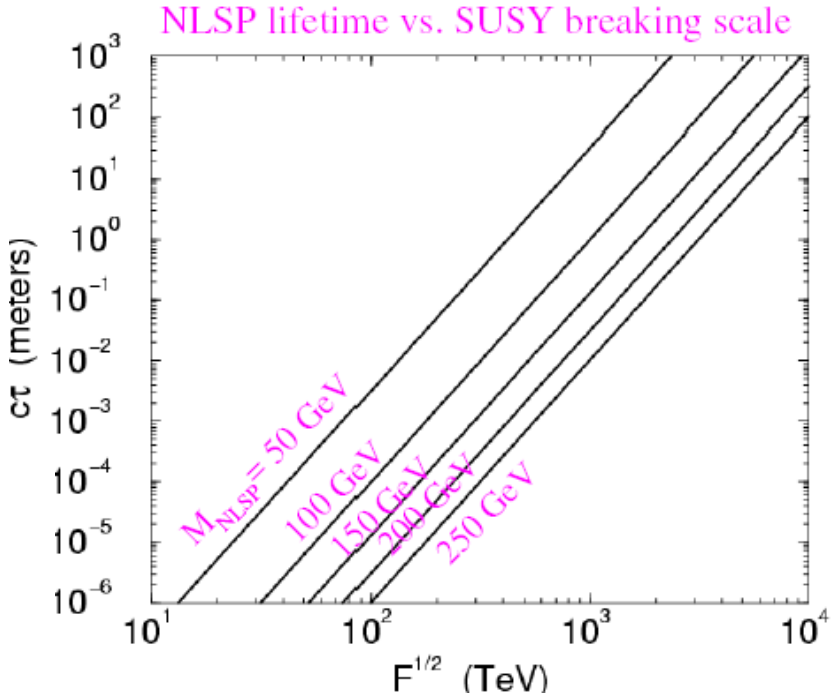
Next we look at some of the new detectors, and at missing energy…

CHAMPS

*CHA*rged *M*assive *P*article*S* -- heavy, slow, and long-lived enough to leave detector

- SUSY breaking scale and lifetime
  - SUSY particle decays to SM partner are $\propto$ to F^{-2}
  - $\sqrt{F}$ not well constrained from ~10TeV/c2 to near GUT scale



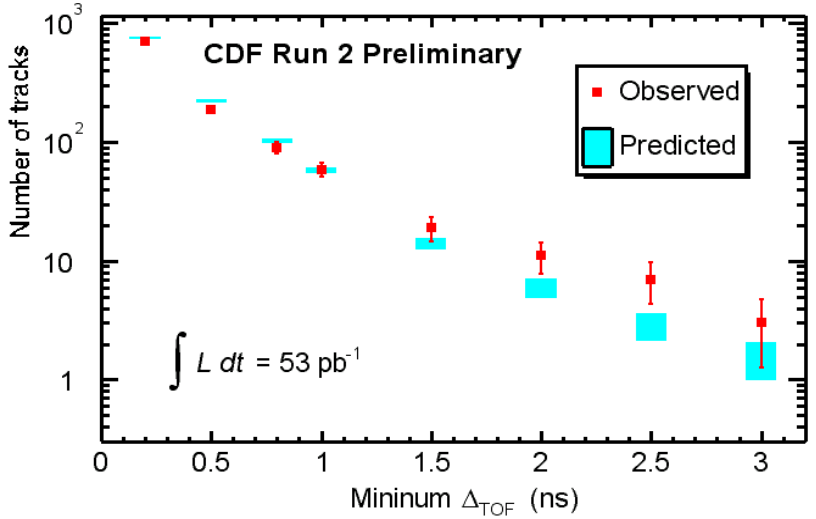


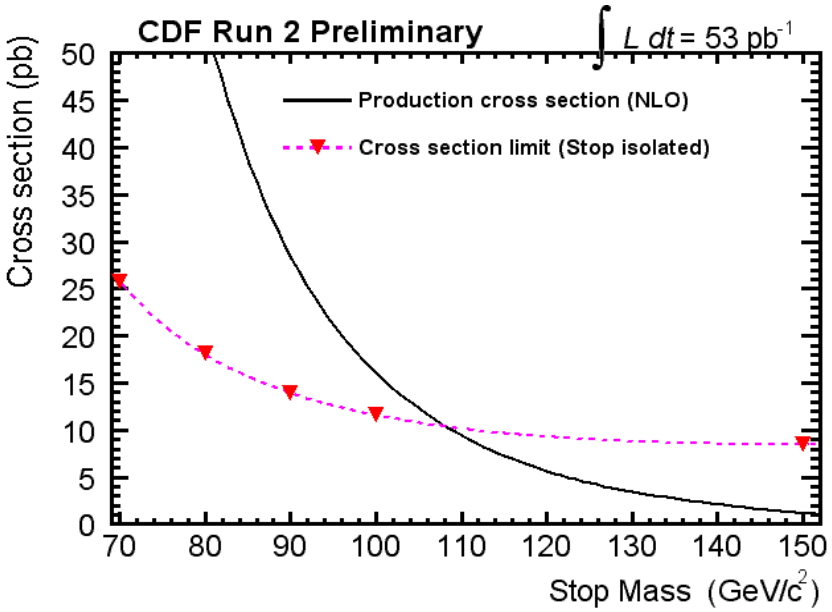
- Time Of Flight detector now installed

  ΔTOF = TOF of candidate – TOF at *c*

CHAMPS

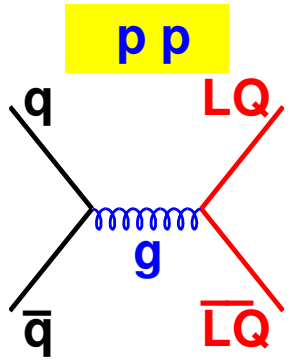
- Backgrounds are from cosmics rays and instrumental sources
  - Muon data used as signal sample
  - Checks made on many samples
- Expect 2.9 ± 0.7(stat) ± 3.1(syst) events, find 7 (no excess)
- For limit setting, a long-lived stop is assumed
  - Initial state charge (~53%) and re-hadronization probability (~43%) effect $\varepsilon_{trigger}$ (~6% for 100 GeV stop)
  - M_{stop} >108 GeV/c^2 at 95% CL
  - ALEPH limit is M_{stop} > 95 GeV/c^2



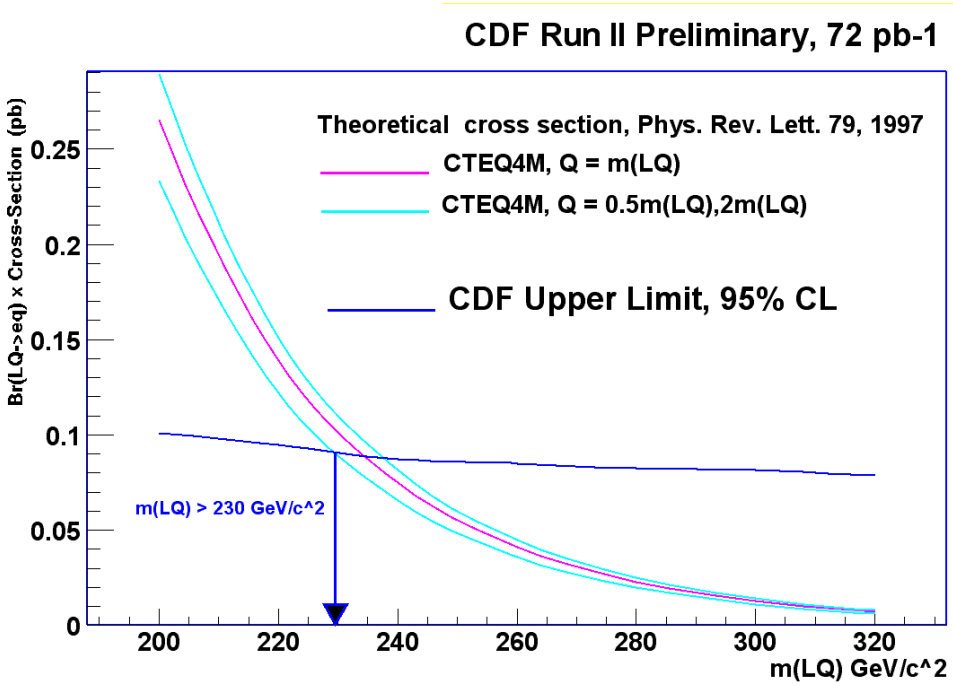


Leptoquarks: LQLQ eejj

- Search in di-electron, di-jet data
- Exploit kinematics of leptoquarks by requiring:
  - $E_T(\text{jet1}) + E_T(\text{jet2}) > 85$ GeV
  - $E_T(e1) + E_T(e2) > 85$ GeV
  - $\text{sqrt}((\Sigma \text{jet} E_T)^2 + (\Sigma e E_T)^2) > 200$ GeV



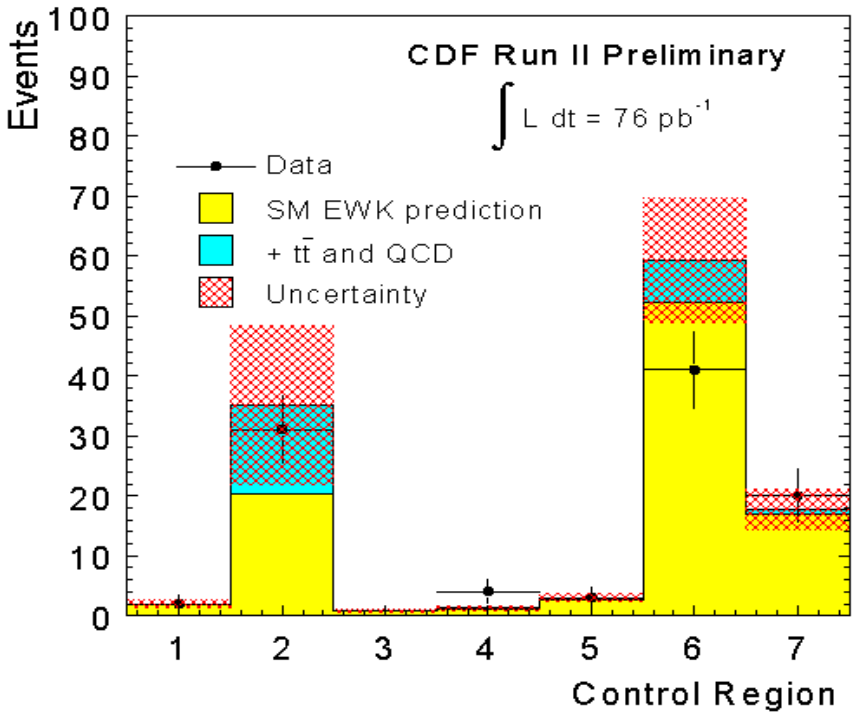
- Expect 3.4±3.2 events, observe 0
  - Limit on m(LQ) > 230 GeV/ c^2 at 95% CL
  - Run I CDF+DØ: $M_{LQ} > 242$ GeV



LQLQ ννjj and MET

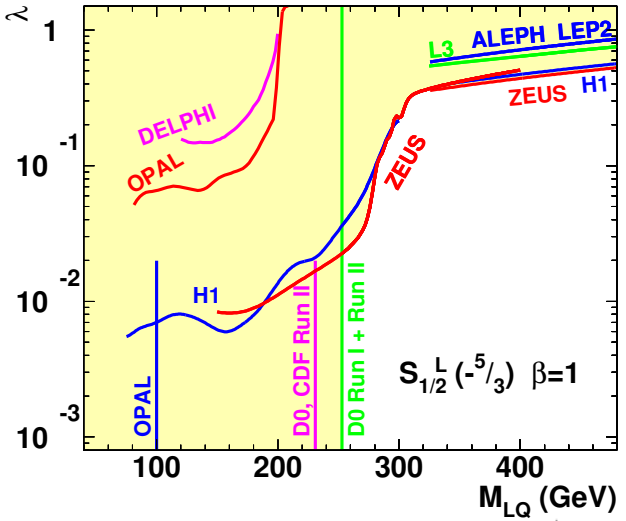
- For LQLQ ννjj, we need a good understanding of Missing Energy (MET)
- MET 'cleanup' includes corrections for…
  - Beam halo cuts
  - Event vertex offset
  - Jet reconstruction
  - Calorimeter timing cuts
  - Corrections due to beam offset
  - Muons

- Control regions studied before 'opening box'
  - 45 < MET < 55 (signal is > 55 GeV)
  - $\Delta\phi$(jet1,jet2) > 165 (signal is < 165)
  - Number leptons > 0 (signal is = 0)



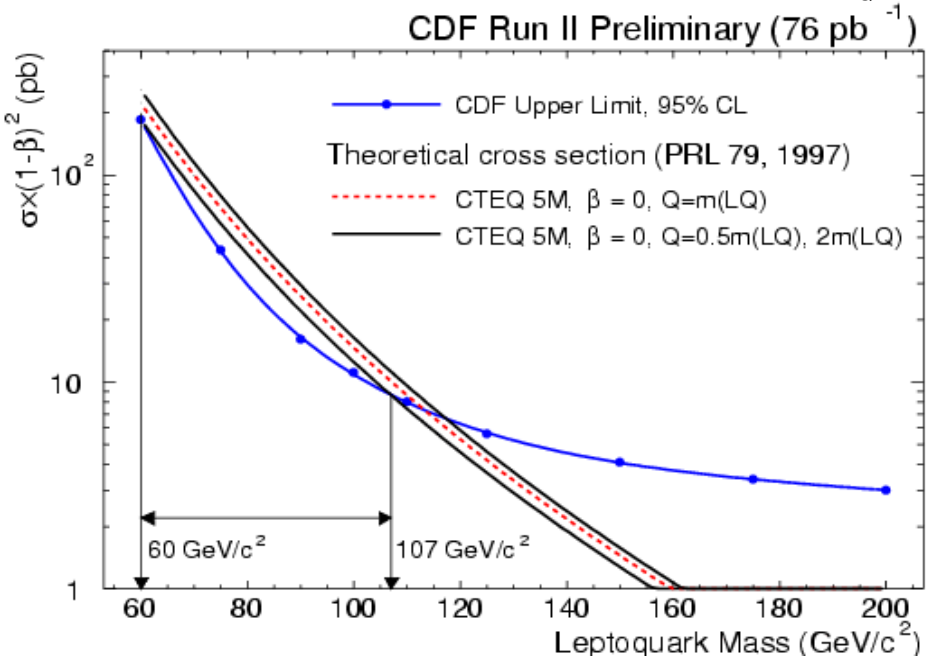
Leptoquarks: LQLQ $\nu\nu jj$

- Limits set for 1st generation LQ mass > 107 GeV/c^2
  - Expect 42.5 ± 7.6(stat) ± 7.5(syst), see 42 in data
  - Run I limit (D0) > 98 GeV/c^2
- First step in a program of SUSY results
  - Squark, gluino, or gravitino MET + jets
  - Stop, sbottom MET + heavy flavor jets



CDF Run II Preliminary

	Events
QCD	7.3
$W \to e\nu + 2$ jets	1.7
$W \to \mu\nu + 2$ jets	8.3
$W \to \tau\nu + 2$ jets	10.3
$Z \to \mu\mu + 2$ jets	0.5
$Z \to \tau\tau + 2$ jets	0.2
$Z \to \nu\nu + 2$ jets	13.4
$t\bar{t}$	0.7
All	42.5 ± 7.6(stat) ± 7.5(syst)
Data	42

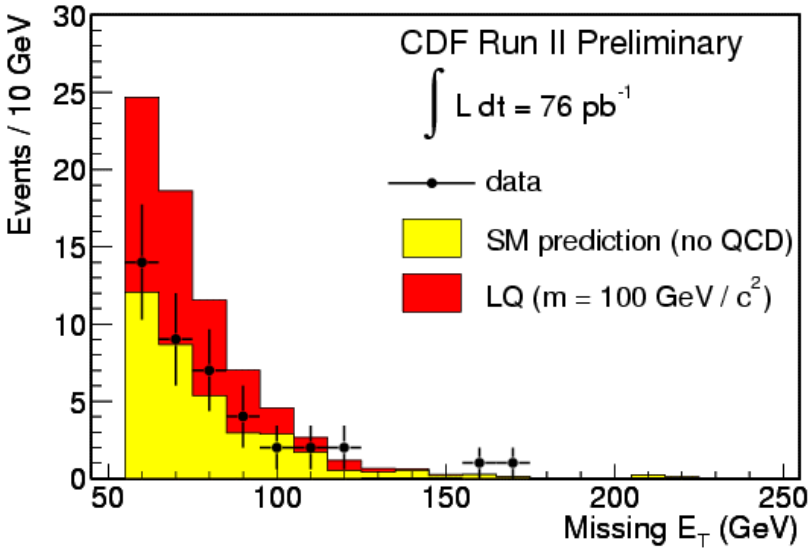


Scorecard

Basic tracking
Basic calorimetry
Basic lepton ID (high p_T)
New detectors fully commissioned
Complete coverage for calorimetry
Missing Energy understood

- Photons
- Precision silicon tracking
- Tau and b jets algorithms
- Low pT lepton ID, fake rates
- Forward tracking and calorimetry
- (Find SUSY! Find the Higgs!)

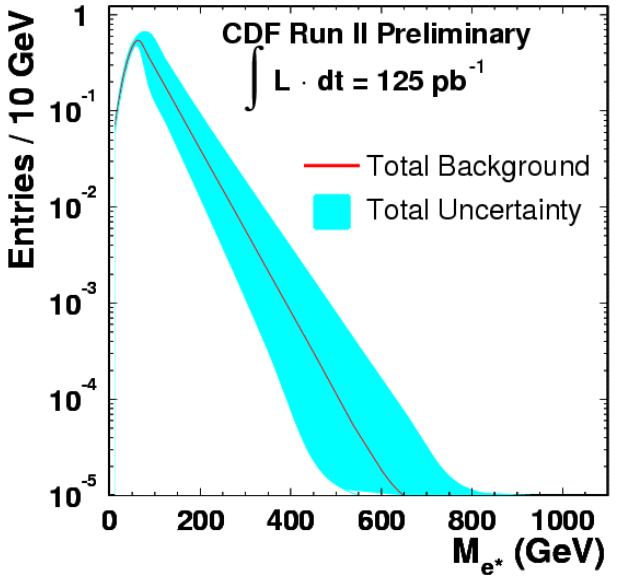
(MET from LQLQ $\nu\nu jj$)

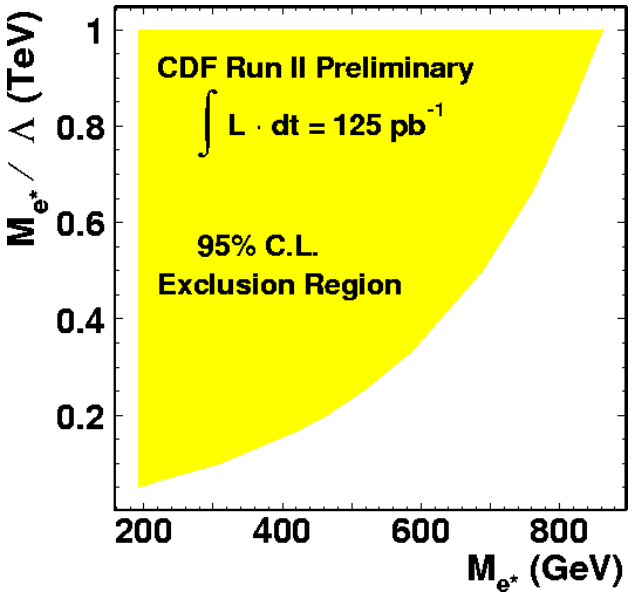


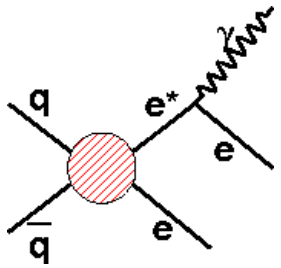
Missing energy under control, next γ, τ, and b…

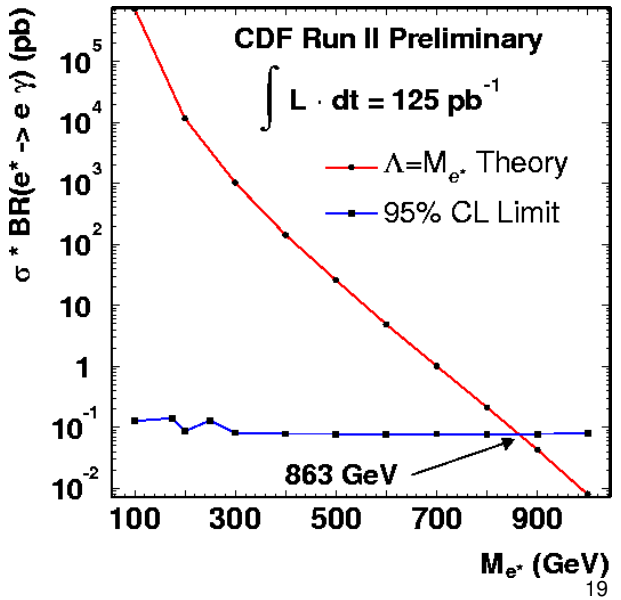
Excited electrons: e* eγ

- Composite electrons can have excited states
  - Signature is p+pbar e+e* e+eγ
  - E_T > 25 GeV for e or γ
- Bkgnd is Zγ (dominant), Z+jet, Multi-jet, W+jet
  - 1.43 events expected in forward region, 1 found
  - 0.74 events expected in central region, 0 found
- 95% CL limit set at 863 GeV/c^2



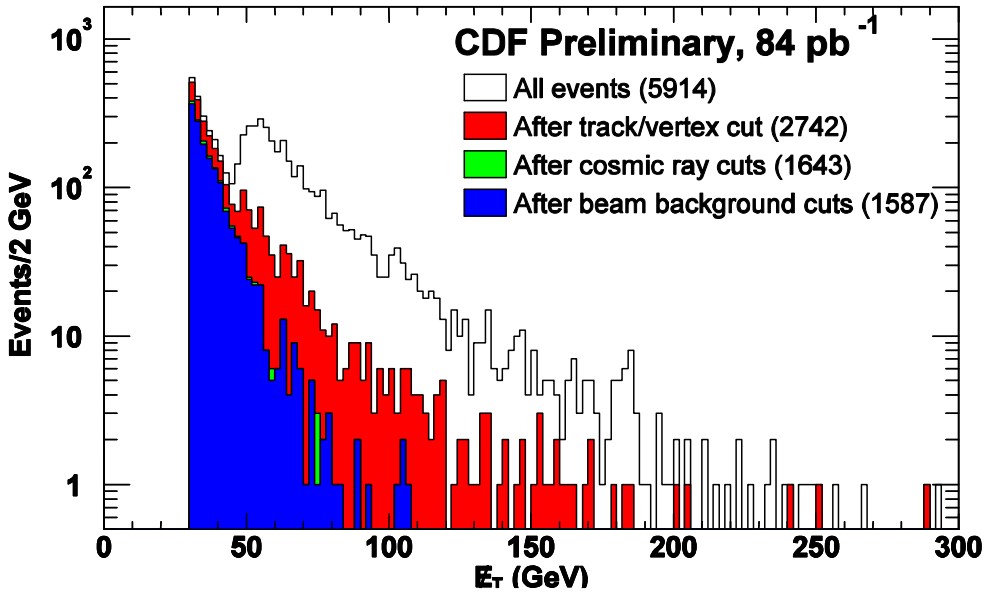




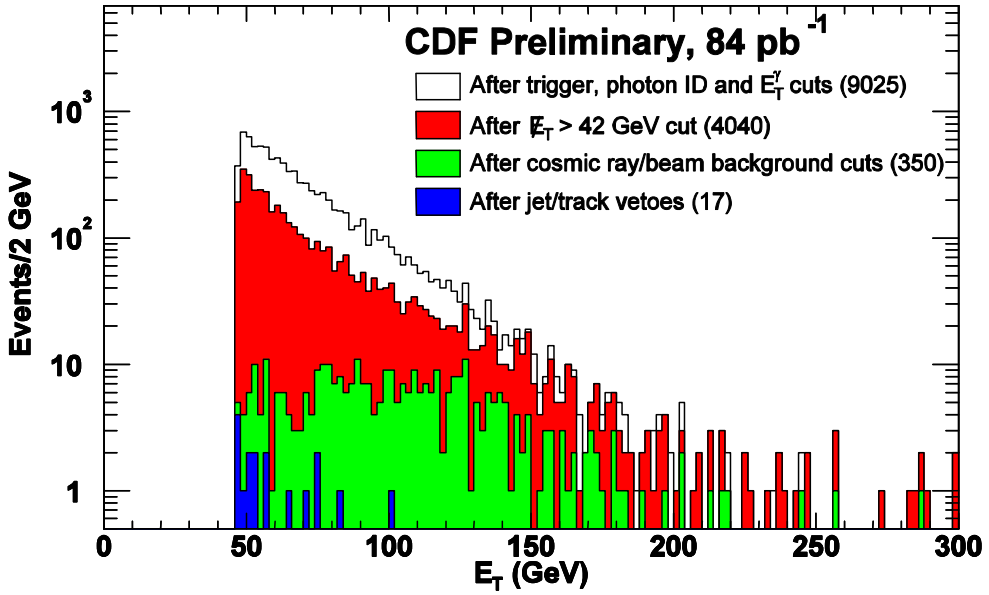


γ + MET

- Channel is sensitive to LED and Supersymmetry
  - Careful study of MET, cosmics, and beam halo required
  - Backgrounds include W eν, Zγ νγ, cosmics
- Optimize search for qq Zγ νγ

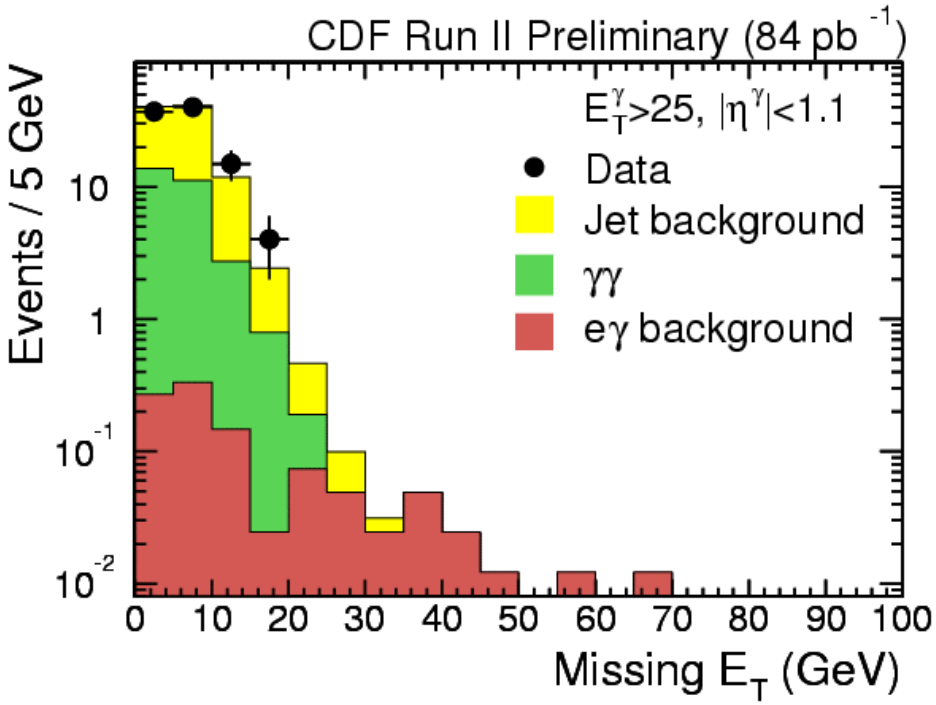


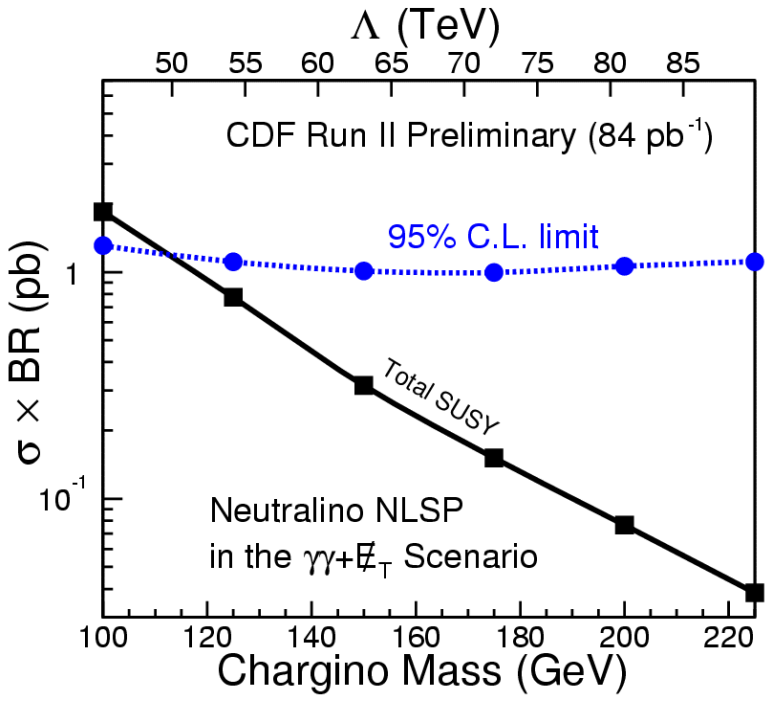
- 18.0±2.1 events expected, 17 observed
  - 95% CL upper limit is 10.2 events
  - Corresponds to a limit on Aεσ of 121 fb or 2.1 times expected Zγ contribution
  - Run I result was 3.1 times Zγ



GMSB γγMET

- Neutralino as NLSP yields signatures of γγMET from gaugino pair production
- Backgrounds from fake (QCD) and real photons (Wγ, Wj, Z ττ, diboson…)
  - Two methods to estimate bkgnd; from MET resolution and Pythia γγ, or sidebands
  - 2 ± 2 expected background for limits; 2 events observed
- Lower limit on mass of lightest chargino > 113 GeV/c^2 at 95% CL

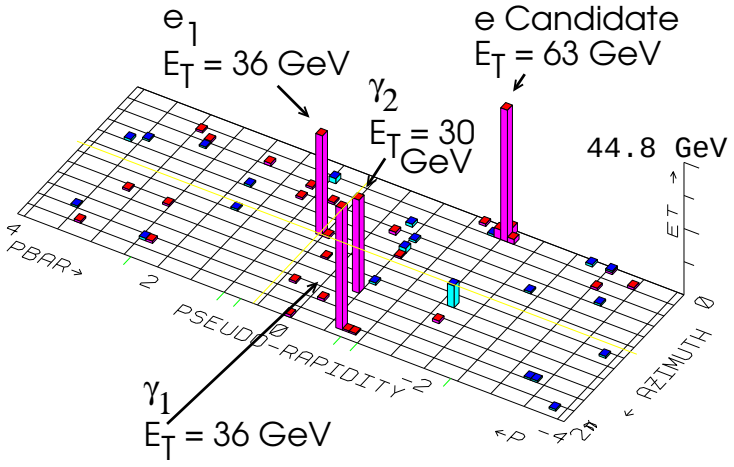




$\gamma\gamma\ell$ and $\gamma\ell$

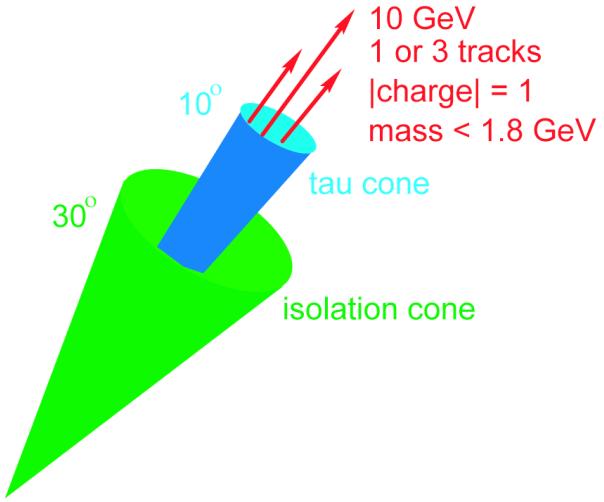
- Motivated by Run I, many searches are underway
- Searched for $\gamma\gamma\ell$ in 84 pb^{-1}
  - > 20 GeV lepton, > 13 GeV photons, isolated
  - 0.27 events expected in electron channel, less in muon
  - 0 events observed in muon or electron channels
- Run II $W\gamma$, $Z\gamma$ cross section measured for $E_T(\gamma) > 7$ GeV, $\Delta R > 0.7$:
  - $\sigma(W\gamma \quad \mu\gamma) = 19.8 \pm 4.5(\text{stat}) \pm 2.4(\text{sys}) \pm 1.2(\text{lum})$ pb (SM: $\sigma(W\gamma)=18.7 \pm 1.3$ pb)
  - $\sigma(W\gamma \quad e\gamma) = 17.2 \pm 3.8(\text{stat}) \pm 2.8(\text{sys}) \pm 1.0(\text{lum})$ pb
  - $\sigma(Z\gamma) \quad = \quad 5.8 \pm 1.3(\text{stat}) \pm 0.7(\text{sys}) \pm 0.3(\text{lum})$ pb (SM: $\sigma(Z\gamma)=5.3 \pm 0.4$ pb)
  - All are consistent with Standard Model
- No ee$\gamma\gamma$MET events yet, but we are looking!

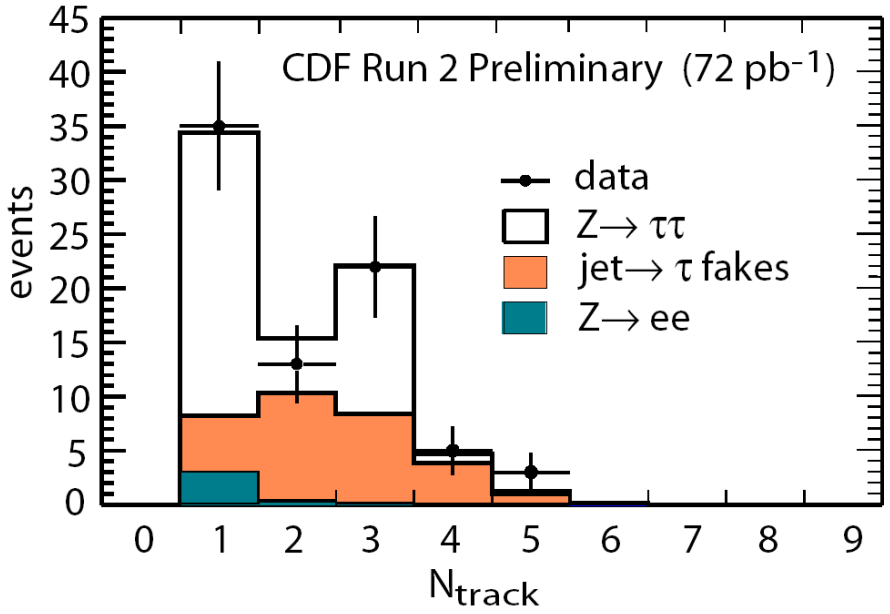
ee$\gamma\gamma\not{E}_T$ Candidate Event

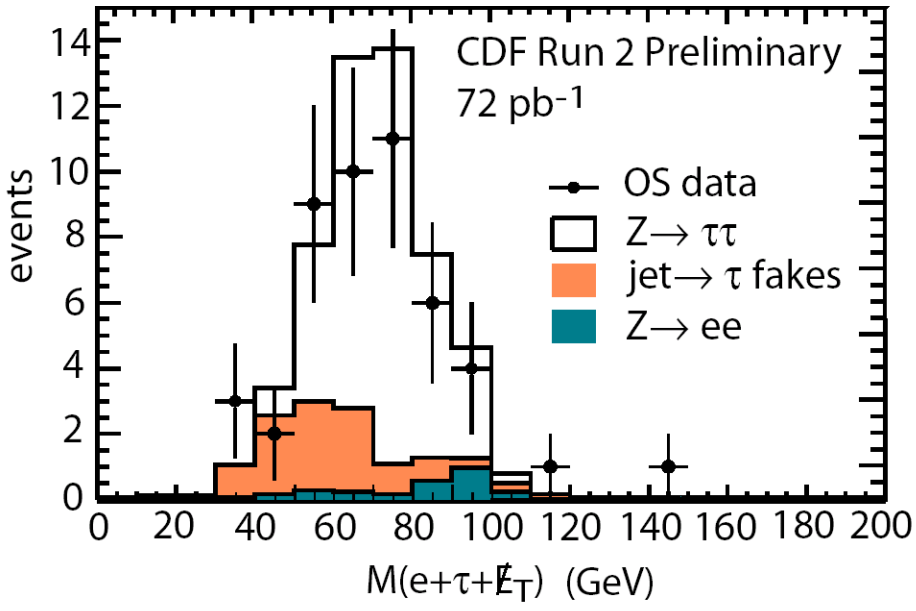


Tau reconstruction: $Z \to \tau\tau$

- Improved tau finding in Run II
  - Complete set of tau and di-tau triggers
  - Revised tau finding algorithm
- Hadronic tau charged track multiplicity
  - Data fit to MC signal plus jet-induced fakes
  - Clear indication of tau in 1 and 3 track bins
- Mass plotted for opposite-sign data
- Finding $Z \to \tau\tau$ is a stepping stone to tau related SUSY and Higgs searches

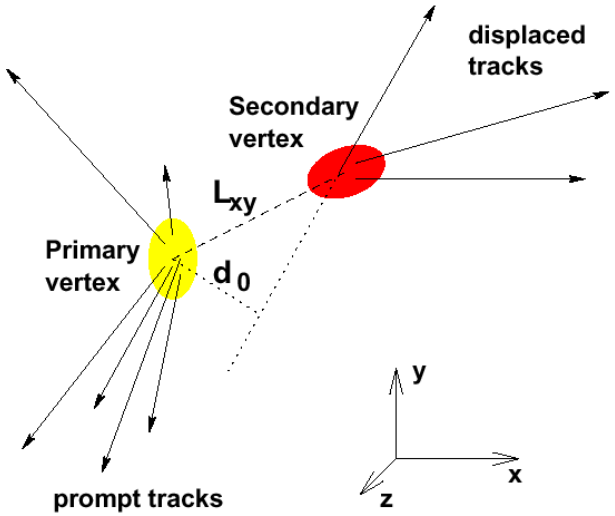


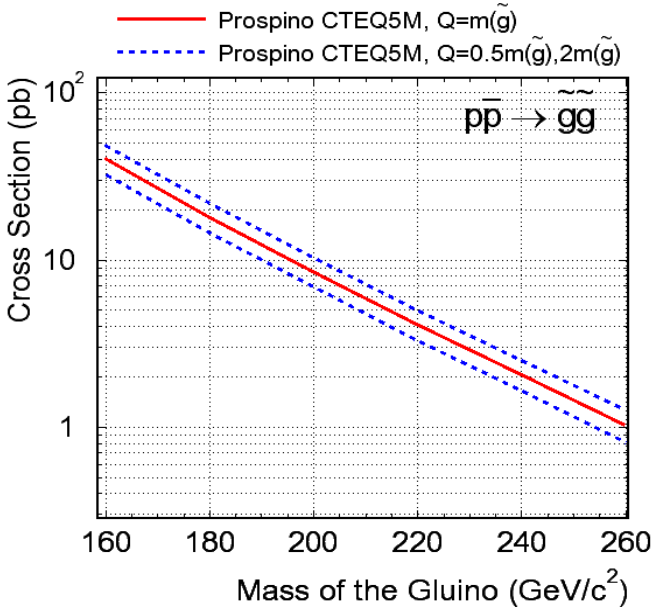




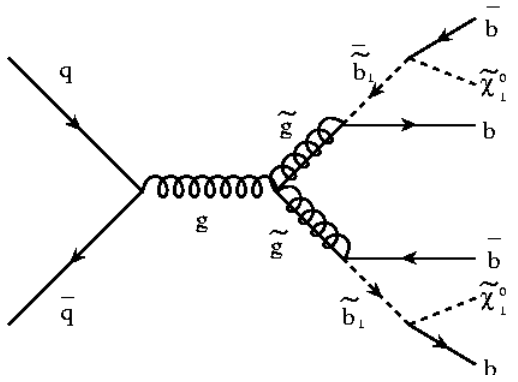
Gluino sbottom bottom

- Displaced vertex b-tag now ready
  - Reuse 2D algorithm from Run I for now
  - Efficiency, fake rate as expected



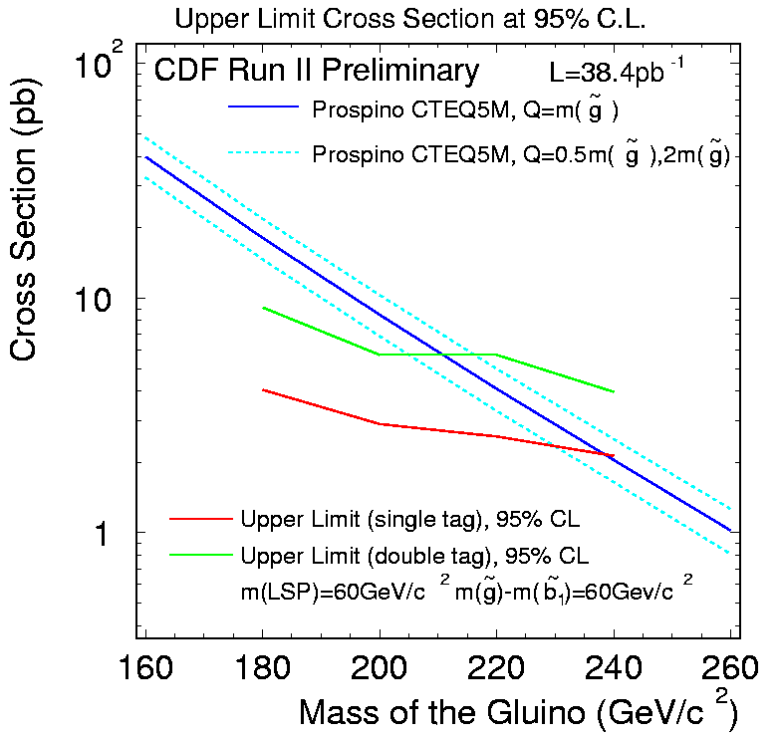


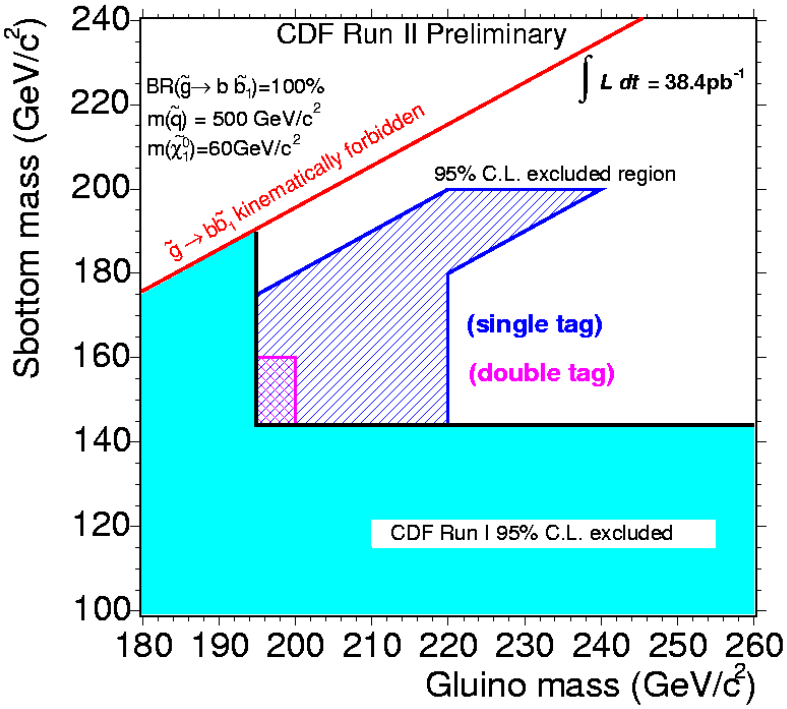
- Gluino production cross section is large, and can decay to sbottom+bottom
  - Signature is 4 b-jets and missing energy
  - Backgrounds include bb, tt, QCD, W/Z+jets
  - Require at least 3 jets, with one or two tags
  - Lepton veto, large MET (50 GeV)



$$\tilde{g}\tilde{g} \to (b\tilde{b}_1)(b\tilde{b}_1) \to (bb\tilde{\chi}_1^0)(bb\tilde{\chi}_1^0)$$

Gluino sbottom bottom





- Exclude sbottom/gluino masses at over 200 GeV/c^2.
  - Large exclusion region with small initial dataset (38.4 pb^{-1})
  - Roughly x4 more data being added
  - Sample sensitivity for m($\tilde{\chi}^0$, $\tilde{g}$, $\tilde{b}$) = (60, 220, 160) GeV/c^2 in table

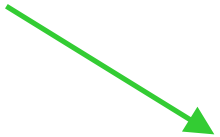
b-tag	Data	Expected Background	Expected Signal
Single	4	5.6 ± 1.4	10.6 ± 1.7
Double	1	0.5 ± 0.1	4.4 ± 0.9

Scorecard?

Basic tracking
Basic calorimetry
Basic lepton ID (high p_T)
New detectors fully commissioned
Complete coverage for calorimetry
Missing Energy understood
Photons
Precision silicon tracking
Tau and b jets algorithms

- Low pT lepton ID & fake rates
- Forward tracking and calorimetry
- (Find SUSY! Find the Higgs!)

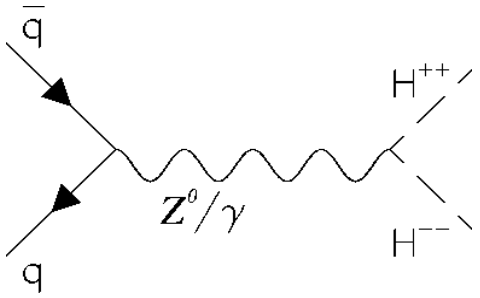
Already at the level of Run I…

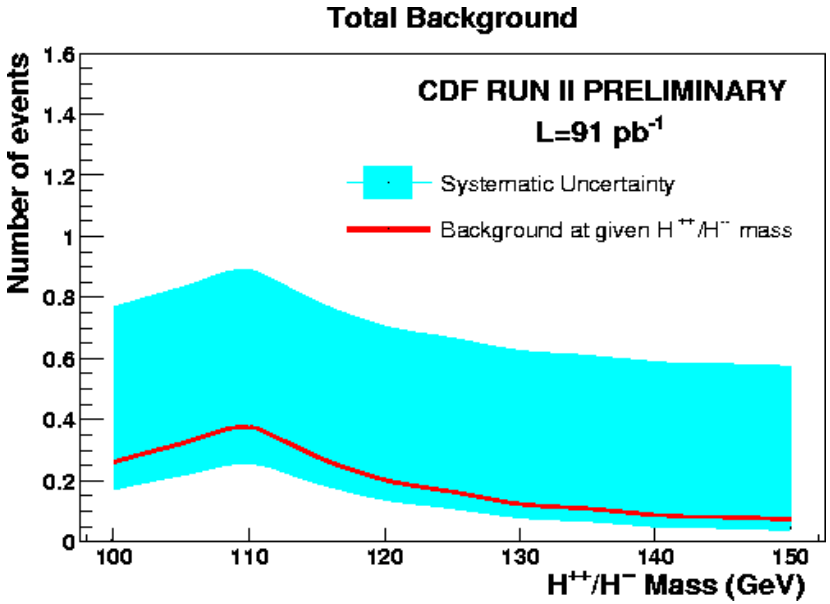


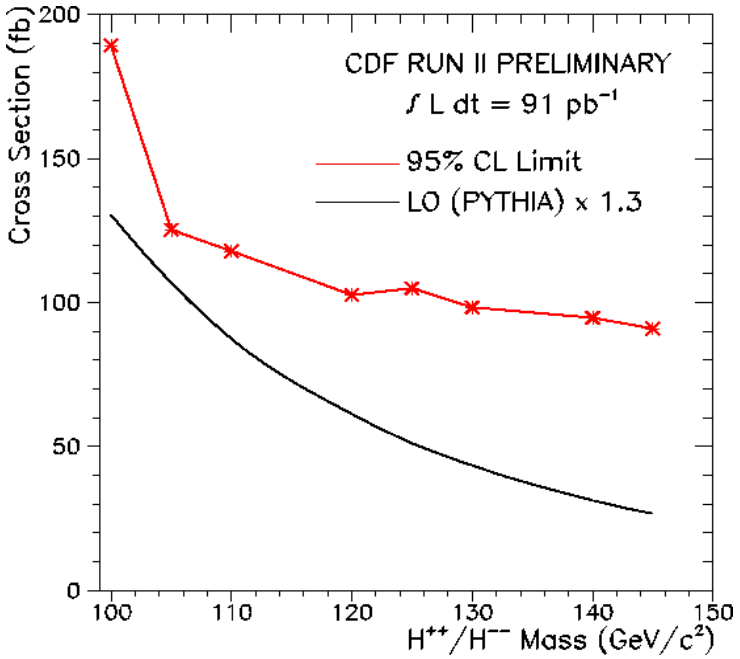
Currently working on forward tracking, tagging, and calorimetry. These are all new, but ready to go!

Doubly-Charged Particles $e^{\pm}e^{\pm}$

- Arise in models with a Higgs triplet
  - Naturally occur in Left-Right models: $SU(2)_L \times SU(2)_R$
  - SUSY LR models predict low-mass H++ (~0.1 to 1 TeV)
- Use same-sign electrons, search for resonance
  - Low mass region (<80 GeV/c^2) used to check backgrounds
- 0 events seen in 91 pb^{-1}
  - Cross section limit set at 95% CL

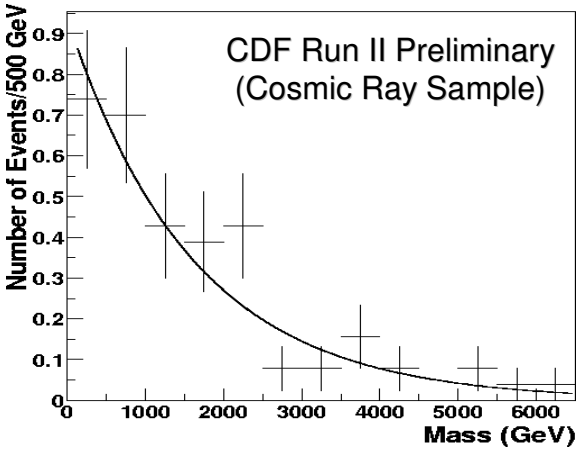


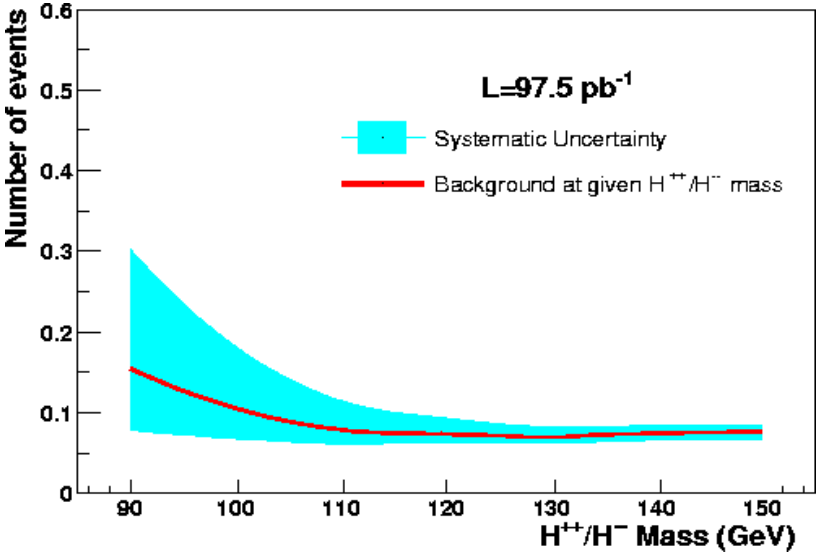


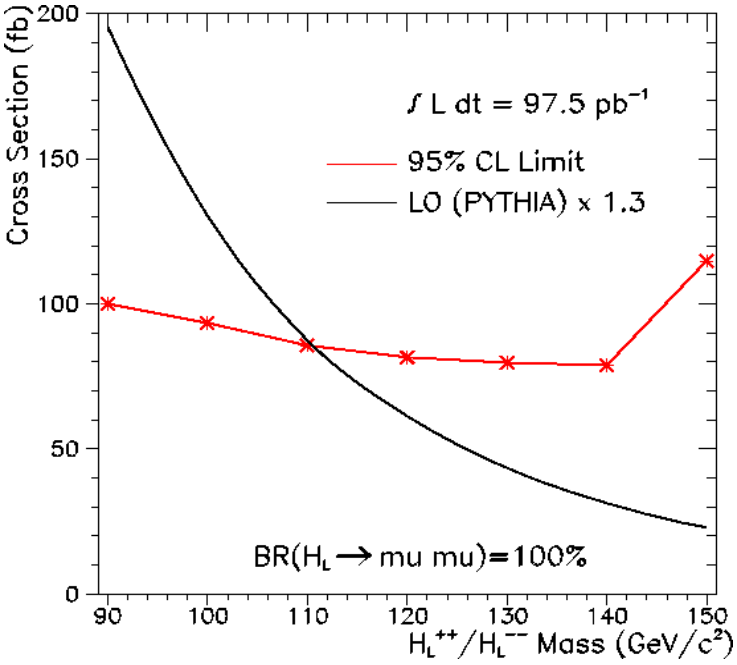


Doubly-Charged Particles $\mu^{\pm}\mu^{\pm}$

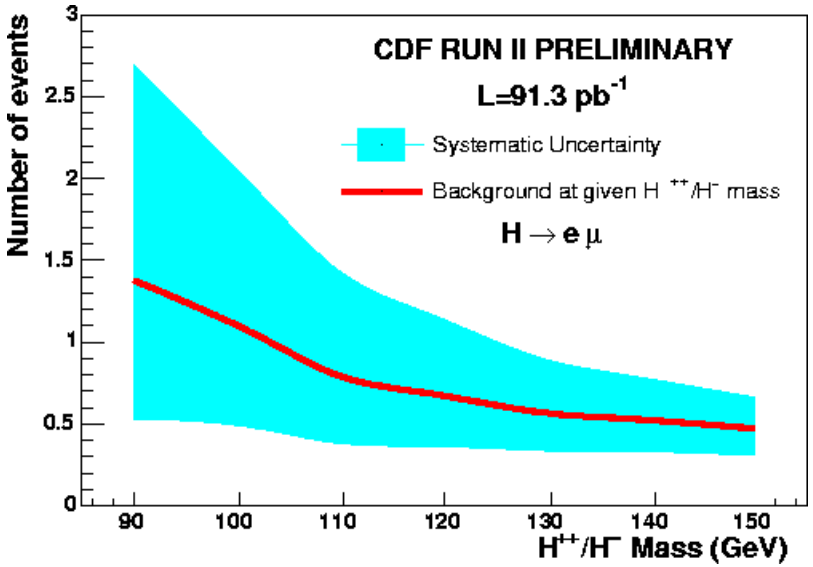
- H^{++} $\mu^{\pm}\mu^{\pm}$ backgrounds
  - Cosmics dominate high end
  - W+jets are dominant below ~100 GeV/c^2
- $3^{+0.4}_{-0.3}$ events expected, 2 observed (160, 760 GeV)
- $M_{H^{++}} > 110$ GeV/c^2 at 95% CL
  - LEP limit is 100 GeV/c^2

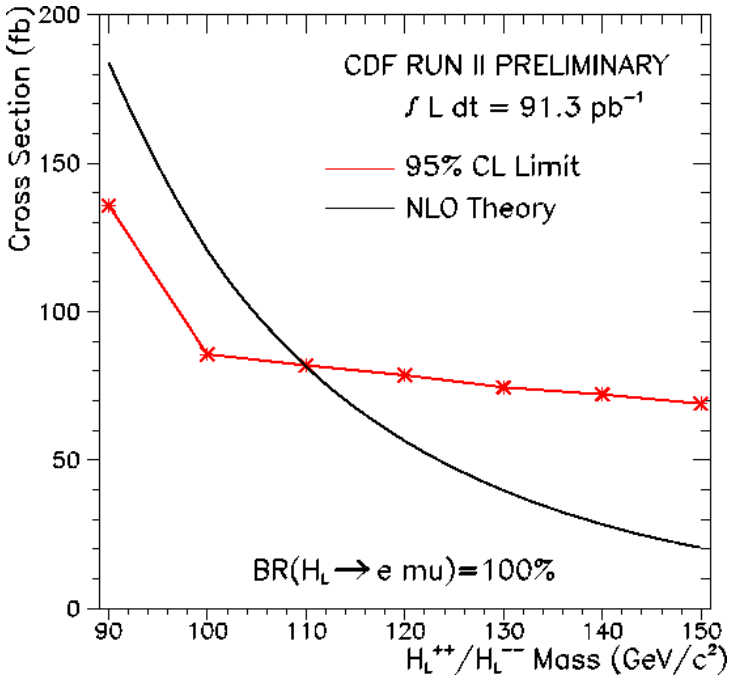






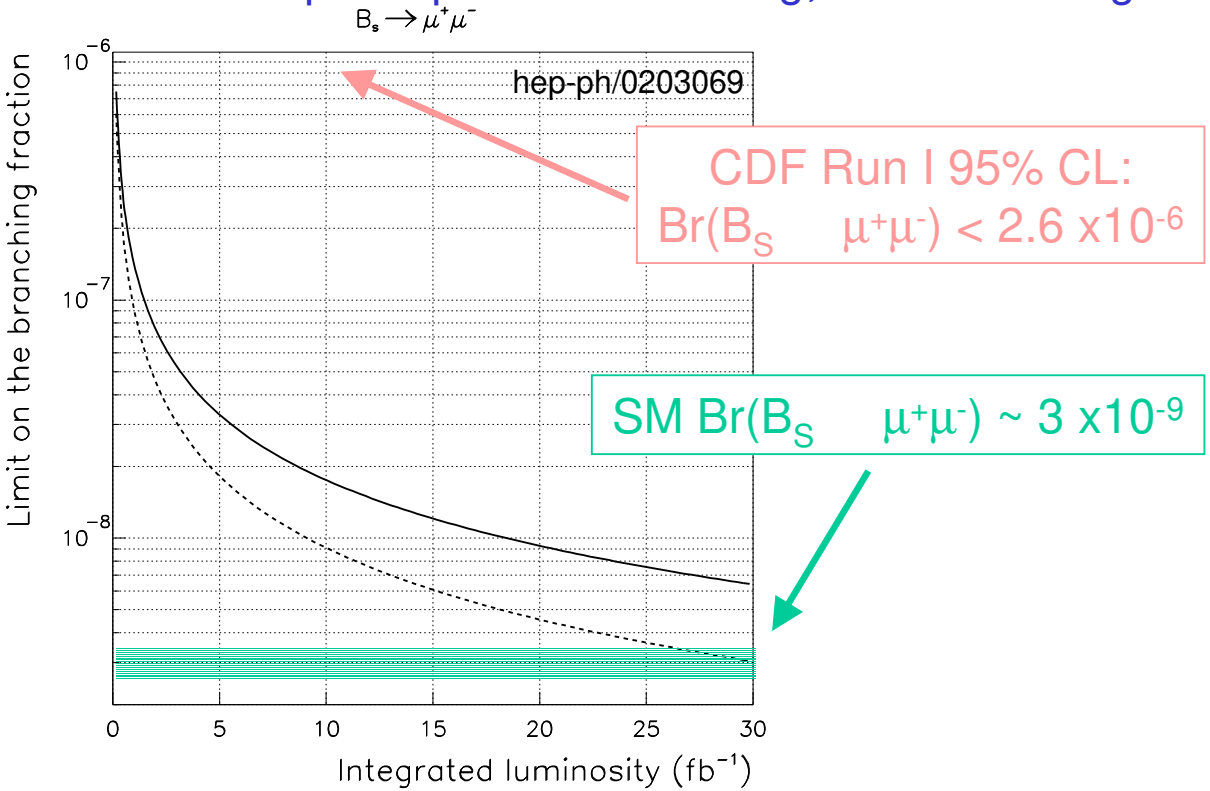
Doubly-Charged Particles $e^{\pm}\mu^{\pm}$

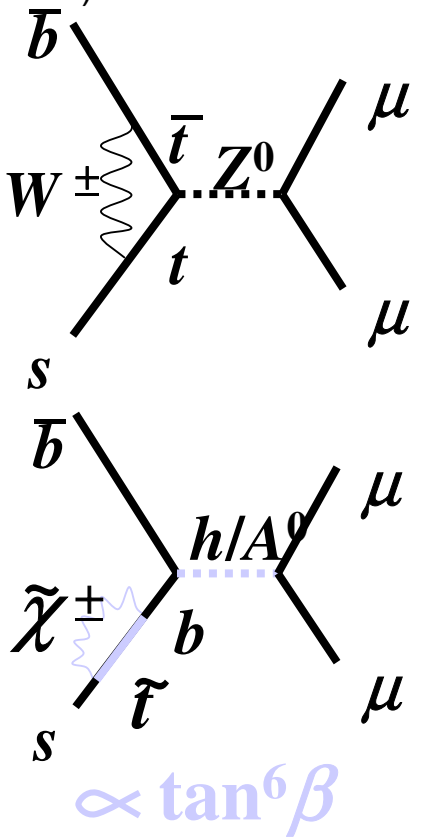




$B_s \quad \mu^+\mu^-$

- Rare decay rates can be modified by new physics
  - Standard Model Br($B_S \quad \mu^+\mu^-$) ~ 10^{-9}
  - SUSY diagrams can modify the Br($B_S \quad \mu^+\mu^-$) to be ~ 10^{-8} or even 10^{-7}
  - massive $\nu \Rightarrow$ SO(10) SUSY (see-saw) $\Rightarrow B_S \quad \mu\mu$
  - Also in SUSY models with $(g-2)_\mu$ deviations (PRL87[2001]251804)
- Search requires precision tracking, understanding of fakes





$B_s \quad \mu^+\mu^-$

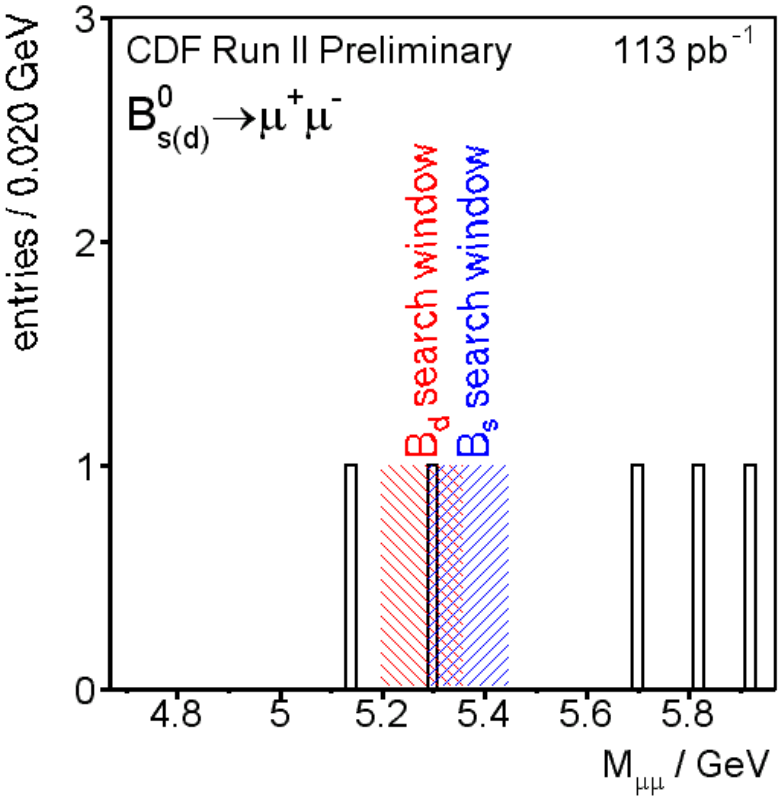
- Expect 0.54±0.20 (B_s) and 0.59±0.22 (B_d) events, 1 event found (both windows)

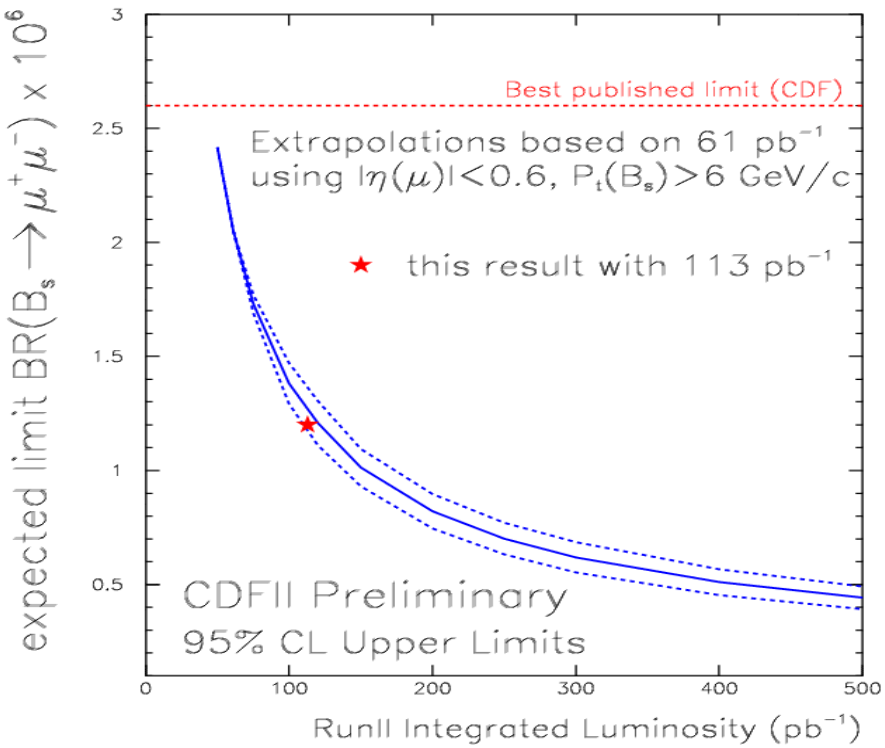
$BR(B_s \quad \mu\mu) < 9.5E\text{-}7$ (90% CL)

$< 1.2E\text{-}6$ (95% CL)

$BR(B_d \quad \mu\mu) < 2.5E\text{-}7$ (90% CL)

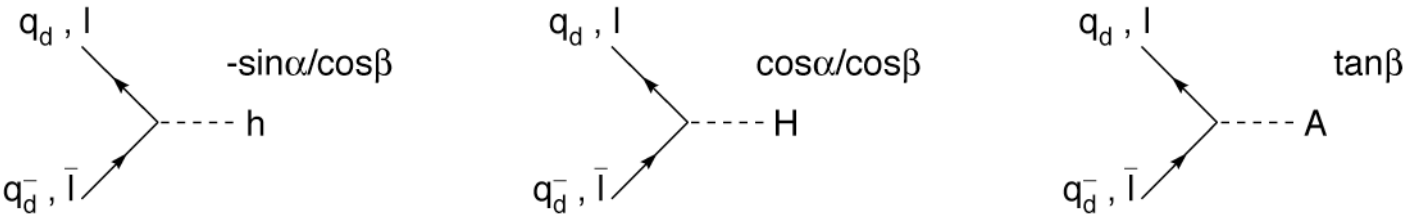
$< 3.1E\text{-}7$ (95% CL)

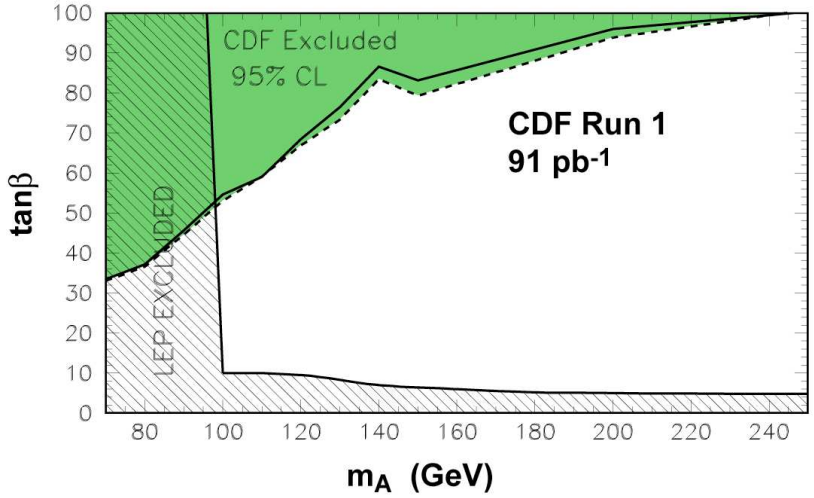




MSSM Higgs + b(b)

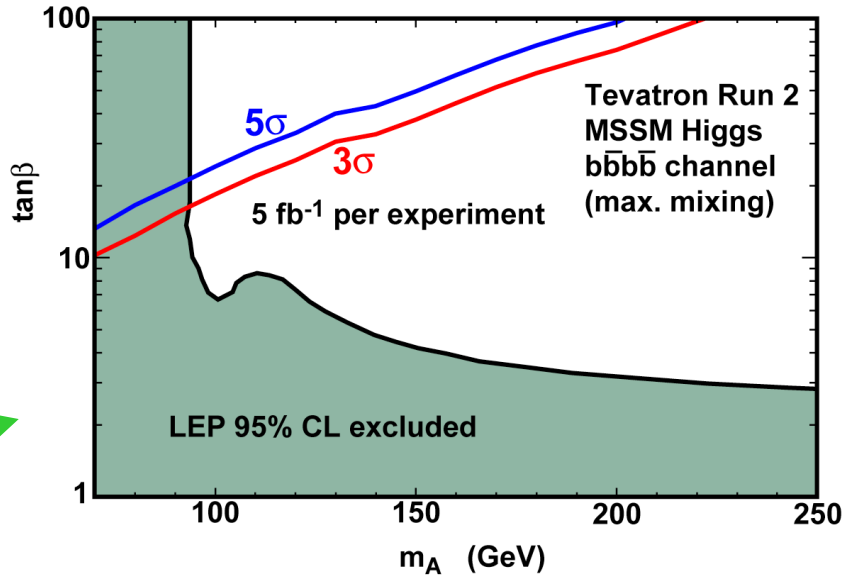
- Of course many more non-SM Higgs channels to search
- MSSM H + bb enhanced for large tanβ: $\sigma(pp \to bbH/bbA/bbh) \propto \tan^2\beta$





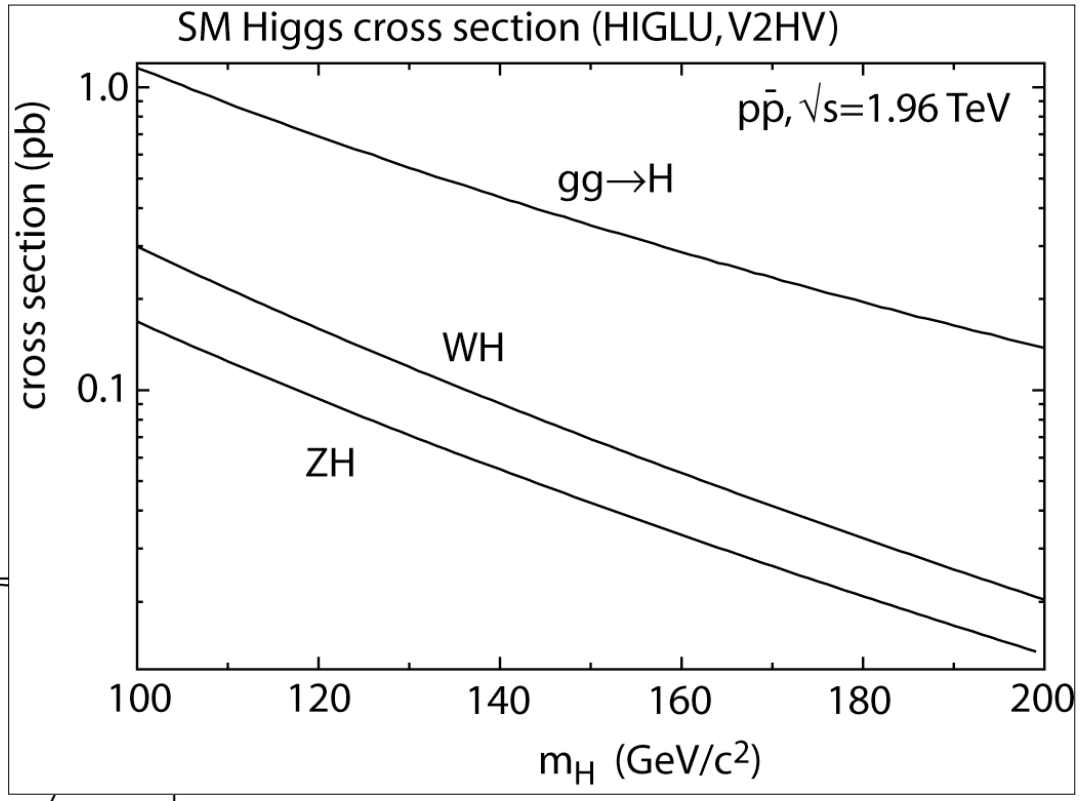
Run I result

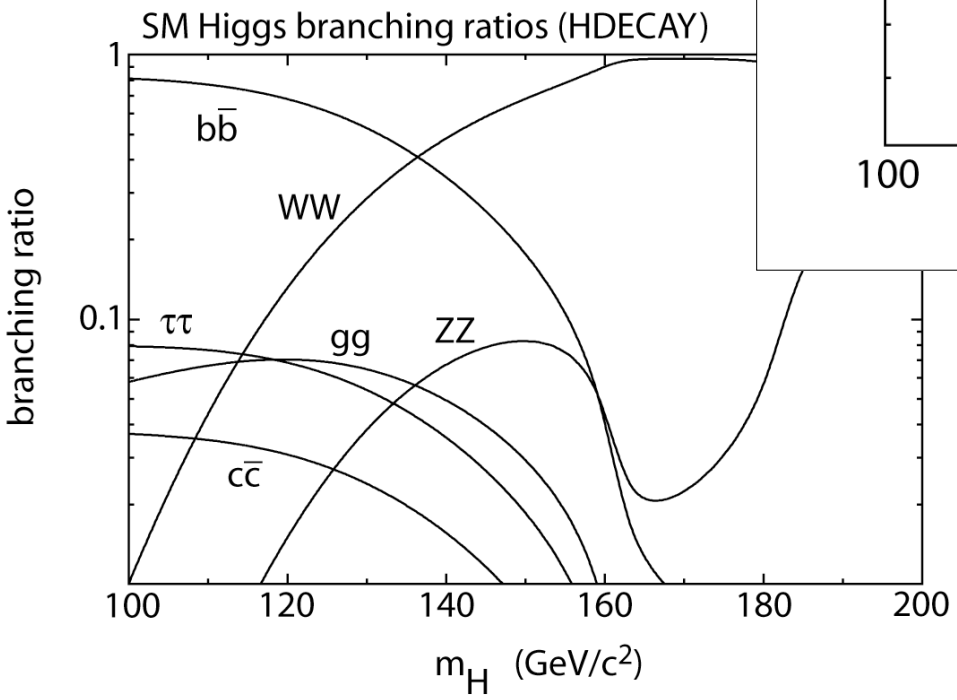
Run II expectation



SM Higgs Production

- gg→H dominates but dijet background too big…
- bb decay modes are best

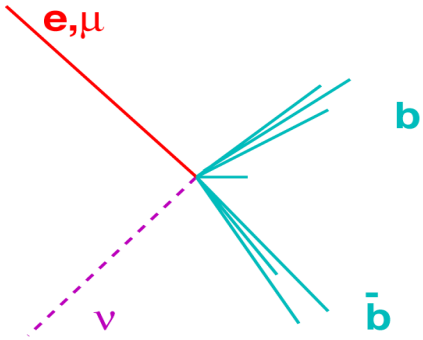




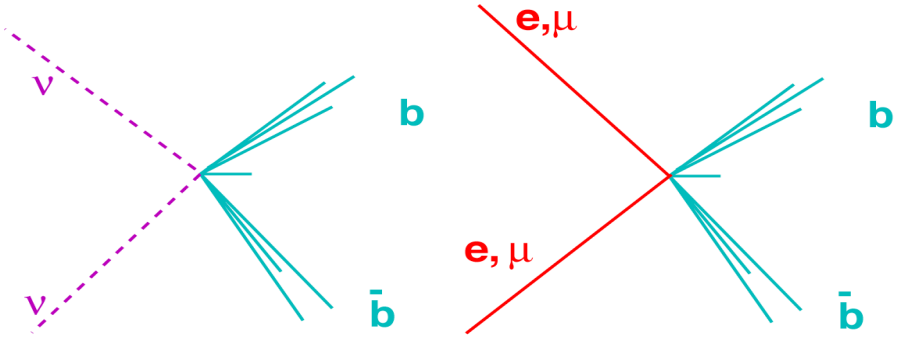
WH+ZH ~300 fb at 115 GeV

SM Higgs Channels

For m_H<135 GeV, bb decays dominate:

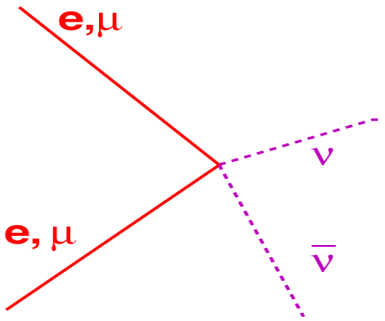


WH

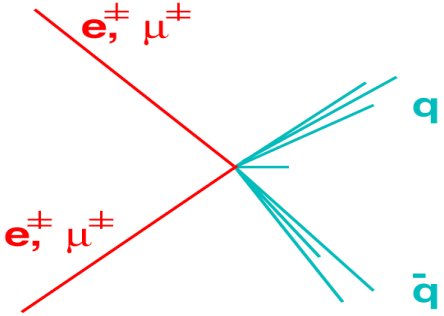


ZH

At m_H>135 GeV, WW decays are important:

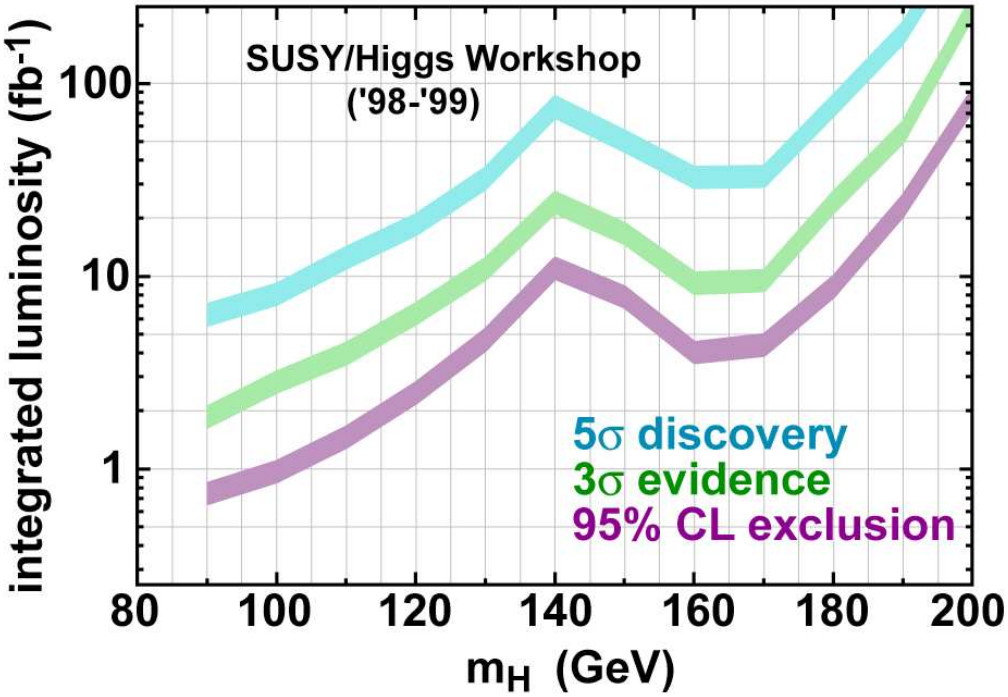


$gg \rightarrow H \rightarrow WW \rightarrow ll\nu\nu$



$ZH/WH \rightarrow WWW/ZWW$

98/99 Run 2 SUSY/Higgs Workshop



- parametrized fast Monte Carlo (no magnet or multiple interaction effects)
- neural network selection
- 10% mass bb mass resolution
- single-bin counting experiment
- nominal systematics

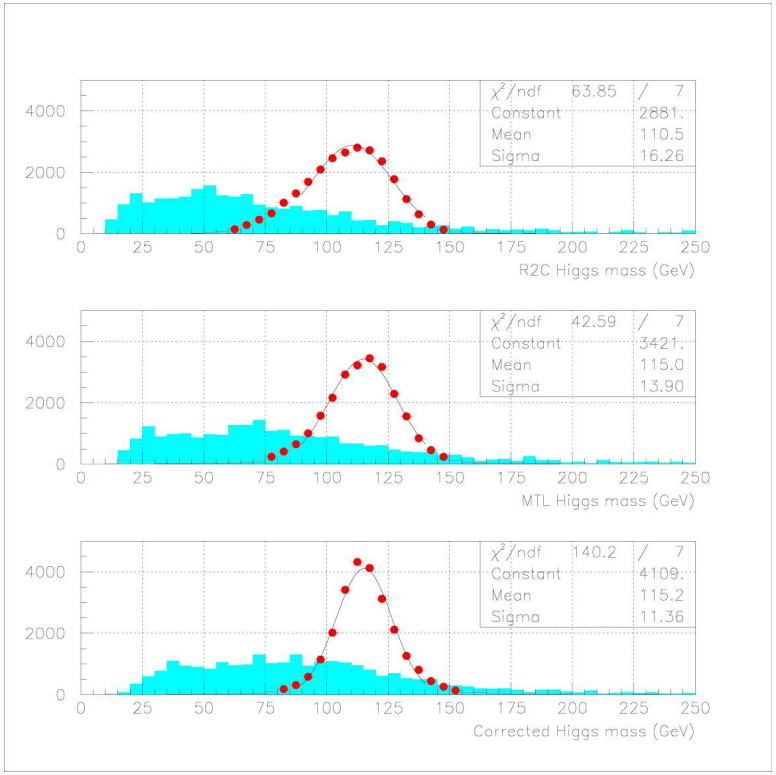
(see hep-ph/0010338)

2003 Higgs Sensitivity Study

- Sensitivity Study revisited: disclaimers and timeline
  - Asked to review the previous study and re-evaluate our SM Higgs reach (by DOE Office of Science)
  - Short time: split work between CDF and D0 along lines of “WH” and “ZH” channels
  - Study completed only very recently and presented to DOE
- Improvements over 1998/99
  - Full Monte Carlo, real data experience to draw upon
  - Experience with neural net Higgs selection (kinematic)
    - CDF estimates x1.6 improvement
    - D0 x2.25 (reduction of integrated luminosity required)
  - Measured b-tag algorithm ε numbers to use
  - Better justification for 10% mass resolution
  - Much better understanding of the backgrounds
- A couple of the key features of the analysis include…

b-Tagging and Mass Resolution

- Mass resolution studied; ~10% is achievable
  - 'hyperball' algorithm; mass correction on n-dimensional space of kinematic variables
  - Will need careful optimization
- Tagging efficiency based on CDF Run II data
  - Use current 2D algorithm
  - Include roll-off in ε near |η|=2
  - Efficiency estimates require detector replacement(!)

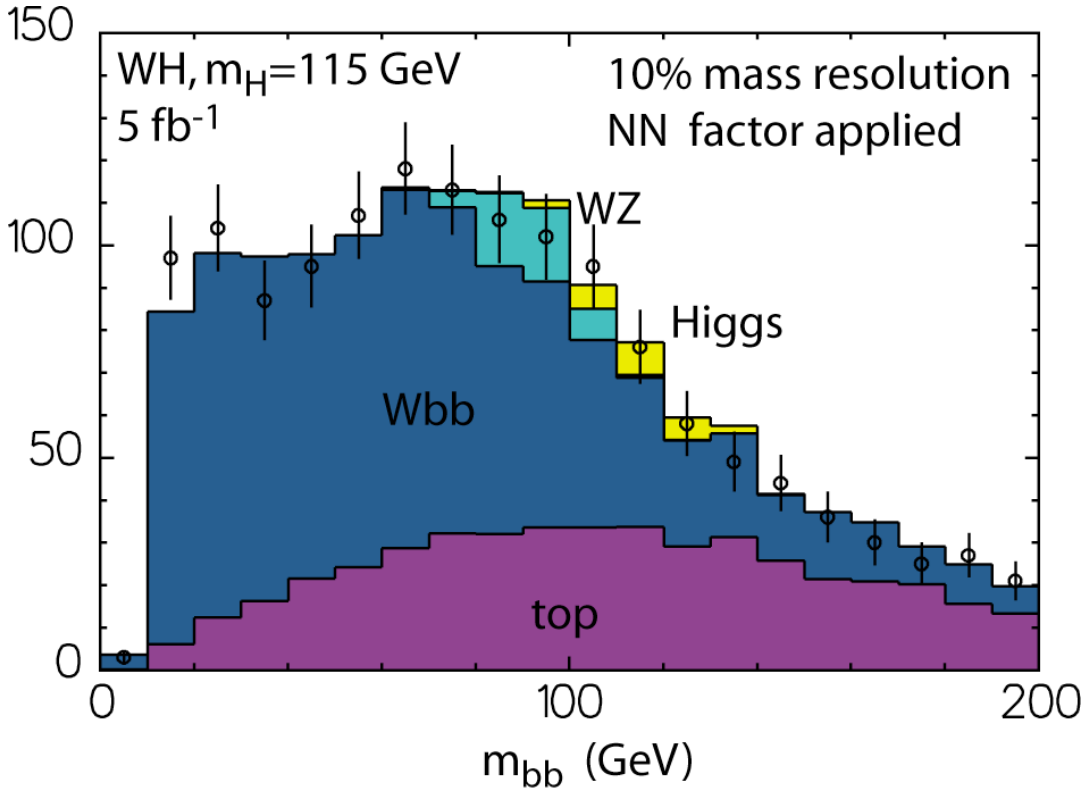


Higgs Mass (GeV/c^2)	110	115	120	130	140
$\geq$ 1 Secvtx (Win 2003)	0.484	0.491	0.496	0.492	0.499
Double Secvtx (Win 2003)	0.089	0.087	0.090	0.089	0.101
$\geq$ 1 Secvtx	0.552	0.554	0.557	0.568	0.579
1 Secvtx + 1 Secvtx.OR.JetPrb<0.05	0.185	0.184	0.191	0.194	0.202
$\geq$ 1 Secvtx (Extended η)	0.661	0.664	0.664	0.677	0.686
Double Secvtx.OR.JetPrb<0.05	0.279	0.279	0.290	0.300	0.314
SHWG Tight (No Eta Dependence)	0.712	0.712	0.710	0.721	0.723
SHWG Loose (No Eta Dependence)	0.347	0.343	0.351	0.359	0.372

Comparison of tagging ε
In old and new study

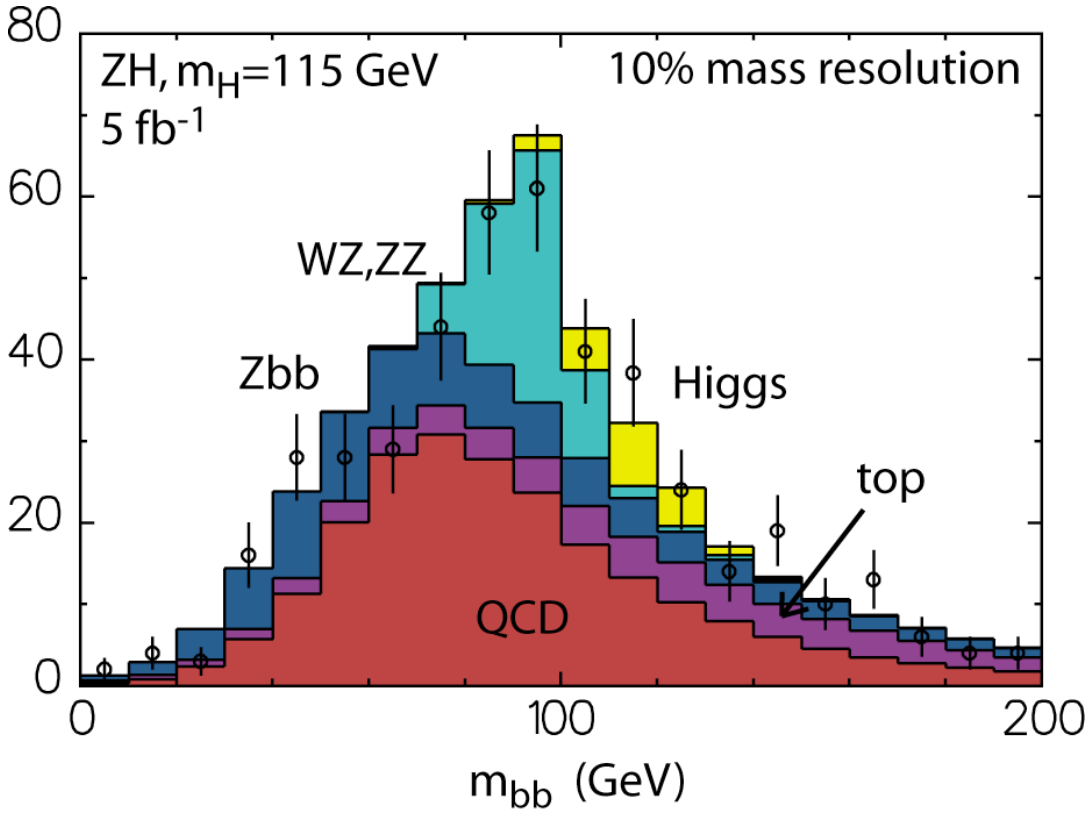
WH channel

- Results for WH channel
  - b-tagging includes declining e at large h
  - 10% mass resolution
  - Signal and background scaled up by x1.6 to reflect neural net selection
  - Understanding the background shapes will obviously be crucial



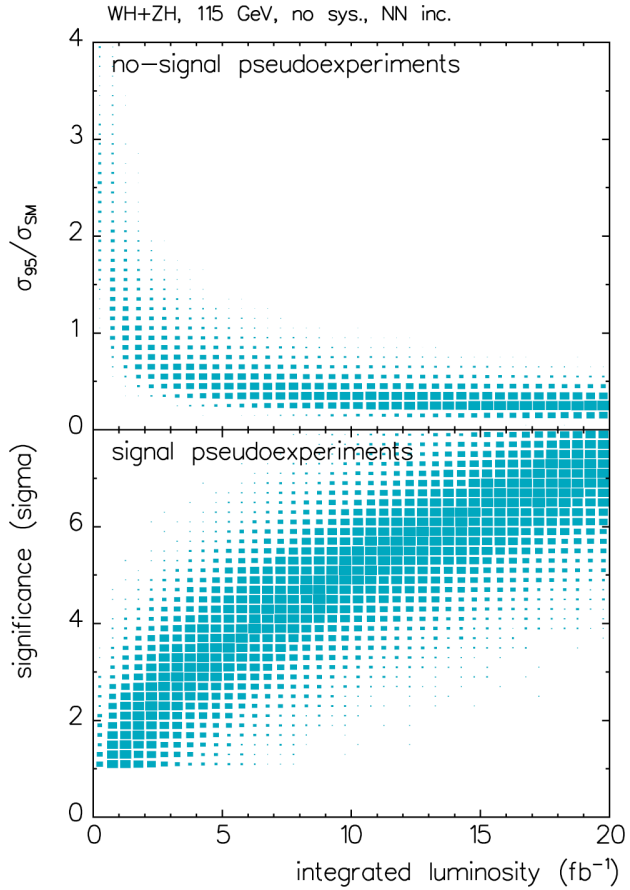
ZH channel

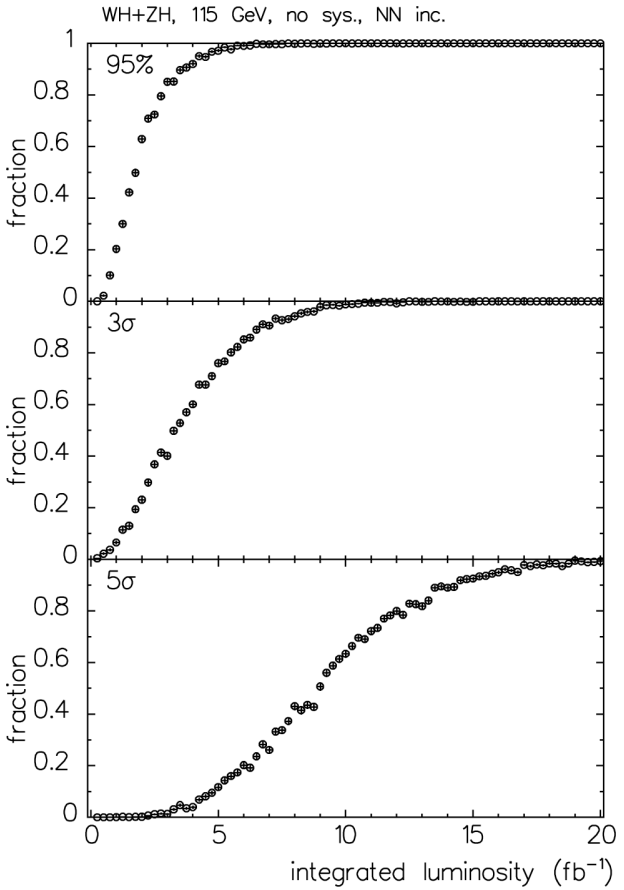
- Results for the ZH channel
  - Incorporate llbb by scaling signal and bkgnd by 1.33
  - Uses neural net selection
  - QCD background from RunII data
  - Significant acceptance from WH channel; need to insure no overlap with lνbb



Final Results, Combined Channels

- Method:
  - Pseudoexperiments where CDF and D0 each have WH and ZH outcomes
  - Form joint likelihood with full m(bb) in both channels
  - Study Bayes and CL_S (ala LEP2) methods (agree to 10%)

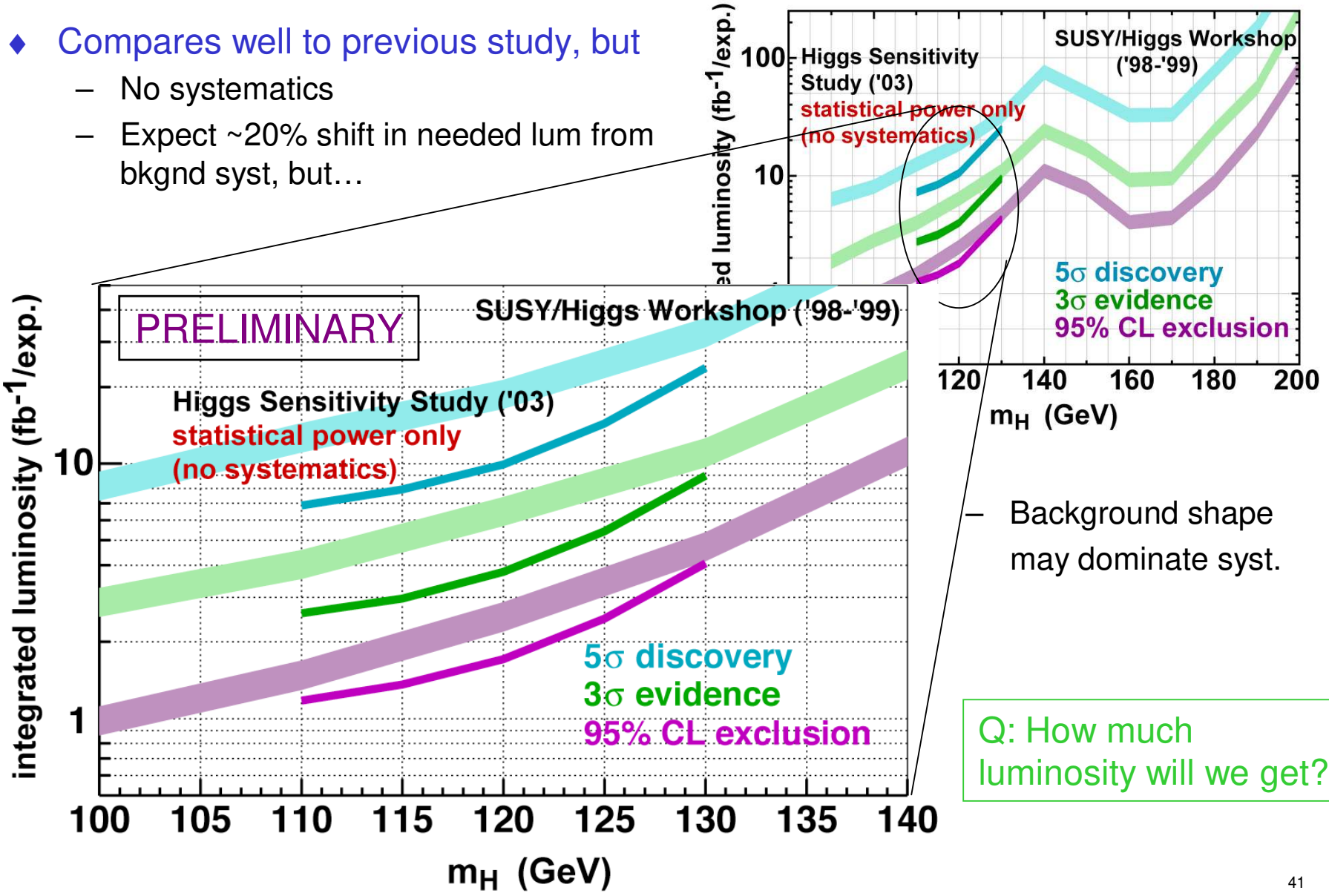




(Shown is for a 115 GeV/c^2 SM Higgs)

Revised SM Higgs Reach Estimate

- Compares well to previous study, but
  - No systematics
  - Expect ~20% shift in needed lum from bkgnd syst, but…
  - Background shape may dominate syst.



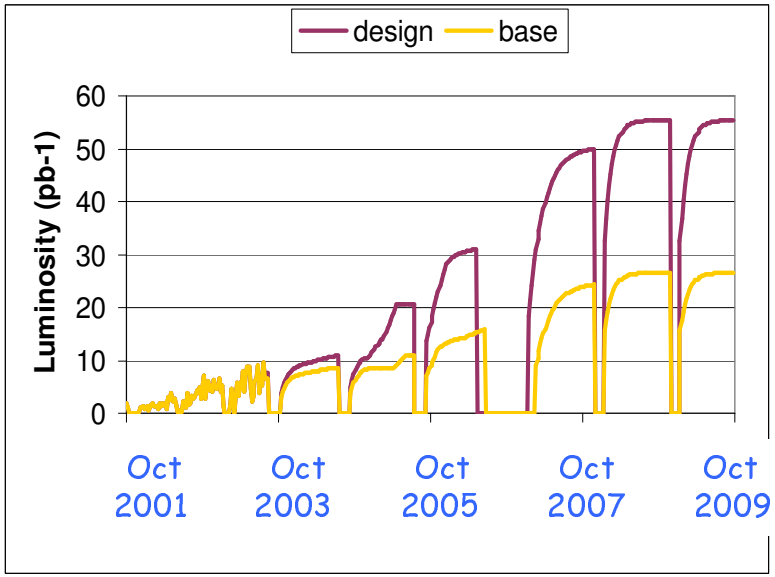
Q: How much luminosity will we get?

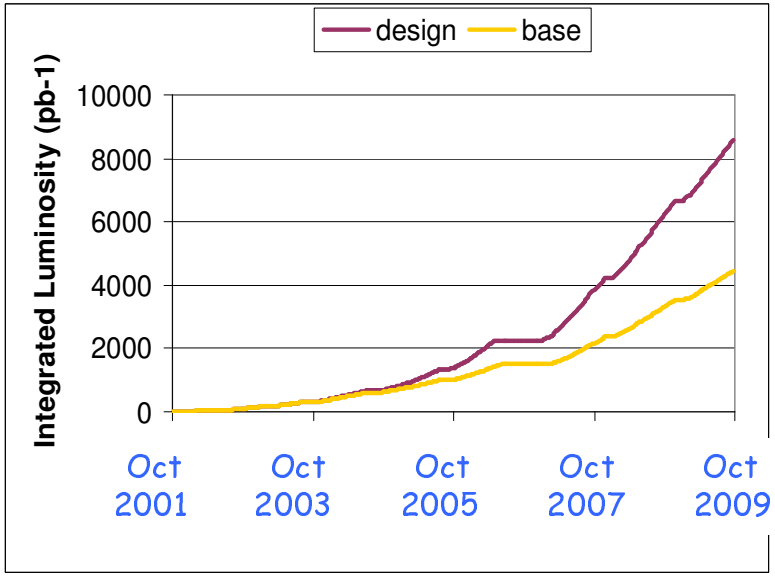
Luminosity Projections

A: Not as much as we want!

- Much more realistic and detailed estimates recently made by Beams Div.
  - Basis of July '03 Lehman review
  - "design" goal requires electron cooling in recycler
  - Shutdown included for silicon replacement
- 5-6 fb^{-1} by LHC turn on?

- Silicon Vertex Detector is crucial; will it survive to the end of Run II?
  - Designed for 2 fb^{-1} and 2 years operation
  - D0 silicon system much more sensitive





"Death" of the Silicon; Modeling the S/N

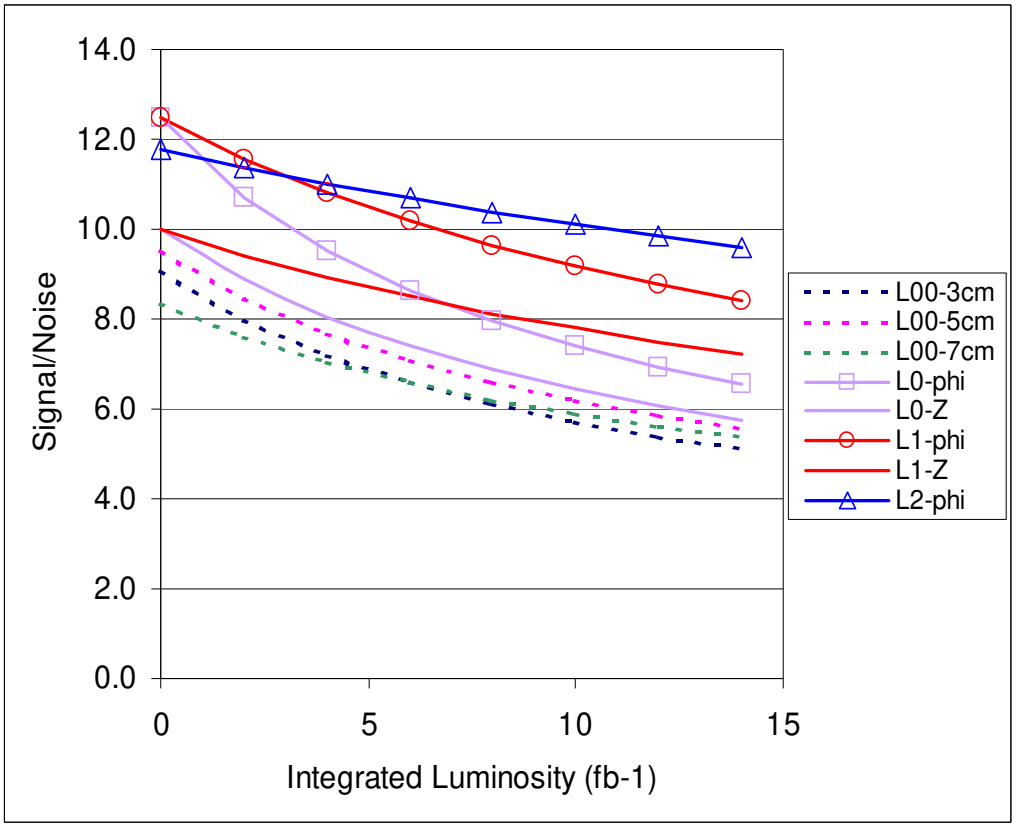
- We expect that the inner silicon layers will eventually be unusable due to low signal-to-noise (S/N)
  - Displaced track triggering will be good to S/N = 8.
  - B-tagging will be degraded at low S/N (in Run I, ε was lost below S/N ~6)

- Noise
  - Shot noise calculated from leakage current
  - Chip noise measured in controlled irradiations

- Signal
  - Double-sided AC-coupled silicon voltage across readout caps
  - ~170V maximum depletion, from burn-in (180V) and other concerns
  - Axial strips are on p-side; can't get axial info while underdepleted
  - Depletion voltage estimates are therefore critical
  - We assume full charge collection throughout Run II

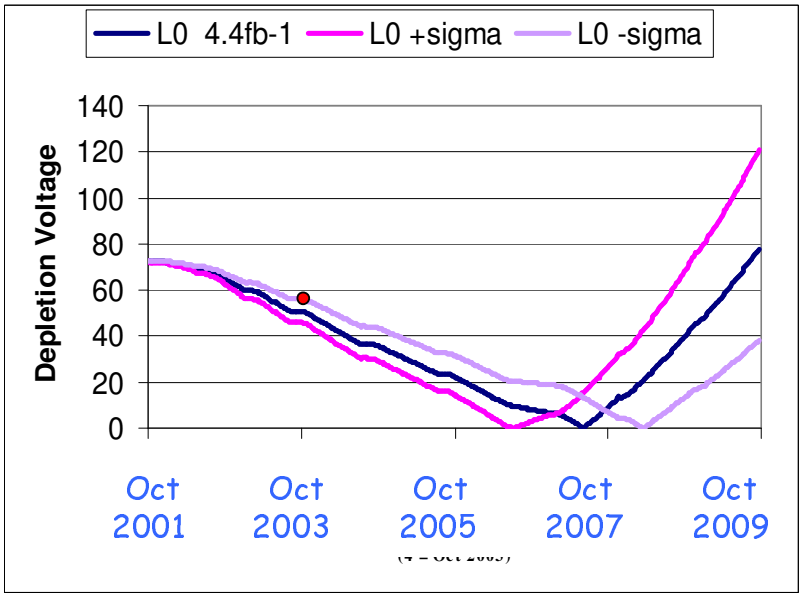
Noise Model; Results

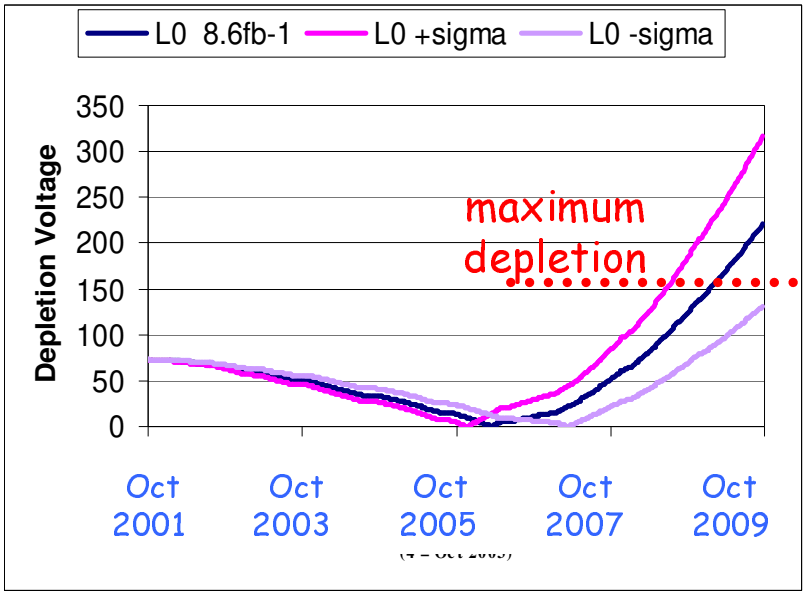
- Noise degrades more steeply at first, then gradually
- S/N follows same trend (assuming full signal collection) and does not quite reach 6 for L0.



S/N begins near 12.5, and is expected to decline gradually

Depletion Voltage Results



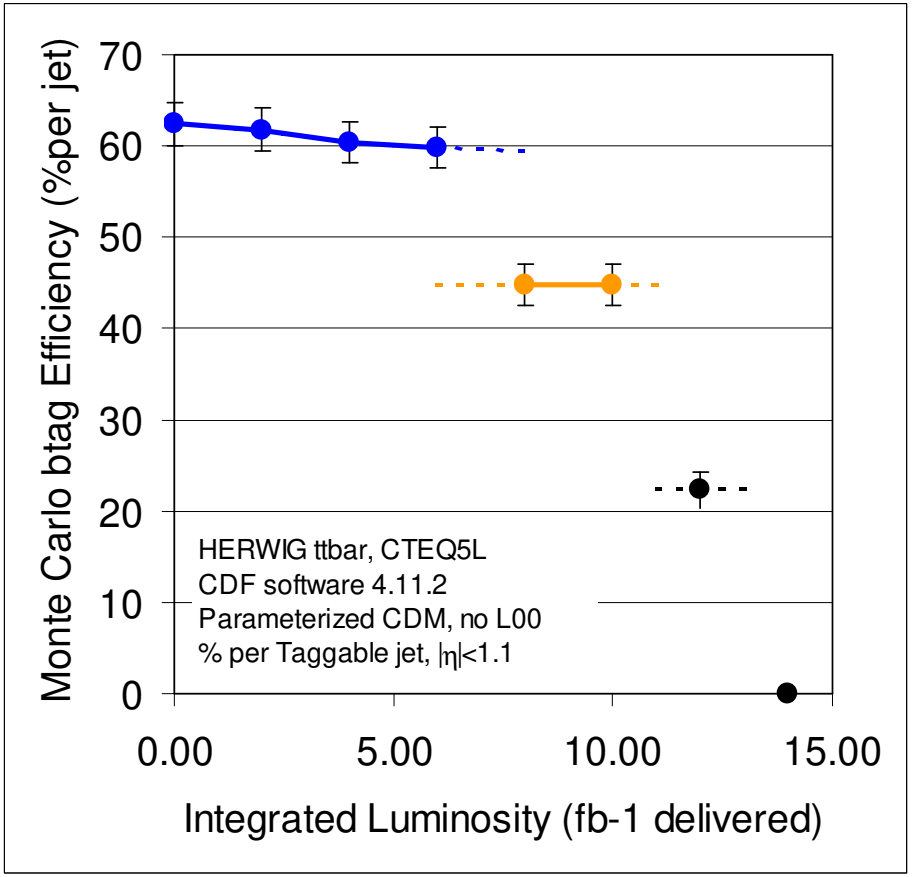


- Results for "Base" luminosity
  - Indicates full depletion throughout RunIIa
  - Bands indicate approximate errors
  - Red dot is measurement from noise study

- Results for "Design" luminosity
  (assumes reasonable TeVatron improvement)
  - Silicon inner layer will die from radiation
  - Long term annealing becomes important
  - Errors are rather large, driven by large ladder to ladder RMS

Degradation in b-tag efficiency

(preliminary results)



- Secondary Vertex Tagging (b jets)
  - HERWIG Monte Carlo study
  - Secondary vertex (b) tagged events
  - Remove L0 from tracking at 6-8 fb^{-1} (orange points)
  - Remove L1 at 10-12 fb^{-1}
- Requirements:
  - b is in the detector ($|\eta|<1.1$)
  - b yields a jet w/ at least two tracks
- L00 not included
  - Not yet in the 'default' tracking
  - Not studied yet for tagging
- Results
  - efficiency still good after S/N degraded
  - L00 must be fully integrated and must survive to maintain tag efficiency

The future for the Run IIa Silicon

Assuming reasonable luminosity, we expect the inner layer will 'die' from underdepletion

The Run IIa silicon should continue to provide good vertex information until (at least) 6 fb^{-1}.

CDF/D0 Run IIb silicon upgrades cancelled in early September, 2003

CDF Run IIa silicon was designed for 2 fb^{-1} and 2 years of operation…

Two years done, only 6 more years to go!

Conclusions

Overall, the detector is working well, and a multitude of searches for new phenomena are underway!

- Higgs results will be challenging, and are driven by luminosity
- New results include searches in
  - Dijet resonances: E6 diquarks, RS graviton LED, excited quarks, W´…
  - Dilepton resonances: Z´, RS graviton
  - Champs: long lived stop
  - Leptoquarks: eejj and $\nu\nu$jj channels
  - Excited electrons: ee* eeγ
  - Photon-rich signatures: γMET, $\gamma\gamma$, $\gamma\gamma\ell$ and $\gamma\ell$,more
  - Stop, sbottom, gluino: competitive limits in $\tilde{b}$, $\tilde{g}$
  - Doubly-charged particles: $H^{\pm\pm}$ $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$
  - Rare decays: B_s $\mu\mu$
- Now that everything is working, many more results to come!