Searches for Exotic Physics at CDF

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For the CDF Collaboration

SLAC Orange Room Seminar

Menlo Park, CA

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Introduction

- CDF at the Fermilab Tevatron
- The “Discovery Watch” idea
- Existing discrepancies
  ... and related new search results
  - Resonances
  - Higgs beyond the standard model
  - Global searches
- Conclusions

Fermilab Complex

LINAC
-Accelerates protons to 400 MeV

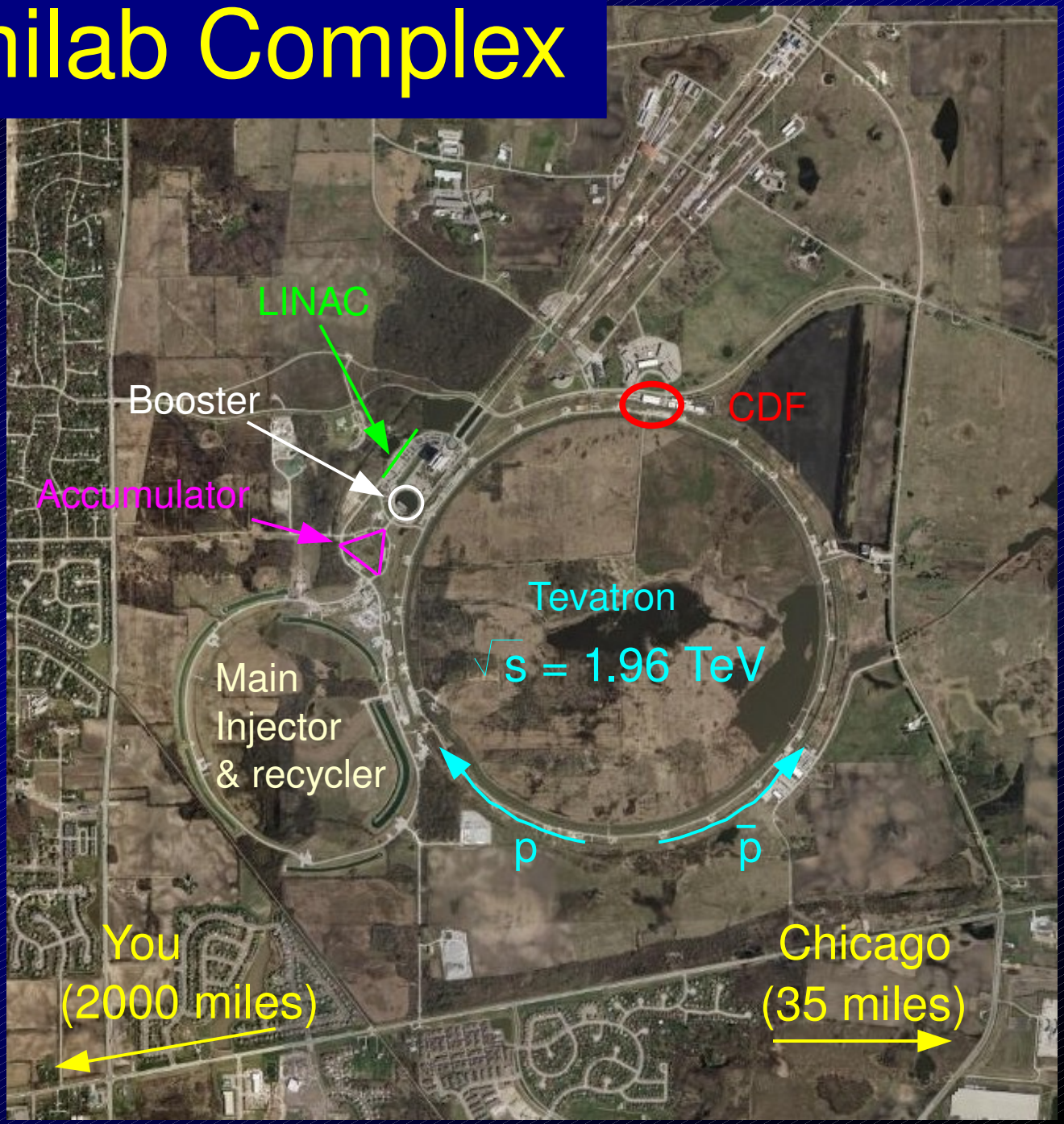
Booster
-Accelerates protons to 8 GeV

Main Injector
-Accelerates protons to 120 GeV
- to nickel target to make $\bar{p}$'s
- to fixed target and ν expts.
-Accelerates p's and $\bar{p}$'s to 150 GeV for injection into Tev.

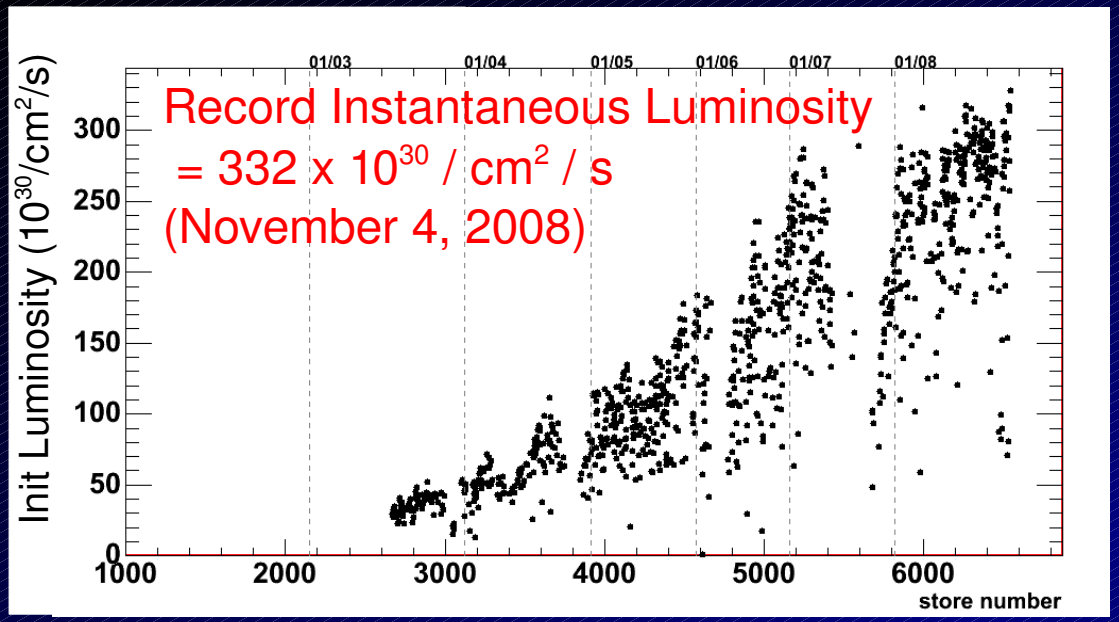
Accumulator
-Receives $\bar{p}$'s

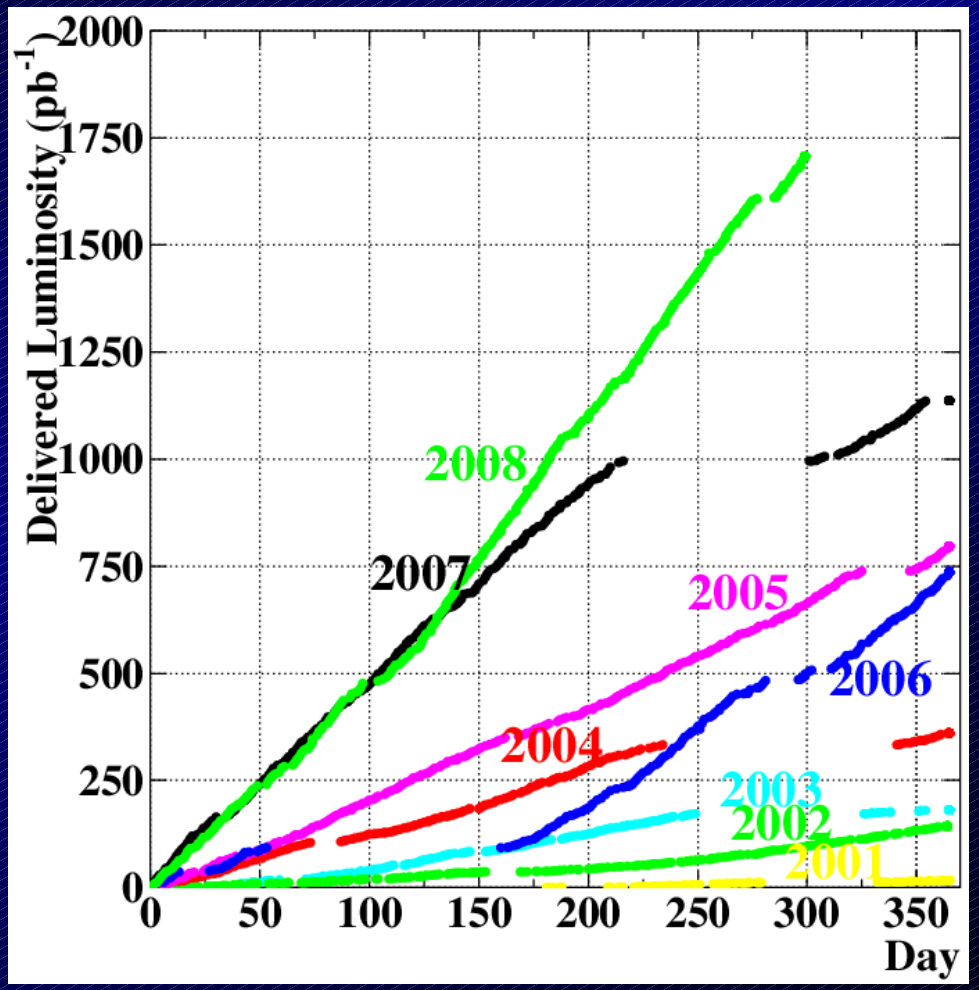
Recycler
-Holds (~400mA) and cools $\bar{p}$'s

Tevatron
-Superconducting synchrotron
-Accel. to 980 GeV and collides
-Counter-rotating helical beams



Tevatron Performance





- Additional records:
  - Integrated for single store: 11.0 pb^{-1}
  - Most $\bar{p}$'s collected in one hour: 27 mA
  - Largest stash of $\bar{p}$'s: 465 mA
- Achievements:
  - Electron cooling of $\bar{p}$ beam
  - Routine operation of two $\bar{p}$ storage rings

Collider Detector at Fermilab

Silicon
- 8 layers
  at r=1.3 cm to 28 cm

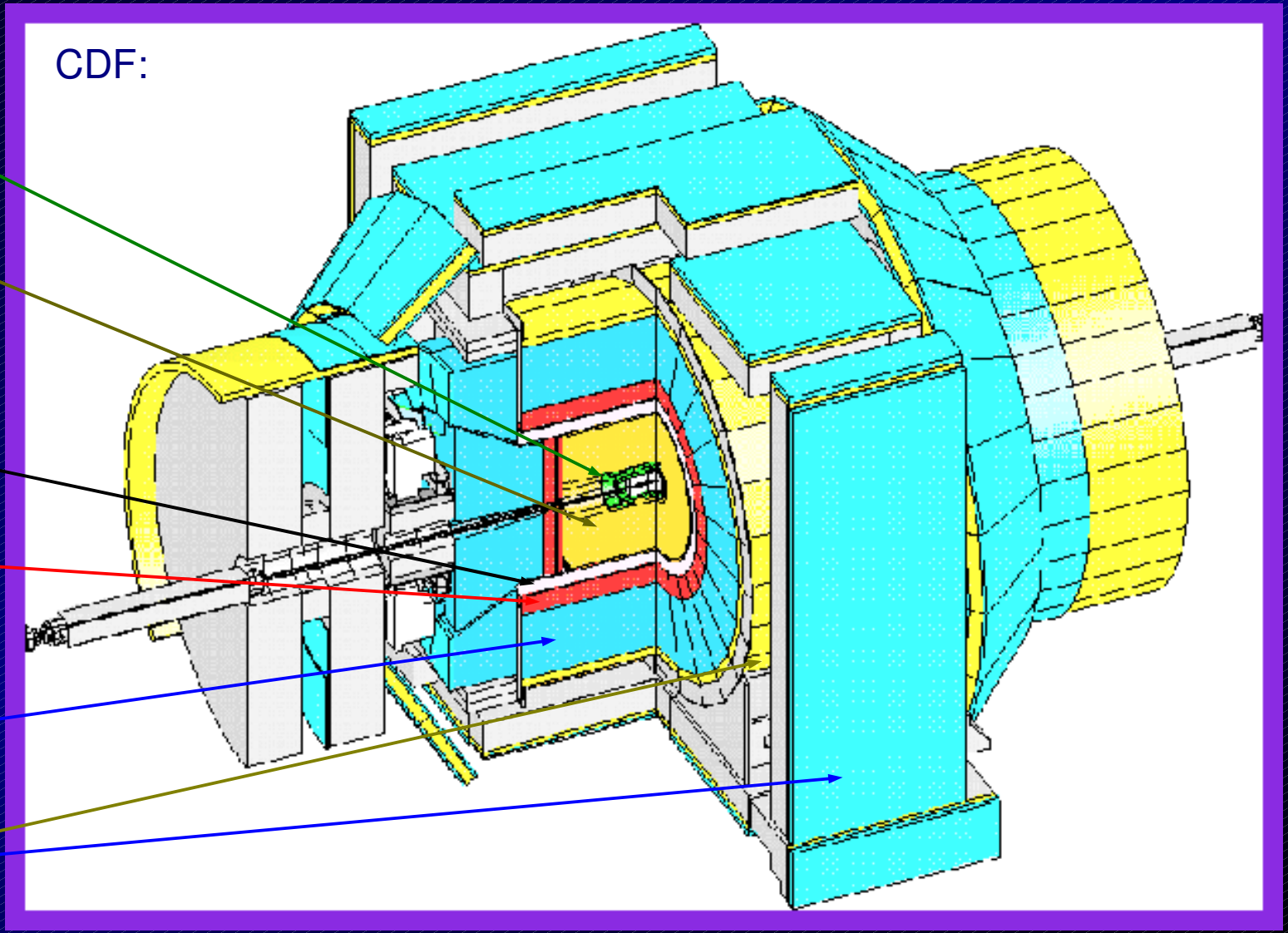
Drift Chamber
- 4 axial + 4 stereo
  "super-layers"
- $|\eta| < 1.1$

1.4T solenoid
- superconducting

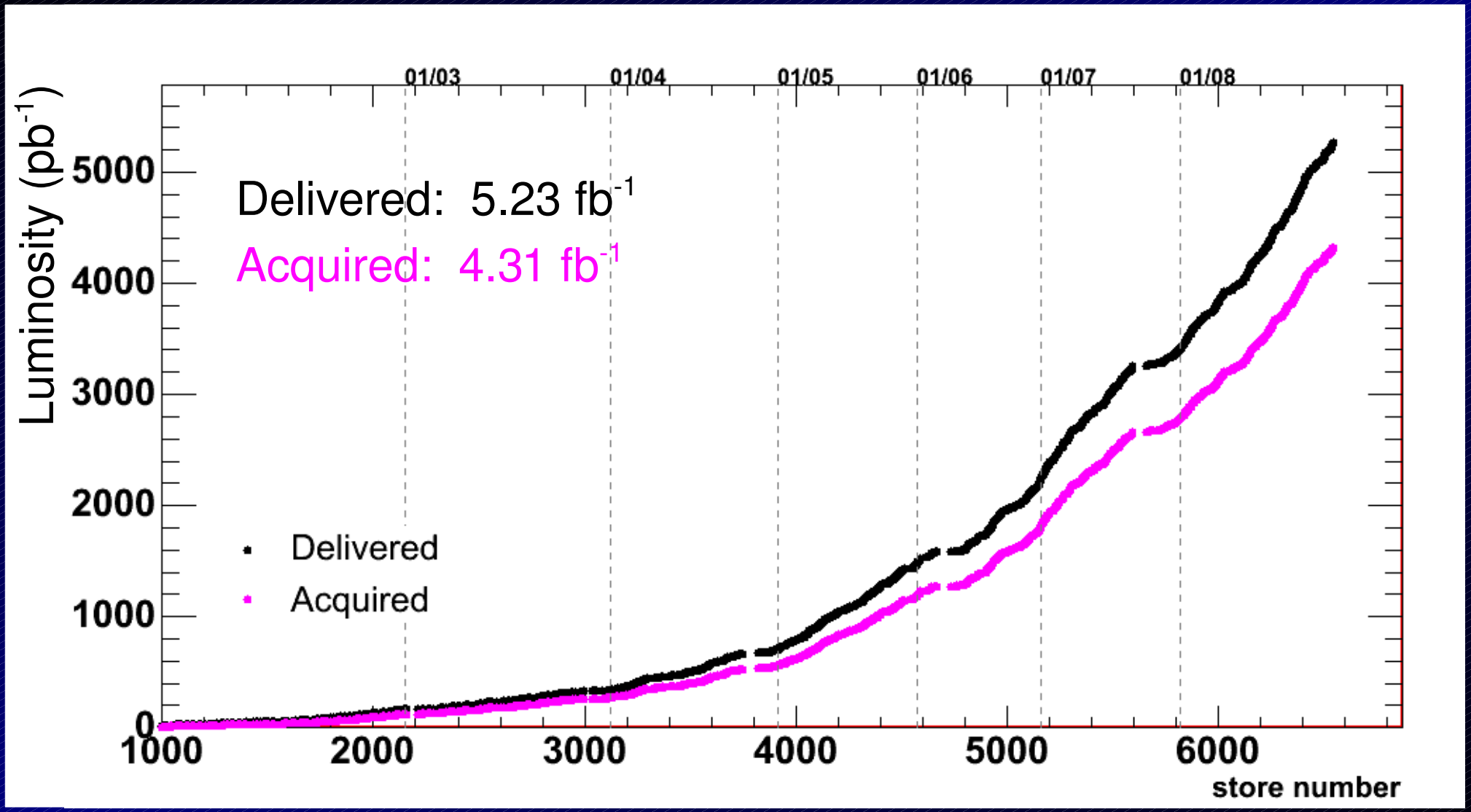
EM calorimeters
- central: $|\eta| < 1.1$
- plug: $1.1 < |\eta| < 3.6$

Hadronic calo.
- central and plug

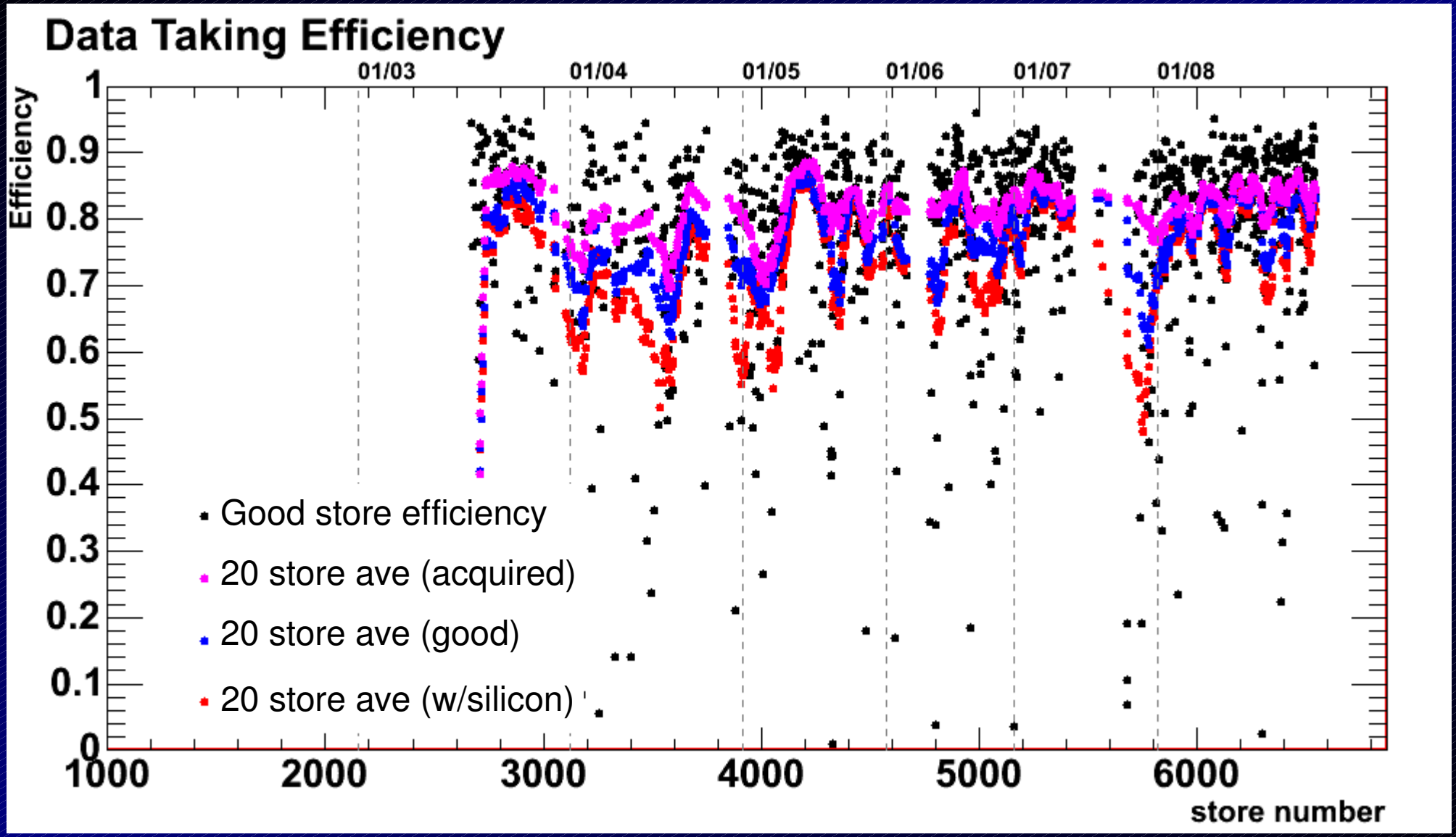
Muon systems
- drift chambers
- 3 systems: $|\eta| < 1.0$



CDF Performance



CDF Performance II



The “Discovery Watch” Idea

History

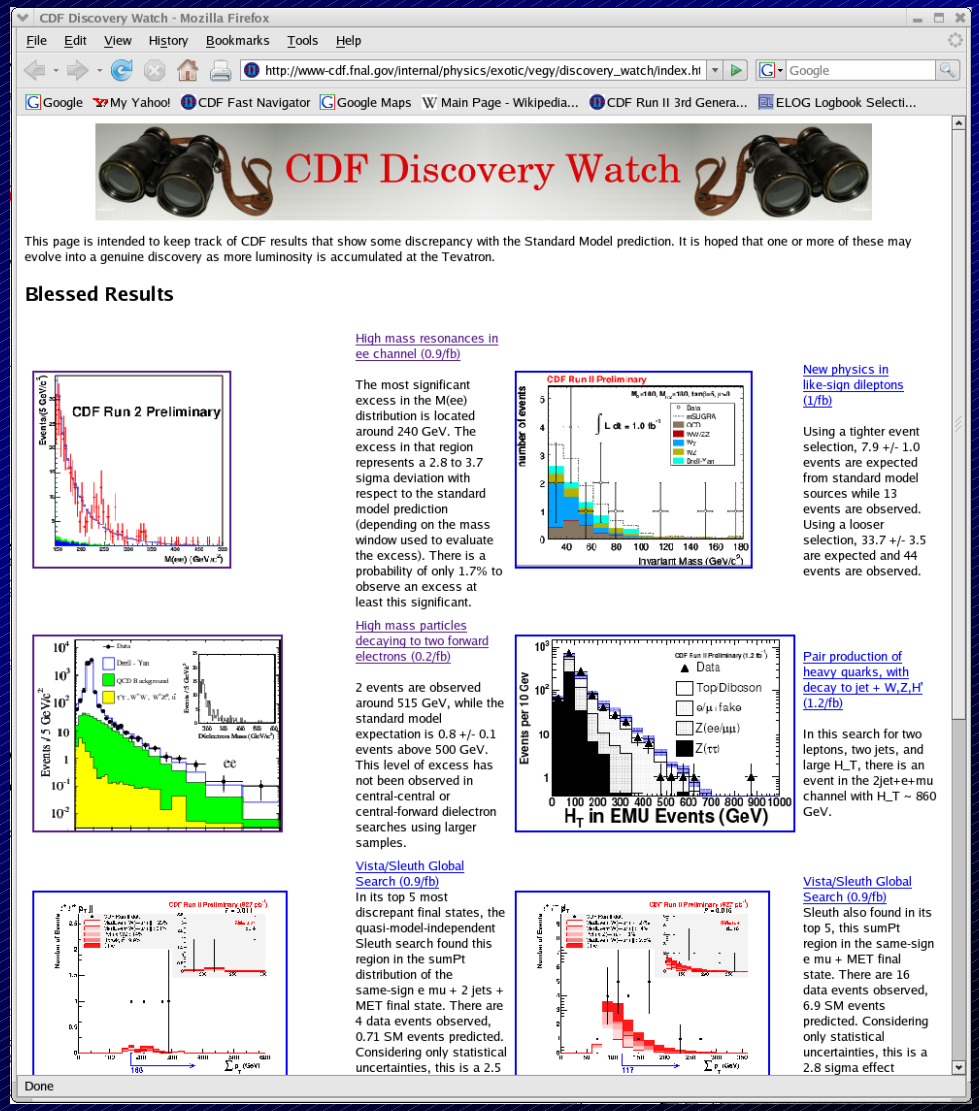
- Initially conceived as an internal tool to:
  - Organize effort onto interesting topics
  - Demonstrate, to funding agencies, cases for running Tevatron $\geq$ 2010

But what is it?

- A collection of CDF results that show some discrepancy compared to the standard model prediction. The discrepancy may appear in:
  - Kinematic distribution
  - Observed number of events (and related cross section limit)
  - Measured parameter
- Such discrepancies, appearing in results using up to 3 fb^{-1}, are candidates for becoming discoveries with the final full CDF Run II data sample

“Discovery Watch”

- There is a webpage
  - Soon to be made public (all the results are public)



Aren't there limitations to doing this?

- Expect statistical fluctuations
  - ~180 Run II publications so far
    - Only some are searches
    - Searches have many channels and many distributions
    - For 180, expect ~8 deviations of $>2\sigma$
- Worse than looking under the lamp post for our keys
  - First we looked only where we had a shot at seeing something, and now we talk about only a subset of those
- You might think of other limitations...
- I am not advocating using this to guide all of CDF's efforts

From the Discovery Watch

- This talk features the highlights from the current Discovery Watch list, and related new results
- They fall into three categories:

  I. Resonances

  II. Higgs beyond the standard model

  III. Global searches

Resonance Searches

- I will present results of three searches for new resonances

(1) Dielectron search, including two forward electrons

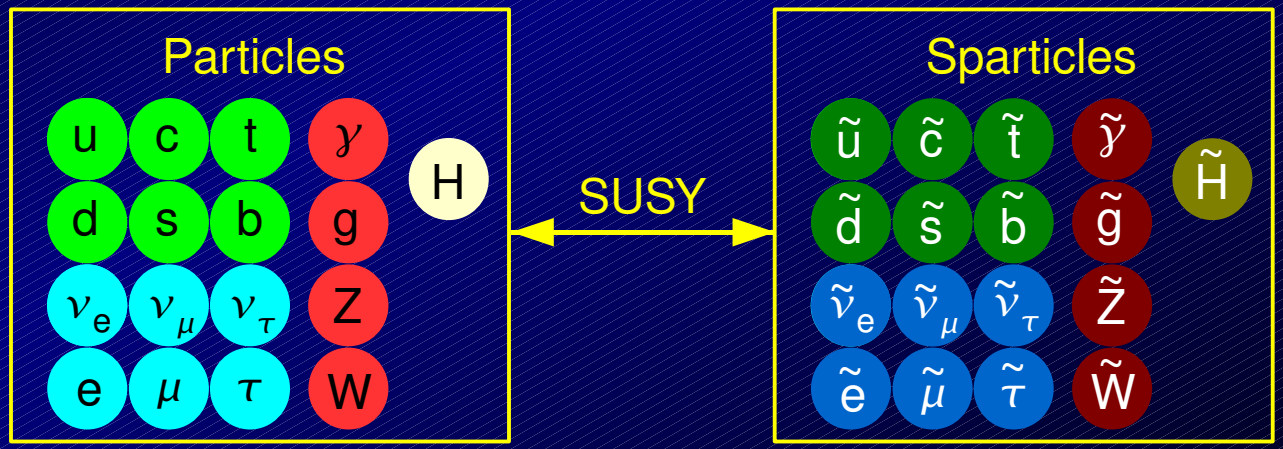
(2) Dielectron search, including ≥ 1 central electron New

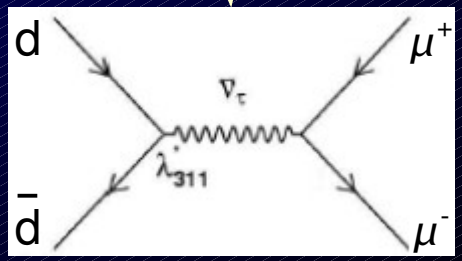
(3) Dimuon search New

Resonances Motivation I

- e^+e^- and $\mu^+\mu^-$ are classic discovery signatures (J/psi, Upsilon, Z)
  - Search in leptonic decays instead of hadronic decays:
    - Lower backgrounds, better identification, better momentum measurement; more than make up for lower branching fraction
- Spin-0:
  - Still searching for a fundamental scalar
  - MSSM Higgs could have enhanced production to dileptons
  - SUSY R-parity violation can yield sneutrinos

- New fermion for every boson, and new boson for every fermion





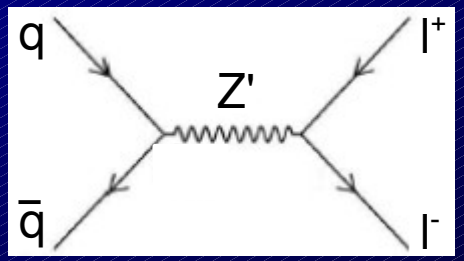
$\lambda = dd\tilde{\nu}$ coupling

Resonances Motivation II

- Spin-1: Z'
  - Heavy neutral gauge boson
  - Unification of forces (as in GUTs) through extended gauge groups such as SO(10) or E6
    - Spontaneous symmetry breaking to SM groups
      - ↪ Additional U(1) gauge group(s)
        - ↪ Z' bosons
  - Breaking E6 can result in various U(1) symmetries
    - Example: $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$

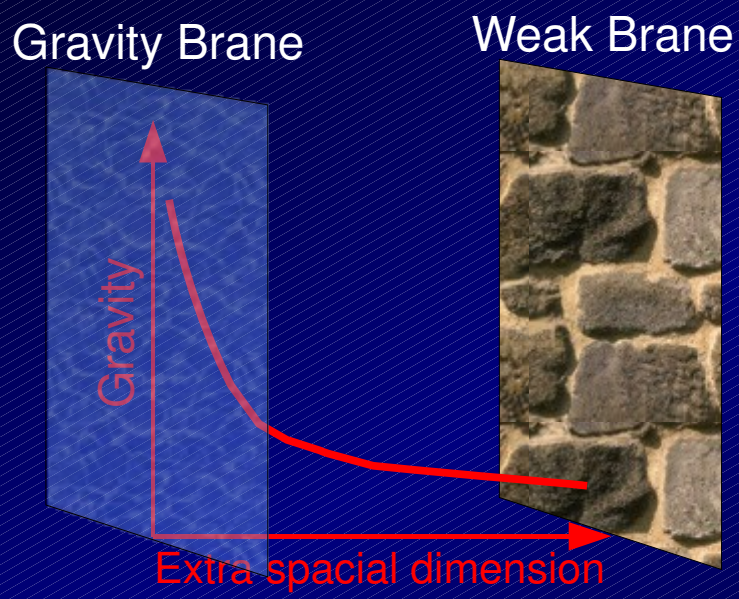
      With $U(1)' = U(1)_\psi \cos\theta + U(1)_\chi \sin\theta$

      ↪ Z_ψ' Z_χ' .....
  - Coupling to SM fields
    - Determined by specifics of the group theory and by weak charge
  - Long-standing discrepancy (~3.2σ) within precision electroweak fits
    - Mixing between Z' and SM Z ?



Resonances Motivation III

- Spin-2: Graviton
  - Graviton in Randall-Sundrum model of warped extra dimensions
  - Seeks to solve hierarchy problem between Planck scale and electroweak scale
  - Exponential warp factor weakens gravity at weak brane compared to gravity brane



- Gravitons propagate everywhere
- Standard model exists within weak (TeV) brane

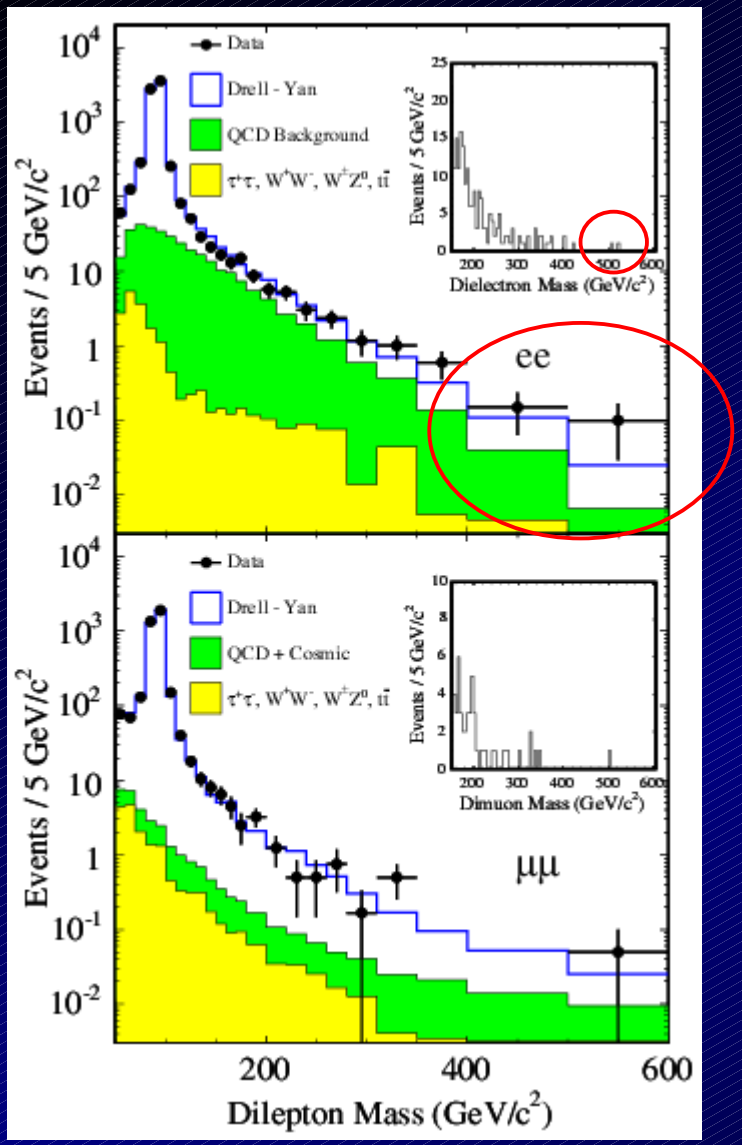
- Prediction for experimental observation:

Excited massive graviton with electroweak scale couplings to SM particles

Forward Electrons

0.2 fb^{-1}

Phys. Rev. Lett. 95, 252001 (2005)



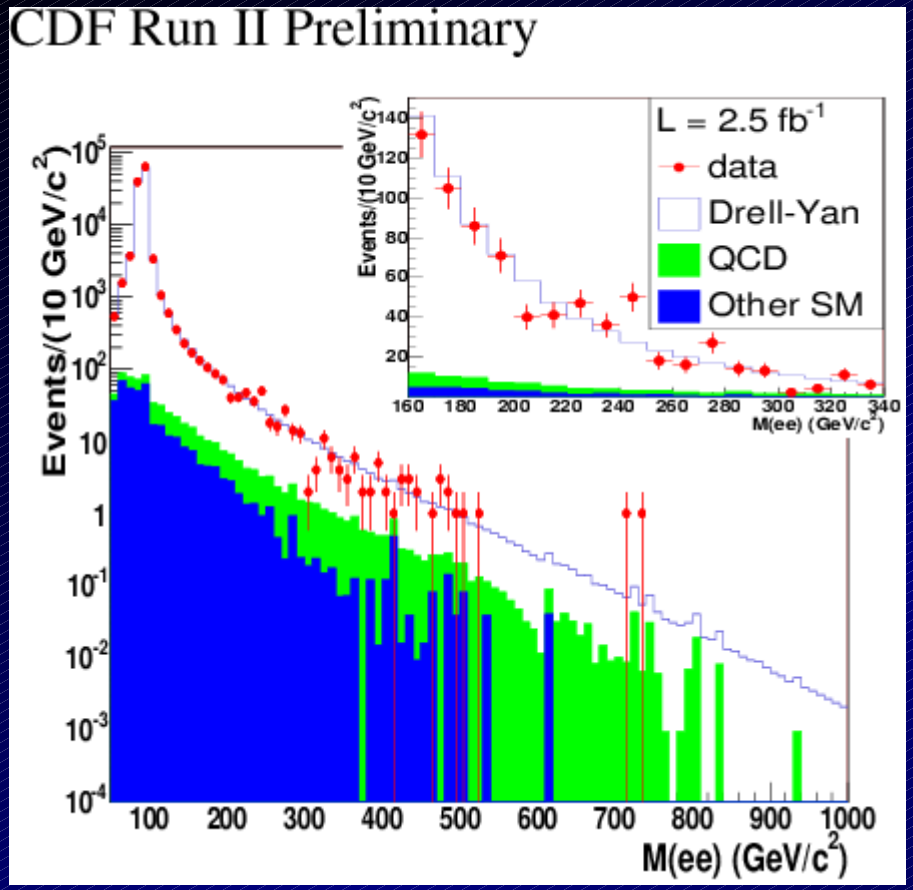
- Central ($|\eta| < 1.1$) and forward ($1.2 < |\eta| < 3.6$) regions
  - ee: central+central, central+forward, forward+forward
  - $\mu\mu$: central+central
- Results:

$m_{\ell\ell}$ (GeV/c^2)	ee Observed	ee Expected	$\mu\mu$ Observed	$\mu\mu$ Expected
> 150	205	212.9 ± 99.3	58	55.3 ± 2.5
> 200	84	78.2 ± 33.4	18	20.9 ± 1.0
> 300	22	13.6 ± 4.4	6	5.2 ± 0.3
> 400	5	2.9 ± 0.7	1	2.3 ± 0.2
> 500	2	0.8 ± 0.1	1	1.2 ± 0.1

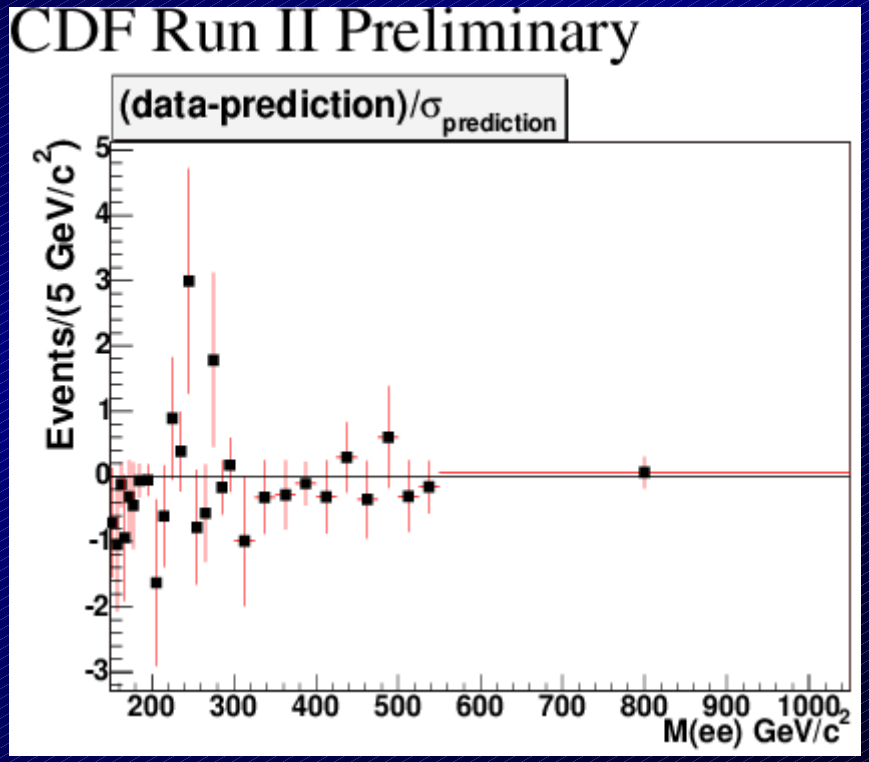
- Two ee events observed around 515 GeV/c^2
  - SM expectation is 0.8 ± 0.1 events above 500 GeV/c^2
  - Both are forward+forward
  - Such excess has not been observed in central+central or central+forward searches using larger samples
- Set limits: $m_{sneutrino} > 725$ GeV/c^2 at 95% C.L.
  $m_{SM\ Z'} > 825$ GeV/c^2 at 95% C.L.
  $m_{Graviton} > 710$ GeV/c^2 at 95% C.L.

e^+e^- Resonance Search

2.5 fb^{-1}



- Two electrons, with E_T > 25 GeV
- central+central and central+forward



- There is a 3.8σ discrepancy in 228-250 GeV/c^2 window
- Probability to observe a fluctuation at least this large somewhere in analysis range, 150-1000 GeV/c^2, is 0.6%. Significance is 2.5σ.

e^+e^- Resonance Limits

2.5 fb^{-1}

Submitted to PRL, arXiv:0810.2059v1

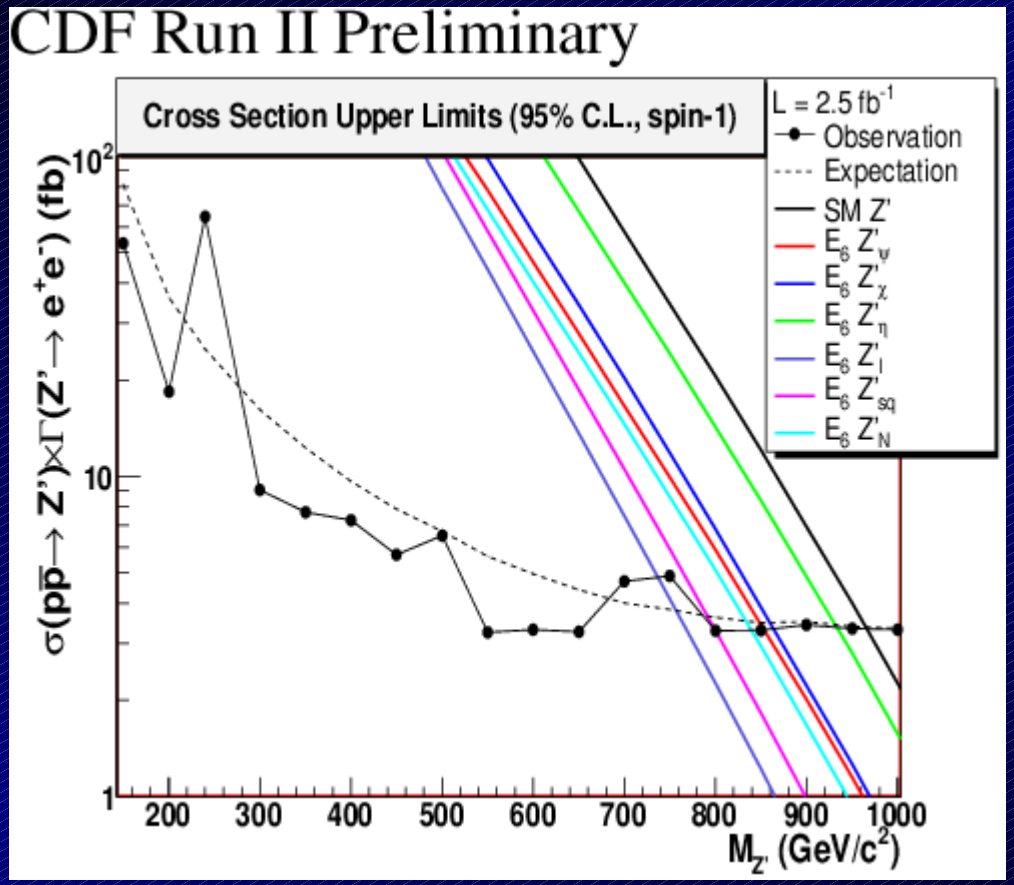
- Spin-1: SM-like Z' mass limit

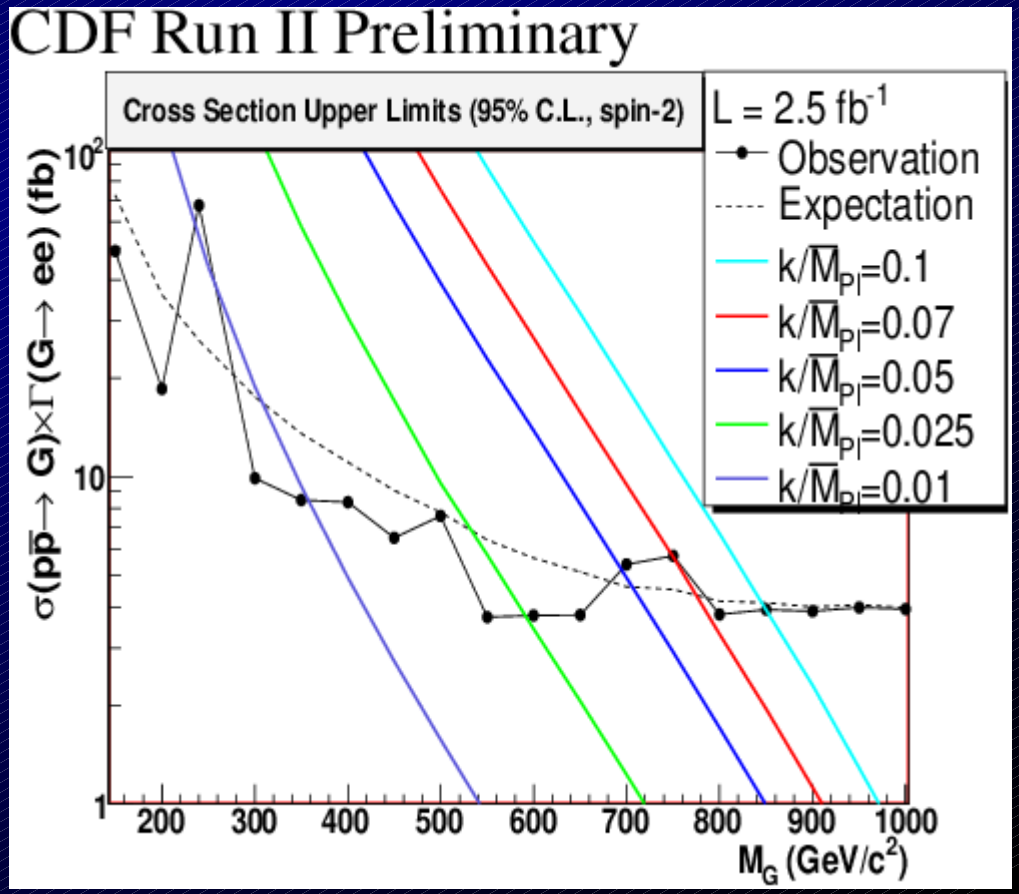
  $m_{SM\ Z'} > 966\ GeV/c^2$ at 95% C.L.

- Spin-2: Randall-Sundrum graviton limit

  $m_G > 850\ GeV/c^2$ at 95% C.L.

  For $\frac{k}{M_{PL}} = \frac{\text{negative curvature}}{\text{Planck mass}} = 0.1$



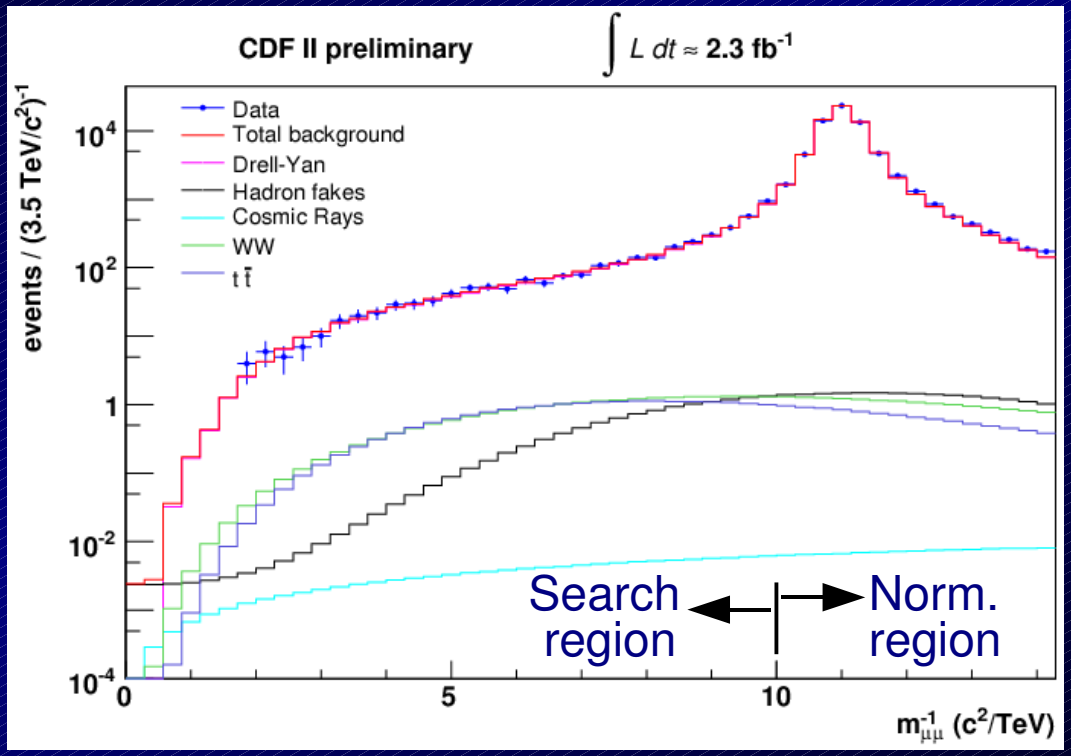


$\mu^+\mu^-$ Resonance Search

2.3 fb^{-1}

Submitted to PRL, arXiv:0811.0053v1

- Search for narrow resonance in Dimuon *inverse* mass spectrum
  - At high mass, curvature resolution is is ~independent of curvature
  - Constant resolution in $1/p_T$ and $1/m$
  - 17% m^{-1} resolution at 1 TeV
- Two muons, with $p_T > 30$ GeV/c
- Backgrounds
  - Electroweak: from Monte Carlo, scaled using Z peak region
  - In-flight kaon decays and jets faking leptons: from jet data, normalized using like-sign data
  - Cosmic rays: from data, normalized using timing information



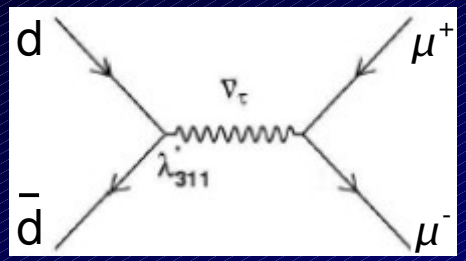
- Data are consistent with SM prediction
  - p-value = 6.6%
- Place limits on the following scenarios
  - Spin-0: R-parity violating SUSY
  - Spin-1: Massive Z'
  - Spin-2: Randall-Sundrum graviton

$\mu^+\mu^-$ Resonance Limit: RPV SUSY 2.3 fb^{-1}

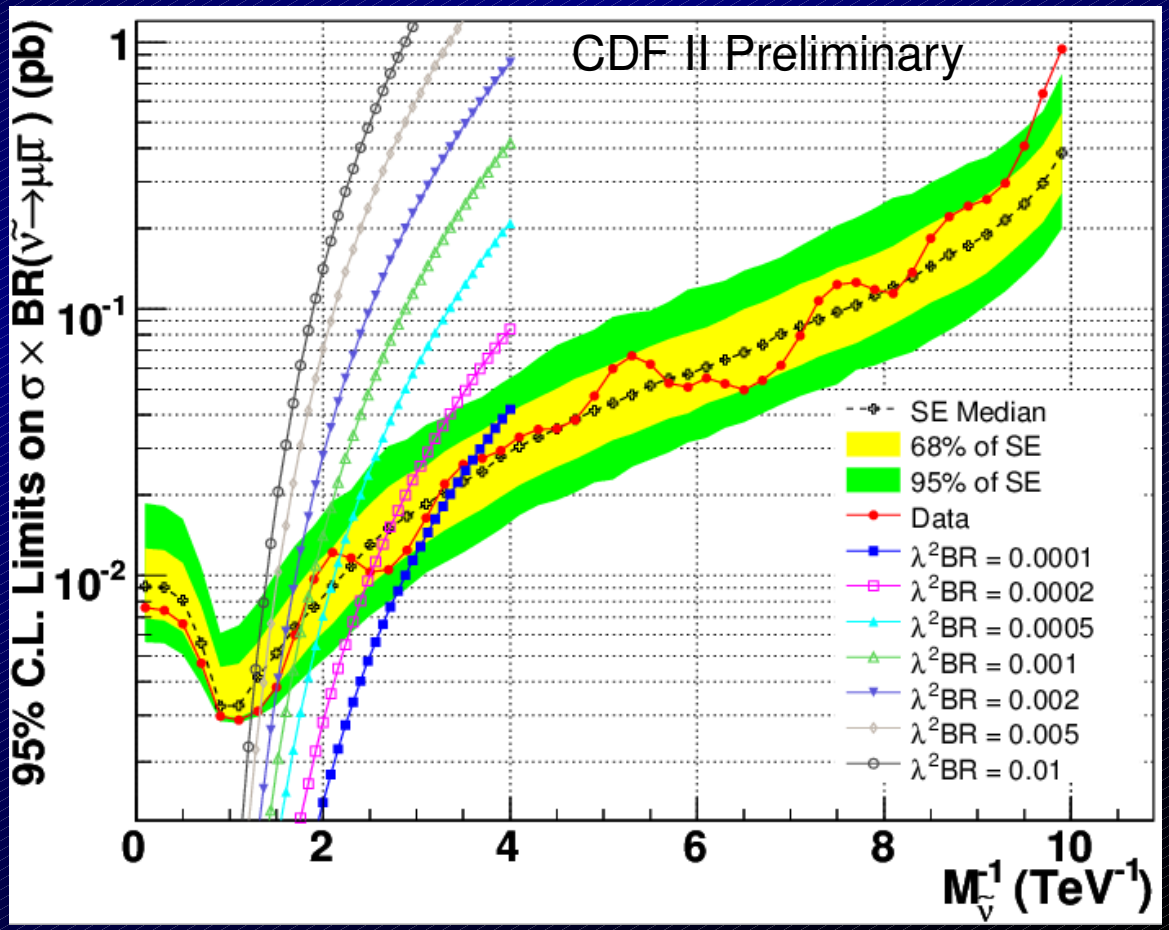
Submitted to PRL, arXiv:0811.0053v1

- Spin-0: sneutrino in R-parity violating SUSY
- Place limits on $\sigma\times$BR($\tilde{\nu}\rightarrow\mu^+\mu^-$) and on $m_{\tilde{\nu}}$ for a variety of values of $\lambda^2\times$BR

λ = dd$\tilde{\nu}$ coupling



$\lambda^2\times$BR	$m_{\tilde{\nu}}$ limit (GeV/c^2)
0.0001	278
0.0002	397
0.0005	457
0.001	541
0.002	662
0.005	751
0.01	810

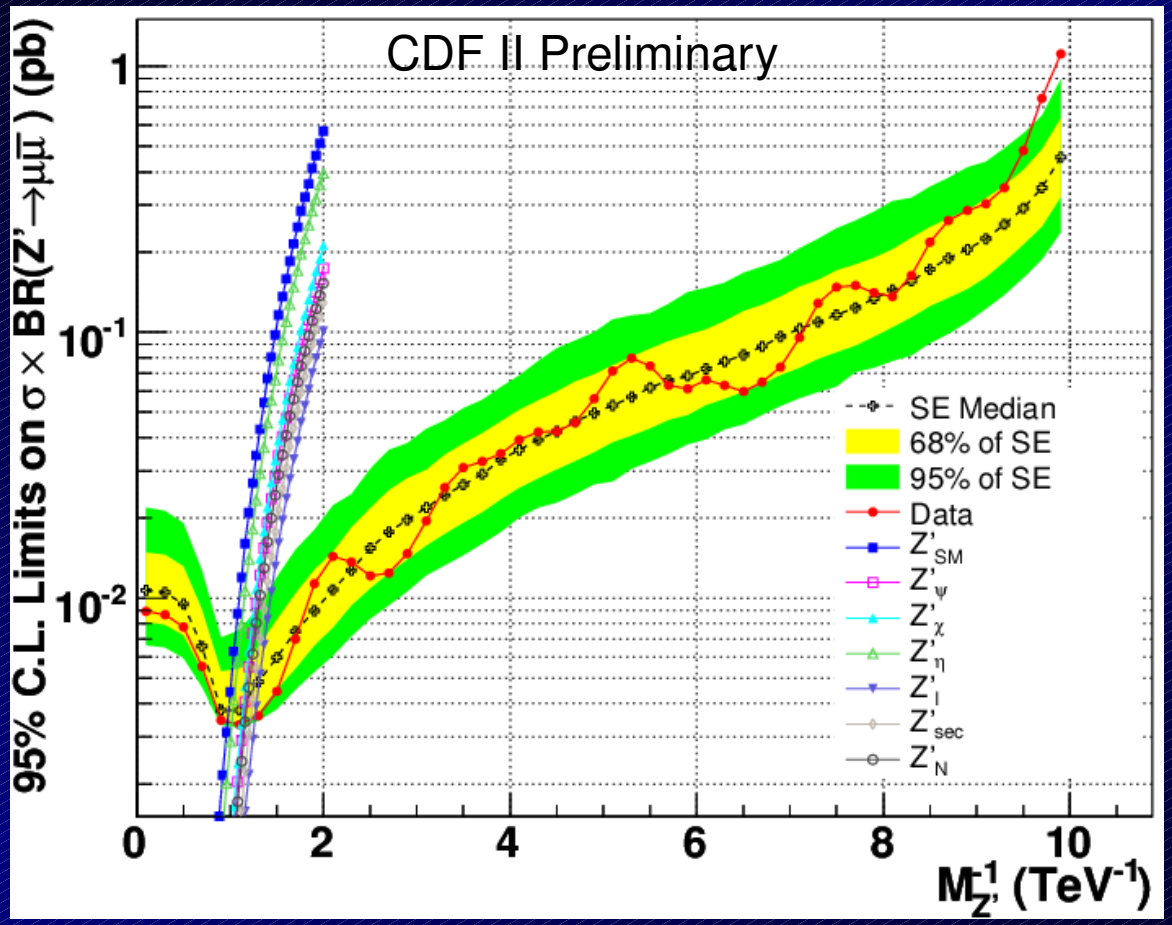


$\mu^+\mu^-$ Resonance Limit: Z'

2.3 fb^{-1}

Submitted to PRL, arXiv:0811.0053v1

- Spin-1: Heavy boson (Z')
- Limits on $\sigma \times BR(Z' \rightarrow \mu^+\mu^-)$ and on $m_{Z'}$ for a variety of models



- Assume no interference between Z' and SM Z/γ^*

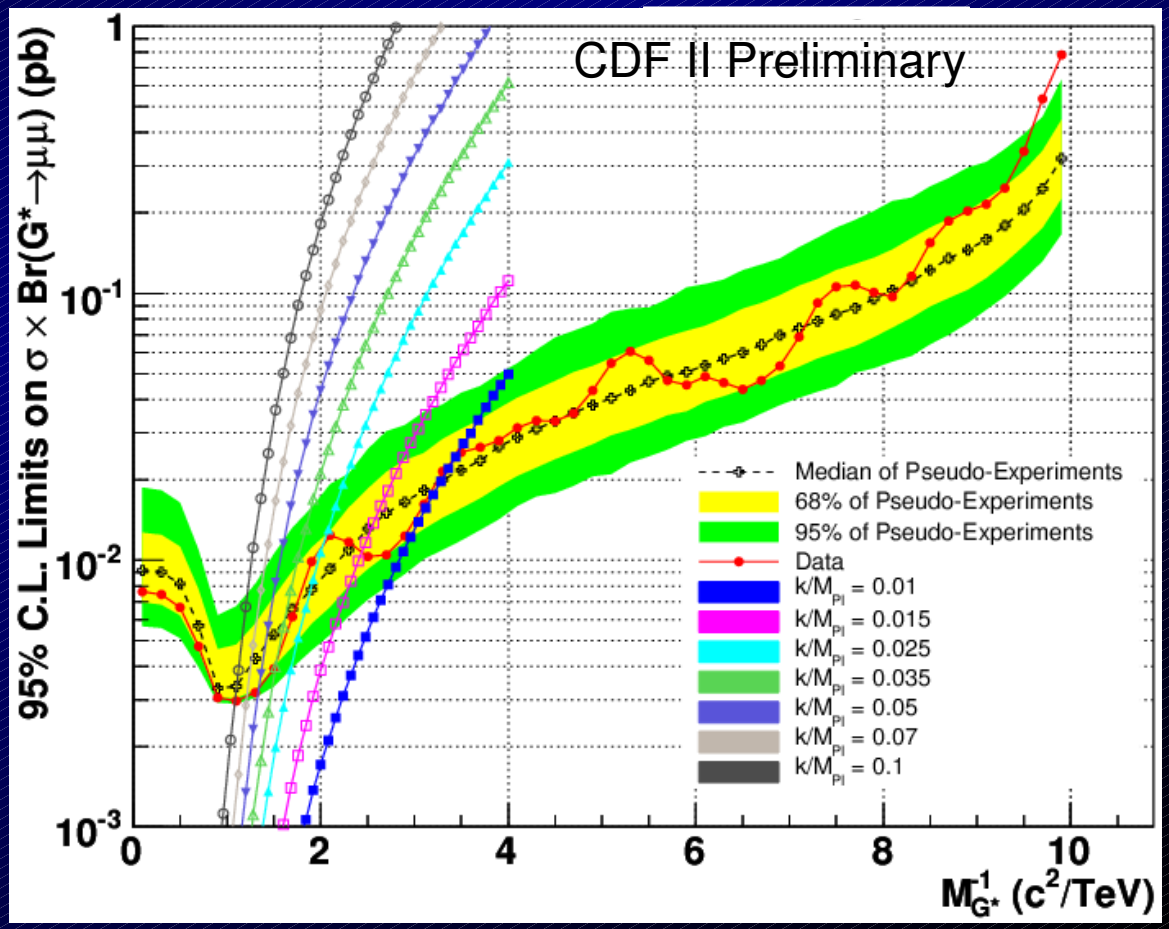
model	$m_{Z'}$ limit (GeV/c^2)
Z'_I	789
Z'_{sec}	821
Z'_N	861
Z'_ψ	878
Z'_χ	892
Z'_η	982
Z'_{SM}	1030

$\mu^+\mu^-$ Resonance Limit: Graviton 2.3 fb^{-1}

Submitted to PRL, arXiv:0811.0053v1

- Spin-2: Search for first excited Randall-Sundrum graviton
- Limits on $\sigma \times BR(G^* \rightarrow \mu^+\mu^-)$ and on m_{G^*} for a variety k/M_{PL}

k/M_{PL}	m_{G^*} limit (GeV/c^2)
0.01	293
0.015	409
0.025	493
0.035	651
0.05	746
0.07	824
0.1	921



Summary of Resonance Searches

(1) Dielectron search, including two forward electrons

(2) Dielectron search, including $\geq$1 central electron New

(3) Dimuon search New

- Mass lower limits at 95% C.L. (in GeV/c^2)

	Search	Lumi	Spin-0 ($\tilde{\nu}$) λ^2BR = 0.01	Spin-1 (Z') Z'_{SM}	Spin-2 (G*) k/M_{PL} = 0.1
(1)	ee and $\mu\mu$	0.20 fb^{-1}	725	825	710
	ee	0.45 fb^{-1}	-	850	-
	ee (and $\gamma\gamma$)	1.3 fb^{-1}	-	923	889
(3)	$\mu\mu$	2.3 fb^{-1}	810	1030	921
(2)	ee	2.5 fb^{-1}	-	966	850

Beyond SM Higgs Searches

- Will present results of three searches for Higgs beyond the standard model

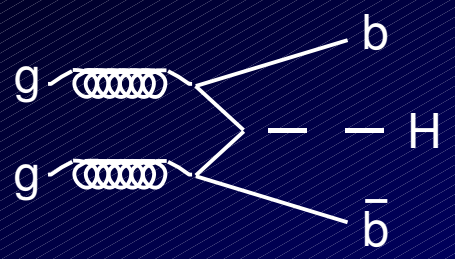
  (1) MSSM Higgs, using bbb channel

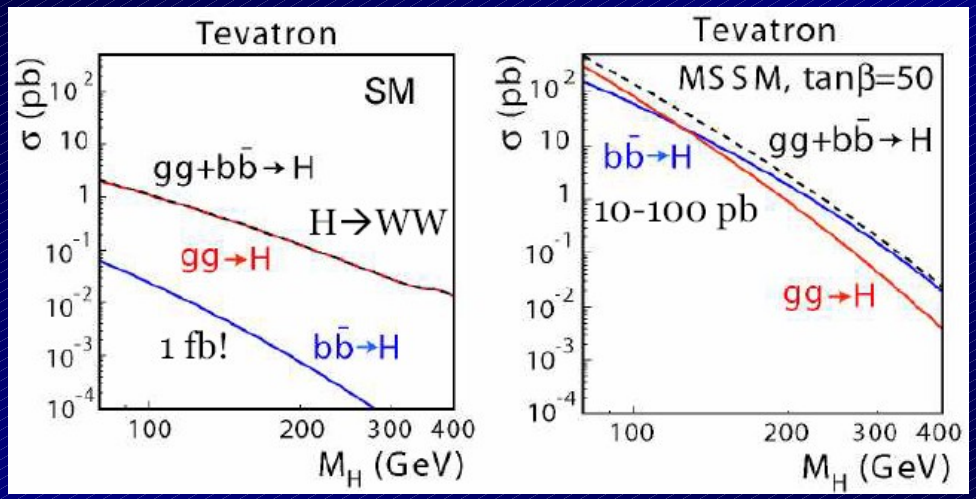
  (2) MSSM Higgs, using $\tau\tau$ channel

  (3) Fermiophobic Higgs, using $\gamma\gamma$ channel New

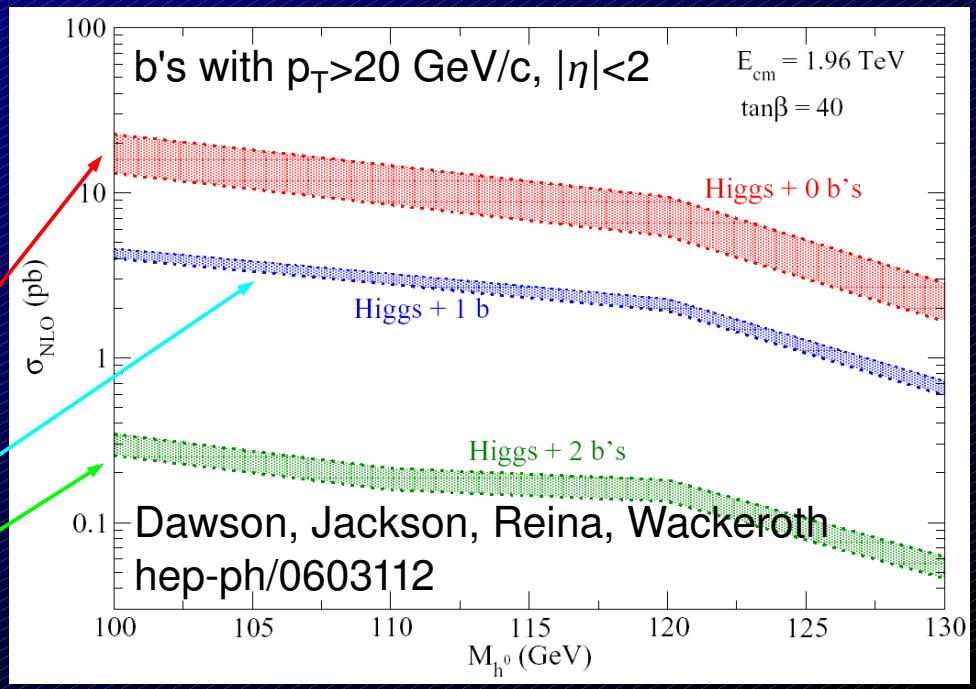
MSSM Higgs: gg → bbH → bbbb

- Production of neutral scalars h, H, A, in association with $b\bar{b}$





- For small m_A (pseudoscalar mass) and large tanβ (d-type / u-type couplings)
  - bb→H production enhanced
  - BR(H→bb)~90%, BR(H→$\tau\tau$)~10%
- Three b-tagged jets
  - Secondary vertex tagging
  - Three leading jets with E_T > 20 GeV
  - $|\eta|$ < 2



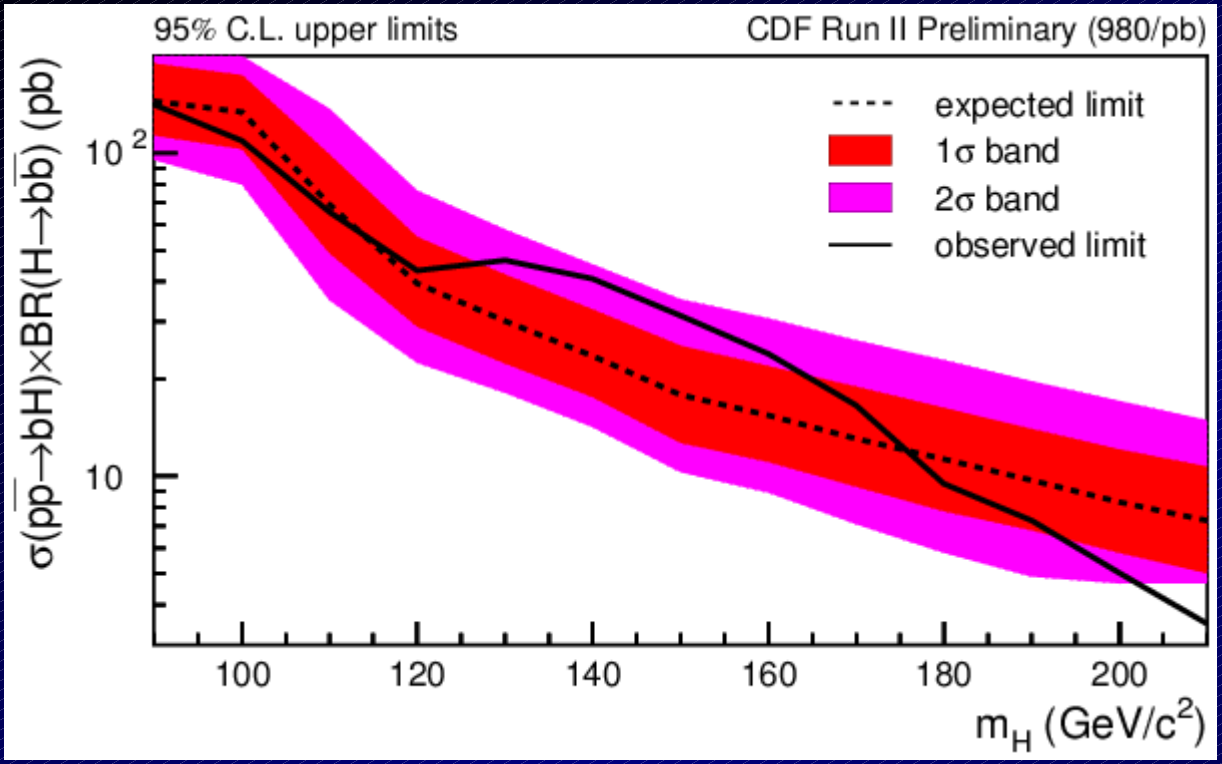
Worse background

Just right

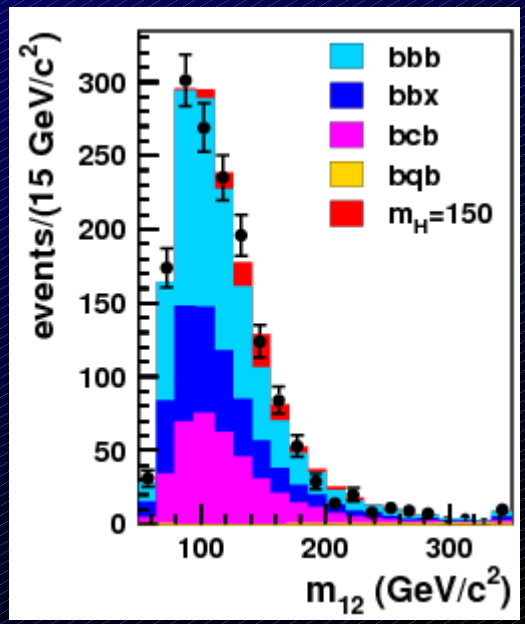
Worse cross section

MSSM Higgs: bbb

0.98 fb^{-1}
(first round)



- Data and background template fit
  - m_{12} = mass of two leading jets
  - Includes hypothetical H
  - shows corresponding excess and deficit



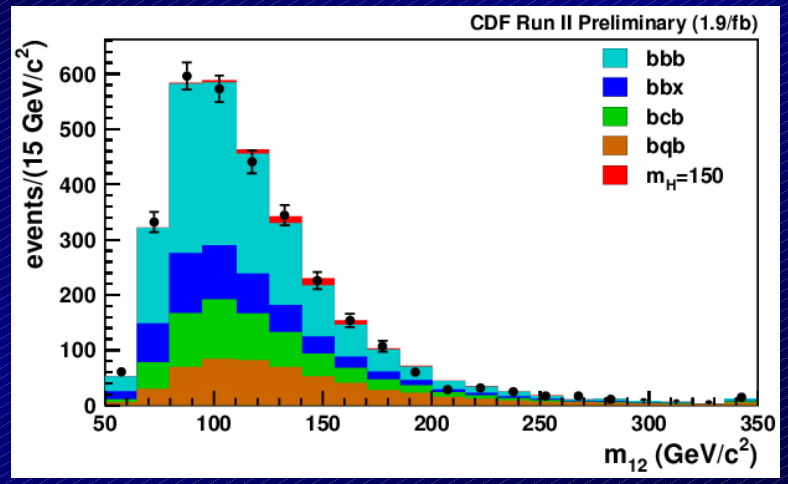
- Upward fluctuation of observed limit compared to expected limit around m_H=140 GeV/c^2

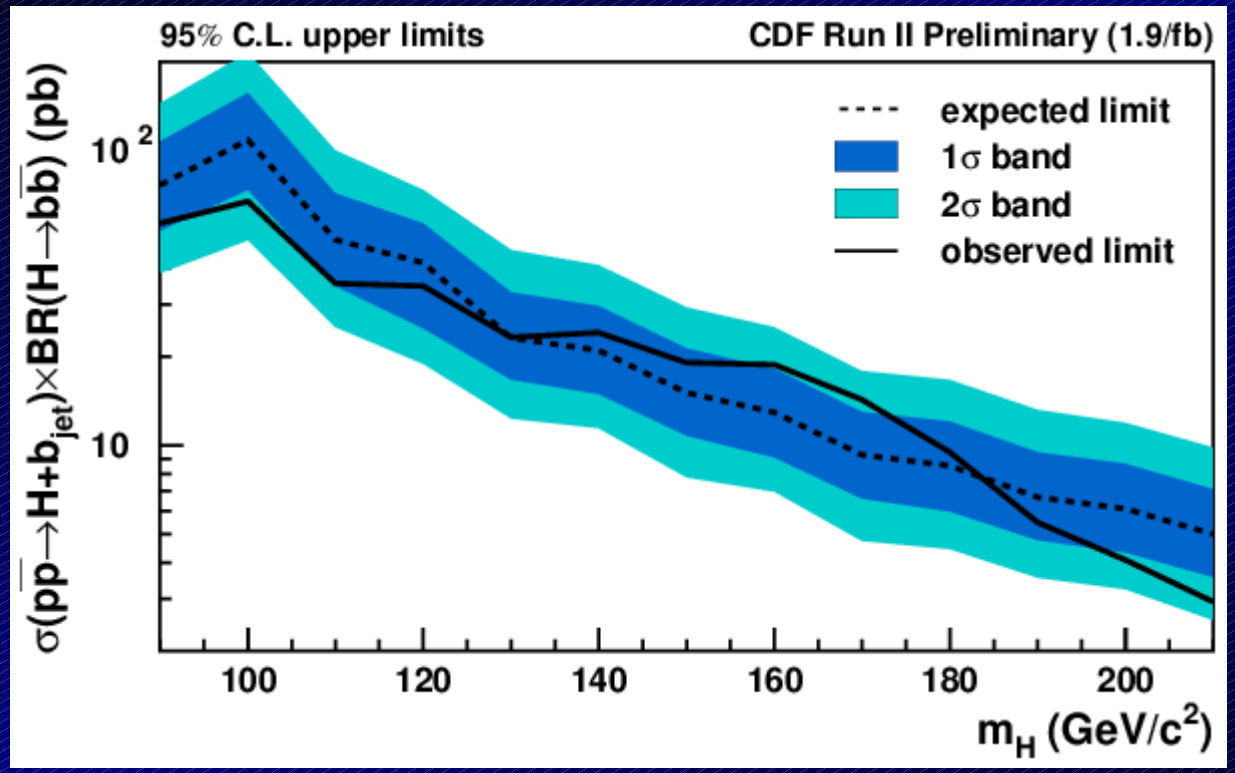
- Downward fluctuation around m_H=200 GeV/c^2

MSSM Higgs: bbb

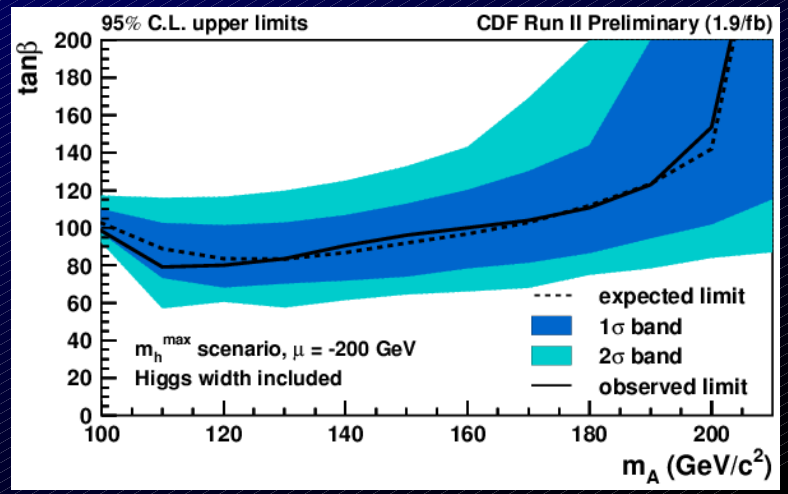
1.9 fb^{-1}

- Analysis updated with twice the data
- Deviations, small though they were, are even smaller now





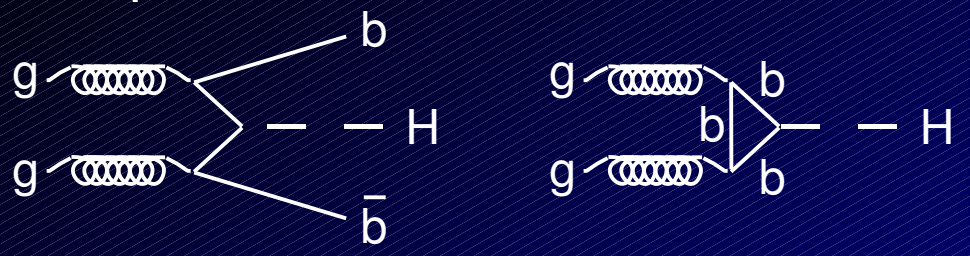
- $\tan\beta$ vs m_A limit
  - Excludes $\tan\beta$ above ~90



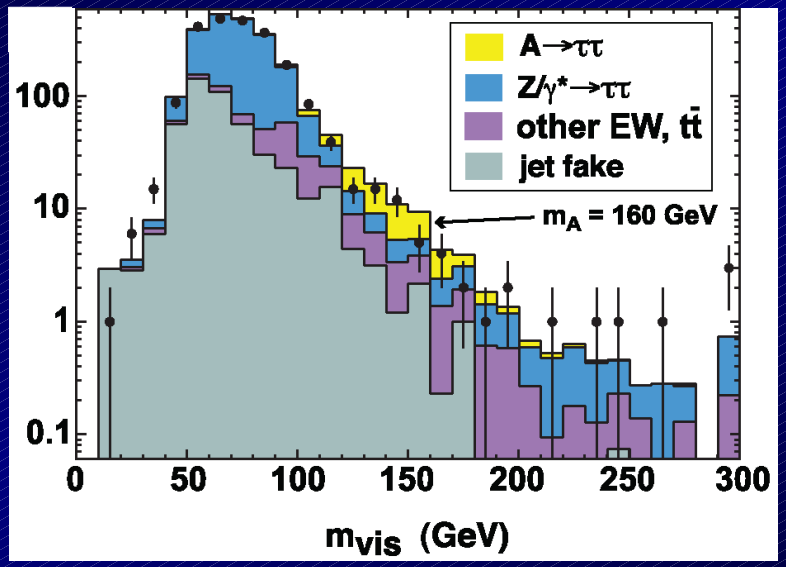
MSSM Higgs: $H \rightarrow \tau\tau$

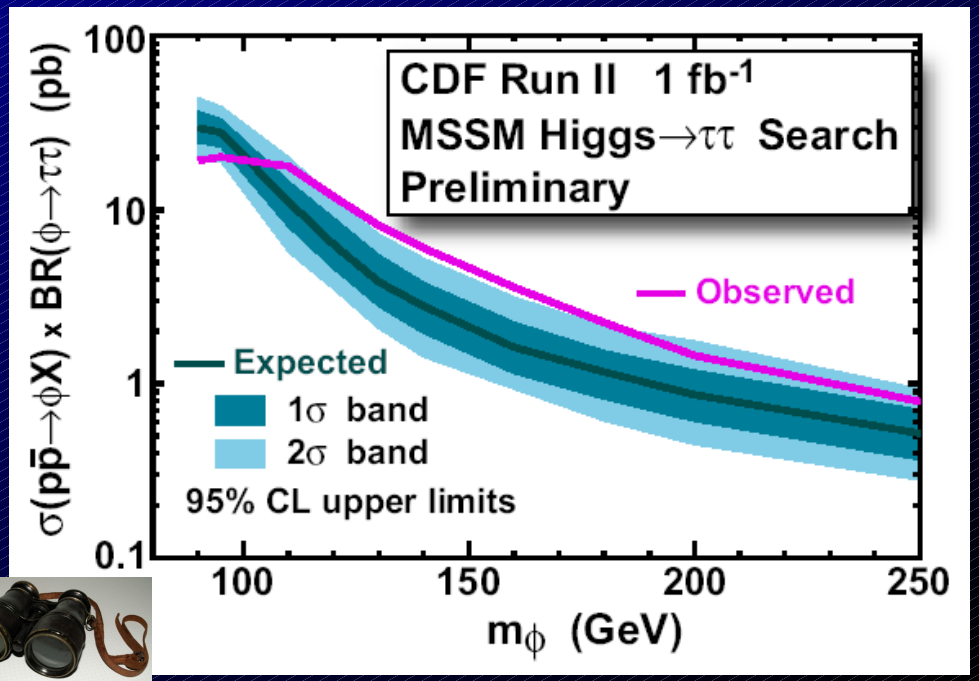
1.0 fb^{-1}
(first round)

- Two processes contribute



- Best signatures
  - One τ decays to e or μ, other hadronic (BR=23%+23%)
  - One τ to e and one τ to μ (6%)
- Selection
  - Leptons: $p_T > 10$ GeV/c
  - Hadronic τ: $p_T > 15$ GeV/c
    mass < 1.8 GeV/c^2
  - Opposite charge
- Significance of excess is <2σ when entire mass range is considered

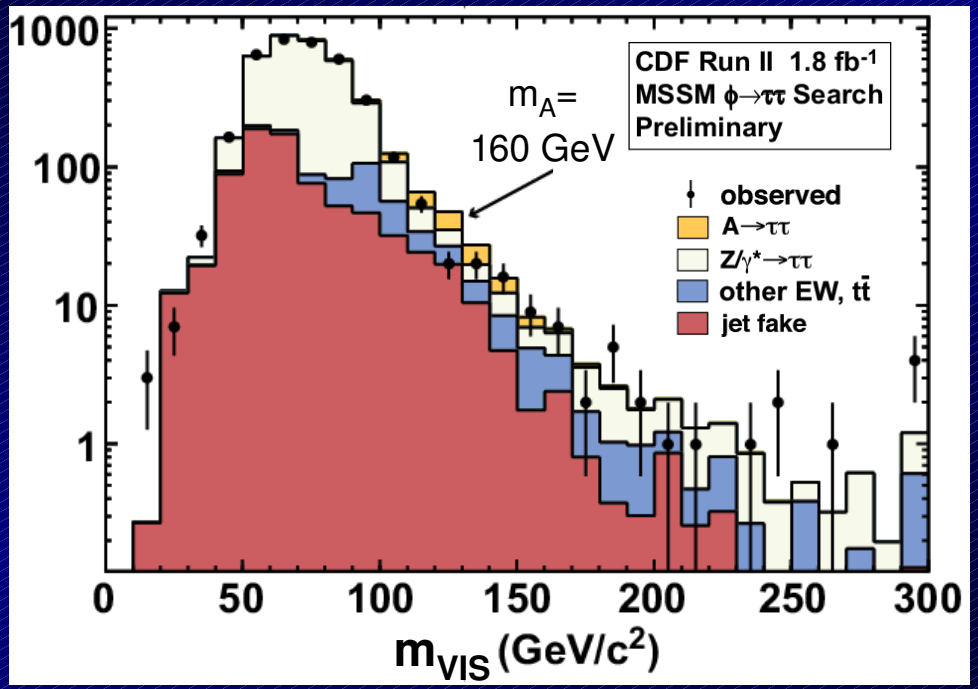


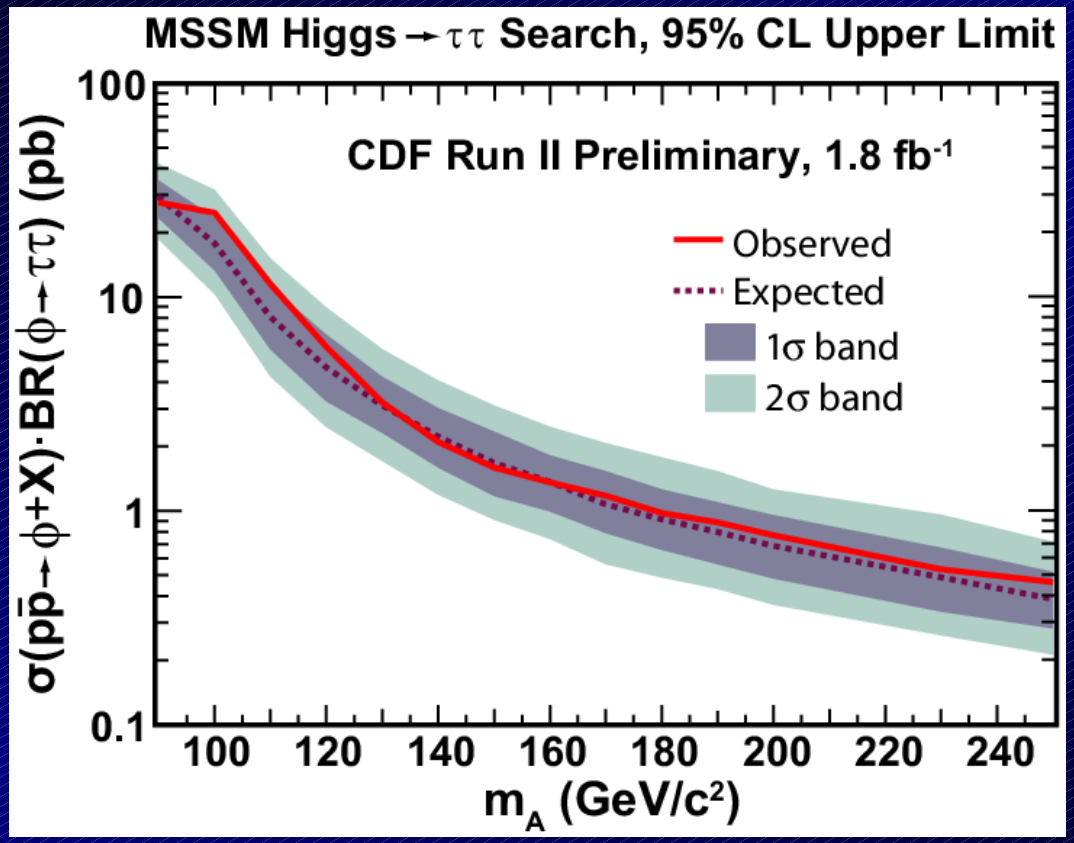


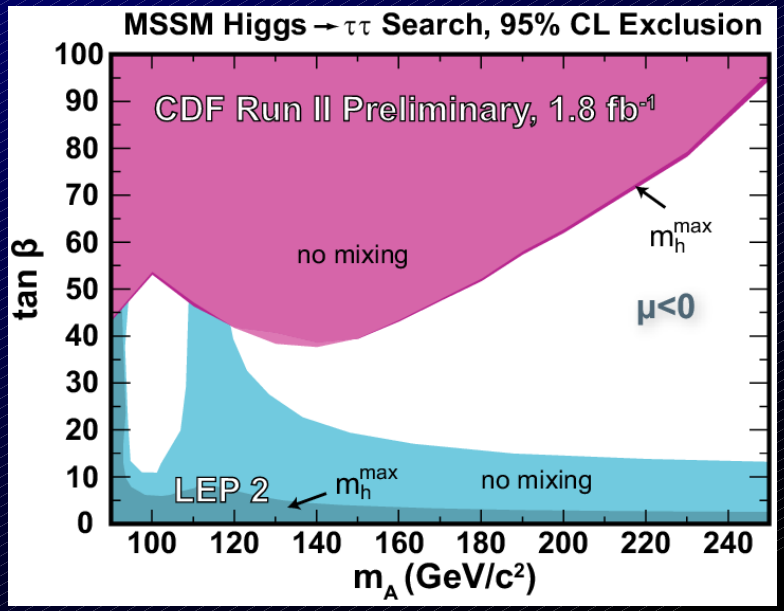
MSSM Higgs: $H \rightarrow \tau\tau$

1.8 fb^{-1}

- Update from 1.0 fb^{-1} to 1.8 fb^{-1}
- Excess is gone
- $\tan\beta$ excluded above ~40 around m_A=140 GeV/c^2







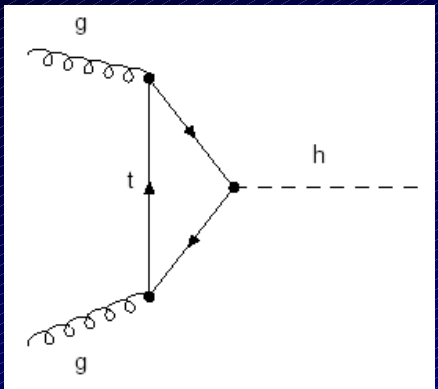
Beyond SM Higgs: $h_f \rightarrow \gamma\gamma$

3.0 fb^{-1}

- SM production

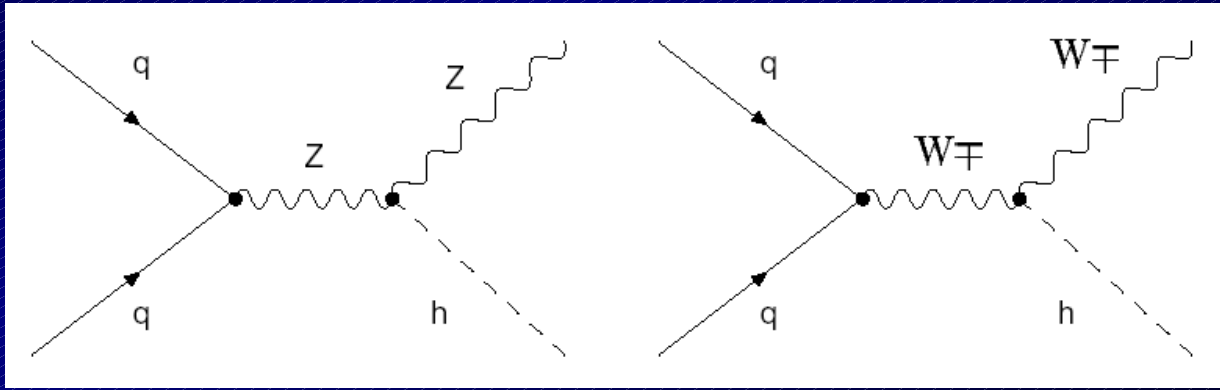
Gluon Fusion

σ ~ 1000 fb (m_h = 120 GeV/c^2)



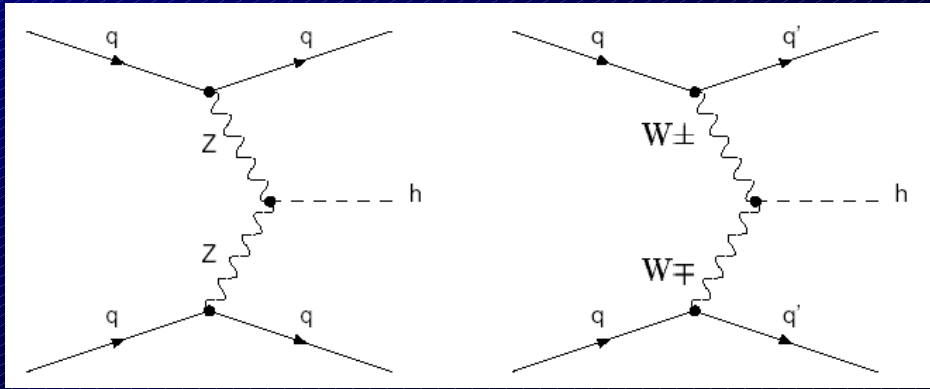
Associated Production

σ ~ 225 fb



Vector Boson Fusion

σ ~ 70 fb

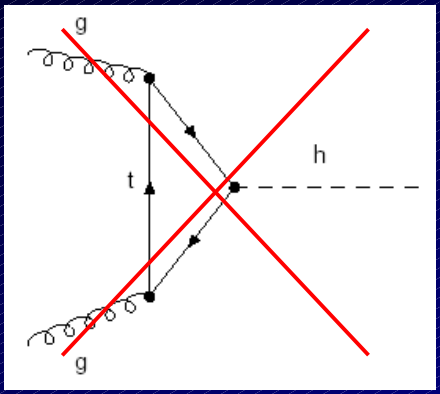


Beyond SM Higgs: $h_f \rightarrow \gamma\gamma$

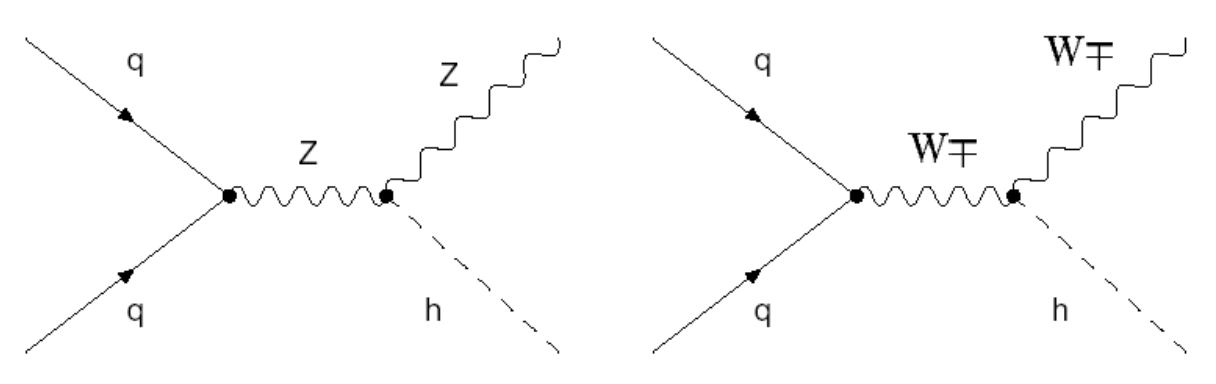
3.0 fb^{-1}

- Fermiophobic Production

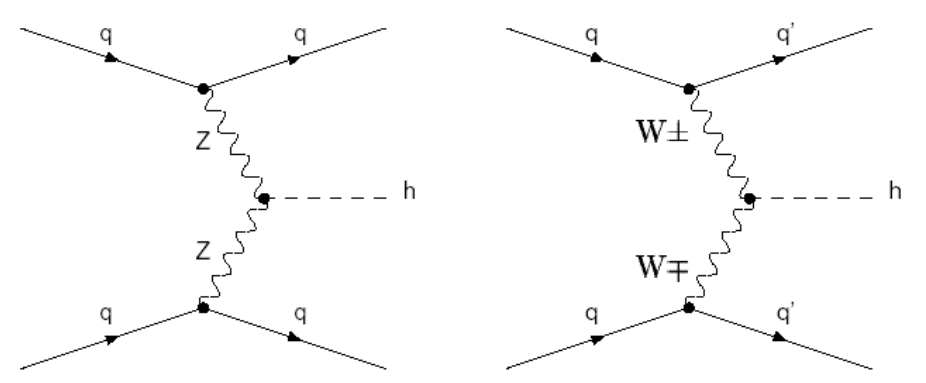
~~Gluon Fusion~~



Associated Production
σ ~ 225 fb



Vector Boson Fusion
σ ~ 70 fb

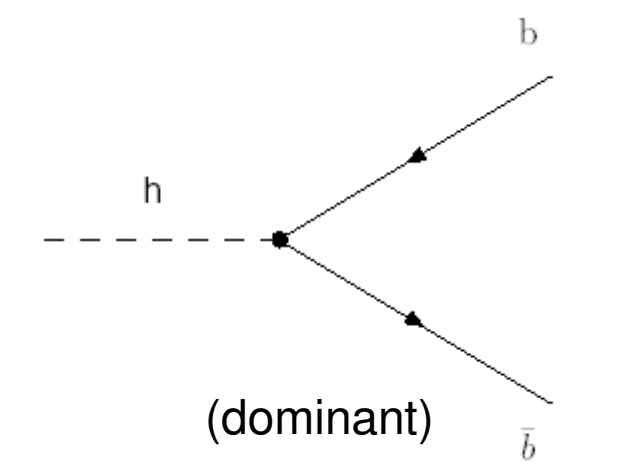


Beyond SM Higgs: $h_f \to \gamma\gamma$

3.0 fb^{-1}

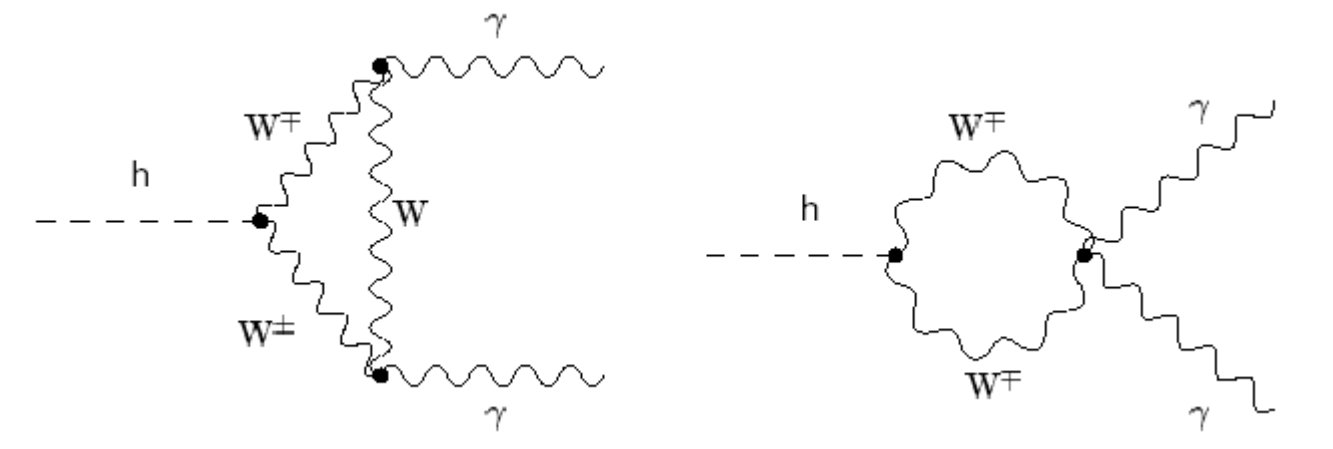
- SM decay

$h \to bb$



$h \to \gamma\gamma$

BR < 0.25%



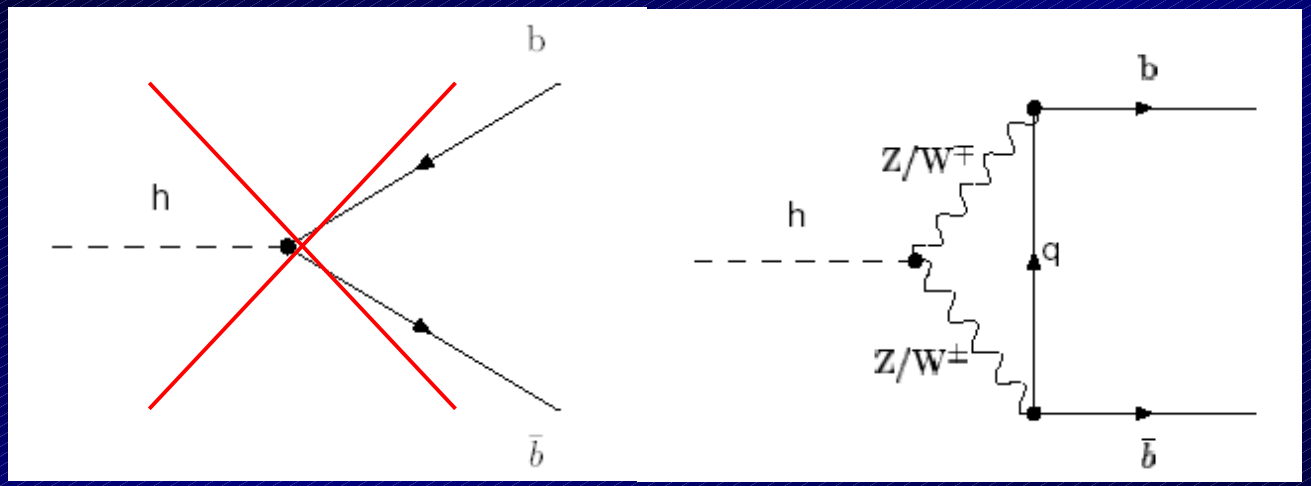
Beyond SM Higgs: $h_f \to \gamma\gamma$

3.0 fb^{-1}

- Fermiophobic decay

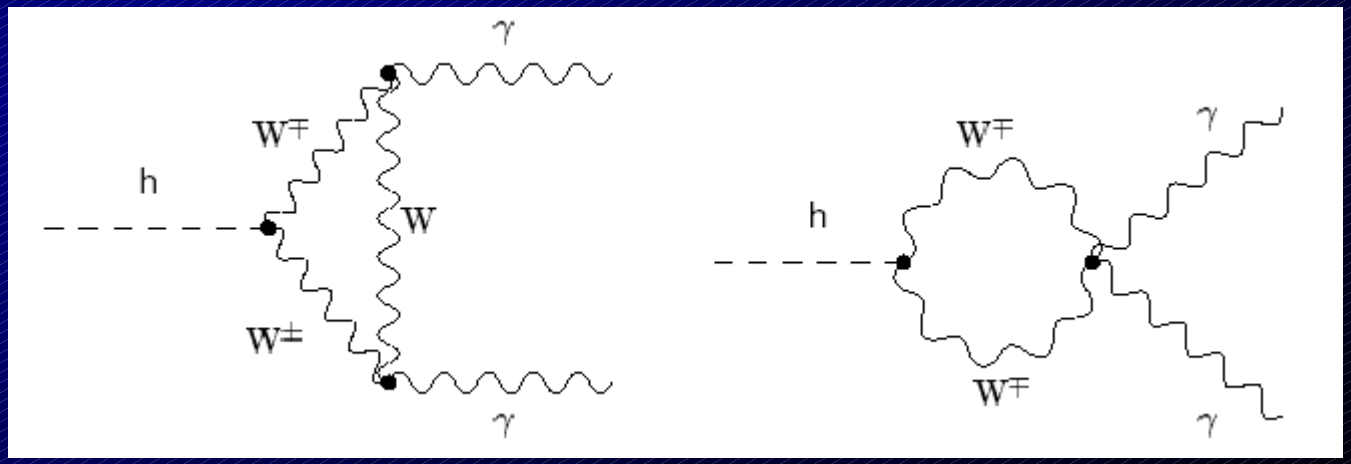
$h \to bb$

Suppressed by m_b^2/m_W^2



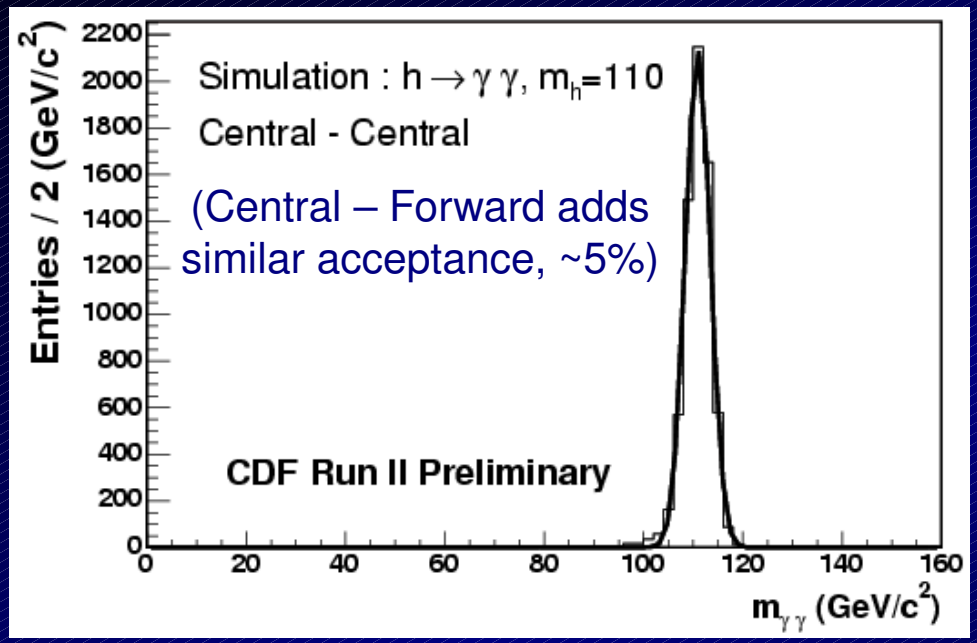
$h \to \gamma\gamma$

(Enhanced by >100×)

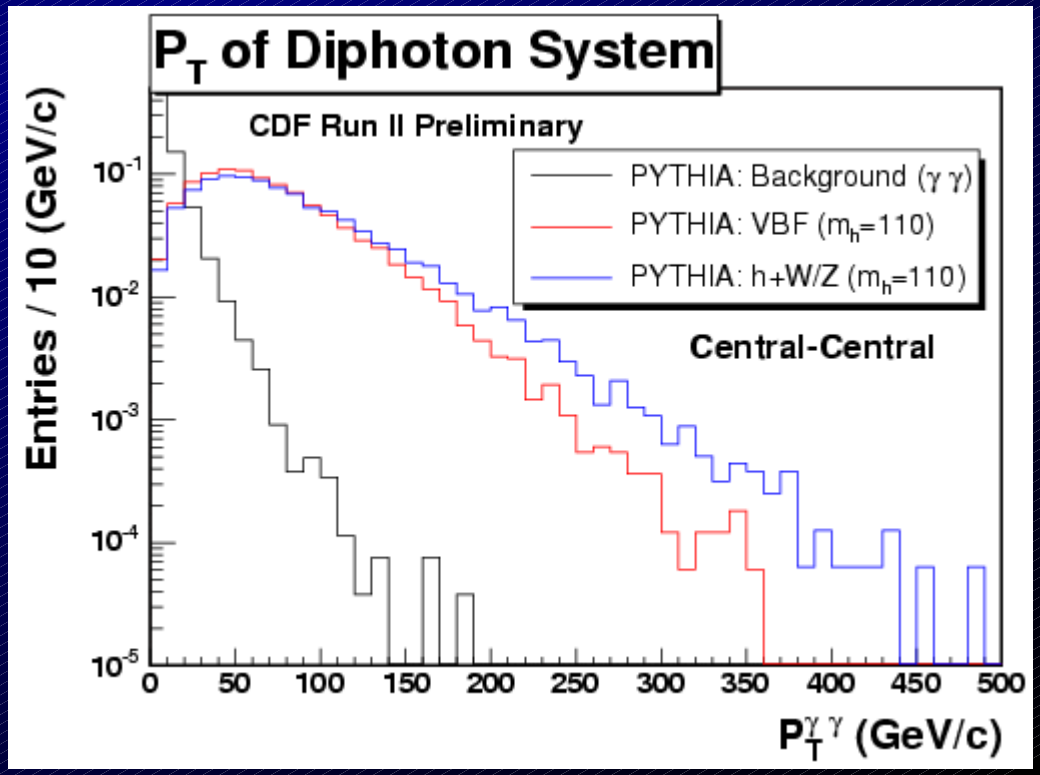


Beyond SM Higgs: $h_f \rightarrow \gamma\gamma$ 3.0 fb^{-1}

- Do we have sensitivity?
  - Not to the SM version (~20×SM with 4 fb^{-1})
  - Use fermiophobic scenario as benchmark



- Selection:
  - Di-photon trigger and photon E_T > 15 GeV
  - Optimize for Associated Production, using expected limit
    ↳ $p_T(\gamma\gamma)$ > 75 GeV/c
  - Keeps ~30% signal, rejects >99.5% bkg

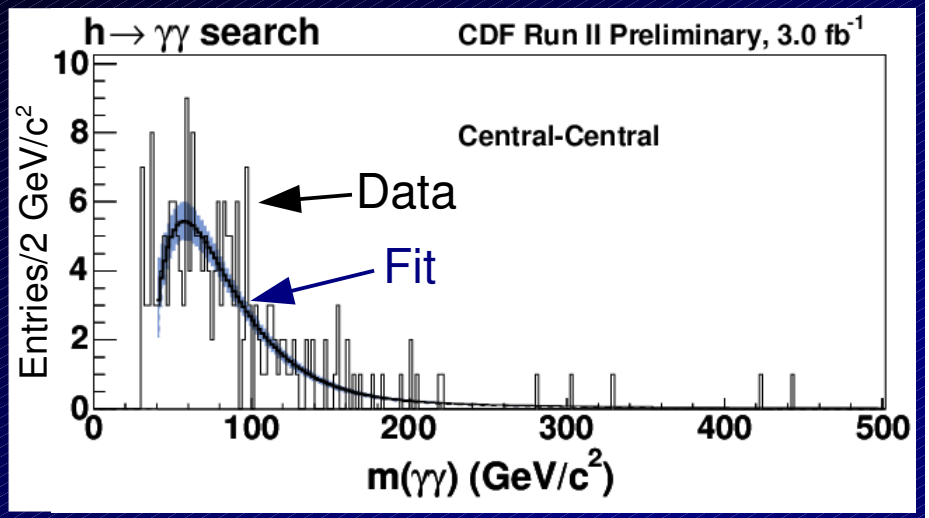


- Good mass resolution: $\frac{\sigma}{\text{mean}} < 3\%$
  - Background: SM $\gamma\gamma$ and QCD fakes
  - Search for narrow peak on smooth bkg
  - Background estimated from sidebands

Beyond SM Higgs: $h_f \rightarrow \gamma\gamma$

3.0 fb^{-1}

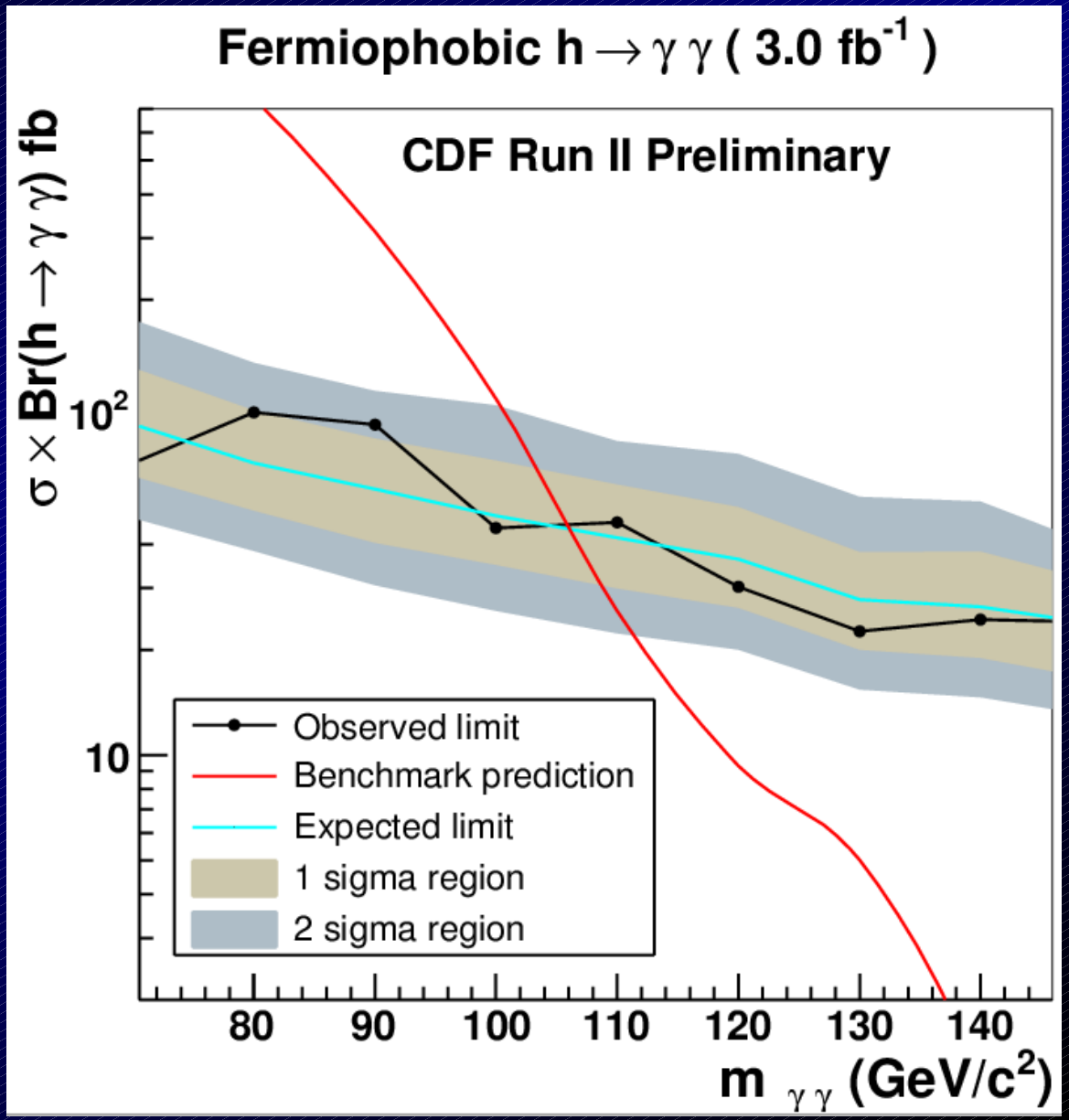
- No significant narrow resonance seen in data
  - Fit used for expected sensitivity and for testing signal hypothesis



- Binned likelihood, to set limits

$m_{h_f} > 106$ GeV/c^2 at 95% C.L.

- Strongest from hadron collider
- LEP limit: m > 109.7 GeV/c^2



Beyond SM Higgs: Wrap up

(1) MSSM Higgs, using bbb channel

- Initial excess has subsided
- Look for update with 6-8 fb^{-1}

(2) MSSM Higgs, using $\tau\tau$ channel

- Initial excess has subsided
- Improvement coming: split into b-tagged and untagged samples, switch to multi-variate approach

(3) Fermiophobic Higgs, using $\gamma\gamma$ channel New

- Not sensitive to SM branching ratios, but interesting to prepare for LHC
- Fermiophobic case (as beyond SM benchmark) gives good limits

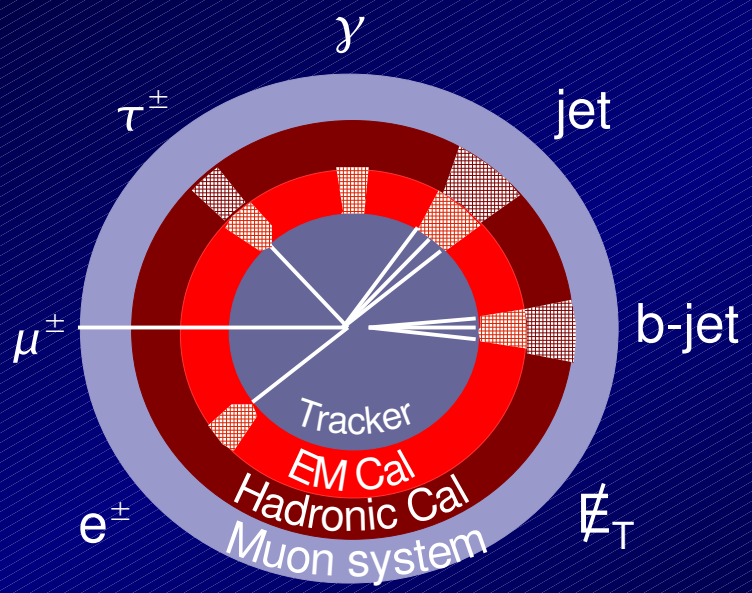
CDF Global Searches

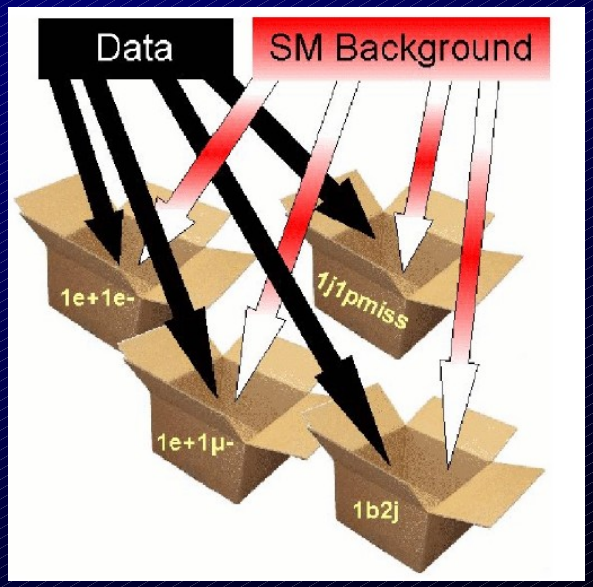
- Model-independent global searches for new high-p_T physics

(1) Vista	Examine population and kinematic features of high-p_T data
(2) Bump Hunter	Search for resonances in invariant mass combinations
(3) Sleuth	Look for excesses at high sum-p_T

Global Search Overview

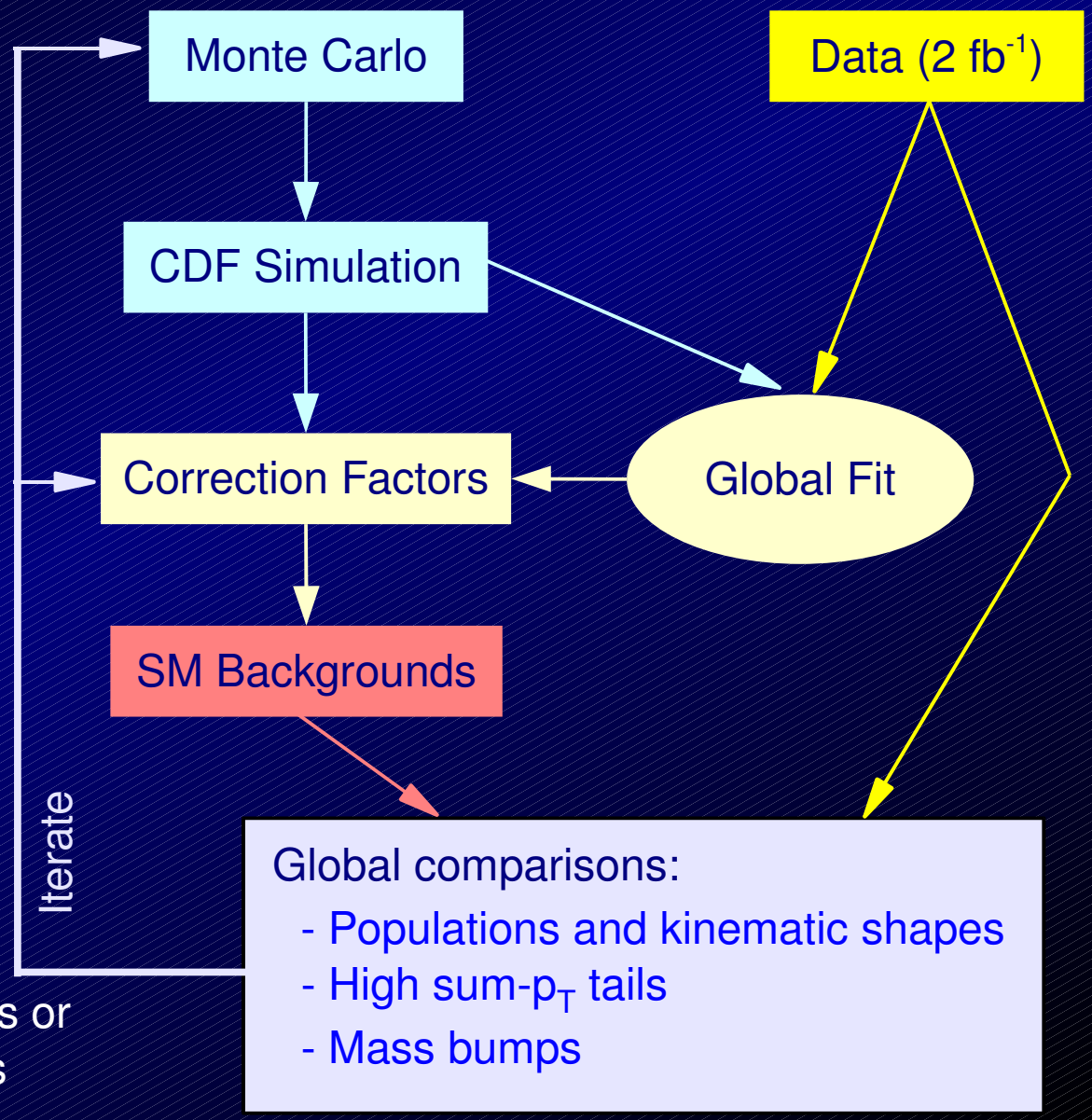
- Capturing data
  - Results use 2 fb^{-1}
  - Events come in on inclusive high-p_T electron, muon, photon, and jet triggers
- Object identification
  - $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$, γ, j, b, $\not{E}_T$
  - $p_T > 17$ GeV/c
- Selecting events
  - Offline requirements such as $E_T(e) > 25$ GeV, $p_T(\mu) > 25$ GeV/c, or $E_T(\gamma) > 60$ GeV, etc.
- Categorization
  - ~4.3 million events partitioned into 399 exclusive final states
  - New categories created as needed





Global Search Strategy

- Use Monte Carlo event generators such as PYTHIA and MadEvent to mimic Standard Model
- Simulate CDF detector response using GEANT-based *CDFSim*
- Fit for 43 correction factors to improve SM prediction
  - Global fit to all final states, subject to external constraints
  - Leading order theory cross sections corrected
  - Object reconstruction efficiencies and mis-identification rates corrected
- Iterate until clear case for new physics or all discrepancies have known sources



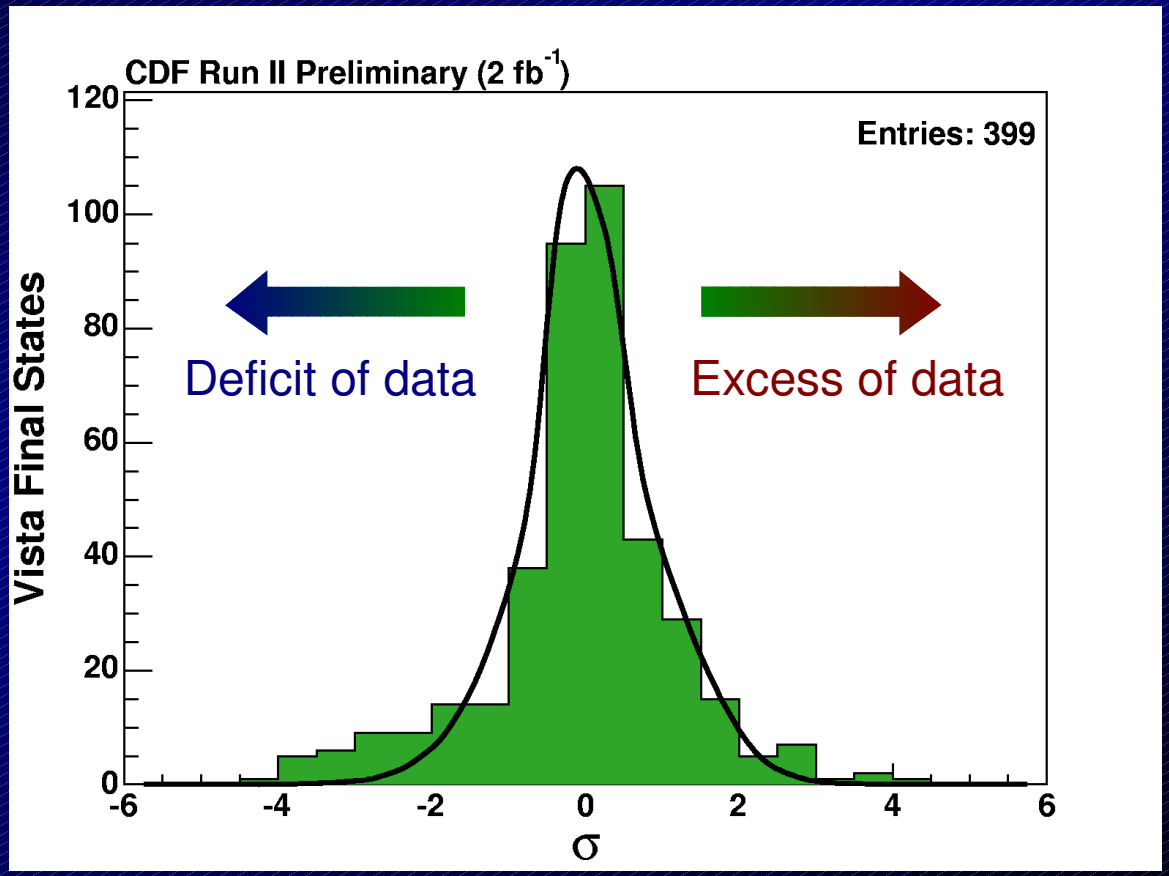
Population Results

- Summary of "Vista" final state population comparisons (data to SM bkg.)

CDF Run II Preliminary (2.0 fb^{-1})

Final State	Data	Background	σ
$be^{\pm}\not{p}$	690	817.7 ± 9.2	-4.3
$\gamma\tau^{\pm}$	1371	1217.6 ± 13.3	$+4.0$
$\mu^{\pm}\tau^{\pm}$	63	35.2 ± 2.8	$+3.7$
$b2j\not{p}$ high-Σp_T	255	327.2 ± 8.9	-3.7
$2j\tau^{\pm}$ low-Σp_T	574	670.3 ± 8.6	-3.6
$3j\tau^{\pm}$ low-Σp_T	148	199.8 ± 5.2	-3.5
$e^{\pm}\not{p}\tau^{\pm}$	36	17.2 ± 1.7	$+3.5$
$2j\tau^{\pm}\tau^{\mp}$	33	62.1 ± 4.3	-3.5
$e^{\pm}j$	741710	764832 ± 6447.2	-3.5
$j2\tau^{\pm}$	105	150.8 ± 6.3	-3.4
⋮	⋮	⋮	⋮

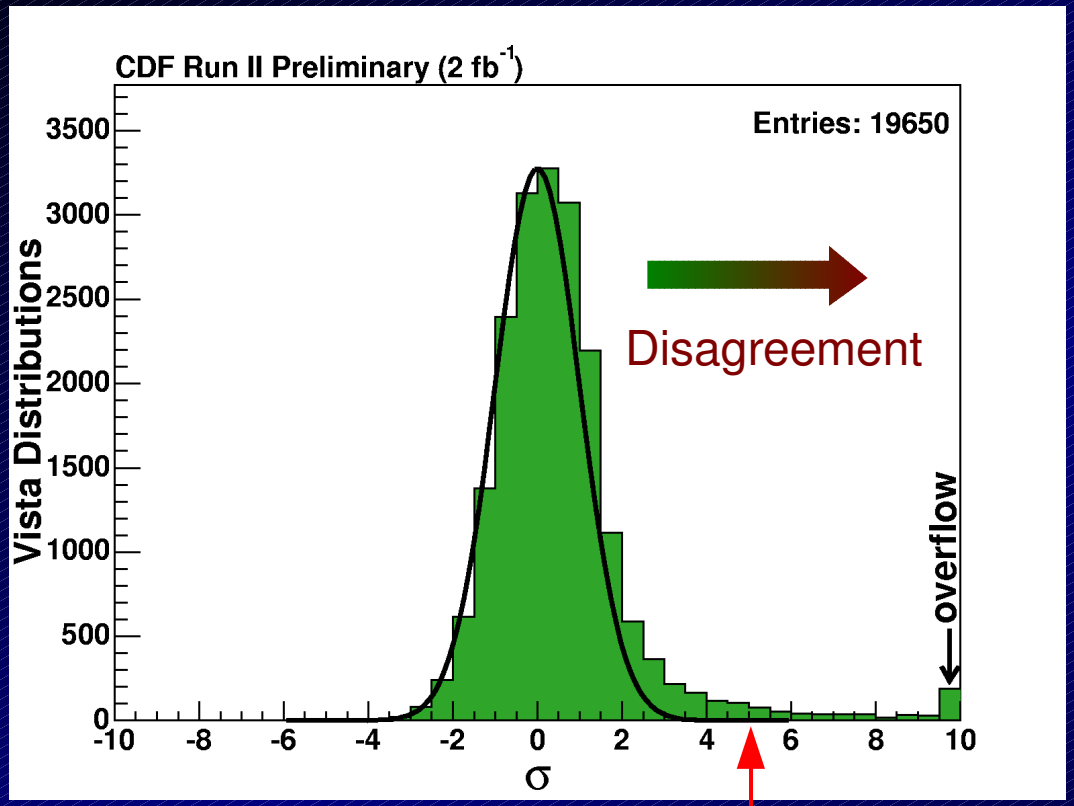
... plus 389 additional, less discrepant, population comparisons



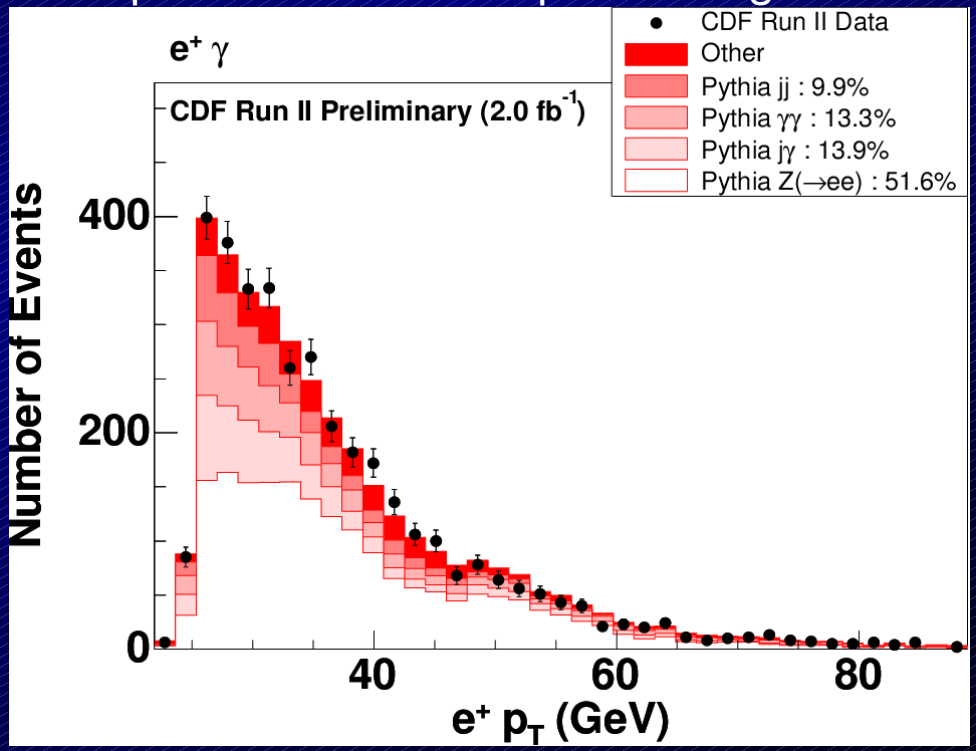
- No population shows a significant discrepancy after accounting for the trials factor (e.g. -4.3σ becomes -2.7σ)

Kinematic Distribution Results

- Summary of "Vista" kinematic shape comparisons (data to SM bkg.)
- Automatically produces and examines 19650 kinematic distributions



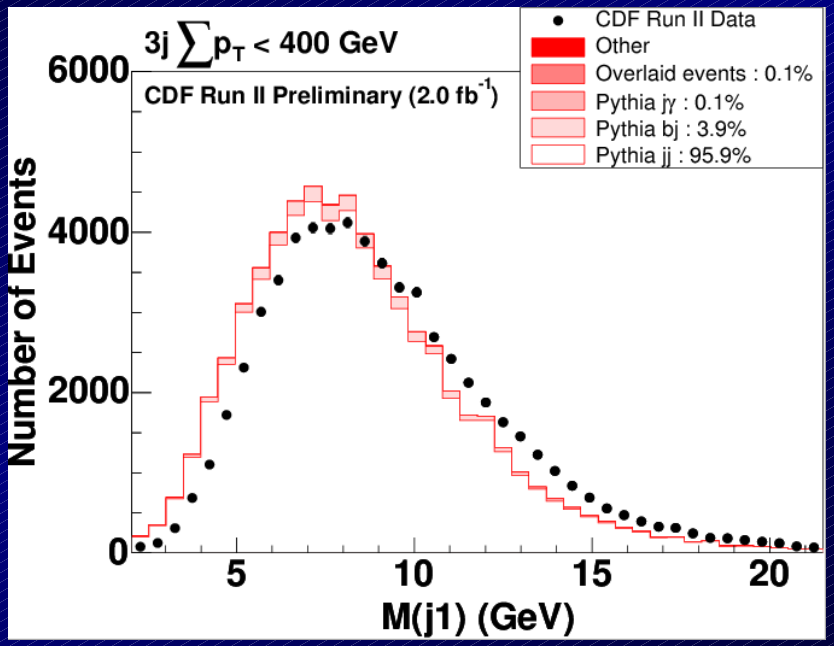
Example from 19095 shapes that agree:

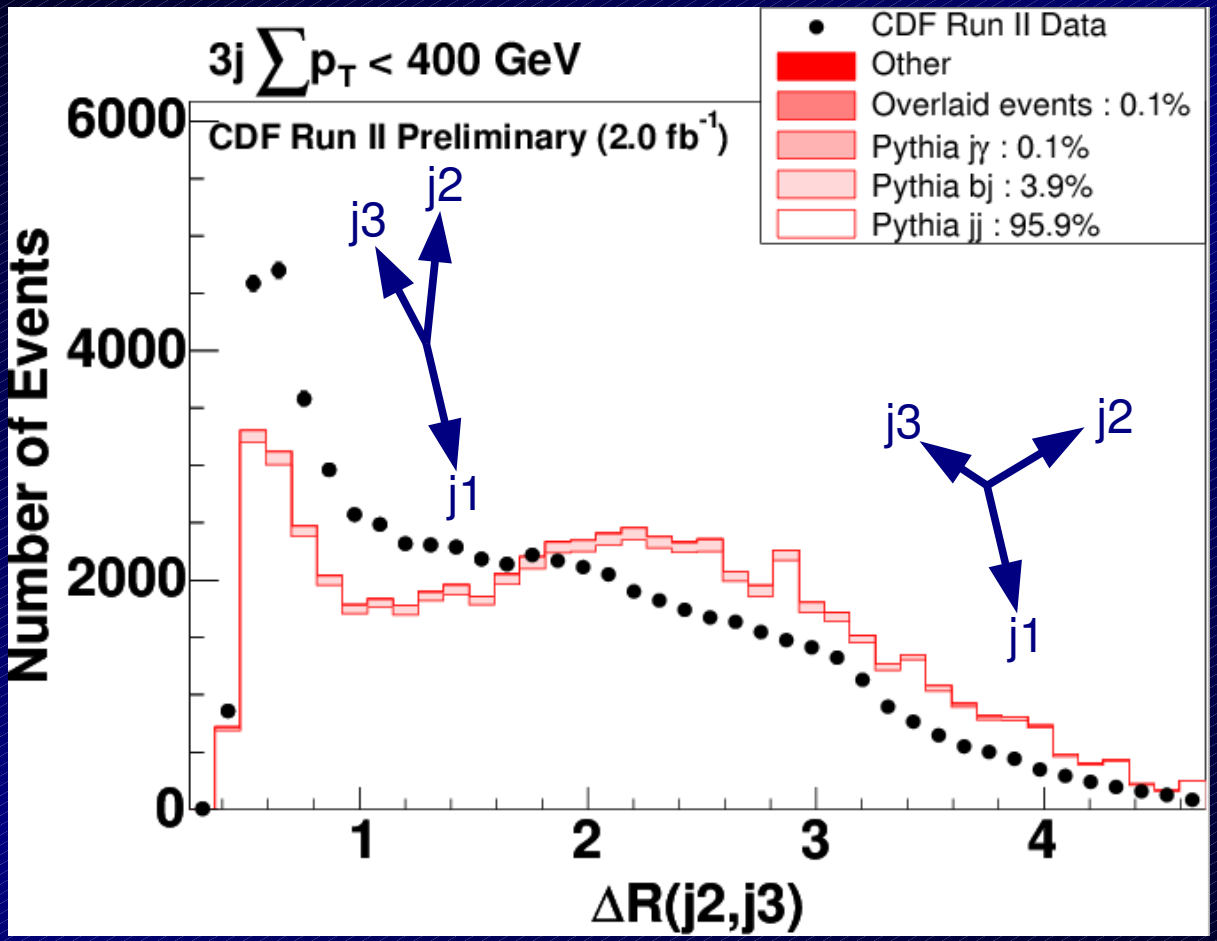


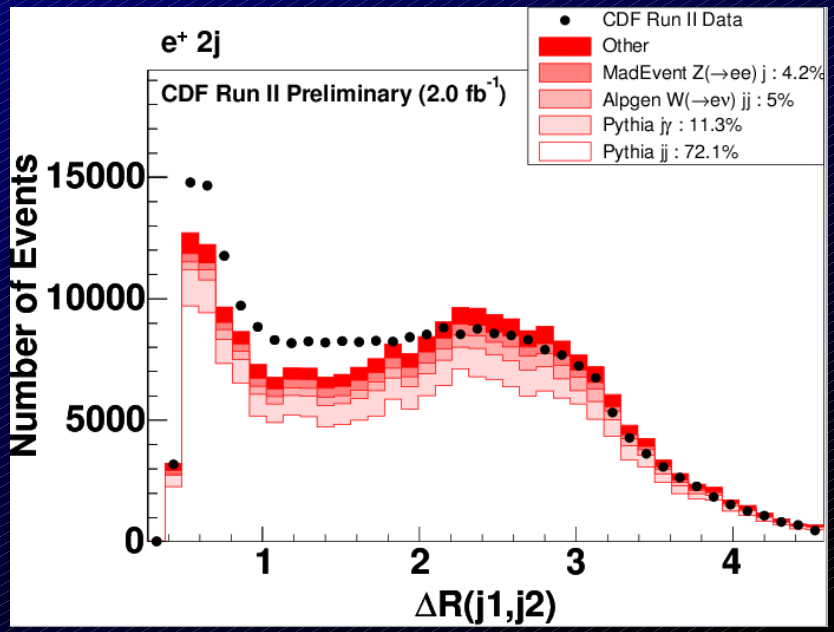
- Inspect the 555 shapes with significant (>5σ) discrepancy more closely ...

Shape Discrepancies

- Soft jet emission modeling problem
- No claims for new physics based on these



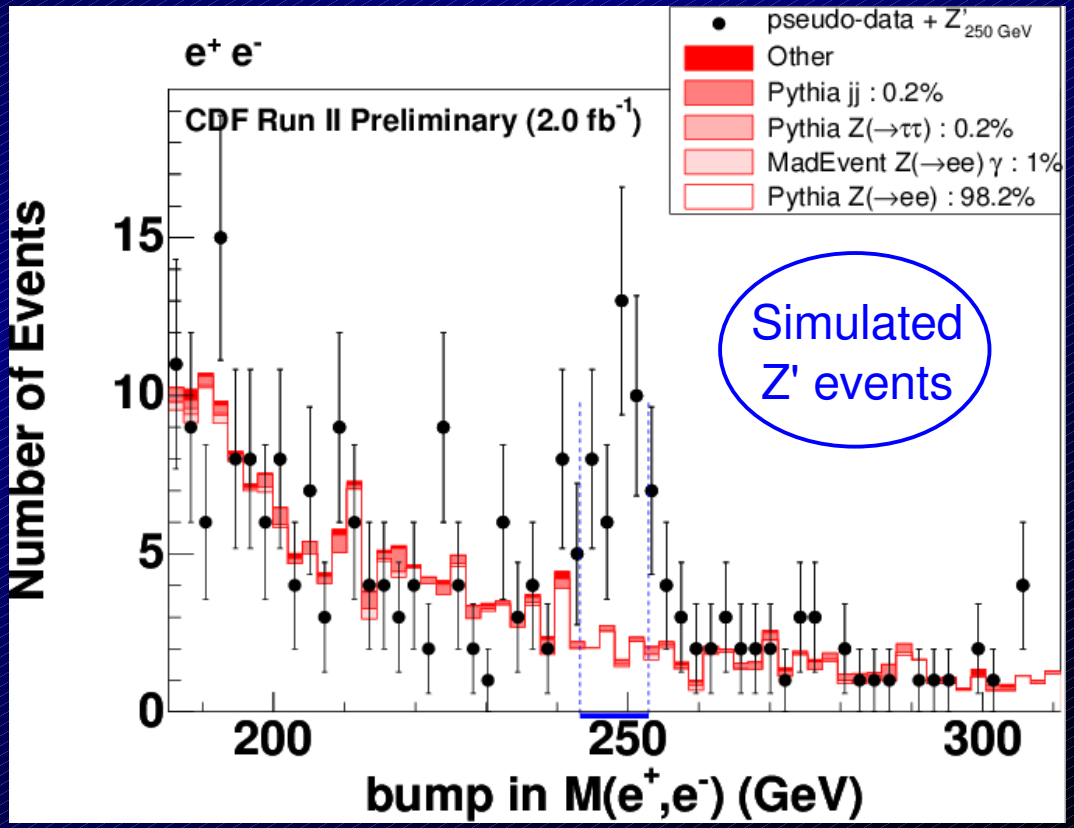




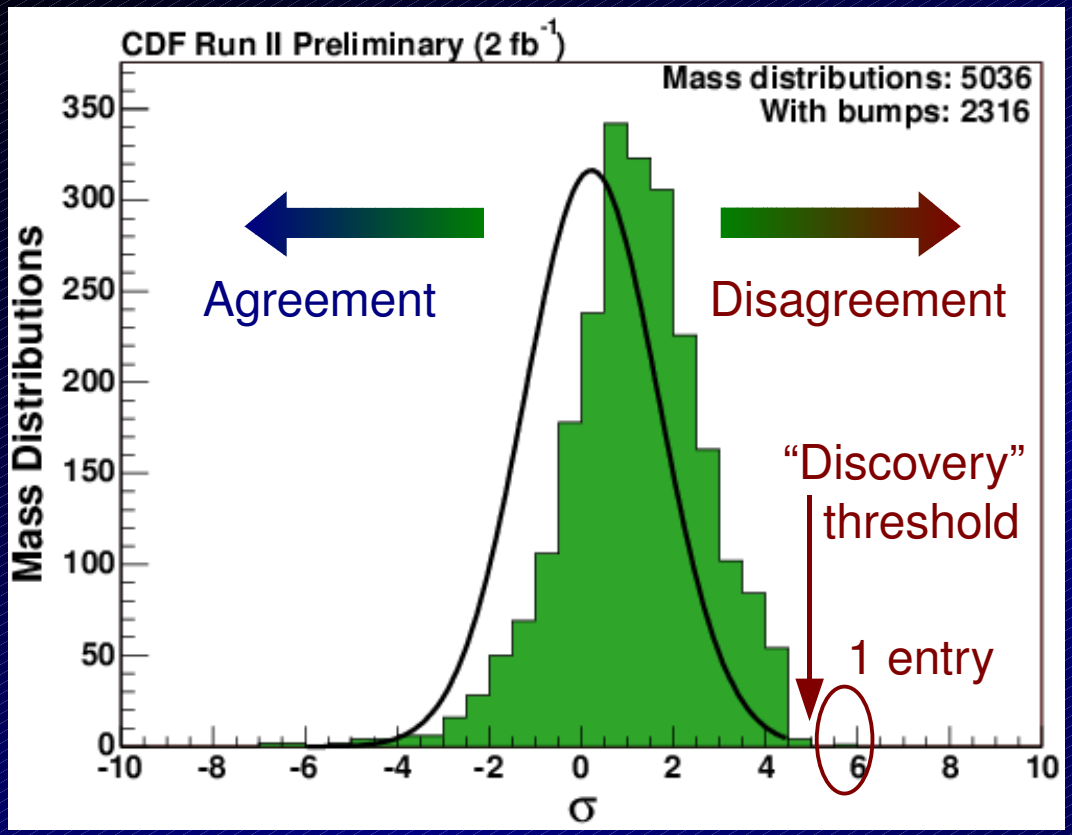
Bump Hunter

- Resonance might show up as bump in invariant mass
- Strategy:
  - Form all object mass combinations
  - Compare data to SM backgrounds
  - Use search window of $2\Delta M$ (ΔM = expected detector mass resolution)
  - Candidate bumps must have:
    - $\geq$ 5 data events
    - Side-bands in better agreement than center
  - Use pseudo-experiments to estimate significance of bumps

Example, using Z' events injected into a mix of pseudo-data based on SM backgrounds:



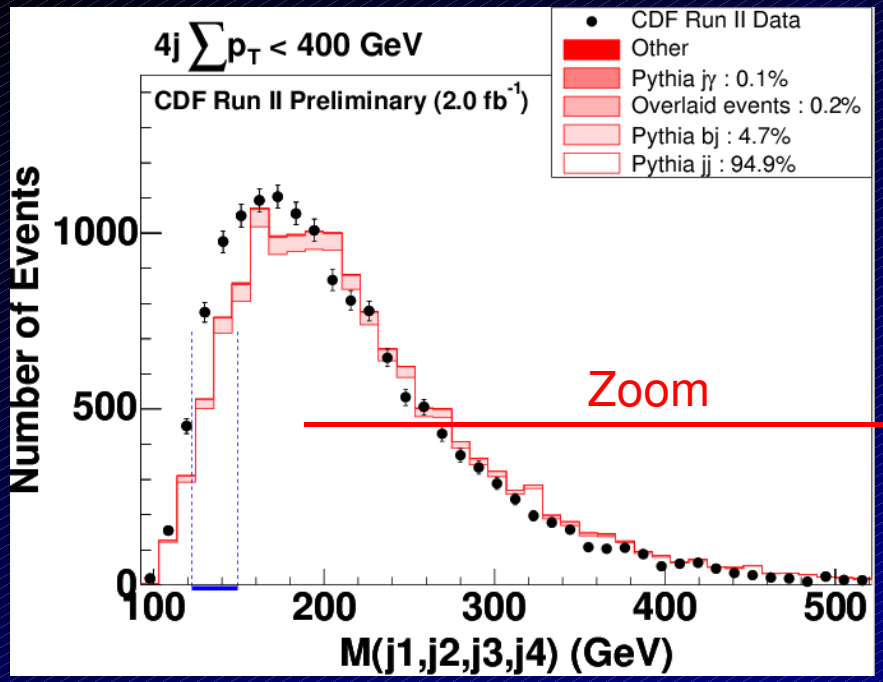
Bump Hunter Results



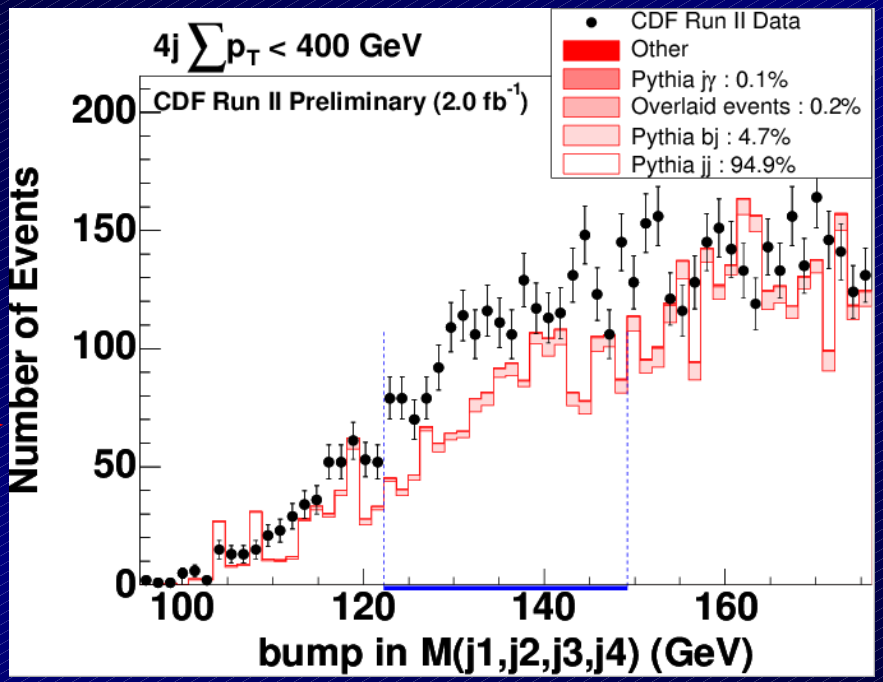
Probability for corresponding bump from pseudo-data to have larger significance than the one found in data

- 5036 mass distributions scanned → 2316 have qualifying bumps
- Shift caused by local deficiencies in the SM prediction
- "Discovery" threshold is 5σ, corresponding to 3σ after trials factor for 5036 distributions

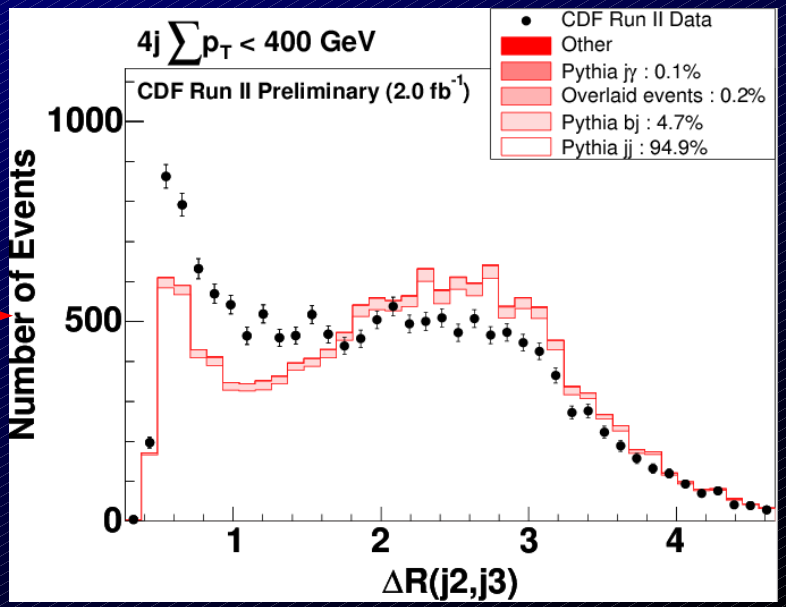
Bump Hunter Results (II)



Zoom



- The only significant bump
  - 4 jets and low Σp_T
- But it's just due to the jet ΔR problem seen before
- No new physics found by the bump hunter in 2 fb^{-1}



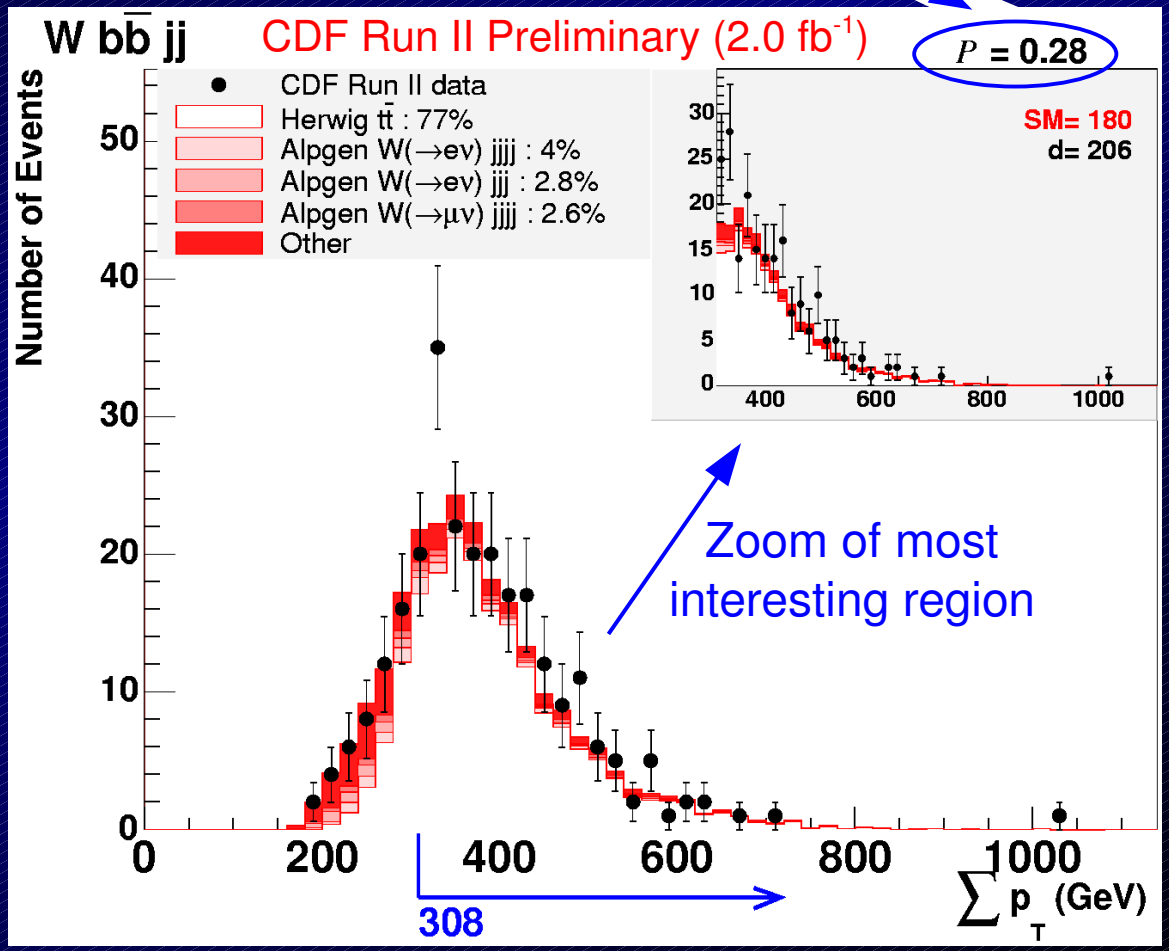
High Σp_T

- "Sleuth" makes three assumptions
  - New physics will show up as excess
  - Excess will be at high Σp_T
  - Excess will be in one final state
- Search variable

$$\Sigma p_T \equiv \Sigma|\vec{p}_T| + |\overrightarrow{\text{uncl}}| + |\vec{\not{p}}_T|$$

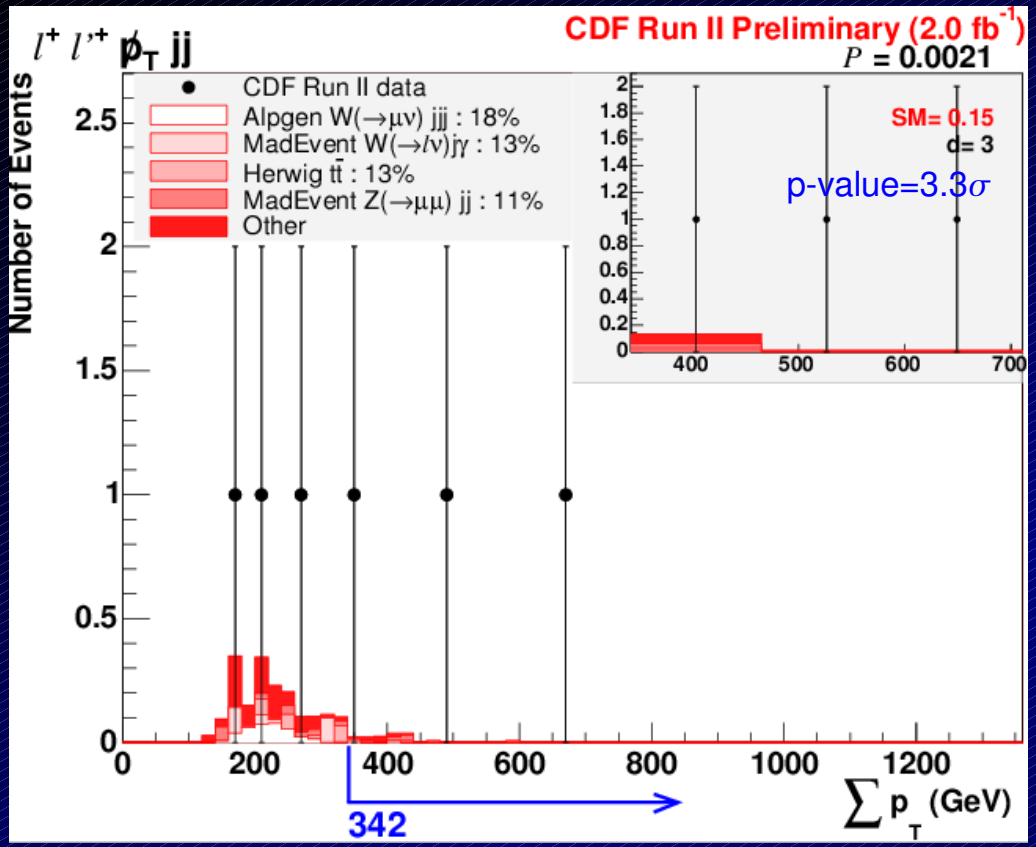
- For each final state
  - Scan the Σp_T distribution
  - Select the one-sided region with most significant excess of data
- Perform pseudo-experiments to evaluate significance
  - P = fraction of pseudo-experiments that find region at least as discrepant in this final state
  - Then account for trials factor of looking at so many final states

Significance of this region

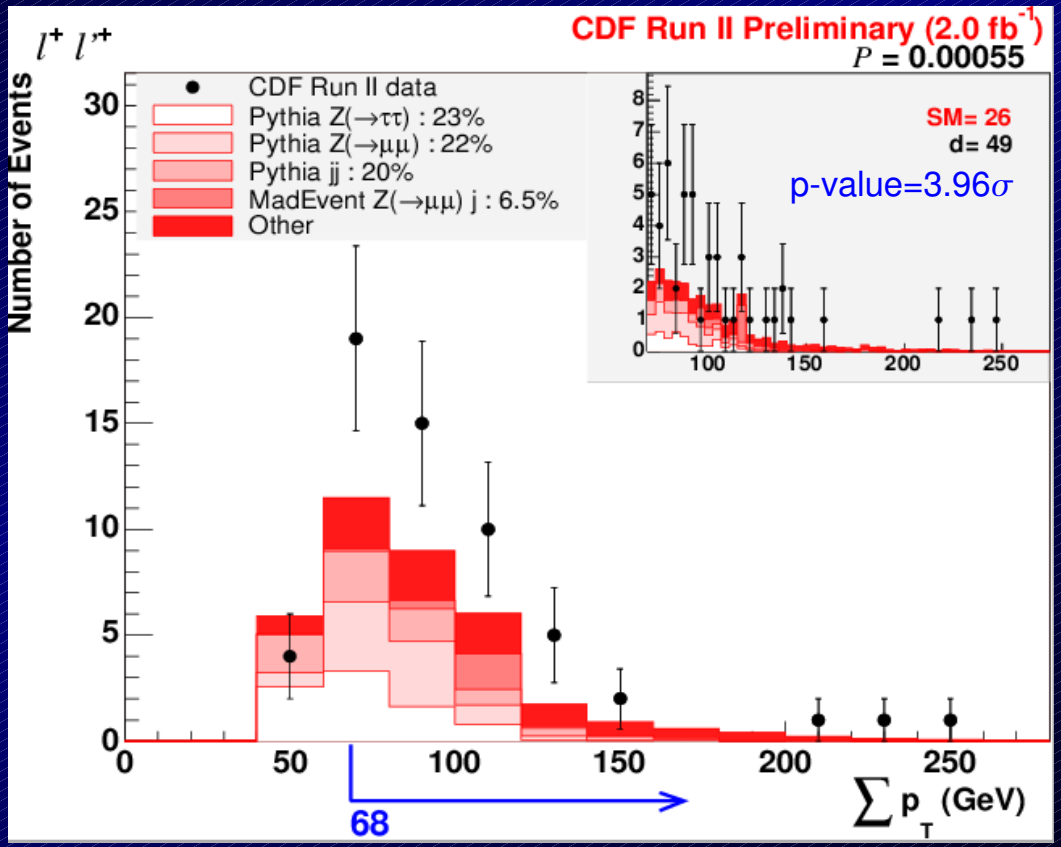


Sleuth Results

#2



#1



- Final state: $e^+ \mu^+ j j \not{p}_T$
- Significance of region:
  P = 0.0021 (2.86σ) before trials factor,
  27% probable after trials factor

- Final state: $e^+ \mu^+$
- Significance of region:
  P = 0.00055 (3.26σ) before trials factor,
  8.5% probable after trials factor

Sleuth Summary

- Top 5 most discrepant high Σp_T tails:

CDF Run II Preliminary (2.0 fb^{-1})

Sleuth Final State	*P*
$e^+ \mu^+$	0.00055
$e^+ \mu^+ j j \not{p}_T$	0.0021
$e^+ \mu^+ \not{p}_T$	0.0042
$\ell^+ \ell^- \ell' \not{p}_T$	0.0047
$\ell^+ \tau^+ \not{p}_T$	0.0065

- Last step is to calculate what fraction of CDF-like experiments would find an excess at least as large as the top Sleuth final state:

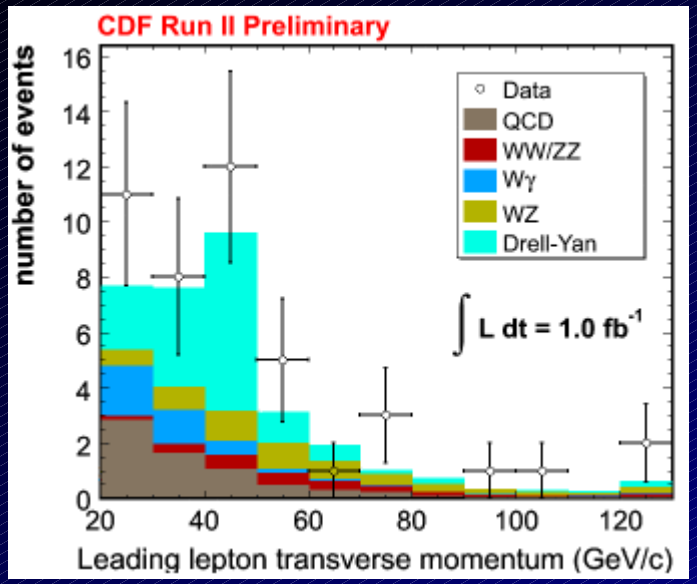
Answer = ~8%

- Therefore, no claim for discovery of new physics using Sleuth on 2 fb^{-1}

(but there certainly can still be new physics in the CDF data)

Aside: Dedicated Same Sign Search

- 1 fb^{-1} search found slight excess (not statistically significant)

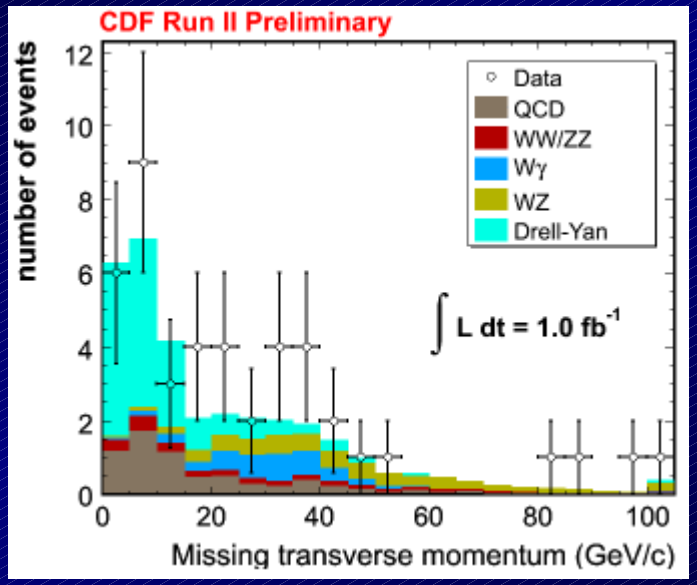


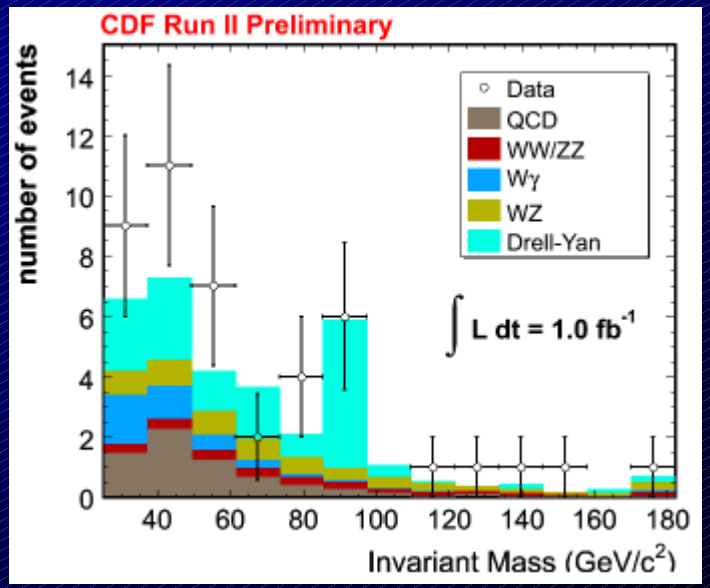
Loose selection: 2 same sign leptons

Expect 33.7 ± 3.5, Observe 44 (7.6% probable)

Tight selection: 2 same sign leptons
& Z region veto & $\not\!\!E_T$ > 15 GeV

Expect 7.9 ± 1.0, Observe 13 (6.1% probable)





- Now updating to 3 fb^{-1}
- If discrepancy just increases with stats, it becomes ~2.5σ

(plus gains in acceptance)

Global Search: Wrap up

1 fb^{-1}: Phys. Rev. D 78, 012002 (2008)
2 fb^{-1}: Submitted to Phys. Rev. D RC

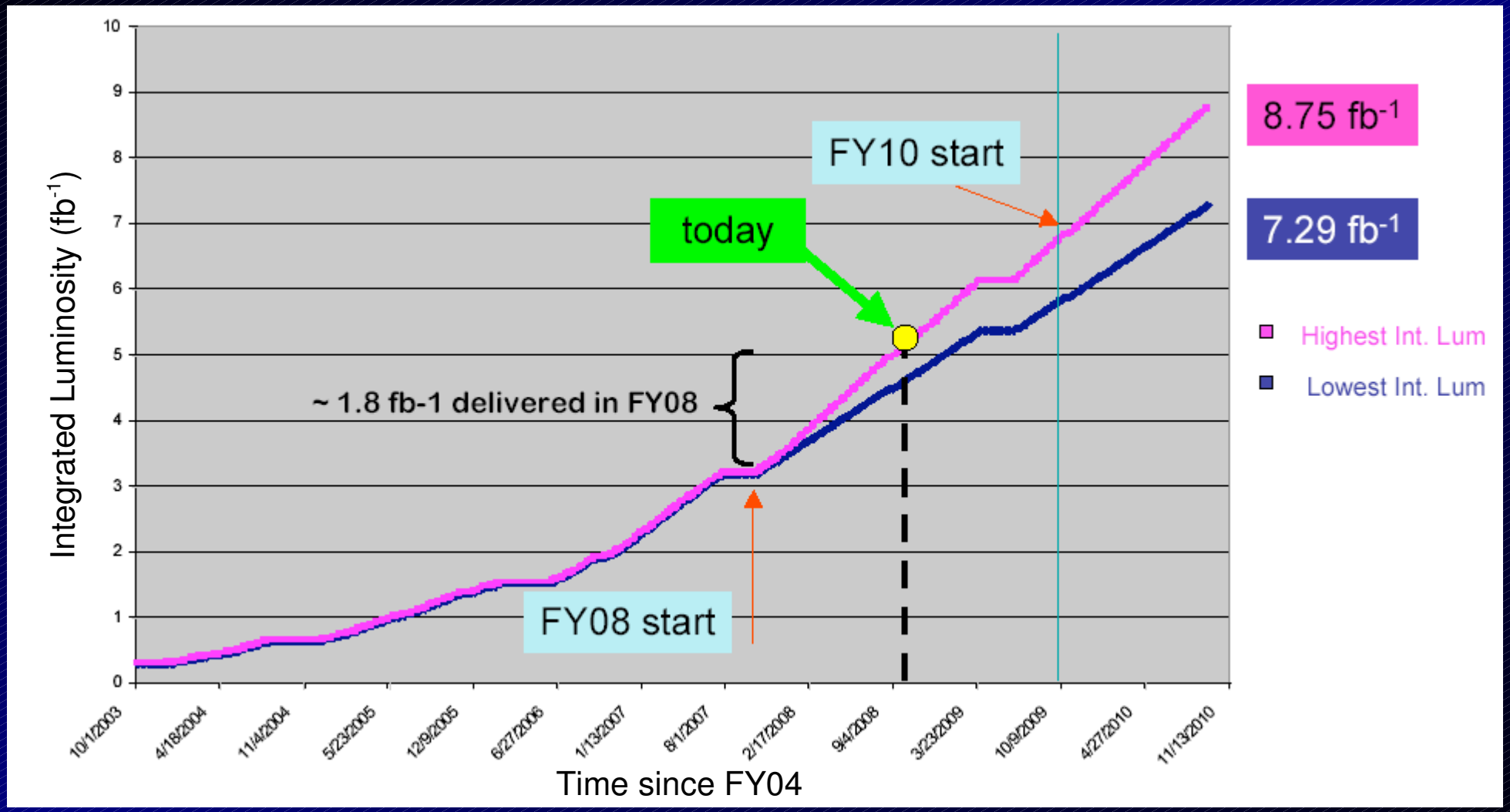
- Find no indication of new physics in populations, kinematic distributions, invariant mass peaks, or high-Σp_T
- Five final states with most discrepant high-Σp_T tails all have same sign leptons
- Provide broad view of high-p_T data samples, and enhance understanding of detectors and standard model simulation
- Happily, they do not rule out new physics

Conclusions I

- The Discovery Watch has guided our attention to the following results
  I. Resonances
     (1) Dielectron search, including two forward electrons
     (2) Dielectron search, including $\geq$1 central electron
     (3) Dimuon search
  II. Higgs beyond the standard model
     (1) MSSM Higgs, using bbb channel
     (2) MSSM Higgs, using $\tau\tau$ channel
     (3) Fermiophobic Higgs, using $\gamma\gamma$ channel
  III. Global searches
     (1) Vista (population and kinematics)
     (2) Bump Hunter
     (3) Sleuth (high sum-p_T)
- List will evolve, with more than factor of two data left to analyze

Conclusions II

- Run II luminosity projections



- More information

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

Backup Slides →

Other CDF "Discoveries"

- Observation of B_s-mixing
  - $\Delta m_s = 17.77 \pm 0.10$ (stat) $\pm$ 0.07 (sys)
- Observation of new baryon states
  - Σ_b and Ξ_b
- WZ discovery (6σ)
- ZZ observation (4.4σ)
- Single top evidence
  - cross section = $2.2^{+0.7}_{-0.6}$ (stat+sys) pb
  - $|V_{tb}| = 0.88^{+0.13}_{-0.12}$ (stat+sys) $\pm$ 0.07 (theory)

Vista Correction Factors

- 43 correction factors, with values and errors obtained from global fit
- Only applicable within the Vista correction model

CDF Run II Preliminary (2.0 fb^{-1})

Code	Category	Explanation	Value	Error	Error(%)
0001	luminosity	CDF integrated luminosity	1990	50	2.6
0002	k-factor	cosmic_ph	0.83	0.05	6.0
0003	k-factor	cosmic_j	0.192	0.006	3.1
0004	k-factor	$1\gamma 1j$ photon+jet(s)	0.92	0.04	4.4
0005	k-factor	$1\gamma 2j$	1.26	0.05	4.0
0006	k-factor	$1\gamma 3j$	1.61	0.08	5.0
0007	k-factor	$1\gamma 4j+$	1.94	0.16	8.3
0008	k-factor	$2\gamma 0j$ diphoton(+jets)	1.6	0.08	5.0
0009	k-factor	$2\gamma 1j$	2.99	0.17	5.7
0010	k-factor	$2\gamma 2j+$	1.2	0.09	7.5
0011	k-factor	W0j W (+jets)	1.38	0.03	2.2
0012	k-factor	W1j	1.33	0.03	2.3
0013	k-factor	W2j	1.99	0.05	2.5
0014	k-factor	W3j+	2.11	0.09	4.3
0015	k-factor	Z0j Z (+jets)	1.39	0.028	2.0
0016	k-factor	Z1j	1.23	0.04	3.2
0017	k-factor	Z2j+	1.02	0.04	3.9
0018	k-factor	2j $\hat{p}_T<150$ dijet	1.003	0.027	2.7
0019	k-factor	2j $150<\hat{p}_T$	1.34	0.03	2.2
0020	k-factor	3j $\hat{p}_T<150$ multijet	0.941	0.025	2.7
0021	k-factor	3j $150<\hat{p}_T$	1.48	0.04	2.7
0022	k-factor	4j $\hat{p}_T<150$	1.06	0.03	2.8
0023	k-factor	4j $150<\hat{p}_T$	1.93	0.06	3.1
0024	k-factor	5j low	1.33	0.05	3.8
0025	k-factor	1b2j $150<\hat{p}_T$	2.22	0.11	5.0
0026	k-factor	1b3j $150<\hat{p}_T$	2.98	0.15	5.0
0027	misId	$p(e\to e)$ central	0.978	0.006	0.6
0028	misId	$p(e\to e)$ plug	0.966	0.007	0.7
0029	misId	$p(\mu\to\mu)$ CMUP+CMX	0.888	0.007	0.8
0030	misId	$p(\gamma\to\gamma)$ central	0.949	0.018	1.9
0031	misId	$p(\gamma\to\gamma)$ plug	0.859	0.016	1.9
0032	misId	$p(b\to b)$ central	0.978	0.021	2.1
0033	misId	$p(\gamma\to e)$ plug	0.06	0.003	5.0
0034	misId	$p(q\to e)$ central	7.09×10^{-5}	1.9×10^{-6}	2.7
0035	misId	$p(q\to e)$ plug	0.000766	1.2×10^{-5}	1.6
0036	misId	$p(q\to\mu)$	1.14×10^{-5}	6×10^{-7}	5.2
0037	misId	$p(b\to\mu)$	3.3×10^{-5}	1.1×10^{-5}	33.0
0038	misId	$p(j\to b)$ $25<p_T$	0.0183	0.0002	1.1
0039	misId	$p(q\to\tau)$	0.0052	0.0001	1.9
0040	misId	$p(q\to\gamma)$ central	0.000266	1.4×10^{-5}	5.3
0041	misId	$p(q\to\gamma)$ plug	0.00048	6×10^{-5}	12.6
0042	trigger	$p(e\to trig)$ plug, $p_T>25$	0.86	0.007	0.8
0043	trigger	$p(\mu\to trig)$ CMUP+CMX, $p_T>25$	0.916	0.004	0.4

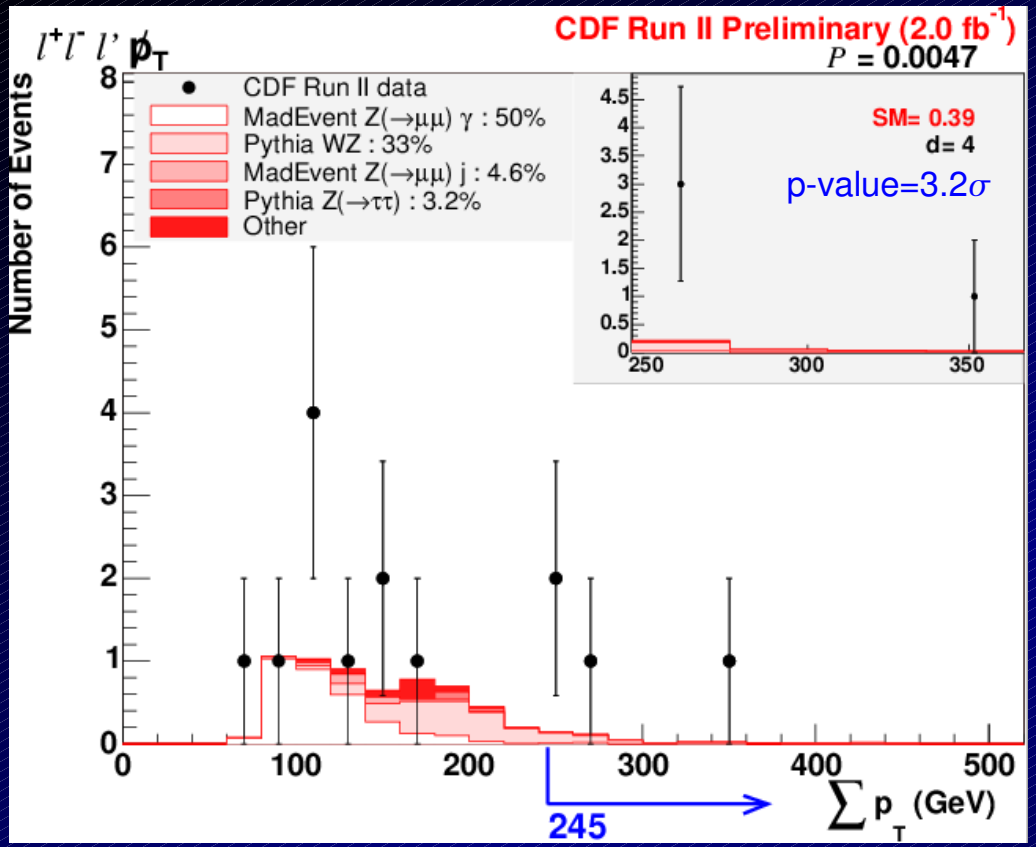
Vista Final State Populations

CDF Run II Preliminary (2.0 fb^{-1})
The calculation of σ accounts for the trials factor

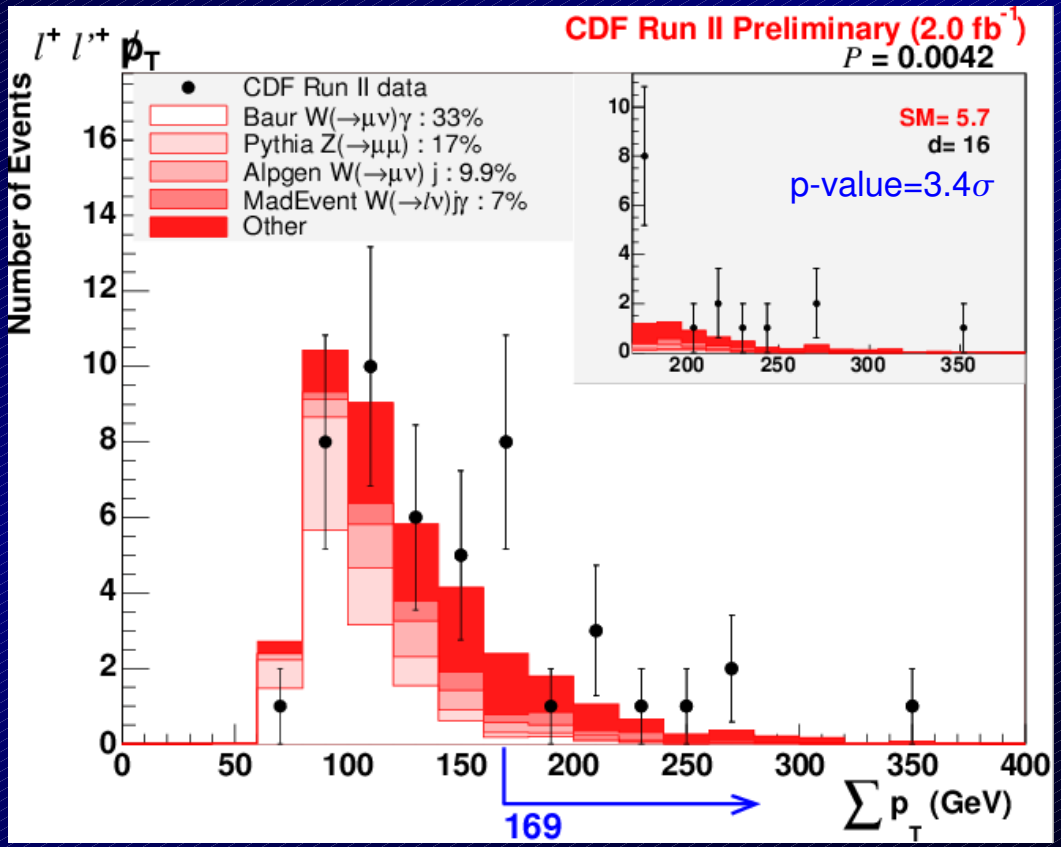
Final State	Data	Background	σ
$be^{\pm}\not{p}$	690	817.7 ± 9.2	−2.7
$\gamma\tau^{\pm}$	1371	1217.6 ± 13.3	+2.2
$\mu^{\pm}\tau^{\pm}$	63	35.2 ± 2.8	+1.7
$b2j\not{p}$ high-Σp_T	255	327.2 ± 8.9	−1.7
$2j\tau^{\pm}$ low-Σp_T	574	670.3 ± 8.6	−1.5
$3j\tau^{\pm}$ low-Σp_T	148	199.8 ± 5.2	−1.4
$e^{\pm}\not{p}\tau^{\pm}$	36	17.2 ± 1.7	+1.4
$2j\tau^{\pm}\tau^{\mp}$	33	62.1 ± 4.3	−1.3
$e^{\pm}j$	741710	764832 ± 6447.2	−1.3
$j2\tau^{\pm}$	105	150.8 ± 6.3	−1.2
$e^{\pm}2j$	256946	249148 ± 2201.5	+1.2
2bj low-Σp_T	279	352.5 ± 11.9	−1.1
$j\tau^{\pm}$ low-Σp_T	1385	1525.8 ± 15	−1.1
2b2j low-Σp_T	108	153.5 ± 6.8	−1
$b\mu^{\pm}\not{p}$	528	613.5 ± 8.7	−0.9
$\mu^{\pm}\gamma\not{p}$	523	611 ± 12.1	−0.8
$2b\gamma$	108	70.5 ± 7.9	+0.1
8j	14	13.1 ± 4.4	0
7j	103	97.8 ± 12.2	0
6j	653	659.7 ± 37.3	0
5j	3157	3178.7 ± 67.1	0
4j high-Σp_T	88546	89096.6 ± 935.2	0
4j low-Σp_T	14872	14809.6 ± 186.3	0
$4j2\gamma$	46	46.4 ± 3.9	0
$4j\tau^{\pm}$ high-Σp_T	29	26.6 ± 1.7	0
$4j\tau^{\pm}$ low-Σp_T	43	63.1 ± 3.3	0
$4j\not{p}$ high-Σp_T	1064	1012 ± 62.9	0
$4j\gamma\tau^{\pm}$	19	10.8 ± 2	0
$4j\gamma\not{p}$	62	104.2 ± 22.4	0
$4j\gamma$	7962	8271.2 ± 245.1	0
$4j\mu^{\pm}\not{p}$	574	590.5 ± 13.6	0
$4j\mu^{\pm}\mu^{\mp}$	38	48.4 ± 6.2	0
$4j\mu^{\pm}$	1363	1350.1 ± 37.7	0
3j high-Σp_T	159926	159143 ± 1061.9	0
3j low-Σp_T	62681	64213.1 ± 496	0
$3j2\gamma$	151	177.5 ± 7.1	0
$3j\tau^{\pm}$ high-Σp_T	68	76.9 ± 3	0
$3j\not{p}$ high-Σp_T	1706	1899.4 ± 77.6	0
$3j\not{p}$ low-Σp_T	42	36.2 ± 5.7	0
$3j\gamma\tau^{\pm}$	39	37.8 ± 3.6	0
$3j\gamma\not{p}$	204	249.8 ± 24.4	0
$3j\gamma$	24639	24899.4 ± 372.4	0
$3j\mu^{\pm}\not{p}$	2884	2971.5 ± 52.1	0
$3j\mu^{\pm}\gamma\not{p}$	10	3.6 ± 1.9	0
$3j\mu^{\pm}\gamma$	15	7.9 ± 2.9	0
$3j\mu^{\pm}\mu^{\mp}$	175	177.8 ± 16.2	0
$3j\mu^{\pm}$	5032	4989.5 ± 108.9	0
3b2j	23	28.9 ± 4.7	0
3bj	82	82.6 ± 5.7	0
3b	67	85.6 ± 7.7	0
$2\tau^{\pm}$	498	512.7 ± 14.2	0
$2\gamma\not{p}$	128	107.2 ± 6.9	0
2γ	5548	5562.8 ± 40.5	0
2j high-Σp_T	190773	190842 ± 781.2	0
2j low-Σp_T	165984	162530 ± 1581	0
$2j2\tau^{\pm}$	22	40.6 ± 3.2	0
$2j2\gamma\not{p}$	11	8 ± 2.4	0
$2j2\gamma$	580	581 ± 13.7	0
$2j\tau^{\pm}$ high-Σp_T	96	114.6 ± 3.3	0
$2j\not{p}$ high-Σp_T	87	80.9 ± 6.8	0
$2j\not{p}$ low-Σp_T	114	79.5 ± 100.8	0
$2j\not{p}\tau^{\pm}$	18	13.2 ± 2.2	0
$2j\gamma\tau^{\pm}$	142	144.6 ± 5.7	0
$2j\gamma\not{p}$	908	980.3 ± 63.7	0
$2j\gamma$	71364	73021.4 ± 595.9	0
$2j\mu^{\pm}\tau^{\mp}$	16	19.3 ± 2.2	0
$2j\mu^{\pm}\not{p}$	17927	18340.6 ± 201.9	0
$2j\mu^{\pm}\gamma\not{p}$	31	27.7 ± 7.7	0
$2j\mu^{\pm}\gamma$	57	58.2 ± 13	0
$2j\mu^{\pm}\mu^{\mp}\not{p}$	11	7.8 ± 2.7	0
$2j\mu^{\pm}\mu^{\mp}$	956	924.9 ± 61.2	0
$2j\mu^{\pm}$	22461	23111.4 ± 366.6	0
$2e^{\pm}j$	14	13.8 ± 2.3	0
$2e^{\pm}e^{\mp}$	20	17.5 ± 1.7	0
$2e^{\pm}$	32	49.2 ± 3.4	0
2b high-Σp_T	666	689 ± 9.4	0
2b low-Σp_T	323	313.2 ± 10.3	0
2b3j low-Σp_T	53	57.4 ± 6.5	0
2b2j high-Σp_T	718	803.3 ± 12.7	0
$2b2j\not{p}$ high-Σp_T	15	21.8 ± 2.8	0
$2b2j\gamma$	32	39.7 ± 6.2	0
$2b2j\mu^{\pm}\not{p}$	14	17.3 ± 1.9	0
$2b2j\mu^{\pm}$	22	21.8 ± 2	0
$2b\mu^{\pm}\not{p}$	11	14.4 ± 2.1	0
2bj high-Σp_T	891	967.1 ± 13.2	0
$2bj\not{p}$ high-Σp_T	25	31.3 ± 3.1	0
$2bj\gamma$	71	54.5 ± 7.1	0
$2bj\mu^{\pm}\not{p}$	12	10.7 ± 1.9	0
$2be^{\pm}2j\not{p}$	30	27.3 ± 2.2	0
$2be^{\pm}2j$	72	66.5 ± 2.9	0
$2be^{\pm}\not{p}$	22	19.1 ± 2.2	0
$2be^{\pm}j\not{p}$	19	19.4 ± 2.2	0
$2be^{\pm}j$	63	63 ± 3.4	0
$2be^{\pm}$	96	92.1 ± 4.1	0
$\tau^{\pm}\tau^{\mp}$	856	872.5 ± 19	0
$\gamma\not{p}$	3793	3770.7 ± 127.3	0
$\mu^{\pm}\tau^{\mp}$	381	440.9 ± 7.3	0
$\mu^{\pm}\not{p}\tau^{\mp}$	60	75.7 ± 3.4	0
$\mu^{\pm}\not{p}\tau^{\pm}$	15	12 ± 2	0
$\mu^{\pm}\not{p}$	734290	734296 ± 4897.8	0
$\mu^{\pm}\gamma$	475	469.8 ± 12.5	0
$\mu^{\pm}\mu^{\mp}\not{p}$	169	198.5 ± 8.2	0
$\mu^{\pm}\mu^{\mp}\gamma$	83	60 ± 3.1	0
$\mu^{\pm}\mu^{\mp}$	25283	25178.5 ± 86.5	0
$j2\gamma\not{p}$	36	30.4 ± 4.2	0
$j2\gamma$	1822	1813.2 ± 27.4	0
$j\tau^{\pm}$ high-Σp_T	52	56.2 ± 2.5	0
$j\tau^{\pm}\tau^{\mp}$	203	252.2 ± 8.7	0
$j\not{p}$ high-Σp_T	4432	4431.7 ± 45.2	0
$j\gamma\tau^{\pm}$	526	476 ± 9.3	0
$j\gamma\not{p}$	1882	1791.9 ± 72.3	0
$j\gamma$	103319	102124 ± 570.6	0
$j\mu^{\pm}\tau^{\mp}$	71	98 ± 3.9	0
$j\mu^{\pm}\tau^{\pm}$	15	12 ± 2	0
$j\mu^{\pm}\not{p}\tau^{\mp}$	26	30.8 ± 2.6	0
$j\mu^{\pm}\not{p}$	109081	108323 ± 707.7	0
$j\mu^{\pm}\gamma\not{p}$	171	171.1 ± 31	0
$j\mu^{\pm}\gamma$	152	190 ± 39.3	0
$j\mu^{\pm}\mu^{\mp}\not{p}$	32	32.2 ± 10.9	0
$j\mu^{\pm}\mu^{\mp}\gamma$	14	11.5 ± 2.6	0
$j\mu^{\pm}\mu^{\mp}$	4852	4271.2 ± 185.4	0
$j\mu^{\pm}$	77689	76987.5 ± 930.2	0
$e^{\pm}4j\not{p}$	903	830.6 ± 13.2	0
$e^{\pm}4j\gamma$	25	29.2 ± 3.6	0
$e^{\pm}4j$	15750	16740.4 ± 390.5	0
$e^{\pm}3j\tau^{\mp}$	15	21.1 ± 2.2	0
$e^{\pm}3j\not{p}$	4054	4077.2 ± 63.6	0
$e^{\pm}3j\gamma$	108	79.3 ± 5	0
$e^{\pm}3j$	60725	60409.3 ± 723.3	0
$e^{\pm}2\gamma$	41	34.2 ± 2.6	0
$e^{\pm}2j\tau^{\pm}$	37	47.2 ± 2.2	0
$e^{\pm}2j\tau^{\mp}$	109	95.9 ± 6.8	0
$e^{\pm}2j\not{p}$	25725	25403.1 ± 209.4	0
$e^{\pm}2j\gamma\not{p}$	30	31.8 ± 4.8	0
$e^{\pm}2j\gamma$	398	342.8 ± 15.7	0
$e^{\pm}2j\mu^{\mp}\not{p}$	22	14.8 ± 1.9	0
$e^{\pm}2j\mu^{\mp}$	23	15.8 ± 2	0
$e^{\pm}\tau^{\pm}$	437	387 ± 5.3	0
$e^{\pm}\tau^{\mp}$	1333	1266 ± 12.3	0
$e^{\pm}\not{p}\tau^{\mp}$	109	106.1 ± 2.7	0
$e^{\pm}\not{p}$	960826	956579 ± 3077.7	0
$e^{\pm}\gamma\not{p}$	497	496.8 ± 10.3	0
$e^{\pm}\gamma$	3578	3589.9 ± 24.1	0
$e^{\pm}\mu^{\pm}\not{p}$	31	29.9 ± 1.6	0
$e^{\pm}\mu^{\mp}\not{p}$	109	99.4 ± 2.4	0
$e^{\pm}\mu^{\pm}$	45	28.5 ± 1.8	0
$e^{\pm}\mu^{\mp}$	350	313 ± 5.4	0
$e^{\pm}j2\gamma$	13	16.1 ± 3.9	0
$e^{\pm}j\tau^{\mp}$	386	418 ± 18.9	0
$e^{\pm}j\tau^{\pm}$	160	162.8 ± 3.5	0
$e^{\pm}j\not{p}\tau^{\mp}$	48	44.6 ± 3.3	0
$e^{\pm}j\not{p}\tau^{\pm}$	11	8.3 ± 1.5	0
$e^{\pm}j\not{p}$	121431	121023 ± 747.6	0
$e^{\pm}j\gamma\not{p}$	159	192.6 ± 10.9	0
$e^{\pm}j\gamma$	1389	1368.9 ± 38.9	0
$e^{\pm}j\mu^{\mp}\not{p}$	42	33 ± 2.9	0
$e^{\pm}j\mu^{\pm}\not{p}$	16	9.2 ± 1.9	0
$e^{\pm}j\mu^{\mp}$	62	63.8 ± 3.2	0
$e^{\pm}j\mu^{\pm}$	13	8.2 ± 2	0
$e^{\pm}e^{\mp}4j$	148	159.1 ± 7	0
$e^{\pm}e^{\mp}3j$	717	743.6 ± 24.4	0
$e^{\pm}e^{\mp}2j\not{p}$	32	41.4 ± 5.6	0
$e^{\pm}e^{\mp}2j\gamma$	10	11.4 ± 2.9	0
$e^{\pm}e^{\mp}2j$	3638	3566.8 ± 72	0
$e^{\pm}e^{\mp}\tau^{\pm}$	18	16.1 ± 1.7	0
$e^{\pm}e^{\mp}\not{p}$	822	831.8 ± 13.6	0
$e^{\pm}e^{\mp}\gamma$	191	221.9 ± 5.1	0
$e^{\pm}e^{\mp}j\not{p}$	155	170.8 ± 12.4	0
$e^{\pm}e^{\mp}j\gamma$	48	45 ± 3.9	0
$e^{\pm}e^{\mp}j$	17903	18258.2 ± 204.4	0
$e^{\pm}e^{\mp}$	98901	99086.9 ± 147.8	0
b6j	51	42.3 ± 3.8	0
b5j	237	192.5 ± 7.1	0
b4j high-Σp_T	26	23.4 ± 2.6	0
b4j low-Σp_T	836	821.7 ± 15.9	0
b3j high-Σp_T	12081	12071 ± 84.1	0
b3j low-Σp_T	2974	2873 ± 31	0

More Sleuth Results

#4



#3



- Final state: $\ell^+ \ell^- \ell' \not{p}_T$
  - ℓ = e or μ
  - ℓ' = e or μ, but different from ℓ
- Significance of region:
  - P = 0.0047 (2.6σ) before trials factor,
  - 50% probable after trials factor

- Final state: $e^+ \mu^+ \not{p}_T$
- Significance of region:
  - P = 0.0042 (2.6σ) before trials factor,
  - 46% probable after trials factor