Searching for New Particles and Phenomena at the Tevatron, HERA, and the LHC

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ICHEP 2000

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- The Accelerators and the Experiments
- Signatures vs. Models: Any Hints?
- Higgs
- SUSY and non-SUSY
- Extra Dimensions

The Accelerators

Tevatron at Fermilab

Run 1: $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

$\rightarrow$ 100 pb^{-1} 1992-1996

Run 2: $p\bar{p}$ collisions at $\sqrt{s} = 2.0$ TeV

$\rightarrow$ 2 fb^{-1} by 2002, 15 fb^{-1} by 2007

HERA at DESY

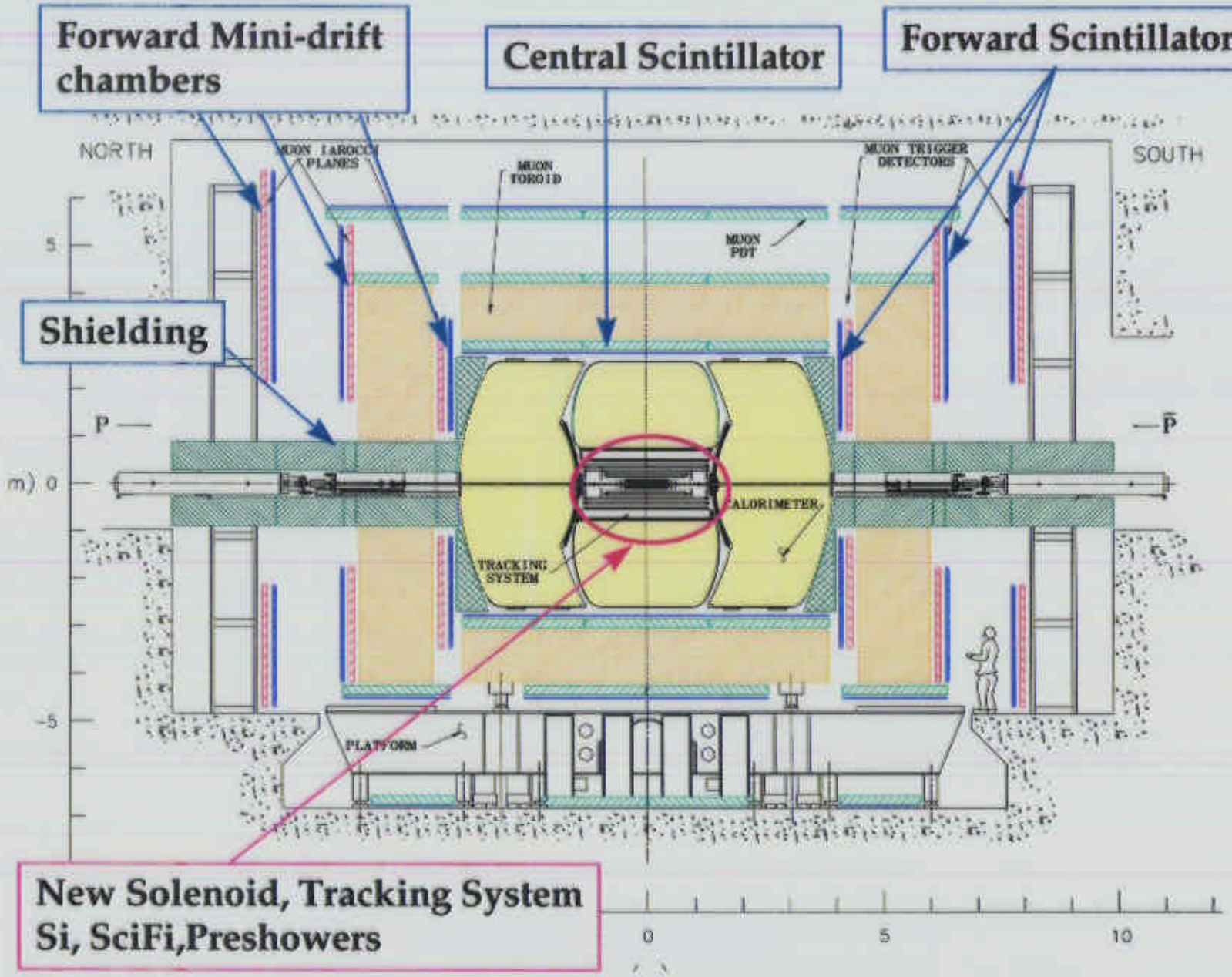
1994-1997: e^+p, 27.6 GeV on 820 GeV, ~48 pb^{-1}
1998-1999: e^-p, 27.6 GeV on 920 GeV, ~18 pb^{-1}
1999-2000: e^+p, 27.6 GeV on 920 GeV, ~50 pb^{-1}

LHC at CERN

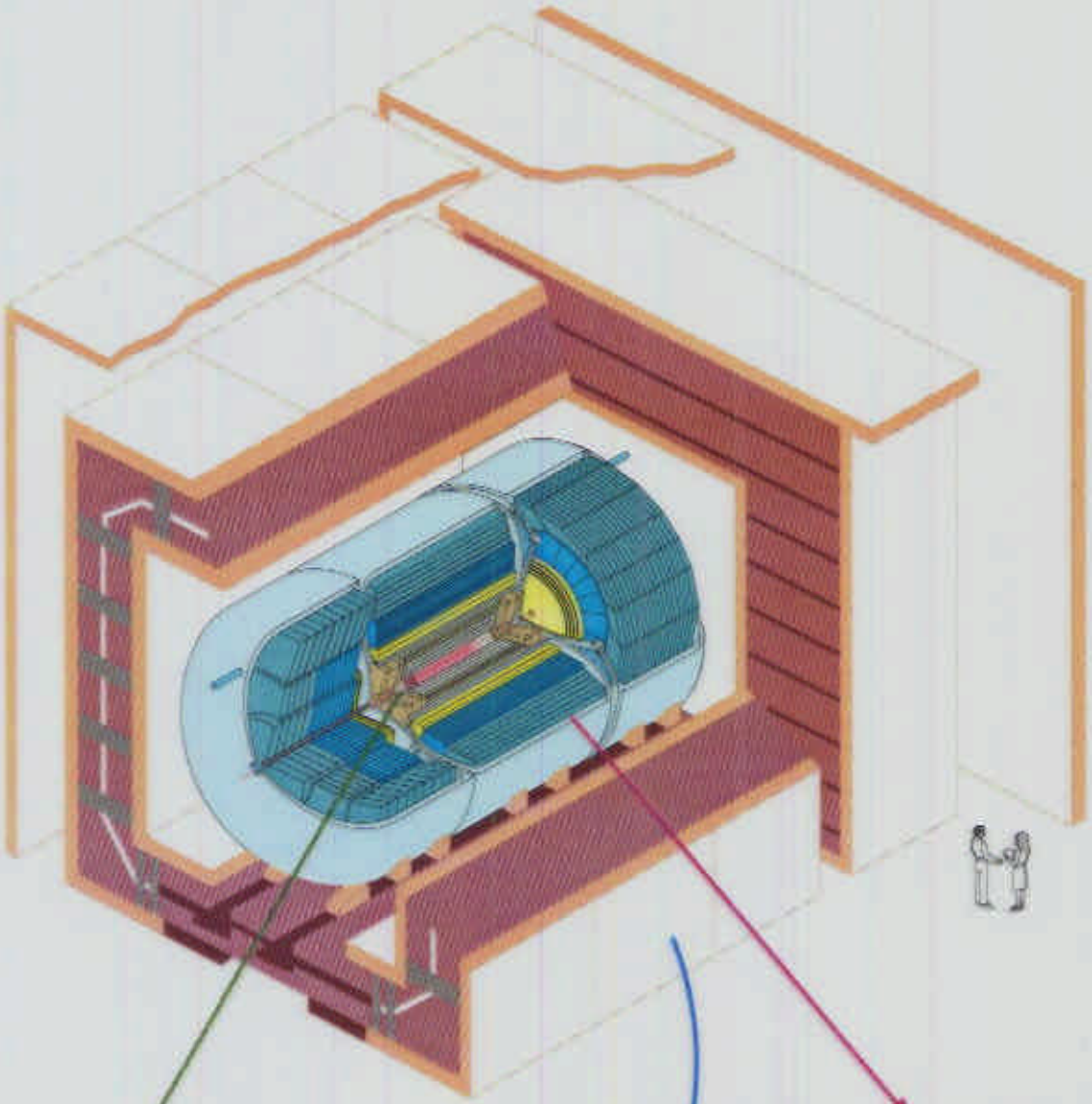
pp collisions at $\sqrt{s} = 14$ TeV starting 2005

30 fb^{-1}/year, increasing to 100 fb^{-1}/year

D0 Upgrade


Forward Mini-drift chambers
Central Scintillator
Forward Scintillator
Shielding
NORTH
SOUTH
MUON TOROID
MUON PDT
MUON TRIGGER DETECTORS
P
$\bar{P}$
TRACKING SYSTEM
PLATFORM
New Solenoid, Tracking System
Si, SciFi,Preshowers
+ New Electronics, Trig, DAQ

DØ in Run 1:



DØ Detector

TRACKING

σ(vertex)=6 mm
σ(rφ) = 60 μm (VTX)
= 180 μm (CDC)
= 200 μm (FDC)

MUON

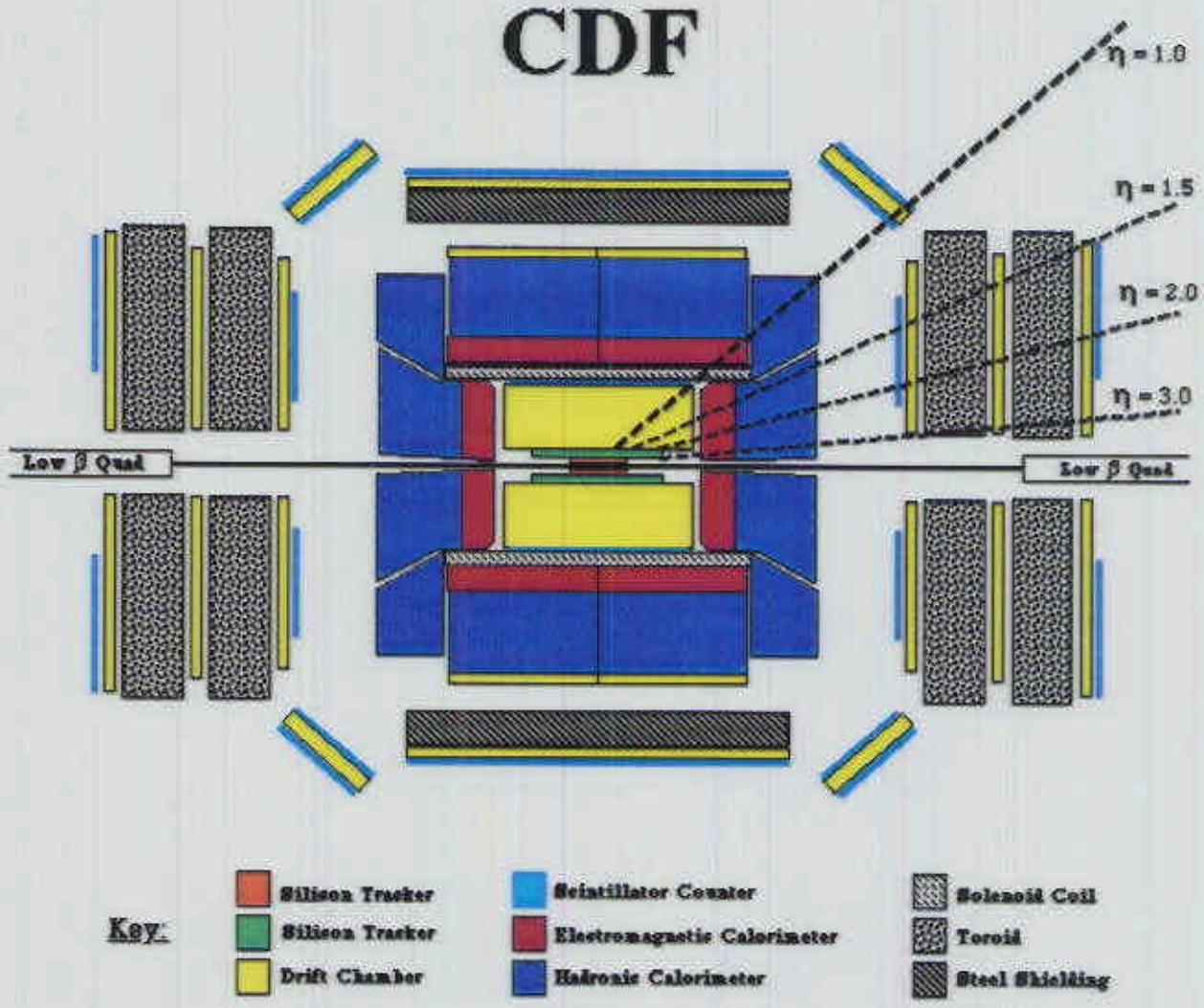
$|\eta| < 3.3$

$\frac{\delta p}{p} = 0.2 \oplus 0.01p$

CALORIMETRY

$|\eta|<4$
$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
$\sigma(EM) = 15\%/\sqrt{E}$
$\sigma(HAD) = 50\%/\sqrt{E}$

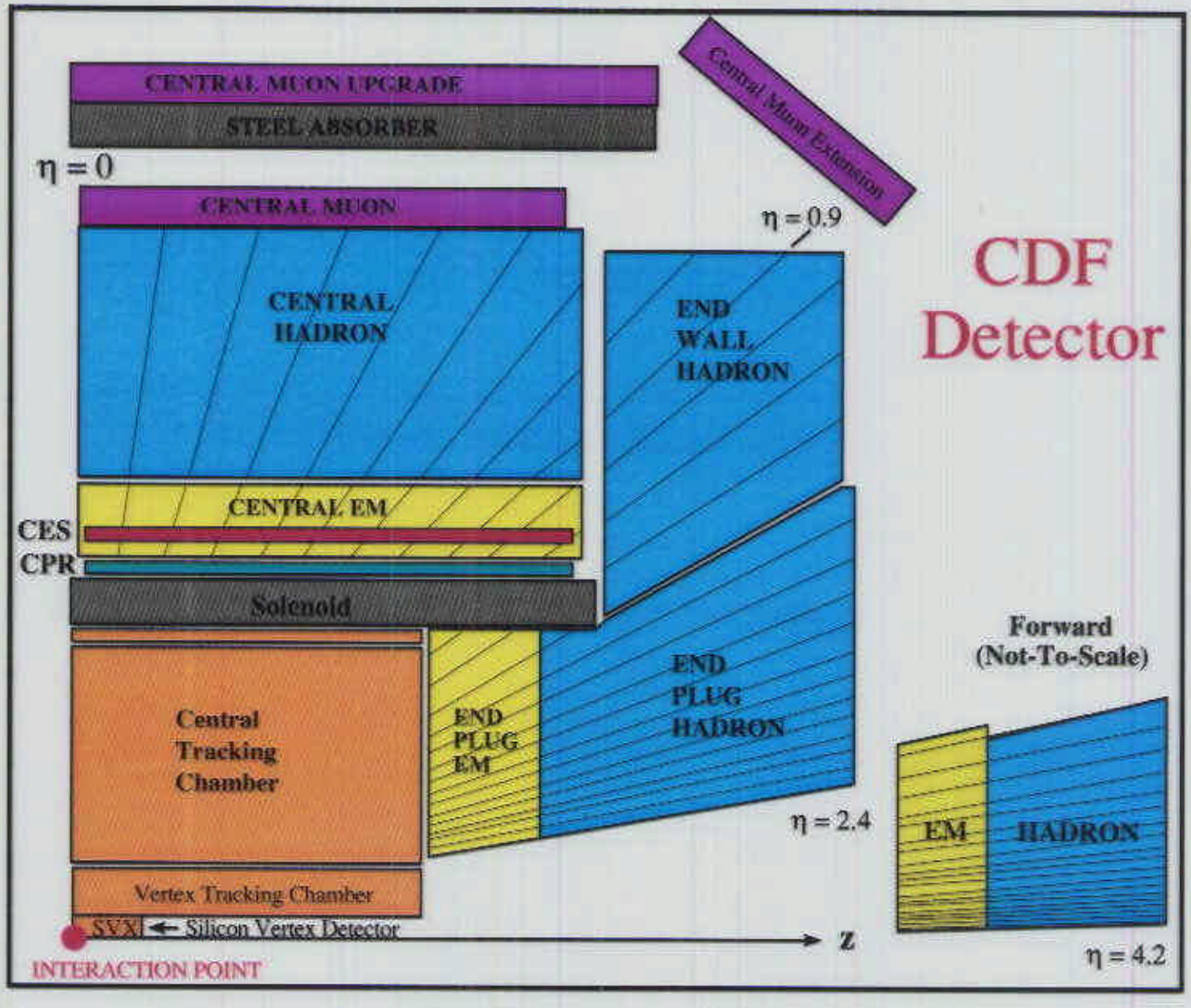
CDF



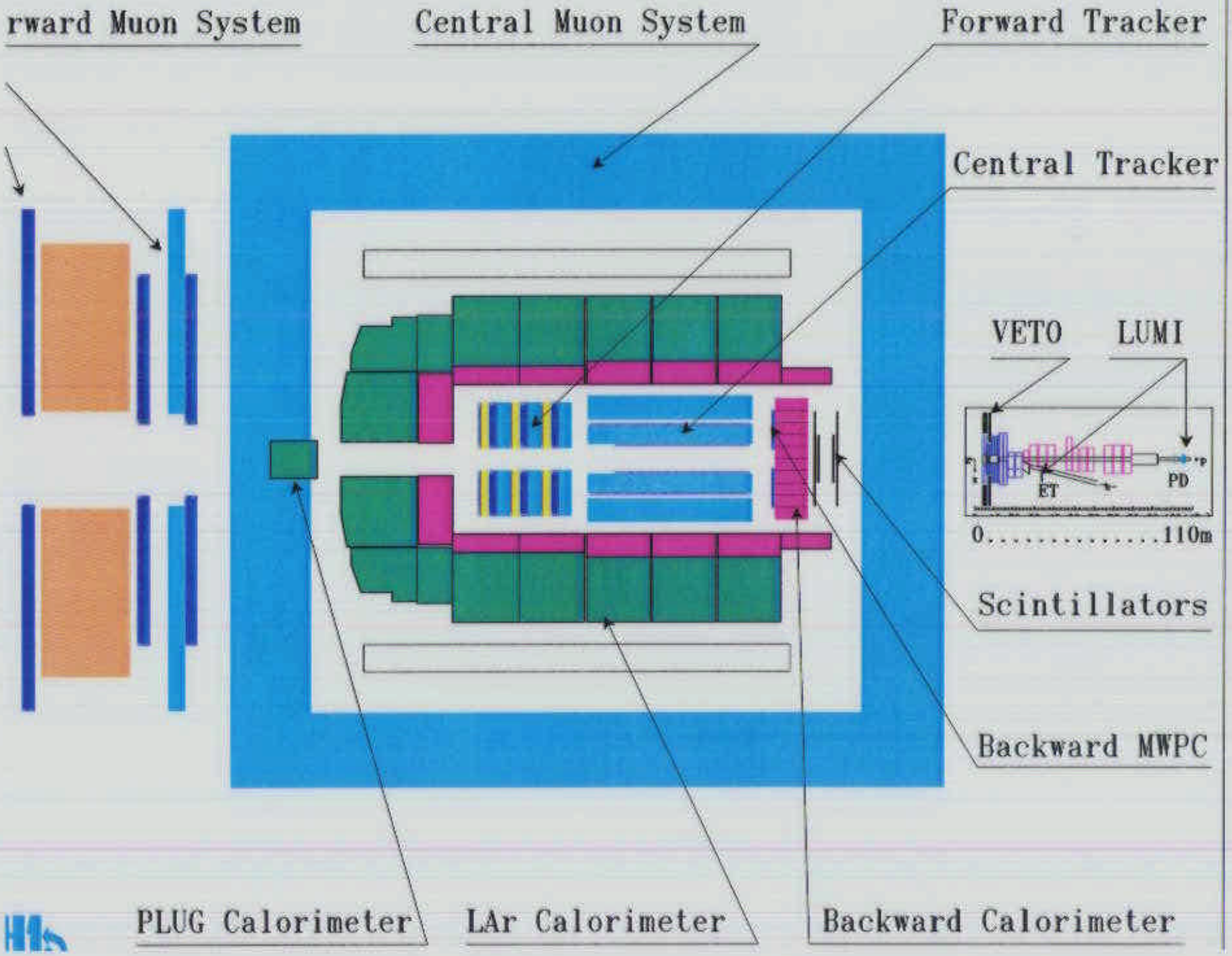
CDF Run 2 Upgrade

- all-new inner tracking
- new scintillating tile endplug calorimeter
- more muon coverage
- new DAQ/trigger electronics
- new online/offline C++ software

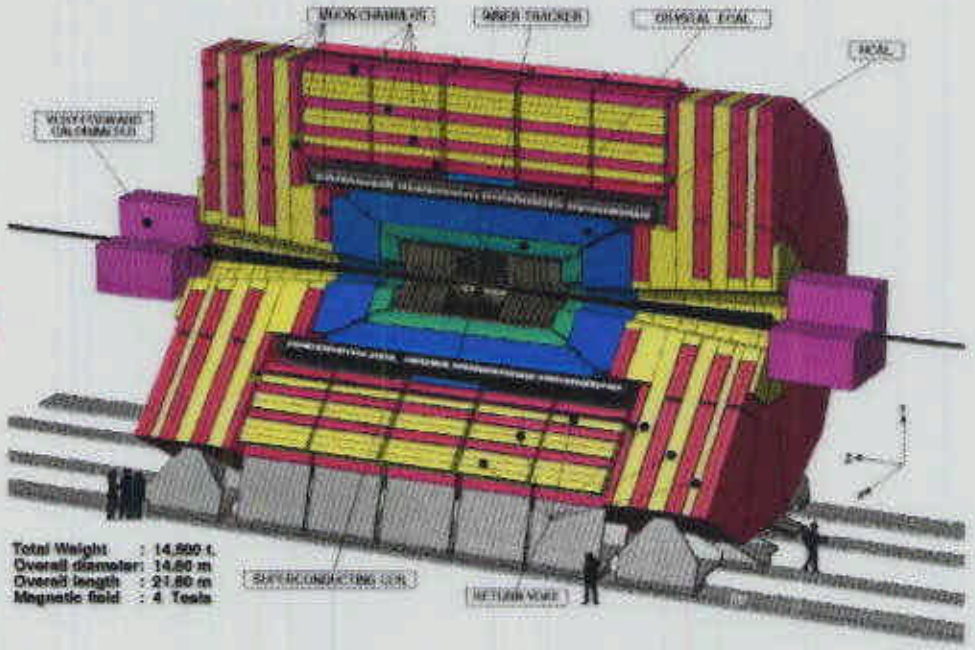
CDF in Run 1:


CENTRAL MUON UPGRADE
STEEL ABSORBER
Central Muon Extension
η = 0
CENTRAL MUON
η = 0.9
CENTRAL HADRON
END WALL HADRON
CDF Detector
CENTRAL EM
CES
CPR
Solenoid
Forward (Not-To-Scale)
Central Tracking Chamber
END PLUG EM
END PLUG HADRON
η = 2.4
EM
HADRON
Vertex Tracking Chamber
SVX
Silicon Vertex Detector
z
INTERACTION POINT
η = 4.2

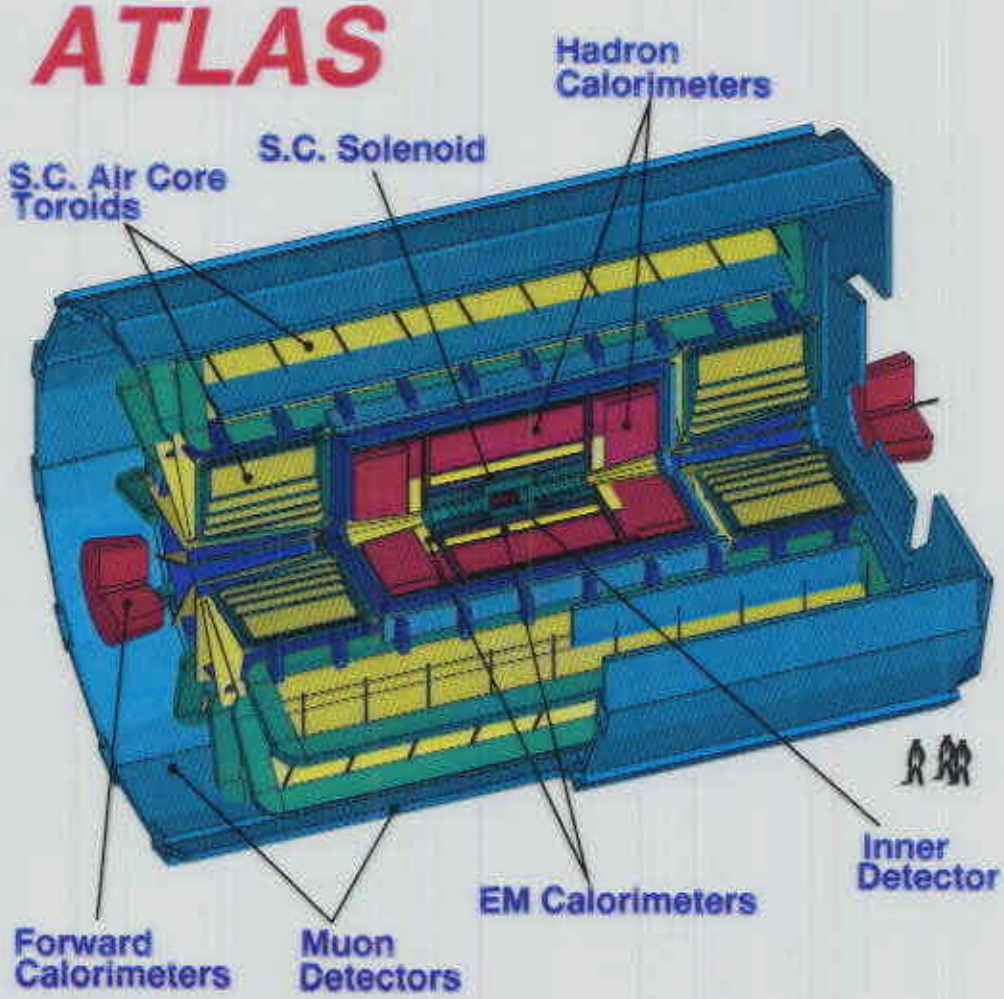
THE H1 DETECTOR



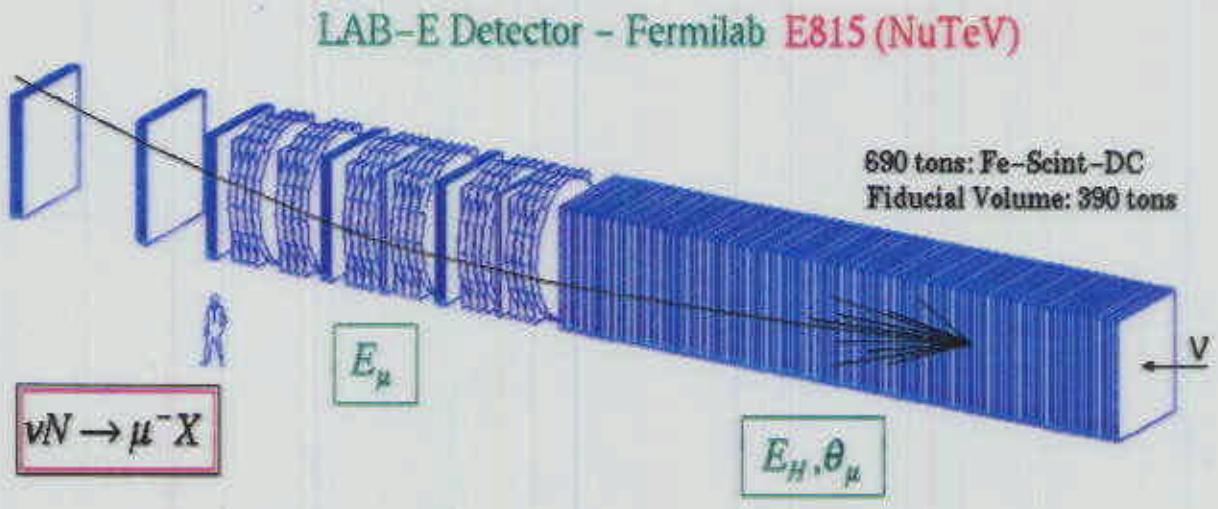
CMS


Total Weight : 14,500 t
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

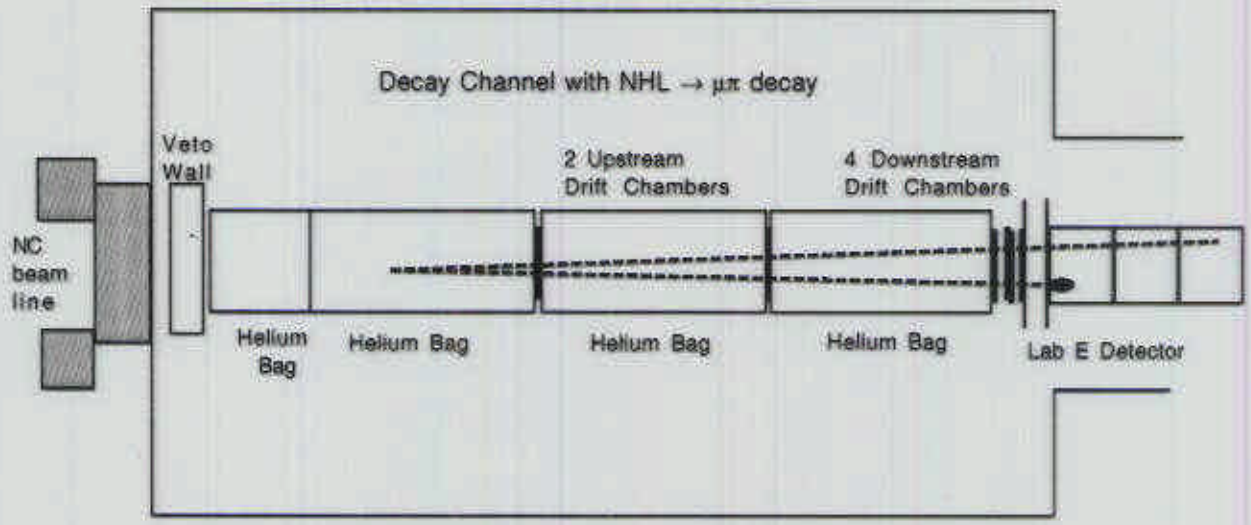
ATLAS


Hadron Calorimeters
S.C. Solenoid
S.C. Air Core Toroids
Inner Detector
EM Calorimeters
Forward Calorimeters
Muon Detectors

NuTeV Dimuon Anomaly



Installed "Decay Channel" detector upstream to search for decays in flight of exotic particles (neutralinos, neutral heavy leptons...)

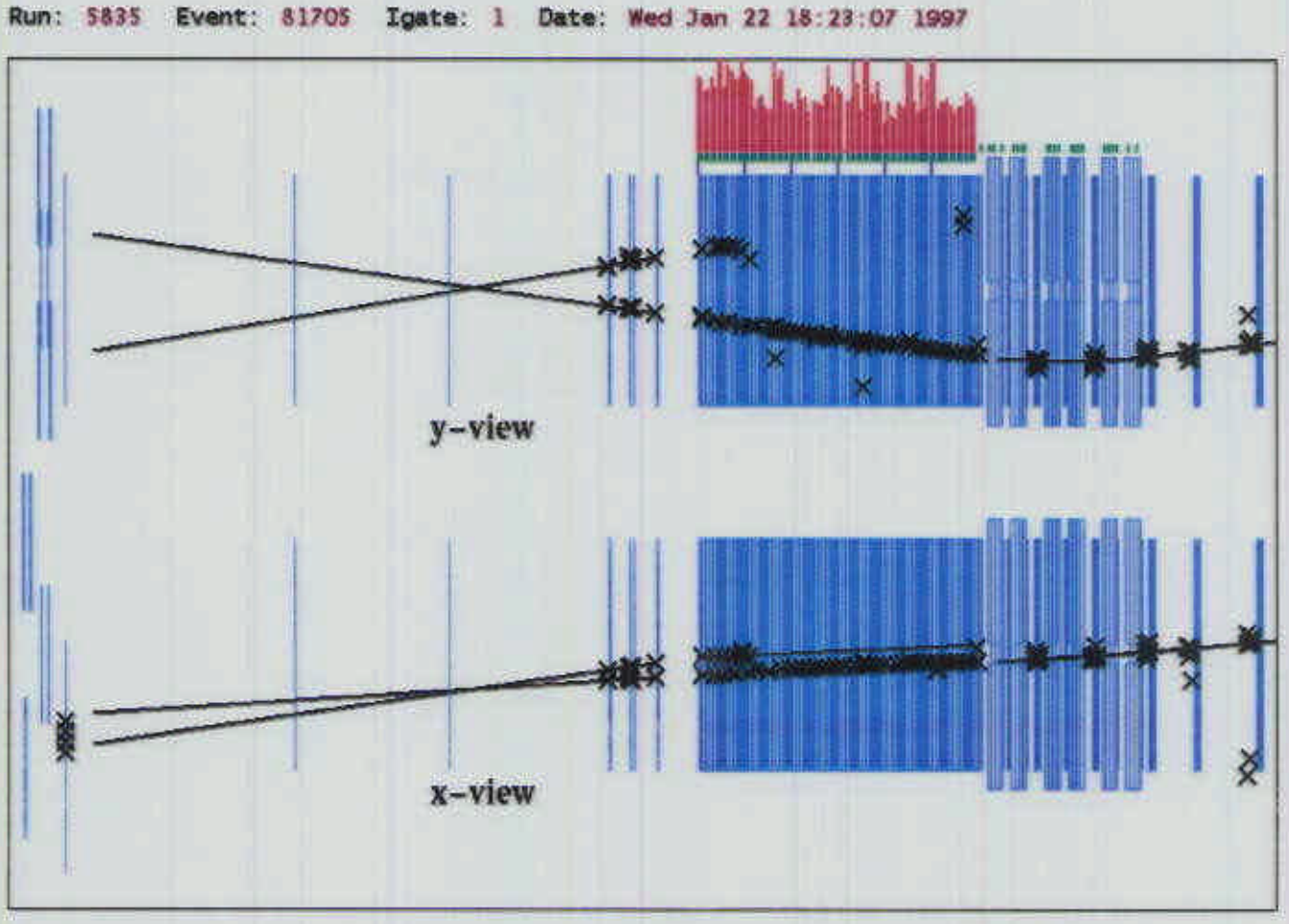


NuTeV has excellent e, mu, pi separation...

Experiment observes:

channel	observed	expected
$\mu\mu$	3	0.04±0.01
$e\mu$	0	0.14±0.02
$\pi\mu$	0	0.13±0.02

- not ν-induced: would see many in chambers
- large (missing) p_T: three-body decay?
- large asymmetry: unlikely to be NHL



What are we looking for?

We do not really know for sure!

→ experiments can trigger on/identify:

- γ
- e, μ (a.k.a. lepton, generically)
- $\tau \rightarrow$ hadrons
- jets
- b, c quark tags
- missing transverse momentum (energy)

→ typically need several in combination

→ need large E_T ($\sim$ 20 GeV or more)

model-based searches

Theoretical ideas lead to predictions for new particle search strategies, leading to specific signatures.

Higgs, SUSY, technicolor, compositeness, etc.

signature-based searches

Take Standard Model as the null hypothesis, explore and see if there are deviations!

Observations of excesses can lead to new models, new signatures...

50 possible three-object search signatures:

γγγ γγℓ γγτ γγj γγb γγ∄⊤

~~γℓℓ γℓτ γℓj~~ γℓb γℓ∄⊤

~~γττ γτj γτb γτ∄⊤~~

~~γjj γjb γj∄⊤~~

~~γbb~~ γb∄⊤

ℓℓℓ ~~ℓℓτ~~ ℓℓj ℓℓb ℓℓ∄⊤

~~ℓττ ℓτj ℓτb~~ ℓτ∄⊤

~~ℓjj ℓjb~~ ℓj∄⊤

~~ℓbb~~ ℓb∄⊤

~~τττ τtj~~ ττb ττ∄⊤

~~τjj τjb~~ τj∄⊤

~~τbb~~ τb∄⊤

~~jjj jjb~~ jj∄⊤

~~jbb~~ jb∄⊤

bbb bb∄⊤

only half of all channels!

CDF: light sbottom?

$m_{\tilde{b}} \sim 3\text{-}4$ GeV

- hypothetical new light scalar quark:

  $\tilde{b} \to c\ell\tilde{\nu}$ with 100% BR

- ALEPH observed excess of double-lepton dijet events (LEPC)

  see 56, expect ~34

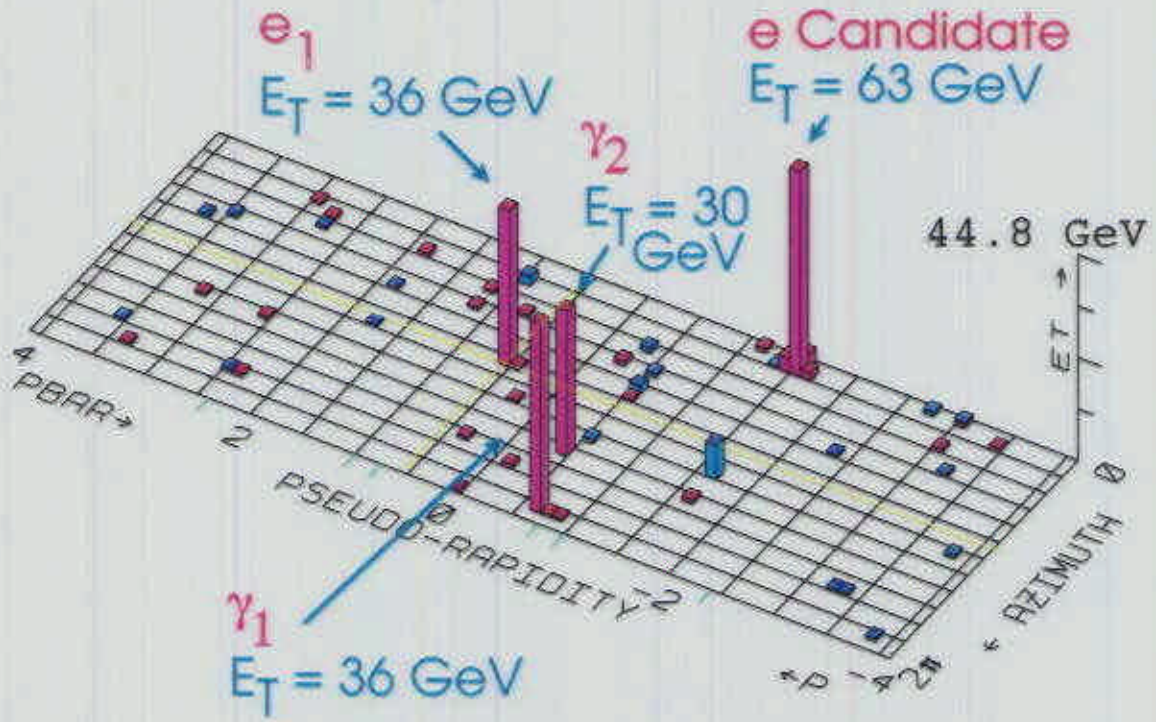
- OPAL presented data at this conference

  see 15, expect ~20

- CLEO, BaBaR, Belle should all see large numbers in off-resonance data

- CDF: "investigating not-well-understood events"

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

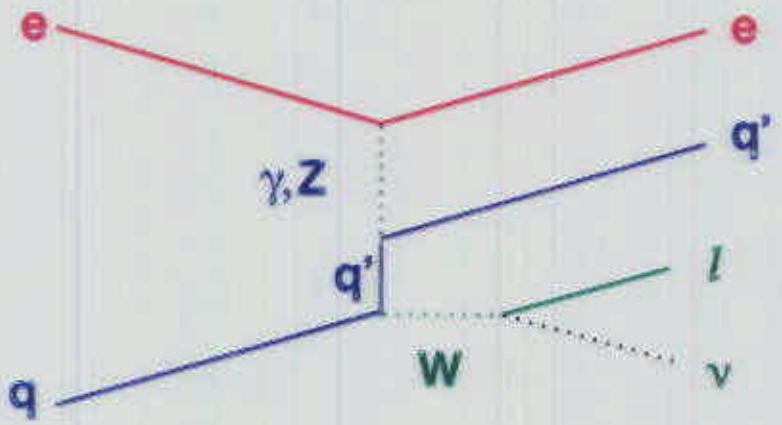


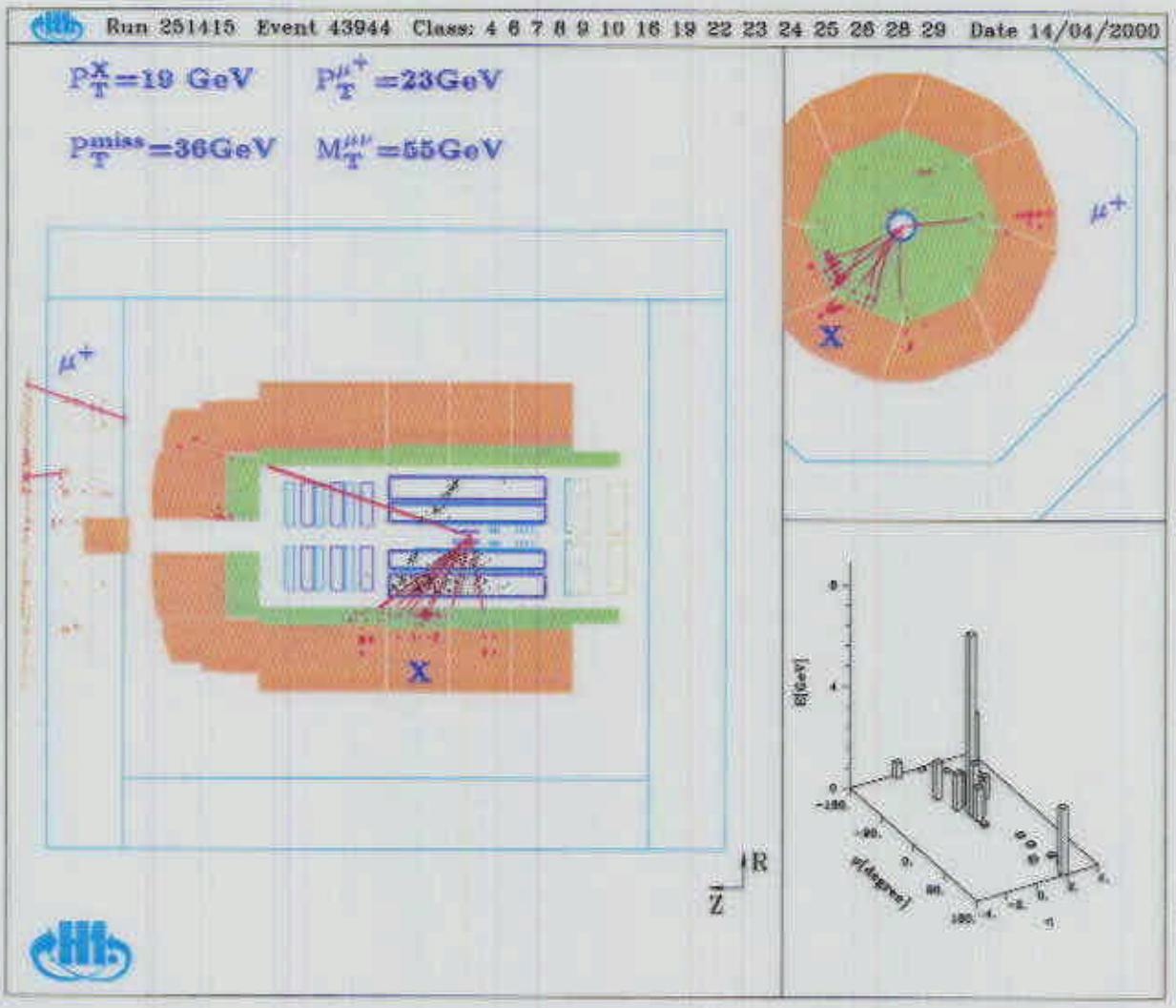
$\not{E}_T = 55$ GeV

- five "objects" in event
- expect $\mathcal{O}(10^{-6})$ such events (a posteriori!)
- searched for $\gamma\gamma\not{E}_T$ inclusively
- interesting result soon on $\ell\gamma\not{E}_T$
- need more data!

HERA: High-p_T Isolated Leptons

Can produce W directly in ep collisions:



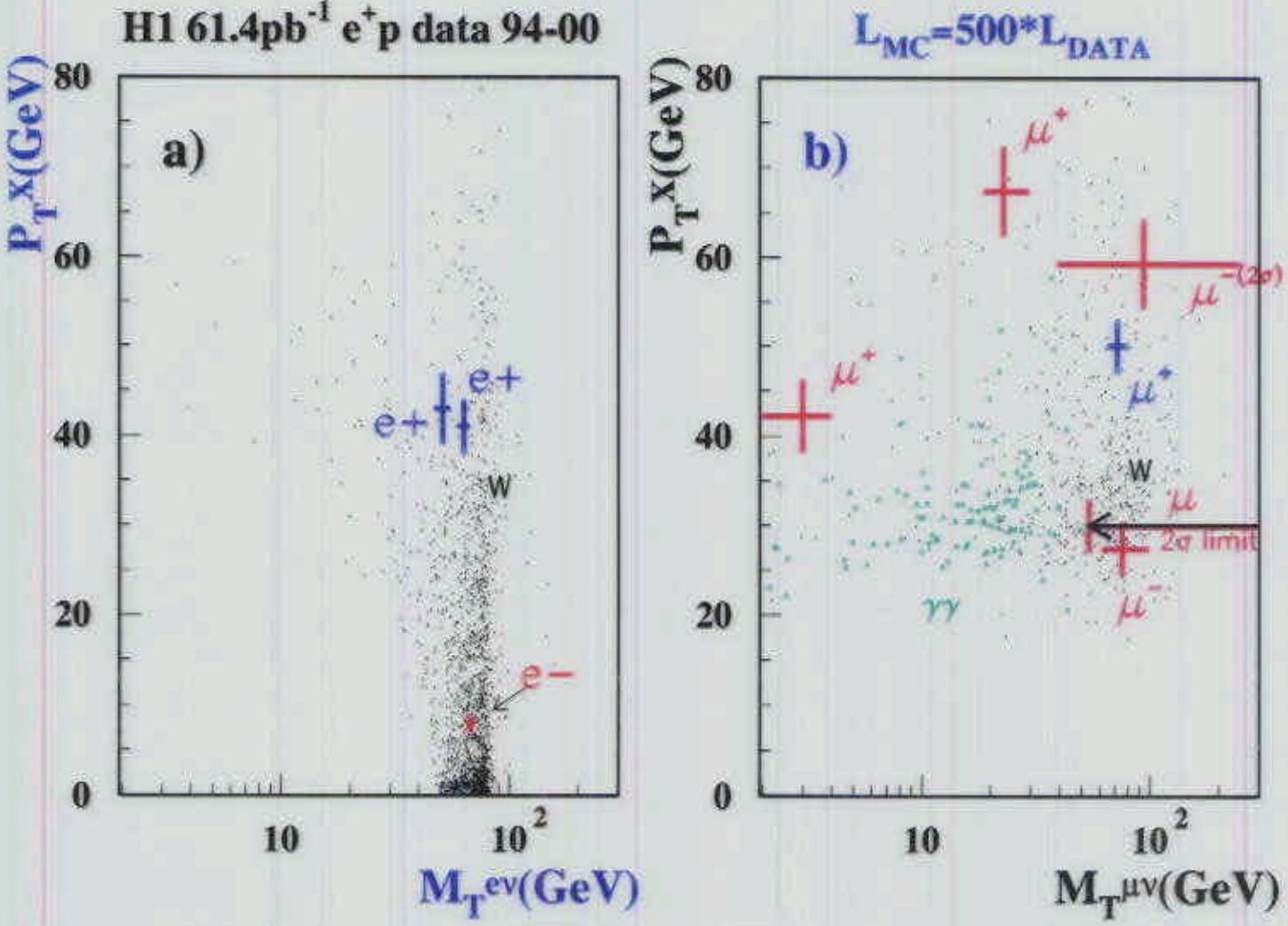


H1,ZEUS 1994-1997 dataset:

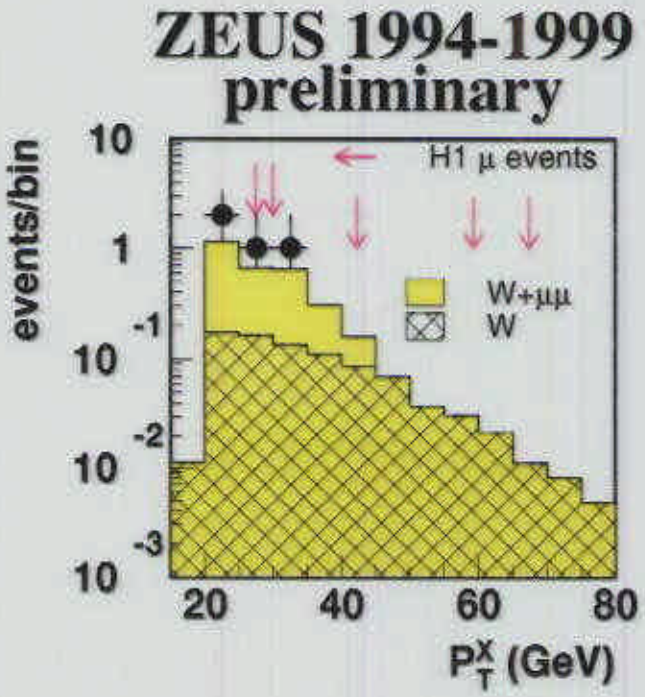
channel	H1	ZEUS
e	1	3
μ	5	0

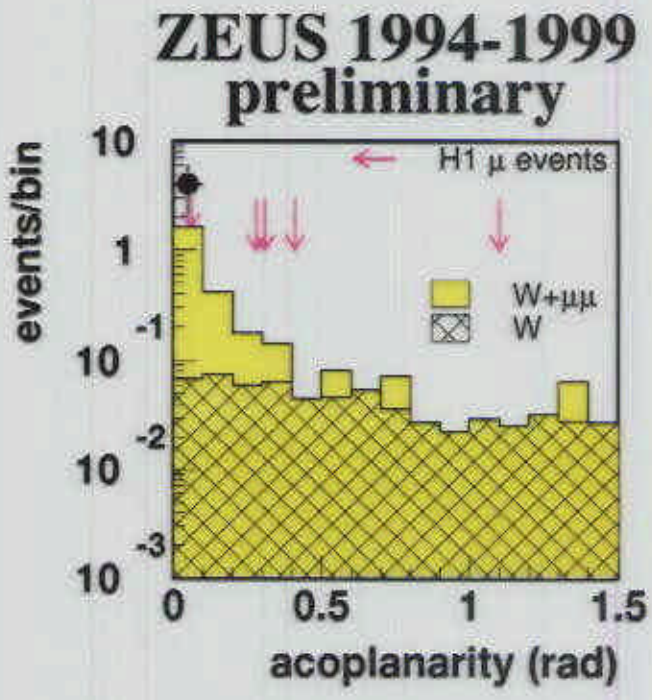
H1,ZEUS 1998-1999 dataset:

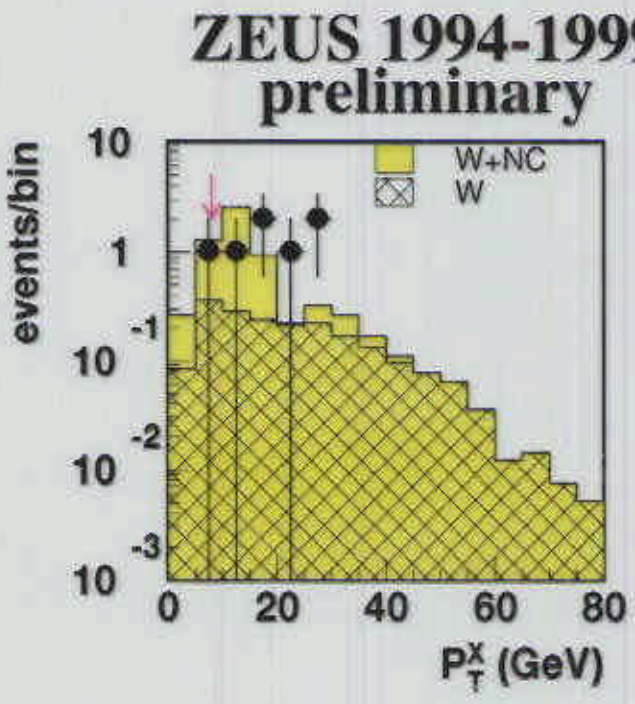
channel	H1	ZEUS
e	0	2
μ	0	0

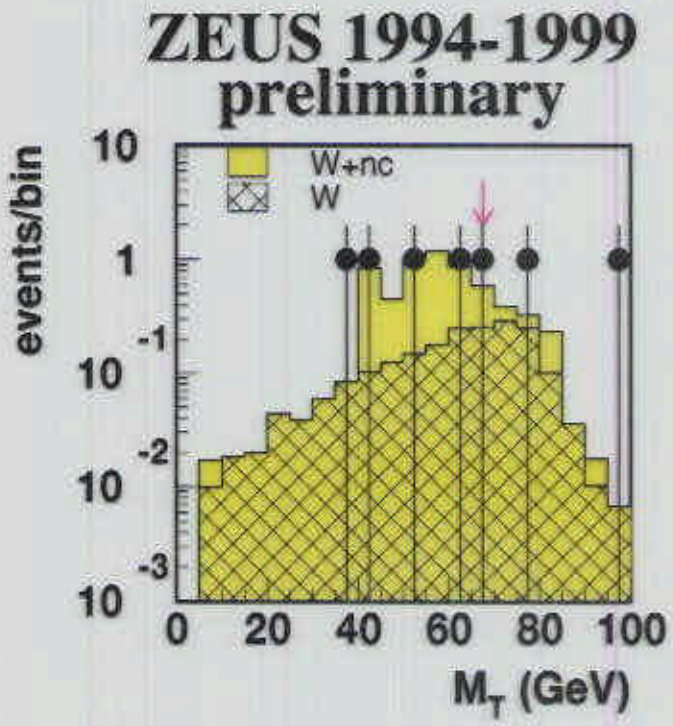


ZEUS final distributions









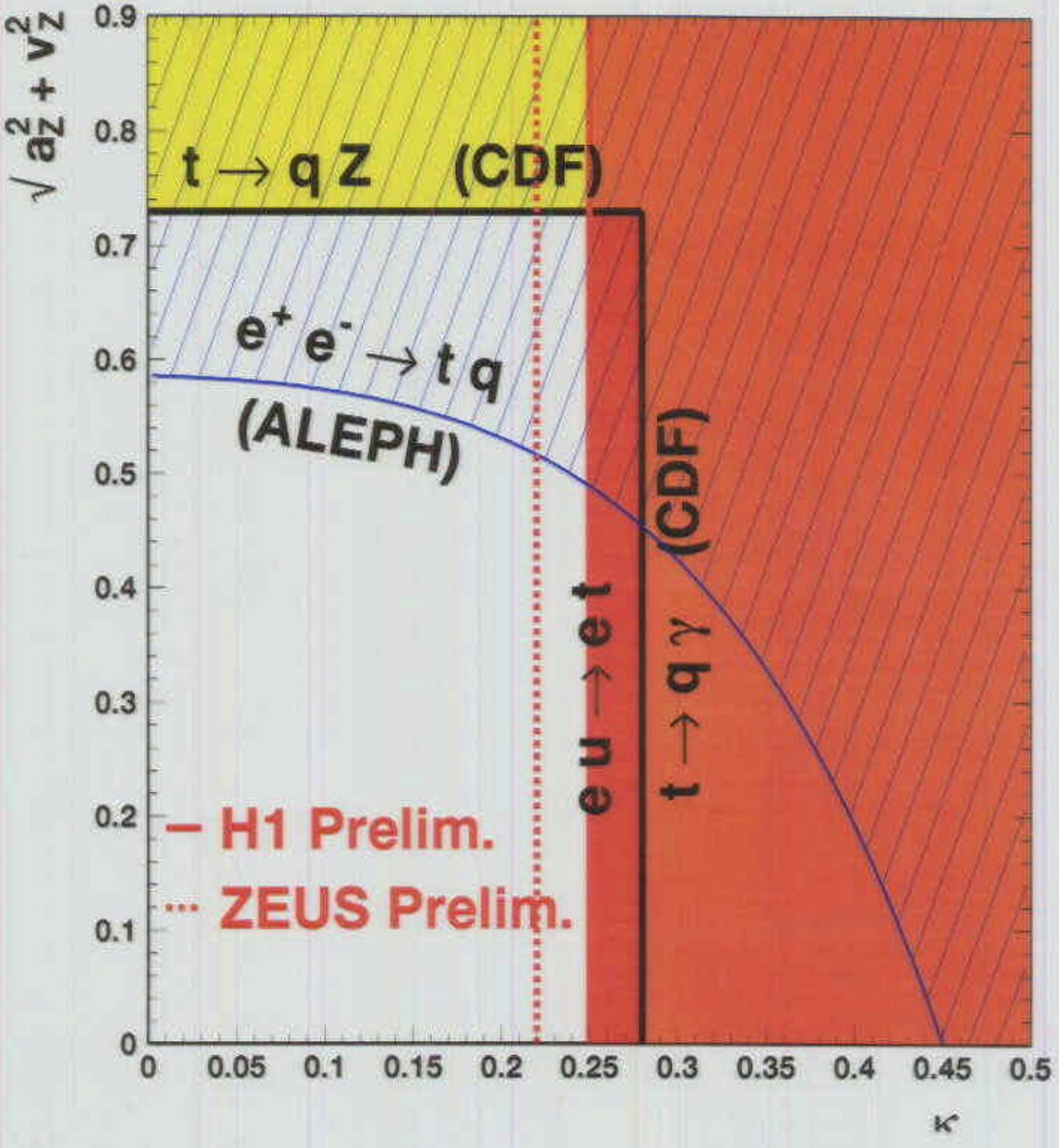
H1, ZEUS, 1994 - 2000 (82 pb^{-1})

lepton $p_T > 25$ GeV:

	H1	ZEUS
e	3 (1.1±0.3)	7 (6.1±0.9)
μ	6 (1.2±0.3)	4 (3.7±0.4)
total	9 (2.3±0.6)	11 (9.8±1.0)

→ H1 sees excess, ZEUS does not!

→ need more data to shed light here...

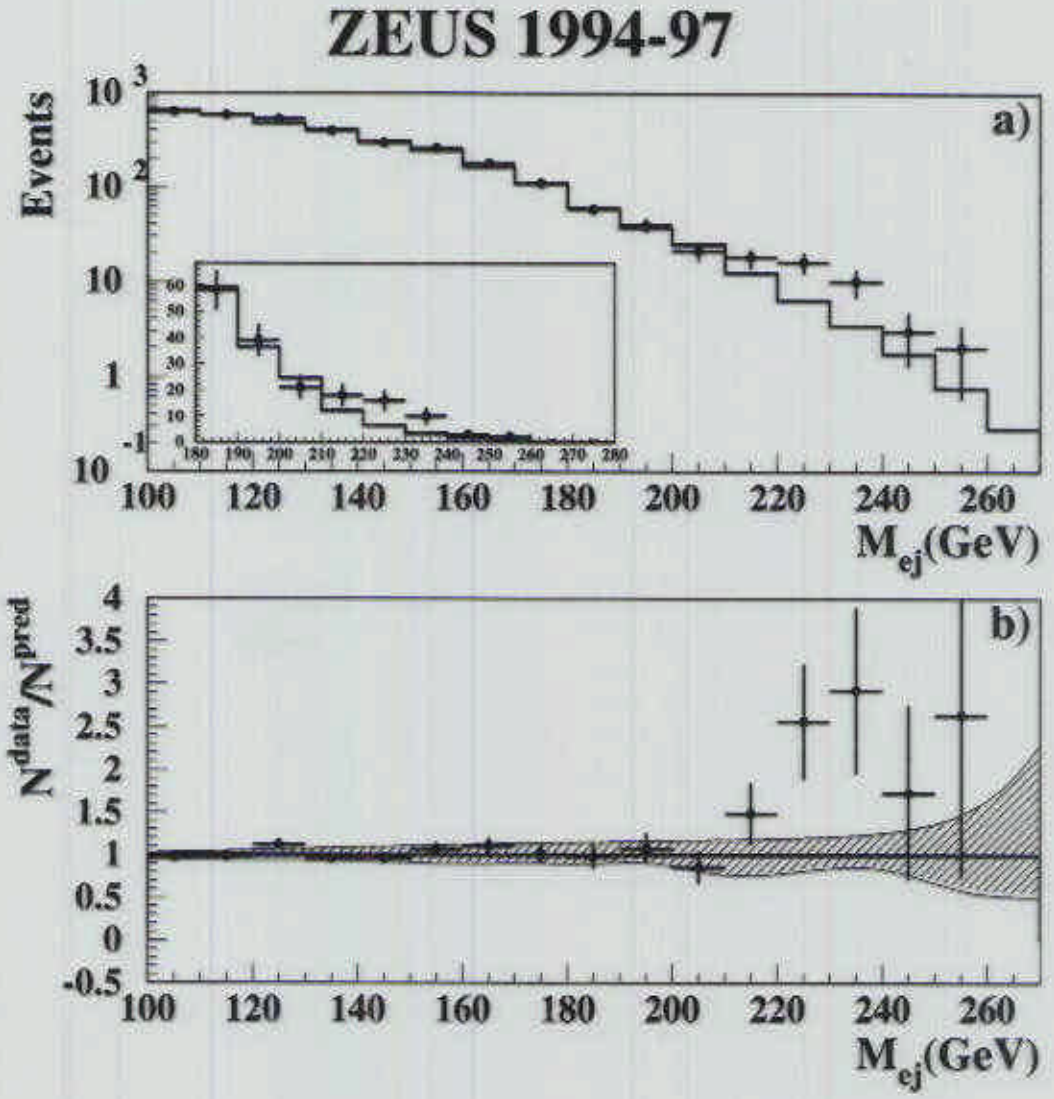

$\sqrt{a_Z^2 + v_Z^2}$
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$t \rightarrow q Z$ (CDF)
$e^+ e^- \rightarrow t q$
(ALEPH)
$e u \rightarrow e t$
$t \rightarrow q \gamma$ (CDF)
– H1 Prelim.
··· ZEUS Prelim.
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
κ

Any hints in existing data?

- CDF: a light "sbottom"?
- CDF: $e\ \not{E}\gamma\gamma$ event
  - → gauge-mediated SUSY models
  - → SUSY with light higgsino
  - → searches in related modes
- H1/ZEUS: high-p_T lepton-jet events
- CDF/DØ : high-E_T jet excess
- H1/ZEUS: high-Q^2 excess
  - → leptoquark searches at Tevatron
  - → large extra dimensions
  - → R-parity-violating SUSY models

HERA High-Q^2 Excess

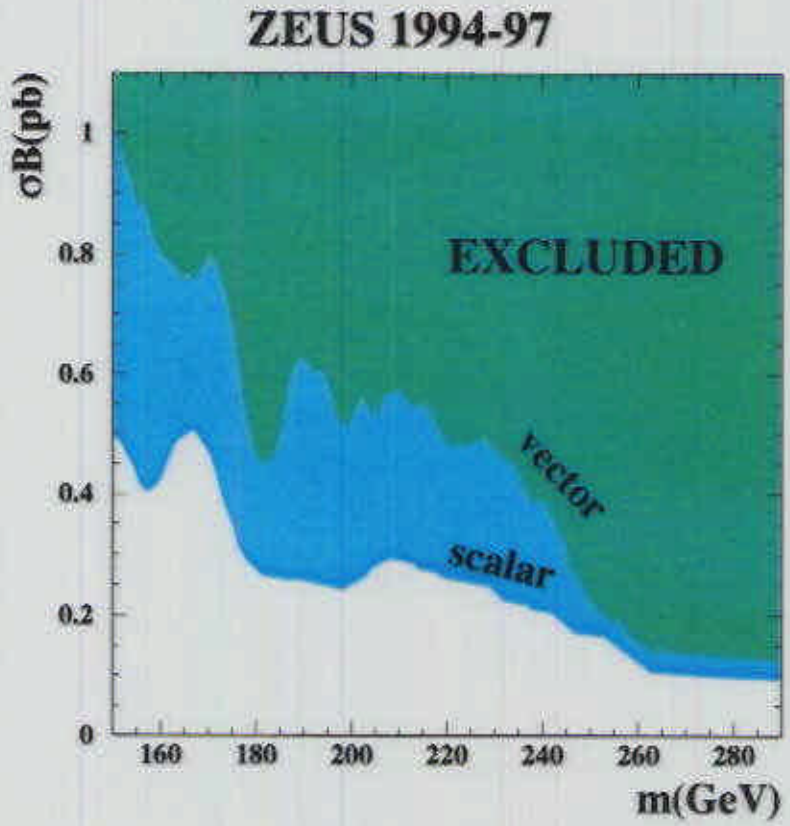
ZEUS: search for resonances in e^+p

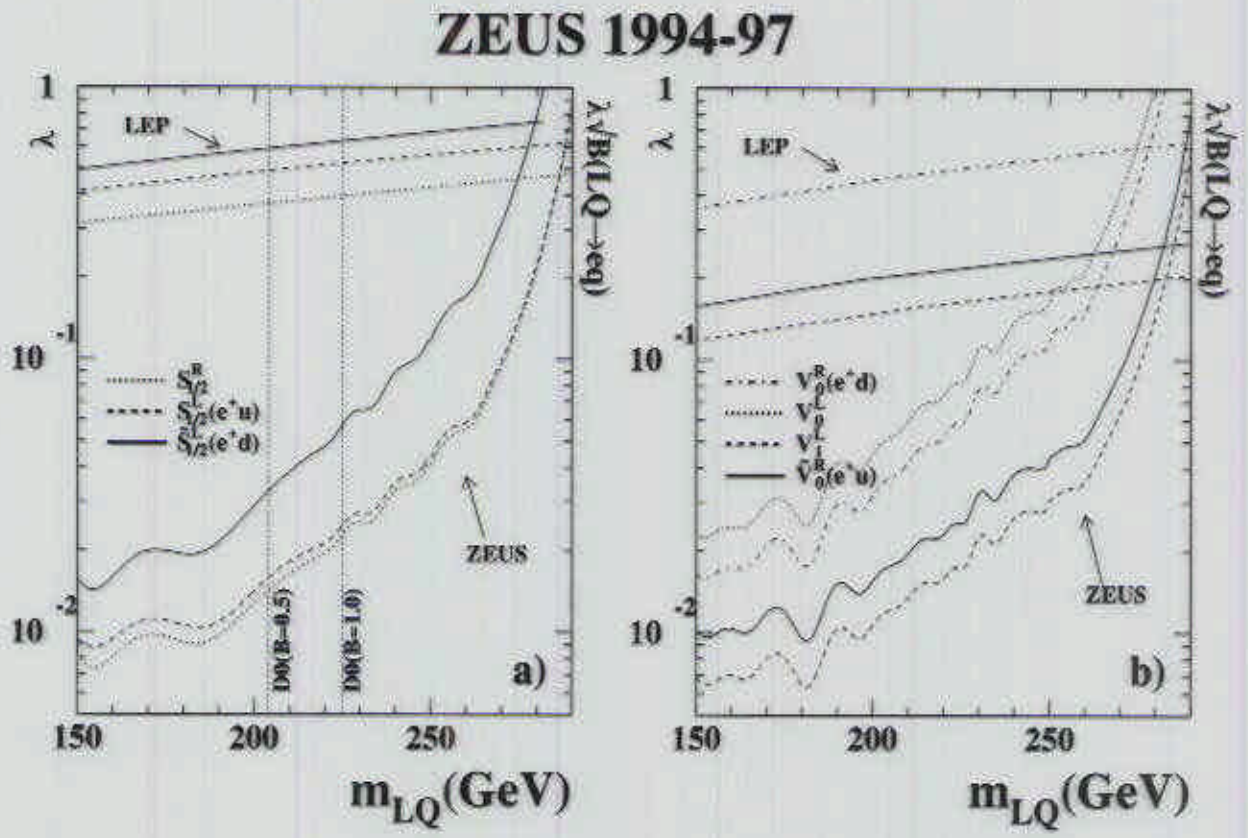


→ see 49 events, expect 25 ± 6, with $M_{ej} > 210$ GeV

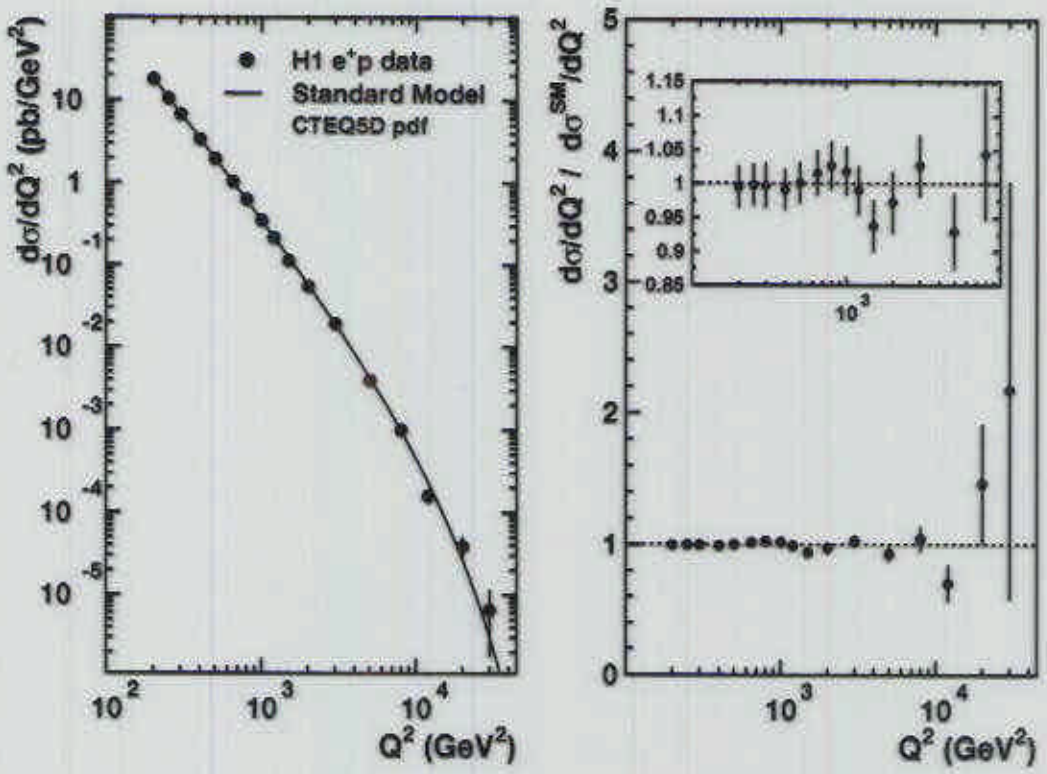
→ angular distribution similar to NC DIS process

→ limits on scalar, vector resonances:

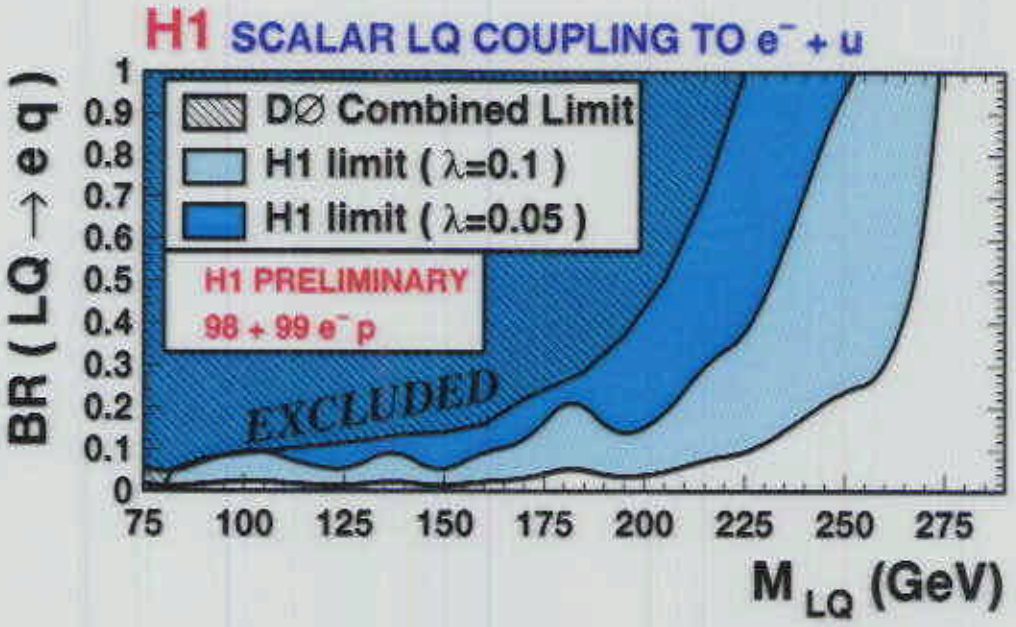




H1 e^+p NC data/SM ratio:

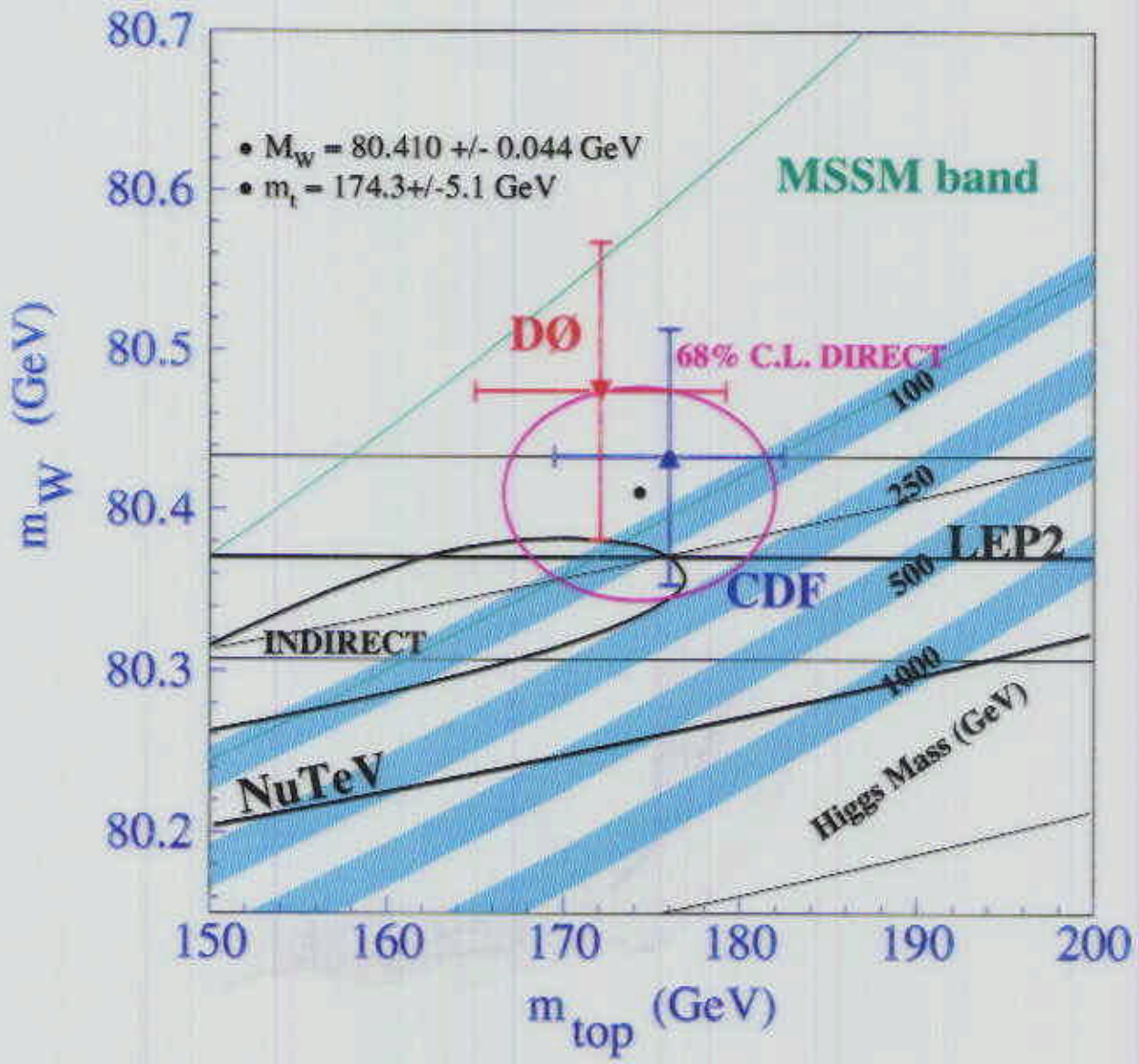


limits on compositeness, large extra dimensions, LQ:



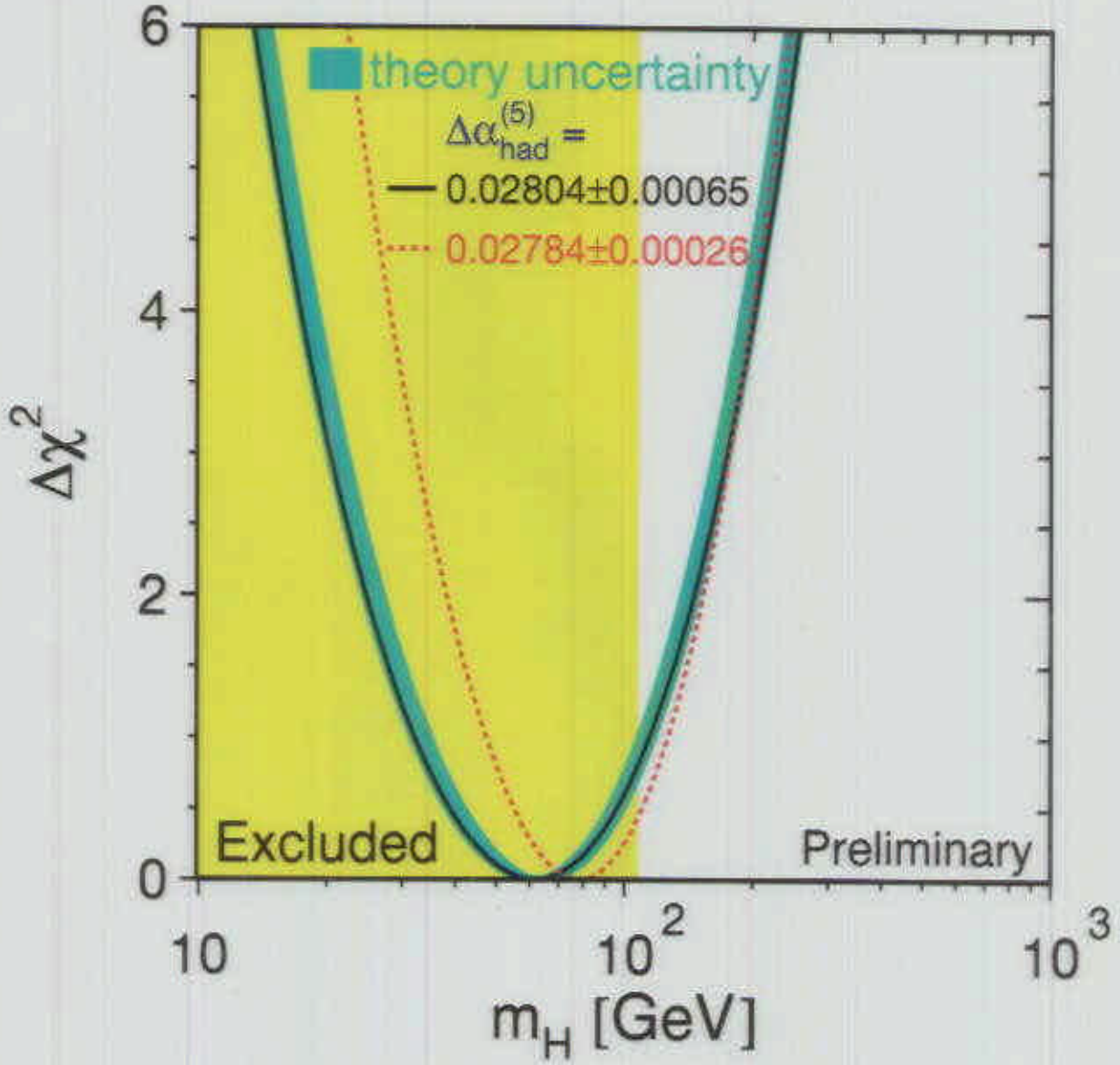
Higgs Search

CDF/DØ Run 1 top and W mass:



World's combined electroweak measurements

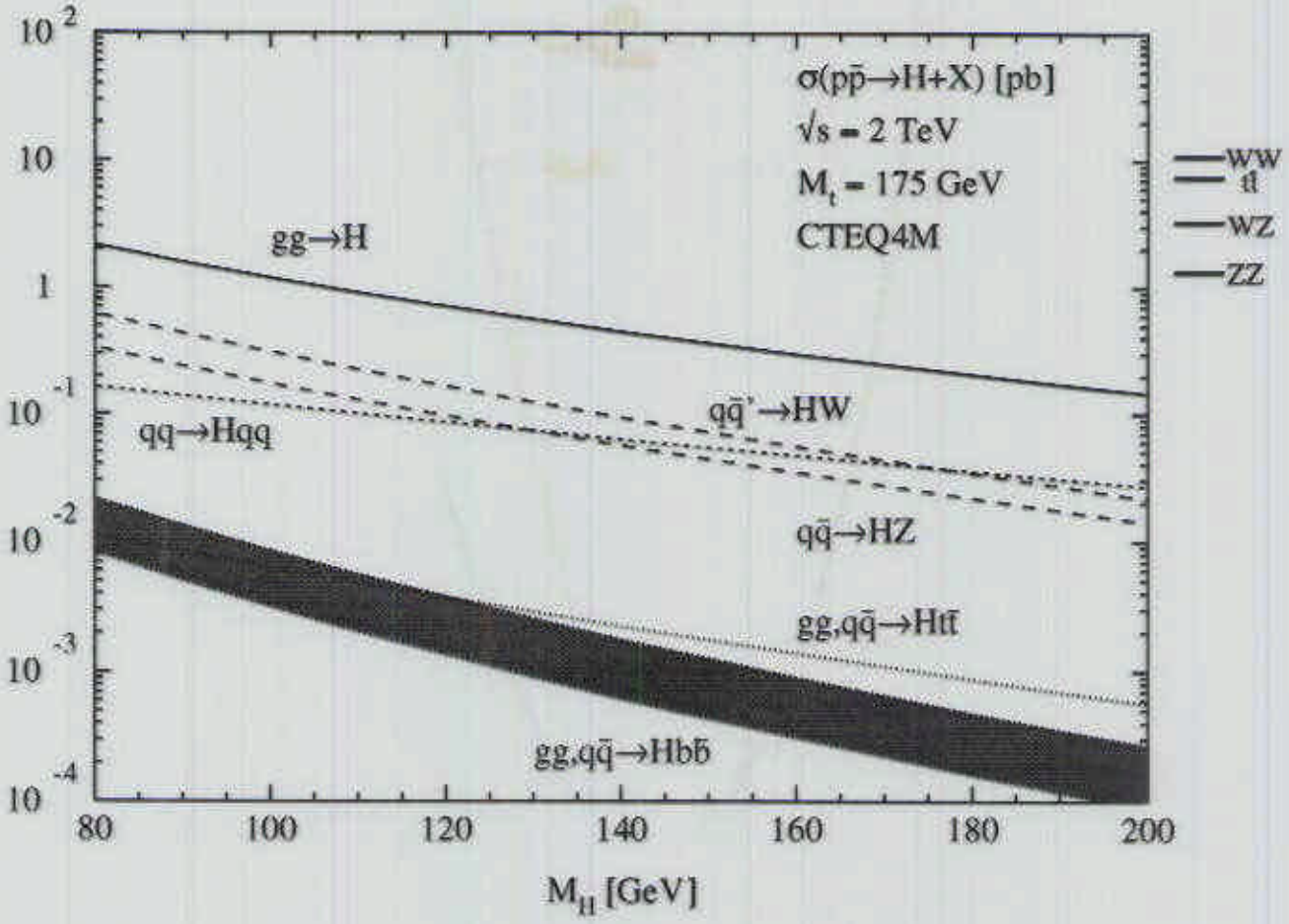
July 2000:



There must be a Higgs or Higgs-like thing out there!

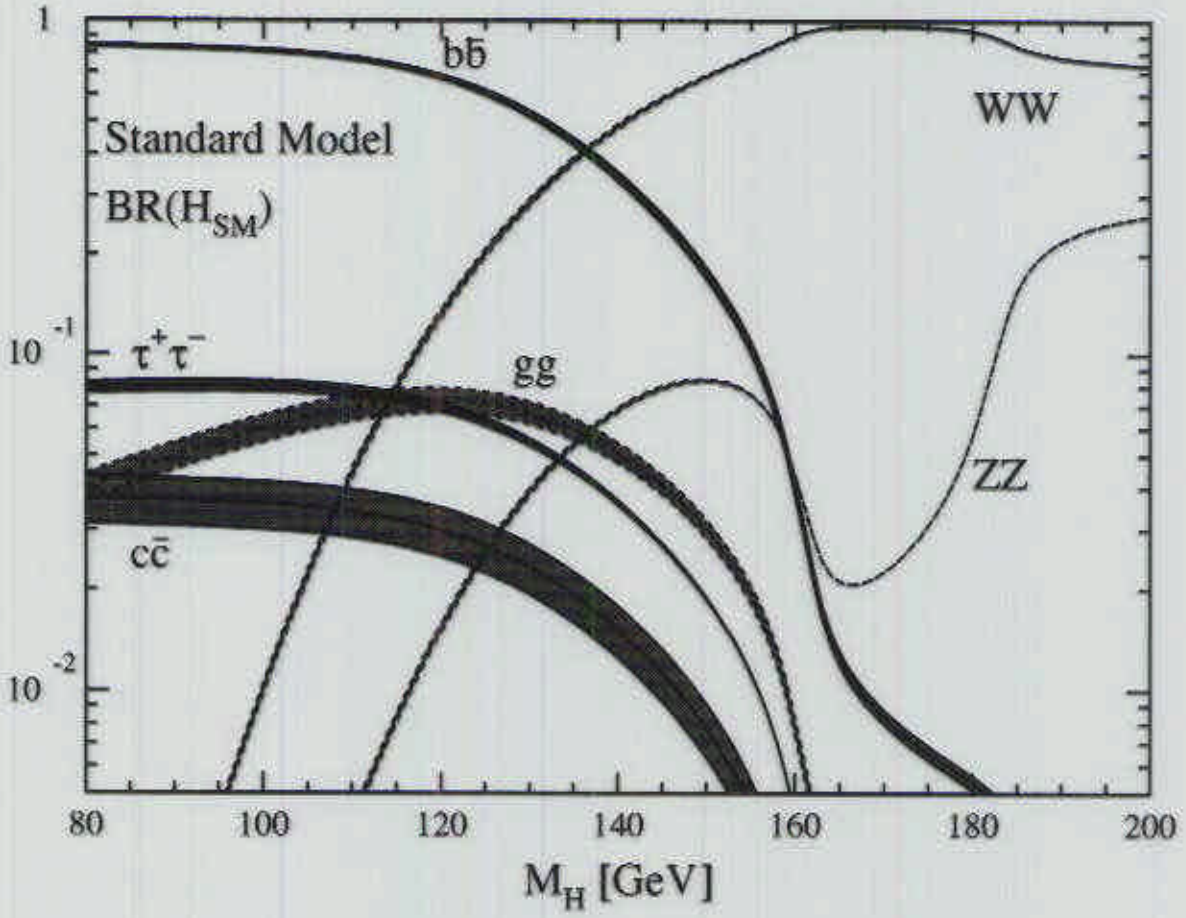
Standard Model Neutral Higgs searches

Higgs production rates at the Tevatron:



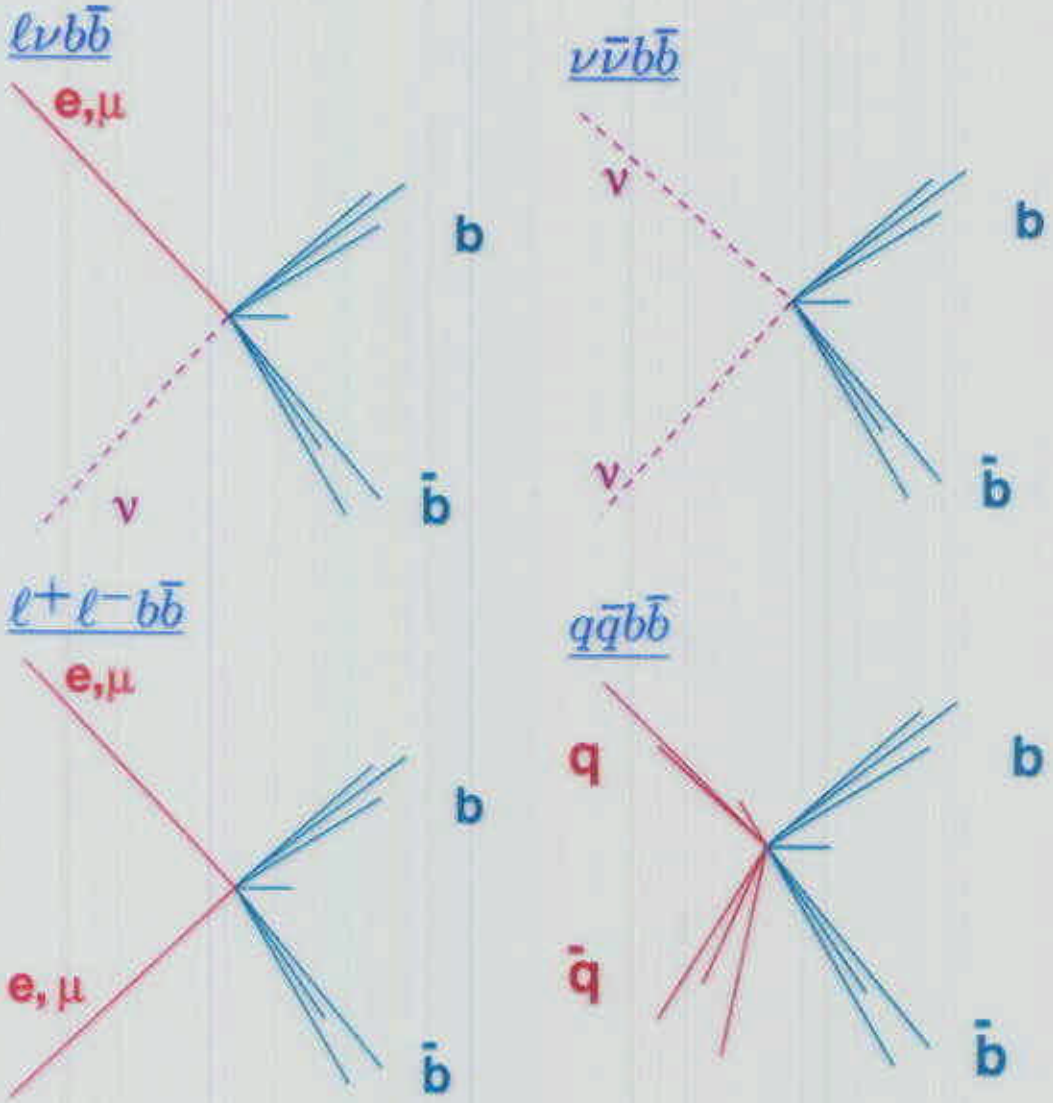
- gg→H dominates, but very difficult to see
- WH, ZH are most accessible
- SUSY enhances some cross sections!

SM Higgs branching ratios:



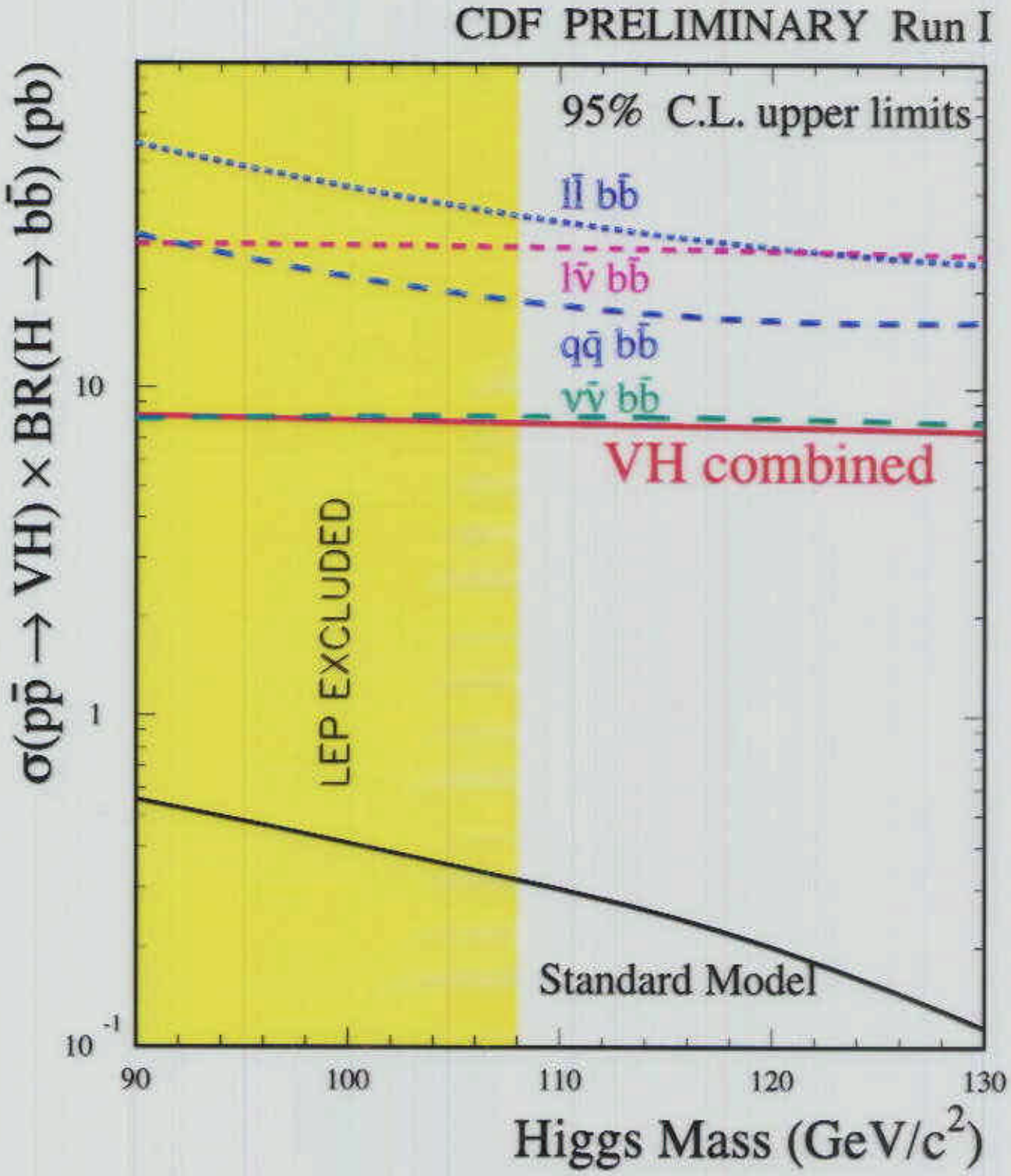
Difficult crossover region near 135 GeV mass!

Low mass SM Higgs channels



main backgrounds: $Wb\bar{b}$, $Zb\bar{b}$, $t\bar{t}$, WZ, single top, QCD

→ no signal in any channel: limits on $\sigma \times BR$

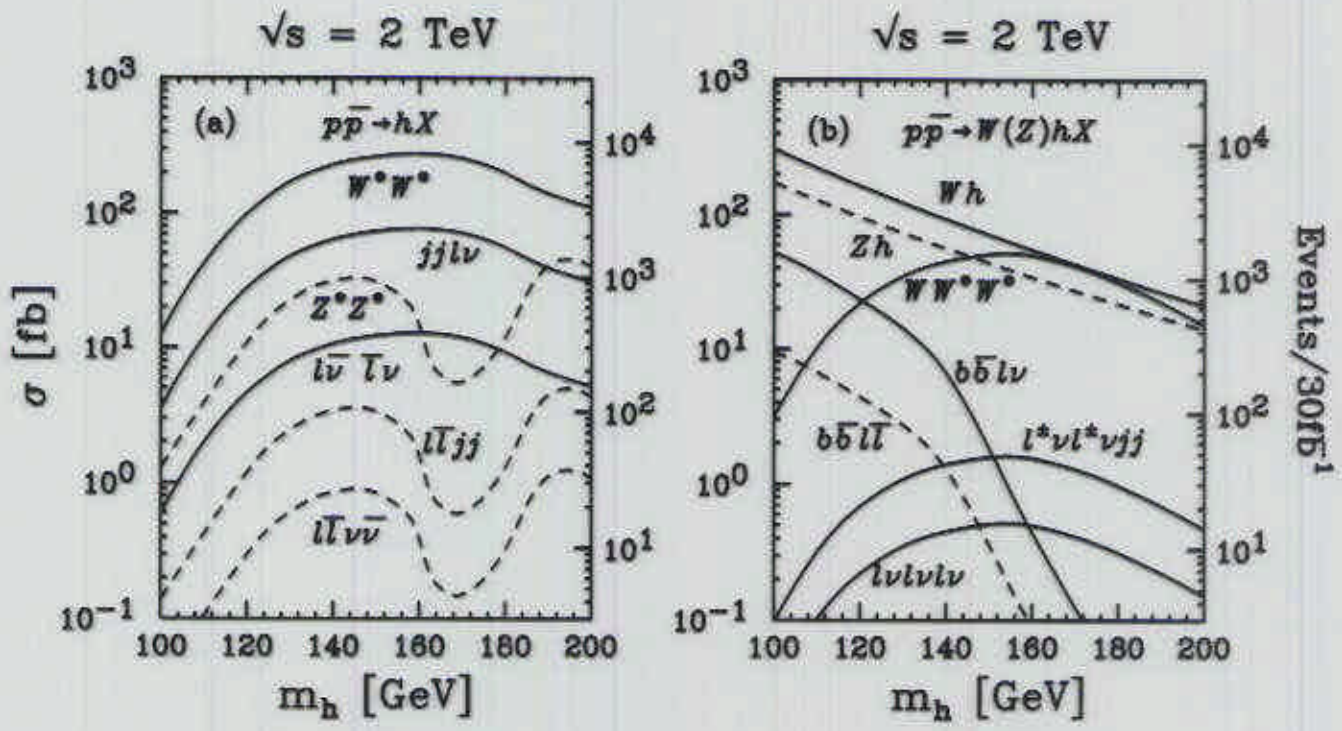


Higgs in Run 2

Low- *and* high-mass SM Higgs

idea: exploit $H \to WW^*$ decays at higher masses

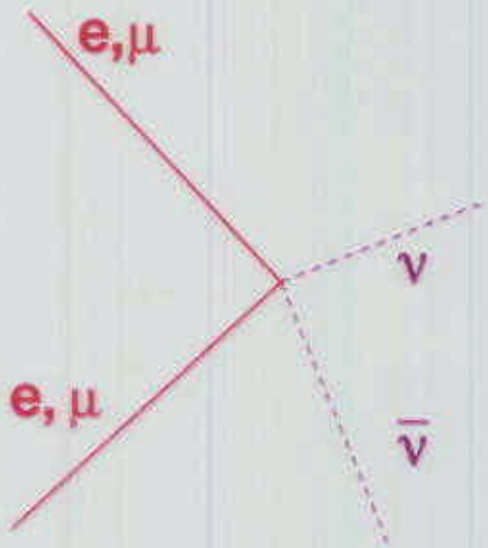
- $gg \to H \to WW^*$
- $ZH \to ZWW^*$
- $WH \to WWW^*$



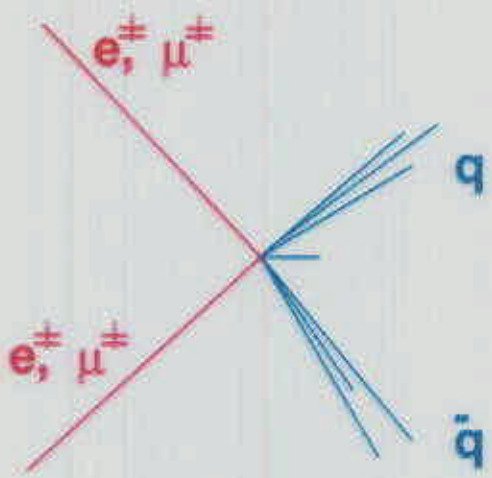
→ dilepton, trilepton, like-sign dilepton plus jets

High-mass SM Higgs channels

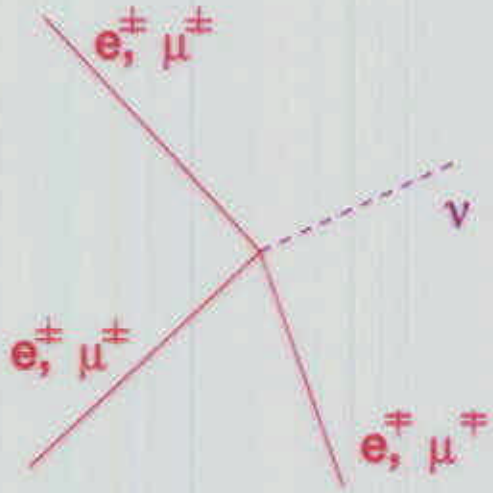
$\ell^+\ell^-\nu\bar{\nu}$



$\ell^\pm\ell^\pm jj$



$\ell^\pm\ell'^\pm\ell^\mp$



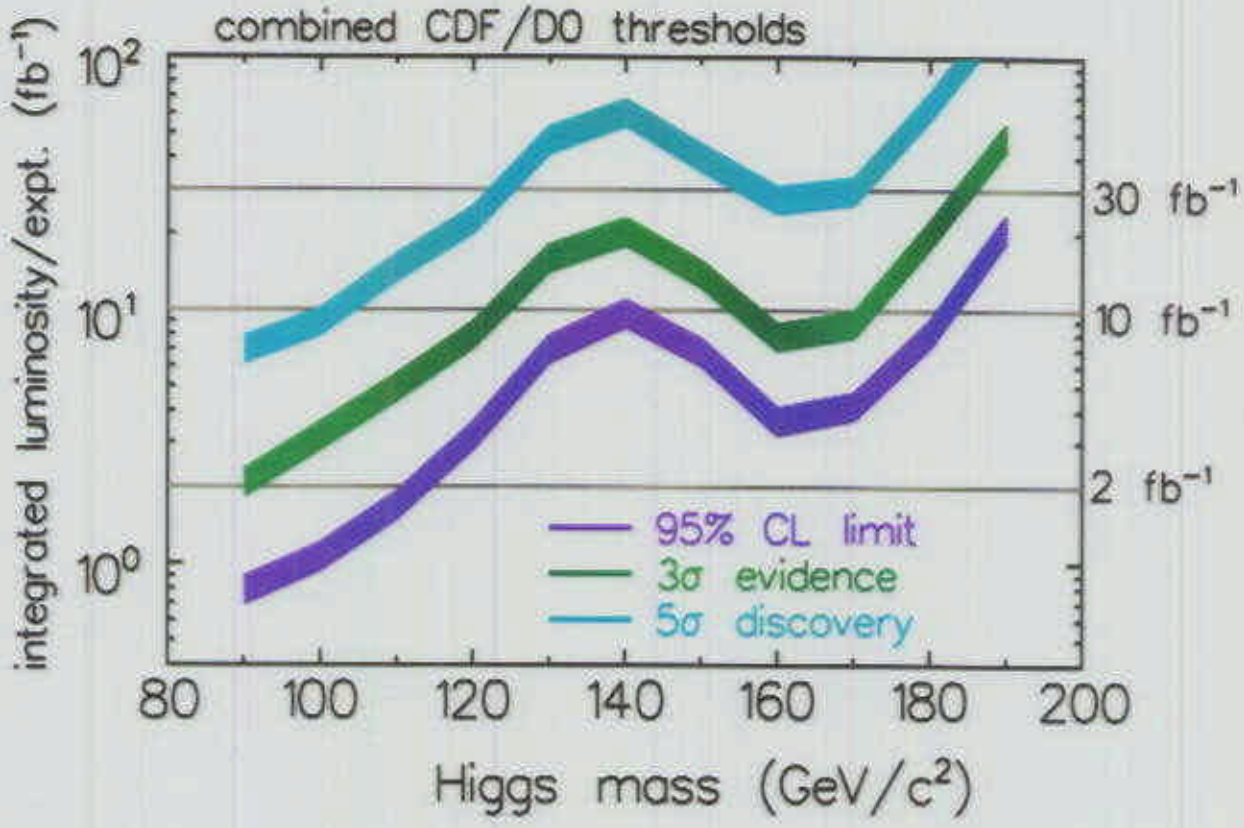
main backgrounds: WW, WZ, ZZ, $t\bar{t}$

→ most powerful channel at high masses: $\ell^\pm\ell^\pm jj$

SM Higgs combined channel thresholds

Tevatron Run 2 SUSY/Higgs Workshop

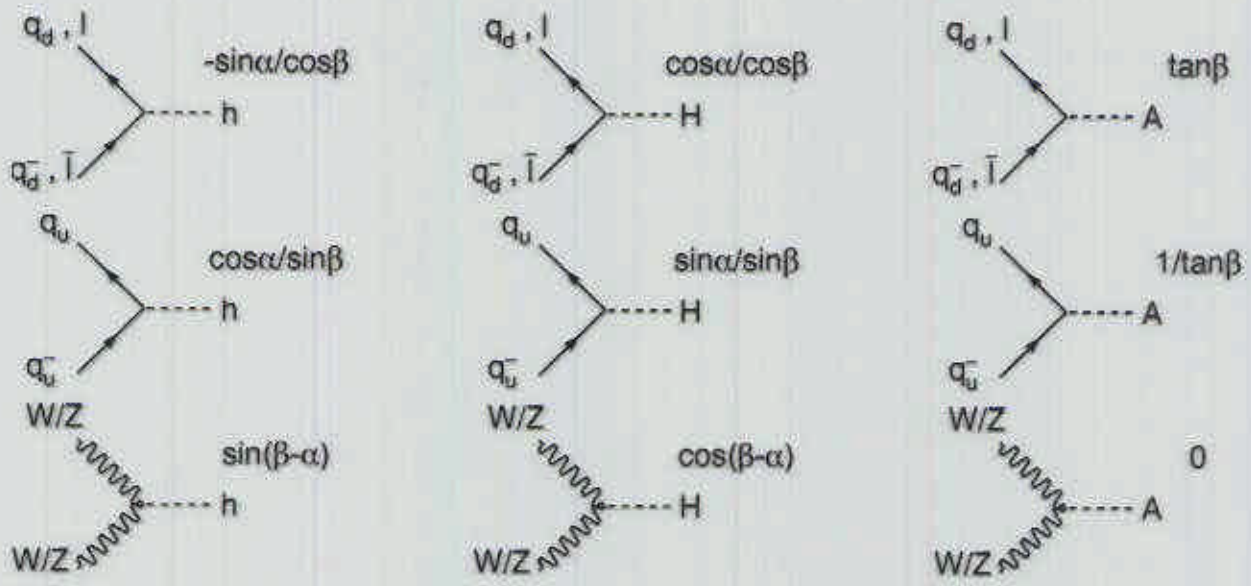
→ two experiments combined
→ 30% better $m_{b\bar{b}}$ resolution than Run 1
→ neural network selection
→ nominal systematic errors: 10% or $1/\sqrt{LB}$



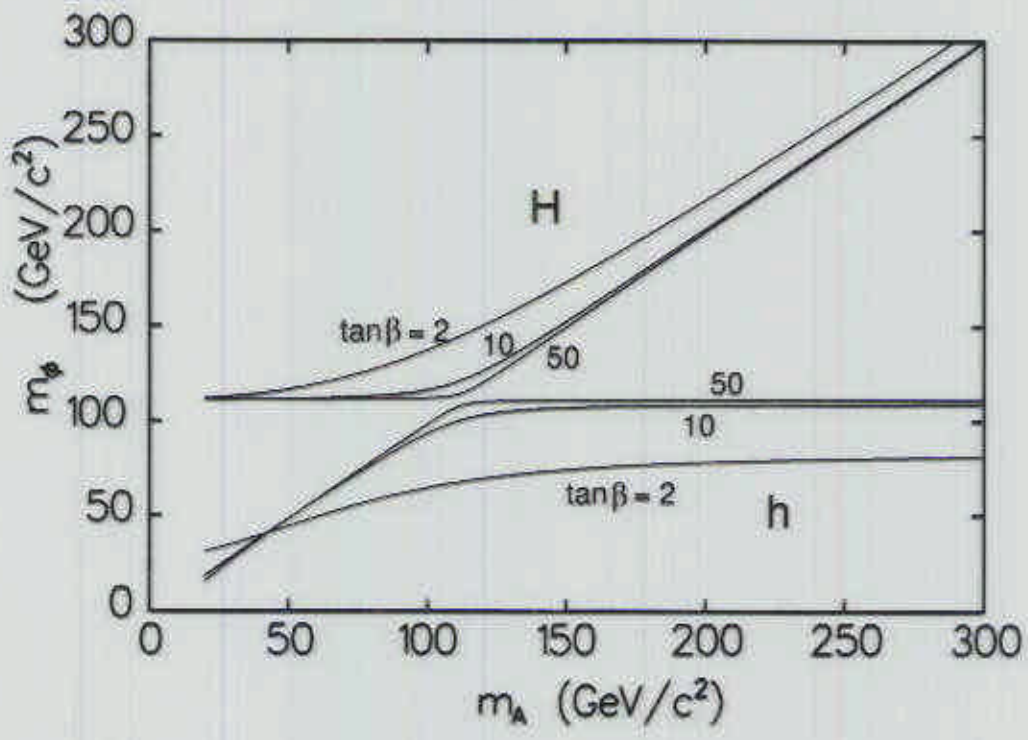
→ bands represent level of "uncertainty" in estimates

SUSY Higgs (MSSM)

Have five Higgs bosons: h,A,H,$H^{\pm}$

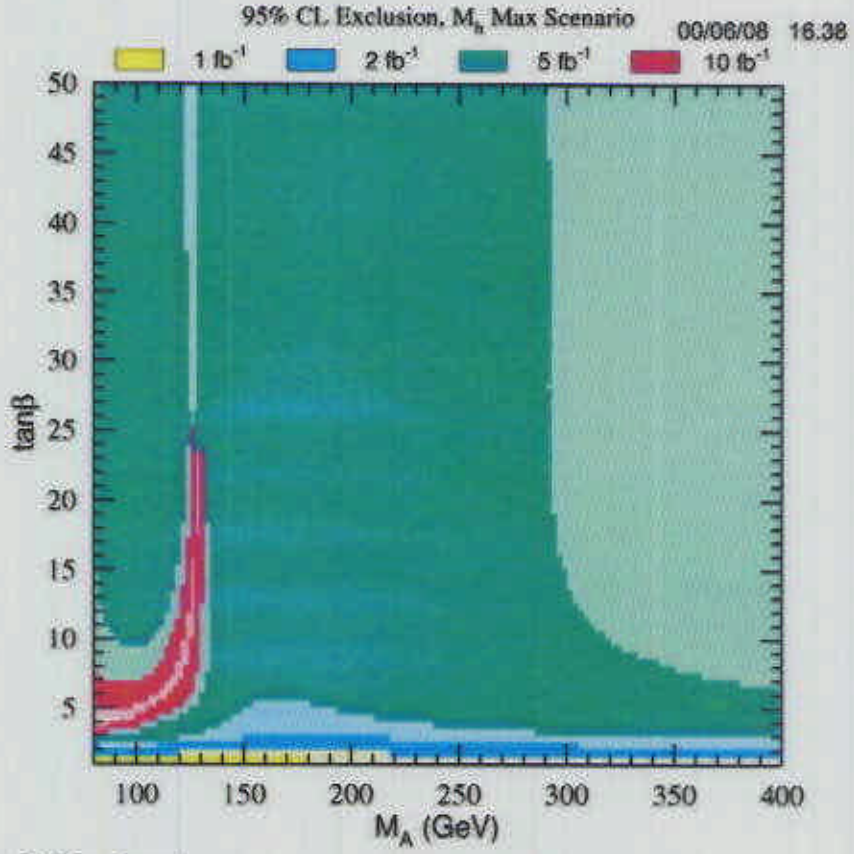


Masses governed by two parameters: m_A, $\tan\beta$

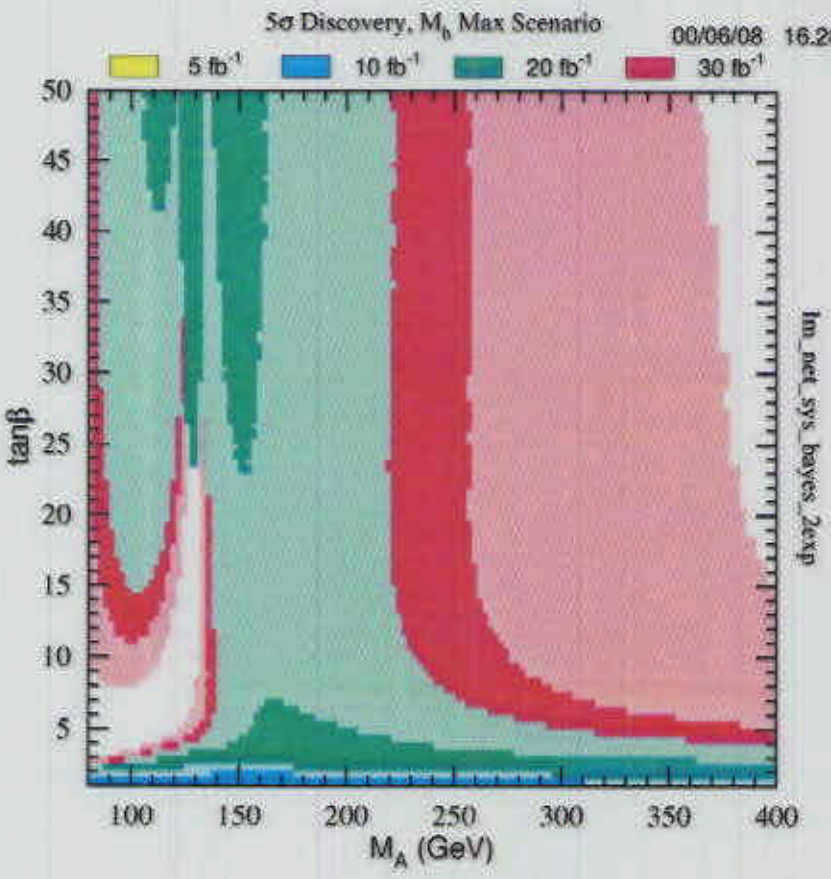


MSSM discovery/exclusion from SM Higgs channels

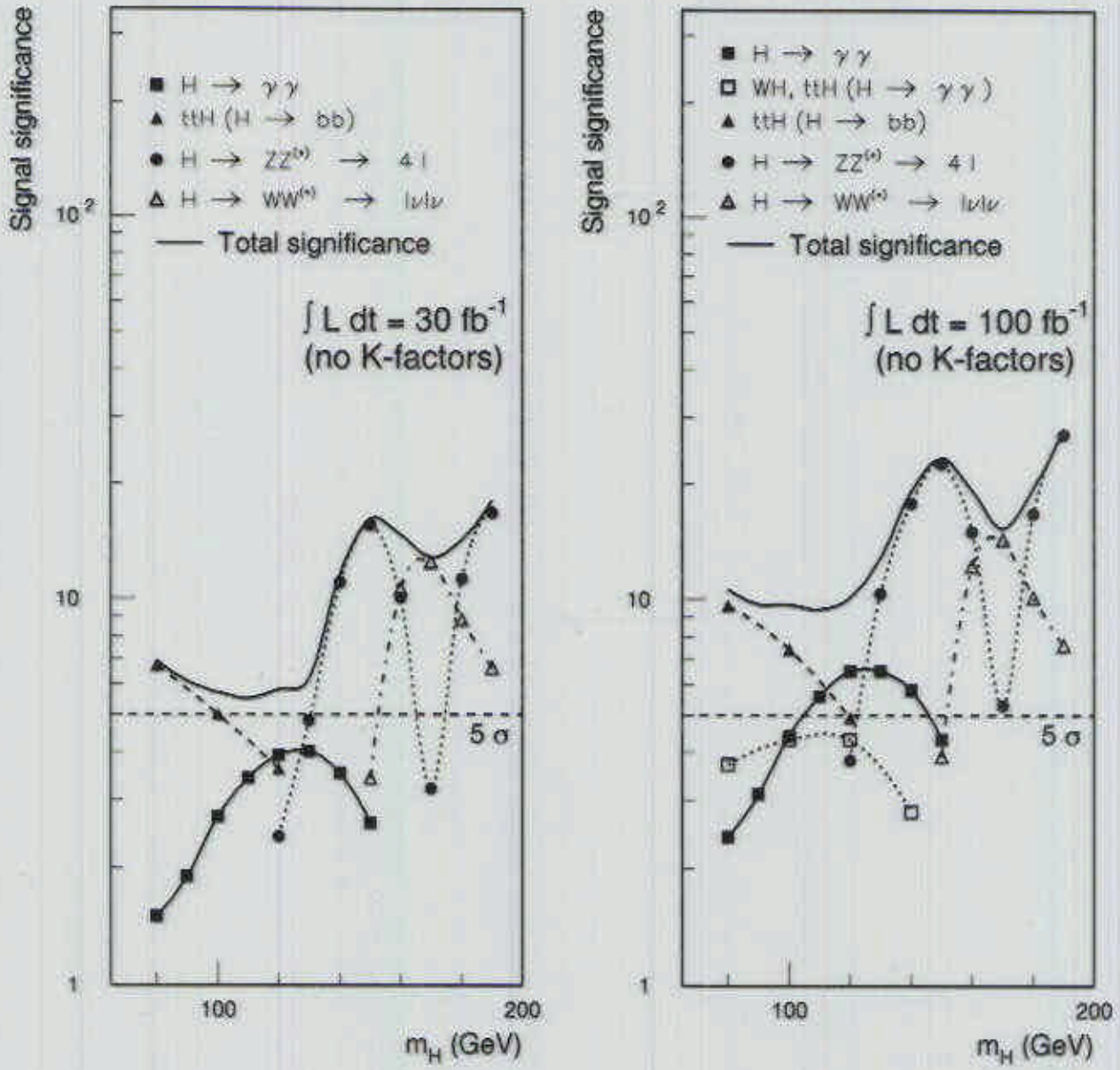
95% CL exclusion



5σ discovery

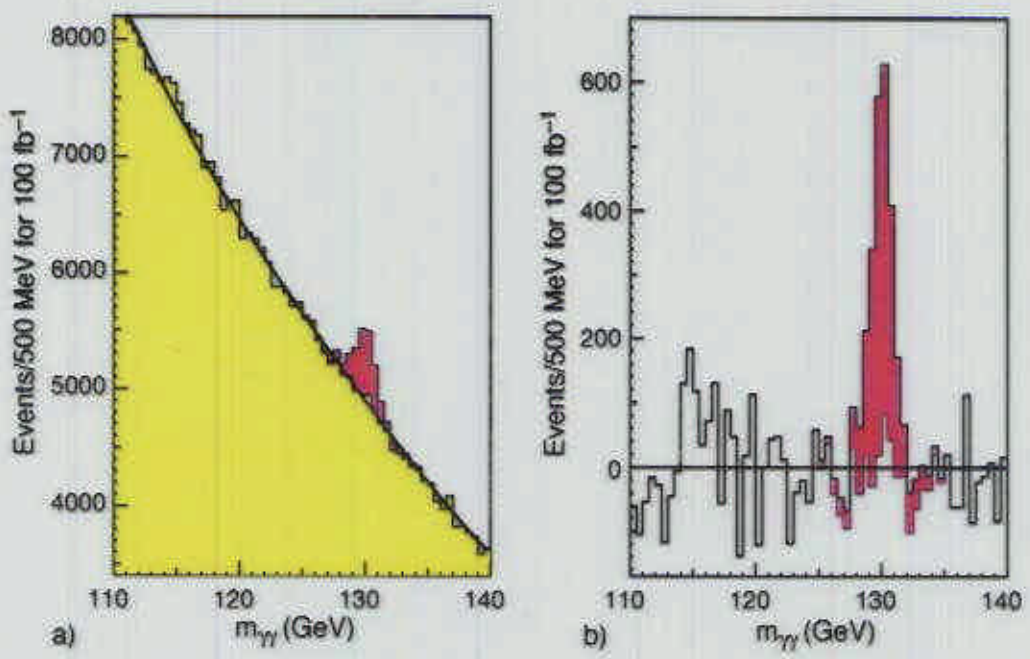


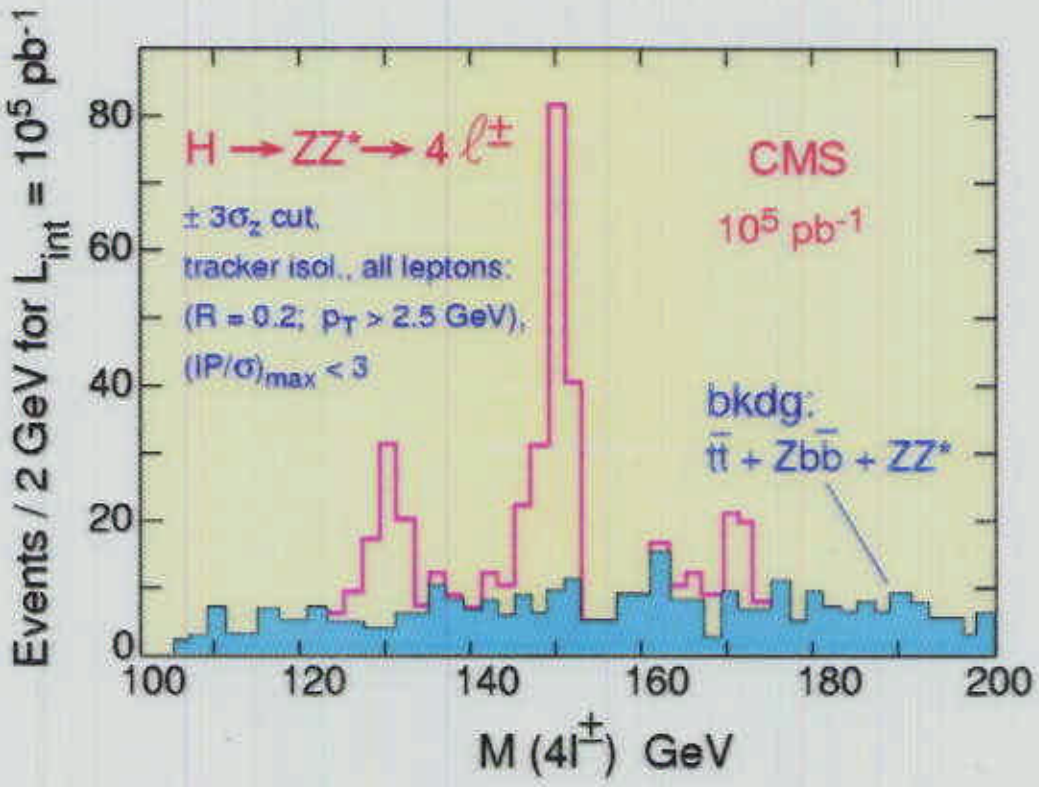
LHC SM Higgs reach:



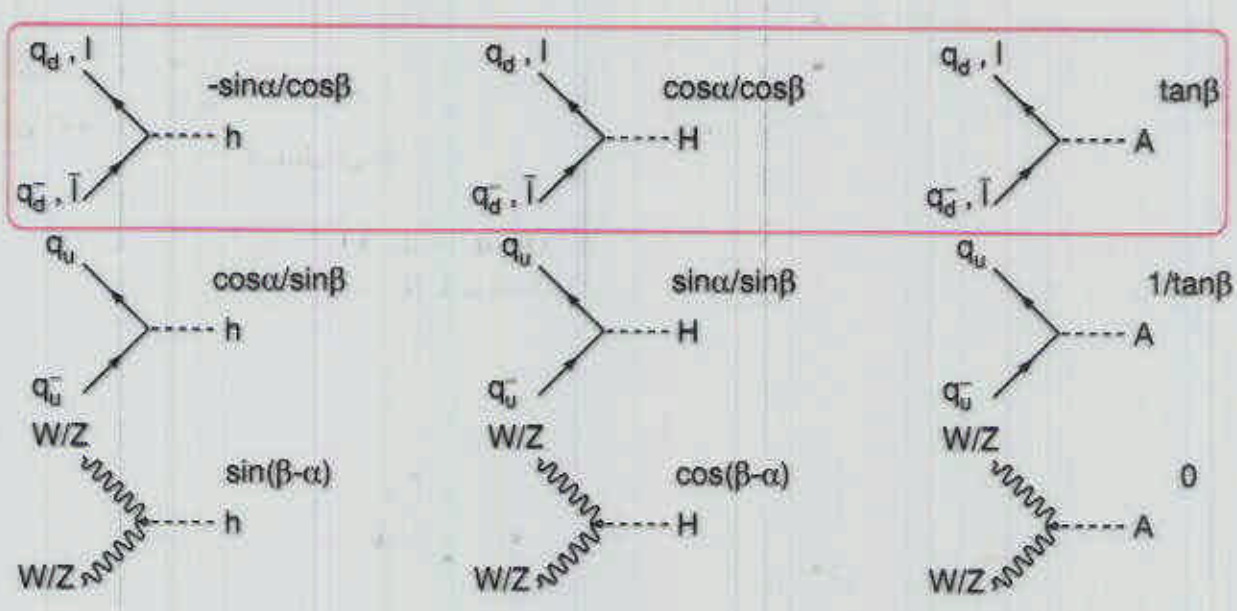
With even just the first year of running LHC experiments will cover the most interesting range for the SM Higgs.

With one or two years of data can measure mass, BR's


Events/500 MeV for 100 fb^{-1}
8000
7000
6000
5000
4000
110
120
130
140
$m_{\gamma\gamma}$ (GeV)
a)
Events/500 MeV for 100 fb^{-1}
600
400
200
0
110
120
130
140
$m_{\gamma\gamma}$ (GeV)
b)

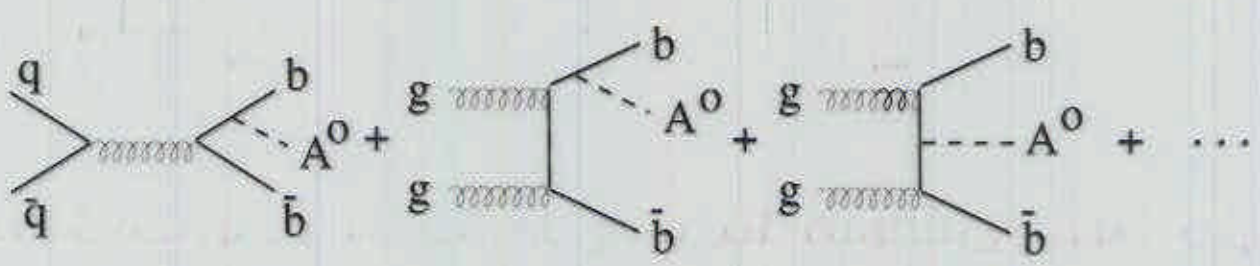

Events / 2 GeV for L_{int} = 10^5 pb^{-1}
80
60
40
20
0
100
120
140
160
180
200
M ($4l^{\pm}$) GeV
H → ZZ* → 4 $\ell^{\pm}$
± 3σ_z cut,
tracker isol., all leptons:
(R = 0.2; p_T > 2.5 GeV),
$(IP/\sigma)_{max}$ < 3
CMS
10^5 pb^{-1}
bkdg:
$t\bar{t}$ + Z$b\bar{b}$ + ZZ*

SUSY Higgs Production at large tan β



→ $b\bar{b}A/b\bar{b}h/b\bar{b}H$ enhanced at large tan β

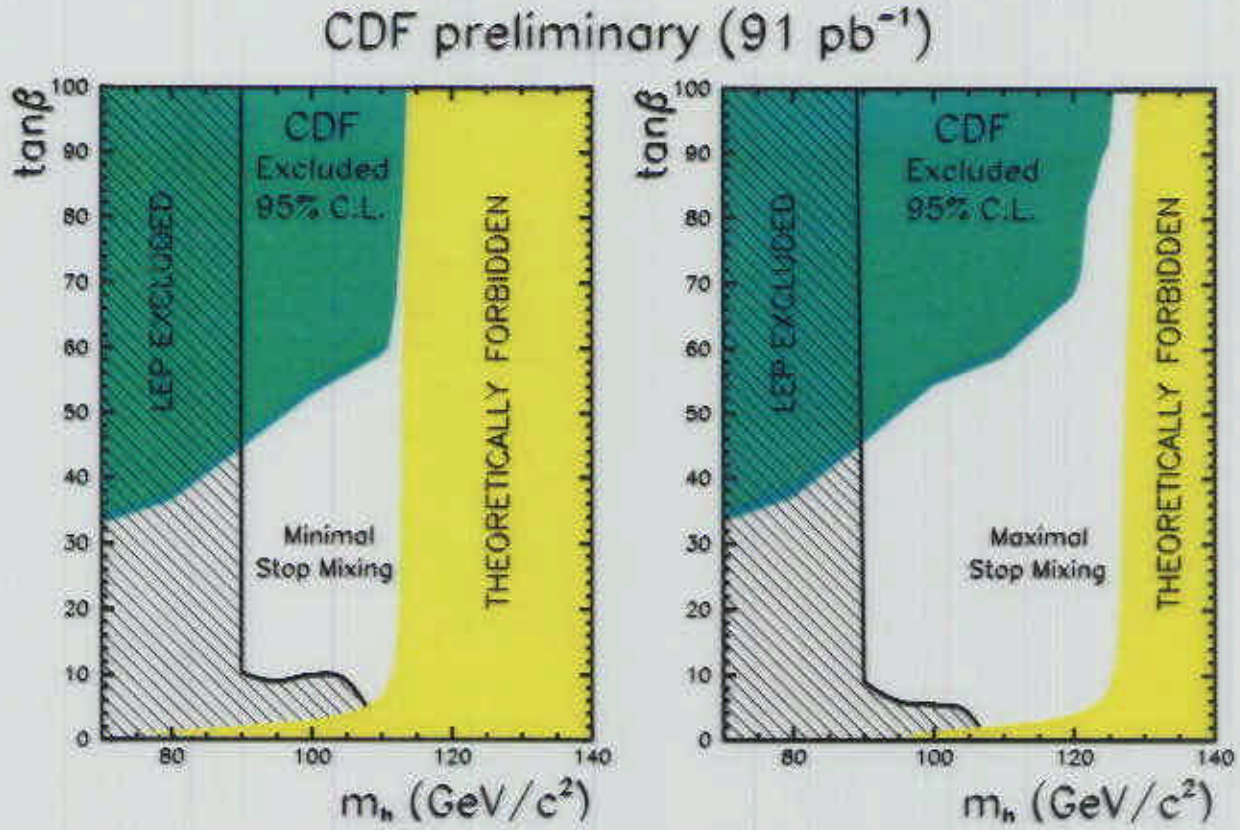
→ cross sections $\propto \tan^2\beta$

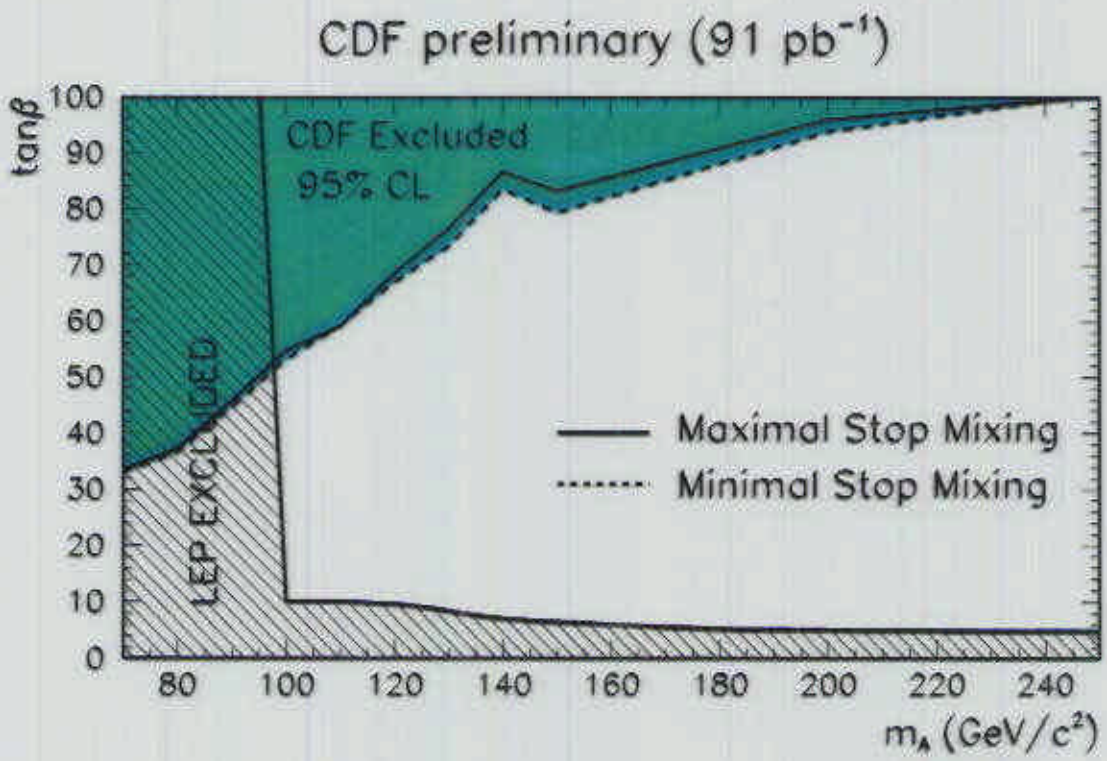


possible search channels:

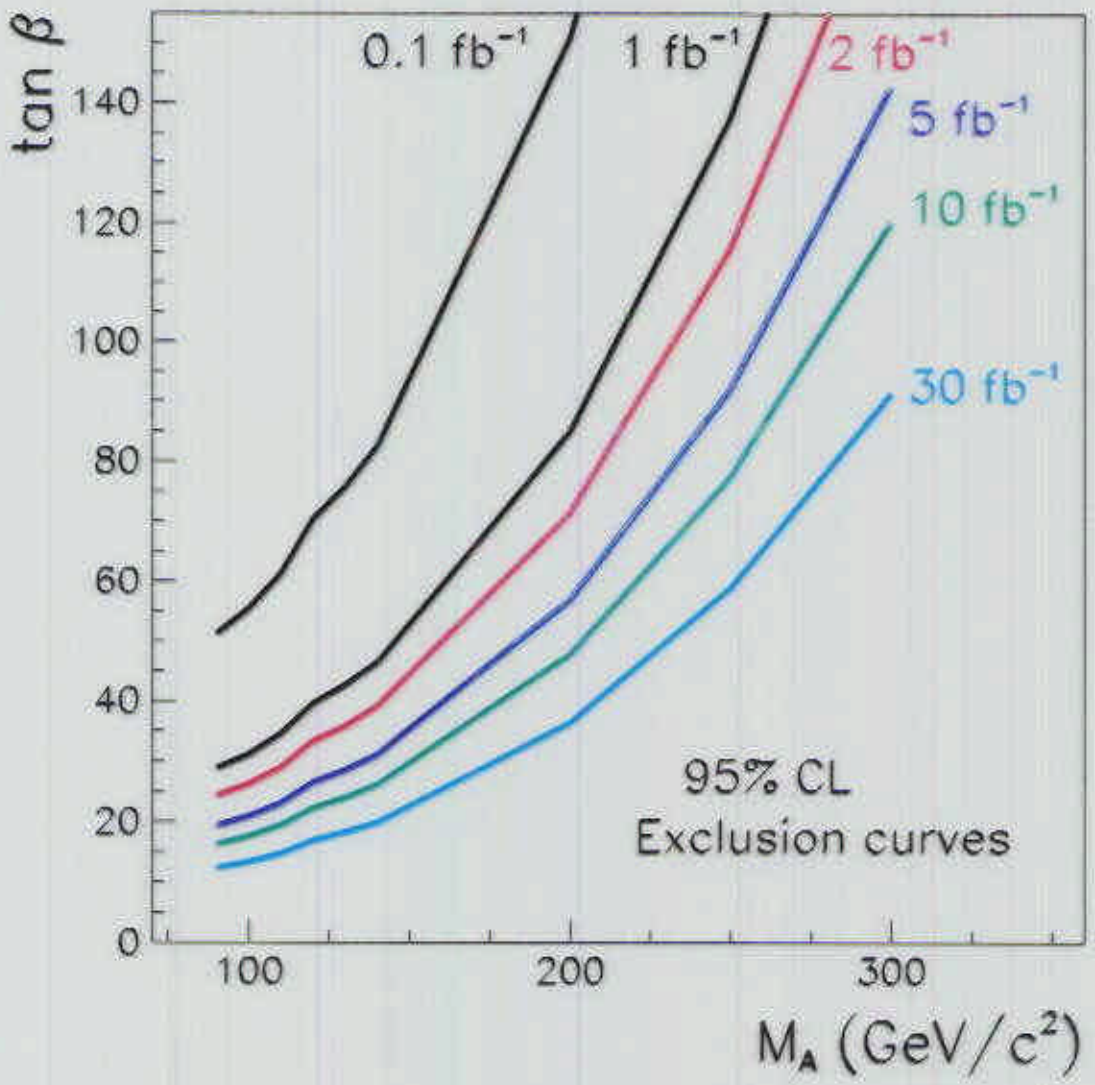
- $b\bar{b}b\bar{b}$
- $\tau\tau j\not{E}_T$
- $\tau bj\not{E}_T$

CDF Run 1 limits on MSSM Higgs in $b\bar{b}b\bar{b}$ channel



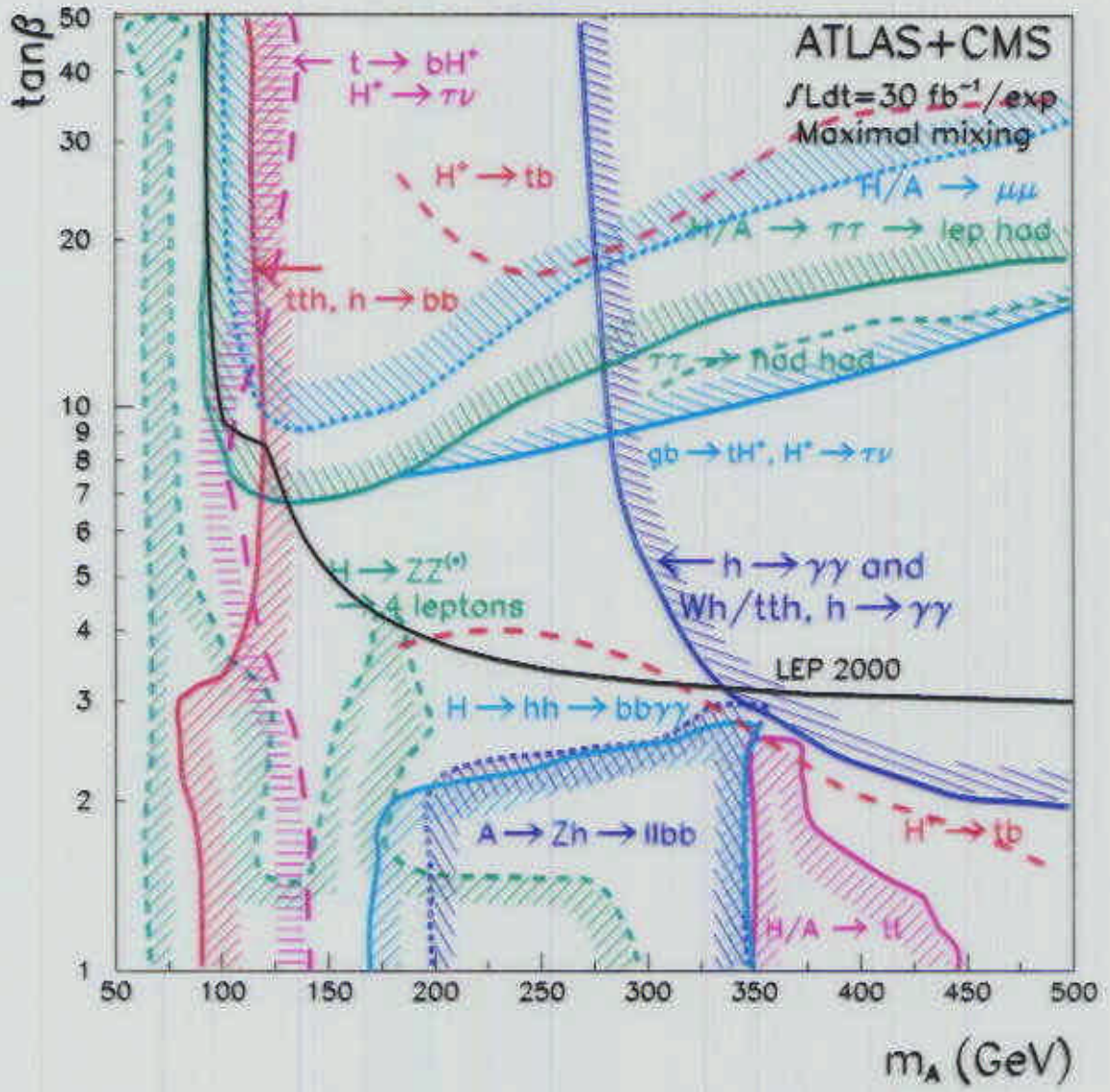


DØ projected reach in $\tan\beta$ versus m_A plane



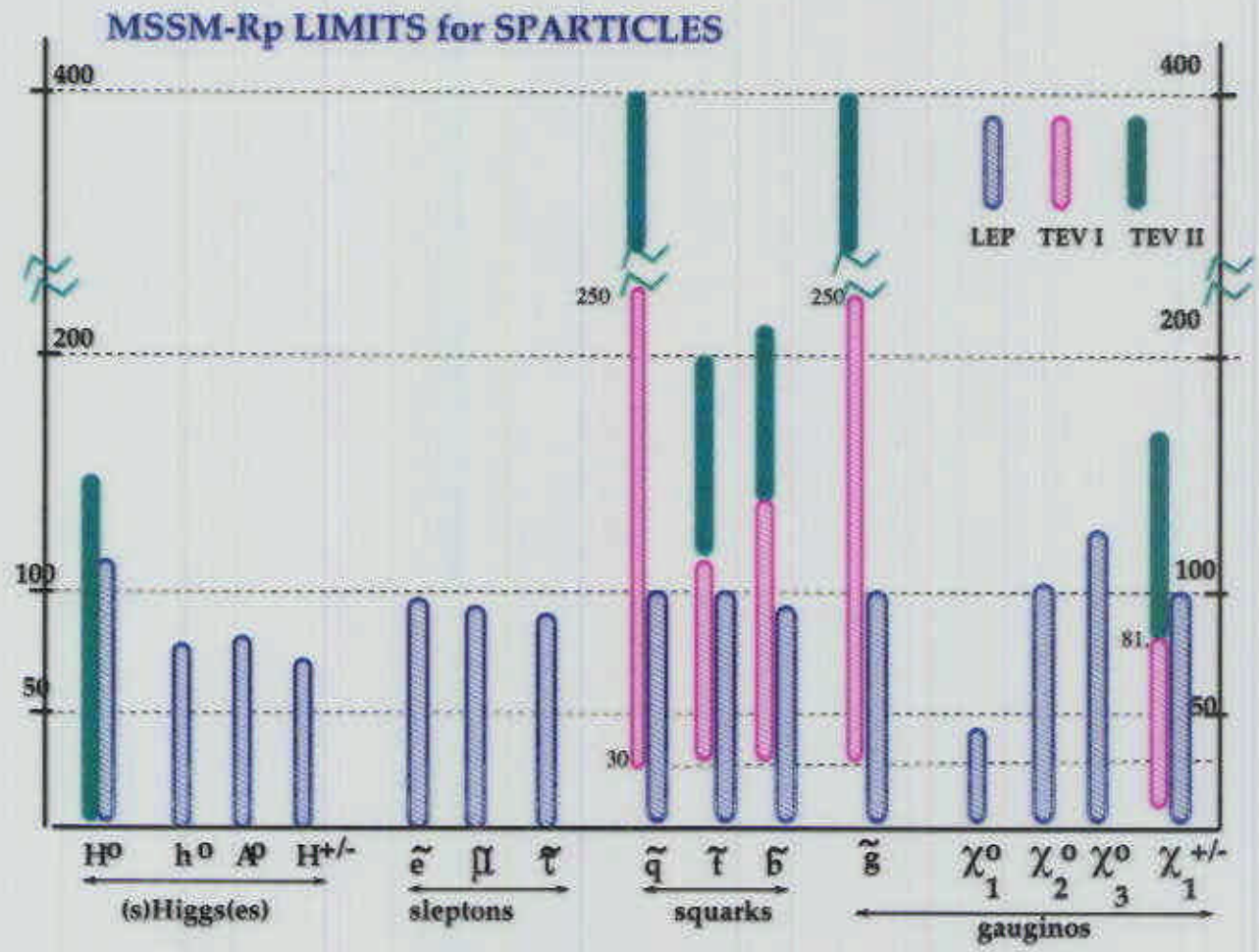
(similar to CDF reach)

LHC coverage of SUSY Higgs space:



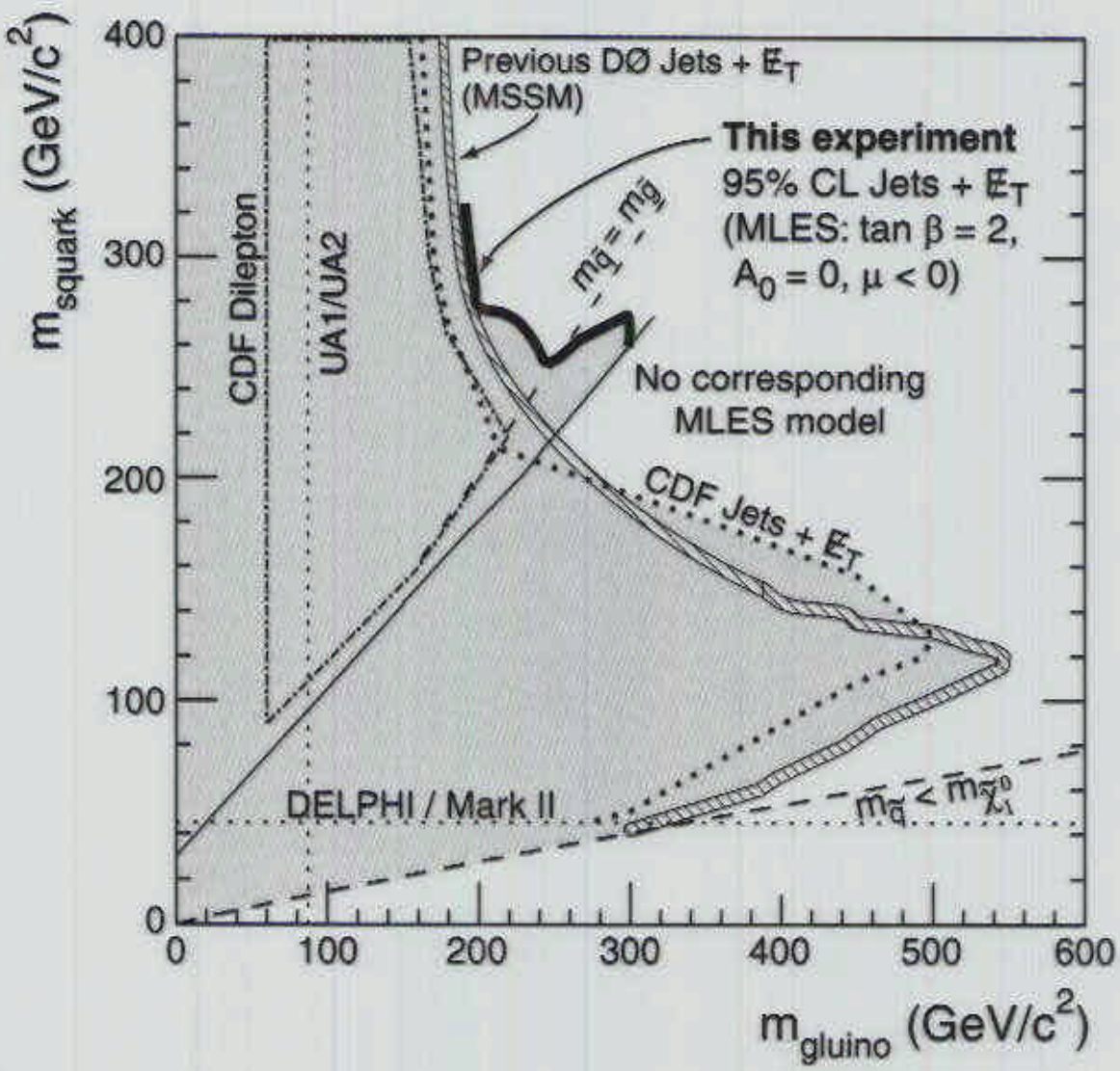
Search for Supersymmetry

- "generic" sparticle searches
- gauge-mediated SUSY breaking: photons
- R-parity-violating SUSY



(Thanks to Aurore Savoy-Navarro!)

→ DØ limits on squarks/gluinos:



new CDF result coming soon...

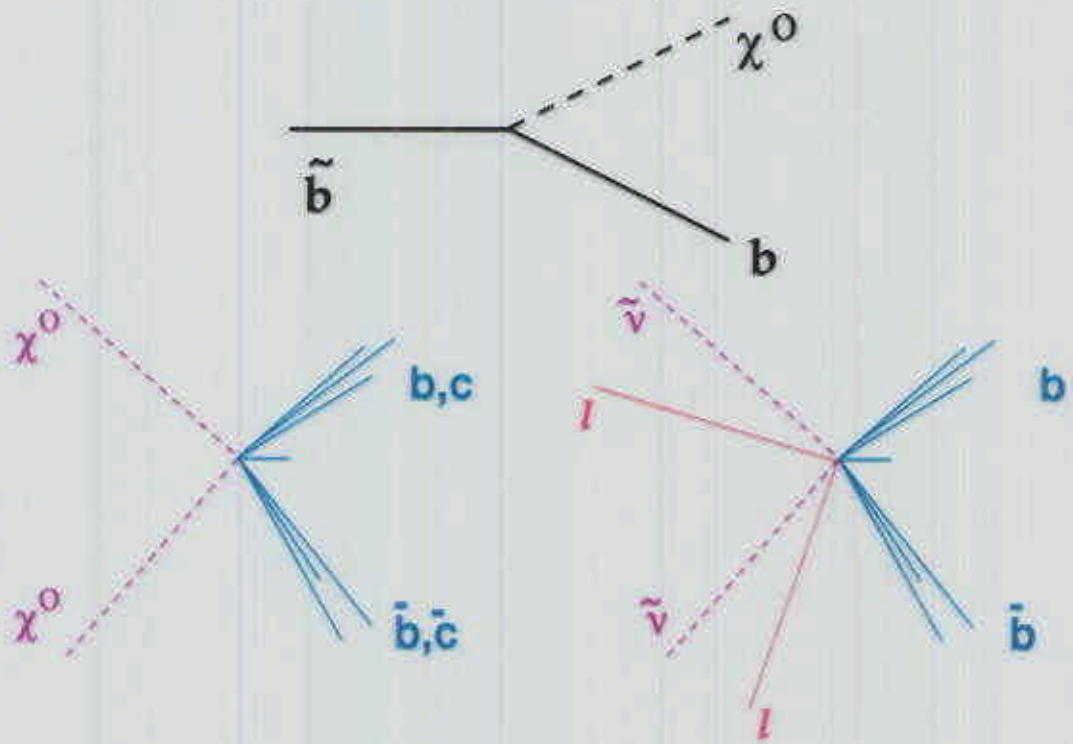
CDF search for stop/sbottom

light stop squark favored in various models

stop can decay by various modes:

- $\chi^{\pm} \to \ell^{\pm}\tilde{\nu}$ gives $\ell\bar{\ell}b\bar{b}\not{E}_T$ final state
- $\tilde{t} \to c\chi^o$ gives $c\bar{c}\not{E}_T$ final state: need charm tagging

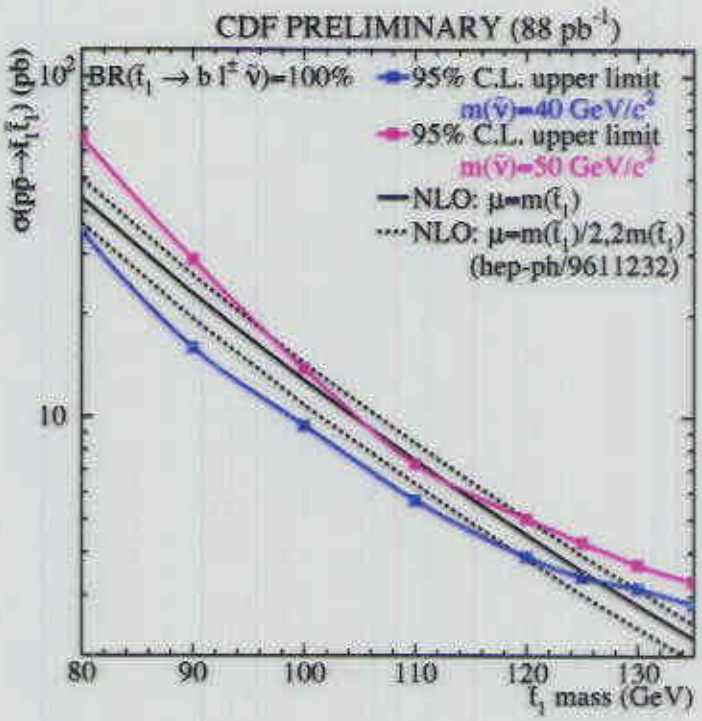
sbottom pair production give similar final state:

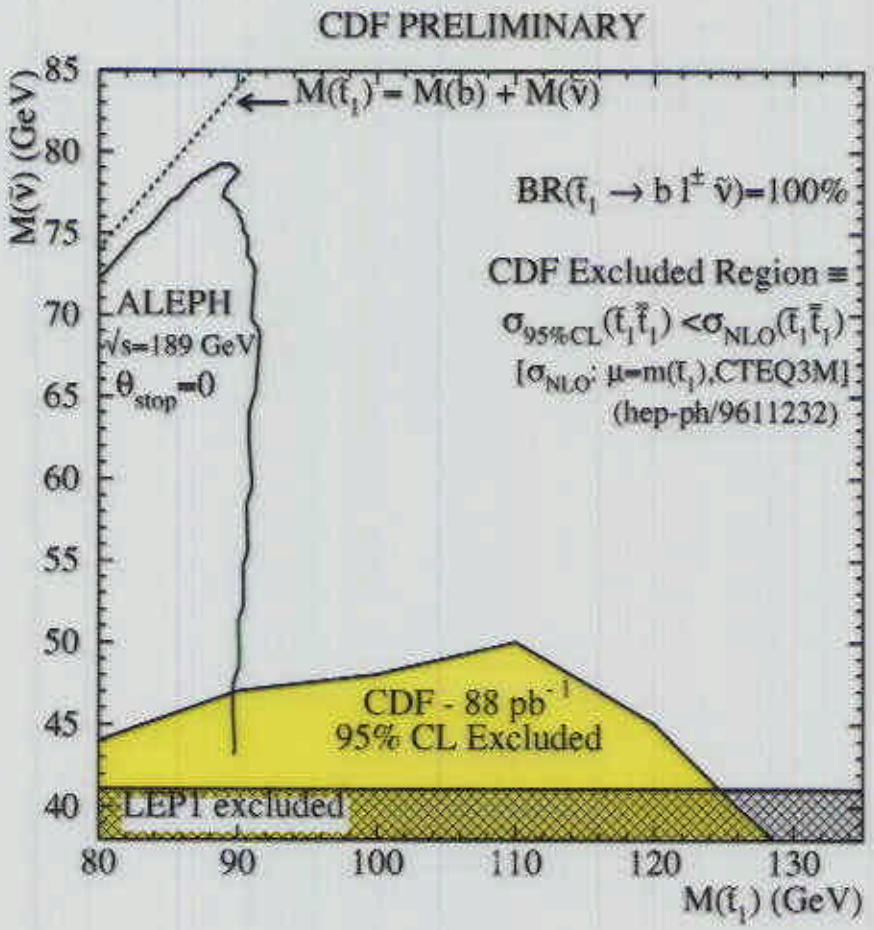


CDF

$\tilde{t} \to b\chi^+$

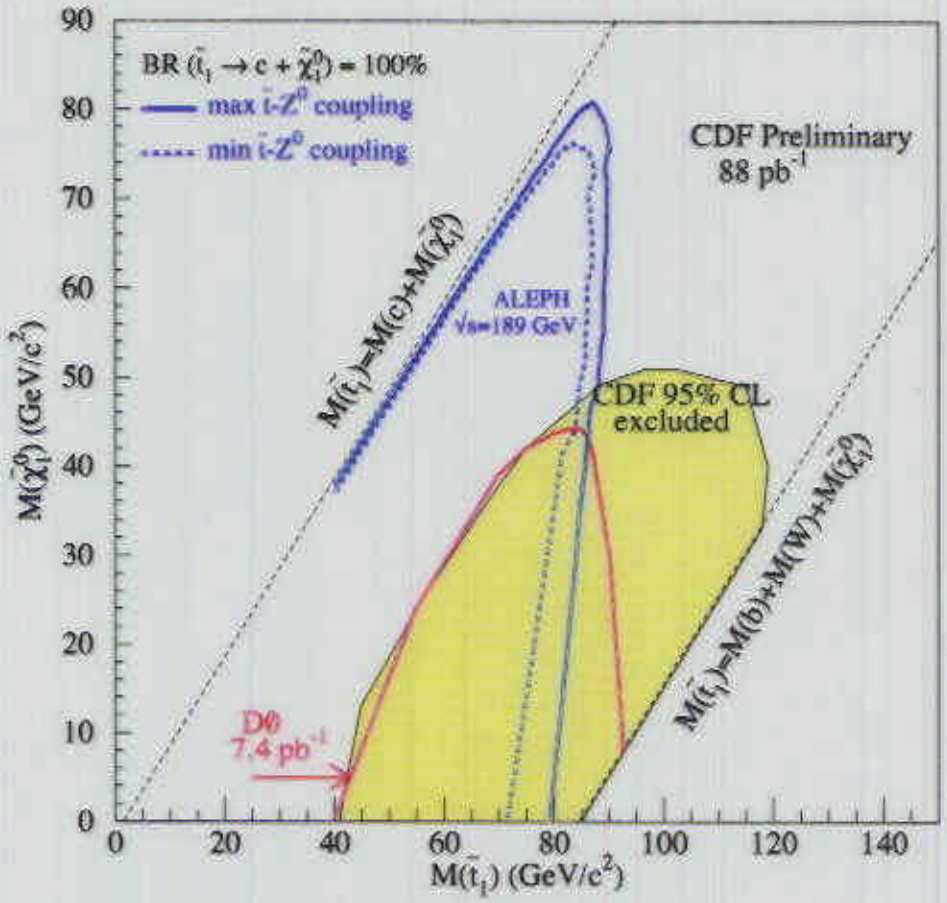
$\chi^+ \to \ell^+\tilde{\nu}$





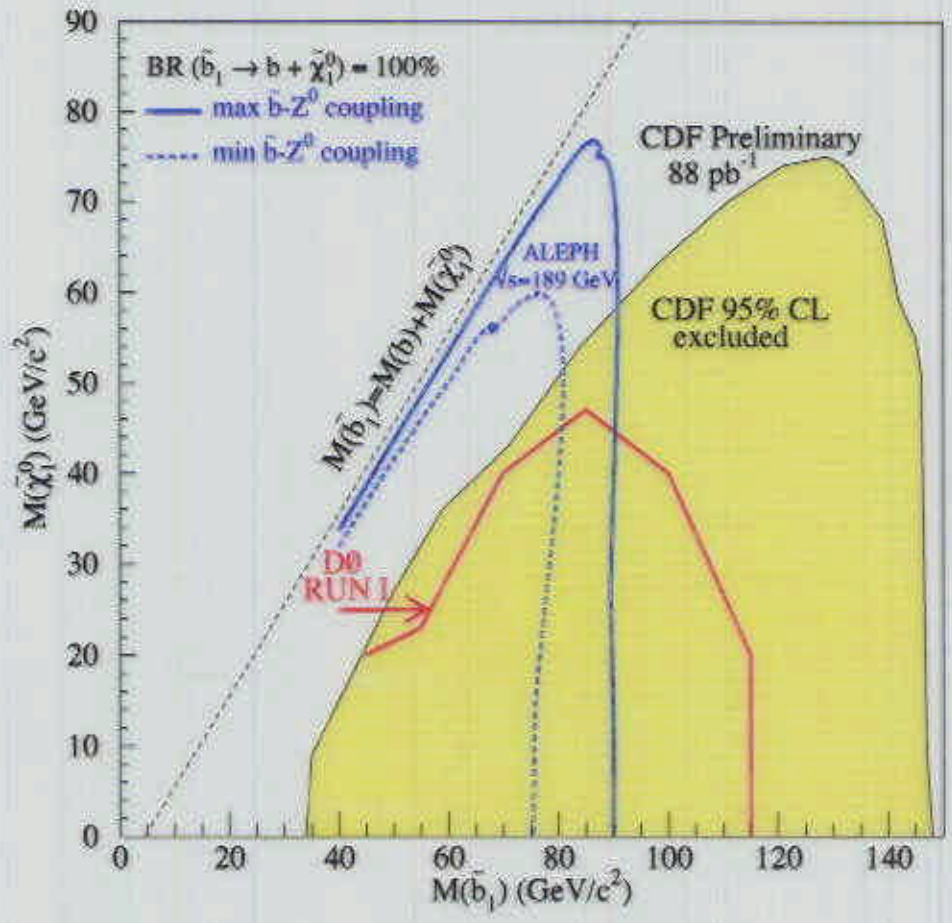
CDF

$c\bar{c}\not{E}_T$



CDF

$b\bar{b}\not{E}_T$

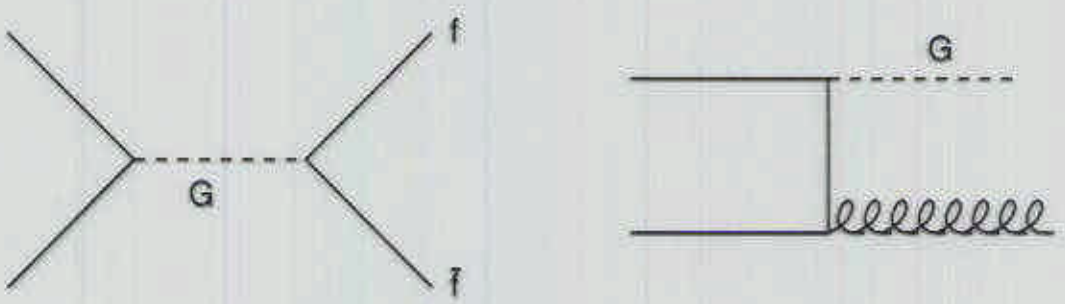


Search for Large Extra Dimensions

If there exist extra dimensions, they can be large, with radii on the order of a millimeter, without conflicting with present data!

Governed by: M_S effective Planck mass
n number of extra dimensions (≥ 2)
λ $\pm\mathcal{O}(1)$

$\rightarrow$ get "towers" of sub-eV-spaced Kaluza-Klein excitations

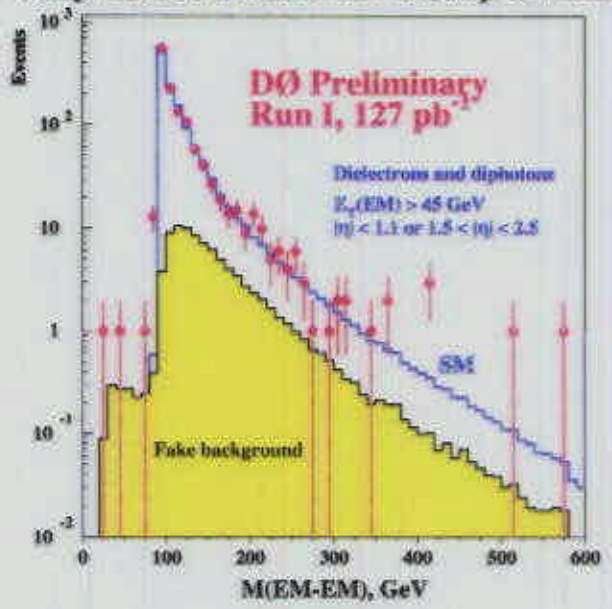


Both indirect and direct signals at colliders.

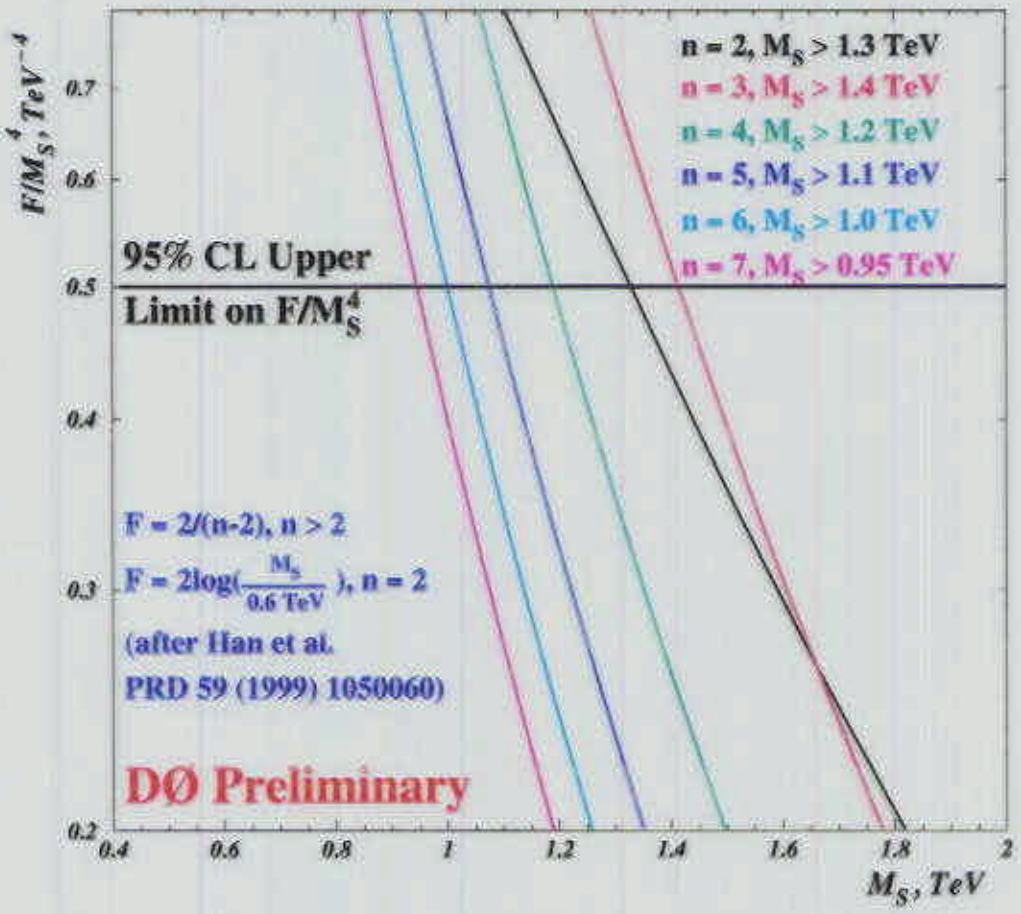
DØ search for extra dimensions in high mass $e^+e^-, \gamma\gamma$ pairs:

Extra dim. would show up as excess at high mass:

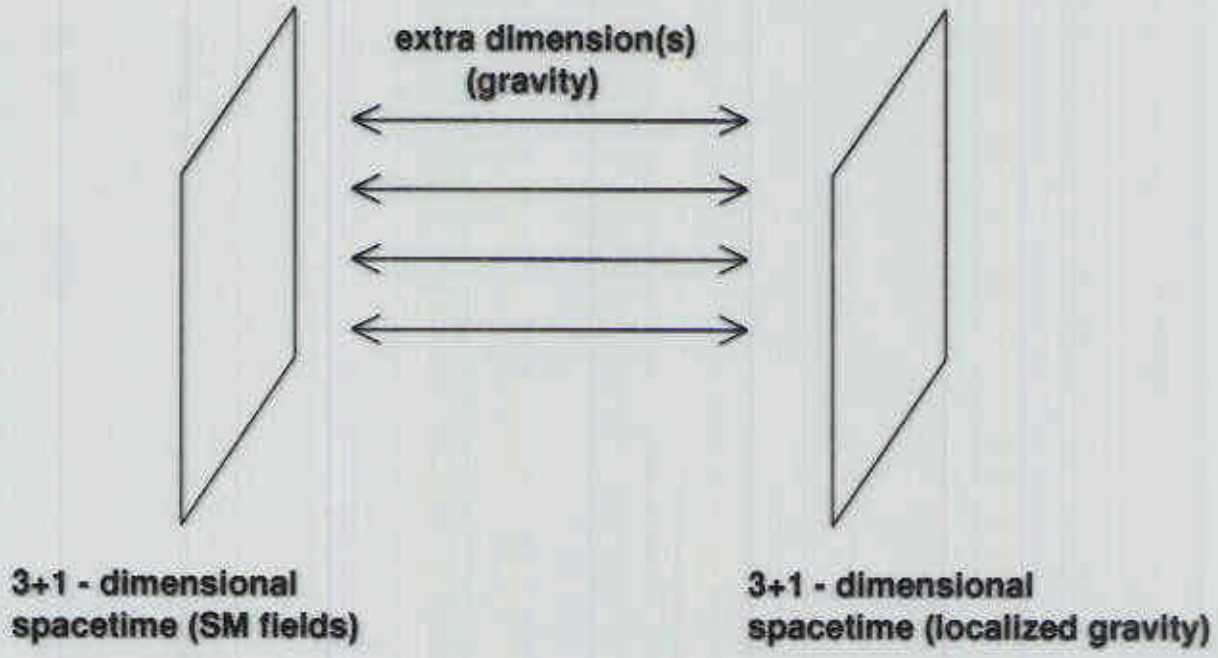
Comparison of the data with the SM predictions



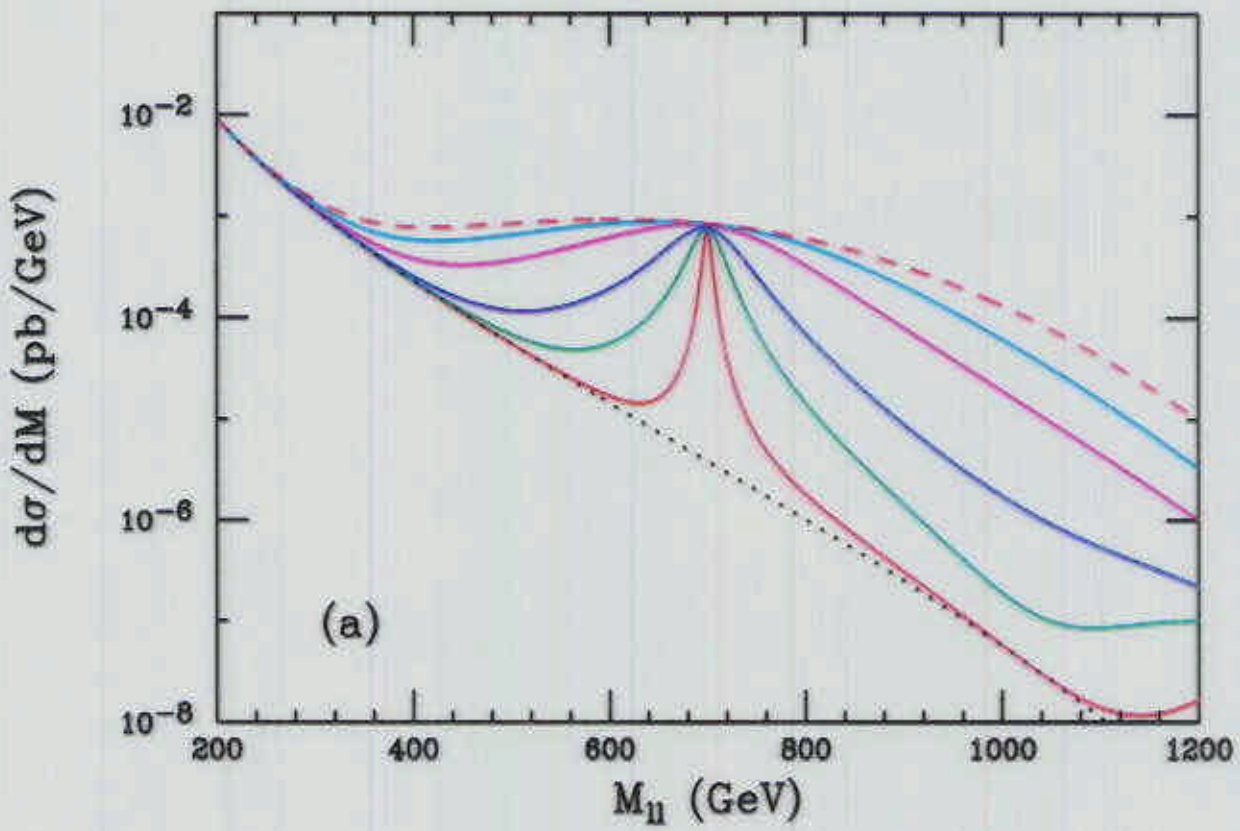
Limits on Large Spatial Extra Dimensions



Randall-Sundrum model

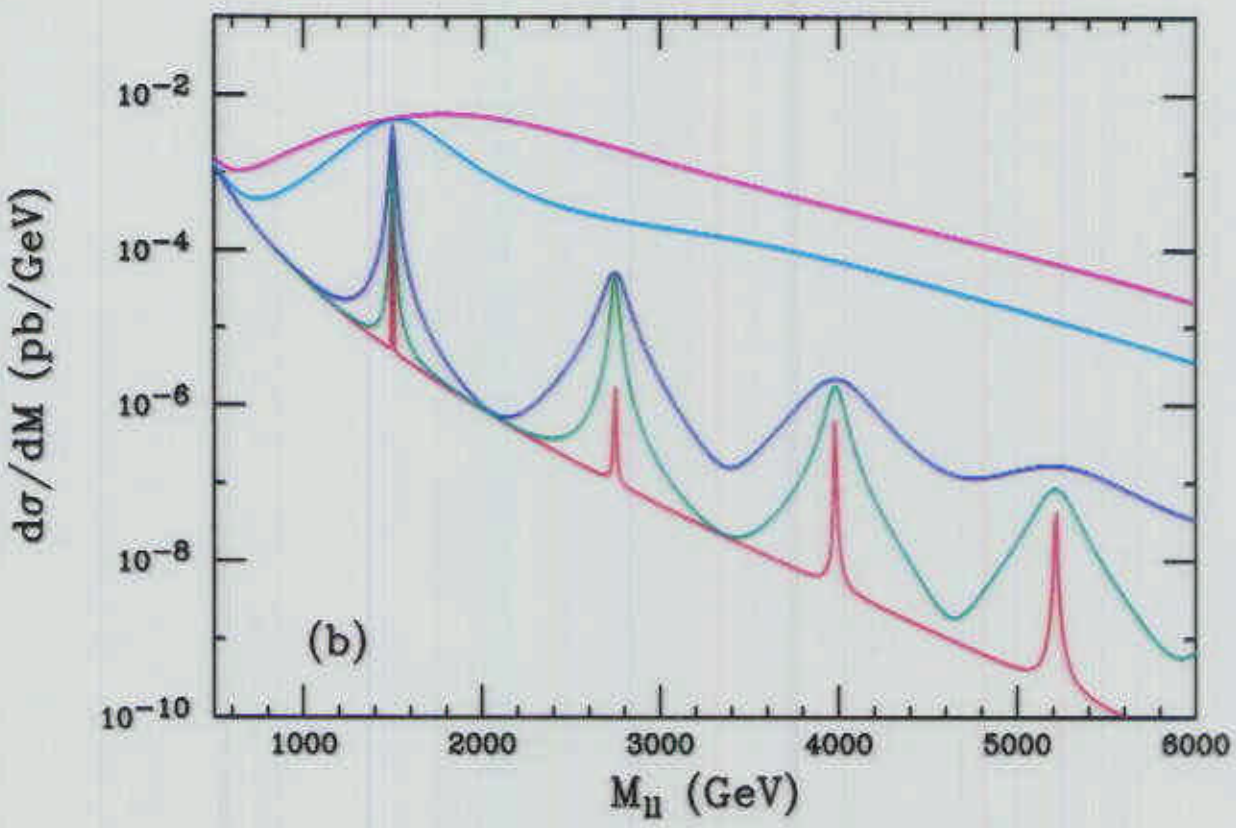


R-S model leads to striking $f\bar{f}$ resonances at the Tevatron...



Davoudiasl, Hewett, Rizzo, Phys. Rev. Lett. 84: 2080 (2000)

... and at the LHC



→ If Cavendish-type experiments do not rule out these models, Tevatron and LHC will have a lot to look for!

What is a 95% CL limit anyway?

No signals...plenty of time to discuss statistics!

Experiments diverging on methods for setting limits.

$$P(data|hypothesis) \neq P(hypothesis|data)$$

Two workshops held (CERN, FNAL) to try to work toward standards.

(One eminent participant wondered why we were not seeing the expected 5% false negatives!!)

Workshop participants agreed on need to base standard method on likelihood, but stopped short of endorsing

- Bayesian,
- Feldman-Cousins,
- CL_s,
- etc. ...

Lots of results not covered here!

- technicolor, compositeness (Tevatron)
- lepton flavor violation (HERA)
- excited leptons (HERA)
- RPV SUSY (HERA, Tevatron)

→ tons of results, alas all negative

Summary

Exciting time in the search for new particles!

- More data soon from upgraded Tevatron and the collider experiments:
  - effective factor of ~50 sensitivity by 2002
  - follow up hints from Run 1
  - sensitive to Higgs up to 190 GeV...

- more data from HERA on the way
  - more high-p_T muon events?
  - any high-mass resonances?

- LHC will fully explore the TeV scale