

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

John Conway

Rutgers University

ICHEP 2000

Osaka, Japan August 2000

- 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

→ 100 pb⁻¹ 1992-1996

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

→ 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

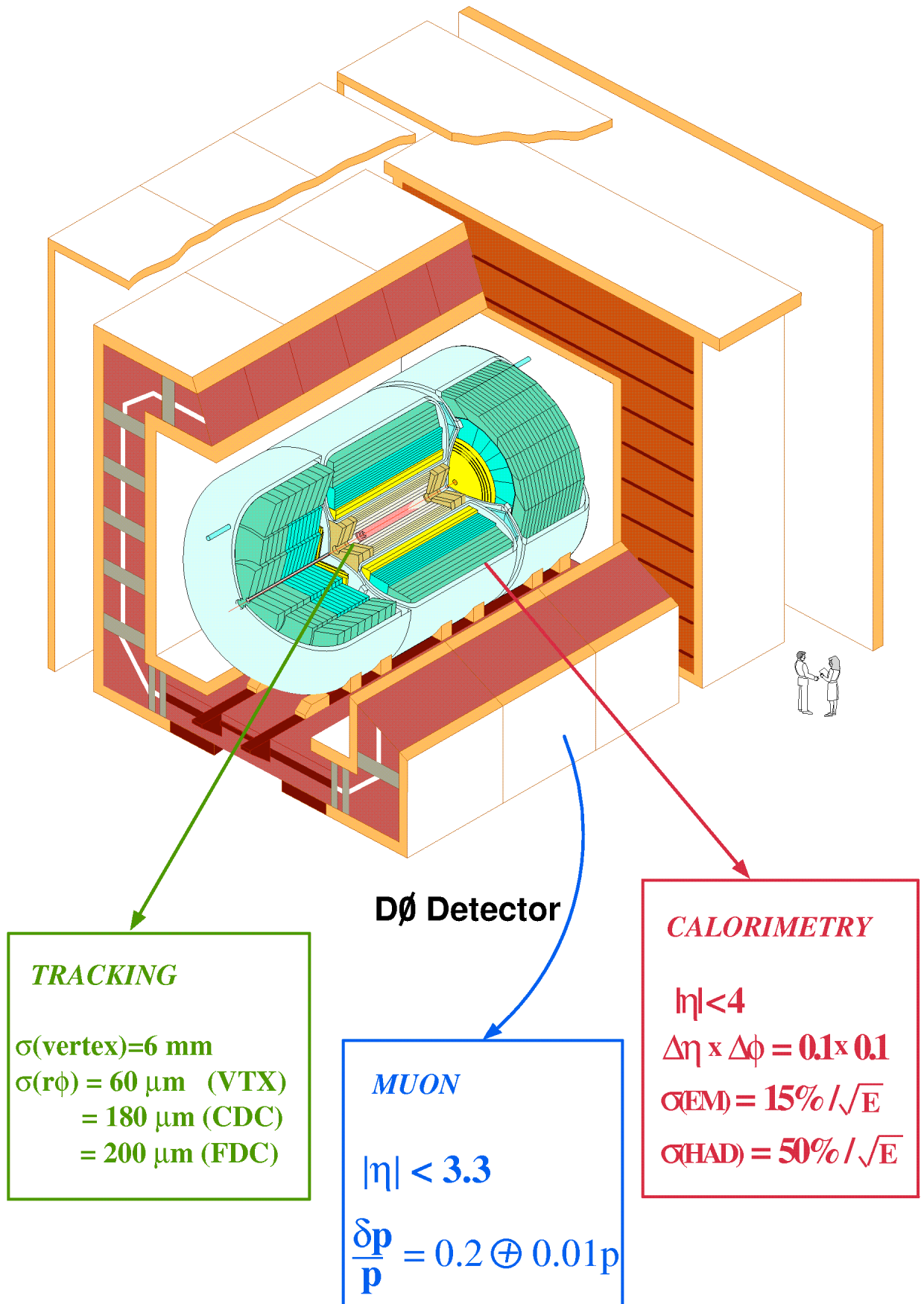
1999-2000: e^+p , 27.6 GeV on 920 GeV, ~ 50 pb⁻¹

LHC at CERN

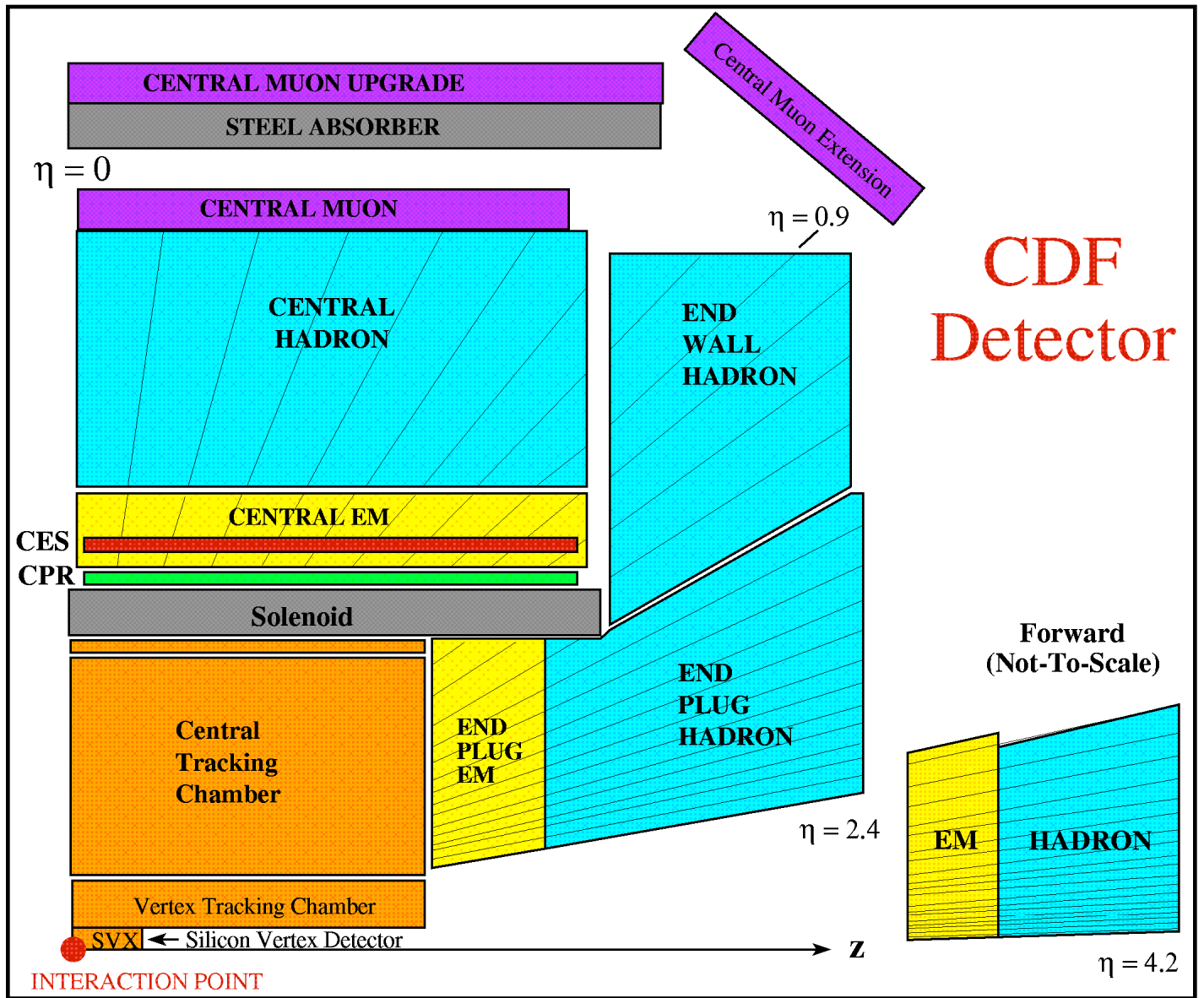
pp collisions at $\sqrt{s} = 14$ TeV starting 2005

30 fb⁻¹/year, increasing to 100 fb⁻¹/year

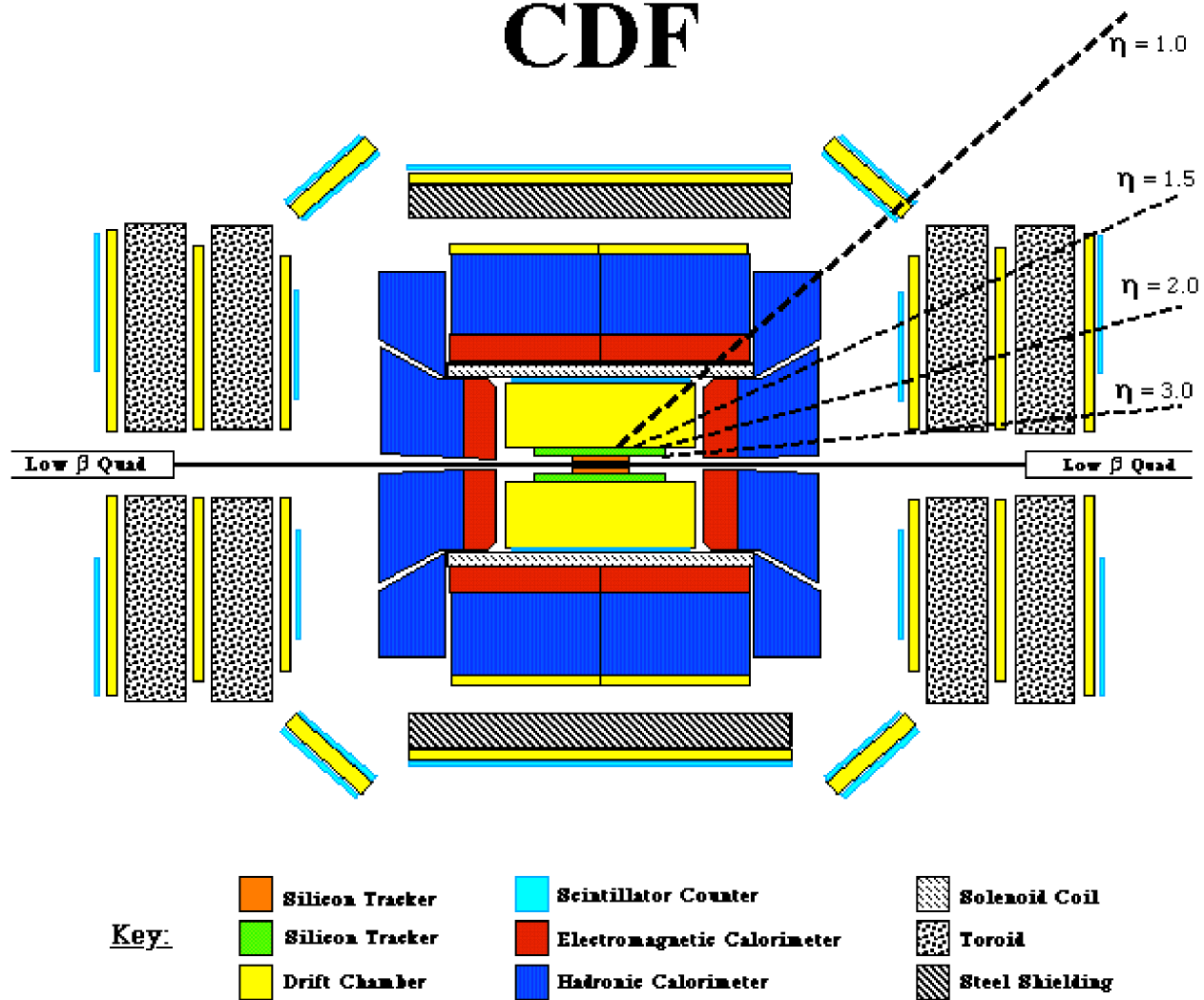
DØ in Run 1:



CDF in Run 1:



CDF



CDF Run 2 Upgrade

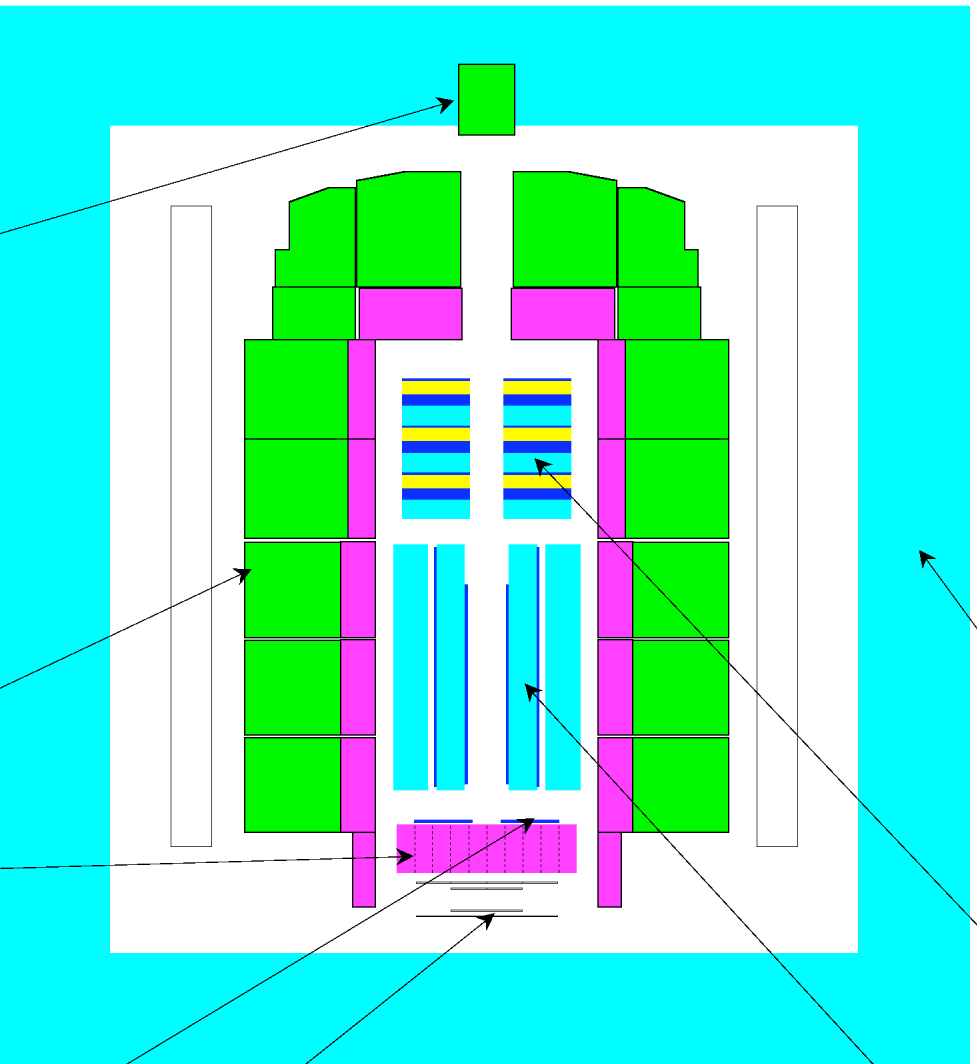
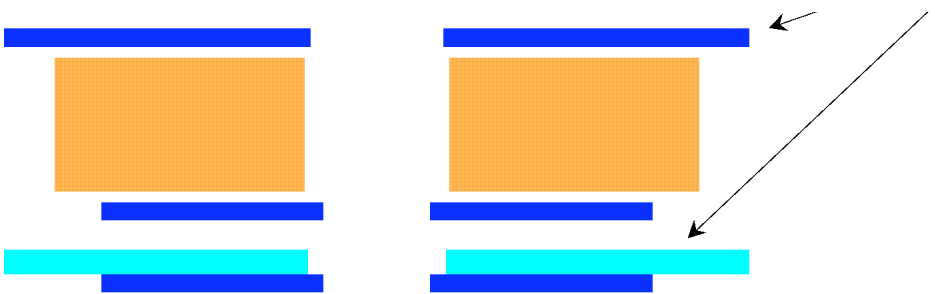
- all-new inner tracking
- new scintillating tile endplug calorimeter
- more muon coverage
- new DAQ/trigger electronics
- new online/offline C++ software

THE H1 DETECTOR

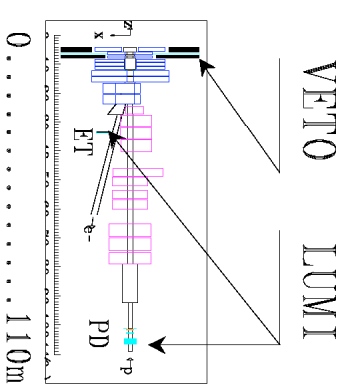
Forward Muon System

Central Muon System

Forward Tracker



Central Tracker



Scintillators

Backward MWPC

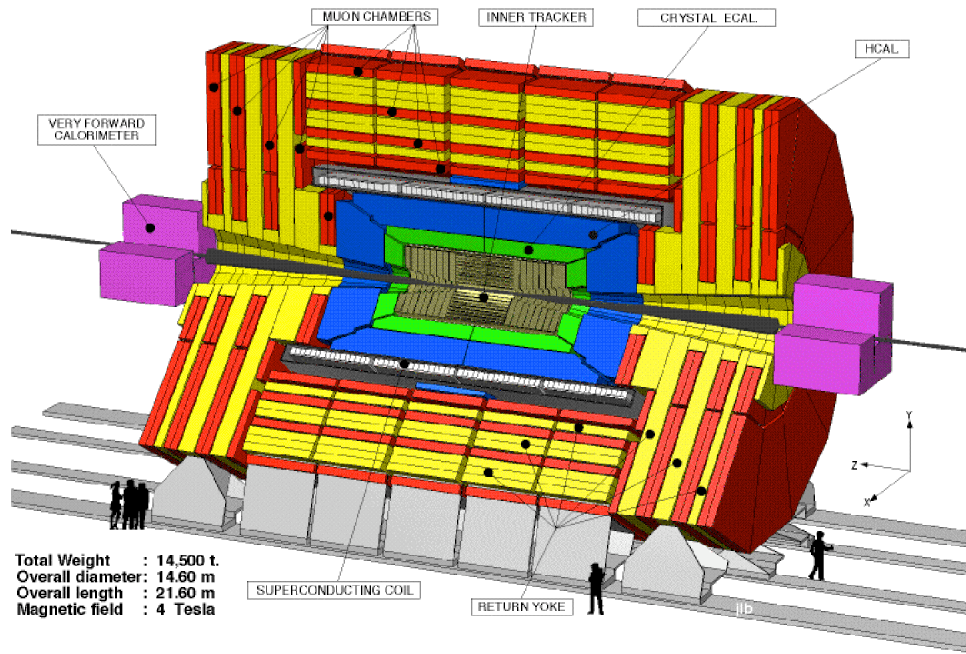
PLUG Calorimeter

LAr Calorimeter

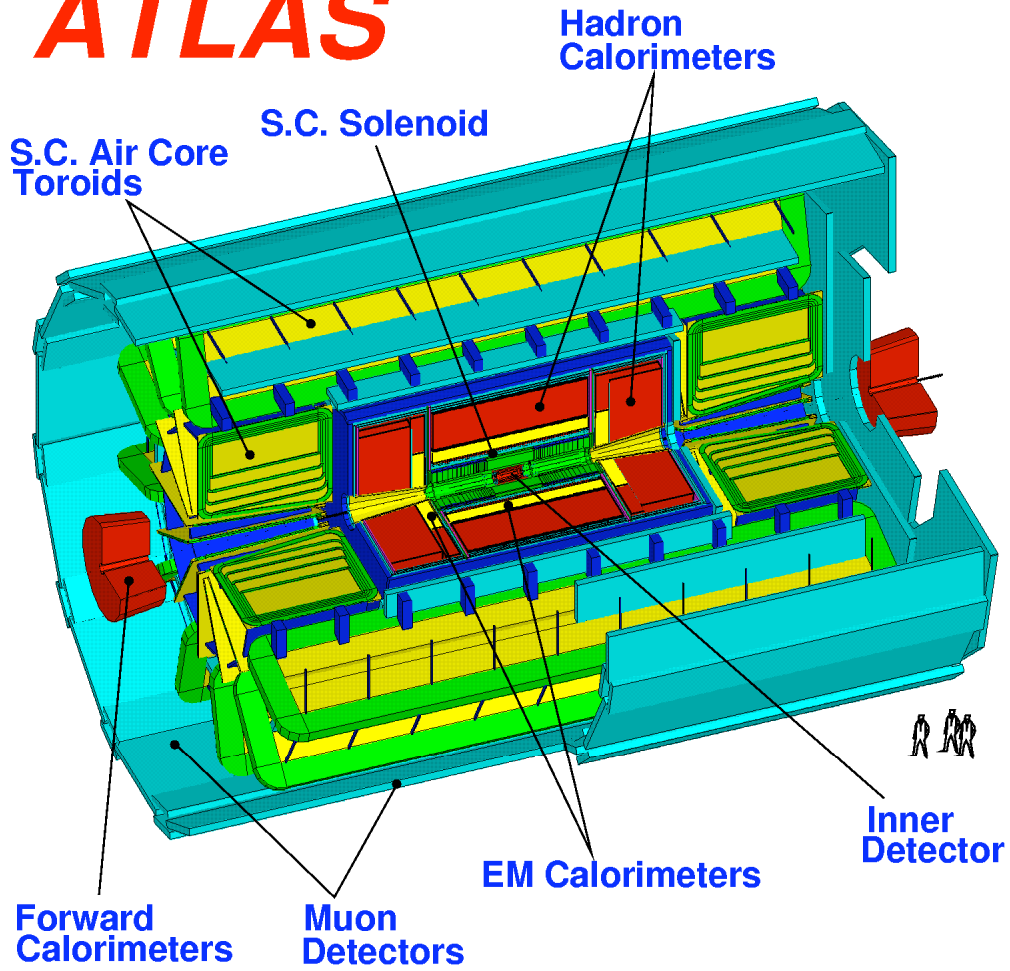
Backward Calorimeter



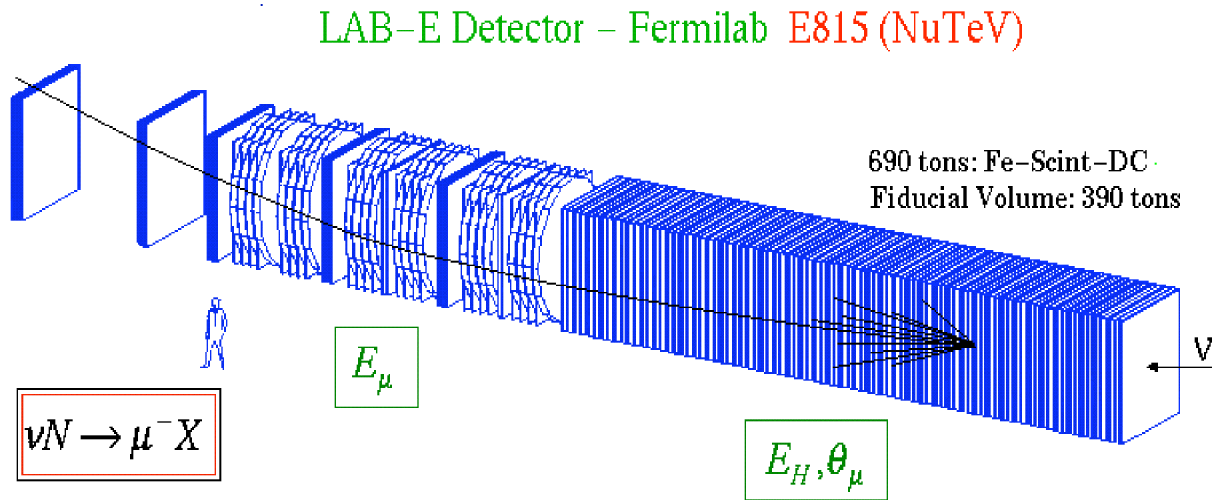
CMS



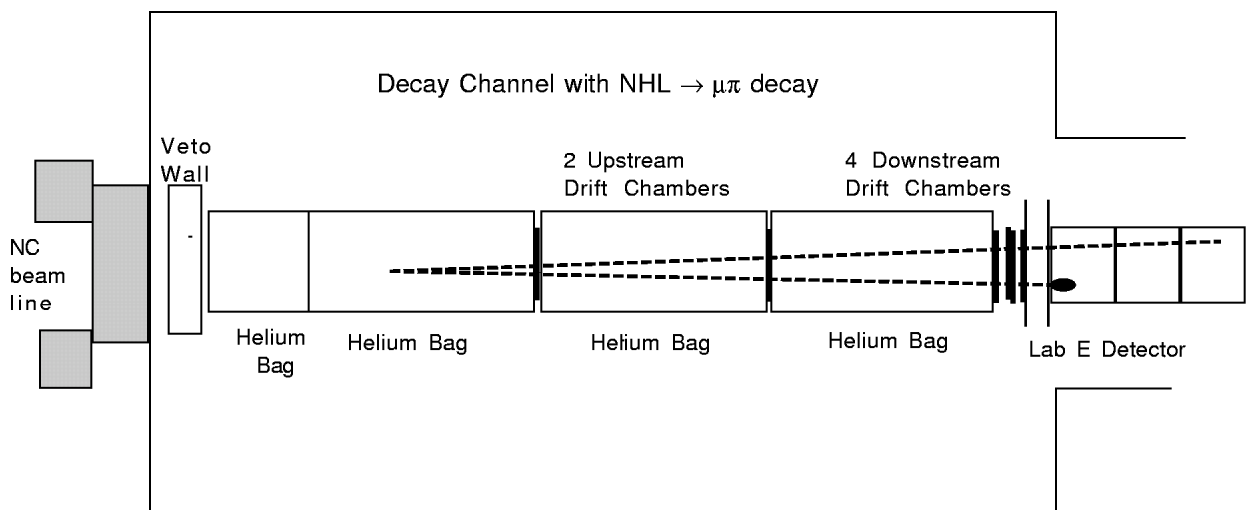
ATLAS



NuTeV Dimuon Anomaly



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



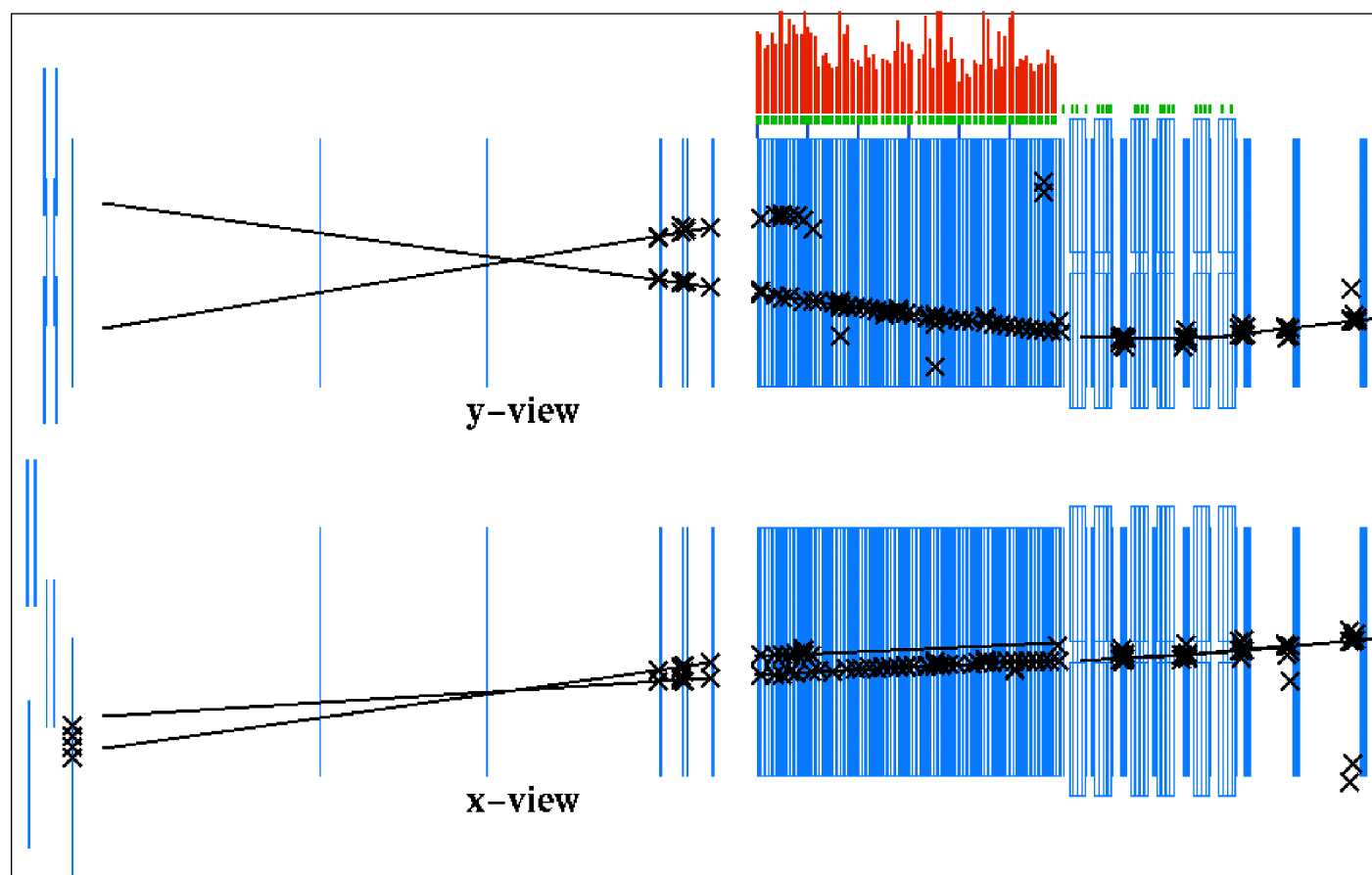
NuTeV has excellent e, mu, pi separation...

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

Run: 5835 Event: 81705 Igate: 1 Date: Wed Jan 22 18:23:07 1997



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 (~ 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:

$\gamma\gamma\gamma$ $\gamma\gamma\ell$ $\gamma\gamma\tau$ $\gamma\gamma j$ $\gamma\gamma b$ $\gamma\gamma\cancel{\tau}$

$\gamma\ell\ell$ $\gamma\ell\tau$ $\gamma\ell j$ $\gamma\ell b$ $\gamma\ell\cancel{\tau}$

$\gamma\tau\tau$ $\gamma\tau j$ $\gamma\tau b$ $\gamma\tau\cancel{\tau}$

$\gamma j j$ $\gamma j b$ $\gamma j\cancel{\tau}$

$\gamma b b$ $\gamma b\cancel{\tau}$

$\ell\ell\ell$ $\ell\ell\tau$ $\ell\ell j$ $\ell\ell b$ $\ell\ell\cancel{\tau}$

$\ell\tau\tau$ $\ell\tau j$ $\ell\tau b$ $\ell\tau\cancel{\tau}$

$\ell j j$ $\ell j b$ $\ell j\cancel{\tau}$

$\ell b b$ $\ell b\cancel{\tau}$

$\tau\tau\tau$ $\tau\tau j$ $\tau\tau b$ $\tau\tau\cancel{\tau}$

$\tau j j$ $\tau j b$ $\tau j\cancel{\tau}$

$\tau b b$ $\tau b\cancel{\tau}$

$j j j$ $j j b$ $j j\cancel{\tau}$

$j b b$ $j b\cancel{\tau}$

$b b b$ $b b\cancel{\tau}$

Any hints in existing data?

- CDF: a light “sbottom” ?
- CDF: $e \cancel{e} \gamma \gamma$ 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

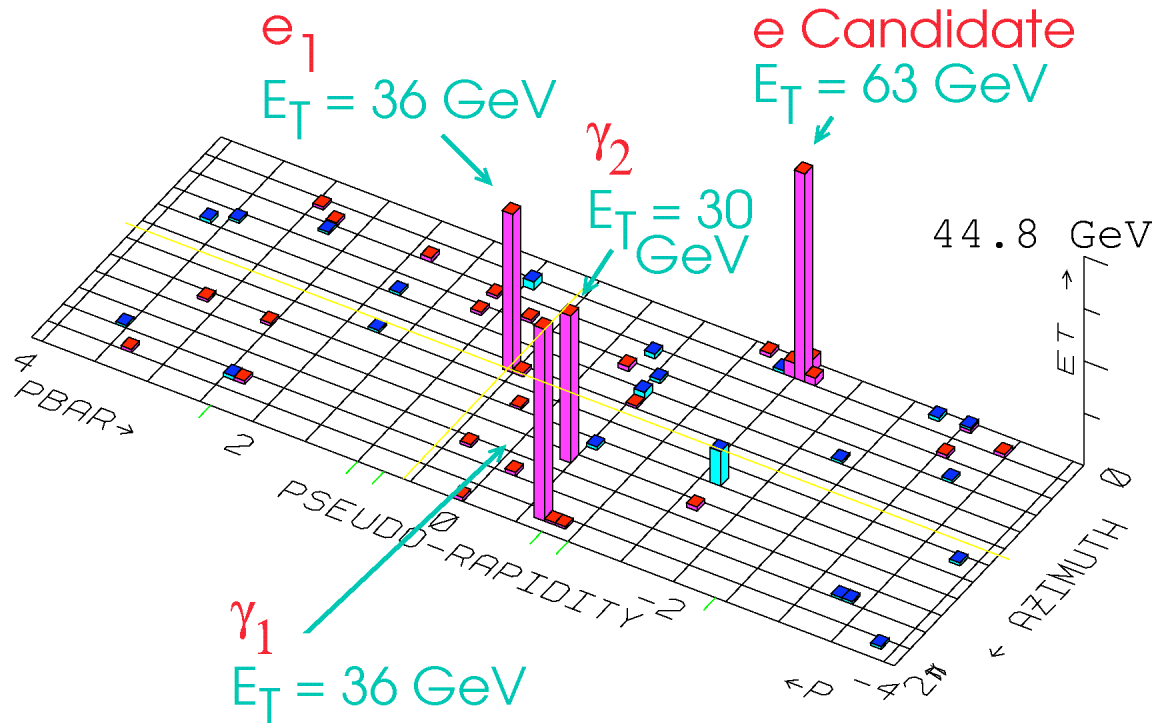
CDF: light sbottom?

- hypothetical new light scalar quark:

$$\tilde{b} \rightarrow cl\tilde{\nu} \text{ with } 100\% \text{ BR}$$

- 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"

$e\bar{e}\gamma\gamma E_T$ Candidate Event

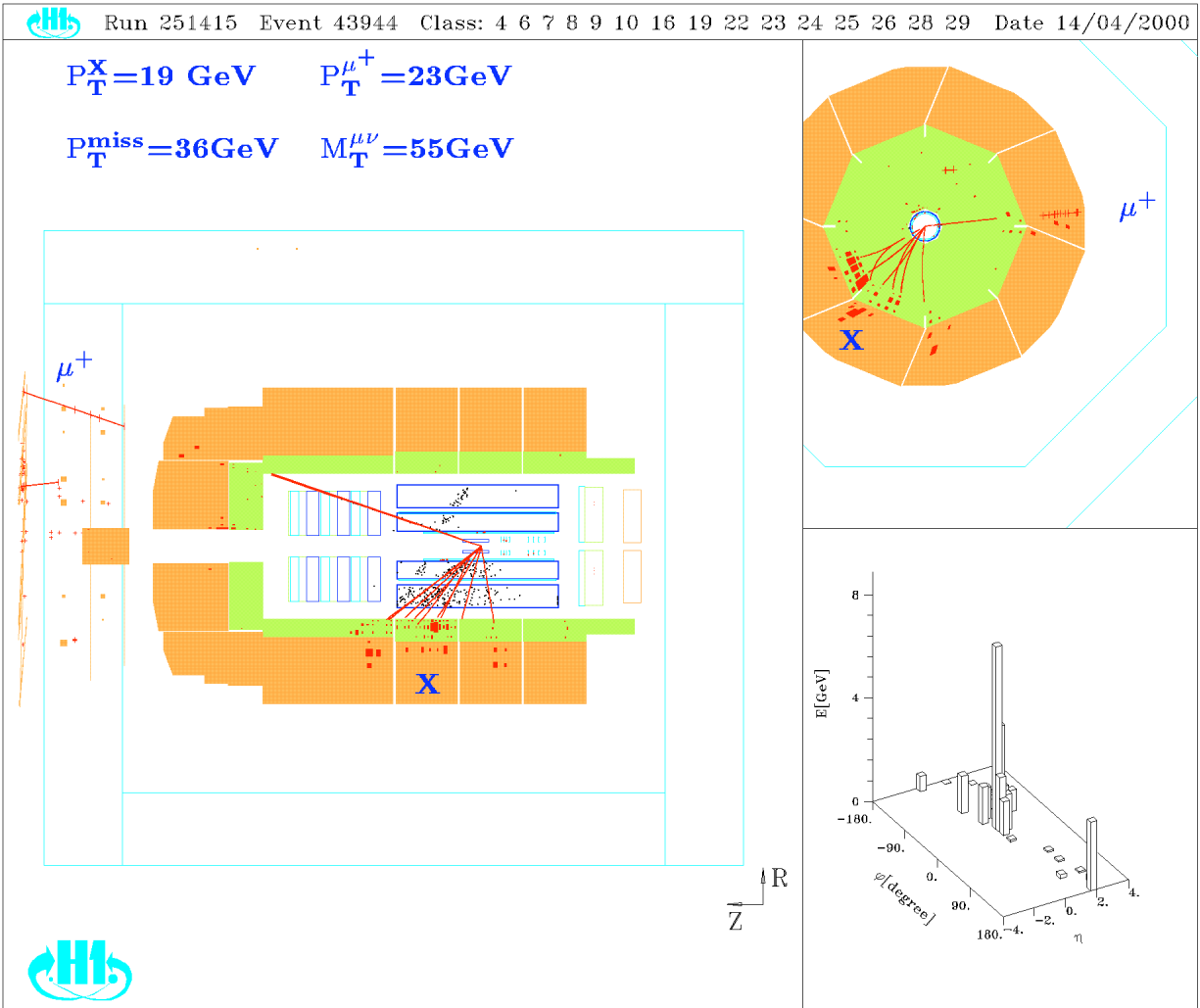
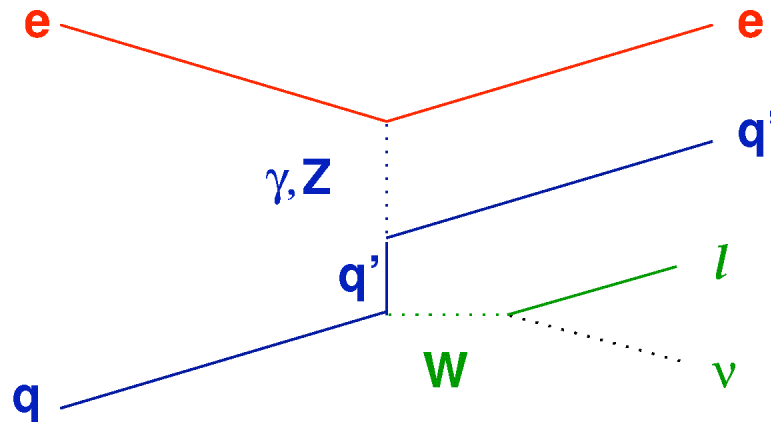


$$E_T = 55 \text{ GeV}$$

- five “objects” in event
- expect $\mathcal{O}(10^{-6})$ such events (a posteriori!)
- searched for $\gamma\gamma E_T$ inclusively
- interesting result soon on $l\gamma E_T$
- need more data!

HERA: High- p_T Isolated Leptons

Can produce W directly in ep collisions:



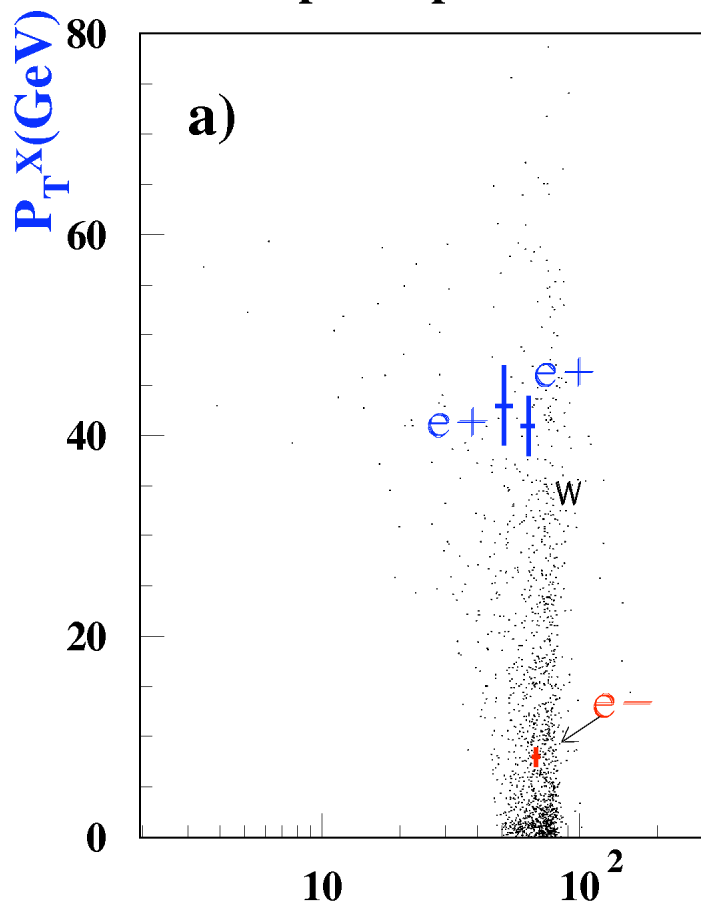
H1,ZEUS 1994-1997 dataset:

channel	H1	ZEUS
e	1	3
μ	5	0

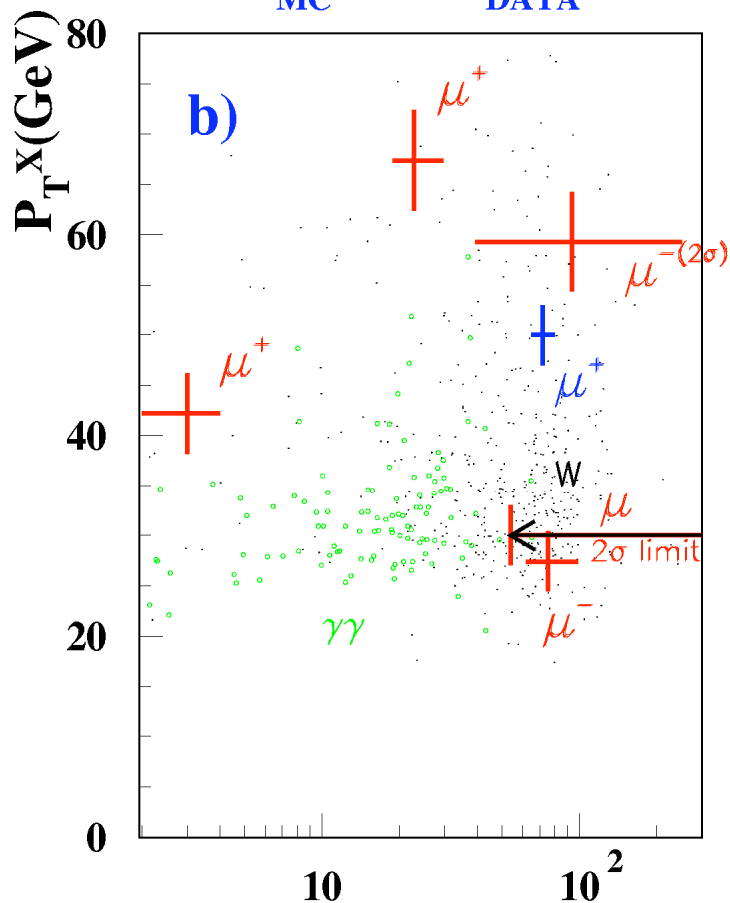
H1,ZEUS 1998-1999 dataset:

channel	H1	ZEUS
e	0	2
μ	0	0

H1 $61.4\text{pb}^{-1} e^+p$ data 94-00

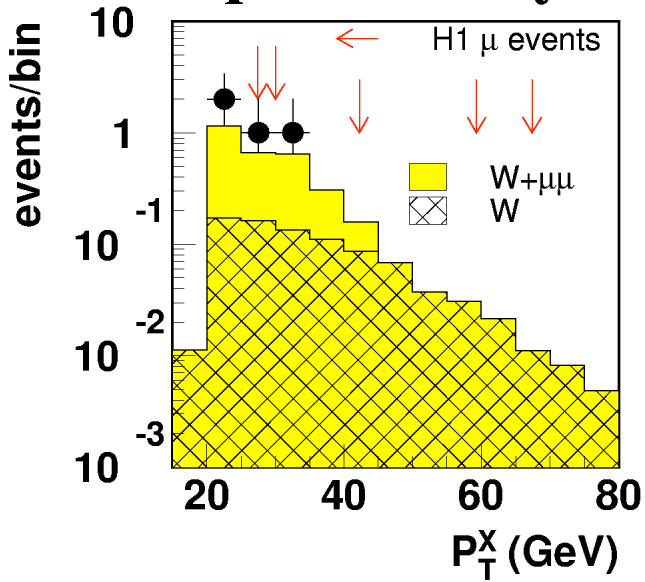


$L_{MC}=500*L_{DATA}$

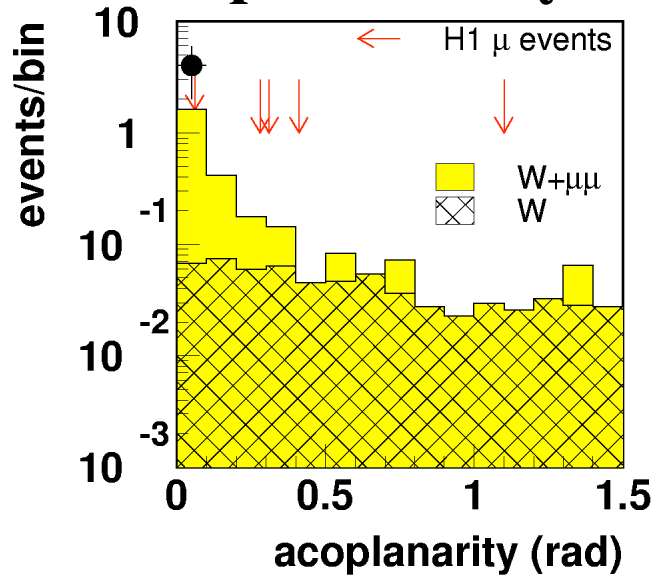


ZEUS final distributions

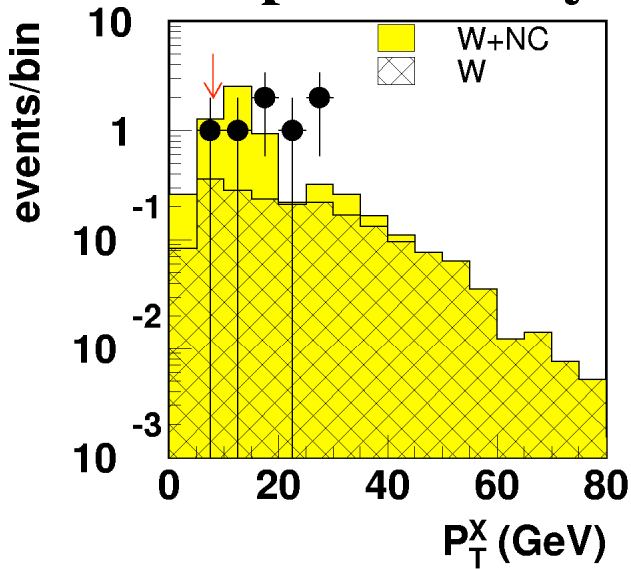
ZEUS 1994-1999 preliminary



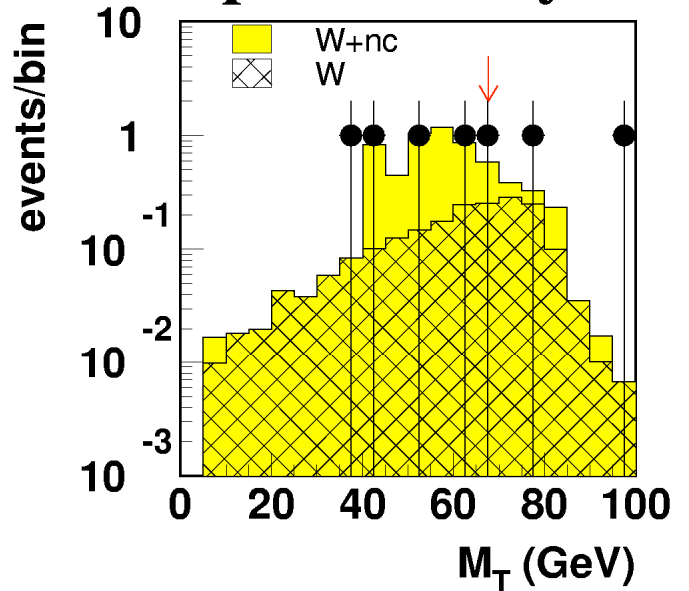
ZEUS 1994-1999 preliminary



ZEUS 1994-1999 preliminary



ZEUS 1994-1999 preliminary



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!

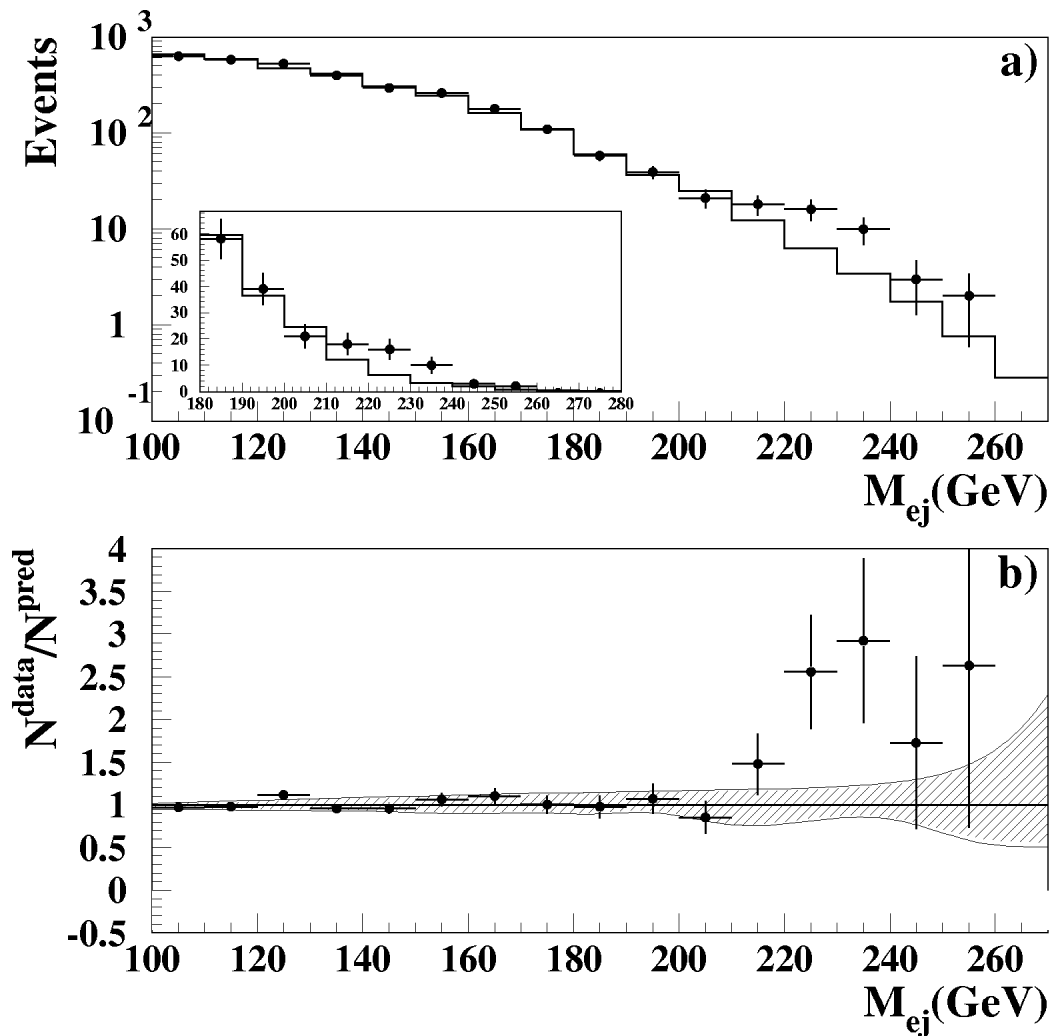
→ need more data to shed light here...

CDF/DØ High- E_T Jet Excess

HERA High- Q^2 Excess

ZEUS: search for resonances in e^+p

ZEUS 1994-97

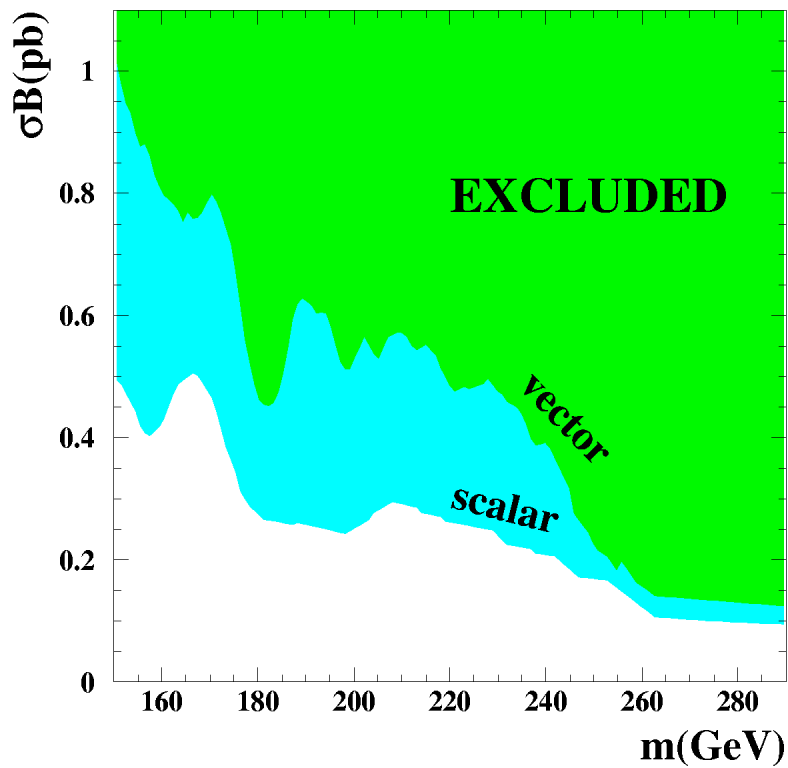


→ see 49 events, expect 25 ± 6 , with $M_{ej} > 210$ GeV

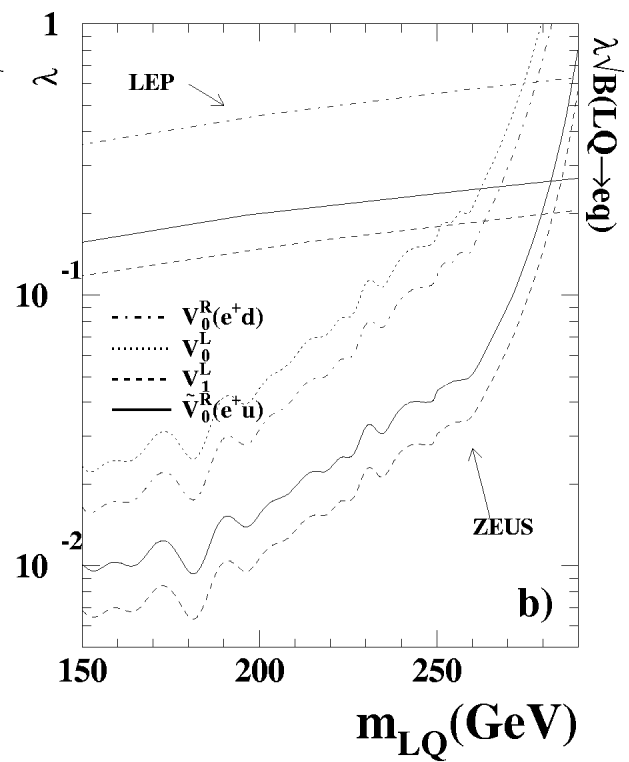
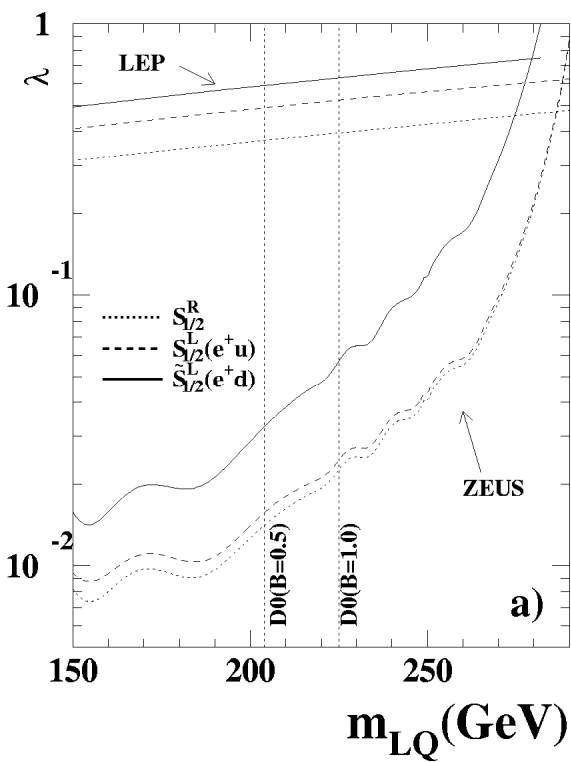
→ angular distribution similar to NC DIS process

→ limits on scalar, vector resonances:

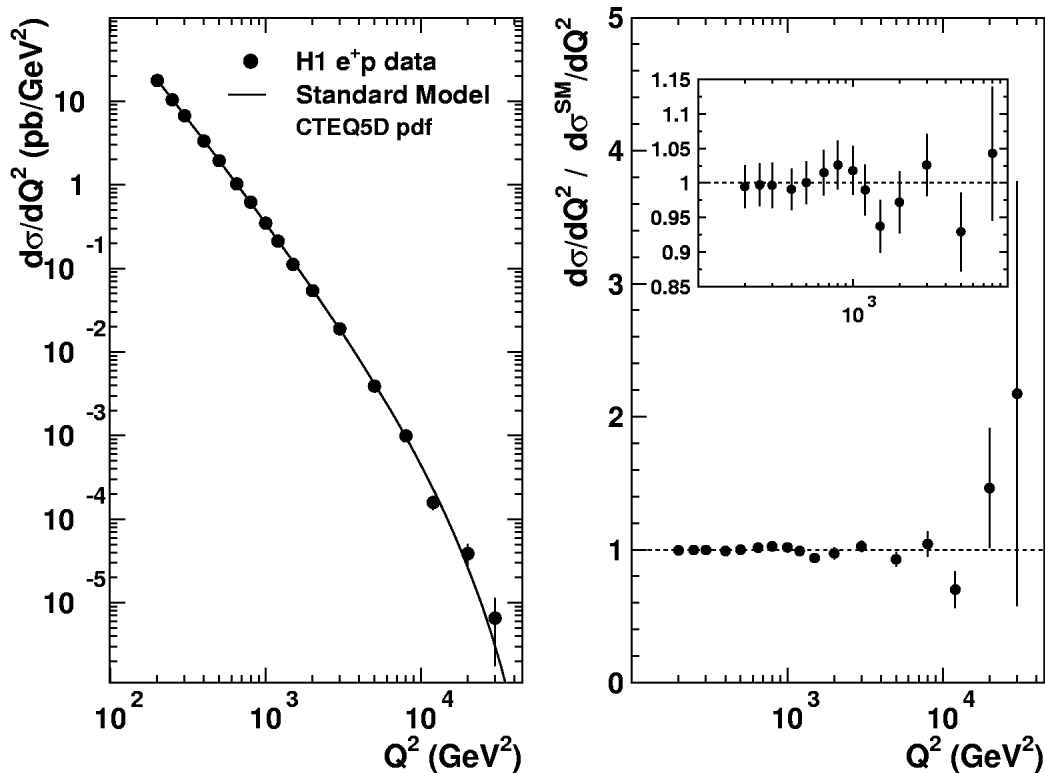
ZEUS 1994-97



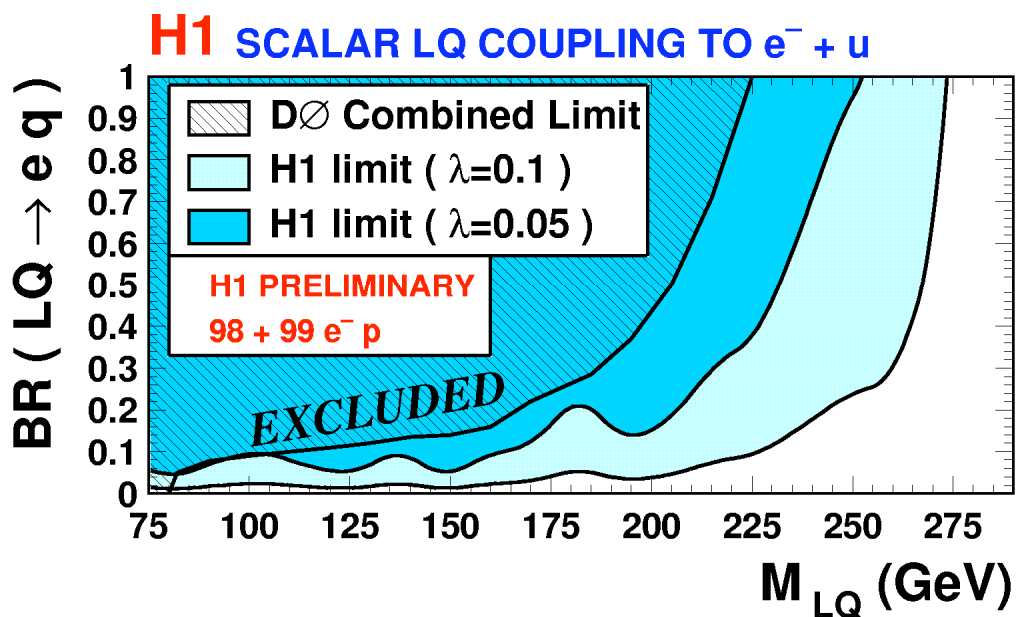
ZEUS 1994-97



H1 e^+p NC data/SM ratio:

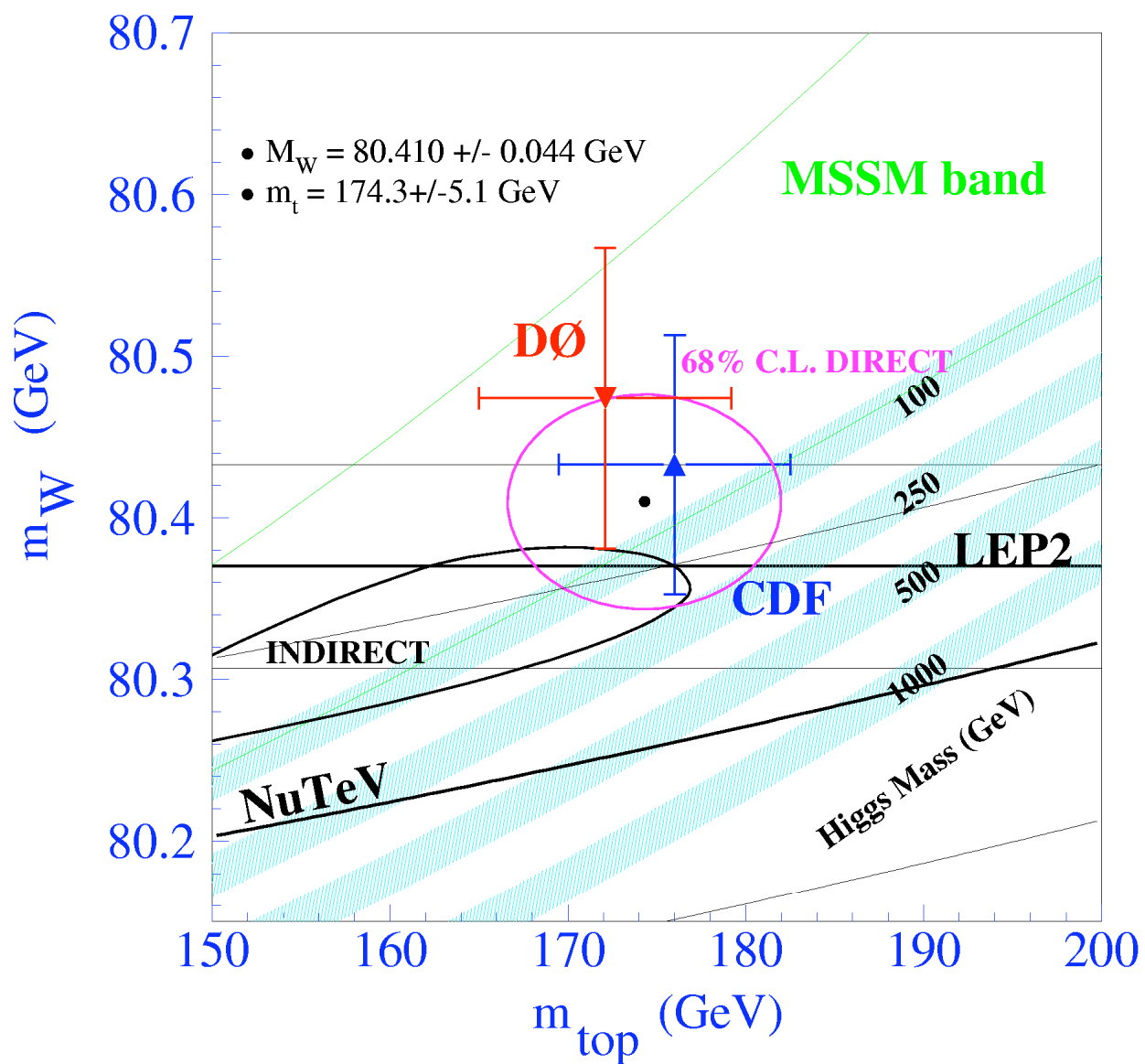


limits on compositeness, large extra dimensions, LQ:



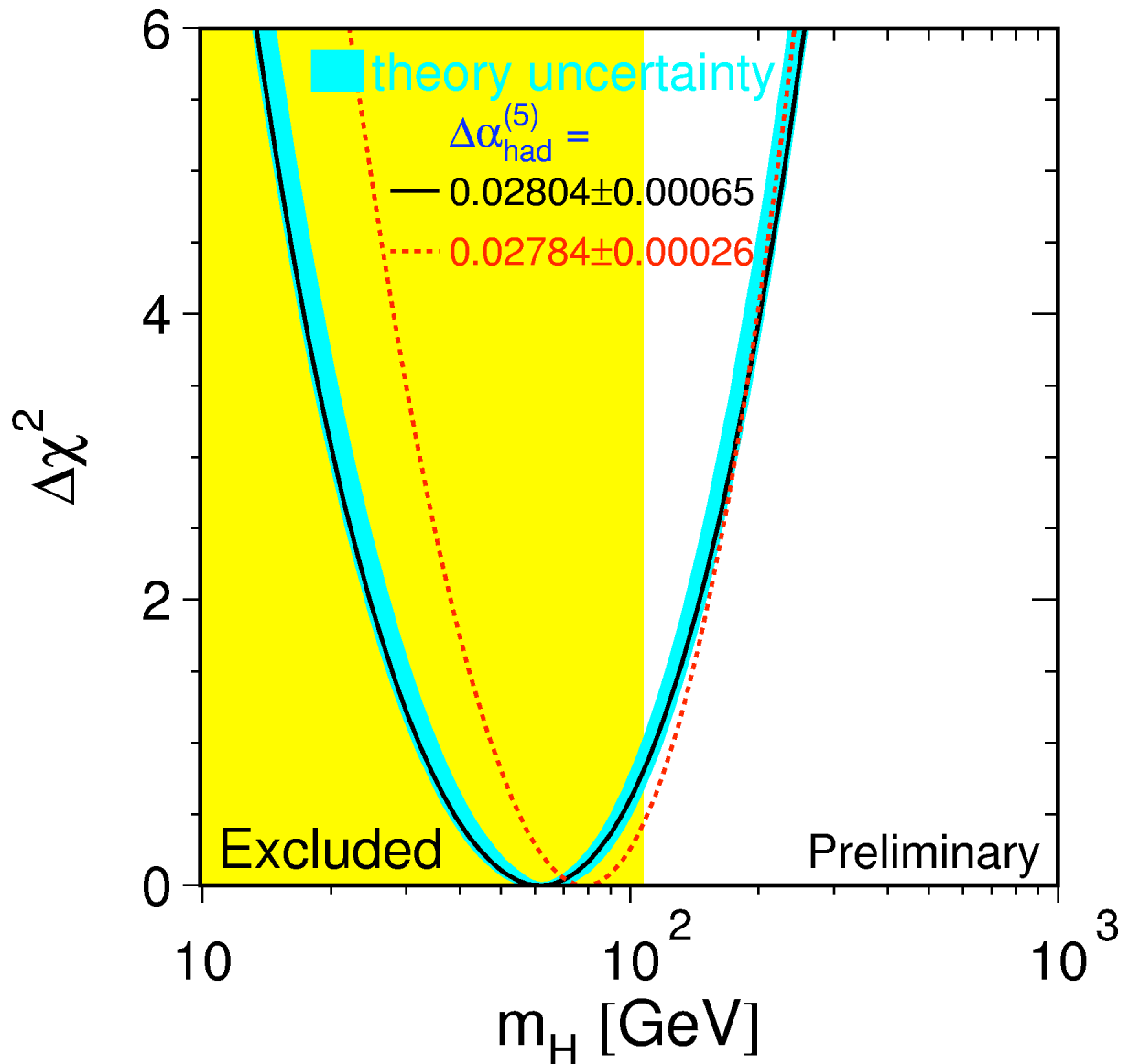
Higgs Search

CDF/DØ Run 1 top and W mass:



World's combined electroweak measurements

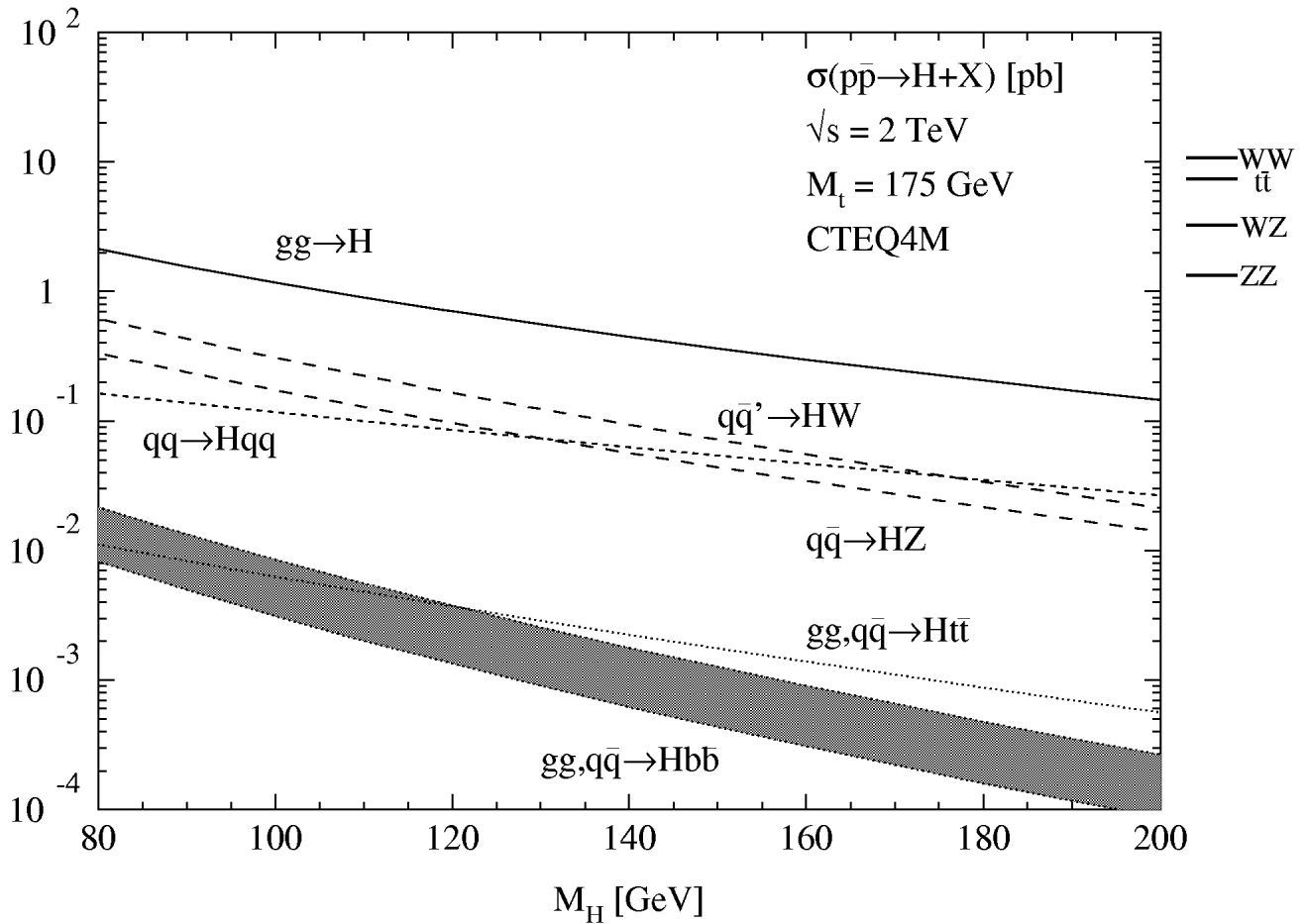
July 2000:



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

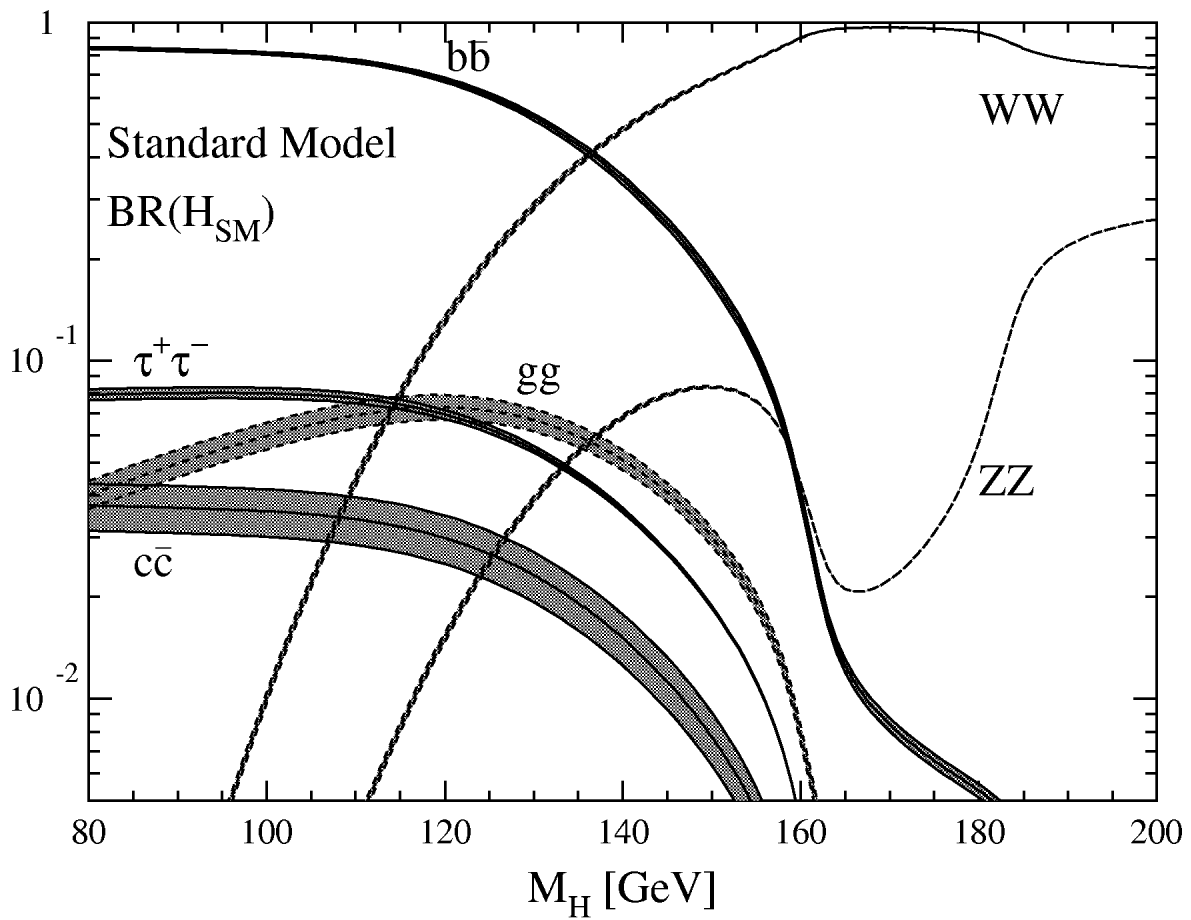
Standard Model Neutral Higgs searches

Higgs production rates at the Tevatron:



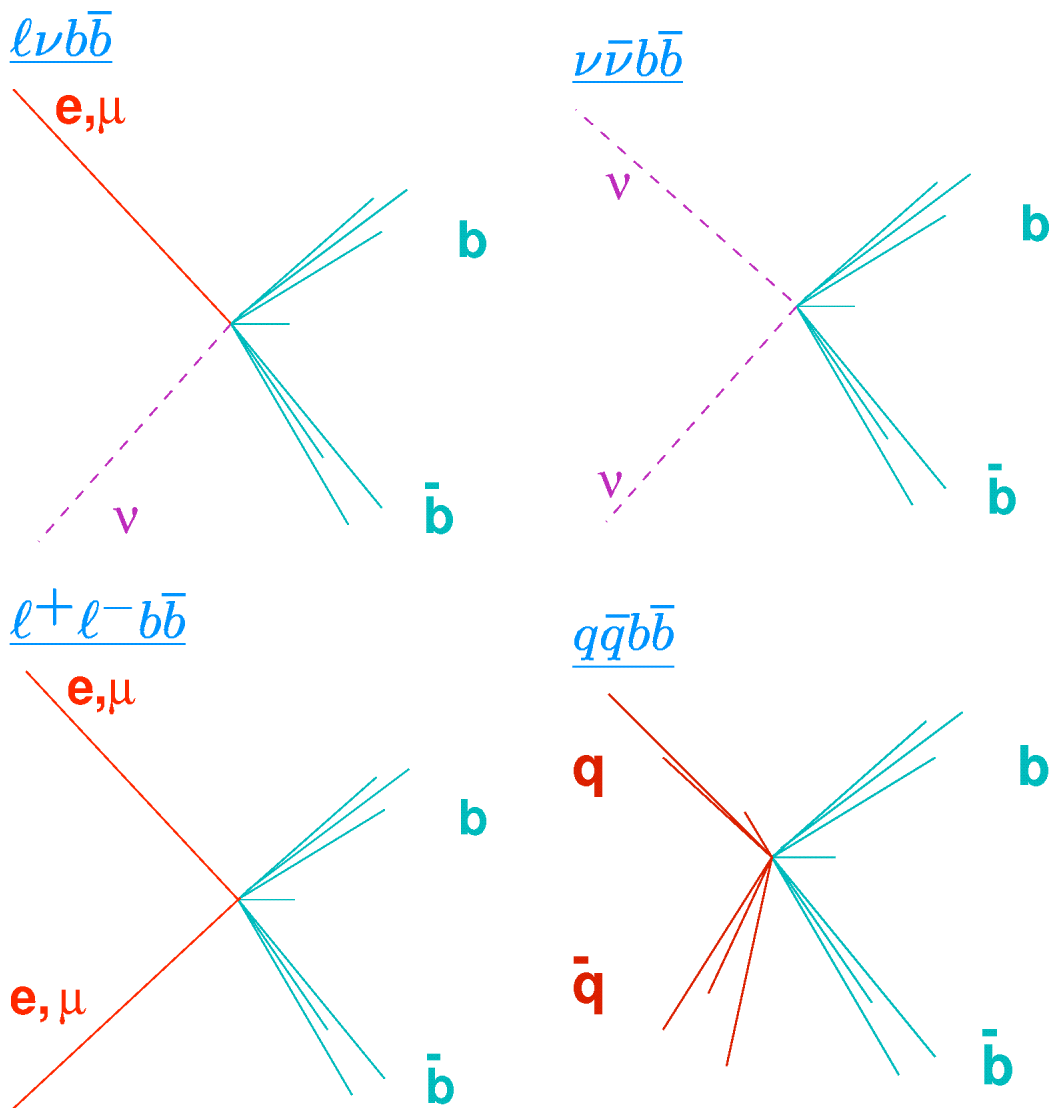
- $gg \rightarrow H$ dominates, but very difficult to see
- WH, ZH are most accessible
- SUSY enhances some cross sections!

SM Higgs branching ratios:



Difficult crossover region near 135 GeV mass!

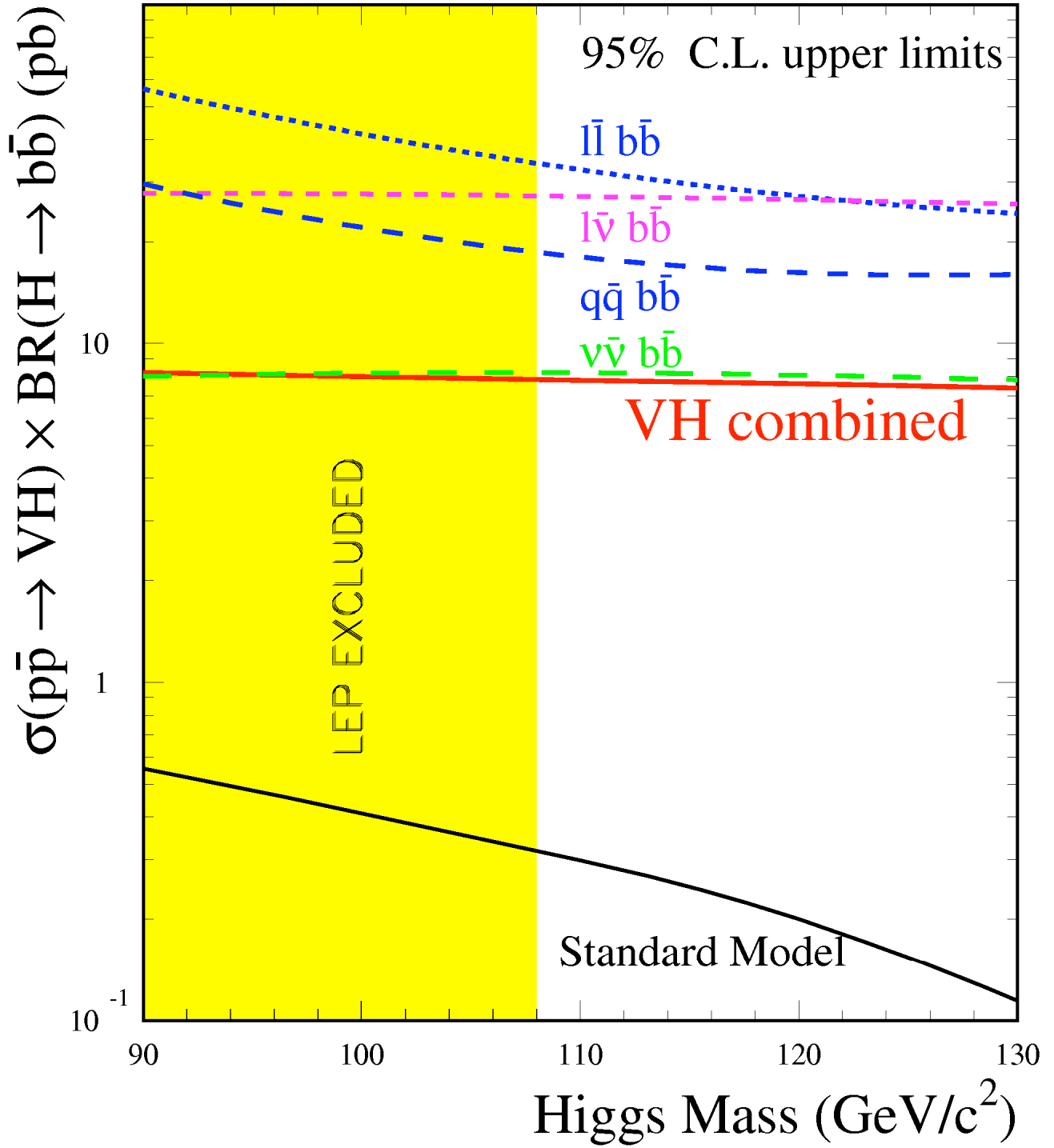
Low mass SM Higgs channels



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

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

CDF PRELIMINARY Run I

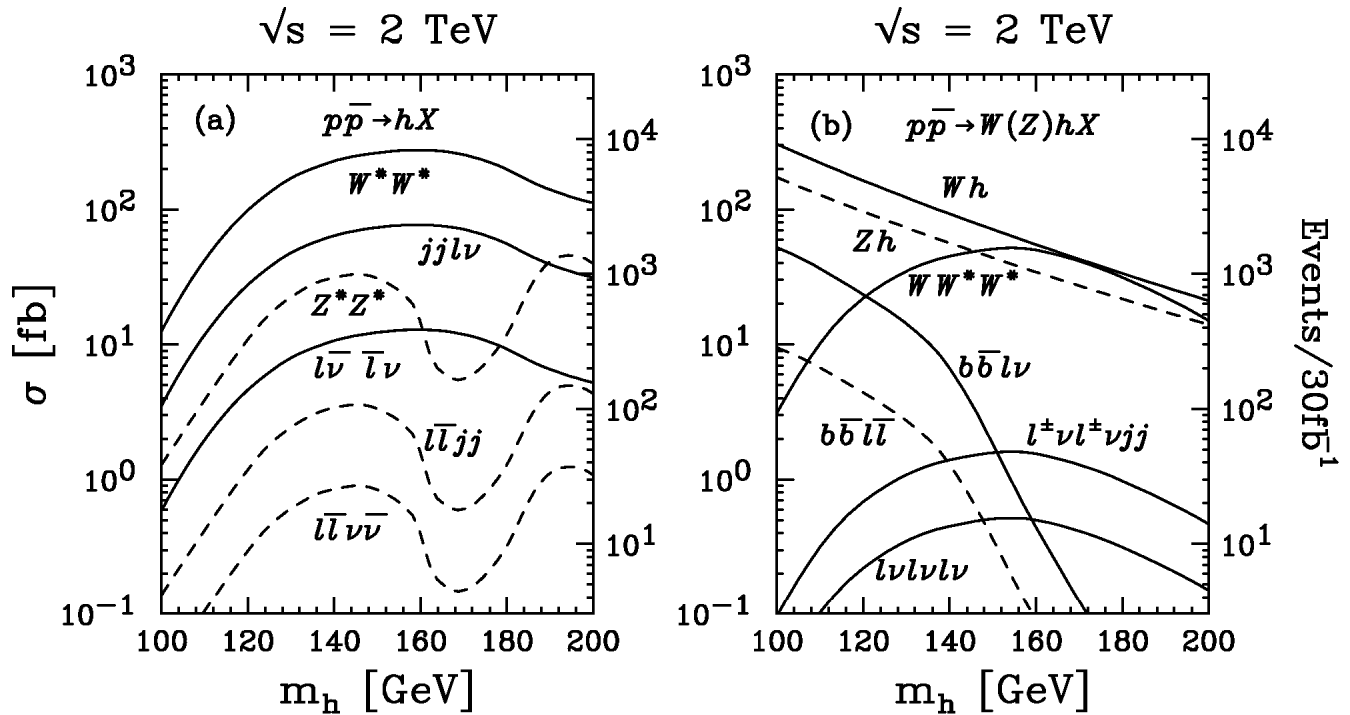


Higgs in Run 2

Low- and high-mass SM Higgs

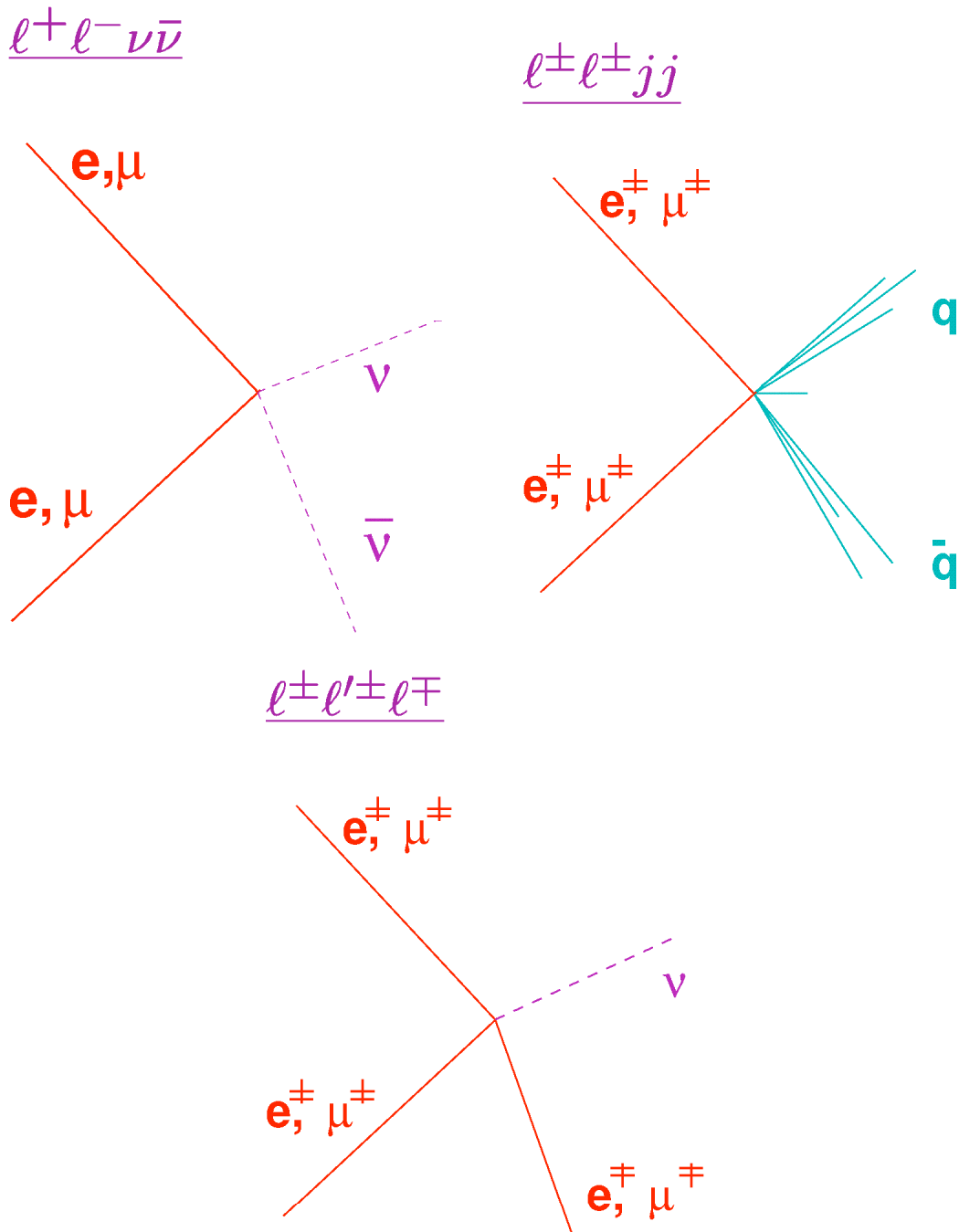
idea: exploit $H \rightarrow WW^*$ decays at higher masses

- $gg \rightarrow H \rightarrow WW^*$
- $ZH \rightarrow ZWW^*$
- $WH \rightarrow WW^*$



→ dilepton, trilepton, like-sign dilepton plus jets

High-mass SM Higgs channels



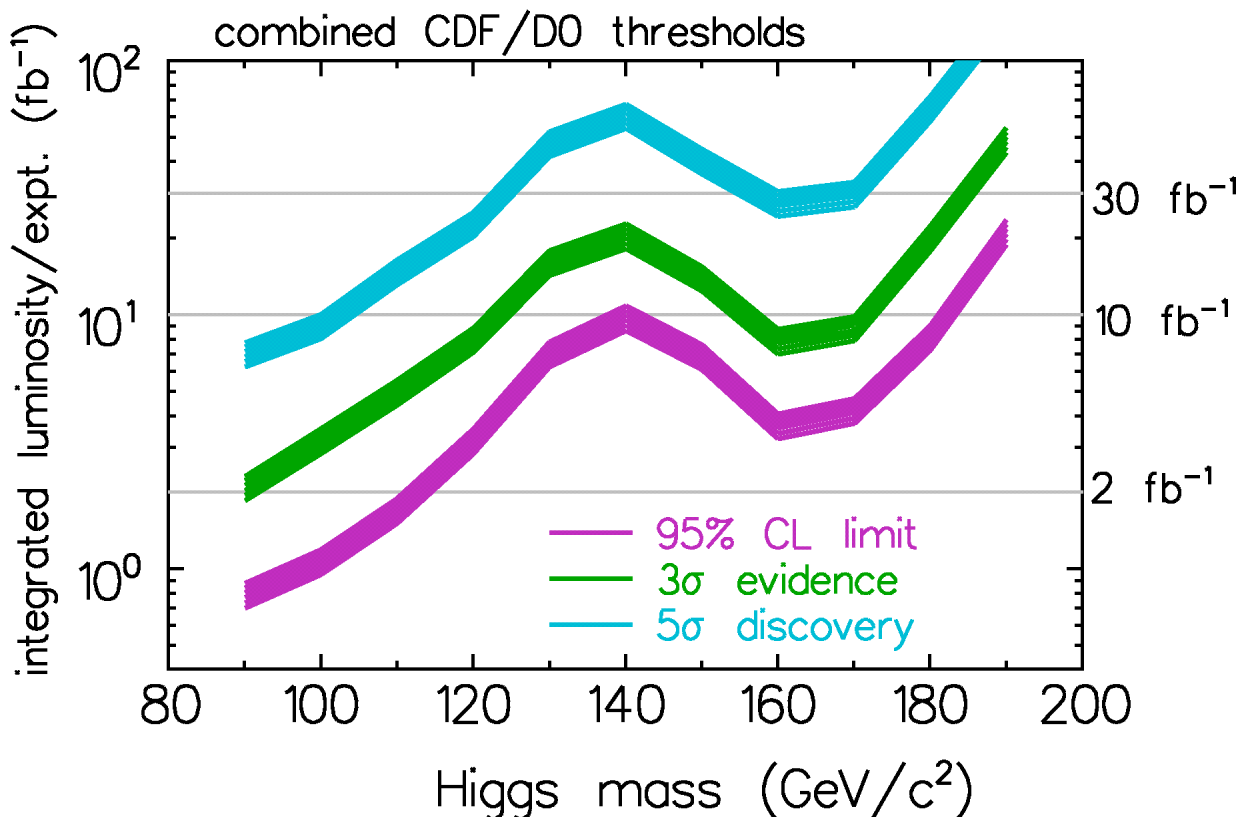
main backgrounds: $WW, WZ, ZZ, t\bar{t}$

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

SM Higgs combined channel thresholds

Tevatron Run 2 SUSY/Higgs Workshop

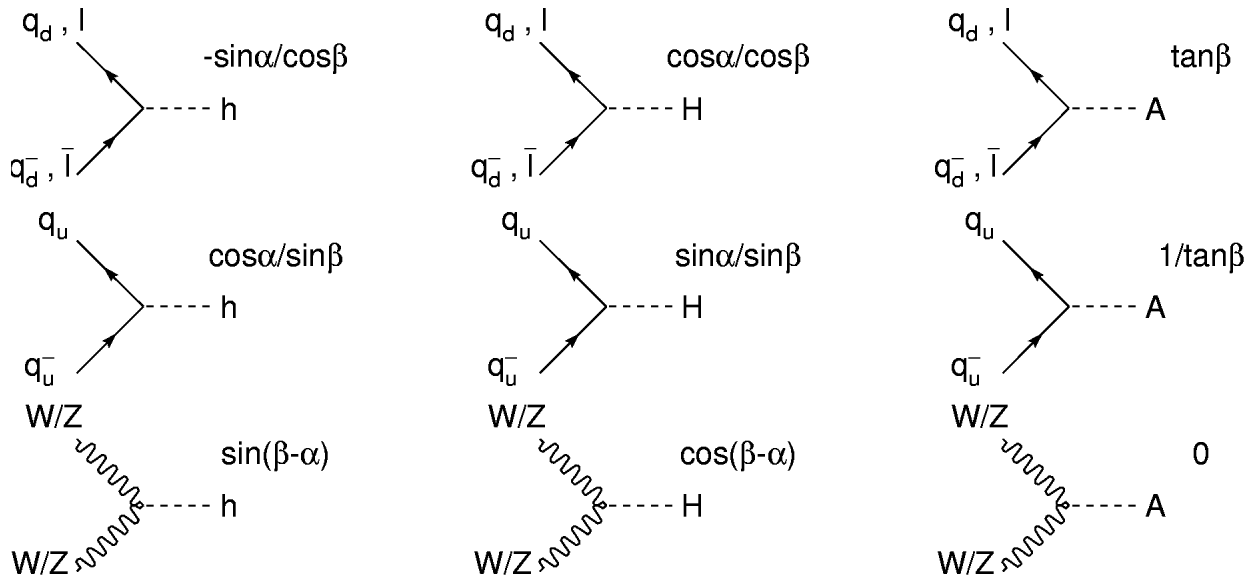
- two experiments combined
- 30% better $m_{b\bar{b}}$ resolution than Run 1
- neural network selection
- nominal systematic errors: 10% or $1/\sqrt{LB}$



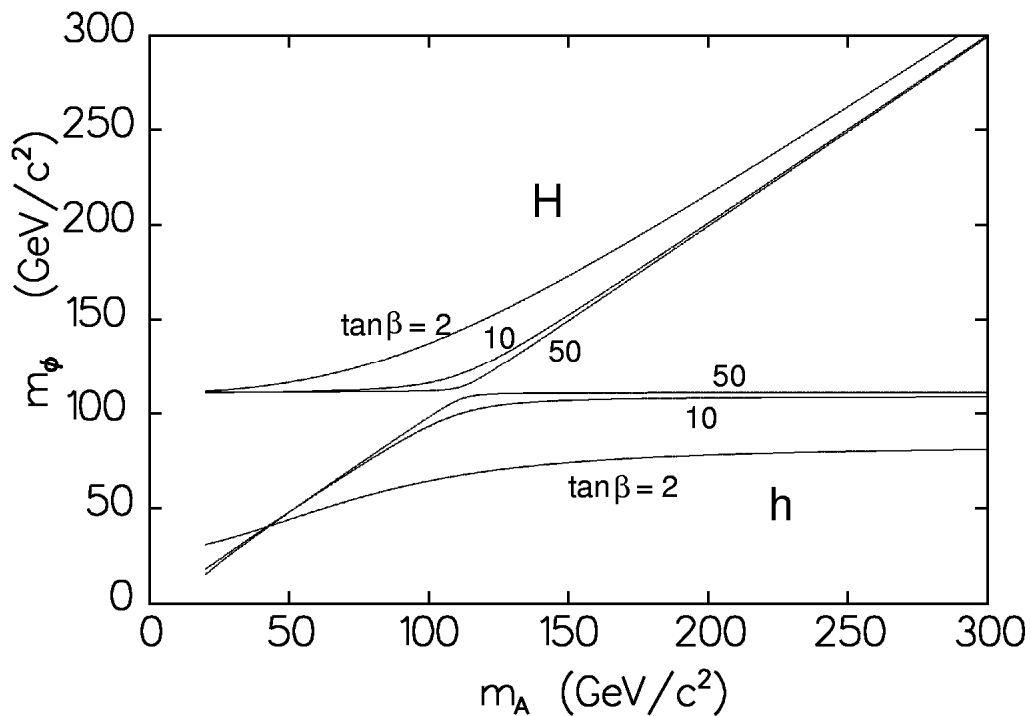
→ bands represent level of “uncertainty” in estimates

SUSY Higgs (MSSM)

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

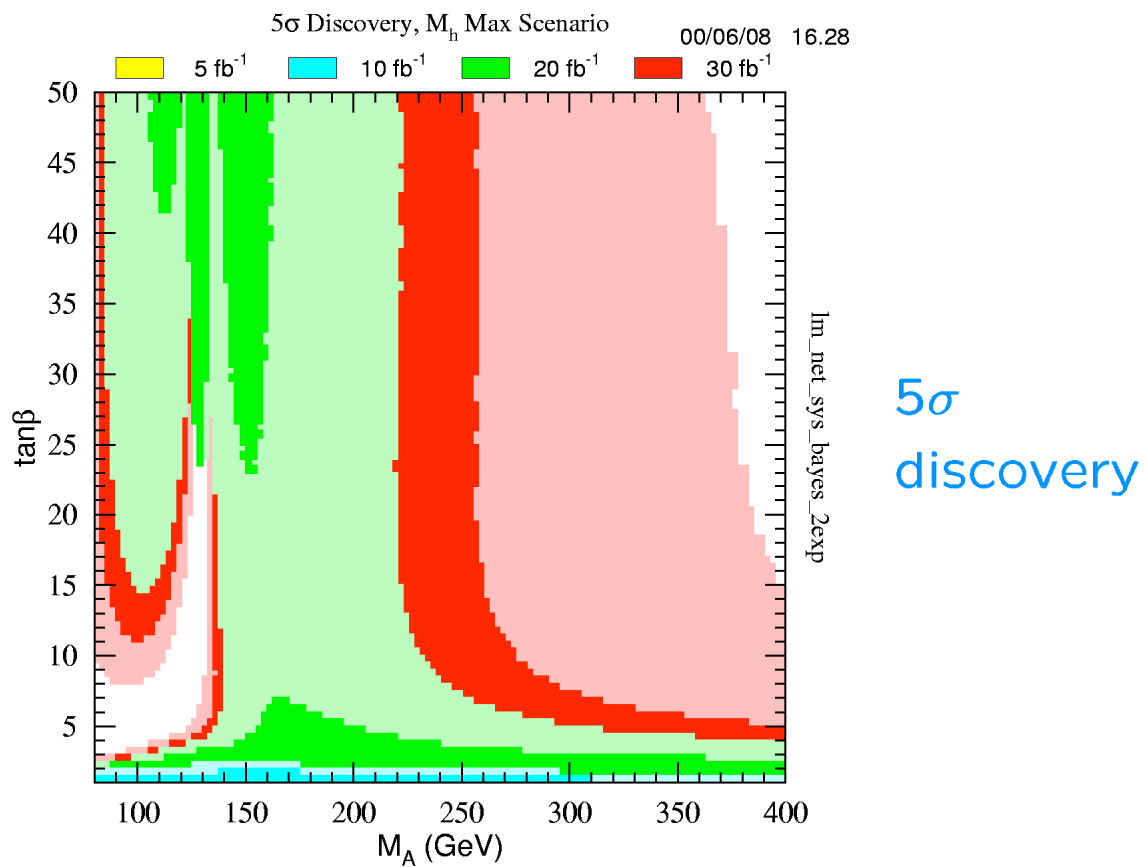
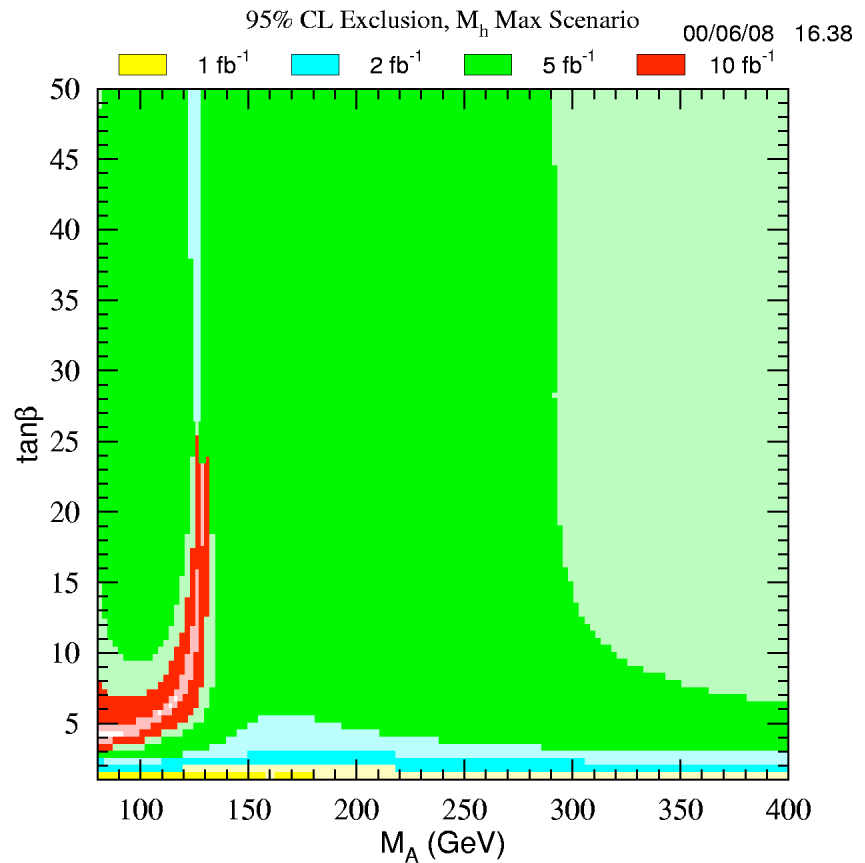


Masses governed by two parameters: $m_A, \tan\beta$

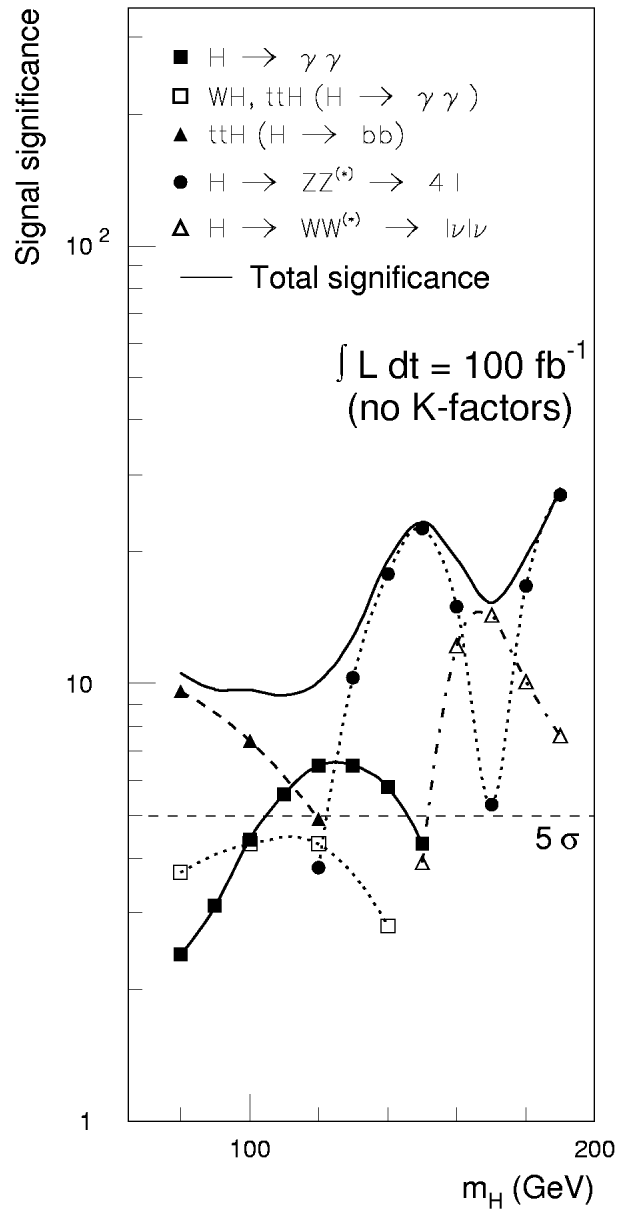
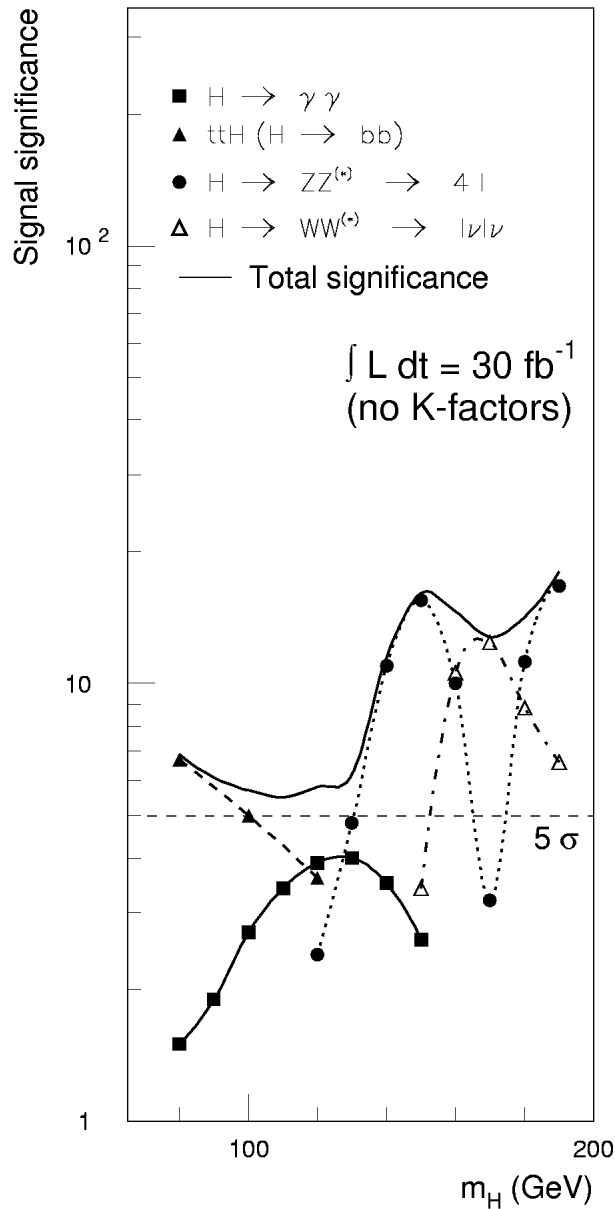


MSSM discovery/exclusion from SM Higgs channels

95% CL
exclusion

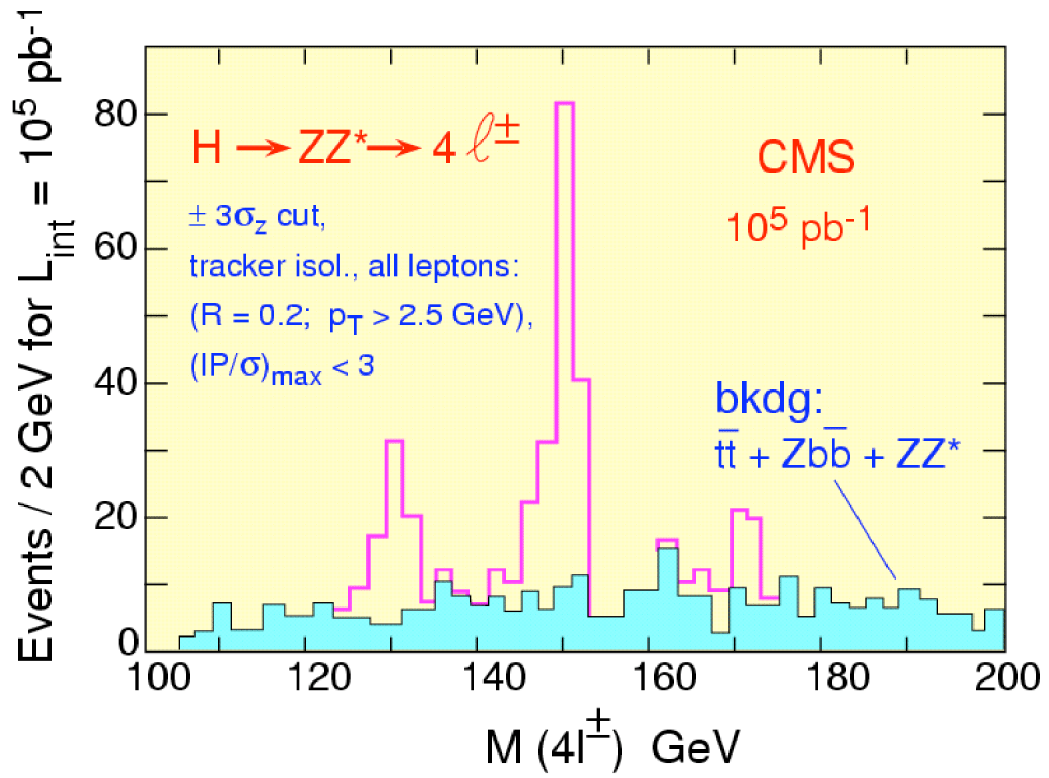
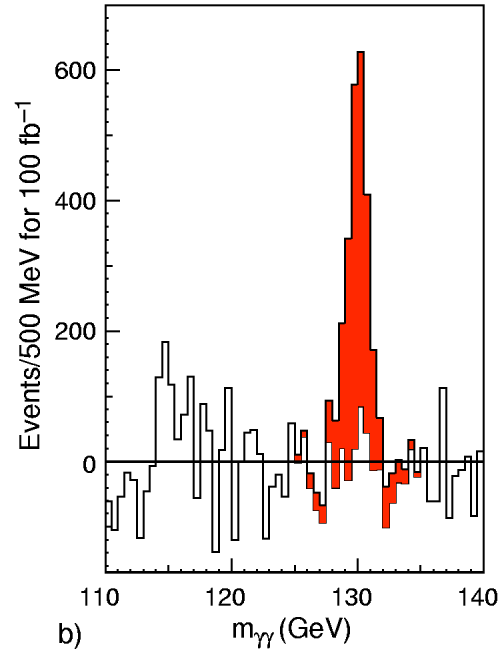
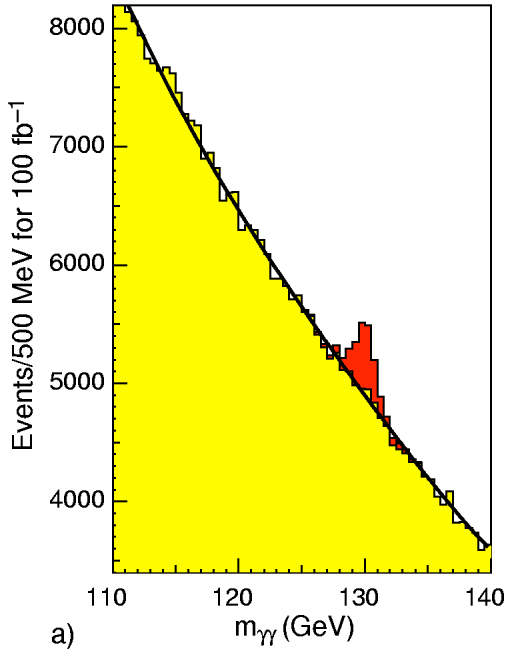


LHC SM Higgs reach:

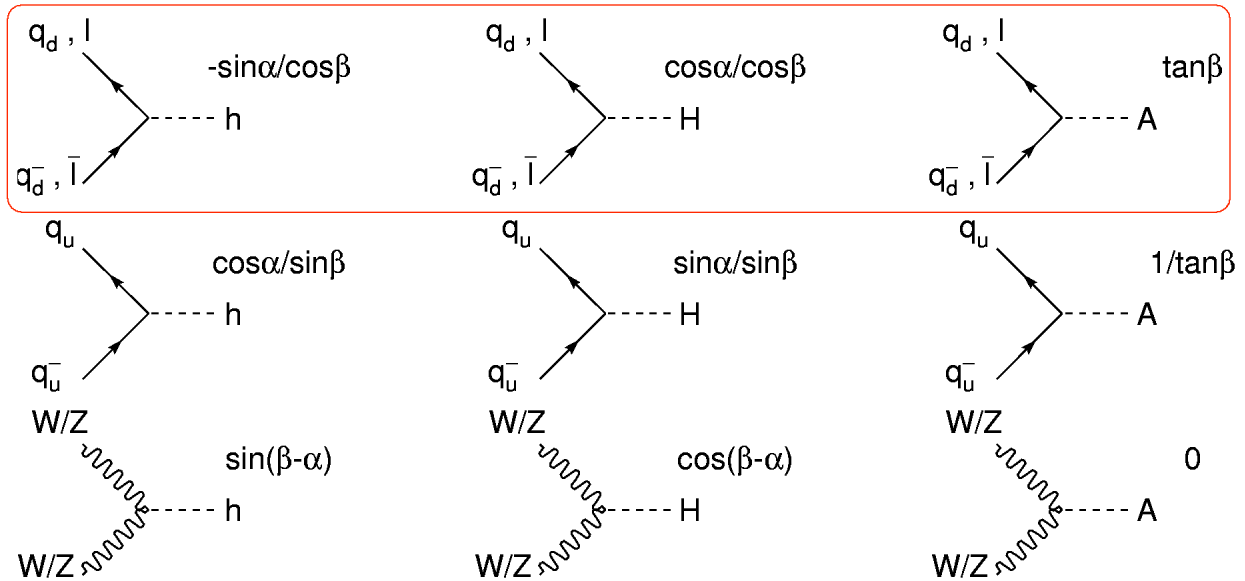


With even just the first year of running LHC experiments will cover the most interesting range for the SM Higgs.

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

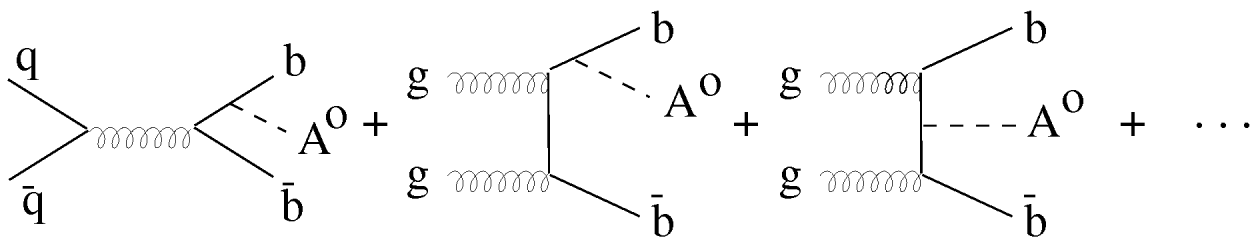


SUSY Higgs Production at large $\tan\beta$



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

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



• $b\bar{b}b\bar{b}$

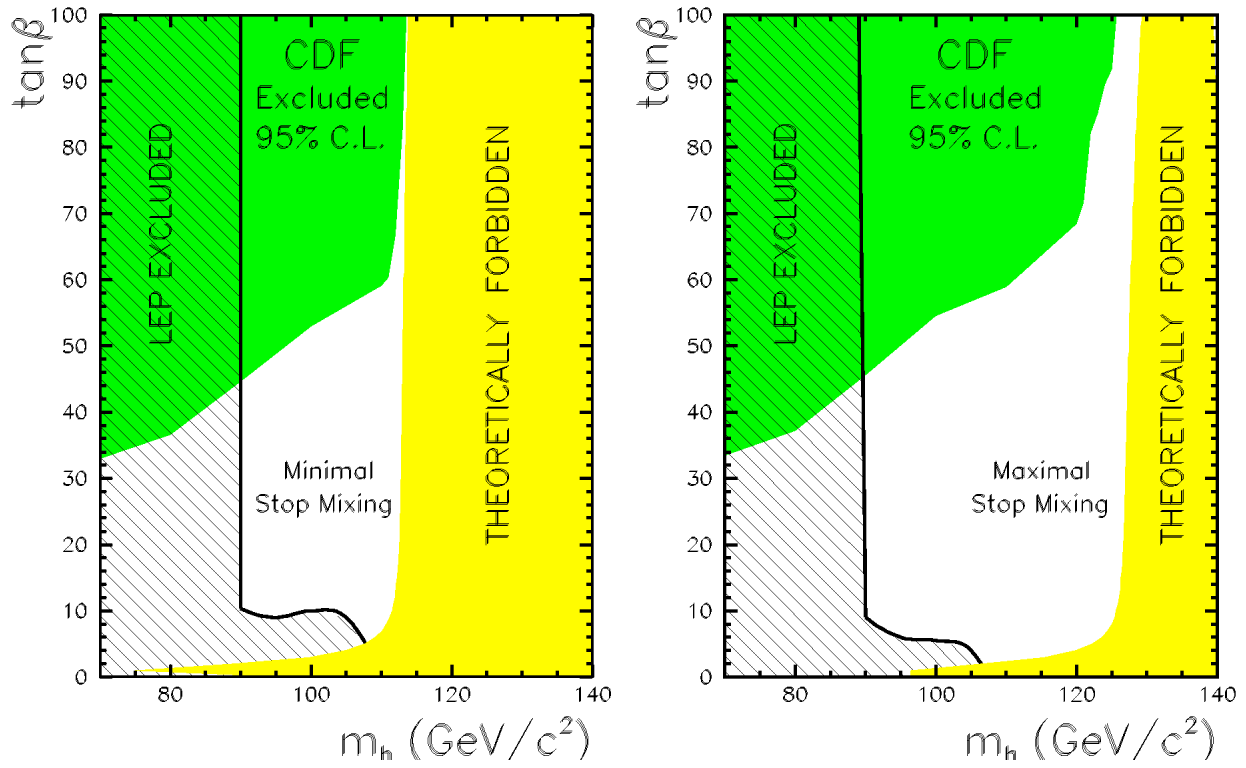
possible search channels:

• $\tau\tau j \cancel{E}_T$

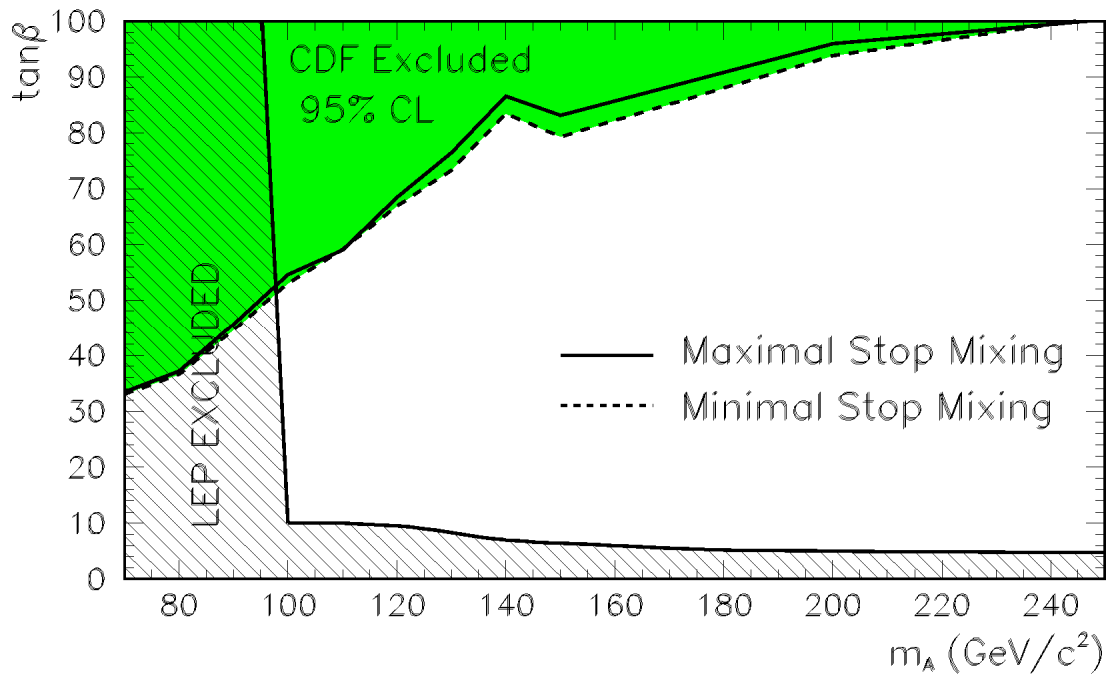
• $\tau bj \cancel{E}_T$

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

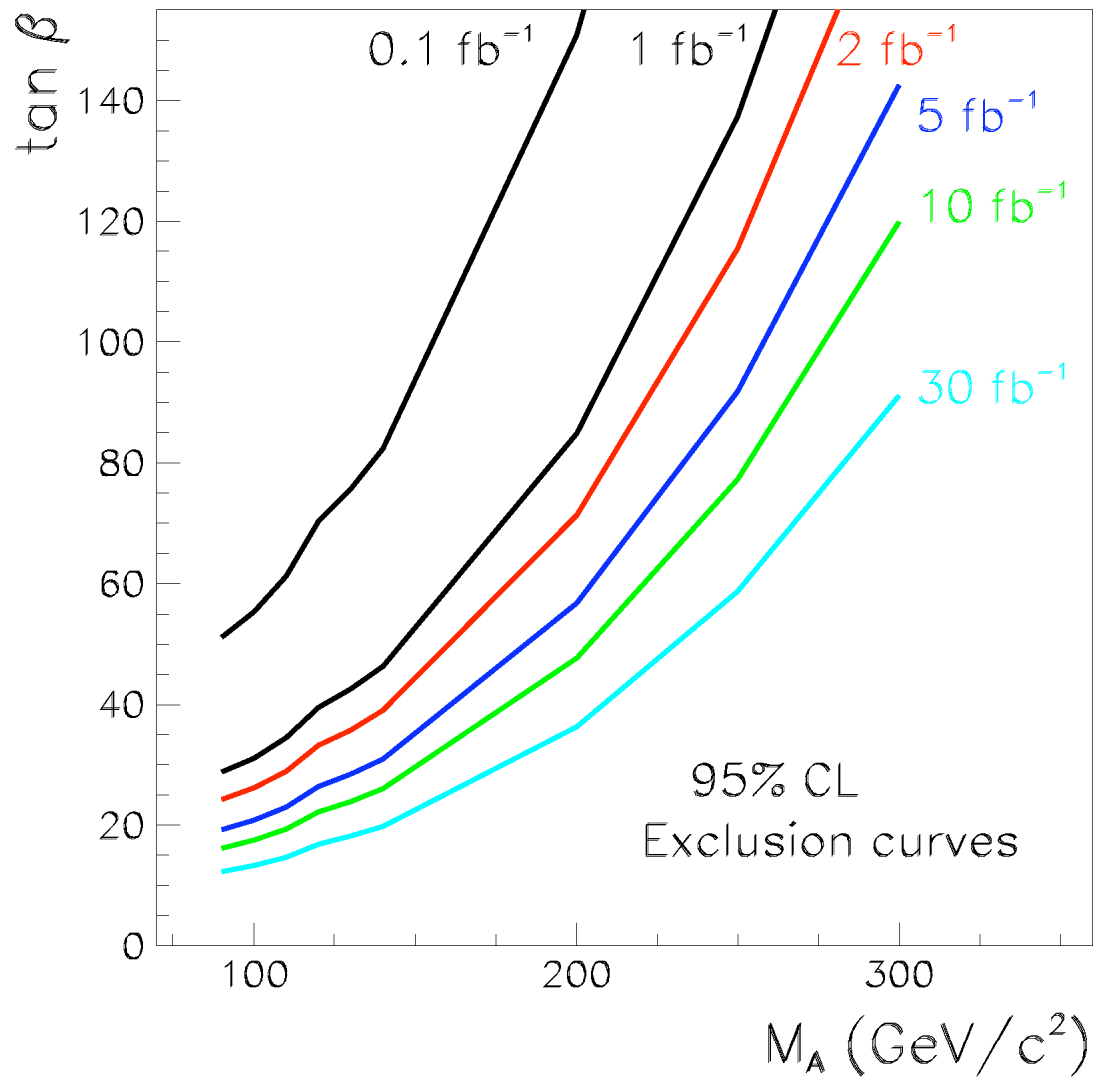
CDF preliminary (91 pb⁻¹)



CDF preliminary (91 pb⁻¹)

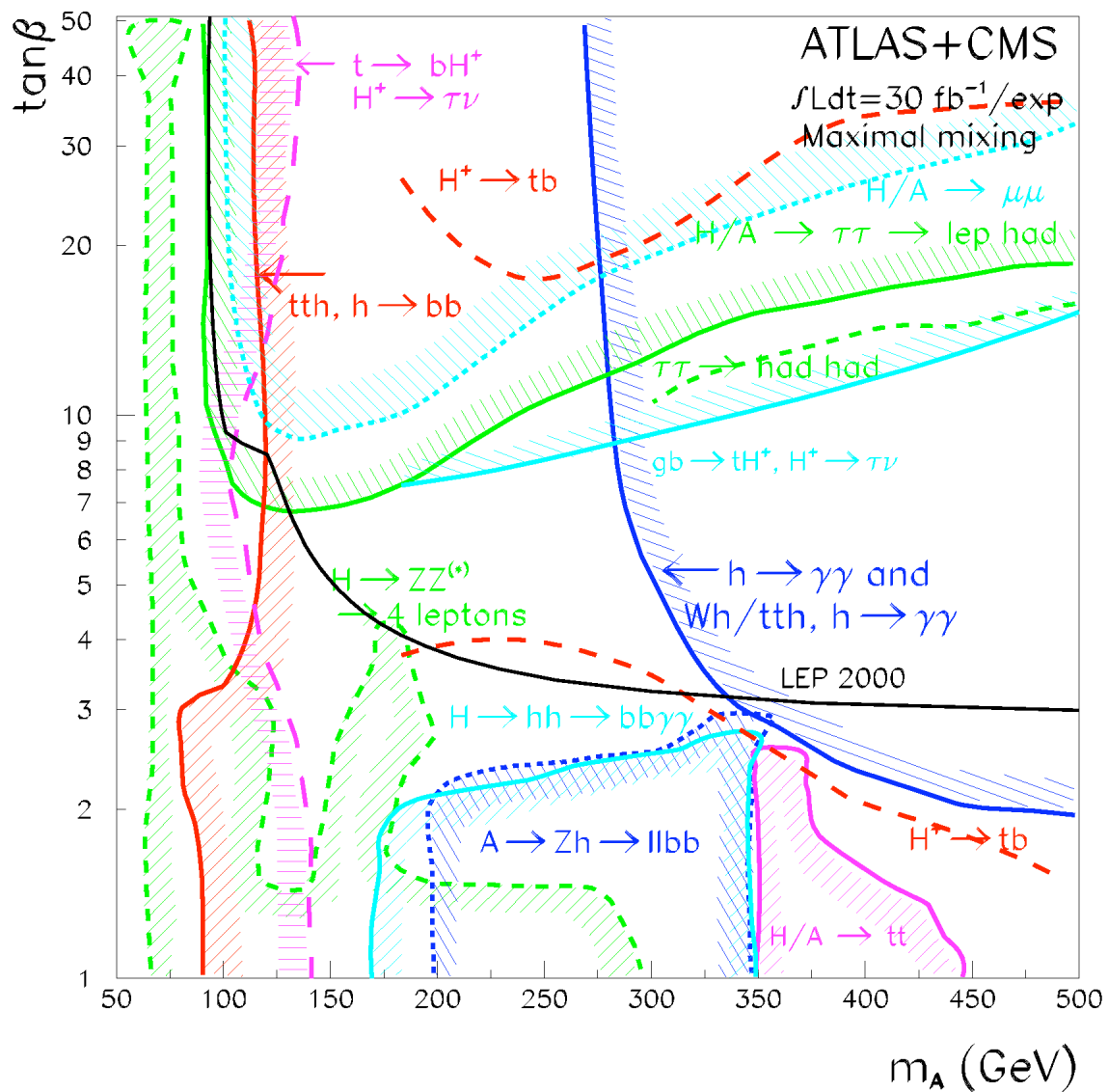


DØ projected reach in $\tan\beta$ versus m_A plane



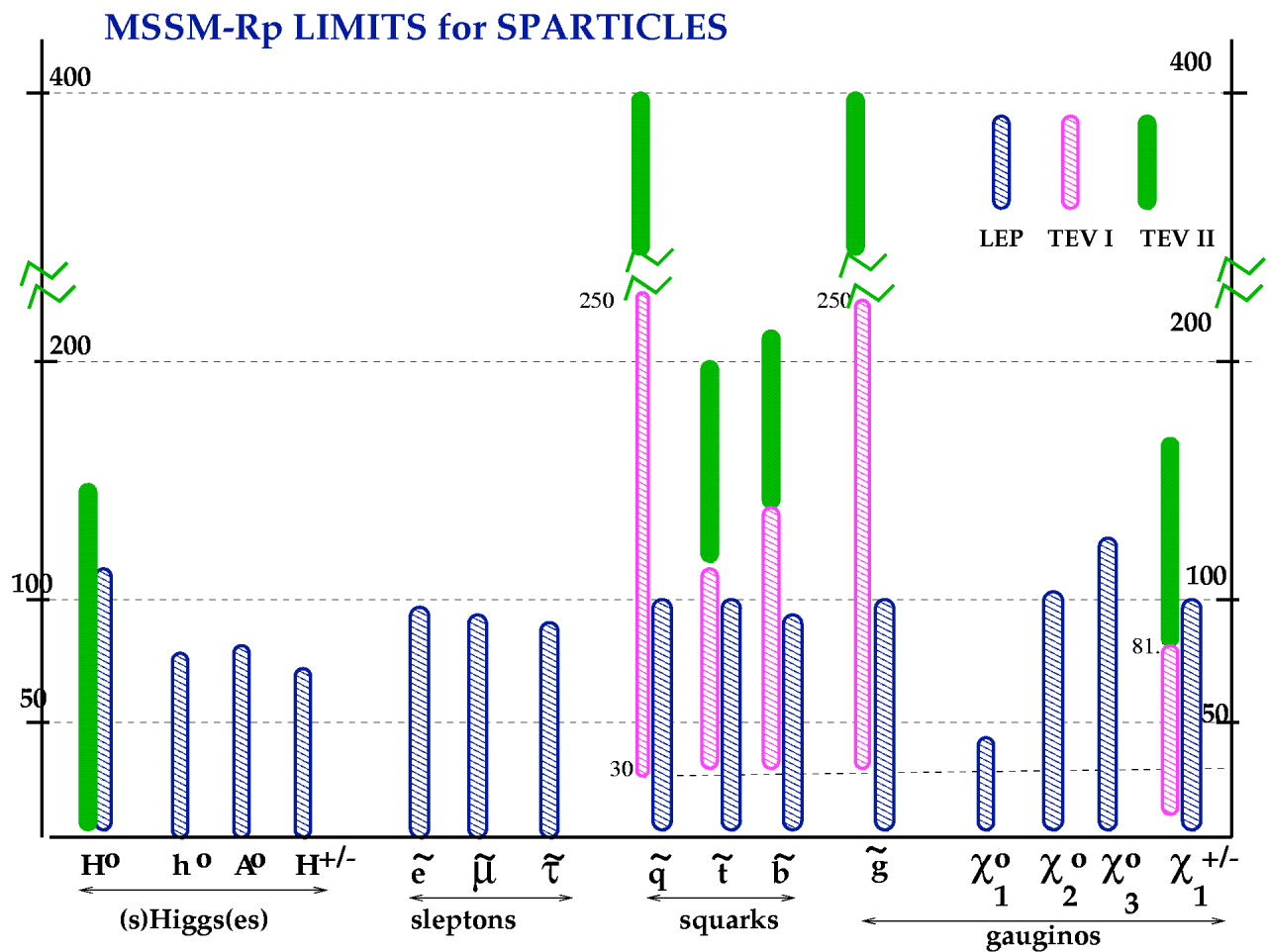
(similar to CDF reach)

LHC coverage of SUSY Higgs space:



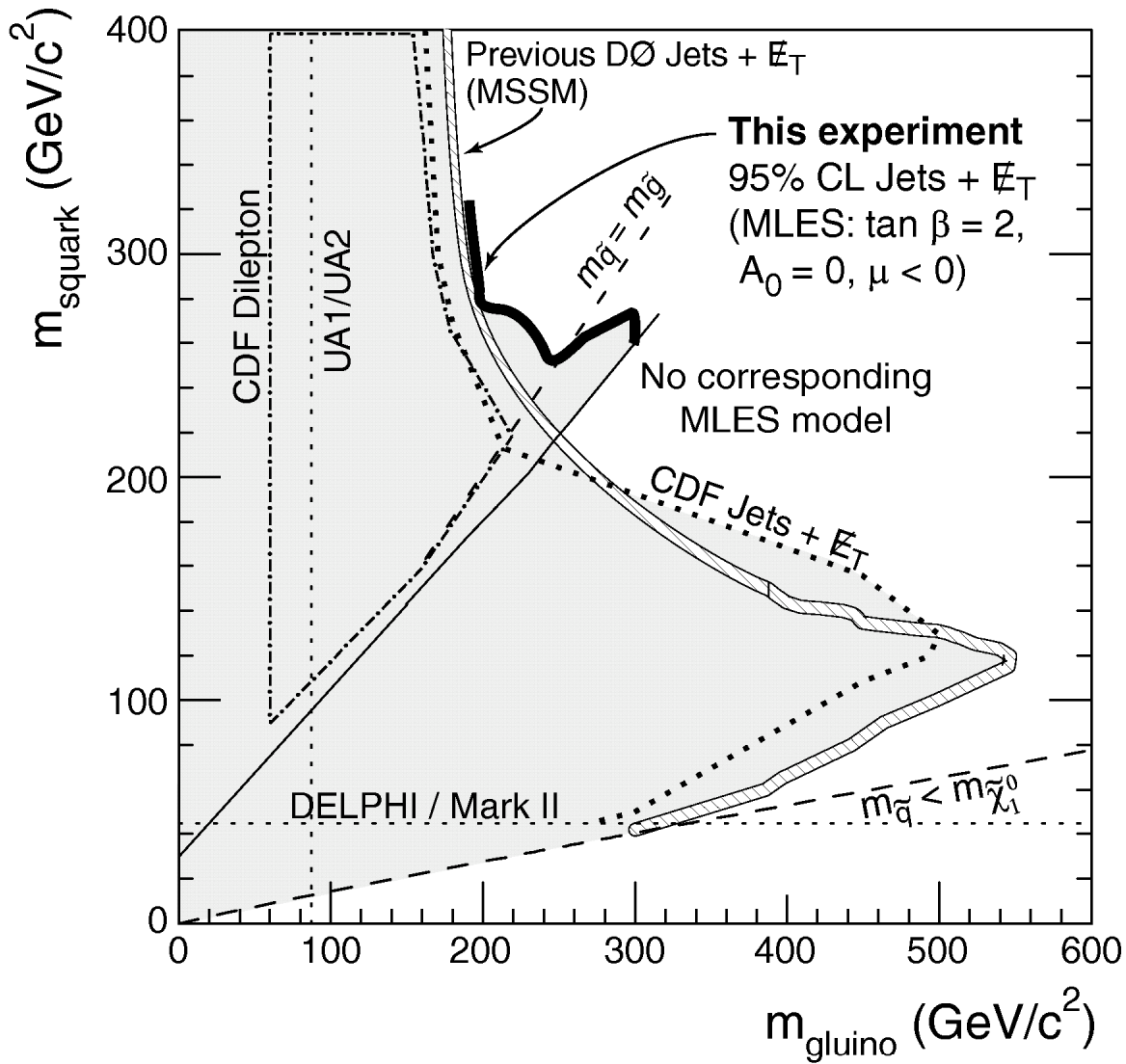
Search for Supersymmetry

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



(Thanks to Aurore Savoy-Navarro!)

→ DØ limits on squarks/gluinos:

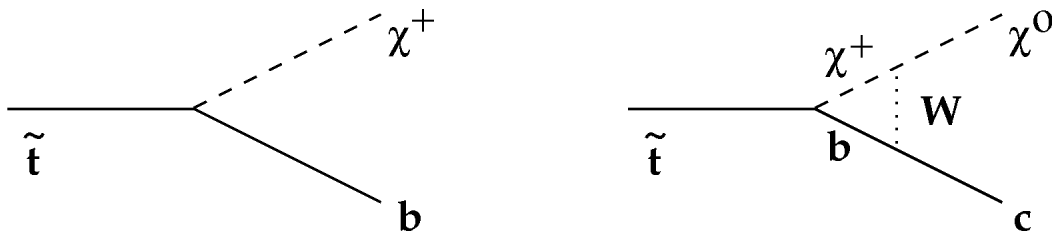


new CDF result coming soon...

CDF search for stop/sbottom

light stop squark favored in various models

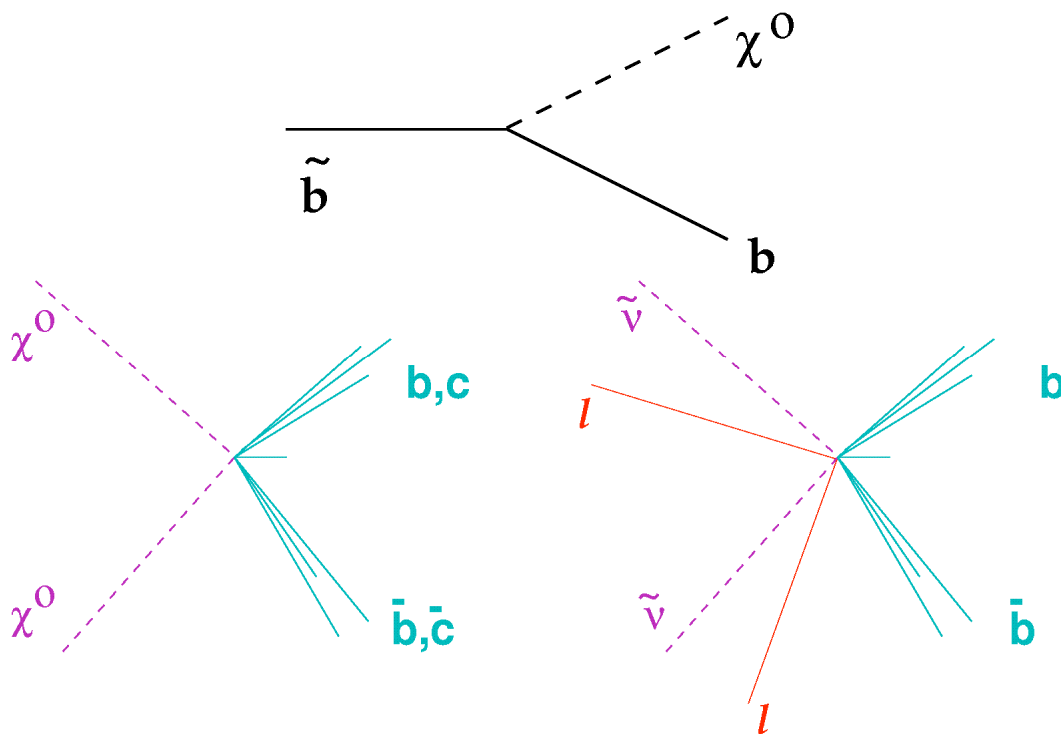
stop can decay by various modes:



• $\chi^\pm \rightarrow l^\pm \tilde{\nu}$ gives $l\bar{l}b\bar{b}\cancel{E}_T$ final state

• $\tilde{t} \rightarrow c\chi^0$ gives $c\bar{c}\cancel{E}_T$ final state: need charm tagging

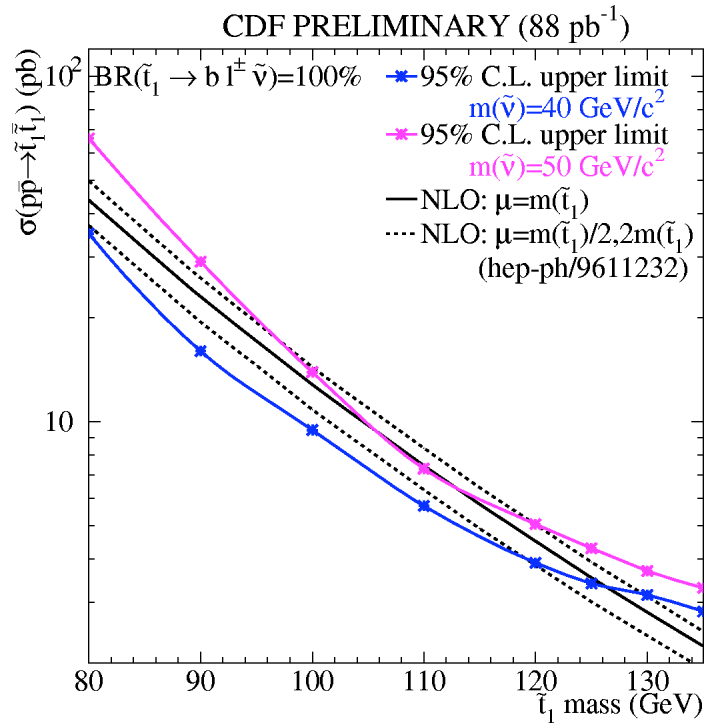
sbottom pair production give similar final state:



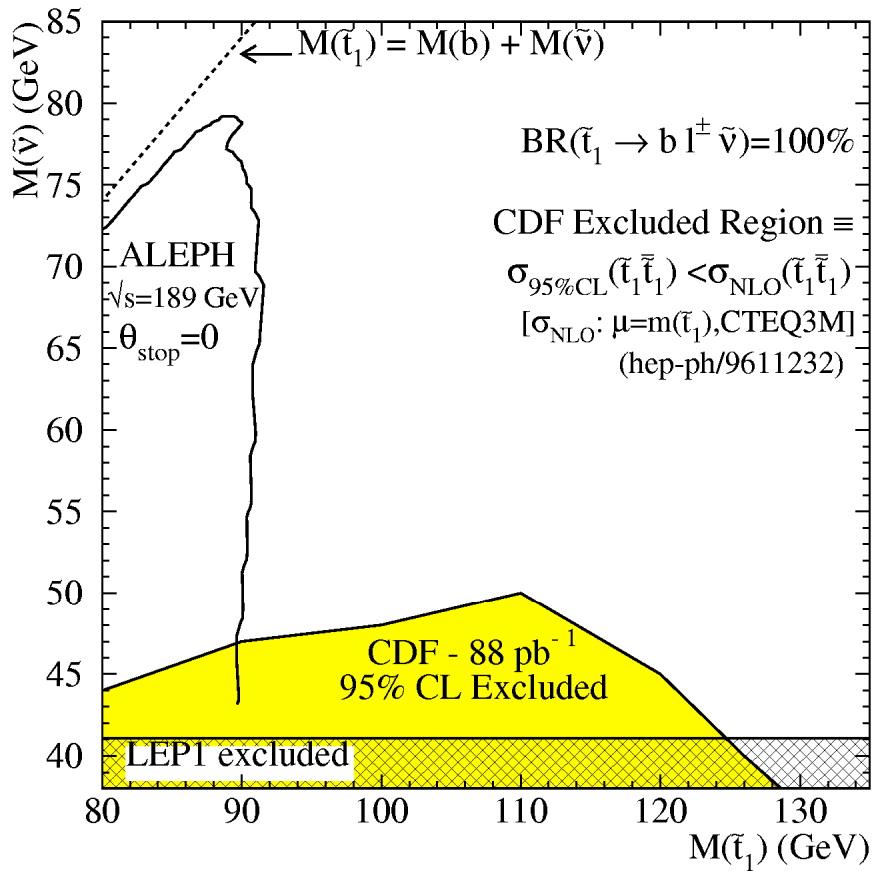
CDF

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

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

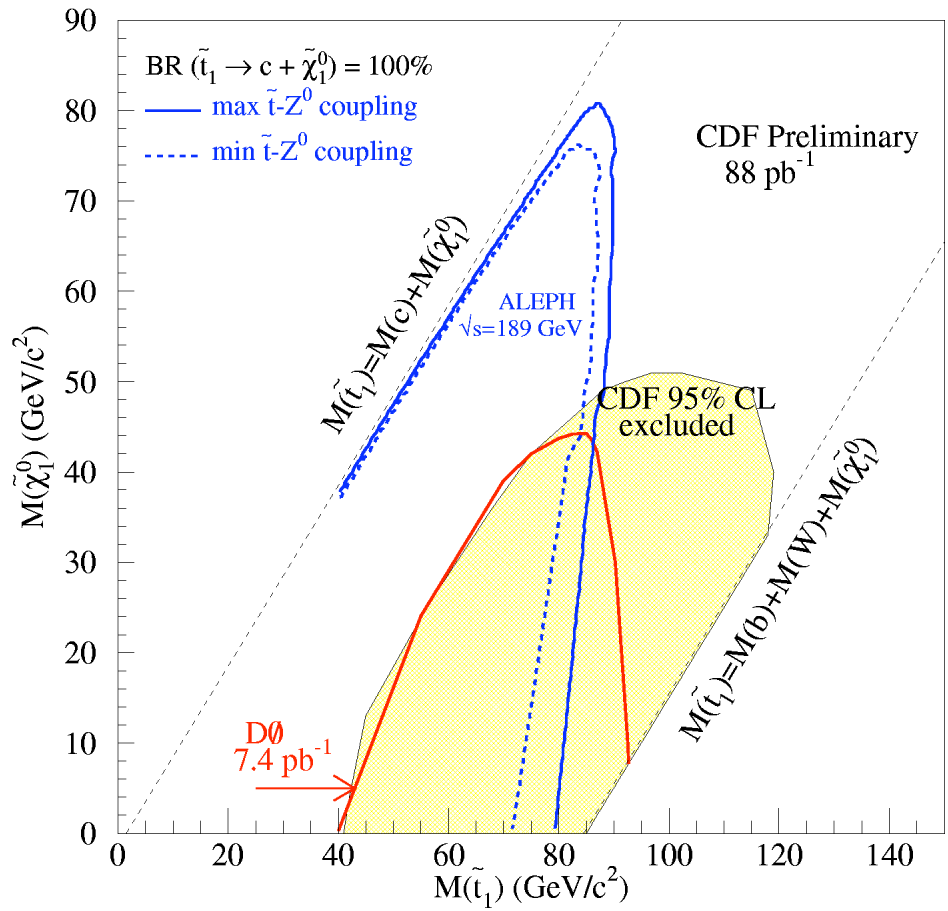


CDF PRELIMINARY



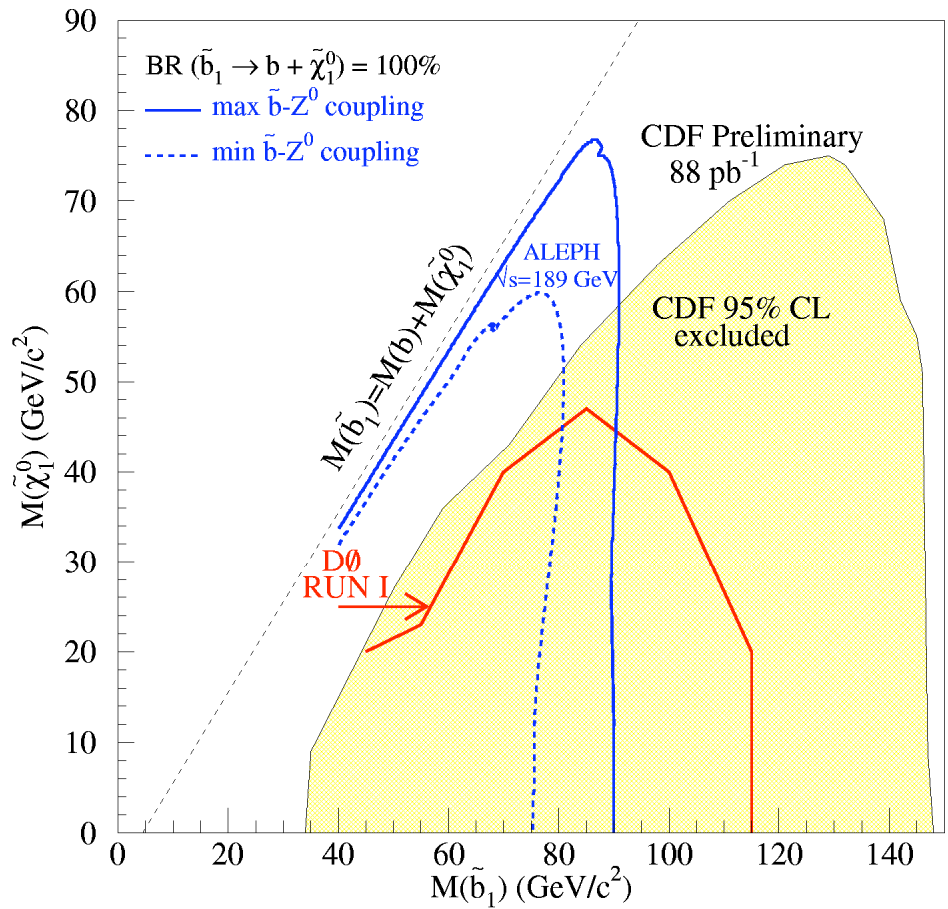
CDF

$c\bar{c}\cancel{\tau}$



CDF

$b\bar{b}\cancel{\tau}$



Search for Large Extra Dimensions

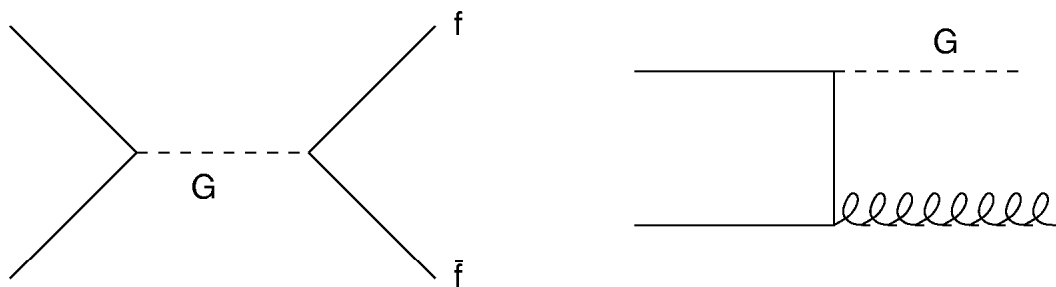
If there exist extra dimensions, they can be large, with radii on the order of a millimeter, without conflicting with present data!

Governed by: M_G effective Planck mass

n number of extra dimensions (≥ 2)

$\lambda \pm \mathcal{O}(1)$

→ get “towers” of sub-eV-spaced Kaluza-Klein excitations

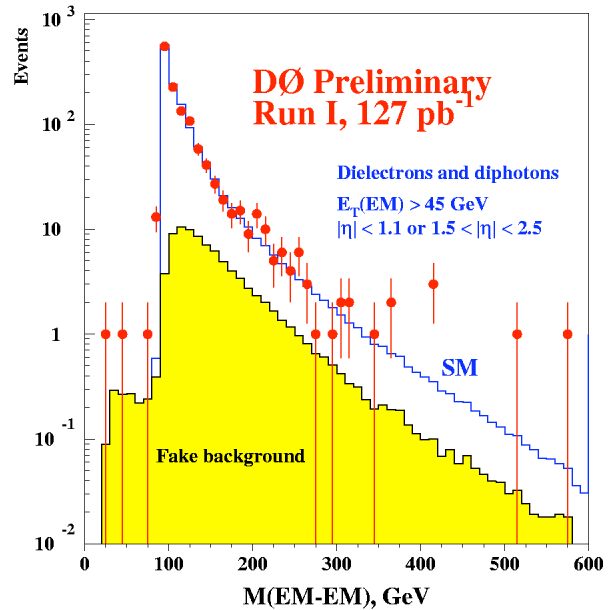


Both indirect and direct signals at colliders.

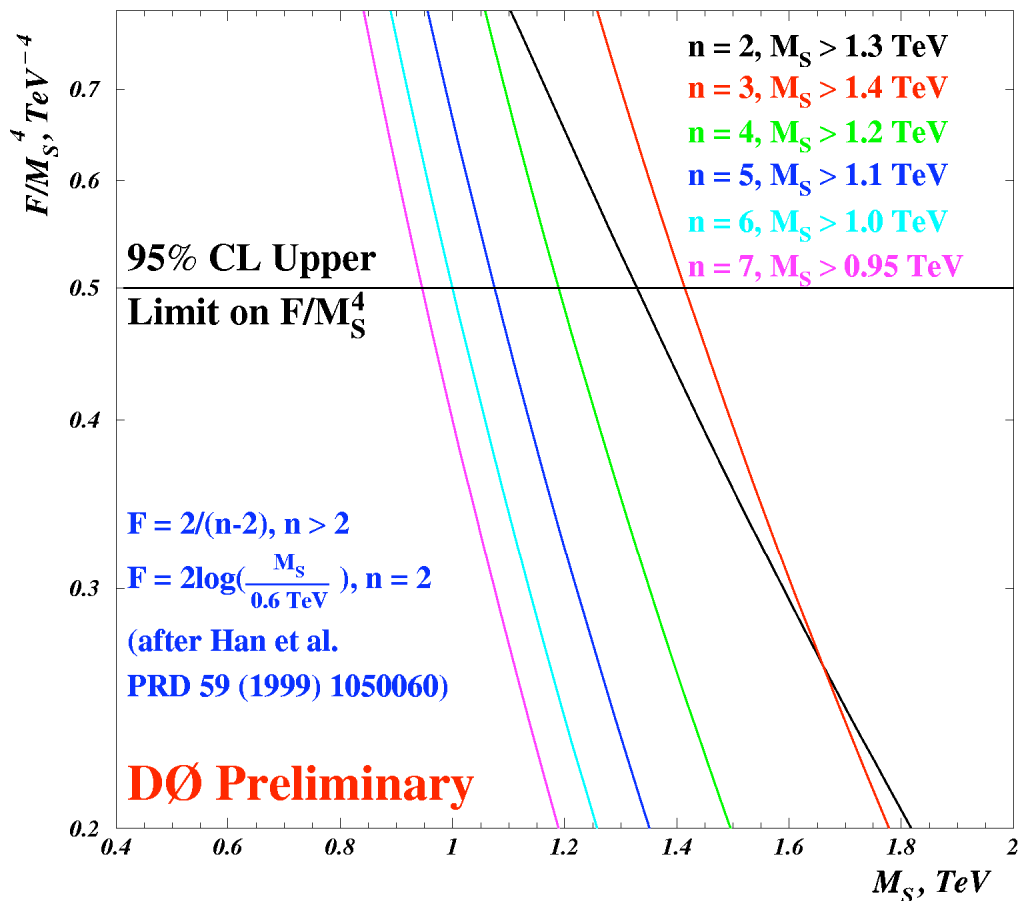
DØ search for extra dimensions in high mass e^+e^- , $\gamma\gamma$ pairs:

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

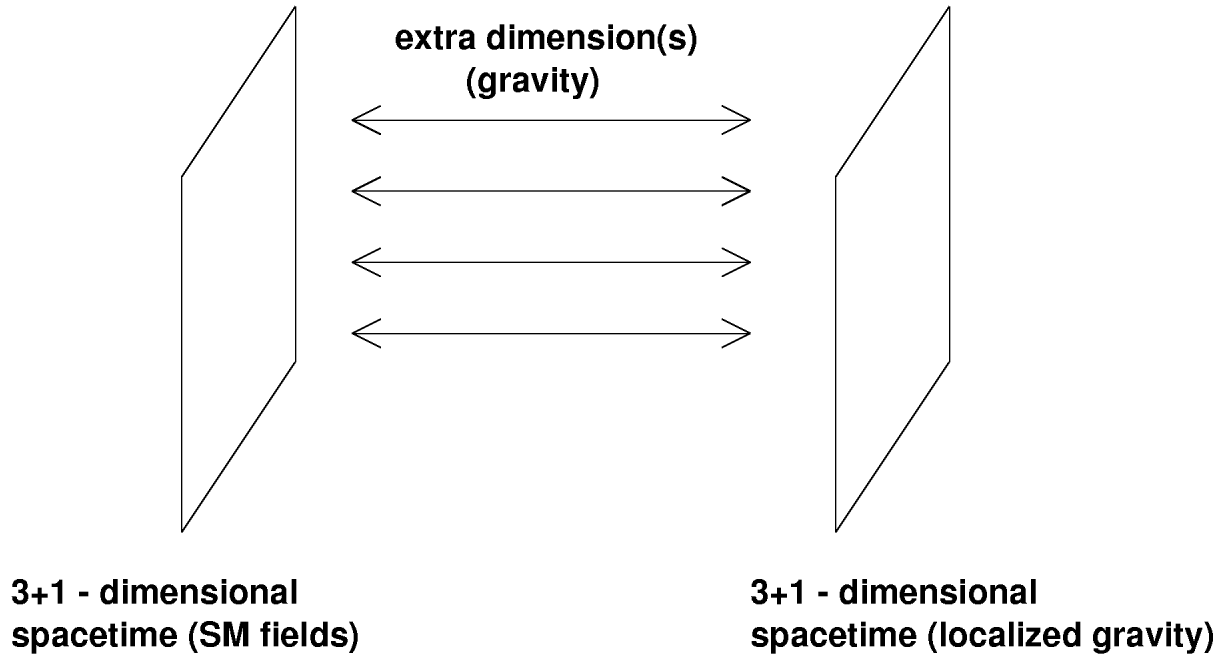
Comparison of the data with the SM predictions



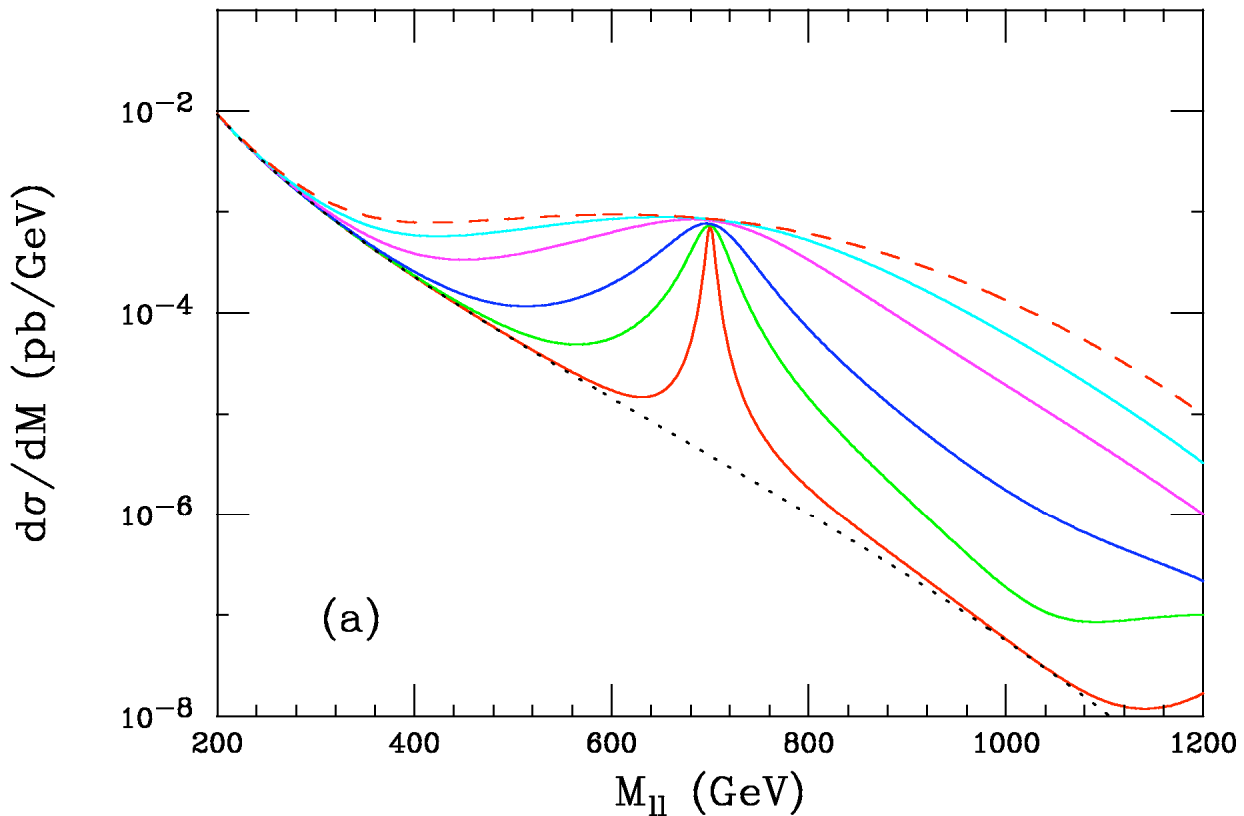
Limits on Large Spatial Extra Dimensions



Randall-Sundrum model

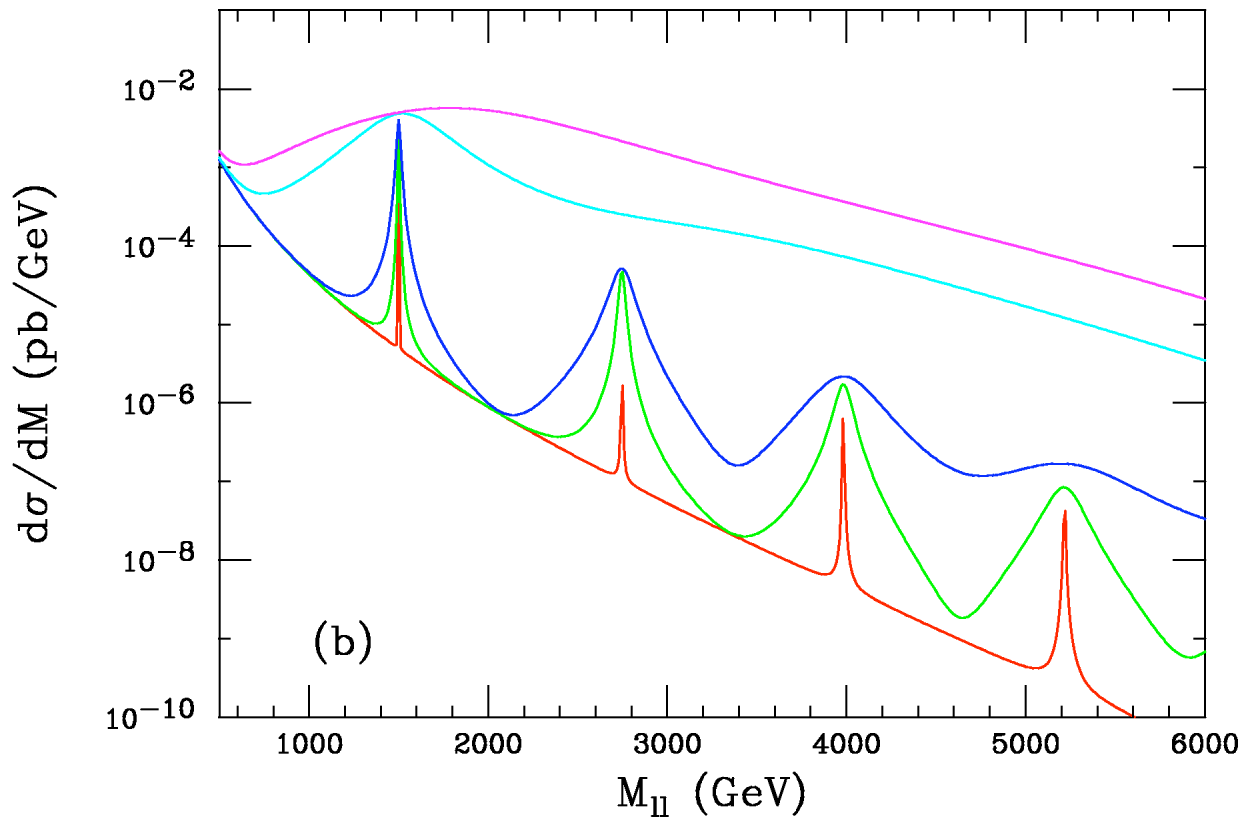


R-S model leads to striking $f\bar{f}$ resonances at the Tevatron...



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.

$$P(\text{data}|\text{hypothesis}) \neq P(\text{hypothesis}|\text{data})$$

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