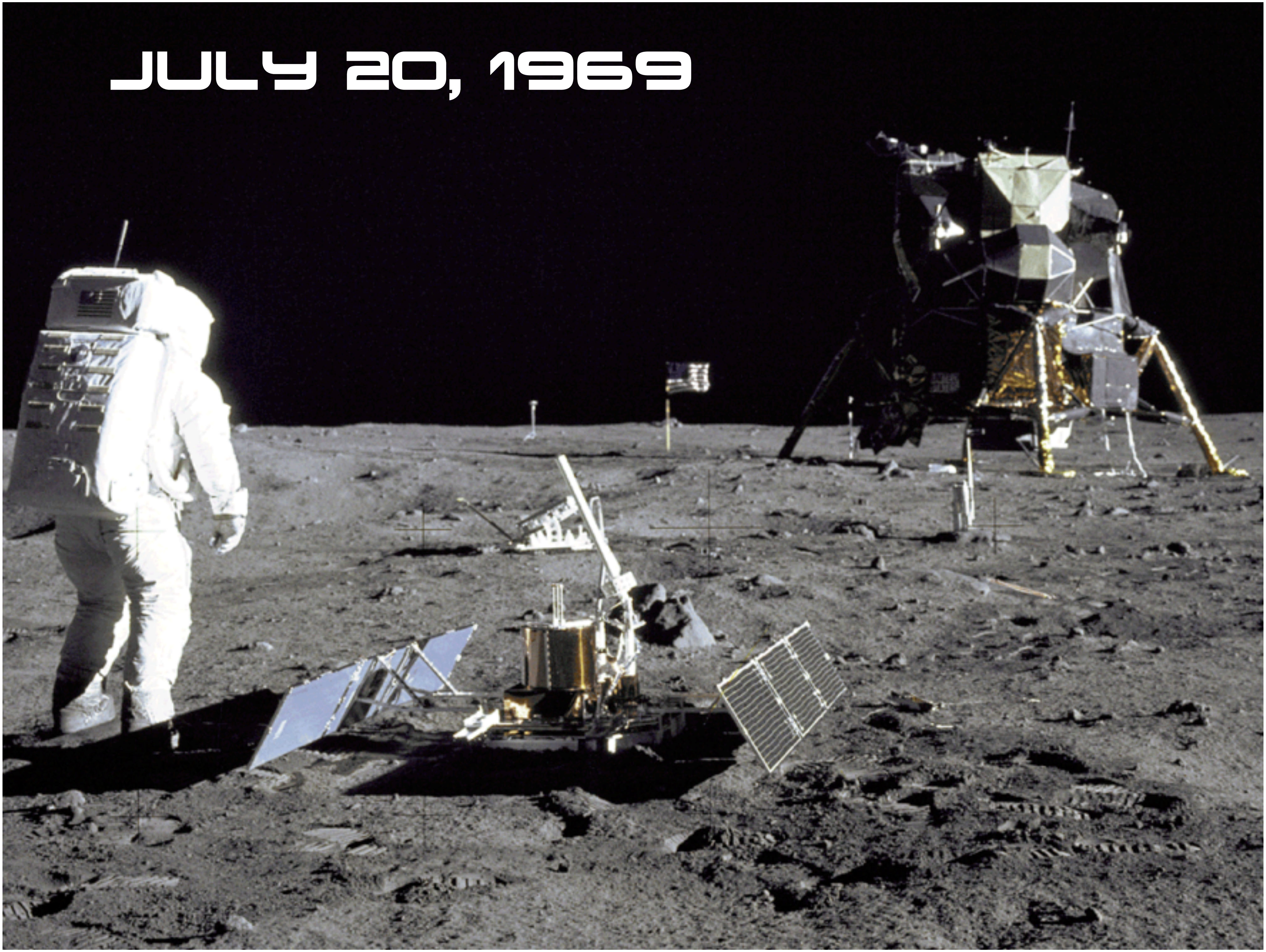
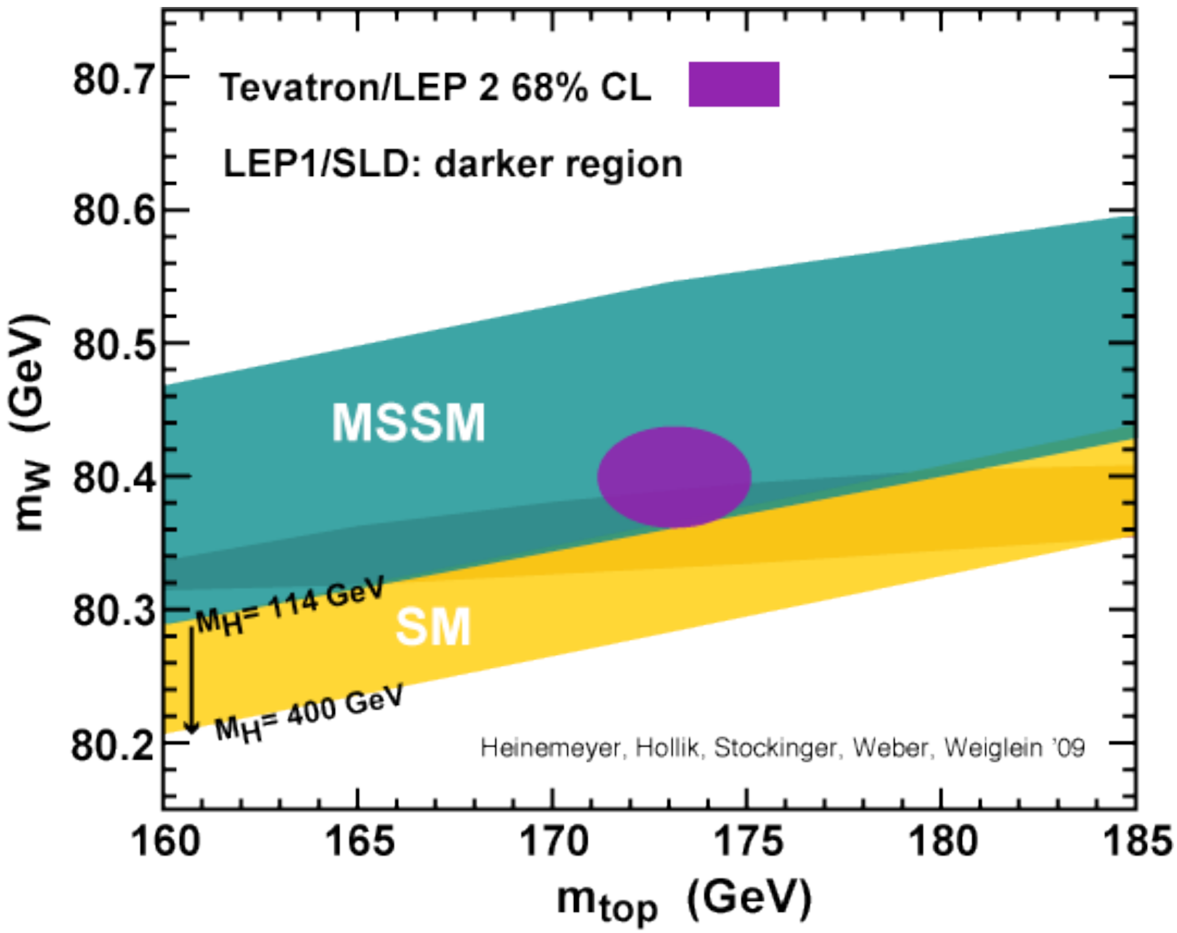
The Search for the Higgs Boson

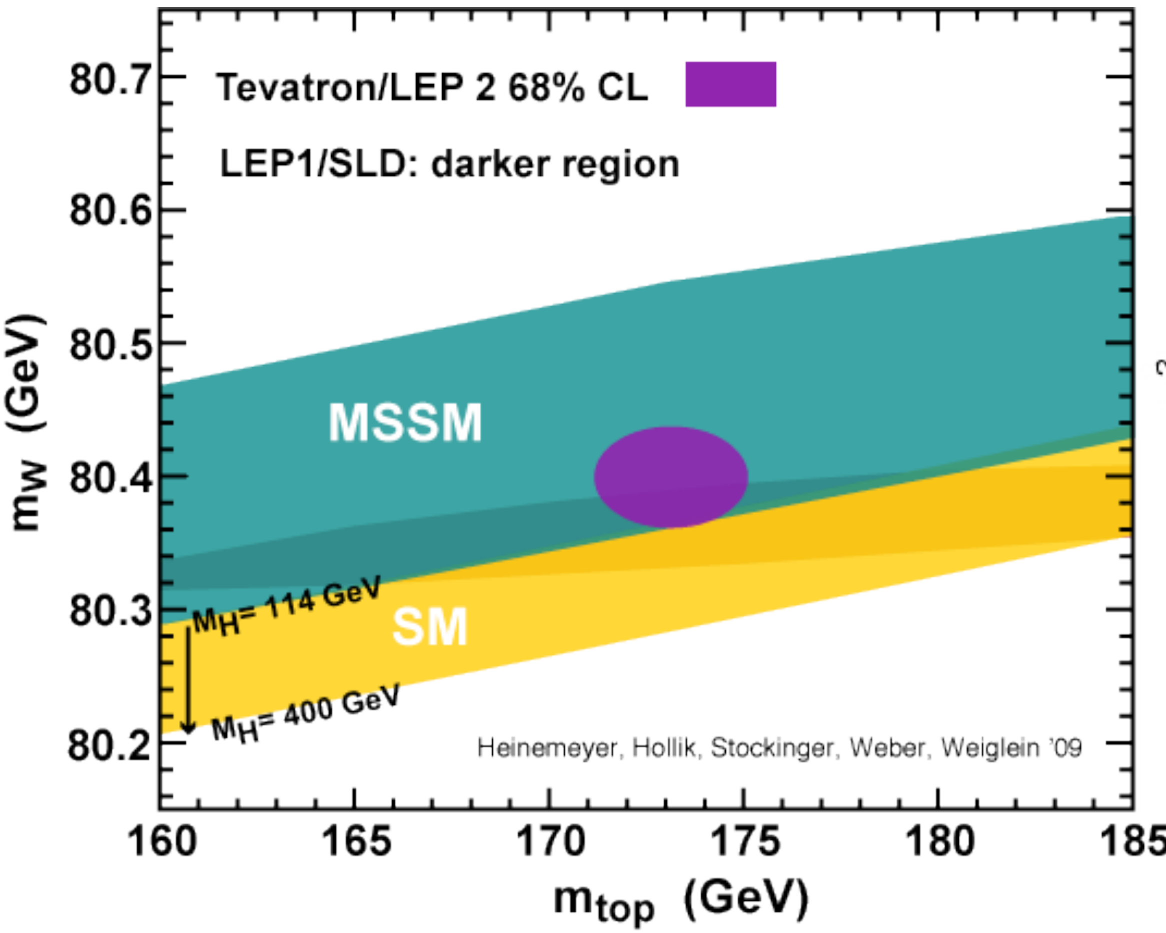
John Conway
University of California, Davis

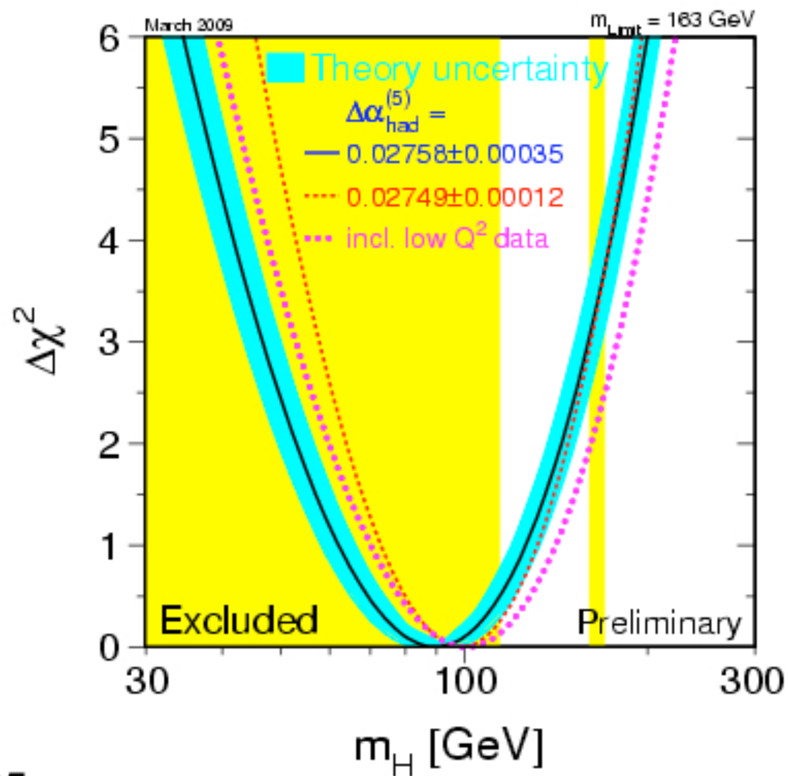
EPS 2009
Krakow, Poland
July 20, 2009

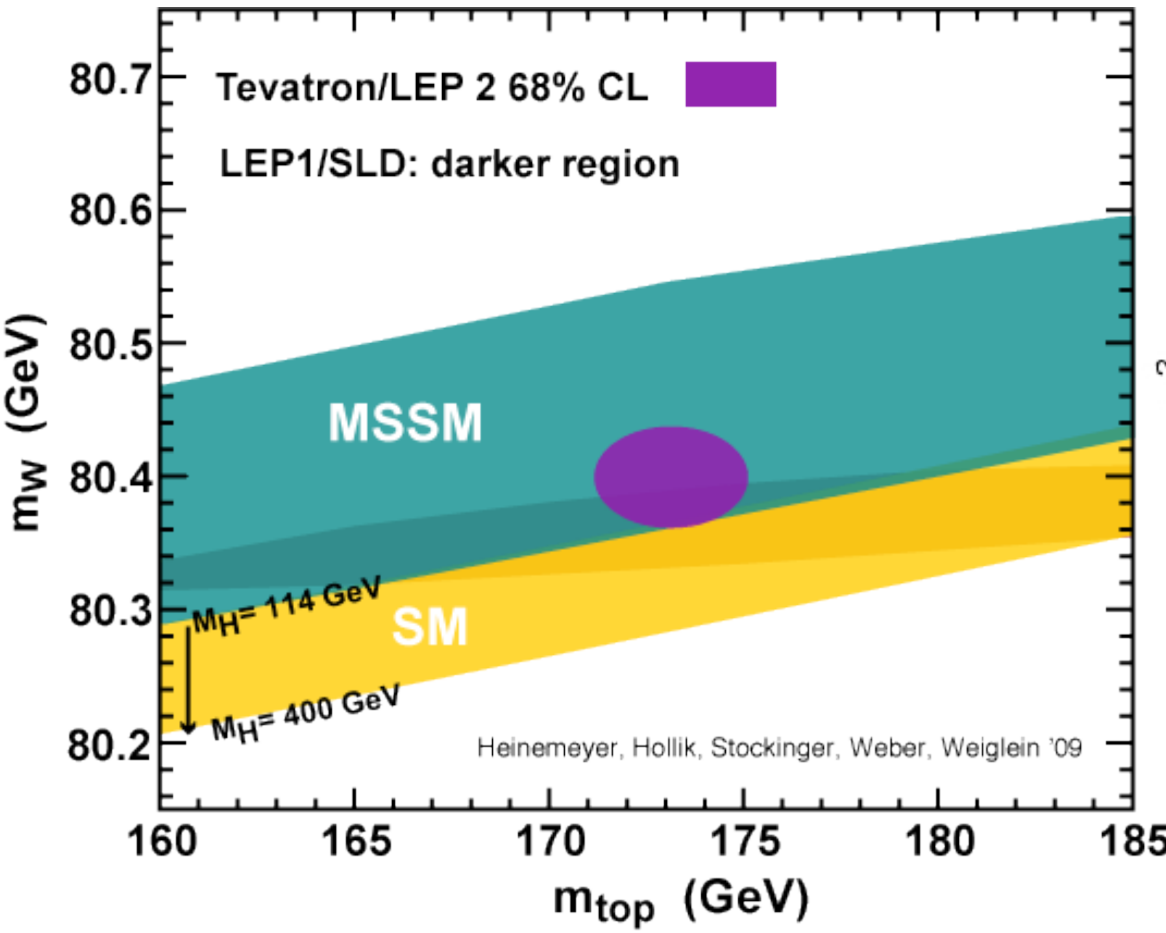

JULY 20, 1969

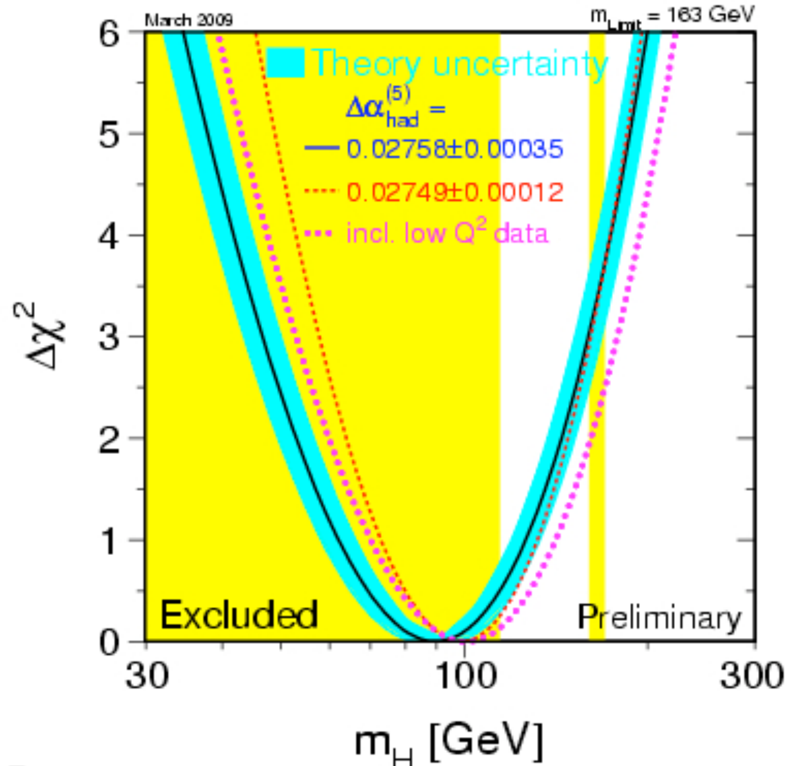


m_W versus m_{top}


Tevatron/LEP 2 68% CL
LEP1/SLD: darker region
MSSM
SM
M_H= 114 GeV
M_H= 400 GeV
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '09
m_W (GeV)
m_{top} (GeV)


March 2009
m_{Limit} = 163 GeV
Theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]





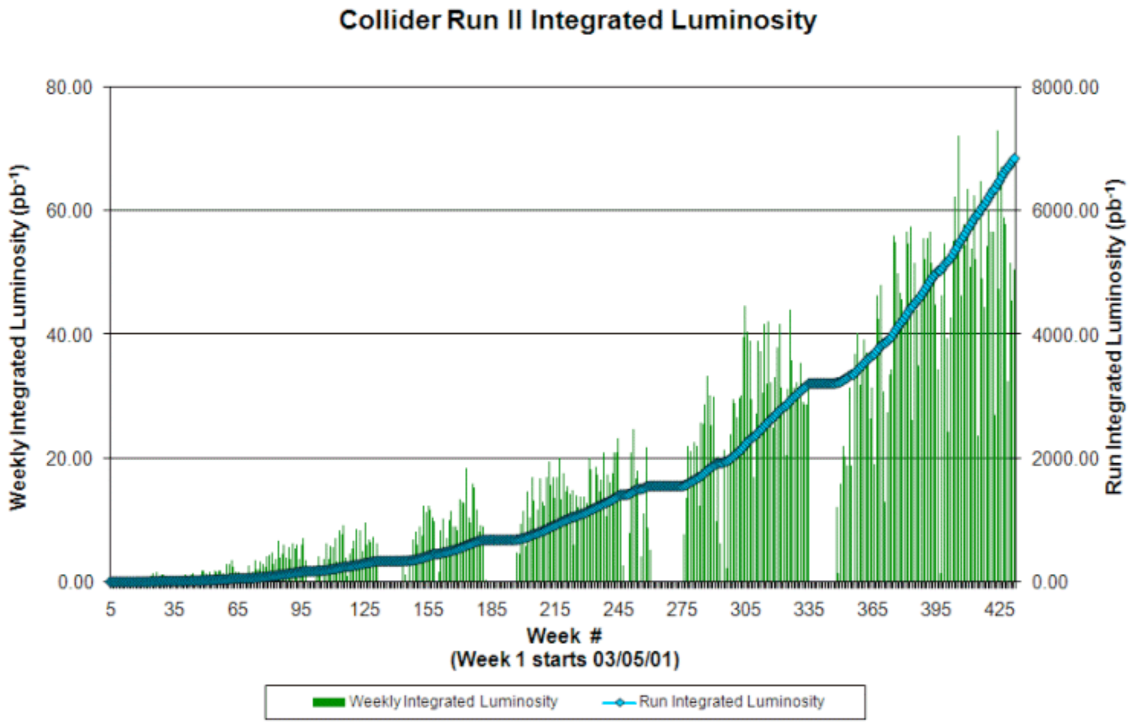
LEP 2/Tevatron/ν precision measurements

⇒ light SM Higgs boson strongly favored

Tevatron Run 2

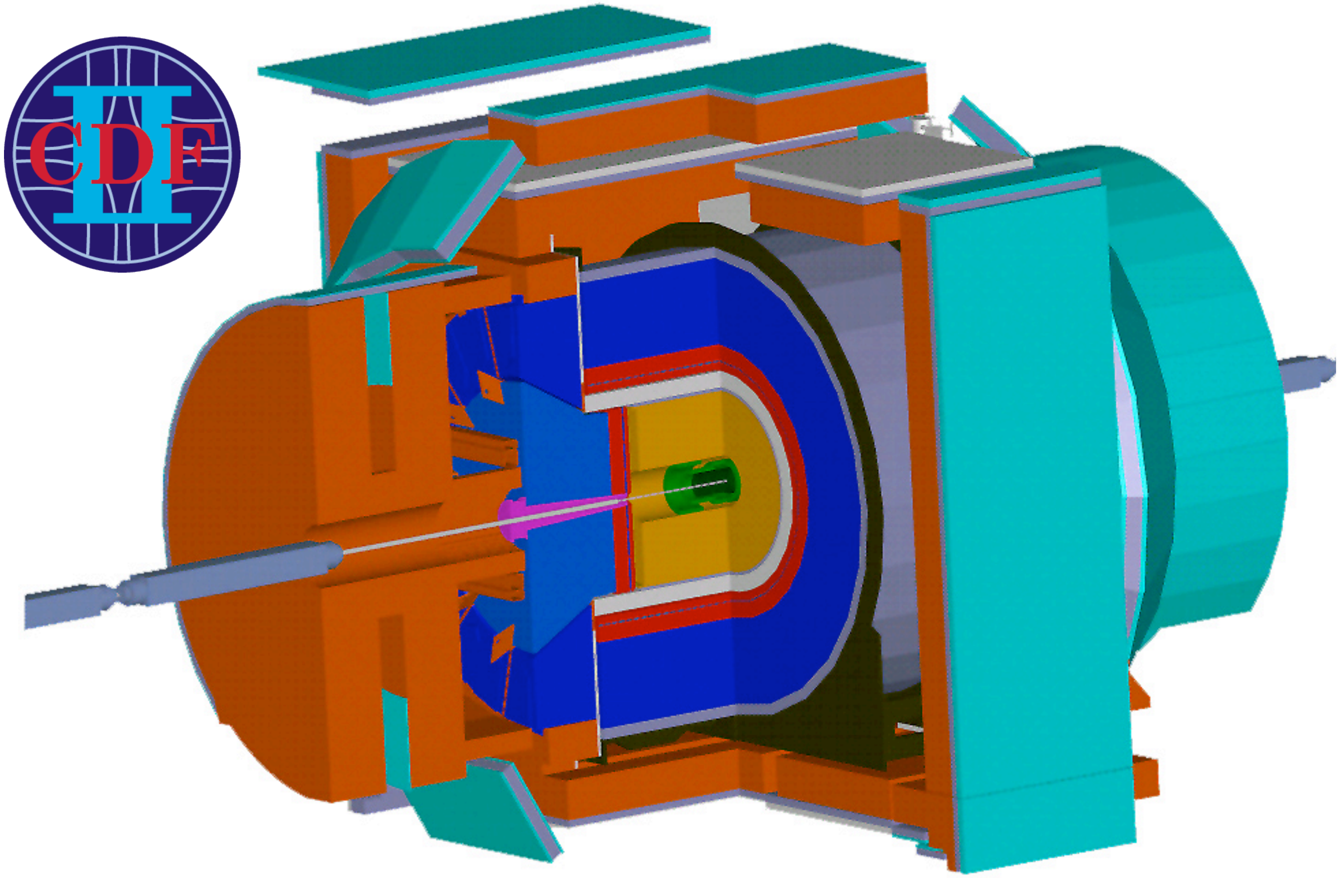
Steady improvements in

- pbar production
- injection efficiency
- turn-around time



Tevatron integrating ~2 fb^{-1} per year

Results here based on up to 4.8 fb^{-1}



<u>leptons</u>

electrons $|\eta| < 2$

muons $|\eta| < 1.5$

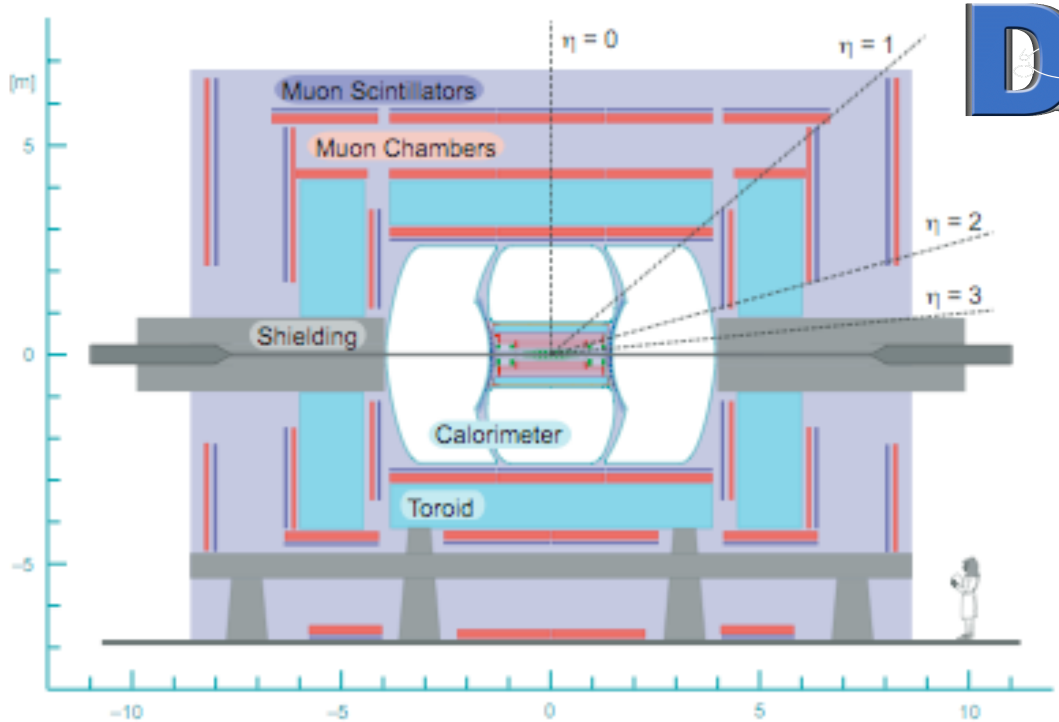
<u>jets</u>

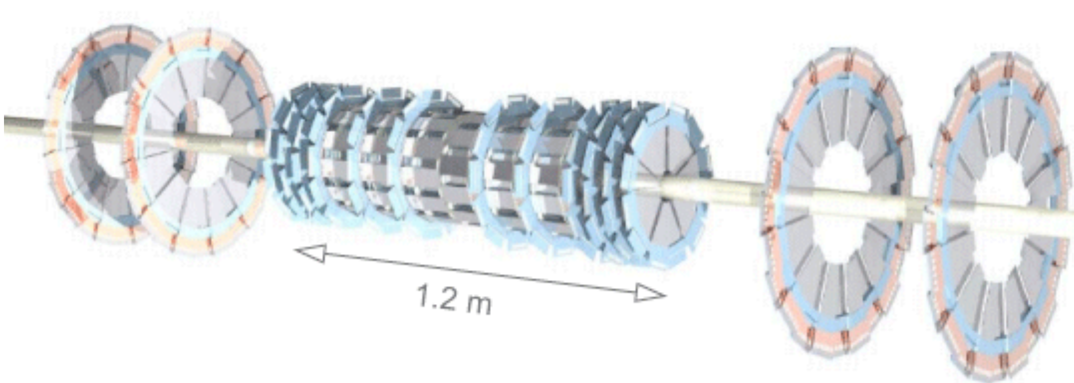
coverage $|\eta| < 2.8$

b tagging $|\eta| < 1.4$

energy scale ~1%

dijet mass: 16%





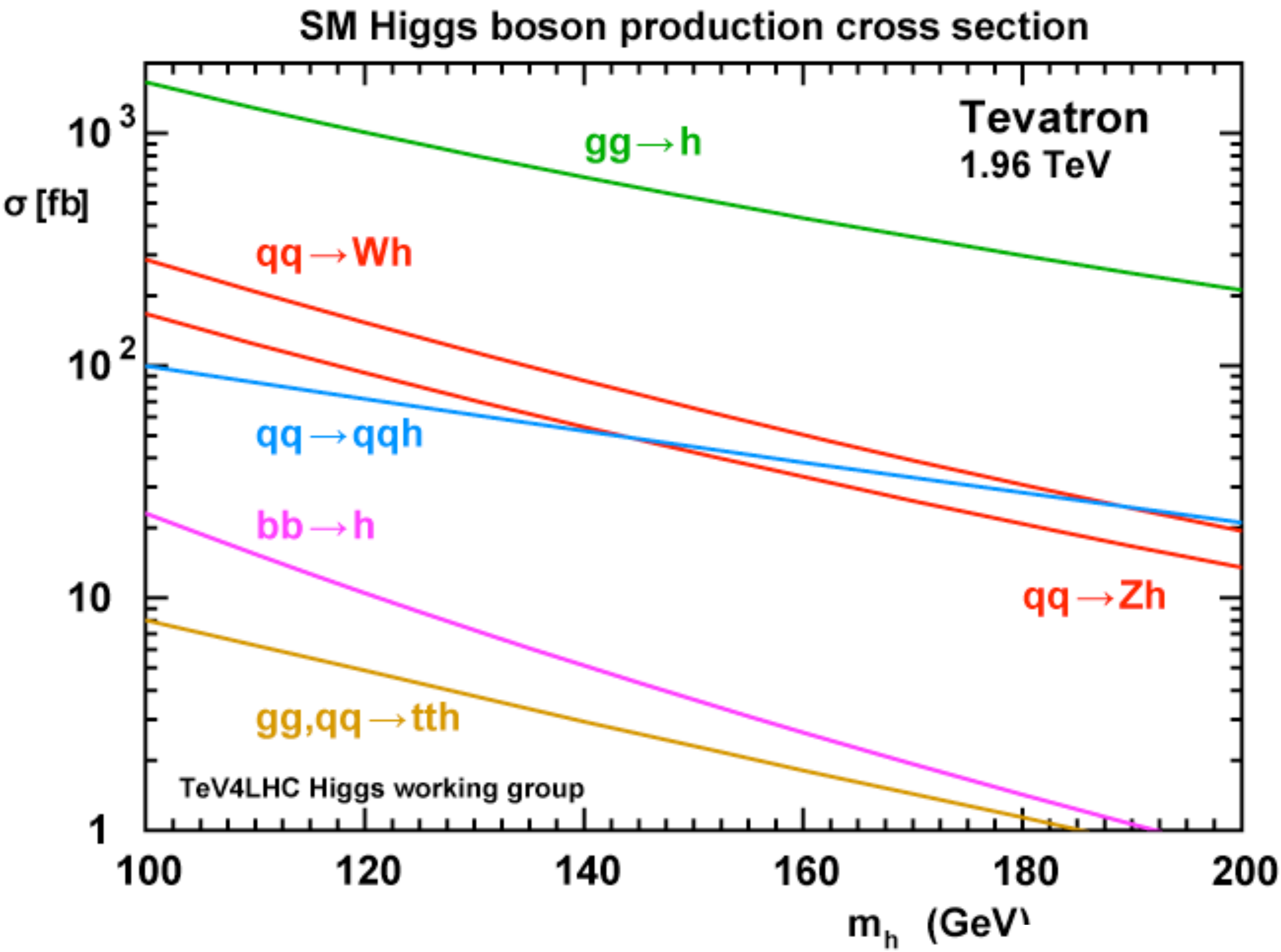
leptons

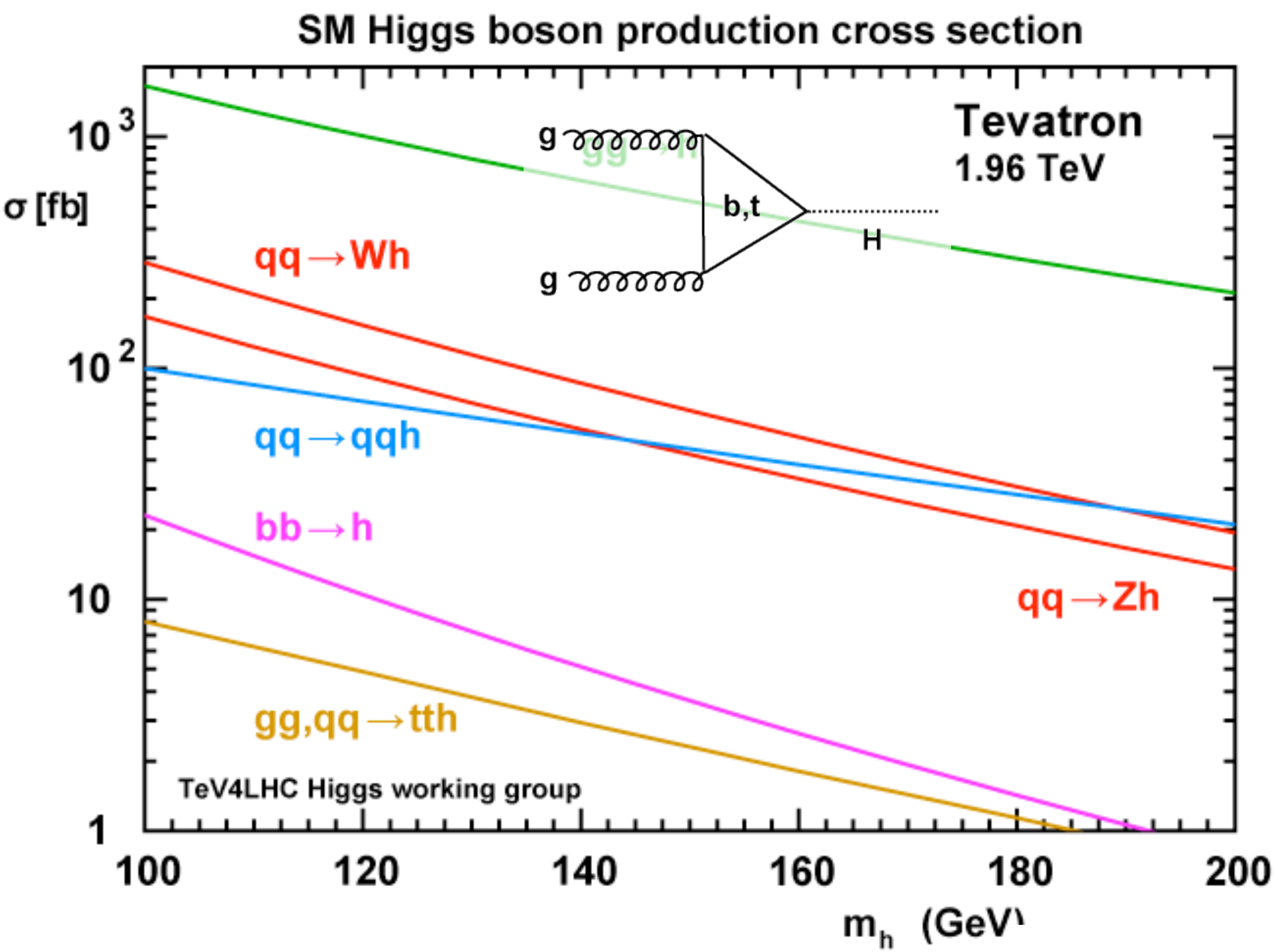
electrons |η|< 2.6
muons |η|< 2

jets

coverage |η|< 3
b tagging |η|< 2
energy scale ~1%

dijet mass ~16%


SM Higgs boson production cross section
Tevatron
1.96 TeV
σ [fb]
10^3
10^2
10
1
gg→h
qq→Wh
qq→qqh
bb→h
qq→Zh
gg,qq→tth
TeV4LHC Higgs working group
100
120
140
160
180
200
m_h (GeV)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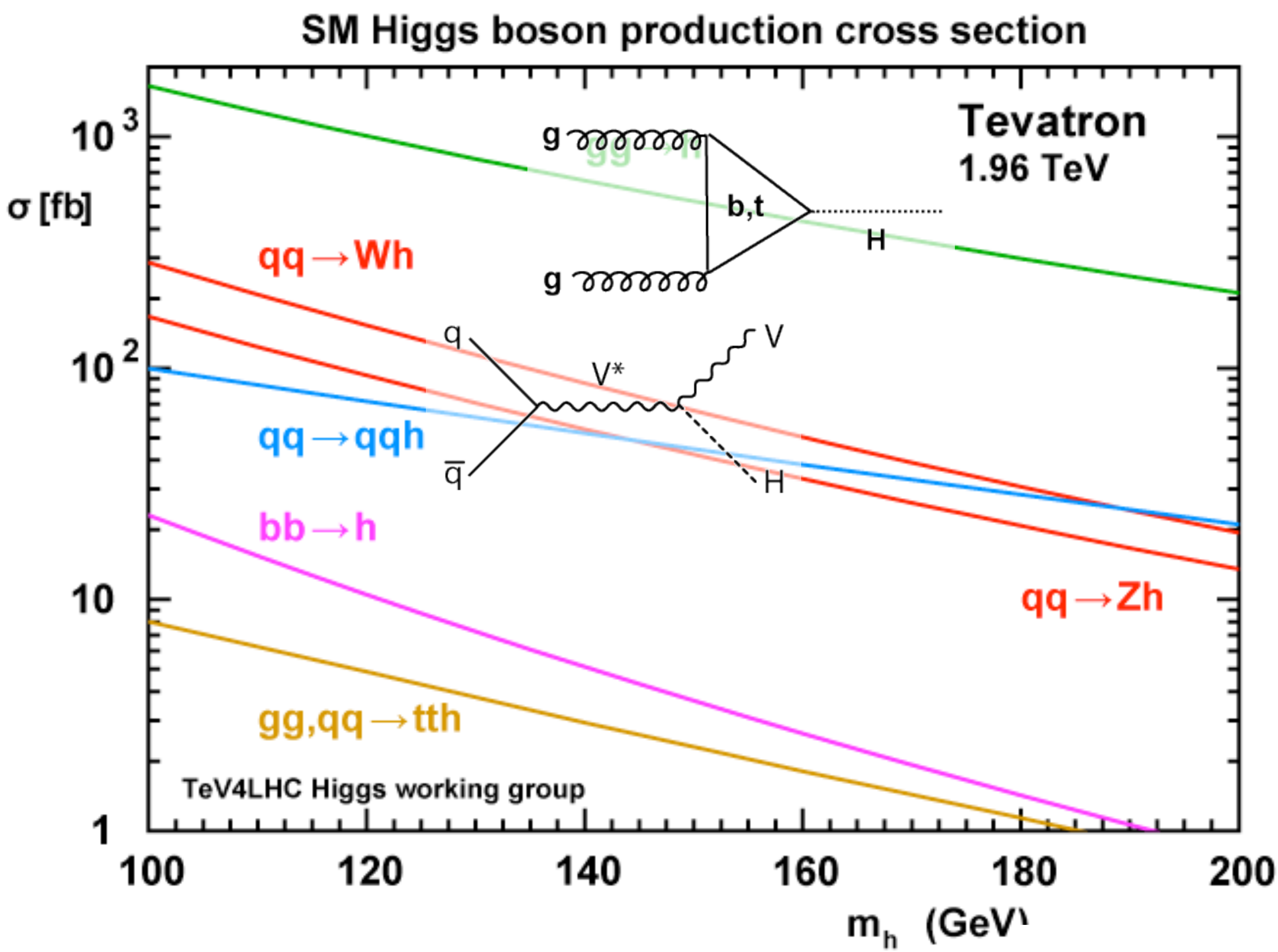
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1.96 TeV
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10^3
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qq→Wh
q
V
V*
qq→qqh
$\bar{q}$
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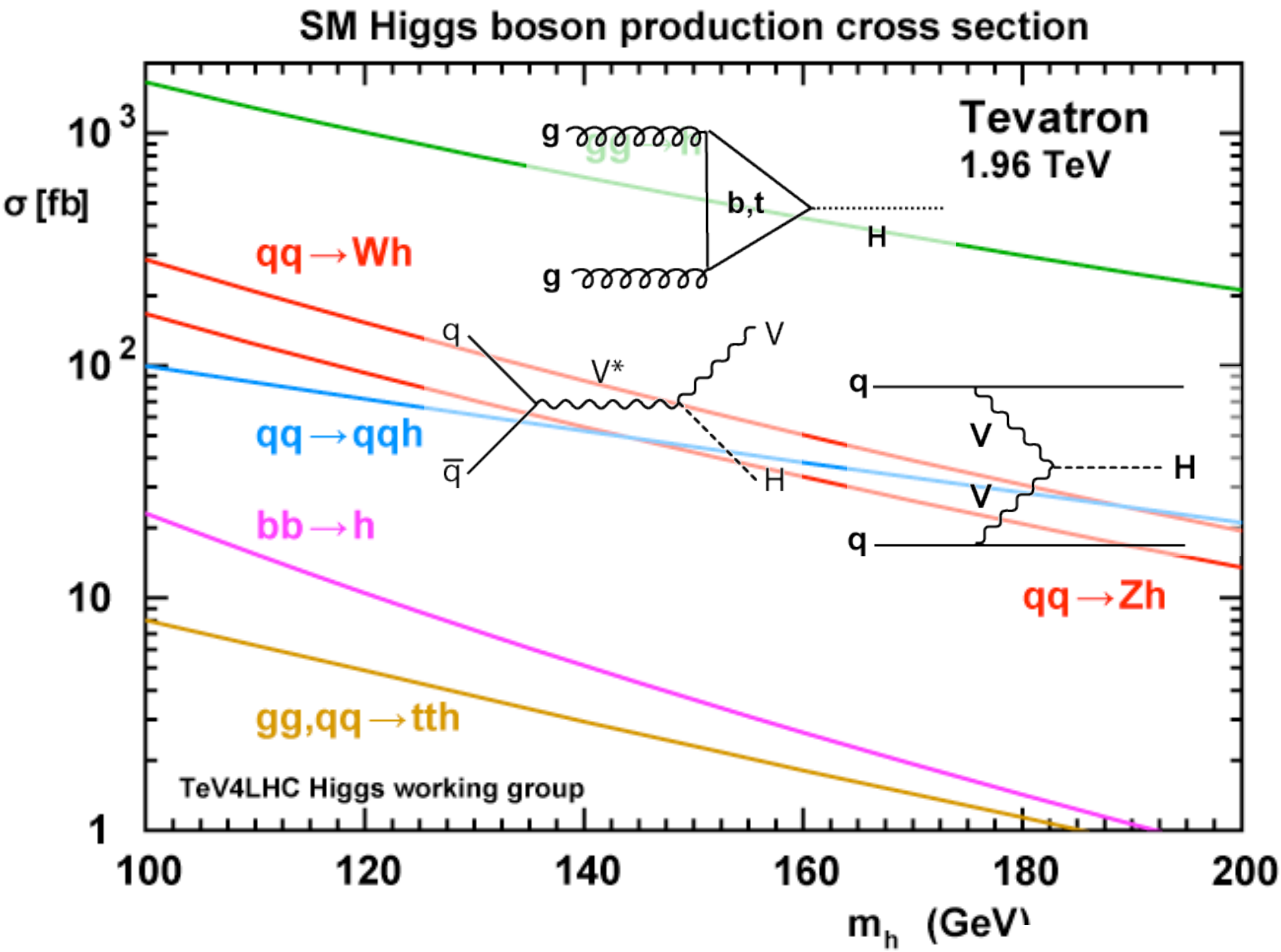
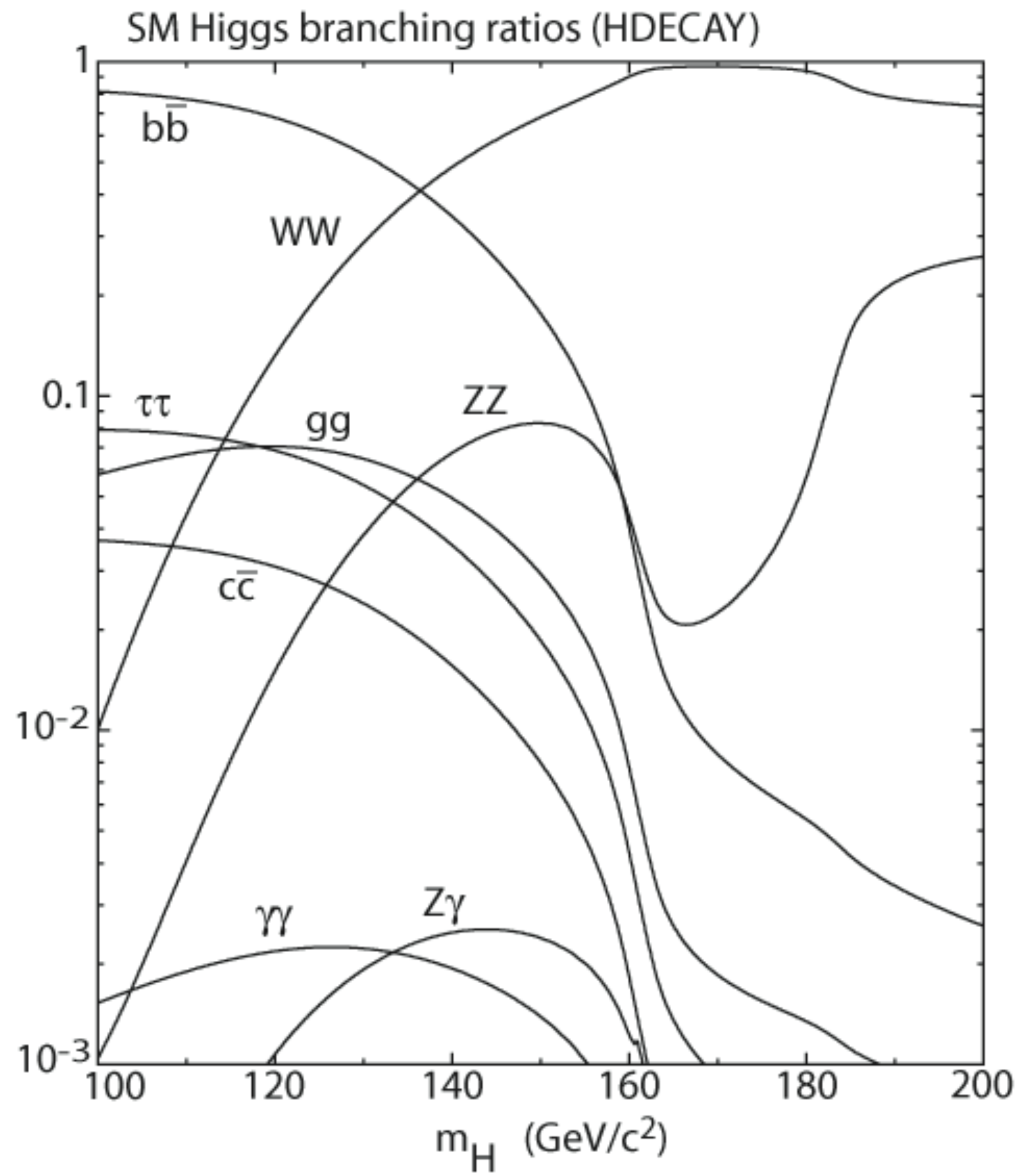


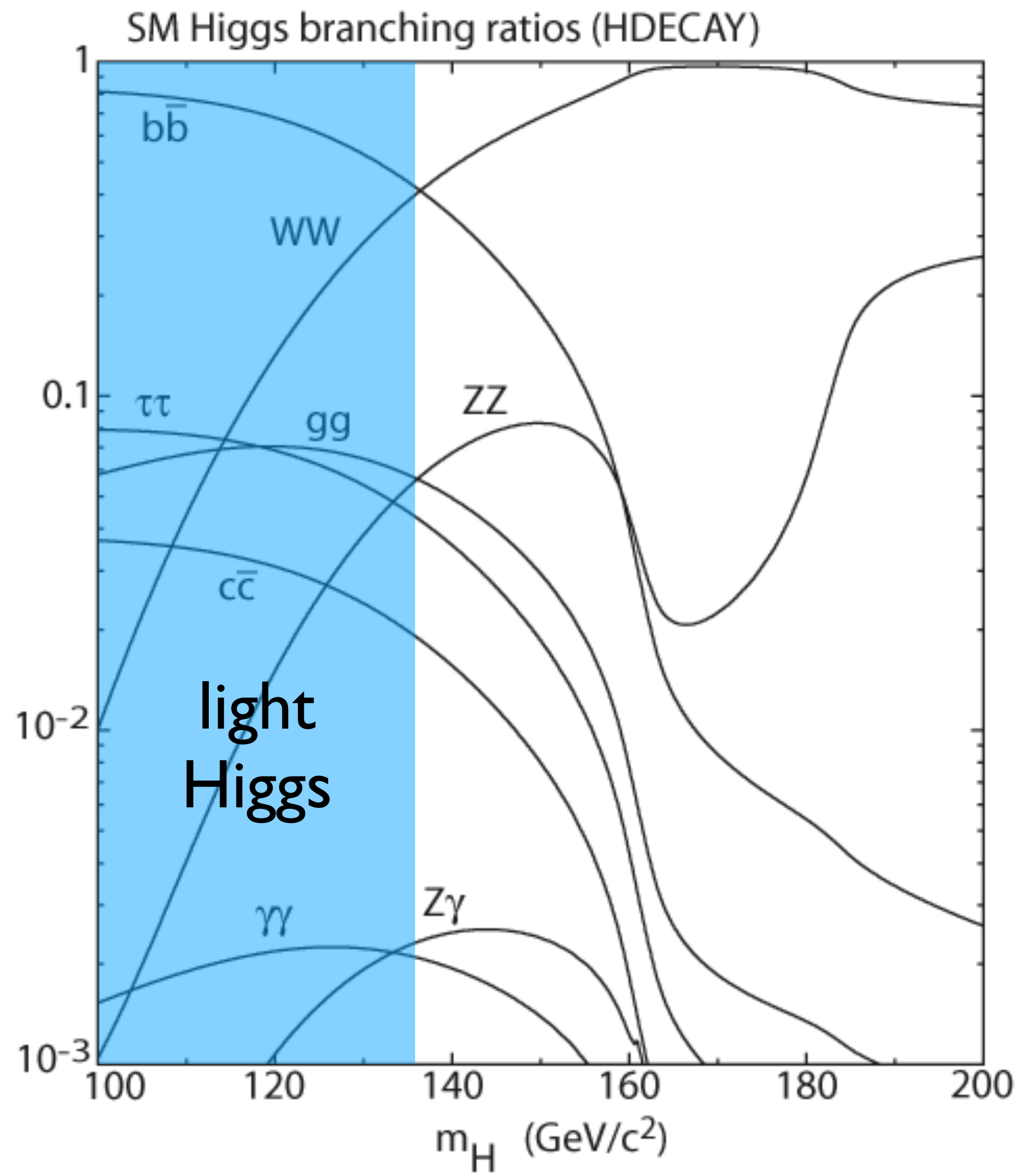
SM Higgs boson production


SM Higgs branching ratios (HDECAY)
1
0.1
10^{-2}
10^{-3}
$b\bar{b}$
WW
ττ
gg
ZZ
$c\bar{c}$
γγ
Zγ
100
120
140
160
180
200
m_H (GeV/c^2)

light SM Higgs boson

bb decay dominates

ττ plays a role

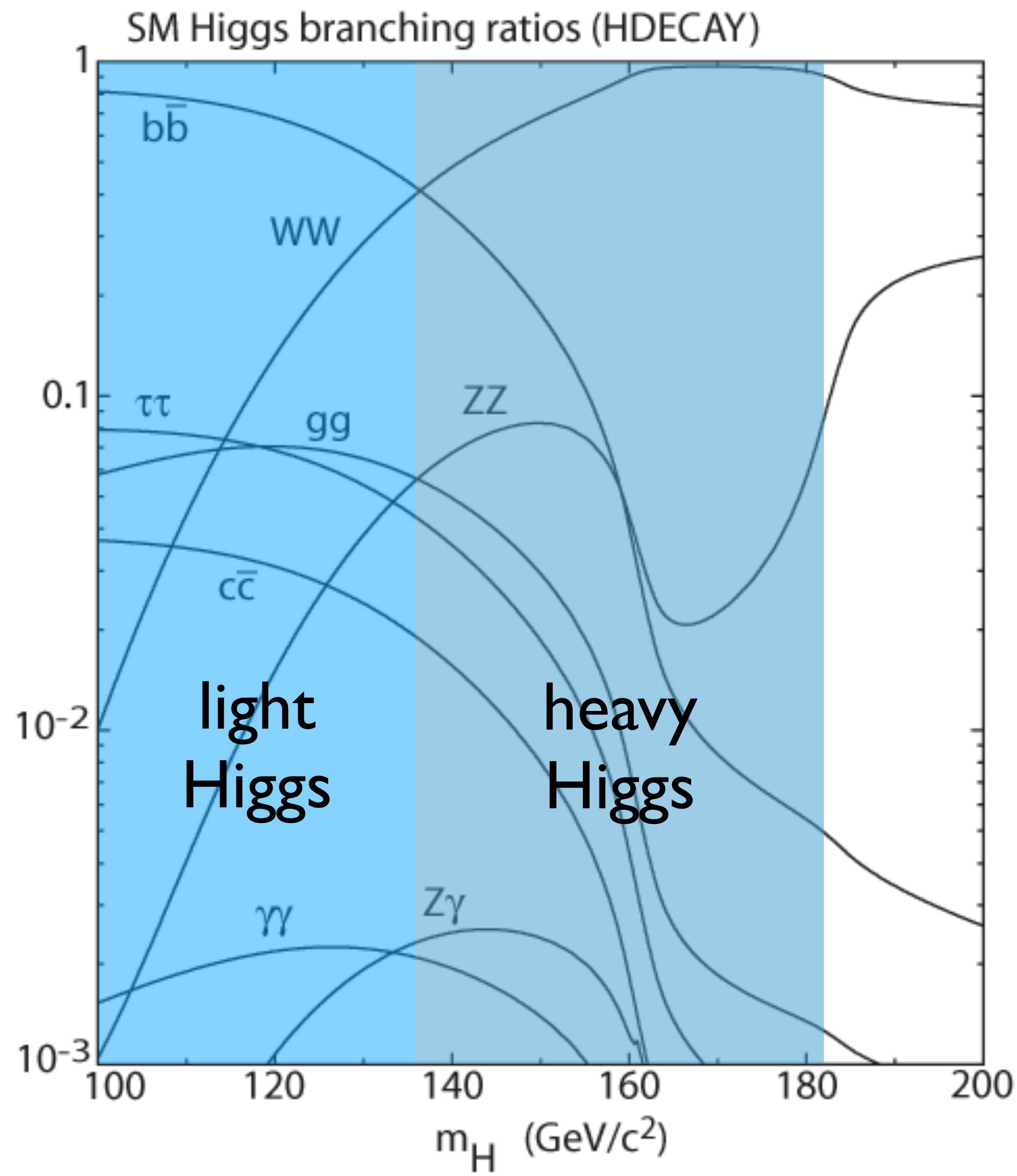


light SM Higgs boson

bb decay dominates
ττ plays a role

heavy SM Higgs boson

WW decay dominates
ZZ: ℓℓ BR too small

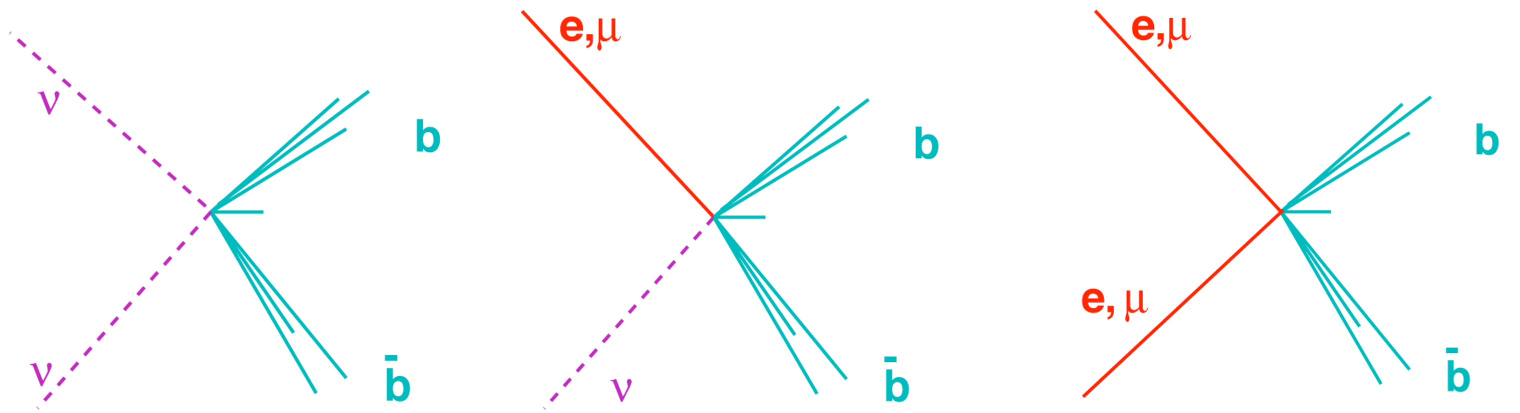


gg→H→bb/ττ suffer too much background

⇒ low mass channels: WH and ZH (with leptons)

$gg \rightarrow H \rightarrow bb/\tau\tau$ suffer too much background

⇒ low mass channels: WH and ZH (with leptons)



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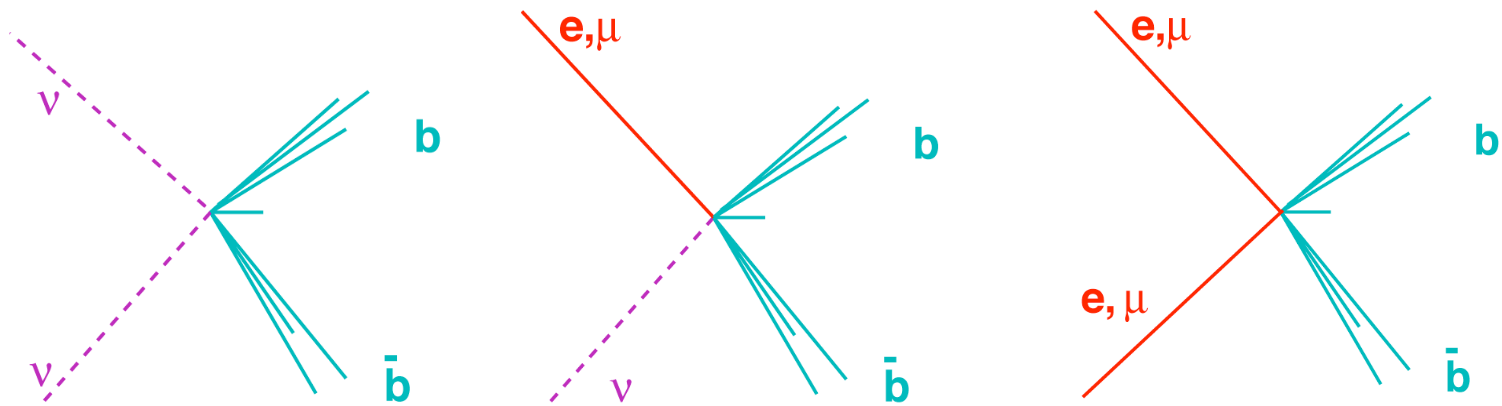
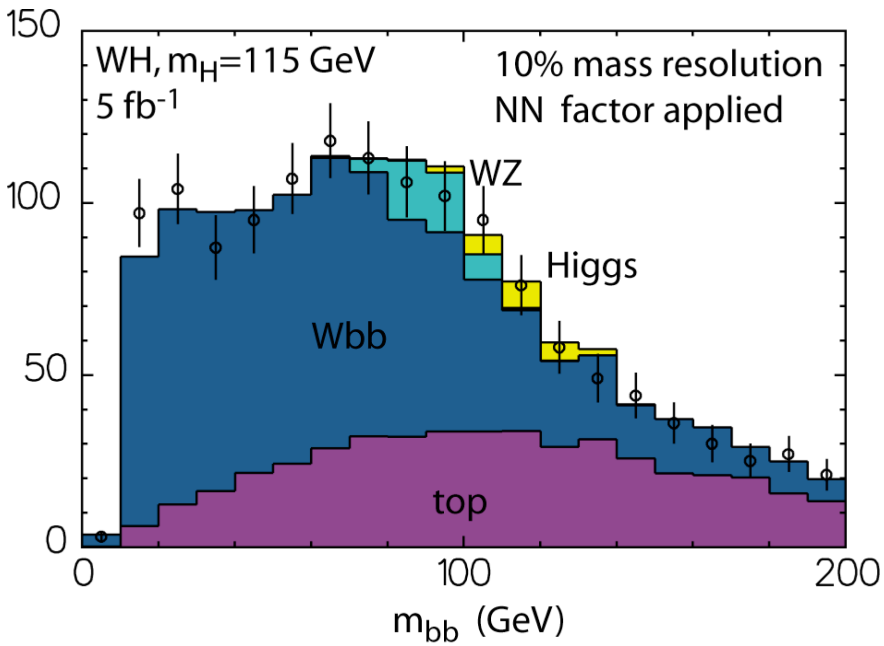
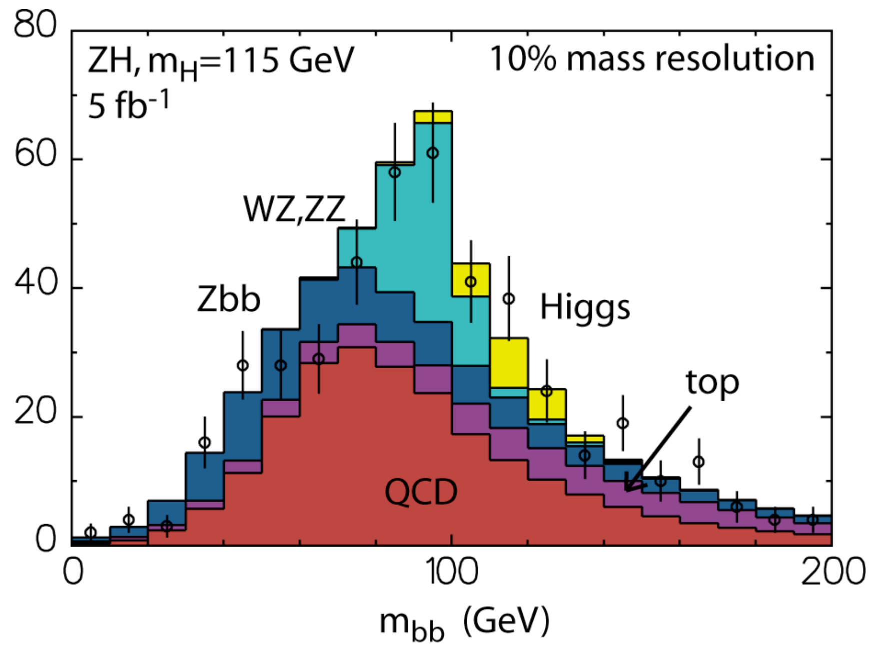


bb modes demand
- excellent b tagging
- sharp bb mass resolution
- solid control of background

Even with optimal conditions, bb modes are a challenge!

2003 Higgs Search Committee report:

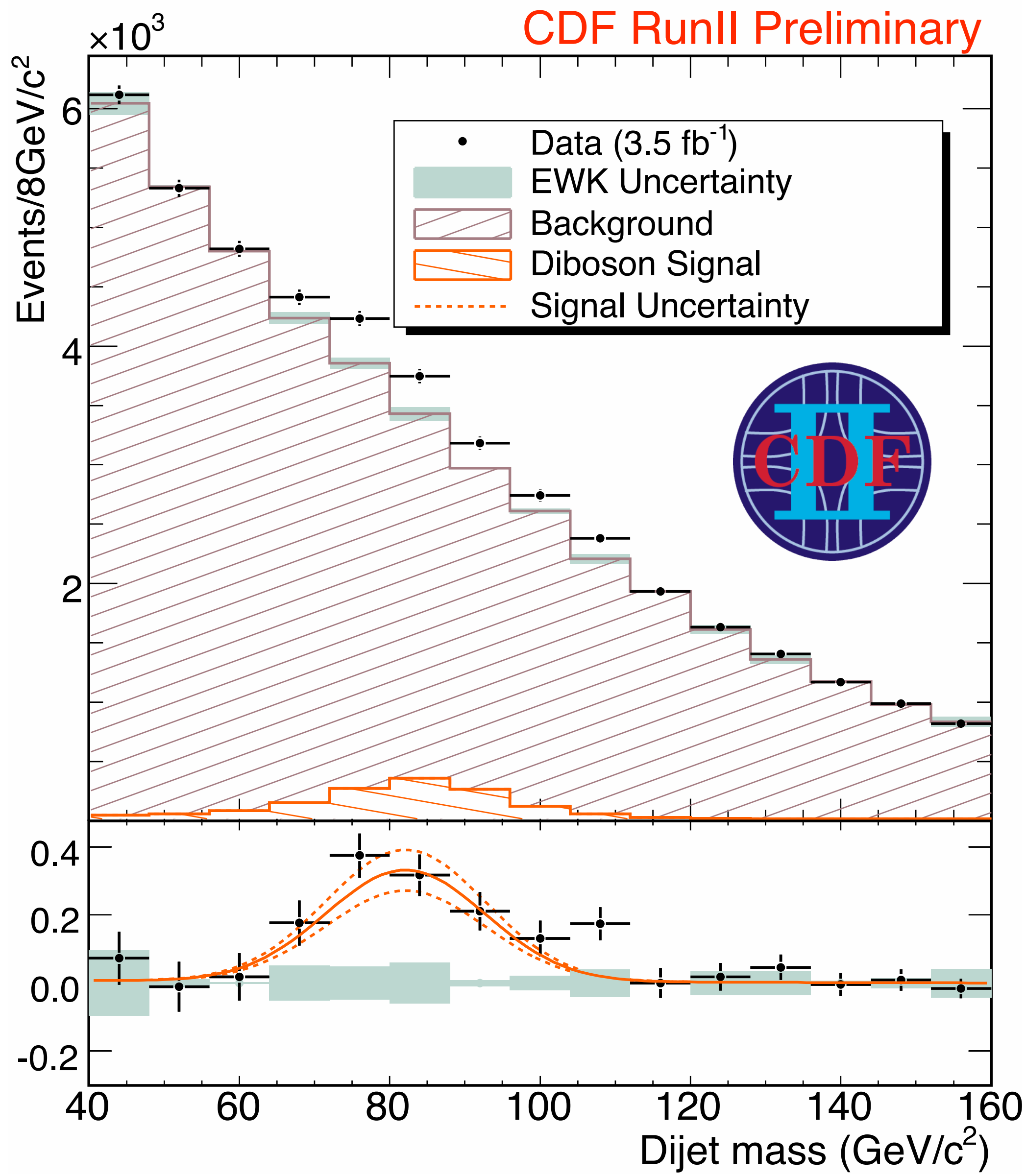




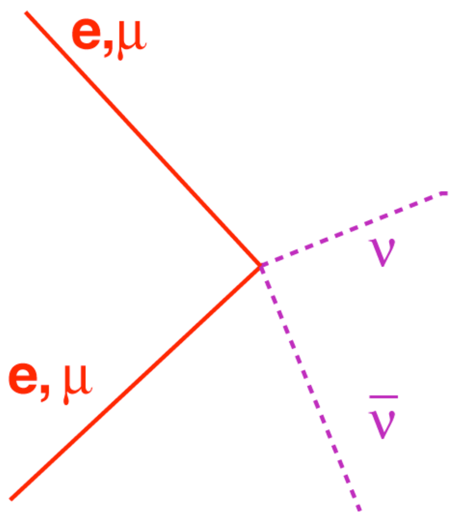
Can we really observe such feeble dijet mass excesses?

Look for WW/WZ in the MET+jets final state

We can reconstruct di-jet mass peak above large background



High mass search channels: $gg \to H \to WW$ (OS leptons)
$VH \to VWW$ (SS leptons)

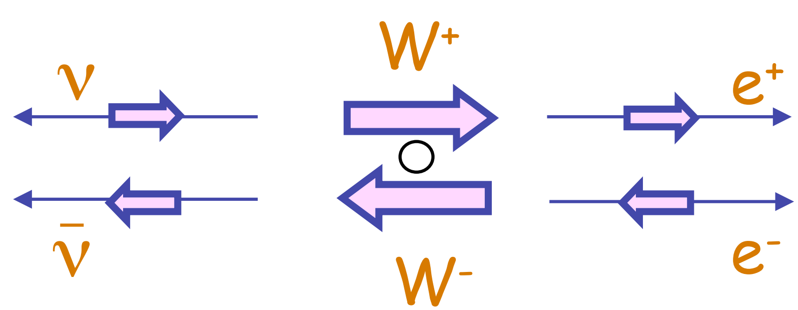


CDF analysis

OS + 0 jets, 1 jet, 2 jets

SS + $\geq$1 jet

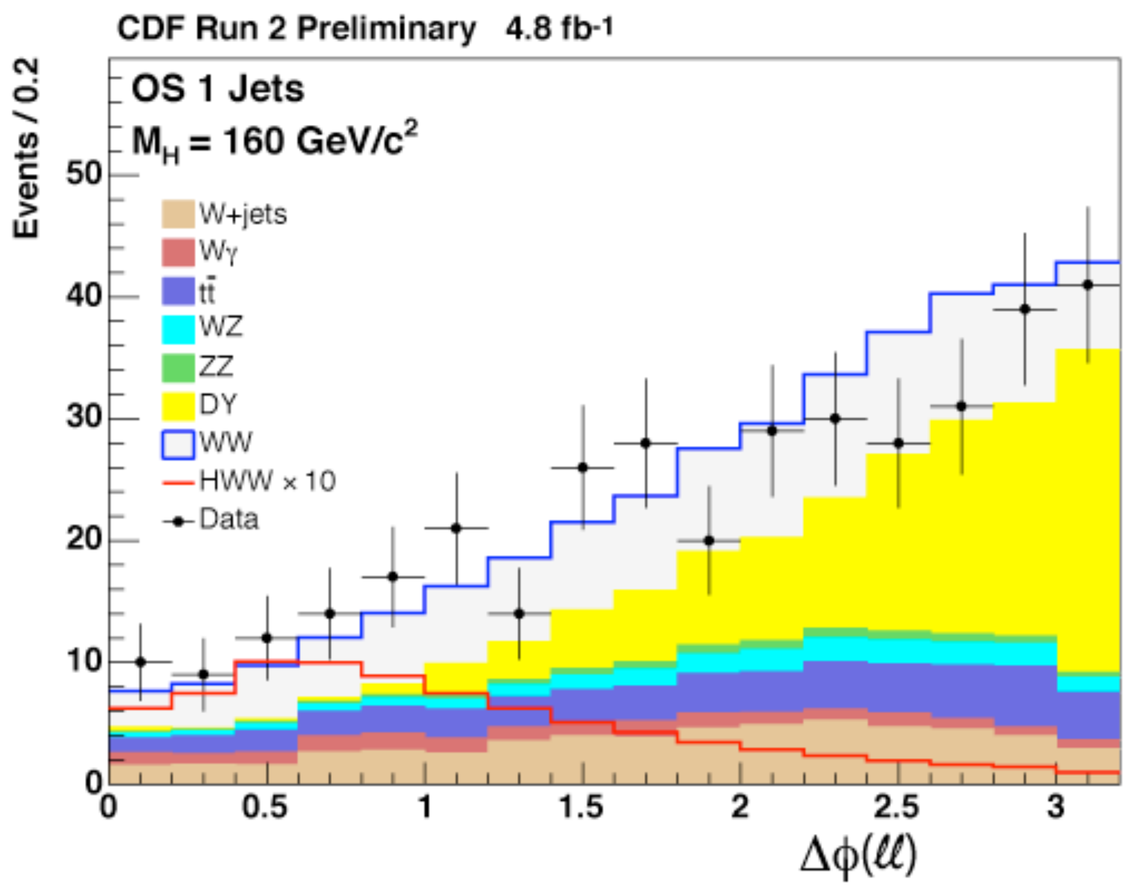
For Higgs, exploit angular correlation of leptons due to W polarization

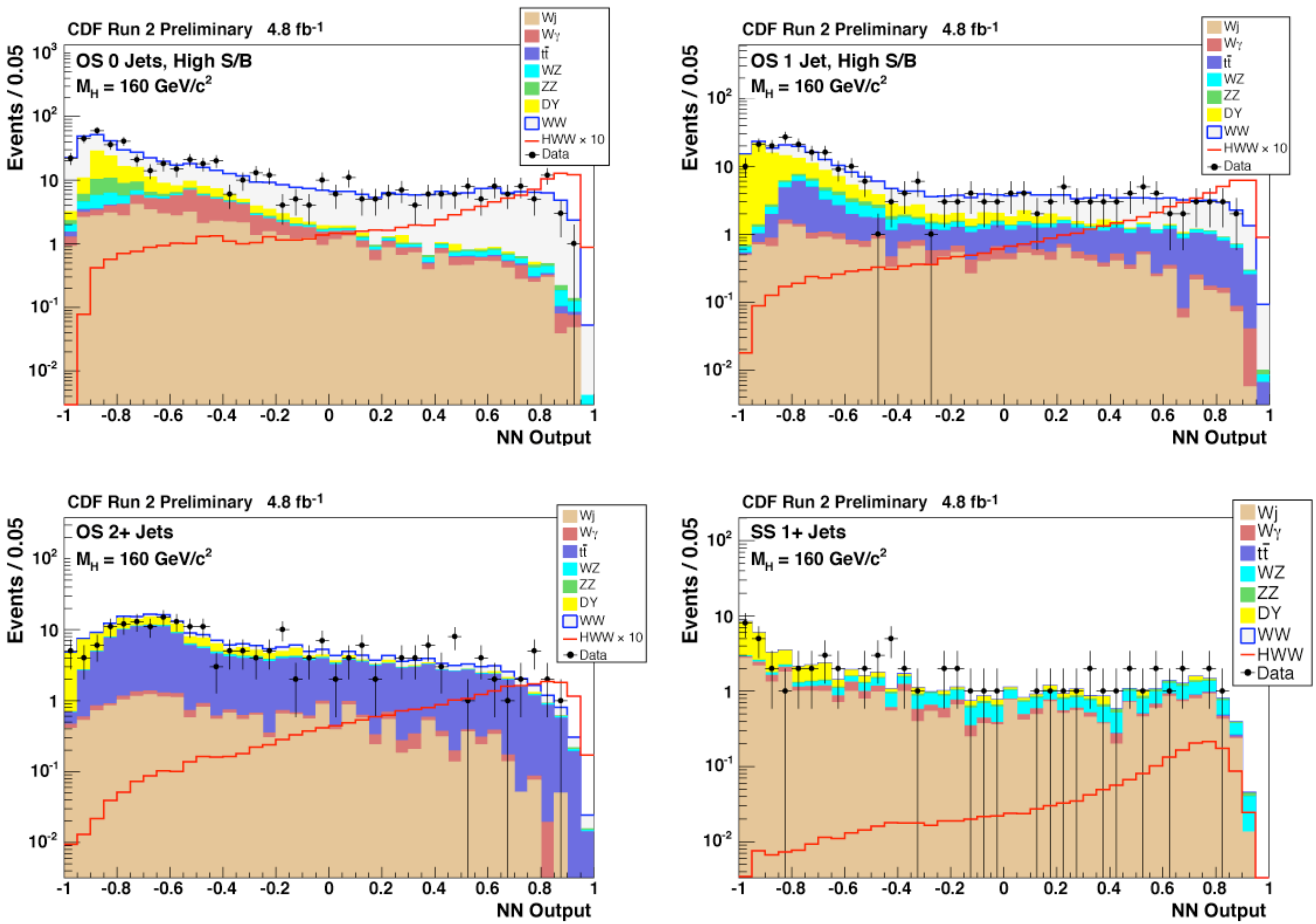


New result shown first at this conference: CDF SM H→WW using 4.8 fb^{-1}

$\Delta\phi(\ell\ell)$ distribution shows effect of spin correlations

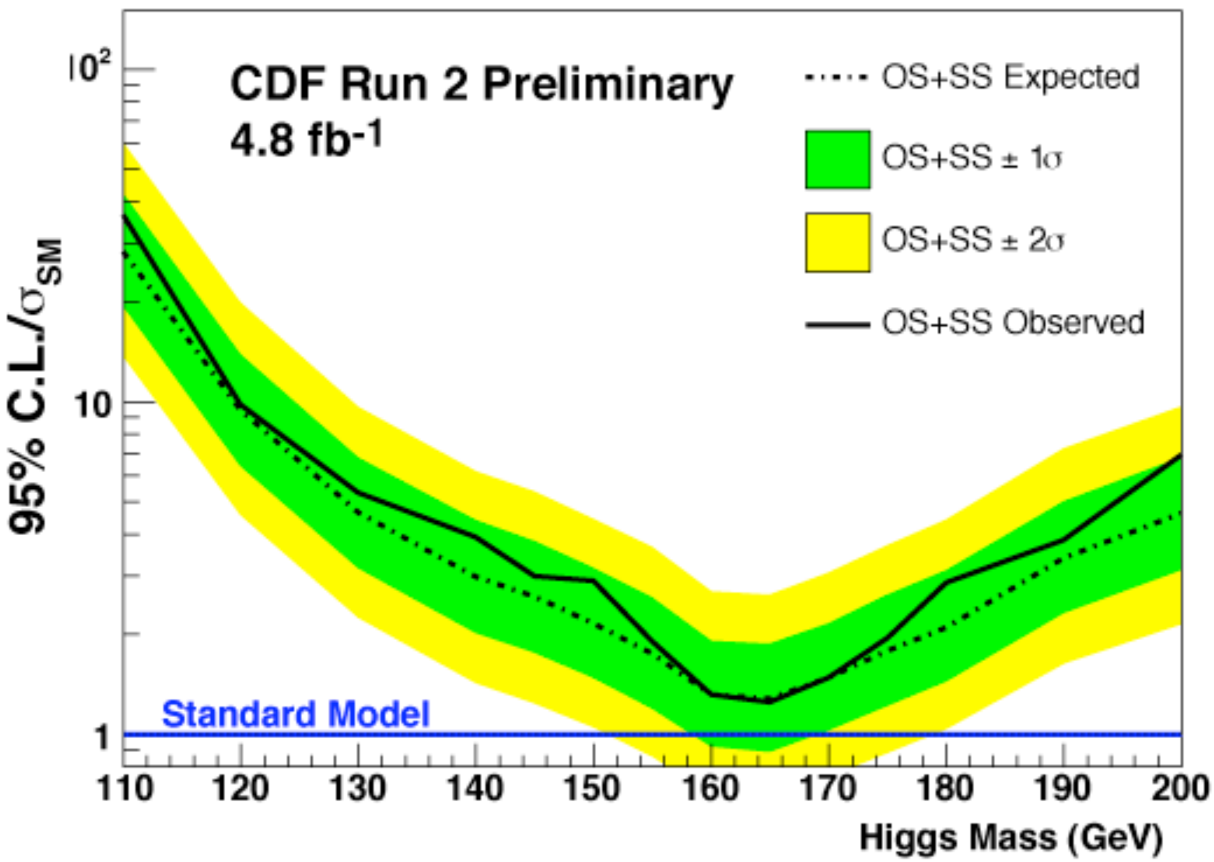
Use NN discriminator on all four channels




CDF Run 2 Preliminary 4.8 fb-1
OS 0 Jets, High S/B
MH = 160 GeV/c2
OS 1 Jet, High S/B
MH = 160 GeV/c2
OS 2+ Jets
MH = 160 GeV/c2
SS 1+ Jets
MH = 160 GeV/c2
Wj
Wγ
tt̄
WZ
ZZ
DY
WW
HWW × 10
HWW
Data
Events / 0.05
NN Output

High Mass - WW

No signal seen - combine all four channels to set limits



D0 has very similar analysis; will update soon with full set

Should we really believe such complicated analyses using neural nets, boosted decision trees, etc?

Existence proof:
single top discovery

Both CDF and D0 achieved >5 sigma significance using ME, NN, BDT

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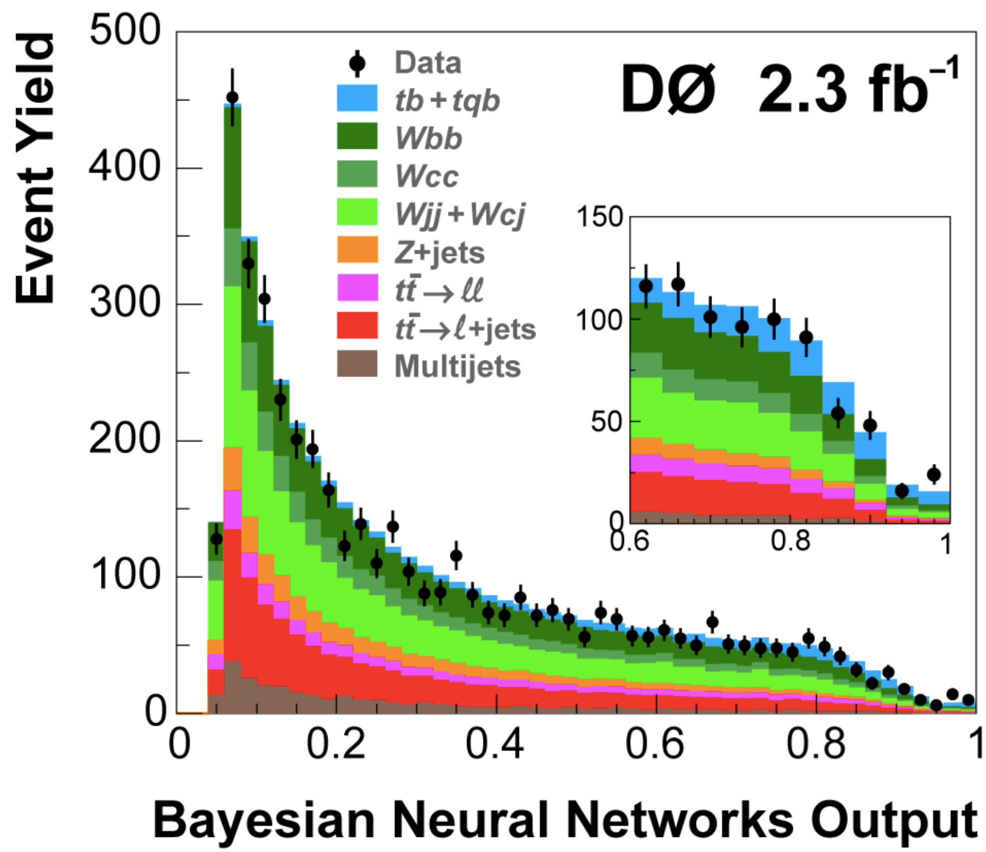

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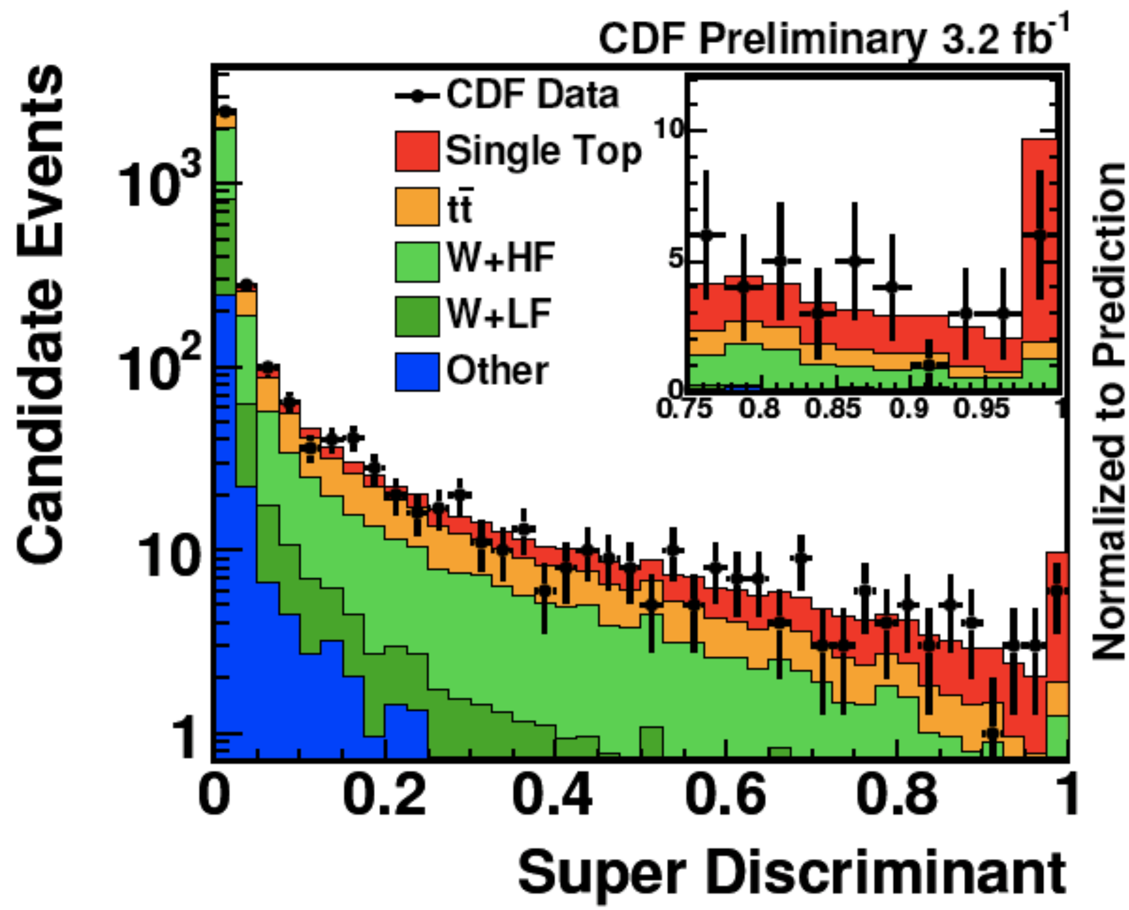
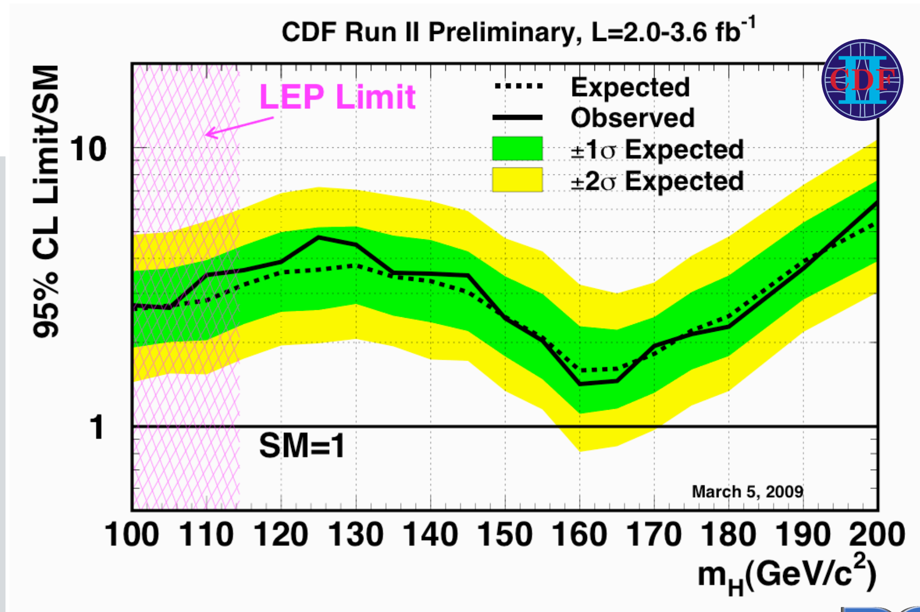


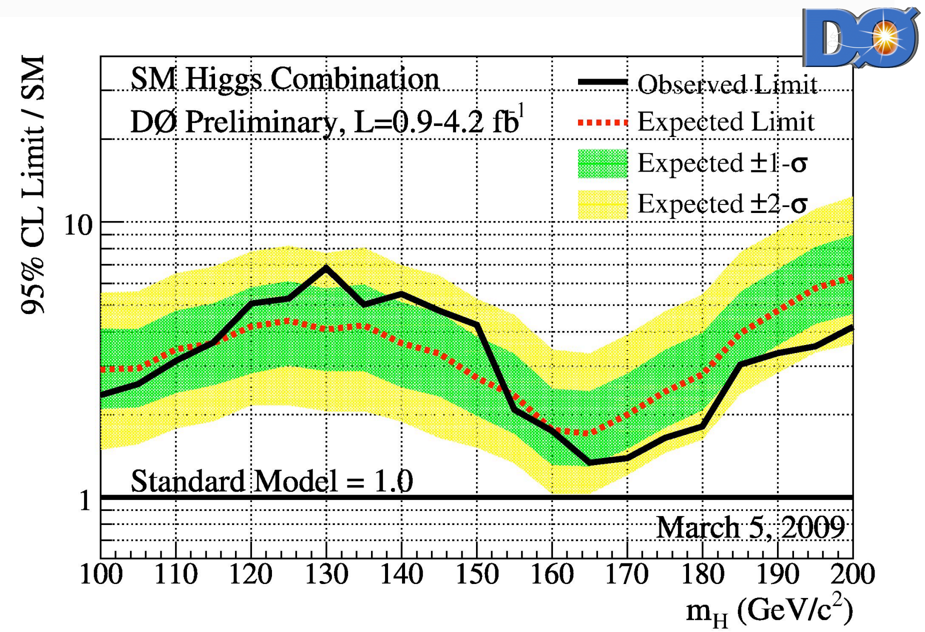
CDF and D0 combine all channels using combined likelihood

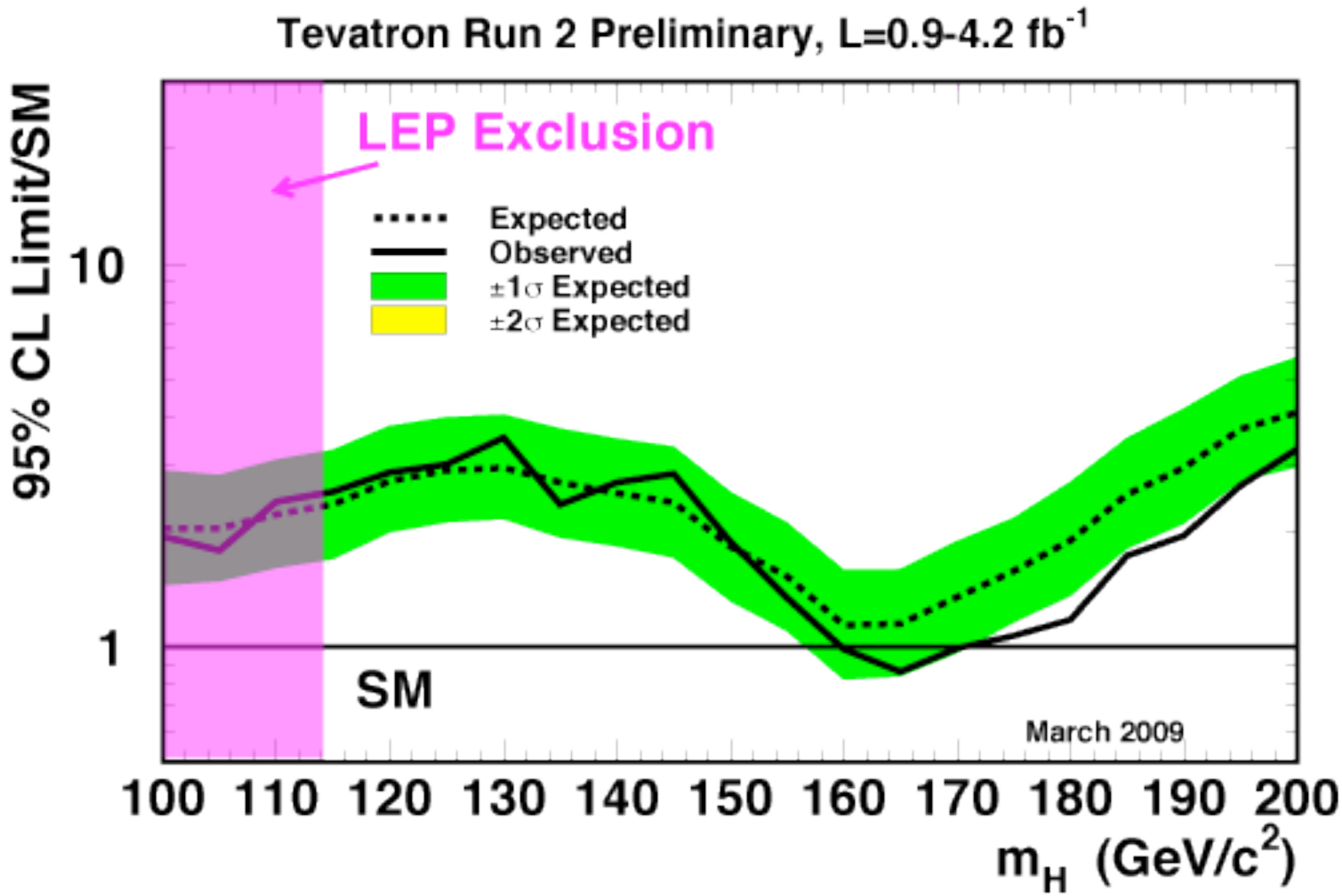
Bayesian, CLs methods

Include (possibly correlated) systematic uncertainties:

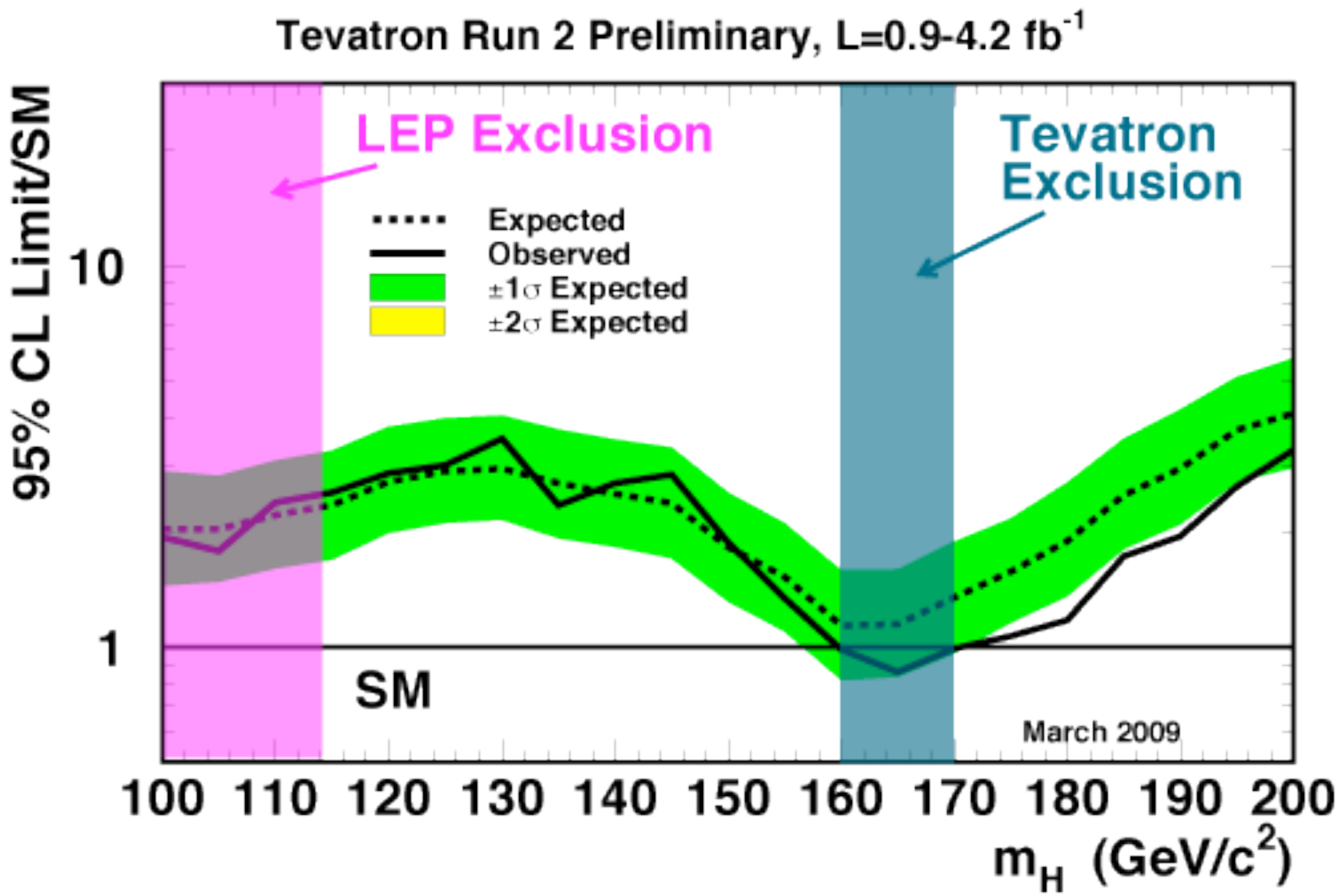
- K factors
- jet energy scale
- lepton efficiency
- b-tag efficiency/scale factors
- MET modeling







CDF + D0 Exclusion Limits



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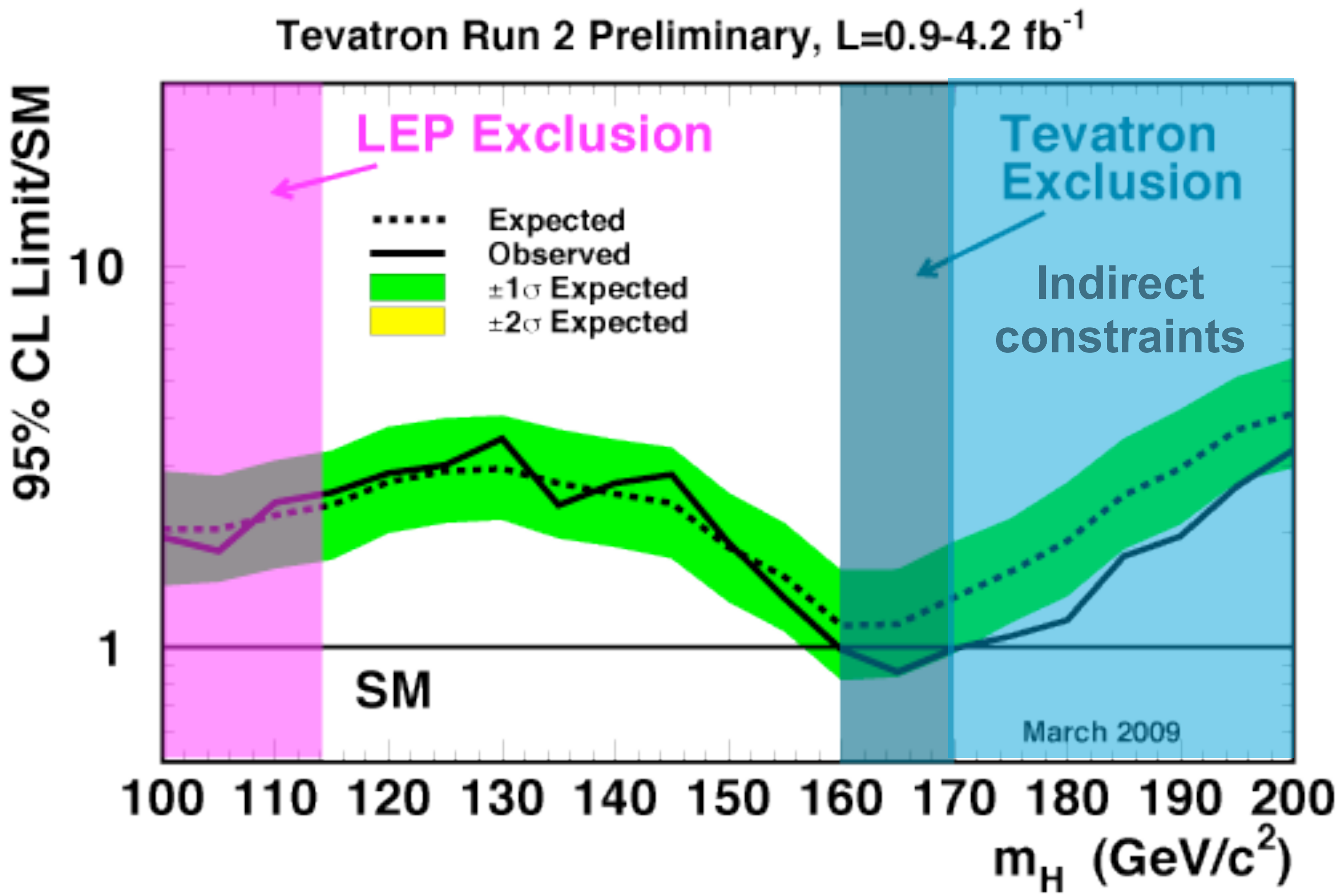

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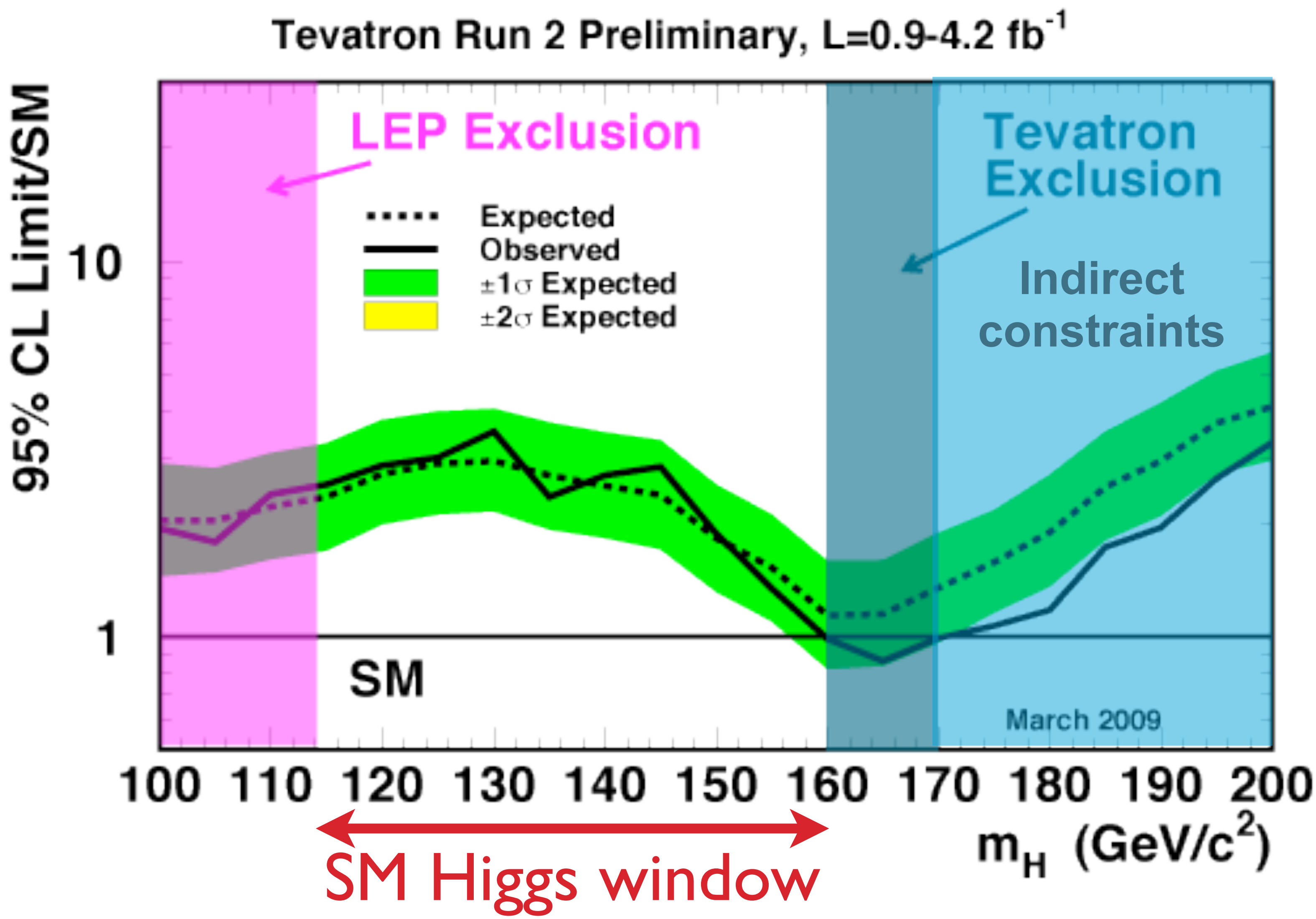

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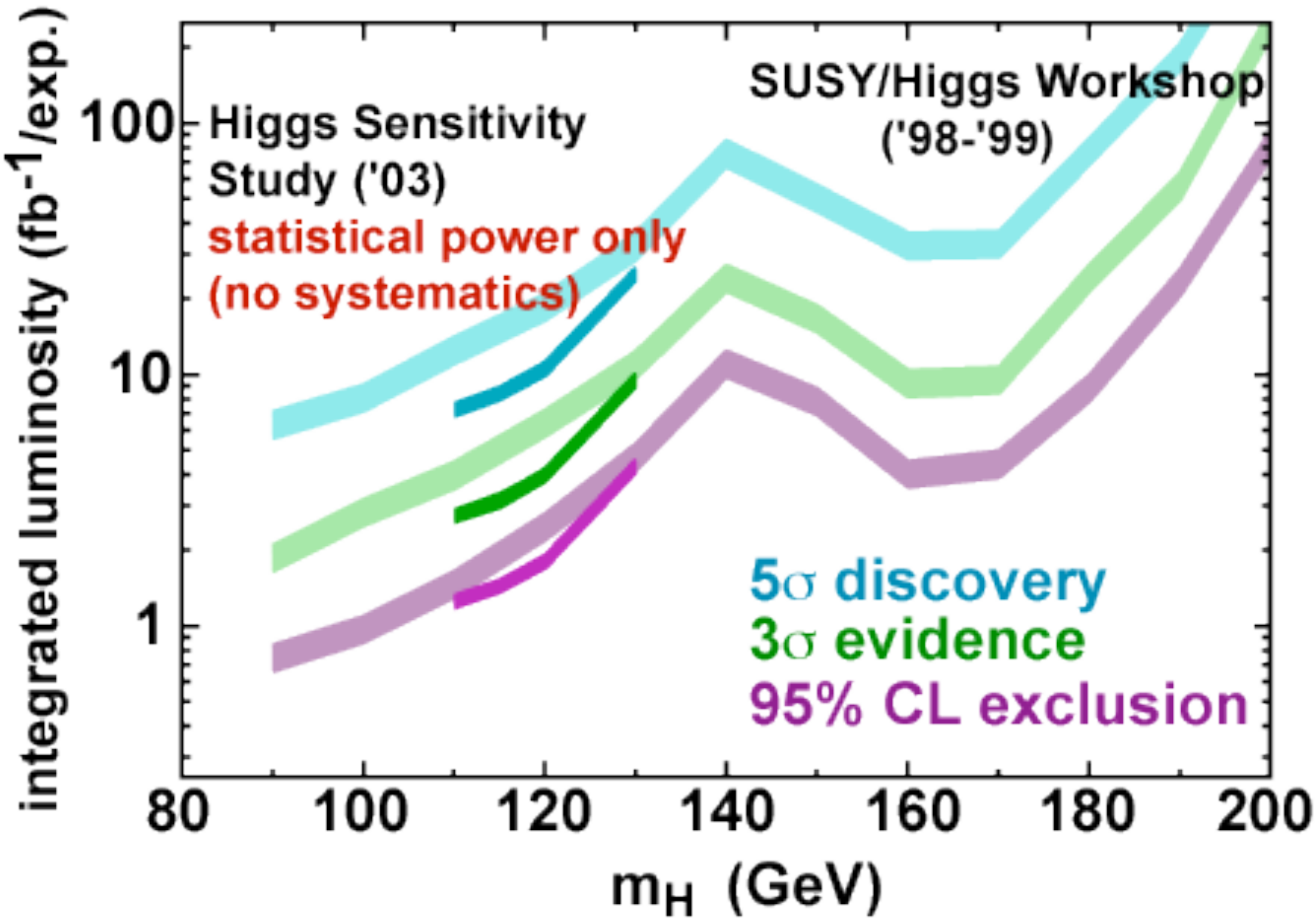
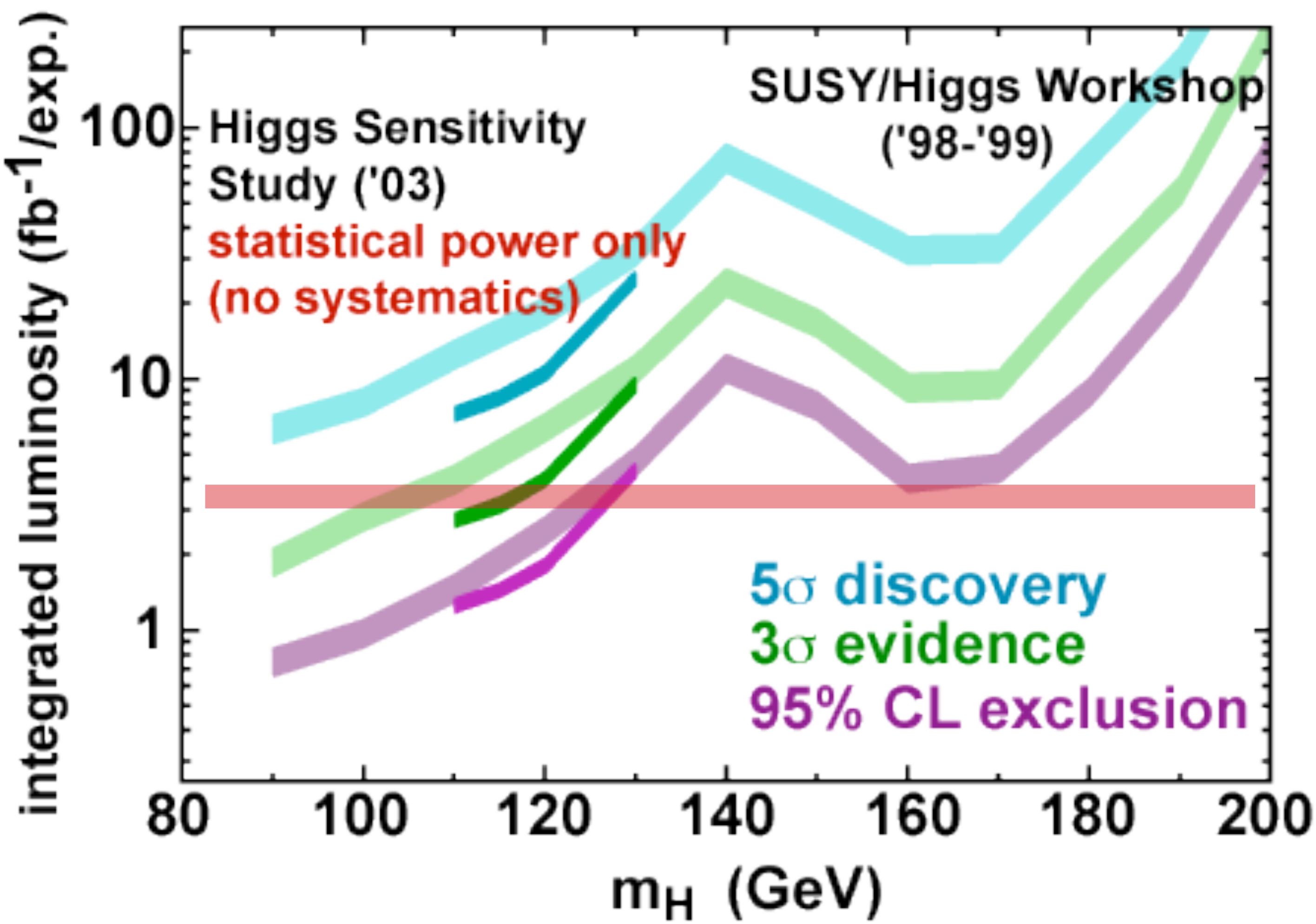
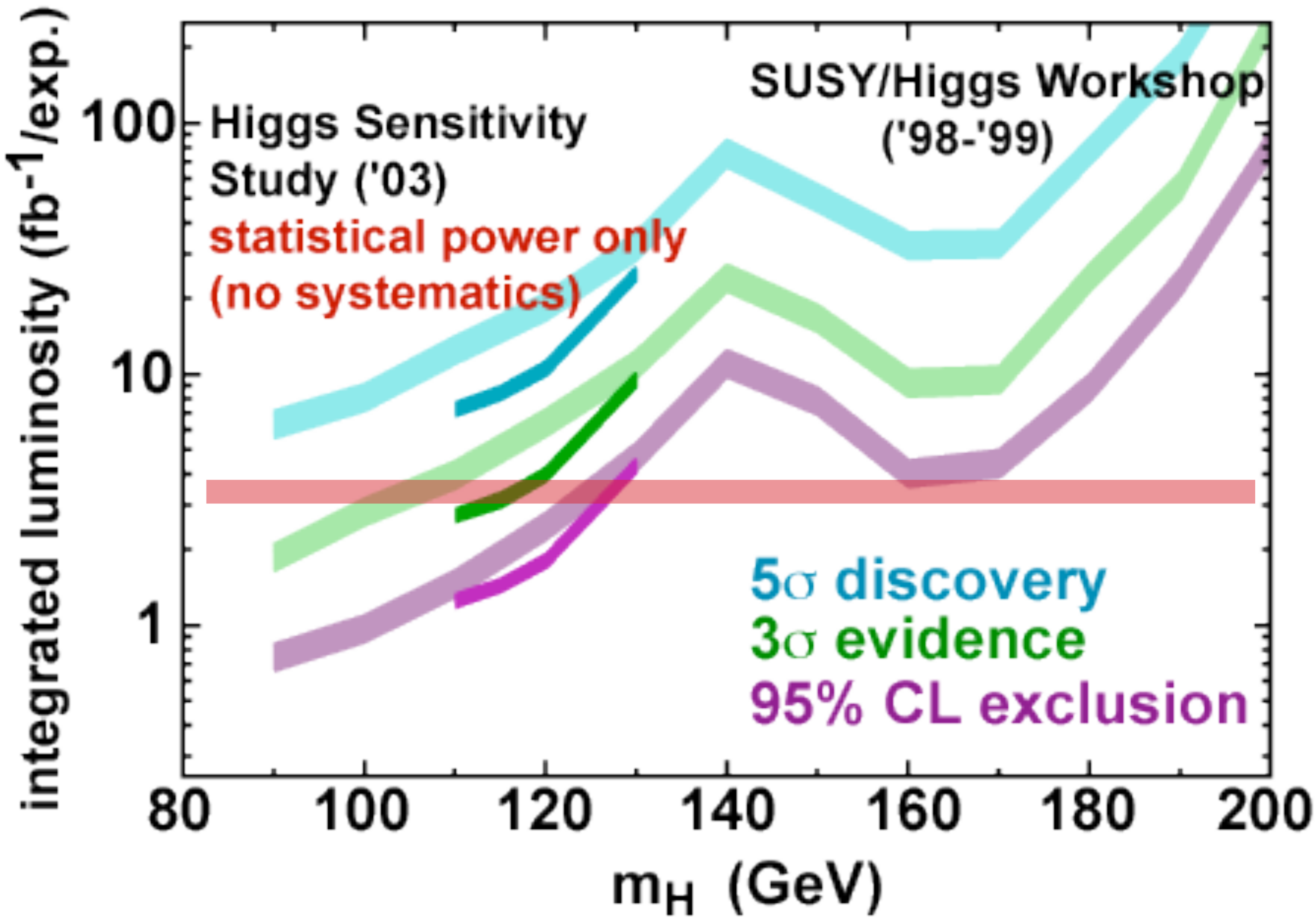

integrated luminosity (fb^{-1}/exp.)
100
10
1
80
100
120
140
160
180
200
m_H (GeV)
Higgs Sensitivity
Study ('03)
statistical power only
(no systematics)
SUSY/Higgs Workshop
('98-'99)
5σ discovery
3σ evidence
95% CL exclusion



present
statistics
(approx.)



present
statistics
(approx.)

Why has the Tevatron not achieved this yet?

Low mass sensitivity not as good as studies:

- new silicon would have improved b-tag coverage
- MET channel ($\nu\nu bb$) trigger efficiency not 100%
- bb mass algorithms not 10% in all channels

Low mass sensitivity not as good as studies:

- new silicon would have improved b-tag coverage
- MET channel ($\nu\nu bb$) trigger efficiency not 100%
- bb mass algorithms not 10% in all channels

Greatly exceeded expectations in a number of areas:

- added tau channels (~10%)
- $\ell\ell bb$ channel much better than expected
- high-mass channels: more powerful methods
- MVA techniques greatly enhance sensitivity
- can still deploy better bb mass algorithms

The "main event" is still the low mass bb channels...

	$\nu\nu bb$	$\ell\nu bb$	$\ell\ell bb$
CDF	2.1 fb^{-1}	2.7 fb^{-1}	2.7 fb^{-1}
D0	1.6 fb^{-1}	2.7 fb^{-1}	4.2 fb^{-1}

We anticipate updates soon in a number of these!

$\nu\nu bb$: expected to be the most sensitive

$\ell\nu bb$: heavily studied final state

$\ell\ell bb$: best m_{bb} resolution, low BR

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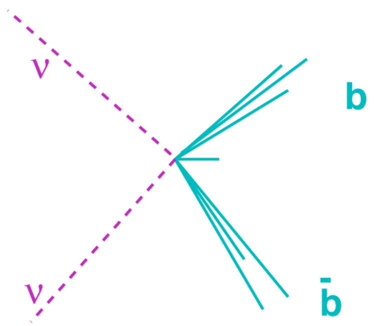
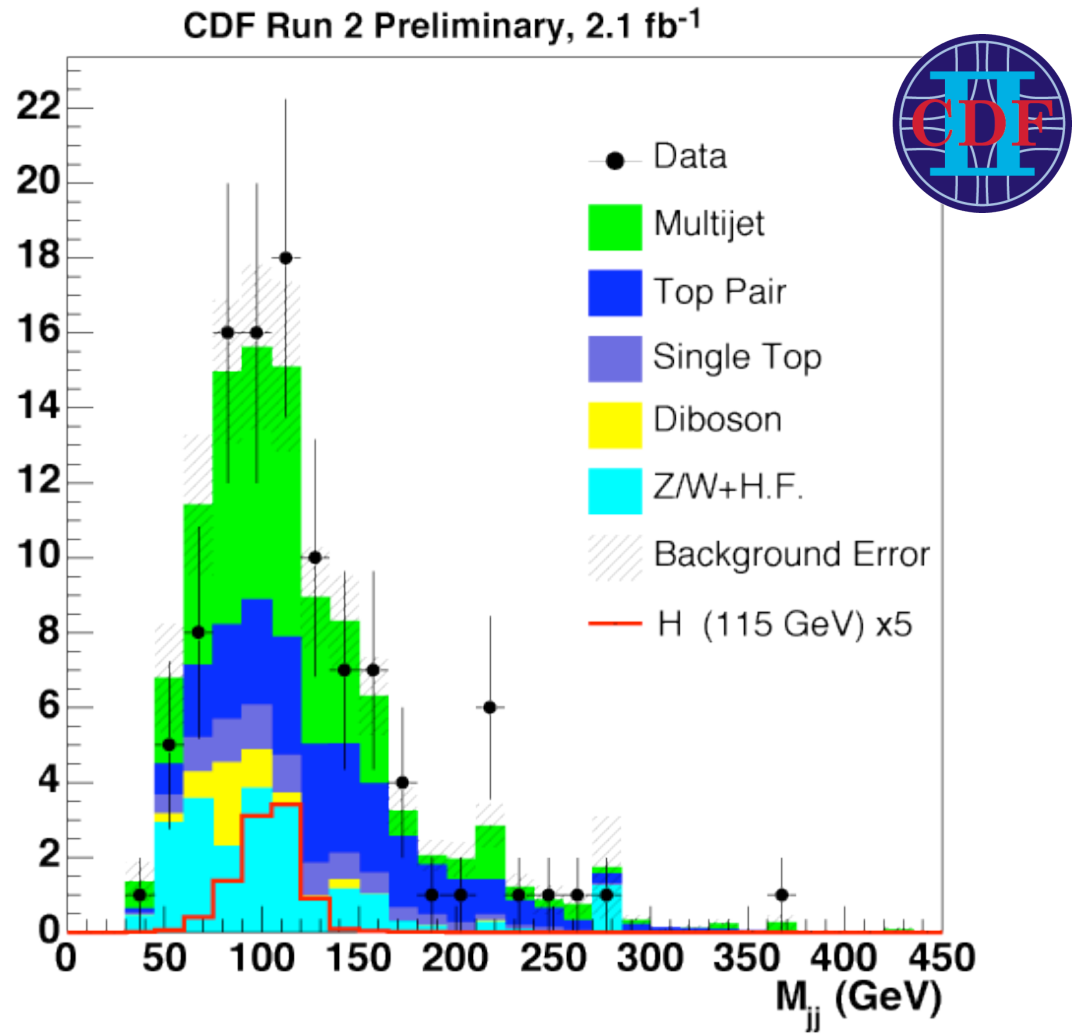
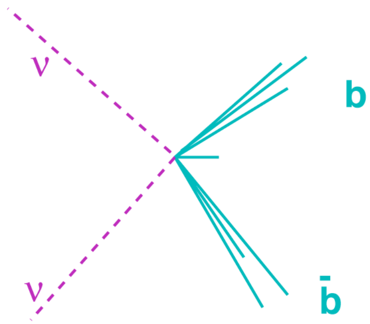
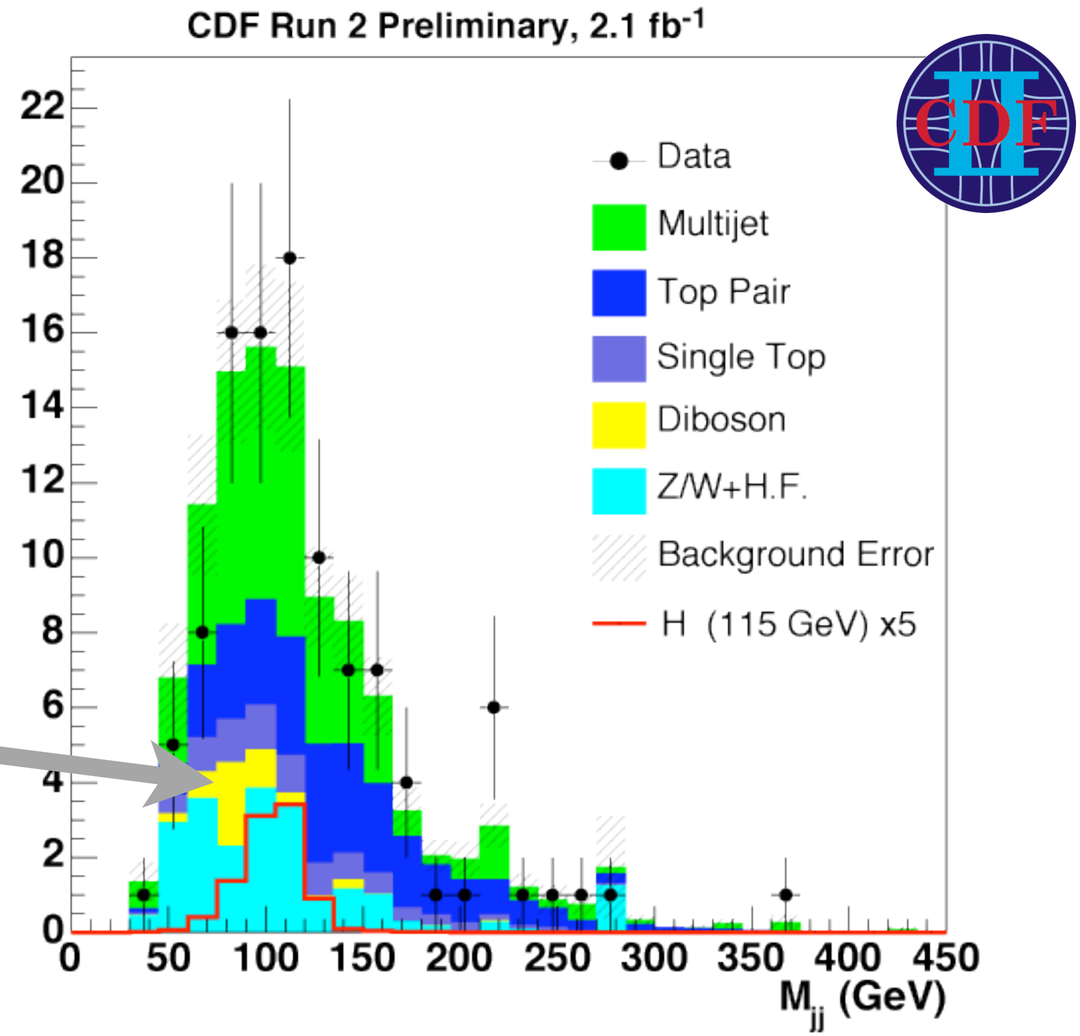
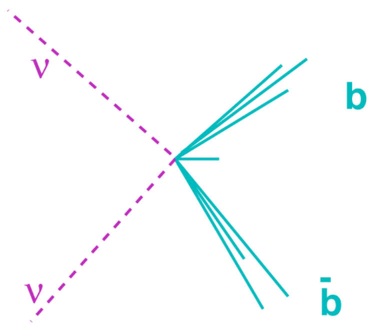

ν
b
ν
b̄


CDF Run 2 Preliminary, 2.1 fb^{-1}
Data
Multijet
Top Pair
Single Top
Diboson
Z/W+H.F.
Background Error
H (115 GeV) x5
M_{jj} (GeV)
0
2
4
6
8
10
12
14
16
18
20
22
0
50
100
150
200
250
300
350
400
450

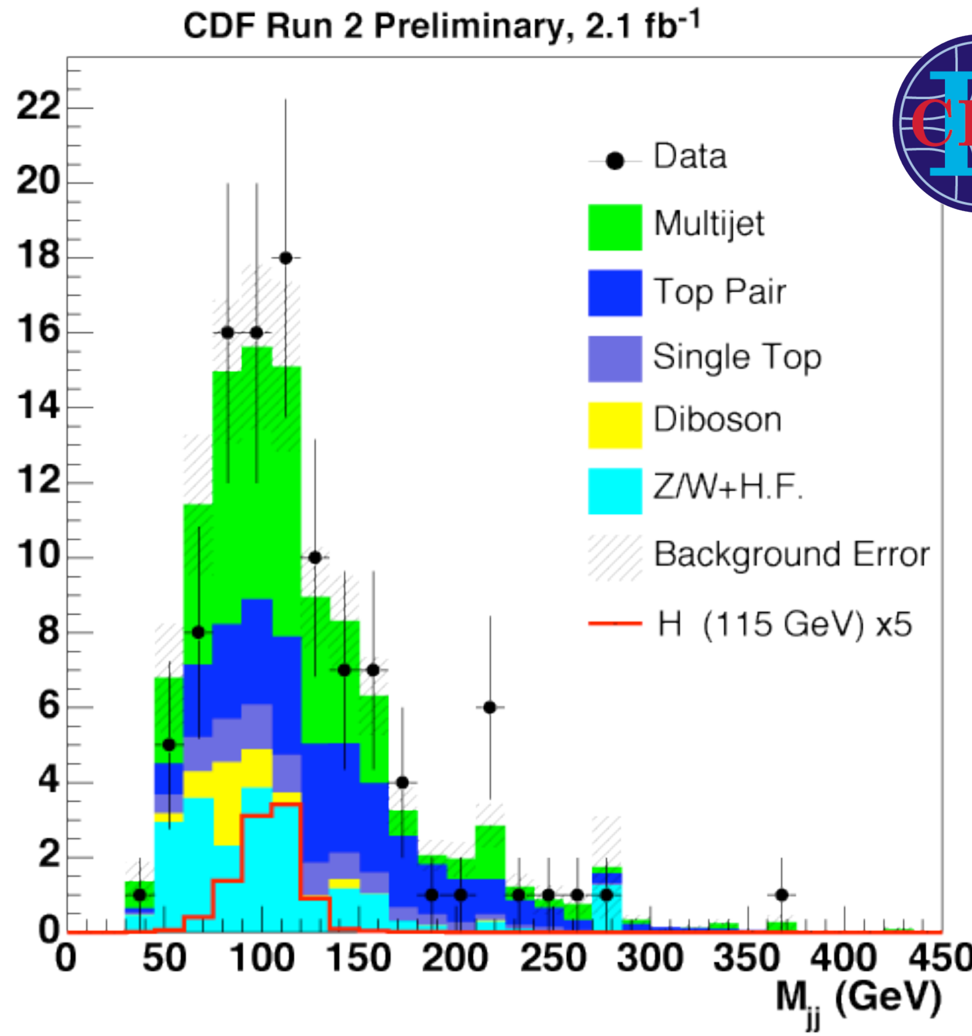




cannot quite see peaking background WZ/ZZ



ν
b
ν
b̄



CDF Run 2 Preliminary, 2.1 fb^{-1}
Data
Multijet
Top Pair
Single Top
Diboson
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Background Error
H (115 GeV) x5
CDF II
0
2
4
6
8
10
12
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16
18
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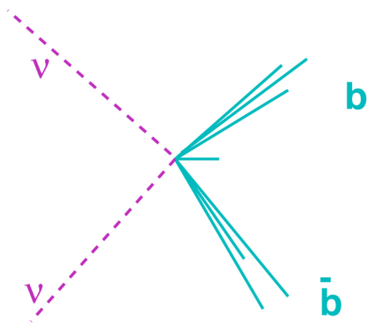
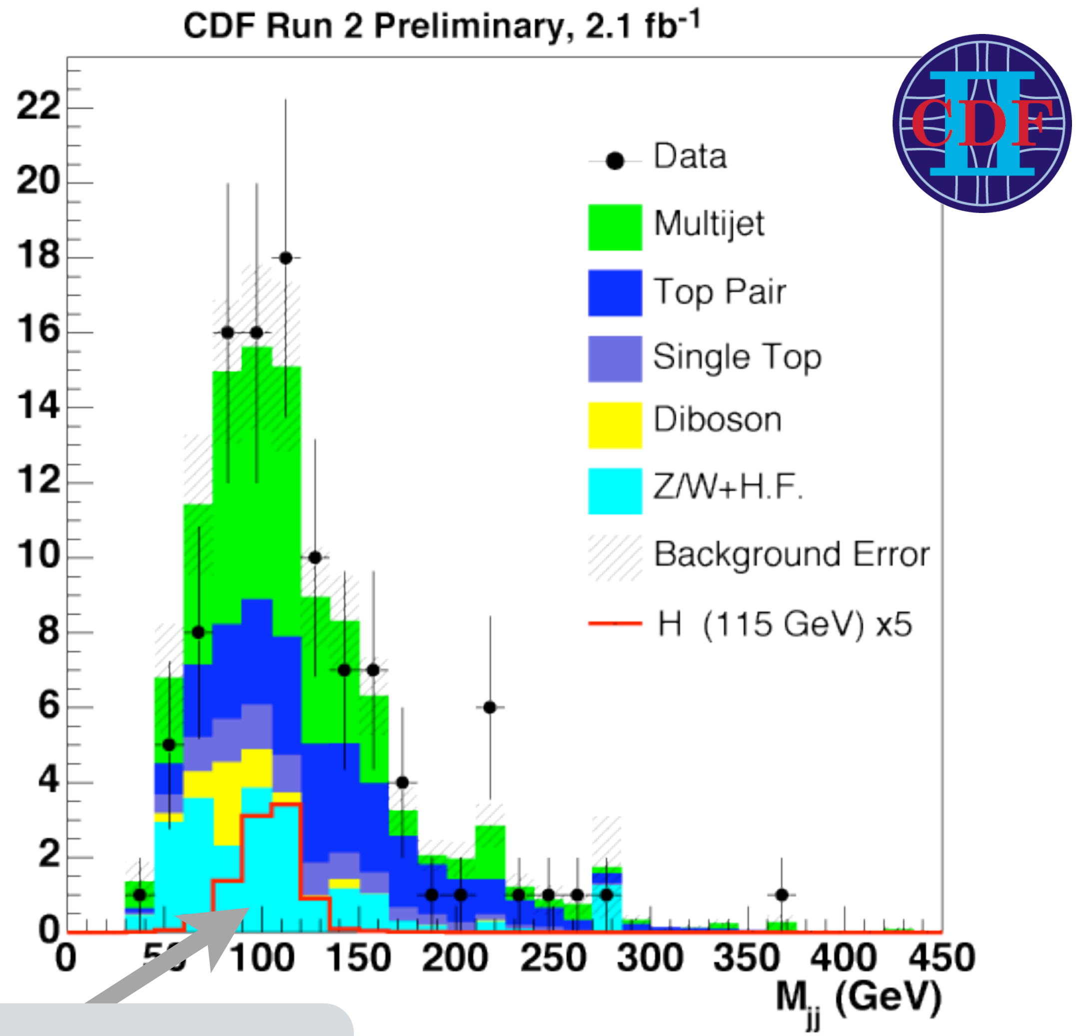
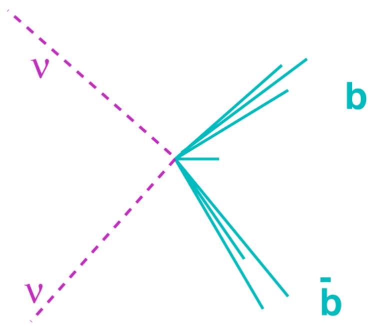
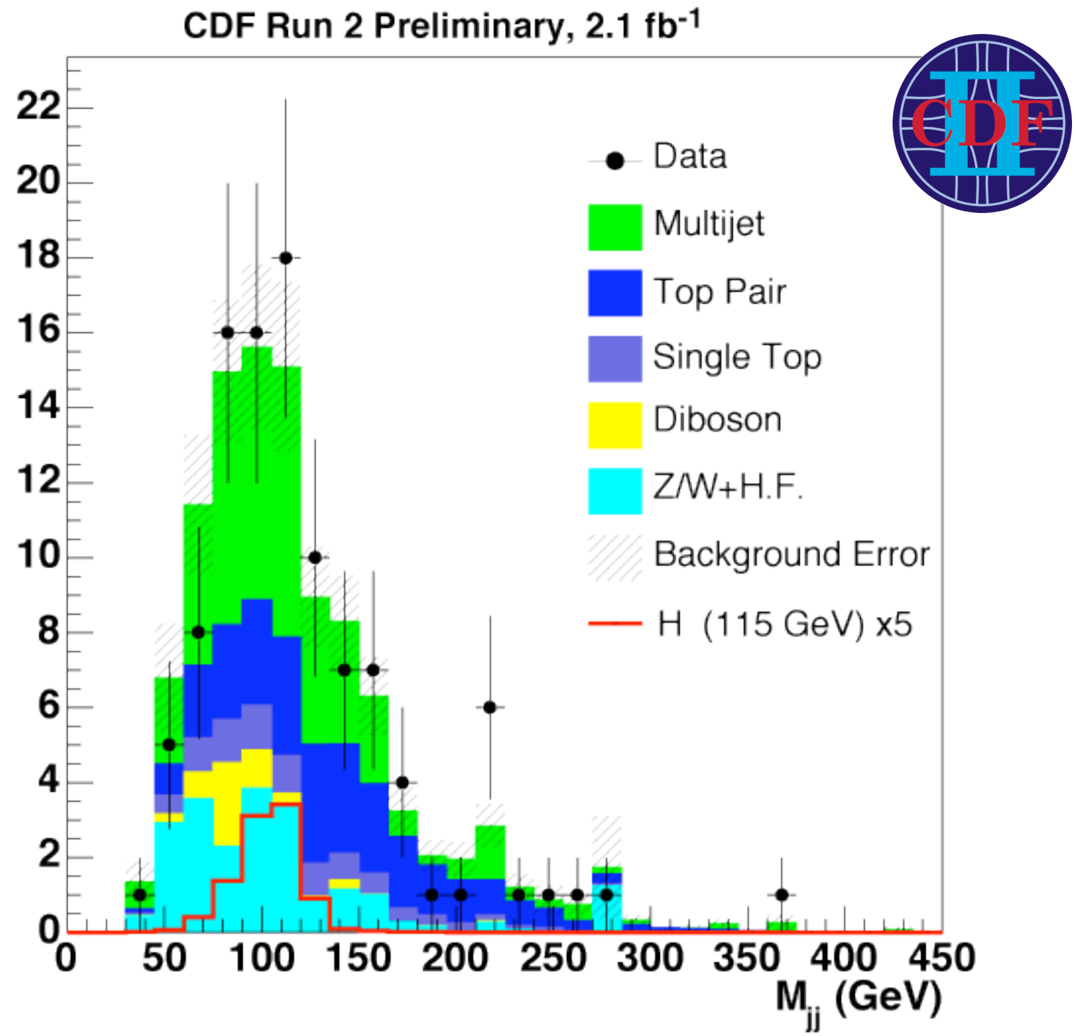
0
50
100
150
200
250
300
350
400
450
M_{jj} (GeV)



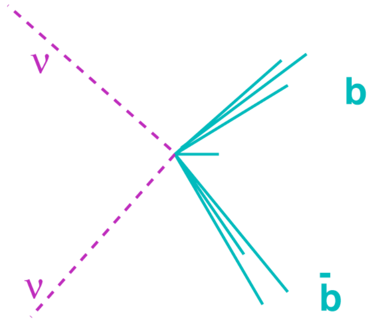


room for improving
Higgs mass resolution

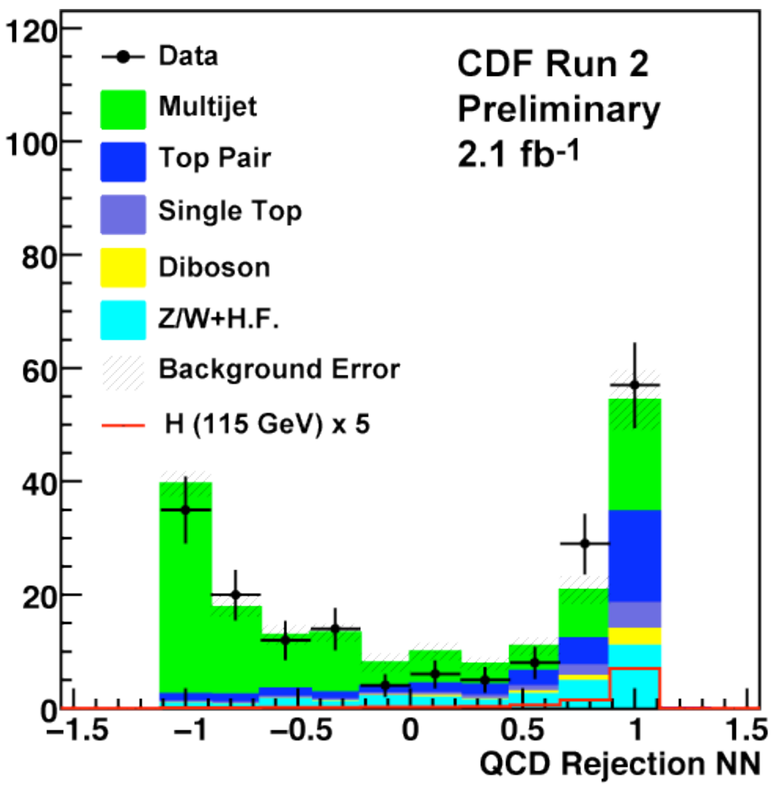


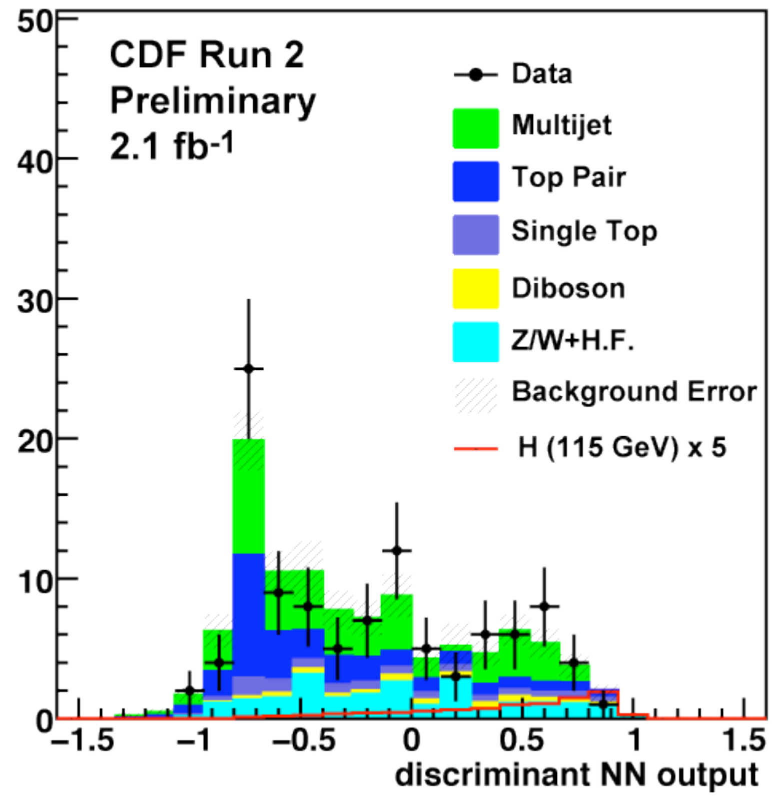


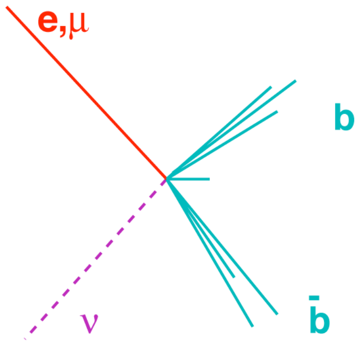
Low Mass - ννbb

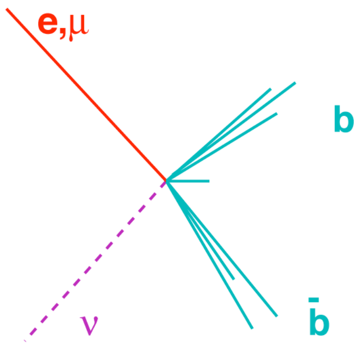


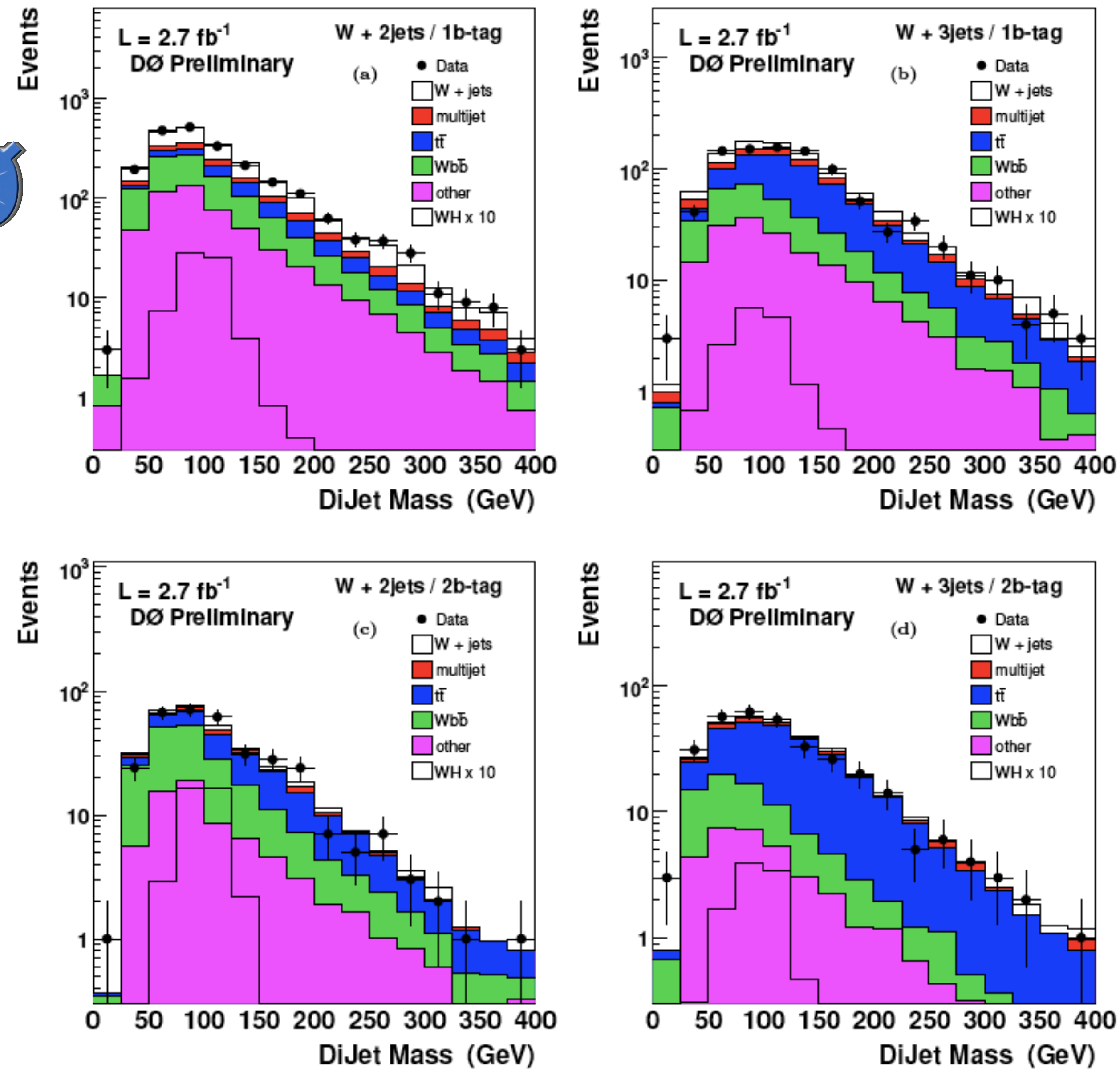
Use neural nets to reduce multijet background, distinguish Higgs signal



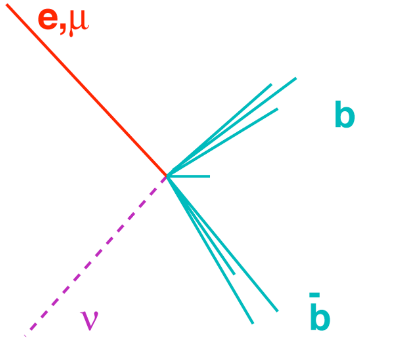



e,μ
b
b̄
ν



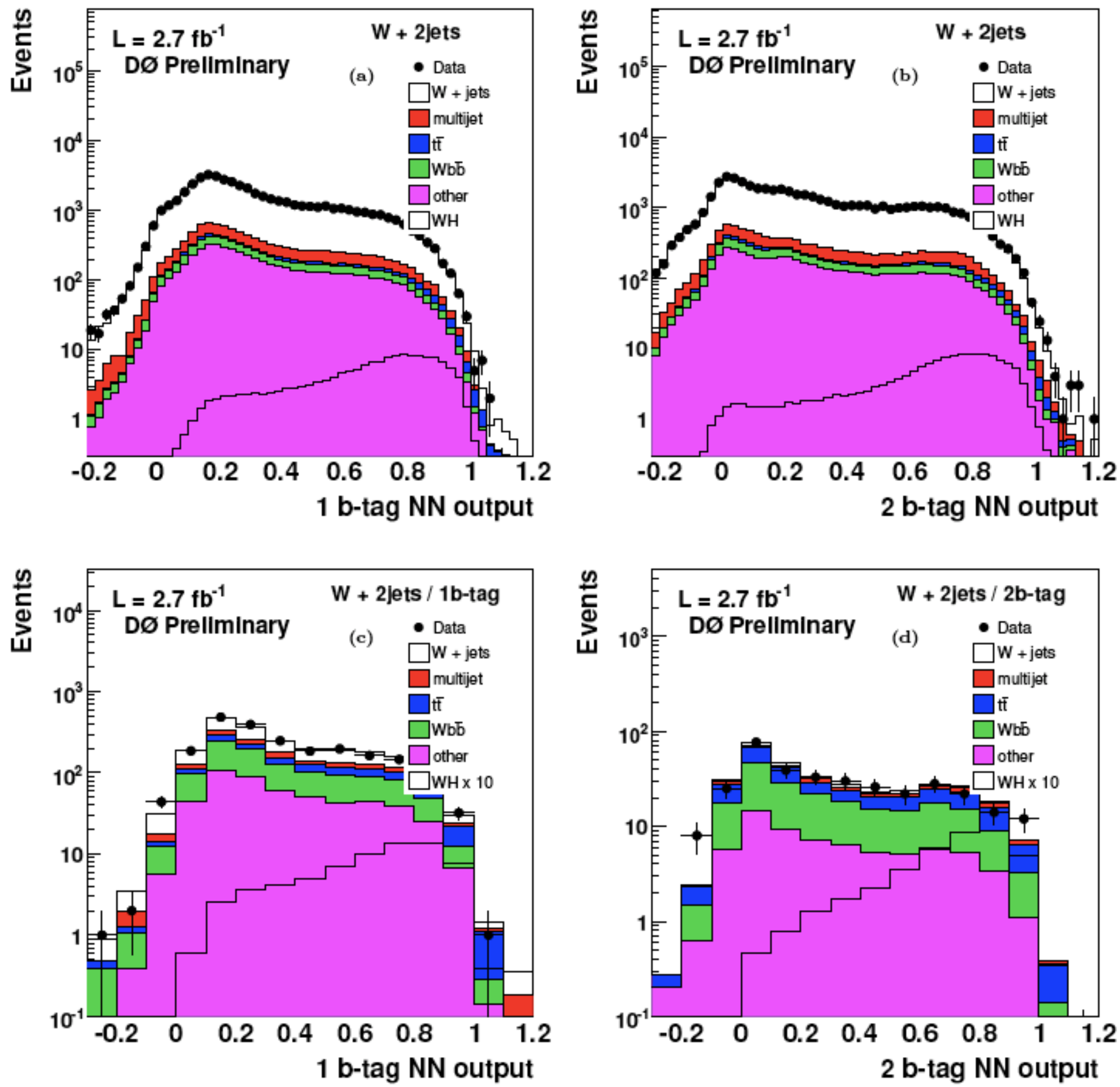


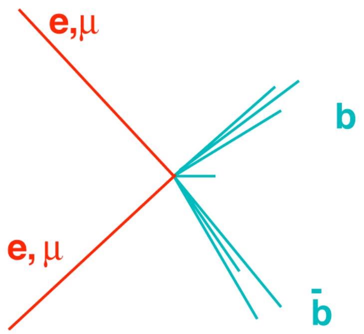
Split sample into 2-jet and 3-jet final states, with 1 or 2 b tags



Split sample into 2-jet and 3-jet final states, with 1 or 2 b tags

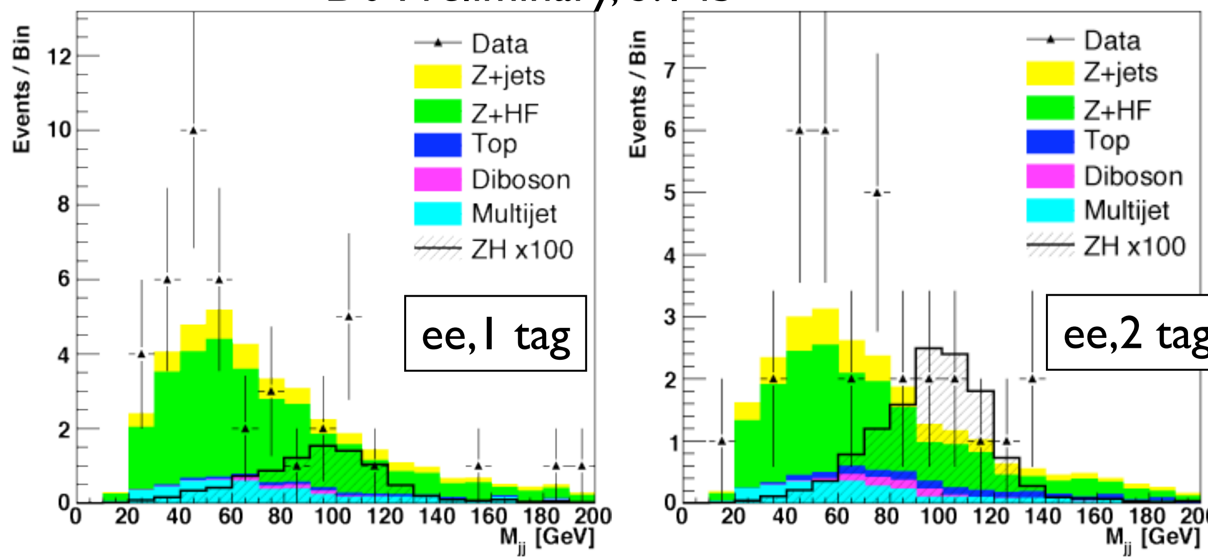
Use NN output to discriminate Higgs signal



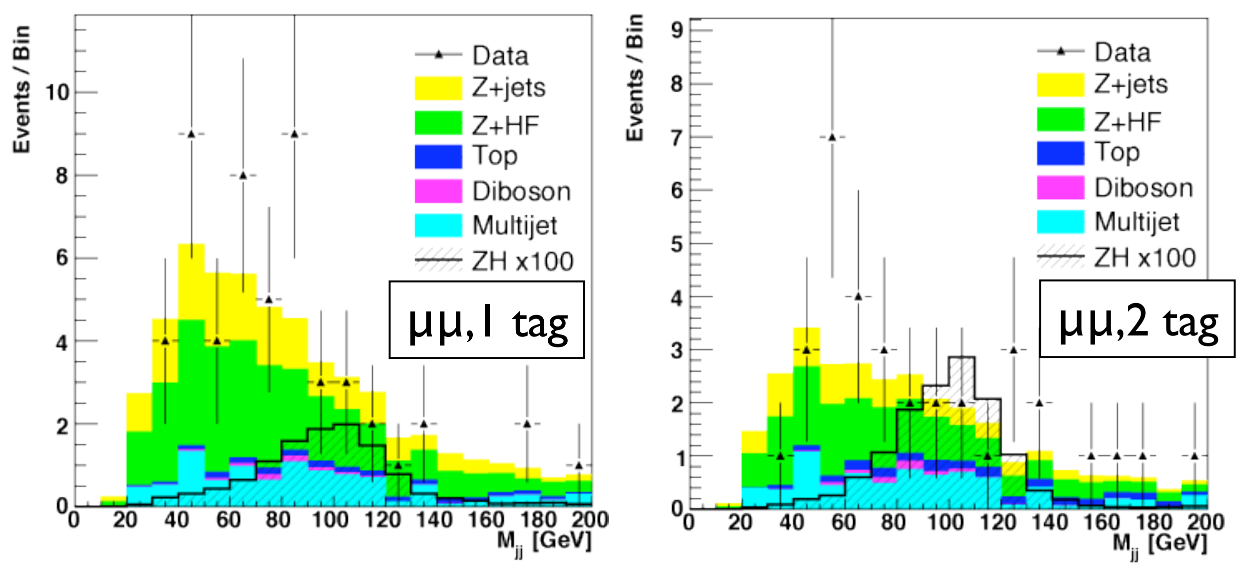


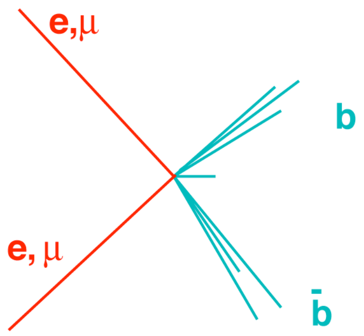
Clean Z tag, no missing energy
⇒ good bb mass

D0 Preliminary, 3.1 fb^{-1}



D0 Preliminary, 4.2 fb^{-1}





Clean Z tag, no missing energy
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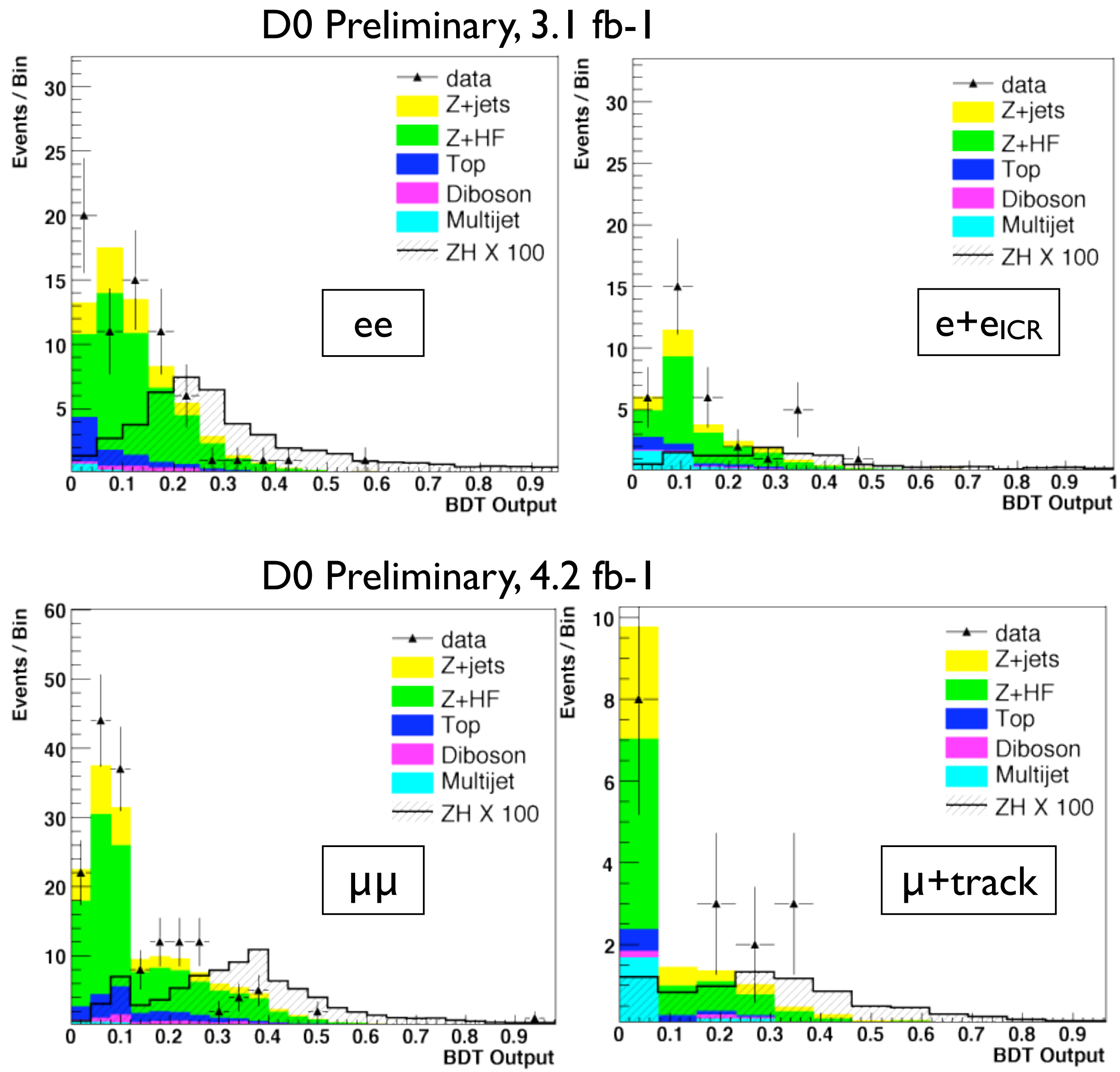
Use binary decision trees to separate signal/background



Higgs search predictions from 2000, 2003 used only bb

Add tau modes! $Z \rightarrow \tau\tau / W \rightarrow \tau\nu$ and/or $H \rightarrow \tau\tau$

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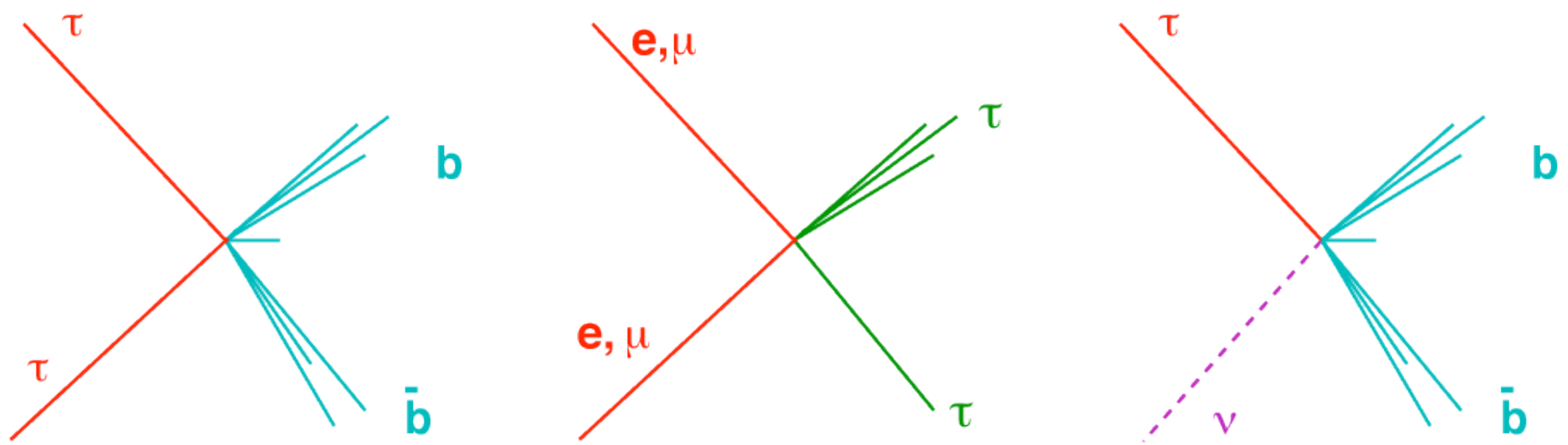

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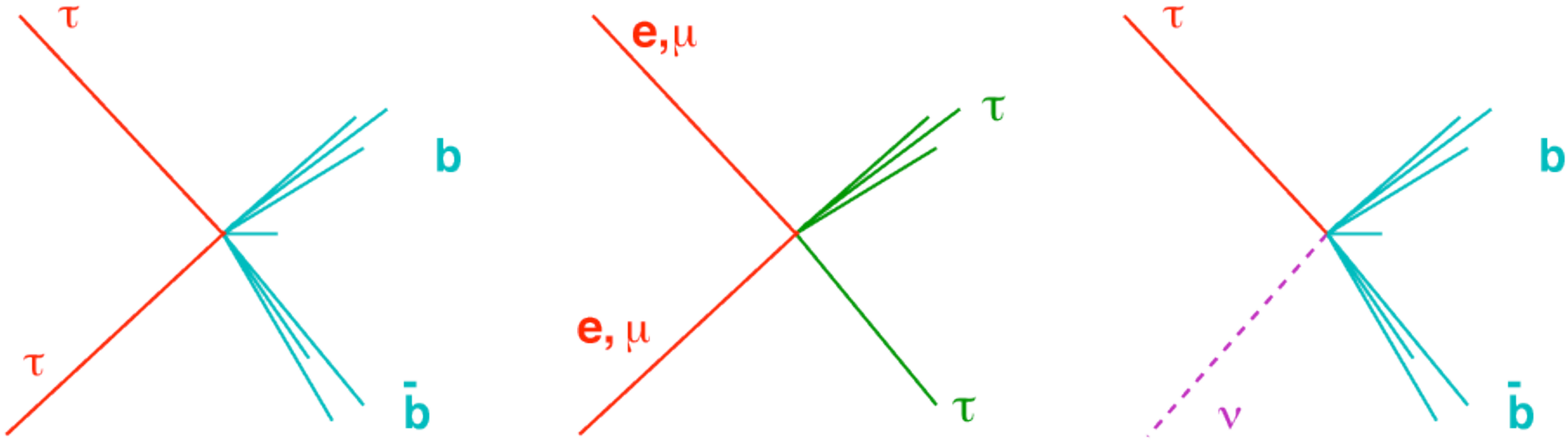

...and others: a sort of "kitchen sink" approach brings about 10% additional sensitivity

With two experiments, over a dozen channels, and complicated MVA techniques, what would a discovery look like?

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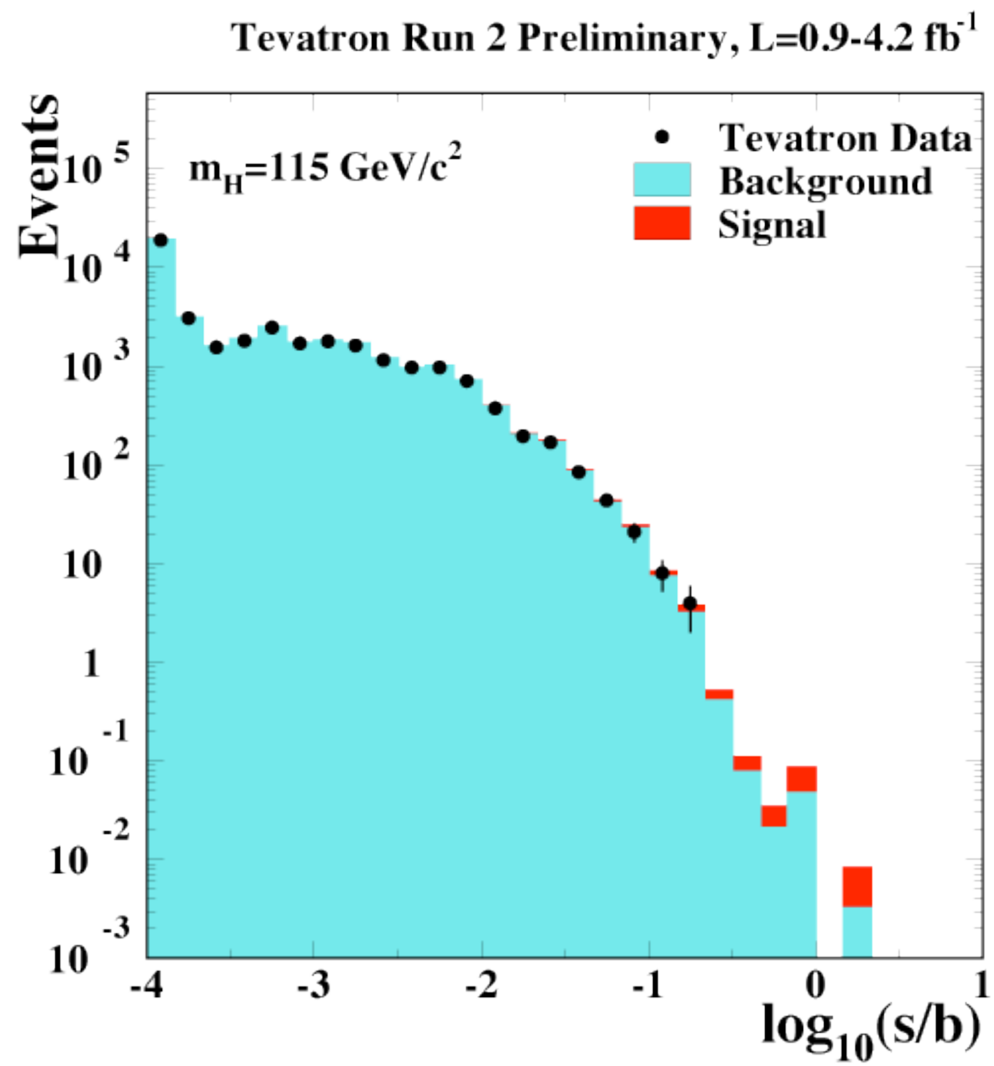
Put each event in bins of S/B histogram:



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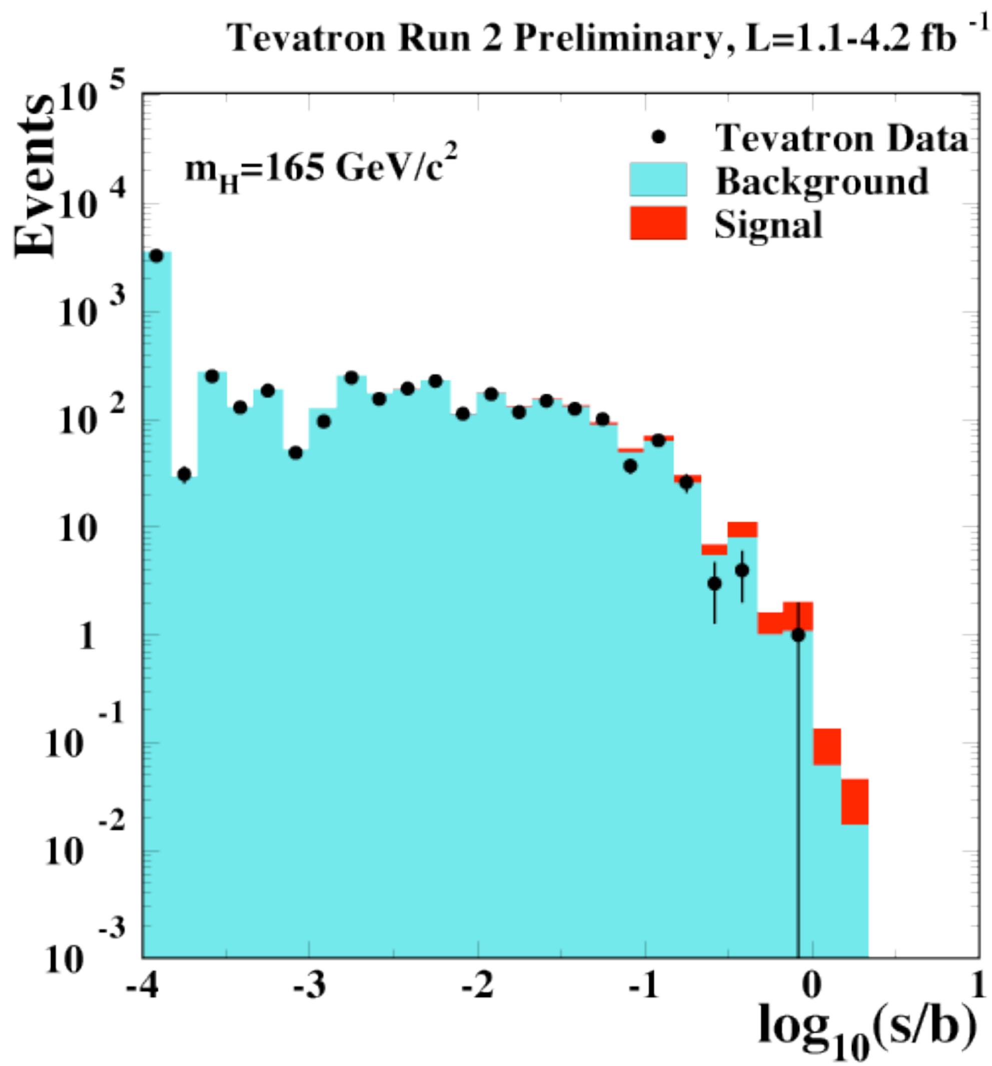

SM Higgs suffers hierarchy problem

$\Rightarrow$ Higgs sector is more complicated?

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MSSM: minimal supersymmetric model greatly reduces hierarchy problem (scalars cancel fermion loops)

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- one doublet gives mass to up type quarks
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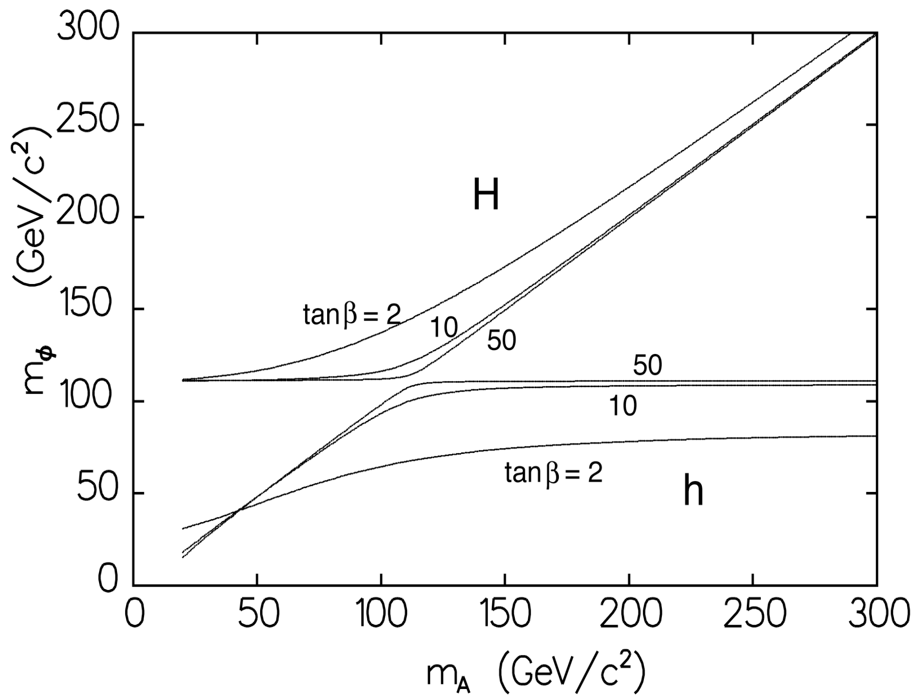
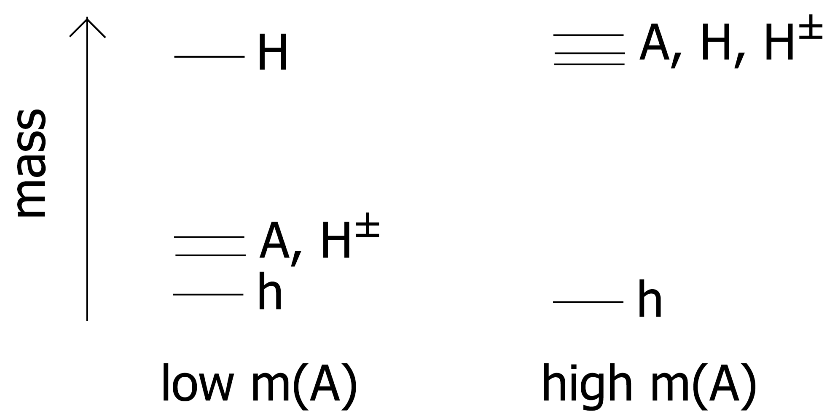
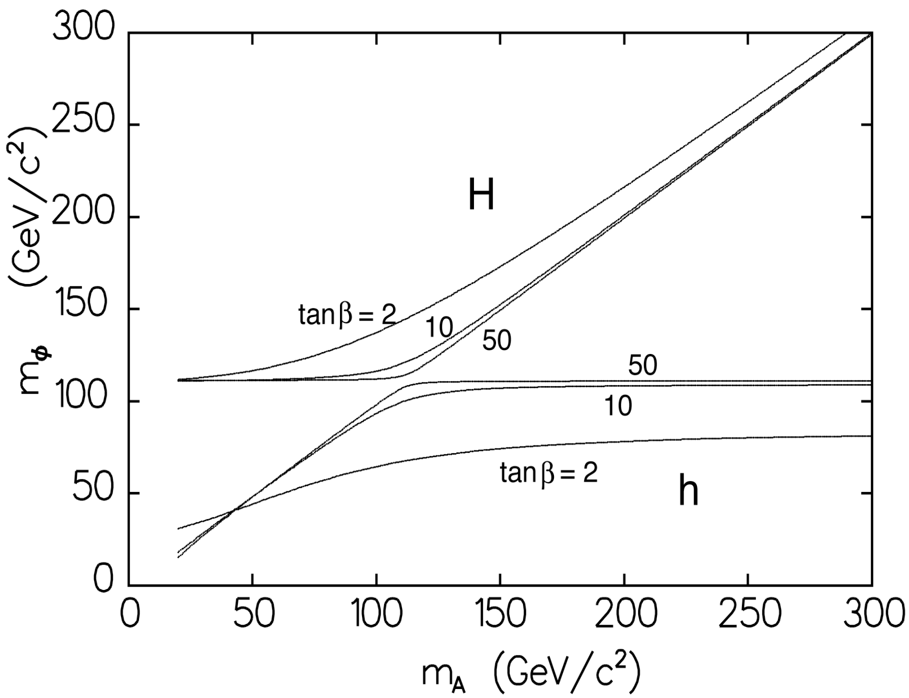
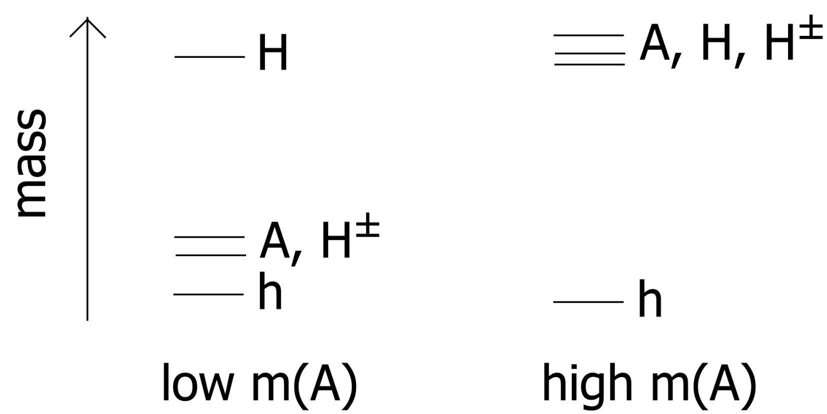
Five Higgs bosons, masses governed by m_A, $\tan\beta$





Almost a no-lose situation: must be a light scalar h





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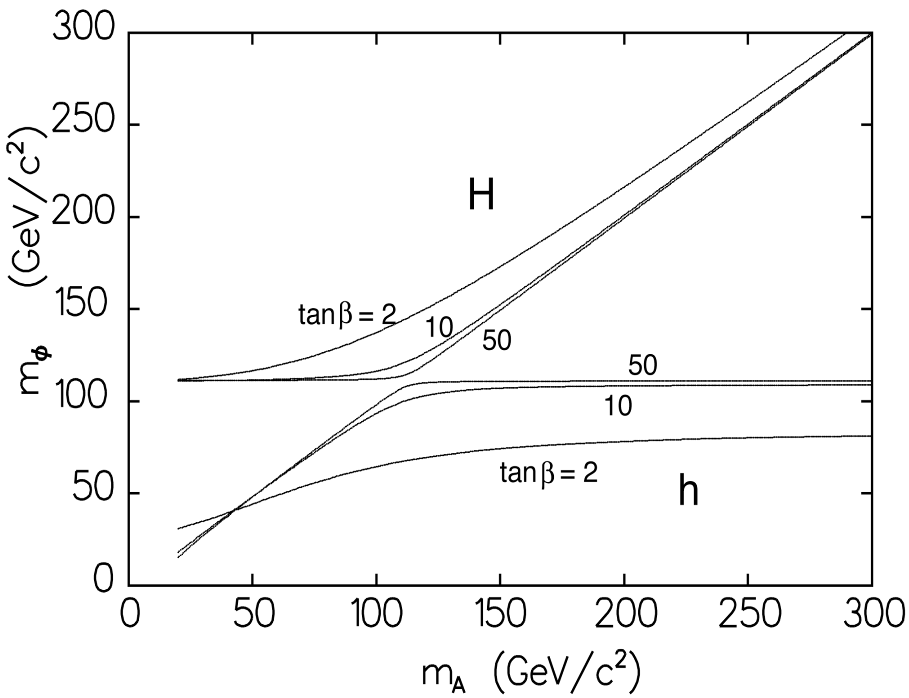
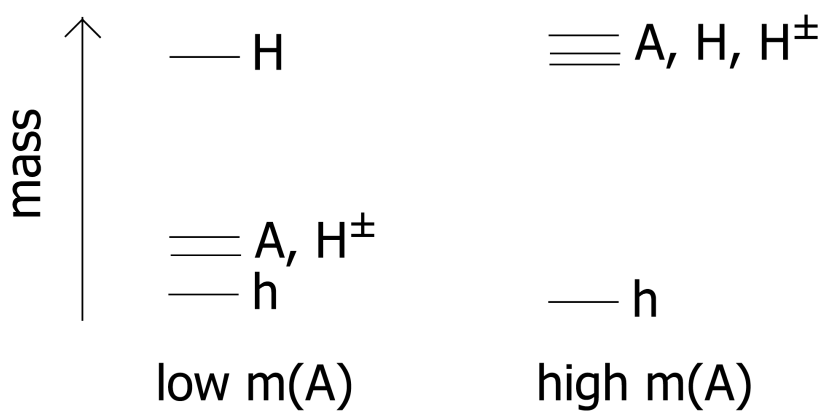
H/A/H± nearly equal mass when m_A large





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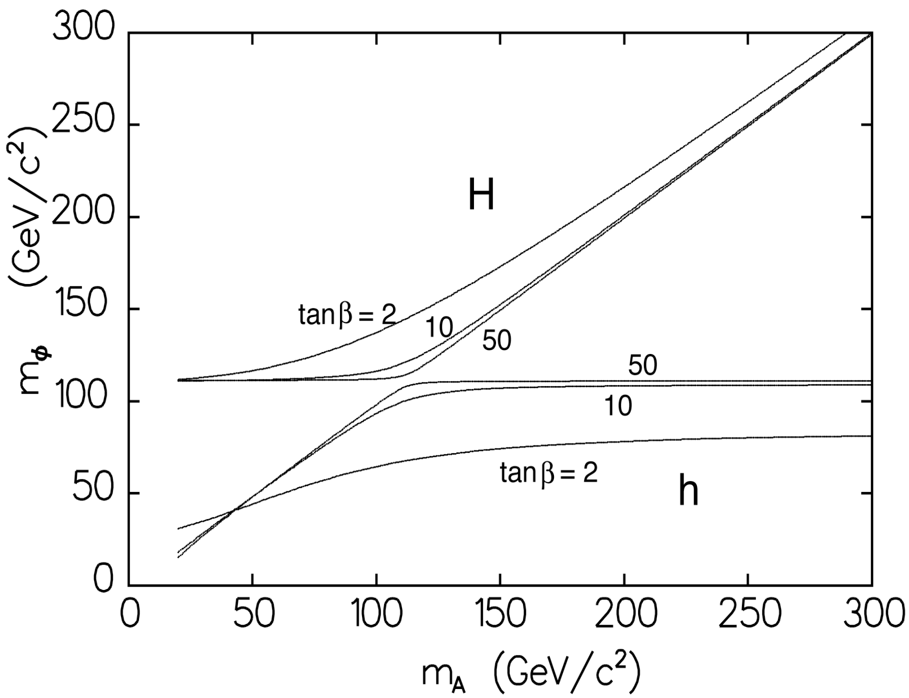
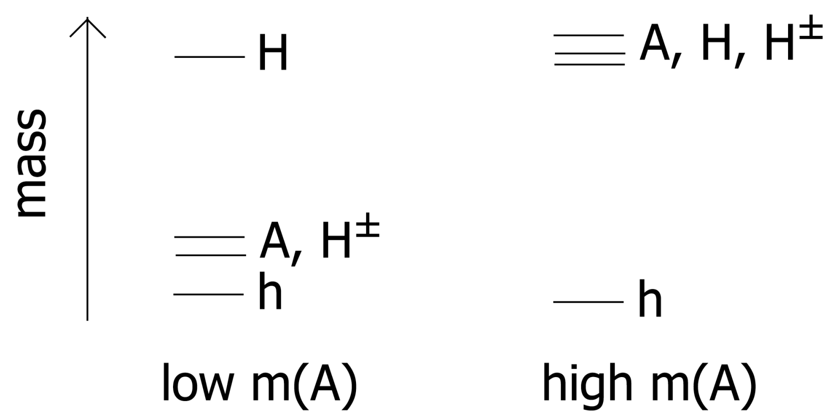
Production of H/A greatly enhanced if $\tan\beta$ large



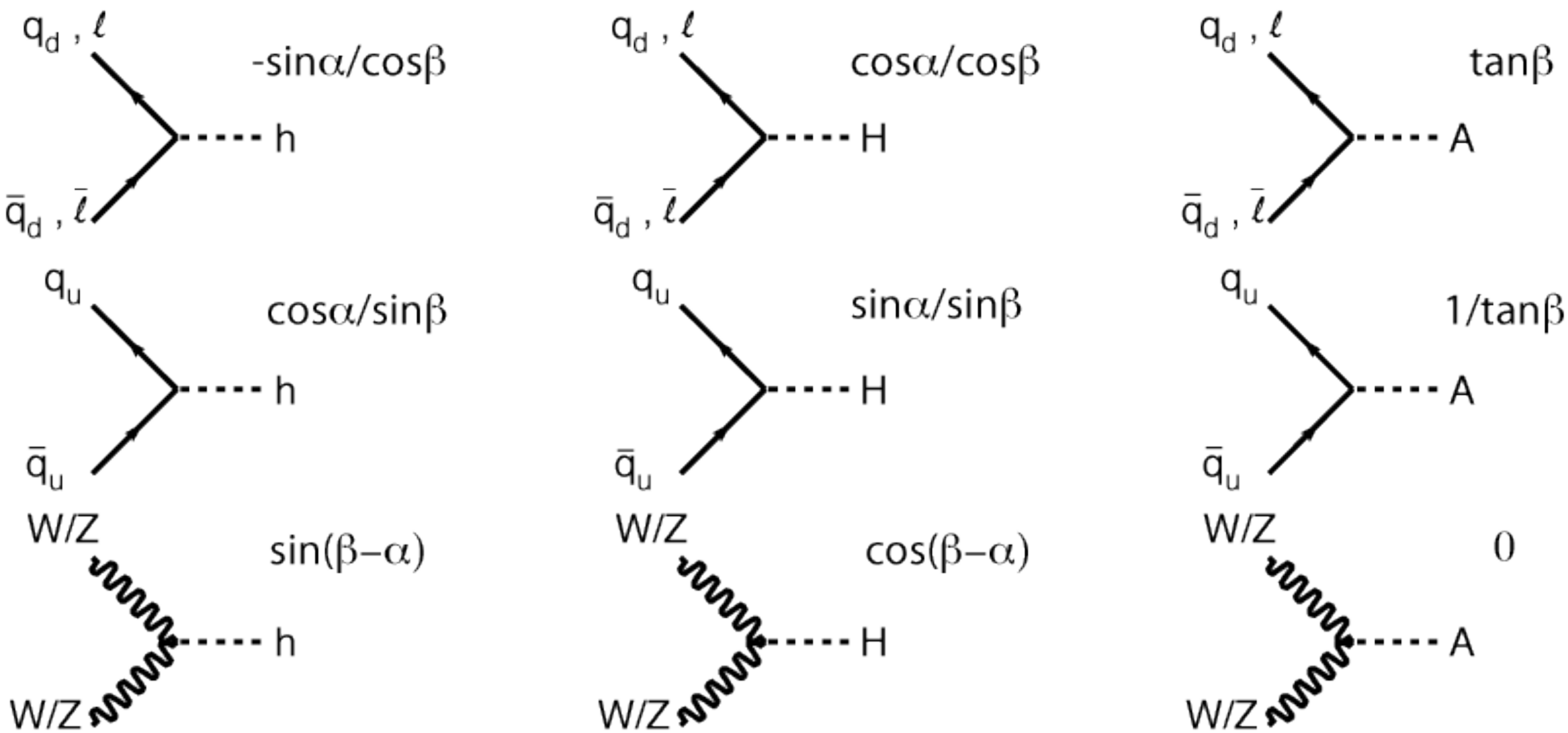


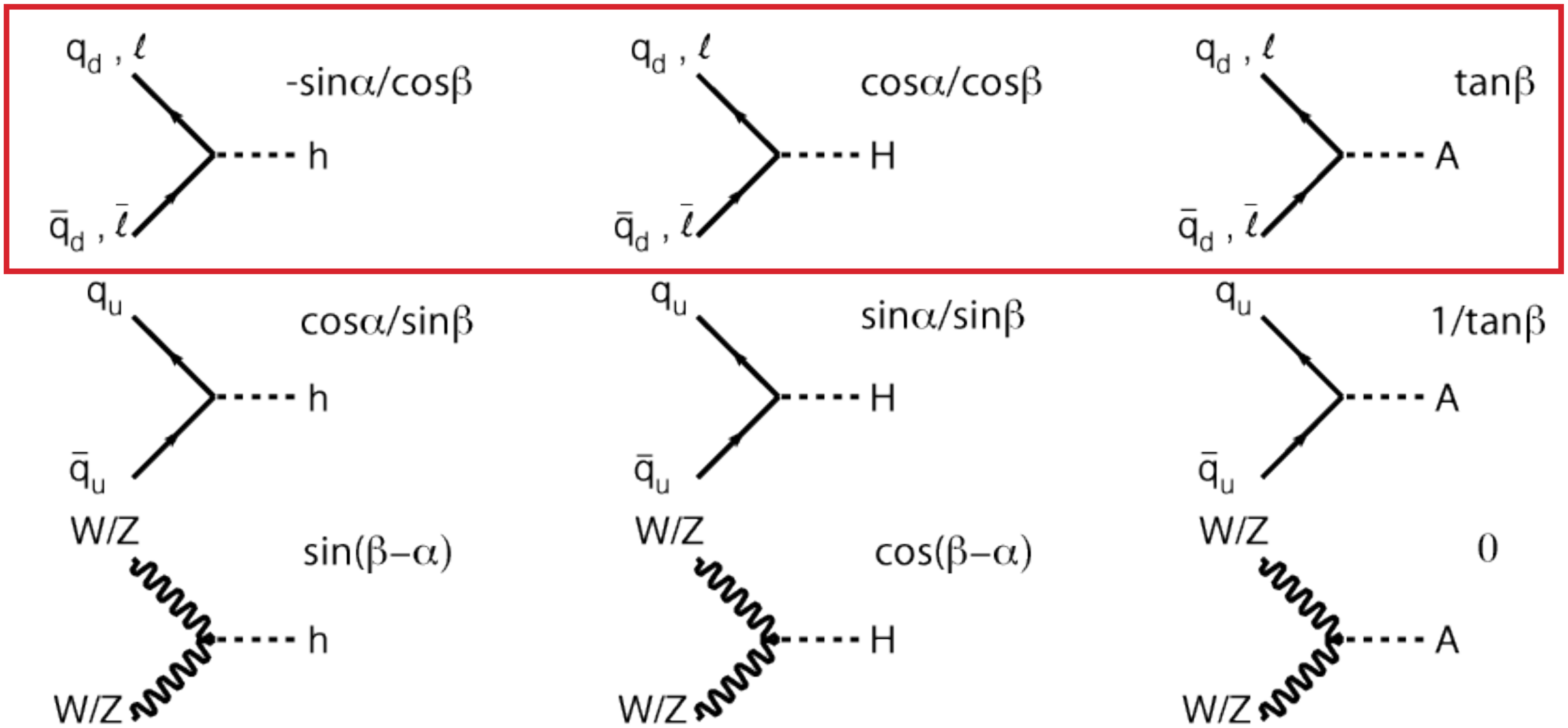
Almost a no-lose situation: must be a light scalar h

H/A/H$^\pm$ nearly equal mass when m_A large

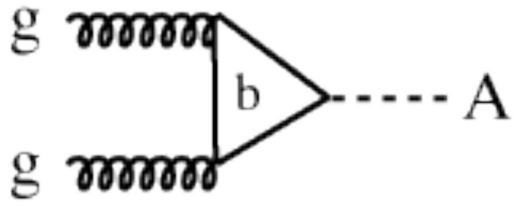
Production of H/A greatly enhanced if tanβ large

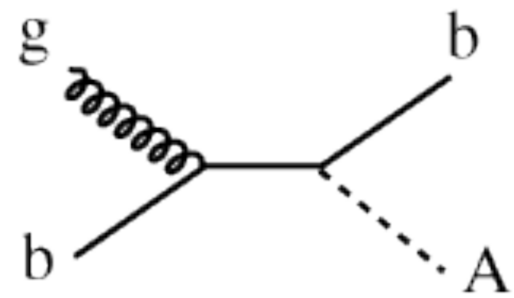
If m_A large may not be able to distinguish SM/MSSM

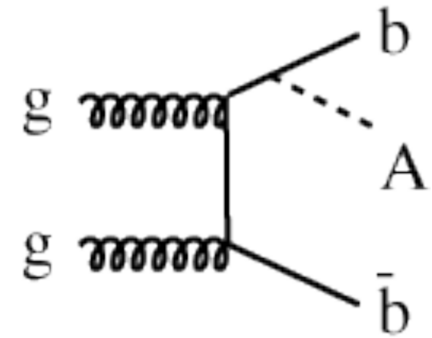

q_d , ℓ
-sinα/cosβ
h
$\bar{q}_d$, $\bar{\ell}$
q_d , ℓ
cosα/cosβ
H
$\bar{q}_d$, $\bar{\ell}$
q_d , ℓ
tanβ
A
$\bar{q}_d$, $\bar{\ell}$
q_u
cosα/sinβ
h
$\bar{q}_u$
q_u
sinα/sinβ
H
$\bar{q}_u$
q_u
1/tanβ
A
$\bar{q}_u$
W/Z
sin(β–α)
h
W/Z
W/Z
cos(β–α)
H
W/Z
W/Z
0
A
W/Z



large tanβ ⇒ enhanced bbϕ coupling

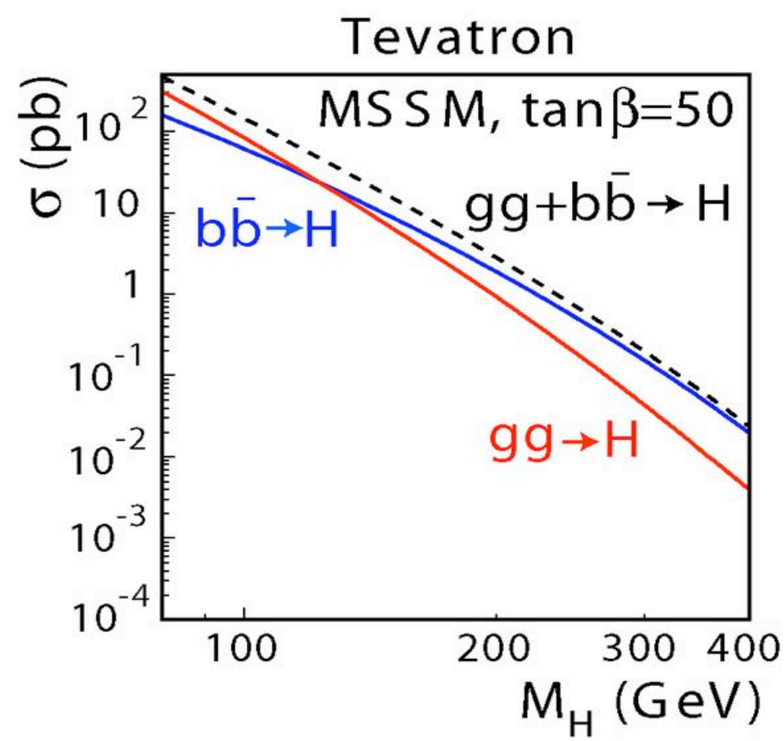


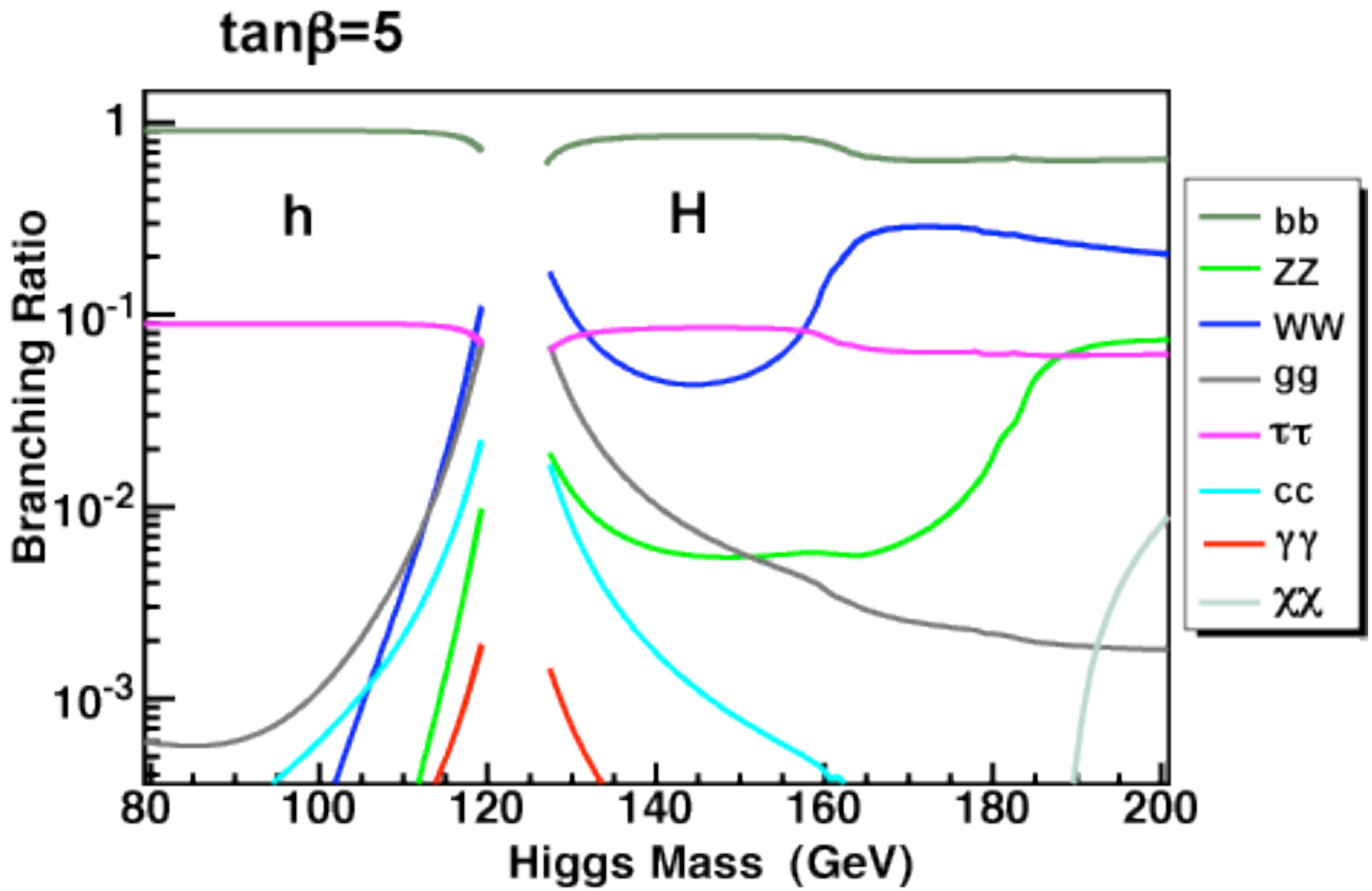




These processes all have cross sections proportional to $\tan^2\beta$

$\tan\beta \sim m_t/m_b \sim 35?$





- bb and ττ decay modes dominate experimentally
- ττ is the most sensitive: main background is Z

Tau pair search: demand one e or μ plus one hadronically decaying tau, or another e or μ

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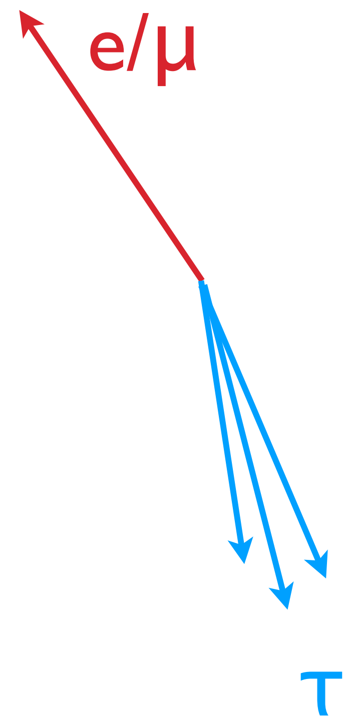

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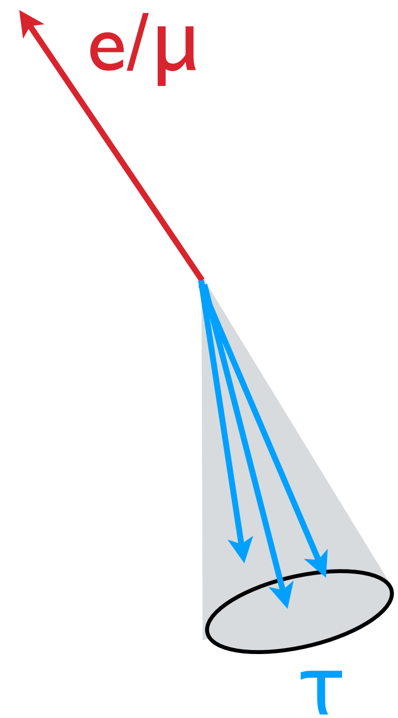
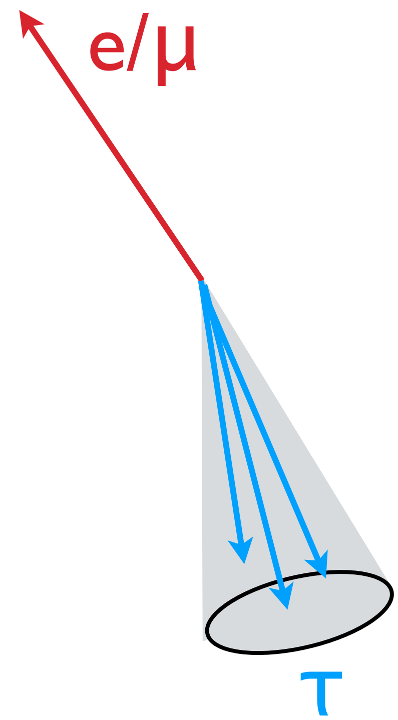


no activity in region outside signal cone

Tau pair search: demand one e or μ plus one hadronically decaying tau, or another e or μ

Main background is from Drell-Yan $Z/\gamma^* \rightarrow \tau\tau$: use mass to distinguish signal from background



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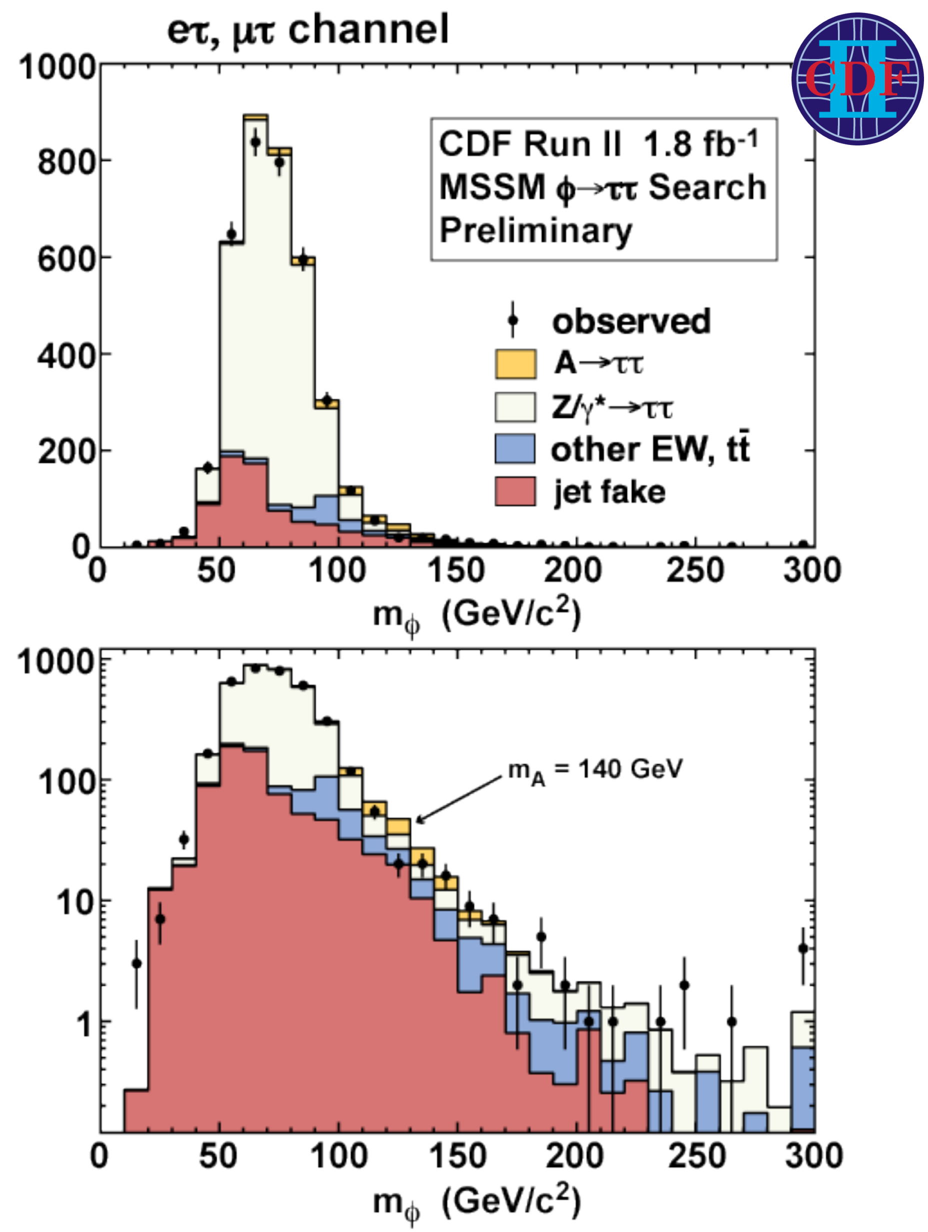
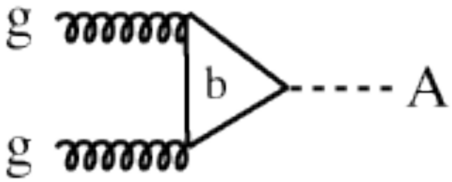
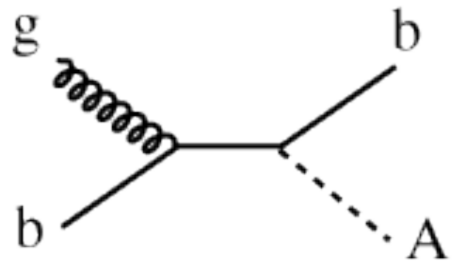
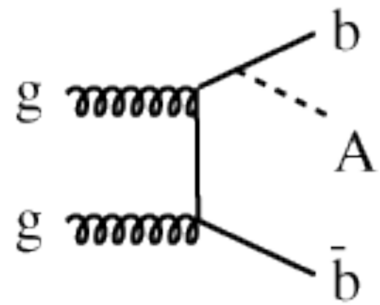
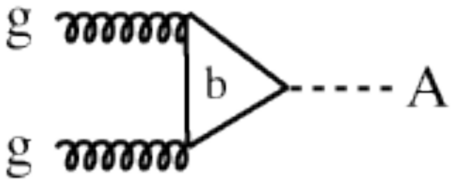
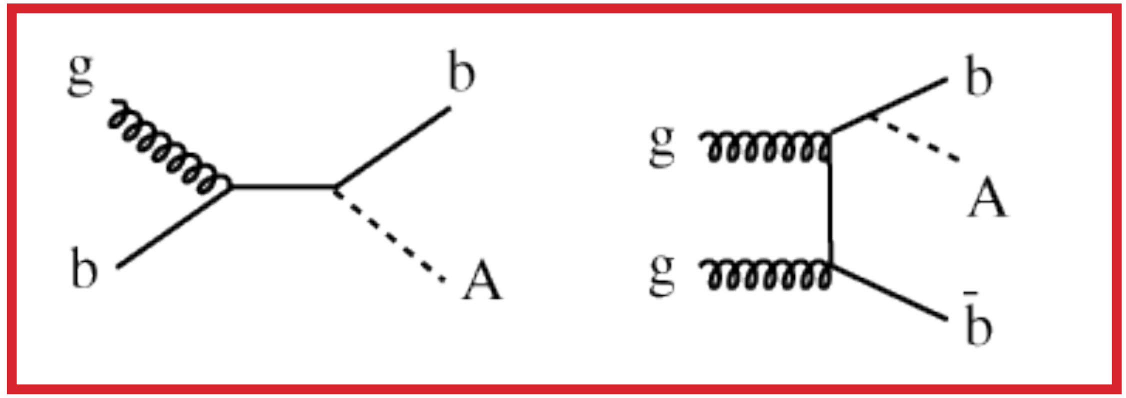


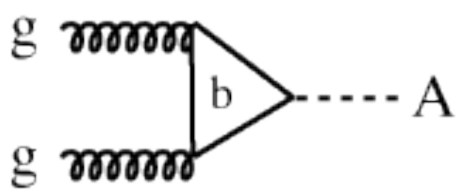

g
g
b
A

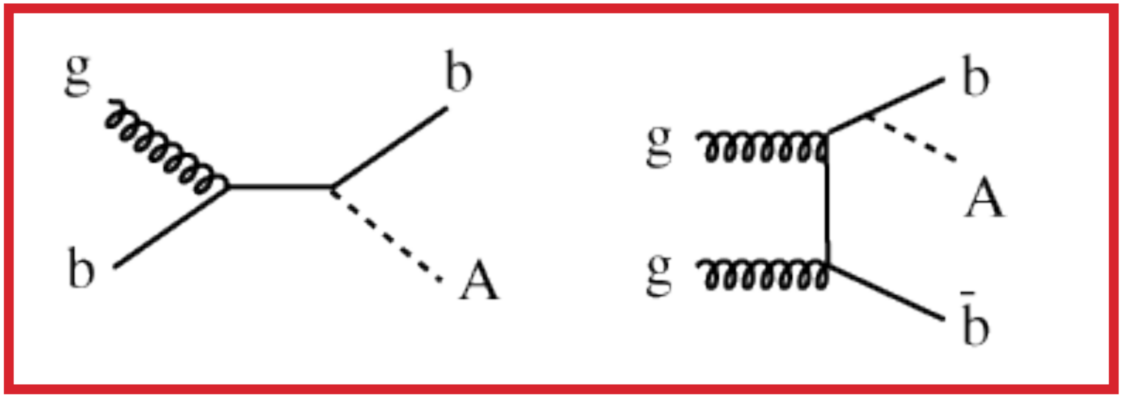

g
b
b
A

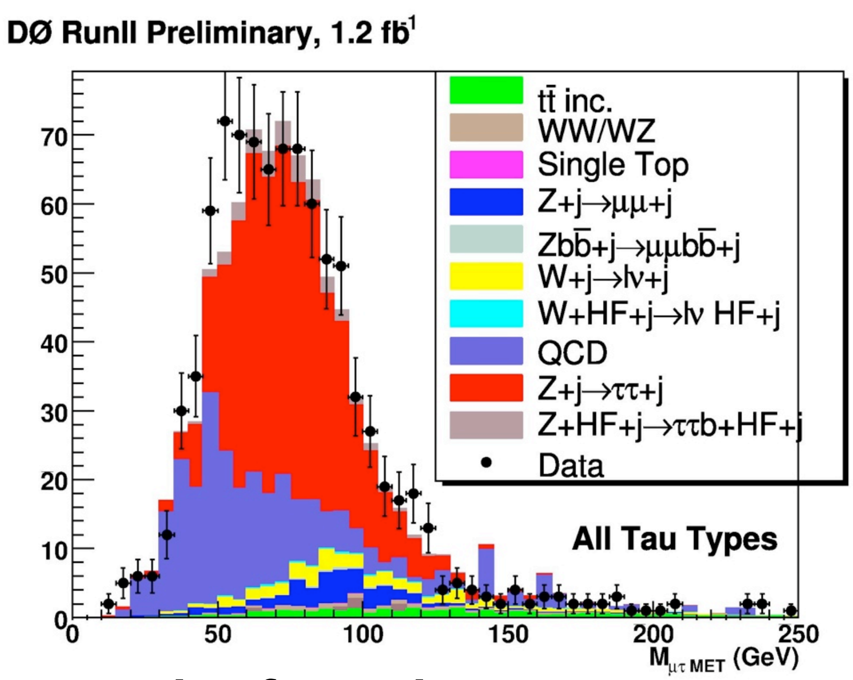

g
g
b
A
b̄


g
g
b
A

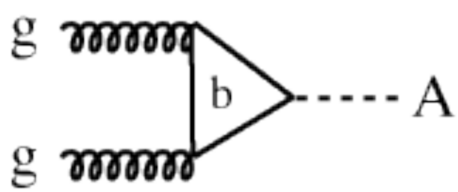

g
b
b
A
g
g
b
A
$\bar{b}$

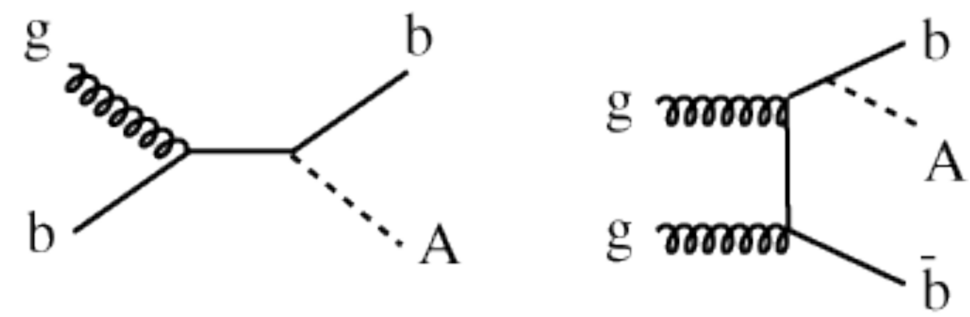


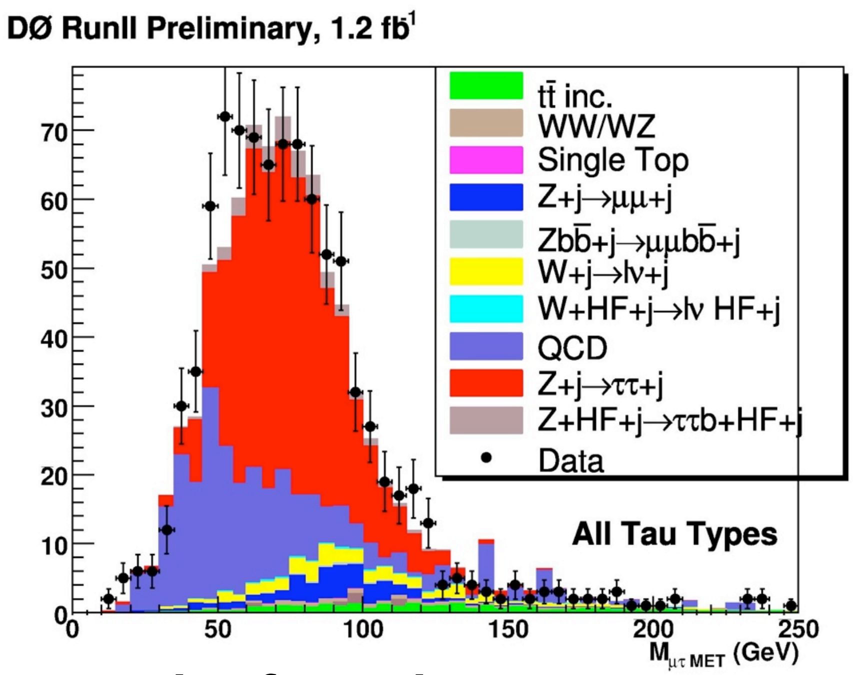




before b tagging







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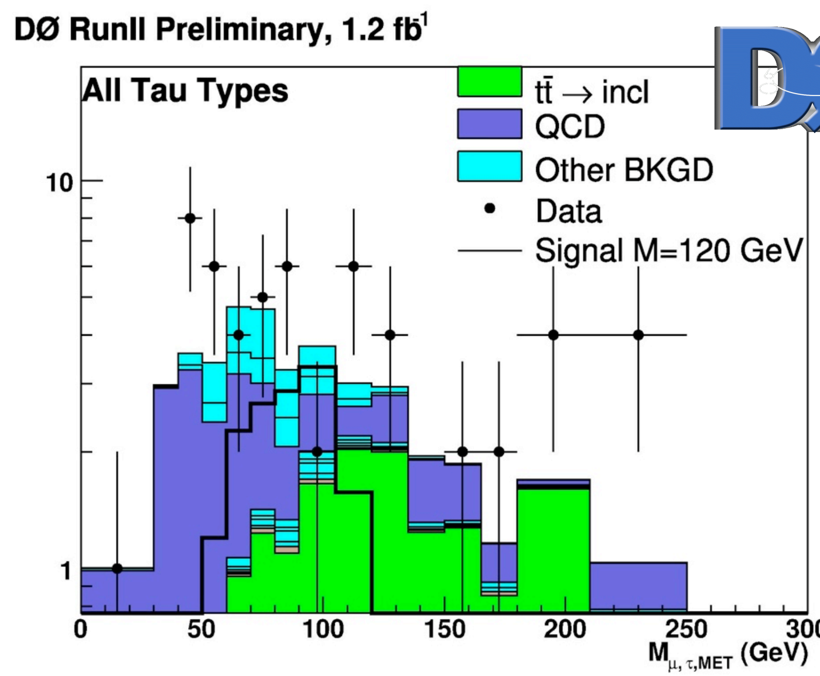
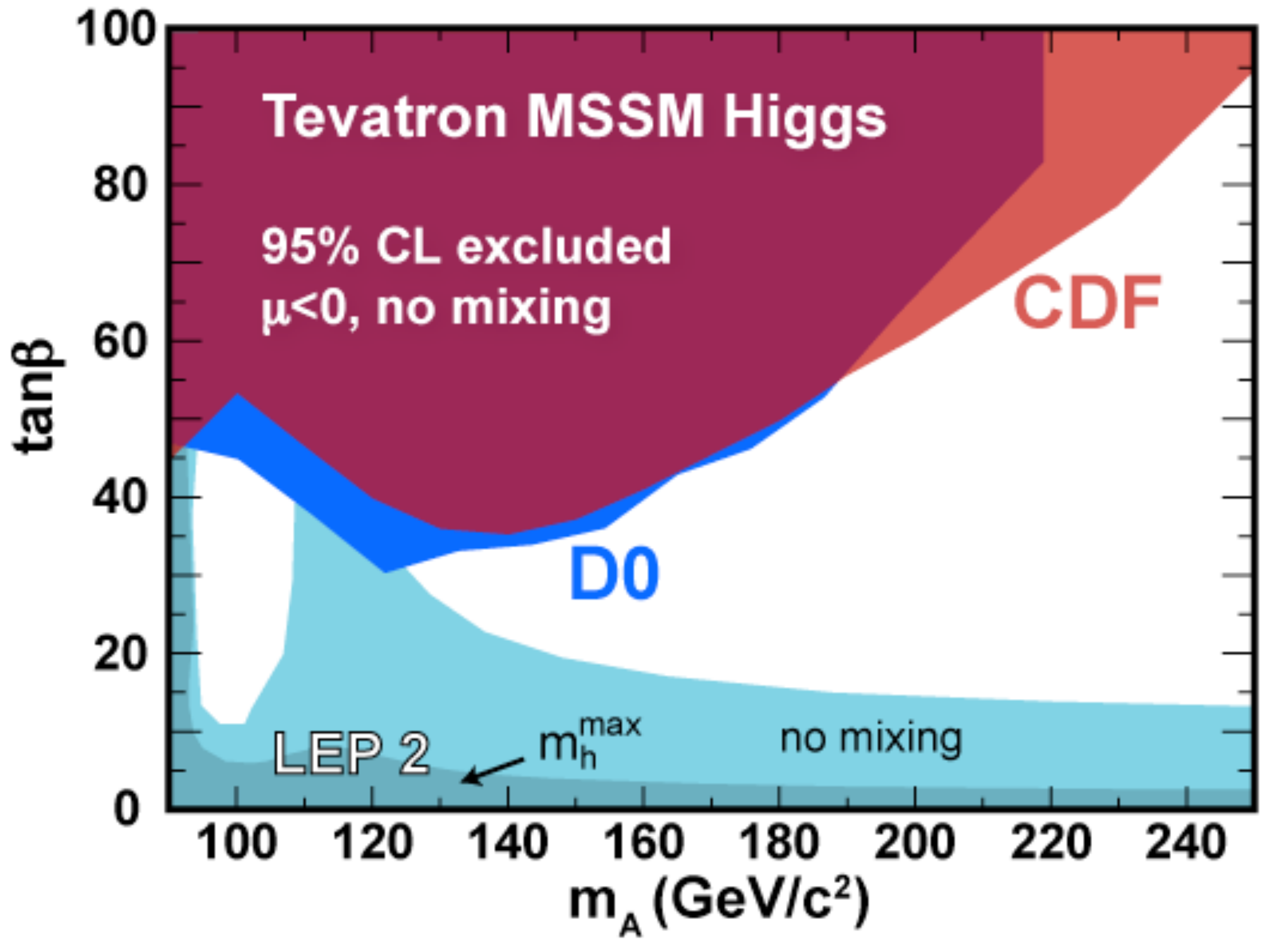
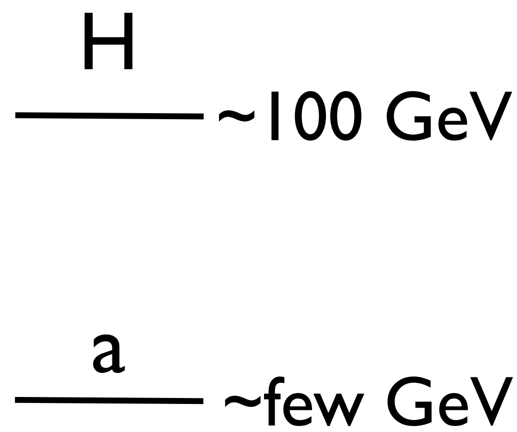


after b tagging



D0: combine all channels, 1.0-2.6 fb^{-1} CDF: 1.8 fb^{-1}

nMSSM: solve “little hierarchy problem” by adding additional Higgs singlet nMSSM: solve "little hierarchy problem" by adding additional Higgs singlet



nMSSM: solve "little hierarchy problem" by adding additional Higgs singlet

H
~100 GeV

$gg \to H \to aa \qquad a \to \mu\mu, \tau\tau$

a
~few GeV

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$gg \rightarrow H \rightarrow aa \qquad a \rightarrow \mu\mu, \tau\tau$

H ~100 GeV

a ~few GeV

D0 searches for $\mu\mu\tau\tau$ events

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~few GeV

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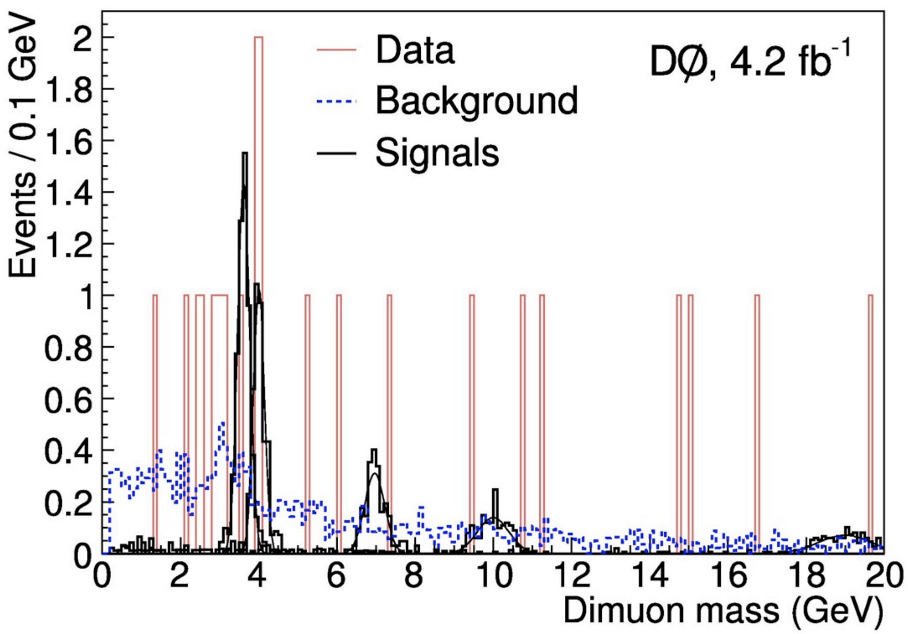

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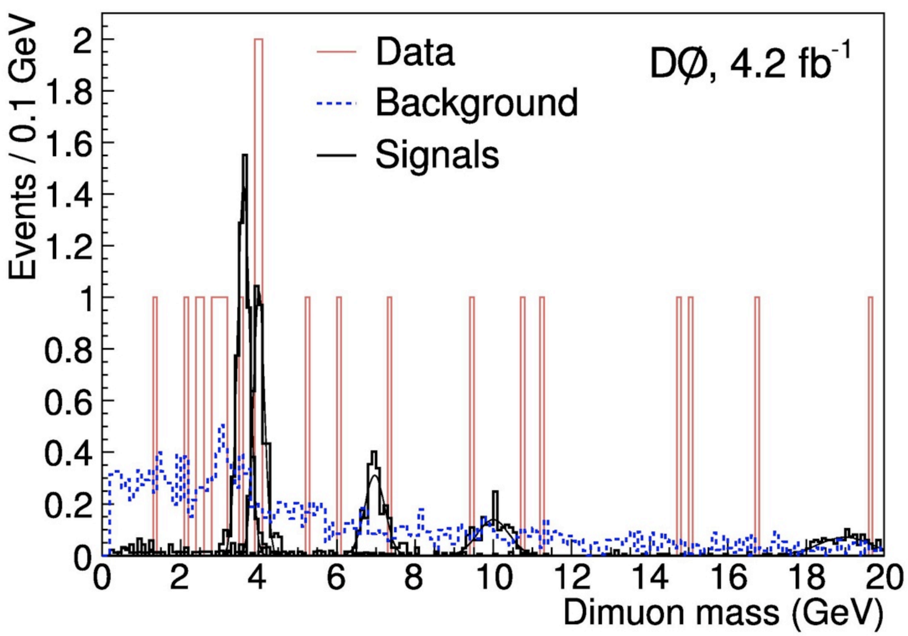
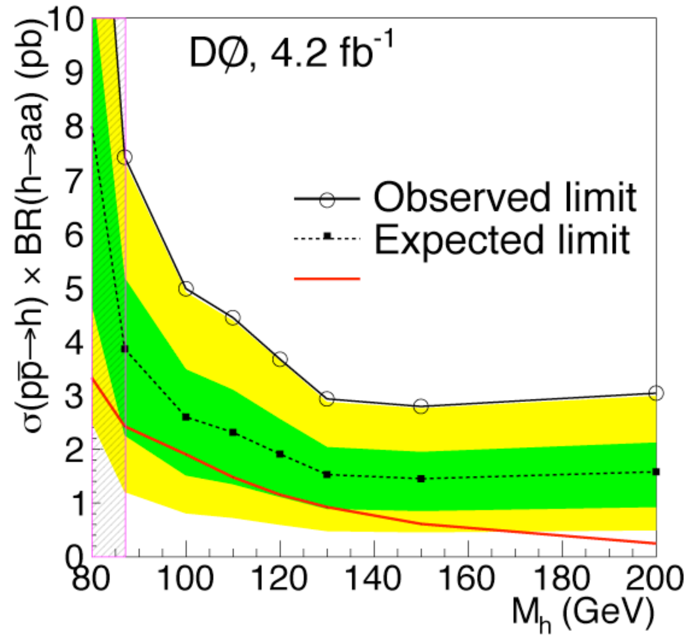
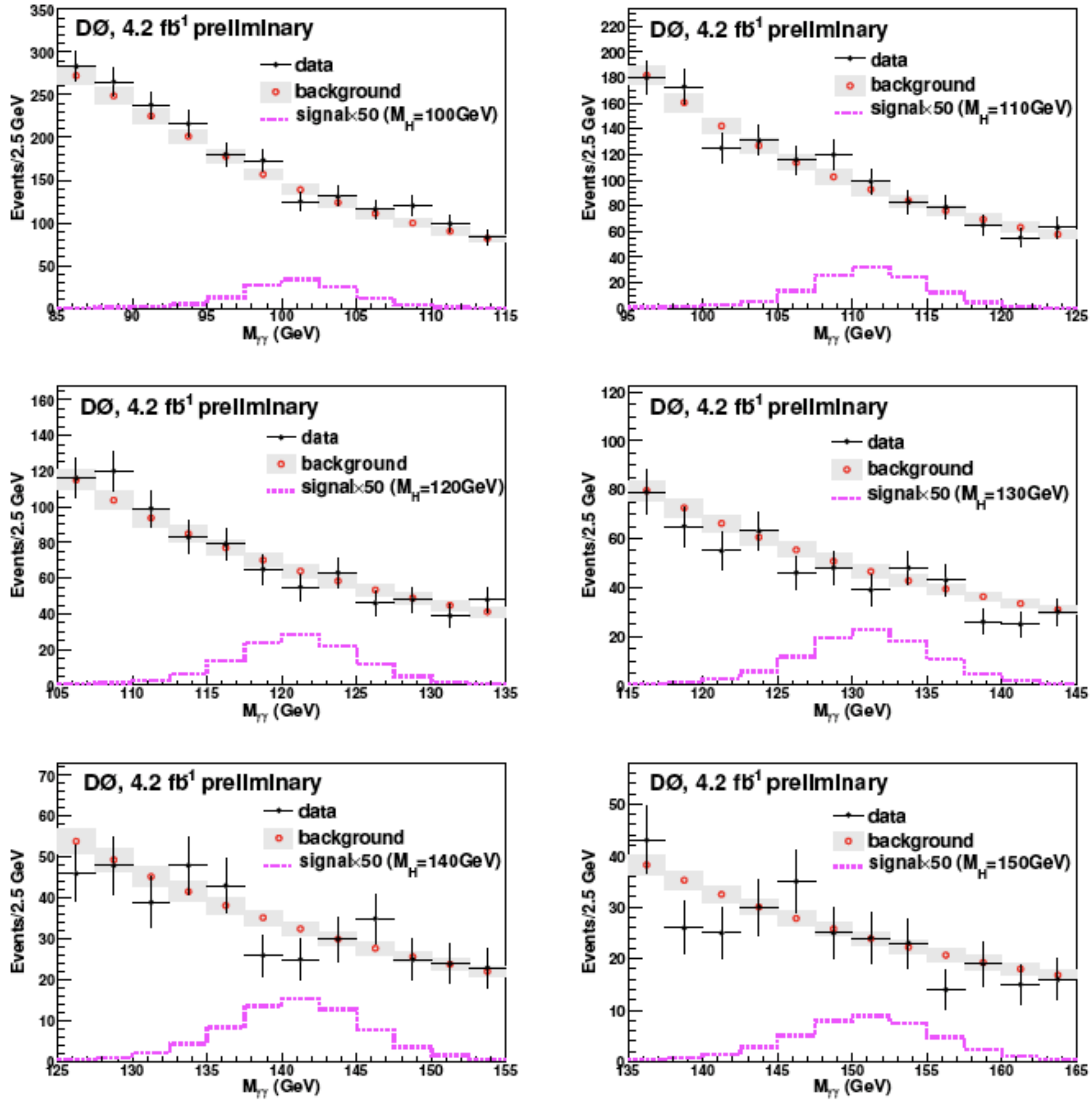




In SM, B(H→γγ)~0.002

In some non-SM models Hff couplings suppressed

D0 and CDF both search for H→γγ

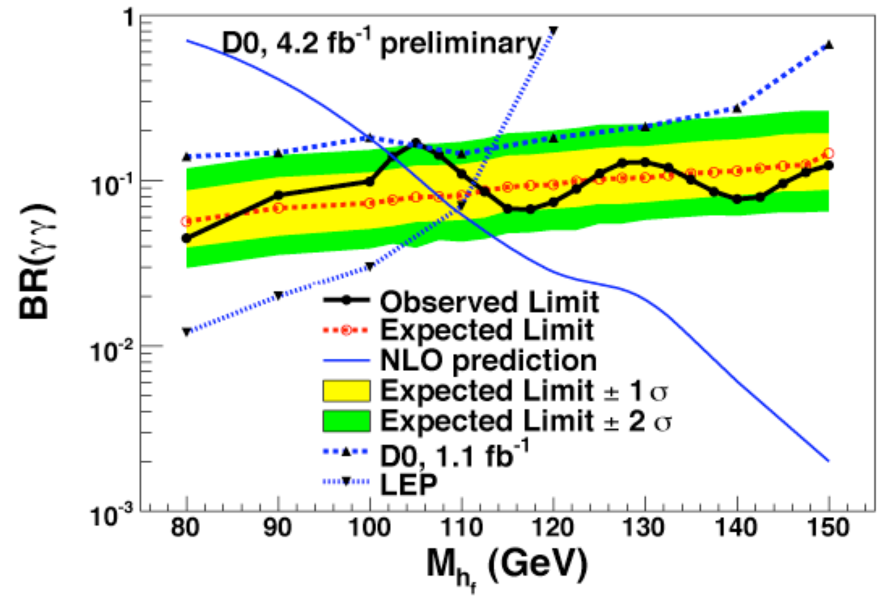


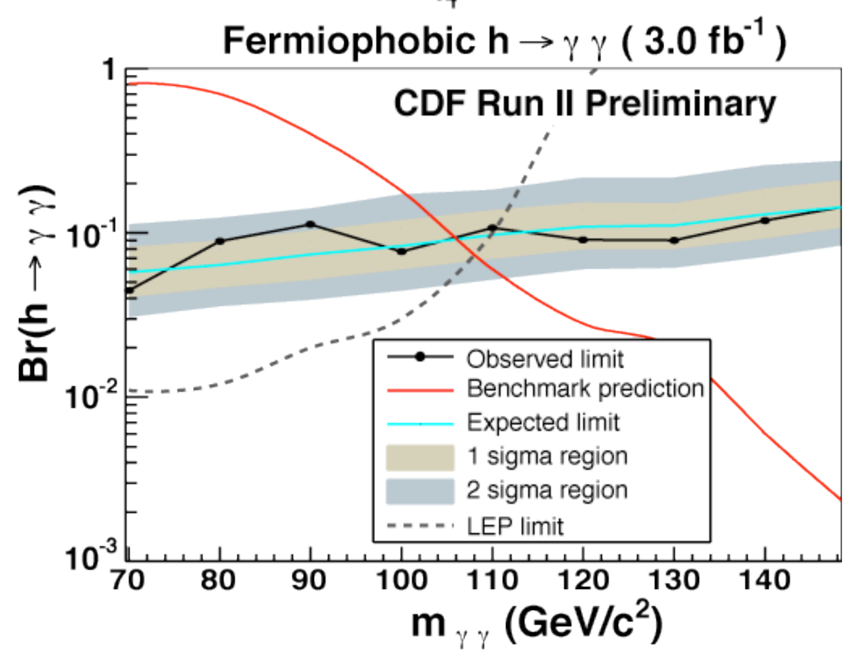
In SM, $B(H\to\gamma\gamma)\sim0.002$

In some non-SM models Hff couplings suppressed

D0 and CDF both search for $H\to\gamma\gamma$

No signal - limits far from SM branching ratio but nearly exceed LEP limits on fermiphobic Higgs bosons

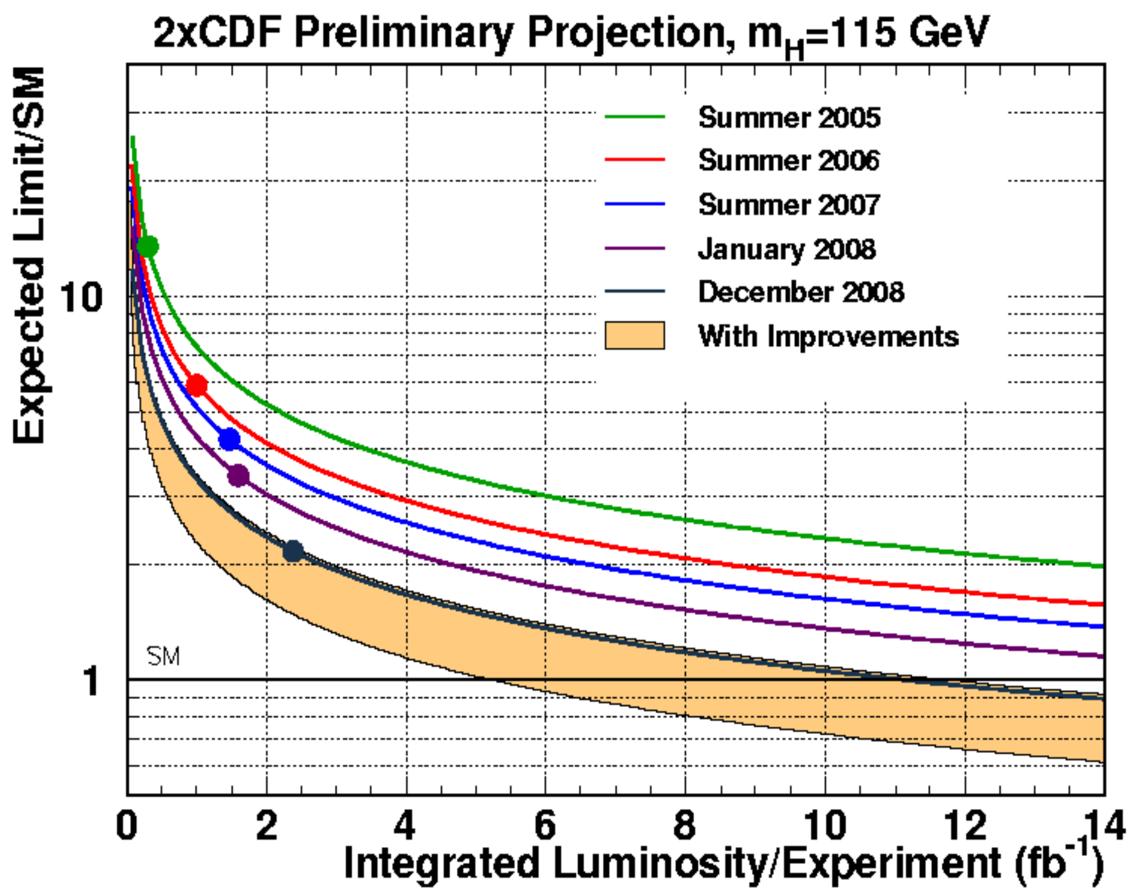




Data really do make us smarter

Limit/SM ratio approaching unity!

Tevatron will likely run through 2011



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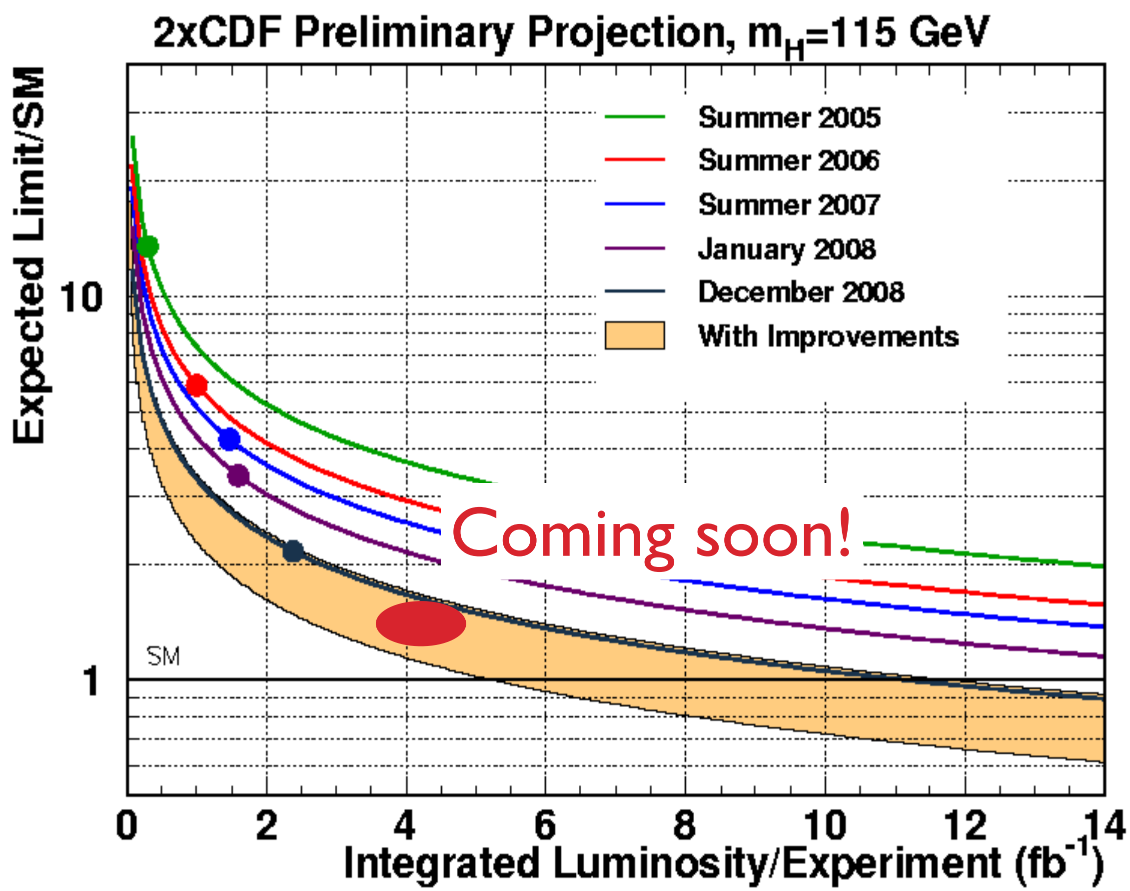

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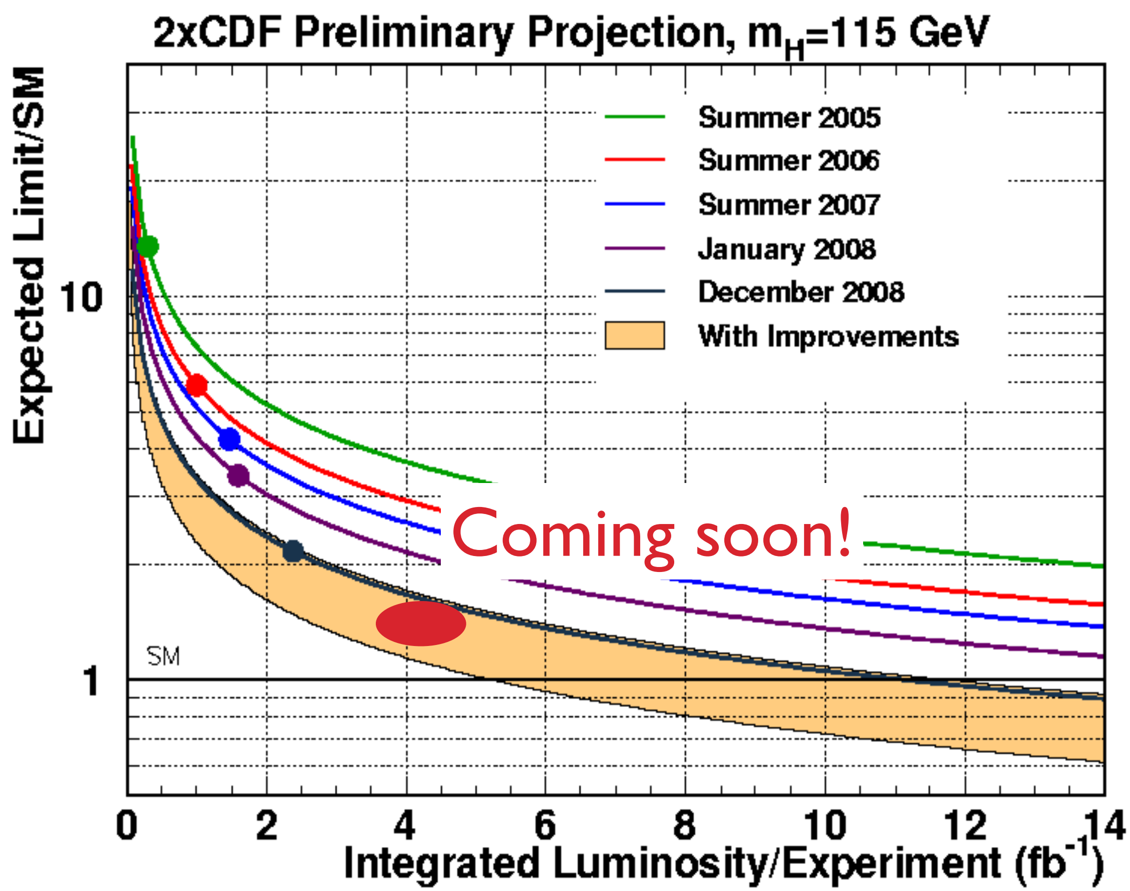
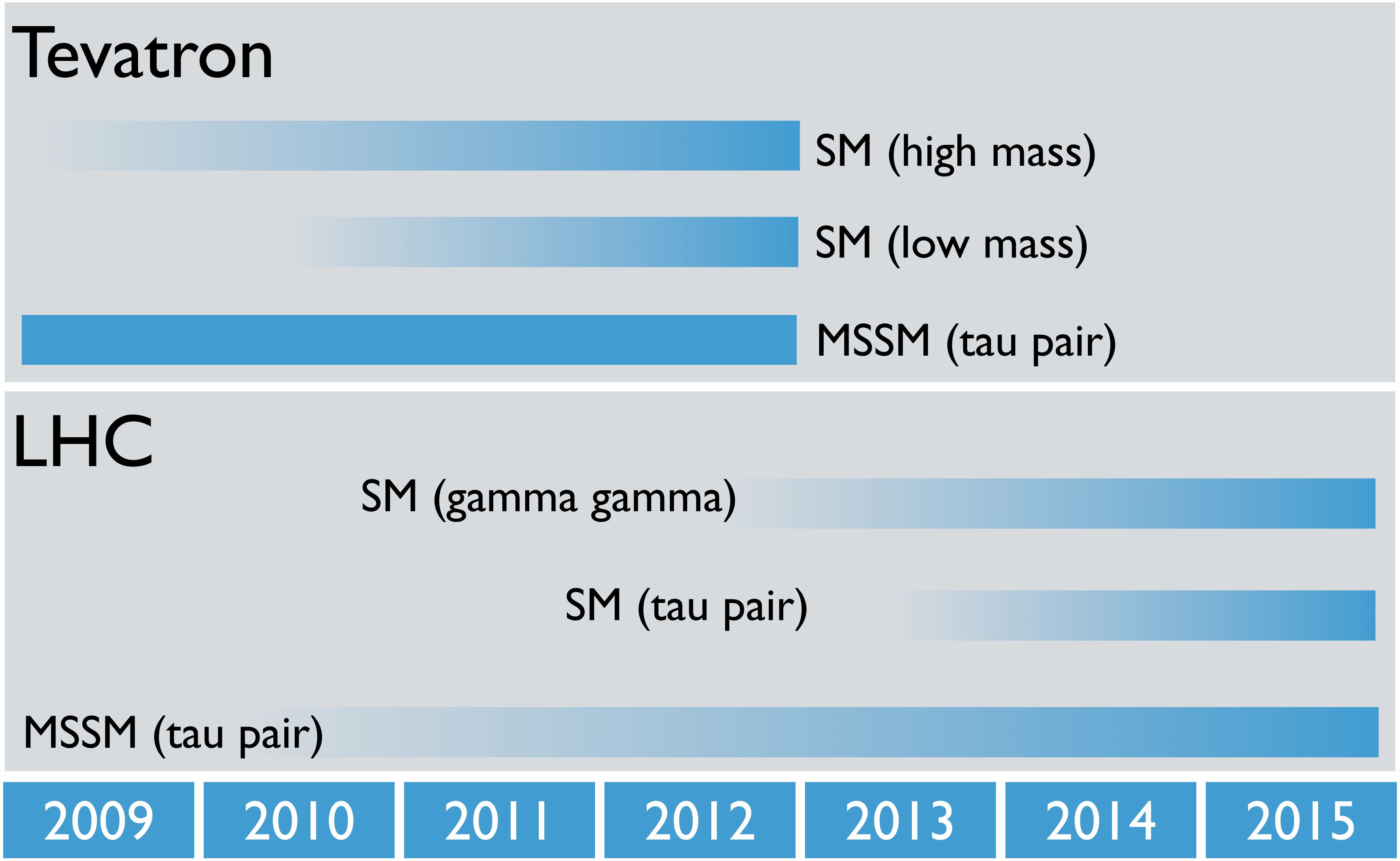


CDF/D0 will likely ultimately have ~10 fb^{-1}/experiment

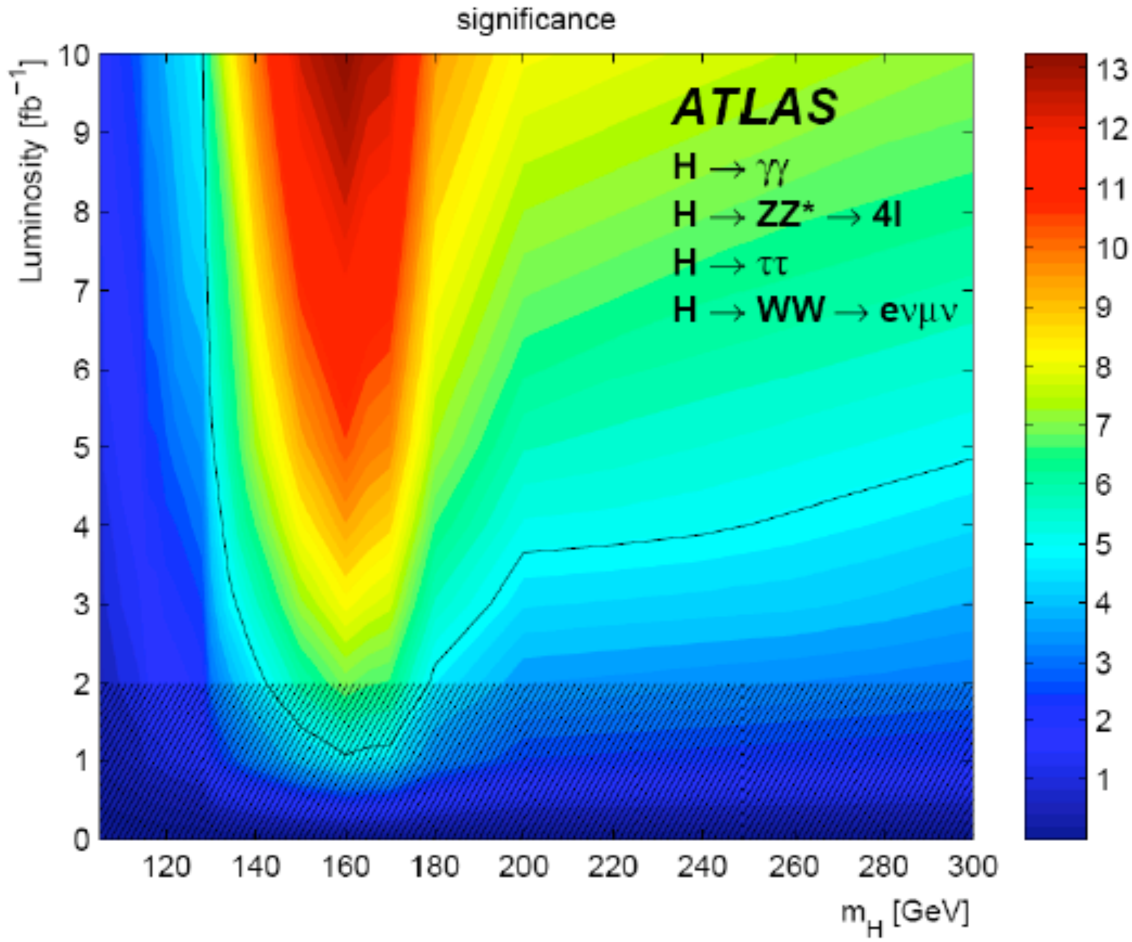


LHC versus Tevatron

March 2009: ATLAS SM Higgs reach at 14 TeV cm energy

Looks very difficult for lowest masses!

CMS: still expect to be able to see a 120 GeV SM Higgs in $\gamma\gamma$ final state with O(10 fb^{-1})



CDF and D0 have drawn first blood in the search for the SM Higgs, excluding the region 160-170 GeV

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New combination soon - expand excluded region

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MSSM search is statistics limited: new scientific ground broken with every update

An SM Higgs at ~120 GeV is exceedingly difficult to discover and will take a number of years more

A 5-sigma discovery by the Tevatron at low mass is very unlikely, but an exclusion could happen soon!

Nature will, in all likelihood, surprise us!