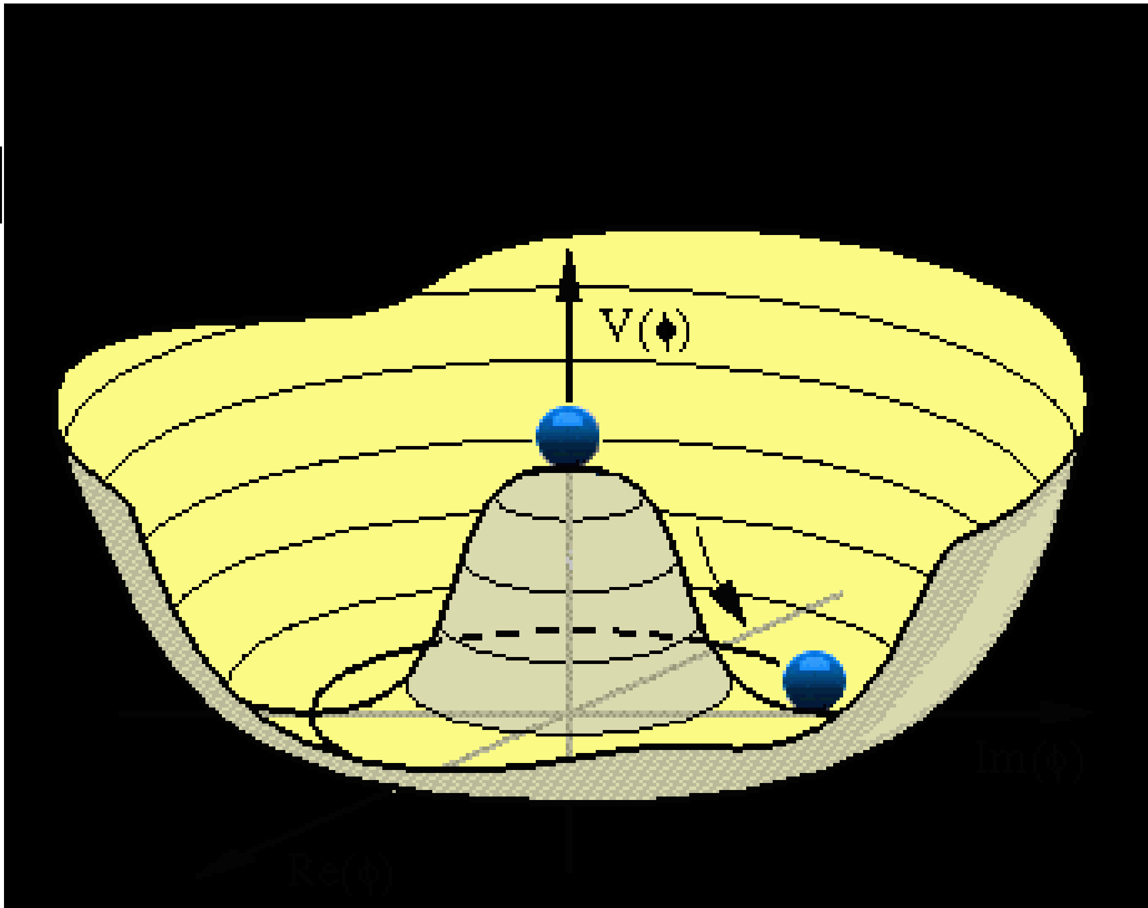
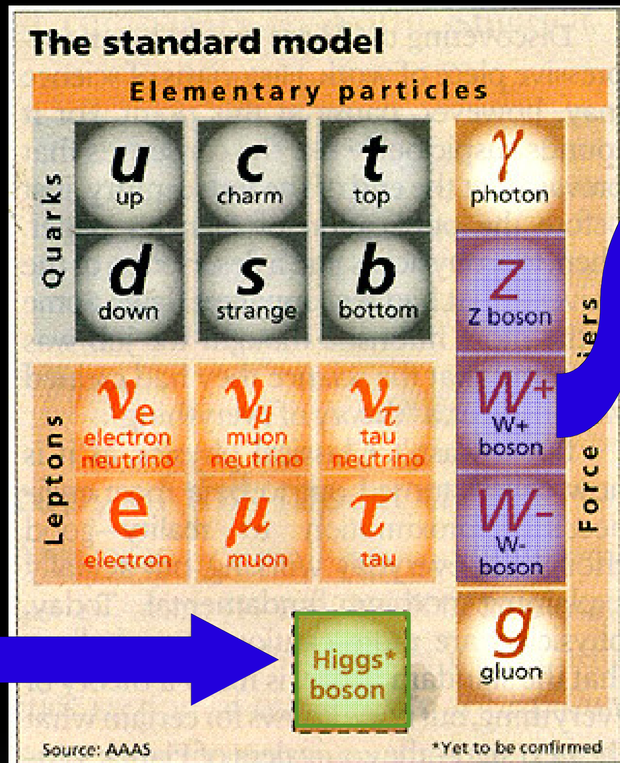


THE SEARCH FOR THE HIGGS BOSON

Daniela Bortoletto
Purdue University

THE STANDARD MODEL HIGGS

SM unifies
weak
and
electro-magnetic
interactions



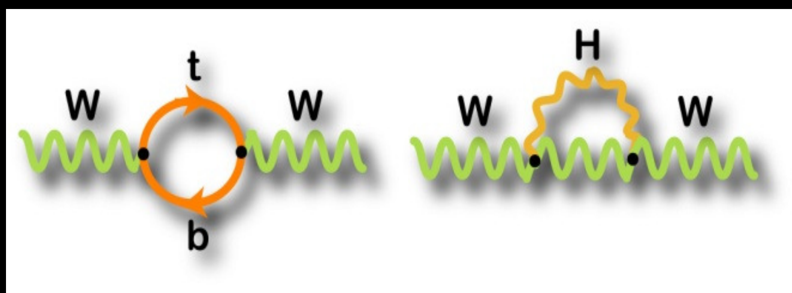
Experimentally:
weak gauge bosons
are massive
$\Rightarrow$ EWK symmetry
breaking

Higgs
mechanism

- **Finding the Higgs boson is essential to confirm the Higgs mechanism**
- **Since the Higgs decays very quickly (10^{-24} s) $\Rightarrow$ it can be observed only through its decays into other particles**
- **The search is difficult since m_H is not predicted in SM**
- **The Higgs couples to mass and decays preferentially to the heaviest objects kinematically allowed**

CONSTRAINTS ON THE HIGGS

- SM parameters (M_W , M_t , Z pole measurements etc)
  - **M_{Higgs}< 158 GeV with 95% C. L.**



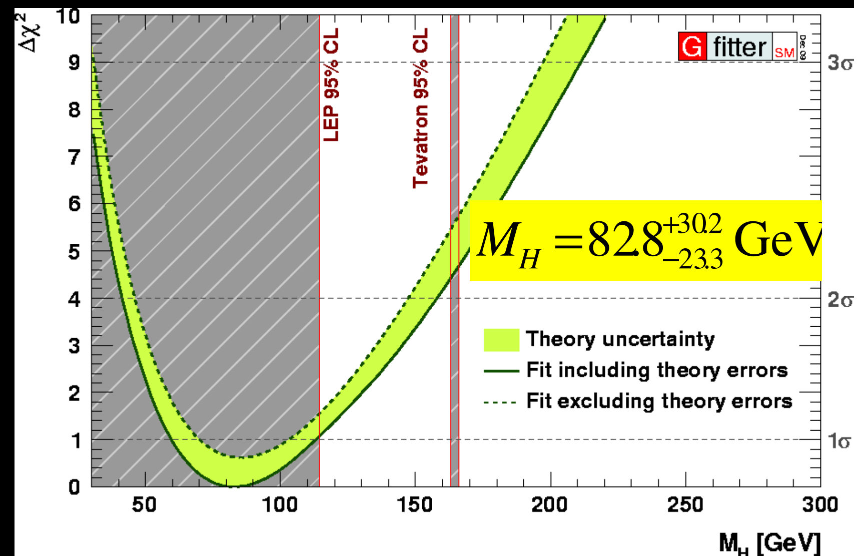
- Including direct searches at the Large Electron Positron Collider and at the TEVATRON proton anti-proton collider

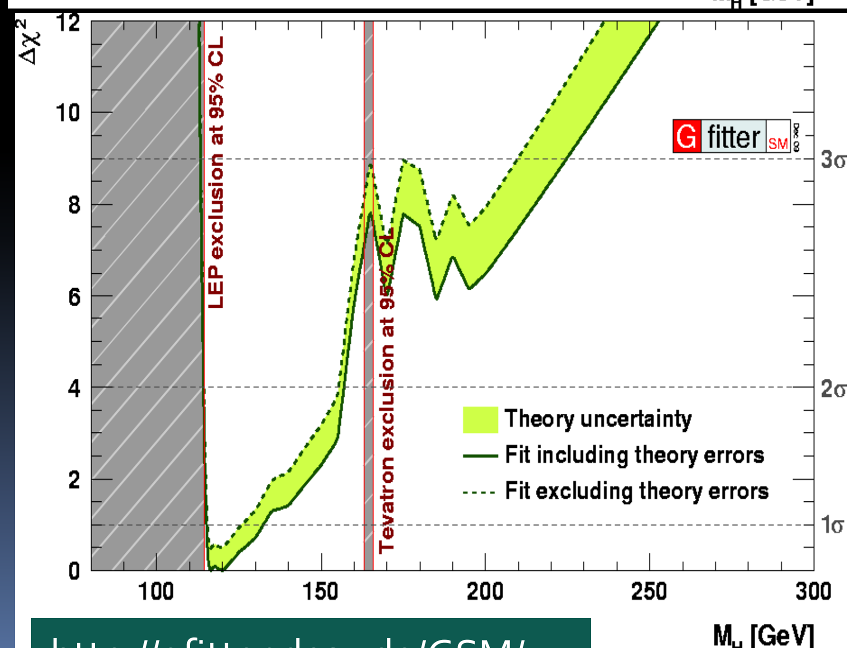
central value ±1σ: $M_H = 119.4^{+13.4}_{-4.0}$ GeV

2σ interval: [114, 157] GeV

The search is continuing at the TEVATRON and at the LHC

WINTER CONFERENCES 2010





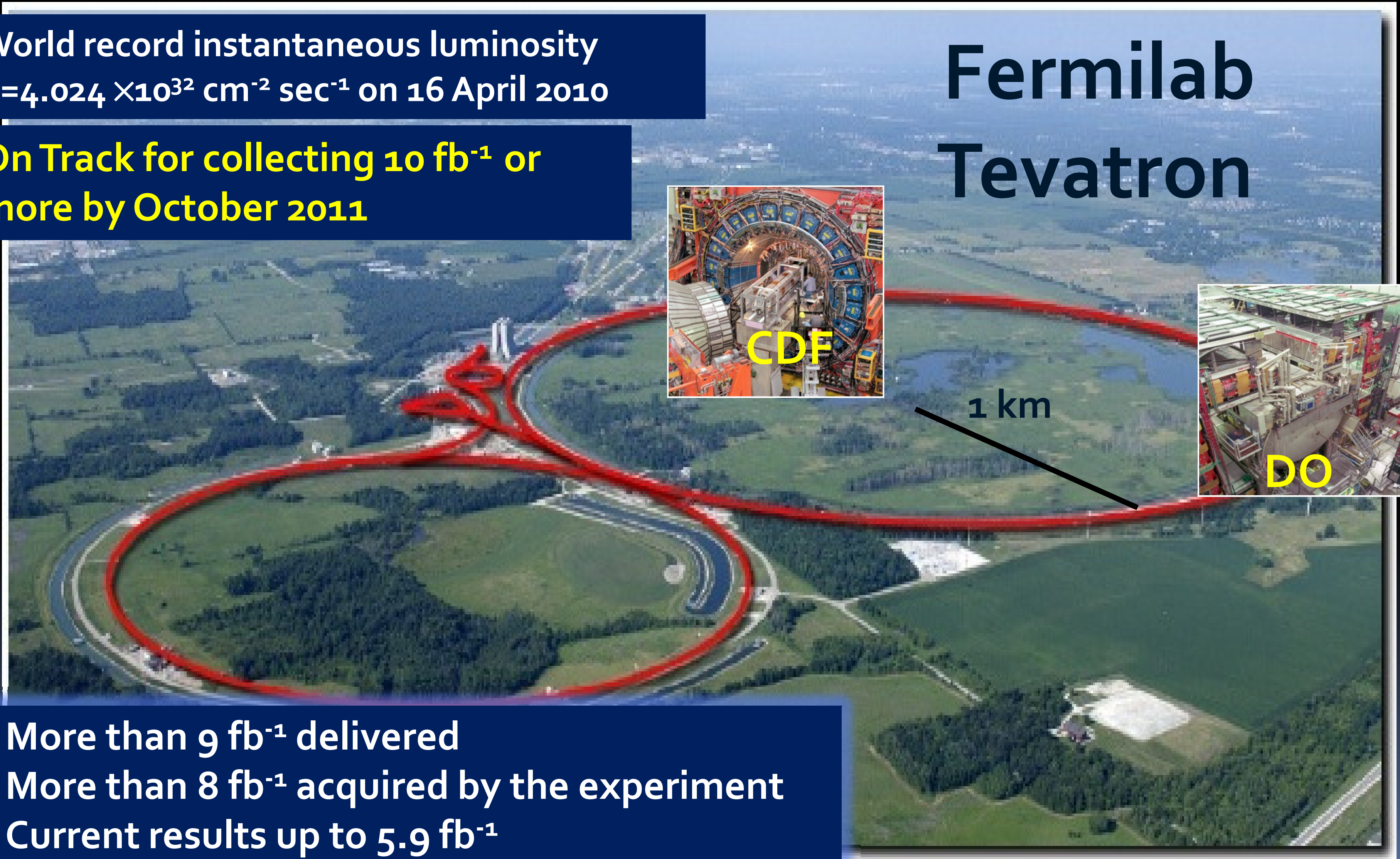
http://gfitter.desy.de/GSM/

The Tevatron

- Proton-antiproton collider with **1.96** TeV center-of-mass energy
- 396 ns between bunches

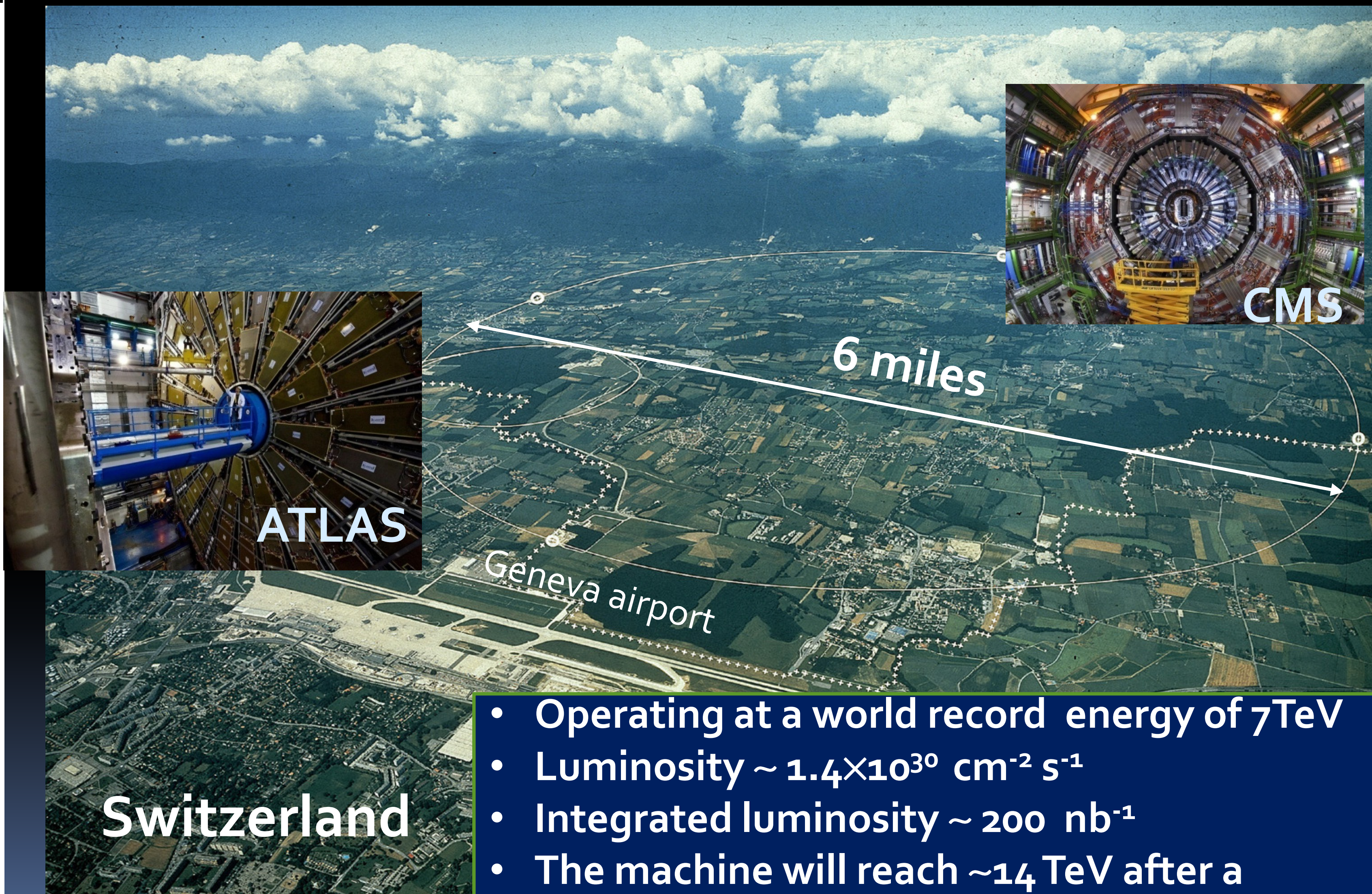
World record instantaneous luminosity
L=4.024 ×10^{32} cm^{-2} sec^{-1} on 16 April 2010

On Track for collecting 10 fb^{-1} or more by October 2011



More than 9 fb^{-1} delivered
More than 8 fb^{-1} acquired by the experiment
Current results up to 5.9 fb^{-1}

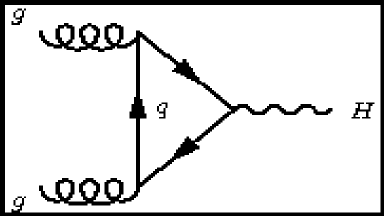
The LHC



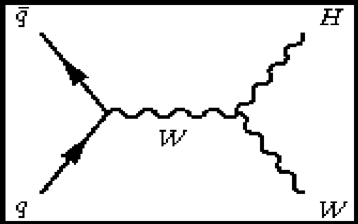
- Operating at a world record energy of 7TeV
- Luminosity ~ 1.4×10^{30} cm^{-2} s^{-1}
- Integrated luminosity ~ 200 nb^{-1}
- The machine will reach ~14 TeV after a shutdown in 2012

HIGGS PRODUCTION

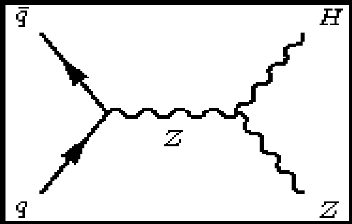
- Four main production mechanisms at hadron colliders



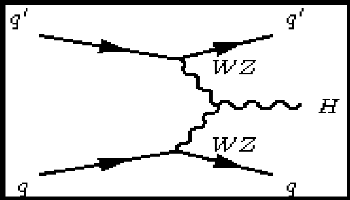
gg→H



$q\bar{q}'$→WH



$q\bar{q}$→ZH

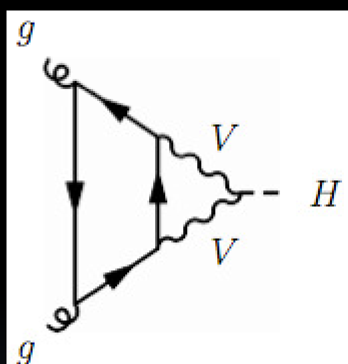


qq'→qq' H (VBF)

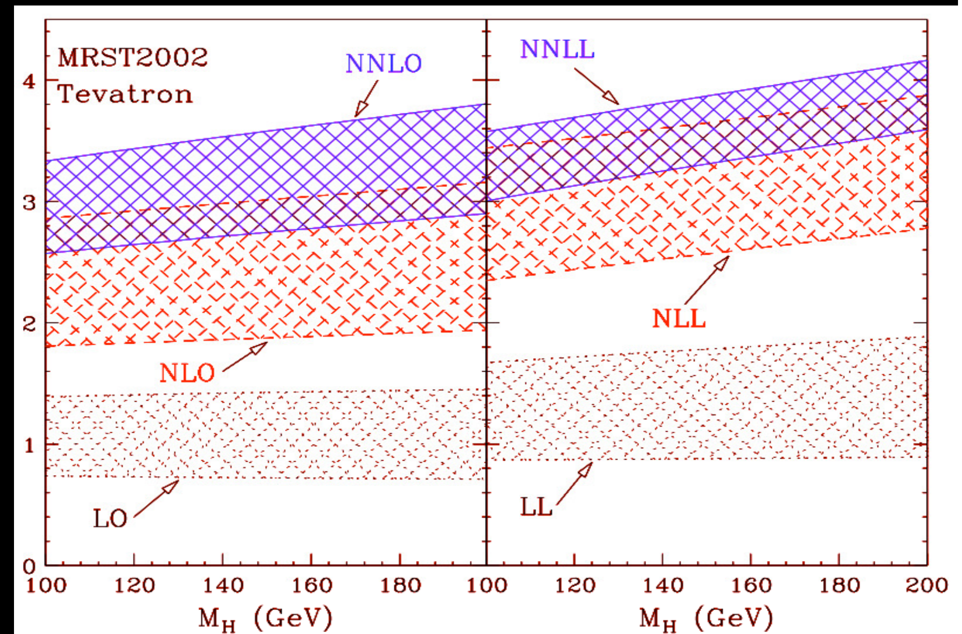
m_H=160 Gev	Tevatron $\sqrt{s}=1.96$GeV		LHC $\sqrt{s}=7$TeV		LHC $\sqrt{s}=14$TeV	
	σ[pb]	%	σ[pb]	%	σ[pb]	%
gg→H	0.439	78	8.49	87	32.6	88
WH	0.050	9	0.25	3	0.61	2
ZH	0.034	6	0.13	1	0.34	1
VBF	0.039	7	0.92	9	3.38	9
TOTAL	0.561	100	17.45	100	36.7	100
RATIO			17 X TEVATRON		66 X TEVATRON	

Theory Progress: ex. gg→H

- NLO corrections ~ doubles σ_{LO}
- NNLO QCD corrections give an additional 40%
- Resummed QCD corrections at NNLL
- Two-loop EW corrections yield up to an 8% boost



$K = \sigma / \sigma_{LO}$



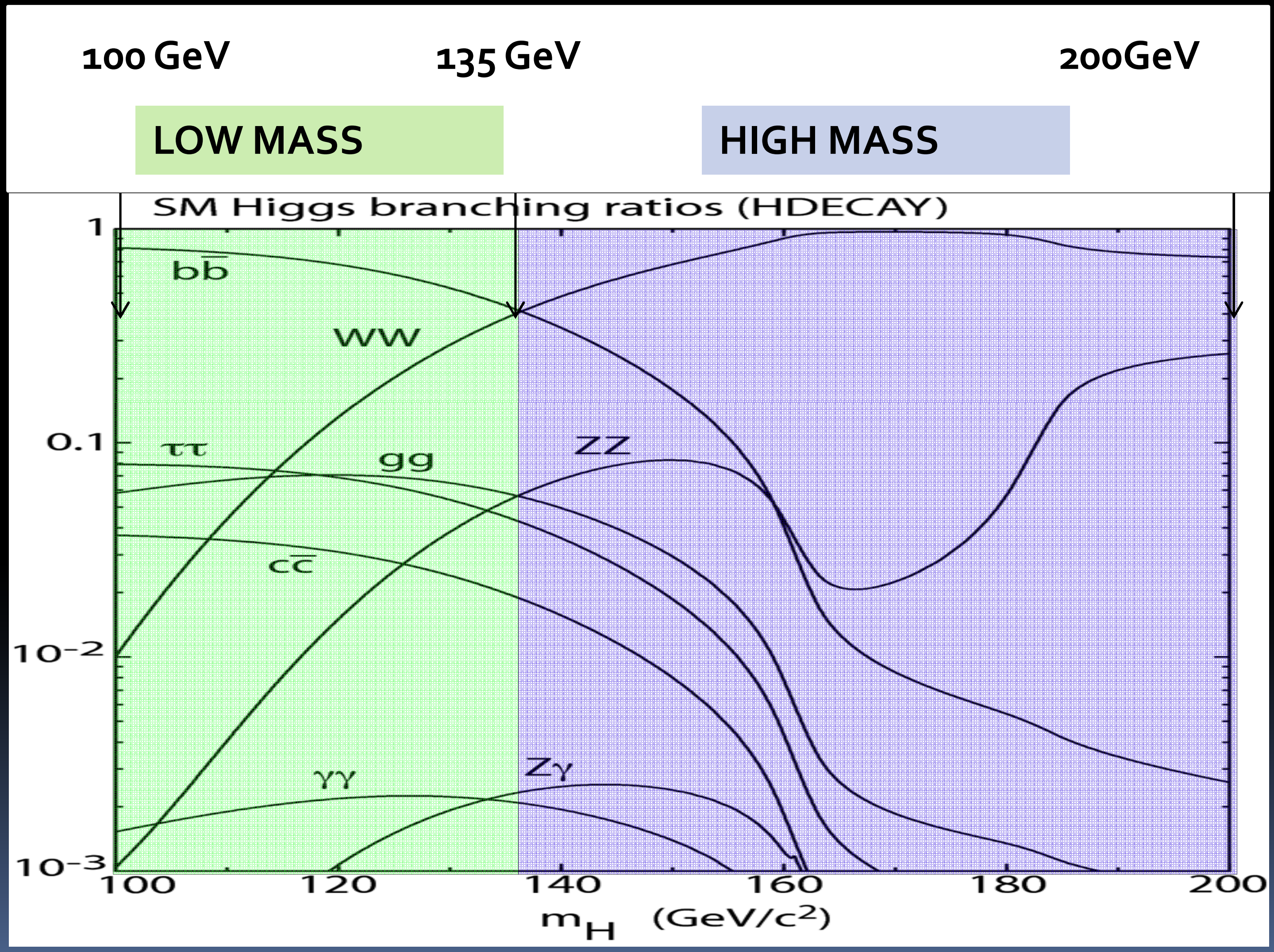
- NLL,NNLL bands: 0.5 $m_H < \mu_F, \mu_R < 2M_H$
- Additional uncertainty on $\sigma(gg \to H)$ for PDF

Total 14% bigger cross section at m_H=160 GeV relative to NNLO

- Catani, de Florian, Grazzini, Nason JHEP **0307, 028 (2003)**
- Aglietti, Bonciani, Degrassi and Vicini, Phys. Lett. B 595, 432 (2004)
- Actis, Passarino, Sturm, Uccirati, Phys. Lett. B **670, 12 (2008)**
- Anastasiou, Boughezal, Petriello, JHEP **0904, 003 (2009)**
- Grazzini, De Florian, Phys. Lett. B **674, 291 (2009)**

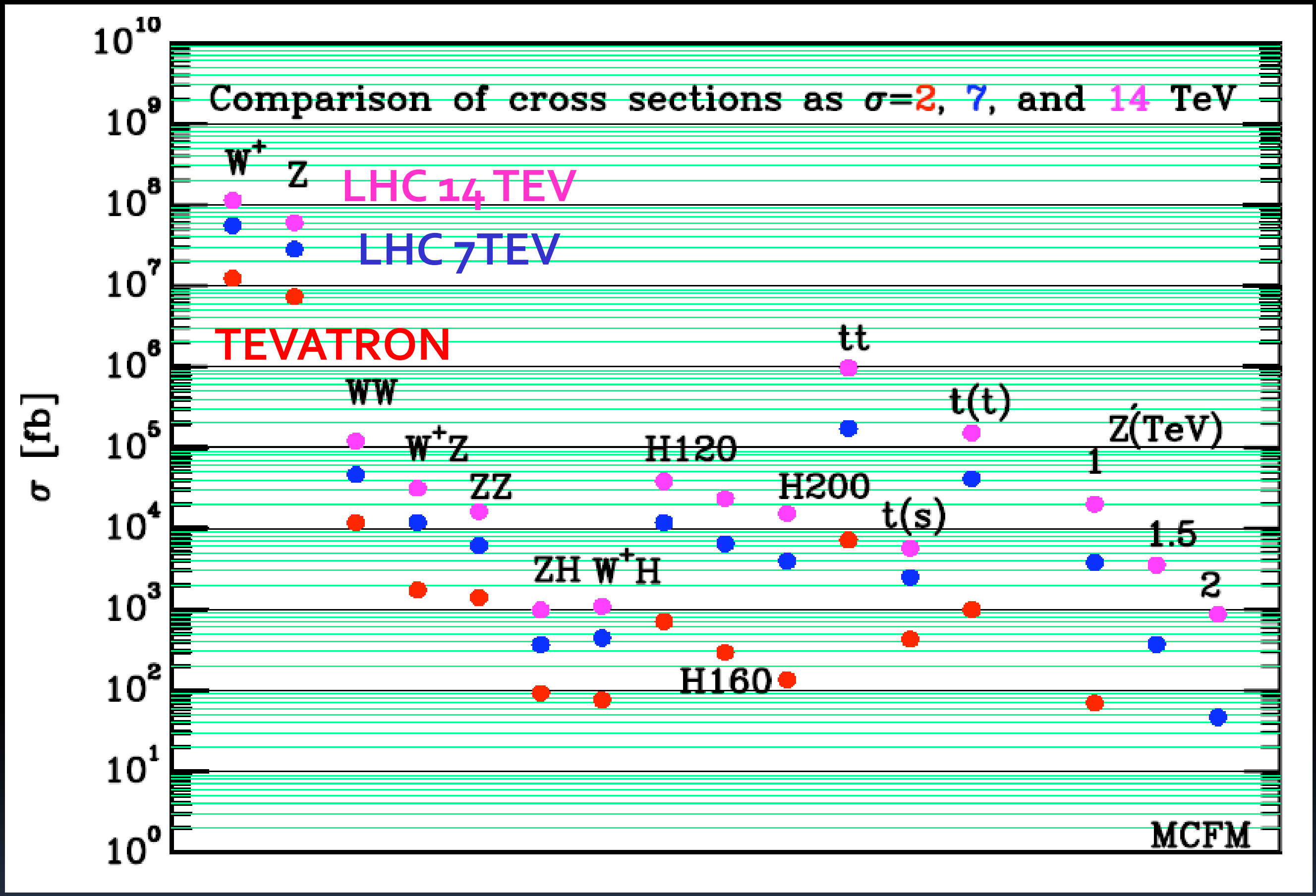
Workshop on Higgs cross section at CERN
http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=92082

HIGGS DECAY



100 GeV
135 GeV
200GeV
LOW MASS
HIGH MASS
SM Higgs branching ratios (HDECAY)
1
0.1
10−2
10−3
bb̄
WW
ττ
gg
ZZ
cc̄
γγ
Zγ
100
120
140
160
180
200
mH (GeV/c2)

The Higgs challenge S/B

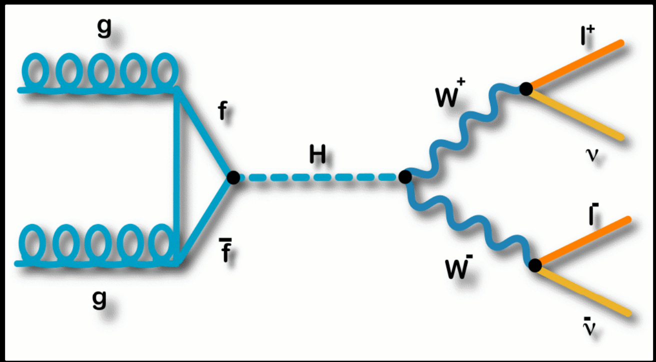


- Many of the background processes have cross section orders of magnitude larger than the Higgs
- Adopt different strategies for low mass/high mass, Tevatron/LHC

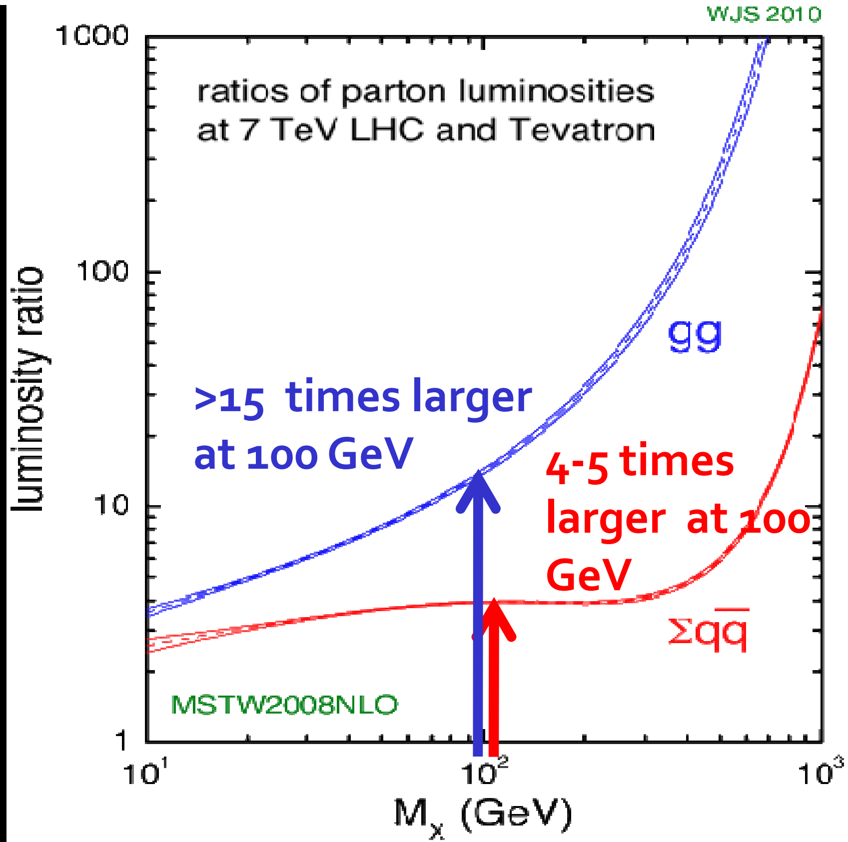
Higgs at the LHC and the Tevatron

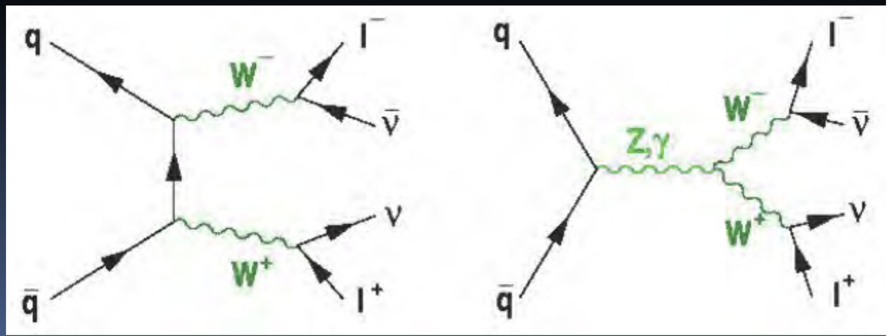
High Mass $M_H > 135$ GeV/c²

Main channel: gg→H→ WW



- Signature: High P_T leptons and Missing transverse energy
- Relatively easy and clean at the LHC and at the Tevatron
- σ(gg →H) LHC $_{7TEV}$ >> TEVATRON
- Backgrounds such as WW and ZZ originate from $q\bar{q}$ rise moderately
  ⇒ S/N rises
  ⇒ LHC competitive with 1fb^{-1}





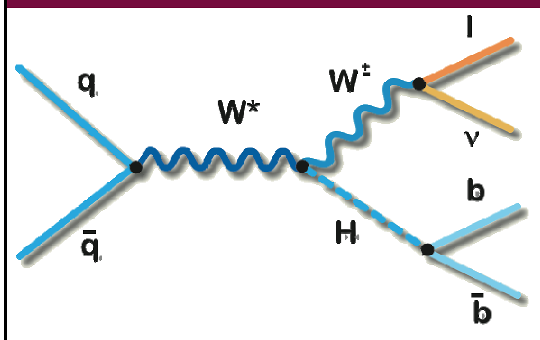
Higgs at the LHC and the Tevatron

Low Mass $M_H < 135$ GeV/c²

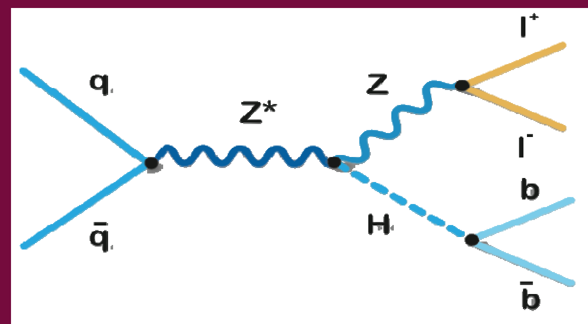
More in D Brown's presentation on Sunday

TEVATRON main channels: W/ZH→bb

$WH \to l\,\nu b\bar{b}$

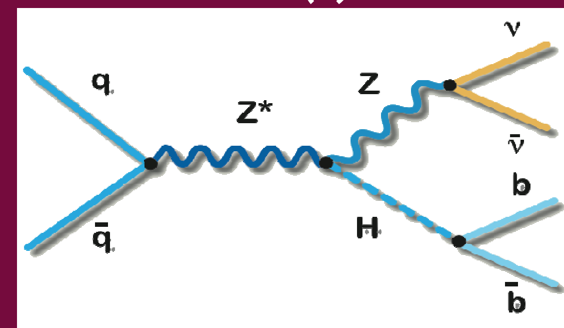


$ZH \to ll\, b\bar{b}$



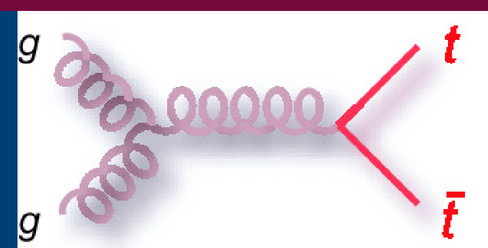
$ZH \to \nu\bar{\nu}\, b\bar{b}$

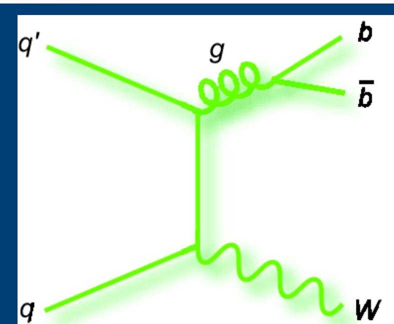
$WH \to (l)\,\nu b\bar{b}$



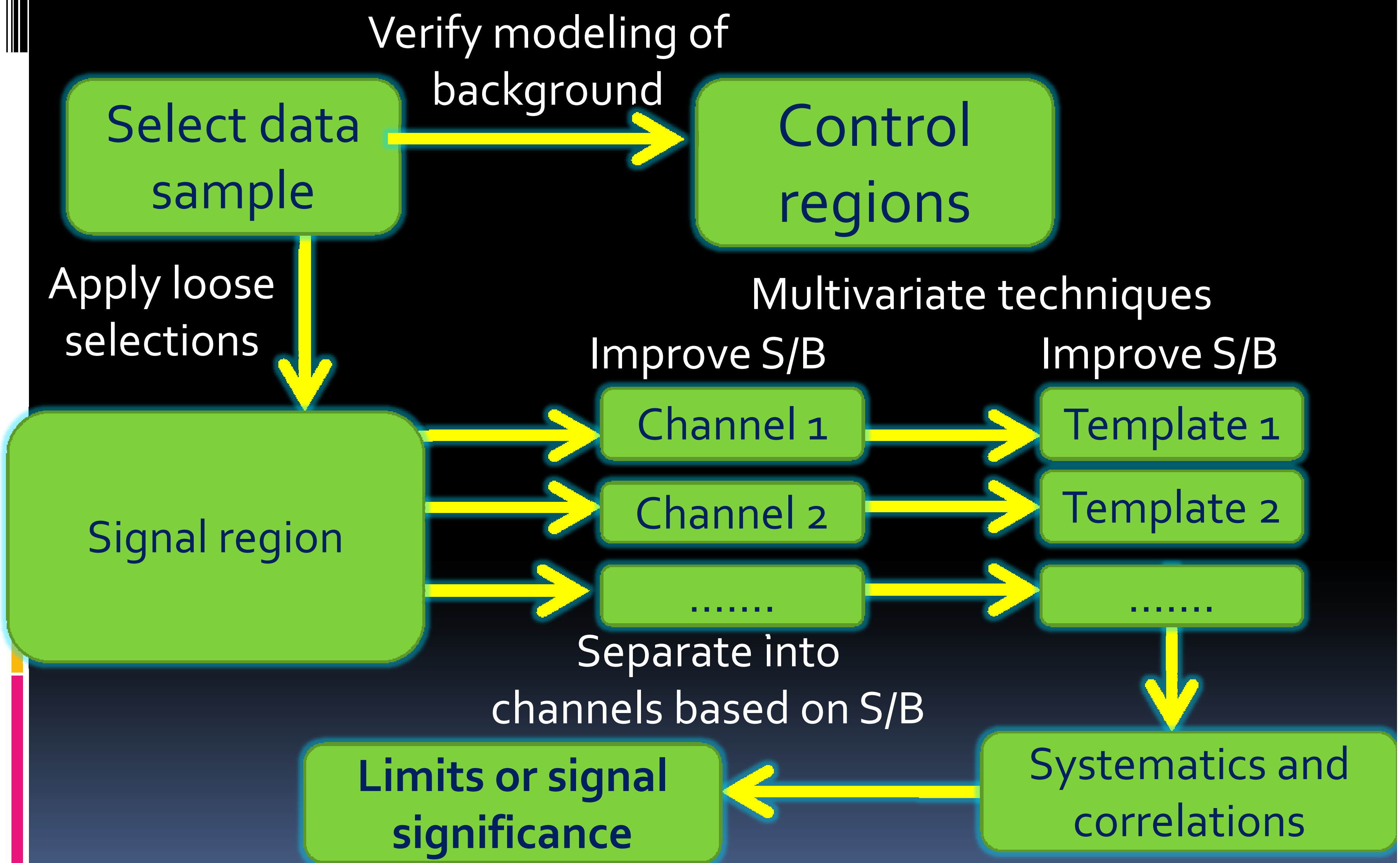
LHC primary discovery channel is gg→H→γγ

- σ(WH/ZH) @ 7 TeV ~ 3-5 x TEVATRON
- W/Z+$b\bar{b}$ & $t\bar{t}$ background have a large increase ⇒ small signal rate ⇒ poor S/N at the LHC
- **gg → H →γγ is tough**
- Br(H →γγ) ≅ 0.2% and large QCD γγ background

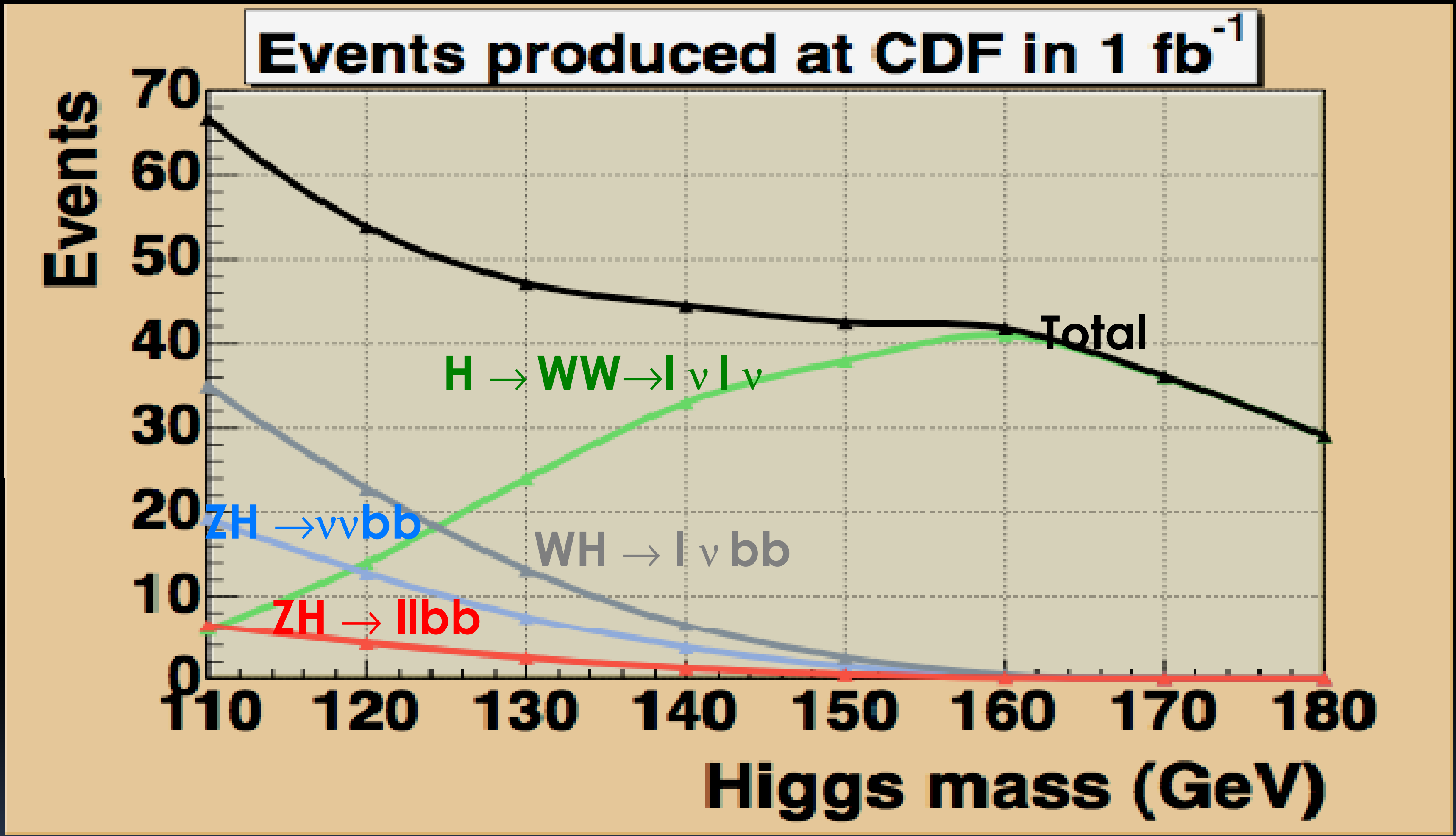




Higgs analyses strategies

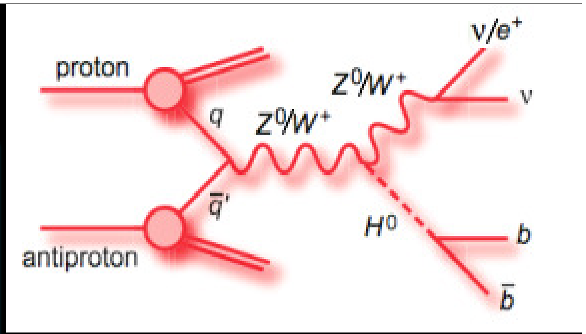


Tevatron Higgs searches



- Critical to have large data sets and good efficiency
- DO and CDF have worked very hard to optimize trigger, b-tagging efficiency, and lepton identification, jet resolution etc.

ZH/WH → MET bb

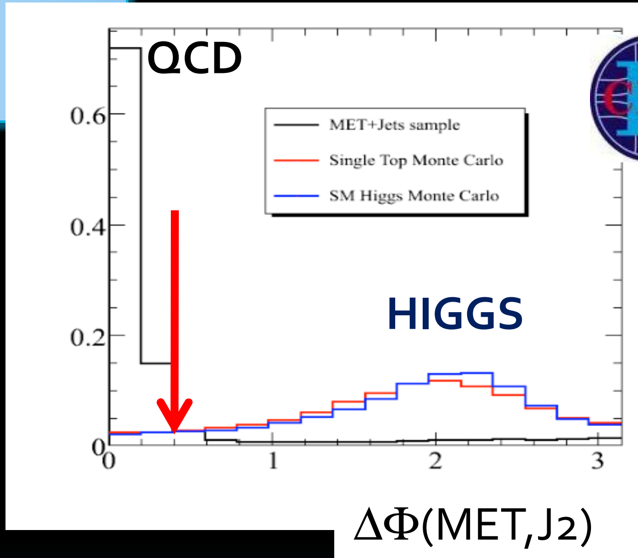


SIGNAL:

- No high P_T visible leptons
- Large Missing E_T= MET
- 2 jets or 3 jets (to catch $W \to \tau\nu$ with $\tau \to$ hadronically)
- Require 1 or 2 b-tags

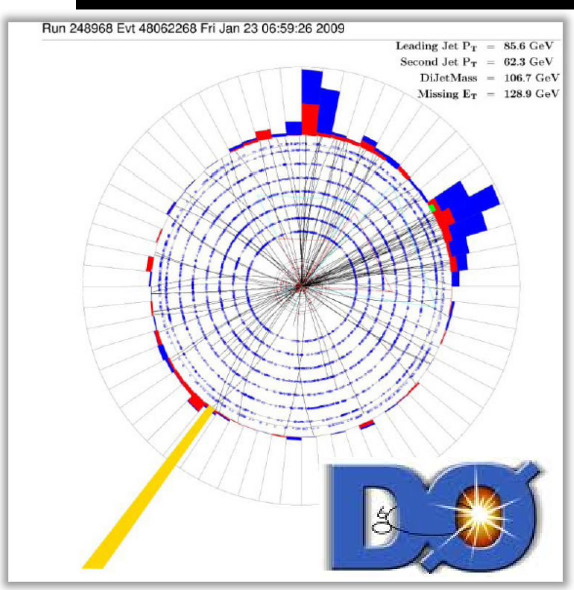
Backgrounds:

- QCD Heavy Flavor,
- *tt, W/Z + bb/cc,*
- Single Top,
- *ZZ, WZ, WW*

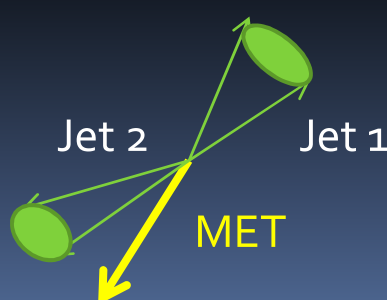


- Di-jet production cross section very large
- Mismeasured jets can create fake MET

$$\vec{E}_T = -\sum \vec{E}_T^{\,i} = MET$$



- Usually fake MET points along the jet with lower energy (often denoted with J2)

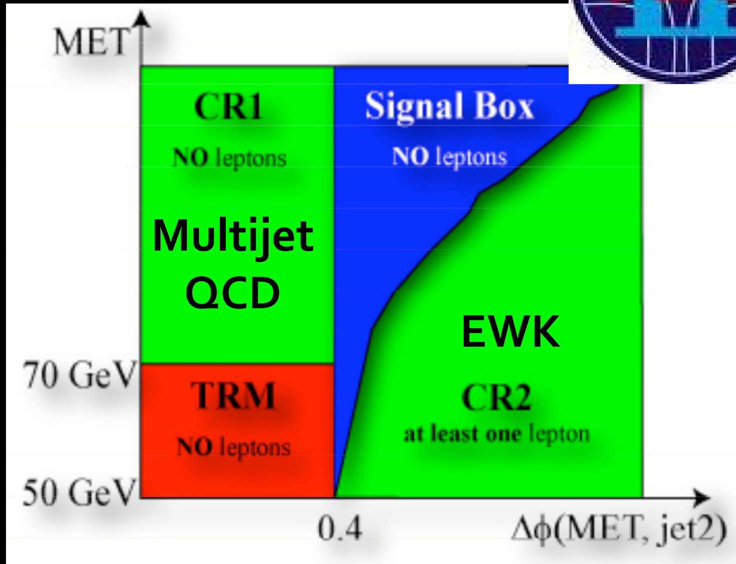


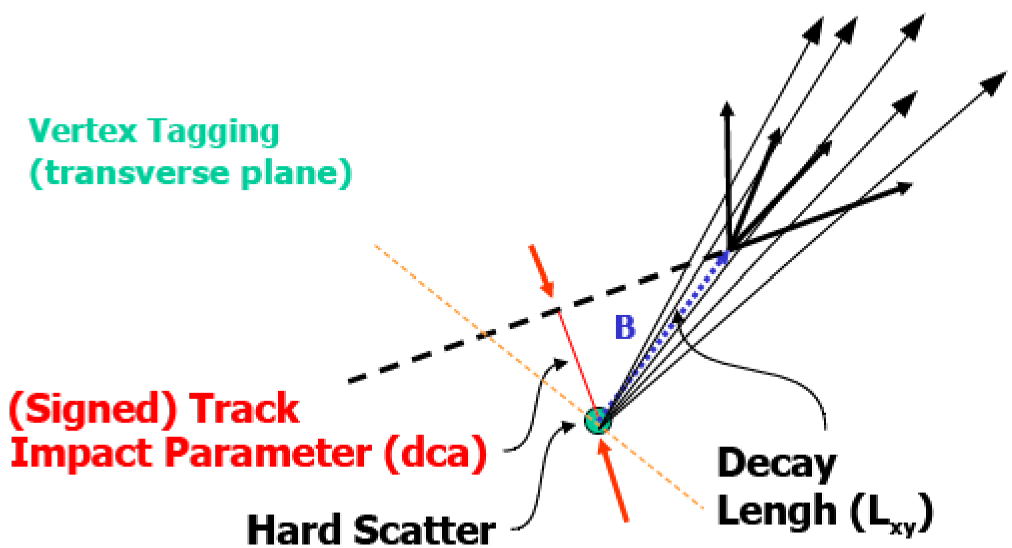
- Calorimeter information can be confirmed by Missing P_T

$$\vec{P}_T = -\sum \vec{p}_T^{\,i,tracks}$$

Signal and Control regions

- Analysis region is defined by:
  - MET > 50 GeV
  - 2 or 3 jets in the detector central region:
    - $E_T(J1) > 35$ GeV and $E_T(J2) > 25$ GeV
      $$\Delta R = \sqrt{\Delta\phi(j_1, j_2)^2 + \Delta\eta(j_1, j_2)^2} > 1$$
    - $\eta(j) < 2$ and $\eta(j_1$ or $J_2) < 0.9$
  - No identified leptons to be ⊥ to WH →lνbb
- Multijet background estimated using data



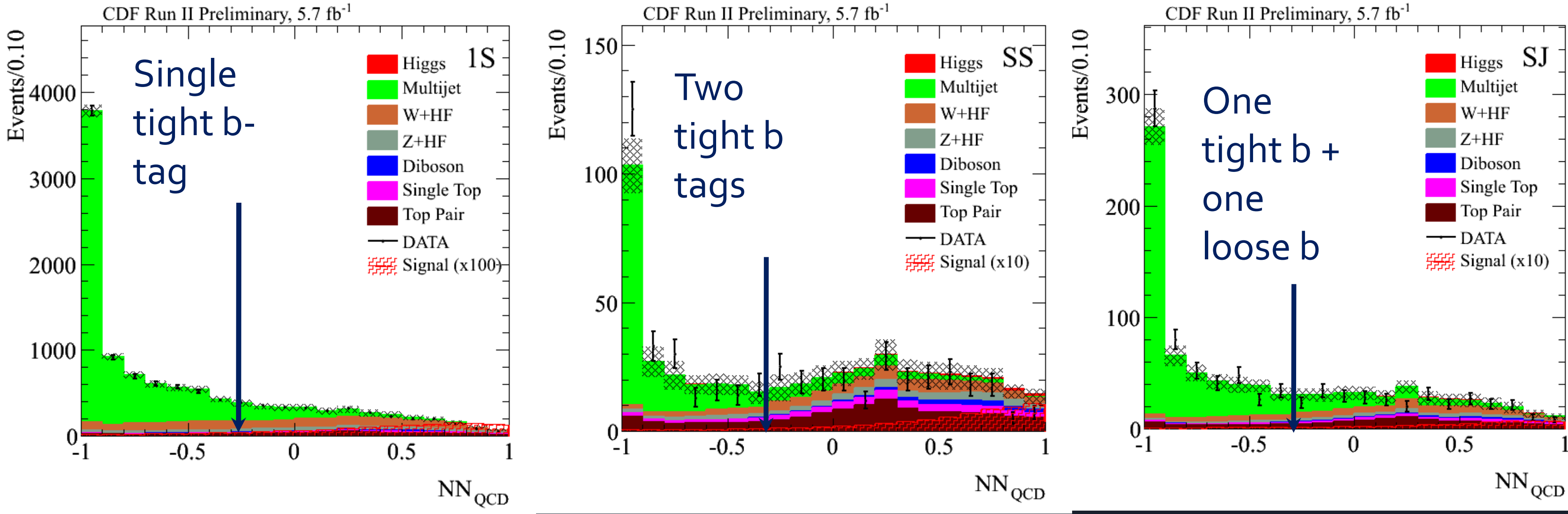


- **b –tagging is essential for low mass analysis ⇒Improves S/B by > 10**
- Long lifetime of b-quarks
  - Impact Parameter based
  - Secondary Vertex reconstruction
  - NN
- **Loose = $\varepsilon_{b\text{-tag}}$ ~50-70% , mistag 1-6 %**
- **Tight = $\varepsilon_{b\text{-tag}}$ ~40-50% , mistag 0.5 %**

Analyze separately ("tight") single & ("loose") double tags

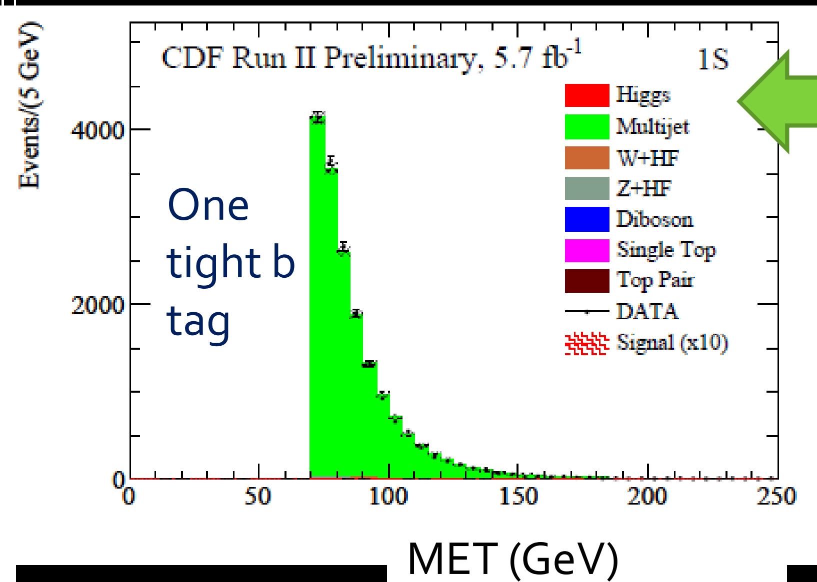
QCD removal

- NN_{QCD} based on 14 kinematical variables to reduce multijet background
- The most important variables in the NN are $\Delta\Phi$(MET, MPT) and MET
- The NN is trained on Signal =ZH and WH, Background=pretag data.



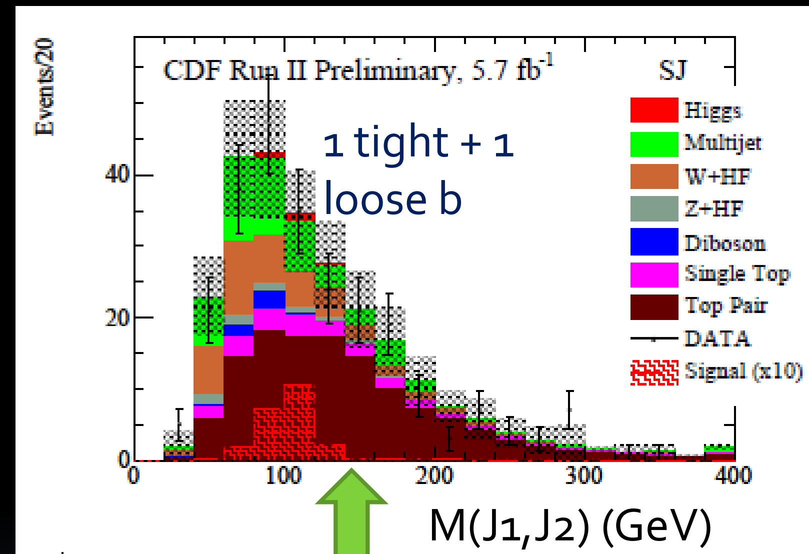
Accepts about 95% of the signal rejects about 87% of the background

Understanding the backgrounds



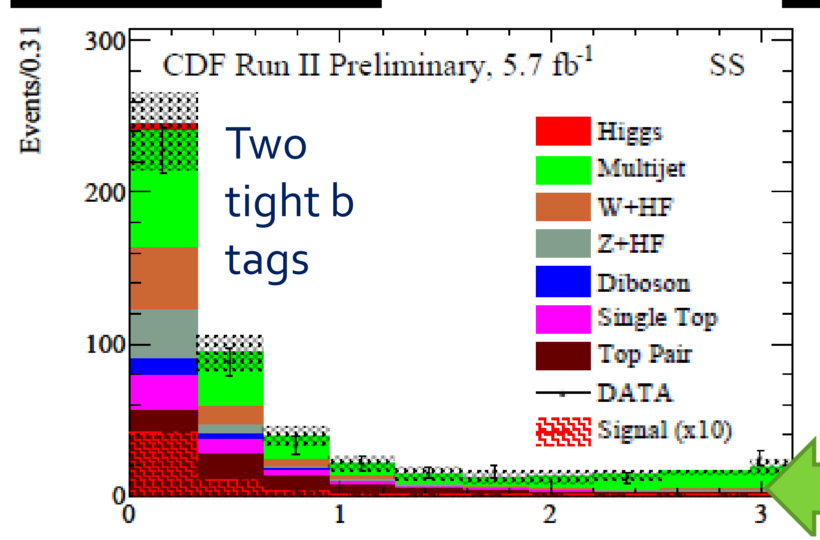
QCD multijet control region

- MET > 70 GeV and $\phi(MET,j_2) < 0.4$



Electroweak control region

- $\phi(MET,j_2) > 0.4$, with leptons



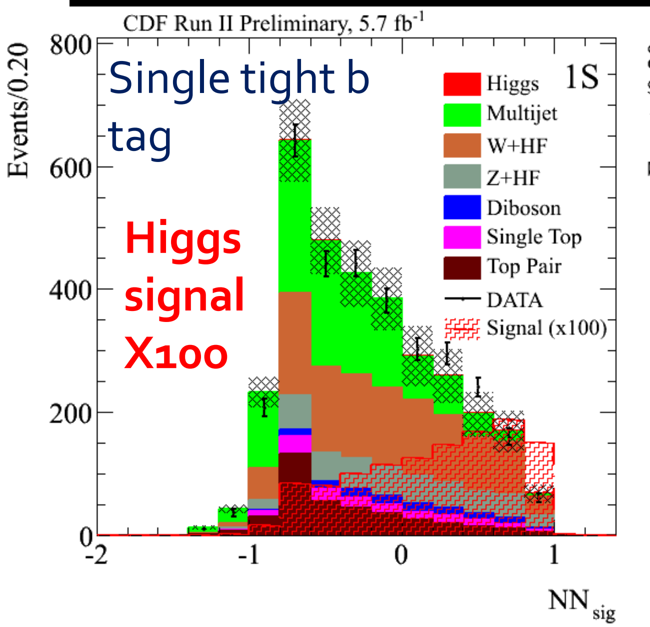
Preselection region

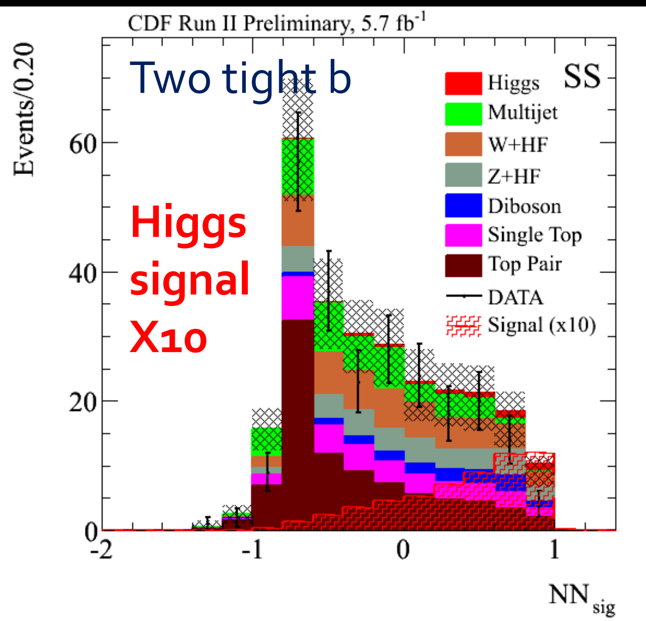
- $\phi(MET,j_2) > 0.4$, with leptons

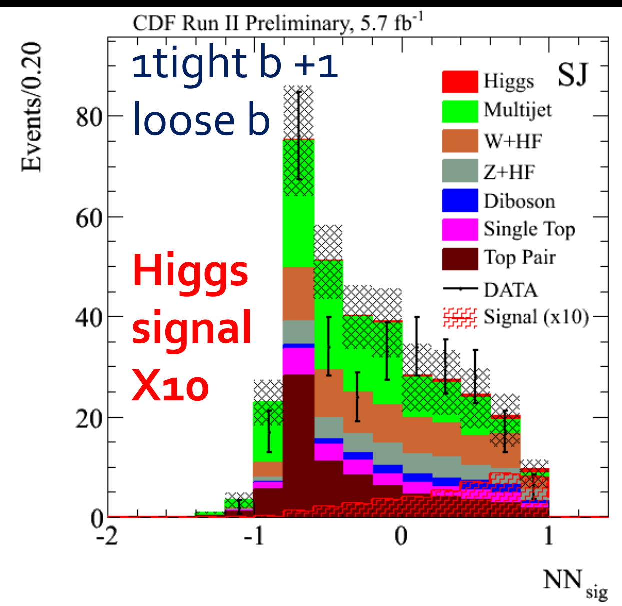
Signal Neural Network

New CDF result for ICHEP

- The final NN_{SIG} is trained on ZH/WH as a signal
  - 75% untagged jet data + 25% tt background in the 2 jet bin
  - 50% untagged jet data + 50% tt in background in the 3 jet bin
- 7 kinematic variables: m(j1,j2) is the most important



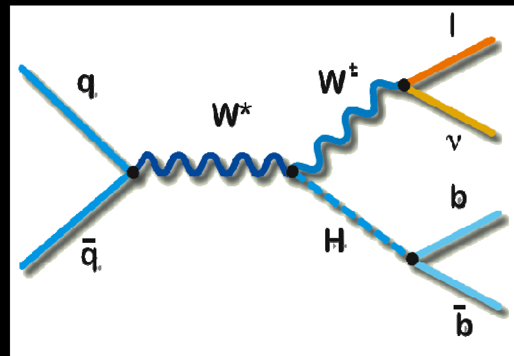




Analysis M_H=115 GeV	Lumi (fb^{-1})	Signal Evts	95% Exp Limit σ/SM	95% Obs Limit σ/SM
CDF NN	**5.7**	**21.8**	**4.0**	**2.3**
DØ	5.2	16.5	4.6	6.1

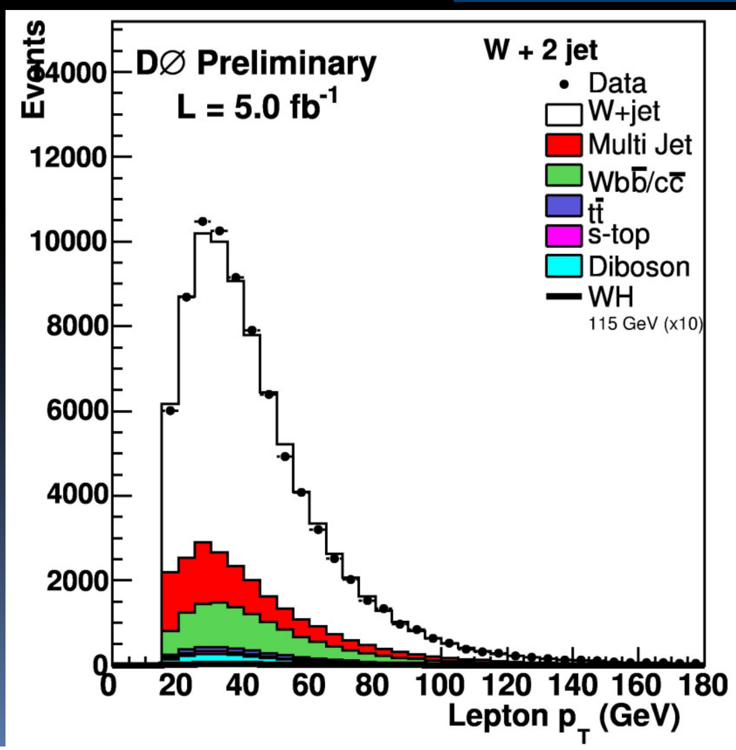
WH→lνbb channel

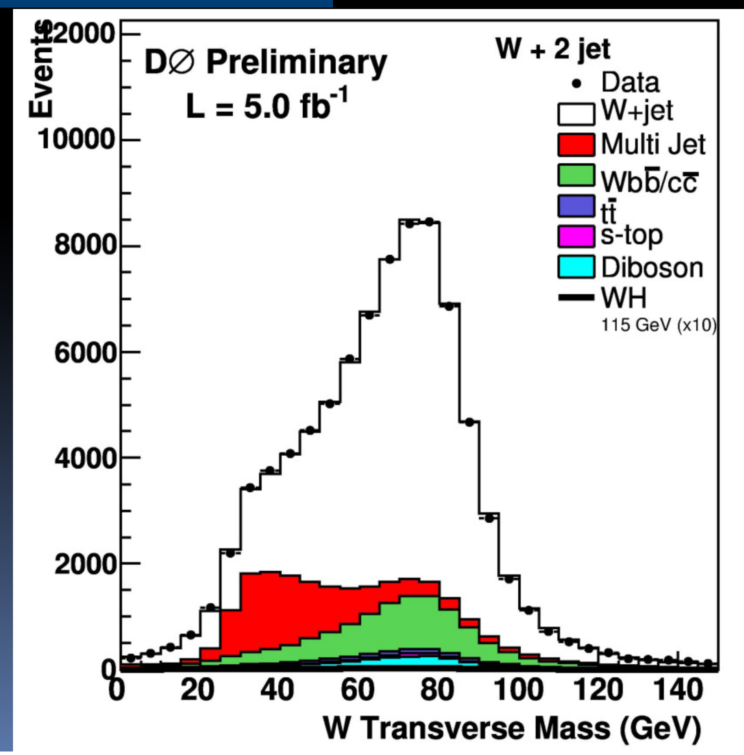
SIGNAL
- Isolated High P_T Lepton
- Large Missing E_T
- 2 – 3 high E_T jets
- Split 1 and 2 b-tags



Backgrounds
- *Wbb, Wcc, Wqq'*
- *tt*, Single top
- non – *W QCD*
- *WZ, WW,Z* $\rightarrow\tau\tau$

Good understanding of the background needed

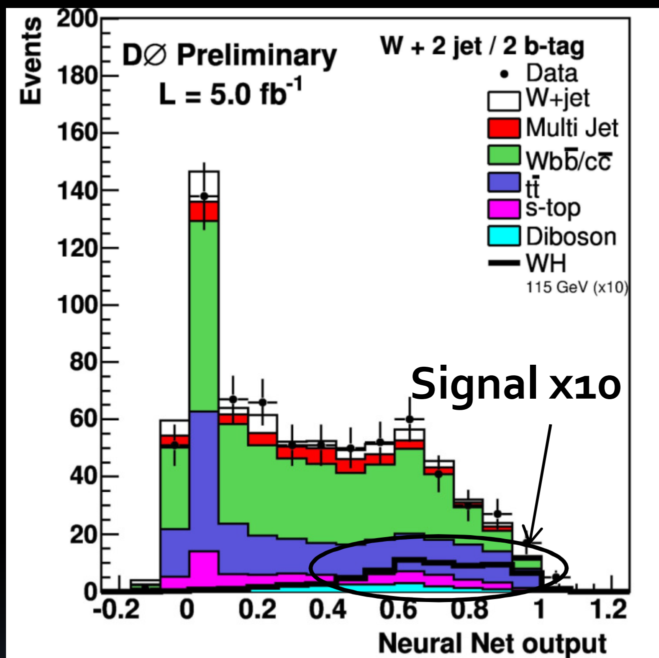


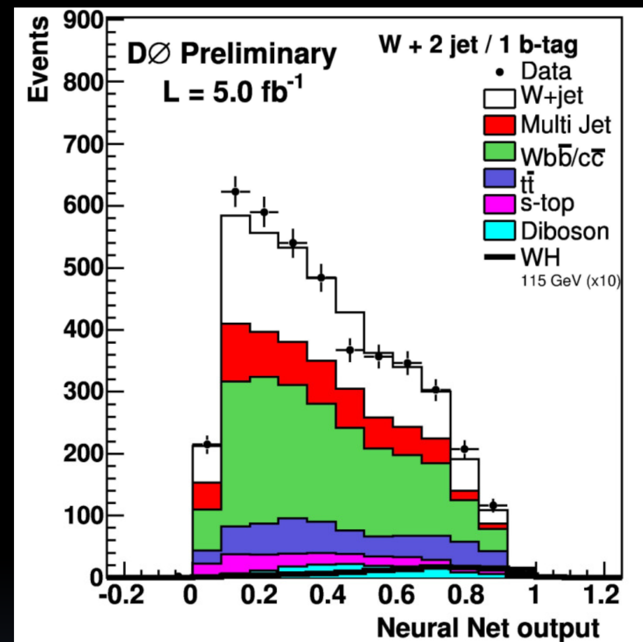


WH→lν final discriminant

New CDF result for ICHEP

- Limits are set using a NN output based on kinematical variables
- 2 Jet and 3 jet events treated separately





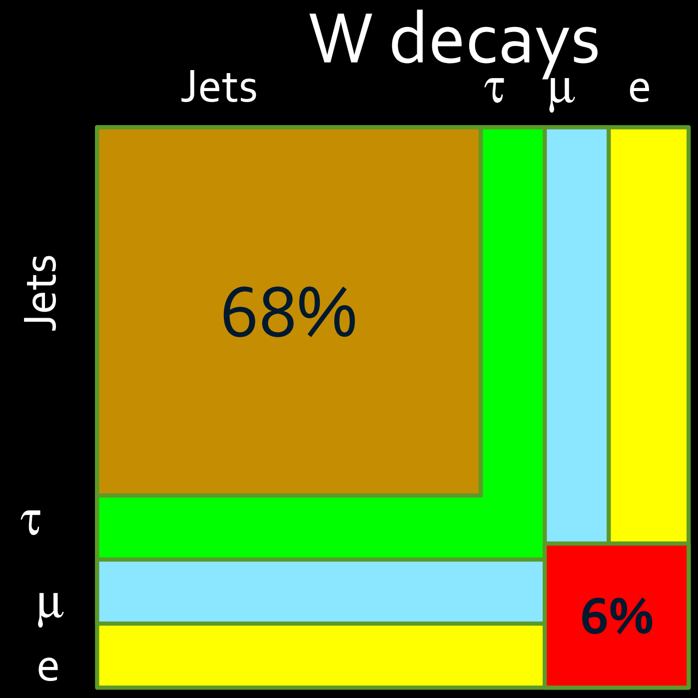
No evidence for the HIGGS

Analysis Mh=115 GeV	L (fb^{-1})	Signal	95% Exp Limit σ/SM	95% Obs Limit σ/SM
CDF (+isolated tracks)	5.7	18.42	3.48	4.47
DO	5.0	12.3	5.1	6.9

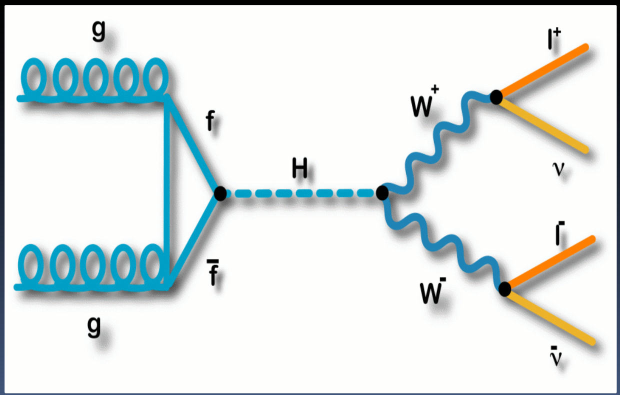
High mass searches

More in A. Canepa's presentation on Sunday

- Higgs→WW
  - BR(W→hadrons)~68%
    - Large QCD background
    - Not used now, work in progress
  - BR(WW→ee,μμ,eμ)~6%
    - Easy and clean triggers on single electron or muon
    - Partially includes τ
    - Dedicated analysis looks at hadronic tau decays



- SIGNAL
  - Two High P_T leptons
  - Large Missing E_T



Backgrounds:
WW, WZ, ZZ,
W + jets, W + γ, tt
$Z^{(*)}$→ll

Signal vs Background

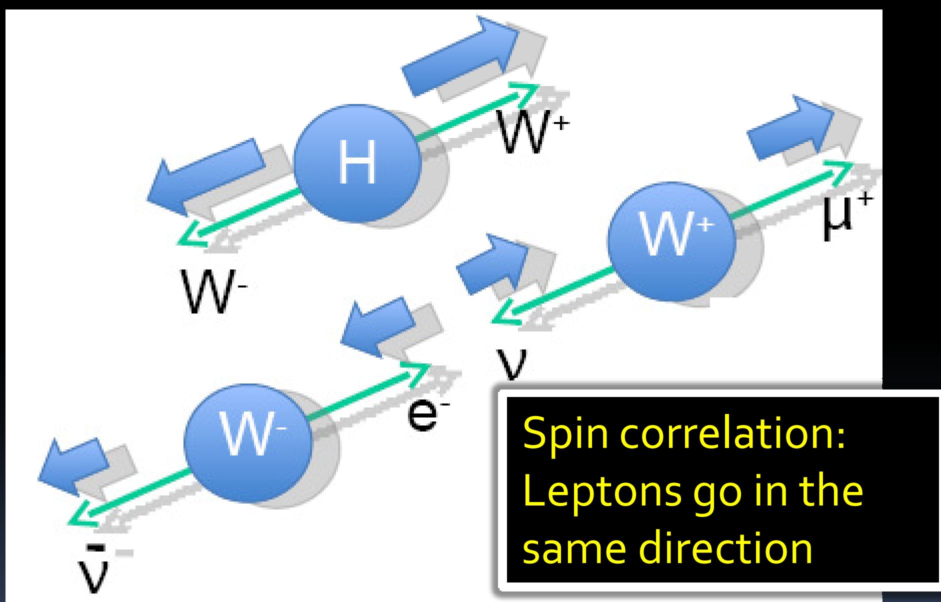
S/B ~0.6 in the most sensitive bin therefore both experiments use multivariate techniques to discriminate between signal and background:

- Matrix Element (ME), Neural Networks (NN)
- Each channel and M_H hypothesis has its own NN

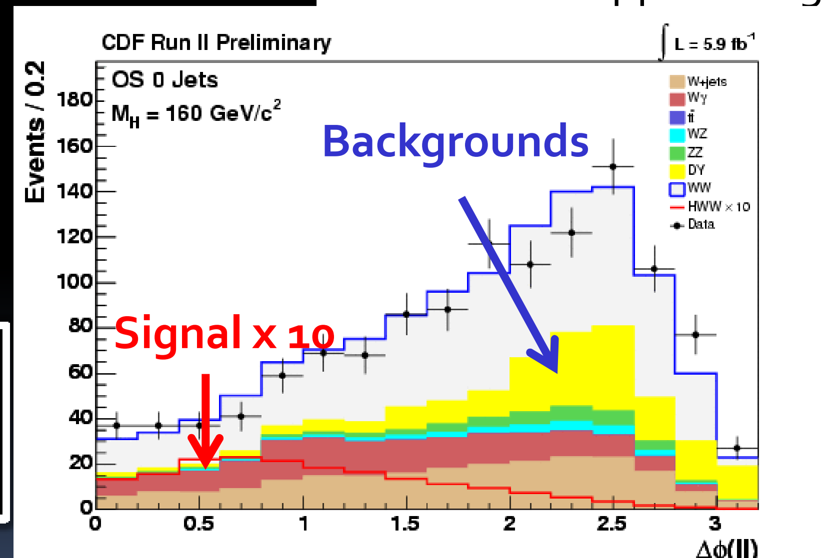
CDF Run II Preliminary $\int \mathcal{L} = 5.9\ \mathrm{fb}^{-1}$

$M_H = 165\ \mathrm{GeV}/c^2$

$t\bar{t}$	228	±	33
DY	520	±	110
WW	748	±	72
WZ	57.7	±	8.0
ZZ	51.7	±	7.1
W+jets	319	±	78
$W\gamma$	184	±	26
Total Background	2108	±	190
$gg \to H$	27.4	±	6.5
WH	4.04	±	0.56
ZH	2.13	±	0.29
VBF	2.25	±	0.37
Total Signal	35.9	±	6.8
Data	2070		



Opposite sign

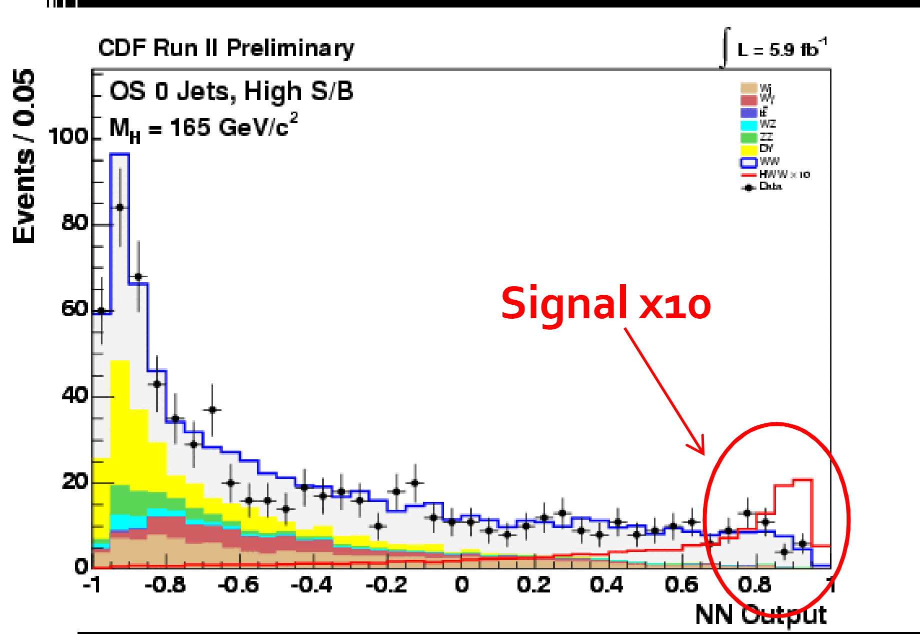


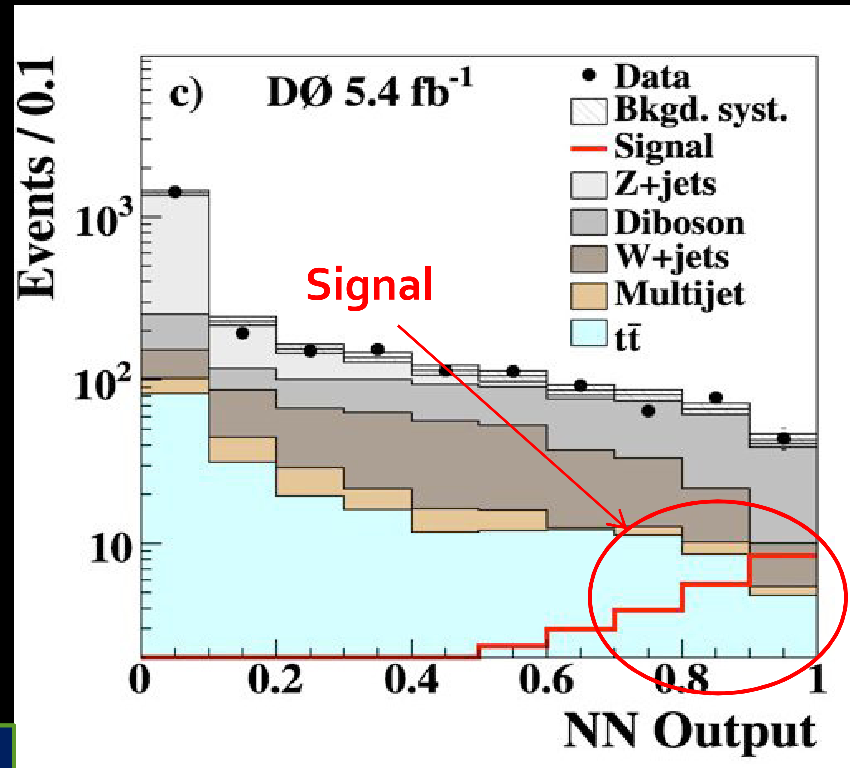
Separate analysis into channels by S/B ratio and lepton purity

- CDF – by jet multiplicity: 0, 1 and 2+ jets, lepton quality (high & low S/B)
- DØ – by di-lepton flavor: ee, eμ, μμ

Final Optimization

New CDF result for ICHEP





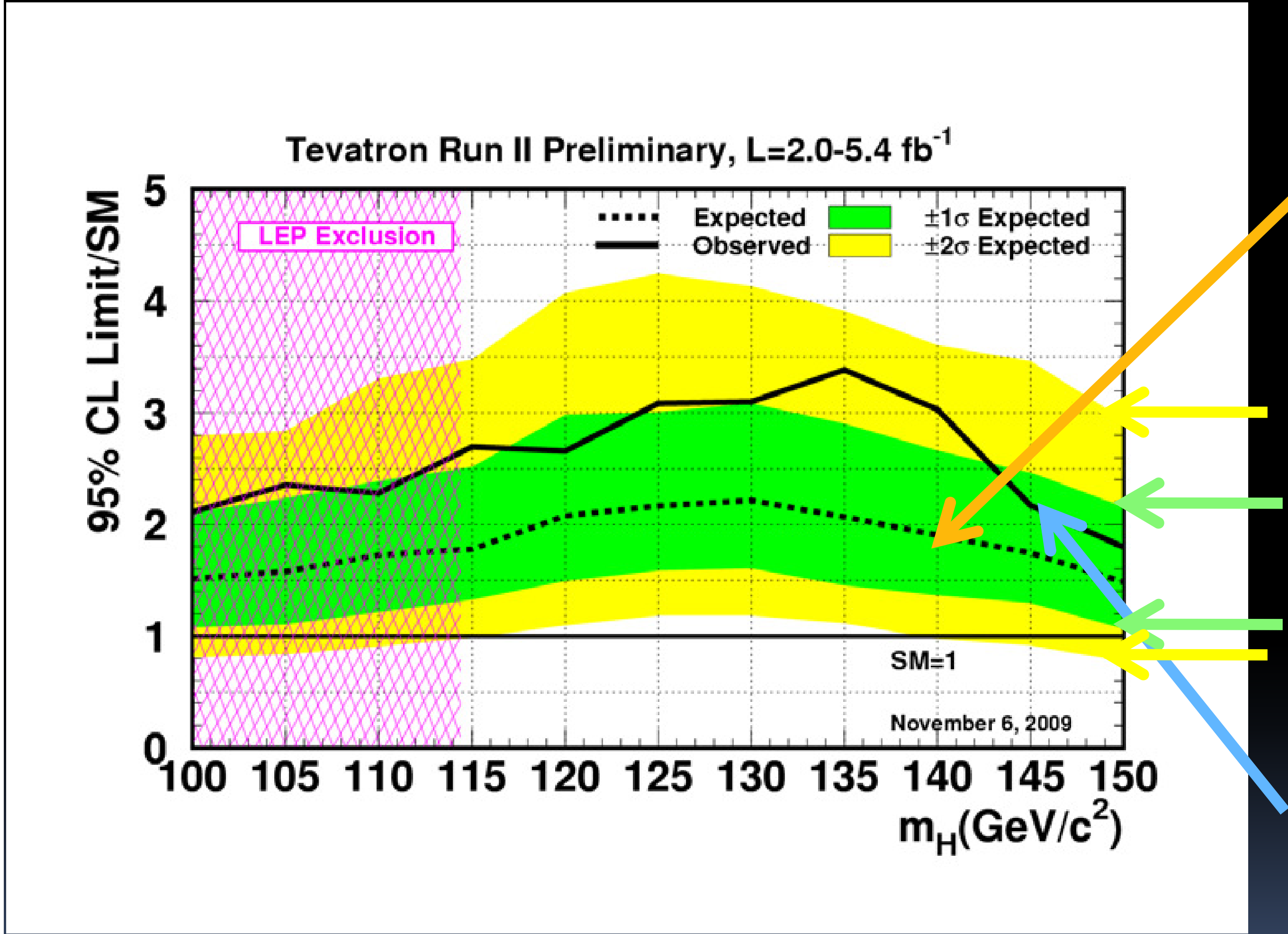
No evidence for the Higgs

Analysis M_H=165 GeV	Lumi (fb^{-1})	Signal Evts	95% Exp Limit **σ/SM**	95% Obs Limit **σ/SM**
CDF NN Including τ	**5.9**	**41.8**	**1.00**	**1.08**
DØ NN	5.4	29.7	1.36	1.55

TEVATRON Combined limits

- Increase the Tevatron reach:
  - Statistically combine all search channels
  - Effectively double the analyzed luminosity
  - Set 95% C.L. upper limits on the Higgs production cross-section
- Test BG(b) only and BG+signal (s+b) hypotheses using Poisson statistics accounting for systematic uncertainties
- Two methods are used for the combination
  - Bayesian integration over likelihood (CDF)
  - Modified frequentist (DØ)
  - Both methods use differential distributions, not only integrated yields.
- The combined results uses **ninety mutually exclusive final states** (36 for CDF and 54 for DØ)

TEVATRON low mass pre-ICHEP

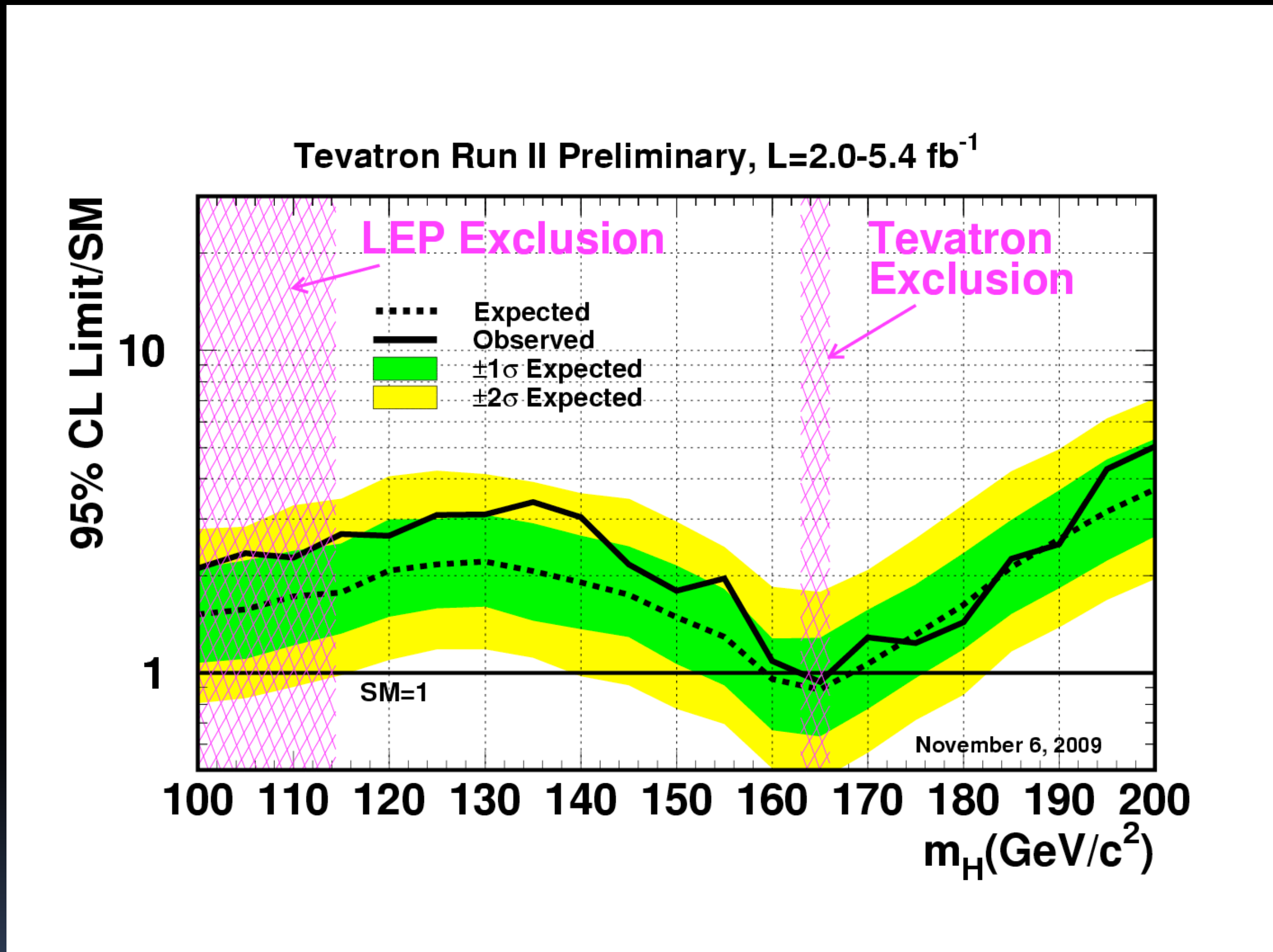


Dashed Lines represent median predicted limits from pseudo-data

Bands represent 1σ and 2σ range of predicted limits

Solid Lines represent observed limits from data analysis

TEVATON high mass pre-ICHEP

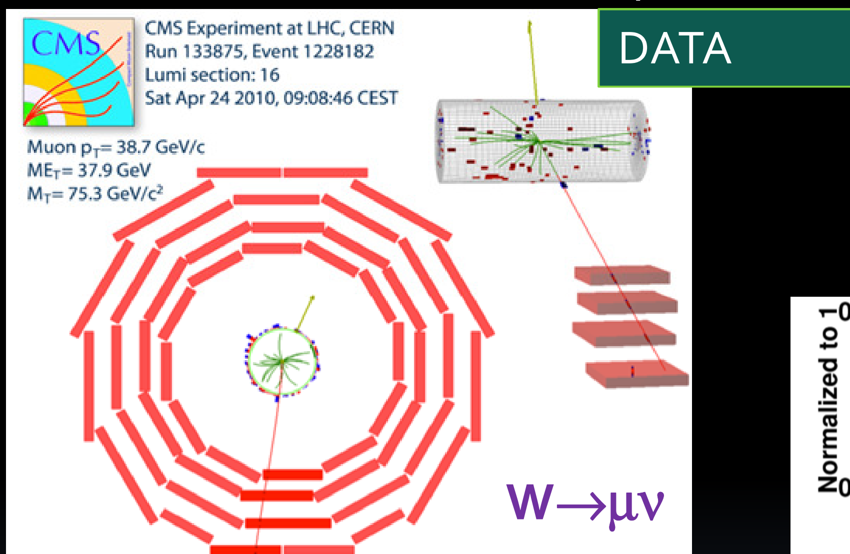


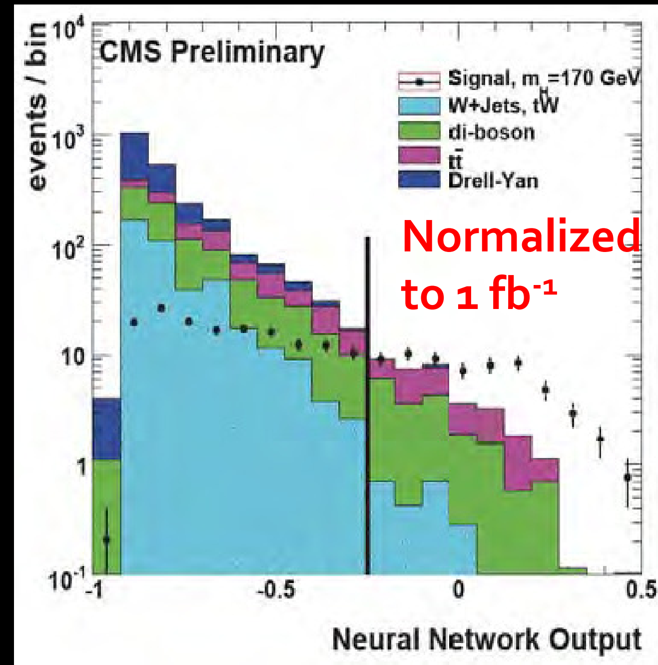
Published Phys. Rev. Lett. 104, 061802 (2010)

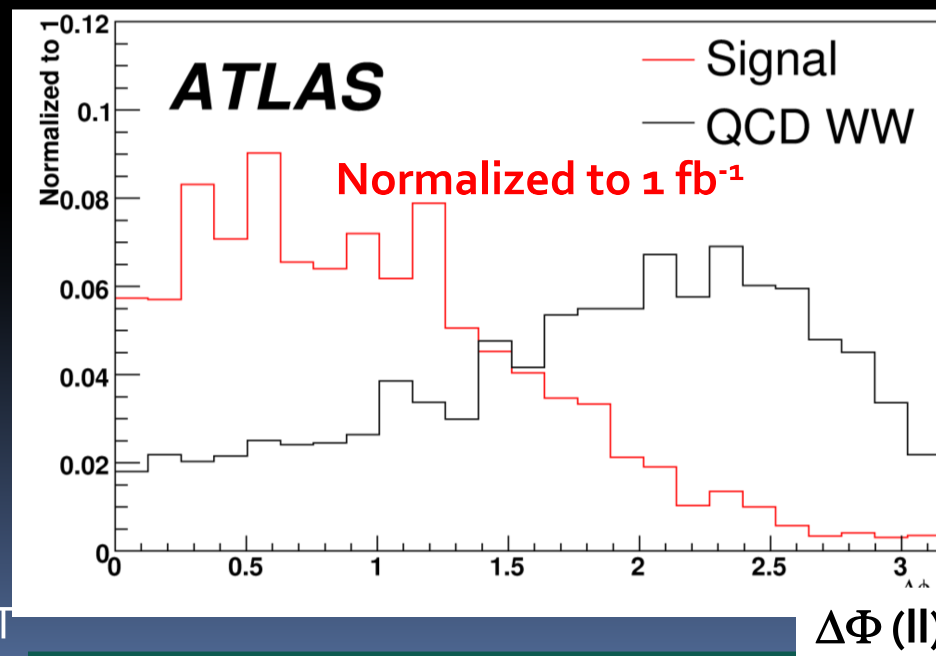
- Observed exclusion 162 < mH < 166 GeV
- Expected exclusion 159 < mH < 169 GeV

LHC H→WW

- For m(Higgs) >135 GeV/c² similar strategy as at the TEVATRON
  - Spin correlations ΔΦ(ll)
  - CMS multivariate techniques



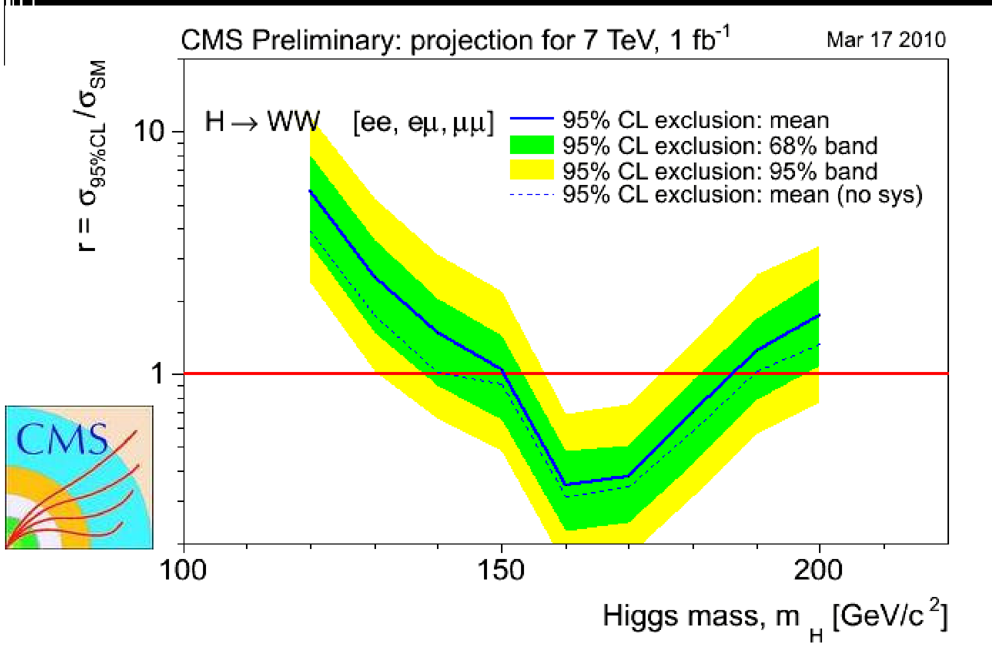


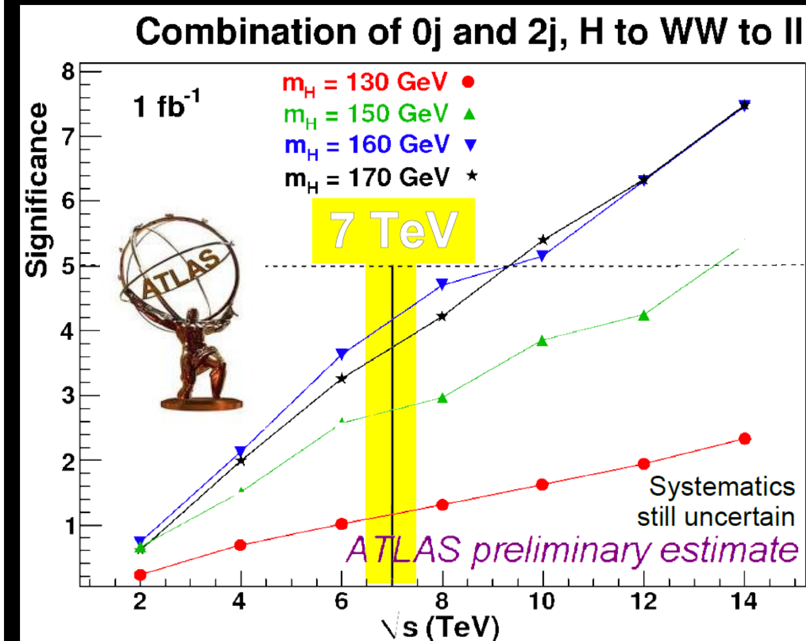


- Backgrounds reduction:
  - WW: ΔΦ & m_{ll}
  - ttbar: central jet veto, ΔΦ& m_{ll}
  - W+jets: lepton id
  - DY reduced by MET requirement
  - WZ/ZZ: 2 leptons in final state, MET

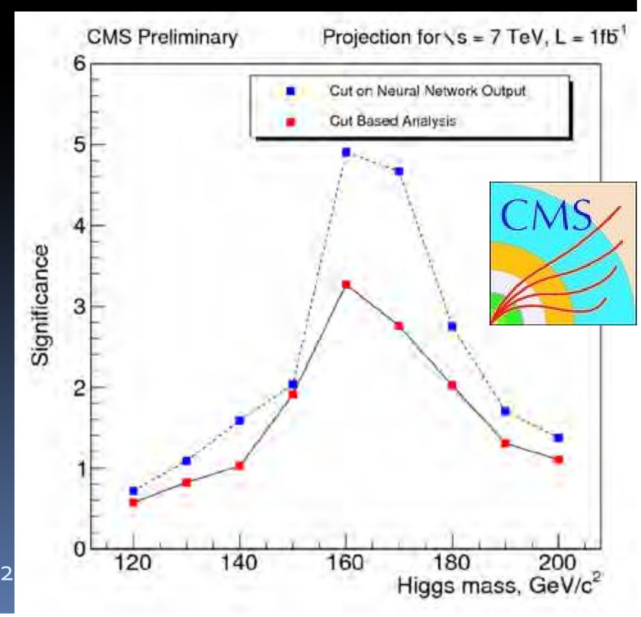
More in J. Maestro's presentation on Sunday

LHC reach @ 7 TEV and 1 fb-1



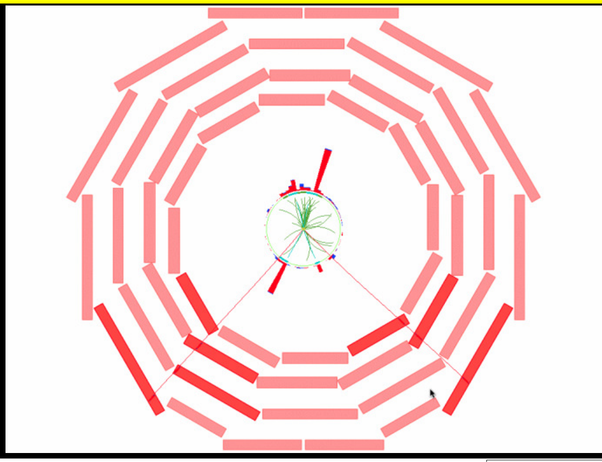


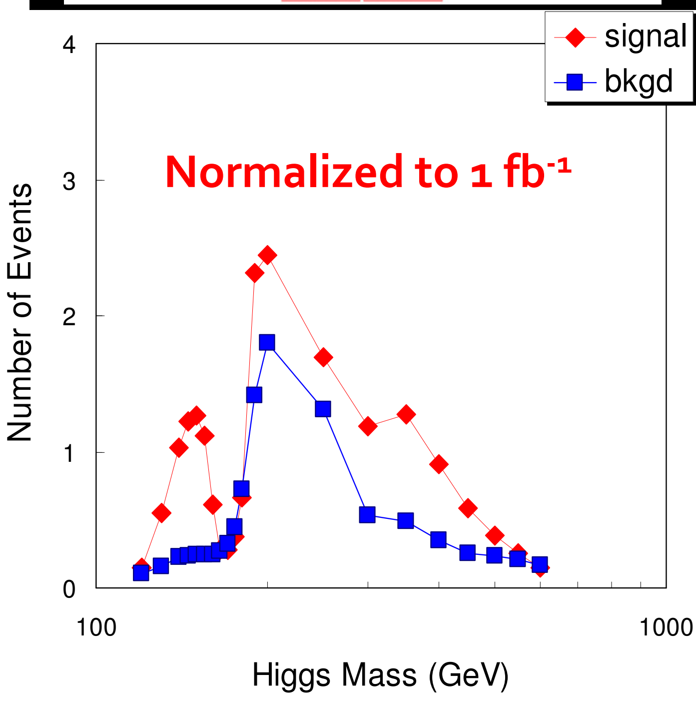
- CMS expected exclusion range : [150-185] GeV
- ATLAS expected exclusion range : [140-185] GeV
- Both experiments have 3-5 σ sensitivity near 160 GeV



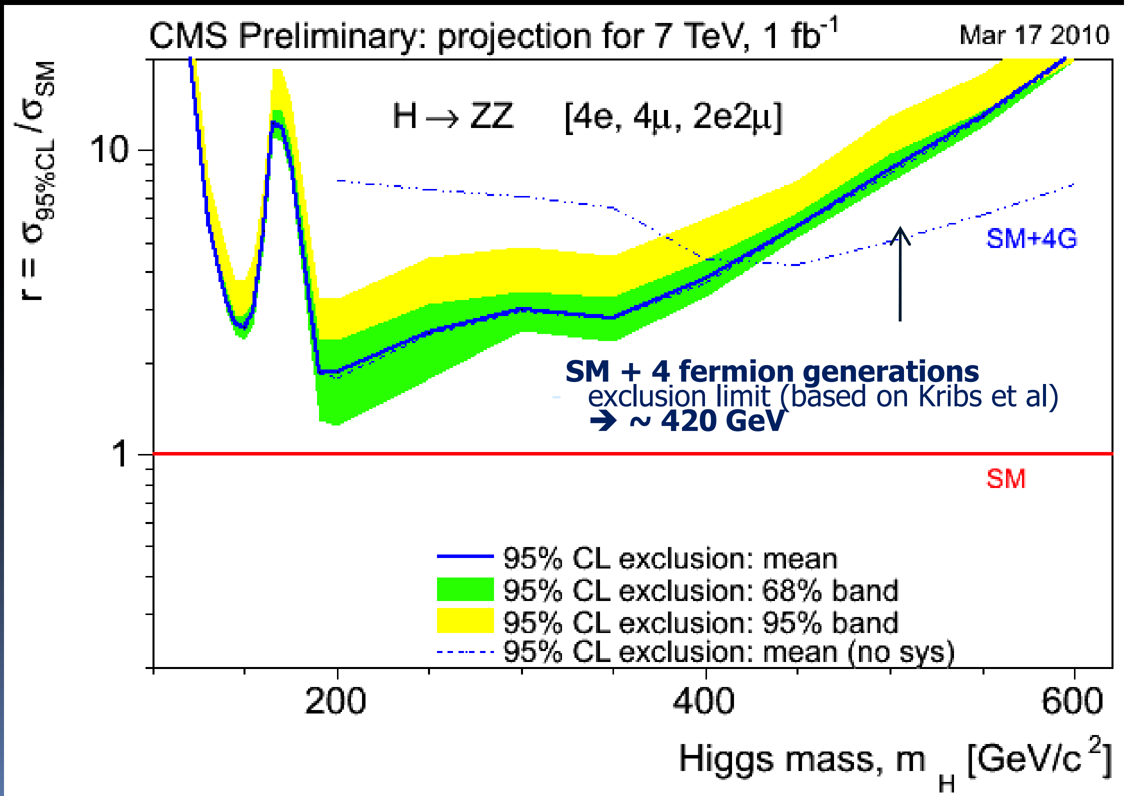
LHC Golden channel H→ZZ

Simulated H → ZZ* → $e^+e^-\mu^+\mu^-$



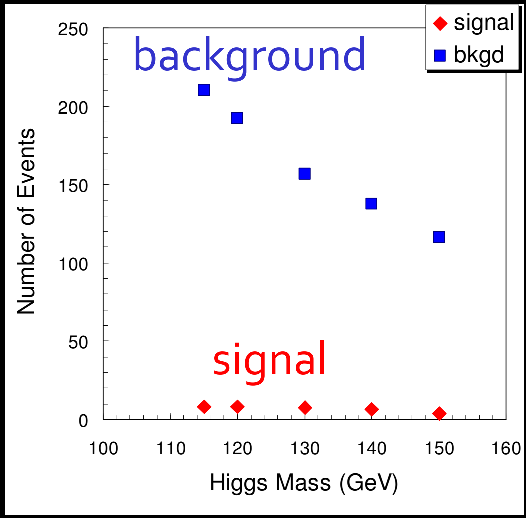


- Four isolated leptons, look for 4l-mass peak
- Backgrounds:
  - ZZ : irreducible background, [assessed from data—Z events]
  - ttbar & Zbbbar removed by lepton isolation & impact parameter veto
- Narrow mass peak, low background
- Low yield ⇒ need to push lepton identification

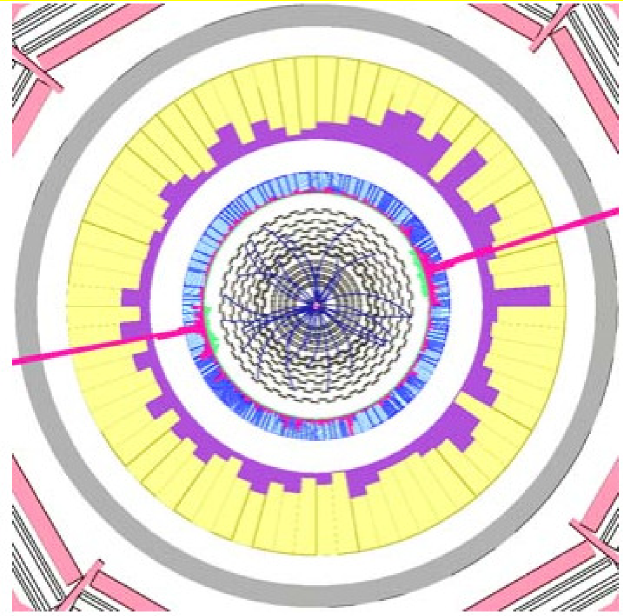


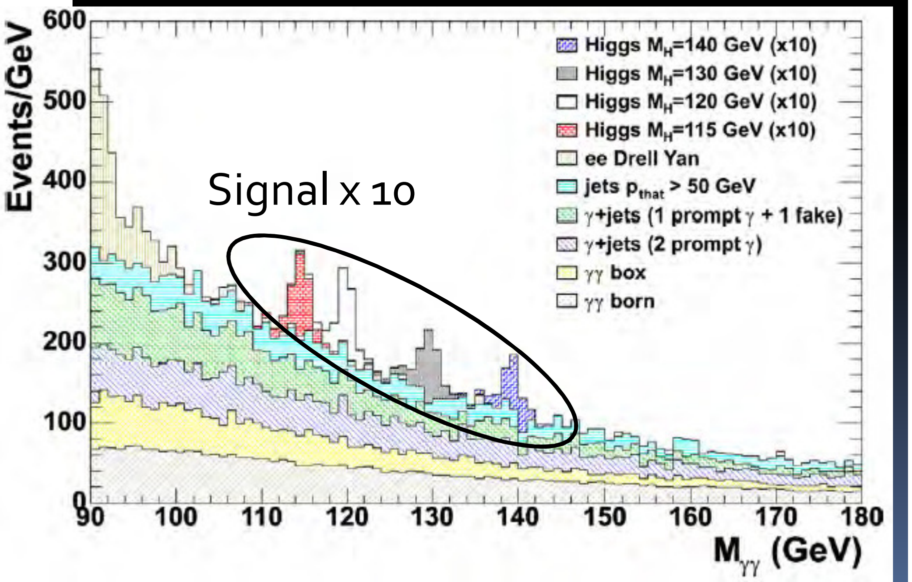
LHC low mass H→γγ

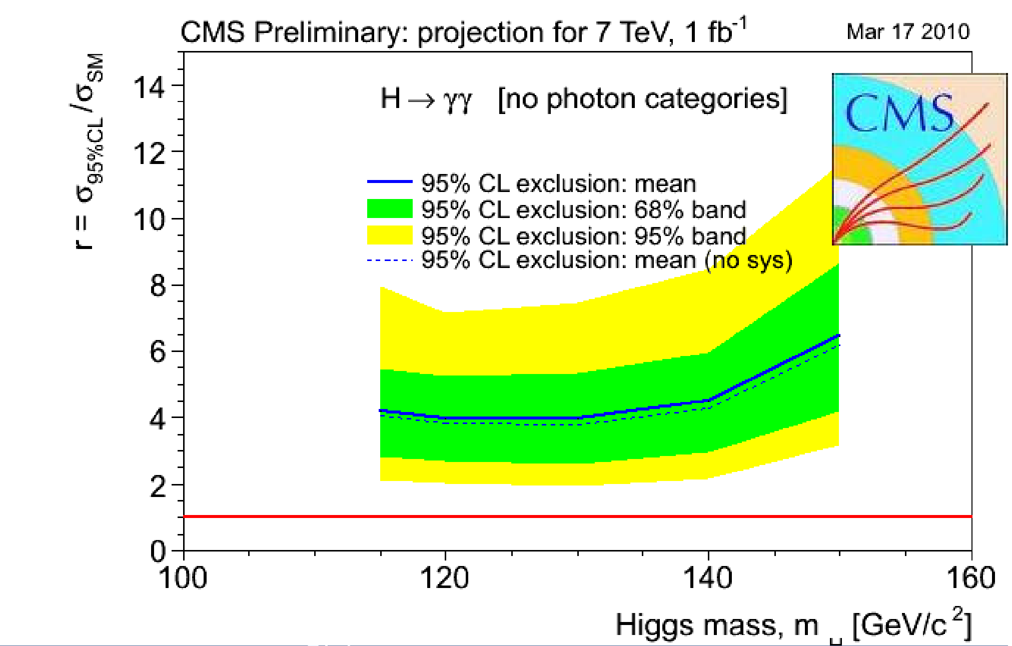
- Two isolated photons search for mass peak
- QCD bkgd is large and partly irreducible,
  - measured from sidebands
- Not a viable mode of low mass SM Higgs in 7 TeV/ 1fb^{-1} run



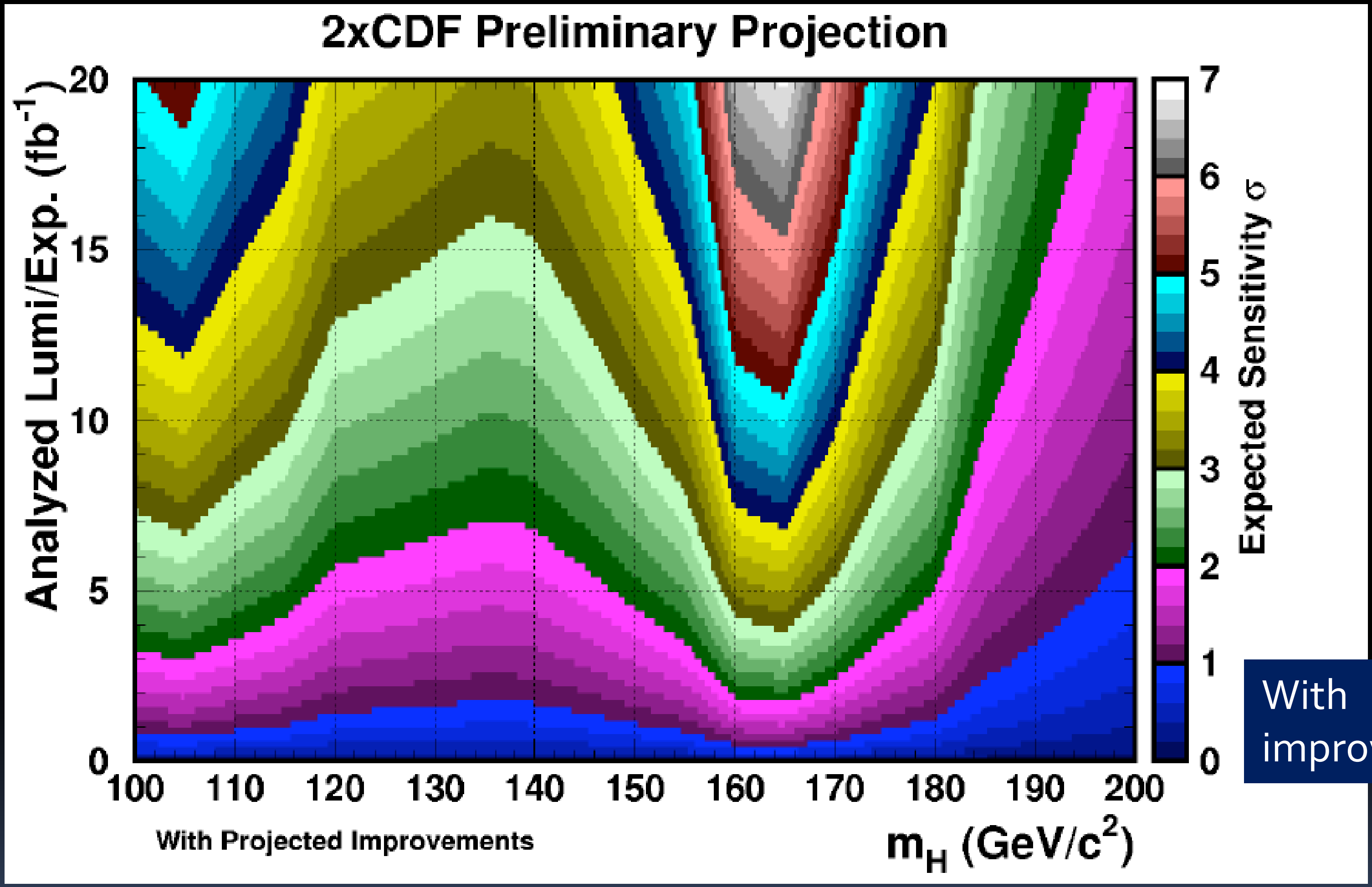
Simulated H →γγ







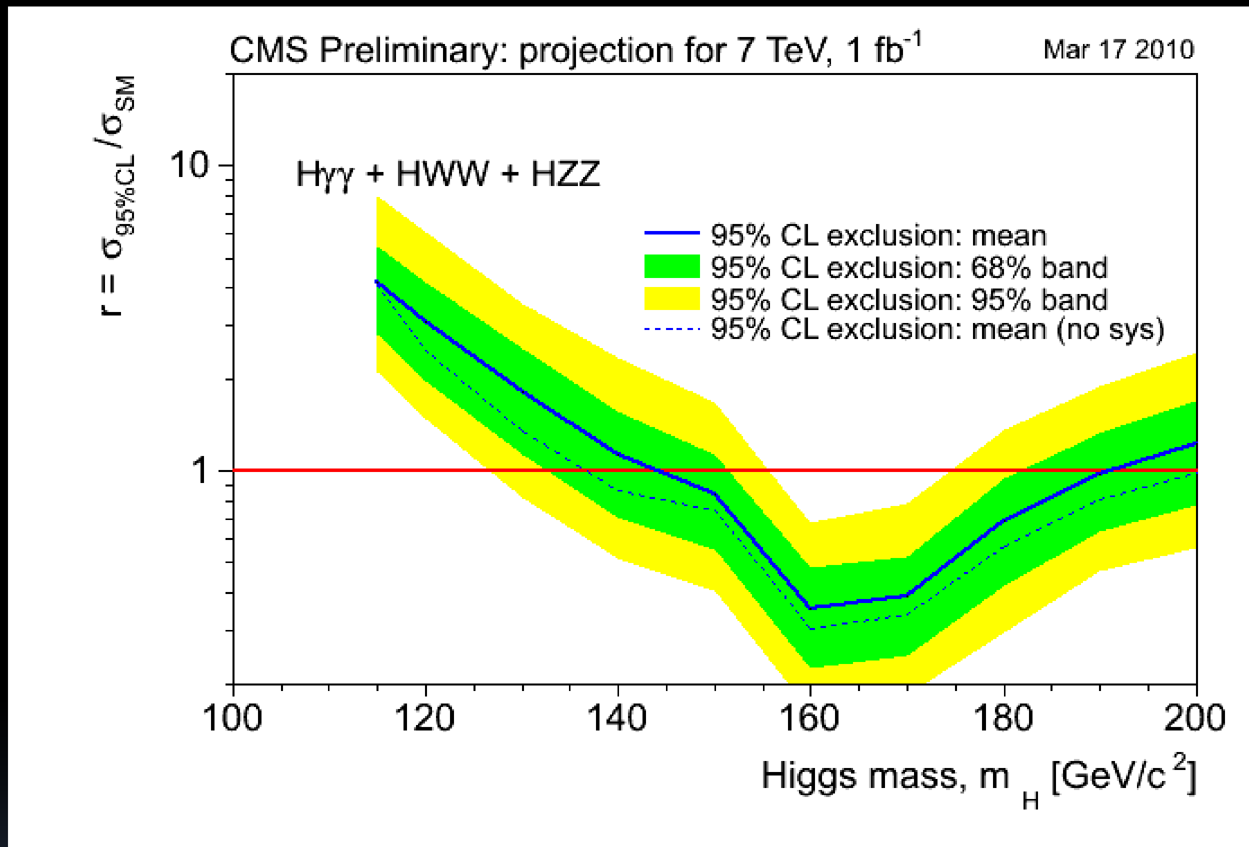
TEVATRON Prospects for the future



With improvements

If the Tevatron were to run for three more years it could accumulate 16fb^{-1} and provide 3σ evidence for the low mass Higgs boson

Summary LHC (CMS as example)



- SM Higgs expected excluded range: 145-190 GeV
- Experiments are evaluating the impact of improvements and including more channels
- With 30 fb^{-1} at 14 TeV center of mass energy the LHC can cover the Higgs mass range 115 GeV up to 1 TeV

Conclusion

New TEVATRON combination will be presented at ICHEP

- The hunt for the Higgs continues
- The TEVATRON, CDF and DØ are working well
- More work is ongoing to improve the sensitivity of the analyses
  - SM Higgs exclusion in the range 162-166 GeV/c^2 @95% C.L.
  - Expected exclusion range 159-168 GeV/c^2
  - 16fb^{-1} could provide 3σ evidence for the low mass Higgs boson
- ATLAS and CMS are collecting the data delivered by the LHC and rediscovering the Standard Model
- The Higgs hunt is started also at the LHC
  - At 7 TeV & with 1 fb^{-1} data, ATLAS & CMS will begin to explore a sizable range of Higgs mass
    - SM Higgs discovery sensitivity: [160-170] GeV
    - SM Higgs exclusion range: [140-200] GeV
  - Low mass SM Higgs searches require 14 TeV & high luminosity running