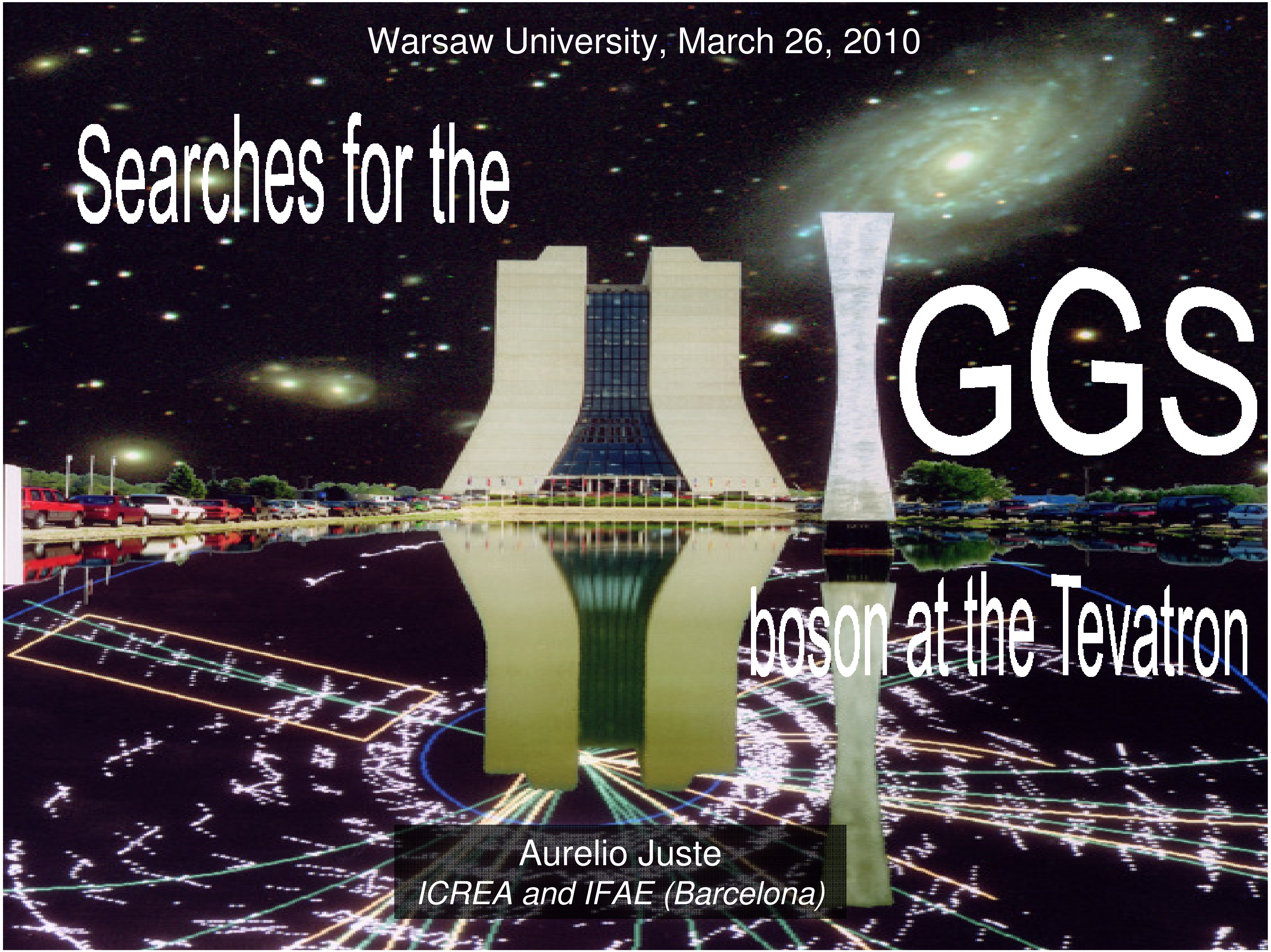

Warsaw University, March 26, 2010
Searches for the
GGS
boson at the Tevatron
Aurelio Juste
ICREA and IFAE (Barcelona)

Laws of Nature at Λ~100 GeV

Gauge Fields:

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$G_\mu^{i(=1,..,8)} \quad W_\mu^{1,2,3} \quad B_\mu$$

Chiral fermion fields (T, T, Y):

$T_3 + Y = Q$

Quarks

(3, 1/2, 1/6)	left-handed
(3, 0, -1/3)	right-handed down-type
(3, 0, 2/3)	right-handed up-type

Leptons

(1, 1/2, -1/2)	left-handed
(1, 0, -1)	right-handed down-type

- The fact that some gauge bosons and the fermions are massive implies that the electroweak symmetry must be necessarily broken:

  $$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$$

  ➔there must exist an outside sector of interactions that break the electroweak symmetry: the "Higgs sector".

- There is no preferred model of the Higgs sector, we just have theories of it. The above structure plus the minimal Higgs sector is what we call:

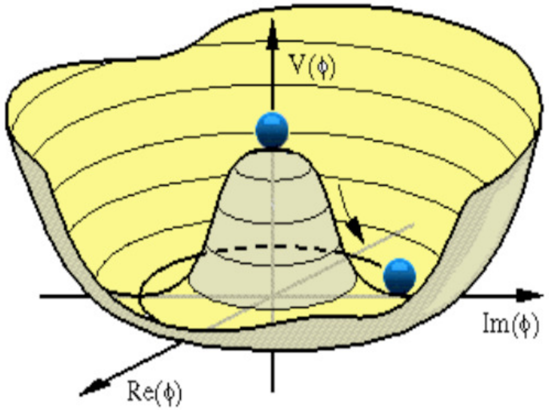
The Standard Model of electroweak and strong interactions

EWSB within the Standard Model

- The most economical way is to introduce a single scalar field:

  (T, T, Y)=(1, 1/2, 1/2)   Higgs doublet

- Higgs self-interactions lead to:



$$V(\phi) = \mu^2 \phi^+ \phi + \lambda\,(\phi^+ \phi)^2;\ \mu^2 < 0,\ \lambda > 0$$

$$\langle \phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \qquad \begin{aligned} v &= (\sqrt{2} G_F)^{-1/2} \\ &= 246\ \text{GeV} \end{aligned}$$

- Fluctuations around <ϕ> are:

$$\phi(x) = e^{i\xi^a(x)\tau_a/2v} \begin{pmatrix} 0 \\ [v + H(x)]\,/\sqrt{2} \end{pmatrix}$$

- Particles generated by $\xi^a(x)$ will constitute the longitudinal degrees of freedom of the weak gauge bosons, whereas H(x) will become the neutral Higgs boson.
- Yukawa Interactions of ϕ(x) with fermions generate their masses and in general flavor physics: CKM matrix and thus, CP-violation.

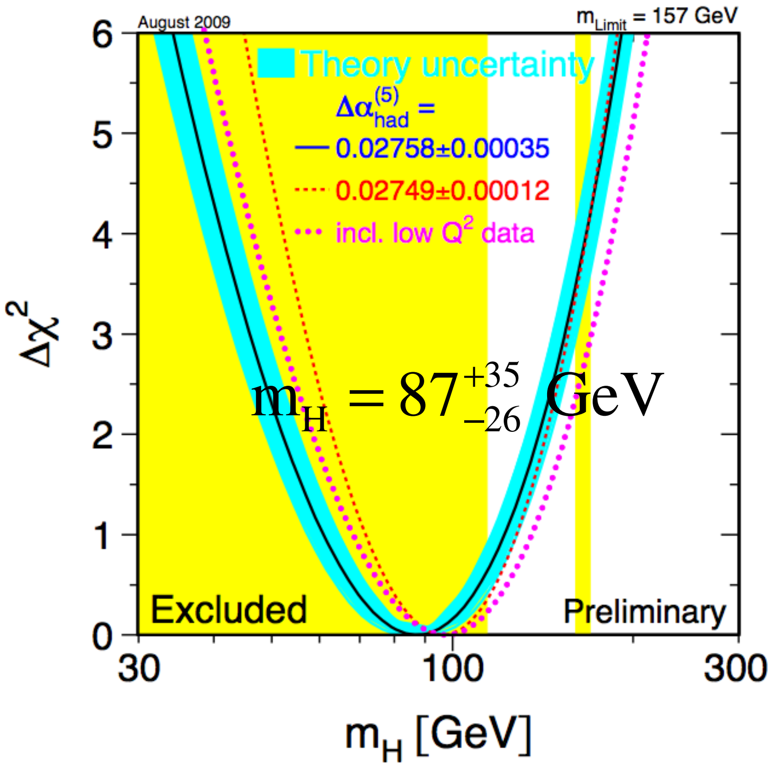
The Higgs mass is not predicted!

$$m_H^2 = 2\lambda v^2$$
$$m_W^2 = g^2 v^2 / 4$$
$$m_Z^2 = (g^2 + g'^2) v^2 / 4$$
$$m_l = \lambda_l v / \sqrt{2}$$
$$m_q = \text{eigenvalue}\,(\lambda_Q) v / \sqrt{2}$$

Stalking the Higgs Boson

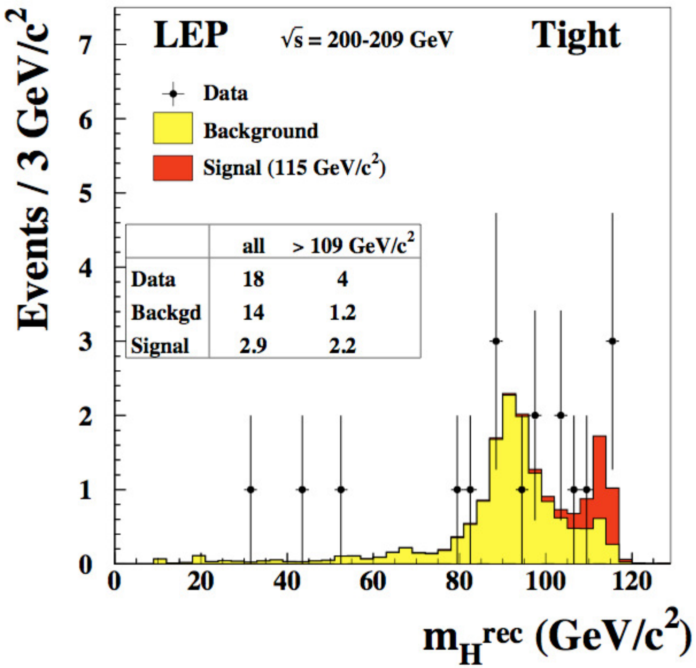
Indirect constraints

- Precision EW observables at the one-loop level.



Direct searches at LEP

- Tantalizing hints (~1.7σ) of a SM-like Higgs boson with m_H~115 GeV:



Kinematic limit: $\sqrt{s}-m_Z$~115.4 GeV

m_H< 157 GeV (95% CL) m_H> 114.4 GeV (95% CL)

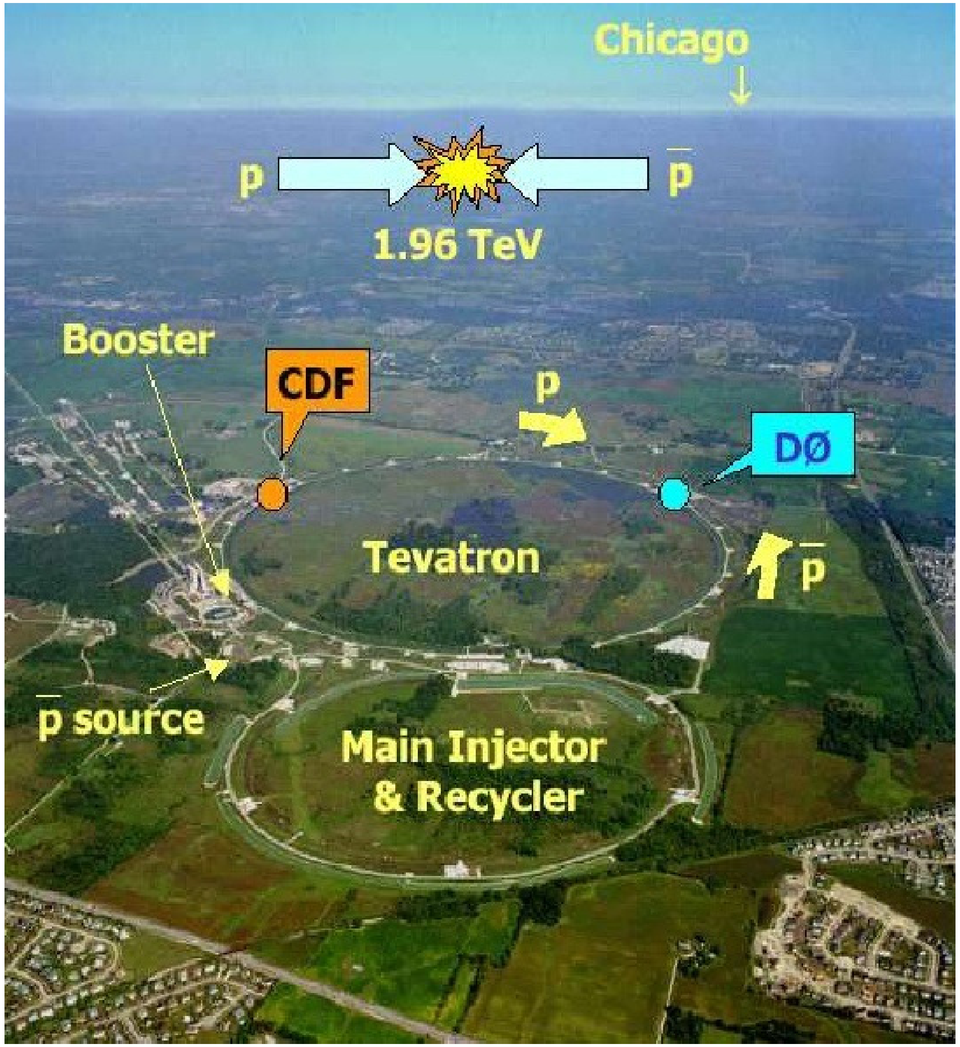
114.4 < m_H< 186 GeV (95% CL)

Tevatron Accelerator

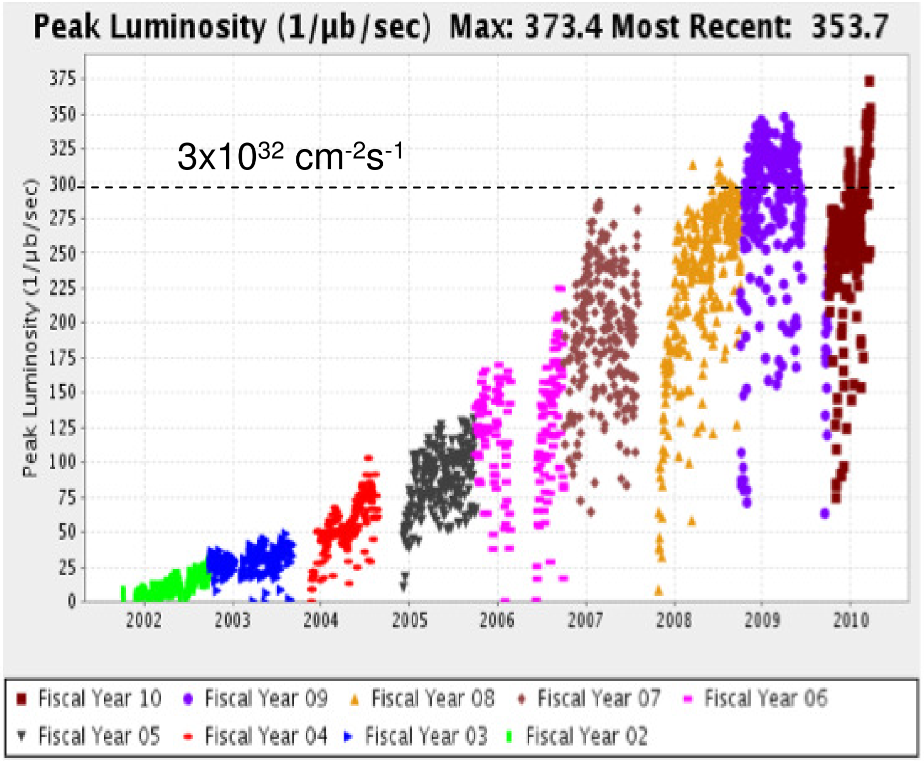
	Run I	Run IIa	**Run IIb**
Bunches in Turn	6×6	36×36	$\mathbf{36 \times 36}$
$\sqrt{s}$ (TeV)	1.8	1.96	**1.96**
Typical L ($cm^{-2}s^{-1}$)	1.6×10^{30}	$1 \text{x} 10^{32}$	$\mathbf{2.8 \times 10^{32}}$
$\int$ Ldt (pb^{-1}/week)	3	15-20	**50-60**
Bunch crossing (ns)	3500	396	**396**
# int./ crossing	2.5	2.5	**7.0**

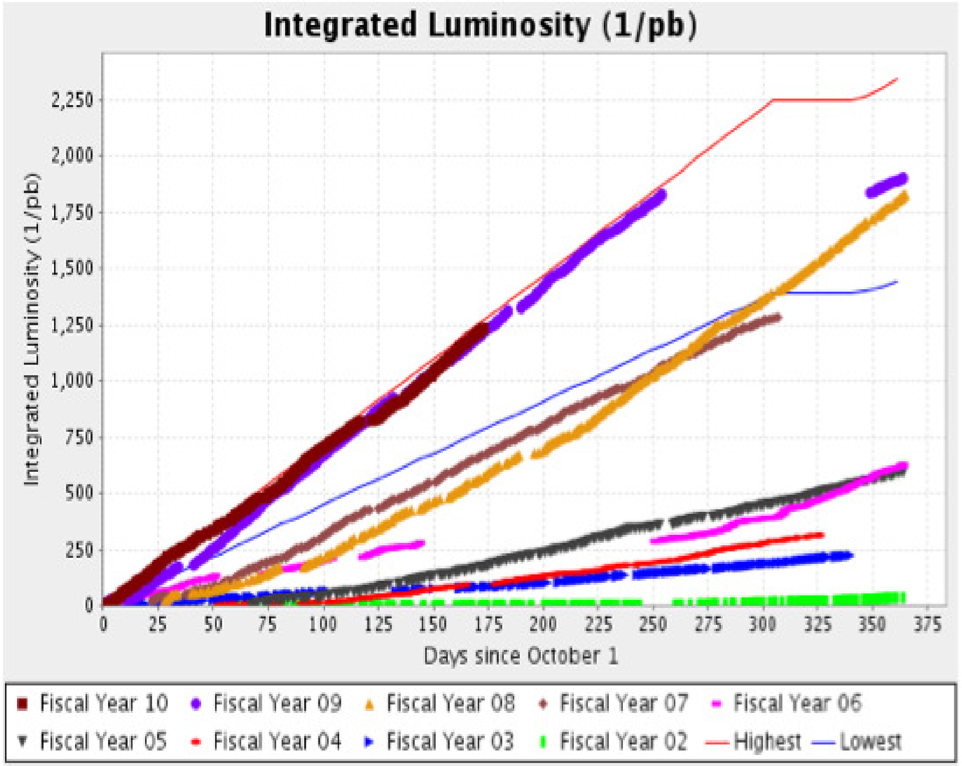
~~World's highest energy collider.~~

World's highest energy $p\bar{p}$ collider.



Tevatron Accelerator

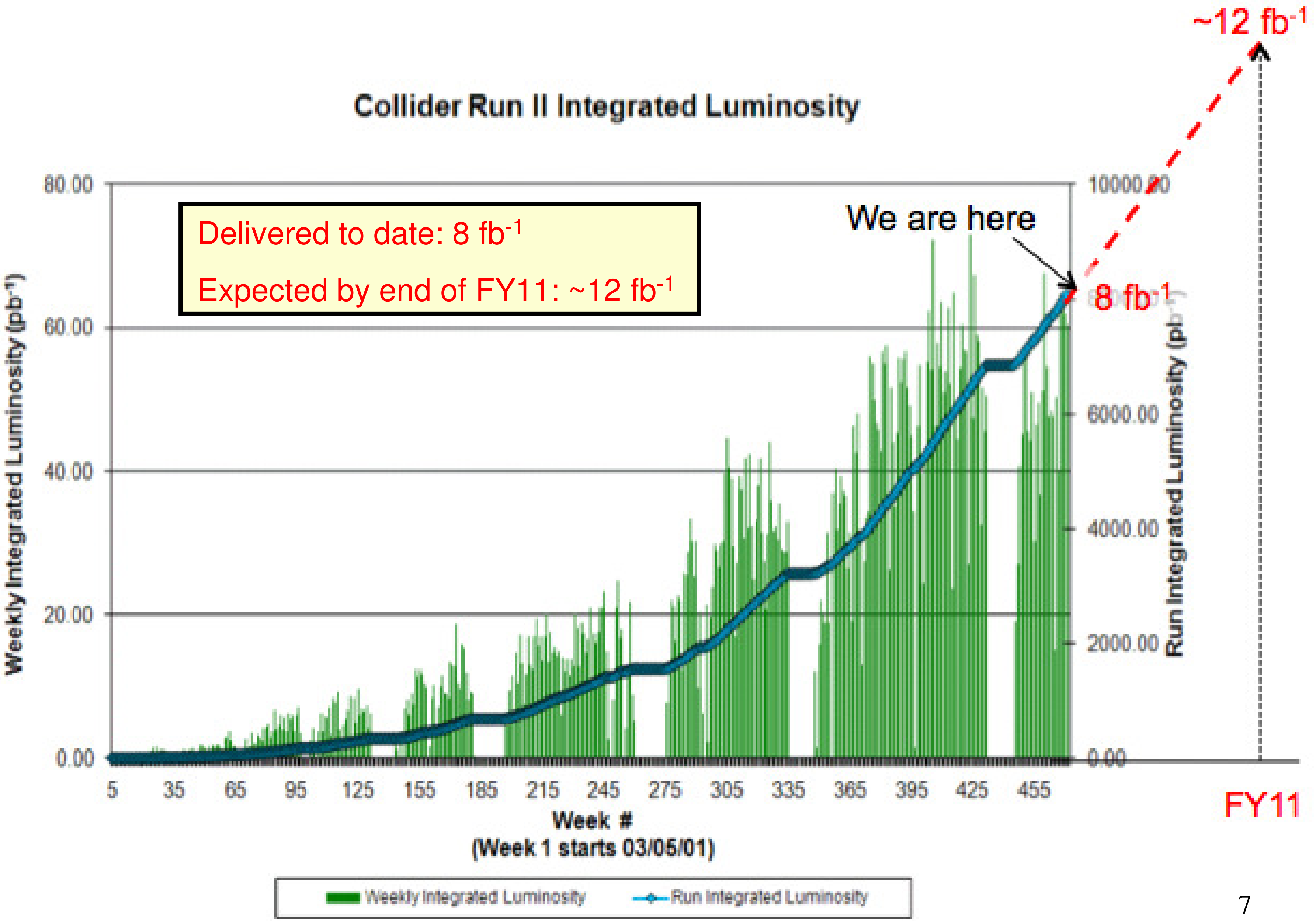




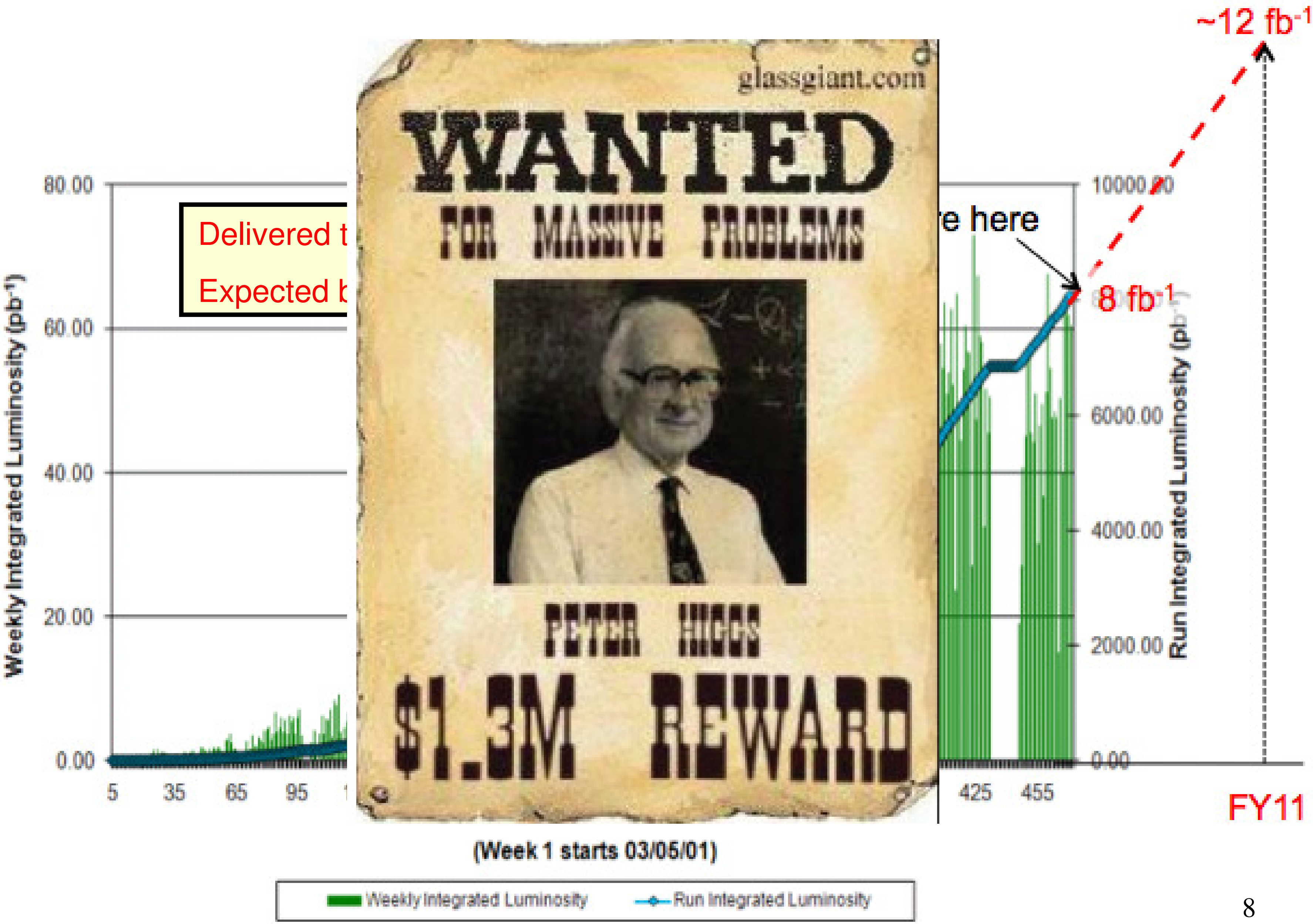
Excellent performance:

- Typical instantaneous luminosity: >3×10^{32} $cm^{-2}s^{-1}$
- Integrated lum./week: ~60 pb^{-1} ➔ equiv. Run I dataset every 2 weeks!
- Can deliver ~2-2.5 fb^{-1}/year.

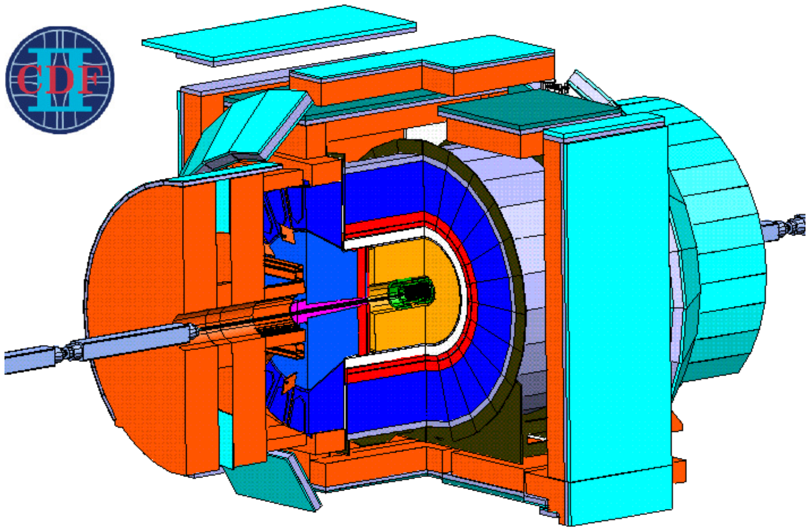
Tevatron Accelerator

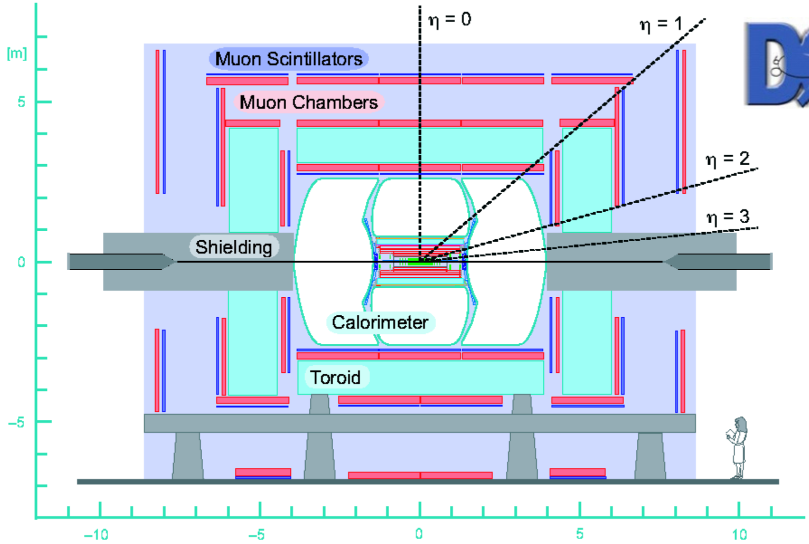


Tevatron Accelerator



CDF and DØ Detectors



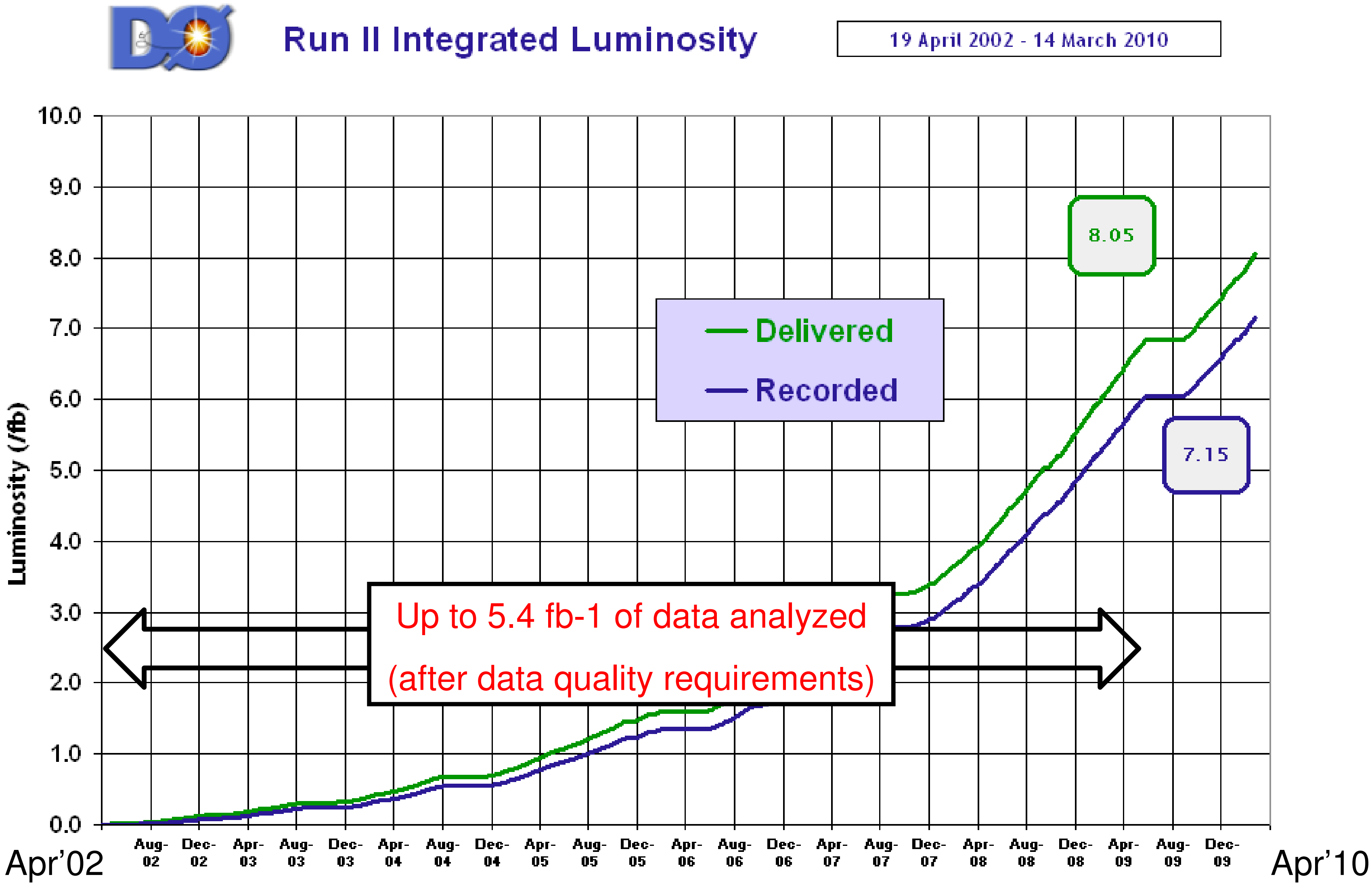


Multipurpose detectors:

- Central tracking system embedded in a solenoidal magnetic field:
  - Silicon vertex detector
  - Tracking chamber (CDF)
    Fiber tracker (DØ)
- Preshowers
- Electromagnetic and hadronic calorimeters
- Muon system

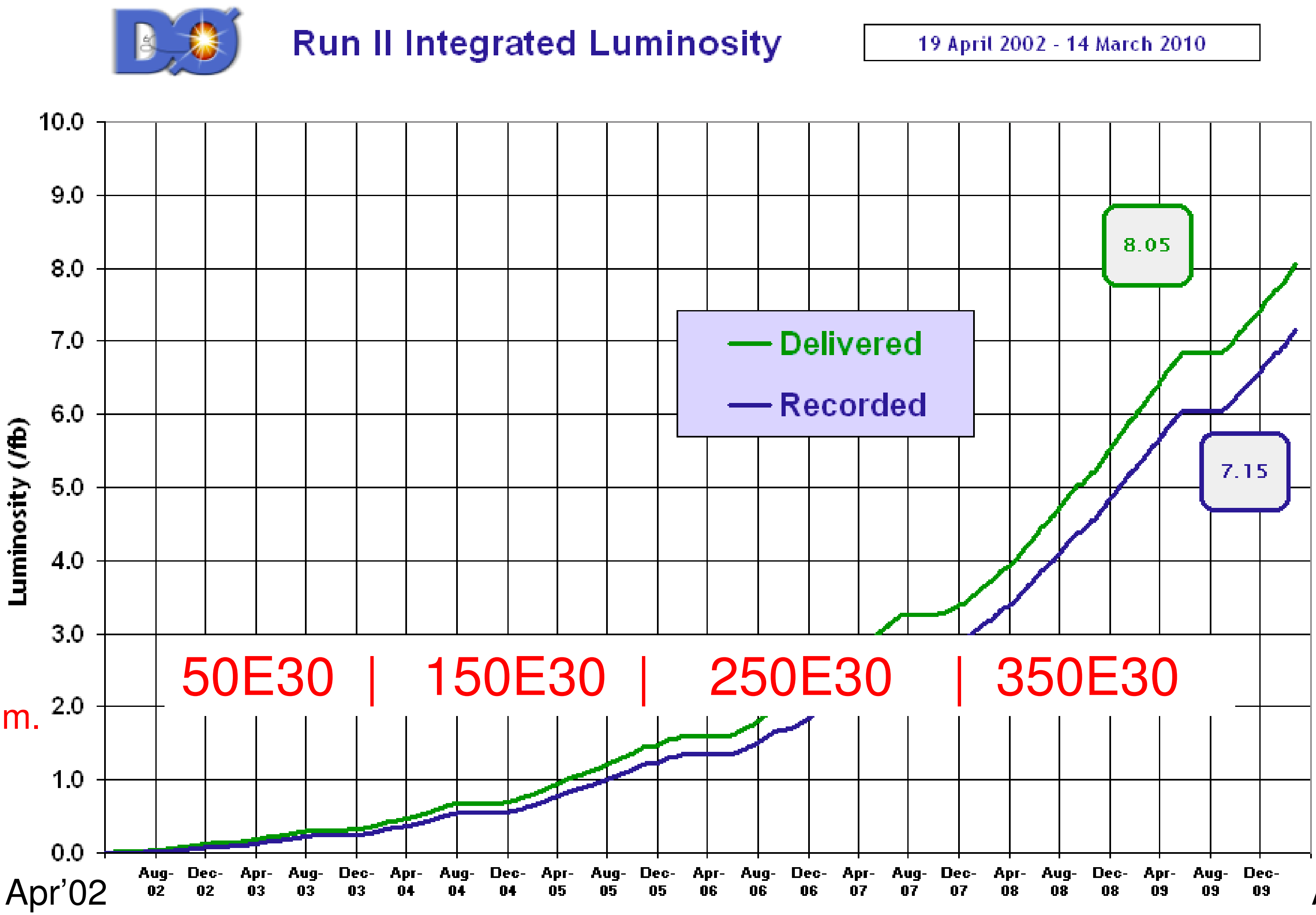
- All detector subsystems expected to survive till the end of the run.
  No further upgrades, stable triggers.
- Data taking efficiency: ~85-90%

Data Set



Expect to ~double this dataset by the end of FY11.

Data Set



Record

Inst. Lum.

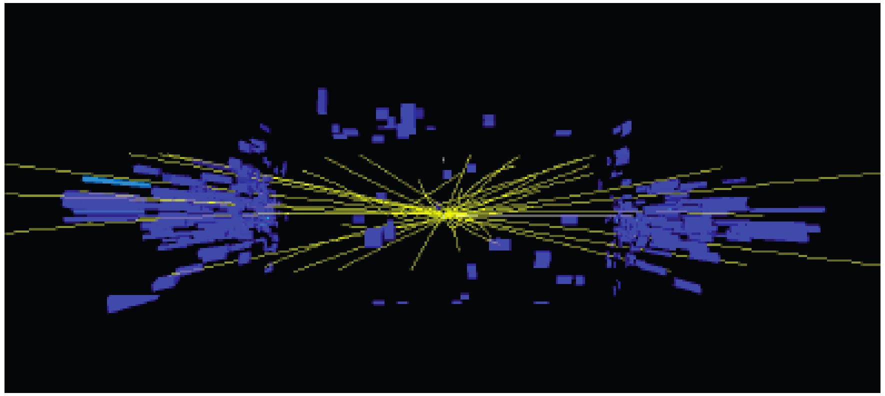
Apr'02

Apr'10

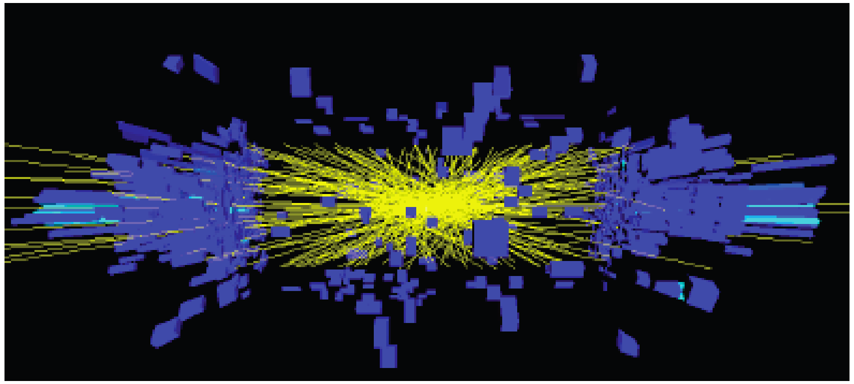
Instantaneous luminosity has been steadily increasing

The Challenges of Higher Luminosity

A random crossing event at @ 60E30 cm^2s^{-1}



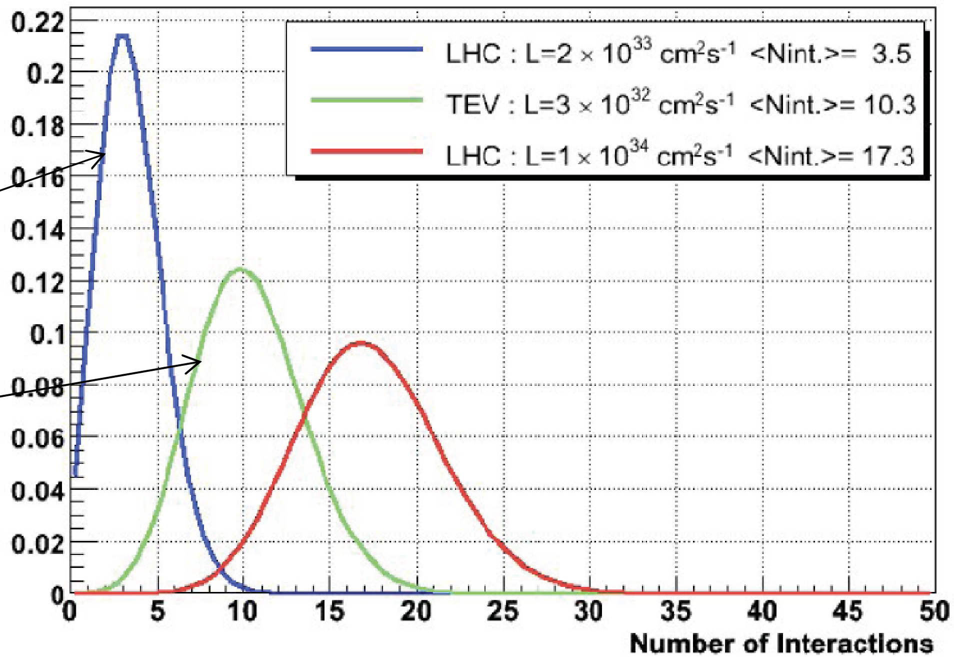
…and at @ 240E30 cm^2s^{-1}



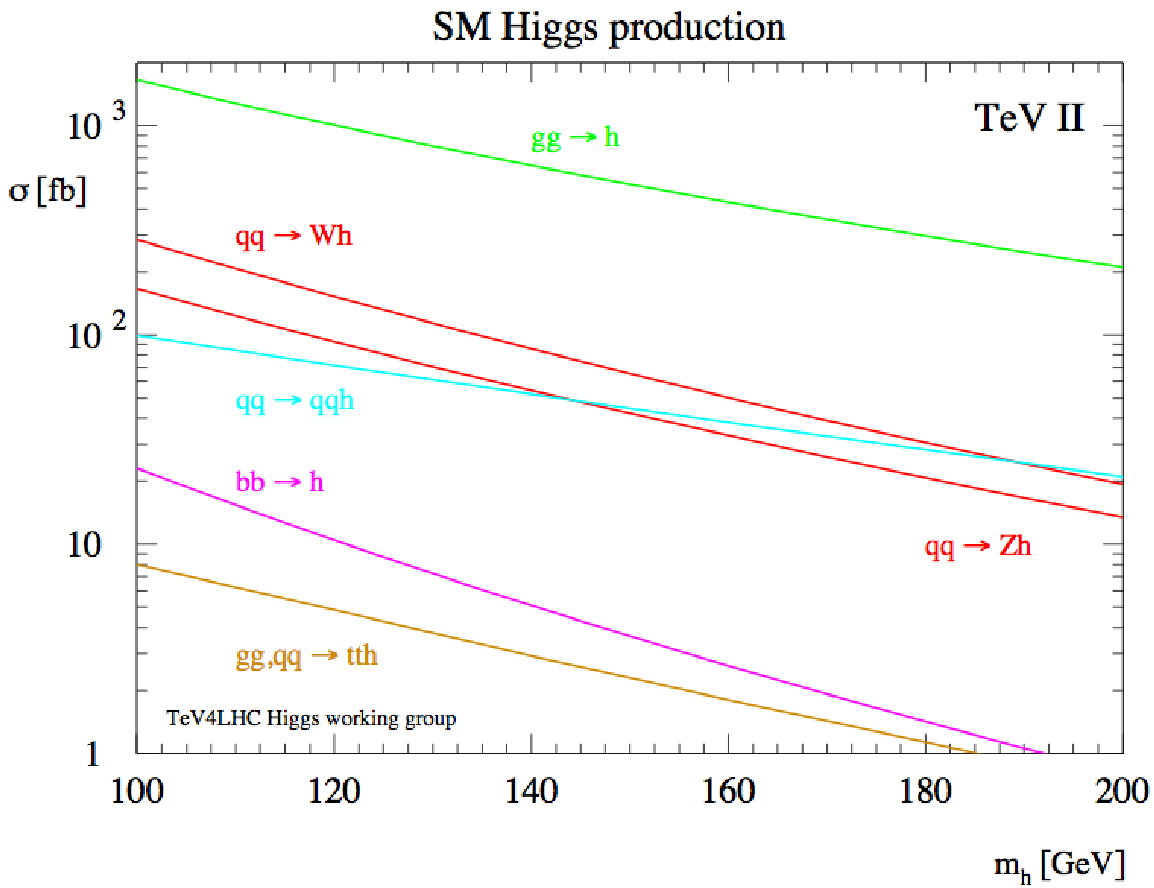
Average number of interactions:

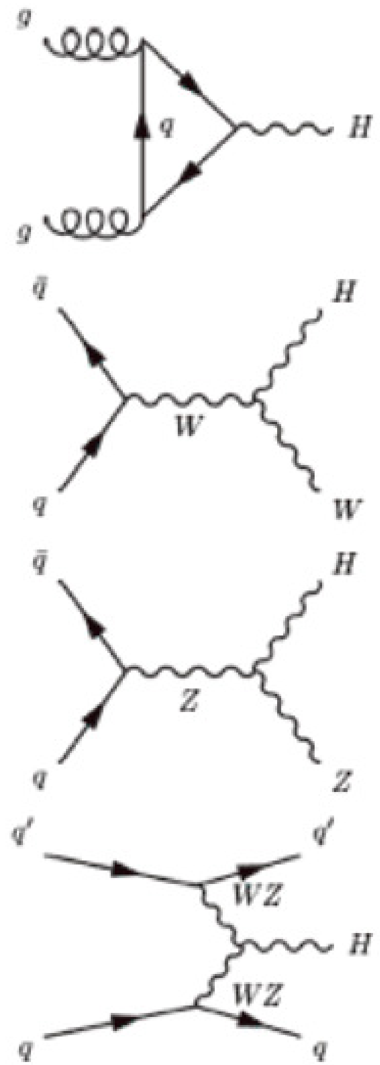
LHC: initial "low" lumi run
(L=2000E30 cm^2s^{-1}): <N>=3.5

TeV: (L=300E30 cm^2s^{-1}): <N>=10



SM Higgs Production at the Tevatron

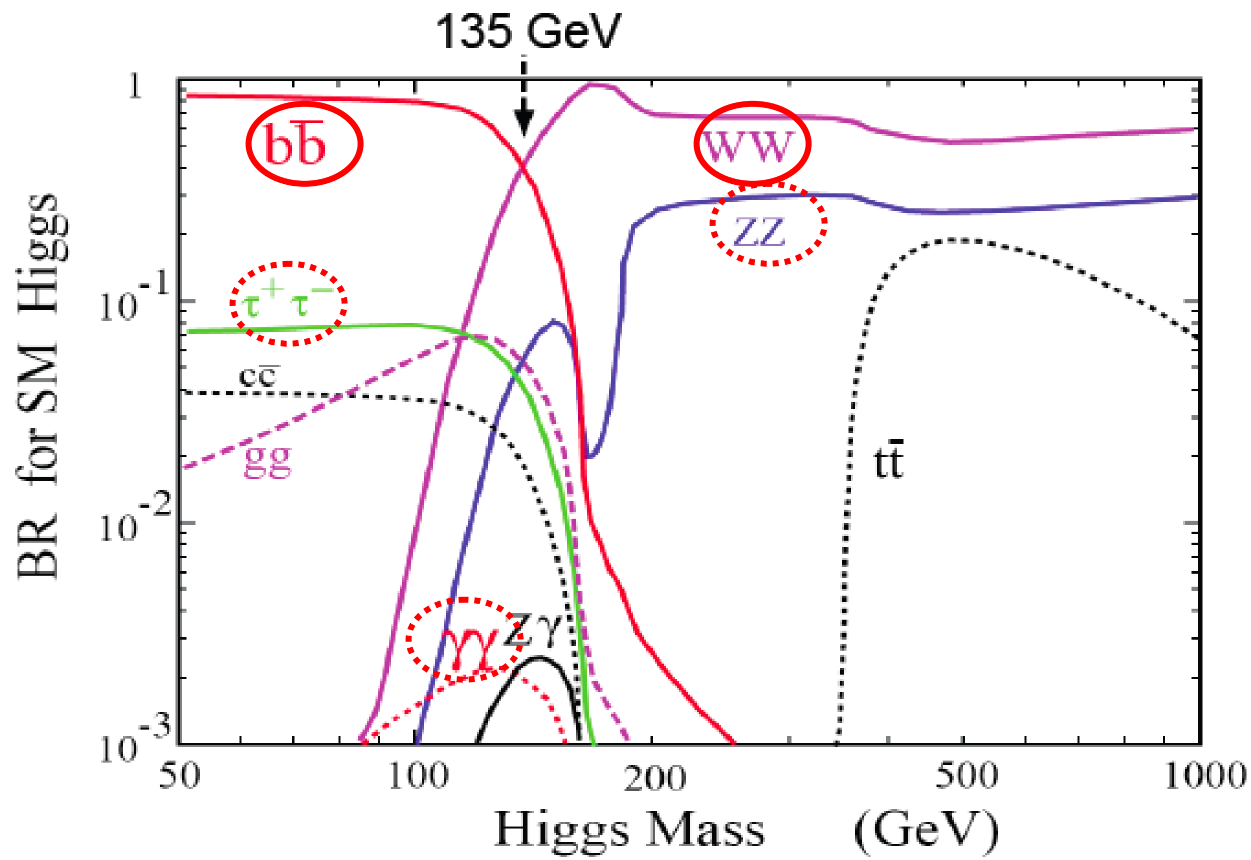




Main production mechanisms (115<m_H<180 GeV):

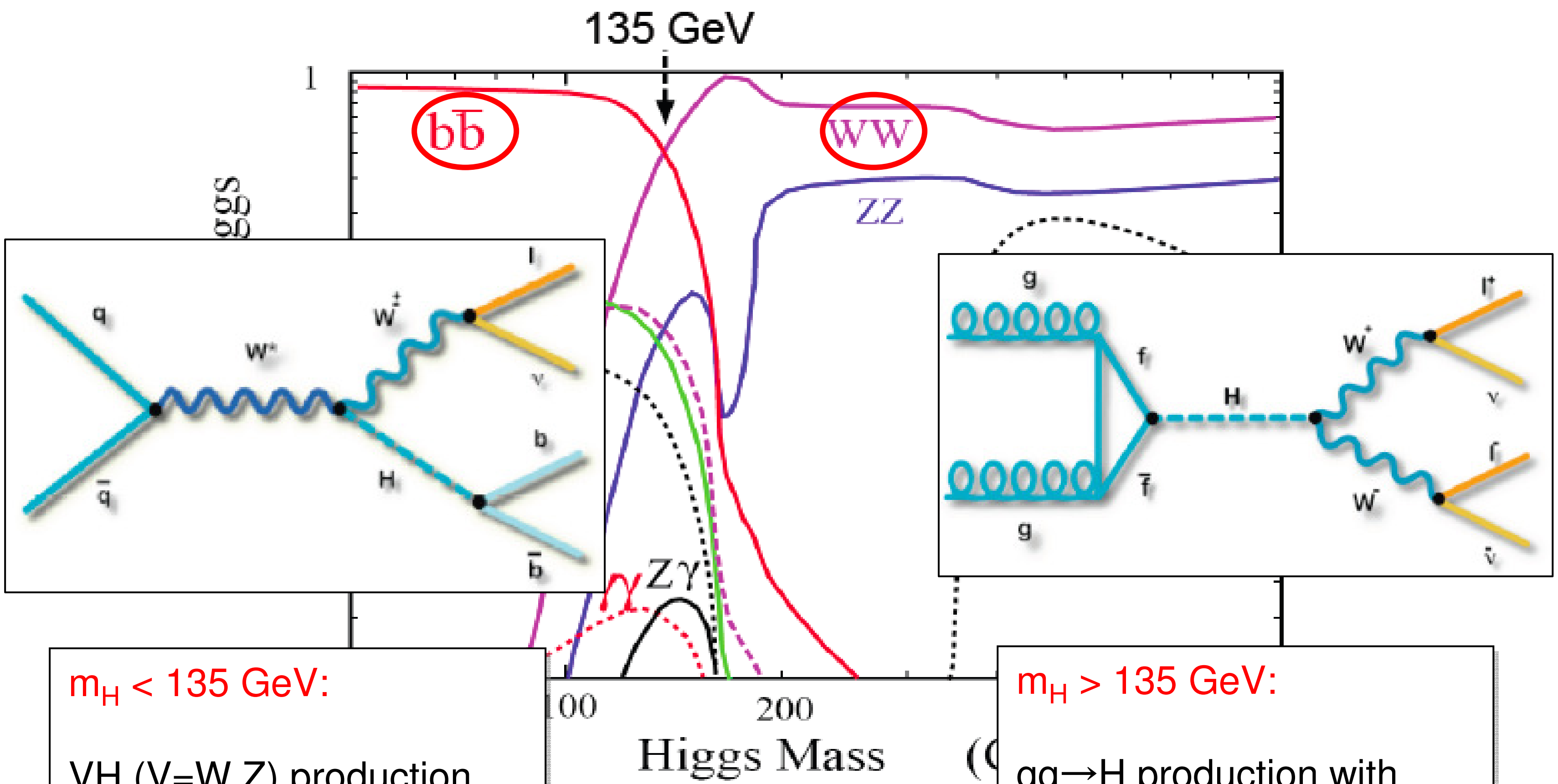
- Gluon fusion (gg→H): σ~0.8-0.2 pb
- Associated production (VH, V=W,Z): σ~0.2-0.02 pb
- Vector boson fusion (VBF): σ~0.1-0.02 pb

SM Higgs Decay Modes



➔ Many decay modes being explored to increase the sensitivity of the search to both a SM and non-SM Higgs boson!

Search Strategy at the Tevatron



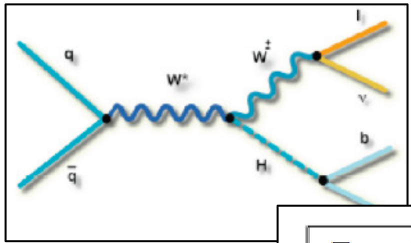
m_H < 135 GeV:

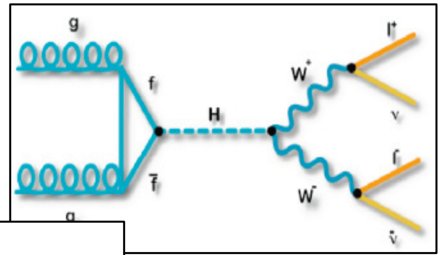
VH (V=W,Z) production with H→bb decay

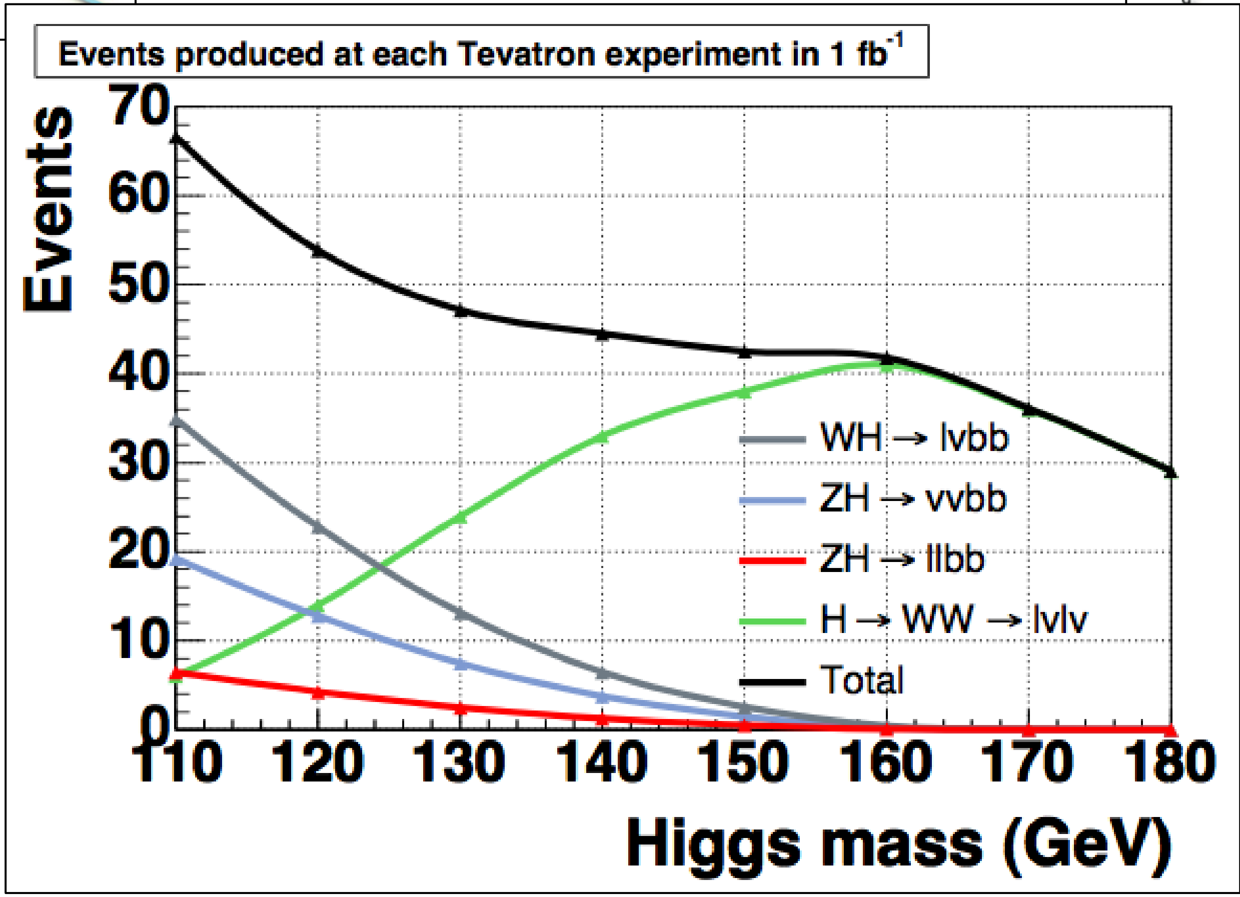
m_H > 135 GeV:

gg→H production with H→WW→lνlν decay

Search Strategy at the Tevatron

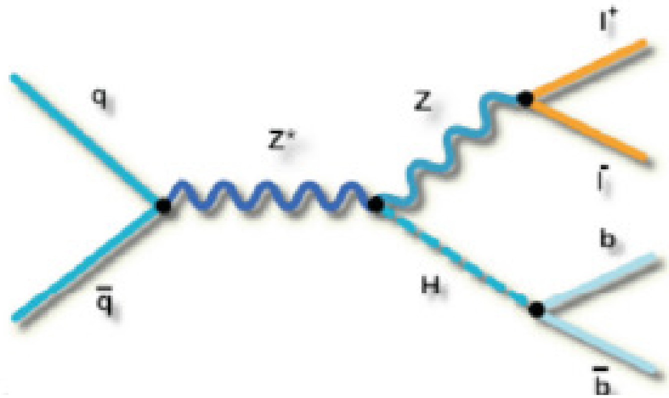




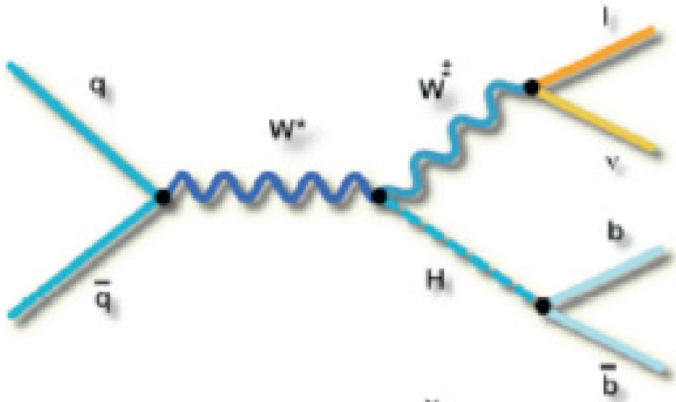


~600-1200 Higgs events produced at the Tevatron
in the main search channels with 10 fb^{-1}!

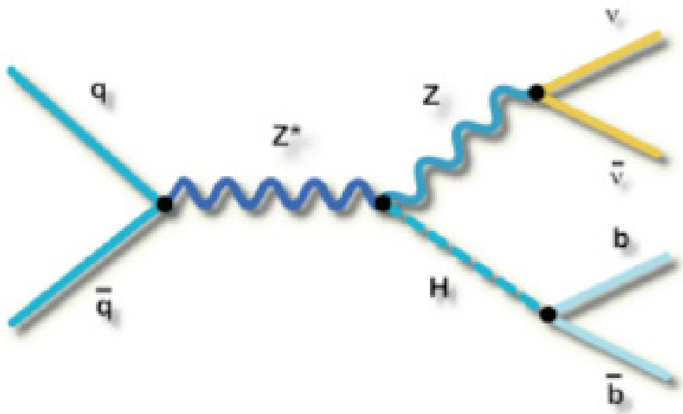
Low Mass SM Higgs Searches



ZH→llbb: dilepton+2 b-jets
Smallest signal rate
Smallest background
Kinematically constrained

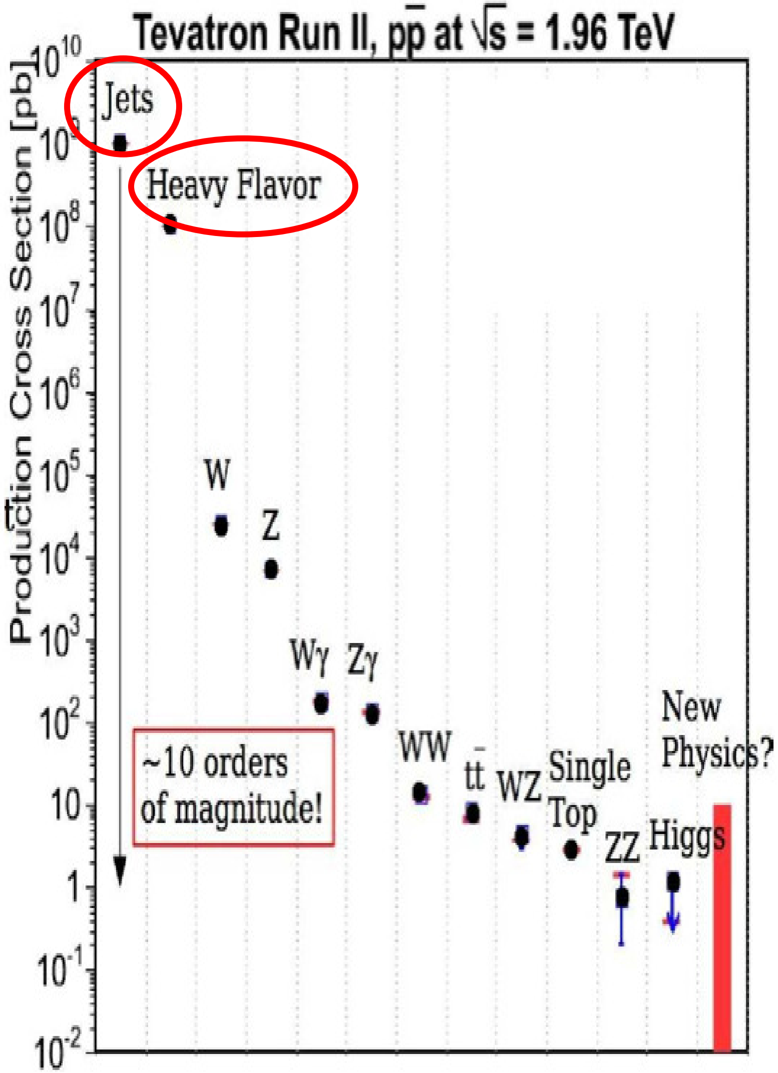


WH→lνbb: lepton+MET+2 b-jets
Largest signal rate
Larger V+jets background

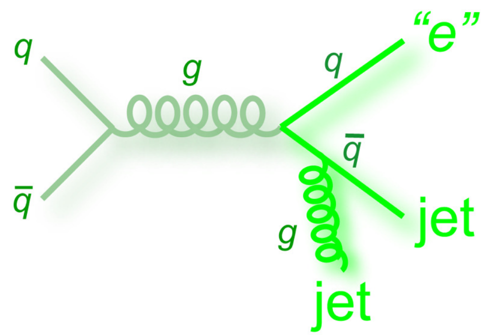


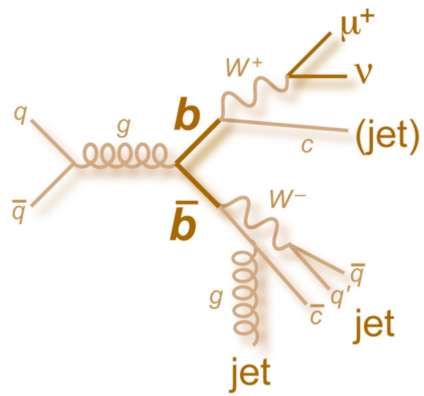
ZH→lνbb: MET+2 b-jets
Comparable signal rate to WH
(significant contribution from
WH→lνbb with missing lepton)
Challenging instrumental background

Backgrounds are Ferocious

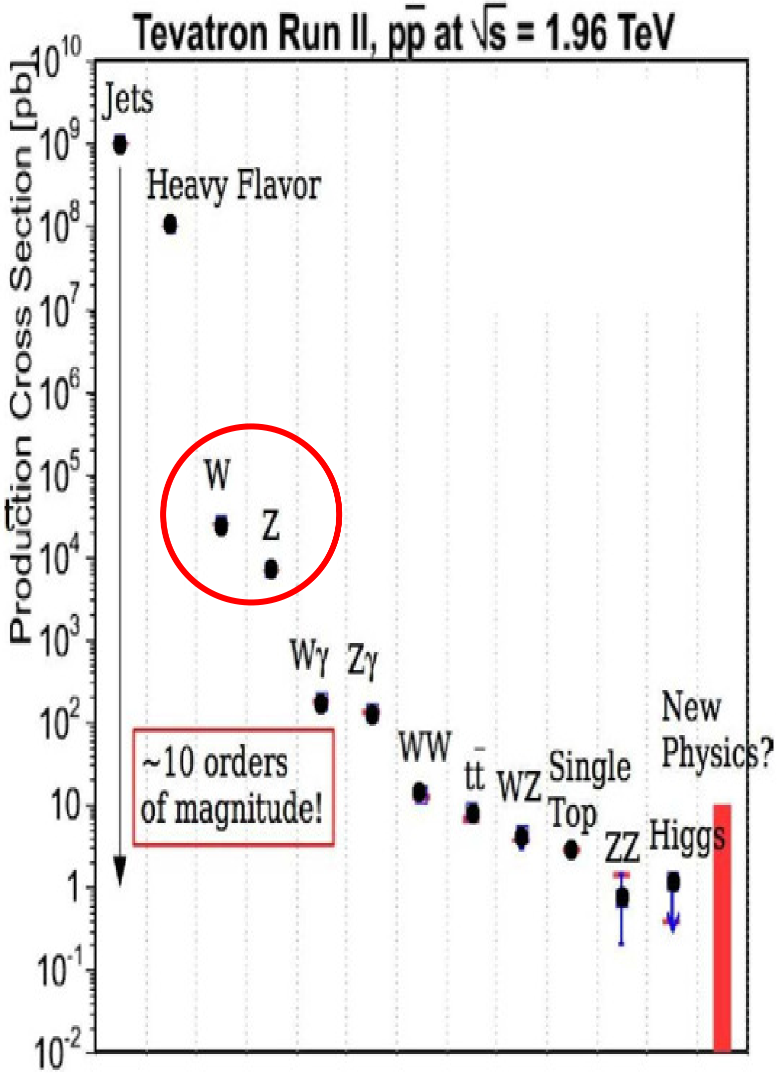


- Instrumental backgrounds: measured directly from data
  - QCD multijet production with mismeasured jets leadings to missing transverse energy or jets misidentified as leptons.

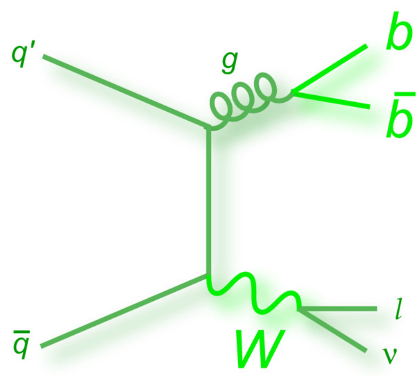


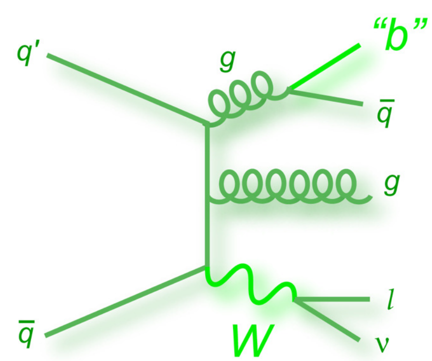


Backgrounds are Ferocious

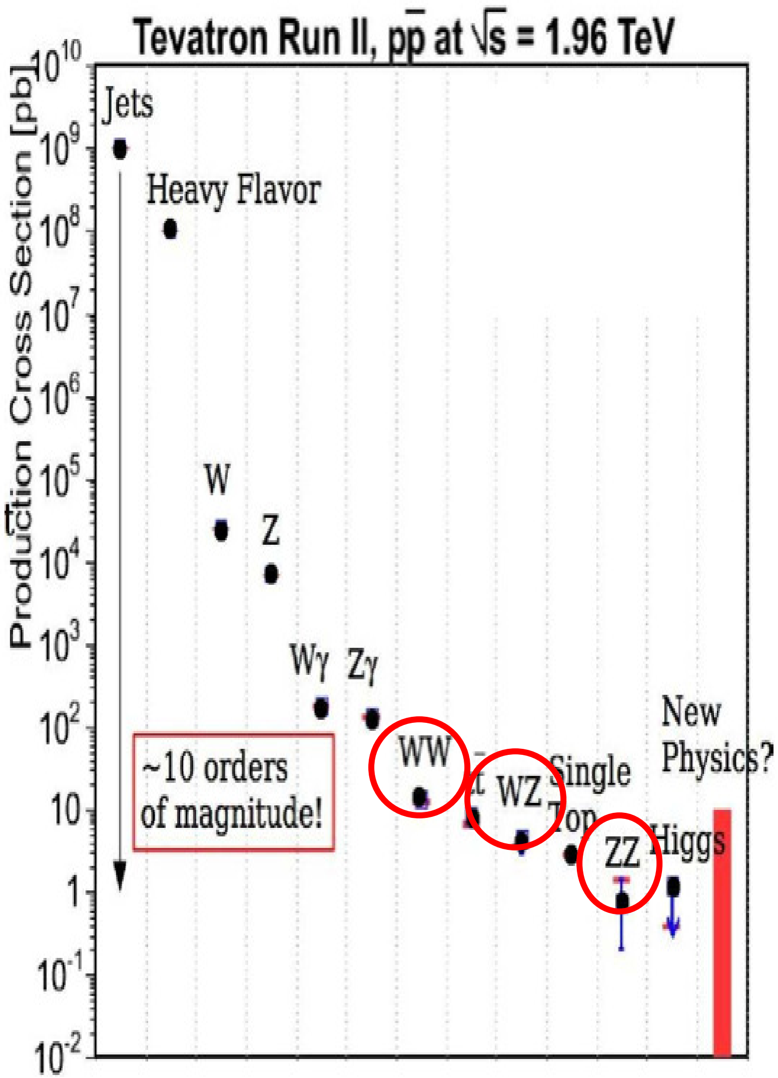


- Instrumental backgrounds: measured directly from data
  - QCD multijet production with mismeasured jets leadings to missing transverse energy or jets misidentified as leptons.
- Physics backgrounds: estimated using simulation and state-of-art theoretical predictions
  - W/Z+jets production (w/ real or misidentified heavy flavor jets)

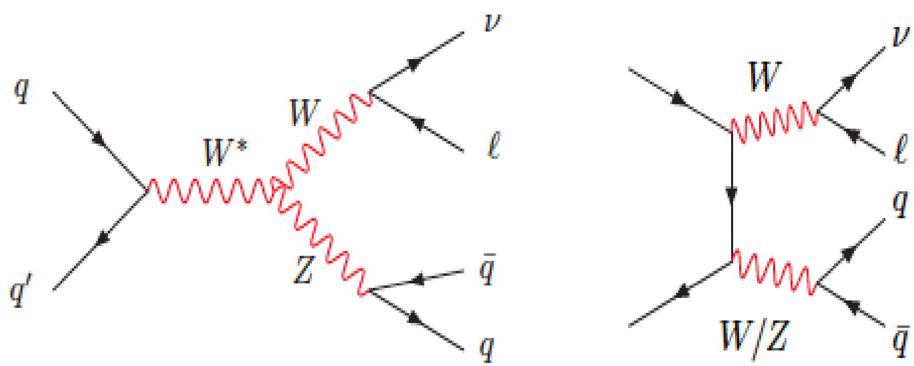




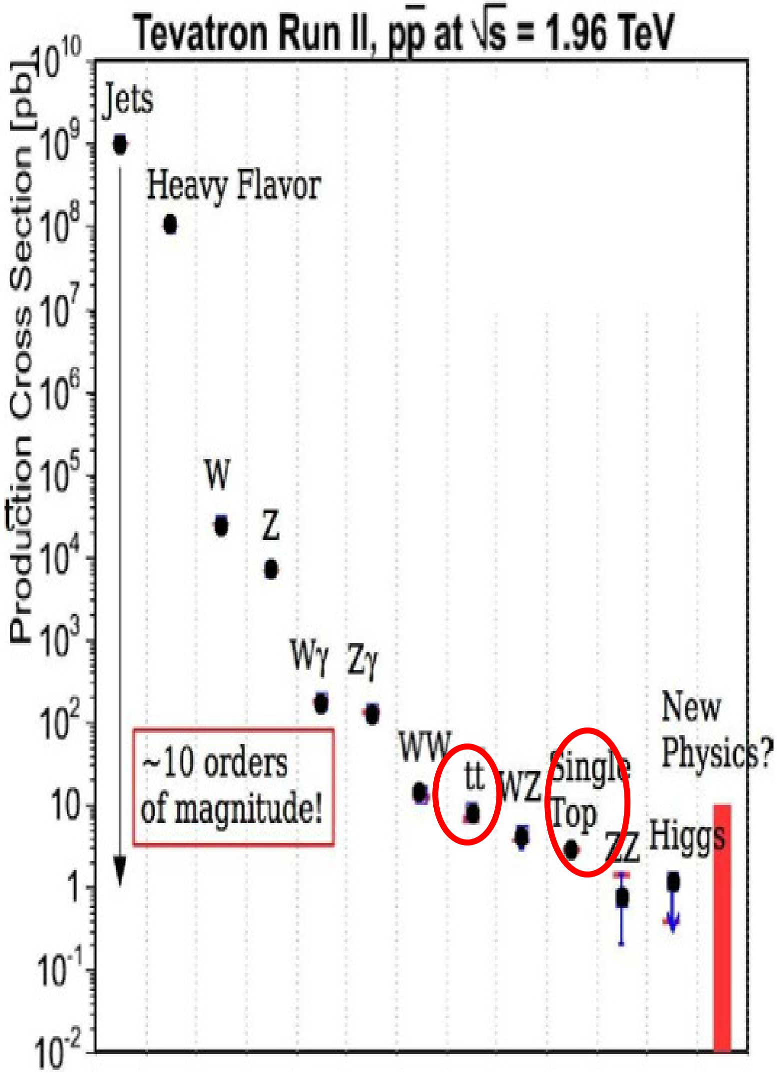
Backgrounds are Ferocious



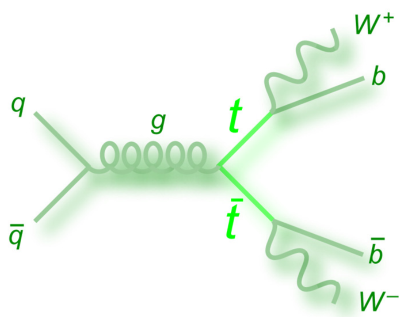
- Instrumental backgrounds: measured directly from data
  - QCD multijet production with mismeasured jets leadings to missing transverse energy or jets misidentified as leptons.
- Physics backgrounds: estimated using simulation and state-of-art theoretical predictions
  - W/Z+jets production (w/ real or misidentified heavy flavor jets)
  - Diboson production

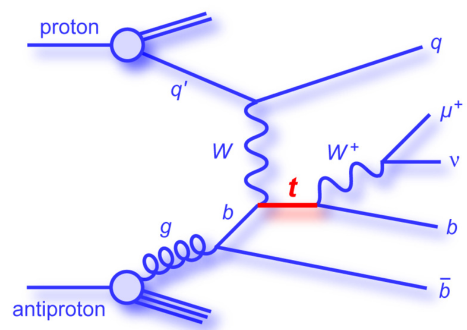


Backgrounds are Ferocious



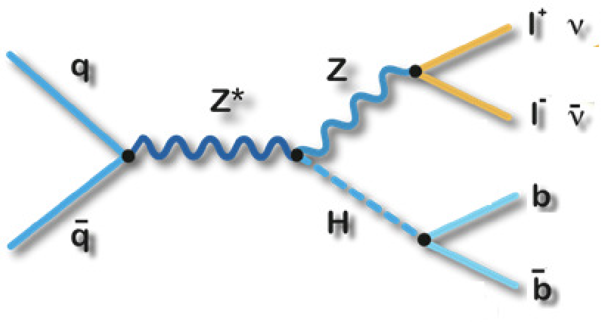
- Instrumental backgrounds: measured directly from data
  - QCD multijet production with mismeasured jets leadings to missing transverse energy or jets misidentified as leptons.
- Physics backgrounds: estimated using simulation and state-of-art theoretical predictions
  - W/Z+jets production (w/ real or misidentified heavy flavor jets)
  - Diboson production
  - Double and single top quark production





➔ Further constrain data modeling in “sideband regions”

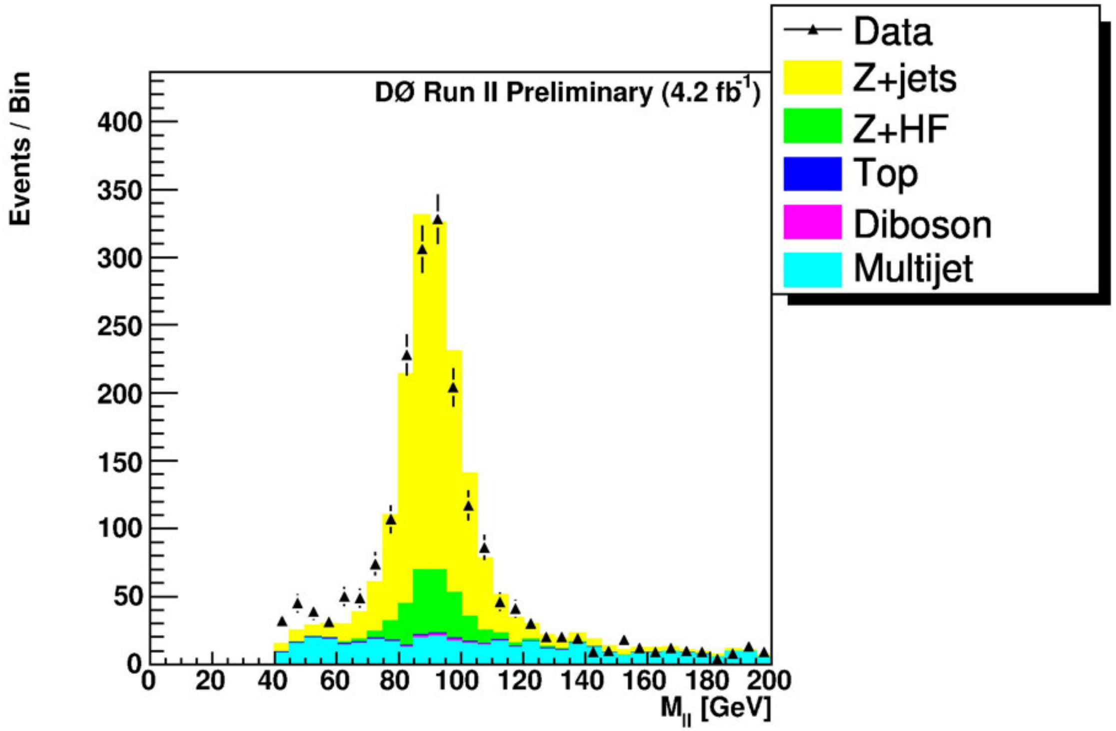
Dilepton + 2 b-jets



Step 1: preselection

- 2 high p_T isolated leptons
- dilepton mass ~ m_Z
- 2 jets

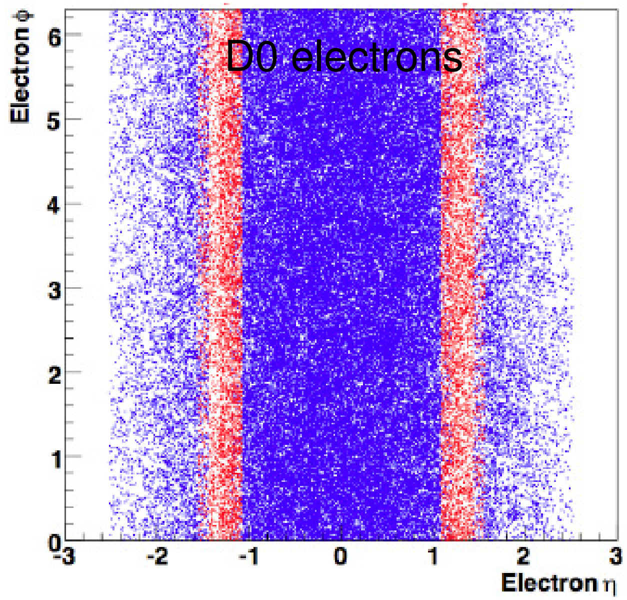
Dominant background is Z+jets

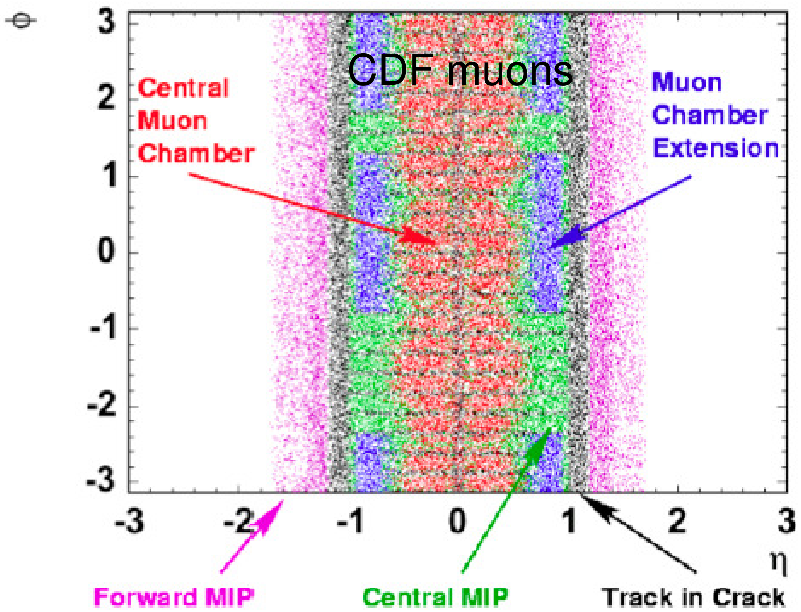


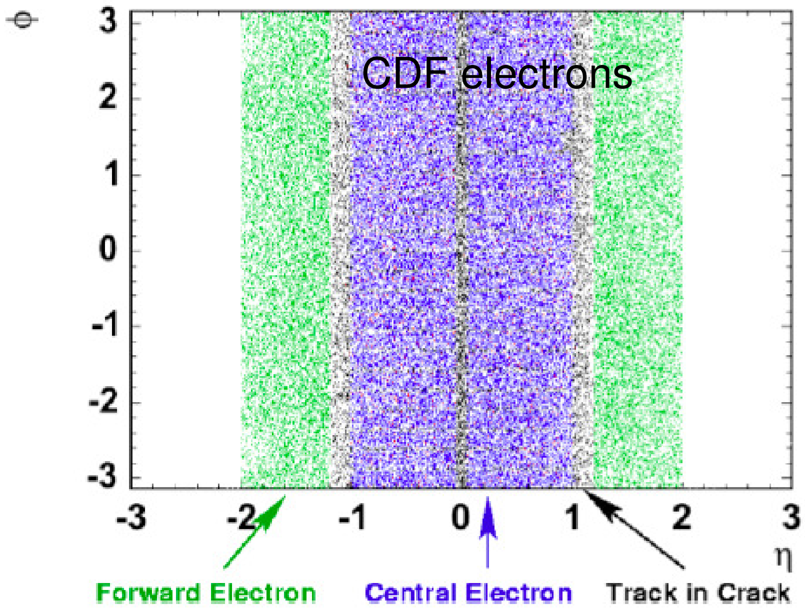
Source	PreTag High S/B
tt	53.01 ± 11.26
WW	5.22 ± 0.71
WZ	117.89 ± 15.95
ZZ	118.14 ± 15.98
$Z \to \tau\tau$	2.98 ± 1.21
Z+jets (bb)	370.93 ± 150.71
Z+jets (cc)	682.59 ± 277.34
Z+jets (lf)	9977.08 ± 1995.42
fakes	541.02 ± 270.51
ZH (120 GeV/c^2)	4.25 ± 0.32
Total Background	11868.9 ± 2038.4
Data	11806

Lepton Identification

- Major effort to improve lepton acceptance:
  - electrons in inter-cryostat regions (D0)
  - isolated tracks pointing to cracks between calorimeter cells (CDF) or consistent with MIP signal in the calorimeter (CDF+D0)
  - ➔ Improvements ~10-30% acceptance
- Not all these lepton categories fire the trigger!
  ➔ collect events through other triggers (e.g. jets+MET)



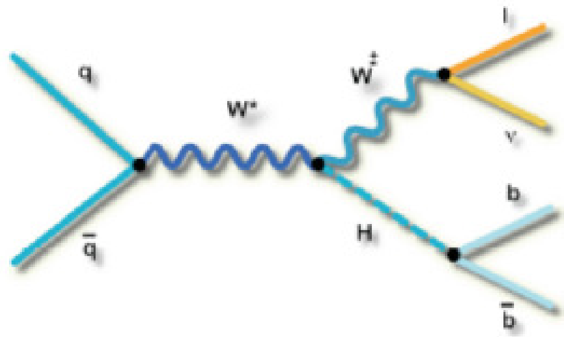




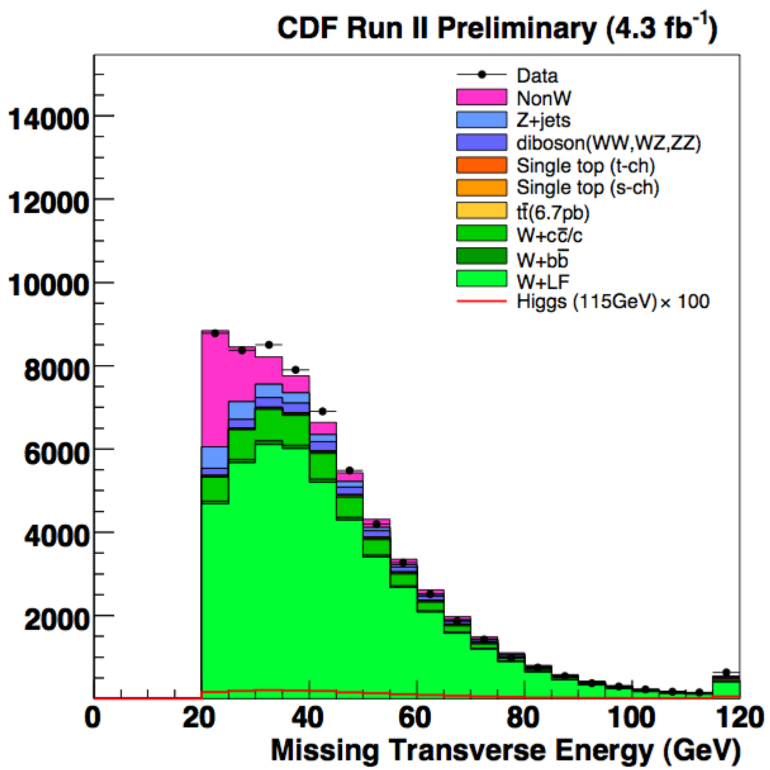
Lepton + MET + 2 b-jets

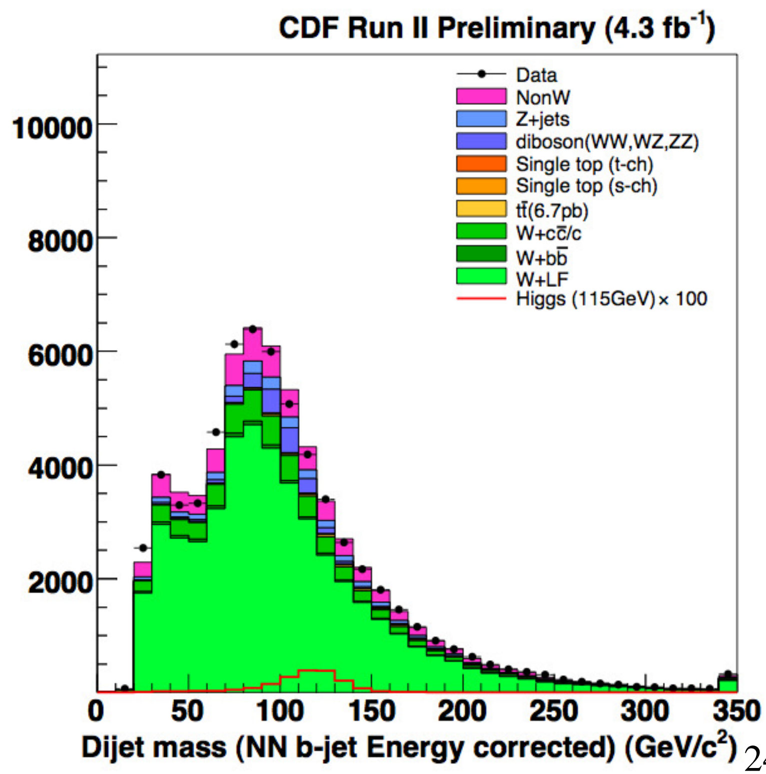
Step 1: preselection

- High p_T isolated leptons
- High MET
- 2 jets



Dominant background is W+jets

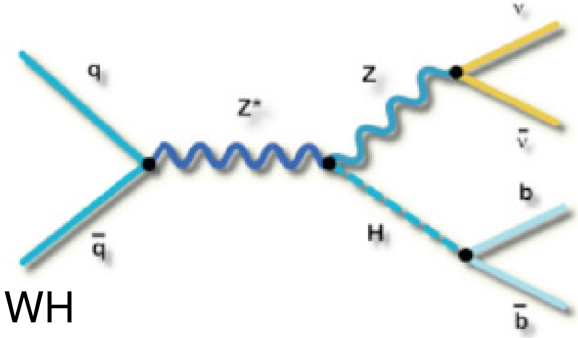


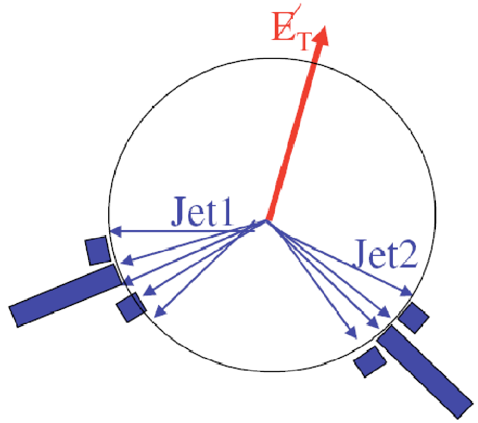


MET + 2 b-jets

Step 1: preselection

- High MET
- 2 acoplanar jets

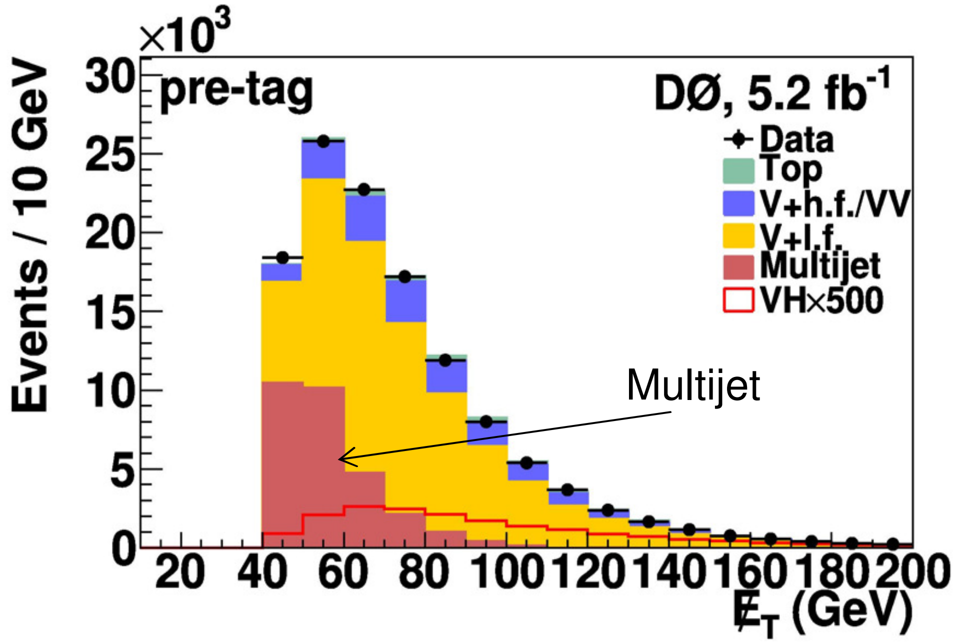


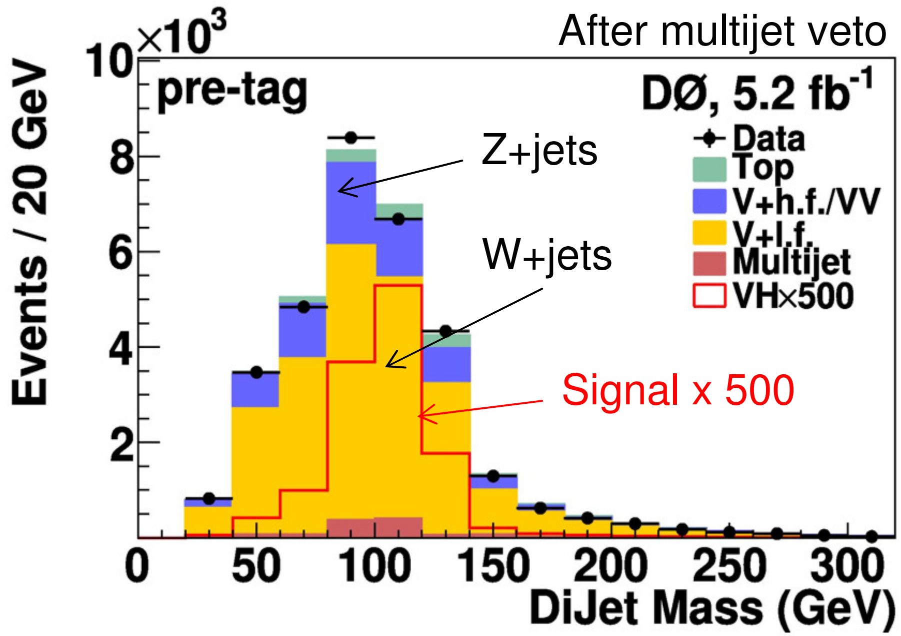


Significant contribution from WH

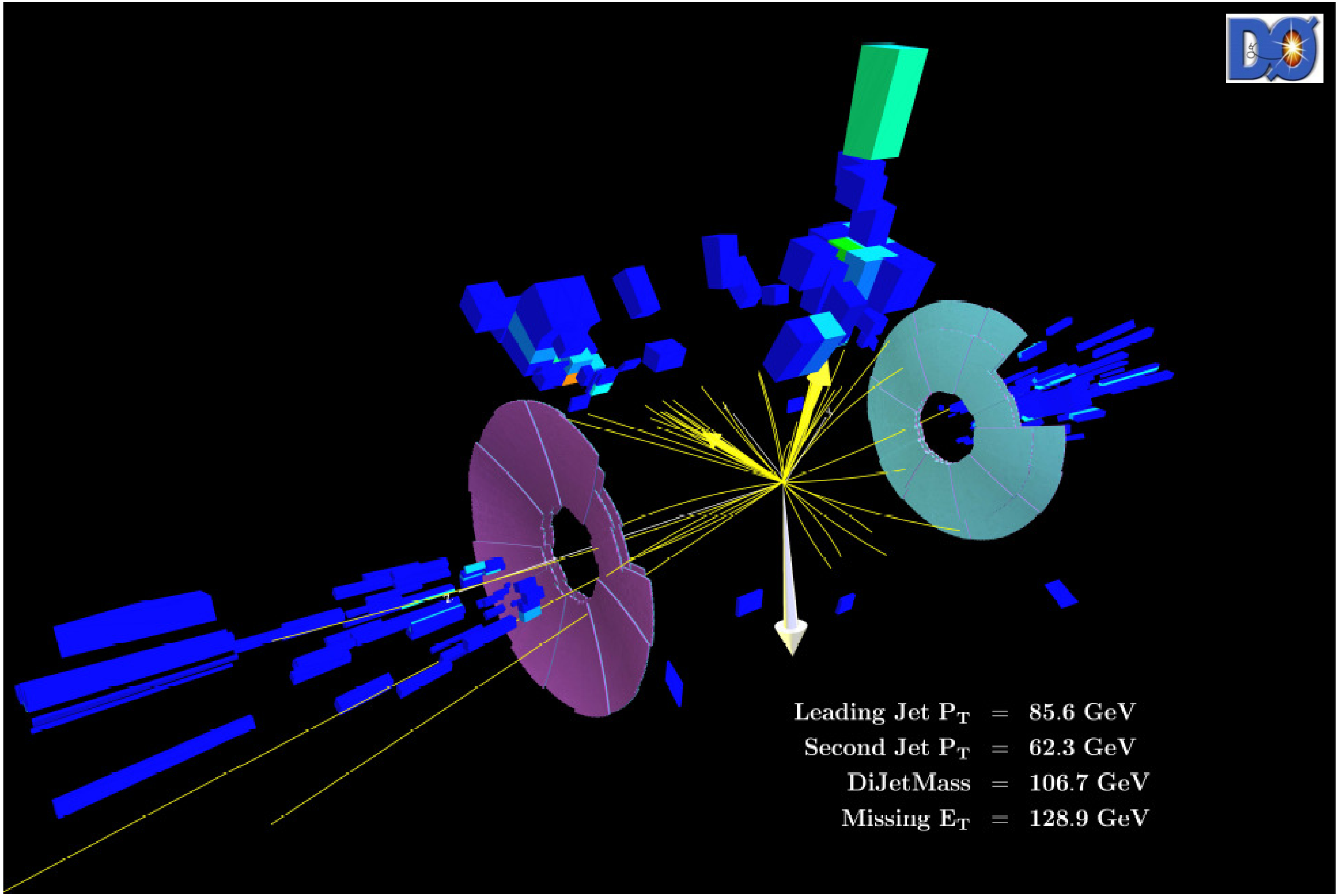
Challenging background from QCD multijets

After careful selection, main bckg is W/Z+jets





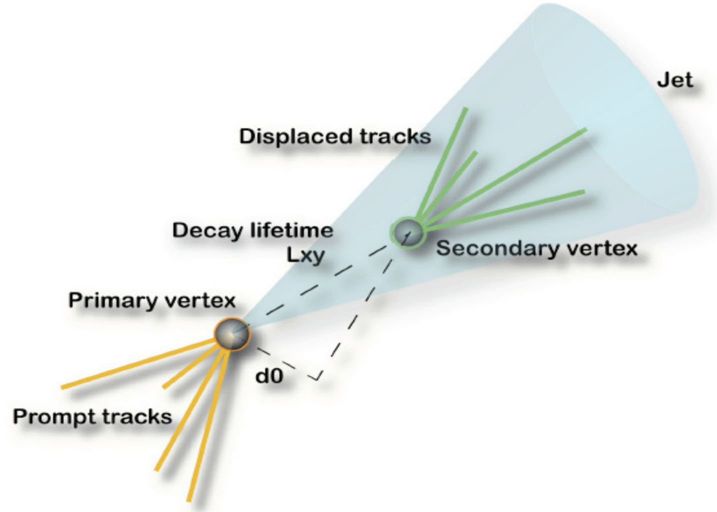
MET + 2 b-jets

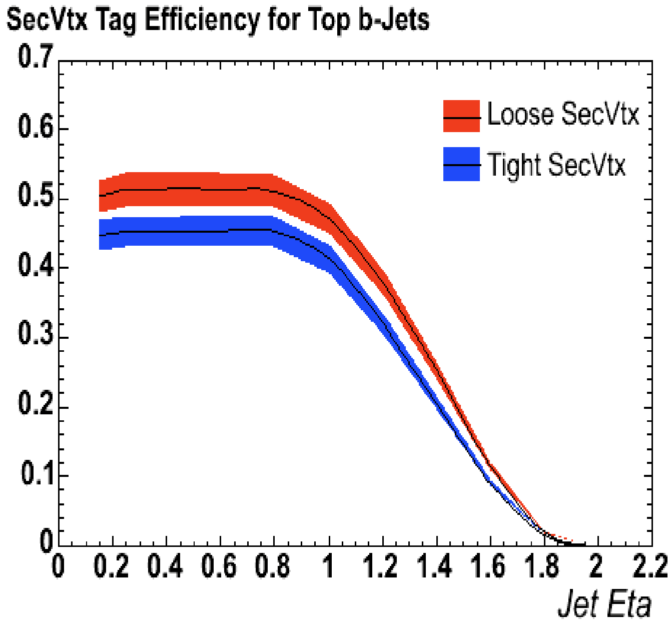


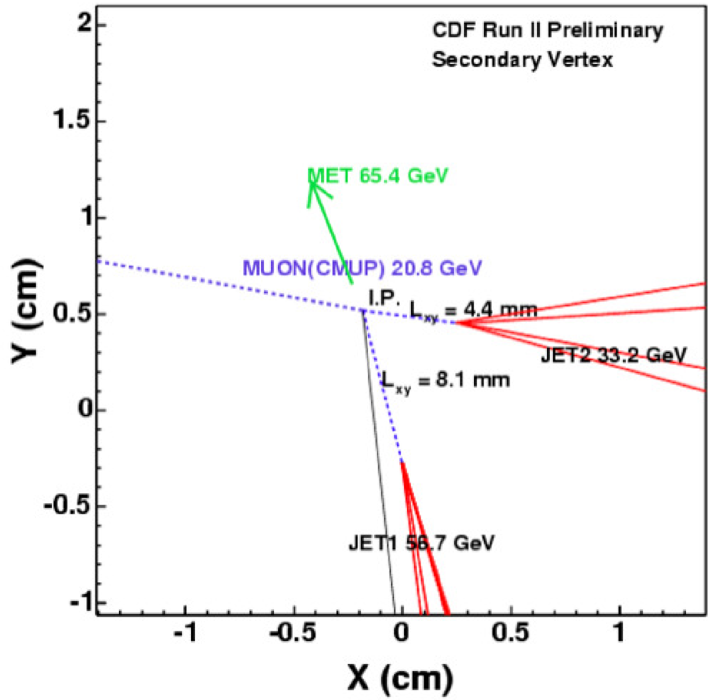
Leading Jet P_T = 85.6 GeV
Second Jet P_T = 62.3 GeV
DiJetMass = 106.7 GeV
Missing E_T = 128.9 GeV

Heavy Flavor Identification

- Critical for searches involving H→bb.
- B-tagging exploits information on:
  - Lifetime: displaced tracks and/or vertices
  - Mass: secondary vertex mass
  - Soft leptons
- Typical performance:
  - B-tagging efficiency: ~40-70%
  - Mistag rate: ~0.5-5%
  - Calibrated in data control samples.







Heavy Flavor Identification

- Critical for searches involving H→bb.
- B-tagging exploits information on:
  - Lifetime: displaced tracks and/or vertices
  - Mass: secondary vertex mass
  - Soft leptons
- Typical performance:
  - B-tagging efficiency: ~40-70%
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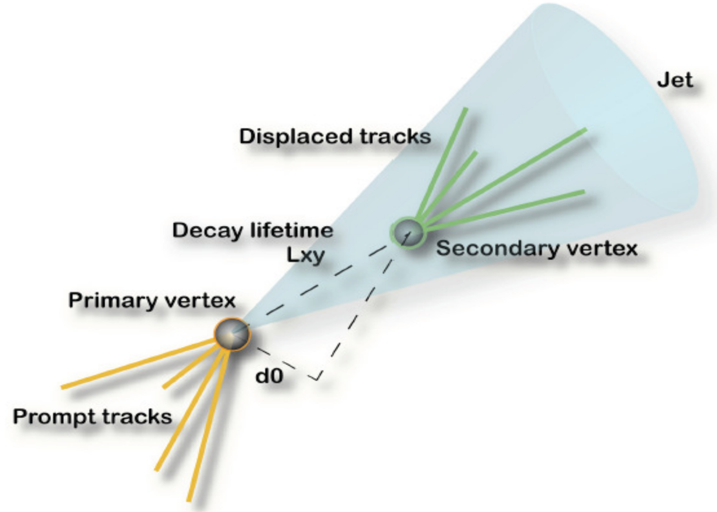
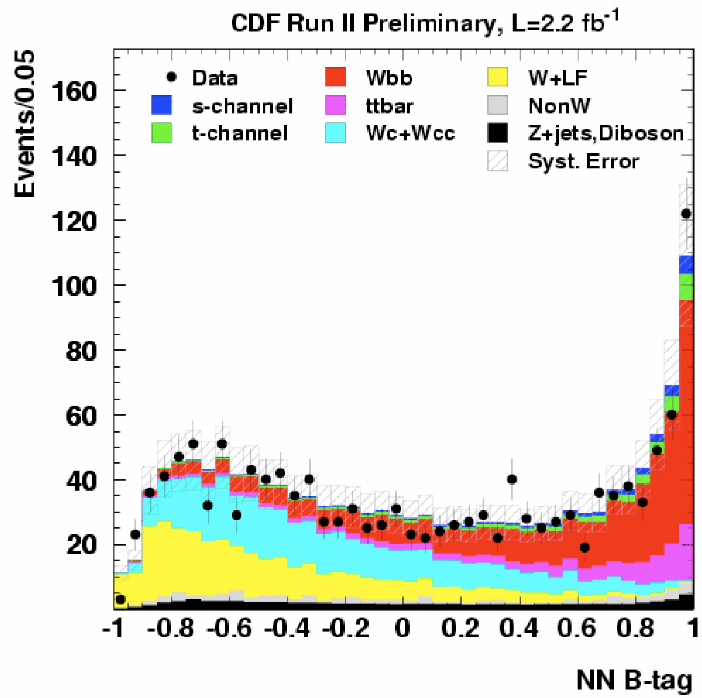
- Use multivariate techniques for improved performance:
  - NN for b-to-c discrimination after secondary vertex tagging





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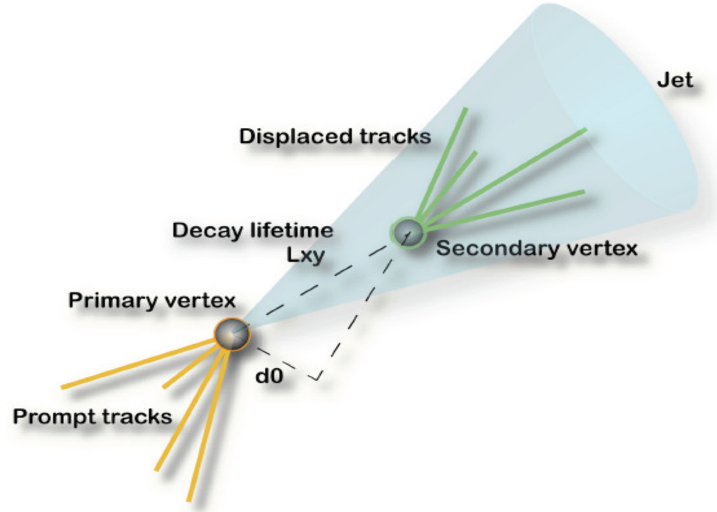

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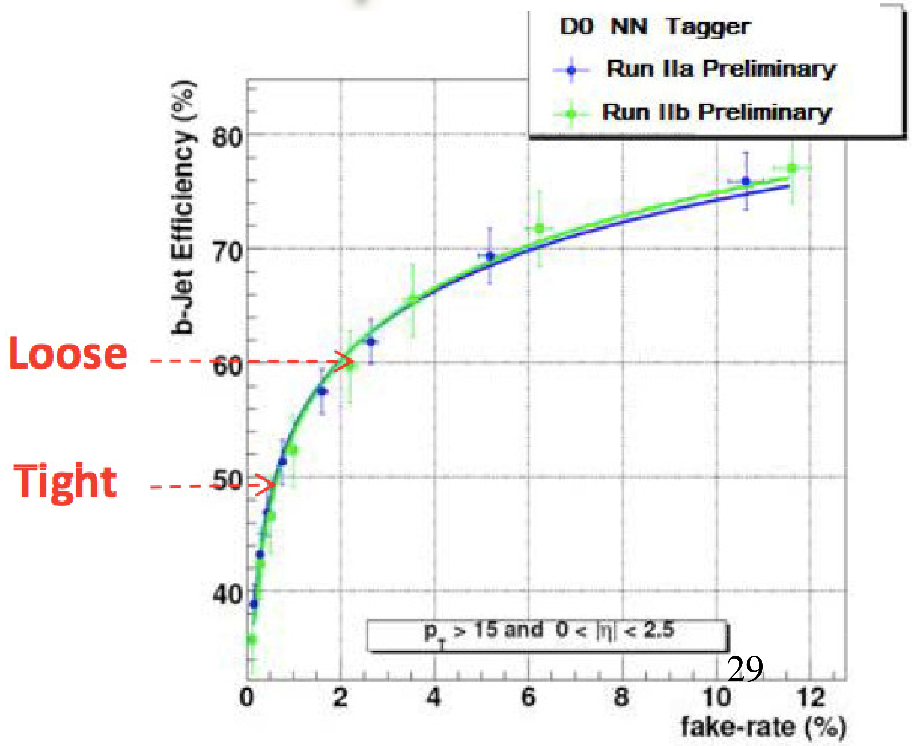
  - NN for b-to-light: continuous tagger (multiple operating points)



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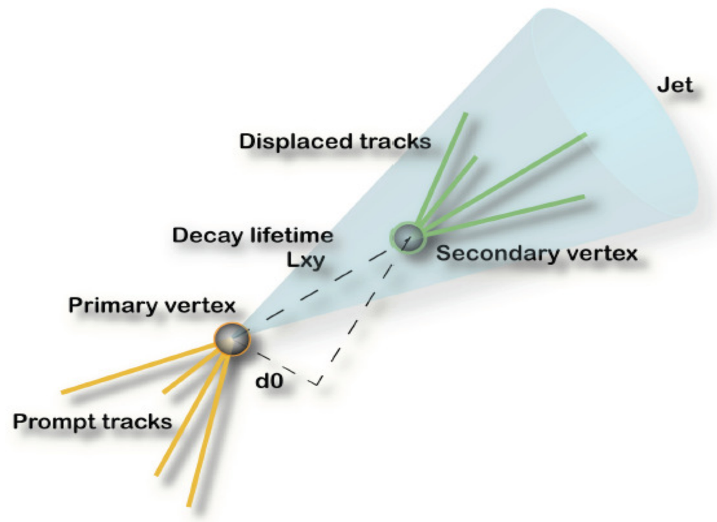

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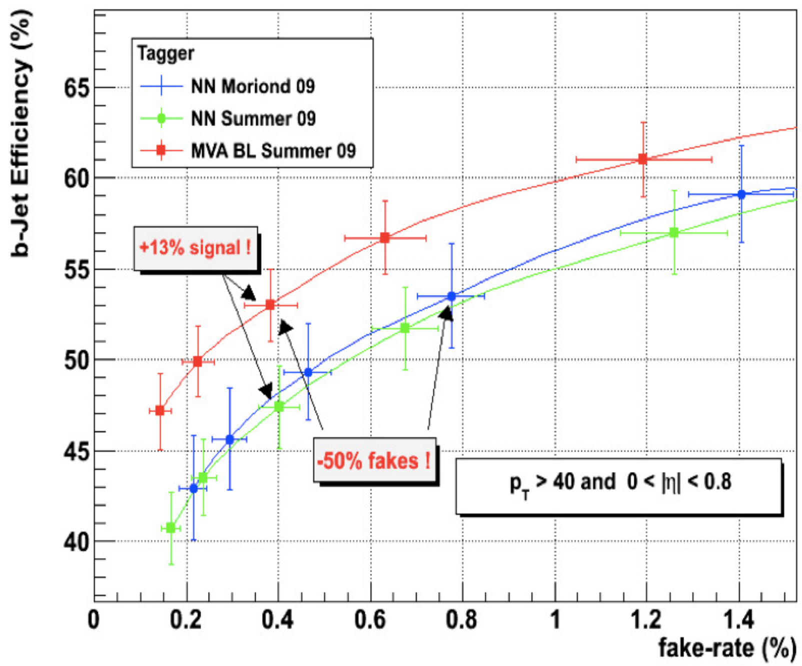
  …and further improved! (*)



(*) Not in analysis yet

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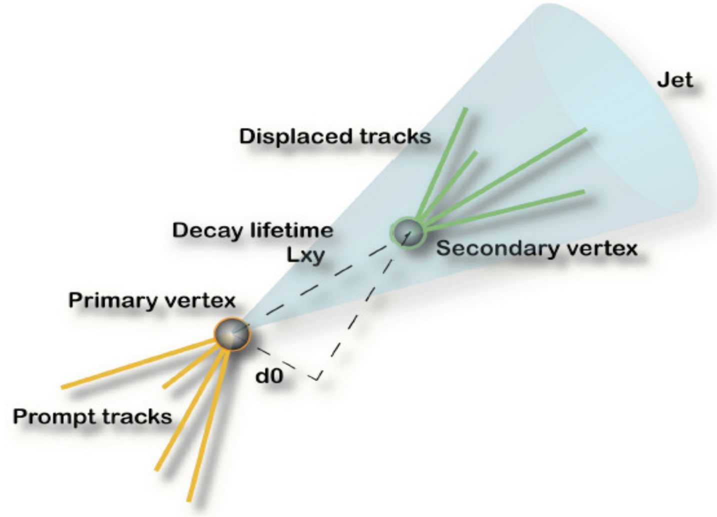

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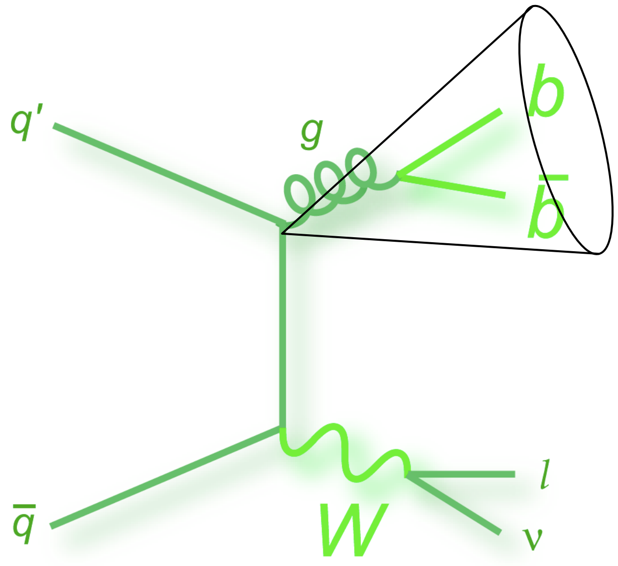
  - NN for b-to-(bb) discrimination (*)



(*) Not in analysis yet

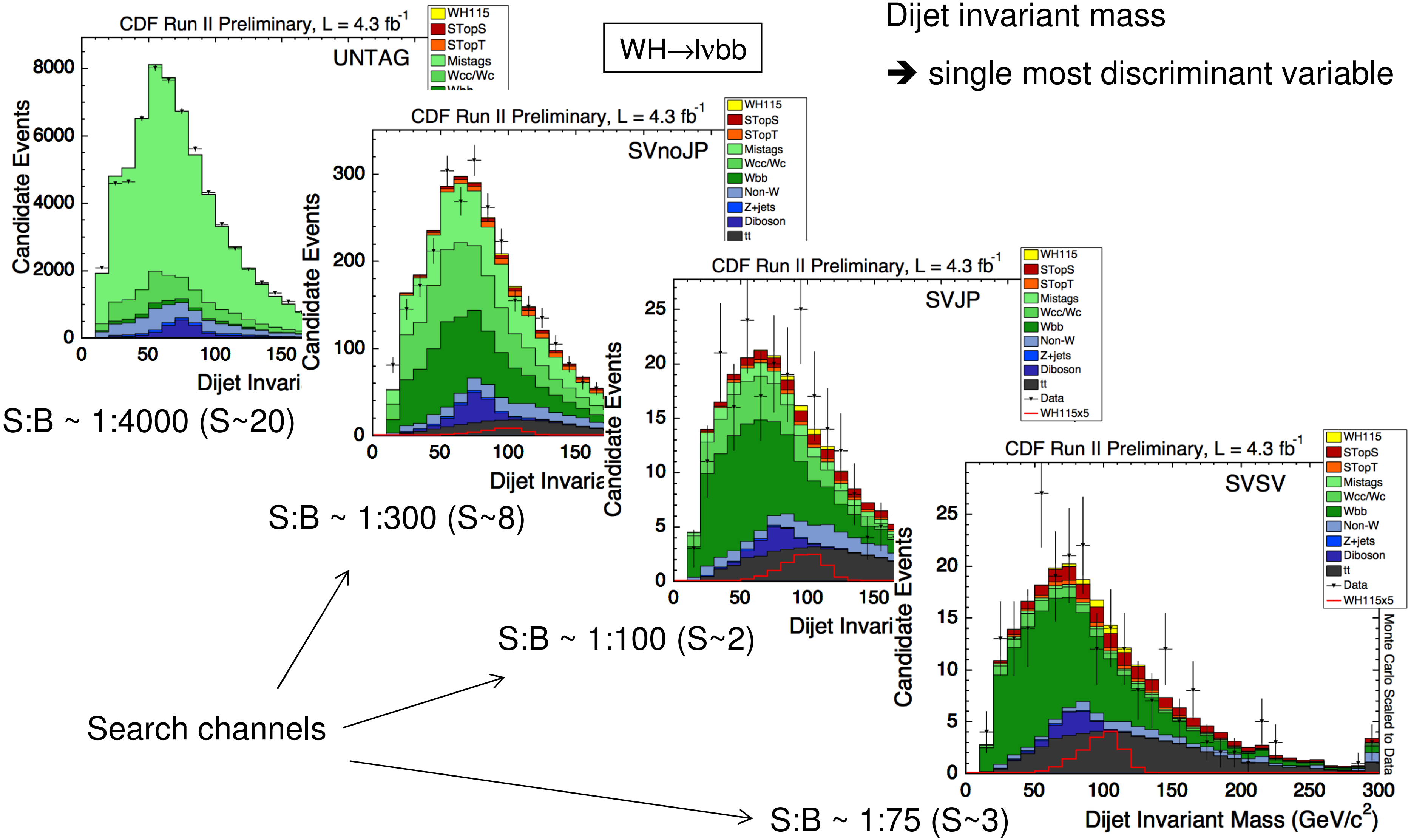
After B-Tagging

Step 2: B-tagging ➔significant improvement to S:B

WH→lνbb

Dijet invariant mass

➔ single most discriminant variable



S:B ~ 1:4000 (S~20)

S:B ~ 1:300 (S~8)

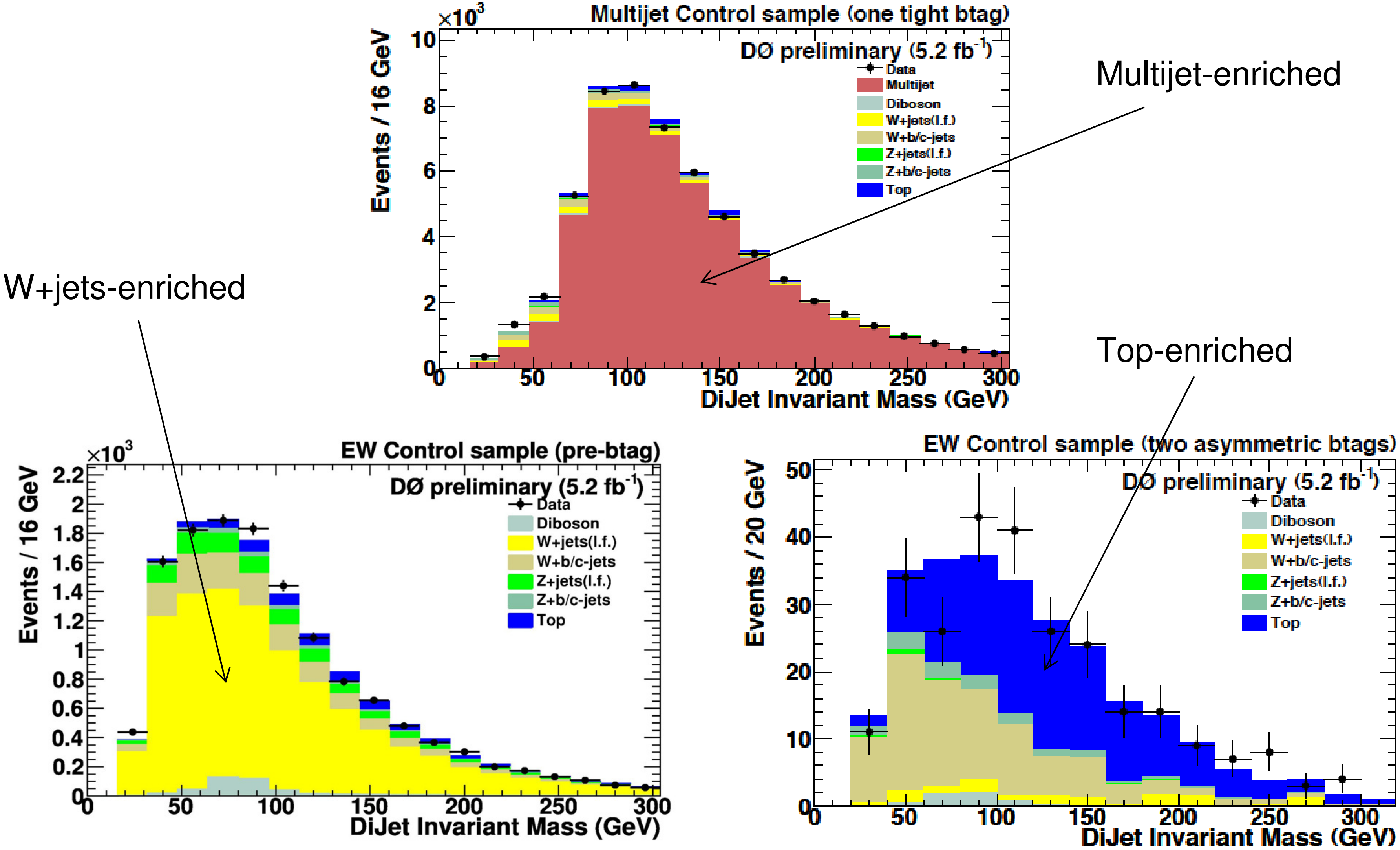
S:B ~ 1:100 (S~2)

S:B ~ 1:75 (S~3)

Search channels

Control Regions

- Step 3: validate background modeling in control regions
- Example: MET+2 b-jets



Dijet Mass Resolution

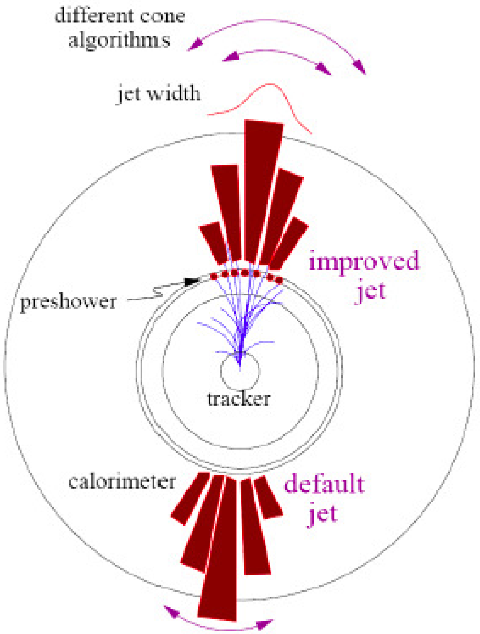
Significant efforts to improve the dijet mass resolution:

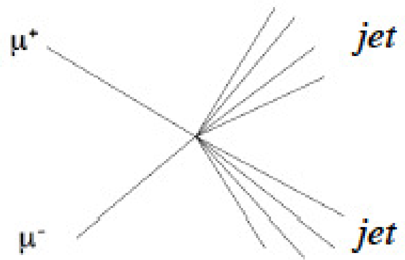
- Develop sophisticated corrections employing information from the tracker, preshower, jet shape variables, semileptonic B-decays, etc.

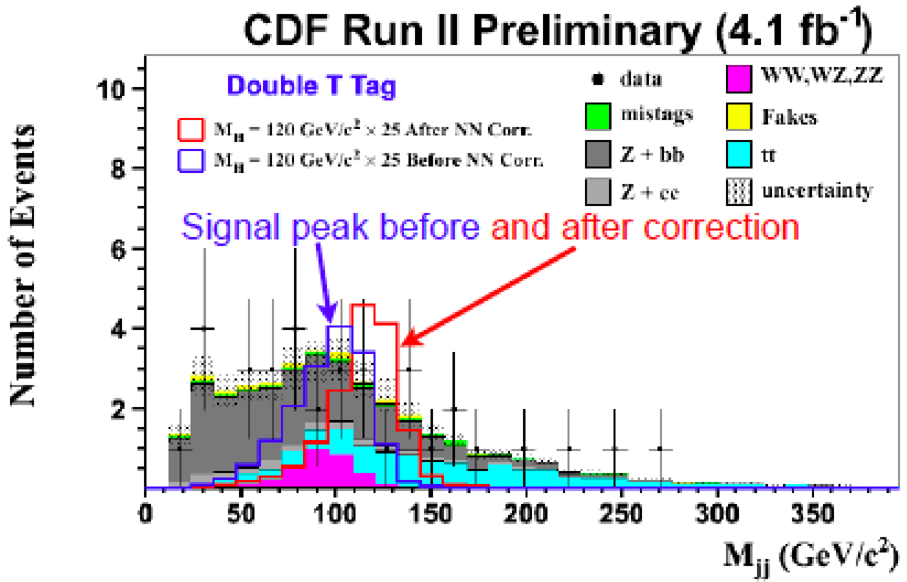
  Example: ZH→ννbb (CDF) ~10% improvement in sensitivity.

- Exploit p_T balance via kinematic fitting in topologies with no intrinsic MET.

  Example: ZH→llbb (CDF and D0) ~10% improvement in sensitivity.







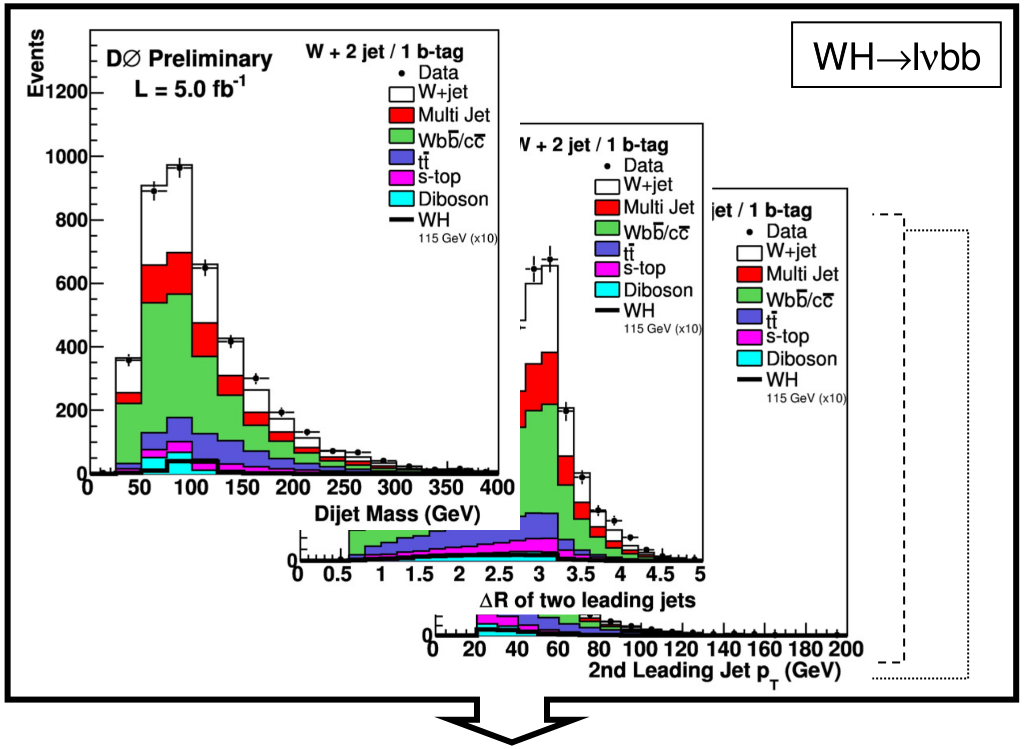
Multivariate Techniques

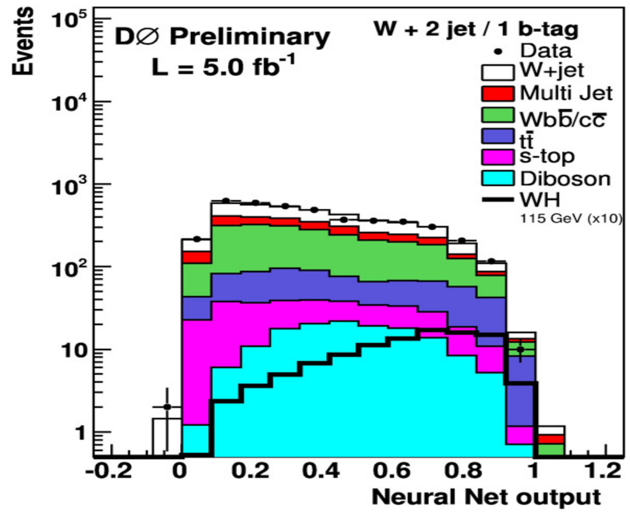
Step 4: final discrimination via multivariate techniques

- Exploit information from several discriminant variables and their correlations.
- Most commonly used: Neural Networks, Decision Trees, Matrix Element Discriminants,…

Typical sensitivity gain compared to single variable is ~15-20%.

Additional ~5-10% from smart combinations.





Systematic Uncertainties

Example: ZH→ννbb (D0). Relative uncertainties in %

Systematic Uncertainty	Type	Signal	Background
Jet Energy Scale	Shape & Norm	2.7	3.5
Jet Reco*ID	Shape & Norm	0.4	0.8
Jet Resolution	Shape & Norm	0.9	0.8
Cross Sections	Flat Norm	6.0	7.5
Mulit-jet Normalization	Flat Norm	–	1.5
Heavy Flavor Fraction	Flat Norm	–	9.8
Parton Distribution Function	Shape only	–	–
Vertex Confirmation	Shape & Norm	2.5	1.5
Taggability	Shape & Norm	3.6	3.3
b-Tagging	Shape & Norm	8.7	7.9
Trigger Efficiency	Shape & Norm	3.5	3.4
μ ID	Shape & Norm	1.1	1.5
EM ID	Shape & Norm	0.2	0.3
Alpgen MLM	Shape only	–	–
Alpgen Event Scale	Shape only	–	–
Alpgen Underlying Event	Shape only	–	–
Luminosity	Flat Norm	6.1	6.1

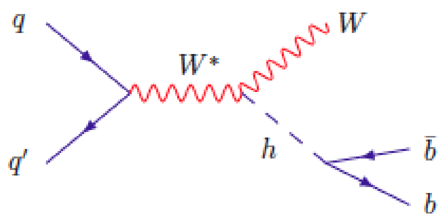
Total: ~15% ~ 20-25%

Systematic uncertainties can affect both shape and normalization of signal and background.

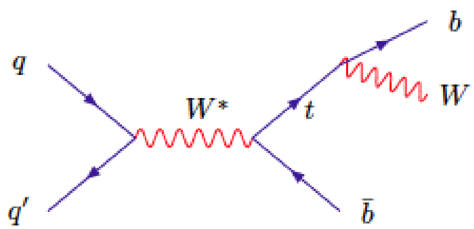
→ Main systematic uncertainties from b-tagging and background modeling.

Building a Strong Foundation

- Validate experimental strategy and tools using SM backgrounds that share characteristics with the signal.

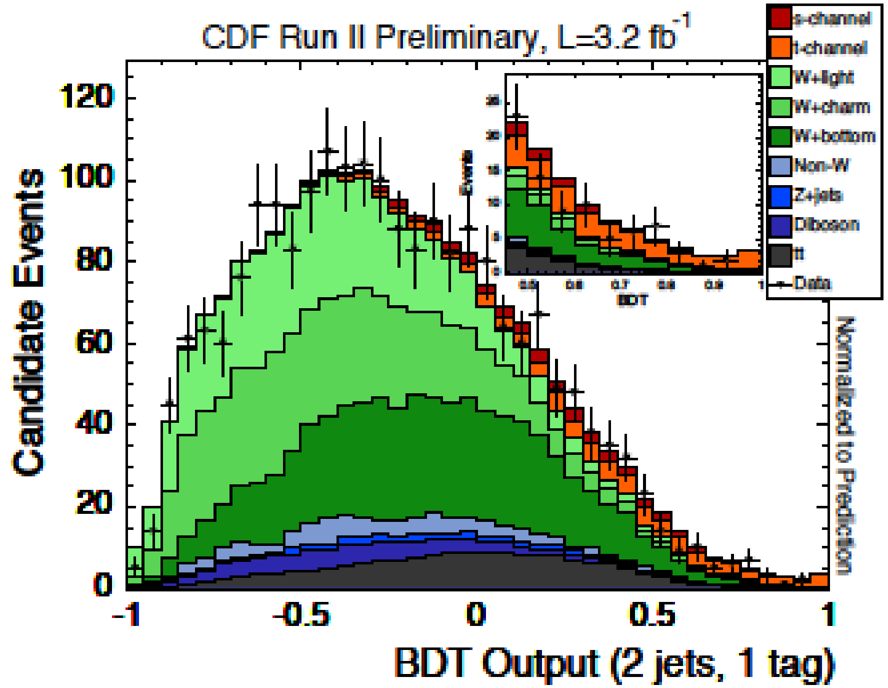


Electroweak single top production



- σ and kinematics sensitive to *tbW* interaction.
- Large W+jets background.
- Required optimizations:
  - Maximize acceptance.
  - Use b-tagging.
  - Use multivariate techniques.
  - Constrain systematic uncertainties using side-band regions in data.

➔ Same optimizations/techniques as for the Higgs searches!



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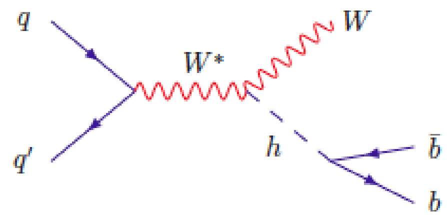

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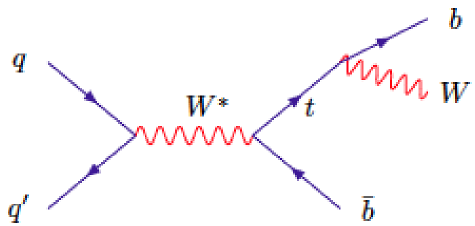

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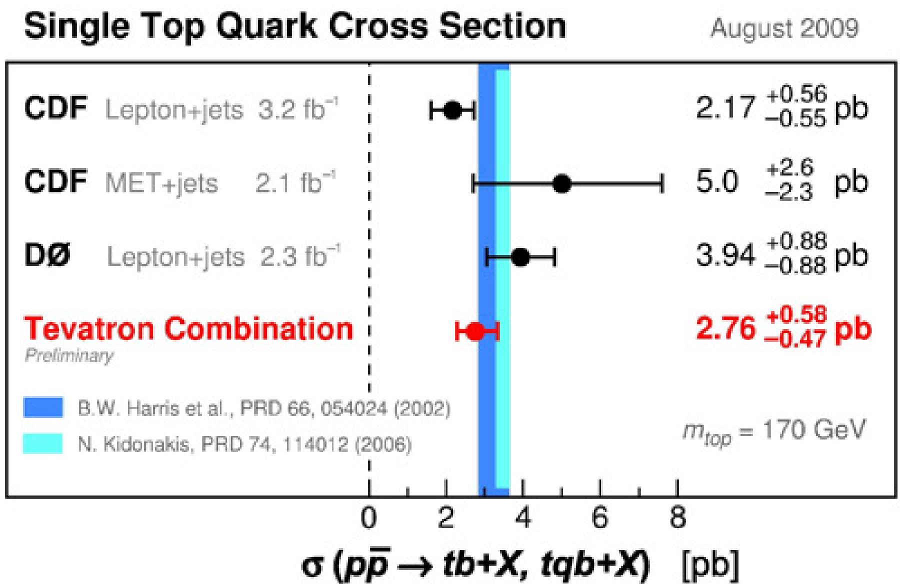
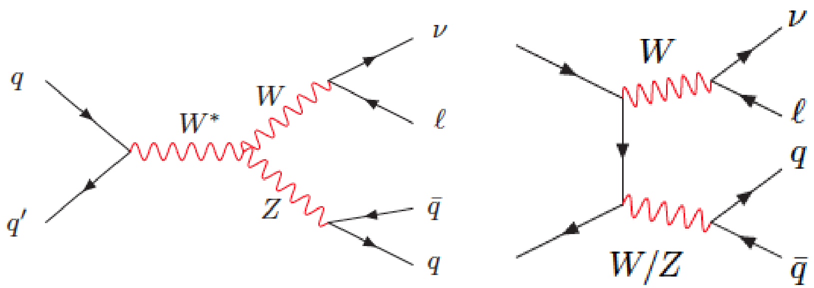


Phys. Rev. Lett. 103, 092001 (2009)
Phys. Rev. Lett. 103, 092002 (2009)

Both experiments observe single top production!

Building a Strong Foundation

Diboson production



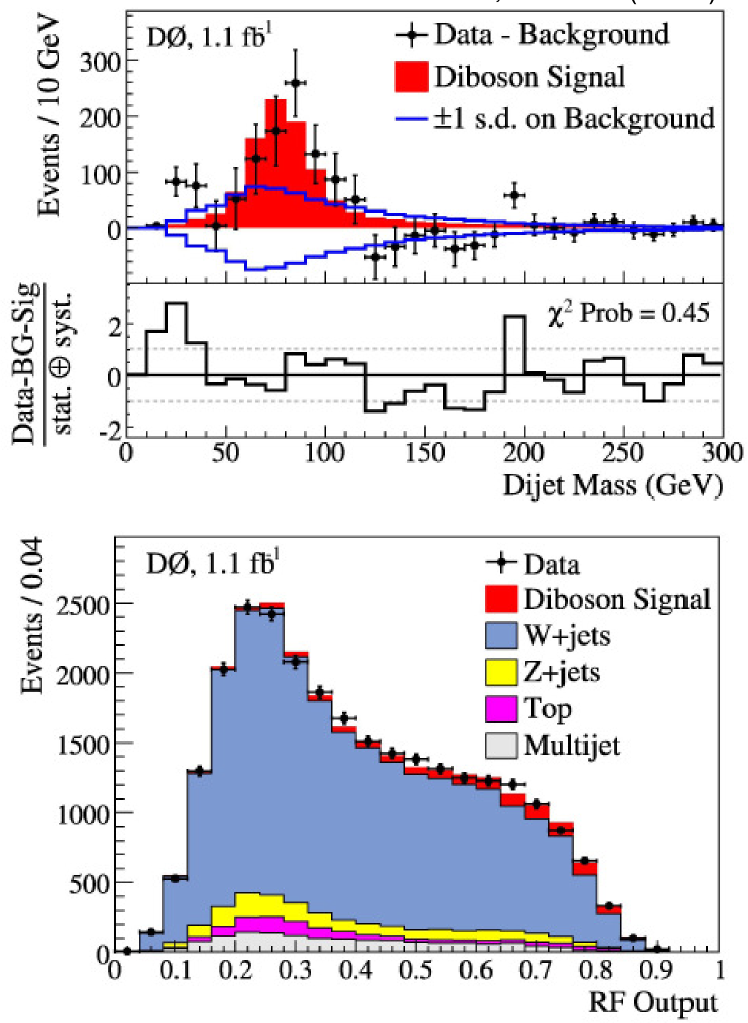
- Probe of non-abelian structure of SM and sensitive to New Physics.
- Small signal in large background.
  Dijet mass is the most sensitive variable.
- Required optimizations:
  - Exploit dijet mass distribution.
  - Use multivariate techniques.
  - Constrain systematic uncertainties using side-band regions in data.

➔ Same optimizations/techniques as for the Higgs searches!

➔ Both experiments measure cross sections consistent with the SM prediction.

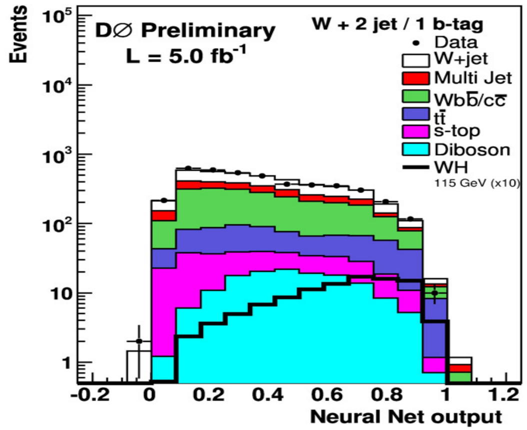
WW/WZ→lνjj

PRL 102, 161801 (2009)



Interpreting the Data

- Use the final discriminant distribution (e.g. NN output) to perform hypothesis testing (S+B vs B-only).
- In absence of an excess, set limits using:
  - The CL_s method or
  - A Bayesian method



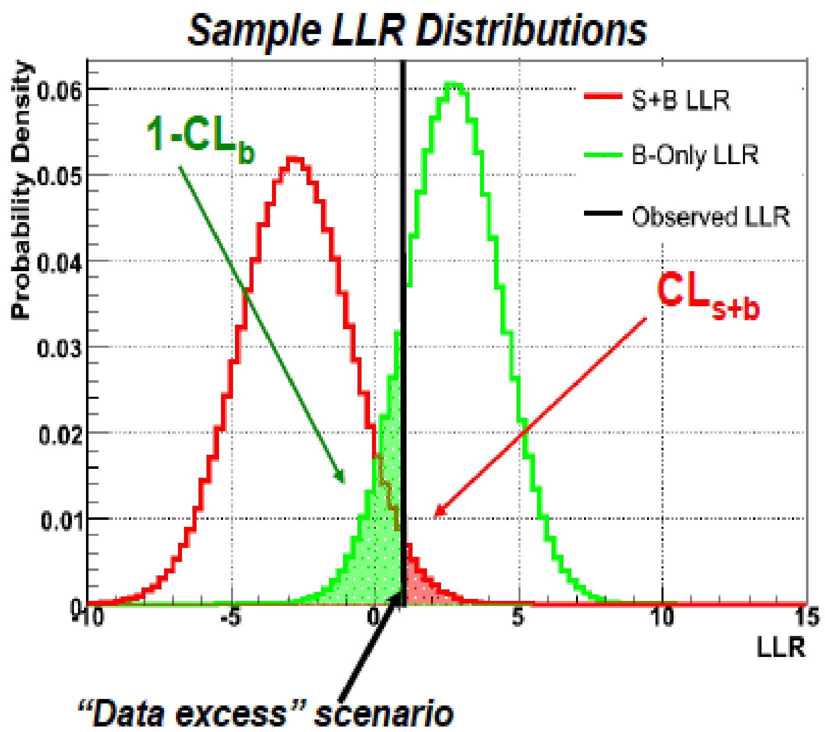
CL_s method

1. Compute the likelihood ratio for S+B vs B-only hypothesis using Poisson statistics:

$$Q(\vec{d};\vec{s},\vec{b}) = \prod_{i=1}^{N_{chan}} \prod_{j=1}^{N_{bins}} \frac{(s+b)_{ij}^{d_{ij}} e^{-(s+b)_{ij}}}{d_{ij}!} \Big/ \frac{b_{ij}^{d_{ij}} e^{-b_{ij}}}{d_{ij}!}$$

$$LLR = -2\ln Q$$

1. Generate pseudo-experiments for S+B and B-only hypotheses via Poisson trial.
   - Systematics are folded in via Gaussian marginalization
   - Correlations held amongst signals and backgrounds
2. Define CL_s: $$CL_s = \frac{CL_{s+b}}{CL_b}$$



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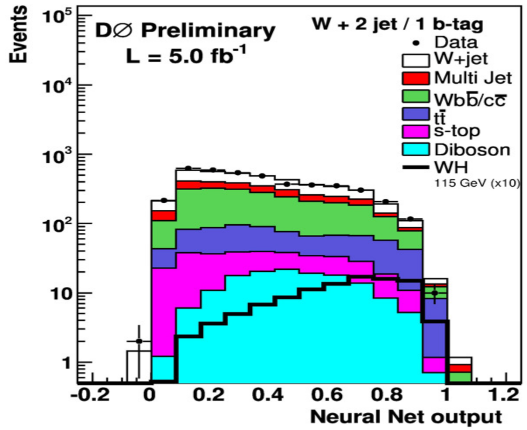

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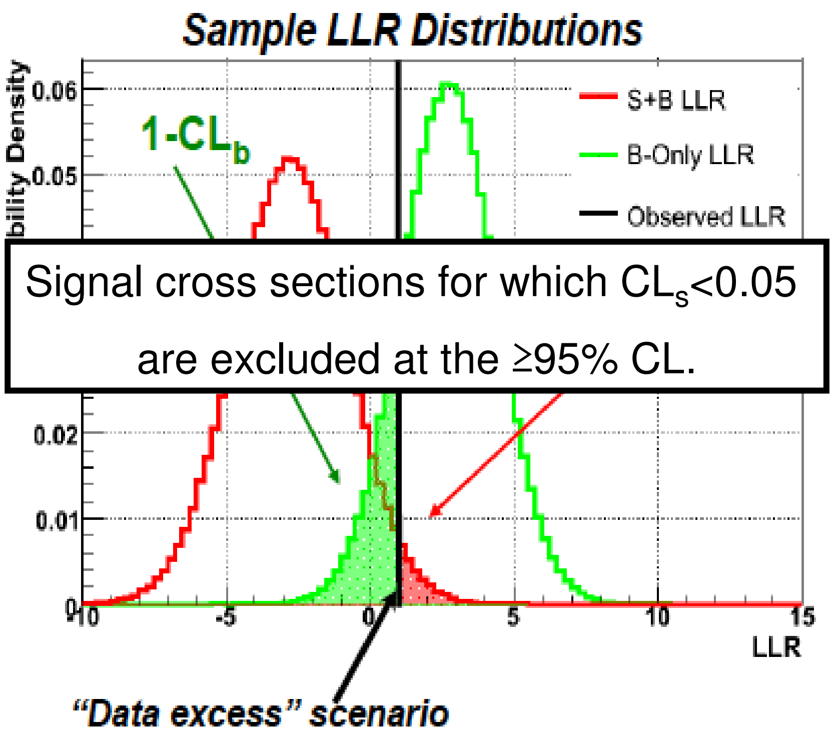
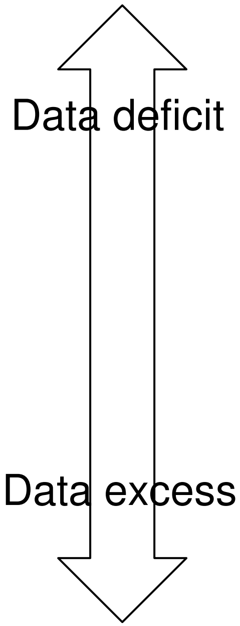
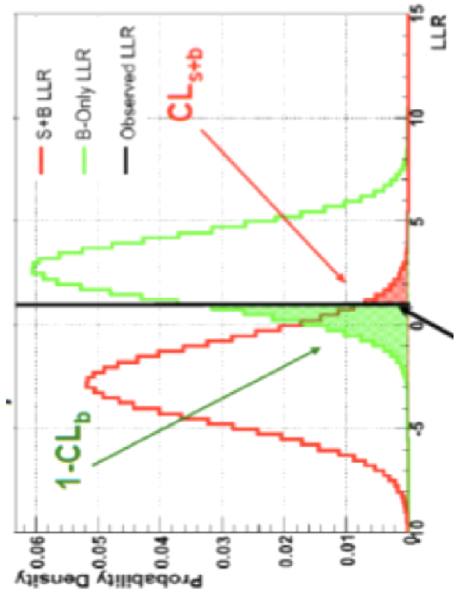


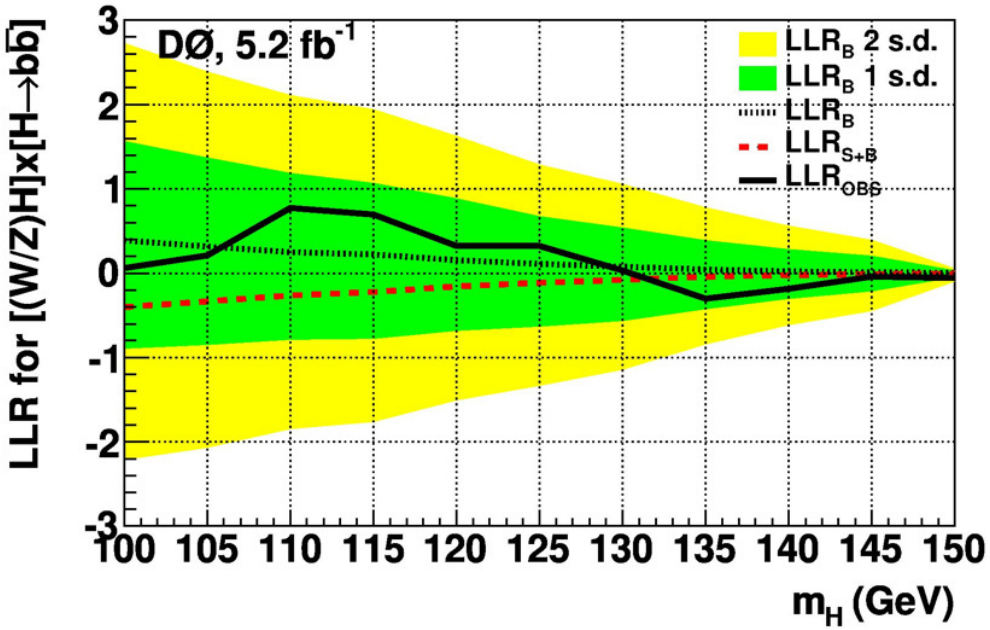
Signal cross sections for which CL_s<0.05 are excluded at the ≥95% CL.

Interpreting the Data





ZH→ννbb



- Dashed lines show S+B and B-only mean value.
- Shaded bands indicate 1 and 2σ variation of B-only distribution
- Solid black line indicates **data observation**

Constraining Systematic Uncertainties

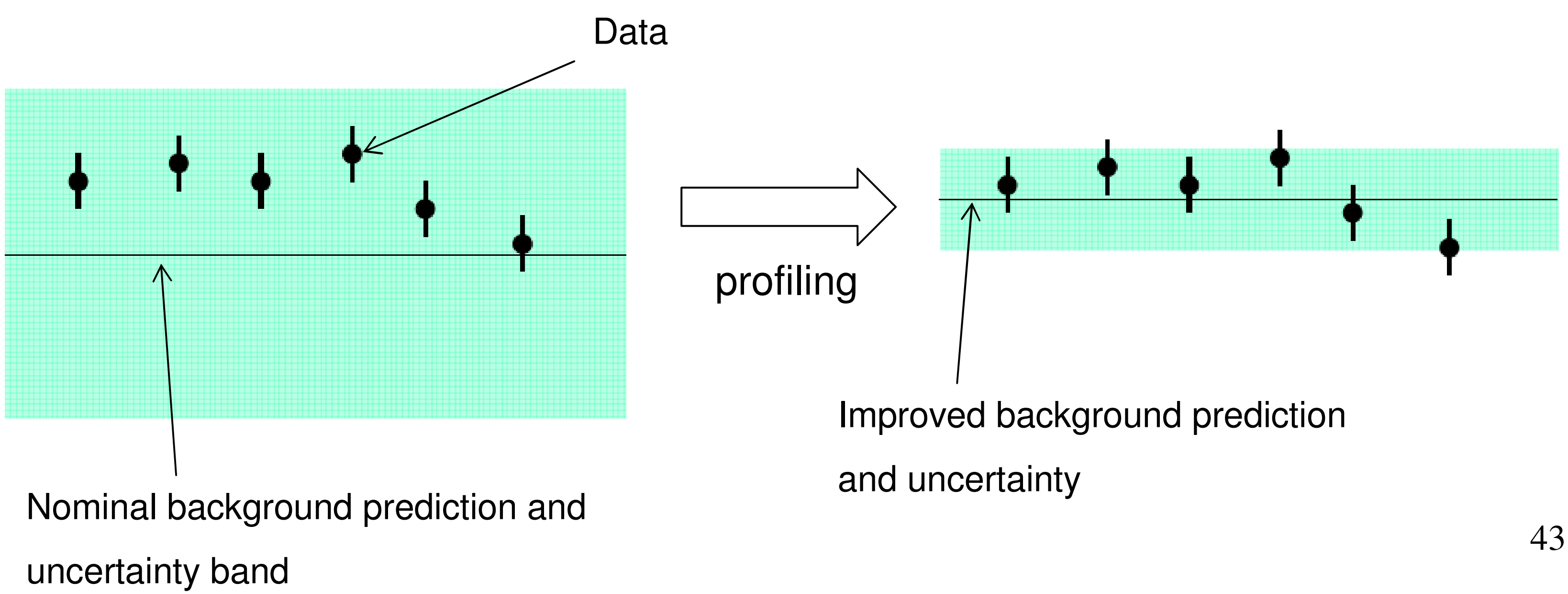
LEP: small background, small systematic uncertainties

Tevatron: large background, large systematic uncertainties (particularly at low mass)

NEW wrt LEP: to counteract the degrading effects of systematic uncertainties, we use a "profile likelihood", obtained by fitting MC expectations to data for each outcome (analogous to "side-band fitting").

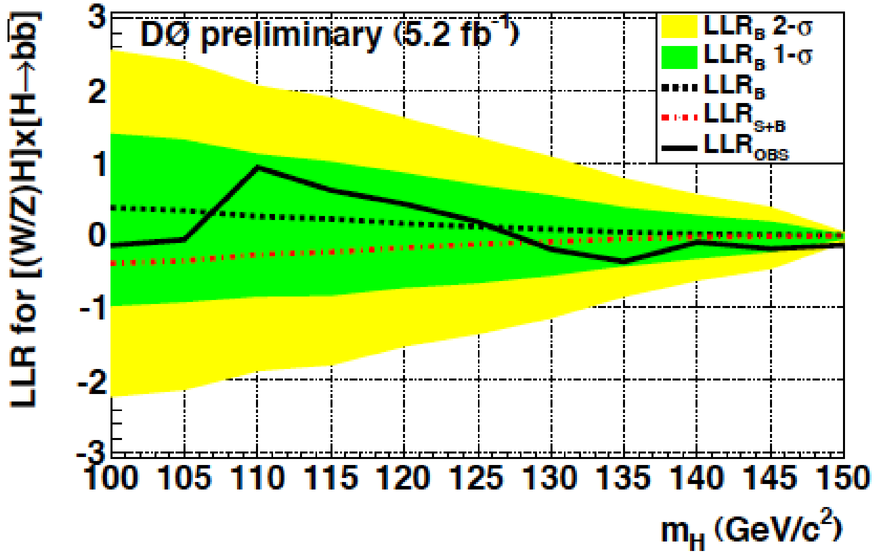
$$LLR = -2\ln Q = -2\ln\left(\frac{L(data \mid s+b;\ \hat{\theta})}{L(data \mid b;\ \hat{\theta})}\right)$$

- Capitalizes on shape and statistics of data to constrain background uncertainties.

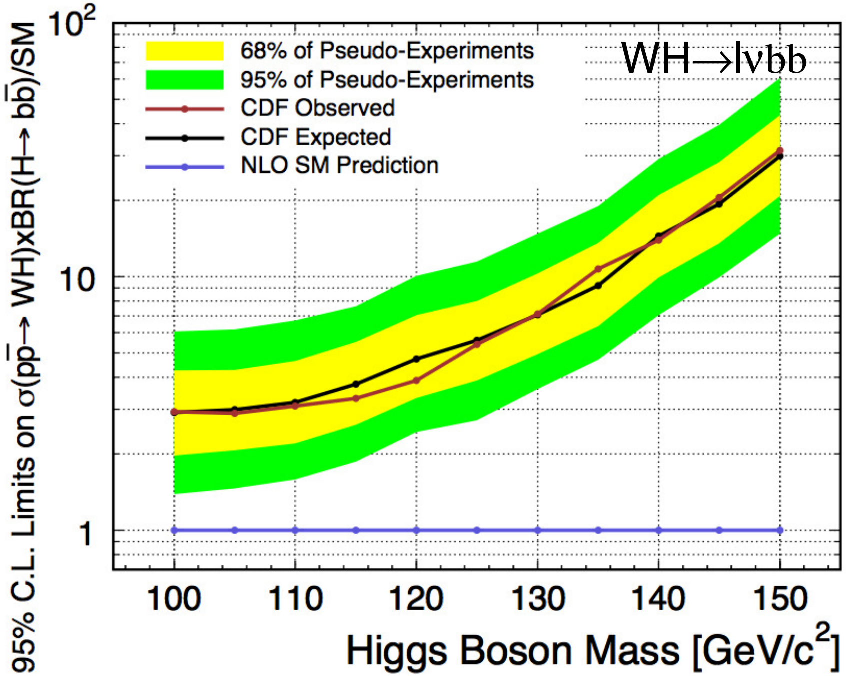


Individual Low Mass Results

Example LLR plot: ZH→ννbb



CDF Run II Preliminary, L = 4.8 fb^{-1}, 2 and 3 jets



95% CL Limits at m_H = 115 GeV

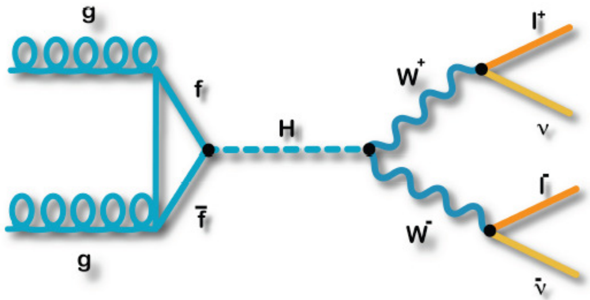
Channel	Limit (σ/SM)	
	CDF	D0
WH→lνbb	3.8/3.3	5.1/6.9
ZH→ννbb	4.2/6.1	4.6/3.7
ZH→l^+l^-bb	6.8/5.9	8.0/9.1
WH→τνbb		22/14

- Limits from individual channels typically a factor of ~4-8 larger than the SM cross section at m_H = 115 GeV.

  ➔ Combination of all contributing channels crucial.

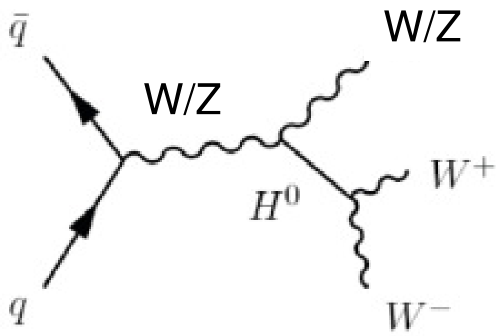
- Note fast degradation of limits for higher m_H.

High Mass SM Higgs Searches



$$H + X \to l^{+}l^{-} + \text{MET}$$

- Two opposite-sign leptons plus MET.
- Dominant contribution from gg→H→WW, but consider also VH and VBF production (~35% more signal).
- Highest sensitivity channel for m_H>135 GeV.



$$VH \to VW^{+}W^{-} \to l^{\pm}l^{\pm} + X,\ l^{\pm}l^{\pm}l^{\mp} + X$$

- Two same-sign leptons and trilepton signatures.
- Provide useful sensitivity both at intermediate and high mass.

➔ Capitalize on improvements in lepton identification and multivariate techniques

$H+X\rightarrow l^+l^-+MET$: Selection and Backgrounds

Signature:
- Two opposite-sign high p_T isolated leptons
- Large MET
- Broad invariant mass distribution

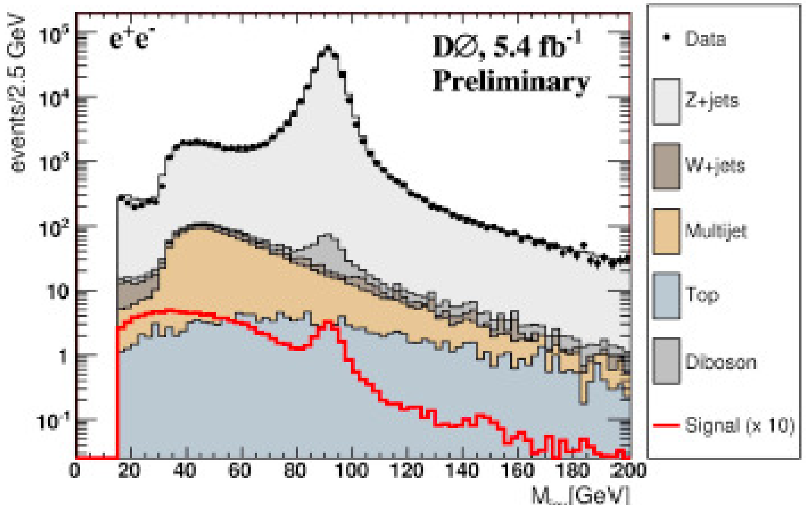
Instrumental backgrounds:
- $Z/\gamma^*\rightarrow l^+l^-$: mismeasured MET
- W+jet/γ: jet/photon misidentified as lepton
- Multijet: both fake jets and MET

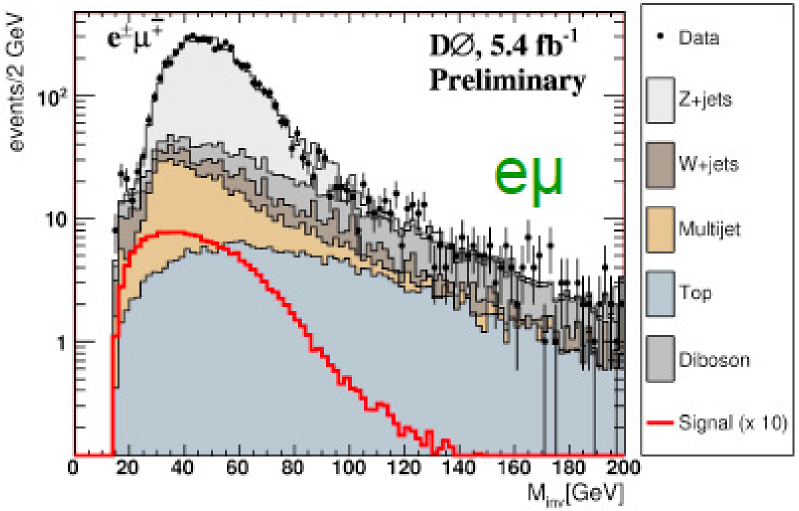
Physics backgrounds:
- Diboson: dominated by $WW\rightarrow l\nu l\nu$
- Top pair production

Signal and background processes normalized with highest order cross section available (NLO or better).

NLO corrections to $p_T(H)$ and $p_T(WW)$.

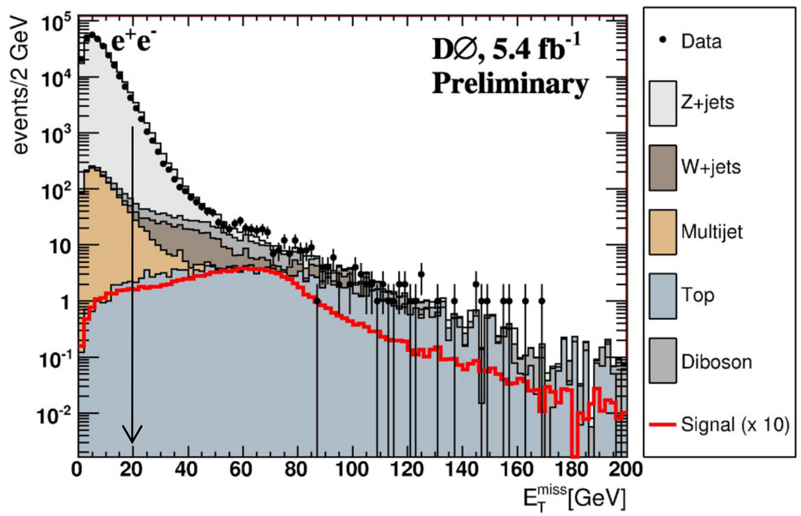
Before MET cut

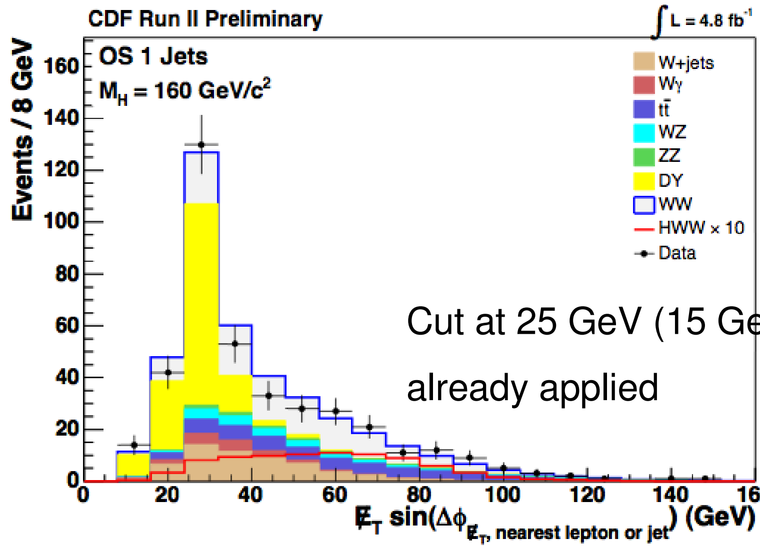




H+X→l^+l^-+MET: Analysis Strategy

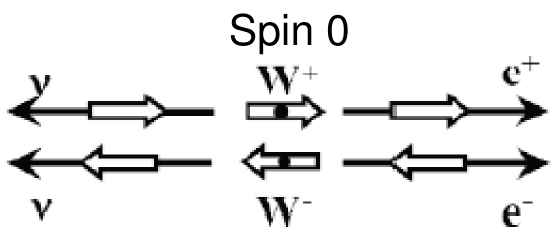
- Suppress $Z/\gamma^* \rightarrow l^+l^-$ via selections on MET and its significance.



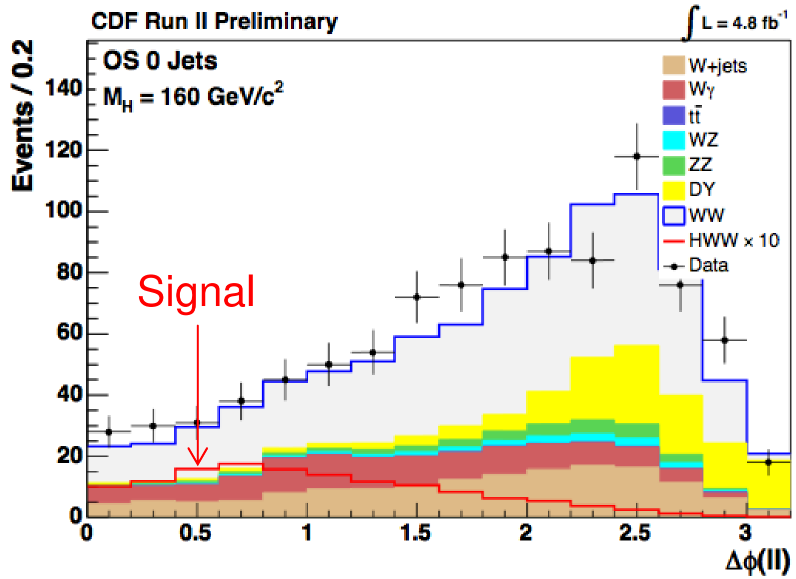


Cut at 25 GeV (15 GeV for eμ) already applied

- Exploit spin correlation between W bosons:



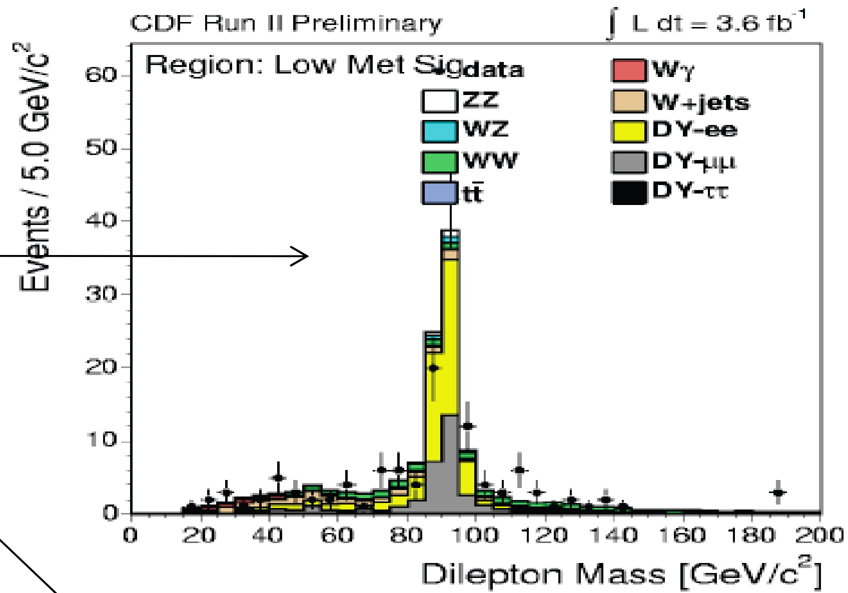
➔ Small angular separation between leptons

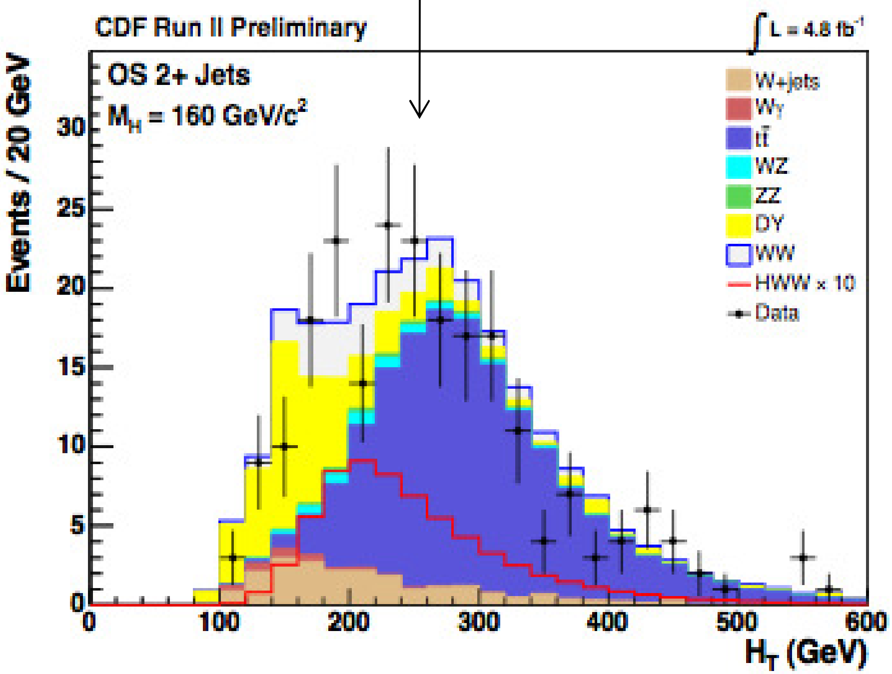


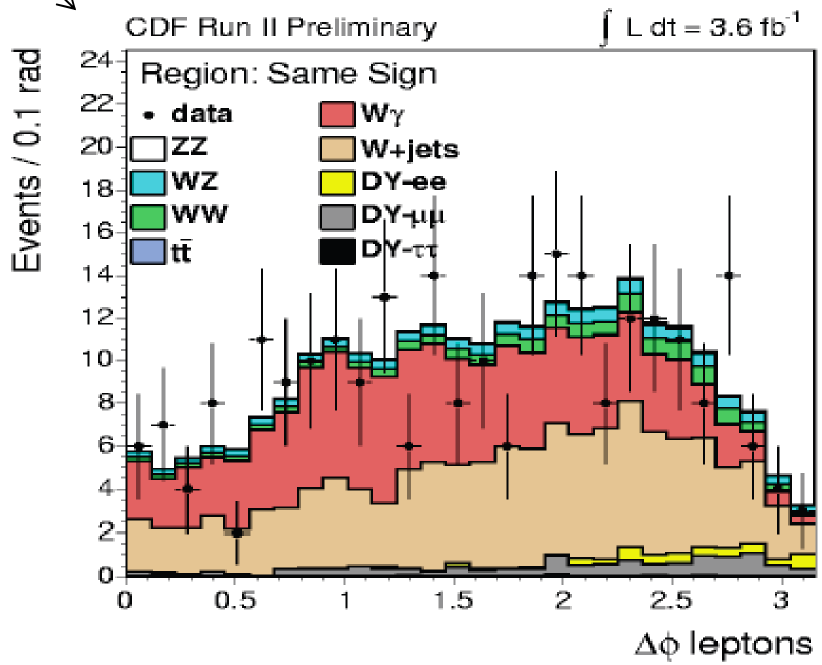
$H+X \rightarrow l^+l^-+MET$: Control Samples

Validate background modeling in signal depleted "side-bands":

- Low MET significance events: $Z/\gamma^* \rightarrow l^+l^-$
- Same-sign events: W+jet/γ
- High H_T events: top quark pairs







H+X→l^+l^-+MET: Final Discrimination

After final selection:

~30 signal events/exp (m_H=160 GeV)

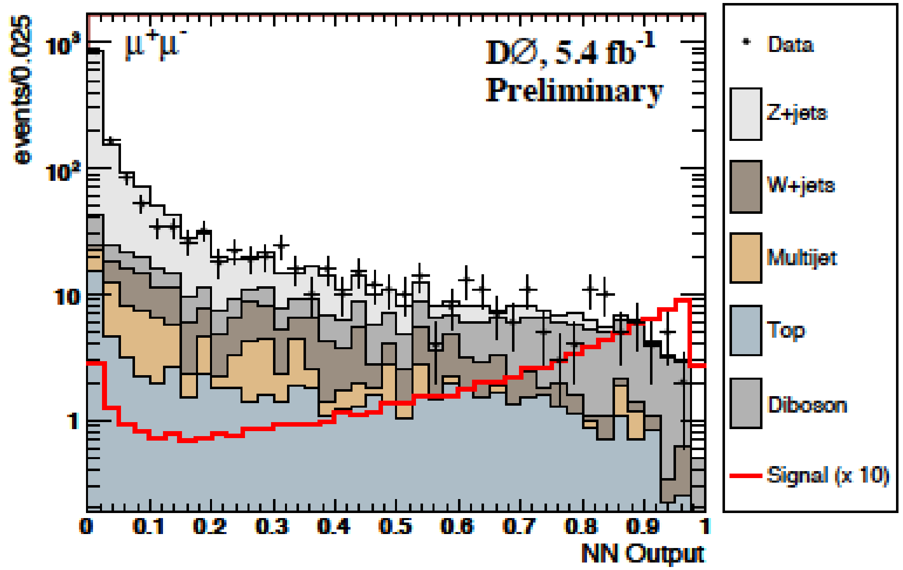
S:B~1:50

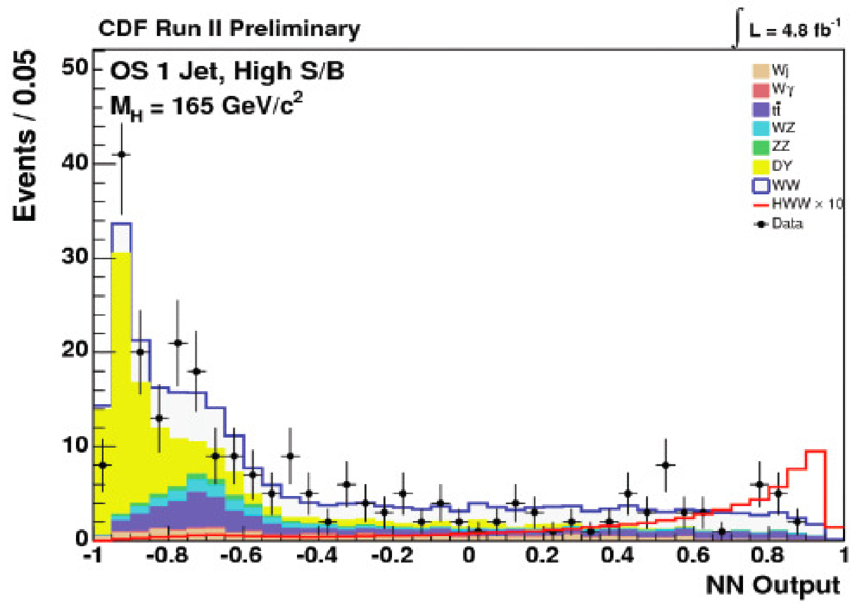
To increase the sensitivity:

- Split samples with different S:B and combine at the end:
  - by lepton flavor (D0)
  - by lepton quality or # jets (CDF)
- Add additional requirements for particular subsamples:
  - Veto b-tag in 2-jet events (CDF): suppress top quark pairs
- Build multivariate discriminants combining several variables:

E.g. D0:

Object Variables	Event Var	Topo Var
P_T^{l1} & P_T^{l2}	$M_{inv}(l,l)$	N Jets
Σ lepton P_T	$M_t^{min}(l,\not\!\!E_T)$	$\Delta\phi(l,l)$
Σ jet P_T (H_T)	$\not\!\!E_T$	$\Delta\phi(\not\!\!E_T,l_1)$
Lepton Quality	$\not\!\!E_t^{scalar}$	$\Delta\phi(\not\!\!E_T,l_2)$



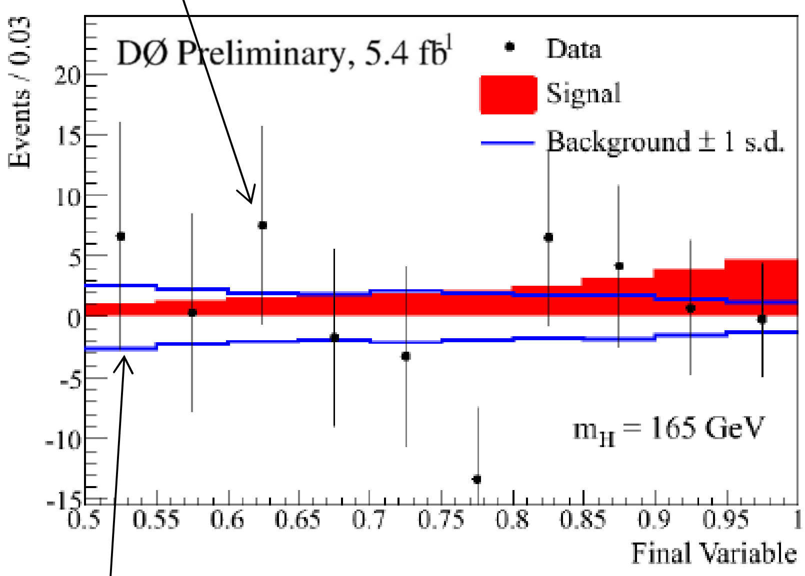


$H+X \rightarrow l^+l^- + MET$: Systematic Uncertainties

Relative uncertainties in %

Systematic Uncertainty	Type	Value
Jet Energy Scale	Shape & Norm	3-17
Jet ID Efficiency	Shape & Norm	6-18
Jet Resolution	Shape & Norm	2
Cross Sections	Flat Norm	6-10
Multijet Background	Flat Norm	2-20
Parton Distribution Function	Flat Norm	8
Lepton ID	Flat Norm	2.5-4
Lepton Momentum Scale	Shape & Norm	2-8
p_T of WW/H/Z	Shape & Norm	1-5
Luminosity	Flat Norm	6.1

Data after background subtraction



Constrained syst. uncertainty on background

Main systematic uncertainties:
- Signal (total 10%): cross section, lepton ID/trigger
- Background (total 13%): cross sections, jet→lepton fake rate, jet ID/resolution/calibration

$VH \rightarrow VW^+W^-$

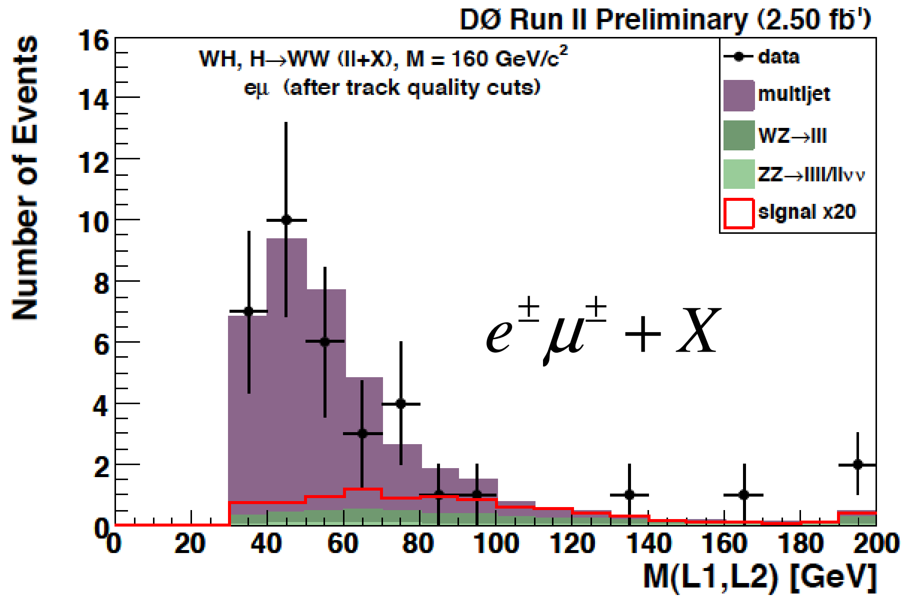
- Additional sensitivity at intermediate/high mass from VH production with H→WW.
- Control backgrounds via same-sign leptons or trilepton requirements.

$$VH \rightarrow VW^+W^- \rightarrow l^{\pm}l^{\pm} + X$$

- Main backgrounds are instrumental:
  - $Z/\gamma^* \rightarrow l^+l^-$ with charge mismeasurement
  - Multijet, W+jet/γ

Exp/obs limit (σ/SM) at m_H = 160 GeV:

CDF: 6.2/5.7 (4.8 fb^{-1})
D0: 10.7/18.2 (3.6 fb^{-1})



$$VH \rightarrow VW^+W^- \rightarrow l^{\pm}l^{\pm}l^{\mp} + X$$

- Split events w/ and w/ Z→ll candidate.
- Main backgrounds:
  - WZ, ZZ
  - WW, Z+jet/γ (fake lepton)

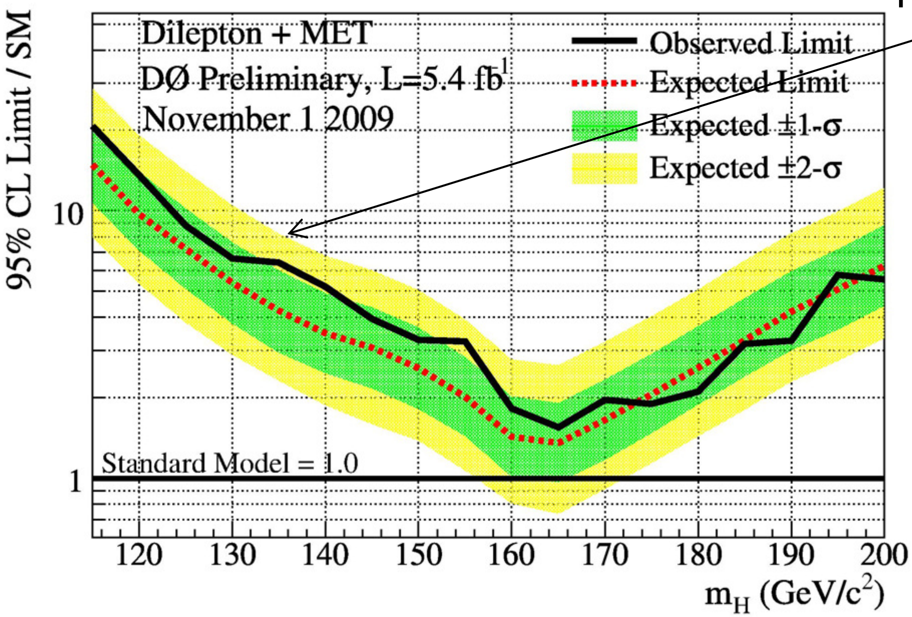
CDF (5.3 fb^{-1}) m_H=165 GeV

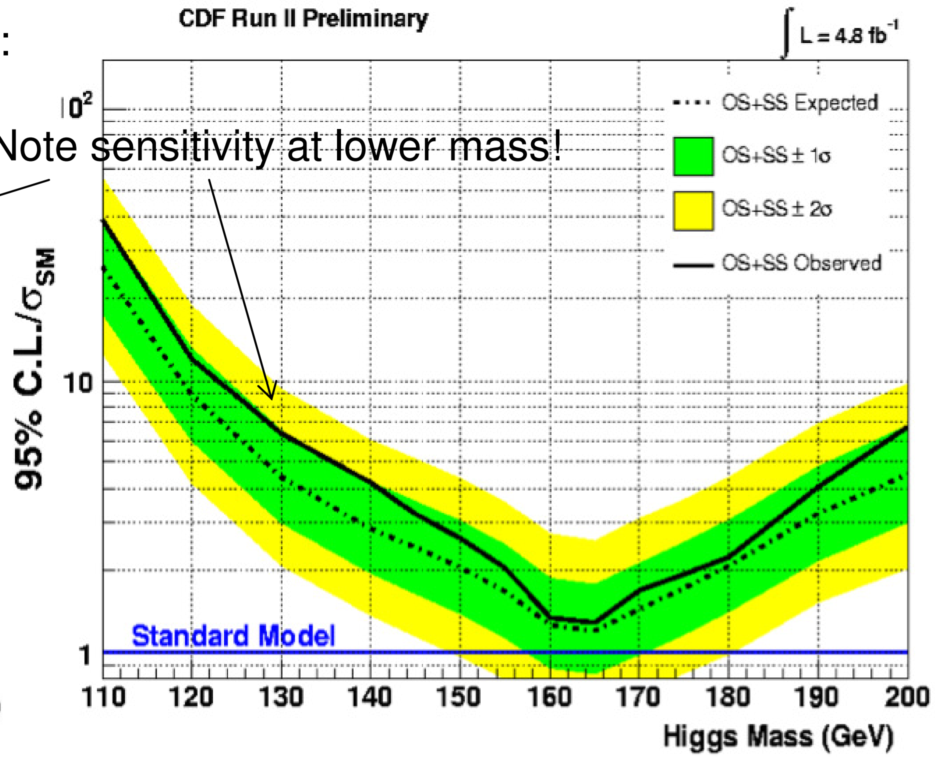
Trileptons (Z):	S/B = 0.6/33
Trileptons (no Z):	S/B = 0.8/14

Individual High Mass Results

Exclusion limits per experiment (Nov 2009):

Note sensitivity at lower mass!





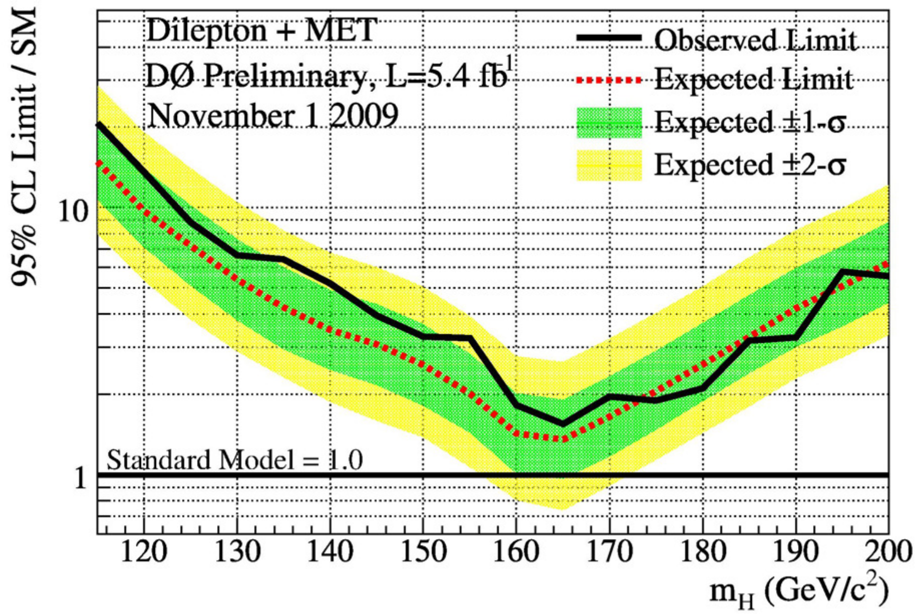
Exp/obs limit (σ/SM) at m_H = 165 GeV:

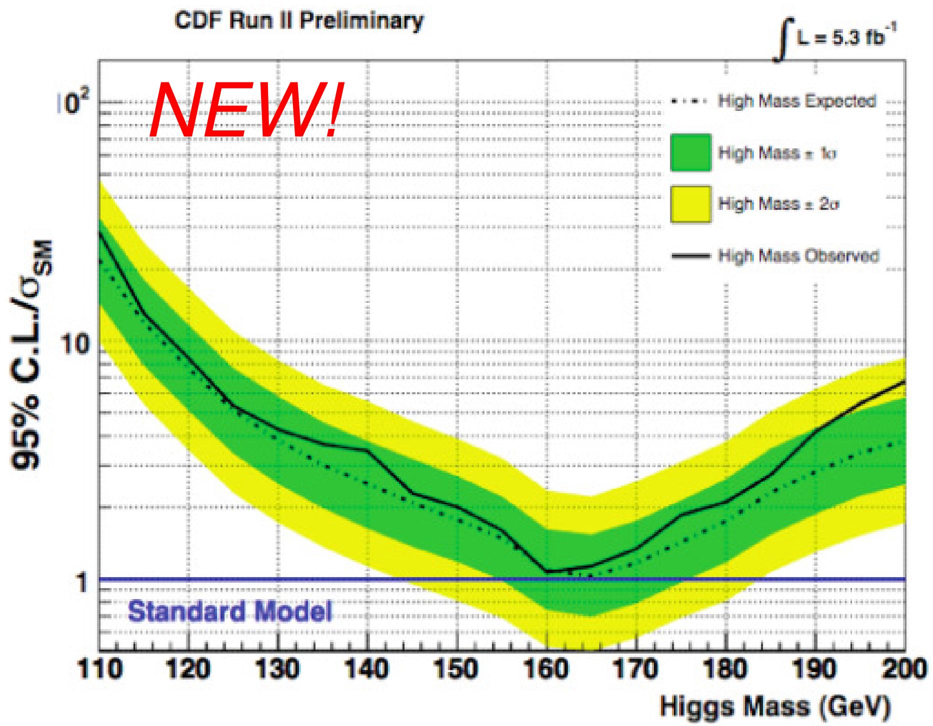
D0 (5.4 fb^{-1}) : 1.36/1.55 (only $H+X\rightarrow l^+l^-$+MET)
CDF (4.8 fb^{-1}): 1.21/1.23 (includes also $VH\rightarrow l^\pm l^\pm+X$)

➔ With additional luminosity and improvements, expect single-experiment exclusions in the near future.

Individual High Mass Results

Exclusion limits per experiment:





Exp/obs limit (σ/SM) at m_H = 165 GeV:

D0 (5.4 fb^{-1}) : 1.36/1.55 (only H+X→l^+l^-+MET)
CDF (5.3 fb^{-1}): 1.03/1.13 (includes also VH→$l^{\pm}l^{\pm}$+X and trileptons)

➔ In fact, CDF's latest update in Moriond 2010 got very close!

Combined Tevatron Limits

Full combination of all analyses from CDF and D0 for best sensitivity

- Combining more than 30 different channels per experiment.

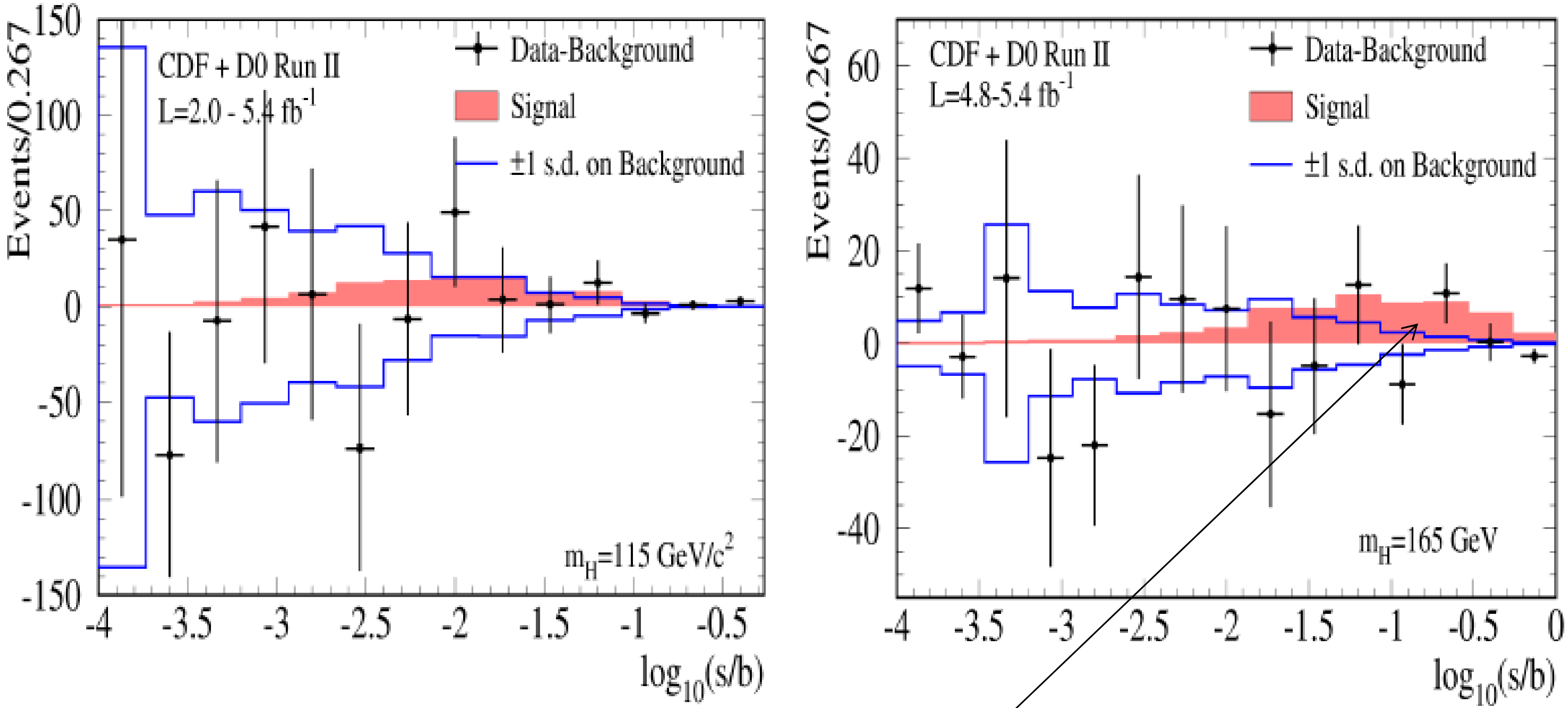
Channel	Luminosity (fb^{-1})
$WH \to \ell\nu b\bar{b}$ 2-jet channels 3×(TDT,LDT,ST,LDTX)	4.3
$WH \to \ell\nu b\bar{b}$ 3-jet channels 2×(TDT,LDT,ST)	4.3
$ZH \to \nu\bar{\nu}b\bar{b}$ (TDT,LDT,ST)	3.6
$ZH \to \ell^+\ell^- b\bar{b}$ (low,high s/b)×(TDT,LDT,ST)	4.1
$H \to W^+W^-$ (low,high s/b)×(0,1 jets)+(2+ jets)+Low-$m_{\ell\ell}$	4.8
$WH \to WW^+W^- \to \ell^\pm\nu\ell^\pm\nu$	4.8
$H + X \to \tau^+\tau^- + 2$ jets	2.0
$WH + ZH \to jjb\bar{b}$	2.0

Channel	Luminosity (fb^{-1})
$WH \to \ell\nu b\bar{b}$ 2×(ST,DT)	5.0
$VH \to \tau\tau b\bar{b}/q\bar{q}\tau\tau$	4.9
$ZH \to \nu\bar{\nu}b\bar{b}$ (ST,TLDT)	5.2
$ZH \to \ell^+\ell^- b\bar{b}$ 2×(ST,DT)	4.2
$WH \to WW^+W^- \to \ell^\pm\nu\ell^\pm\nu$	3.6
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$	5.4
$H \to \gamma\gamma$	4.2
$t\bar{t}H \to t\bar{t}b\bar{b}$ 2×(ST,DT,TT)	2.1

Analyses available as of HCP09.
Latest updates not included.

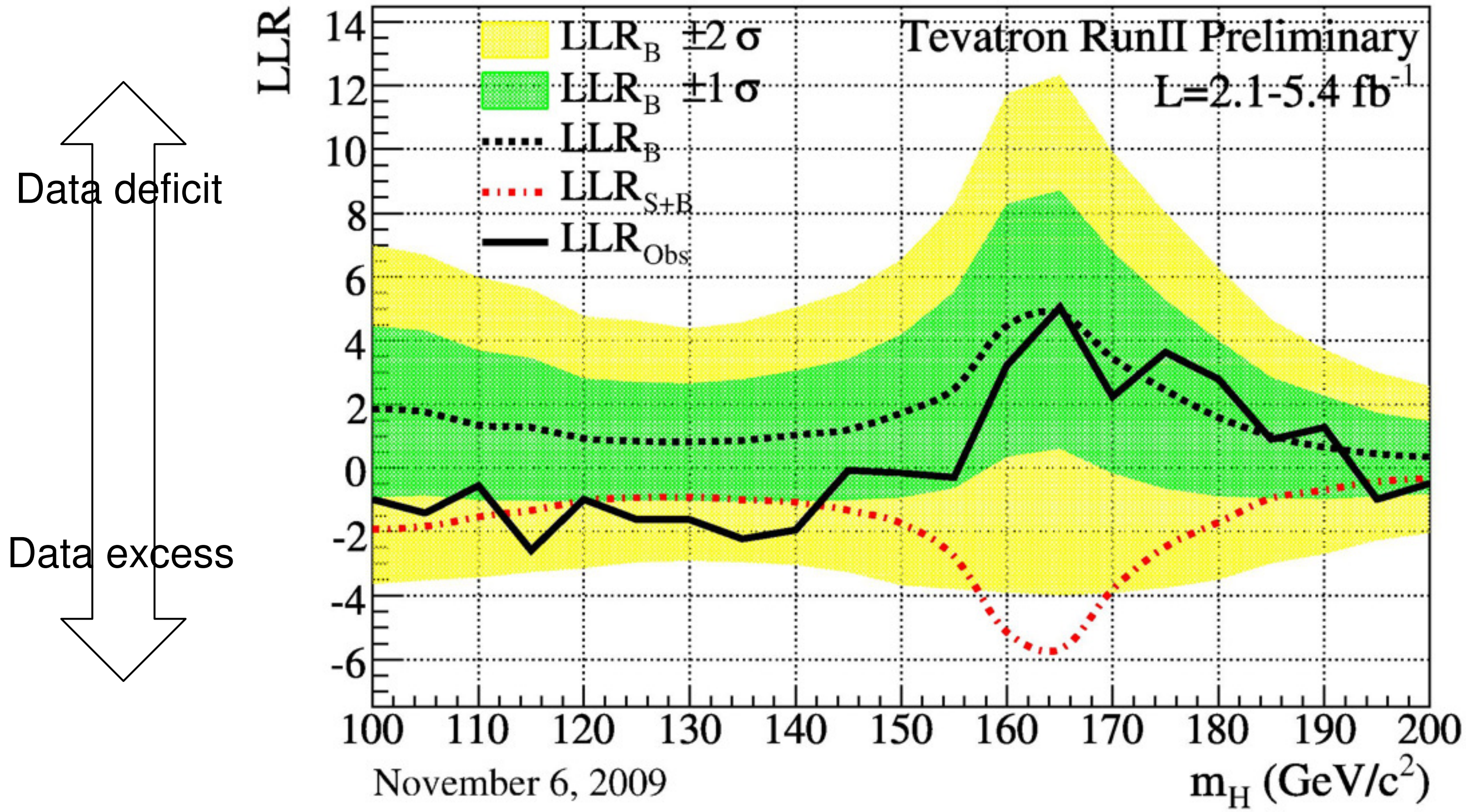
- More than 50 different sources of systematic uncertainties are considered (including correlations among channels and experiments), and constrained in sidebands.
- Use different techniques to cross check calculations (Bayesian, modified frequentist) → results agree within ~5-10%

Visualizing the Tevatron Data



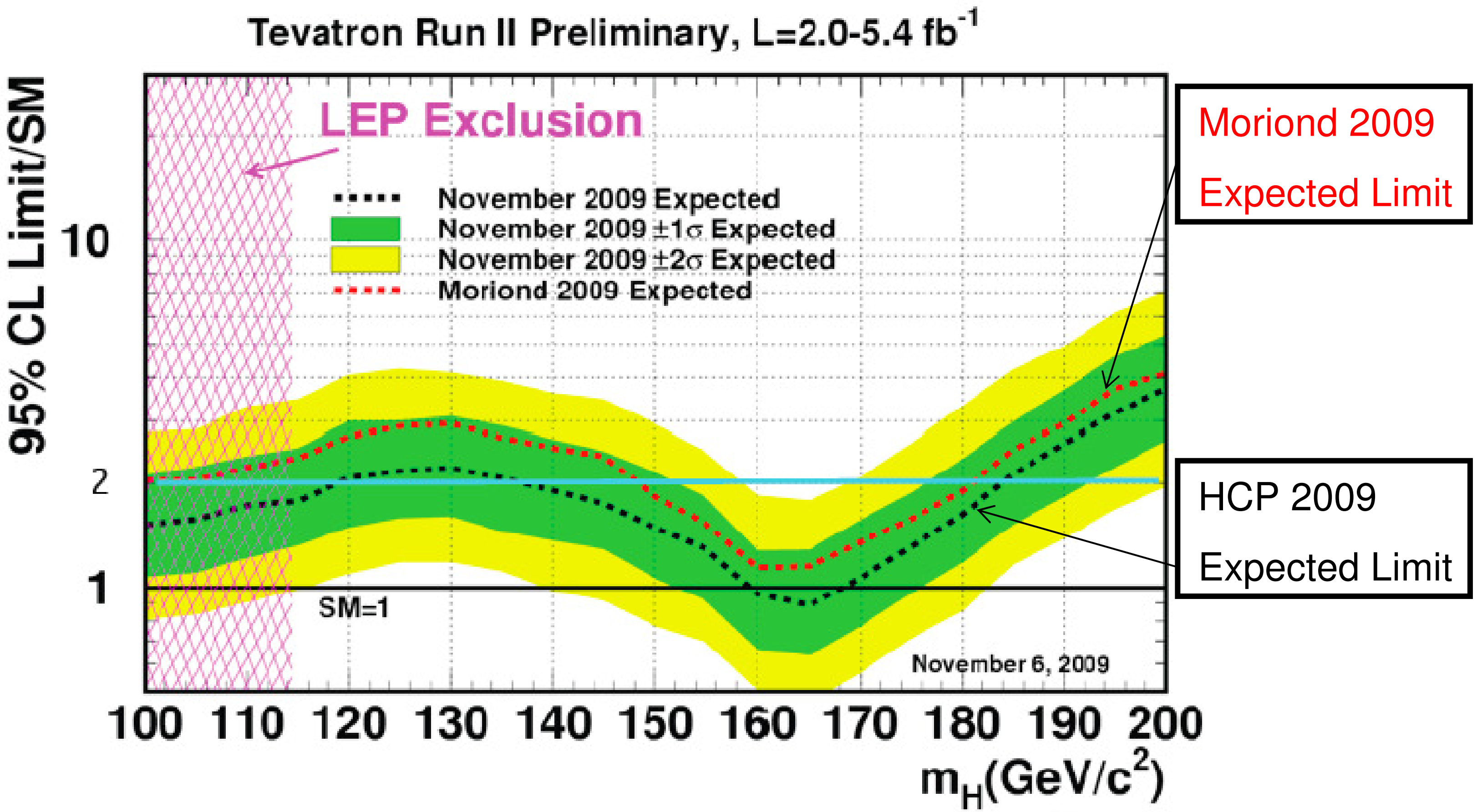
- The background model has been constrained by the data.
- Data consistent with the background-only hypothesis within the systematic uncertainties.
- Significant sensitivity at high mass!

Any Hints of a Higgs Boson?



- A-priori sensitivity >1σ up to m_H=185 GeV and >2σ for m_H=158-170 GeV.
- “Signal-like” excess at low mass but also consistent with background-only hypothesis.

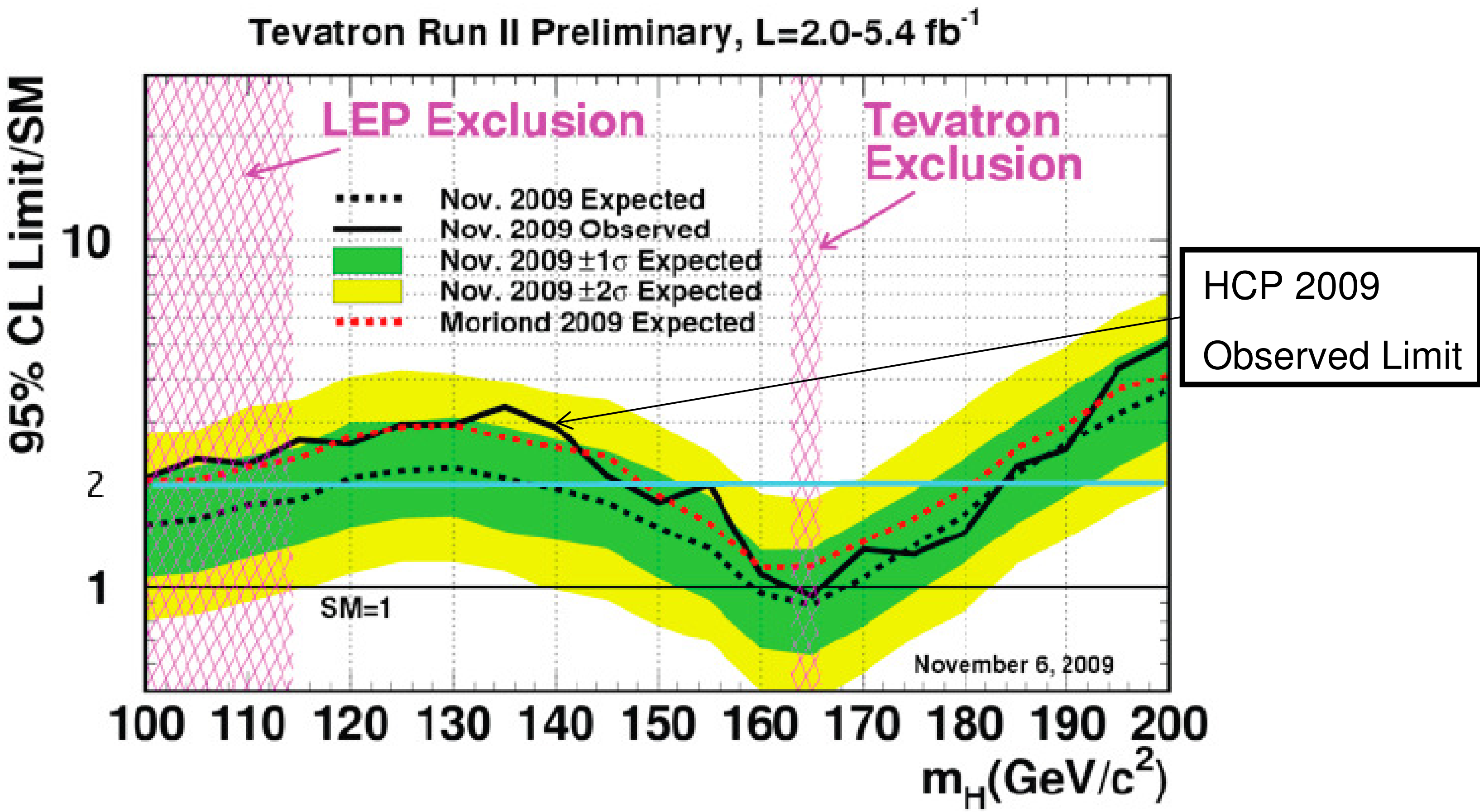
Improved Sensitivity



Significant improvements across the whole mass range since Moriond 2009:

- Expected exclusion range from 159 to 168 GeV
- Better than 2.2 x SM sensitivity for all mass points below 185 GeV
- At m_H=115 GeV expected limit 1.8 x σ_{SM}

Improved Sensitivity



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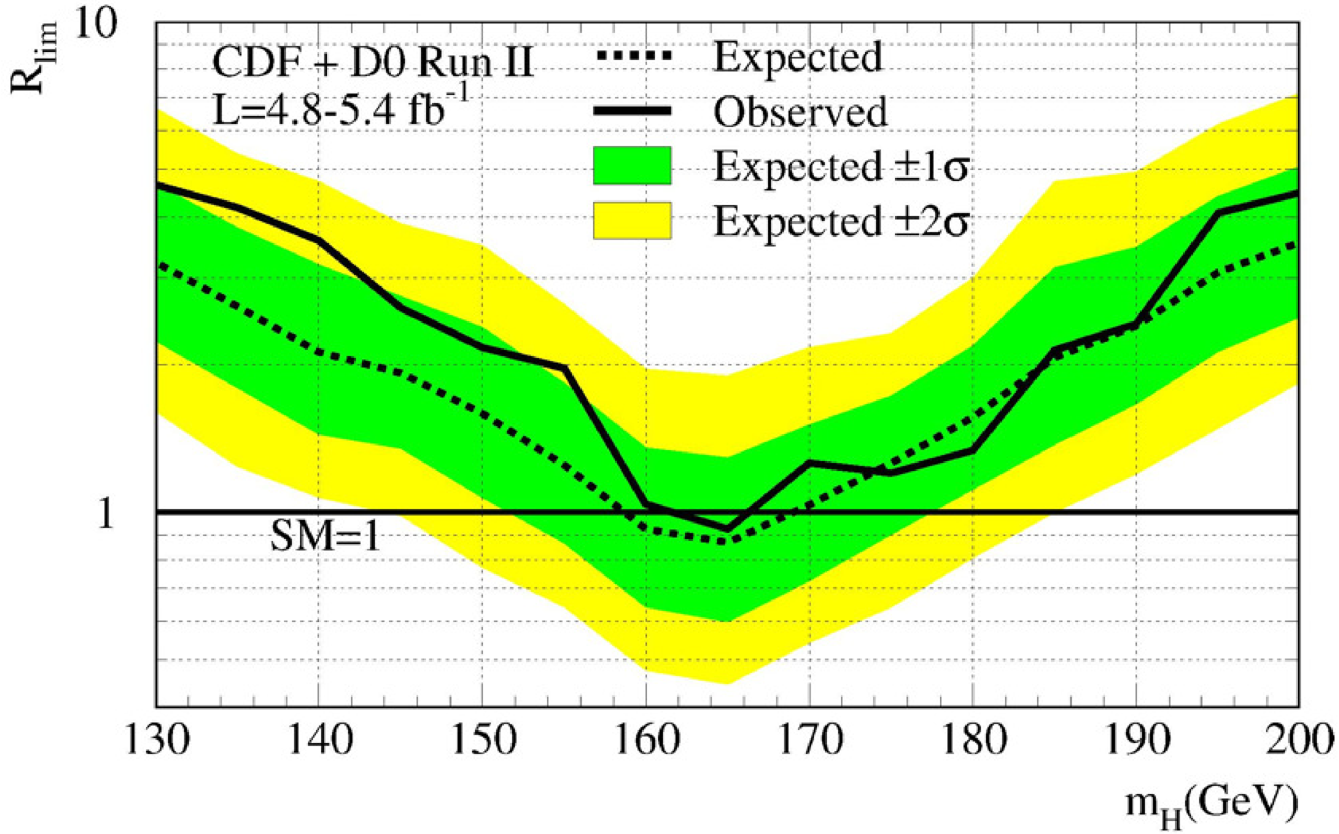
PRL 104, 061802 (2010)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 12 FEBRUARY 2010

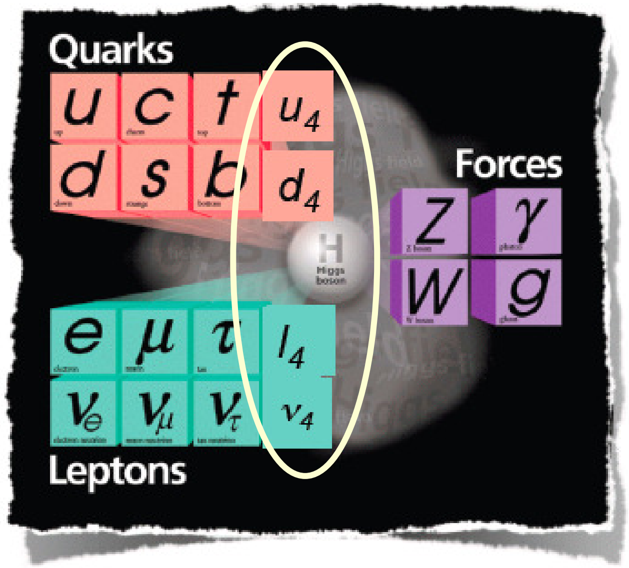
Combination of Tevatron Searches for the Standard Model Higgs Boson in the W^+W^- Decay Mode



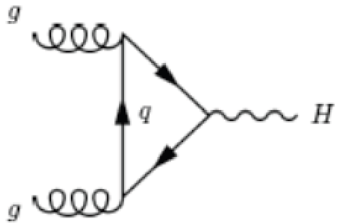
- First joint CDF+D0 publication on SM Higgs: Phys. Rev. Lett. 104, 061802 (2010).
- Set 95% C.L. exclusion: 162-166 GeV (159-169 expected).

4^{th} Generation Interpretation

- Sequential 4^{th} generation of fermions.
- Main constraints:
    - Invisible Z width at LEPI: $M_{\nu 4}$>50 GeV
    - Direct searches at Tevatron: M_{u4}>256 GeV
    - Generational mixing, EWK oblique parameters
    - LEP2 bounds for unstable ν4 : $M_{\nu 4}$>100 GeV

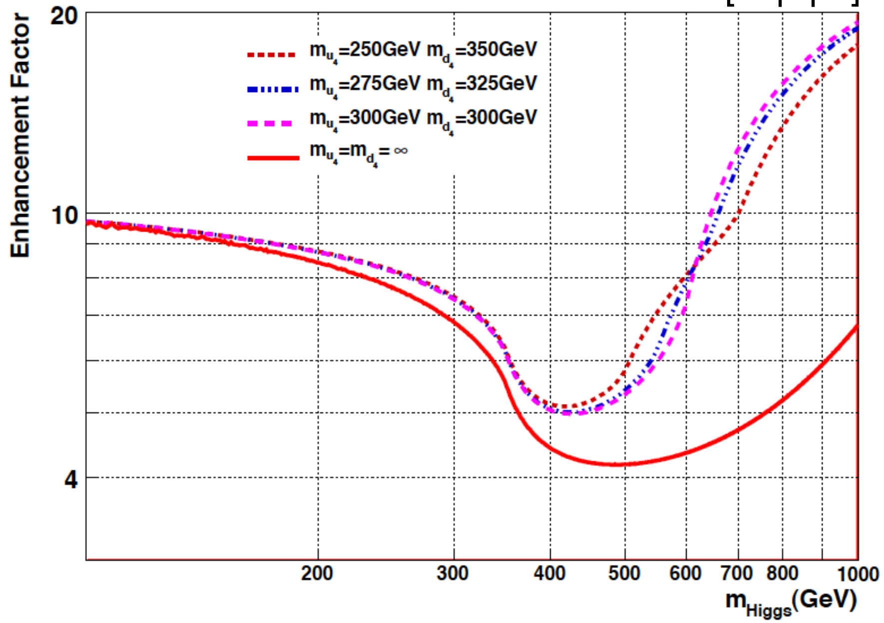


- Additional quarks enhance by x3 ggH coupling.



- Higgs production cross sections:
    - gg→H enhanced by ~x9!
    - VH and VBF remain at SM rate.

arXiv:0908.2653 [hep-ph]



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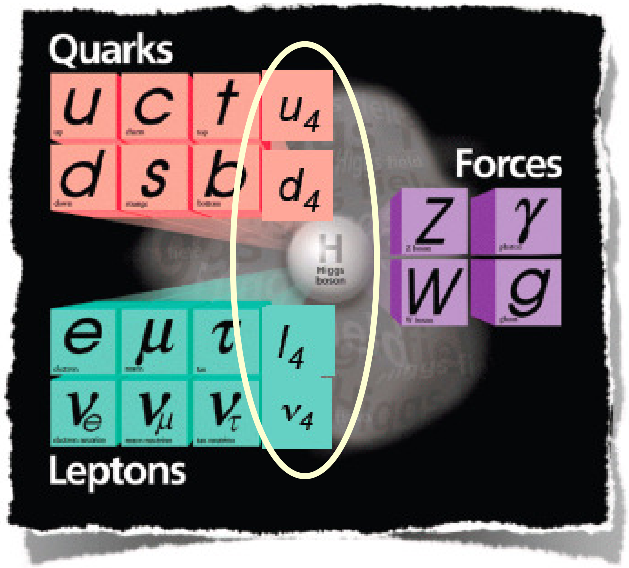

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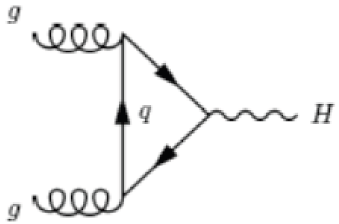

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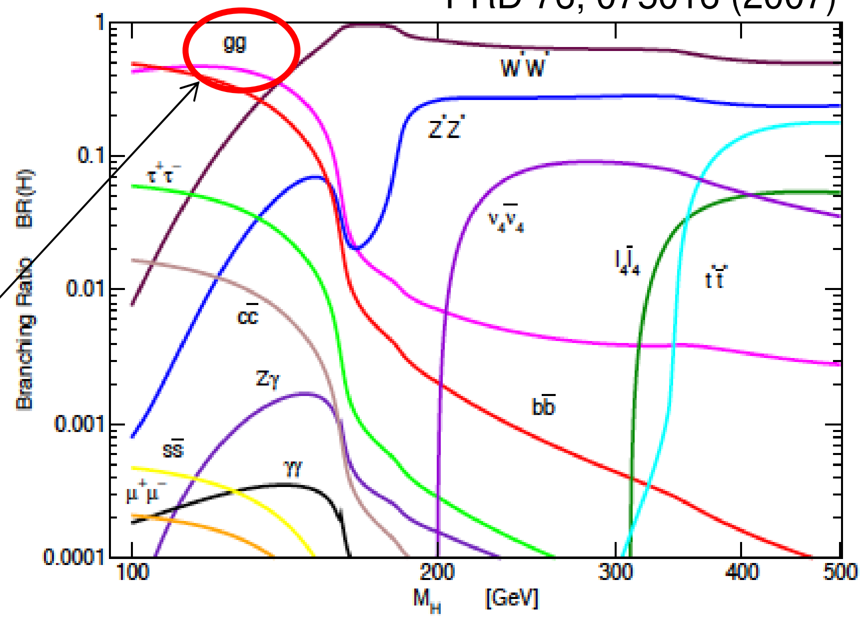
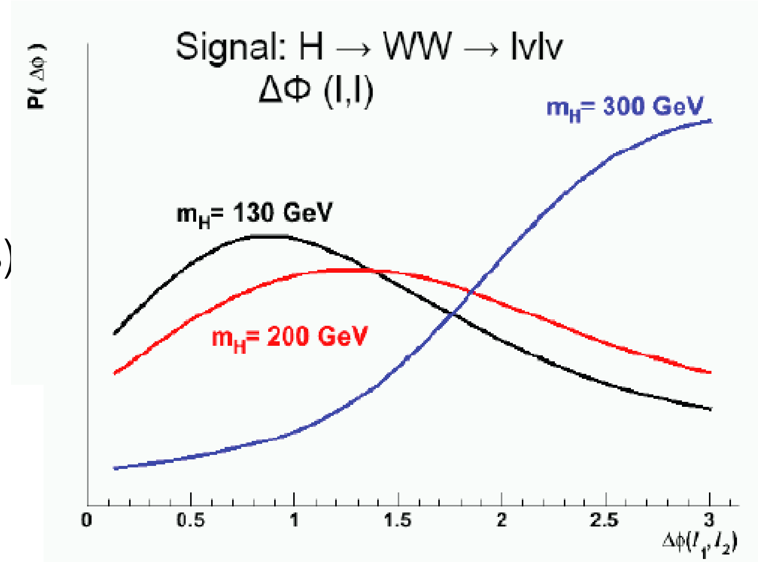
PRD 76, 075016 (2007)

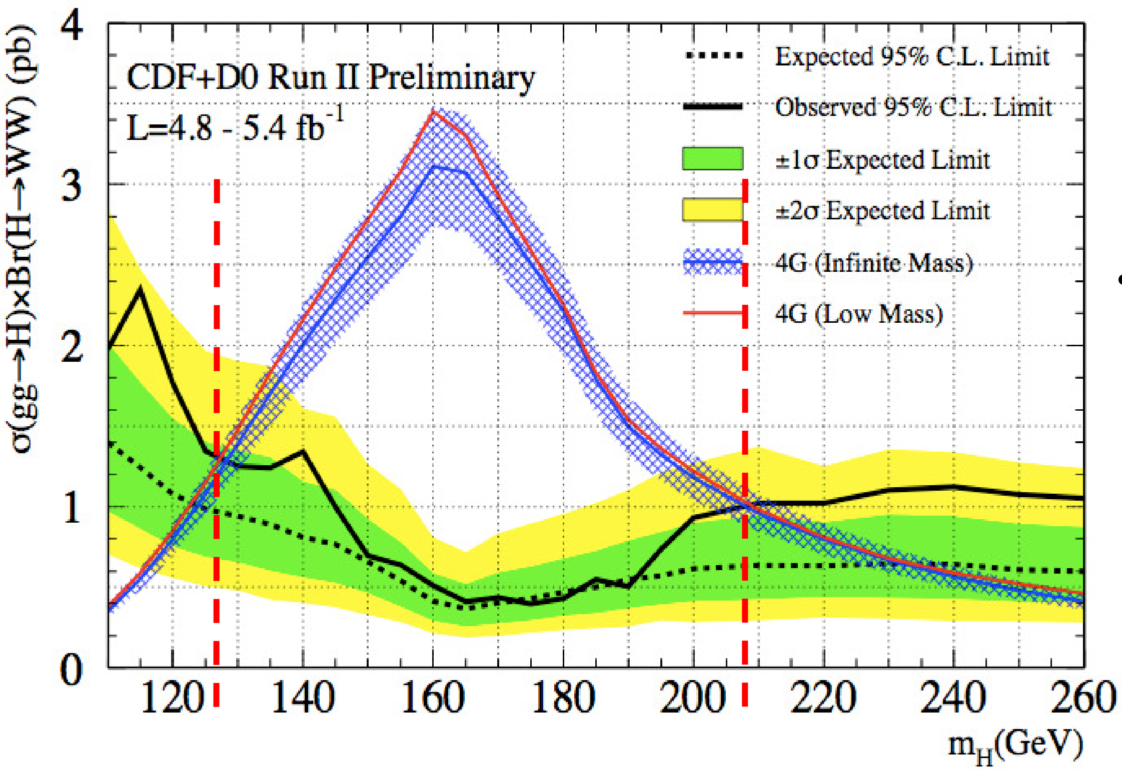


- Higgs decay BRs:
  - H→gg significantly increased at low mass.
  - H→WW dominant mode for m_H>135 GeV.

4^{th} Generation Interpretation

- Reinterpretation of SM high mass searches:
  - Consider gg→H→WW signal only.
  - Extend mass range to 260 GeV.
  - Re-optimize analysis (relax $\Delta\phi$ cuts, retrain NNs)



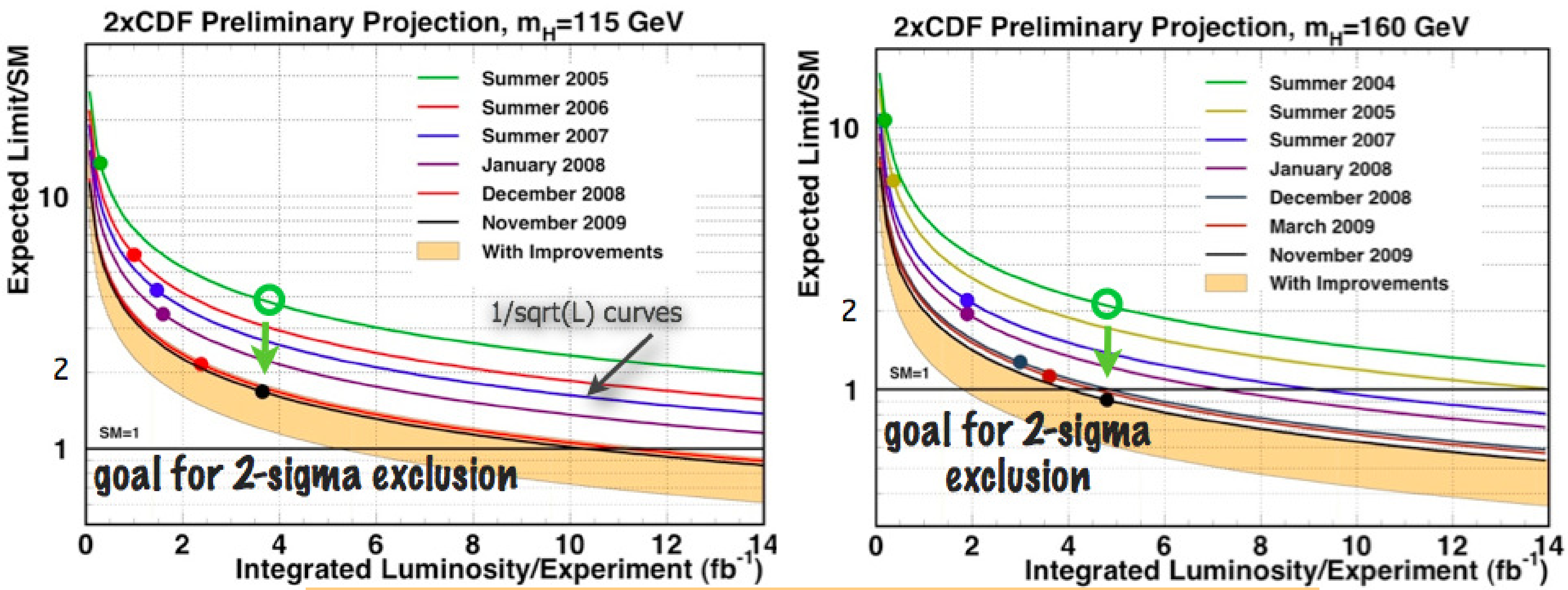


- Assuming a 4^{th} generation of fermions masses beyond currently experimental bounds:

$$\boxed{130 < m_H < 210 \text{ GeV}}$$

is excluded at 95% CL.

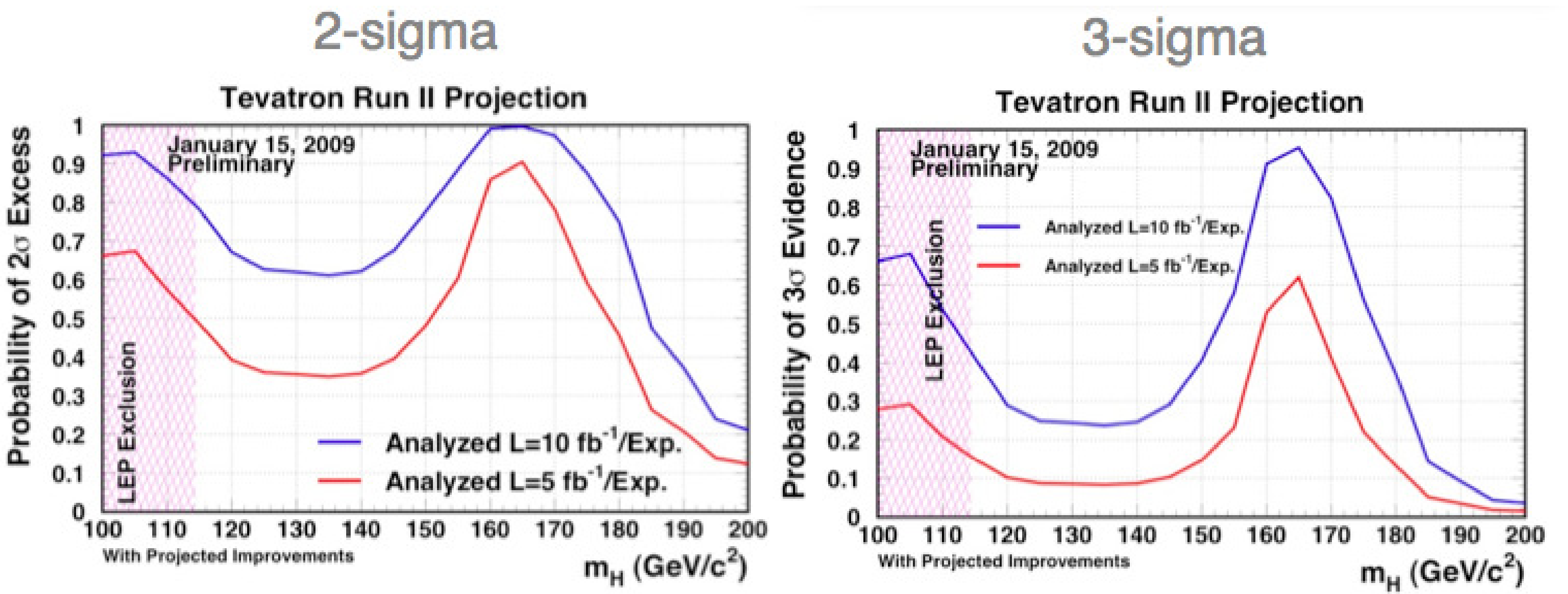
SM Higgs Prospects



Orange band: assumed analysis improvements wrt 2007 analysis (x1.5 and x2.25)

- Limits have improved faster than $1/\sqrt{L}$ due to analysis improvements.
- Major effort underway to continue to improve sensitivity:
  - Optimized object identification/resolution
  - Optimized selections and signal-to-bckg discrimination
  - Reduced systematic uncertainties
  - Adding new channels, adding more data!

SM Higgs Prospects

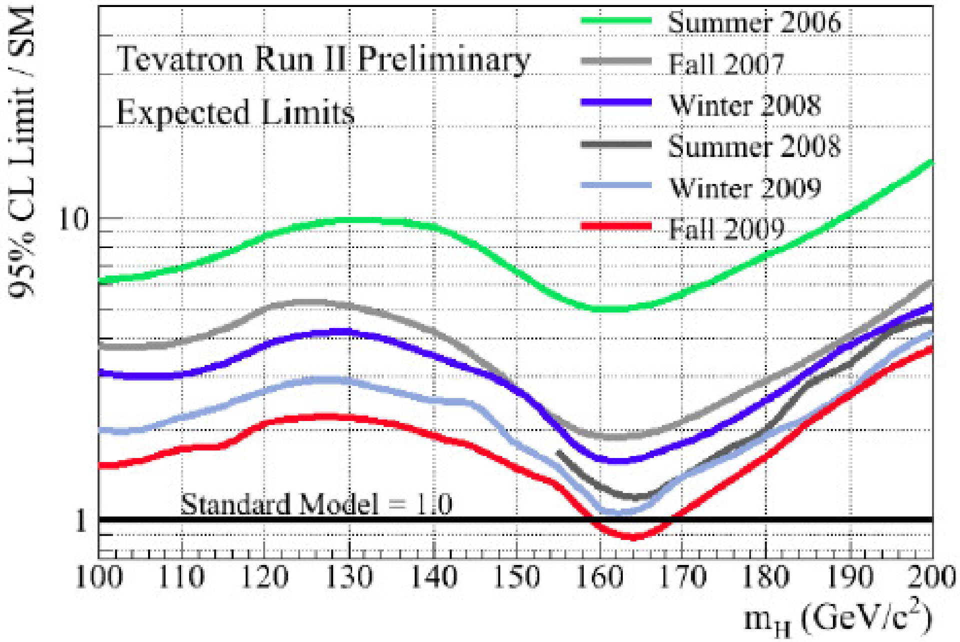


- These are "a-priori sensitivities" (i.e. not taking into account current observed limits).
- Median projected reach assuming improvements ("bottom of orange band") and 10 fb^{-1}/exp:
  - Exclude at 95% CL up to m_H~185 GeV.
  - Considerable probability of 3σ evidence at low and high mass.

→ Tevatron complements LHC at low mass (H→bb vs H→γγ, ττ)

Conclusions

- The Tevatron Higgs program continues to make steady progress in sensitivity thanks to the excellent performance of the accelerator and detectors and continued improvements in algorithms and analysis techniques.

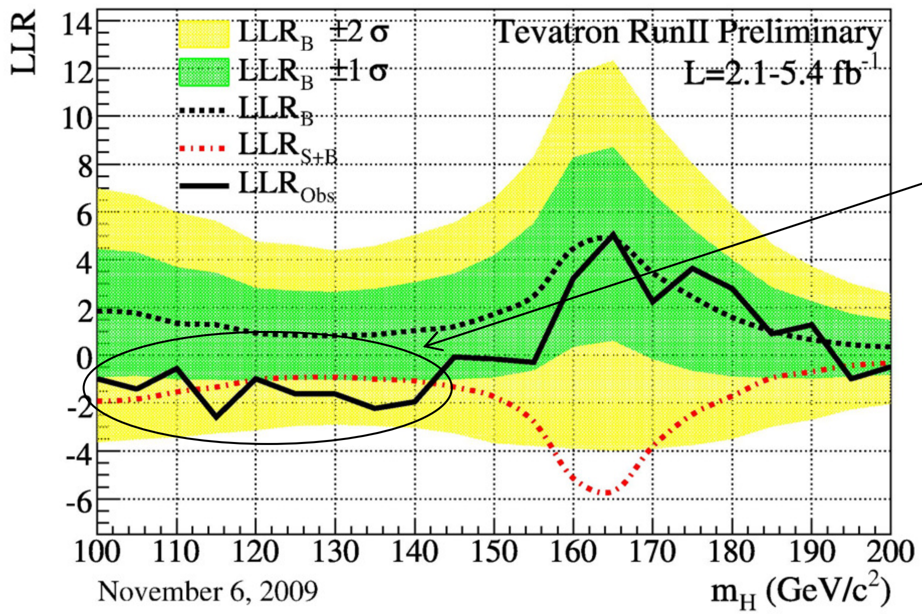


Expect to double dataset with FY11 running!

- With 10 fb^{-1}/exp + additional improvements underway expect to be able to exclude at 95% C.L. up to m_H~185 GeV (if the Higgs doesn't exist)….

Conclusions

- The Tevatron Higgs program continues to make steady progress in sensitivity thanks to the excellent performance of the accelerator and detectors and continued improvements in algorithms and analysis techniques.



- With 10 fb^{-1}/exp + additional improvements underway expect to be able to exclude at 95% C.L. up to m_H~185 GeV (if the Higgs doesn't exist)….
  … or we may have first evidence!

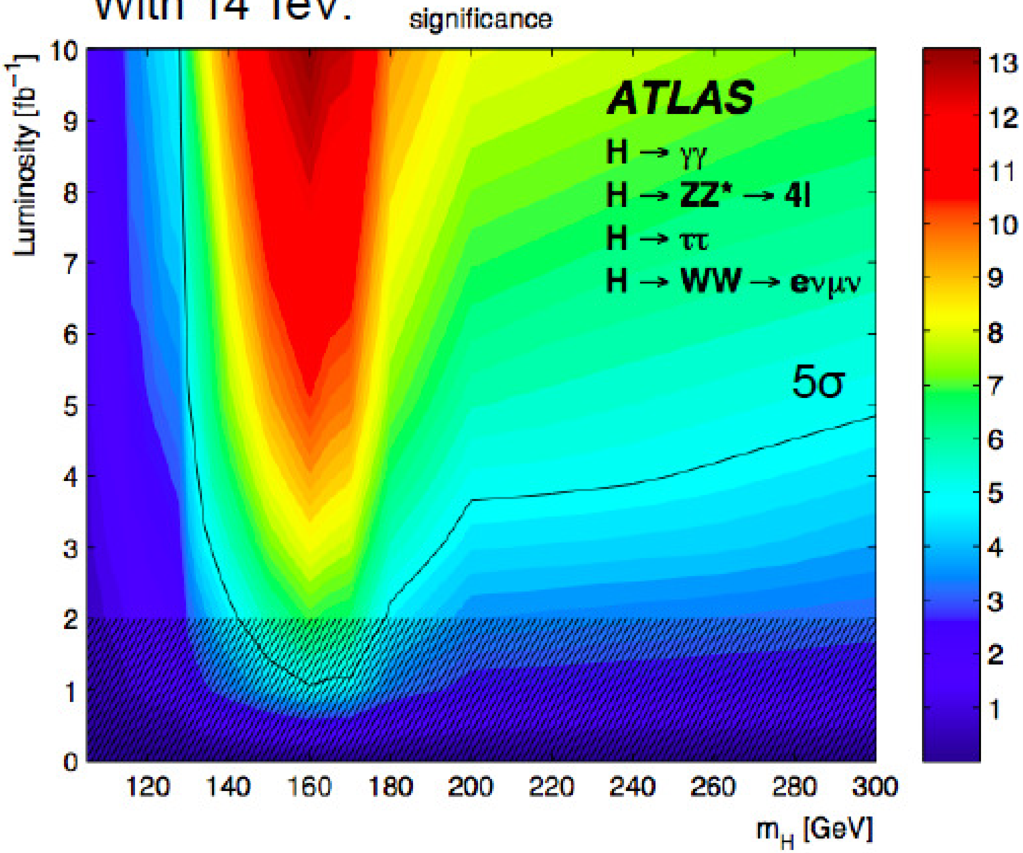
Exciting prospects for concurrent analysis of Tevatron and LHC data!

Backup

LHC discovery potential

ATLAS as an example, similar conclusions from CMS

With 14 TeV:



$m_H > 130$ GeV

Main channels $H \to WW$ and $H \to ZZ$

Discovery with few fb^{-1} up to masses favourable by the SM possible

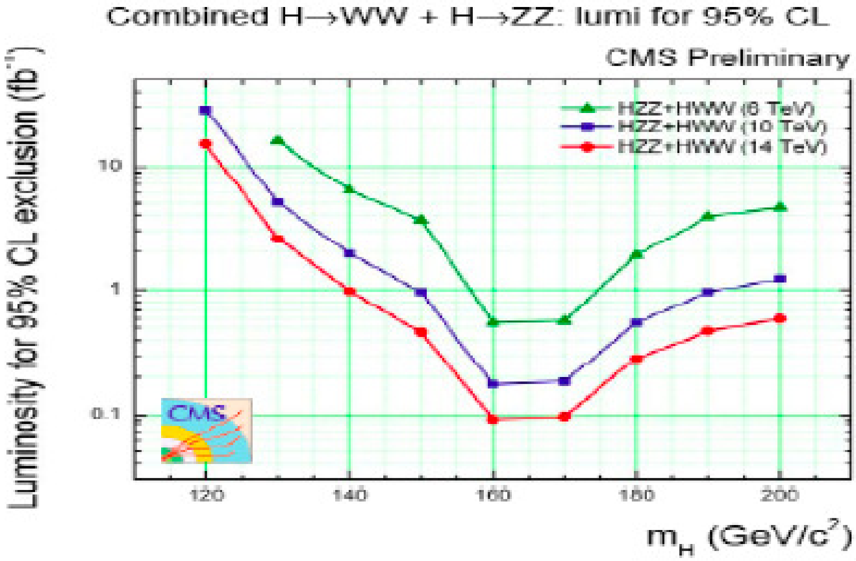
$m_H < 130$ GeV

Main channels $H \to \gamma\gamma$ and $H \to \tau\tau$

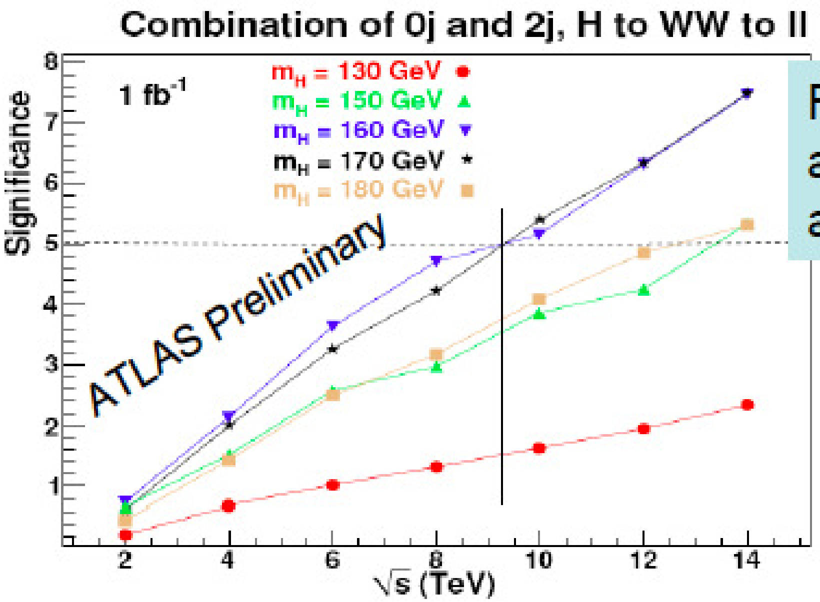
Challenging, a few years of running may be needed

CERN-OPEN-2008-020

Input to Charmonix Workshop



Luminosity needed for 95% CL exclusion at 10 TeV (m_H~160 GeV): 0.2 fb^{-1}



Fast Simulation and simplified analysis

> 5σ possible for m_H~160 GeV at 10 TeV and ~1fb^{-1} good data

Cross section calculations

Using up-to-date cross section calculations (arXiv:hep-ph/0607308 except where noted):

- **gg→H:** NNLL QCD, b quark contribution at NLO, 2 loop ewk corrections, changed since last Summer (arXiv:0901.2427 [hep-ph]), newer PDF set, consistent choice of α_s, 10% uncertainty
  - +12% at M_H=100 GeV
  - -8% at M_H=200 GeV
  - -4% at M_H=170 GeV
- **WH/ZH:** NNLO in QCD, NLO ewk, 5% uncertainty
- **Vector boson fusion:** NLO QCD, 10% uncertainty

CDF and DØ using common values (and correlated uncertainties) for cross sections of background processes: tt and single top (10%), diboson production (6%)

W/Z+jets(heavy flavour): considered uncorrelated (constrainted from data)
Multijet background: estimated from data (uncorrelated)

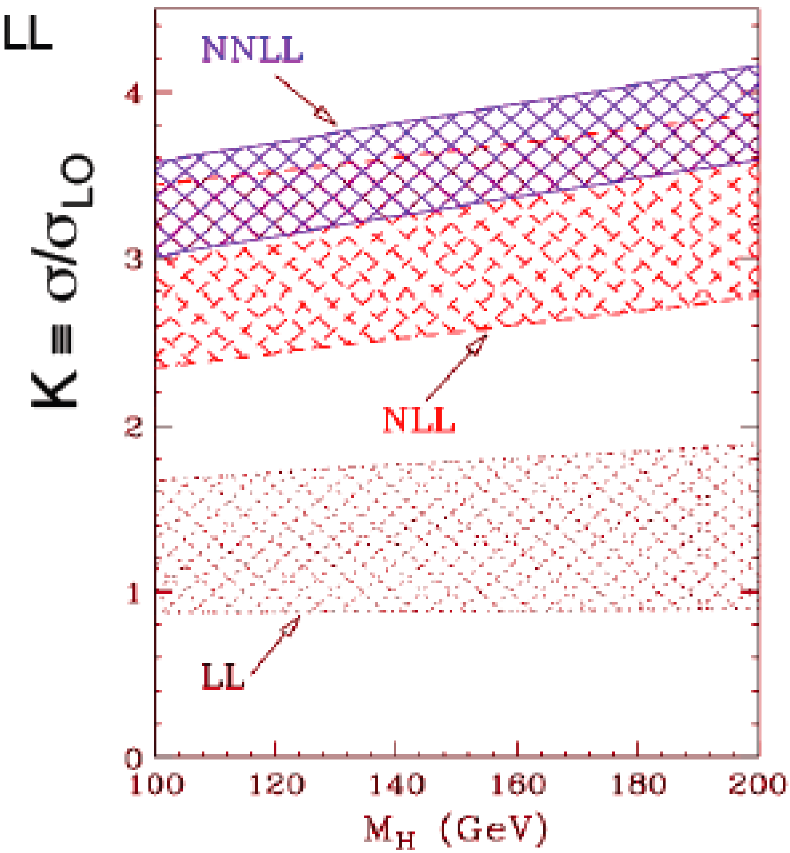
Recent gg→H Production Cross Section Progress

- NLO corrections -- ~80% (almost double the cross section)!
- NNLO QCD corrections -- An additional 40% on top of that!
  Residual uncertainty ~10%. Catani, de Florian, Grazzini, Nason
  JHEP **0307**, 028 (2003) hep-ph/0306211

Also resummed QCD corrections at NNLL

NLL,NNLL bands: $0.5m_H < \mu_F, \mu_R < 2M_H$.
Bands on LO and LL unreliable.

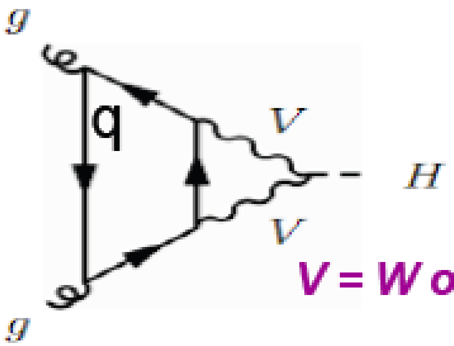
We take a ±12% uncertainty
on $\sigma_{gg\to H}$ for scale and PDF



Recent gg→H Production Cross Section Progress

- Two-loop EW corrections yield up to an 8% boost in cross section
- b-quark QCD corrections improved
- Total 14% bigger cross section at m_H=160 GeV relative to NNLO

2-Loop EW diagram:
6 quark flavors contribute



V = W or Z

Catani, de Florian, Grazzini, JHEP **0307**, 028 (2003)
Aglietti, Bonciani, Degrassi and Vicini, Phys. Lett. B 595, 432 (2004)
Used by the Tevatron at ICHEP08

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)
http://www.itp.uzh.ch/events/higgsboson2009 7-9 Jan.2009, Zurich
Used by the Tevatron at Moriond 2009

Parton Distribution Functions Are Important for gg→H

- MSTW released a new PDF set on January 5, 2009
  ("MSTW 2008")
  Includes Tevatron Run II High-E_t Jet Data
  (Less of an excess than Run I data)

- Effect: high-*x* gluon PDF x α_s is less.

Impact is ~15% **downward** shift in gg→H cross section

Included in Moriond 2009 Tevatron Higgs results

Dilepton + missing E_T analysis

Changes since Moriond 2009

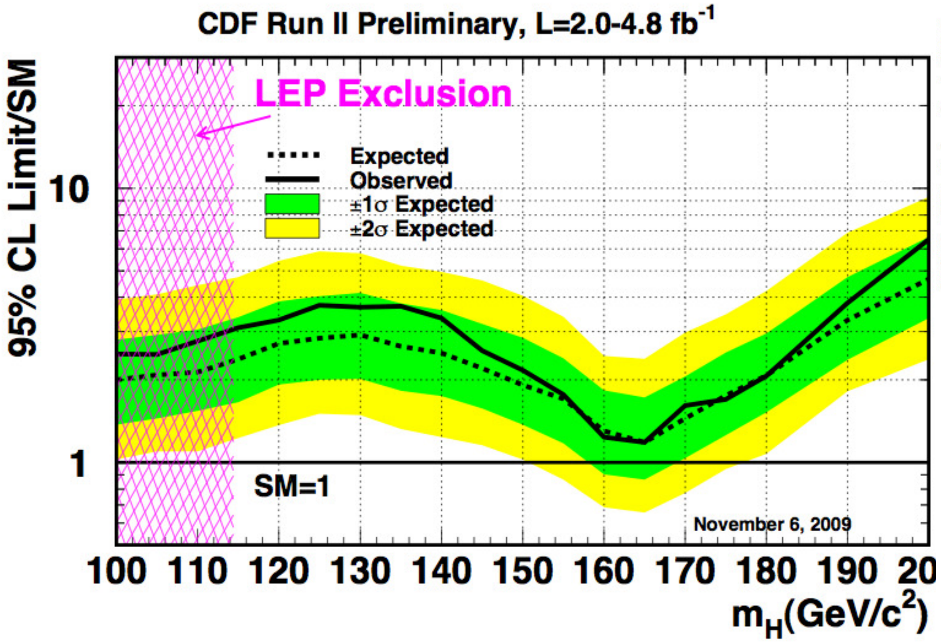
CDF:
- Increased dataset from 3.6 to 4.8 fb^{-1}
- Likelihood based central electron ID
  - 10% improvement in efficiency with same fake rate
- Additional triggerable muon categories
- Low M_{ll} analysis
- $gg \rightarrow H$ cross section systematic uncertainty depends on Njets

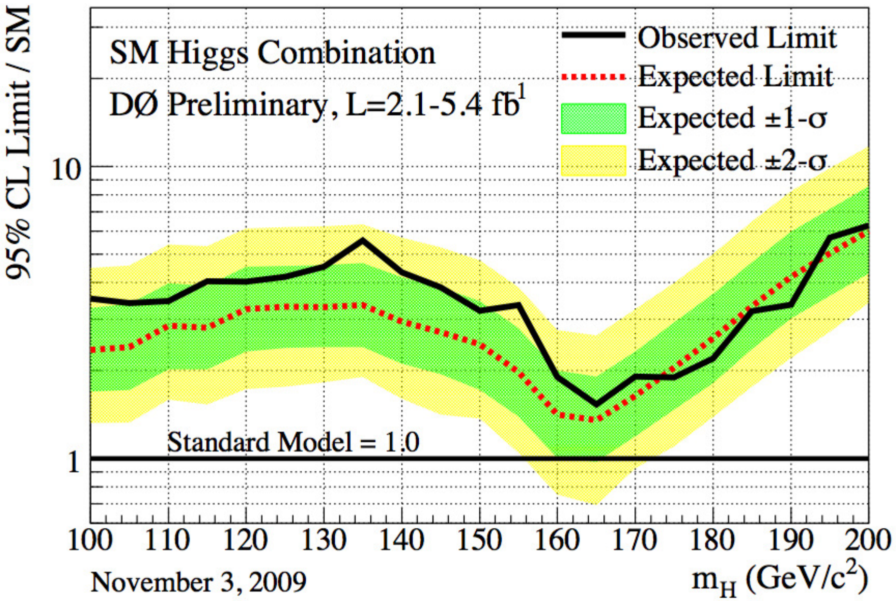
DØ:
- Increased dataset in ee and eμ channels from 4.2 to 5.4 fb^{-1} and in μμ channel from 3.0 to 5.4 fb^{-1} (adding higher jet multiplicities in μμ)
- New Neural Network
  - Now with Njets distribution and enhanced W+jets content in training
- Small changes in selection and systematics
- Small changes in background modeling

Both experiments with ~20% improvement in expected sensitivity

SM Higgs Combined Limits

- Calculation of limits and combination:
  - Using Bayesian and CLs approaches (consistent within ~5%).
  - Incorporate systematic uncertainties (including correlations) using pseudo-experiments.
  - Some uncertainties are effectively constrained by data.





At m_H = 115 GeV:

Exp. limit: 2.38 x SM
Obs. limit: 3.12 x SM

At m_H = 165 GeV:

Exp. limit: 1.19 x SM
Obs. limit: 1.18 x SM

At m_H = 115 GeV:

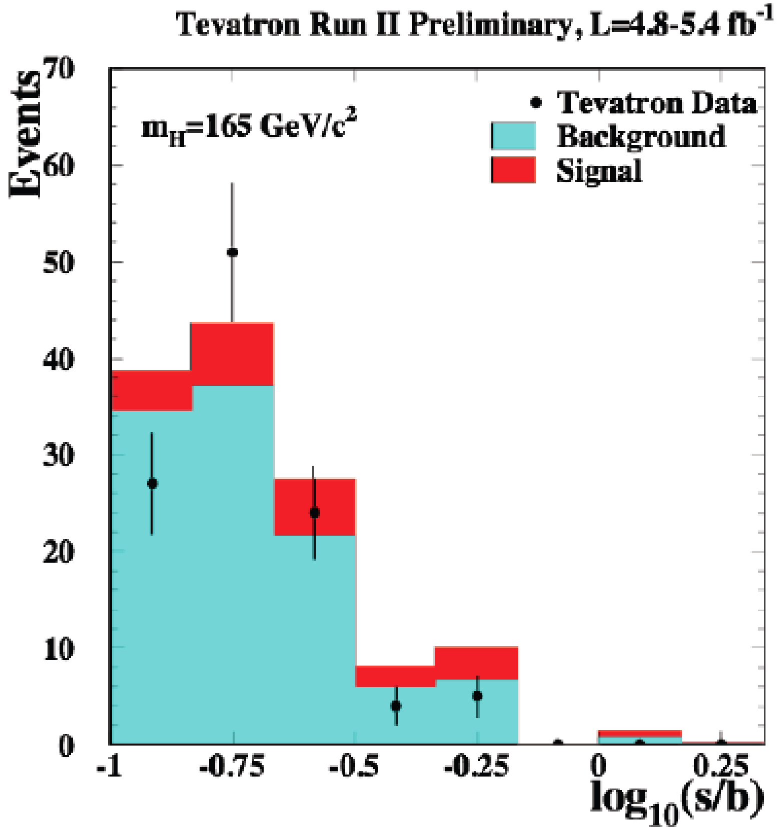
Exp. limit: 2.80 x SM
Obs. limit: 4.05 x SM

At m_H = 165 GeV:

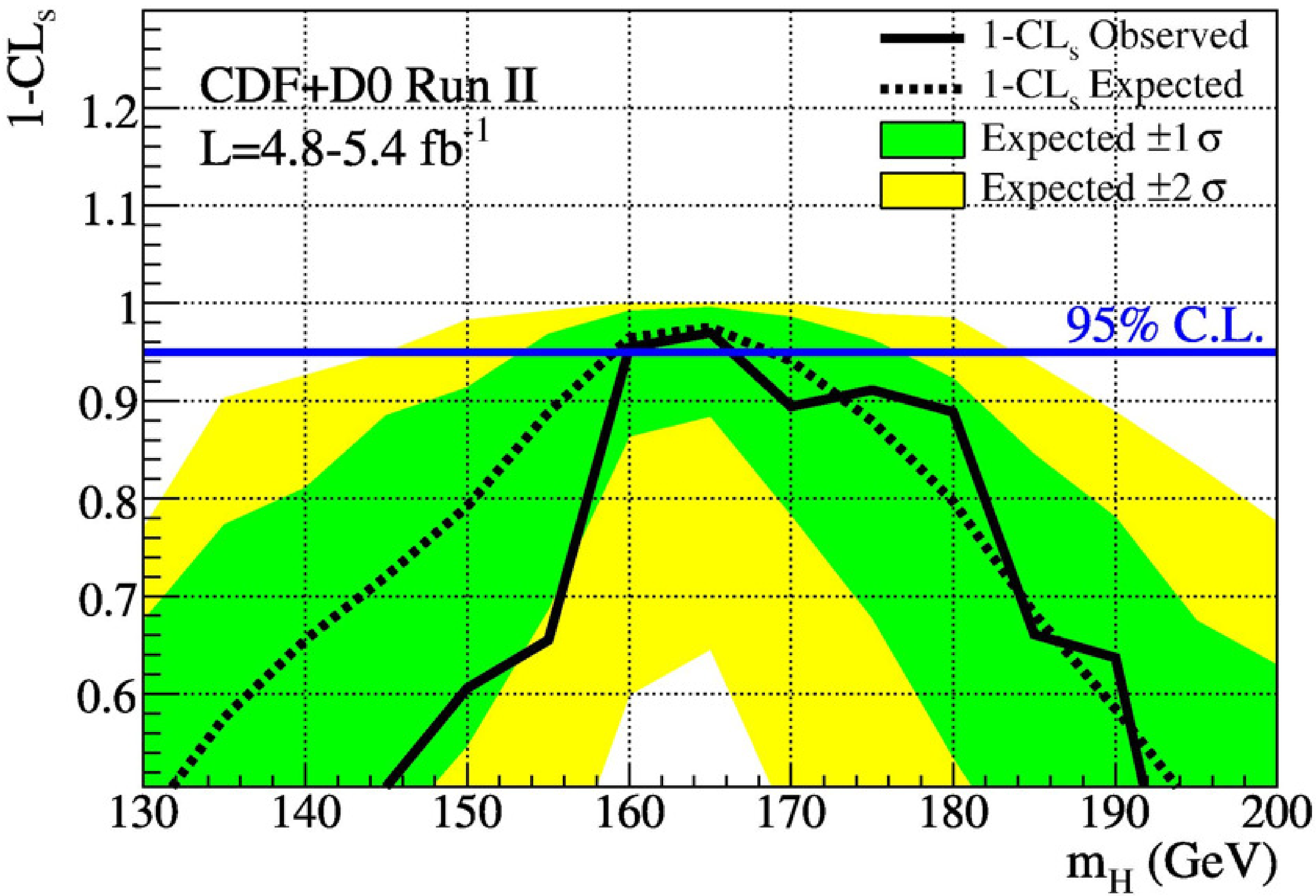
Exp. limit: 1.35 x SM
Obs. limit: 1.53 x SM

Distribution of different s/b bins

$\log_{10}$s/b,	Signal,	Bkgr,	Data
-1.083	7.86	96.45	90
-0.916	4.19	34.44	27
-0.75	6.52	37.09	51
-0.583	5.80	21.62	24
-0.416	2.22	5.84	4
-0.25	3.41	6.61	5
-0.083	0	0	0
0.083	0.71	0.64	0
0.25	0.14	0.09	0



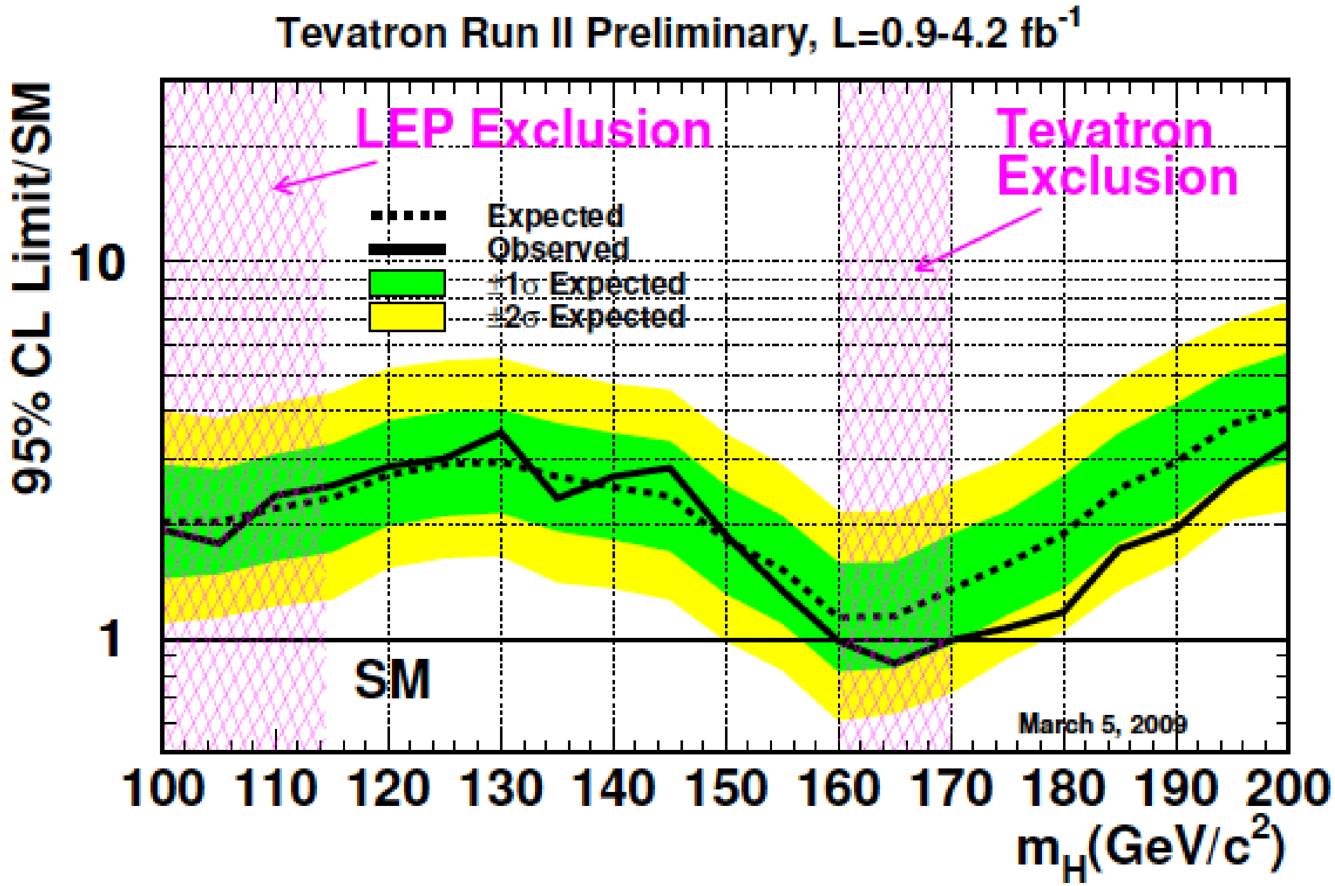
Exclusion Probability vs m_H



Still, 160-170 GeV excluded ≥90% C.L.

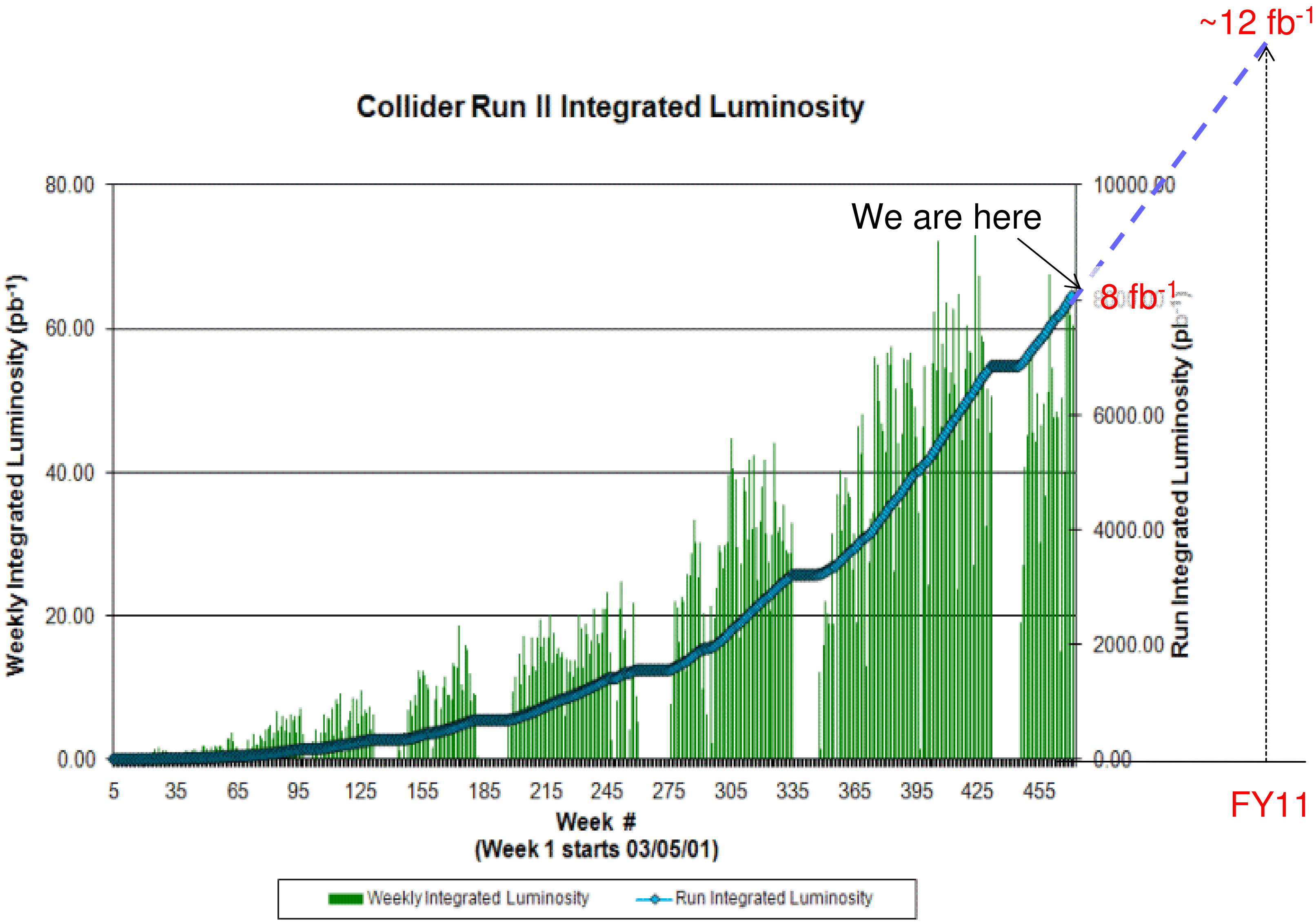
As the a-priori sensitivity continues to improve, it will become more stable.

Reminder: Moriond 2009 Limits

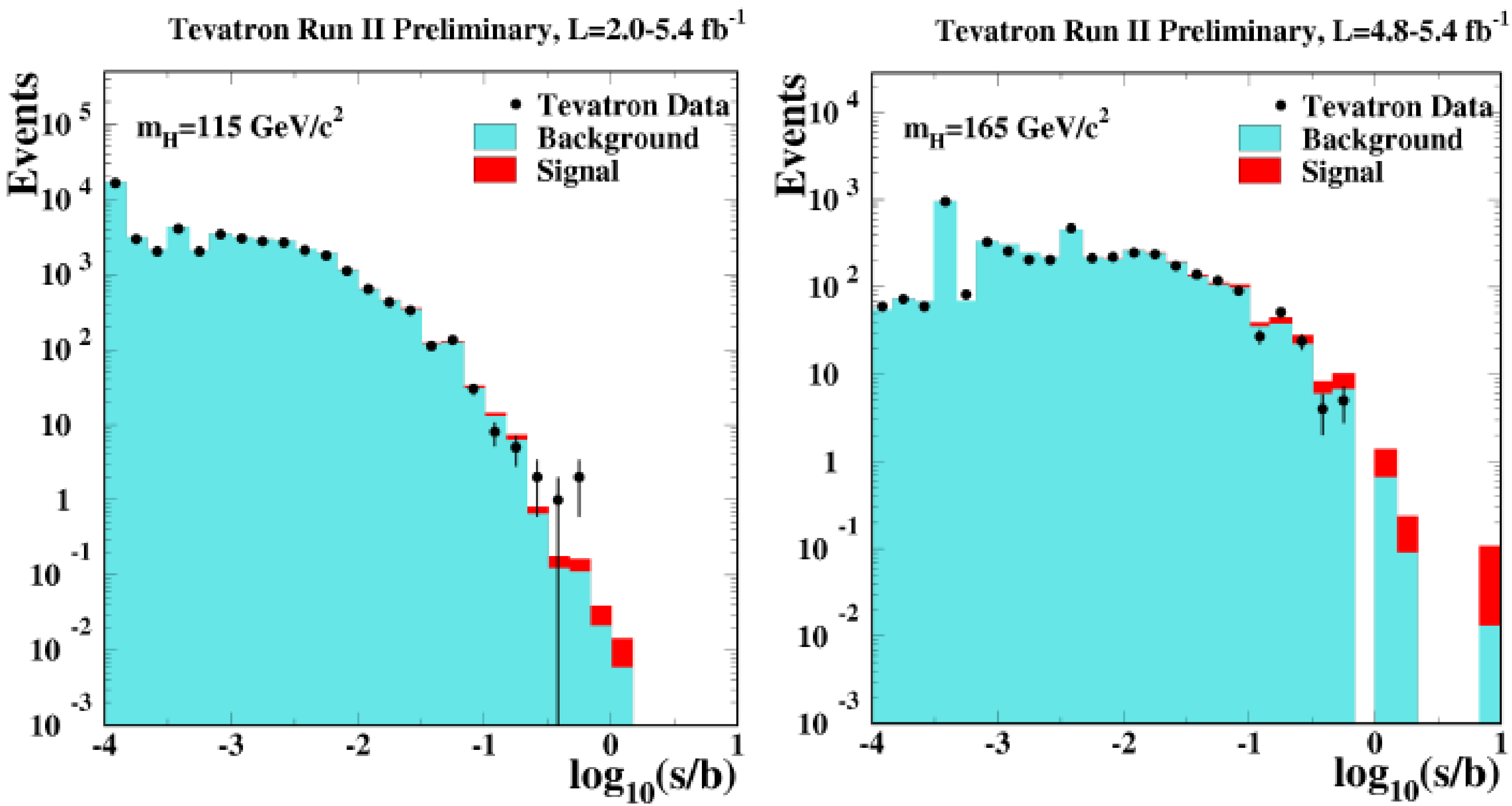


- Observed exclusion range from 160 to 170 GeV.
- No a-priori expected exclusion.

Tevatron Accelerator

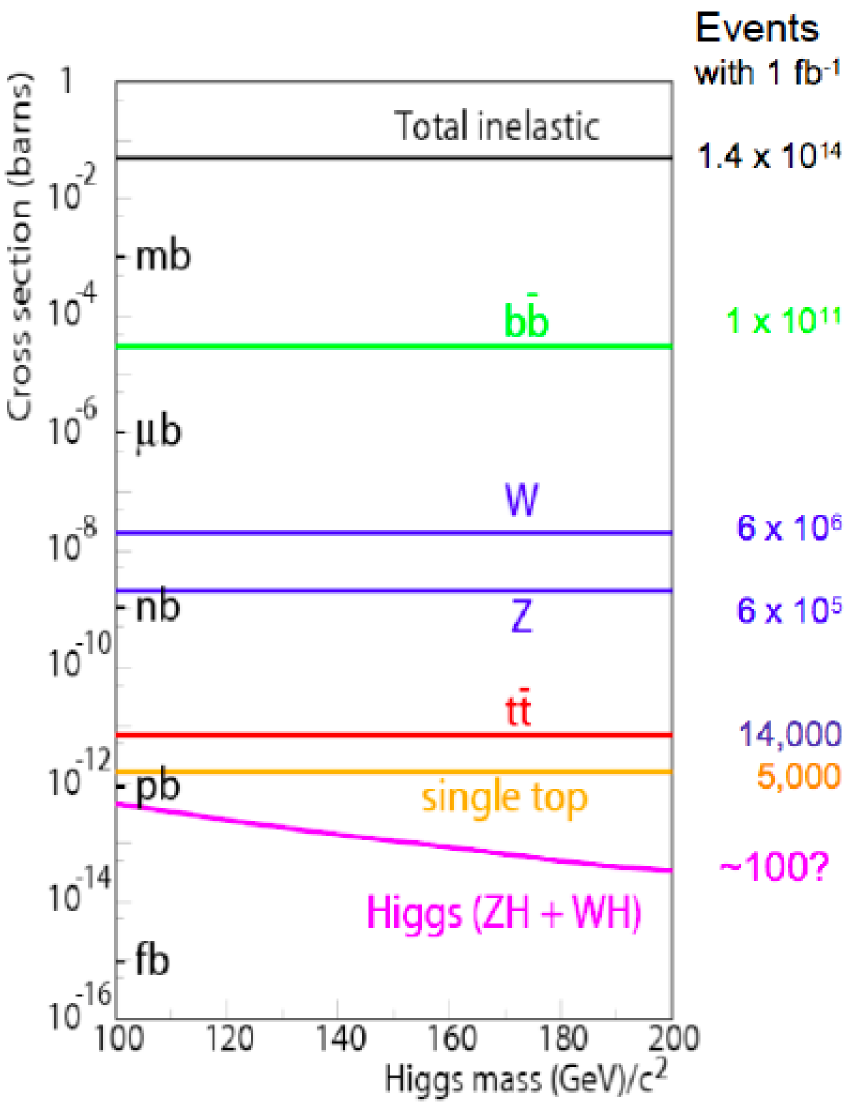


Visualizing the Tevatron Data



(*) Log(s/b) evaluated using best fit to data.

Higgs Production at the Tevatron



Experimental conditions:

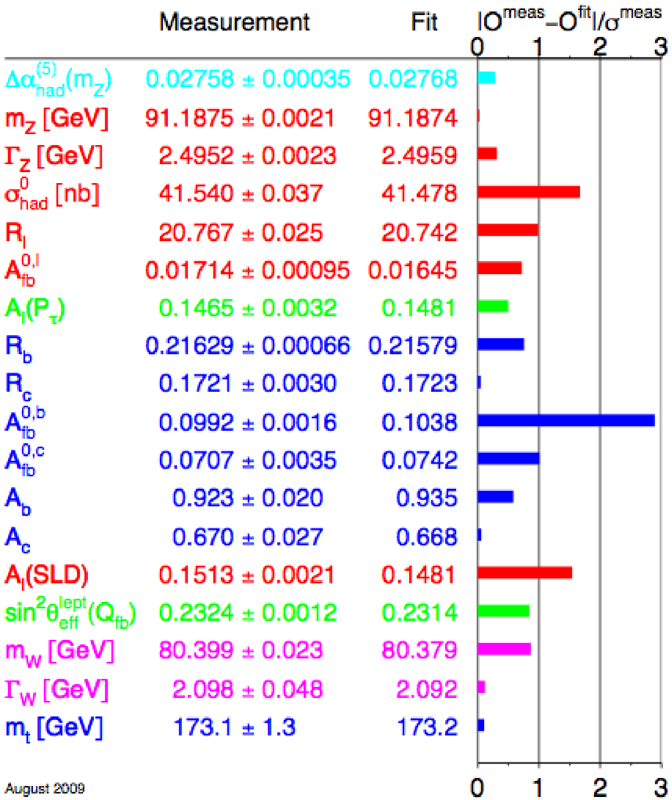
- like drinking from a fire hose: σ_{inel} ~ 70 mb
  Collision rate: 2.5 MHz
  10 “uninteresting” events/crossing @300E30 cm^2s^{-1}
- like panning for gold: $\sigma_{inel}/\sigma_{H+X}$ ~ 10^{12}

  Only 1 in 10^{12} events may be a Higgs event!

➔ High luminosity and highly efficient and selective triggers crucial

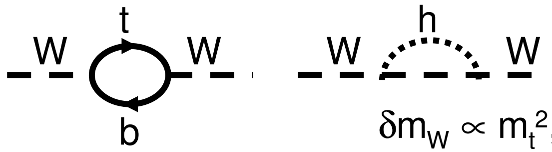
The Success of the Standard Model

- During the last decade the SM has been confirmed experimentally beyond reproach.



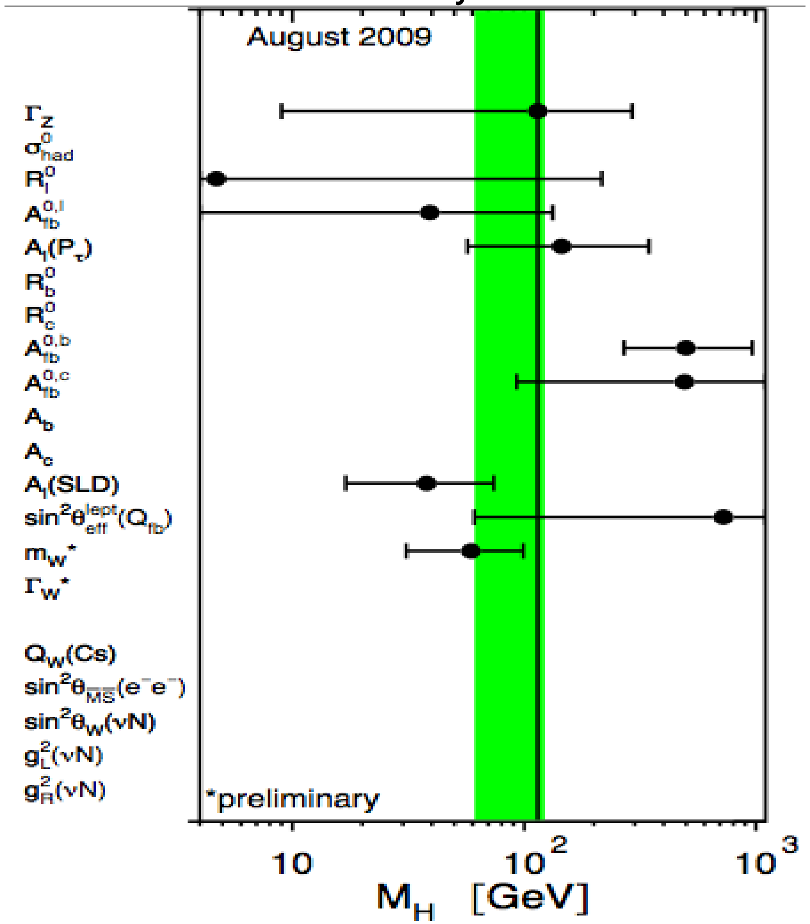
- However, the dynamics for EWSB still awaits direct experimental verification.

- The high accuracy achieved allows to perform tests at the quantum level:



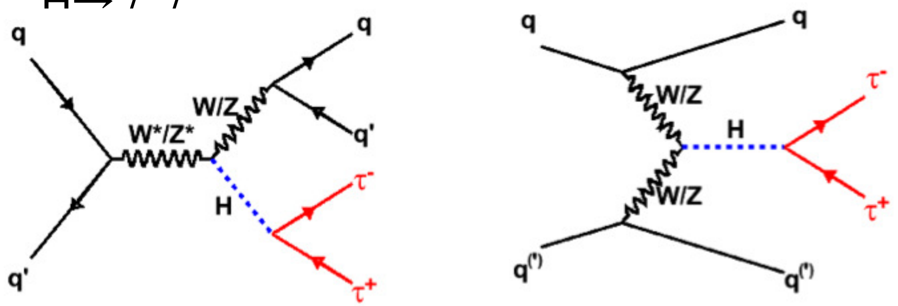
$\delta m_W \propto m_t^2, \ln(m_H/m_W)$

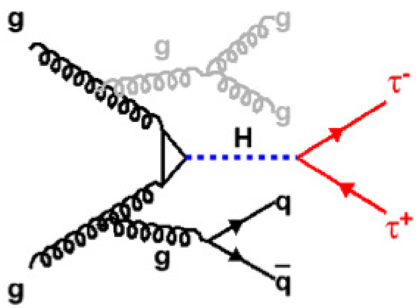
➔ some sensitivity to the EWSB sector



ττjj Final States

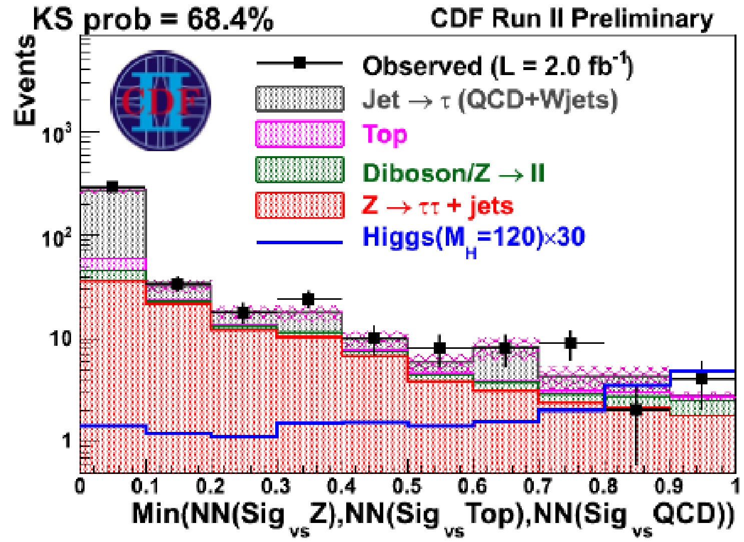
- $H\to\tau\tau$: second largest BR(~8%) at low mass.
- Select events with $\tau_l\tau_h$jj final state
  ➔ sensitive to ZH ($Z\to\tau\tau$, $H\to bb$),VH ($V\to jj$, $H\to\tau\tau$) and vector boson/gluon fusion with $H\to\tau\tau$

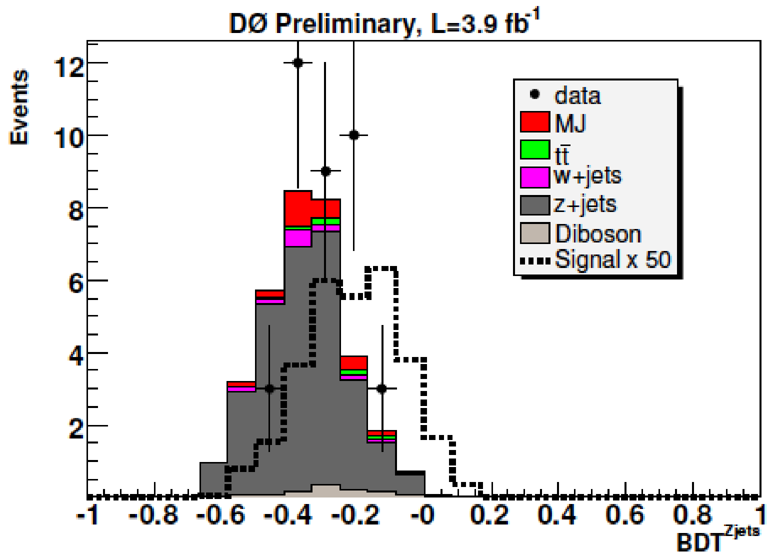




Exp/obs limit (σ/SM) at m_H = 115 GeV:

CDF: 25/26 (2.0 fb^{-1})
D0: 16/27 (4.9 fb^{-1})





H(→γγ)+X

- Tiny BR in SM (~0.2%) but large enhancements possible in some beyond-SM scenarios (e.g. fermiophobic Higgs).
- One of the most promising channels at the LHC. It also contributes at the Tevatron!

- Event selection:

  2 photons with p_T>25 GeV and $|\eta|$<1.1

  NN-based photon ID (D0).

- Consider all Higgs boson production modes.
- Main backgrounds estimated from data:
  - Direct QCD γγ (~60%)
  - γ+j and dijet (jet →γ)

- Use diphoton mass spectrum:

Exp/obs limit (σ/SM) at m_H = 115 GeV:

CDF: 19/22 (5.4 fb^{-1})
D0: 18/16 (4.2 fb^{-1})