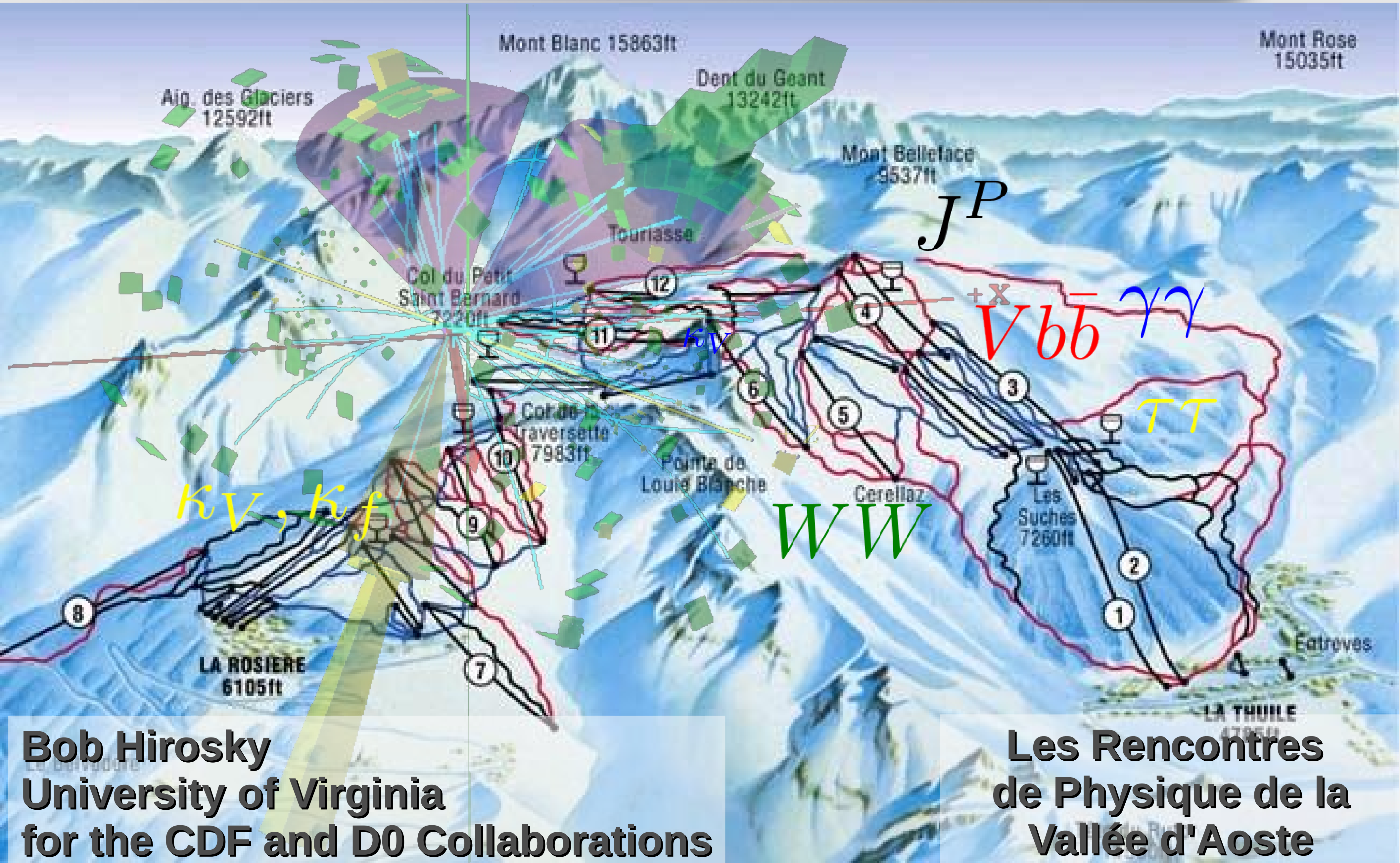
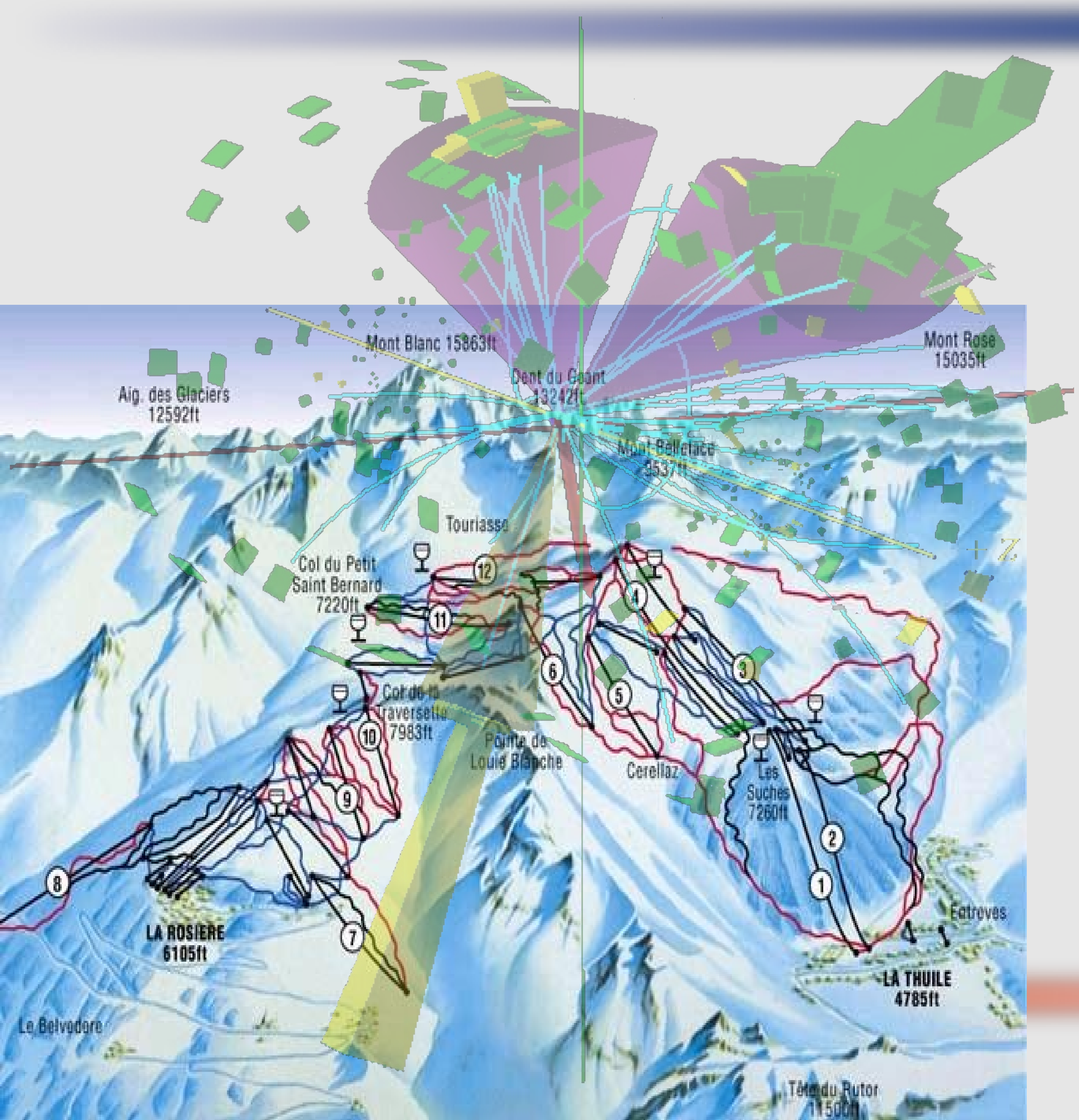
Higgs Boson Properties at the Tevatron



Bob Hirosky
University of Virginia
for the CDF and D0 Collaborations

Les Rencontres
de Physique de la
Vallée d'Aoste

Higgs Boson Properties at the Tevatron

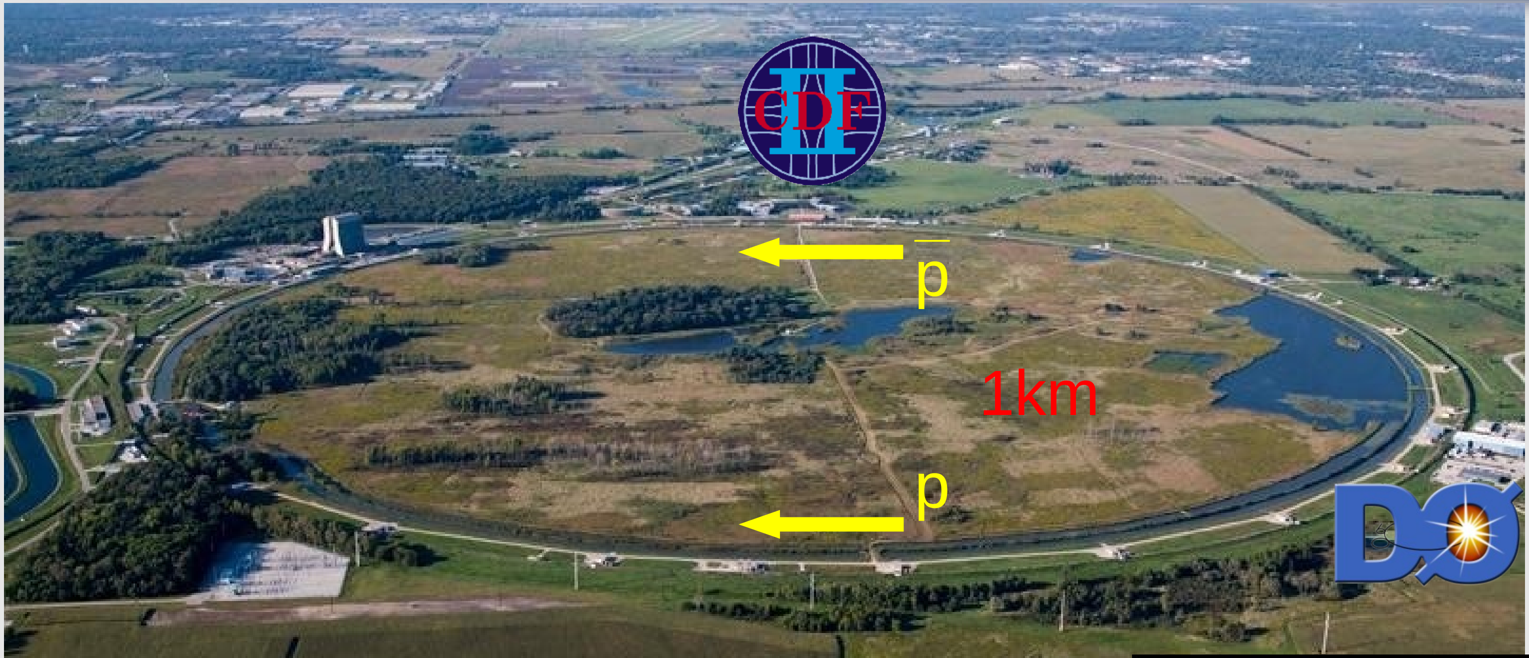


- Recap: SM Higgs boson search results from Tevatron

  - signal significance
  - coupling params

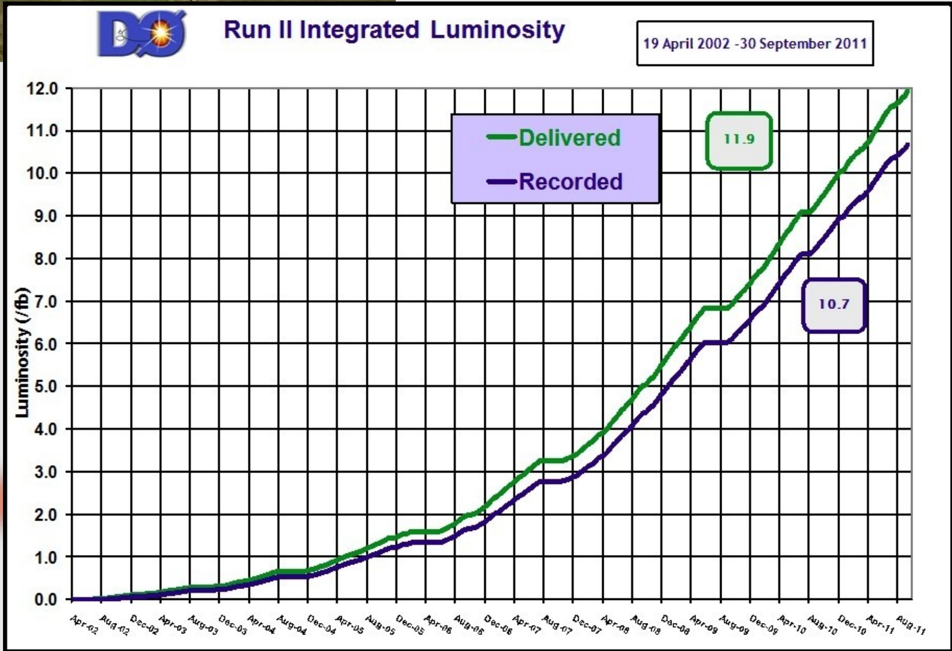
- Latest Spin/Parity studies in the H-> $b\bar{b}$ final state

The Tevatron: Run 2



10 year program of data collection, worlds highest energy $p\bar{p}$ collisions

~ 10 fb^{-1} events recorded / per experiment



Brief history of our SM Higgs production

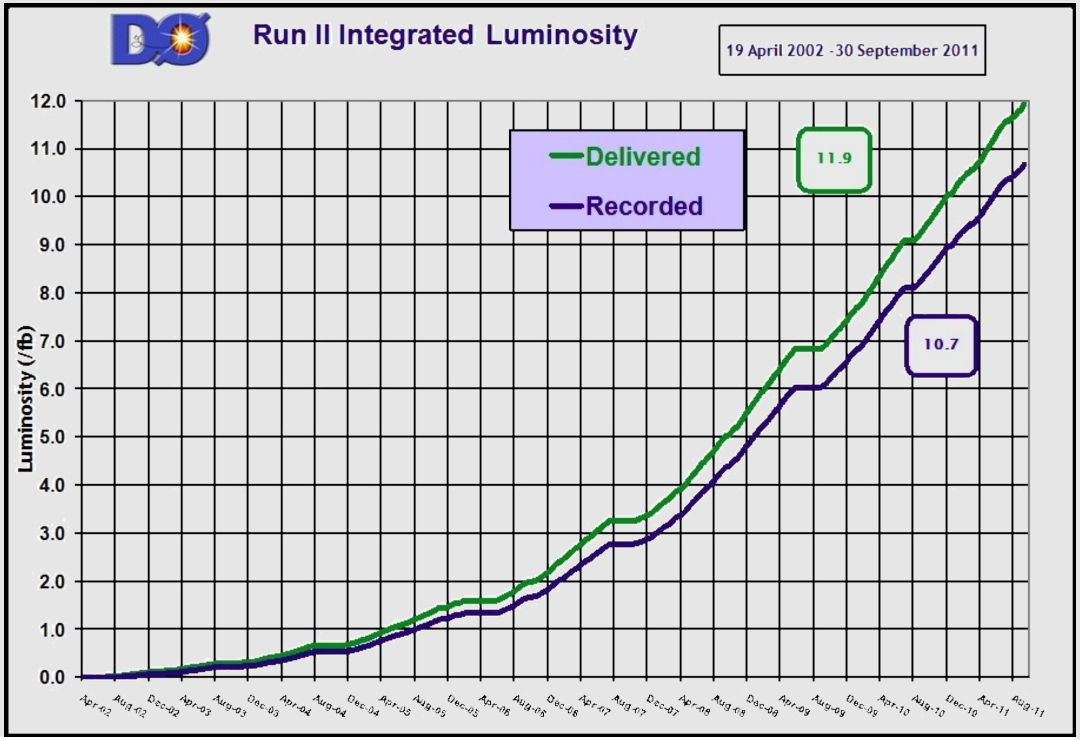
MH=125 GeV
#VH, H->bb
SM expectation (all VH final states)

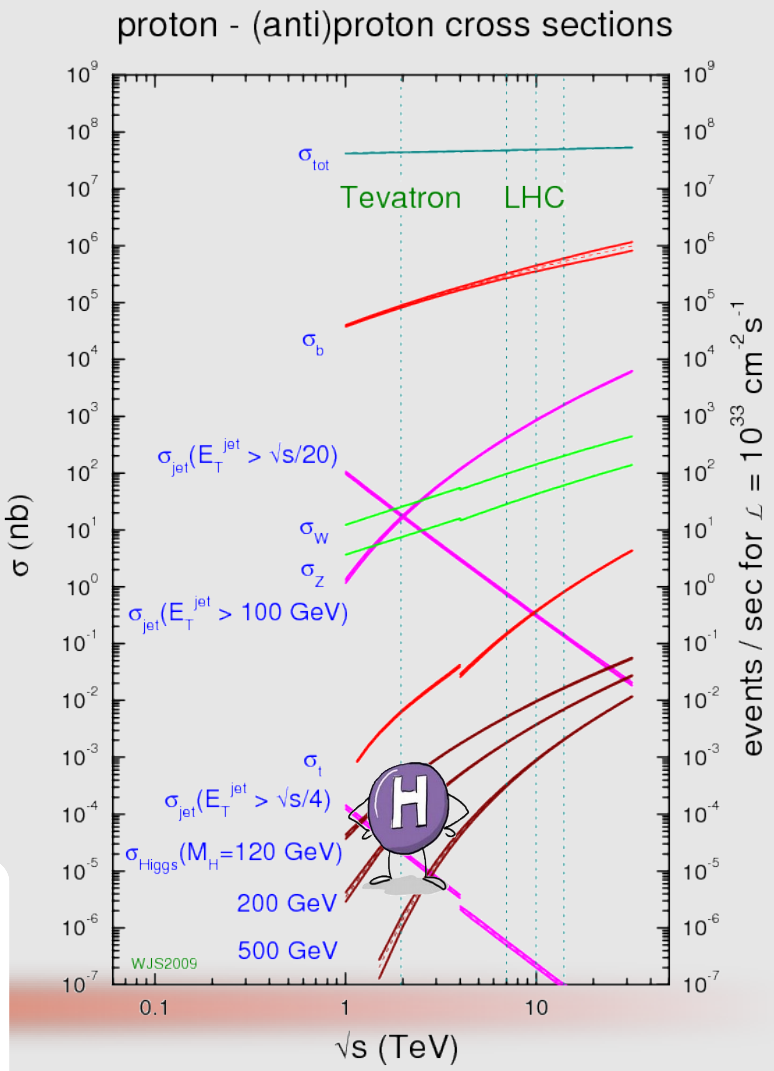
Various background expectations

1200

600

120





Extraordinarily challenging: need to effectively suppress several orders of magnitude of background, preserving handful of signal events.

History of searches

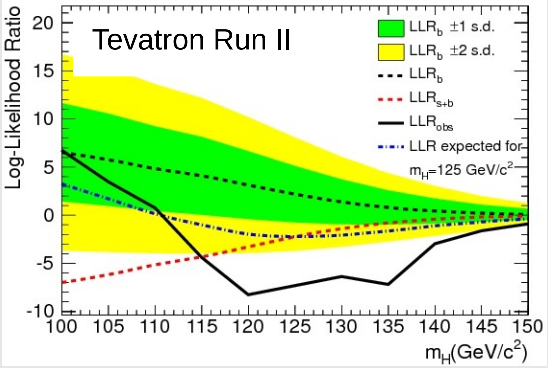
LEP (1989 – 2000): m_H > 114.4 GeV@95% CL

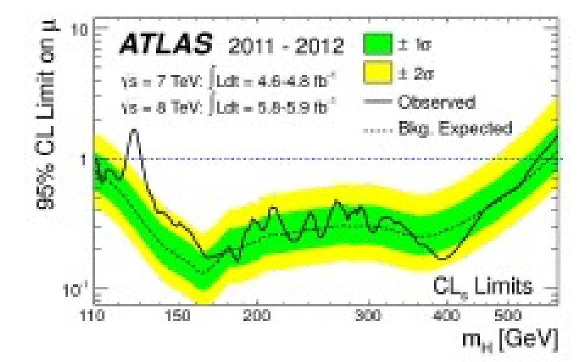
Tevatron Run II (2002-2011):
- First post-LEP exclusion (2009)
- First evidence of Higgs-like particle decaying to a pair of b-quarks

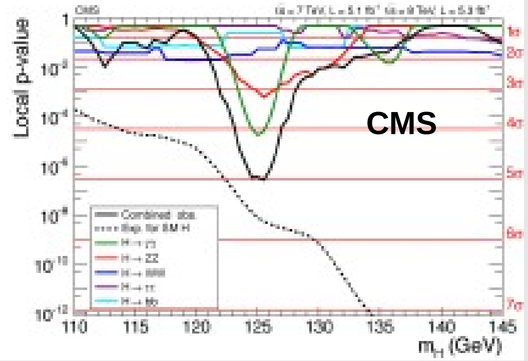
Phys. Rev. Lett. 109, 071804 (2012) (July 2012)

LHC (2009 – 2012):
- Excluded wide mass range (~110–600 GeV, except window ~125 GeV)
- Discovery of new Higgs-like boson mainly through γγ and ZZ decays

(July 2012)







Many details in following talks

History of searches

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(July 2012)

Substantial LHC progress in each channel

- Higgs observation confirmed in bosonic channel
- Strong indications of fermionic decays at LHC (primarily ττ channel)

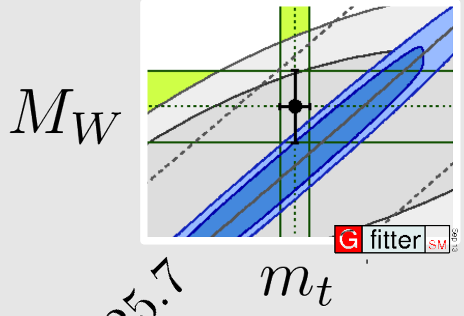
We have **a** Higgs boson:

Firmly establish the fermionic decays and properties in all channels

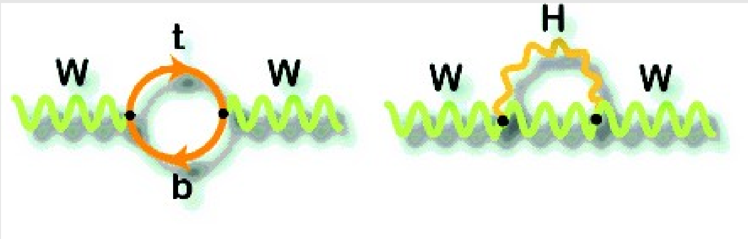
Beyond the SM Higgs

Big picture: test consistency of SM

- Measure ALL Higgs boson properties / constrain possible anomalies
  What's possible? Conservatively: Anything we haven't ruled out!
- Refine precision tests of EW sector



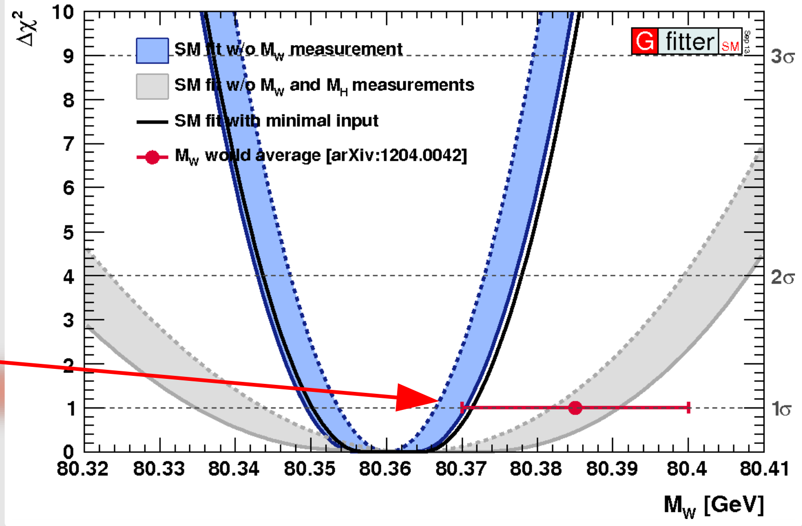
<= famous “triple point” plot of EW observables



With an improved world average around 10 MeV dominated by the Tevatron

=>we will have increasingly strong indirect tests of Higgs mass values

Significant anomaly could be detected with improved precision, if central value drifts slightly apart from EW fit.



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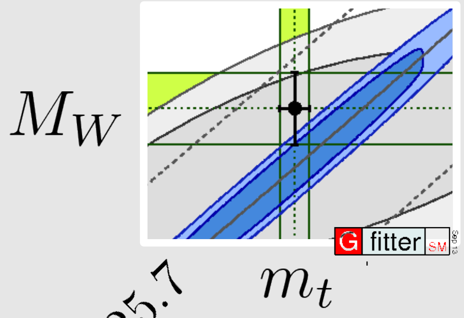

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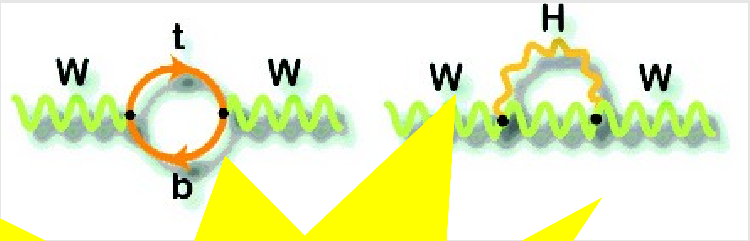
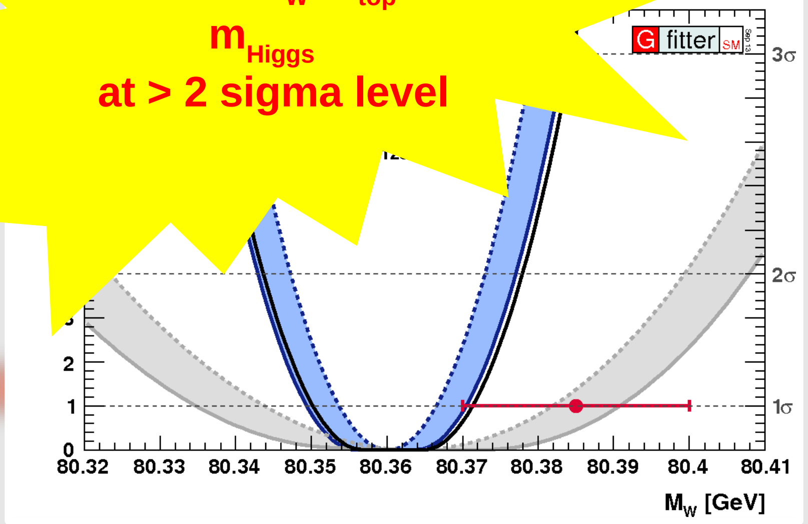


With an improved world average around 10 MeV dominated by the Tevatron

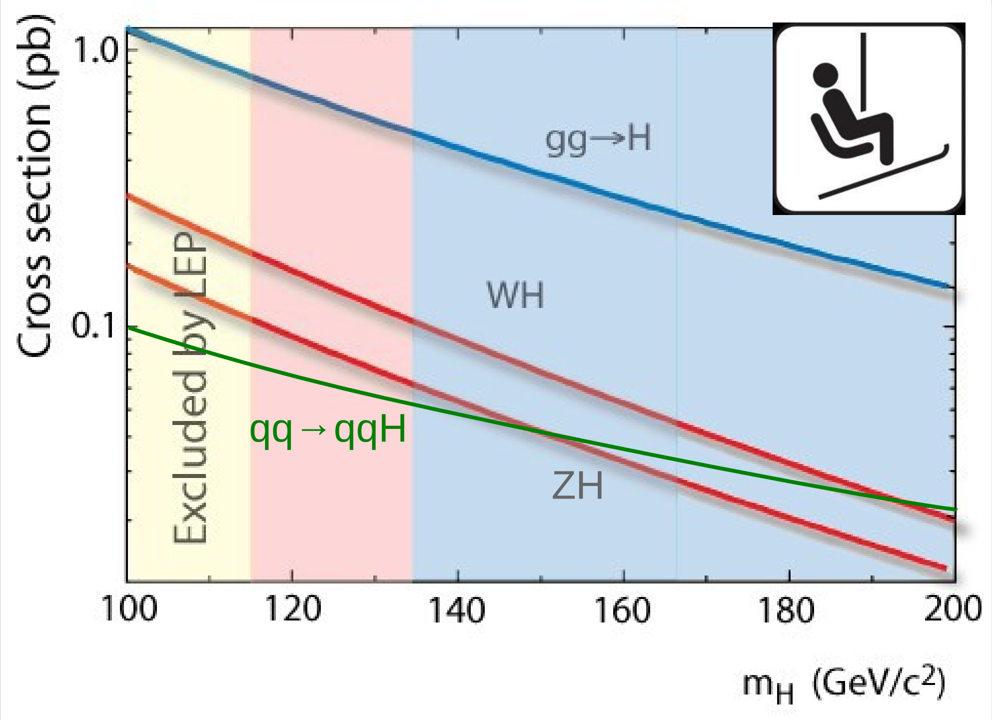
=>we will have increasingly strong indirect tests of Higgs mass values

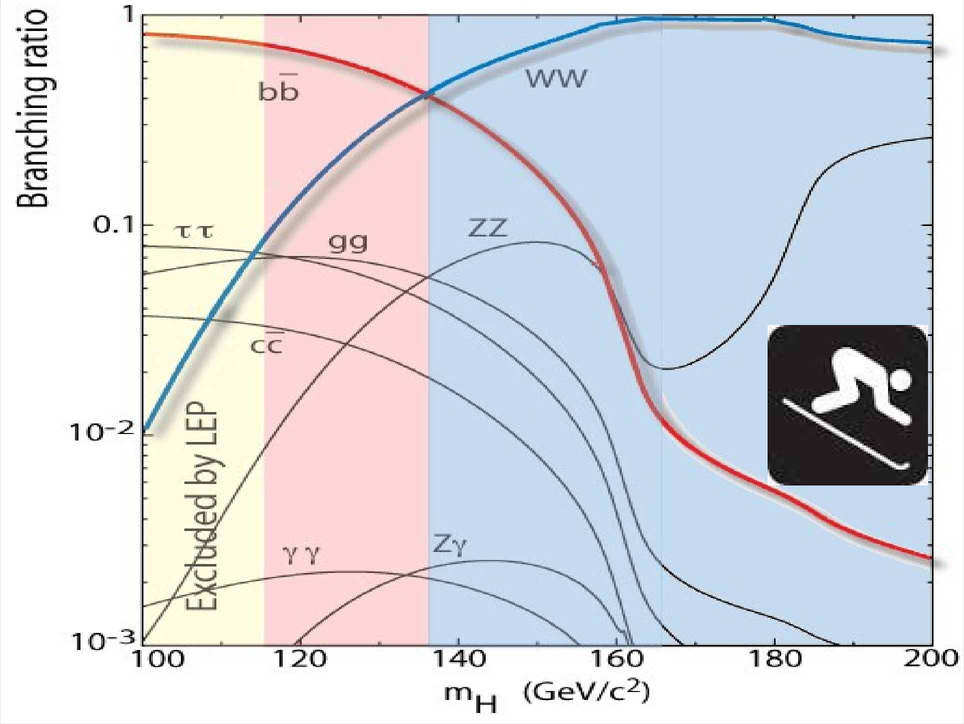
Sensitivity to SM (in)consistency with m_W m_{top} m_{Higgs} at > 2 sigma level

Significant anomaly could be detected with improved precision, if central value drifts slightly apart EW fit.



Higgs production and decay at the Tevatron





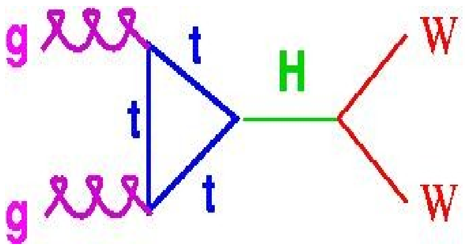
Complex phenomenology: various possibilities for production and decay
=> many search channels

Significantly larger phase space for extended models

Dominant analysis channels

"High" mass (M_H > 135 GeV) dominant decay:

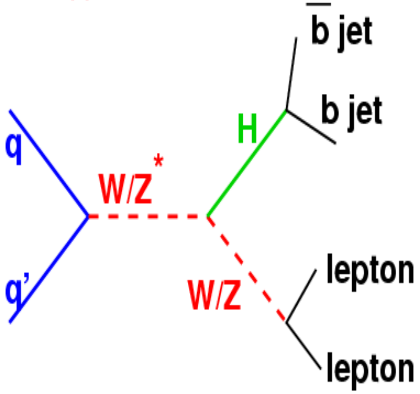
$H \to WW^{(*)}$ $gg \to H \to WW \to \ell\nu\ell'\nu'$



Strength of Tevatron analyses

Low mass (M_H < 135 GeV) dominant decay:

$H \to b\bar{b}$



$WH \to \ell\nu b\bar{b}$

$ZH \to \ell^+\ell^- b\bar{b}$

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

use associated production modes to get better S/B

These are the main search channels, but there has been an extensive program of measurements in all channels to extend the sensitivity to a SM Higgs

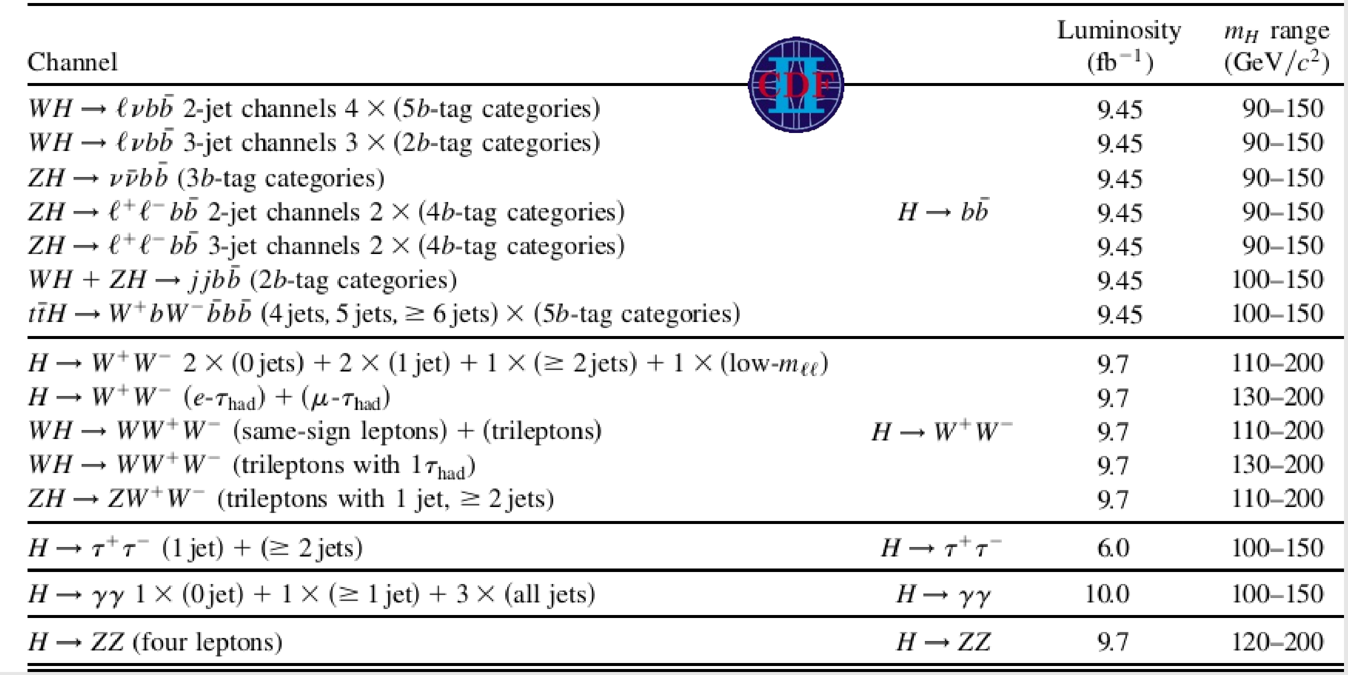
Channels studied

All papers now published

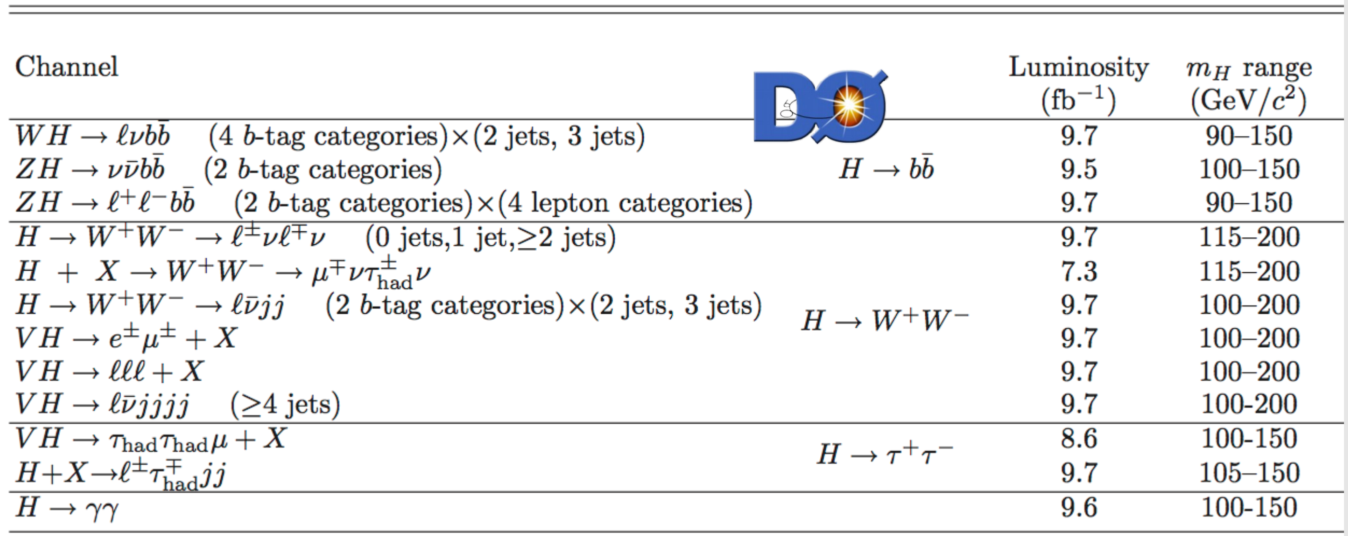
All favored SM channels searched

Full luminosity used in almost all channels

Divide and conquer strategy.



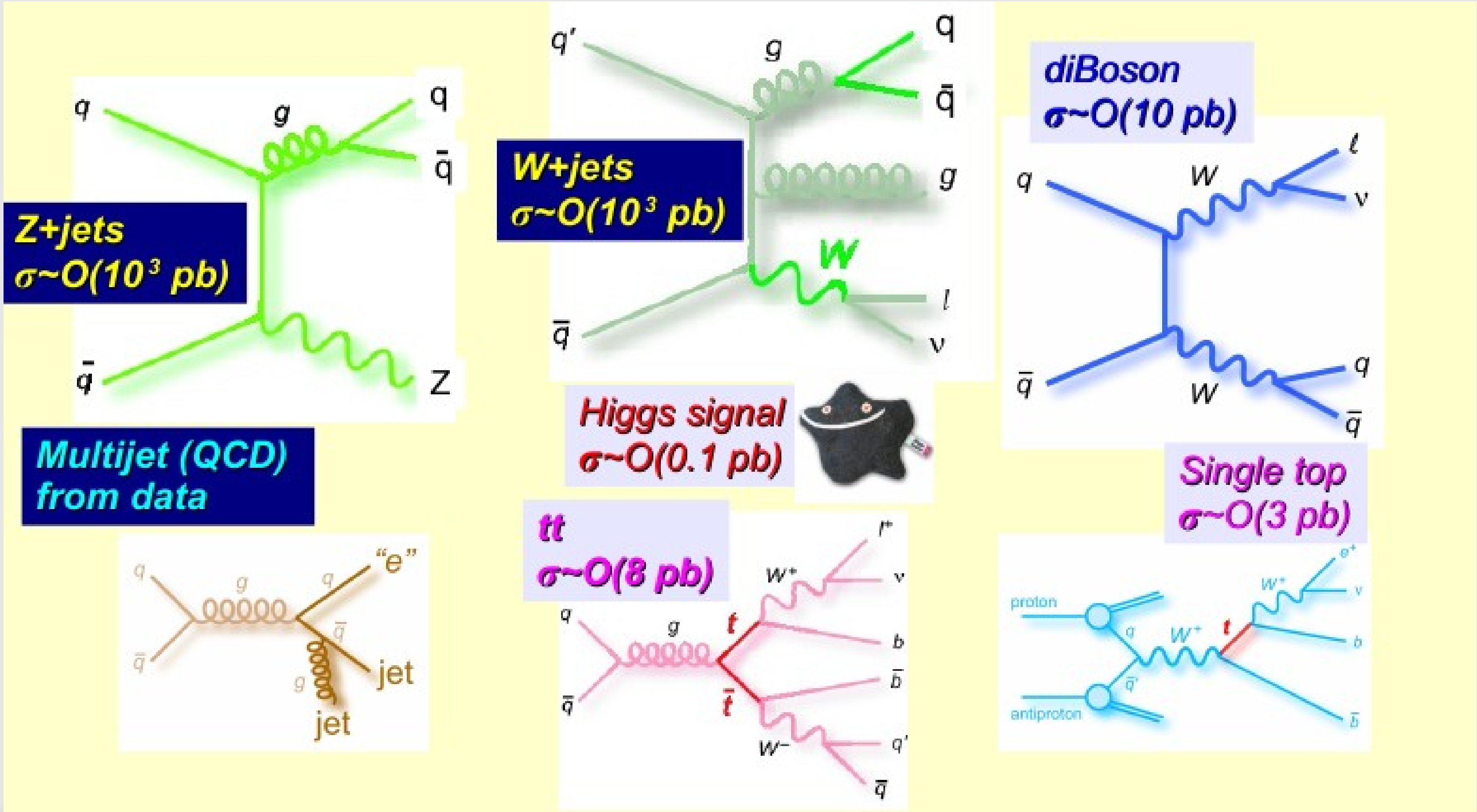
Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4 × (5b-tag categories)	$H \to b\bar{b}$	9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3 × (2b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (3b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2 × (4b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels 2 × (4b-tag categories)		9.45	90–150
$WH + ZH \to jjb\bar{b}$ (2b-tag categories)		9.45	100–150
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$ (4 jets, 5 jets, ≥ 6 jets) × (5b-tag categories)		9.45	100–150
$H \to W^+W^-$ 2 × (0 jets) + 2 × (1 jet) + 1 × (≥ 2 jets) + 1 × (low-$m_{\ell\ell}$)	$H \to W^+W^-$	9.7	110–200
$H \to W^+W^-$ (e-τ_{had}) + (μ-τ_{had})		9.7	130–200
$WH \to WW^+W^-$ (same-sign leptons) + (trileptons)		9.7	110–200
$WH \to WW^+W^-$ (trileptons with 1τ_{had})		9.7	130–200
$ZH \to ZW^+W^-$ (trileptons with 1 jet, ≥ 2 jets)		9.7	110–200
$H \to \tau^+\tau^-$ (1 jet) + (≥ 2 jets)	$H \to \tau^+\tau^-$	6.0	100–150
$H \to \gamma\gamma$ 1 × (0 jet) + 1 × (≥ 1 jet) + 3 × (all jets)	$H \to \gamma\gamma$	10.0	100–150
$H \to ZZ$ (four leptons)	$H \to ZZ$	9.7	120–200



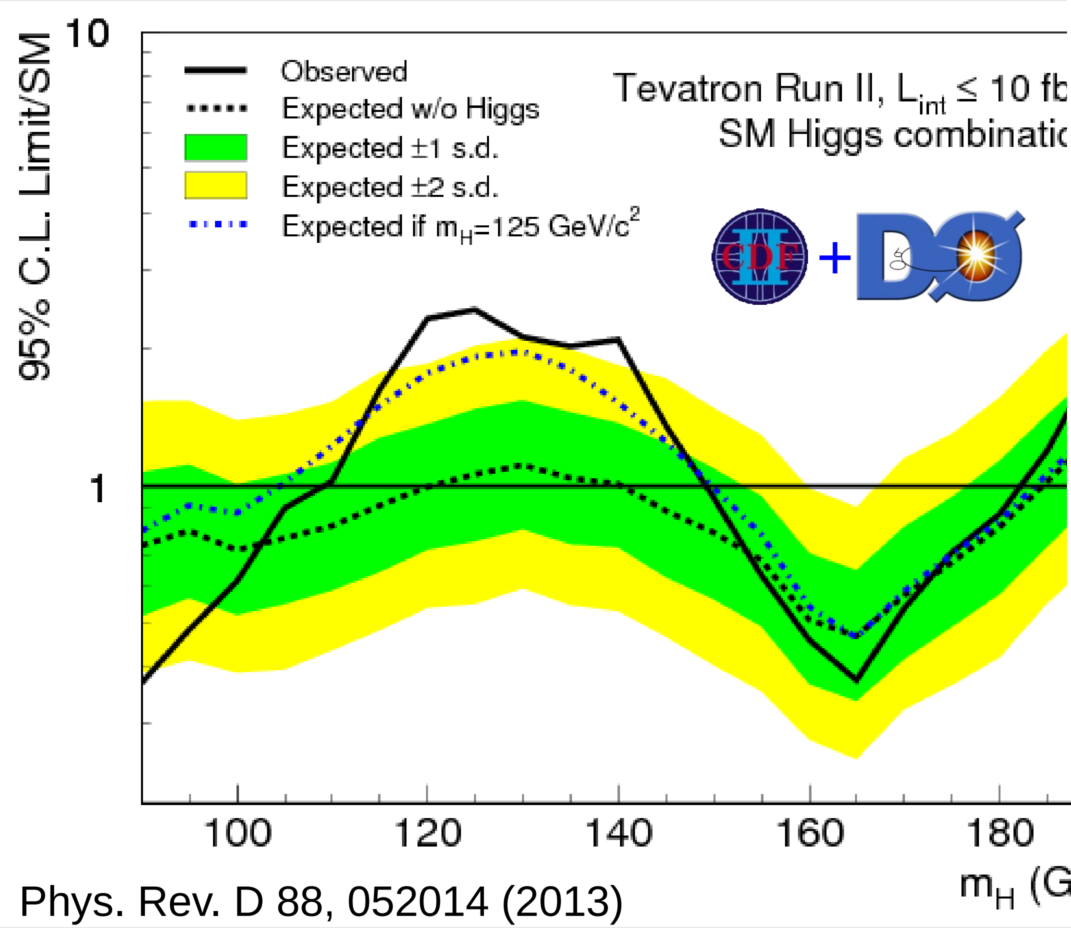
Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ (4 b-tag categories)×(2 jets, 3 jets)	$H \to b\bar{b}$	9.7	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)		9.5	100–150
$ZH \to \ell^+\ell^- b\bar{b}$ (2 b-tag categories)×(4 lepton categories)		9.7	90–150
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$ (0 jets,1 jet,≥2 jets)	$H \to W^+W^-$	9.7	115–200
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{\mathrm{had}}\nu$		7.3	115–200
$H \to W^+W^- \to \ell\bar{\nu}jj$ (2 b-tag categories)×(2 jets, 3 jets)		9.7	100–200
$VH \to e^\pm\mu^\pm + X$		9.7	100–200
$VH \to \ell\ell\ell + X$		9.7	100–200
$VH \to \ell\bar{\nu}jjjj$ (≥4 jets)		9.7	100-200
$VH \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}\mu + X$	$H \to \tau^+\tau^-$	8.6	100-150
$H+X \to \ell^\pm\tau^\mp_{\mathrm{had}}jj$		9.7	105–150
$H \to \gamma\gamma$		9.6	100-150

Backgrounds

- Model background processes w/ ALPGEN+PYTHON, PYTHIA, & COMPHEP
- Normalized with highest order cross sections available (NLO or better)



Tevatron Combined Limits



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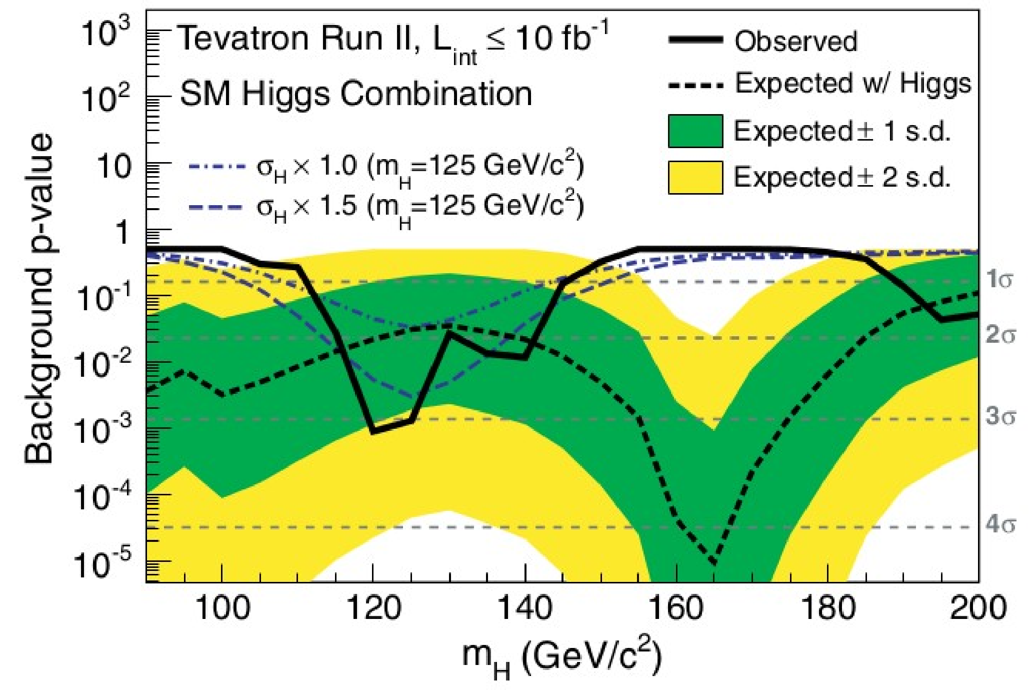


Observed exclusion:
90 < mH <107 GeV,
149 < mH < 182 GeV

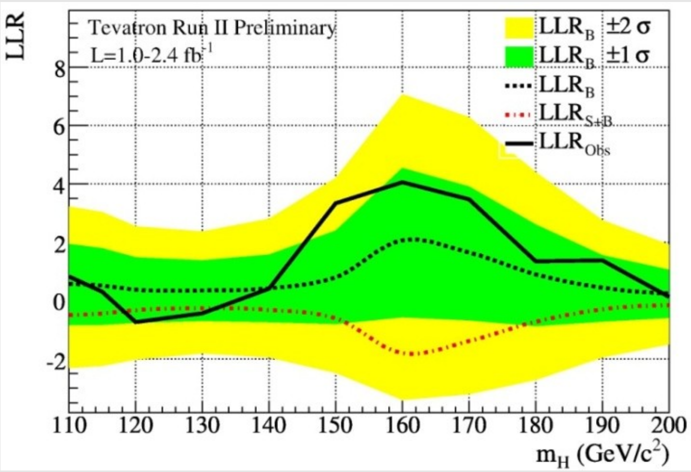
Expected exclusion:
90 < mH < 121 GeV,
140< mH < 184 GeV

Significant excess, ≥ 3 sigma for 120-125 GeV

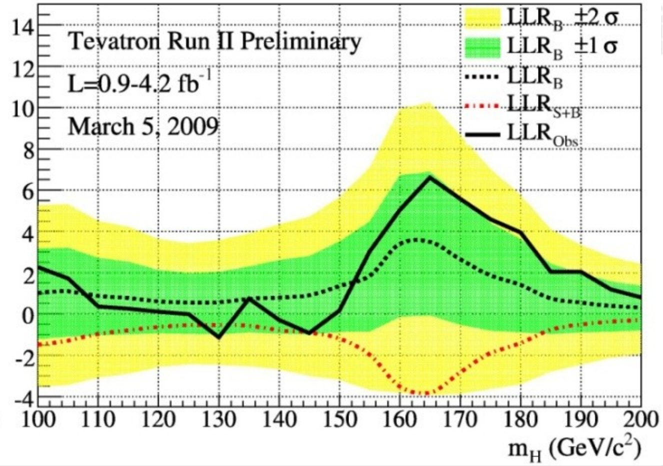
History of Tevatron Search Results
(LLR plots)

<== S-like | B-like ==>

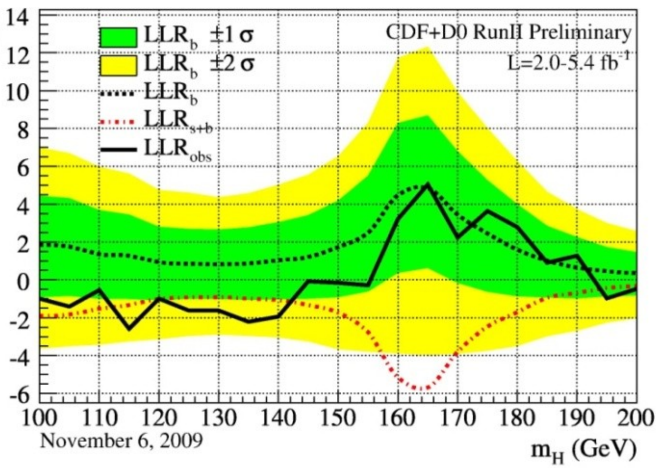
Data of **2007**; up to 2.4 fb-1



Data of **2008**; up to 4.2 fb-1

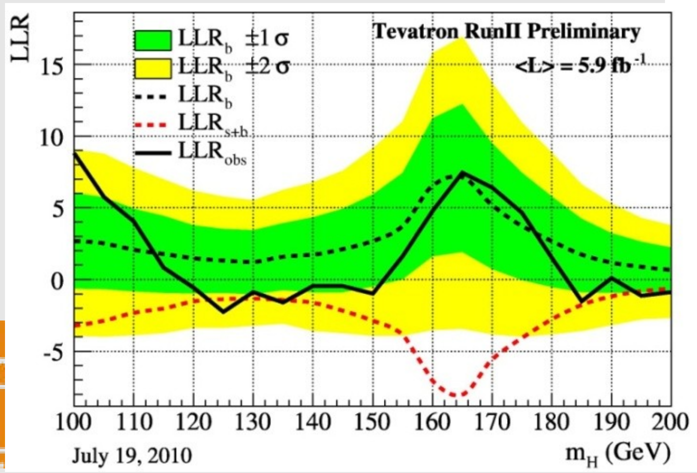


Data of mid **2009**; up to 5.4 fb-1

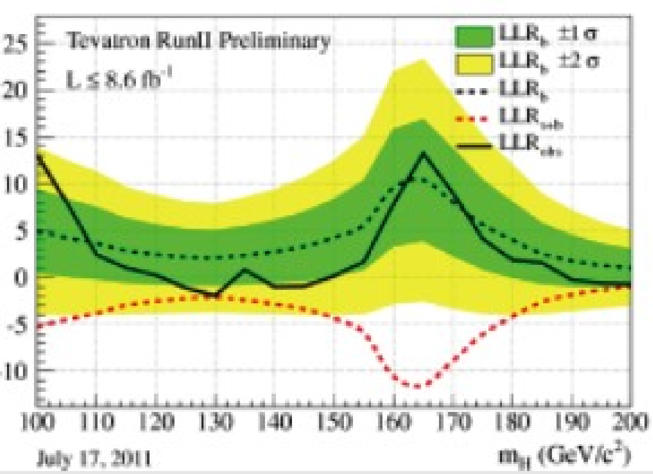


Time

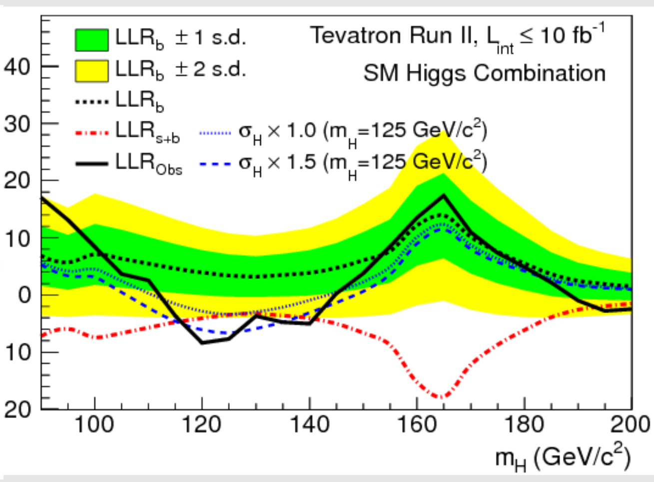
Data of mid **2010**; up to 5.9 fb-1



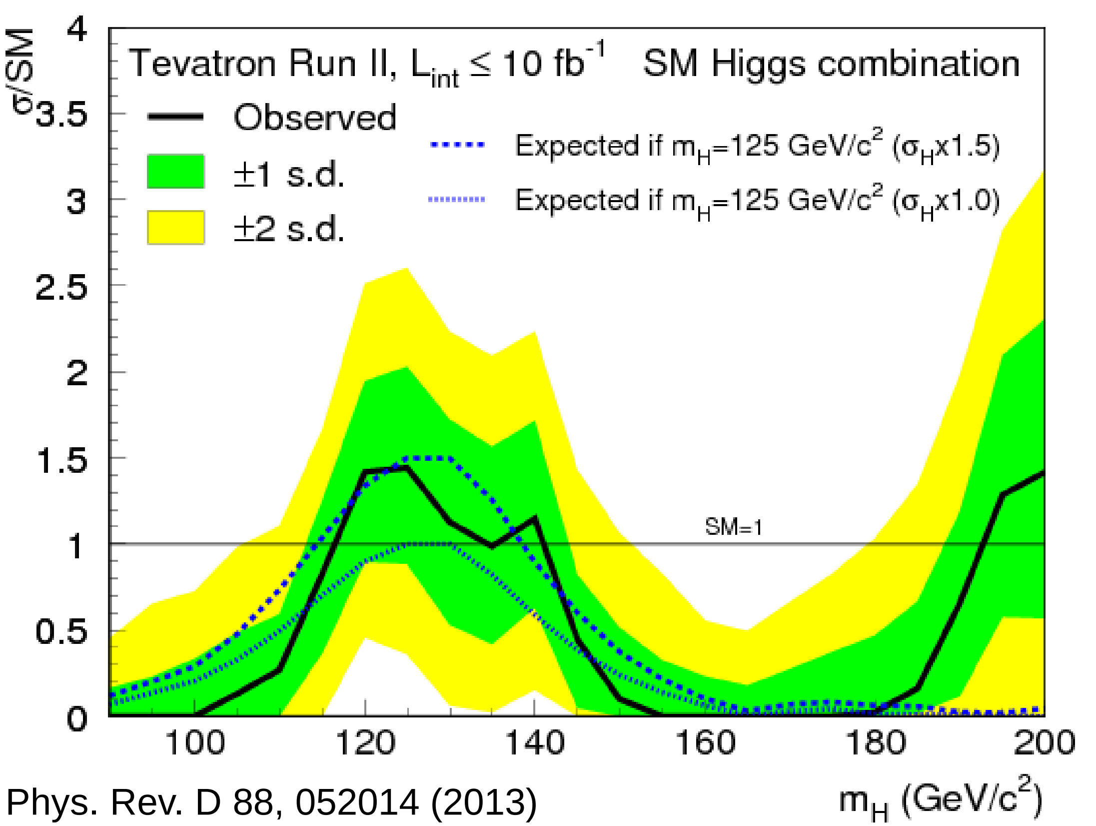
Data of mid **2011**; up to 8.6 fb-1



Full data set; up to 10 fb-1



Quantifying the excess:
Best Fit Signal Rate



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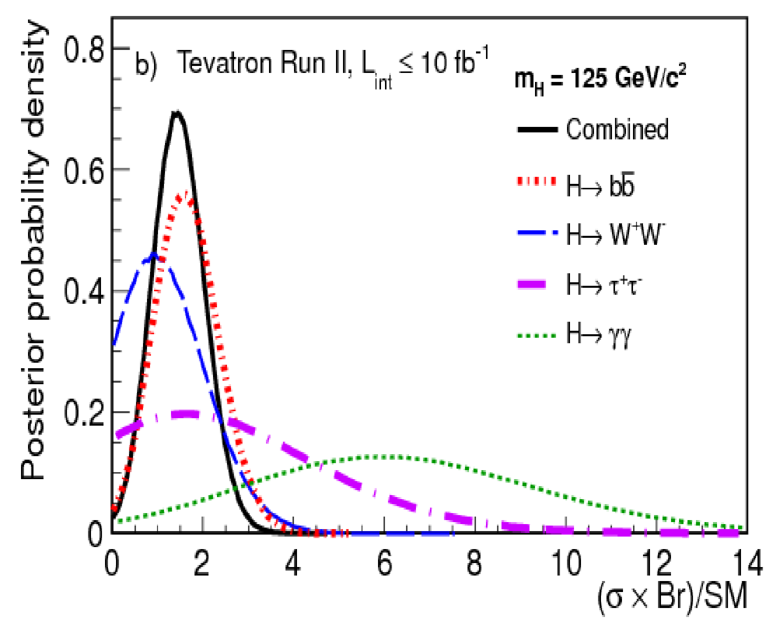
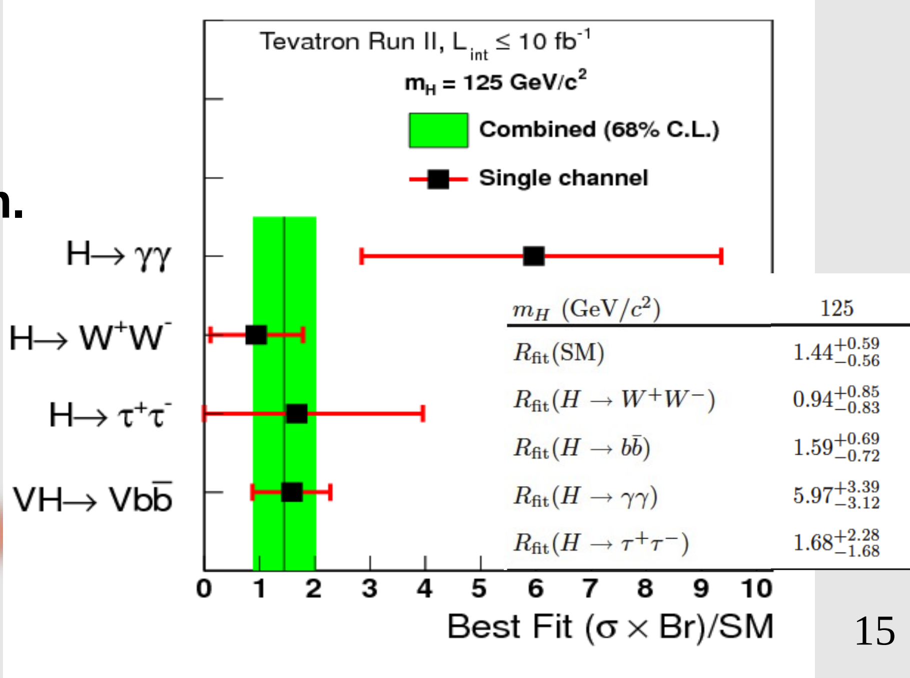


- **Max. likelihood fit to data, signal rate as free parm.**
- **Best-fit signal rate at mH=125 GeV:**

$$\sigma_{fit} / \sigma_{SM} = 1.44 \pm 0.59$$

Consistent with SM Higgs.

Consistent across channels



m_H (GeV/c^2)	125
$R_{\rm fit}$(SM)	$1.44^{+0.59}_{-0.56}$
$R_{\rm fit}(H \to W^+W^-)$	$0.94^{+0.85}_{-0.83}$
$R_{\rm fit}(H \to b\bar{b})$	$1.59^{+0.69}_{-0.72}$
$R_{\rm fit}(H \to \gamma\gamma)$	$5.97^{+3.39}_{-3.12}$
$R_{\rm fit}(H \to \tau^+\tau^-)$	$1.68^{+2.28}_{-1.68}$

Probing Higgs Boson Couplings

- Several production and decay mechanisms contribute to signal rates per channel => **interpretation is difficult**

(arXiv:1209.0040)

- A better option: measure deviations of couplings from the SM prediction

  Basic assumptions

  - only one underlying state at mH~125 GeV, with negligible width,
  - it is a CP-even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched).
- Additional assumption made in this study: no added invisible Higgs decay modes
- Under these assumptions all production cross sections and BRs can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings.

Examples

$$\sigma(gg \to H)\mathrm{BR}(H \to WW) = \sigma_{\mathrm{SM}}(gg \to H)\mathrm{BR}_{\mathrm{SM}}(H \to WW)\frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$$

$$\sigma(WH)\mathrm{BR}(H \to bb) = \sigma_{\mathrm{SM}}(WH)\mathrm{BR}_{\mathrm{SM}}(H \to bb)\frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2}$$

$$\kappa_g = f(\kappa_t, \kappa_b, M_H)$$

$$\kappa_H = f'(\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, M_H)$$

$$\Gamma_{b\bar{b}}, \Gamma_{c\bar{c}}, \Gamma_{\tau\bar{\tau}} \propto \kappa_f^2$$

$$\Gamma_{WW} \propto R^2 \kappa_V^2, R = \kappa_W / \kappa_Z$$

$$\Gamma_{ZZ} \propto \kappa_V^2$$

$$\Gamma_{gg} \propto (0.95\kappa_f + 0.05\kappa_V)^2$$

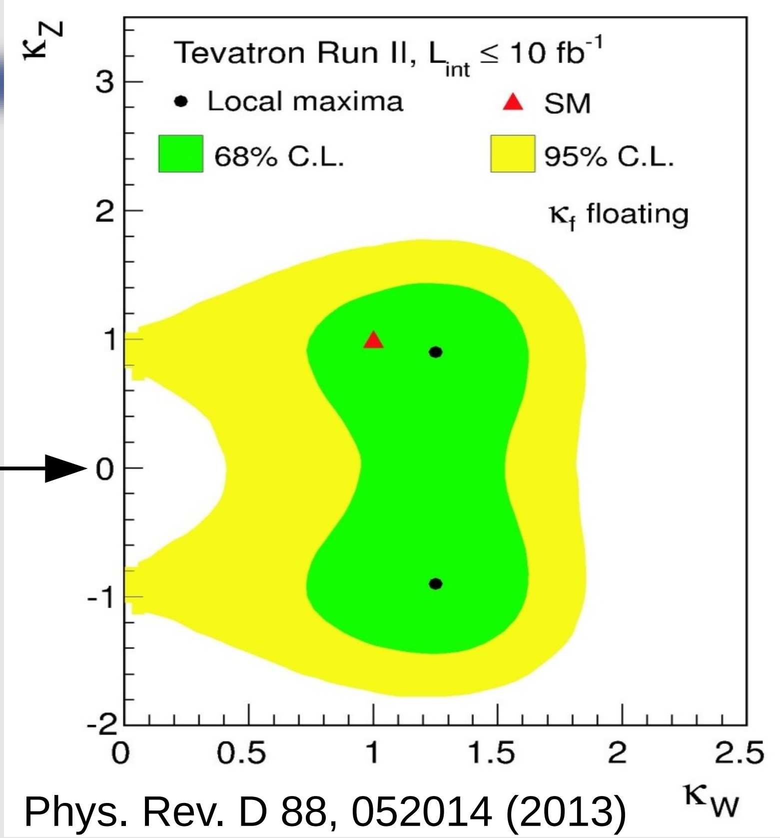
$$\Gamma_{\gamma\gamma} \propto (1.28\kappa_V - 0.28\kappa_f)^2$$

Probing Higgs Boson Couplings

When both κ_W and κ_Z vary independently →

- κ_f integrated over
- Best fit: $(\kappa_{W,}\ \kappa_Z) = (1.25,\pm 0.90)$

The point $(\kappa_W, \kappa_Z) = (0, 0)$ corresponds to NO Higgs boson production or decay in the most sensitive search modes at the Tevatron and is not included within the 95% C.L. region due to the significant excess of events in the SM Higgs boson searches @ 125 GeV



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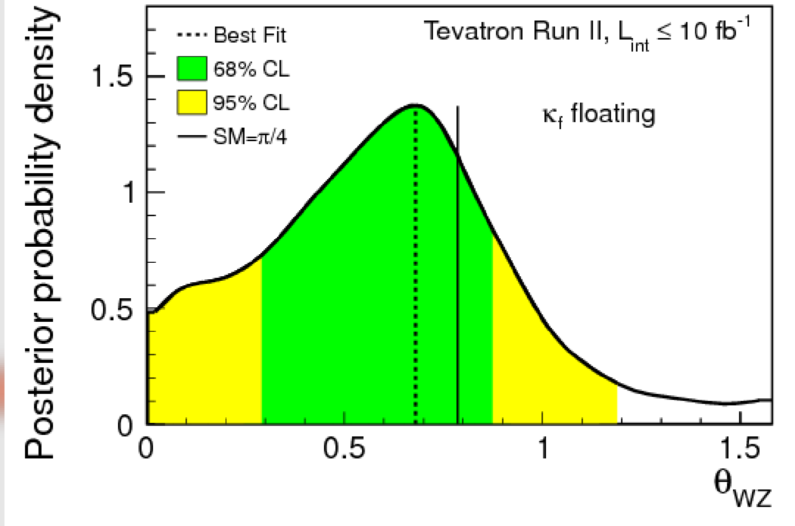
Probe SU(2)V custodial symmetry by measuring the ratio $\lambda_{WZ}=\kappa_W/\kappa_Z$

Measure $\theta_{WZ} = \tan^{-1}(\kappa_Z/\kappa_W) = \tan^{-1}(1/\lambda_{WZ})$

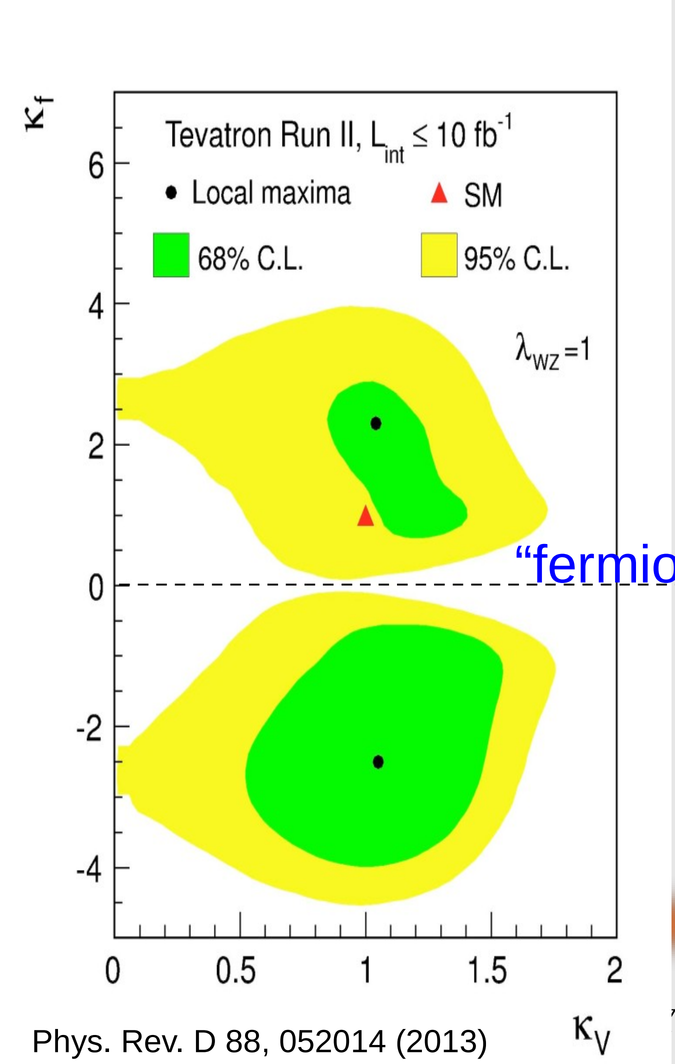
$$\theta_{WZ} = 0.68^{+0.21}_{-0.41} \rightarrow \lambda_{WZ}=1.24^{+2.34}_{-0.42}$$



Properties - couplings

Measure simultaneously κ_V and κ_f (assuming now $\lambda_{WZ}=1$).

- Asymmetry is from the excesses in the H → γγ
  - Two minima: $(\kappa_V, \kappa_f)=(1.05,−2.40)$ & $(1.05, 2.30)$
- Good agreement with SM predictions, in agreement with ATLAS/CMS.



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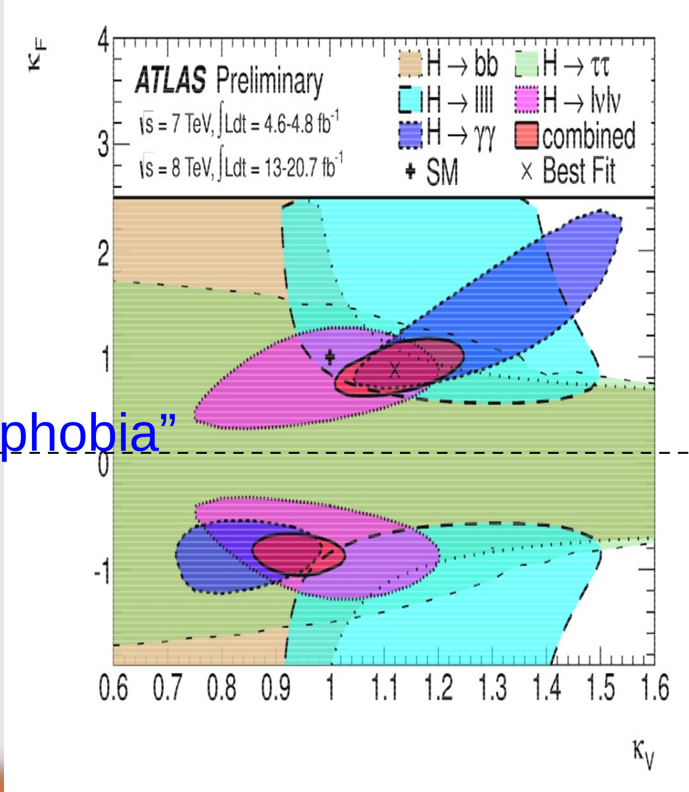
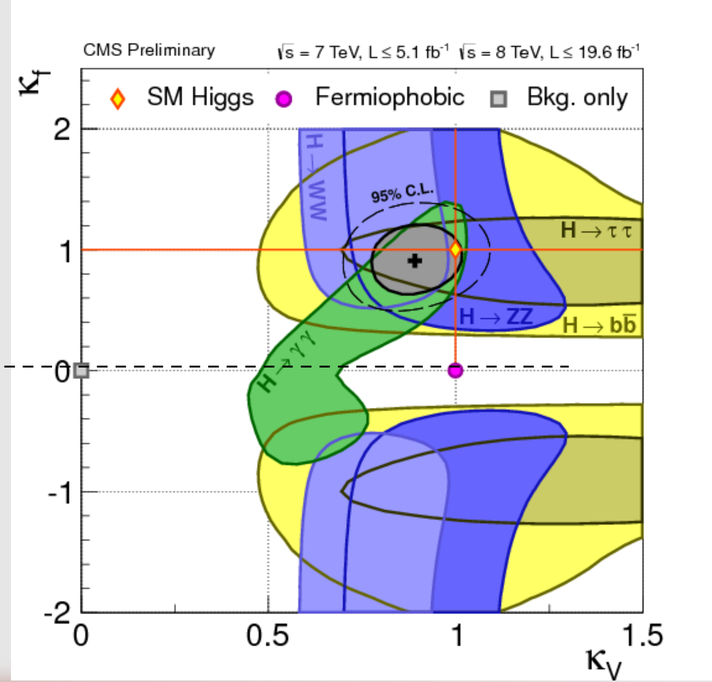
“fermiophobia”

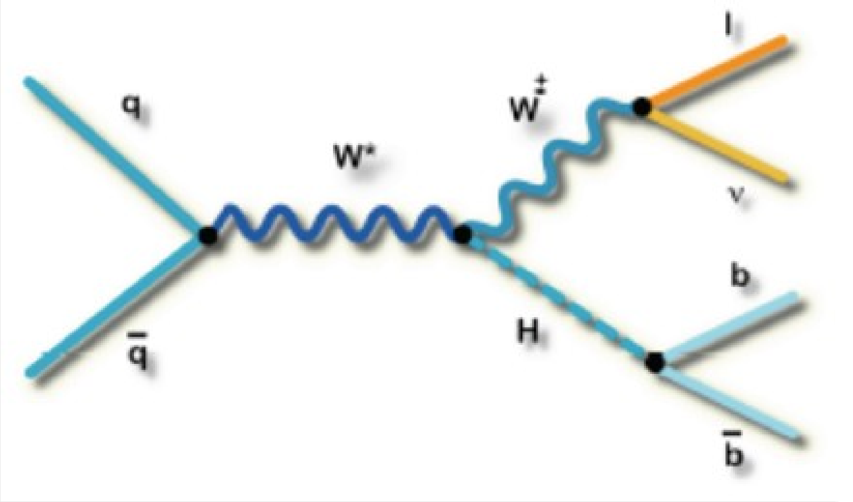




See most recent results in following talks

Tevatron favored decays

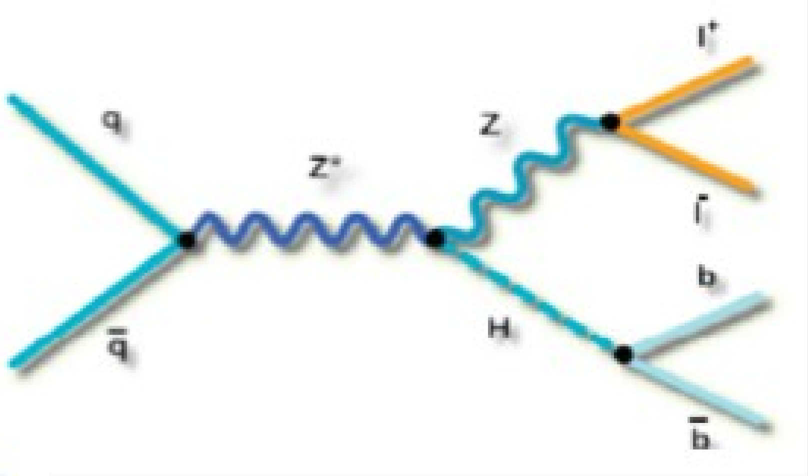
Details: Low Mass Channels



WH→lνbb: MET+l+bb

Large production cross section

Higher backgrounds than in ZH→llbb

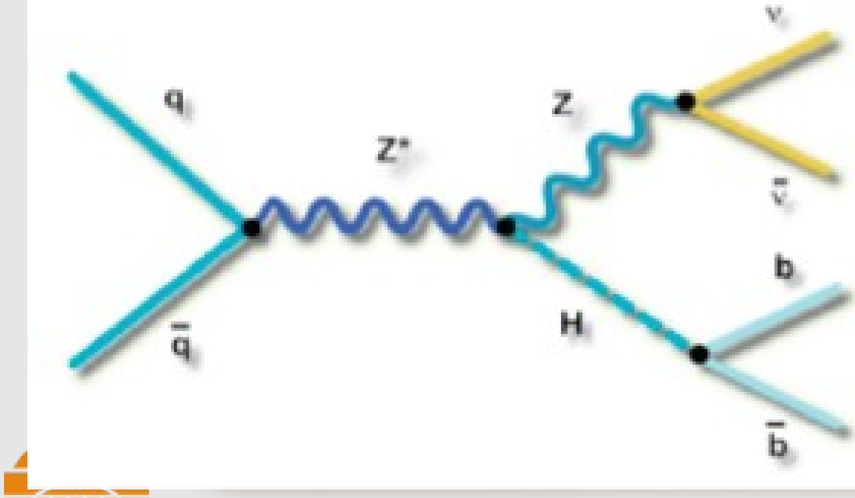


ZH→llbb: ll+bb

Low background

Fully constrained

Small Signal



ZH→νvbb: MET+bb

Signal 3x larger than ZH→llbb

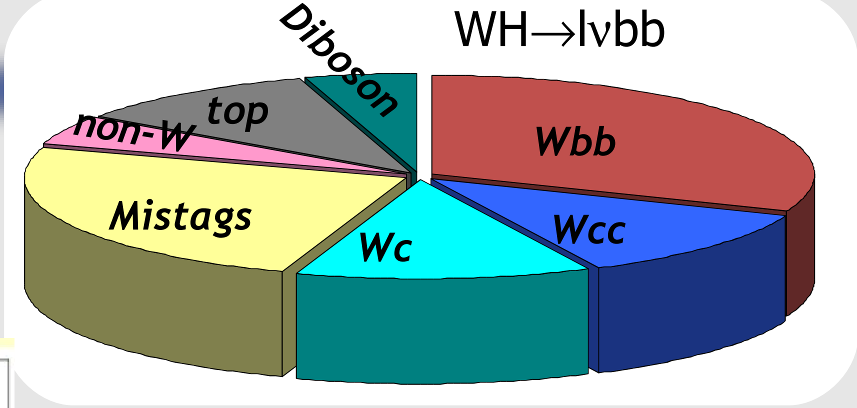
(+ contributions from WH)

Difficult to model backgrounds

Optimizing sensitivity in Low Mass Higgs Searches

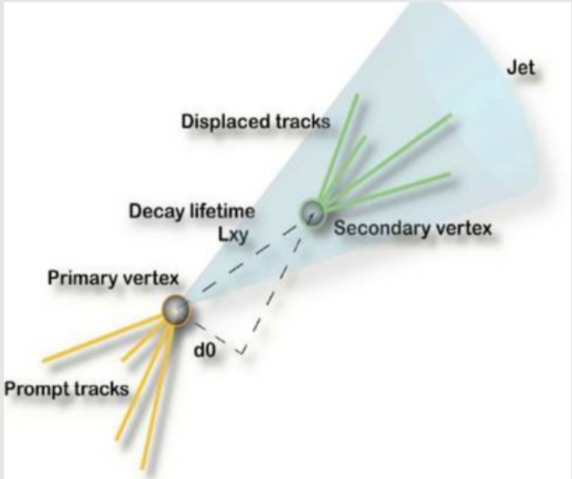
(1) Increase lepton reconstruction and selection efficiencies

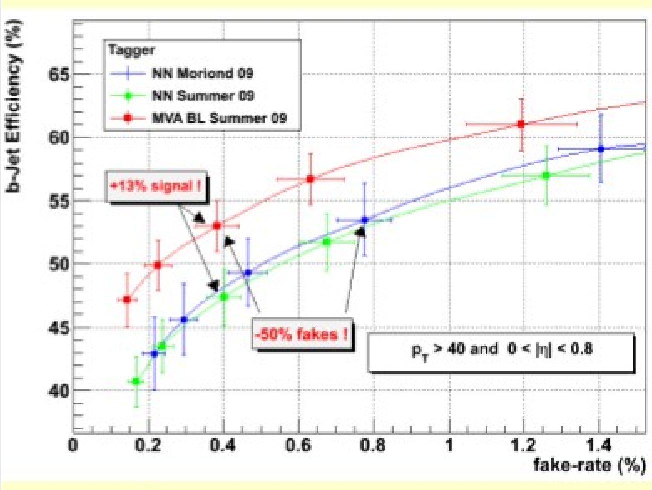
(2) Understand background



Specific to low mass analyses:

b-tagging





(3) Reduce the background by tagging b-quark jets

D0 VH analyses:

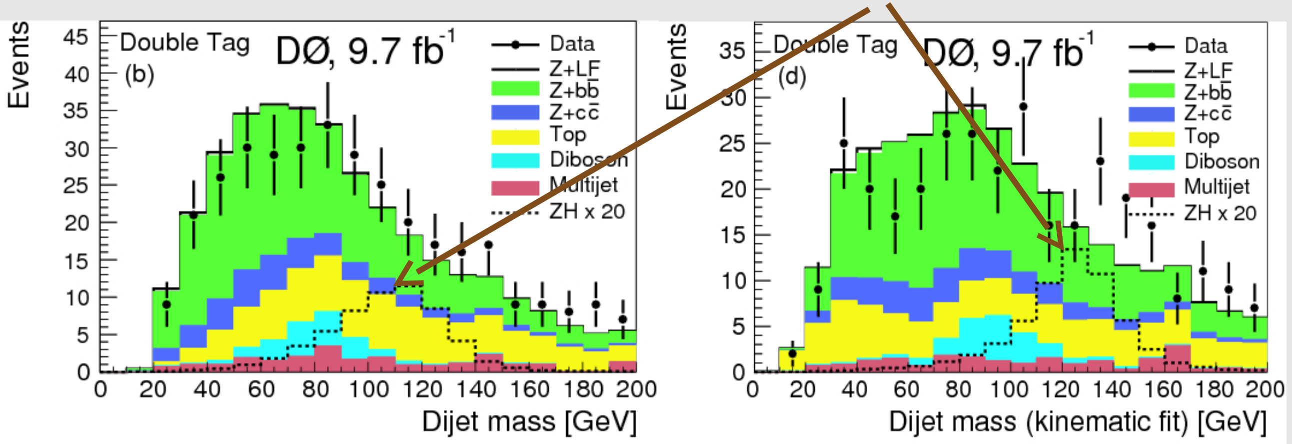
	Before b-tagging	2 tight tags
s/b	1/7000	1/200

(4) **Optimize dijet mass resolution**

(e.g. Talk by S. Shaw)

needs precise calibration and resolution for gluon and quark jets separately

Kinematic fit in ZH→llbb (15% sensitivity gain)



From Dijet mass to MultiVariate Analysis

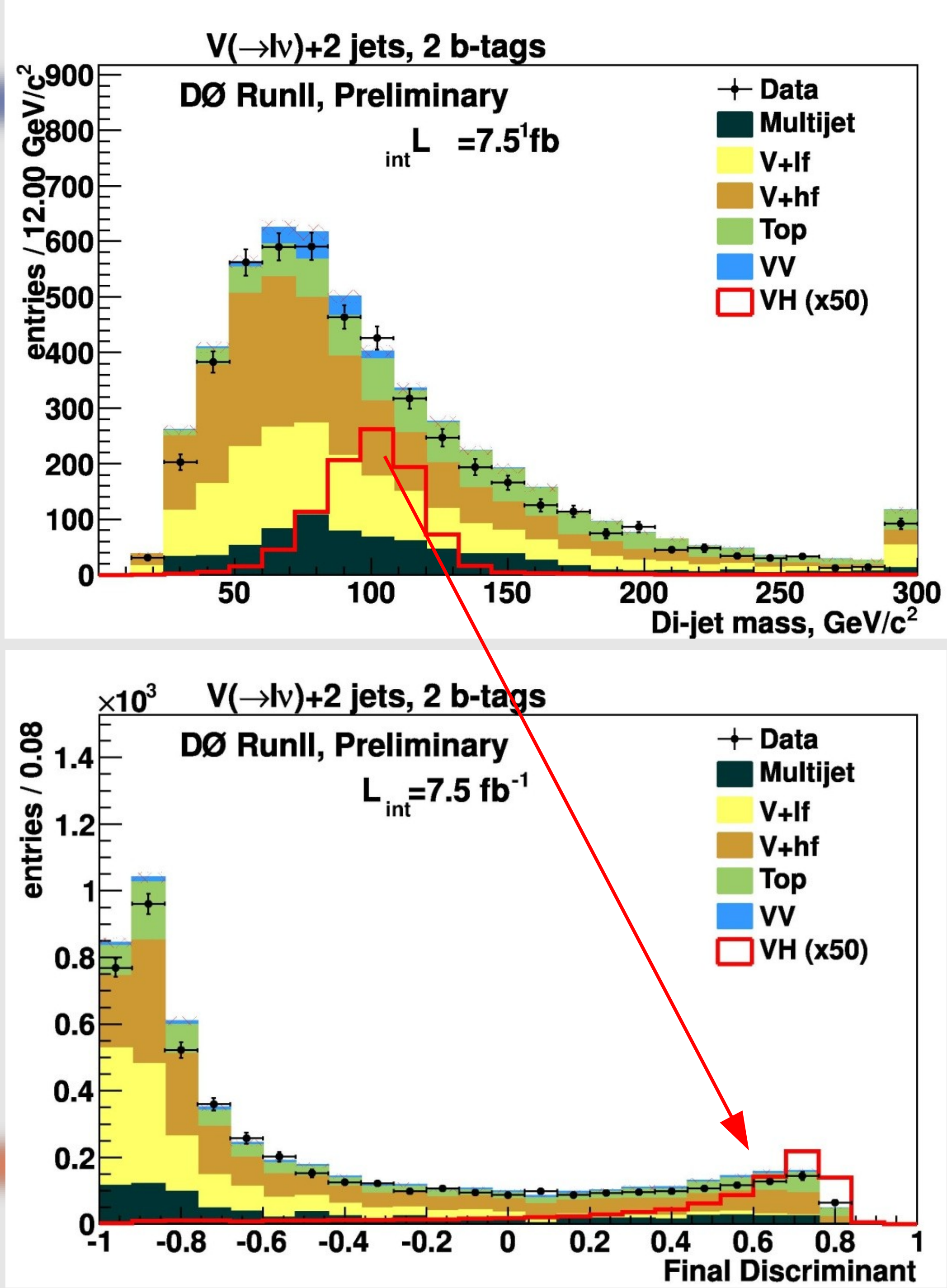
- To improve S/B -> utilize full kinematic event information

- Multi Variate Analyses
  - Neural Networks
  - Boosted Decision Trees

(Or use Matrix Element Calculations to determine probability for an event to be signal- or background-like)

- Approaches validated in 1st Single Top observation @ D0 Phys. Rev. Lett. 103, 092001 (2009)
- Combine these approaches
- Visible gain obtained

  (~25% in sensitivity)



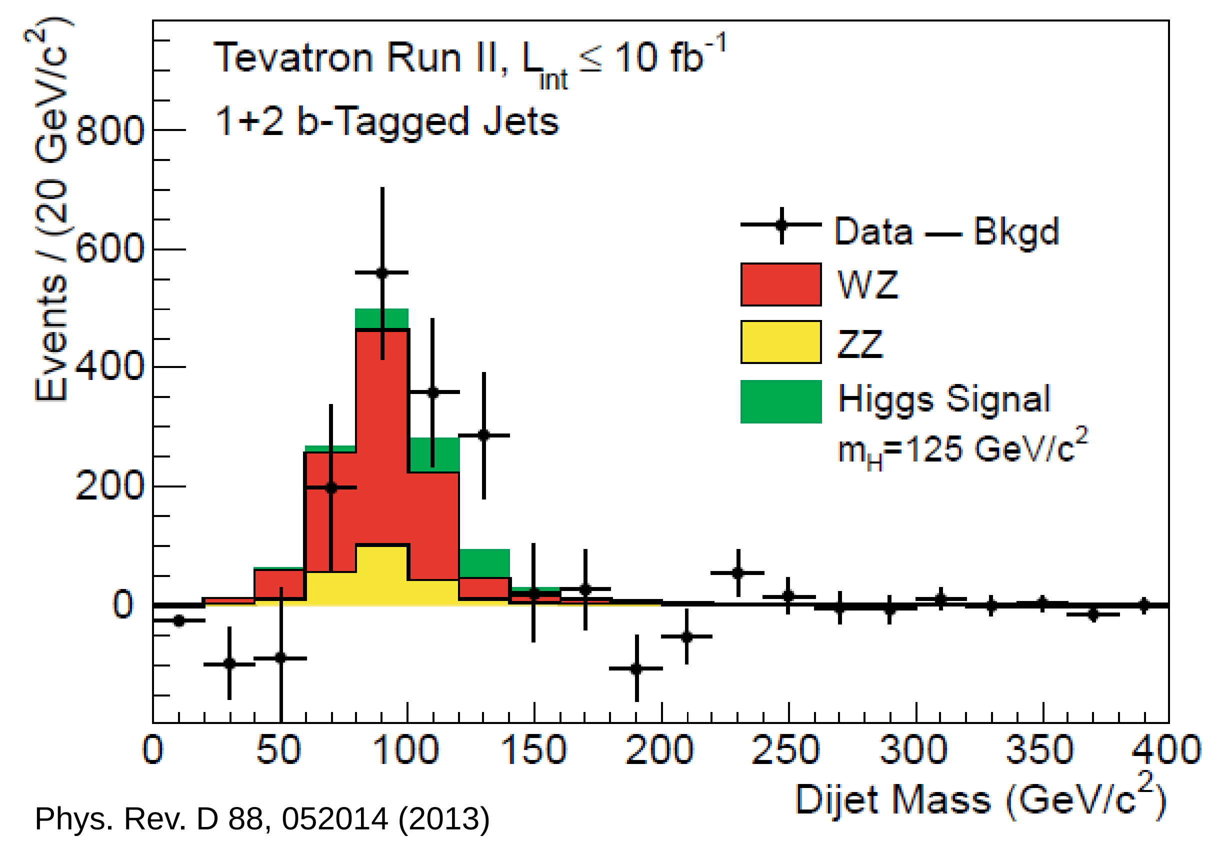
Benchmarks:
Dibosons to Heavy Flavor

CDF-D0 combination on the same data set/techniques as for H->bb,
i.e. WZ, ZZ with Z->bb, same 3 final states, same b-tagging categorizations

cross-section:

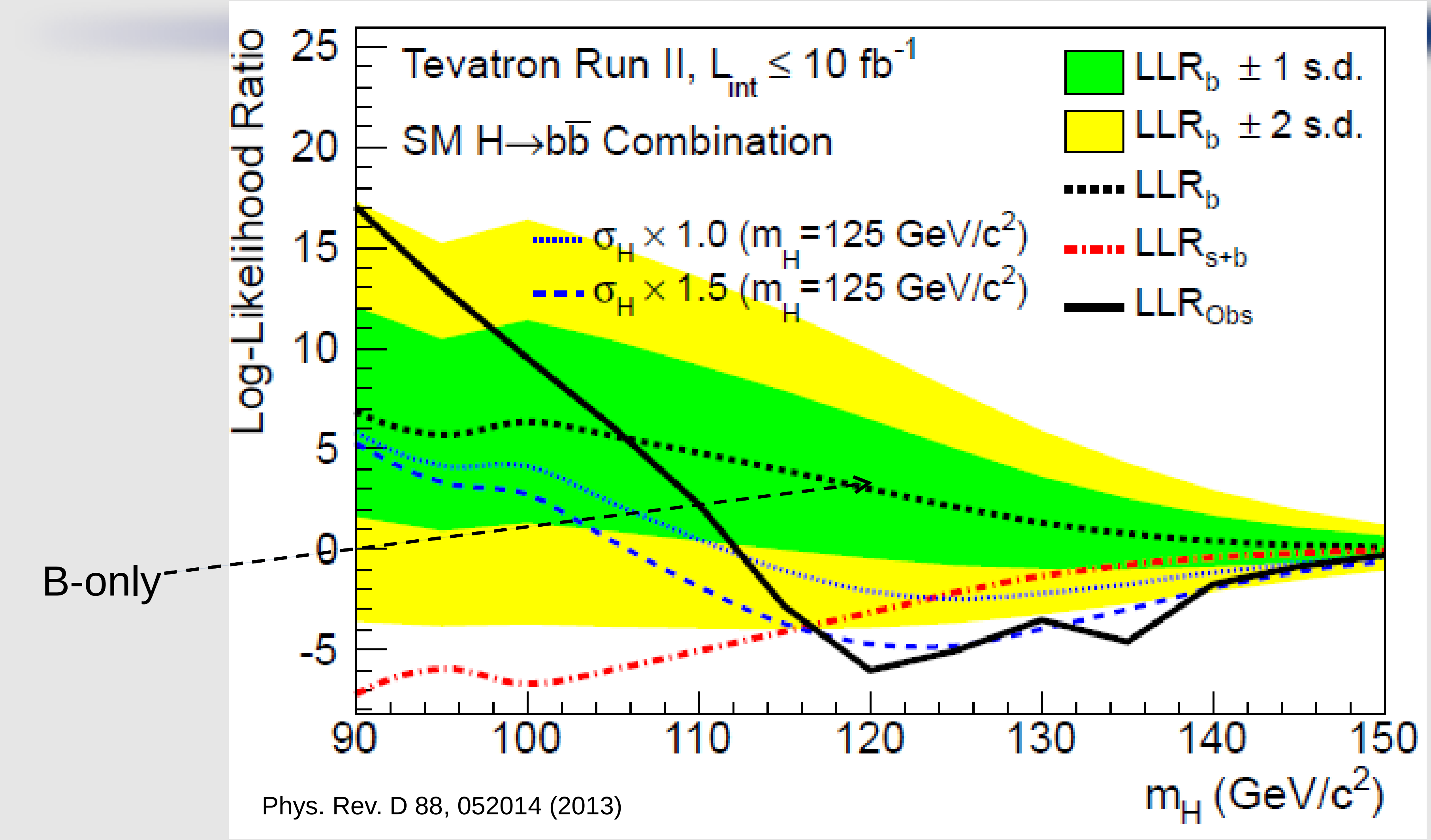
3.0 +/- 0.9 pb
(NLO: 4.4 +/- 0.3 pb)

=> Sensitivity to
SM-like H->bb



Phys. Rev. D 88, 052014 (2013)

Combined Log-Likelihood Ratio for H → bb



Phys. Rev. D 88, 052014 (2013)

Shape consistent with LLR expected in presence of 125 GeV Higgs, prefers slightly stronger strength than SM

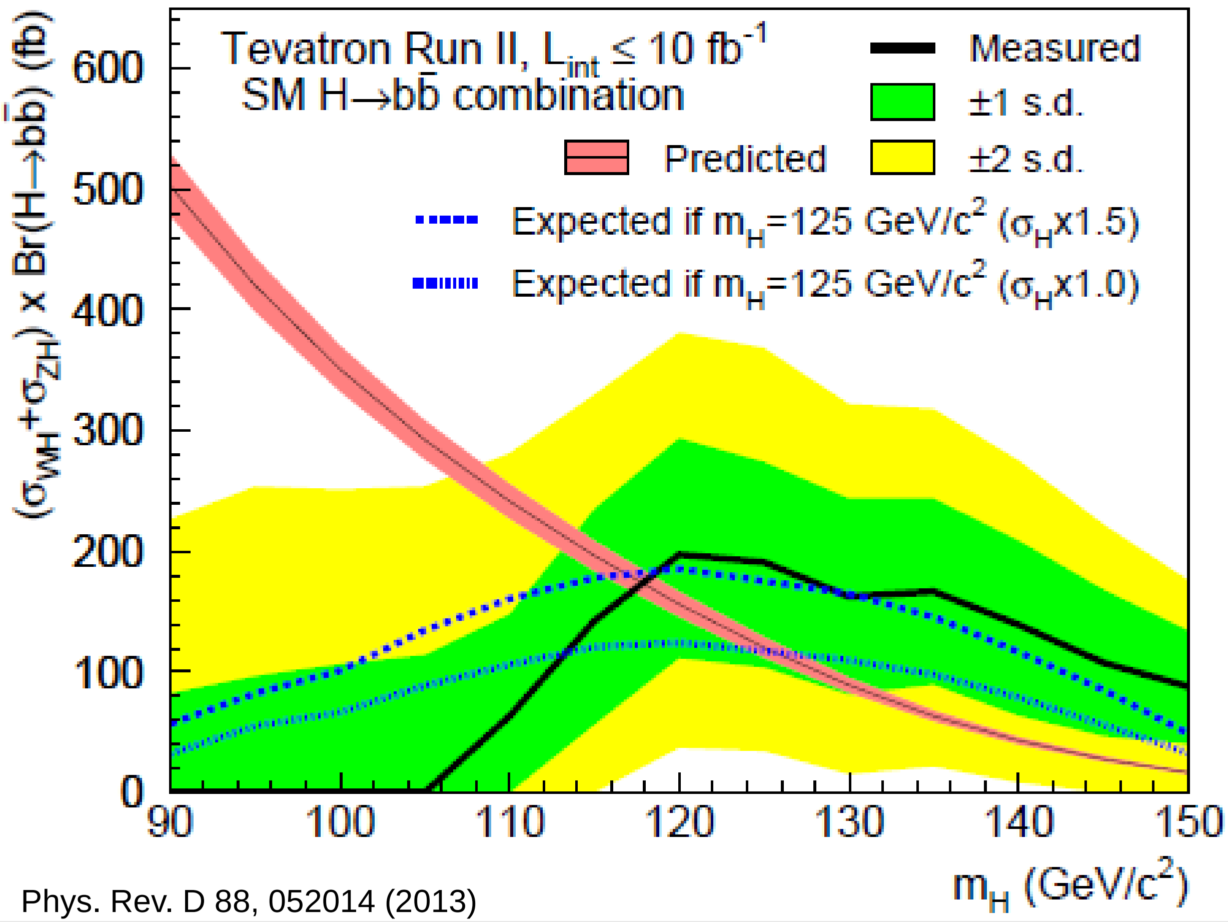
Combined σ x BR measurement

$$(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b})$$

= 0.19 ± 0.09 pb

SM Higgs @ 125 GeV:

$$0.12 \pm 0.01 \text{ pb}$$



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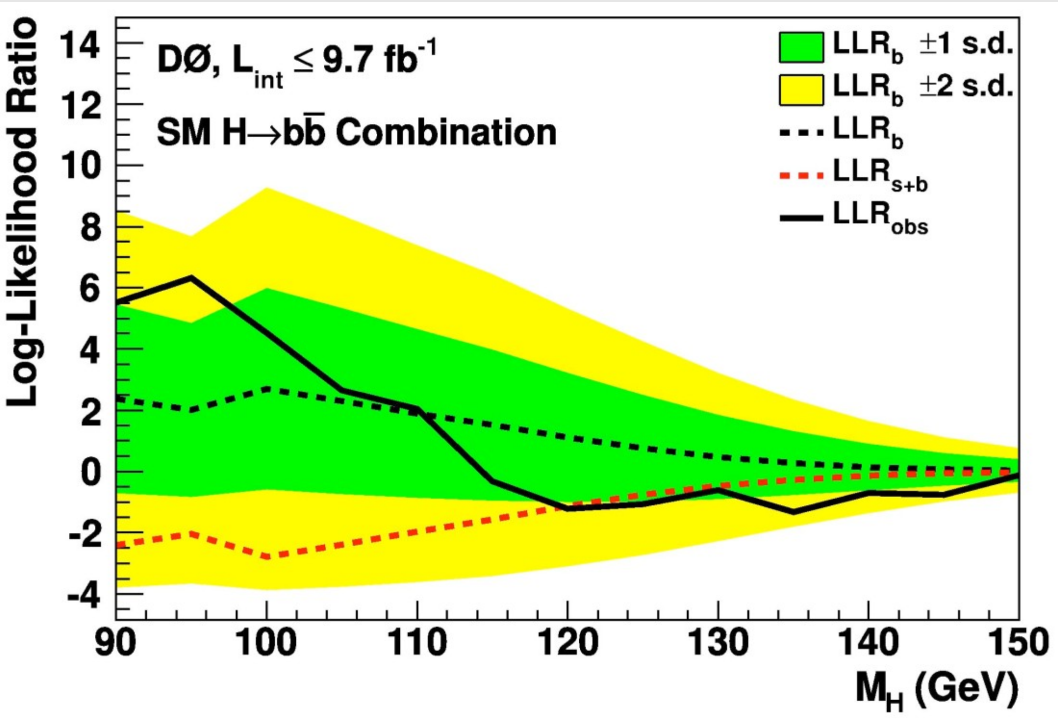
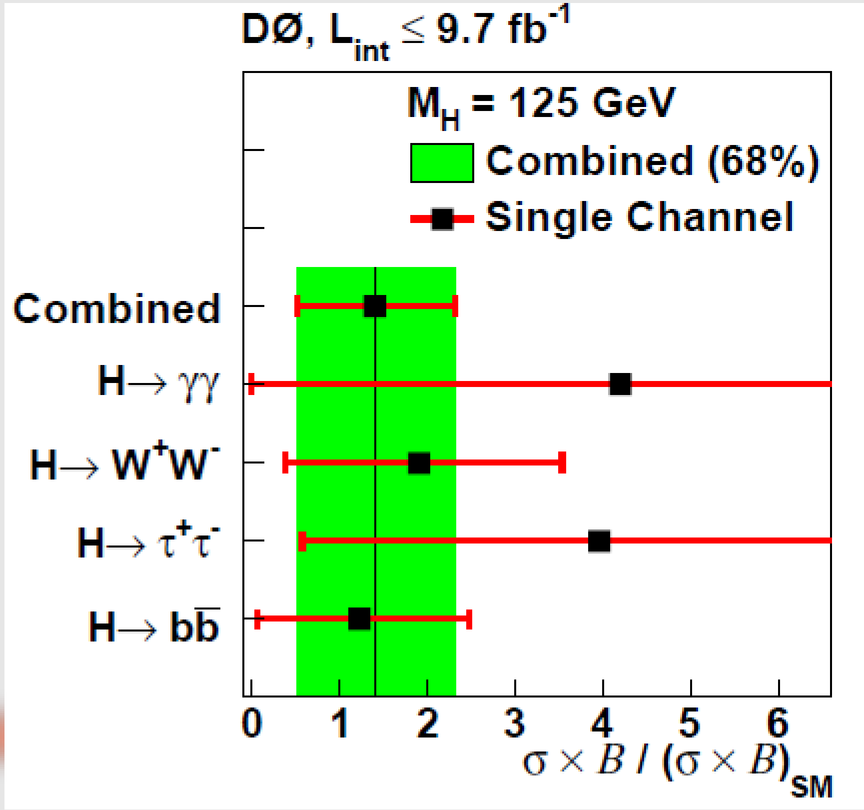
Tevatron: σ(VH) = 1.6 ± 0.7 (stat. + syst.) × SM
CMS: σ(VH) = 1.0 ± 0.5 (stat. + syst.) × SM
ATLAS: σ(VH) = 0.2 ± 0.6 (stat. + syst.) × SM

Spin@D0
Starting from VH⟶Vbb Results

- 3 Analyses: WH->lvbb, ZH->llbb, ZH->vvbb
- Same inputs as for final Tevatron and D0 Higgs combination.
  => excess compatible with SM Higgs

- Best fit H->bb cross section: $1.23^{+1.24}_{-1.17}$ × SM



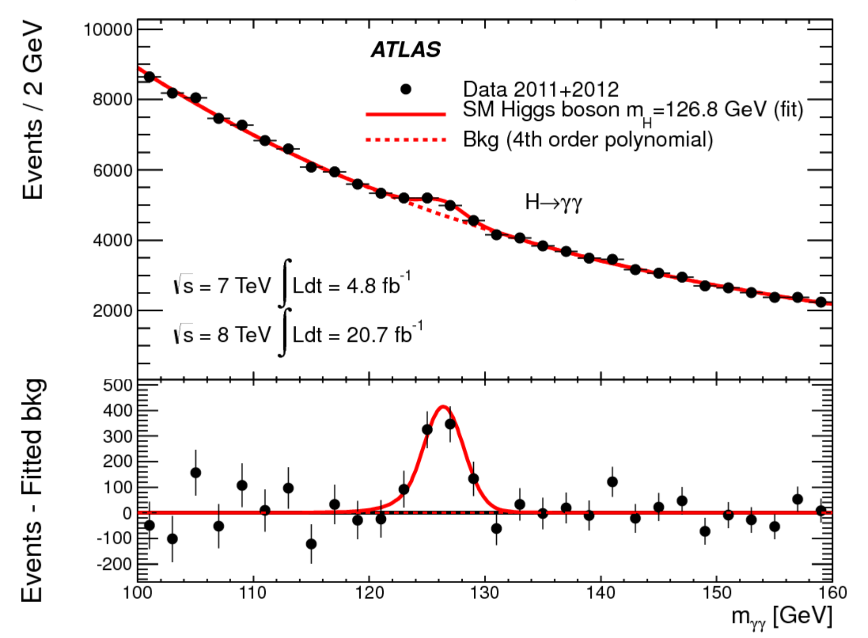


Higgs Spin and Parity: Introduction

SM predicts a spin J and parity P combination $J^P = 0+$

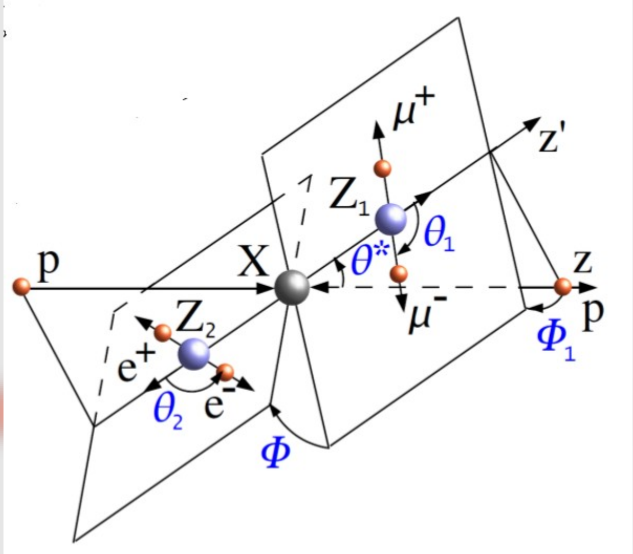
Other considerations are 2+ (graviton-like couplings) and 0- (pseudoscalar)

Spin 1 ruled out with observation of decay $H \rightarrow \gamma\gamma$ (Landau-Yang Theorem)



Measurements using bosonic decay modes, take advantage of angular correlations and kinematics of Higgs decay products

At ATLAS and CMS, all measurements are consistent with $J^P = 0+$



Spin and Parity at the Tevatron

For associated Higgs (**VH, V=W/Z**), production processes are different depending on JP assignment

For 0+, production is S-wave; $\sigma \sim\beta$ near threshold

For 0-, production is P-wave; $\sigma \sim\beta^3$ near threshold

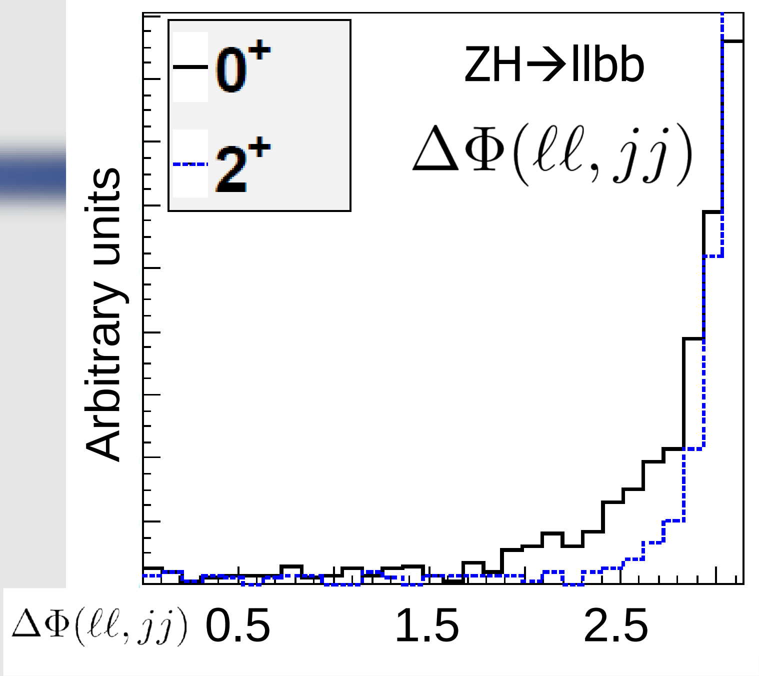
For 2+, mostly D-wave contribution for graviton-like couplings; $\sigma \sim\beta^5$

At the Tevatron we expect the kinematic differences to come from different behaviors at the production threshold

β = V/H 3-momentum, C.O.M. frame

Details in
Ellis, Hwang, Sanz, You, JHEP **1211**, 134 (2012)
cf. also
Miller, Choi, Eberle, Muhlleitner, and Zerwas, PLB **505**, 149 (2001)

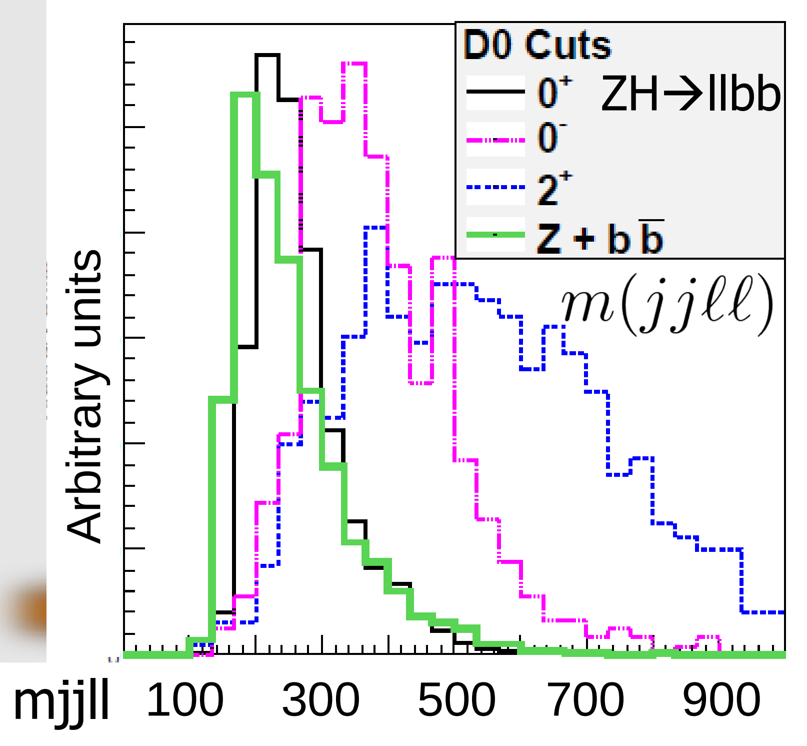
Testing Spin and Parity (ideal MC)

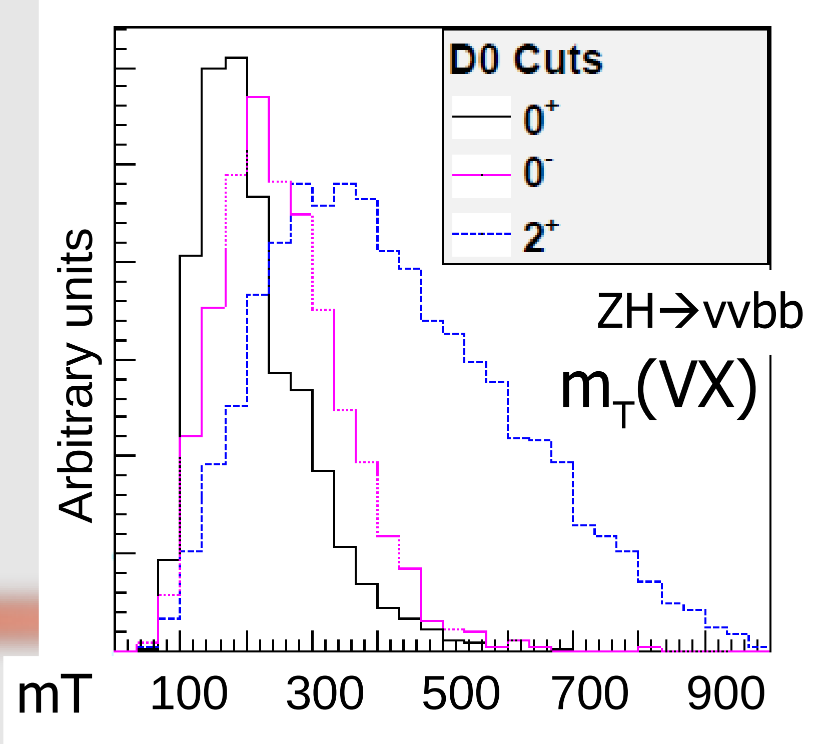


Visible mass of Vbb system very sensitive to J^P assignment

Good separation from backgrounds for 2+ and 0- as well, <u>much better than for SM Higgs</u>!

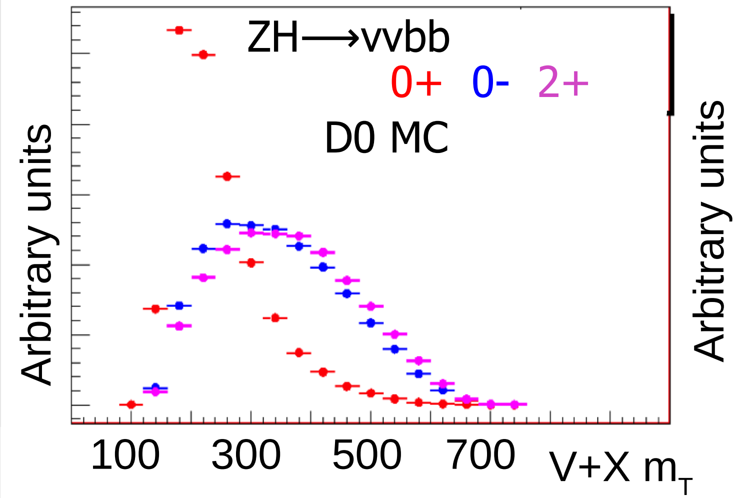
*plots from Ellis, Hwang, Sanz, You, JHEP **1211**, 134 [2012]*

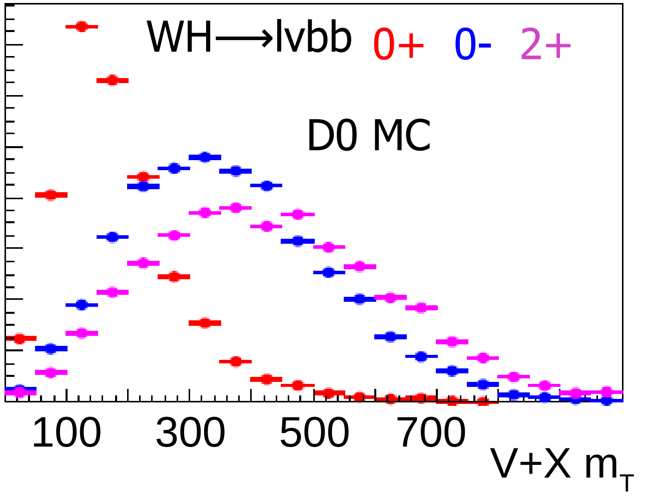


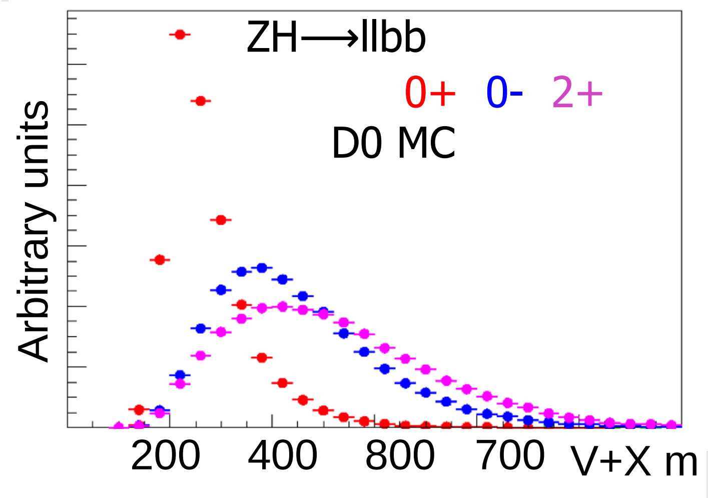


Generating signals

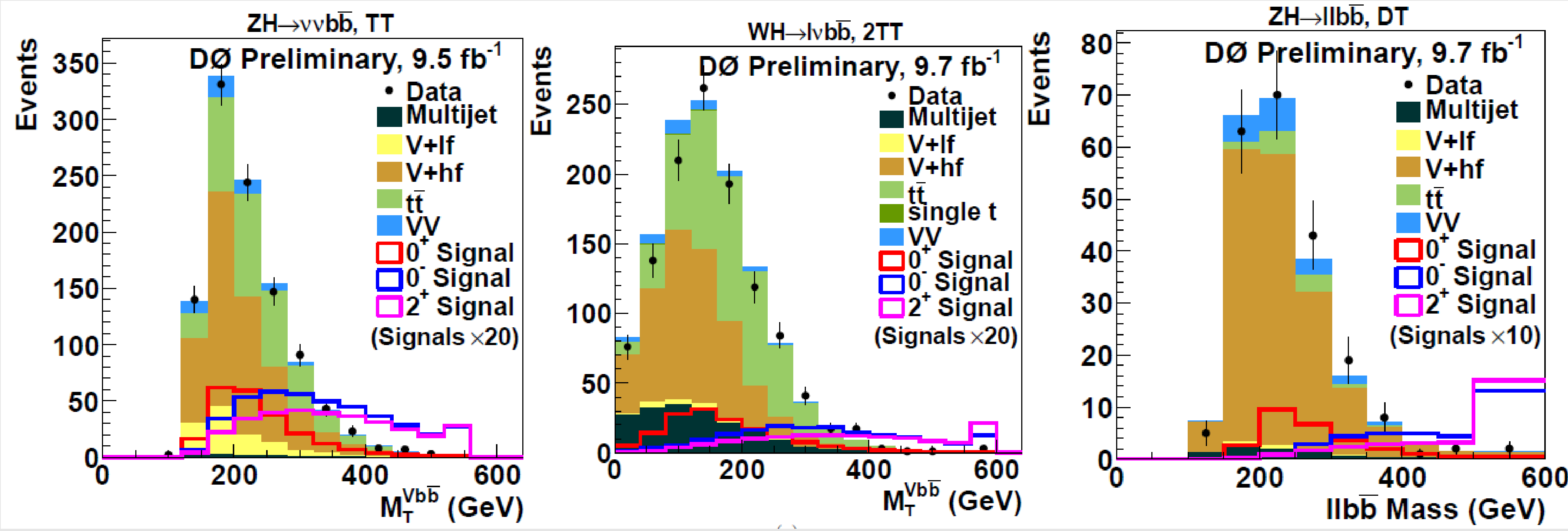
- Generate 0-, 2+ signal with MADGRAPH5; interfaced to PYTHIA for showering
  - Use RS graviton model, initial normalization to SM σ x Br
    Note: no generic Spin-2 model
  - Only considering VH processes (no e.g. gg or VBF)
- MADGRAPH 0+ VH checked against PYTHIA VH; good agreement
- Observe similar separation to that predicted w/o detailed simulation







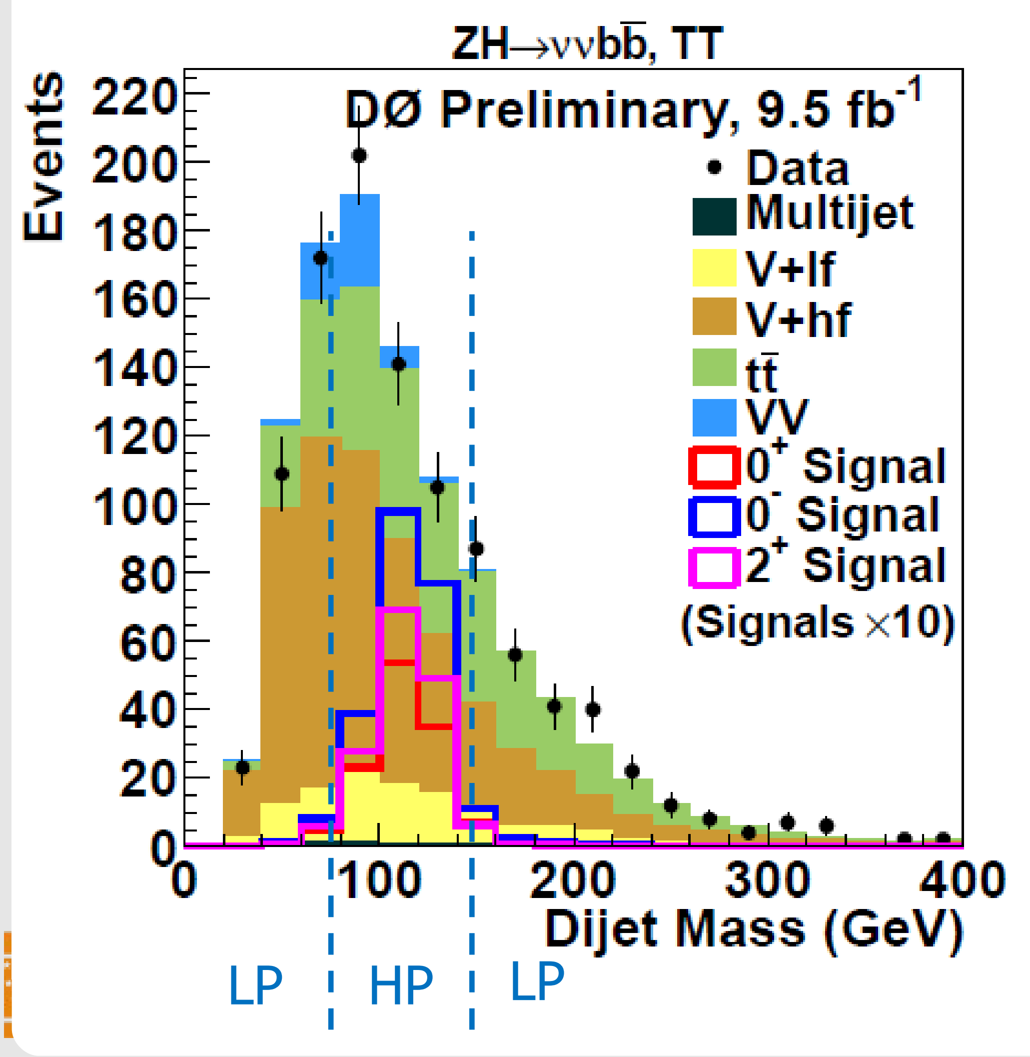
Visible Mass in VH Channels

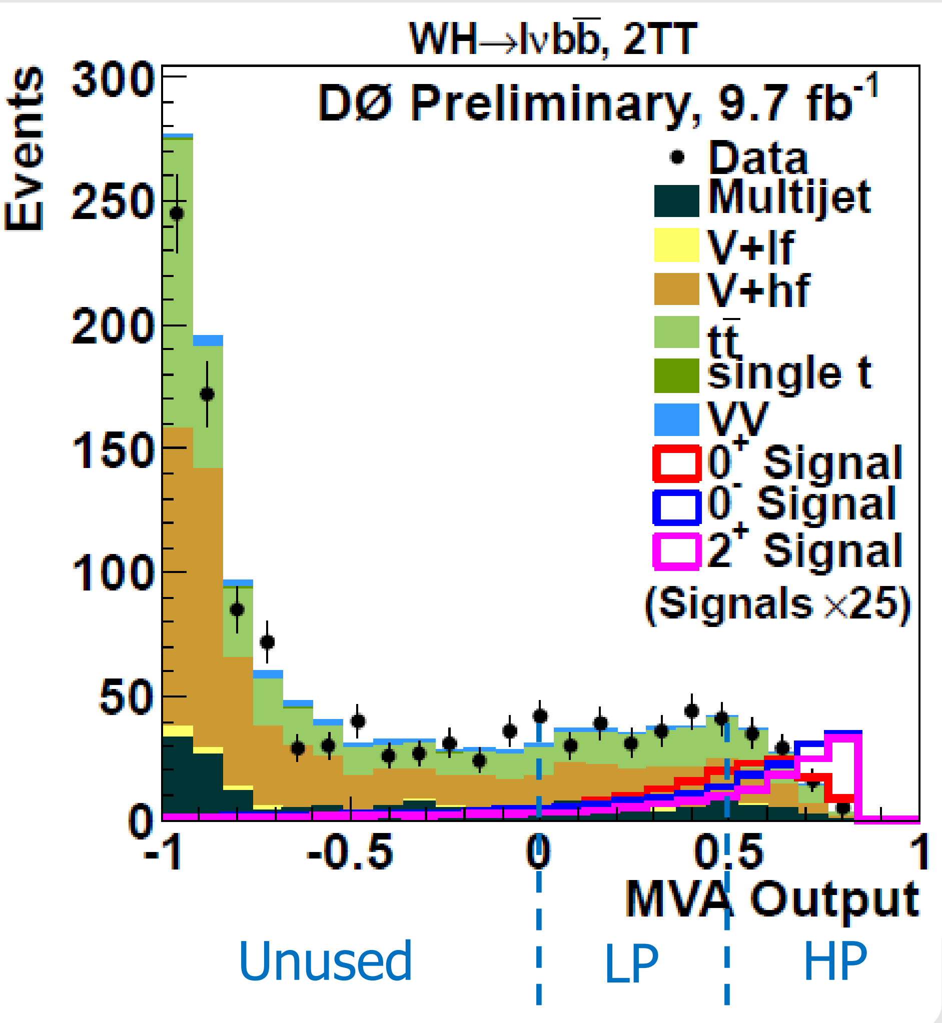


- Tightest b-tag sub-channel shown (upper edge bins combined due to stats.)
- Good separation between different signals
- We can still do better on the backgrounds

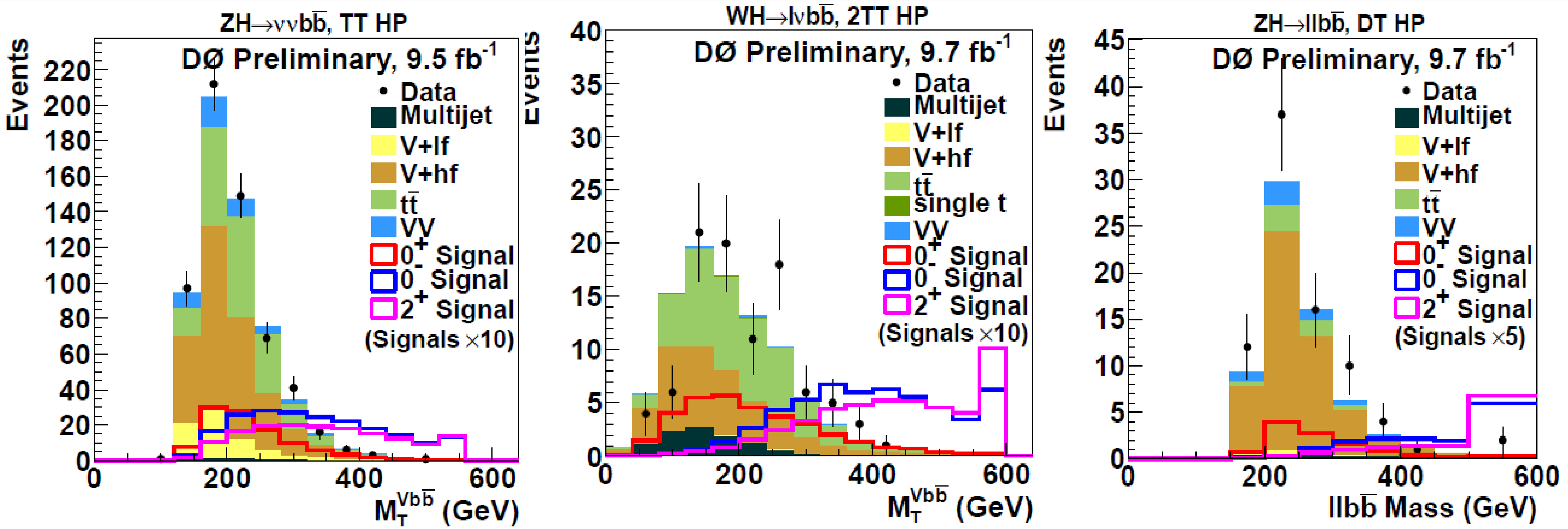
Additional Discrimination

- Take advantage of known mass/event properties
  - vvbb, llbb => use dijet mass M_{bb} to define High/Low Purity (HP/LP) regions
  - lvbb => MVA output to make HP/LP regions
- Separate channels for statistical analysis





Final Variables



Tightest, highest purity, b-tag channel shown for each analysis

Large separation between SM/0+ and 0- or 2+

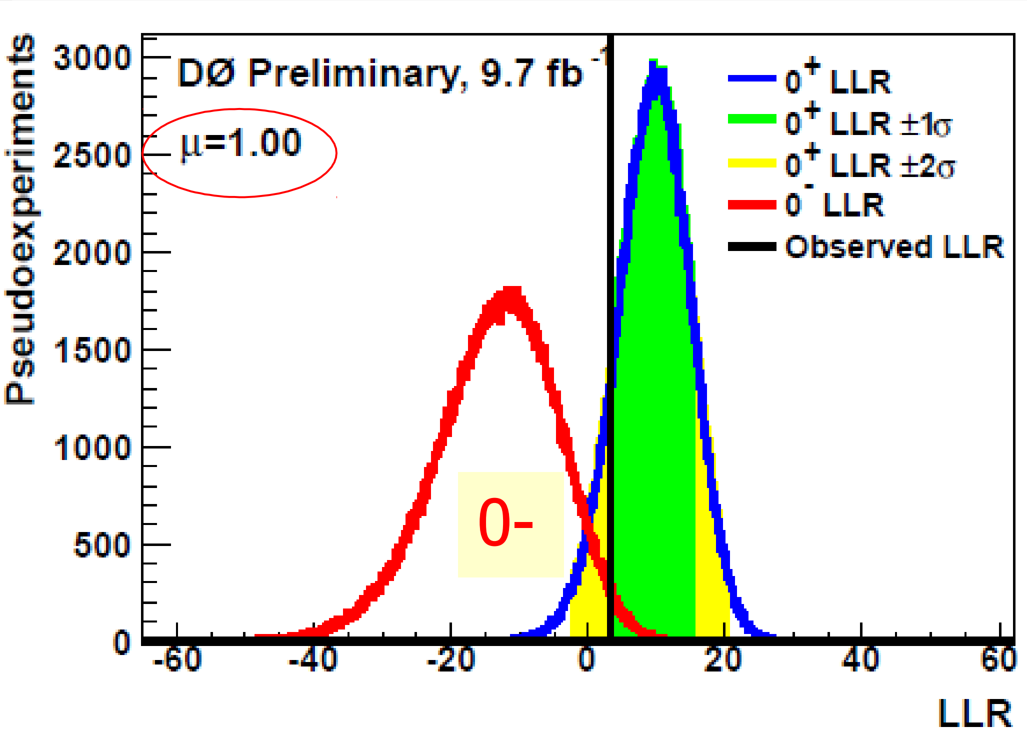
Higgs Spin Results

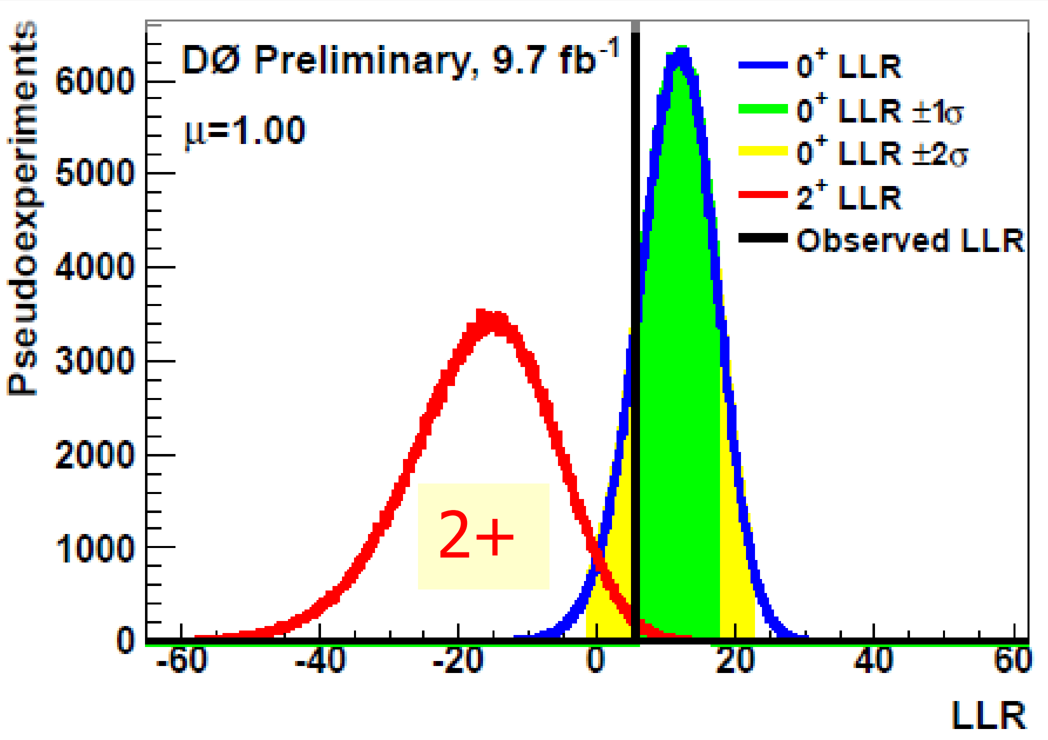
- Use CLs to quantify model preference, log-likelihood ratio (LLR) as test statistic

$$LLR = -2\log(L(H1)/L(H0))$$

H1: 0- signal + Background or 2+ signal + Background
H0: 0+ signal + Background

Compute for 2 different signal scale factors μ on SM σ(VH)×Br(bb)
1.00 (SM-like, shown) and 1.23 (D0 measured rate)





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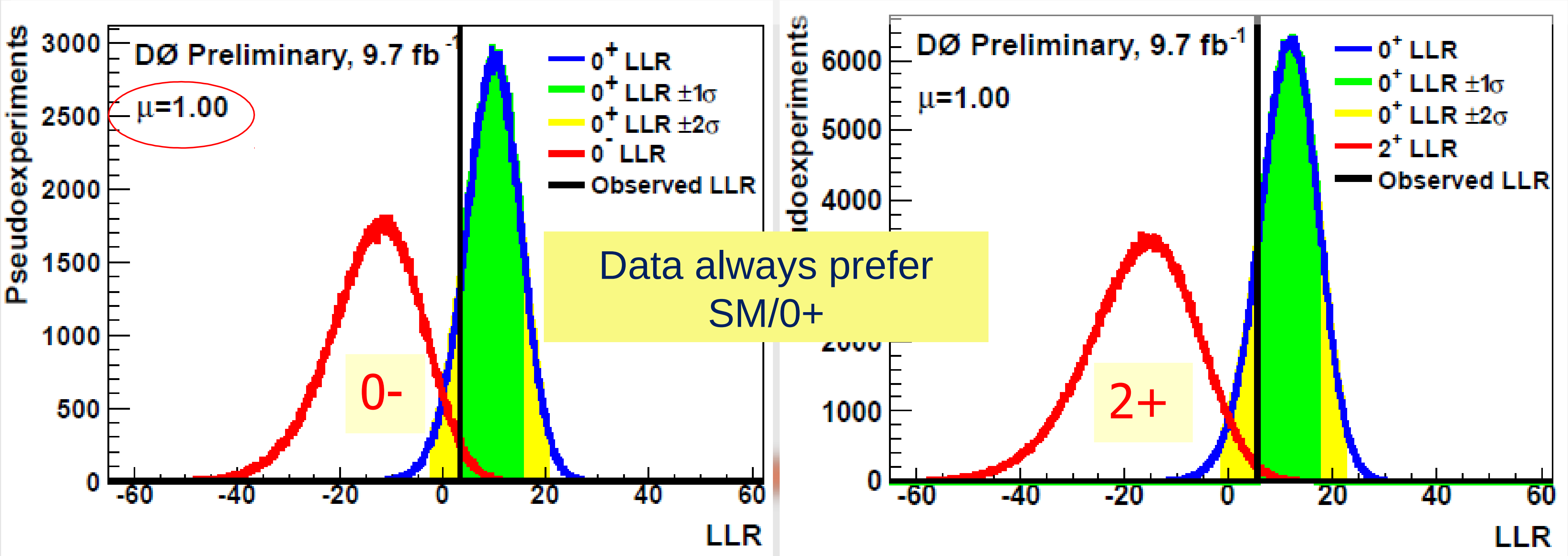


Data always prefer SM/0+

0-

2+

Higgs S/P Results

- CLs=CL_H1/CL_H0
- CLx=P(LLR ≥ LLRobs|x)
- Interpret 1-CLs as C.L. for exclusion of 0- or 2+ in favor of 0+

For SM signal strength

- **We exclude 0- model at > 97.9% C.L.**
- **Expected exclusion is 3.1 s.d. (μ=1.0)**
- **We exclude 2+ model at > 99.2% C.L.**
- **Expected exclusion is 3.2 s.d. (μ=1.0)**

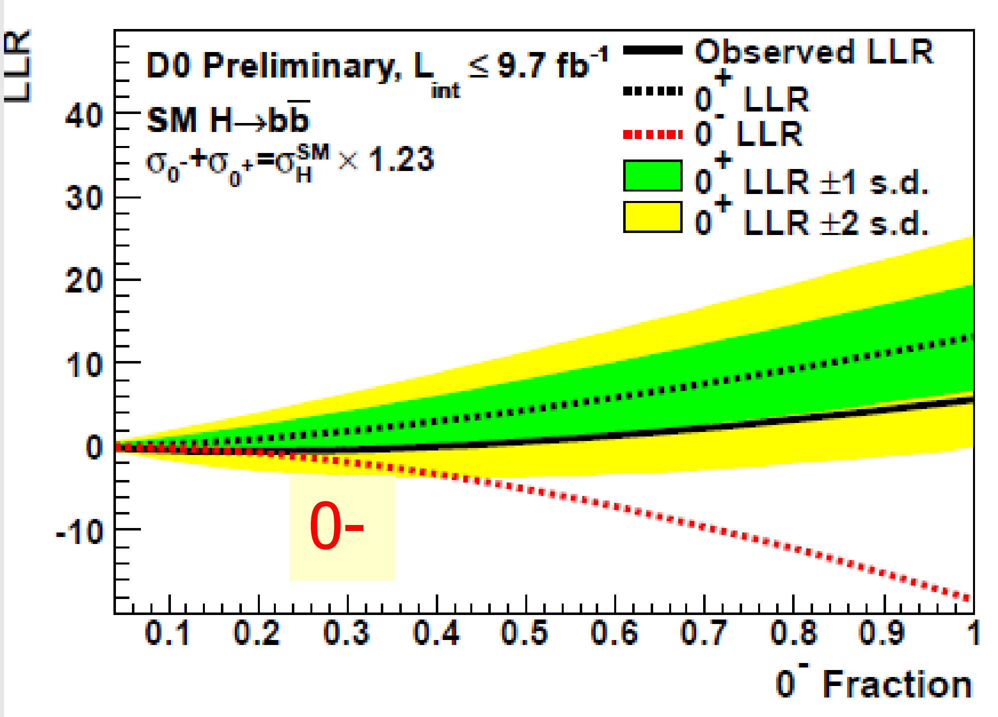
	Results 0-	Result in s.d. 0-	Results 2+	Result in s.d. 2+
SM Signal strength				
1 – CLs Exp. (μ=1.00)	**0.998**	**3.1**	**0.9992**	**3.2**
1 – CLs Obs. (μ=1.00)	**0.979**	**2.3**	**0.992**	**2.4**
Best Fit Signal strength				
1 – CLs Exp. (μ=1.23)	**0.9997**	**3.5**	**0.9999**	**3.7**
1 – CLs Obs. (μ=1.23)	**0.995**	**2.5**	**0.999**	**3.0**

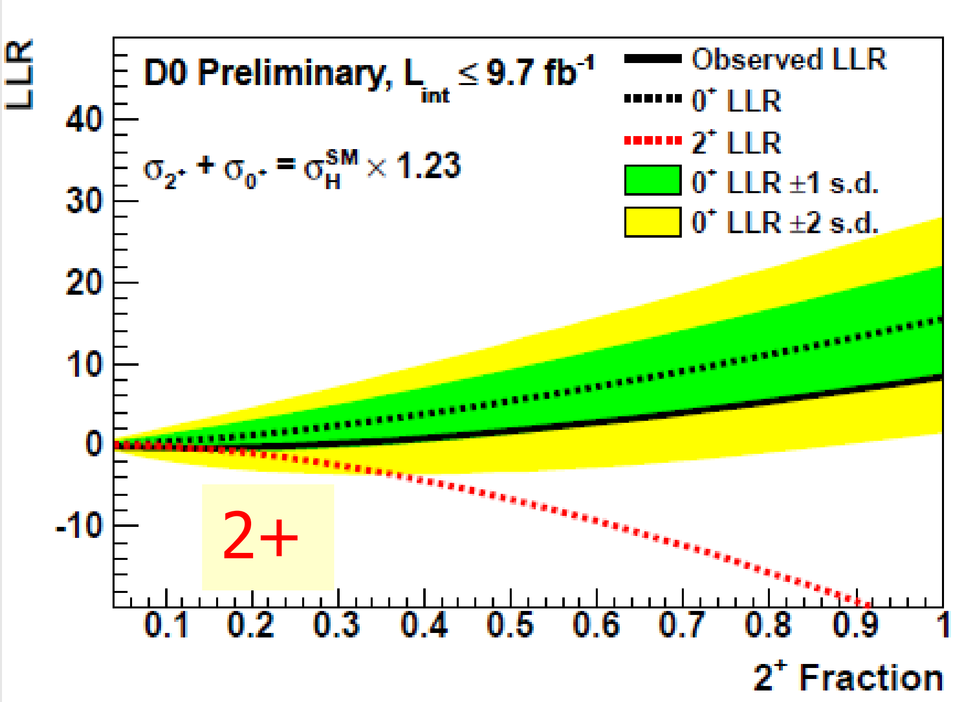
Single Tevatron experiment has sensitivity competitive with LHC experiments

D0 Conference Notes: 6387, 6406

Signal Admixtures

- **Allow possibility of both a 0- (or 2+) and 0+ signal in data**
  - **Vary 0- (or 2+) Fraction fx from 0 to 1**
  - **H1: μ × (σ•Br(->bb))SM × [0- × fx + 0+ × (1 – fx)] + Background**
  - **H0: μ × (σ•Br(->bb))SM × 0+ (i.e. pure 0+) + Background**
- **Fix μ to observed (1.23xSM) or expected (1.00xSM), compute LLR, CLs**





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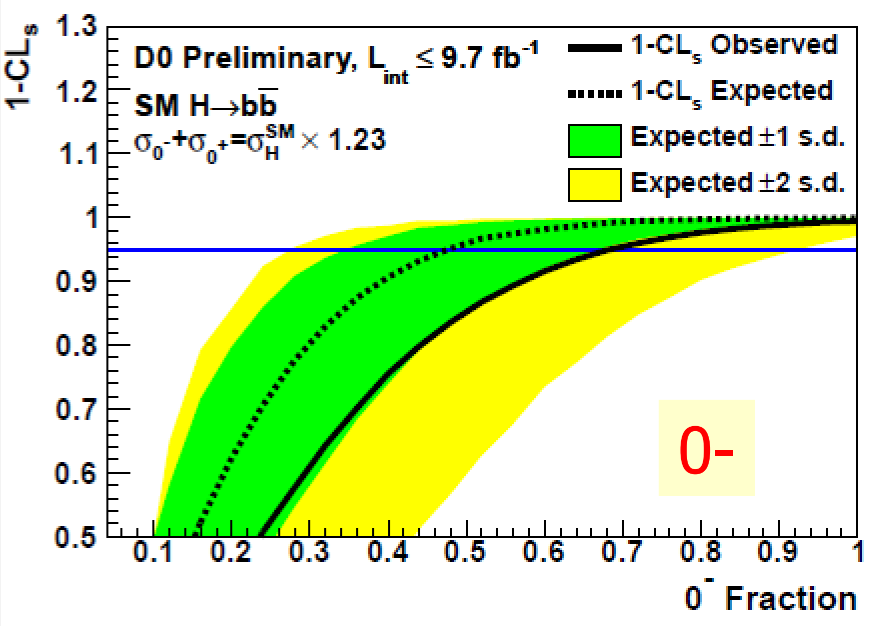
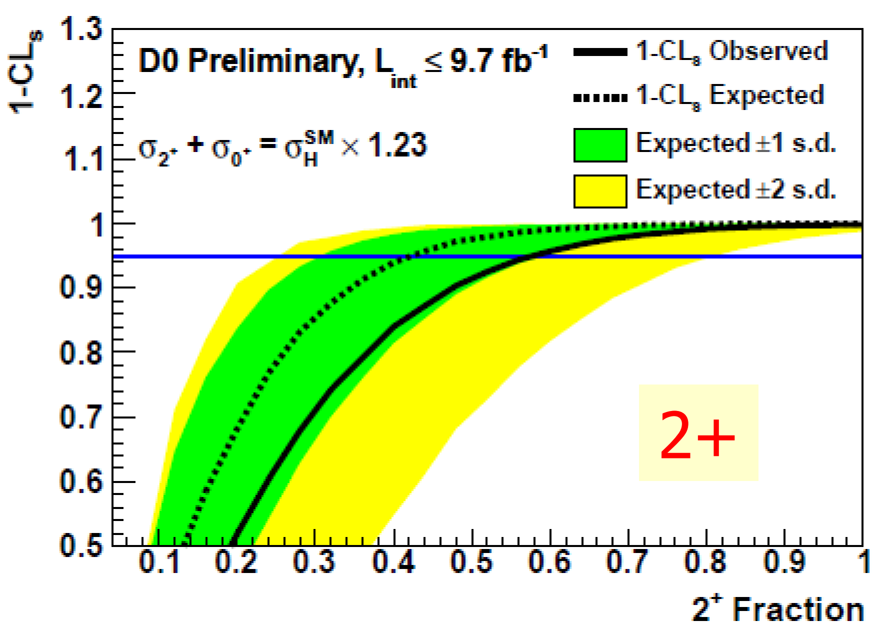


Exclude f0- > 0.67 at 95% C.L.



Exclude f2+ > 0.57 at 95% C.L.

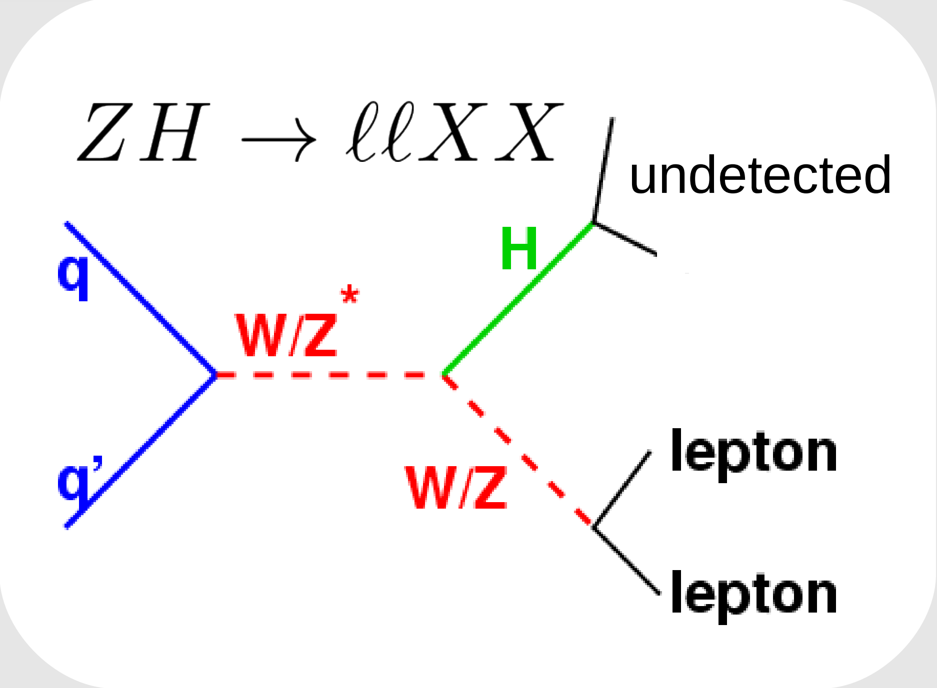
Analysis: σ_{ZH} x BR(H -> invisible)

New

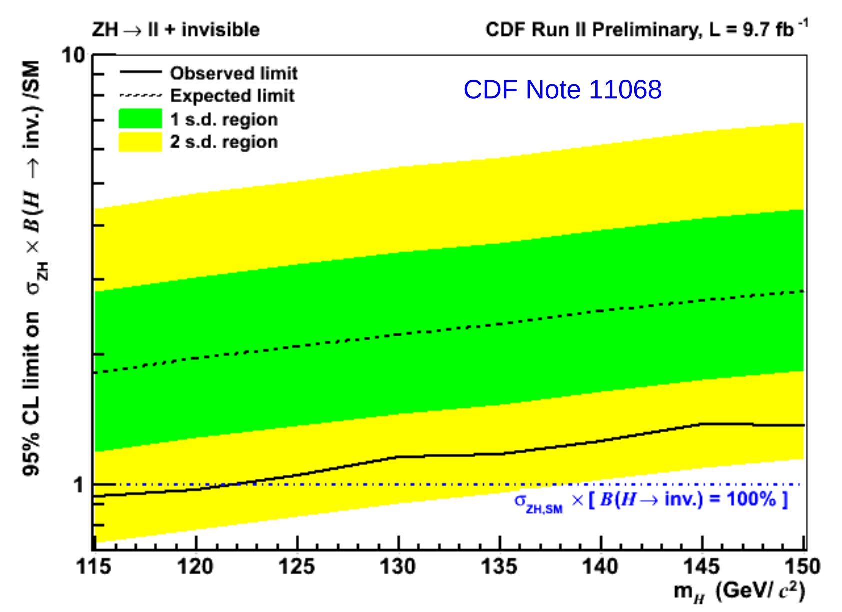
New from CDF

First Tevatron search for H-> invisible

- Exclude σ_{ZH} x BR(H -> invisible) > 90 fb for MH=125 GeV at 95% CL
- Exclude 100% BR (invisible), for M_H<120 at 95% CL



$$ZH \to \ell\ell XX$$

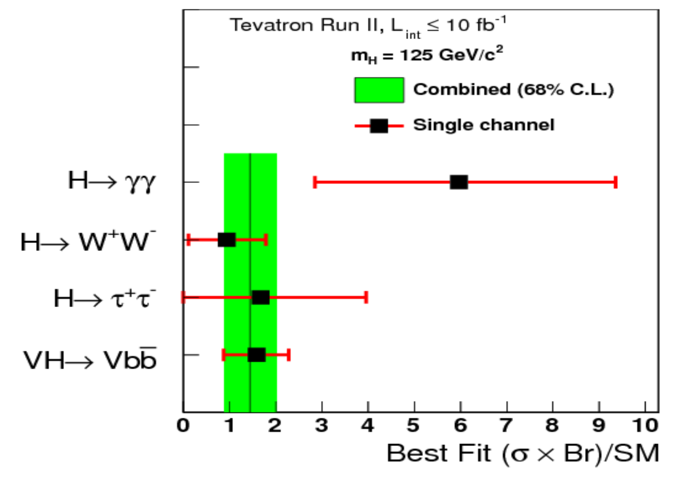


Details: See Young Scientist's Talk by Christiana Principato

Summary: 1

Latest Tevatron results based on full Run II data set in all major search channels are all now published in PRD

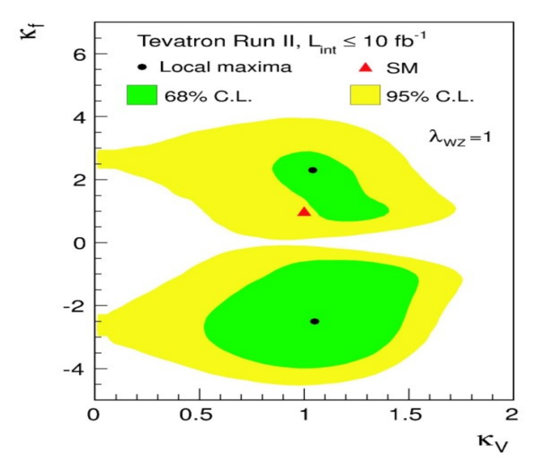
Phys. Rev. D 88, 052014 (2013)



Signal strengths in 4 decay channels (bb,tt,γγ,WW), and results on Higgs couplings to fermions, W, Z, are consistent with the SM

Published evidence for WH/ZH production with H→bb (7/2012), where H is consistent with a SM Higgs boson of 125 GeV. So far the only evidence in a $b\bar{b}$ decay channel of the Higgs

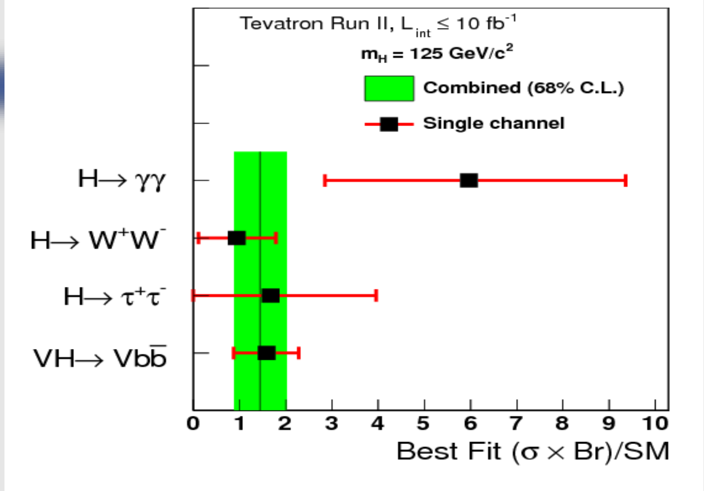
Phys. Rev. Lett. 109, 071804 (2012)



Summary: 2

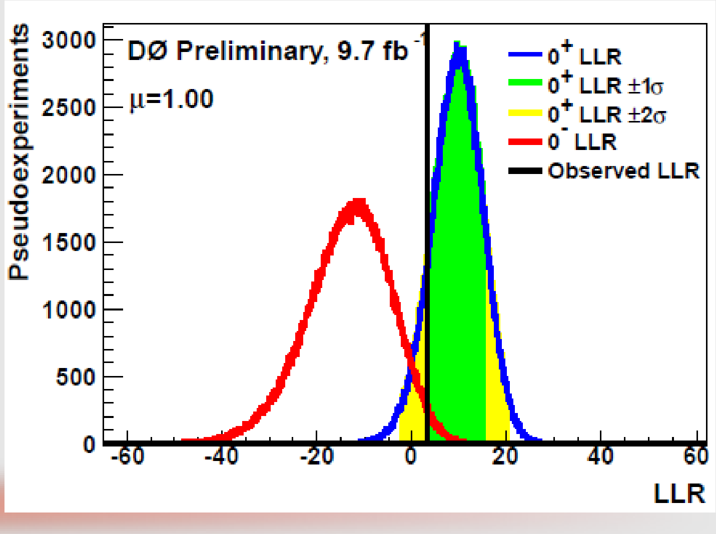
Preliminary

D0 spin and parity tests (first in bb final states) favor J^P=0+; reject J^P=0- and 2+ (graviton-like couplings) at 97.9% and 99.2% C.L, assuming SM strength



Higgs signal at D0 cannot contain (at 95%CL) more than ~ 67% or 57% of 0- or 2+

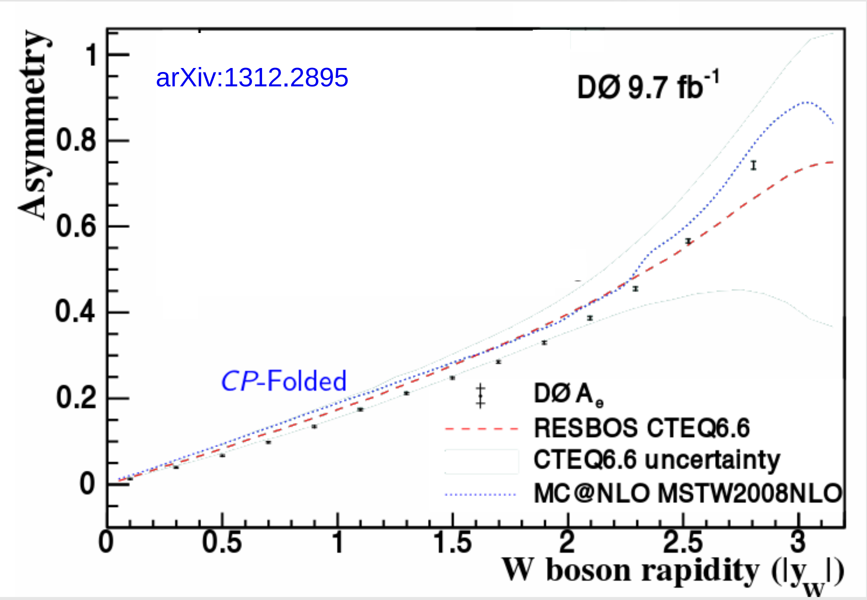
Final publications on Higgs are approaching for Tevatron: these results plus combination with CDF, could effectively exclude J^P 0- and 2+ hypotheses in $b\bar{b}$ final states



Outlook

Combining results in VH decays w/ improvements in measures of m_W, m_{top}:

Tevatron data continue to probe and constrain physics of the EW sector

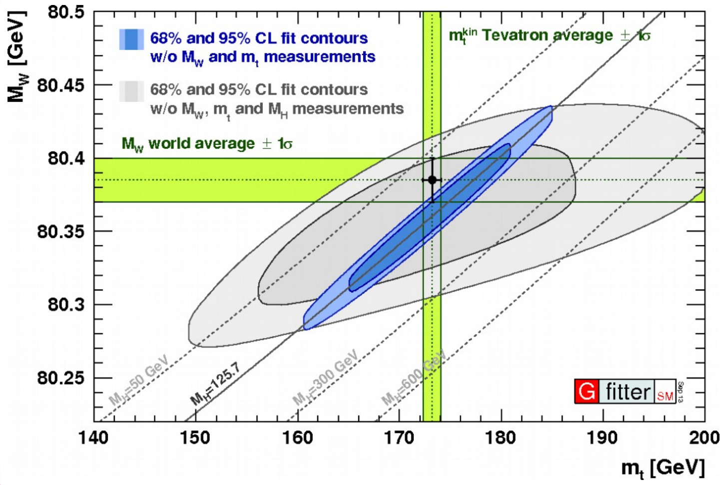


m_W:

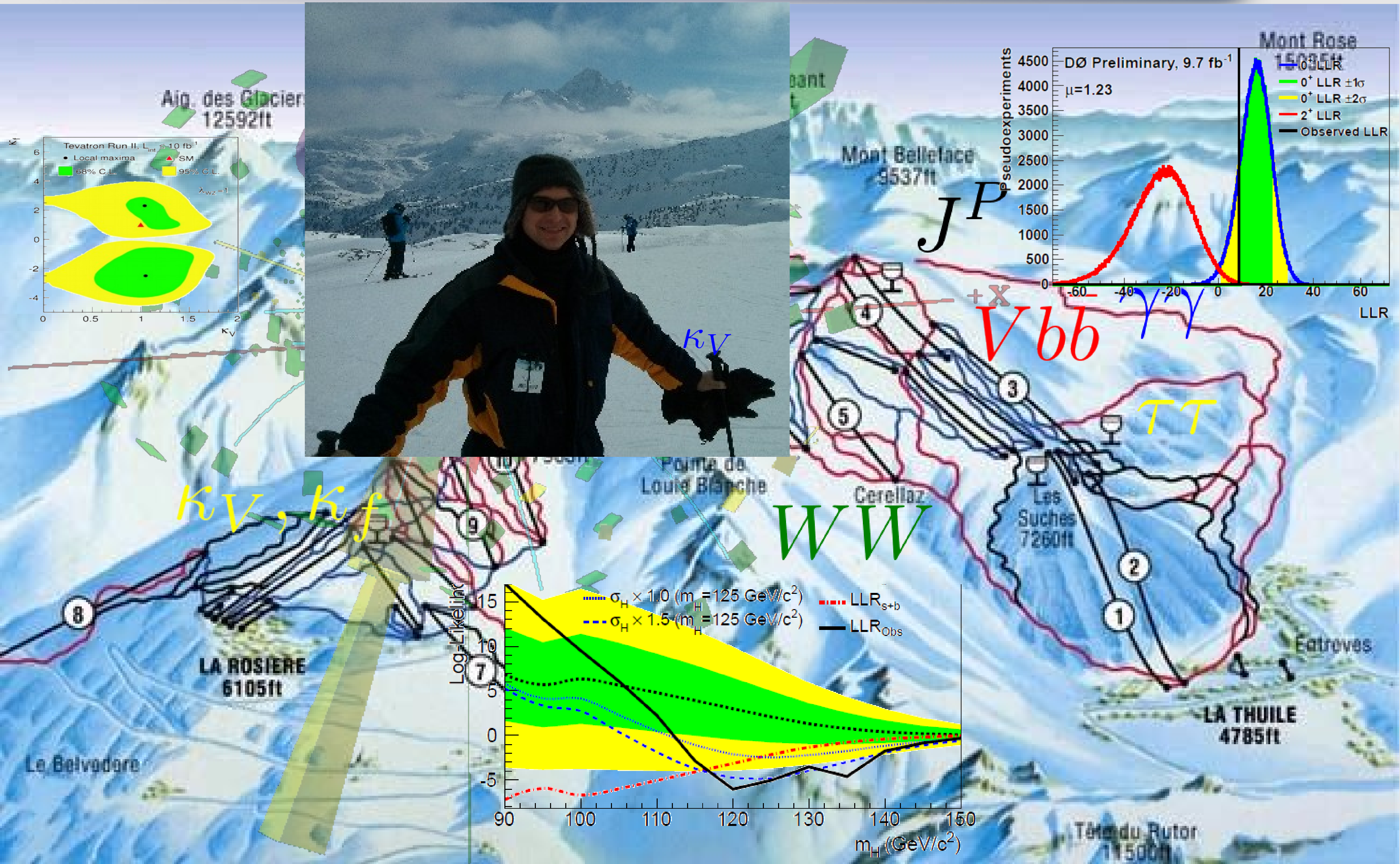
- Significant improvements on PDF constraints from W asymmetry => dominant uncertainty
- Further reductions, “going fwd”
- Calibrations scale w/ statistics
- 10 MeV uncertainty not unreasonable

m_{top}:

- First world-combination in progress!
- More precise Tevatron measures to come soon



Thanks!


Aig. des Glaciers
12592ft
Tevatron Run II, $L_{int} \leq 10\ fb^{-1}$
Local maxima
SM
68% C.L.
95% C.L.
$\lambda_{WZ}=1$
κ_f
κ_V
0
0.5
1
1.5
2
6
4
2
0
-2
-4
Mont Belleface
9537ft
Mont Rose
15035ft
DØ Preliminary, 9.7 fb^{-1}
μ=1.23
Pseudoexperiments
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-60
-40
-20
0
20
40
60
LLR
0^+ LLR
0^+ LLR ±1σ
0^+ LLR ±2σ
2^+ LLR
Observed LLR
J^P
κ_V
$Vb\bar{b}$
$\gamma\gamma$
$\tau\tau$
WW
κ_V, κ_f
Pointe de
Louie Blanche
Cerellaz
Les
Suches
7260ft
Entreves
LA THUILE
4785ft
LA ROSIERE
6105ft
Le Belvedere
Tête du Rutor
11500ft
1
2
3
4
5
7
8
9
10
Log-Likelihood
15
10
5
0
-5
90
100
110
120
130
140
150
m_H (GeV/c^2)
$\sigma_H \times 1.0$ (m_H=125 GeV/c^2)
$\sigma_H \times 1.5$ (m_H=125 GeV/c^2)
LLR_{s+b}
LLR_{Obs}

backups