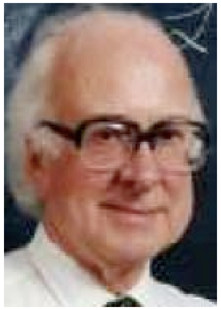
Higgs searches



Yuji Enari

LPNHE, Paris Universites VI & VII

IN2P3-CNRS

October 20th 2011

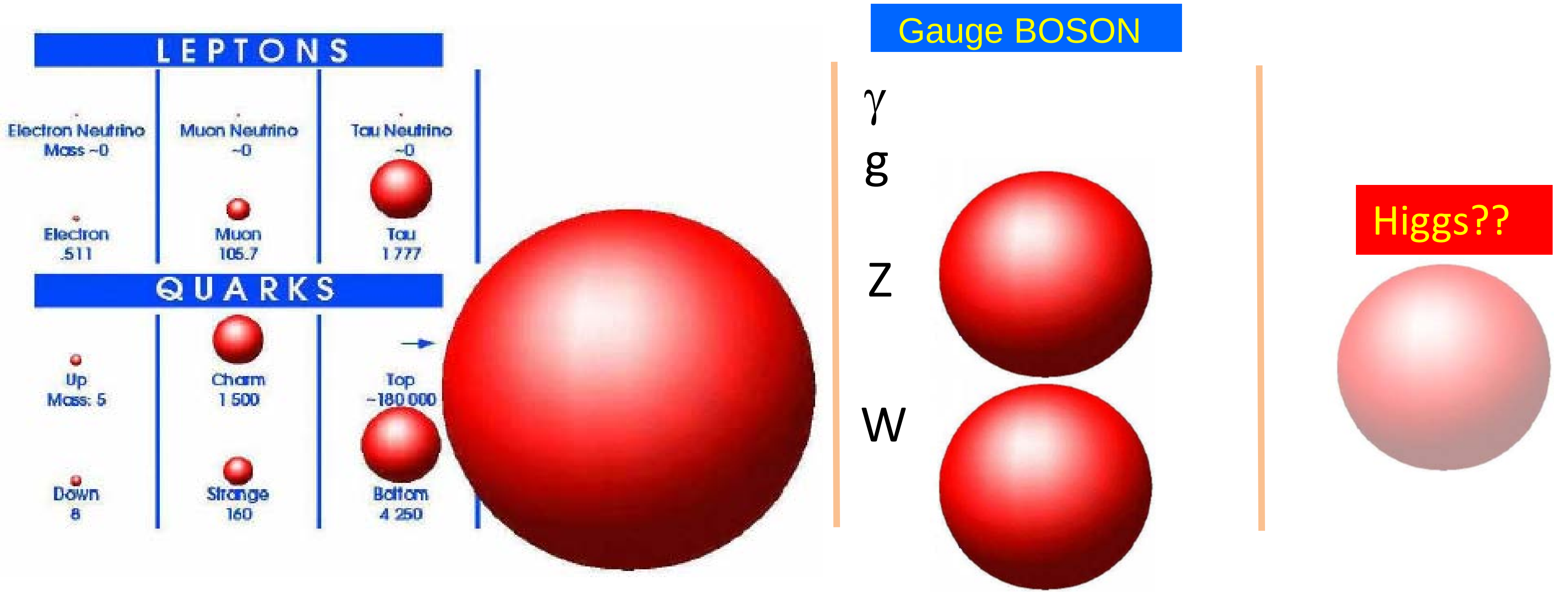
A story at U.S. airport

- Officer: Why you come to US?
- Me: I'm researcher, working on particle physics….
- Officer: ……
- Me: It's high energy experiment at Fermilab….
- Officer: **Low Mass HIGGS**?
- Me: Yes, yes, yes! That's right! Why do you know my work?!
- Officer: Ha Ha ha!

Officer wanted to know about Higgs!

Why Higgs boson is important?

- We don’t know about origin of mass.



- Gauge theory is build with mass less particle.
  - Can not just add mass term.

  → Higgs mechanism

Electroweak symmetry breaking

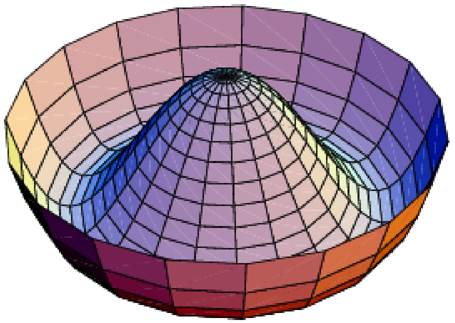
- Higgs mechanism [with U(1) vector field]

$$L = (D_\mu\phi)^*(D^\mu\phi) - V(\phi) - \tfrac{1}{4} F_{\mu\nu}F^{\mu\nu}$$

$$D_\mu \equiv \partial_\mu + ieA_\mu, \quad F_{\mu\nu} \equiv \partial_\nu A_\mu - \partial_\mu A_\nu$$

$$V(\phi) = \mu^2\phi^*\phi + |\lambda|(\phi^*\phi)^2$$

  - ϕ is complex scalar doublet: Higgs field



– $e^2A_\mu A^\mu\phi^*\phi$ in $(D_\mu\phi)^*(D^\mu\phi)$

$\langle\phi\rangle = v/\mathrm{sqrt}(2)$

Spontaneous symmetry breaking

$\mu^2>0$ (hot) potential minimum at $\phi=0$

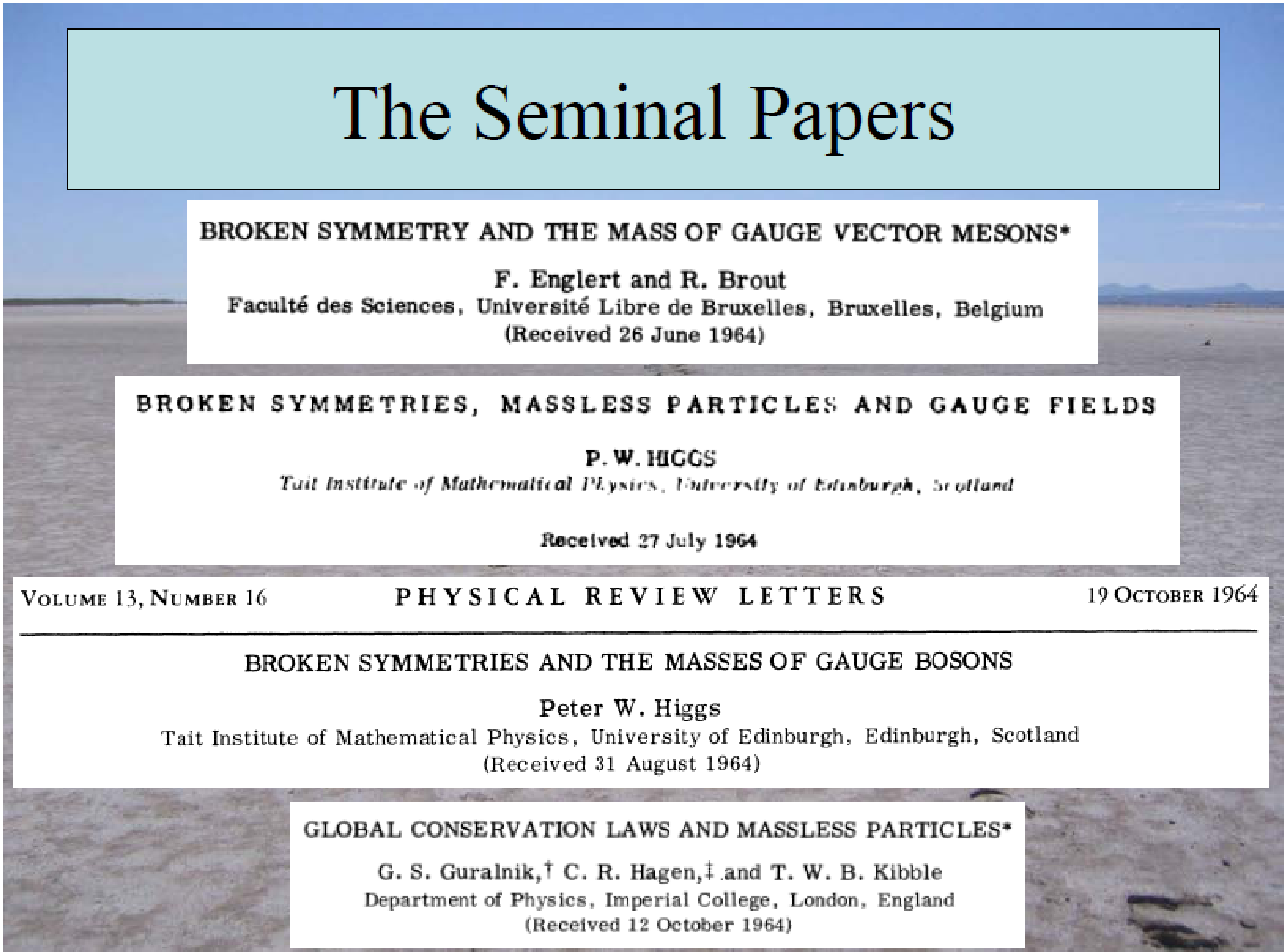
$\mu^2<0$ (cold=present world) at $\phi\neq0$

$(e^2v^2)/2\cdot A_\mu A^\mu$ ← mass term!!

- One Higgs doublet in SM
  – 4 degree of freedom – 3 x (gauge boson) → one Higgs boson

Why we call Higgs boson?

- 2011 Higgs Hunting workshop by J. Ellis



The Seminal Papers

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Why we call Higgs boson?

- 2011 Higgs Hunting workshop by J. Ellis

The Englert-Brout-Higgs Mechanism

- **Vacuum expectation value of scalar field**
- Englert & Brout: June 26th 1964
- First Higgs paper: July 27th 1964
- Pointed out loophole in argument of Gilbert if gauge theory described in Coulomb gauge
- Accepted by Physics Letters
- Second Higgs paper with explicit example sent on July 31st 1964 to Physics Letters, rejected!
- Revised version (Aug. 31st 1964) accepted by PRL

Why we call Higgs boson?

- 2011 Higgs Hunting workshop by J. Ellis

The Englert-Brout-Higgs Mechanism

Englert & Brout

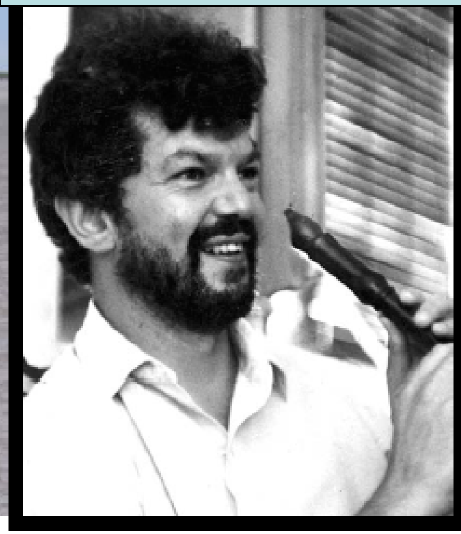


FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a)$\to (2\pi)^4 ie^2 g_{\mu\nu}\langle\varphi_1\rangle^2$, (b)$\to -(2\pi)^4 ie^2(q_\mu q_\nu/q^2)\times\langle\varphi_1\rangle^2$.

Guralnik, Hagen & Kibble

We consider, as our example, a theory which was partially solved by Englert and Brout,[5] and bears some resemblance to the classical theory of Higgs.[6] Our starting point is the ordinary electrodynamics of massless spin-zero particles, characterized by the Lagrangian

$$\mathcal{L} = -\tfrac{1}{2}F^{\mu\nu}(\partial_\mu A_\nu - \partial_\nu A_\mu) + \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + \varphi^\mu \partial_\mu \varphi + \tfrac{1}{2}\varphi^\mu \varphi_\mu + ie_0 \varphi^\mu q \varphi A_\mu,$$

With no loss of generality, we can take $\eta_2 = 0$, and find

$$(-\partial^2 + \eta_1^2)\varphi_1 = 0,$$

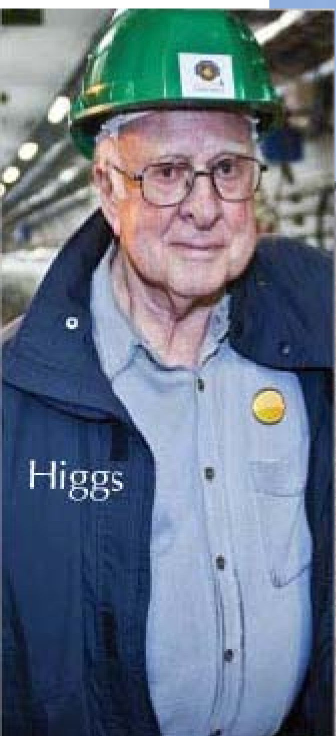
$$-\partial^2 \varphi_2 = 0,$$

$$(-\partial^2 + \eta_1^2) A_k^T = 0,$$

where the superscript T denotes the transverse part. The two degrees of freedom of A_k^T combine with φ_1 to form the three components of a

Why we call Higgs boson?

- 2011 Higgs Hunting workshop by J. Ellis



The Higgs boson

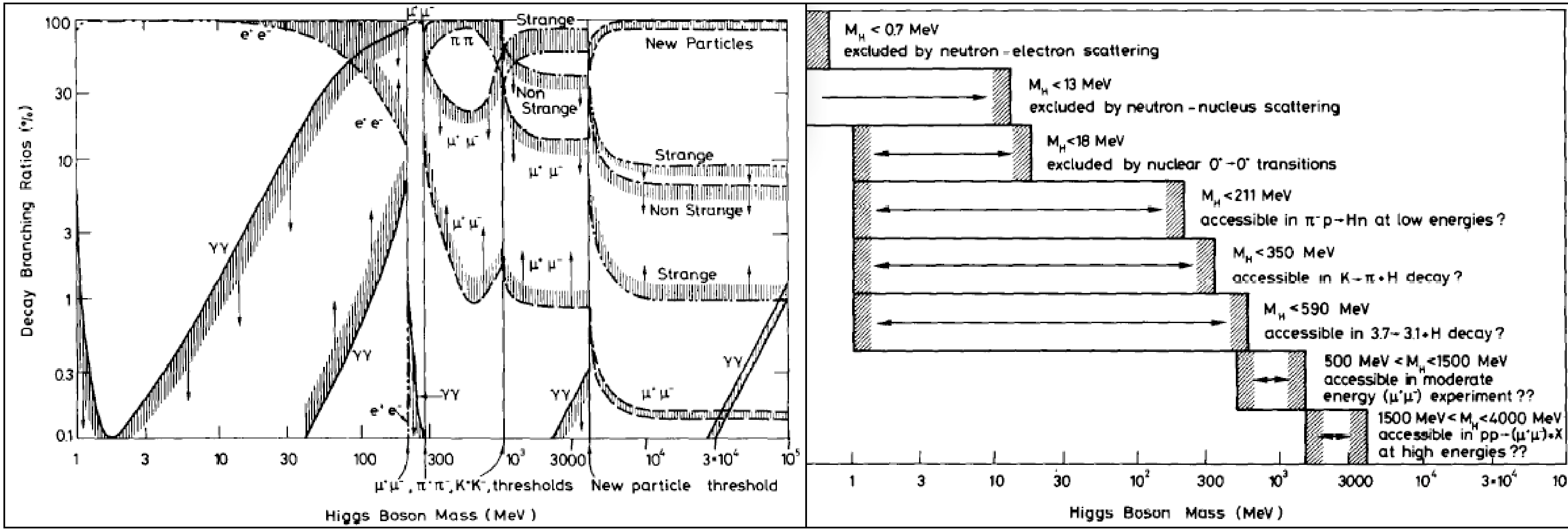
- **Higgs pointed out a massive scalar boson**

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$

- "… an essential feature of [this] type of theory … is the prediction of incomplete multiplets of vector and scalar bosons"
- Englert, Brout, Guralnik, Hagen & Kibble did not comment on its existence

History of Higgs hunting



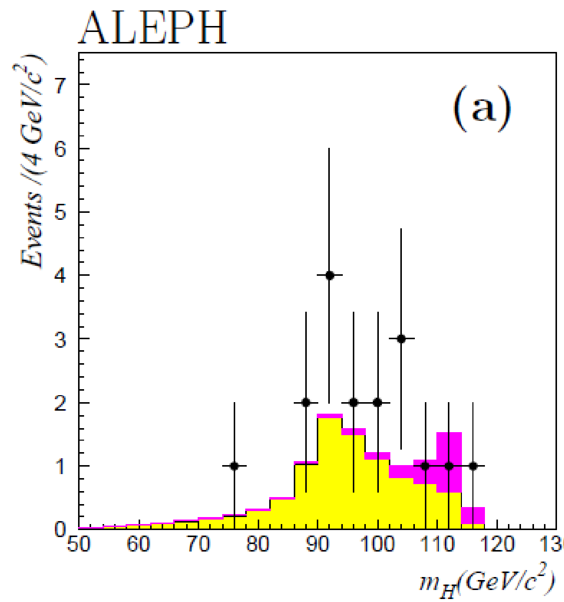
- Higgs search at 1975: MeV scale.

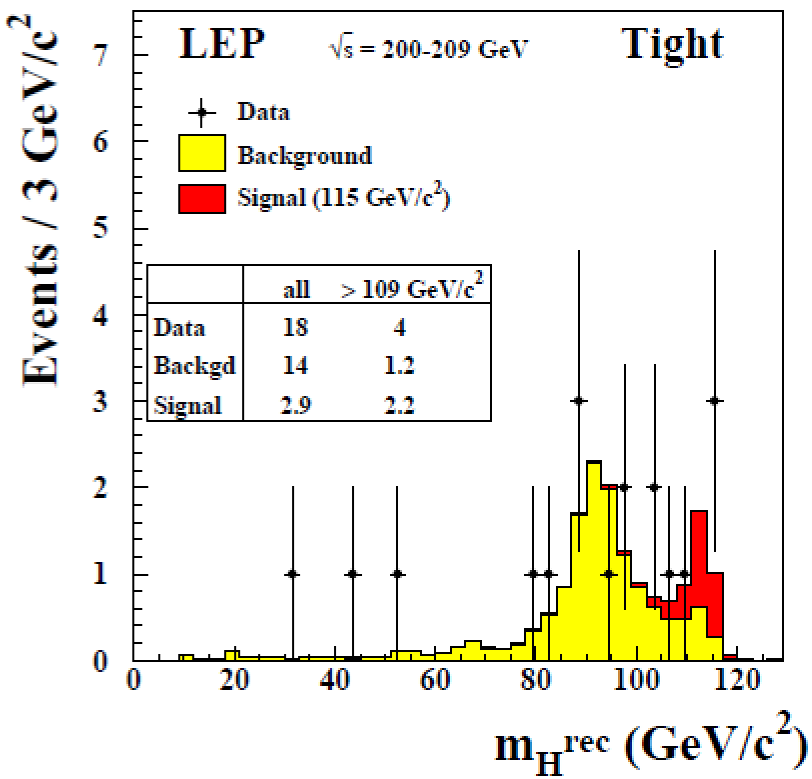
J. Ellis

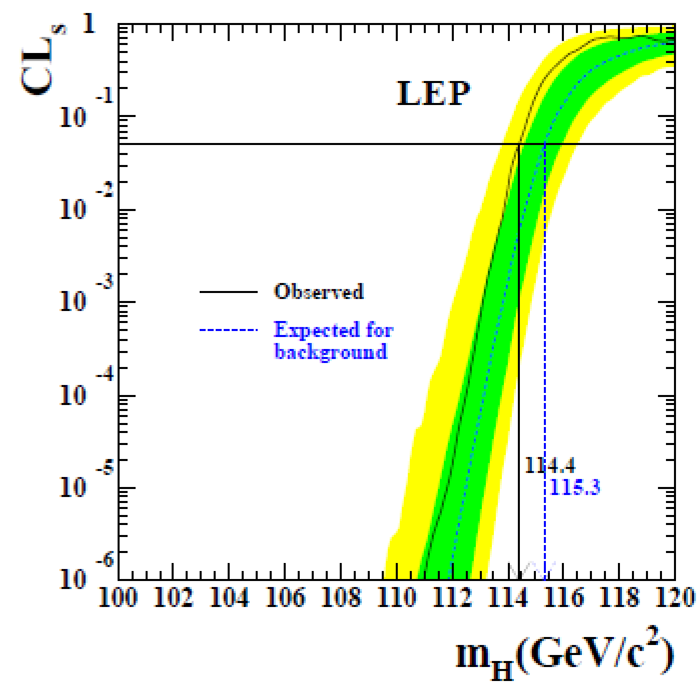
> We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A famous excess from LEP

- $e^+e^- \rightarrow ZH \rightarrow llbb$
  - $M_H > 114.4$ GeV @ 95% C.L.
    - Still strongest limit in "low mass" region

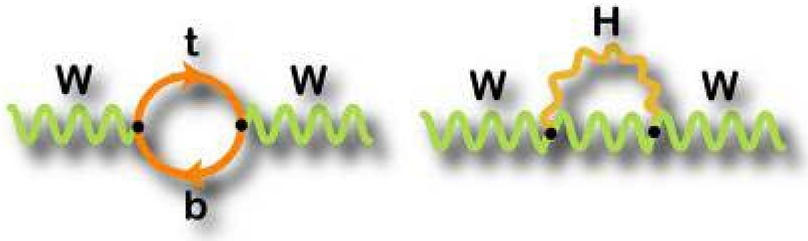




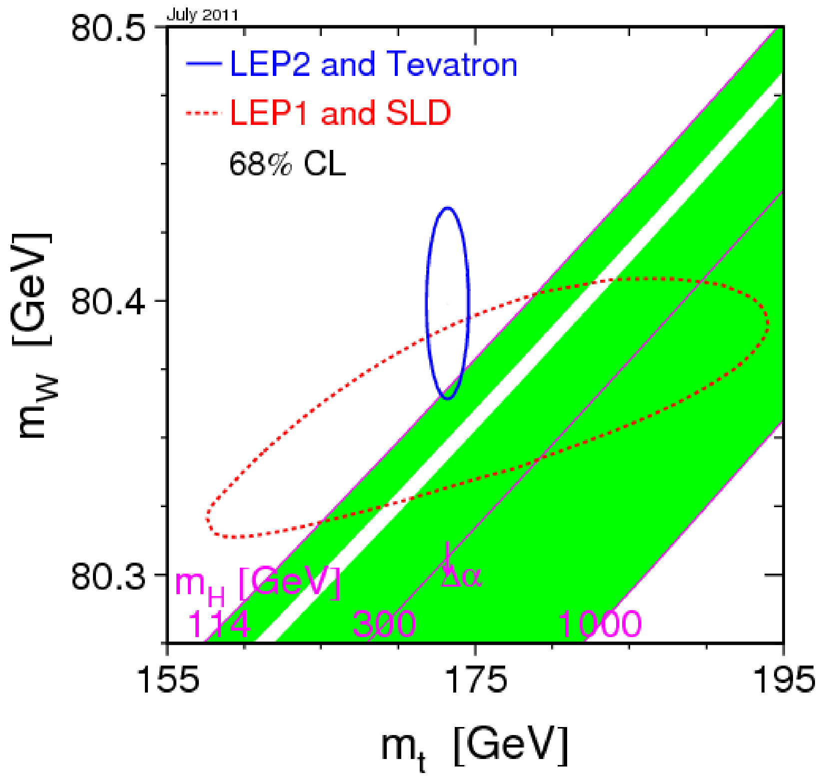


Indirect constraints

- Indirect constraints
  - EW global fitting



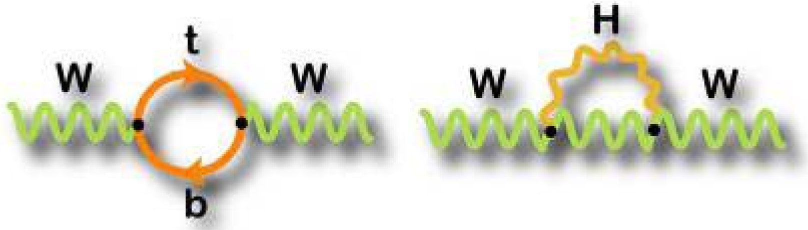
LEPEWWG @ 95% C.L.
$m_H < 161$ GeV



- Direct search result
  - LEP direct search $M_H > 114.4$ GeV @ 95% C.L.
  - Tevatron direct search excludes
    - 156 GeV < M_H < 177 GeV   with 95% C.L

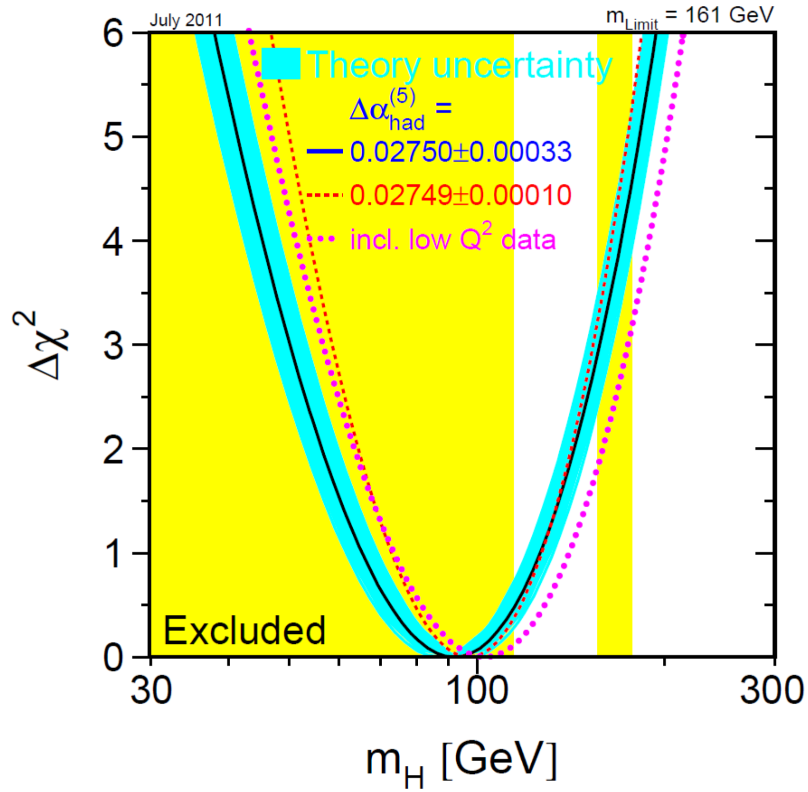
Indirect constraints

- Indirect constraints
  - EW global fitting



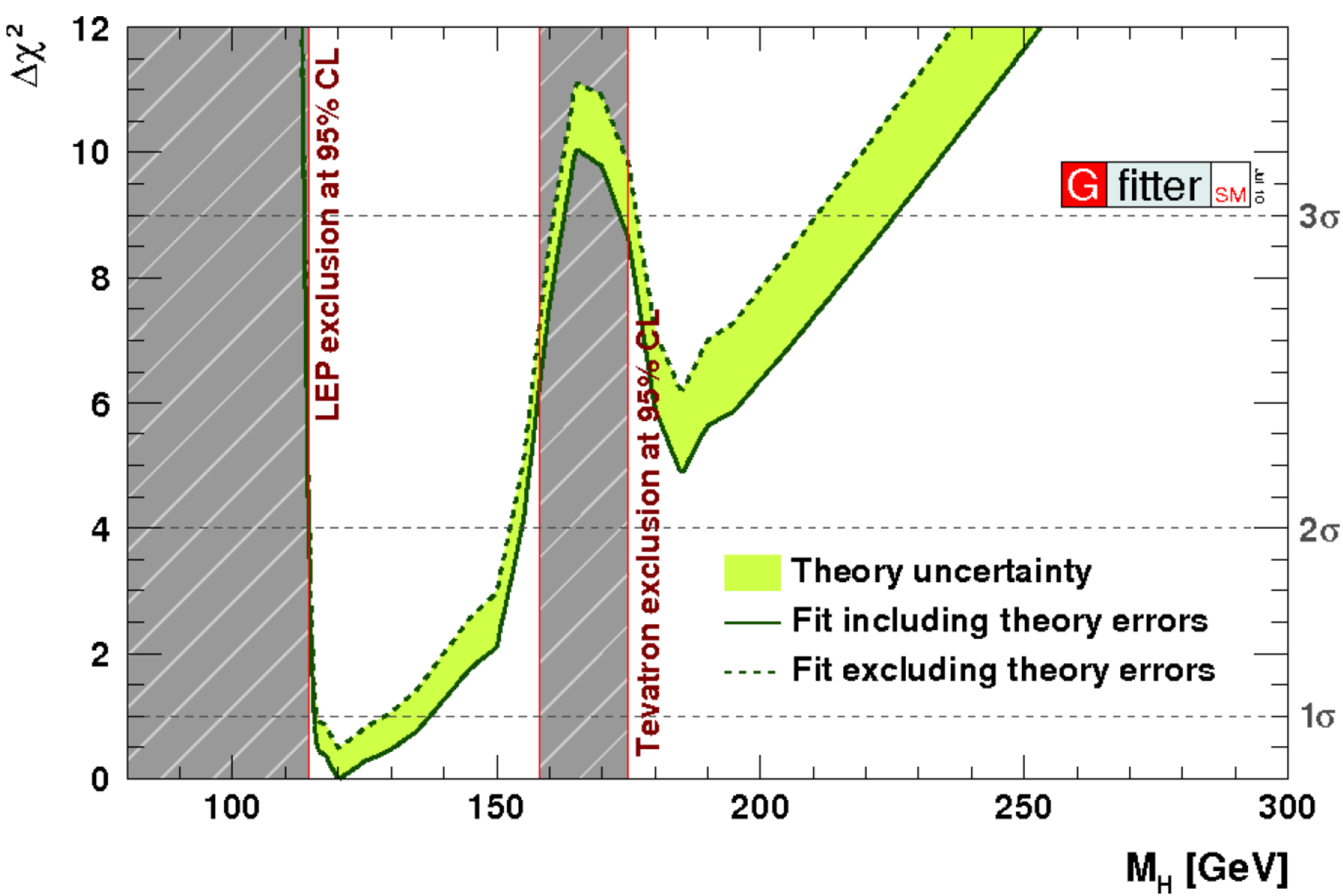
LEPEWWG @ 95% C.L.
m_H < 161 GeV

Best fit: $M_H = 92\ \text{GeV}\ ^{+34}_{-26}$ GeV



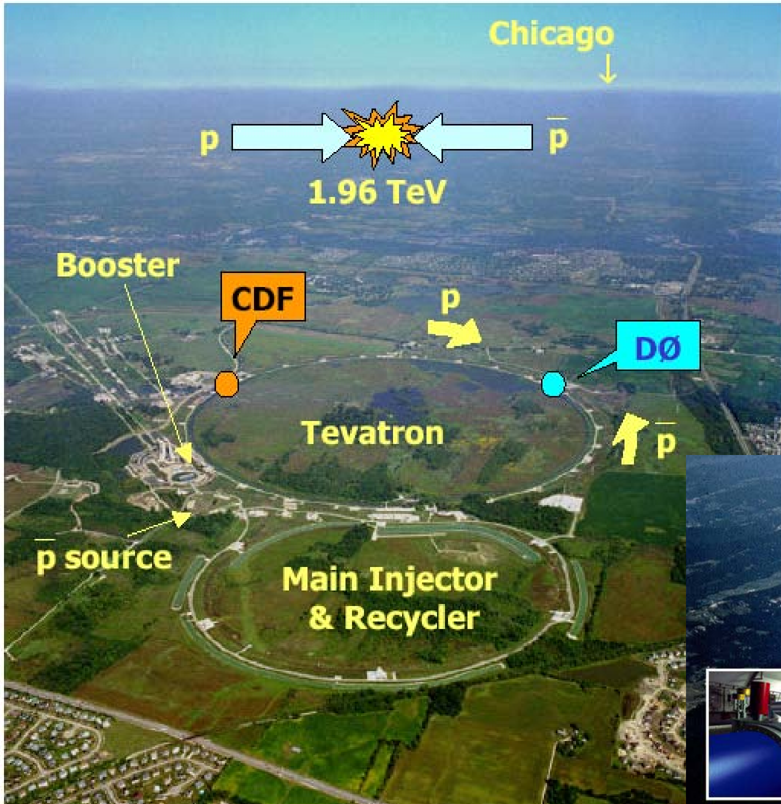
- Direct search result
  - LEP direct search M_H > 114.4 GeV @ 95% C.L.
  - Tevatron direct search excludes
    - 156 GeV < M_H < 177 GeV with 95% C.L

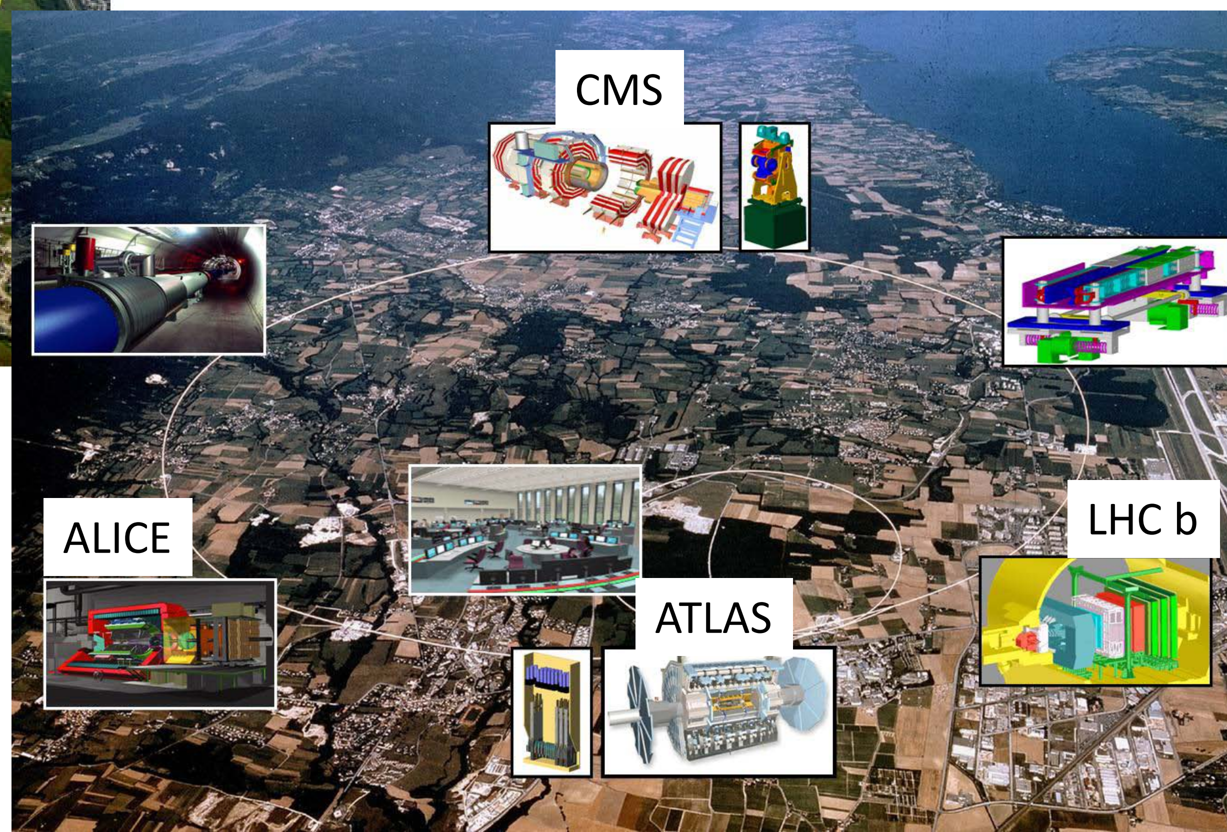
Combine indirect and direct



Direct Higgs search @ Hadron collider

	Tevatron	&	LHC
Collision	ppbar	&	pp
Energy	2 TeV	&	7 TeV
$\int Ldt$ now	8.6 fb^{-1}	&	2 fb^{-1}
2012	10 fb^{-1}	&	10 fb^{-1}



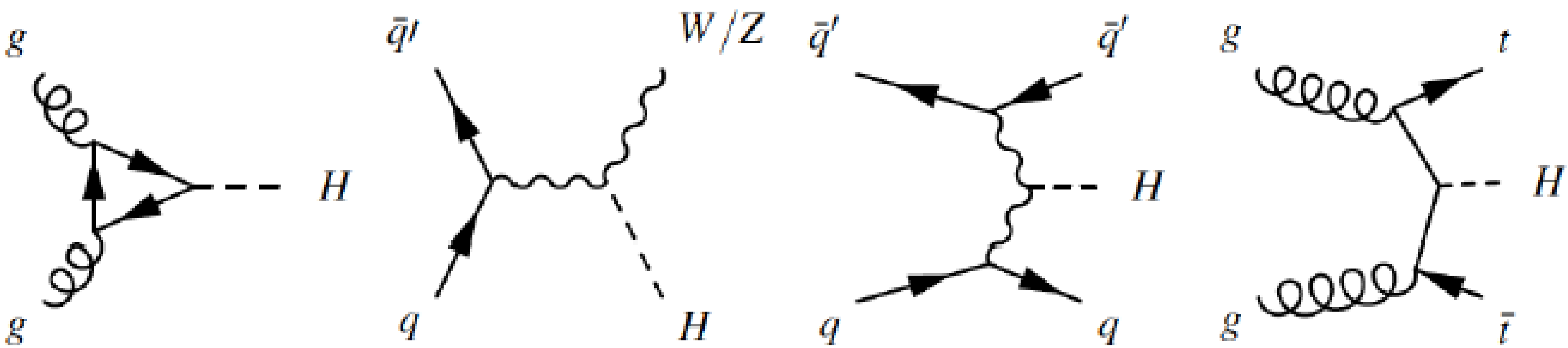


<u>For SM Higgs search</u>

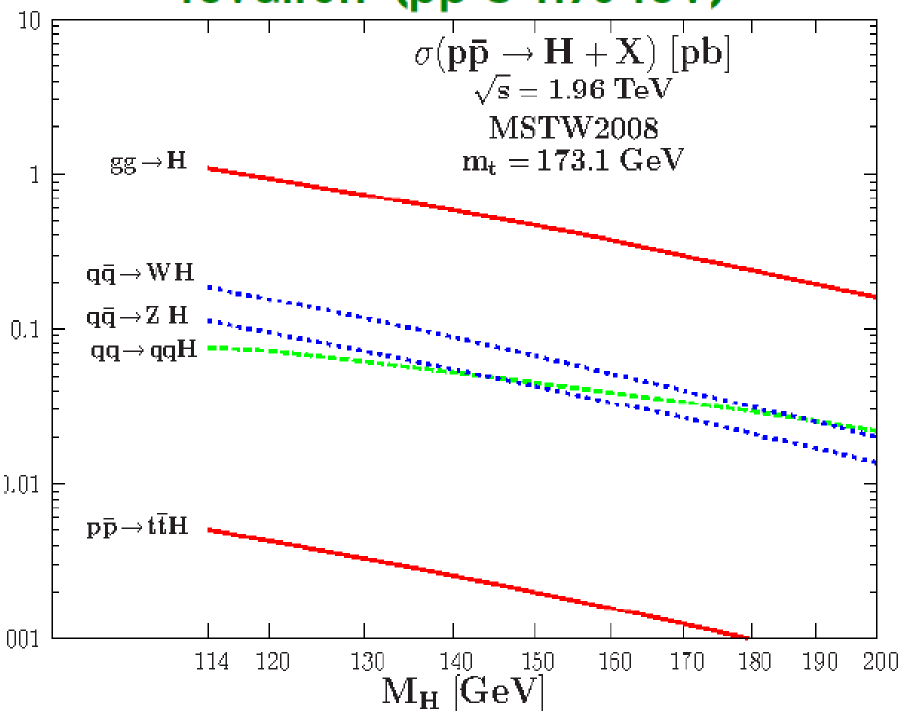
CDF & DZero from TeV

ATLAS & CMS from LHC

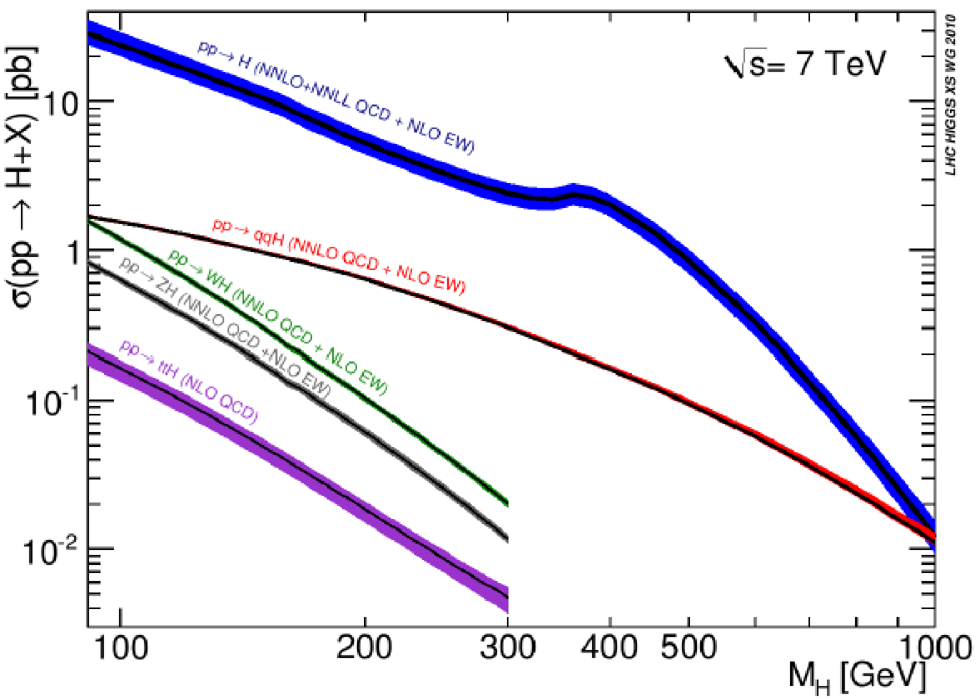
Higgs production at Hadron collider



Tevatron ($p\bar{p}$ @ 1.96 TeV)

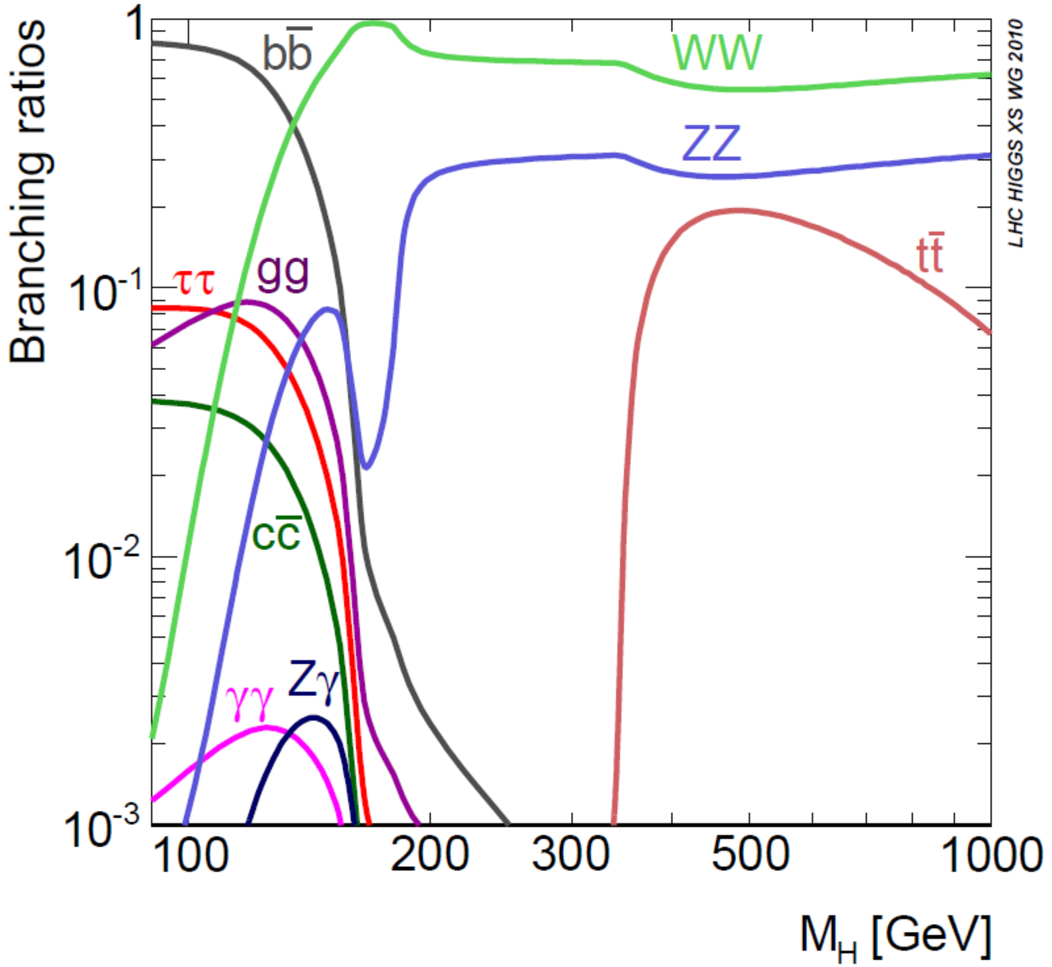


LHC (pp @ 7 TeV)

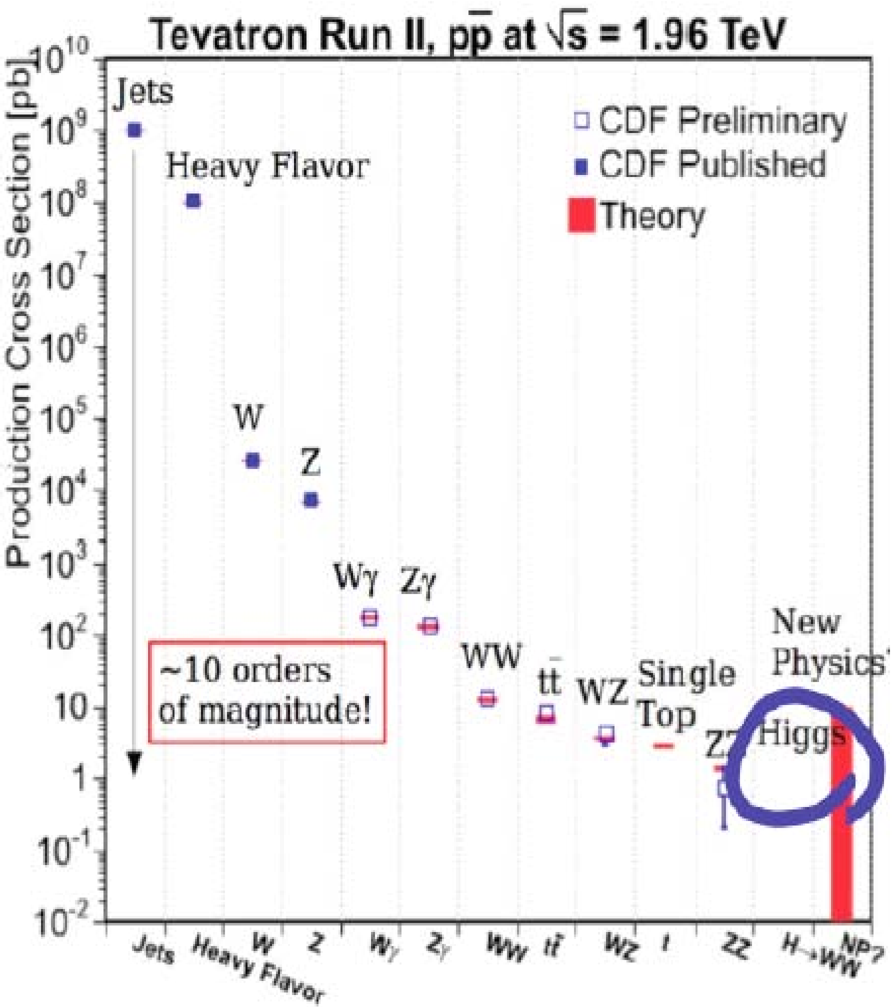


Higgs Decay branching ratio

- Low Mass
  - H→bb
  - H→ττ
  - H→γγ
- Medium Mass
  - H→WW
- High Mass
  - H→WW
  - H→ZZ
  - H→tt : not considered.



Background and Signal



- Jets: QCD processes
- Heavy flavor: QCD process with heavy quarks (b, c).
- W, Z: W/Z+jets.
  (V+n jets)/(V+ n+1 jets) ~ 5.
- ~ 9 order magnitude difference between signal and background.

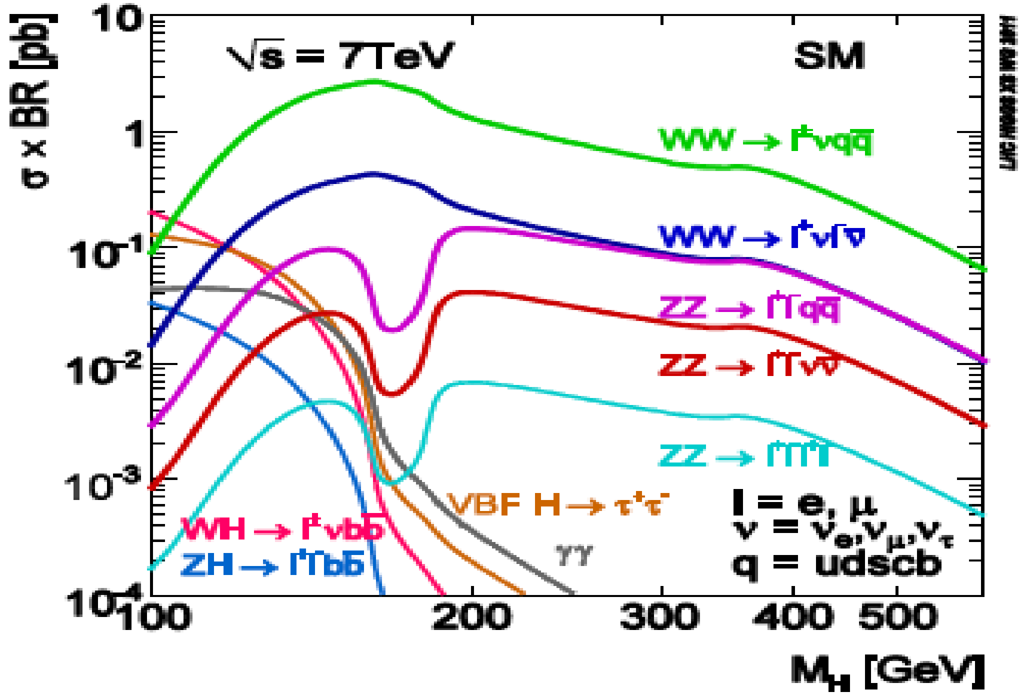
Energy Dependence of Cross Section

Why LHC is discovery machine?!

√s (TeV)	2	7	10	14
W	1	5	7	10
WW	1	10	16	26
ttbar	1	79	200	443
ggH	1	22	43	79
qqH	1	26	53	98

- Normalized with NLO cross section at √s = 2 TeV.
- ttbar and Higgs production cross section increase significantly, compared to background processes W(Z)+jet and diboson.
- Also, ATLAS & CMS have excellent detectors, compared to CDF and DZero.

Cross section x Branching ratio



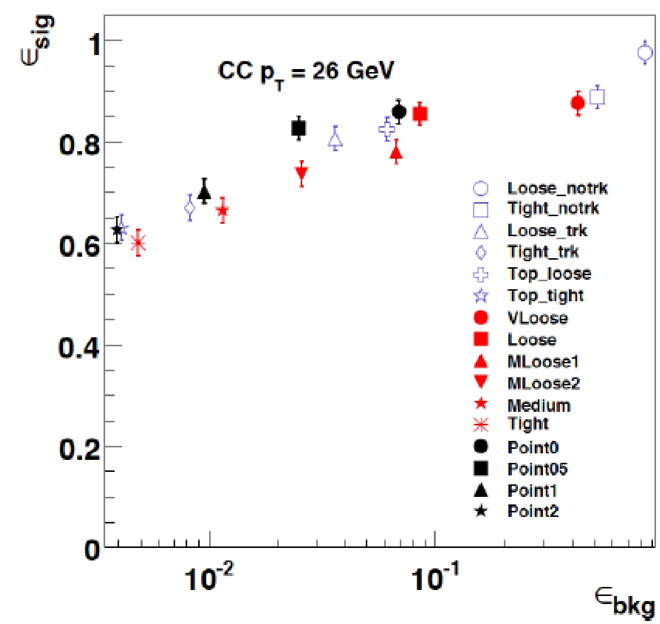
ZH→νν bb	WH→lν bb	ZH→ll bb	H→WW→lνlν	H→ZZ→llll
MET+bb	l+MET+bb	2l(e/μ)+bb	2l(e/μ) + MET	4l (e/μ)

Multi-Jet (MJ) Background:

HIGH → LOW

General idea of selection

- How many lepton in the event?
  - Number of electron or muon in the signal.
  - Hadronic tau decay has different story.
    - Leptonic tau is assigned to e or mu
- Is there large MET?
  - How many neutrino in the final states?
- How many jets associated?
- Do you reconstruct W→lν?
- Do you reconstruct Z→ll?
- Do you reconstruct V→jj?

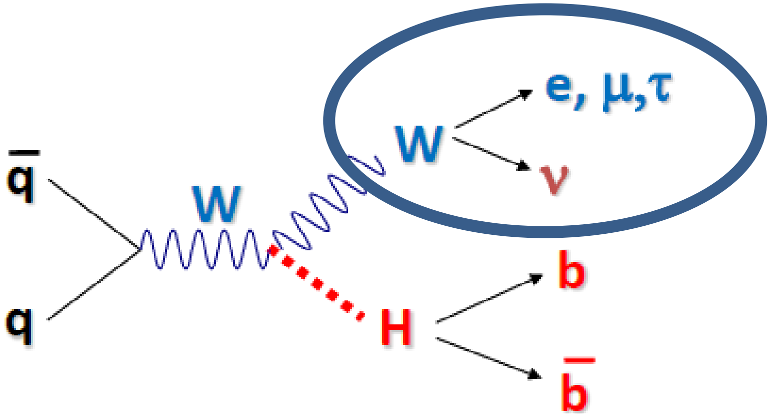


Analysis procedure

Higgs hunter's wish
Gain sensitivity as much as possible!
- More signal, less background!

1. Selection
   - Reconstruction of boson
2. Background Modeling
   - How to model Multi-jet, How to check Modeling.
3. Optimization
   - How to improve analysis?
4. Signal extraction
   - Multivariate Analysis
5. Evaluate Result
   - Systematic uncertainty
   - Confidence level, limit setting procedure

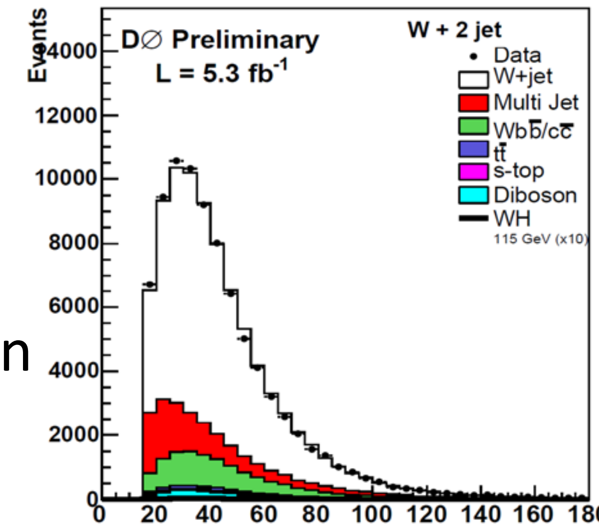
W boson Reconstruction



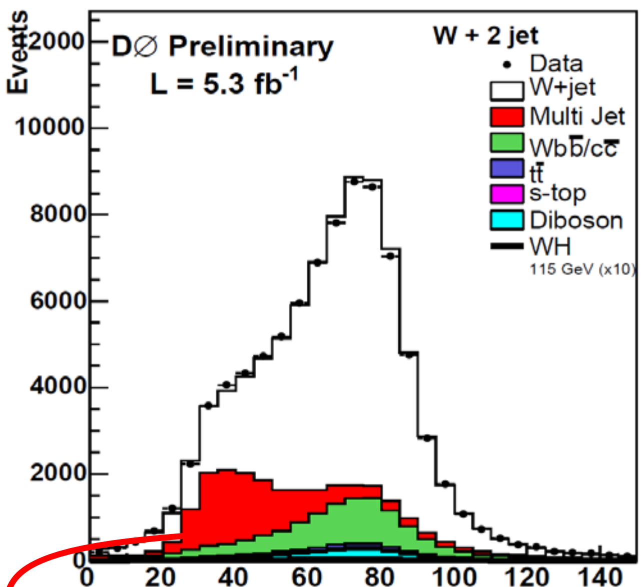
Lepton:

electron/ muon

pT > 15 GeV



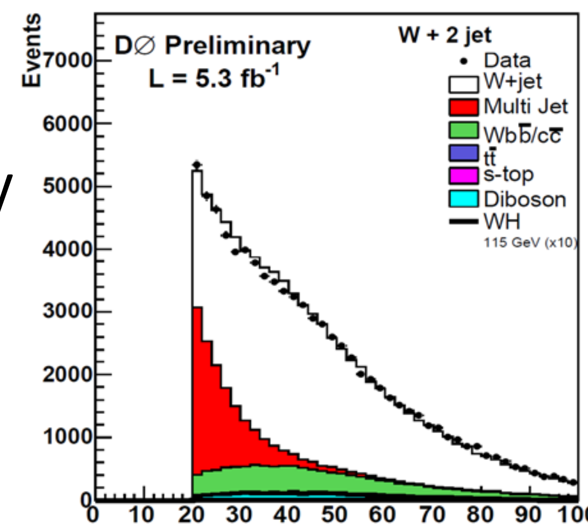
Lepton pT (GeV)



W Transverse Mass (GeV)

Missing E_T

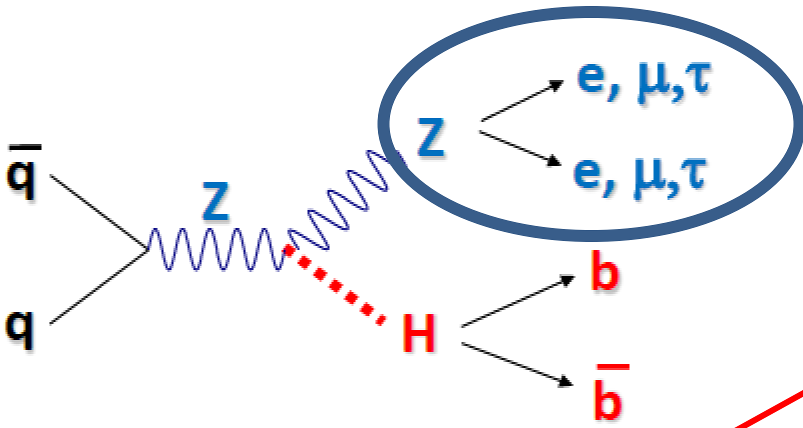
MET> 20 GeV



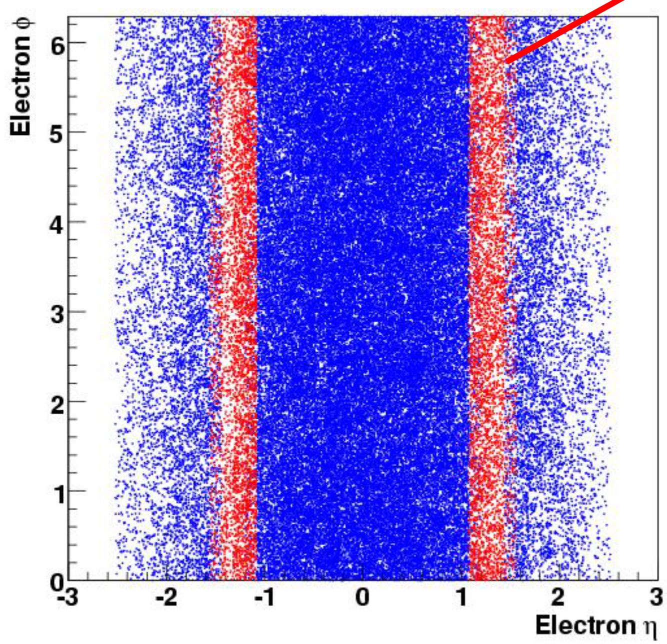
Missing ET (GeV)

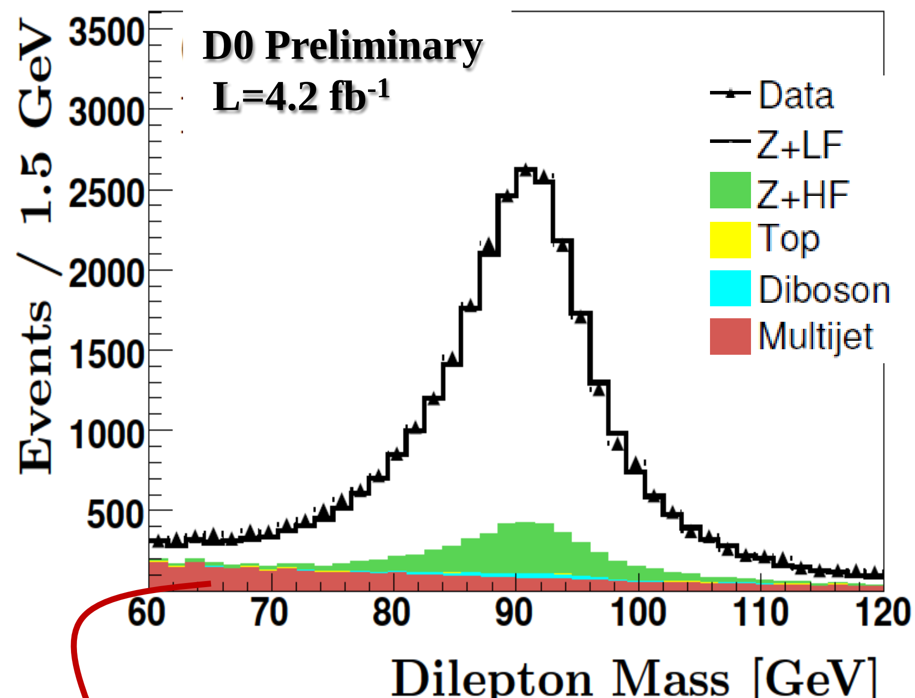
Multi-Jet Background is estimated from Data.

Z boson Reconstruction



- Increase signal acceptance
  - Inclusion of isolated tracks
  - Electron in GAP
  - Lowering pt cut on lepton
    - pT> 10 GeV





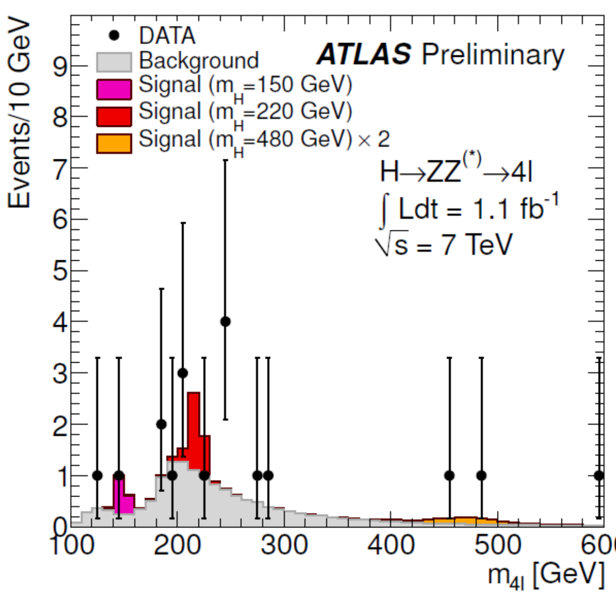
Multi-Jet BG is estimated from Data.

H→ZZ

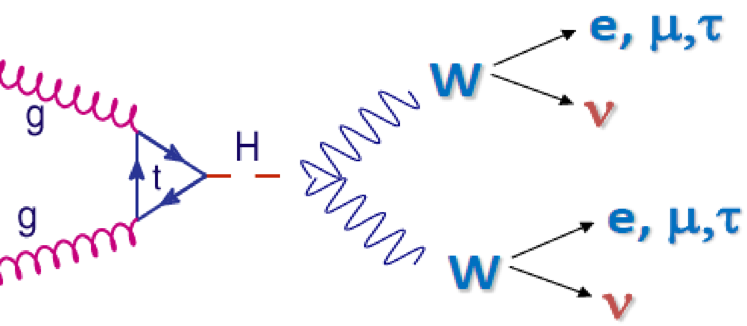
- Discovery channel for high mass
  - Non negligible contribution to low mass

l: electron or muon.
Br(Z→ll) = 3.3% (each, ee + μμ = 6.6%)
Br(Z→νν) = 20 %
Br(Z→jj) = 70%

- 3 major modes
  - Z→ll, Z→ll
    - Small signal yields, but extremely clean
    - 4e, 4μ, 2e+2μ channel
    - One of Z allows to be off-shell.
    - pT>4 GeV for lowest lepton
  - Z→ll, Z→νν
    - Larger signal yields, clean
  - Z→ll, Z→jj
    - Largest signal yield, large background

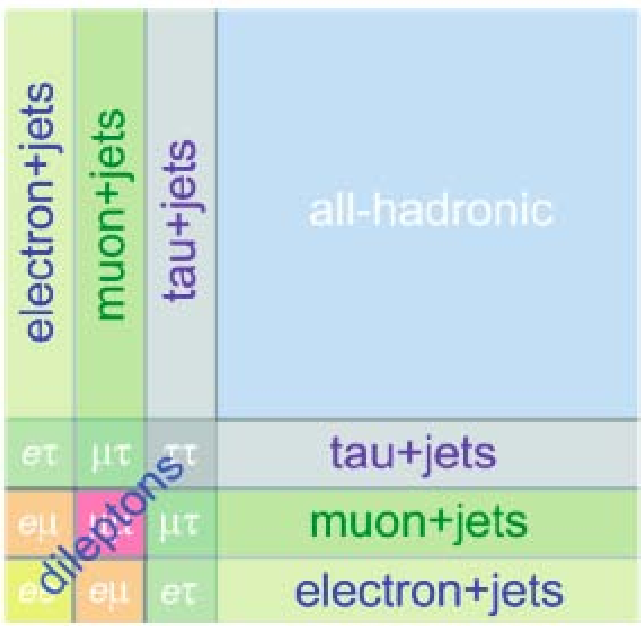


H→WW

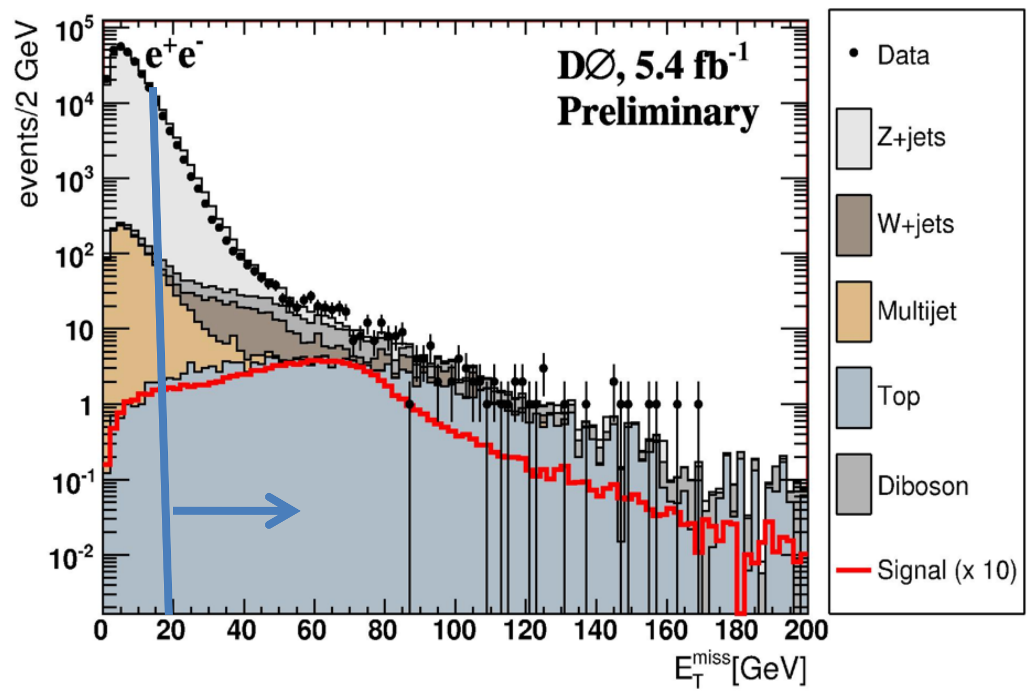


Signature: two high pT leptons + MET

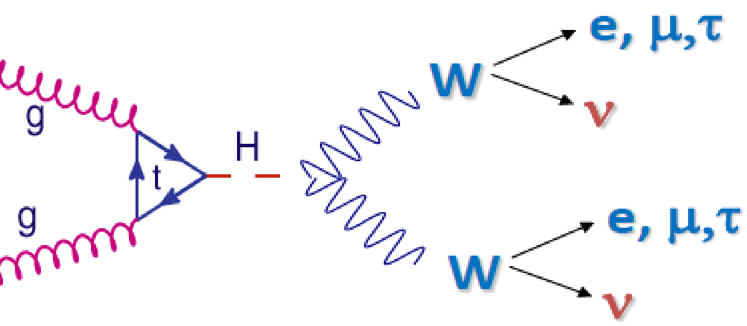
- Highest sensitivity channel for m_H>125 GeV.
- Dominant contribution from gg→H→WW, but consider also VH and VBF production (~35% more signal).



~5%



H→WW



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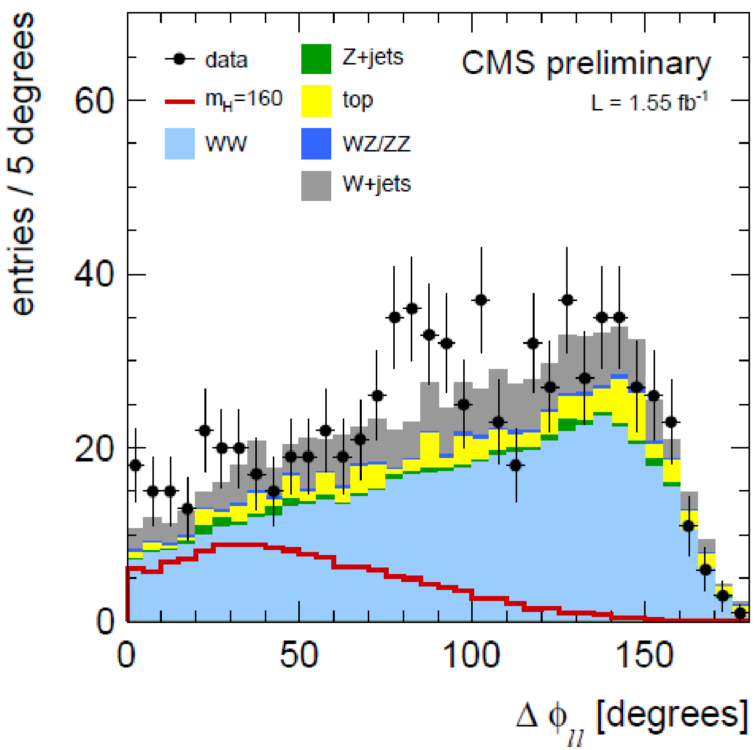
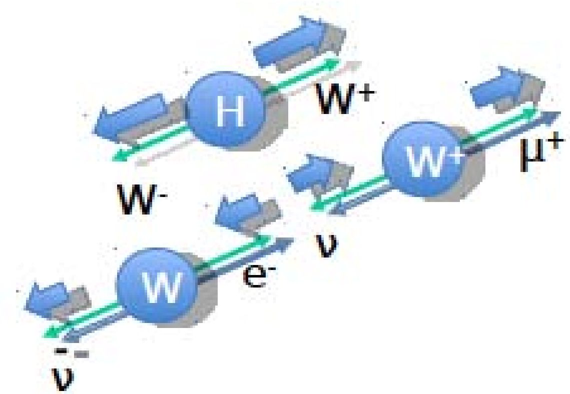


Physics backgrounds:

- Top pair production
- Diboson: dominated by WW→lνlν

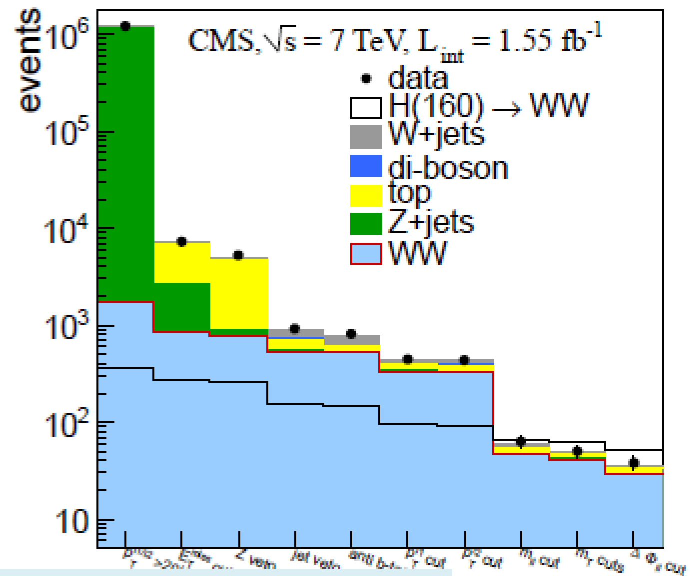
➔ exploit spin correlation between W bosons:



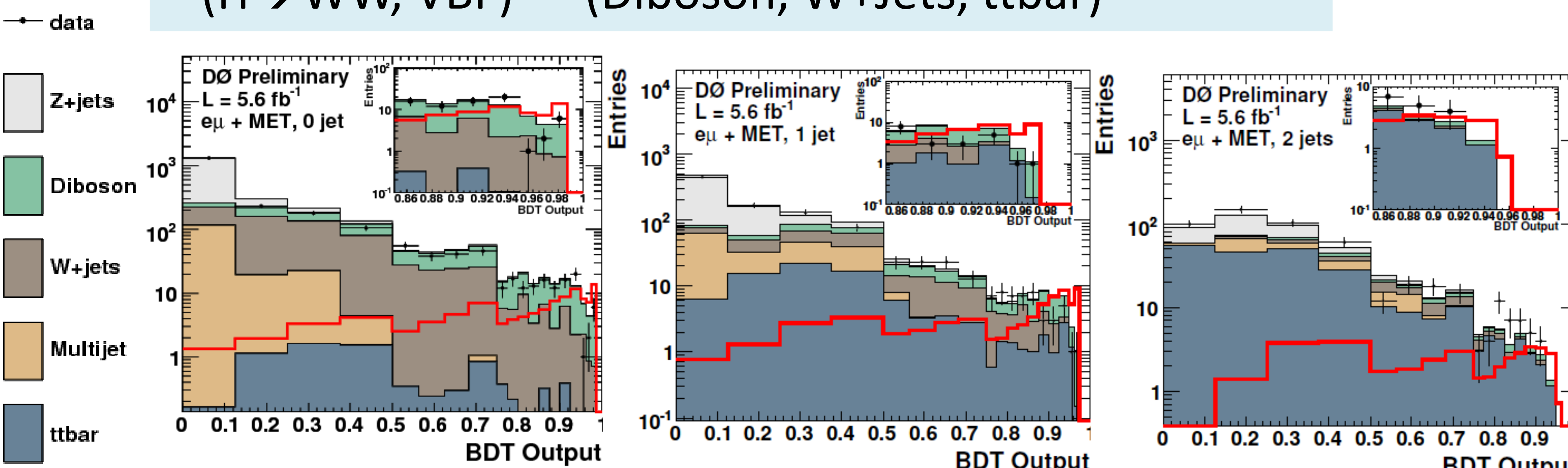
Small angular separation between leptons

H→WW

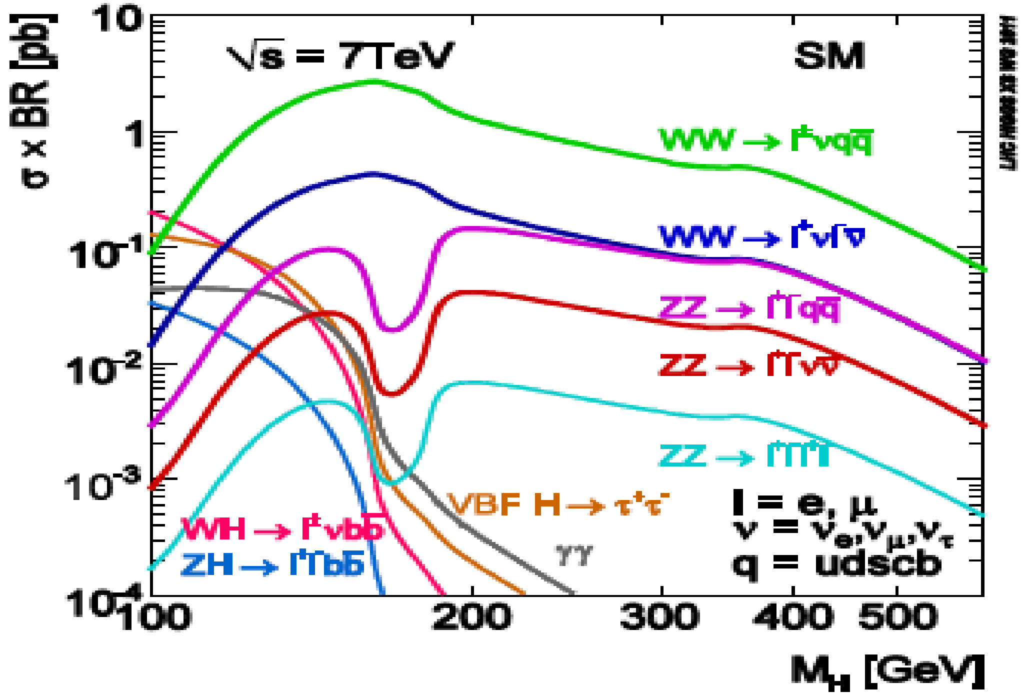
- Checked yields from very basic cuts. (all experiments)
- Compare ee, eμ and μμ
  - Which one is most sensitive?
- Signal extraction separately in 0 jet, 1jet and 2jet sample



Both signal and background have different processes.
(H→WW, VBF) (Diboson, W+Jets, ttbar)



Cross section x Branching ratio

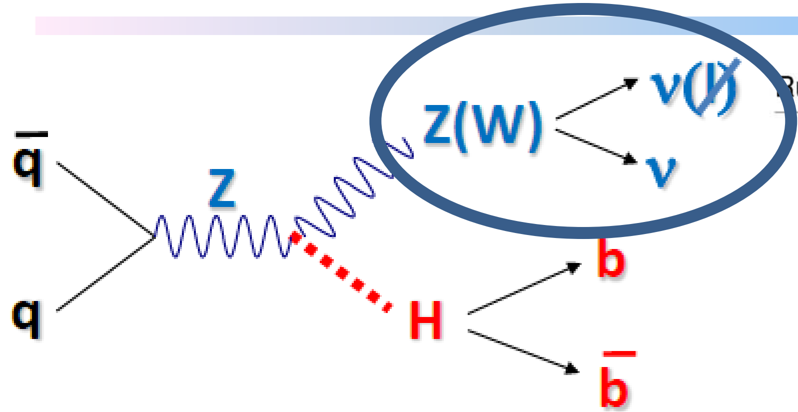


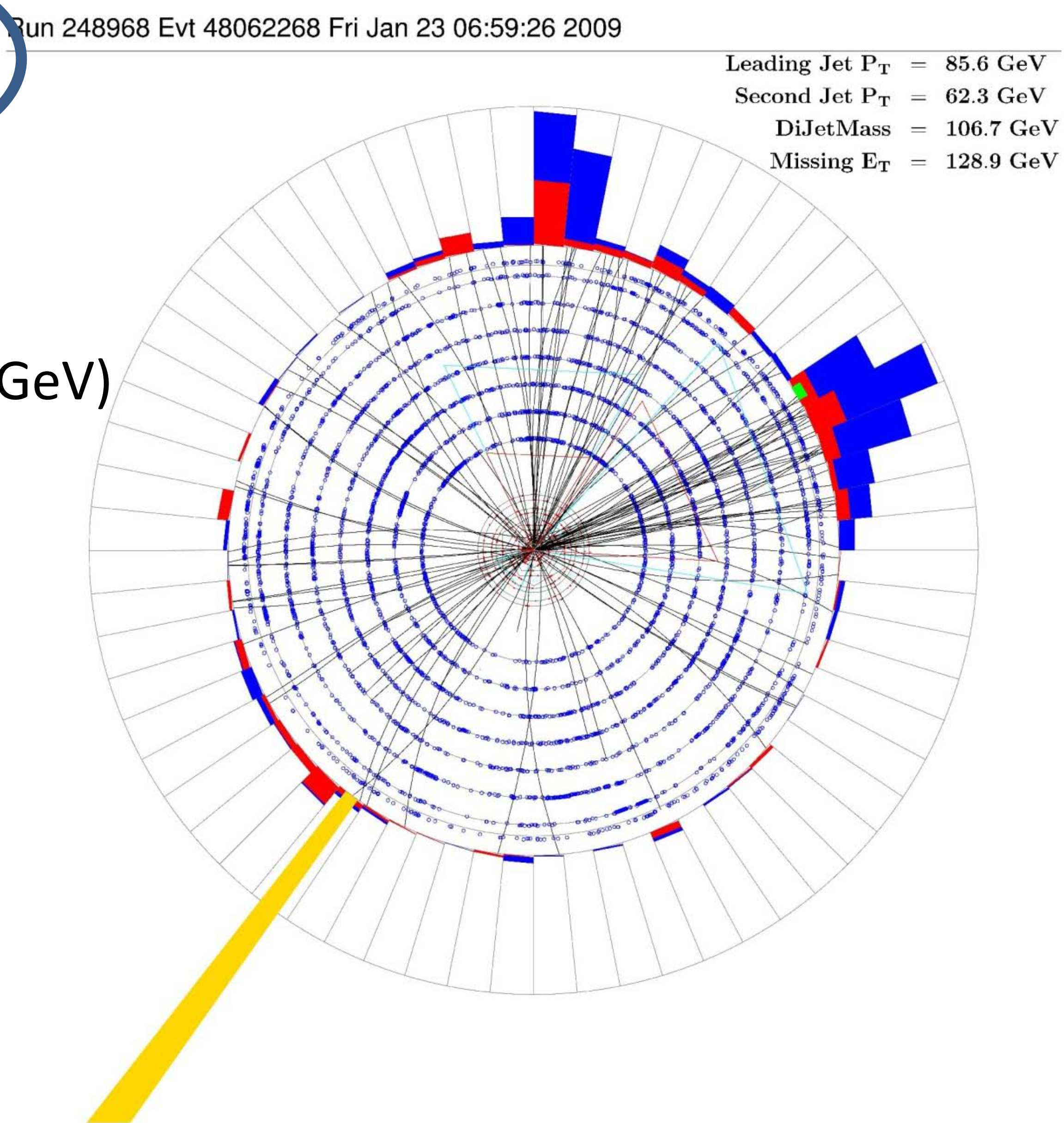
ZH→νν bb	WH→lν bb	ZH→ll bb	H→WW→lνlν	H→ZZ→llll
MET+bb	l+MET+bb	2l(e/μ)+bb	2l(e/μ) + MET	4l (e/μ)

Multi-Jet (MJ) Background:

HIGH → LOW

Z→νν reconstruction





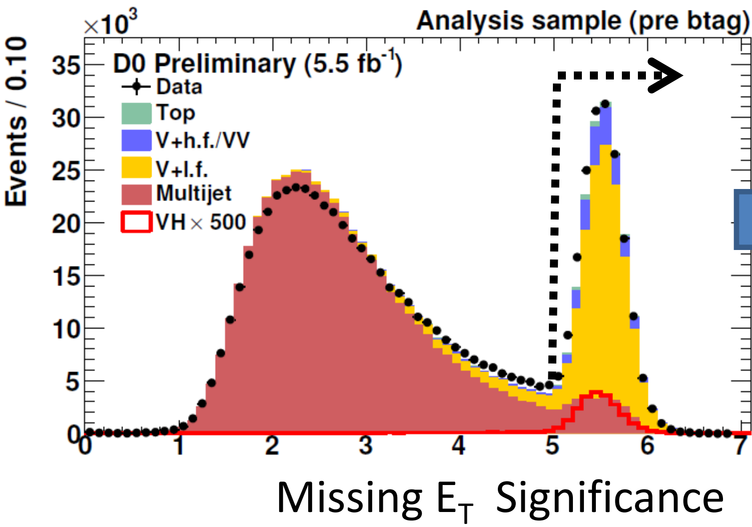
- Jets + large MET (>40 GeV)

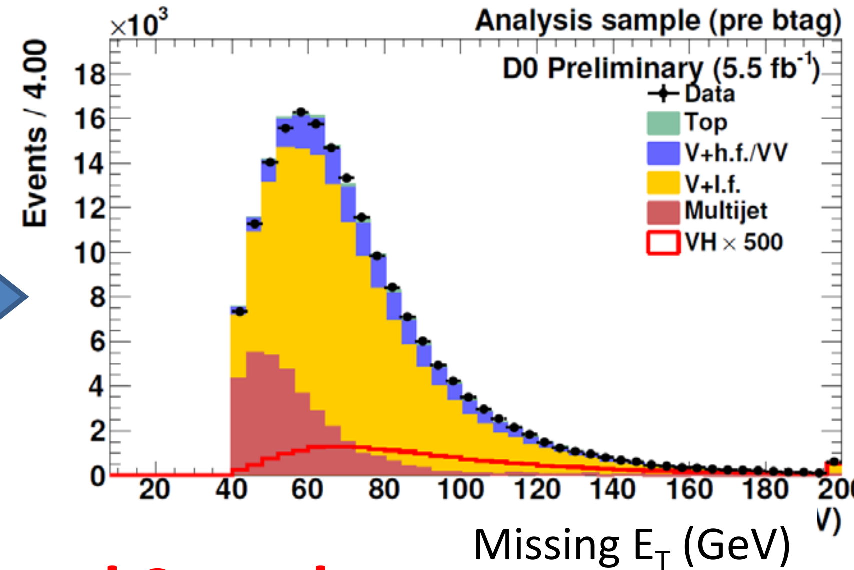
  Expect high multi-jet Background

  - **Signal sample**
  - **Control sample**
    - **→Multi-Jet**
    - **→Electro-weak**

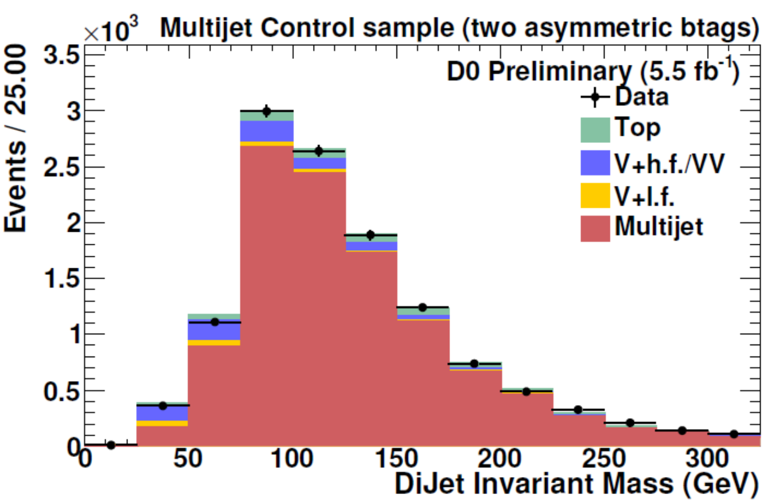
Multi-jet BG treatment in ZH→vvbb

Multi-jet BG: mis-measurement in MET.



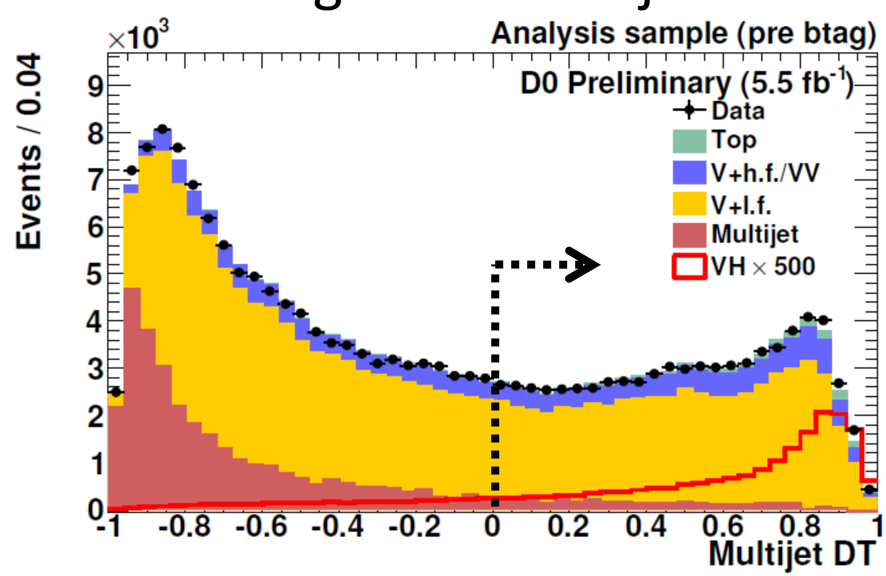


Multi-Jet Control Sample

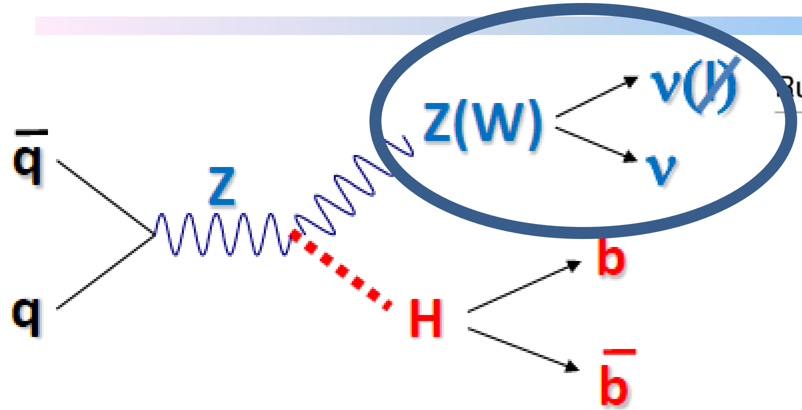


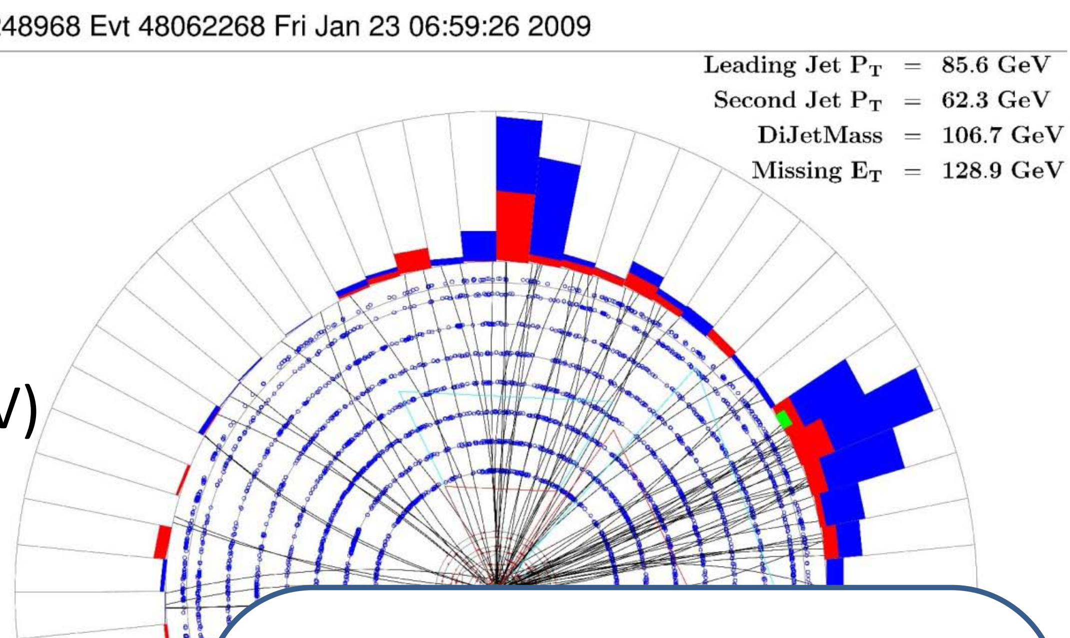
Signal Sample:

Train MVA against Multi-jet BG



Z→νν reconstruction



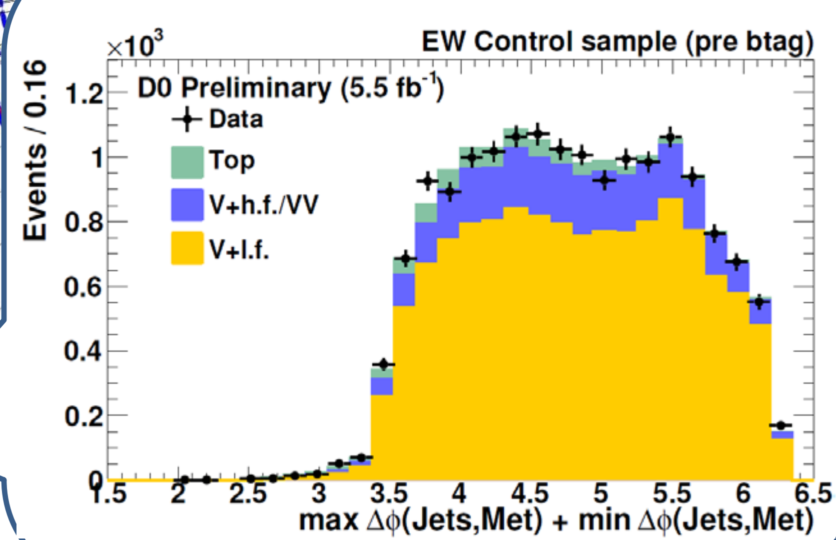


- Jets + large MET (>40 GeV)

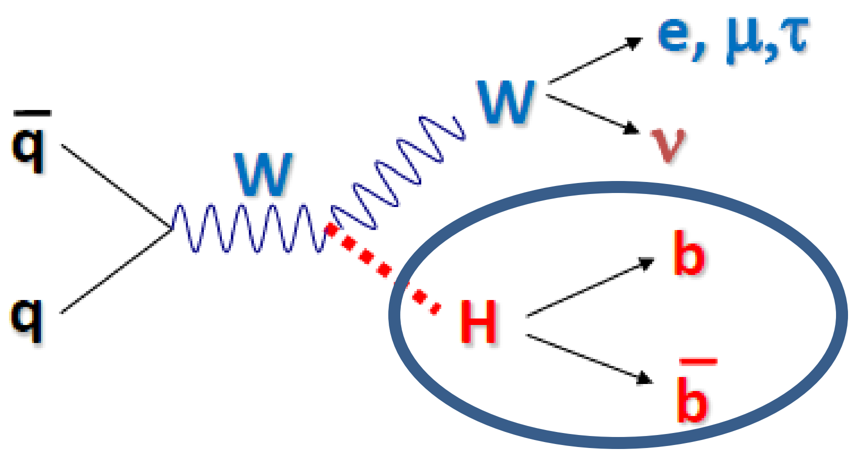
  Expect high multi-jet Background

  - **Signal sample**
  - **Control sample**
    - →**Multi-Jet**
    - →**Electro-weak**

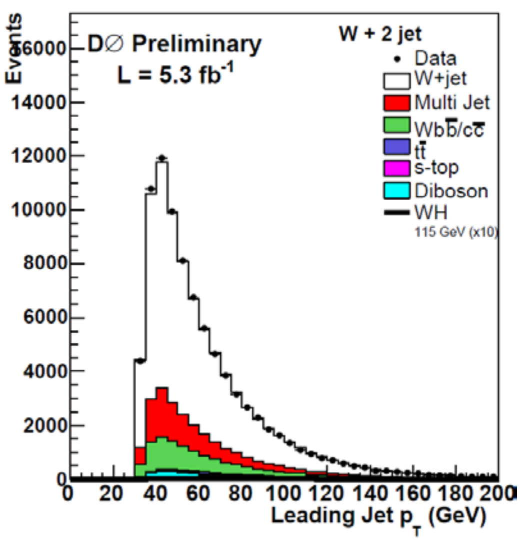
  W→μν, subtract muon pT

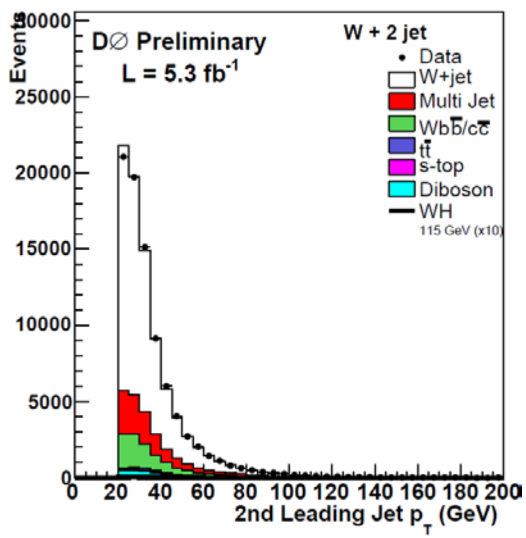


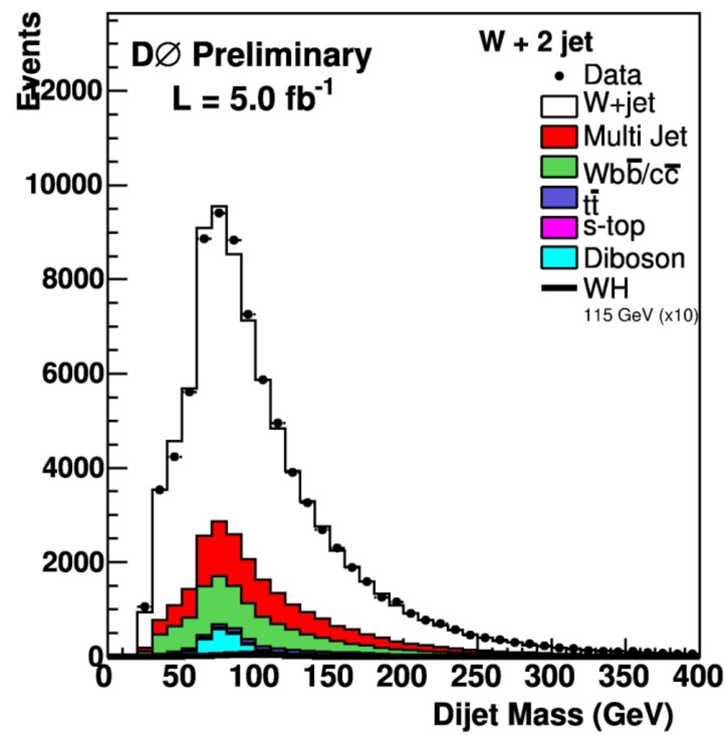
Higgs Candidate Reconstruction



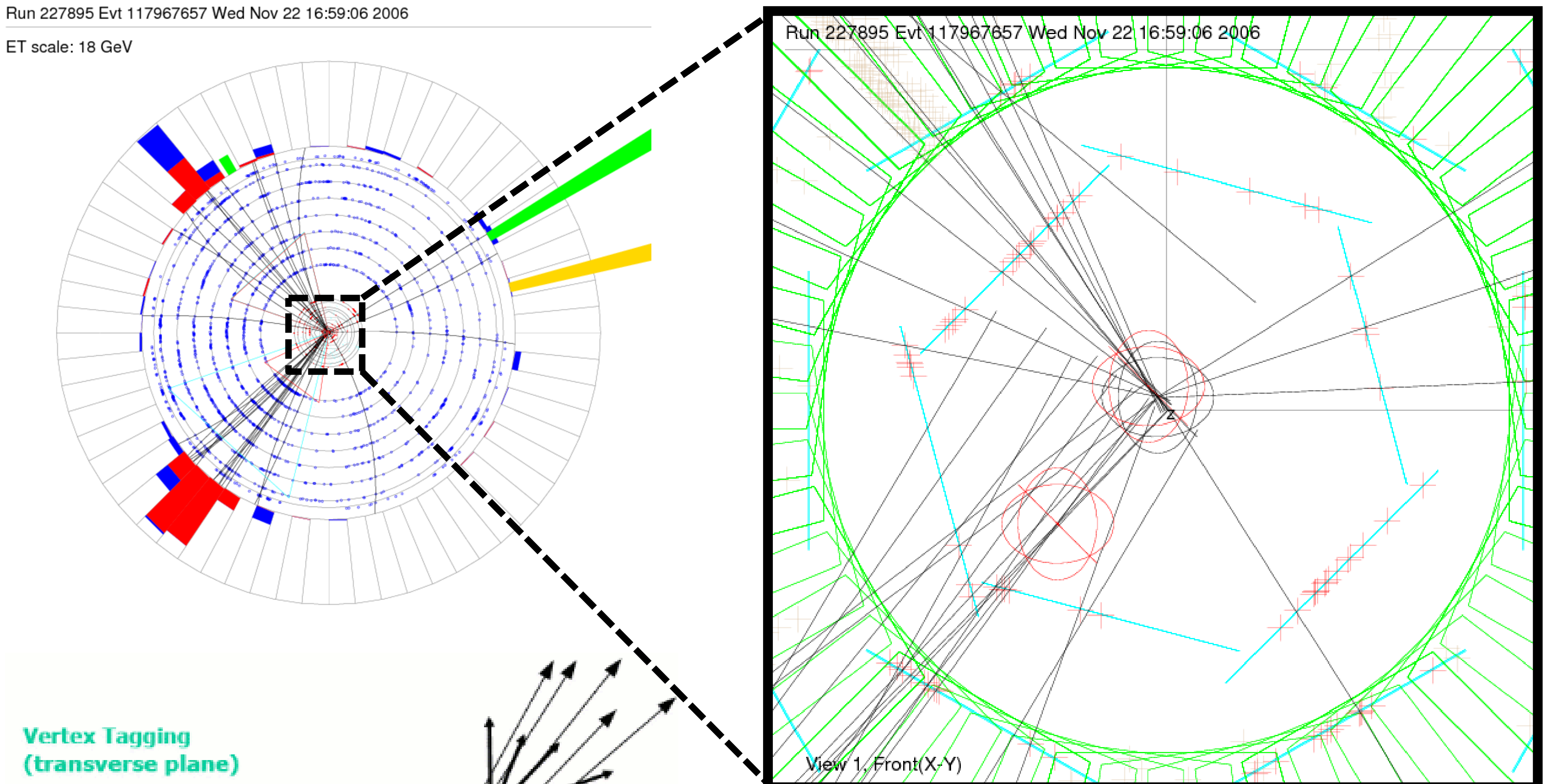
- Jet : Jet with R=0.5 $R=\sqrt{(\phi^2+\eta^2)}$

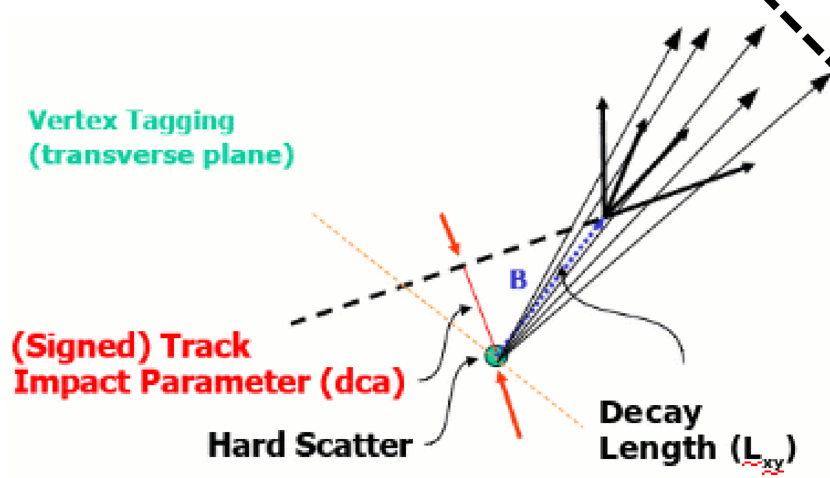






b-Jet Identification





Neural Net b-tagger

Combination of SV & dca

- Loose: 70% eff, 4.5% fake
- Tight : 50% eff, 0.3% fake

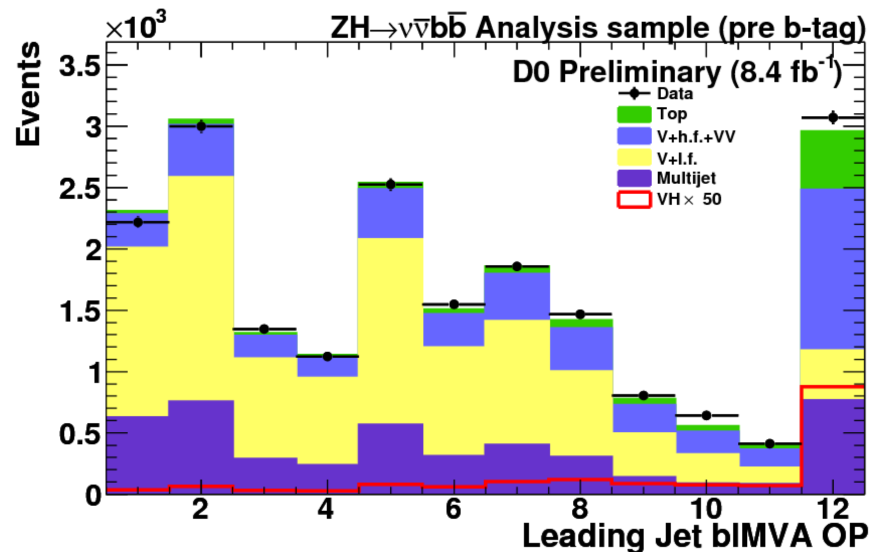
H→bb: Usage of b-jet ID

Define orthogonal samples

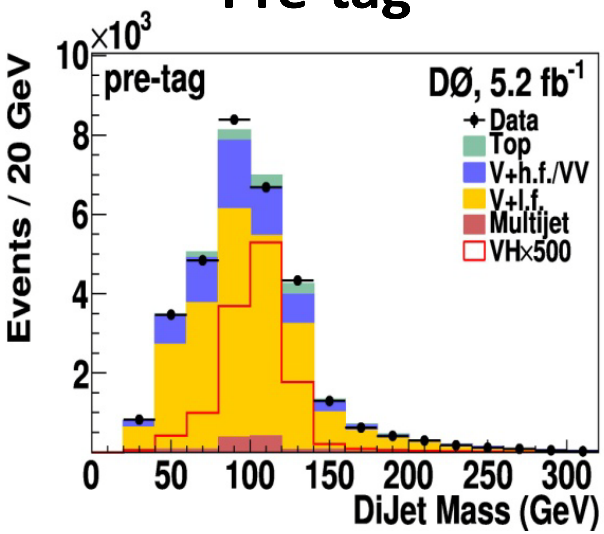
if Two Loose (2-btag)
→ S/N ~ 1:50

else if 1 Tight (1-btag)
→ S/N ~ 1 : 300

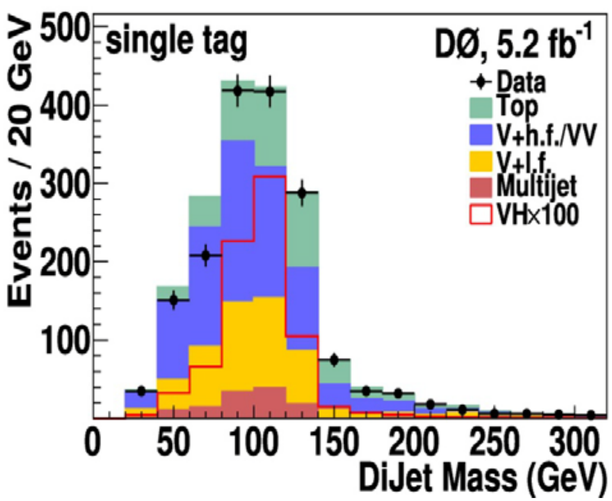
Sample composition changes
→ Optimize separately.



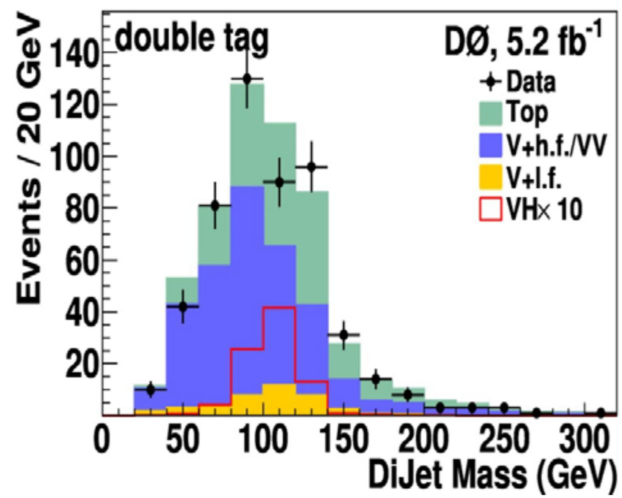
Pre-tag



1-btag



2-btag

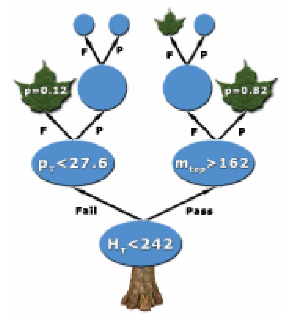


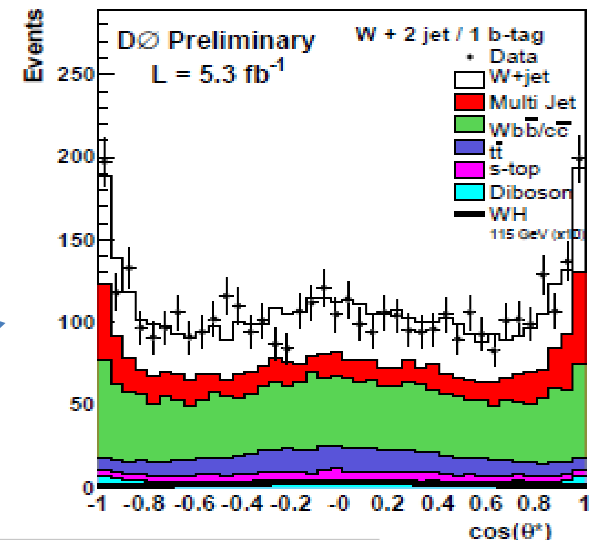
BG: W+light | W+light, W+bb/cc | W+bb/cc, ttbar

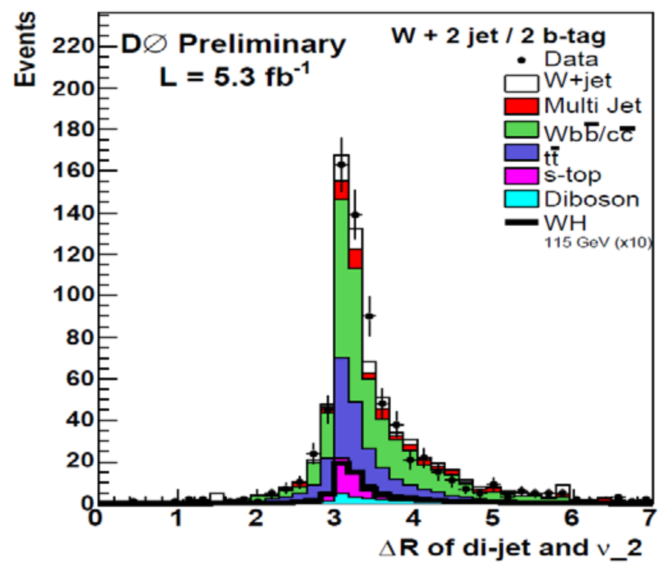
MultiVariate Technique

- All three analysis using Decision tree based technique.
- The most sensitive input is dijet mass. And other sensitive variables are
  - <u>Spin correlation</u>
  - <u>Neutrino direction</u>

  →Sensitivity gain: 15-20 % compared to dijet mass.
- Training:
  - 1-btag, 2-btag separately.
  - Use part of MC sample for train.







In total, ~ 20 input variables.

MVA usage @ CDF/D0

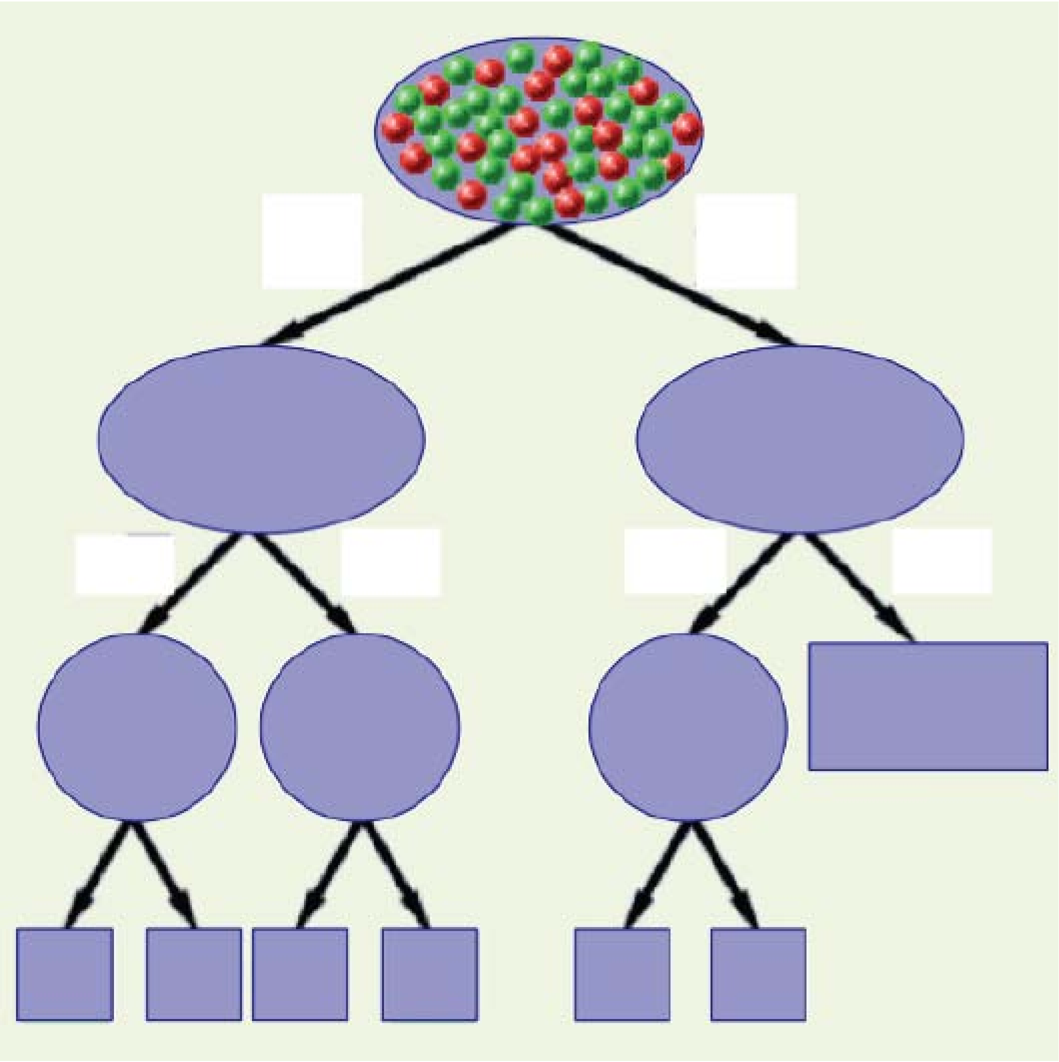
- D0 analyses often use BDT with TMVA
  - "Stochastic gradient boosting" seems to be good.
  - Matrix Element analysis: takes time, not processing recently.
- CDF analyses use various MVA
  - BNN, NEAT, NN, Support Vector Machine, ...
  - NN is often used in the corrections (dijet mass, trigger turn-on)
  - Proceed Matrix Element analysis (not this summer)
- Key feature / Trend
  - Trying to reduce number of input variable
  - Trying to find optimal usage

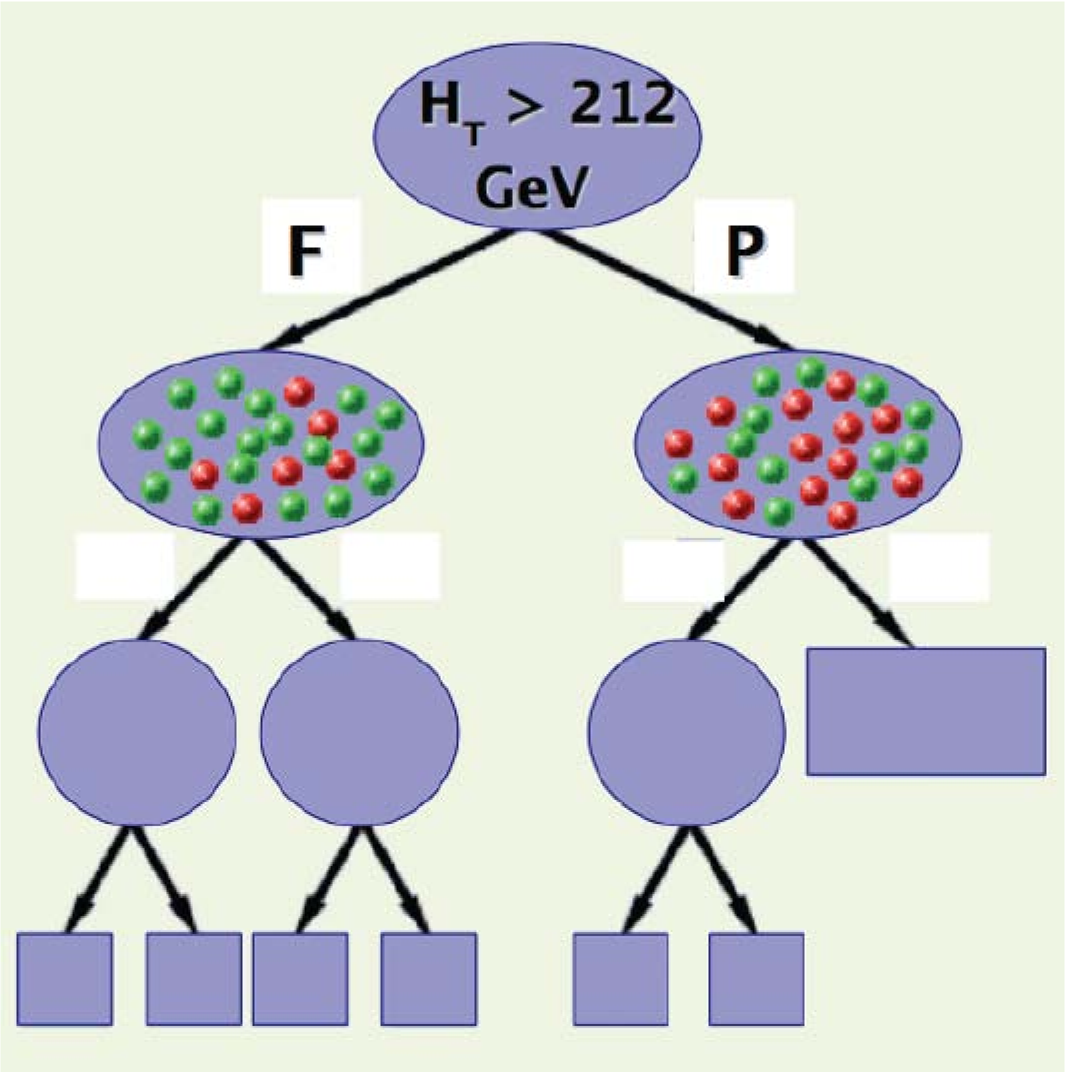
An interesting example from DØ $l\nu b\bar{b}$

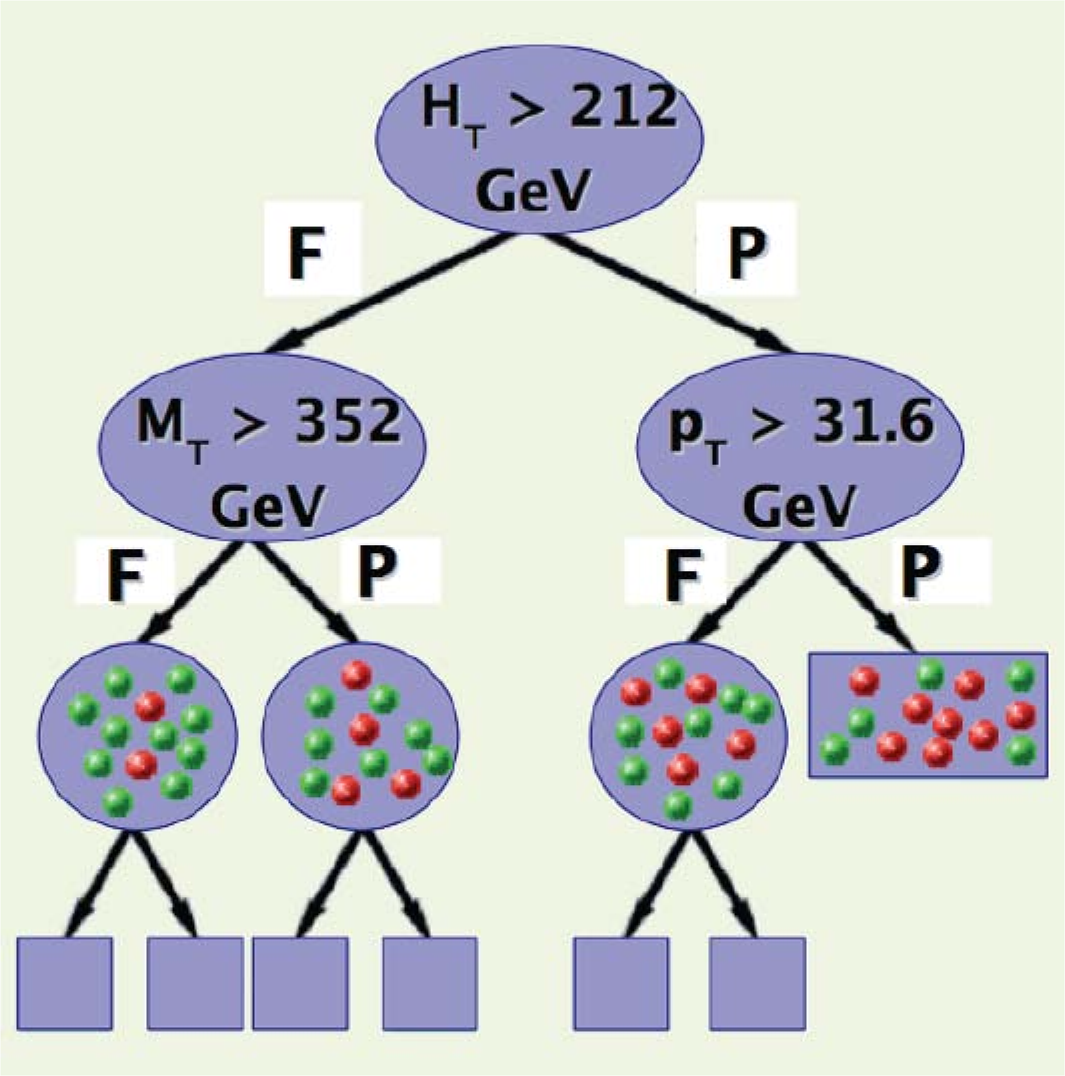
== Build MVA in order to choose input variable ==

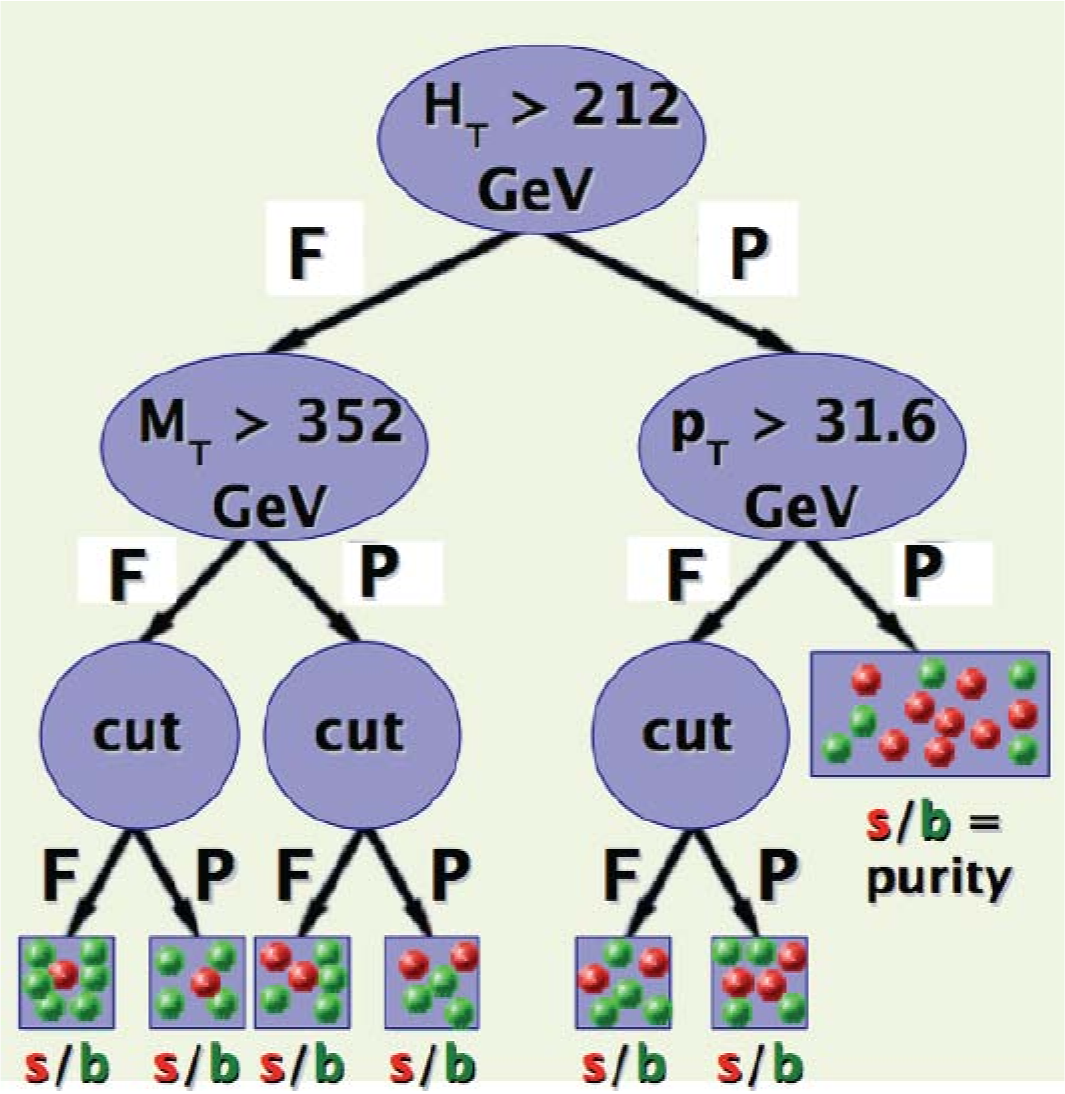
MVA for ttbar vs WH and MVA for Wbb/cc vs WH

→ Use **the union of** the most powerful 14 variables of **two MVAs** for final MVA



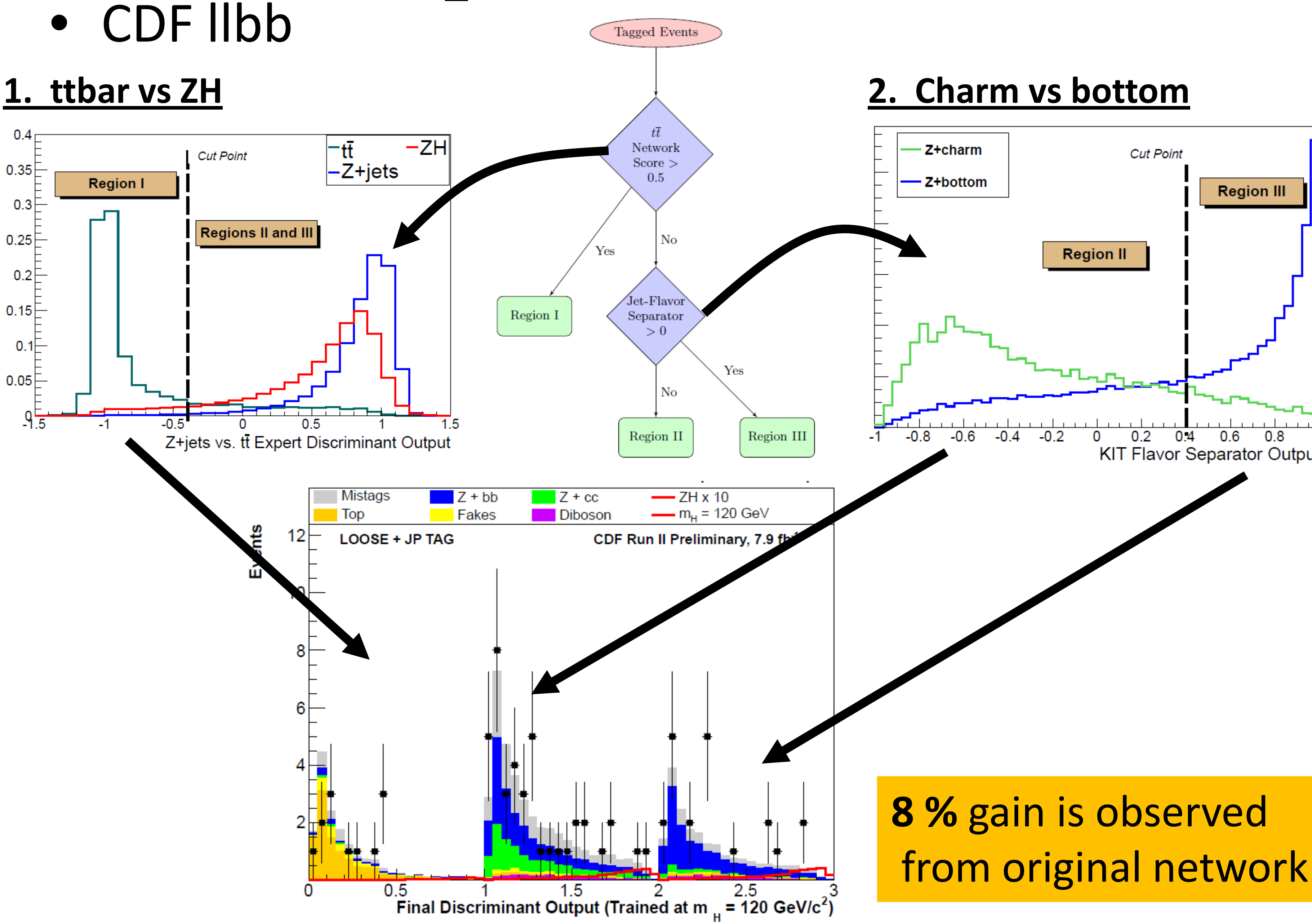

H_T > 212 GeV
F
P


H_T > 212 GeV
F
P
M_T > 352 GeV
p_T > 31.6 GeV
F
P
F
P


H_T > 212 GeV
F
P
M_T > 352 GeV
p_T > 31.6 GeV
F
P
F
P
cut
cut
cut
F
P
F
P
F
P
s/b = purity
s/b
s/b
s/b
s/b
s/b
s/b

An example of MVA optimization

- CDF llbb



8 % gain is observed from original network.

How much you can gain from MVA?

- VH→llbb, lvbb, vvbb case:
  - 20-25% gain in sensitivity on top of dijet mass.
    - Because dijet mass has most of information.
- H→WW case:
  - More than 40% gain in sensitivity on top of $\Delta\phi(l,l)$
    - No resonance! You need to have MVA!
- H→ZZ case:
  - Not much difference…
- H→$\gamma\gamma$ case:
  - Potentially you can get extra.
  - di-photon mass resolution is driving sensitivity.
    -

Limit setting, combination

At Tevatron: **High background (BG) and sizable systematic uncertainties**
→ Test **BG(b)** only and **BG+signal (s+b)** hypotheses
using **Poisson statistics accounting for systematic uncertainties.**

- We use two methods
  - Bayesian method (CDF) : Bayesian integration over likelihoods

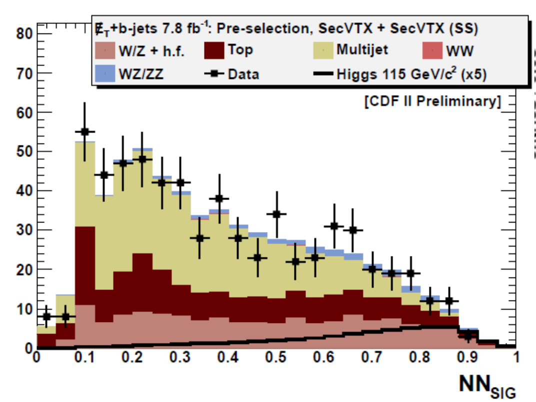
$$\mathcal{L}(R,\vec{s},\vec{b}|\vec{n},\vec{\theta}) \times \pi(\vec{\theta}) = \prod_{i=1}^{N_C} \prod_{j=1}^{Nbins} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}} / n_{ij}! \times \prod_{k=1}^{n_{np}} e^{-\theta_k^2/2}$$

  - Modified Frequentist method, CLs (DØ)

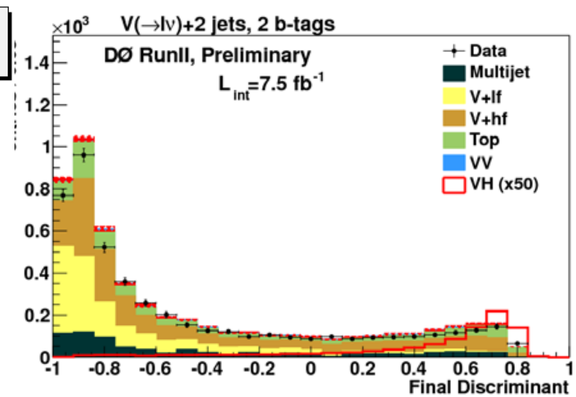
$$LLR = -2 \ln \frac{p(\mathrm{data}|H_1)}{p(\mathrm{data}|H_0)}, \quad CL_b = p(LLR \geq LLR_{obs}|H_0) \quad CL_{s+b} = p(LLR \geq LLR_{obs}|H_1) \quad CL_s = \frac{CL_{s+b}}{CL_b}$$

- Both methods use differential distributions, not only integrated yields.

CDF WH→ννbb



DØ WH→lνbb



Systematic Uncertainty

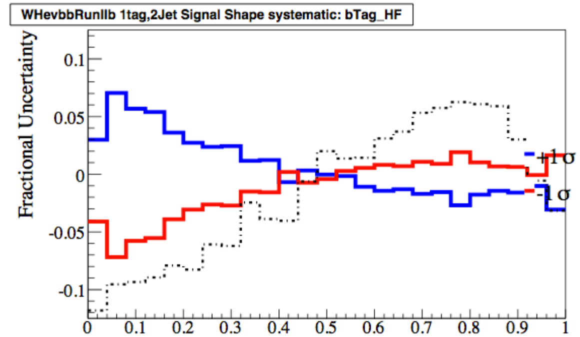
- In case of WH→lνbb (%)

Source	W→eν	W→μν
Luminosity	6.1	6.1
BG X section	6-20	6-20
Lepton ID/Trigger	2-3	3-5
Jet ID	1-2	1-2
Jet Energy Scale	2-5	2-5
b-Jet ID	9-11	9-11
Multi-Jet BG	1.0	1.0
PDF, MC Model	2-3	2-3

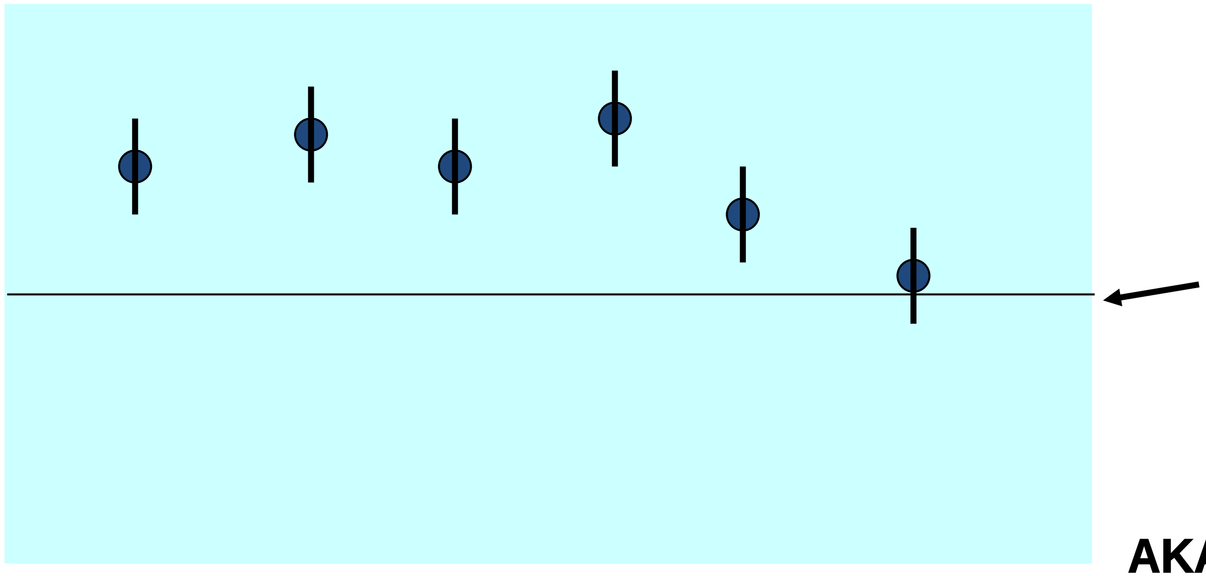
Flat Systematics

W+hf: 20%
Diboson : 6%
ttbar : 10%
Single top: 12%

Shape Systematics

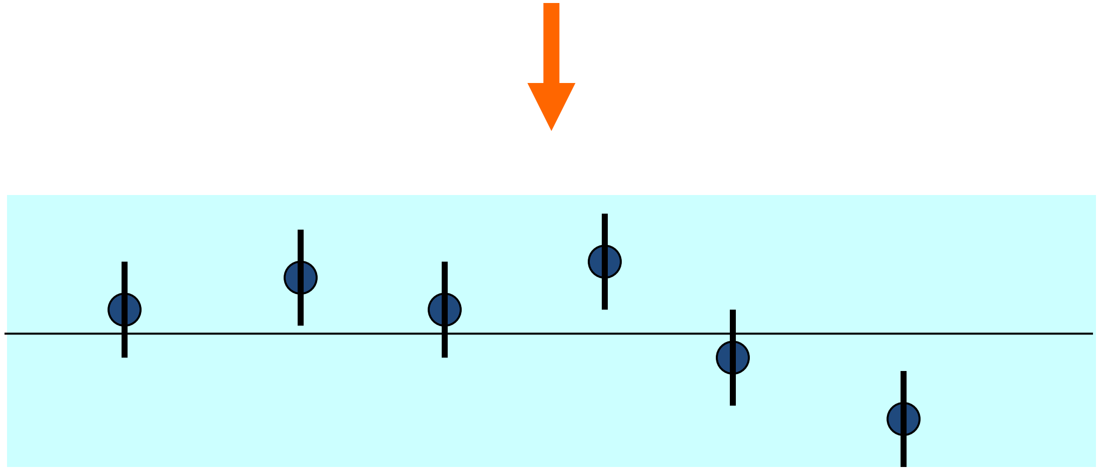


Background profiling



Background prediction

+ uncertainty

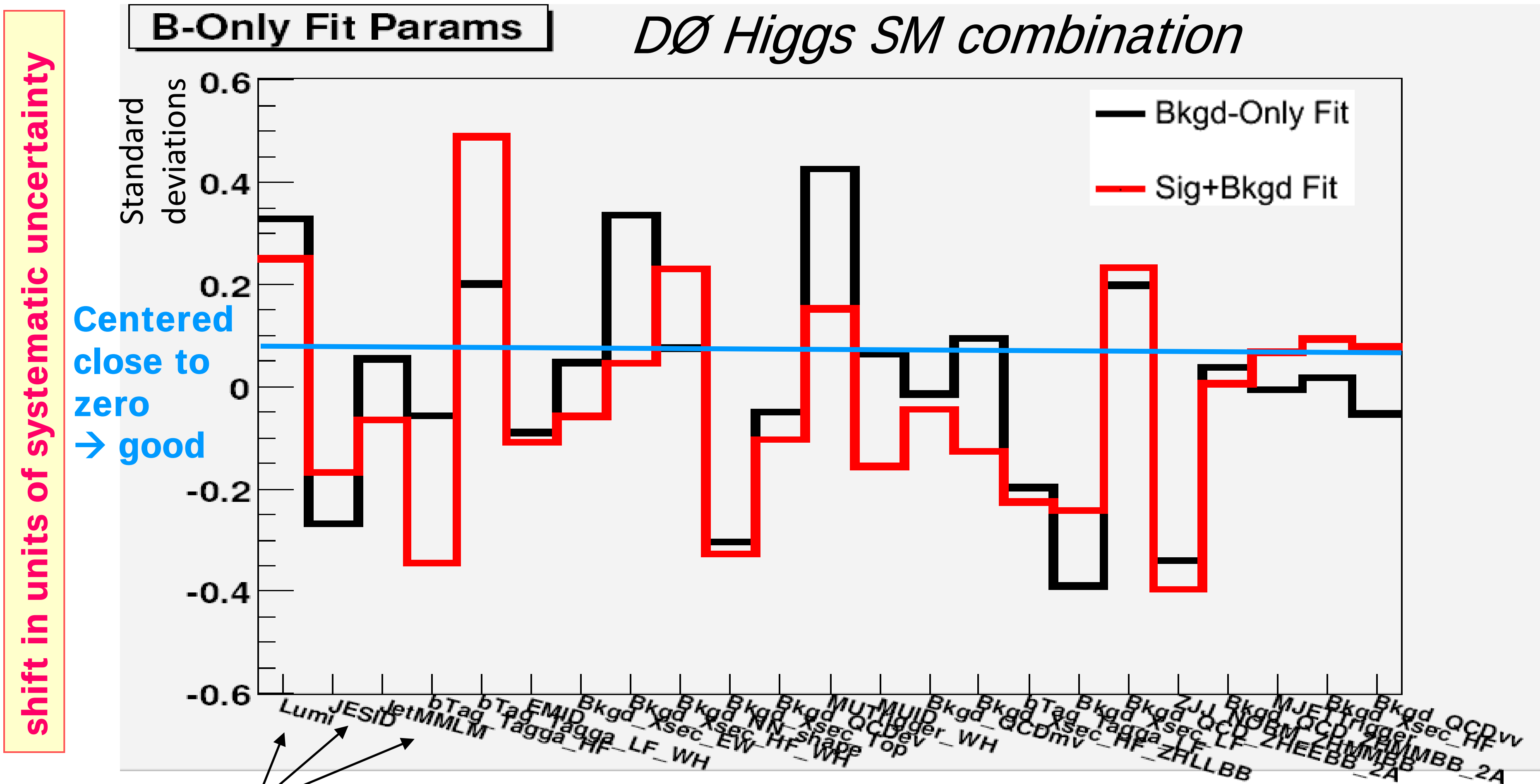


AKA side band fitting
uncertain parameters introduced in the χ^2 of the fit allow shifting of central value of the background estimation

Systematic uncertainty width gets also constrained

Shape of the systematic is also taken into account

Background profiling



Fitted Nuisance parameters for each systematic uncertainty

Input: Data,

Signal, BG (Wbb, Wjj, top, singletop, diboson, multi-jet)

When we have result.

- Now Higgs analysis become very complex.
- How sure the analysis is correct?

→ Measure real processes

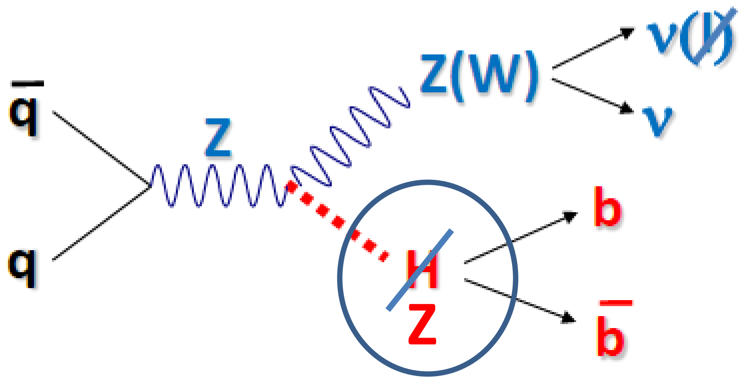
– Replace H to W or Z.

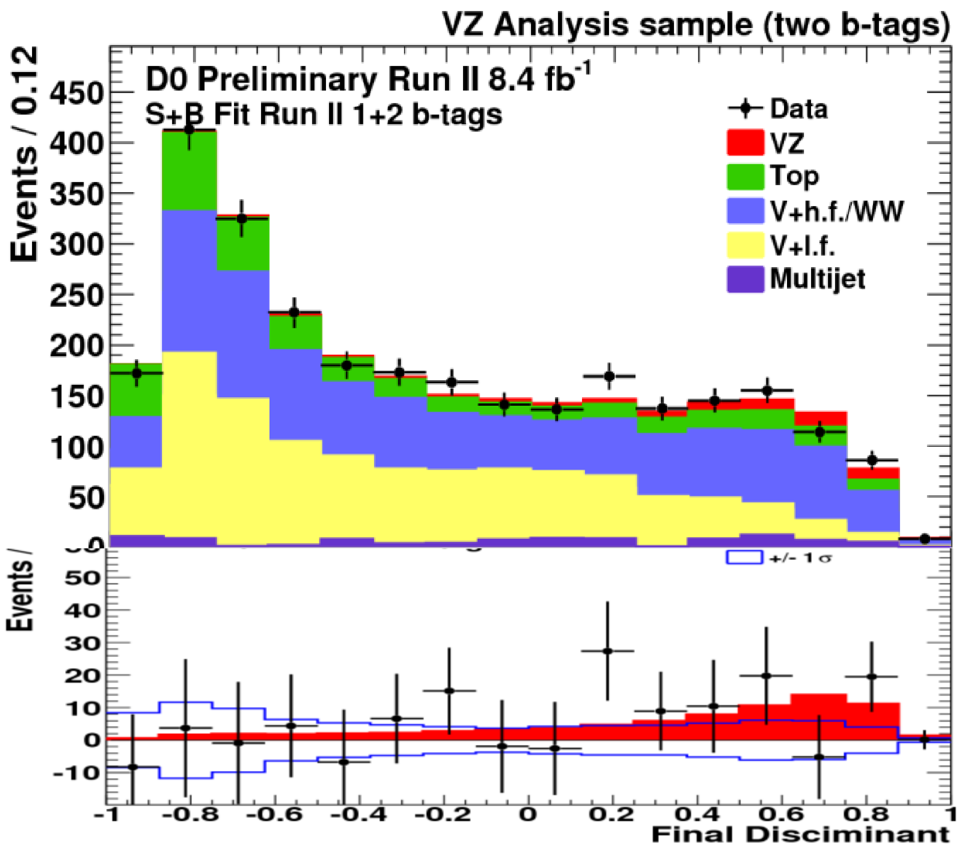
Try to look for diboson process with exact same procedure.

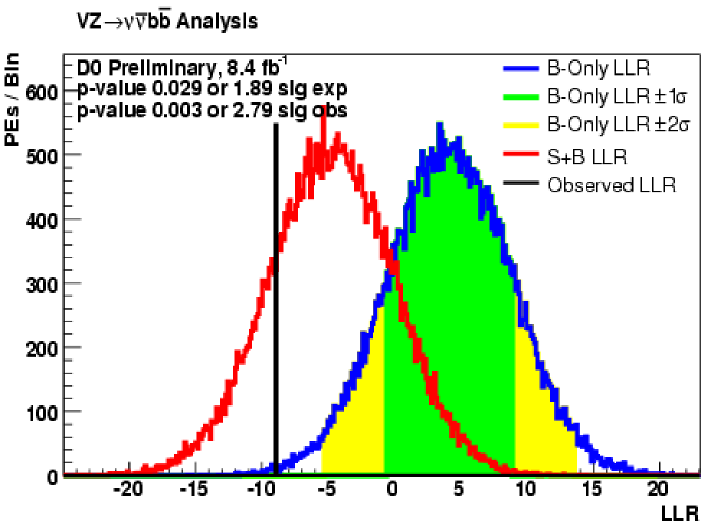
For m_H=115 GeV
$WH \rightarrow l\nu bb$: σ = 26 fb
$ZH \rightarrow \nu\nu bb$: σ = 15 fb
$ZH \rightarrow llbb$: σ = 5 fb
Total VH: σ = 46 fb

Replace Z with H
$WZ \rightarrow l\nu bb$: σ = 105 fb
$ZZ \rightarrow \nu\nu bb$: σ = 81 fb
$ZZ \rightarrow llbb$: σ = 27 fb
Total VZ: σ = 213 fb

Confirmation of Higgs analysis.







Cross-section measurement:
$\sigma(WZ+ZZ)_{mes}/\sigma_{SM}$= **1.5 ± 0.5**
2.8 s.d. from BG only hypo.

Tevatron combination

- Full combination of all analyses from CDF and D0 for best sensitivity
- Combining ~20 search channels (10 per experiment). <L>~8.0 fb^{-1}

Channel	Luminosity (fb^{-1})
$WH \to \ell\nu bb$ 2-jet channels 4×(TDT,LDT,ST,LDTX)	7.5
$WH \to \ell\nu b\bar{b}$ 3-jet channels 2×(TDT,LDT,ST)	5.6
$ZH \to \nu\bar{\nu}b\bar{b}$ (TDT,LDT,ST)	7.8
$ZH \to \ell^+\ell^- b\bar{b}$ 2×(TDT,LDT,ST)	7.7
$H \to W^+W^-$ 2×(0 jets,1 jet)+(2 or more jets)+(low-$m_{\ell\ell}$)+(e-τ_{had})+(μ-τ_{had})	8.2
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)	8.2
$ZH \to ZW^+W^-$ (tri-leptons with 1 jet)+(tri-leptons with 2 or more jets)	8.2
	8.2
$H + X \to \tau^+\tau^-$ (1 jet)+(2 jets)	6.0
$WH \to \ell\nu\tau^+\tau^- / ZH \to \ell^+\ell^-\tau^+\tau^-$ (ℓ-ℓ-τ_{had})+(e-μ-τ_{had})+(ℓ-τ_{had}-τ_{had})	6.2
$WH + ZH \to jjb\bar{b}$ (GF,VBF)×(TDT,LDT)	4.0
$H \to \gamma\gamma$ (CC,CP,CC-Conv,PC-Conv)	7.0
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (lepton) (4jet,5jet)×(TTT,TTL,TLL,TDT,LDT)	6.3
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (no lepton) (low met,high met)×(2 tags,3 or more tags)	5.7

Channel	Luminosity (fb^{-1})
$WH \to \ell\nu b\bar{b}$ (LST,LDT,2,3 jet)	8.5
$ZH \to \nu\bar{\nu}b\bar{b}$ (LST,LDT)	8.4
$ZH \to \ell^+\ell^- b\bar{b}$ (TST,TLDT,ee,$\mu\mu$,ee_{ICR},$\mu\mu_{trk}$)	8.6
$H+X \to \ell^{\pm}\tau^{\mp}_{had}jj$	4.3
$VH \to \ell^{\pm}\ell^{\pm} + X$	5.3
$H \to W^+W^- \to \ell^{\pm}\nu\ell^{\mp}\nu$ (0,1,2+ jet)	8.1
$H \to W^+W^- \to \mu\nu\tau_{had}\nu$	7.3
$H \to W^+W^- \to \ell\bar{\nu}jj$	5.4
$H \to \gamma\gamma$	8.2

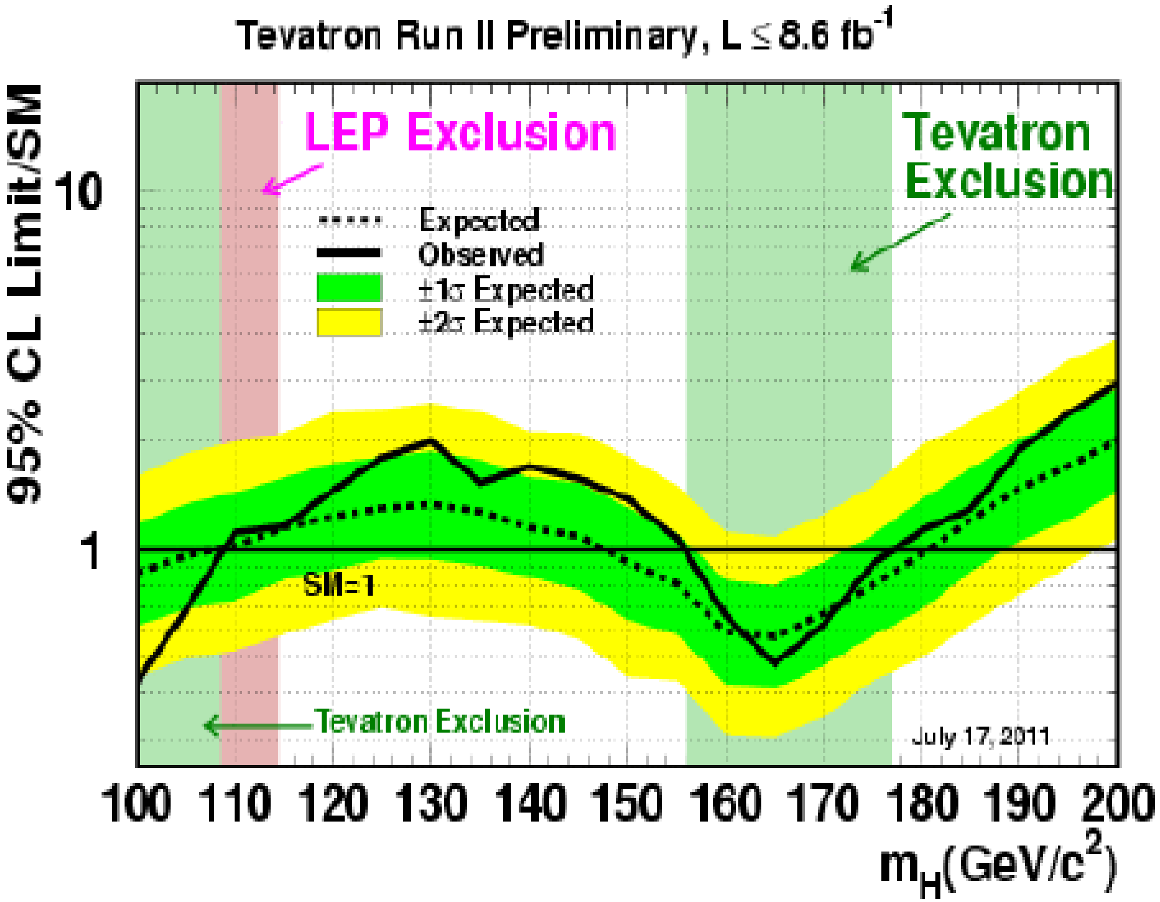
- More than **50 different sources of systematic uncertainties** are considered (including correlations among channels and experiments), and constrained in sidebands.
- Use different techniques to cross check calculations (Bayesian, modified frequentist)
  → results agree within ~5-10%.

Correlation between analysis on syst.

- Treatment of systematic uncertainties
  - Systematics are included via Gaussian smearing of expected number of events.
  - Correlations of systematic uncertainties are included across all input channels.
  - CLs method fits uncertainty parameter values for each hypothesis
  - Bayesian method integrates over uncertainty parameters.

- Correlated uncertainties between CDF and DZero analyses
  - Luminosity (4%),
  - Cross section: Higgs(6%,12%), top(10%), single top(10%), diboson(6%).
- Correlated uncertainties in CDF
  - b-tagging(5-12%), JES(3-10%), gluon radiation (3-4%).
- Correlated uncertainties in Dzero
  - b-tagging(4-15%), JES(3-5%), JetID/resolution(3-5%)

Tevatron combination, result

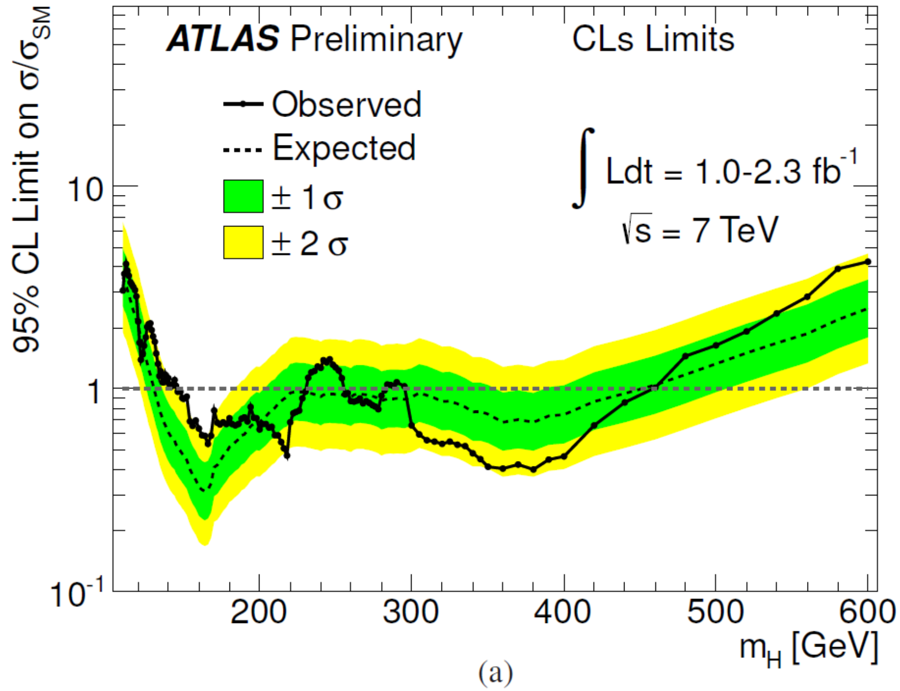


SM Higgs excluded @ 95% C.L.

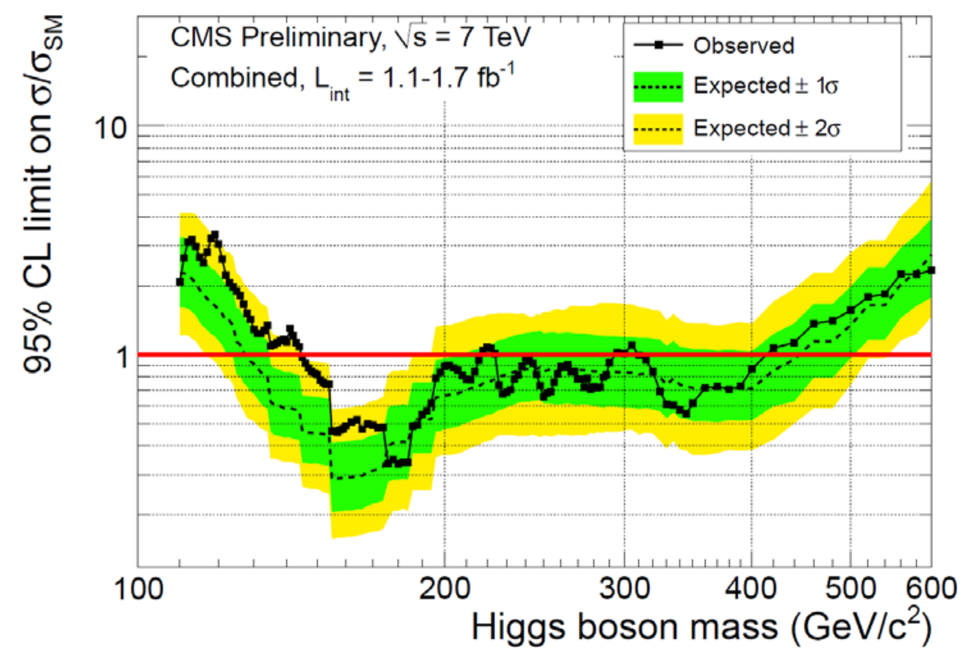
$156 < m_H < 177$ GeV obs ($148 < m_H < 180$ GeV exp)

$100 < m_H < 108$ GeV obs ($100 < m_H < 109$ GeV exp)

Combined limit from ATLAS and CMS



(a)



Atlas excluded

146 GeV < M_H < 230 GeV,

256 GeV < M_H < 282 GeV

296 GeV < M_H < 459 GeV

@ 95% CL

Expected: 131 GeV < MH < 450 GeV

CMS excluded

145 GeV < M_H < 216 GeV

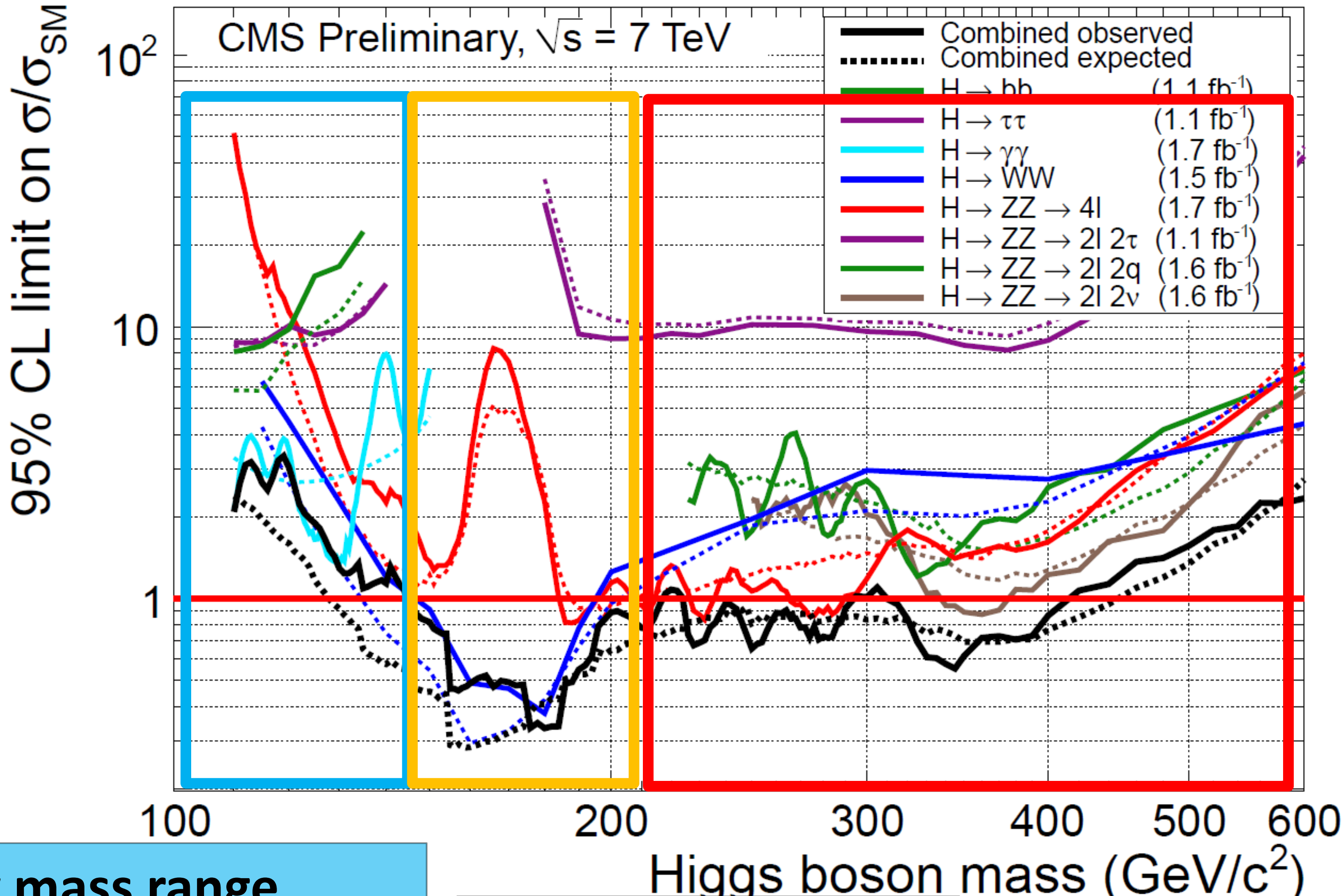
226 GeV < M_H < 288 GeV

310 GeV < M_H < 400 GeV

@ 95% CL

Expected: 130 GeV < M_H < 440 GeV

Individual limits



Low mass range

Main: H→γγ

sub: H→WW, H→bb, H→ττ

Midium mass range

Main: H→WW

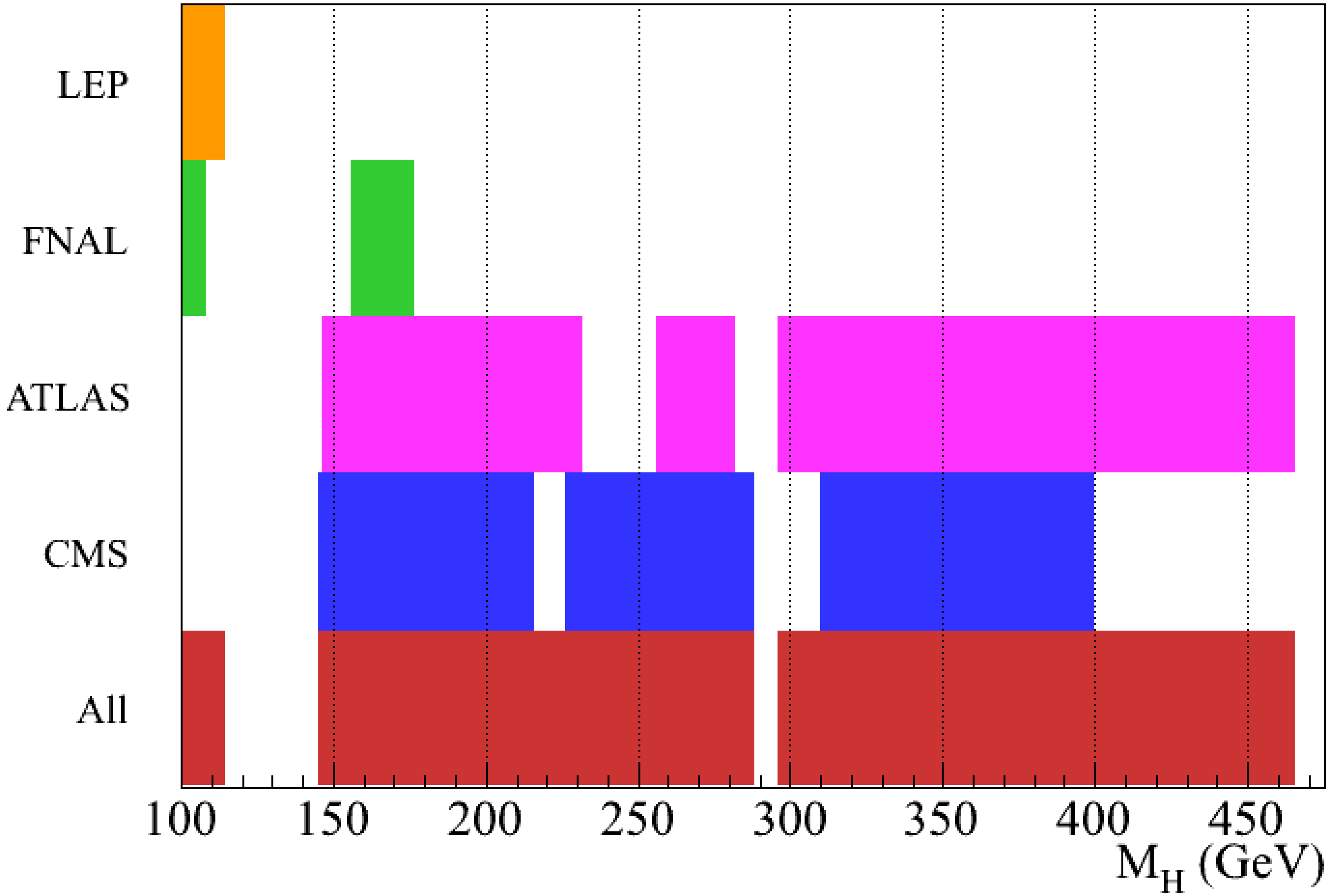
sub: H→ZZ→llll

High mass range

Main: H→ZZ

sub: H→WW

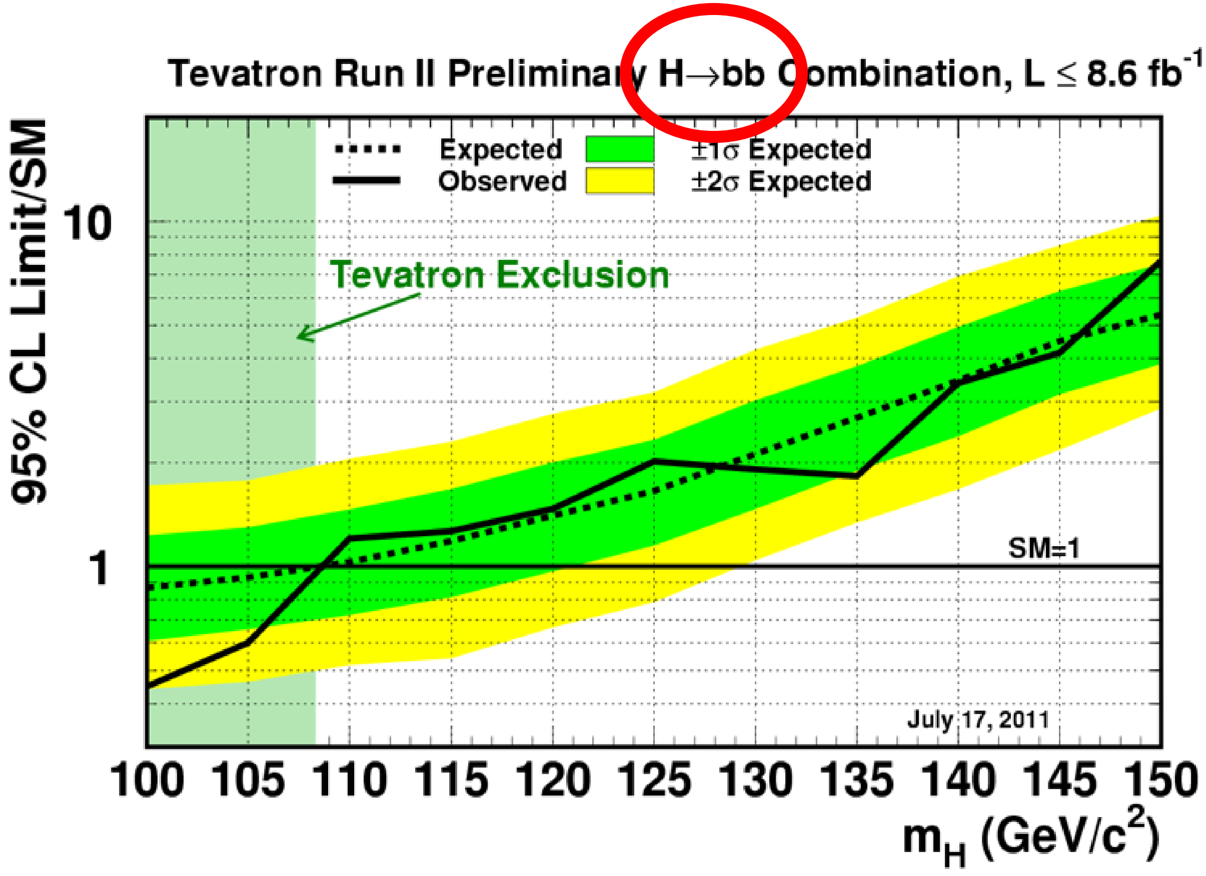
Excluded region at 2011 Summer



- Low mass region is till open, which is favored by indirect limits, and theory.
- We can access there by Moriond 2012 or ICHEP 2012.

Low mass region

- Tevatron result is still the most sensitive at low mass region



What's happen if we don't fine any?

- Gauge theory needs something TeV scale
  - No Higgs, no new phenomena in LHC?!
    → This is indication of new physics!

- If Higgs is not there, there should be something else.
  - It could be just we can not find it because "something" is waiting at higher energy scale..

We didn’t discuss

- Uncertainty on Higgs production cross section
  - At LHC, we can measure cross section.
  - At LHC, we can exclude even we assign large uncertainty.
- What’s next if we find Higgs.
  - Measure property! Continue to look for others.
- Beyond Standard Model Higgs
  - 4^{th} Generation
    - Limit gets tighten
  - Fermiophobic Higgs
    - No gluon fusion
  - MSSM Higgs
    - $\tau\tau$ mode is highly sensitive. Good to keep eye on bf→bbb from Tevatron
  - NMSSM Higgs
  - Double charged Higgs

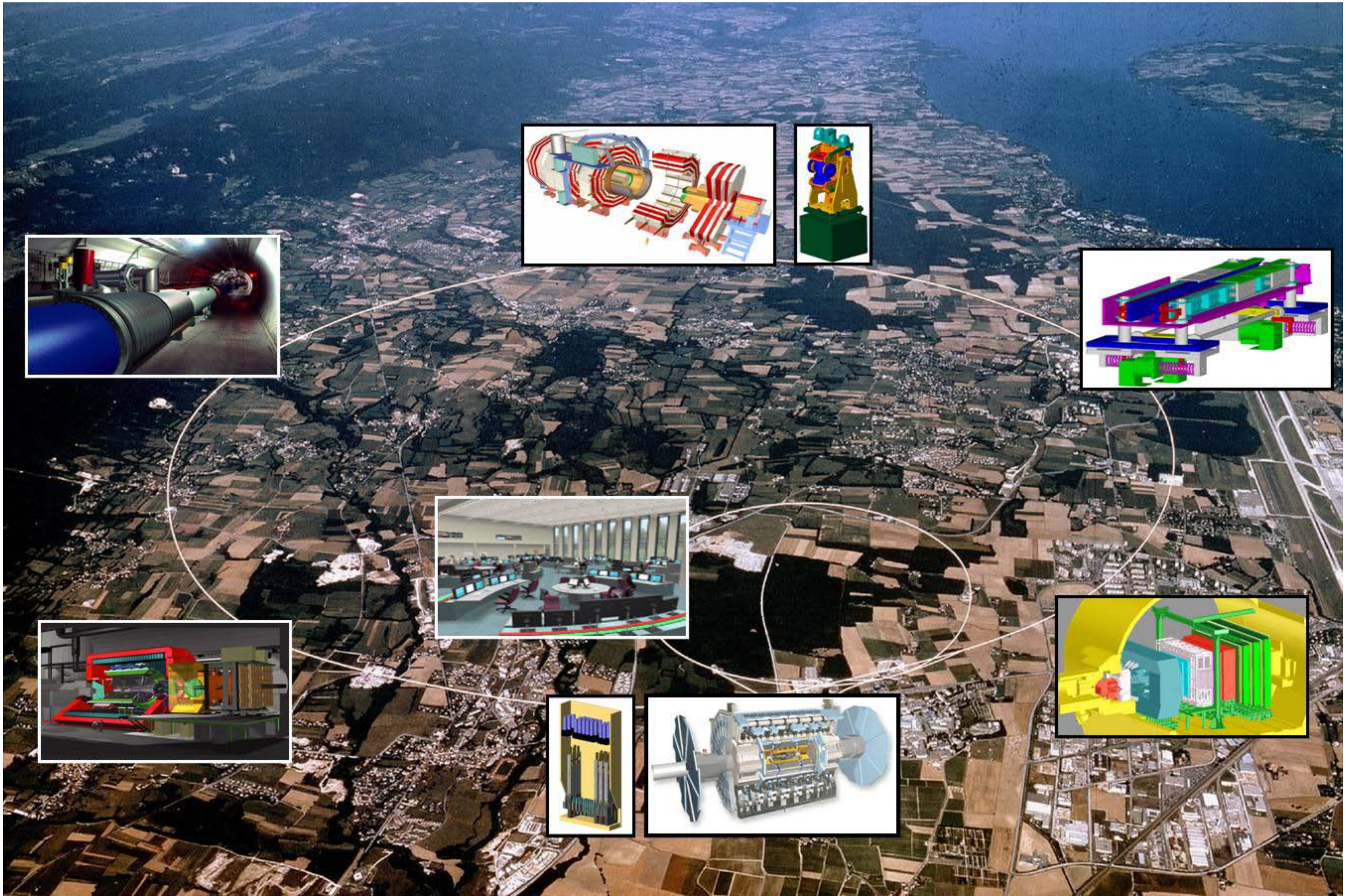
We are lucky!

- The year of 2011 or 2012 will be recorded as year of Higgs
  - Discover or exclude Higgs boson.
    This was Goal for 40 years!
- We can do analysis by ourselves.
  - Excellent opportunity is still open!

- Tevatron operation has been terminated.
  - Luminosity: ~ 10 fb^{-1}

- LHC operation
  - Lumi = 10 fb^{-1} @ 7 TeV by end of 2012
    → SM higgs can be discovered or excluded upto M_H=600 GeV.
  - 19 months shutdown for maintenance.
    - High energy, high luminosity operation is expected.

A Happy Higgs Hunting!



BACK UP

Matrix Element approach

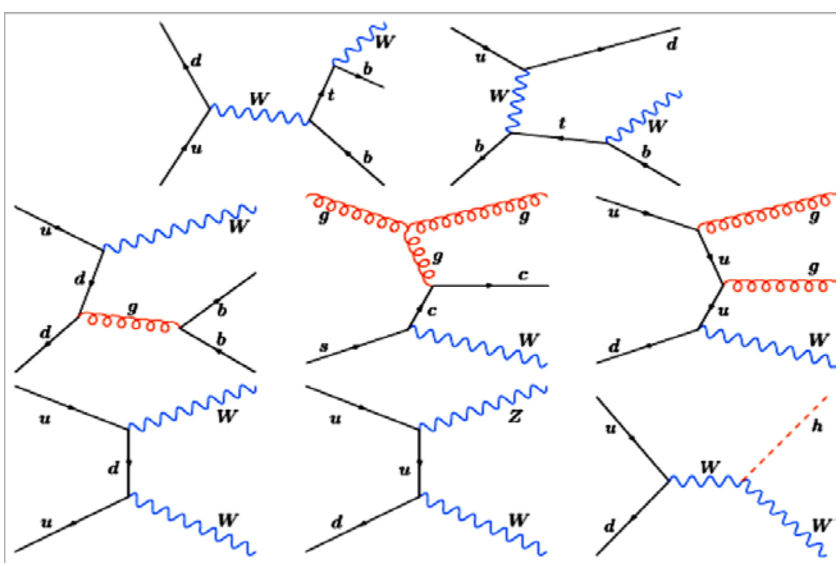
- Get event probability from Matrix Element
  - Need to integrate all event, takes long time.
- Calculate the differential cross section of each physics process with 4 momentum for all object (except MET).

Detector response (Transfer function)

$$d\sigma(\vec{x}) = \sum_{i,j} \int d\vec{y} \left[\underbrace{f_i(q_1, Q^2)dq_1 \times f_j(q_2, Q^2)dq_2}_{p.d.f} \times \underbrace{\frac{\partial \sigma_{hs,ij}(\vec{y})}{\partial \vec{y}}} \times \overbrace{W(\vec{x}, \vec{y})} \times \underbrace{\Theta_{parton}(\vec{y})} \right]$$

Parton level cut

<u>Matrix Element for hard scatter collision</u>

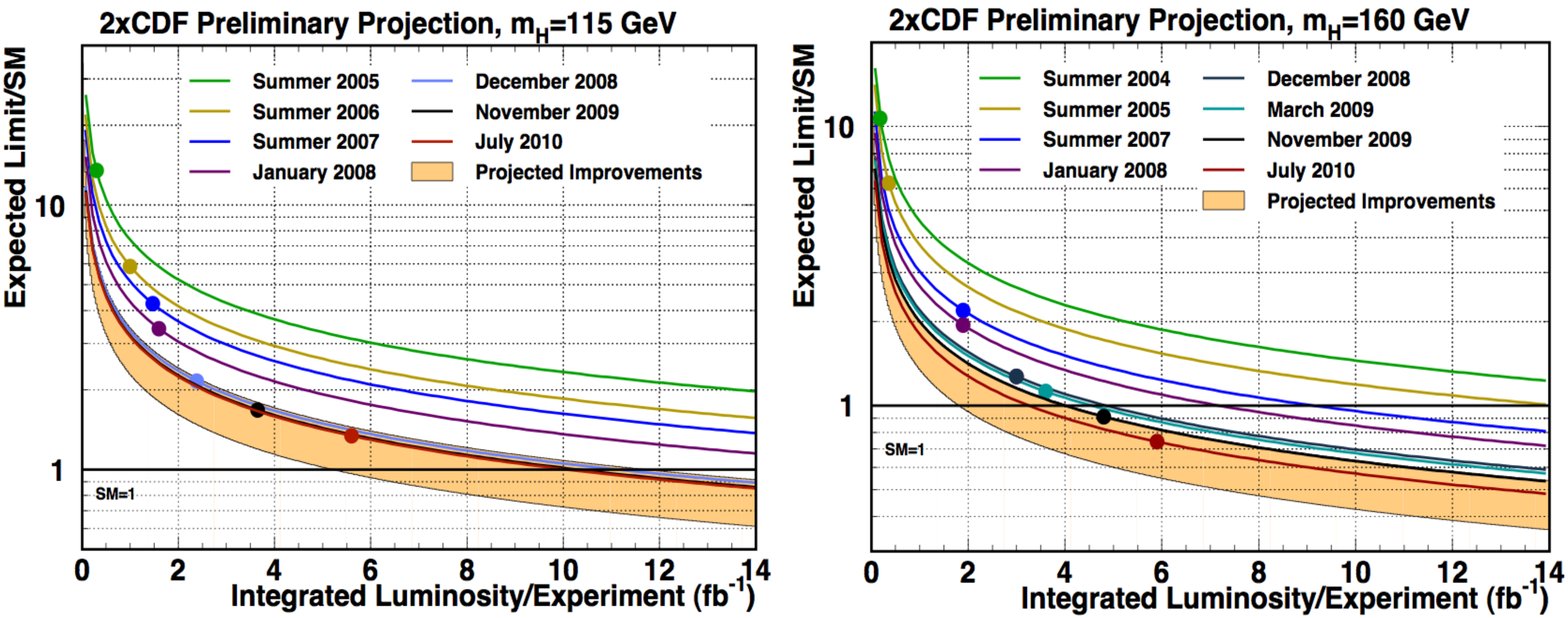


Discriminant is defined as

$$D_{WH}(\vec{x}) = \frac{P_{WH}(\vec{x})}{P_{WH}(\vec{x}) + P_B(\vec{x})}$$

$P_B(\vec{x})$; combined probability of Wbb,Wcg, Wgg, s-top, WW and WZ.

Projection, how to improve analysis?



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

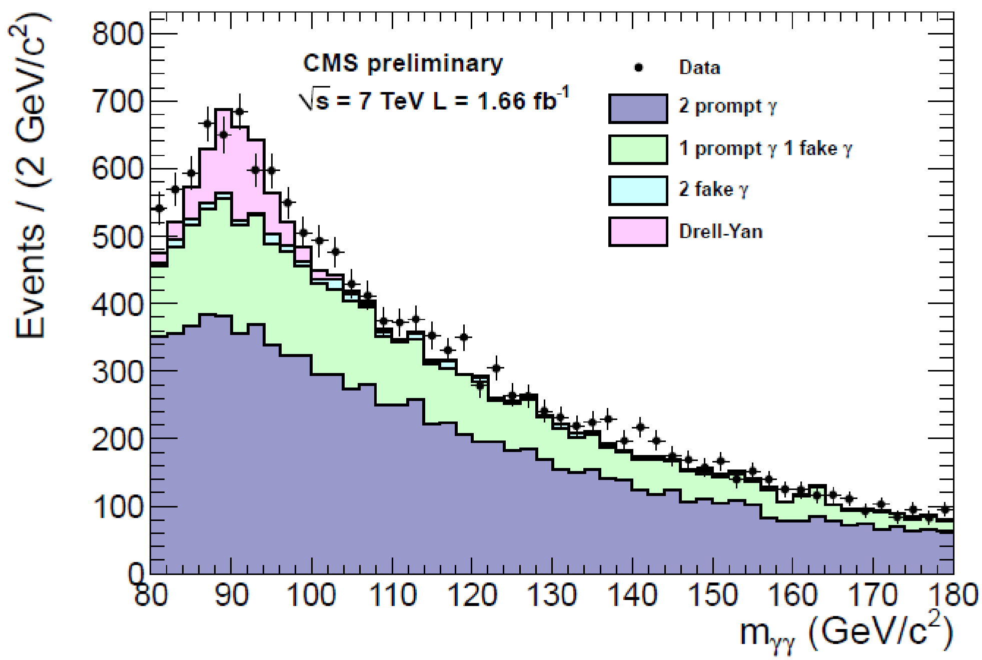
- Limits have improved faster than $1/\sqrt{L}$ due to analysis improvements.
- Major effort underway to continue to improve intrinsic sensitivity:
  - Optimized object identification/resolution
  - Optimized selections and signal-to-bckg discrimination
  - Reduced systematic uncertainties
  - Adding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

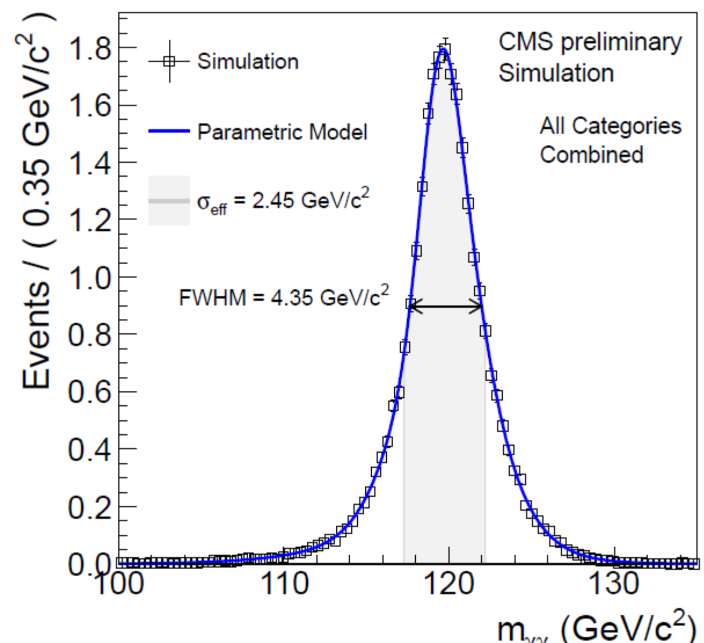
Way to look the result

- Compare new and old analysis
  - Yield: signal, background: is it same ratio?
  - Result: Is it on the expected by luminosity?
    - Sensitivity S = s / sqrt(s+b), if you have α times more data, your sensitivity increase $\sqrt{\alpha}$.
- If S is worse than expected:
  - Detector performance? Larger background?
    - Radiation damage? High luminosity effect?
  - Trigger efficiency?
- If S is better than expected:
  - Trigger/ID efficiency?
  - Better resolution?
  - Introducing good discriminant?
  - Change analysis strategy?

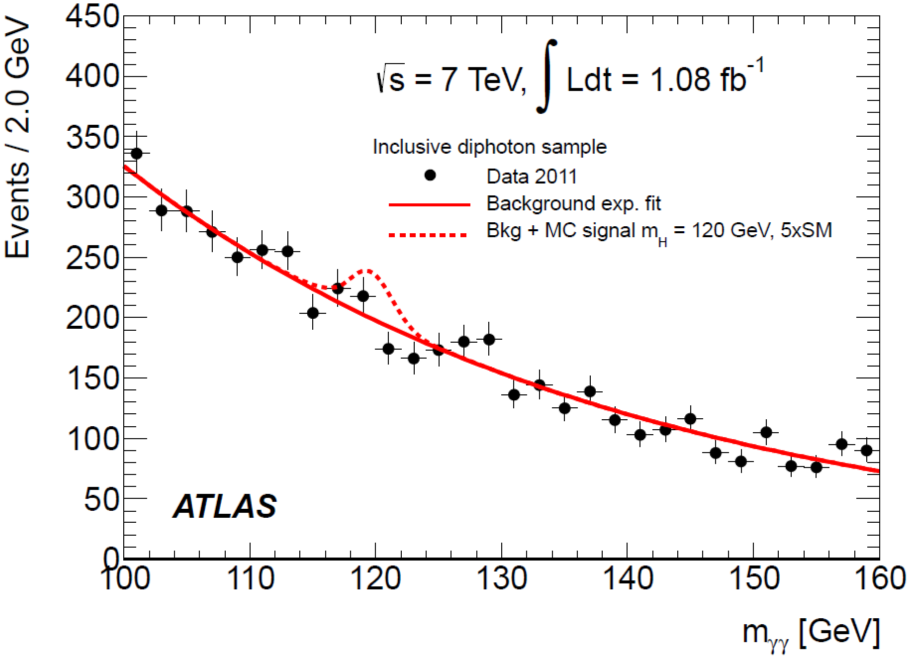
$H \rightarrow \gamma\gamma$

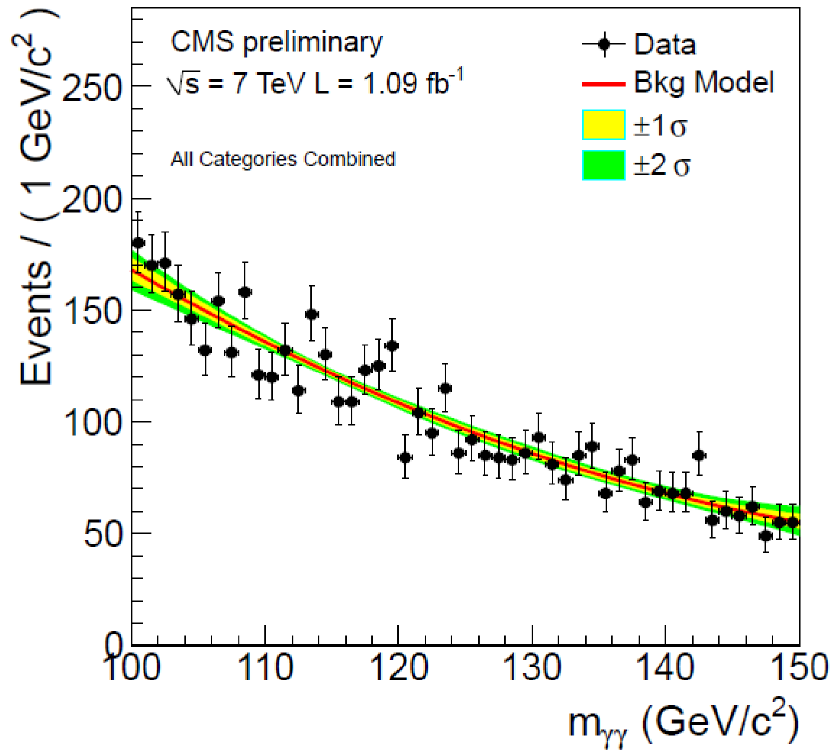
- $Br(H \rightarrow \gamma\gamma) = 0.8\%$. Why this channel can be discovery channel?
  - No sub-decay of photon (compared to W, Z, τ)
  - High reconstruction efficiency
  - Very high di-photon mass resolution
    - Di-jet mass resolution is 10-15%, di-photon mass is 2-3%!





H→γγ





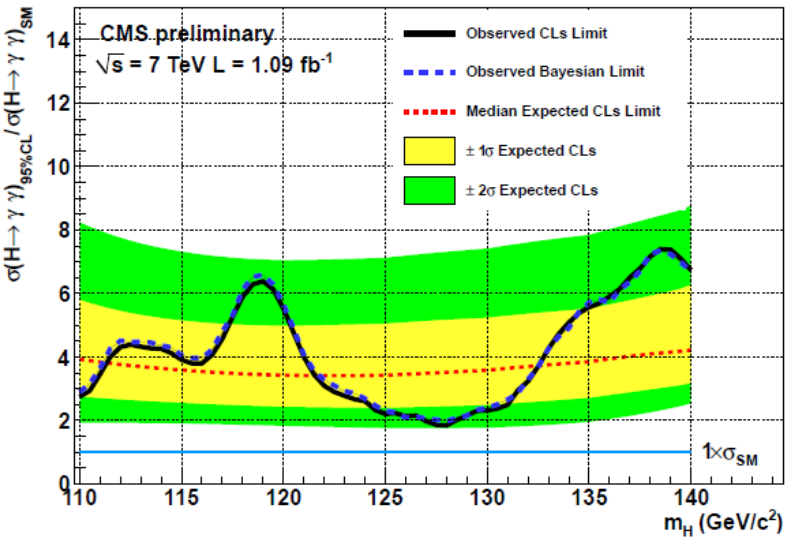
- Make categories in
  - Different eta and quality (CMS)
  - Converted/Uncoverted photon
- Similar background rates
- Similar resolution.

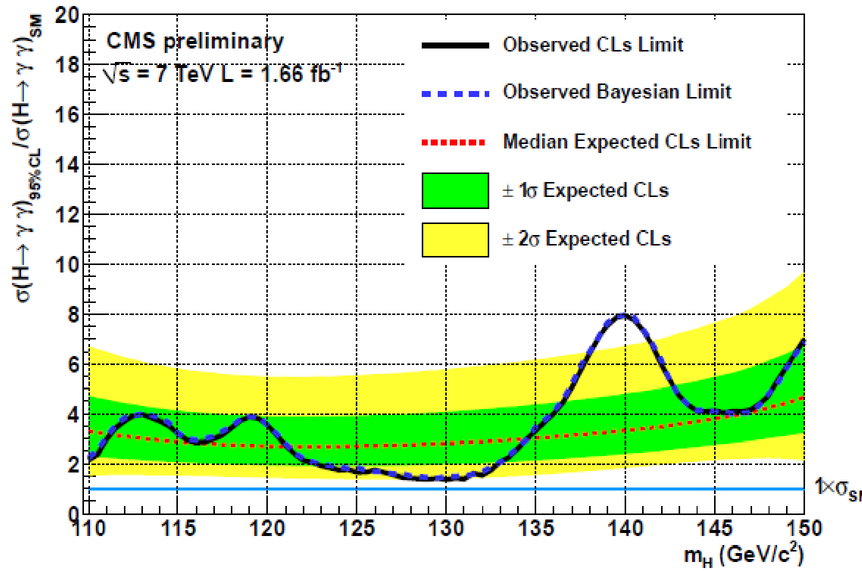
  Almost identical sensitivity.

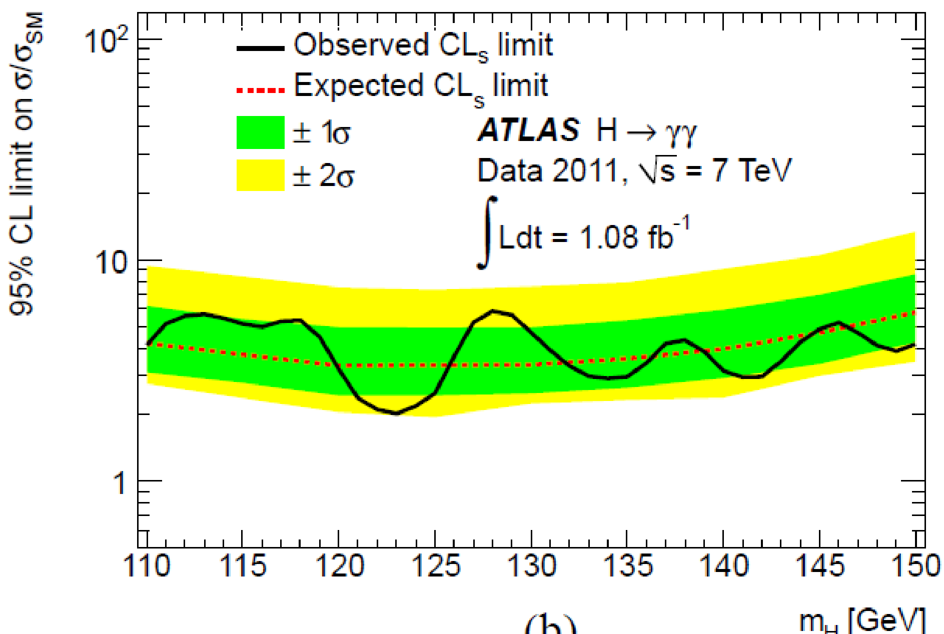
Expected Limit at 120 GeV

	ATLAS	CMS-1	CMS-2
Lumi	1.08	1.09	1.66
Limit	3.3	3.4	2.7

H→γγ, limits







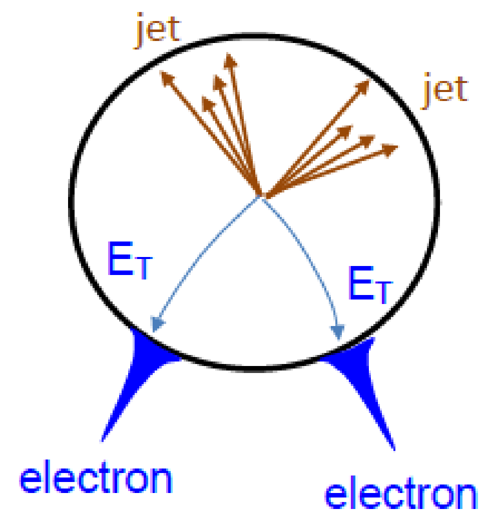
(b)

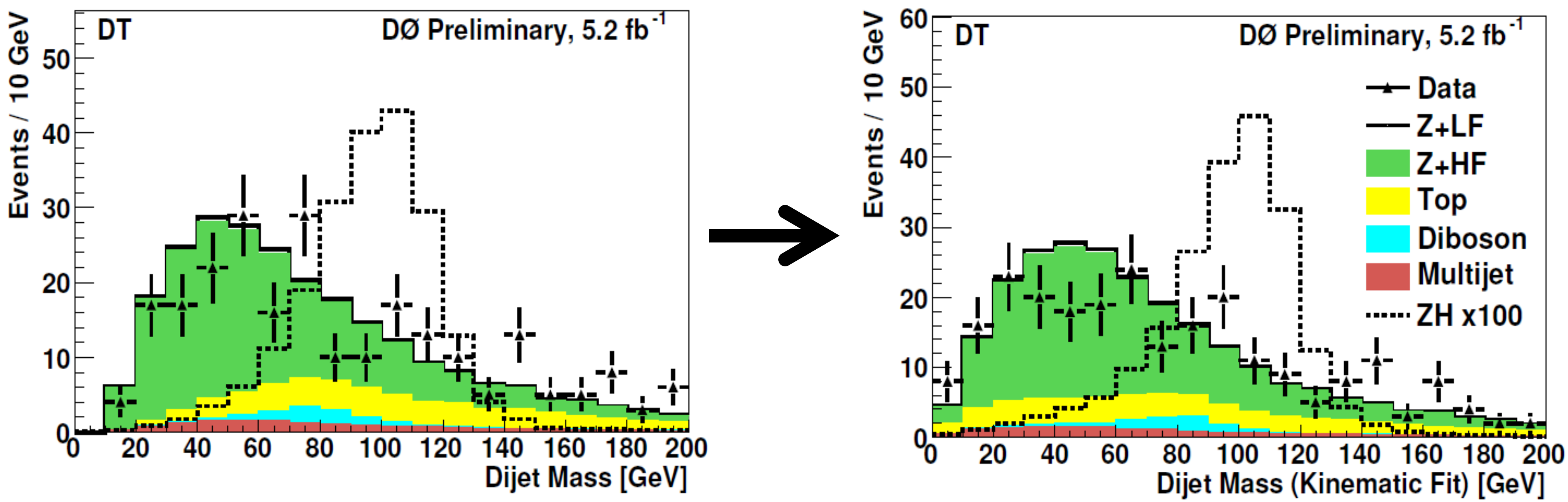
Expected limit at 120 GeV

	ATLAS	CMS-1	CMS-2
Lumi	1.08	1.09	1.66
Limit	3.3	3.4	2.7

Dijet system in ZH→llbb

- ZH→llbb
  - No real missing ET
  - Use full kinematics information
    - Dijet Mass can be constrained

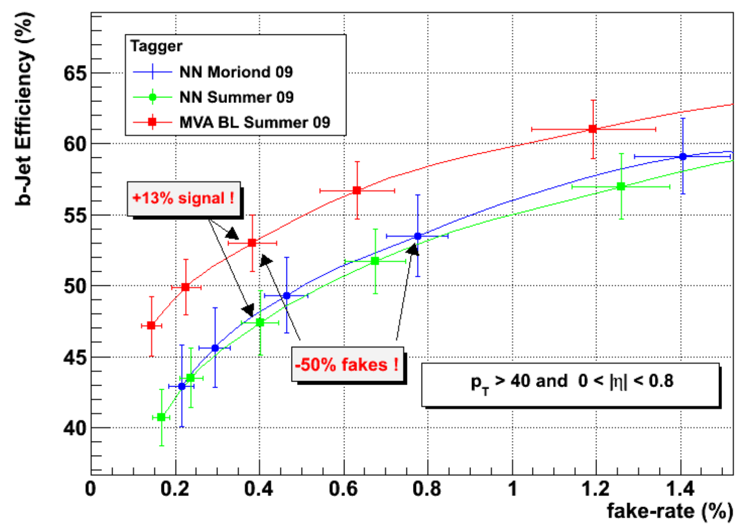




15 % improvement on Mass resolution

Way to look the result

- Compare new and old analysis
  - Yield: signal, background: is it same ratio?
  - Result: Is it on the expected by luminosity?
    - Sensitivity S = s / sqrt(s+b), if you have α times more data, your sensitivity increase $\sqrt{\alpha}$.
- If S is worse than expected:
  - Detector performance? Larger background?
    - Radiation damage? High luminosity effect?
  - Trigger efficiency?
- If S is better than expected:
  - Trigger/ID efficiency?
  - Better resolution?
  - Introducing good discriminant?
  - Change analysis strategy?

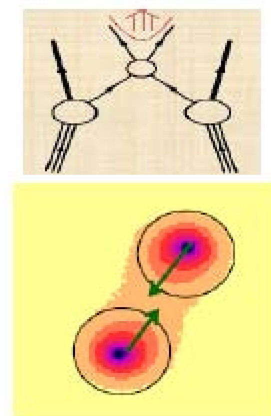


Way to look the result

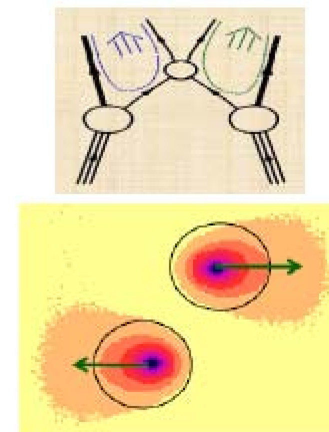
- Compare new and old analysis
  - Yield: signal, backgr
  - Result: Is it on the e
    - Sensitivity S = s / sc
      your sensitivity incr
- If S is worse than ex
  - Detector performar
    - Radiation damage?
  - Trigger efficiency?
- If S is better than ex
  - Trigger/ID efficienc
  - Better resolution?
  - Introducing good di
  - Change analysis str

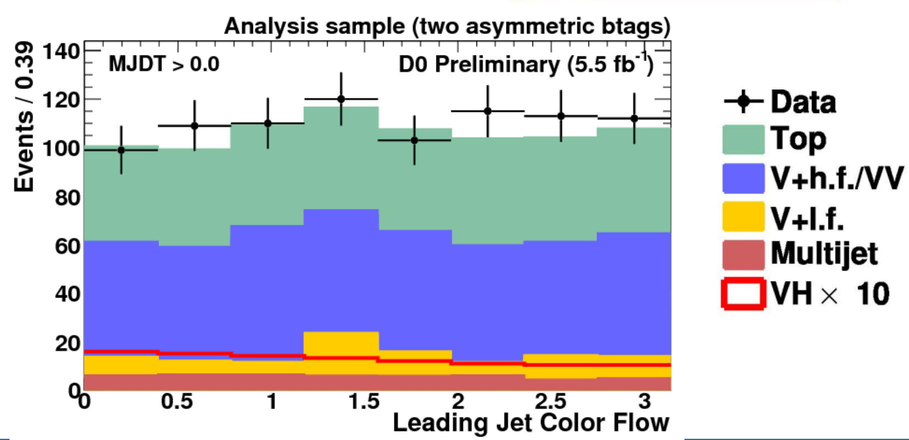
Ex. Color flow variables

Signal
color singlet



W+jets
color octet.

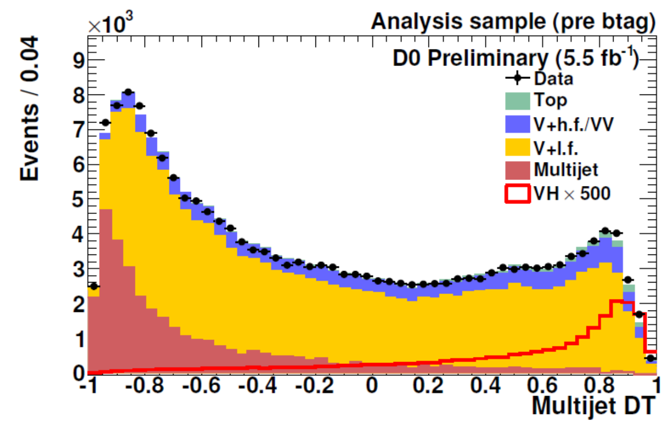


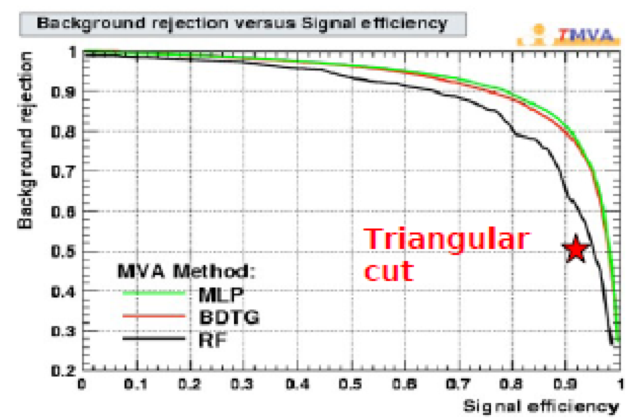


Way to look the result

- Compare new and old analysis
  - Yield: signal, backgrour
  - Result: Is it on the expe
    - Sensitivity S = s / sqrt(s
      your sensitivity increase
- If S is worse than expe
  - Detector performance
    - Radiation damage? Higl
  - Trigger efficiency?
- If S is better than expe
  - Trigger/ID efficiency?
  - Better resolution?
  - Introducing good discri
  - Change analysis strateg

MVA on multi-Jet BG regjection



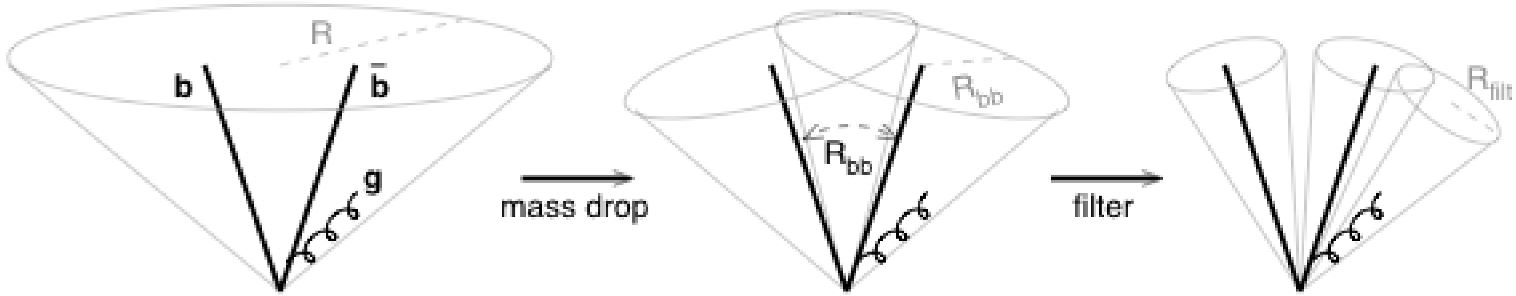


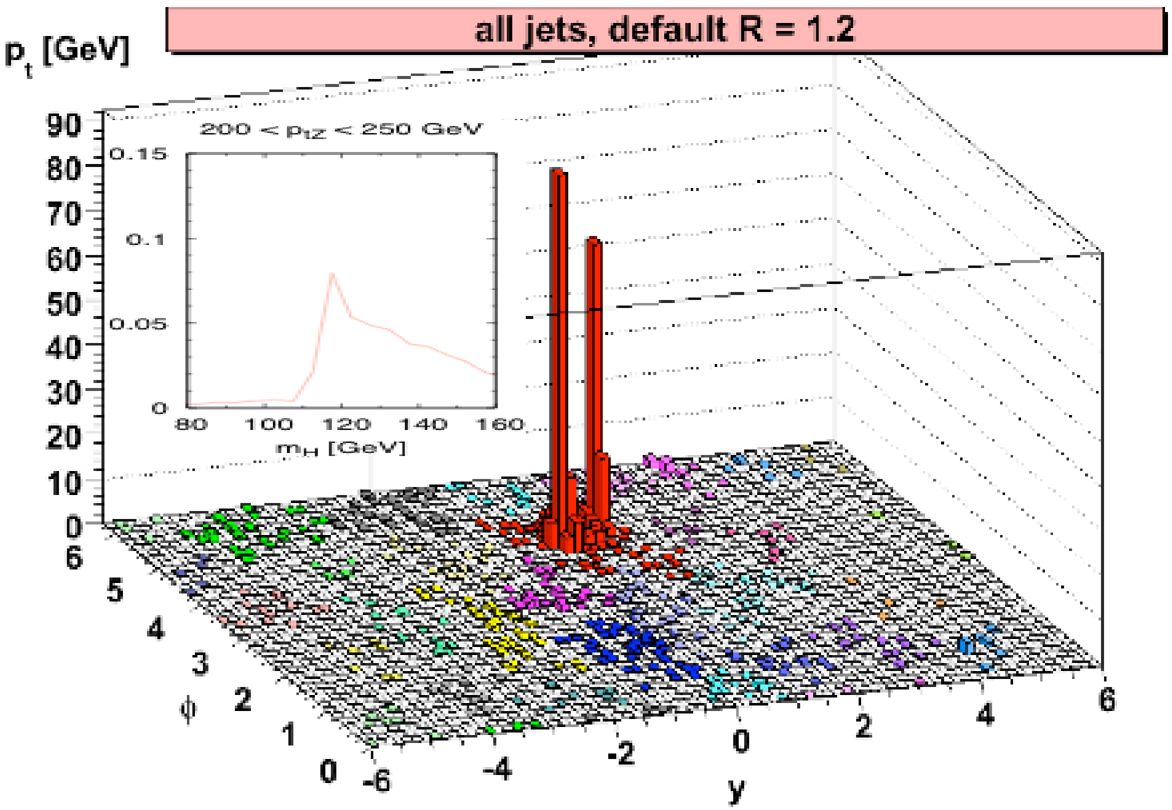
Improvements

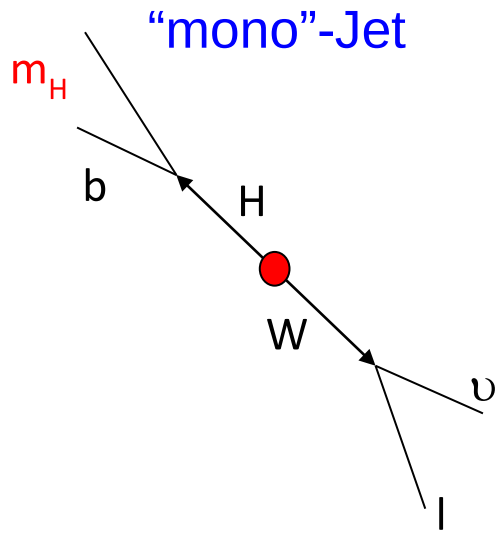
Type	Projected Improvement	WH→lνbb	ZH→llbb	ZH→ννbb	H→WW	Other Channels
Lepton ID	MVA Electron ID	1%	5%	-1%	3%	3%
	Improved MuonID/tracking	4%	3%	-2%	0%	3%
	Add Isolated Tracks	2%	0%	-1%	3%	2%
	Add ICR Electrons	2%	0%	-1%	3%	2%
	Add EC Electrons	0%	0%	0%	0%	2%
	Improved energy scale	1%	2%	0%	2%	5%
Trigger/Reco	Trigger/Reconstruction Efficiency	5%	3%	0%	0%	5%
Jet Selection	Dijet Mass Resolution	10%	10%	10%	0%	0%
	MVA B-ID	5%	5%	5%	0%	0%
	MVA Bottom vs Charm	4%	4%	4%	0%	0%
MVA Analysis	Enhanced Techniques	10%	10%	10%	10%	10%
	New signal separation variables	5%	5%	5%	5%	5%
	MVA QCD Rejection	3%	1%	0%	3%	3%
	Matrix Element Discriminants	5%	5%	5%	5%	3%
	Kinematic Fitting	5%	0%	0%	0%	3%
Optimization	Track Variables	5%	3%	0%	5%	5%
	Optimized B-ID Usage	3%	3%	3%	0%	0%
	Optimized Jet Treatment	3%	8%	0%	0%	0%
New Channels	HWWetau	0%	0%	0%	0%	5%
	Vhetaujj	0%	0%	0%	0%	3%
	HZZ	0%	0%	0%	0%	3%
	VH->trileptons	0%	0%	0%	0%	3%
	Additional Decay Modes	5%	5%	0%	5%	5%
	Existing Improvements:	57%	70%	29%	41%	
	Planned Improvements:	36%	27%	23%	12%	
	Total:	113%	116%	59%	58%	

Yellow are existing improvements to be propagated to final analysis
White are the areas we are working on.

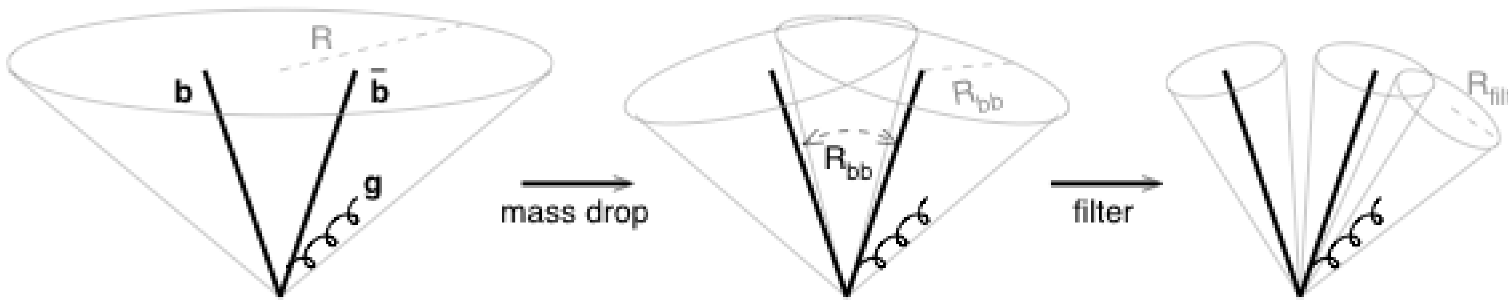
A Boosted Higgs

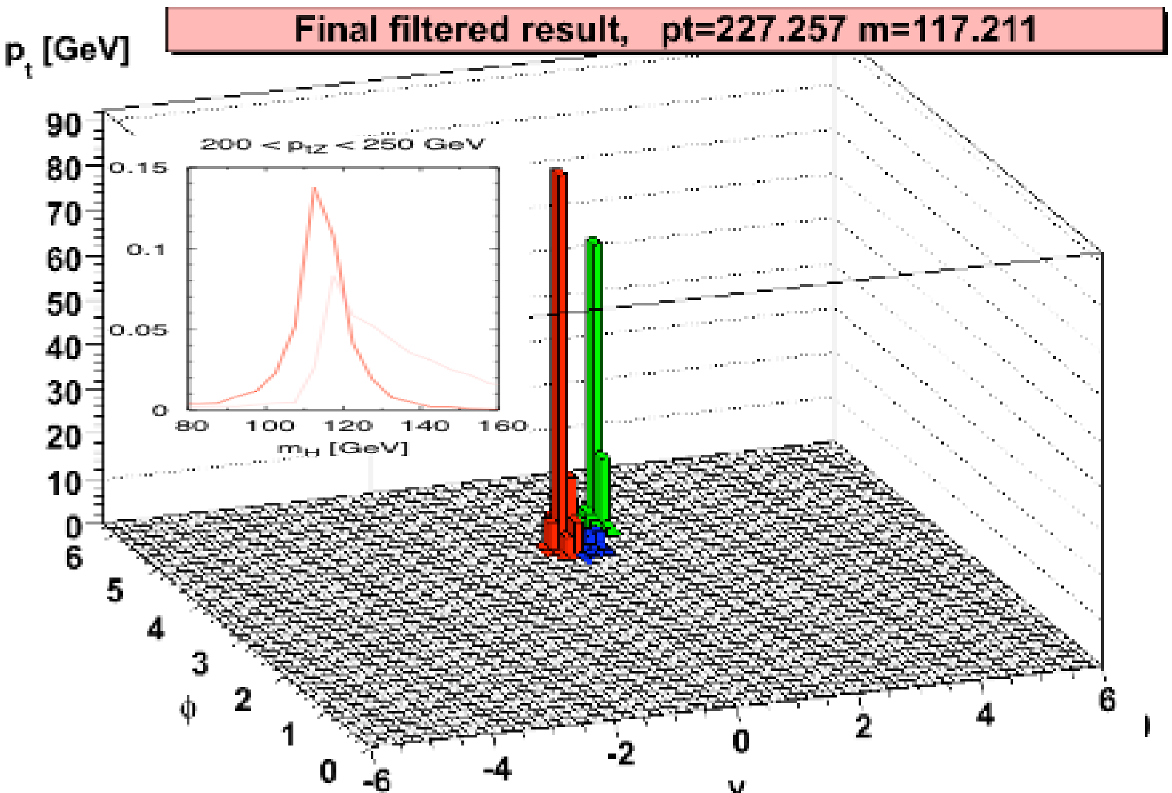


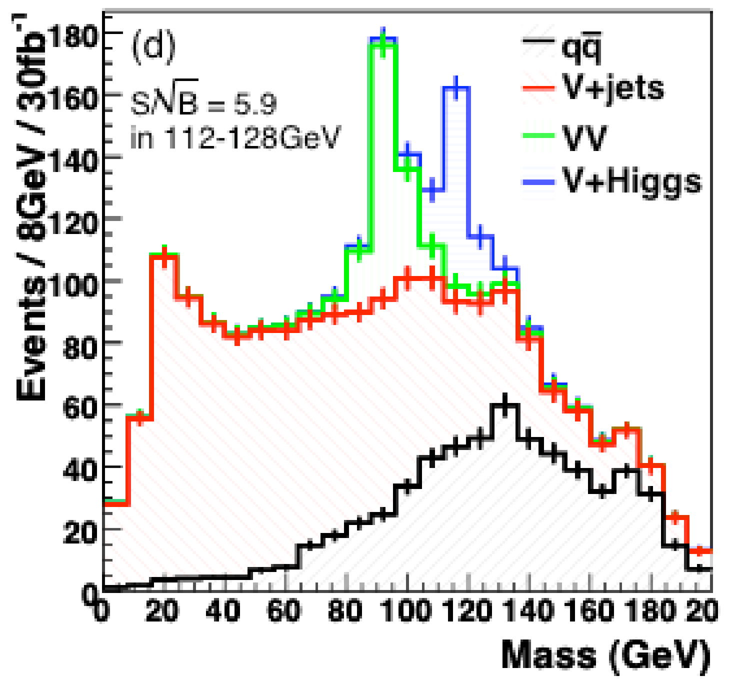




A Boosted Higgs

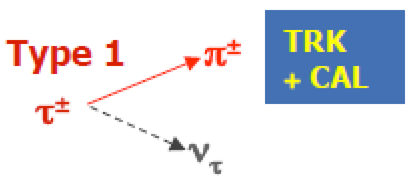




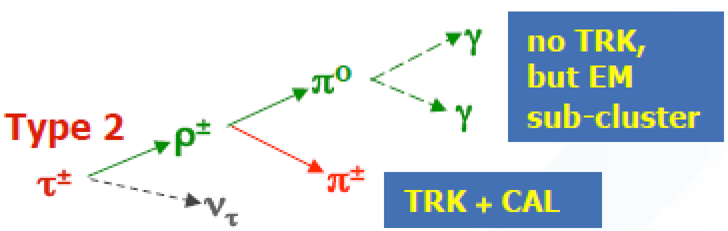


Tau final states

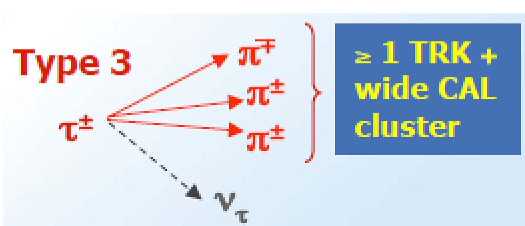
- Hadronic decay of tau
  - 65% of tau decay is hadronic.
  - Tau has long life time ($c\tau$=87 μm)
  - Always associated with neutrino



Br: 11.5 %



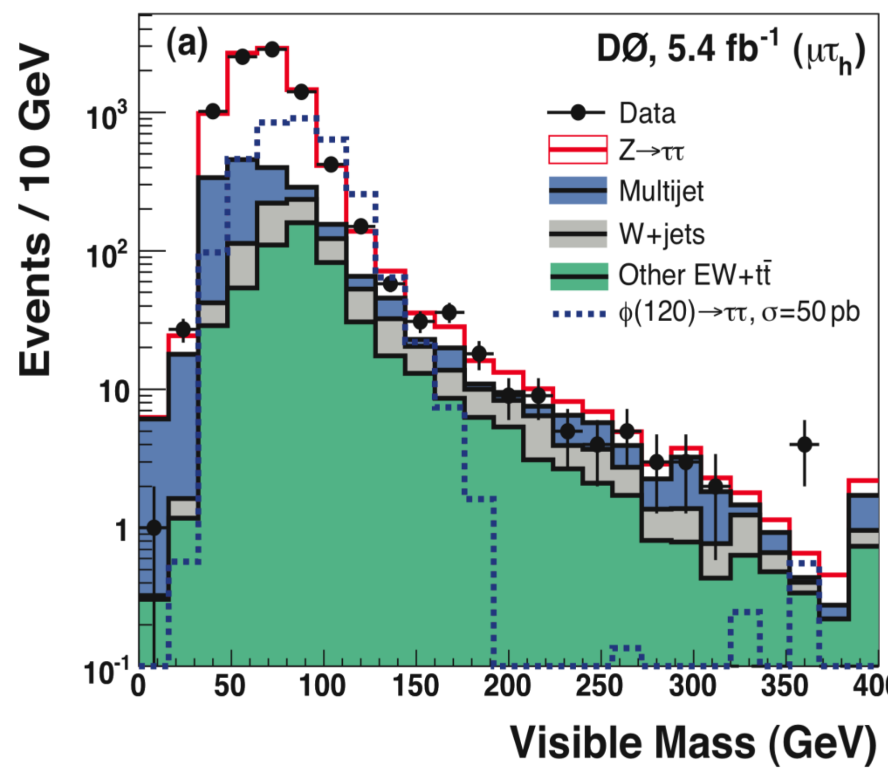
Br: 36.5 %



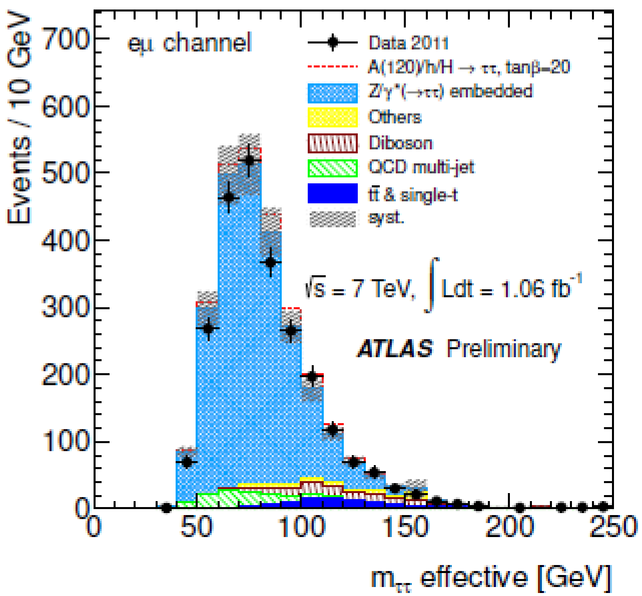
Br: 15 %

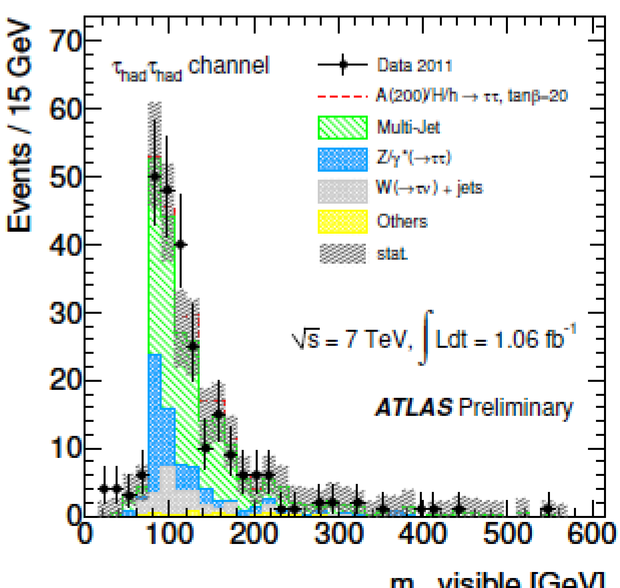
H→ττ

$$M_{VIS} = \sqrt{(P^{\tau 1} + P^{\tau 2} + \not{P}_T)^2}$$

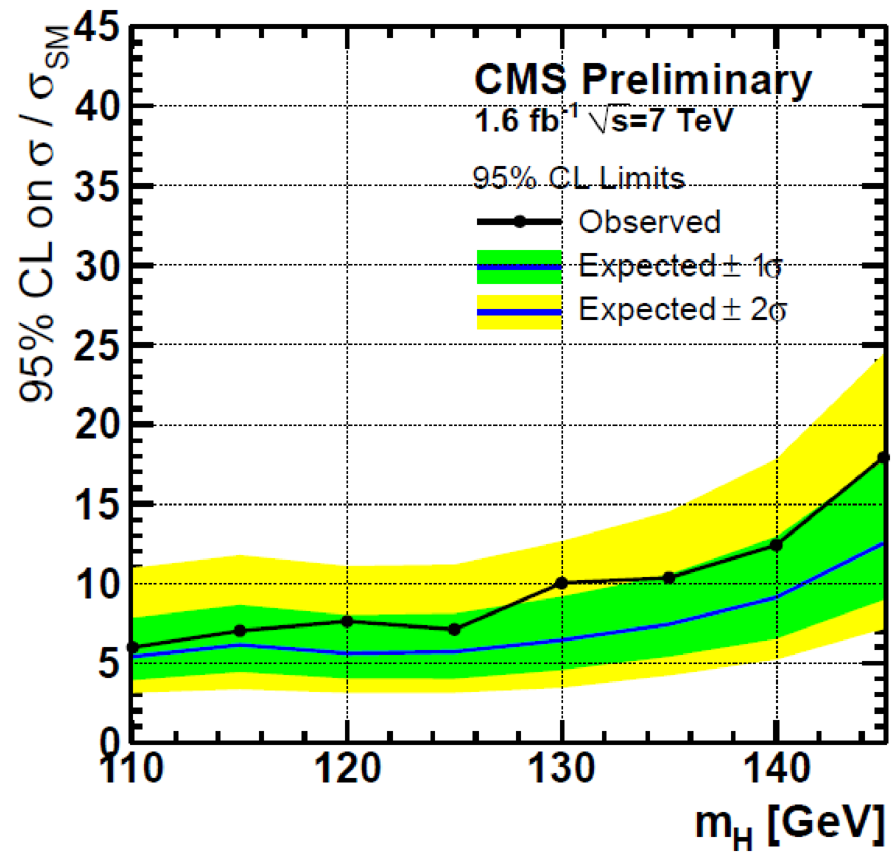


Tau final states





- In Higgs search, e-μ and both tau decay into hadronic mode are included.
  - Tau tau mode is very important channel for MSSM higgs.

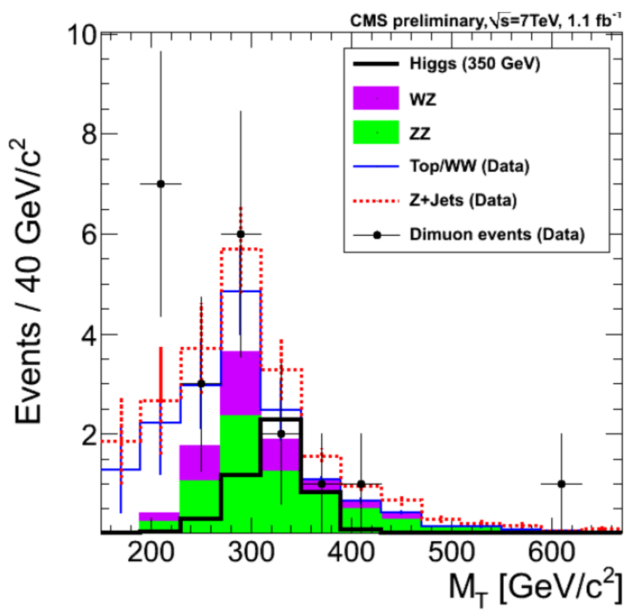


H→ZZ

- Discovery channel for high mass
  - Non negligible contribution to low mass

l: electron or muon.
Br(Z→ll) = 3.3% (each, ee + μμ = 6.6%)
Br(Z→νν) = 20 %
Br(Z→jj) = 70%

- 3 major modes
  - Z→ll, Z→ll
    - Small signal yields, but extremely clean
    - 4e, 4μ, 2e+2μ channel
    - One of Z allows to be off-shell.
    - pT>4 GeV for lowest lepton
  - Z→ll, Z→νν
    - Larger signal yields, clean
  - Z→ll, Z→jj
    - Largest signal yield, large background



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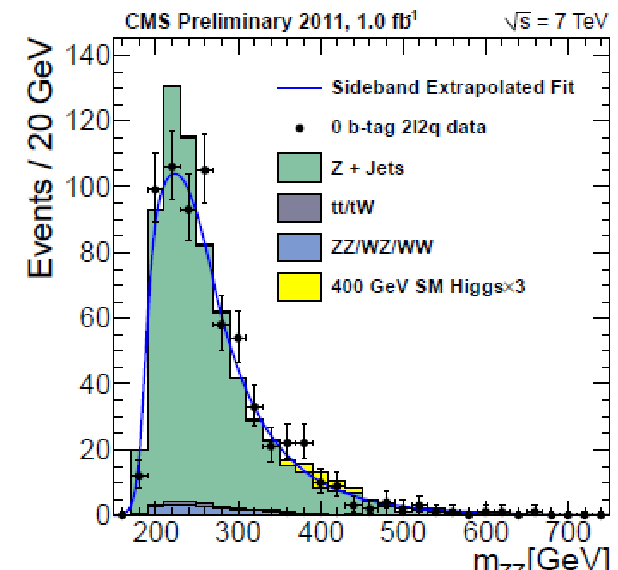
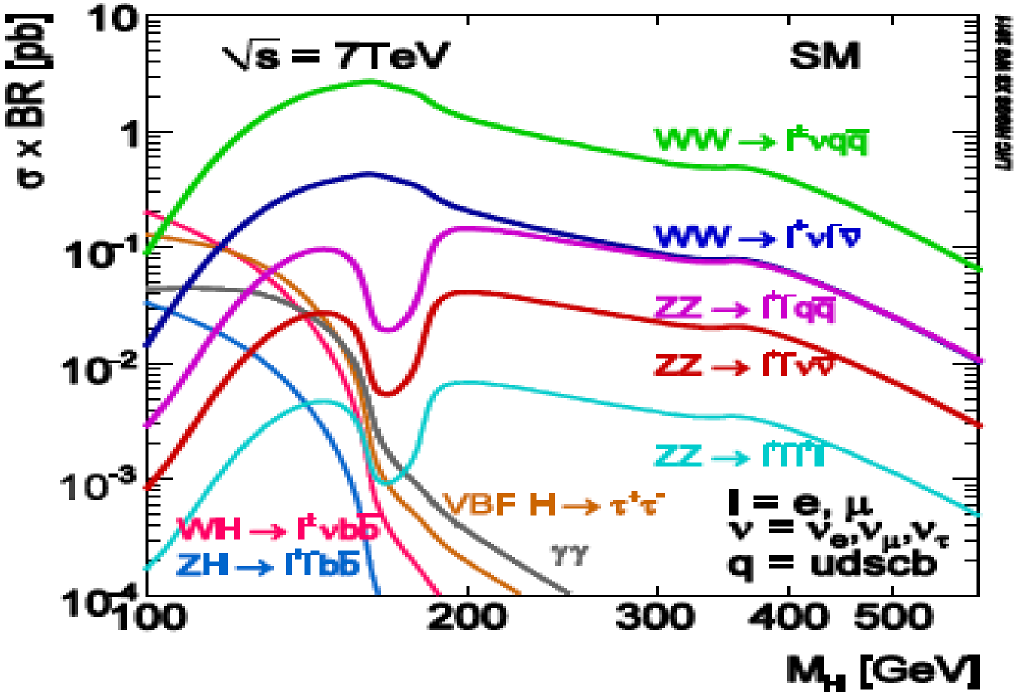


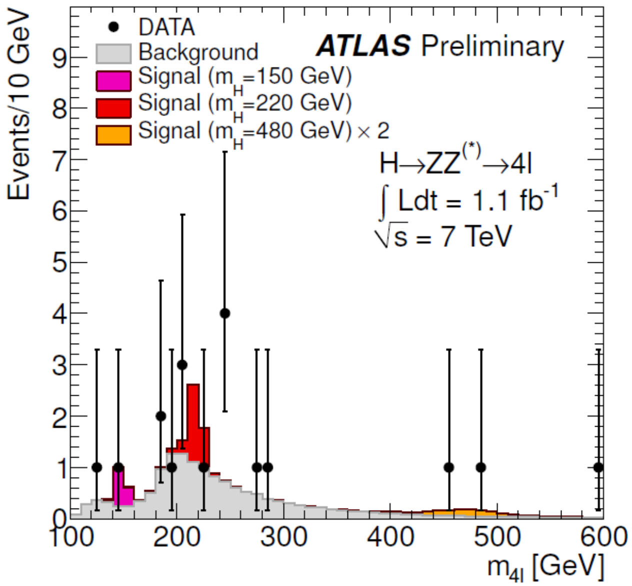
Cross section x Branching ratio

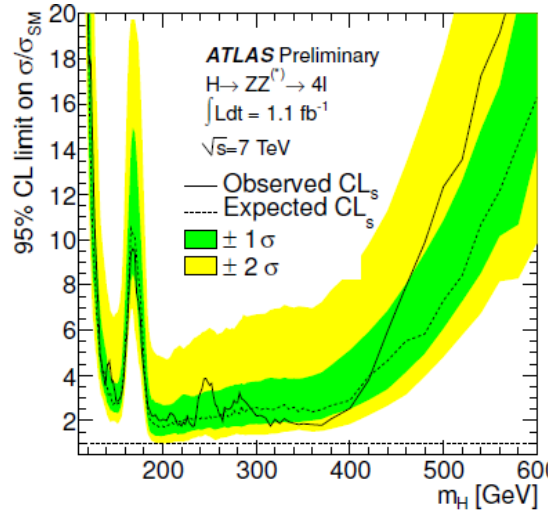


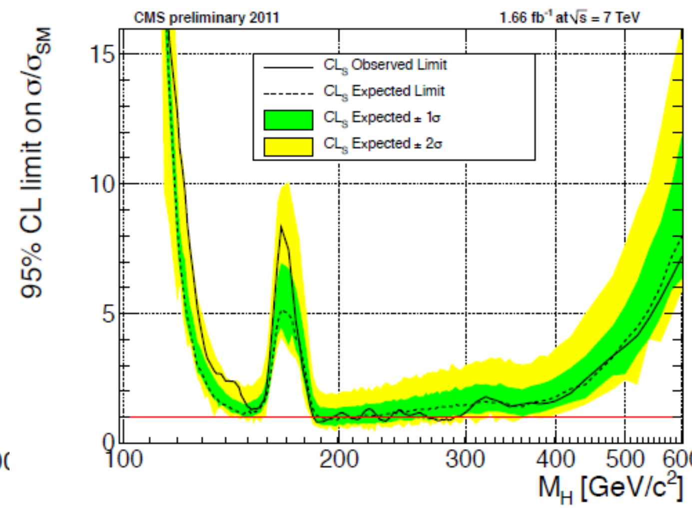
- Control Multi-Jet (MJ) background is key point
  - Amount of MJ depends on number of lepton and resonance.

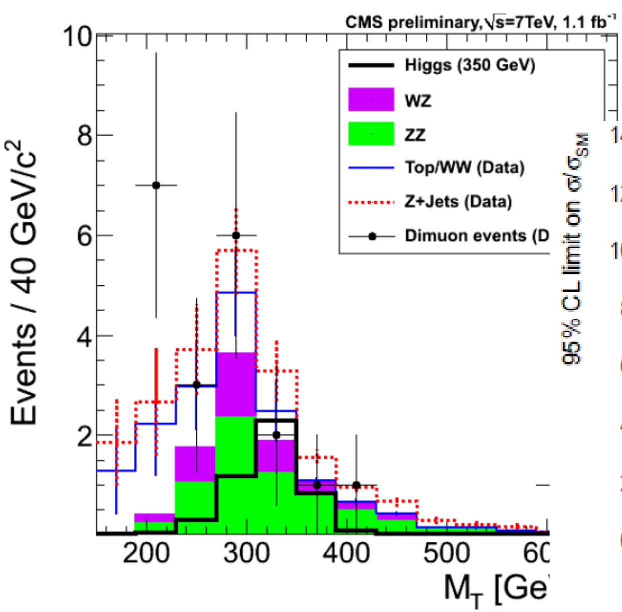
  jjjj >> vvjj > lvjj > lvbb > lljj ~ γγ > lvlv > llvv > llll
  - l: electron or muon
  - Photon channel has different story
  - Tau channels has also different story
-

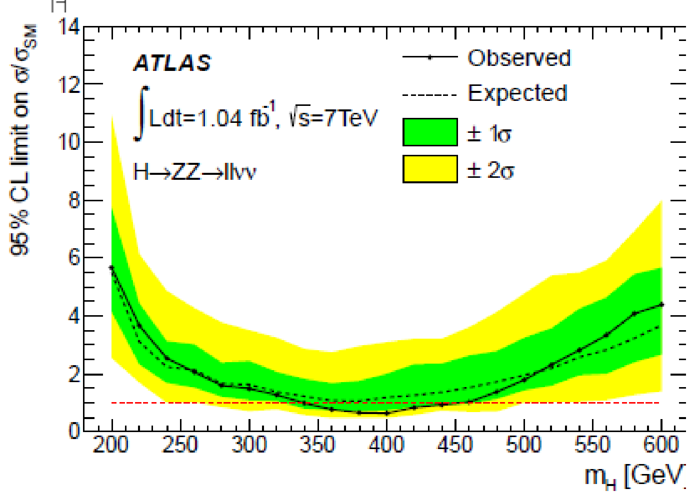
H→ZZ

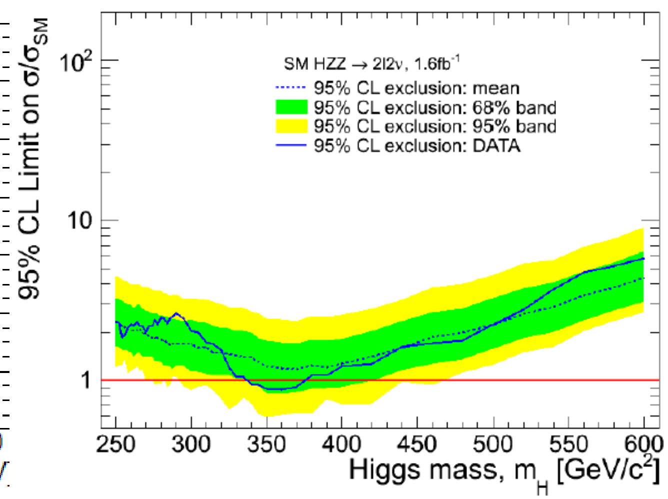

DATA
Background
Signal (m_H=150 GeV)
Signal (m_H=220 GeV)
Signal (m_H=480 GeV) × 2
ATLAS Preliminary
$H \to ZZ^{(*)} \to 4l$
$\int Ldt = 1.1\ fb^{-1}$
$\sqrt{s}$ = 7 TeV
Events/10 GeV
m_{4l} [GeV]


ATLAS Preliminary
$H \to ZZ^{(*)} \to 4l$
$\int Ldt = 1.1\ fb^{-1}$
$\sqrt{s}$=7 TeV
Observed CL_s
Expected CL_s
± 1σ
± 2 σ
95% CL limit on σ/σ_{SM}
m_H [GeV]


CMS preliminary 2011
1.66 fb^{-1} at $\sqrt{s}$ = 7 TeV
CL_s Observed Limit
CL_s Expected Limit
CL_s Expected ± 1σ
CL_s Expected ± 2σ
95% CL limit on σ/σ_{SM}
M_H [GeV/c^2]

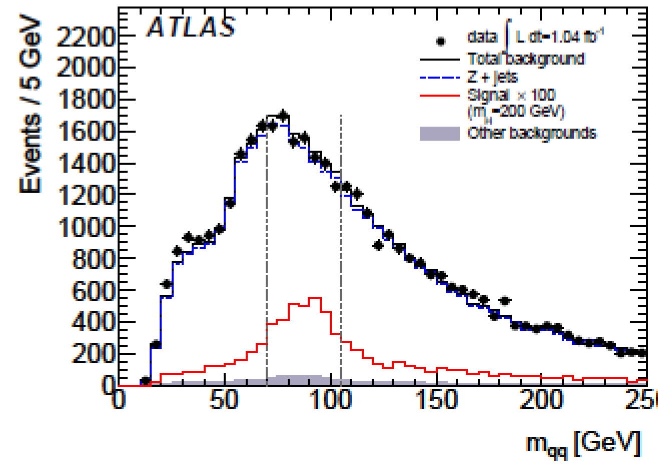

CMS preliminary, $\sqrt{s}$=7TeV, 1.1 fb^{-1}
Higgs (350 GeV)
WZ
ZZ
Top/WW (Data)
Z+Jets (Data)
Dimuon events (D
Events / 40 GeV/c^2
M_T [Ge

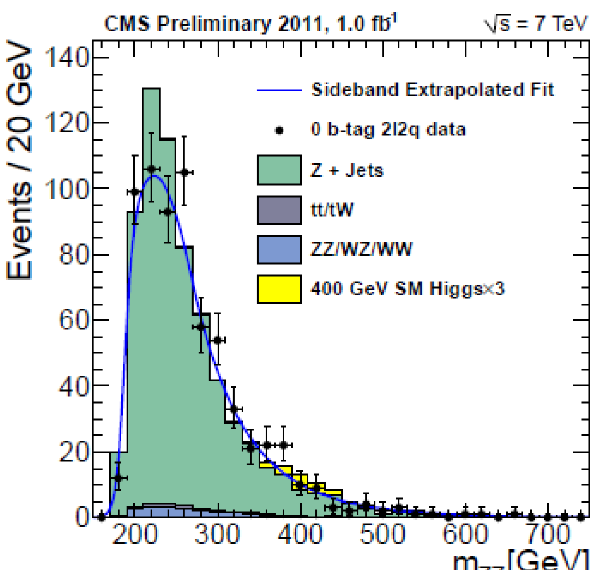

ATLAS
$\int Ldt=1.04\ fb^{-1}$, $\sqrt{s}$=7TeV
$H \to ZZ \to ll\nu\nu$
Observed
Expected
± 1σ
± 2σ
95% CL limit on σ/σ_{SM}
m_H [GeV

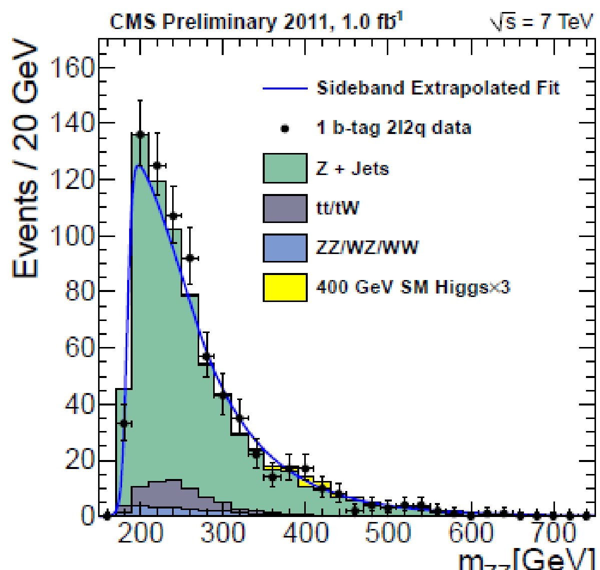

SM HZZ → 2l2ν, 1.6fb^{-1}
95% CL exclusion: mean
95% CL exclusion: 68% band
95% CL exclusion: 95% band
95% CL exclusion: DATA
95% CL Limit on σ/σ_{SM}
Higgs mass, m_H [GeV/c^2]

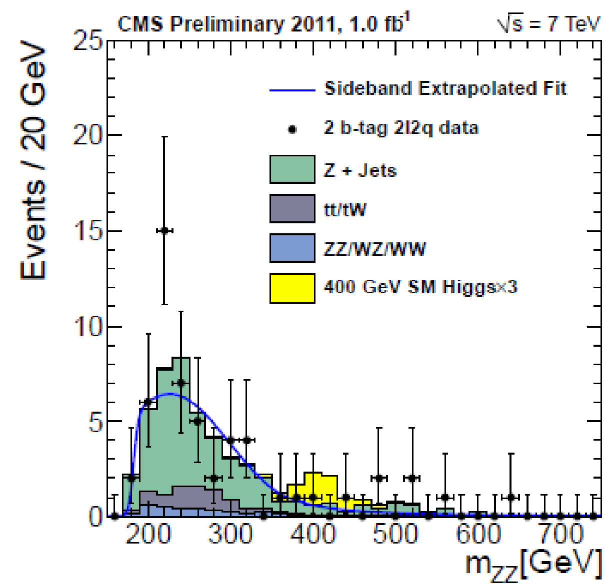
H→ZZ→lljj

- In order to reduce BG,
  - $|m_{ll} - m_Z| < 15$ GeV
  - $70 < mjj < 105$ GeV
    → high mass range only.
- Tighter ID criteria
- Use bID for Z→bb

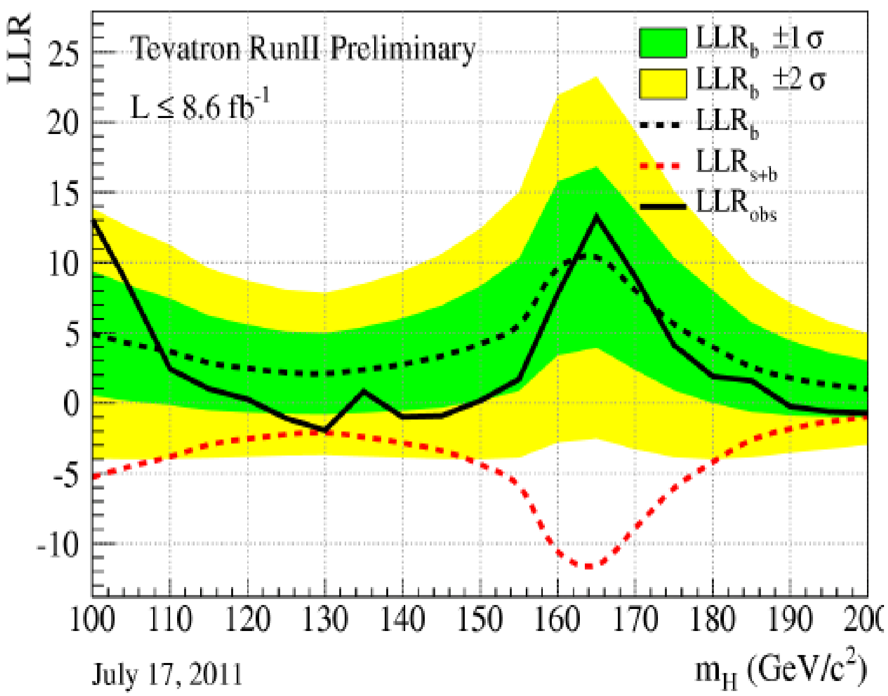


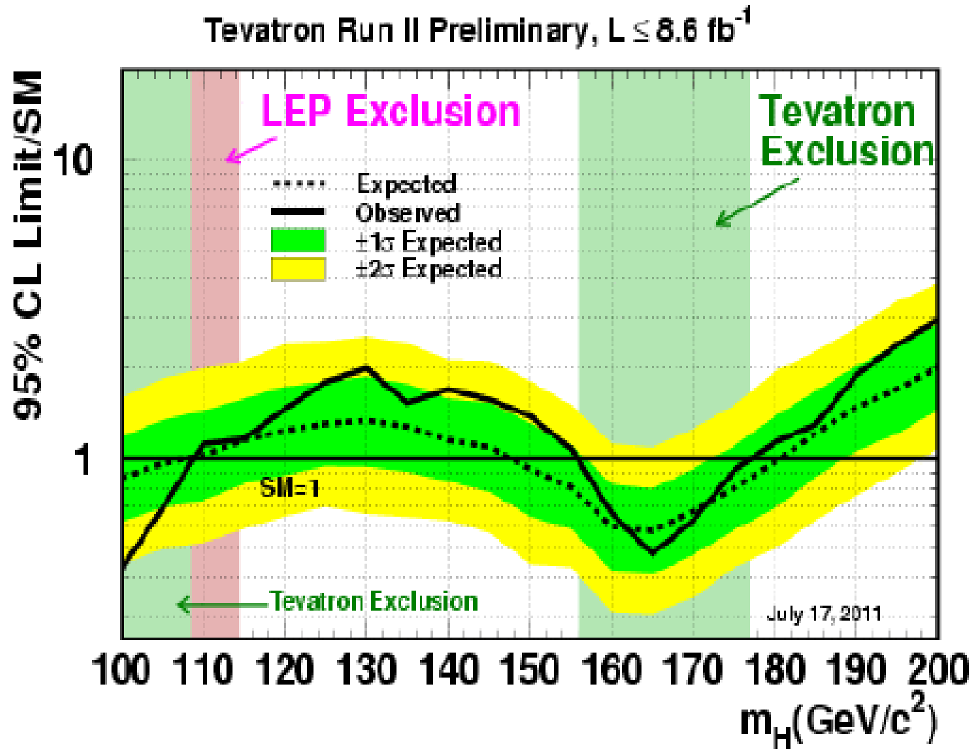






Tevatron Result





- Most signal-like excess
  - Consistent with 130 GeV Higgs

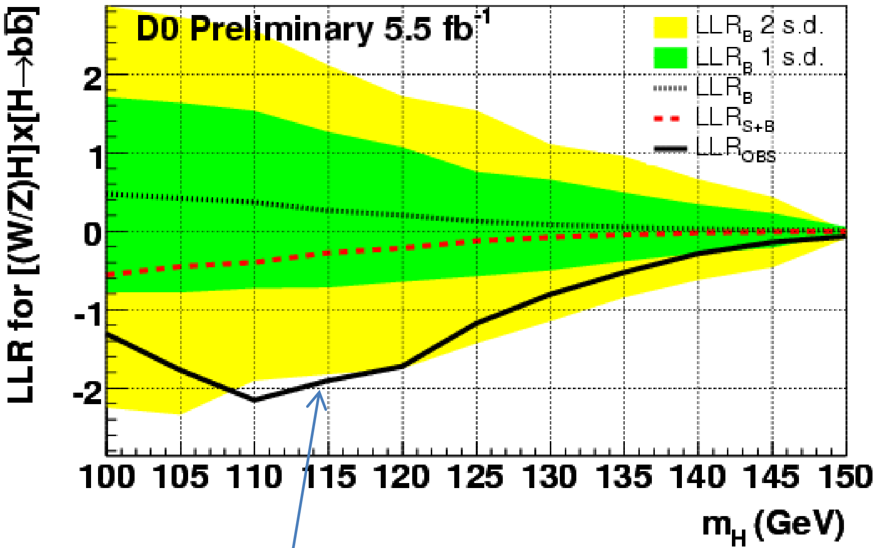
SM Higgs excluded @ 95% C.L.

$156 < m_H < 177$ GeV obs ($148 < m_H < 180$ GeV exp)

$100 < m_H < 108$ GeV obs ($100 < m_H < 109$ GeV exp)

Check on the excess: signal injection

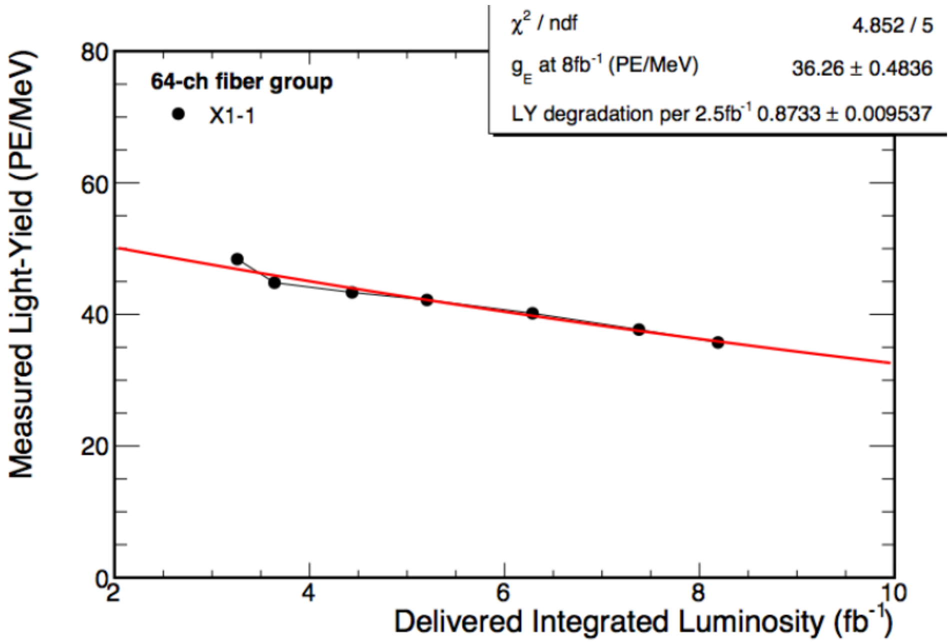
- Inject expected signal event of MH=115 GeV and check how limit curve look like.
- With current luminosity, we suppose to have ~ 1 sigma excess in wide range due to mass resolution.
- Looks consistent what we observe in MH~ 130 GeV.

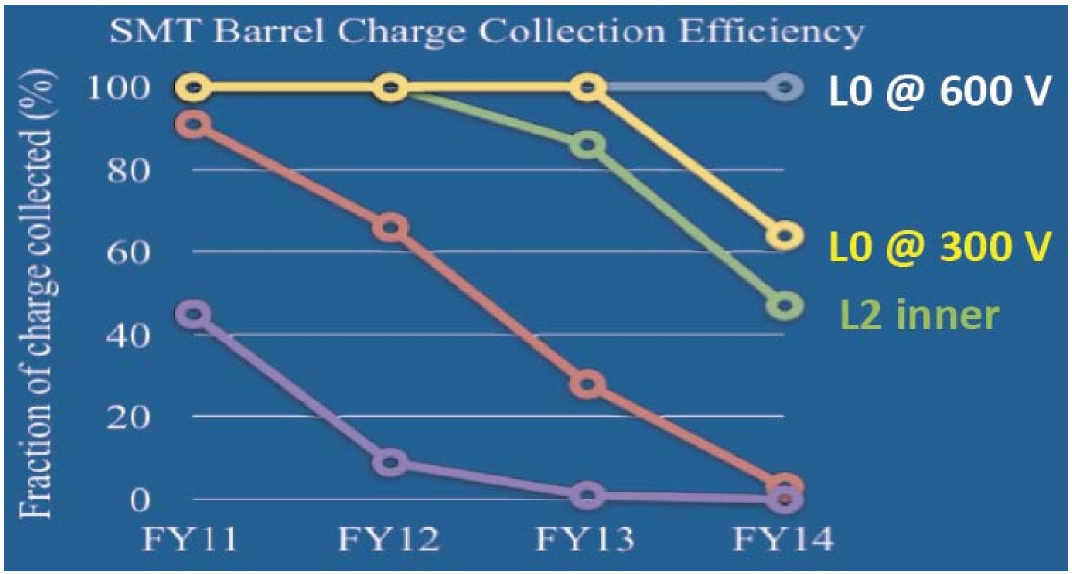


Injected signal of this plot:
ZH→vvbb with scale factor of 4.2

Need to consider degradations

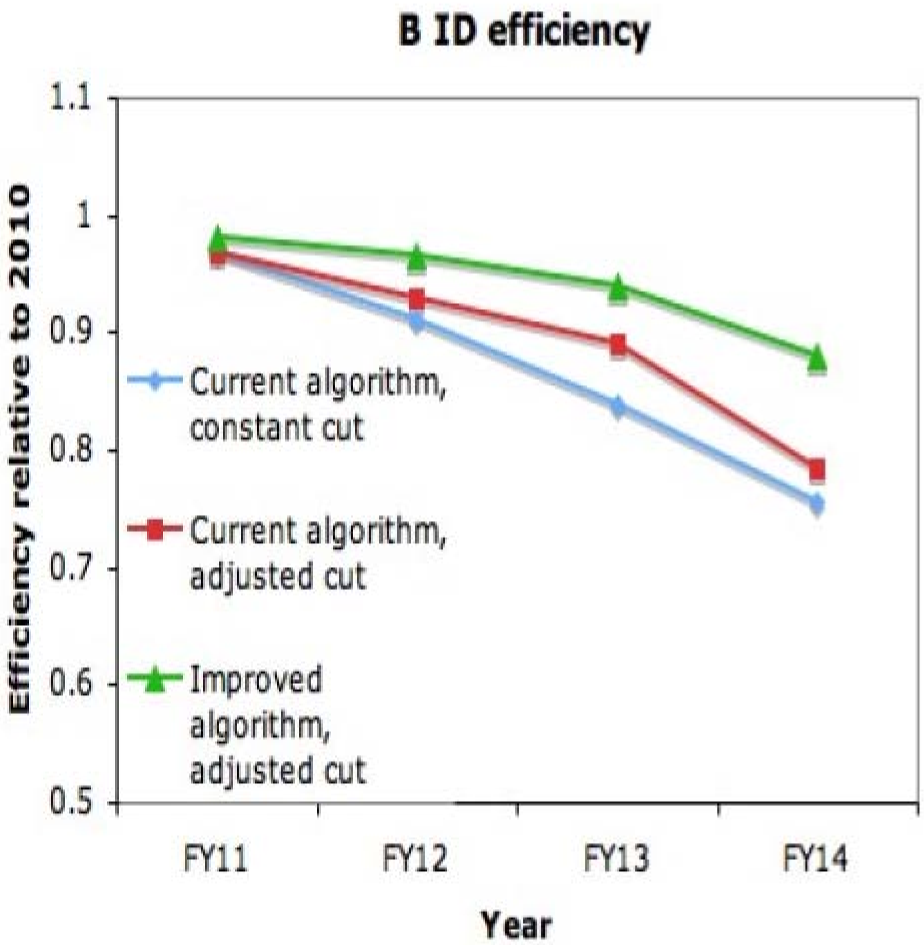
- Dzero Tracker consists from scintillation fibers
- 10% light yield loss per 2.5 fb^{-1} of luminosity.

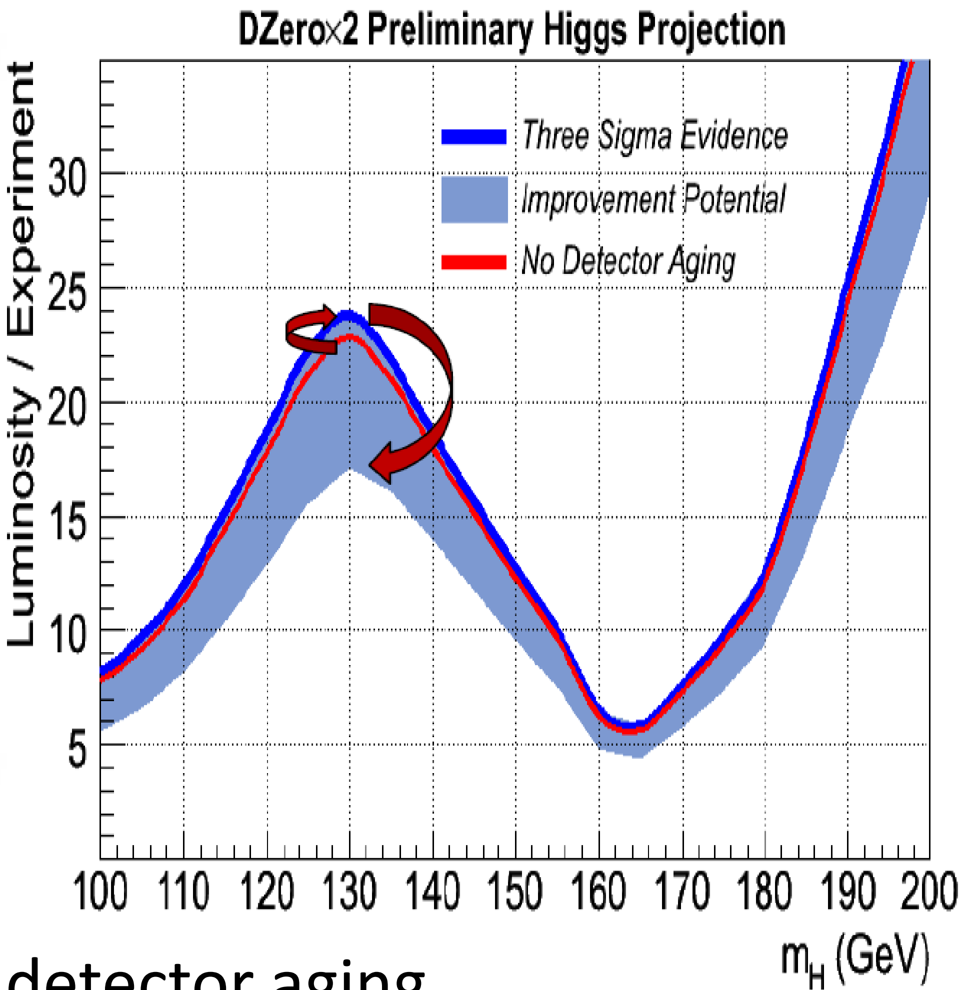




- Silicon detector will reach the limitation on bias voltage in order to compensate gain drop due to radiation.

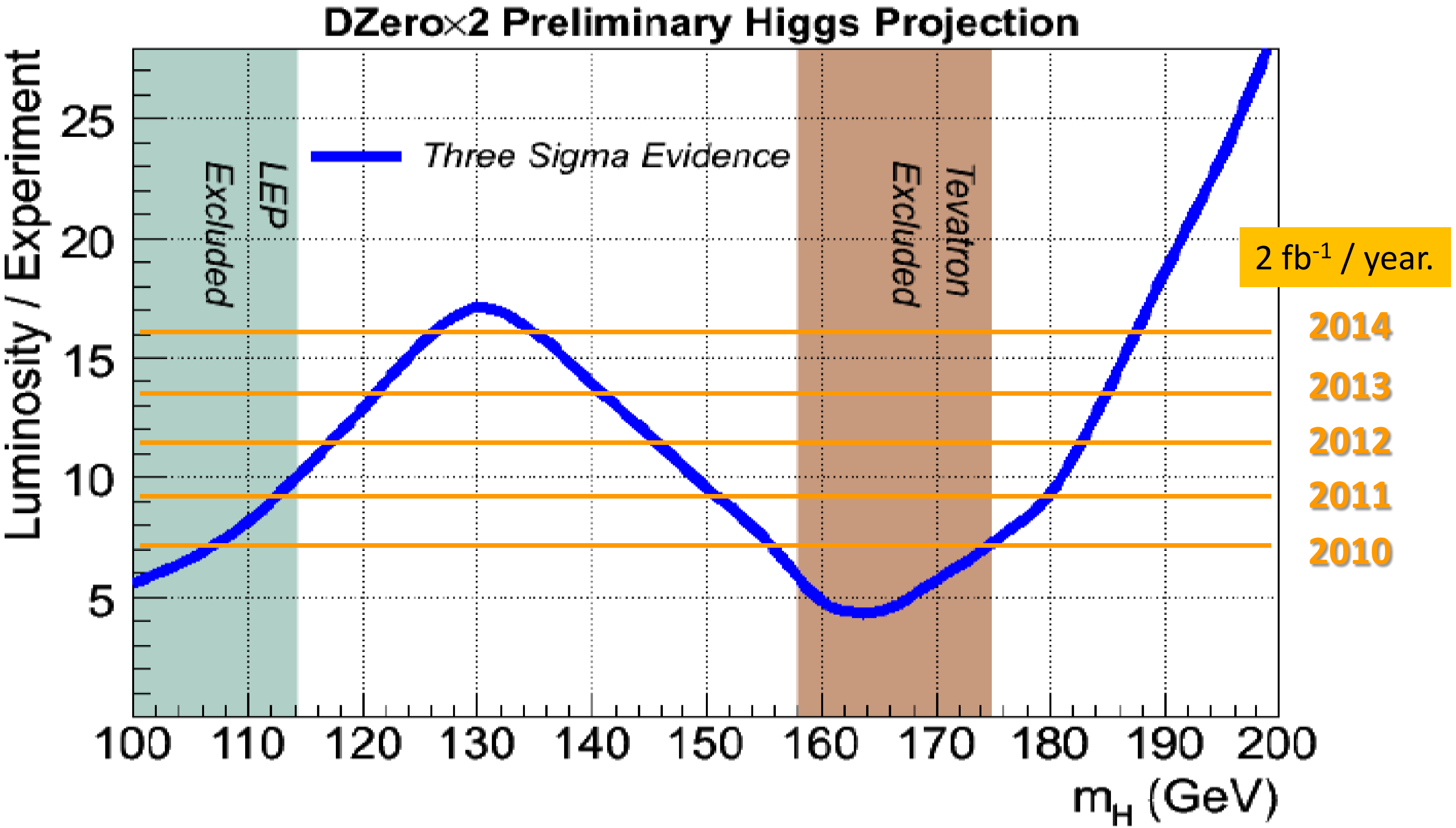
Expected detector aging.





- Reasonable estimation on detector aging
  - Degradation affects only latest dataset.
- Ambitious but achievable improvements is considered.

2 × Dzero on 3σ observation



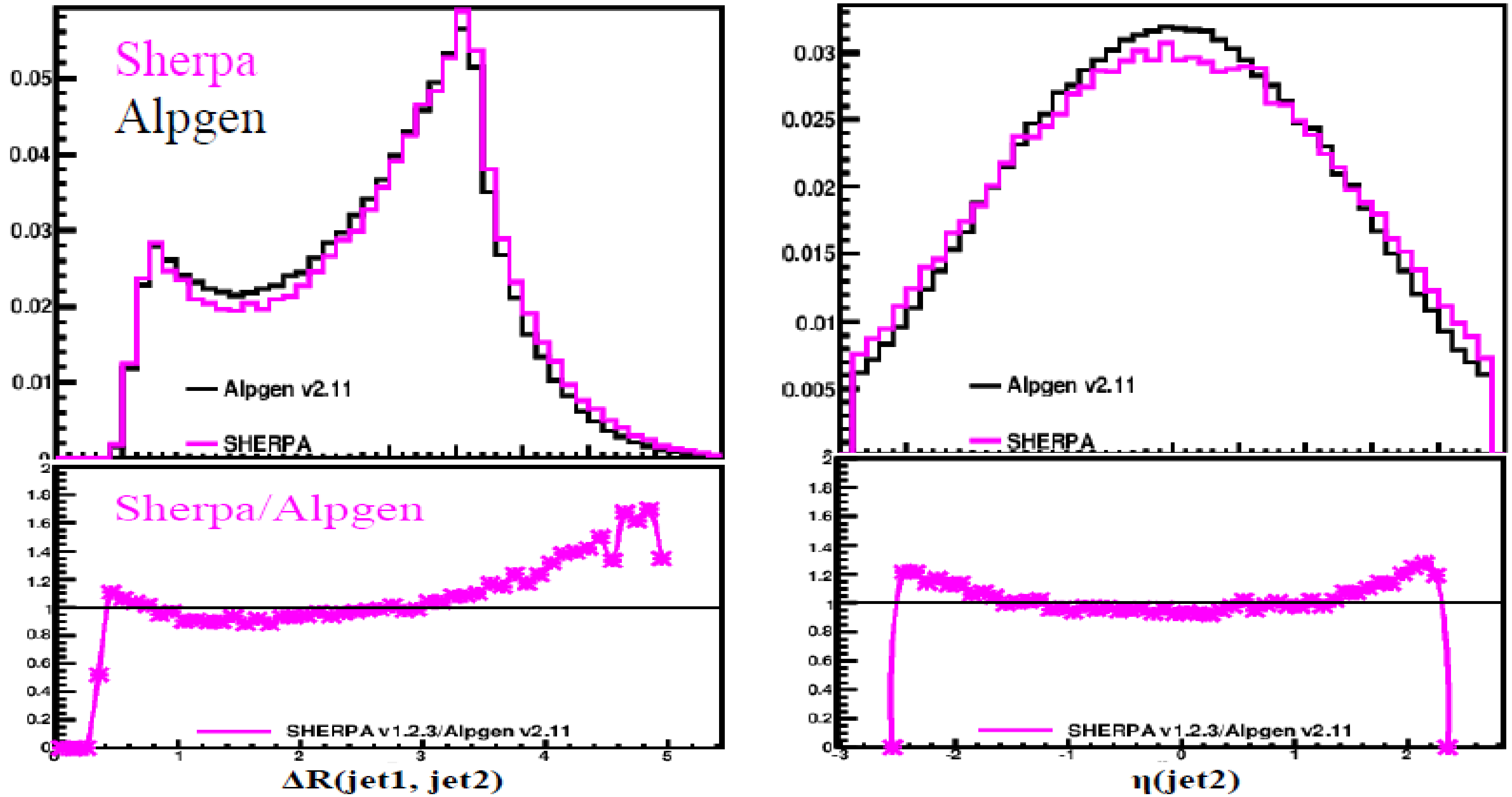
- Required lumi. to make 3σ observation including improvements and detector aging effects.

V+Jets Modeling

- ALPGEN+PYTHIA is used in both CDF and D0.
  - DØ analyses apply reweighting from extracted from data to V+Jets monte carlo.
  - Lepton η, Jet η, angle between jets, W pT

Consistency check between lepton, data epoch, final state, etc..

Plots courtesy of Adam Martin



New feature on DØ b-tagging

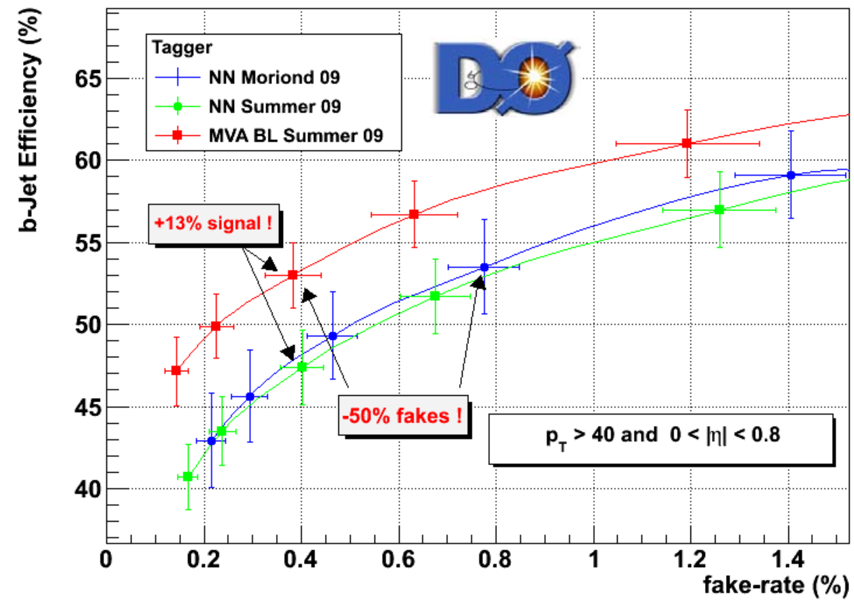
- MVA tagger
  - Better performance
- Modeling
  - Update on TRF, Fake rate measurement
    - Systematic uncertainty reduced by 50% on fake rate.
- Usage
  - Application of TRF
  - Use all operating point.

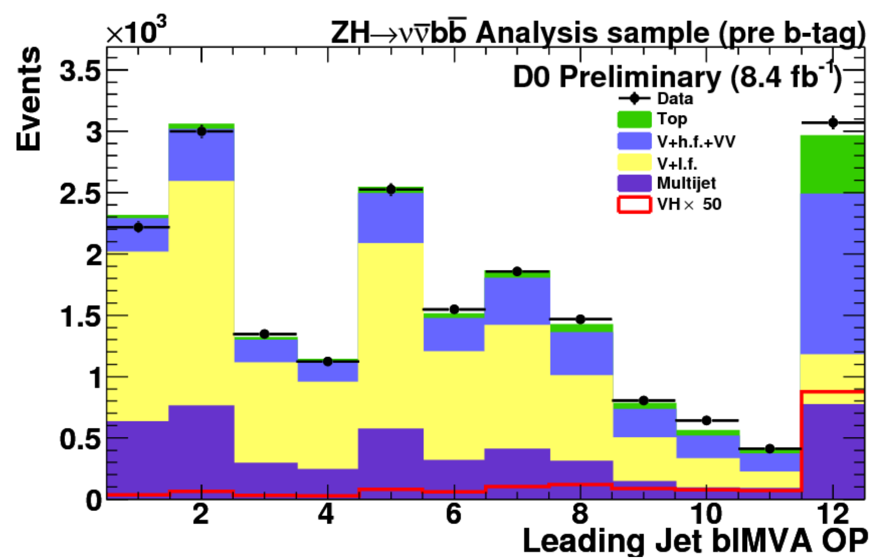
  Use shape of bID MVA output in the final MVA

Two orthogonal sample

2 b-tag: both jet pass Loosest tag

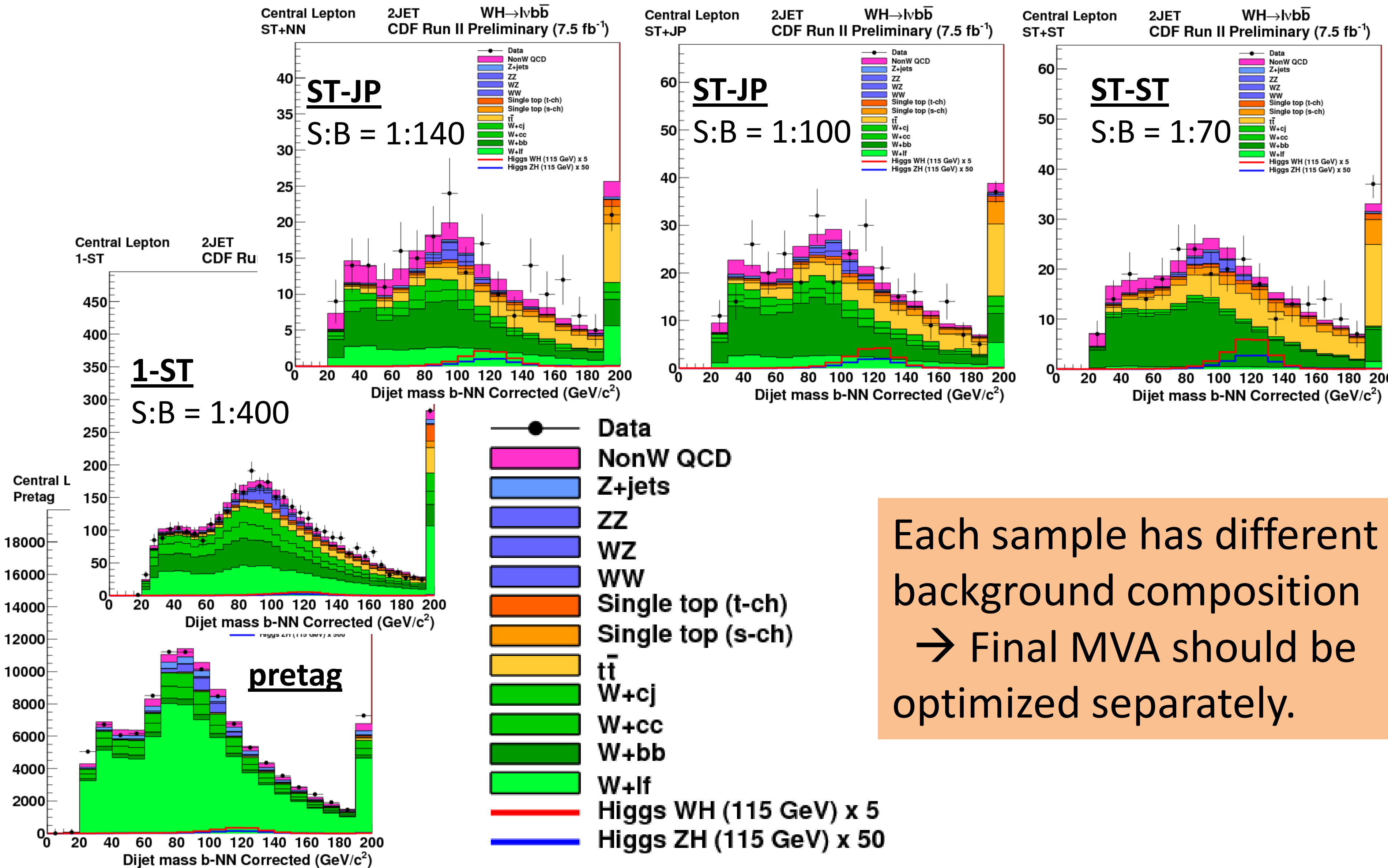
1 b-tag: one of jet pass Loosest tag





bID usage in CDF analysis

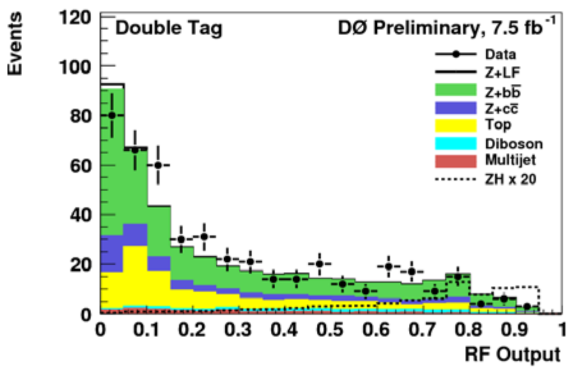
- Four orthogonal b-tagged sample

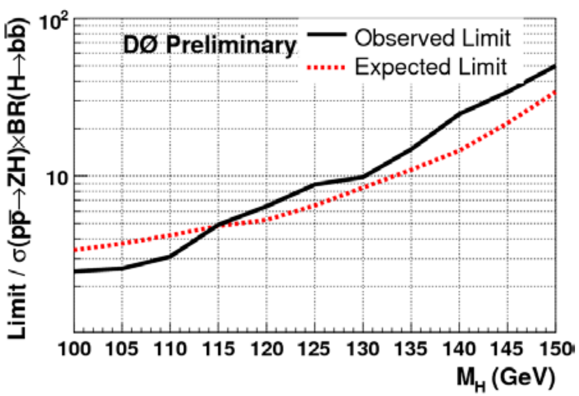


Each sample has different background composition
→ Final MVA should be optimized separately.

Results from DØ

ZH→llbb̄ ∫L*dt*=8.6 fb^{-1}



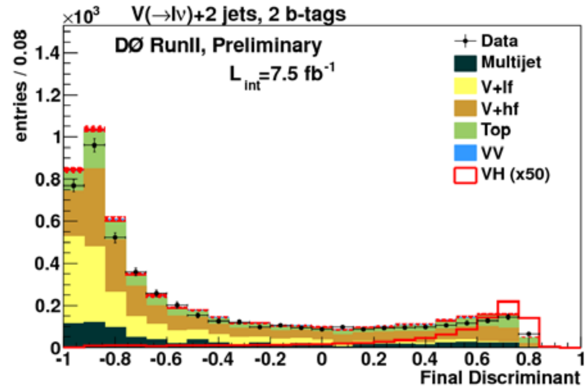


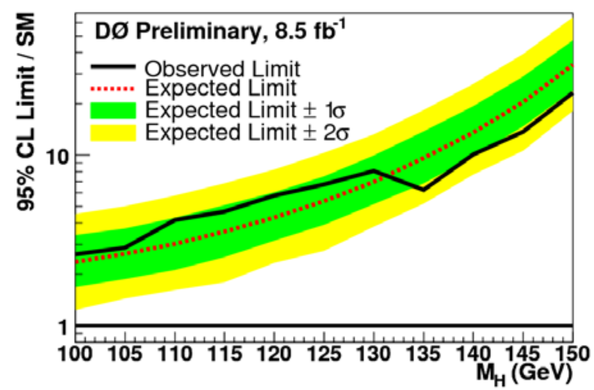
95% CL Exp (obs) Limit

4.8 (**4.9**) x SM

@ MH=115 GeV

WH→lνbb̄ ∫L*dt*=8.5 fb^{-1}



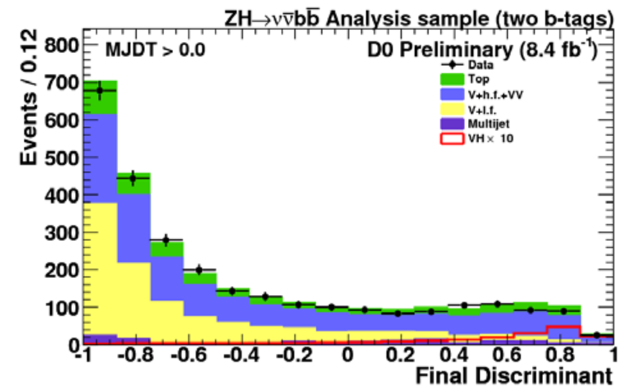


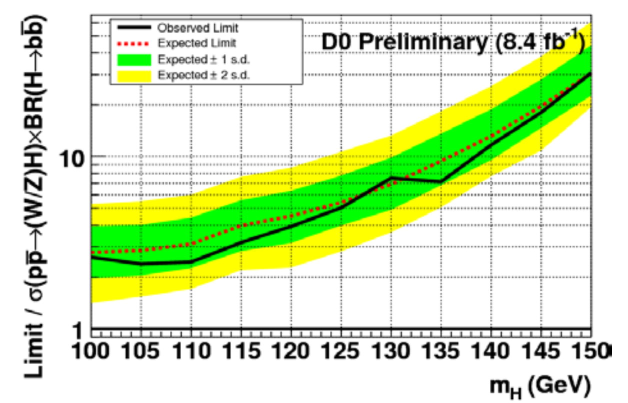
95% CL Exp (obs) Limit

3.5 (**4.6**) x SM

@ MH=115 GeV

VH→ννbb̄ ∫L*dt*=8.4 fb^{-1}





95% CL Exp (obs) Limit

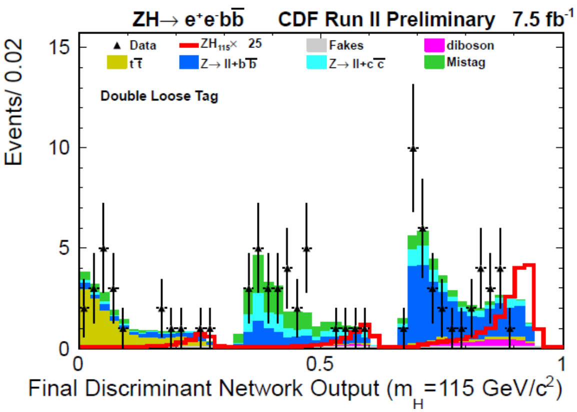
4.0 (**3.2**) x SM

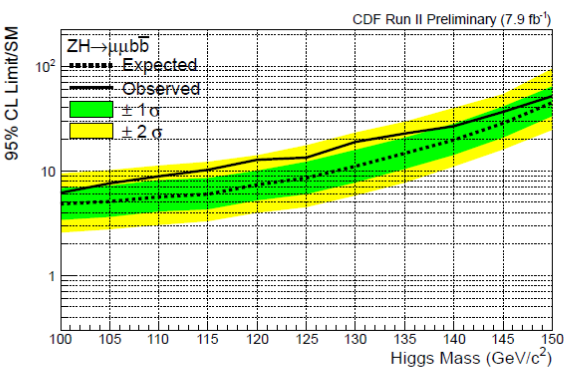
@ MH=115 GeV

10% gain on top of Lumi

Results from CDF

ZH→llb$\bar{b}$ ∫L*dt*=7.9 fb^{-1}





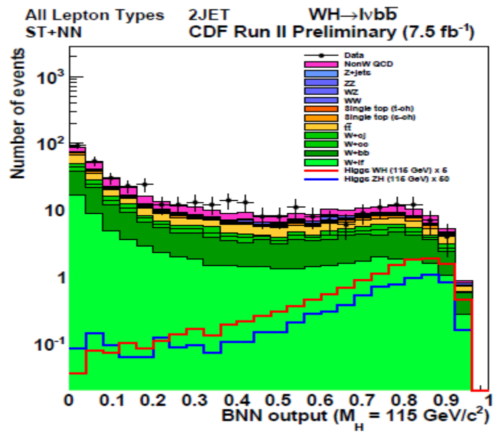
95% CL Exp (obs) Limit

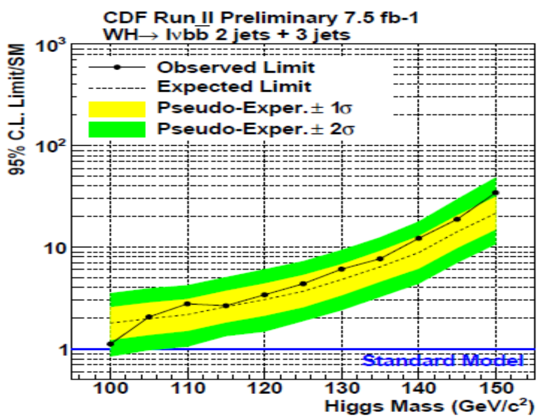
3.9 (4.8) x SM

@ MH=115 GeV

20% gain on top of Lumi

WH→lνb$\bar{b}$ ∫L*dt*=7.5 fb^{-1}





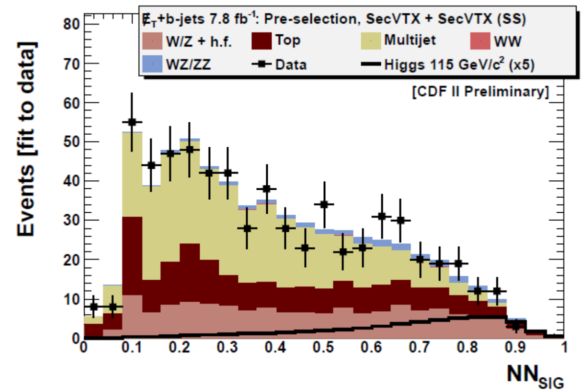
95% CL Exp (obs) Limit

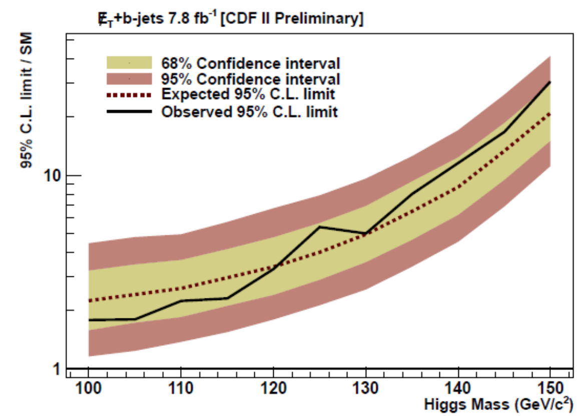
2.7 (2.6) x SM

@ MH=115 GeV

13% gain on top of Lumi

VH→ννb$\bar{b}$ ∫L*dt*=7.8 fb^{-1}





95% CL Exp (obs) Limit

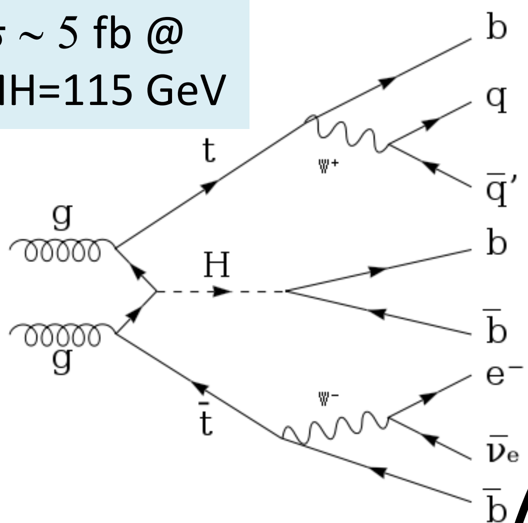
2.9 (2.3) x SM

@ MH=115 GeV

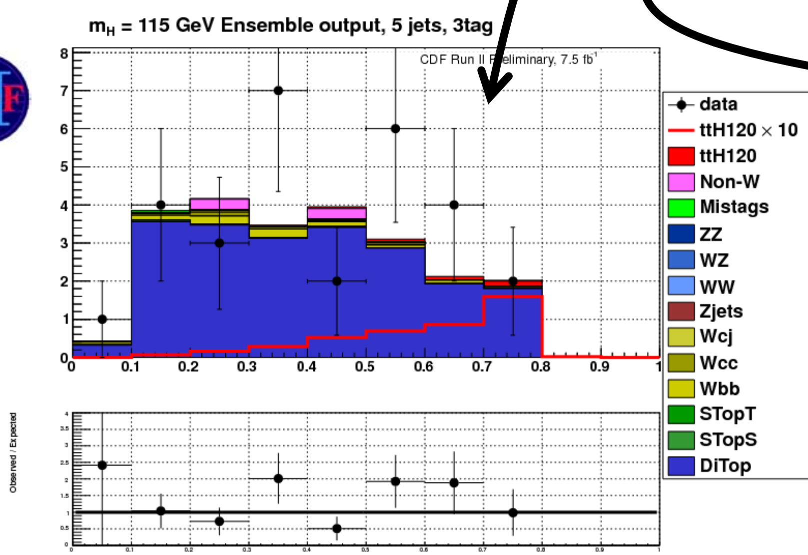
18% gain on top of Lumi

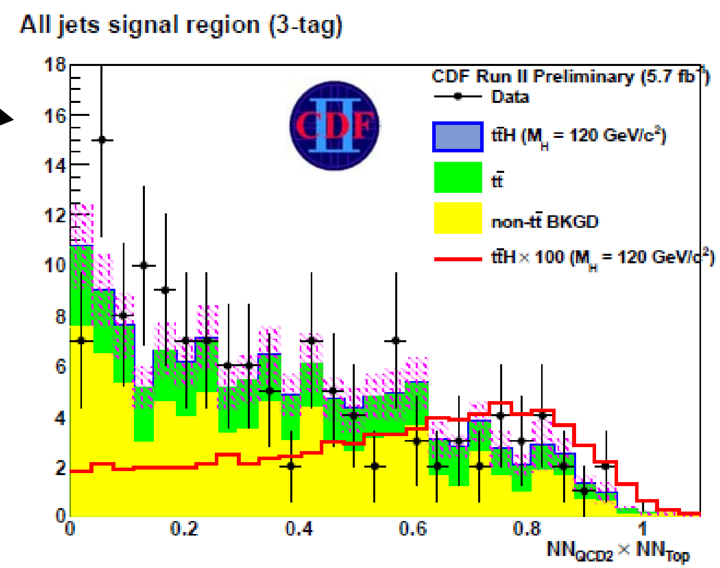
Search for ttH production

σ ~ 5 fb @
MH=115 GeV



- Search H→bb with ttbar.
- Three modes in t→blν, t→bjj
  - a. Lepton+jets + H→bb: l+MET+jets
  - b. { ~~Lepton~~+jets + H→bb: MET+ jets
  - All jets + H→bb : Jets.

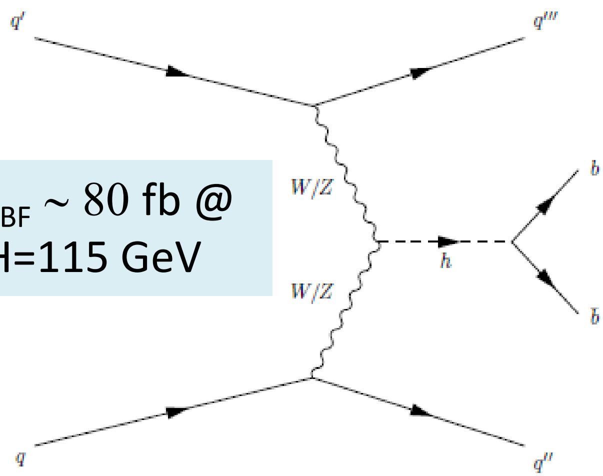




L=7.5 fb^{-1} at MH=115 GeV
exp. = 11.7 x SM, obs = 22.9 x SM

L=5.7 fb^{-1} at MH=115 GeV
exp. = 20.2 x SM, obs = 28.1 x SM

VH and VBF → jjb$\bar{b}$

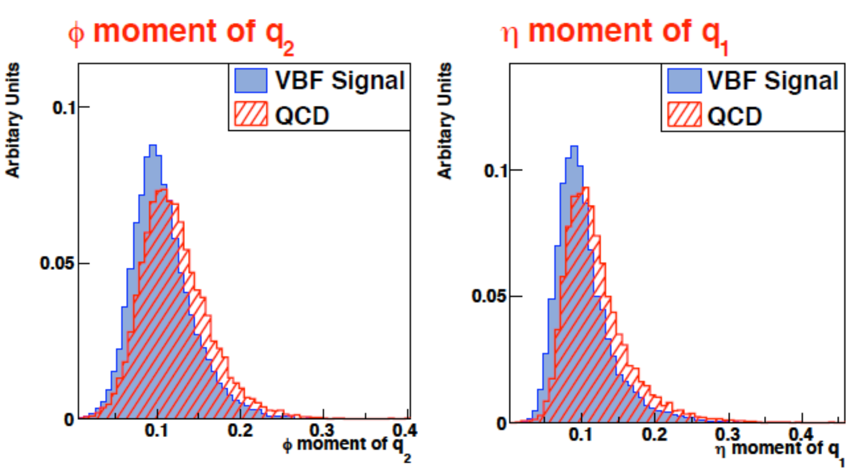


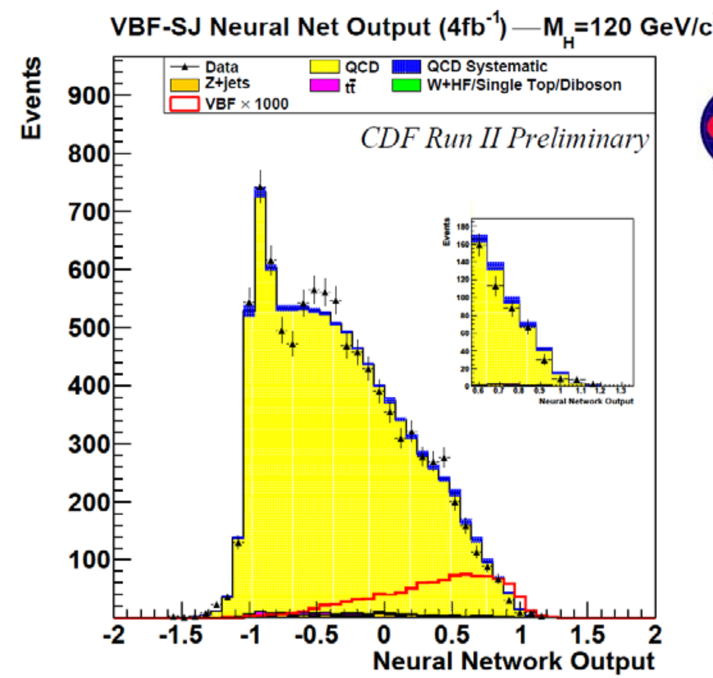
σ_{VBF} ~ 80 fb @ MH=115 GeV

- Other signatures with all jets

  Signature: 4 or 5 Jets with 2 b-tags.
  - VH--> V→jj, H→bb
    50<Mjj<120 GeV
  - VBF→ forward jets + H→bb
    Mjj>120 GeV

- QCD BG is dominant background (98%)
  - Data driven estimation
  - Cross check with side band region
- Use NN with jet shape information

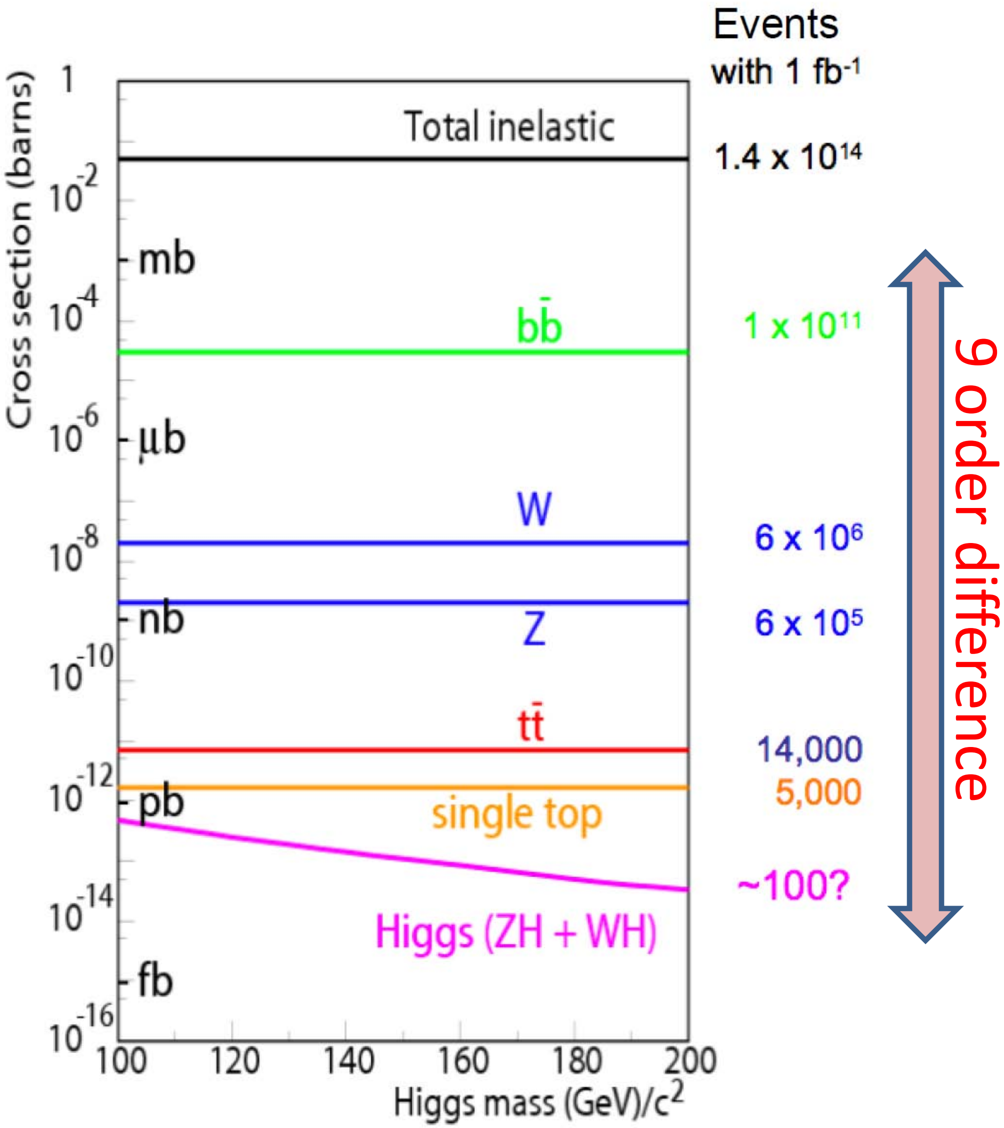




L=4.0 fb^{-1} at MH=115 GeV
exp. = 17.8 x SM, obs = 9.1 x SM

Background and Signal

- Cross section at $\sqrt{s}$ = 1.96 TeV



Background Estimation

Multi-Jet : from data

W+Jet
Z+Jets
ttbar,
} ALPGEN/Pythia

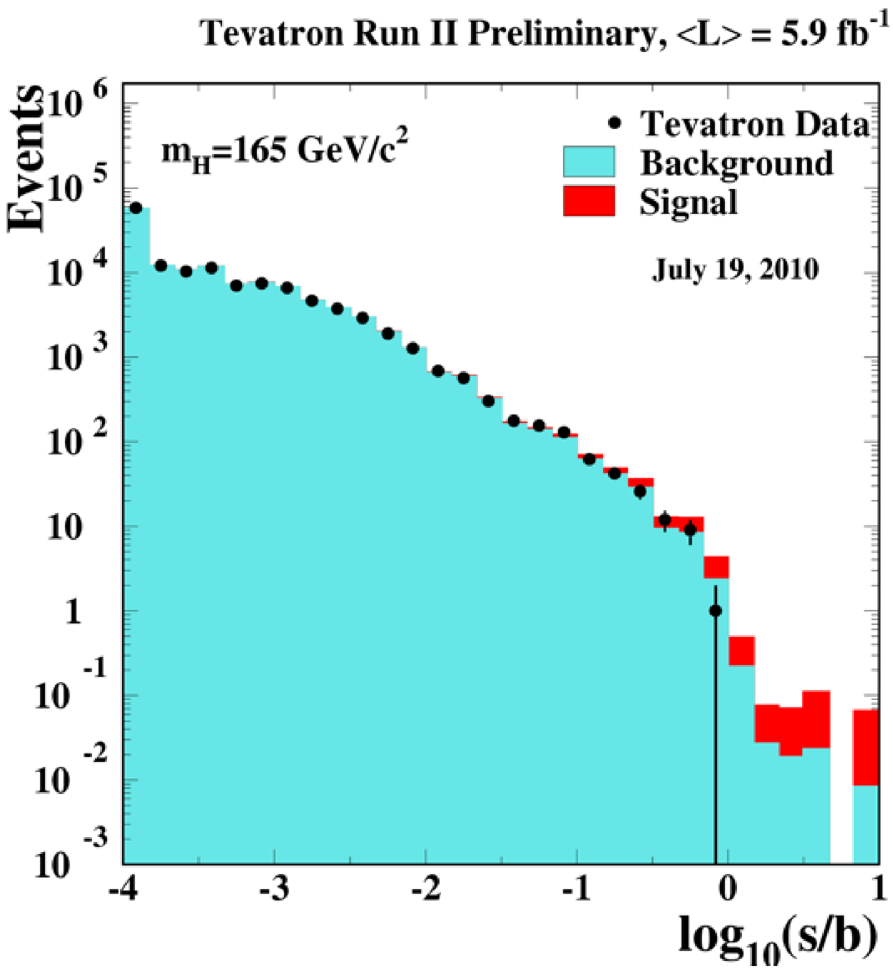
Diboson Pythia

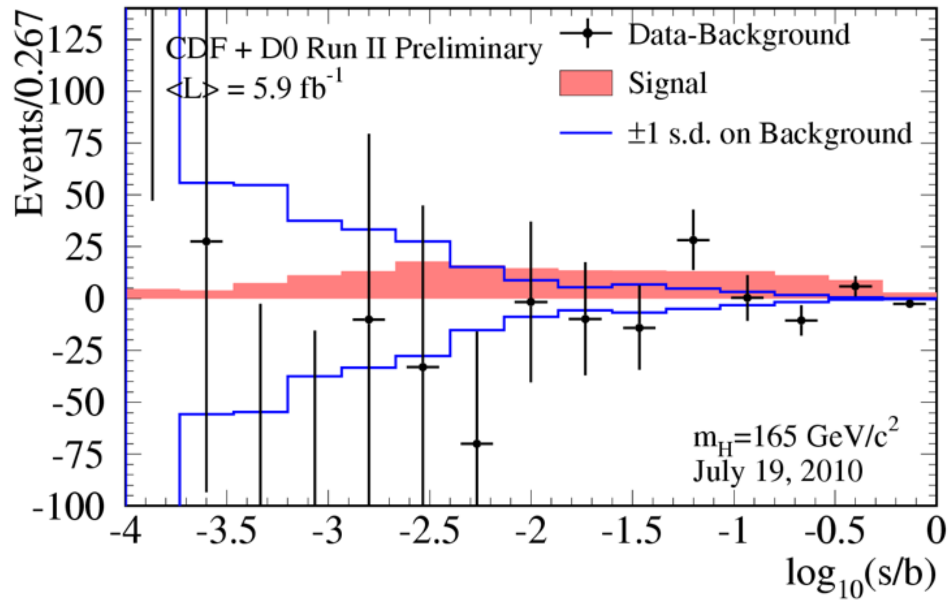
s-top COMPHEP

Signal Estimation

WH/ZH Pythia

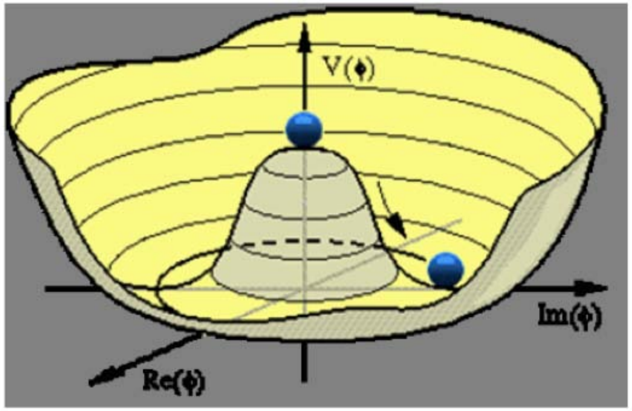
Tevatron combination, cont.





- Inputs are binned histogram (i.e. RF output).
- Sort out by S/B across all channels.

The SM Lagrangian related to Higgs



$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{2} \mathrm{Tr}\left(W_{\lambda\rho} W^{\lambda\rho}\right) \\
& -\frac{1}{4} B_{\lambda\rho} B^{\lambda\rho} \\
& + W_{\lambda}^{+} W^{-\lambda} m_W^2 \left(1 + \frac{H}{v}\right)^2 \\
& + \frac{1}{2} Z_{\lambda} Z^{\lambda} m_Z^2 \left(1 + \frac{H}{v}\right)^2 \\
& + \left\{ \bar{\psi} \frac{i}{2} \gamma^{\lambda} D_{\lambda} \psi + h.c. \right\} \\
& - \bar{\psi} M \psi \left(1 + \frac{H}{v}\right) \\
& + \frac{1}{2} \partial_{\lambda} H \partial^{\lambda} H - \frac{1}{2} m_H^2 H^2 \left[1 + \frac{H}{v} + \frac{1}{4}\left(\frac{H}{v}\right)^2\right]
\end{aligned}
$$

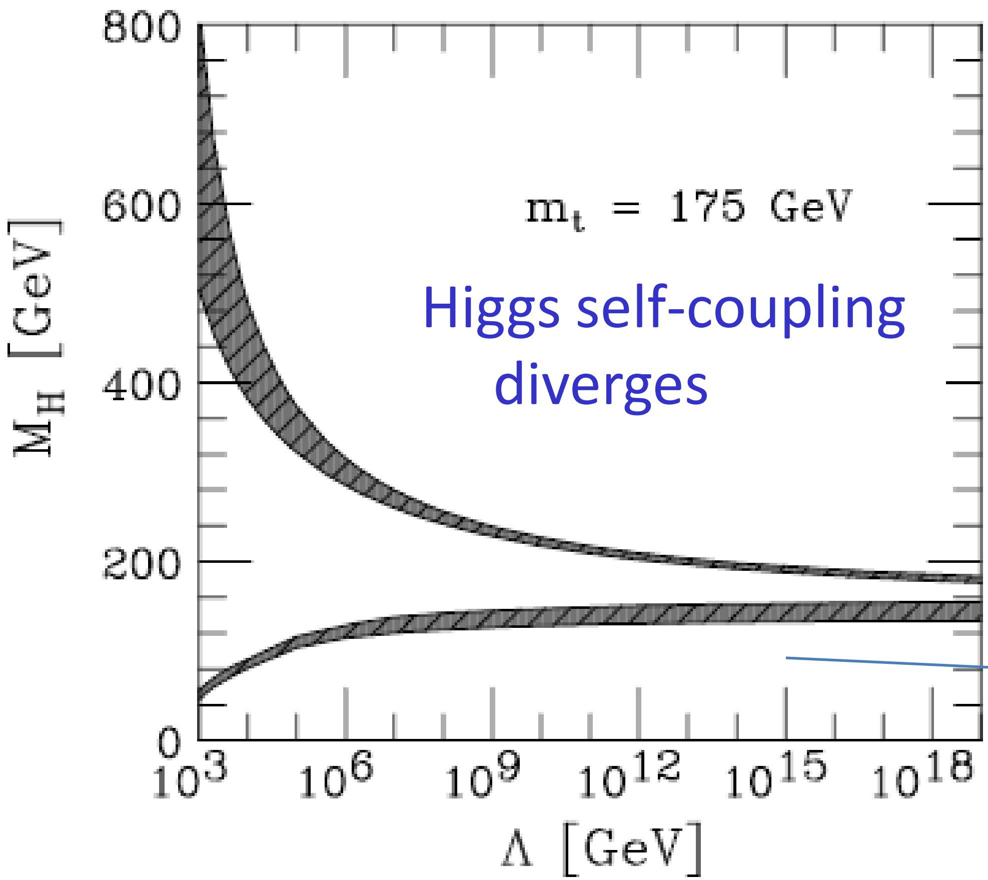
W, Z mass term and coupling to Higgs

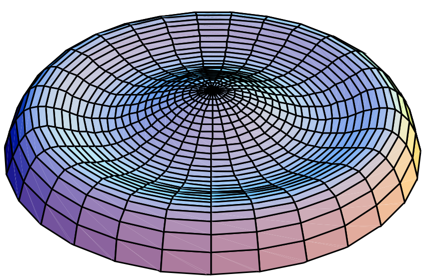
Fermions mass term and coupling to Higgs

Dynamic term and Higgs self coupling

Constraints on Higgs Mass

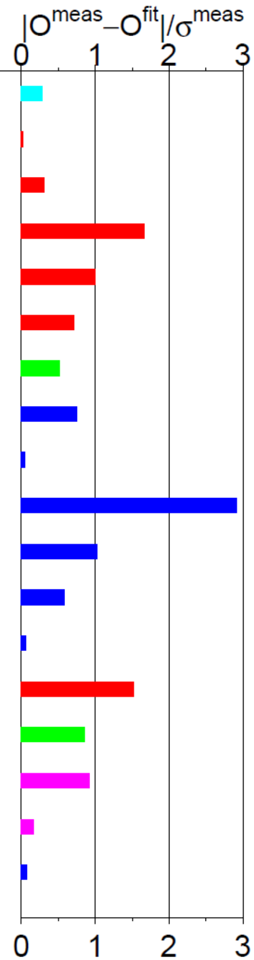
- Higgs Mass is a parameter, but there are boundary.



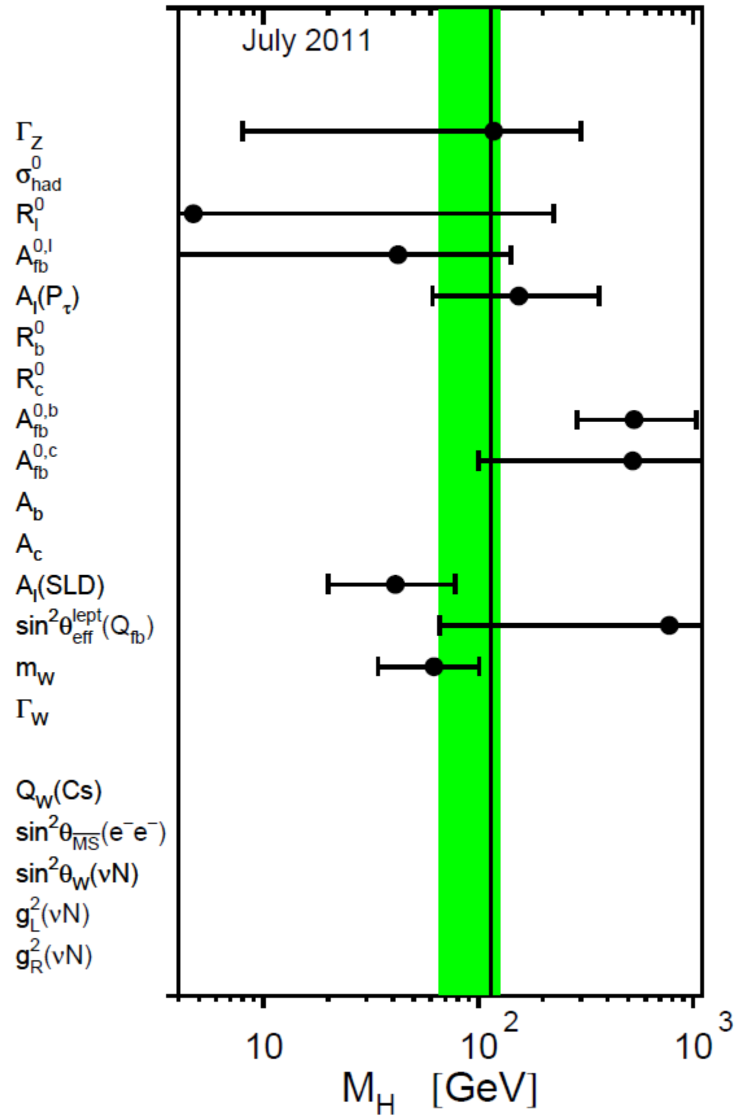


unstable vacuum

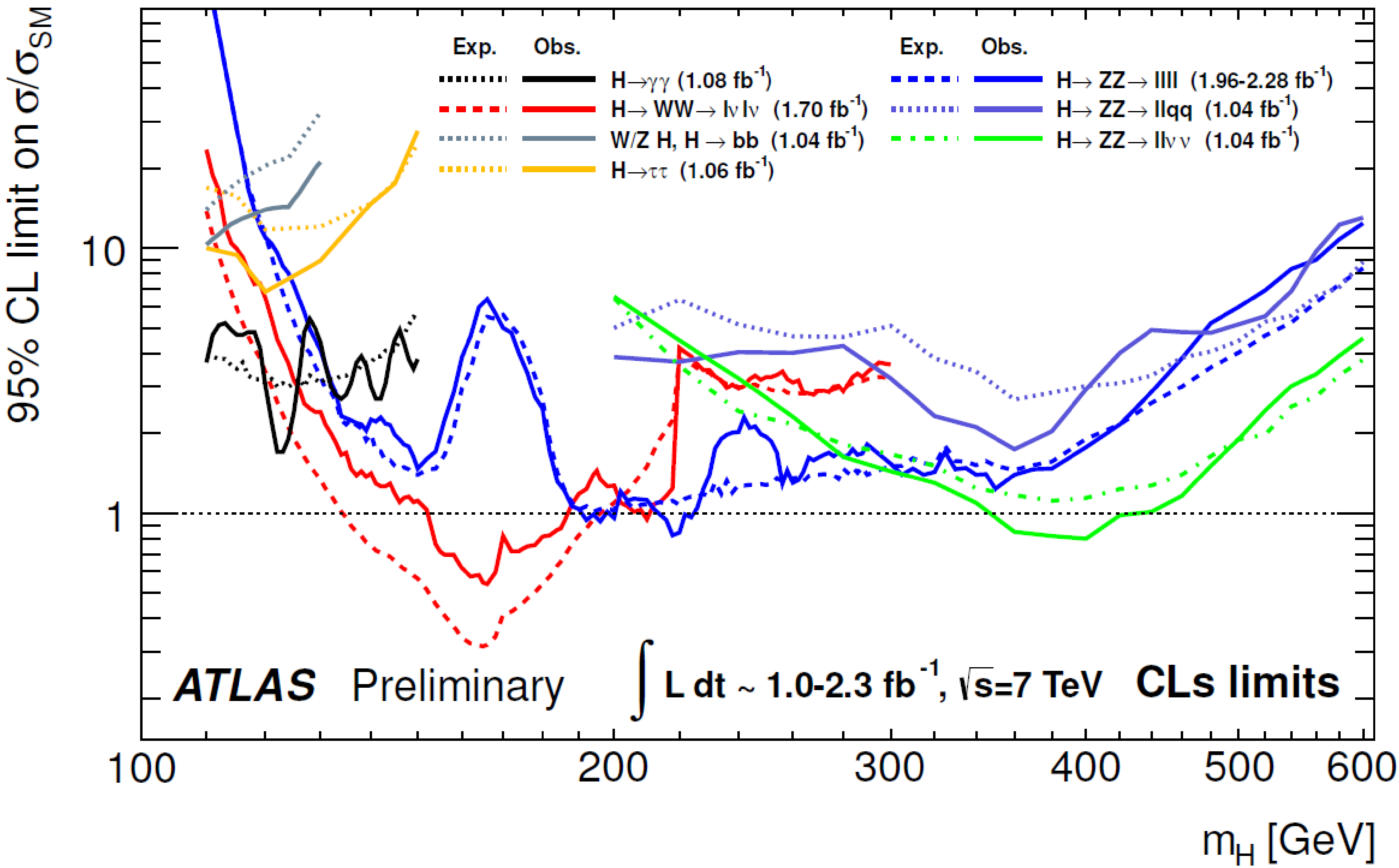
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1039
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
$A_l(SLD)$	0.1513 ± 0.0021	0.1482
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



July 2011



ATLAS results



Background and Signal