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Search for a light Higgs boson at DØ

Samuel Calvet

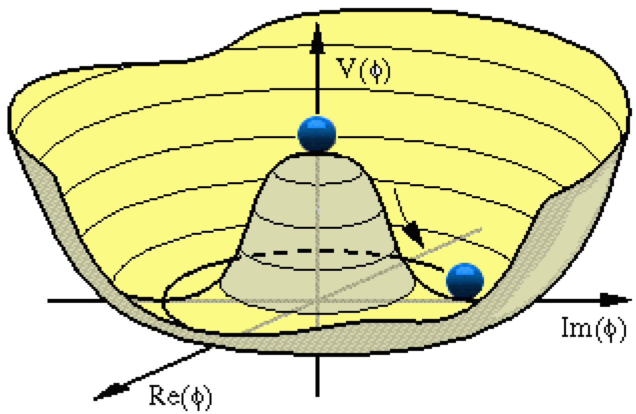
CPPM - March 20th 2009

Outline

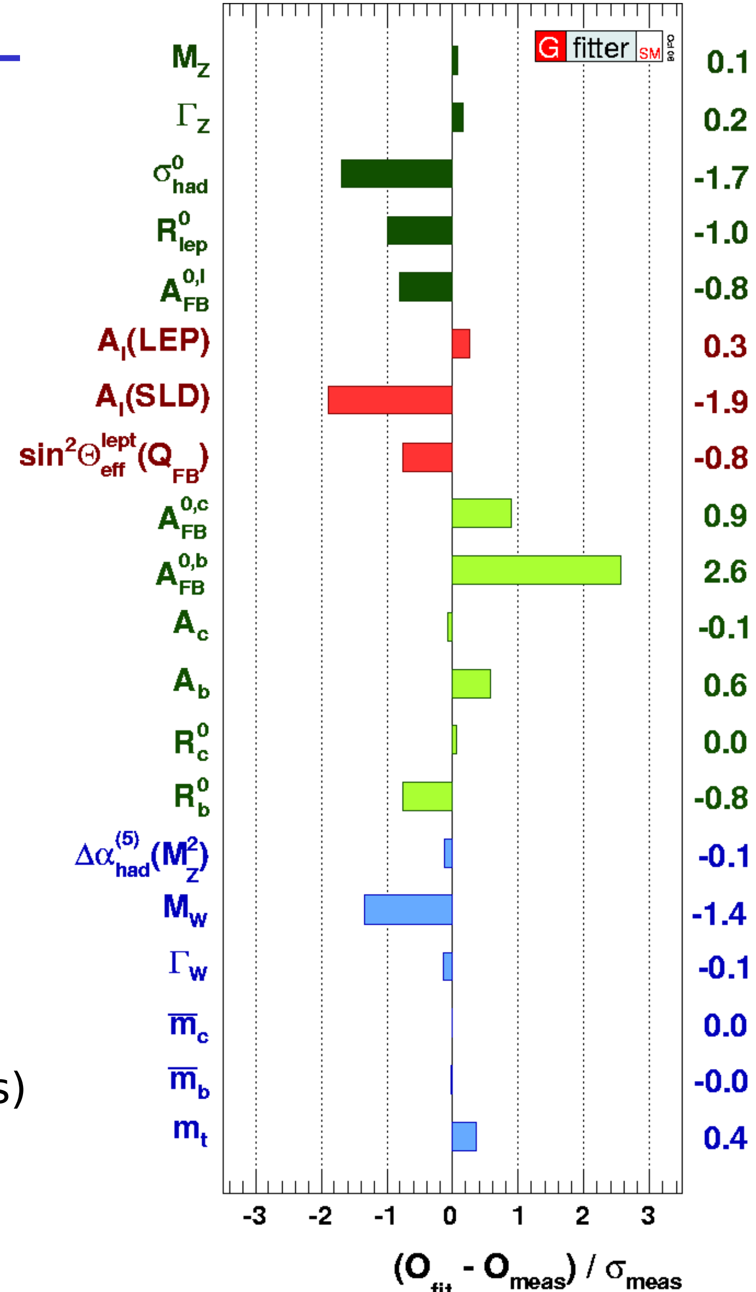
- Constraints
  on the Higgs mass
- DØ detector
- Common tools
  - B-tagging
  - (Boosted) Decision Tree
  - Matrix Element Discriminant
- Low mass Higgs searches
- Prospective

Introduction

- So far, the Standard Model is successful
- Higgs Mechanism:
  - Scalar field in a potential...



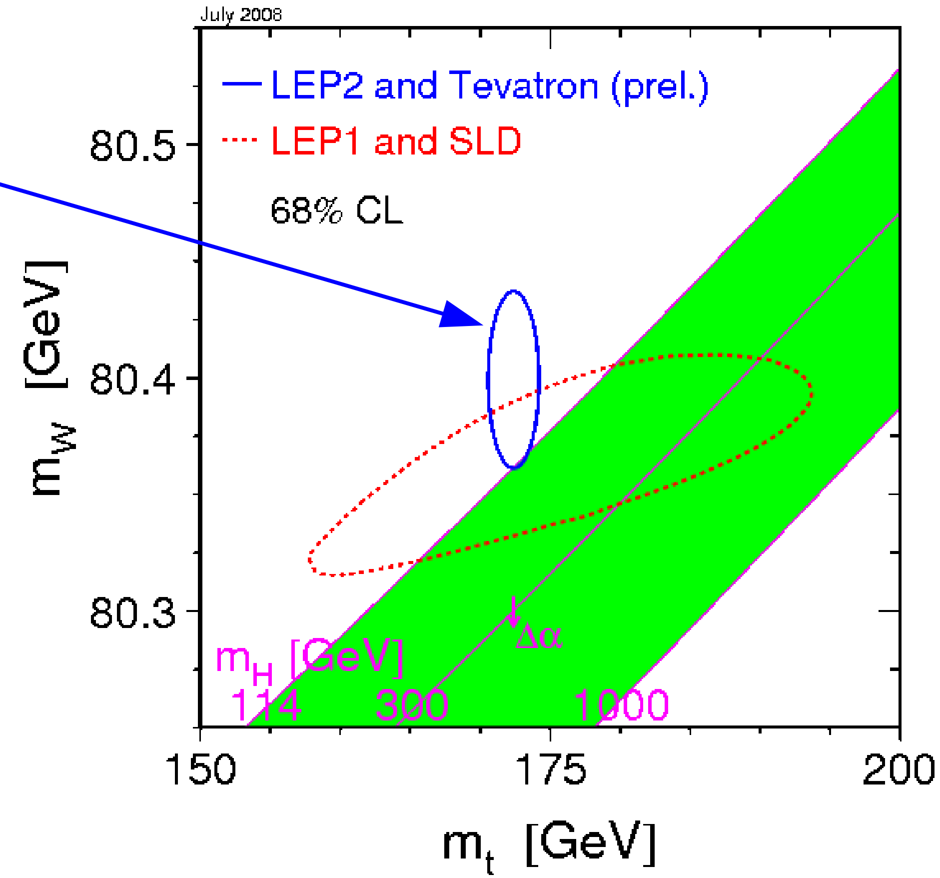
  - ... breaks the EW symmetry
  - → massive gauge bosons
  - → massive fermions (Yukawa couplings)
  - → a massive Higgs boson
- But not yet observed



Indirect constraints

- Direct measurements of top and W masses point to a light Higgs boson

July 2008



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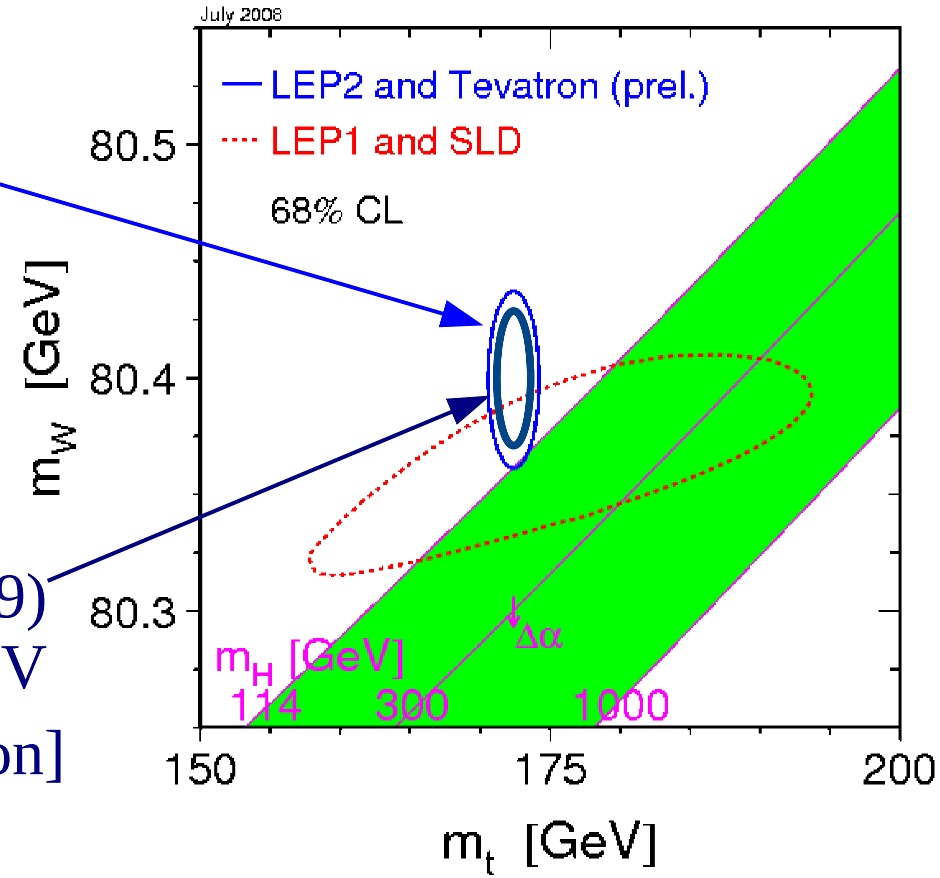
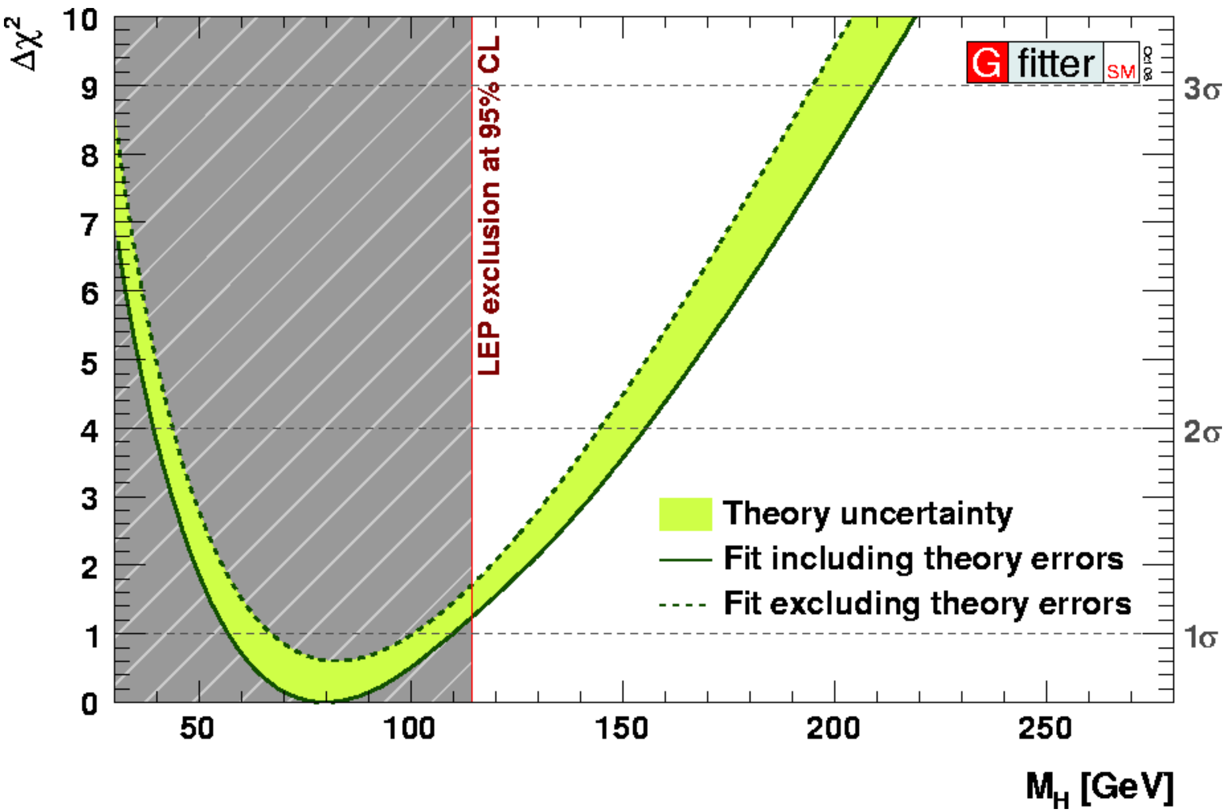


... including the W mass
of DØ Run II (Moriond '09)
m_W = 80.401 +/-0.044 GeV
[naive personal extrapolation]

Global fit

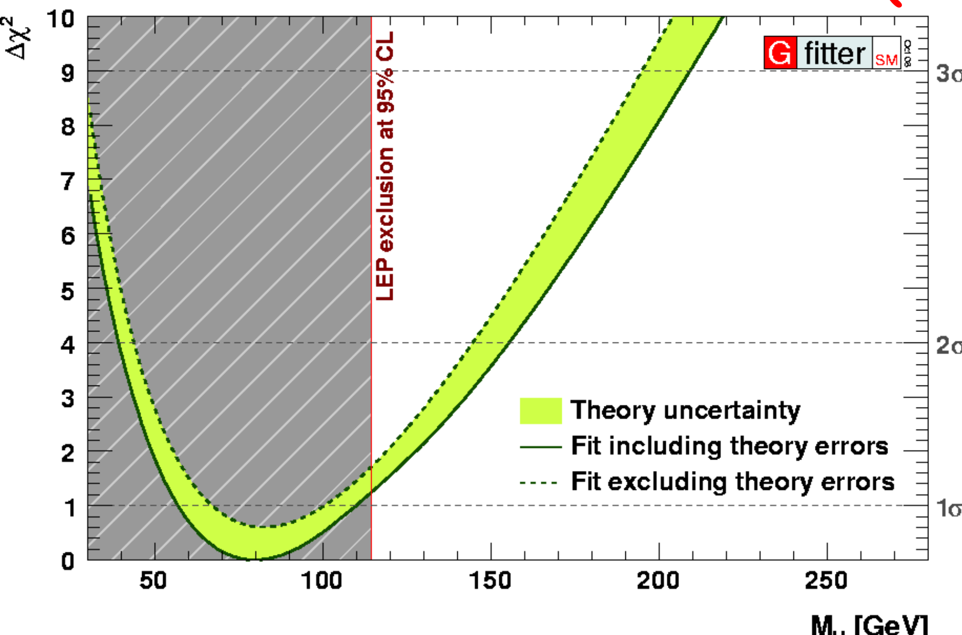
- Global electroweak fits indicate a low mass Higgs :
  - $m_H = 80^{+30}_{-23}$ GeV

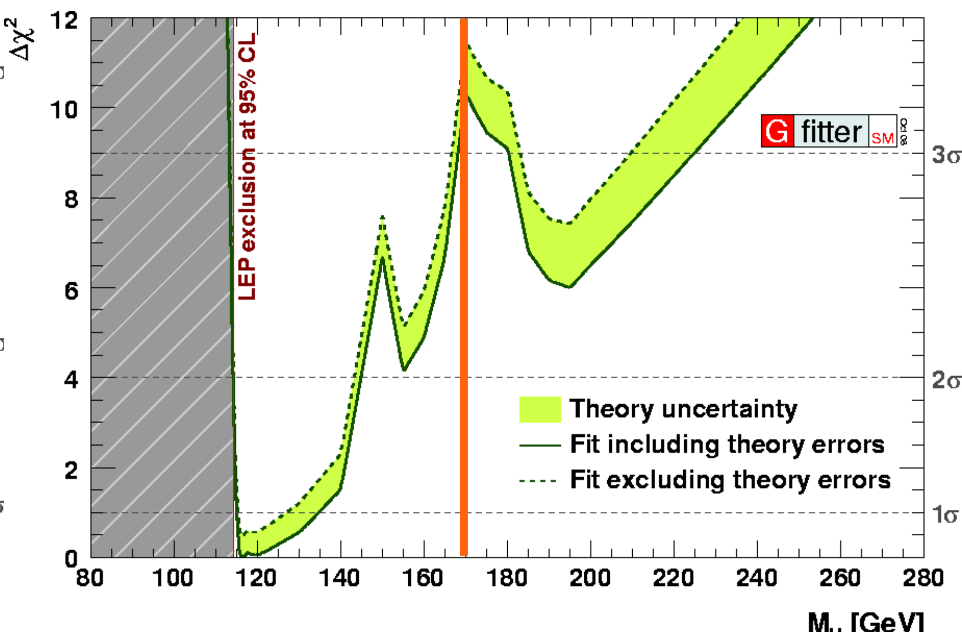


Global fit

- Global electroweak fits indicate a low mass Higgs :
  - $m_H = 80^{+30}_{-23}$ GeV
- If one includes direct searches from LEP (m_H>114.4 GeV) and Tevatron ($m_H \neq$170 GeV) :
  - $M_H = 116.4^{+18.3}_{-1.3}$ GeV

Low mass Higgs preferred
(in SM)



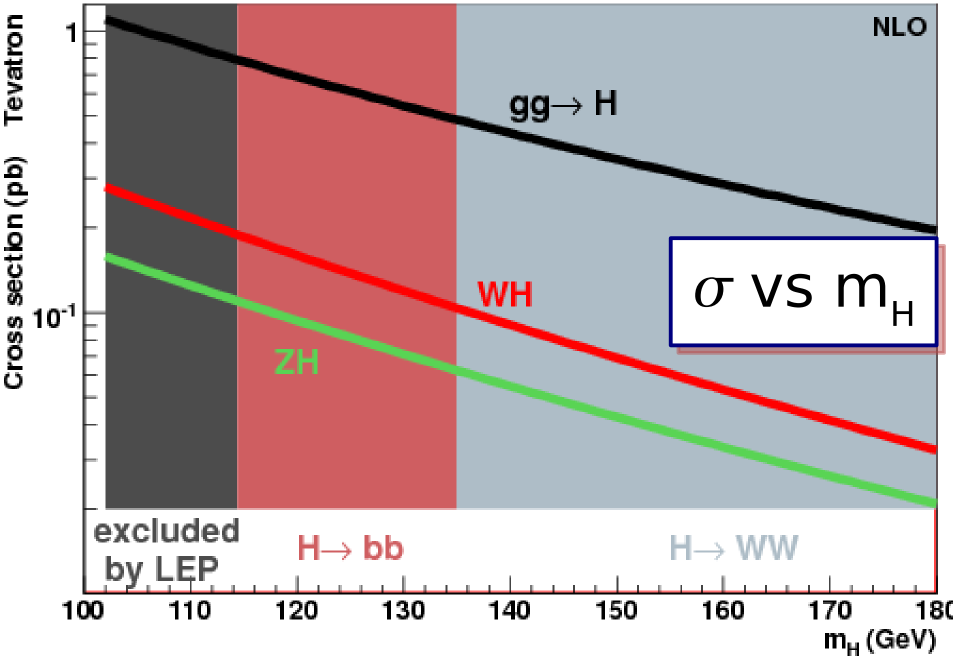


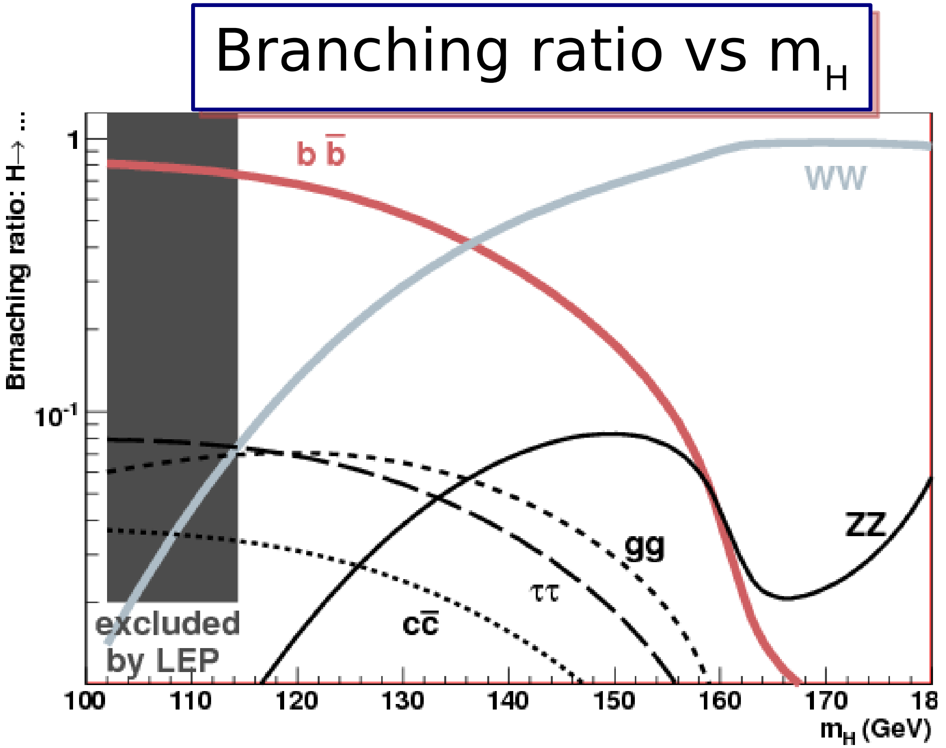
Strategy @ Tevatron

- High mass (m_H>135 GeV) searches can look for gg→H→WW production
- Low mass: gg→H→bb has too much QCD background

→ search for associated productions

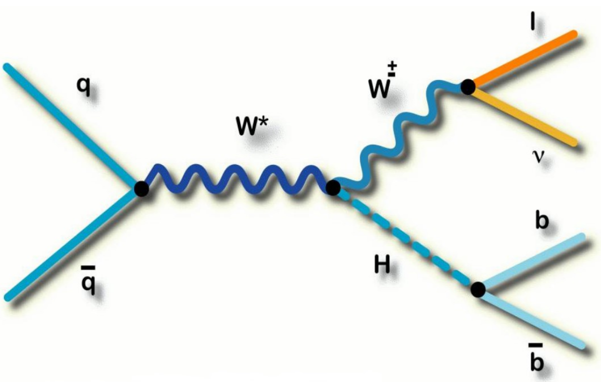
  - **WH**
  - **ZH**

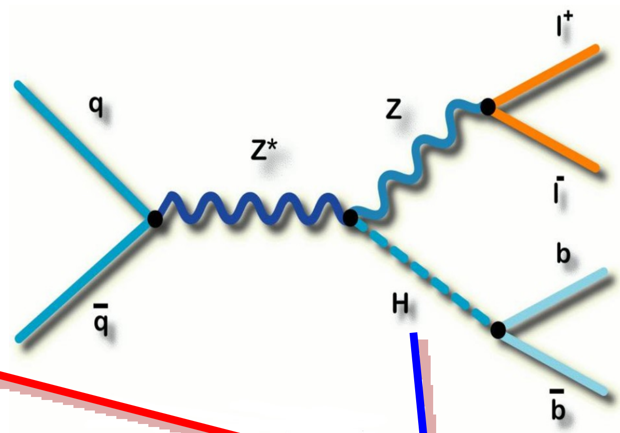


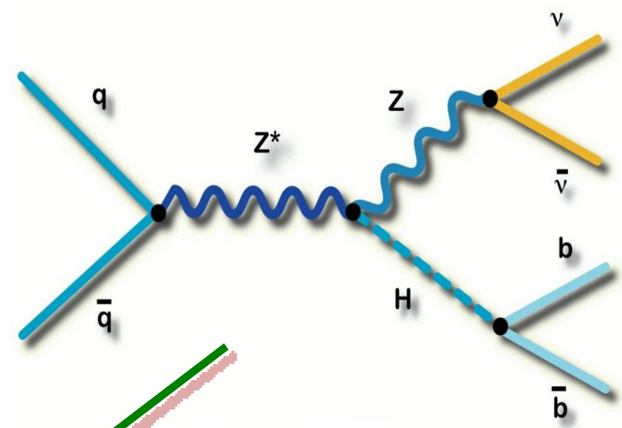


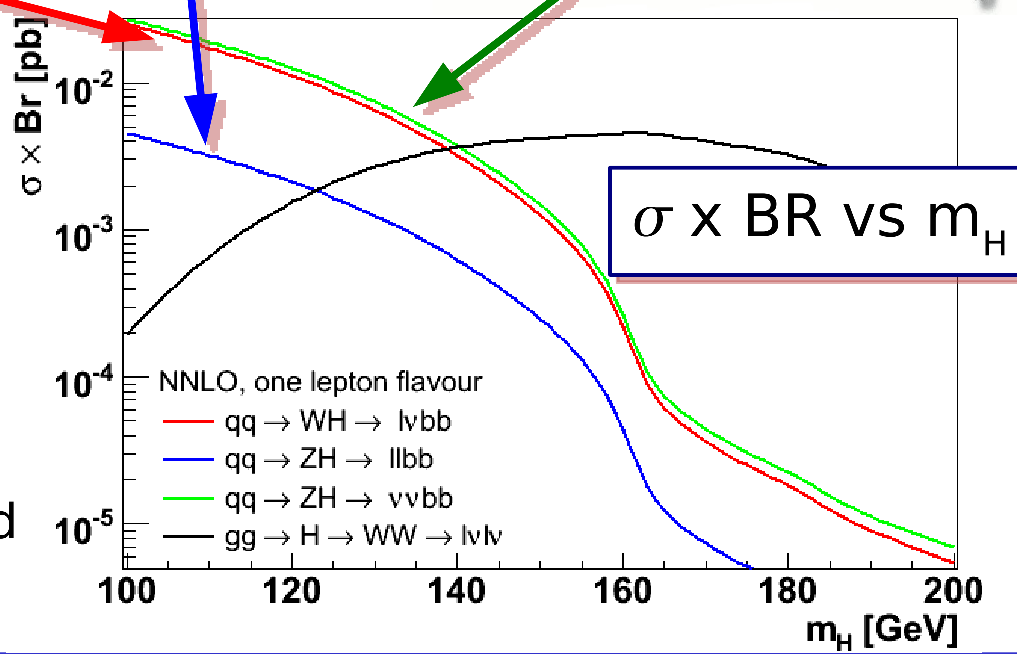
Strategy @ Tevatron

- Low mass Higgs searched in 3 main topologies:





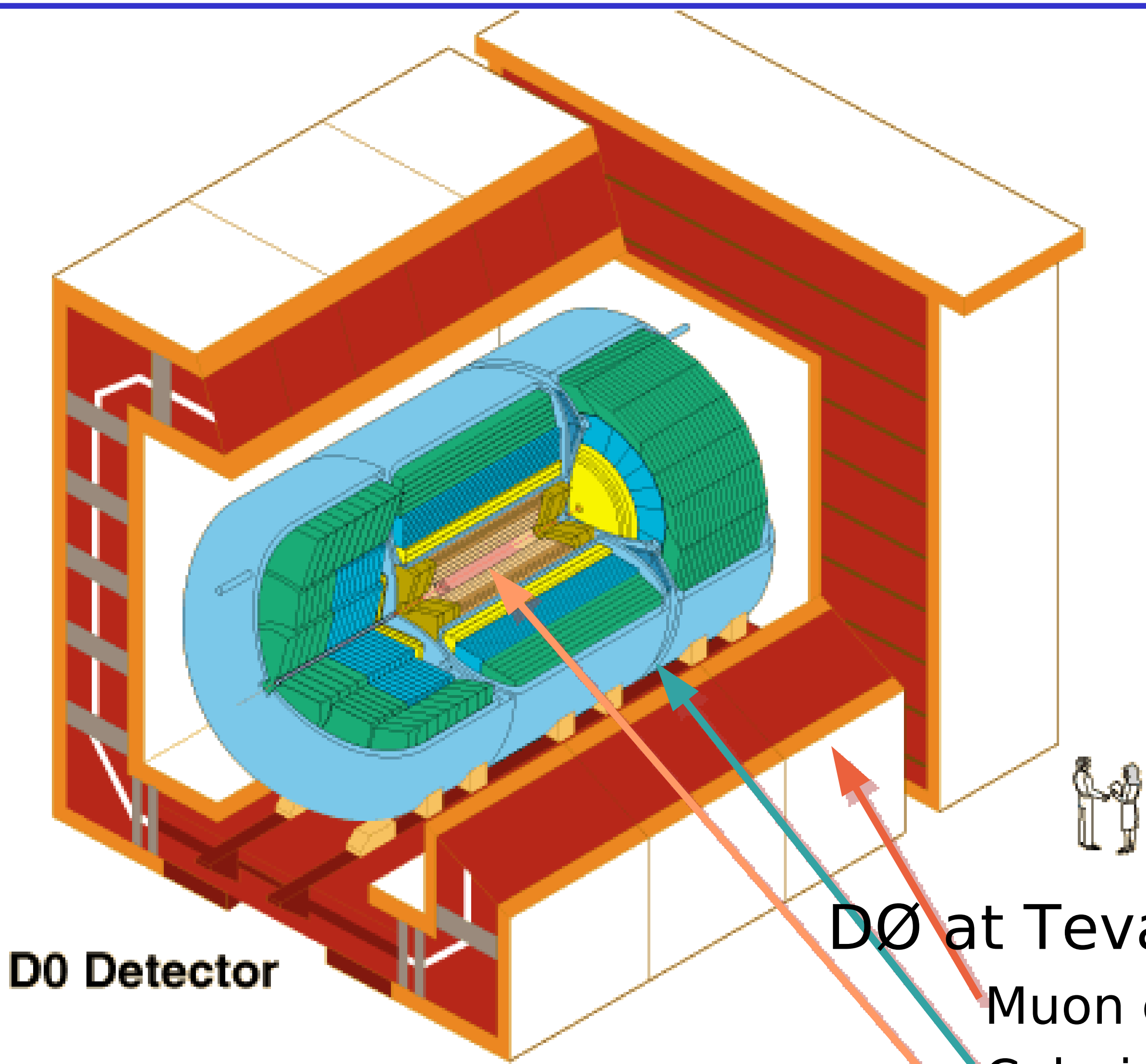




  - 2 jets from b-quarks
    → **b-tagging**
  - **lepton**(s) and/or missing transverse energy (**MET**)
- But also :
  - H→$\gamma\gamma$
  - W(→qq')H(→$\tau\tau$)

Not presented today

Detector & analysis data sets



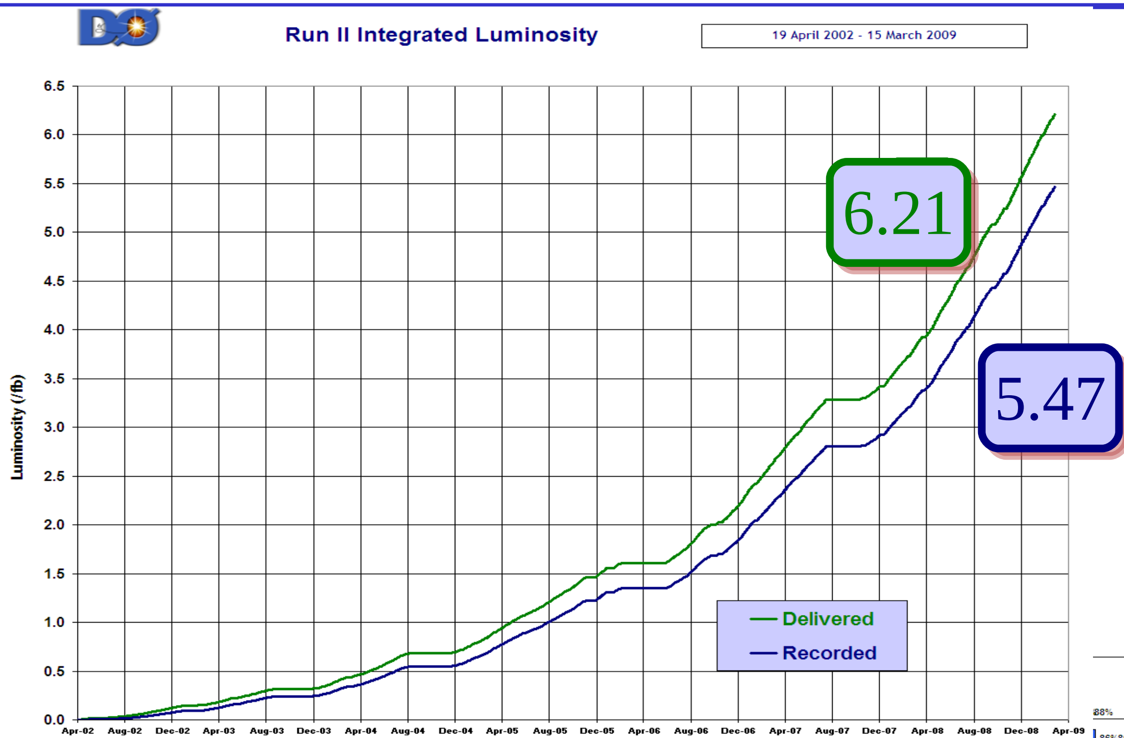
DØ at Tevatron ($\sqrt{s}$=1.96TeV):

Muon chambers

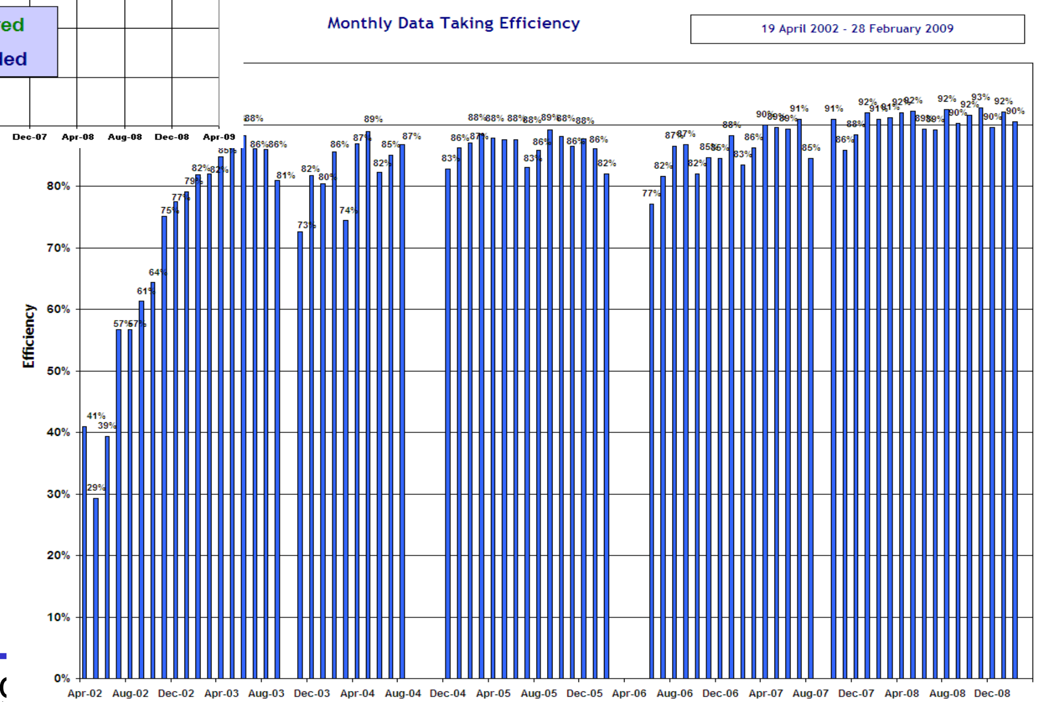
Calorimeter

Tracker (incl. silicon vertex detector)

Detector & analysis data sets



Tevatron works very well...



... and DØ has a high data taking efficiency (>90%)

Background/signal simulation

- W+jets, Z+jets, $t\bar{t}$ contributions
  - are evaluated using the **alpgen** generator (interfaced with **pythia**)
- WW, WZ, ZZ, WH, ZH
  are produced with **pythia**
- Single-top events
  - are generated with **comphep** (interfaced with **pythia**)

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- Instrumental background (multijet events):

  → **Estimated from the data**

Tools

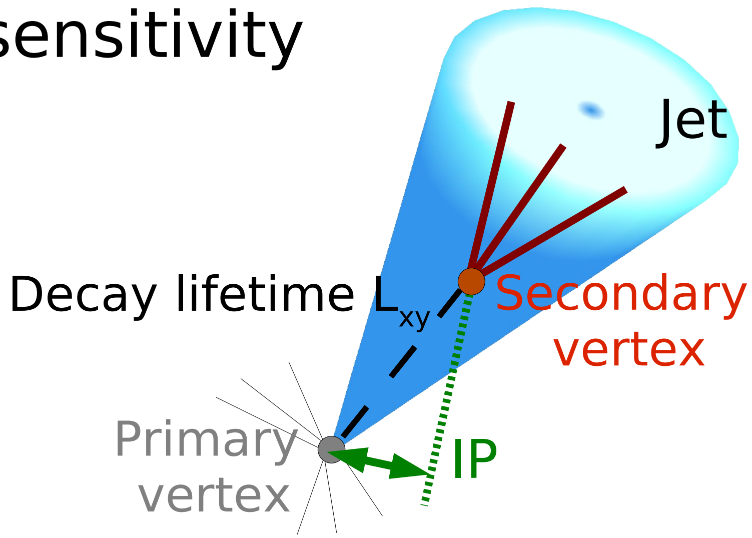
B-tagging

(Boosted) Decision Tree

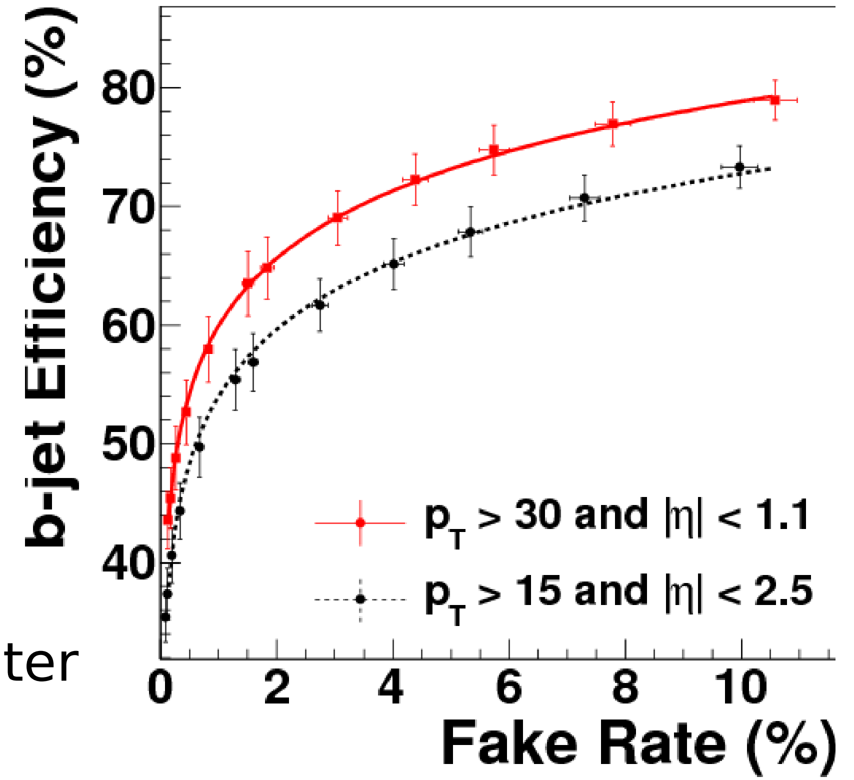
Matrix Element Discriminant

b-tagging

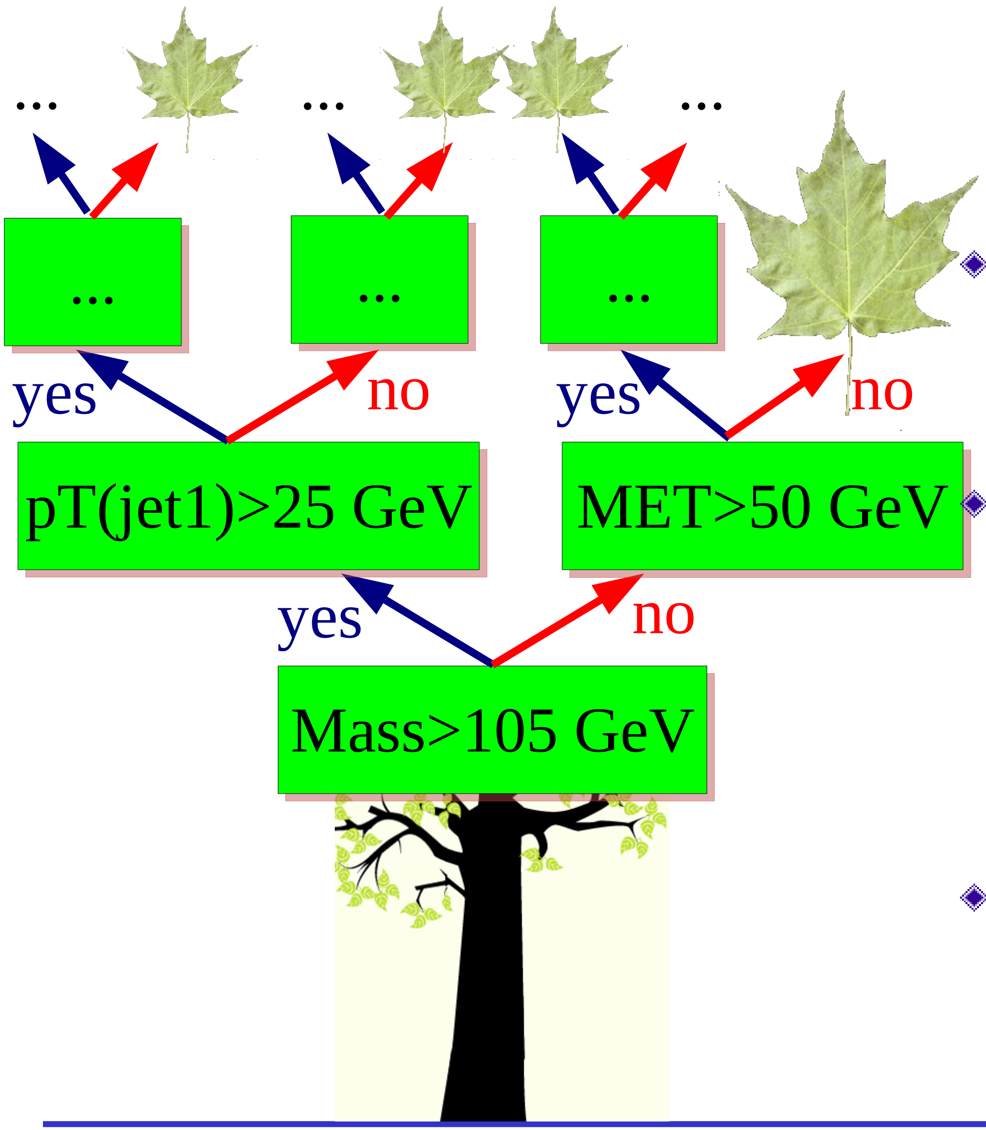
- Use **long lifetime of b-quarks** to improve the sensitivity



- Neural Network using outputs from other taggers:
  - Jet Lifetime Impact Parameter
  - Counting Signed Impact Parameter
  - Secondary Vertex Tagger



Multivariate techniques: Decision Tree



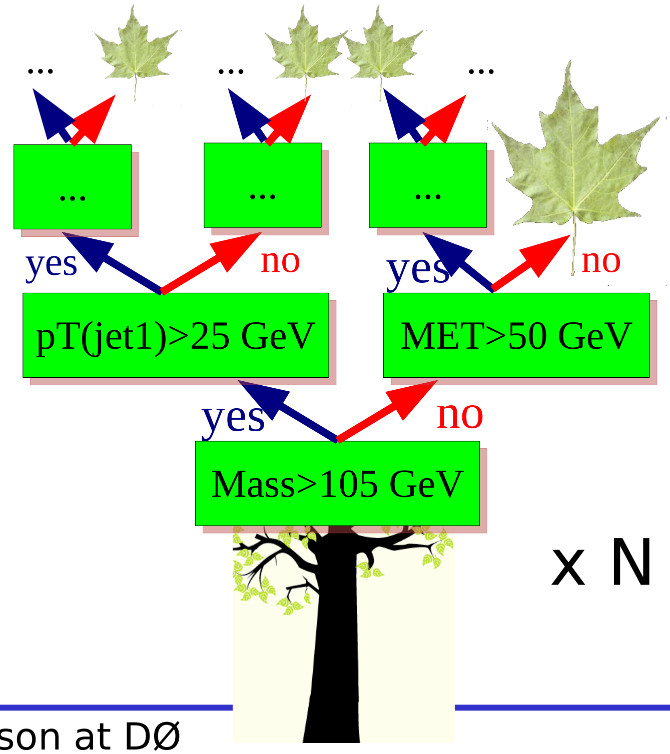
- Use a set of discriminant variables, and train a DT on signal and background samples
- At each node, algorithm chooses the best variable, and the best cut to apply
- At the end: leaves
  - When there is too few events (<~100)
  - Purity is high enough
- In the analysis, discriminant output=purity of the leave

Boosted Decision Tree

- Goal: want to **get back the signal** events falling in “**background-like”** leaves

- Idea:
  - a) Train one tree
  - b) Boost the weights of misclassified events
  - c) Re-train the tree

- Iterate N times...
- ... and combine the N trees in 1 output



Matrix element discriminant

- Build a discriminant using **LO matrix element** (ME)

$$d\sigma(\vec{x}) = \sum_{i,j} \int d\vec{y} \left[f_i(q_1, Q^2) dq_1 \times f_j(q_2, Q^2) dq_2 \times \frac{d\sigma_{hs,ij}(\vec{y})}{d\vec{y}} \times W(\vec{x}, \vec{y}) \times \Theta_{\text{Parton}}(\vec{y}) \right]$$

Observed state

State at parton level

Differential cross-section to observe the state $\vec{x}$ from the parton level state $\vec{y}$

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Observed state

State at parton level

- →Probability density functions P($\vec{x}$): **P**$_{\textbf{signal}}(\vec{x})$, **P**$_{\textbf{bckgrd}}(\vec{x})$

Matrix element discriminant

- Build a discriminant using **LO matrix element** (ME)

$$\underbrace{d\sigma(\vec{x})}_{\text{Observed state}} = \sum_{i,j} \int \underbrace{d\vec{y}}_{\text{State at parton level}} \left[\overbrace{f_i(q_1, Q^2)dq_1 \times f_j(q_2, Q^2)dq_2}^{\text{pdf}} \times \overbrace{\frac{d\sigma_{hs,ij}(\vec{y})}{d\vec{y}}}^{\text{ME}} \times \underbrace{W(\vec{x}, \vec{y})}_{\text{Detector response (transfer function)}} \times \overbrace{\Theta_{\text{Parton}}(\vec{y})}^{\text{Parton level cuts (to avoid singularities)}} \right]$$

- →Probability density functions $P(\vec{x})$: $\mathbf{P}_{\mathbf{signal}}(\vec{x})$, $\mathbf{P}_{\mathbf{bckgrd}}(\vec{x})$

- Discriminant : $\boxed{D(\vec{x}) = \dfrac{\mathbf{P}_{\mathbf{signal}}(\vec{x})}{\mathbf{P}_{\mathbf{signal}}(\vec{x}) + \mathbf{P}_{\mathbf{bckgrd}}(\vec{x})}}$

relative probability for an event to come from signal or background

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Observed state ($\vec{x}$)

State at parton level ($\vec{y}$)

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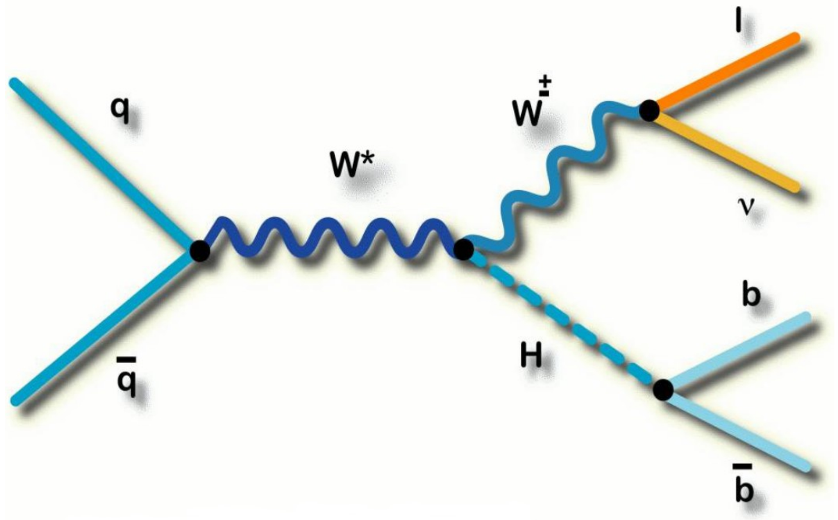
relative probability for an event to come from signal or background

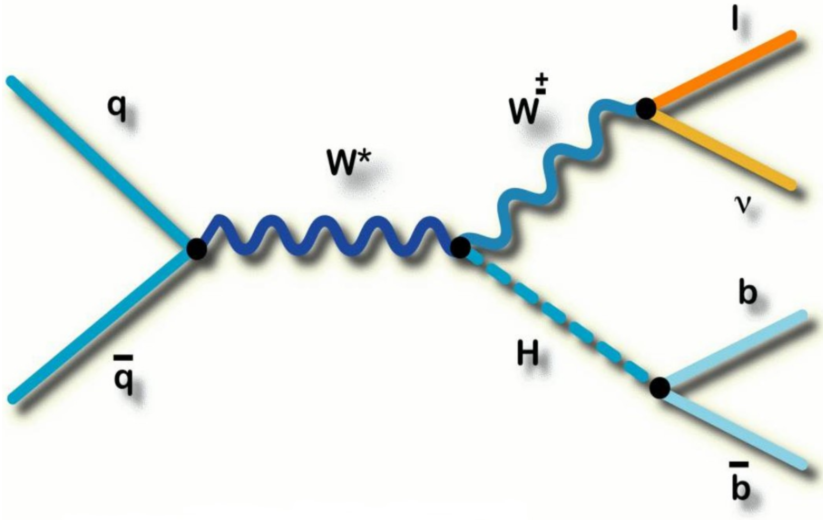
- Need huge CPU power

$W(\rightarrow l\nu)H(\rightarrow b\bar{b})$



W(→lν)H(→bb)

- Clear signature:
  - Isolated lepton
    - *e* or μ
  - MET
  - 2 b-quarks



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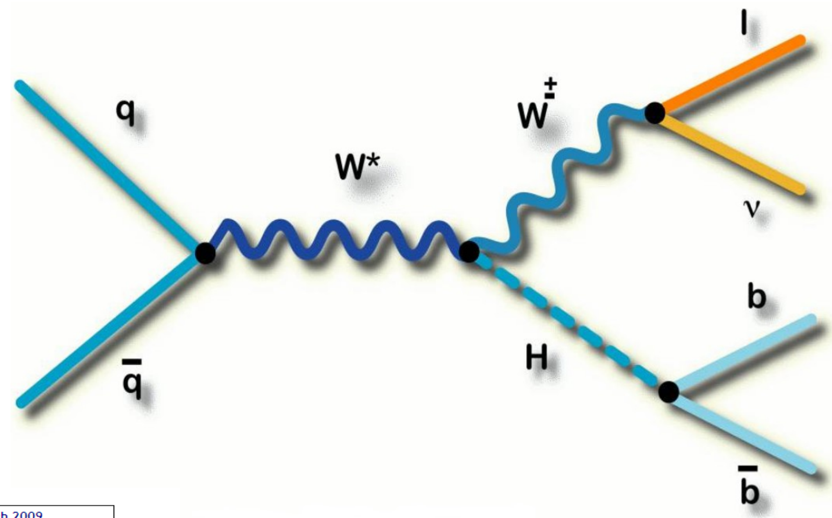
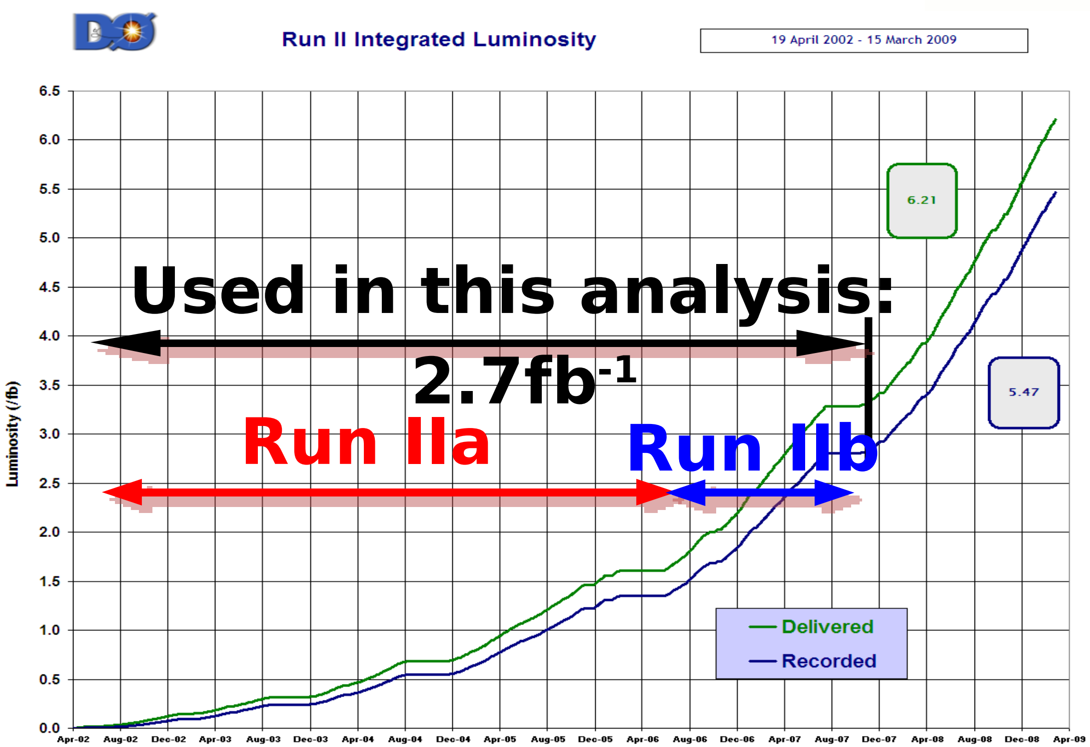




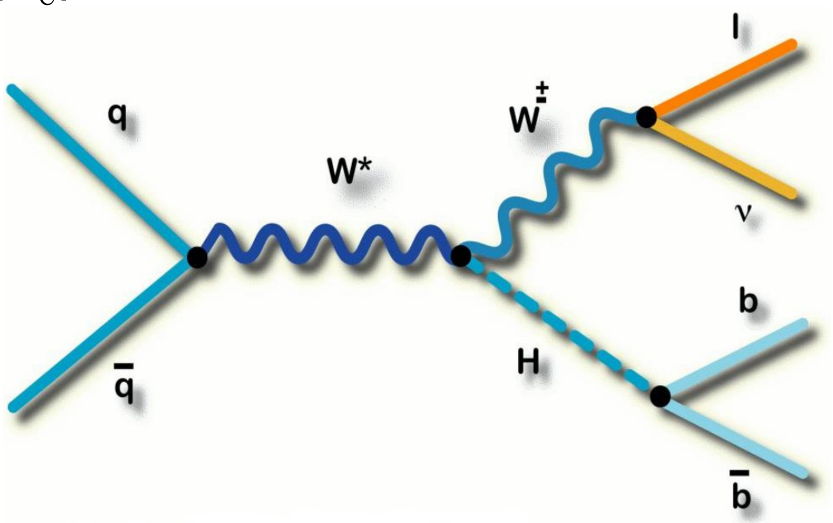
- Analysis uses 2.7 fb^{-1} of data, divided into 2 parts :
  - Run IIa (~1.1 fb^{-1})
  - Run IIb (~1.6 fb^{-1})

Instrumental background

- Instrumental background (multijet events):
  - Jet can fake an isolated electron
  - μ from a semi-leptonic heavy quark decay appears as isolated
  - **Estimated from the data**:
    - Probability for a lepton coming from a jet to be seen as isolated

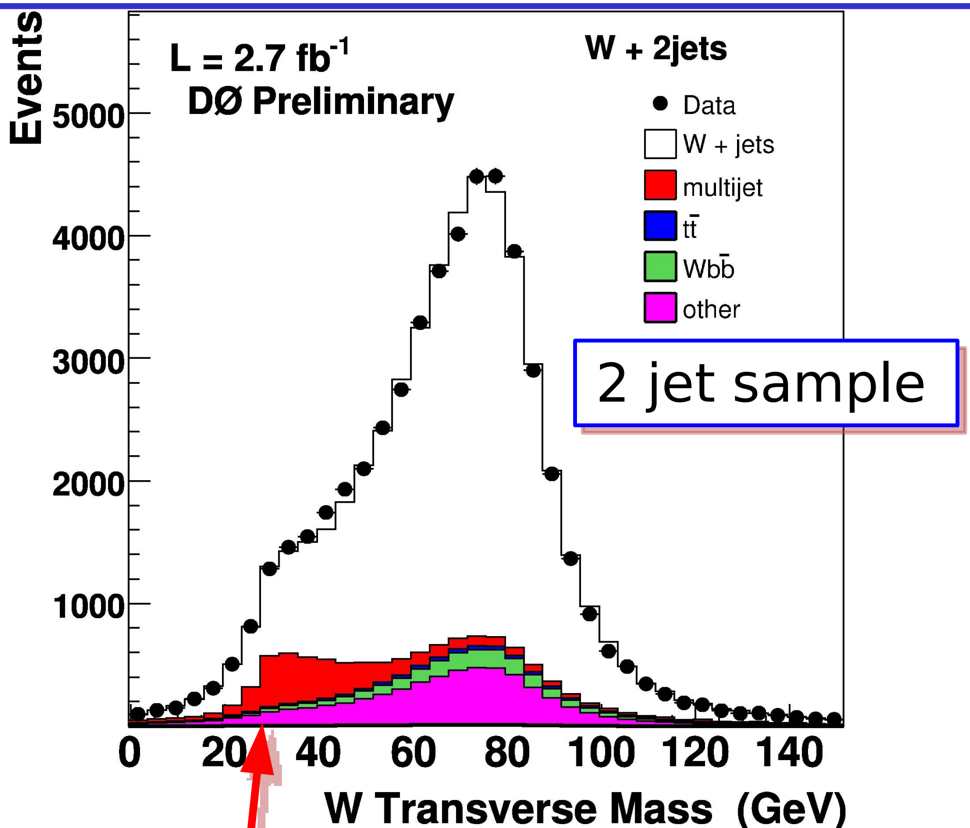
Selection

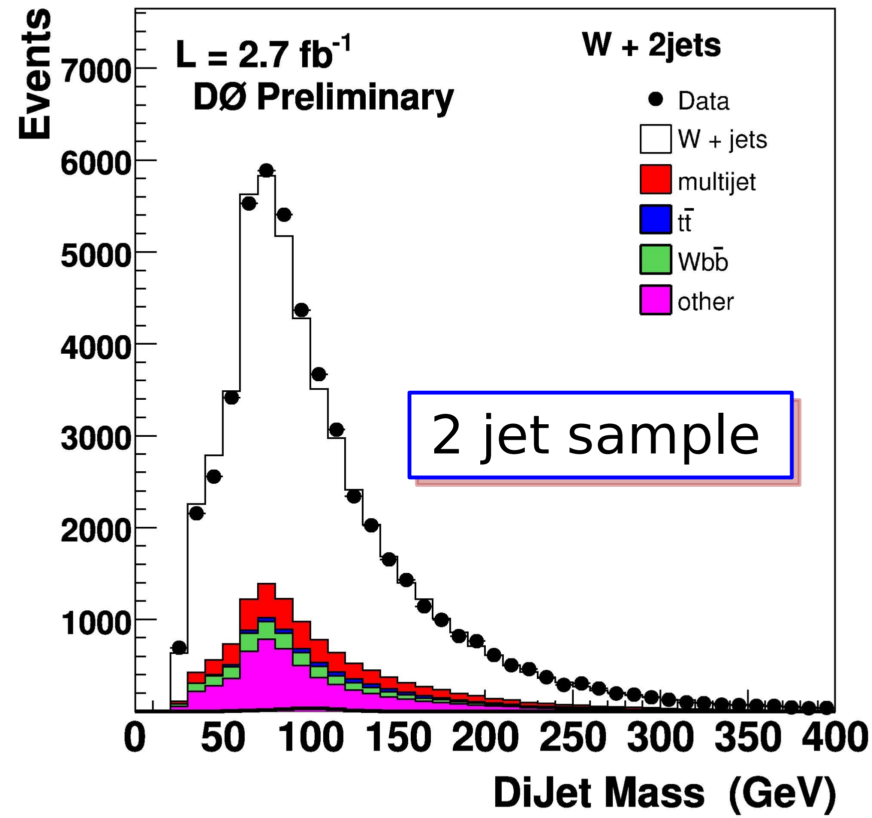
- *e* channel
  - Exactly one isolated electron :
    - pT>15 GeV, $|\eta_e|<1.5$ or $1.5<|\eta_e|<2.5$
  - MET>20 GeV (25 GeV if $1.5<|\eta_e|$)
- μ channel
  - Exactly one isolated μ :
    - pT>15 GeV, $|\eta_\mu|<2.0$
  - MET>20 GeV



- Both channels :
  - **Divide the analysis into 2 parts**
    depending whether there are **2** or **3** jets (pT>20 GeV)
  - Σ pT(jet) > 60 (90) GeV in the 2 (3) jet sample
  - Cut against multijet background: $M_T^W>40-0.5\text{xMET}$
    - M_T^W: W transverse mass

Good agreement after selection



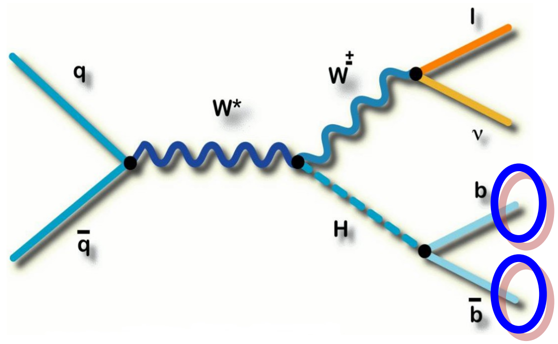


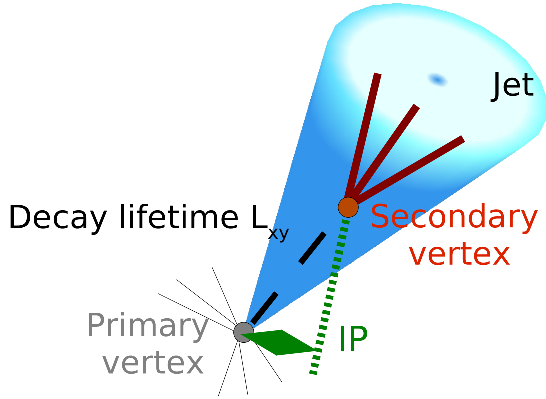
Mutijet background
at low transverse mass

Electron & Muon channels merged

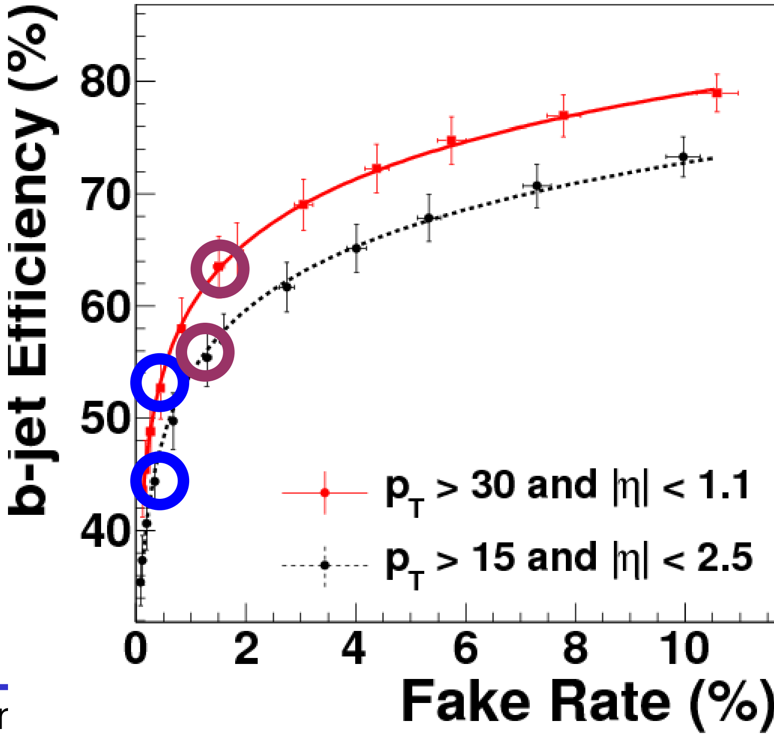
b-tagging

- Use long lifetime of b-quarks to improve the sensitivity



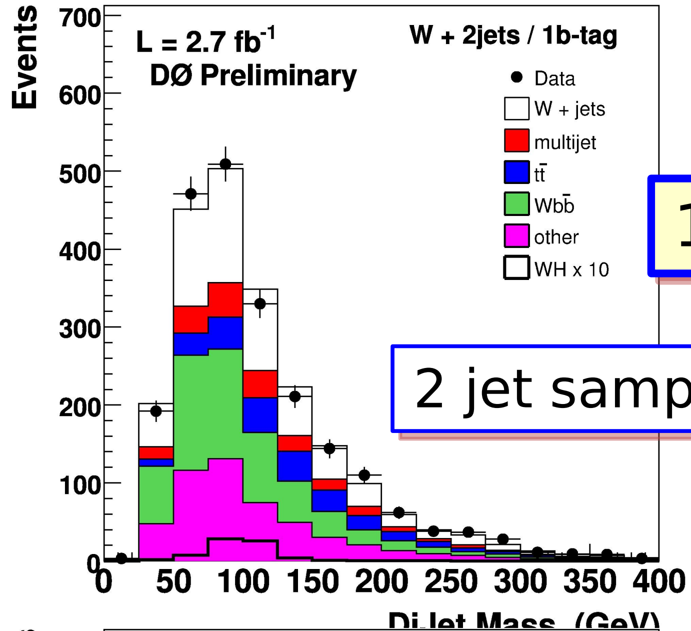


- Form 2 exclusive samples:
  - 2 **loose** b-tagged jets
  - 1 **tight** and 0 loose b-tagged jet

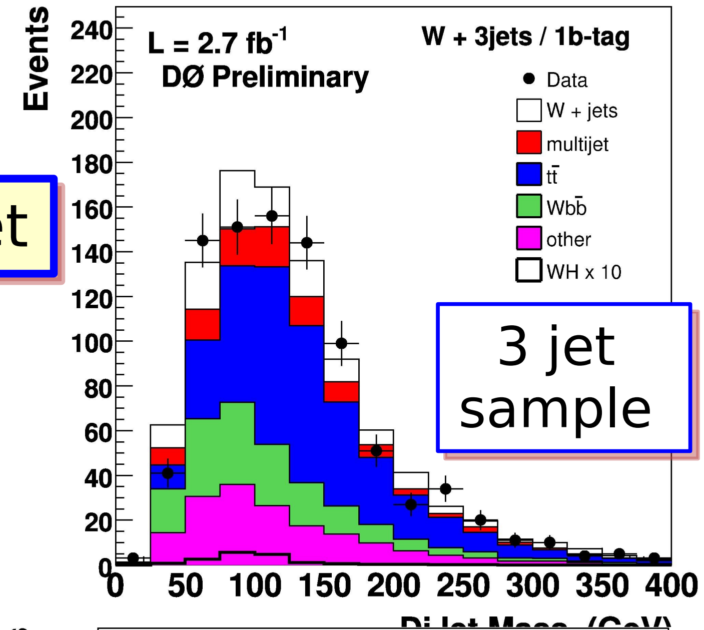


Good agreement after b-tagging

1 tight b-tagged jet

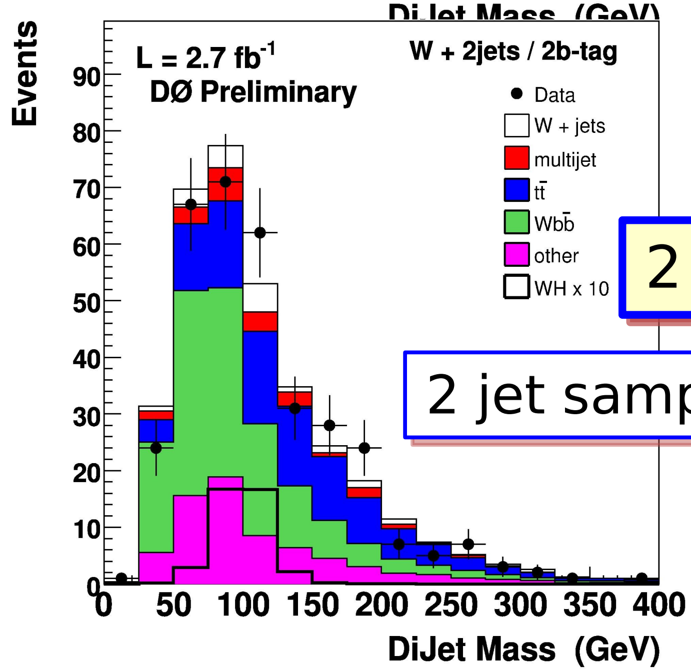


2 jet sample

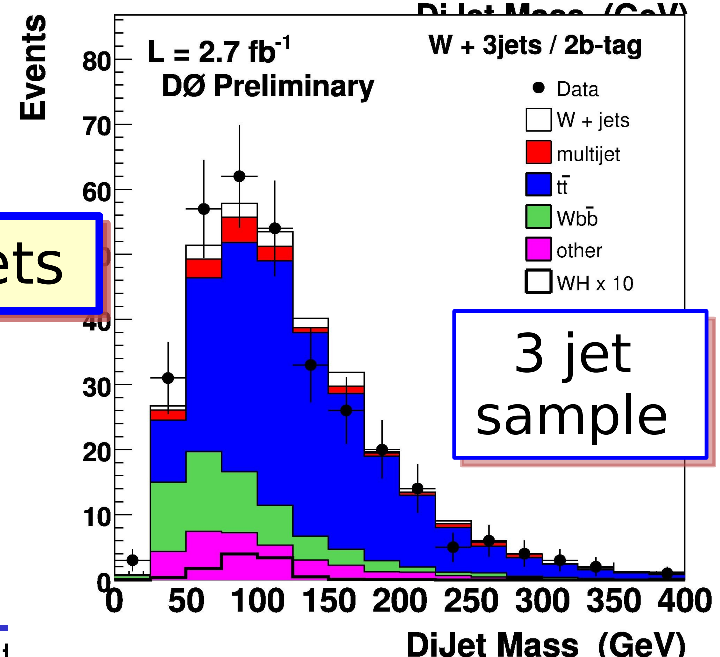


3 jet sample

2 loose b-tagged jets



2 jet sample



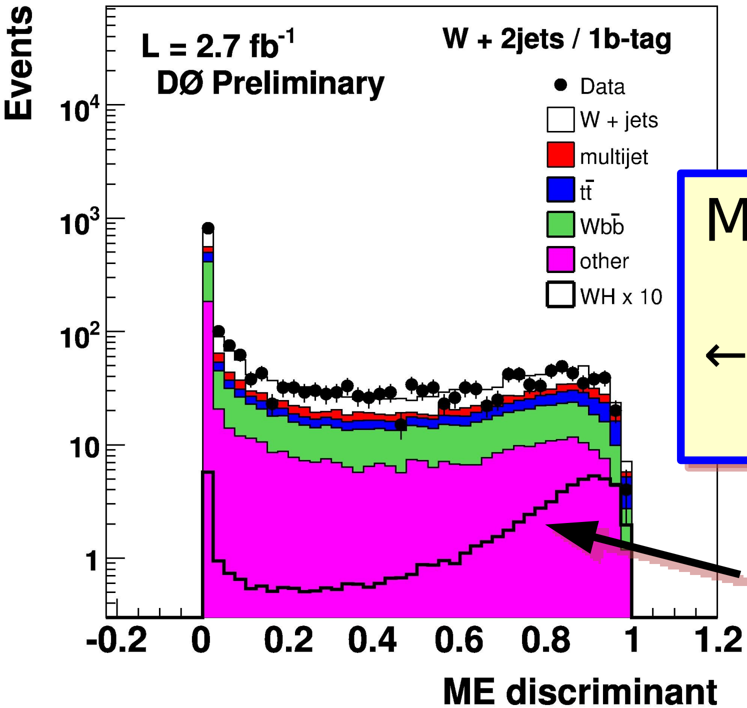
3 jet sample

Multivariate techniques (1)

- Matrix-element based discriminant (for the 2-jet sample)

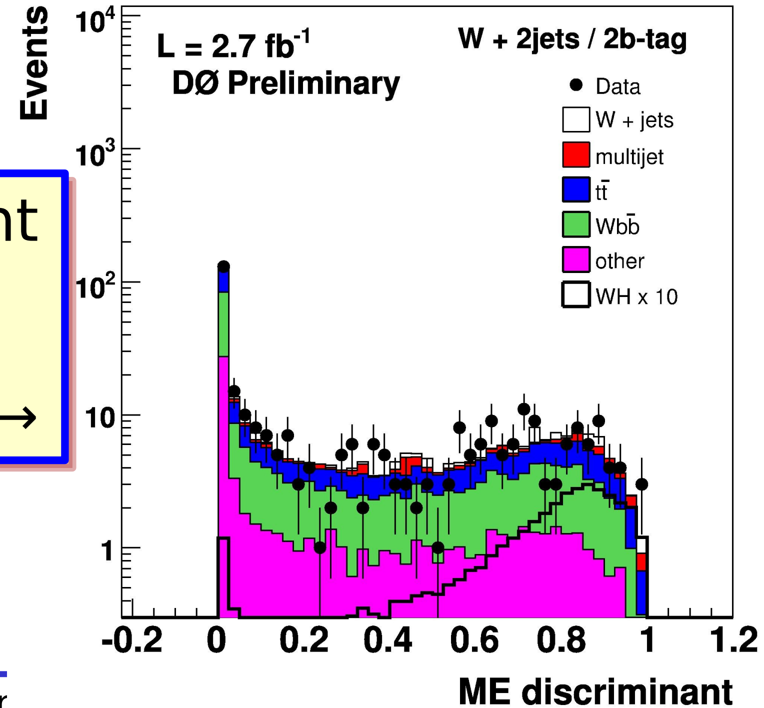
$$d\sigma(\vec{x}) = \sum_{i,j} \int d\vec{y} \left[f_i(q_1, Q^2)dq_1 \times f_j(q_2, Q^2)dq_2 \times \frac{d\sigma_{hs,ij}(\vec{y})}{d\vec{y}} \times W(\vec{x},\vec{y}) \times \Theta_{\mathrm{Parton}}(\vec{y}) \right]$$

→ relative probability for an event to come from WH decay or background



ME discriminant (2 jets)
← 1 tight b-tag
2 loose b-tag →

WH

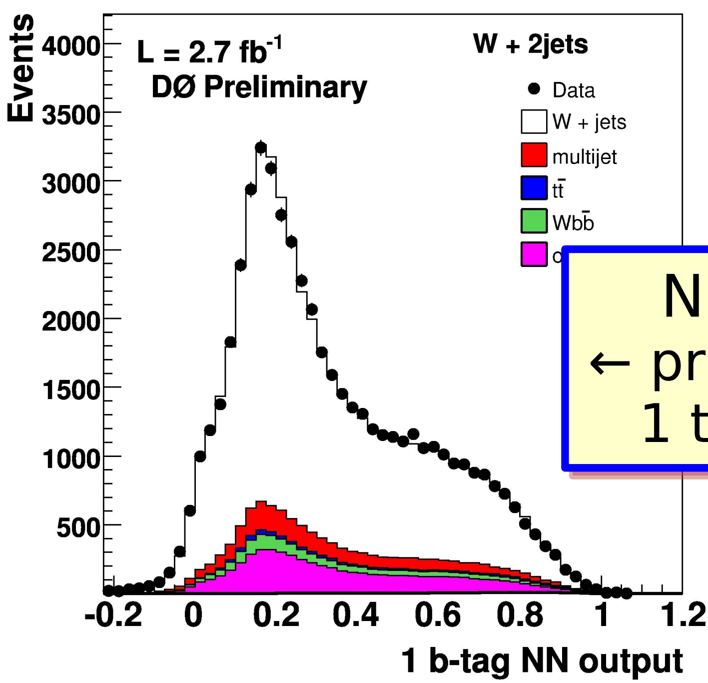


for light Higgs boson

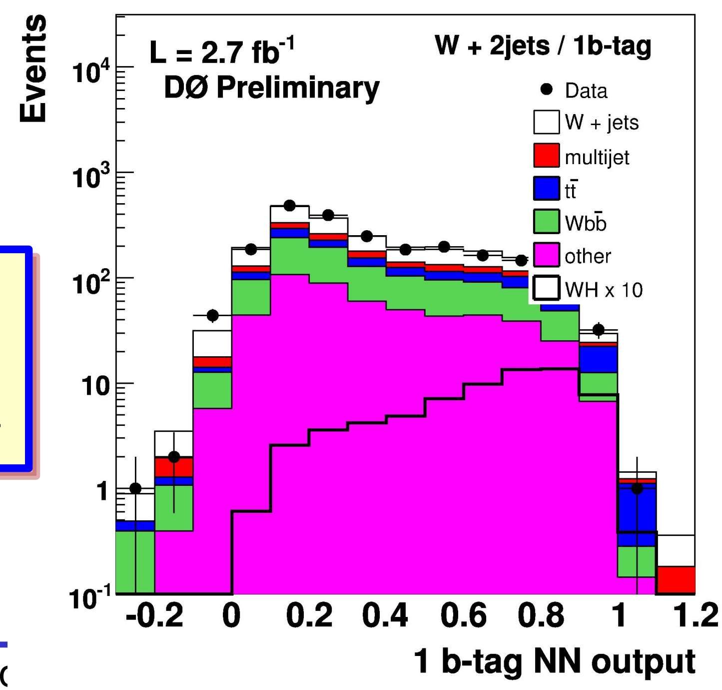
Multivariate techniques (2)

- Increase the sensitivity in the 2-jet sample with a neural network (NN) using as inputs:
  - Matrix element discriminant
  - pT's, ΔR, $\Delta\varphi$, invariant mass of the 2 leading jets
  - pT of the dijet system
- 8 trained NN's: electron/muon X 1-/2- tags samples X RunIIa/RunIIb

  → Gain of 20% of sensitivity wrt M(jet1, jet2) only



NN output
← pre-b-tag
1 tight b-tag →



Systematics uncertainties

- Main uncertainties
  - Cross sections: 11-20%
  - Shape of the Wjj dijet invariant mass: 10%
  - Shape of the Wbb dijet invariant mass: 5-10%
  - Lepton reconstruction/identification: 5-6%
  - Jet identification/calibration: 2-6%
  - Jet fragmentation: 5%
  - Trigger efficiencies : 3-5%
  - b-tagging efficiency:
    - 2-5% (per heavy quark jet)
    - 25% (per light quark jet)

Results

- No excess of events observed → set limits using...
  - the NN output (2-jet samples)
  - di-jet invariant mass (3-jet samples)

- ... for the 16 individual analysis
  - electron/muon X 1-/2- tags samples X RunIIa/RunIIb X 2/3 jets

- .... at 95% of CL, modified frequentist CL_s approach

- ... using the *log-likelihood ratio* (of Signal+Background [S+B] vs Background [B] hypotheses) as test statistic

Log-likelihood ratio (brief reminder)

- Given a set of predictions, observations and systematic uncertainties
  - We use a χ^2-test to describe how well the B (resp. S+B) hypothesis fits the data/pseudo-data samples

$$Q' = -2Log\left(\frac{\chi^2_{min}(\textsc{Test}|\vec{D})}{\chi^2_{min}(\textsc{Null}|\vec{D})}\right)$$

Q'=~0 → not sensitive

|Q'| >> 1 → very sensitive

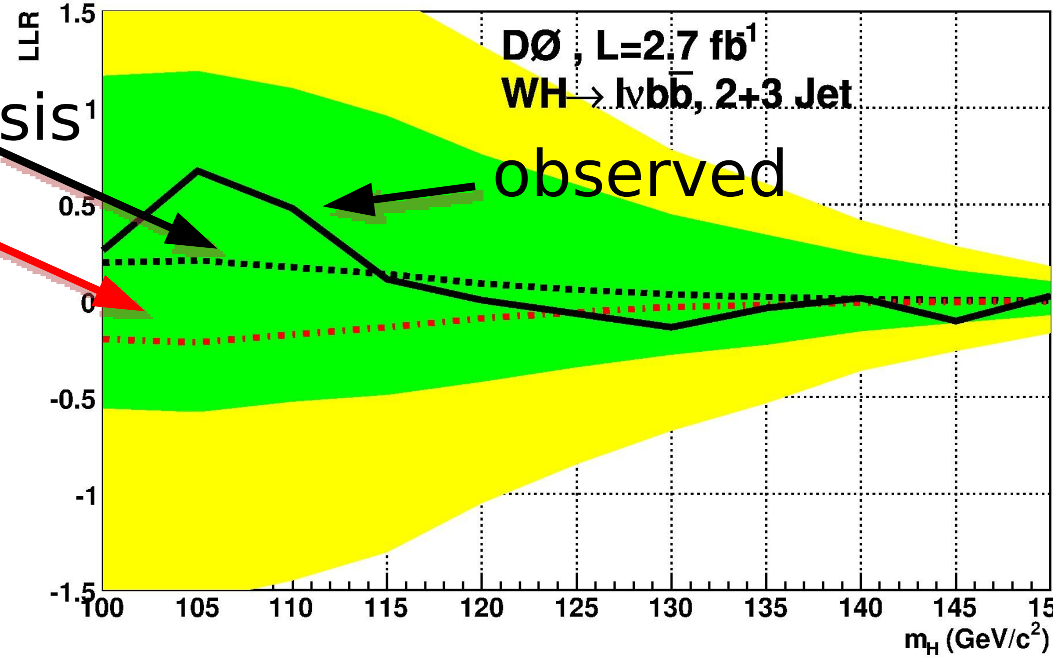
  - → Give a feeling of exclusion/discovery power of an analysis

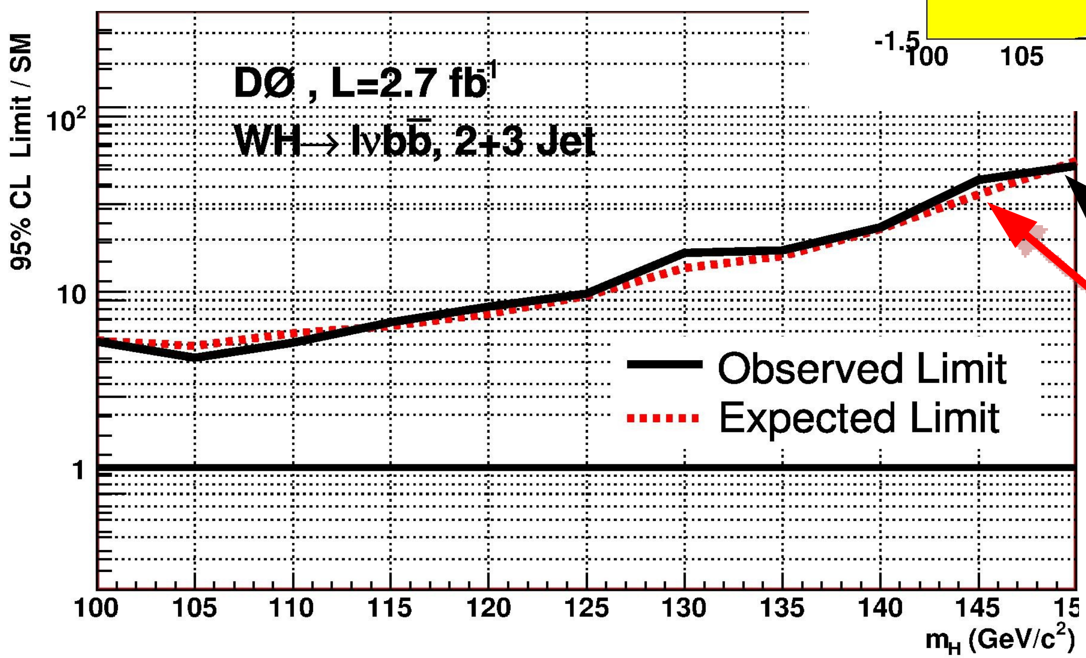
- Allows to modify the predictions within the systematics uncertainties to better fit the data
  - → Reduces the impact of the systematic uncertainties

Results

Log-likelihood ratio:
- background (B) hypothesis
- signal + B hypothesis

± 1 std. deviation
± 2 std. deviations

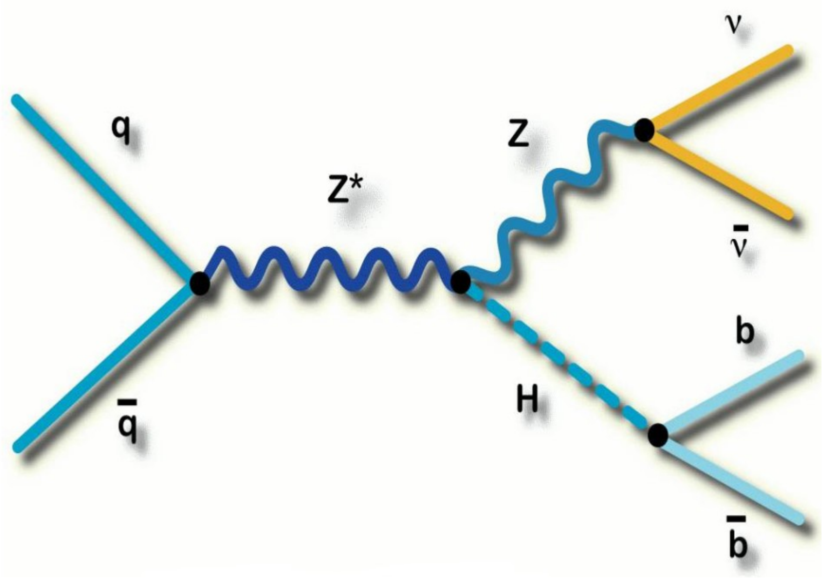




σ Limit/SM:
Observed
Expected

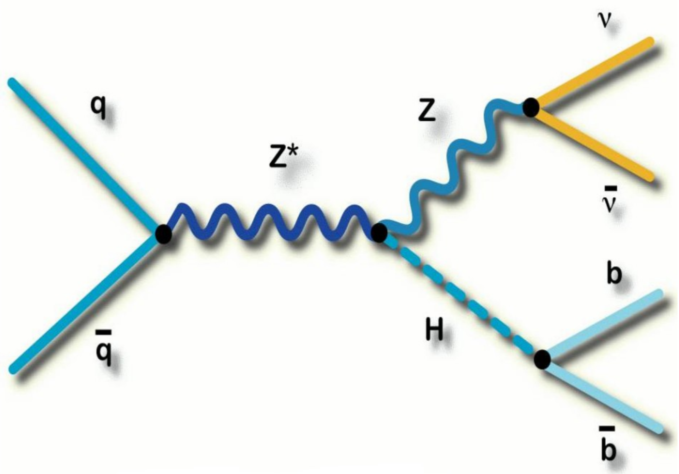
@115 GeV:
exp (obs) : 6.4 (6.7)

$Z(\rightarrow \nu\nu)H(\rightarrow b\bar{b})$



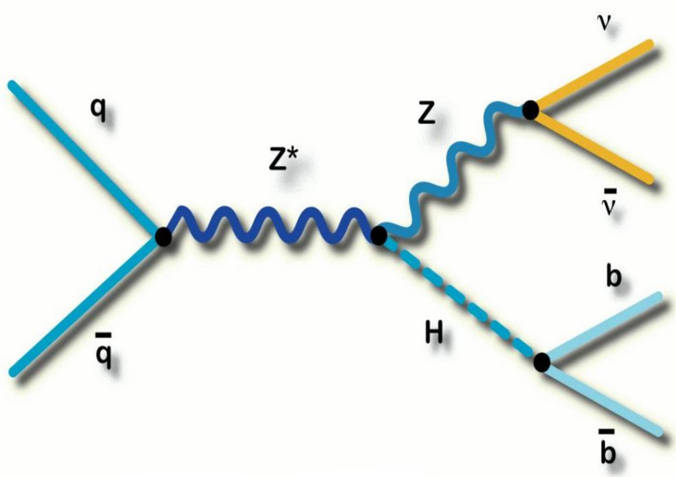
$Z(\to\nu\nu)H(\to bb)$

- Signature:
  - MET (=pT of Z boson)
  - 2 b-quark jets

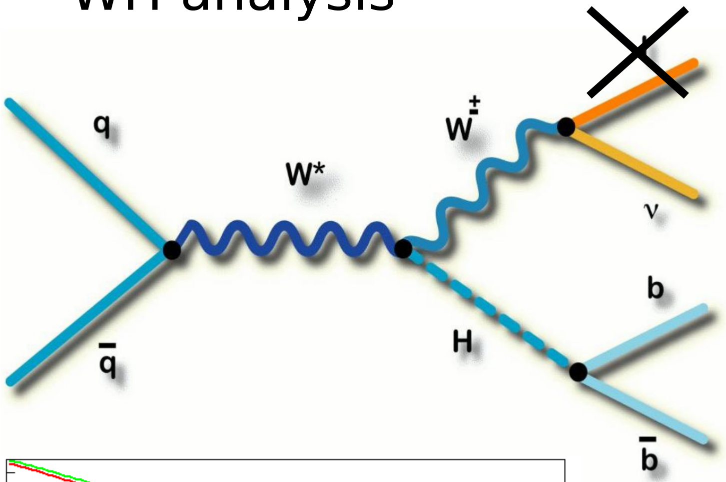


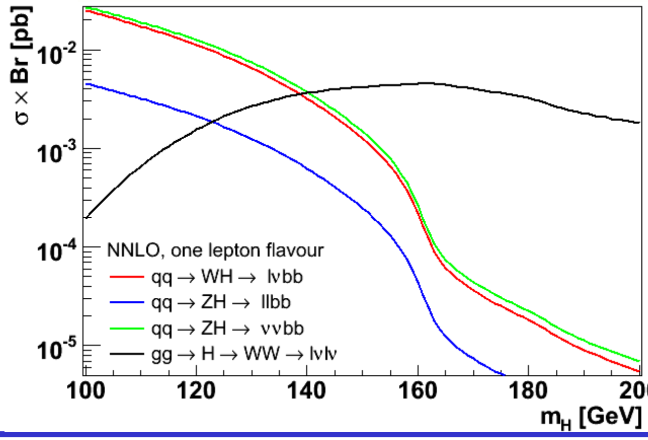
Z(→$\nu\nu$)H(→bb)

- Signature:
  - MET (=pT of Z boson)
  - 2 b-quark jets

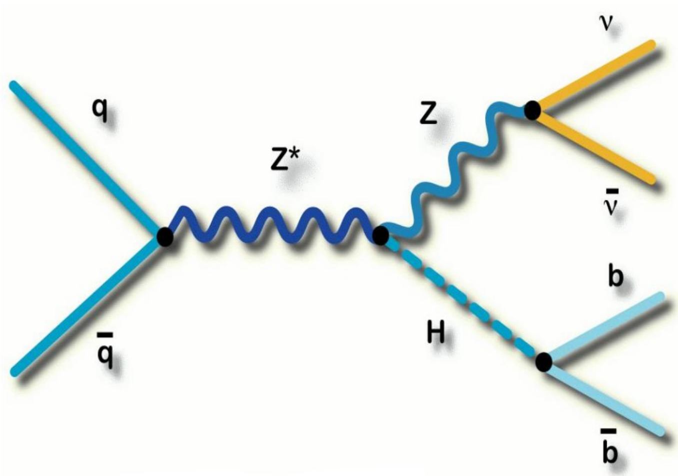


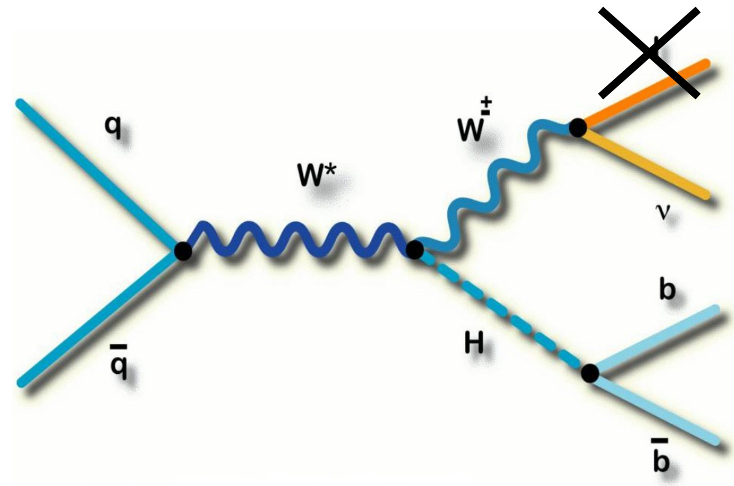
- Also sensitive to WH:
  - Where the lepton is not reconstructed/identified
  - Complementary with the WH analysis

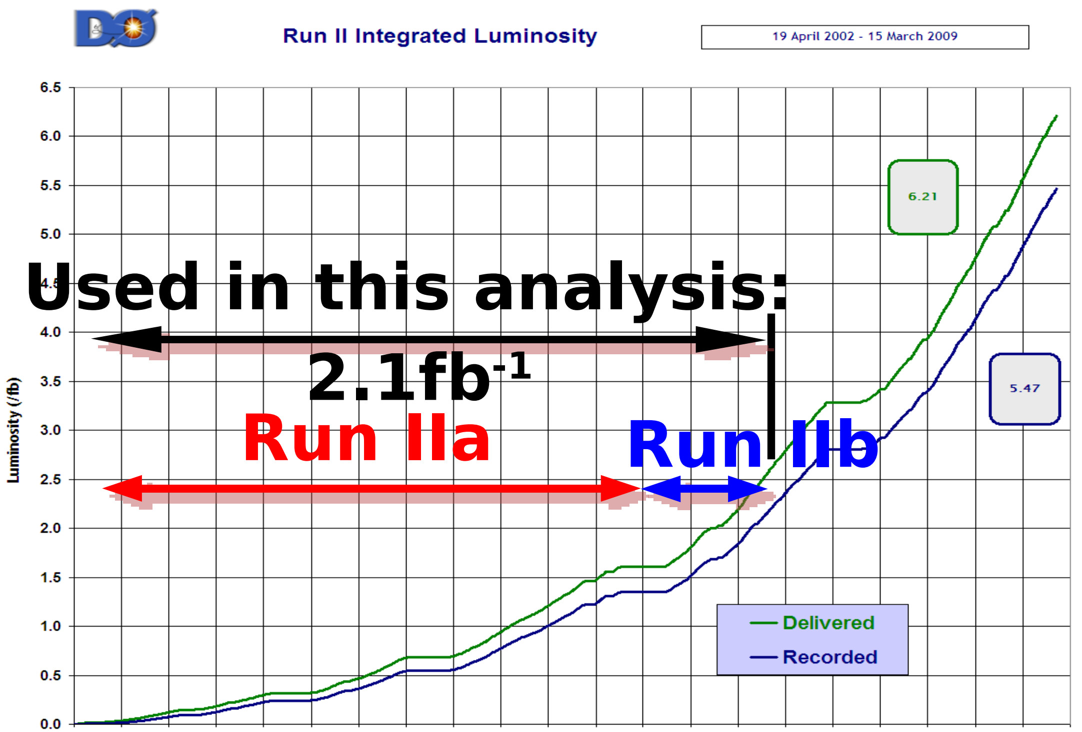




Z(→$\nu\nu$)H(→bb)





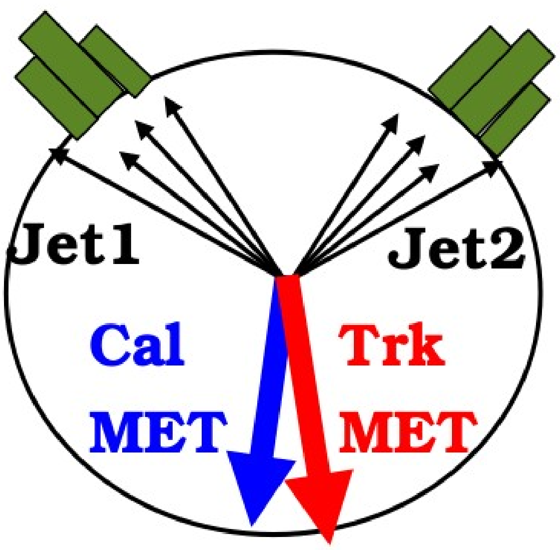


- 2.1 fb^{-1} of data, divided into 2 parts:
  - Run IIa
  - Run IIb

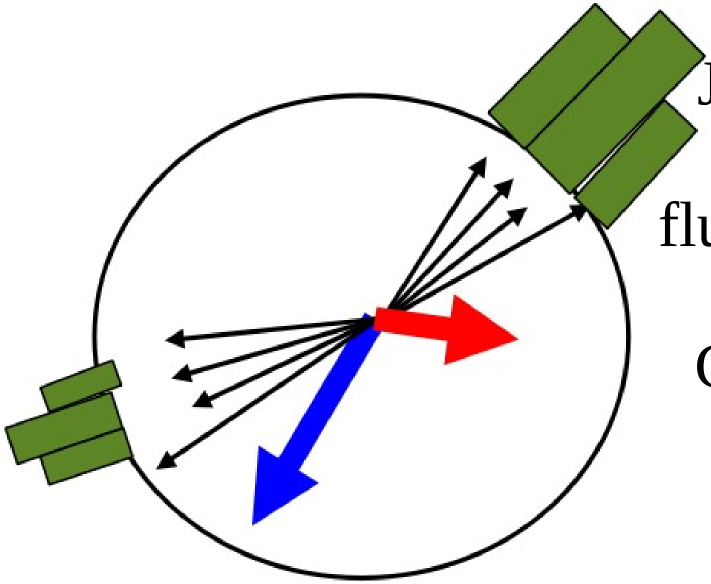
$Z(\to\nu\nu)H(\to bb)$

- Good trigger (jets+MET) modeling is crucial

- Multijet background:
  - In analysis sample:
    cut: $\Delta\varphi$(calorimetric MET, MET from tracks)<$\pi/2$
  - Multijet background estimated from data with $\Delta\varphi>\pi/2$:



$\Delta\varphi<\pi/2$

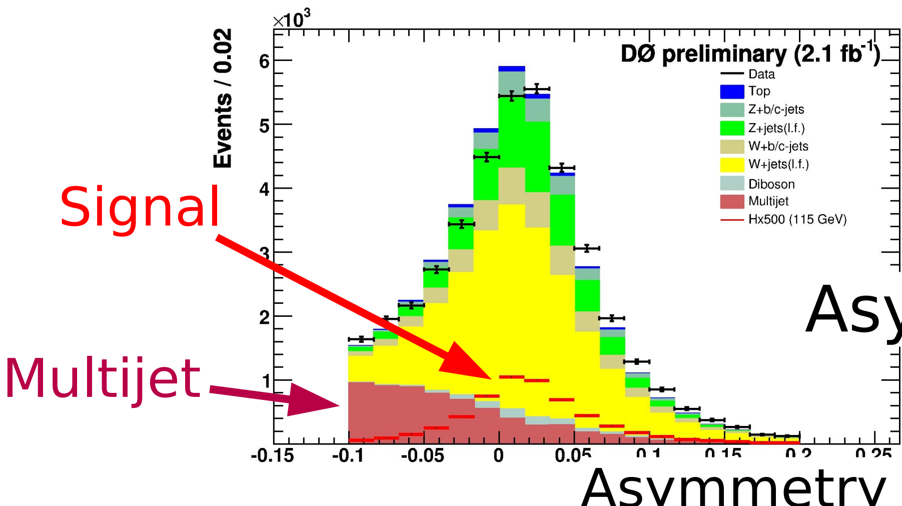


$\Delta\varphi>\pi/2$

Jet whose energy fluctuates up → fake Cal. MET

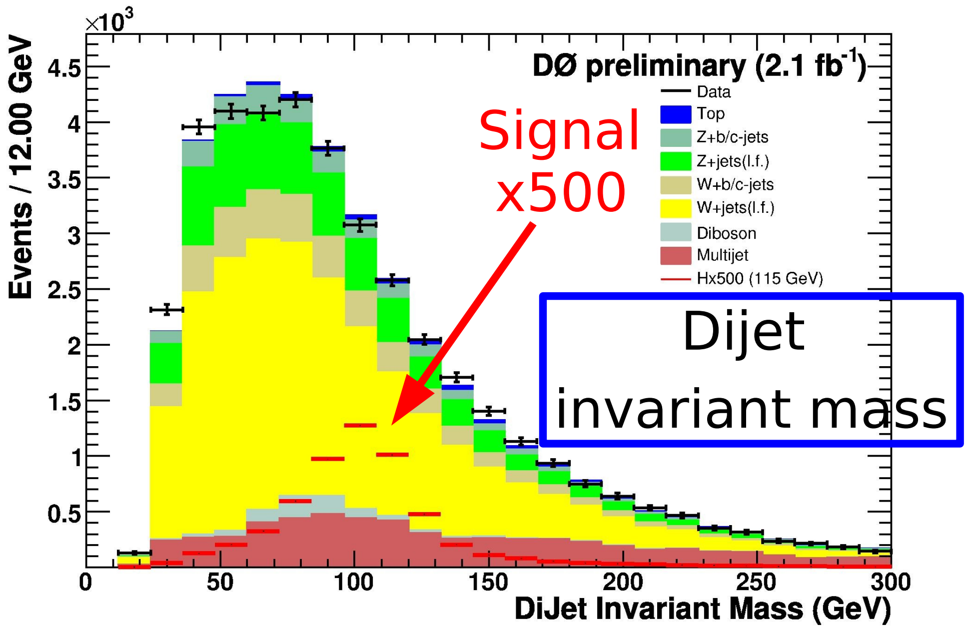
Z(→$\nu\nu$)H(→bb): Selection

- $\Delta\varphi$(calorimetric MET, MET from tracks)<$\pi/2$
- 2 or 3 jets (pT>20 GeV)
- $\Delta\varphi$(jet1, jet2)<165° → against multijet bckgrd
- MET: → against multijet bckgrd
  - MET>50 GeV,
  - MET>80-40x$\Delta\varphi_{min}$(MET, jet)
- Veto on *e* and μ → against W→lν
- -0.1<Asymmetry<0.2 → against multijet bckgrd

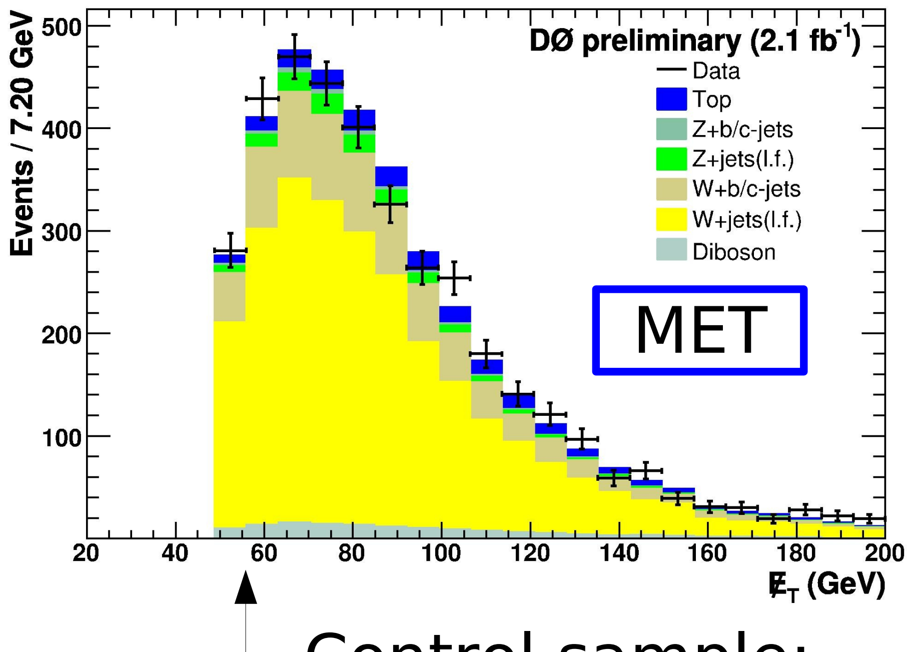


$$\text{Asymmetry} = \frac{\text{MET} - |\Sigma \vec{pT}_{jet}|}{\text{MET} + |\Sigma \vec{pT}_{jet}|}$$

Good agreement after selection



Analysis sample

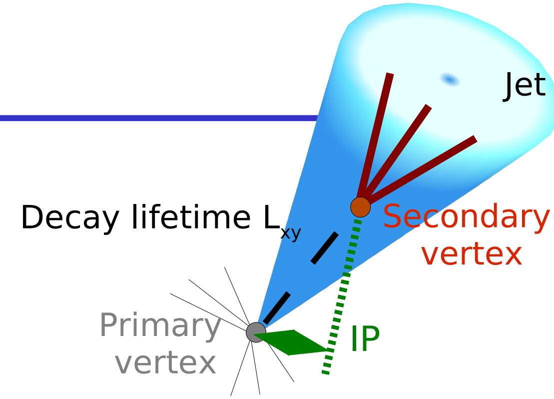


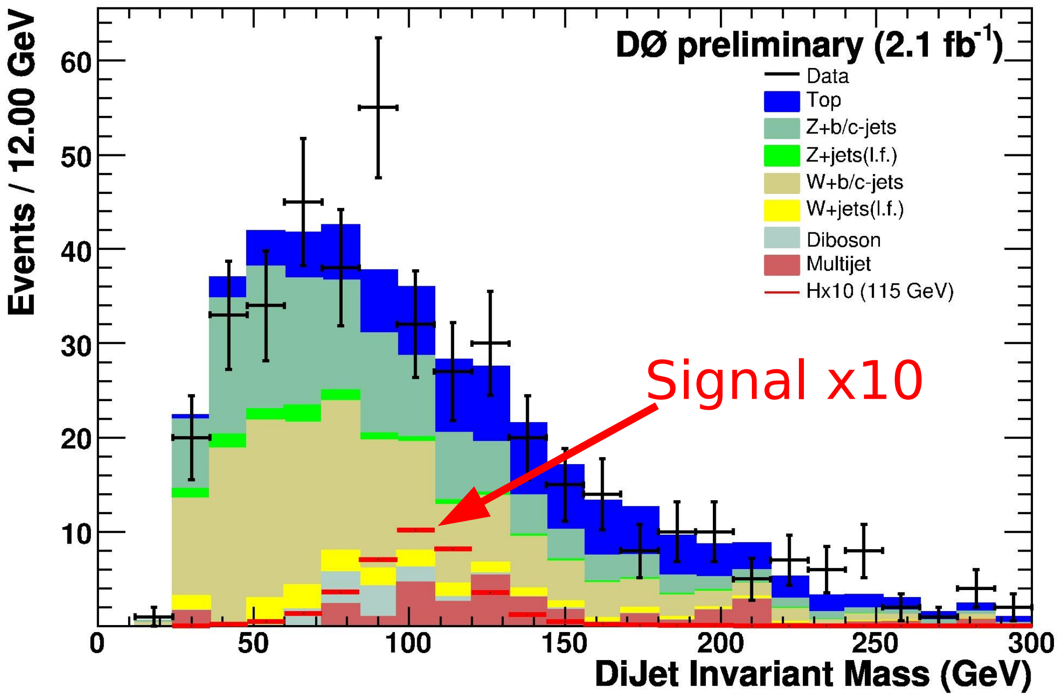
Control sample:

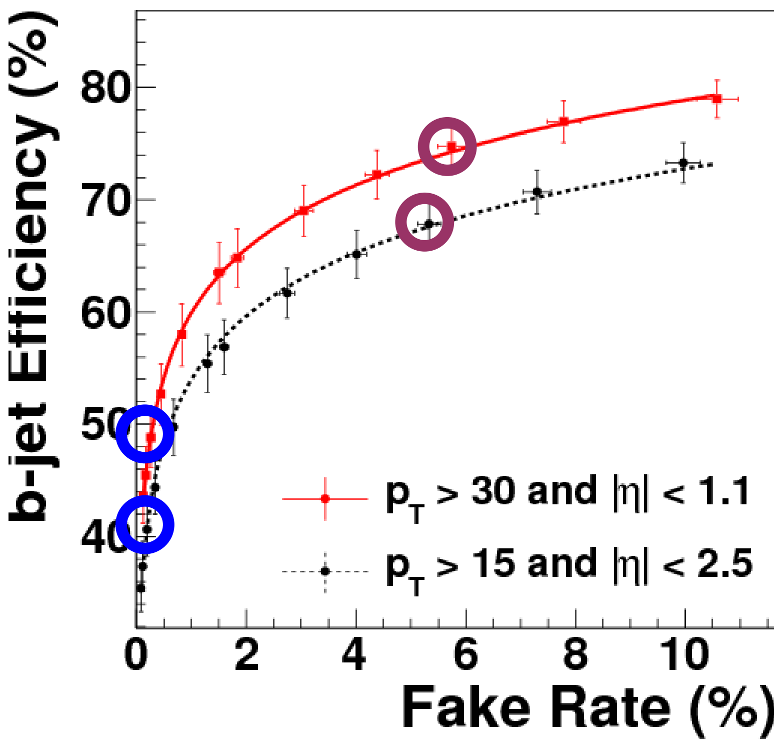
Same as analysis but require one μ

b-tagging

- 1 **tight** and 1 **loose** b-tagged jet

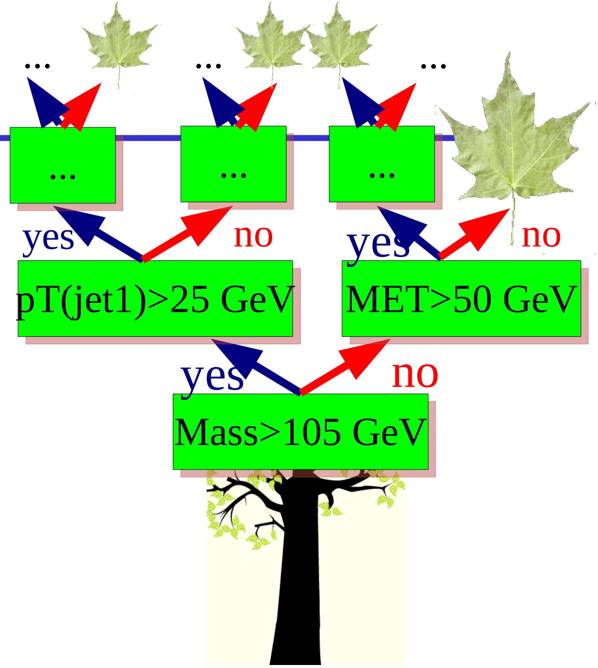




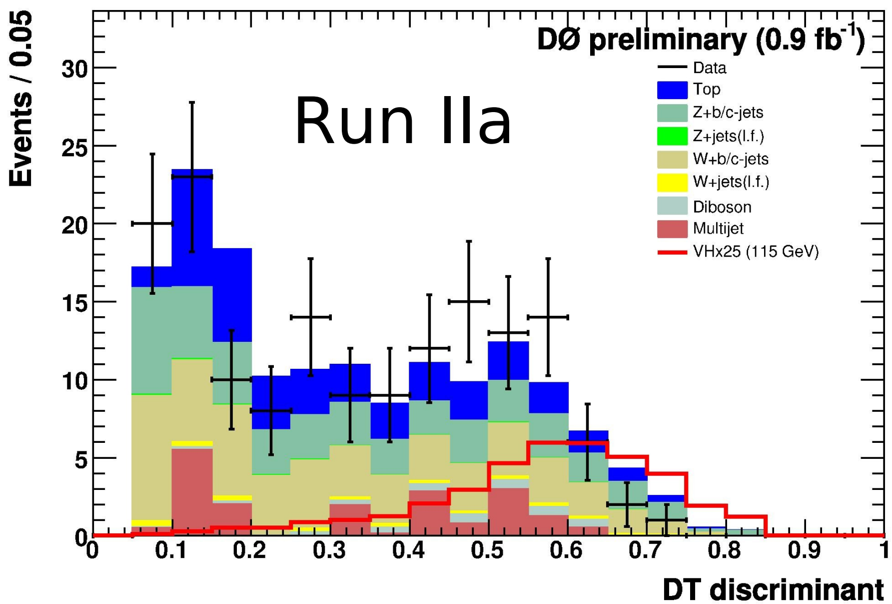


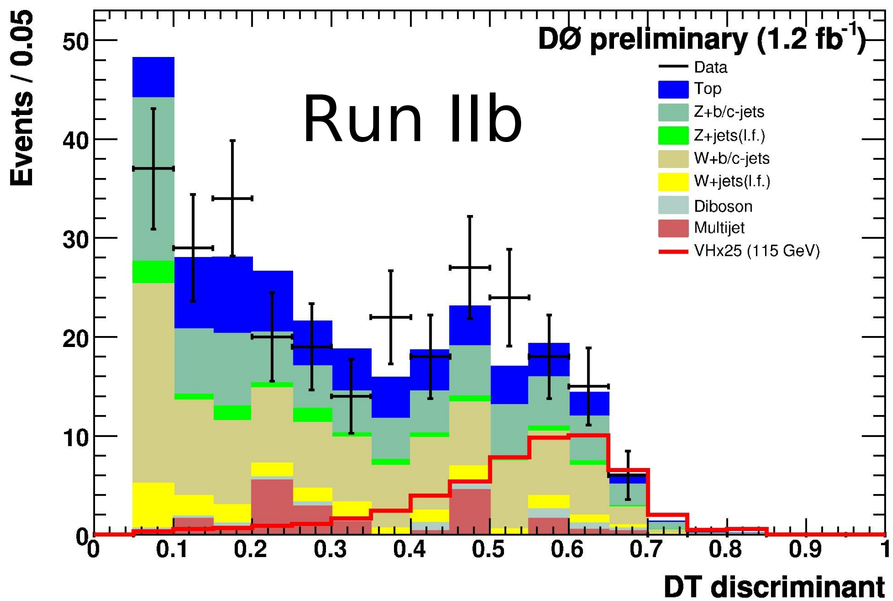
Dijet invariant mass after b-tagging

Boosted decision tree



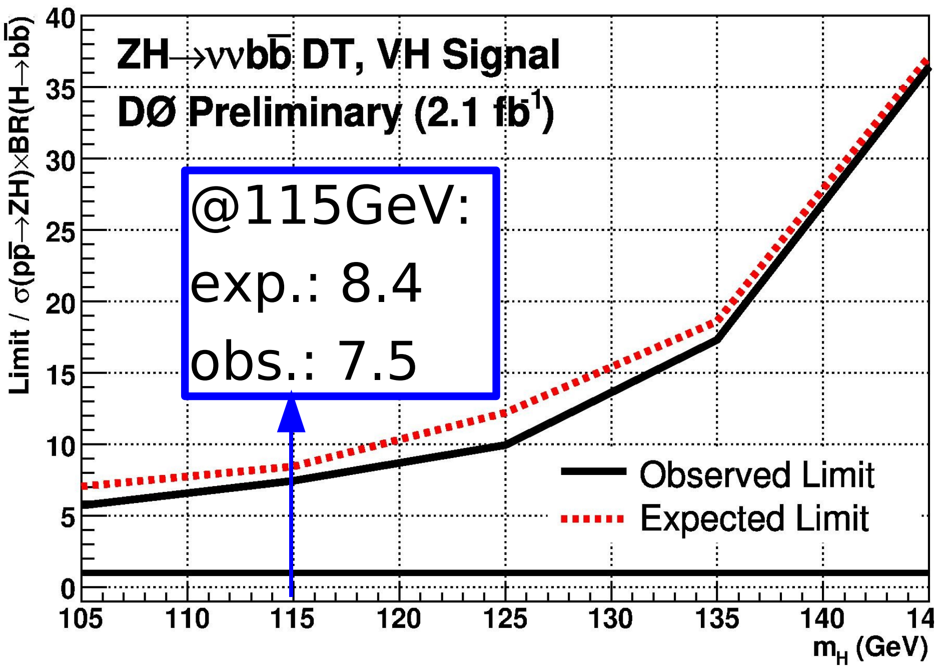
- Build BDT for each data taking period
- Example of used variables:
  - MET, ΣpT_{jet}, $\overrightarrow{\Sigma pT}_{jet}$
  - $\Delta\varphi_{min}$(MET, jets), $\Delta\varphi_{max}$(MET, jets)
  - $\Delta\varphi$(jet1, jet2), ΔR(jet1, jet2)
  - Di-jet invariant mass
  - ...

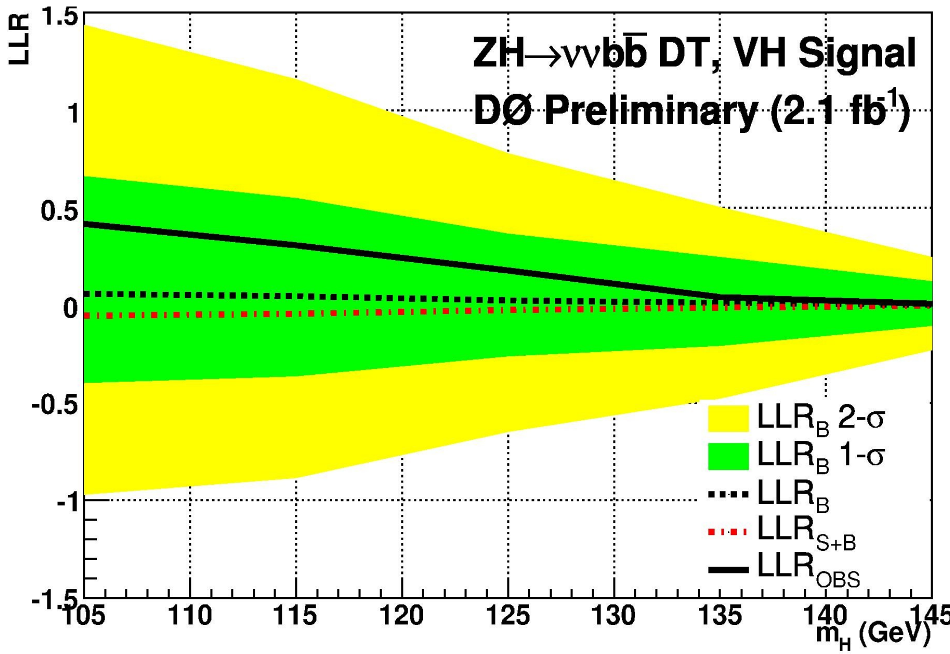




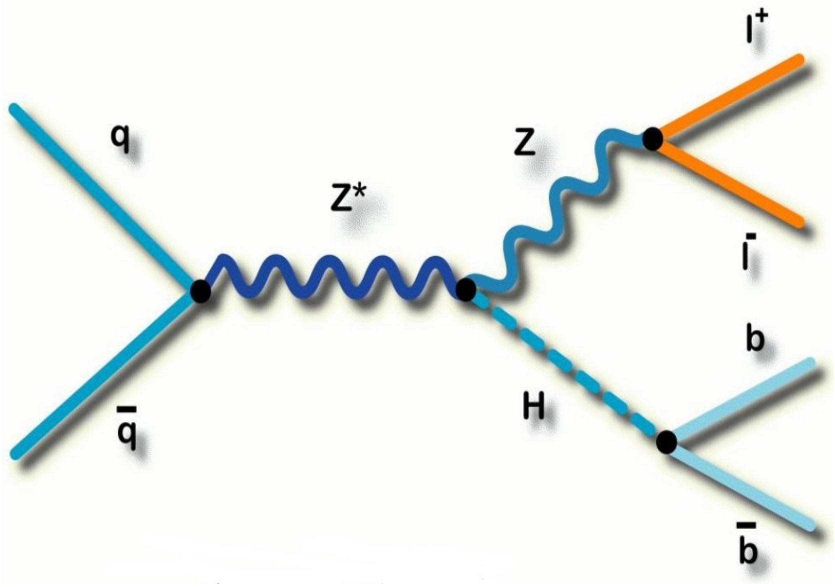
Results

- Main systematics:
  - Cross-sections: 6% (signal), 6-16% (background)
    - Fractions of W+bb/cc in W+jets: 50%
  - Lumi: 6.1%
  - B-tagging: 6%
  - Trigger: 5.5%
- No excess wrt. background expectation → set a limit:

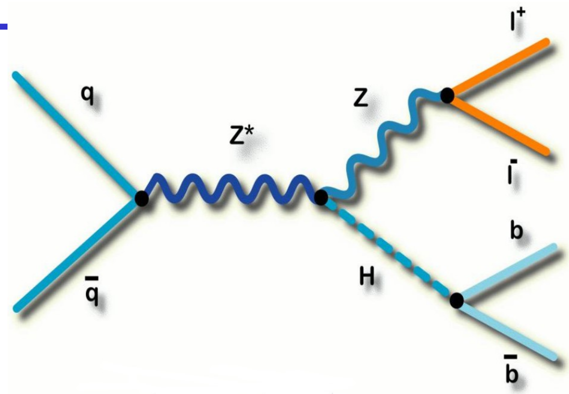




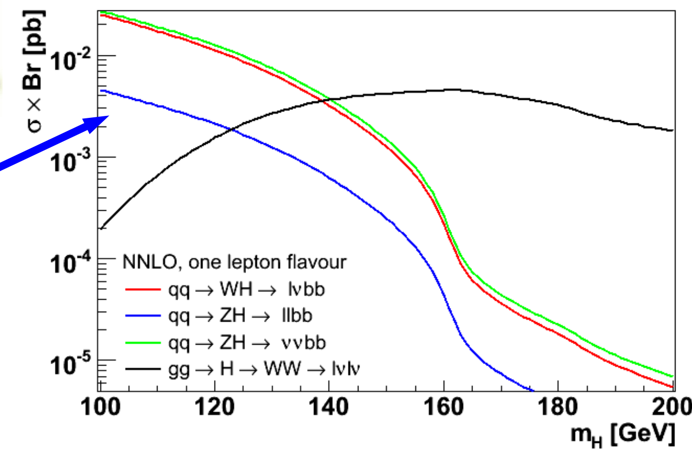
$Z(\to ll)H(\to b\bar{b})$



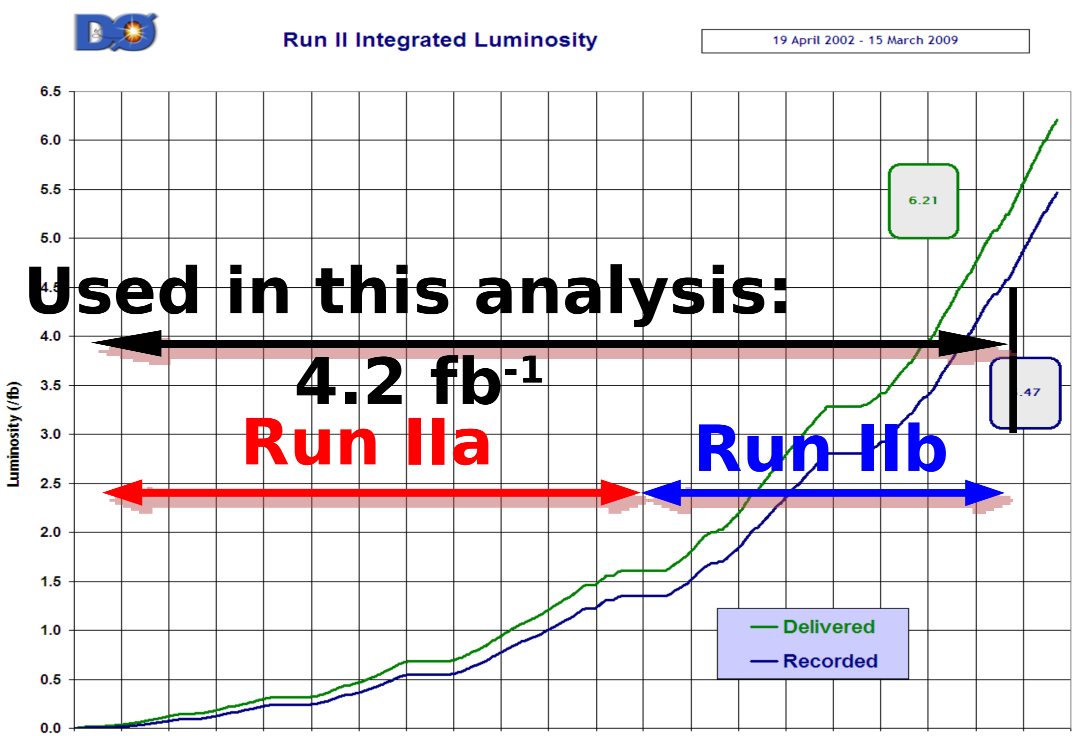
Z(→ll)H(→bb)



- Clear signature
  - 2 leptons (e or μ)
  - 2 b-quark jets



- Low background…
- … but production rate is low



- 4.2 fb -1 of data, divided into 2 parts:
  - Run IIa
  - Run IIb

Z(→ll)H(→bb): Selection

- $\geq$2 jets (pT1>20, pT2>15 GeV)
- Electron channel:
  - 2 electrons, pT>15 GeV
    - $|\eta_{det}|<1.1$ or $1.5<|\eta_{det}|<2.5$
      - Shower shape criteria
      - Matched to a track
    - Or in gap : $1.1<|\eta_{det}|<1.5$
      - Tau NN inspired criteria
  - Di-electron mass: 70<M<110 GeV

Z(→ll)H(→bb): Selection

- ≥2 jets (pT1>20, pT2>15 GeV)
- Electron channel:
  - 2 electrons, pT>15 GeV
    - $|\eta_{det}|<1.1$ or $1.5<|\eta_{det}|<2.5$
      - Shower shape criteria
      - Matched to a track
    - Or in gap : $1.1<|\eta_{det}|<1.5$
      - Tau NN inspired criteria
  - Di-electron mass: 70<M<1
- Muon channel:
  - 2 muons, pT>10 GeV
    - Isolation Mu1*Isolation Mu2 < 0.03
  - Or 1 muon (pT>10 GeV) + 1 track (pT>20 GeV)
    - Isolation Mu*Isolation track < 0.01
  - Di-muon mass: 70<M<130 GeV, opposite sign

$$\text{Isolation}=\frac{\overbrace{\Sigma pT_{tracks}+\Sigma E_T(\text{cells in calo.})}^{\text{In a cone centered on the muon}}}{pT_{muon}}$$

Z(→ll)H(→bb): instrumental background

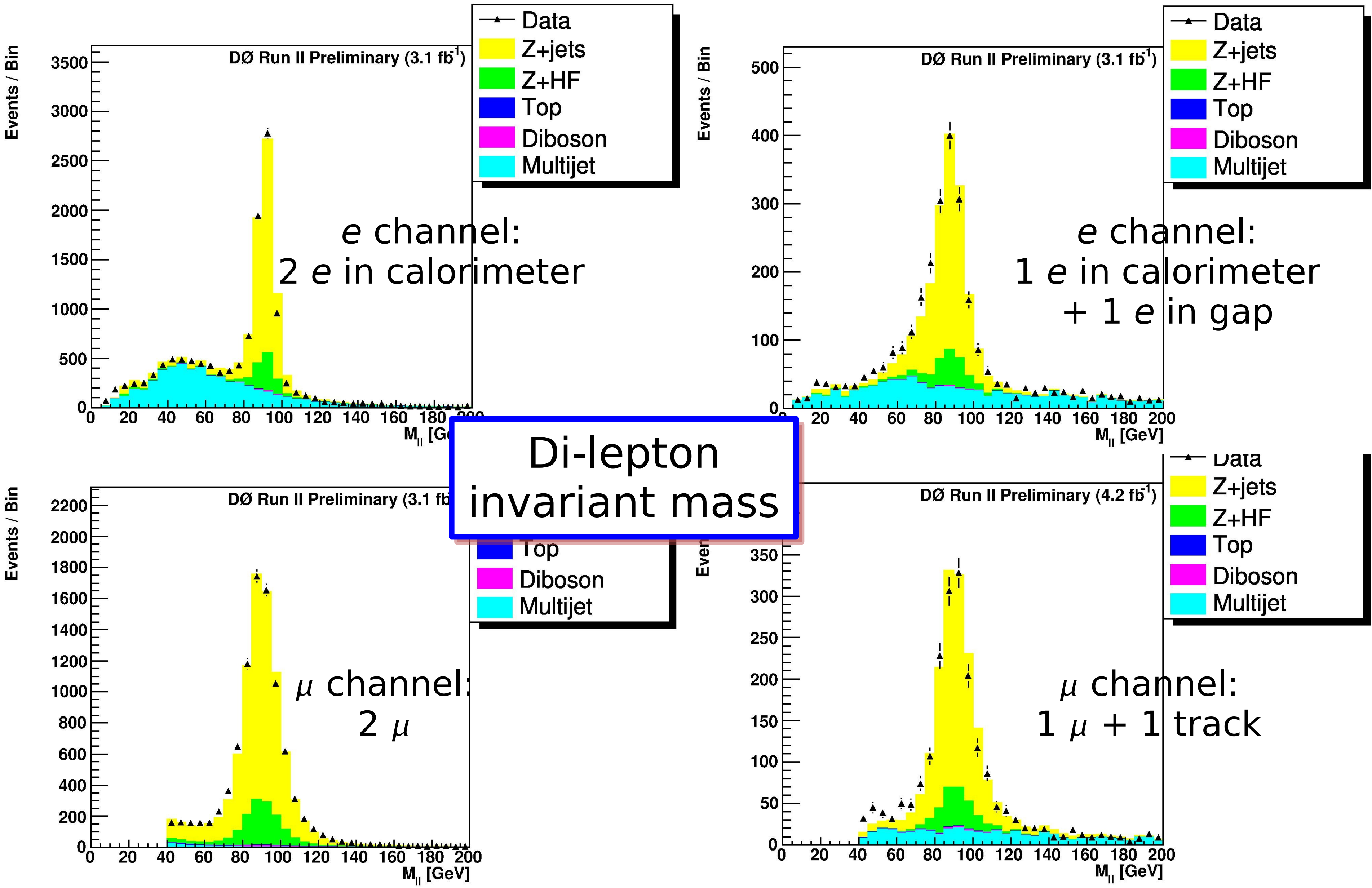
- ≥2 jets (pT1>20, pT2>15 GeV)
- Electron channel:
  - 2 electrons, pT>15 GeV
    - $|\eta_{det}|<1.1$ or $1.5<|\eta_{det}|<2.5$
      - Shower shape criteria
      - Matched to a track
    - Or in gap : $1.1<|\eta_{det}|<1.5$
      - Tau NN inspired criteria
  - Di-electron mass: 70<M<110 G
- Muon channel:
  - 2 muons, pT>10 GeV
    - Isolation Mu1*Isolation Mu2 <
  - Or 1 muon (pT>10 GeV) + 1 track (pT>20 GeV)
    - Isolation Mu*Isolation track < 0.01
  - Di-muon mass: 70<M<130 GeV, opposite sign

Estimated from data

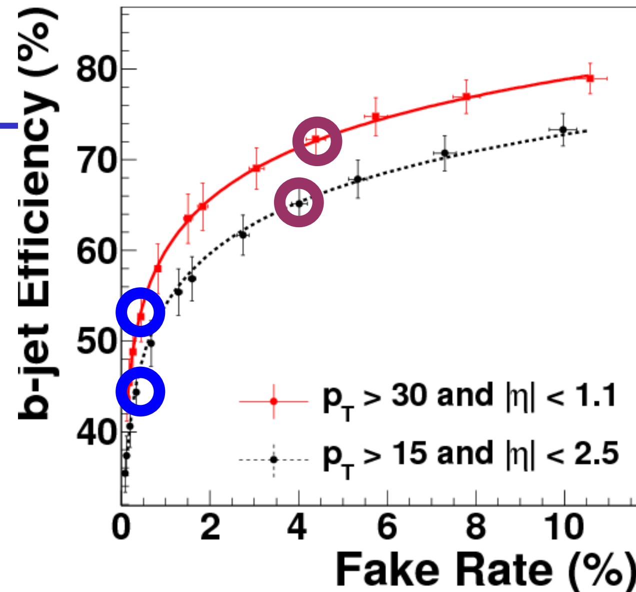
Electron channel:
- Same sign electrons
- Invert the shower shape criteria
- Invert the NN criteria

Muon channel:
- Invert the isolation cut
- Track and Mu with same sign

Good agreement after selection

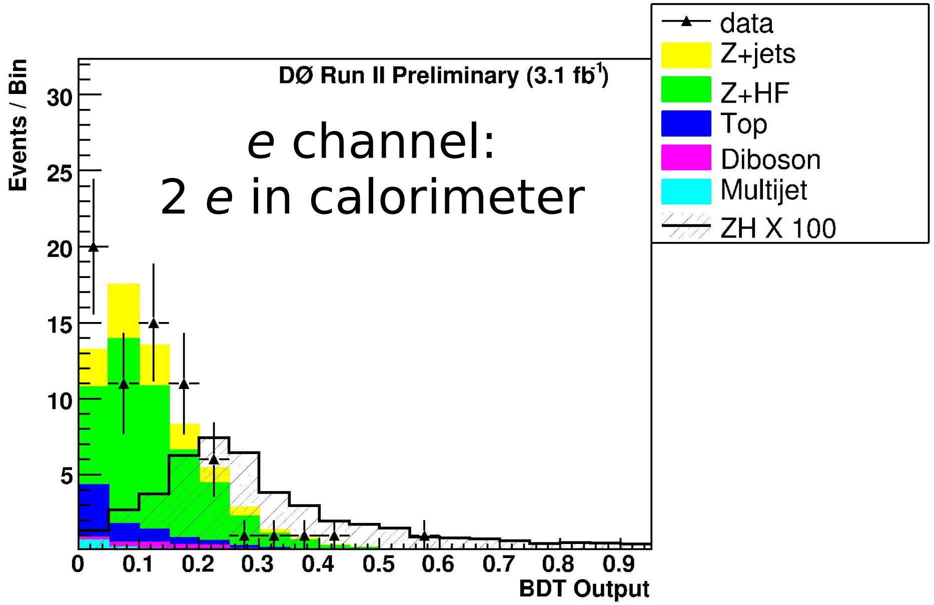


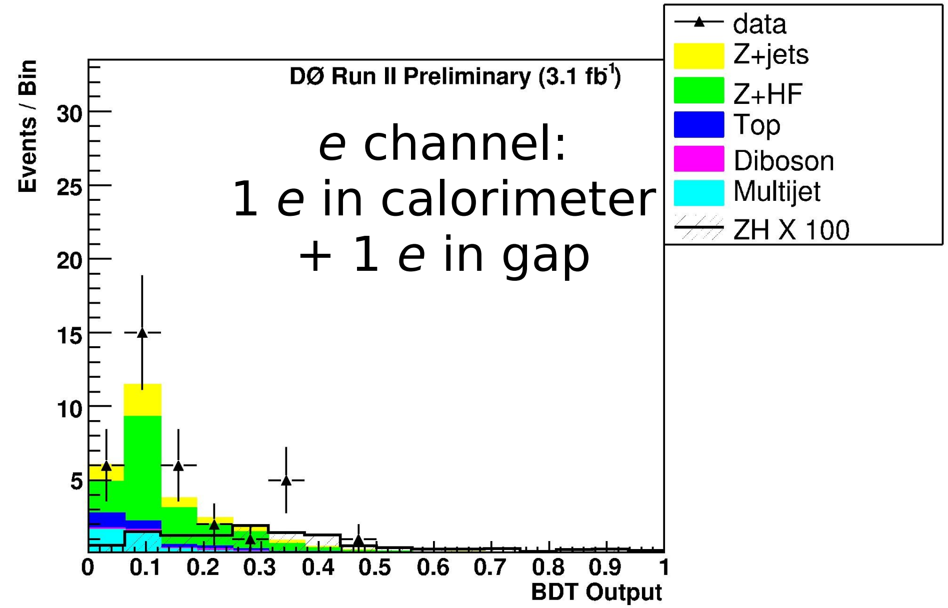
B-tagging, KF, BDT



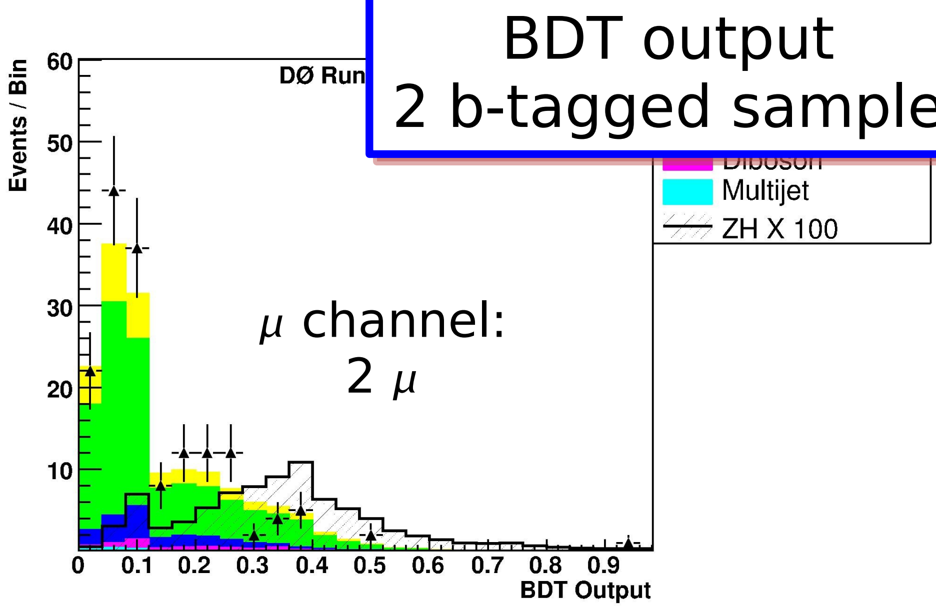
- Form 2 exclusive samples:
  - 2 **loose** b-tagged jets
  - 1 **tight** and 0 loose b-tagged jet
- Kinematic fitting
  - Allow energies and angles to fluctuate according to the detector resolution → minimize the χ^2 under the constraints:
    - Di-lepton mass: $M_Z \pm \Gamma_Z$
    - Momentum in the transverse plan of HZ system: 0 ± 7 GeV
- Boosted Decision Tree for each b-tagged sample:
    - pT, η, invariant mass of the jets
    - $\Delta\eta$(jet1, jet2), $\Delta\varphi$(jet1, jet2), ...
    - ΔR(lep1, lep2), $\Delta\varphi$(lep1, lep2), ...
    - Spin correlations, ...

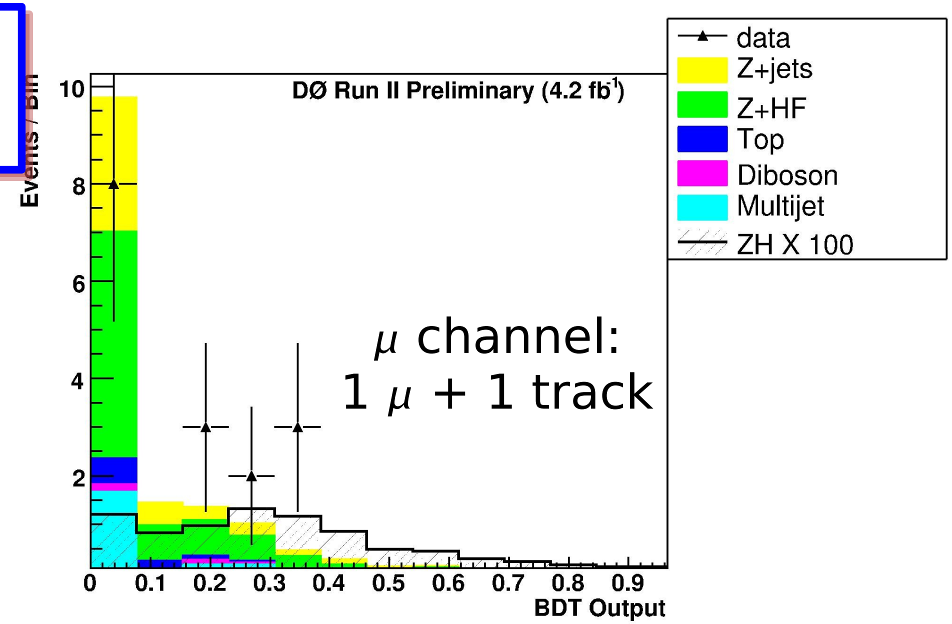
After multivariate discriminants





BDT output
2 b-tagged sample

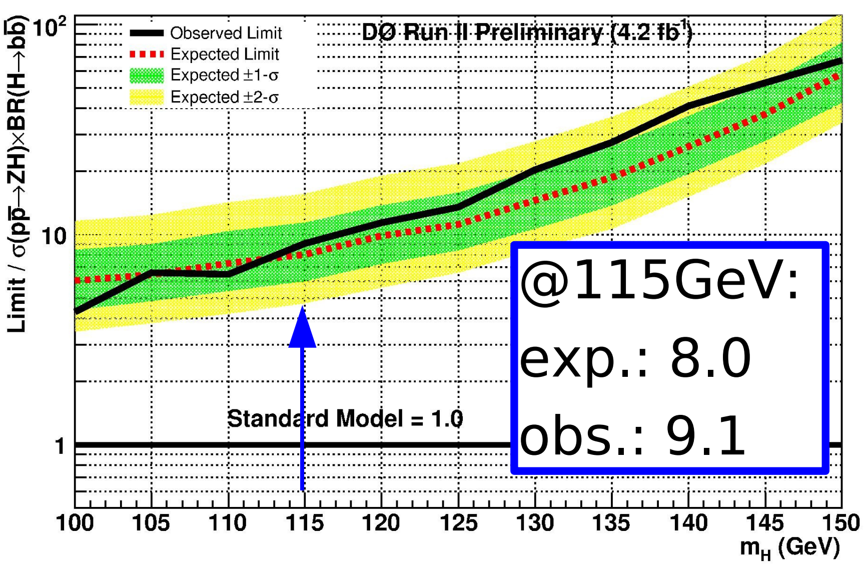


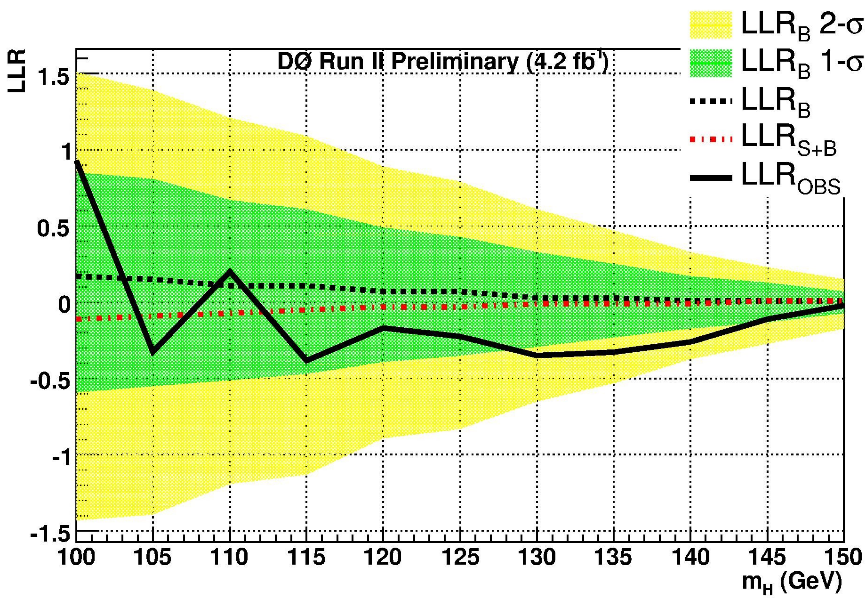


Results

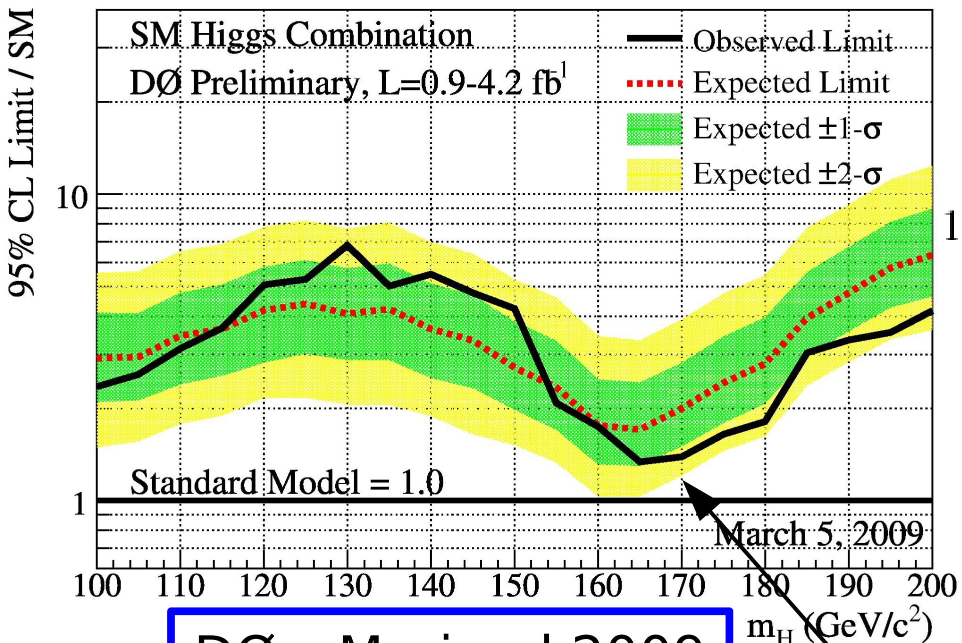
- Main systematics:
  - Cross-sections
    - Z+jets: 10%
    - Z+bb/cc: 30%
  - Lumi: 6.1%
  - Multijet background: 20%(ee)-50%($\mu\mu$)

- No excess wrt. background expectation → set a limit:

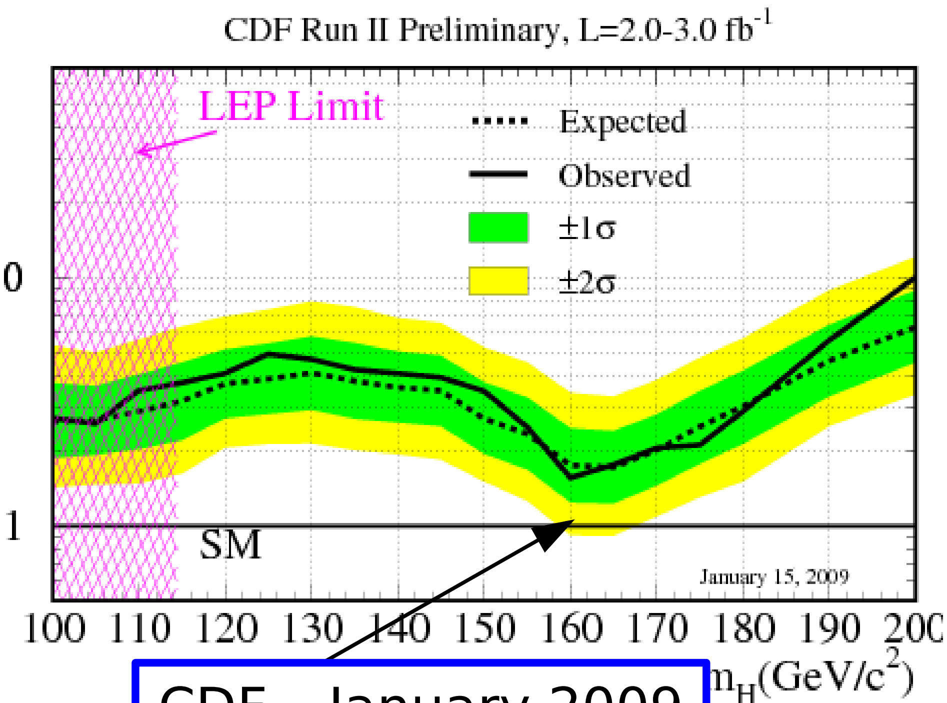




Combination



DØ – Moriond 2009



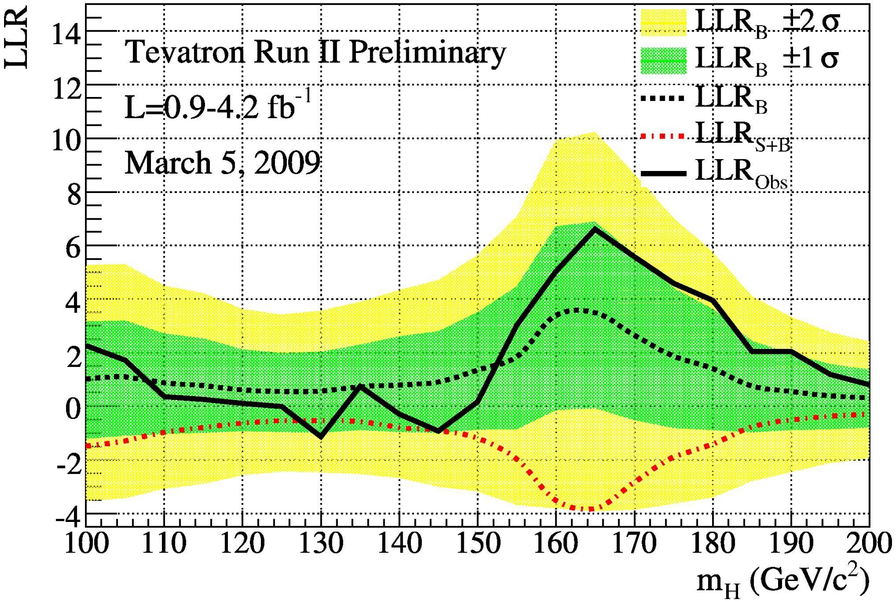
CDF – January 2009

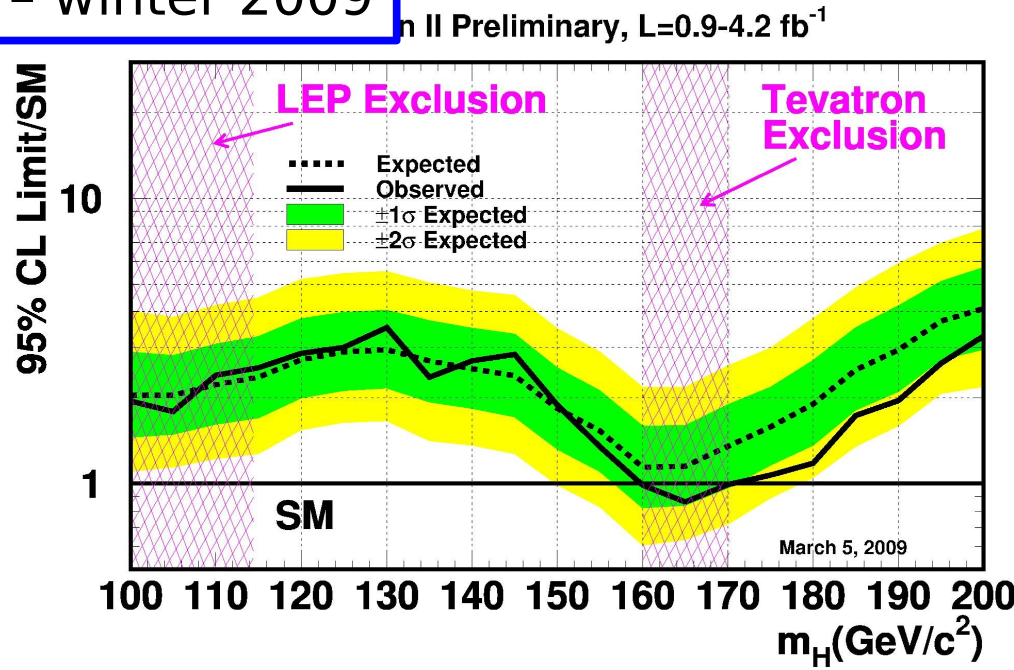
Exp. (obs.) @115 GeV:
DØ: 3.6 (3.7) xSM
CDF: 3.2 (3.8) xSM

Close to the exclusion @~160 GeV
for each experiment

Combination

Tevatron – winter 2009

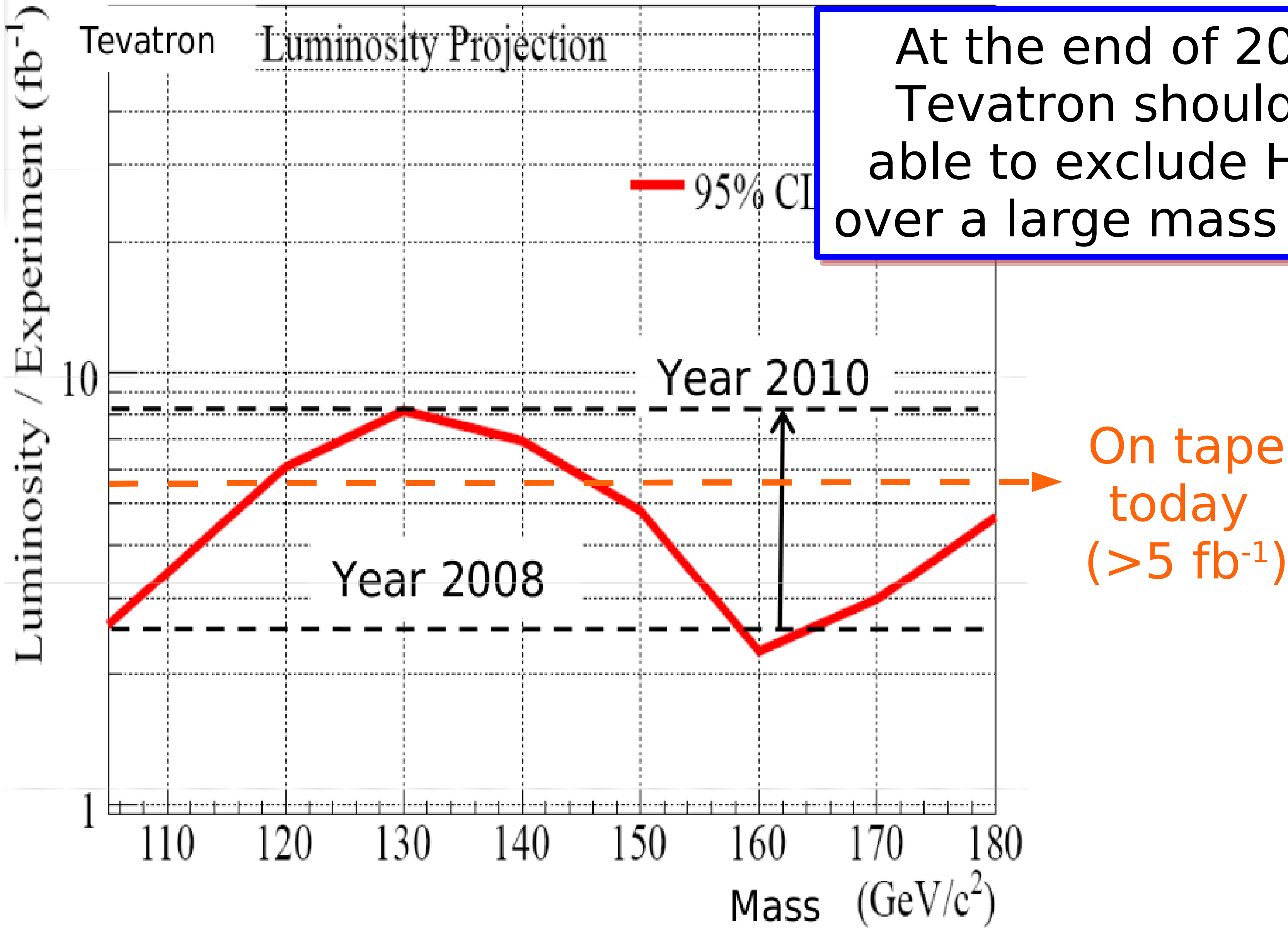




160-170 GeV exclusion !

Prospective

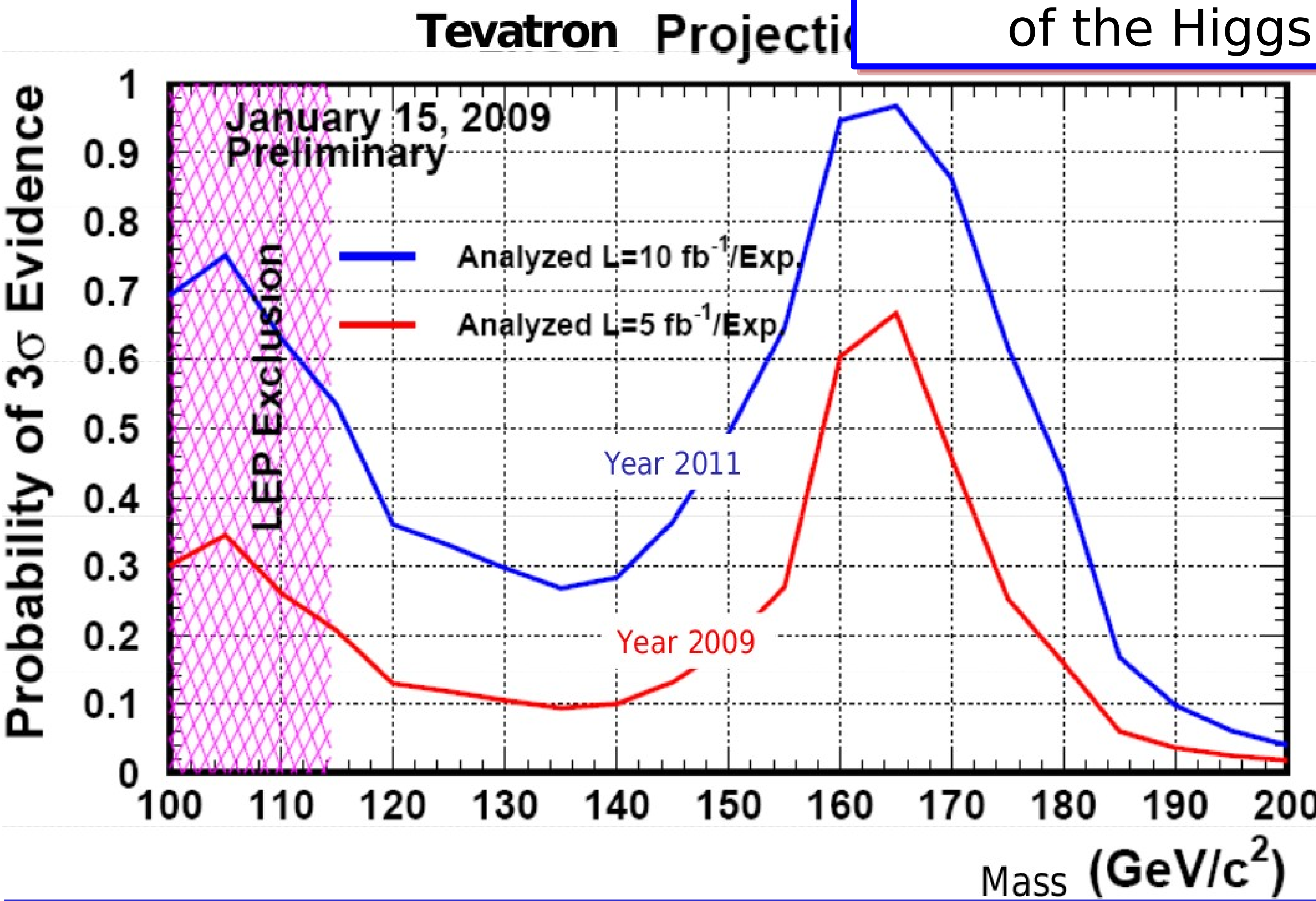
Exclusion potential @ Tevatron



At the end of 2010, Tevatron should be able to exclude Higgs over a large mass range

Evidence potential @ Tevatron

... or to see a evidence of the Higgs



Conclusion

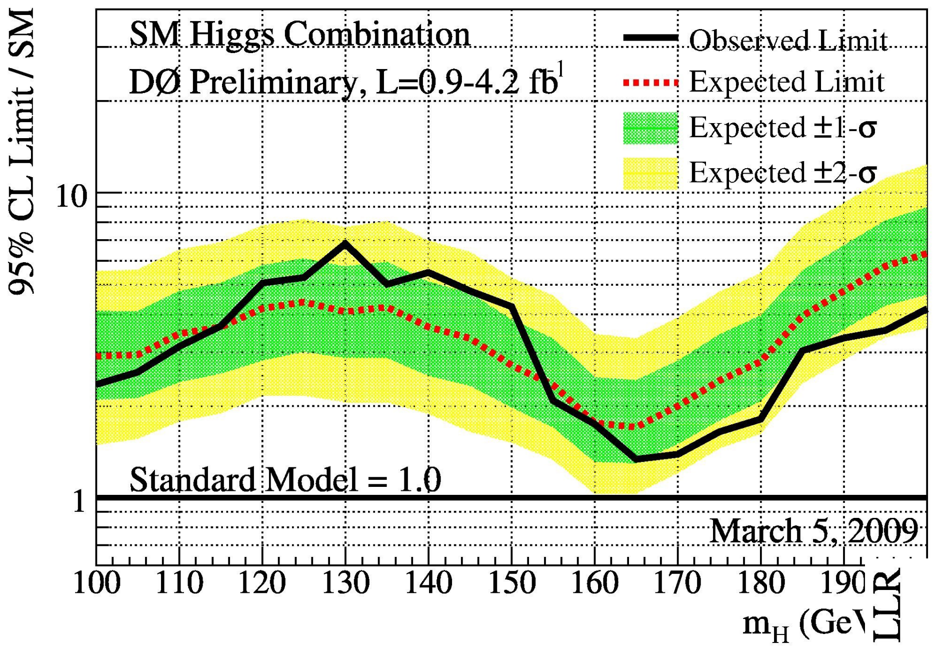
- Nice results
  - WH [2.7 fb^{-1}]
  - $ZH \rightarrow \nu\nu bb$ [2.1 fb^{-1}]
  - $ZH \rightarrow llbb$ [4.1 fb^{-1}]

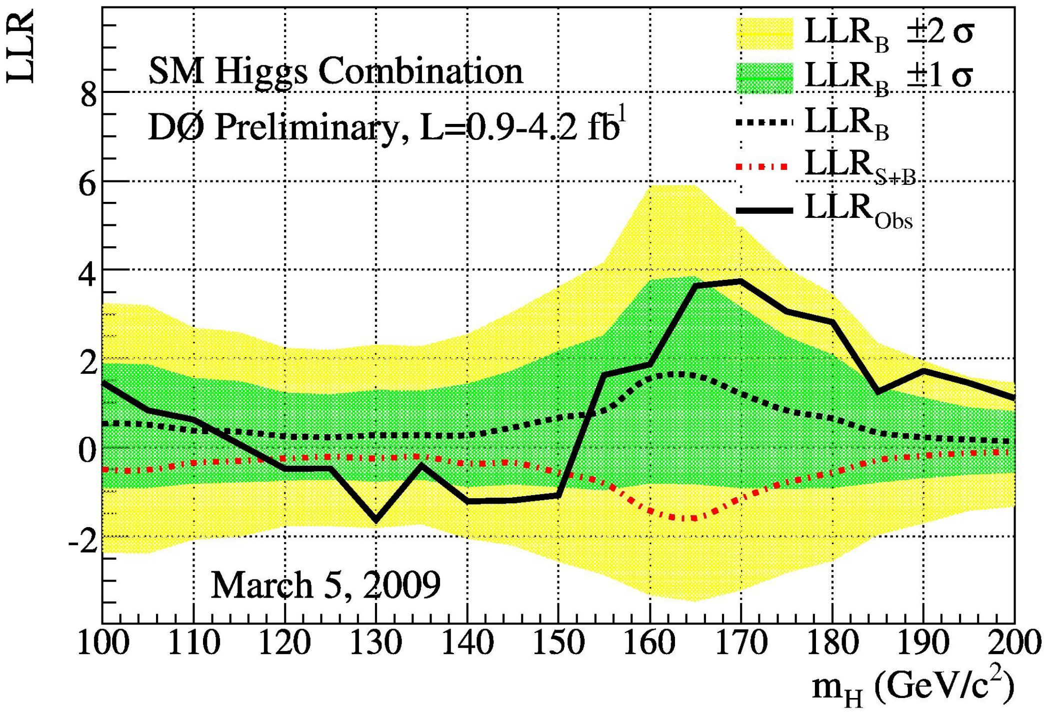
- Improvements underway
  - Further improvements in lepton identification
  - Improvements in b-tagging (e.g., b/c separation)
  - ...
  - Additional integrated luminosity [>5 fb^{-1}]

- Evidence of Higgs boson is possible

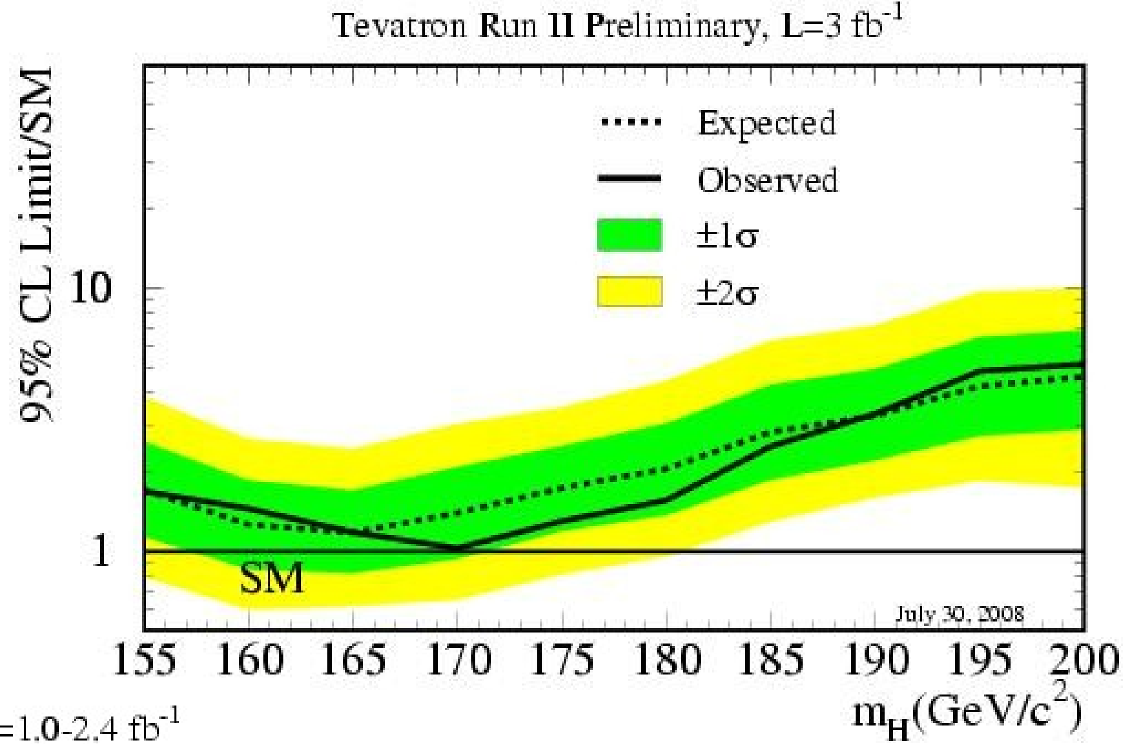
Backup

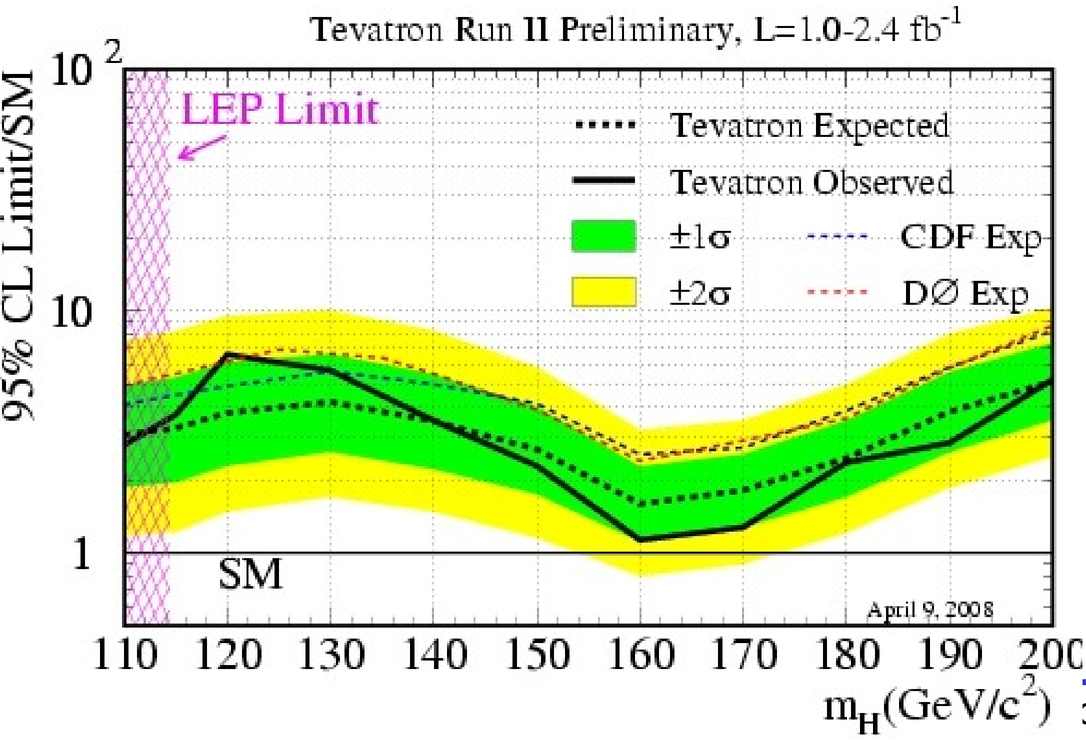
Combination

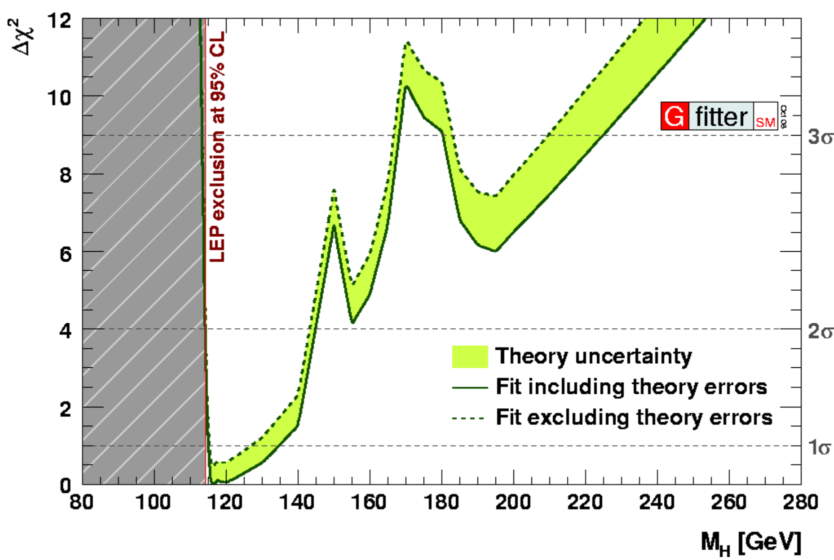




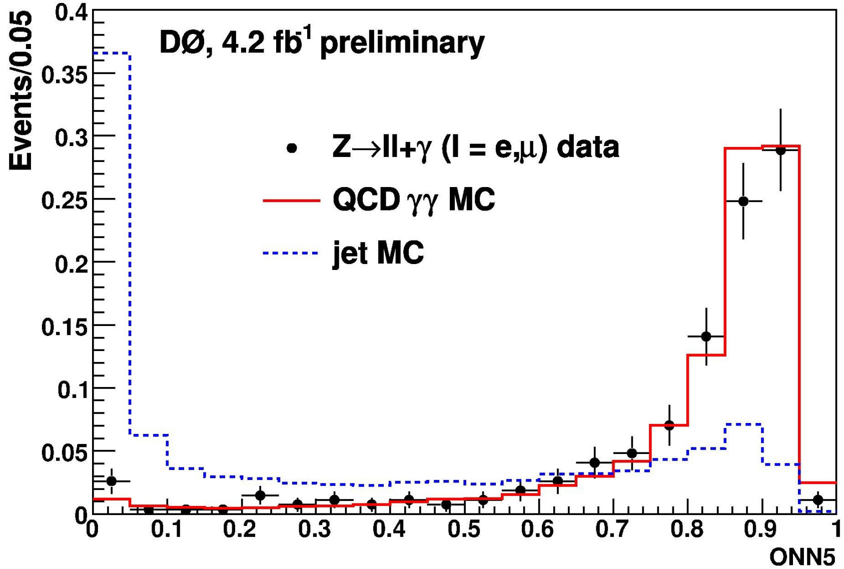
Exclusion limits

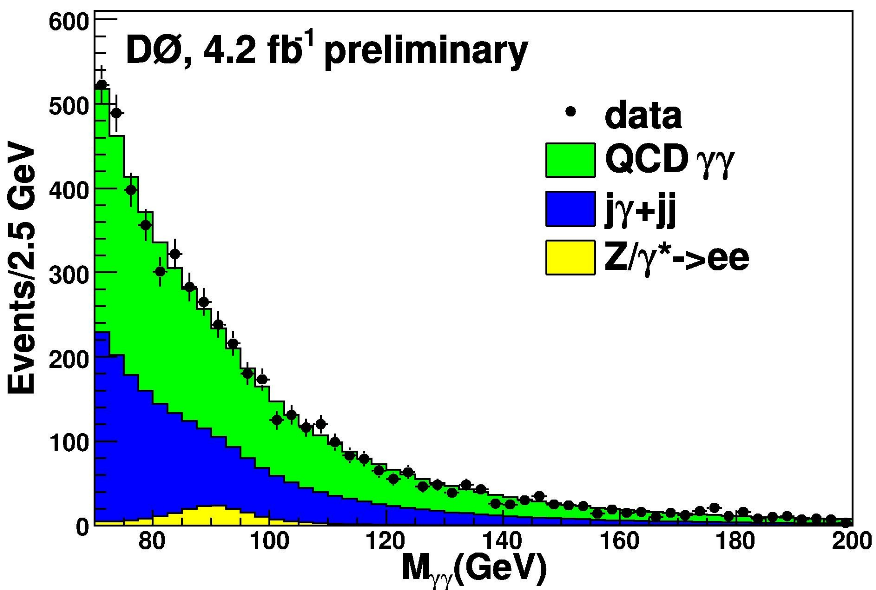


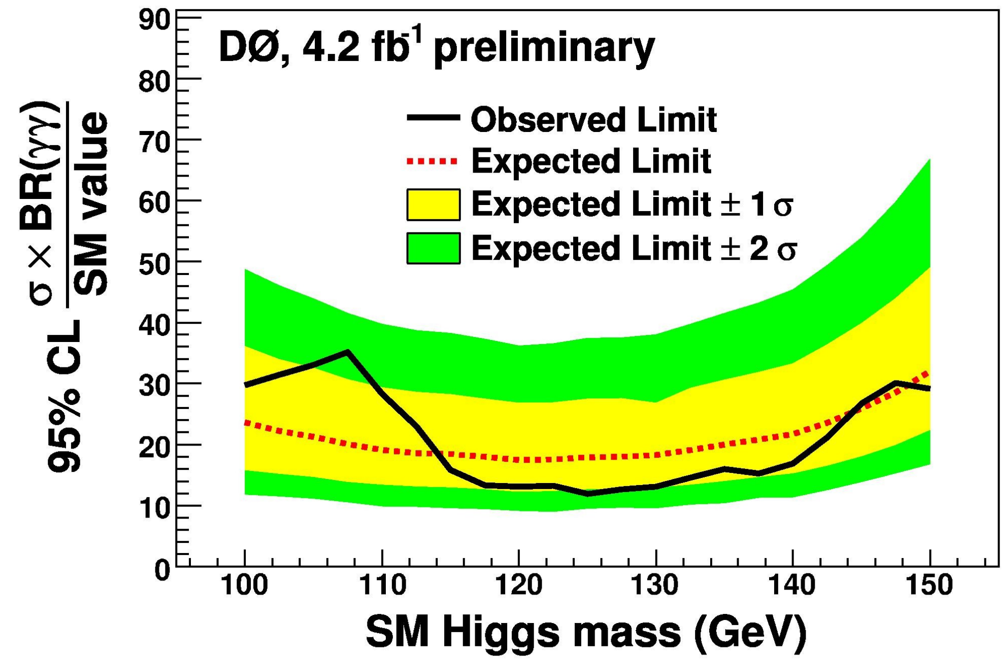




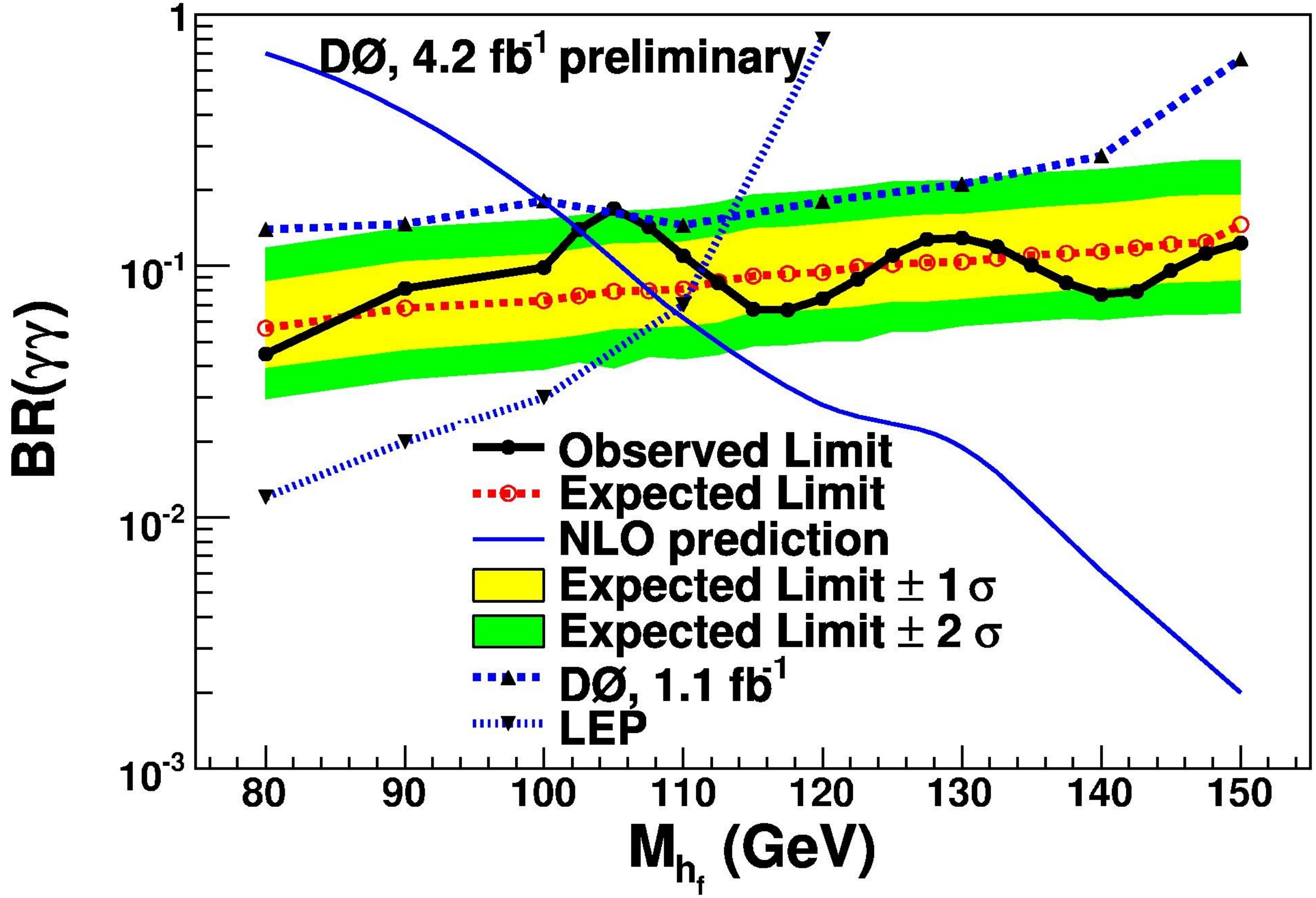
H → $\gamma\gamma$



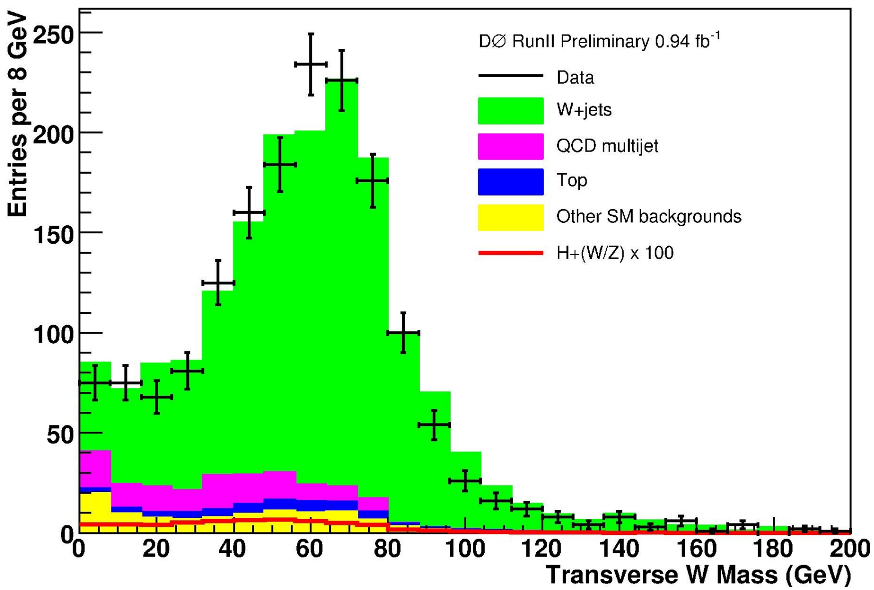


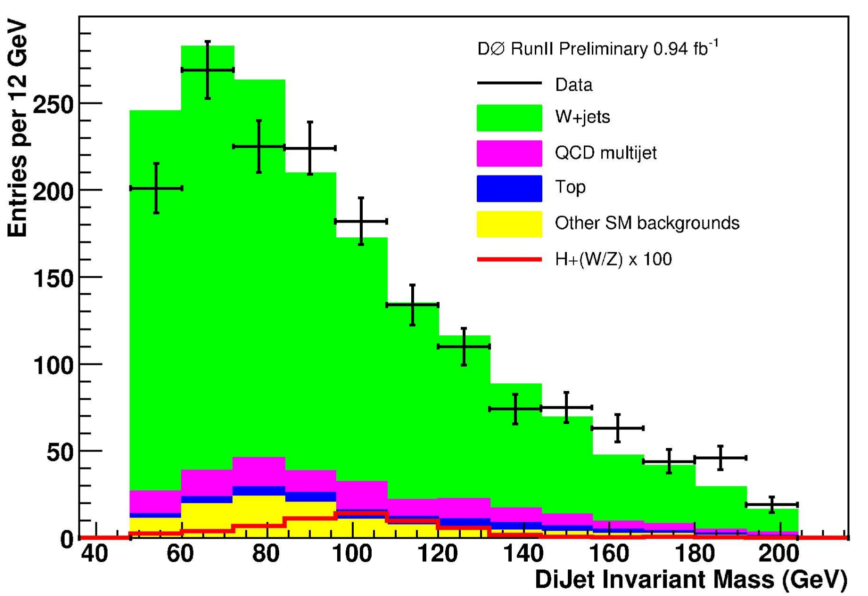


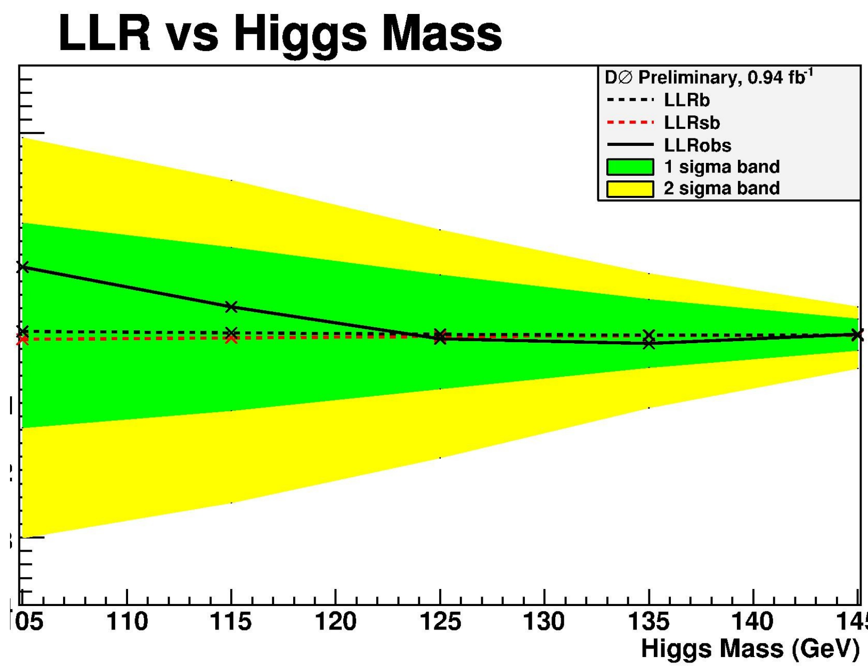
H → $\gamma\gamma$, fermiophobic



WH→$\tau\nu$bb


DØ RunII Preliminary 0.94 fb^{-1}
Data
W+jets
QCD multijet
Top
Other SM backgrounds
H+(W/Z) x 100
Entries per 8 GeV
0
50
100
150
200
250
0
20
40
60
80
100
120
140
160
180
200
Transverse W Mass (GeV)


DØ RunII Preliminary 0.94 fb^{-1}
Data
W+jets
QCD multijet
Top
Other SM backgrounds
H+(W/Z) x 100
Entries per 12 GeV
0
50
100
150
200
250
40
60
80
100
120
140
160
180
200
DiJet Invariant Mass (GeV)


LLR vs Higgs Mass
DØ Preliminary, 0.94 fb^{-1}
LLRb
LLRsb
LLRobs
1 sigma band
2 sigma band
05
110
115
120
125
130
135
140
145
Higgs Mass (GeV)