# Standard Model Higgs Boson Searches at D∅

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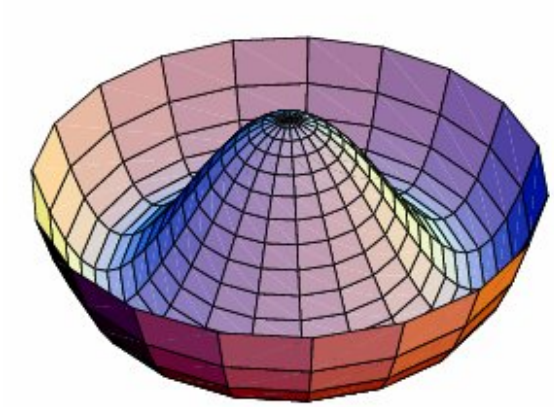
# Outline

- SM Higgs: what we know about it
- DØ detector
- Search for SM Higgs in individual channels
  - low mass: $WH \rightarrow l\nu\, bb$, $ZH \rightarrow ll\, bb$, $ZH \rightarrow \nu\nu\, bb$
  - high mass: $H \rightarrow WW \rightarrow$ leptons
  - intermediate mass: $WH \rightarrow WWW^* \rightarrow l^{\pm} l^{\pm\prime} + X$
- Combined DØ limits for SM Higgs production
- Prospects and conclusions

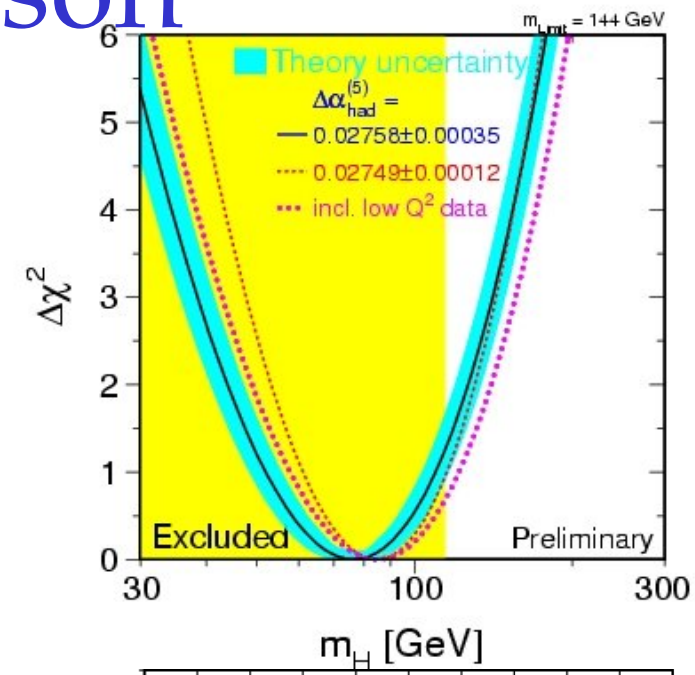
# Why Higgs ?

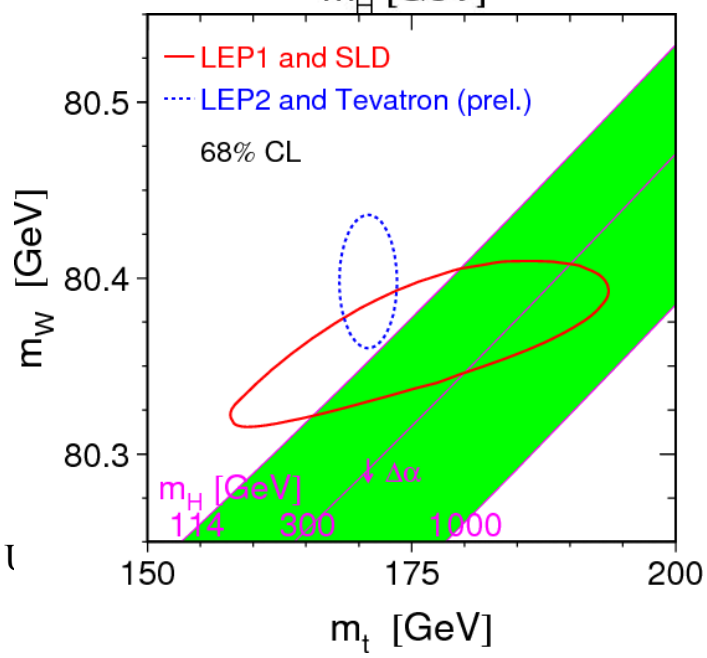
- W and Z bosons are massive
  - EW symmetry must be broken
- The simplest EWSB mechanism involves addition of two complex (Higgs) scalar fields
- When symmetry breaks down, these fields acquire non-zero vacuum expectation value



# The Higgs Boson

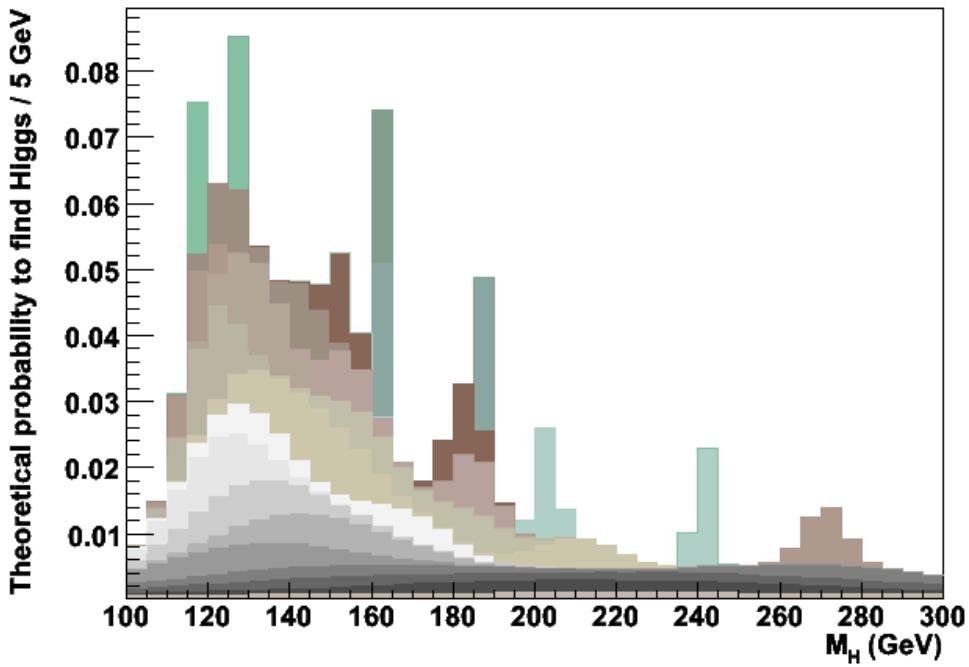
- Higgs: last undiscovered fundamental particle in SM
- Higgs mass: not predicted by theory, but constrained by experiment:
  - Direct searches at LEP II: $M_H$>114.4 GeV @ 95% CL
  - EW data indirect constraint: $M_H$<144 GeV @ 95% CL, or < 182 GeV incl. LEP II limit
  - preferred value $M_H=76^{+33}_{-24}$ GeV (uncertainties at 68% CL)



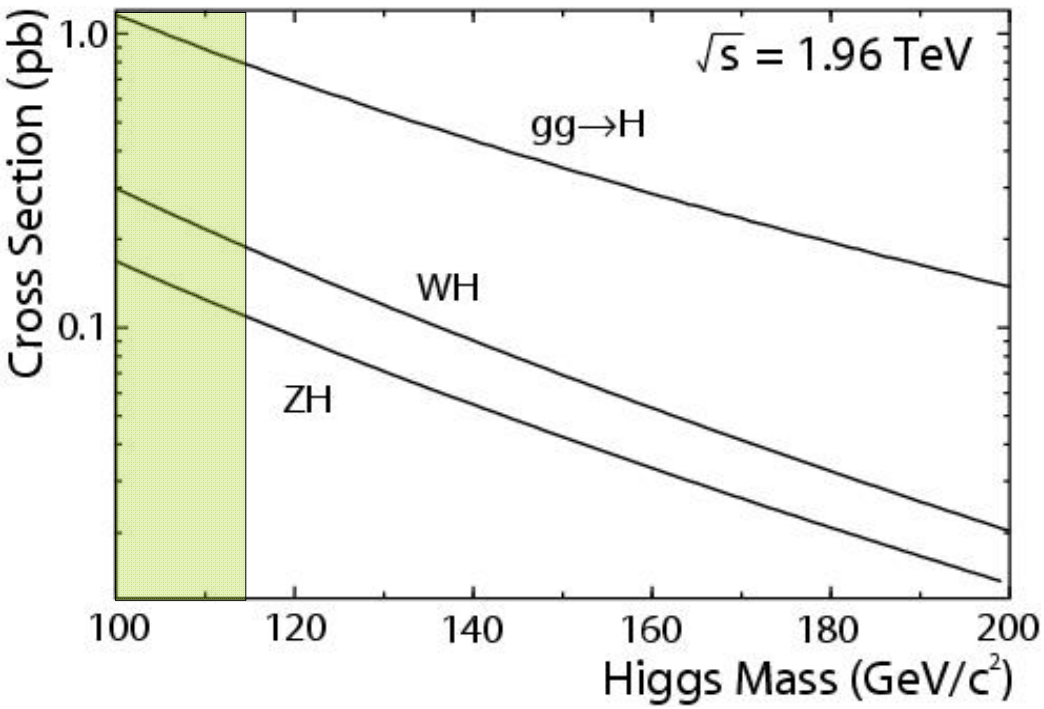



# Is Higgs mass predicted by theory ?

Higgs mass can't be predicted within SM — no SM parameter relation can be stable under renormalization — Iliopoulos, hep-ph 0603146
Higgs mass is 161.8033989 GeV — El Naschie, Chaos Sol. & Frac. 23 (2005) 739
Higgs mass is $10^{18}$ GeV — Batakis & Kehagias, Phys. Lett. B253 (1991) 149
T. Schüker, arXiv:0708.3344: collected 51 predictions

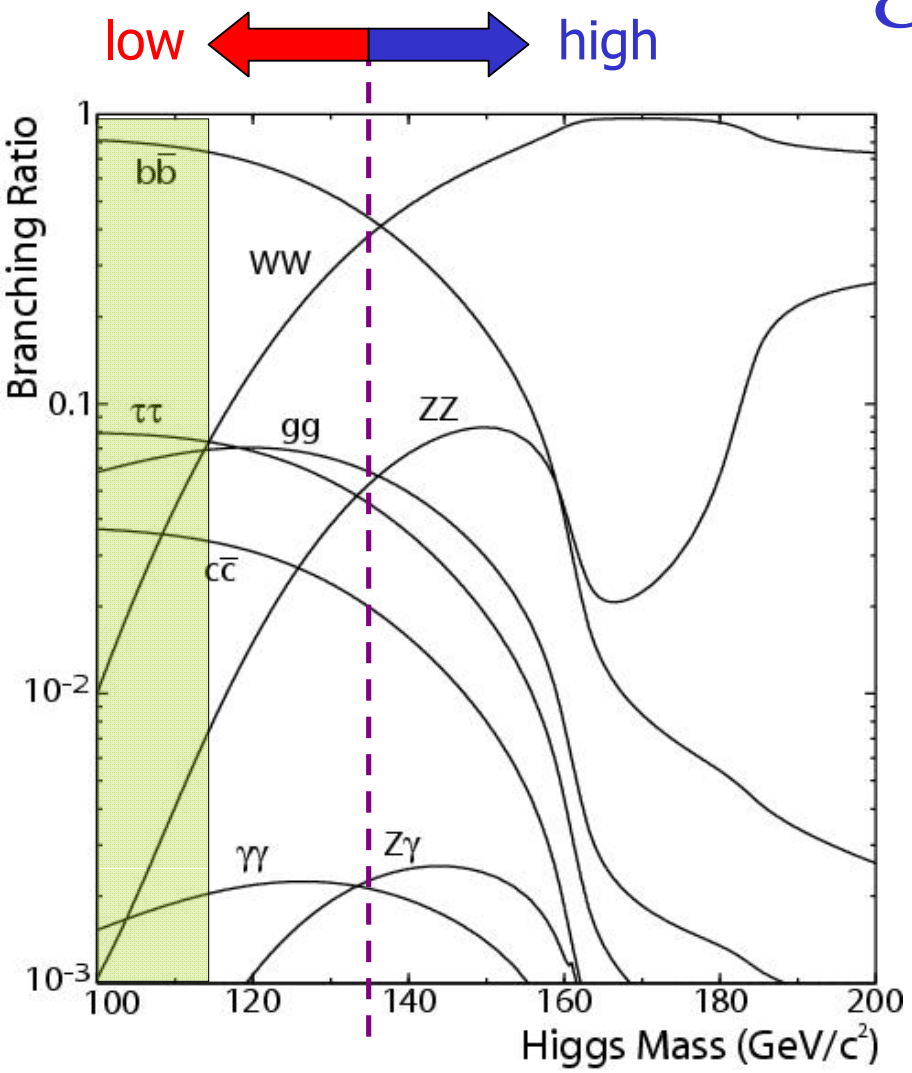


# SM Higgs production at Tevatron



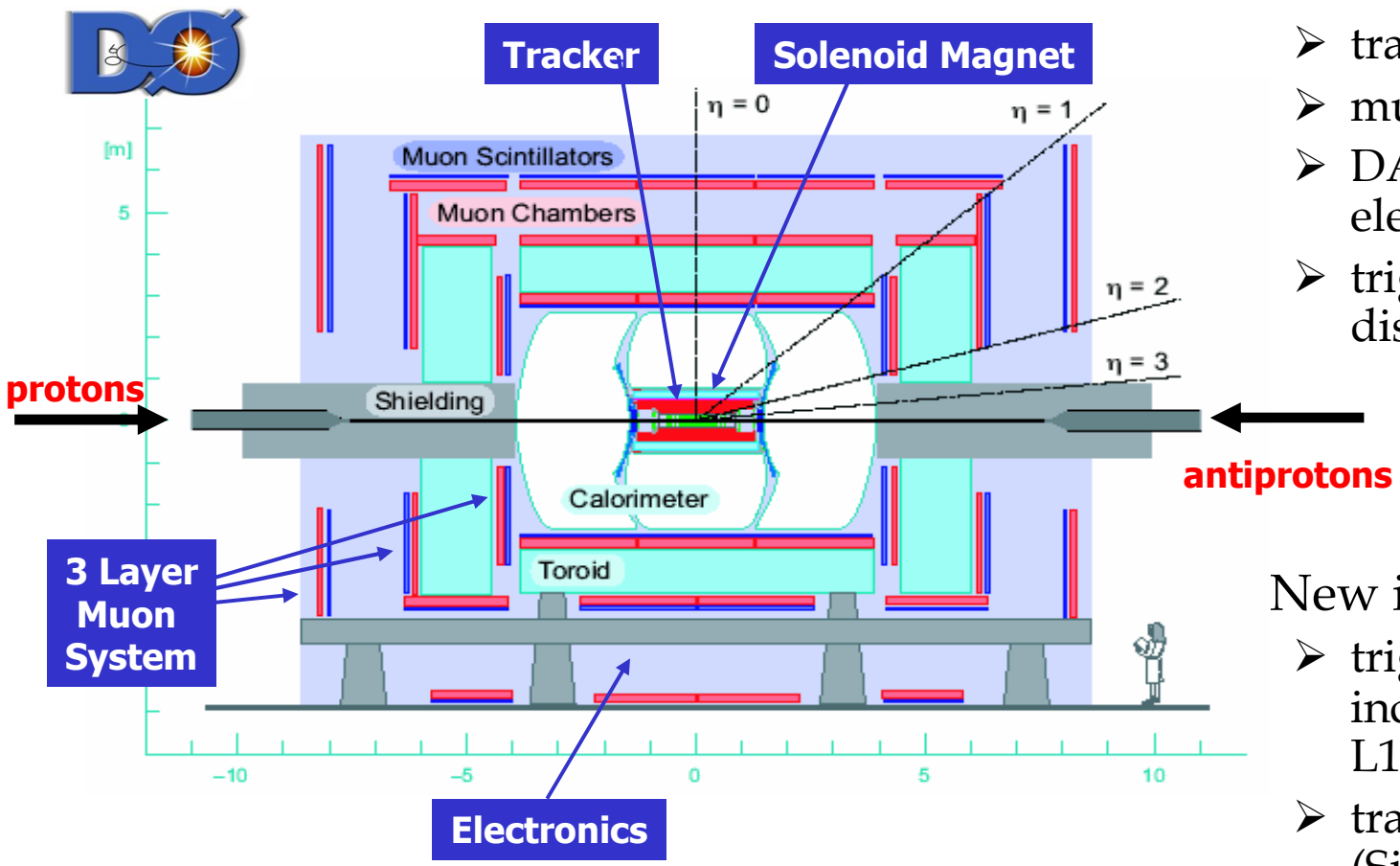

- Direct production (gluon fusion) gg→H
  - highest production rate
- Associated production WH/ZH
  - vector bosons decaying to e/μ + ν help to trigger / extract the signal

# SM Higgs decay




- Low mass, $M_H$<135 GeV
  - dominating mode H→bb
- High mass, 135<$M_H$<200 GeV
  - dominating mode H→WW*
- Region near $M_H$=135 GeV (intermediate mass) is particularly difficult

# DØ detector



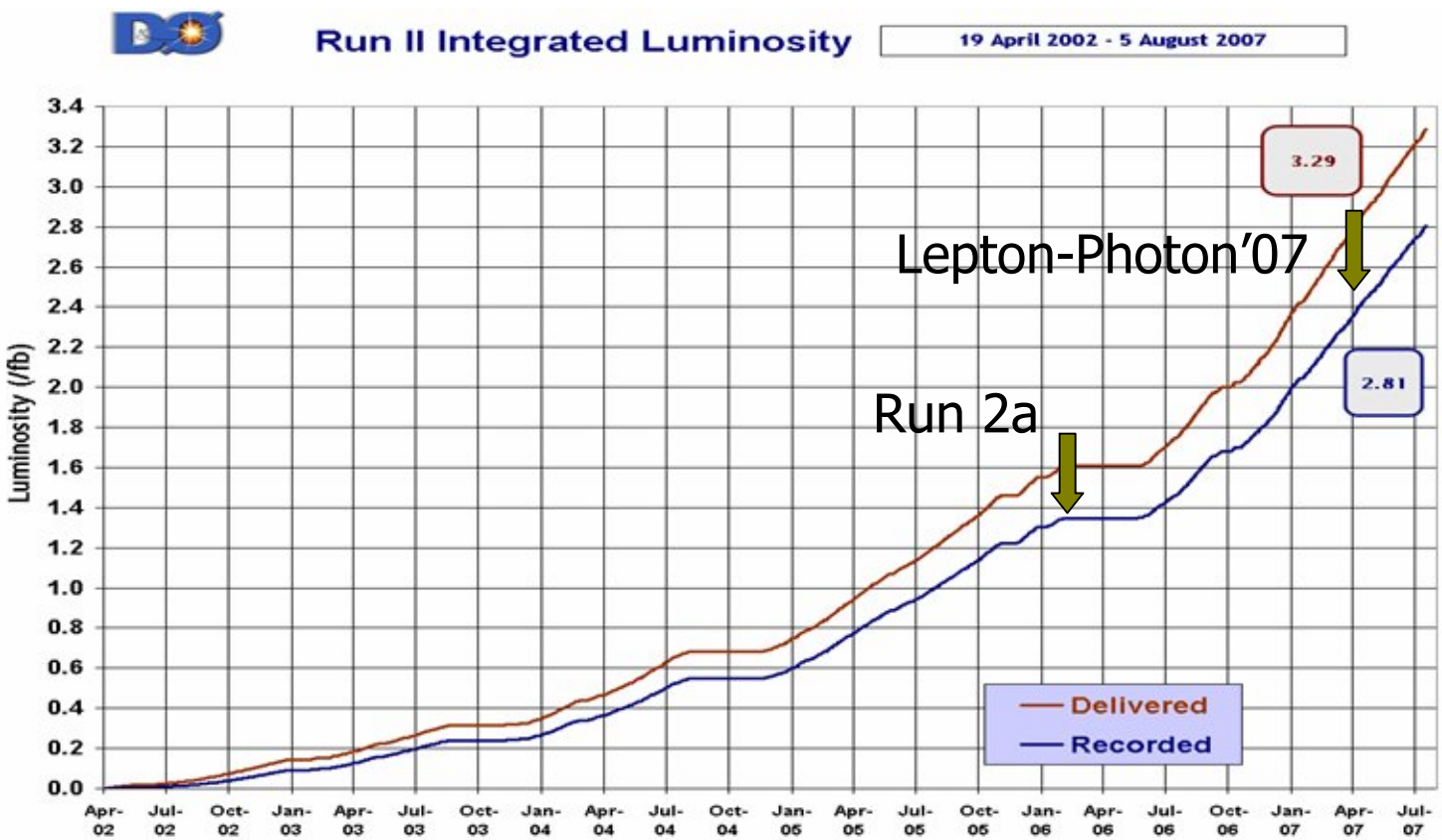

- New in Run 2a:
  - tracking in B-field
  - muons up to $|\eta|<2$
  - DAQ and CAL electronics upgrades
  - triggers on tracks and displaced vertices

New in Run 2b:

- trigger upgrade, including new L1 calorimeter trigger
- tracker upgrade (Silicon Layer 0)

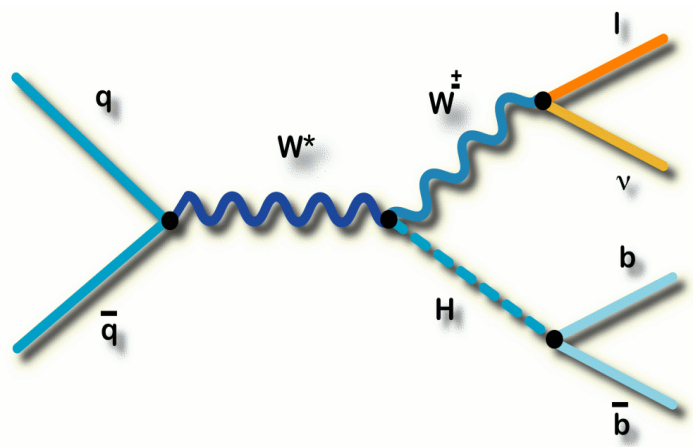
# Data set

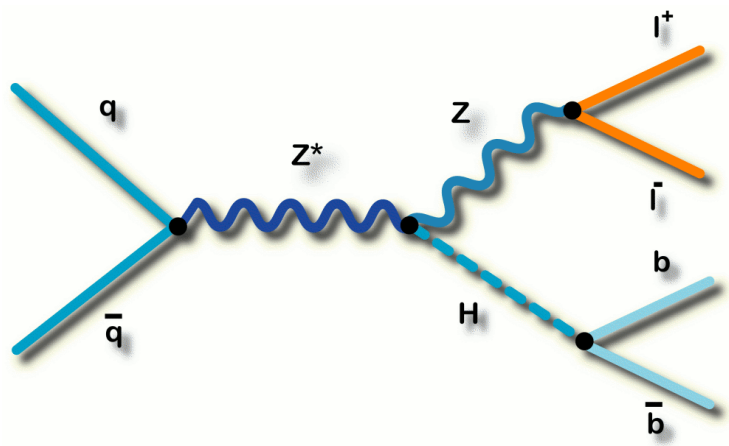
- L = 1.1 $fb^{-1}$: Run2a (ended Feb/06)
- L = 1.7 $fb^{-1}$: Lepton-Photon'07 (+ June/06 – April/07)



# Low mass SM Higgs

- Main mode: VH, H→bb (V=W,Z)
  - WH → e/μ ν + bb: high $p_T$ isolated lepton, missing $E_T$, two b-jets
  - ZH → ee/μμ + bb: two high $p_T$ isolated leptons with Z invariant mass, two b-jets
  - ZH → νν + bb: high missing $E_T$, two b-jets



# Backgrounds to VH

- VH is high background mode
- V + jets: dominant
  - dominated by non-b-jets → efficient b-tagging
  - V+bb: non-reducible, but non-resonant → good dijet invariant mass resolution
- top production
  - ttbar → l + jets: top is heavy → look at sum of energies of objects in the event
  - single top: identical signature, look at kinematics (yesterday's signal is today's background…)

# Backgrounds to VH (2)

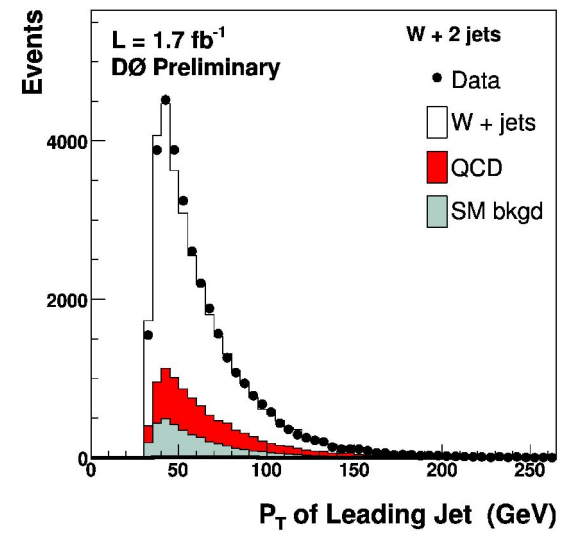
- dibosons
  - relatively low background, and V is lighter than H
  - V(Z→bb) is a good benchmark !
- multijets
  - difficult to model
  - calculate their contribution using known probability for jets to fake isolated leptons (matrix method)
  - need good missing $E_T$ resolution and efficient lepton identification

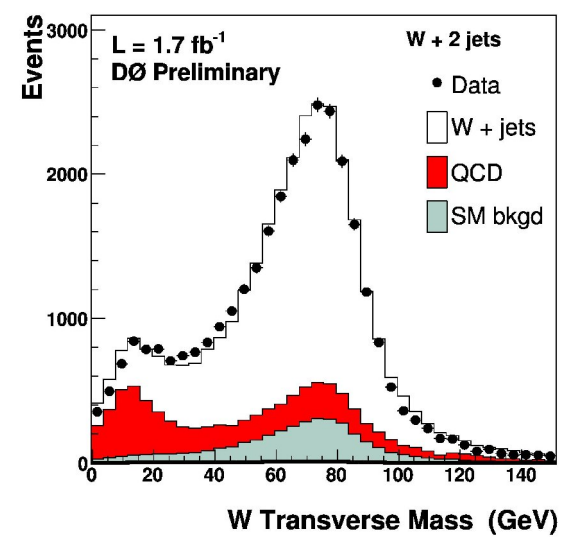
# WH→lν bb (l=e,μ)

L = 1.7 $fb^{-1}$ NEW

- Selection:
  - e/μ : $p_T$>15 GeV, |η| < 1.1(e) / 2(μ)
  - missing $E_T$ > 20 GeV
  - 2 jets $p_T$>25/20 GeV, |η| < 2.5
  - single or double b-tagging
- (e/μ)×(1b/2b) = 4 channels

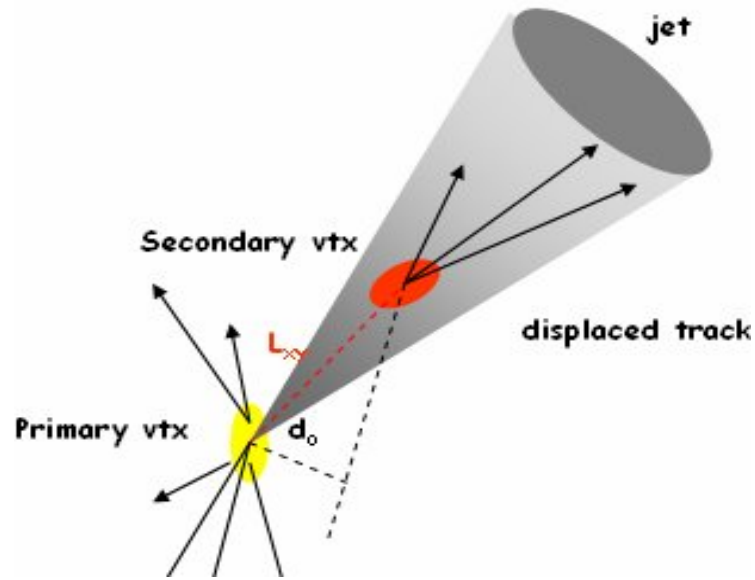
Good understanding of data before tagging !

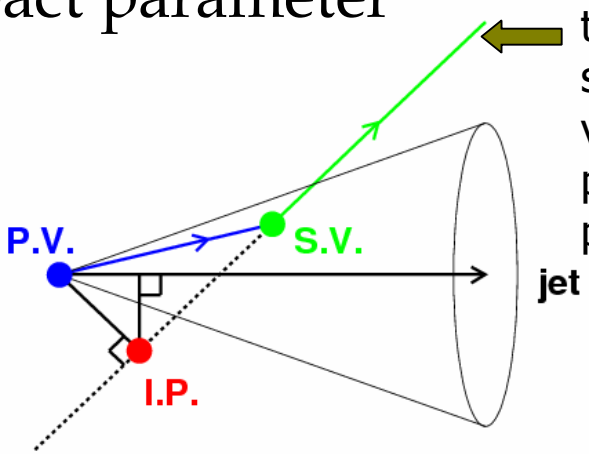


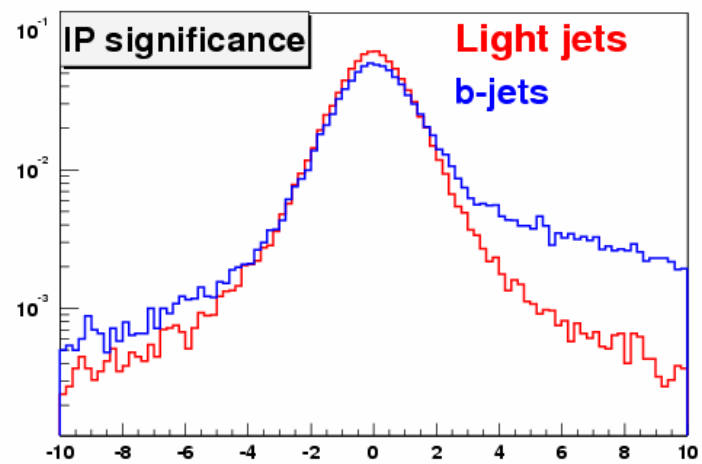
# b-tagging

- b-tagging is crucial for H→bb
  - improves S/B by a factor of 10—20
  - Secondary vertex tagger: look for displaced vertices
  - Lifetime based tagger: look for tracks with significant positive impact parameter



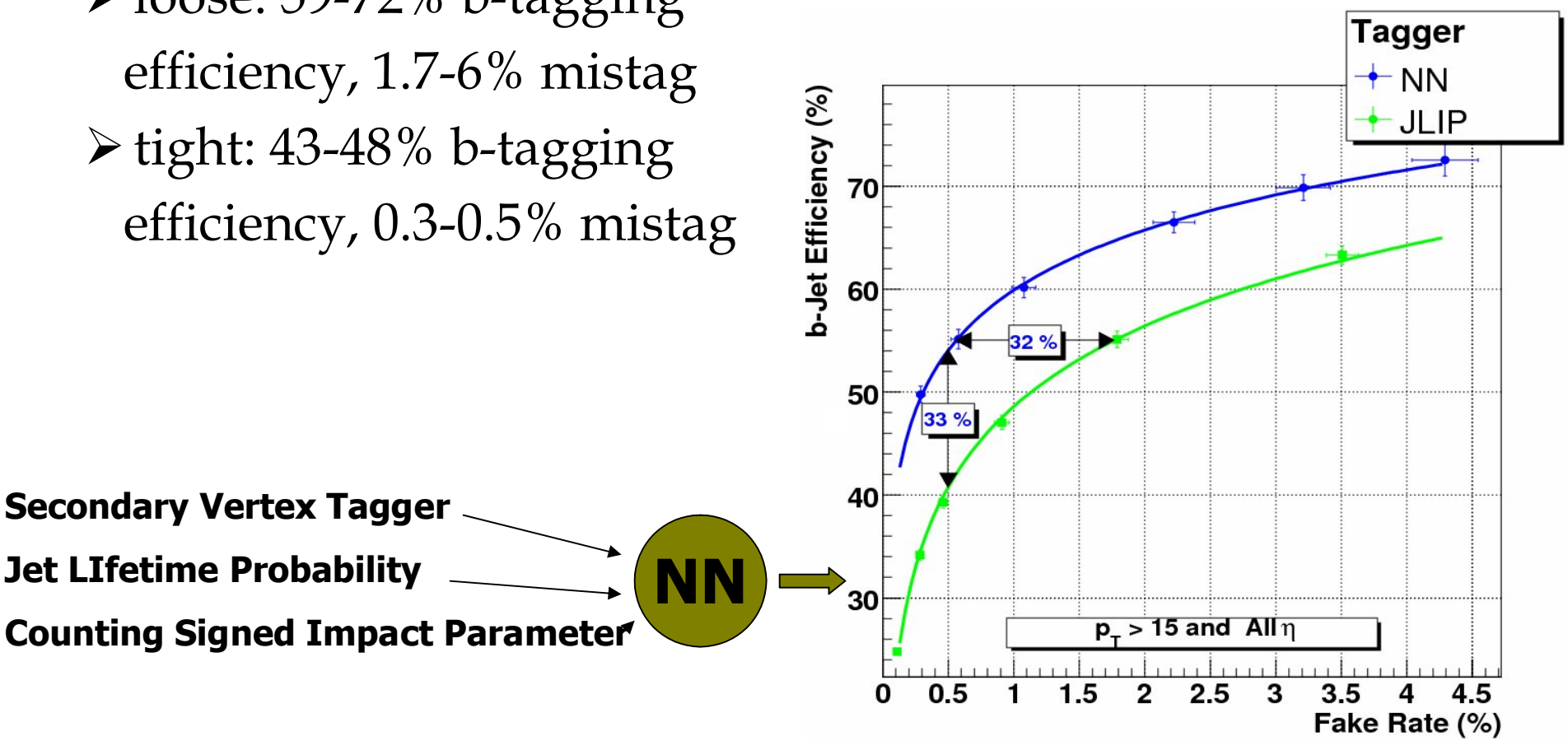




track from secondary vertex: large positive impact parameter !



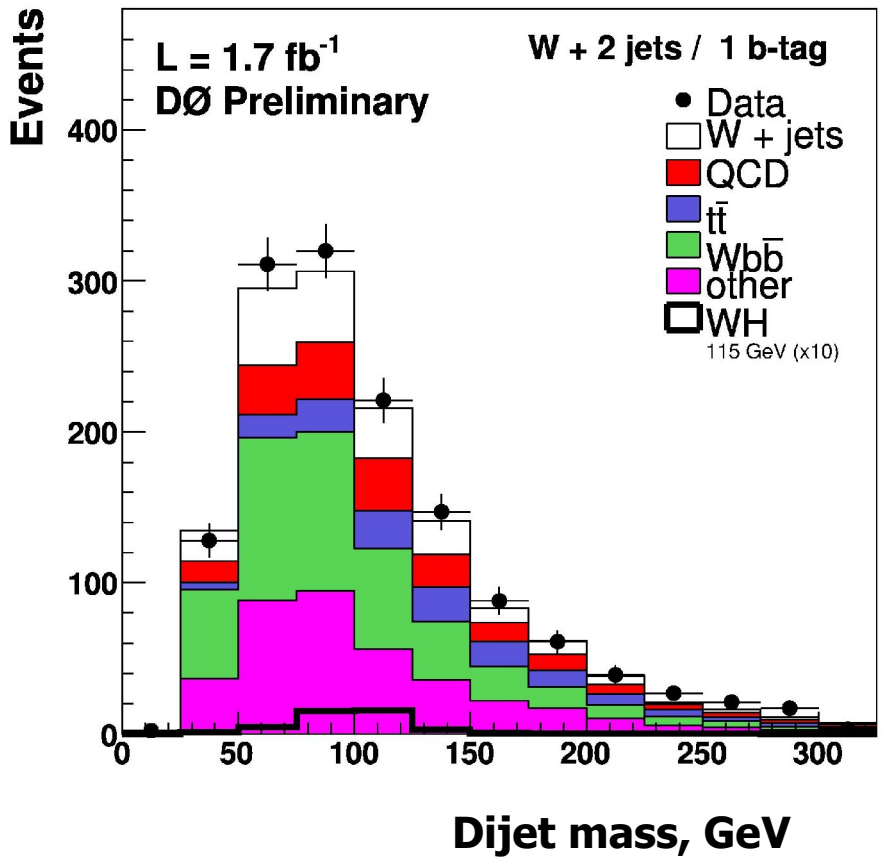
# Neural Network b-tagger

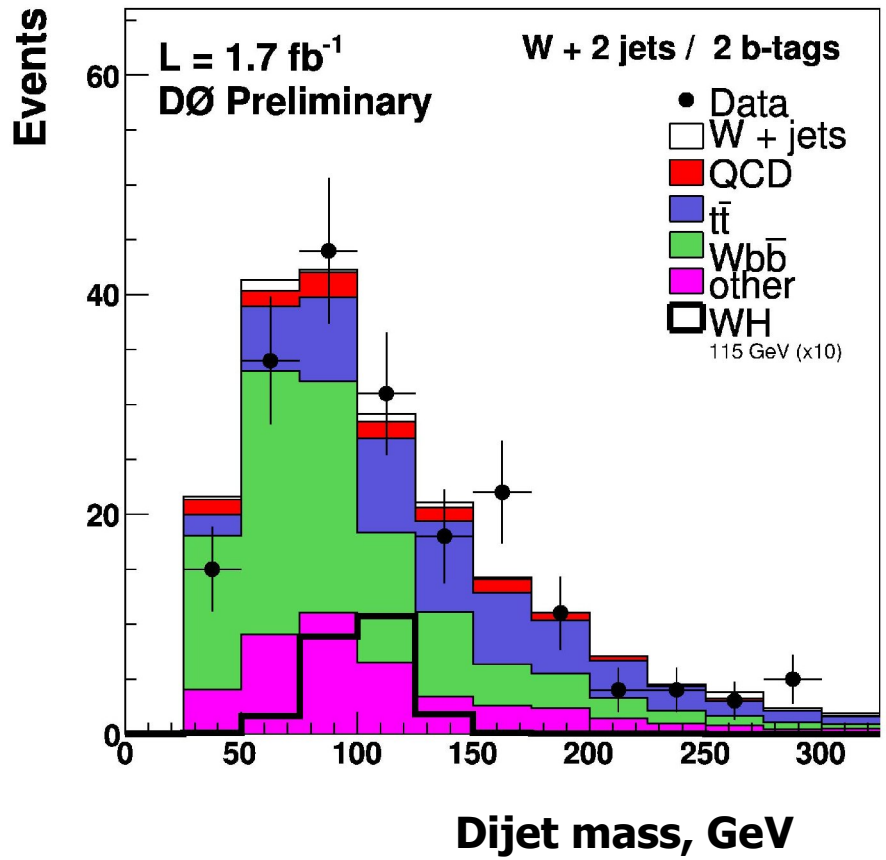
- DØ uses Neural Network b-tagging algorithm
  - loose: 59-72% b-tagging efficiency, 1.7-6% mistag
  - tight: 43-48% b-tagging efficiency, 0.3-0.5% mistag



# WH→lν bb (l=e,μ): after b-tagging

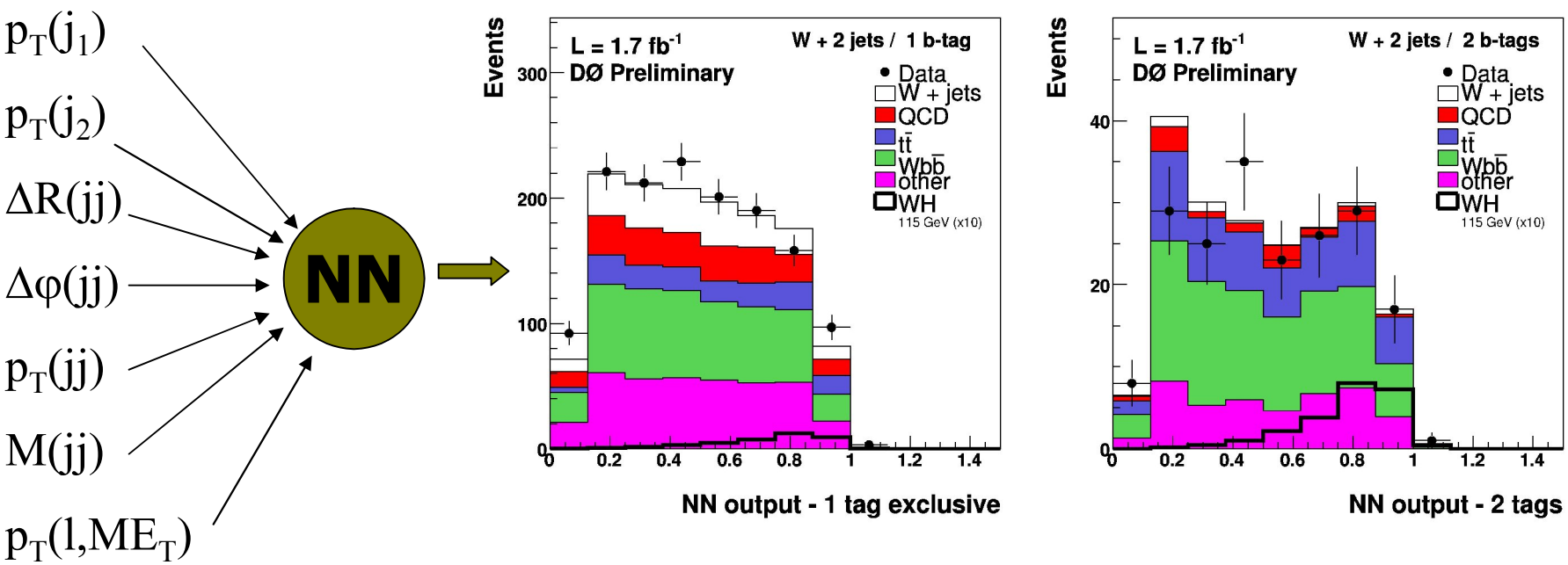
2 tags: lower fraction of QCD, W+jets, higher fraction of tt, Wbb



# WH→lν bb (l=e,μ): limits

- Use neural network to separate signal from background
- Fit the NN output



# Limits setting procedure

- Method: CLS (LEP)
  - Test statistics: log likelihood ratio LLR = $-2lnQ$

    $$Q = L(s+b)/L(b),\ L(x) = e^{-x}\, x^d/d!$$

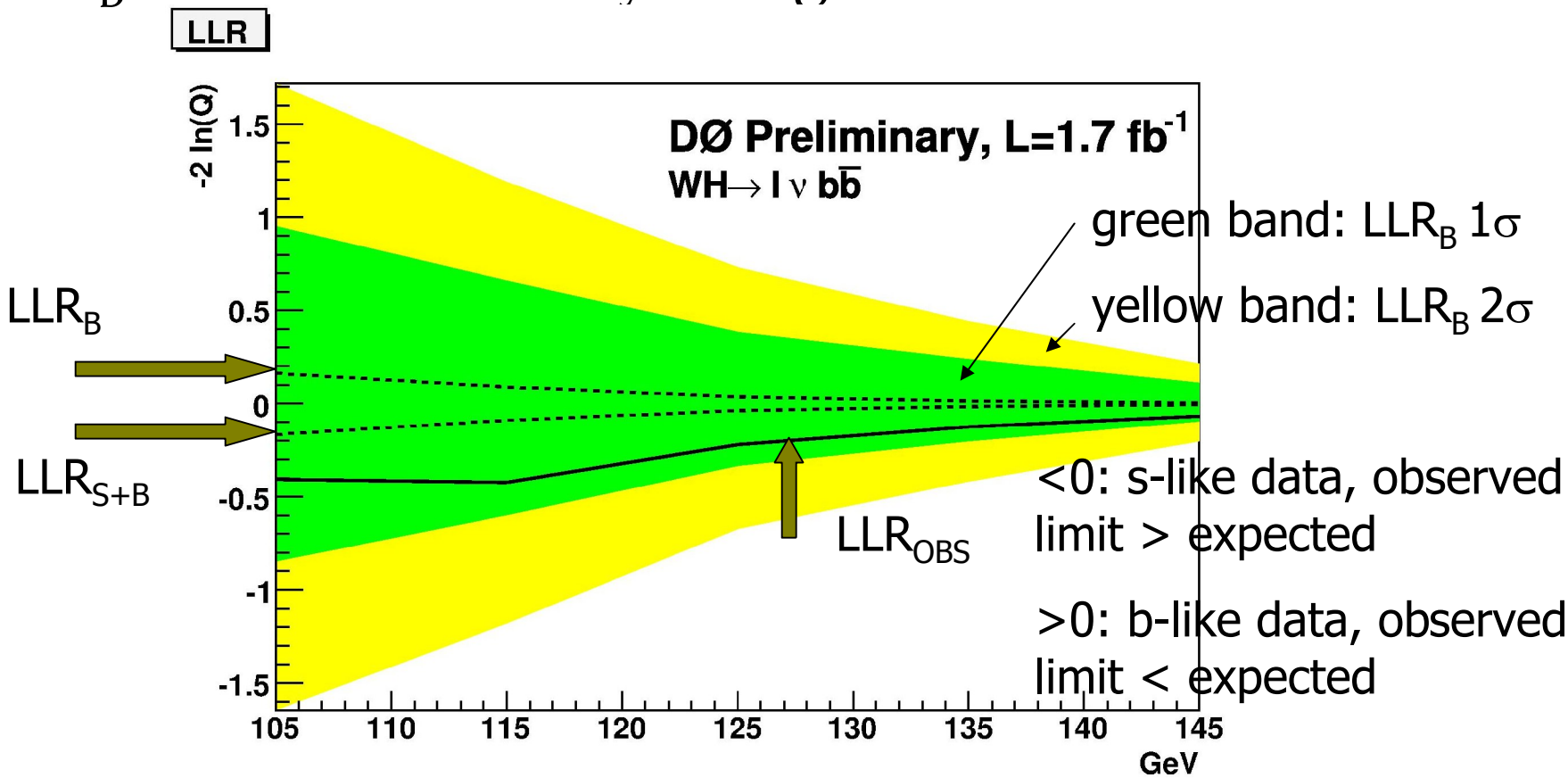
    $s$: expected number of signal events

    $b$: expected number of background events

    $d$: actual number of events
  - $LLR_{S+B}$ : expected mean (or median) value of LLR for the S+B hypothesis
  - $LLR_B$ : same for the background-only hypothesis
  - $LLR_{OBS}$ : actual LLR observed in data

# Log Likelihood Ratio

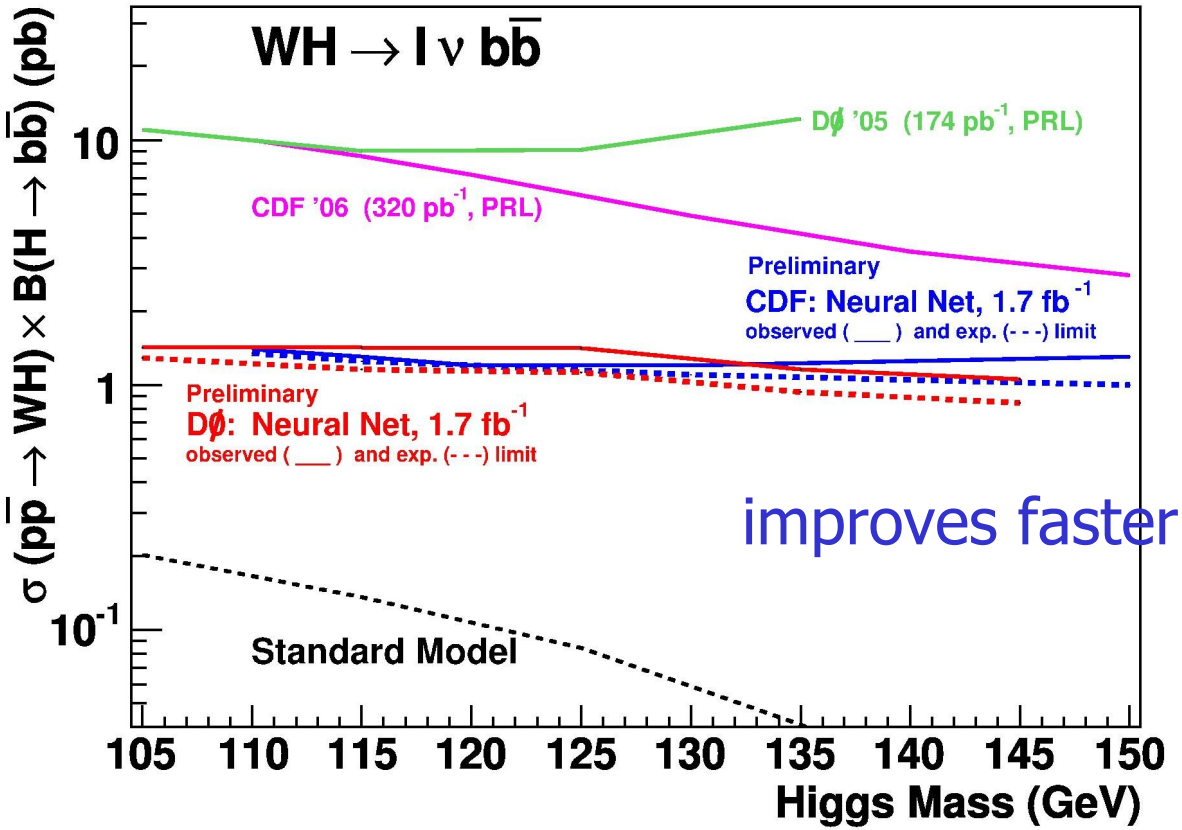
- $LLR_B$ – $LLR_{S+B}$ separation: discriminating power
- $LLR_B$ width: sensitivity to signal-like fluctuation



# WH→lν bb (l=e,μ): result

- Result @$M_H$=115 GeV:

  $\sigma_{95}$/SM = 9.1(exp)/11.1(obs)



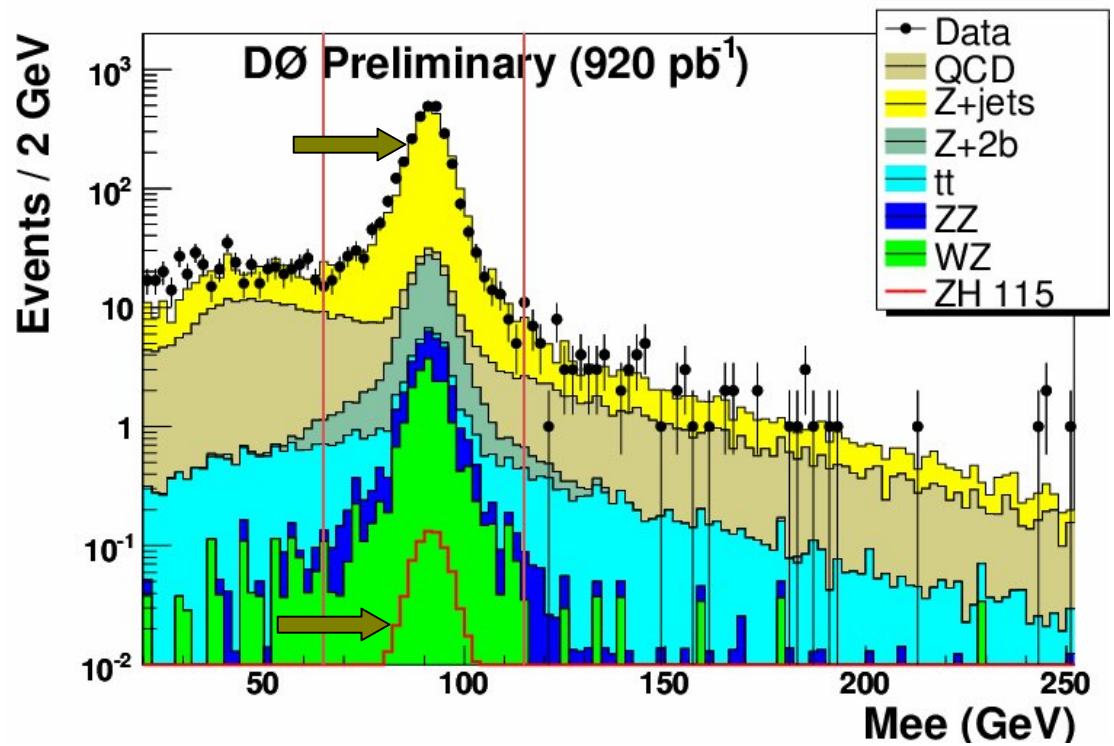

improves faster than √L !

# ZH→ll bb (l=e,μ)

- More difficult than WH:

  $\sigma_{ZH}<\sigma_{WH}$, Br(Z→ll)<Br(W→lν)

- Z→ll provides a nice handle !

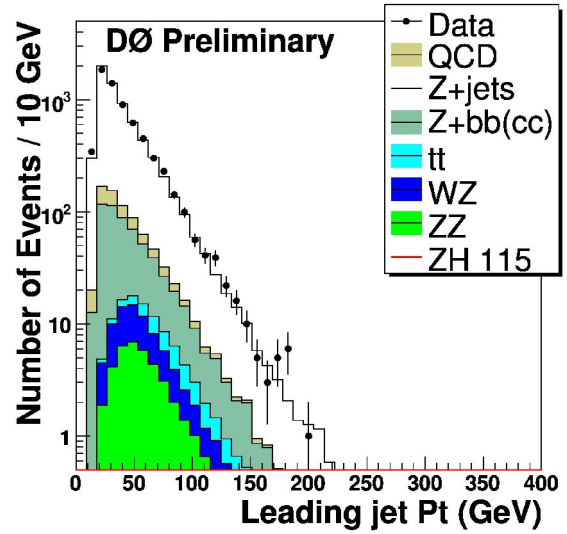


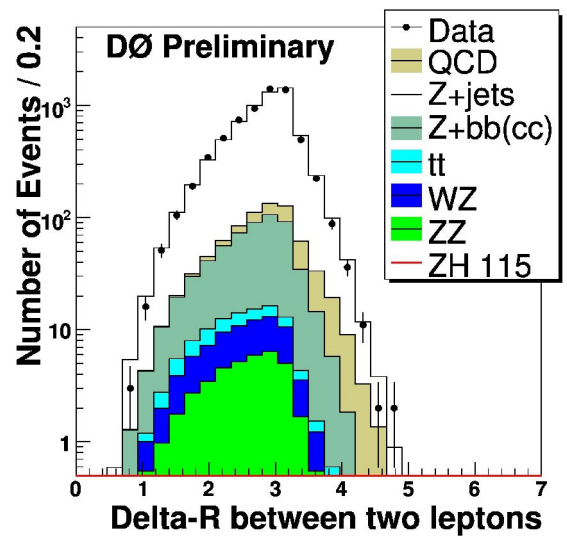
# ZH→ll bb (l=e,μ)

L = 1.1 $fb^{-1}$

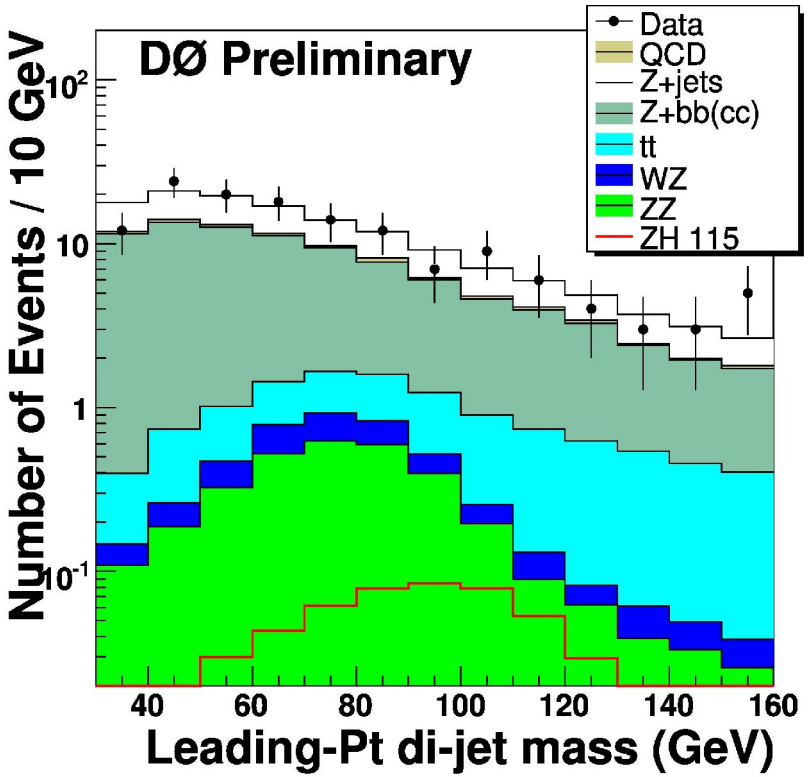
- Selection:
  - e/μ : $p_T$>15(e)/10(μ) GeV, |η|< 2.5(e) / 2(μ)
  - 70<$M_{ll}$<110 GeV
  - 2 jets $p_T$>15 GeV, |η|< 2.5
  - single or double b-tagging
- (ee/μμ)×(1b/2b) = 4 channels

Good understanding of data before tagging !

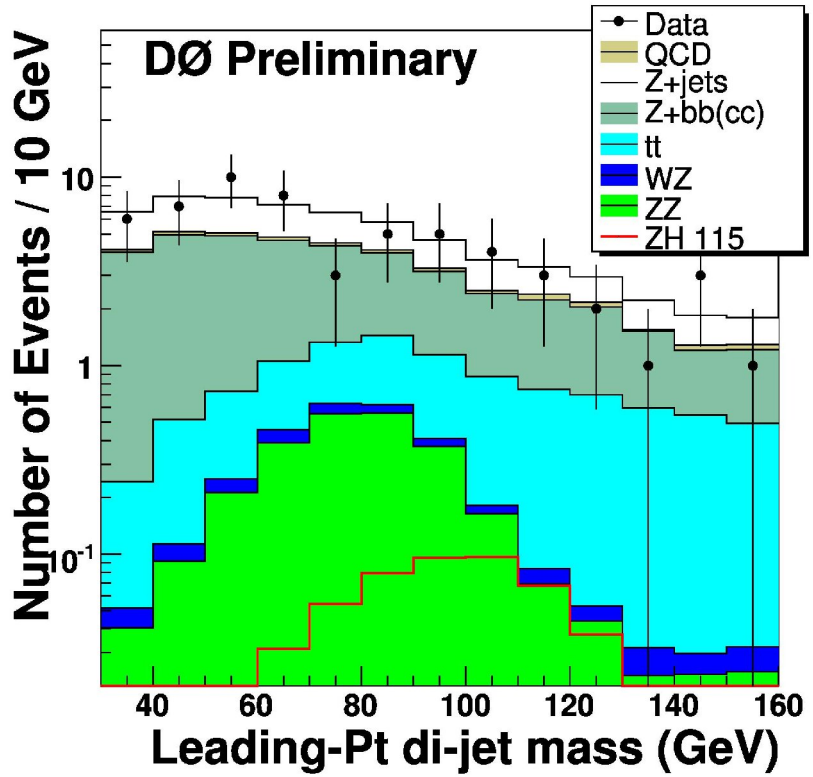


# ZH→ll bb (l=e,μ): after b-tagging



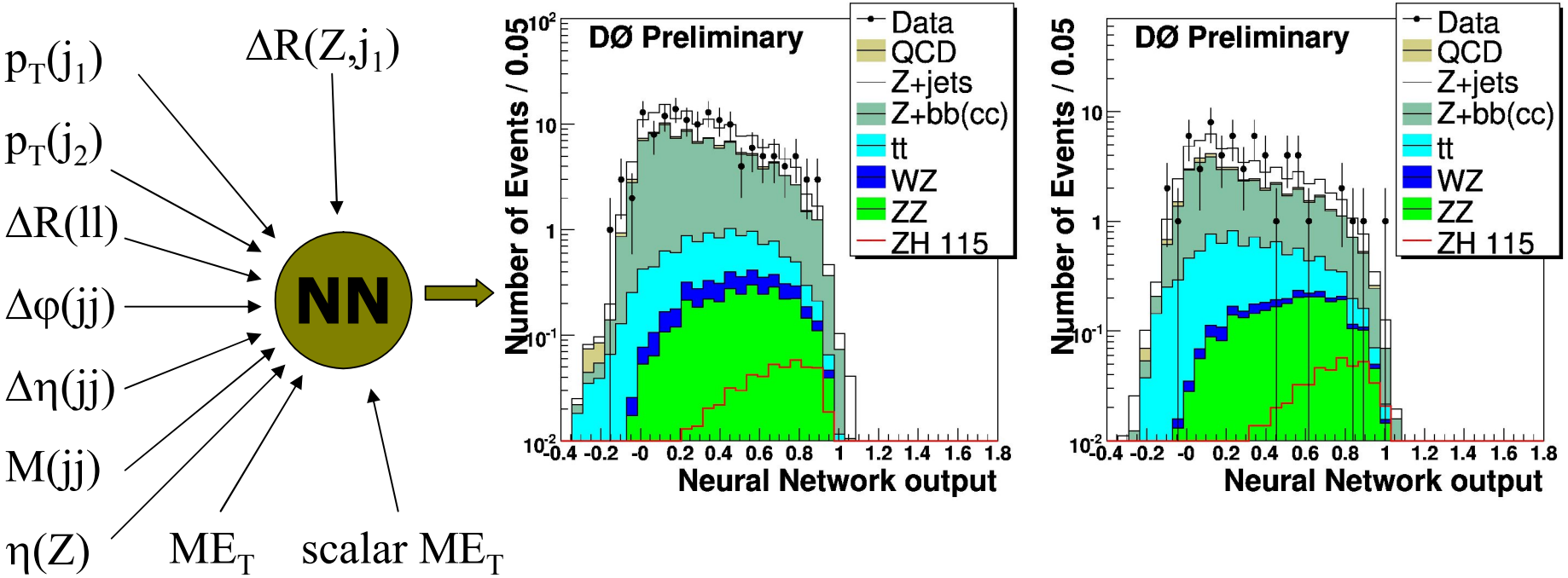

single tag




double tag

# ZH→ll bb (l=e,μ): limits

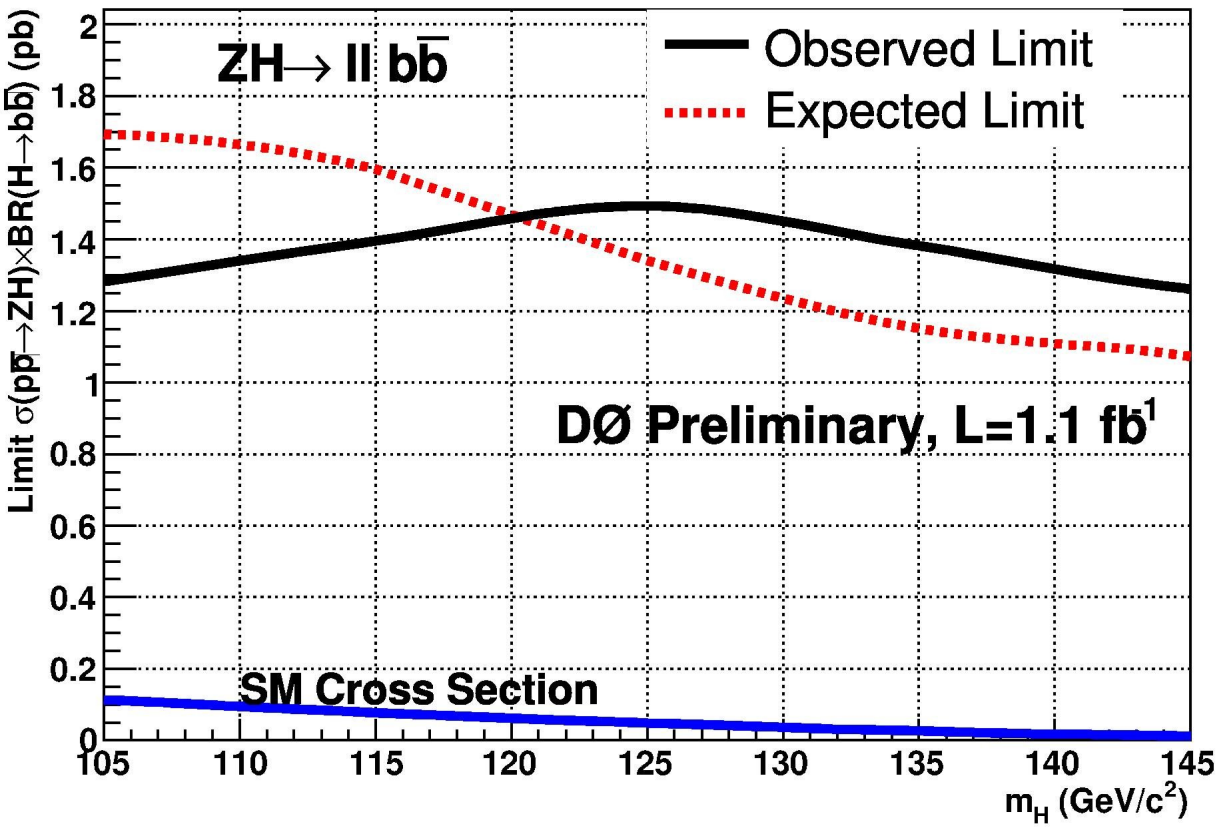
- Use neural network to separate signal from background
- Fit the NN output



# ZH→ll bb (l=e,μ): result

- Result @$M_H$=115 GeV:

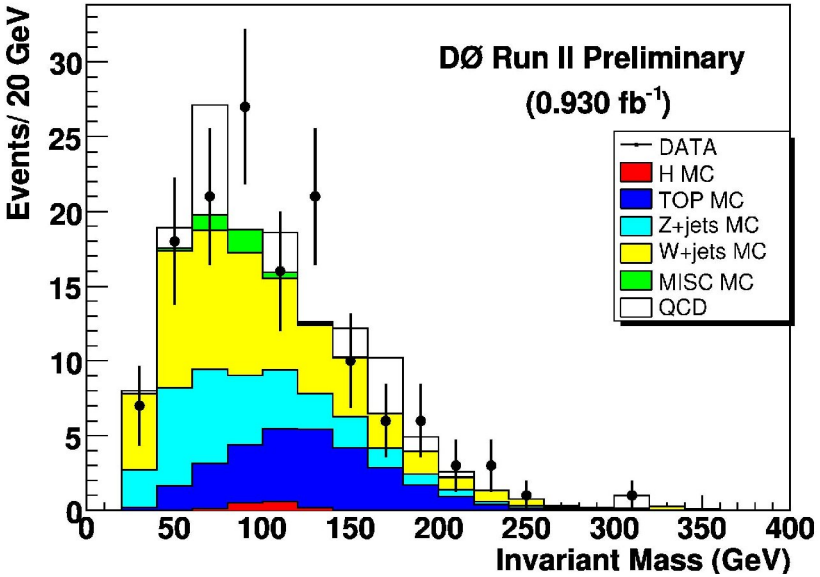
  $\sigma_{95}$/SM = 20.4(exp)/17.8(obs)



# ZH→νν bb

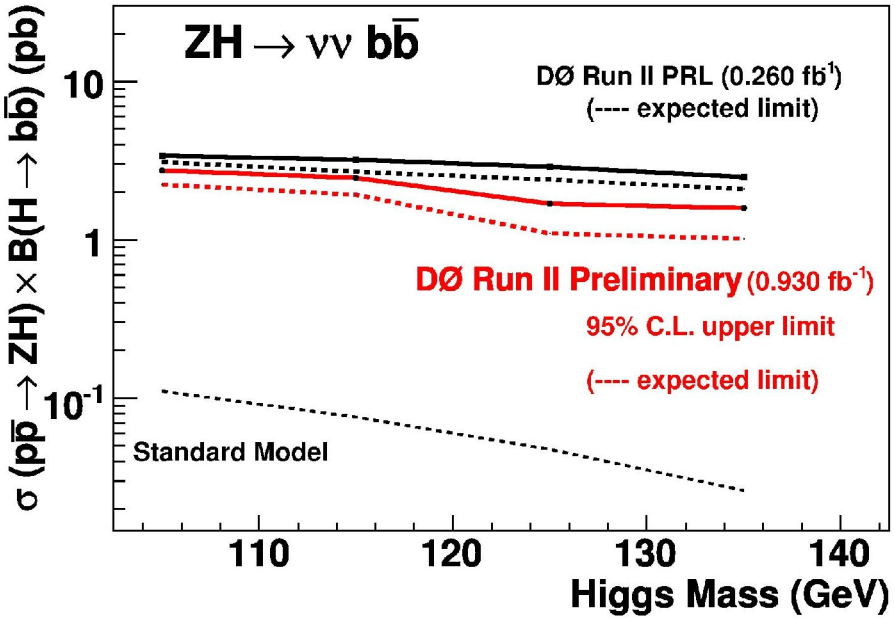
L = 0.9 $fb^{-1}$

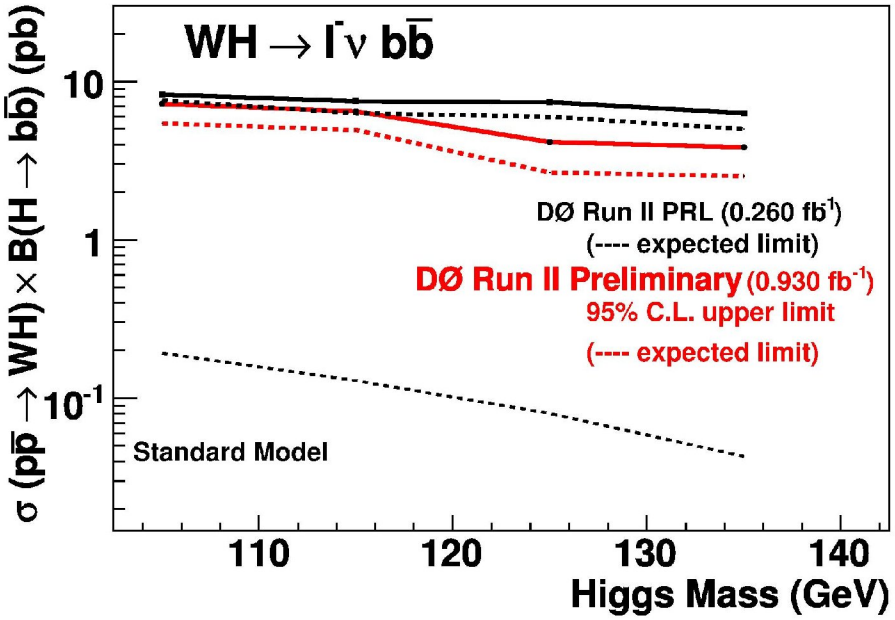
- Selection:
  - dedicated trigger (jets+$ME_T$)
  - missing $E_T$>50 GeV
  - 2 acoplanar jets $p_T$>20 GeV, $|\eta| < 2.5$
  - double b-tagging



# ZH→νν bb: result

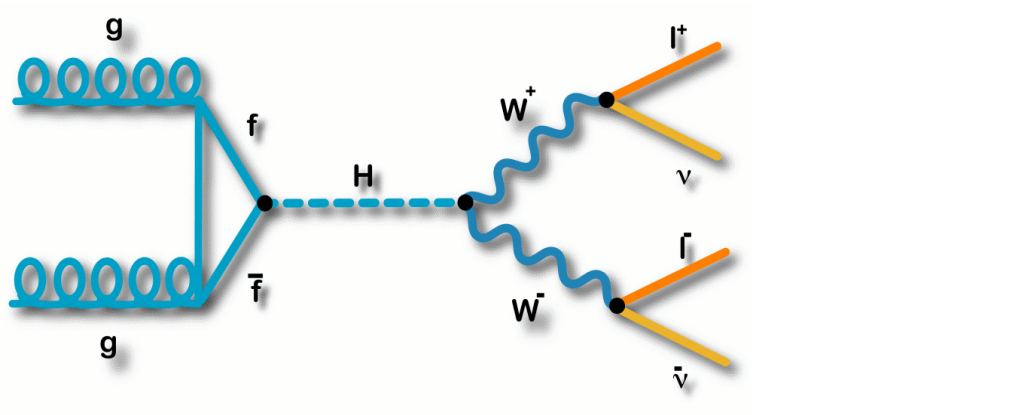
- Limits produced for two cases: Z→νν and W→łν, combined sensitivity is similar to W→lν
- New analysis with neural network selection and more data is under way



# High mass SM Higgs

- Main mode: gg → H →WW* → lν l′ν′ (l, l′=e,μ)
  - two high $p_T$ isolated leptons, missing $E_T$
  - three main channels (ee, eμ, μμ)
  - start probing other channels (μτ)
- Can't reconstruct the Higgs mass (escaping ν's)



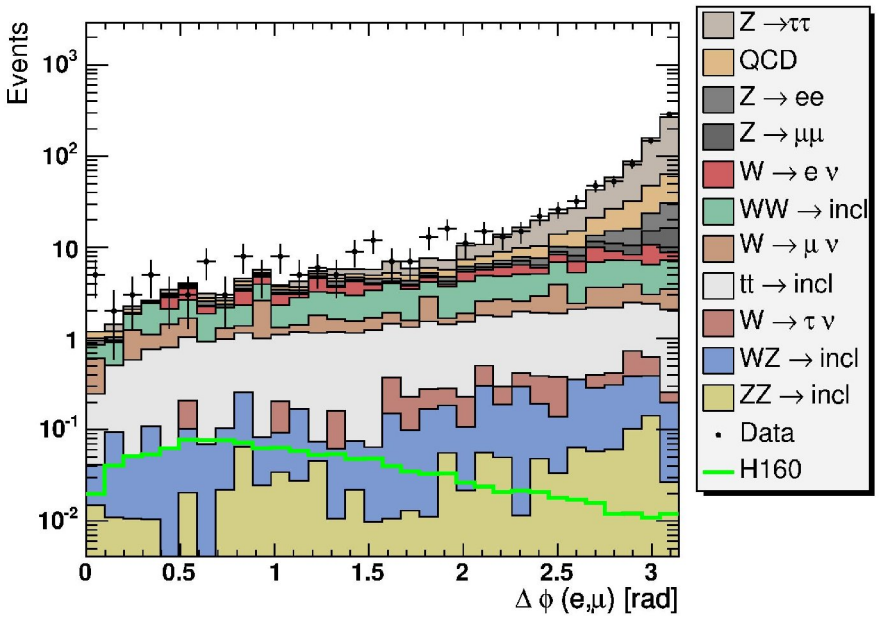
# Backgrounds to H→WW*

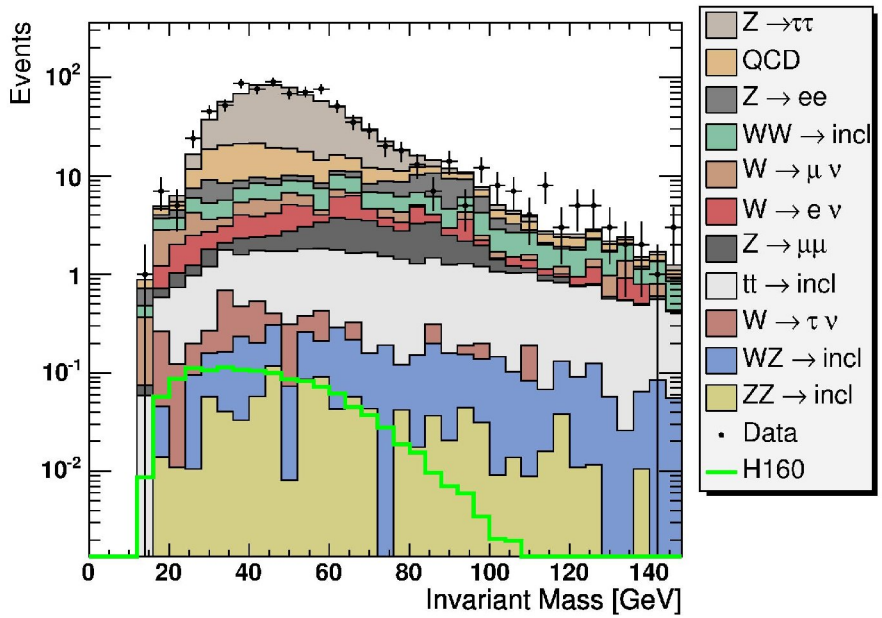
- H→WW* is low background mode
- Dibosons: main background
  - WW* irreducible, separate from the signal based on angular correlation $\Delta\varphi(l,l')$ – Higgs is a scalar !
- W+jets and multijets
  - need good lepton identification
- Z→ττ : specific for eμ channel and channels involving taus

# H→WW*→lν l′ν′ (l,l′=e,μ)

L = 1.7 $fb^{-1}$ NEW

- Selection:
  - e/μ : $p_T$>15(e)/10(μ) GeV, |η| < 3(e) / 2(μ)
  - missing $E_T$>20 GeV + other kinematic cuts
  - (ee/eμ/μμ) = 3 channels

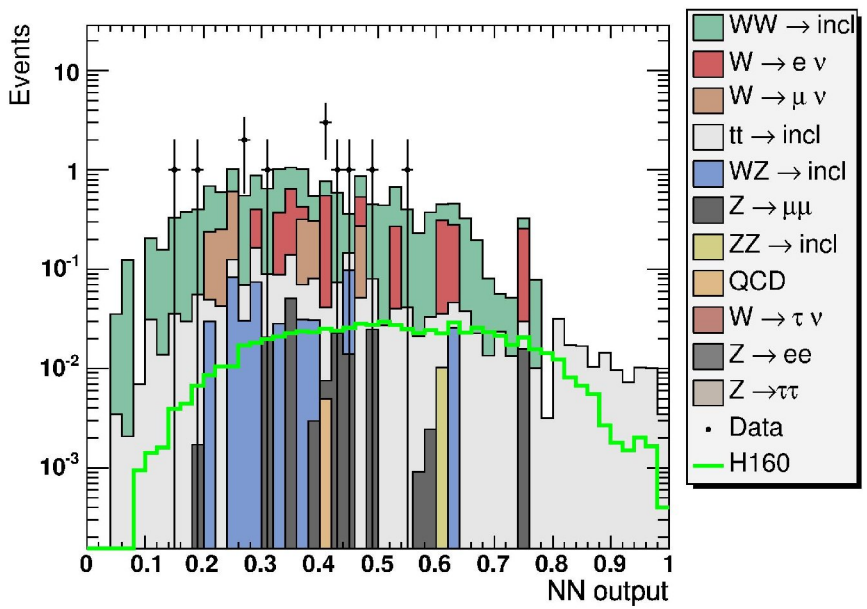


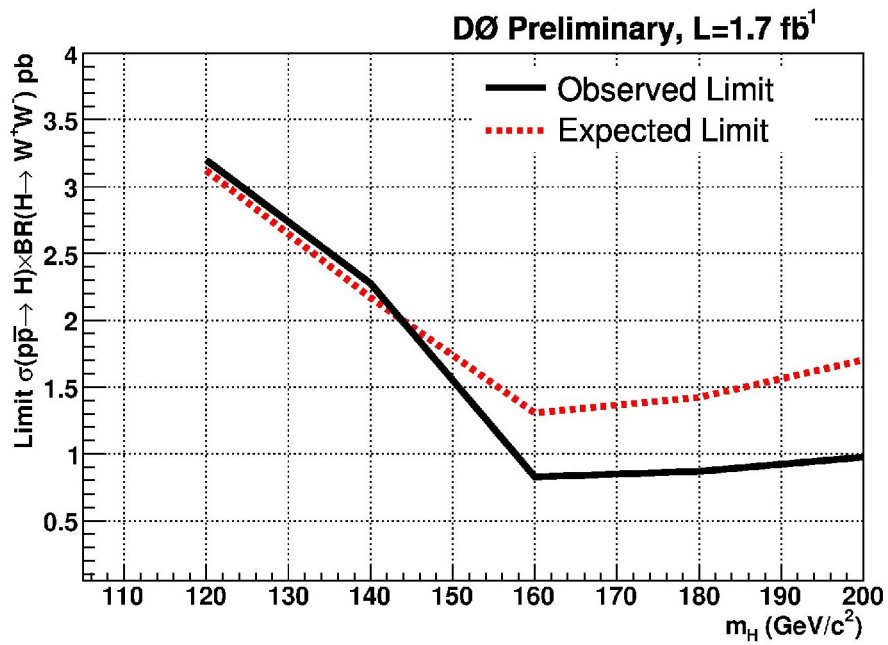




control plots at the preselection level for eμ channel

# H→WW*→lν l′ν′: result

- Using Neural Network to set limits
- Limits as shown: 1.7 $fb^{-1}$ eμ combination
- Coming soon: full 1.7 $fb^{-1}$ combination with neural network



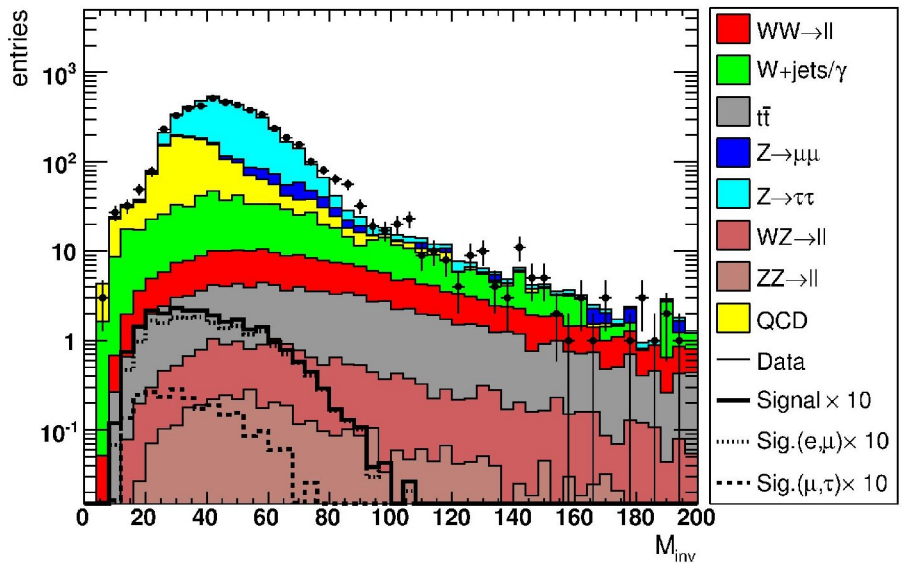



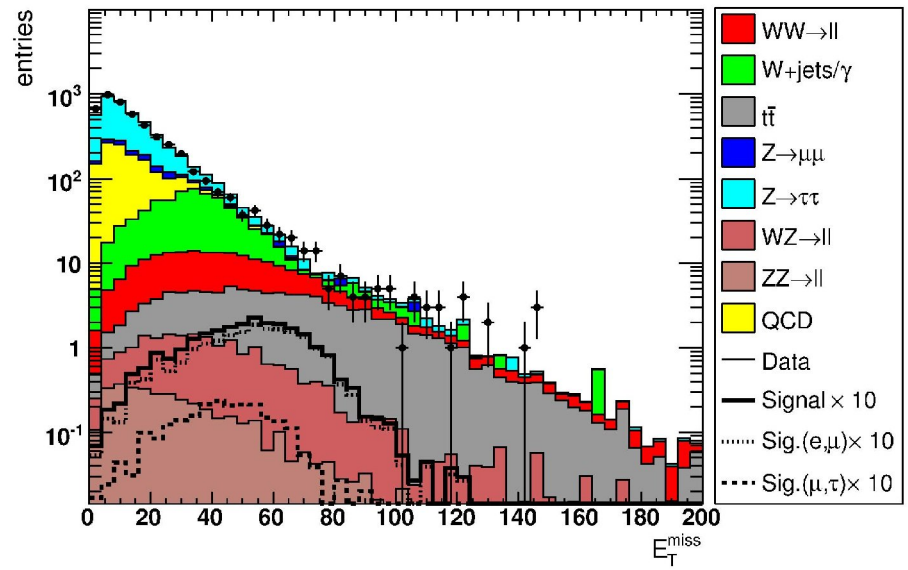
# $H \rightarrow WW^* \rightarrow \mu\nu_\mu \tau_{had}\nu_\tau$

NEW

$L = 1.0\ fb^{-1}$

- Selection:
  - leptons: $p_T$>10(τ) / 12(μ) GeV
  - 1-prong taus (π-like or ρ-like)
  - large missing $E_T$
  - topological cuts

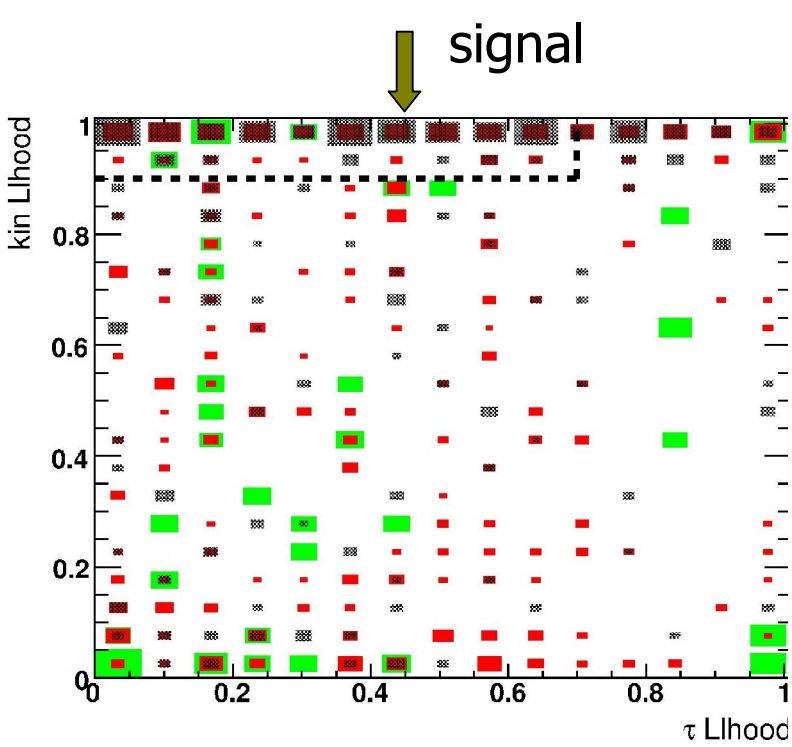


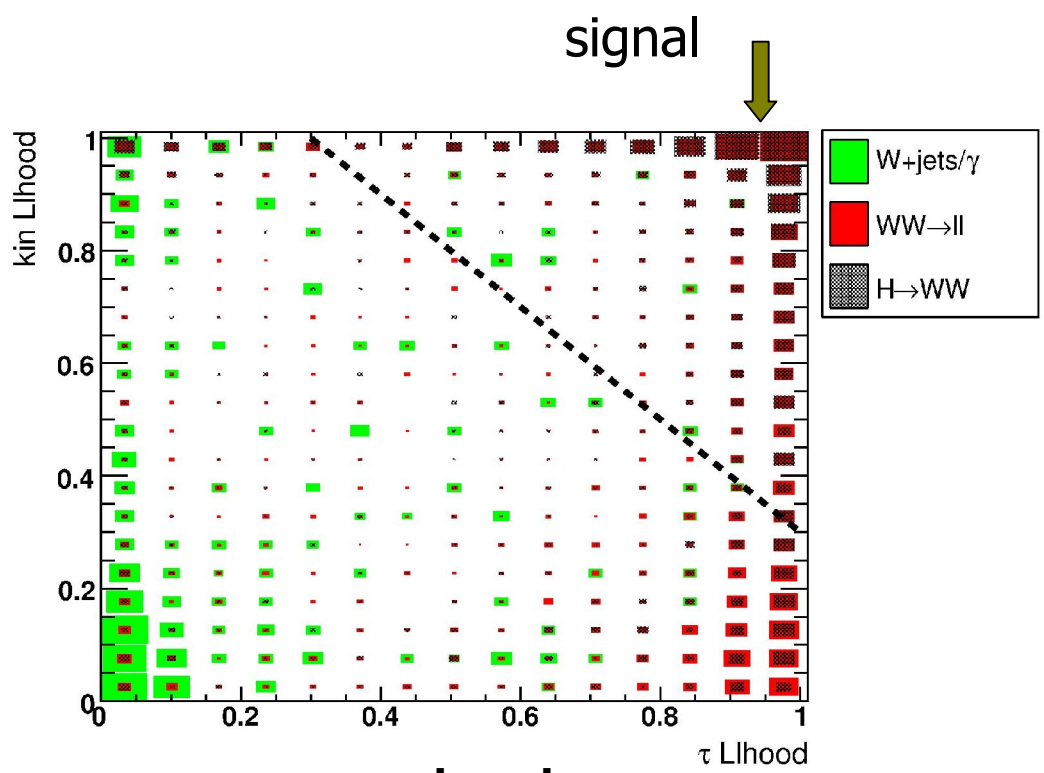

stay orthogonal to eμ !

# $H \rightarrow WW^* \rightarrow \mu\nu_\mu \, \tau_{had}\nu_\tau$

- Use 2D likelihood to separate signal from background (event kinematics vs τ properties)
- Limit setting: cut & count




**π-type taus**

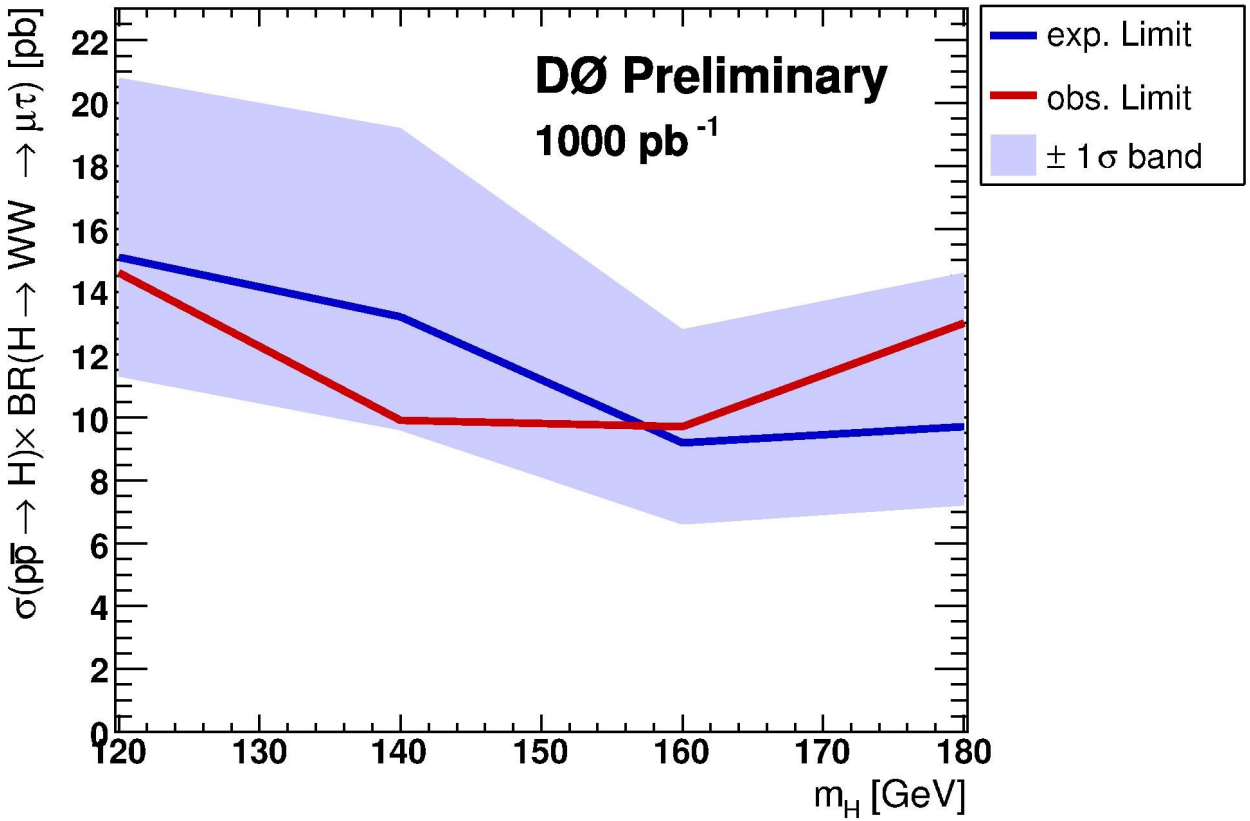



**ρ-type taus**

# $H \rightarrow WW^* \rightarrow \mu\nu_\mu \tau_{had}\nu_\tau$: result

- Result @$M_H$=160 GeV:

  $\sigma_{95}$/SM = 36(exp)/38(obs)



# Intermediate mass SM Higgs

- At Higgs mass ~135 GeV, production cross section is already low, but WW* channel is not yet fully open
- Additional mode: VH → VVV* → $l^{\pm}l^{\pm\prime}$ + X ($l$, $l'$=e,μ)
  - signature: two same sign high $p_T$ isolated leptons, missing $E_T$, additional jets or leptons

# Backgrounds to VVV*

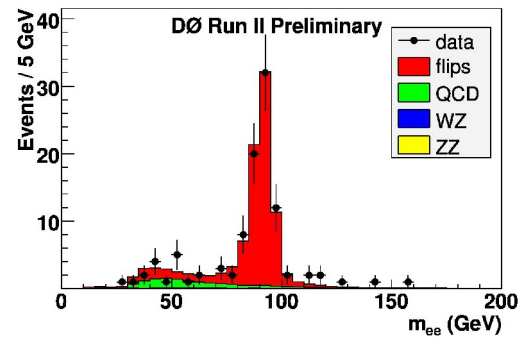
- VVV* is low background mode
- Dibosons: main physical background
  - no irreducible background (VVV* production much lower than Higgs signal)
  - good benchmark
- Instrumental background: main problem
  - events with mismeasured lepton charge, mostly from $Z/\gamma^* \rightarrow ll$ – charge flips
  - multijets and W+jets where jets fake isolated leptons

# $WH \rightarrow WWW^* \rightarrow l^{\pm} l^{\pm\prime} + X$ ($l,l'=e,\mu$)

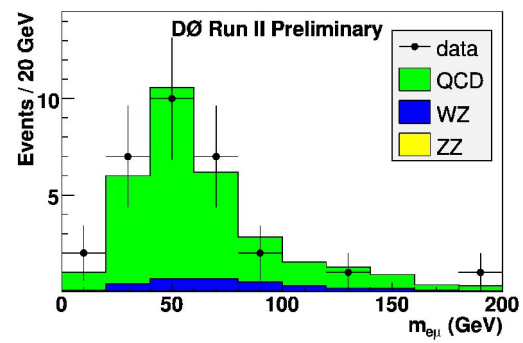
$L = 1.0\ fb^{-1}$ NEW

- Important for intermediate Higgs masses $M_H$~140 GeV
- Low, mostly instrumental background
  - charge flips: compare charge measurements in the tracker vs muon system ($\mu$) / $\Delta\varphi$(tr,EM) (e)
- Selection:
  - same sign e/$\mu$ : $p_T$>15 GeV, $|\eta| < 1.1(e)/2(\mu)$ + track quality cuts
- 3 channels (ee, e$\mu$, $\mu\mu$)

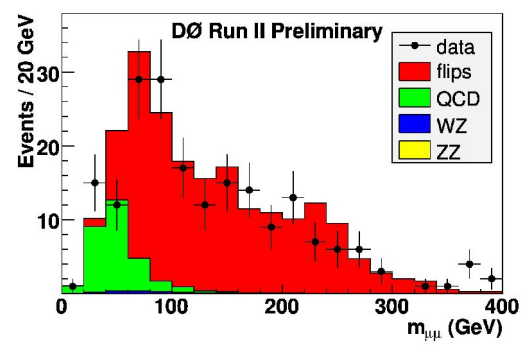
ee




e$\mu$

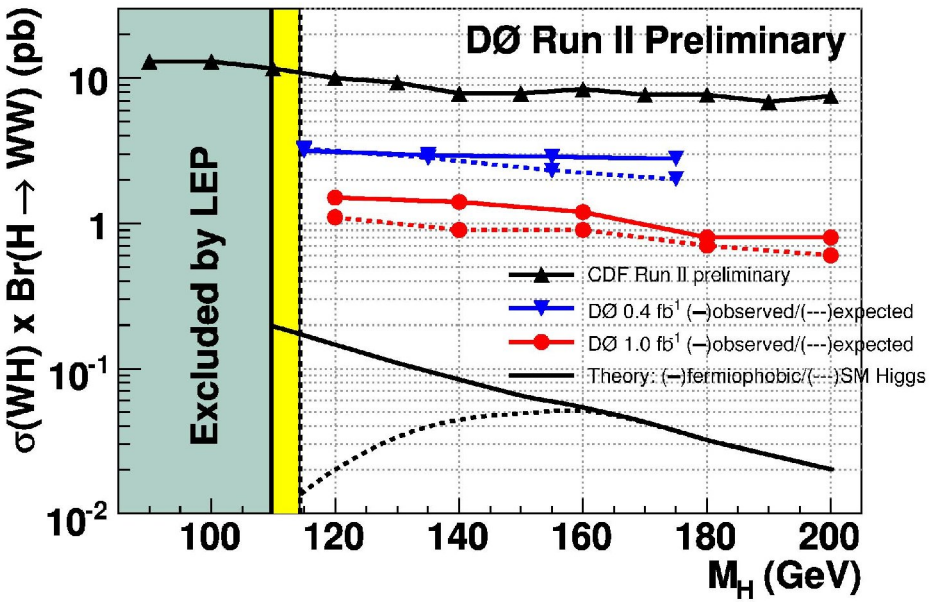



$\mu\mu$



# $WH \rightarrow WWW^* \rightarrow l^{\pm}l^{\pm\prime} + X$: result

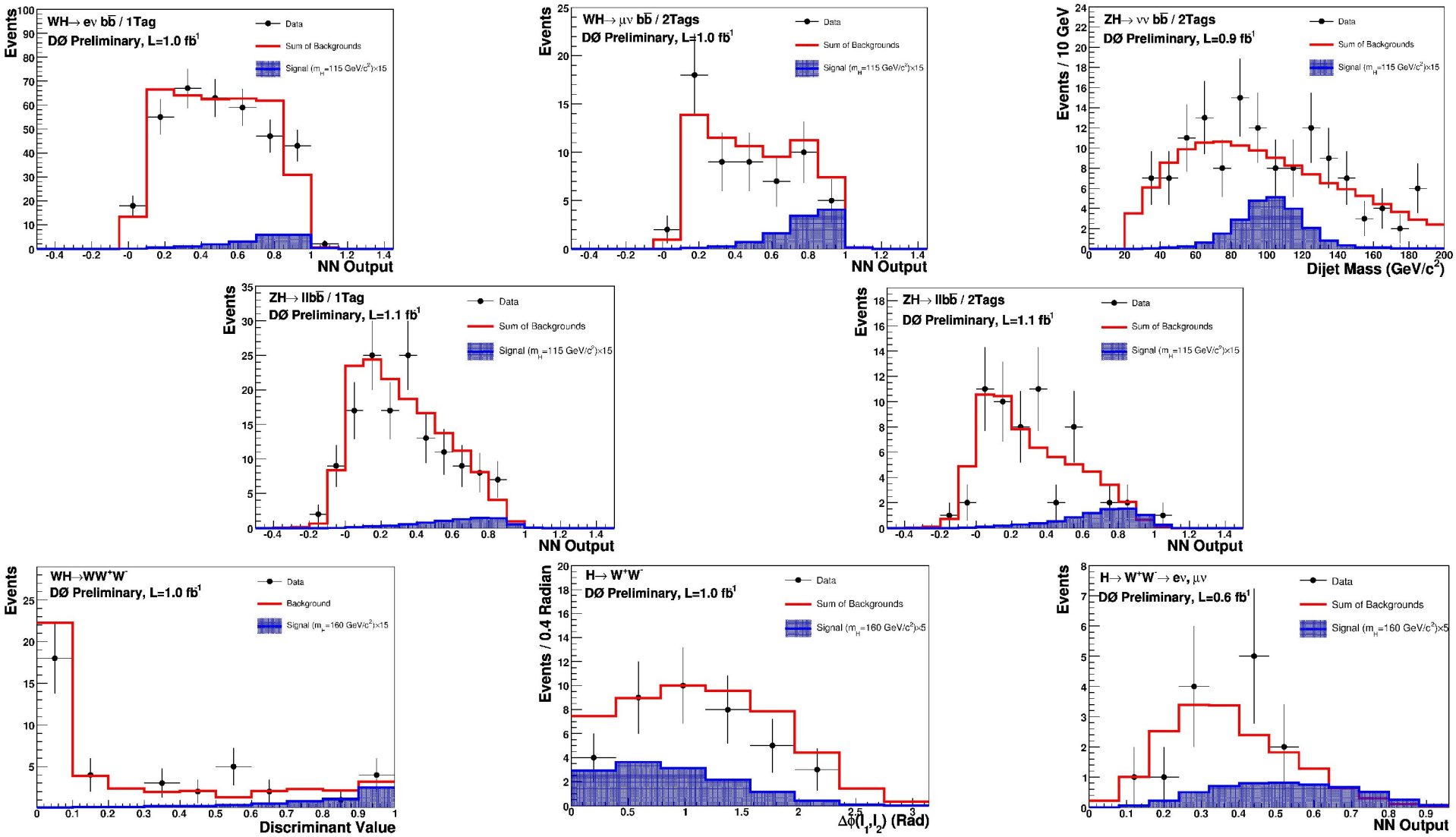
- Use 2D likelihood discriminant to separate signal from background (vs instrumental background and vs dibosons)
- Limit setting: fit the likelihood distribution
- Result @$M_H$=160 GeV: $\sigma_{95}$/SM = 18(exp)/25(obs)
- Result @$M_H$=140 GeV: $\sigma_{95}$/SM = 21(exp)/33(obs)



# Combining the results

| | | | |
|---|---|---|---|
| WH→lν bb | 1.7 $fb^{-1}$ (NN) | e/μ, 1b/2b | 2+2 |
| ZH→ll bb | 1.1 $fb^{-1}$ (NN) | e/μ, 1b/2b | 2+2 |
| ZH→νν bb | 0.9 $fb^{-1}$ | Z→νν,<br>W→łν (2b) | 2 |
| H→WW* | 0.9 $fb^{-1}$ (ee,μμ)<br>1.7 $fb^{-1}$ (eμ;NN) | ee, eμ, μμ | 3 |
| WH→WWW* | 1 $fb^{-1}$ | ee, eμ, μμ | 3 |

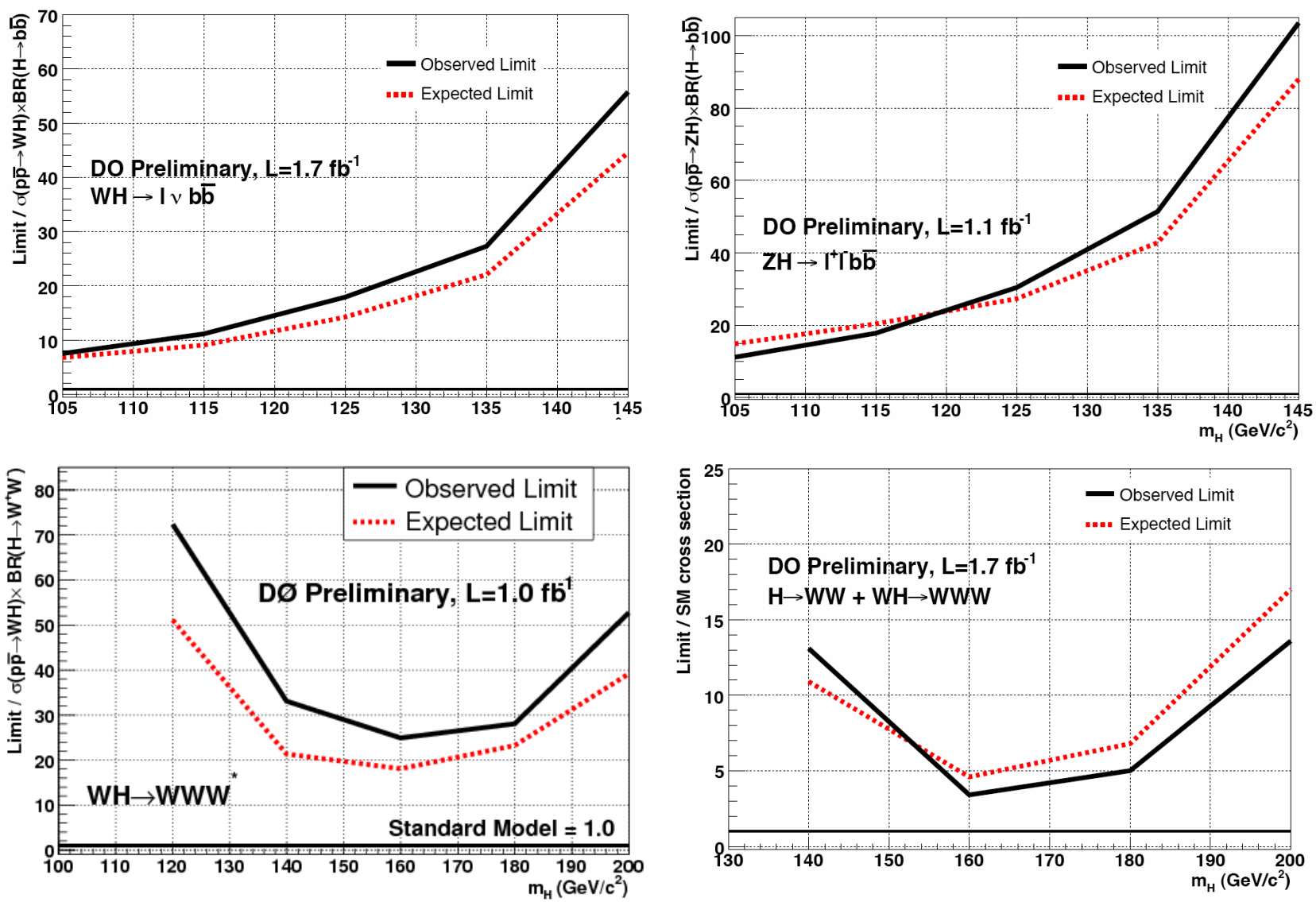
# Combination: inputs



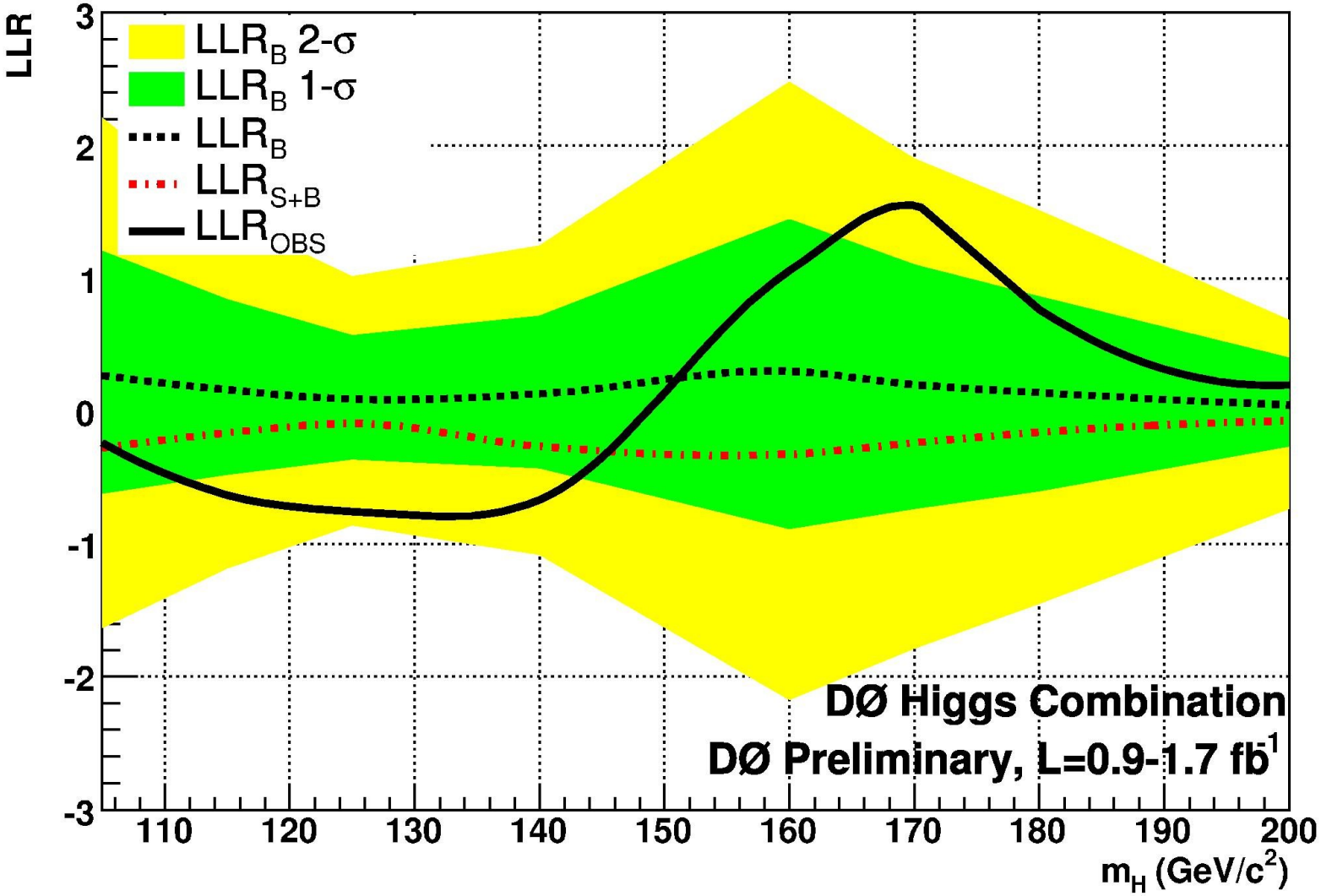
# Systematics

- Main sources:
  - luminosity/normalization (6%)
  - QCD background (15-50%)
  - input background cross section (6-18%)
  - b-tagging (3-5% ST, 7-9% DT)
  - jet energy scale (2-5%), jet identification (3-7%)
  - lepton identification + trigger (4-10%)
- Systematic uncertainties are included in the likelihood (``profiling'')
- Background is constrained by maximizing profile likelihood (``sideband fitting'')

# Partial combinations

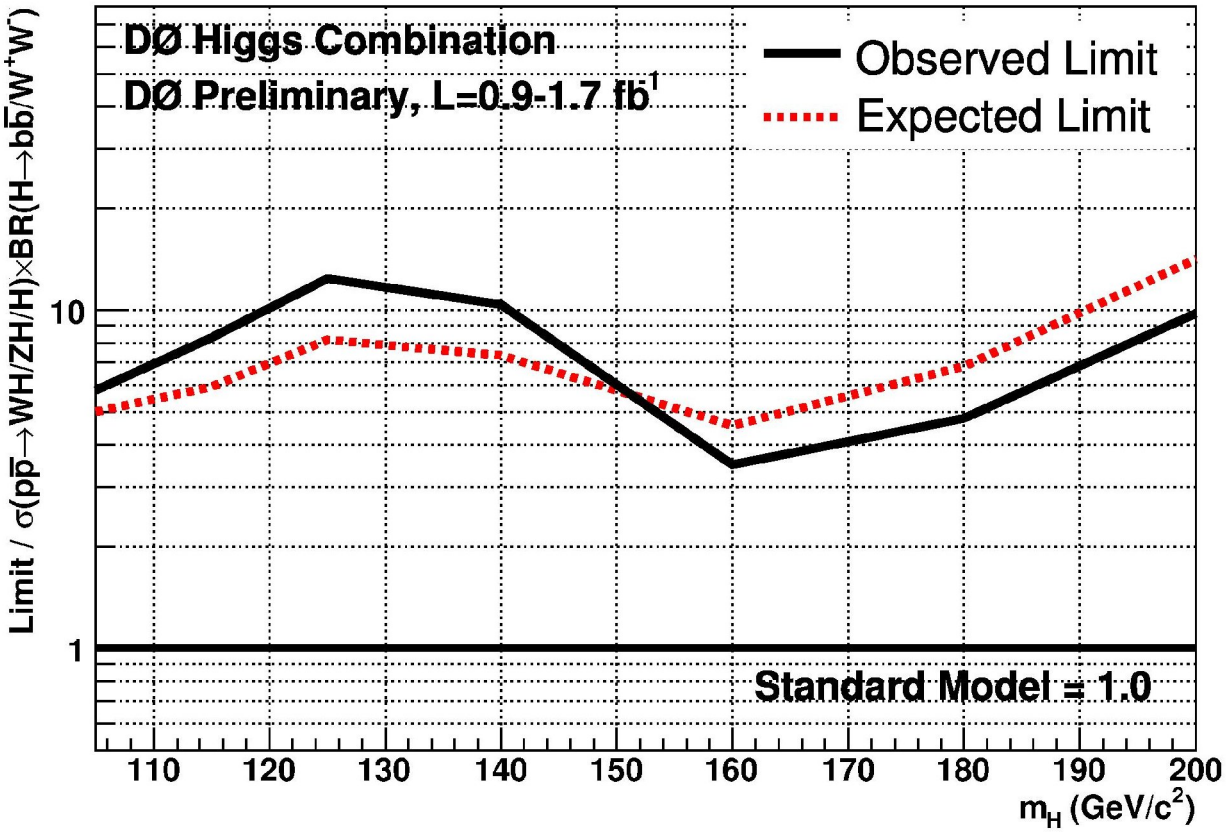


# Log Likelihood Ratio

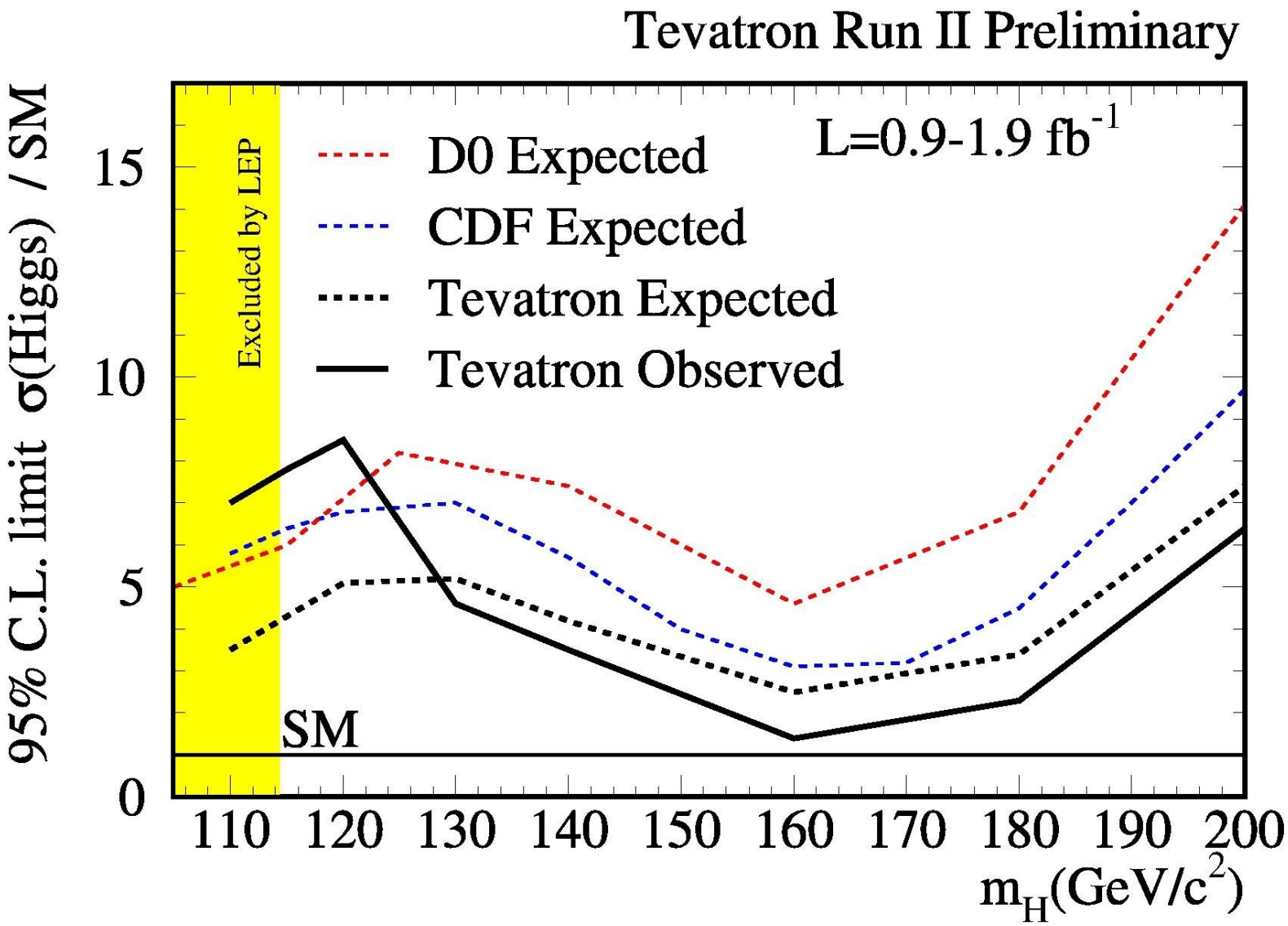


# Combination: result

- $M_H$=115 GeV: $\sigma_{95}$/SM = 6.0 (expected)/8.3 (observed)
- $M_H$=160 GeV: $\sigma_{95}$/SM = 4.6 (expected)/3.5 (observed)



# Combined DØ and CDF limits



# Prospects

- Update all principal analyses to 2 $fb^{-1}$
- Improve object identification (forward electrons, better efficiency, jet resolution)
- Advanced methods (matrix element – plan to update WH→lν bb to 2 $fb^{-1}$,…)
- More channels (τ final states, …)

# Conclusions

- DØ is searching for SM Higgs boson in the mass range up to 200 GeV
- In many channels, limits improve linearly with luminosity due to improved detector understanding and advanced analysis techniques
- Very soon we'll be probing Higgs at $M_H$=160 GeV

# Fasten your seatbelts, we are approaching the SM prediction