LCWS07, Hamburg, May 30-June 3, 2007

# SM and BSM Higgs Searches at DØ

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# The Success of the SM

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

| | Measurement | Fit | $\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$ |
|---|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | $0.02758 \pm 0.00035$ | 0.02768 | |
| $m_Z$ [GeV] | $91.1875 \pm 0.0021$ | 91.1875 | |
| $\Gamma_Z$ [GeV] | $2.4952 \pm 0.0023$ | 2.4957 | |
| $\sigma^0_{had}$ [nb] | $41.540 \pm 0.037$ | 41.477 | |
| $R_l$ | $20.767 \pm 0.025$ | 20.744 | |
| $A^{0,l}_{fb}$ | $0.01714 \pm 0.00095$ | 0.01645 | |
| $A_l(P_\tau)$ | $0.1465 \pm 0.0032$ | 0.1481 | |
| $R_b$ | $0.21629 \pm 0.00066$ | 0.21586 | |
| $R_c$ | $0.1721 \pm 0.0030$ | 0.1722 | |
| $A^{0,b}_{fb}$ | $0.0992 \pm 0.0016$ | 0.1038 | |
| $A^{0,c}_{fb}$ | $0.0707 \pm 0.0035$ | 0.0742 | |
| $A_b$ | $0.923 \pm 0.020$ | 0.935 | |
| $A_c$ | $0.670 \pm 0.027$ | 0.668 | |
| $A_l$(SLD) | $0.1513 \pm 0.0021$ | 0.1481 | |
| $\sin^2\theta^{lept}_{eff}(Q_{fb})$ | $0.2324 \pm 0.0012$ | 0.2314 | |
| $m_W$ [GeV] | $80.398 \pm 0.025$ | 80.374 | |
| $\Gamma_W$ [GeV] | $2.140 \pm 0.060$ | 2.091 | |
| $m_t$ [GeV] | $170.9 \pm 1.8$ | 171.3 | |

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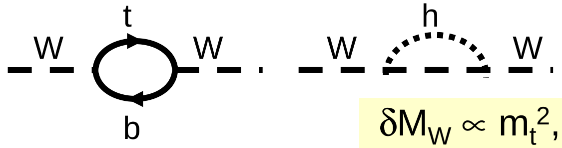
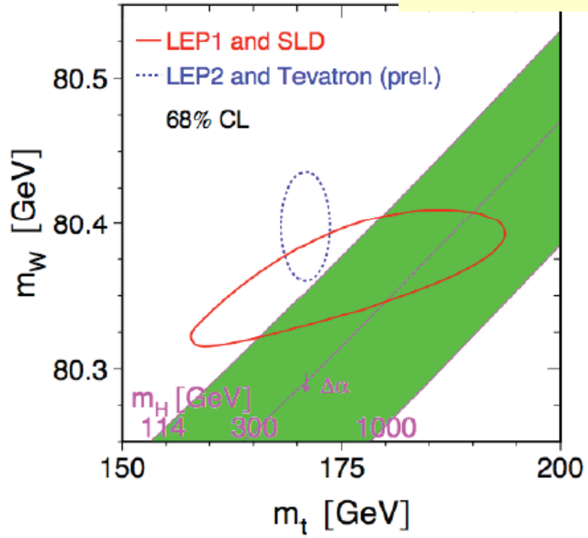
- However, the dynamics for EWSB still awaits direct experimental verification.

- The high accuracy achieved (both experimental and theoretical) allows to perform tests at the quantum level:




$$\delta M_W \propto m_t^2,\ \ln(m_h/M_W)$$



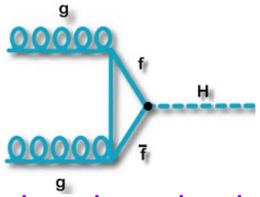

$\Rightarrow$ some sensitivity to the EWSB sector (requires careful interpretation)

- Current “experimental knowledge” on the SM-like Higgs:
  - Direct searches at LEP II: $m_h$>114.4 GeV @ 95% CL
  - Fits to precision EW data: $m_h$<144 GeV @ 95% CL

Data “favors” a light Higgs boson

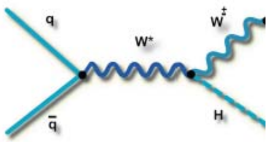
# SM Higgs at the Tevatron

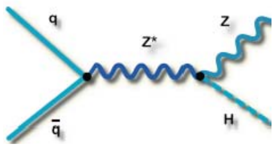
- Main production mechanisms (115<$m_h$<180 GeV):
  - Gluon fusion ($gg \rightarrow h$):




$\sigma$~0.8-0.2 pb

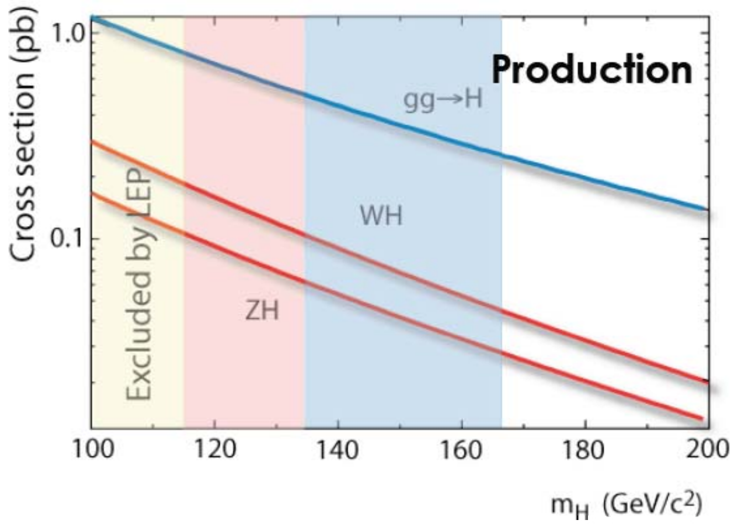
  - Associated production (Vh, V=W,Z):

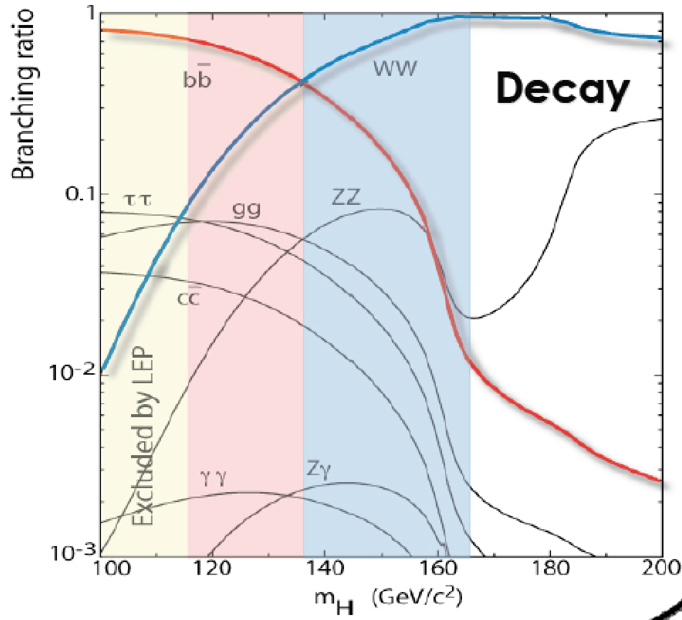


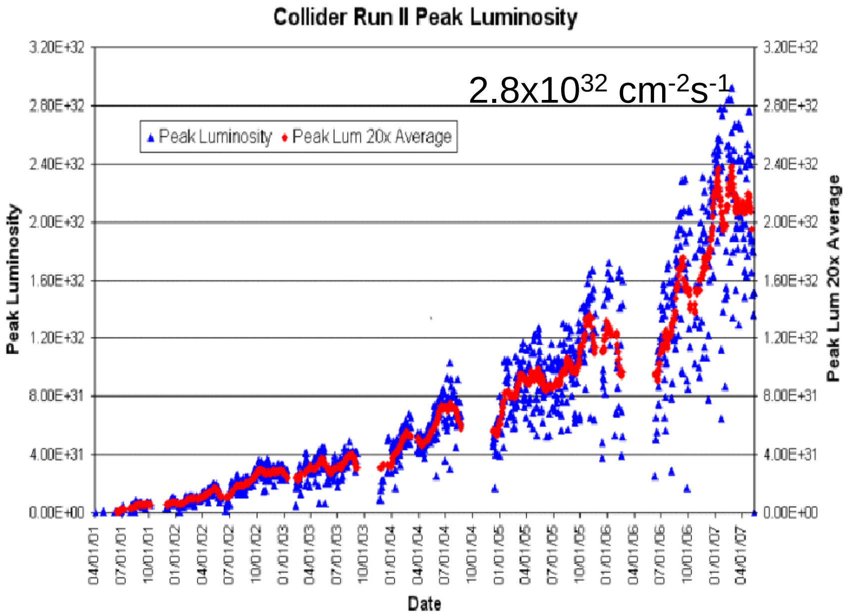

$\sigma$~0.2-0.03 pb $\sigma$~0.1-0.01 pb

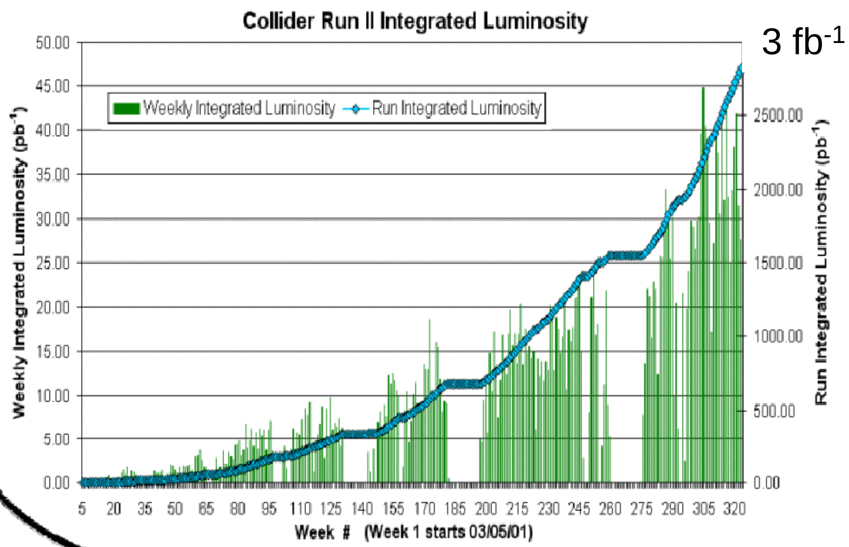
- Dominant decay channels:
  - $m_h$<135 GeV: $h \rightarrow bb$
  - $m_h$>135 GeV: $h \rightarrow WW^{(*)}$
- Search strategy:
  - Capitalizes on leptons to be able to trigger and select a sample enriched in EW instead of QCD processes.
  - Low mass region:
    dominated by $Wh \rightarrow l\nu bb$, $Zh \rightarrow l^+l^-bb$, $Zh \rightarrow \nu\nu bb$
  - High mass region:
    dominated by $gg \rightarrow h \rightarrow WW^{(*)} \rightarrow l^+\nu l'^-\nu$
  - Complement e.g. with $Wh \rightarrow WWW^{(*)}$



# Tevatron Performance

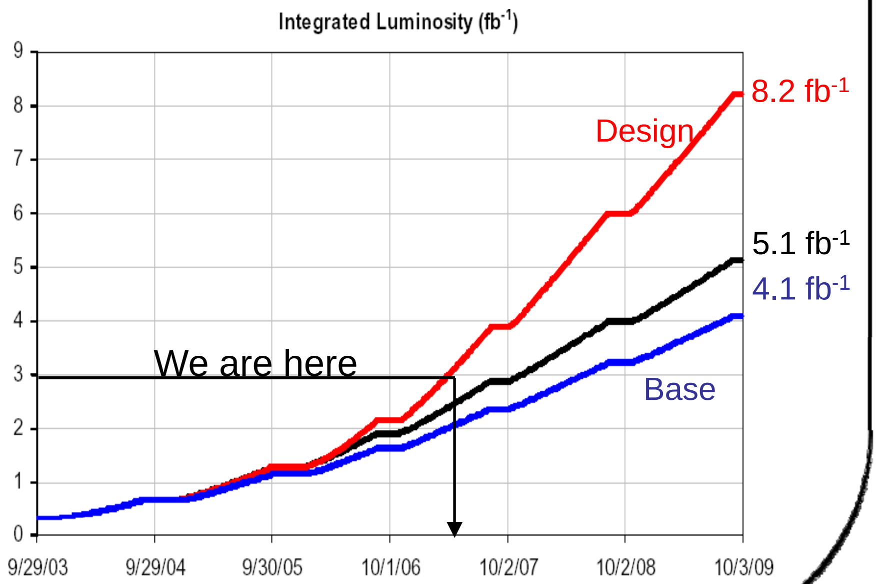


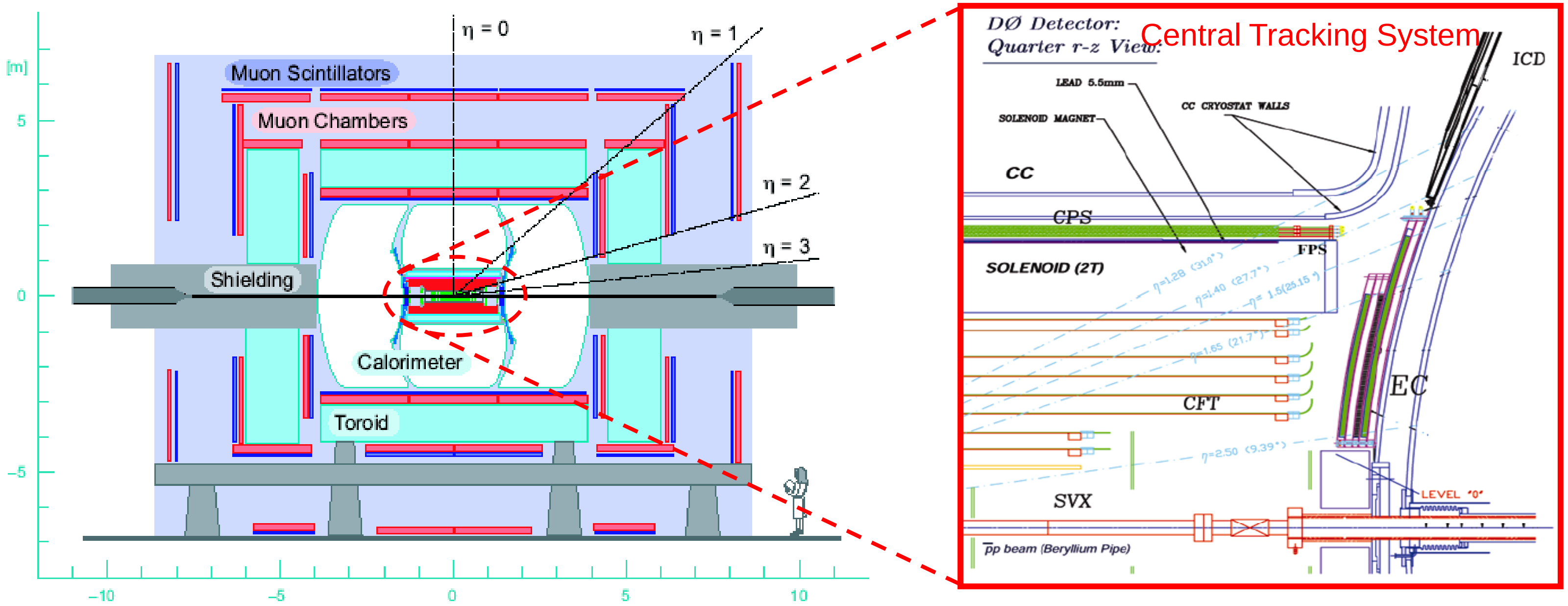

Excellent performance by the accelerator:

- Peak luminosity: $\geq 2\text{x}10^{32}$ cm$^{-2}$s$^{-1}$ (record: ~$3\text{x}10^{32}$ cm$^{-2}$s$^{-1}$)
- Weekly integrated luminosity: ~35 pb$^{-1}$ (record: ~45 pb$^{-1}$)
- Delivered integrated luminosity: ~3 fb$^{-1}$

- Performance is matching expectations for the design integrated luminosity of ~8 fb$^{-1}$ by 2009.



# DØ Detector

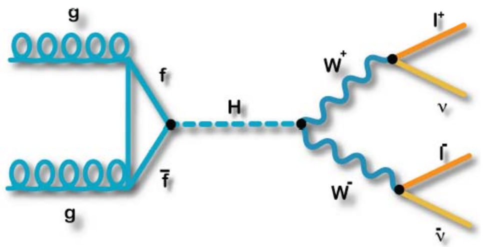



- Features:
  - Central tracking system in a 2 T solenoidal field:
    - Silicon Tracker (|η|<3)
    - Scintillating Fiber Tracker (|η|<1.5)
  - Central and forward preshowers
  - LAr/U calorimetry (|η|<4.2)
  - Muon system (3 layers, (|η|<2.0)
- Run IIb upgrades for further improved performance:
  - L1 trigger: CAL, Track and CAL+Track
  - Additional silicon layer (LØ) at R=1.6 cm.

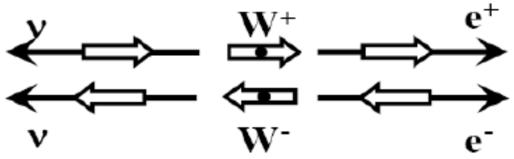
- Multipurpose detector well suited for Higgs search:
  - Lepton (e, μ, τ) identification
  - Jets and MET reconstruction
  - Jet flavor ID via displaced tracks and soft-leptons
- Data taking efficiency: 85-90%
- Recorded luminosity to date: ~2.5 $fb^{-1}$
- Results discussed here: ≤1 $fb^{-1}$

# Gluon Fusion

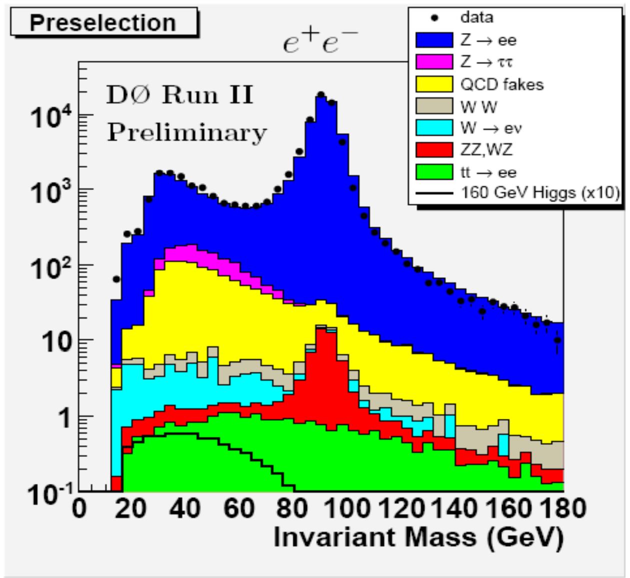
- Highest sensitivity channel for $m_h$>135 GeV.
- <u>Experimental signature</u>:

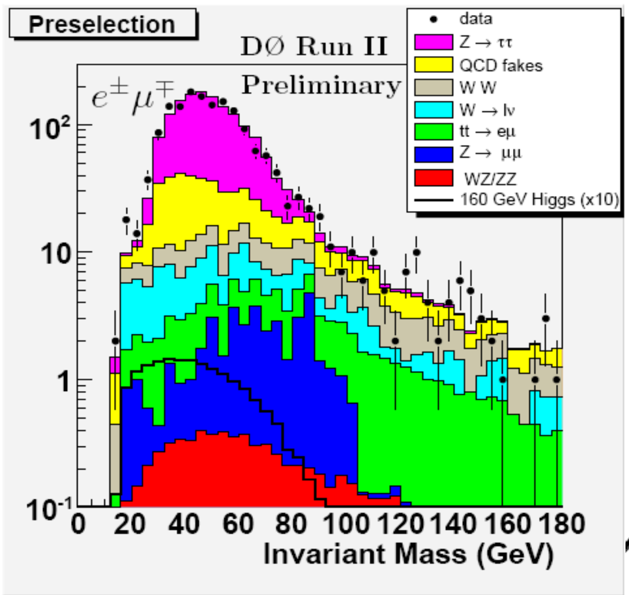



  - 2 high $p_T$ leptons (ee,eμ,μμ) from W boson decays
  - Large MET from missing neutrinos
  - Low ΔΦ(l,l) because of spin-0 Higgs decay




- <u>Backgrounds</u>: Drell-Yan, Diboson, W+jets, QCD, top
- <u>Event selection</u>:
  - Preselection: 2 opposite charge high $p_T$ leptons
  - MET > 20 GeV
  - $\sum p_{T,jet}$< 100 GeV (ttbar veto)
  - Additional kinematic cuts (e.g. $m_{ll}$)
  - ΔΦ(l,l)<2.0
- Main background after full selection is WW (~70%). Run II measurements agree with NLO calculations.

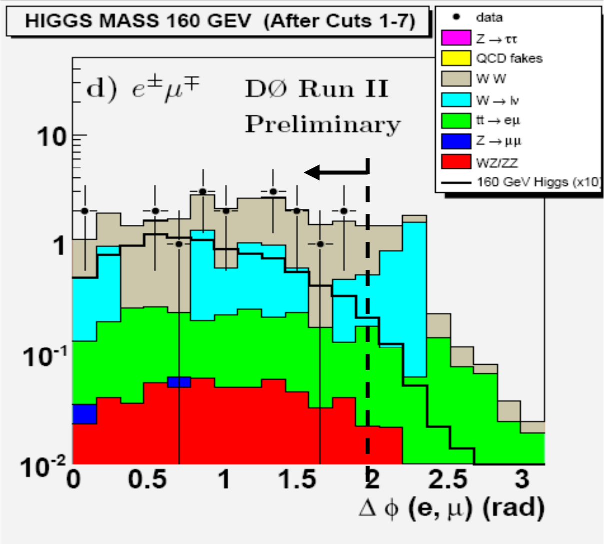


# Gluon Fusion (cont'd)

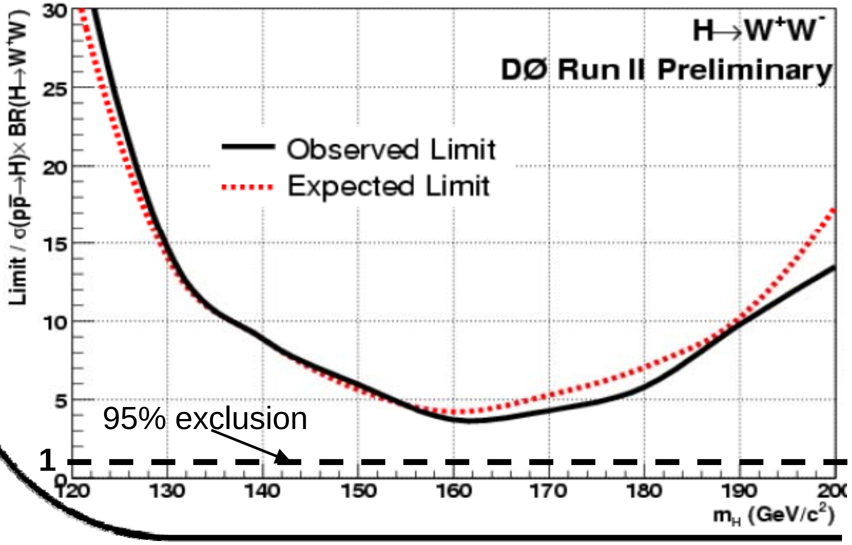
*Expected/Observed Events in 1 $fb^{-1}$*

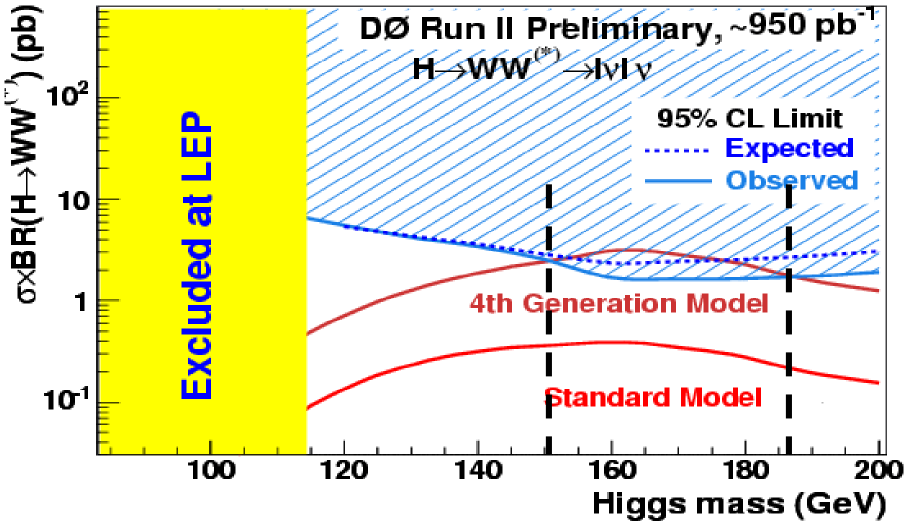
| Channel | Signal ($m_h$=160 GeV) | Background | Data |
|---|---|---|---|
| ee | 0.42 | 10.3 | 10 |
| eμ | 0.97 | 24.4 | 18 |
| μμ | 0.35 | 9.8 | 9 |
| Total | 1.74 | 44.5 | 37 |




- Cross section limit based on counting experiment after full selection.
- 95%CL limit ($m_h$=160 GeV):
  $\sigma_{95} < 4\ \sigma_{SM}$ (expected)
  $\sigma_{95} < 4\ \sigma_{SM}$ (observed)

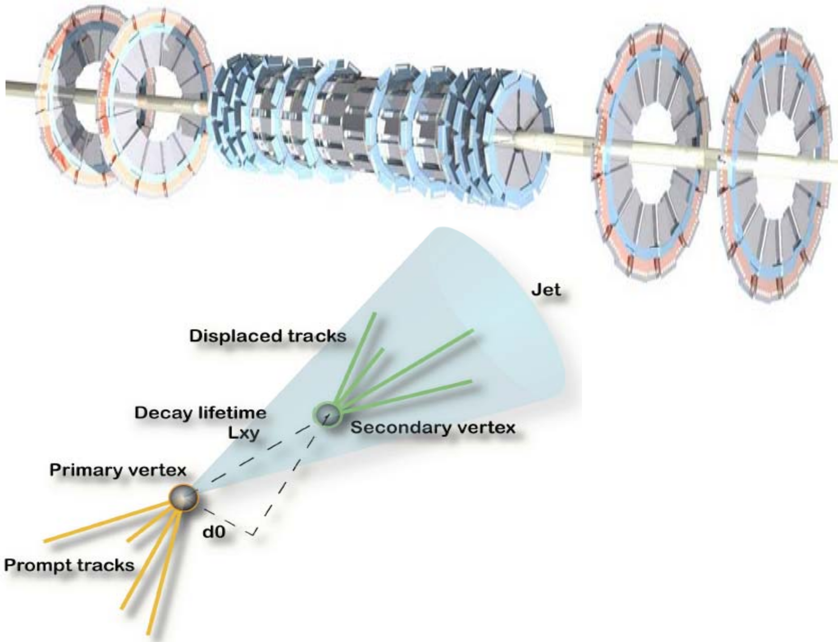
4th generation model excluded for $m_h$=150-185 GeV

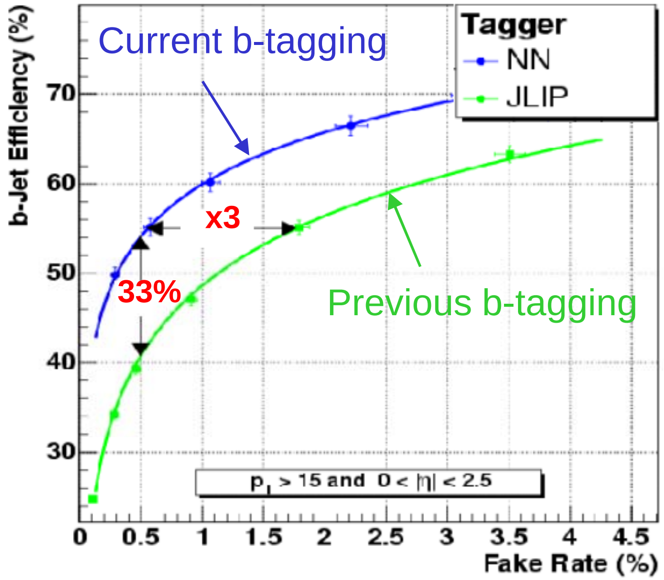


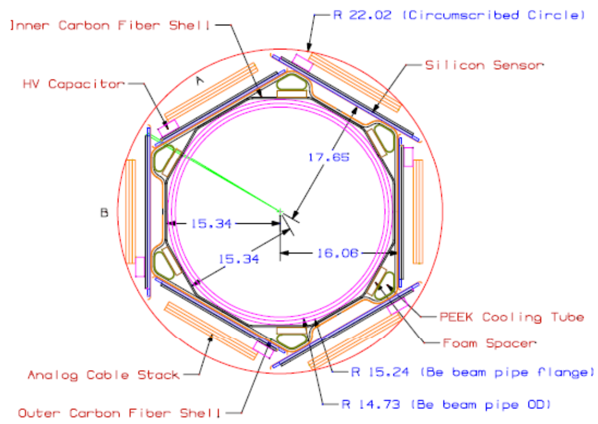
# B-Tagging

- High b-tagging performance critical for searches involving h→bb.



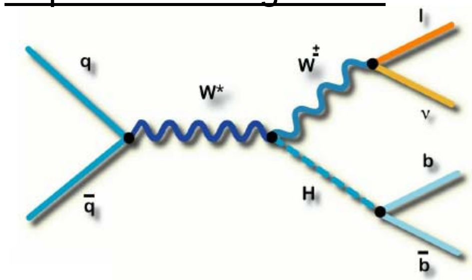




- Significantly improved performance for new NN b-tagger combining 7 variables based on previously existing secondary vertex and impact parameter taggers.
- Multiple operating points ranging from TIGHT (eff=50%, fake=0.4%) to LOOSE (eff=70%, fake=4.5%)
- Further improvements expected:
  - NN b-tagger including soft-lepton taggers.
  - Improved impact parameter resolution (by x2) from addition of LØ silicon detector.



# Associated Production (Wh→lνbb)

- Experimental signature:



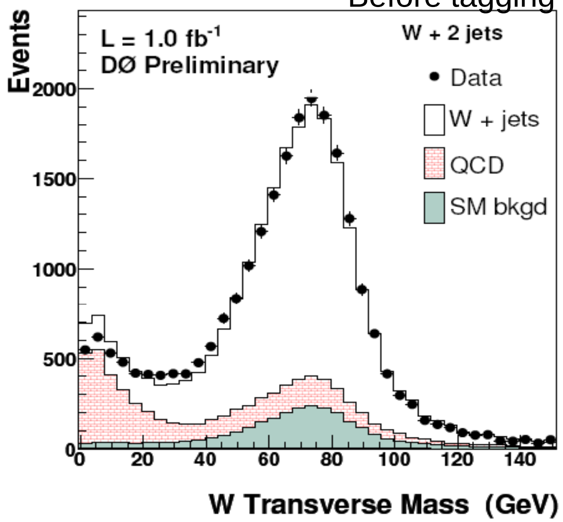

  - High $p_T$ isolated lepton
  - Large MET
  - 2 b-jets
- Event selection:
  - 1 isolated e(μ), $p_T$>20 GeV, |
  - MET > 20 GeV
  - 2-3 jets, $p_T$>20 GeV, |η|<2.5
  - 1 tight b-tag (1-tag sample) OR
    2 loose b-tags (2-tag sample)

  With respect to previous analysis:

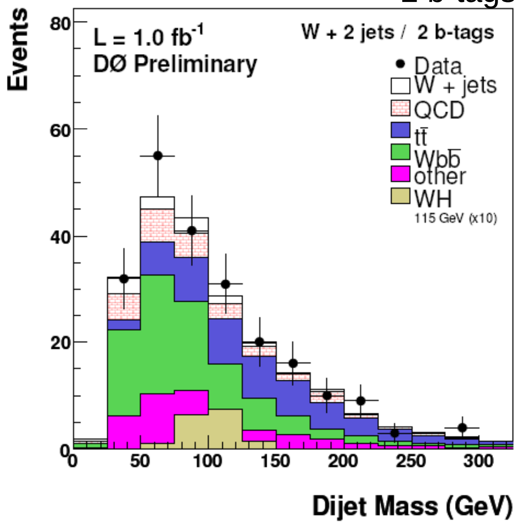
  ⇒ +47% sensitivity in μ channel from trigger OR (eff~100%)

  ⇒ +15% sensitivity from orthogonal 1-tag and 2-tag
- Backgrounds: W+jets (65-50%), top (15-30%), QCD
- Main discriminant variable: $m_{jj}$ distribution.
- Multivariate analyses under development.
  E.g. matrix-element based discriminant as sensitive as cut-based analysis despite 30-40% less sensitive selection.

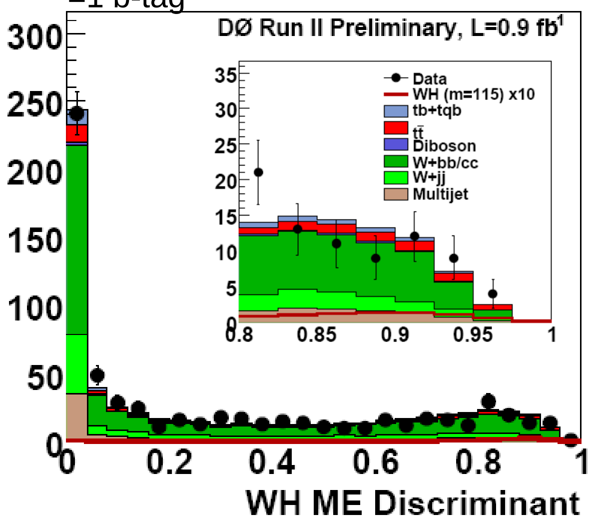
Before tagging




2 b-tags

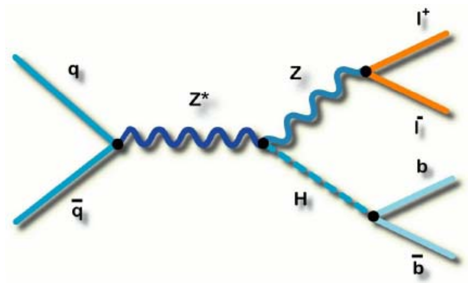



=1 b-tag



# Associated Production ($Zh \to l^+l^-bb$)

- Experimental signature:

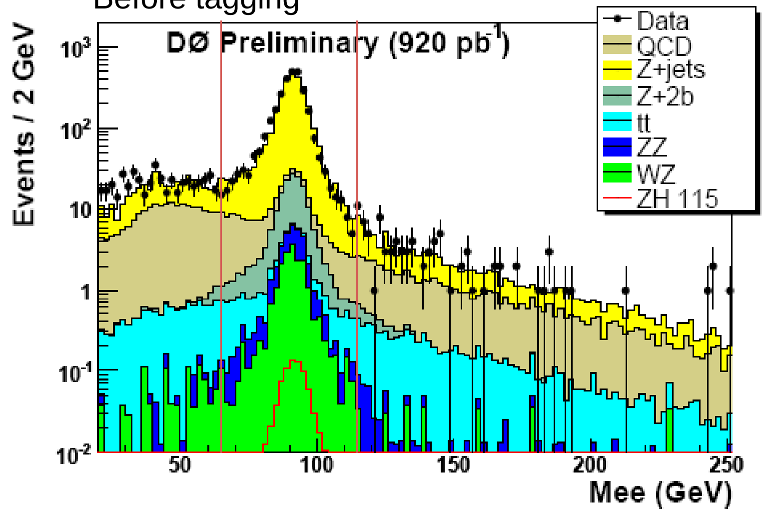



  - Two high $p_T$ isolated leptons
  - Low MET
  - 2 b-jets

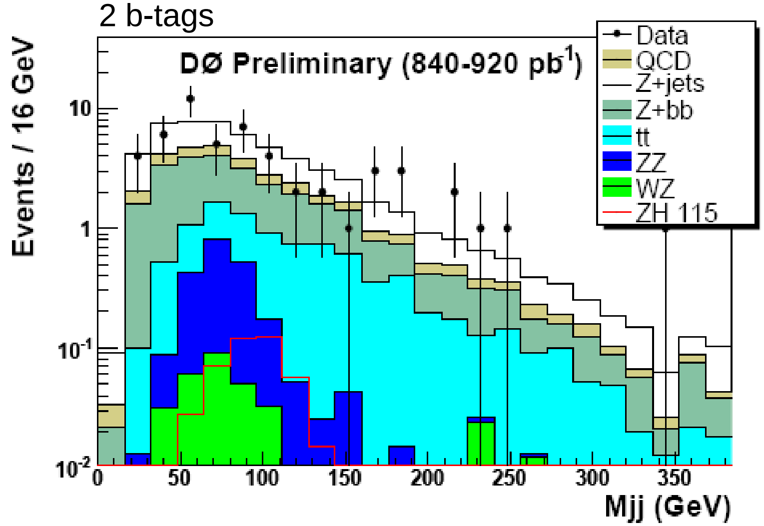
- Event selection:
  - 2 isolated $e(\mu)$, $p_T>15$ GeV, $|\eta|<1.1$ or $1.5<|\eta|<2.5$ ($|\eta|<2.0$)
  - Z mass window cut:
    ee: $65<m_{ll}<115$ GeV
    $\mu\mu$: $70<m_{ll}<110$ GeV
  - $\geq 2$ jets, $p_T>15$ GeV, $|\eta|<2.5$
  - 2 loose b-tags (4% mistag rate)
- Backgrounds: Z+jets (~80%), top, dibosons

- Main discriminant variable: $m_{jj}$ distribution.
- Multivariate analyses under development.

Before tagging

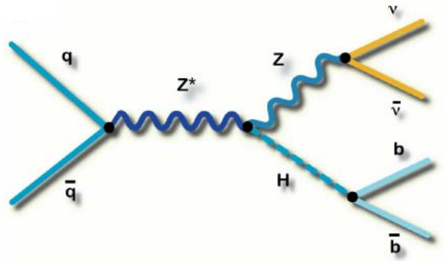



2 b-tags



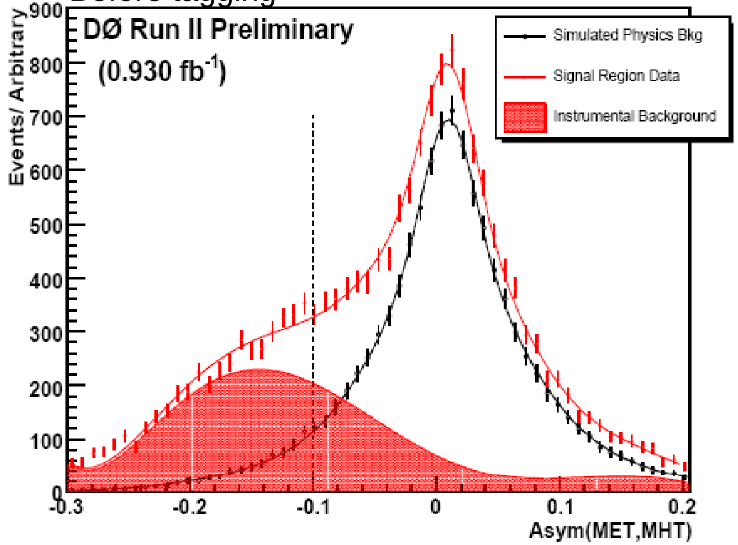
# Associated Production ($Zh \rightarrow \nu\nu bb$)

- Experimental signature:

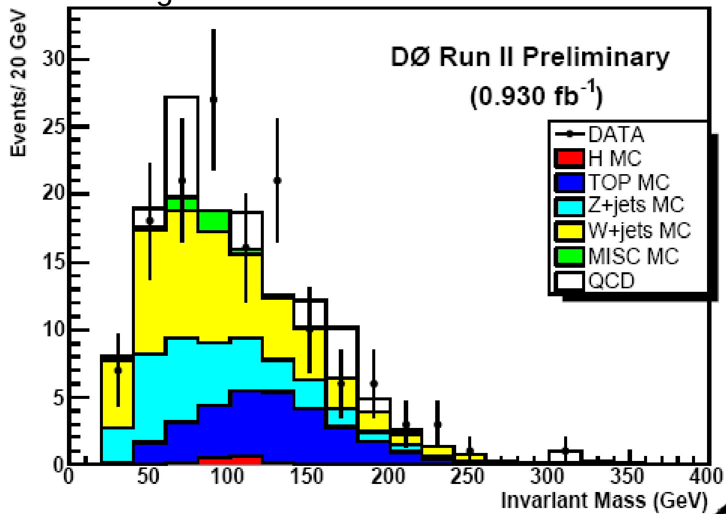



  - Large MET
  - 2 b-jets
- Main event selection criteria:
  - Trigger based on large vectorial missing $H_T$
  - MET>50 GeV
  - ≥2 jets, $p_T$>20 GeV, $|\eta|$<1.1 or 1.4<$|\eta|$<2.5
    Not back-to-back: $\Delta\phi$>165 deg
  - -0.1<Asymmetry(MHT,MET)<0.2
  - 2 b-tags: 1 tight + 1 loose b-tag
- Backgrounds:
  - Physics (87%): W+jets (40%), Z+jets, tt
  - Instrumental (13%): QCD multijets
    (estimated from sideband in data)
- Significant acceptance for $Wh \rightarrow l\nu bb$ with undetected e/$\mu$ or $l=\tau(\rightarrow$had).
- Main discriminant variable: $m_{jj}$ distribution.
- Multivariate analyses under development.

Before tagging




2 b-tags



# Associated Production Limits

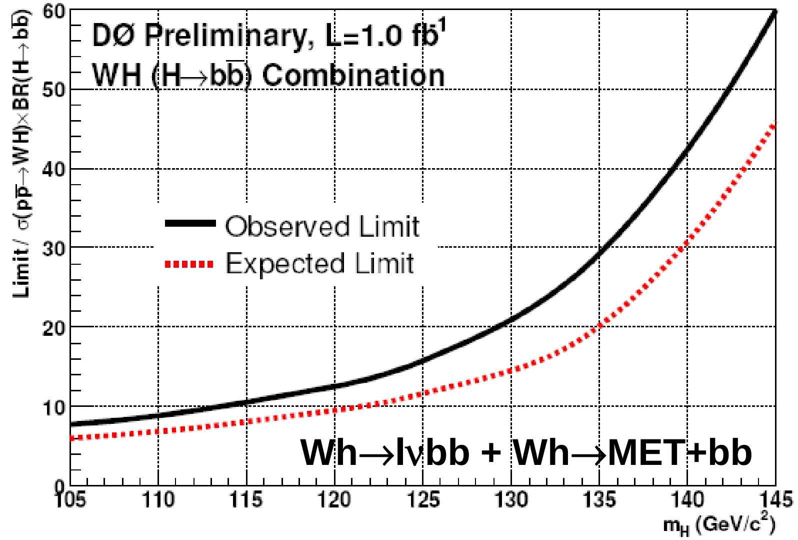
*Expected/Observed Events in 1 $fb^{-1}$*
($m_h$=115 GeV, *70<$m_{jj}$<130 GeV)*

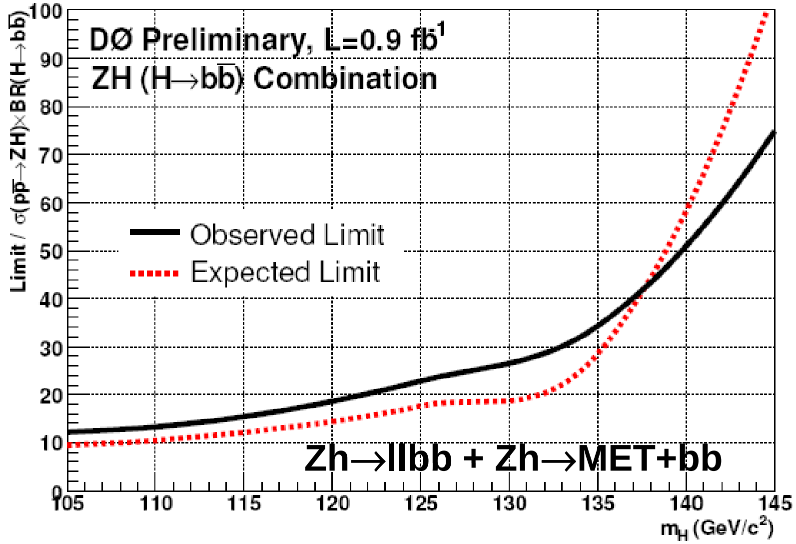
| Process | Signal | Bckg | Data | S/√B |
|---|---|---|---|---|
| Wh→lνbb(2-tag) | 1.45 | 86.6 | 91 | 0.156 |
| Wh→lνbb(1-tag) | 1.48 | 365.2 | 339 | 0.077 |
| Zh/Wh→MET+bb | 0.83/0.54 | 55.3 | 63 | 0.184 |
| Zh→llbb | 0.37 | 19.8 | 17 | 0.083 |
| Total | 4.67 | 526.9 | 510 | |

- Wh combined 95% CL limits ($m_h$=115 GeV):
  $\sigma_{95} < 8.1\ \sigma_{SM}$ (expected)
  $\sigma_{95} < 10.6\ \sigma_{SM}$ (observed)

- Zh combined 95% CL limits ($m_h$=115 GeV):
  $\sigma_{95} < 12.2\ \sigma_{SM}$ (expected)
  $\sigma_{95} < 15.4\ \sigma_{SM}$ (observed)

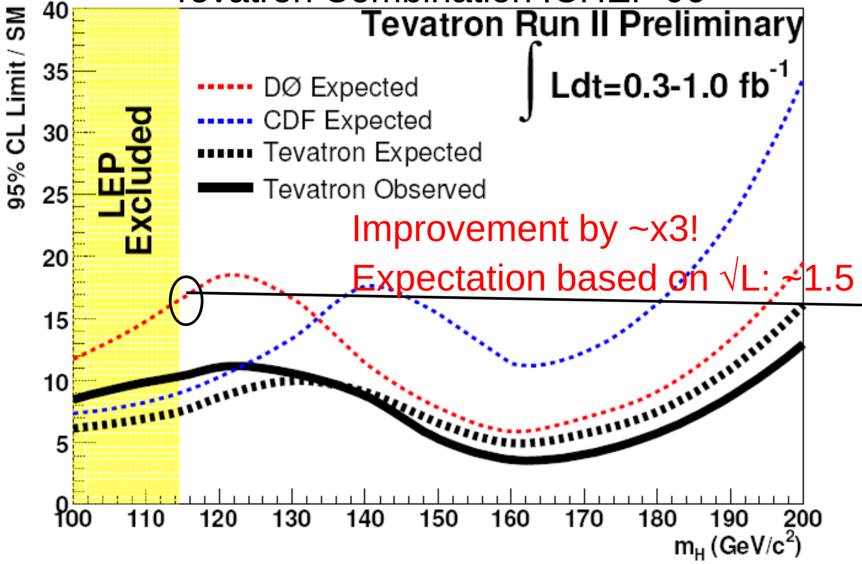
- Different channels have different sensitivity: important to keep separate in the combination.



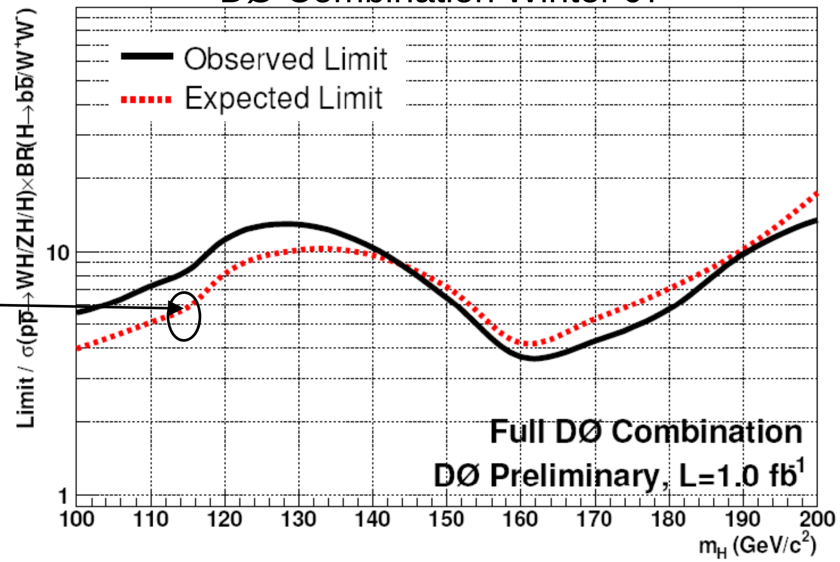



# Combined Limits and Prospects

Tevatron Combination ICHEP'06




DØ Combination Winter'07




- Prospects:

(optimized operating point, Improved b-tag NN, continuous b-tagging, layer-Ø,..) → B-tagging

(ME/NN discriminants,..) → Multivariate Techniques

(kinematic fiting, b-specific corrections,…) → Improved Mass Resolution

(Wh→WWW$^{(*)}$, Zh/1-tag, taus, h→WW$^{(*)}$ →lvjj,… ) → New Channels

| Ingredient | Equiv. Lumi. Gain | $\sigma_{95}/\sigma_{SM}$ ($m_h$=115 GeV) | $\sigma_{95}/\sigma_{SM}$ ($m_h$=160 GeV) |
|---|---|---|---|
| **DØ (1 fb$^{-1}$)** | - | **5.9** | **4.2** |
| Lumi = 2 fb$^{-1}$ | 2 | 4.2 | 3.0 |
| B-tagging | 2 | 3.0 | 3.0 |
| Multivariate Techniques | 1.7 | 2.3 | 2.3 |
| Improved Mass Resolution | 1.5 | 1.8 | 2.3 |
| New Channels | 1.3/1.5 | 1.6 | 1.9 |
| Reduced Systematics | 1.2 | 1.5 | 1.7 |
| Two Experiments | 2 | 1.1 | 1.2 |

**Luminosity needed for 95% CL exclusion: ~2.5 fb$^{-1}$ ~3.0 fb$^{-1}$**

(*) Potential improvements in acceptance (lepton ID, trigger, etc) not included in above table.

# Higgs Boson(s) Beyond the SM

- The simple SM Higgs mechanism may not be realized in Nature.
- Many extended models of EWSB possess a limit in which they are indistinguishable from the SM ("decoupling limit"): e.g. 2HDM, extra dimensions, composite models, etc.

  ➔ SM-like Higgs searches provide useful information.

- In particular, within the generic (Type II) 2HDM:
  - $\Phi_u$ and $\Phi_d$ couple respectively to up- and down-type fermions; $\tan\beta = v_d/v_u$.
  - After EWSB, four massive scalars ($h^0$,$H^0$,$H^{\pm}$) and one massive pseudo-scalar ($A^0$)

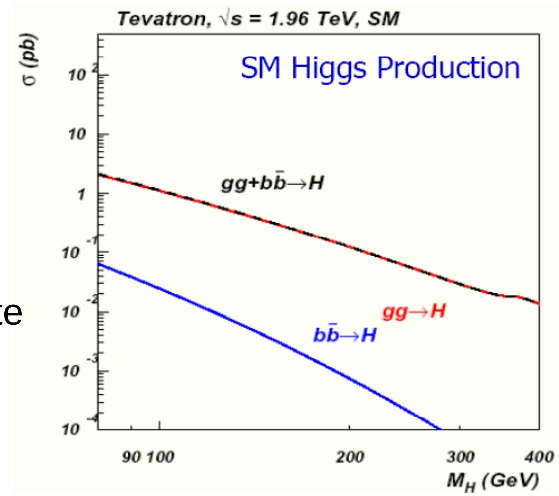
  Most successful of them is SUSY:
  - EWSB typically explained by radiative corrections
  - Requires light h: $m_h$<135-140 GeV
  - MSSM: described via a handful of additional parameters: $\tan\beta$, $\mu$, A and gaugino masses

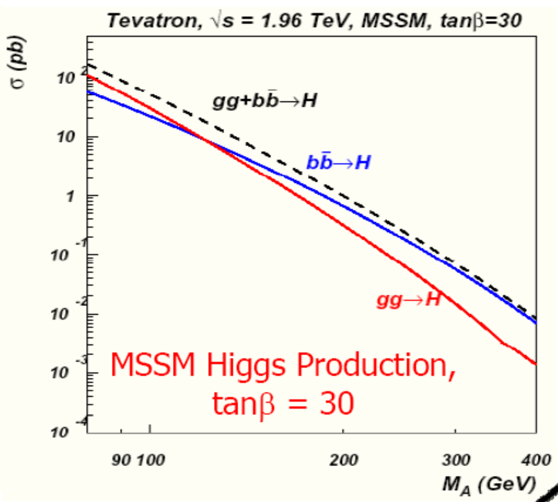
- MSSM at large $\tan\beta$:
  - $\Phi^0=\{h^0/H^0,A^0\}$ nearly degenerated in mass
  - $\sigma_{\Phi+X} \propto \tan^2\beta$

  ⇒ Significant increase in production rate!!
  - For low and intermediate masses:

    BR($\Phi^0 \to bb$)~90%

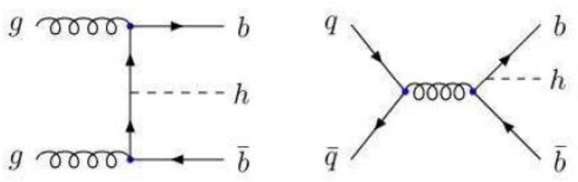
    BR($\Phi^0 \to \tau^+\tau^-$)~10%



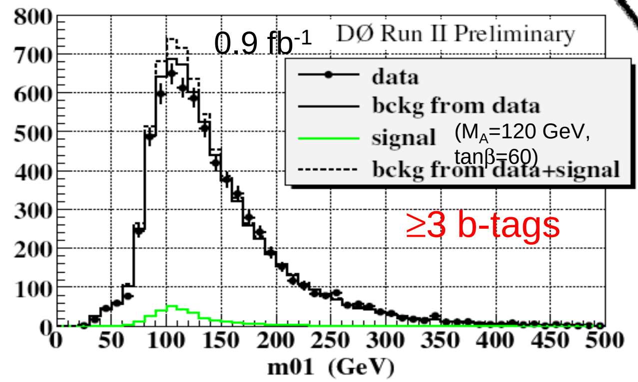



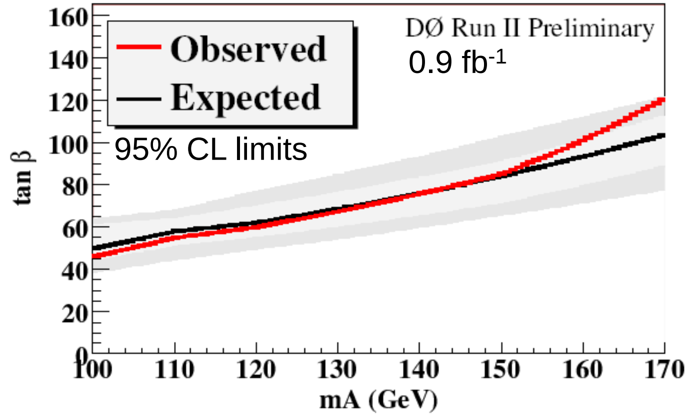
# MSSM Higgs ($\Phi \to bb$)

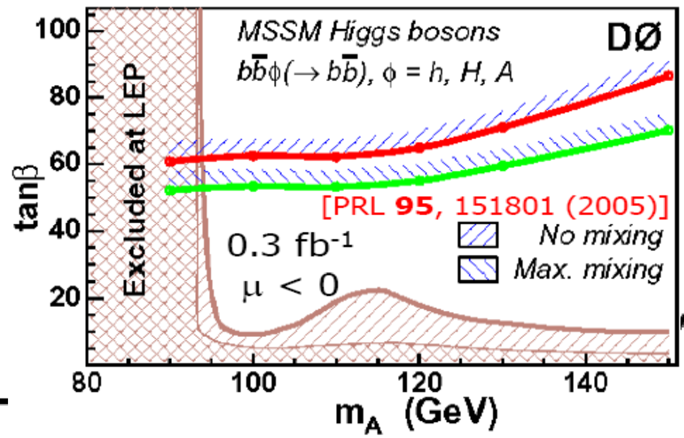
- Search for $\Phi$+b(b) associated production with $\Phi \to bb$.




- Experimental signature:
  - $\geq$3 b-tagged jets with $p_T$>40, 25, 15 GeV.
  - Invariant mass of leading two jets peaks at $M_\Phi$
- Backgrounds dominated by heavy flavor-enriched QCD multijets:
  - Shape extracted from 2-tag sample (including kinematic bias from 3rd b-tag)
  - Rate normalized outside the "signal region" (for each point in $M_A$ and $\tan\beta$) plane.
- Good agreement between data and background model $\Rightarrow$ limits on $\sigma_{\Phi b(b)}BR(\Phi \to bb)$ set via the $CL_s$ method.
- Interpret cross section limits as upper $\tan\beta$ limits (currently using tree-level cross sections, i.e. w/o NLO and stop mixing effects – not directly comparable to published 0.3 fb$^{-1}$ result).
  - Moderate improvement (~15%) over published result despite not being as well optimized.
  - Maximum sensitivity expected for $\mu$<0 and "maximum mixing".

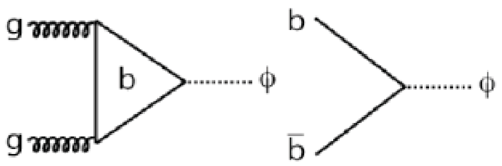


# MSSM Higgs ($\Phi\rightarrow\tau^+\tau^-$)

- Search for $\Phi\rightarrow\tau^+\tau^-$ complementary to $\Phi\rightarrow bb$: lower BR but also lower backgrounds.



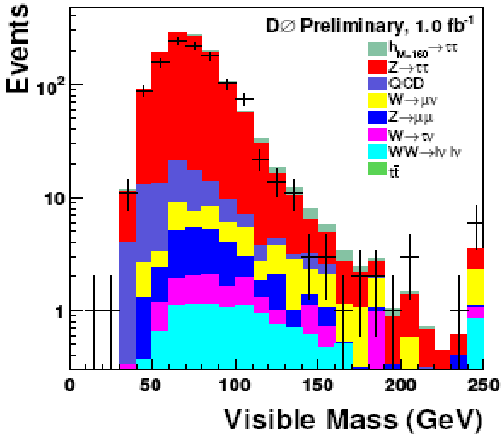

$\Phi\rightarrow\tau_\mu\tau$

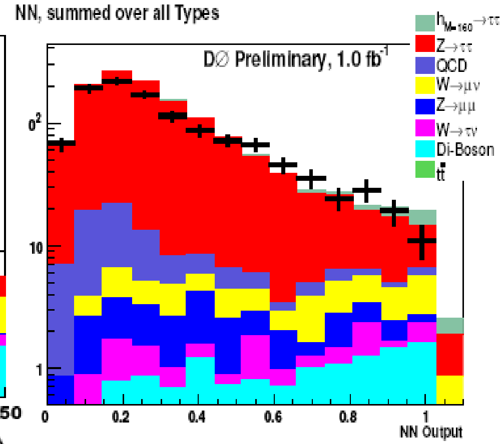
- <u>Main event selection criteria</u>:
  - One isolated $\mu$, $p_T>15$ GeV
  - One $\tau$ candidate, $p_T>15(20)$ GeV
  - $NN_\tau>0.9(0.95)$; $\Delta R_{\mu\tau}>0.5$
  - $M_W^{vis}<20$ GeV (reduce W+jets bckg)

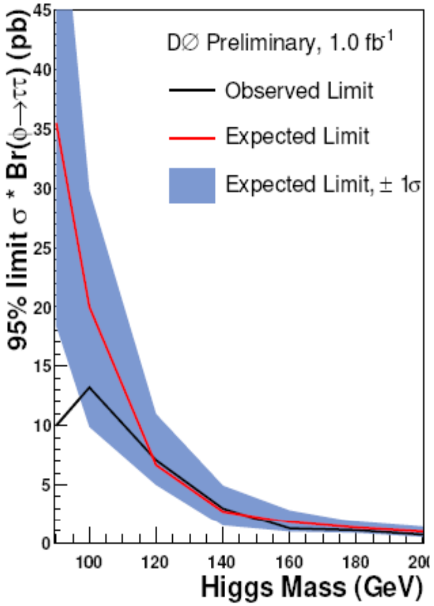
$$M_W^{vis} = \sqrt{2E_\mu \not{E}_T \frac{p_\mu}{p_{T,\mu}}(1-\cos\Delta\phi)}$$

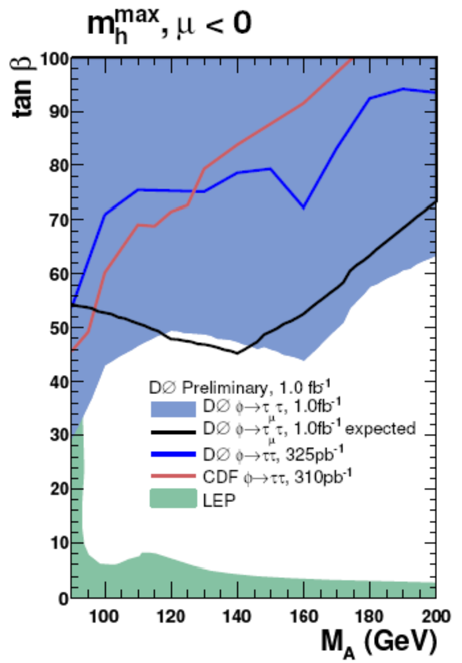
- <u>Dominant bckg after selection</u>: $Z\rightarrow\tau^+\tau^-$ (90%).
- Mass-dependent NN selection for optimal S/B separation ($M^{vis}$, $\mu$ and $\tau$ kinematic variables).

- Good agreement between data and bckg model $\Rightarrow$ limits on $\sigma_\Phi BR(\Phi\rightarrow\tau^+\tau^-)$ via the $CL_s$ method.
- Interpret cross section limits within MSSM in the $m_h^{max}$ and no-mixing scenarios.



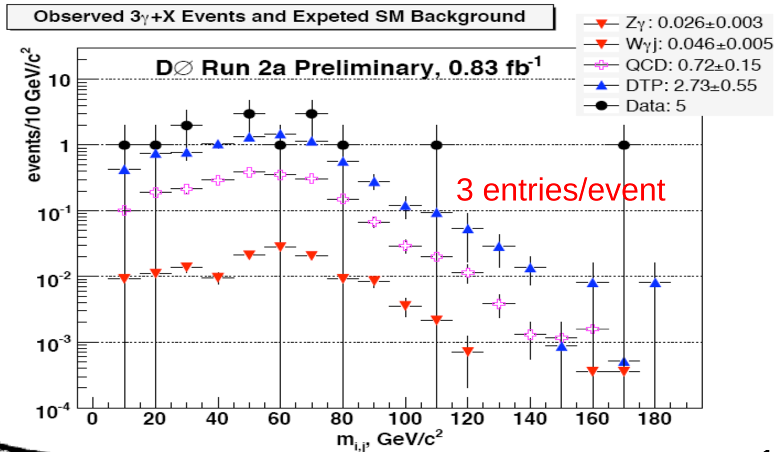
# Fermiophobic Higgs

- In certain 2HDM, couplings of light Higgs to fermions is suppressed. If sufficiently light, BR($h_f \to \gamma\gamma$)~1.
- Search for associated $h_f H$ production via the $h_f W H$ interaction in the multi-photon final state.

$$p\bar{p} \to h_f H^{\pm} \to h_f h_f W^{\pm} \to \gamma\gamma\gamma(\gamma) + X$$

  - In 2HDMs, for tanβ>1, $M_H$ <200 GeV, $M_h$<90 GeV: BR($h_f \to \gamma\gamma$)~1 and BR($H \to h_f W$)~1.
- Experimental signature:

  ≥3 γ, $E_T$>30, 20, 15 GeV with |η|<1.1
- Main background: direct 3γ production (78%); estimated from MC, corrected for the ratio of direct di-photons in data vs. MC.
- Good agreement between data (5 events) and background model (3.5 0.6).



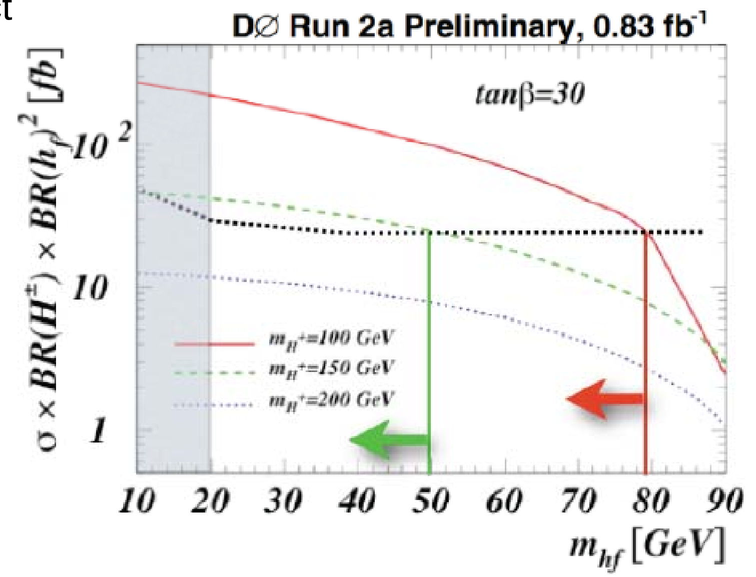

- No apparent structure in the di-photon mass spectrum. Further improve S/B by requiring $p_T(3\gamma)$>25 GeV:

  observed: 0 events,

  expected: 1.1 0.2 events

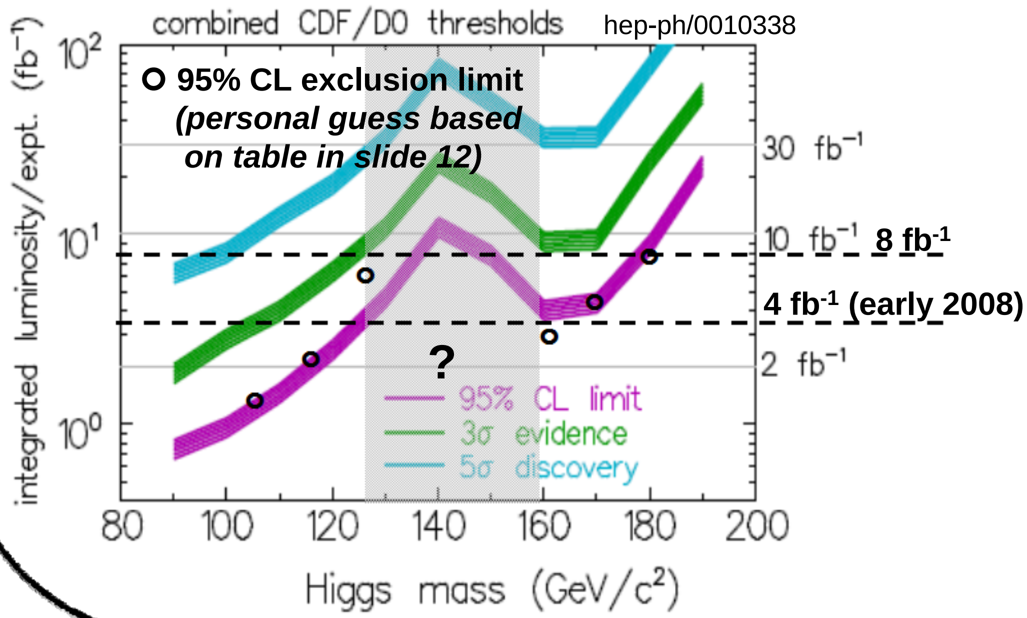
  ⇒ σ($h_f H$)<25.3 @ 95% CL.

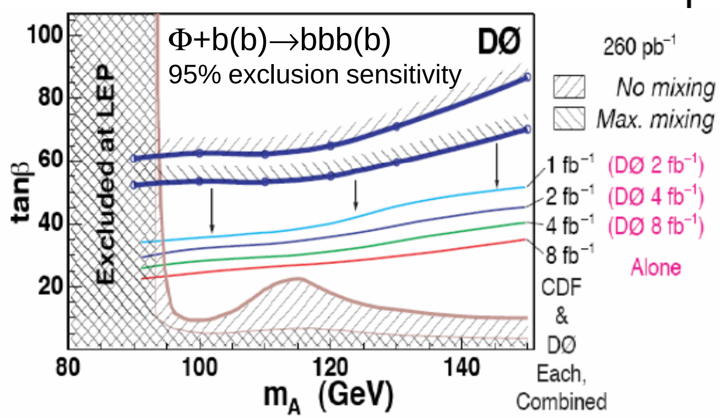
- Limits presented as exclusion in $M_h$ for different $M_H$ and tanβ values.
- Sensitivity depends strongly (weakly) on $M_H$ (tanβ).

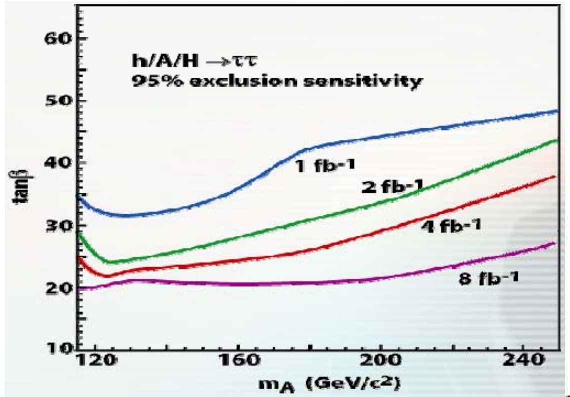


# Summary

- Wide variety of searches for SM or BSM Higgs with 1 $fb^{-1}$ show no evidence of signal.
- The accelerator and the DØ detector are performing extremely well.
  - 2.5 $fb^{-1}$ of data already recorded; expect ~4(8) $fb^{-1}$ delivered in 2007(2009).
- We continue to learn how to squeeze the last drop of information out of the data.
  - Ongoing work to increase acceptance, add channels not considered before, invariant mass resolution improvements, sophisticated analysis techniques, etc.
  - Goal: continue to beat down √L scaling!
  - Analysis teams are growing!!
  - Very important: the same is happening at CDF!!!
- A very exciting time for the Higgs search at the Tevatron!!!!



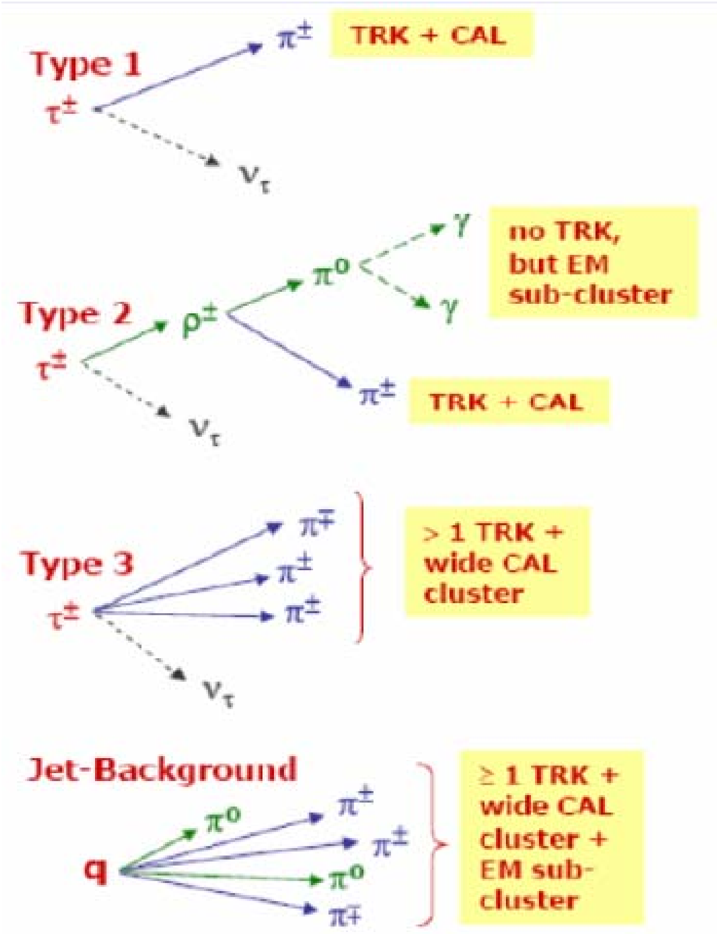



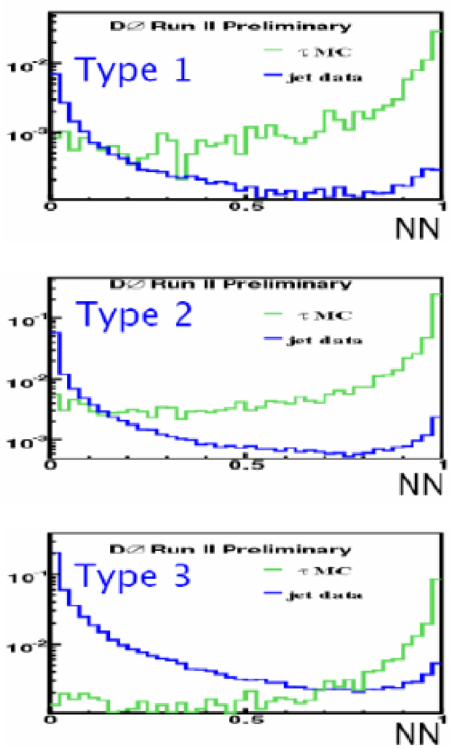



# Backup

# Tau Identification

- NN-based identification for each of three tau categories.




Performance ($p_T$>15 GeV)

| Tau Type | 1 | 2 | 3 |
|---|---|---|---|
| Reconstruction | | | |
| Jets | 1.5 | 10 | 38 |
| Taus | 9.1 | 50 | 20 |
| NN > 0.9 | | | |
| Jets | 0.04 | 0.2 | 0.8 |
| Taus | 5.8 | 37 | 13 |

$\Rightarrow$ Validated in $Z \to \tau\tau$ cross section measurement.