Searches for neutral MSSM Higgs bosons with DØ

presented by

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On behalf of the DØ Collaboration

Fermilab Joint Experimental-Theoretical Seminar

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Outline

- Introduction:
  - Higgs in the MSSM
  - Data sample and the D0 detector
- Search for Higgs in the $\tau\tau$ channel:
  - arXiv:0805.2491[hep-ex]
- Search for associated Higgs production in the 3b channel:
  - arXiv:0805.3556[hep-ex]
- Interpretation in the MSSM
- Conclusions & Prospects

Will only cover new results using ~1fb^{-1}

(>2 fb^{-1} results are coming soon)

[Thanks to all Tevatron colleagues]

Higgs bosons in the MSSM

- In MSSM have 2 Higgs doublets
  - H_u (H_d) couple to up- (down-) type fermions
  - Ratio of their VEV's: $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
  - 5 Higgs particles after the EWSB:
    - h, H: CP-even, neutral
    - A: CP-odd, neutral
    - H^+, H^- (not part of this talk)
  - At tree level, 2 independent parameters: m_A and $\tan\beta$

- At large $\tan\beta$:
  - Coupling of A, h/H to down-type fermions, e.g. *b*-quark, enhanced wrt SM $\rightarrow$ production amplitude $\sim\tan\beta \rightarrow$ cross section $\sim\tan^2\beta$
  - h/H & A (denoted by ϕ) ~degenerate in mass $\rightarrow$ further increase in cross-section

Discovery potential now!

MSSM Higgs boson production

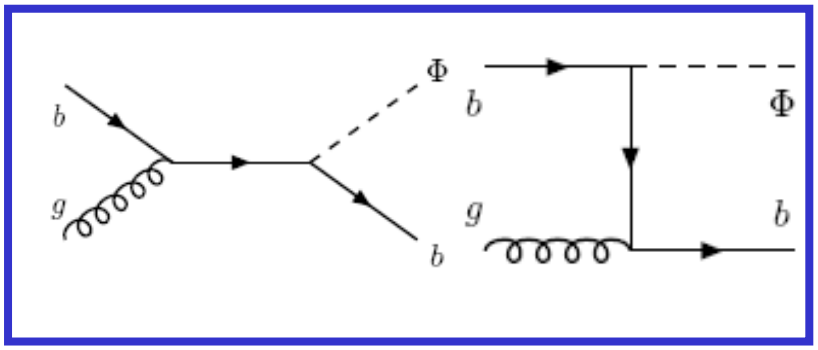
For low & intermediate masses:

- Br ($\phi \rightarrow \tau\tau$) ~10%, Br ($\phi \rightarrow$ bb) ~90%

- Signatures:
  - Higgs decays to 2 τ's
  - Further decays of τ's define final states

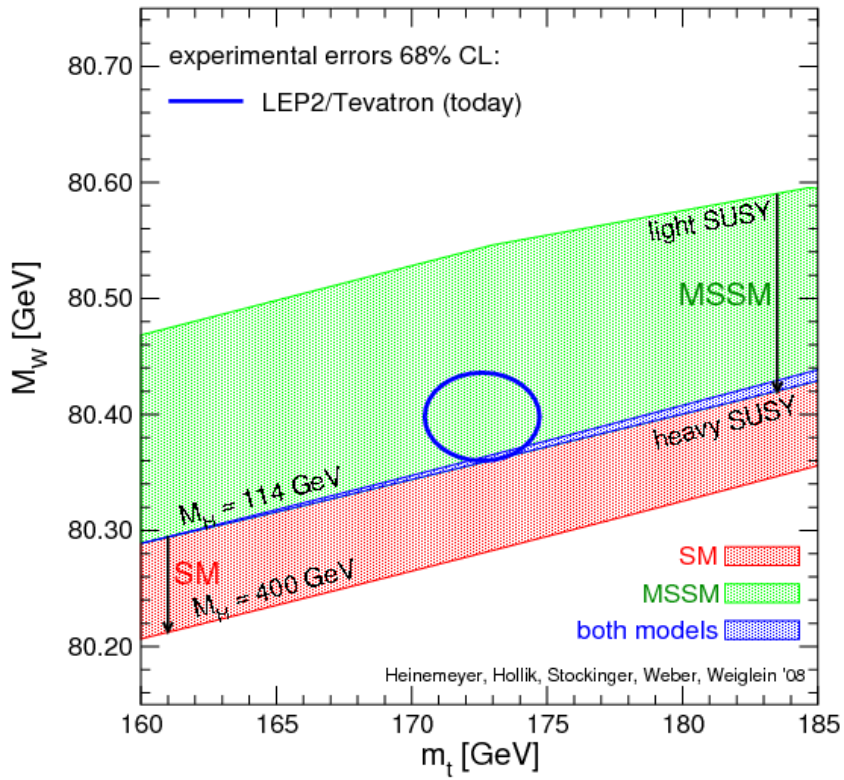
$\phi \rightarrow \tau\tau$

  - 2 high p_T b-quarks from Higgs
  - 1 extra b-quark
  - Search for peak in dijet invariant mass



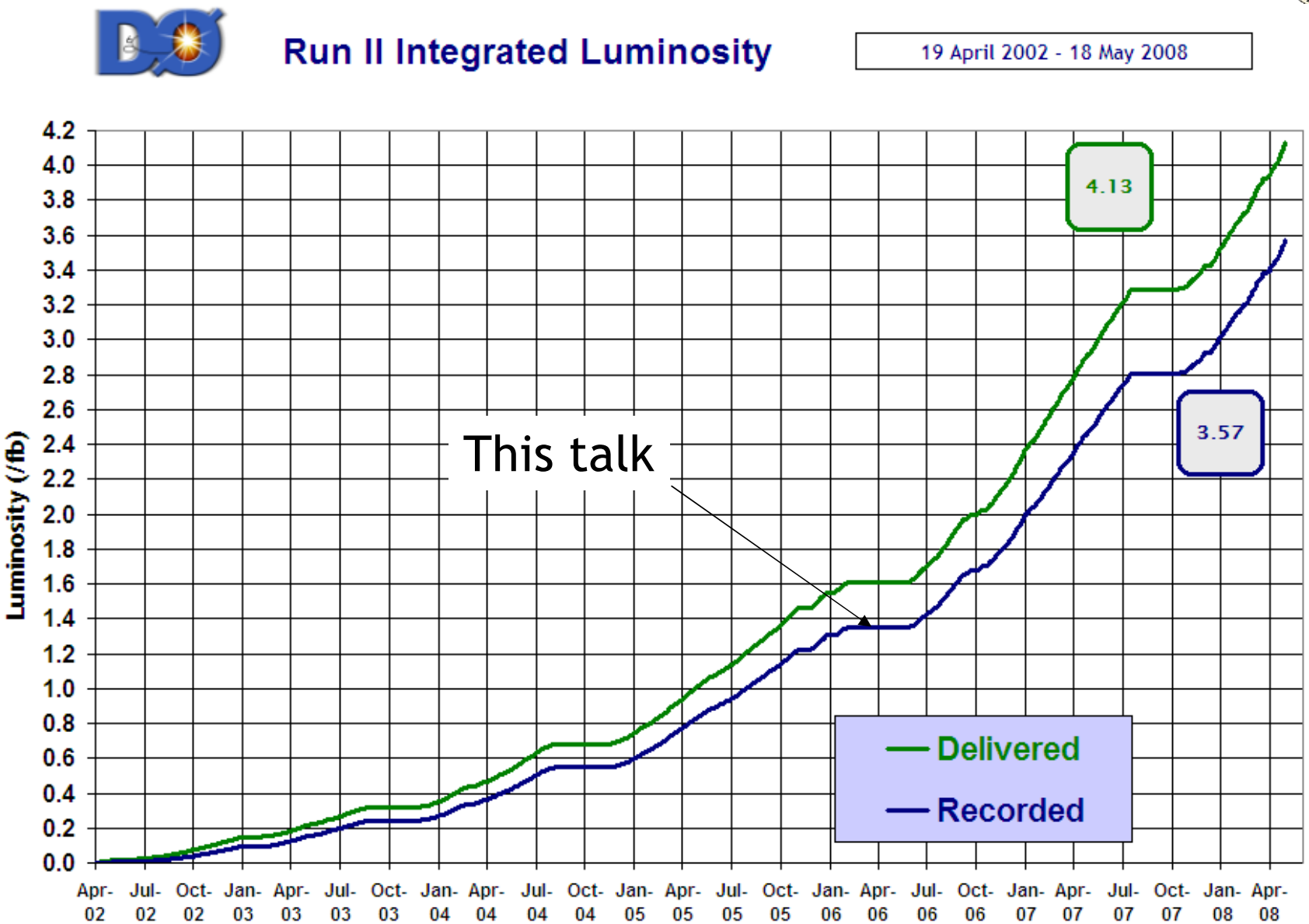
$\phi \rightarrow$ bb: 3b

Why these channels?



- Real discovery potential before we reach SM sensitivity
- The experimental challenge:
  - Identifying a τ signal in large background
  - Finding a bb mass peak at a hadron collider

Data sample


Run II Integrated Luminosity
19 April 2002 - 18 May 2008
Luminosity (/fb)
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
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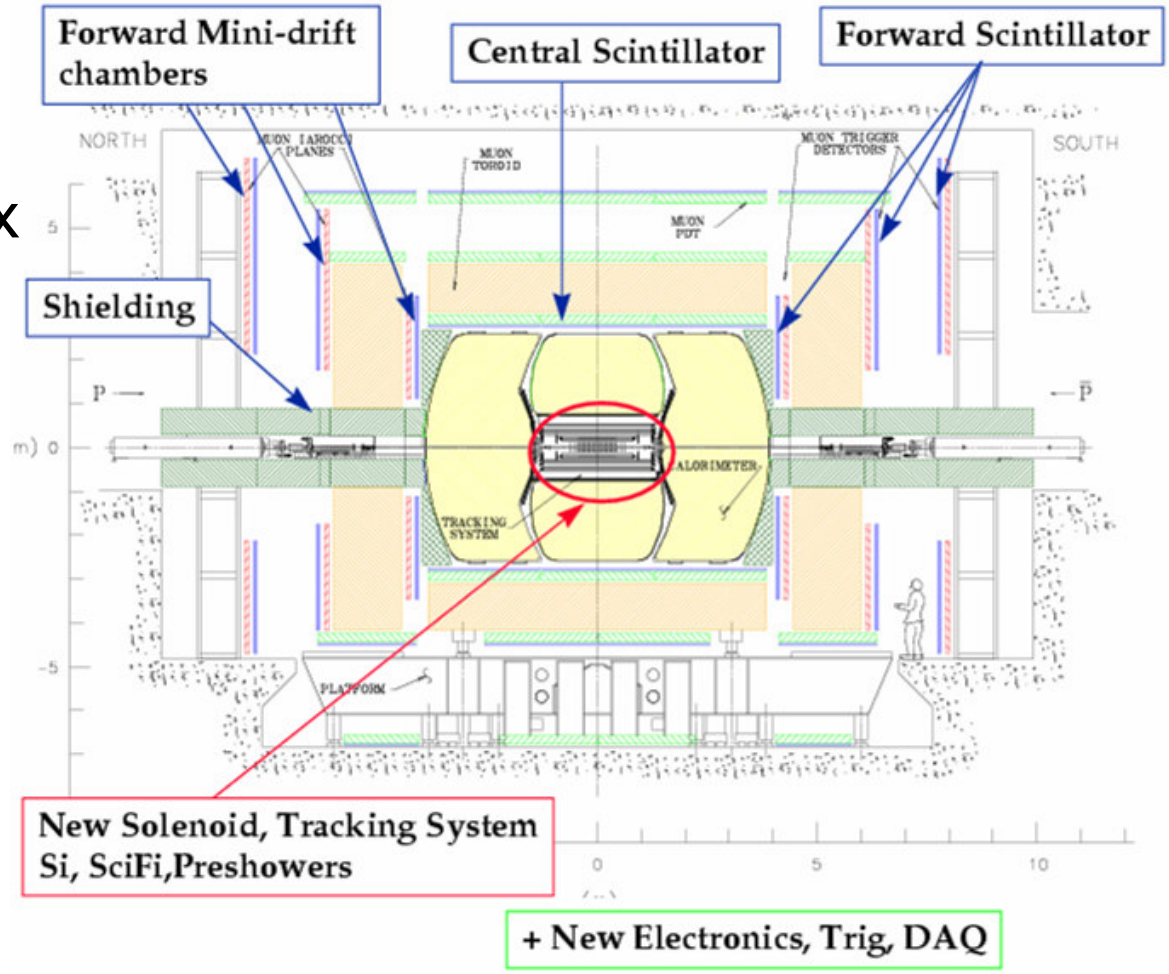
Apr-02 Jul-02 Oct-02 Jan-03 Apr-03 Jul-03 Oct-03 Jan-04 Apr-04 Jul-04 Oct-04 Jan-05 Apr-05 Jul-05 Oct-05 Jan-06 Apr-06 Jul-06 Oct-06 Jan-07 Apr-07 Jul-07 Oct-07 Jan-08 Apr-08
4.13
3.57
This talk
Delivered
Recorded

DØ detector

- Detector extensively upgraded for Run IIa
  - New silicon vertex detector
  - New tracking system
  - Upgraded muon chambers
  - New solenoid & preshowers



How we present results

- For each search channel we first calculate:
  - Model independent limit for cross section times branching ratio, $\sigma \times Br$

- MSSM translation:
  - Calculate exclusion in m_A - $\tan\beta$ plane

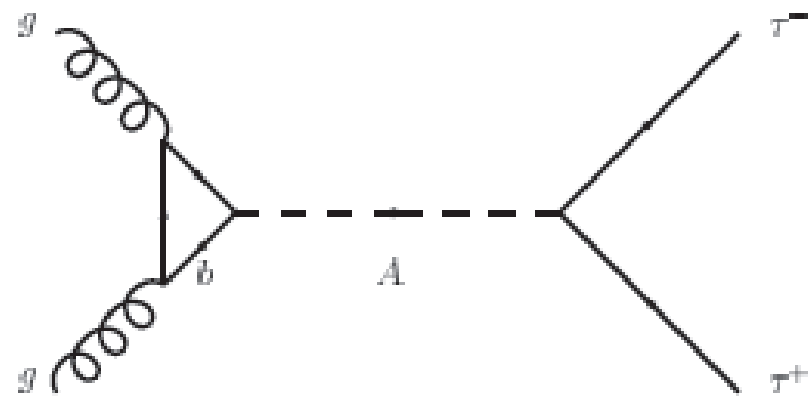
The $\phi \rightarrow \tau\tau$ channel

- Taus decay within the inner detector, ~17% to e, μ, ~65% to hadrons. Three channels used:

  $\tau \rightarrow \mu\ \nu\nu + \tau \rightarrow$ hadrons ν, $\tau_\mu \tau_h$

  $\tau \rightarrow e\ \nu\nu + \tau \rightarrow$ hadrons ν, $\tau_e\ \tau_h$

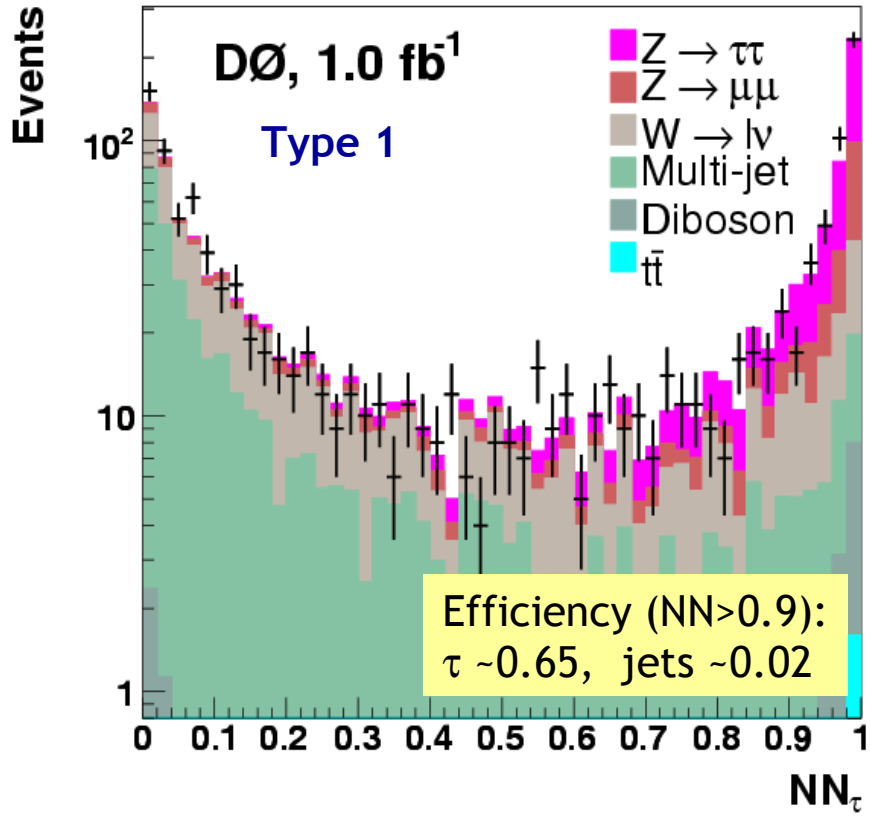
  $\tau \rightarrow e\ \nu\nu + \tau \rightarrow \mu\ \nu\nu$, $\tau_e\ \tau_\mu$

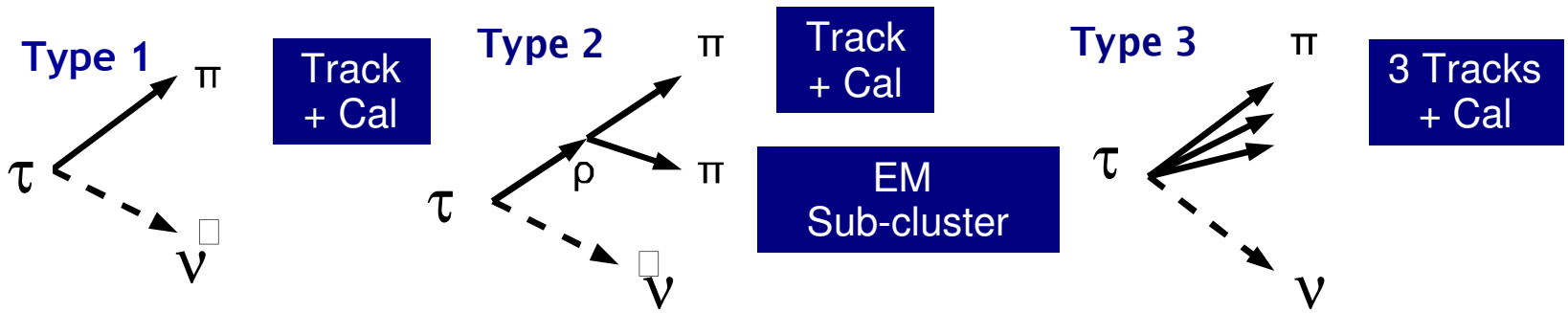


- At least 2 neutrinos in the final state:
  - Not possible to reconstruct $\tau\tau$ invariant mass
- Backgrounds:
  - $Z \rightarrow \tau\tau$ (same final state)
  - Z/W+jets/multijet w. misidentified leptons/jets
  - Diboson, top with real taus (small cross section)
  - Electro-weak processes from PYTHIA normalized to (N)NLO
  - Multijet from data
- Strategy for all 3 final states:
  - Remove backgrounds other than $Z \rightarrow \tau\tau$ and search for excess from Higgs

Tau identification

- Tau ID= identification of hadronically decaying taus
- Three tau types, distinguished detector signature
- Neural Network (NN) trained for each tau type to separate jets from taus





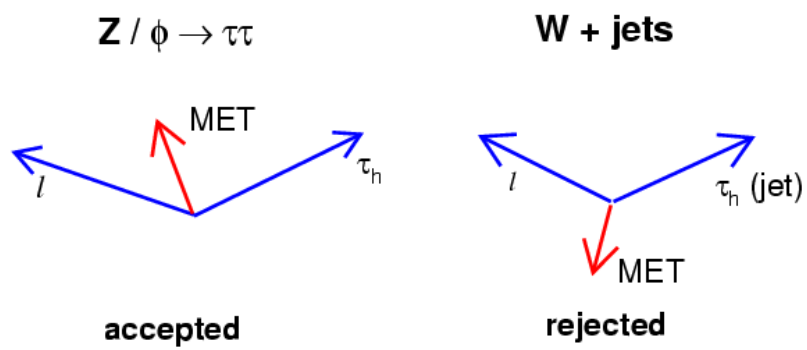
Event selection

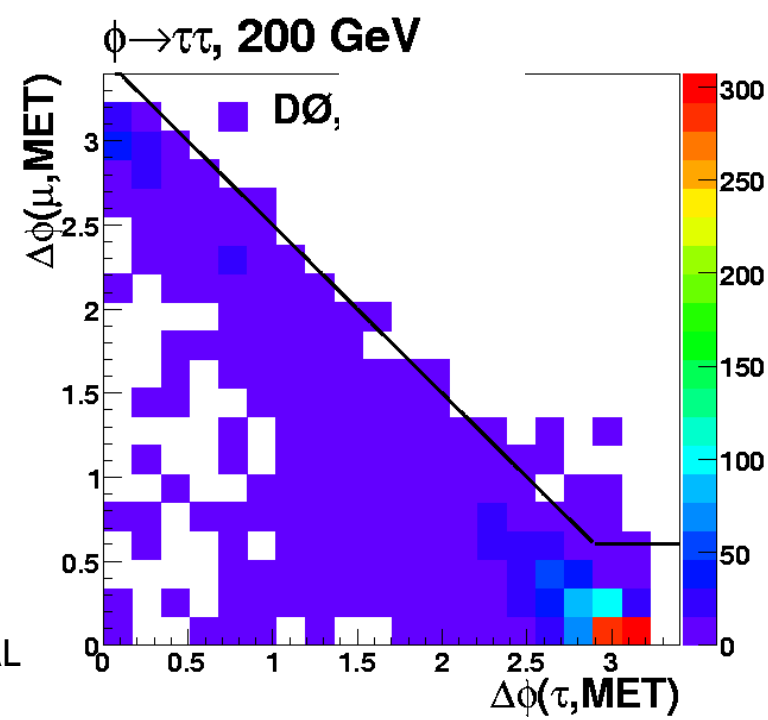
- Hadronic channels, $\tau_\mu\tau_h$, $\tau_e\tau_h$
  - One isolated e/μ p_T > 15 GeV
  - One τ p_T > 16.5 GeV (type 1,2), 22 GeV (type 3)
  - $\tau_e\tau_h$: additional selection to remove Z $\rightarrow$ ee

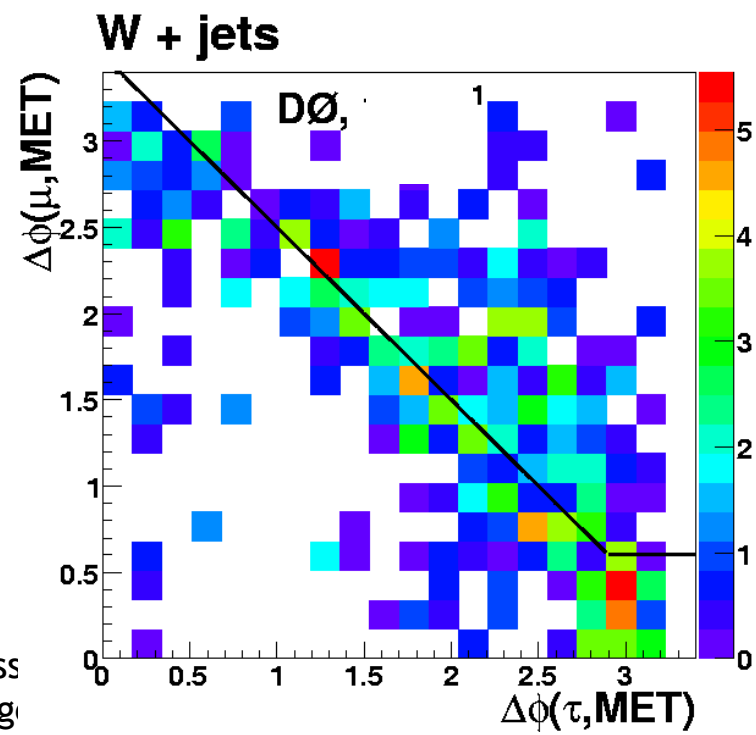
- Leptonic channel: $\tau_e\tau_\mu$
  - Exploit cleaner environment & more neutrinos
  - One isolated e, p_T >12 GeV
  - One isolated μ, p_T > 10 GeV
  - The two leptons must be oppositely charged

Final selection $\tau_{e/\mu}\tau_h$

- Tau ID NN > 0.9 (types 1, 2), 0.95 (type 3)
- Transverse mass:
  - m_T < 40 GeV ($\tau_\mu\tau_h$)
  - m_T < 50 GeV($\tau_e\tau_h$)
- Require $\Delta\phi(e,\tau) > 1.6$ (larger multijet background)
- Reject W+jet events:
  - cut in the $\Delta\phi(l,MET)$-$\Delta\phi(\tau,MET)$ plane

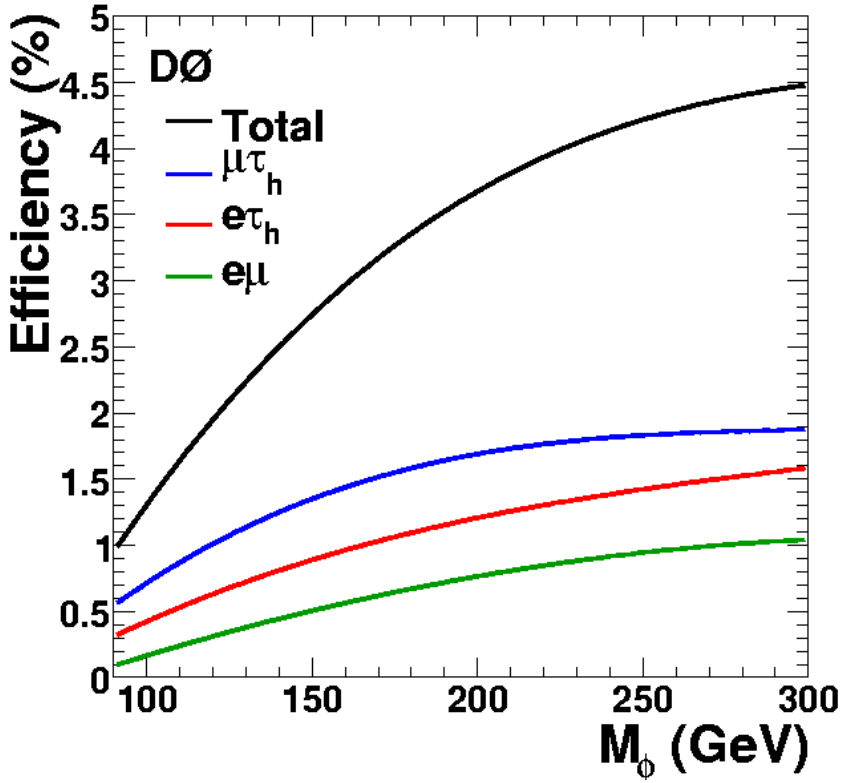






Final selection $\tau_e\tau_\mu$

- Selection based on leptons and MET to remove multijet & W backgrounds
  - $p_T(e) + p_T(\mu) + MET > 65$ GeV
  - $m_T^{min}(l,MET) < 10$ GeV
  - $\Delta\phi_{min}(l,MET) < 0.3$
- Final selection to remove top events:
  - $H_T < 70$ GeV



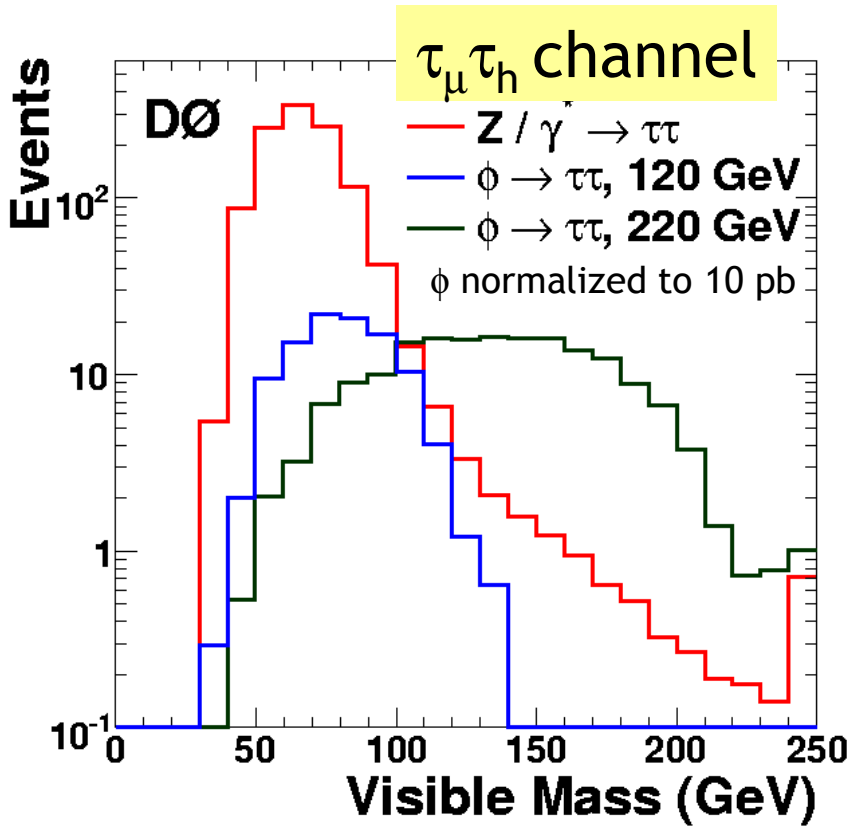
Similar efficiencies but background worse in $e\tau_h$ channel

Visible mass

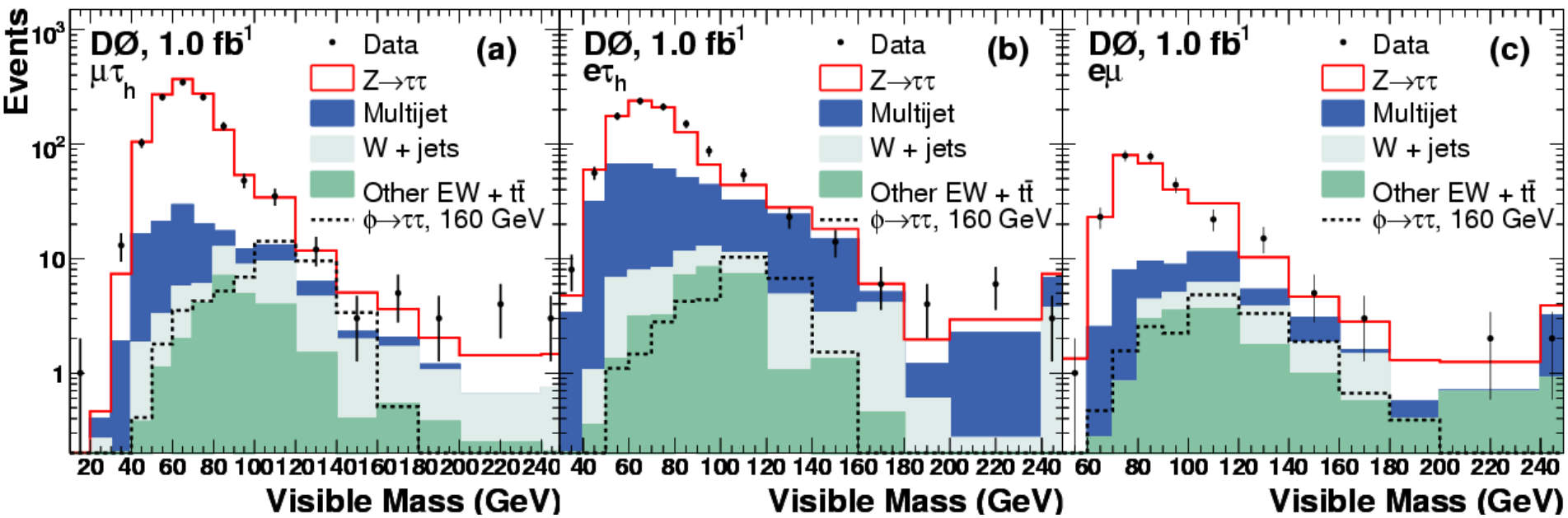
- Not possible to reconstruct ττ mass, use visible mass:

$$m_{\mathrm{vis}} = \sqrt{\left(p^{\tau_1} + p^{\tau_2} + \not{E}_{\mathrm{T}}\right)^2}$$

- Can be computed for any event



Visible mass



Main background at this stage:

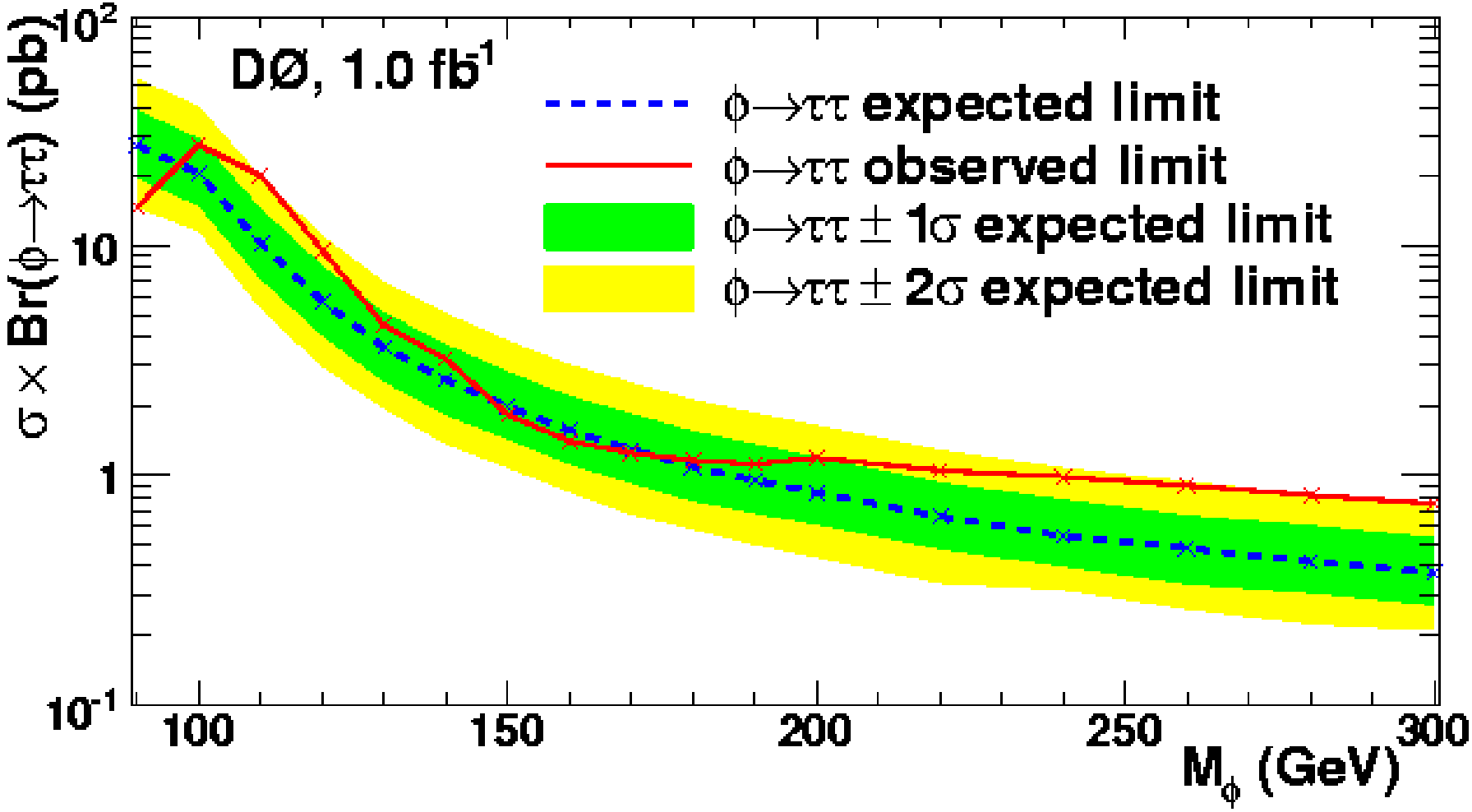
$Z \rightarrow \tau\tau$ (small contribution from EW and multijet)

Systematic uncertainties

- Systematic uncertainties:
  - Most important:
    - Luminosity 6%, Z cross section 5%, Tau ID 5-10%, $Z \rightarrow ee$ 13%
    - Shape uncertainties: Energy scale, Trigger

- Use Modified Frequentist approach to calculate limit on $\sigma \times Br$

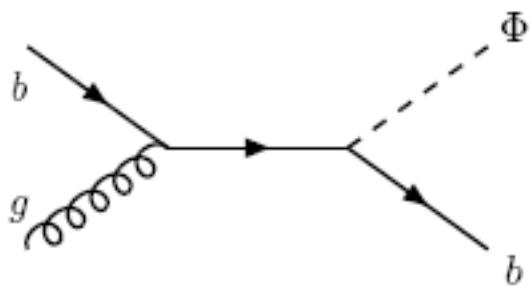
Cross section×Br limit

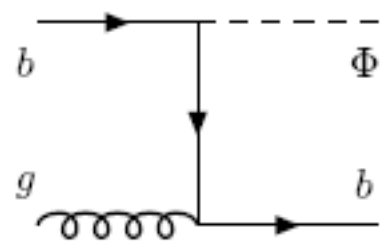


Small excess at high mass from $\tau_\mu\tau_h$ channel

The 3b channel

- Search for the $b\phi \rightarrow bbb$ process
- $gb \rightarrow \phi b$:
  - cross section = $\sigma_{SM} \times 2 \times \tan^2\beta$ at tree level

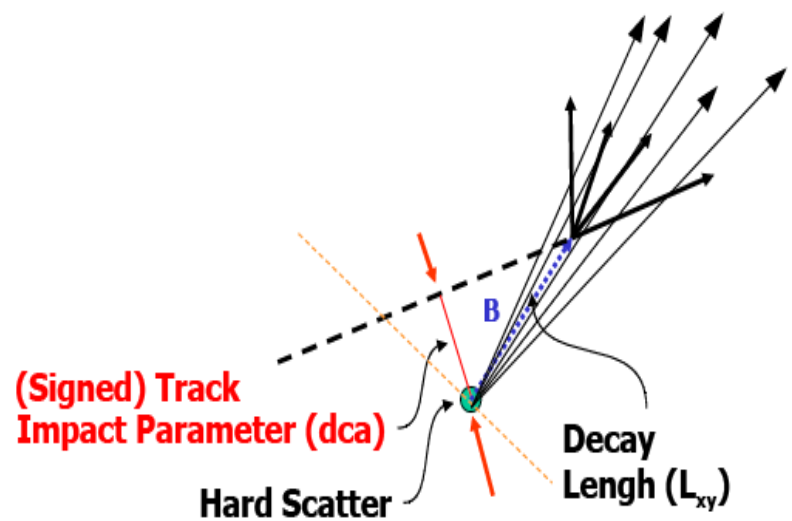




- Look for Higgs + 1b:
  - Three to five jets $p_T > 20$ GeV, $|\eta| < 2.5$
  - At least three b-tagged jets
  - Two leading b-tagged jets $p_T > 25$ GeV

b-jet identification

- B-hadrons are long-lived:
  - Search for displaced vertices



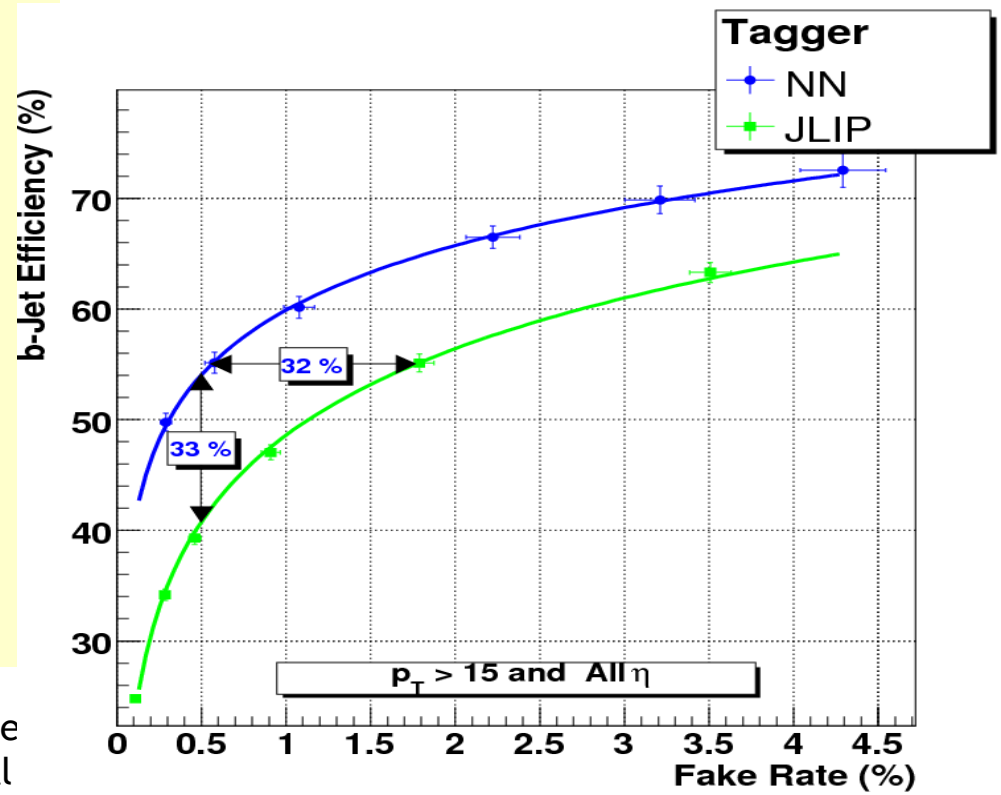
Neural Net tagger

- Secondary vertex & dca based inputs, derived from basic taggers

Combine in Neural Network:

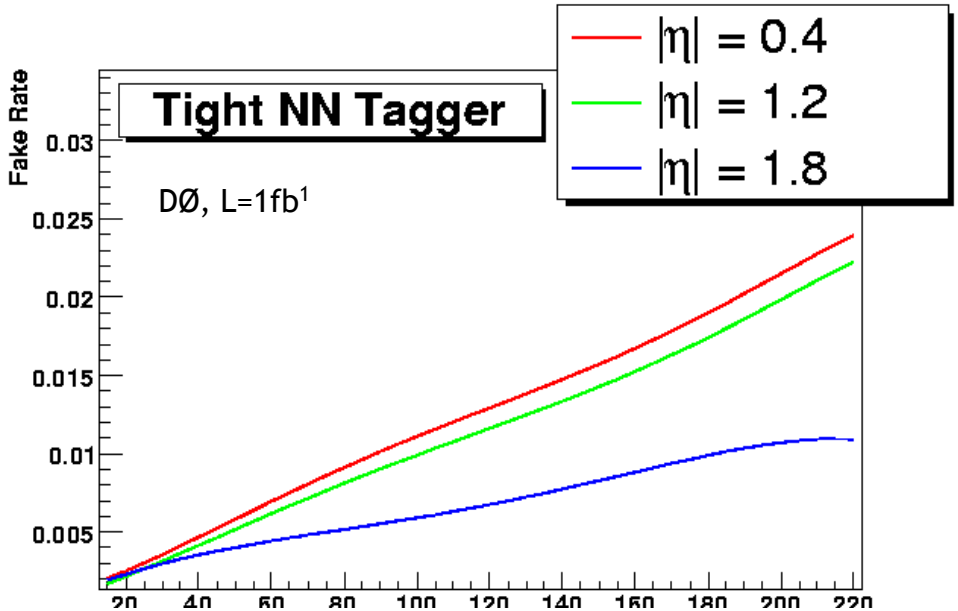
- vertex mass
- vertex number of tracks
- vertex decay length significance
- chi2/DOF of vertex
- number of vertices
- two methods of combined track impact parameter significances

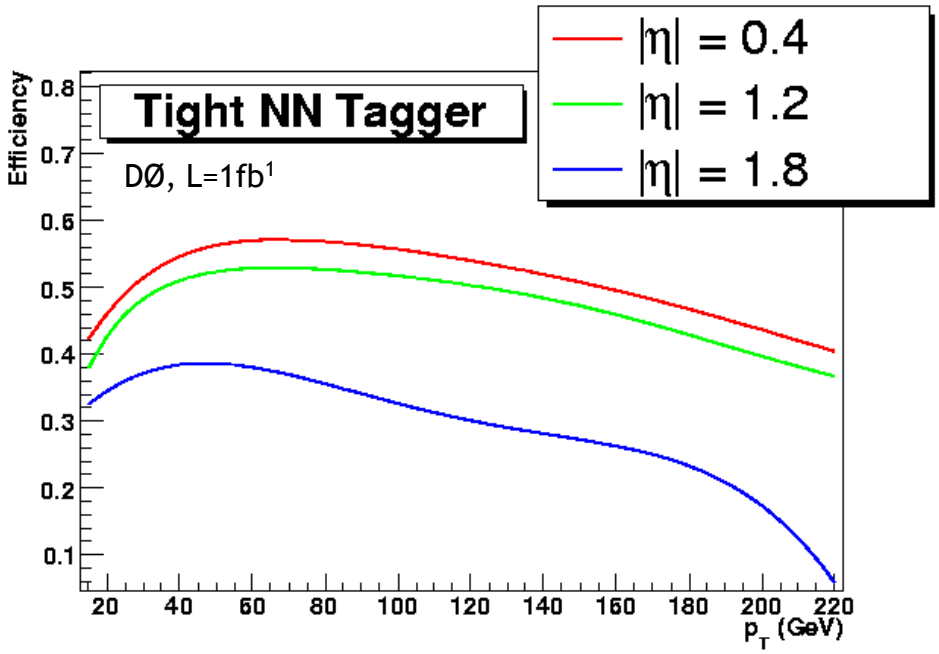
- High efficiency, purity
- **Loose ~ 70% eff, 4.5% mistag**
- **Tight ~ 50% eff, 0.5% mistag**



b-tagging

- MC and data b-tagging disagree
  - Measure performance on data
  - Parameterize efficiency & fake rate as function of p_T and η
  - Use to correct MC
- Fake tags of light jets are due to badly reconstructed tracks or interactions with detector material
  - Measured using QCD data
  - Fake rate rises with jet p_T
- Extended the p_T range of the tag-rates up to 200 GeV





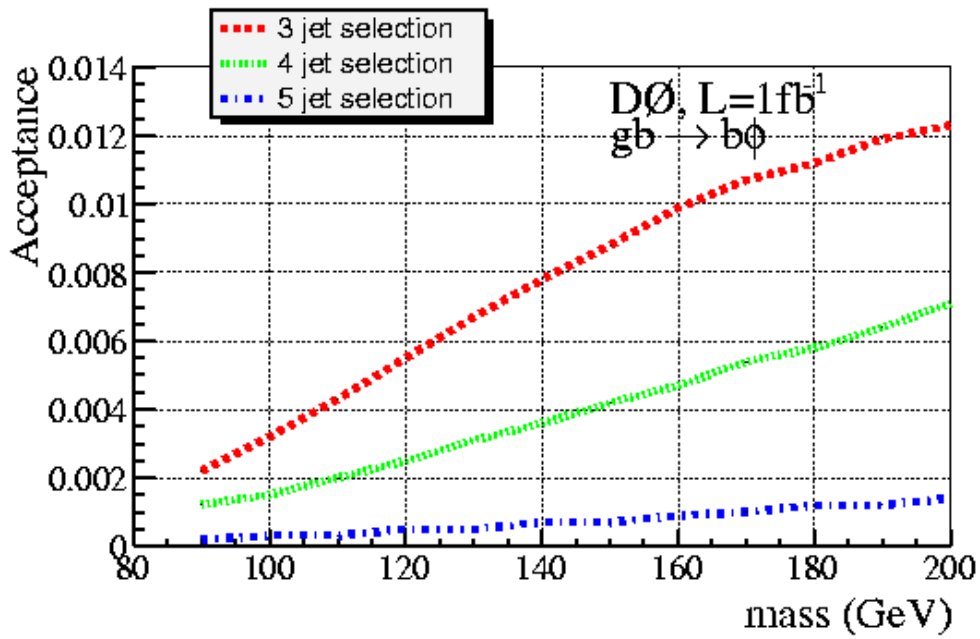
Trigger

A major challenge

- How do we record enough 3b events for analysis without making the trigger rate explode or cut to hard?
  - Multijet cross sections are huge
- Employ impact parameter b-tag in the trigger:
  - Efficiency ~90%, background rejection >75%
- Also require:
  - 3 jets p_T > 15 GeV, 2 jets p_T > 25 GeV
  - vertex within silicon detector
- Trigger efficiency: 60-70%

Signal samples

- Higgs signal: SM signal generated with PYTHIA
  - bg->bH
  - SM Higgs, narrow width approximation
  - Use NLO SM cross sections from MCFM
  - Reweight PYTHIA events using MCFM kinematics:
    - Use the leading b (not from Higgs) distribution to correct acceptance:
      - Reweight vs η[b] and p_T[b]
  - SM→MSSM enhancement computed with FeynHiggs



Analysis overview

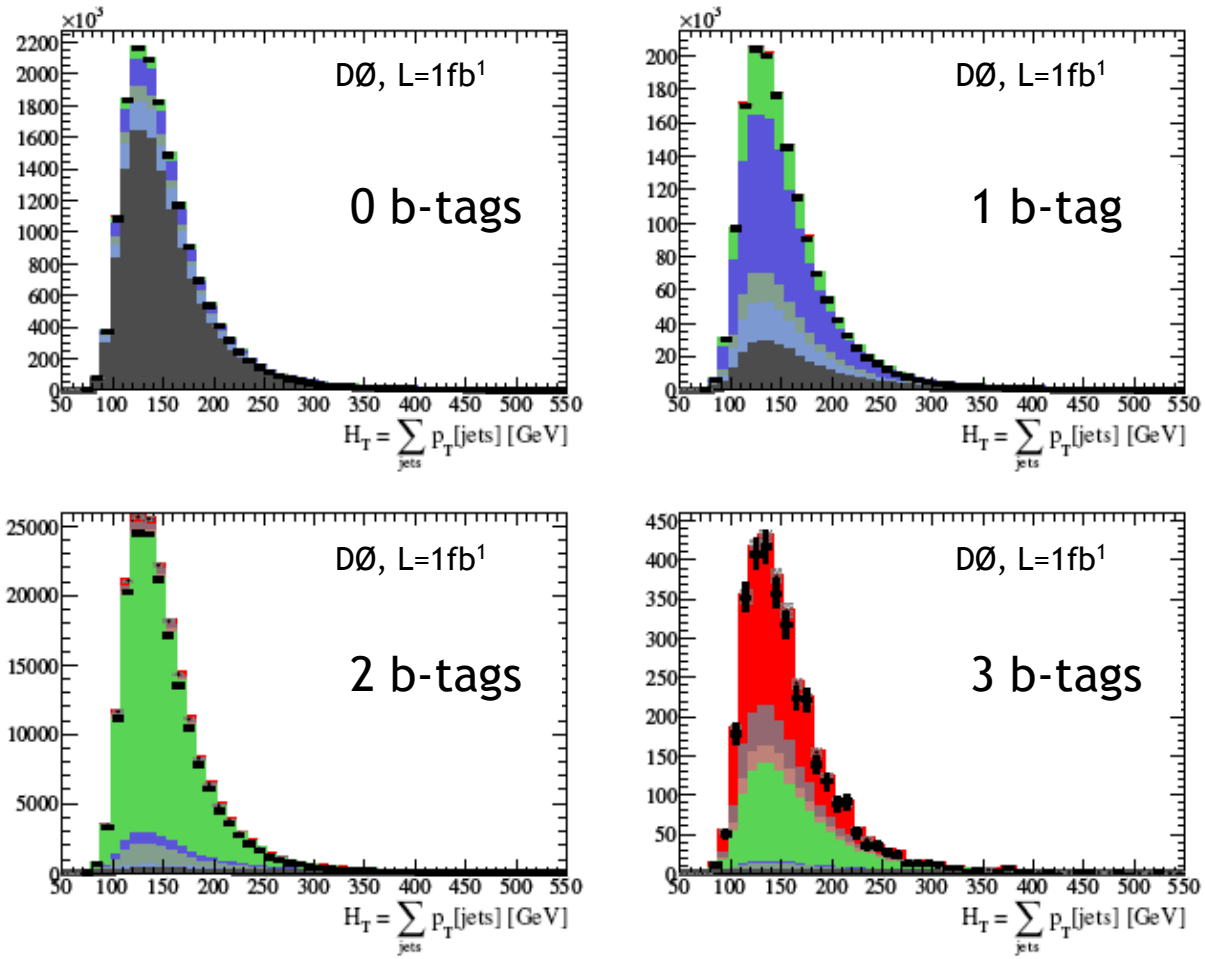
- Background is QCD multijet production:
  - Use bb+x, cc+x, bbbb+x,bbcc+x (Alpgen)
  - Fit simulated background samples to data to obtain composition
  - Construct data-driven background model from double b-tagged data and correction factor from MC
- Separate analysis in 3-,4-,5-jet channel
- Use 2 likelihood discriminants to reduce background:
  - Low-mass Higgs (M_H < 130 GeV)
  - High-mass Higgs (M_H > 130 GeV
- Optimize the expected sensitivity:
  - b-tagging criteria
  - Number of jet-pairs/event
  - Cut on likelihood
- Look for an excess in the dijet mass, M_{bb}:
  - **Use only shape, as background normalization is unknown**

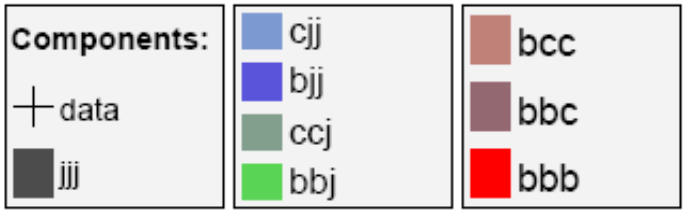
Background modeling

A major challenge

- Background: multijets, especially bbb (bbc) and bbj
  - Normalization:
    - Theoretical cross sections have very large errors
    - bbb/c bkg not reducible with b-tagging:
      - may also contain component of indistinguishable signal making normalization from data impossible
  - Shape: determined from data and MC
    - Shape differences due to b-tagging and kinematics of heavy flavour
  - Bkg composition: from data (assuming no signal). Use several b-tagging "operating points" with different number of jets b-tagged

Background composition



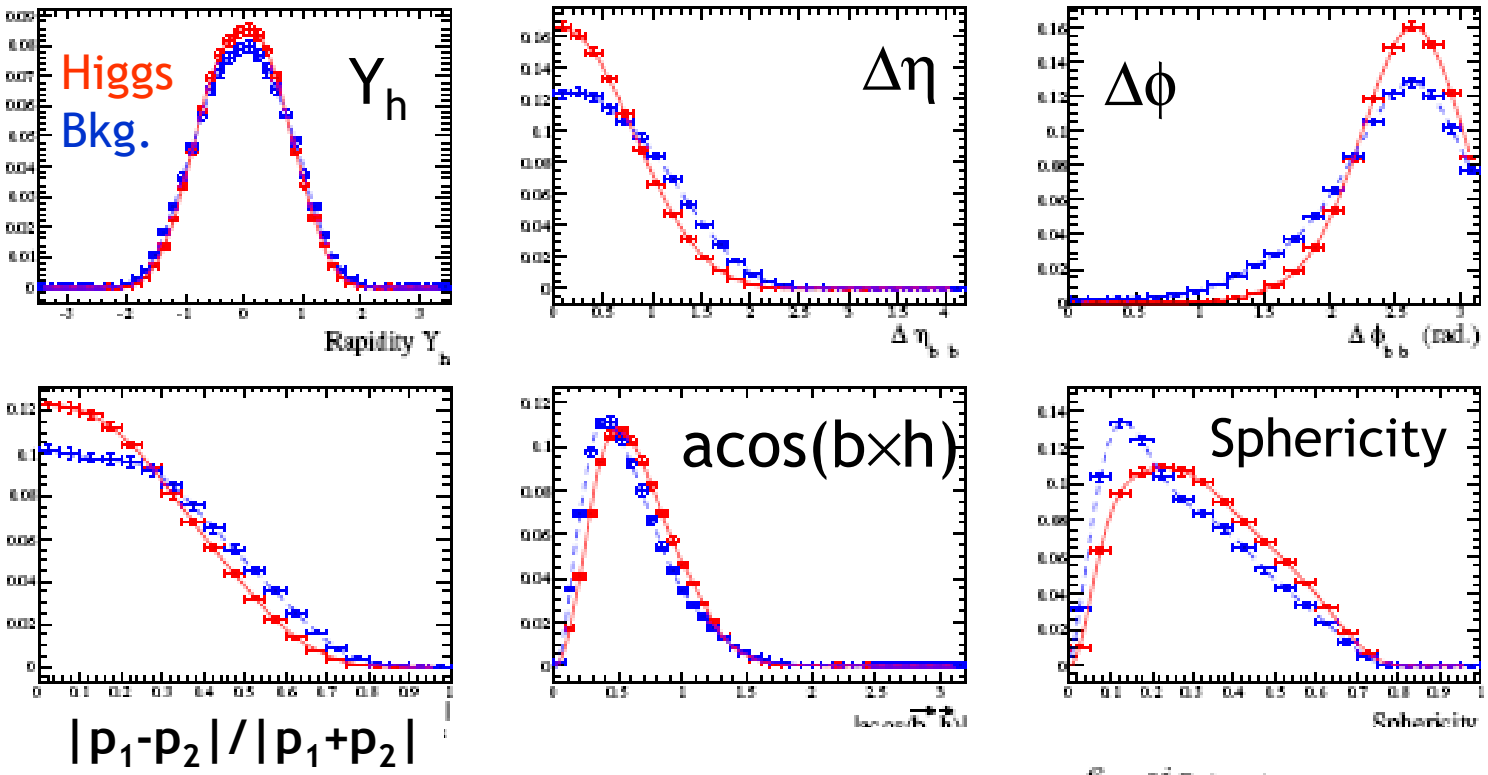


Main backgrounds:
3 tags: bbb ~50%
bbj ~30%
bbc+bcc ~17%
ccj ~2%
jjx~1%

2 tags: bbj

Likelihood discriminant

- Build a likelihood based on six well modeled kinematic variables:



$$\mathcal{D}(x_1, \ldots, x_6) = \frac{\prod_i^6 p_i^{sig}(x_i)}{\prod_i^6 p_i^{sig}(x_i) + \prod_i^6 p_i^{bkg}(x_i)},$$

Pdf's from simulation, separate low-mass(<130 GeV) and high-mass likelihoods

Final background shape

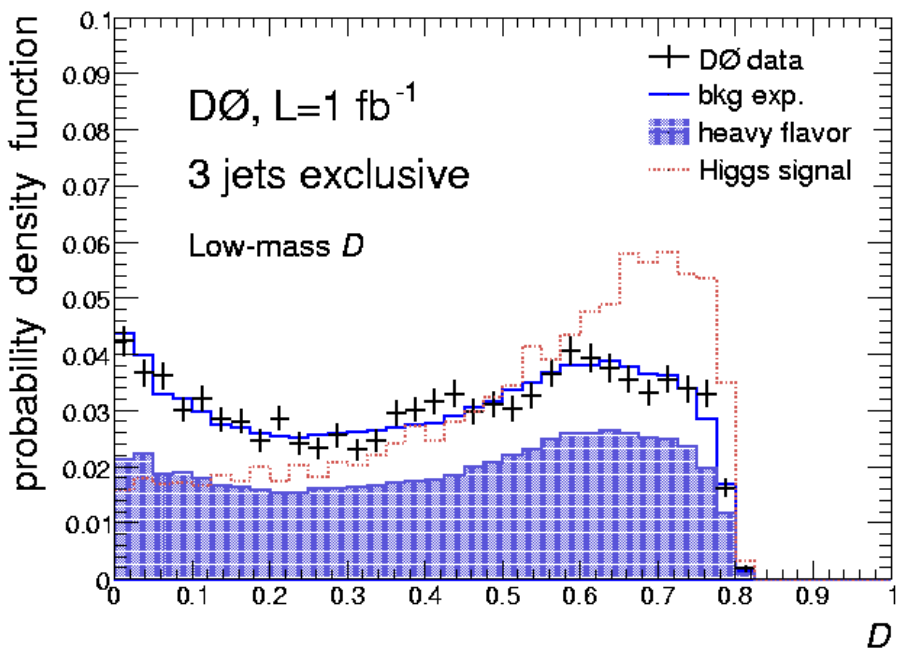
- bbj and bbb backgrounds are similar:
  - Use the double tagged data to predict the triple b-tagged shape in the 2D likelihood and M_{bb} plane:

2tag data

$$S^{exp}_{3\mathrm{Tag}}(\mathcal{D}, M_{bb}) = \frac{S^{MC}_{3\mathrm{Tag}}(\mathcal{D}, M_{bb})}{S^{MC}_{2\mathrm{Tag}}(\mathcal{D}, M_{bb})} S^{data}_{2\mathrm{Tag}}(\mathcal{D}, M_{bb}).$$

3tag prediction

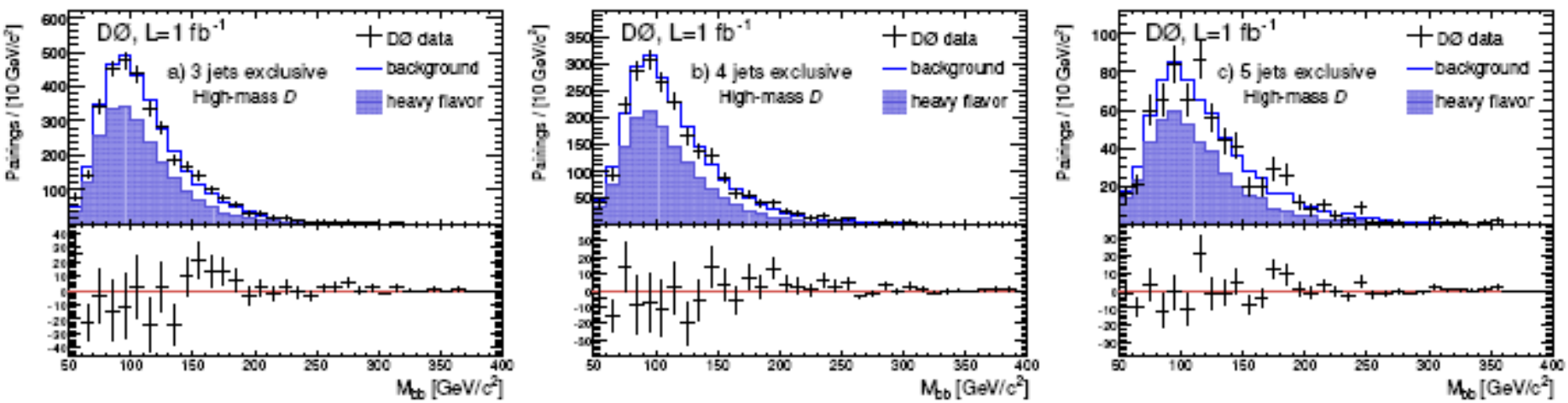
MC correction factor



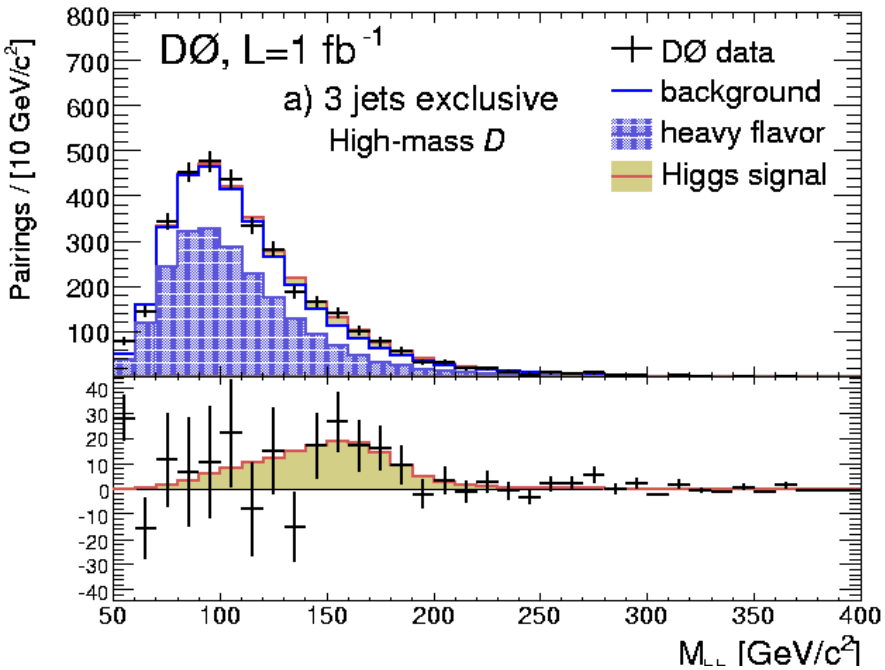
Invariant mass

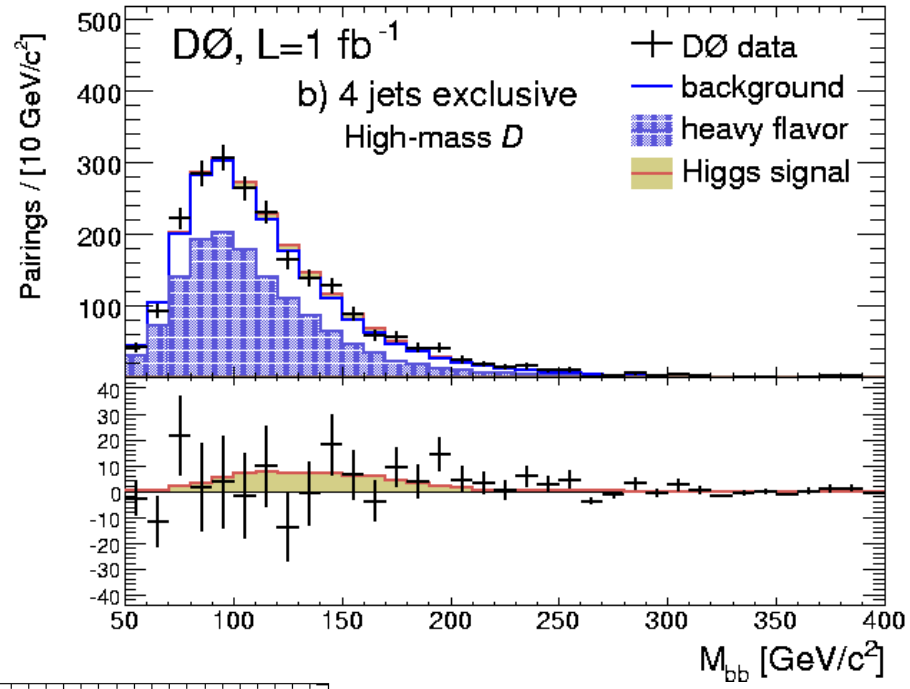
- A total of 3,224/2,503/704 events in the 3/4/5-jet channel
- Verify data-background agreement in low-likelihood region
- Then check the high-likelihood region
  - Reasonable data and background agreement

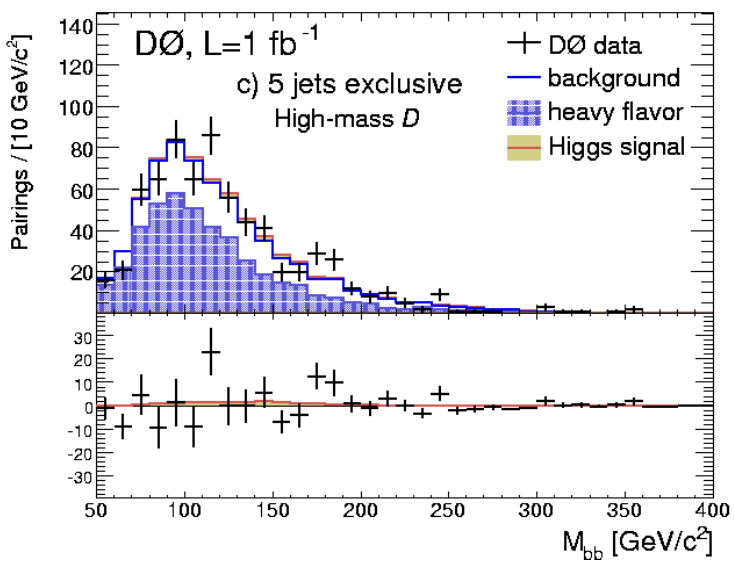
Cut on D~0.5



Invariant mass with signal



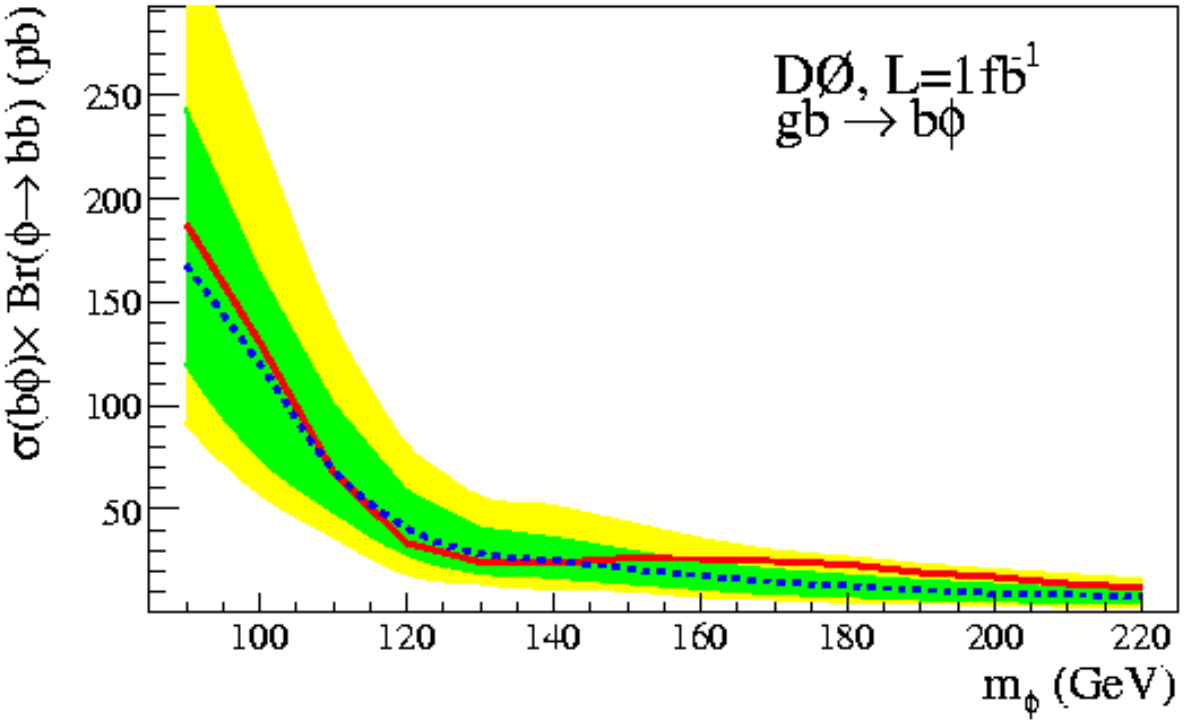




Include Higgs signal which fits best to data

$\sigma \times$ Br limits

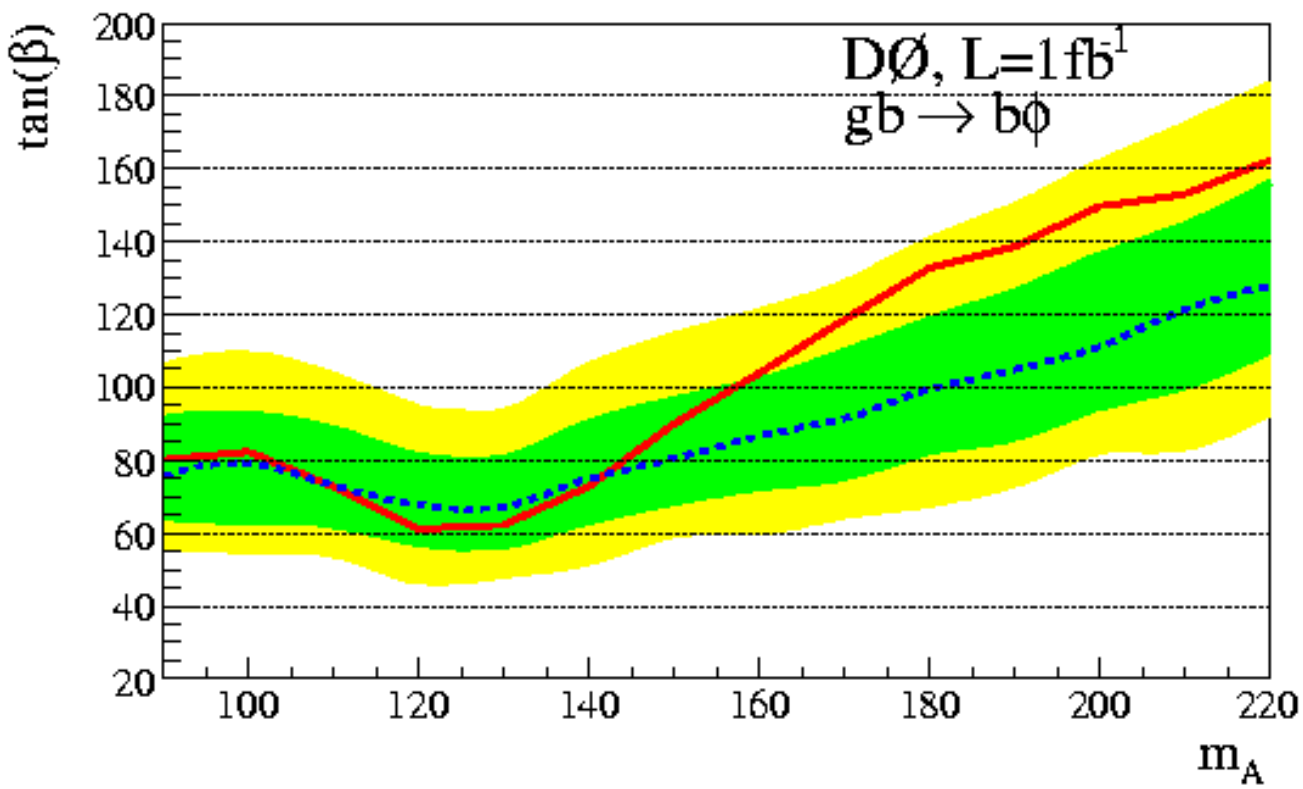
Use the Modified Frequentist approach to calculate the limit on $\sigma \times Br$. Only the shape of the M_{bb} distribution is used.
Combination of 3-,4- and 5-jet samples.



Largest deviation around 180 GeV: 1-CL$_b$ = 4% (1.7σ)

Tree level tanβ limits

Calculate the limit in the [tanβ, m_A] plane assuming tree level enhancement: $2 \times \tan^2\beta \times 0.9$. Only the shape of the M_{bb} distribution is used. Combination of 3-,4- and 5-jet samples.

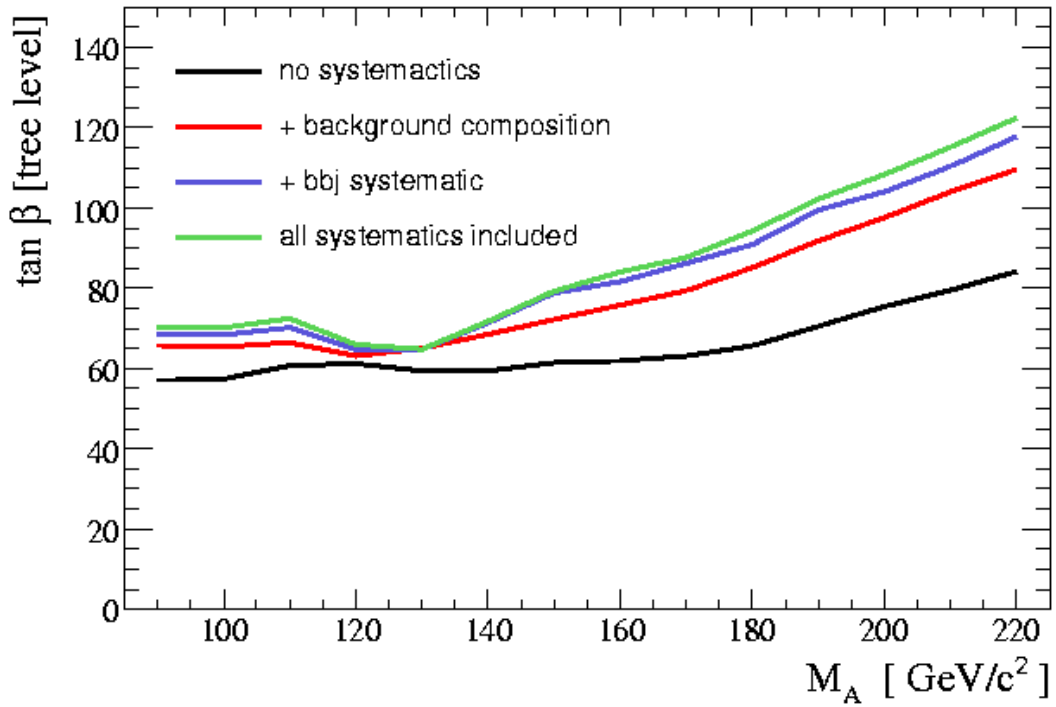


Systematic Errors

- Signal systematics:17-20%

- Background shape (dominant):

  The normalization is unknown, only the uncertainties on the background shape matters:
  - bbb vs bbj fraction
  - bbb vs. bbj kinematic
  - bbb vs. bbj b-tag shape
  - b jet energy scale resolution
  - b-tag trigger (different efficiency for 2tag and 3tag events

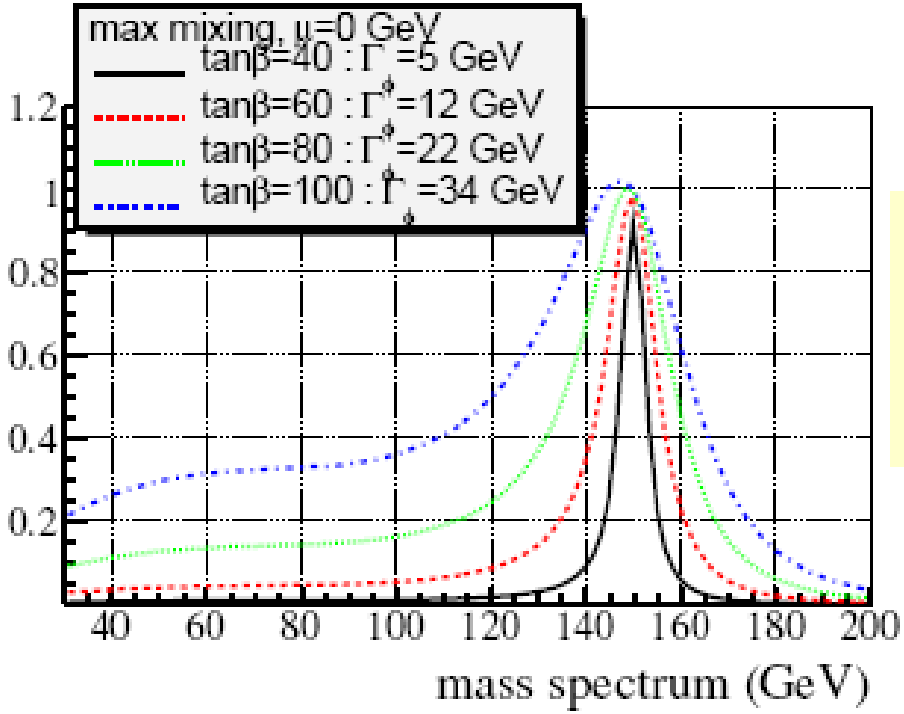


Scenario Dependence

- Two effects to be accounted for:
  - The production cross section enhancement depends on the details of the MSSM scenario beyond LO
    - MSSM/SM enhancement factors are computed with FeynHiggs* for two "benchmark" scenarios:
      - "m_h^{max}": max. mass of lightest CP-even state h
      - "no-mixing": stop mixing parameter, $X_t = 0$
  - With increasing $\tan\beta$, the width of ϕ (Γ_ϕ) is not negligible with respect to the experimental resolution

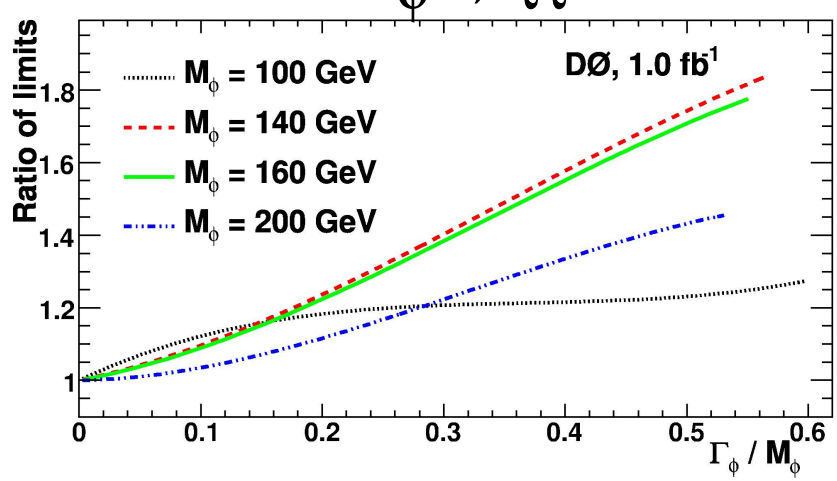
*http://www.feynhiggs.de

Width of ϕ



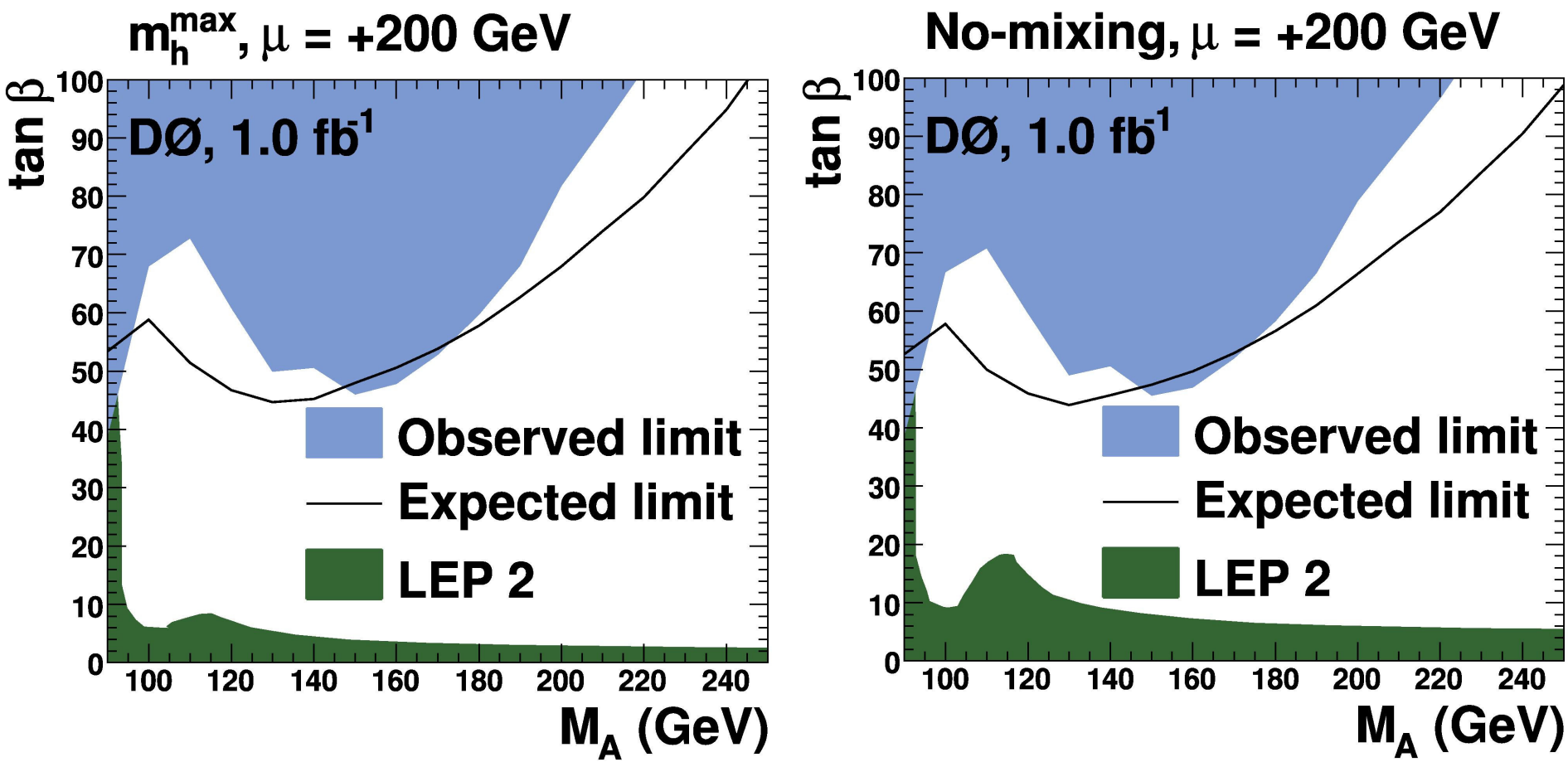
The width is simulated by a weighted combination of MC samples with different Higgs masses

$\phi \rightarrow \tau\tau$



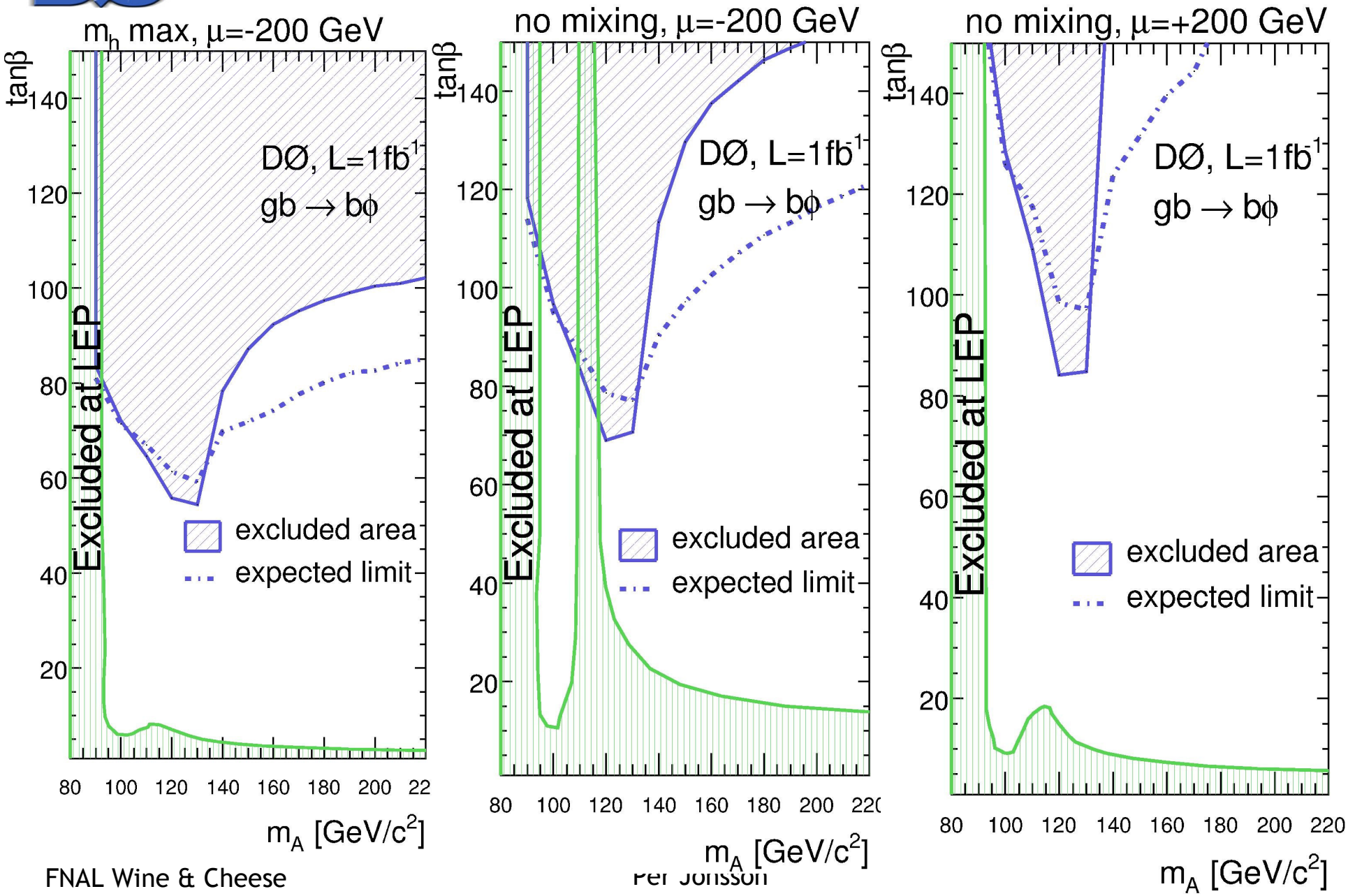
MSSM interpretation $\phi \rightarrow \tau\tau$

Loop corrections and width from FeynHiggs



- Excluded regions largely insensitive to scenario and μ:
  - Different from bh → bbb channel

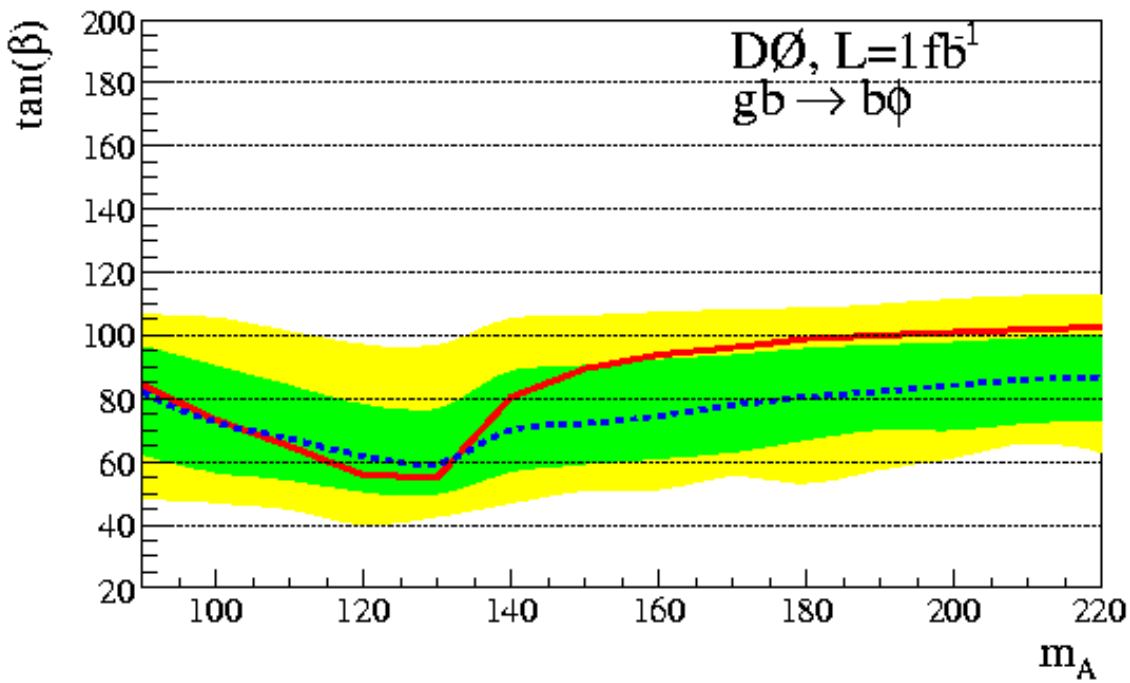
MSSM interpretation $b\phi \rightarrow bbb$



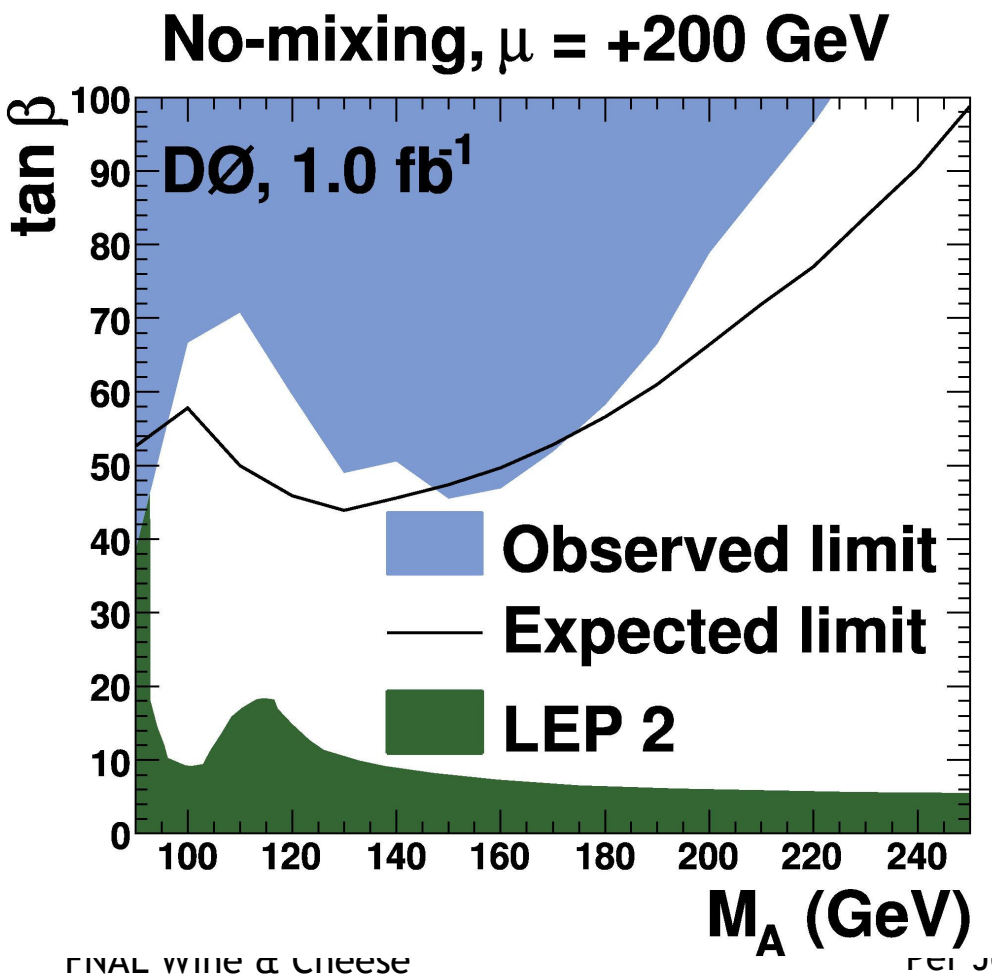
MSSM interpretation $b\phi \rightarrow bbb$

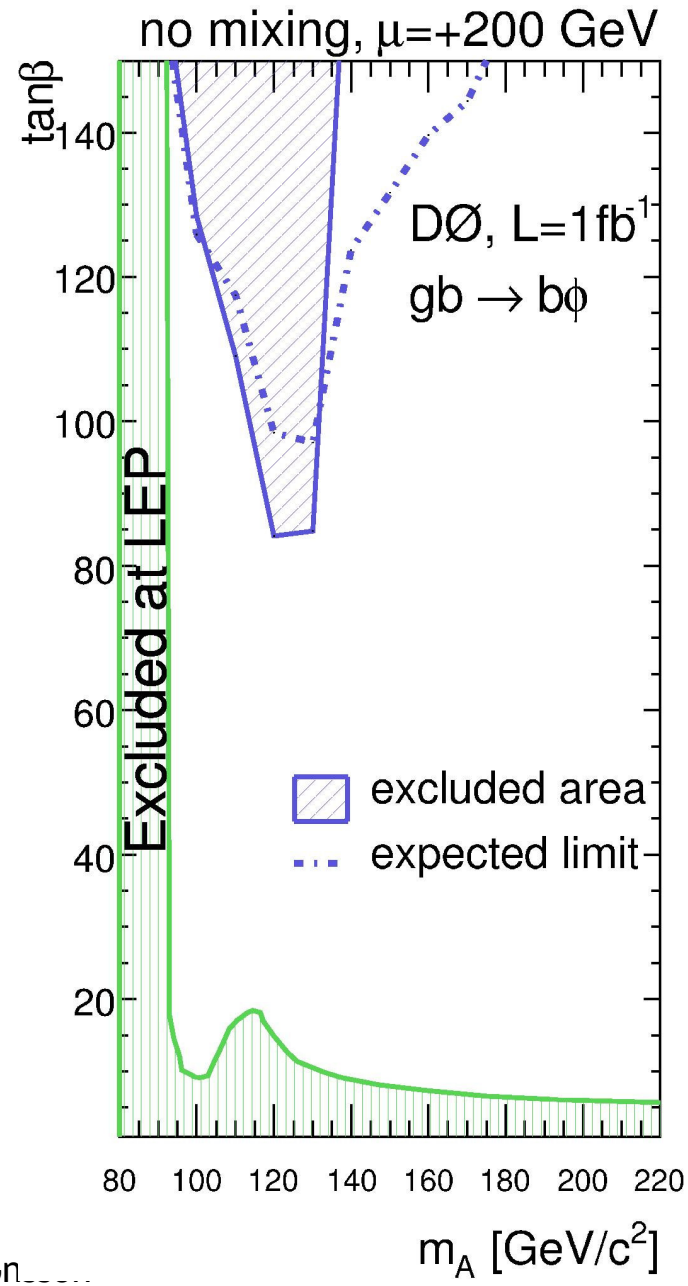
- Strongest limits for the m_h^{max} scenario with $\mu<0$
  - Large sensitivity to μ and its sign through loop corrections:
    - Negative μ gives enhanced production
    - No exclusion below for m_h^{max} , $\mu>0$.
  - Tau channel more sensitive and less dependent on MSSM scenario

- The observed limits above M_A=140 GeV are weaker than the expectation, due to the slight excess around 180 GeV

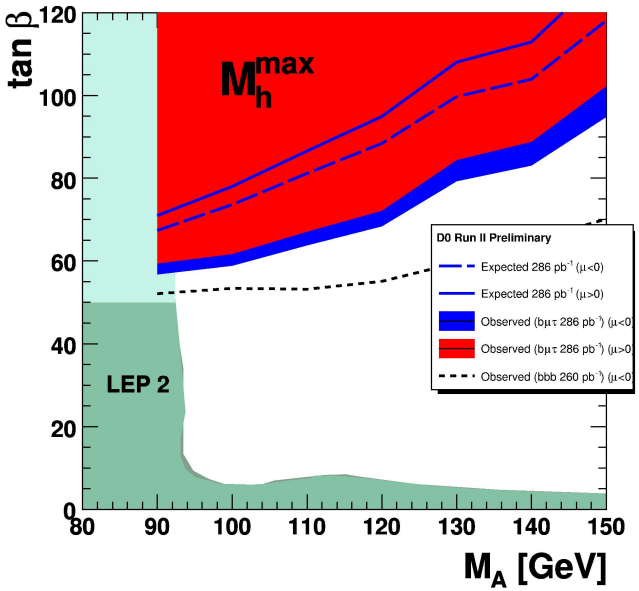


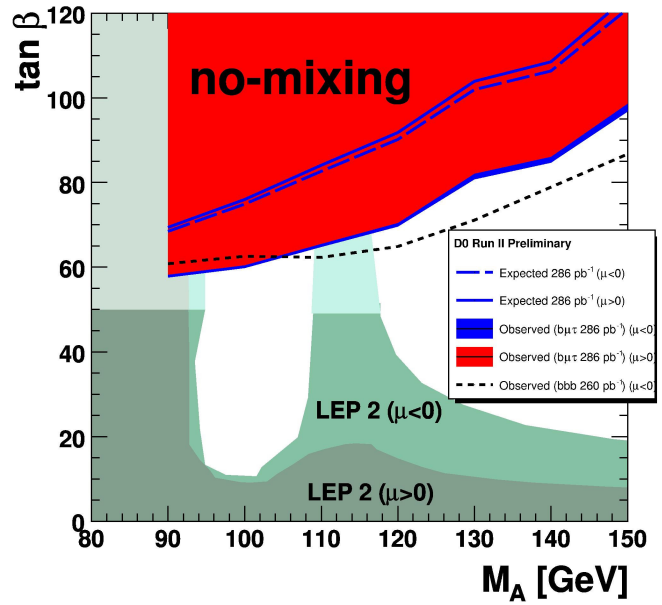
Side by side


No-mixing, μ = +200 GeV
DØ, 1.0 fb-1
tan β
Observed limit
Expected limit
LEP 2
M_A (GeV)


no mixing, μ=+200 GeV
tanβ
DØ, L=1fb-1
gb → bϕ
Excluded at LEP
excluded area
expected limit
m_A [GeV/c2]

$b\phi \rightarrow b\tau\tau$ and combination





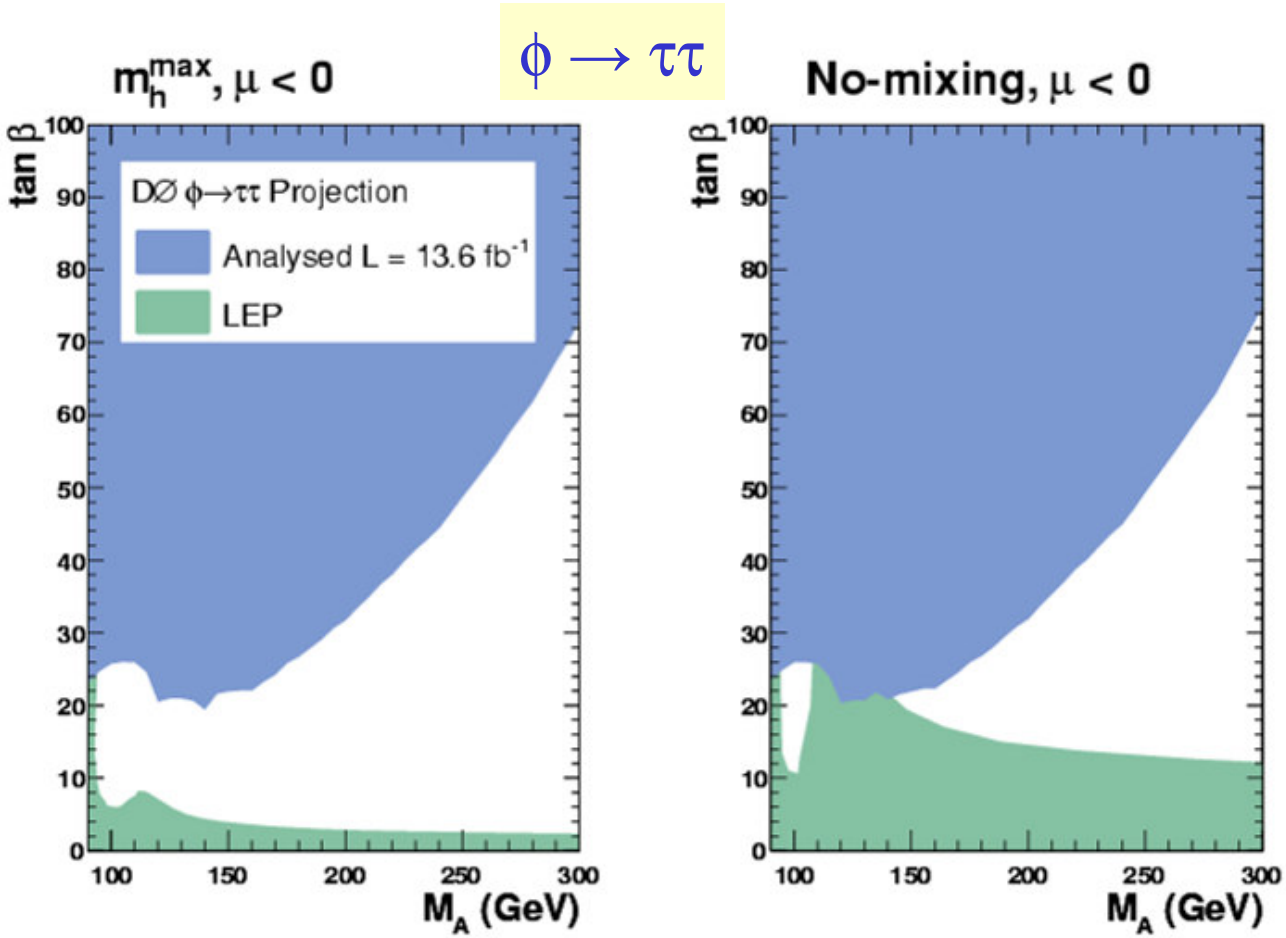
Two more pieces to the search:

- The $b\phi \rightarrow b\tau\tau$ channel:
  - New results on their way

- Combination of results:
  - In progress with new results

Projections

Projections for full 2010 dataset (2 experiments)



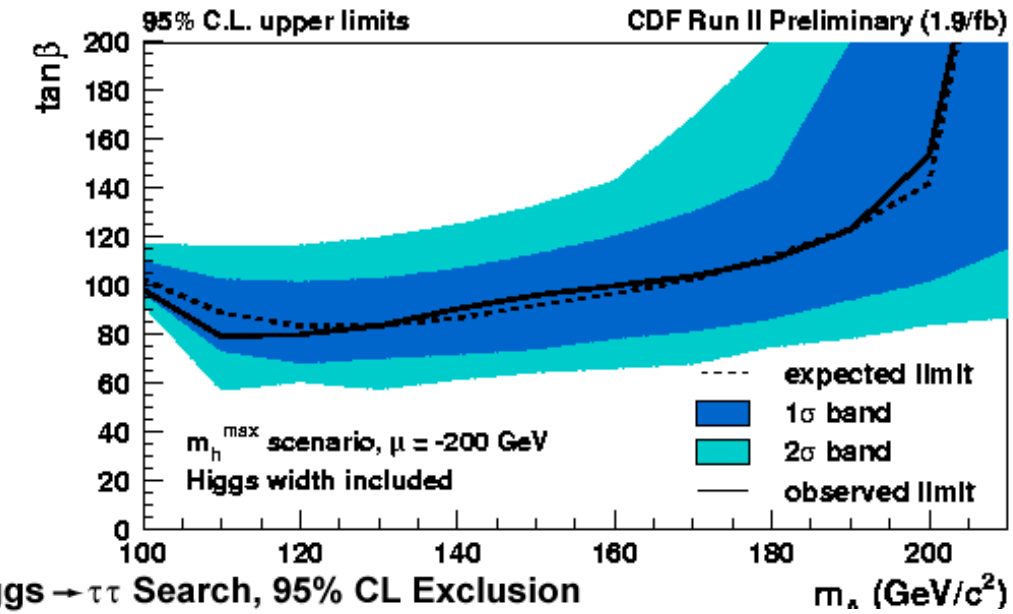
Conclusions and Outlook

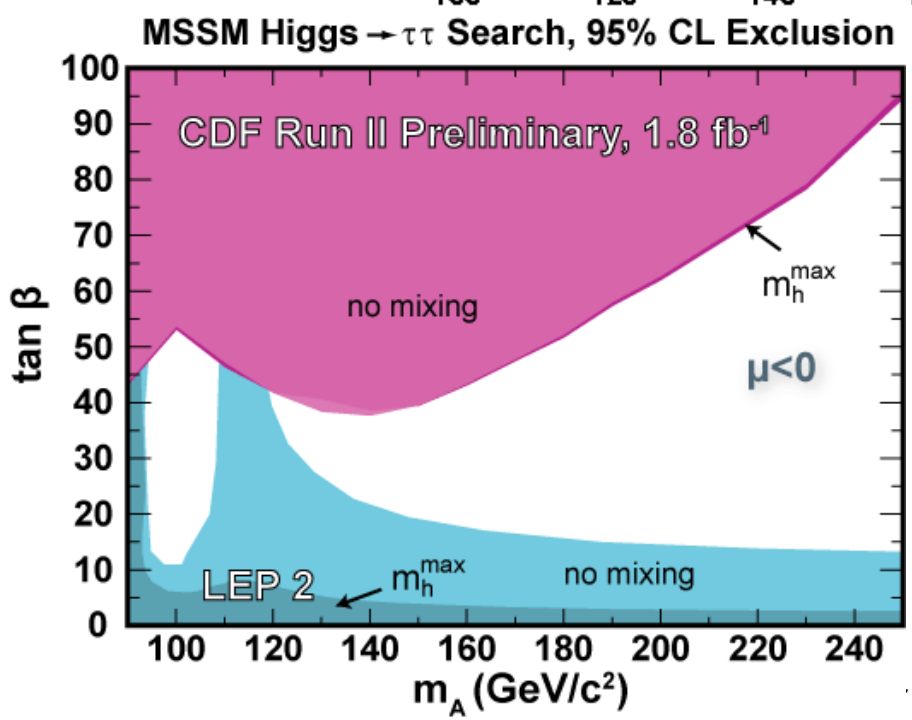
- DØ is seaching for neutral MSSM Higgs at high $\tan\beta$ in both the $\tau\tau$ and 3b channels:
  - New result in both channels with 1 fb^{-1}
  - Data agree with backgrounds, no significant excess observed
  - New cross section limits interpreted in the [$\tan\beta$, M_A] plane in different MSSM scenarios

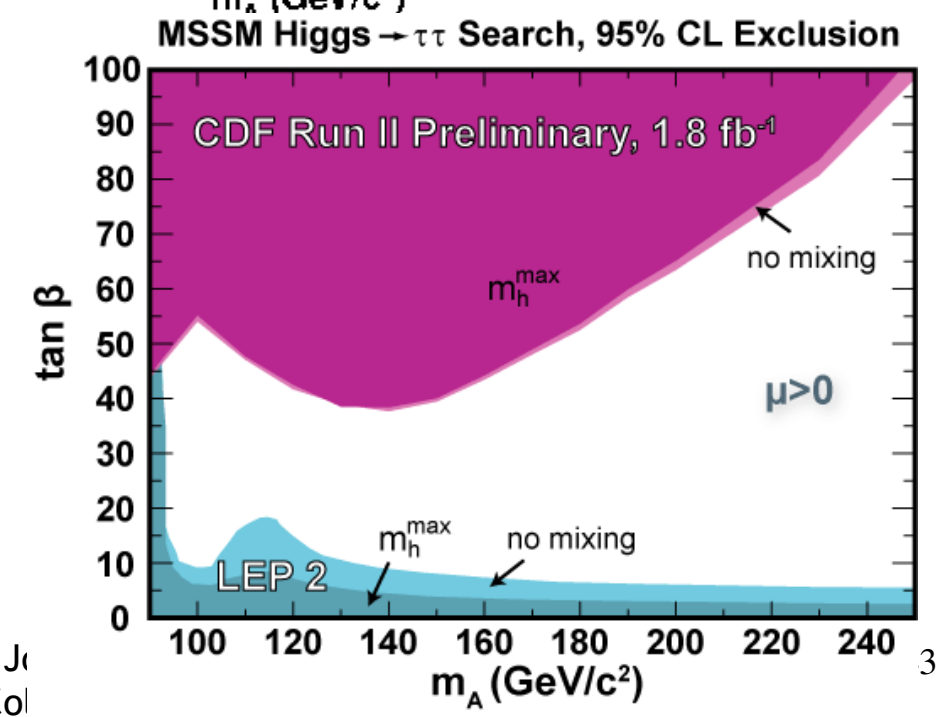
- Analysis methods and procedures now well established:
  - Expect results with >2 times more data soon
- Combination of different channels underway
  - The $b\phi \rightarrow b\tau\tau$ channel is also coming

Backup slides

CDF results


95% C.L. upper limits
CDF Run II Preliminary (1.9/fb)
tan β
m_h^{max} scenario, μ = -200 GeV
Higgs width included
expected limit
1σ band
2σ band
observed limit
m_A (GeV/c²)


MSSM Higgs → ττ Search, 95% CL Exclusion
CDF Run II Preliminary, 1.8 fb⁻¹
no mixing
m_h^{max}
μ<0
LEP 2
m_h^{max}
no mixing
tan β
m_A (GeV/c²)


MSSM Higgs → ττ Search, 95% CL Exclusion
CDF Run II Preliminary, 1.8 fb⁻¹
m_h^{max}
no mixing
μ>0
LEP 2
m_h^{max}
no mixing
tan β
m_A (GeV/c²)

Tau ID efficiency

Efficiency(%)

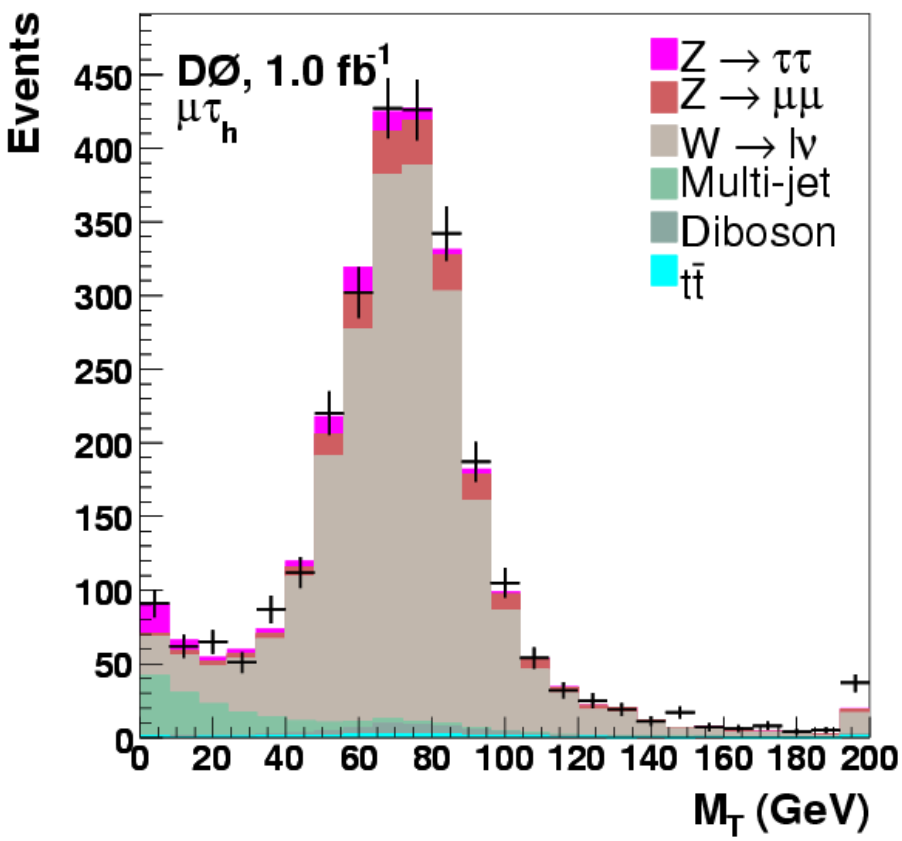
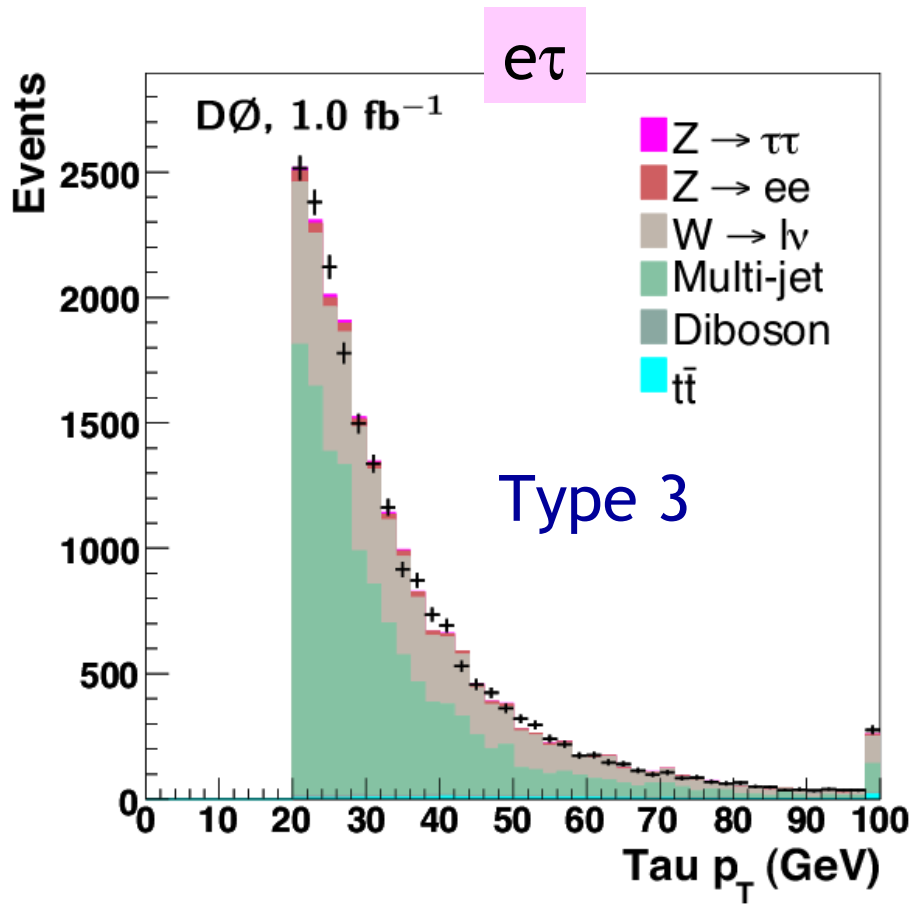
Tau Type	1	2	3
Reconstruction			
Jets	1.5	10	38
Taus	9.1	50	20
NN > 0.9			
Jets	0.04	0.2	0.8
Taus	5.8	37	13

MSSM benchmarks

- Five additional parameters due to radiative correction
  - M_{SUSY} (parameterizes squark, gaugino masses)
  - X_t (related to the trilinear coupling $A_t \rightarrow$ stop mixing)
  - M_2 (gaugino mass term)
  - μ (Higgs mass parameter)
  - M_{gluino} (comes in via loops)

- Two common benchmarks
  - Max-mixing - Higgs boson mass m_h close to max possible value for a given $\tan\beta$
  - No-mixing - vanishing mixing in stop sector $\rightarrow$ small mass for h

	m_h-max	no-mixing
M_{SUSY}	1 TeV	2 TeV
X_t	2 TeV	0
M_2	200 GeV	200 GeV
μ	±200 GeV	±200 GeV
m_g	800 GeV	1600 GeV

Background

- Normalize W+jets for each τ type:
  - Select W enriched sample
  - Fit transverse mass
- Normalize multijet as a function of p_T :
  - Check modeling in NN < 0.8