# Searches of Beyond Standard Model Higgs Boson at the Tevatron collider

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**3rd Higgs Hunting Conference**

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# Motivations

**Why beyond Standard Model (BSM) searches ?**

If a new particle was to be discovered : does it fit with our current understanding ? Does it come alone ? **Where to look** for more hints ?

**BSM searches allow to**

1. test specific models (supersymetric extensions, little Higgs, ...),
2. perform a wide scan of **final states** / **topologies**.

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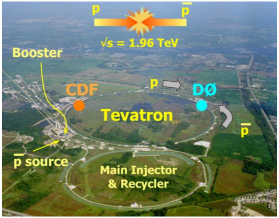
**In the context of BSM Higgs bosons searches at Tevatron :**

Analysis of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

$\tau$-lepton and $b$-quark final state : sensitive to SUSY scenarios.

Photon final state probes fermiophobic Higgs boson.



## $\tau$-lepton identification

65% of hadronic decay ($\equiv \tau_{\text{had}}$)

**Typical signatures :**

- narrow calorimeter shower
- low tracks multiplicity

**Main background :** jets

DØ : 65% efficiency for 98% rejection
CDF : 50% efficiency for 99% rejection

## $b$-jet identification

**Typical signatures :**

- secondary displaced vertex
- higher invariant mass
- soft muon inside the jet

**Main background :** $c$-jets, light jets

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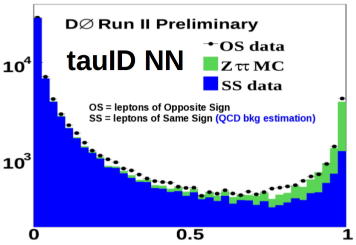
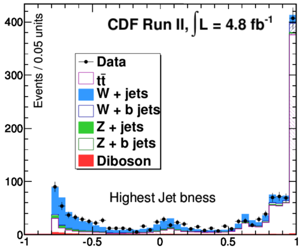
For each object, exploitation of full information with Multivariate analysis




*Nucl. Phys. Proc. Suppl. 218, 291 (2011)*




*Nucl. Instrum. Methods A 663, 37 (2011)*

# Overview

1. **Supersymetric extensions of the Standard Model**
   - MSSM Higgs bosons
   - Next-to-MSSM Higgs bosons
2. **No supersymetric scenarios**
   - Doubly charged Higgs boson
   - Fermiophobic Higgs boson
3. **Summary and conclusions**

# Phenomenology and search strategy

**MSSM Higgs sector :** 2 doublets $\hat{H}_u, \hat{H}_d$ coupling to up and down quarks

- After EWSB, 5 Higgs bosons : $\boldsymbol{\phi} = (h^0, H^0, A^0)$ and $\boldsymbol{H^{\pm}}$
- Tree level predictions depend on $(m_A, \tan\beta)$ $\tan\beta \equiv \langle H_d \rangle / \langle H_u \rangle$
- Coupling : $g_{\phi b\bar{b}} \propto (\tan\beta)\, g^{\text{sm}}_{Hb\bar{b}}$
  sensitive to **high** $\tan\beta$
- Decay :
  - $\phi \to b\bar{b} \sim 90\%$
  - $\phi \to \tau\tau \sim 10\%$ cleaner

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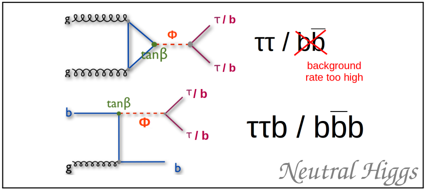


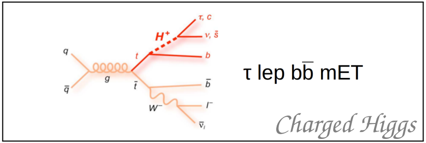

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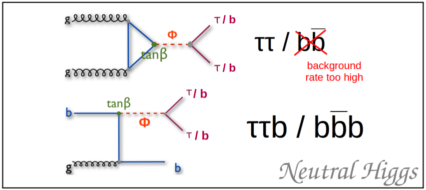
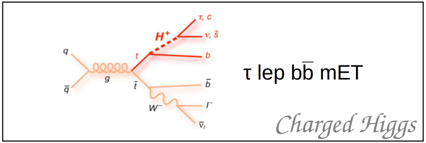



**Next-to-MSSM Higgs sector :**

- Dynamical generation of $\mu\,\hat{H}_u\,\hat{H}_d$ term : $\lambda\,\hat{S}\,\hat{H}_u\,\hat{H}_d$, with $\mu_{\text{eff}} = \lambda\langle\hat{S}\rangle$,
- $h^0 \to b\bar{b}$ strongly reduced but $h^0 \to aa$ with $m_a = \mathcal{O}(5)$ GeV,
- The pseudo scalar "$a$" decays mostly in $\mu\mu$ and $\tau\tau$.

# Neutral MSSM Higgs bosons searches

1. $\phi \to \tau\tau$
2. $b\phi \to b\tau\tau$
3. $b\phi \to b\bar{b}b$
4. Combinations

# Overview of single and combined channels

## Integrated luminosity ($fb^{-1}$) of single channels :

$\phi \to \tau\tau$

| | CDF | DØ |
|---|---|---|
| $\tau_\mu\tau_{\rm had}$ | 1.8 | 7.3 |
| $\tau_e\tau_{\rm had}$ | 1.8 | 1.0 |
| $\tau_e\tau_\mu$ | 1.8 | 5.4 |

$b\phi \to b\tau\tau$

| | CDF | DØ |
|---|---|---|
| $b\tau_\mu\tau_{\rm had}$ | – | 7.3 |
| $b\tau_e\tau_{\rm had}$ | – | 3.7 |
| $b\tau_e\tau_\mu$ | – | – |

$b\phi \to b\bar{b}b$

| CDF | DØ |
|---|---|
| 2.6 | 5.2 |

## Combinations with corresponding luminosity ($fb^{-1}$) :

- CDF : $\tau_\mu\tau_{\rm had} + \tau_e\tau_{\rm had} + \tau_e\tau_\mu \quad (1.8)$
- DØ :
  - $\tau_\mu\tau_{\rm had}\ (5.4) + \tau_e\tau_\mu\ (5.4)$
  - $\tau_\mu\tau_{\rm had}\ (7.3)\ +\ b\tau_\mu\tau_{\rm had}\ (7.3)\ +\ b\bar{b}b\ (5.2)$

**! New for Summer 2012 !**

- Tevatron :
  - $\tau\tau$ : 1.8 (CDF) + 2.2 (DØ)
  - **$b\bar{b}b$ : 2.6 (CDF) + 5.2 (DØ)**

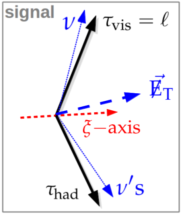
# Search for $\phi \to \tau\tau$ @ CDF

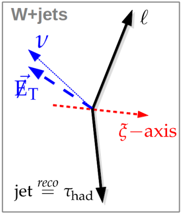
*Phys. Rev. Lett. 103, 201801 (2009)*

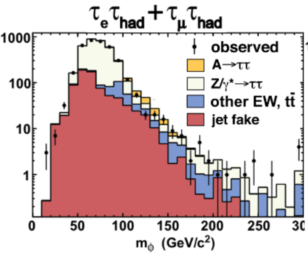
**Data samples :** 1.8 $\mathrm{fb}^{-1}$ of data analyzed in $\mu\tau_{\text{had}}$, $e\tau_{\text{had}}$ and $e\mu$ final states.

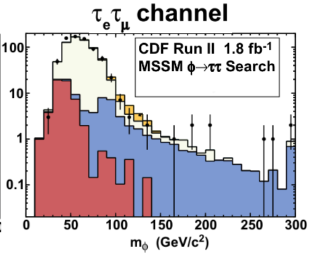
**Analysis overview :**

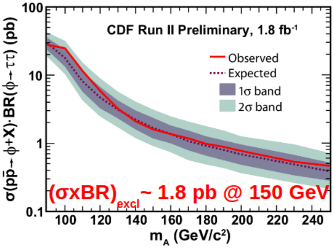
- Isolated leptons of high $p_T$, with one $\tau_{\text{had}}$ of opposite electric charge
- Suppression of $\sim$ **85%** of $W$+jets : exploit relative direction of $\not\!\!E_T$ with the reconstructed di-$\tau$ system (keeping **95%** of signal).



# MSSM constraints from $\phi \to \tau\tau$ results

**How to extract parameters constraints from $\sigma \times \mathcal{BR}$ limits ?**

- Compute $\sigma \times \mathcal{BR}$ as a function of theoretical parameters $(m_A, \tan\beta)$,
- Radiative corrections introduce more parameters : benchmark scenarios

$$( m_h^{\max}\text{-mixing} \oplus \text{No-mixing} ) \otimes \mu = \pm 200 \text{ GeV}$$

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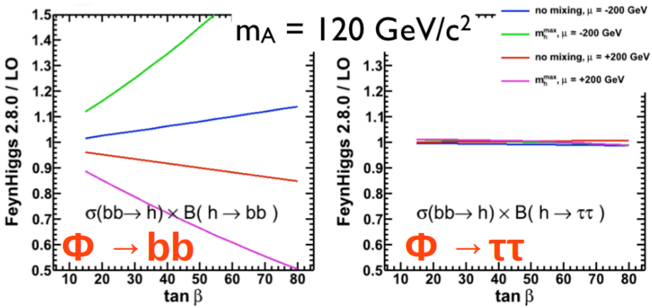


Important feature of $\tau\tau$ channels : **insensitive to MSSM scenario**

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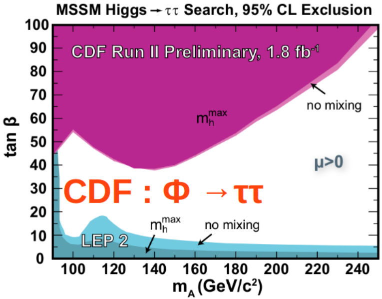
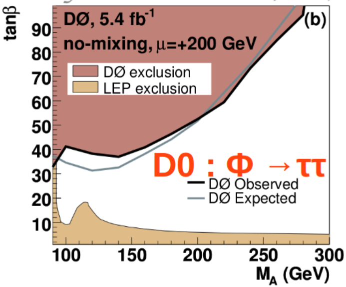



Phys. Lett. B 707, 323 (2012)




$\tau\tau$ channels are sensitive to $\tan\beta \sim 35 - 40$ at low mass

# Update on $\phi \to \tau_\mu \tau_{\text{had}}$ @ DØ

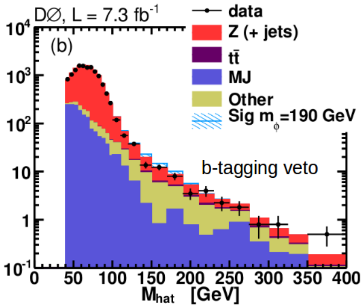
**New : published in PLB !**

*Phys. Lett. B 710, 569 (2012)*

**Data samples : 7.3 fb$^{-1}$** of data analyzed in the $\mu\tau_{\text{had}}$ final states.

**Analysis overview :**

- Isolated leptons of high $p_T$, with one $\tau_{\text{had}}$ of opposit electric charge
- $b$-jet veto for the combination with $b\tau\tau$
- $Z \to \tau\tau$ modeling using $Z \to \mu\mu$ data (high stat $\to$ syst reduction)




| | $\tau\tau$ |
|---|---|
| $Z$(+jets) | 11547 ± 634 |
| $t\bar{t}$ | 25 ± 4 |
| MJ | 1343 ± 236 |
| Other | 560 ± 25 |
| Total background | 13474 ± 684 |
| Data | 13344 |
| Signal $m_\phi = 100$ GeV | 1165 |
| Signal $m_\phi = 190$ GeV | 70 |

Sensitivity to $(\tan\beta, m_A)$ parameters $\to$ see next slides on DØ combination !

# Neutral MSSM Higgs bosons searches

1. $\phi \to \tau\tau$
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3. $b\phi \to b\bar{b}b$
4. Combinations

# Search for $b\phi \to b\tau_\mu\tau_{\text{had}}$ @ DØ

**New : published in PRL !**

*Phys. Rev. Lett. 107, 121801 (2011)*

**Data sample :** 7.3 $\text{fb}^{-1}$ of data analyzed in the $\mu\tau_{\text{had}} + b$-jet final state.

**Analysis overview :**

- final state mixes hadronic $\tau$ and $b$-jets : challenging !
- requiring additional $b$-jet reduces $Z$+jets bkg more than the signal :

$$\frac{\sigma^{\text{incl}}(Z)}{\sigma(Z + b_{\text{tag}})} < 0.005 \qquad \frac{\sigma^{\text{incl}}(\phi)}{\sigma(\phi + b_{\text{tag}})} \sim 0.16 \qquad \Rightarrow \textbf{gain S/B at low mass}$$

- Sophisticated signal extraction : $D_f \equiv \text{Likelihood}(D_{t\bar{t}}, D_{\text{MJ}}, \text{NN}_b, M_{\text{hat}})$
  $D_i \equiv$ discriminant against bkg $i$ ; $M_{\text{hat}} \sim$ minimal center-of-mass energy

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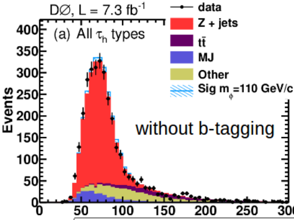
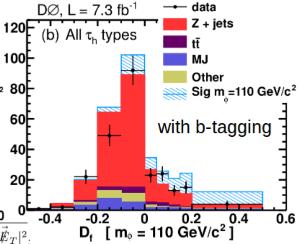
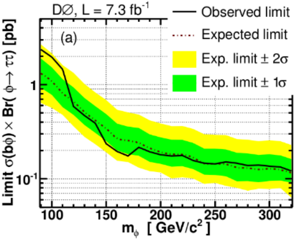



$M_{\text{hat}} \equiv \sqrt{(E^{\mu\tau_h} - p_z^{\mu\tau_h} + \not{E}_T)^2 - |\vec{p}_T^{\,\tau_h} + \vec{p}_T^{\,\mu} + \vec{\not{E}}_T|^2}$.

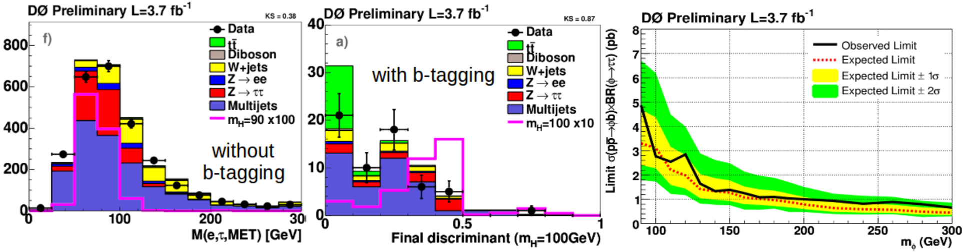
# Search for $b\phi \to b\tau_e\tau_{\text{had}}$ @ DØ

*DØ-conf 5974 (2011)*

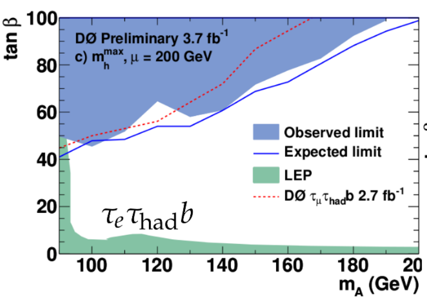
**Data sample :** $3.7\ \text{fb}^{-1}$ of data analyzed in the $e\tau_{\text{had}} + b$-jet final state.

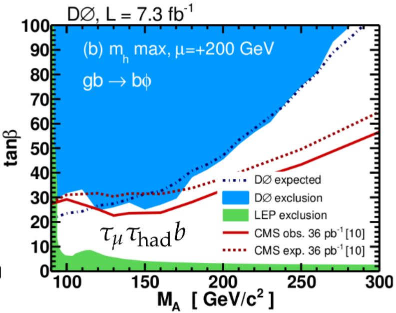
**Analysis overview :**

- Same motivation : S/B gain at low mass wrt $\tau_e\tau_{\text{had}}$,
- Electron channel : bigger contribution of MJ background,
- Sophisticated signal extraction, based on MVAs for MJ and $t\bar{t}$ (for each signal mass hypothesis).



# MSSM constraints from $b\phi \to b\tau\tau$ results




**Comments :**

- $b\tau_e\tau_{\text{had}}$ as sensitive as a previous $b\tau_\mu\tau_{\text{had}}$ with less luminosity (2.7fb$^{-1}$),
- $b\tau_\mu\tau_{\text{had}}$ sensitive to $\tan\beta \lesssim 30$ for $m_A \lesssim 150$ GeV,
- $b\tau_\mu\tau_{\text{had}}$ : best single channel constraint on $(\tan\beta, m_A)$ from Tevatron !

# Neutral MSSM Higgs bosons searches

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2. $b\phi \rightarrow b\tau\tau$
3. $b\phi \rightarrow b\bar{b}b$
4. Combinations

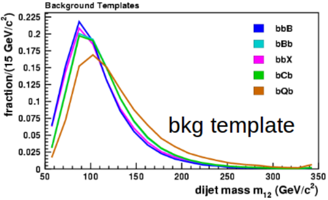
# Search for $b\phi \rightarrow b\bar{b}b$ @ CDF

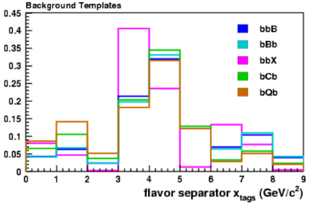
Now published : *Phys Rev. D 85, 032005 (2012)*

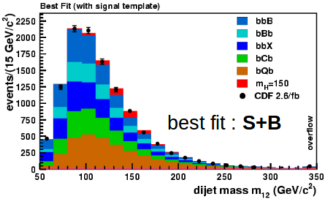
**Data sample :** 2.6 fb$^{-1}$ of data analyzed in the 3$b$-jets final state.

**Analysis overview :**

- Very challenging : MJ flavor composition and shape modeling !
- Signal signature : bump in $m_{b\bar{b}}$, taken as 2 leading jets invariant mass,
- Build a variable sensitive to fraction of light, $c$ and $b$-jets : $x_{\text{tag}}$
- Sig and bkg modeling based on 2D templates : $x_{\text{tag}}$ vs di-jet mass
- Test the presence of signal : 2D-fit in data in the B or S+B hypothesis



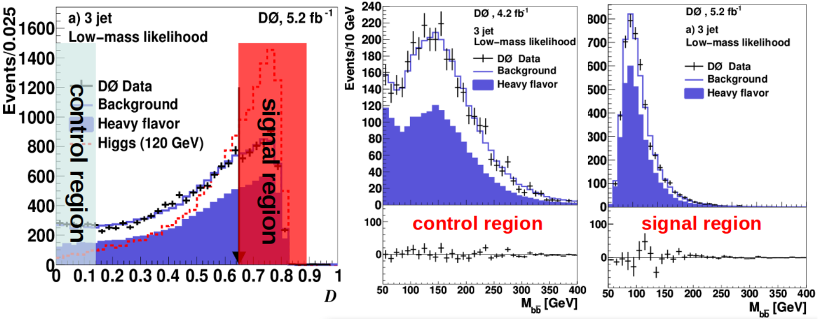
# Search for $b\phi \to b\bar{b}b$ @ DØ

*Phys. Lett. B 698, 97 (2011)*

**Data sample :** 5.2 fb$^{-1}$ of data analyzed in the 3$b$-jets final state.

**Analysis overview :**

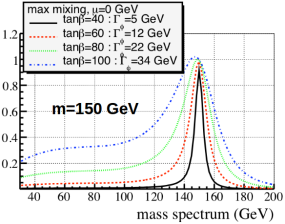
- Flavor composition : global fit in different b-tag data samples,
- Likelihood to discriminate signal from $b\bar{b}$ bkg (without $M_{b\bar{b}}$),
- Validation of background prediction in low Likelihood region.



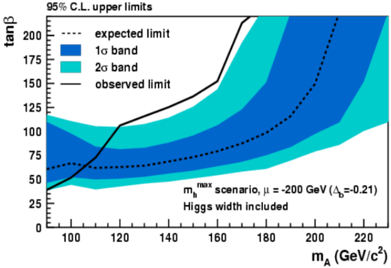
# Results of $b\phi \to b\bar{b}b$ searches

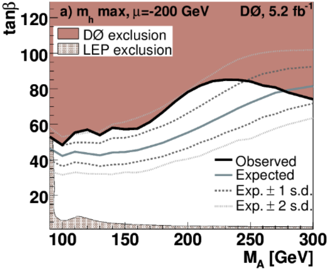
**Signal modeling for high $\tan\beta$ :**

- Higgs width not negligible for $\tan\beta \gtrsim 50$ compared to detector resolution ($\sim 20\%$).
- Effect taken into account via $\mathcal{BW}(\tan\beta)$ for the MSSM interpretation.




**MSSM constraints :** Higgs width not negligible for $\tan\beta \gtrsim 50$



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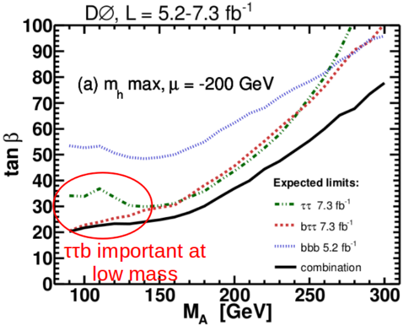
# DØ combination : $\tau_\mu \tau_{\text{had}} + \tau_\mu \tau_{\text{had}} b + b\bar{b}b$

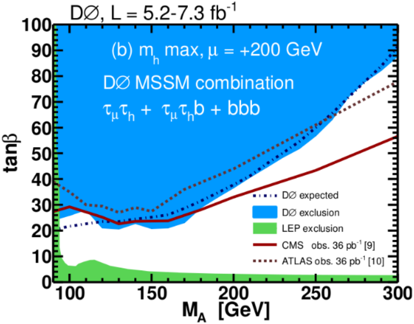
**New : published in PLB !** *Phys. Lett. B 710, 569 (2012)*

**Data sample :**

- 7.3 fb$^{-1}$ of $\tau_\mu \tau_{\text{had}}$
- 7.3 fb$^{-1}$ of $\tau_\mu \tau_{\text{had}} b$
- 5.2 fb$^{-1}$ of $b\bar{b}b$

Most stringent constraint on $(\tan\beta, m_A)$ from a single Tevatron experiment. Comparable with 36 pb$^{-1}$ LHC analysis



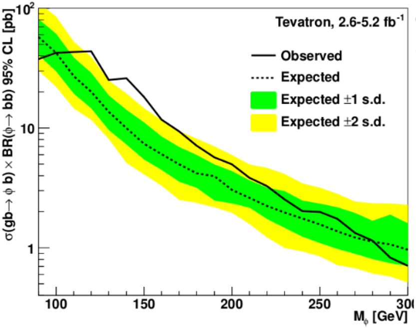
# Tevatron combination : $b\phi \to b\bar{b}b$

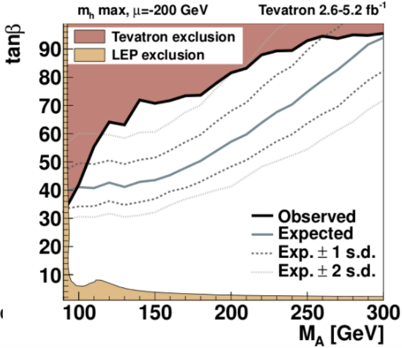
**New for summer 2012 !** *Submitted to Phys. Rev. D RC*

**Data sample :**

- CDF : 2.6 fb$^{-1}$ of $b\bar{b}b$
- DØ : 5.2 fb$^{-1}$ of $b\bar{b}b$

Challenging final state (MJ, $b$-jet trigger, ...) but reaches a sensitivity of $\tan\beta \sim 40$ at low mass. Channel studied at **Tevatron only** !

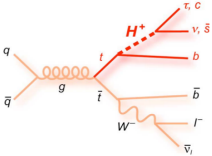


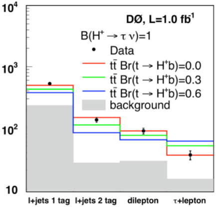



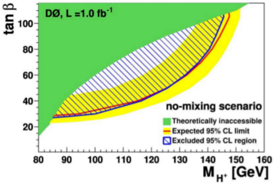
# MSSM charged Higgs boson searches

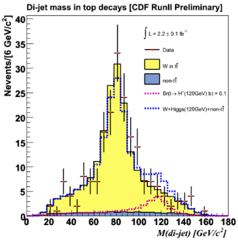
**Search strategy :** look at SM deviation in $t\bar{t}$ events

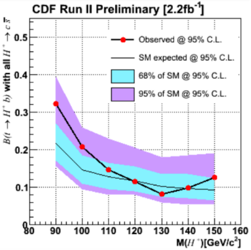
- $H^+ \to \tau\nu : \ell + \tau$ channel
- $H^+ \to c\bar{s} : \ell$+jets channel




### $H^+ \to \tau\nu$ by DØ

- look at $\mathcal{BR}$ of $t\bar{t}$ decay,
- possible for $\tan\beta > 1$

*PLB 682, 278 (2009)*

### $H^+ \to c\bar{s}$ by CDF

- $2^{\text{nd}}$ bump in $m_{jj}$,
- possible for $\tan\beta < 1$

# Overview

1. **Supersymetric extensions of the Standard Model**
   - MSSM Higgs bosons
   - Next-to-MSSM Higgs bosons
2. **No supersymetric scenarios**
   - Doubly charged Higgs boson
   - Fermiophobic Higgs boson
3. **Summary and conclusions**

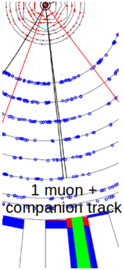
# Search for $h \to aa$ @ DØ

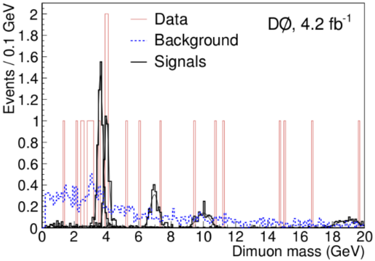
*Phys. Rev. Lett. 103, 061801 (2009)*

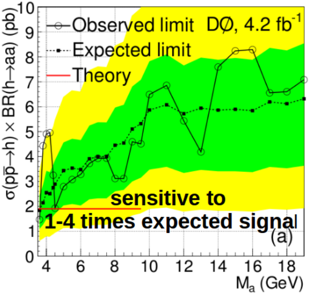
**Data sample :** 4.2 $\text{fb}^{-1}$ of data analyzed in the $\mu\mu\mu\mu$ and $\mu\mu + \not\!\!E_T$ final state.

**Analysis overview :**

- $aa \to \mu\mu\mu\mu$ : select 2 extremely colinear muon pairs,
- $aa \to \mu\mu\tau\tau$ : select 1 colinear muon pair + $\not\!\!E_T$ (from colinear $\tau$'s),
- For one pair : reconstruct only one muon and associate a "companion track" (due to the muon chamber granularity)
- Main background : MJ with heavy hadrons decaying into muon.



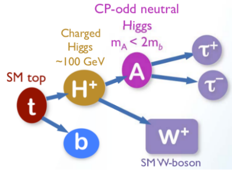



# Search for $H^+ \to W^+ A(\to \tau\tau)$ @ CDF

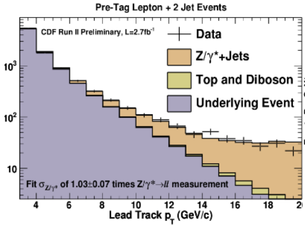
**Data sample :** 2.7 $\text{fb}^{-1}$ of analyzed data in the $\ell$+jets+low $p_T$ track final state

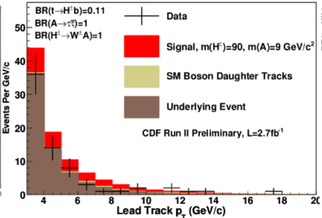
**Analysis overview :**

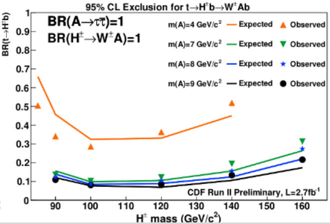
- Look at SM deviation in $t\bar{t}$ events
- $\tau$'s very softs : easily lost in usual $t\bar{t}$ decay
- look at highest low $p_T$ track ($p_T < 20$ GeV)
- Challenging : modeling of MJ with heavy flavour and MB ("Underlying Event")
- Bkg modeling validation : $\sigma_{Z\to\ell\ell}$ measurement




First look at this phase space region !



# Overview

# Search for $H^{++}$ @ DØ

**New : published in PRL !**

*Phys. Rev. Lett. 108, 021801 (2012)*

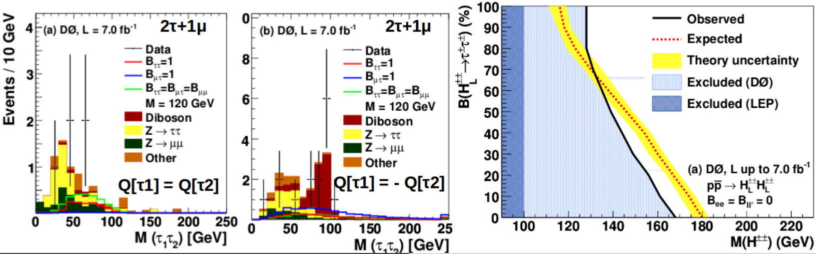
**Motivations :** doubly charged Higgs are predicted by :

- models with larger gauge symmetry, like $SU(3)_c \otimes SU(3)_L \otimes U(1)_Y$.
- Seesaw mechanism giving mass to neutrinos (with Higgs triplets).

**Data sample :** 7.3 $\text{fb}^{-1}$ of analyzed data with at least 1 muon and at least 2 $\tau$

**Analysis overview :**

- Production of doubly charged Higgs : $q\bar{q} \to H^{++}H^{--}$
- Decay : $H^{++} \to \tau\tau, \mu\tau, \mu\mu$ (given by $m_\nu$ hierarchy),
- Splitting events according $\tau$ and $\mu$ multiplicity,

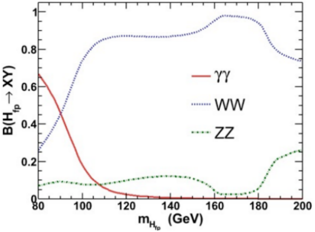


# Fermiophobic Higgs search at Tevatron

**Motivations :** Several SM extensions (composite Higgs, several doublets, ...) predict Higgs boson weakly coupled to fermions. **Limit case :** $g_{Hff} = 0$

**Consequences**

- $\sigma(gg \to H) = 0$
- dominant decay mode : $\gamma\gamma$



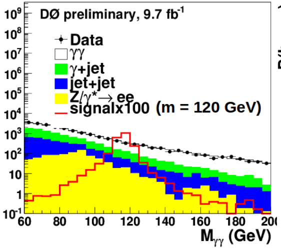

**Single channels with corresponding luminosity ($\mathbf{fb^{-1}}$) :**

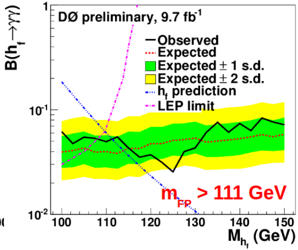
- DØ : $\gamma\gamma$ (9.7), $VH \to \ell^{\pm}\ell^{\pm} + X$ (5.2)
- CDF : $\gamma\gamma$ (10.0), $WW$ (8.2), $WH \to 3W$ (8.2), $ZH \to ZWW$ (8.2)

**Combination (sept 2011)** including the following channels

- DØ : $\gamma\gamma$ (8.2), $VH$ (5.2)
- CDF : $\gamma\gamma$ (8.2), $WW$ (8.2), $WH$ (8.2), $ZH$ (8.2)

# Search for $H_{FP} \to \gamma\gamma$



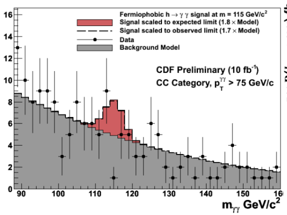



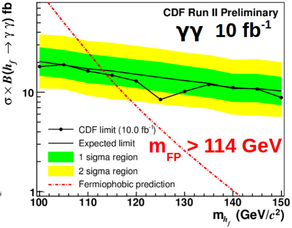

## DØ :

- Data-driven method for bkg shape/composition
- MVA for signal extraction, with kinem+$\gamma$ID

## CDF :

- Data-driven method for bkg shape,
- split in 12 samples (based on $\eta^{\gamma}$ and $p_T^{\gamma\gamma}$) to improve S/B



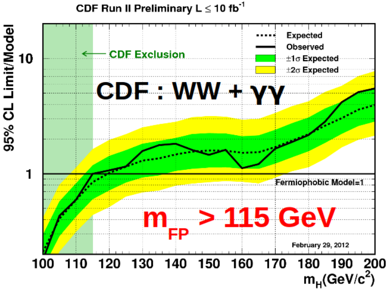



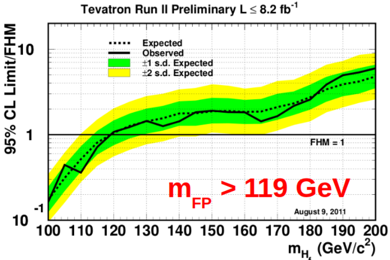
# Combined search for fermiophobic Higgs

**CDF combination :**

- Re-interpretation SM Higgs search in $H \to WW$ (10 fb$^{-1}$)
- $gg \to H$ signal is removed.
- $H \to \gamma\gamma$ is added (7 fb$^{-1}$).

expected exclusion : 119 GeV




**Tevatron combination :**

- $H \to \gamma\gamma$ : DØ (8.2), CDF (7.0)
- $H \to WW$ : DØ (5.3), CDF (8.2)

expected exclusion : 119 GeV

# Overview

# Summary and conclusions

**Concluding comments :**

- Tevatron searches of BSM Higgs boson(s) up to 10 $\text{fb}^{-1}$,
- Many searches not presented (Hidden Valley, CP violation scenario, ...)

**Supersymetric Higgs bosons :**

- $\phi \to \tau\tau$ at Tevatron allow to constraint $\tan\beta$ down to $\sim 35$
- **Legacy** Tevatron result, DØ comb $(\tau\tau + \tau\tau b + b\bar{b}b)$ : $(\tan\beta)_{\text{excl}} \sim 20$
- **Unique** at Tevatron and **first time** presented : ***$b\bar{b}b$* Tevatron combination.** $(\tan\beta)_{\text{excl}} \sim 40$ and $\sim 2\sigma$ excess observed (will be investigated with full dataset)

**No supersymetric extension :**

- Doubly charged Higgs : $m_{H^{++}} > 128$ GeV
- Good sensitivity to $\gamma\gamma$ decay mode at Tevatron for fermiophobic Higgs boson. Tevatron combination results in $m_{\text{FP}} > 119$ GeV.

# BACKUP

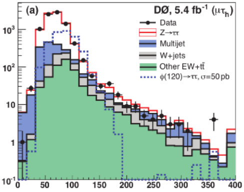
# Search for $\phi \to \tau\tau$ @ DØ

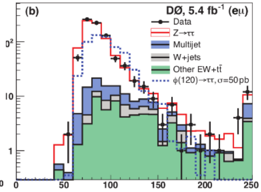
Now published : *Phys. Lett. B 707, 323 (2012)*

**Data samples :** 5.4 fb$^{-1}$ of data analyzed in the $\mu\tau_{\text{had}}$ and $e\mu$ final states.

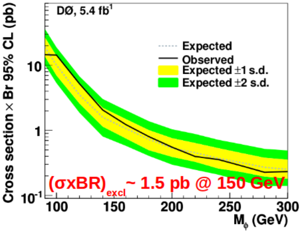
**Analysis overview :**

- Isolated leptons of high $p_T$, with one $\tau_{\text{had}}$ of opposit electric charge
- reduction of jet$\to$ $\tau_{\text{had}}$ bkg by tight $\tau$ID criteria,
- $M_T(\ell, \not{E}_T) < 50$ GeV to further supress $W$+jets,
- Data-driven estimation of multijets background.

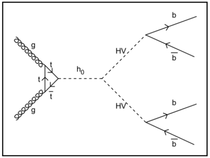



$$M_{\text{vis}} = \sqrt{(p_{\tau^1_{\text{vis}}} + p_{\tau^2_{\text{vis}}} + \not{E}_T)^2}$$



# Hidden valley related search




**Motivations :** Hidden Valley models assume additional confining gauge group weakly coupled to SM sector :

- prediction of long lived particles (HV),
- Higgs boson can decay in HV particles.

**Data sample :** 5.8 $\text{fb}^{-1}$ of analyzed data in the $\geq 3$ jets final state

**Analysis overview :**

- search for displaced vertices
- Main background : heavy flavour jets and mistag light jets
- Data-driven bkg modelling