

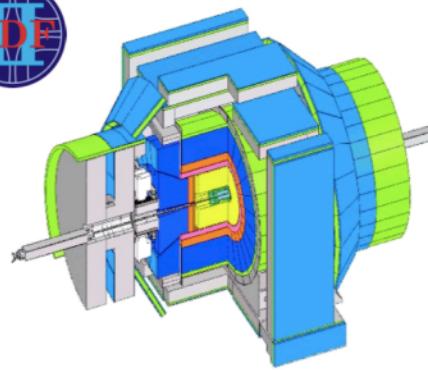
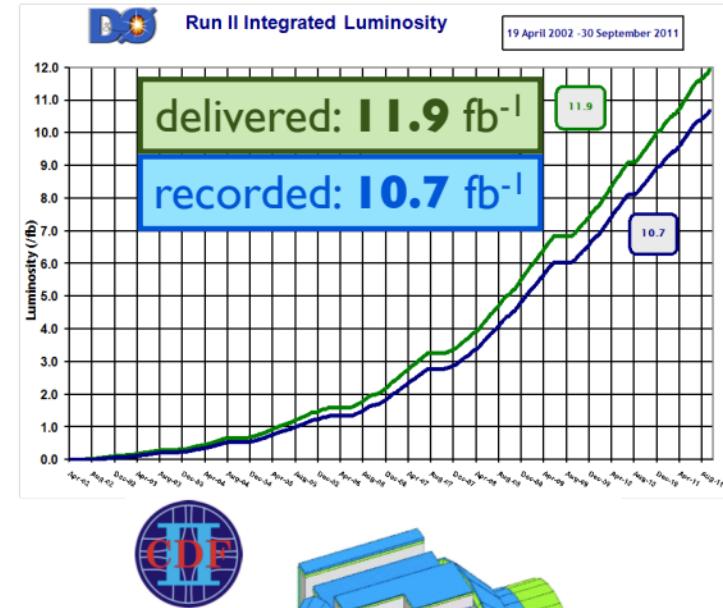
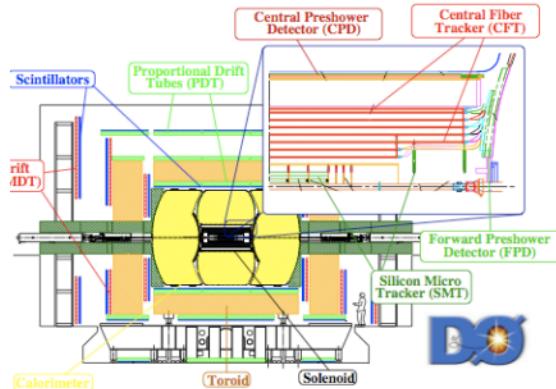


*Susy Higgs bosons searches in $p\bar{p}$
collisions at $\sqrt{s} = 1.96$ TeV
Focusing on SPP contributions*

Fabrice Couderc



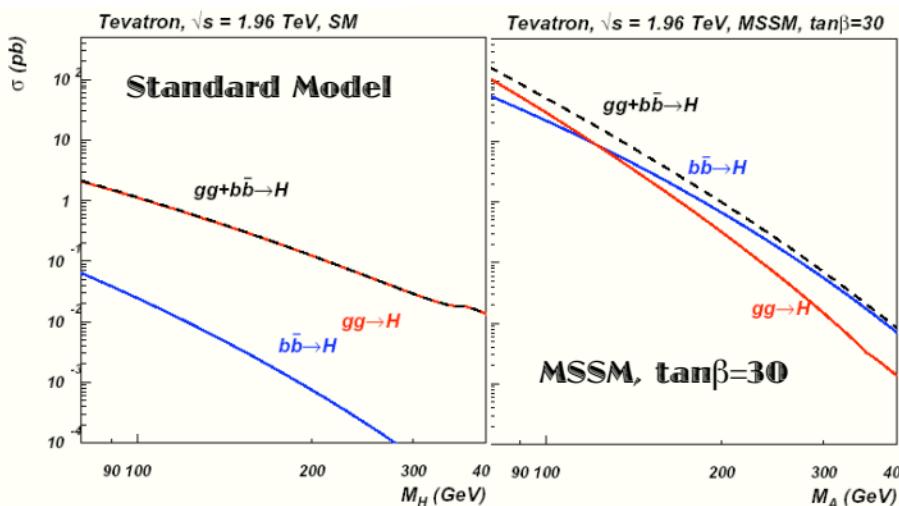
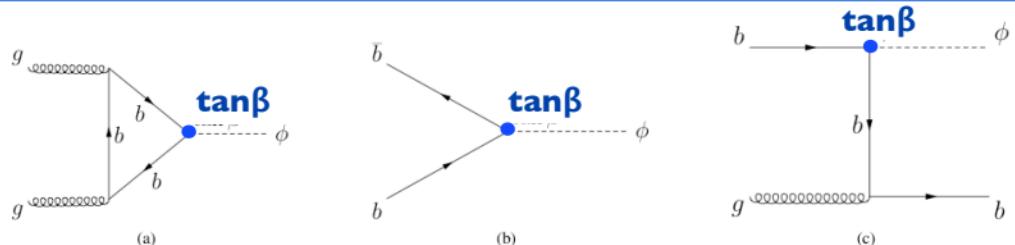
- ✓ Introduction
- ✓ MSSM Higgs searches
 - ◆ inclusive $h \rightarrow \tau\tau$ search
 - ◆ associated hb production
 - bbb final state
 - $\tau\tau b$ final state
- ✓ Conclusions





Higgs sector in the MSSM

- MSSM: exactly 2 Higgs doublets coupling to down-type quarks (vev v_d), and up-type quarks (vev v_u). $\tan\beta = v_u/v_d$
NB: $\tan\beta \sim 35 = m_t/m_b$ is appealing (large $\tan\beta$)
- After EW breaking: 5 physical states
 - ▶ 3 neutral Higgs bosons: h/H (CP-even) and A (CP-odd)
convention: $m_h < m_H$, $h/H/A$ generically denoted Φ
 - ▶ 2 charged Higgs bosons: H^\pm
- At tree level: EW breaking controlled by M_A and $\tan\beta$.
Radiative corrections make it more model dependent
- High $\tan\beta$ regime:
 - ▶ h/A or H/A are degenerate in mass $\sigma_{\text{prod}} \times 2!$
 - ▶ coupling to b quarks enhanced by $\tan\beta$
 - ▶ neutral Higgs: $\mathcal{B}(\phi \rightarrow b\bar{b}) \approx 90\%$ and $\mathcal{B}(\phi \rightarrow \tau^+\tau^-) \approx 10\%$

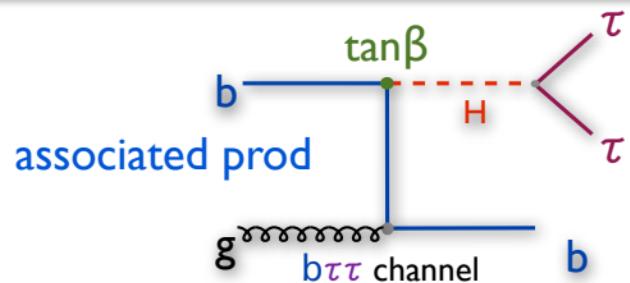
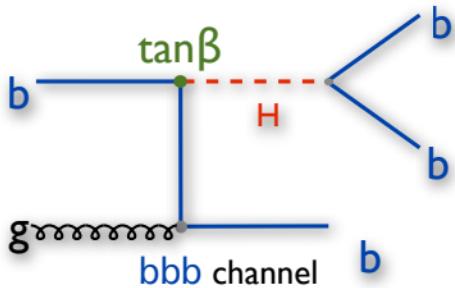
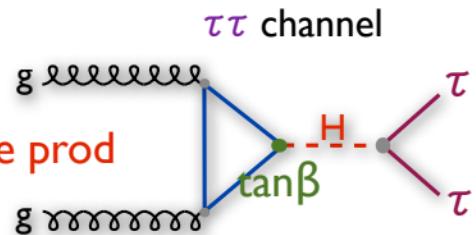
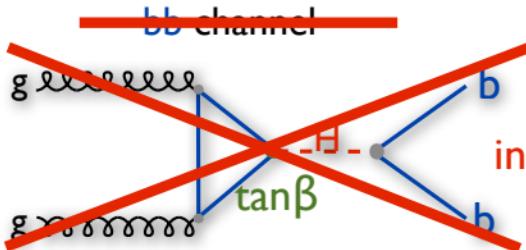


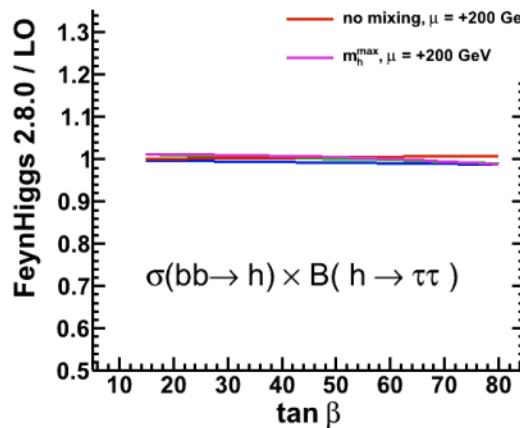
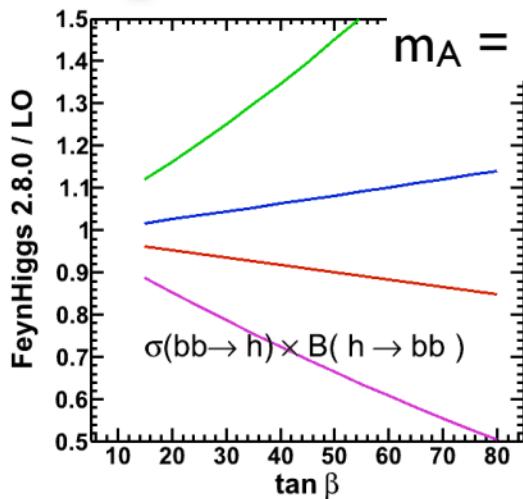
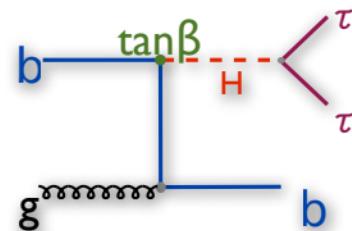
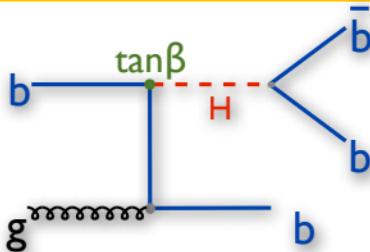
enhanced by $\tan^2\beta$ compared to SM

Enhancement at high $\tan\beta$: appreciable production rate at the Tevatron

@ LO

$$\sigma(b\bar{b} \rightarrow \phi)_{\text{MSSM}} = 2 \times \tan^2 \beta \times \sigma(b\bar{b} \rightarrow \phi)_{\text{SM}}$$

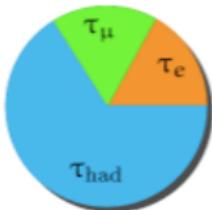
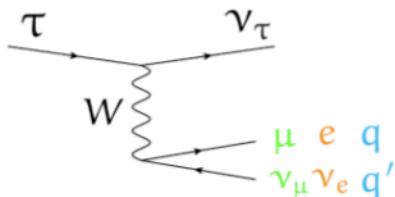




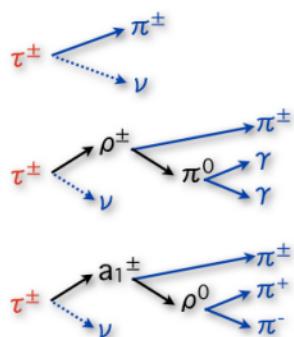
Beyond tree level, $h \rightarrow \tau\tau$ modes are less sensitive to the MSSM parameters than $h \rightarrow bb$

τ -lepton channels peculiarities:

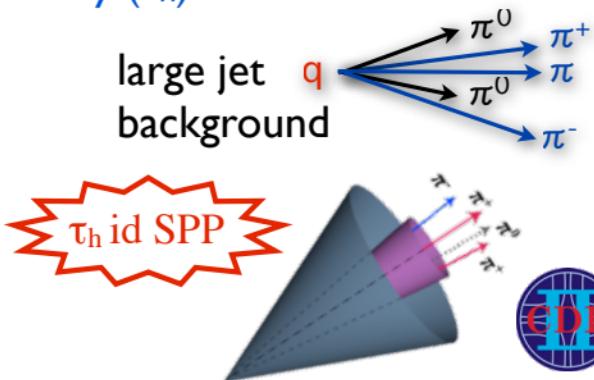
- several channels to combine
- relatively "soft" decay products
(multijet background, triggering...)



Need to reconstruct τ hadronic decay (τ_h)



- + NN_τ based on isolation, shower shape, trk-cal consistency variables

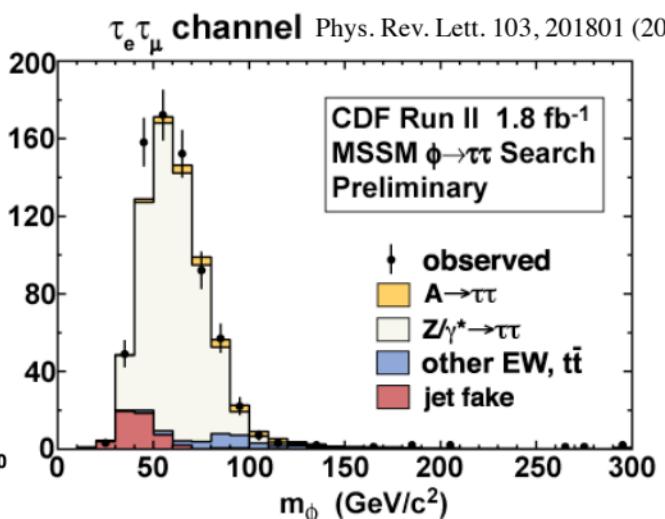
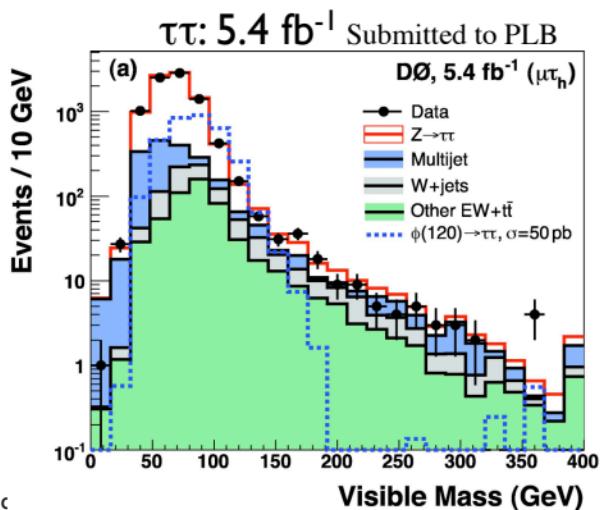
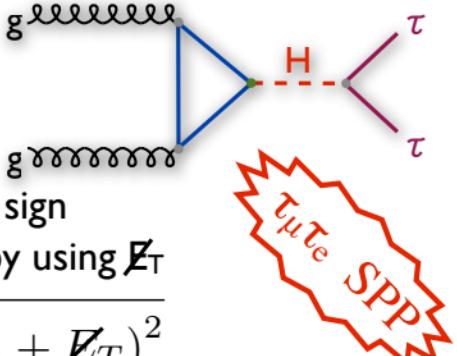


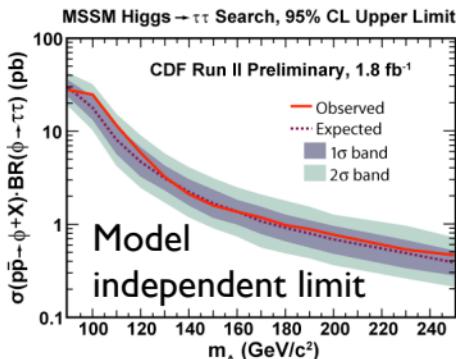
τ ID performance

- D $\bar{\Omega}$: eff=65% vs fake rate = 2.5%
- CDF: eff=50% vs fake rate < 1%

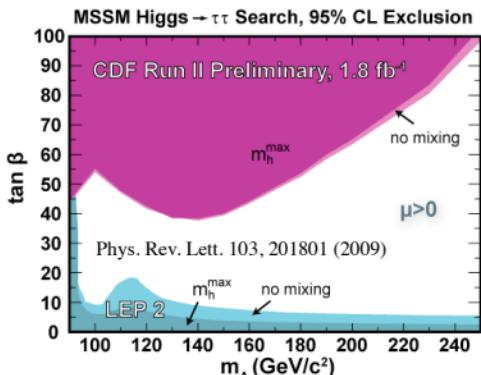
- DØ: $\tau_\mu \tau_h$, $\tau_\mu \tau_e$ (5.4 fb^{-1})
1.0 fb^{-1} result: Phys. Rev. Lett. **101**, 071804 (2008)
- CDF: $\tau_\mu \tau_h$, $\tau_e \tau_h$, $\tau_\mu \tau_e$ (1.8 fb^{-1})
- Search for 2 high p_T isolated leptons, opposite sign
- Escaping neutrinos info is partially recovered by using \cancel{E}_T
- Look for a bump in:

$$M_{vis} = \sqrt{(p_{\tau_h} + p_\mu + \cancel{E}_T)^2}$$

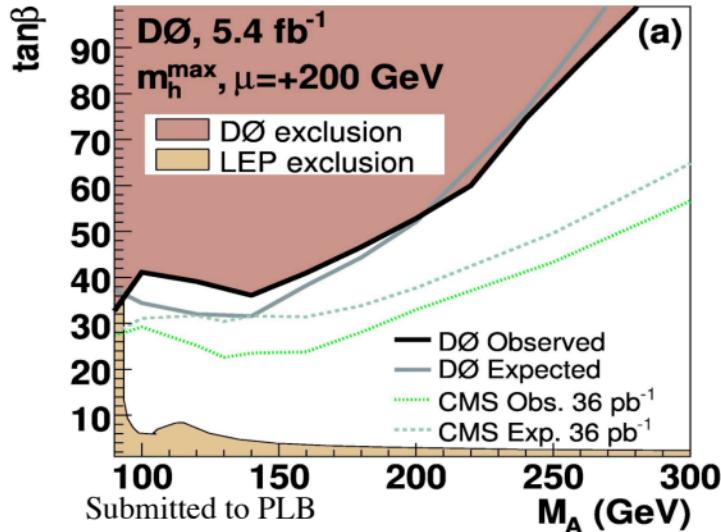




Data compatible with bkg



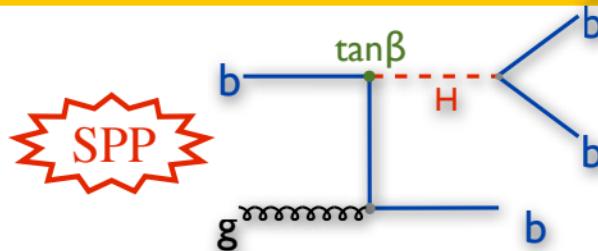
translation in MSSM parameter space



Reaching the interesting region of
 $\tan \beta \approx 30-40$ for $M_A < 200 \text{ GeV}$

Also DØ (2.2 fb^{-1})+CDF combo

- $b\Phi \rightarrow bbb$ selection:
 - ▶ 3 to 5 high p_T jets
 - ▶ at least 3 b-tagged jets



DØ : 1.0 fb^{-1} Phys. Rev. Lett. **101**, 221802 (2008)
 DØ : 5.2 fb^{-1} Phys. Lett. B **698**, 97 (2011)
 CDF: 2.6 fb^{-1} Submitted to PRD

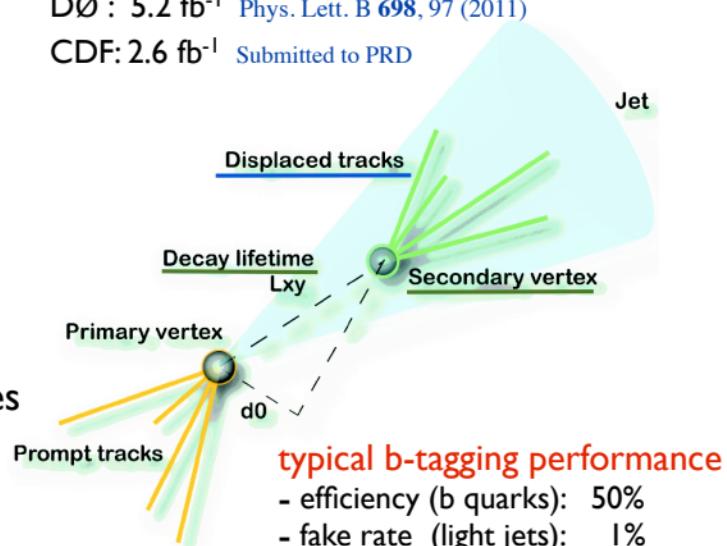
- Large multijets background:
 - ▶ Triggering
 - ▶ Powerful b-tagger
 - ▶ Challenging background model

b-tagging @ DØ: combine var. in a multivariate discriminant

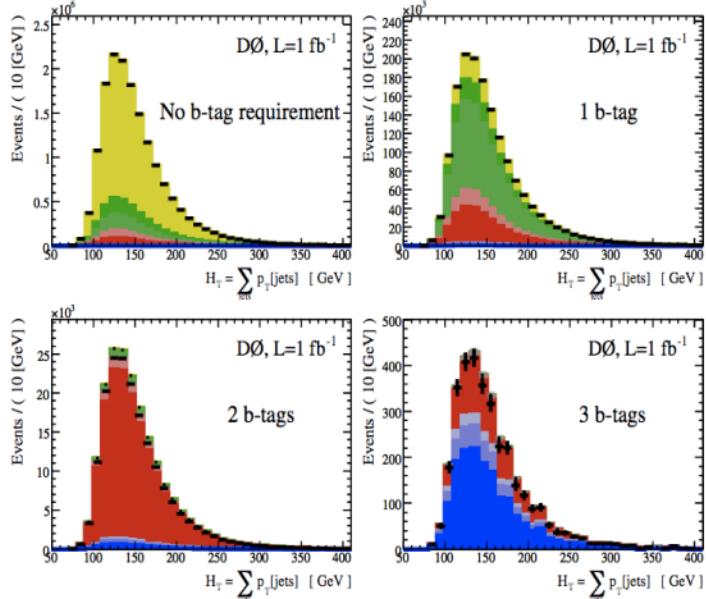
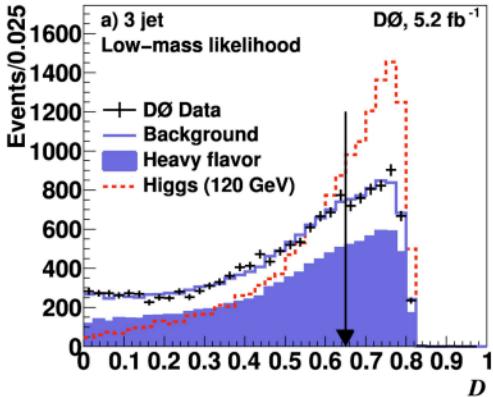
b-tagging @ CDF: displaced vertices

+ L_{xy}/σ cut

+ vertex mass separation



- ✓ Likelihood discri to enhance S:B ratio



- ✓ signal to bkg discri. only relies on dijet mass shape
- ✓ bkg composition from global fit to: 0/1/2/3 b-tag samples
- ✓ bkg shape from data using the 2 b-tag sample (signal free) via:

$$S_{3tag}^{exp}(M_{bb}, \mathcal{D}) = \frac{S_{3tag}^{MC}(M_{bb}, \mathcal{D})}{S_{2tag}^{MC}(M_{bb}, \mathcal{D})} \times S_{2tag}^{DATA}(M_{bb}, \mathcal{D})$$

Components

+ data

■ jjj

■ cij

■ bjj

■ ccj

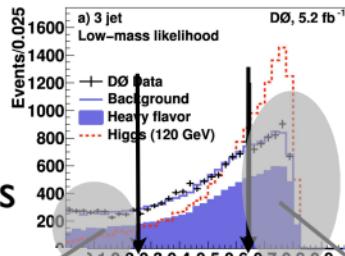
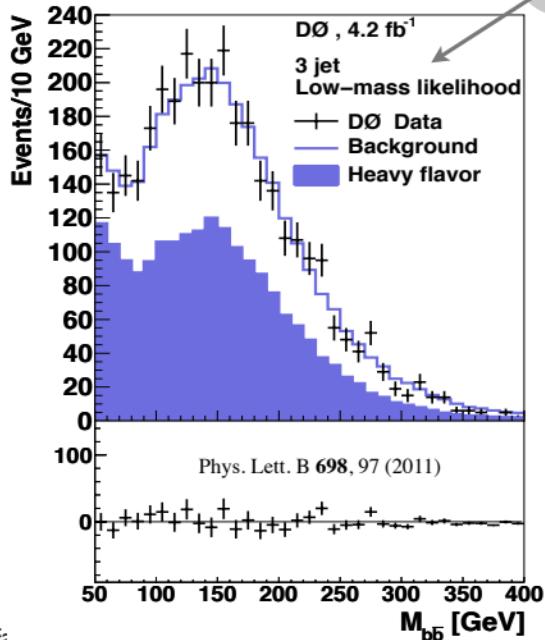
■ bbj

■ bcc

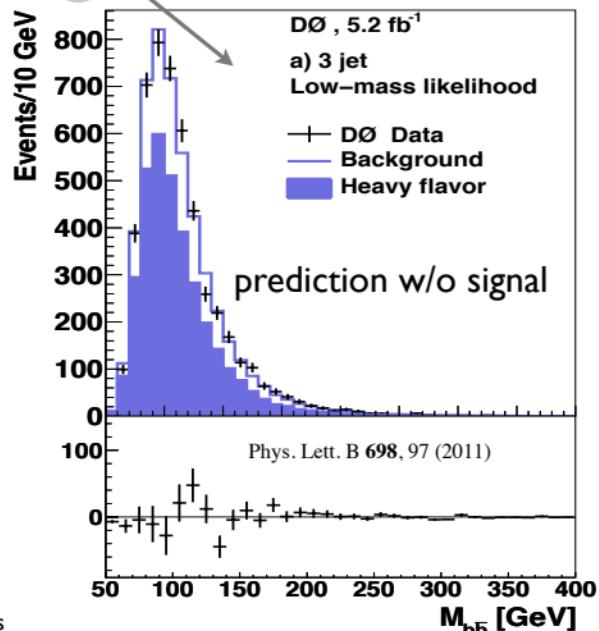
■ bcc

■ bbb

Control region: low D region not sensitive to the presence of a Higgs boson.



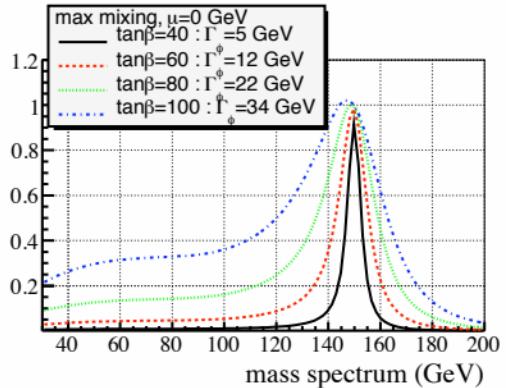
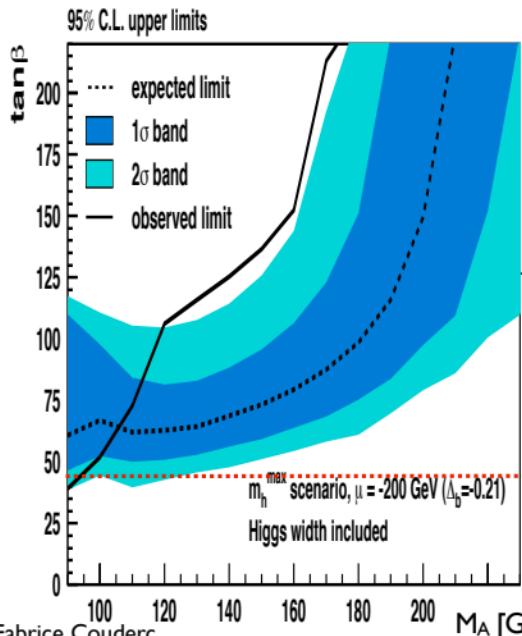
Signal region: high likelihood region.



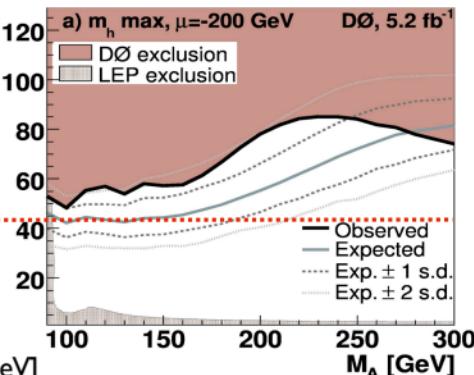
Very sensitive to radiative corrections

High $\tan\beta$: signal width effect not negligible
(compared to the experimental mass resolution).

$$\frac{d\sigma}{dm} = \sigma(m, \tan\beta, \Gamma = 0) \times BW(m, m_\phi, \tan\beta)$$



Exp. sensitivity down
to $\tan\beta=45$



Data compatible
with bkg but
both collab. see a
broad excess at
the 1-2 σ level.

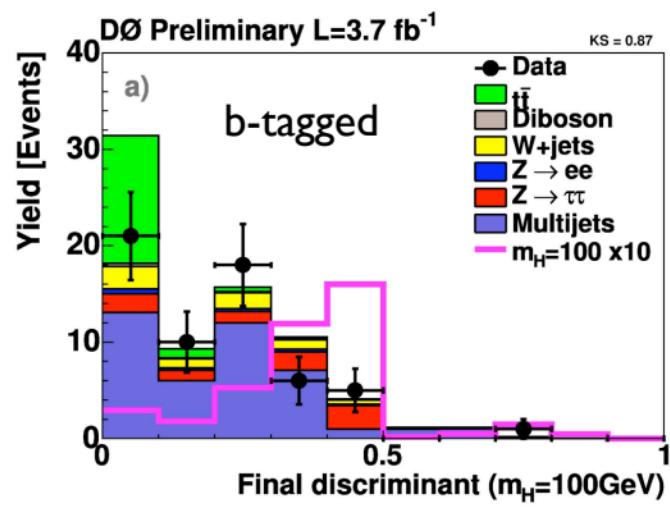
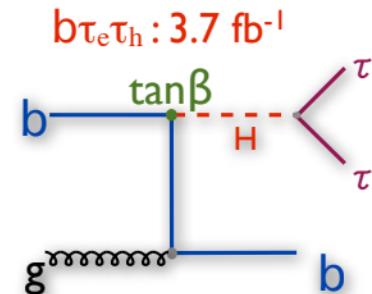
- Channel complementary to

- $b\Phi \rightarrow bbb$: lower \mathcal{Br} but much lower bkg, less sensitive to radiative corrections
- $\Phi \rightarrow \tau\tau$: more sensitive near the Z peak

$$\frac{\sigma(Z b_{tag})}{\sigma(Z \text{incl})} < 0.005$$

$$\frac{\sigma(\phi b_{tag})}{\sigma(\phi \text{incl})} = 0.16$$

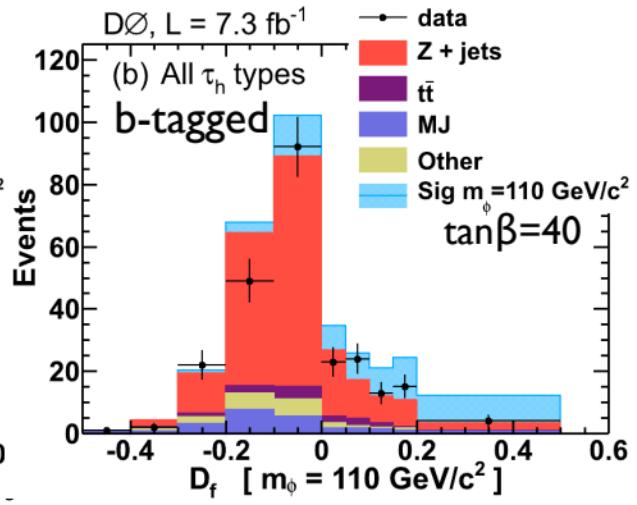
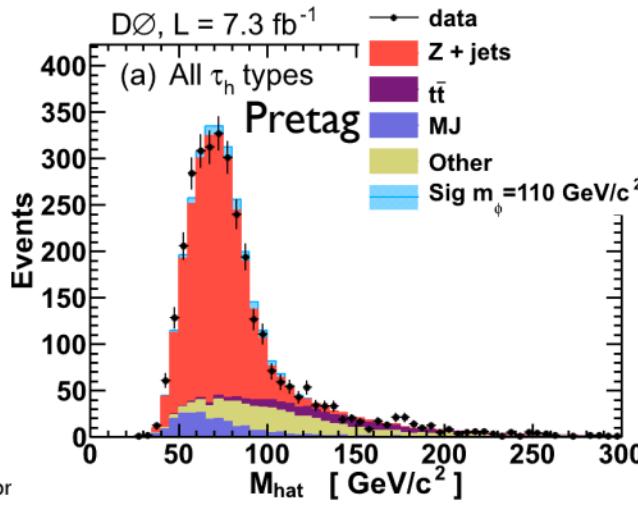
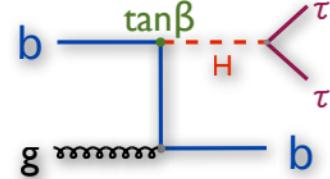
- $Z \rightarrow \tau\tau$: require one b-tag jet
- Specific discriminant against main backgrounds: multijets (D_{MJ}) and $t\bar{t}$ (D_{tt}).
- Final discri: $(D_{MJ}+10) \times D_{tt} / 20$




 $b\tau_\mu\tau_h : 7.3 \text{ fb}^{-1}$

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

- Specific discriminants against main backgrounds: $t\bar{t}$ (D_{tt}), multijets (D_{MJ}) and $Z \rightarrow \tau\tau$ (NN_b)
- Final discri: D_f likelihood formed with D_{tt} , D_{MJ} , NN_b , $M_{\hat{h}}$
- Main background ($Z \rightarrow \tau\tau$) constrained from data using $Z \rightarrow \mu\mu$.
Greatly reduces the loss of sensitivity due to syst. uncertainties.

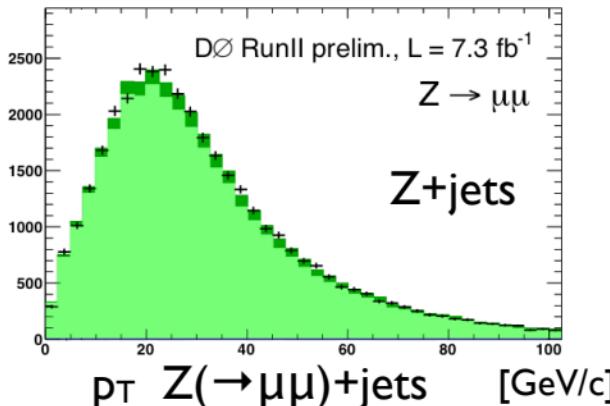


Dominant background for both $h \rightarrow \tau_\mu \tau_h$ and $b h \rightarrow \tau_\mu \tau_h$ is the Z

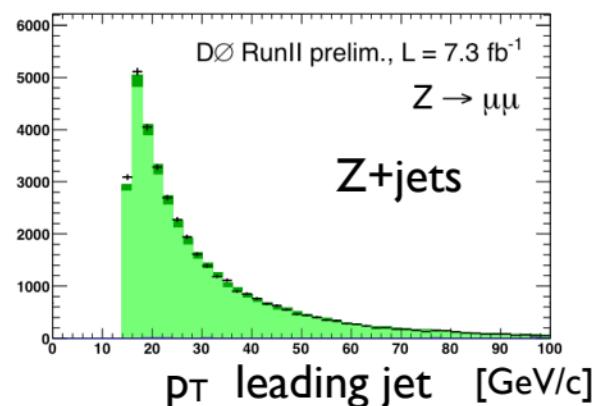
For instance, the uncertainty on the Z normalisation is dominated by systematic errors: 9.7%!!! (not including τ ID)

Constrain $Z \rightarrow \tau\tau$ ($Z+0/1/>=2$ jets and $Z+b$ -jets) from $Z \rightarrow \mu\mu$ samples

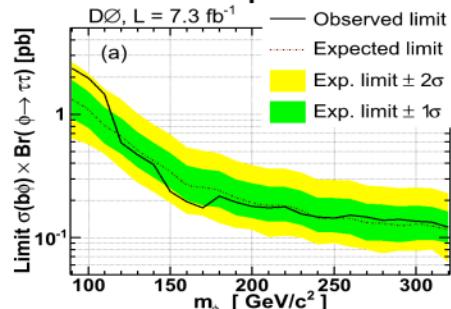
$$\frac{\sigma_{N_{\mu\tau_h}^{pred}}}{N_{\mu\tau_h}^{pred}} = \frac{\sigma_{N_{\mu\mu}^{data}}}{N_{\mu\mu}^{data}} \oplus \frac{\sigma_{\epsilon_\mu}}{\epsilon_\mu} \oplus \frac{\sigma_{\epsilon_{trig}}}{2 - \epsilon_{trig}} = 3.2\% \text{ vs } 9.7\%$$



MSSM Higgs searches



model independent limit

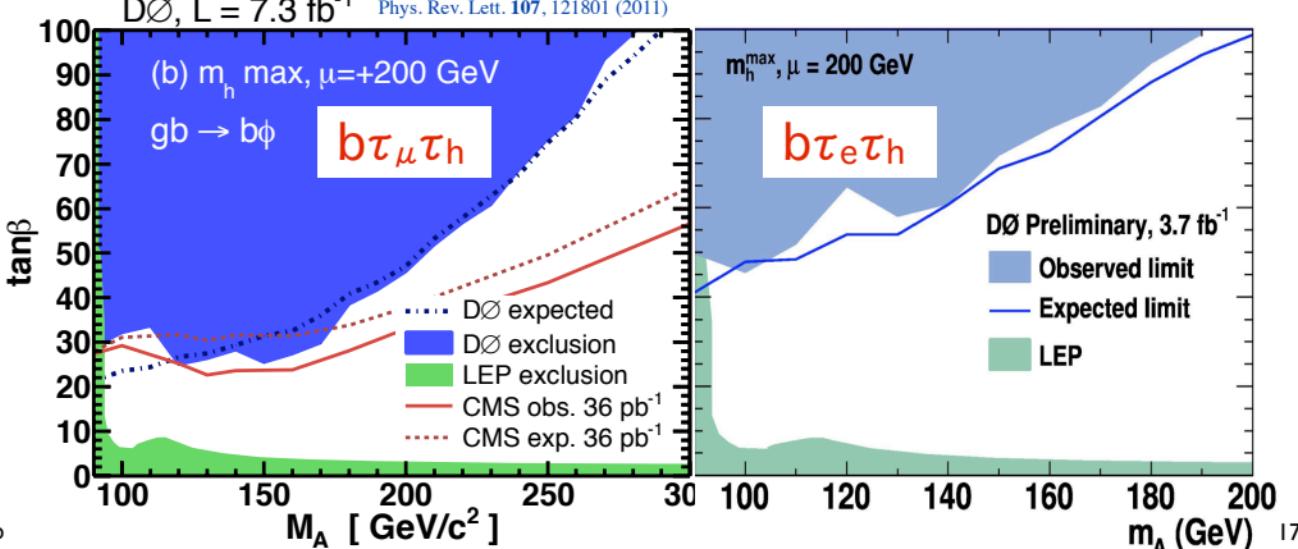


Data compatible with background

At low mass:

most stringent limits to date obtained in a direct search at Tevatron

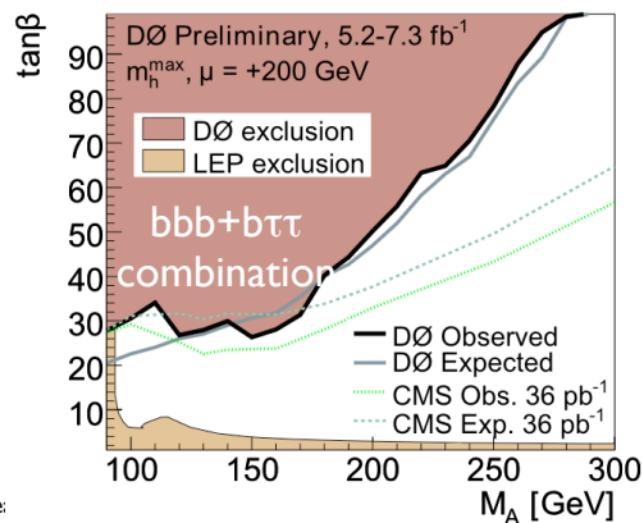
 ($b\tau_\mu\tau_h$ submitted to PRL)

 DØ, L = 7.3 fb⁻¹ Phys. Rev. Lett. 107, 121801 (2011)


- Report results with up to 7.3 fb^{-1}
- Also H^+ searches and NMSSM, fermiophobic, H^{++} searches....
- Reaching the interesting region of $\tan\beta \approx 20-30$
- $b\tau_\mu\tau_h$ is (still) competitive with LHC inclusive $\tau\tau$ searches. This is also a different and complementary channel (involving b-tagging)...
- Several modes with similar sensitivity: combine.
- SPP group involvement has been very strong:
 - bbb
 - $b\tau\tau$
 - $\tau_e\tau_\mu$ + re-analyse $\tau_\mu\tau_h$ (on-going)
 - Final D0 combination (on-going)
publication submission imminent



DØ bbb + b τ combination



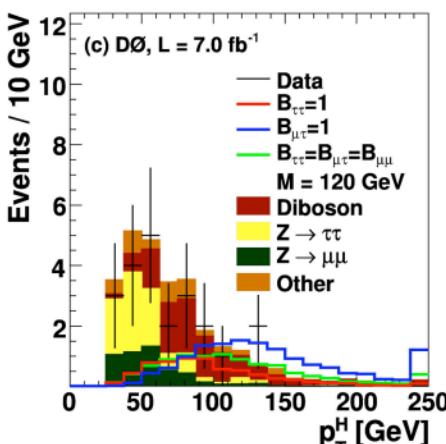


Backup

- Arise in Little Higgs, Left-Right symmetry, $SU(3)_L \times U(1)_Y$ gauge symmetry models (and can be supersymmetrized).
- Search for $H^{++} \rightarrow \mu\mu/\mu\tau/\tau\tau$: $\tau\tau$ search premiere at a hadron collider and most stringent limits in these channels

$H^{++}: 7.0 \text{ fb}^{-1}$

Selection:
at least 1 μ + 2 τ_h



MSSM F --

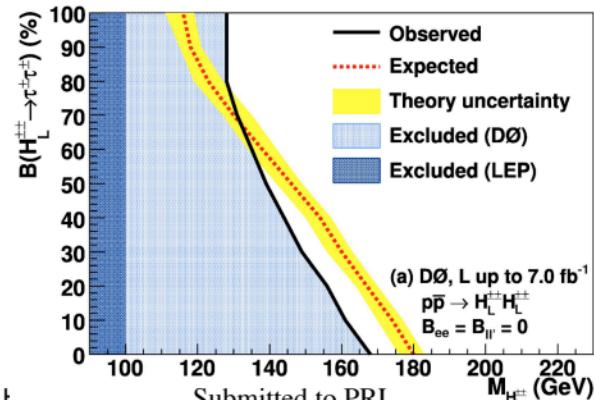
obs. (exp.) limits

$$\mathcal{B}(H^{++} \rightarrow \tau\tau) = 1 : m(H_L^{++}) > 128 \text{ (116)} \text{ GeV}$$

$$\mathcal{B}(H^{++} \rightarrow \mu\tau) = 1 : m(H_L^{++}) > 144 \text{ (149)} \text{ GeV}$$

$$\mathcal{B}(H^{++} \rightarrow \mu\tau) = \mathcal{B}(H^{++} \rightarrow \tau\tau) = \mathcal{B}(H^{++} \rightarrow \mu\mu) = 1/3 : m(H_L^{++}) > 138 \text{ (130)} \text{ GeV}$$

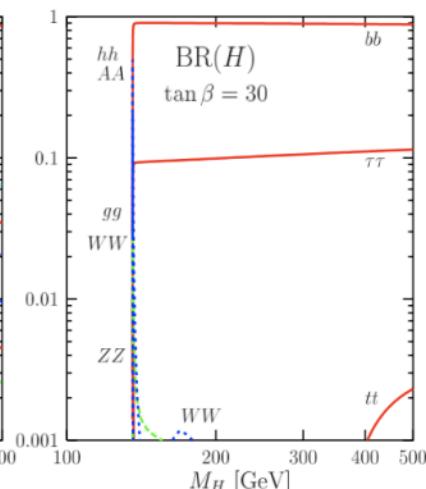
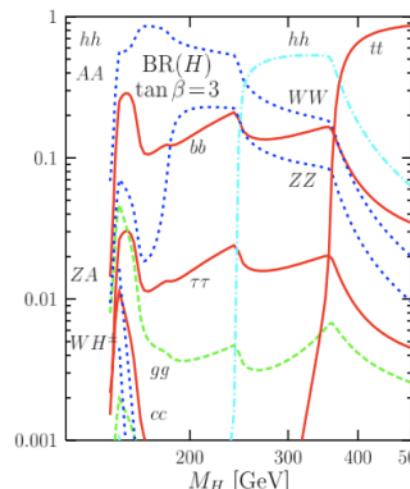
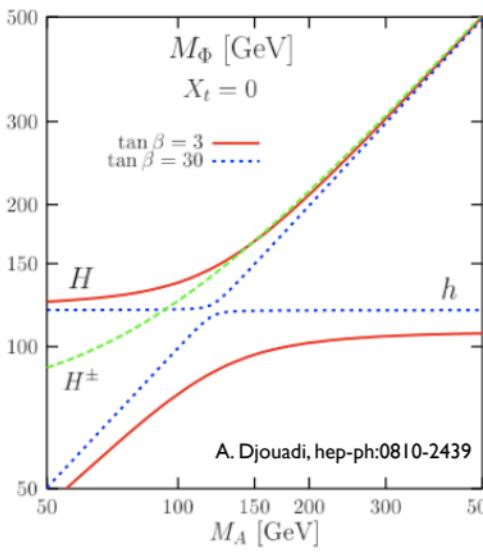
$$\mathcal{B}(H^{++} \rightarrow \tau\tau) + \mathcal{B}(H^{++} \rightarrow \mu\mu) = 1, \text{ scan:}$$



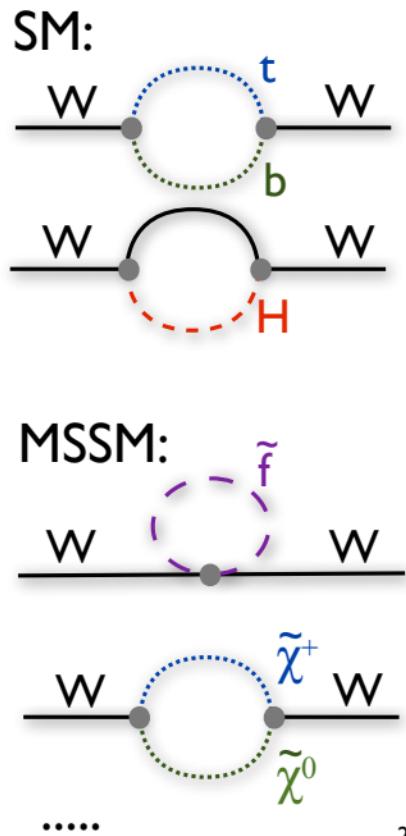
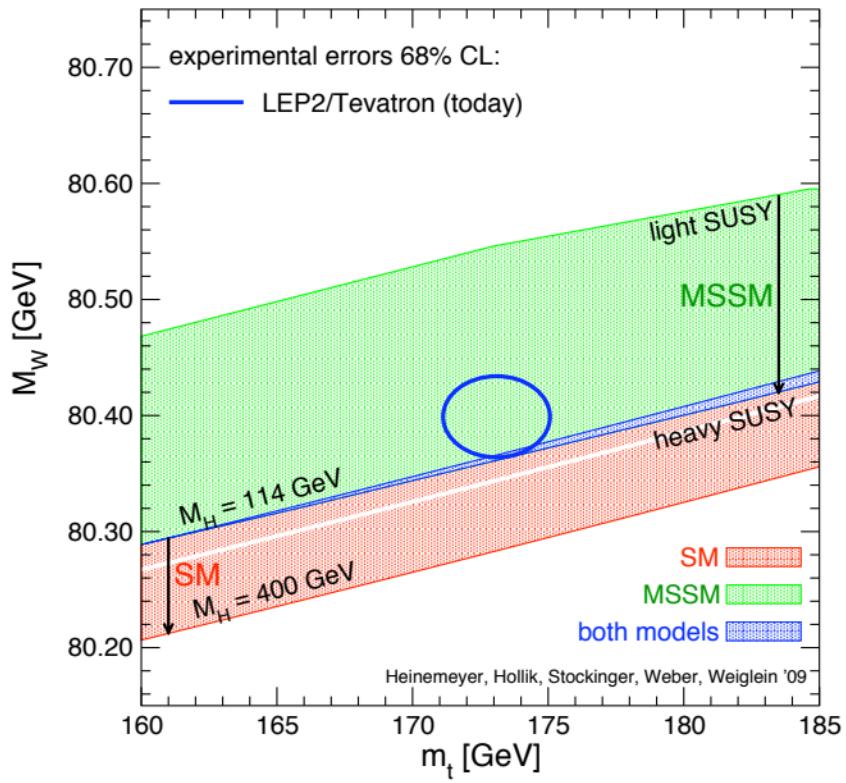
Submitted to PRL

MSSM dedicated Higgs searches at the TeVatron usually takes place in the high $\tan\beta$ regime:

- ▶ h/A or H/A are degenerate in mass $\sigma_{\text{prod}} \times 2!$
- ▶ coupling to b quarks enhanced by $\tan\beta$
- ▶ neutral Higgs: $\mathcal{B}(\phi \rightarrow b\bar{b}) \approx 90\%$ and $\mathcal{B}(\phi \rightarrow \tau^+\tau^-) \approx 10\%$
- ▶ charged Higgs: if $m_{H^\pm} < m_{\text{top}}$: $\mathcal{B}(H^\pm \rightarrow \tau^\pm \nu_\tau) \approx 1$



Why looking to the MSSM?



If data are compatible with background:

1. place limits in a model independent way

2. place limits into 4 different scenarios

use *FeynHiggs* or *CPSuperH* to get the
MSSM cross sections

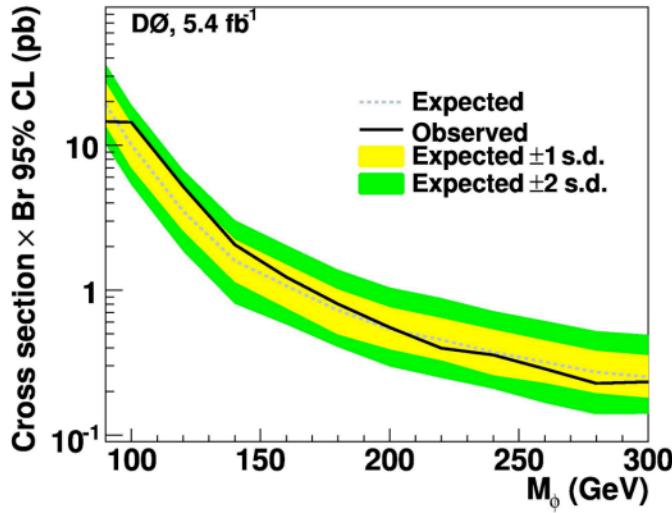
- m_h^{max} scenario:

- * $X_t = 2 \text{ TeV};$
- * $\mu = \pm 0.2 \text{ TeV};$
- * $M_2 = 0.2 \text{ TeV};$
- * $m_{\tilde{g}} = 0.8 \text{ TeV}$
- * $M_{SUSY} = 1 \text{ TeV}$

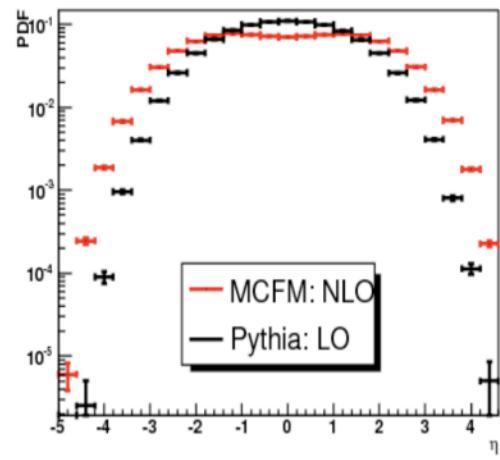
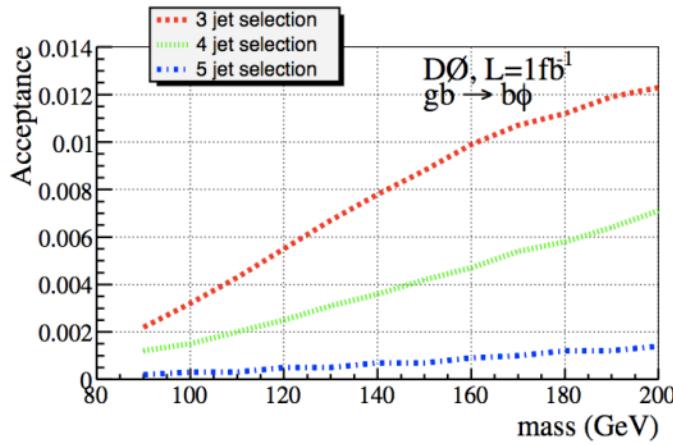
- No-mixing scenario:

- * $X_t = 0 \text{ TeV};$
- * $\mu = \pm 0.2 \text{ TeV};$
- * $M_2 = 0.2 \text{ TeV};$
- * $m_{\tilde{g}} = 1.6 \text{ TeV};$
- * $M_{SUSY} = 2 \text{ TeV}$

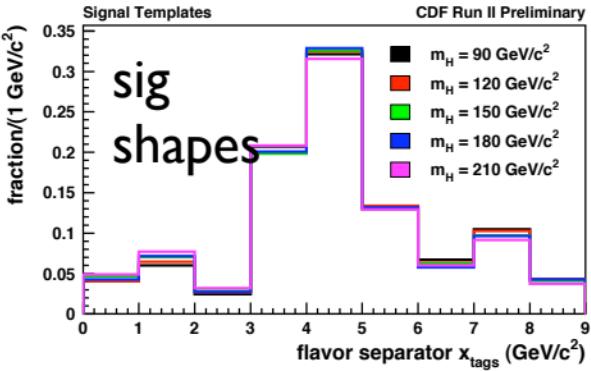
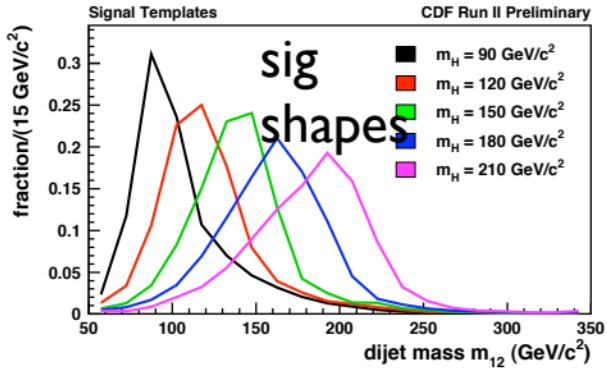
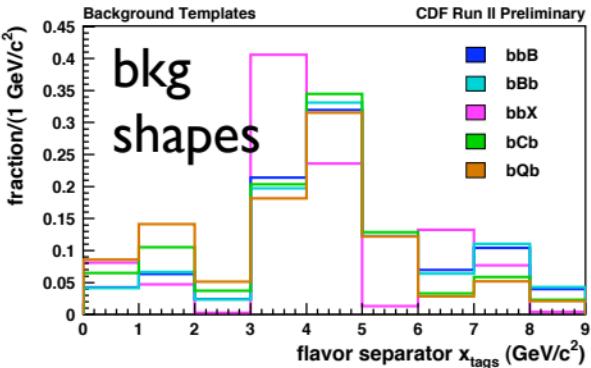
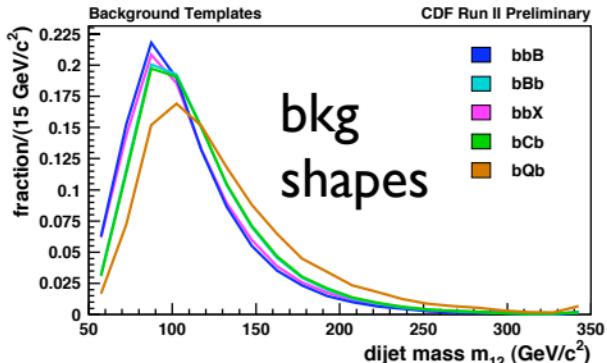
M. S. Carena, S. Heinemeyer, C. E. M. Wagner, and G. Weiglein, Eur. Phys. J. C 26, 601 (2003).

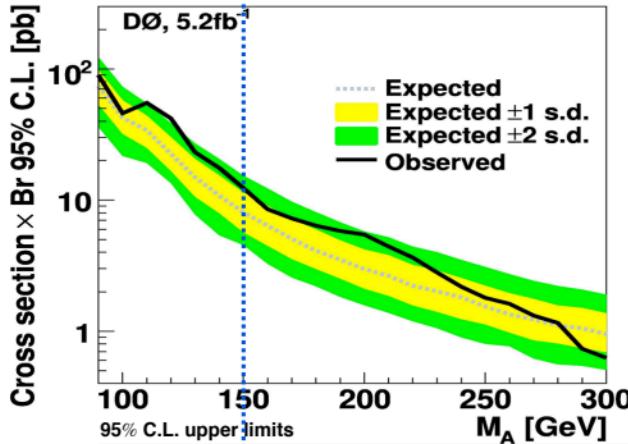


- **Signal simulation:** pythia $bg \rightarrow bH$ but spectator b quark kinematics reweighted to NLO (MCFM)

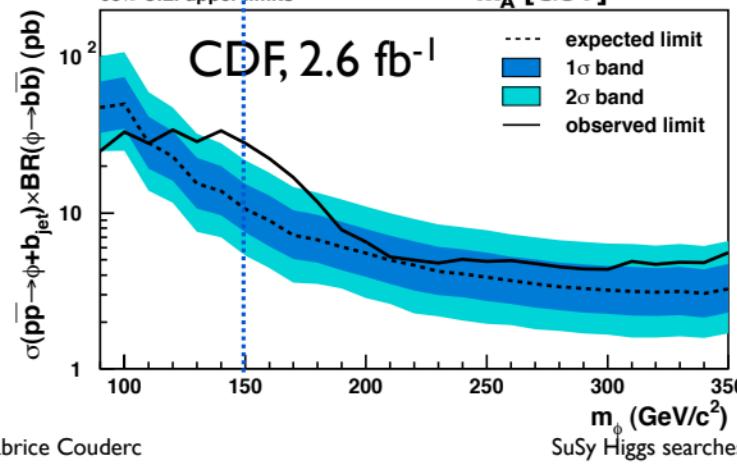


bbb background modeling

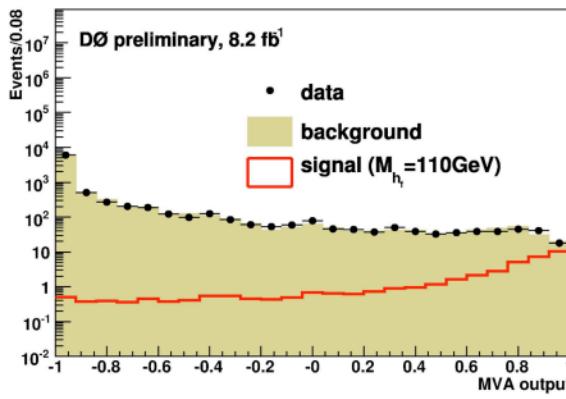
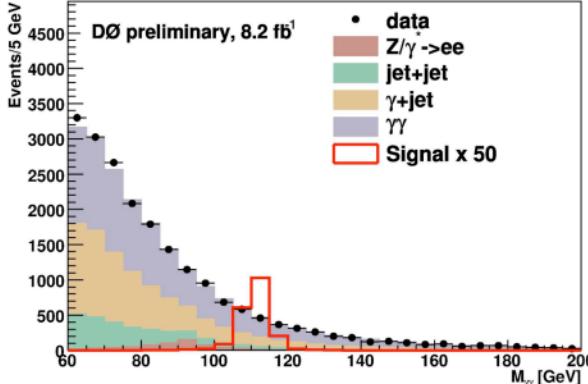




Model independent limit,
neglecting the width

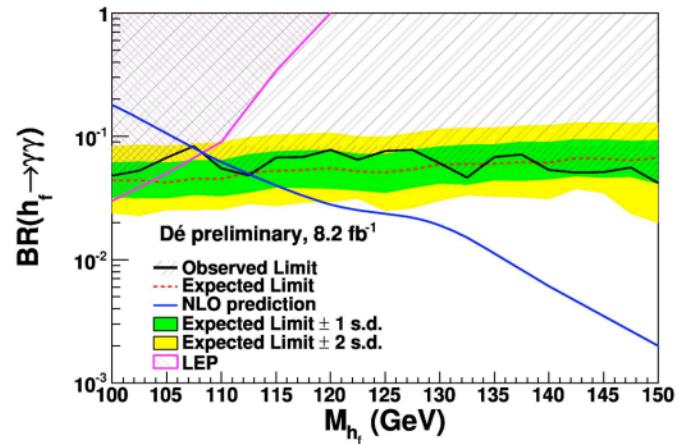


In the narrow width
approx. CDF result gives:
p-value: 0.23% (3σ)
and 2.5% including trial
factor (2.2σ)



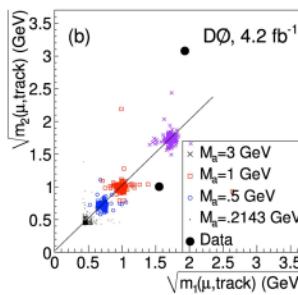
- Fermiophobic Higgs:
- No coupling to fermions
 - same W/Z couplings as in SM
 - production via WH / ZH

Excludes $m_{H_f} < 112\text{ GeV}/c^2$



[Phys. Rev. Lett. 103, 061801 \(2009\)](#)

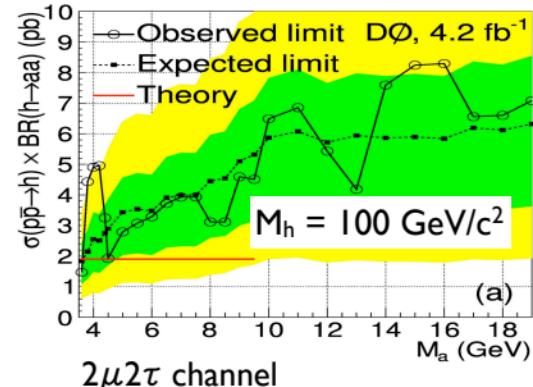
- NMSSM: $gg \rightarrow h \rightarrow aa, a \rightarrow \mu\mu$ or $\tau\tau$
 - If $m_a < 2m_\tau$: $h \rightarrow aa \rightarrow \mu\mu\mu\mu$
 - Two pairs of collinear muons
 - If $m_a > 2m_\tau$: $h \rightarrow aa \rightarrow \mu\mu\tau\tau$
 - Back-to-back μ and τ pairs



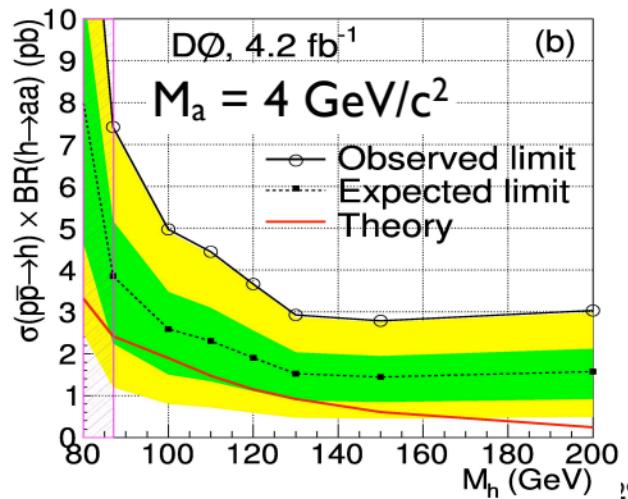
4 μ channel, limit:
 $\mathcal{B}(a \rightarrow \mu\mu) < 7\%$
 while theo ($M_a < 2m_c$):
 $\mathcal{B}(a \rightarrow \mu\mu) \sim 10\%$

M_a (GeV)	Window	Eff.	N_{bckg}	N_{obs}	$\sigma \times \text{BR}$ [exp] obs (fb)
0.2143	± 15	17%	0.001 ± 0.001	0	[10.0] 10.0
0.3	± 50	16%	0.006 ± 0.002	0	[9.5] 9.5
0.5	± 70	12%	0.012 ± 0.004	0	[7.3] 7.3
1	± 100	13%	0.022 ± 0.005	0	[6.1] 6.1
3	± 230	14%	0.005 ± 0.002	0	[5.6] 5.6

MSSM Higgs



2 $\mu 2\tau$ channel



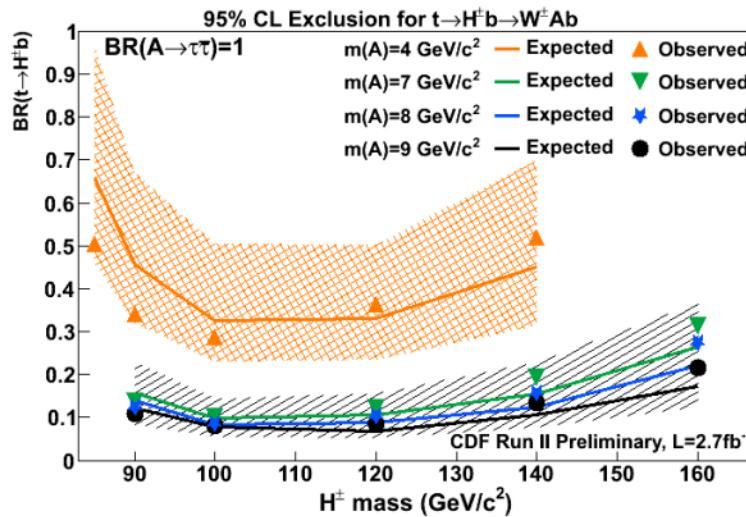
19

$$t \rightarrow H^\pm b \rightarrow W^\pm Ab \rightarrow W^\pm b\tau\bar{\tau}$$

If a charged higgs of around ~ 100 GeV exists, then the branching ratio of top to charged higgs may be as high as 10 to 40%

This search assumes the mass of the light psuedo-scalar higgs boson is less than twice the b-quark mass, a region not experimentally excluded

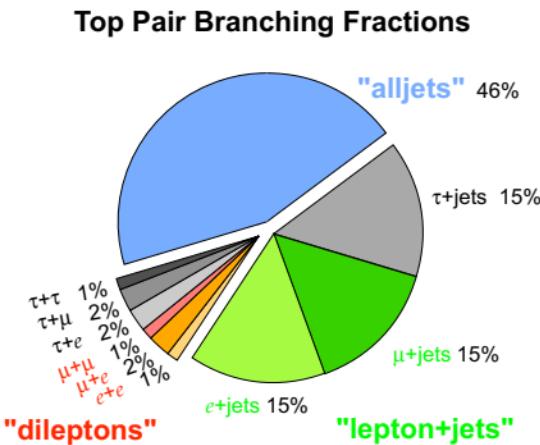
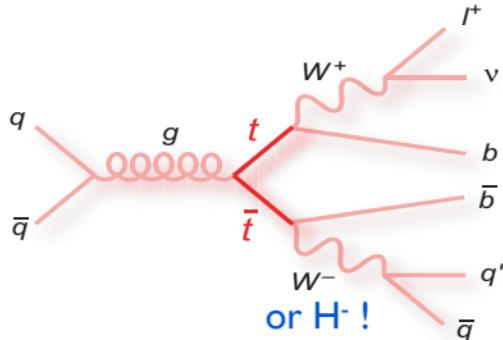
This is the first limits on this decay mode

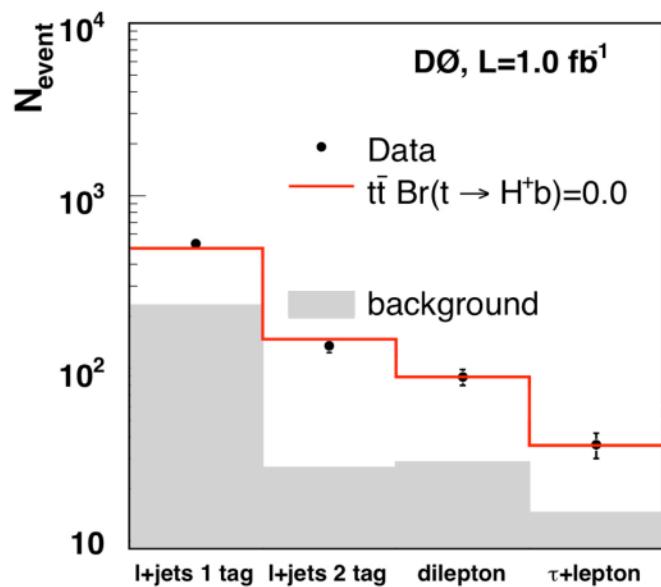
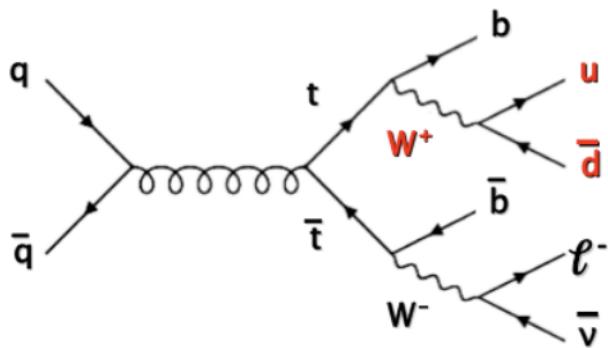


Expect for $M_a < 2m_b$:
 $\mathcal{B}(H^+ \rightarrow W^+ a_1) \sim 50\%$

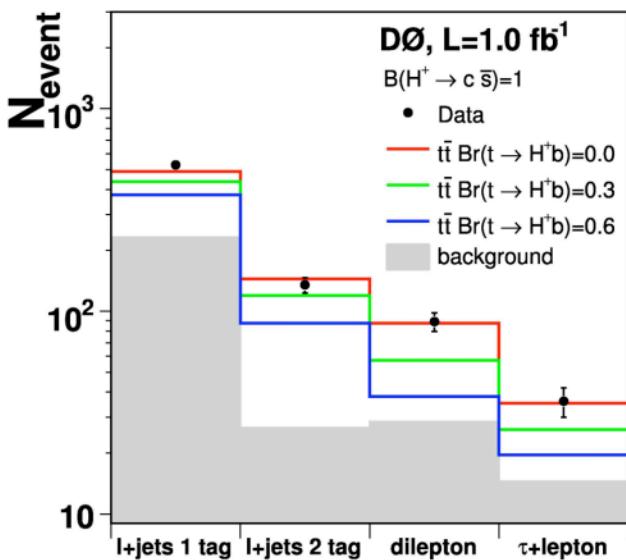
CDF preliminary

- If $m_{H^+} < m_{\text{top}}$:
 $t \rightarrow H^+ b$ opens
- H^+ decays are very different from W^+ decays:
 - ✓ high $\tan\beta$: $B(H^+ \rightarrow \tau^+ \nu) = 1$
 - ✓ leptophobic: $B(H^+ \rightarrow c \bar{s}) = 1$
- Changes the different channels contributions: compare all the measured cross sections

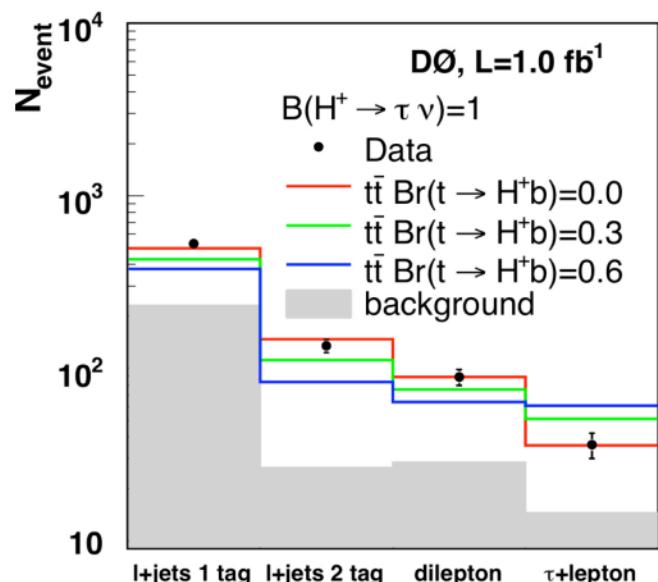


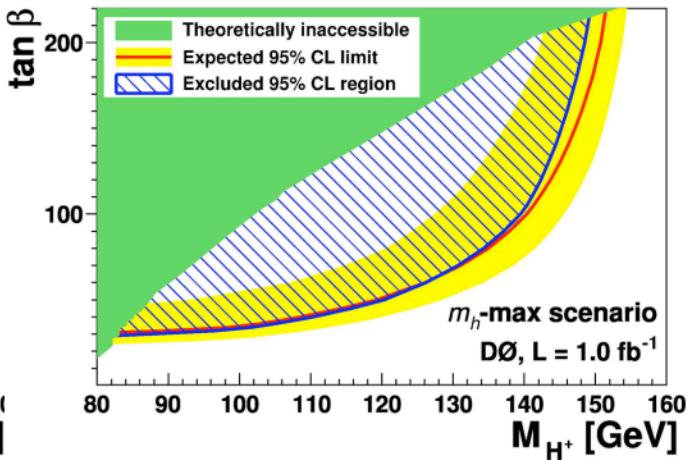
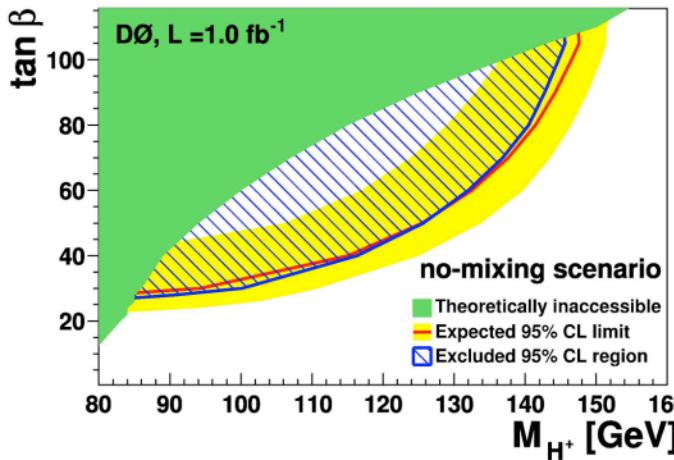


leptophobic Higgs



tauonic Higgs



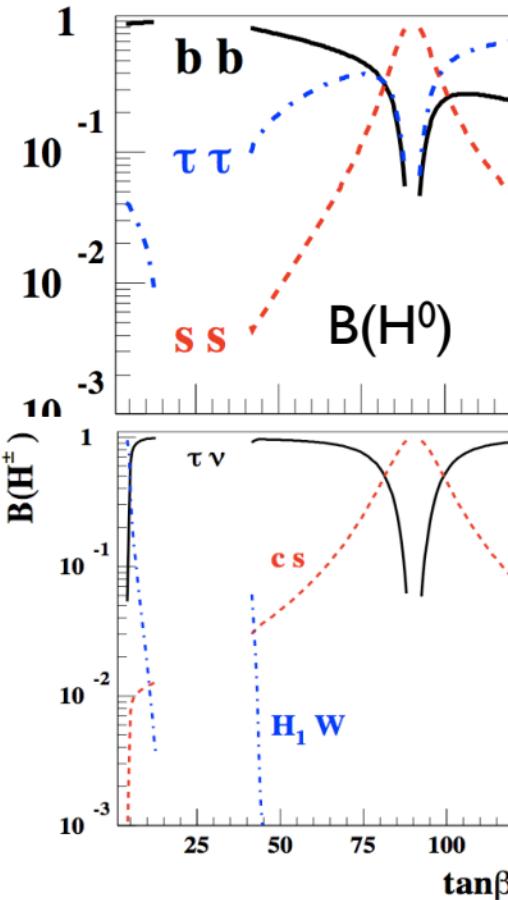


arXiv:0908.1811, submitted to PLB

method based only on cross section ratios:

arXiv:0903.5525, submitted to PLB

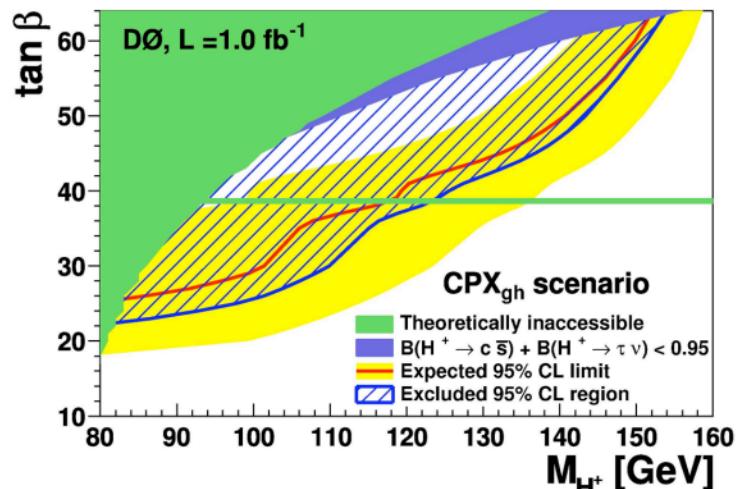
Another strategy:
The topological method
PRL 102, 191802 (2009)



CPX benchmark scenario:

- coupling to s-quark dramatically enhanced compare to b
- **strangephilic Higgs bosons**
- $B(H^\pm \rightarrow cs) \approx 1$

Lee, Peters, Pilaftsis, and C. Schwanenberger, arXiv:0909.1749



MSSM Higgs searches