BSM Higgs Boson Searches at the Tevatron Collider

Frank Filthaut
Radboud University Nijmegen / Nikhef
for the D0 and CDF Collaborations

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Contents

Contents

Many details omitted
- theory references (computations use FeynHiggs)
- detailed discussions of statistical treatment, systematics

MSSM Higgs Phenomenology: Tree Level

- Higgs bosons in the MSSM: "Type-II" Two-Higgs Doublet Model

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

  - 5 Higgs bosons: H, h, A (neutral), $H^\pm$ (charged)
  - dependence on 2 new parameters: M_A, $\tan\beta \equiv v_u/v_d$
  - Masses:

$$m_{h,H}^2 = \frac{1}{2}\left(m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4 m_Z^2 m_A^2 \sin^2(2\beta)}\right)$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

MSSM Higgs Phenomenology: Tree Level

- Higgs bosons in the MSSM: “Type-II” Two-Higgs Doublet Model

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

  - 5 Higgs bosons: H, h, A (neutral), $H^\pm$ (charged)
  - dependence on 2 new parameters: M_A, $\tan\beta \equiv v_u/v_d$
  - Masses:
    - $m_h < m_Z$ (!)
  - Couplings:
    - neutral:

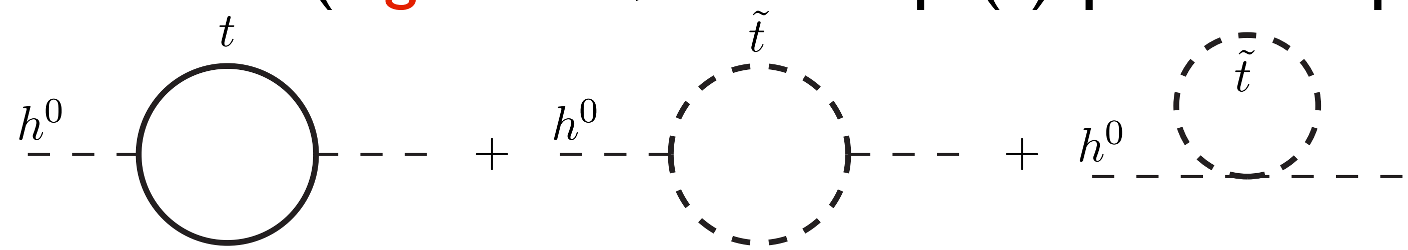
SM particle type	h coupling	H coupling	A coupling
up-type quarks	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$
down-type quarks, $\ell^\pm$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\tan\beta$
W, Z bosons	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0

$H^\pm tb$ coupling $\sim V_{tb} m_t \cot\beta(1-\gamma_5) + m_b \tan\beta(1+\gamma_5)$

α: CP-even Higgs mixing parameter

Beyond Tree Level

- Substantial corrections (e.g. to m_h, from top (s)quark loops)

$\Delta(m^2_{h^0}) =$ 

  - mass/coupling dependence on other SUSY parameters

- Embodied in several scenarios (allowing to evade LEP bounds)

Scenario	m_h^{max}	no-mixing	gluophobic	small α_{eff}
$\tilde{t}_1$, $\tilde{t}_2$ mixing parameter X_t	2 TeV	0	-0.75 TeV	-1.1 TeV
Higgs bilinear coupling μ	$\pm$200 GeV	$\pm$200 GeV	$\pm$300 GeV	2 TeV
SU(2) gaugino mass M_2	200 GeV	200 GeV	300 GeV	500 GeV
gaugino mass $m_{\tilde{g}}$	0.8 TeV	1.6 TeV	0.5 TeV	0.5 TeV
sfermion SUSY breaking parm. M_{SUSY}	1 TeV	2 TeV	0.35 TeV	0.8 TeV

tuned to maximize m_h

between top squarks

suppressed $gg \to h$

suppressed $h \to bb, \tau\tau$

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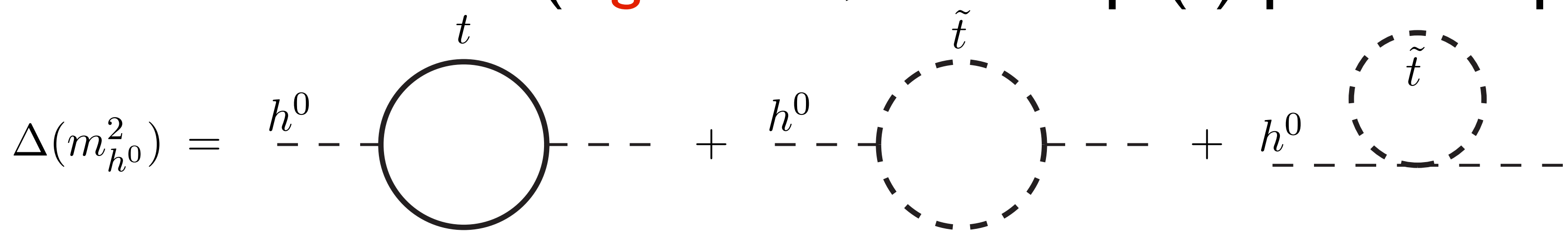

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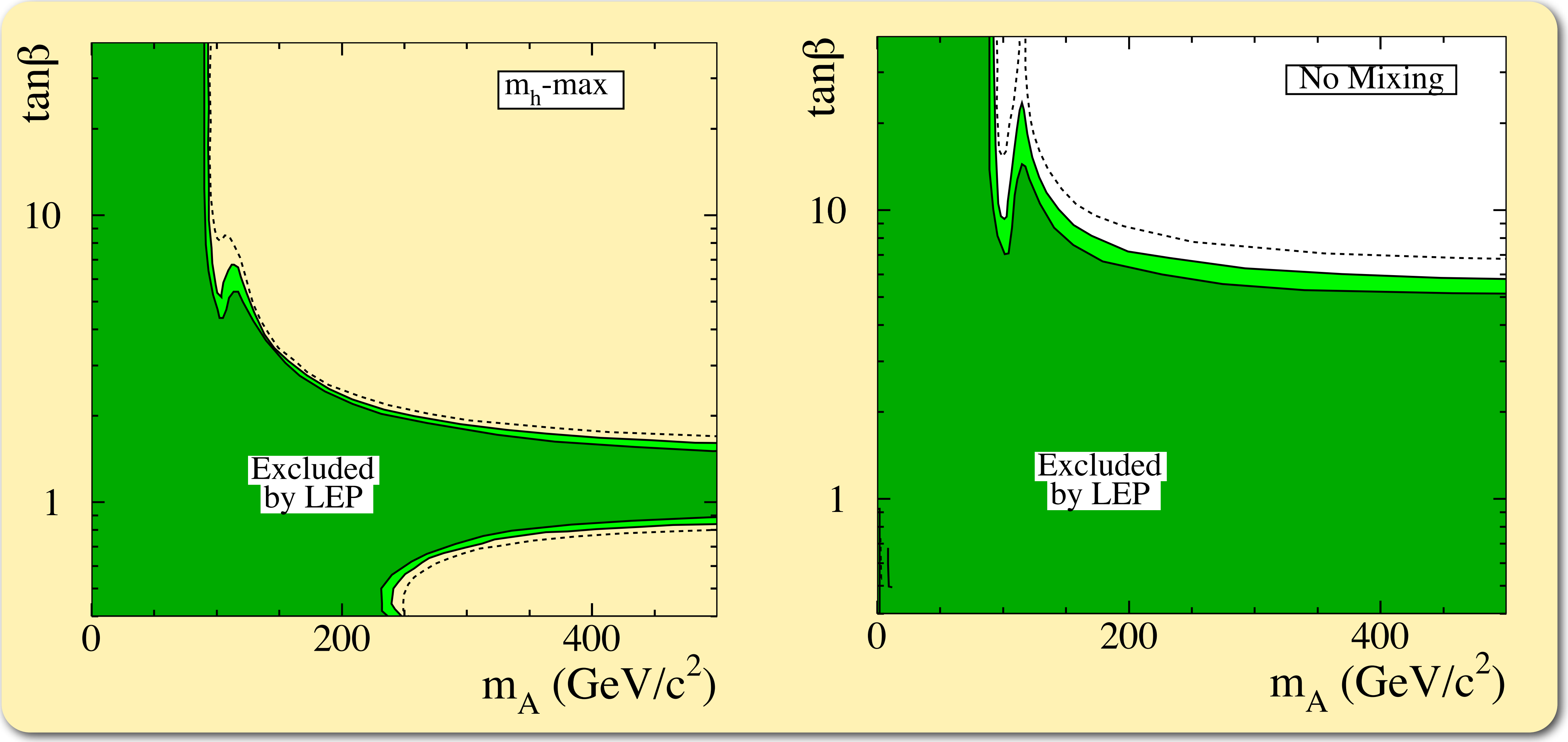
Main focus of Tevatron analyses

MSSM Higgs Production at the Tevatron

- LEP analyses focused on ZH associated production
  - ➠ exclusion mainly at low tanβ



MSSM Higgs Production at the Tevatron

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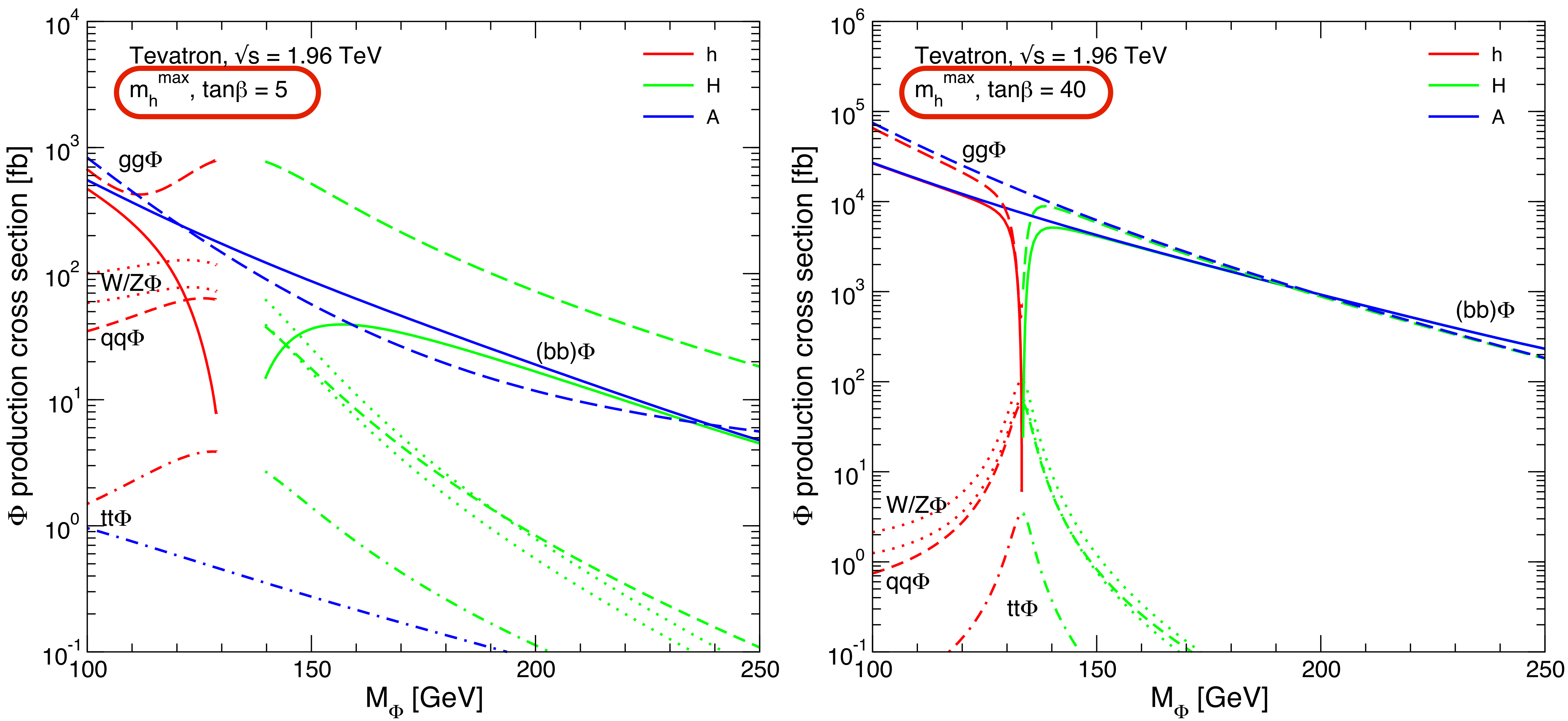
- Most of the Tevatron programme focuses on high tanβ
  - ➠ complementarity: different production mechanisms



(Tev4LHC WG)

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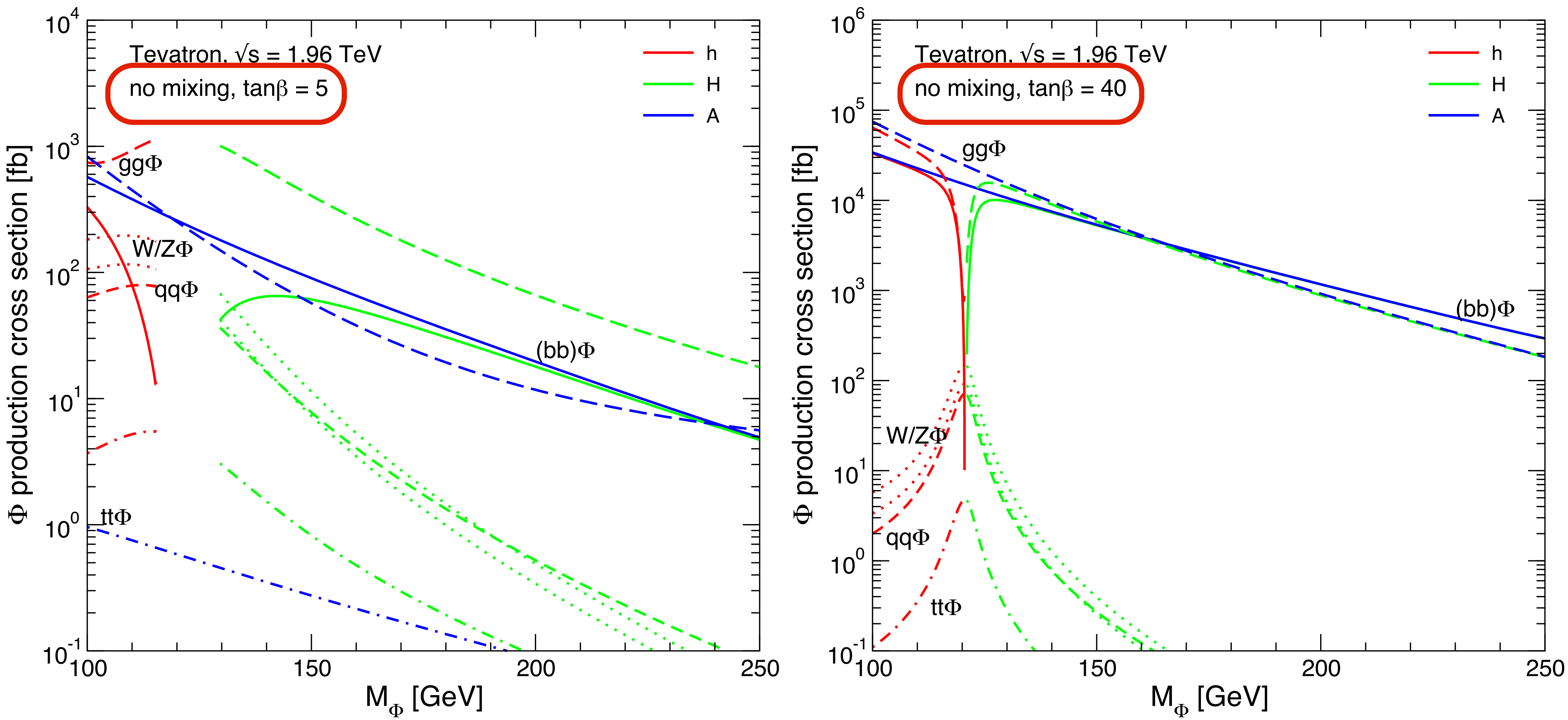

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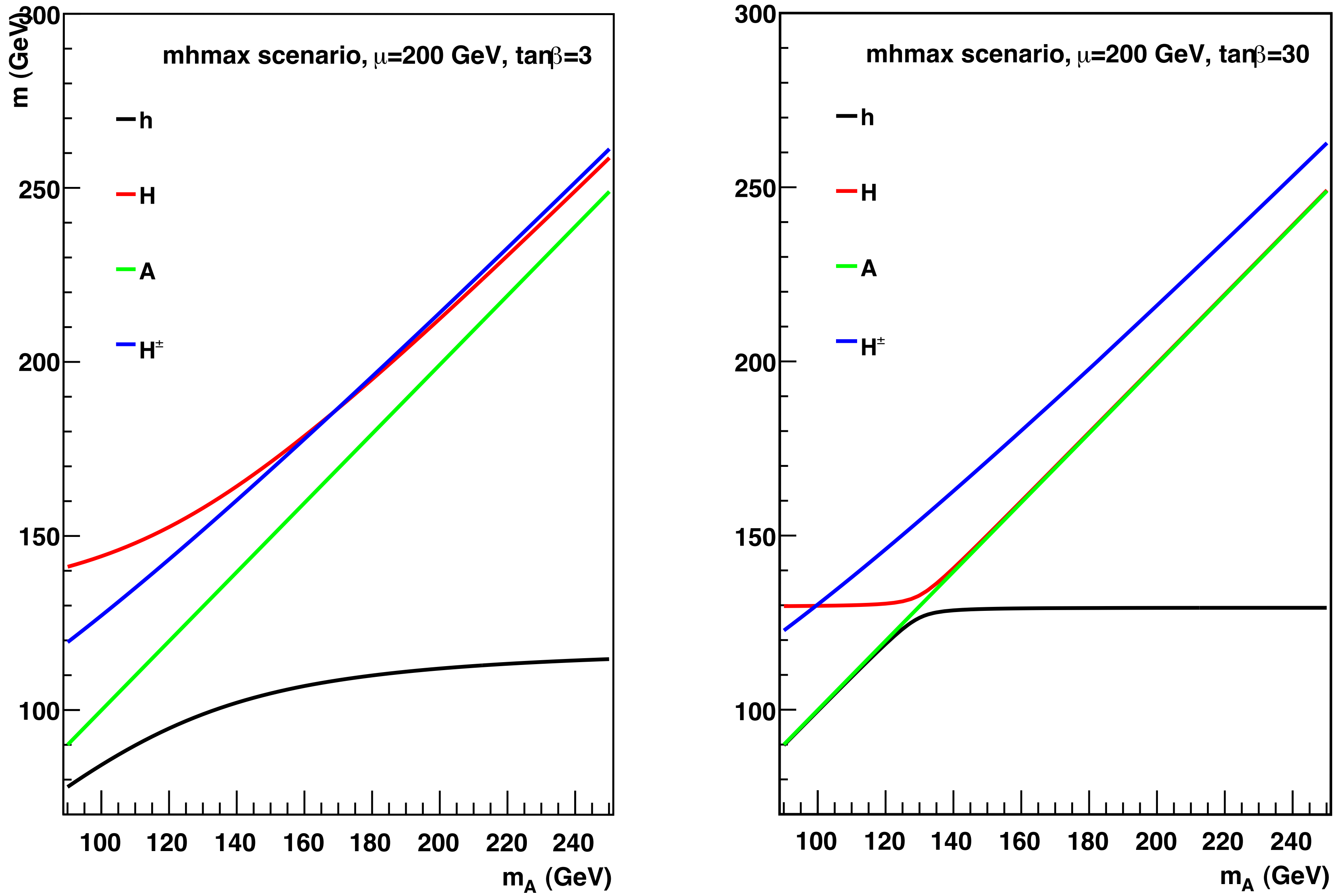

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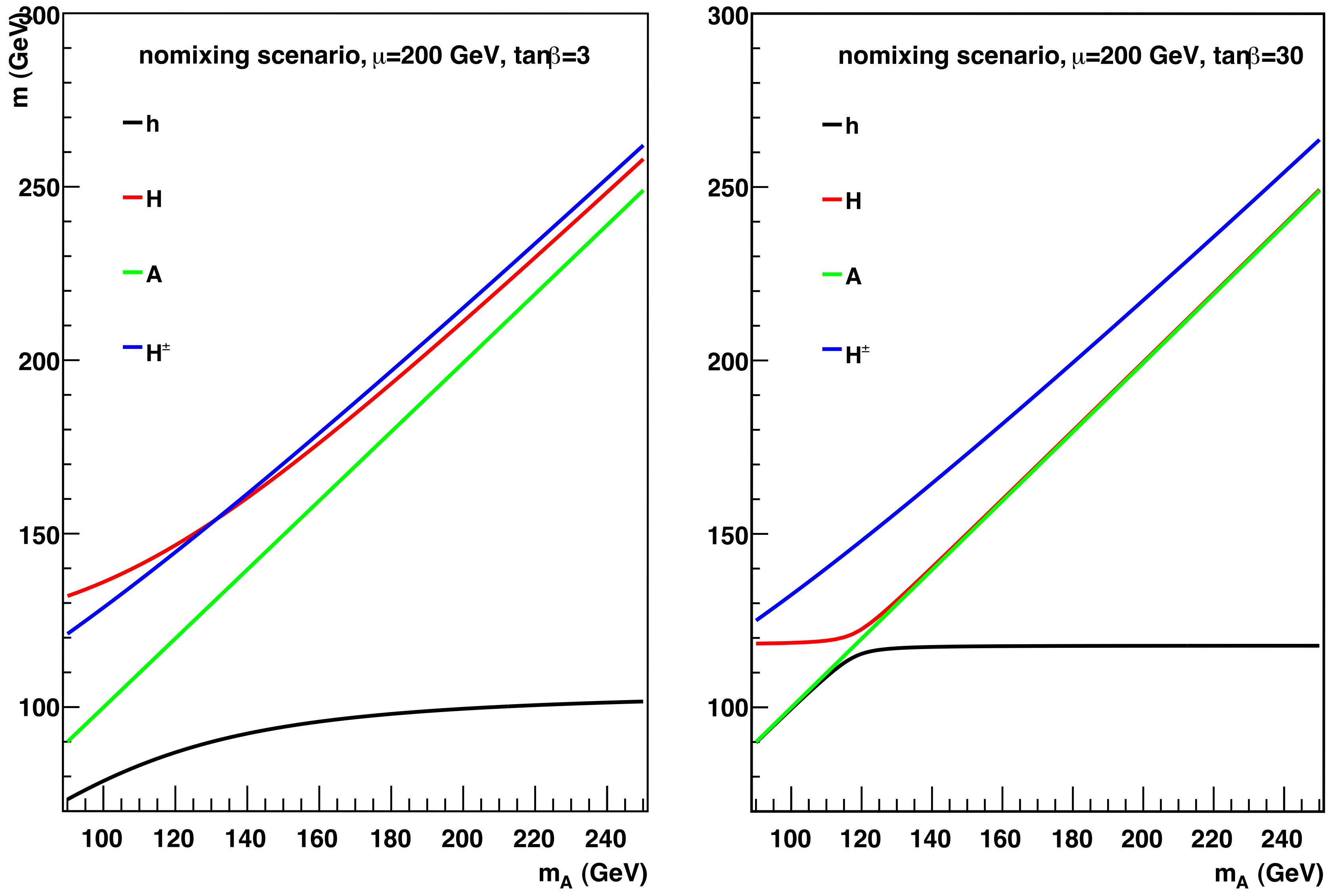

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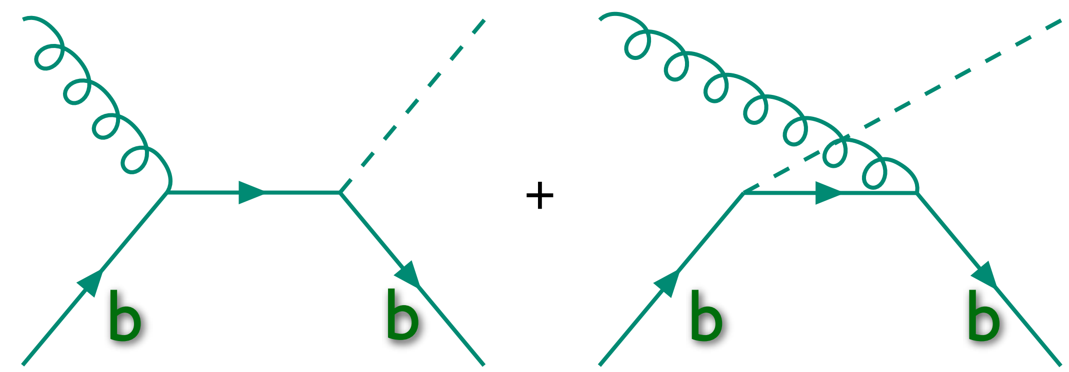
- General feature:
  - masses, production cross sections for A, h/H very similar ➠ "Φ"
  - production of "other CP-even boson (H/h) ~ negligible

Analyses don't attempt to identify individual Higgs bosons, but look for an overall excess instead

bΦ → bbb

update from 1.9 fb^{-1}

- Largest branching fraction (~90%) ... but need extra b jet to be visible
  - triple b-tagged data, look for excess in invariant mass spectrum of leading b-tagged jets
  - emphasis on understanding multijet background



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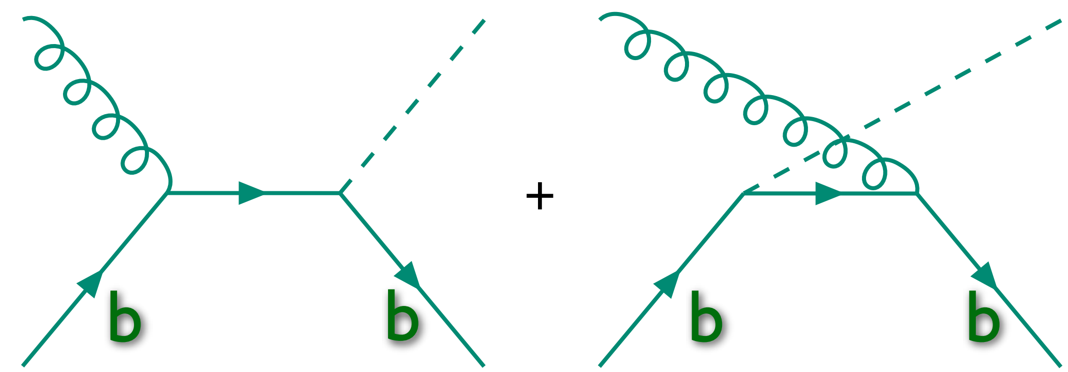
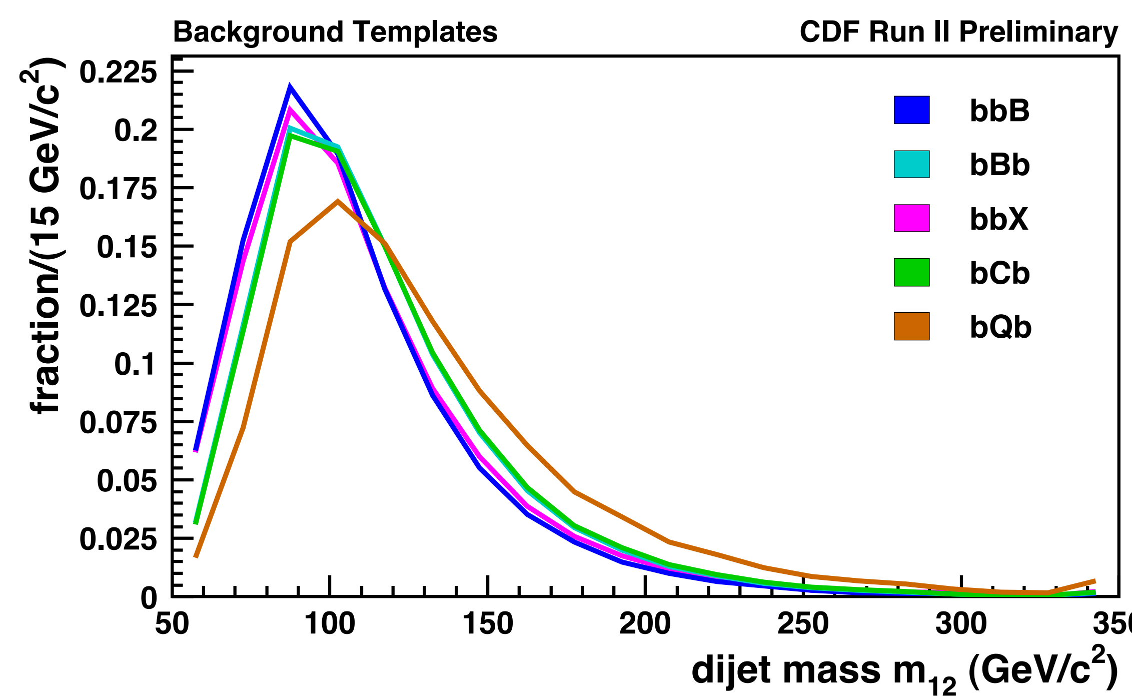
  - template fit including also signal
    - in absence of significant excess, use likelihood ratio to derive limits





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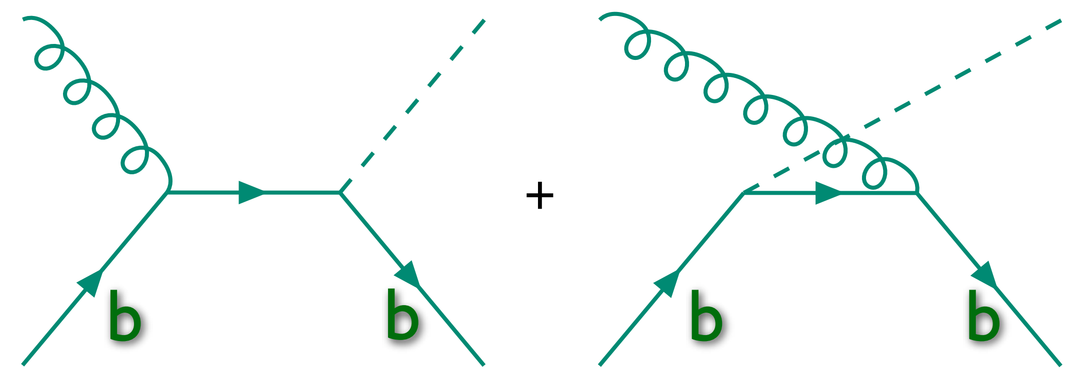

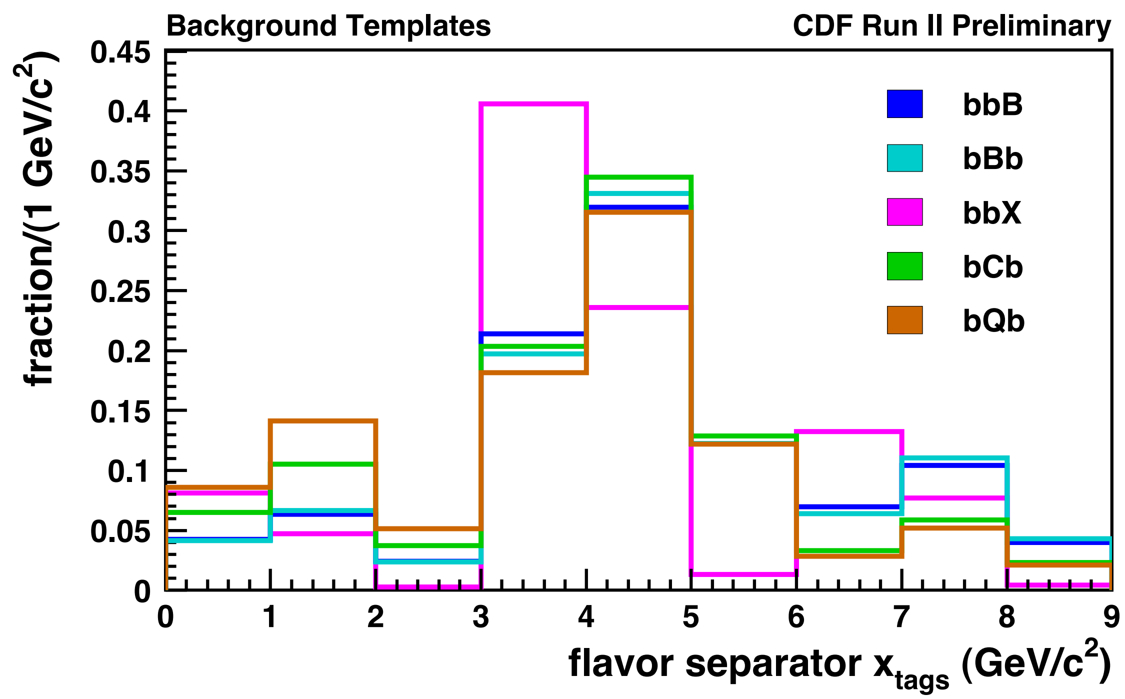

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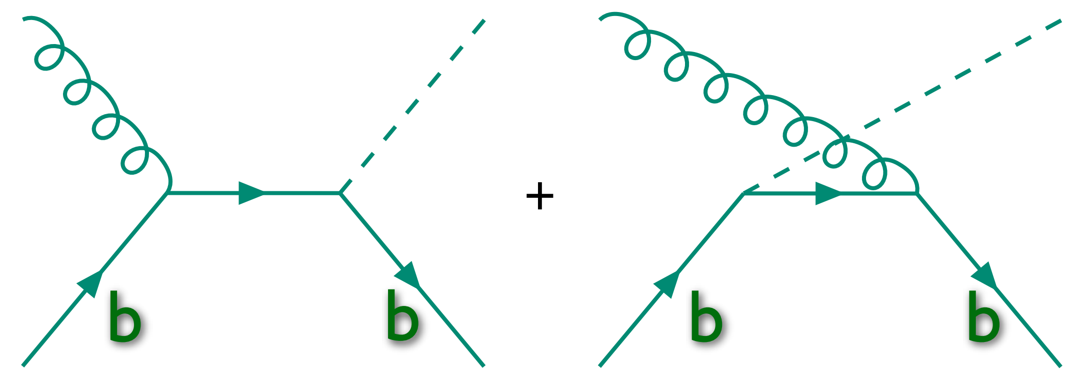

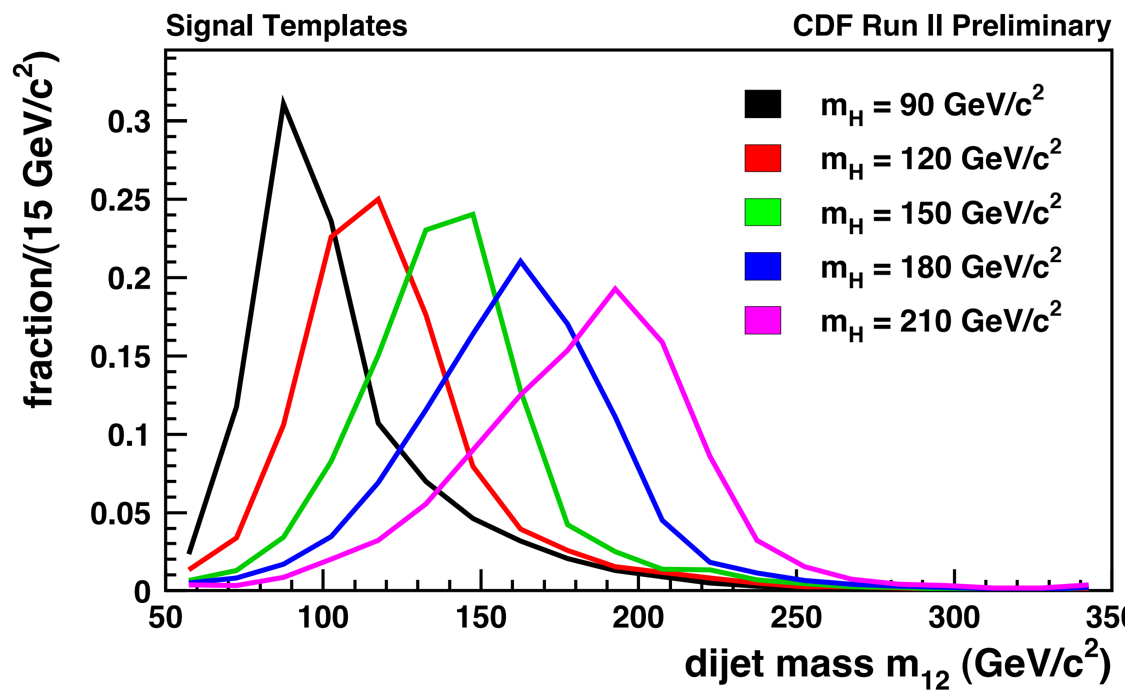

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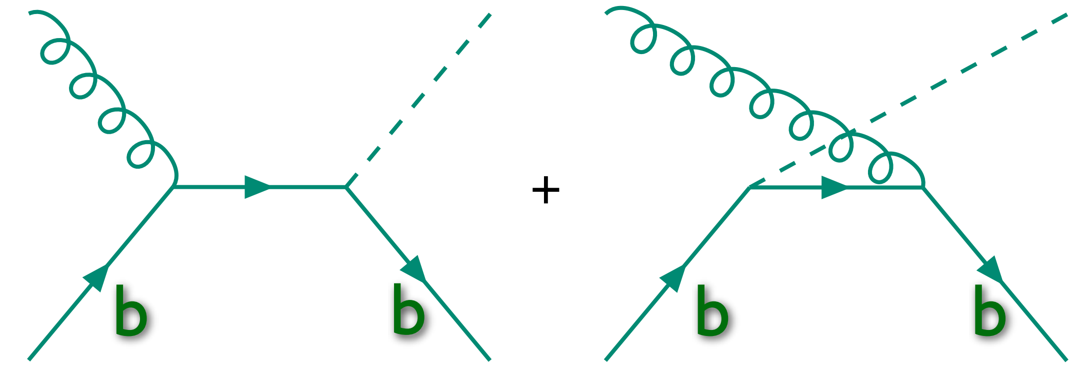

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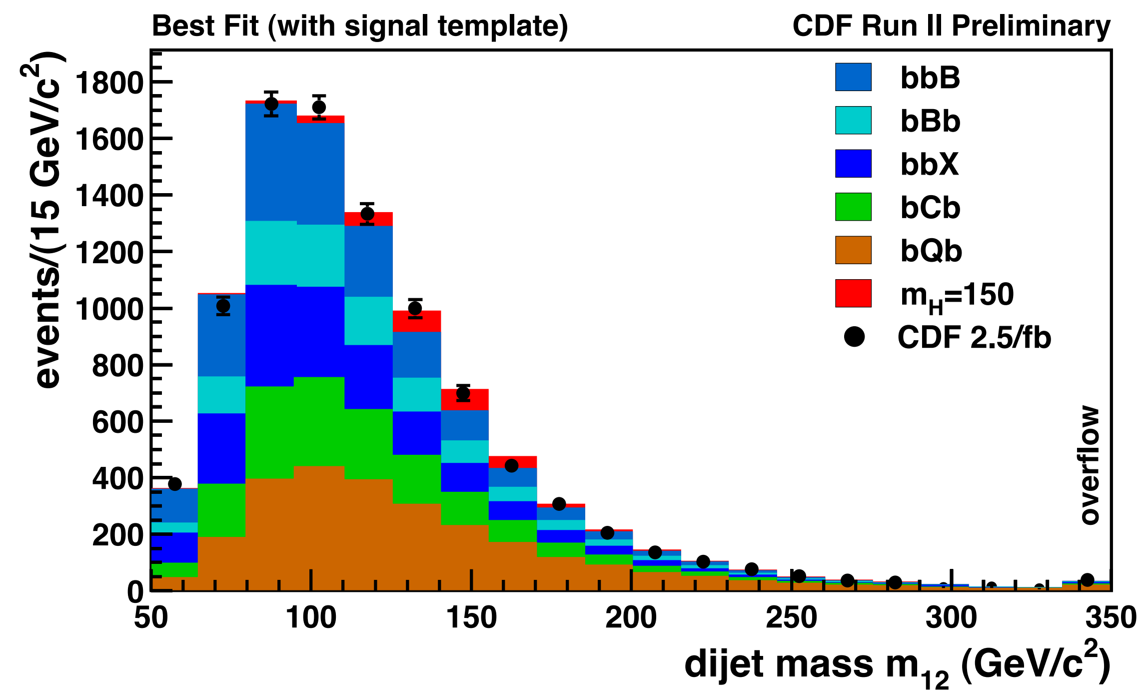
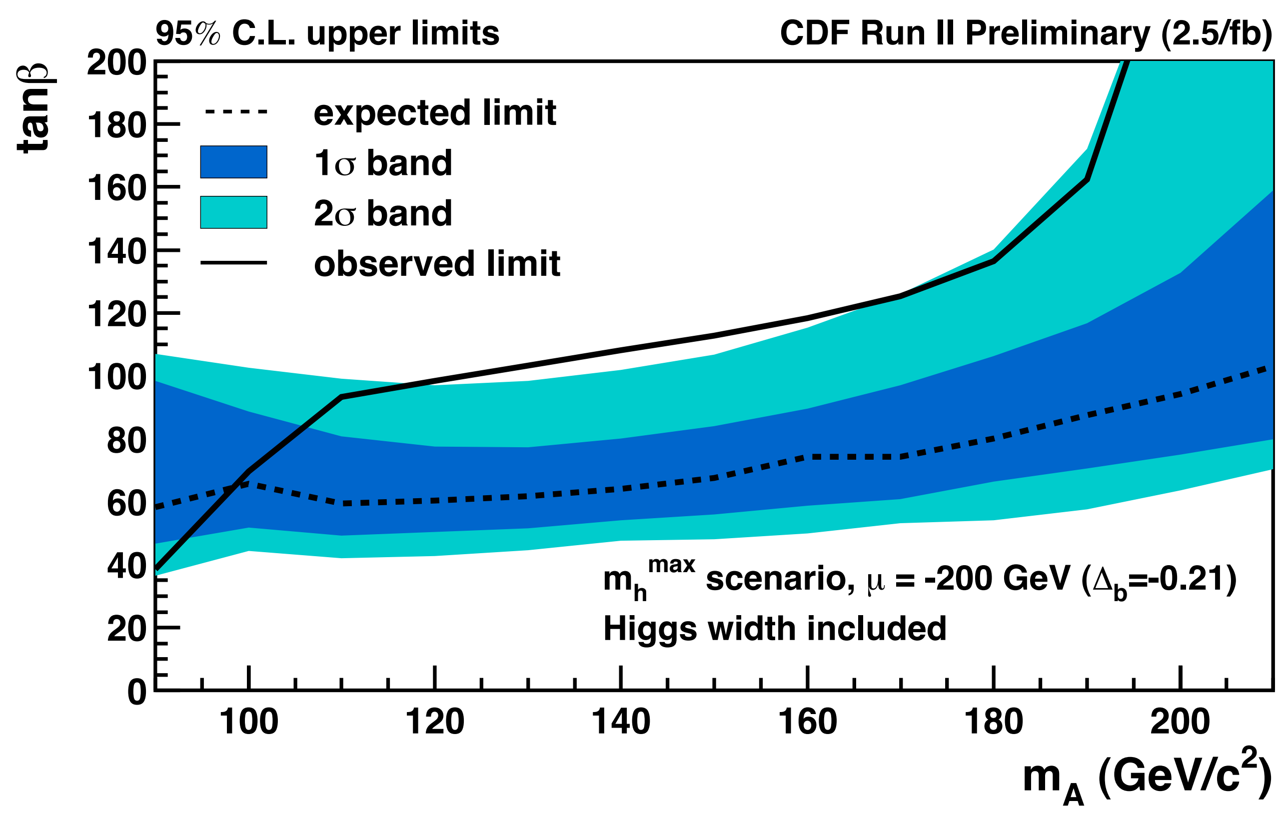


$$Q \equiv \frac{\mathcal{L}(\text{data}|s+\hat{b})}{\mathcal{L}(\text{data}|\hat{\hat{b}})}$$

bΦ → bbb (2)

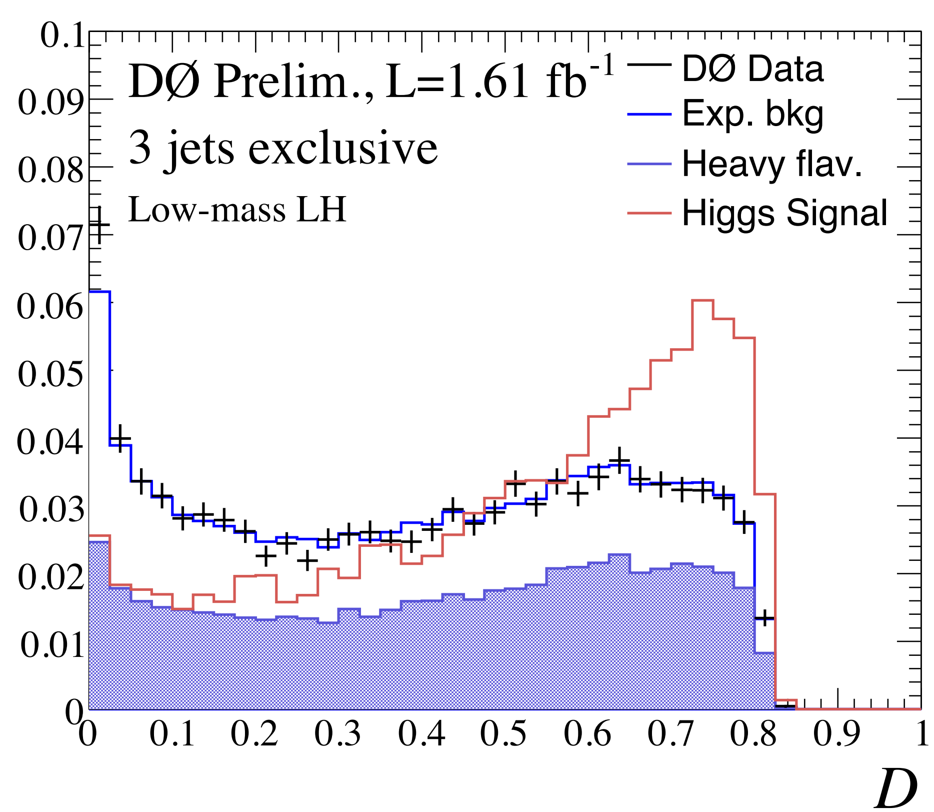
- For high tanβ, the decay widths Γ_Φ become substantial
  - resonance less easily distinguished ➟ loss of sensitivity

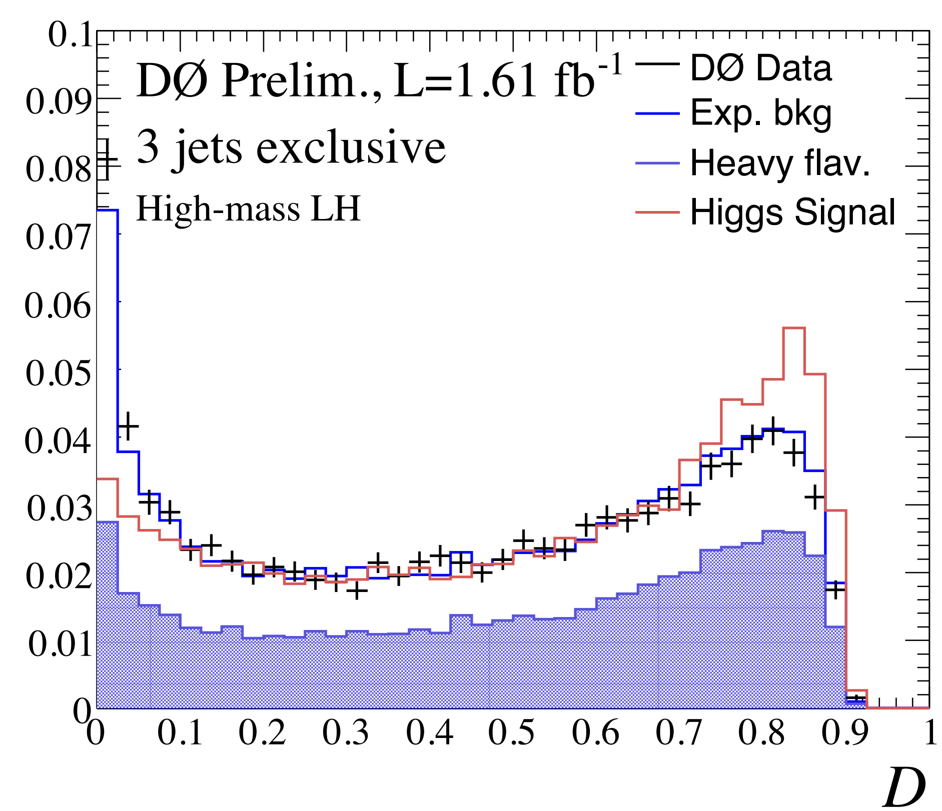


$\Delta_b \propto \tan\beta \cdot \mu$

bΦ → bbb (3)

- D0 analysis (2.6 fb^{-1}):
  - separation into 3/4/5-jet samples
  - flavour composition estimated using multiple b-tagging criteria
  - likelihood discriminant to improve S/B ratio $\mathcal{D} = \frac{P_{\text{sig}}(\vec{x})}{P_{\text{sig}}(\vec{x}) + P_{\text{bkg}}(\vec{x})}$
    - using topological information
    - obtain from double-tagged data, use to predict triple-tagged bkgd





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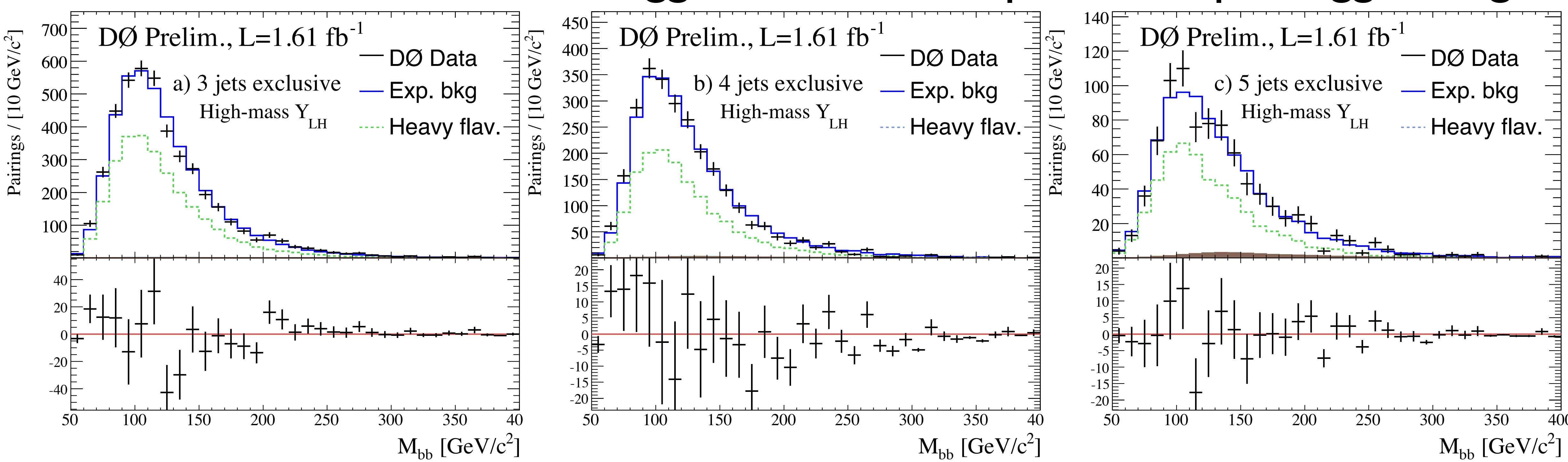

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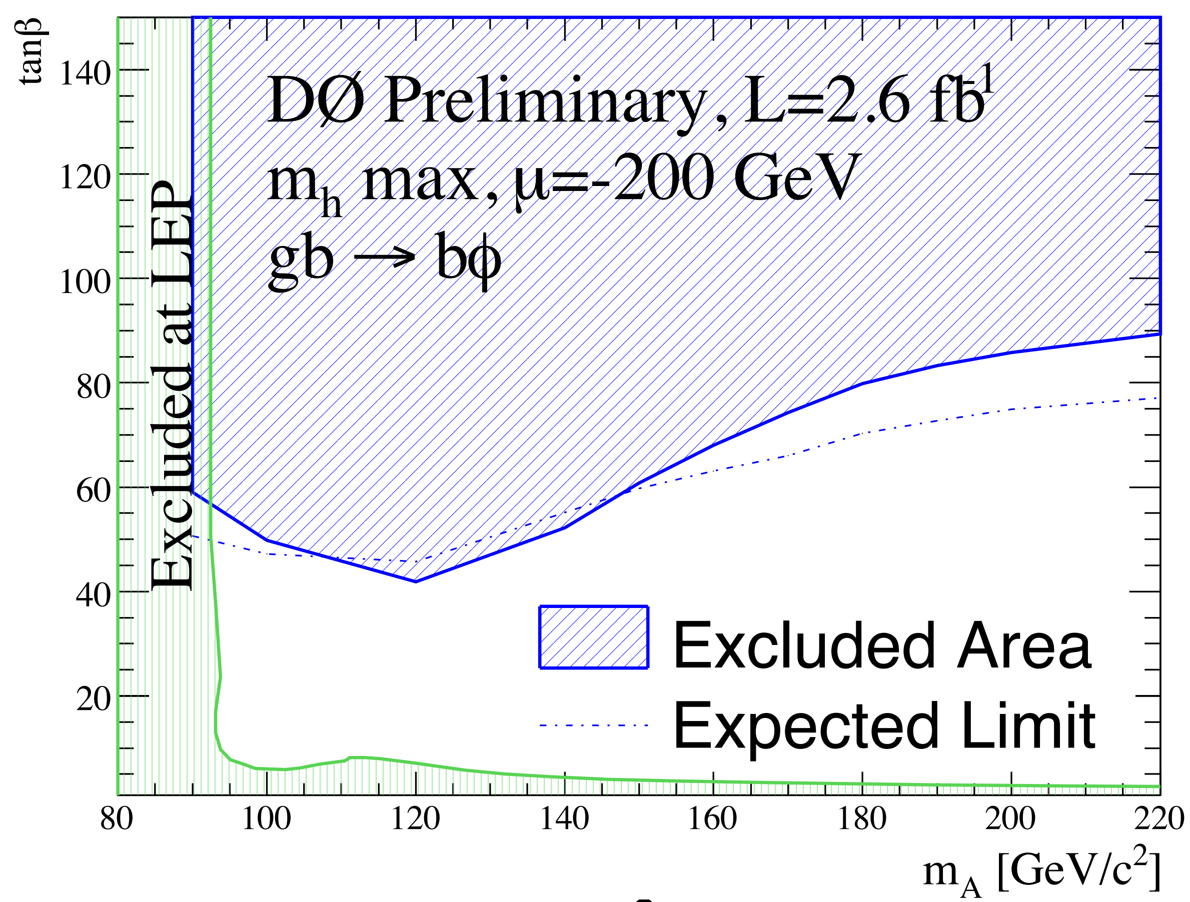
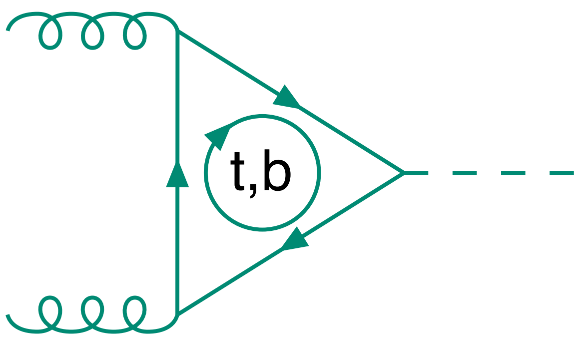
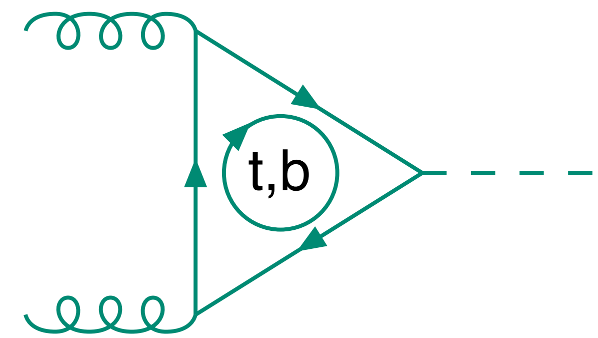


$\Phi \rightarrow \tau^+\tau^-$



- Branching fraction only ~ 0.1, but much cleaner!
  ➠ can use this decay mode with gluon fusion channel
- but need ≥ 1 leptonic decay: $\tau_\mu\tau_{had}$, $\tau_e\tau_{had}$, $\tau_e\tau_\mu$
- τ decays ➠ no sharp mass peak
- substantial backgrounds: $Z \rightarrow \tau^+\tau^-$, W+jets, multijets

$\phi \to \tau^+\tau^-$



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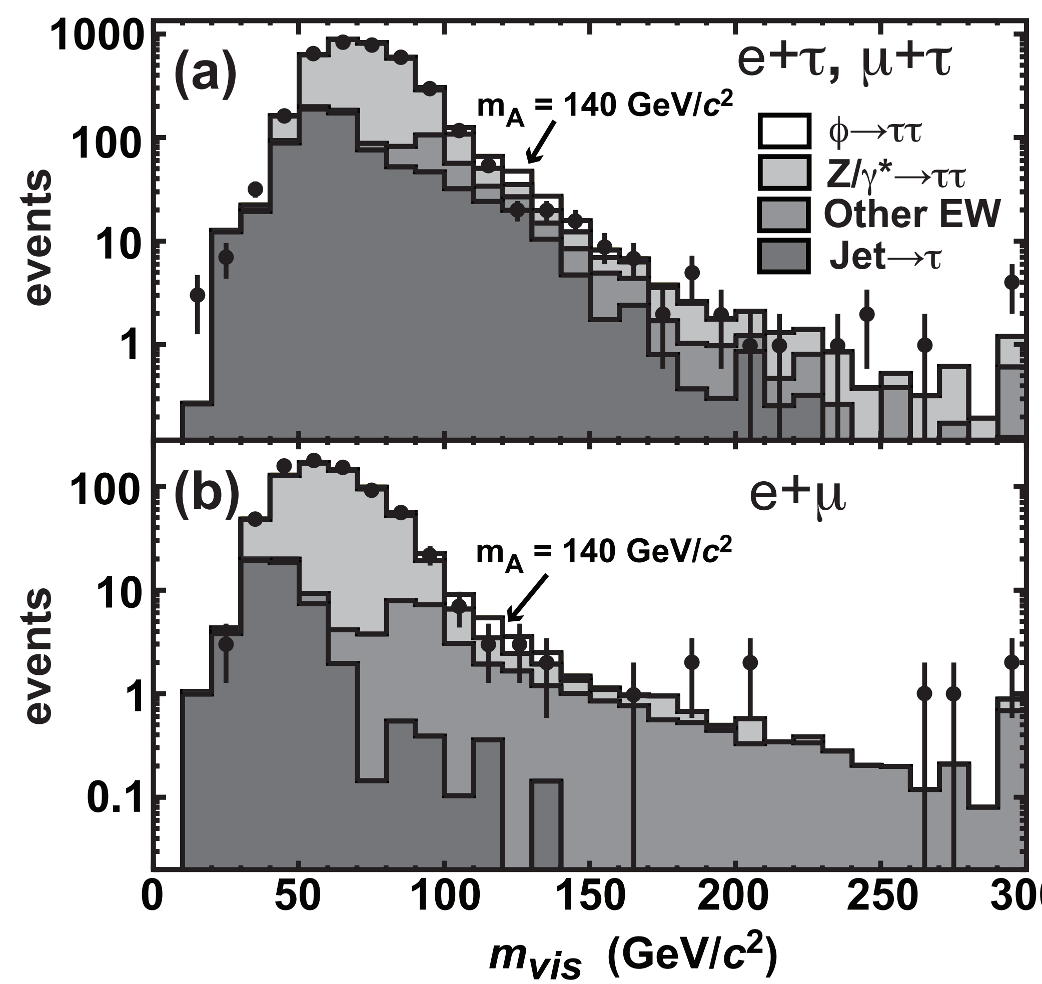
- CDF published analysis (1.8 fb^{-1}):
  - using "visible mass"

$$m^2_{vis} = (p_{\tau_1} + p_{\tau_2} + \not{p}_T)^2$$
$$\not{p}_T \equiv (\not{E}_T, \not{E}_x, \not{E}_y, 0)$$

  - $Z \to \tau^+\tau^-$ from MC: energy scale
  - instrumental backgrounds: from initial looser τ_{had} selection, known fake rate



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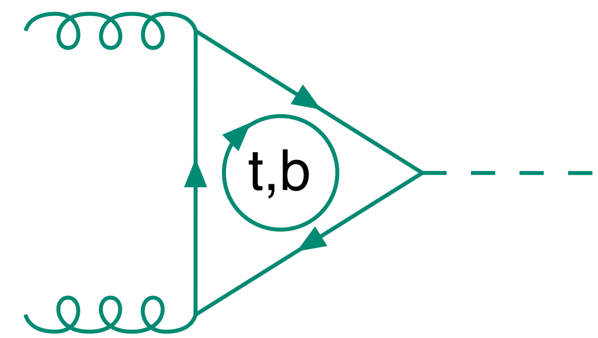

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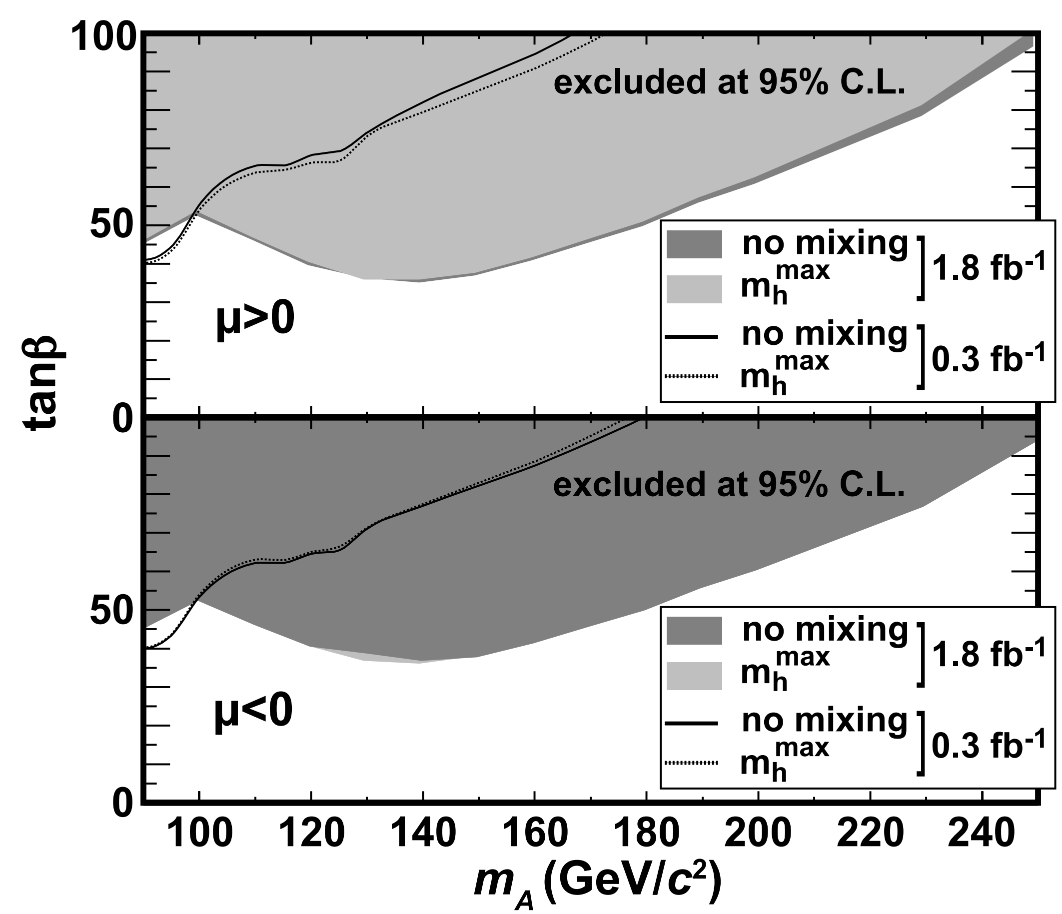
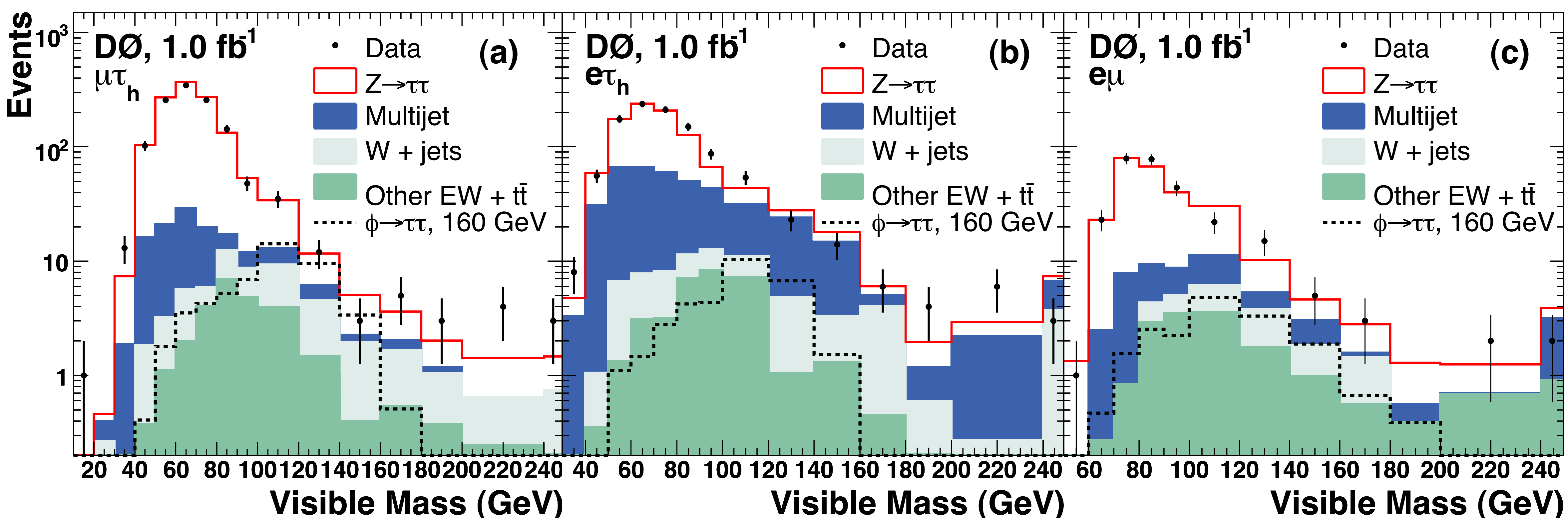


small model dependence!

$\phi \to \tau^+\tau^-$ (2)

- D0: extended published analysis (1 fb^{-1}) by 1.2 fb^{-1} ($\tau_\mu\tau_{had}$)
- Analysis similar to CDF ($Z \to \tau^+\tau^-$, instrumental backgrounds)
  - optimised (NN) identification of $\tau \to \pi\nu_\tau$, $\tau \to \rho\nu_\tau$, 3-prong decays
  - additional rejection against W ($\to$ e/μ ν) + jets background (M_T)



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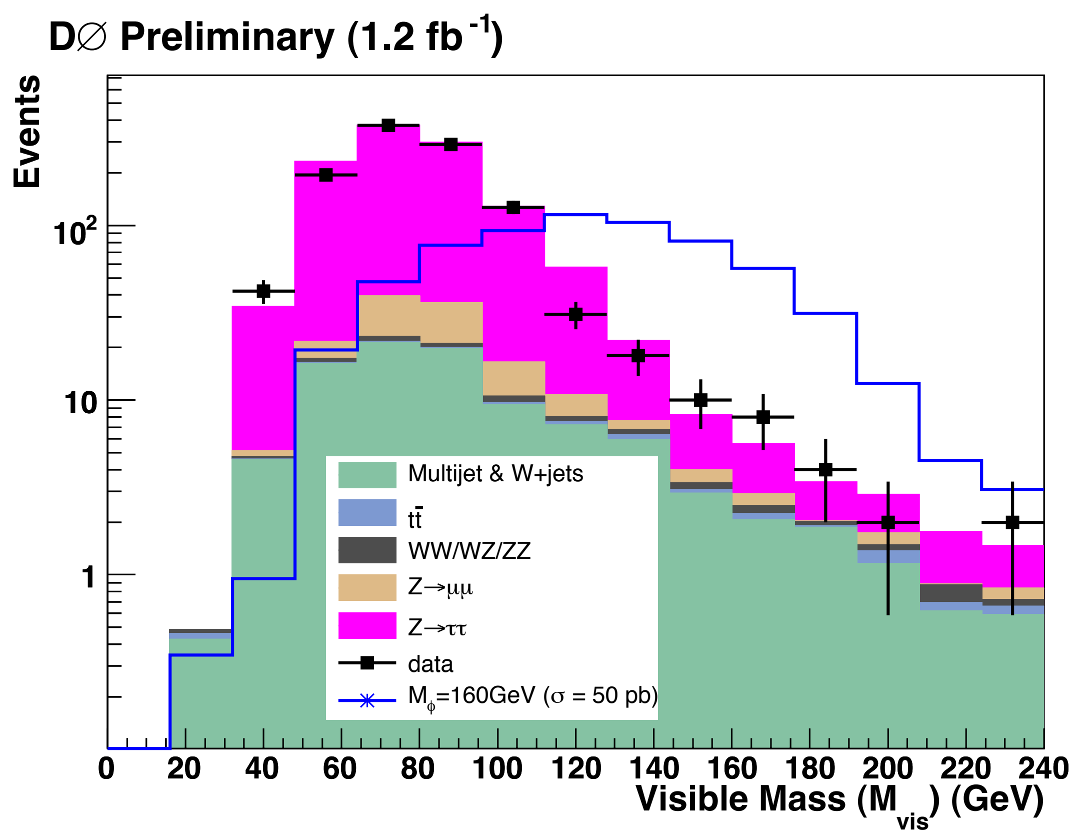

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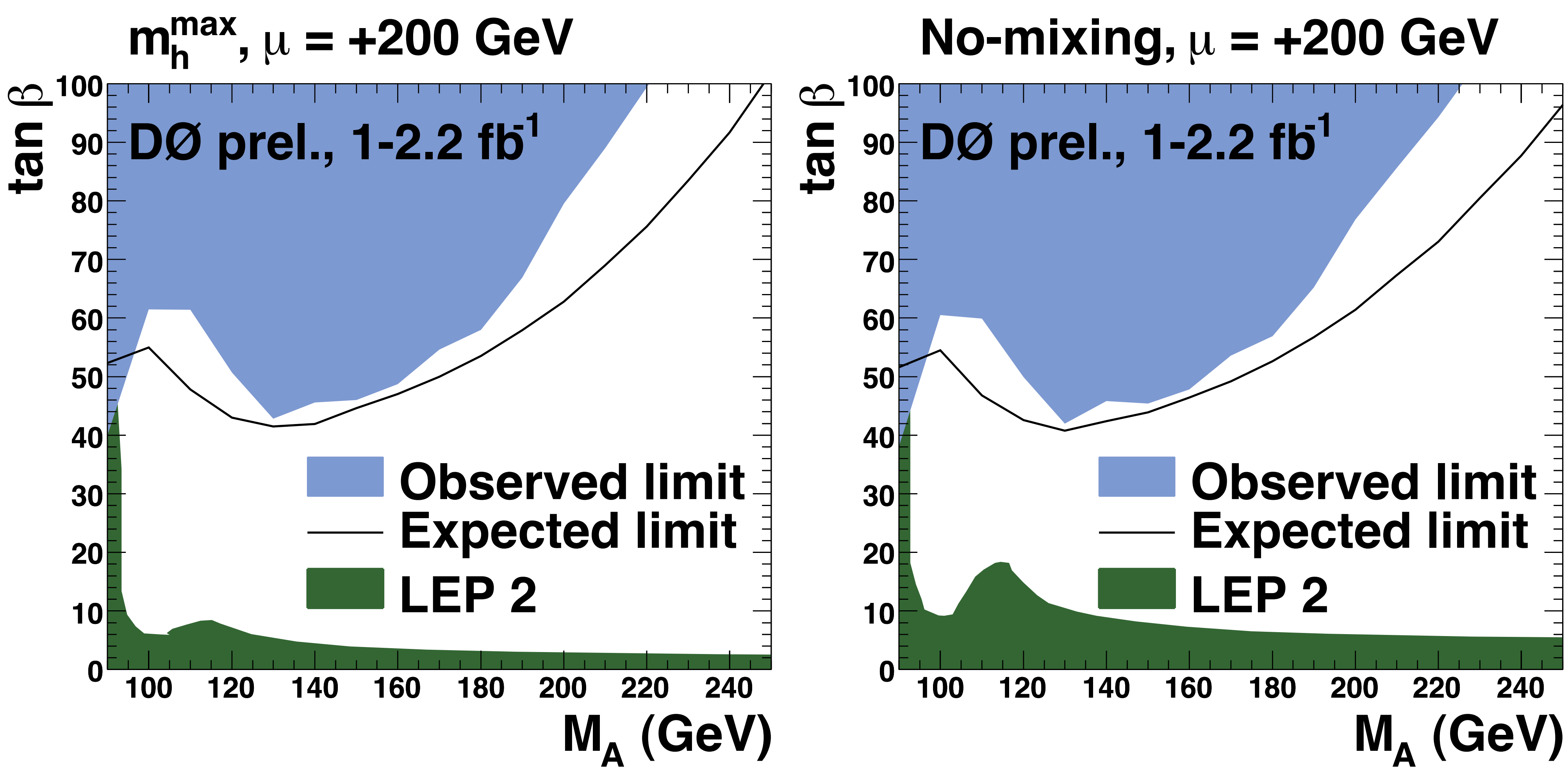
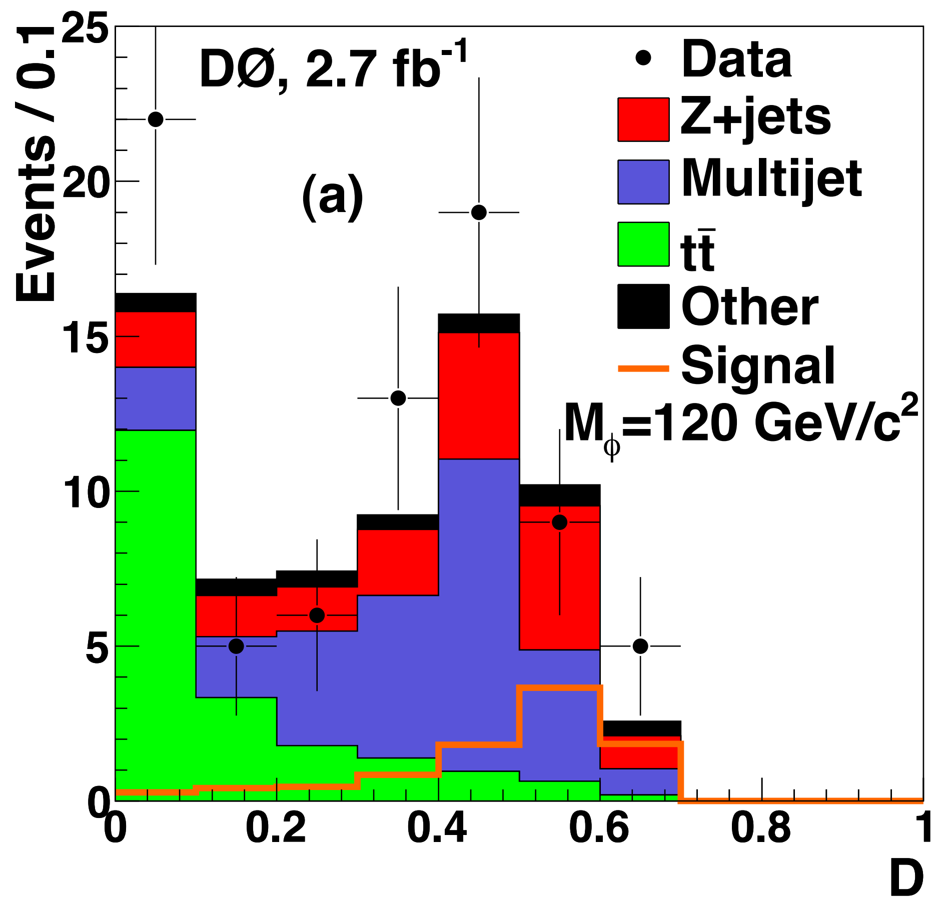


Limits generally (slightly) more restrictive than for bbb final state

$b\Phi \rightarrow b\tau^+\tau^-$

published

- Small overlap with inclusive $\tau^+\tau^-$ search, reduced $Z \rightarrow \tau^+\tau^-$ background at low m_Φ ➠ complementarity
- D0 published analysis (2.7 fb^{-1}, $\tau_\mu\tau_{had}$):
  - dominant backgrounds: tt, multijet, Z+jets
  - estimate multijet background from same-sign events
  - enrich further using two (tt, multijet) multivariate discriminants



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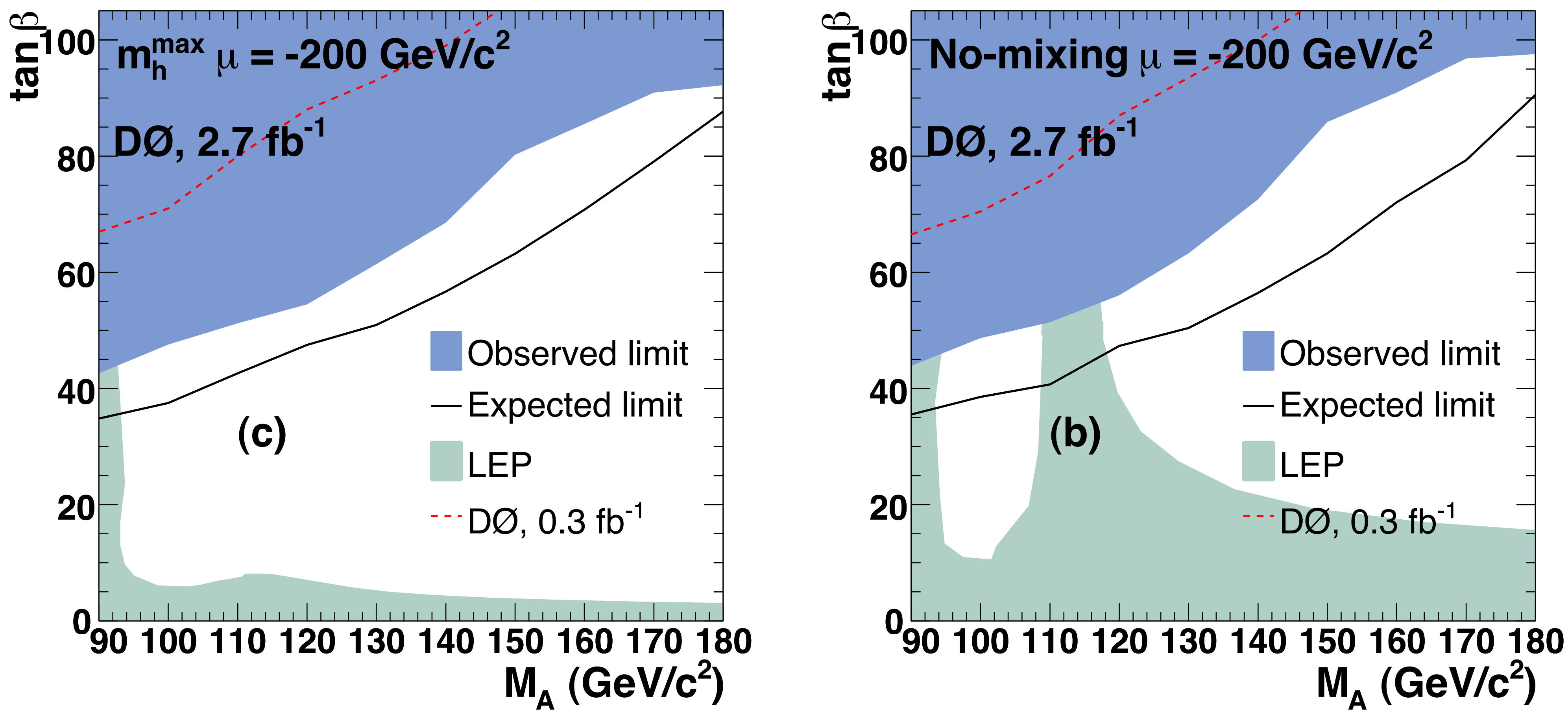

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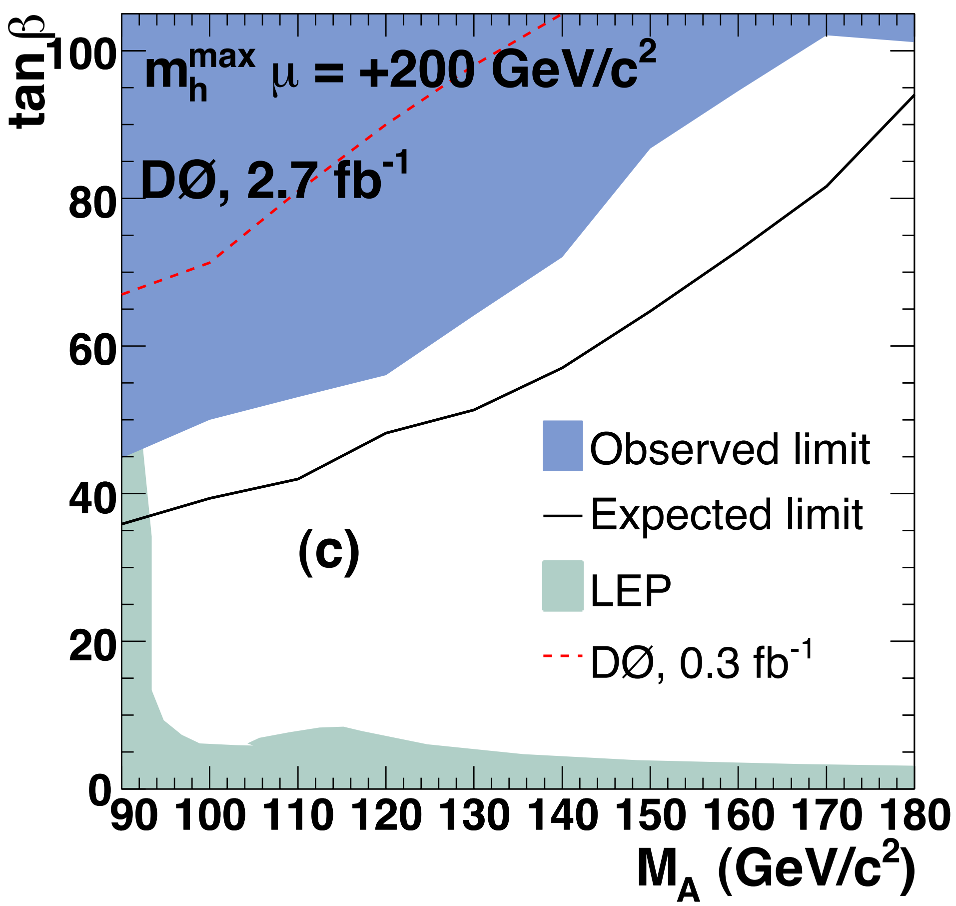
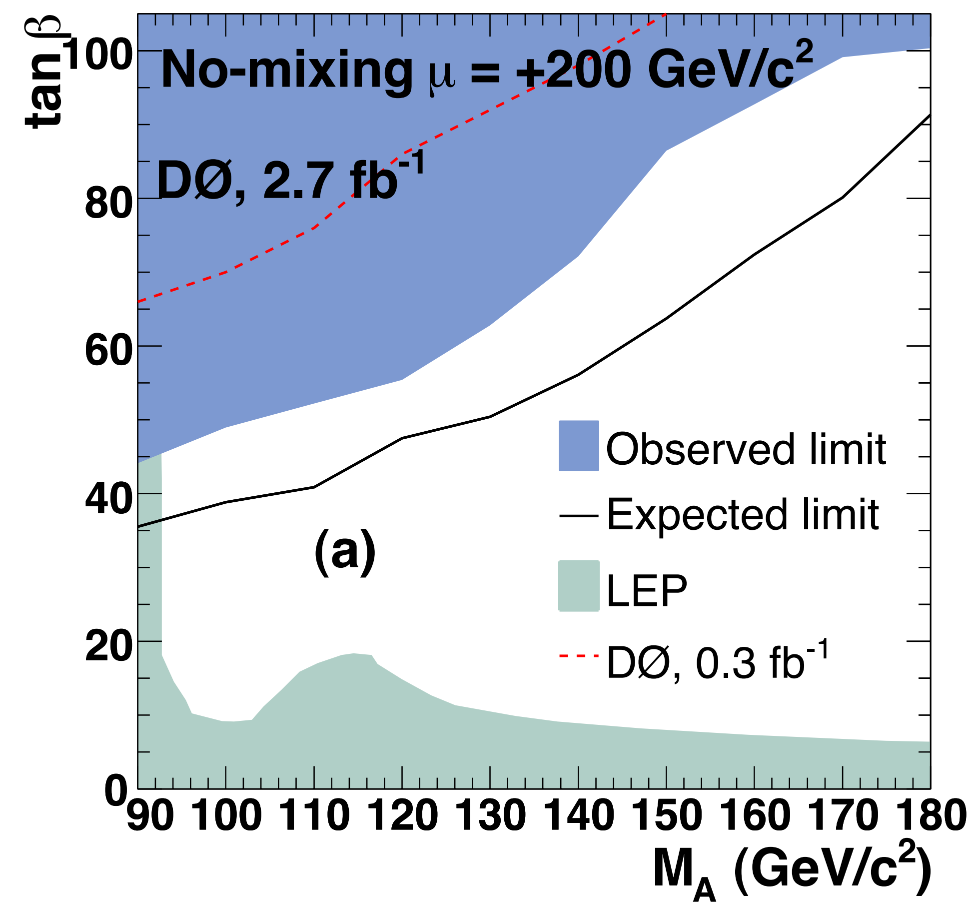
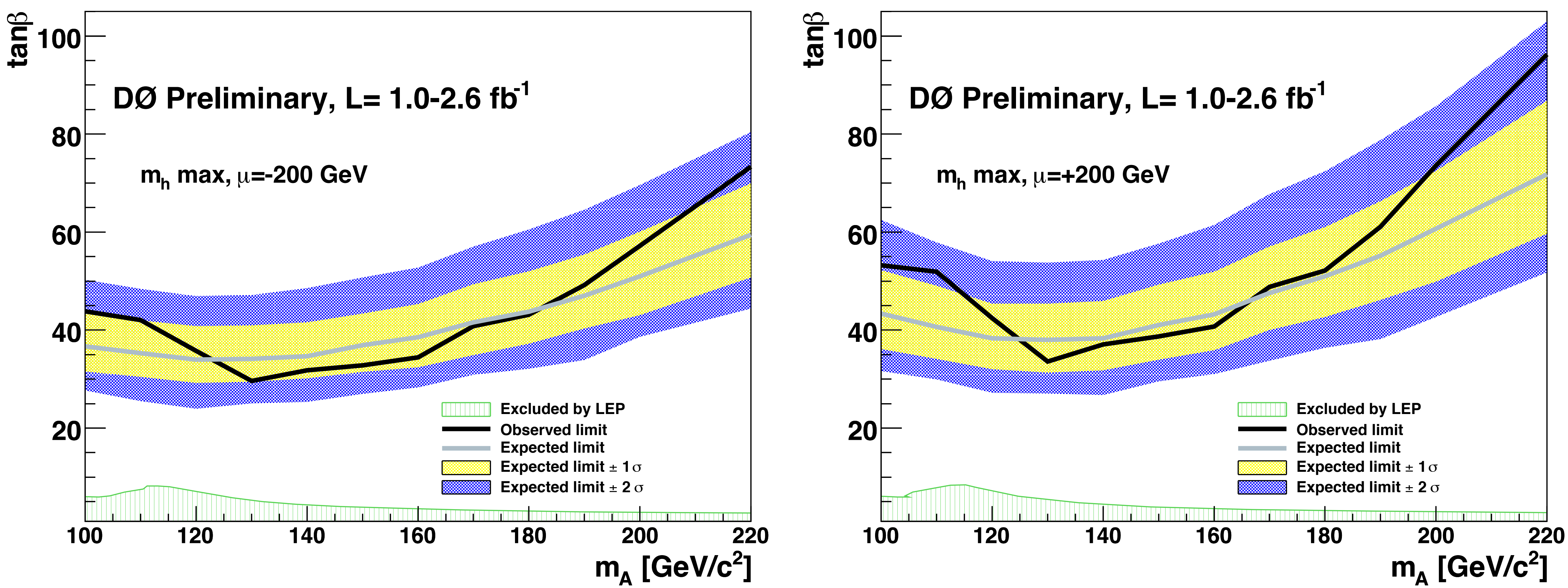




Combinations

- Several channels with similar sensitivity
  ➠ combining results makes sense!
- D0: combination of all neutral MSSM Higgs boson results



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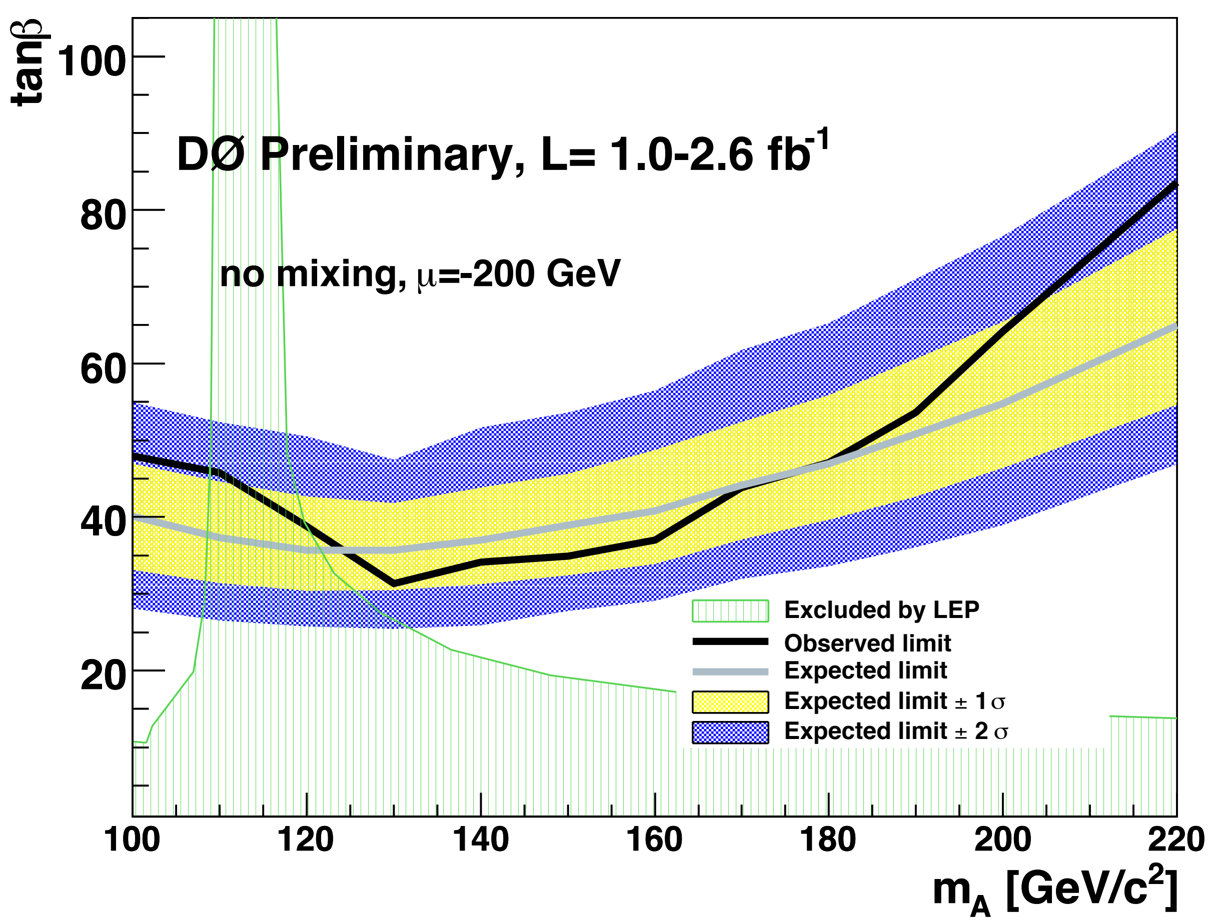

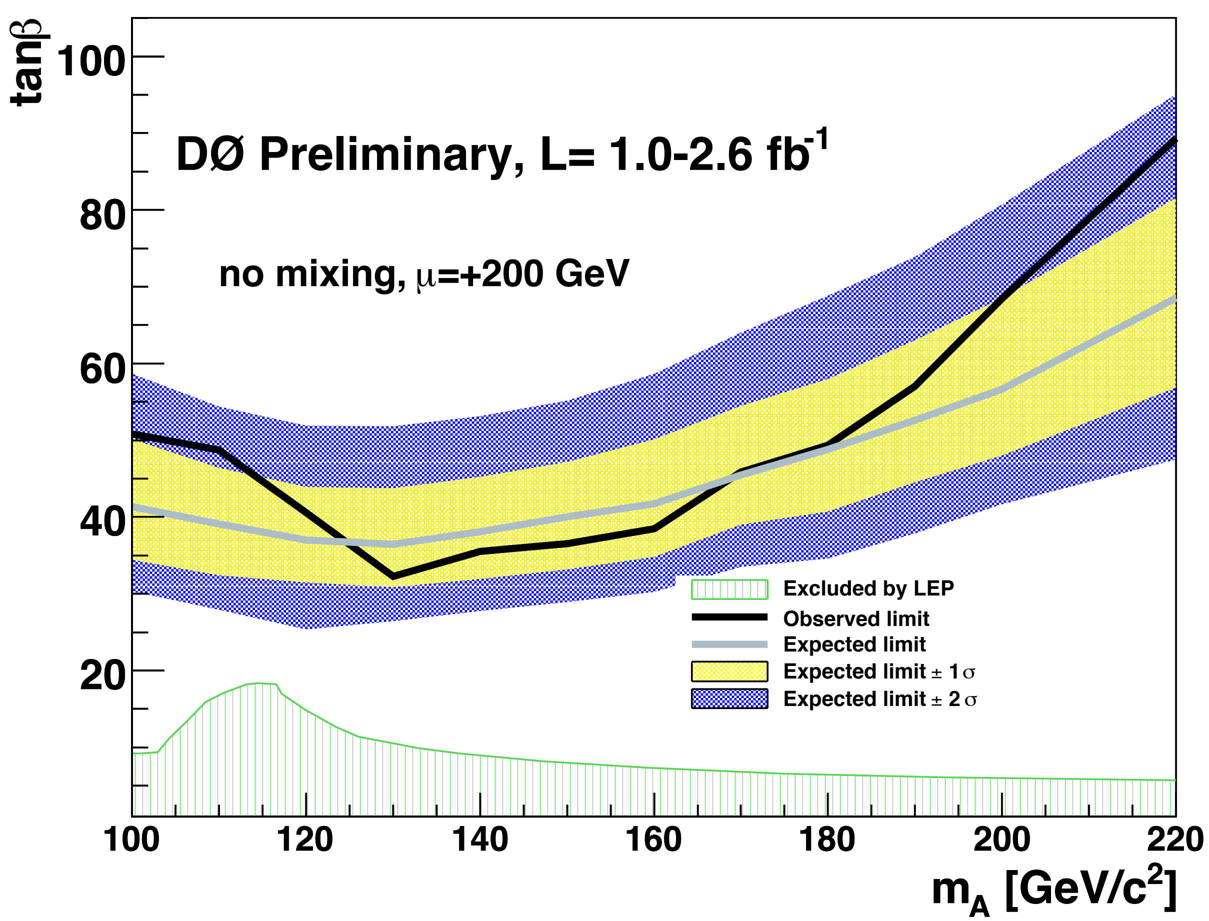

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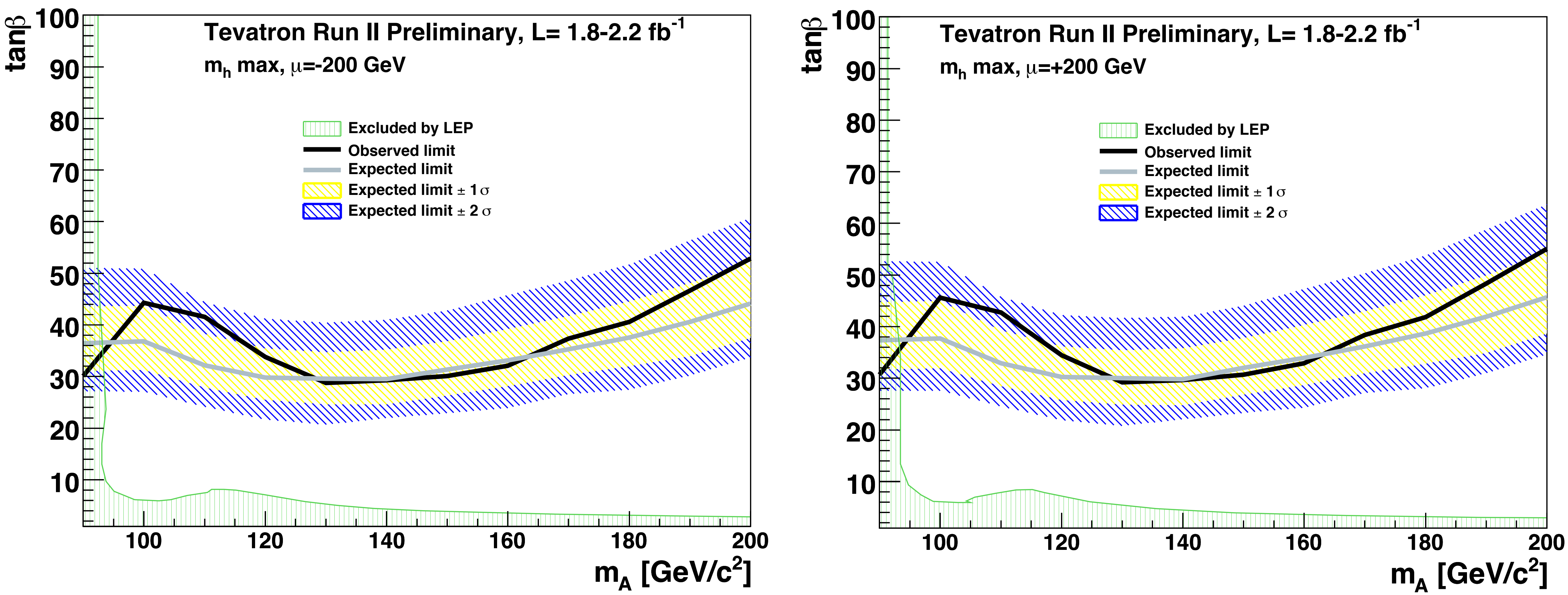
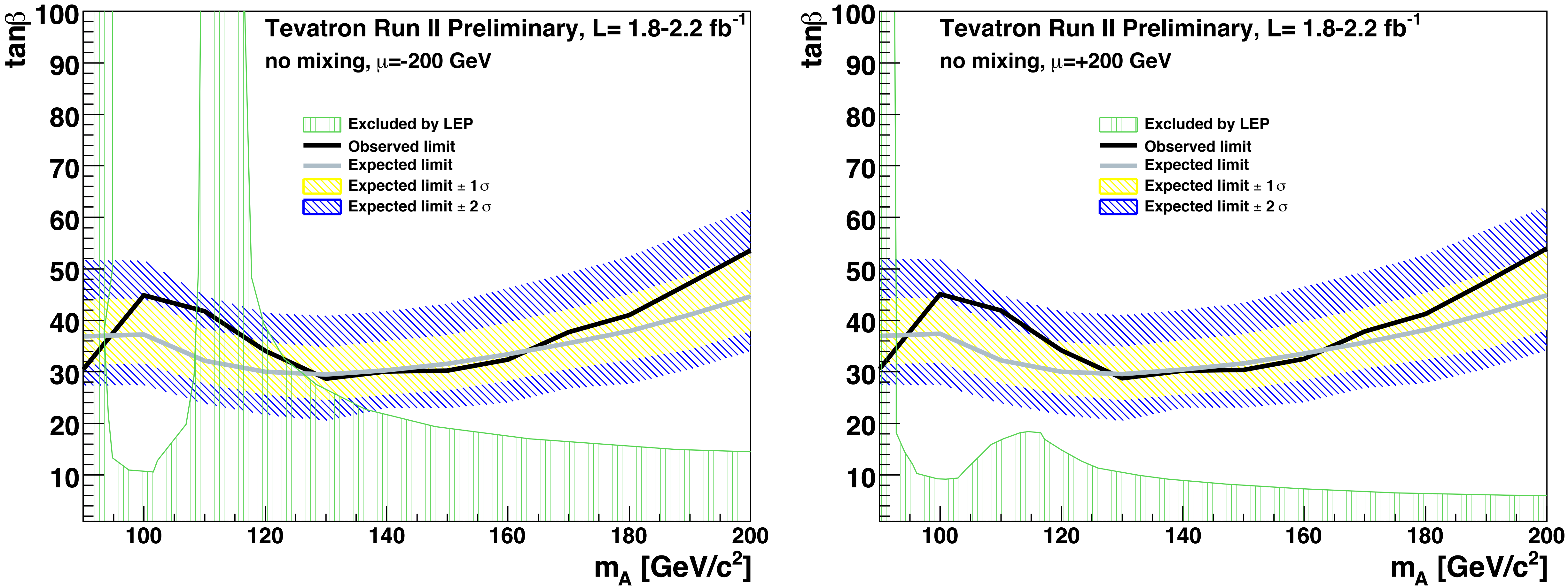
- Tevatron: combination of $\tau^+\tau^-$ results



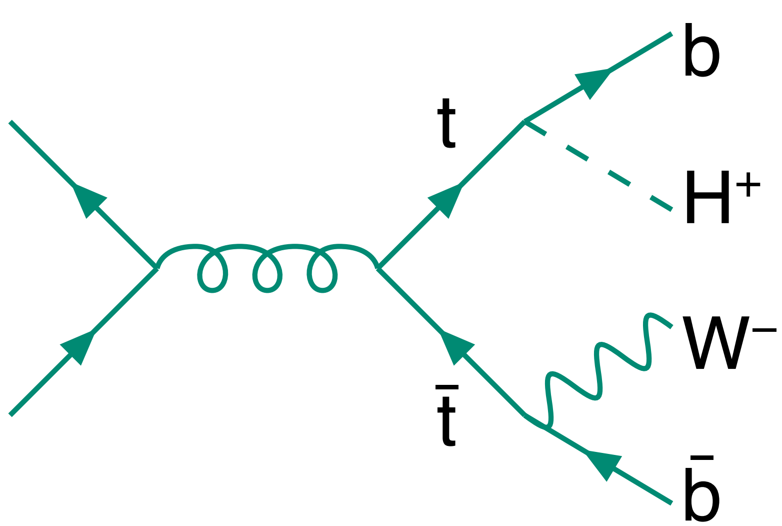
Combinations

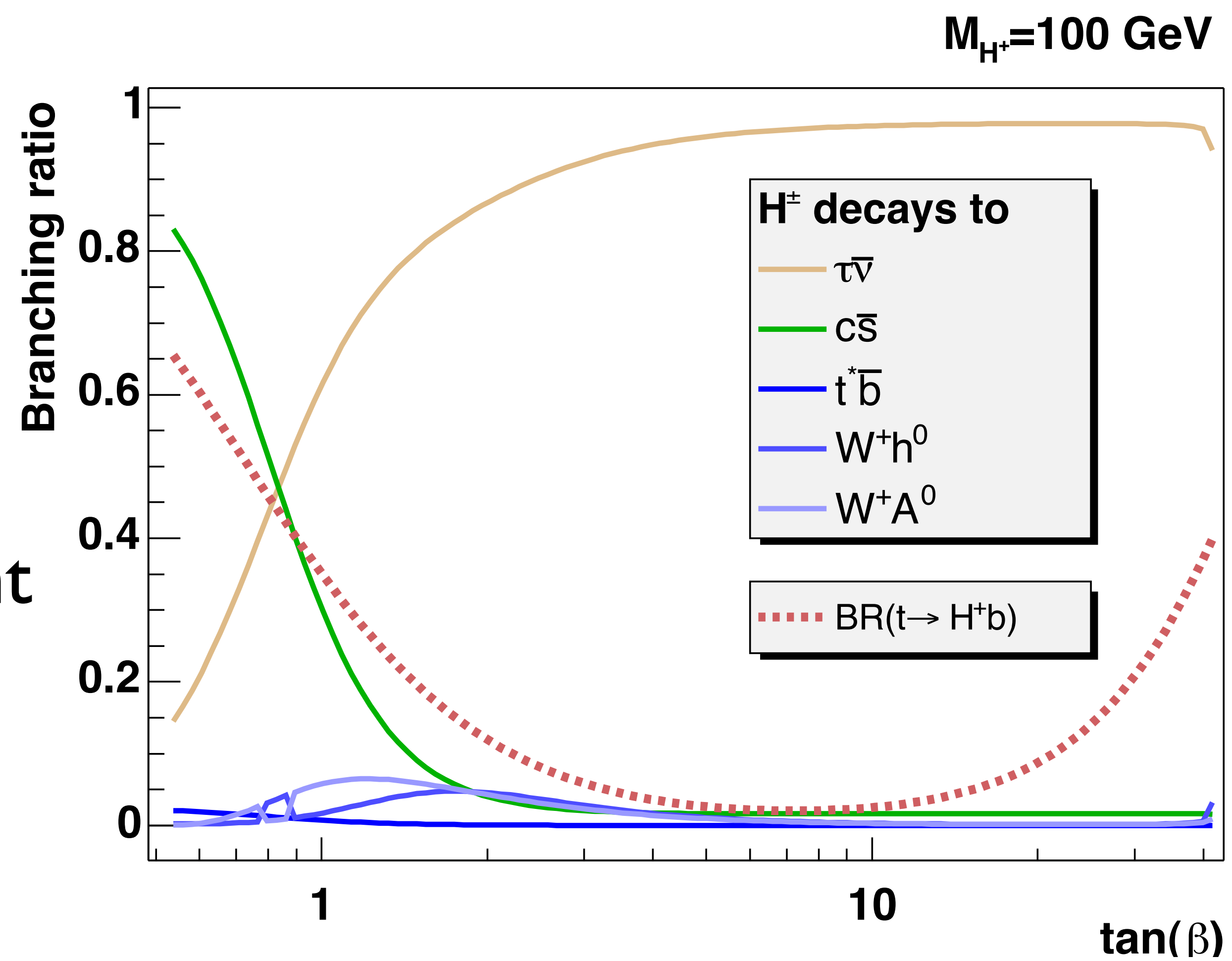
- Several channels with similar sensitivity
  ➠ combining results makes sense!
- D0: combination of all neutral MSSM Higgs boson results
- Tevatron: combination of $\tau^+\tau^-$ results



Charged Higgs Bosons

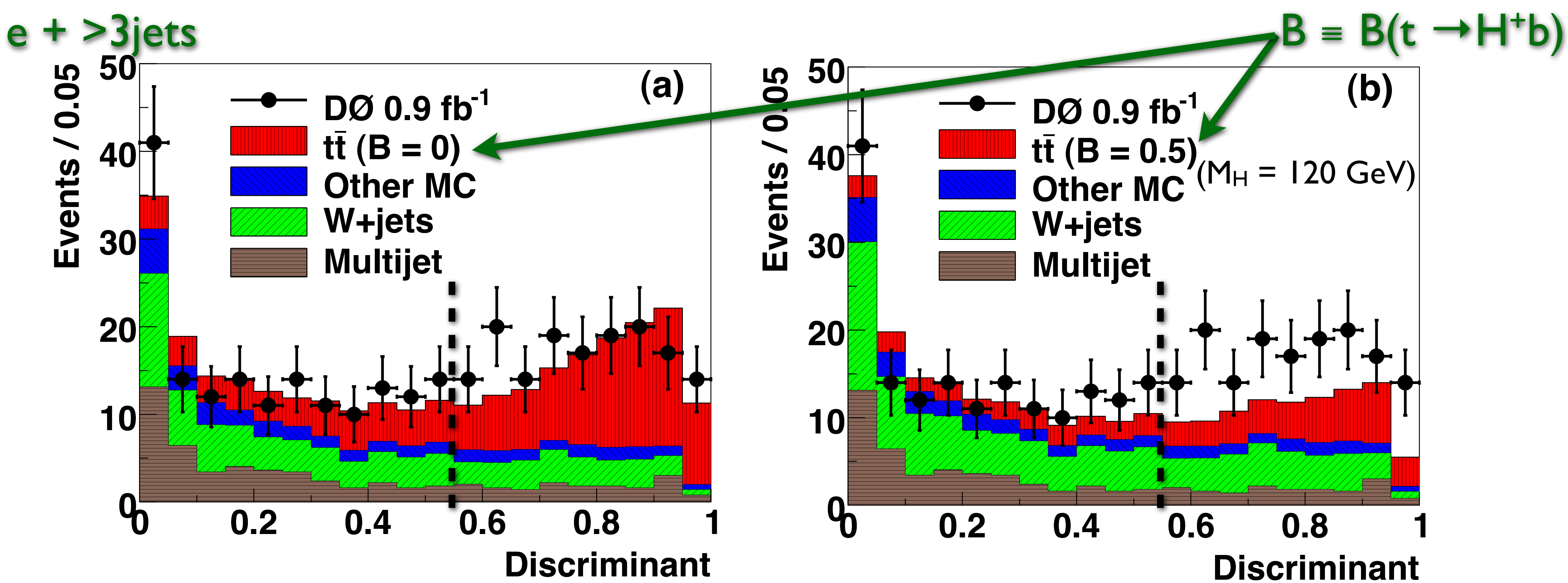
- Focus on $t \rightarrow H^+b$ decays (heavy $H \rightarrow tb$ out of Tevatron reach)
- exploited in multiple ways to search for $H \rightarrow cs, \tau\nu$ decays in tt events
  - modified distribution of tt events over l+jets, l+l, and $l+\tau_{had}$ final states
    - l = e, μ
  - peak in l+jets di-jet invariant mass spectrum ($H \rightarrow cs$)





Charged Higgs Bosons: $H \to \tau\nu$

- High tanβ: dominant decay mode
- D0 analysis (0.9 fb^{-1}) of $l+\tau_{had}$ mode:
  - separate 3-jet, >3-jet channels
  - significant background from W+jets ➠ likelihood discriminant (kinematic/topological variables)
  - Fix σ(tt) to SM value



published

Charged Higgs Bosons: H→τν

- High tanβ: dominant decay mode
- D0 analysis (0.9 fb^{-1}) of l+τ_{had} mode:
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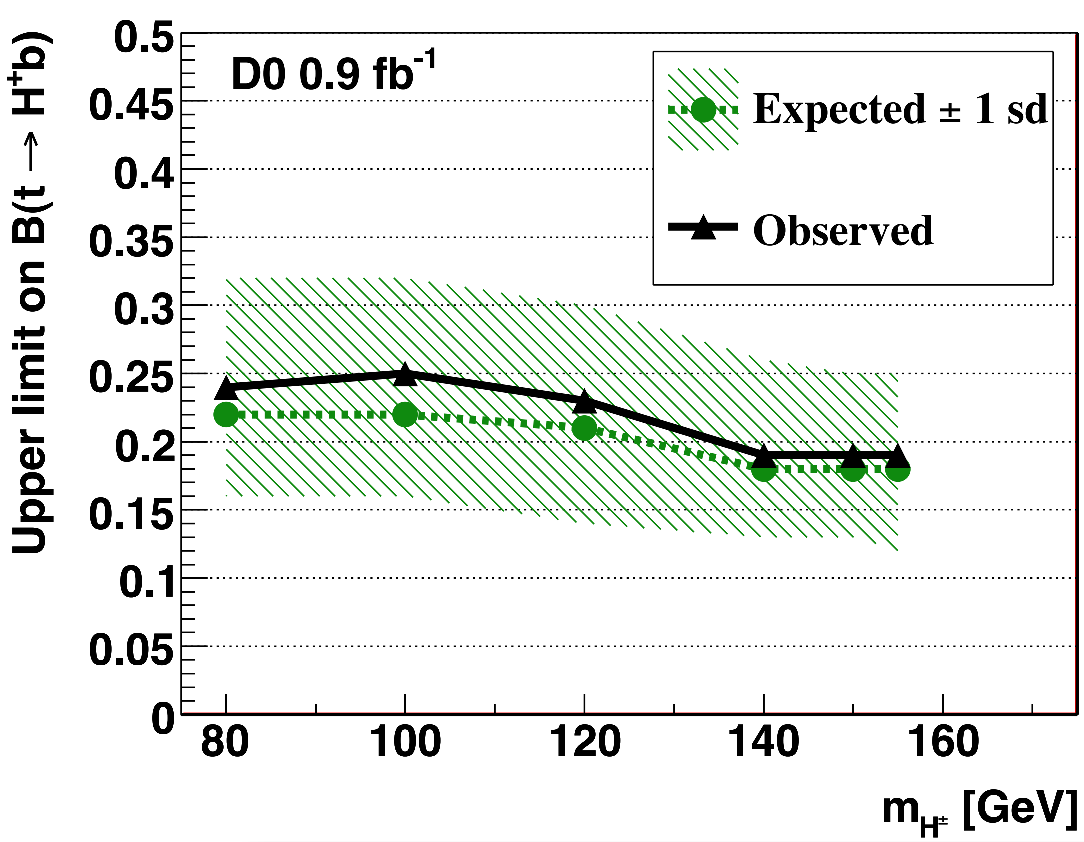
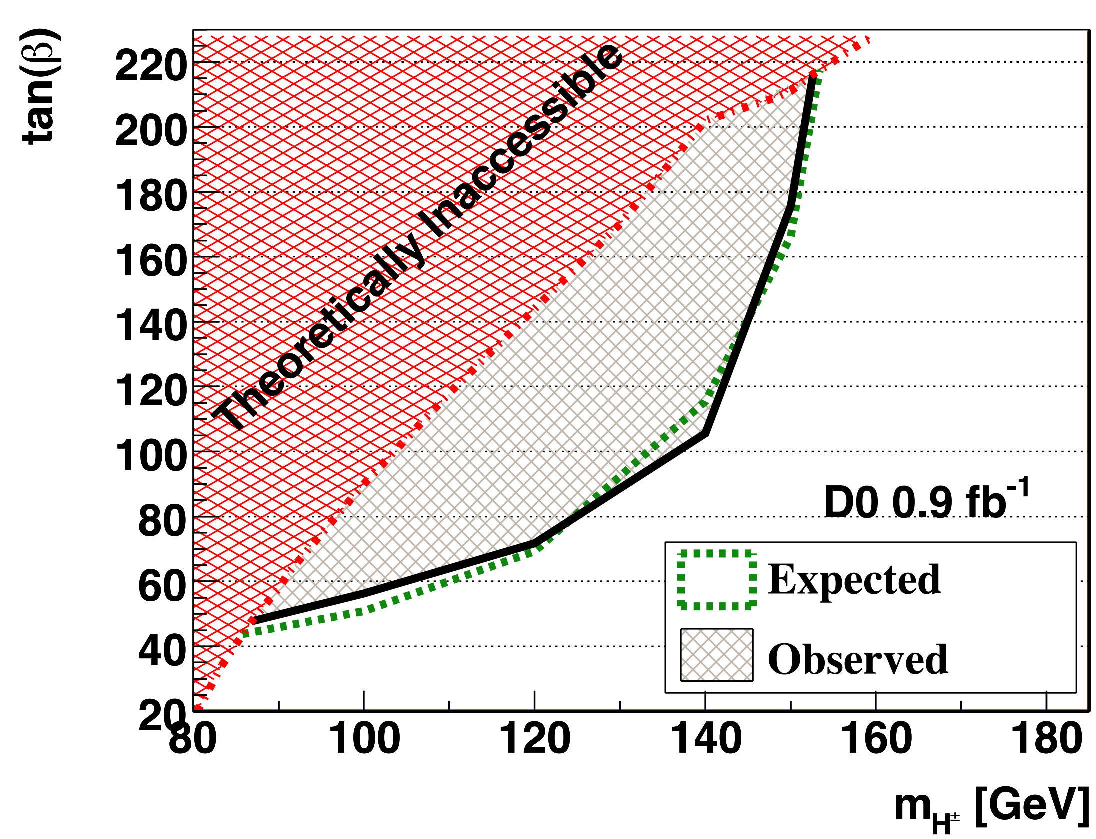




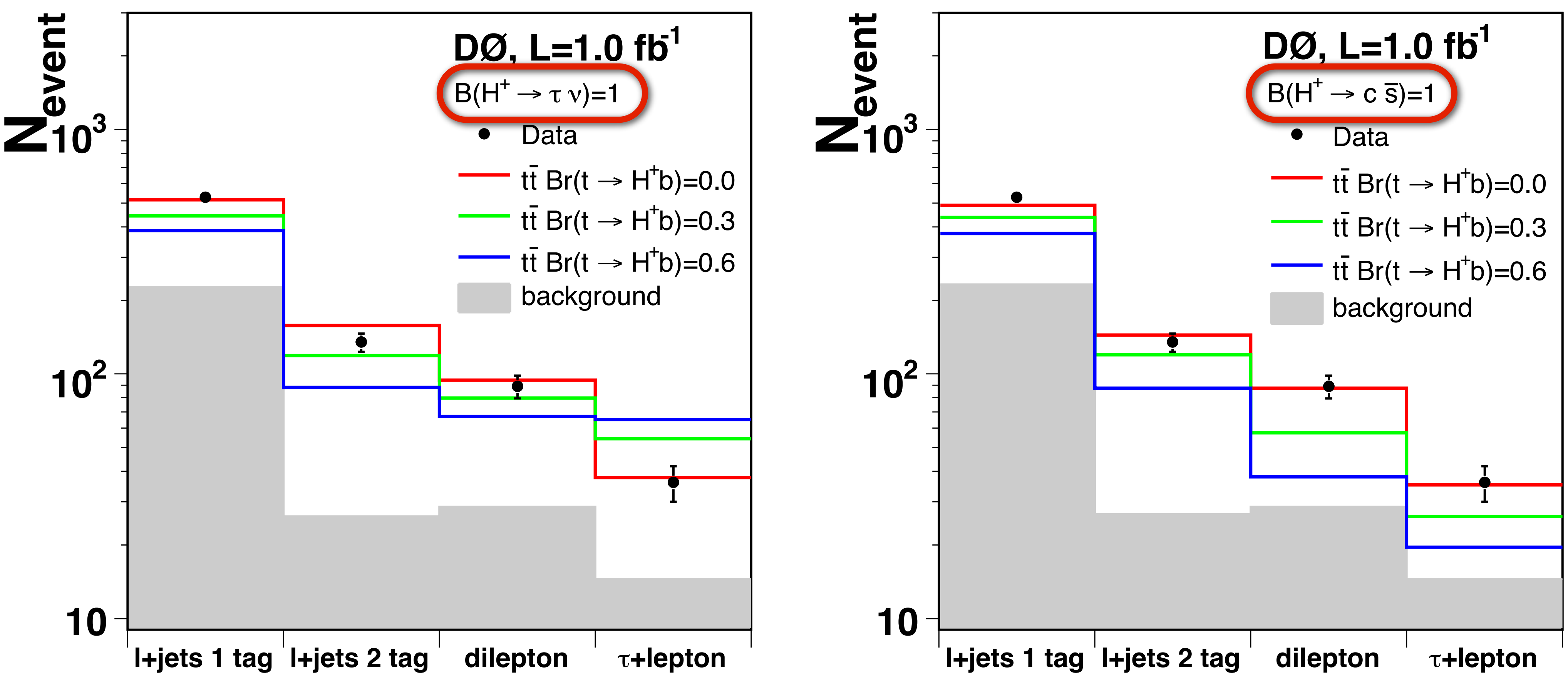
Method does not exploit depletion in other final states...

Charged Higgs Bosons: Combination

published

- Better alternative: consider l+jets, l+l, l+τ_{had} channels simultaneously
- D0 analysis (1 fb^{-1}):
  - follow earlier individual analyses, but use $\varepsilon(M_H)$

nall M_H!



M_H = 80 GeV

Charged Higgs Bosons: Combination

published

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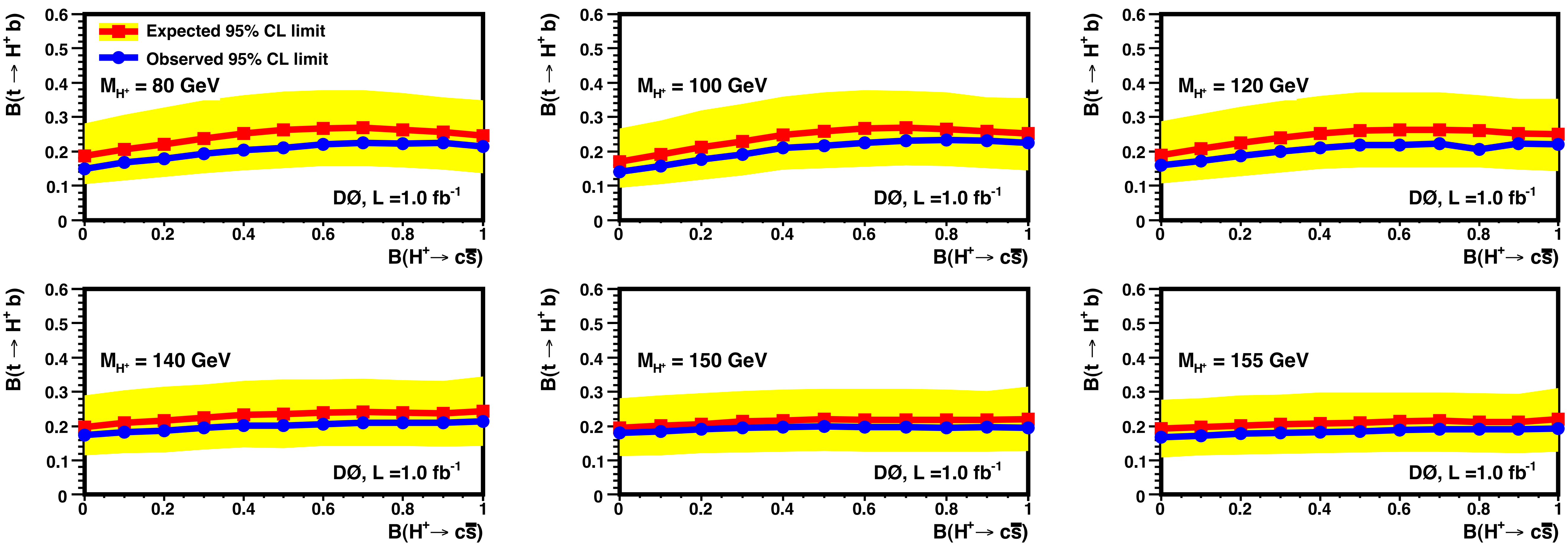

Assuming $B(H \rightarrow \tau\nu) + B(H \rightarrow cs) = 1$

published

Charged Higgs Bosons: Combination

- Better alternative: consider l+jets, l+l, l+τ_{had} channels simultaneously
- D0 analysis (1 fb^{-1}):
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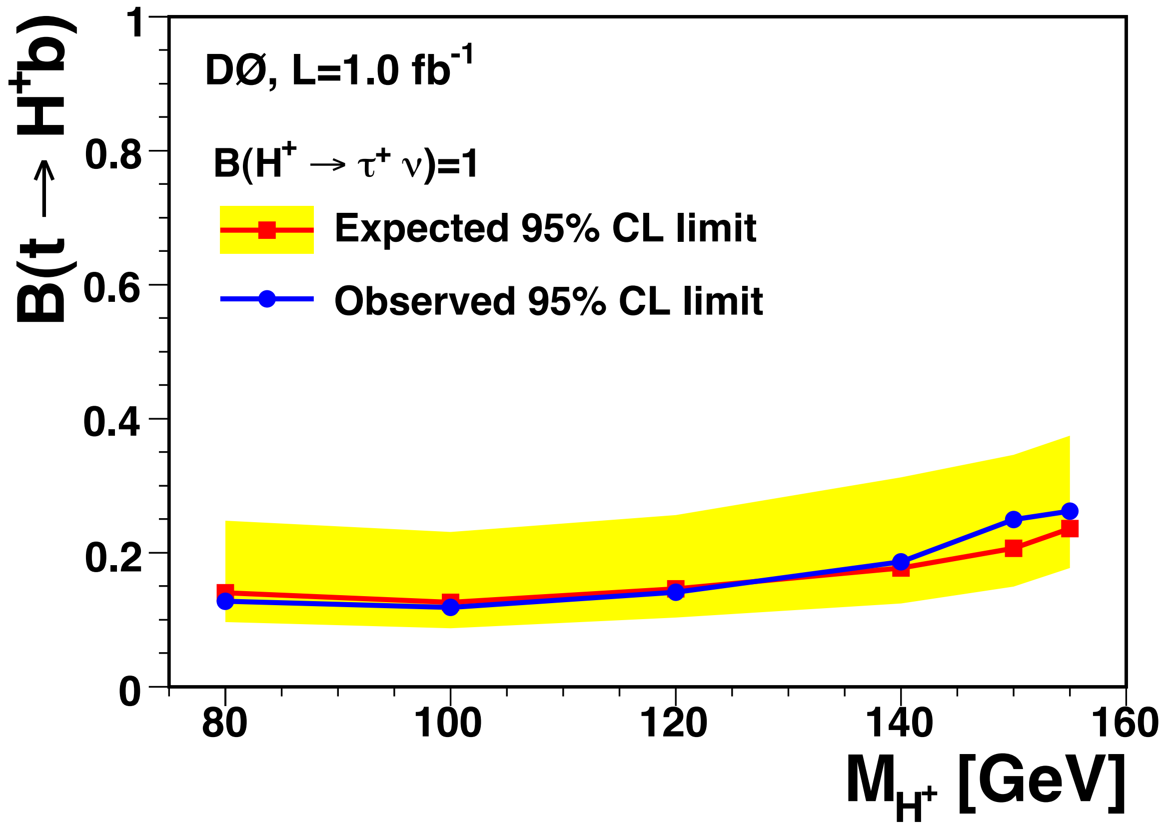
  - allows for simultaneous fits of $\sigma(tt)$ ➠ improvement for small M_H!



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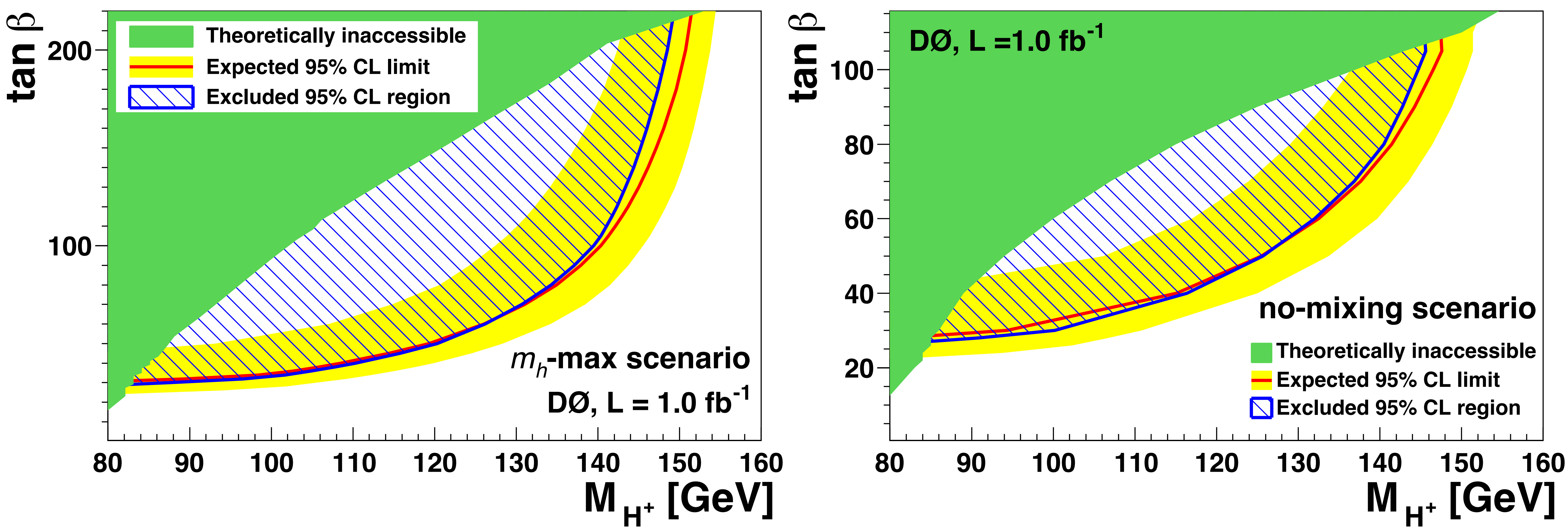
  - Interpretation in various MSSM scenarios



Charged Higgs Bosons: Combination

published

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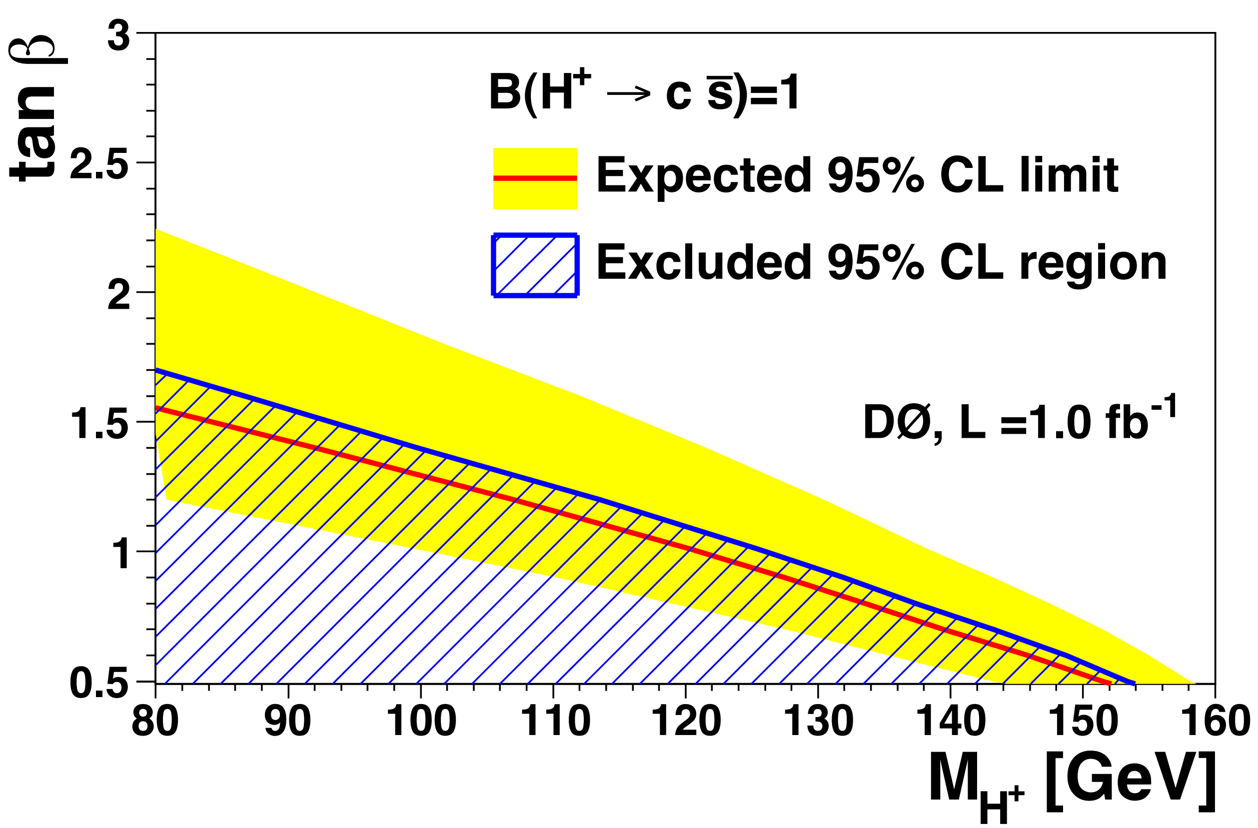

Leptophobic Higgs: MSSM for low tanβ, Multi-Higgs Doublet models

published

Charged Higgs Bosons: Combination

- Better alternative: consider l+jets, l+l, l+τ_{had} channels simultaneously
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  - follow earlier individual analyses, but use $\varepsilon(M_H)$
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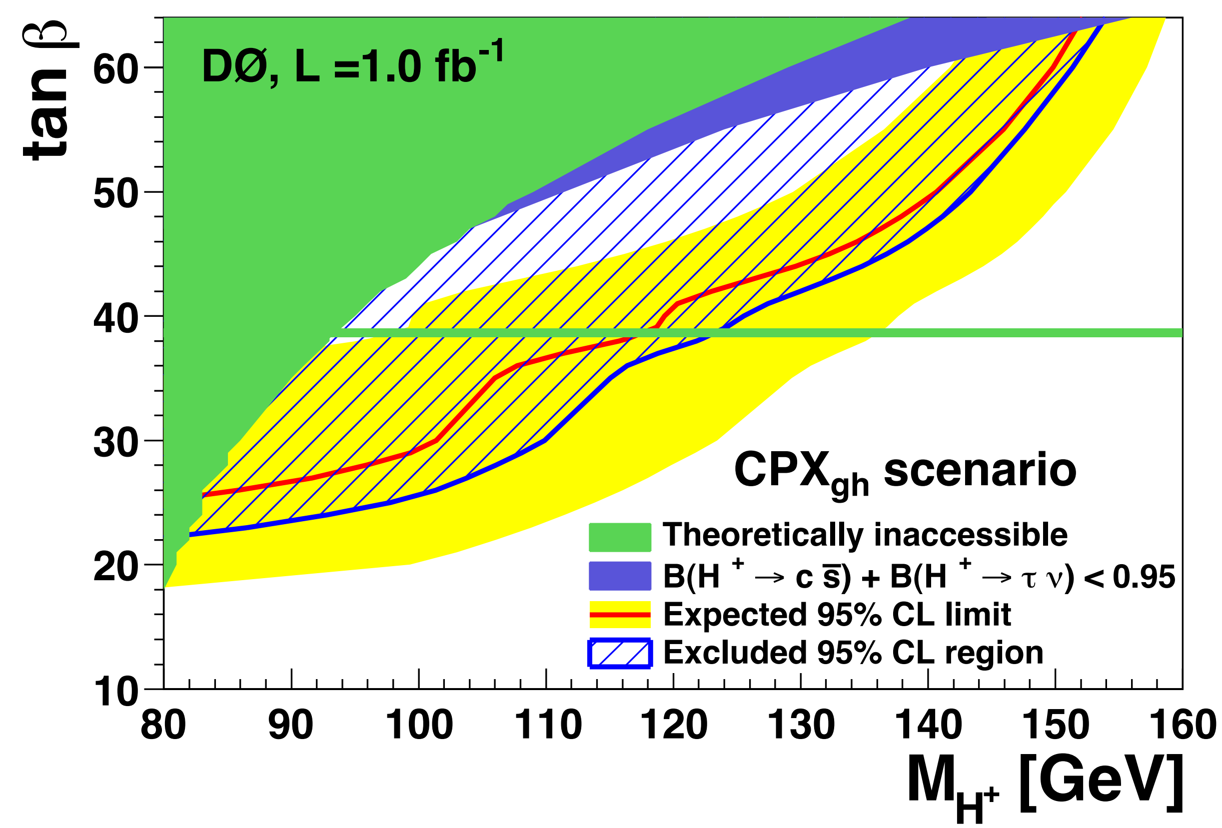
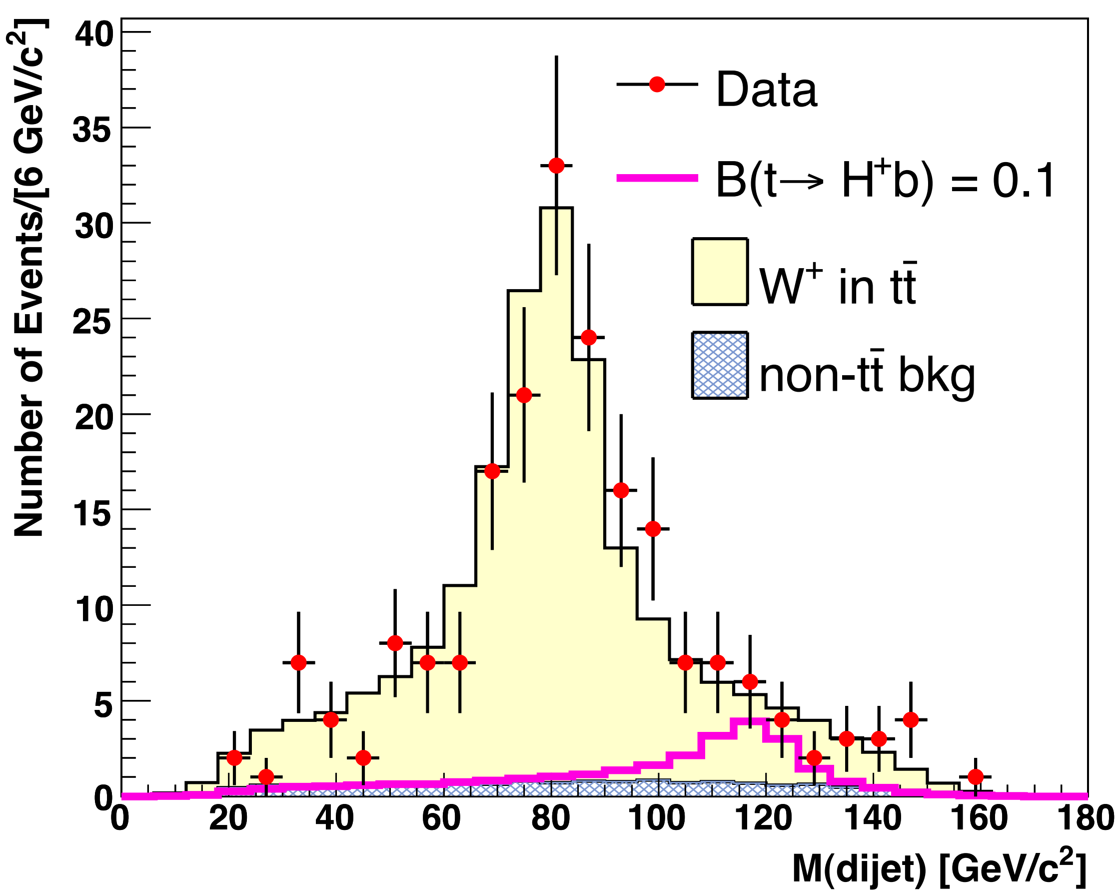
  - Interpretation in various MSSM scenarios

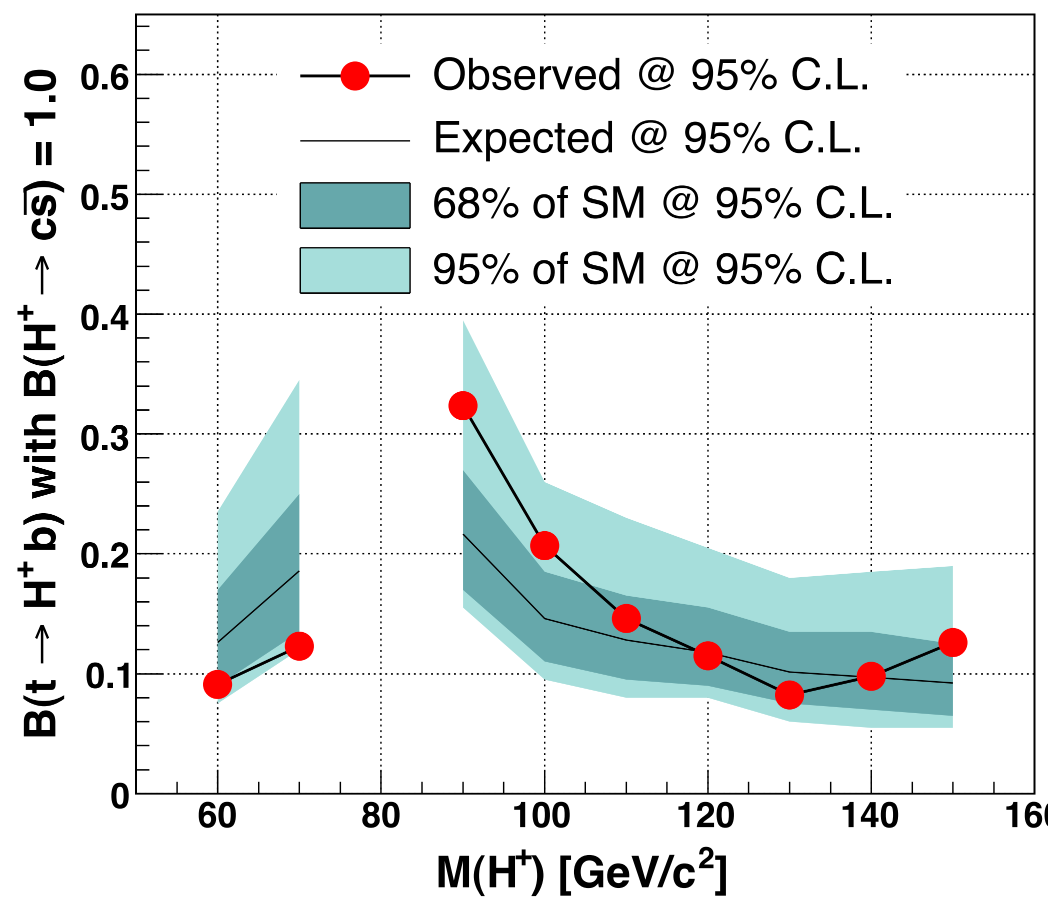
CPX_{gh} scenario: substantial $H \to cs$ fraction even for high $22 < \tan\beta < 55$



Charged Higgs Bosons: H→cs

- CDF analysis (2.2 fb^{-1}) of double-tagged l+jets final states:
  - kinematic fit using m_t, (leptonic) M_W constraints
  - binned ML fit to non-b di-jet mass distribution



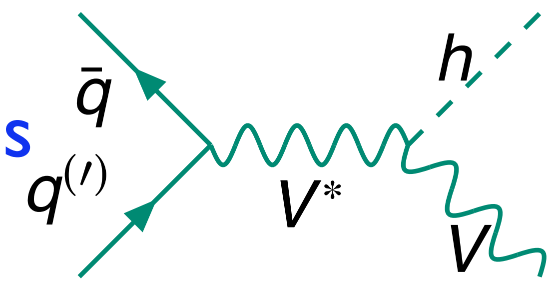


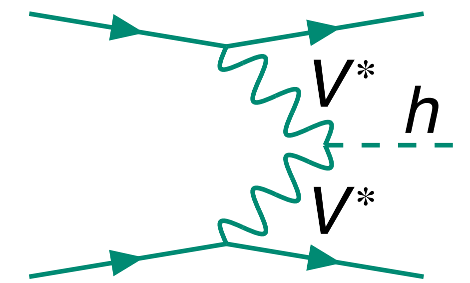
Overall tt counts not constrained ➠ reduced sensitivity at $M_H \approx M_W$

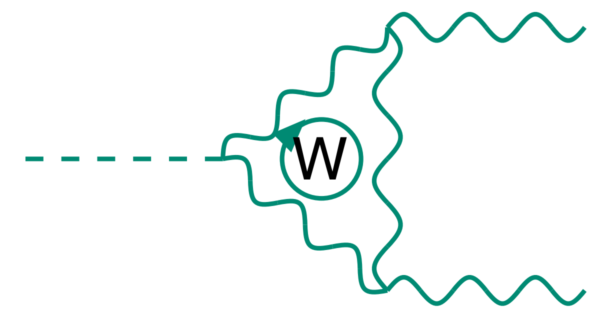
update from 2.7 fb^{-1}

Fermiophobic Higgs: H $\rightarrow\gamma\gamma$

- Possible in various (more exotic) SM extensions
- Benchmark model: SM couplings to vector bosons, no couplings to fermions
- D0 analysis (4.2 fb^{-1}):
  - Vh and VBF production lumped together (no "V" selection)
  - NN γ identification







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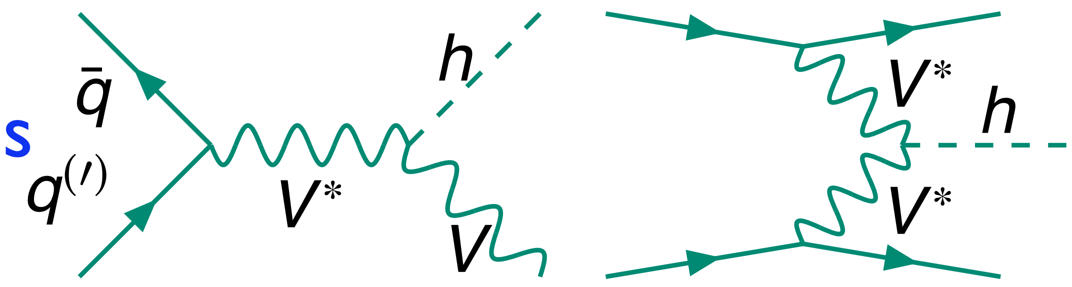

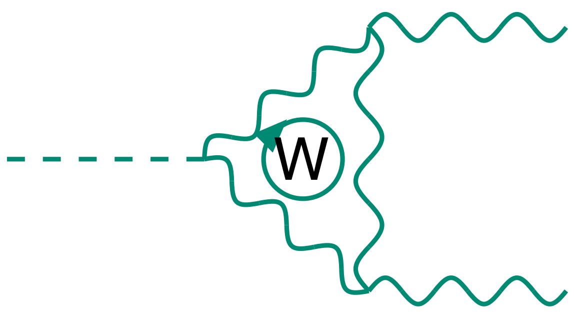

- D0 analysis (4.2 fb^{-1}):
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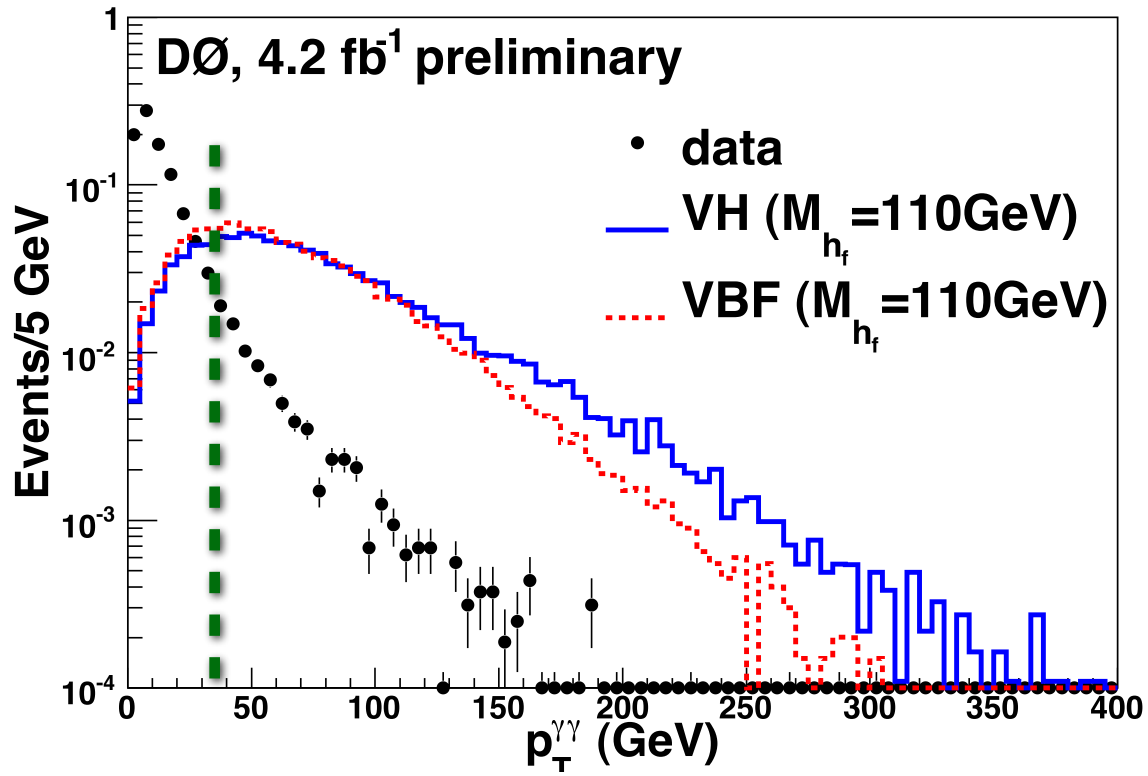
  - NN γ identification
  - cut on $p_T(\gamma\gamma)$



update from 2.7 fb^{-1}

Fermiophobic Higgs: H →γγ

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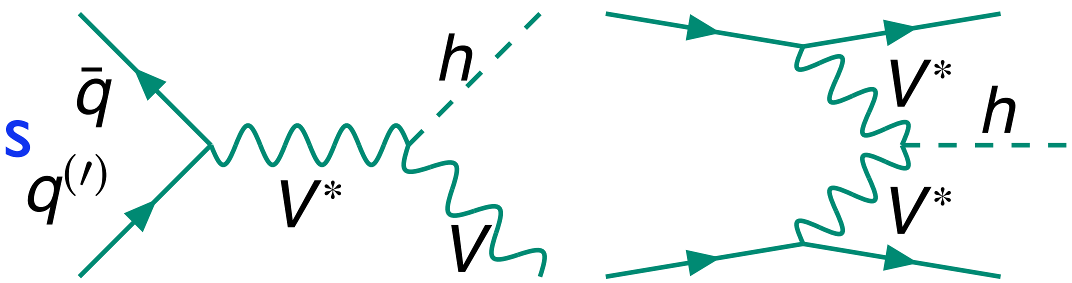
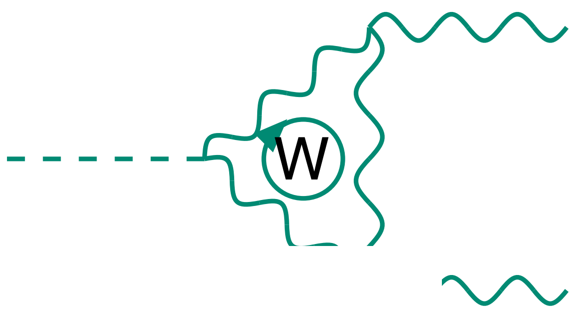
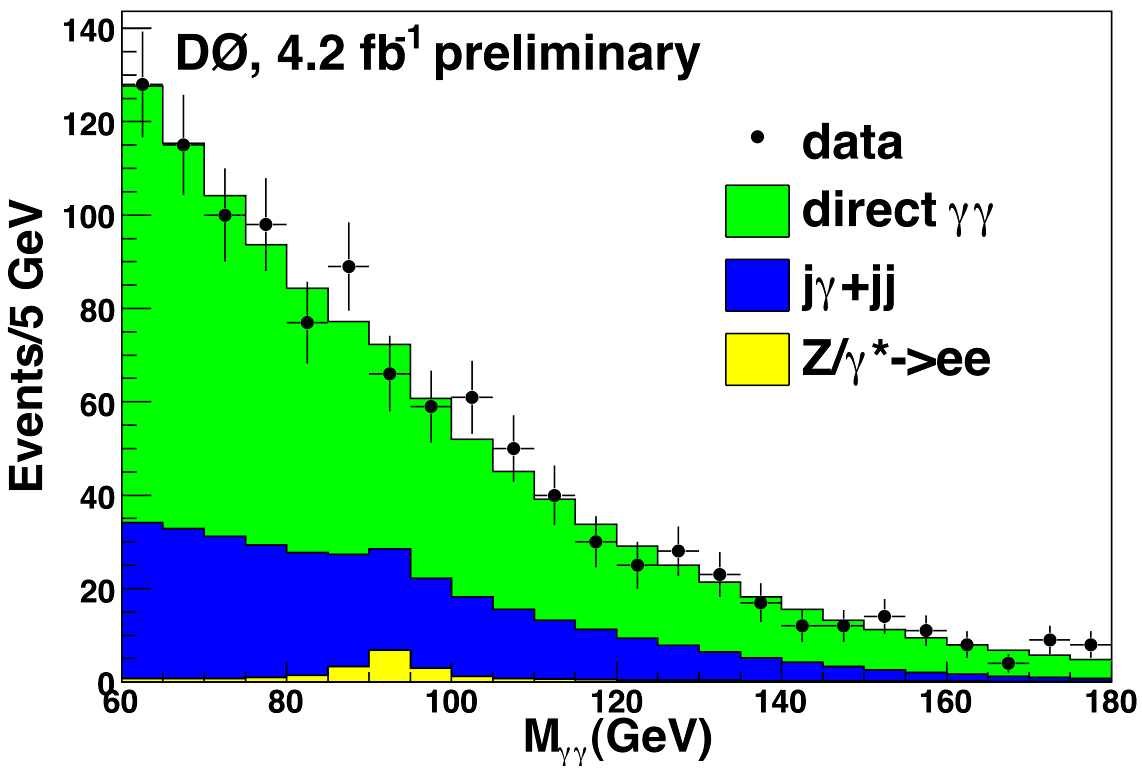
- Benchmark model: SM couplings to vector bosons, no couplings to fermions
- D0 analysis (4.2 fb^{-1}):
  - Vh and VBF production lumped together (no "V" selection)
  - NN γ identification
  - cut on $p_T(\gamma\gamma)$
  - jj/γj identified using known fake rates
  - fit signal in 20 GeV mass window







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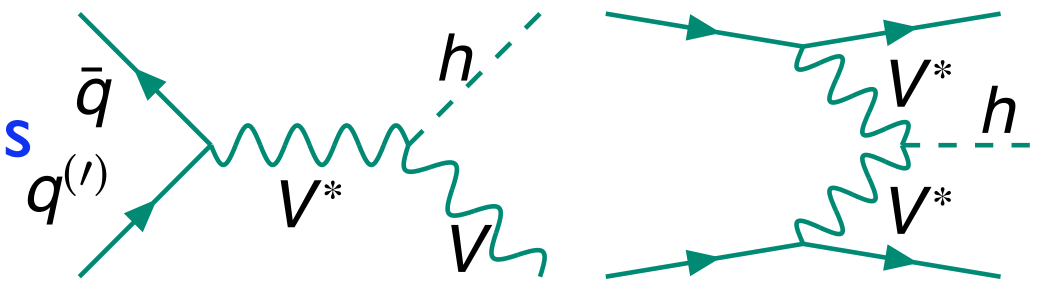

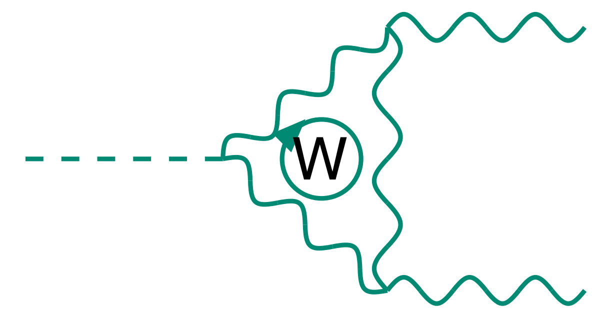

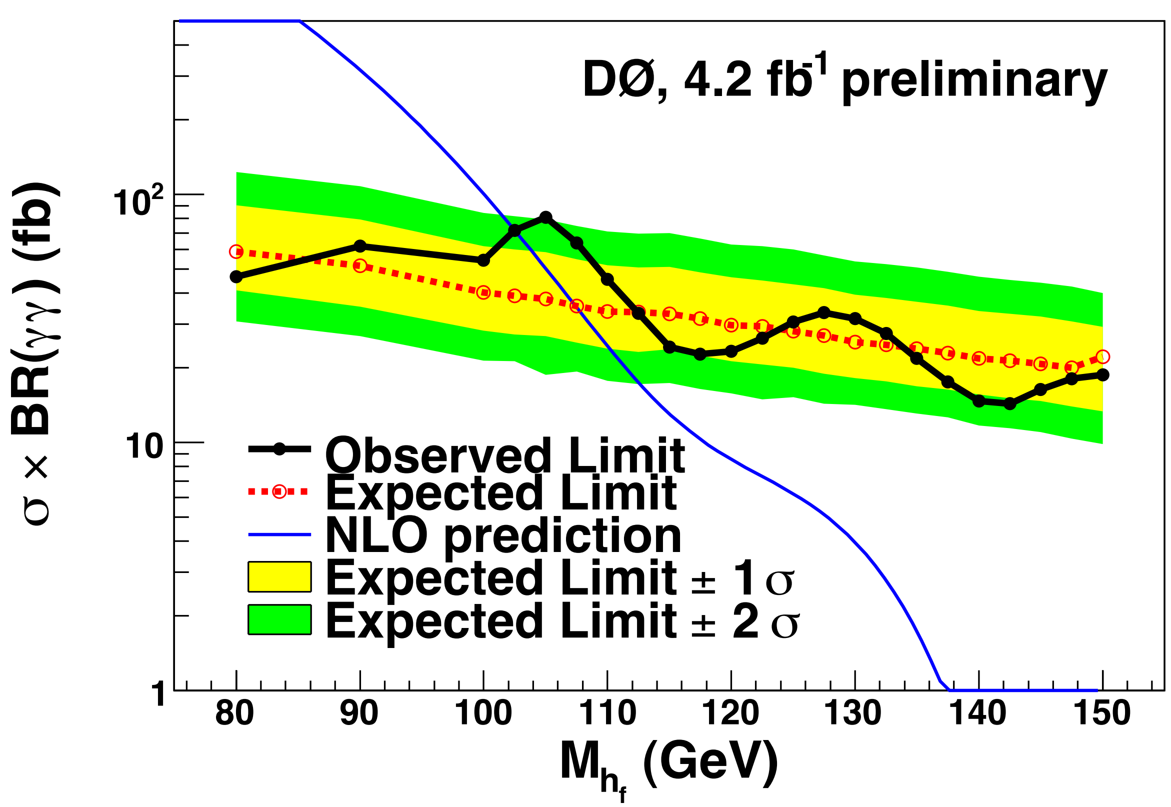

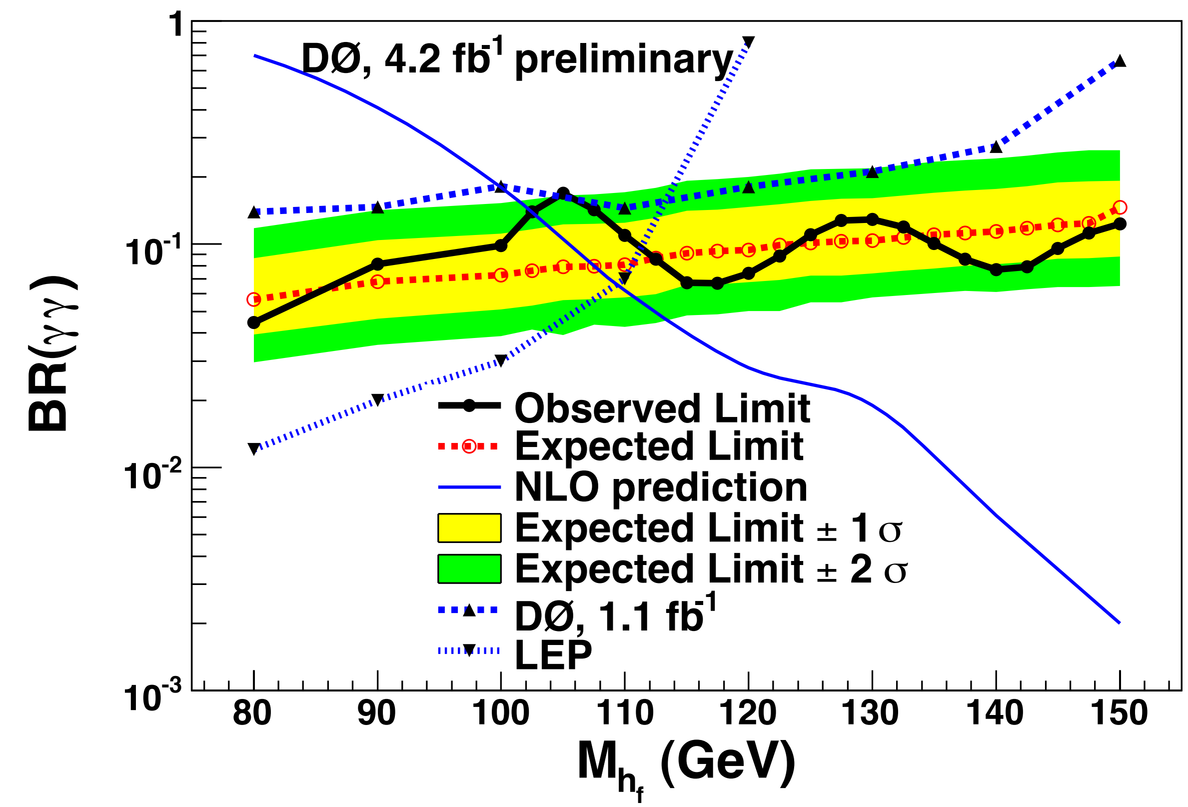

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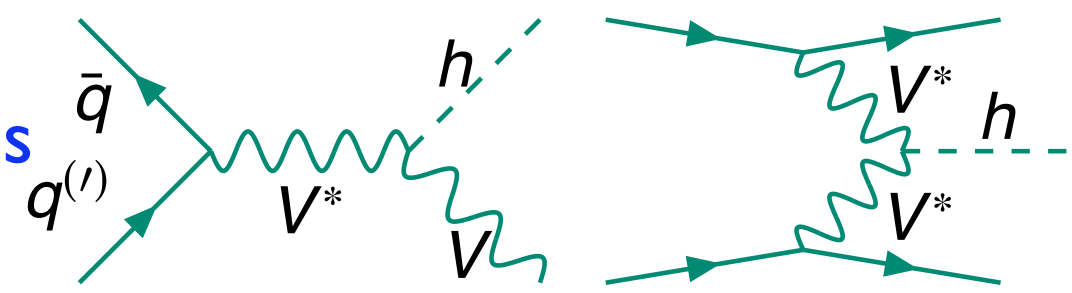
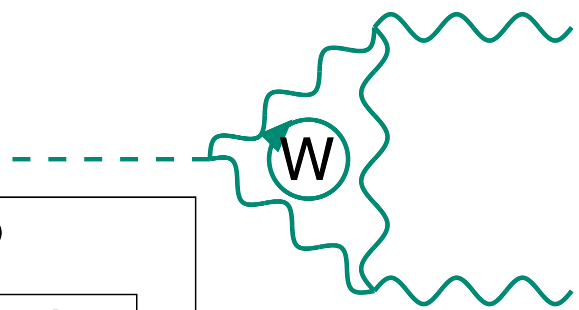
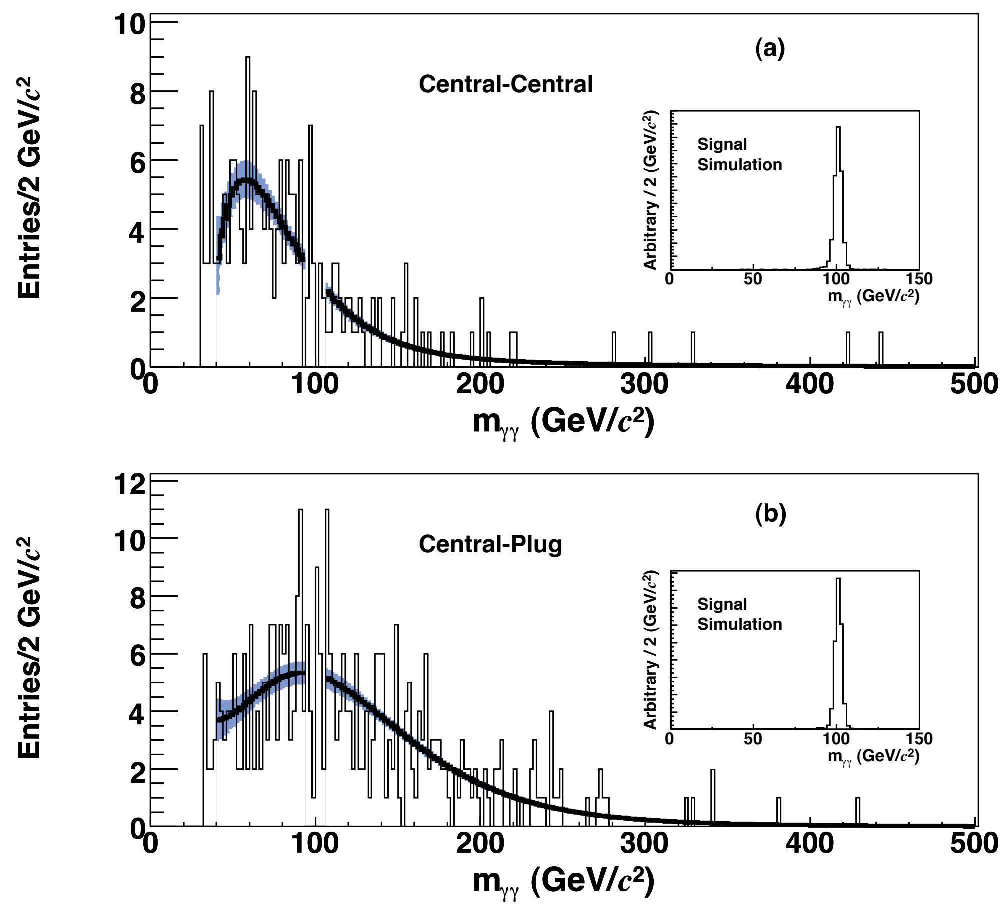
Fermiophobic Higgs: H →γγ

- Possible in various (more exotic) SM extensions
- Benchmark model: SM couplings to vector bosons, no couplings to fermions
- CDF analysis (3 fb^{-1}):
  - Vh and VBF production lumped together (as in D0 analysis)
  - $p_T(\gamma\gamma)$ > 75 GeV
  - fit with 10 GeV signal mass window







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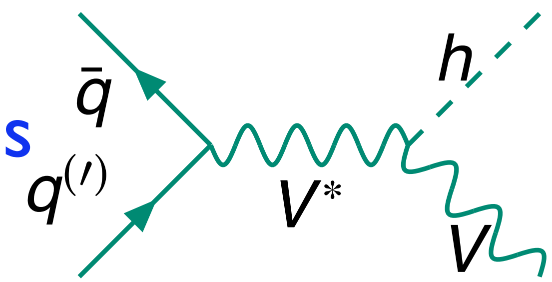
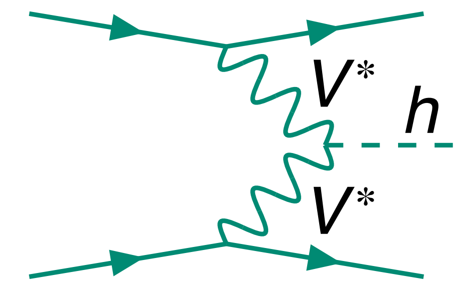
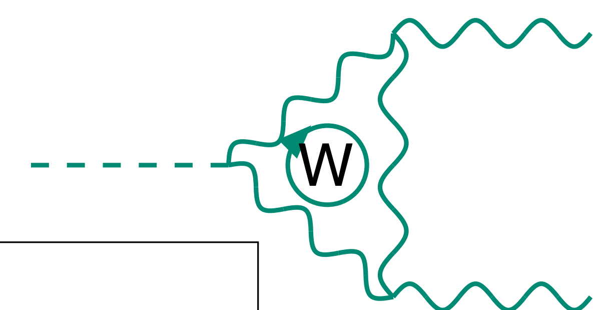
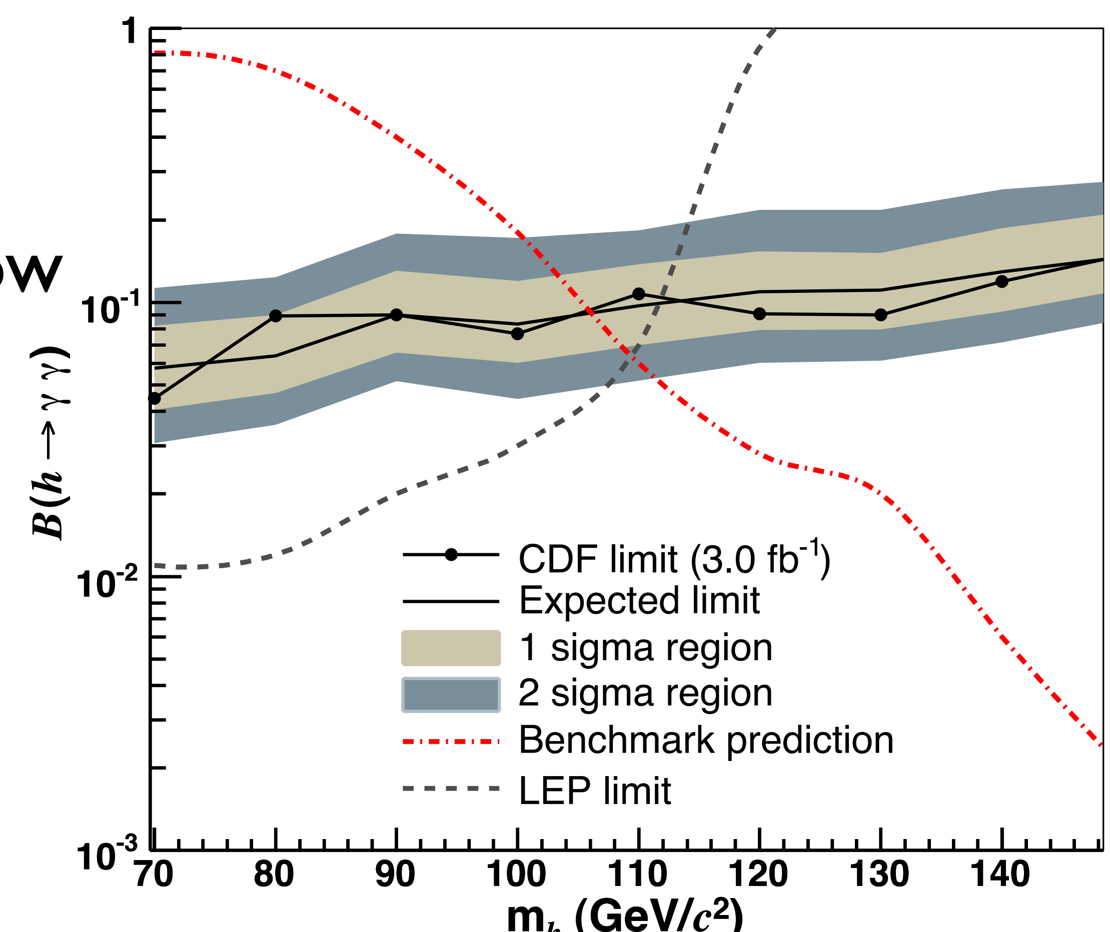


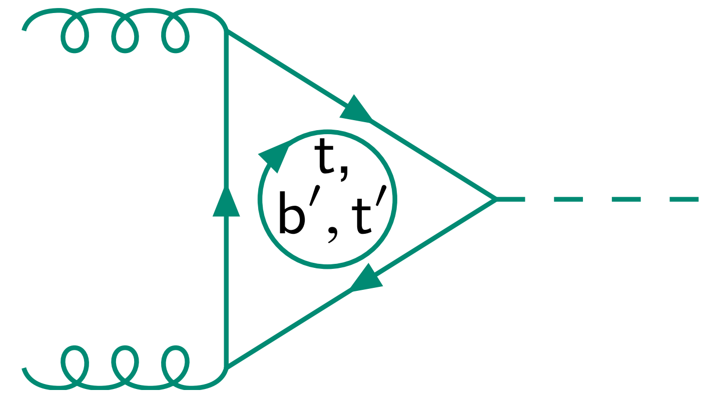




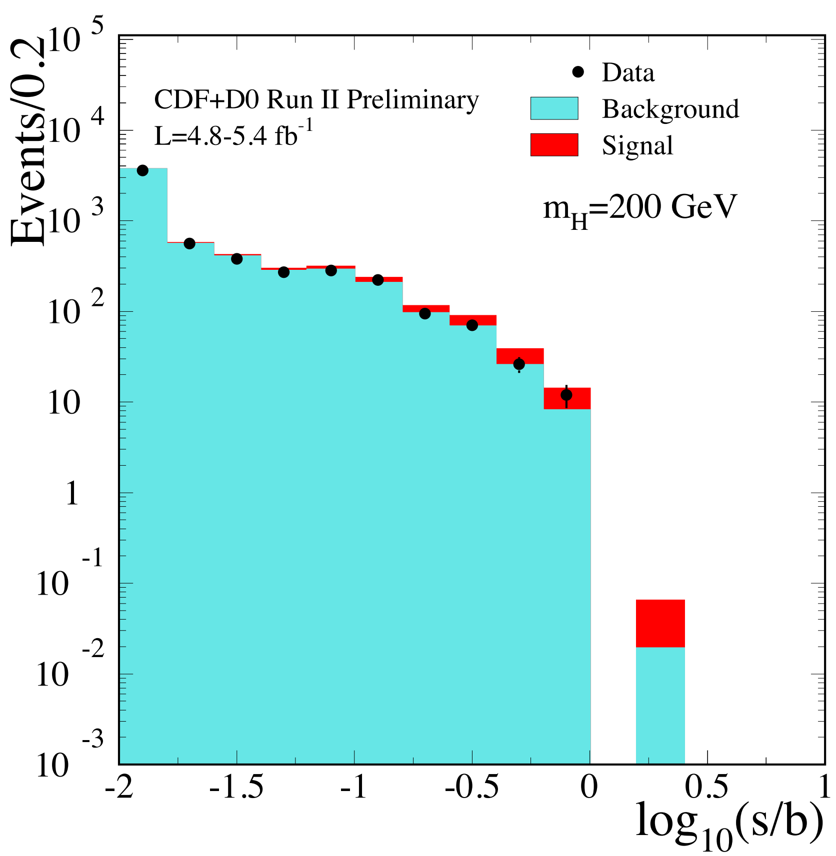


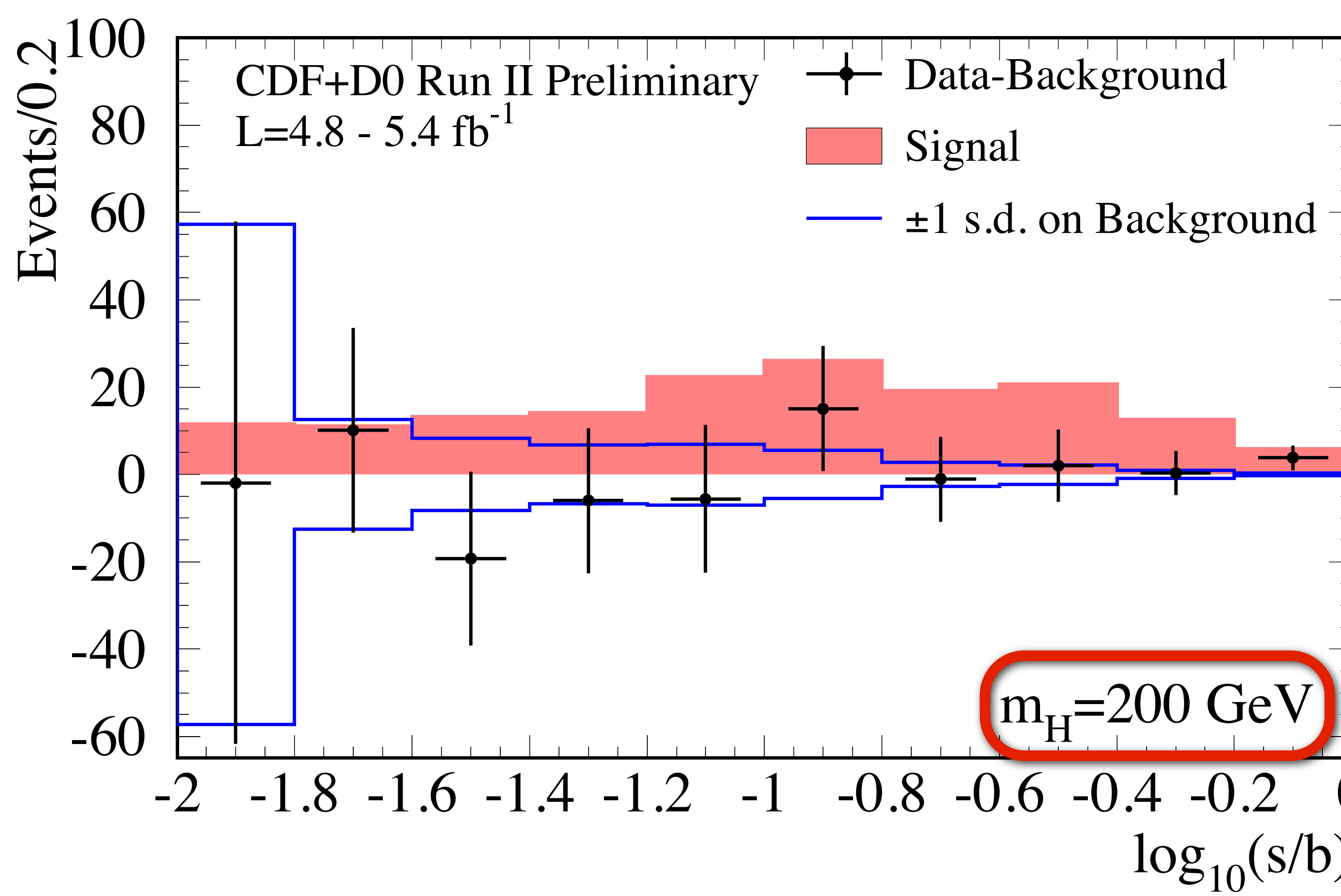
submitted

Four Fermion Generations



- Straightforward SM extension
  - evade $N_\nu=3$ constraint by heavy ν
  - enhanced $gg \to H$ cross section (factor 7.5 - 9)
- Tevatron combined analysis (CDF 4.8 fb^{-1}, D0 5.4 fb^{-1}) adjusting corresponding SM $H \to W^+W^-$ search:
  - correct signal acceptance for different VH, VBF admixtures





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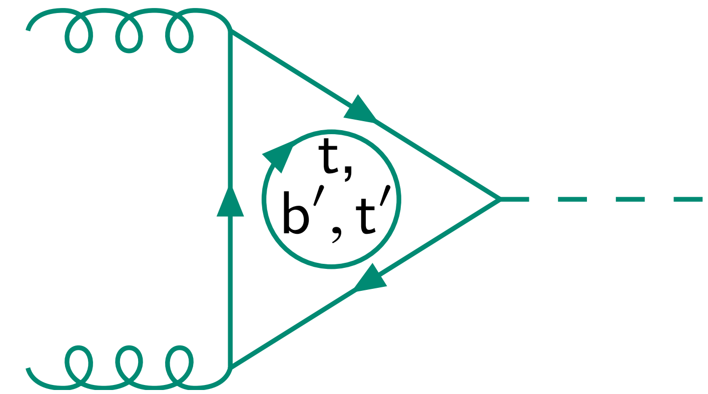
Four Fermion Generations



- Straightforward SM extension
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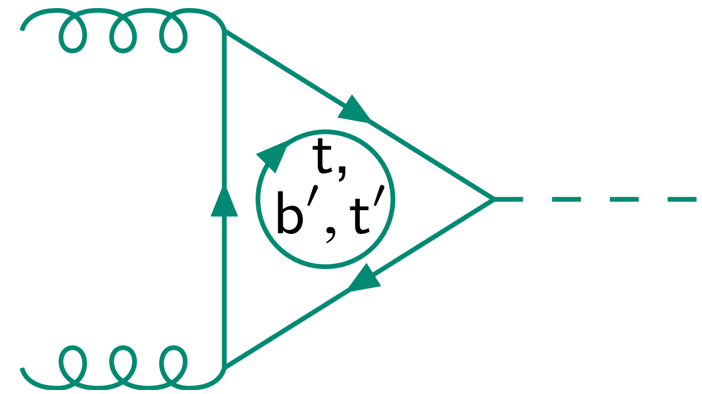
- Tevatron combined analysis (CDF 4.8 fb^{-1}, D0 5.4 fb^{-1}) adjusting corresponding SM H → W^+W^- search:
  - correct signal acceptance for different VH, VBF admixtures
  - H → W^+W^- branching fraction affected by decays to heavy fermions ➠ 2 scenarios (both: $m_{b'}$, $m_{t'}$ ~ 400 - 500 GeV):
    - m_l = 100 GeV, m_ν = 80 GeV
    - m_l = m_ν = 1 TeV

Four Fermion Generations



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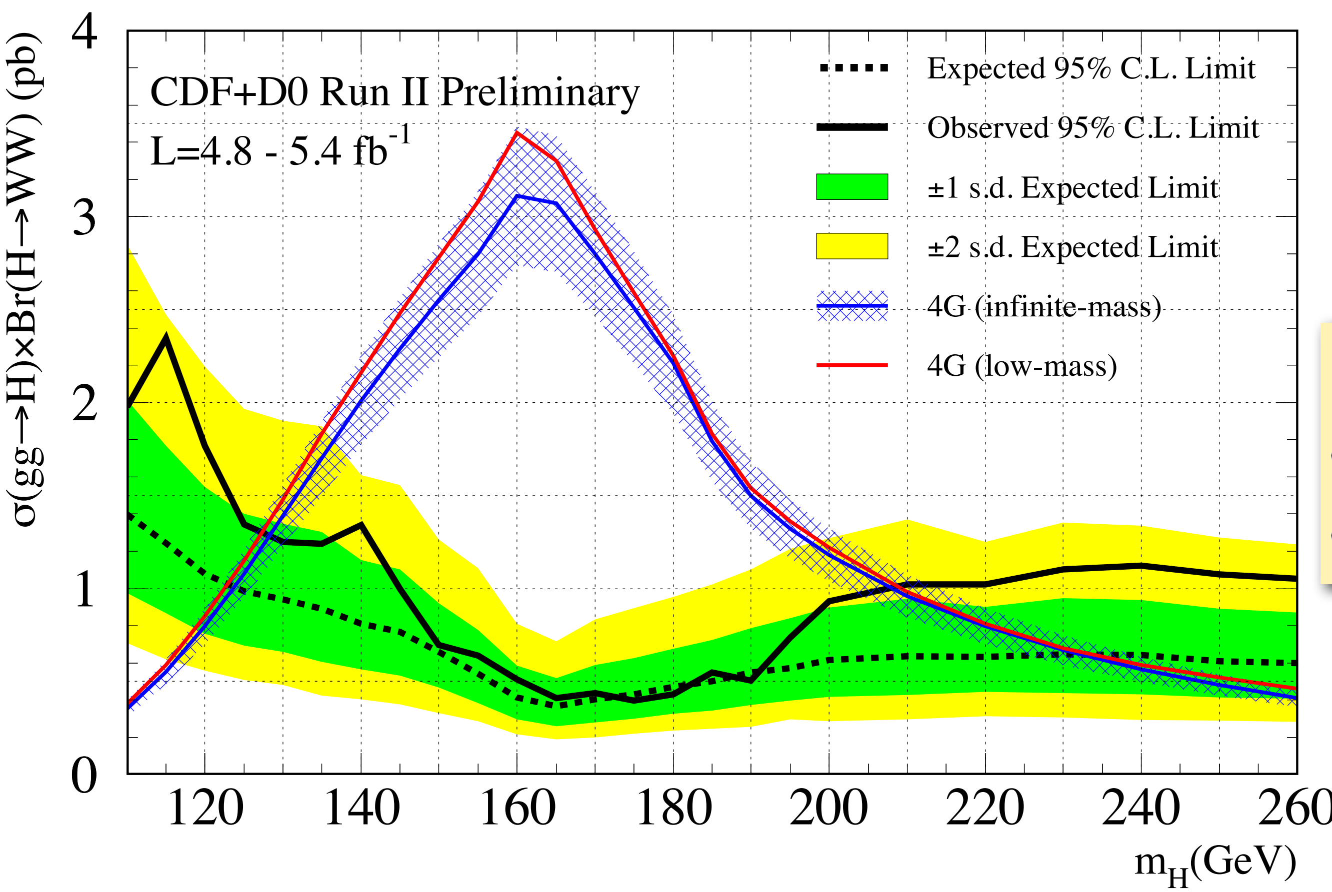


Significantly increased exclusion region
- low mass: 131 GeV < M_H < 204 GeV
- high mass: 131 GeV < M_H < 208 GeV

NMSSM Higgs Phenomenology

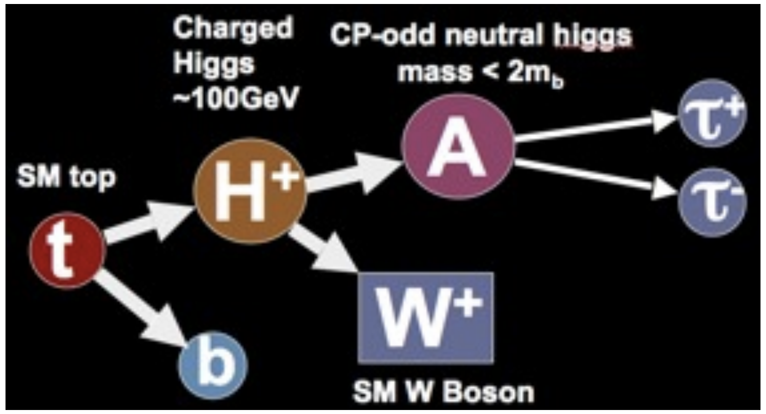
- NMSSM: adds one gauge singlet superfield
  - preserves $\rho=1$
  - SSB: replaces μ (MSSM) with dimensionless coupling constant
- Higgs sector:
  - additional CP-odd (a) and CP-even (h) Higgs boson

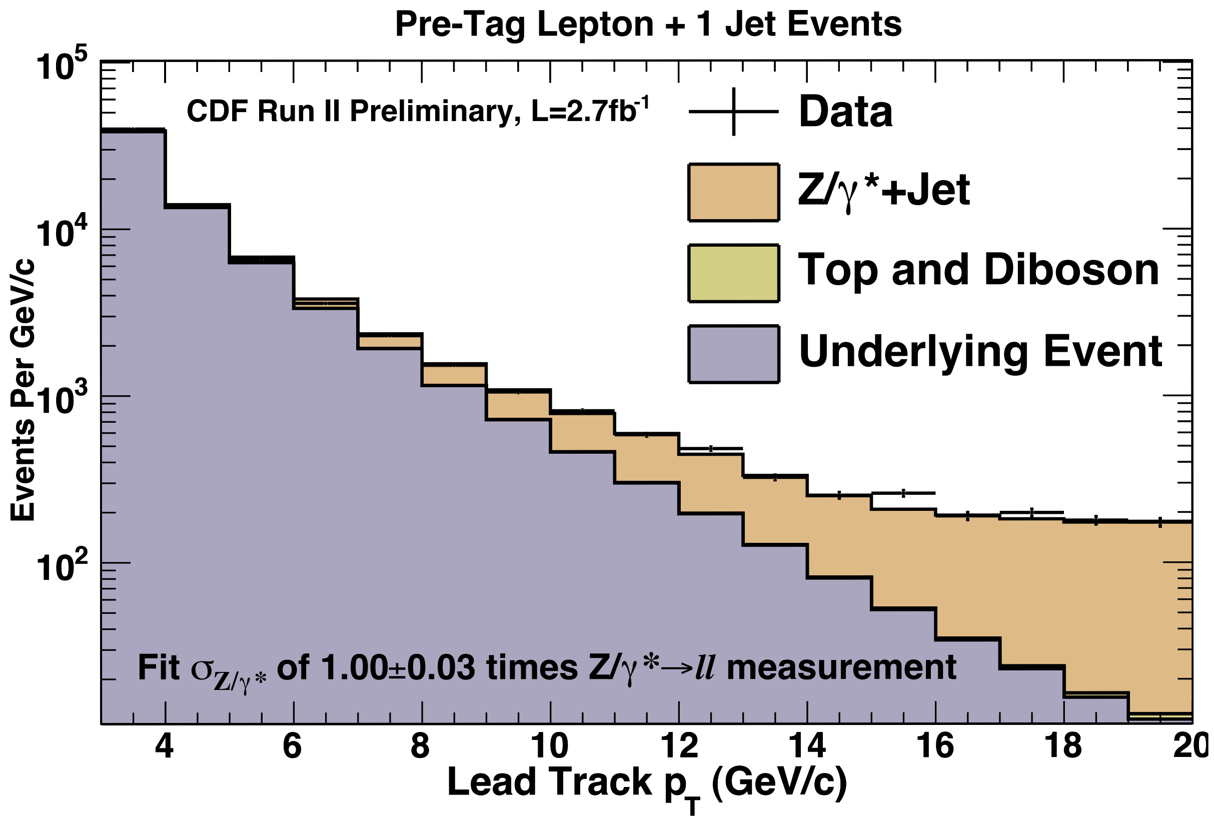
- Allows for Higgs loophole at LEP:
  - SM-like h (within LEP kinematic reach), decaying mostly as $h \to aa$
  - $M_a < 2m_b$: $a \to \tau\tau$, gg, cc
    ➠ only looked for by OPAL in MSSM context
    - limited to $m_h < 86$ GeV

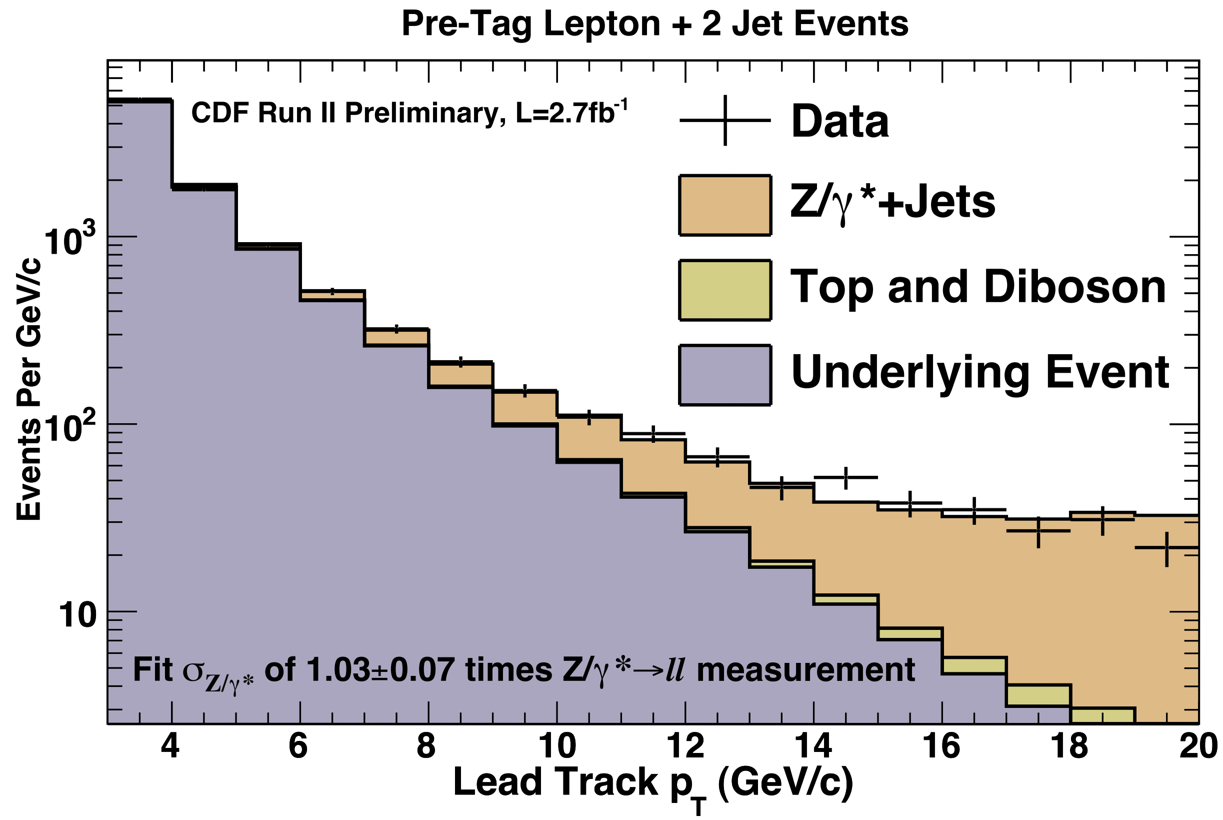
new

NMSSM: Charged Higgs Boson

- CDF analysis (2.7 fb-1): search in l+jets sample (regular tt event w/ extra $\tau^+\tau^-$ pair)
  - soft τ's ➠ identify through add'l isolated track
  - backgrounds:
    - underlying event (universal p_T spectrum, check in l+1/2jet events)
    - Z/γ^*+jets (1 lepton missed or from τ decay)







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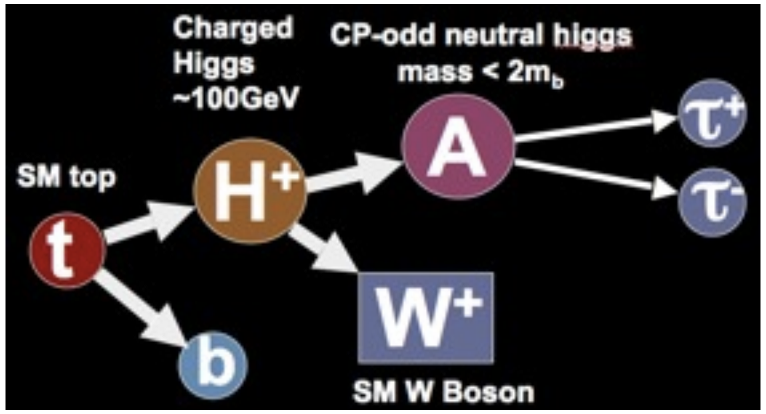
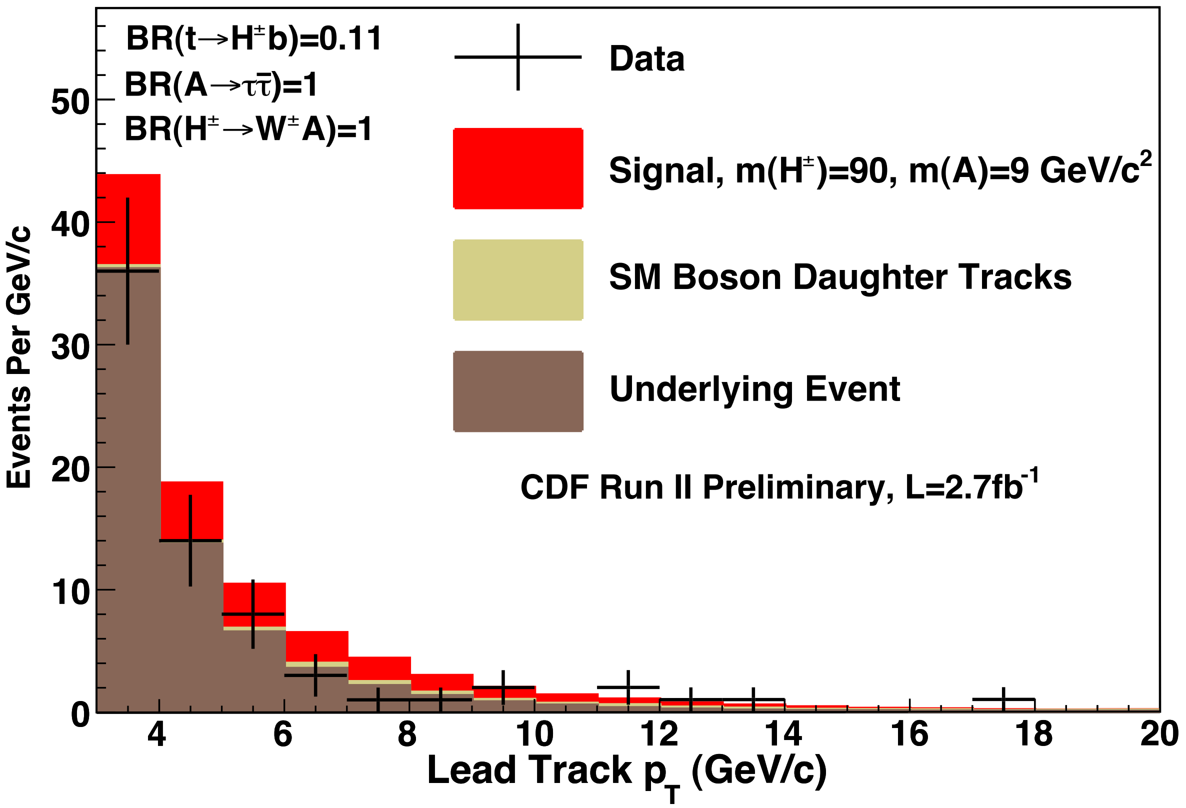


Fit as function of both m_a and M_H

- UE normalisation inferred from b-tagged 3-jet data
- signal shown at exclusion level



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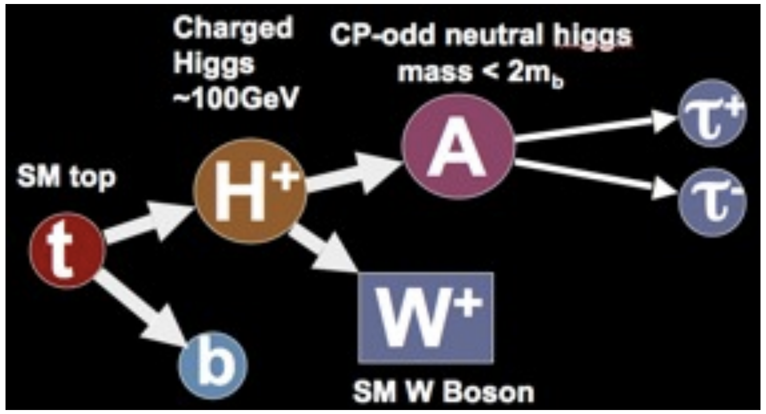

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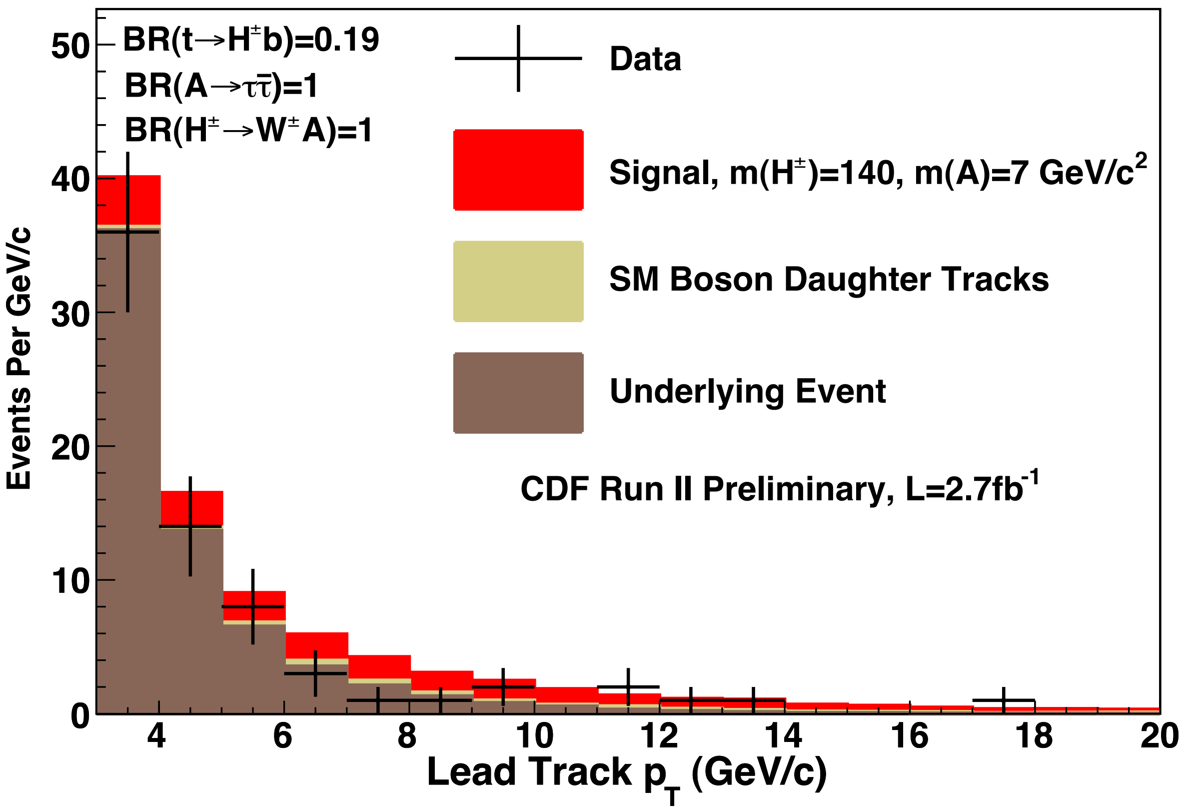

new

NMSSM: Charged Higgs Boson

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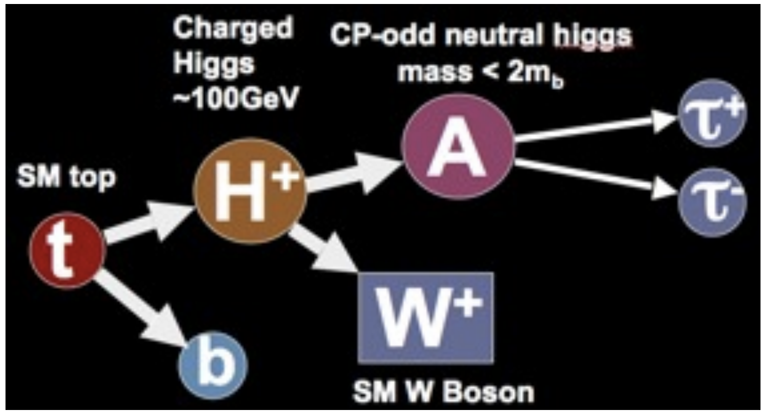
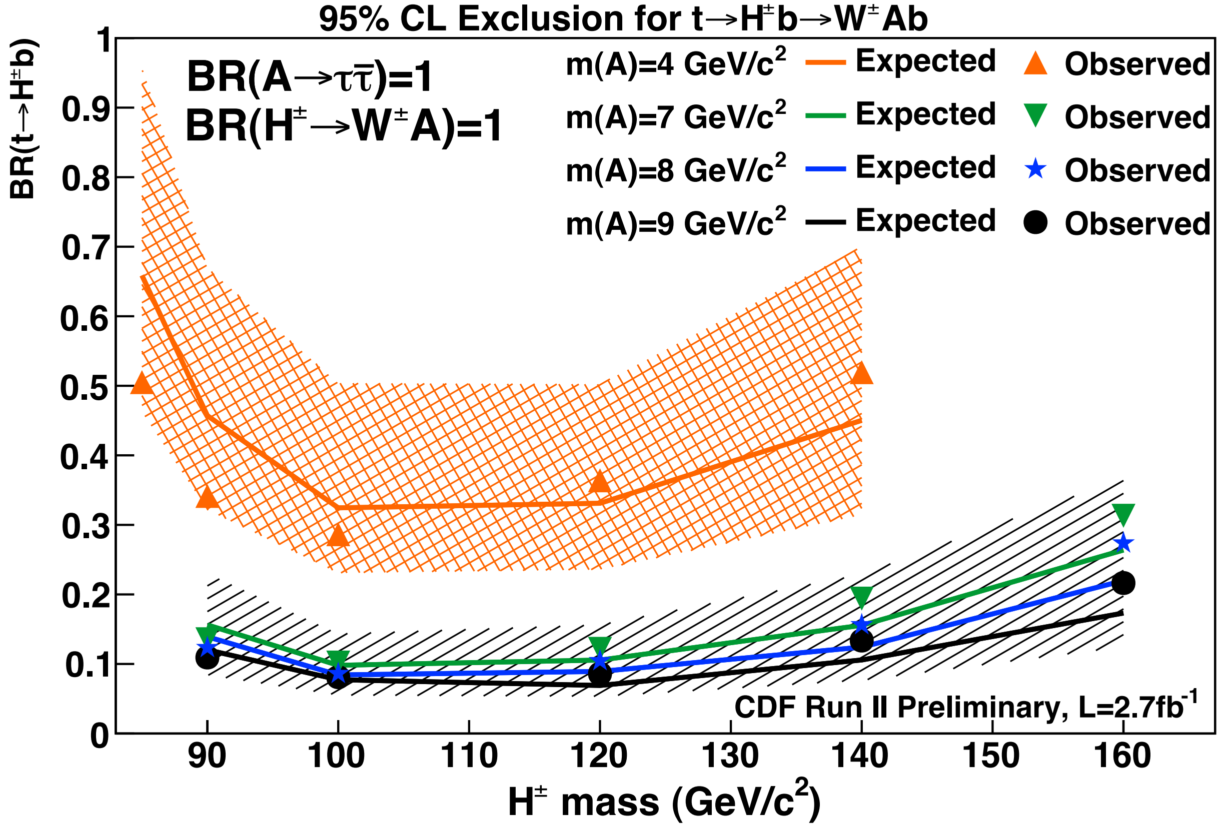
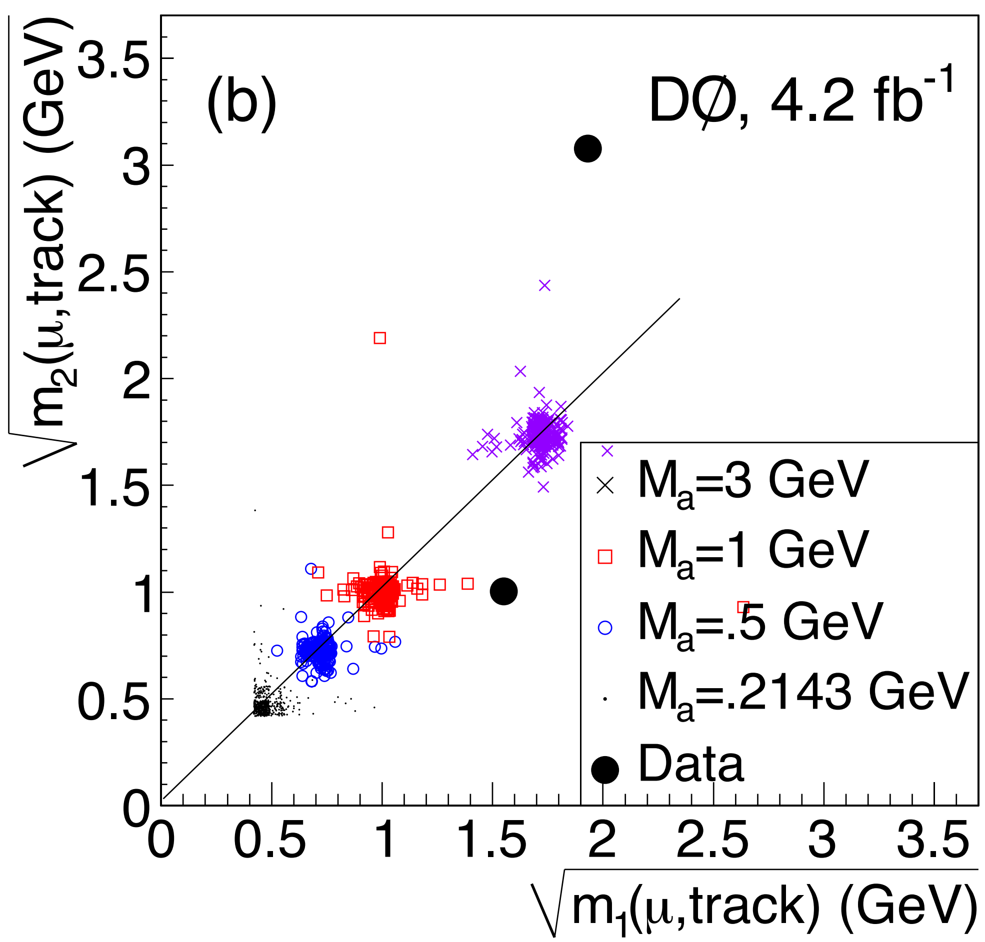




published

NMSSM: Neutral Higgs Boson

- D0 analysis (4.2 fb^{-1}): search for $gg \rightarrow h \rightarrow aa$, with $a \rightarrow \mu^+\mu^-/\tau^+\tau^-$ in inclusive dimuon events (p_T > 10 GeV)
  - $2m_\mu < m_a < 2m_\tau$: muons too collinear to be reconstructed separately ➠ association with track (R < 1) only (NB: BF uncertain)



- tight (μ+track) isolation criteria
- efficiency for collinear tracks from K_S

$$\sigma(p\bar{p} \rightarrow h + X) \cdot B(h \rightarrow aa) \cdot B(a \rightarrow \mu^+\mu^-)^2 < 10\,\text{fb}$$

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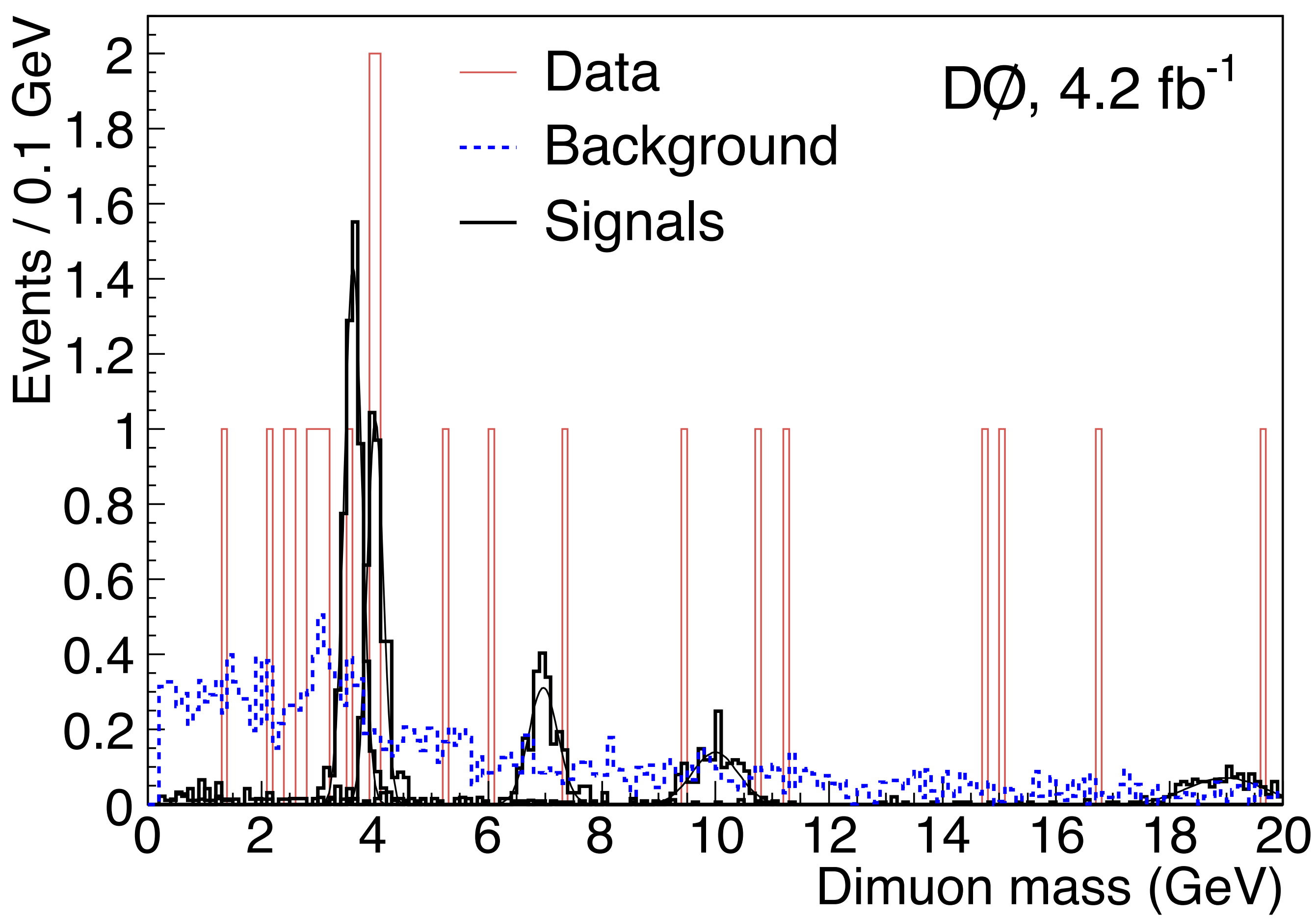
  - $m_a > 2m_\tau$ ($\mu^+\mu^-\tau^+\tau^-$): reconstruct $a \rightarrow \mu^+\mu^-$ candidates explicitly
    - use of muons ➠ low efficiency



- collimated τ not individually identified: $\not{E}_T$ / μ / e
- background estimated from low-$\not{E}_T$ region

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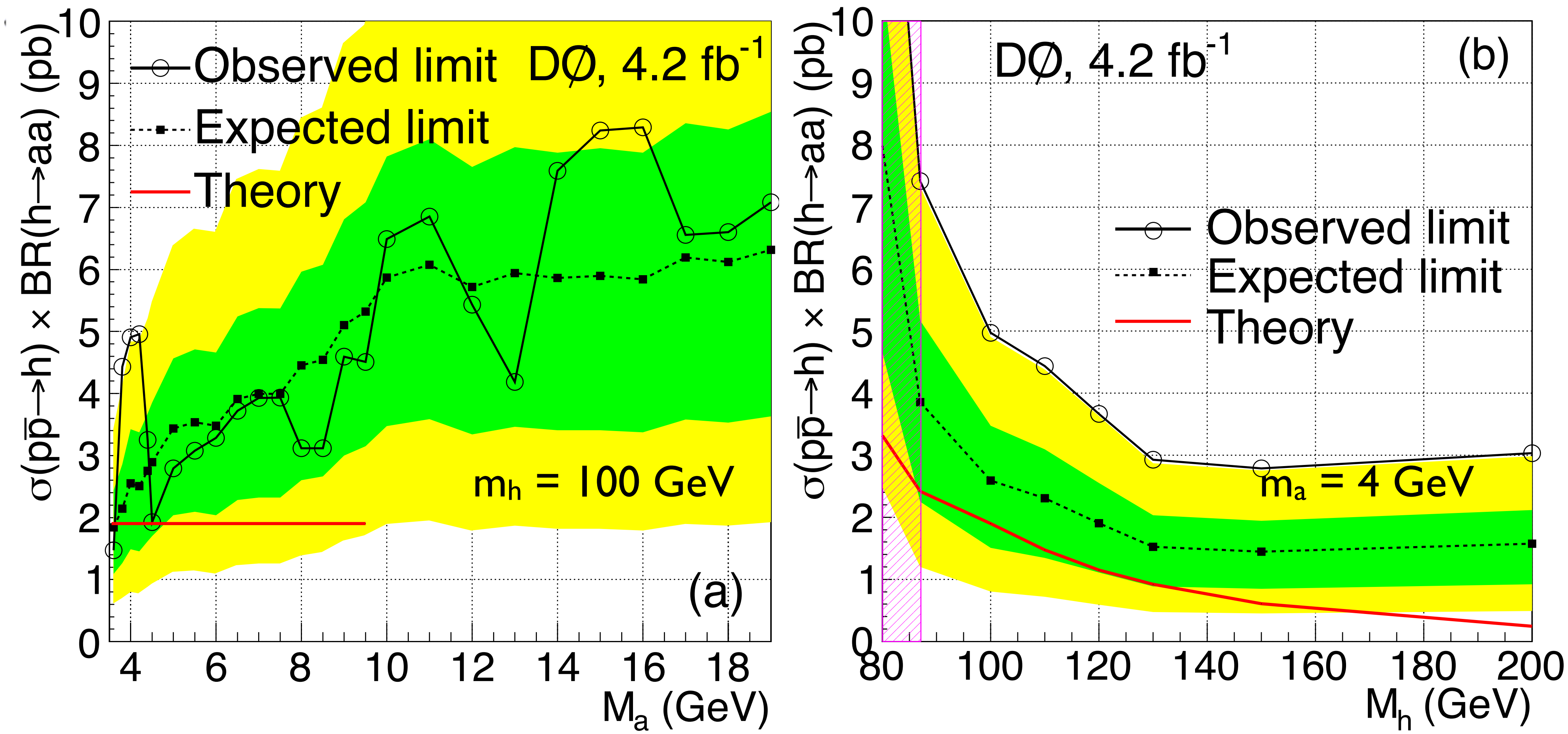

Not Discussed

- Fermiophobic Higgs boson searches
  - CDF $W^{\pm}h \rightarrow W^{\pm}W^{+}W^{-}$ (2.7 fb^{-1})
  - D0 $hhW^{\pm} \rightarrow \gamma\gamma\gamma\gamma W^{\pm}$ (0.8 fb^{-1})

- Doubly charged Higgs boson searches
  - D0 $H^{++}H^{--} \rightarrow \mu^{+}\mu^{+}\mu^{-}\mu^{-}$ (1.1 fb^{-1})
  - CDF $H^{++}H^{--} \rightarrow l^{+}\tau^{+}l^{-}\tau^{-}$ (0.3 fb^{-1})

Conclusion & Outlook

- Consolidation in mainstream MSSM analyses
- First MSSM combinations have been performed
- Analyses with significantly larger datasets are underway
- In the near future, the Tevatron will likely continue to play an important role in BSM Higgs physics