Beyond-SM Higgs Searches at the Tevatron and LHC

Andy Haas

SLAC National Accelerator Laboratory

for the

DØ, CDF, ATLAS, CMS Collaborations

Aspen Particle Physics Conference

Jan. 17-23, 2010

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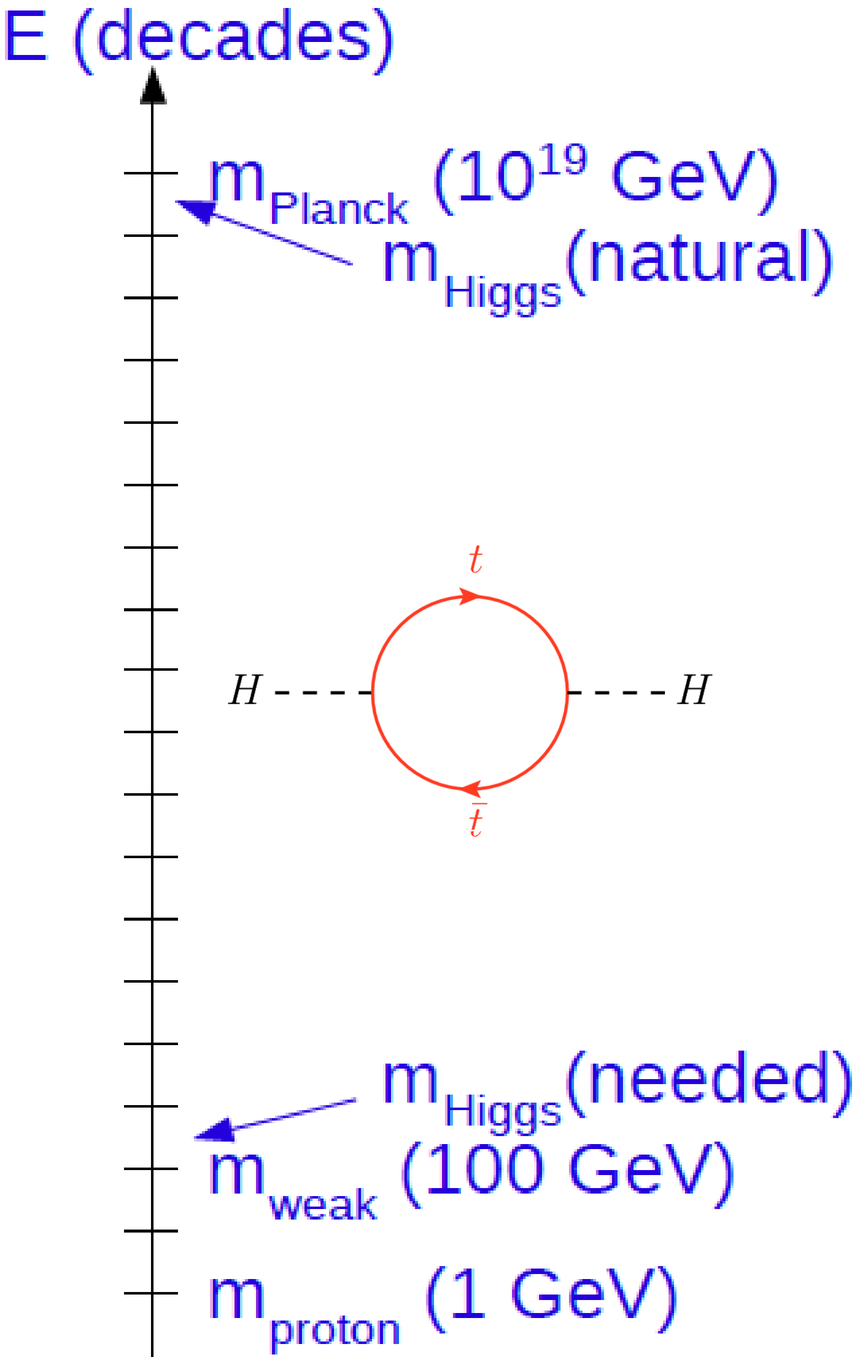
Outline

- Why we should expect a more complicated Higgs sector
- Tevatron searches: MSSM (h/H/A, H^{+-}), NMSSM
- LHC prospects
- Conclusions



Hierarchy Problem:

Radiative corrections to m_H depend quadratically on new physics scale

$$\Delta m_H^2 \supset \frac{G_F \Lambda^2}{4\sqrt{2}\pi^2}\left(6\,m_W^2 + 3\,m_Z^2 + m_H^2 - 12\,m_t^2\right)$$

Possible "solutions":

1) New physics at TeV scale:
   SUSY, Technicolor, ...

-> ***More complicated Higgs sector!***

2) Quantum gravity scale is ~TeV:
   Large extra dimensions

3) Oh well, we're just really lucky!

MSSM Higgses

Two Higgs doublets: H_u and H_d

5 Higgses: h, H, A, $H^{+/-}$

tanB -> ratio of H_u/H_d VEVs

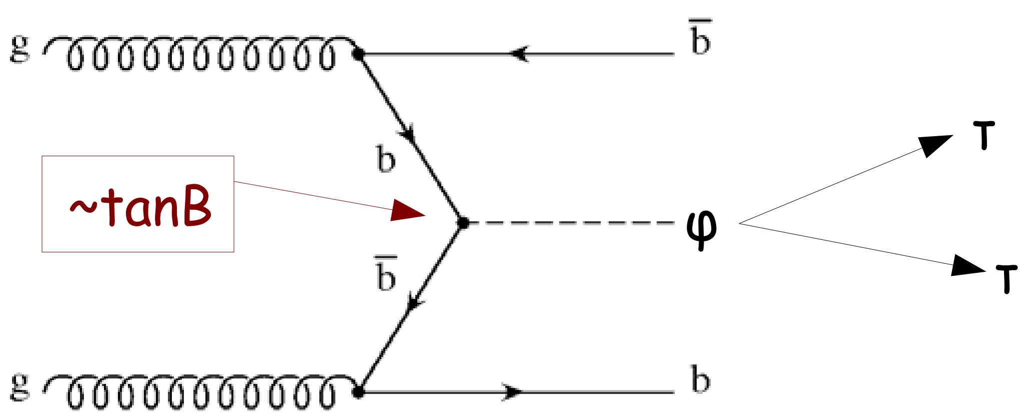
- If large could explain m_t/m_b ~35

At large tanB, degenerate h/H and A (φ):

- Production cross-section goes like $\tan^2 B$!
- BR(φ->bb)~90%, BR(φ->ττ)~10%, BR(φ->μμ)~0.03%

m_h^{max} **scenario:**

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

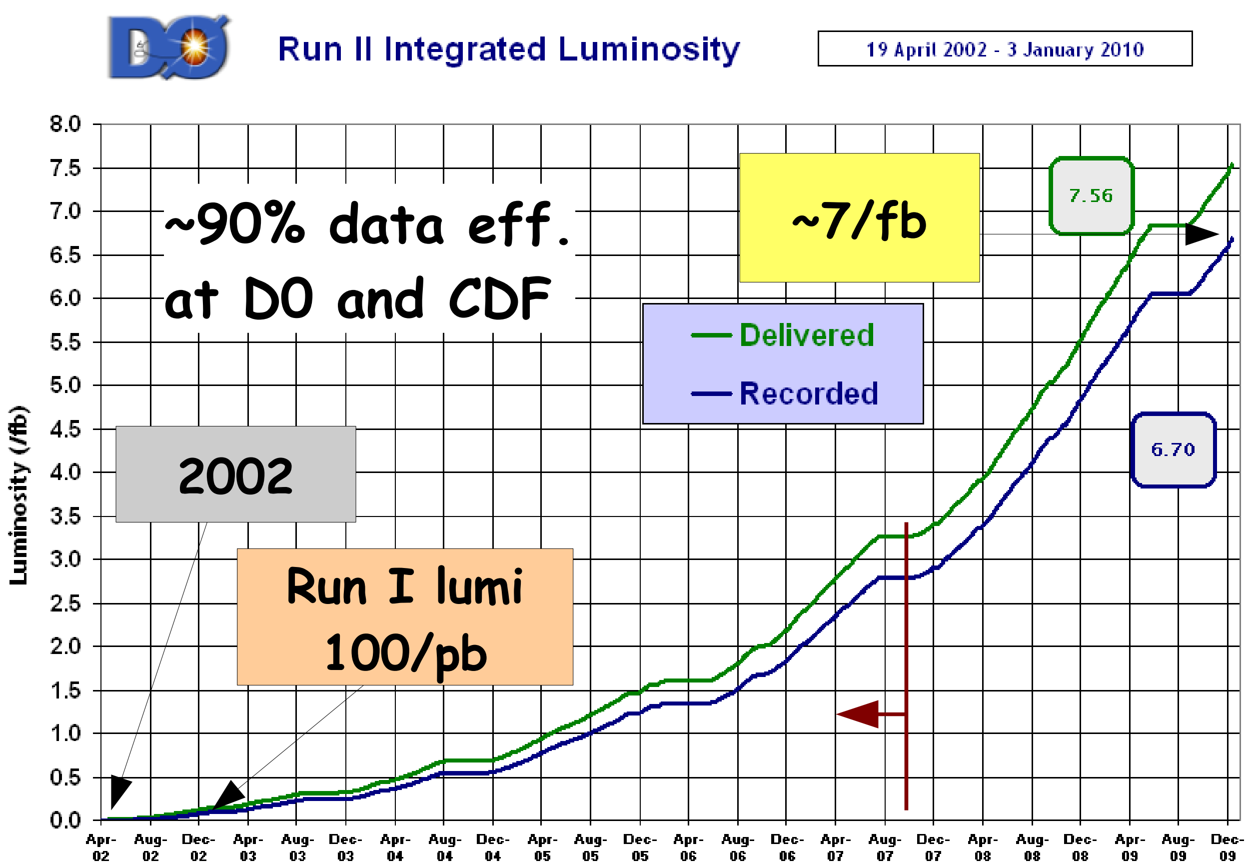


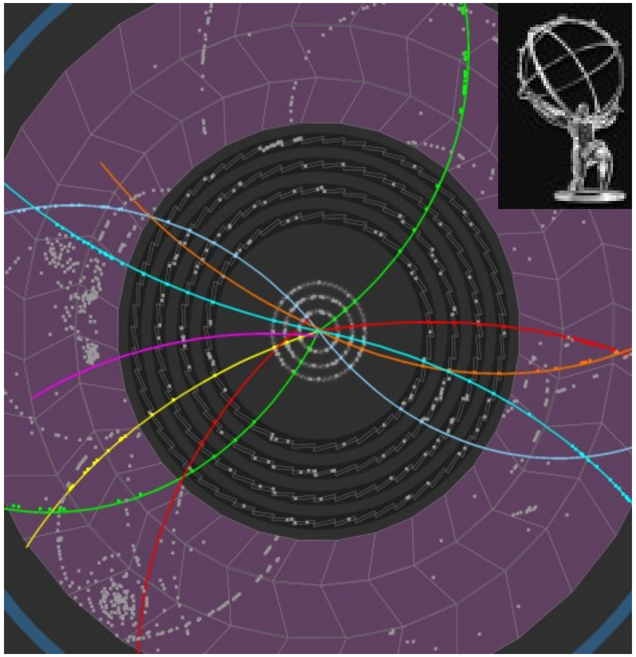
Tevatron:	LHC:
• φ->ττ	• φ->ττ
• bφ->b(ττ)	• bφ->b(ττ)
• bφ->b(bb)	• φ->μμ
	• bφ->b(μμ)

Tevatron and LHC Data

Tevatron to deliver ~12/fb by 2011

Many BSM Higgs analyses only using first ~1/2 of data so far…





LHC has data!

~10/μb, mostly at .9 TeV and some at 2.36 TeV

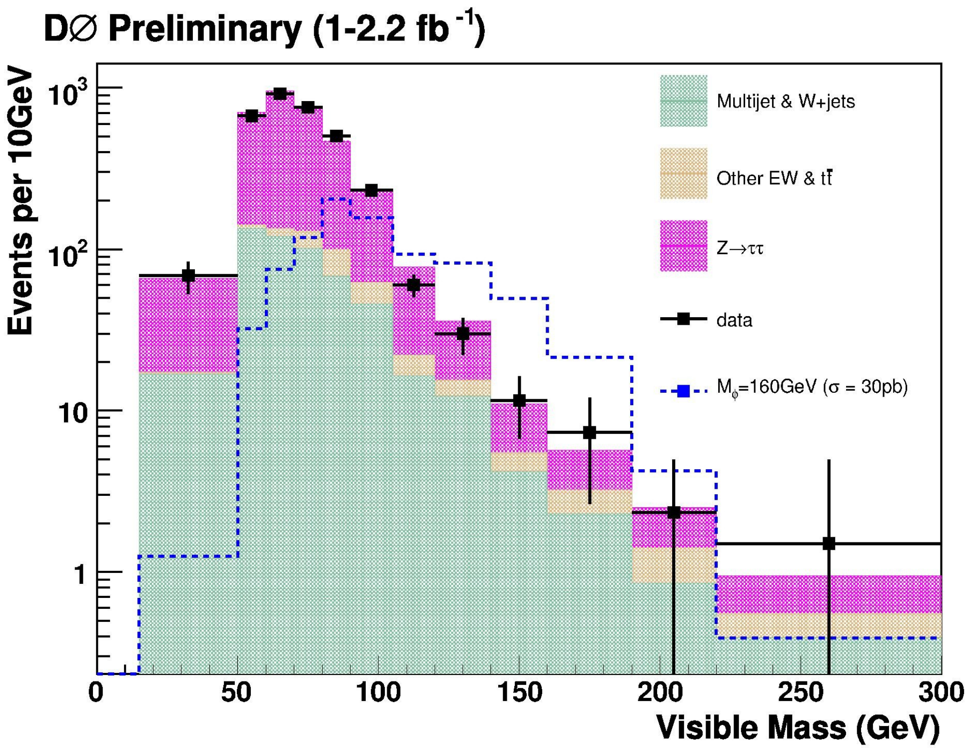
(Tevatron delivers ~100/μb *each second*!)

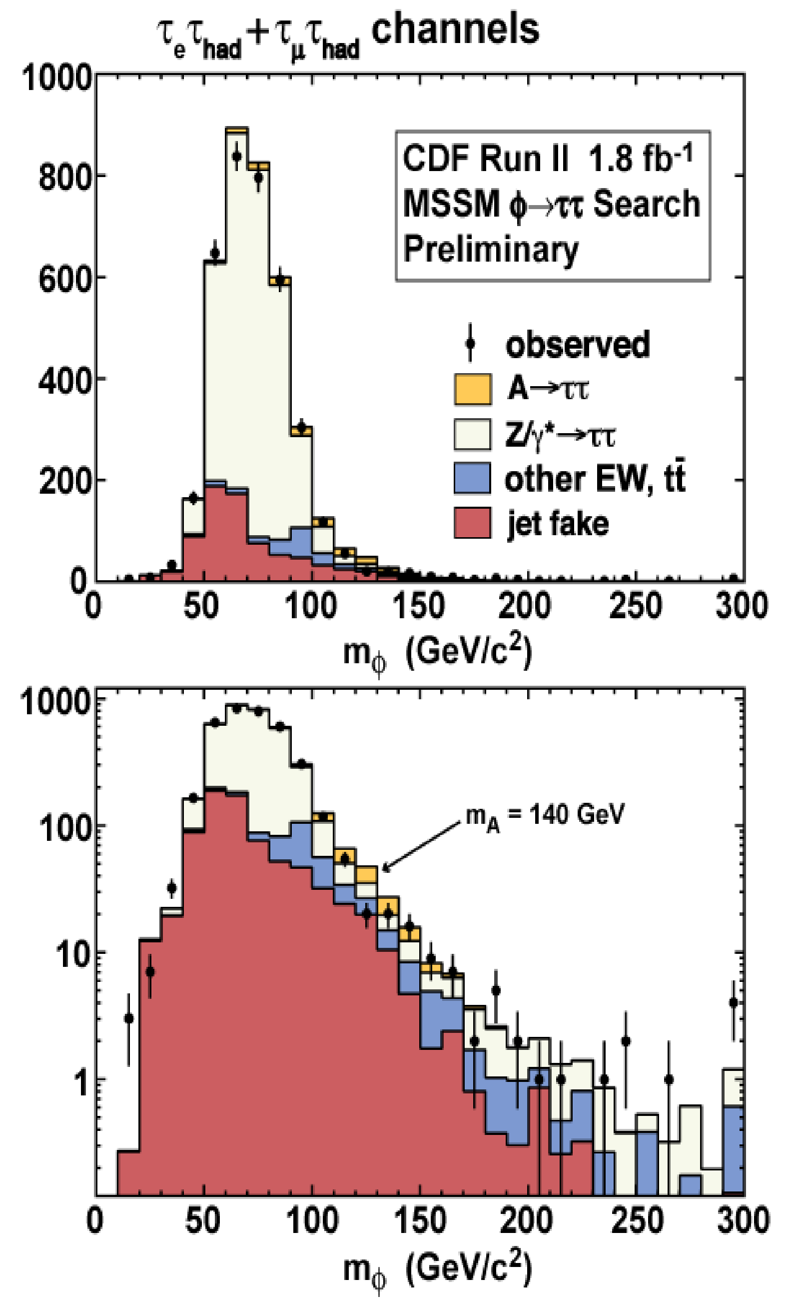
Tevatron φ->ττ

Require at least one leptonic tau decay

Use *visible mass* :

$$m_{\text{vis}} = \sqrt{(p^{\tau_1} + p^{\tau_2} + \not{E}_T)^2}$$





D0 bφ->b(ττ)

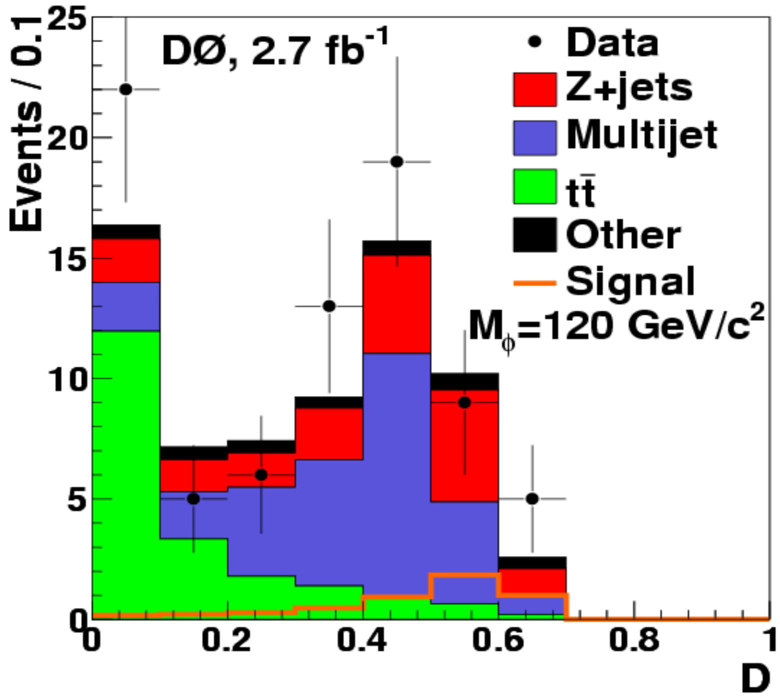
D0 has an orthogonal search requiring an additional b-jet

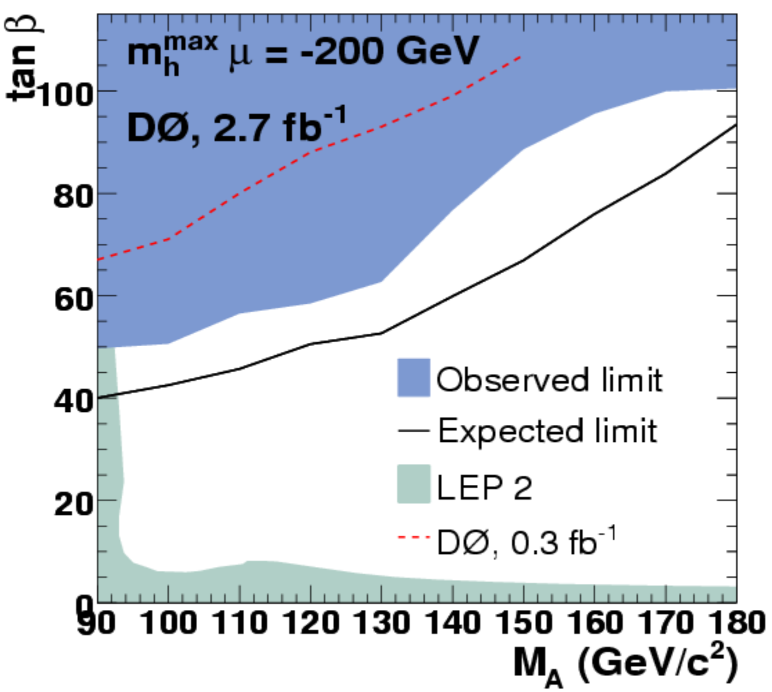
Requires one muonic tau decay

NN against tt, LH against multijet

Discriminant: D = NN x LH

Comparable sensitivity to φ->ττ channel





Tevatron bφ->b(bb)

At least 3 b-tagged jets

Large multijet background:

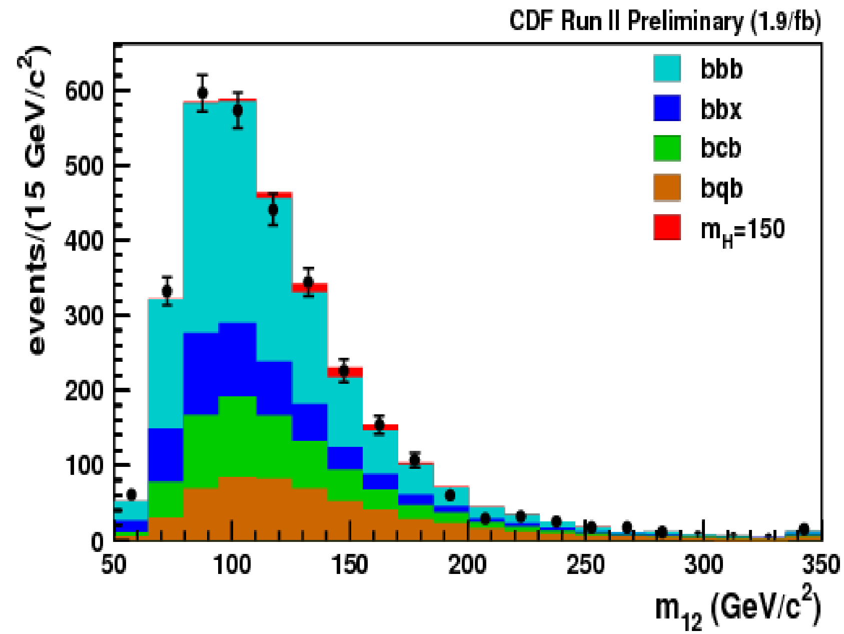
Estimate from 2 b-tagged data and MC

Composition:

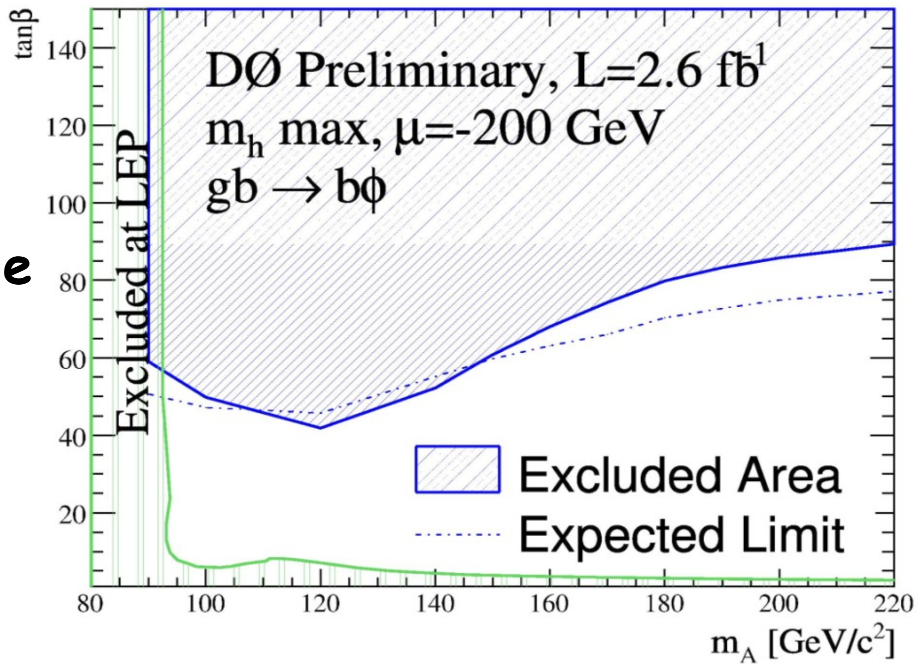
Sec. vertex mass (CDF)

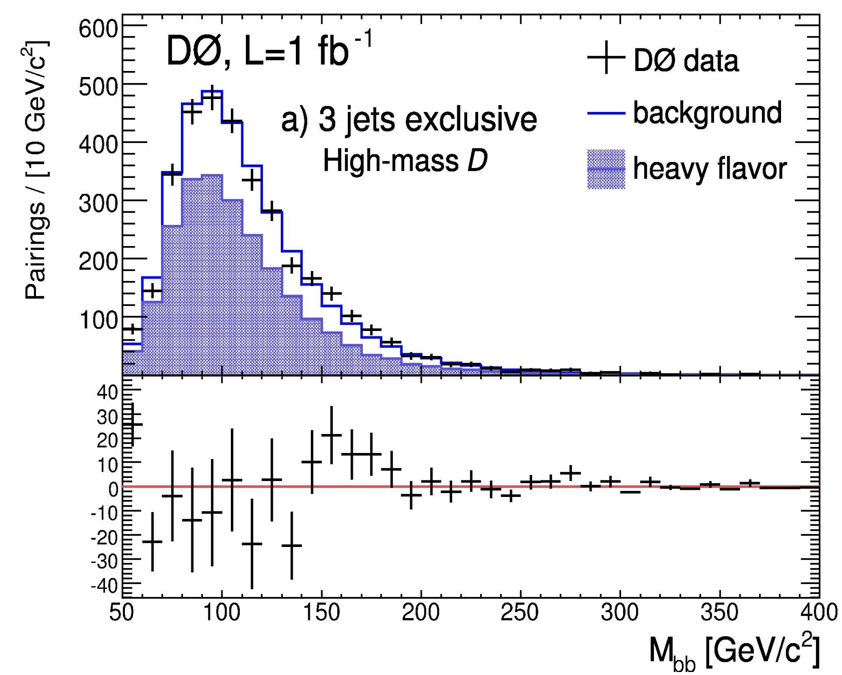
Fit to multiple b-tagging criteria (DØ)

Look for peak in dijet mass



Comparable to φ->ττ

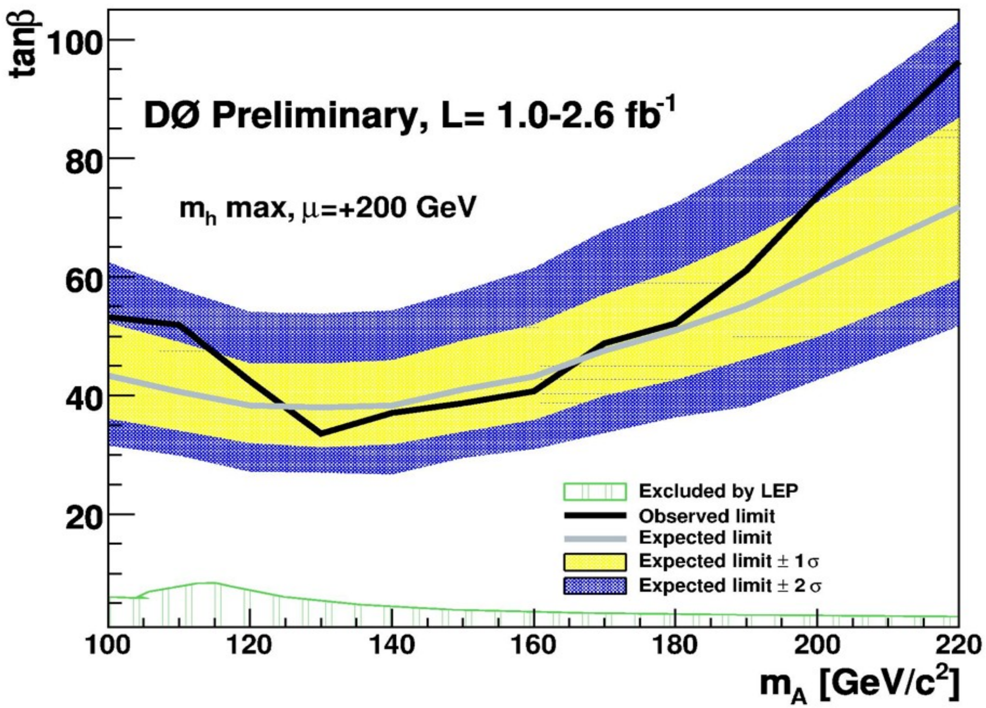




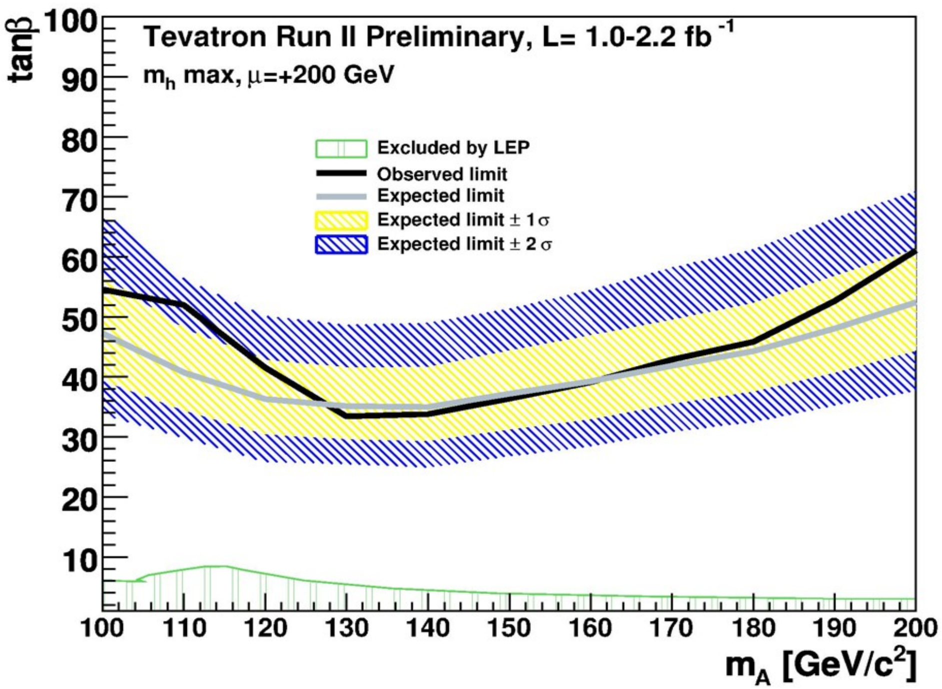
MSSM Combination

Same machinery as for SM

Combine across D0 channels:



And for φ->ττ between D0/CDF:



Reaching interesting tanB~35 range

tanB limit ~ $L^{1/4}$ (factor 2 more lumi lowers tanB by 1.2)

With full Tevatron lumi, sensitive down to tanB~20

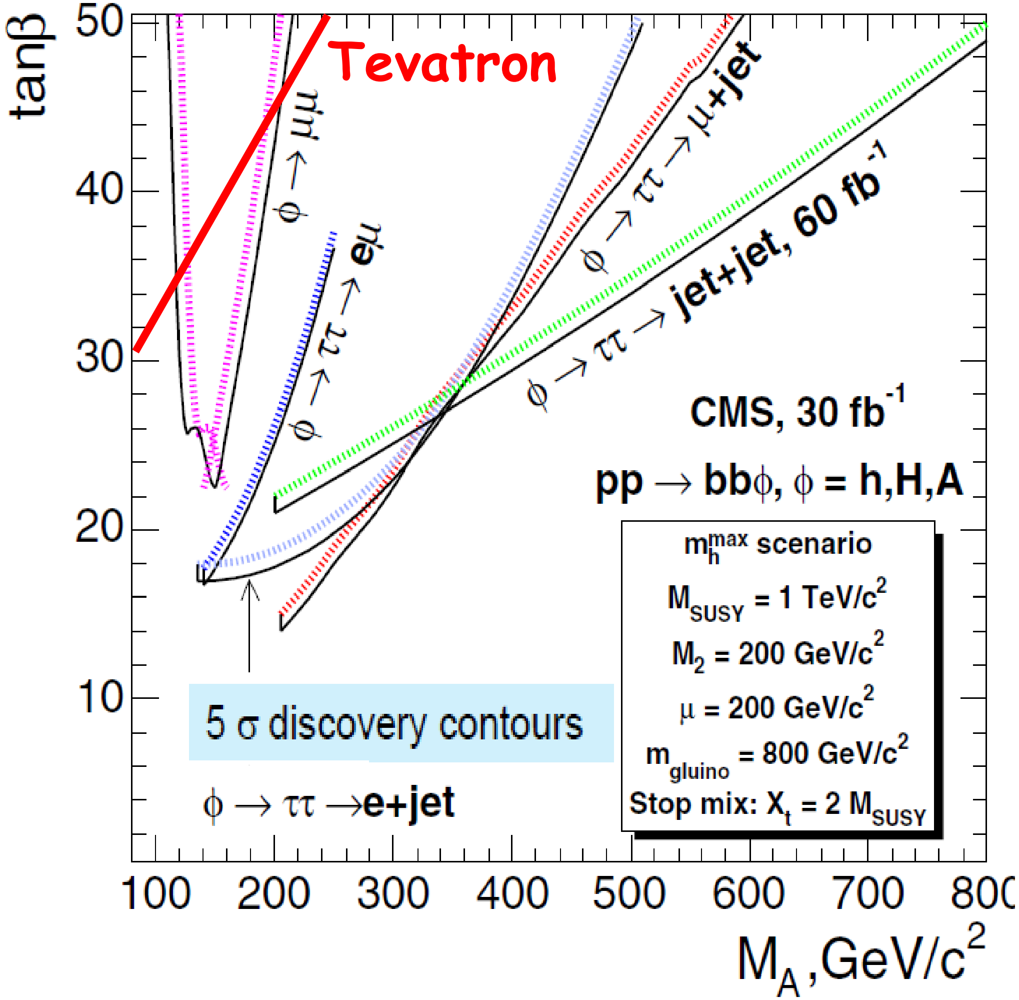
Ruling out SM-like Higgs < ~135 GeV would be another constraint...

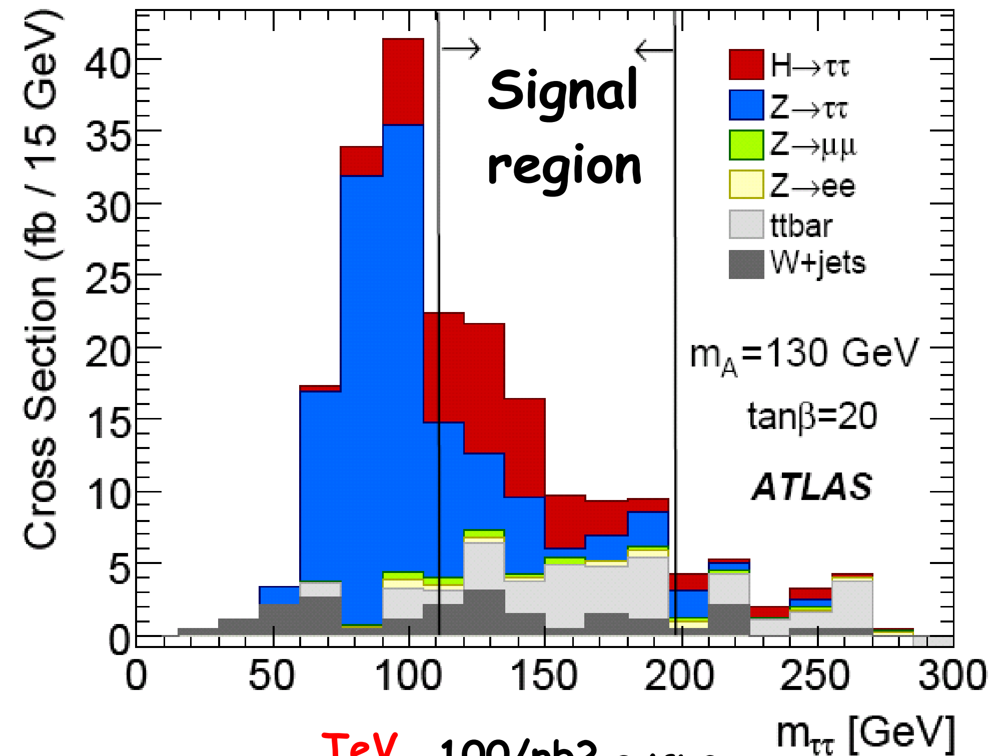
LHC MSSM Prospects for φ->ττ

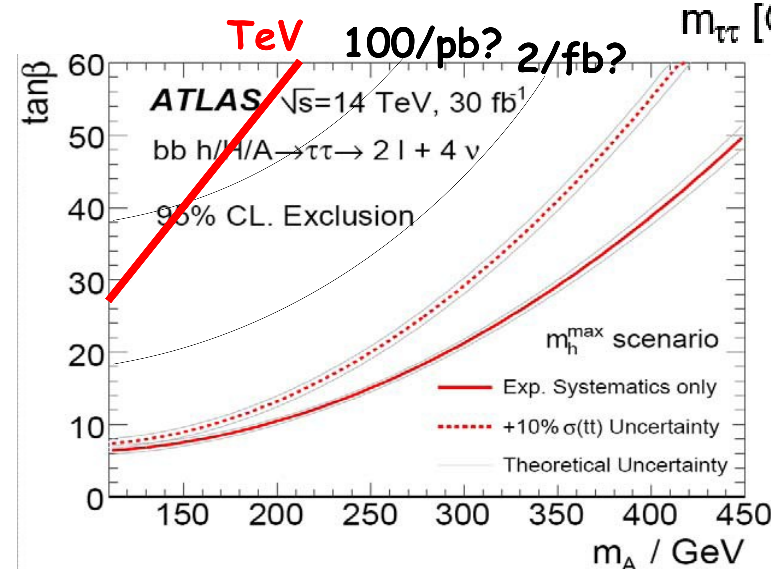
ATLAS and CMS consistent

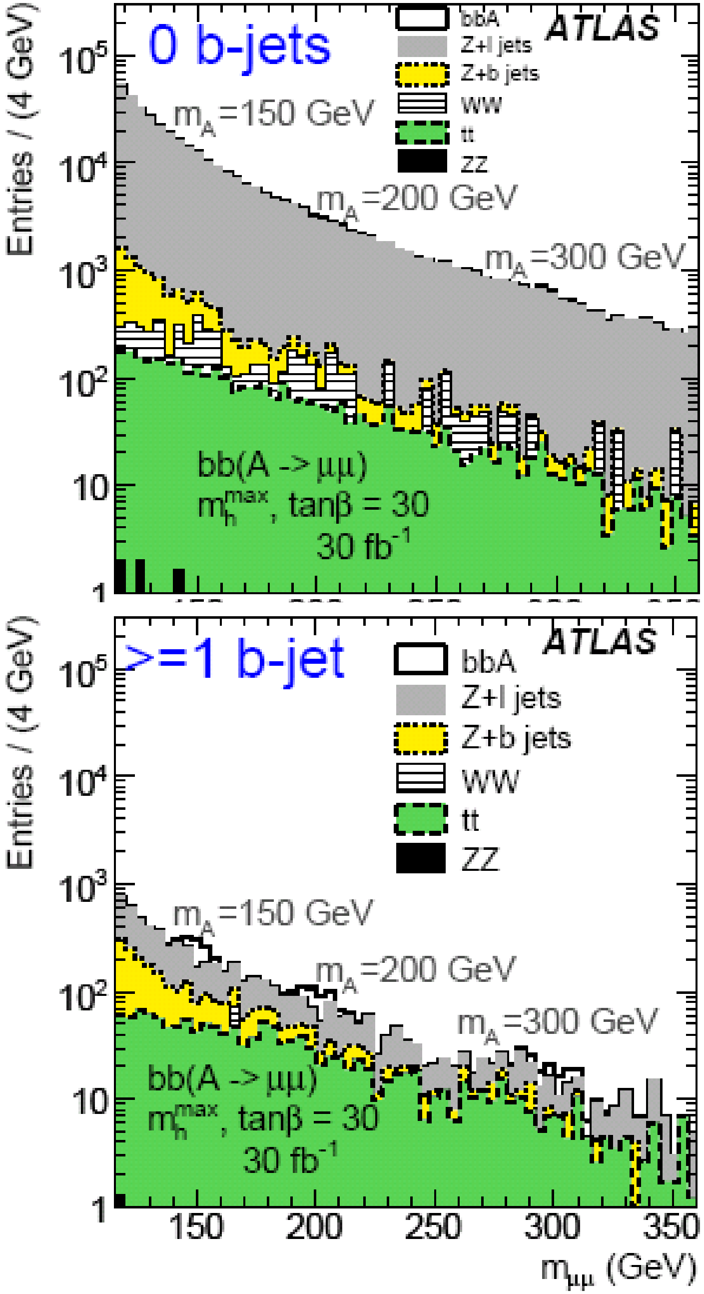
7/10 TeV are 10% effects until high mass

ttbar background at high mass





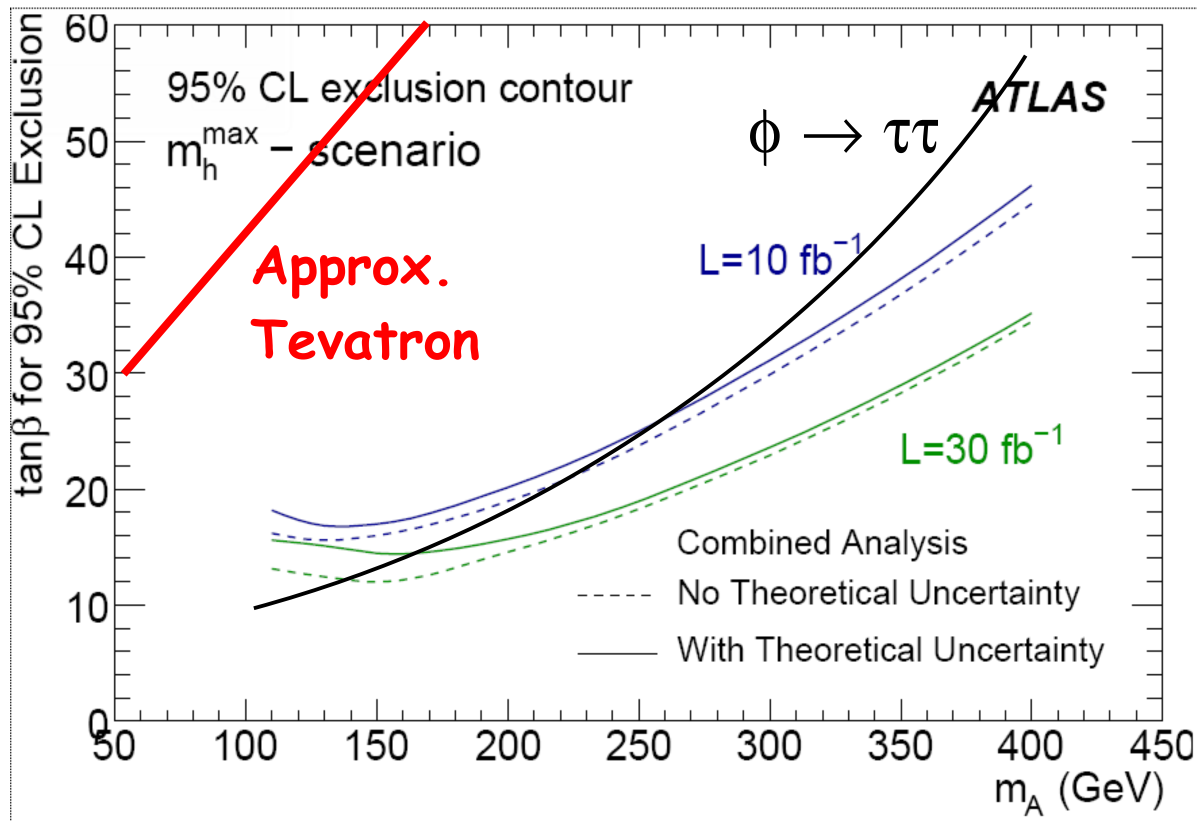




ATLAS also studies $\phi \to \mu\mu$

- BR to muons is 300 times smaller!
- 0 and 1 b-jet channels: $b(\phi) \to b(\mu\mu)$

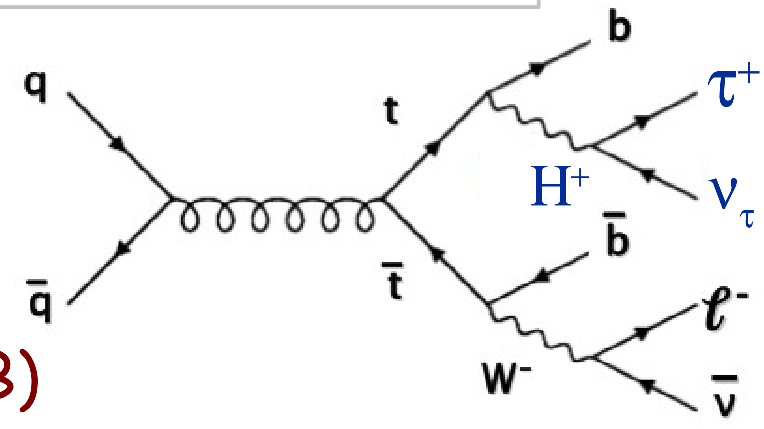
Comparable sensitivity to $\phi \to \tau\tau$



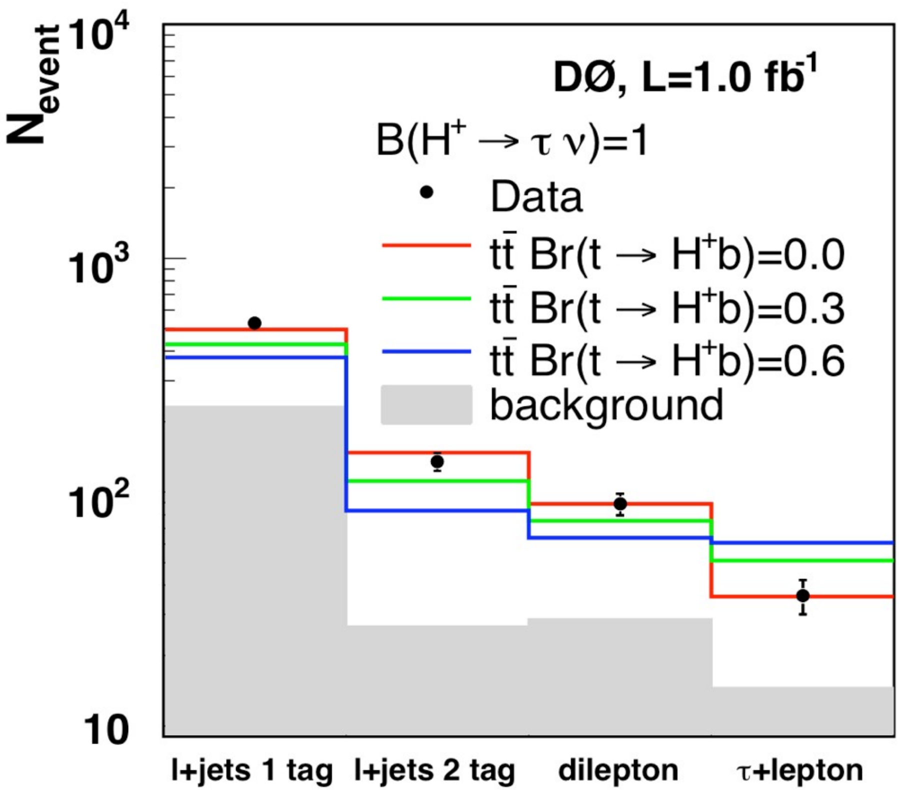
Tevatron Charged Higgs Searches

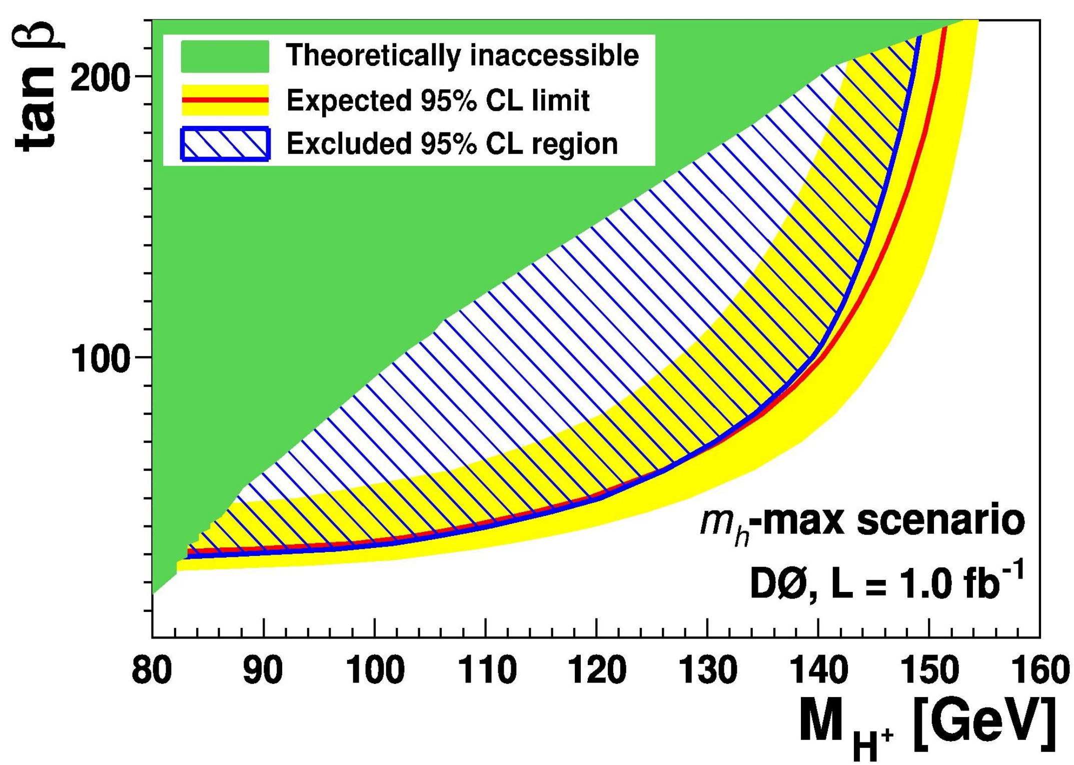
Look for $t \to H^+b$ decays

$H^+ \to \tau\nu_\tau$ ~100% instead of $W^+ \to \tau\nu_\tau$ ~10%



CDF also has search for $H^+ \to cs$ (low tanB)





LHC Charged Higgs Searches

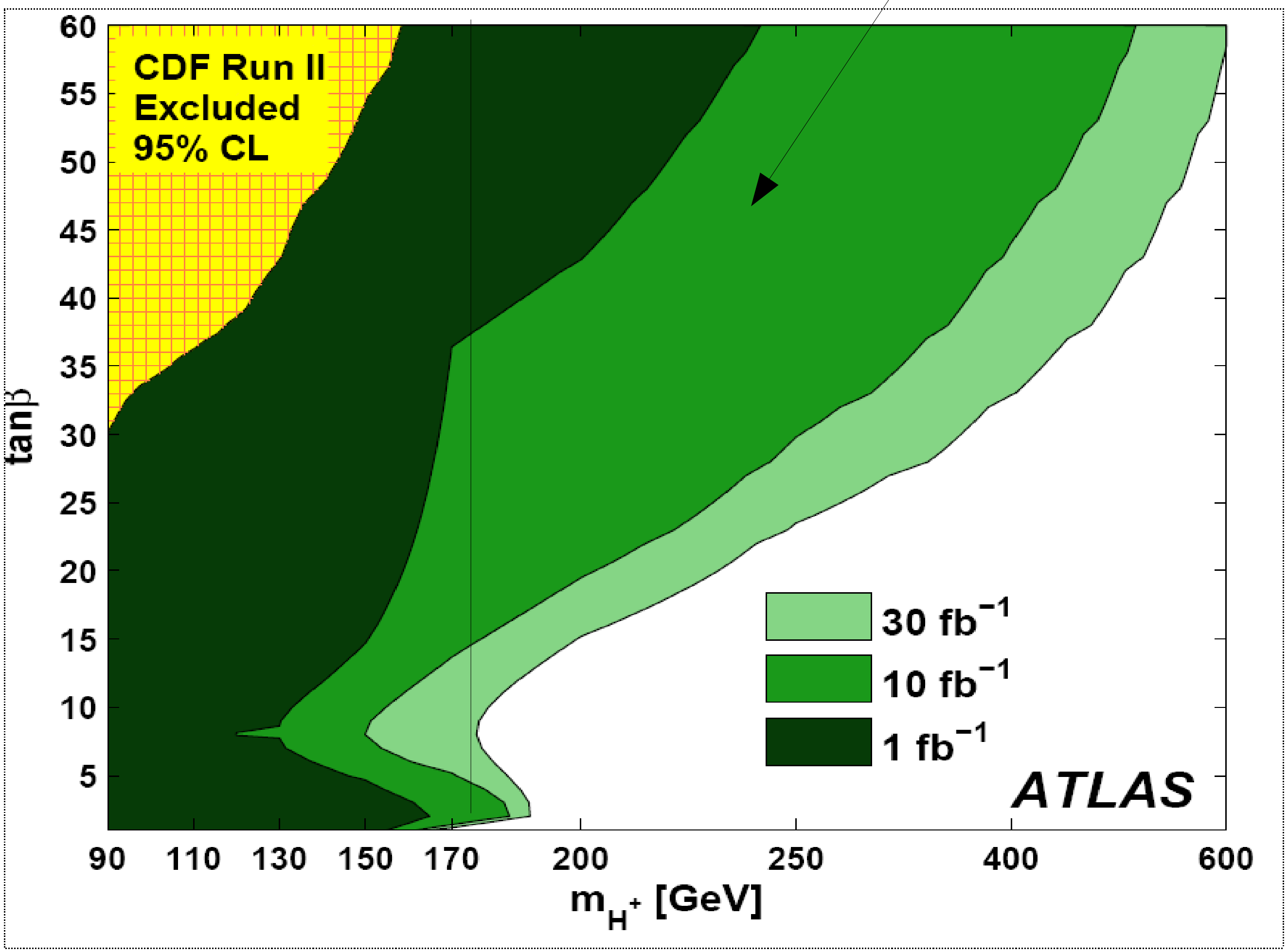
Production via: $gg \rightarrow H^{\pm}tb$ **and** $gb \rightarrow H^{\pm}t$

Decay modes:

$$H^{\pm}t \rightarrow \nu\tau_H bqq$$

$$H^{\pm}t \rightarrow tbt \rightarrow bWbbW \rightarrow bqqbbl\nu$$

t->H⁺b decays



LHC makes large sensitivity improvements with just 1/fb...

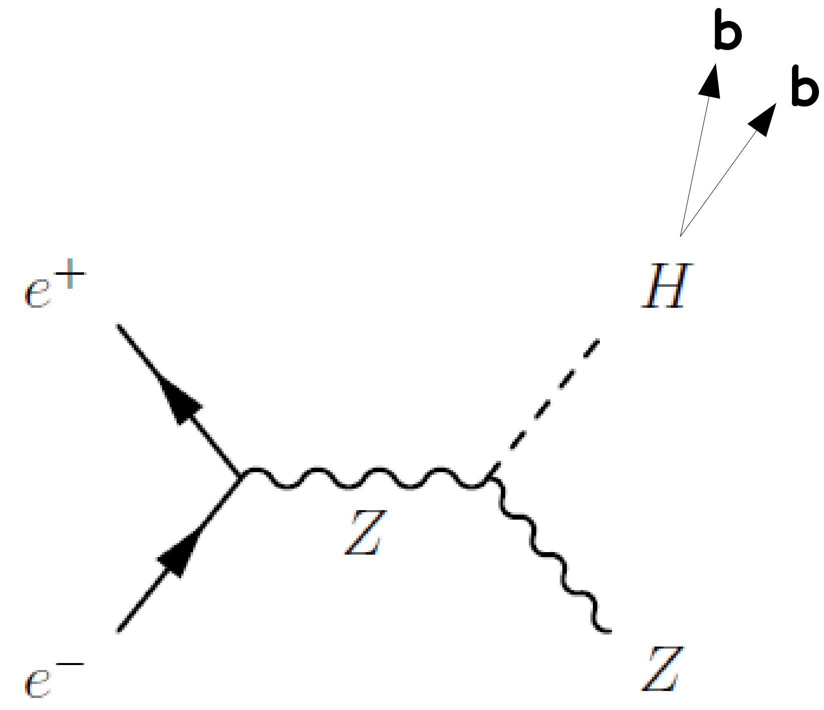
LHC is a top-factory!

Going Beyond the MSSM...

"Little Hierarchy Problem"

MSSM prefers a light "h" ~ 95 GeV

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \frac{3\, m_t^4}{4\pi^2 v^2} \ln \frac{M_S^2}{m_t^2} + \ldots$$



... but LEP says m_h>114.4 GeV !

Possible solutions:

1) Coupling to Z is reduced
   or BR(h->bb) is reduced

-> More complicated Higgs sector than MSSM...

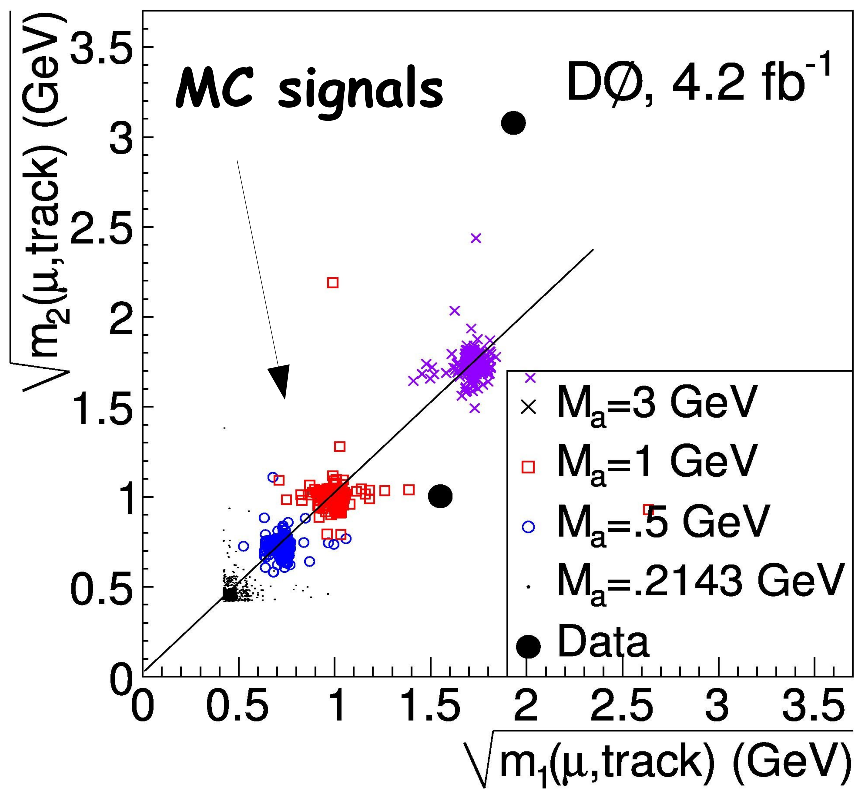
2) We just happen to live in a world with large stop mixing!

D0 Higgs Searches in NMSSM

New *very light* *pseudo-scalar* : "a"
h->aa decay dominates

$2m_\mu < m_a < 2m_\tau$:
Search for h->aa->4μ

Two pairs of collinear muons
(look for two mu+track pairs)
Backgrounds: Multijet, Z->μμ+jets



Limits: BR(a->μμ)<7%
Constrains m_a range in NMSSM

M_a (GeV)	Window (MeV)	Eff.	N_{bckg}	N_{obs}	$\sigma \times$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

D0 Higgs Searches in NMSSM

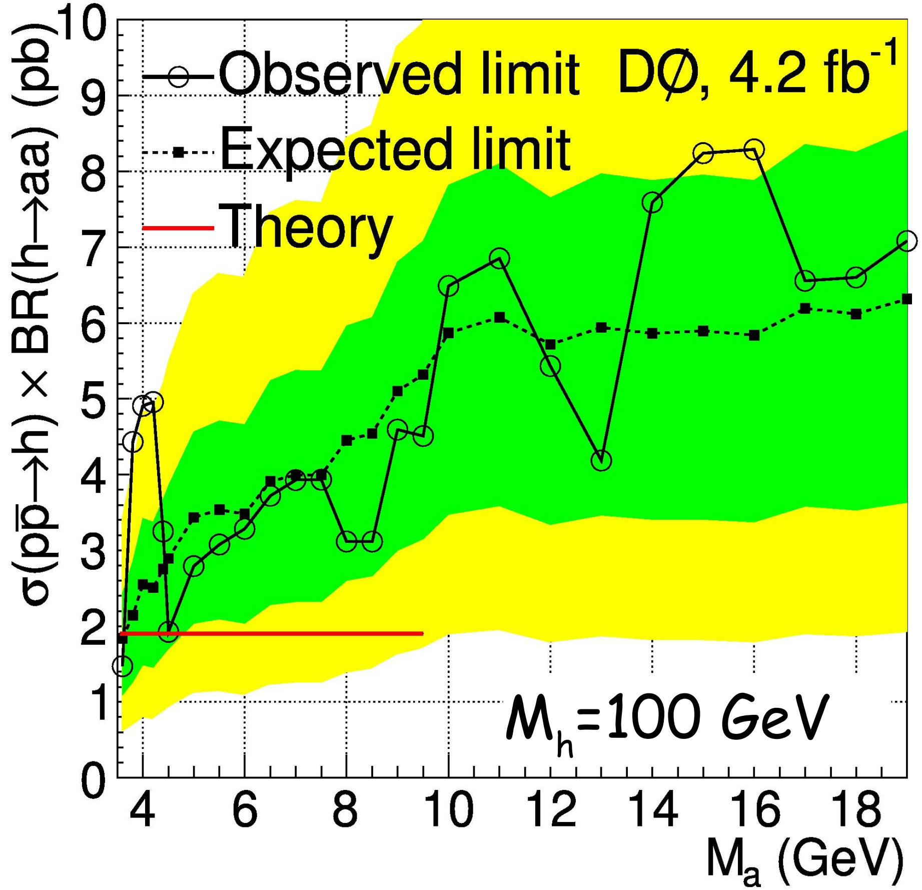
$2m_\tau < m_a < 2m_b$:

Search for h->aa->2μ2τ

(lower BR than 4τ, but cleaner)

Backgrounds: Multijet, γ*+jets, ...

Look for peak in $M_{\mu\mu}$



Exclude 1-2x expected cross-section

2 sigma excess at 4 GeV!

Tevatron could cover full m_a range

LHC will be competitive with ~100/pb

OPAL search for Zh(->4τ): m_h>86 GeV

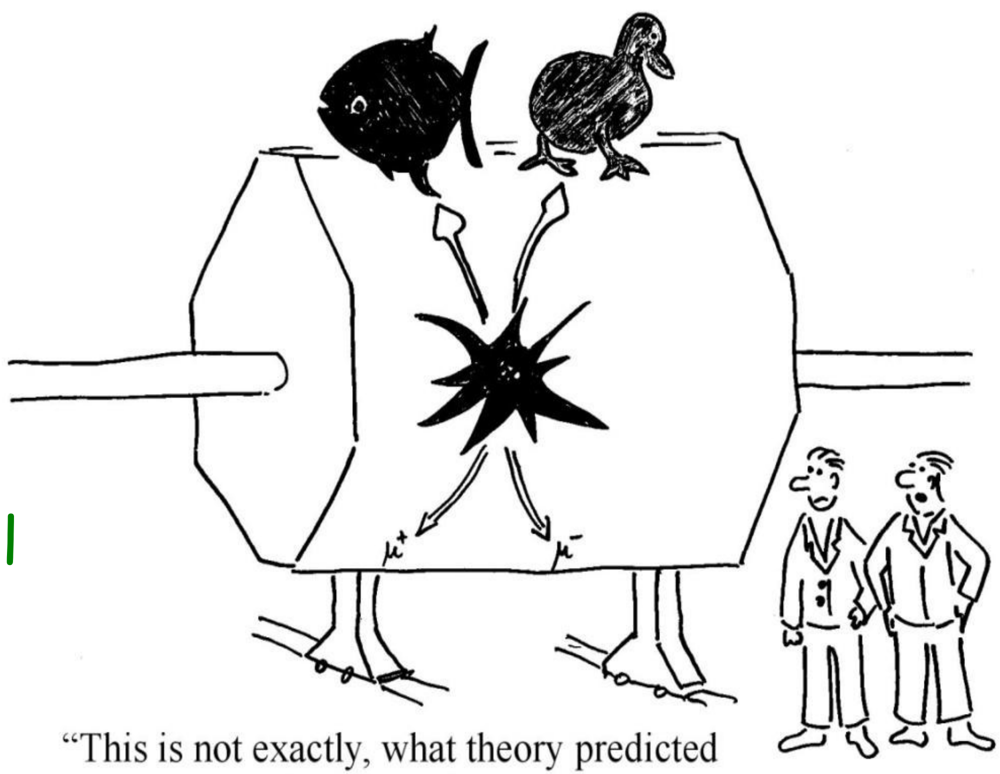
Recent preliminary ALEPH search extends to m_h>~100 GeV

Going Even Further Beyond...

- CP violating Higgs(es)
- Invisible Higgs
- Technicolor
- Higgsless models
- Little Higgs
- Hidden Valley
- ...

Leave no stone unturned!

Active LHC studies ongoing in all these areas and more...



"This is not exactly, what theory predicted for the Higgs decay!"

Conclusions

Hopefully the Higgs sector will be richer than the SM's...

Experiments mostly focused on SUSY Higgs so far

- Tevatron MSSM searches
  - exclude H/A down to tanB~30, for small masses
  - some H^{+} at large tanB
- LHC will extend to much higher masses and lower tanB, starting with ~1/fb of data (2011?)
- D0 NMSSM searches start to exclude, LHC will be more sensitive

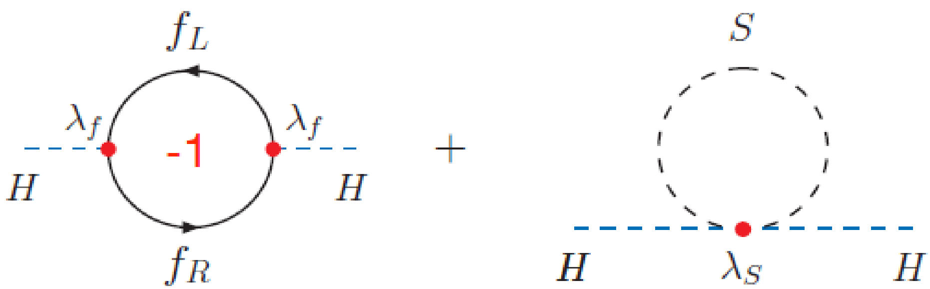
And we're ready for the unexpected!

Non-SM Higgs discovery – a great start to a revolution!

Backup

Supersymmetry offers a beautiful solution to the hierarchy problem...

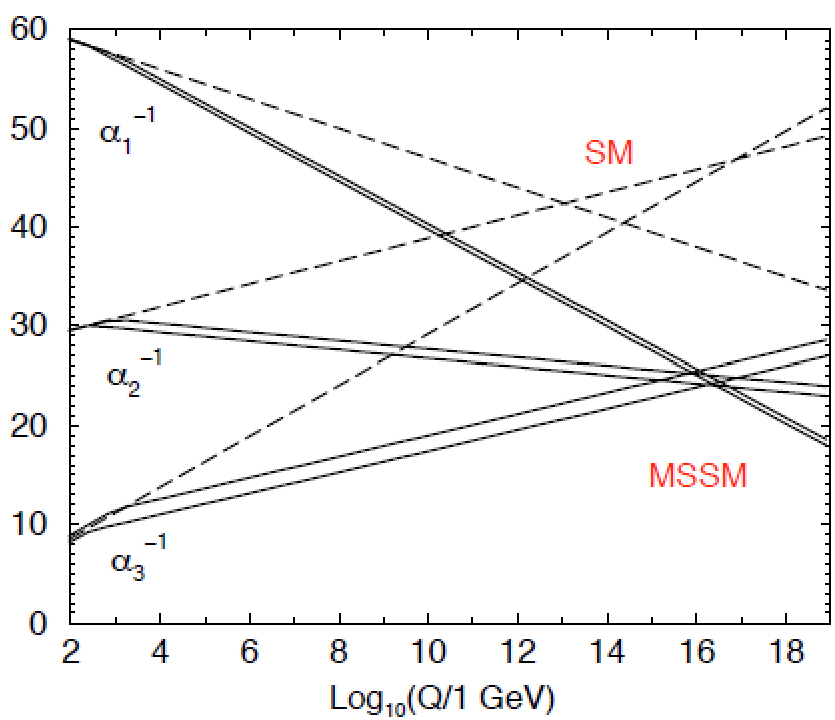
$$\lambda_S = \lambda_f^2$$



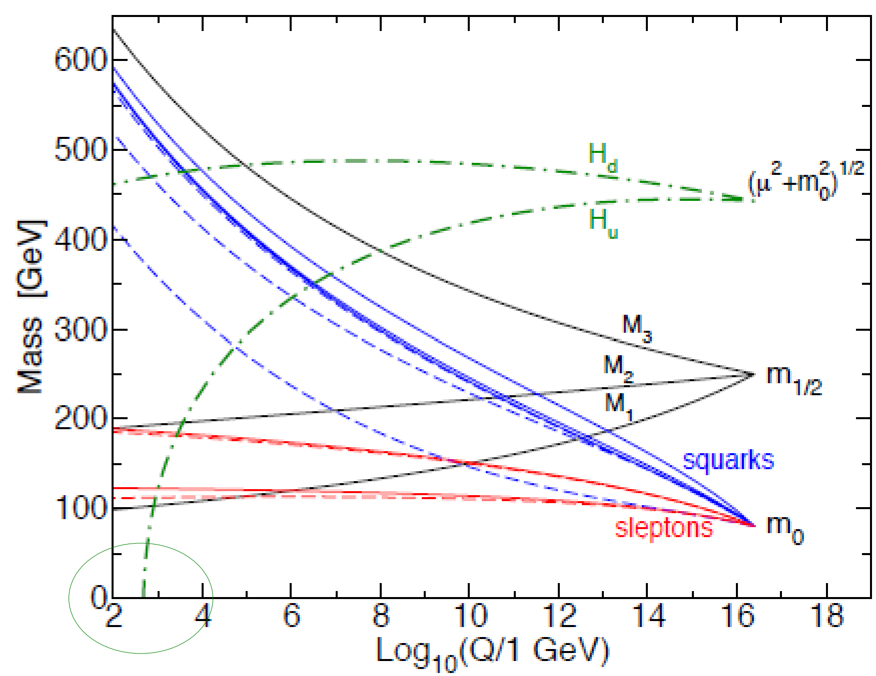
= 0

$$\Delta m_H^2 \propto \frac{\lambda^2}{16\pi^2} M_S^2$$

Gauge coupling unification:



Radiative EWSB, Dark matter, ...

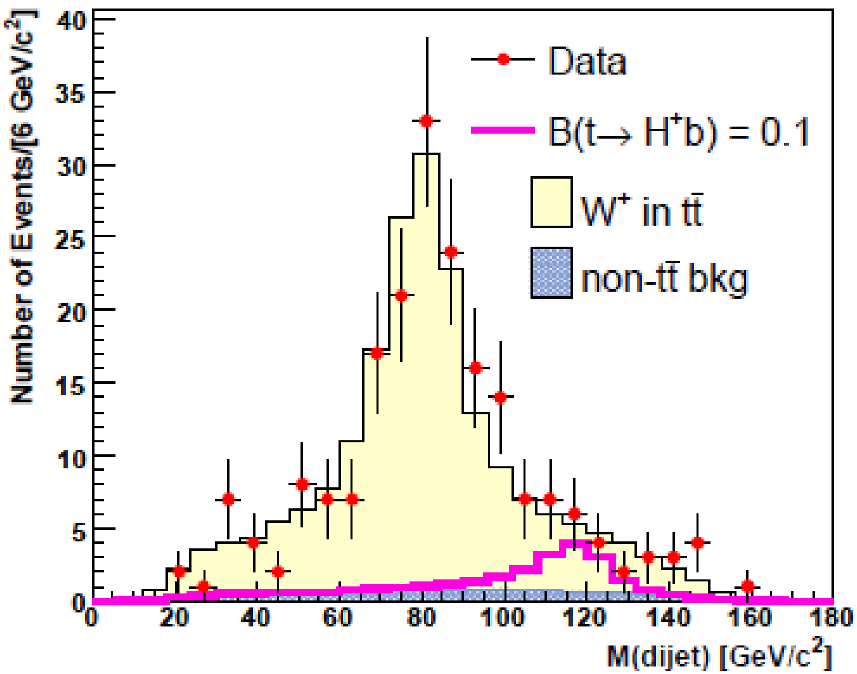


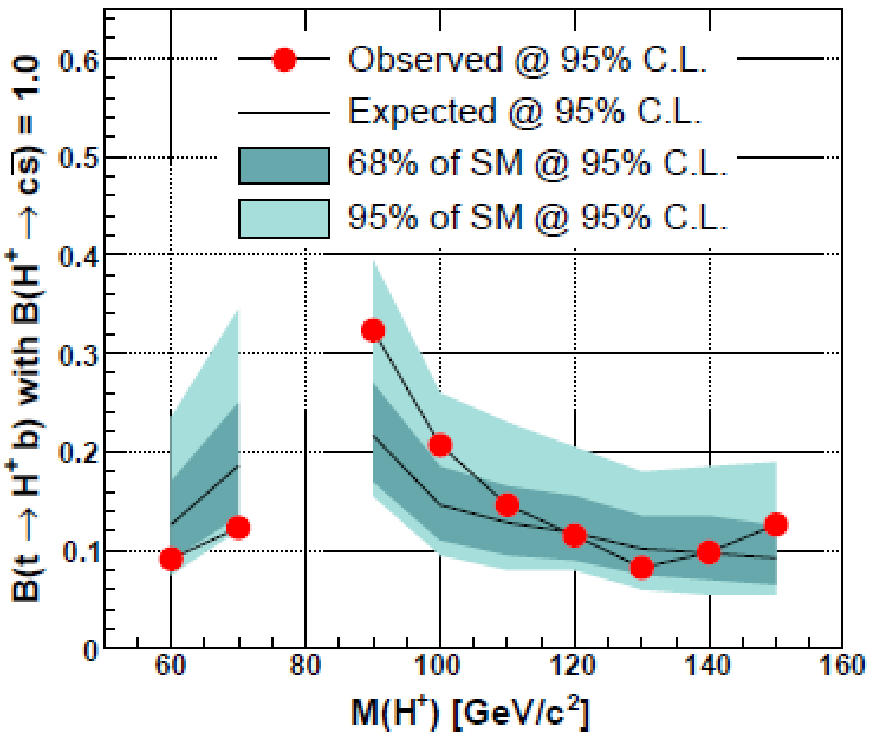
CDF H^+->cs Search

Low tanB search

H^+->cs dominates for m_H<~130 GeV

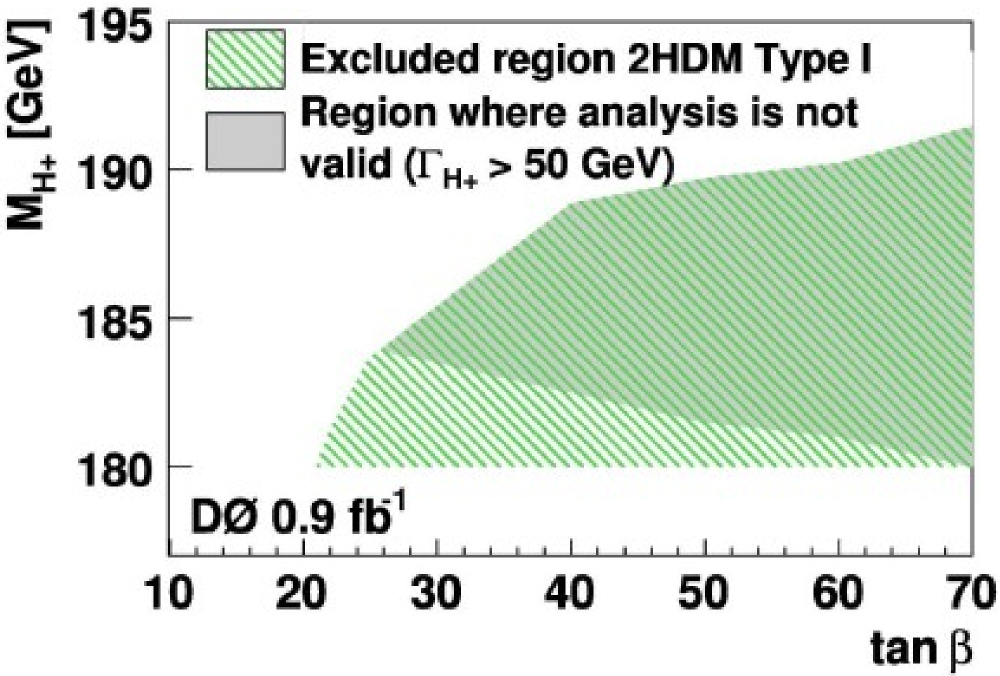
Look at di-jet mass of jets from top decay



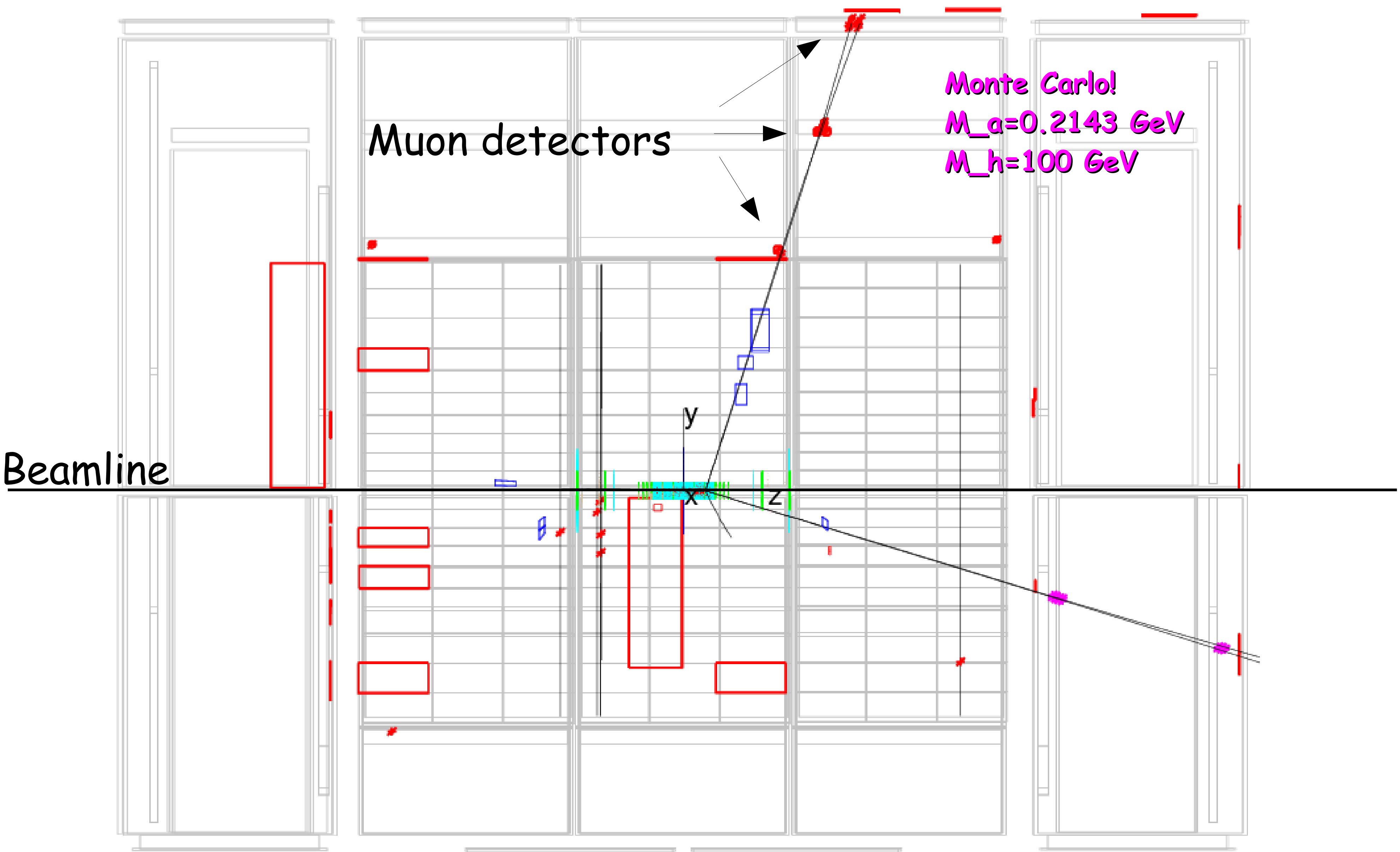


Result on search for a heavy charged Higgs boson

- A region in the M_{H+} vs tan β plane has been excluded at the 95% C.L. for Type I 2HDMs.
- The analysis sensitivity is currently not sufficient to exclude regions of tan $\beta < 100$ in the Type II 2HDM.
- In a Type III 2HDM, the width of the Higgs boson depends quadratically on the mixing parameter, limiting our ability to exclude regions in M_{H+}-ξ parameter space.



h→aa→4μ


Muon detectors
Monte Carlo!
M_a=0.2143 GeV
M_h=100 GeV
Beamline
y
x
z

D0 Higgs Searches in NMSSM

New *very light pseudo-scalar* : "a"

h->aa decay dominates

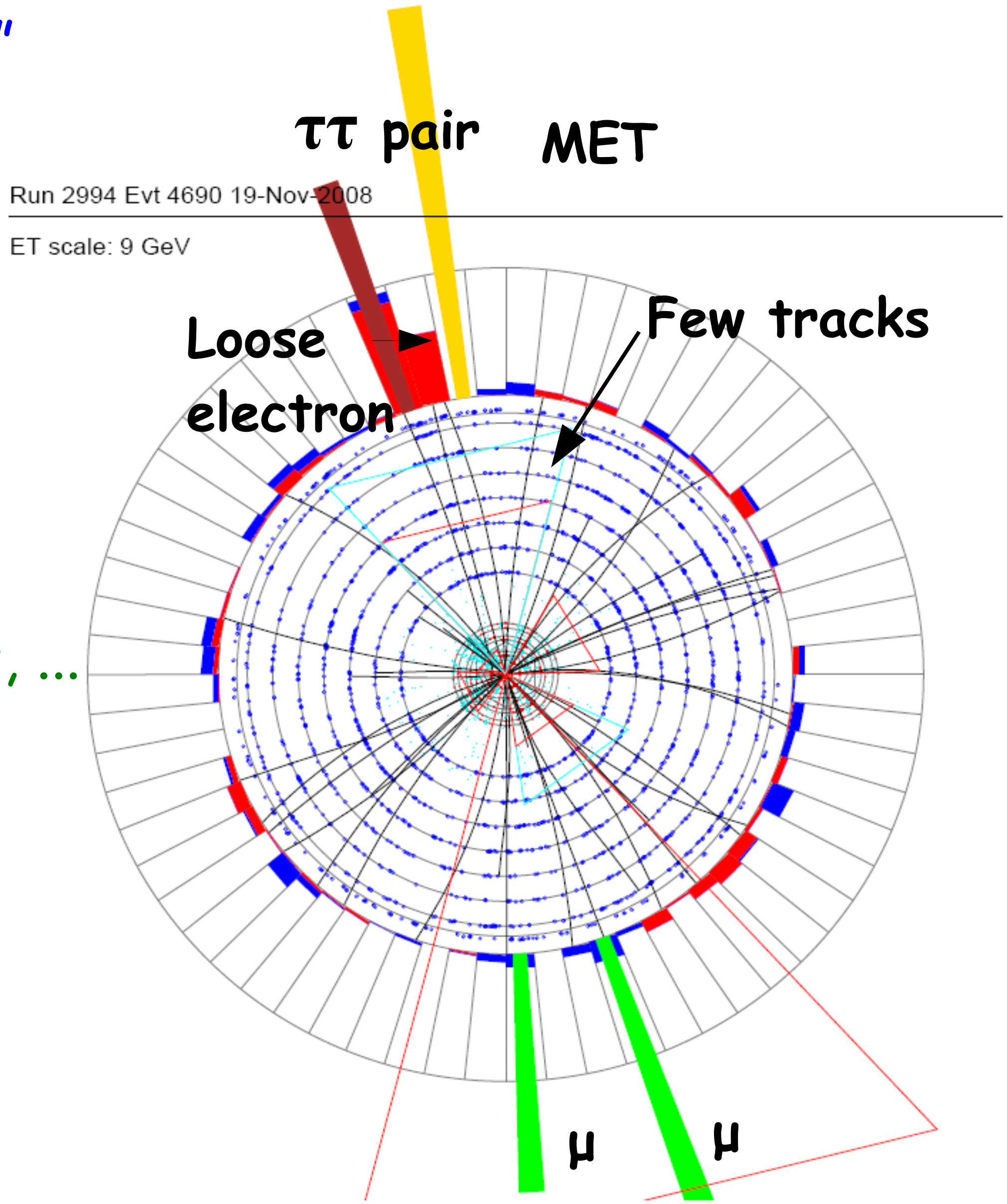
$2m_\tau < m_a < 2m_b$:

Search for h->aa->2μ2τ

(lower BR than 4τ, but cleaner)

Backgrounds: Multijet, Z/γ*+jets, ...

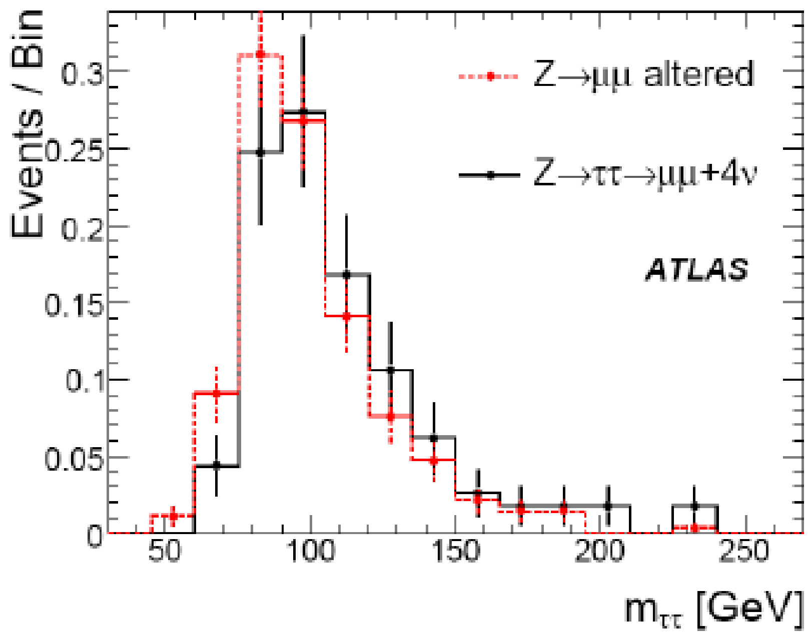
Look for peak in $M_{\mu\mu}$

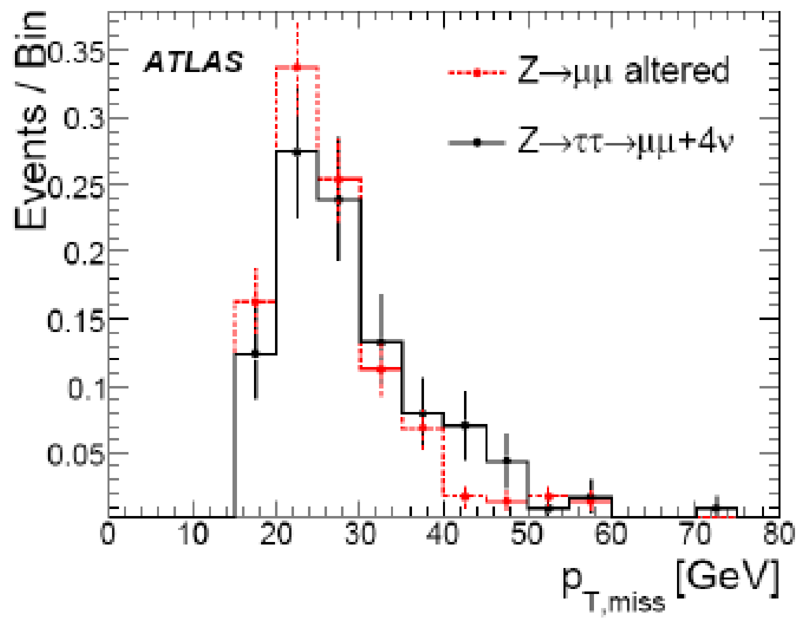


Backgrounds to the Di-Tau Analysis

For mA < 200 GeV, dominant background is Z + jets with Z → tau tau

- **This is an irreducible background**
- **The shape and normalization can be taken from data-driven control samples**
- **Scale the energy of the Z → mu mu events collected in collision data to match that expected from Z → tau tau**





For mA ≥ 200 GeV, ttbar events become a significant background

- **Can get a handle on this by cutting on the jet multiplicity ($N_{jets} \leq 2$)**

MSSM Higgs Di-Muon Analysis

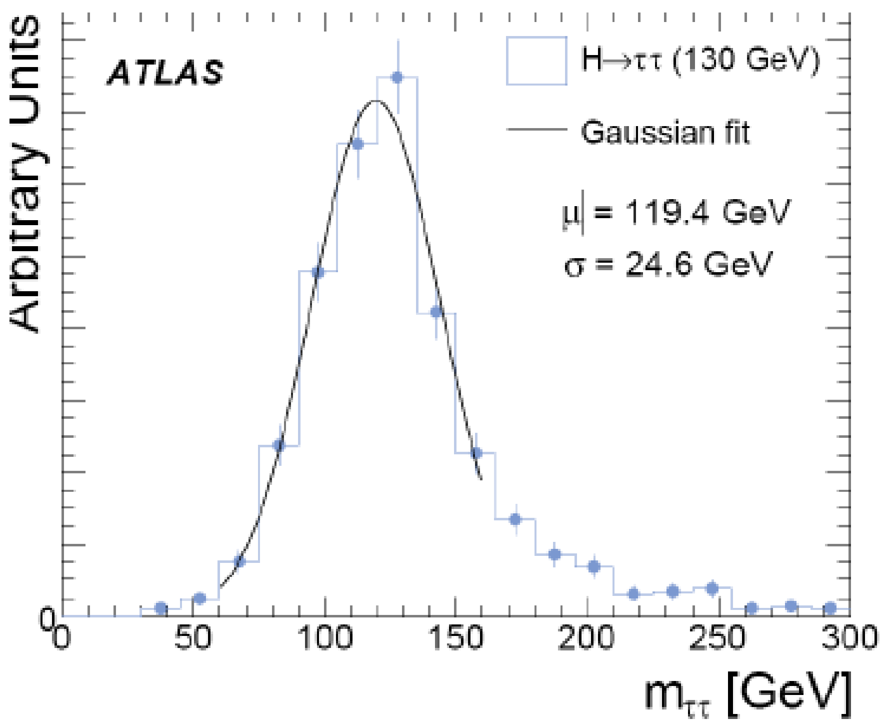
Some advantages

- Cleaner signal than the di-tau analysis
- Excellent mass resolution (~3% versus ~20% for the di-tau)

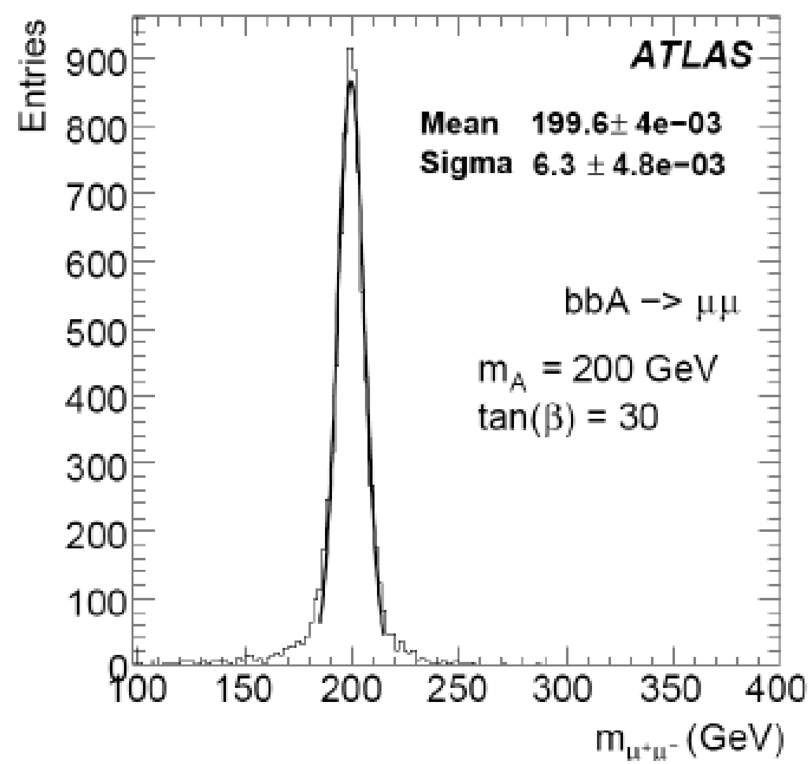
Disadvantage

- h/A/H di-muon ranching ratio is ~300% smaller than that of the di-tau

MSSM h/A/H→tau tau mass (collinear)



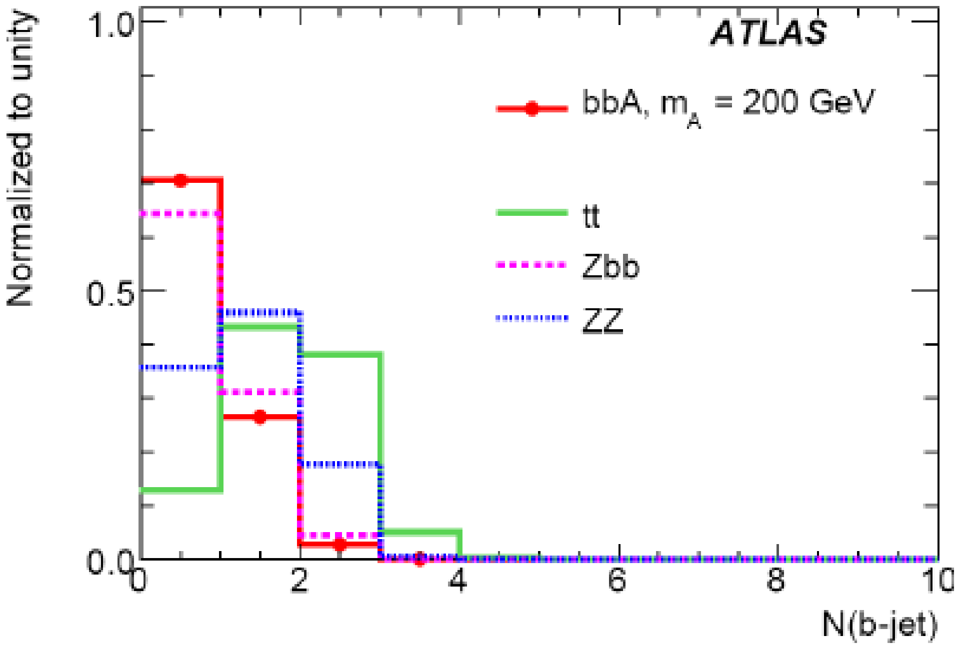
MSSM h/A/H→μμ mass



MSSM Higgs Di-Muon Analysis

Divide the analysis into two uncorrelated channels

- 0 b-jets channel (to suppress the ttbar background)
- ≥1 b-jets channel (suppress the Z background; impose additional cuts to reduce ttbar)''



Data-driven background estimation

- For higher masses the tail of the Z resonance provides a large irreducible background, sensitive to detector systematic effects
- BR(h/A/H→ee) ~0
- BR(Z→μμ) = BR(Z→ee), so use Z→ee events from data as a control sample

Charged MSSM Higgs

Production mode greatly depends on $m_{H\pm}$

Three different analyses for a low mass ($m_{H\pm} < m_{top}$)

- $t\bar{t} \to bH^{\pm}bW \to b\tau_H \nu bqq$
- $t\bar{t} \to bH^{\pm}bW \to b\tau_L \nu bqq$
- $t\bar{t} \to bH^{\pm}bW \to b\tau_H \nu bl\nu$

Two analyses considered for a high mass ($m_{H\pm} > m_{top}$)

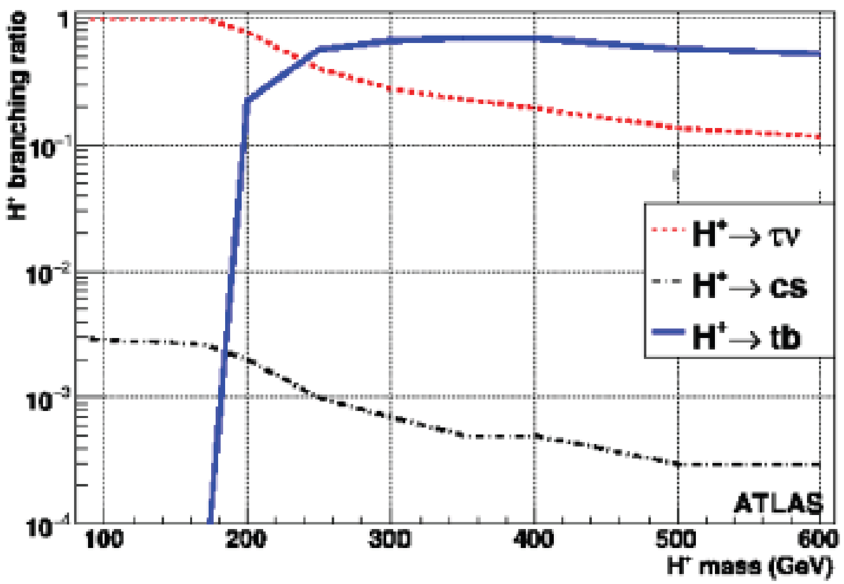
- **Production via:** $gg \to H^{\pm}tb$ **and** $gb \to H^{\pm}t$
- **Decay modes:**

$$H^{\pm}t \to \nu\tau_H bqq$$
$$H^{\pm}t \to tbt \to bWbbW \to bqqbbl\nu$$

Dominant Backgrounds

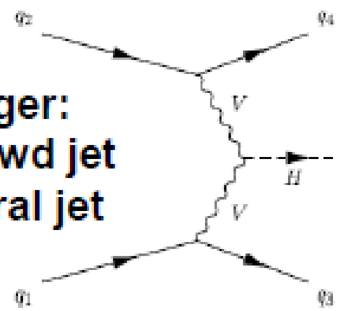
- ttbar (primary)
- QCD di-jets
- W+jets
- Single top

"m_h-max" scenario with tanβ = 35



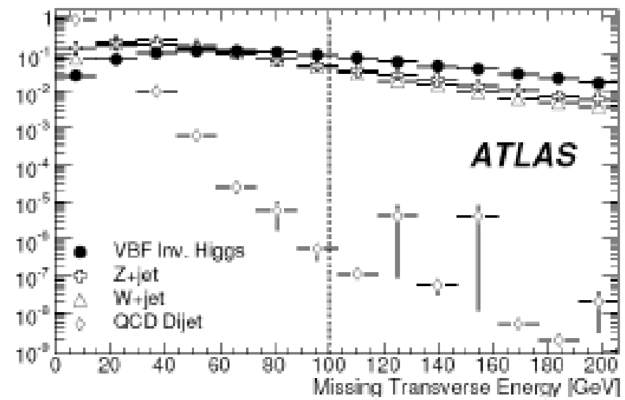
Invisible Higgs

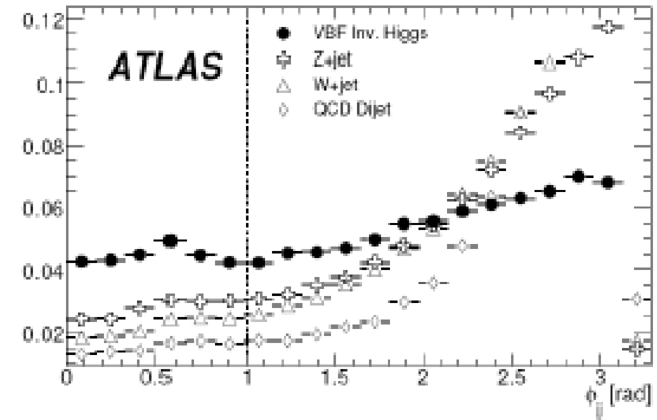
H production via VBF



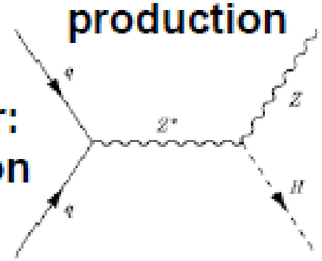
Trigger: MET+fwd jet +central jet

Cut-based and tagging jet azimuthal angle shape analysis



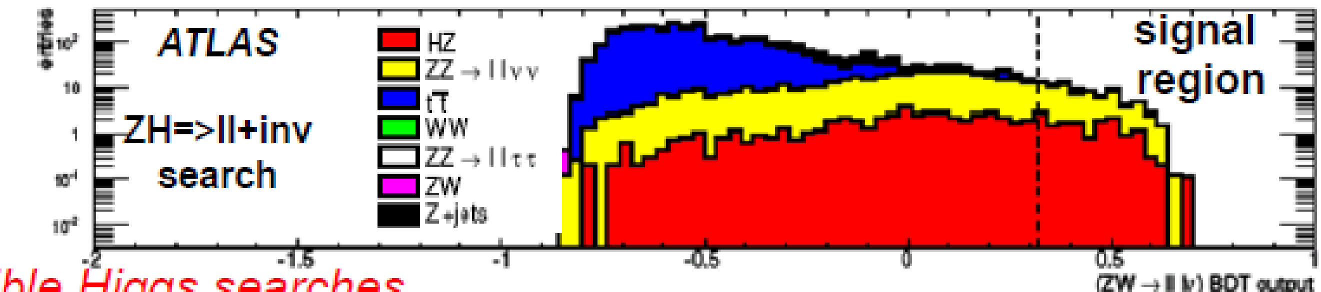


HZ associated production



Trigger: (di)lepton

Boosted Decision Tree (BDT) analysis



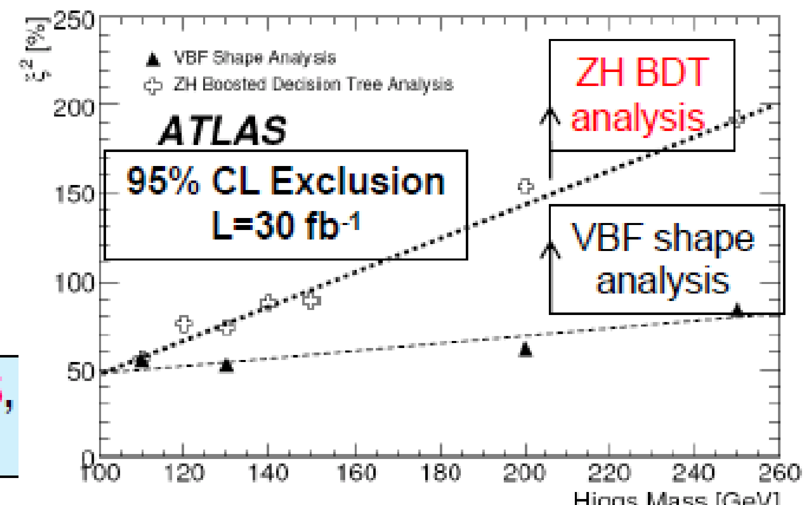
see also CMS poster on invisible Higgs searches

Reach of VBF shape analysis and ZH BDT analysis

$$\xi^2 = BR(H \to inv.)\frac{\sigma_{BSM}}{\sigma_{SM}}$$

VBF shape analysis more performant at high H mass
combine both channels (VBF and ZH) to establish signal.

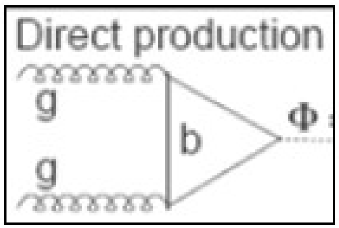
Signal excluded (observable) with 30 (~100) fb-1 for $\xi^2 > 0.5$, as e.g. for σ_{BSM} => 0.5 σ_{SM} and 100% BR_{inv}



Extra Dimensions

5D Randall–Sundrum model:

Scalar sector: Radion ϕ and Higgs h

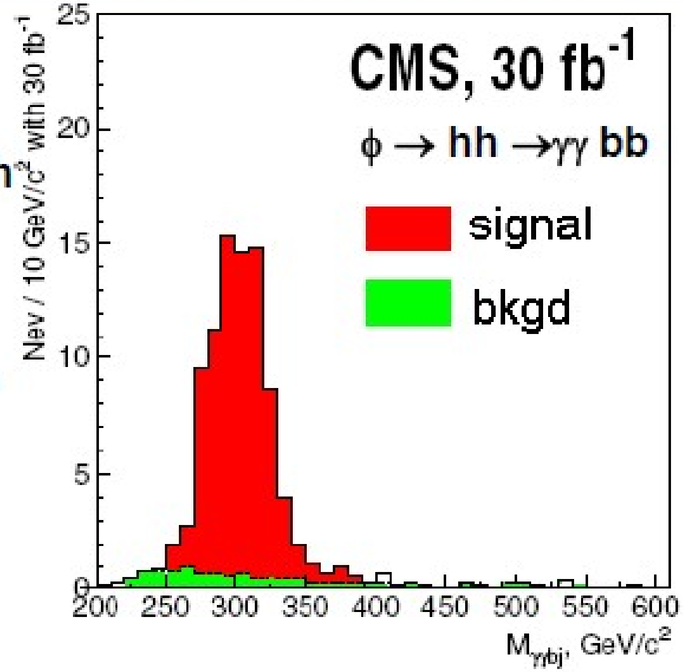


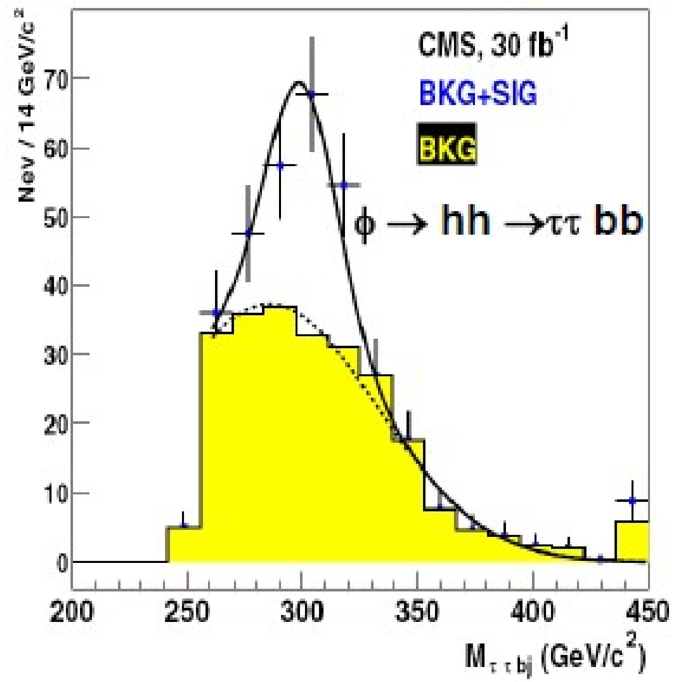
$\phi \rightarrow hh \rightarrow \gamma\gamma\ bb$

$\phi \rightarrow hh \rightarrow \tau\tau\ bb$

$m_\phi = 300$ GeV

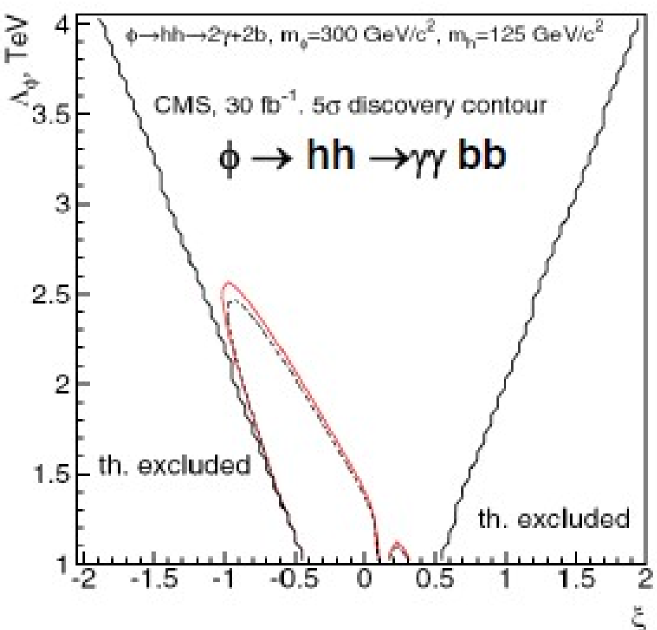
$m_h = 125$ GeV

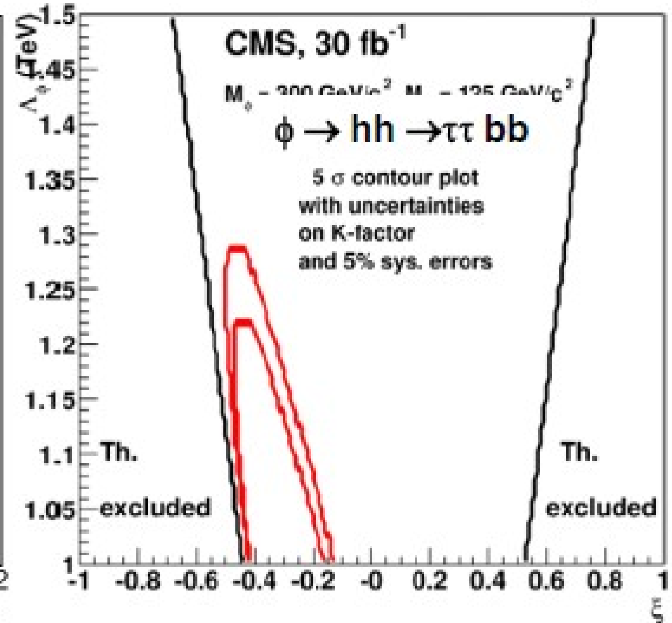




RS scalar sector parameters:

- **Higgs - radion mix. parameter ξ**
- **radion mass m_ϕ**
- **Higgs mass m_h**
- **v.e.v of the radion field Λ_ϕ.**





Littlest Higgs Model - Doubly Charged Higgs

*Littlest Higgs or **Minimal "Little Higgs" model***
N. Arkani-Hamed et al, JHEP07(2002)034

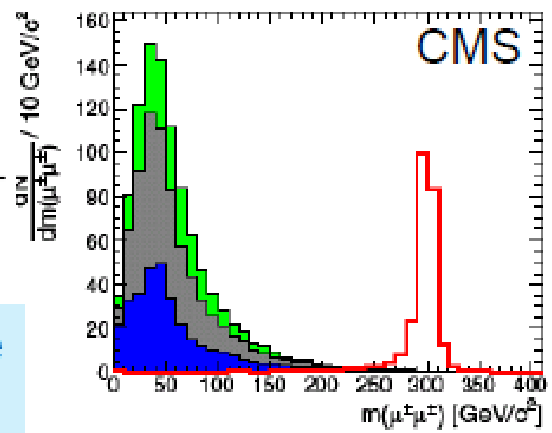
Predicts **a light SM-like Higgs-like particle**
a new set of **heavy gauge bosons *W', Z'***
a vector-like **heavy quark T pair** and
a pair of doubly charged Higgs bosons

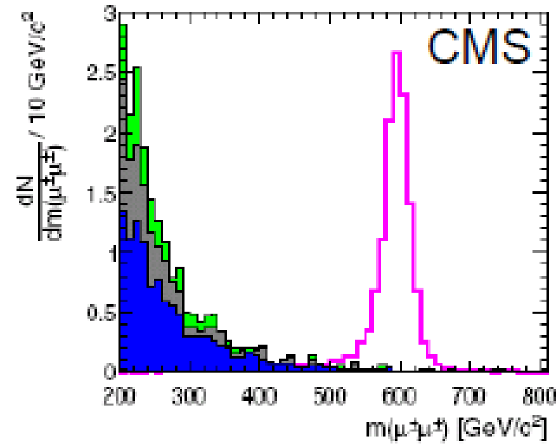
Search in four lepton final states

Consider pair production and leptonic decay

Pair production (Drell-Yan): $pp \rightarrow \Delta^{++}\Delta^{--}$

Decay (LV): $\Delta^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$



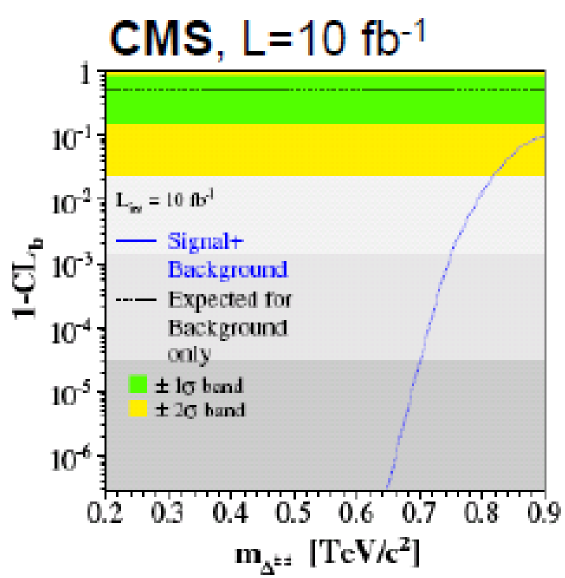


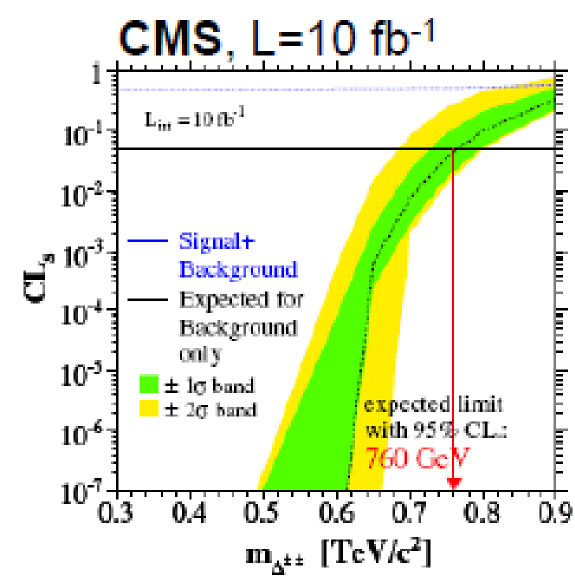
Reconstruct invariant mass of same charge leptons -> very small SM background

Four muon channel, L=10 fb^{-1}

Exclude (95%CL) signal masses up to **760 GeV**

Detect => 5 σ signal for masses up to **650 GeV**



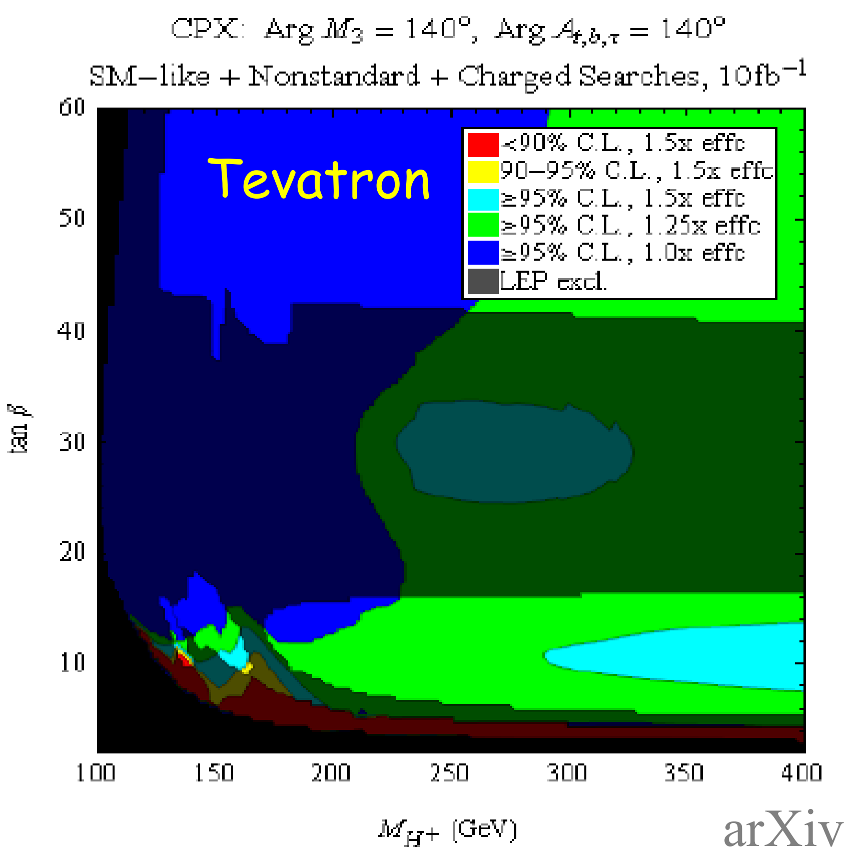


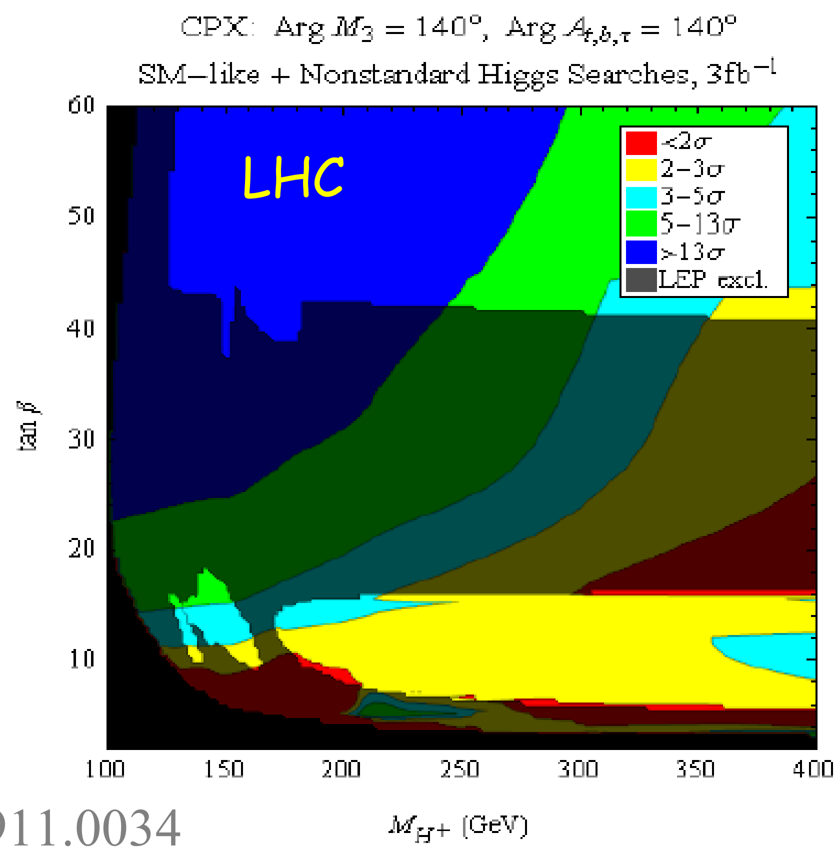
CP Violating Higgses

MSSM, but now CP-even h/H can *mix* with A

Combine SM-like + non-SM searches

Should be able to cover full parameter space?





arXiv:0911.0034

What About *Low* tanB ?

Very tough, only ~SM-like production cross-sections

- Some hope for gg->H->γγ/WW/ZZ ? Needs study!
- Can we ever see φ->tt? SLHC?