BSM Higgs Physics at LHC (CMS)

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Iran, Tehran October 2013

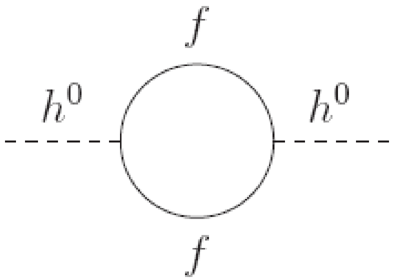
Why BSM ?

- ***Problems of the Standard Model***
  - *"huge fine-tuning is needed to have m_H ~ 125 GeV after the radiative corrections"*
  - *"Big hierarchy problem":*
    - Λ *(M_{GUT}~10^{16} GeV or M_P ~ 10^{18}GeV) >> M_Z*
  - **Does not include Dark Matter particle(s)**

The Higgs gives us a hard time!

- Both the EW symmetry breaking and fermion masses are economically achieved by the fundamental scalar, Higgs.

"Fine tuning problem"



- But the quantum correction is UV sensitive:

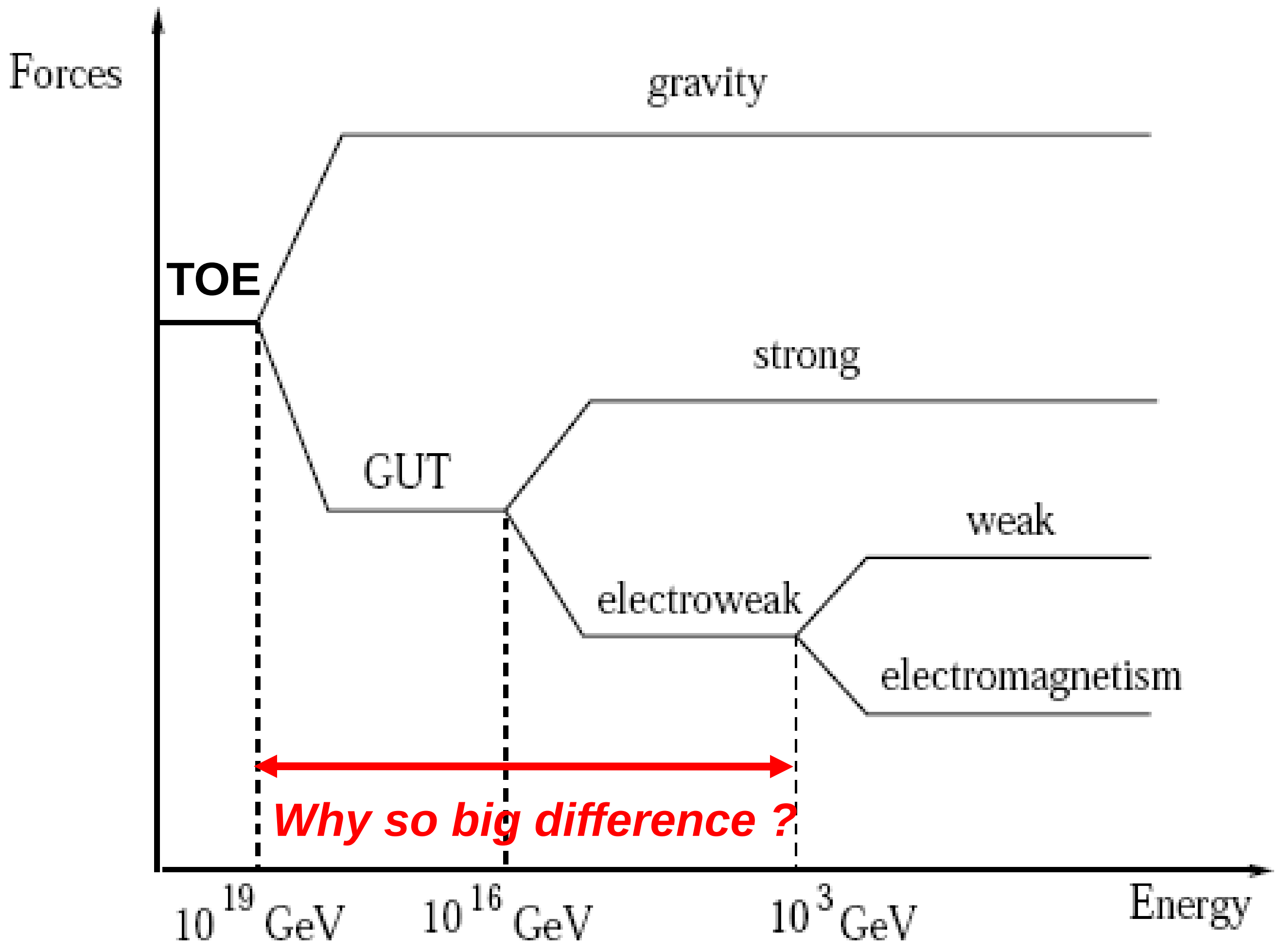
$$\delta M_H^2 = \frac{|y_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln\frac{\Lambda_{UV}}{m_f}\right]$$

- In SM, $\Lambda_{UV} = M_p \sim 10^{19}$ GeV

How big is fine tuning !

$$\begin{aligned}(M_H)_{phys} &= (M_H)_{bare} + \delta M_H \\ 100\text{GeV} &\sim (10000000000000000100\text{GeV})_{bare} \\ &\quad -(10000000000000000000\text{GeV})_{QC} \\ &\Rightarrow \textit{Gauge Hierarchy Problem}\end{aligned}$$

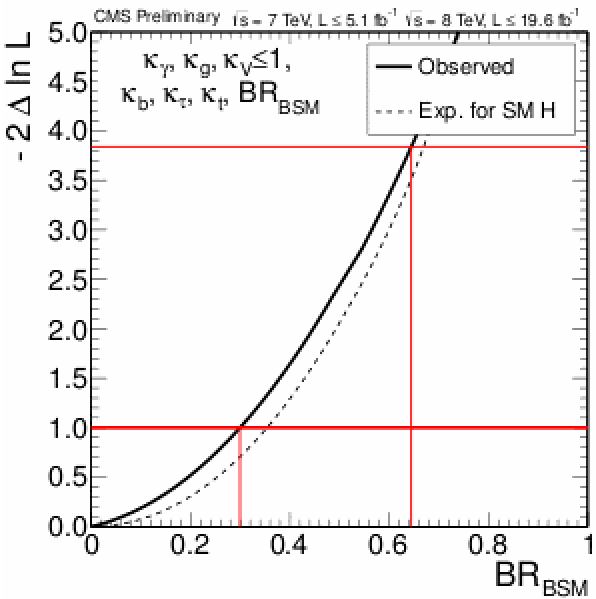
“Hierarchy problem”



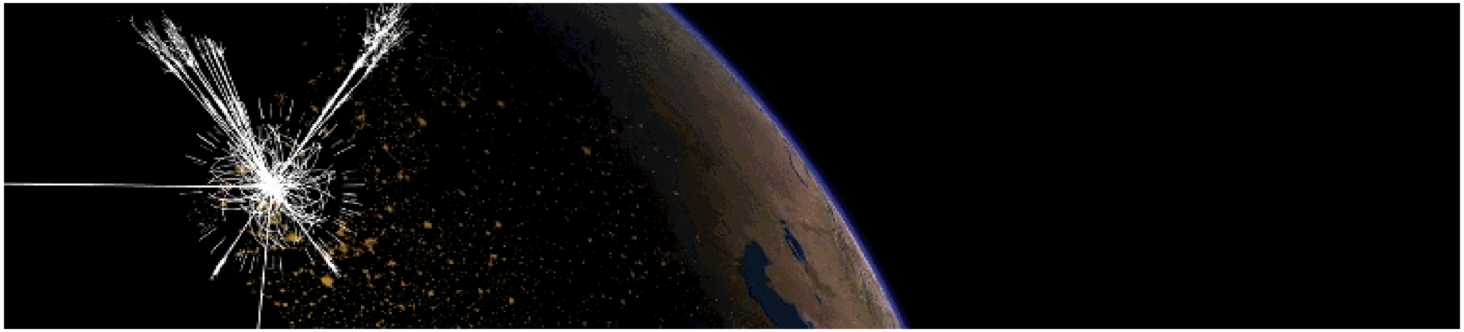
Searches for BSM Physics with Higgs bosons

- Non SM decays of h(125)

The present accuracy of Higgs boson measurement (in CMS) allows BR(h->BSM decays) < 0.65 at 95 % CL CMS PAS HIG-13-005



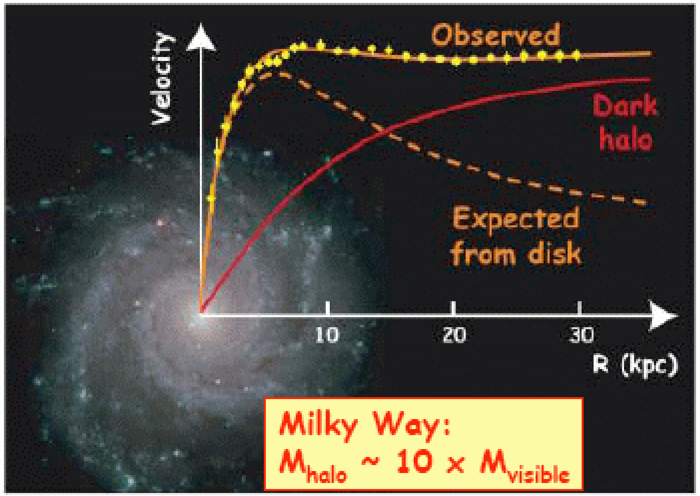
- Additional Higgs bosons
- precise coupling measurements for h(125)



Searches for H->invisible decays at LHC

Detection of Dark Matter

Evidence for dark matter



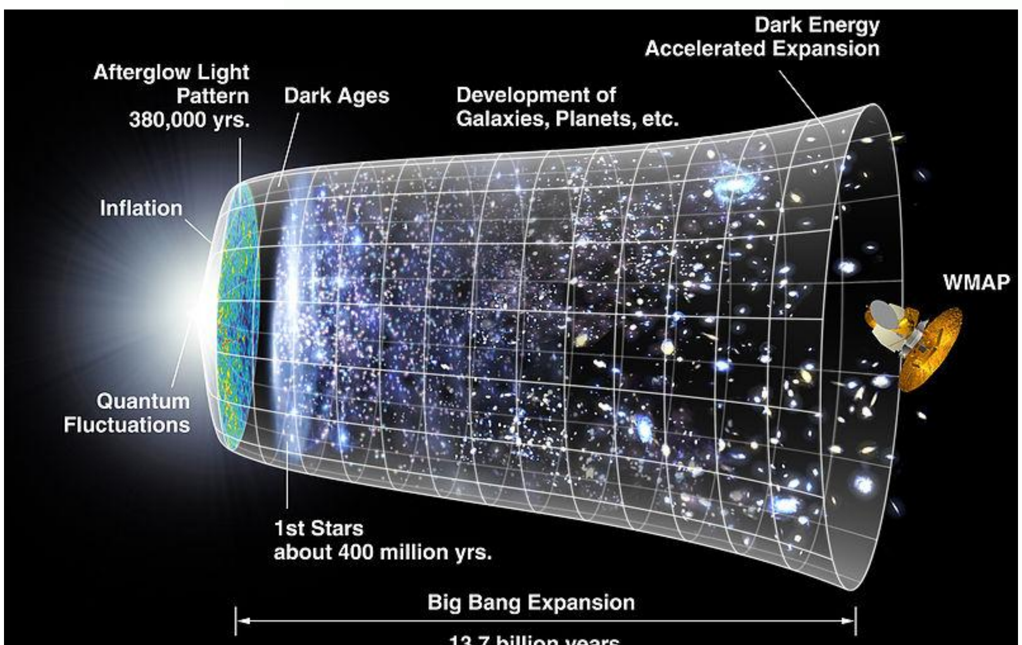
Rotation curves

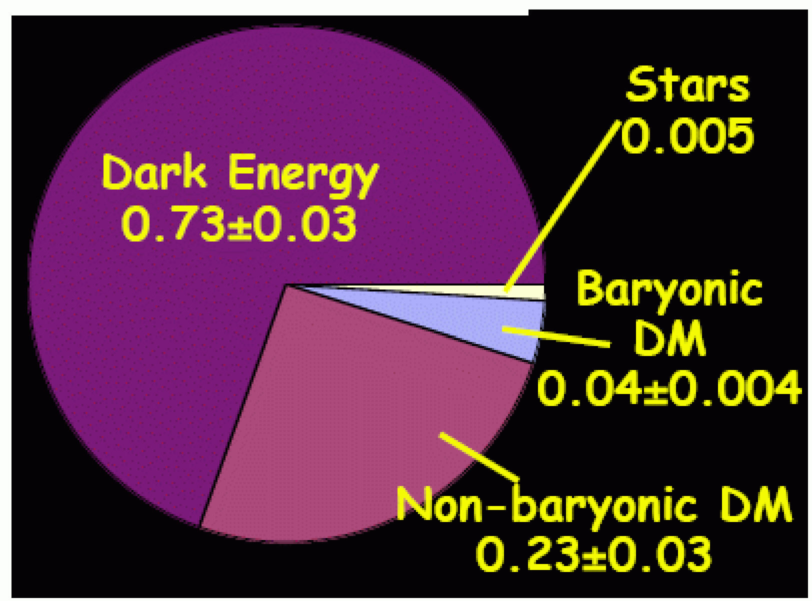
↓

Dark Matter

OR

MOdified Newtonian Dynamics
(acceleration ≠ GM/r)





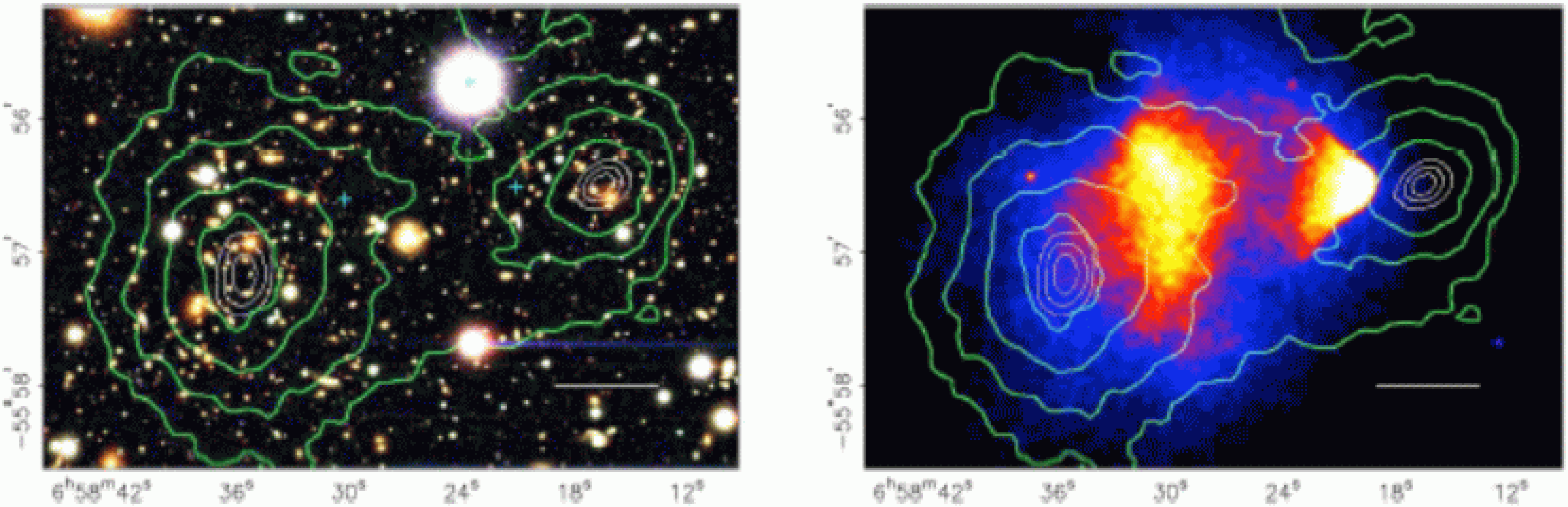
and is flat (Ω_T = 1.01 ± 0.01)

WMAP lunched in 2001 from Florida. 9 years data released in 2012

A new confirmation of dark matter (astro-ph/0608407)

A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER *

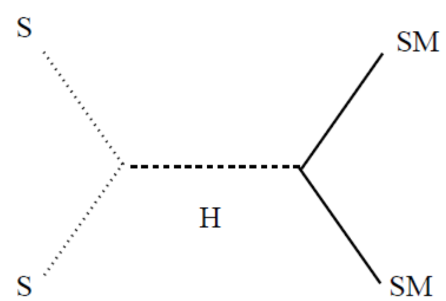
Douglas Clowe[1], Maruša Bradač[2], Anthony H. Gonzalez[3], Maxim Markevitch[4,5], Scott W. Randall[4], Christine Jones[4], and Dennis Zaritsky[1]

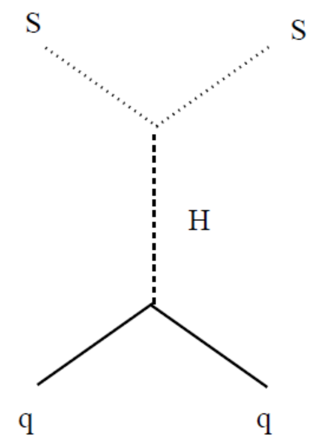


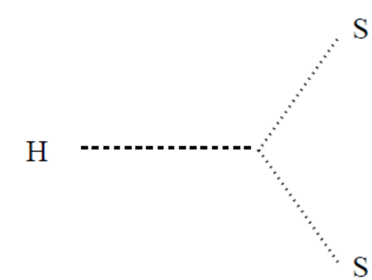
Two galaxy clusters collide.
Most baryonic matter is in the gas.
The gas is stopped in the collision, the stars continue.
Grav. lensing shows that the potential follows the stars.
Hence most of the matter is hidden around the stars.
No alternative theory of gravitation can explain this.

One of simplest models of DM: Higgs-portal DM

- DM consists of real scalars S, or vectors V or Majorana fermions f which interact with the SM fields only through the Higgs boson
  - It is the simplest extension of the SM







DM annihilation **direct detection scattering** **invisible Higgs width**

Y.Mambrini arXiv:1108.0671

Z_2 symmetry -> DM is stable
No DM - Higgs mixing
No cosmological domain walls

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \,,$$
$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu \,,$$
$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi}\chi \,. \quad (1)$$

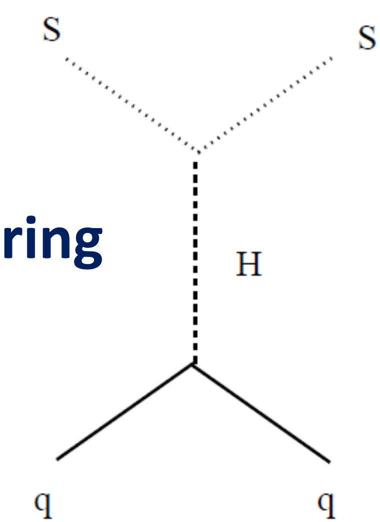
Connection between LHC H->inv. and XENON measurements

$$\sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_S+m_N)^2},$$

$$\sigma^{SI}_{V-N} = \frac{\lambda^2_{hVV}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(M_V+m_N)^2},$$

$$\sigma^{SI}_{f-N} = \frac{\lambda^2_{hff}}{4\pi\Lambda^2 m_h^4}\frac{m_N^4 M_f^2 f_N^2}{(M_f+m_N)^2},$$

DM-nucleon scattering (by XENON exp.)



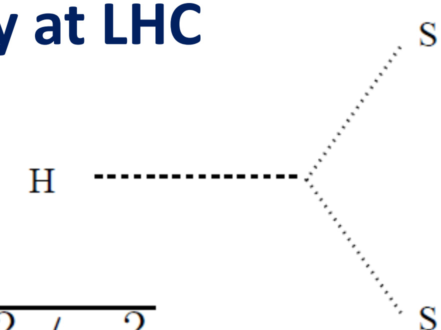
where f_N – Higgs-nucleon coupling

$$\Gamma^{\rm inv}_{h\to SS} = \frac{\lambda^2_{hSS} v^2 \beta_S}{64\pi m_h},$$

$$\Gamma^{\rm inv}_{h\to VV} = \frac{\lambda^2_{hVV} v^2 m_h^3 \beta_V}{256\pi M_V^4}\left(1 - 4\frac{M_V^2}{m_h^2} + 12\frac{M_V^4}{m_h^4}\right)$$

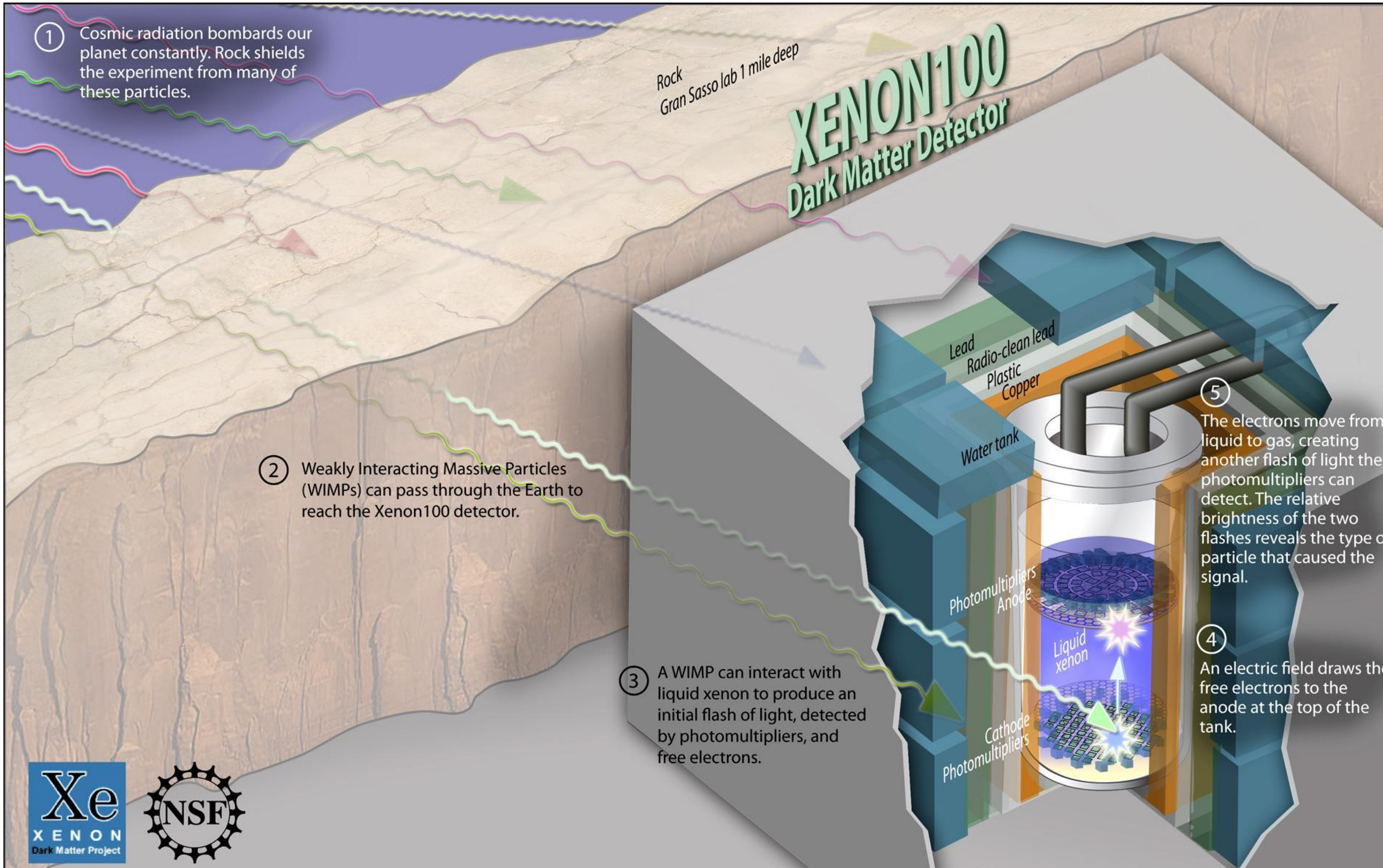
$$\Gamma^{\rm inv}_{h\to\chi\chi} = \frac{\lambda^2_{hff} v^2 m_h \beta_f^3}{32\pi\Lambda^2}, \quad \text{where } \beta_X = \sqrt{1-4M_X^2/m_h^2}$$

H->invisible decay at LHC



A. Djouadi et. al. arXiv:1112.3299

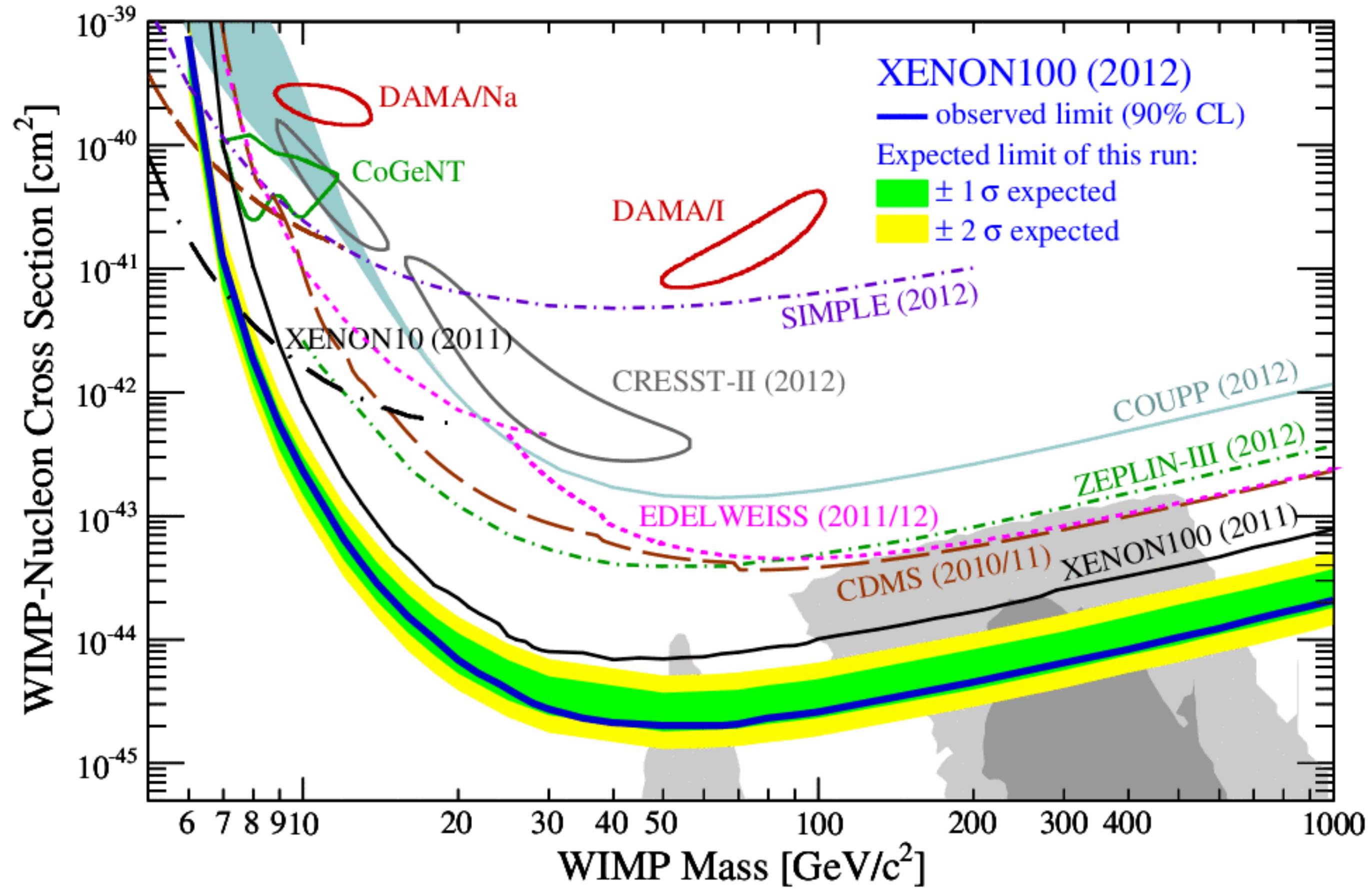
DM (WIMP) detection on Earth with XENON experiment (I)



Start data taking in 2007 at Gran Sasso in Italy. Current XENON100 – 165 L xenon. Plan for 1000 L

DM (WIMP) detection on Earth with XENON experiment (II)

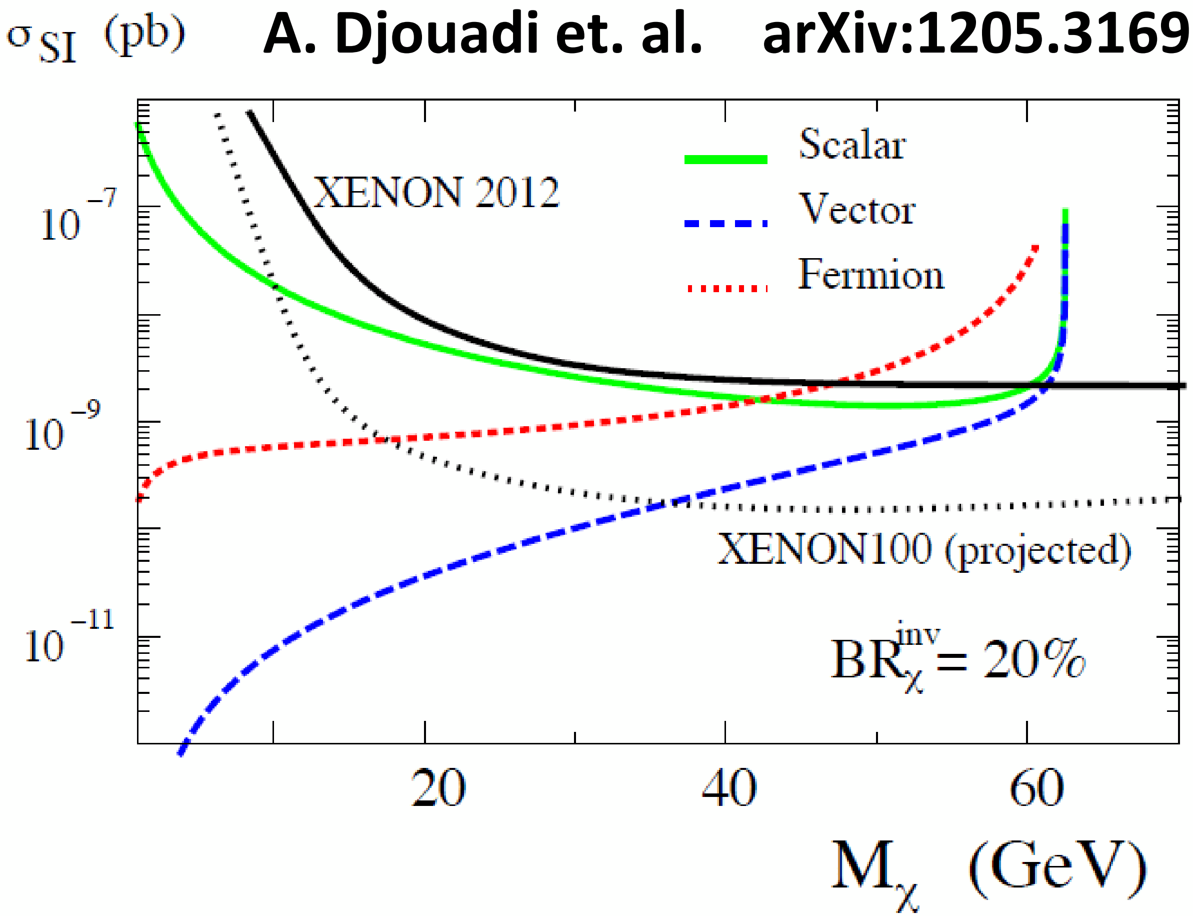
XENON collaboration, arXiv:1207.5988



m_h / 2

XENON and LHC H->invisible constraints on DM

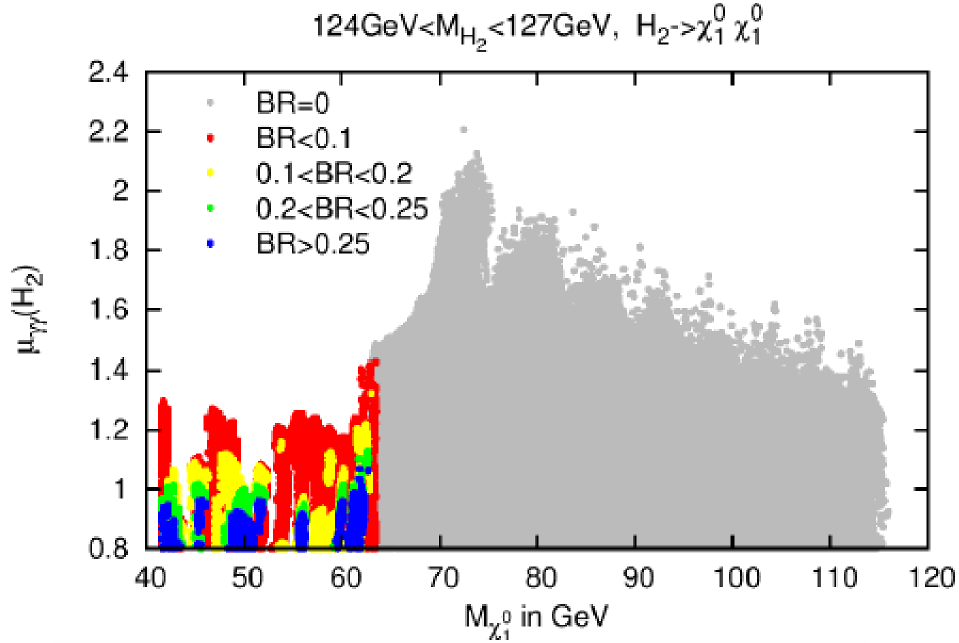
A. Djouadi et. al. arXiv:1205.3169



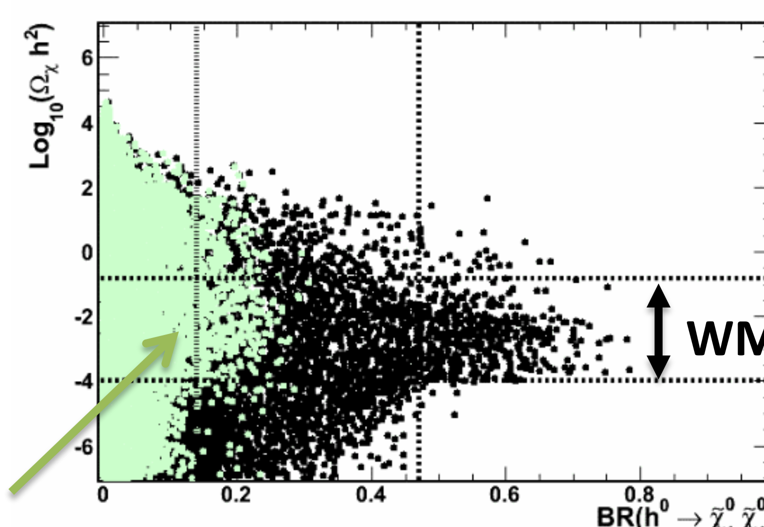
- **LHC is currently most sensitive DM detection apparatus, at least in the context of simple Higgs-portal models**

H->invisible BR in (N)MSSM

- **NMSSM $H_2 \to \chi^0\chi^0$**
  King, arXiv:1211.5074



- **pMSSM $h \to \chi^0\chi^0$**
  Djouadi arXiv:1211.4004

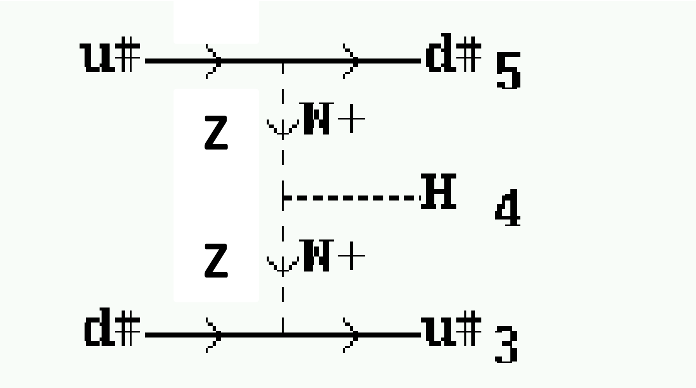


Compatible with LHC Higgs data (green color)

H->invisible: topologies proposed for LHC searches

- **VBF H->invis.**
  - D. Zeppenfeld, O.J.Eboli 2000
- **ZH, H->invis., Z->$\ell\ell$, bb**
  - D.P. Roy, D. Choudhuri 1994
  - Recently R. Godbole et al arXiv:1211.7015
- **gg->H+jet, H->invisible**
  - A. Djouadi at al arXiv:1205.3169

VBF H->invisible analysis



VBF Higgs production features:

- two jets in forward-backward direction with large rapidity separation
- large di-jet invariant mass
- no jets in the central detector region

EWK Z+jj as benchmark process

EWK Z+jj vs VBF H+jj

- **EWK Z+jj production graphs**

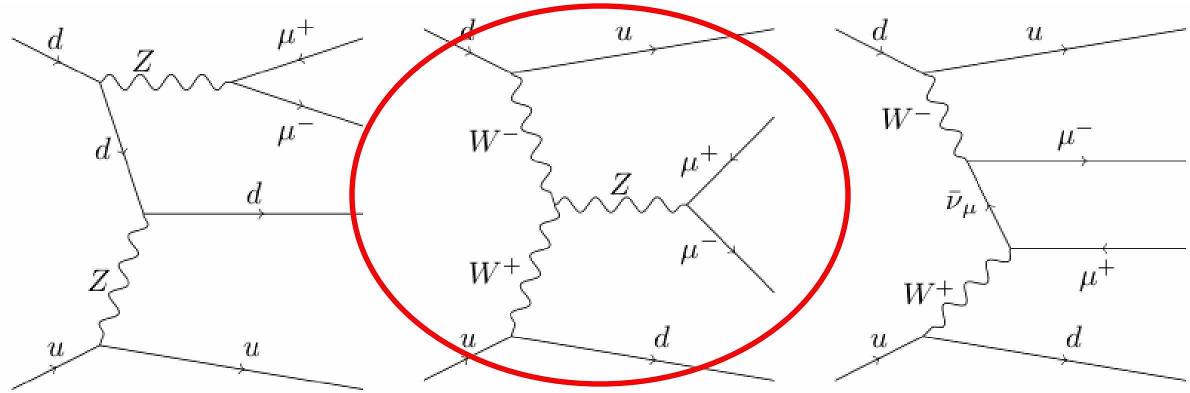
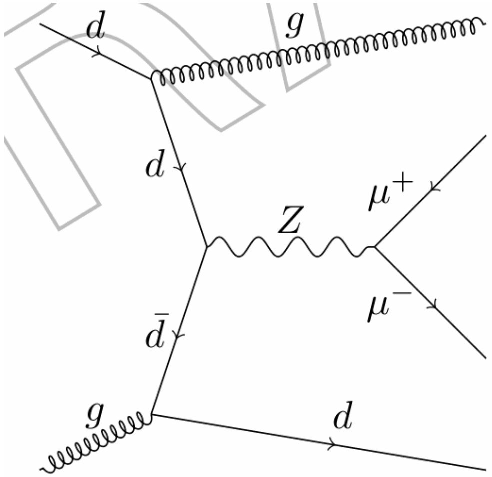


Figure 1: Representative diagrams for EWK $\ell\ell$ jj production processes. Left - bremsstrahlung, middle - VBF process, right - multiperipheral .

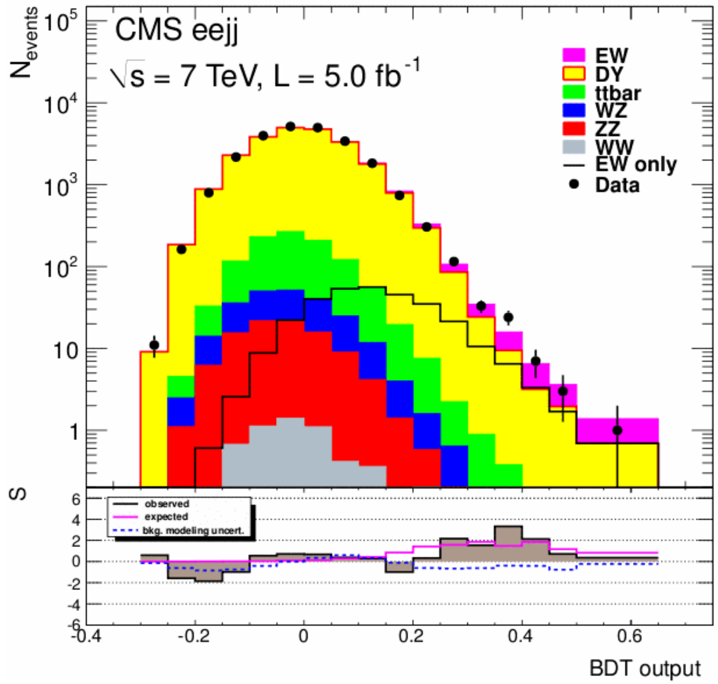
- **DY Z+jets production – dominant background**

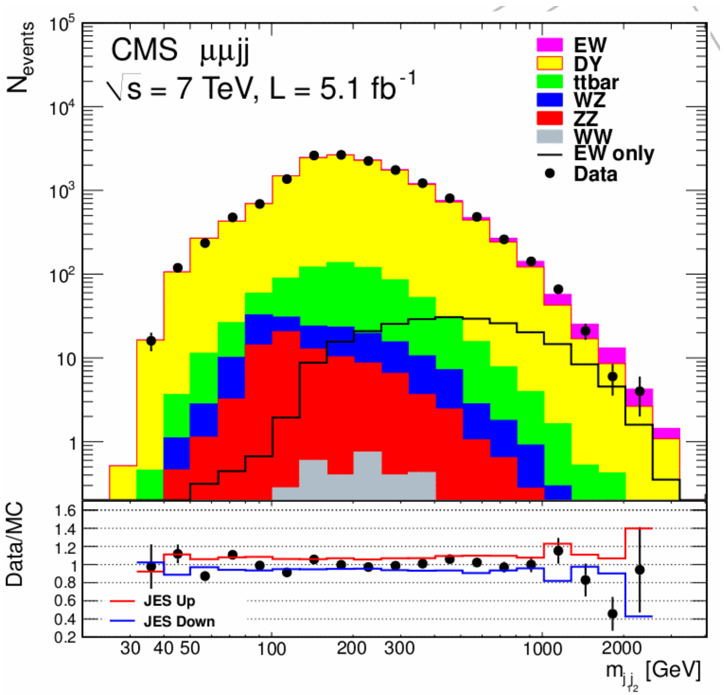


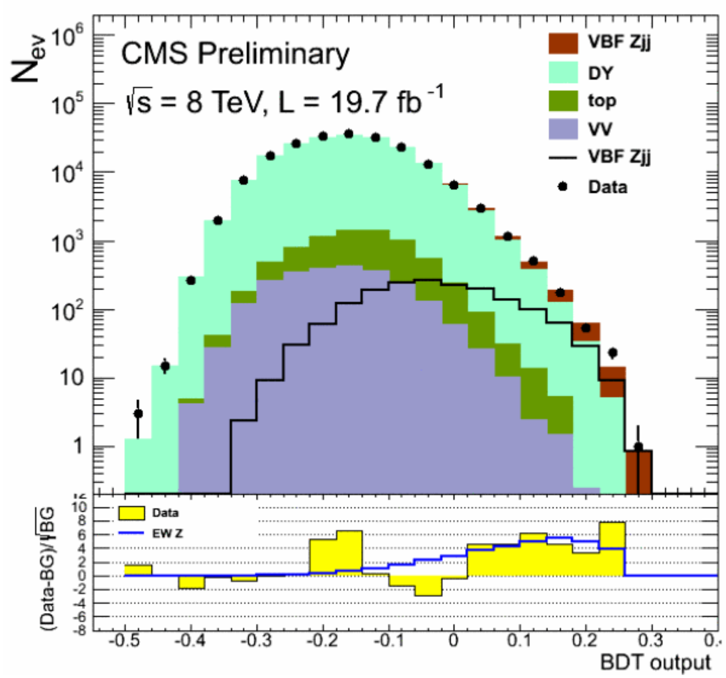
+ many more types of processes with α_{QCD}^2

Extracting EWK Z+jj signal

- Signal significance:
  - 2.6 for 7 TeV
  - 4.9 for 8 TeV
- Agreement with SM predictions







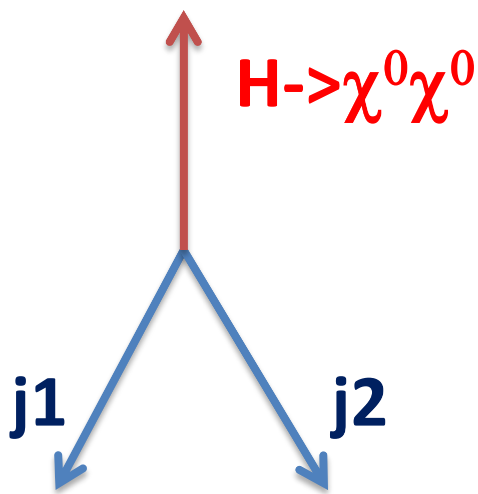
What did we learn from EWK Z+jj analysis useful for VBF H ?

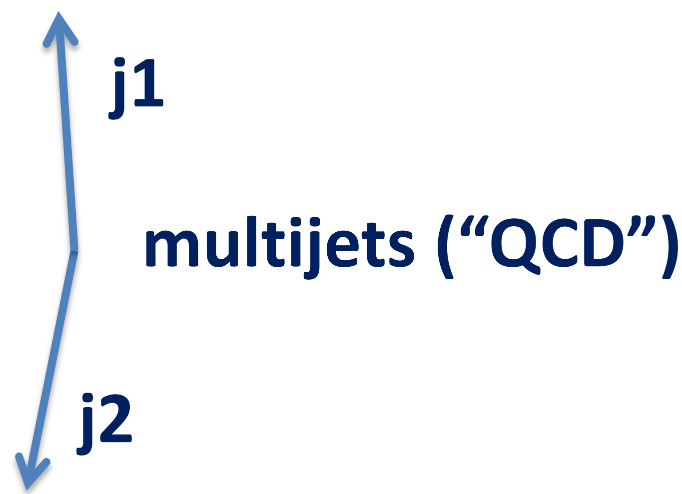
- Identify and solve problem with Jet Energy Scale in the forward region
  - *important for all VBF Higgs analyses*
- Study central jet veto performance (although did not use it in final selections)
- Found that MadGraph Monte Carlo does not describe well m_{JJ} and $y^{*}= y_{Z}-0.5(y_{j1}+y_{j2})$ data distributions for DY Z+jets
  - *use NLO corrections from MCFM program*
- Agreement with SM predictions made us sure that we understand our selections and systematics (tagging jets,…)

VBF H->invisible: offline signal selections and topology

- two jets p_T>50 GeV, $|\eta|$<4.7
- m_{jj} > 1100 GeV
- $\Delta\eta_{jj}$ > 4.2
- E_T^{miss} > 130 GeV
- $\Delta\phi_{jj}$ < 1.0
- Central jet veto

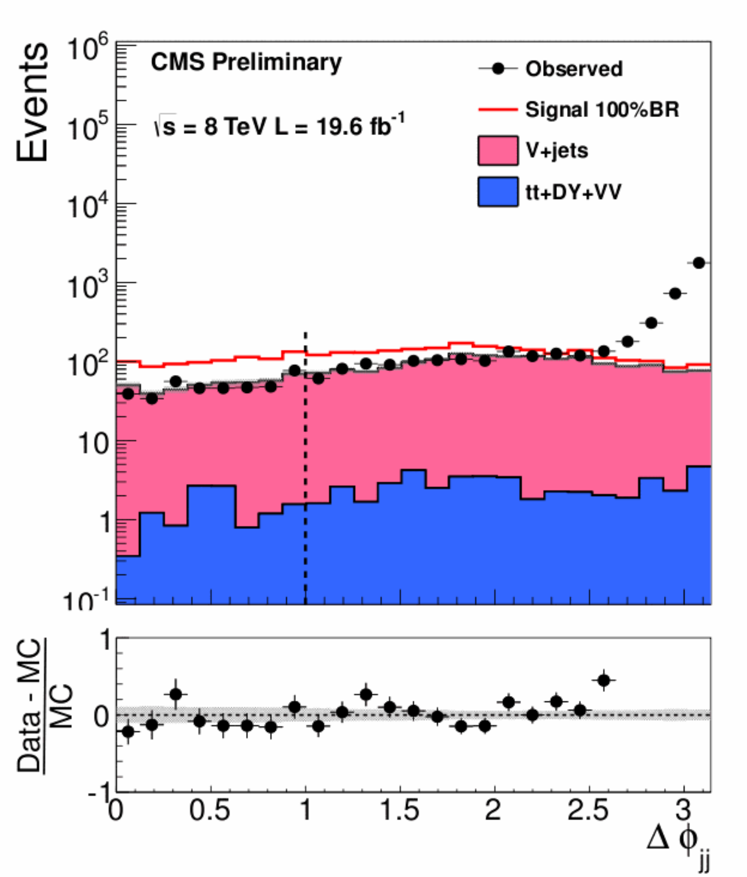
Signal: small $\Delta\phi_{jj}$
QCD: large $\Delta\phi_{jj}$



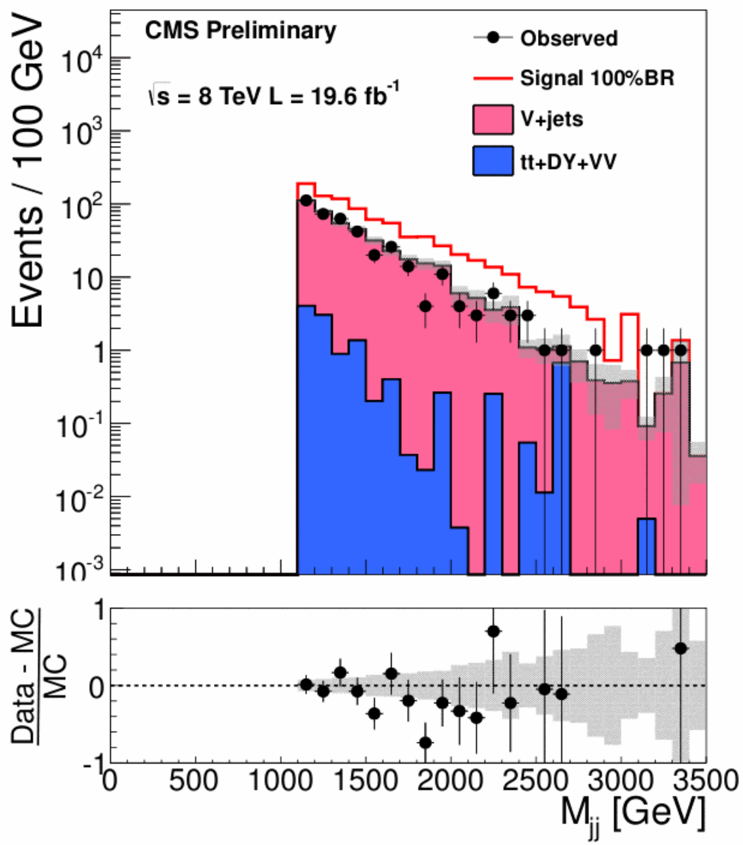


$\Delta\phi_{jj}$ and m_{jj}

- $\Delta\phi_{jj}$ after selections on:
  - m_{jj}, E_T^{miss}, $\Delta\eta_{jj}$, CJV



- m_{jj} after selections on
  - $\Delta\phi_{jj}$, E_T^{miss}, $\Delta\eta_{jj}$, CJV



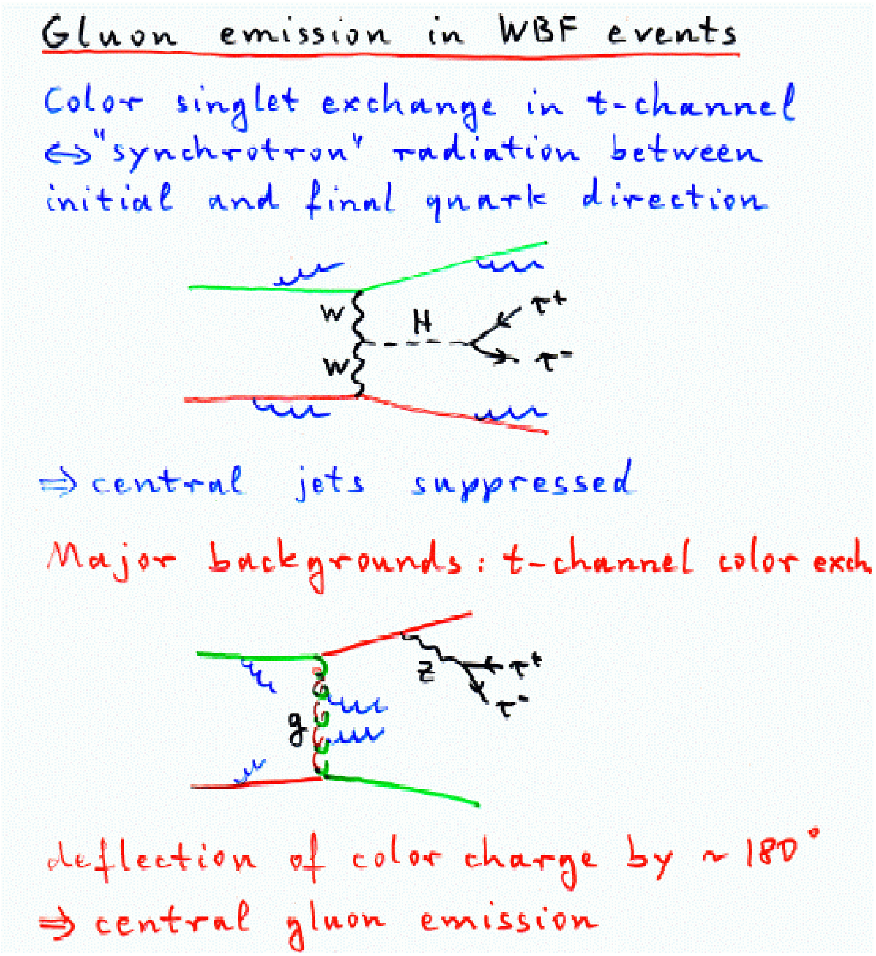
Central Jet Veto ("rapidity gap") in VBF (VV->H) production

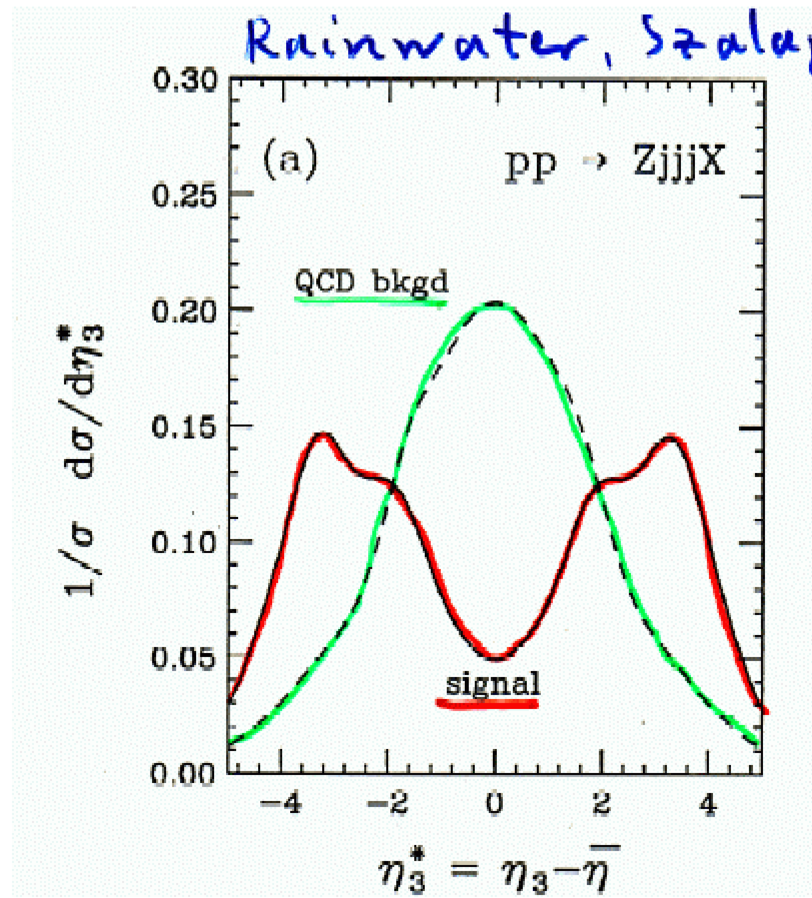
first discussed in :

Yu. Dokshitzer, V. Khoze and S. Troyan, Sov.J.Nucl. Phys. 46 (1987) 712

Yu. Dokshitzer, V. Khoze and T. Sjostrand, Phys.Lett., B274 (1992) 116

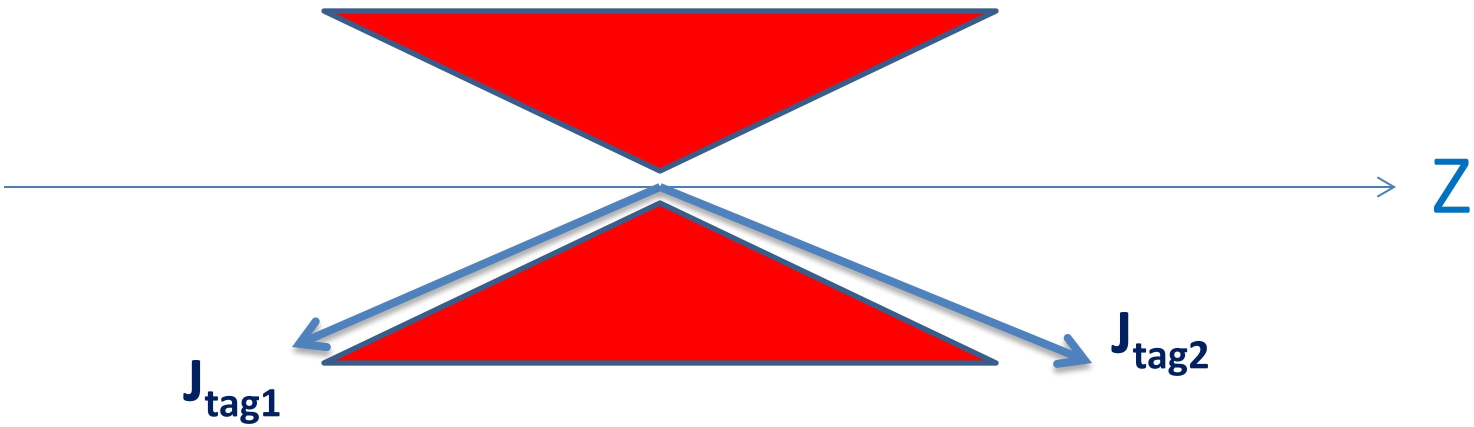
From D. Zeppenfeld talk on TeV4LHC, 2004





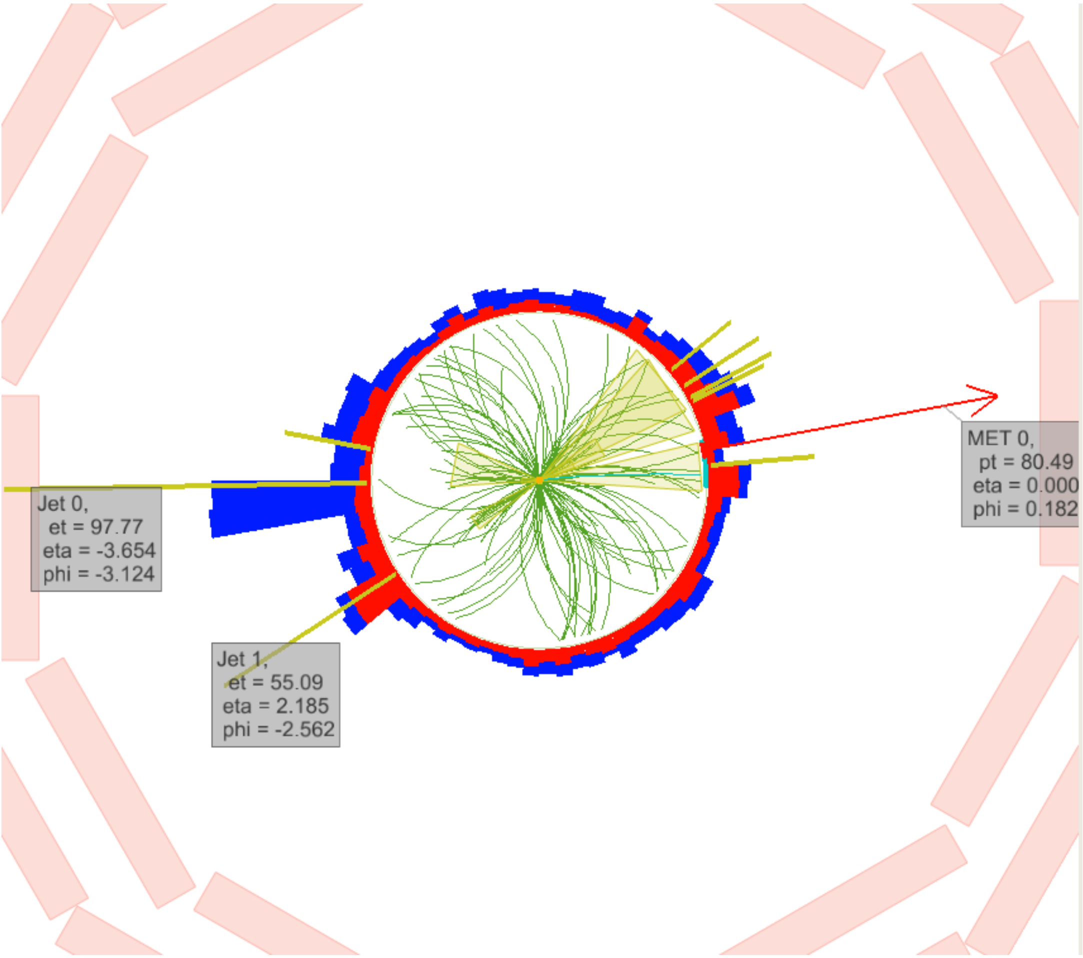
Veto region in CJV

$$\eta_{tag.j}^{min} < \eta^{j3} < \eta_{tag.j}^{max}$$



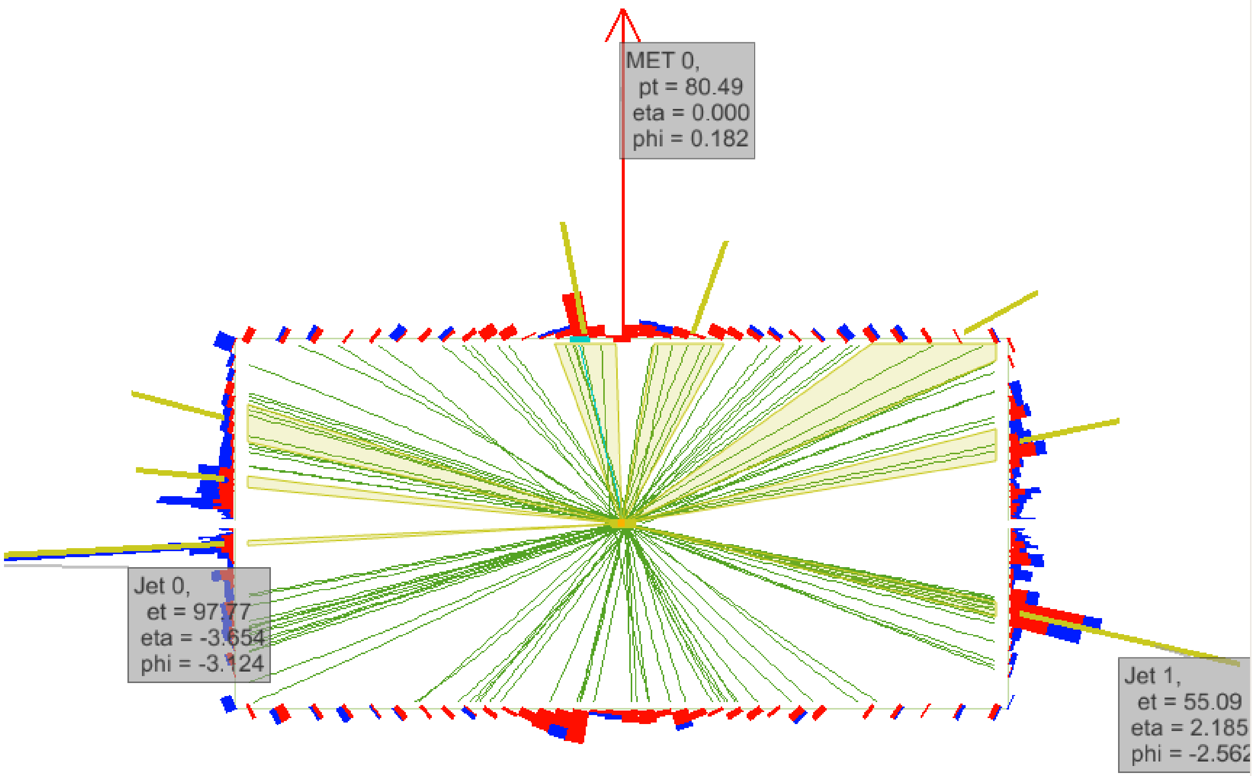
- reject event with j_3 “between” two tagging jets in η

Signal region, with CJV (x,y view)



	▽pT	eta	phi
0	97.8	-3.654	-3.124
1	55.1	2.185	-2.562
2	27.0	-0.200	0.084
3	24.8	2.286	0.502
4	23.4	-2.044	2.958
5	23.0	0.359	0.575
6	21.6	-2.901	0.472
7	20.4	1.349	0.691

Signal region, with CJV (Z view)



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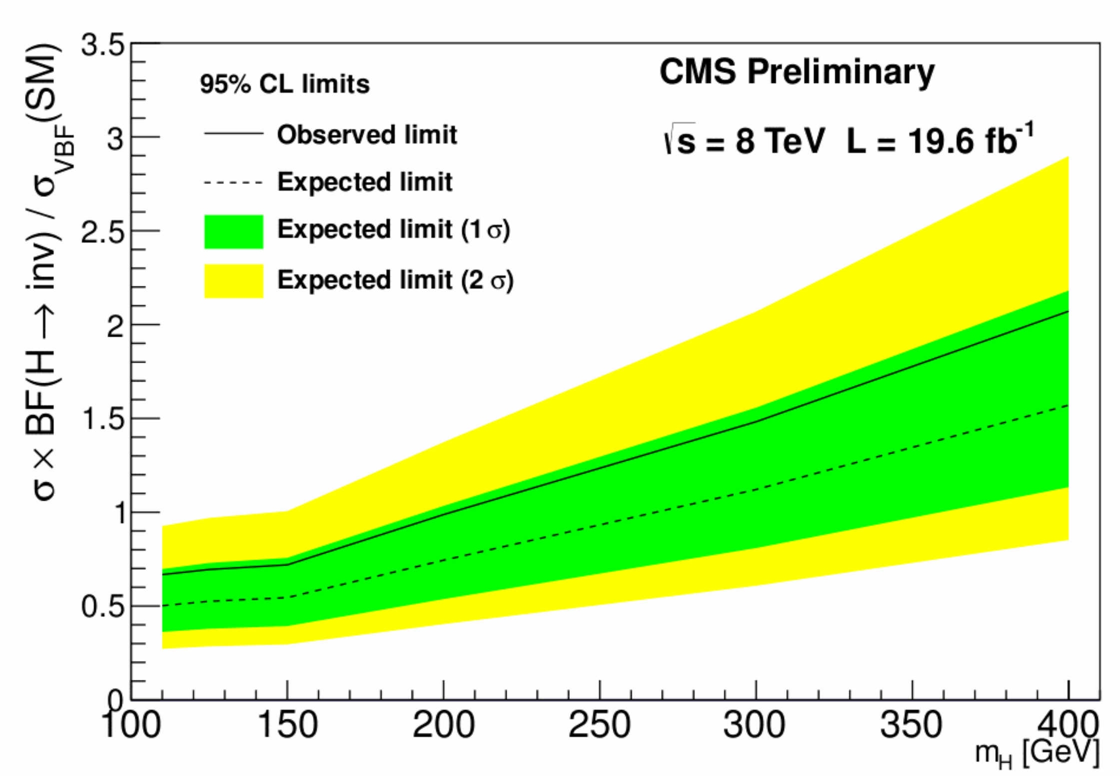
7	20.4	1.349	0.691

Cut-and-counting analysis

- **All background are obtained from data-driven methods with minimized dependence of MC**
- **QCD multijet bkg. is reduced to ~ 10 % level**
- **Number of events after all selections**

Background	N_{est}
$Z \rightarrow \nu\nu$	$102 \pm 30\,(\text{stat.}) \pm 26\,(\text{syst.})$
$W \rightarrow \mu\nu$	$67.2 \pm 5.0\,(\text{stat.}) \pm 15.1\,(\text{syst.})$
$W \rightarrow e\nu$	$68.2 \pm 9.2\,(\text{stat.}) \pm 18.1\,(\text{syst.})$
$W \rightarrow \tau\nu$	$54 \pm 16\,(\text{stat.}) \pm 18\,(\text{syst.})$
QCD multijet	$36.8 \pm 5.6\,(\text{stat.}) \pm 30.6\,(\text{syst.})$
Other SM	$10.4 \pm 3.1\,(\text{syst.})$
Total	$339 \pm 36\,(\text{stat.}) \pm 50\,(\text{syst.})$
Observed	390

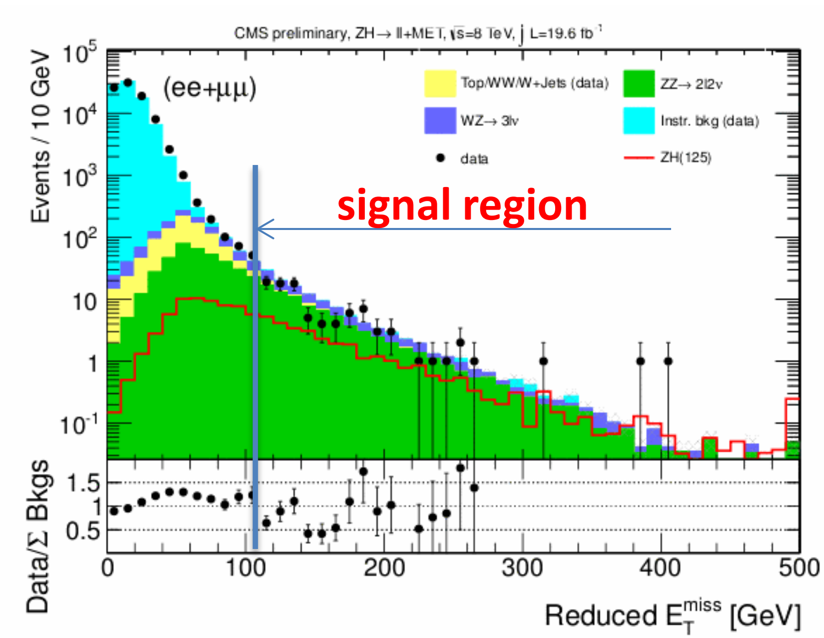
Upper limit on BR(H->invisible) in VBF analysis



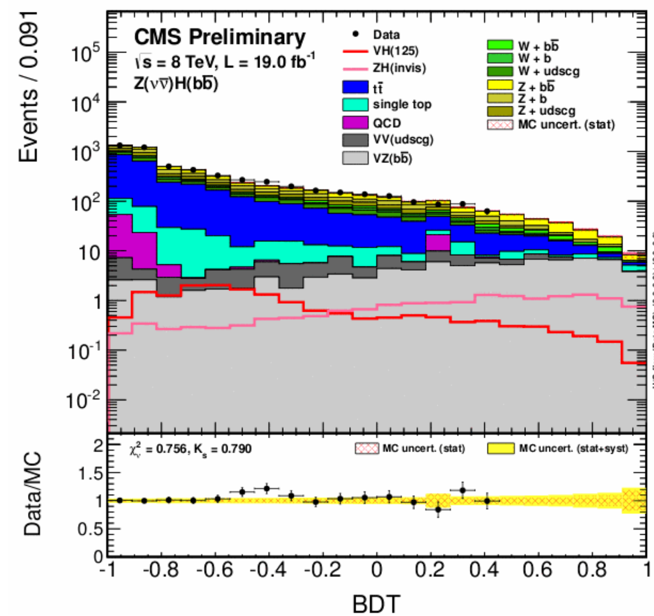
- At m_h=125 GeV
  - 0.53 expected – the best limit so far among ATLAS and CMS analyses with ZH, H->invisible, Z->ℓℓ,bb
  - 0.69 observed; within 1σ of expected

Upper limits from ZH, H->invisible analyses

- Z->$\ell\ell$, for m_h=125 GeV
  - Expected 0.91
  - Observed 0.75
- Z->bb, for m_h=125 GeV
  - Expected 2.04
  - Observed



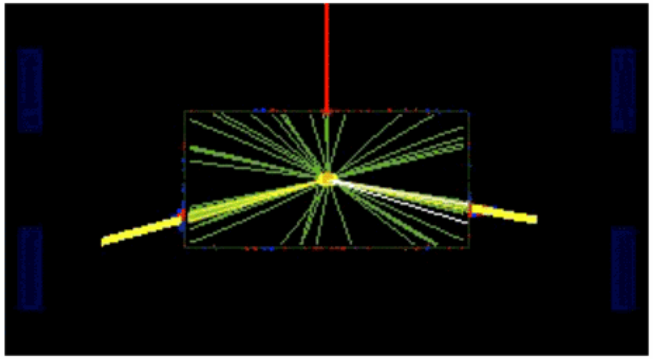
m_T(Z,H) shape analysis



BDT shape analysis

Summary on H->invisible analyses

- **VBF H->invisible mode has the best sensitivity which can be improved using shape instead of counting analysis**



Event 191202:51:82701983

- **Combination of all H->invisible modes provides upper limit on BR – 0.54 (0.46 expected) better then indirect limit from visible SM modes, 0.65.**
- **Analysis will become really interesting for physics once sensitivity better than ~ 30 % will be reached with 14 TeV data**

Higgs analysis in the framework of SUSY models (MSSM, NMSSM,…)

- Super Symmetry (SUSY) is one of the possible solutions of “SM problems”
  - SUSY is symmetry relating particles of integer spin (bosons) and particles of spin ½ (fermions). Each particle has a partner (“sparticle”) with the same quantum numbers, but spin.
  - SUSY must be explicitely broken since m_{spart} != m_{part}

SUSY solution for "fine tuning problem"

- One way to solve the gauge hierarchy problem is introducing a new boson in the loop of δM_H^2. Because fermion and boson have different statistic, such that

$$\delta M_H^2 \sim \frac{|y_f|^2}{16\pi^2}\left[-\Lambda_{UV}^2 + m_f^2\mathcal{O}(1)\right] + \frac{|y_b|^2}{16\pi^2}\left[+\Lambda_{UV}^2 - m_b^2\mathcal{O}(1)\right]$$

- SUSY algebra

$$Q|\text{fermion}\rangle = |\text{boson}\rangle\,,\ \ Q|\text{boson}\rangle = |\text{fermion}\rangle$$

guarantees that $|y_f|^2 = |y_b|^2$. If one can also manages $|m_b^2 - m_f^2| < TeV$, the gauge hierarchy problem is solved.

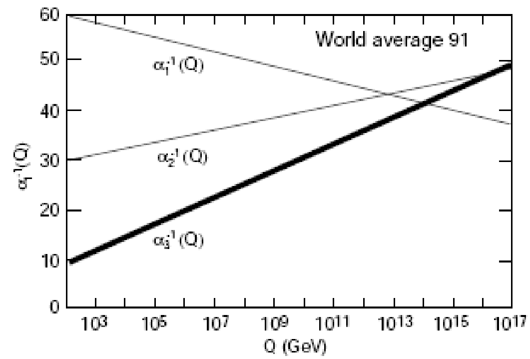
SUSY and gauge couplings unification

- RG running of the gauge coupling

$$\frac{1}{\alpha_i(M_X)} = \frac{1}{\alpha_i(M_Z)} - \frac{\beta_i}{4\pi} \ln\left(\frac{M_X^2}{M_Z^2}\right)$$

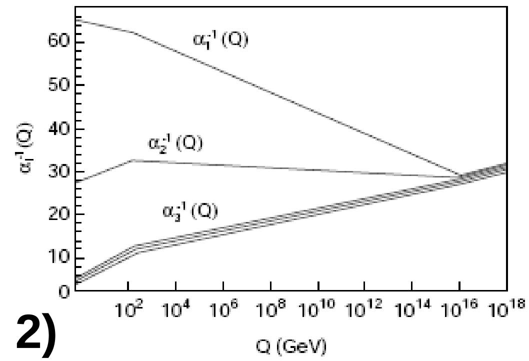
- For SM, the beta function is

$$\begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} F + \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix} N_H$$



- With SUSY, the running becomes

$$\begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} F + \begin{pmatrix} \frac{3}{10} \\ \frac{5}{6} \\ 0 \end{pmatrix} N_H$$



N_H number of Higgs doublets (SM = 1, MSSM = 2)
F number of flavors, SM = MSSM = 3

MSSM and
Higgs bosons in MSSM

- Unconstrained MSSM is the most "economic" version of SUSY
  - Minimal gauge group $SU(3)_C xSU(2)_L xU(1)_Y$
  - Minimal particle content; tree generation of spin ½ quarks and leptons [no right handed neutrino] as in SM; **The Higgs sector consists of two scalar doublet fields H_u and H_d that leads, after EW symmetry breaking to five Higgs particles : two CP even h, H bosons, a pseudoscalar A boson and two charged $H^{+/-}$ bosons**
  - R parity conservation: $Rp = (-1)^{2S+3B+L}$
  - Minimal set of soft SUSY-breaking terms
  - Unconstrained MSSM has 124 free parameres (104 from SUSY breaking terms + 19 parameters of the SM)
- Constrained MSSM (or phenomenological MSSM) reduces number of free parameters to 22
  - all the soft SUSY-breaking parameters are real => no new source of CP-violation in addition to the one from CKM matrix
  - no FCNC at tree level
  - the soft SUSY-breaking masses and trilinear couplings of the 1^{st} and 2^{nd} sfermion generations are the same at low energy
- So far most of the MSSM Higgs boson searches at LHC were performed within the framework of phenomenological MSSM (pMSSM) without assuming any particular soft SUSY-breaking scenario (mSUGRA, AMSB, GMSB, ..)

At tree level Higgs sector of MSSM is determined by two parameters:

M_A and $\tan(\beta)$

$1 < \tan(\beta) = v_2/v_1 = (v \sin(\beta)) / (v \cos(\beta)) < 60$

where v_1 and v_2 are vacuum expectation values (vev) of the neutral components of two Higgs doublets.

$v_1^2 + v_2^2 = v^2 = 2M_Z^2 / (g_2^2 + g_1^2) = (246\ \text{GeV})^2$

Higgs masses at tree level

$$m_{H,h}^2 = ½[(m_A^2 + m_Z^2) \pm ((m_A^2 + m_Z^2)^2 - 4m_Z^2 m_A^2 (\cos^2 2\beta))^{1/2}]$$

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

$m_h < m_Z$

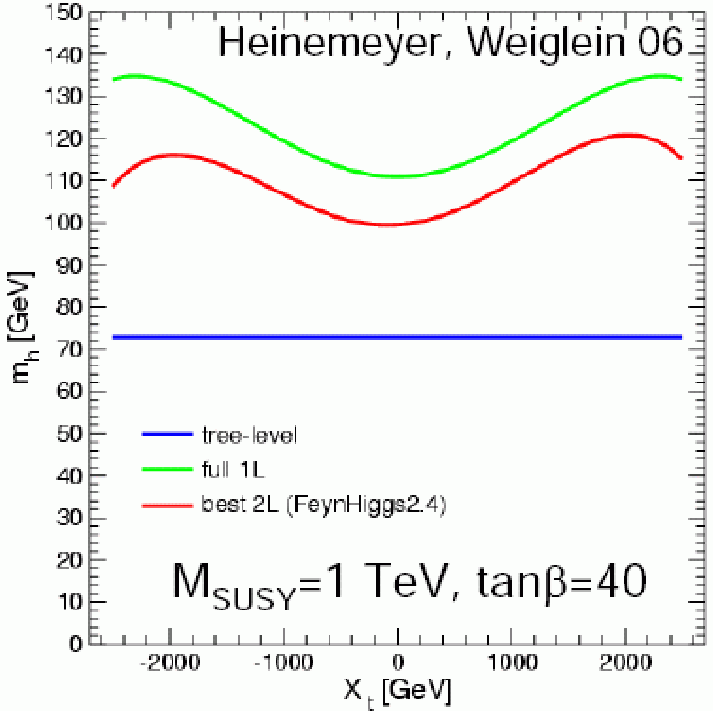
The radiative corrections increase the upper bound of m_h significantly

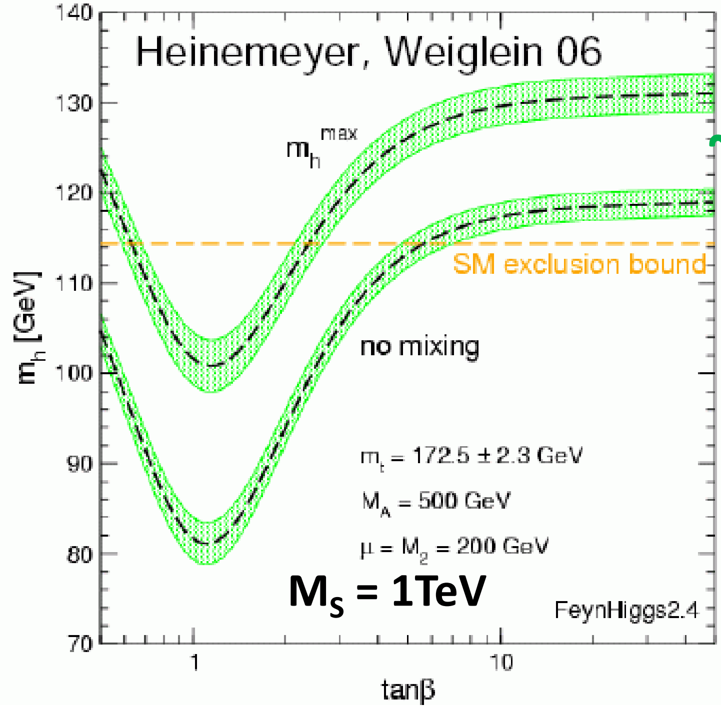
$$\epsilon = \frac{3\,\bar{m}_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\,M_S^2}\right)\right]$$

with leading 1 loop corrections

there $X_t = A_t - \mu/\tan(\beta)$, $M_S^2 = ½\,(M_{stop1}^2 + M_{stop2}^2)$
A_t is trilinear Higgs-stop coupling, μ is Higgs-higgsino mass parameter

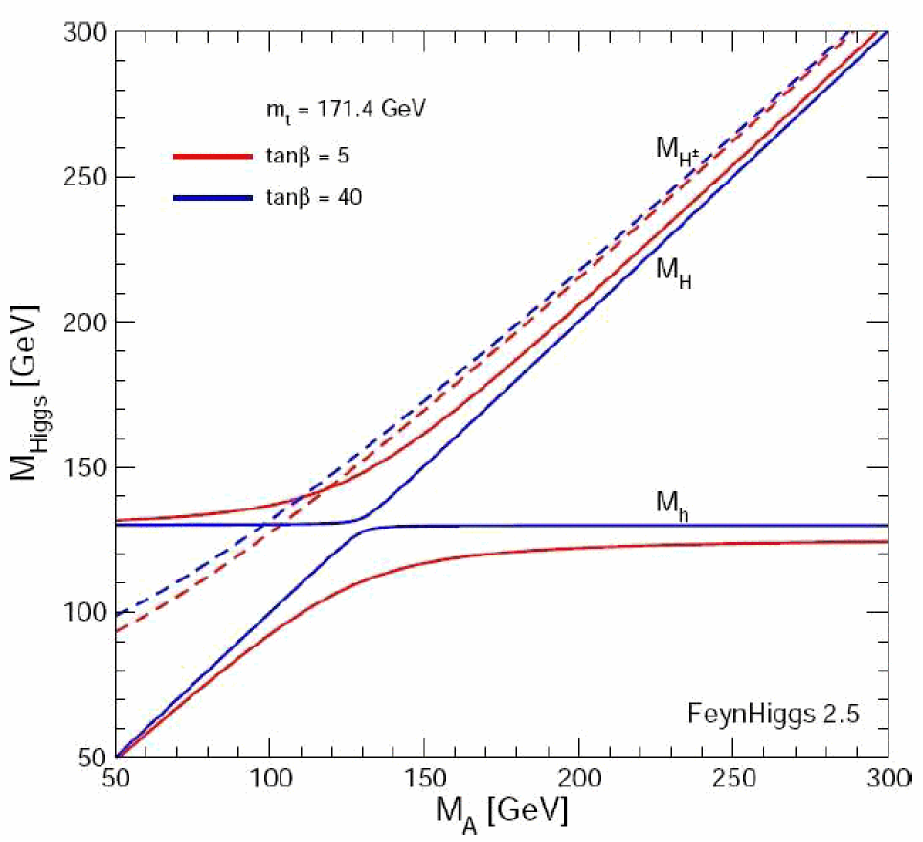
M_h reaches maximum value at $X_t = 2\,M_S$ (FD) and local minimum at $X_t = 0$; these are two scenarios (**m_h^{max}** and **no-mixing**) used in LEP Higgs searches:
M. Carena, S. Heinemeyer, C.E.M. Wagner and G. Weiglein, hep-ph/0202167.





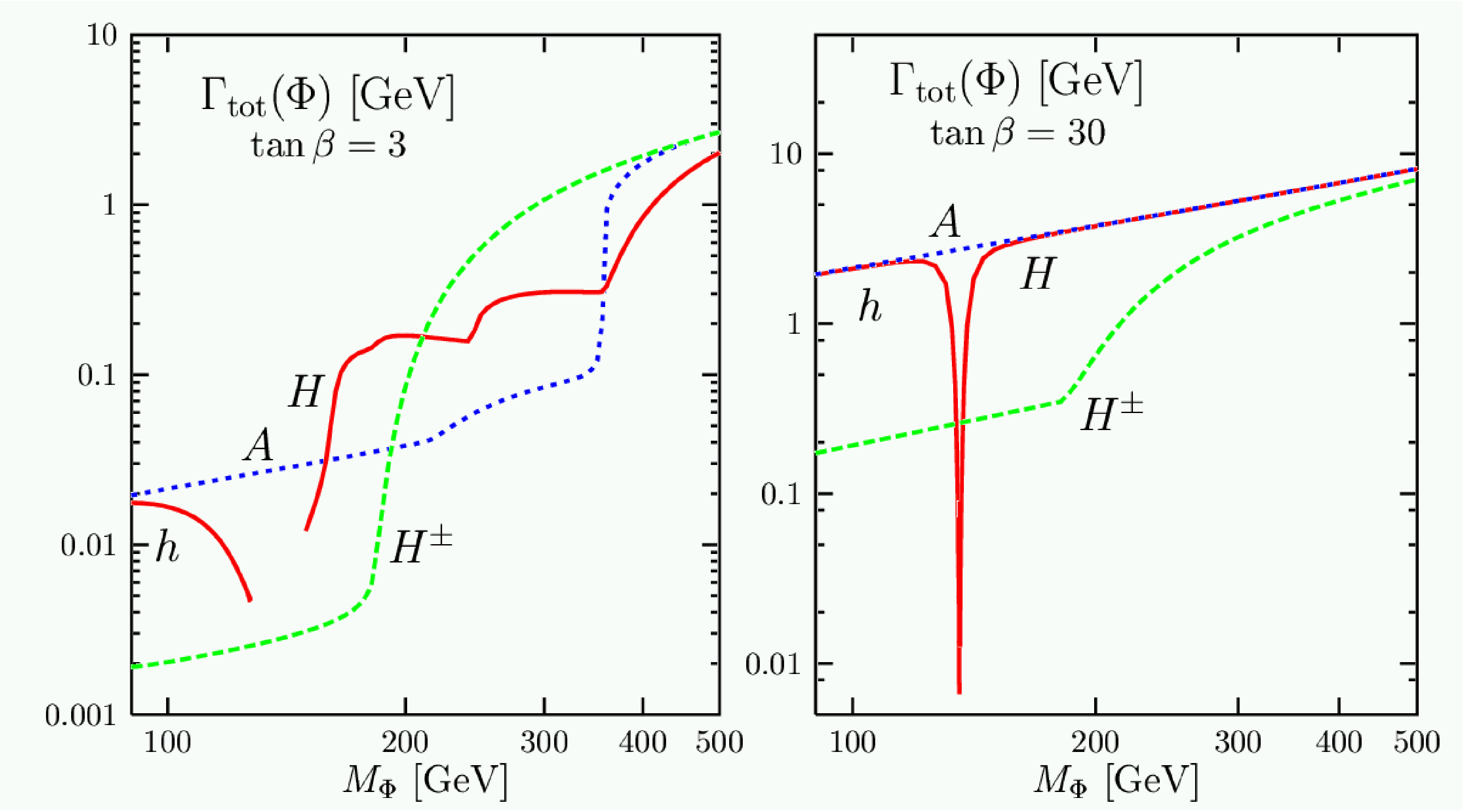
$\Delta^{th} m_h$ ~ 3 GeV

Masses of MSSM Higgs bosons



- **Five Higgs bosons in 2HD and MSSM model:**
  two CP-odd h, H; one CP-even A, two charged $H^{+/-}$

Total width of MSSM Higgs bosons



Neutral Higgs boson couplings to fermions and gauge bosons in the MSSM at tree level normalized to the SM Higgs boson couplings $g_{Hff}=(2^{1/2}G_\mu)^{1/2}m_f$, $g_{HVV} = (2^{1/2}G_\mu)^{1/2}M_V^2$ and the couplings of two Higgs bosons with one gauge boson, normalized to $g_W = (2^{1/2}G_\mu)^{1/2}$ for $g_{\Phi H+W-}$ and $g_Z=(2^{1/2}G_\mu)^{1/2}M_Z$ for $g_{\Phi AZ}$

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$	$g_{\Phi AZ}$	$g_{\Phi H^\pm W^\mp}$
$H_{\rm SM}$	1	1	1	0	0
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\mp\cos(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$	$\pm\sin(\beta-\alpha)$
A	$\cot\beta$	$\tan\beta$	0	0	1

α is a mixing angle between neutral components for two Higgs doublets H_1^0, H_2^0 to give the physical CP-even Higgs bosons h, H

$$\cos2\alpha = -\cos2\beta \, ((M_A^2-M_Z^2)/(M_H^2-M_h^2))$$

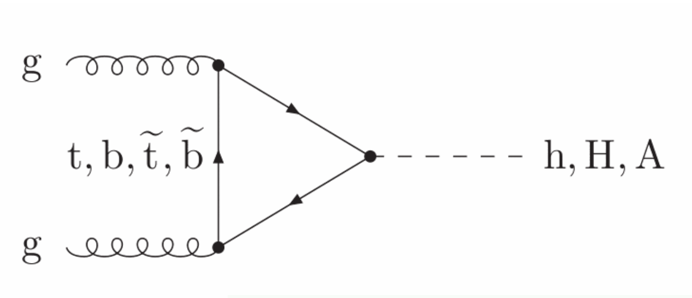
Radiative corrections introduce dependence on other parameters :

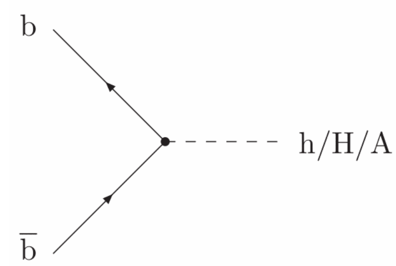
μ, M_2, M_{gluino} + 5 "physical" parameters: $m_{stop1,2}$, $m_{sbottom1,2}$, θ_{stop}

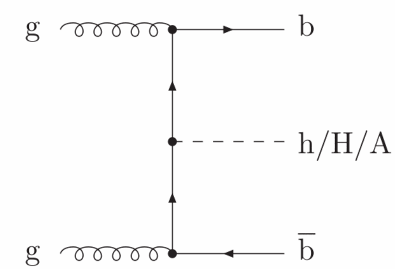
or

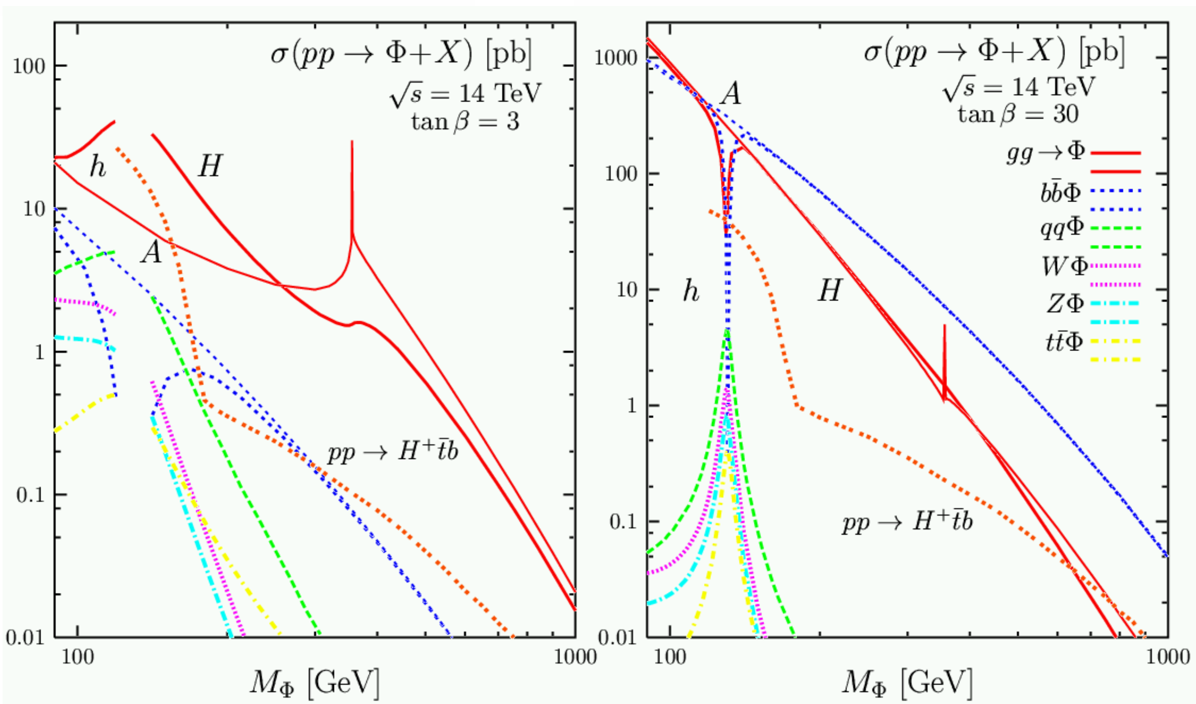
μ, M_2, M_{gluino} + 5 "unphysical parameters": m_{stopL}, m_{stopR}, $m_{sbottomR}$, A_t, A_b

MSSM neutral ϕ->ττ : the most sensitive channel at high values of tan β









- $g_{\phi bb}^{MSSM} = g_{\phi bb}^{SM} \times \tan\beta$ (ϕ=A) at tree level
- Br ($\phi \to \tau\tau$) ~ 10 %

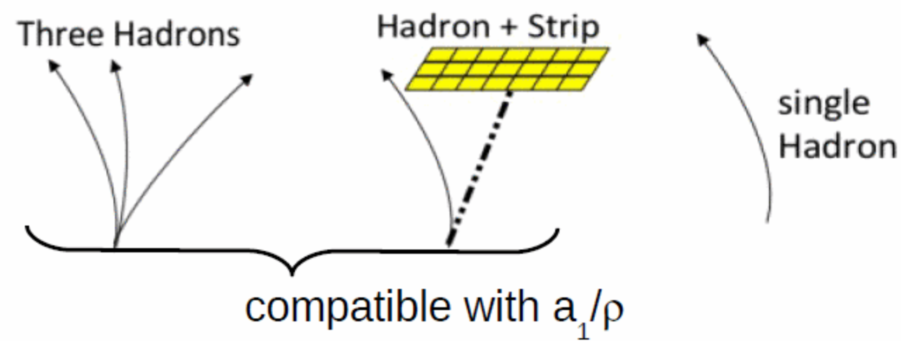
τ identification (I)

- **Step 1: decay mode finding**

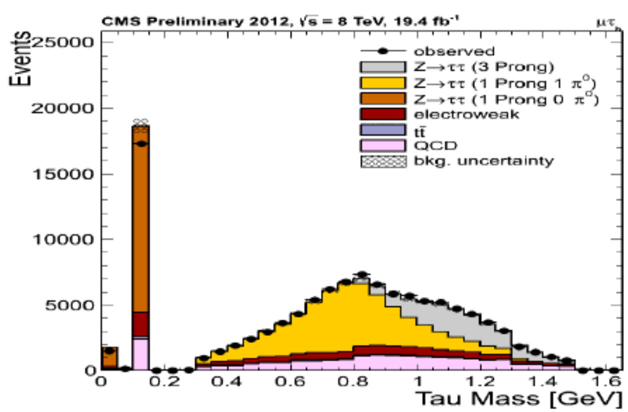
Reconstructed using the Hadron plus Strips (HPS) algorithm

τ_h

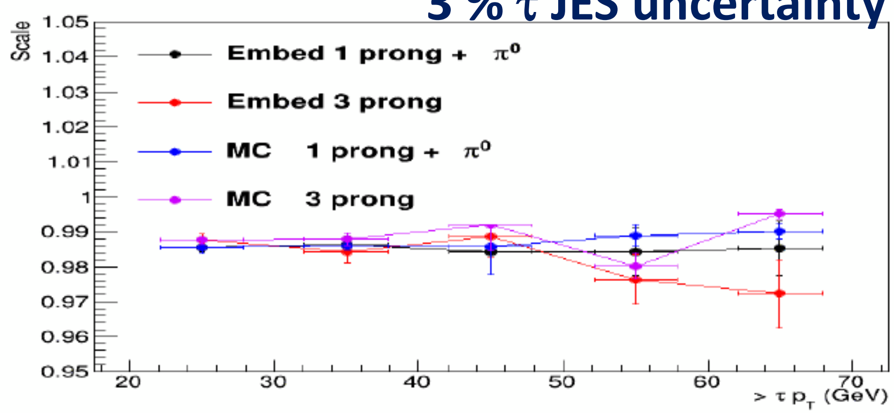
- $\tau^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau}$
- $\tau^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}\nu_{\tau}$
- $\tau^{\pm} \to \pi^{\pm}\pi^{0}\nu_{\tau}$
- $\tau^{\pm} \to \pi^{\pm}\nu_{\tau}$



- Correct tau energy scale with the tau mass
  - Fitting MC to data → a shift in respect to data would indicate a incorrect tau energy scale

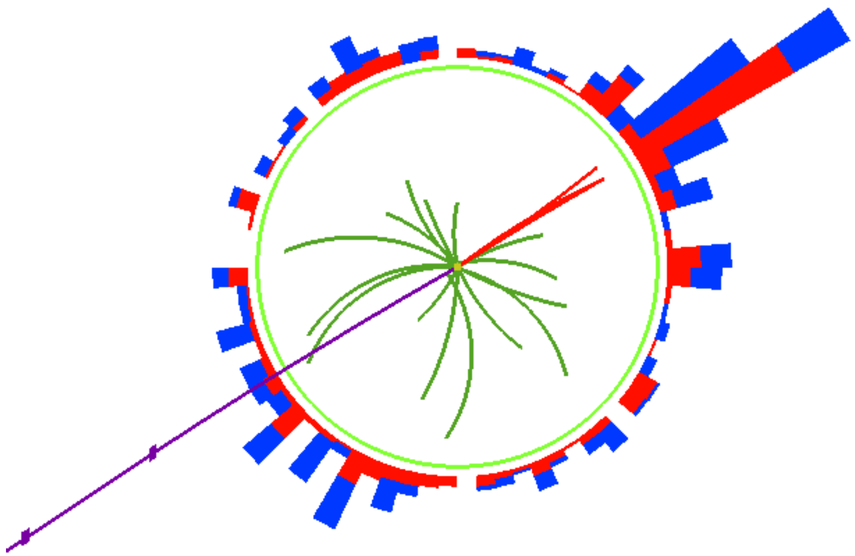


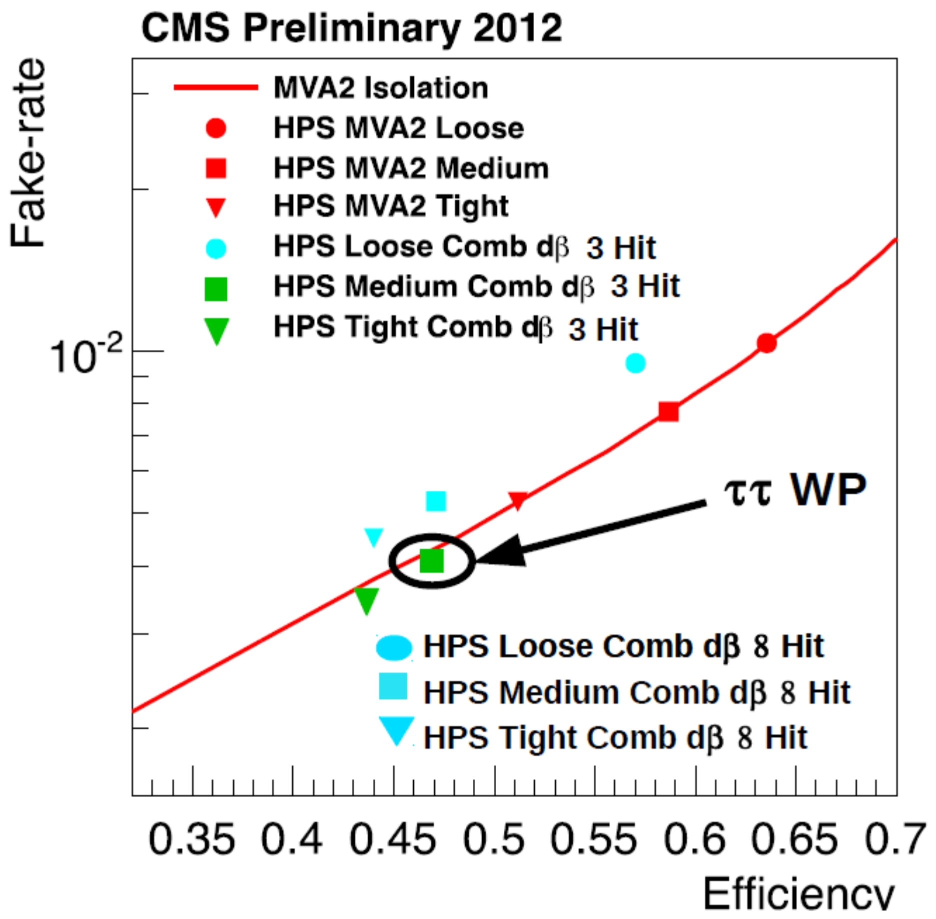
~ 3 % τ JES uncertainty



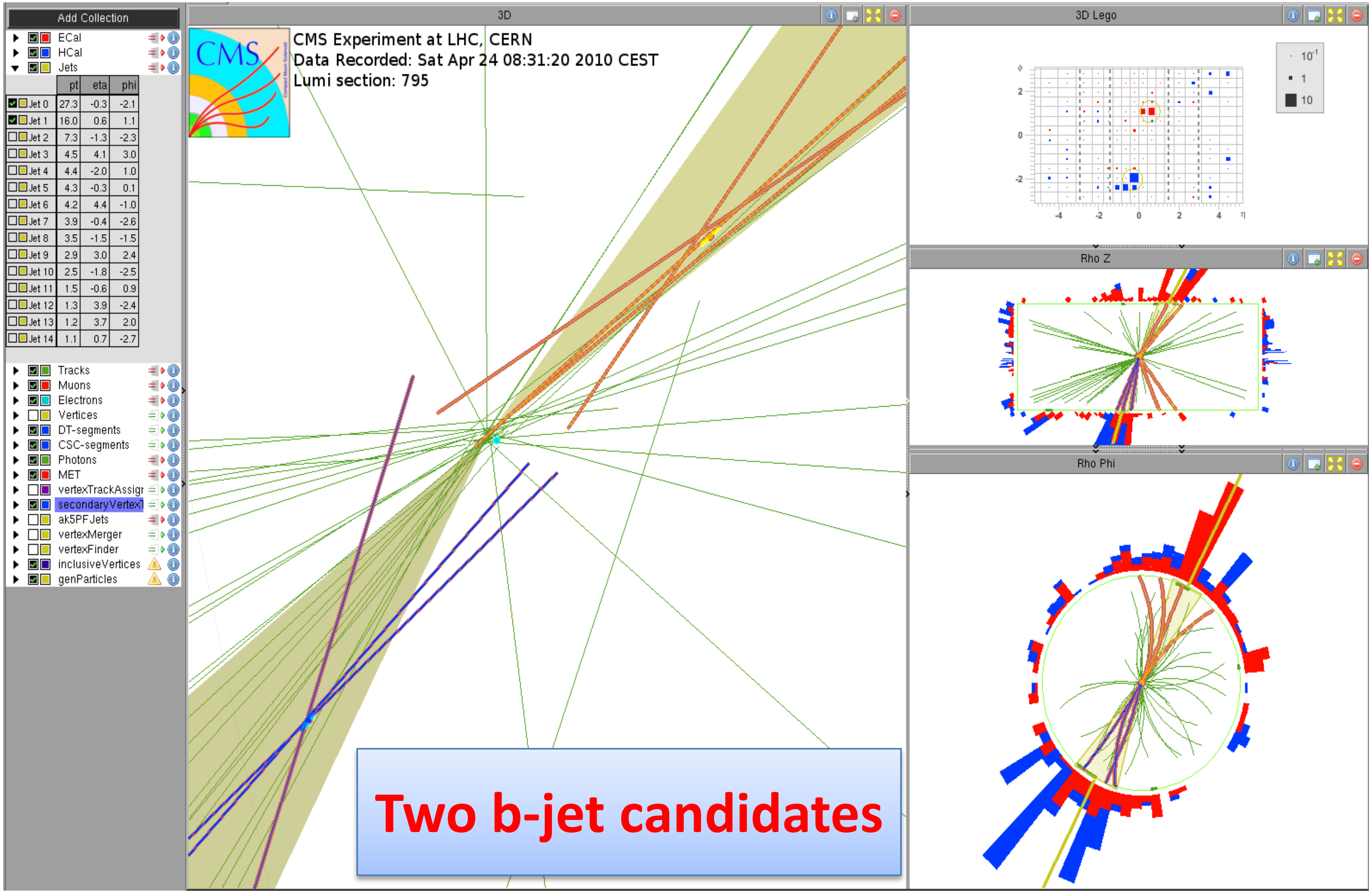
τ identification (II)

- **Step2: isolation of τ_h**





B-tagging

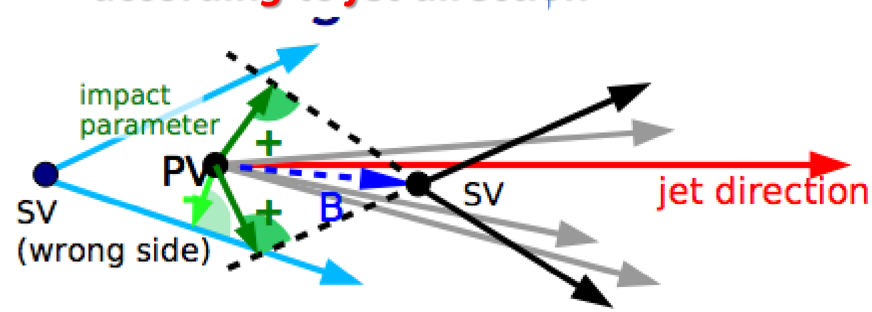


Add Collection
ECal
HCal
Jets
pt eta phi
Jet 0 27.3 -0.3 -2.1
Jet 1 16.0 0.6 1.1
Jet 2 7.3 -1.3 -2.3
Jet 3 4.5 4.1 3.0
Jet 4 4.4 -2.0 1.0
Jet 5 4.3 -0.3 0.1
Jet 6 4.2 4.4 -1.0
Jet 7 3.9 -0.4 -2.6
Jet 8 3.5 -1.5 -1.5
Jet 9 2.9 3.0 2.4
Jet 10 2.5 -1.8 -2.5
Jet 11 1.5 -0.6 0.9
Jet 12 1.3 3.9 -2.4
Jet 13 1.2 3.7 2.0
Jet 14 1.1 0.7 -2.7
Tracks
Muons
Electrons
Vertices
DT-segments
CSC-segments
Photons
MET
vertexTrackAssigr
secondaryVertex1
ak5PFJets
vertexMerger
vertexFinder
inclusiveVertices
genParticles
3D
CMS
CMS Experiment at LHC, CERN
Data Recorded: Sat Apr 24 08:31:20 2010 CEST
Lumi section: 795
3D Lego
Rho Z
Rho Phi
Two b-jet candidates

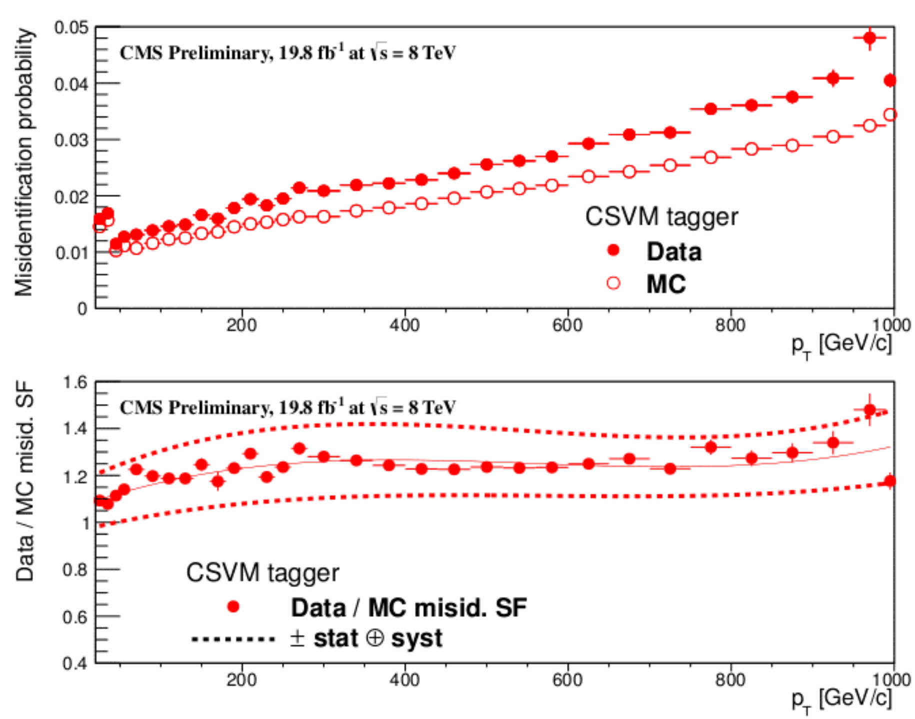
CMS b-tagging algorithms used in 2012 data analyses (PAS BTV-13-001)

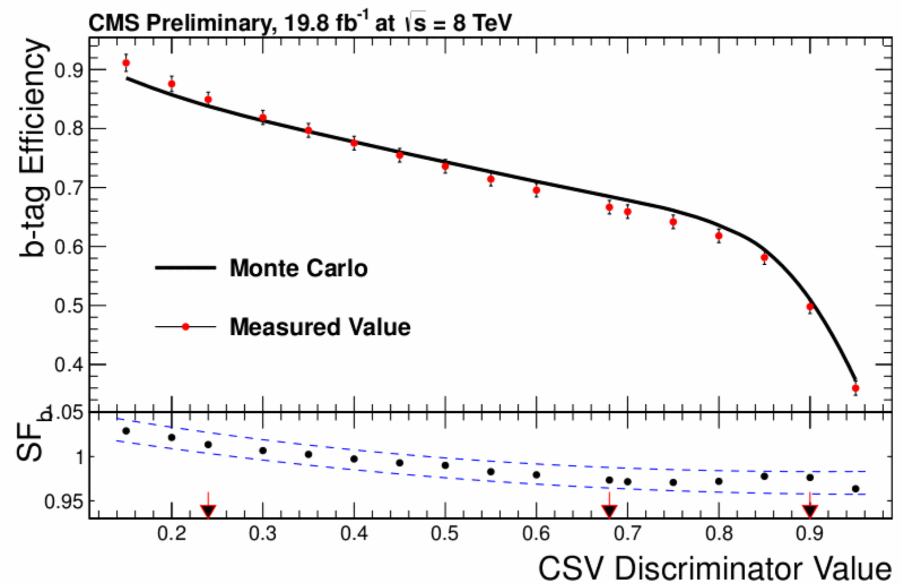
- **Track Counting**
  - high purity; use 3rd track 3d ip significance
- **Jet Probability**
  - use 3d ip significance of all tracks to build likelihood that all tracks come from PV
- **Combined Secondary Vertex**
  - uses SVs and track-based life-time information to build likelihood- -based discriminator between jets from b, c, or light quarks and g's

Signs of Impact parameter and of vertex decay length are defined according to jet direction



• CMS b-tagging performance with 8 TeV data





Fake rate:

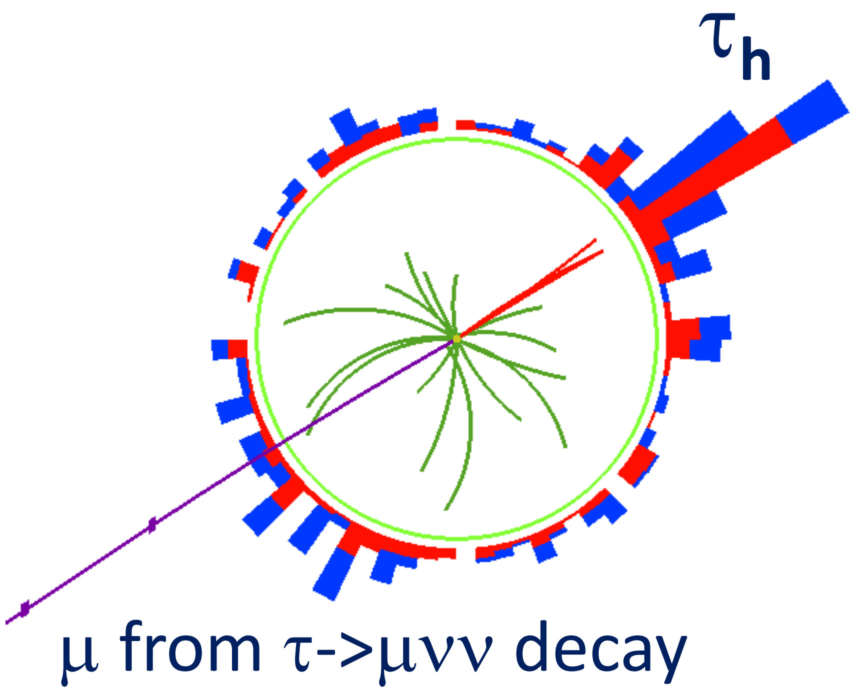
for 80 < p_T^j < 120 GeV

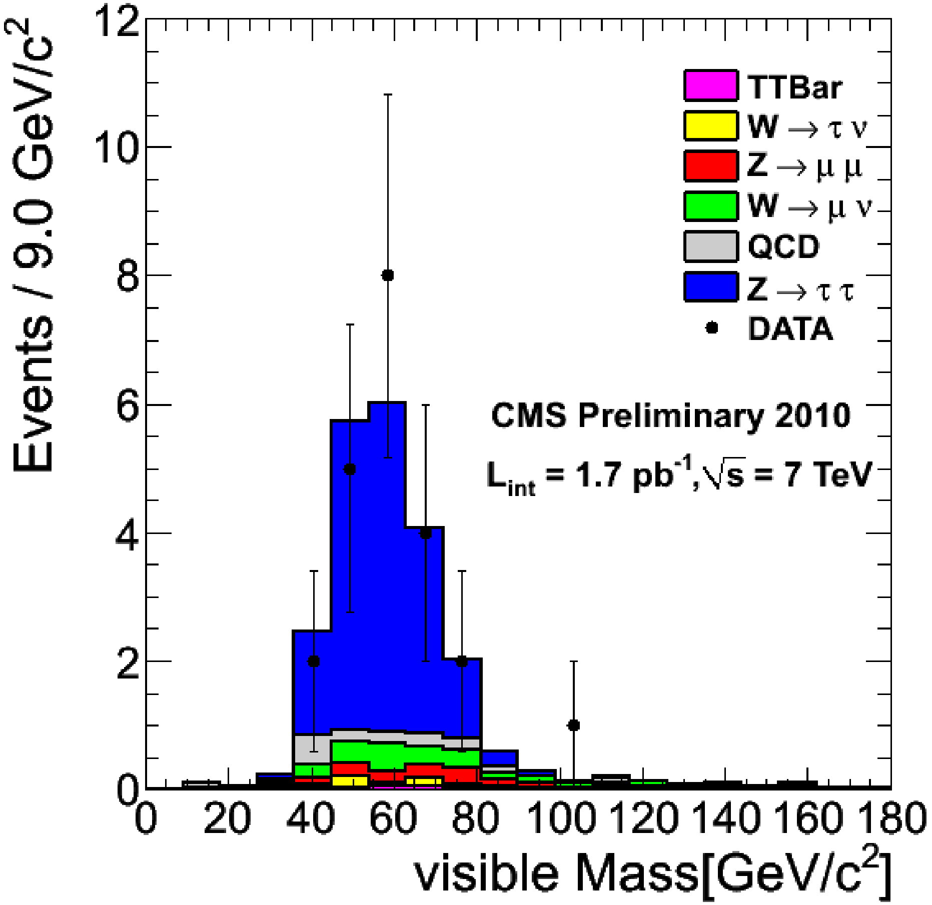
|η| < 2.4

b tagger	misidentification probability	SF_{light}
JPL	0.0944 ± 0.0004	$1.03 \pm 0.01 \pm 0.07$
CSVL	0.0990 ± 0.0004	$1.10 \pm 0.01 \pm 0.05$
JPM	0.0105 ± 0.0002	$1.10 \pm 0.02 \pm 0.20$
CSVM	0.0142 ± 0.0002	$1.17 \pm 0.02 \pm 0.15$
TCHPT	0.0026 ± 0.0001	$1.27 \pm 0.06 \pm 0.27$
JPT	0.0013 ± 0.0001	$1.11 \pm 0.07 \pm 0.31$
CSVT	0.0016 ± 0.0001	$1.26 \pm 0.07 \pm 0.28$

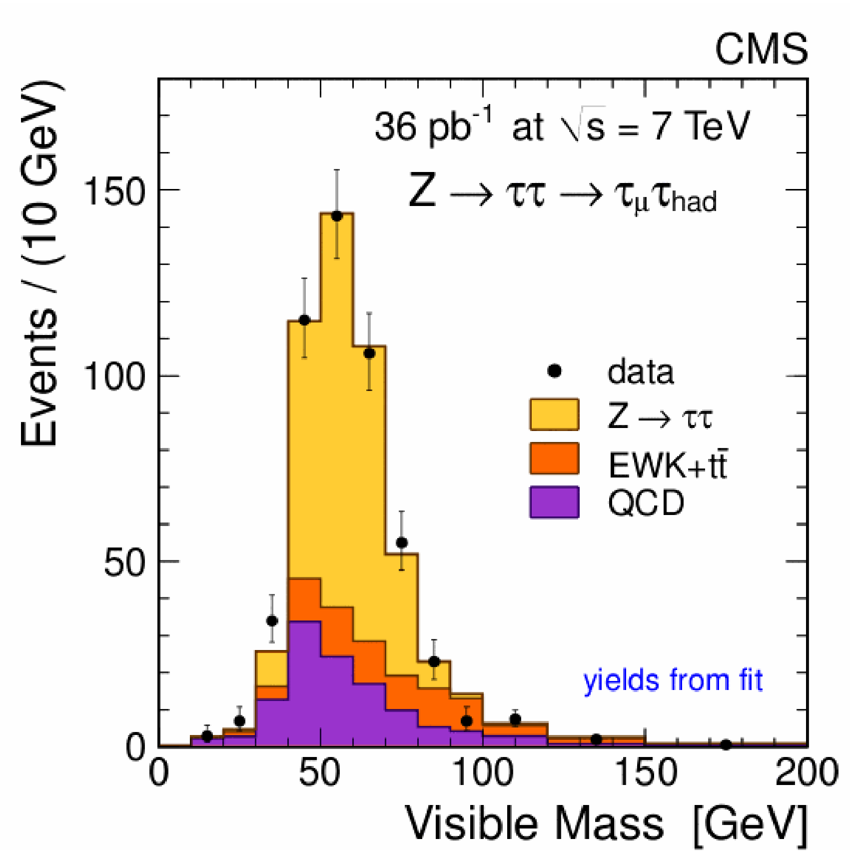
Preparation for pp->ϕ+X, ϕ->$\tau\tau$ discovery

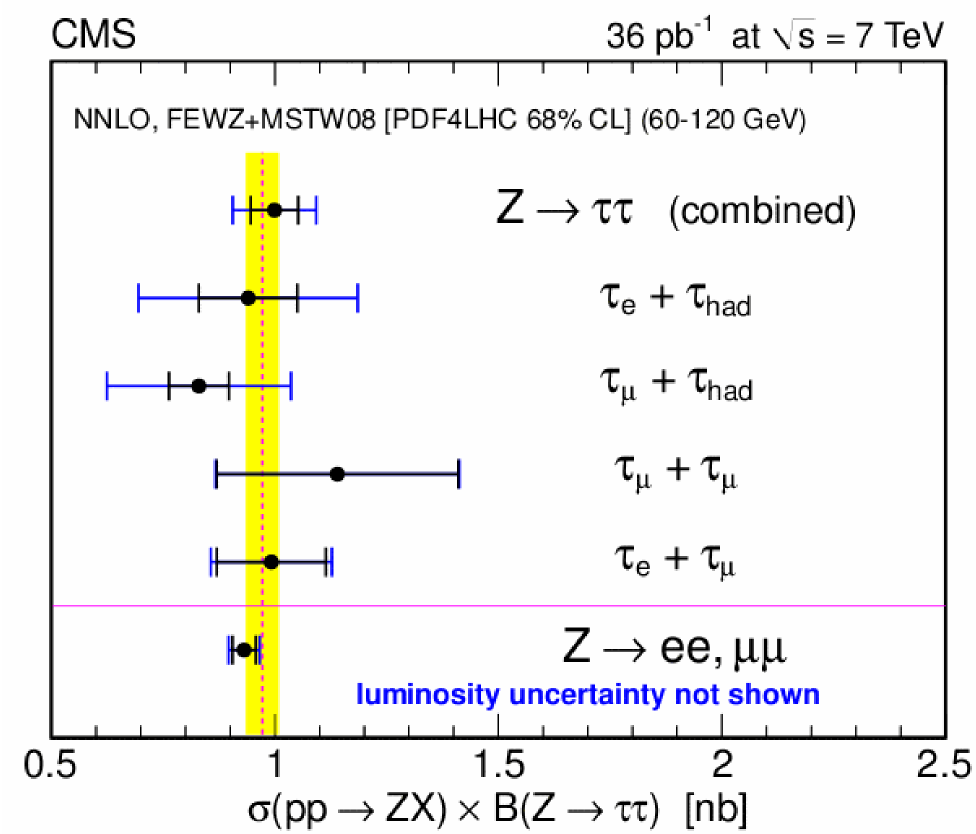
- CMS "discovery" of Z->$\tau\tau$, 2010, 1.7 pb^{-1}





CMS $Z \to \tau\tau$ measurement, 36 pb^{-1}





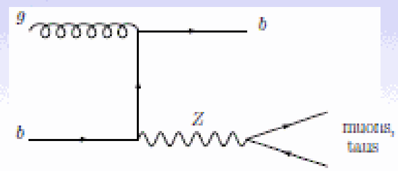
Z+b as a benchmark for MSSM H+b

$Z + b$ as a test case

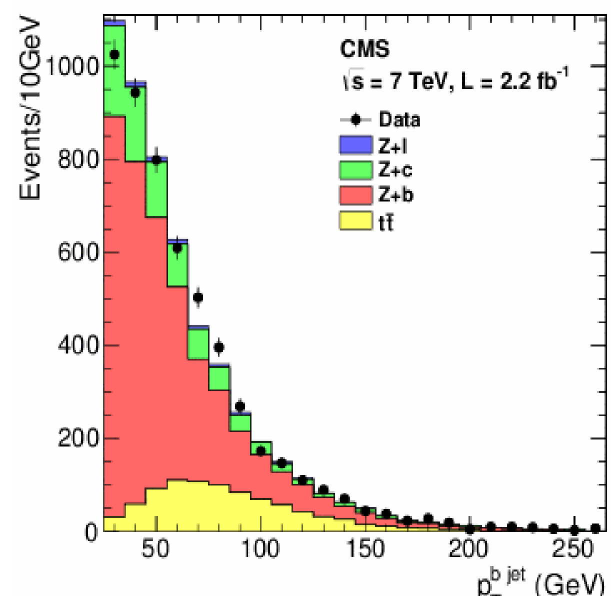
J. Campbell talk on CMS meeting, 2006

- The production of $Z + b$ is very similar to that of $H + b$, even lying in a similar kinematic region for a low mass Higgs.
- Theoretically, the two processes have the same inputs and uncertainties.
  - same initial state, similar (x, Q^2)
  - the same H and Z decays
- Test the experimental analysis procedure by re-discovering the Z –

  a) $Z+$ one jet which is b-tagged ;



1st CMS Z+b analysis with 2.2 fb^{-1} at 7 TeV

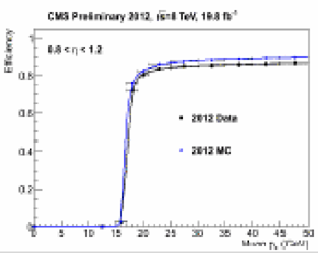


- **Data vs MC comparizon**
  - **kinematics => acceptance**
  - **cross-sections 4FS vs 5FS**
    - **relevant for low mass Higgs boson**
- **b-PDF – to be studied**

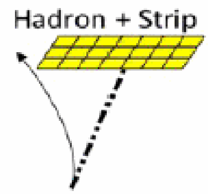
CMS SUSY H->ττ analysis, 2013

Analysis Flow

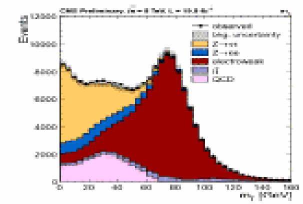
Trigger



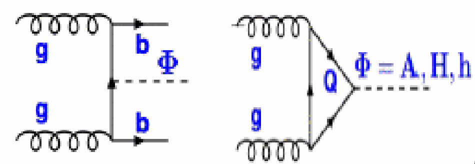
Object selection



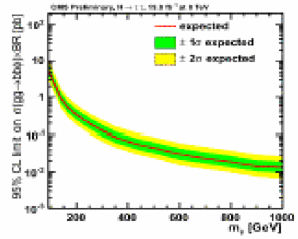
Background estimation



Categorization



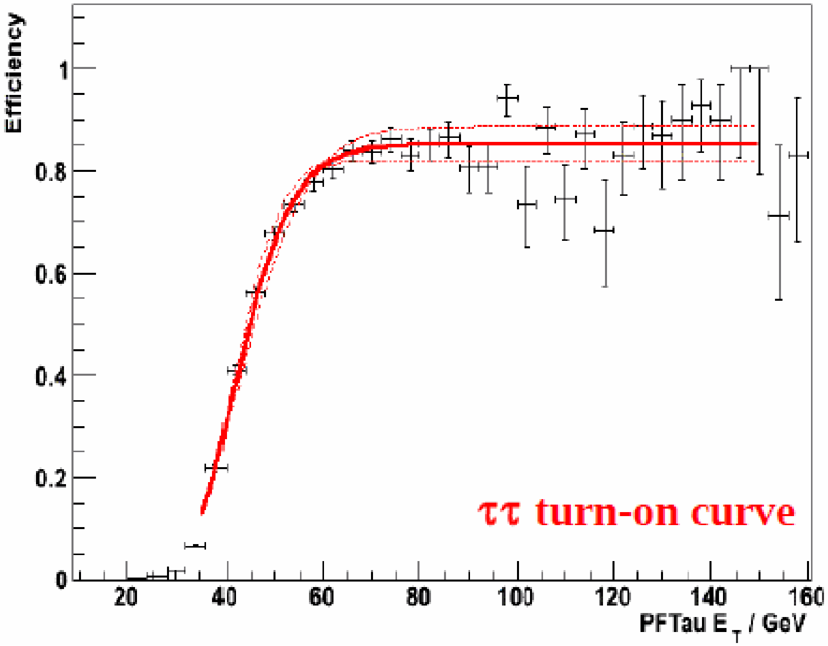
Interpretation



Triggers

- Distinct triggers for each channel
  - $\mu\tau$: isolated μ > 17 GeV + isolated τ > 20 GeV
  - $e\tau$: e > 22 GeV + isolated τ > 20 GeV
  - $e\mu$: μ > 17(8) GeV + e > 8(17) GeV
  - $\mu\mu$: μ > 17 GeV + μ > 8 GeV
  - $\tau\tau$: 2 isolated τ > 35 GeV
    - Using parked dataset
      - Not need to use ditau+jet trigger

} Not changed since HCP 2012



Event selection overview

- Two well reconstructed, isolated leptons of opposite sign:

channel	p_T	$\|\eta\|$	p_T	$\|\eta\|$
$e\mu$	> 20 GeV (e/μ)	< 2.3 (e/μ)	> 10 GeV (μ/e)	< 2.3 (μ/e)
$e\tau$	> 24 GeV (e)	< 2.1 (e)	> 20 GeV (t)	< 2.1 (τ)
$\mu\mu$	> 20 GeV (μ)	< 2.1 (μ)	> 10 GeV (μ)	< 2.1 (μ)
$\mu\tau$	> 20 GeV (μ)	< 2.1 (μ)	> 20 GeV (τ)	< 2.3 (τ)
$\tau\tau$	> 45 GeV (τ)	< 2.1 (τ)	> 45 GeV (τ)	< 2.1 (τ)

- $e\mu$: $D_\zeta = P_\zeta - 1.85 \cdot P_\zeta^{vis} > -20$ GeV
- $e\tau$, $\mu\tau$: $M_T < 30$ GeV
- $\mu\mu$: Special BDT trained for rejection of $Z/\gamma^* \rightarrow \mu\mu$ events

Categorization

B-Tag:

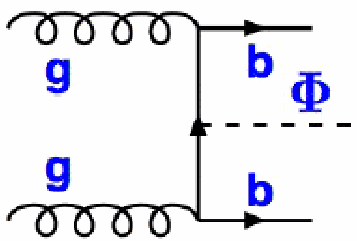
≥ 1 b-tagged jets with p_T > 20 GeV
< 2 jets with p_T > 30 GeV

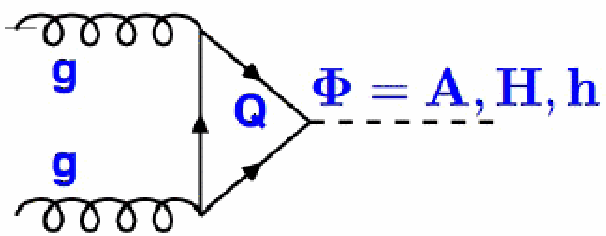
Sensitive to $bb\Phi$

No-B-Tag (inclusive):

no b-tagged jets with p_T > 20 GeV

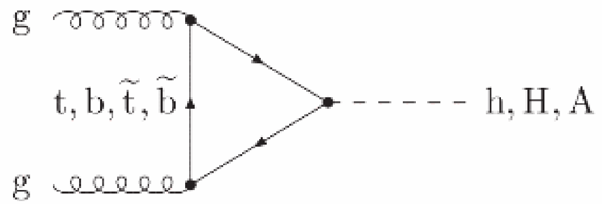
Contains rest of signal events.





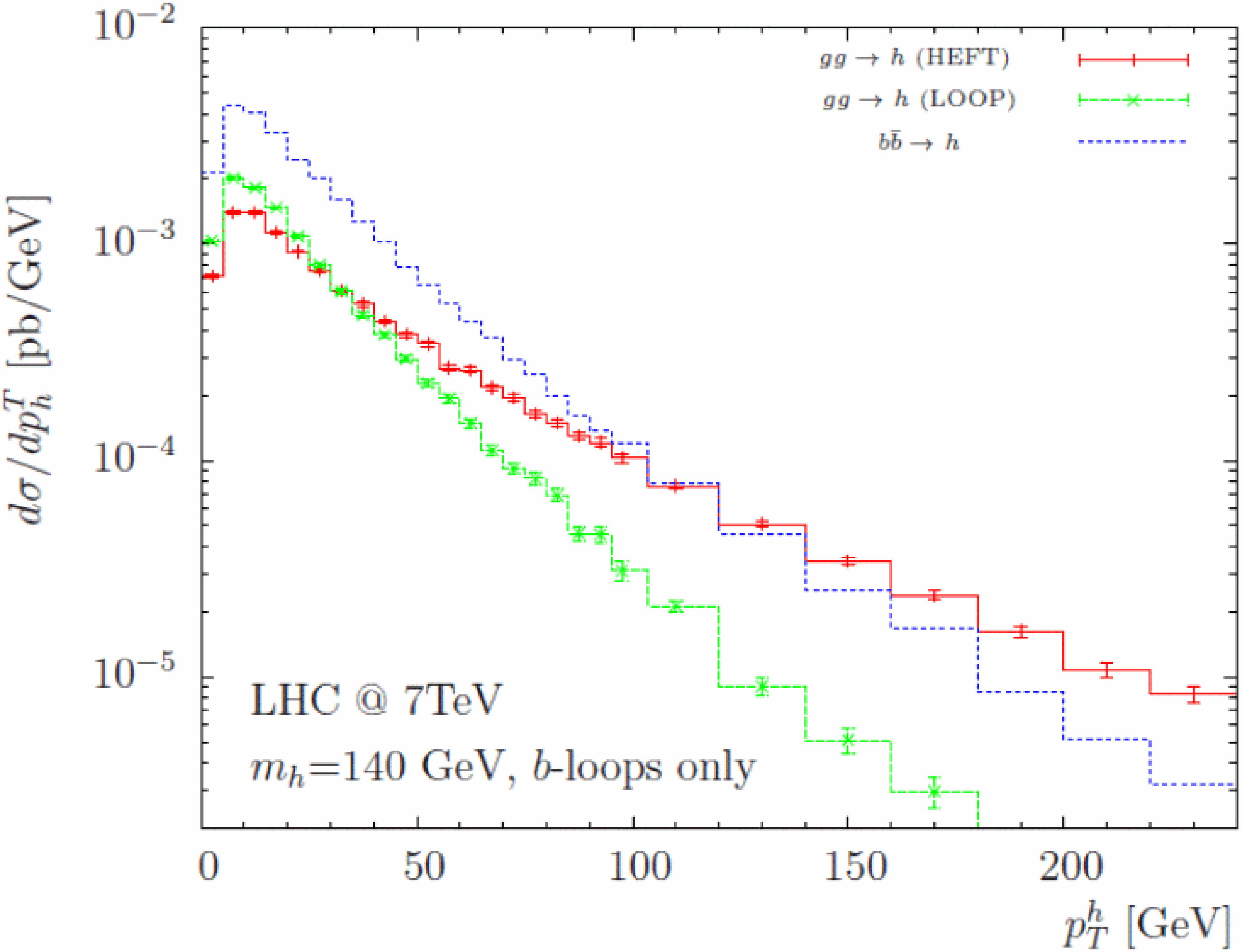
- The chosen categorization is Higgs-p_T independent in order to stay as model independent as possible

gg->H in SM and MSSM



- **At high tanβ and in m_h^{max} scenario b-loop dominates in MSSM gg->h production leading to change of p_T^H in comparison with SM gg->h where top loop dominates:**
  1. *Spira et al. hep-ph/0604156*
  2. *J. Alwall, Q Li, F. Maltoni arXiv:1110.1728*
  3. *E.Bagnaschi, G. Degrassi, P. Slavich, A.Vicini. arXiv:1111.2854*

J. Alwall, Q Li, F. Maltoni arXiv:1110.1728



Acceptance of kinematic selections

- **Acceptance selections at generator level (corresponds to current CMS cuts at reconstruction level):**
  - electron from $\tau \to e\nu\nu$ decay: $p_T > 20$ GeV, $|\eta| < 2.1$
  - τ_h from $\tau \to$ hadrons(τ_h) ν decay: $p_T > 20$ GeV, $|\eta| < 2.3$
  - $\Delta R_{e\tau} > 0.5$

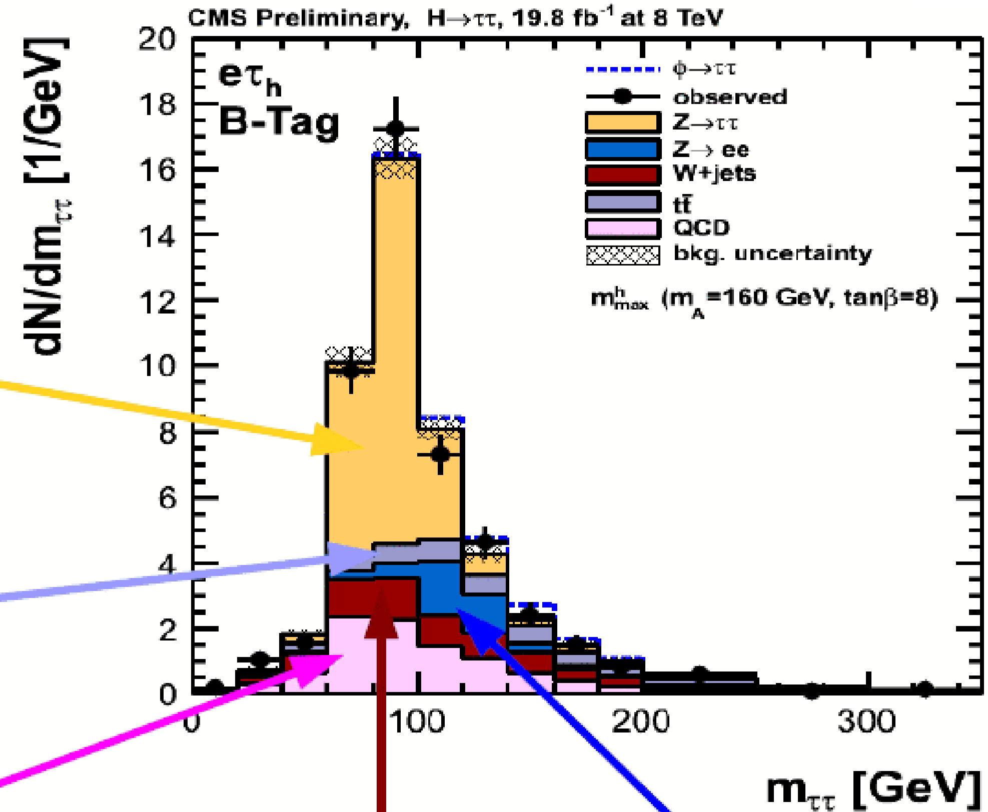
M_{H} [GeV]	Acceptance, PYTHIA gg $\to$ H	Acceptance, re-weighted for b-loop	Correction factor
140	0.072 ± 0.001	0.070 ± 0.001	0.97 ± 0.01
400	0.149 ± 0.001	0.152 ± 0.001	1.02 ± 0.02

Table 1: The $e + \tau_{\mathrm{h}}$ acceptances before and after re-weighting to correct for b-loop contribution.

Background estimation in $\Phi \rightarrow \tau\tau$

$Z/\gamma^* \rightarrow \tau\tau$:
- Embedding: in $Z \rightarrow \mu\mu$, replace μ by sim. τ decay
- Normalized from $Z \rightarrow \mu\mu$ events

ttbar:
- From simulation
- Normalization from sideband



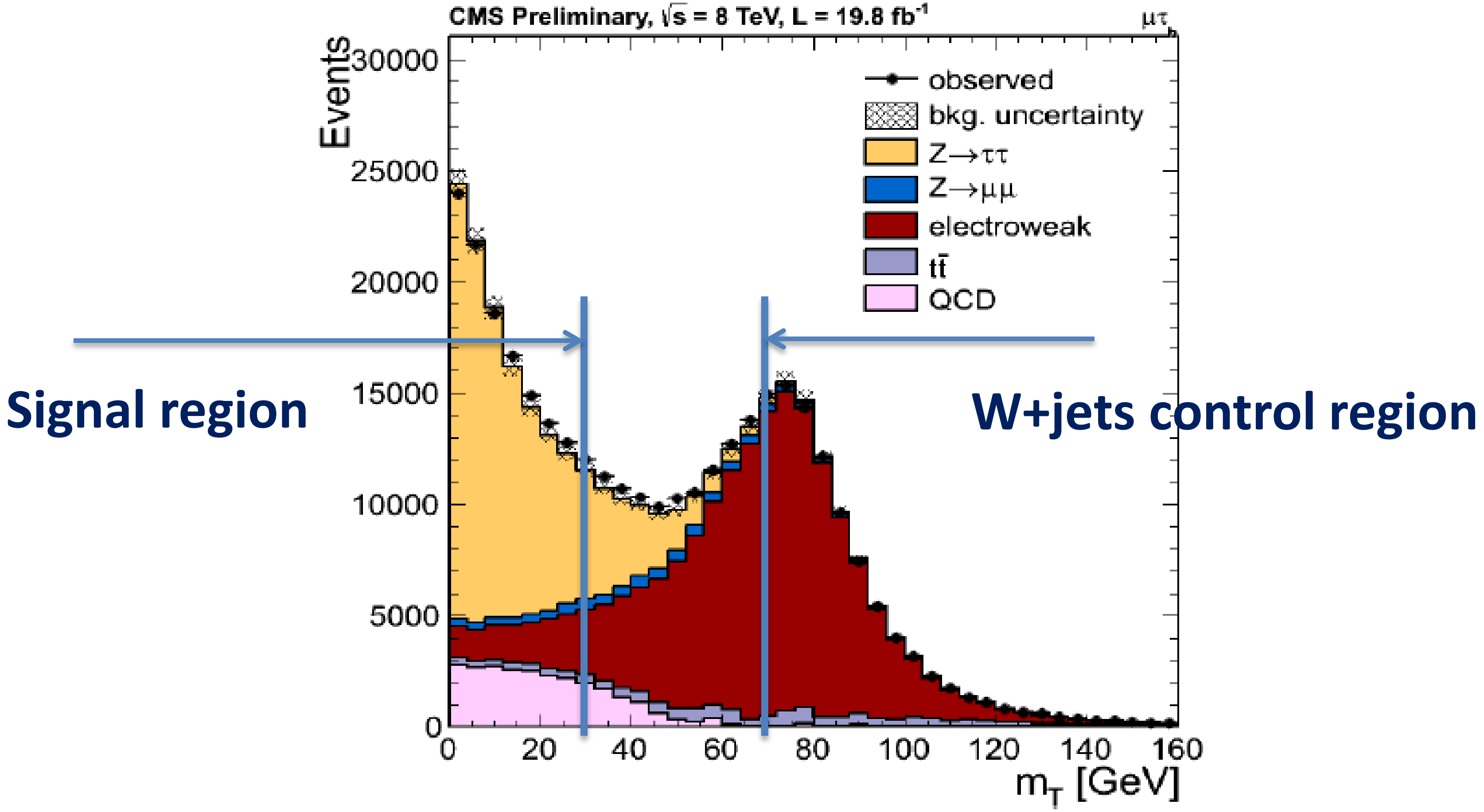
QCD:
- Normalization & shape taken from SS/OS or fakerate

Di-boson/W+jets:
- From simulation or data
- Normalization from sideband

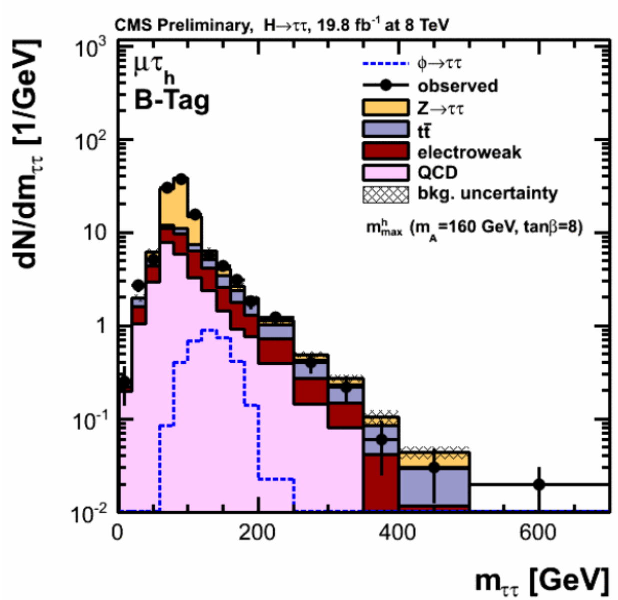
$Z/\gamma^* \rightarrow ee\ (\mu\mu)$:
- From simulation or data
- Corrected for jet $\rightarrow \tau$, $e/\mu \rightarrow \tau$ fakerate

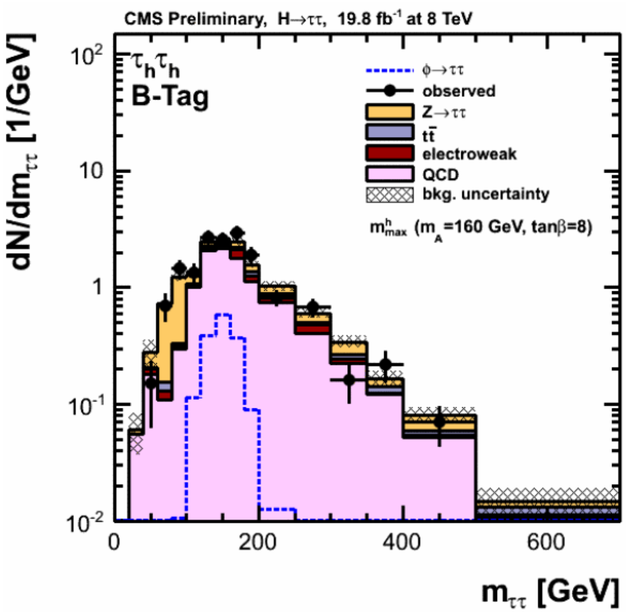
Example: control region for W+jets bkg

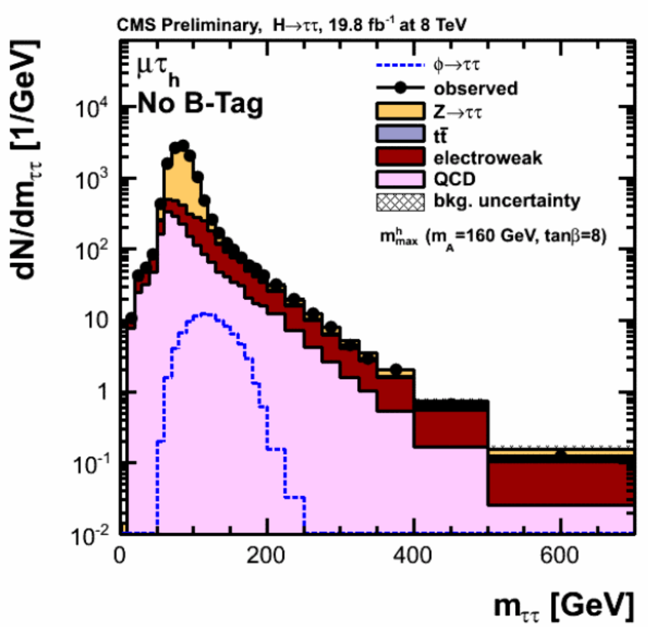
- **Normalize W+jets MC on $m_T > 70$ GeV region**
- **Predict W+jets event yield in signal region $m_T < 30$ GeV using m_T shape from MC**

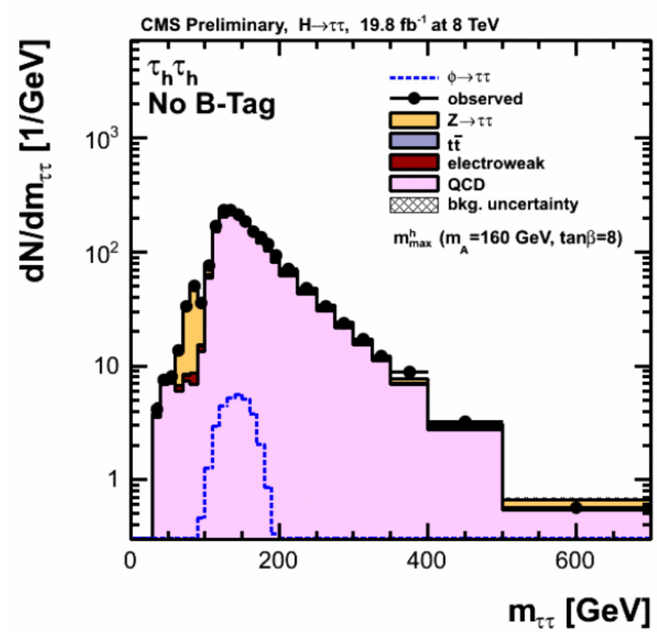


• $\mu\tau_h$ ττ mass after all selections • $\tau_h\tau_h$



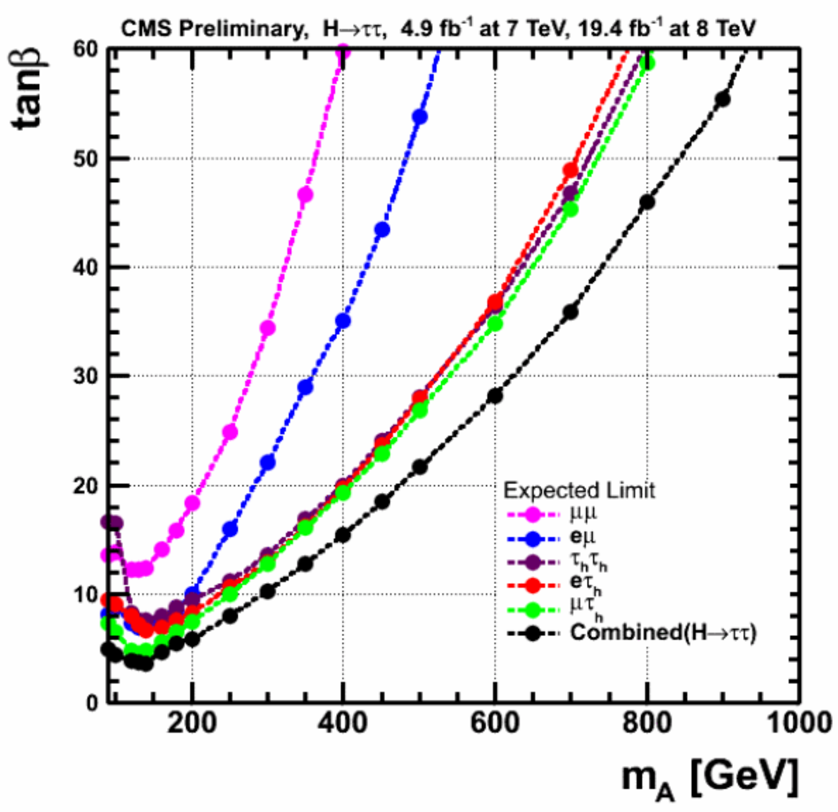




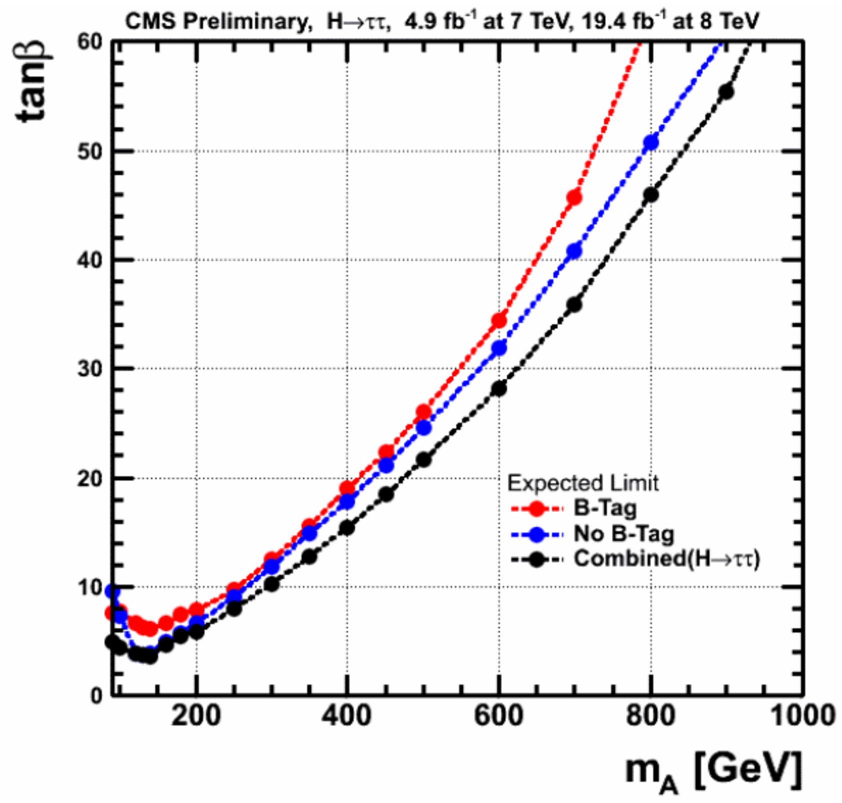


Sensitivity in M_A-tanβ plane for different event categories

- τ decay modes

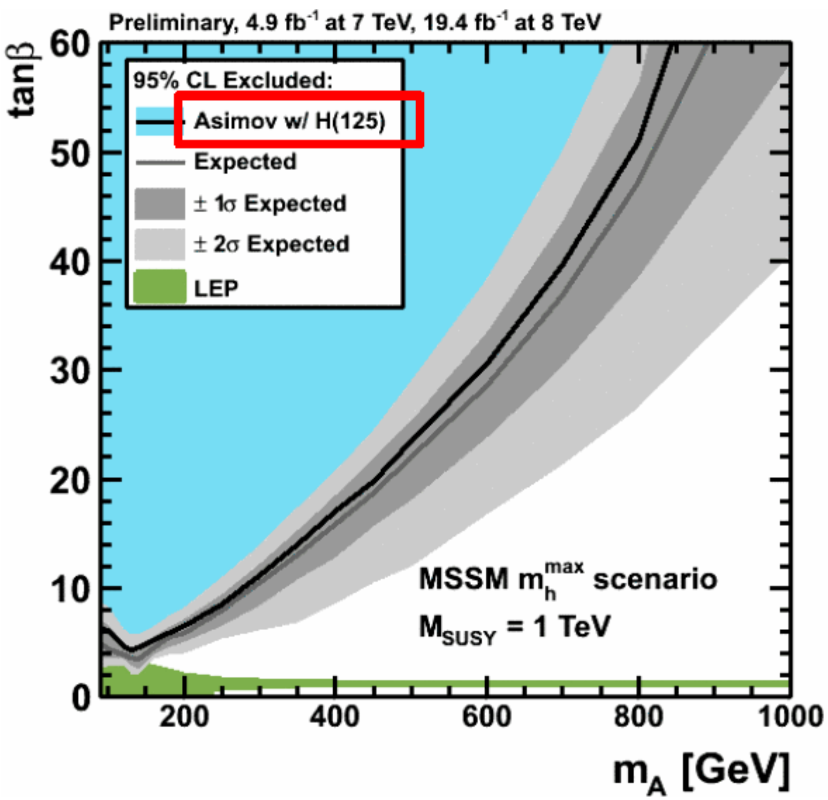


- b-tag. vs no-b-tagging

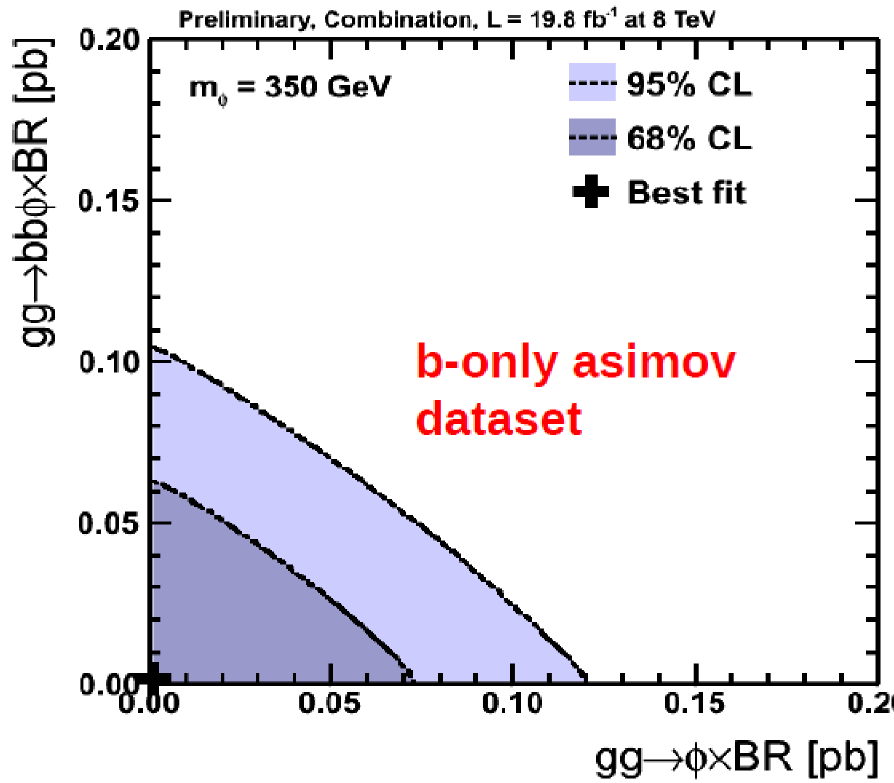


Expected exclusion limits

- In m_A-tanβ plane



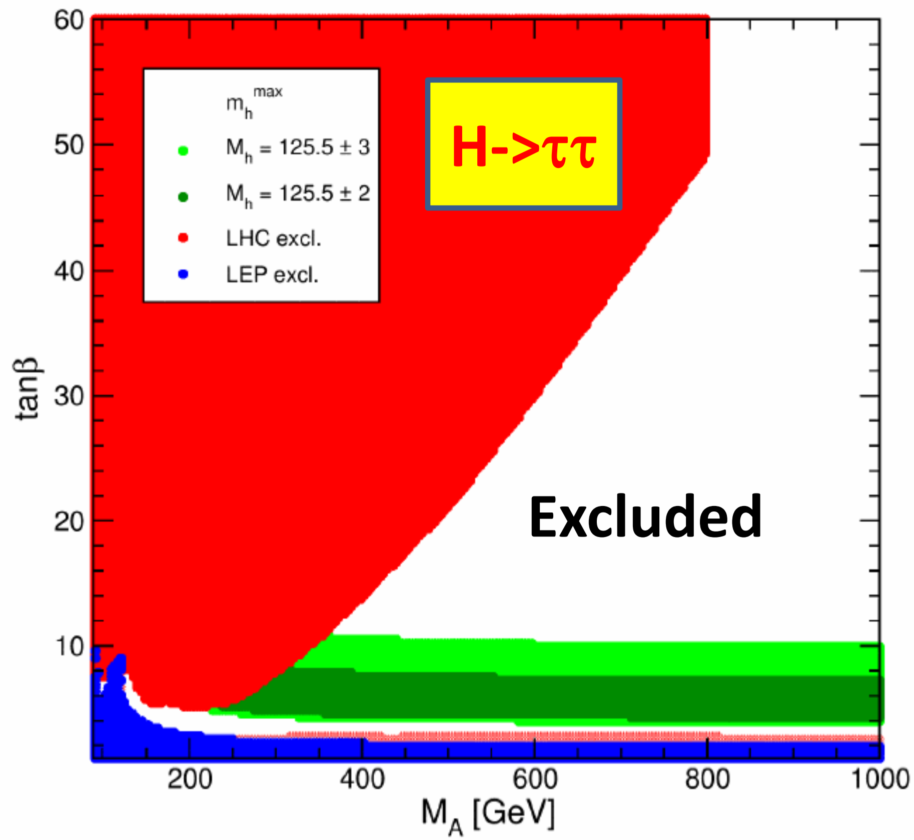
- model independent



MSSM benchmark scenarios (I)
(from M. Carena et al arXiv:13027033)

- m_h^{max} updated scenario:
  - green strip is allowed region of M_A-tanβ

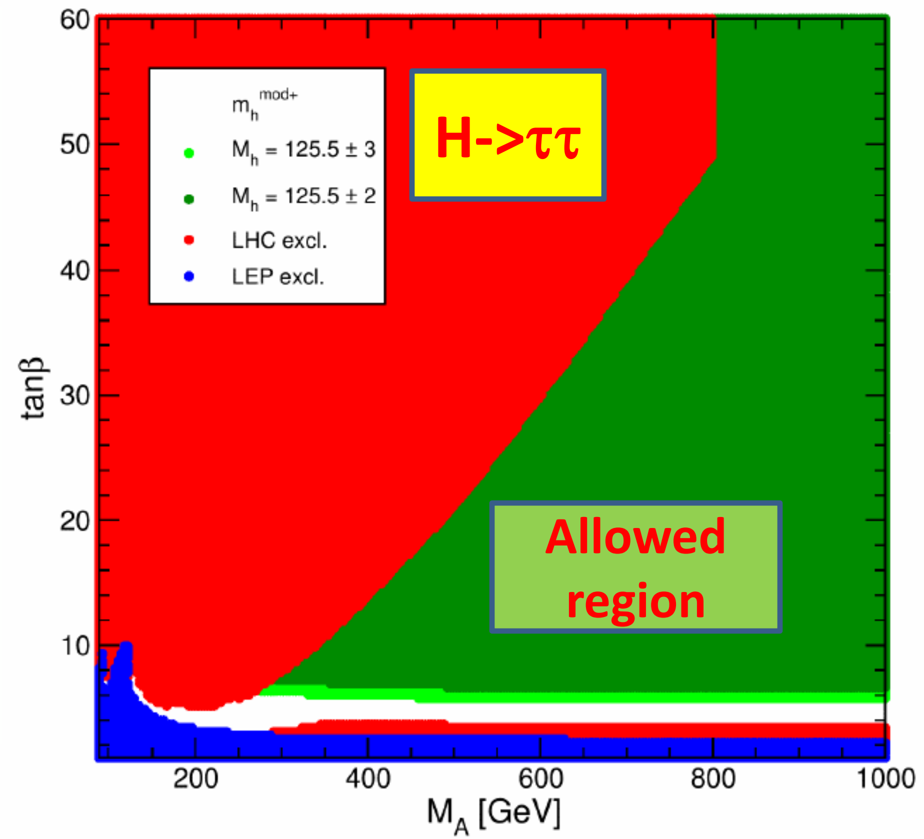
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\rm SUSY} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\rm OS} &= 2\, M_{\rm SUSY} \text{ (FD calculation)}, \\
X_t^{\overline{\rm MS}} &= \sqrt{6}\, M_{\rm SUSY} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$



MSSM benchmark scenarios (II)
(from M. Carena et al arXiv:13027033)

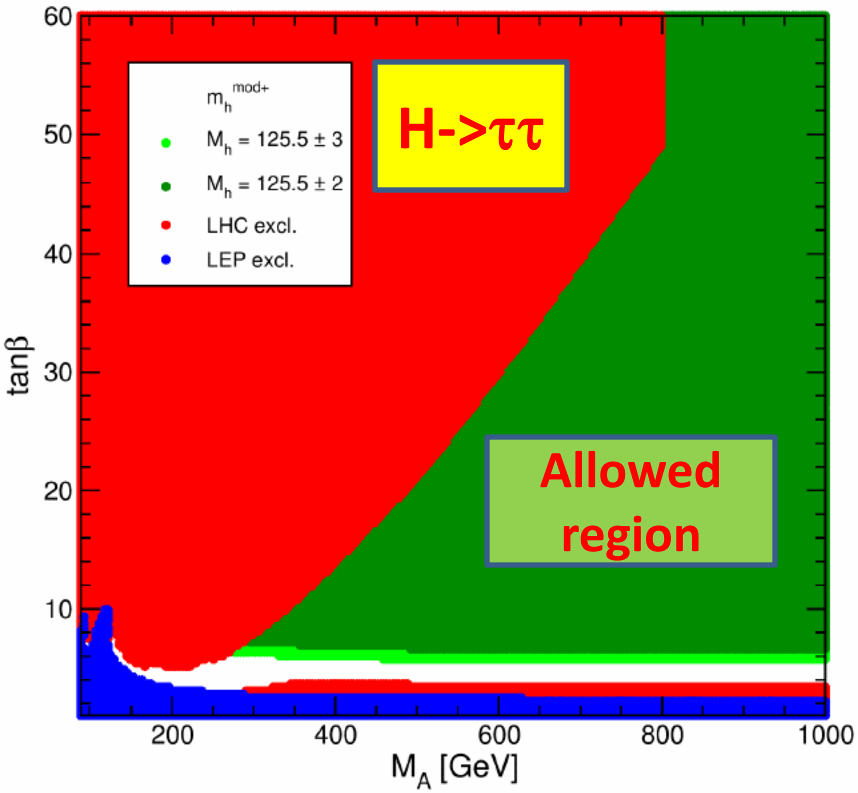
- m_h^{mod} scenario:
  - green area is allowed region of M_A-tanβ

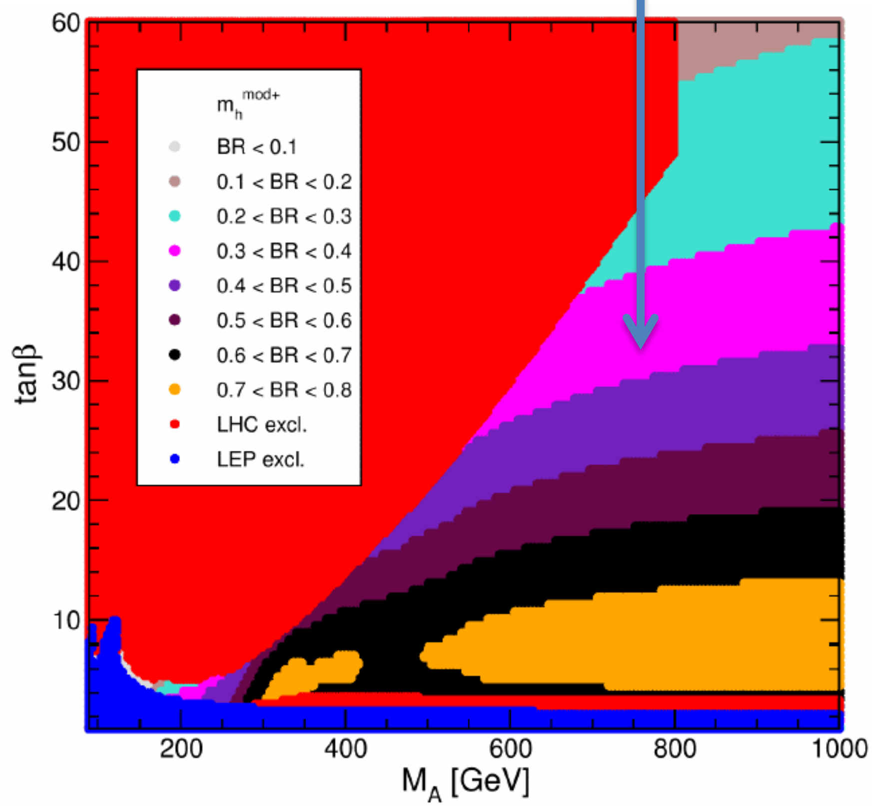
$$
\begin{aligned}
m_t &= 173.2\ \mathrm{GeV}, \\
M_{\mathrm{SUSY}} &= 1000\ \mathrm{GeV}, \\
\mu &= 200\ \mathrm{GeV}, \\
M_2 &= 200\ \mathrm{GeV}, \\
X_t^{\mathrm{OS}} &= 1.5\, M_{\mathrm{SUSY}}\ (\mathrm{FD\ calculation}), \\
X_t^{\overline{\mathrm{MS}}} &= 1.6\, M_{\mathrm{SUSY}}\ (\mathrm{RG\ calculation}), \\
A_b = A_\tau &= A_t, \\
m_{\tilde{g}} &= 1500\ \mathrm{GeV}, \\
M_{\tilde{l}_3} &= 1000\ \mathrm{GeV}\ .
\end{aligned}
$$



How to access allowed region ?
(from M. Carena et al arXiv:13027033)

- m_h^{mod} updated scenario:
  - green area is allowed region of M_A-tanβ
  - A/H decays to charginos/neutralinos are open here
    - Latest LHC analysis H/A->cc->4l+MET arXiv:0709.1029





Latest development: "hMSSM"

A. Djouadi et.al. arXiv:1307.5205

- For m_A >>M_Z and heavy sparticles ~> 1 TeV measured value of m_h defines radiative corrections at any order
  - no need anymore for "benchmark" scenarios
- Only three input parameters in hMSSM
  - β, m_h, m_A

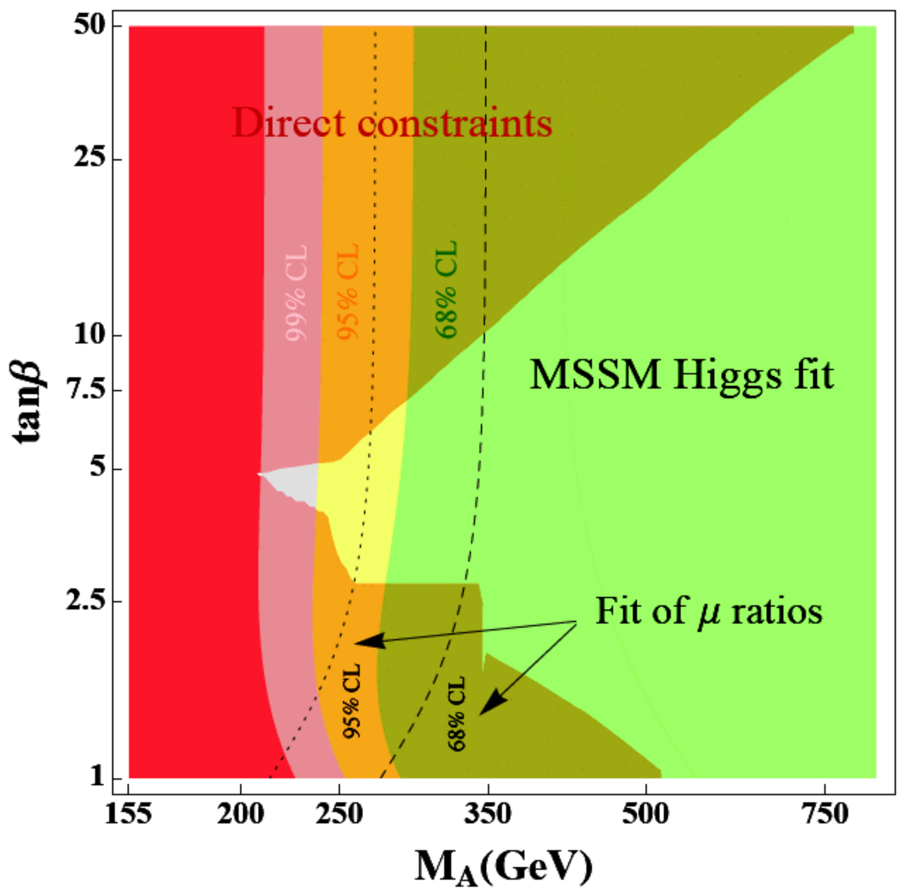
$$\text{hMSSM}: \quad \begin{aligned} M_H^2 &= \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2c_\beta^2+M_A^2s_\beta^2)-M_A^2M_Z^2c_{2\beta}^2}{M_Z^2c_\beta^2+M_A^2s_\beta^2-M_h^2} \\ \alpha &= -\arctan\left(\frac{(M_Z^2+M_A^2)c_\beta s_\beta}{M_Z^2c_\beta^2+M_A^2s_\beta^2-M_h^2}\right) \end{aligned}$$

$$M_{H\pm} \simeq \sqrt{M_A^2+M_W^2}$$

m_A-tanb in "hMSSM"

from A. Djouadi et.al. arXiv:1307.5205

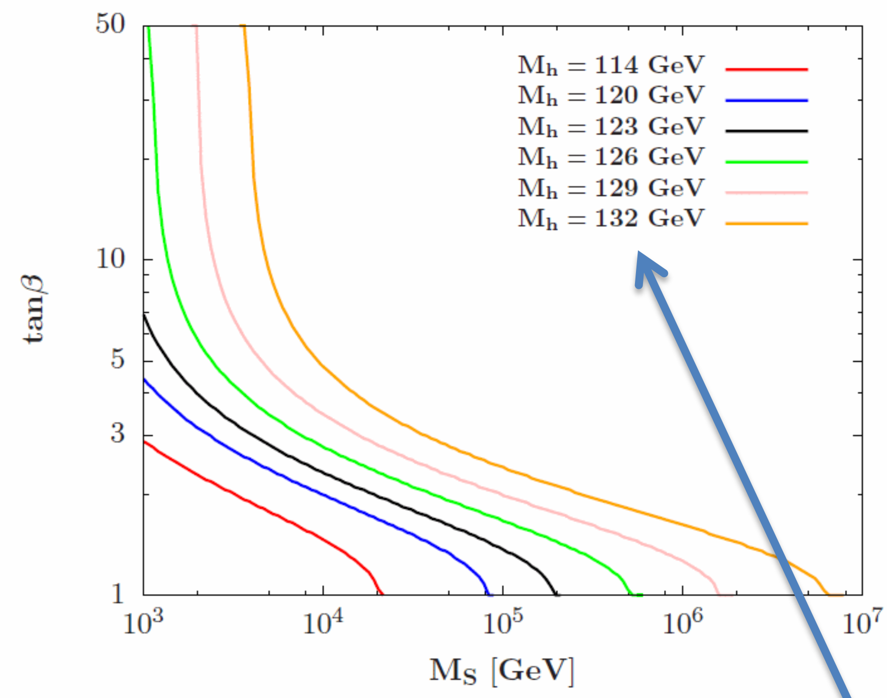
- From LHC measurement of h and searches for $H/A/H^+$

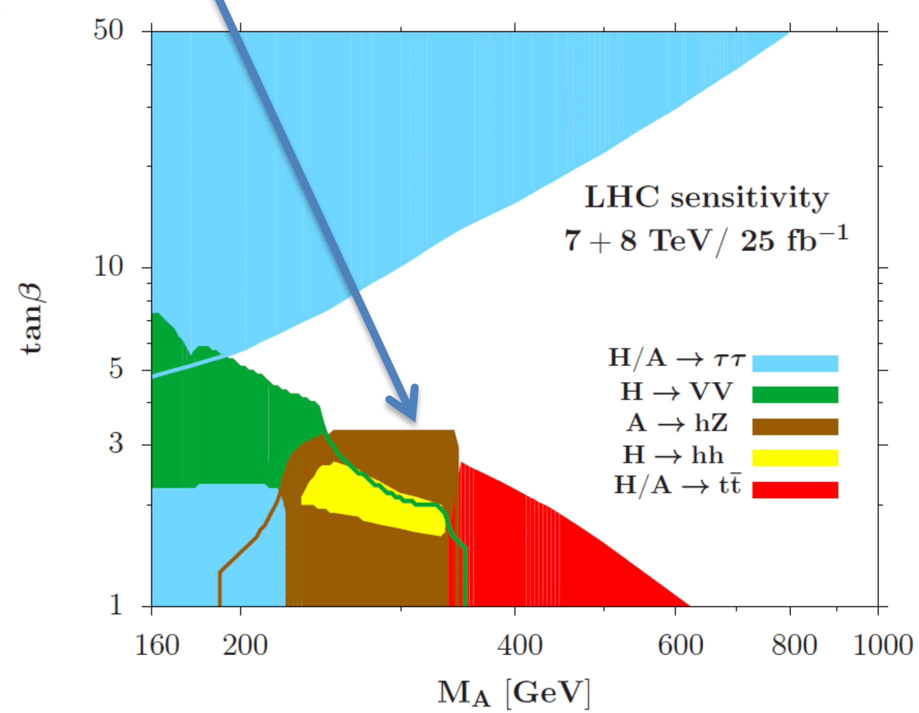


Is low tanβ region excluded ?

(from A. Djouadi arXiv:1304.1787)

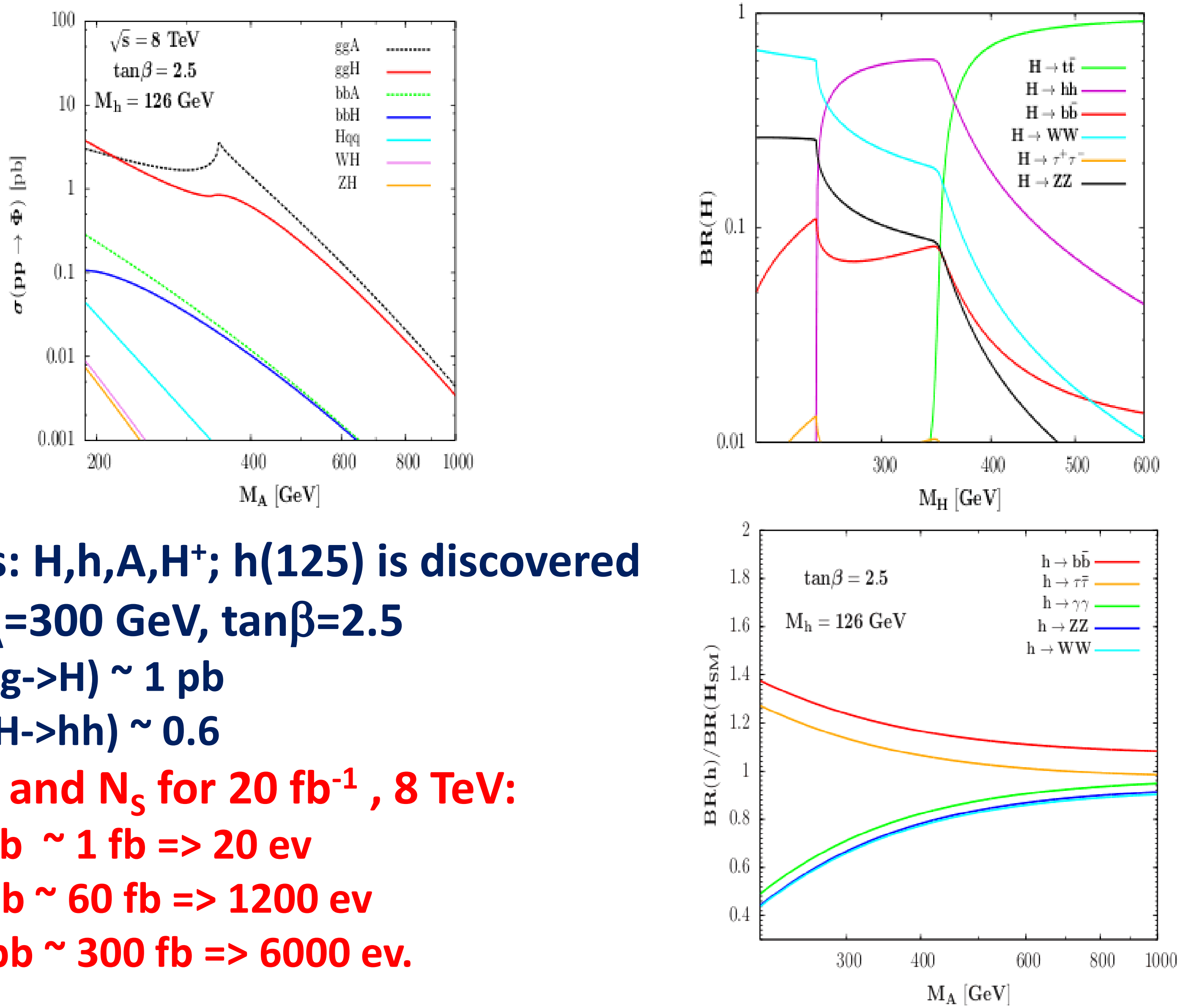
- Low tanβ region is not excluded for large M_S
- Accessible with a number of channels:





with m_t uncertainty 3 GeV (from tt~ cross-section) $\Delta^{th}m_h$ is ~ 6 GeV

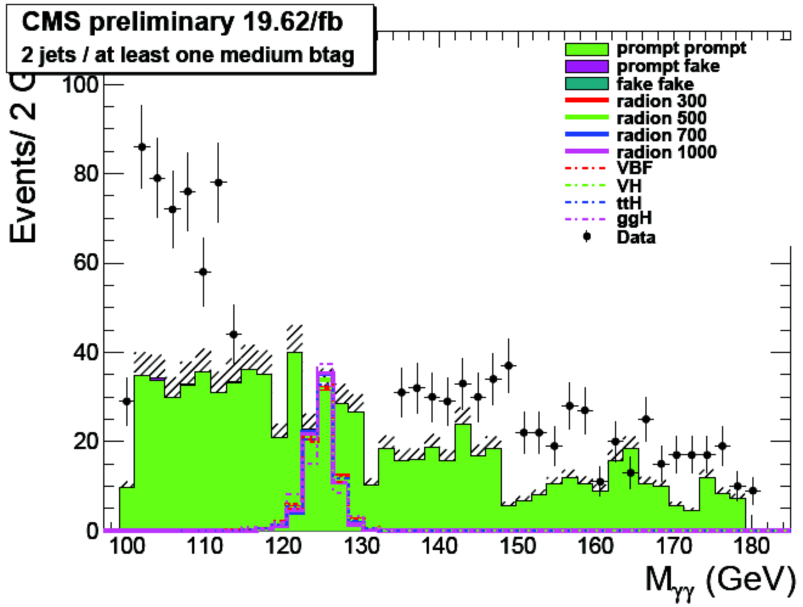
H->hh mode at low tanβ MSSM

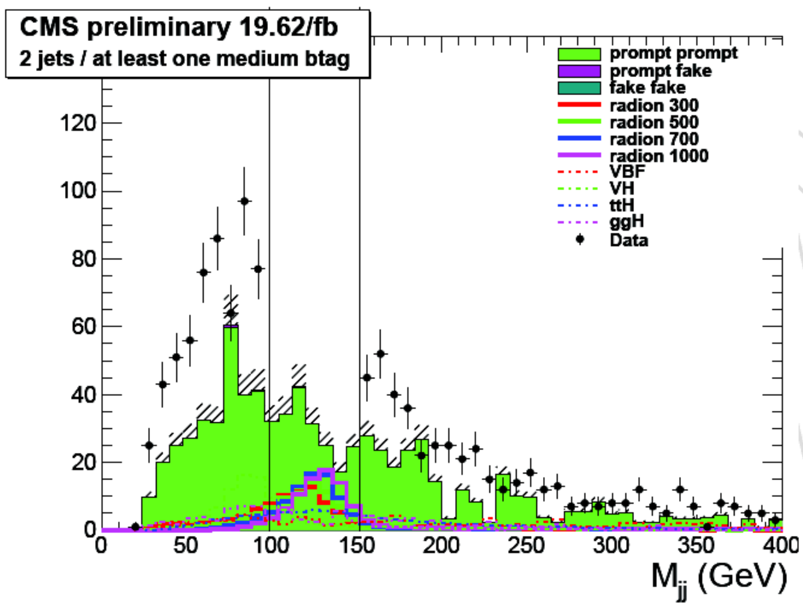


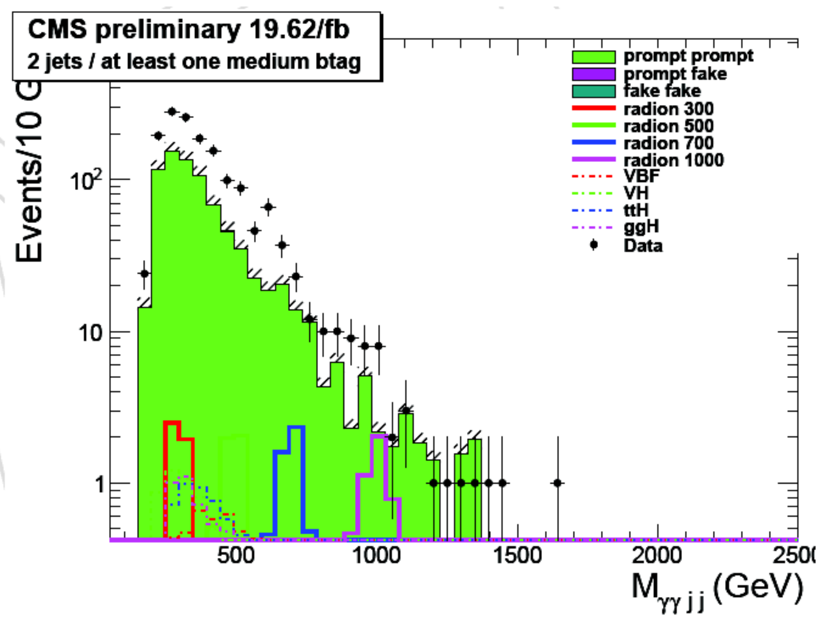
- Scalars: H,h,A,H^+; h(125) is discovered
- For m_A=300 GeV, tanβ=2.5
  - σ(gg->H) ~ 1 pb
  - Br(H->hh) ~ 0.6
- σ x Br and N_S for 20 fb^{-1} , 8 TeV:
  - γγbb ~ 1 fb => 20 ev
  - ττbb ~ 60 fb => 1200 ev
  - bbbb ~ 300 fb => 6000 ev.

H->h(125)h(125)->γγbb (I)

- **Search strategy**
  - select γγjj events with at least 1 b-tag
  - select events within m_{jj} and $m_{\gamma\gamma jj}$ mass windows
  - fit $m_{\gamma\gamma}$ for selected events



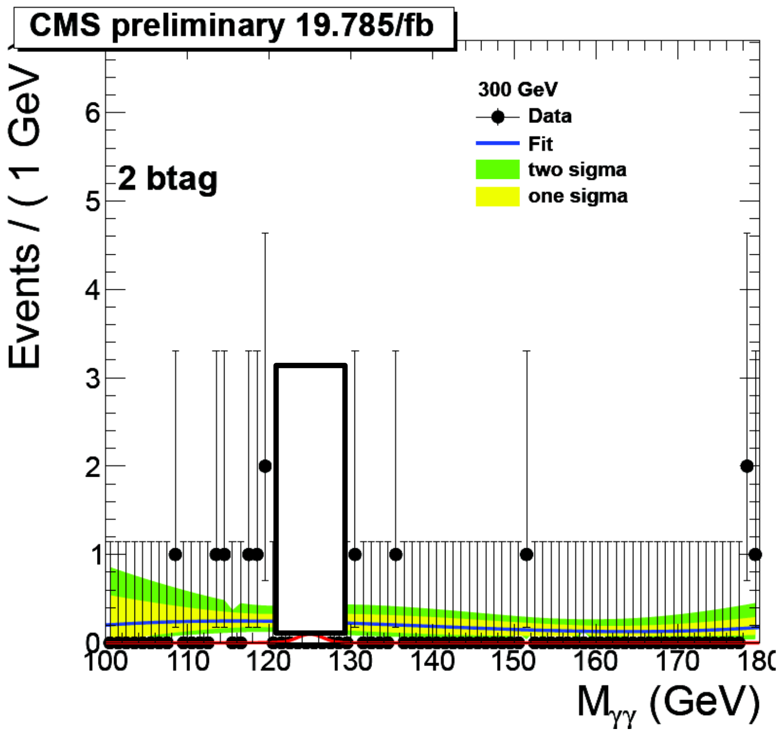




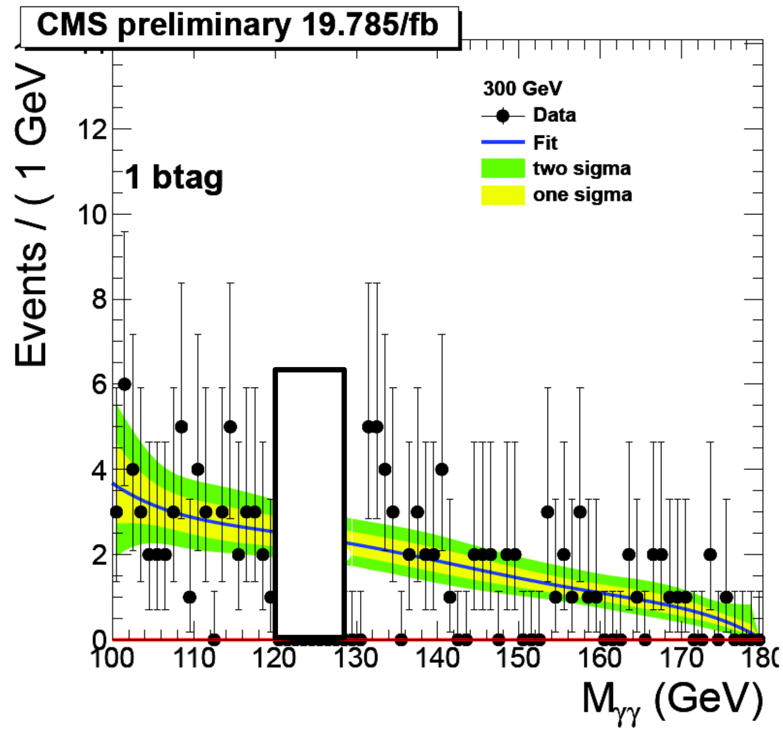
H->h(125)h(125)->γγbb (II)
m_H=300 GeV with tanβ=2.5

- σ x B for signal ~ 1.3 fb for m_H=300 GeV
  - Signal efficiency for 2b-tag category ~ 0.06
- $m_{\gamma\gamma}$ after m_{jj} and $m_{\gamma\gamma jj}$ mass window selections

Expected N_S ~ 1.5 ev

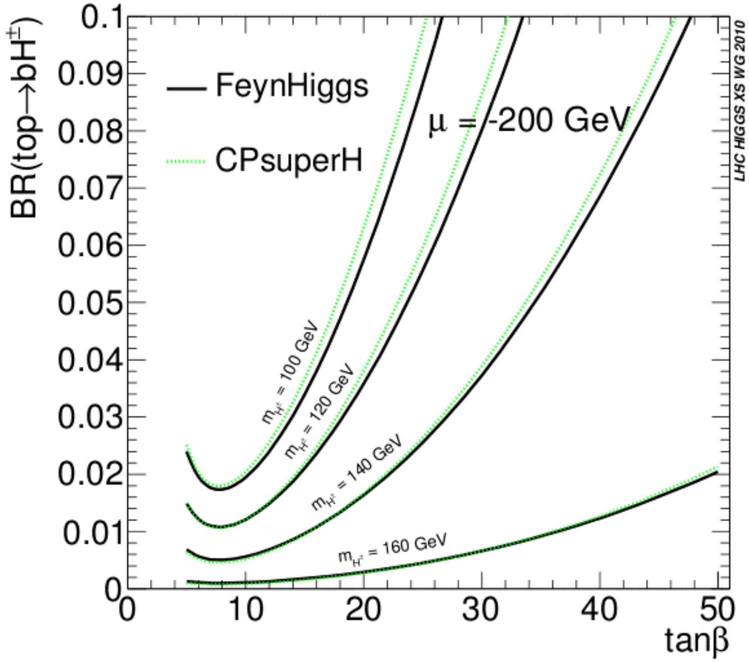


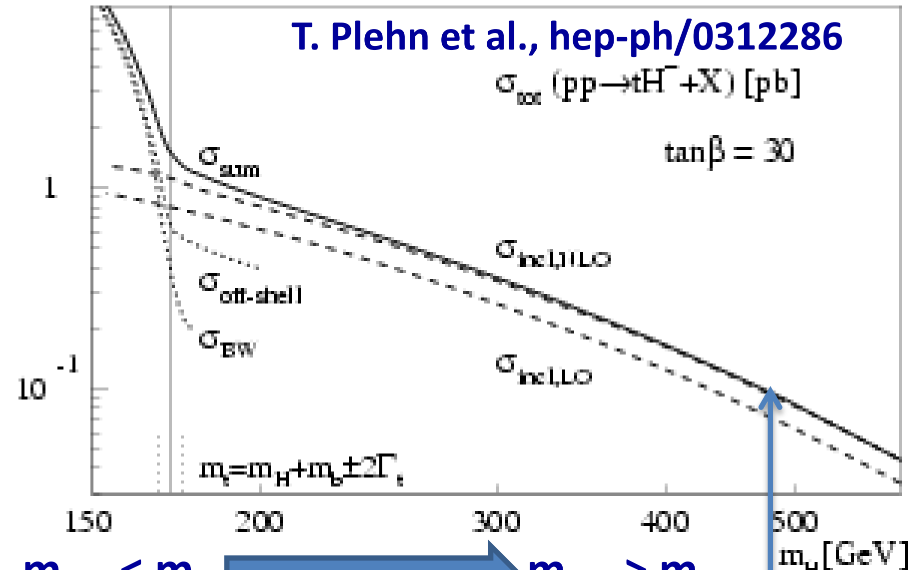
Expected N_S ~ 2.0 ev



Searches for t->H^+b ($m_{H+} < m_t$)

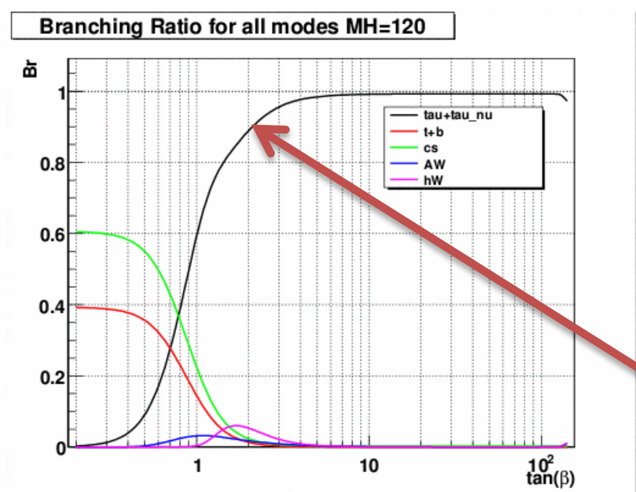
$$g_{H^+\bar{t}b} \quad \propto \quad m_b \tan\beta(1+\gamma_5) + m_t \cot\beta(1-\gamma_5)$$





$m_{H+} < m_t$ → $m_{H+} > m_t$

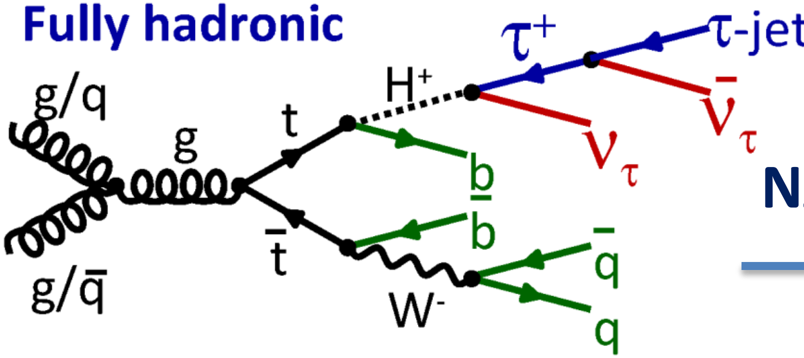
pp->tbH^+ is in MC@NLO (T.Plehn et al)
recipie for $m_{H+} \sim m_t$: add tt and tbH^+
4FS and 5FS NLO calculations exist



- ***Study decay mode $H^+\to\tau\nu$ assuming BR($H^+\to\tau\nu$)=1***

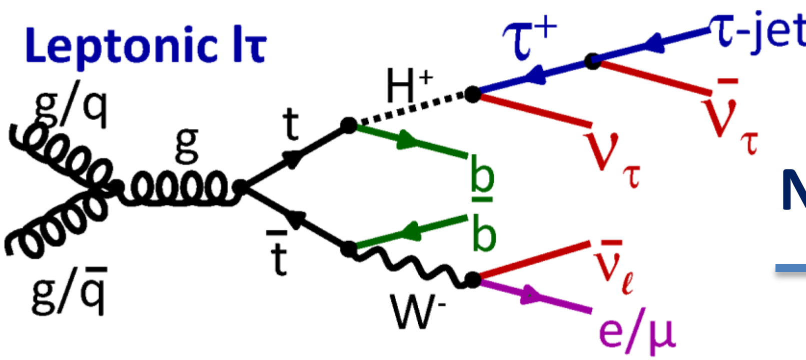
CMS $H^+\to\tau\nu$. Topologies considered:

Fully hadronic



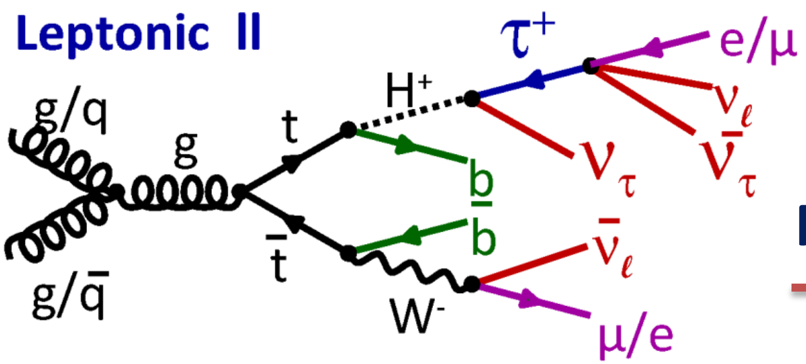
$N_{tt}^{SUSY} > N_{tt}^{SM}$

Leptonic lτ

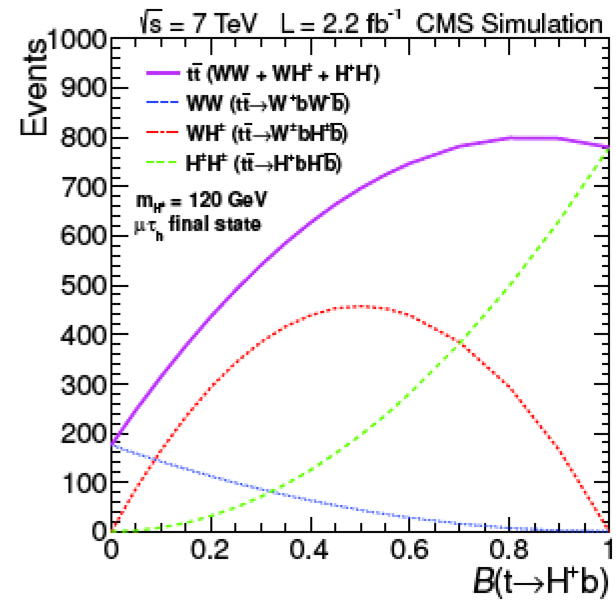


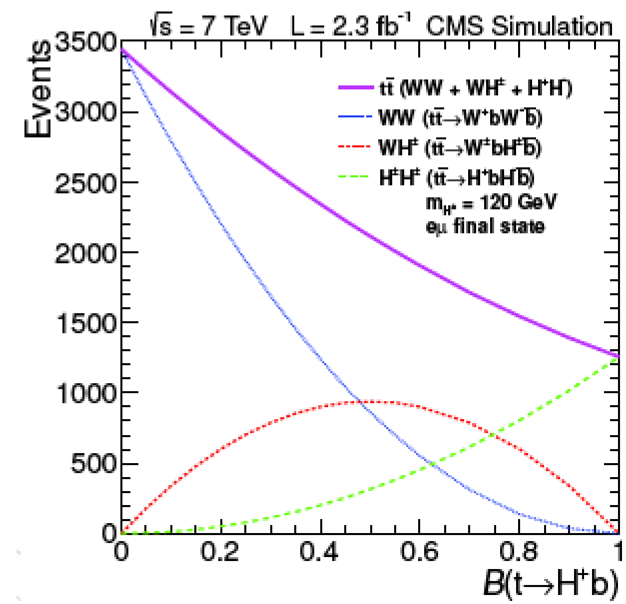
$N_{tt}^{SUSY} > N_{tt}^{SM}$

Leptonic ll



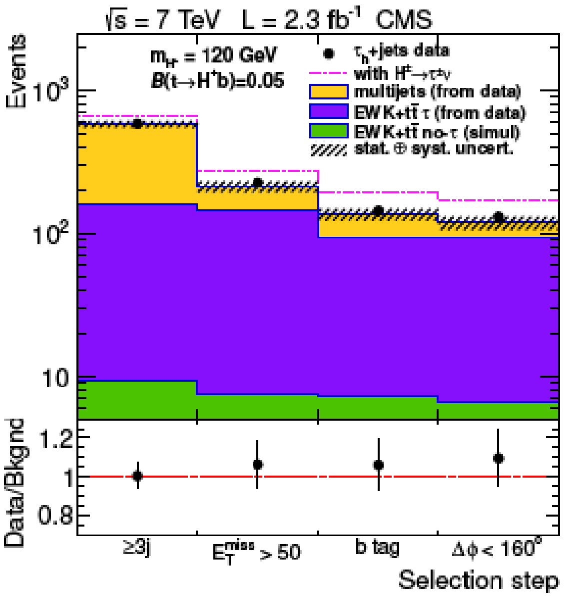
$N_{tt}^{SUSY} < N_{tt}^{SM}$



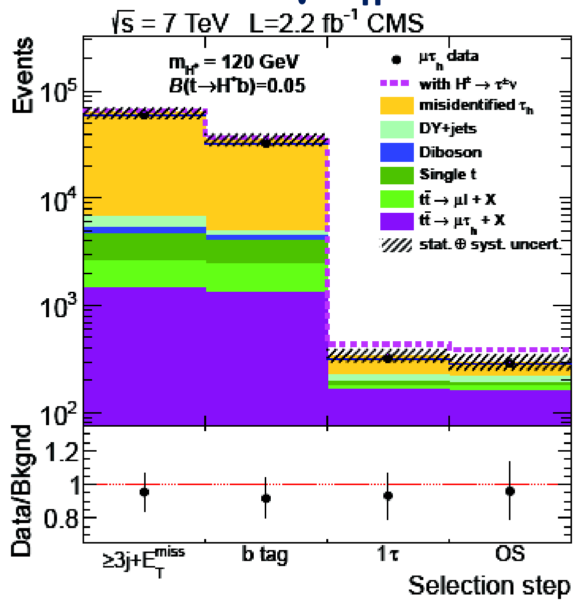


Event yields for individual analyses $H^+ \to \tau\nu$:

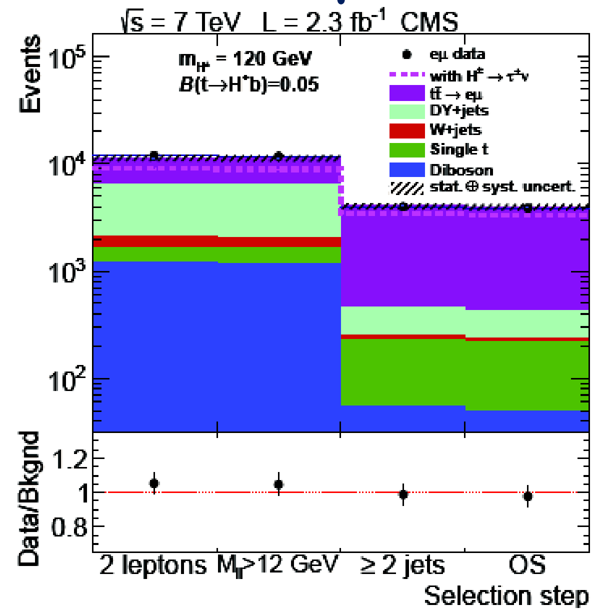
τ_h+jets

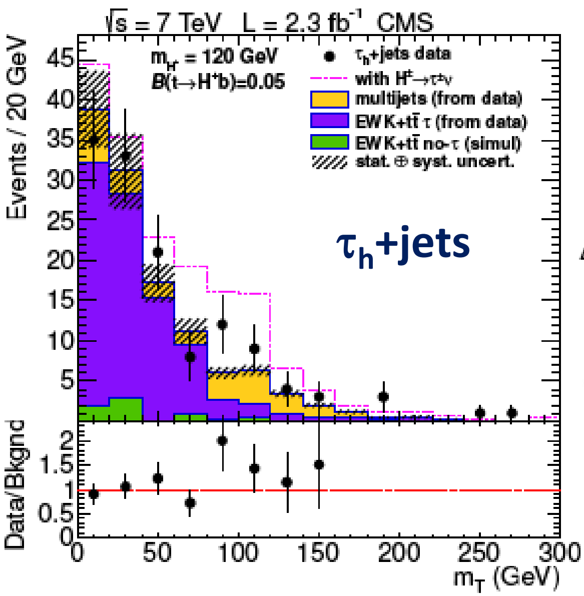


$\mu\tau_h$



$e\mu$





Access or deficit of events in data is related to the difference between MSSM and SM tt~ event yields:

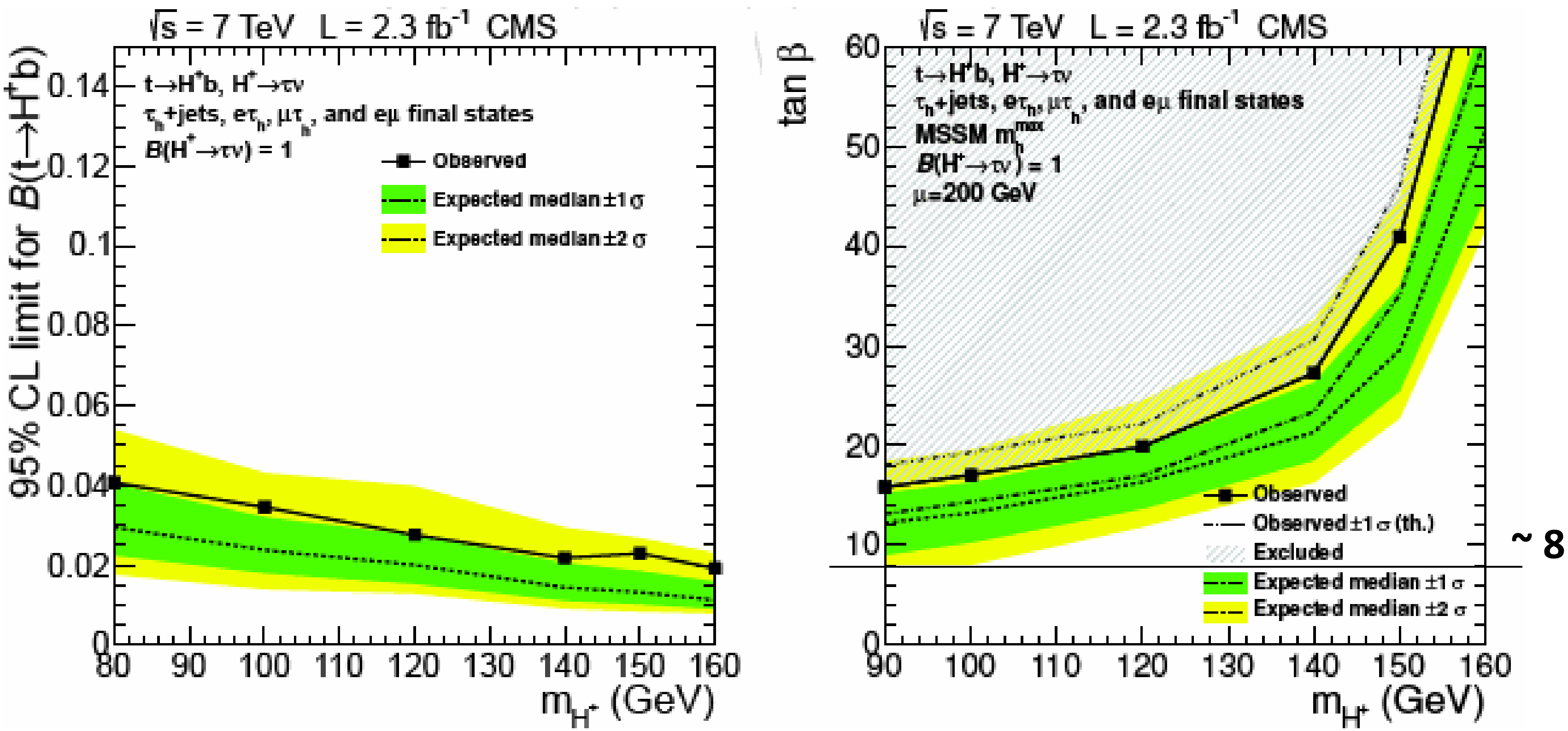
$$\Delta N = N_{t\bar{t}}^{\mathrm{MSSM}} - N_{t\bar{t}}^{\mathrm{SM}} = 2x(1-x)N_{\mathrm{WH}} + x^2 N_{\mathrm{HH}} + [(1-x)^2 - 1]N_{t\bar{t}}^{\mathrm{SM}}.$$

$x = Br(t \to H^+ b)$

τ_h+jets channel is most sensitive, since most of the tt~->WbWb background is measured from the data and m_T shape is used

Results of $H^+ \to \tau\nu$ analysis with 2.3 fb^{-1}

JHEP 1207 (2012) 143



At tanβ ~ 8 Br(t->H⁺b) has a minimum in MSSM at a given μ

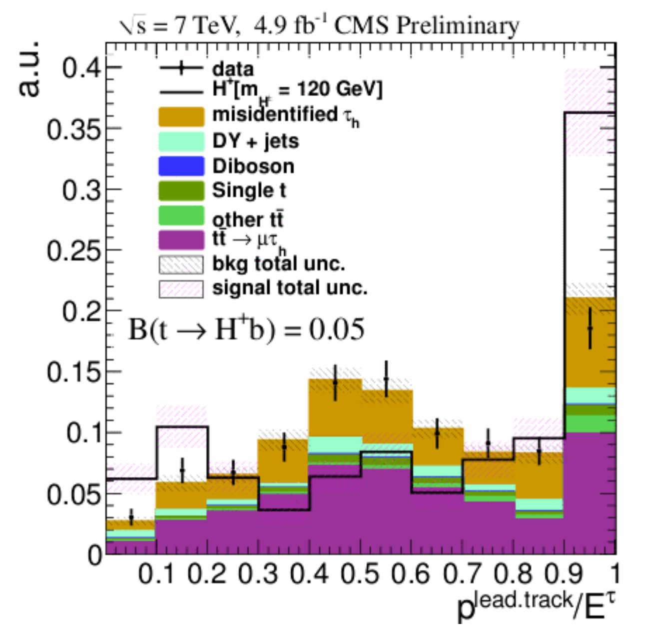
In the next iteration of analysis with whole 2011/12 dataset it might be possible to exclude m_{H+} < ~ 130 GeV, since for this mass region exp. exclusion limits on Br(t->H⁺b) might be smaller than minimal possible values in MSSM m_h^{max}

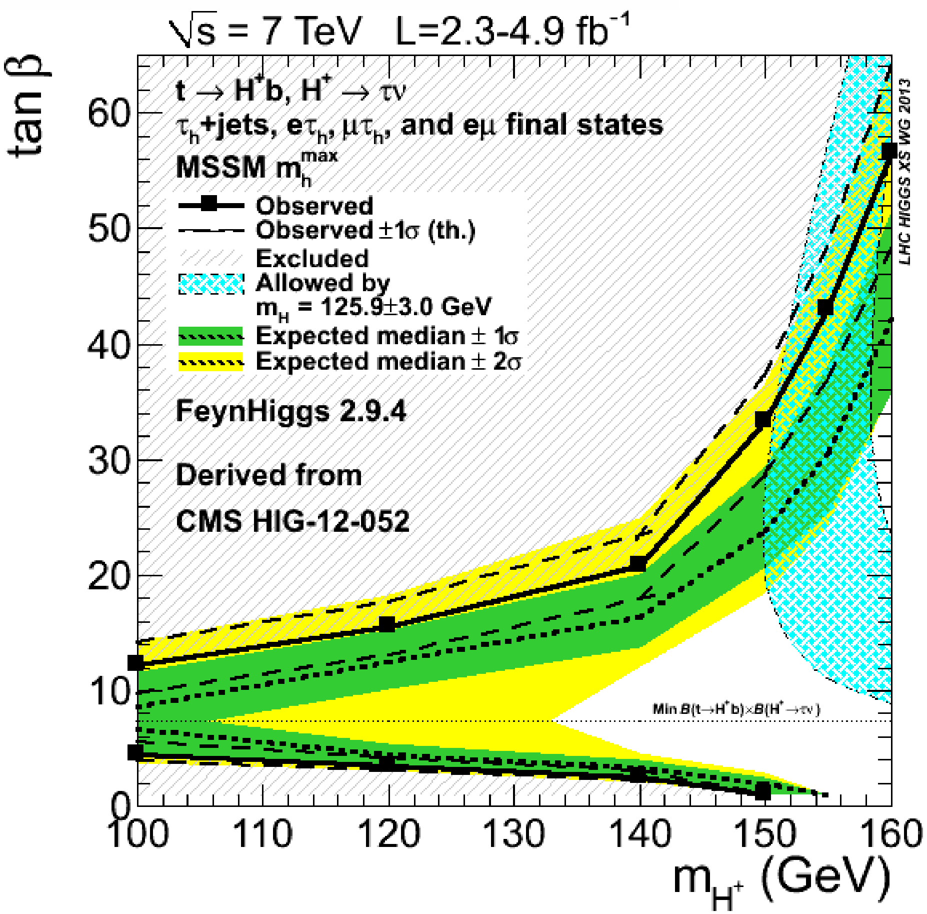
Update for light H^+ analysis with 2.3 -4.9 fb^{-1}

- to understand m_{H+}-tanβ plots remember the H^+tb coupling structure:

$$g_{H^+\bar{t}b} \propto m_b \tan\beta(1+\gamma_5) + m_t \cot\beta(1-\gamma_5)$$

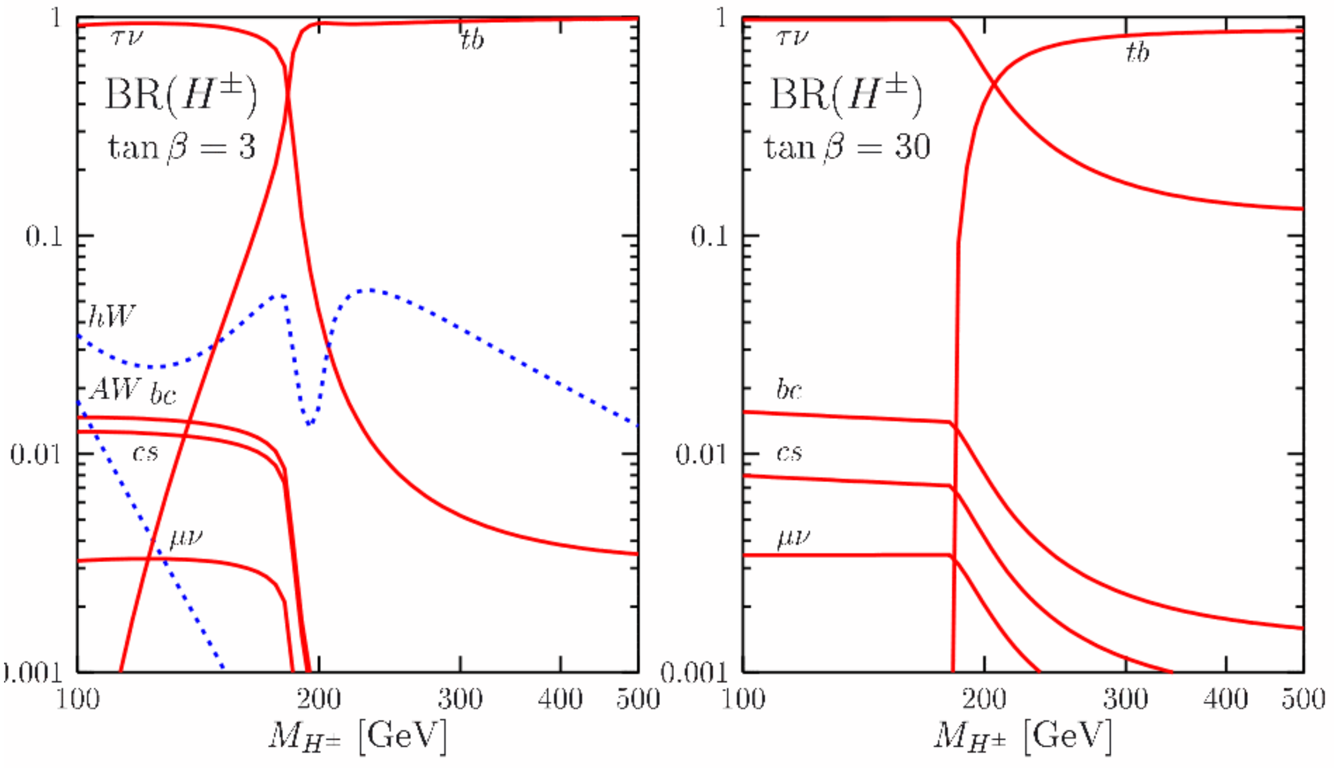
$\mu\tau_h$ analysis is updated with 4.9 fb^{-1} at 7 TeV and using shape of τ polarization variable





Heavy charged Higgs decay modes to be searched for at 14 TeV runs

- $\tau\nu$, tb, Wh
- Production process: gb->tH$^+$



From A. Djouadi “Anatomy of EW Symmetry Breaking. Part II”. hep-ph/0503173

NMSSM and Higgs bosons in NMSSM

- **Enlarged (pseudo-)scalar and neutralino sector:** 2 complex doublets $\hat{H}_u, \hat{H}_d$, 1 complex singlet $\hat{S}$

7 bosons:	$H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos:	$\tilde{\chi}_i^0$ $(i = 1, ..., 5)$

- **Significant changes of the phenomenology**

Resent NMSSM scans of LHC h(125):

S.F. King, M. Muehlleitner, R. Nevzorov, K. Walz

arXiv:1211.5074, accepted by Nucl. Phys. B,

"Natural NMSSM Higgs Bosons"

S.F. King, M. Muehlleitner, R. Nevzorov

Nucl. Phs. B860 (2012) [arXiv:1201.2671[hep-ph]]

"NMSSM Higgs Benchmarks Near 125 GeV"

Next-to Minimal Supersymmetric Standard Model

Field content:

NMSSM superfields = MSSM superfields + Higgs superfield singlet $\hat{S}$

Superpotential:

$$W_{\text{NMSSM}} = W_{\text{MSSM}}|_{\mu=0} - \lambda\,\hat{S}\,\hat{H}_d^1\,\hat{H}_u^2 + \lambda\,\hat{S}\,\hat{H}_d^2\,\hat{H}_u^1 + \frac{1}{3}\,\kappa\,\hat{S}^3$$

2 new coupling parameters: λ, κ ($\hat{H}_d$, $\hat{H}_u$: Higgs doubled superfields)

μ term of the MSSM: $W_{MSSM} = \ldots\mu\hat{H}_d^1\,\hat{H}_u^2 + \ldots$

$\rightarrow$ dynamically generated in the NMSSM **$\mu=\lambda\langle S\rangle$**

(scalar Higgs singlet field has a vacuum expectation value v_S)

Soft-breaking part extended: New parameters: m_S^2, A_λ, A_κ

Higgs Bosons in the NMSSM: Part 1: Masses Heidi Rzehak Higgs Days at Santander, 18 September 2013

- **solve "μ-problem" of MSSM (Kim, Nilles 1984)**
  - **μ must be order of SUSY breaking scale M_{SUSY}**
    - **two scales in the MSSM theory – EWSB and M_{SUSY}**
    - **one scale in the NMSSM theory – M_{SUSY}**

$\mathcal{NMSSM}$ $\mathcal{S}$calar $\mathcal{B}$oson $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

- **Vast literature on NMSSM scalar boson of $\sim$ 125-126 GeV**

  Hall eal; Ellwanger; Gunion eal; King,MMM,Nevzorov; Albornoz Vasquez eal; Cao eal; Gabrielli eal; Ellwanger, Hugonie; Kang eal; Cheung eal; Jeong eal; Hardy eal; Kim eal; Arvanitaki eal; ...

- **Compatibility of NMSSM scalar boson mass with LHC Searches:**

  $\star$ Upper mass bounds + corrections to the MSSM, NMSSM scalar boson mass:

  MSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$

  NMSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$

  $\Rightarrow M_H \approx 126$ requires:

  MSSM: $\Delta m_h \approx 85$ GeV ($\tan\beta$ large) $\Rightarrow$ large corrections are needed $\rightsquigarrow$ conflict with fine-tuning

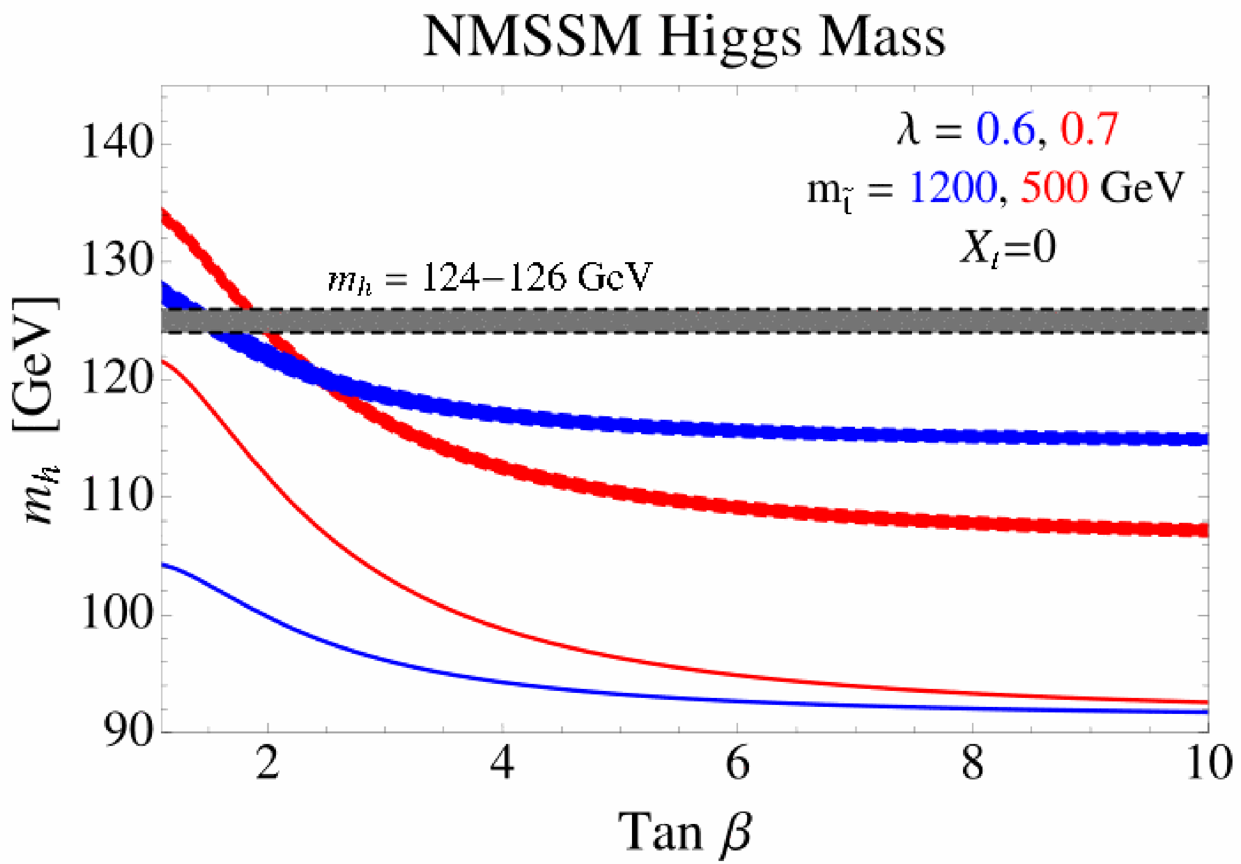
  NMSSM: $\Delta m_h \approx 55\,$GeV $(\lambda = 0.7, \tan\beta = 2)$

  $\Rightarrow$ NMSSM requires less fine-tuning

  Hall,Pinner,Ruderman; Ellwanger; Arvanitaki,Villadoro; King,MMM,Nevzorov; Kang,Li,Li; Cao,Heng,Yang,Zhang,Zhu

NMSSM Scalar Boson Mass in View of the LHC Results

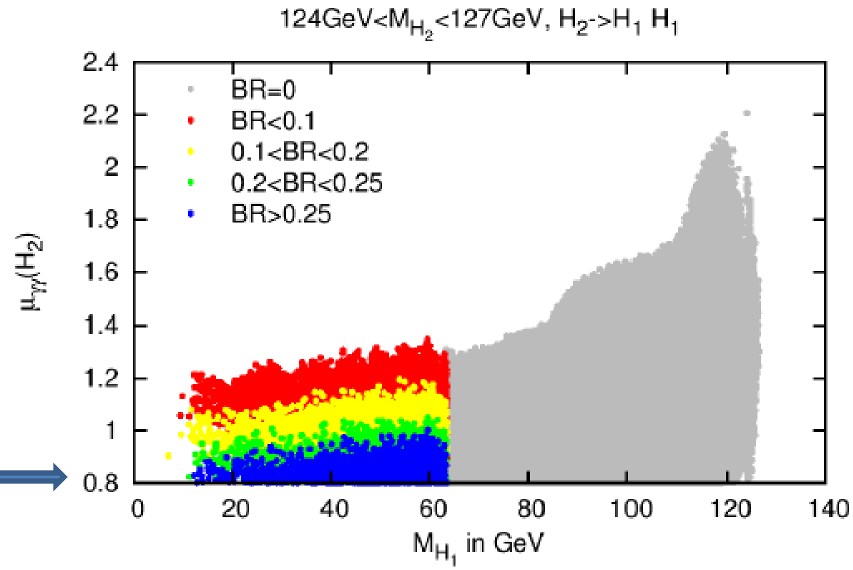
Hall,Pinner,Ruderman 1112.2703

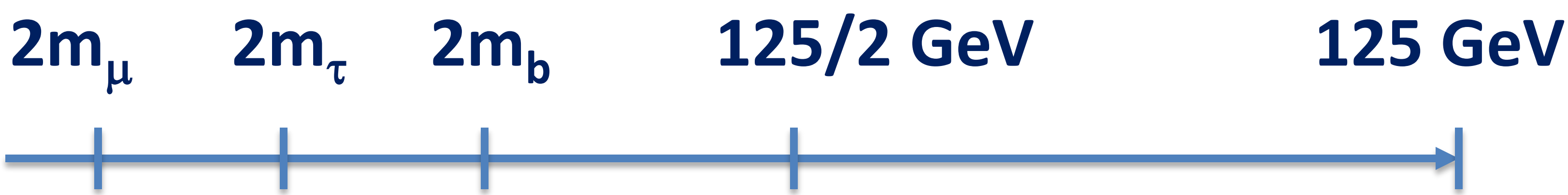


- ◇ m_h maximized for small values of $\tan\beta$
- ◇ $m_h \approx 126$ GeV can be achieved also for zero mixing $X_t = 0$ and $m_{\tilde{t}_1} \geq 500$ GeV

Landscape for NMSSM

- Scalars:
  - H1,H2,H3; $m_{H1} < m_{H2} < m_{H3}$
  - A1, A2: $m_{A1} < m_{A2}$
- LHC discovered H2(125)
- How to access H1 and H3
  - H2(125)->H1H1, Br ~ 10-20 %
  - H3->H2(125)H1
- Favorable final state decay modes depend on m_{H1}

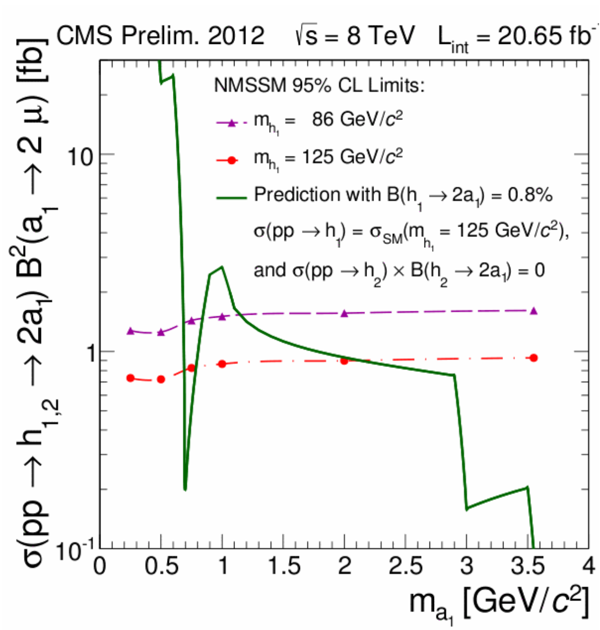




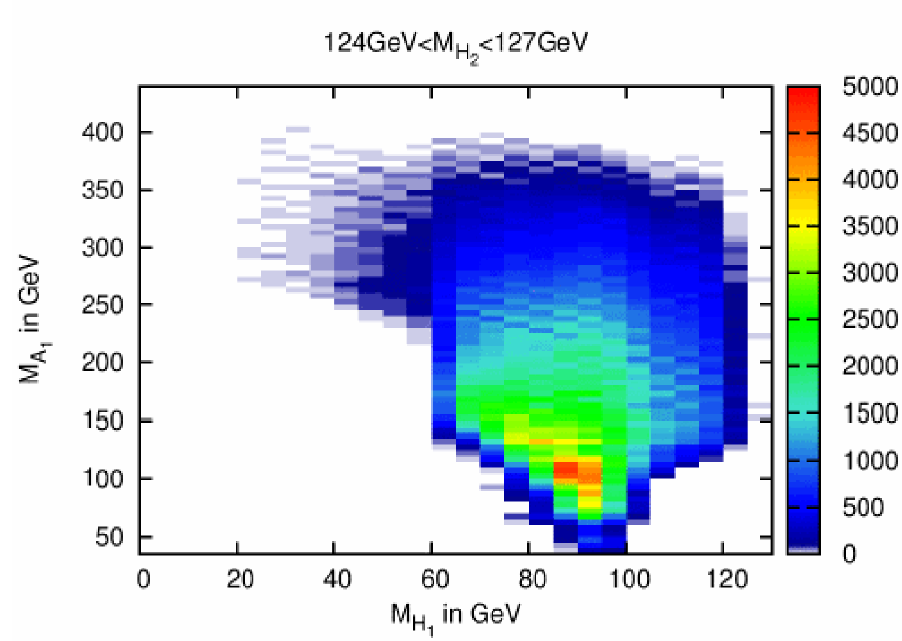
m_{H1} axis

H2(125)->H1H1: $2m_\mu < m_{H1} < 2m_\tau$

- H2->H1H1->μμμμ
  - CMS PAS HIG-13-010



Although recent NMSSM scans do not favor very low $m_{A1,\ H1}$

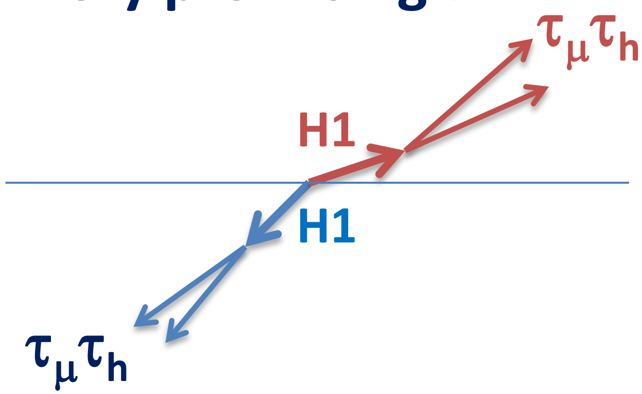


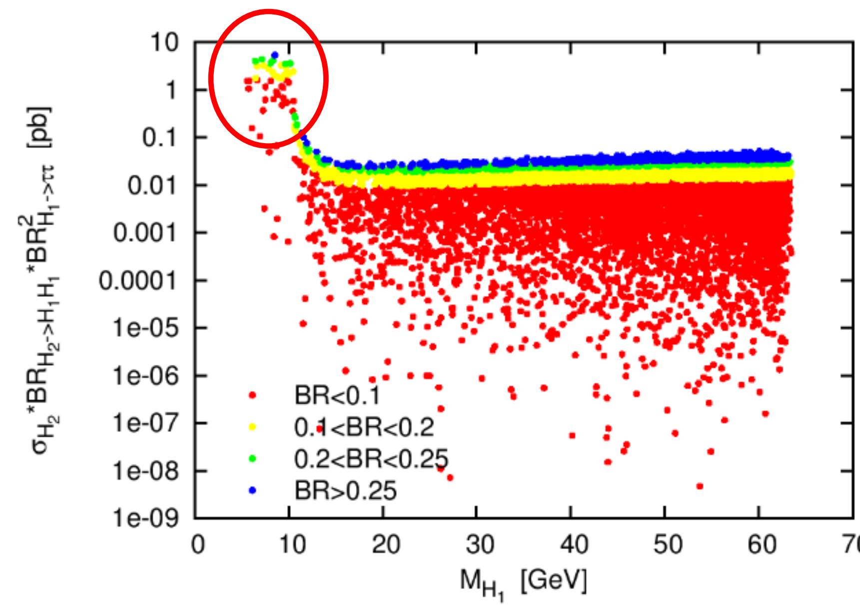
$2m_\mu$ $2m_\tau$ $2m_b$ 125/2 GeV 125 GeV

m_{H1} axis

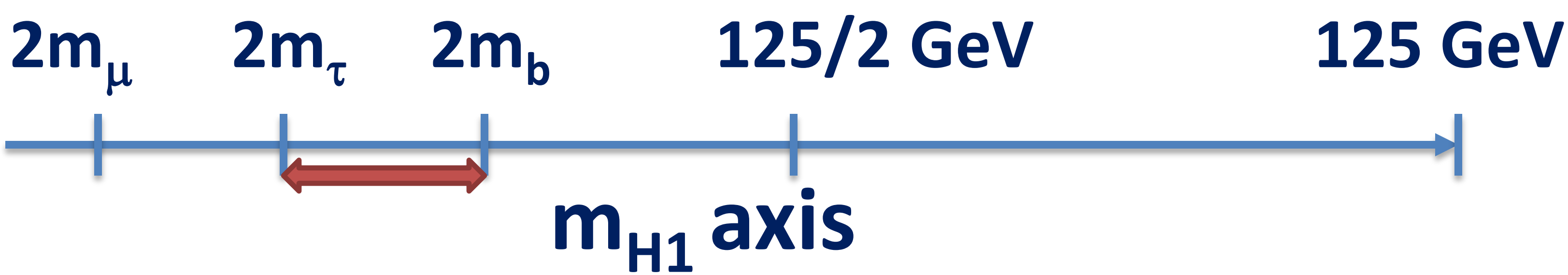
H2(125)->H1H1: $2m_\tau < m_{H1} < 2m_b$

- H2->H1H1->$\tau\tau\tau\tau$ ~ 3 pb => 60K ev. for 20 fb^{-1} at 8 TeV
  - $\tau_\mu\tau_h\tau_\mu\tau_h$ with SS μ's looks very promising !





  - on going analysis



H2(125)->H1H1: $2m_b < m_{H1} < m_{H1}/2$ (I)

- H2->H1H1->ττbb; ~ 0.4 pb => 8 K events for 20 fb^{-1} at 8 TeV
- $\tau_\mu\tau_h$bb mode looks hopeless with SUSY H->$\tau_\mu\tau_h$ selections:

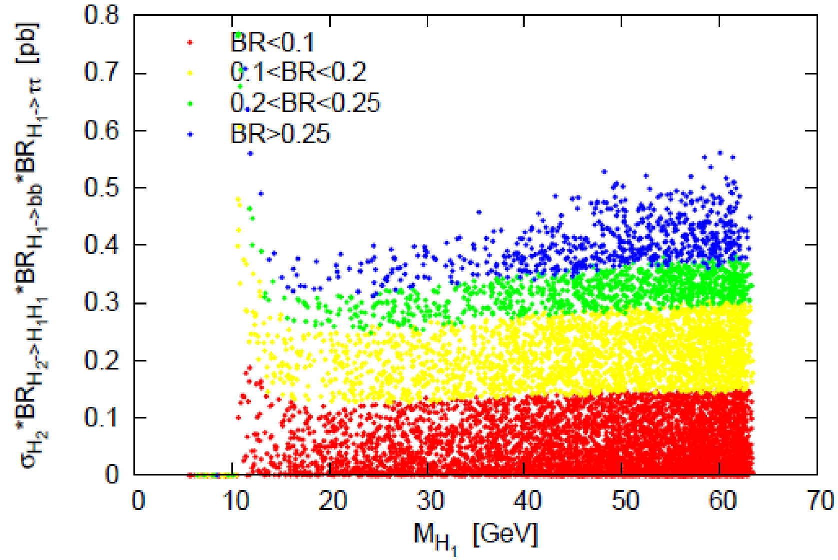
  p_T^μ>20 GeV, $|\eta^\mu|$<2.1

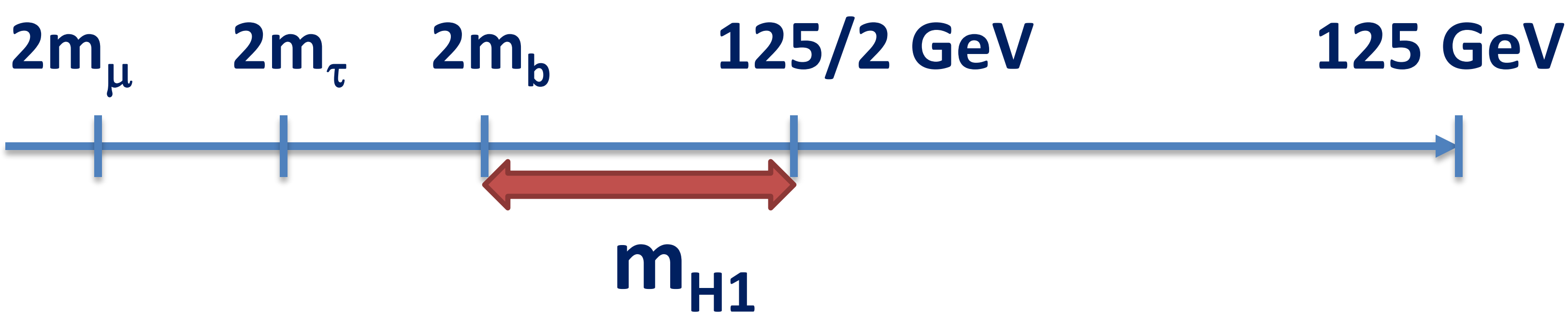
  $p_T^{\tau h}$ > 20 GeV, $|\eta^{\tau h}|$<2.3

  two jets p_T>25 GeV, $|\eta|$<2.4

  at least one b-tag jets

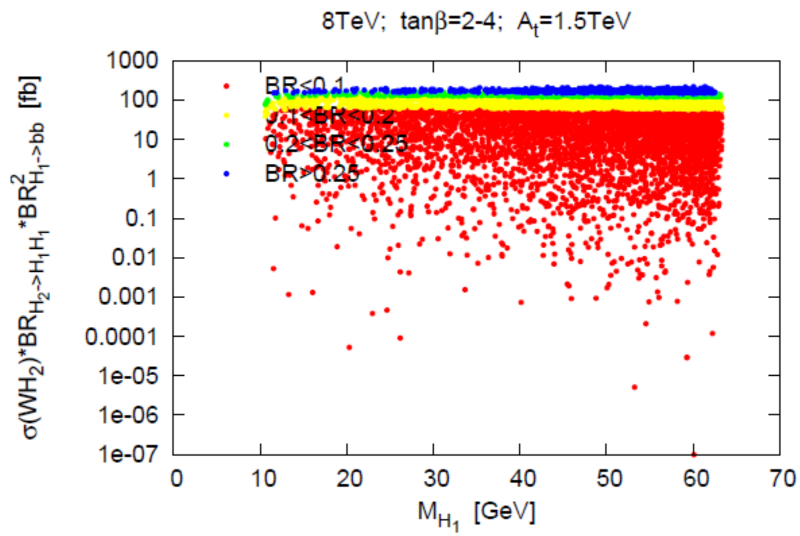
  - N_S~ 2-6 for m_{H1} (20-60) GeV
  - N_B ~ 3K from data

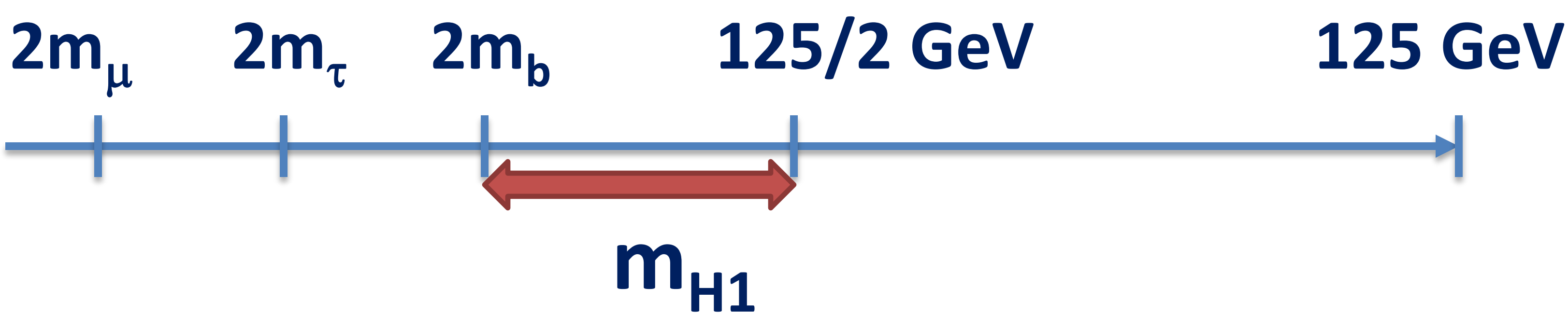




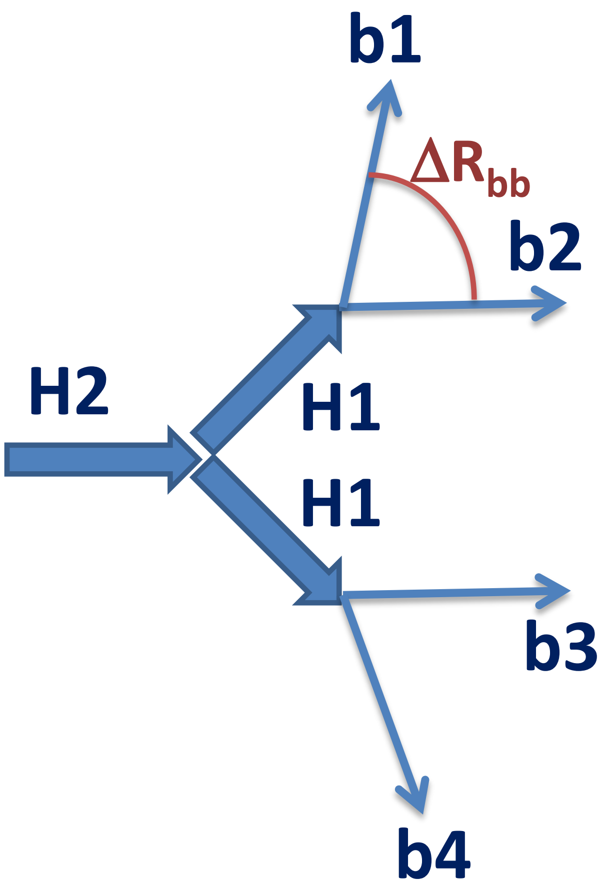
H2(125)->H1H1: $2m_b < m_{H1} < m_{H1}/2$ (II)

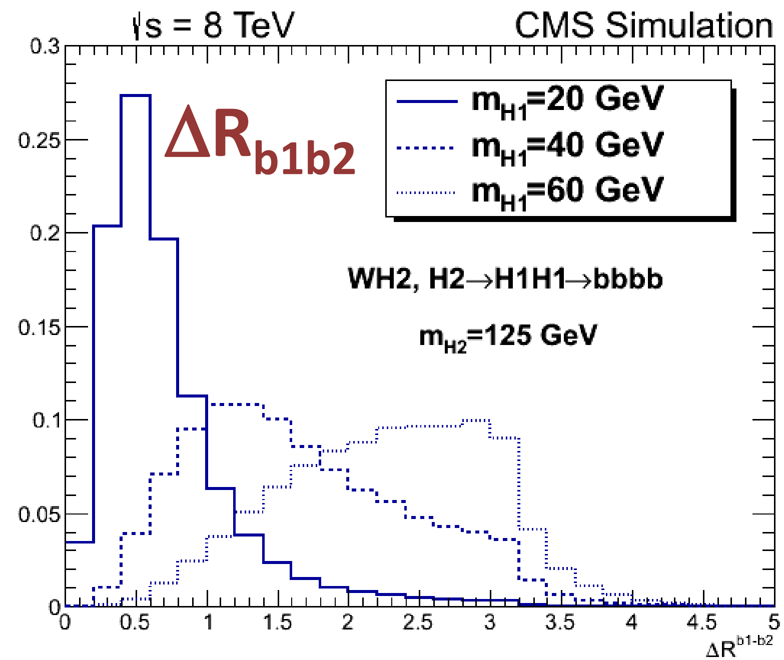
- WH2->H1H1->bbbb, 100 fb => 2000 ev with 20 fb^{-1} => 400 ev. with W->e/μ ν
- Particle level estimates with VH->bb analysis selections
  - $p_T^{\mu} > 24$ GeV, $|\eta^{\mu}|<2.1$
  - $p_T^{e} > 27$ GeV, $|\eta^{e}|<2.5$
  - $p_T^{b}>20$ GeV, $|\eta^{b}| < 2.4$

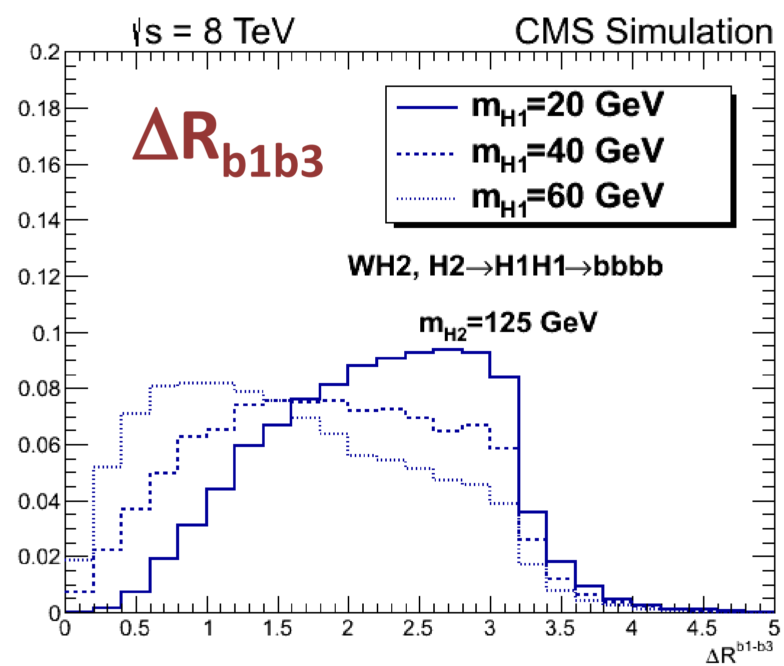




ΔR_{bb} and b-jet definition

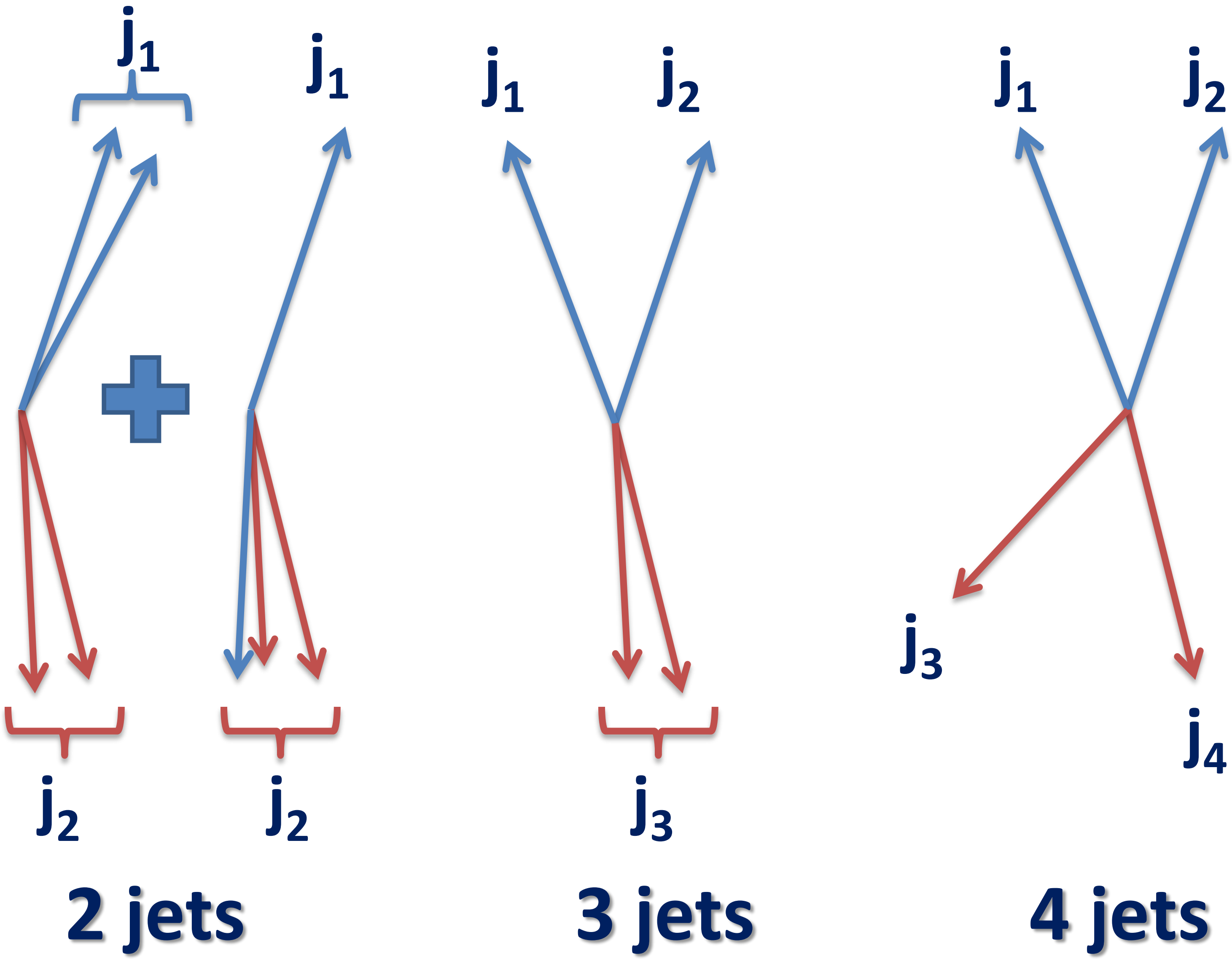






$\Delta R_{bb} < 0.5$ => consider as one jet

b-jet topologies in $H1_1$->bb + $H1_2$->bb



Lepton Selection	N events at 20 fb^{-1} for a given m_{H1}		
	20 GeV	40 GeV	60 GeV
σ Br^2(H1->bb) Br(W->e/μ ν)		400	
cuts on p_T^{ℓ}, η^{ℓ}	284	284	284
$\|\eta^b\| < 2.4$	203	194	199
ΔR(b-l) > 0.5	186	178	182

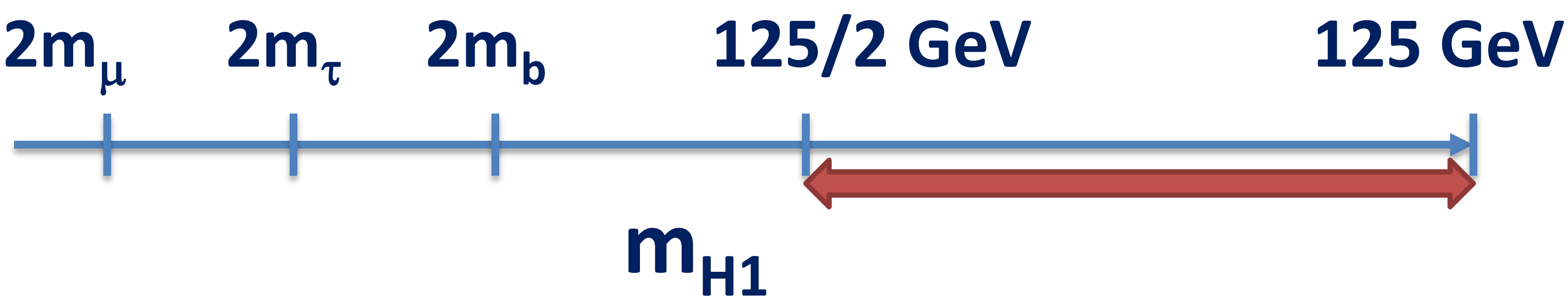
Jets selection and b-tagging			
	20 GeV	40 GeV	60 GeV
two jets/passed p_T cut	16.9/16.6	5.8/3.8	7.8/6.8
three jets/passed p_T cut	105/14.4	26/14	57/24
four jets/passed p_T cut	63/3.7	146/15	117/31
sum/passed p_T cut	185/35	178/33	182/62
Tagging with Inclusive Vertex Finder*: 0.5^4	2.2	2.1	3.9

Rare not reducible backgrounds for WH2->H1H1->bbbb need to be estimated

- Z+tt
- ttbb
- W+bbbb, W->$\ell\nu$
- WZ+bb, W->$\ell\nu$, Z->bb
- From DPS
  - W+bb & bb
  - W+bb & Z->bb
  - W & bbbb

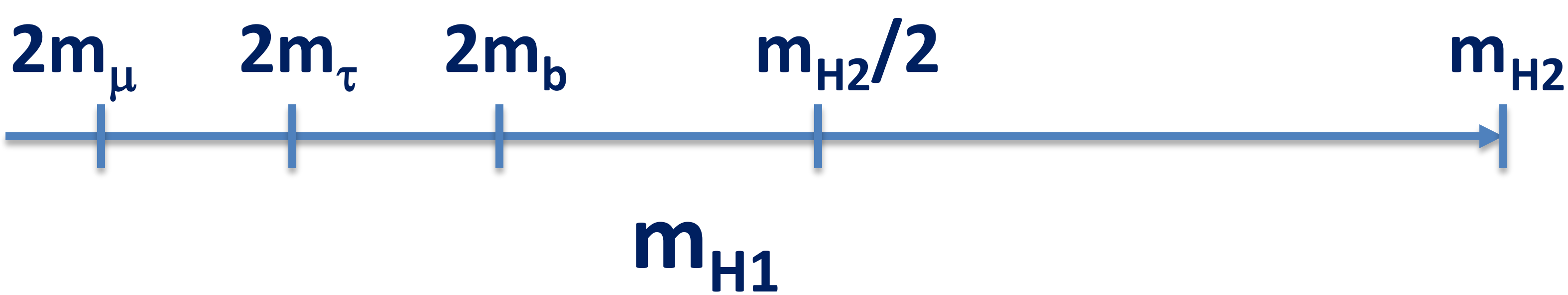
H3->H2(125)H1: $m_{H2}/2 < m_{H1} < m_{H2}$

- **It is for 14 TeV LHC:**
  - **H3(300-600 GeV)->H2H1->$W_\ell W_h$bb, proposed in arXiv:1301.0453**
  - **H3(300-500 GeV)->H2H1->bbbb, KIT started analysis. They conclude that:**
    - ggf $\rightarrow H_3 \rightarrow H_1 H_2 \rightarrow$bbbb is an interesting search channel
      - xsec at 8 TeV is 54 fb **170 fb at 14 TeV**
      - TMVA Optimization
      - $\frac{s}{\sqrt{b}}$ may reach 8.47 for 14 TeV and high luminosity **500 fb^{-1}**
    - Data driven method promising
    - Todo
      - understand influence of trigger



conclusion about NMSSM part of talk

- good prospects for H2(125)->H1H1->ττττ at 8 TeV
  - Higgs-Exotics lunched analysis; $2m_\tau < m_{H1} < 2m_b$
- difficult region $2m_b < m_{H1} < m_{H2}/2$
  - most probably need 14 TeV data
  - WH2->H1H1->bbbb – need bkg. estimations
  - H2->H1H1->bbbb – not addressed yet
- good prospects for H3->H2(125)H1->WWbb, bbbb at 14 TeV
  - Higgs-Exotics lunched analysis; $m_{H1} > 60$ GeV
- still need to be considered decays H1(~100 GeV)->A1A1



2 Higgs Doublet Model

See for example "Theory and phenomenology of two-Higgs-doublet model". G.C.Branco at.al. Phys.Reports 516 (2012) 1-102

Theoretical structure of the 2HDM

- The scalar fields of the 2HDM are complex SU(2) doublet, hypercharge-one fields, Φ_1 and Φ_2.
  - the most general scalar potential:

$$\begin{aligned}\mathcal{V} = {} & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] + \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 \\ & + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \big[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\big]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\},\end{aligned}$$

  - compare to SM with single doublet scalar field Φ:

$$\text{scalar potential } V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$M_H^2 = 2\lambda v^2 = -2\mu^2 \quad m_e = \frac{\lambda_e v}{\sqrt{2}} \;, \; m_u = \frac{\lambda_u v}{\sqrt{2}} \;, \; m_d = \frac{\lambda_d v}{\sqrt{2}}$$

- **Yukawa couplings are given by:**

$$-\mathcal{L}_{\rm Y} = \overline{U}_L \Phi_a^{0\,*} h_a^U U_R - \overline{D}_L K^\dagger \Phi_a^- h_a^U U_R + \overline{U}_L K \Phi_a^+ h_a^{D\,\dagger} D_R + \overline{D}_L \Phi_a^0 h_a^{D\,\dagger} D_R$$
$$+\overline{N}_L \Phi_a^+ h_a^{L\,\dagger} E_R + \overline{E}_L \Phi_a^0 h_a^{E\,\dagger} E_R + \text{h.c.}\,,$$

  - **where h_a^U and h_a^U are Yukawa coupling matrices and K is CKM matrix; a=1,2**
- **It yields however three-level FCNC mediated by neutral Higgs exchange, since only one of h_a^U and h_a^D are diagonal**
- **The problem is solved by imposing discrete symmetry on the Higgs and fermion fields to set two of four Yukawa coupling matrices to zero**

Four possibilities exist in the 2HDM:

1. Type-I Yukawa couplings: $h_1^U = h_1^D = h_1^L = 0$,
2. Type-II Yukawa couplings: $h_1^U = h_2^D = h_2^L = 0$.
3. Type-X Yukawa couplings: $h_1^U = h_1^D = h_2^L = 0$,
4. Type-Y Yukawa couplings: $h_1^U = h_2^D = h_1^L = 0$.

The four types of Yukawa couplings can be implemented by a discrete $\mathbb{Z}_2$ symmetry, with the following charge assignments:

		Φ_1	Φ_2	U_R	D_R	E_R	U_L, D_L, N_L, E_L
Type I		$+$	$-$	$-$	$-$	$-$	$+$
Type II	(MSSM like)	$+$	$-$	$-$	$+$	$+$	$+$
Type X	(lepton specific)	$+$	$-$	$-$	$-$	$+$	$+$
Type Y	(flipped)	$+$	$-$	$-$	$+$	$-$	$+$

Couplings and free parameters

- **Higgs couplings to fermions**

	$h\overline{U}U$	$h\overline{D}D$	$h\overline{E}E$	$H\overline{U}U$	$H\overline{D}D$	$H\overline{E}E$	$iA\overline{U}\gamma_5 U$	$iA\overline{D}\gamma_5 D$	$iA\overline{E}\gamma_5 E$
Type I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$-\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type X	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$-\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$-\cot\beta$	$-\tan\beta$	$\cot\beta$

- **couplings to bosons:**

$c_{\beta-\alpha}$	$s_{\beta-\alpha}$
HW^+W^-	hW^+W^-
HZZ	hZZ
ZAh	ZAH
$W^\pm H^\mp h$	$W^\pm H^\mp H$

- **Free parameters :**
  - m_h, m_H, m_A, m_{H+}, α, β, m_{12}

Recent scans in 2HDM with LHC h(126)

- **from arXiv:1305.4587, Ferreira, Santos. Sher, Silva**

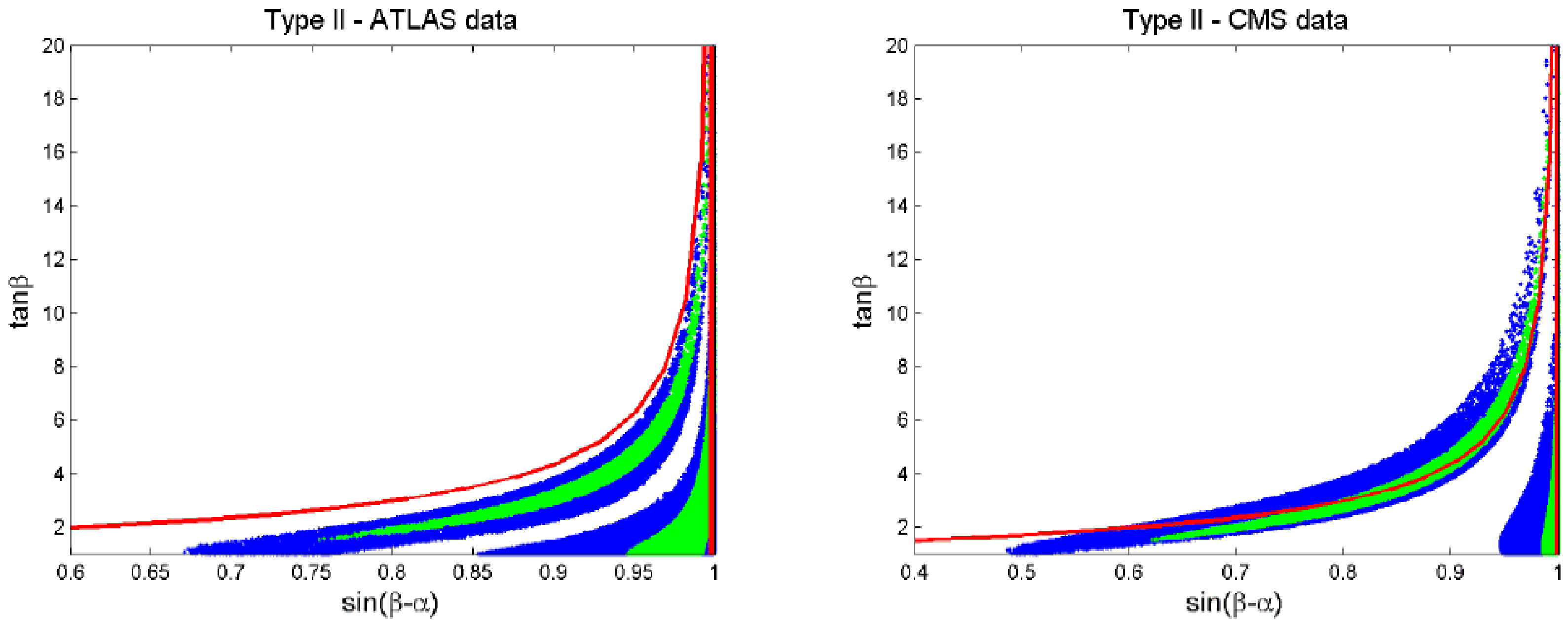
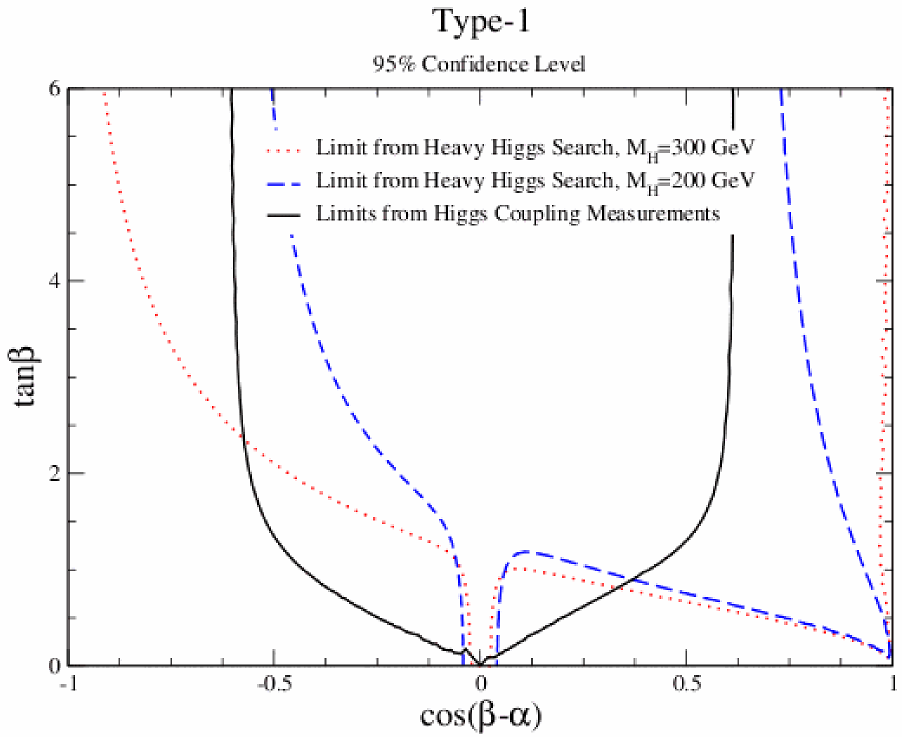


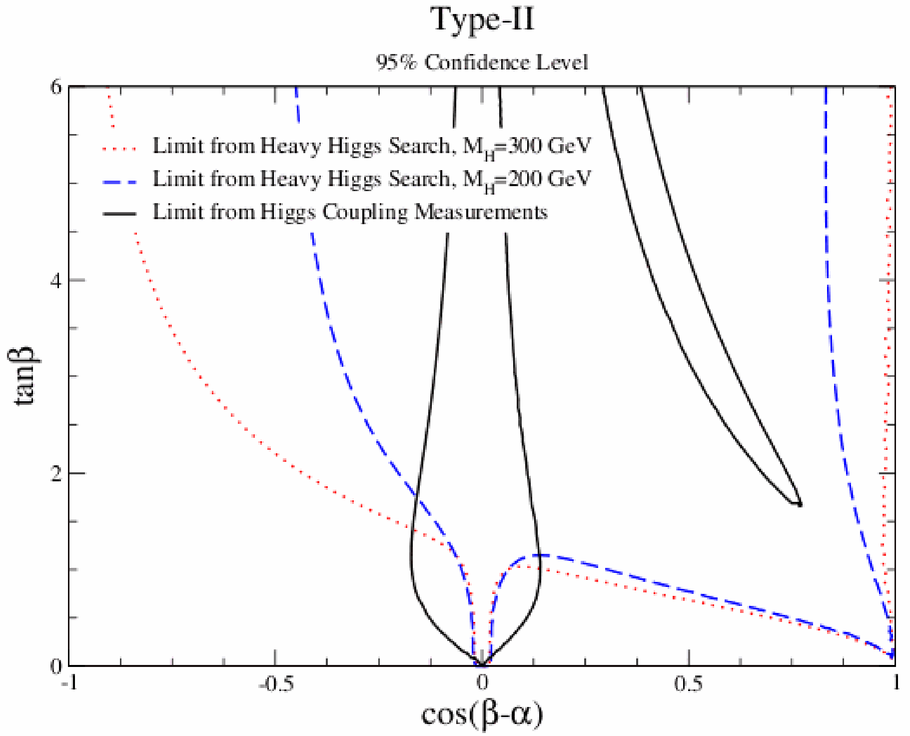
Figure 3: Points in the $(\sin(\beta-\alpha), \tan\beta)$ plane that passed all the constraints in model type II using the ATLAS data analysis (left) and using the CMS data analysis (right) at 1σ in green (light grey) and 2σ in blue (dark grey). Also shown are the lines for the SM limit $\sin(\beta-\alpha) = 1$ and for the limit $\sin(\beta+\alpha) = 1$.

Recent scans in 2HDM with LHC h(126) and H->VV

- from arXiv:1305.1624, Chen, Dawson, Sher



(a)



(b)

- **Recent discussion by Howard E. Haber on "Higgs Days in Santander 13", Sept. 2013:**

  However, there are various reasons to consider the more general 2HDM without imposing an additional discrete symmetry on the model.

  1. It would be useful to consider a formalism that can treat all four Yukawa coupling types simultaneously. (After all, experiment should decide which Yukawa interactions are relevant in nature.)

  2. It may be that the suppression of tree-level Higgs-mediated FCNCs is a consequence of some new high scale physics. When this new physics is integrated out, the effective low energy 2HDM takes on its most general form.

- **Strategy for benchmarks in the general 2HDM with a new set of free parameters will be proposed soon to ATLAS and CMS**

Conclusions

- Very reach physics program for BSM Higgs boson searches at LHC
- We expect to have a second discovery in Higgs sector during LHC and HL-LHC operation
- You are very welcome to join our searches