Search for Higgs Particles in MSSM SUSY

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for the CMS Collaboration

ICHEP Conference, July 6th 2012

MSSM Higgs Phenomenology

- 2 Higgs doublets ➔ 5 physical Higgs Bosons:
  - 2 CP-even neutrals: h, H scalar
  - 1 CP-odd neutral: A pseudo-scalar
  - 2 charged: H^+, H^-

- At Born level Higgs sector of MSSM described by 2 Parameters: M_A, tan β

$$M_{H^+}^2 = M_A^2 + M_W^2$$

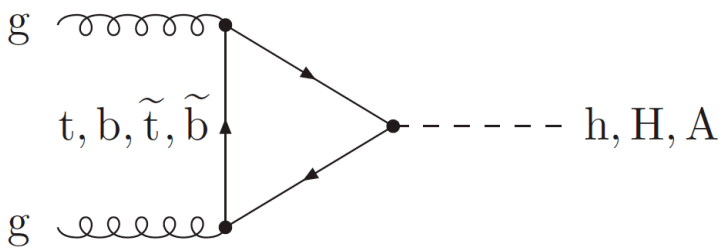
$$M_{h/H}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right)$$

$$\alpha = \frac{1}{2}\arctan(\tan 2\beta \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2})$$

(Dependency on SUSY Parameters via radiative Corrections)

Neutral MSSM Higgs Bosons

- 2 main Production Processes:



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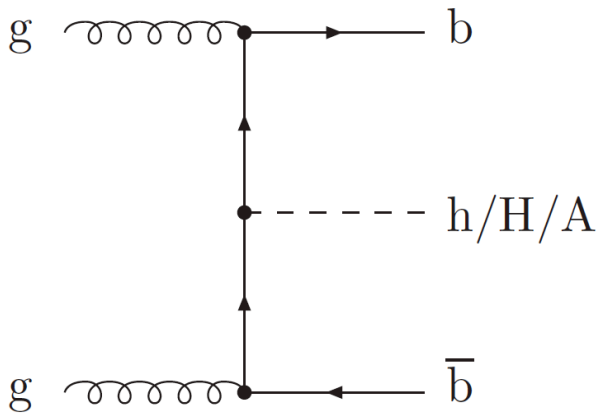
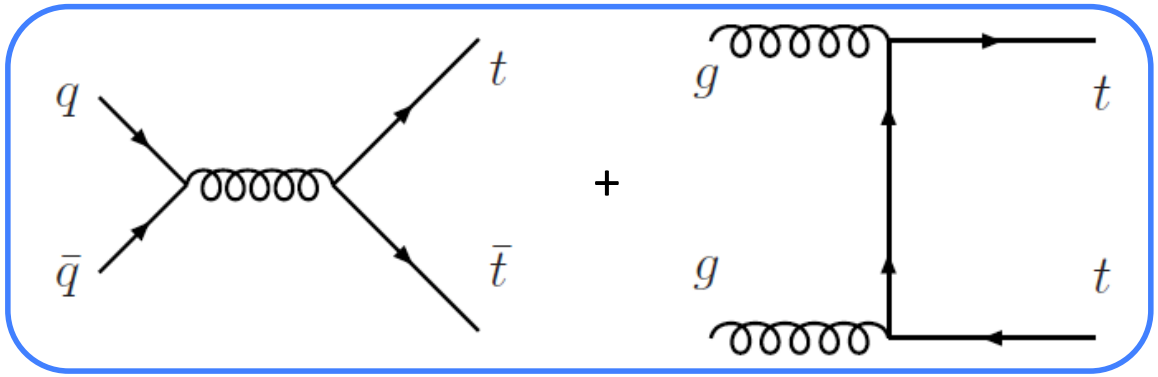


Cross-section increases proportional tan β^2
(for tan $\beta \gtrsim 7$)

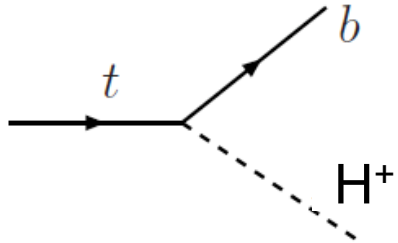
- Dominant Decay modes are bb and ττ
(tt relevant at large M_A and low β only, experimentally no accessible yet)

Charged MSSM Higgs Bosons

- $M_{H^+} \lesssim m_{top}$ Standard Model tt Production

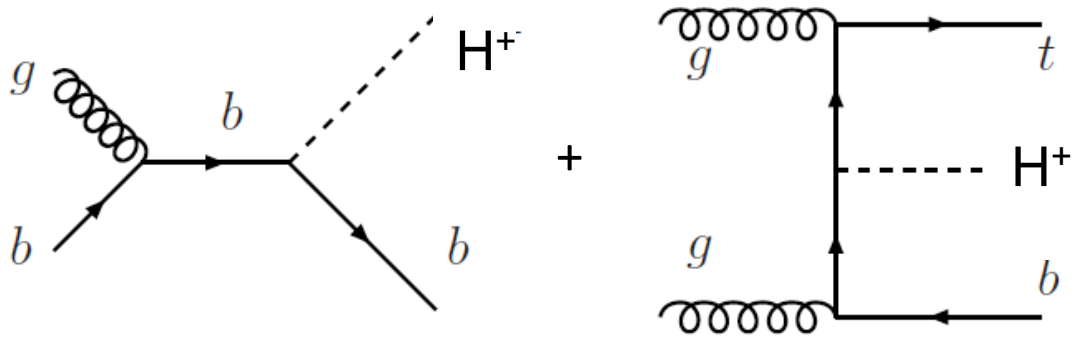


with



Dominant Decay mode: $H^+ \rightarrow \tau\nu$

- $M_{H^+} \gtrsim m_{top}$ not yet analyzed by CMS



Dominant Decay mode: $H^+ \rightarrow tb$

MSSM Higgs Search Channels

- $pp \rightarrow tt,\ t \rightarrow H^+b,\ H^+ \rightarrow \tau\nu$
- $pp \rightarrow \phi,\ \phi \rightarrow \tau\tau$
- $pp \rightarrow \phi b,\ \phi \rightarrow bb$
  - Semileptonic b decays
  - Hadronic b decays
- $pp \rightarrow \phi,\ \phi \rightarrow \mu\mu$

ϕ: h + H + A

$H^+ \rightarrow \tau\nu$ Analysis

Analysis sensitive to:

- $t\bar{t} \rightarrow H^{\pm}W^{\mp}b\bar{b}$
- $t\bar{t} \rightarrow H^{\pm}H^{\mp}b\bar{b}$

3 Final states are studied:

- **τ_{had} + Jets**

τ_{had}: Particles produced in hadronic τ decay

$$H^{\pm} \rightarrow \tau\nu \rightarrow \tau_{had}\nu, W^{\mp} \rightarrow jj$$

- **τ_{had} + e/μ**

$$H^{\pm} \rightarrow \tau\nu \rightarrow \tau_{had}\nu, W^{\mp} \rightarrow \mu\nu/e\nu$$
$$H^{\pm} \rightarrow \tau\nu \rightarrow \tau_{had}\nu, W/H^{\mp} \rightarrow \tau\nu \rightarrow \mu\nu\nu/e\nu\nu$$
$$H^{\pm} \rightarrow \tau\nu \rightarrow e\nu\nu/\mu\nu\nu, W/H^{\mp} \rightarrow \tau\nu \rightarrow \tau_{had}\nu$$

- **e+μ**

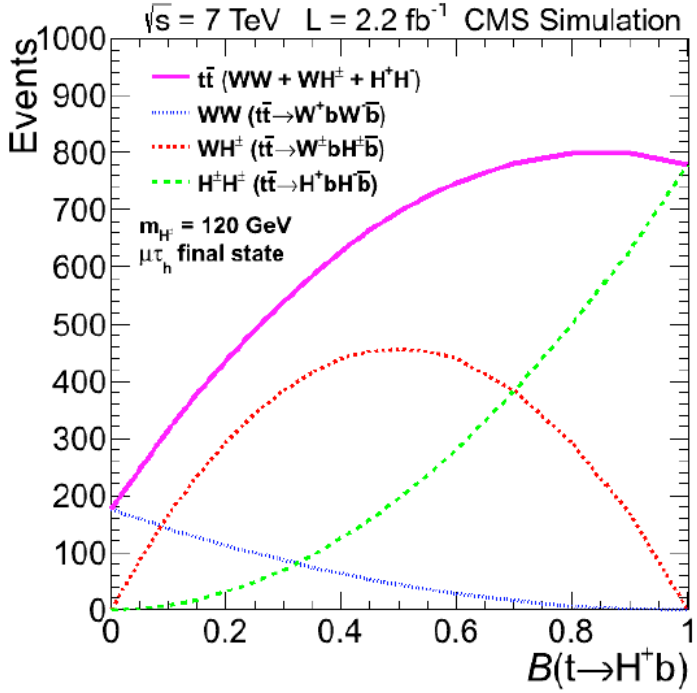
$$H^{\pm} \rightarrow \tau\nu \rightarrow e\nu\nu/\mu\nu\nu, W^{\mp} \rightarrow \mu\nu/e\nu$$
$$H^{\pm} \rightarrow \tau\nu \rightarrow e\nu\nu/\mu\nu\nu, H^{\mp} \rightarrow \tau\nu \rightarrow \mu\nu\nu/e\nu\nu$$

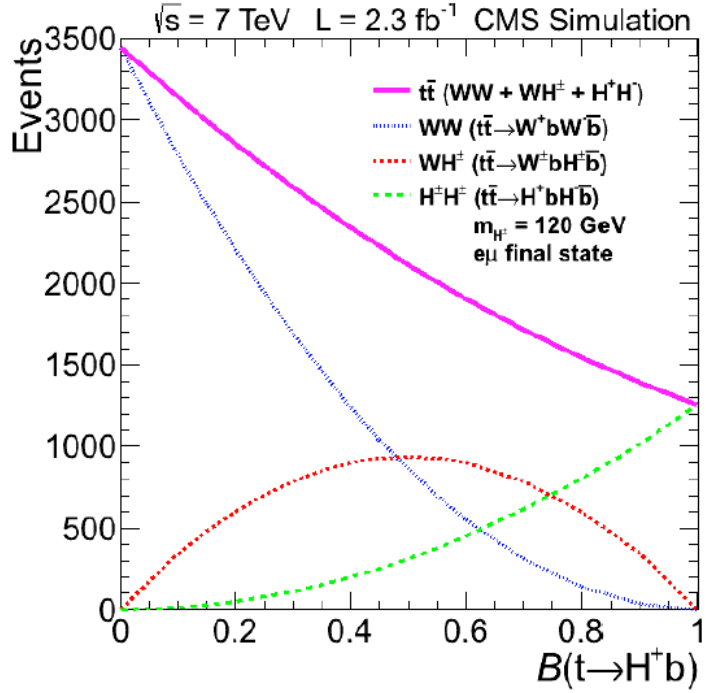
$H^+ \rightarrow \tau\nu$ Event Selection

	τ_{had}+Jets	e/μ+τ_{had}	e+μ
Trigger	$\tau_{had}+E_T^{miss}$	Electron+2 Jets/ single Muon	Electron+Muon
Lepton Selection			
	$P_T^{\tau} > 40$ GeV very tight Tau Id.	$P_T^{e} > 35$ GeV $P_T^{\mu} > 30$ GeV isolated	$P_T^{e} > 20$ GeV $P_T^{\mu} > 20$ GeV isolated
Jets	≥ 3 Jets of $P_T > 30$ GeV ≥ 1 b-tagged	≥ 2 Jets of $P_T > 35$ (30) GeV ≥ 1 b-tagged	≥ 2 Jets of $P_T > 20$ GeV
E_T^{miss}	> 50 GeV $\Delta\phi(\tau_{had},E_T^{miss}) < 160^o$	> 45 GeV for e+τ_{had} > 40 GeV for μ+τ_{had}	
		Opposite Charge Lepton Pair	

Veto Events with additional isolated Electrons or Muons

$H^+ \rightarrow \tau\nu$ Signal Extraction





Note:

non-zero BR($t \rightarrow H^+b$) increases Event yield in τ_{had}+Jets and e/μ+τ_{had} Channels, while Event yield in e+μ Channel decreases with BR($t \rightarrow H^+b$)

Event yields observed in τ_{had}+Jets, e/μ+τ_{had} and e+μ Channels in Agreement with Background Expectation

➔ Proceed with setting Limit on BR($t \rightarrow H^+b$)

$H^+ \rightarrow \tau\nu$ Result

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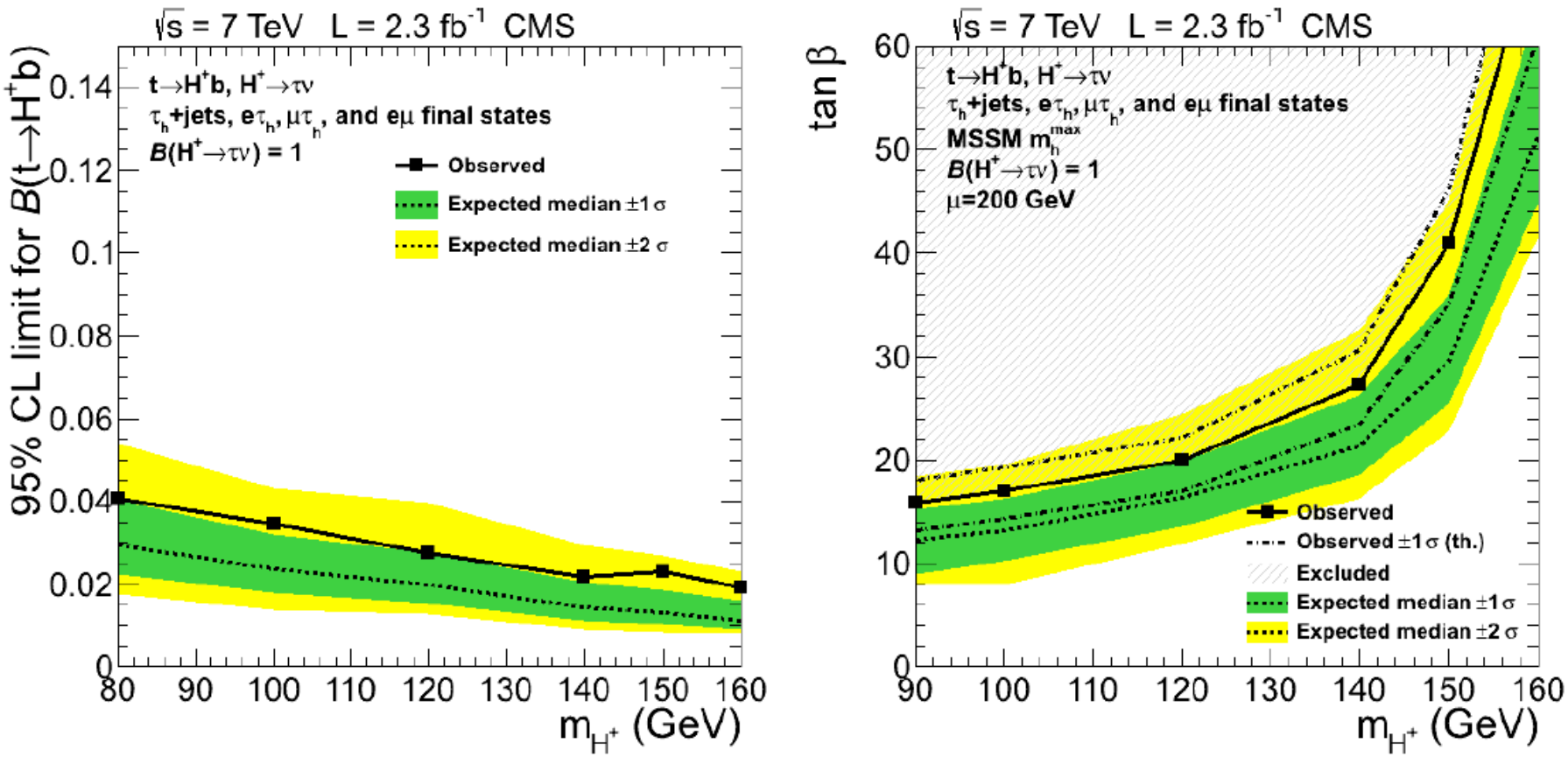


Upper limit on BR(t → H^+b) excludes region of large tan(β) in MSSM Parameter space for $M_{H^+}/M_A \lesssim m_{top}$.

$\phi \rightarrow \tau\tau$ Analysis

$\phi \rightarrow \tau\tau$ Signal searched for in 3 τ decay Channels:

ϕ: h + H + A

- e+μ
- e+τ_{had}
- μ+τ_{had}

τ_{had}: Particles produced in hadronic τ decay

Please see also Poster:
"Higgs Boson searches in the $H \rightarrow \tau\tau$ channel" (A. Bethani)

$\phi \rightarrow \tau\tau$ Event Selection

Trigger

Events triggered by e+μ, e+τ_{had} and μ+τ_{had} Triggers
P_T thresholds 10-20 GeV

Lepton Selection

Electrons	**Muons**	**τ_{had}**
P_T > 10-20 GeV	P_T > 10-20 GeV	P_T > 20 GeV
$\|\eta\|$ < 2.1 (2.3 for e + μ)	$\|\eta\|$ < 2.1	$\|\eta\|$ < 2.3
isolated	isolated	Tau Id.
		Veto against e/μ

Opposite Charge Lepton Pair

Veto Events with additional isolated Leptons

Suppression of W+jets Background

E_T^{miss} required to point in Direction of visible τ Decay products

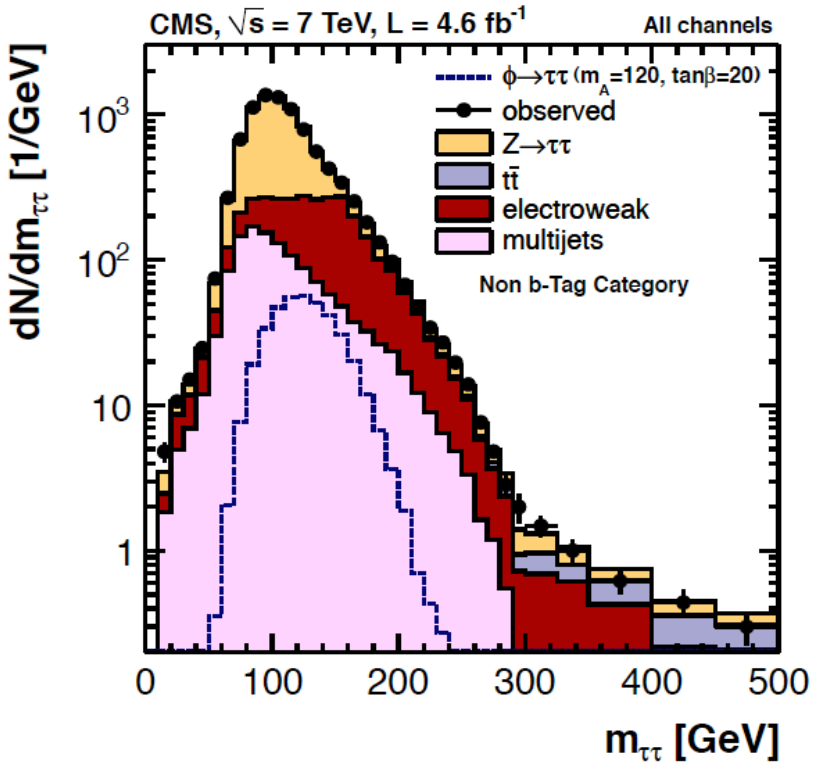
Selected Events analyzed in 2 Categories: no-b-Tag and b-Tag

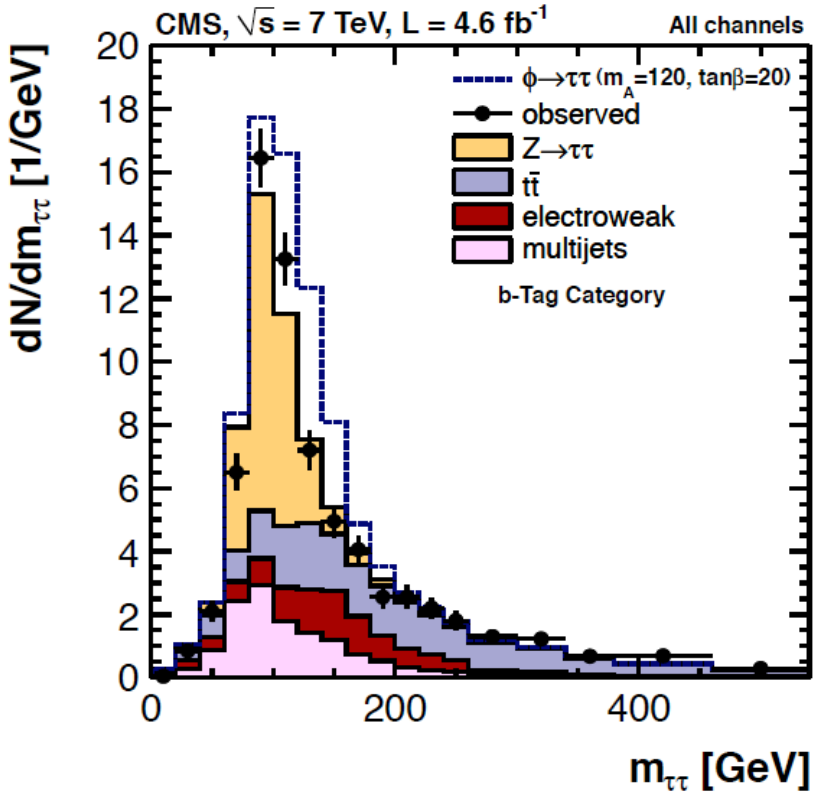
ττ Mass Reconstruction

Mass of τ Lepton pair reconstructed via Likelihood technique, based on:

- τ decay Kinematics
- Compatibility of reconstructed E_T^{miss} with Neutrino hypotheses

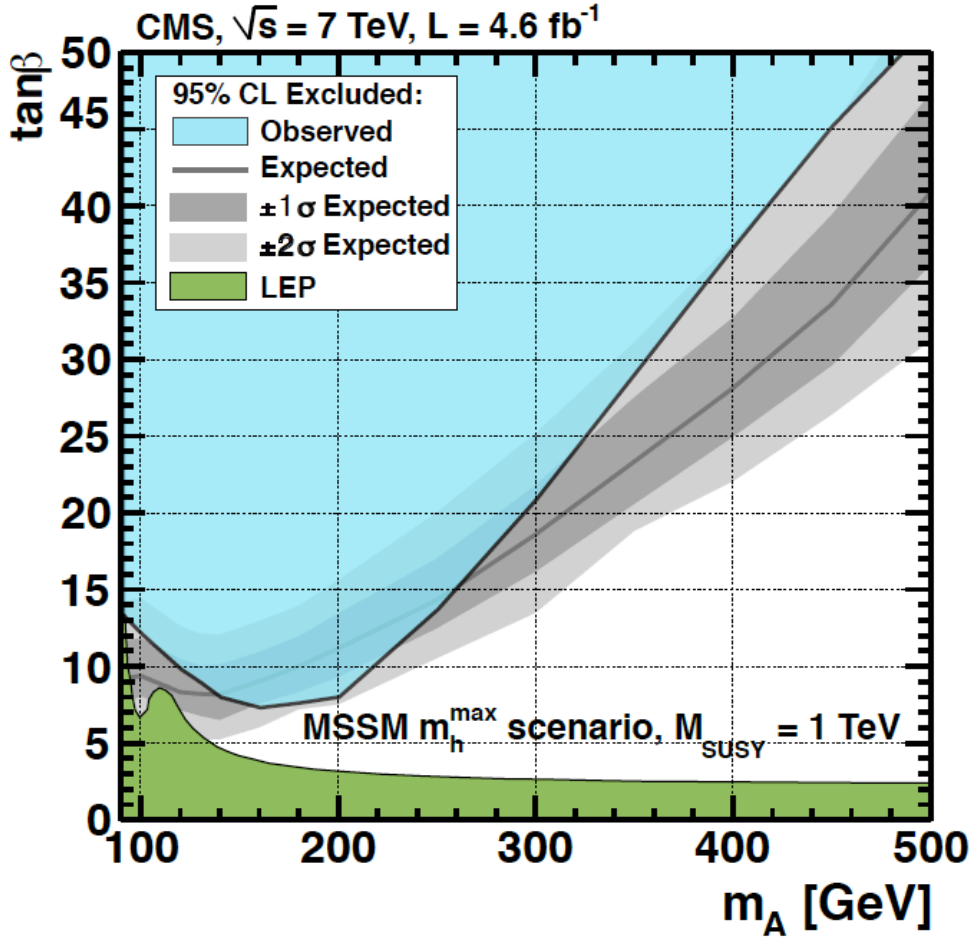
➔ $m_{\tau\tau}$ Resolution ~20% (almost Gaussian)





➔ Distribution observed in Data in Agreement with Background Expectation

$\phi \rightarrow \tau\tau$ Result



hep-ex/12024083

Limit obtained by scanning tan(β) for each Mass hypothesis M_A:

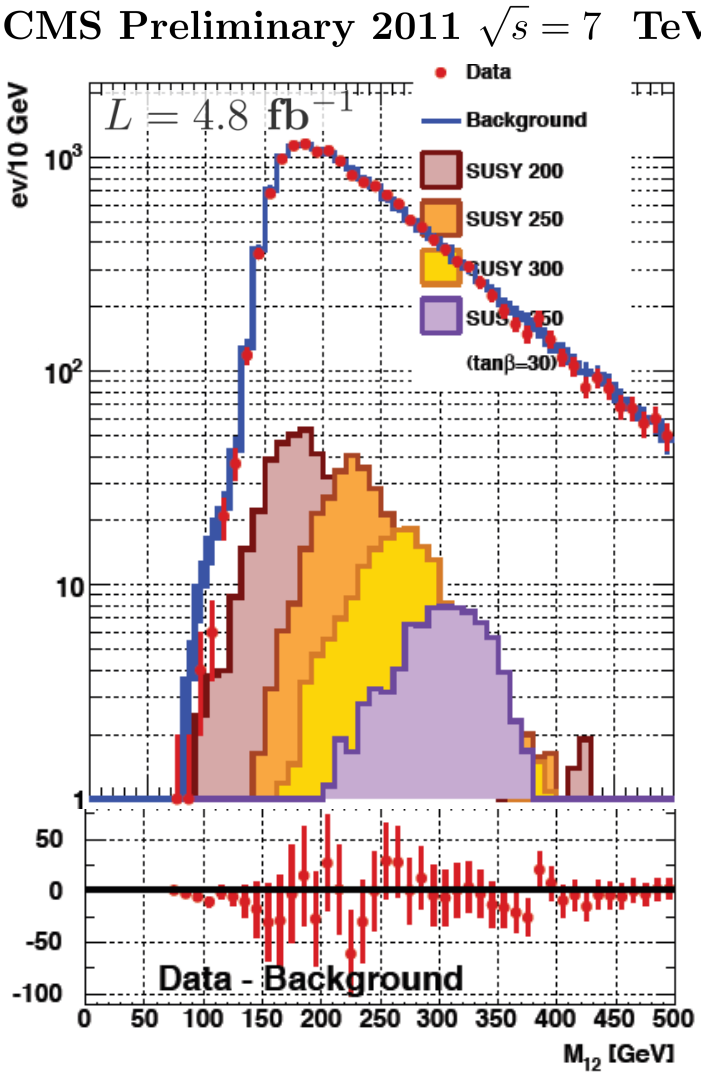
- Cross-section • BR for gg → ϕ and bb → ϕ computed as function of M_A, tan(β)
- Dependence of M_h and M_H on tan(β) taken into account

$\phi \rightarrow bb$ Event Selection

	Semileptonic	Hadronic
Trigger	Muon+1/2 Jets ≥ 1/2 b-tagged	2/3 Jets ≥ 2 b-tagged
Jets	≥ 2 Jets of P_T > 30 GeV + 3rd Jet of P_T > 20 GeV all 3 b-tagged	≥ 3 Jets: ✪ P_T^{1st} > 46 (60) GeV P_T^{2nd} > 38 (53) GeV P_T^{3rd} > 20 GeV all 3 b-tagged
Muon	P_T > 15 GeV (no Isolation applied)	-

✪ Jet P_T Threshold depends on Higgs Mass hypothesis:
lower (higher) Thresholds used for M_ϕ < 180 GeV (M_ϕ > 180 GeV),
driven by Trigger Thresholds

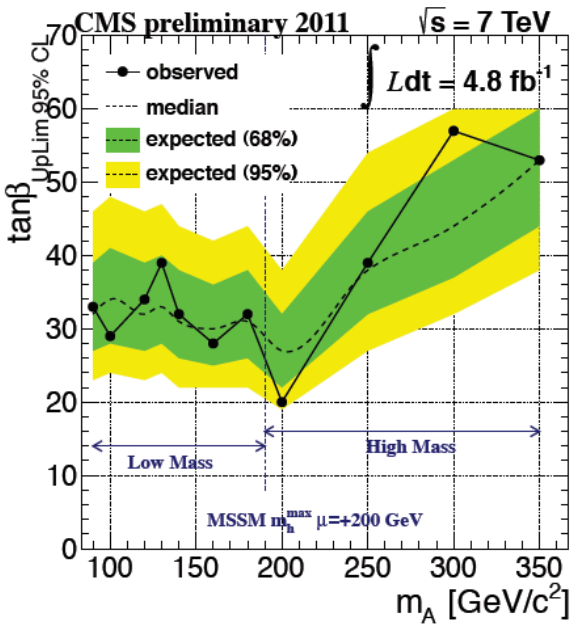
ϕ → bb Result



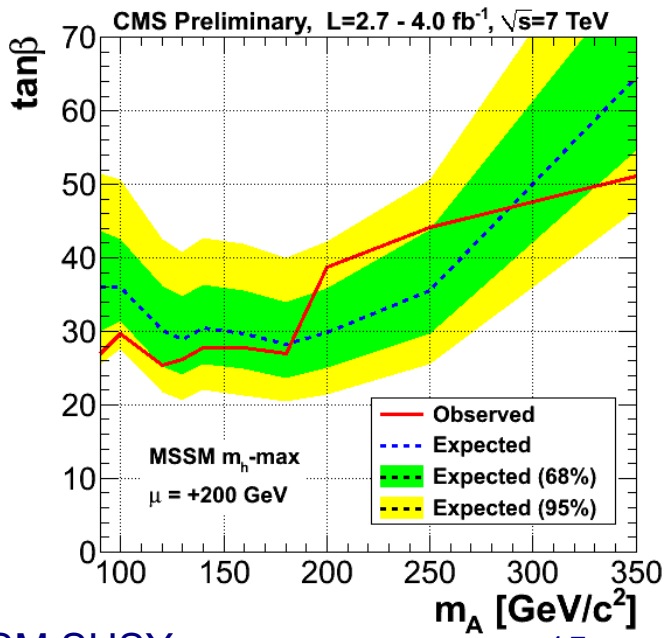
Data in Agreement with Background Prediction

- ➔ Set upper Limit on pp → ϕb Production Cross-section • BR(ϕ→bb) by fitting observed M_{12} Distribution
- ➔ non-Observation of ϕ → bb Signal excludes region of large tan(β) in MSSM Parameter space

Semileptonic



Hadronic



M_{12} Resolution ~15%

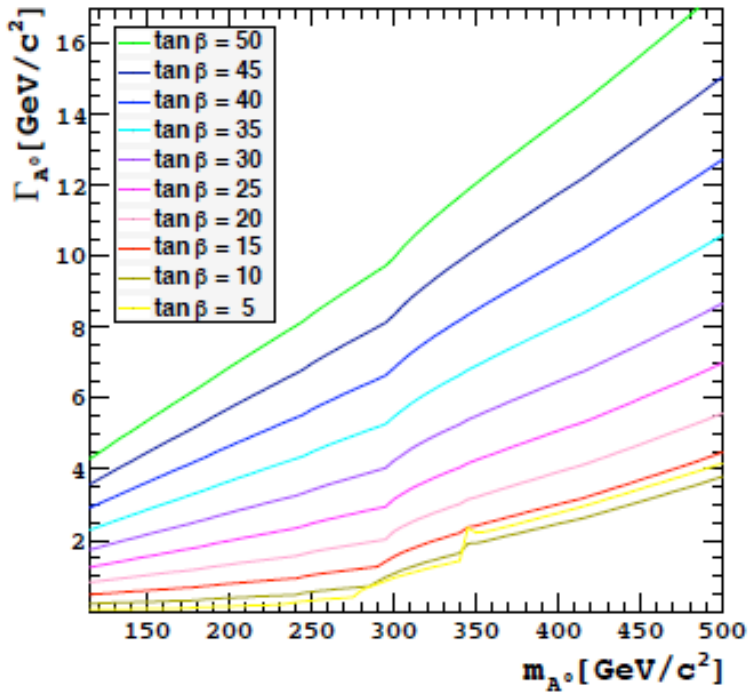
CMS PAS HIG-12-026

CMS PAS HIG-12-027

$\phi \rightarrow \mu\mu$ Analysis

Small Branching ratio (few times 10^{-4}), but also:

Muons reconstructed very efficiently in CMS
and with very good Mass Resolution
(almost comparable to Higgs width)



Please see also Poster:
"Search for Neutral MSSM Higgs Bosons in the $\mu^+\mu^-$ final state with the CMS experiment in pp Collisions at $\sqrt{s}$ = 7 TeV" (A. Perieanu)

$\phi \rightarrow \tau\tau$ Event Selection

Trigger

Single Muon

Muon Selection

≥ 2 Muons
$P_T^{1st} > 30$ GeV
$P_T^{2nd} > 20$ GeV
$|\eta| < 2.1$
isolated

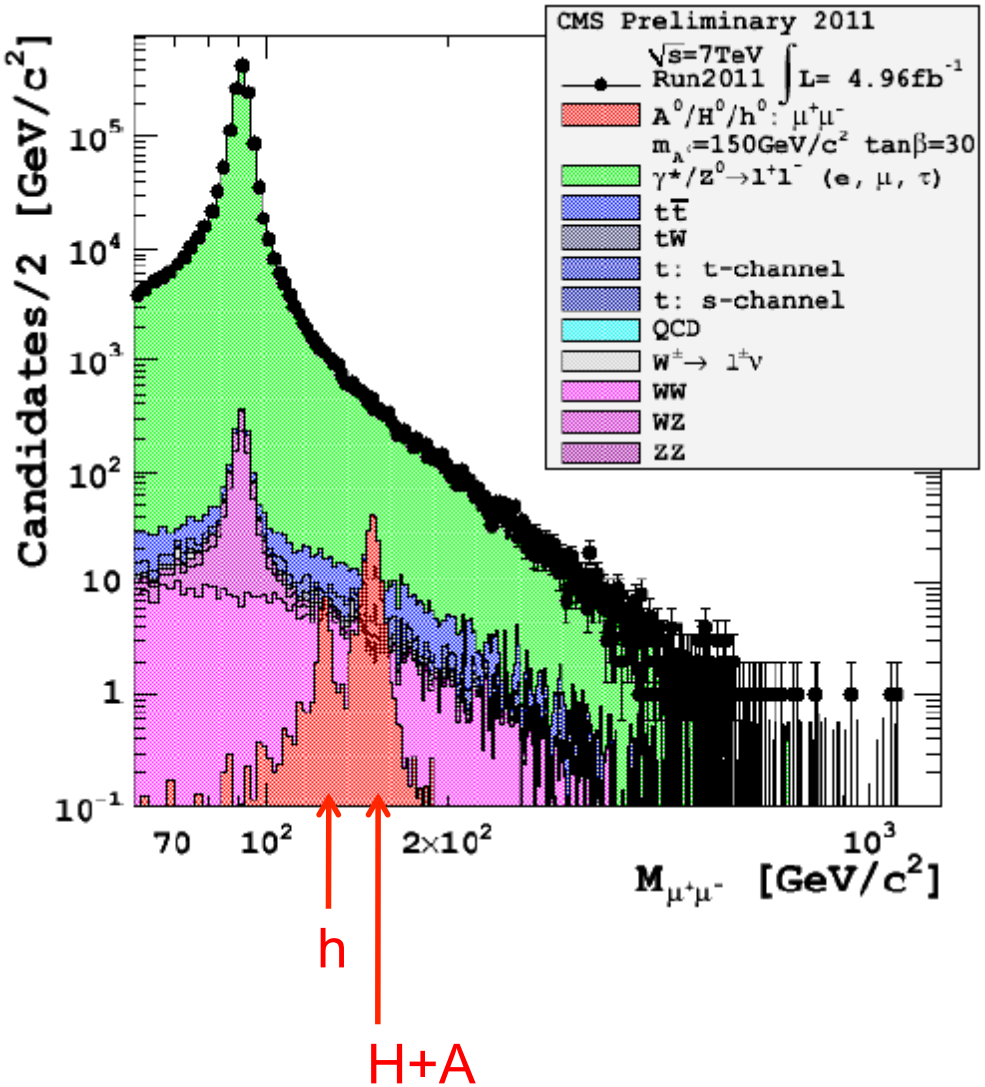
Opposite Charge Muon Pair

Suppression of tt Background

$E_T^{miss} < 30$ GeV

Selected Events analyzed in 3 Categories: b-Tag, 3rd Muon and neither

$\phi \rightarrow \mu\mu$ Result

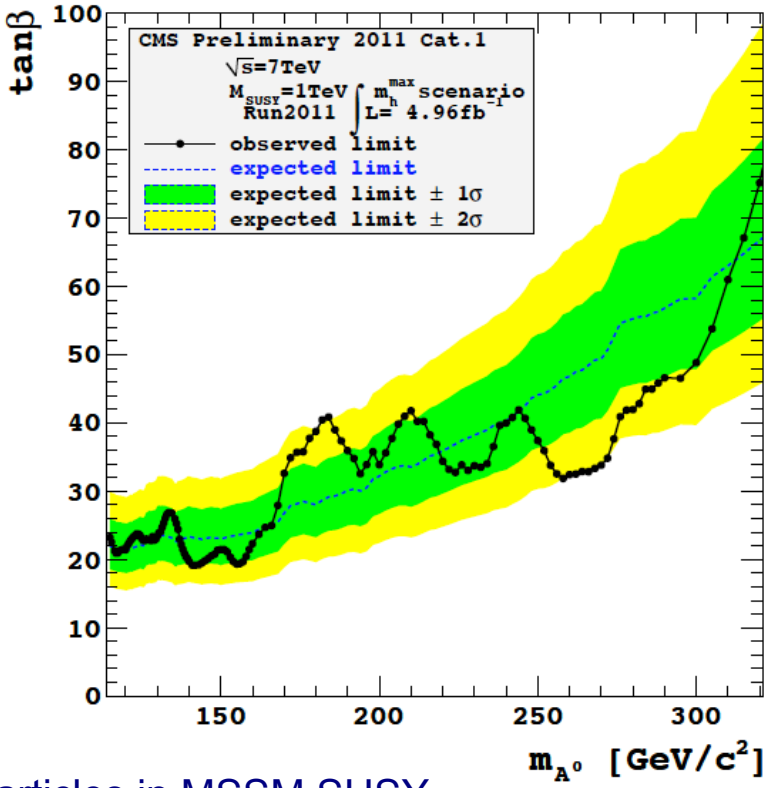


$M_{\mu\mu}$ Resolution ~3%

Observed di-Muon Mass Spectrum in Agreement with Background-only Hypothesis

➔ Set Limit

CMS PAS HIG-12-011



Summary

MSSM Higgs Signals have been searched for in:

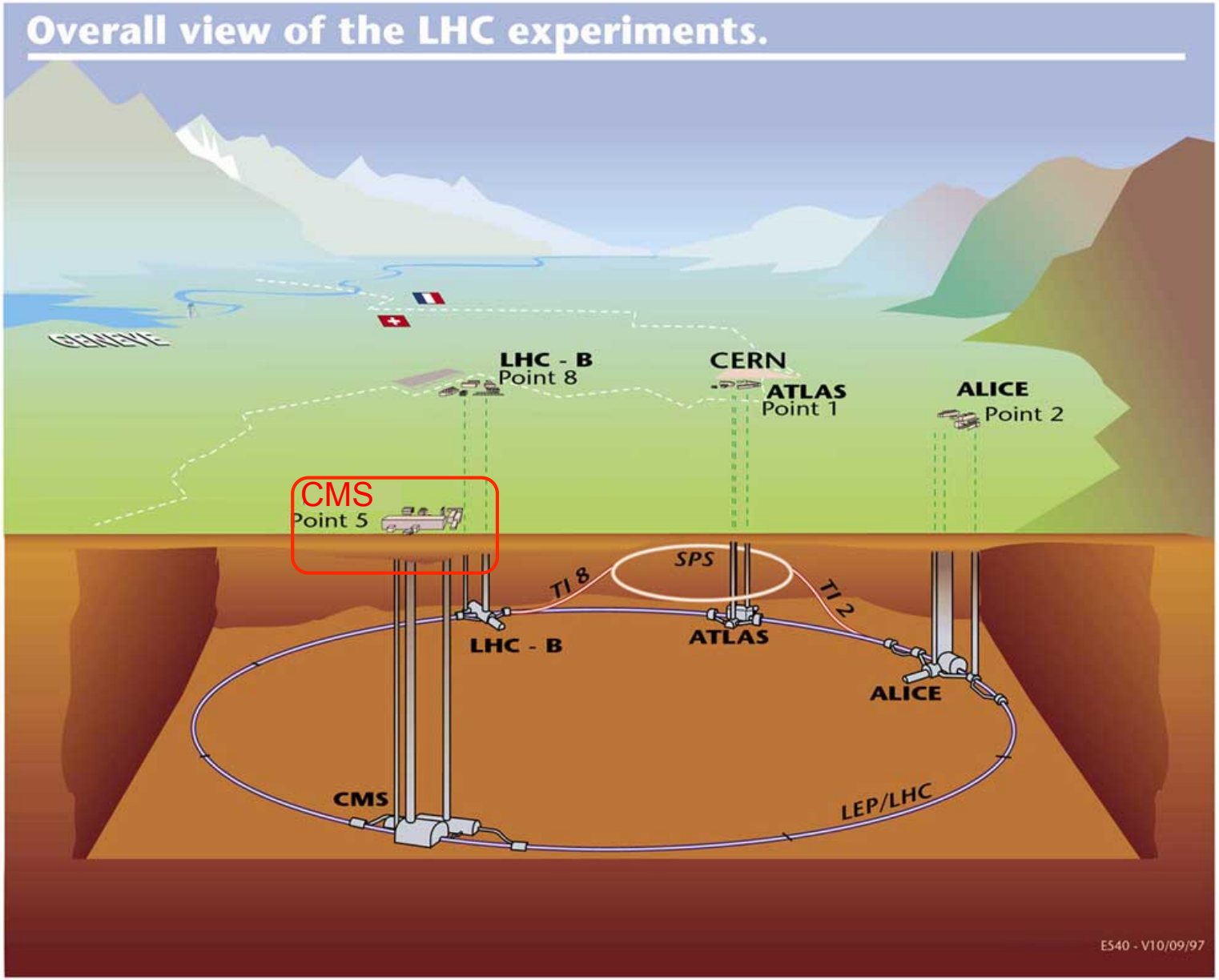
- $pp \rightarrow tt,\ t \rightarrow H^+b,\ H^+ \rightarrow \tau\nu$
- $pp \rightarrow \phi,\ \phi \rightarrow \tau\tau$
- $pp \rightarrow \phi b,\ \phi \rightarrow bb$
- $pp \rightarrow \phi,\ \phi \rightarrow \mu\mu$

No evidence for MSSM Higgs Signal observed in CMS Data

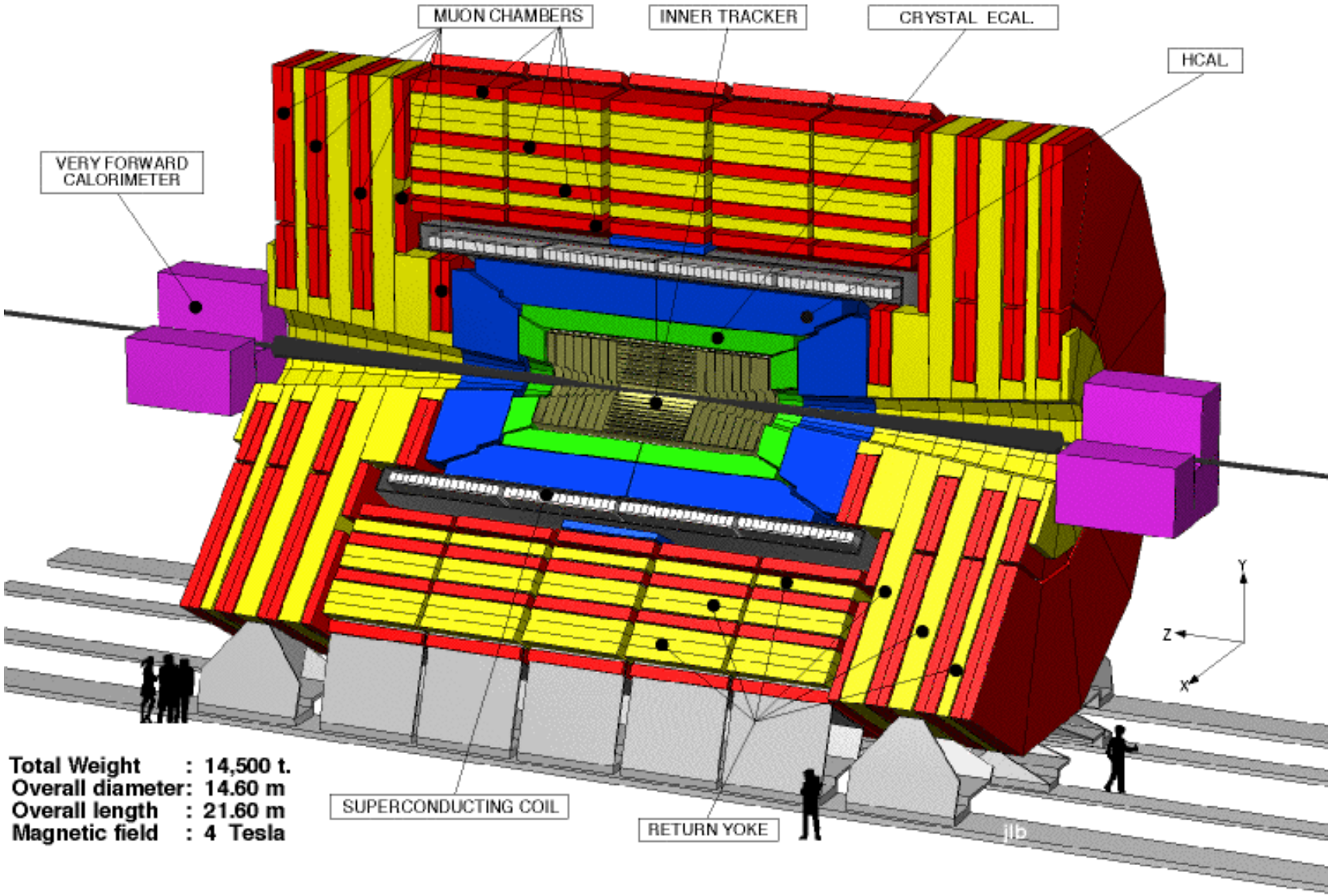
➔ Stringent Limits are set on MSSM Higgs Production

Backup Material

The CMS Experiment



The CMS Detector

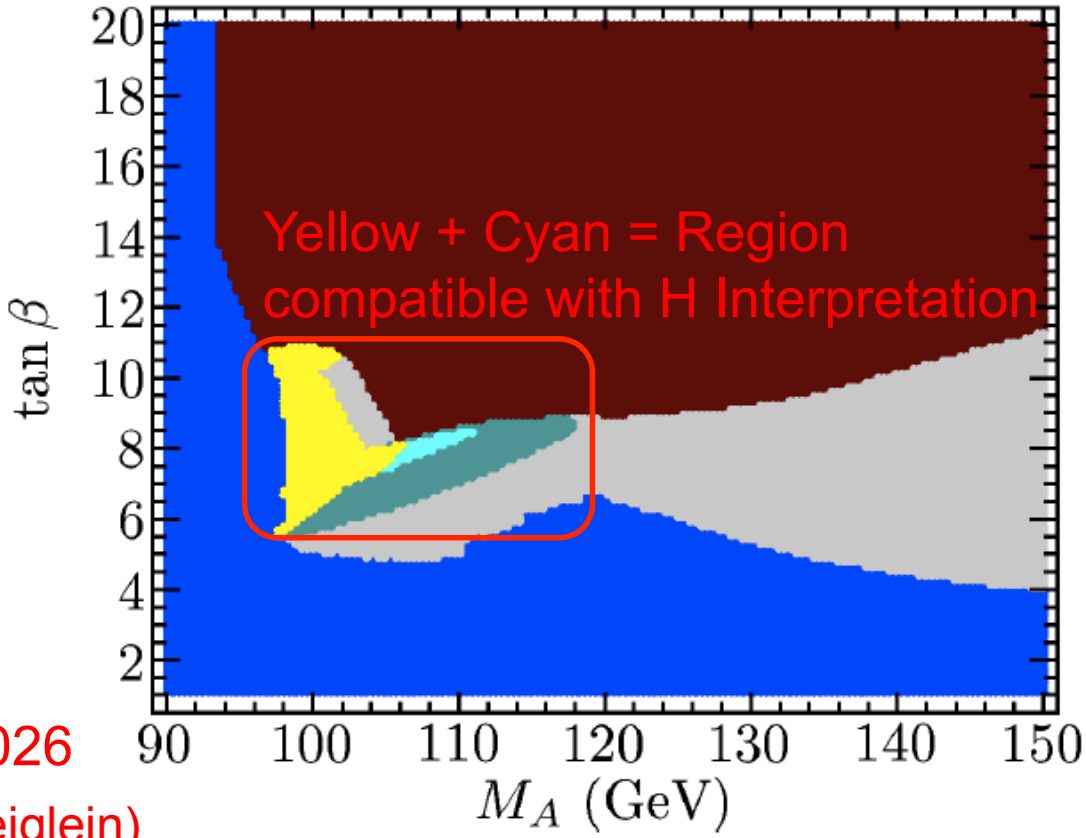


Is it an h, H or A ?

- Pseudo-scalar A does not couple to WW, ZZ

➔ disfavored

- Heavy scalar H possible Interpretation; however, only small region in Parameter space compatible with $\phi \rightarrow \tau^+\tau^-$ Searches at CMS and ATLAS



hep-ph/1112.3026

(S. Heinemeyer, O. Stal, G. Weiglein)

➔ Light scalar h most likely Hypothesis (in my opinion)

Implications of M_h ~ 125 GeV

Decoupling Regime (M_A >> M_Z)

$$M_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]$$

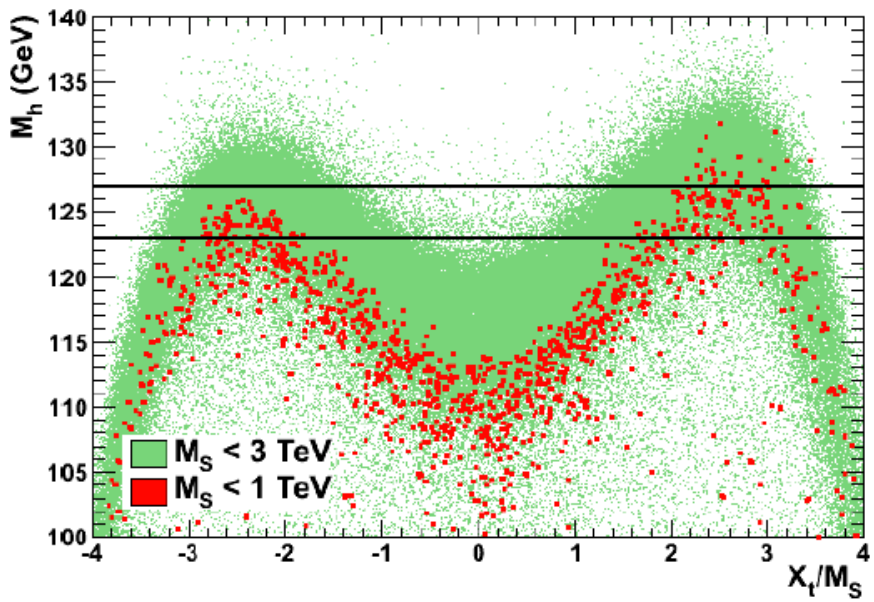
M_h ~ 125 GeV favors:

- large SUSY breaking parameter

$$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

- maximal stop Mixing parameter

$$X_t = A_t - \mu \cot\beta \sim \sqrt{6} M_S$$

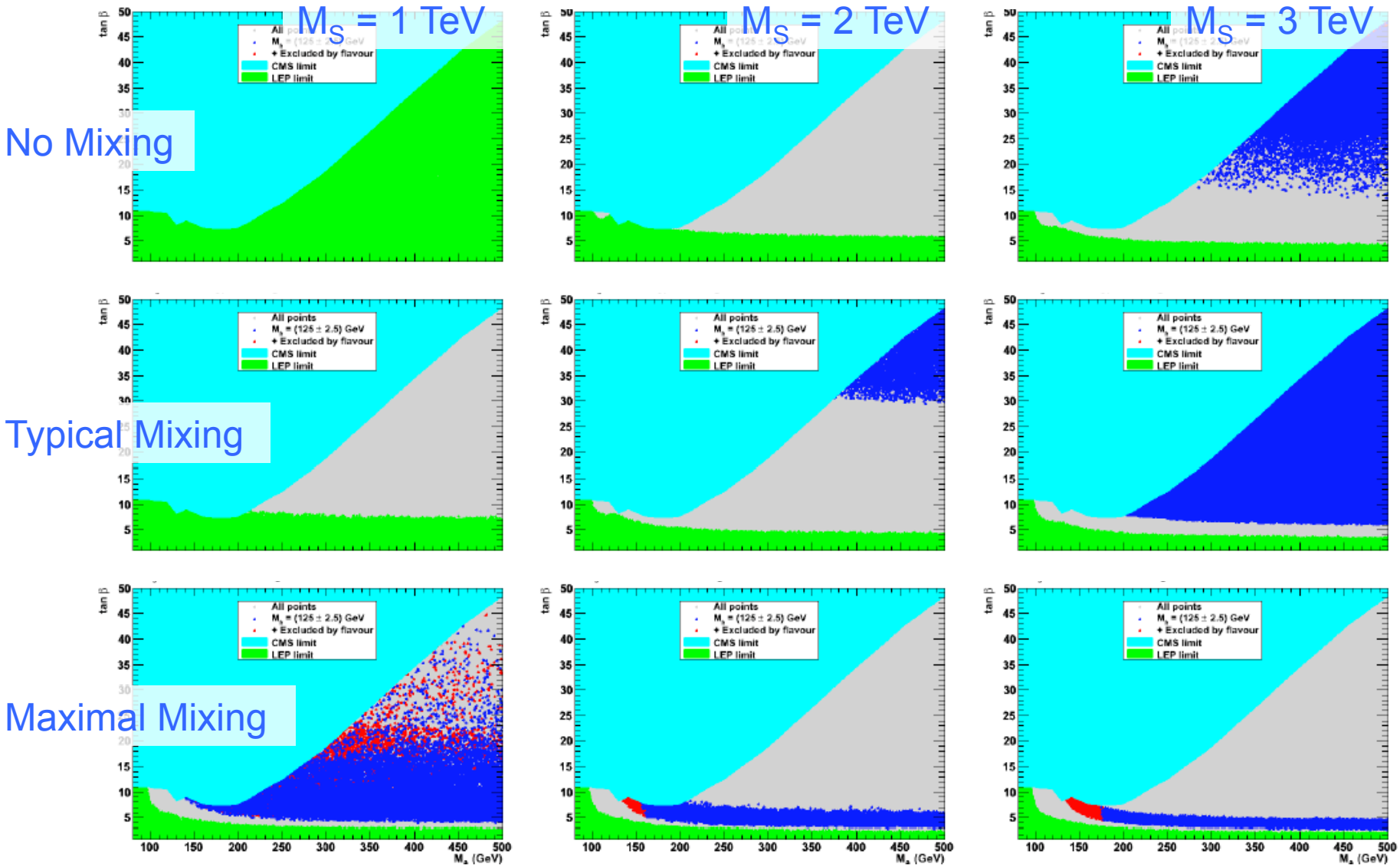


hep-ph/1112.3028

(A. Arbey, M. Battaglia, A. Djouadi. N. Mahmoudi, J. Quevillon)

See also Talk presented by N. Mahmoudi at this Conference

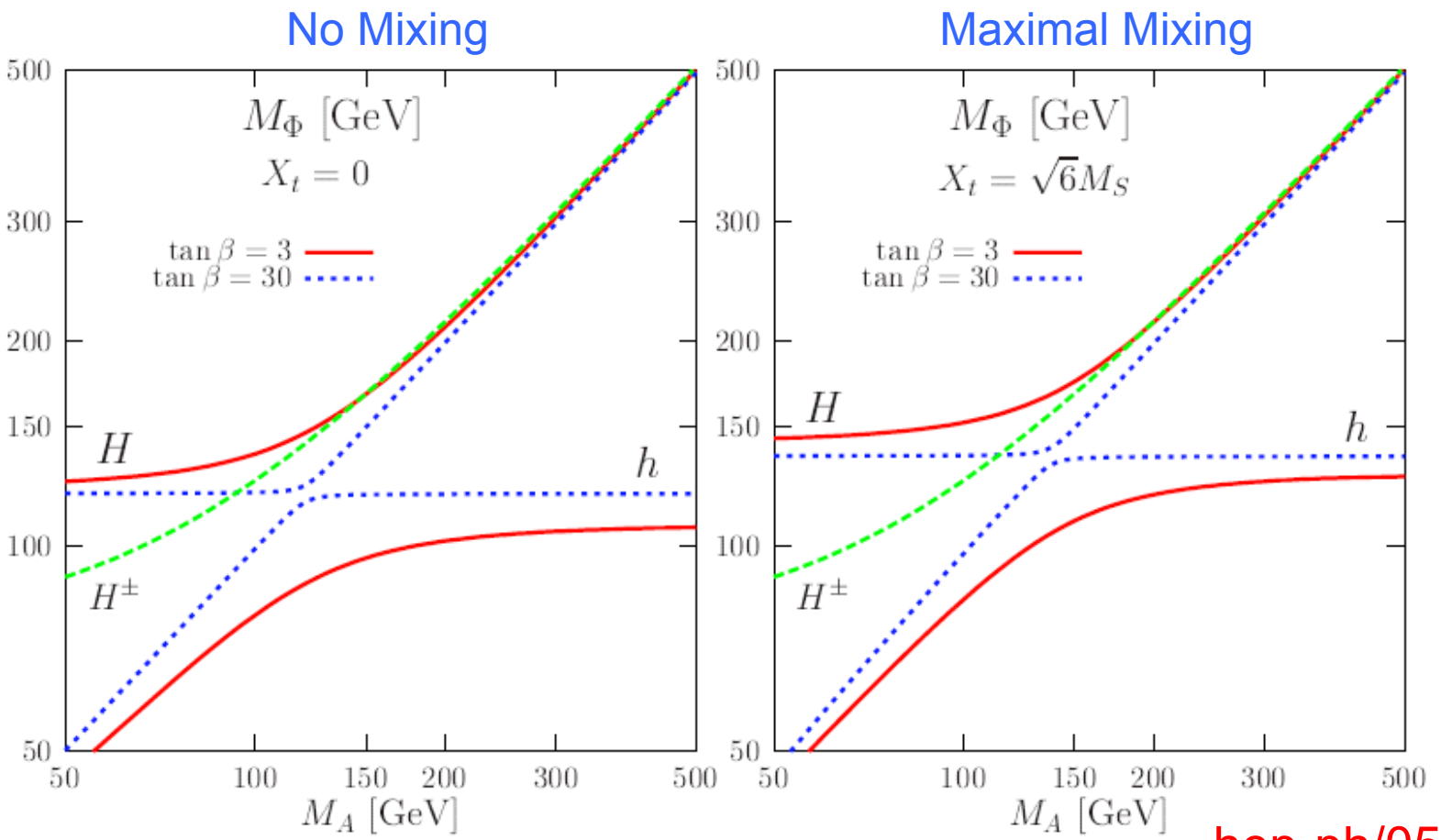
M_h ~ 125 GeV in M_A, tan β Plane



dark blue Points: compatible with M_h ~ 125 GeV, $\phi \rightarrow \tau\tau$, $Bs \rightarrow \mu\mu$, $B \rightarrow \tau\nu$ and $b \rightarrow s\gamma$

http://indico.cern.ch/getFile.py/access?contribId=6&sessionId=1&resId=0&materialId=slides&confId=162621

MSSM Higgs Masses

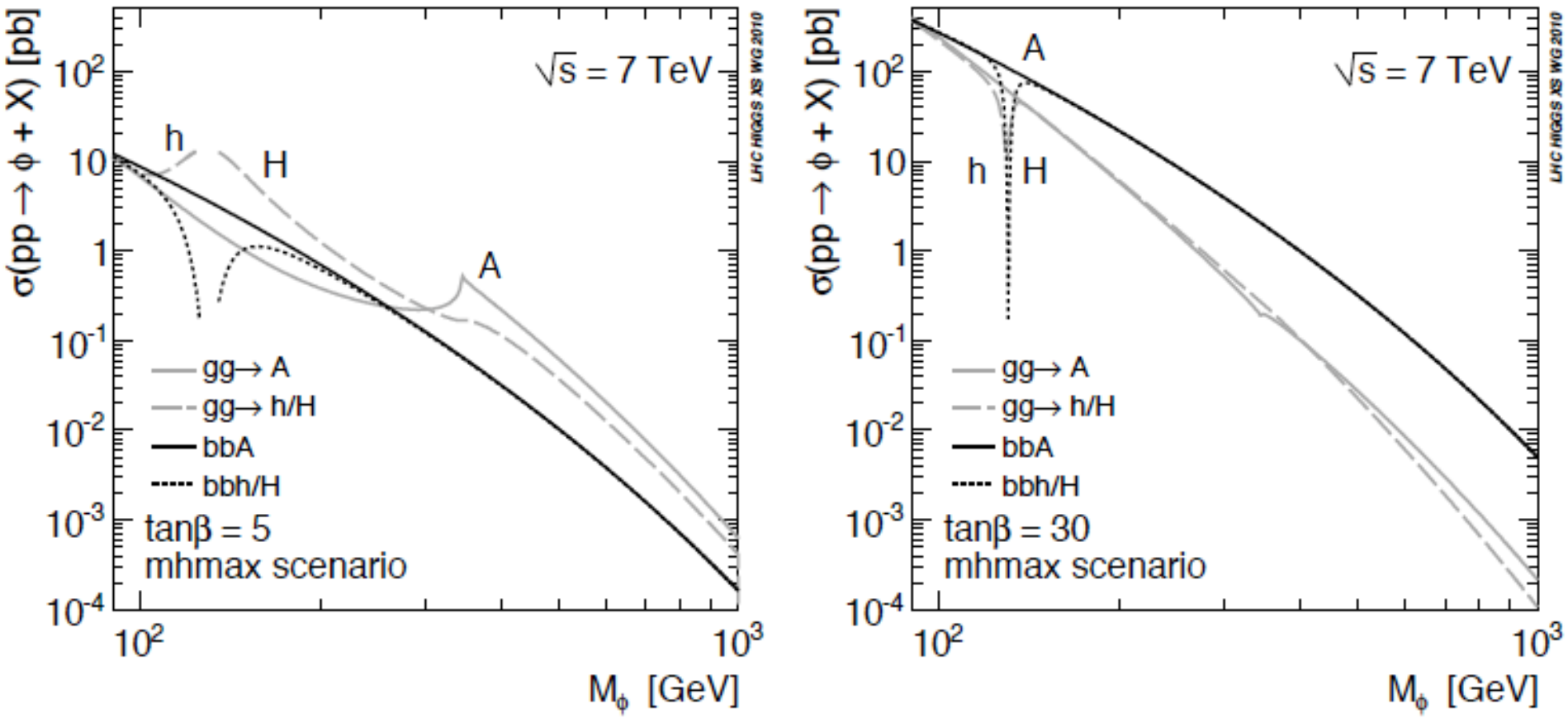


hep-ph/0503173

- for moderate and large tan β pseudo-scalar A is degenerate in Mass with one of scalar MSSM Higgs Bosons (either h or H)
- Mass of light scaler h increases with stop Mixing parameter X_t

Neutral MSSM Higgs Cross-section

hep-ph/11010593



Neutral MSSM Higgs Decay modes

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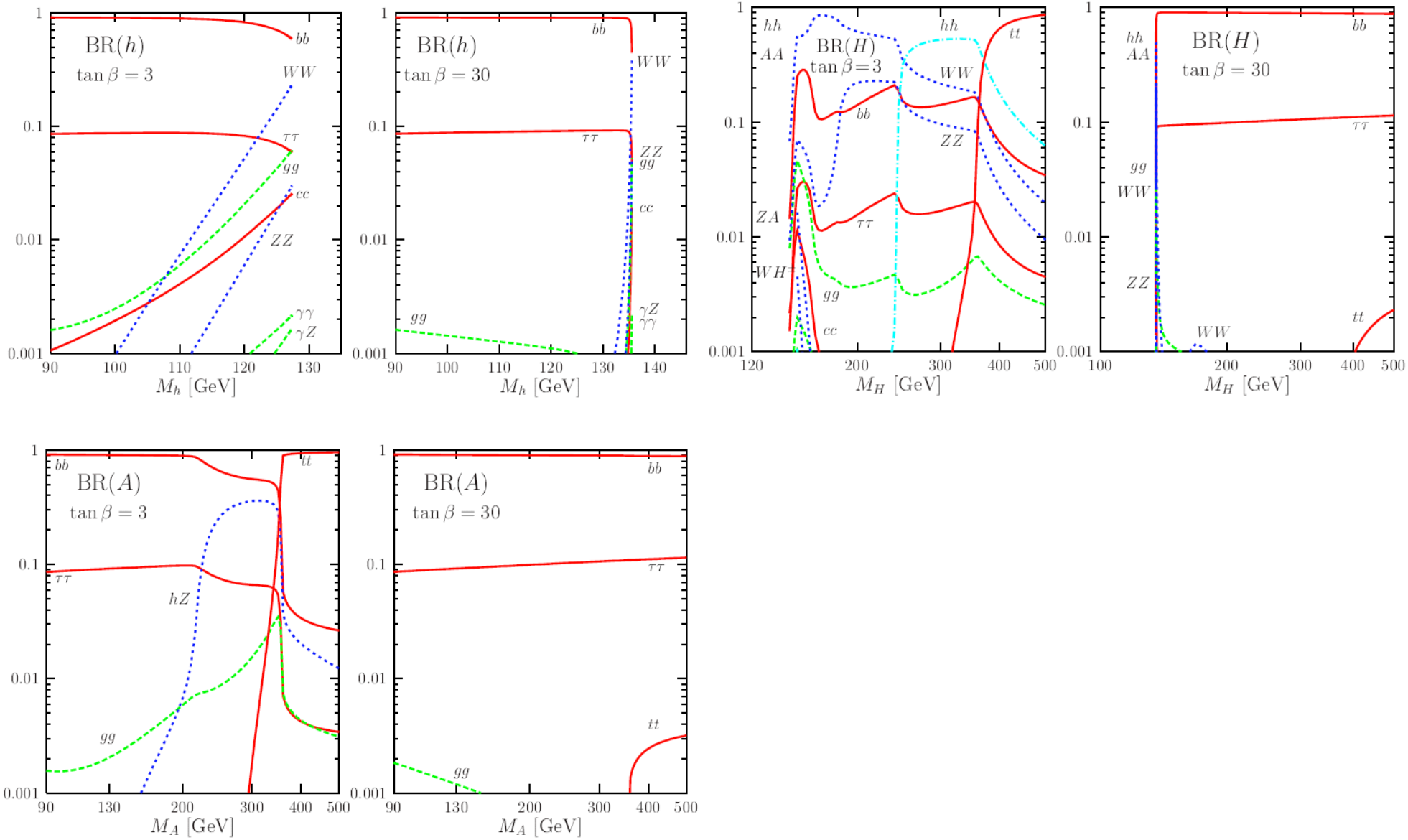
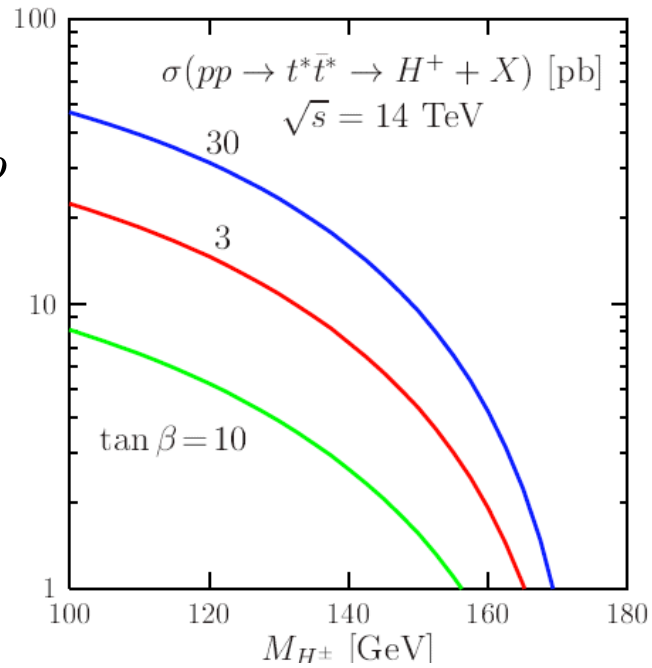


Charged MSSM Higgs Decay modes

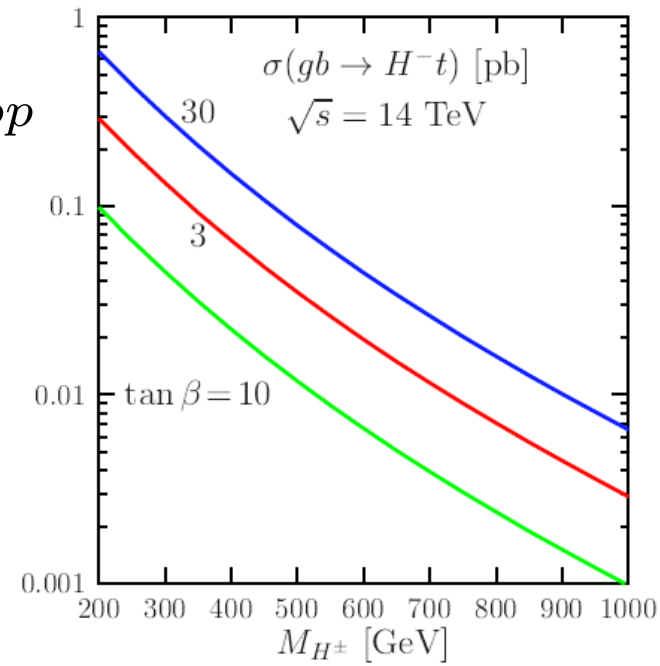
hep-ph/0503173

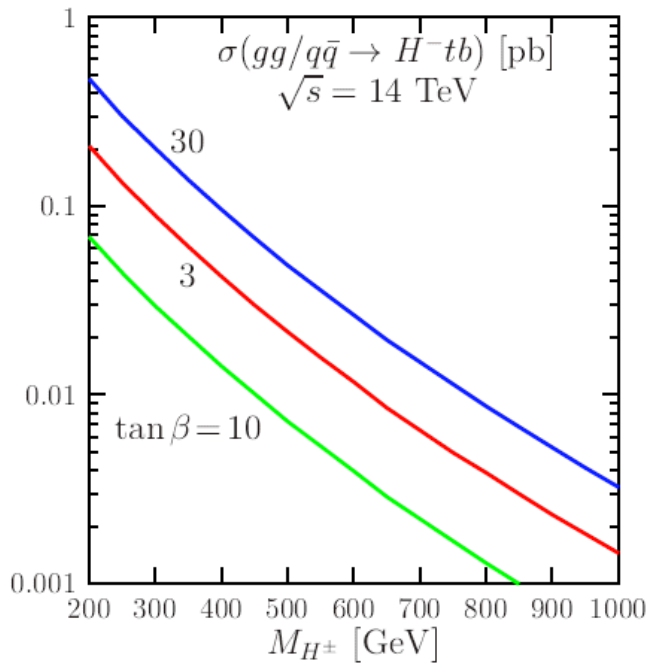
$M_{H^+} \lesssim m_{top}$



NOTE:
Center-of-Mass Energy = 14 TeV

$M_{H^+} \gtrsim m_{top}$





Charged MSSM Higgs Decay modes

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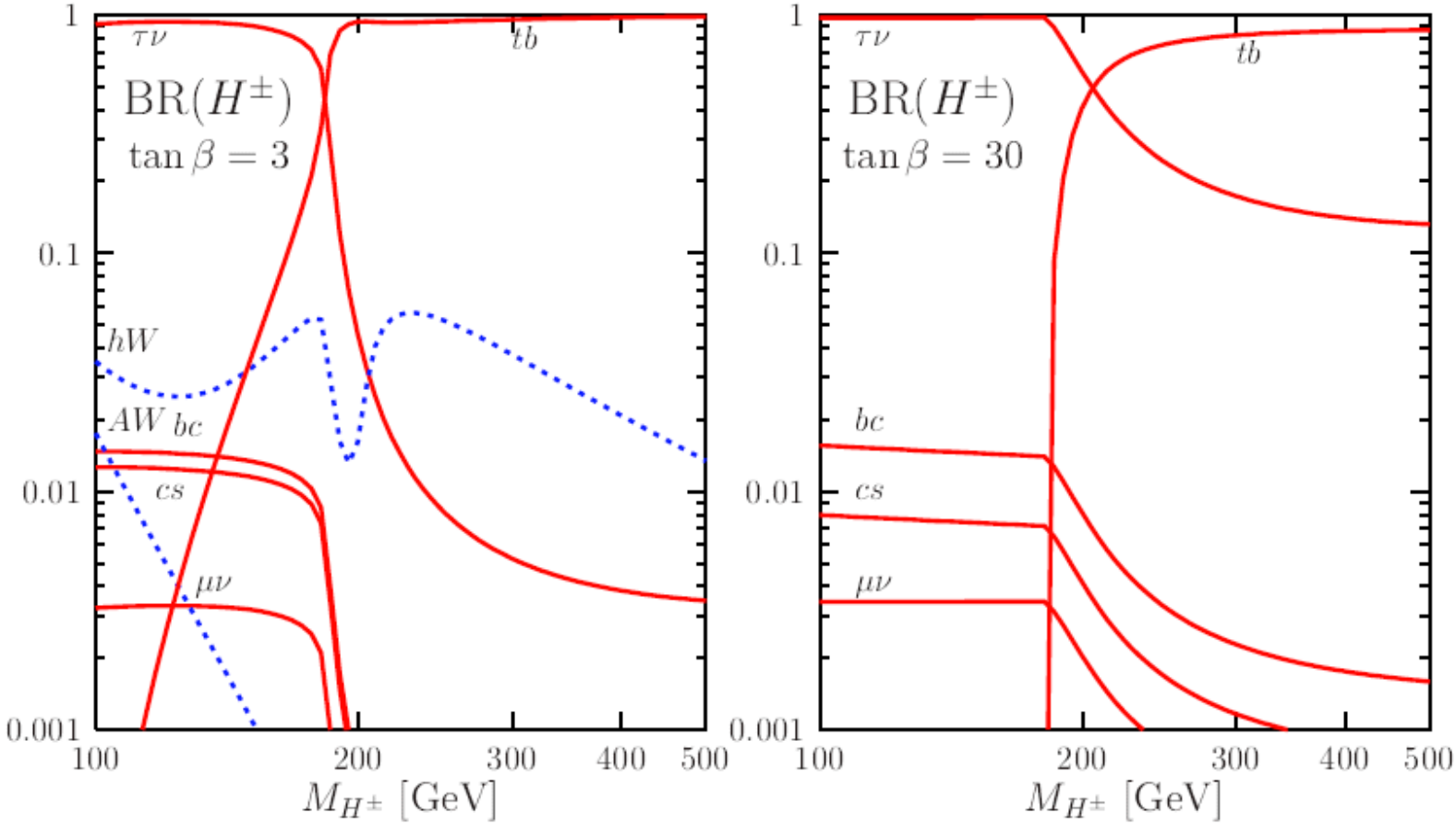
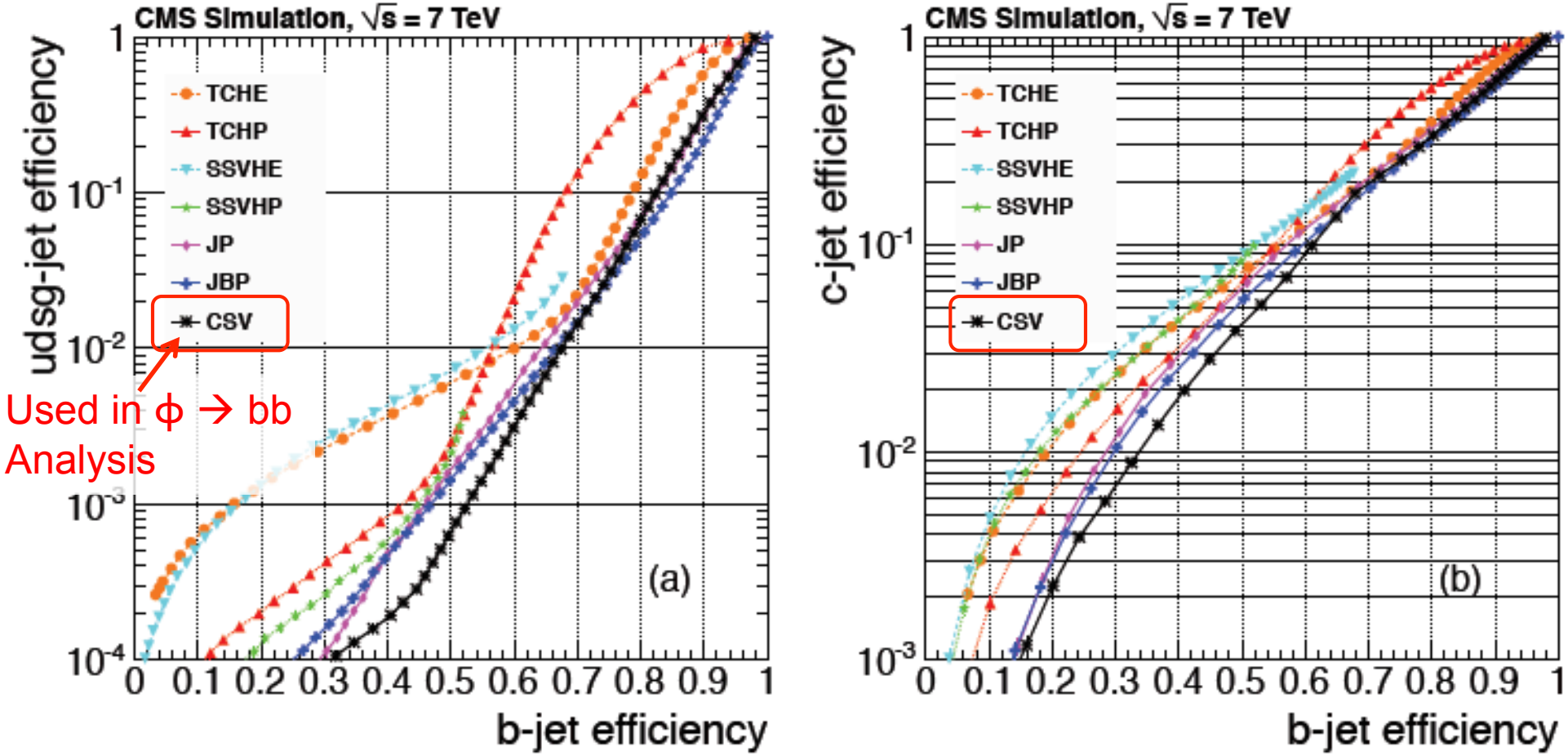


b-Tagging Algorithm

Combined Secondary Vertex (CSV)

- Compute separate Likelihood Ratios for b/c-Quark and b/light-Quark Discrimination
- CSV discriminator = 0.25 • Likelihood(b/c-Quark)
  + 0.75 • Likelihood(b/light-Quark)
- Input Variables used for computing Likelihood:
  - Vertex category (real, “pseudo”, “no vertex”)
  - Flight path Significance $|PV\text{-}SV|/\sigma_{SV\text{-}PV}$
  - Mass of Tracks associated to SV
  - Number of Tracks associated to SV
  - Σ P of Tracks associated to SV/Σ P of all Tracks in Jet
  - Pseudo-rapidities wrt. Jet axis of Tracks associated to Vertex
  - 2d IP Significance of first Track raising Mass above charm Threshold (Tracks are sorted in order of decreasing IP Significance)
  - Number of all Tracks in Jet
  - 3d IP Significances for each Track in Jet

b-Tagging Performance



b-tag Efficiencies and mistag Rates for c-Quarks/light-Quarks + gluons validated in Data

Please see also Poster:
"Identification of b-quark jets in the CMS experiment" (S. Malik)

$\phi \rightarrow bb$ Background Estimation

- Multijet Background estimated from Data, using 3-Jets Events with 2 b-tags, weighted by Probability for 3rd Jet to pass b-tag:

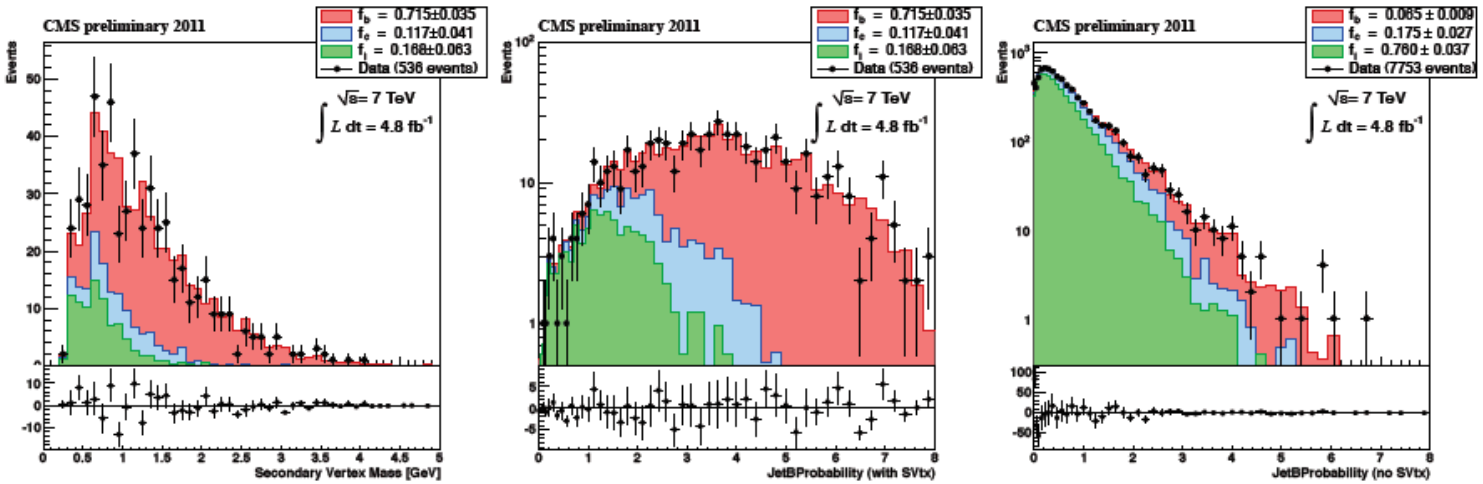
$$F(x;bbb) = F(x;bbj) \times P^{3rd-j}_{b-tag}(j)$$

- Probability for 3rd Jet to pass b-tag parametrized by Jet E_T and η; given by summing Products of Jet flavor fraction f and b-tagging Efficiency/mistag Rate ε for b + c + light Quarks:

$$P^{3rd-j}_{b-tag}(j) = \epsilon_b \cdot f_b + \epsilon_c \cdot f_c + \epsilon_{light} \cdot (1 - f_b - f_c)$$

- Jet flavor fractions f obtained from $\phi \rightarrow bb$ depleted Control region in Data, by fitting:

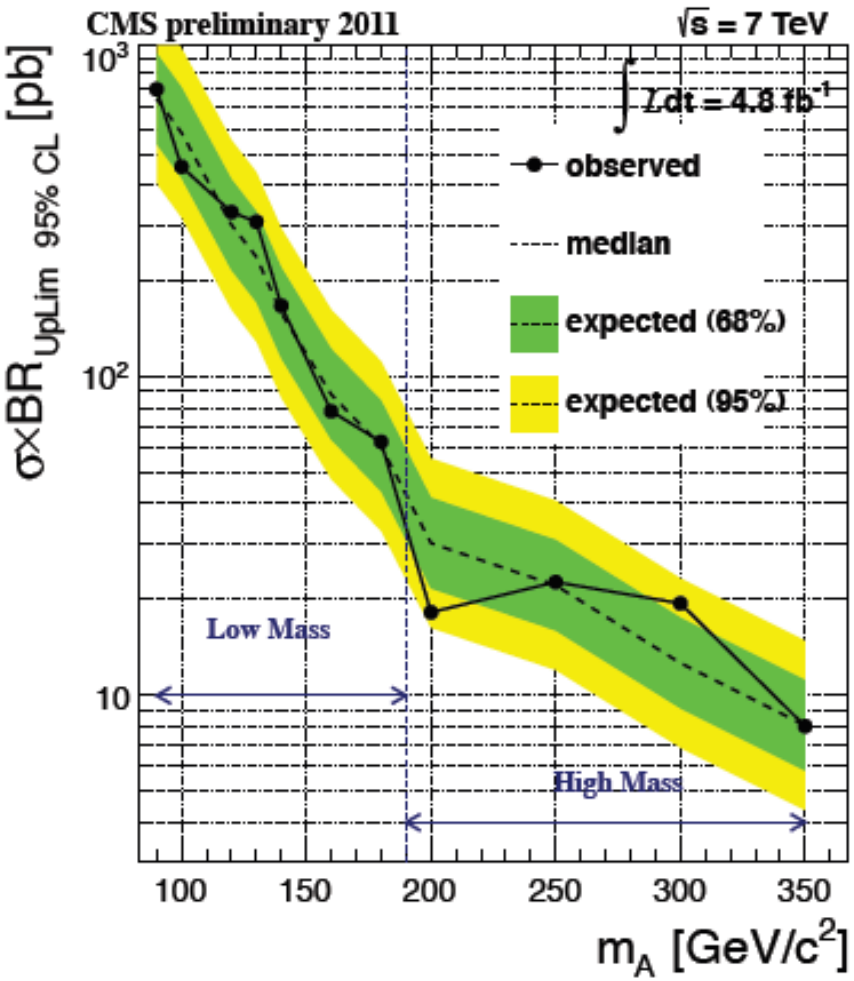
for each Jet E_T, η bin



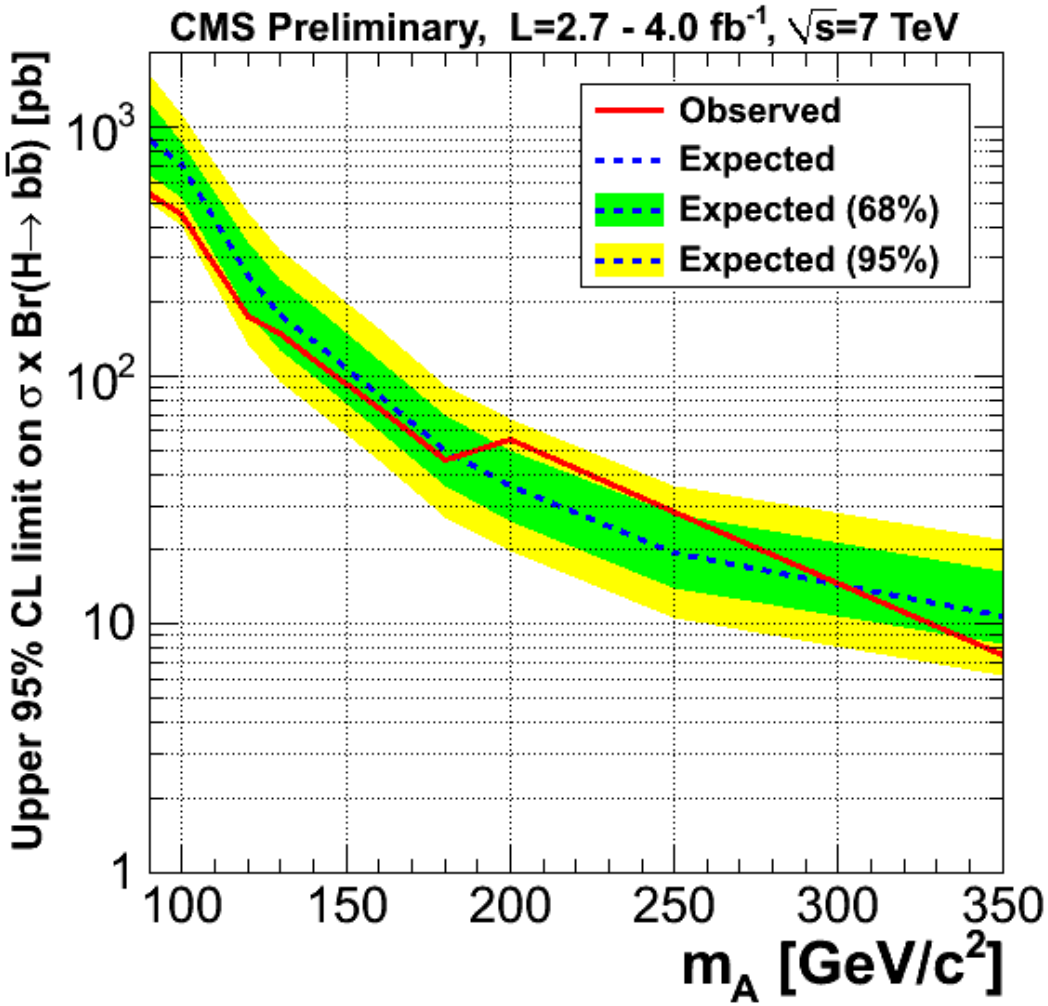
- b-tagging Efficiencies/mistag Rates ε taken from Monte Carlo Simulation (corrected for Data/MC differences)

$\phi \rightarrow bb$ Cross-Section Limits

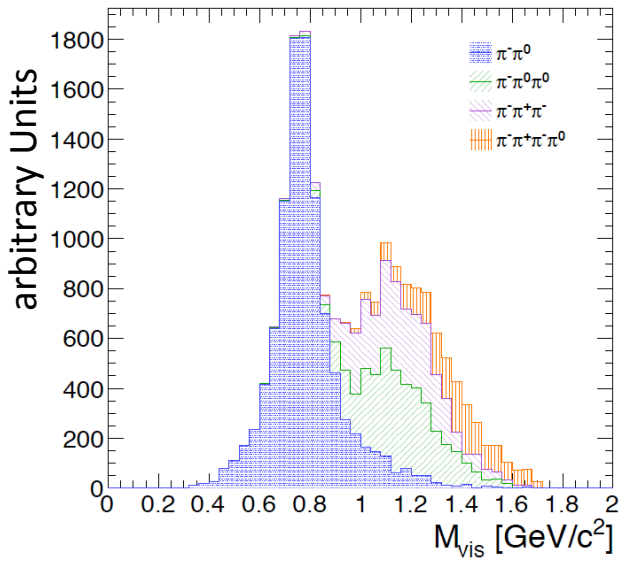
Semileptonic



Hadronic



τ Decay Modes

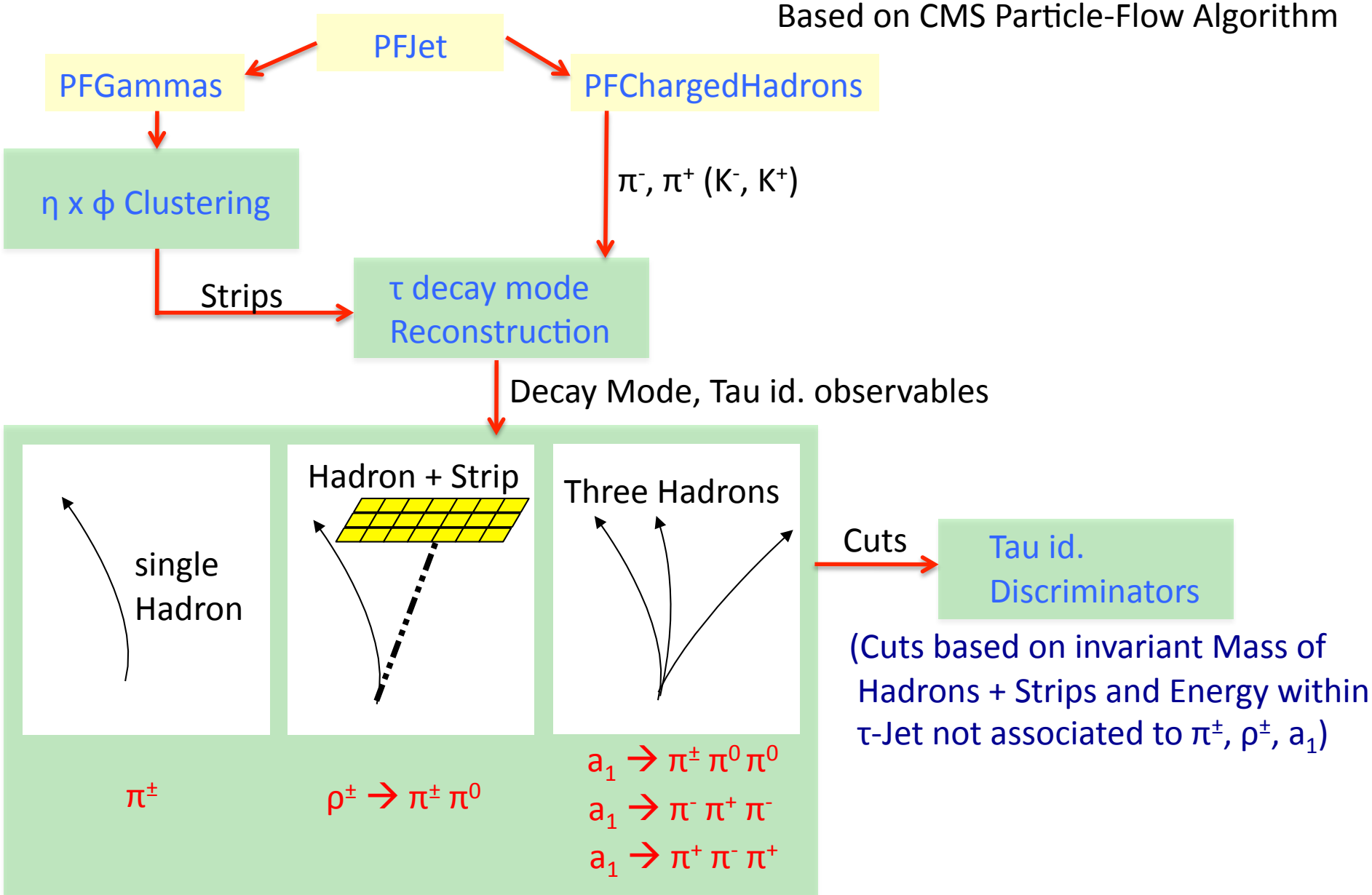


Decay Mode	Resonance	Mass (MeV/c^2)	Branching ratio(%)
$\tau^- \to e^-\bar{\nu}_e\nu_\tau$			17.8 %
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$			17.4 %
$\tau^- \to h^-\nu_\tau$			11.6 %
$\tau^- \to h^-\pi^0\nu_\tau$	ρ	770	26.0 %
$\tau^- \to h^-\pi^0\pi^0\nu_\tau$	$a1$	1200	10.8 %
$\tau^- \to h^-h^+h^-\nu_\tau$	$a1$	1200	9.8 %
$\tau^- \to h^-h^+h^-\pi^0\nu_\tau$			4.8 %
Other hadronic modes			1.7%

Tau Identification ≅ Reconstruction of well-known Vector Meson resonances

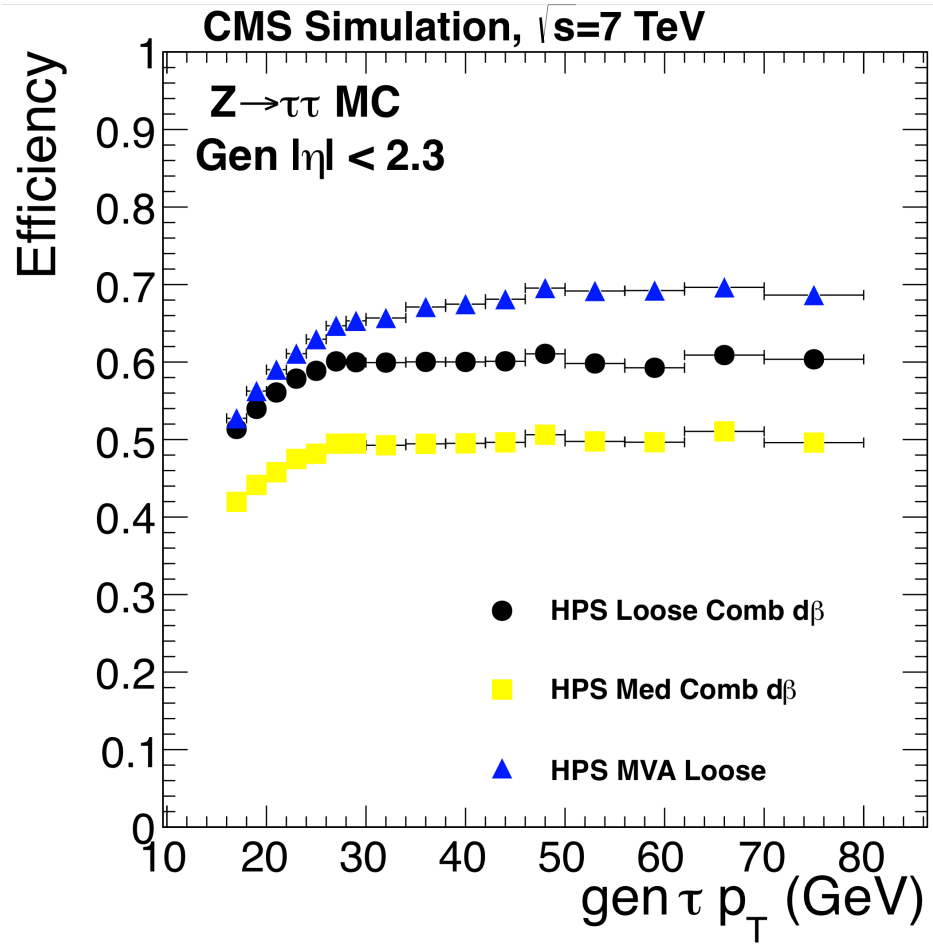
The Hadron + Strips τ Id. Algorithm

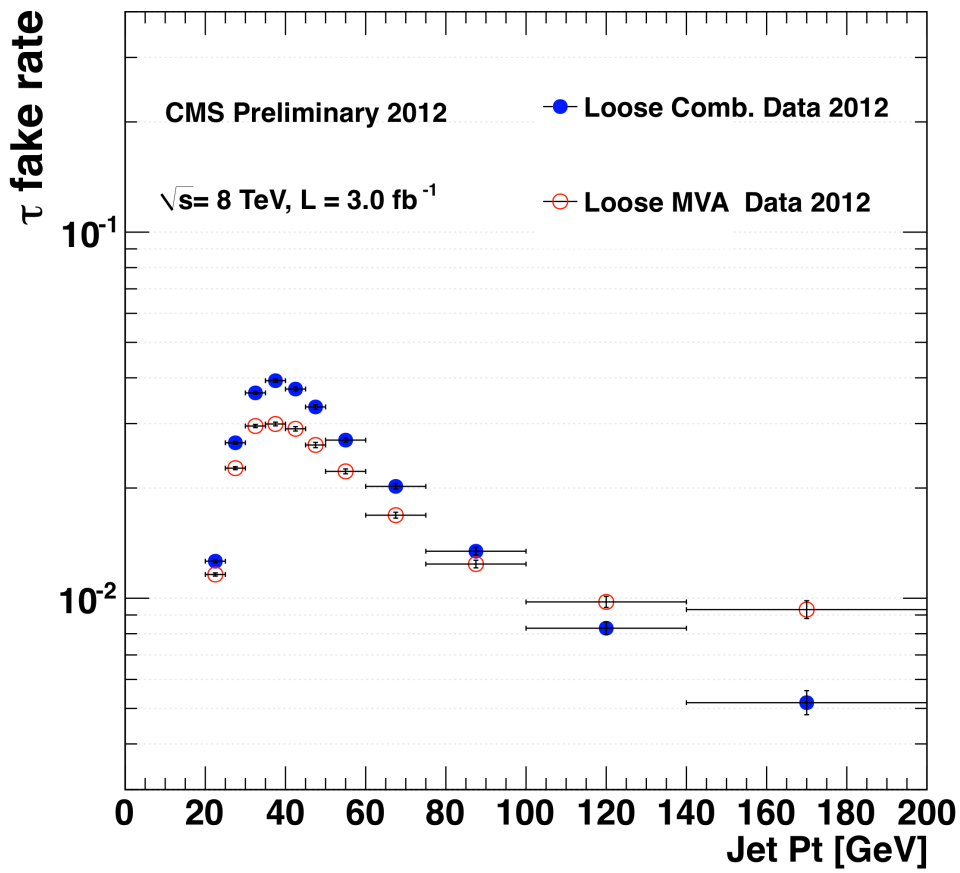
Based on CMS Particle-Flow Algorithm



(Cuts based on invariant Mass of Hadrons + Strips and Energy within τ-Jet not associated to $\pi^{\pm}$, $\rho^{\pm}$, a_1)

CMS τ Id. Performance





Please see also Poster:
"Tau id commissioning results from pp collisions at √s = 7/8 TeV with data collected at CMS" (R. Khurana)

$H^+ \rightarrow \tau\nu$ Background Estimation

τ_{had} + Jets

- Multijet Background estimated from Data, by selecting Events passing all Selection criteria except Tau id. and weighting selected Events by Jet → τ_{had} Fake-rates measured in Control region
- EWK + tt Background with genuine τ_{had}s obtained from Data, by selecting Events with μ instead of τ_{had} and replacing reconstructed Muons by simulated τ Leptons
- (small) EWK + tt Background with fake τ_{had}s (e → τ_{had} + mu → τ_{had}) taken from the Monte Carlo simulation

τ_{had} + e/μ

- (dominant) Multijet Background estimated by Jet → τ_{had} Fake-rate method
- Other backgrounds taken from Monte Carlo simulation

e+μ

- Backgrounds taken from Monte Carlo simulation

$\phi \rightarrow \tau\tau$ Background Estimation

- dominant $Z \rightarrow \tau\tau$ Background estimated by selecting $Z \rightarrow \mu\mu$ Events in Data and replacing reconstructed Muons by simulated τ Leptons
- Multijet Background obtained from same Charge Lepton Pairs
- W+jets Background estimated from Data, by extrapolating Event yield measured in Control region to Signal region
- $Z \rightarrow ee$, $Z \rightarrow \mu\mu$, tt and Diboson backgrounds taken from MC Simulation (corrected for $e \rightarrow \tau_{had}$ Fake-rate measured in Data)

➔ Observed Event yields in no-b-tag and b-tag Categories of $e+\mu$, $e+\tau_{had}$ and $\mu+\tau_{had}$ Channels Agreement with Background Expectation

$H \rightarrow \tau^+\tau^-$ Event Yields

Process	$e+\tau_{had}$ Non b-Tag	$e+\tau_{had}$ b-Tag	$\mu+\tau_{had}$ Non b-Tag	$\mu+\tau_{had}$ b-Tag
$Z \rightarrow \tau\tau$	14259 ± 1037	135 ± 9	29795 ± 2114	259 ± 18
Multijets	6404 ± 301	100 ± 7	6387 ± 115	160 ± 9
W+jets	5432 ± 377	39 ± 3	9563 ± 628	110 ± 9
$Z \rightarrow ll$	6146 ± 502	28 ± 4	924 ± 115	3 ± 1
$t\bar{t}$	47 ± 7	75 ± 11	101 ± 15	145 ± 20
Dibosons	105 ± 22	1 ± 1	217 ± 46	5 ± 2
Total Background	32392 ± 1249	378 ± 17	46987 ± 2211	681 ± 30
$H \rightarrow \tau\tau$	279 ± 29	26 ± 4	502 ± 52	45 ± 6
Data	32051	391	47178	680

M_A = 120 GeV
tan(β) = 20

Process	$e+\mu$ Non b-Tag	$e+\mu$ b-Tag
$Z \rightarrow \tau\tau$	11718 ± 797	112 ± 11
Multijet and W+jets	474 ± 147	15 ± 5
$t\bar{t}$	161 ± 15	289 ± 35
Dibosons	527 ± 84	55 ± 10
Total Background	12881 ± 815	471 ± 38
$H \rightarrow \tau\tau$	161 ± 10	17 ± 1.6
Data	12761	468

M_A = 120 GeV
tan(β) = 20

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Higgs → $\tau^+\tau^-$ Limit

MSSM Higgs	Expected $\tan\beta$ limit					
m_A [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Obs. $\tan\beta$ limit
90	5.19	7.01	8.37	10.6	12.8	12.2
100	6.49	7.45	8.78	10.8	13.4	11.8
120	4.50	6.47	8.09	9.89	12.0	9.84
130	5.37	6.71	7.85	9.69	11.5	9.03
140	5.62	6.63	7.90	9.69	11.6	8.03
160	5.57	6.99	8.51	10.4	12.5	7.11
180	6.75	8.14	9.53	11.3	13.8	7.50
200	7.84	9.12	10.5	12.8	15.0	8.46
250	10.3	12.3	13.9	16.8	19.4	13.8
300	13.5	15.7	18.4	21.4	24.5	20.9
350	17.7	20.1	23.0	26.9	31.1	29.1
400	21.9	24.3	27.9	32.4	37.3	37.3
450	25.0	29.2	33.3	38.8	44.7	45.2
500	30.3	35.7	40.5	47.1	55.0	51.9