Searches for Beyond SM Higgs* at CMS

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*Higgs ≡ Brout-Englert-Higgs scalar boson

Introduction

BSM Physics Scenarios and exit strategies

[Howie Haber, LBNL SUSY Workshop, 2011]

Possible scenarios include:

1. A SM-like Higgs boson is discovered. No evidence for BSM physics is evident.
2. A SM-like Higgs boson is discovered. Separate evidence for BSM physics emerges.
3. A light Higgs-like scalar is discovered, with properties that deviate from the SM.
4. A very heavy scalar state is discovered.
5. No Higgs boson candidate is discovered, and the entire mass range for a SM-like Higgs boson below 1 TeV is excluded.

In the last three cases, theoretical consistency implies that BSM physics must exist at the TeV energy scale that is observable at the LHC (with sufficient luminosity). Cases 4 and 5 would likely be incompatible with TeV-scale supersymmetry, whereas cases 2 and 3 would strongly encourage supersymmetric enthusiasts.

Case 1 would strongly cast doubts on the principle of naturalness. Nevertheless, is it still Possible to learn about physics at higher mass scales?

Outline

- Flavour constraints/physics from CMS

  CMS PAPER BPH-11-020

  $B_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

- MSSM Higgs searches

  - MSSM Charged Higgs $t \to H^+b$

    CMS PAS -HIG-11-019

  - MSSM Neutral Higgs $pp \to \Phi X ; \Phi = h, H, A$

    CMS PAS -HIG-11-029

- Double Charged Higgs searches $\Phi^{++} \to l^+l^+$

  CMS PAS -HIG-12-005

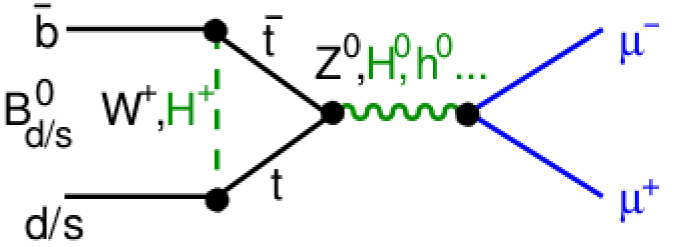
- NMSSM light pseudoscalar Higgs $a \to \mu^+\mu^-$

  CMS PAS -HIG-12-004

- Personal remarks and Summary

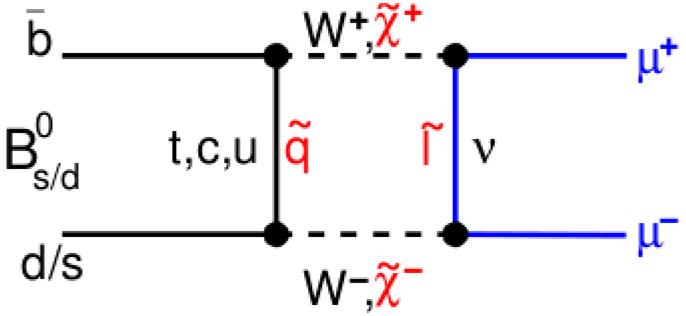
Flavour Physics from CMS

Why search for $B_{s,d} \to \mu^+\mu^-$?



Decays highly suppressed in SM (Buras 2010)

- Forbidden at tree level
- b → s(d) FCNC transition only through Penguin or box
- Helicity suppressed by factors of $(m_\mu/m_B)^2$



Standard Model expectations

$$\begin{aligned}
\mathcal{B}(B^0_s \to \mu^+\mu^-) &= (3.2 \pm 0.2) \times 10^{-9} \\
\mathcal{B}(B^0 \to \mu^+\mu^-) &= (1.0 \pm 0.1) \times 10^{-10}
\end{aligned}$$

Sensitivity to new physics

- 2HDM, MSSM
- sensitivity to extended Higgs boson sector
- provide constraints on parameter space

State of art - previous constraints

- At the Tevatron

Upper limit	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$
D0[1]	5.1×10^{-8}	n/a
CDF[2]	4.0×10^{-8}	6.0×10^{-9}

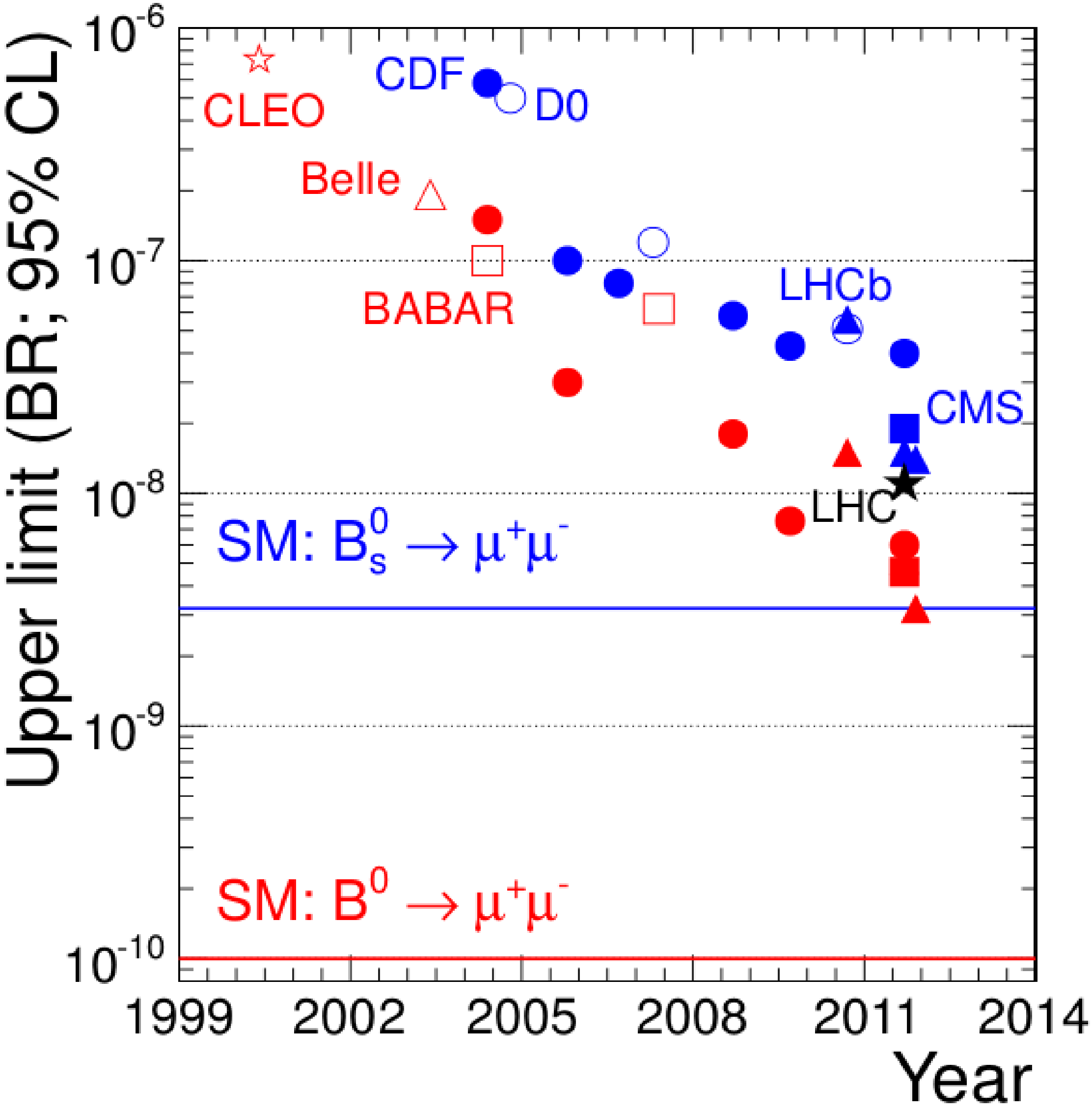
[1] 6.1 fb^{-1}, PL, B693, 539
[2] 7 fb^{-1}, PRL, 107, 191801

- At the LHC:

Upper limit	$B_s^0 \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$
CMS[3]	1.9×10^{-8}	3.6×10^{-9}
LHCb[4]	1.4×10^{-8}	3.2×10^{-9}
CMS + LHCb	1.1×10^{-8}	n/a

[3] 1.1 fb^{-1}, PRL, 107, 191802
[4] 0.4 fb^{-1}, PL, B708, 55

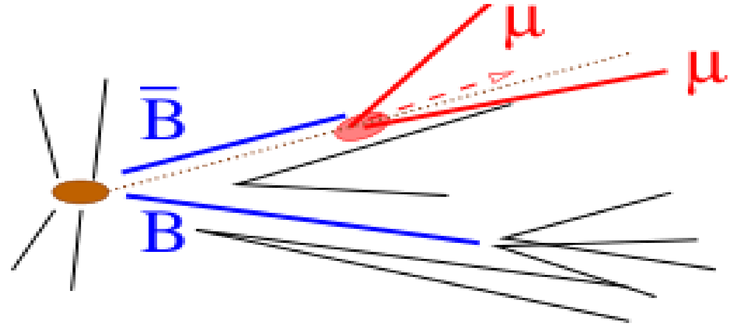
(all upper limits at 95%CL)



- CDF[2] also has $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$

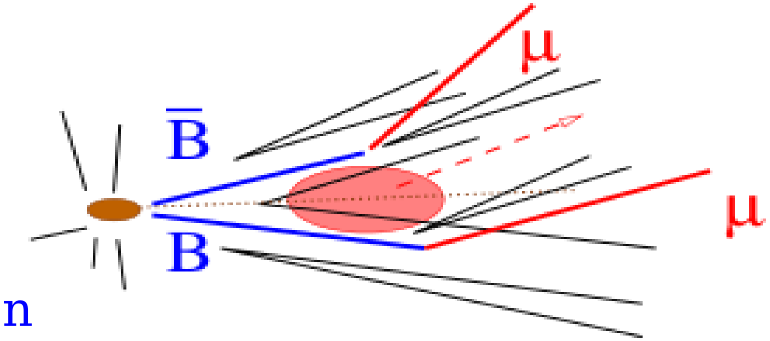
Event characteristics

Signal characteristics:



- Two muons from a single decay vertex
- Mass compatible with B_s (or B^0)
- Well reconstructed secondary vertex
- Momentum aligned with flight direction

Background sources:



- Two semi-leptonic B decays (gluon splitting)
- One semi-leptonic B decay + misidentified hadron
- Rare B decays
  - peaking background $B_s^0 \to K^+K^-$
  - non-preaking bkg $B_s^0 \to K^-\mu^+\nu$
- Combinatorial bkg : Evaluated from data in $m_{\mu\mu}$ sideband
- Validation/Calibration of MC: $B^{\pm} \to J/\psi K^{\pm}, B_s^0 \to J/\psi\phi \to \mu^+\mu^-K^+K^-$

Key ingredients: Good di-muon vertex, correct B mass assignment, pointing angle

Signal selection (before unblinding of signal window)

Mass window requirement:

- Resolution : 36 (70) MeV in barrel (endcap)
- 5.3-5.45 (5.2 – 5.3) GeV for $B_s (B^0)$ signal

Selection cuts differentiated:

- barrel ($|\eta| < 1.4$) & endcap regions

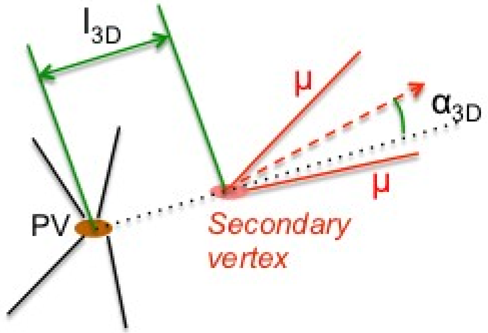
Single muon and B candidate selection:

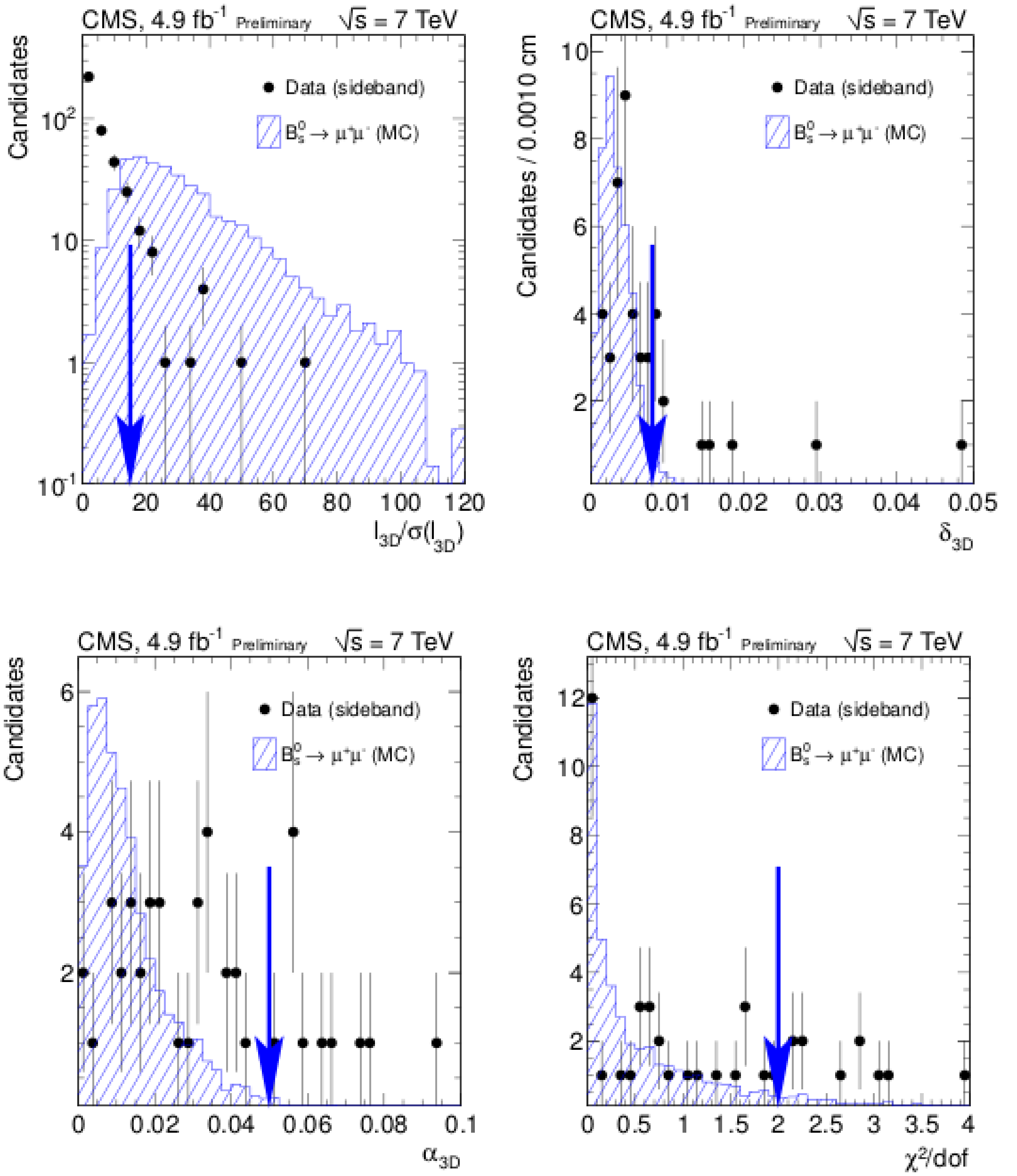
-$p_T(\mu) > 4.0$ GeV, $p_T(B) > 6.5$ GeV

Primary vertex consistent with p(B) dir.

Discriminating variables:

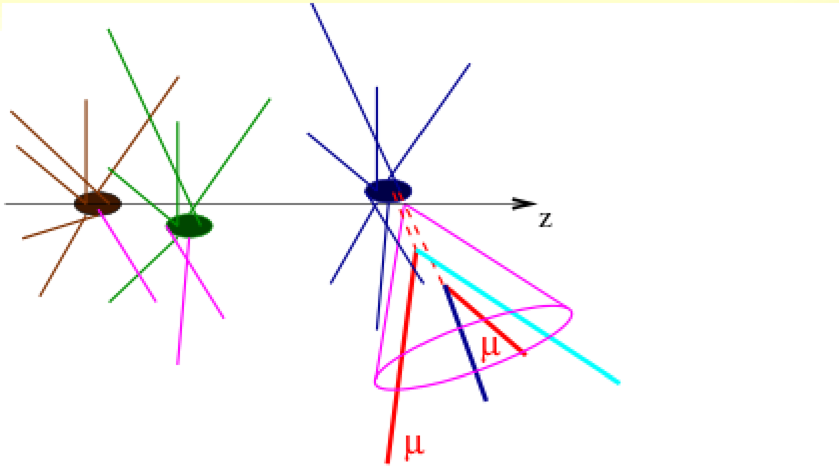
- flight length significance $l_{3d}/\sigma(l_{3d}) > 15$ (20)
- 3D impact param δ_{3d} and significance
- pointing angle $\alpha_{3D} < 50$ (25)mrad
- B vertex fit quality $\chi 2$/dof < 1.6



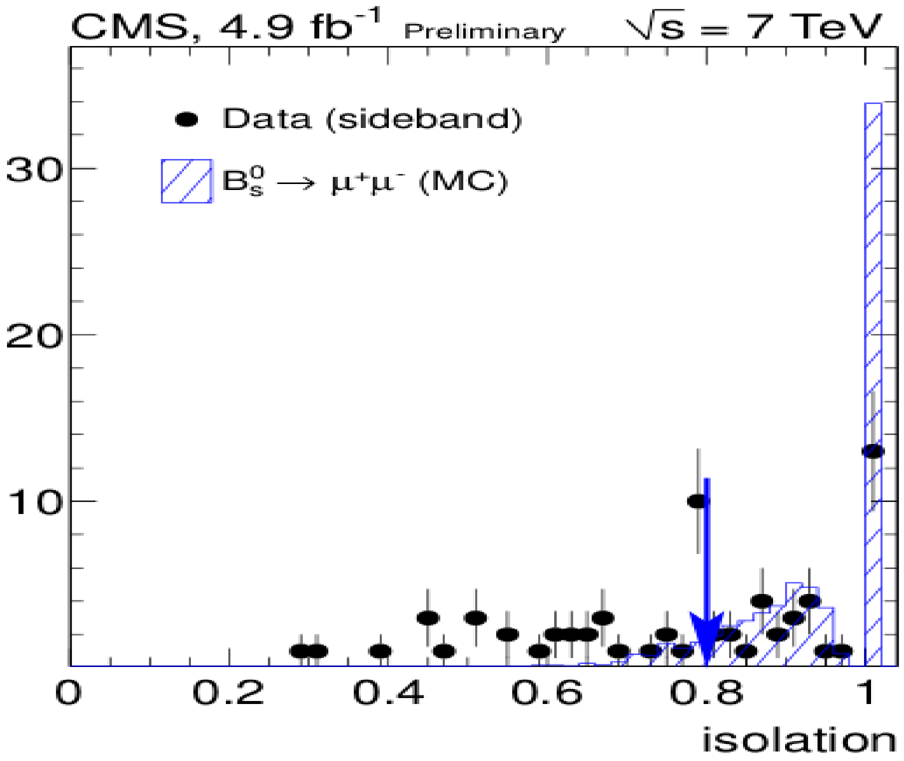


Side band region (GeV): 4.9 – 5.2 and 5.45 – 5.9

Signal selection : isolation



$$I = \frac{p_\perp(\mu^+\mu^-)}{p_\perp(\mu^+\mu^-) + \sum\limits_{\Delta R<0.7} p_\perp}$$



Relative isolation of muon pairs

- Cone with △R < 0.7
- Include all tracks with p_T > 0.9 GeV from same PV

B vertex isolation:

- based on tracks reconstructed in the proximity of the secondary B vertex
- avoid PU dependence (tracks associated to no PV)
- distance of closest track to B vertex < 300 microns

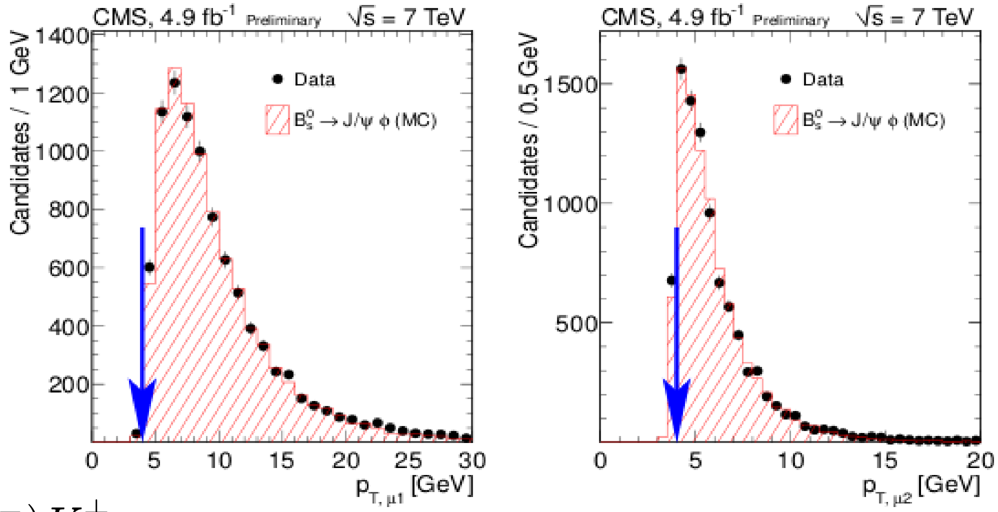
Validate in $B_s^0 \to J/\psi\phi$ MC

Validation and normalization

Validation of simulation is performed with two exclusive decay modes

a) Validation of B^+ MC (Normalization sample see next): $B^+ \to J/\psi(\mu^+\mu^-)K^+$

b) Validation of B^0_s signal MC (control sample): $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$



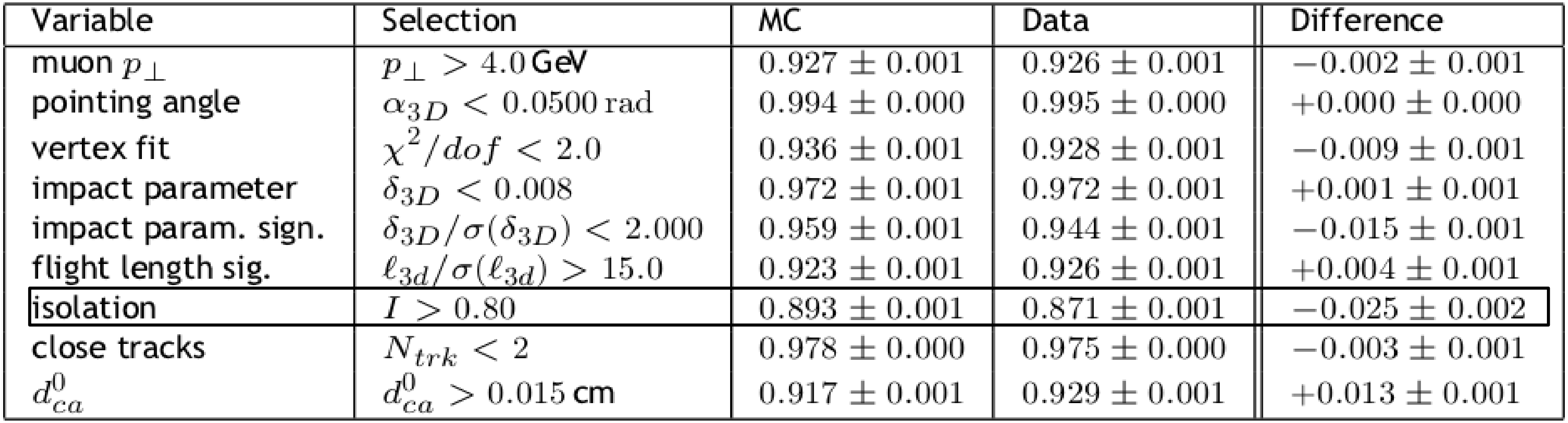
Good agreement with simulation after sideband subtraction

- Residual differences as systematics

Systematic Uncert added in quad:

- For a) : 4% (largest isolation)
- For b) : 3%

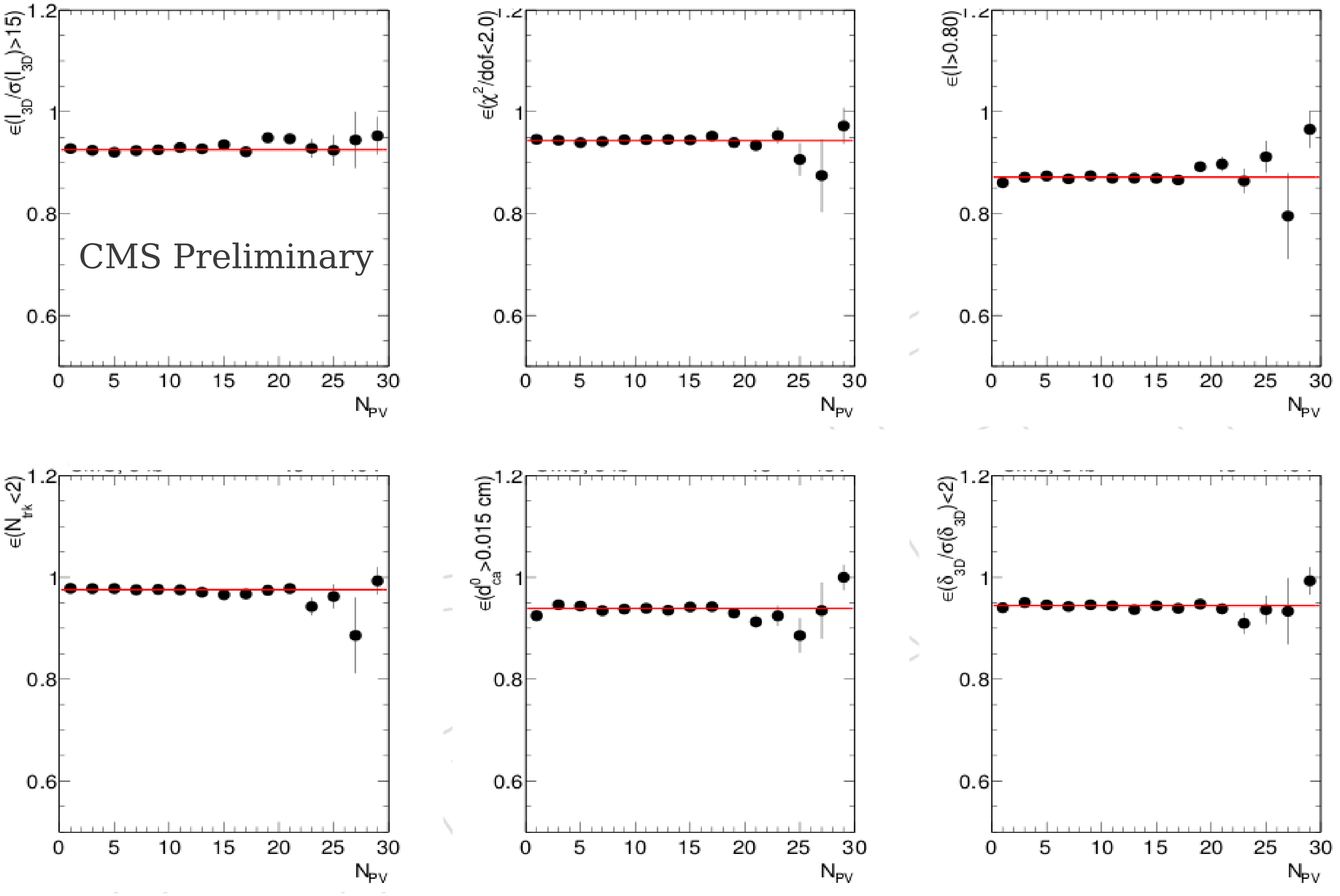
$B^+ \to J/\psi(\mu^+\mu^-)K^+$



Variable	Selection	MC	Data	Difference
muon $p_\perp$	$p_\perp > 4.0$ GeV	0.927 ± 0.001	0.926 ± 0.001	-0.002 ± 0.001
pointing angle	$\alpha_{3D} < 0.0500\,\mathrm{rad}$	0.994 ± 0.000	0.995 ± 0.000	$+0.000 \pm 0.000$
vertex fit	$\chi^2/dof < 2.0$	0.936 ± 0.001	0.928 ± 0.001	-0.009 ± 0.001
impact parameter	$\delta_{3D} < 0.008$	0.972 ± 0.001	0.972 ± 0.001	$+0.001 \pm 0.001$
impact param. sign.	$\delta_{3D}/\sigma(\delta_{3D}) < 2.000$	0.959 ± 0.001	0.944 ± 0.001	-0.015 ± 0.001
flight length sig.	$\ell_{3d}/\sigma(\ell_{3d}) > 15.0$	0.923 ± 0.001	0.926 ± 0.001	$+0.004 \pm 0.001$
isolation	$I > 0.80$	0.893 ± 0.001	0.871 ± 0.001	-0.025 ± 0.002
close tracks	$N_{trk} < 2$	0.978 ± 0.000	0.975 ± 0.000	-0.003 ± 0.001
d^0_{ca}	$d^0_{ca} > 0.015$ cm	0.917 ± 0.001	0.929 ± 0.001	$+0.013 \pm 0.001$

Pileup (in)dependence

Selection efficiency Vs N_{PV} in data: $B^+ \to J/\psi(\mu^+\mu^-)K^+$



No pileup dependence observed.

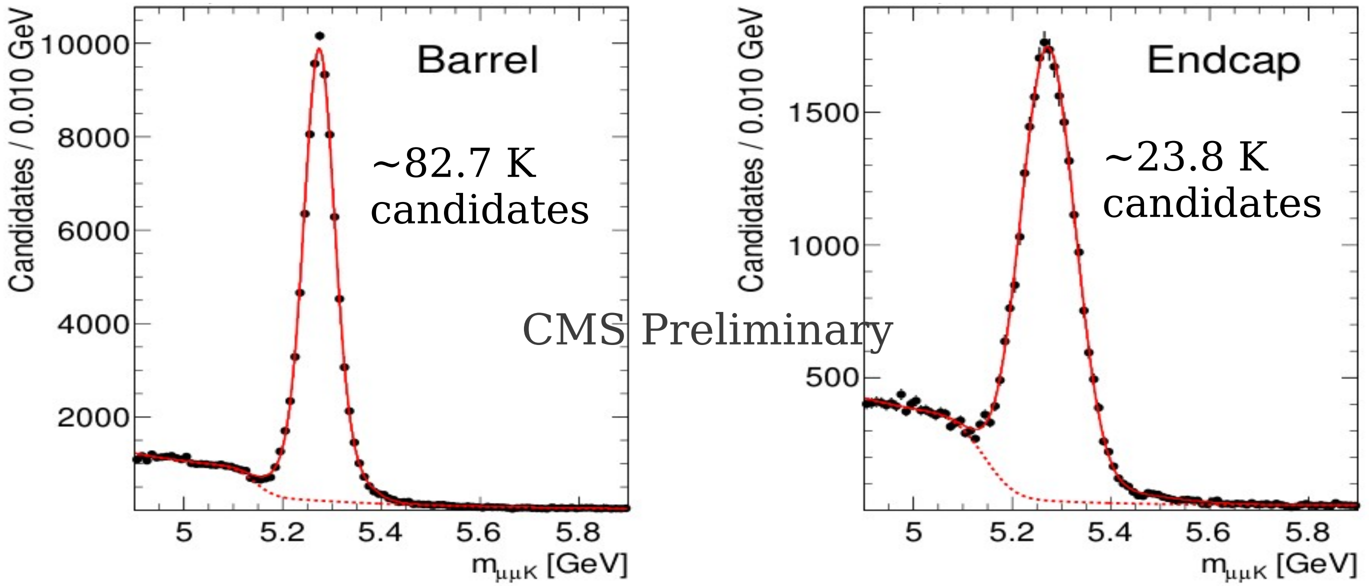
Branching Ratios

Branching ratios are measured separated in barrel and endcap

- Many of the systematic uncertainties cancel in the ratio
- No need for absolute luminosity and b-quark cross section
- Large B^+ yield and well known branching ratio (3% uncert.)
- Ratio of fragmentation f_u/f_s is from PDG (13% uncert.)

From PDG

$$\mathrm{Br}(B_s \to \mu^+\mu^-) = \frac{N(B_s \to \mu^+\mu^-)}{\boxed{N(B^+ \to J/\psi K^+)}} \boxed{\frac{f_u}{f_s}} \frac{\epsilon_{\mathrm{tot}}^{B^+}}{\epsilon_{\mathrm{tot}}^{B_s}} \mathrm{Br}(B^+ \to J/\psi K^+)$$



Background estimates

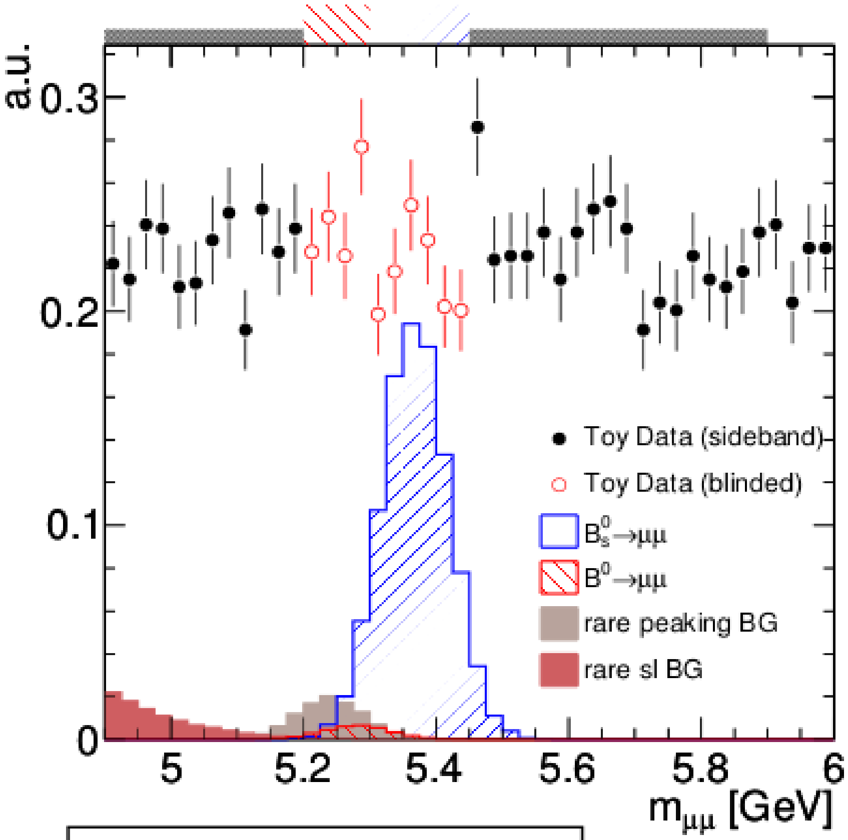
Combinatorial background:

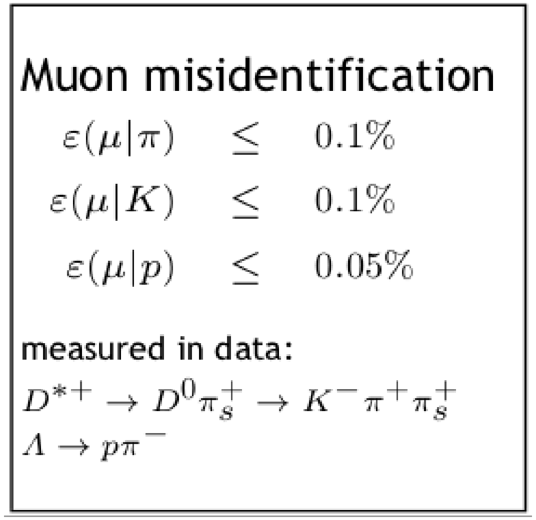
- Measured in data from B mass sidebands
- Interpolate to SR under flat-shape assumption

Preaking background:

- B → hh background with two muons with misidentified hadrons
- Measure the mid-ID rate in data
- Apply to MC bkg sample with mis-ID probability

Non-peaking CKM suppressed background from simulations (mostly at low masses)




Muon misidentification

$$\varepsilon(\mu|\pi) \leq 0.1\%$$

$$\varepsilon(\mu|K) \leq 0.1\%$$

$$\varepsilon(\mu|p) \leq 0.05\%$$

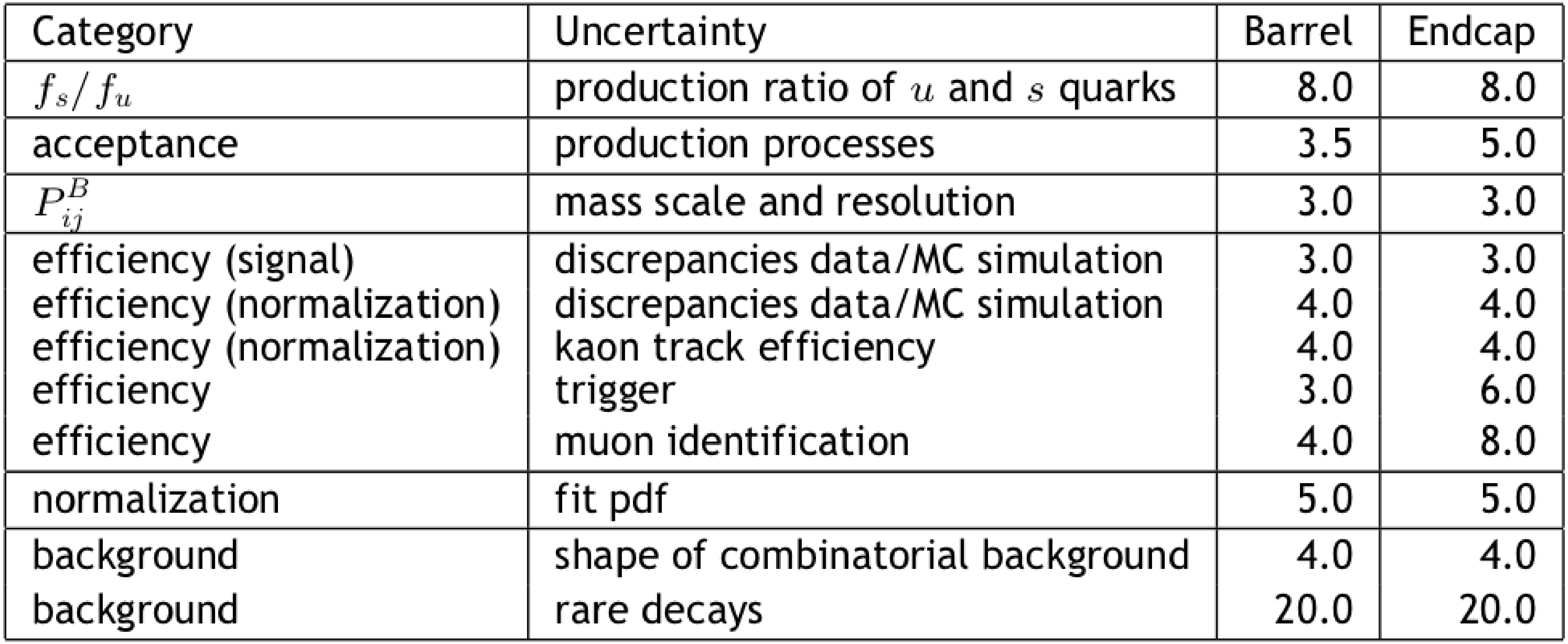
measured in data:

$D^{*+} \to D^0\pi_s^+ \to K^-\pi^+\pi_s^+$

$\Lambda \to p\pi^-$

Systematic uncertainties

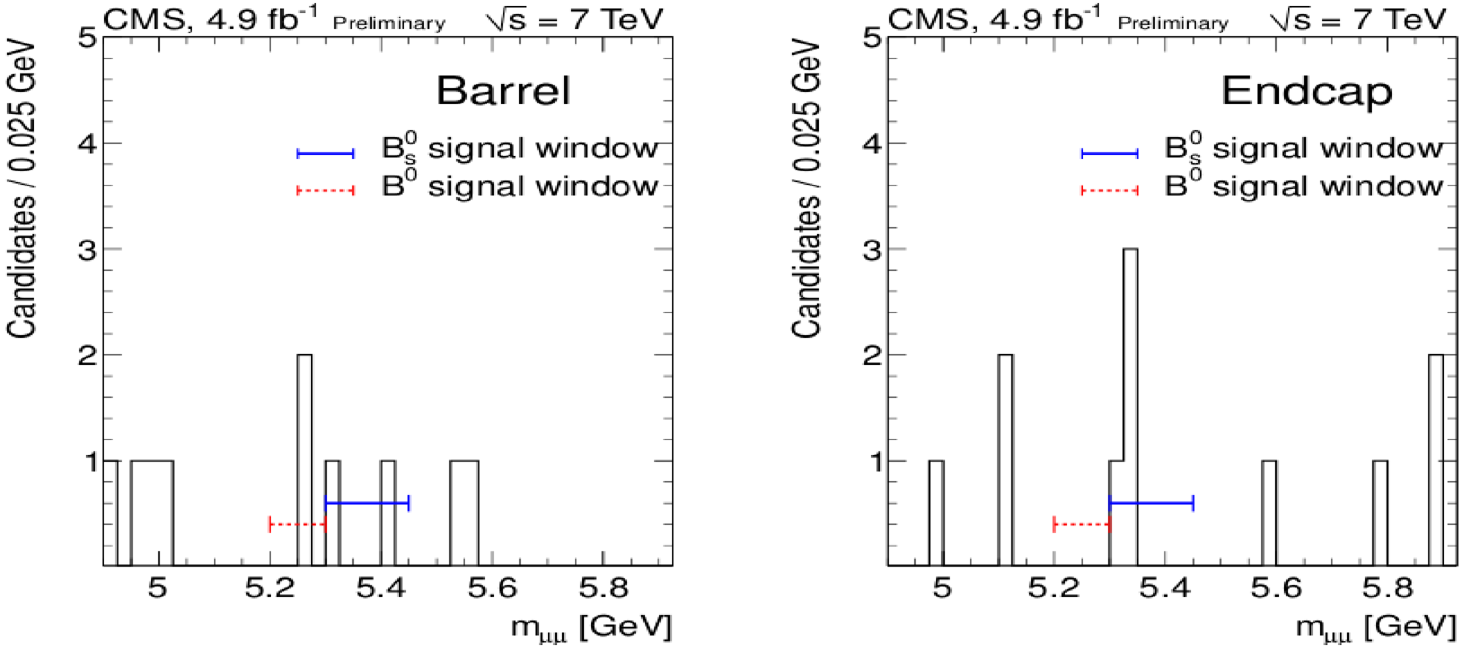
Systematic uncertainties propagated into upper limit calculation
(Errors are in %)



Category	Uncertainty	Barrel	Endcap
f_s/f_u	production ratio of u and s quarks	8.0	8.0
acceptance	production processes	3.5	5.0
P_{ij}^B	mass scale and resolution	3.0	3.0
efficiency (signal)	discrepancies data/MC simulation	3.0	3.0
efficiency (normalization)	discrepancies data/MC simulation	4.0	4.0
efficiency (normalization)	kaon track efficiency	4.0	4.0
efficiency	trigger	3.0	6.0
efficiency	muon identification	4.0	8.0
normalization	fit pdf	5.0	5.0
background	shape of combinatorial background	4.0	4.0
background	rare decays	20.0	20.0

Results

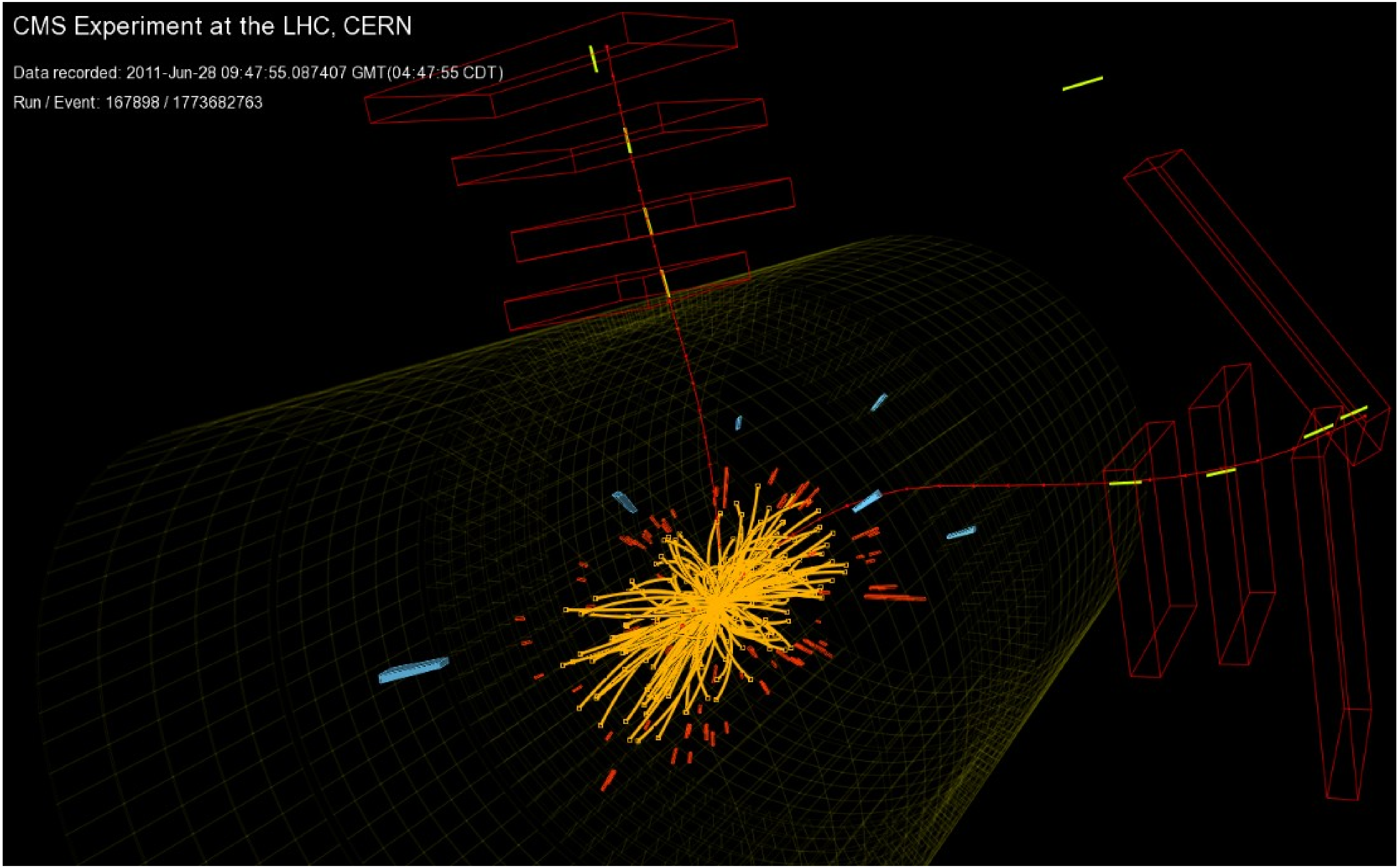
Variable	$B^0 \to \mu^+\mu^-$ Barrel	$B_s^0 \to \mu^+\mu^-$ Barrel	$B^0 \to \mu^+\mu^-$ Endcap	$B_s^0 \to \mu^+\mu^-$ Endcap
Signal	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
Combinatorial bg	0.40 ± 0.34	0.59 ± 0.50	0.76 ± 0.35	1.14 ± 0.53
Peaking bg	0.33 ± 0.07	0.18 ± 0.06	0.15 ± 0.03	0.08 ± 0.02
Sum	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56
Observed	2	2	0	4



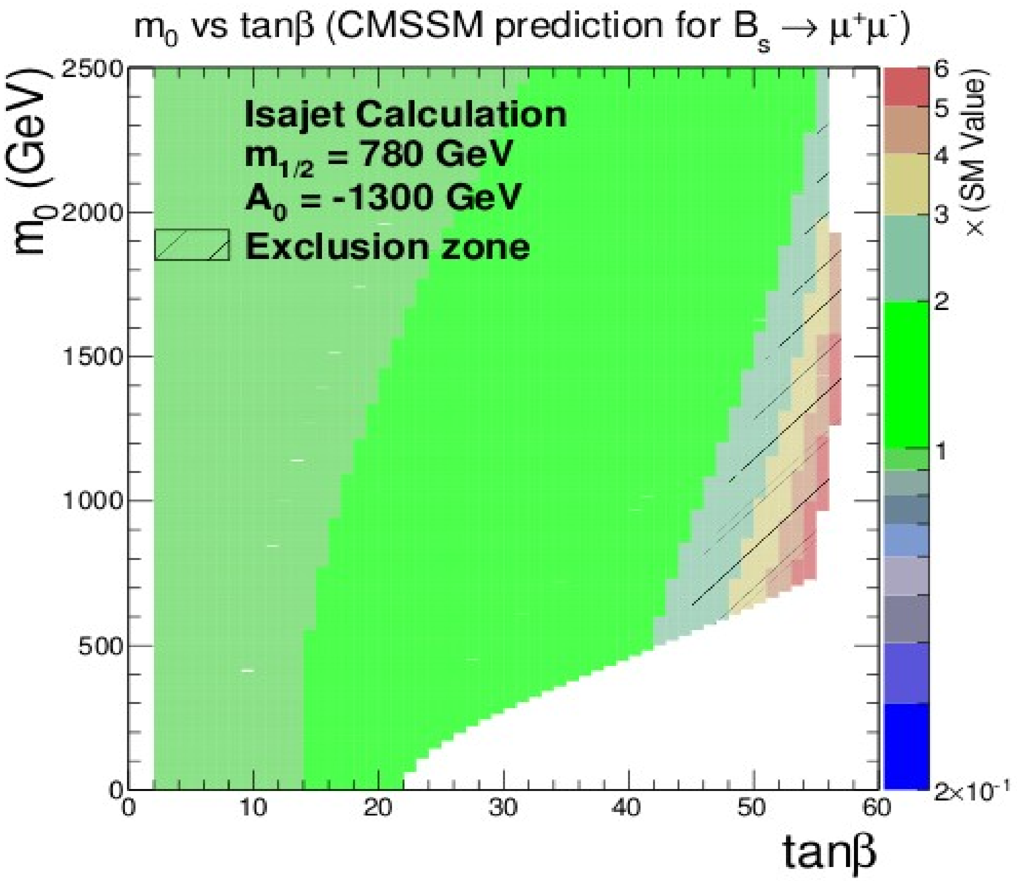
- Upper limit on $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ and $\mathcal{B}(B^0 \to \mu^+\mu^-)$

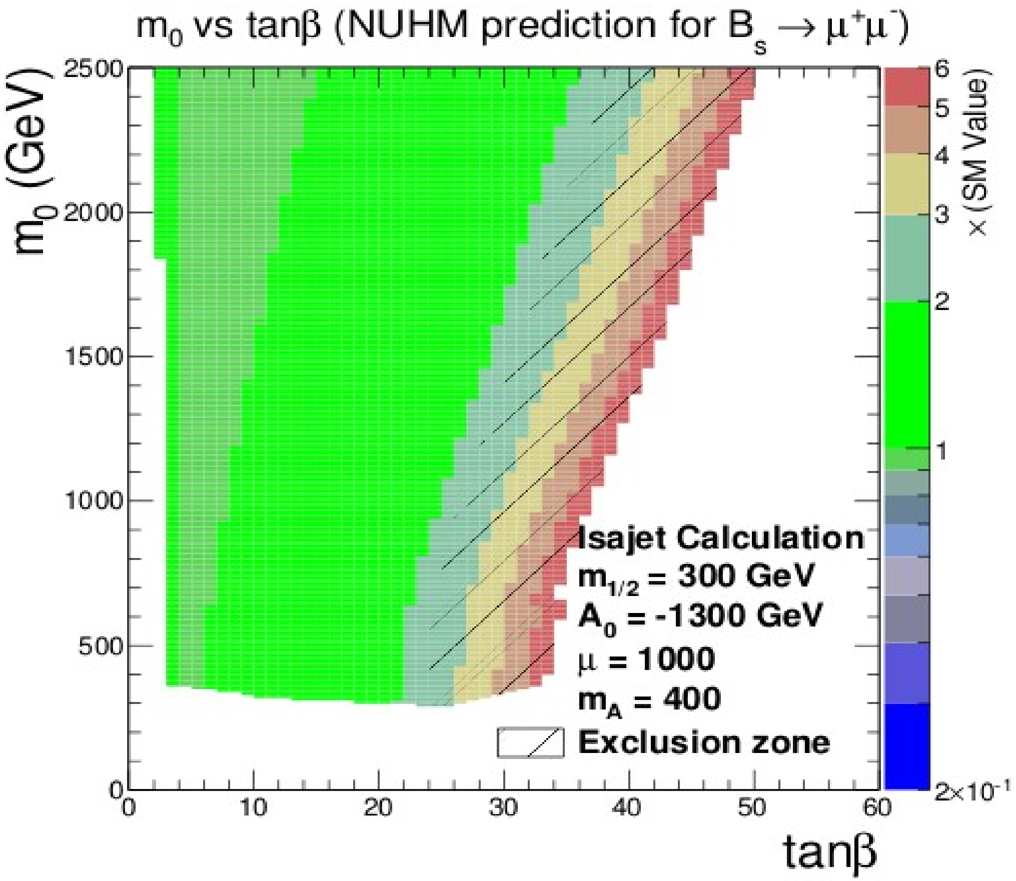
upper limit (95%CL)	observed	(median) expected
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	7.7×10^{-9}	8.4×10^{-9}
$\mathcal{B}(B^0 \to \mu^+\mu^-)$	1.8×10^{-9}	1.6×10^{-9}

Candidate event



Implication to new physics

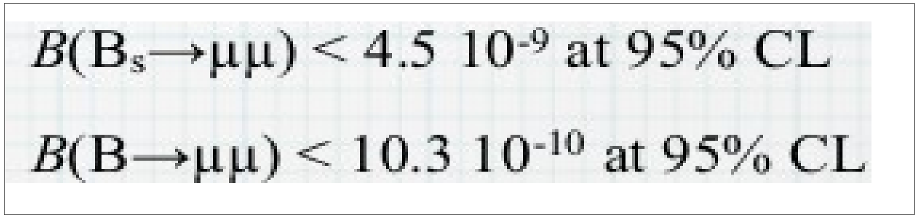




Empty regions due to previous upper limit and other published data

Strongly impacts are large tanβ

By the time of this study: New LHCb results



$B(B_s \to \mu\mu) < 4.5\ 10^{-9}$ at 95% CL

$B(B \to \mu\mu) < 10.3\ 10^{-10}$ at 95% CL

MSSM Higgs searches

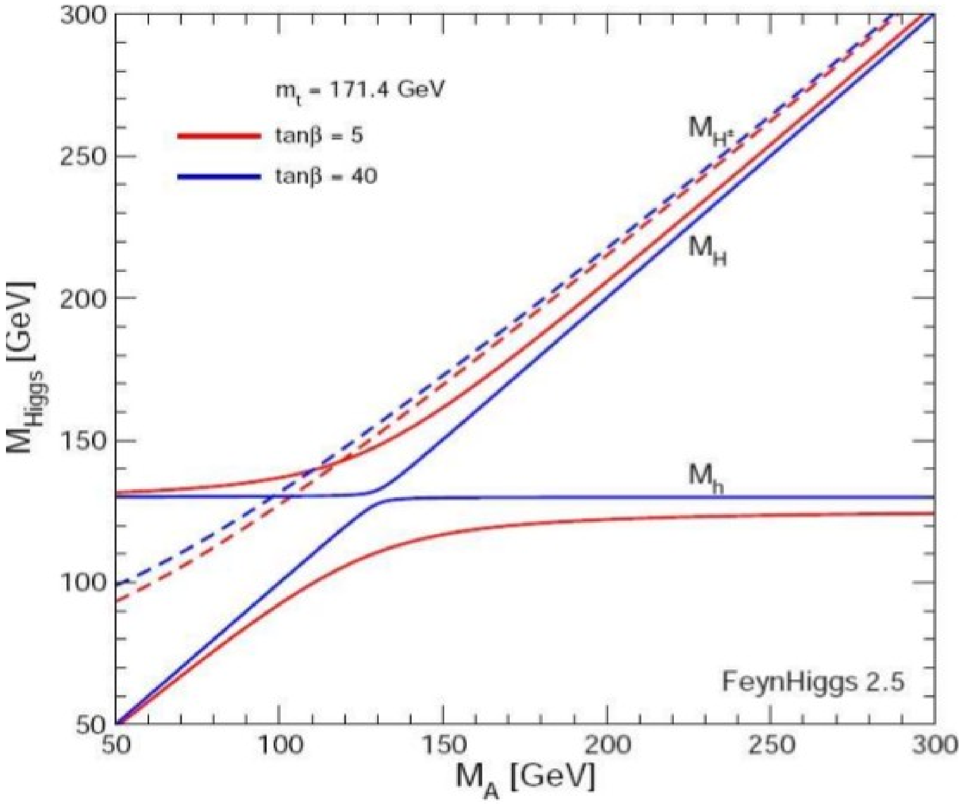
MSSM Higgs

PHENOMENOLOGY

- Two Higgs Doublets
- Five Higgs Bosons:

  h/H (CP = +1), A (CP = -1), $H^{\mp}$
- Tree level: Two free parameters

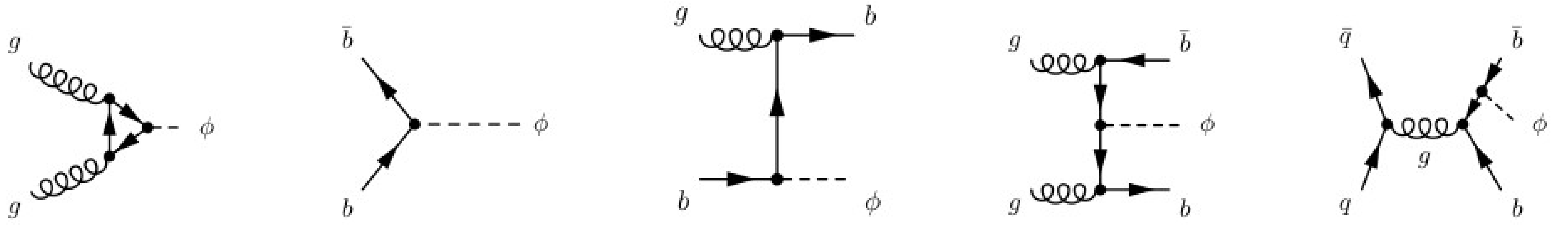
  $(m_A, \tan\beta)$, radiative corr introduces other dependences
- h standard-model like
- Production cross section scales as $\tan^2\beta$



Production and decay of MSSM Higgs

Neutral Higgs Boson (h/H/A): BR (τ leptons) ~ 10%, BR (bbar) ~ 90% (challenging!)

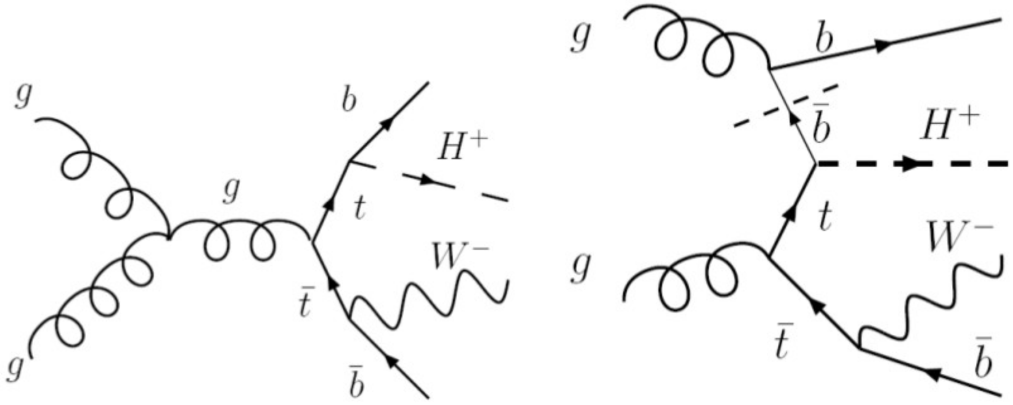
- Gluon-Fusion or *b*-Quark Associate Production



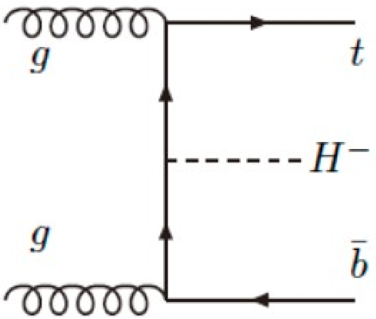
Charged Higgs boson

Charged Higgs $H^{\pm}$

If $M(H^{\pm}) < m_{top}$; Lower limit LEP ~ 80 GeV



$pp \rightarrow tbH^{\pm}$ for $M_{H^{\pm}} \gtrsim m_{top}$



Observation is a direct sign of BSM

- Light H (< m_{top})

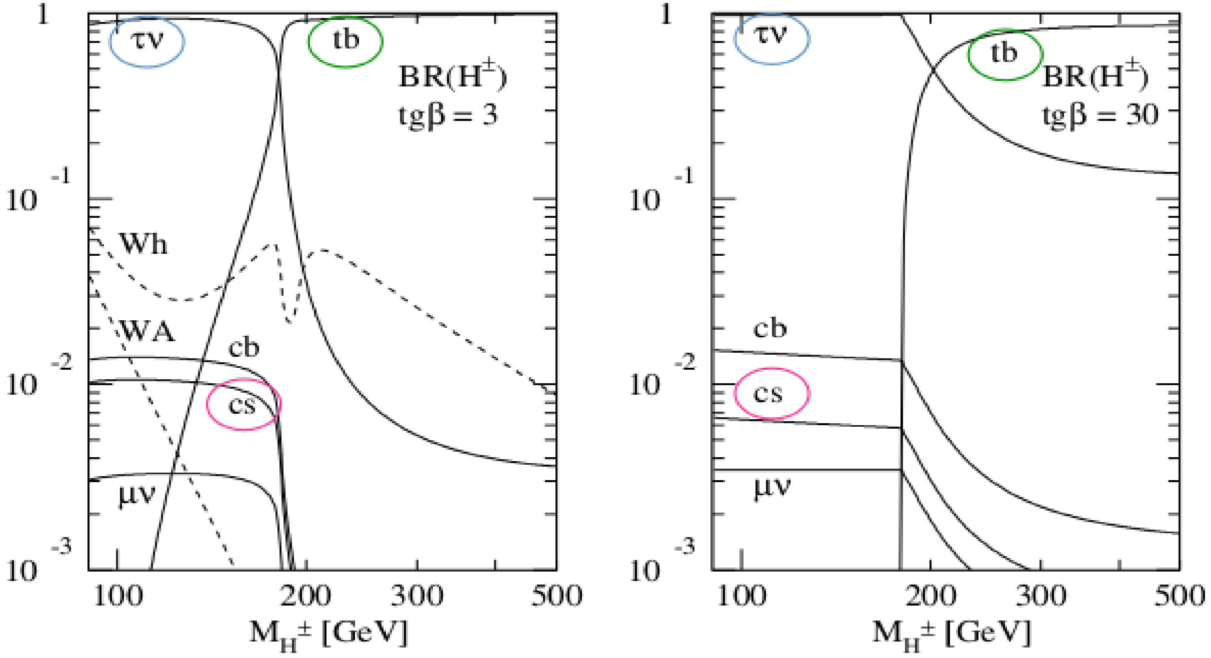
Dominant decay: $H^{\pm} \rightarrow \tau^{\pm}\nu$

- Heavy Higgs (> m_{top})

$$B(H^{\pm} \rightarrow \tau^{\pm}\nu) \sim 10\%$$

Also depends on tanβ

M. Gomez-Bock et al., arXiv:0712.2419



Charged Higgs boson

General strategy

- Suppress QCD multijets
- Separate signal from bkg using M_T
  - Also use M_T for shape analysis (ττ)

Backgrounds (ττ) :

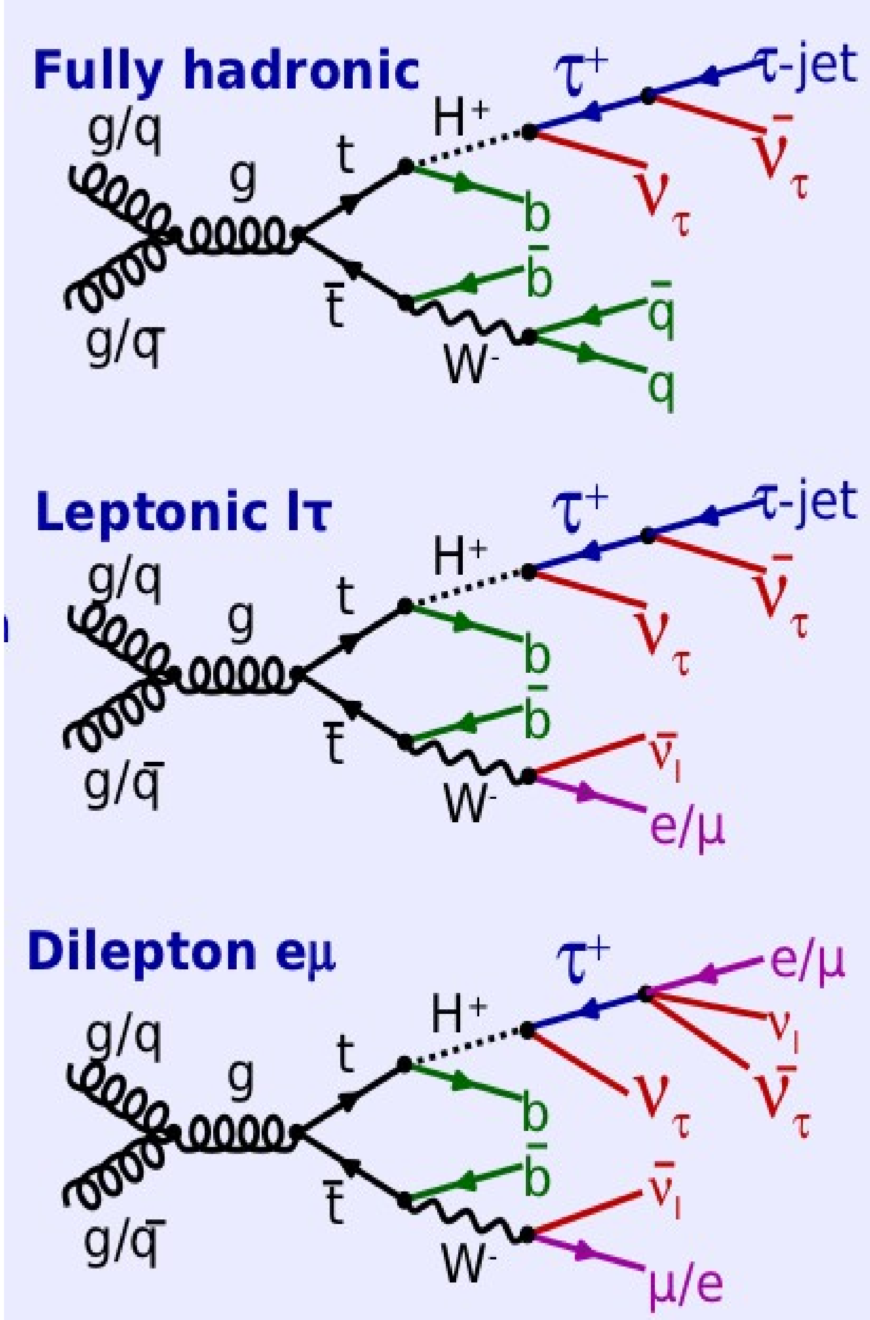
- QCD multijets (measure in data)
- EWK ttbar (measure in data; tau embeded)
- Other backgrounds:
  - EWK + ttbar with fake taus

Backgrounds (lτ) [Major bkg: ttbar, W+Jets]:

- Fake taus (measure in data)
- Other EWK (genuine) taus from simulations

Backgrounds (eμ) [Major bkg: ttbar] :

- Cleanest channel
- Selection similar to ttbar xsec measurement



Charged Higgs (hadronic taus)

Event selection

$P_T(\tau) > 40$ GeV, atleast 3 Jets with $p_T > 30$ GeV, MET > 50 GeV, atleast 1 btag jet

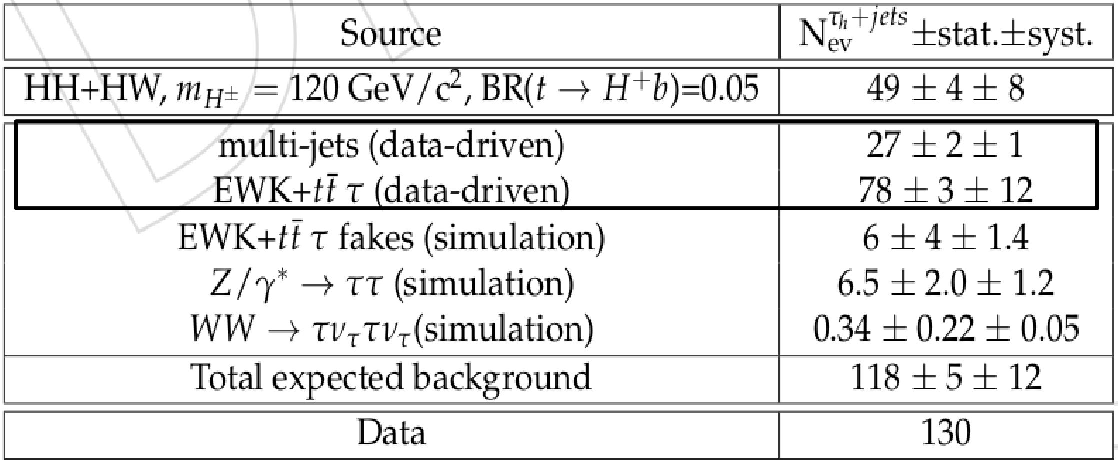
$\Delta\phi$ ($p_T(\tau)$ – MET) < 160^0; pt (tracks) > 20 GeV with lepton veto

$W \rightarrow \tau\,\nu$ is suppressed using $R = p^{trk} / p(\tau) > 0.7$

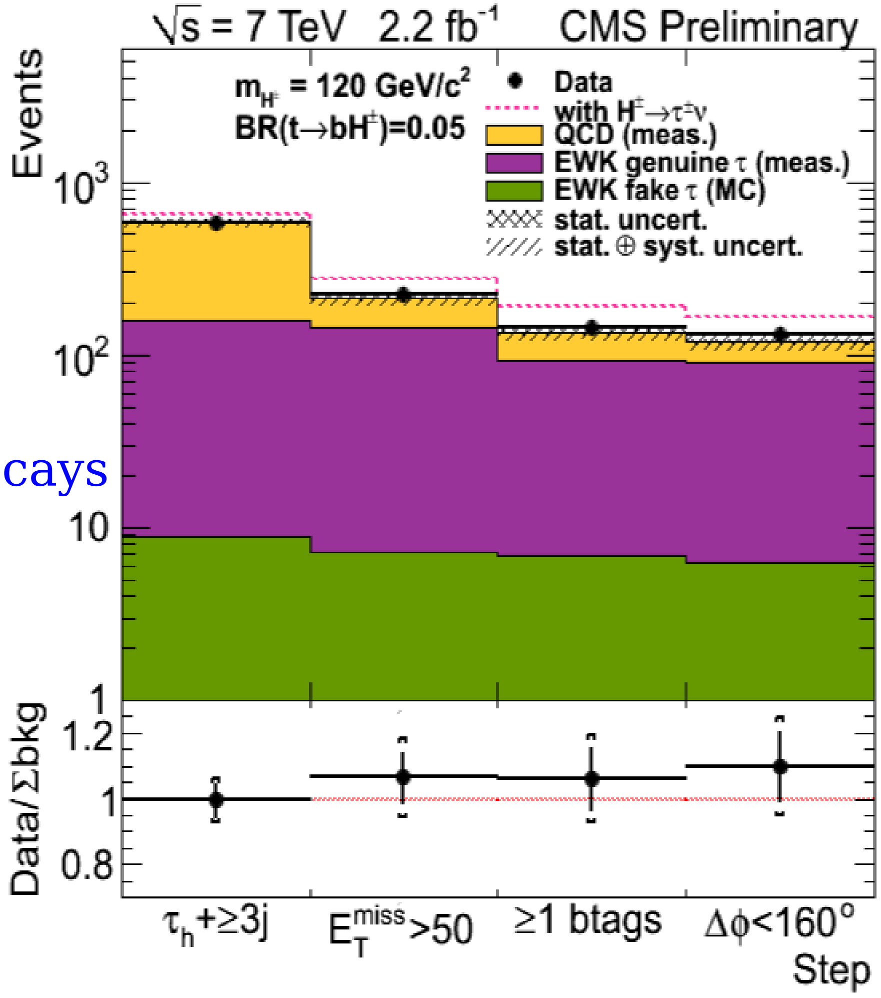
QCD multijet bkg (fake taus) measured in data

EWK ttbar (embedding method)

- Define control sample in data
- select high p_T muons (lepton universality assumed)
- Replace muons by taus from simulated tau decays



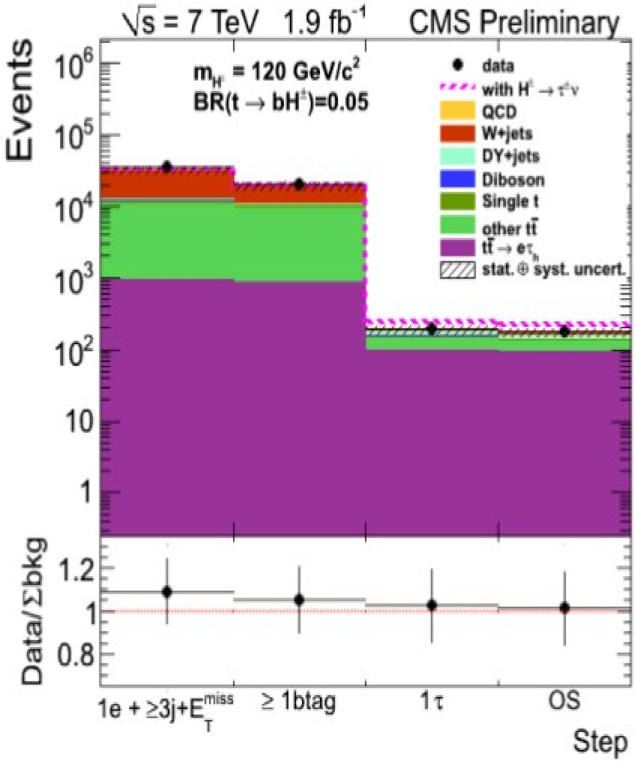
Source	$N_{ev}^{\tau_h+jets}$ ±stat.±syst.
HH+HW, $m_{H^\pm} = 120$ GeV/c^2, BR($t \rightarrow H^+ b$)=0.05	49 ± 4 ± 8
multi-jets (data-driven)	27 ± 2 ± 1
EWK+$t\bar{t}$ τ (data-driven)	78 ± 3 ± 12
EWK+$t\bar{t}$ τ fakes (simulation)	6 ± 4 ± 1.4
$Z/\gamma^* \rightarrow \tau\tau$ (simulation)	6.5 ± 2.0 ± 1.2
$WW \rightarrow \tau\nu_\tau\tau\nu_\tau$(simulation)	0.34 ± 0.22 ± 0.05
Total expected background	118 ± 5 ± 12
Data	130

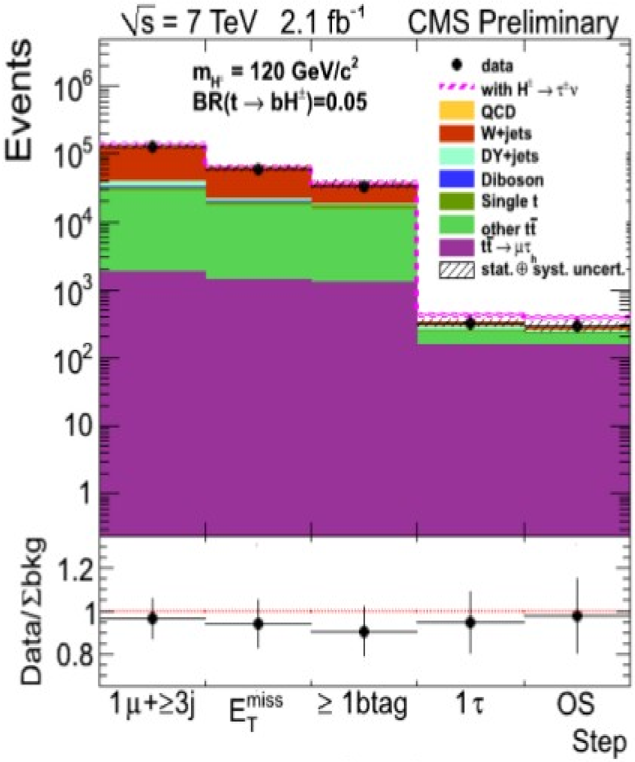


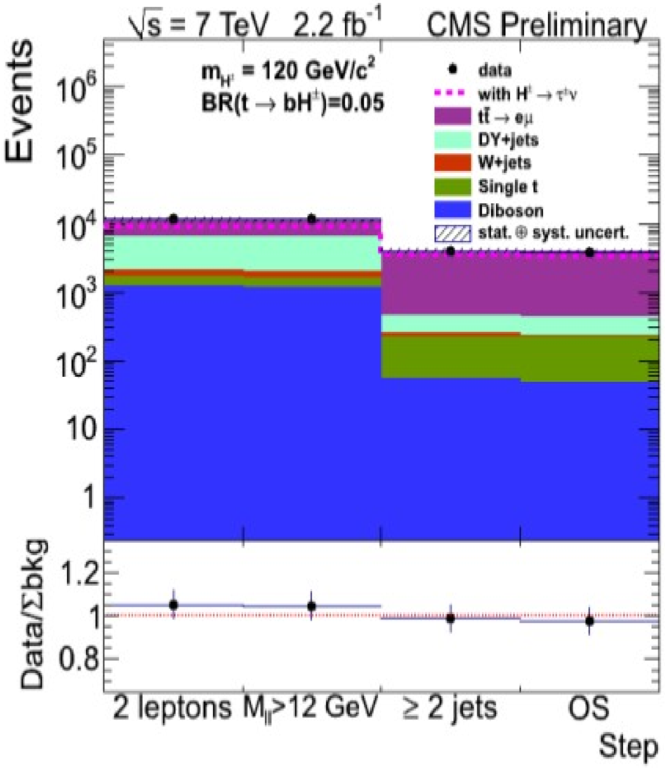
Charged Higgs (lτ & eμ)

$$H^{\pm} \rightarrow e^{\pm}\tau_h^{\mp}, \mu^{\pm}\tau_h^{\mp}$$

$$H^{\pm} \rightarrow e^{\pm}\mu^{\mp}$$

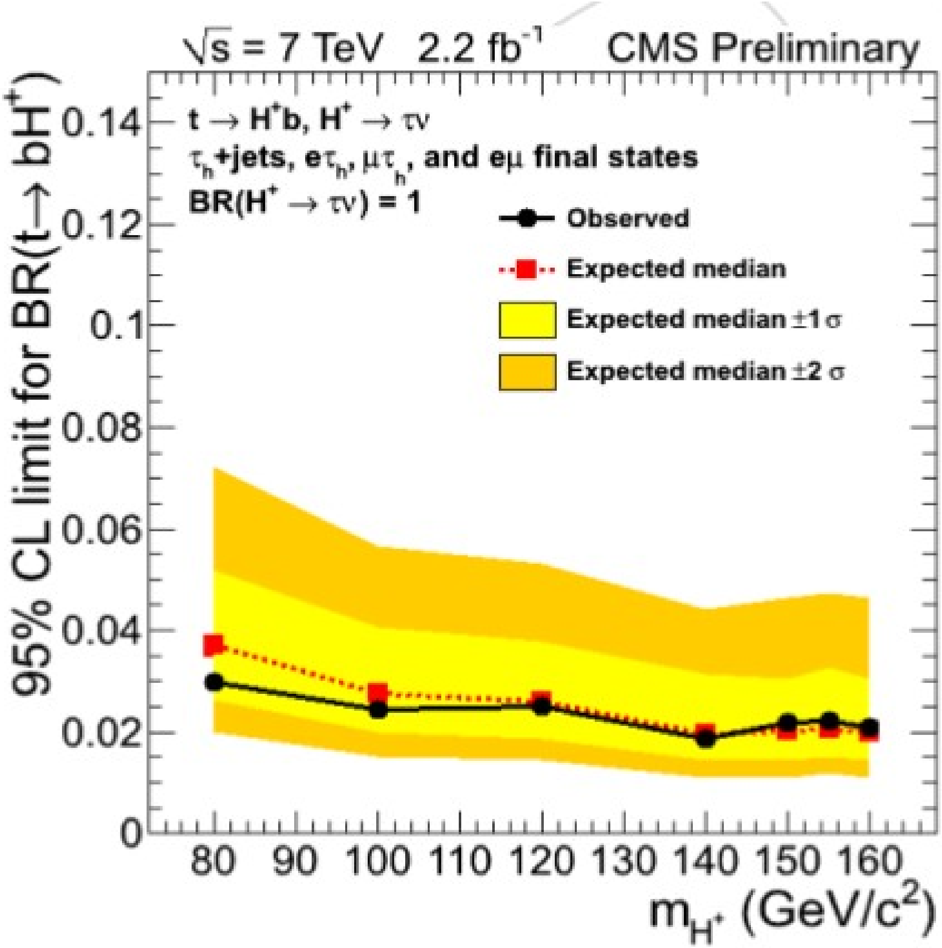


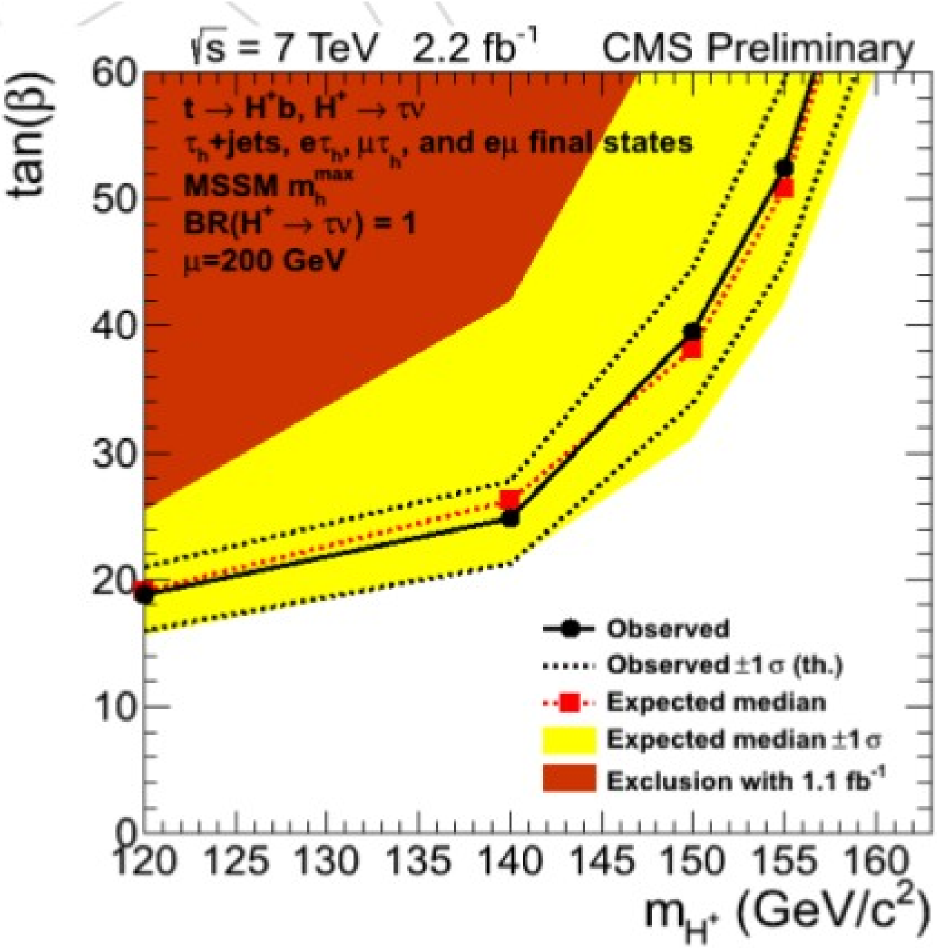




Good agreement between expectation and observation

Charged Higgs





Significant constrain on the BR (CDF/D0 results for 80 -155 GeV, H$^\pm$ ⇒ BR ~20%)

$$\boxed{BR(t \rightarrow H^{+}b) < 2 - 3\%}$$

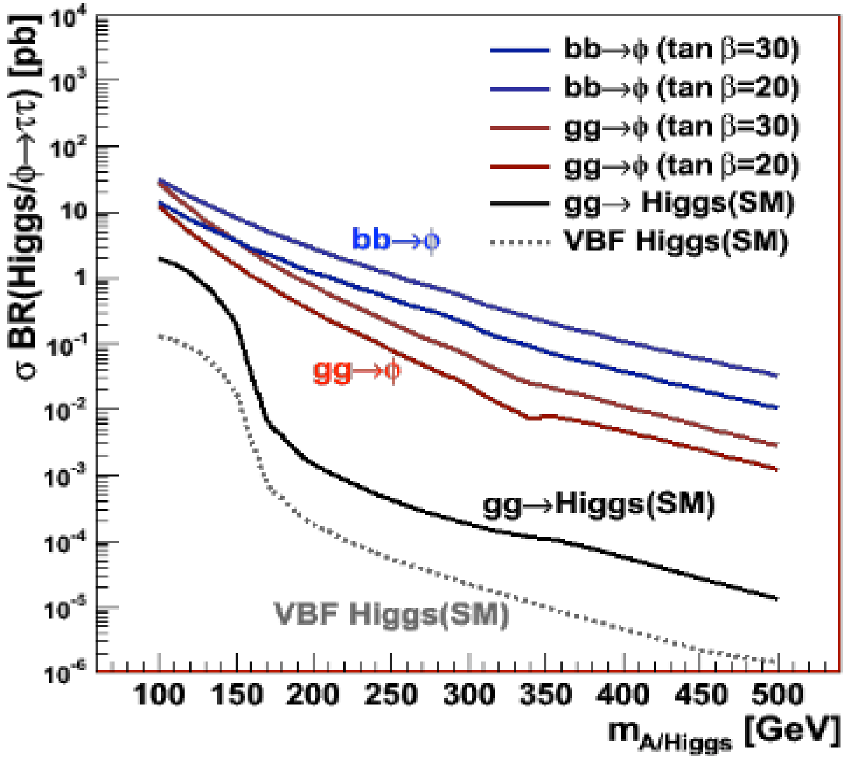
Excludes a large region in m(H) - tanβ plane

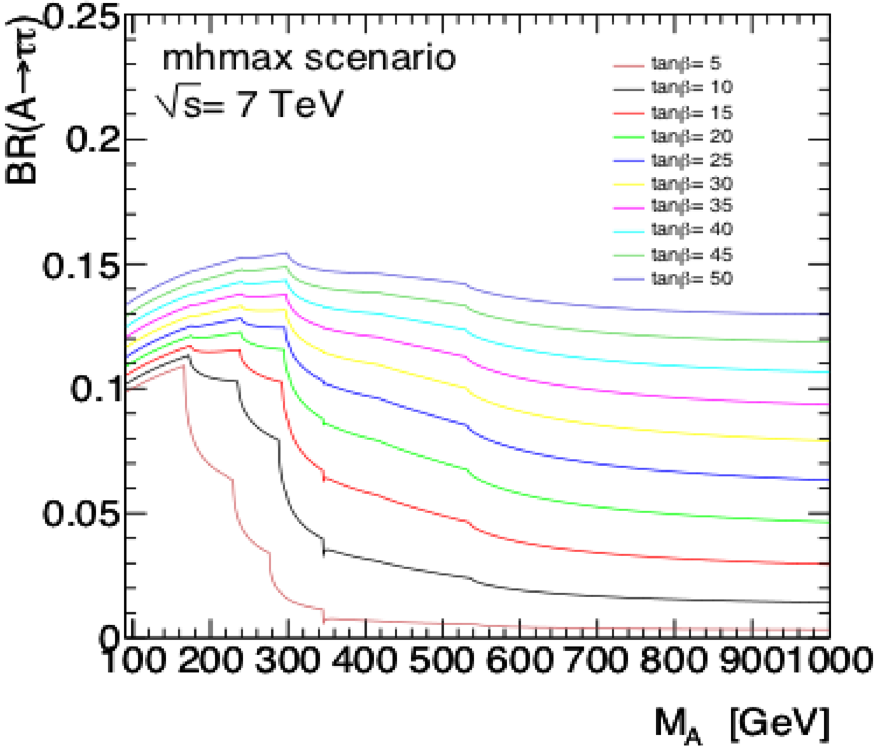
MSSM Neutral Higgs (h, H, A)

Enhanced coupling to b-quarks and tau-leptons

Decays to b-quark and tau pairs enhanced at all masses

- MSSM Neutral Higgs decay
  - $\Phi \rightarrow \tau^+\tau^- \rightarrow \ell\ell, \ell h, hh + \nu' s$
  - $\Phi \rightarrow b\bar{b}$ is difficult.





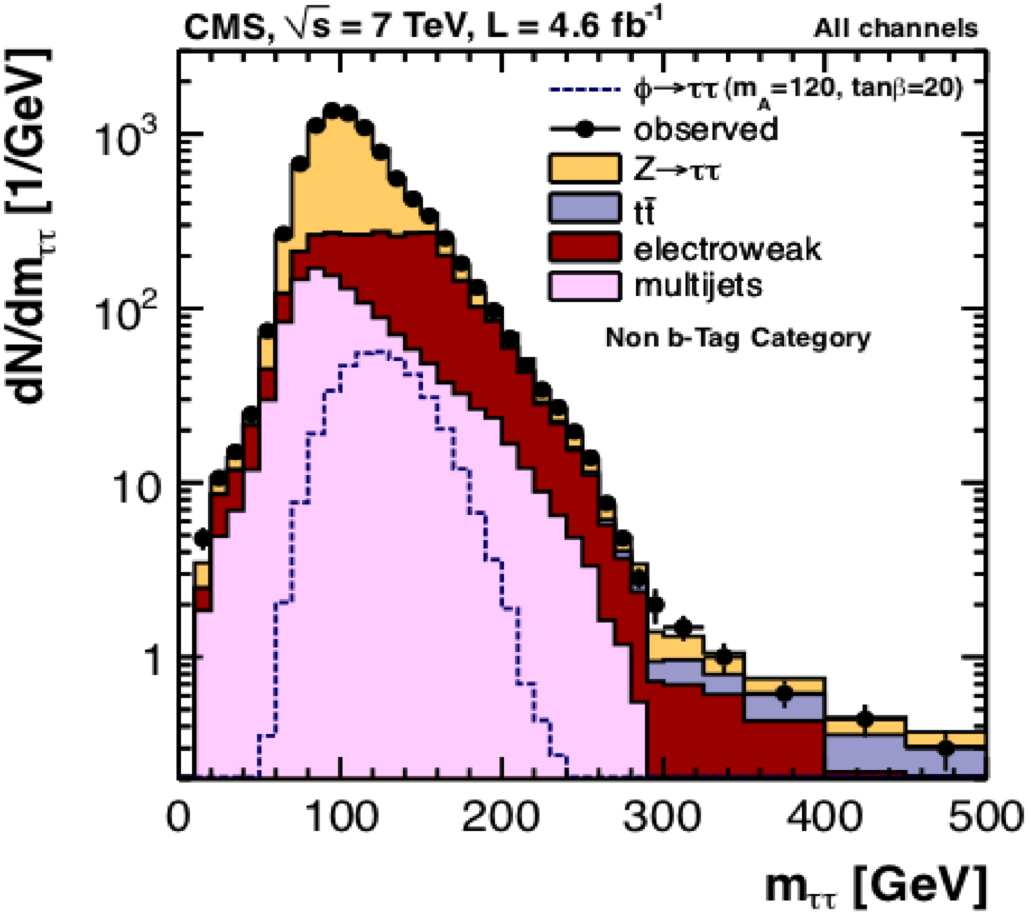
MSSM Neutral Higgs

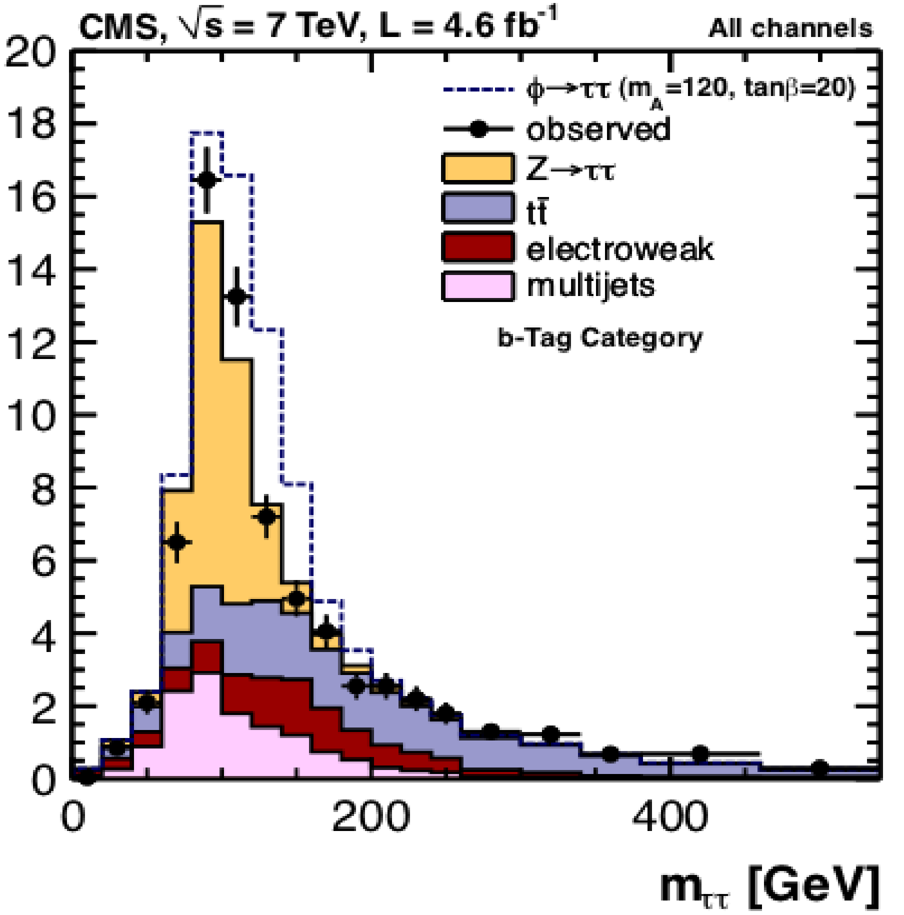
Tau pairs reconstructed in decays leptons (e/μ)+ hadrons (1 or 3 prong) or eμ

Kinematic fit to obtain tau pair mass

- used to search for H to tt contribution

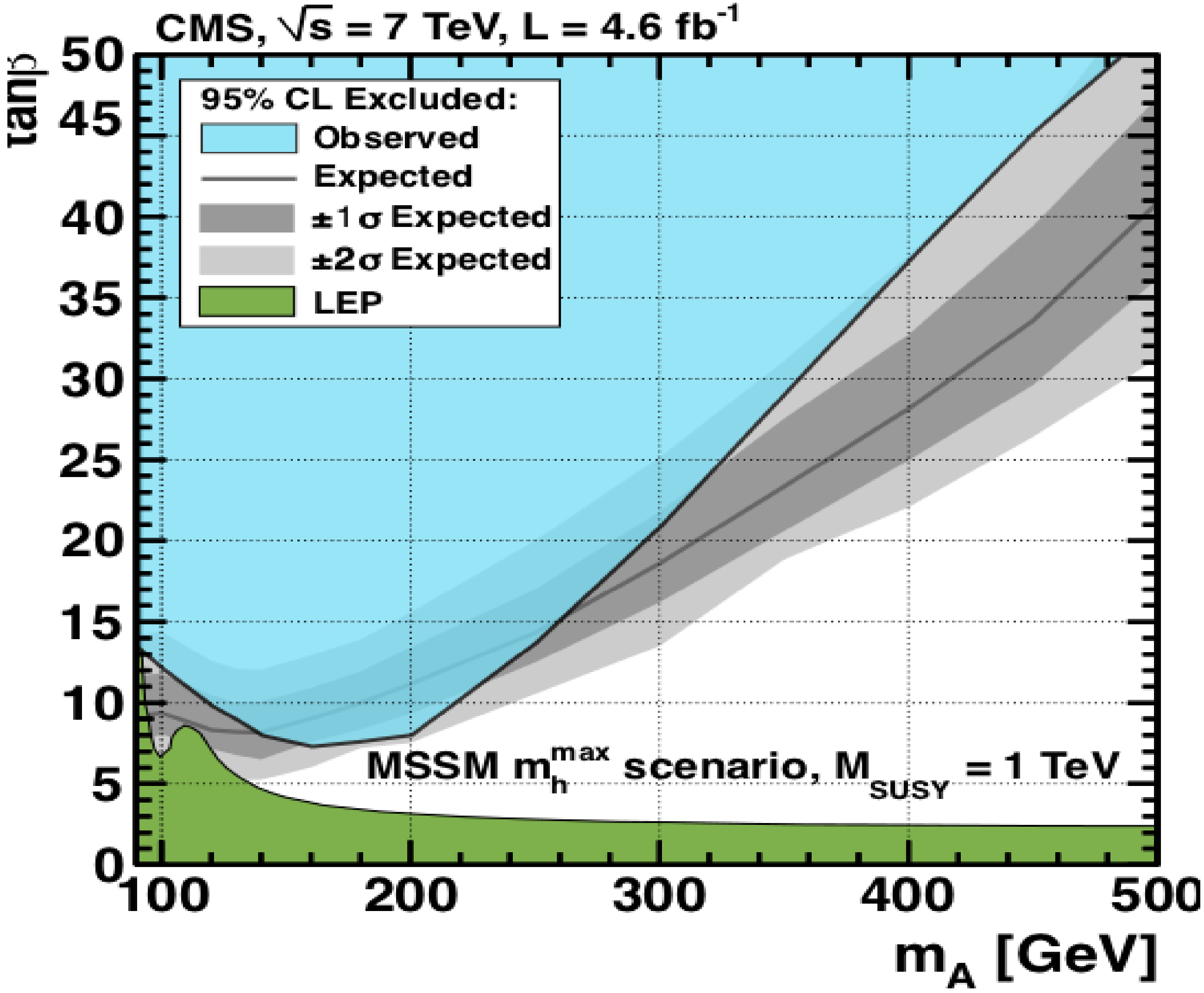
Two main categories : non-b-tagged and b-tagged (to enhance bbΦ)





MSSM Neutral Higgs

$$\phi \rightarrow \tau^{+}\tau^{-}(e\tau_h, \mu\tau_h, e\mu)$$



This excludes previously unexplored region:

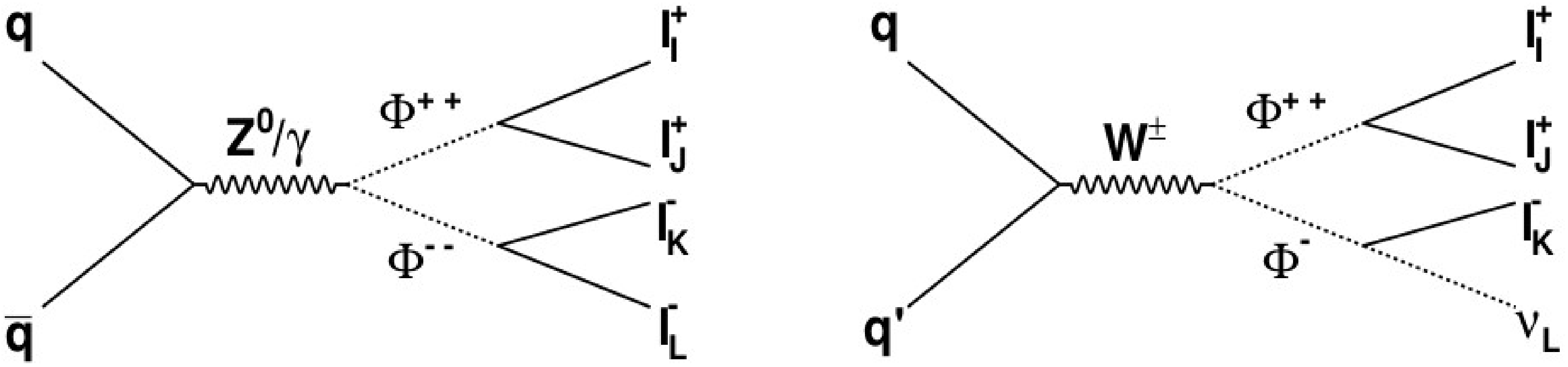
- reaching as low as tanβ = 7.1 and m_A = 160 GeV

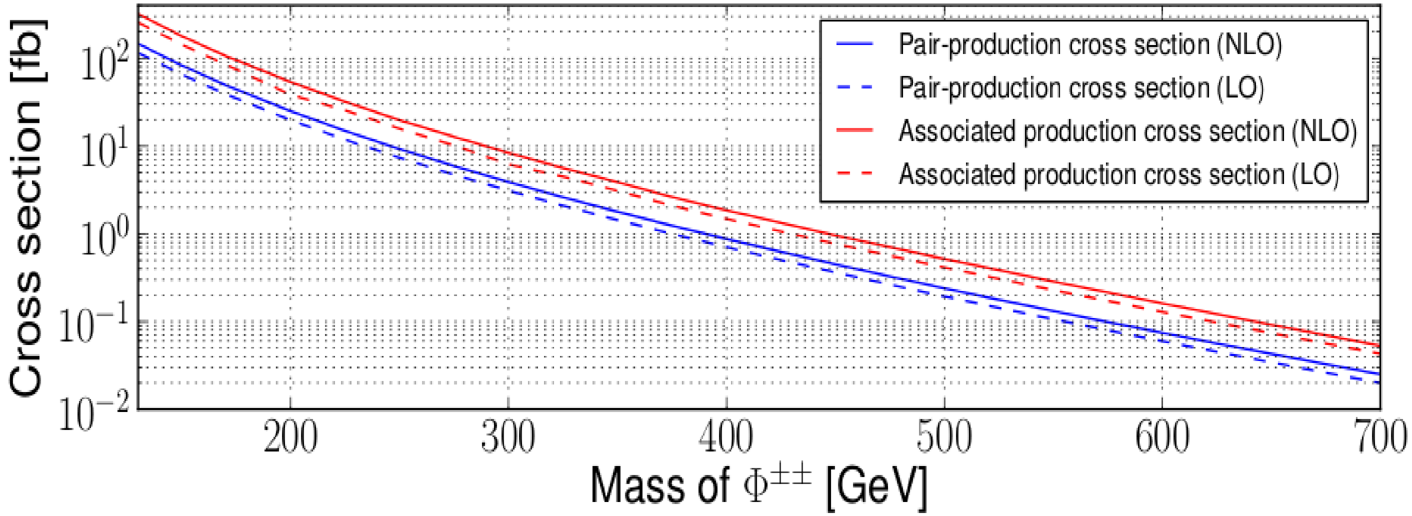
Double charged Higgs search

Minimal seesaw model of Type-II with one triplet scalar field

[Magg, Wetterich, Schechter, Valle, Mohapatra, Senjanovic]

Essentially is a search for like-sign dileptons



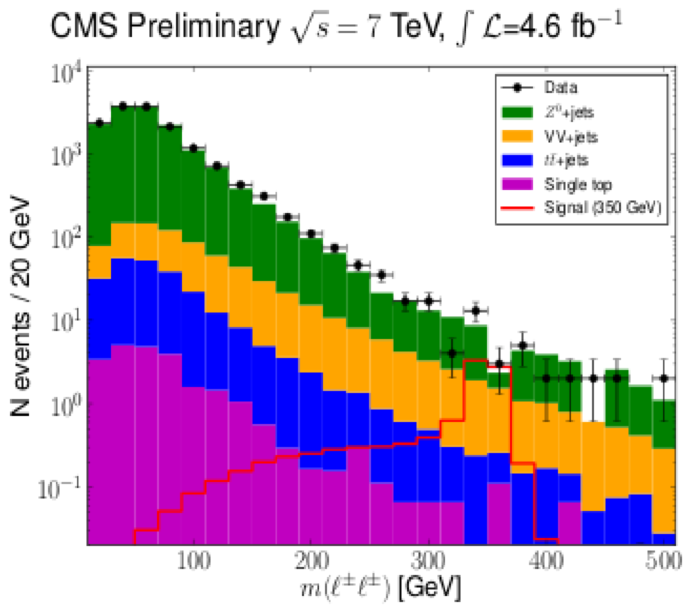


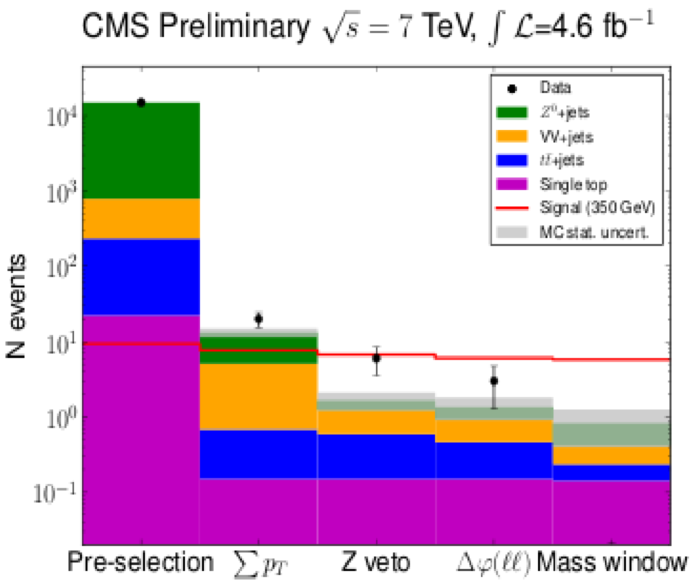
4 benchmark point used (BP1 – BP4) [Kadastik, Raidal, Rebane, 2008]

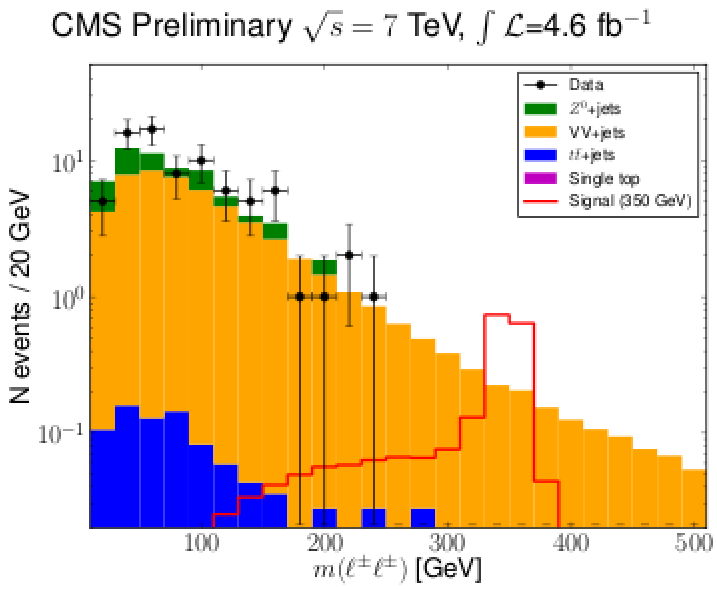
- to probe different characteristic of neutrino mass matrix

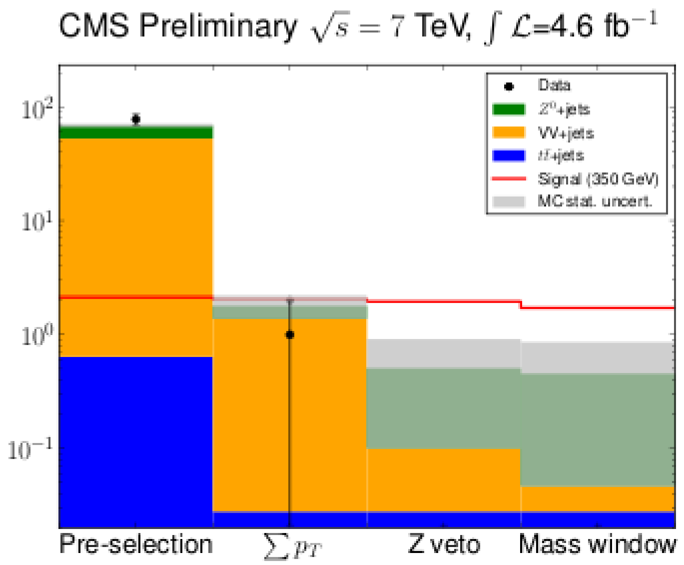
Double charged Higgs searches

Tri-lepton and Quadlepton Modes in all lepton flavours

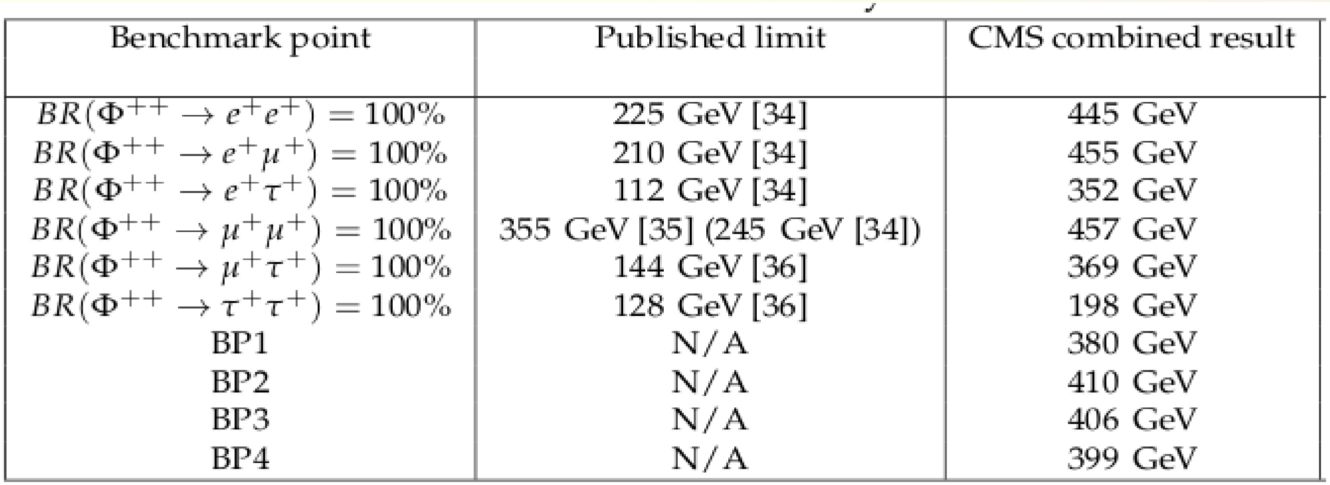






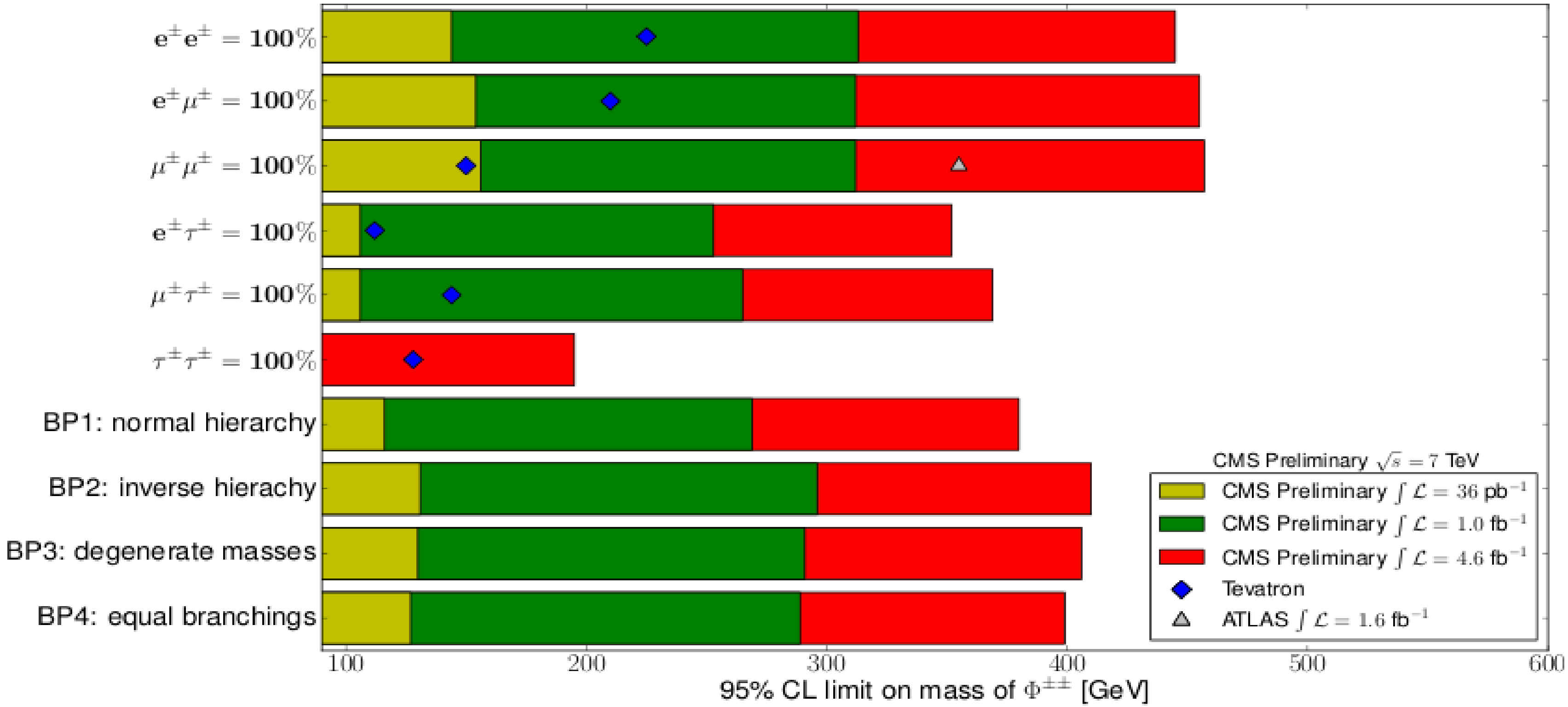


Double charged Higgs searches



Benchmark point	Published limit	CMS combined result
$BR(\Phi^{++} \to e^+e^+) = 100\%$	225 GeV [34]	445 GeV
$BR(\Phi^{++} \to e^+\mu^+) = 100\%$	210 GeV [34]	455 GeV
$BR(\Phi^{++} \to e^+\tau^+) = 100\%$	112 GeV [34]	352 GeV
$BR(\Phi^{++} \to \mu^+\mu^+) = 100\%$	355 GeV [35] (245 GeV [34])	457 GeV
$BR(\Phi^{++} \to \mu^+\tau^+) = 100\%$	144 GeV [36]	369 GeV
$BR(\Phi^{++} \to \tau^+\tau^+) = 100\%$	128 GeV [36]	198 GeV
BP1	N/A	380 GeV
BP2	N/A	410 GeV
BP3	N/A	406 GeV
BP4	N/A	399 GeV

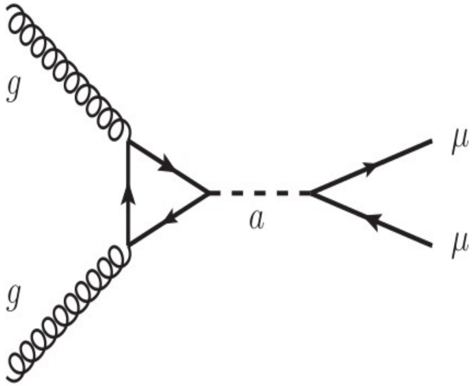
CMS PAS HIG-12-005



NMSSM light pseudoscalar higgs $a_1 \to \mu^+\mu^-$

Next-to-Minimal Supersymmetric Standard Model (NMSSM):

- Adds singlet scalar field, thus expanding the Higgs sector
- Three CP-even (h_1, h_2, h_3) and two CP-odd (a_1, a_2) and two charged scalars $H^\pm$



A light (~10 GeV) boson is produced

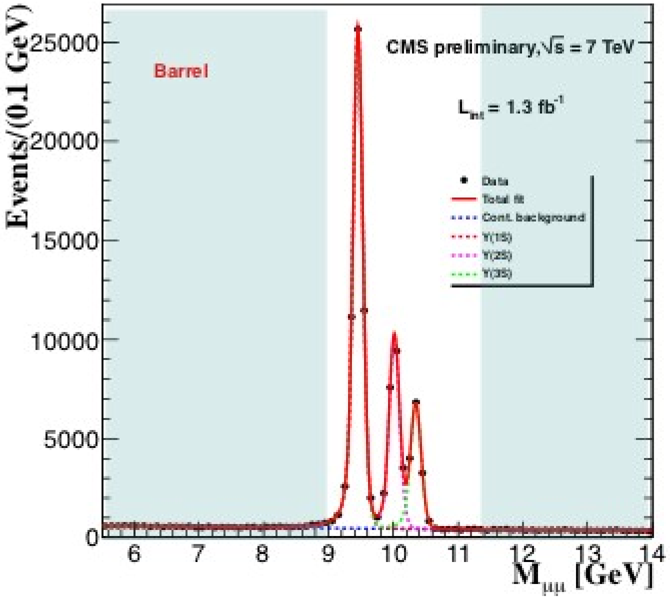
Search for a_1 in its decays to OS dimuons

Analysis strategy :

- Select isolated OS muons with $p_T > 4$ GeV

  $p_T(\mu\mu) > 6$ GeV

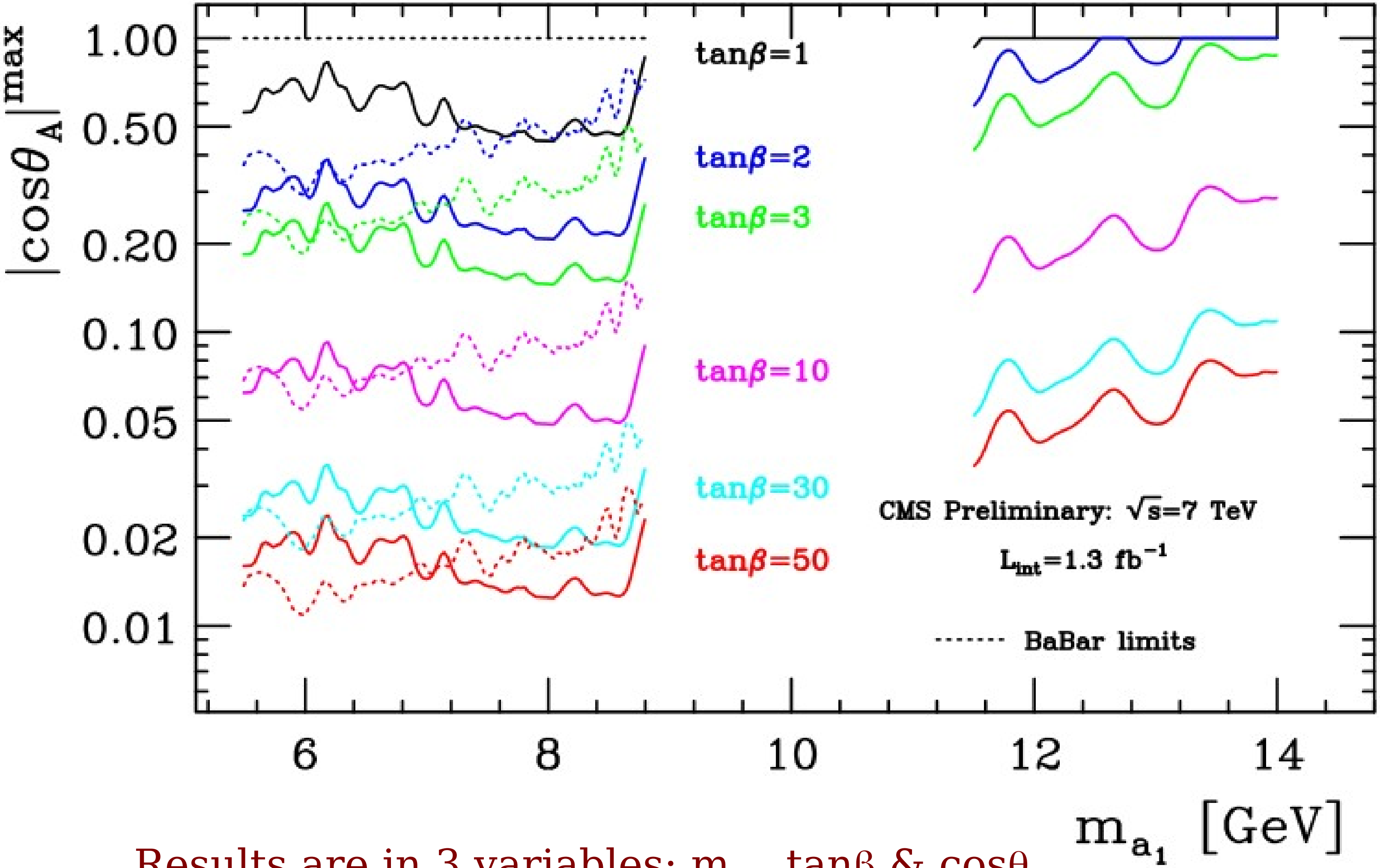
- Search below/above the upsilon peaks
  - $5.5 < M(\mu\mu) < 8$ GeV
- $11.5 < M(\mu\mu) < 14$ GeV



Trigger Challenges :

Use special dimuon trigger which include dimuon inv mass and DCA (distance of closest approach to beam axis) < 0.5

NMSSM light pseudoscalar higgs $a_1 \rightarrow \mu^+\mu^-$



Results are in 3 variables: m_{a1}, tanβ & $\cos\theta_A$

The dashed lines are the results from BaBar

Solid lines are the CMS results

Few personal remarks

Revisit the Higgs and MSSM

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}X_t + \log\frac{M_{\rm SUSY}^2}{M_t^2}\right] + \cdots$$

Important parameters for MSSM Higgs:

- tanβ and M_A
- the SUSY breaking scale M_S
- the mixing parameter in the stop sector $X_t = |A_t - \mu \cot\beta|$;
  - A_t is the trilinear scaling coupling
  - μ is the mass parameter for the Higgs in the superpotential

M_h^{max} can be obtained:

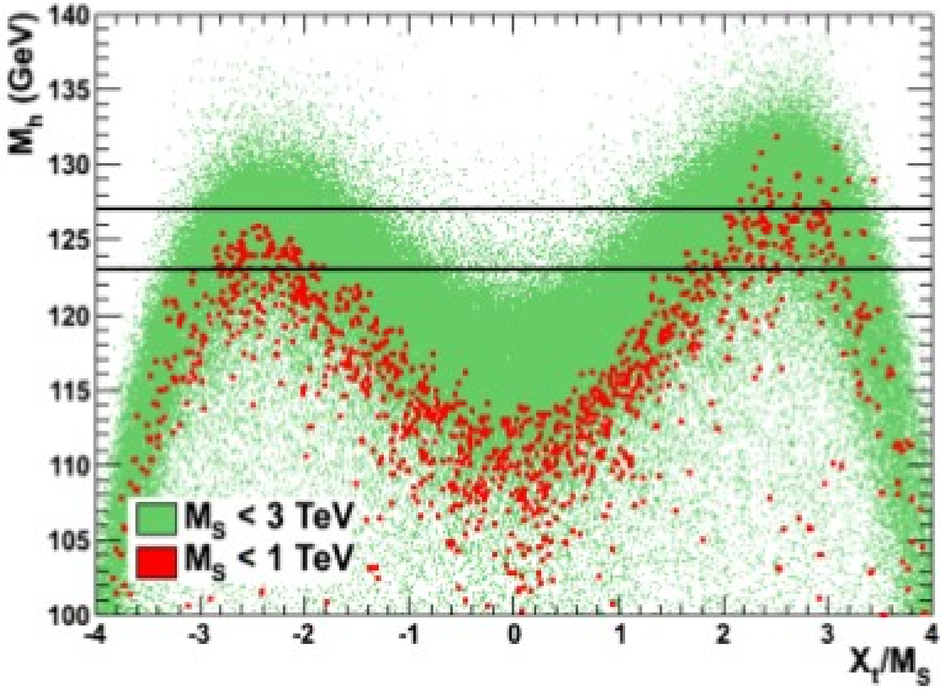
- a decoupling regime with a heavy pseudoscalar Higgs boson (M_A ~1 TeV)
- large tanβ, → tanβ > 10
- heavy stops → large M_S
- maximal mixing scenario ($X_t = |A_t - \mu \cot\beta|$): $X_t = \sqrt{6}M_S$
- minimal mixing scenario $X_t \sim 0$

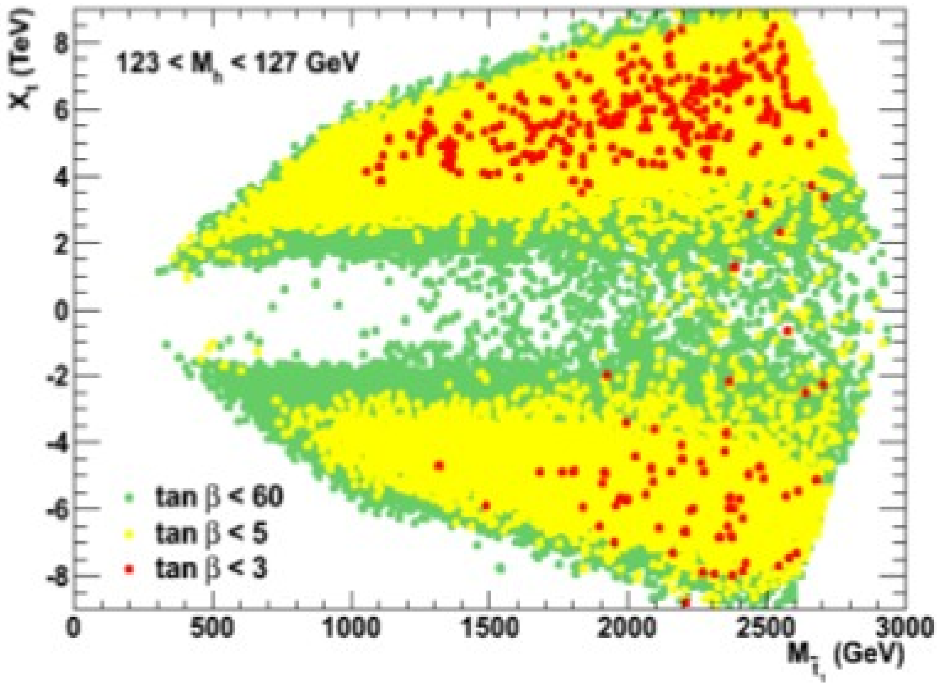
Consequences in pMSSM

Based on talks this morning, consider higgs to be $123 < M_h \text{ (GeV)} < 127$

The consequences of this in pMSSM (19 parameter)

A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162





A large part of the pMSSM still survives

No mixing cases ($X_t \sim 0$) is excluded for $M_S < 1$ TeV

- Even at $M_S < 3$ TeV, chances are narrow

Small stop masses are still allowed

Consequences of Higgs results for BSM Higgs

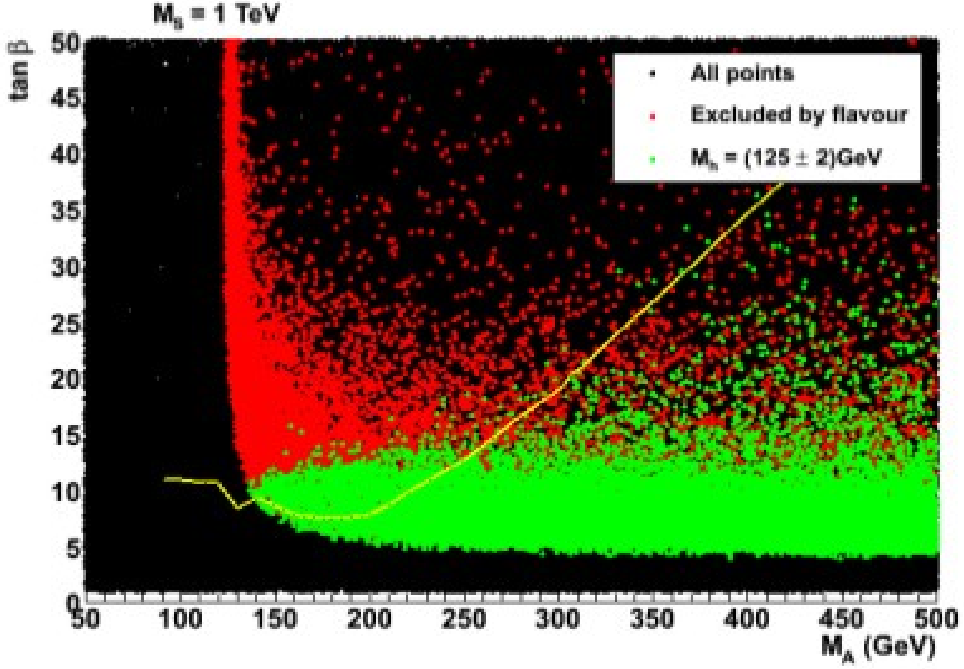
Now let us apply other constraints discussed earlier: $123 < M_h \text{ (GeV)} < 127$

- Direct $A \to \tau^+\tau^-$
- Constraints from $BR(B_s \to \mu^+\mu^-)$
- Dark matter direct detection constraints (XENON)

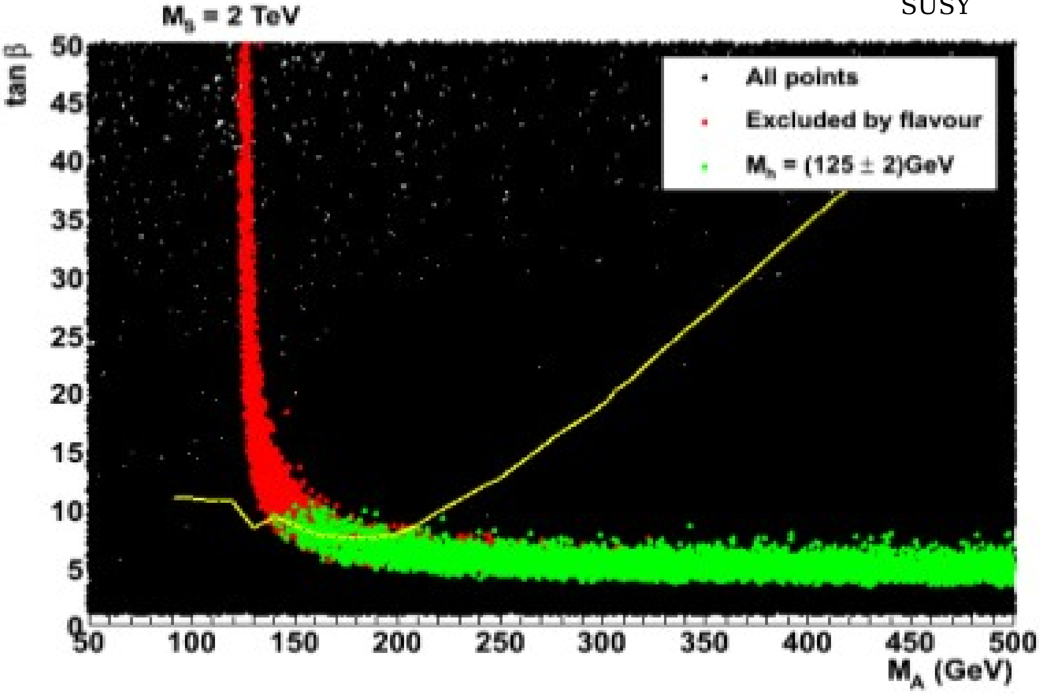
In the maximal mixing case ($X_t = \sqrt{6}\, M_S$)

Preliminary results: Nazila Mahmoudi, Moriond EWK

1 TeV M_{SUSY}



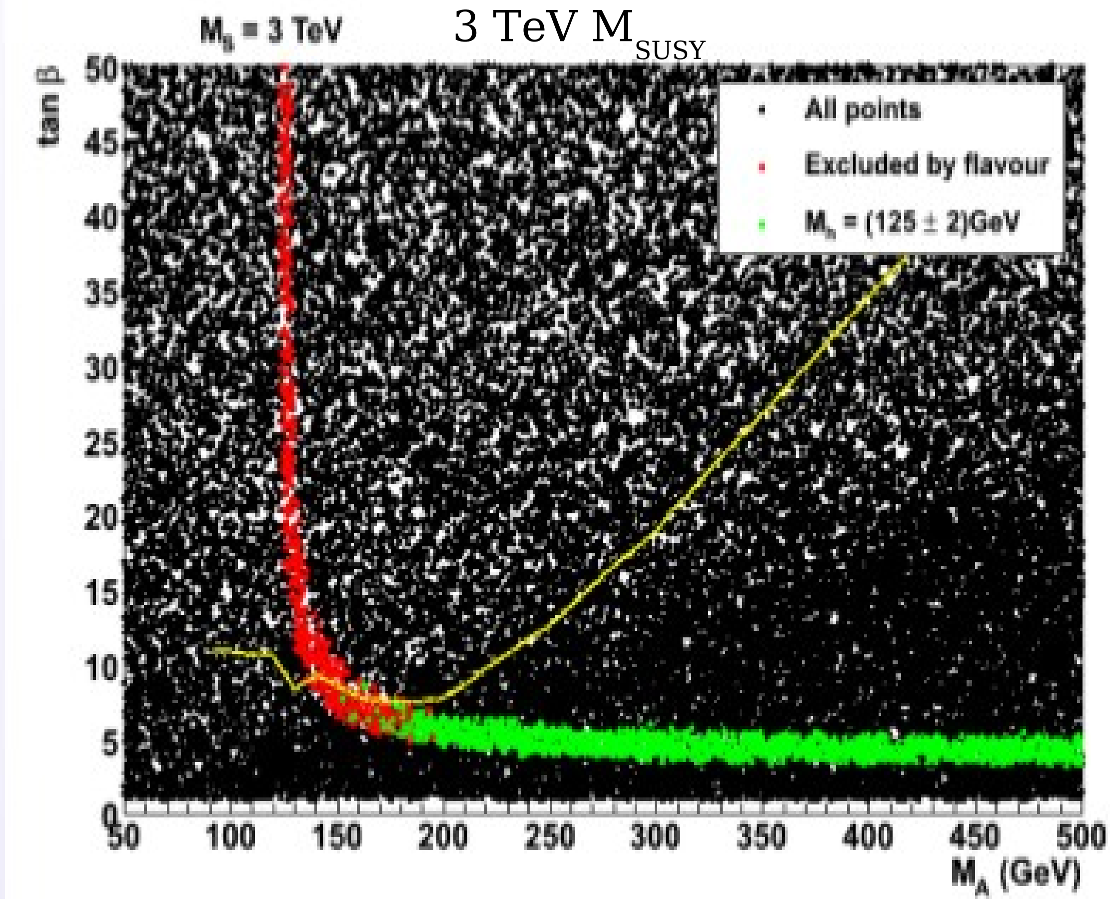
2 TeV M_{SUSY}



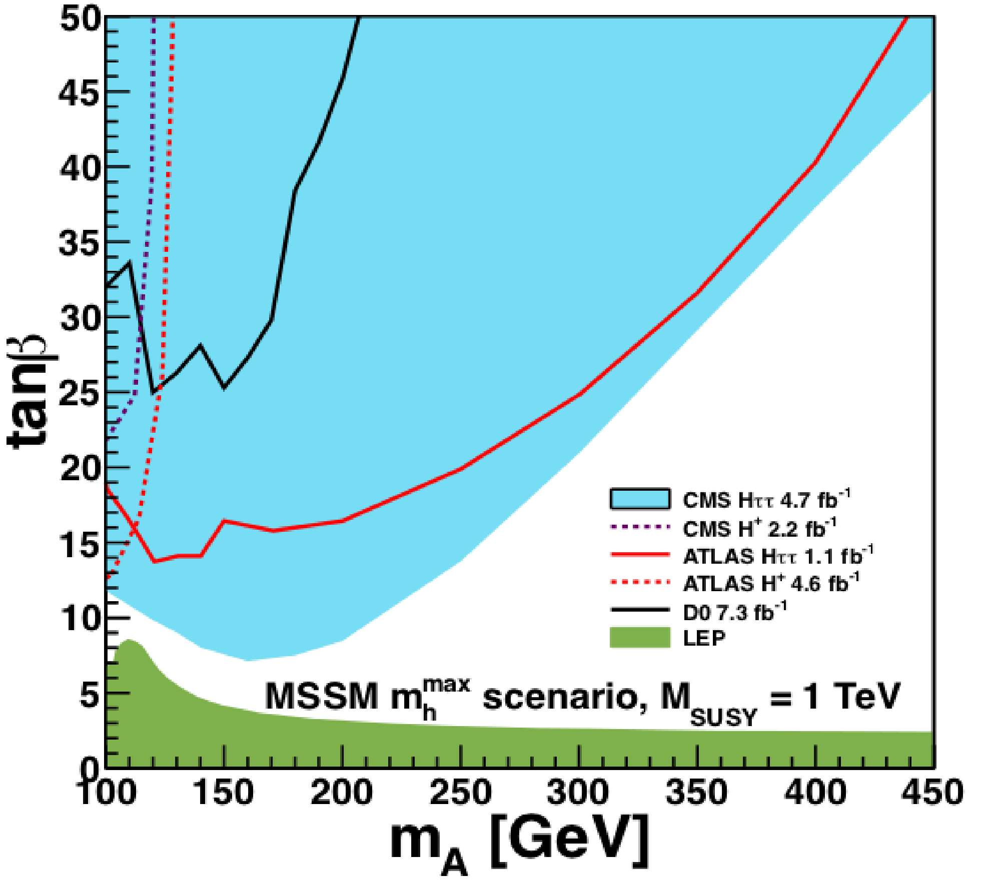
Flavour constraints: $b \to s\gamma,\, B \to \tau\nu$ and new LHCb B_s results

Consequences of Higgs results for BSM Higgs

In the maximal mixing case ($X_t = \sqrt{6}\, M_S$) 123 < M_h (GeV) < 127



3 TeV M_{SUSY}



Very strong constraint on the neutral Higgs searches!

Flavour constraints: $b \to s\gamma, B \to \tau\nu$ and new LHCb B_s results

Summary and Conclusion

Search for rare decays has been performed.

- New upper limit on BR for B_s and B^0 using 2011 data

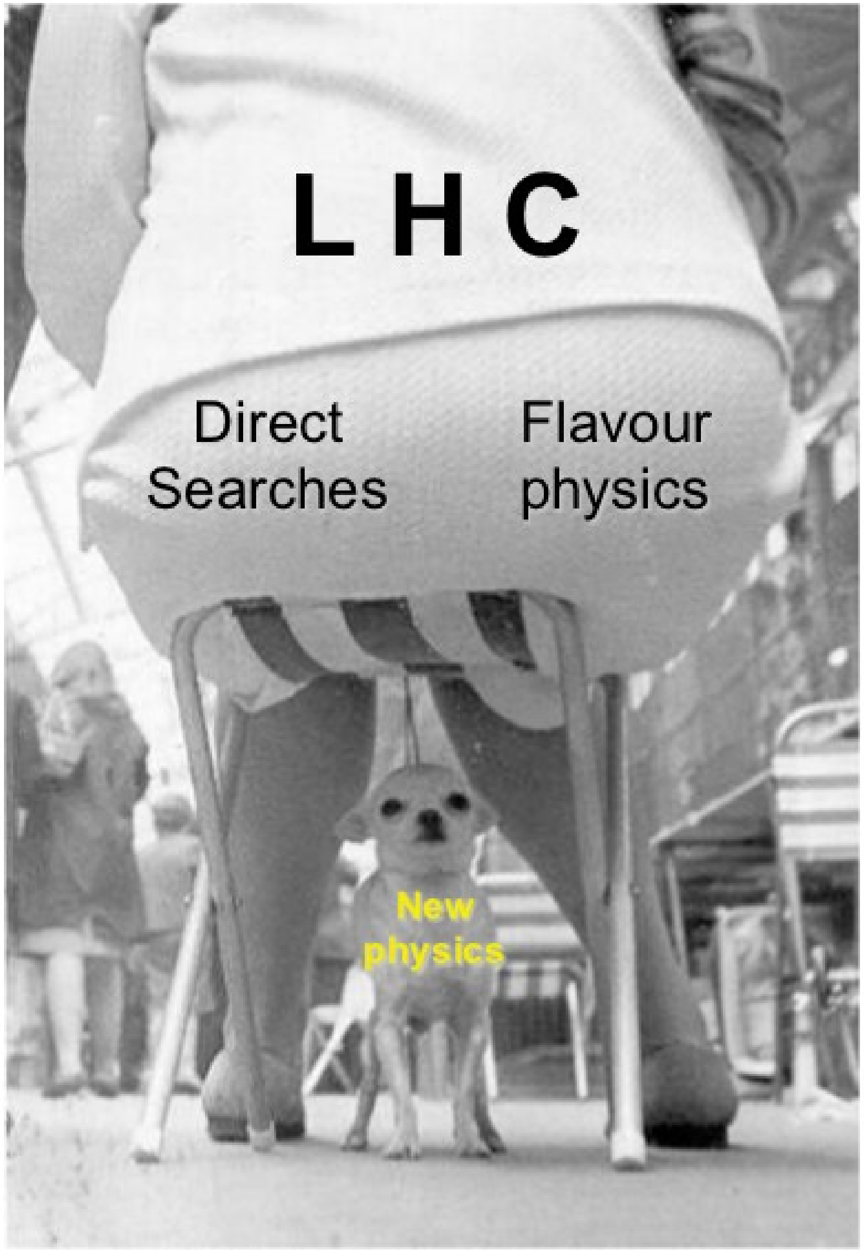
CMS has made searches sensitive to beyond the minimal higgs of the SM.

No evidence for non-standard higgs production or decay is found.

MSSM higgs parameter space is constrained by the studied modes.

With the expected > 15 fb^{-1} @ 8 TeV is likely to shed light on new physics.

BSM Physics @ 8 TeV

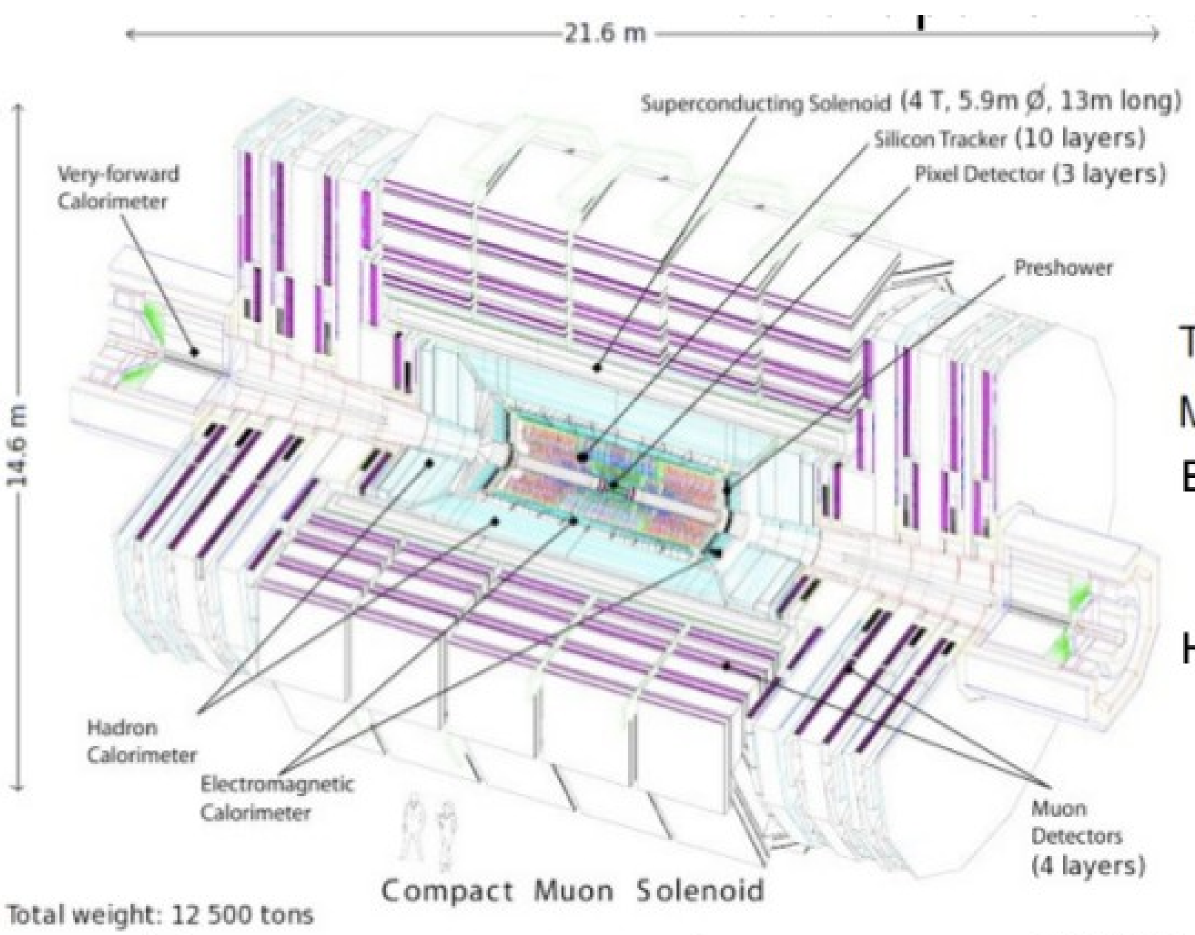


...AND YOU THINK YOU HAVE STRESS..

But don’t be desperate (yet)

Backup Slides

CMS detector



Tracker: $\sigma/p_T \simeq 1.5 \times 10^{-4} \times p_T \oplus 0.005$

Muon standalone @ 1 TeV: $\sigma/p_T \simeq 0.10$

Electromagnetic energy resolution

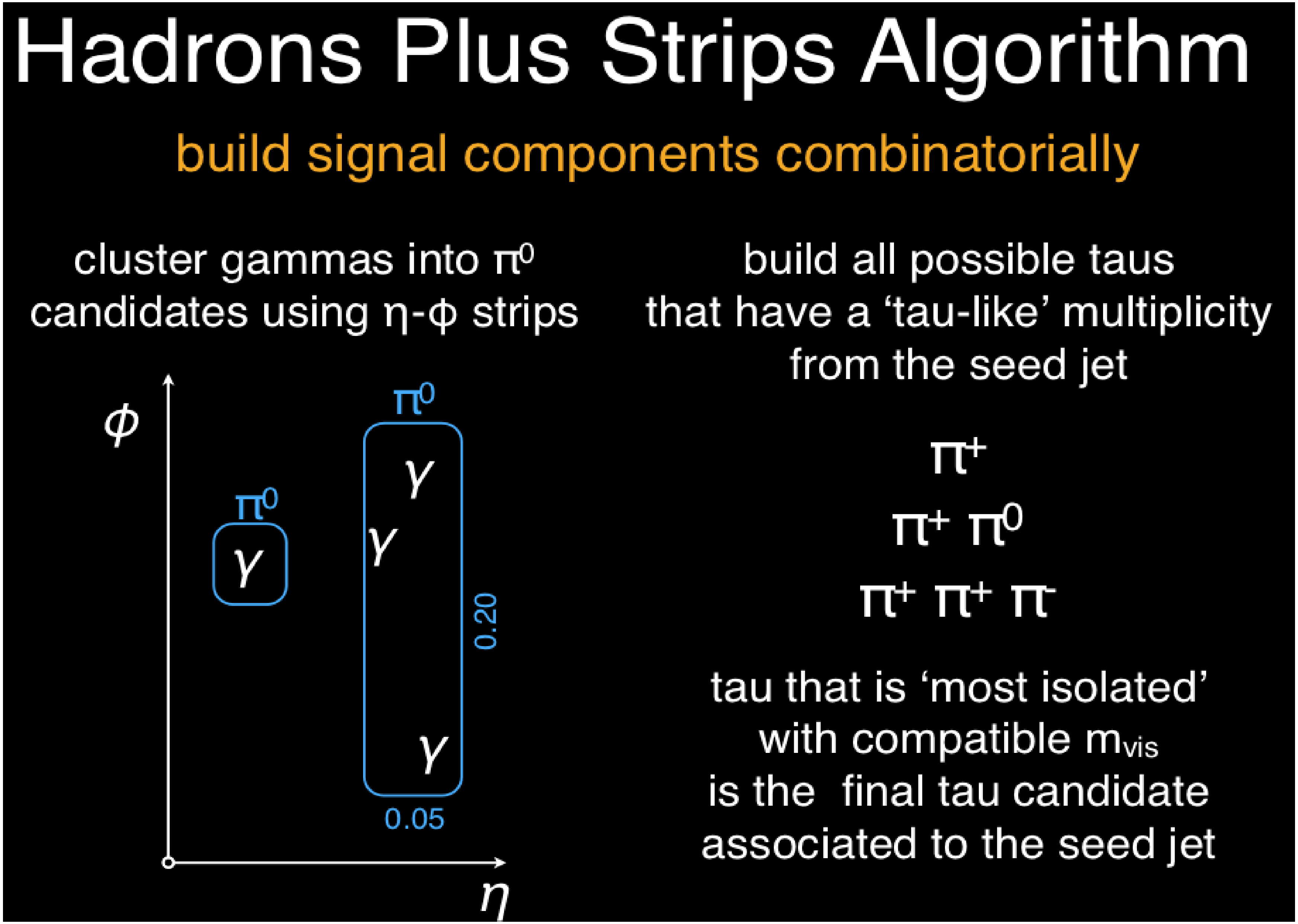
$$\frac{\sigma(E)}{E} = \frac{3\%}{\sqrt{E}} + 0.3\%$$

Hadronic energy resolution

$$\frac{\sigma(E)}{E} = \frac{100\%}{\sqrt{E}} + 5\%$$

- Trigger system setup to reduce input rate of 40MHz down to 100-200 Hz
  - ✓ Hardware level-1 40MHz → 100 kHz followed by PC farm with near-final reconstruction resolution
  - ➡ No triggering on inner tracks at L1 (available only in a couple of years)
  - ➡ Final trigger stage can select muons, electrons, photons, jets, MET, displaced vertices

Taus



Hadrons Plus Strips Algorithm

build signal components combinatorially

cluster gammas into π^0 candidates using η-ϕ strips

build all possible taus that have a 'tau-like' multiplicity from the seed jet

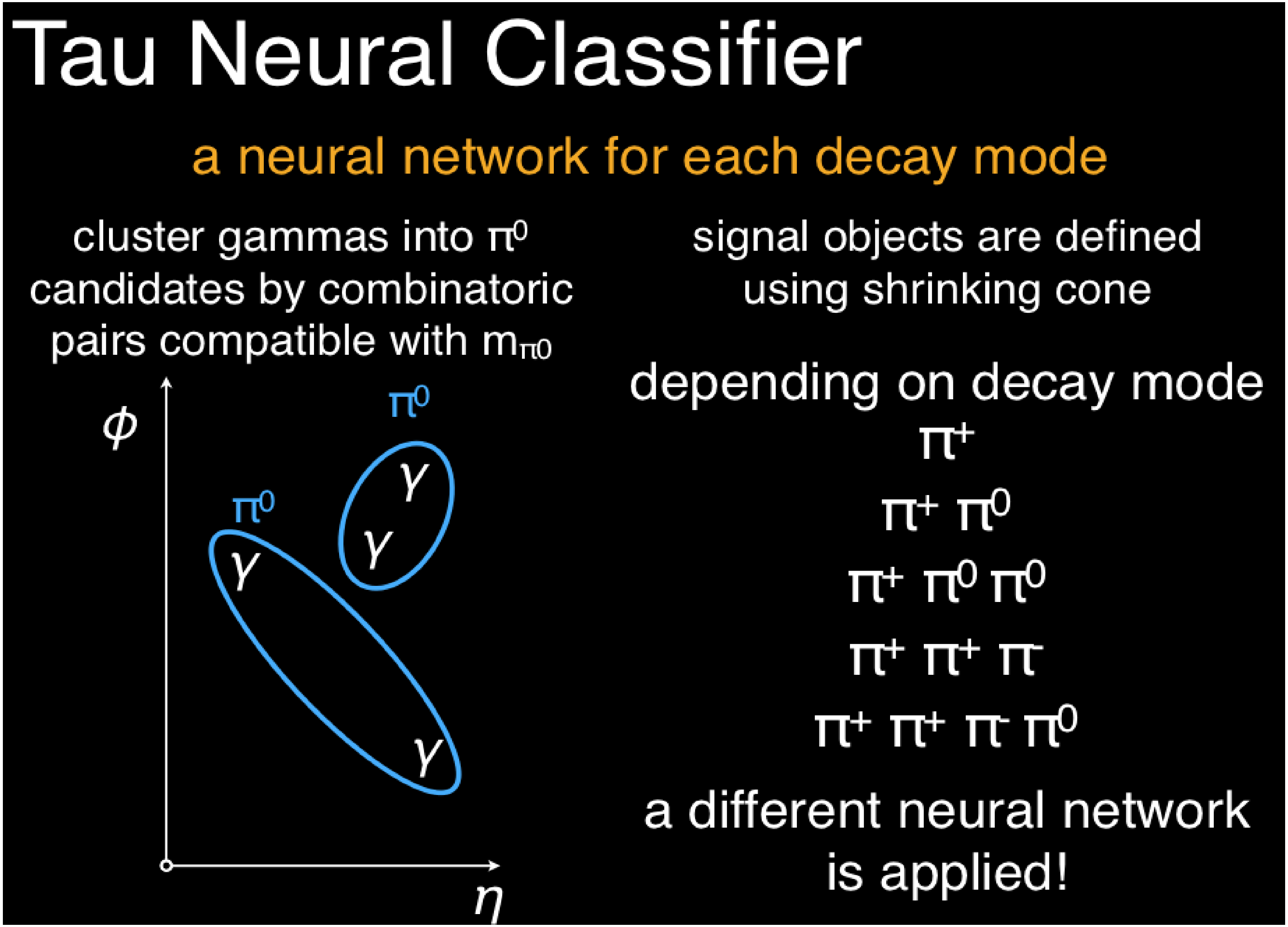
π^+

$\pi^+ \pi^0$

$\pi^+ \pi^+ \pi^-$

tau that is 'most isolated' with compatible m_{vis} is the final tau candidate associated to the seed jet

Taus



Tau Neural Classifier

a neural network for each decay mode

cluster gammas into π^0 candidates by combinatoric pairs compatible with $m_{\pi 0}$

signal objects are defined using shrinking cone

depending on decay mode

π^+

$\pi^+ \pi^0$

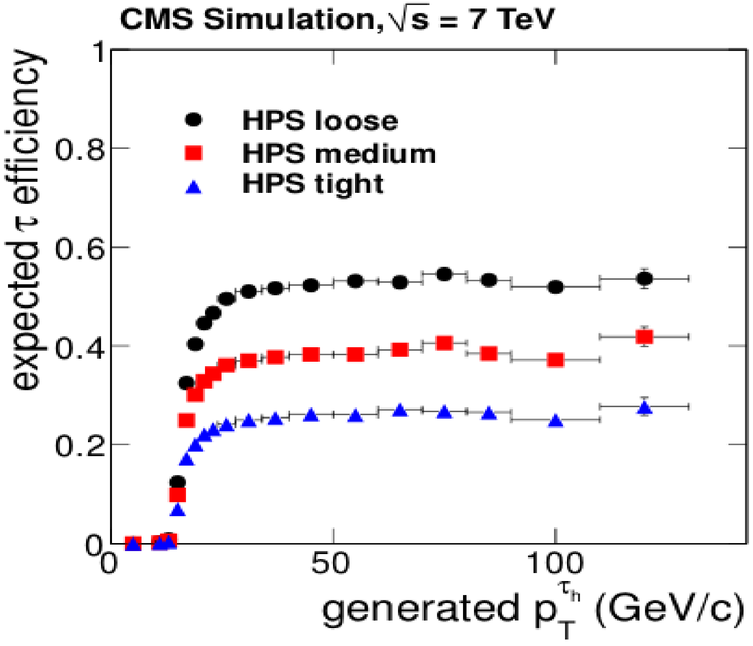
$\pi^+ \pi^0 \pi^0$

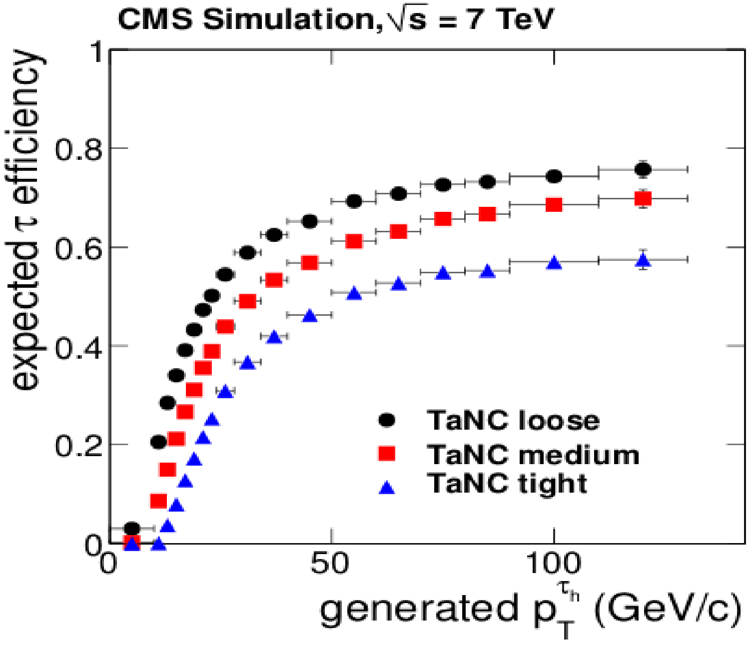
$\pi^+ \pi^+ \pi^-$

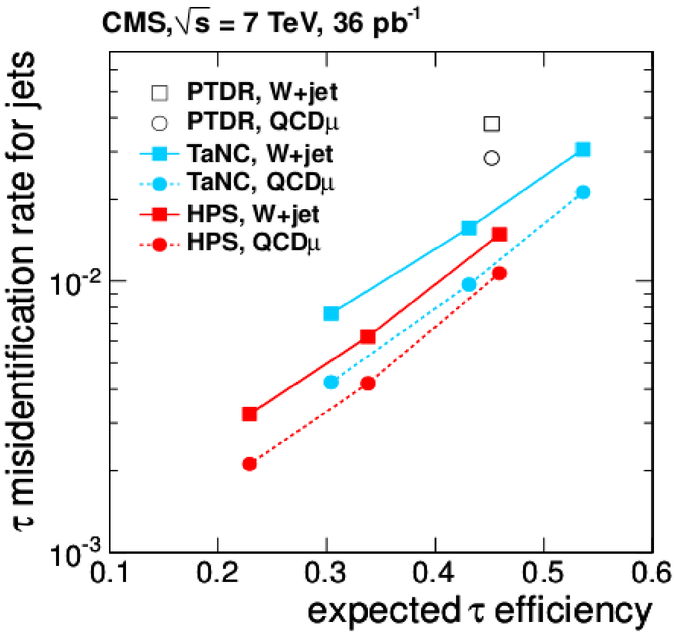
$\pi^+ \pi^+ \pi^- \pi^0$

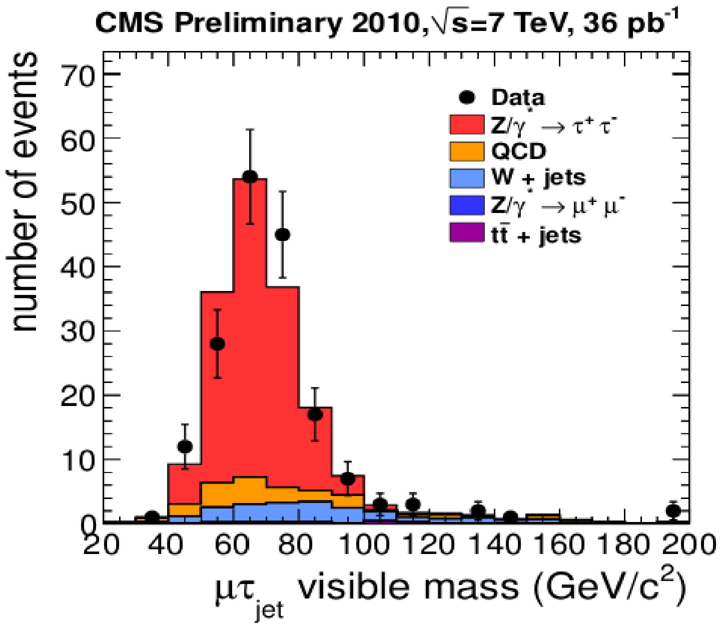
a different neural network is applied!

Taus

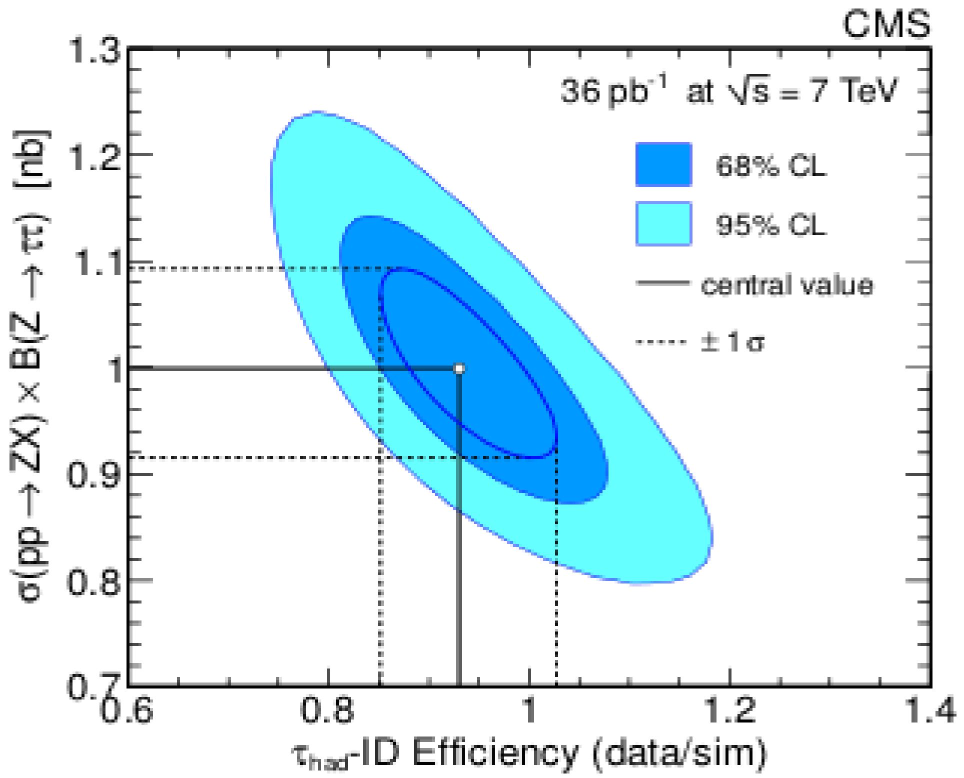

CMS Simulation, $\sqrt{s}$ = 7 TeV
expected τ efficiency
1
0.8
0.6
0.4
0.2
0
HPS loose
HPS medium
HPS tight
0
50
100
generated $p_T^{\tau_h}$ (GeV/c)

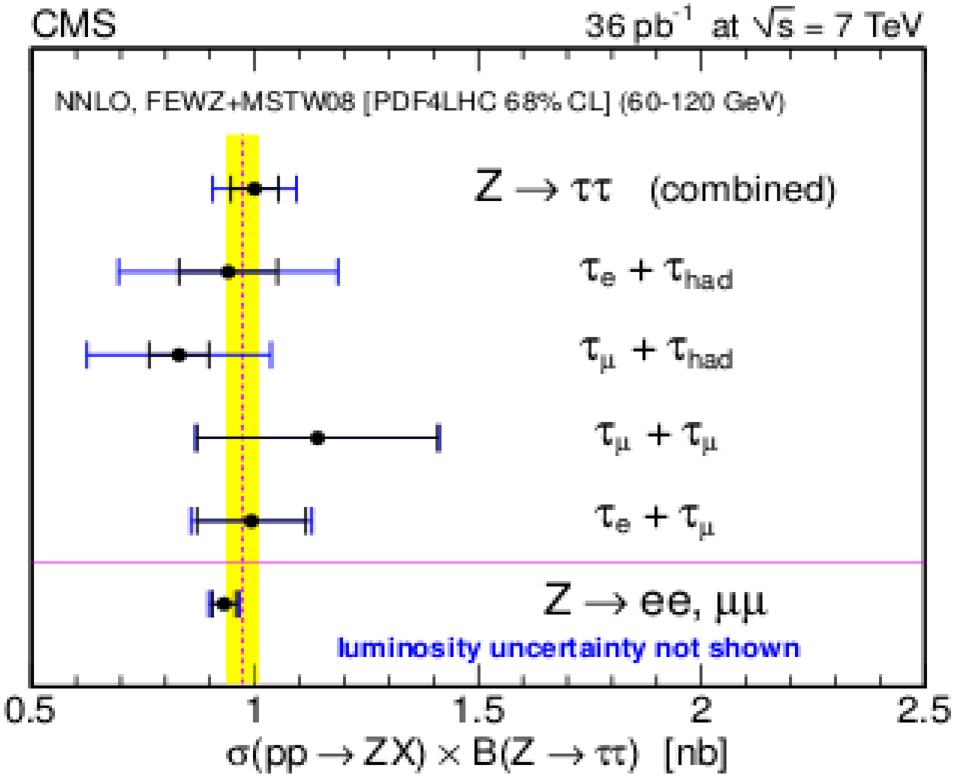

CMS Simulation, $\sqrt{s}$ = 7 TeV
expected τ efficiency
1
0.8
0.6
0.4
0.2
0
TaNC loose
TaNC medium
TaNC tight
0
50
100
generated $p_T^{\tau_h}$ (GeV/c)


CMS, $\sqrt{s}$ = 7 TeV, 36 pb^{-1}
τ misidentification rate for jets
10^{-2}
10^{-3}
PTDR, W+jet
PTDR, QCDμ
TaNC, W+jet
TaNC, QCDμ
HPS, W+jet
HPS, QCDμ
0.1
0.2
0.3
0.4
0.5
0.6
expected τ efficiency


CMS Preliminary 2010, $\sqrt{s}$=7 TeV, 36 pb^{-1}
number of events
70
60
50
40
30
20
10
0
Data
$Z/\gamma^* \rightarrow \tau^+\tau^-$
QCD
W + jets
$Z/\gamma^* \rightarrow \mu^+\mu^-$
$t\bar{t}$ + jets
20
40
60
80
100
120
140
160
180
200
$\mu\tau_{jet}$ visible mass (GeV/c^2)

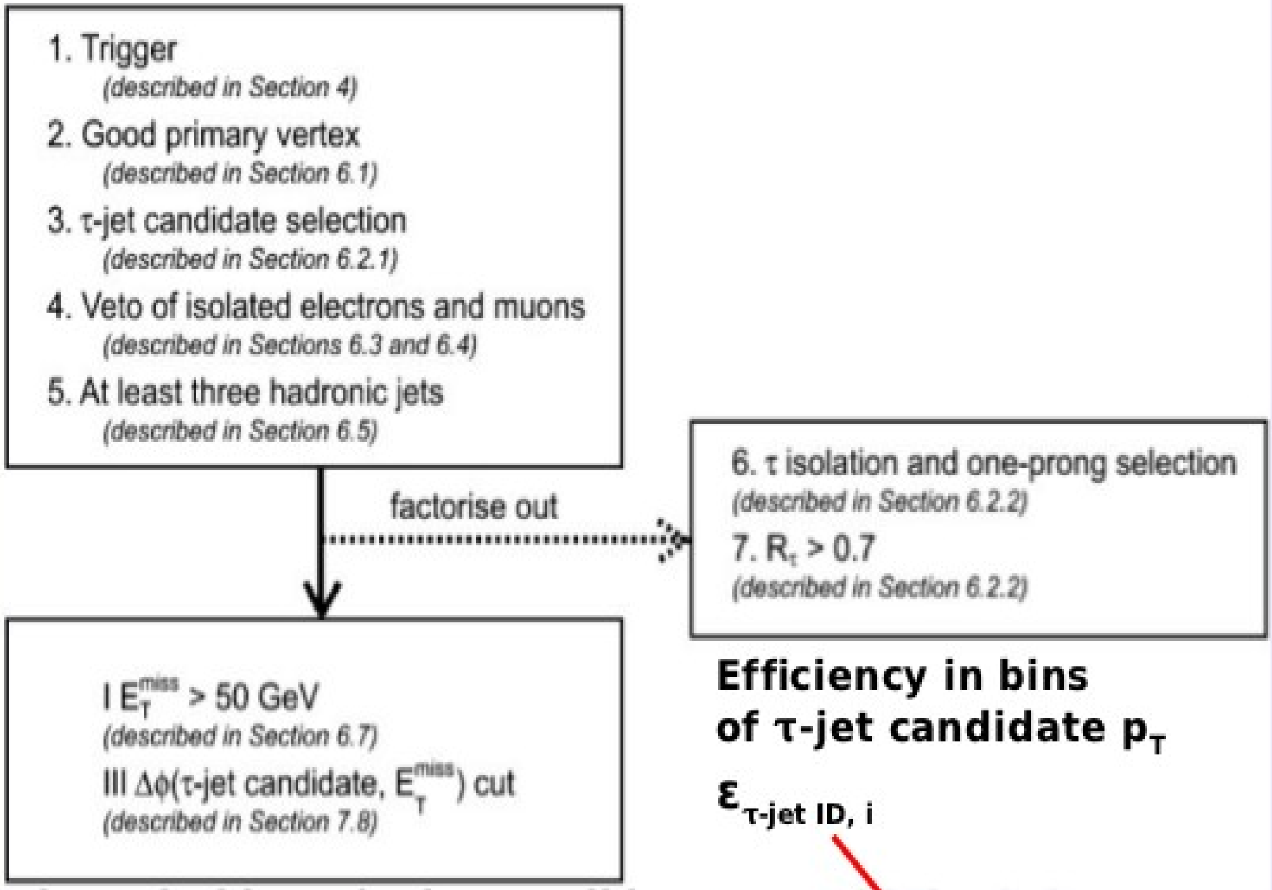
Taus


CMS
36 pb^{-1} at $\sqrt{s}$ = 7 TeV
68% CL
95% CL
central value
± 1σ
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.8
1
1.2
1.4
τ_{had}-ID Efficiency (data/sim)
σ(pp → ZX) × B(Z → ττ) [nb]


CMS
36 pb^{-1} at $\sqrt{s}$ = 7 TeV
NNLO, FEWZ+MSTW08 [PDF4LHC 68% CL] (60-120 GeV)
Z → ττ (combined)
$\tau_e + \tau_{had}$
$\tau_\mu + \tau_{had}$
$\tau_\mu + \tau_\mu$
$\tau_e + \tau_\mu$
Z → ee, μμ
luminosity uncertainty not shown
0.5
1
1.5
2
2.5
σ(pp → ZX) × B(Z → ττ) [nb]

MSSM – Charged Higgs QCD

- τ isolation, one prong, R_τ selections were factorized out from E_T^{miss} and Δϕ
- b tagging left out due to negligible effect on m_T shape
- EWK events (MC) subtracted from data to obtain number of QCD multi-jet events
- Shape normalized to N^{QCD}



1. Trigger
(described in Section 4)
2. Good primary vertex
(described in Section 6.1)
3. τ-jet candidate selection
(described in Section 6.2.1)
4. Veto of isolated electrons and muons
(described in Sections 6.3 and 6.4)
5. At least three hadronic jets
(described in Section 6.5)

factorise out

6. τ isolation and one-prong selection
(described in Section 6.2.2)
7. $R_\tau > 0.7$
(described in Section 6.2.2)

I E_T^{miss} > 50 GeV
(described in Section 6.7)
III Δϕ(τ-jet candidate, E_T^{miss}) cut
(described in Section 7.8)

Efficiency in bins of τ-jet candidate p_T

$\varepsilon_{\tau\text{-jet ID},\,i}$

m_T shape in bins of τ-jet candidate p_T

Number of events in m_T bin *j* for τ-jet p_T bin *i* (before normalization to N^{QCD}):

$$N_{ij} = \left(N^{\text{data}}_{basic\ selections+\text{I}+\text{III},\ ij} - N^{\text{EWK MC}}_{basic\ selections+\text{I}+\text{III},\ ij} \right) \times \varepsilon_{\tau\text{-jet ID},\ i}$$

MSSM – Charged Higgs QCD

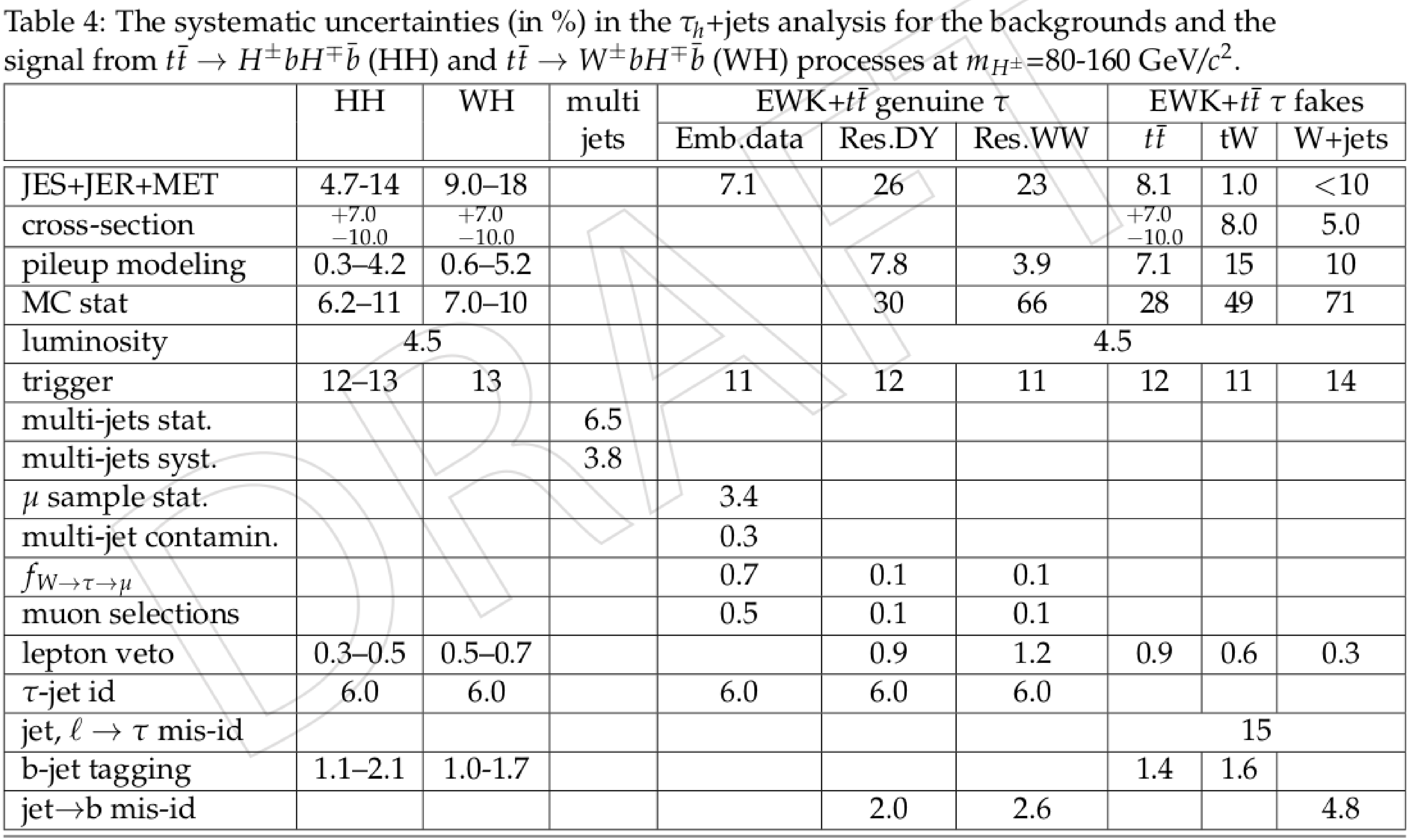


Table 4: The systematic uncertainties (in %) in the τ_h+jets analysis for the backgrounds and the signal from $t\bar{t} \rightarrow H^{\pm}bH^{\mp}\bar{b}$ (HH) and $t\bar{t} \rightarrow W^{\pm}bH^{\mp}\bar{b}$ (WH) processes at $m_{H^{\pm}}$=80-160 GeV/c^2.

	HH	WH	multi jets	EWK+$t\bar{t}$ genuine τ			EWK+$t\bar{t}$ τ fakes		
				Emb.data	Res.DY	Res.WW	$t\bar{t}$	tW	W+jets
JES+JER+MET	4.7-14	9.0–18		7.1	26	23	8.1	1.0	$<$10
cross-section	$^{+7.0}_{-10.0}$	$^{+7.0}_{-10.0}$					$^{+7.0}_{-10.0}$	8.0	5.0
pileup modeling	0.3–4.2	0.6–5.2			7.8	3.9	7.1	15	10
MC stat	6.2–11	7.0–10			30	66	28	49	71
luminosity	4.5				4.5				
trigger	12–13	13		11	12	11	12	11	14
multi-jets stat.			6.5						
multi-jets syst.			3.8						
μ sample stat.				3.4					
multi-jet contamin.				0.3					
$f_{W\rightarrow\tau\rightarrow\mu}$				0.7	0.1	0.1			
muon selections				0.5	0.1	0.1			
lepton veto	0.3–0.5	0.5–0.7			0.9	1.2	0.9	0.6	0.3
τ-jet id	6.0	6.0		6.0	6.0	6.0			
jet, $\ell \rightarrow \tau$ mis-id							15		
b-jet tagging	1.1–2.1	1.0-1.7					1.4	1.6	
jet$\rightarrow$b mis-id					2.0	2.6			4.8

MSSM – Charged Higgs QCD

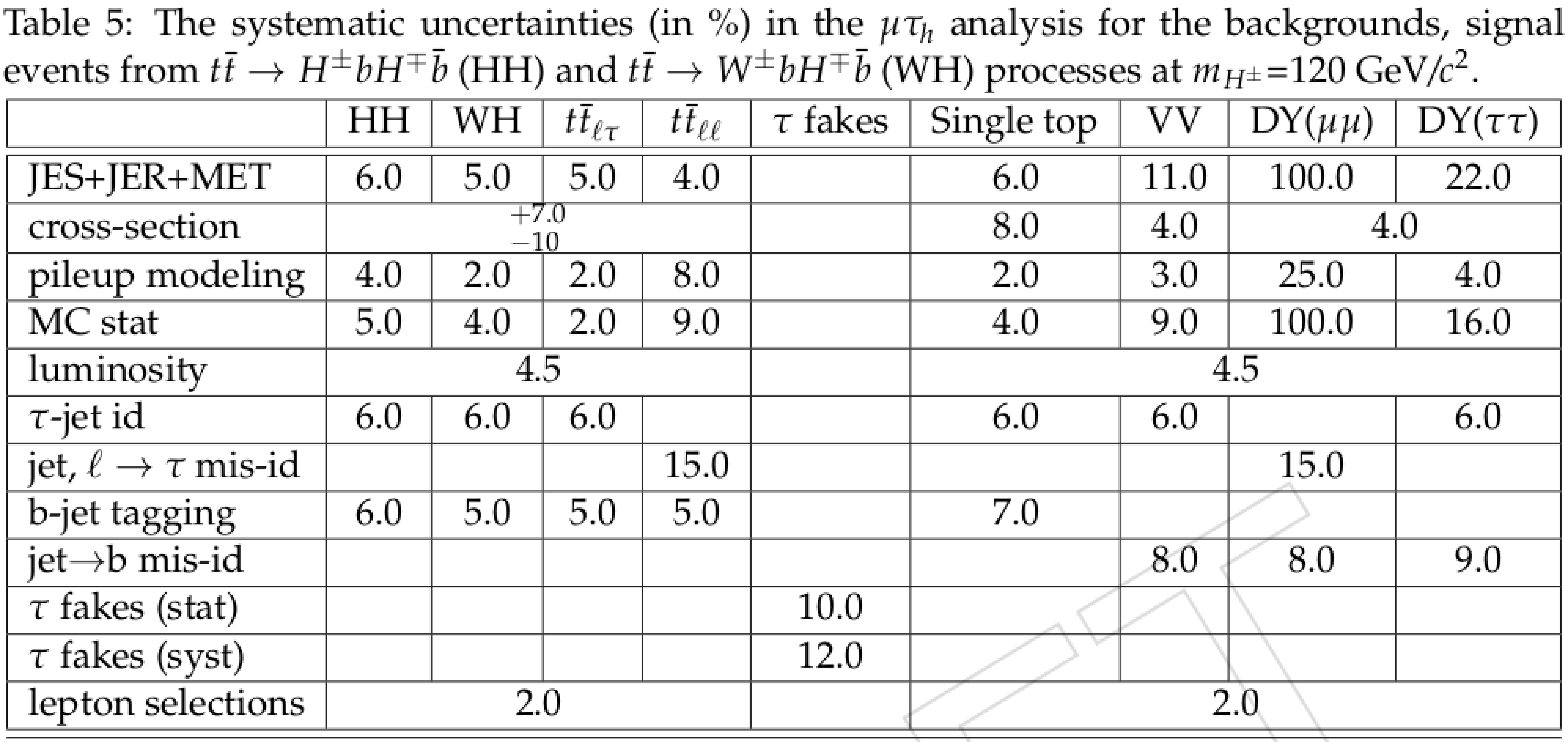


Table 5: The systematic uncertainties (in %) in the $\mu\tau_h$ analysis for the backgrounds, signal events from $t\bar{t} \to H^{\pm}bH^{\mp}\bar{b}$ (HH) and $t\bar{t} \to W^{\pm}bH^{\mp}\bar{b}$ (WH) processes at $m_{H^{\pm}}$=120 GeV/c^2.

	HH	WH	$t\bar{t}_{\ell\tau}$	$t\bar{t}_{\ell\ell}$	τ fakes	Single top	VV	DY($\mu\mu$)	DY($\tau\tau$)
JES+JER+MET	6.0	5.0	5.0	4.0		6.0	11.0	100.0	22.0
cross-section	$^{+7.0}_{-10}$					8.0	4.0	4.0	
pileup modeling	4.0	2.0	2.0	8.0		2.0	3.0	25.0	4.0
MC stat	5.0	4.0	2.0	9.0		4.0	9.0	100.0	16.0
luminosity	4.5					4.5			
τ-jet id	6.0	6.0	6.0			6.0	6.0		6.0
jet, $\ell \to \tau$ mis-id				15.0				15.0	
b-jet tagging	6.0	5.0	5.0	5.0		7.0			
jet$\to$b mis-id							8.0	8.0	9.0
τ fakes (stat)					10.0				
τ fakes (syst)					12.0				
lepton selections	2.0					2.0			

MSSM – Charged Higgs QCD

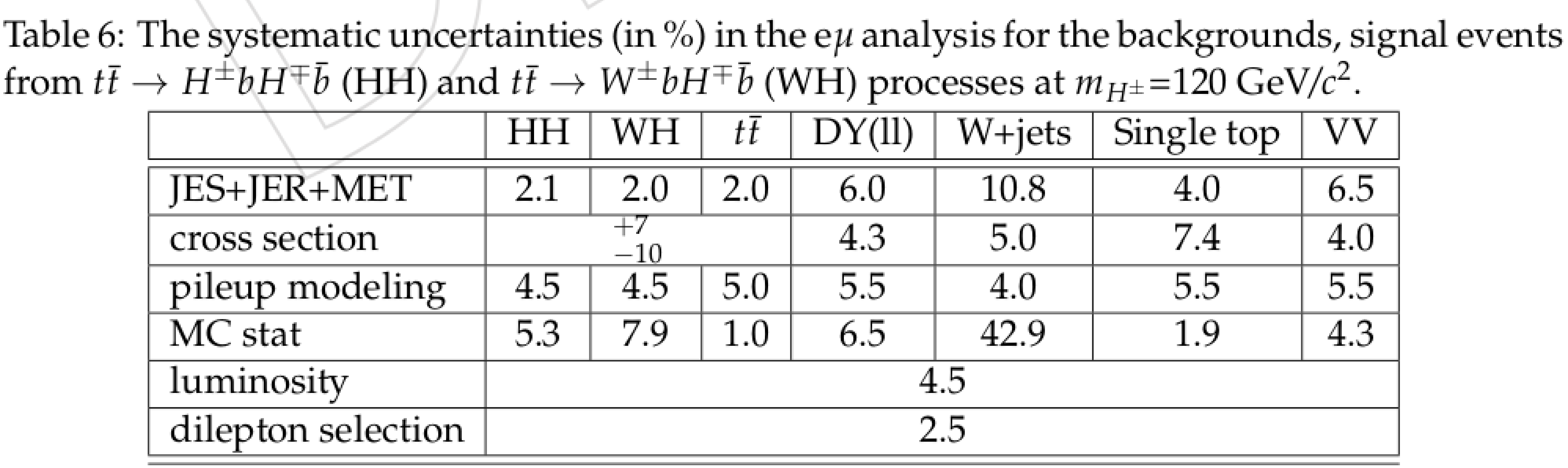
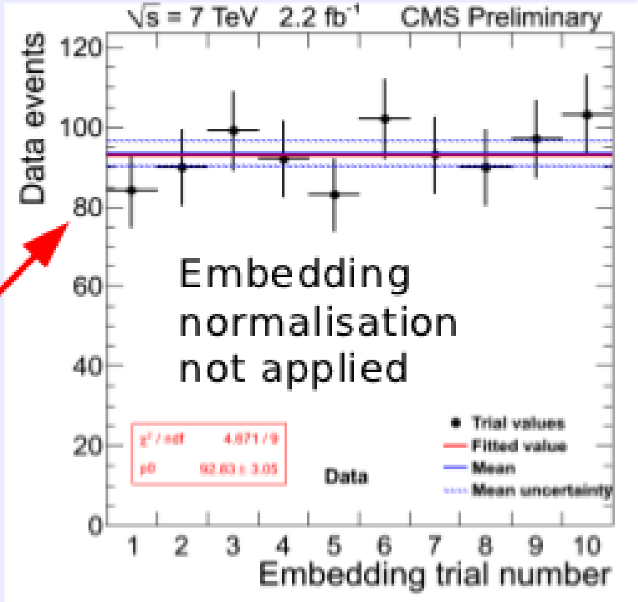


Table 6: The systematic uncertainties (in %) in the eμ analysis for the backgrounds, signal events from $t\bar{t} \to H^{\pm}bH^{\mp}\bar{b}$ (HH) and $t\bar{t} \to W^{\pm}bH^{\mp}\bar{b}$ (WH) processes at $m_{H^{\pm}}$=120 GeV/c^2.

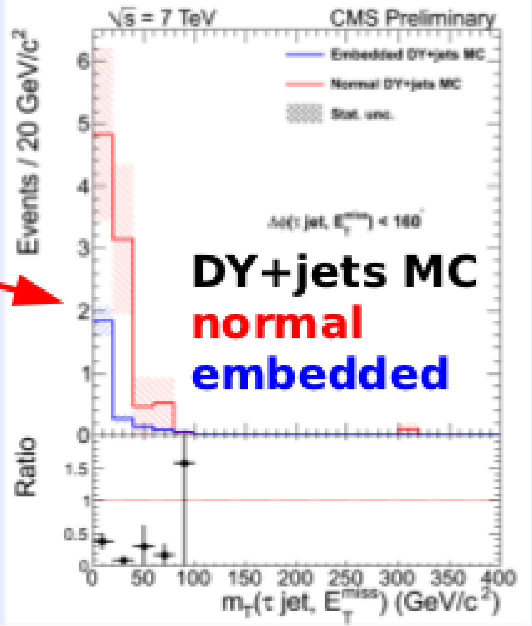
	HH	WH	$t\bar{t}$	DY(ll)	W+jets	Single top	VV
JES+JER+MET	2.1	2.0	2.0	6.0	10.8	4.0	6.5
cross section	$^{+7}_{-10}$			4.3	5.0	7.4	4.0
pileup modeling	4.5	4.5	5.0	5.5	4.0	5.5	5.5
MC stat	5.3	7.9	1.0	6.5	42.9	1.9	4.3
luminosity	4.5						
dilepton selection	2.5						

MSSM – Charged Higgs (replacement method)

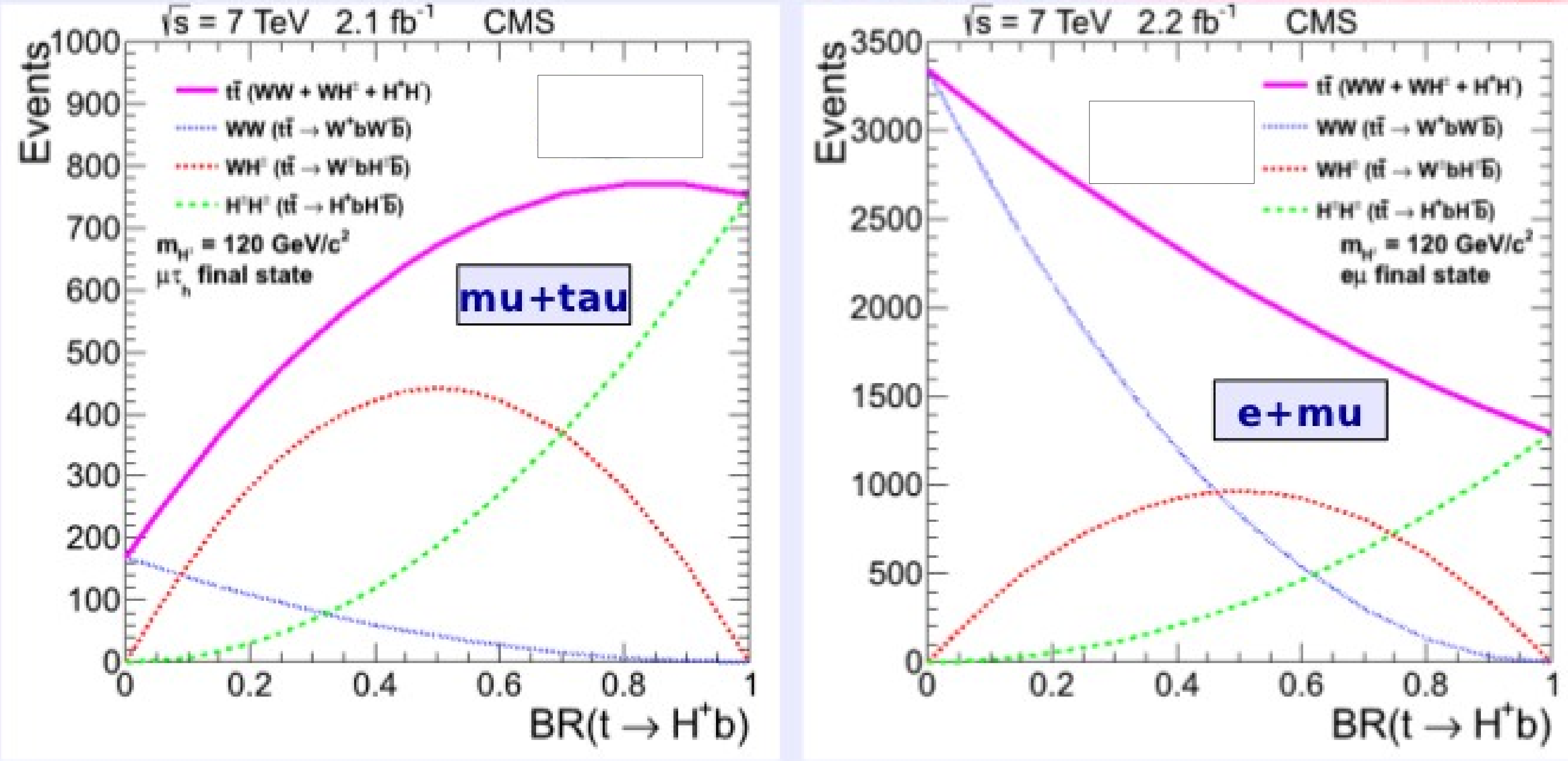
- Normalization
  - Tau trigger by applying efficiency as a function of τ-jet p_T
  - MET trigger by requiring caloMET (with tau added) > 60 GeV
  - Muon trigger and ID efficiency measured with Tag and Probe
- Multiple embedding trials in order to improve statistical precision
  - Mean value of 10 trials



- Residual background from ditau events (DY and diboson (WW))
  - Veto of second μ is tighter cut than veto of second τ jet (μ ID is more efficient than τ-jet ID)
  - $N^{total} = N^{emb.\ data} + N^{res.\ MC\ DY} + N^{res.\ MC\ WW}$, where $N^{res.\ MC} = N^{normal\ MC} - N^{emb.\ MC}$



MSSM – Charged Higgs



- Upper limit for BR(t → bH⁺)=x with
  - $N_{up} = N_{tt}^{SUSY} - N_{tt}^{SM} = N_{WH}\,2(1-x)x + N_{HH}x^2 + N_{tt}^{SM}((1-x)^2-1)$
- Excess of events expected in fully hadronic, e/mu+tau, while in e+mu we expect a deficit

MSSM – Neutral Higgs

- ***b-Tag category:*** We require at most one jet with $p_{\mathrm{T}} > 30$ GeV and at least one b-tagged jet with $p_{\mathrm{T}} > 20$ GeV.
- ***Non b-Tag category:*** We require at most one jet with $p_{\mathrm{T}} > 30$ GeV and no b-tagged jet with $p_{\mathrm{T}} > 20$ GeV.

The SM search has three categories:

- ***VBF category:*** We require at least two jets with $p_{\mathrm{T}} > 30$ GeV, $|\Delta\eta_{jj}| > 4.0$, $\eta_1 \cdot \eta_2 < 0$, and a dijet invariant mass $m_{jj} > 400$ GeV, with no other jet with $p_{\mathrm{T}} > 30$ GeV in the rapidity region between the two jets.
- ***Boosted category:*** We require one jet with $p_{\mathrm{T}} > 150$ GeV, and, in the eμ channel, no b-tagged jet with $p_{\mathrm{T}} > 20$ GeV.

- ***0/1 Jet category:*** We require no more than one jet with $p_{\mathrm{T}} > 30$ GeV, and if such a jet is present, it must have $p_{\mathrm{T}} < 150$ GeV.

MSSM – Neutral Higgs

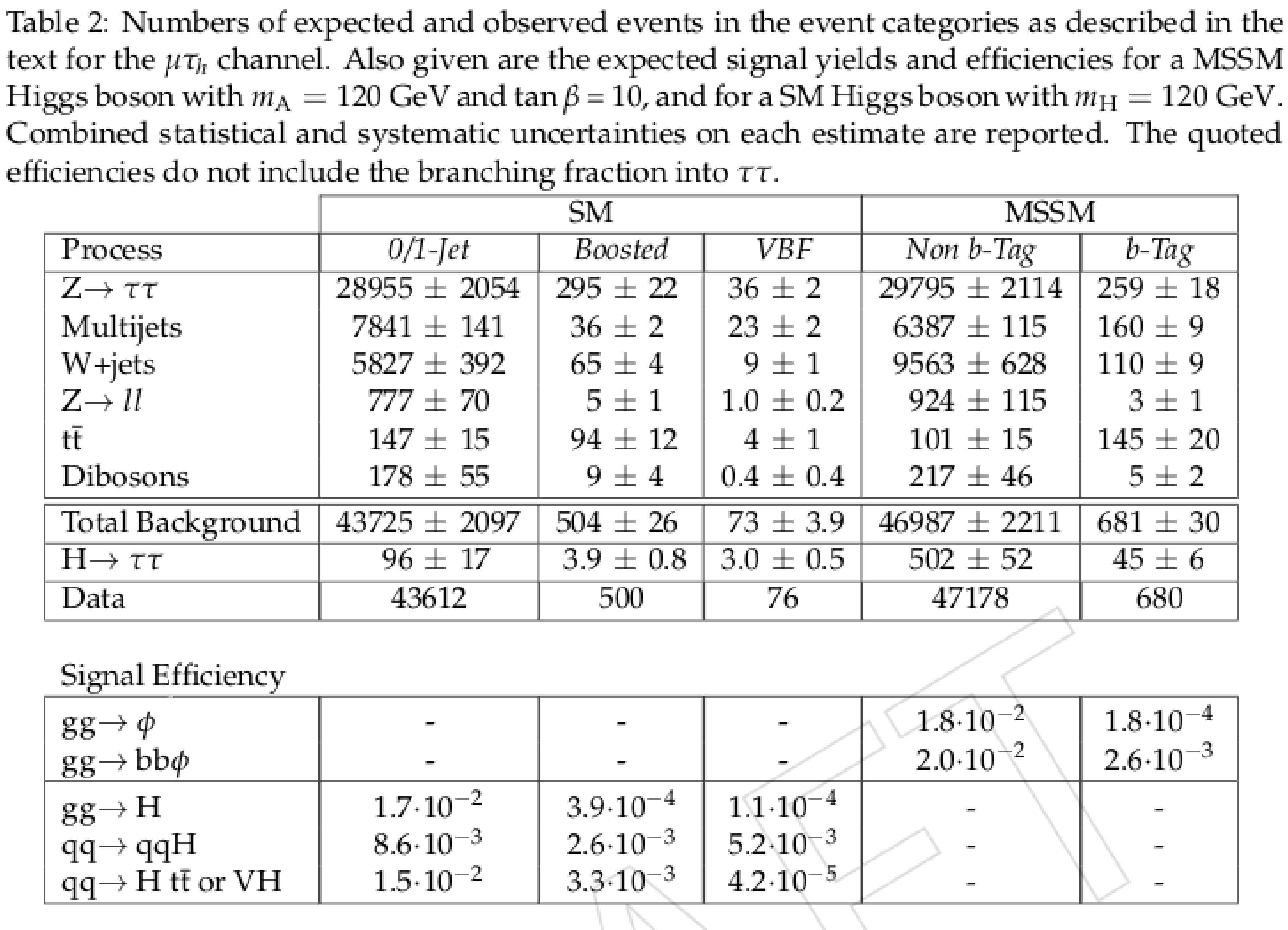


Table 2: Numbers of expected and observed events in the event categories as described in the text for the $\mu\tau_h$ channel. Also given are the expected signal yields and efficiencies for a MSSM Higgs boson with $m_A = 120$ GeV and $\tan\beta = 10$, and for a SM Higgs boson with $m_H = 120$ GeV. Combined statistical and systematic uncertainties on each estimate are reported. The quoted efficiencies do not include the branching fraction into $\tau\tau$.

	SM			MSSM	
Process	*0/1-Jet*	*Boosted*	*VBF*	*Non b-Tag*	*b-Tag*
$Z\rightarrow\tau\tau$	28955 ± 2054	295 ± 22	36 ± 2	29795 ± 2114	259 ± 18
Multijets	7841 ± 141	36 ± 2	23 ± 2	6387 ± 115	160 ± 9
W+jets	5827 ± 392	65 ± 4	9 ± 1	9563 ± 628	110 ± 9
$Z\rightarrow ll$	777 ± 70	5 ± 1	1.0 ± 0.2	924 ± 115	3 ± 1
$t\bar{t}$	147 ± 15	94 ± 12	4 ± 1	101 ± 15	145 ± 20
Dibosons	178 ± 55	9 ± 4	0.4 ± 0.4	217 ± 46	5 ± 2
Total Background	43725 ± 2097	504 ± 26	73 ± 3.9	46987 ± 2211	681 ± 30
$H\rightarrow\tau\tau$	96 ± 17	3.9 ± 0.8	3.0 ± 0.5	502 ± 52	45 ± 6
Data	43612	500	76	47178	680

Signal Efficiency

$gg\rightarrow\phi$	-	-	-	$1.8\cdot10^{-2}$	$1.8\cdot10^{-4}$
$gg\rightarrow bb\phi$	-	-	-	$2.0\cdot10^{-2}$	$2.6\cdot10^{-3}$
$gg\rightarrow H$	$1.7\cdot10^{-2}$	$3.9\cdot10^{-4}$	$1.1\cdot10^{-4}$	-	-
$qq\rightarrow qqH$	$8.6\cdot10^{-3}$	$2.6\cdot10^{-3}$	$5.2\cdot10^{-3}$	-	-
$qq\rightarrow H\,t\bar{t}$ or VH	$1.5\cdot10^{-2}$	$3.3\cdot10^{-3}$	$4.2\cdot10^{-5}$	-	-

Doubly charged higgs

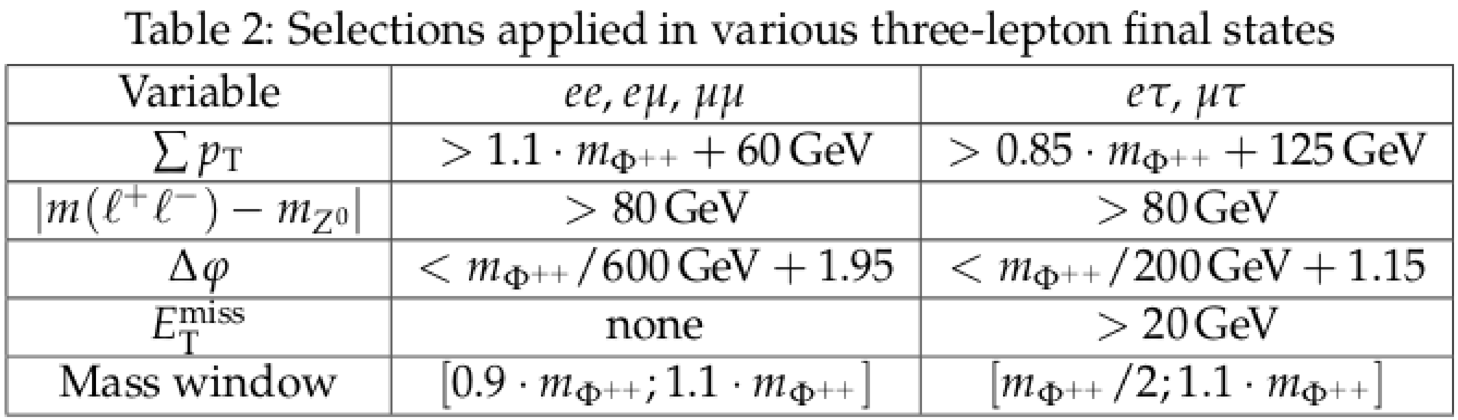


Table 2: Selections applied in various three-lepton final states

Variable	$ee, e\mu, \mu\mu$	$e\tau, \mu\tau$
$\sum p_{\mathrm{T}}$	$> 1.1 \cdot m_{\Phi^{++}} + 60\,\mathrm{GeV}$	$> 0.85 \cdot m_{\Phi^{++}} + 125\,\mathrm{GeV}$
$\lvert m(\ell^+\ell^-) - m_{Z^0}\rvert$	$> 80\,\mathrm{GeV}$	$> 80\,\mathrm{GeV}$
$\Delta\varphi$	$< m_{\Phi^{++}}/600\,\mathrm{GeV} + 1.95$	$< m_{\Phi^{++}}/200\,\mathrm{GeV} + 1.15$
$E_{\mathrm{T}}^{\mathrm{miss}}$	none	$> 20\,\mathrm{GeV}$
Mass window	$[0.9 \cdot m_{\Phi^{++}}; 1.1 \cdot m_{\Phi^{++}}]$	$[m_{\Phi^{++}}/2; 1.1 \cdot m_{\Phi^{++}}]$

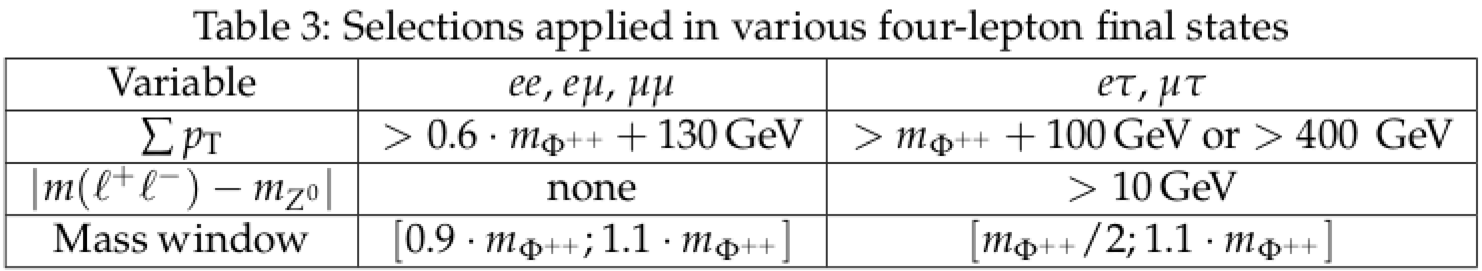


Table 3: Selections applied in various four-lepton final states

Variable	$ee, e\mu, \mu\mu$	$e\tau, \mu\tau$
$\sum p_{\mathrm{T}}$	$> 0.6 \cdot m_{\Phi^{++}} + 130\,\mathrm{GeV}$	$> m_{\Phi^{++}} + 100\,\mathrm{GeV}$ or > 400 GeV
$\lvert m(\ell^+\ell^-) - m_{Z^0}\rvert$	none	$> 10\,\mathrm{GeV}$
Mass window	$[0.9 \cdot m_{\Phi^{++}}; 1.1 \cdot m_{\Phi^{++}}]$	$[m_{\Phi^{++}}/2; 1.1 \cdot m_{\Phi^{++}}]$

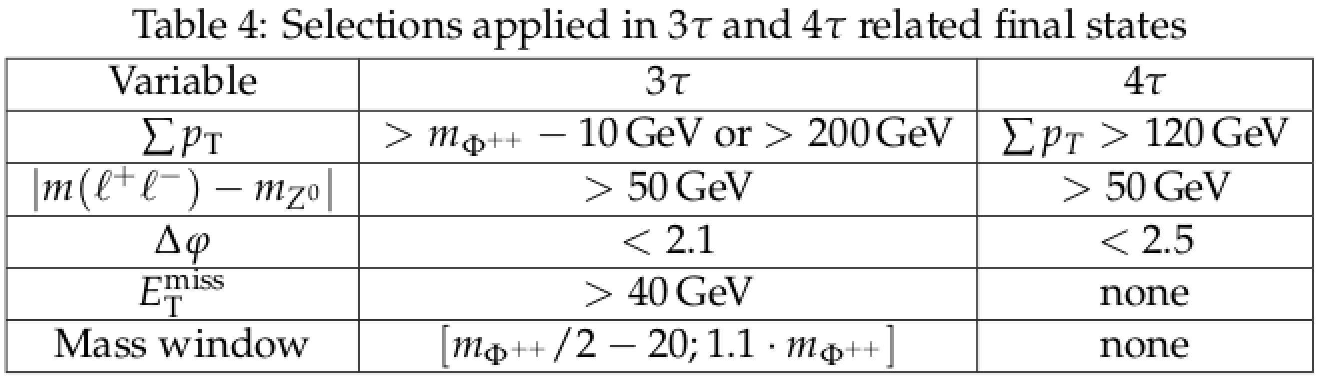


Table 4: Selections applied in 3τ and 4τ related final states

Variable	3τ	4τ
$\sum p_{\mathrm{T}}$	$> m_{\Phi^{++}} - 10\,\mathrm{GeV}$ or $> 200\,\mathrm{GeV}$	$\sum p_T > 120\,\mathrm{GeV}$
$\lvert m(\ell^+\ell^-) - m_{Z^0}\rvert$	$> 50\,\mathrm{GeV}$	$> 50\,\mathrm{GeV}$
$\Delta\varphi$	< 2.1	< 2.5
$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 40\,\mathrm{GeV}$	none
Mass window	$[m_{\Phi^{++}}/2 - 20; 1.1 \cdot m_{\Phi^{++}}]$	none

Doubly charged higgs

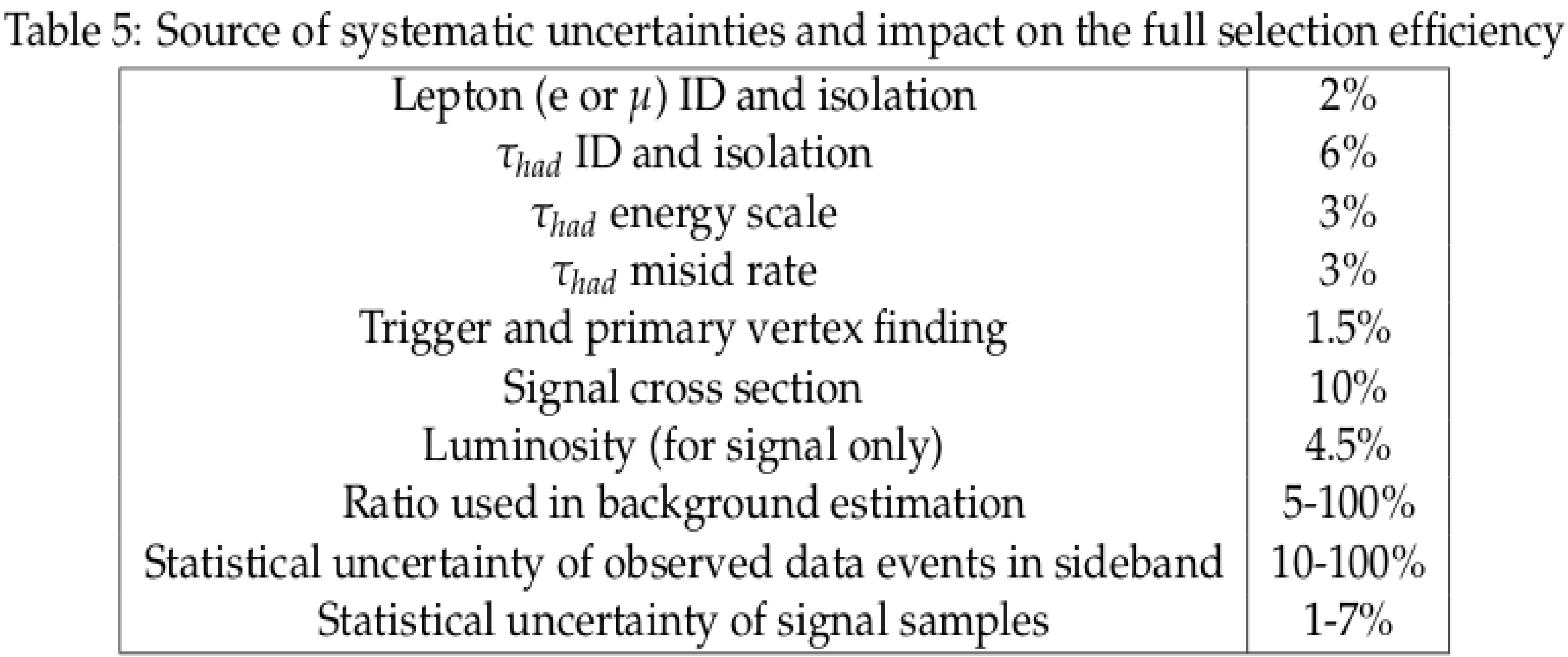


Table 5: Source of systematic uncertainties and impact on the full selection efficiency

Lepton (e or μ) ID and isolation	2%
τ_{had} ID and isolation	6%
τ_{had} energy scale	3%
τ_{had} misid rate	3%
Trigger and primary vertex finding	1.5%
Signal cross section	10%
Luminosity (for signal only)	4.5%
Ratio used in background estimation	5-100%
Statistical uncertainty of observed data events in sideband	10-100%
Statistical uncertainty of signal samples	1-7%

Light pseudoscalar Higgs

For the QCD background, we use a first-order polynomial probability density function (PDF). Each Υ is parametrized via a double Crystal Ball (CB) function. A CB function is formed convoluting a core Gaussian resolution with a power law side tail describing final state radiation. The resolution of one CB is left free in the fit but is constrained to be the same for all the three resonances. The resolution of the other CB function is determined from the fit on the Υ(1S) peak, and forced to scale with the mass of the other two resonances. As the resonances overlap, we fit for the presence of all three Υ states simultaneously. Therefore the PDF consists of three double CB functions. The mean of the CB of the Υ(1S) is left free in the fit, to accommodate a possible bias in the momentum scale calibration. The number of free parameters is reduced by fixing the Υ(2S) and Υ(3S) mass difference, relative to Υ(1S), to their world average values.

The fit to the Υ shape and continuum background is performed in the two acceptance regions (barrel and endcaps) separately, as shown in Figure 2. The number of events of Υ and continuum determined from the fit are given in Table 1.

Table 1: Summary of the number of events of Υ and continuum background from the invariant mass fit. The Υ contribution is summed over the three resonances.

Contribution	Number of events (barrel)	Number of events (endcap)
Υ	93753 ± 396	95876 ± 454
Continuum background	41210 ± 320	45792 ± 385