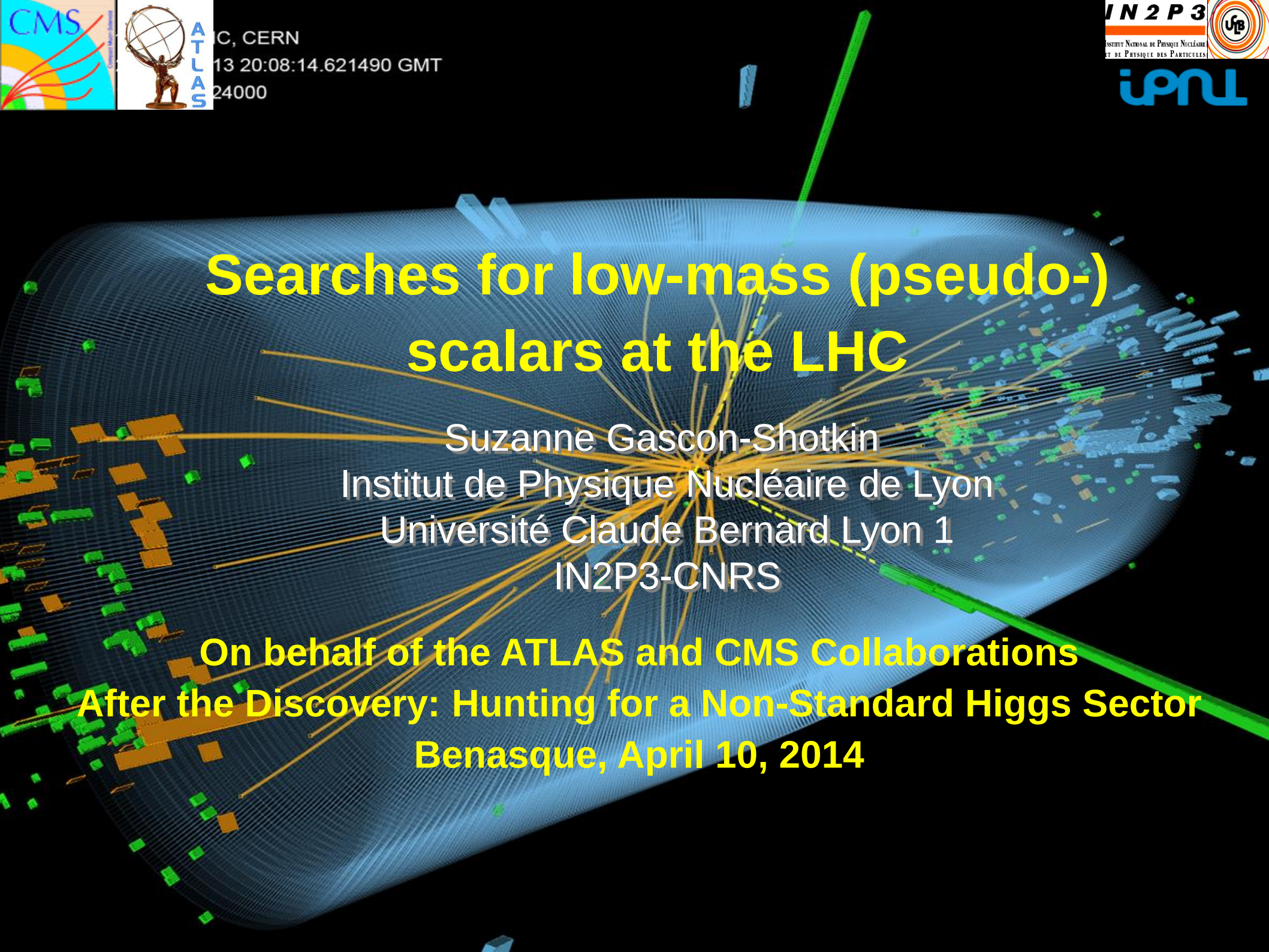

Searches for low-mass (pseudo-) scalars at the LHC

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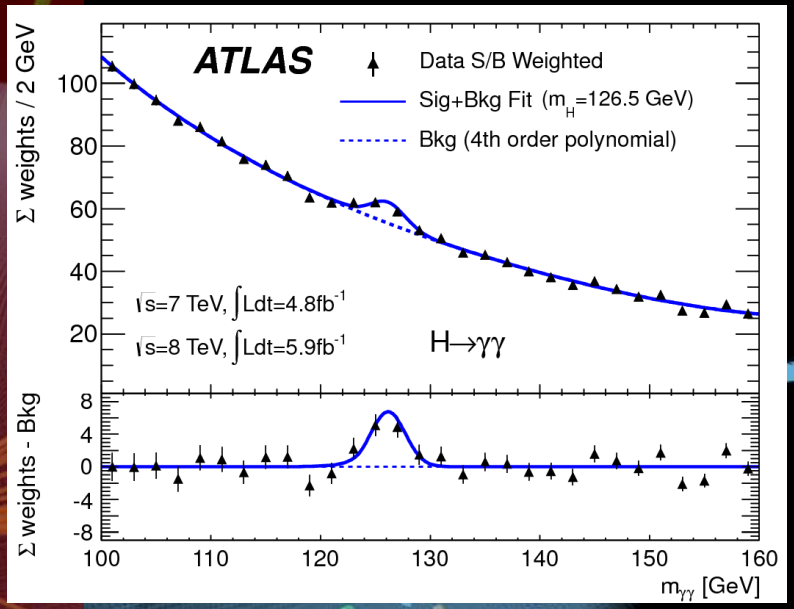
On behalf of the ATLAS and CMS Collaborations

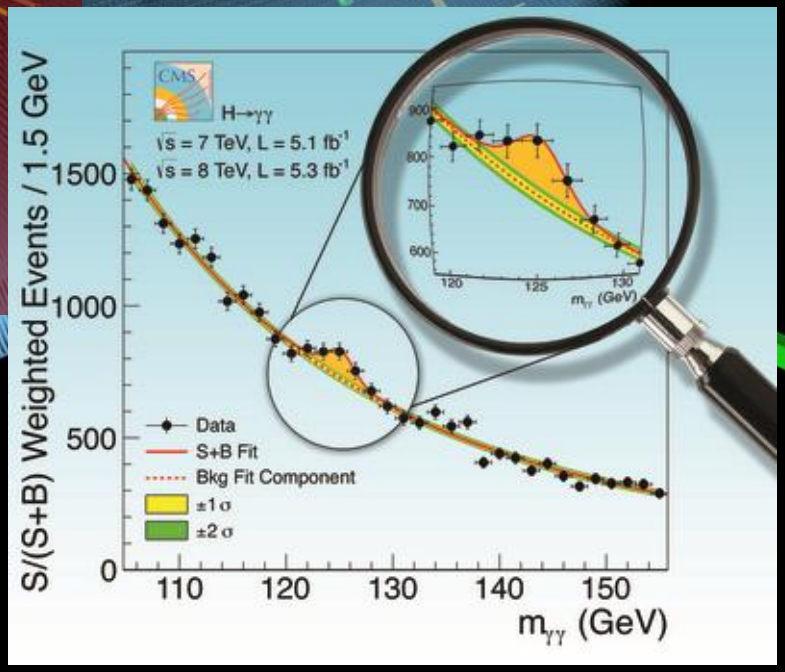
After the Discovery: Hunting for a Non-Standard Higgs Sector

Benasque, April 10, 2014

Outline

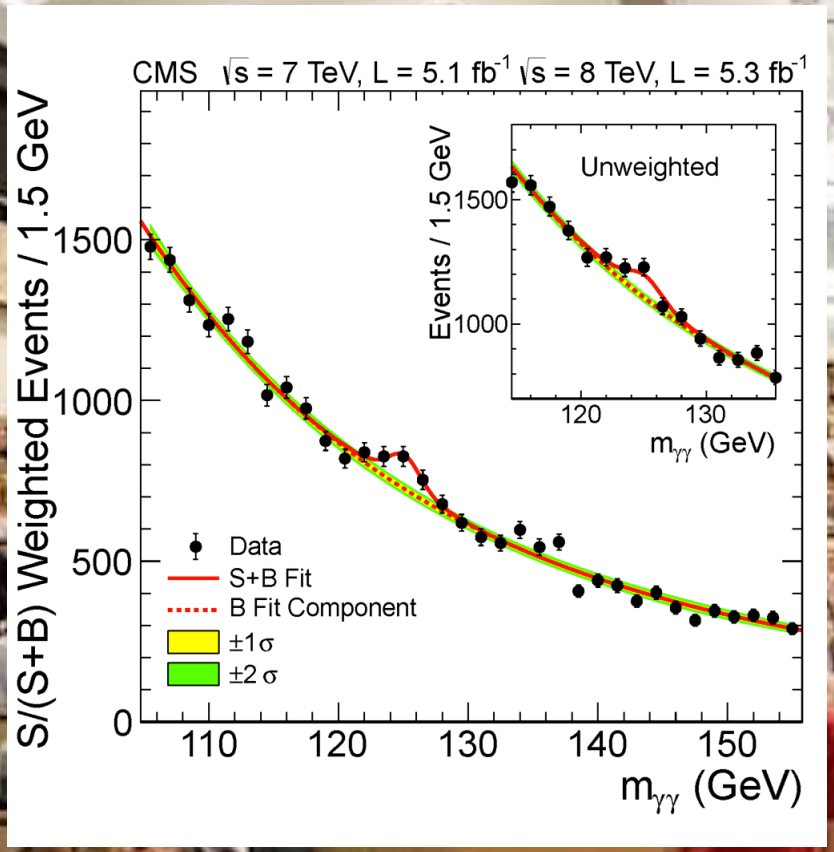
- Introduction: One scalar discovered, are there others at even lower masses?
- BSM models allowing low-mass (pseudo)-scalars
- Results from LHC Run 1:
  - MSSM: neutral scalars
  - MSSM: charged scalars
  - NMSSM: scalars and pseudoscalars
  - Scalars in Fermiophobic and 4th generation
- Challenges for LHC Run 2 and beyond
- Summary and Conclusion
- Acknowledgements

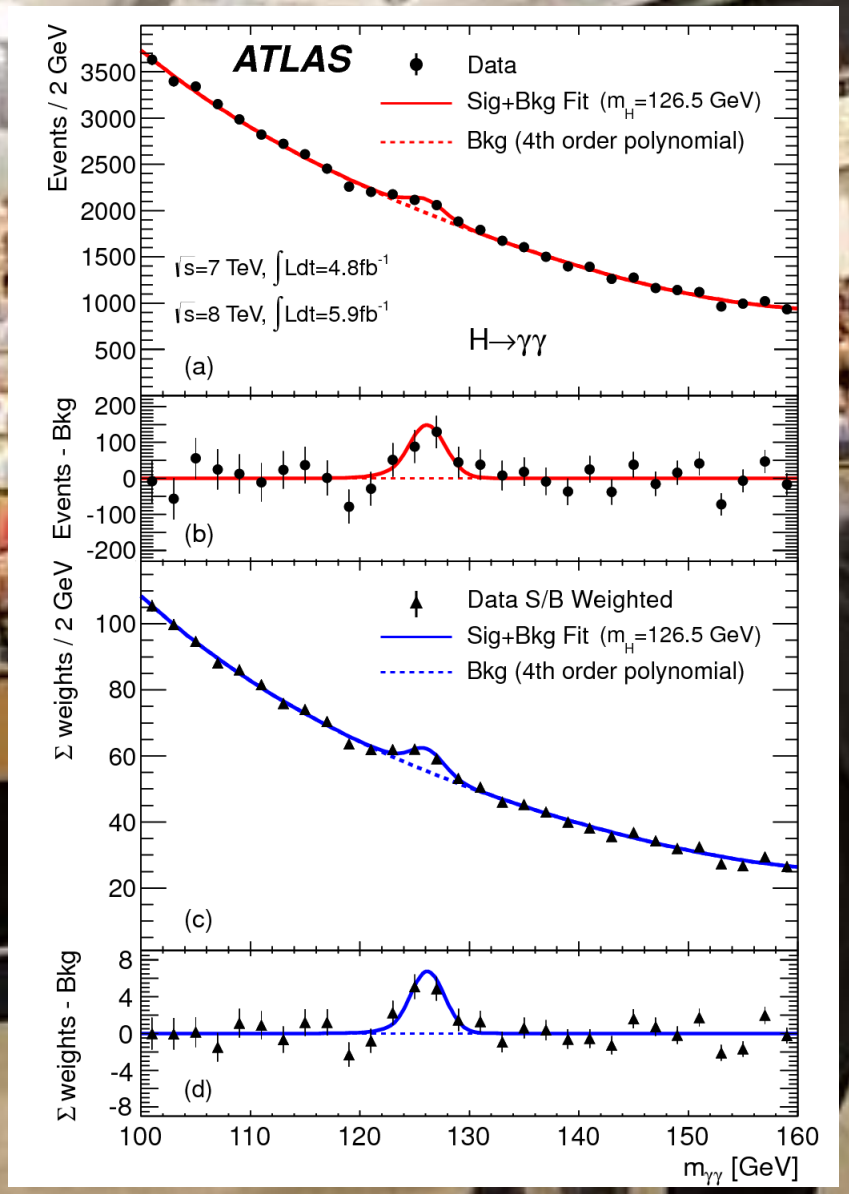




Introduction: July 4 2012, 9:30 AM…..

- "This result constitutes evidence for the existence of a new massive state that decays into two photons."



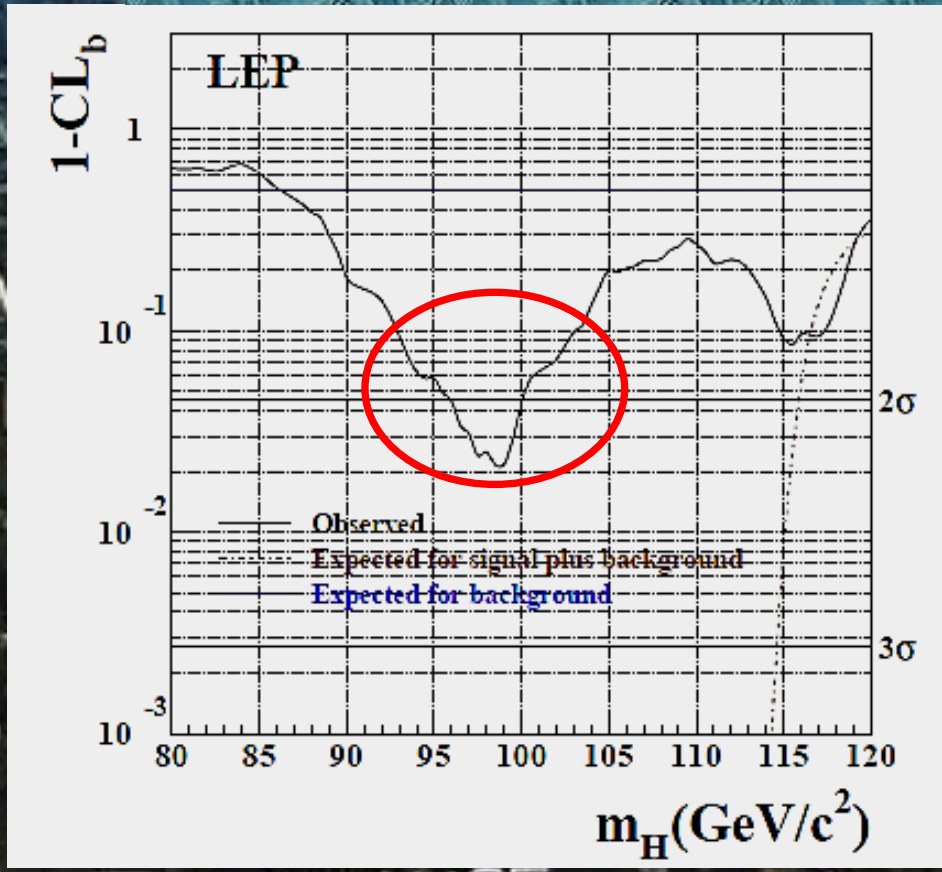


- "Clear evidence for the production of a neutral boson …is presented."

Introduction: Is (was) there something else with m<125 GeV?

- Final LEP SM Higgs boson search results: >2σ excess at mH= GeV. Has contributed to sustained interest by both theorests and experimentalists in the possibility of additional low-mass (pseudo-) scalars

LEPHWG, Phys. Lett. B565:61-75,2003



- Subject of this talk: **ATLAS** and **CMS** searches during **LHC Run 1** for additional scalars/pseudoscalars with m<125 GeV,, by definition in a BSM context.

- New (pseudo-)scalars are either searched for alone, or in a context where the scalar with m~125 GeV is one of the other Higgs bosons in the model

- Searches covered include: Neutral and charged scalars, scalars decaying to 2 pseudoscalars, directly-produced pseudoscalars.

Introduction: BSM Models allowing low-mass (pseudo)scalars

- 2HDM (Two Higgs-Doublet Models) : General, includes MSSM

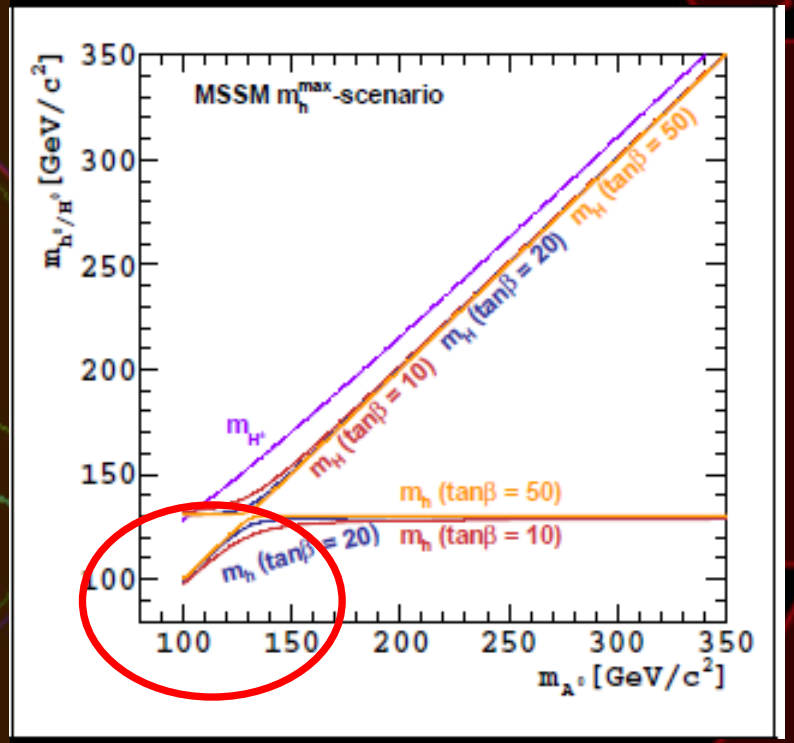
- MSSM (Minimal Supersymmetric Standard Model) : 2 neutral scalars : h, H; 1 pseudoscalar A; 2 charged H^{+-} mostly in Mh-Max scenario
  - Also low-MH scenario : mH~125 GeV and m{H^{+-}, A, h} <125 GeV

- NMSSM (Next-to MSSM): MSSM + 1 Singlet: 3 neutral scalars h_1, h_2, h_3; 2 pseudoscalars a1, a2; 2 charged H^{+-}

- DarkSusy: $\chi_0 \rightarrow n_D$ ('dark' undetected neutralino) + γ_D ('dark' massive weakly-interacting photon)

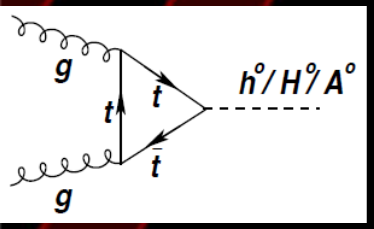
- MCHM (Minimal Composite Higgs Model)
- Fermiophobic Higgs Models
- 4th Generation of fermions
- ….
- see J. Gunion's talk for a complete theoretical review

CMS HIG-12-011

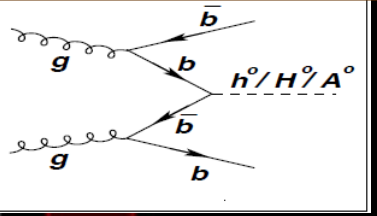


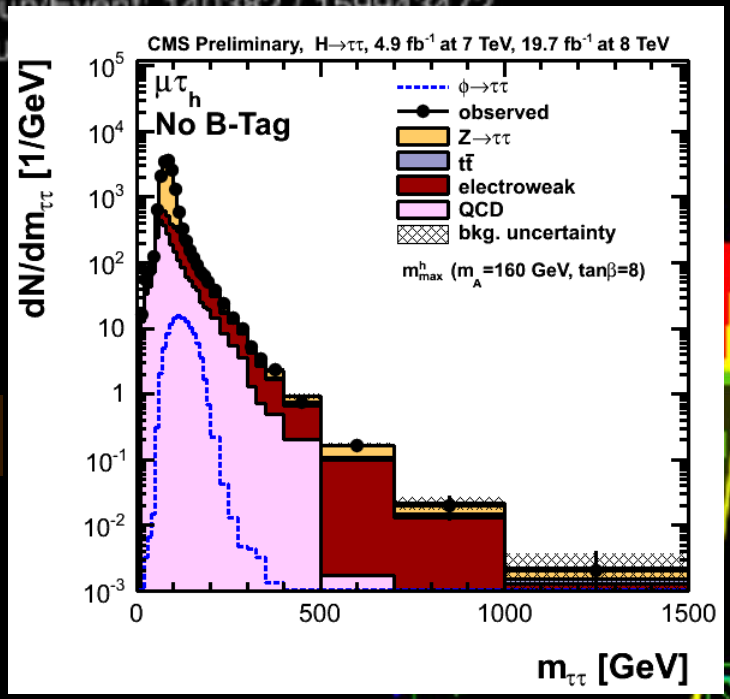
Neutral scalars Φ (MSSM):τ channels, CMS, 7/8 TeV

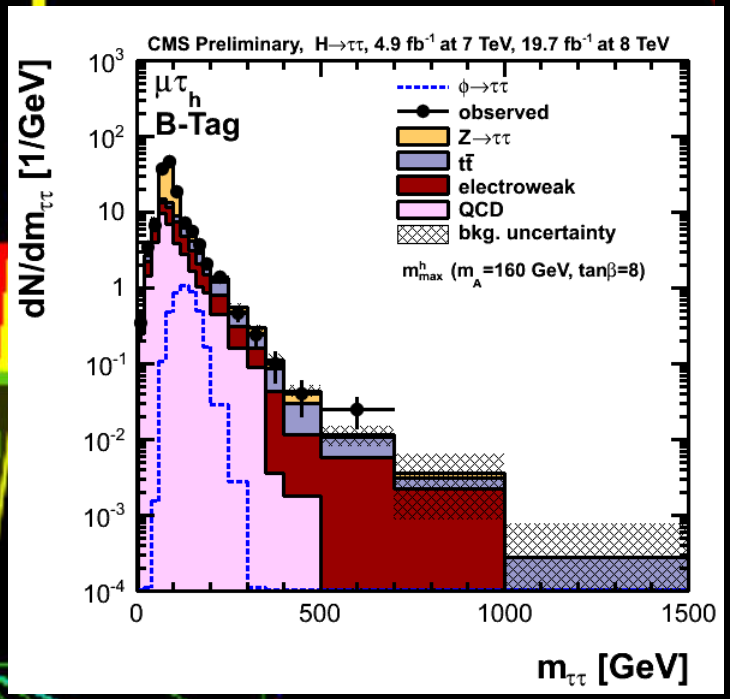
- gg→Φ→ττ

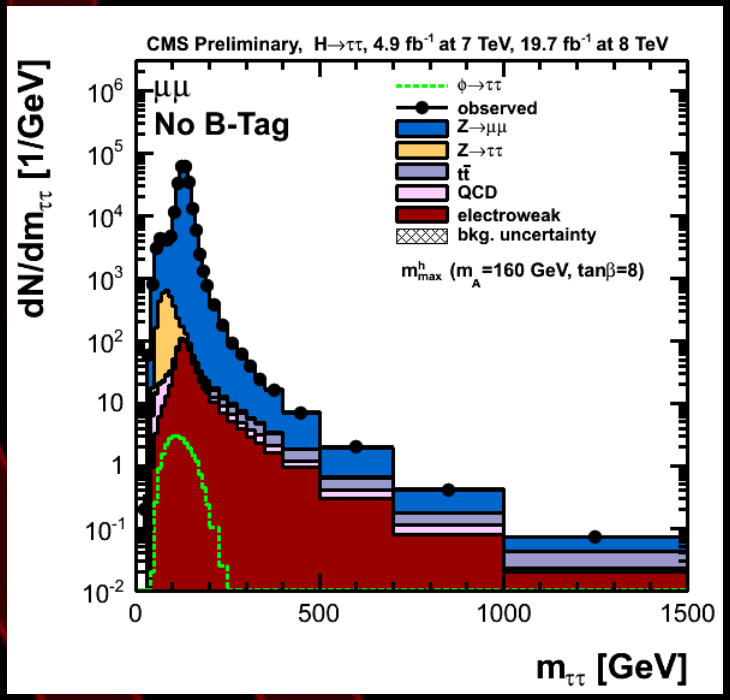


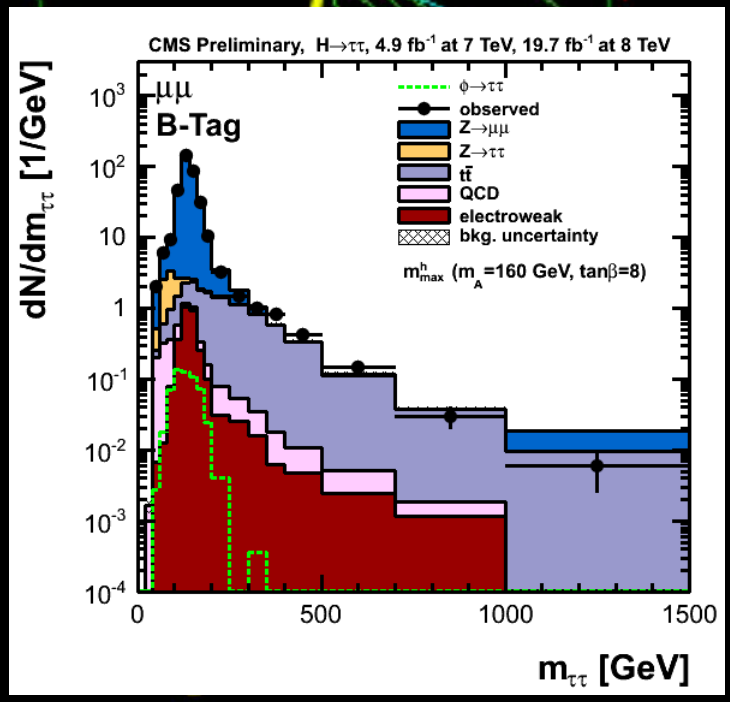
- gg→bbΦ→bbtt











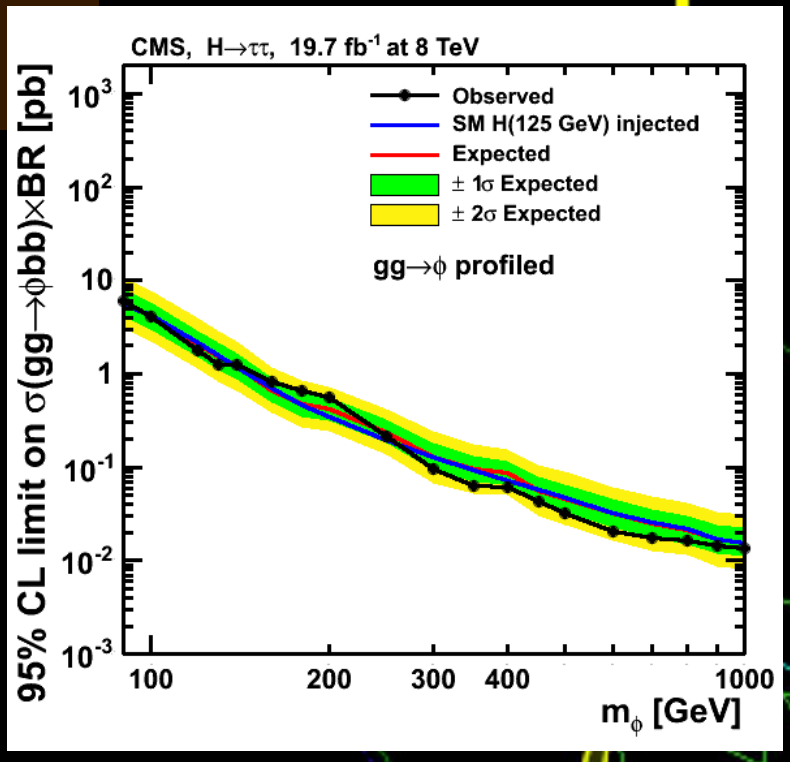
CMS HIG-13-021

- Channels: $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$, b/no b-tag categories
- Simultaneous binned LH fit in 10 categories to $m\tau\tau$ or $m\tau\tau$ x m_{vis} (for $\mu\mu$ channel)

Neutral scalars Φ (MSSM): τ channels, CMS, 7/8 TeV

CMS HIG-13-021

- Upper limits on σ X BR(Φ→ττ) :



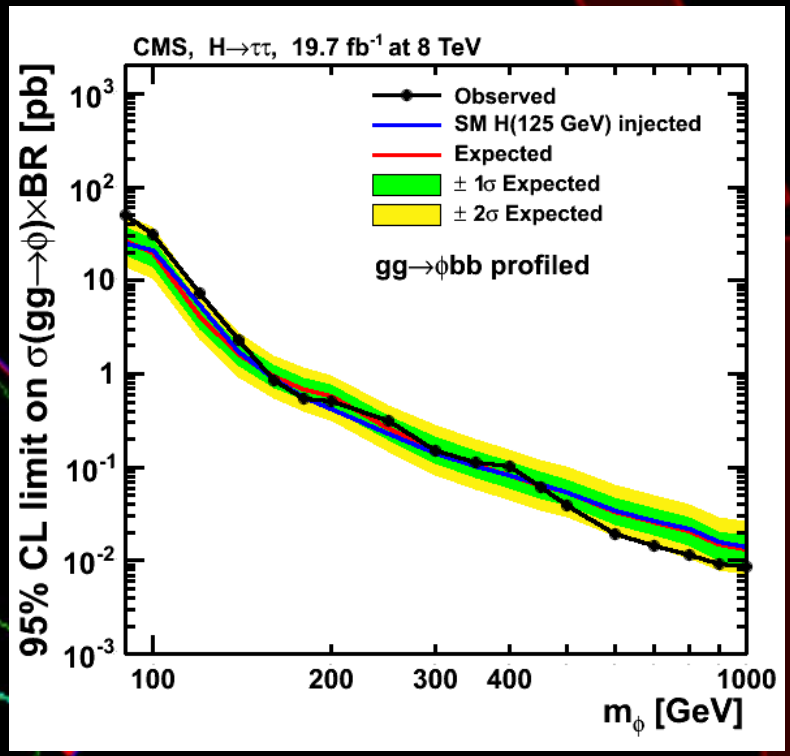


Table 7: 95% CL upper limits for $\sigma \cdot BR(gg\Phi)$ (pb) as a function of M_Φ.

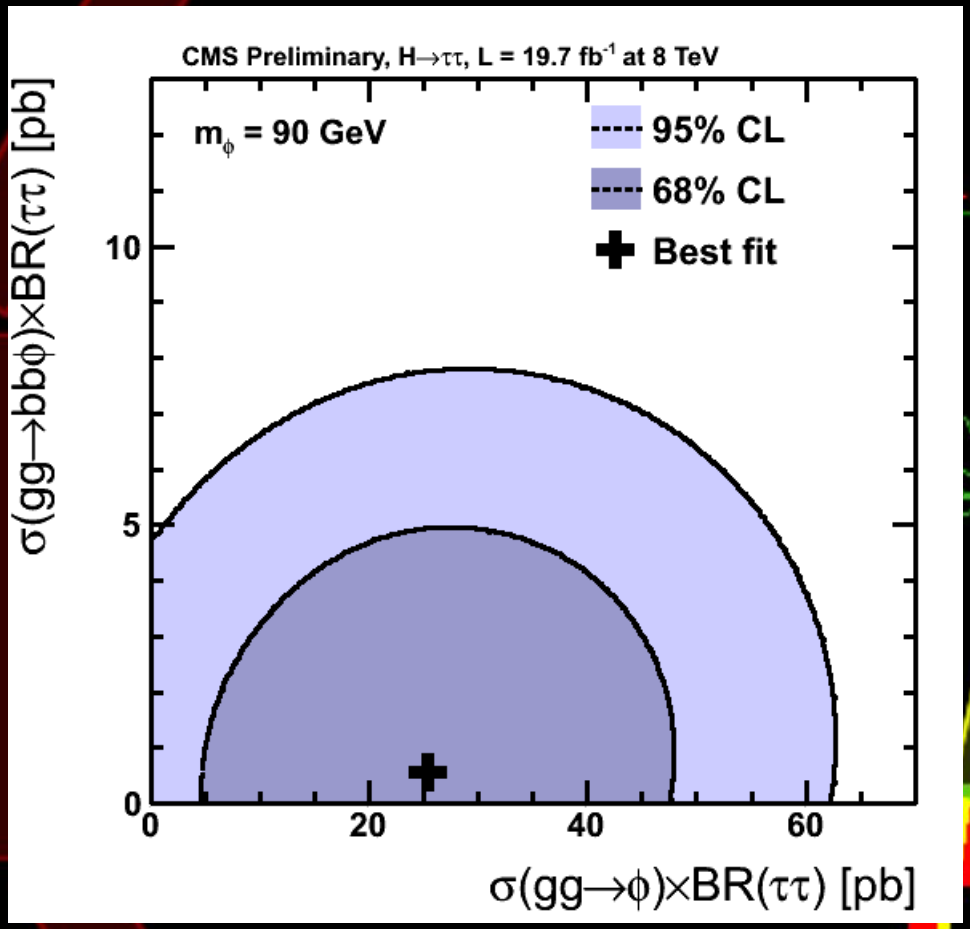
MSSM Higgs	Expected $\sigma \cdot BR$ ($gg\Phi$) limit					Observed
m_Φ [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	$\sigma \cdot BR$ ($gg\Phi$) limit
90 GeV	13.8	18.6	26.1	37.2	50.9	50.2
100 GeV	10.5	14.1	19.8	27.9	37.8	31.3
120 GeV	2.29	3.03	4.14	5.71	7.56	7.38

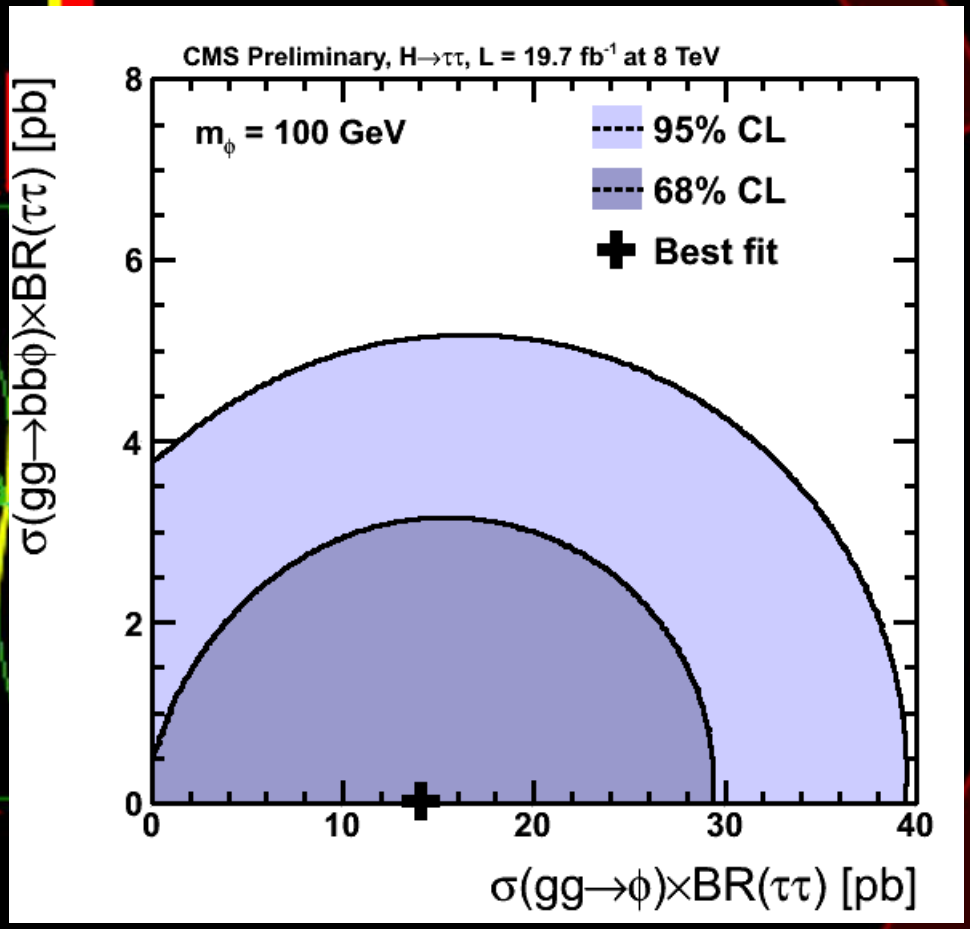
Table 8: Expected range and observed 95% CL upper limits for $\sigma \cdot BR(bb\Phi)$ (pb) at 8 TeV center-of-mass energy as a function of M_Φ.

MSSM Higgs	Expected $\sigma \cdot BR$ ($bb\Phi$) limit					Observed
m_Φ [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	$\sigma \cdot BR$ ($bb\Phi$) limit
90 GeV	3.11	4.15	5.79	8.07	10.9	6.03
100 GeV	2.24	2.99	4.17	5.85	7.85	4.14
120 GeV	1.13	1.50	2.09	2.93	3.93	1.76

Neutral scalars Φ (MSSM):τ channels, CMS, 7/8 TeV

CMS HIG-13-021





- Relative importance of gg→Φ→ττ and gg→bbΦ→bbττ channels for low-mass Φ

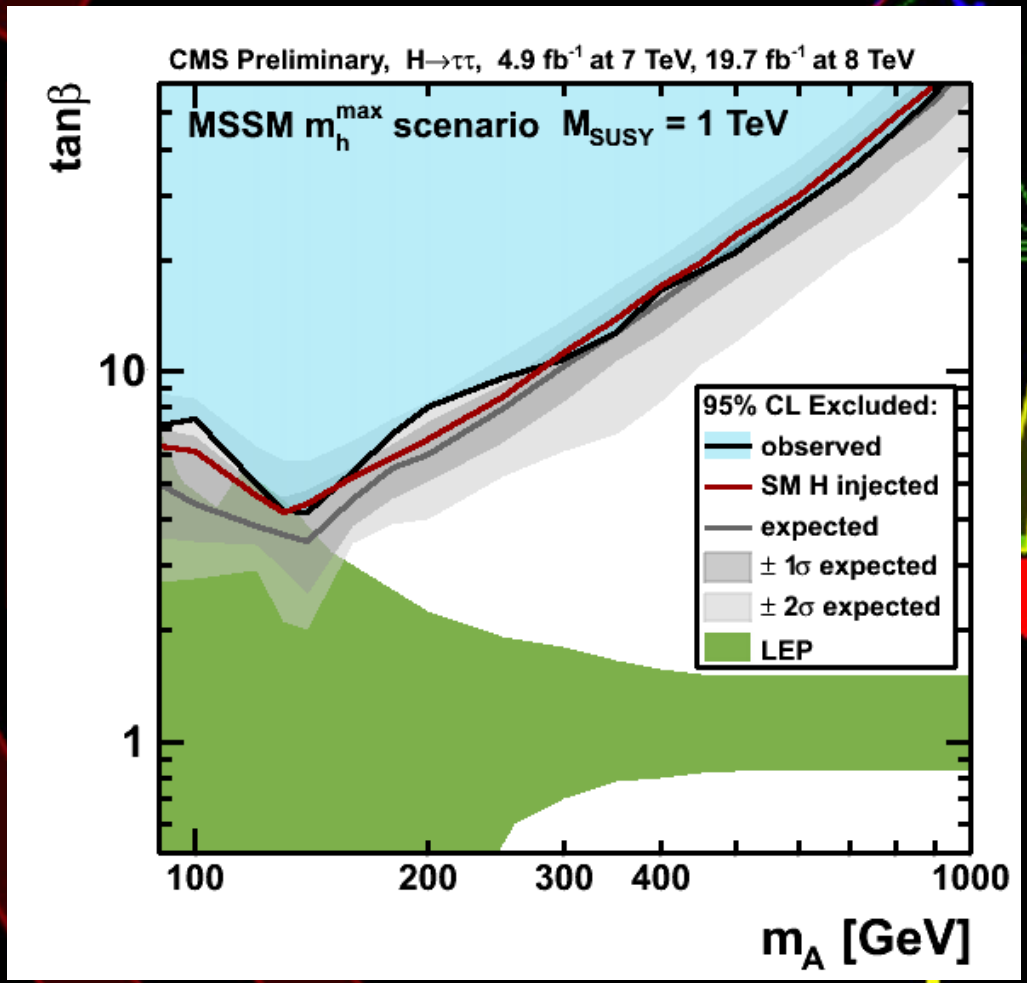
Neutral scalars Φ (MSSM): τ channels, CMS, 7/8 TeV

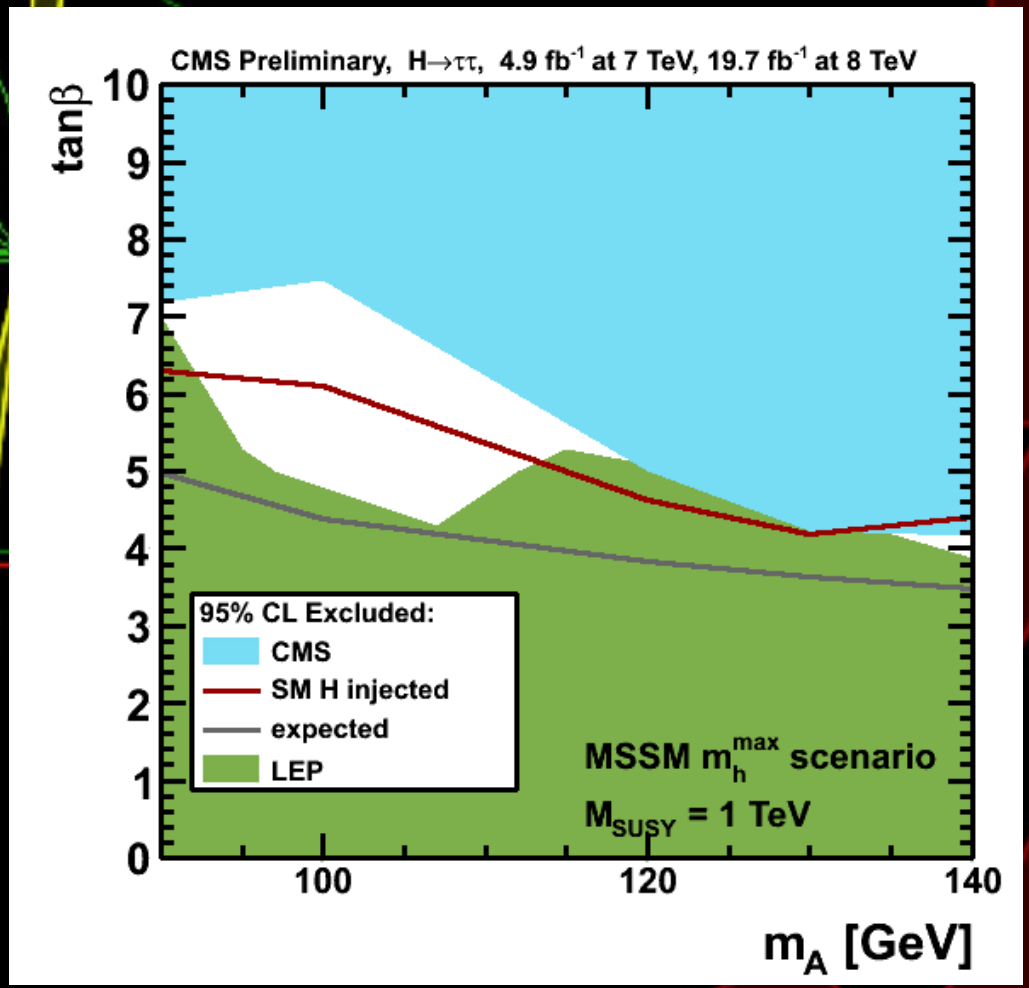
CMS HIG-13-021

Table 6: Expected range and observed 95% CL upper limits for $\tan\beta$ as a function of M_A, for the MSSM search.

MSSM Higgs	Expected $\tan\beta$ limit					Observed
m_A [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	$\tan\beta$ limit
90 GeV	2.70	3.56	4.98	7.02	8.71	7.19
100 GeV	2.77	3.48	4.38	6.68	8.44	7.48
120 GeV	2.92	3.42	3.84	4.94	6.30	5.01

- Exclusion in the tanβ-mA plane: only a small window left for low masses

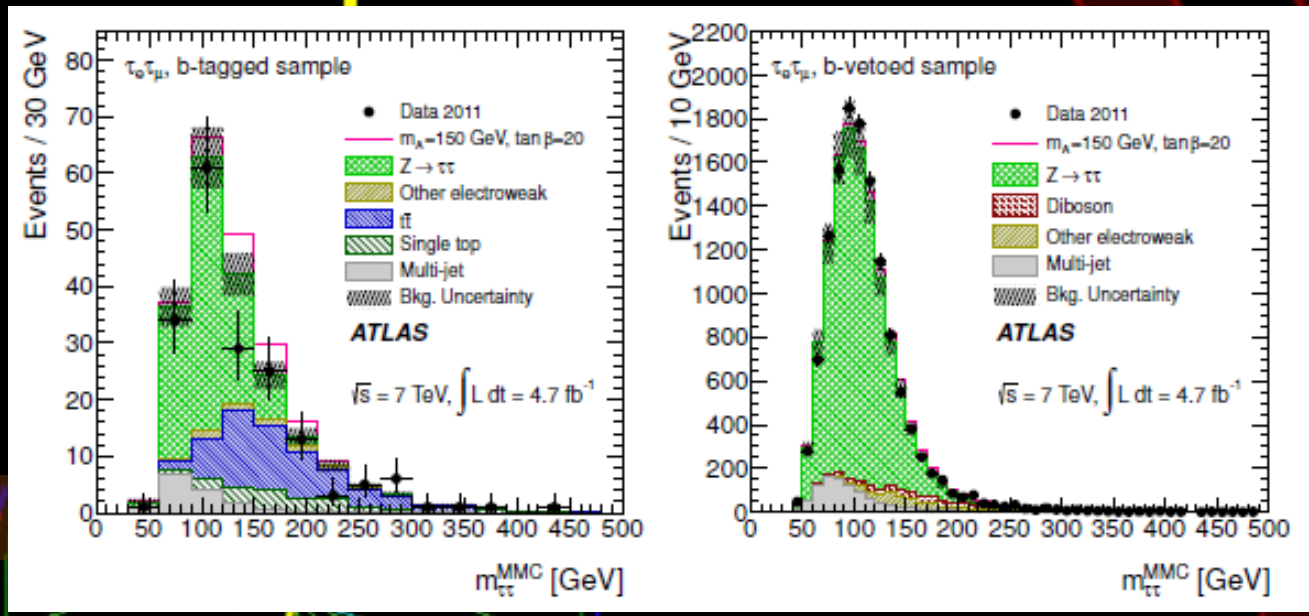




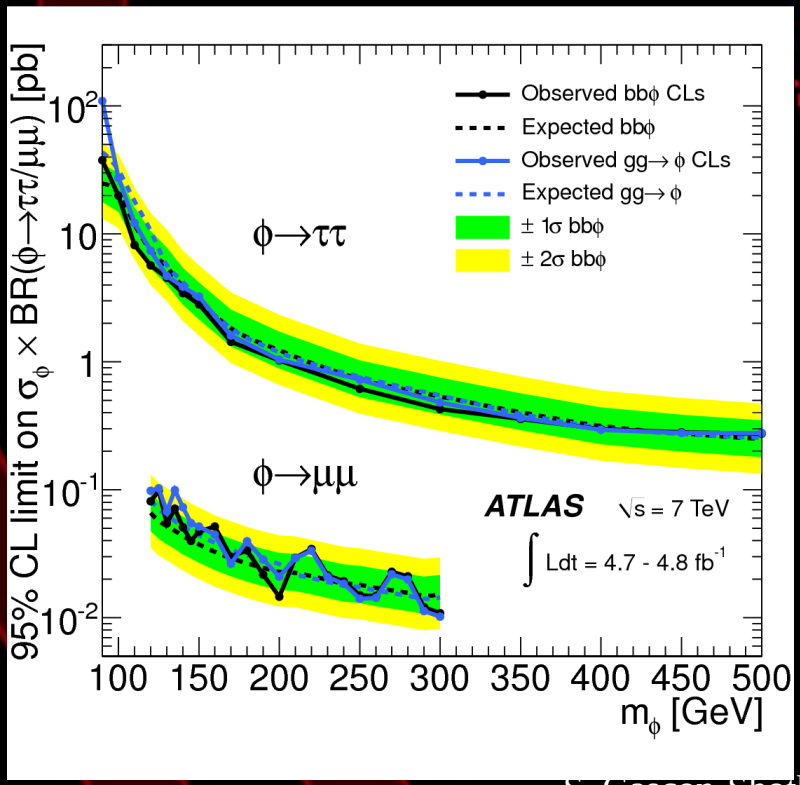
Neutral scalars Φ (MSSM): τ channels, ATLAS, 7 TeV

JHEP02(2013)095

- gg→Φ→ττ
- Channels: $e\tau_h$, $\mu\tau_h$, $e\mu$, $\tau_h\tau_h$, b/vetoed/b-tagged categories
- Simultaneous binned LH to pdf-weighted $m_{\tau\tau}$



- Upper limits on σ X BR(Φ→ττ)



- Background estimated by 'ABCD method': eμ (Charge correlation, Lepton isolation) $\tau_h\tau_h$ (Charge correlation Hadronic τ decay identification requirement)

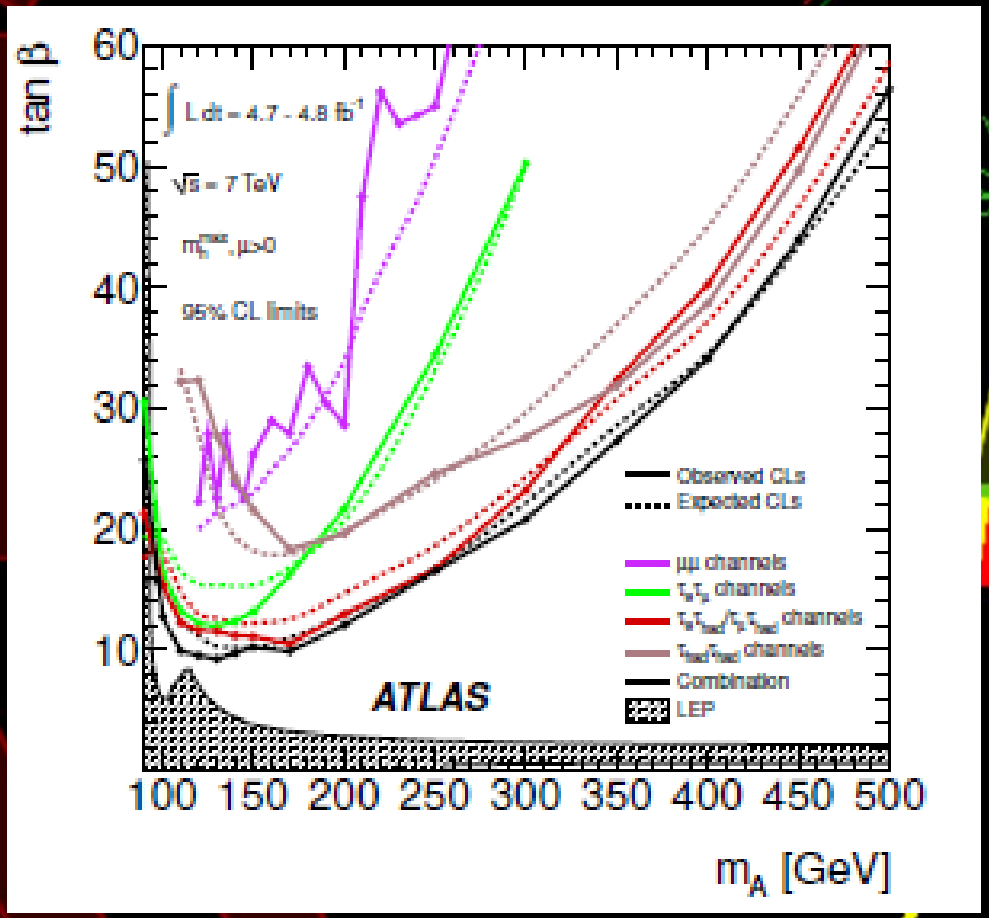
$$n_A = n_B \times \frac{n_C}{n_D} \equiv n_B \times r_{C/D},$$

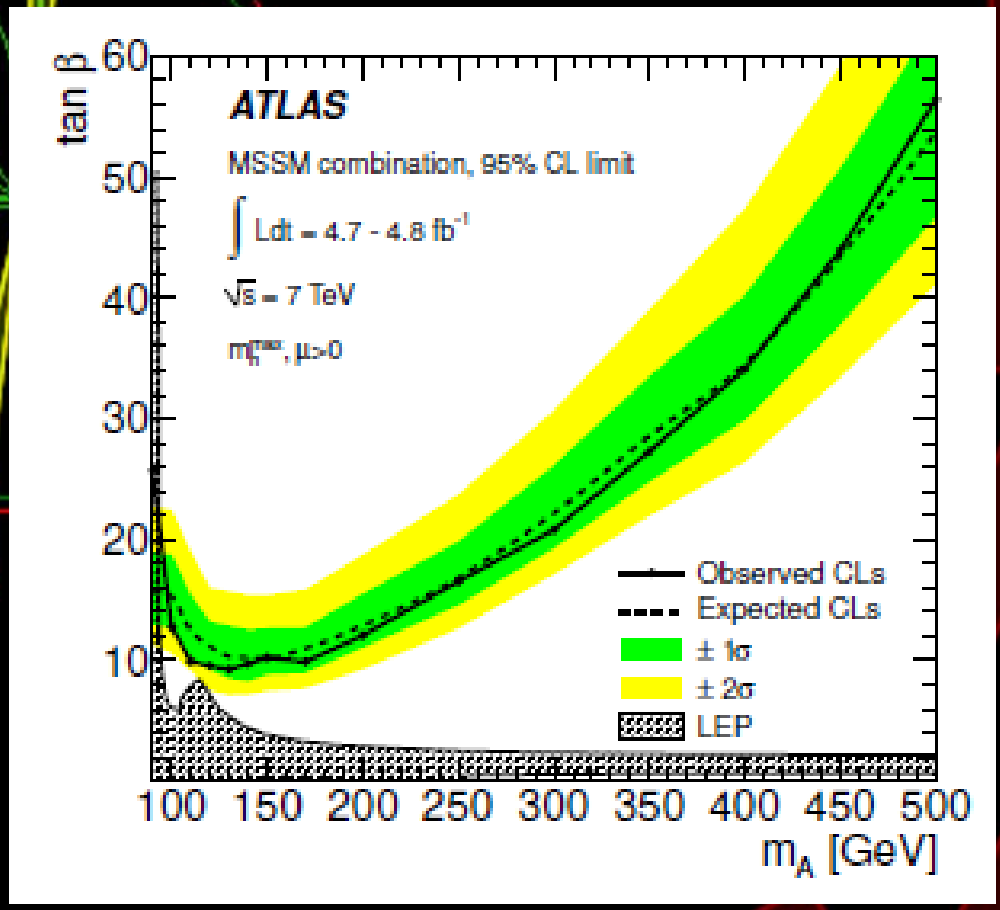
Neutral scalars Φ (MSSM): τ channels, ATLAS, 7 TeV

Data recorded: Sun Jul 18 04:24:49 2010 PDT
Run/Event: 140382 / 159943472
Lumi section: 171

JHEP02(2013)095

- Exclusion in the tanβ-mA plane:

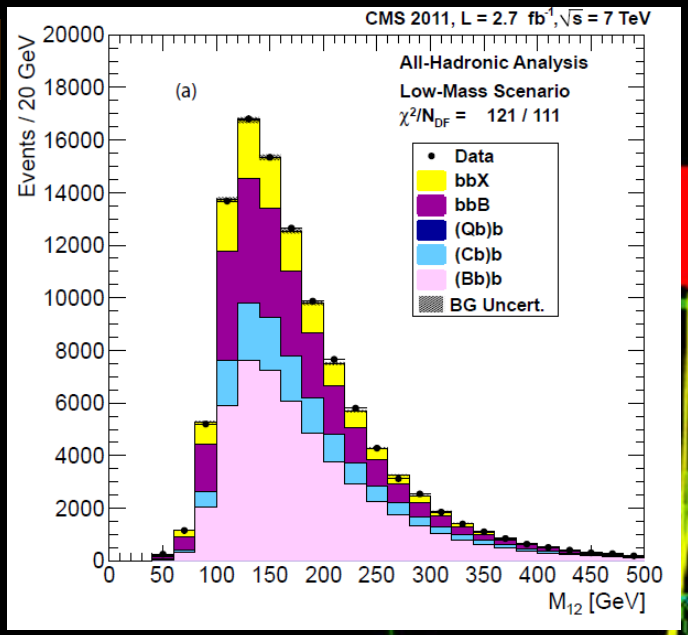


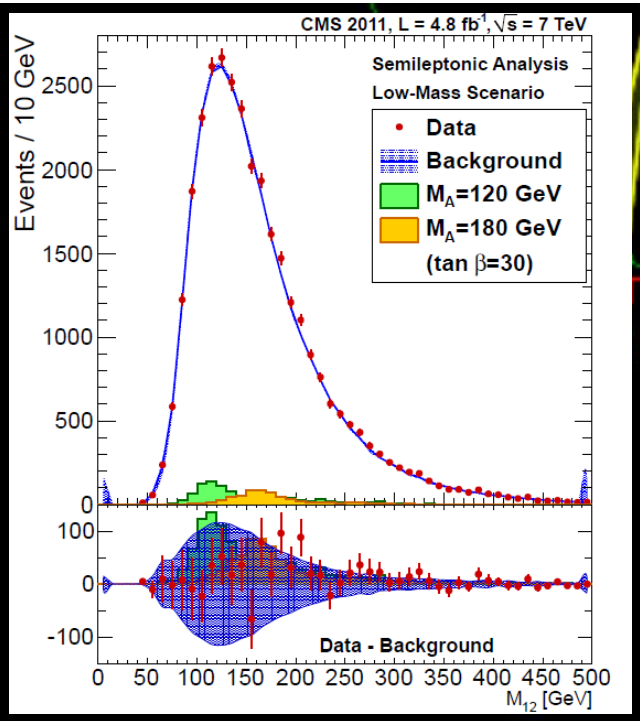


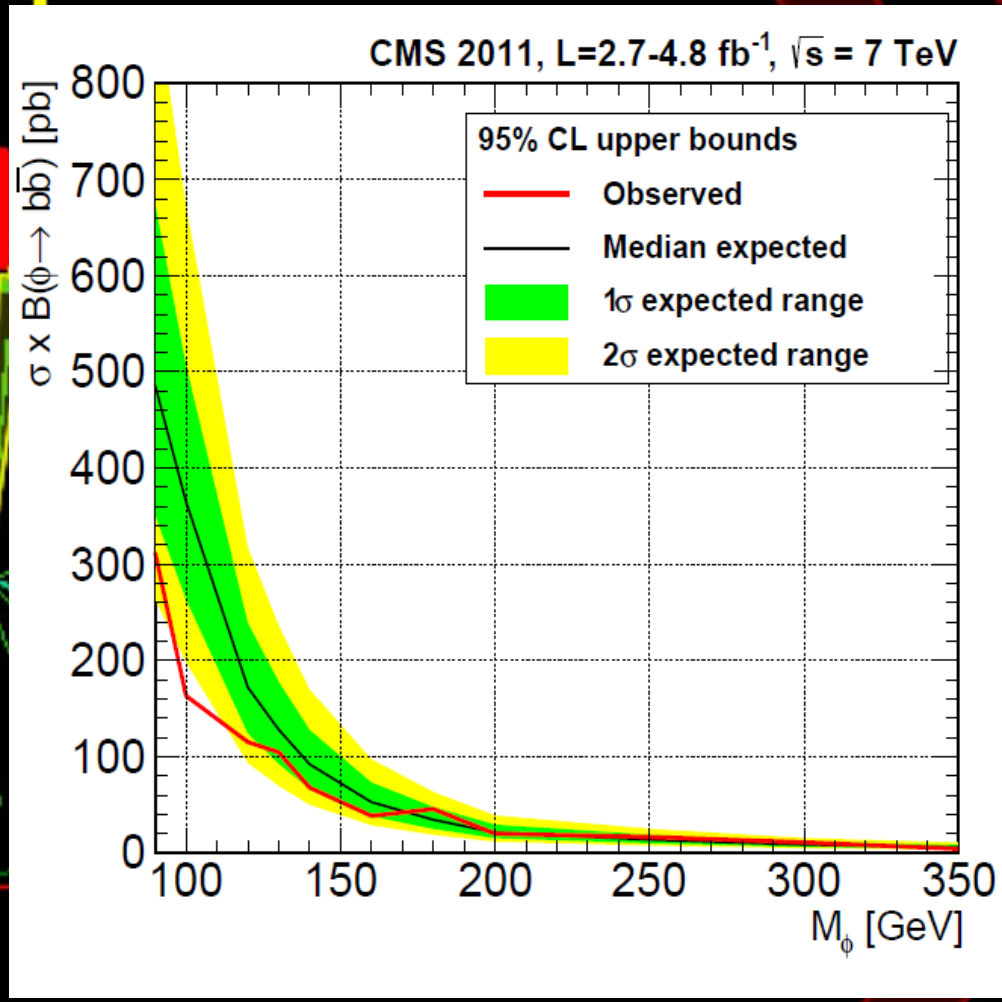
Neutral scalars Φ (MSSM): >=3b channel, CMS, 7 TeV

Phys. Lett. B 722 (2013) 207

- gg→bbΦ→bbbb
- 3 b-tagged jets, 'all-hadronic' or 'semi-leptonic' with muon
- All-hadronic: 2D background templates in m(j1,j2) X b-tag variable
- Semileptonic: binned LH fit to m(j1,j2)
- High sensitivity to large tan β scenarios





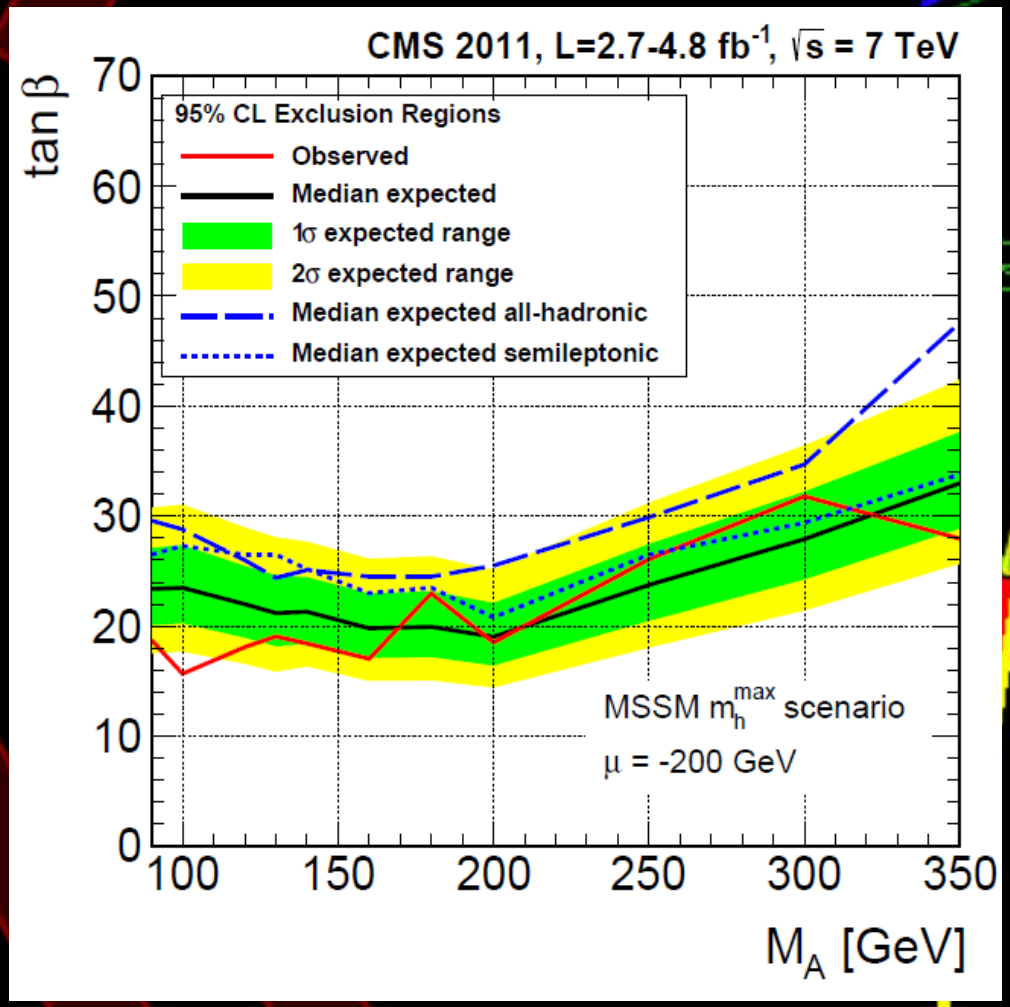


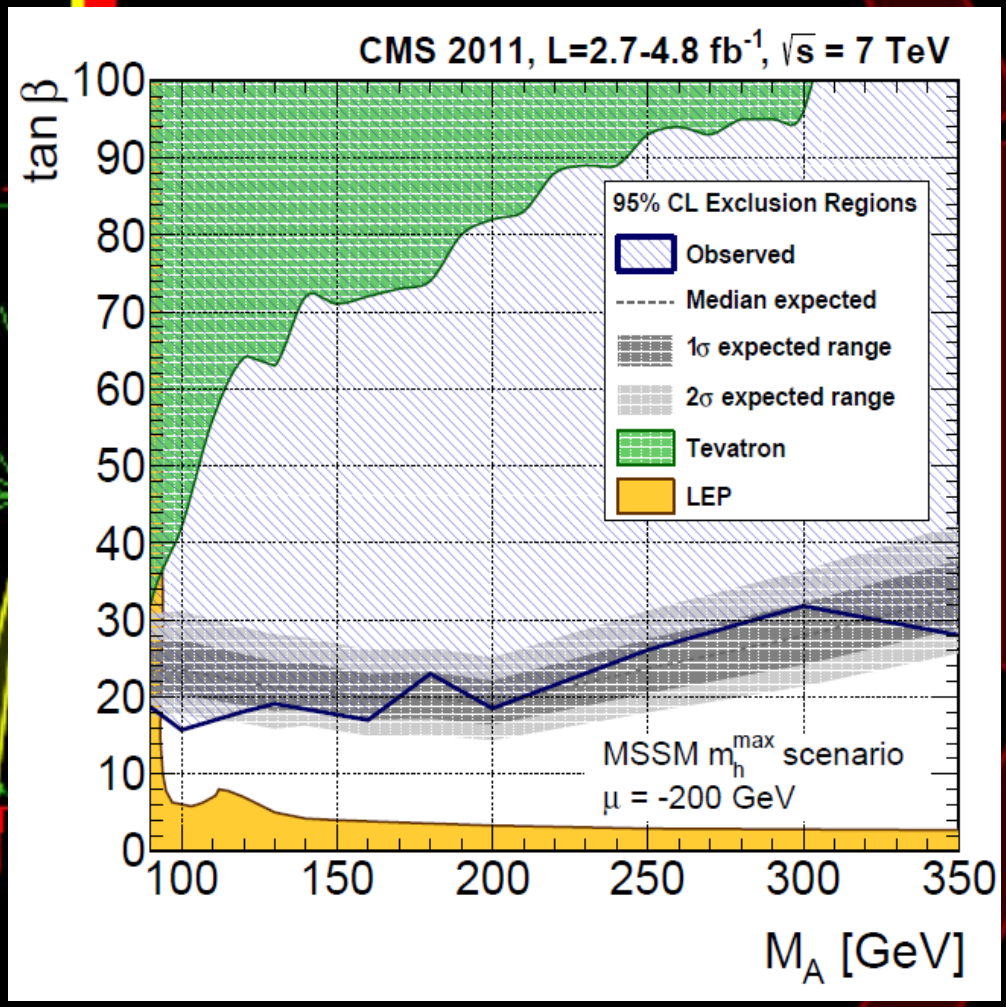
- Upper limits on σ X BR(Φ→bb) : ~312 pb for Mφ = 90 GeV , ~120pb for Mφ = 120 GeV

Neutral scalars Φ (MSSM): >=3b channel, CMS, 7 TeV

Phys. Lett. B 722 (2013) 207

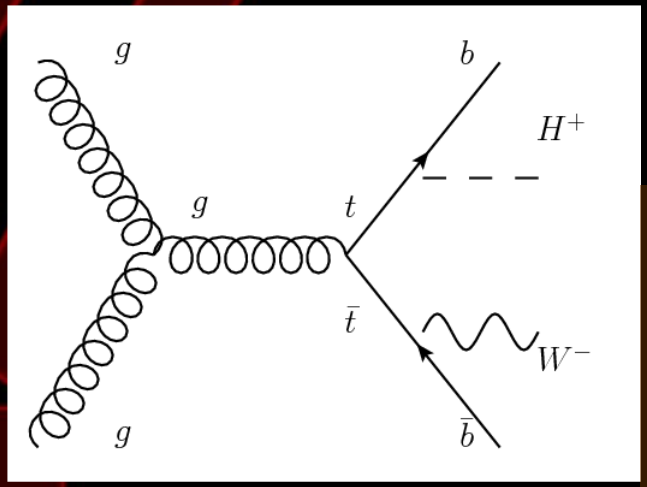
- Exclusions in the tanβ-mA plane:



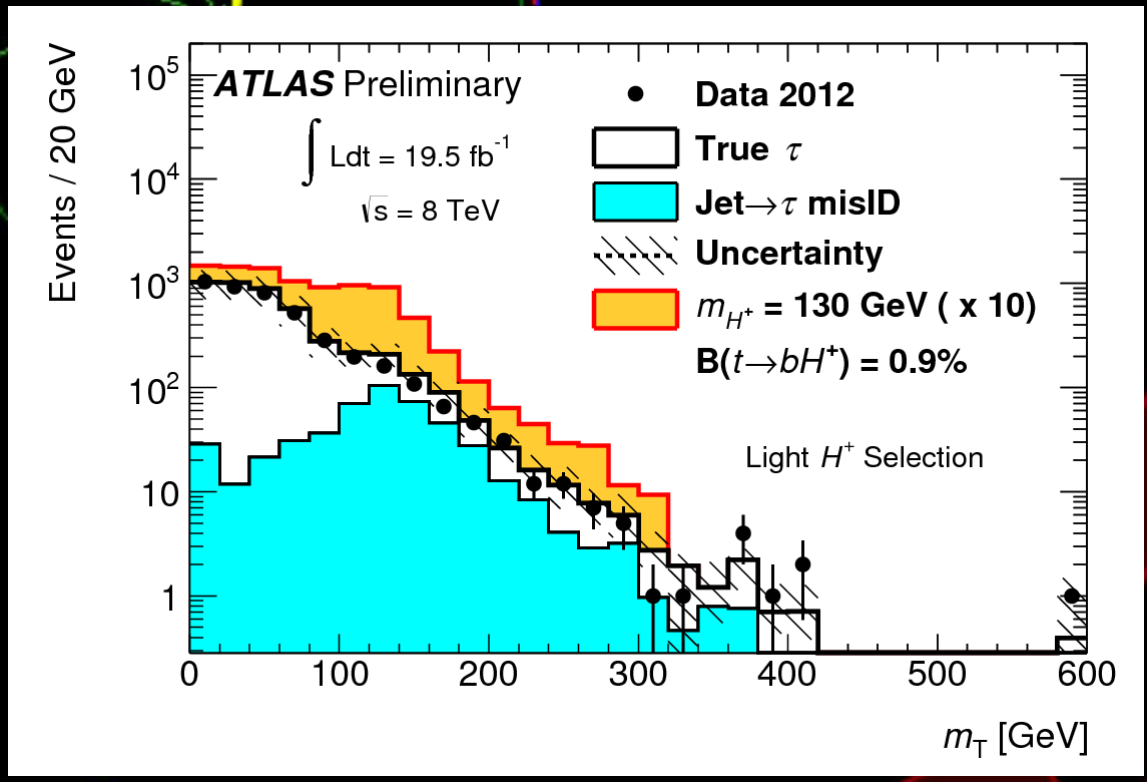


Charged Scalars (MSSM): τν channel, ATLAS, 8 TeV

ATLAS-CONF-2013-090



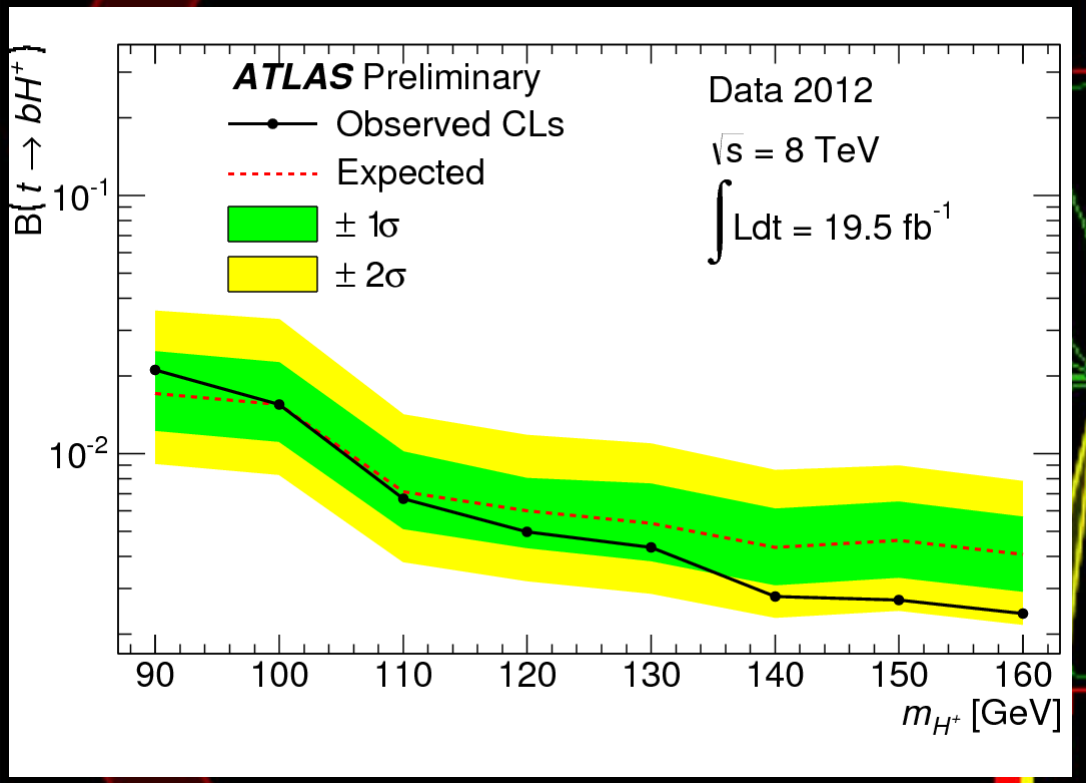
- Scenario mH+<mt, gg→ttbar→bH^+ +bW
- H+→τν assumed 100%, both τ and W decay hadronically
- Binned LH fit to the 'transverse mass' m_T, background model from data



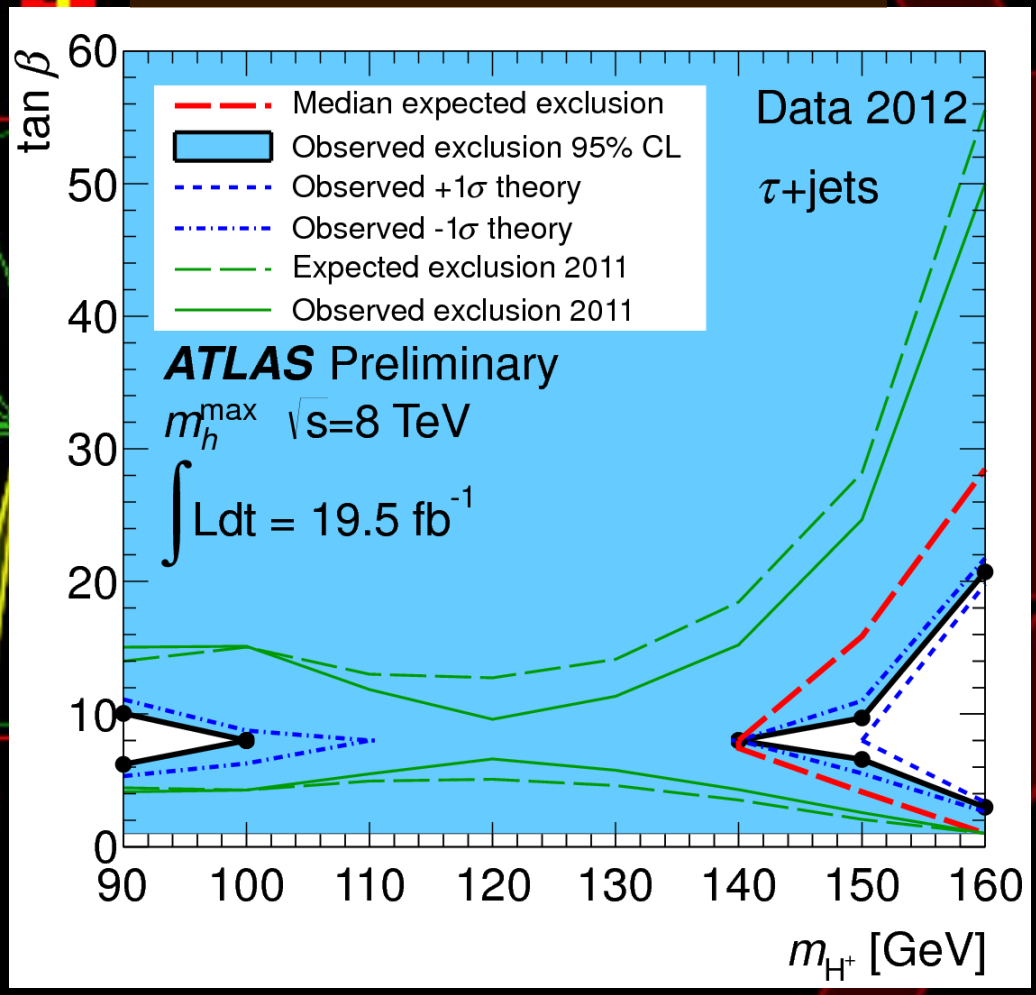
Charged Scalars (MSSM): τν channel, ATLAS, 8 TeV

ATLAS-CONF-2013-090

- Upper limits on BR(t→bH⁺), between 0.24 and 2.1%



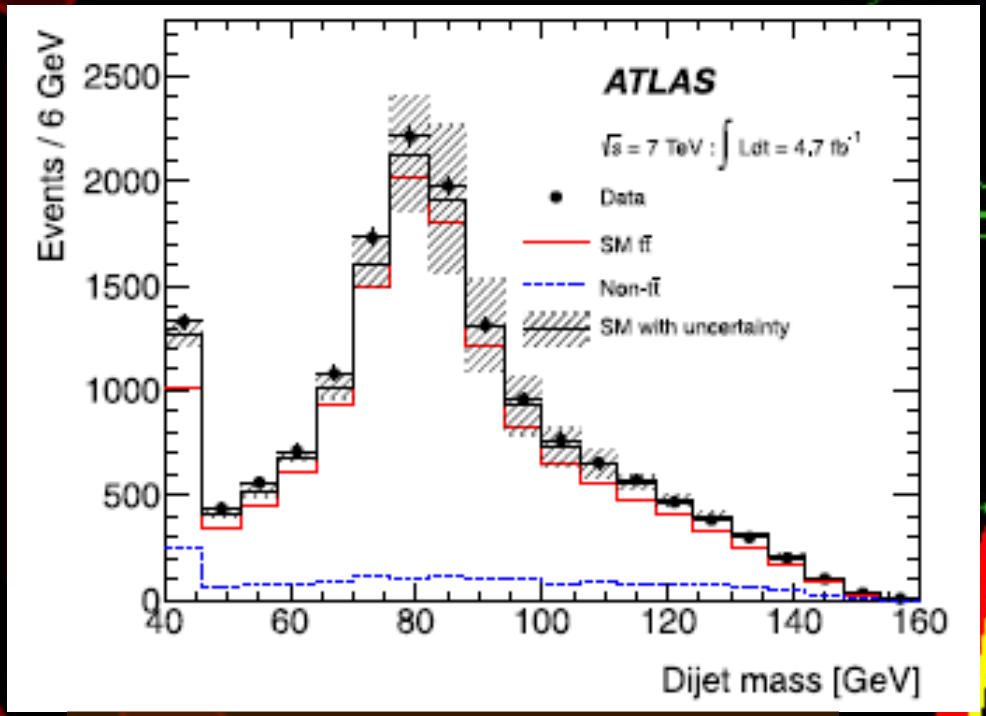
- Exclusions in the tanβ-mA plane:



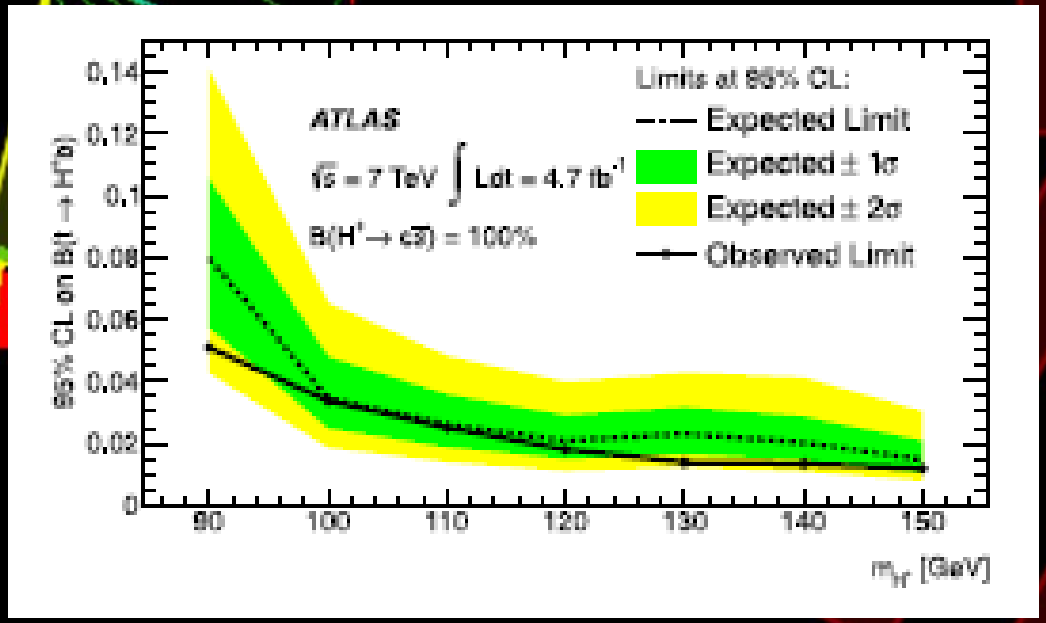
Charged Scalars (MSSM): csbar channel, ATLAS, 7 TeV

Eur. Phys. J. C, 73 6 (2013) 2465

- Scenario mH+<mt, gg→ttbar→bH⁺+bW
- H+→csbar assumed 100%, W decays leptonically
- Upper limits on BR(t→bH⁺), between 5% and 1.8%



Higgs mass	Expected limit (stat.⊕ syst.)	Observed limit (stat.⊕ syst.)
90 GeV	0.080	0.051
100 GeV	0.034	0.034
110 GeV	0.026	0.025
120 GeV	0.021	0.018



- Binned LH fit to the dijet mass distribution, jets assigned to ‘W’ or ‘H+’ t quark based on kinematic fit result

Scalars decaying to pseudoscalars (NMSSM /Dark Susy): 4μ channel, CMS, 7/8 TeV

- $h \rightarrow 2a + X \rightarrow 4\mu + X$
- $2m_\mu < m_{a1} < 2m_\tau$

CMS-HIG-13-010

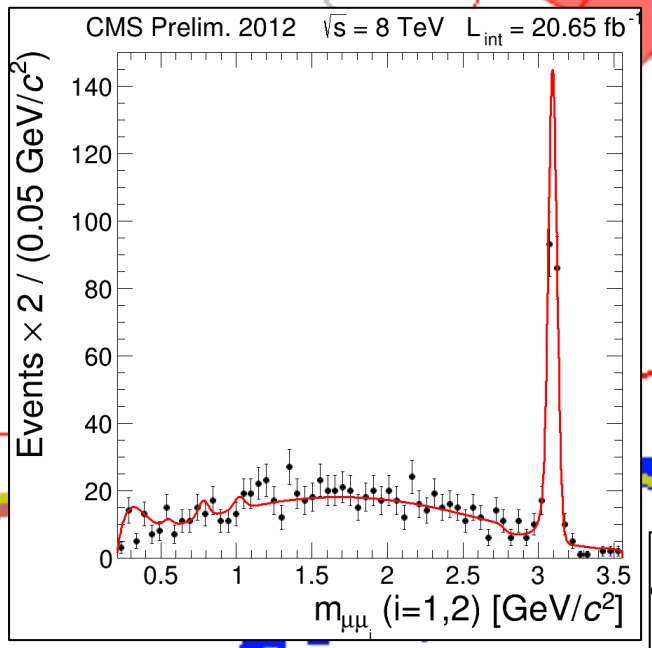
Muon 1,
pt = 11.19
eta = -1.795
phi = 1.042

Muon 0,
pt = 13.11
eta = -1.797
phi = 1.042

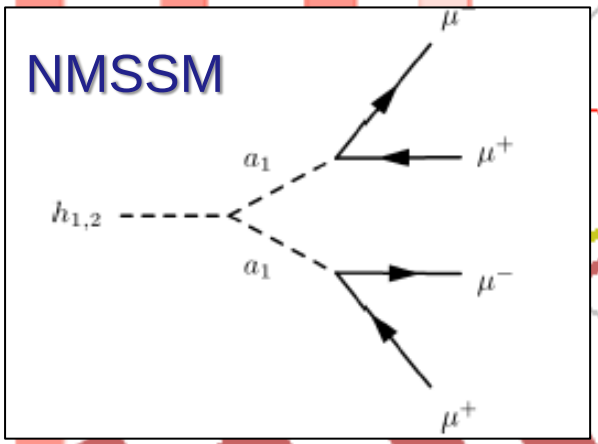
Muon 2,
pt = 9.42
eta = 0.295
phi = -2.864

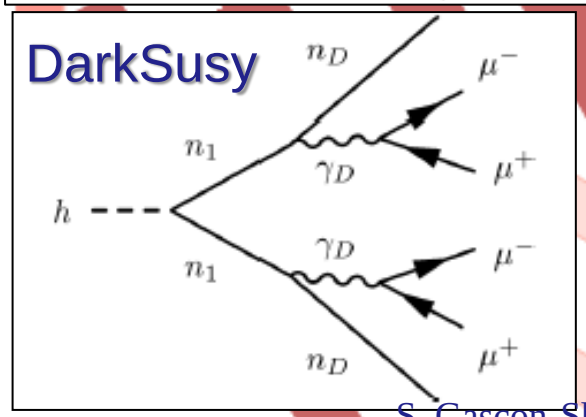
MET 0,
pt = 26.47
eta = 0.000
phi = 0.068

Muon 3,
pt = 22.44
eta = 0.288
phi = -2.850

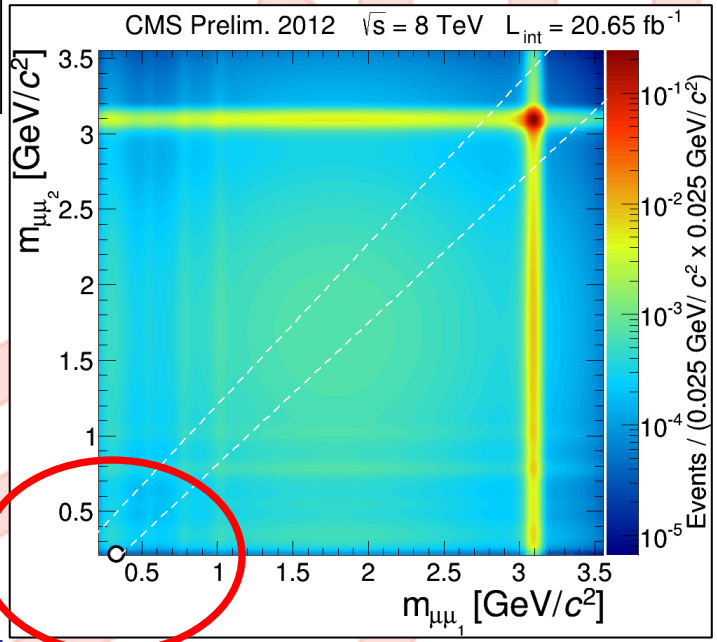


- one candidate event





- 2D background templates in $m(\mu,\mu)_i$ from data control samples, both J/ψ and bbar



Scalars decaying to pseudoscalars: 4μ channel, CMS, 7/8 TeV

Muon 1,
pt = 11.19
eta = -1.795
phi = 1.042

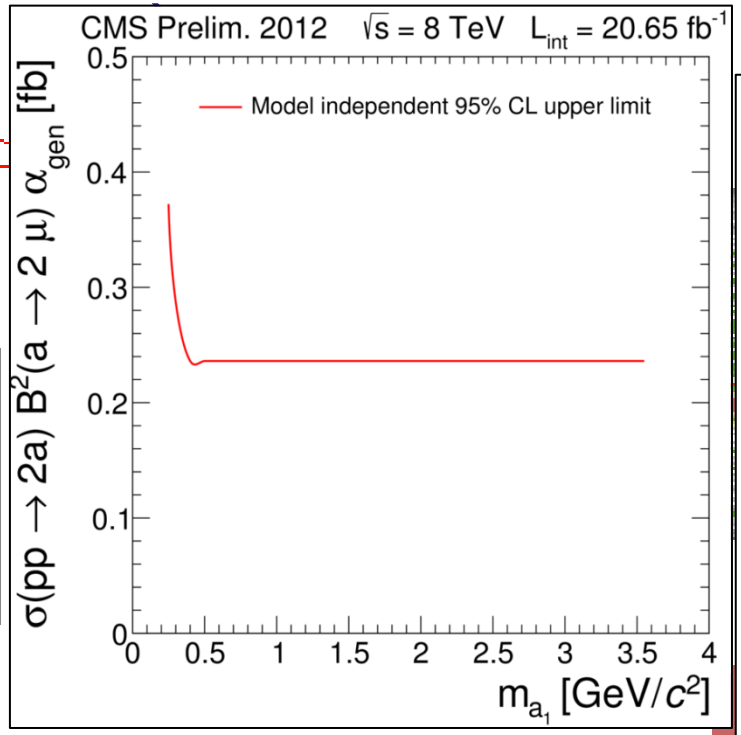
Muon 2,
pt = 9.42
eta = 0.295
phi = -2.864

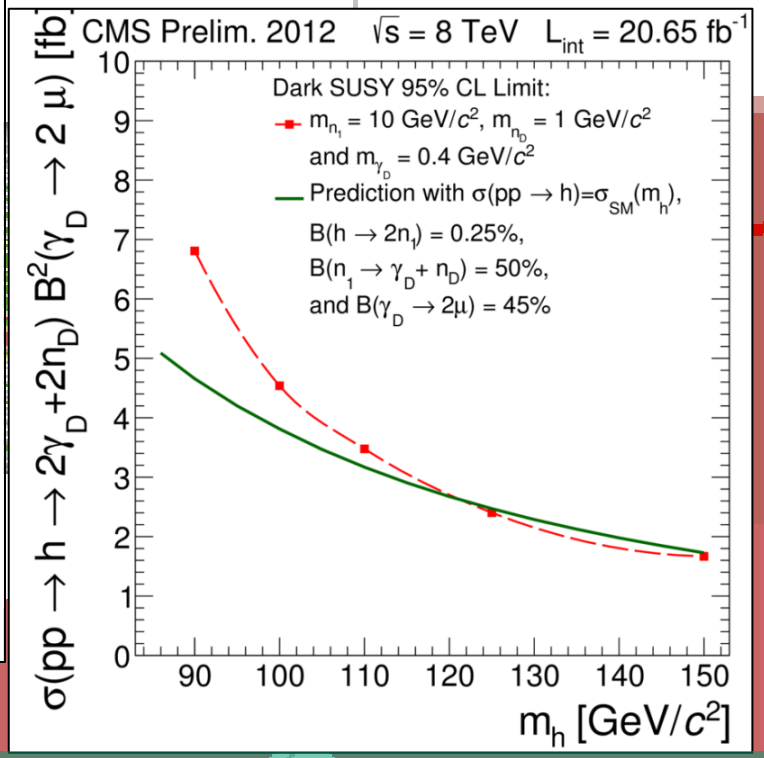
Muon 0,
pt = 13.11
eta = -1.797
phi = 1.042

Muon 3,
pt = 22.44
eta = 0.288
phi = -2.850

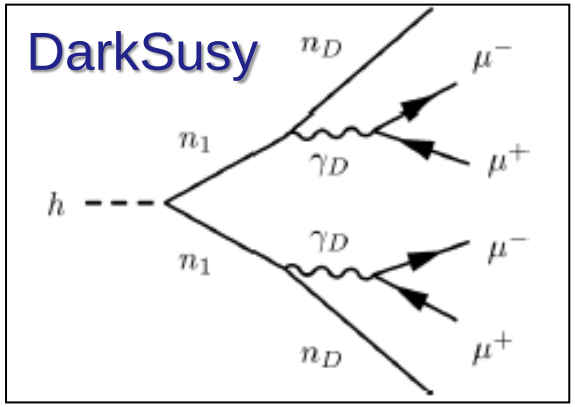
- Upper limits on $\sigma(pp \rightarrow 2a)X$ $BR^2(a \rightarrow 2\mu)X$ α_{gen}

CMS-HIG-13-010





DarkSusy



- $BR(\gamma_D \rightarrow 2\mu)$ up to 45%
- m_{h1}>86 GeV (WMAP, LEP)

- σ X BR^2 limits in DarkSUSY context as function of m_h, for $\{m_{n1, nD, \gamma D}\}$={10, 1, 0.4 GeV}

Scalars decaying to pseudoscalars: 4μ channel, CMS, 7/8 TeV

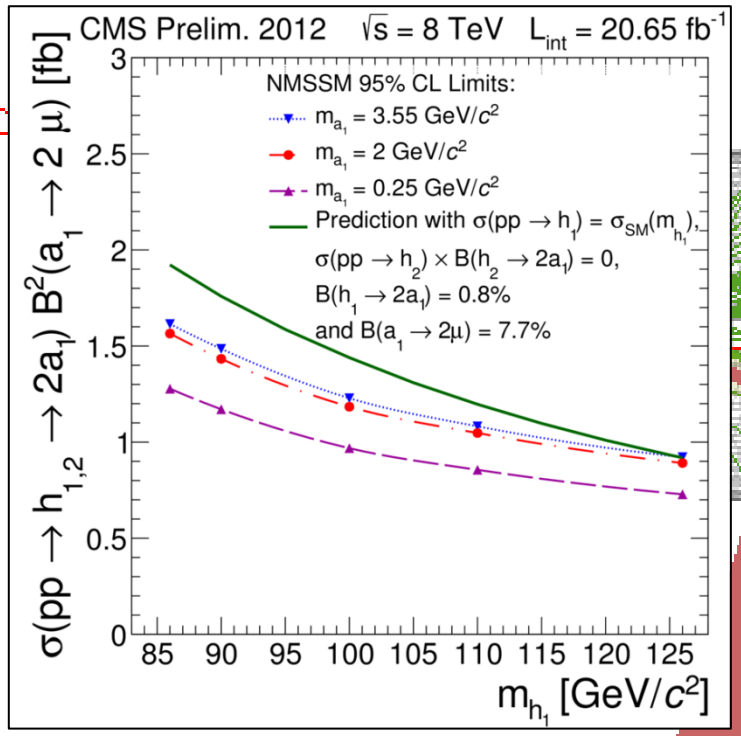
Muon 1,
pt = 11.19
eta = -1.795
phi = 1.042

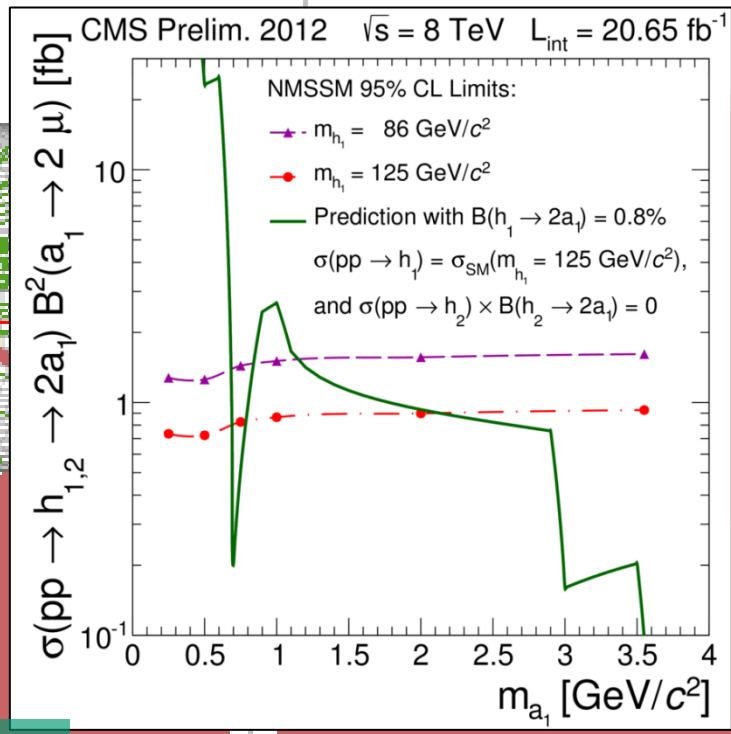
Muon 2,
pt = 9.42
eta = 0.295
phi = -2.864

Muon 0,
pt = 13.11
eta = -1.797
phi = 1.042

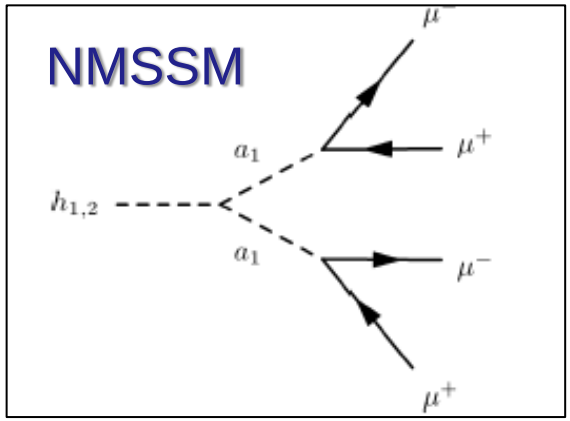
Muon 3,
pt = 22.44
eta = 0.288
phi = -2.850

CMS-HIG-13-010





- BR($a_1 \to 2\mu$) high for $2m_\mu < m_{a1} < 2m_\tau$

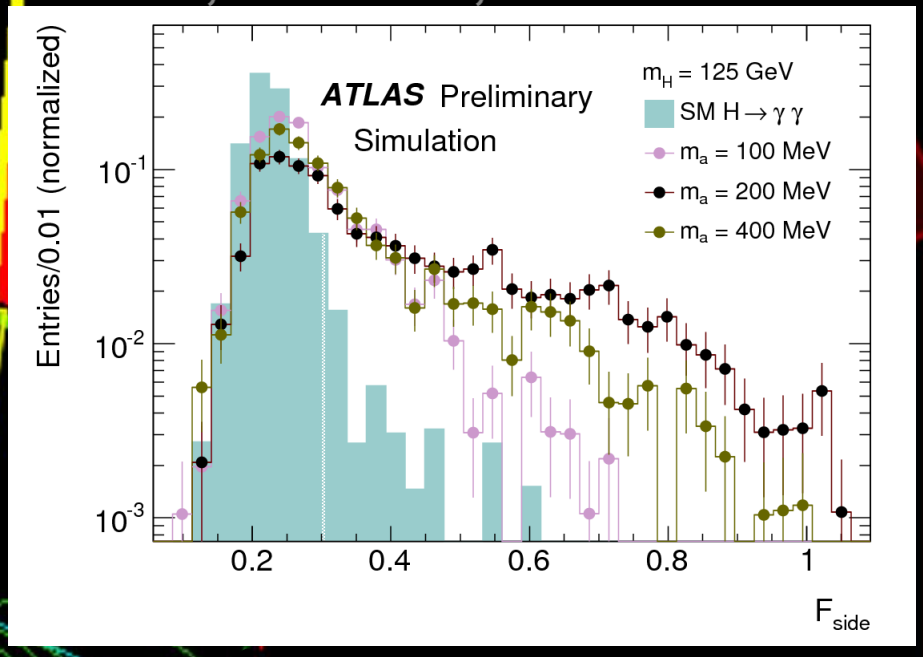


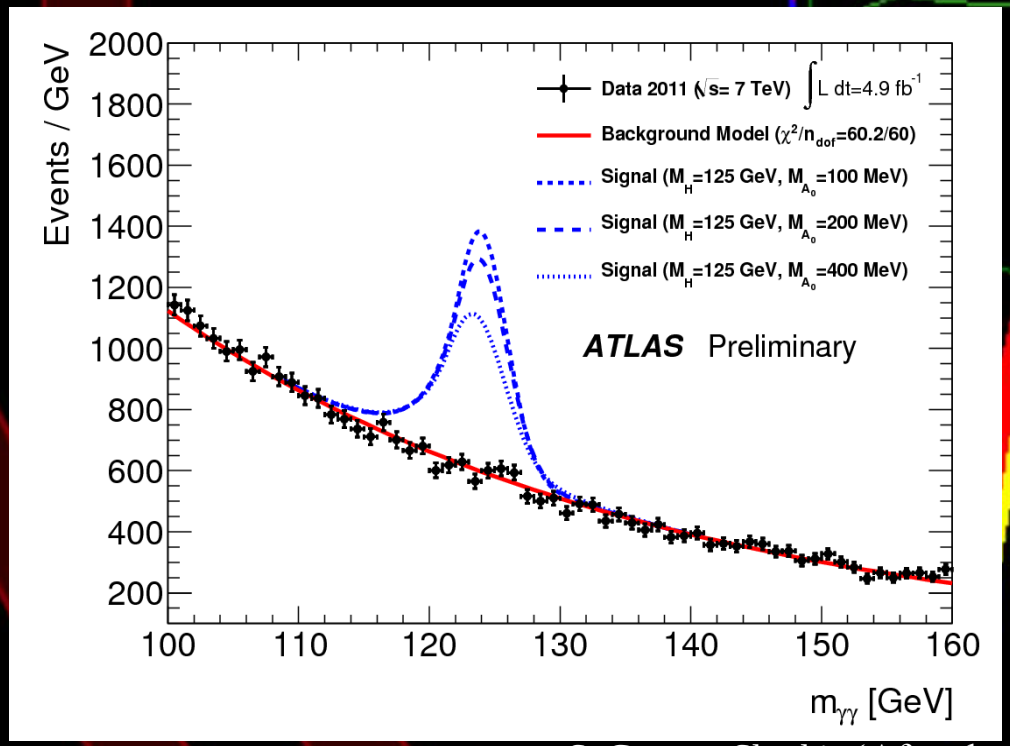
- σ X BR^2 limits in NMSSM context as function of m_{h1}, for $\{m_{a1}\}$={0.25, 2, 3.55 GeV}
- as function of m_{a1}, for $\{m_{h1}\}$={86, 125 GeV}

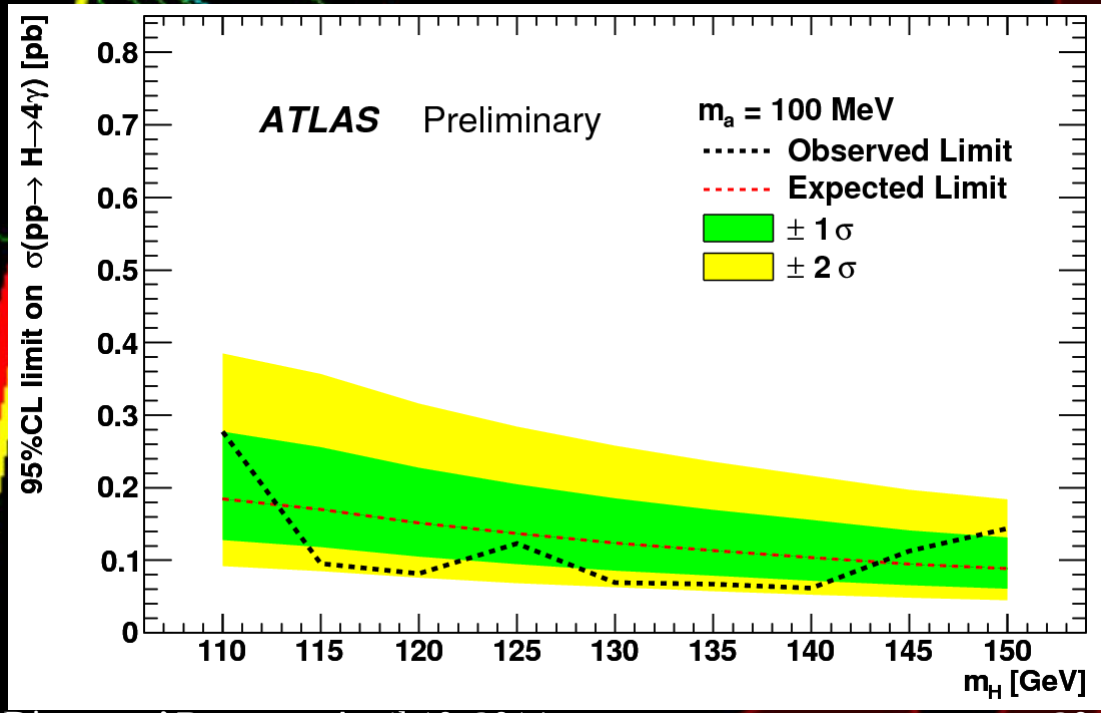
Scalars decaying to pseudoscalars (NMSSM/MCHM): 4γ channel, ATLAS, 7 TeV

ATLAS-CONF-2012-079

- h→2a →2γ + 2γ
- a decay photons highly boosted➔less collimated EM showers than H→γγ photons
- Suppress from γ identification variables most sensitive to shower inner structure
- Signal model much broader than for H, background fit from data
- Upper limits on σ (pp→H→4γ) for $110<m_h<150$ GeV and $110<m_a<400$ MeV



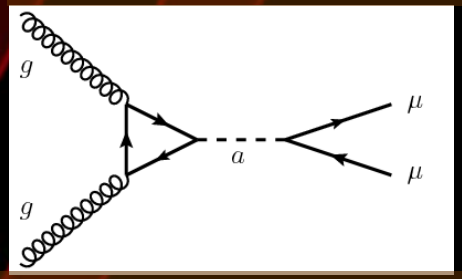




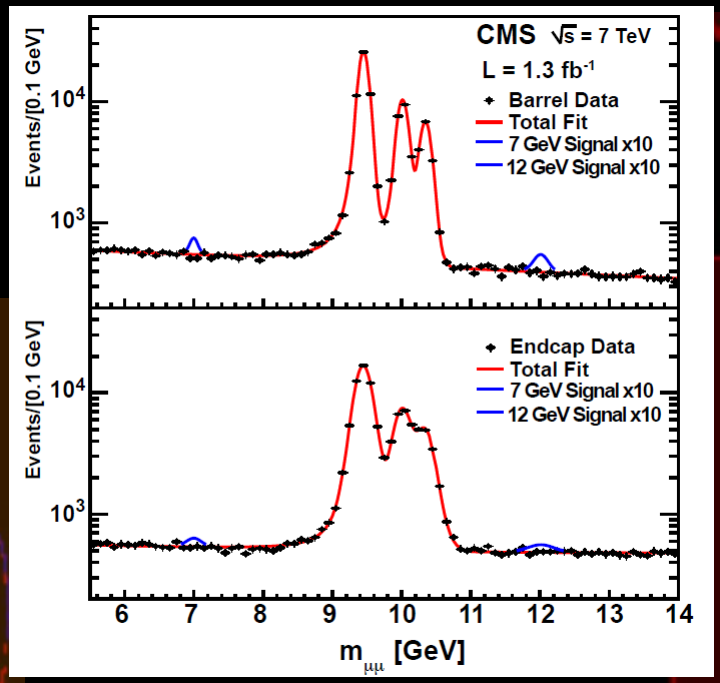
Pseudoscalar to dimuons (NMSSM): CMS, 7 TeV

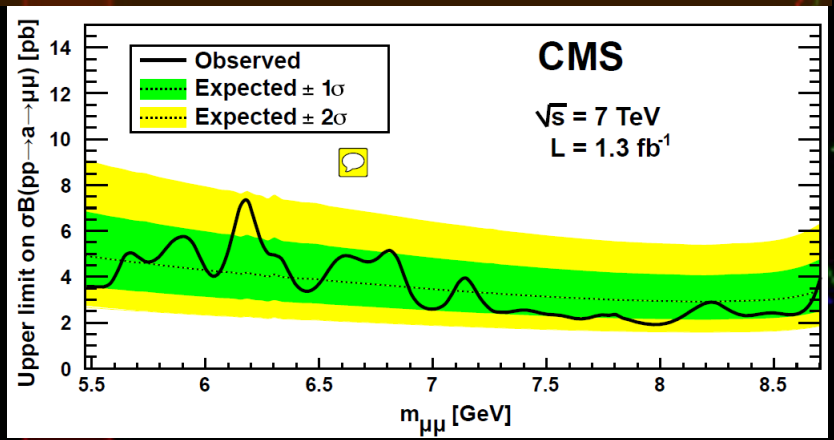
PRL 109, 121801 (2012)

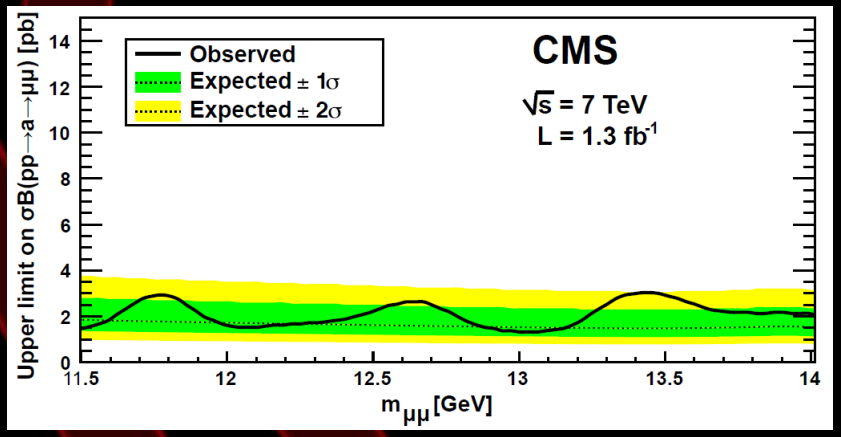
- gg→a→μμ

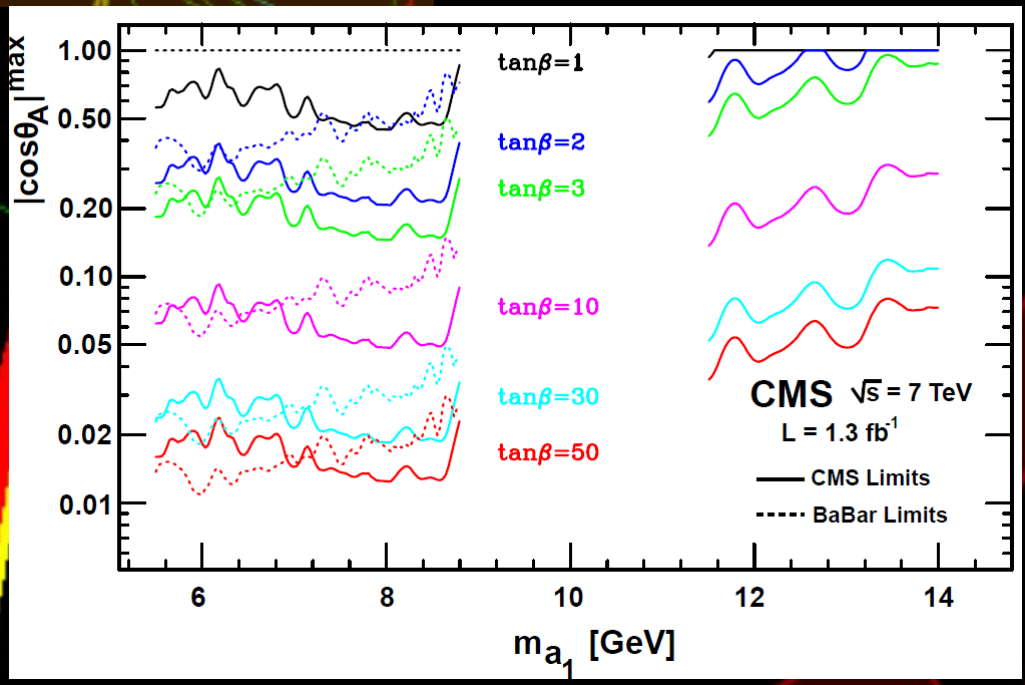


- $m_{a1}<2m_B$ possible
- Unbinned LH fit to $m_{\mu\mu}$, background model from data
- σ X BR(pp→a→μμ) limits in 2 mass regimes (avoid bottomonium)
- Limits on $\cos\theta_A$, $a_1 = \cos\theta_A\, a_{MSSM} + \sin\theta_A a_S$ tighter than those from BaBar for a significant portion of the mass range









Fermiophobic Higgs boson, diphoton channel, ATLAS (7 TeV) & CMS (7/8 TeV)

- Event Classes: Untagged, dijet, lepton and MET tags

- PDFs of S & B in a 2D LH fit ($m_{\gamma\gamma}$, π_T =pt/ $m_{\gamma\gamma}$)

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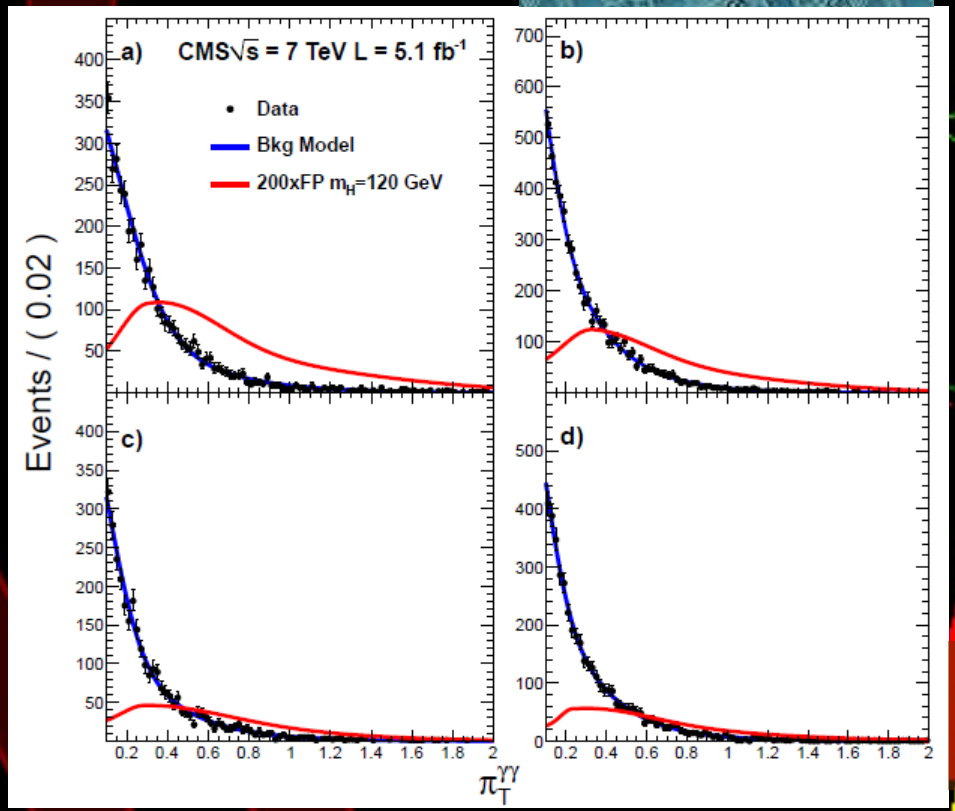
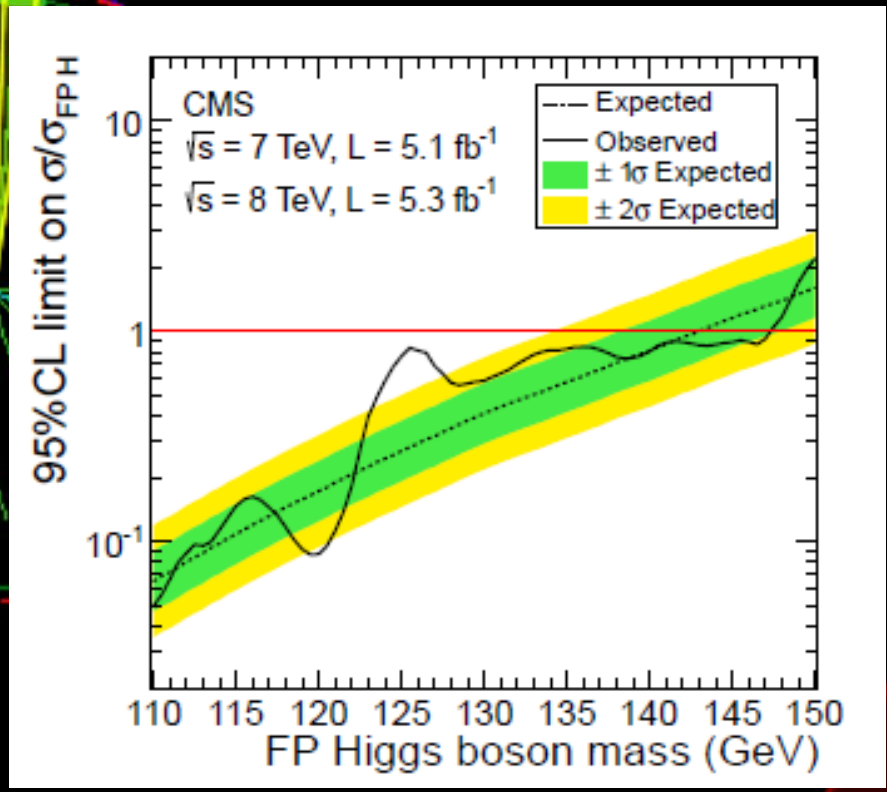


Physics Letters B725(2013)36–59

- A fermiophobic Higgs boson is excluded at 95% confidence level in the mass range 110–147 GeV and at 99% in the range 110-133 GeV

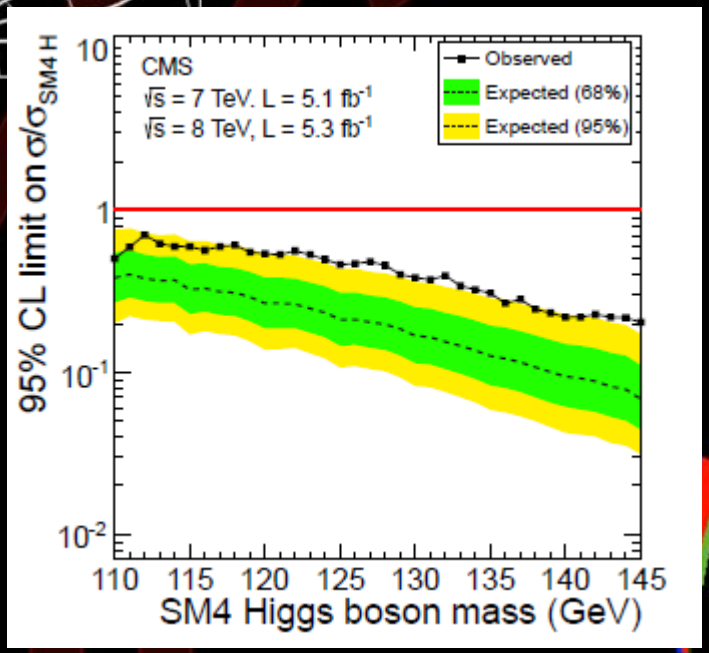


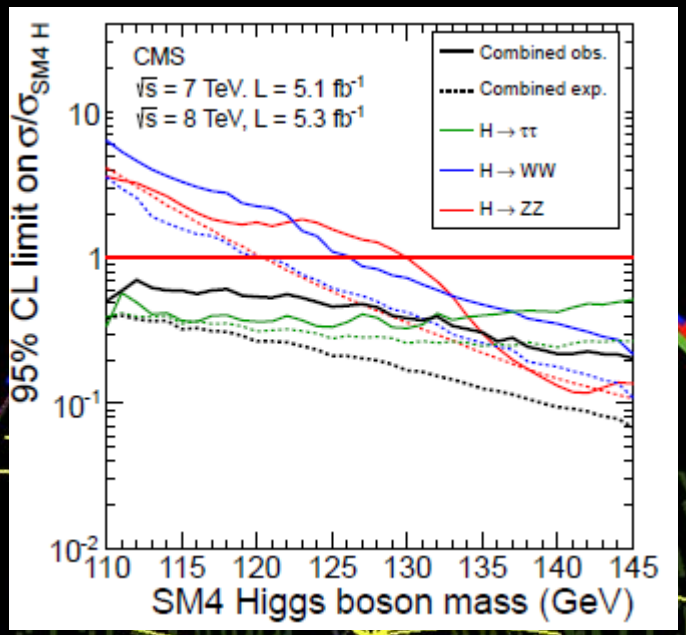
- ATLAS 7 TeV result : Excluded 110.0–118.0 GeV and 119.5–121.0 GeV

Eur. Phys. J. C (2012) 72:2157

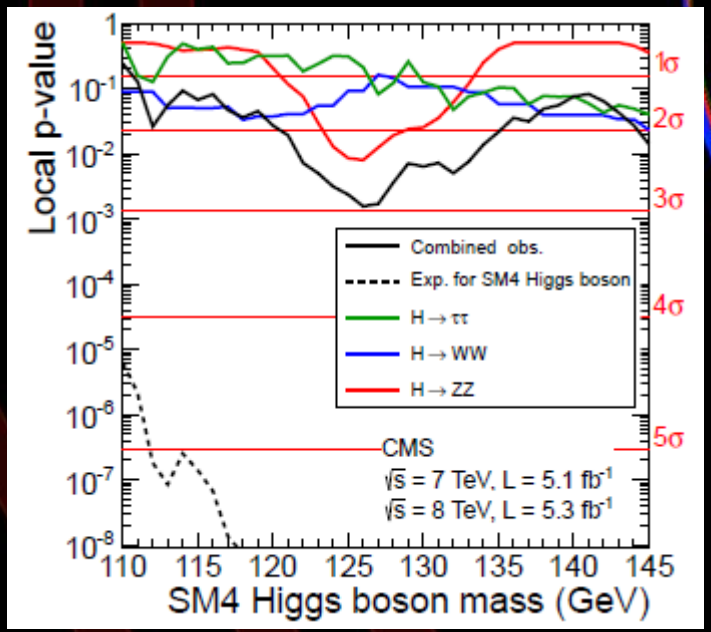
Higgs boson in 4th Generation: tt, WW, ZZ channels,CMS,7/8 TeV

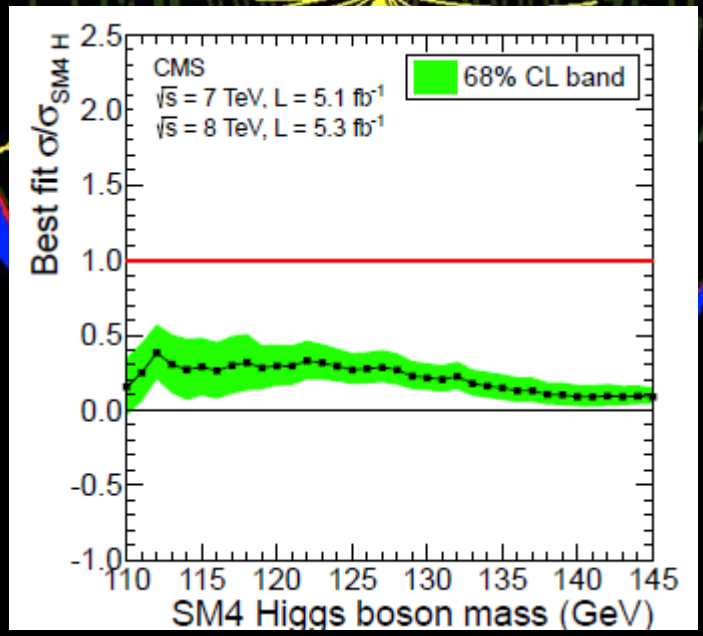
Physics Letters B725(2013)36–59





- Reinterpretation of SM Higgs search results
- An SM4 Higgs boson is excluded at 99% confidence level in the mass range 100–600 GeV and at 99.9% in the range 100-560 GeV

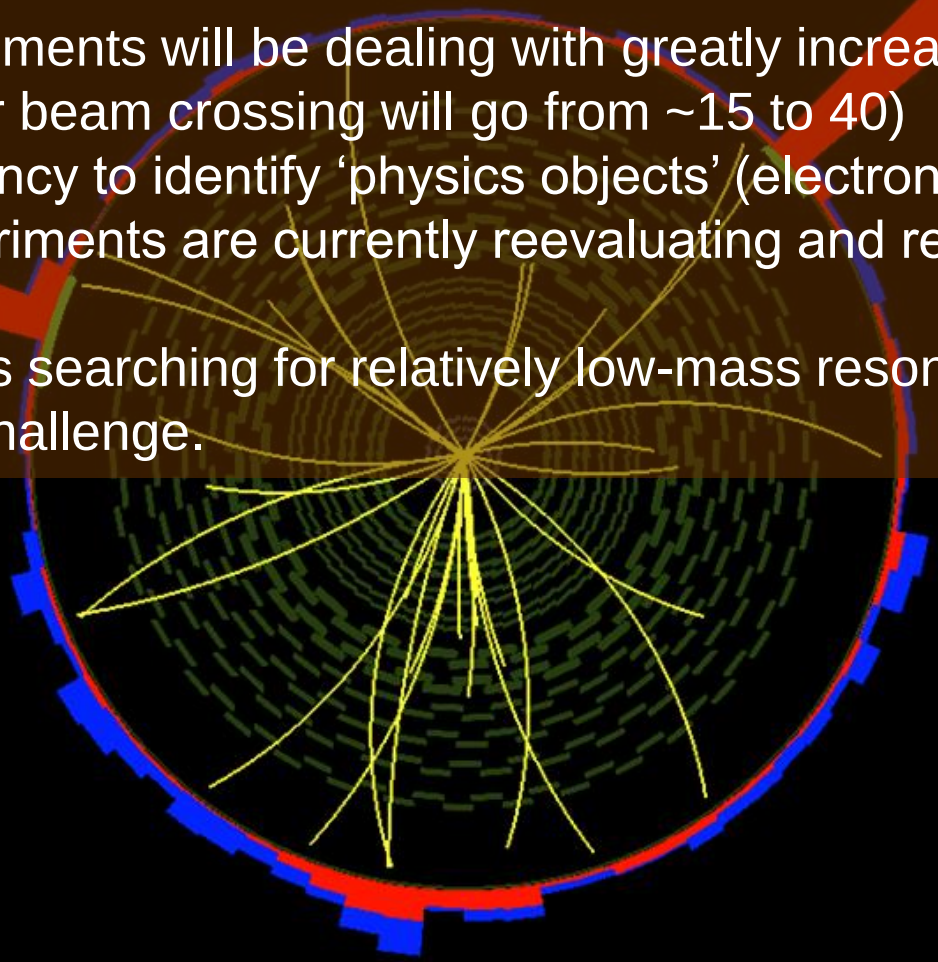




CMS Experiment at
Data recorded: Sun
Run/Event: 194108
Lumi section: 575

Challenges for low-mass searches in Run 2

- The increase in center-of-mass energy from 8 to 13 or 14 TeV is usually accompanied by a sizeable increase in production cross sections (in general X2 for SM Higgs)
- However the LHC experiments will be dealing with greatly increased pileup (number of interactions per beam crossing will go from ~15 to 40)
- This will affect the efficiency to identify 'physics objects' (electrons, photons, muons, jets…) . The experiments are currently reevaluating and reworking the relevant algorithms.
- In particular, for analyses searching for relatively low-mass resonances, triggering will be a major challenge.



Summary and Conclusion

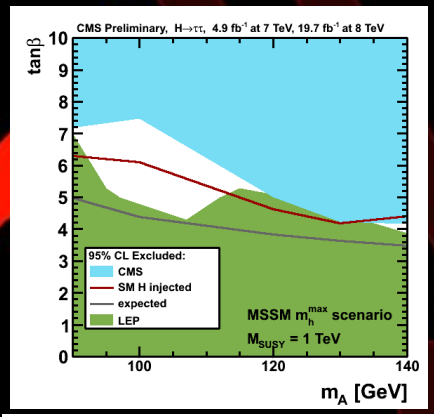
- MSSM neutral scalars:
  - Model-independent limits of a few to several tens of pb on sigmaX BR
  - The entire tanb-mA plane is expected to be excluded in the mh-max scenario, but a small window is left between 90 GeV<mA<120 GeV and 4.4<tanBeta<7.6

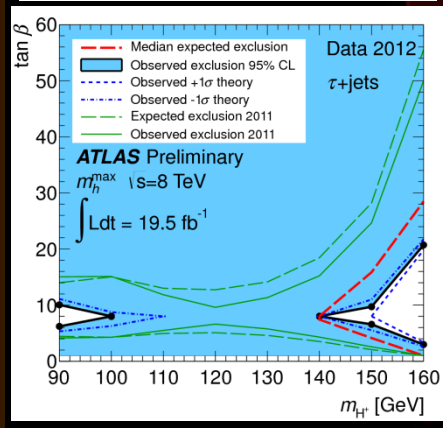
- MSSM charged scalars: A very small window in the mh-max scenario is left between 90 GeV<mH+<100 GeV and 6<tanBeta<10

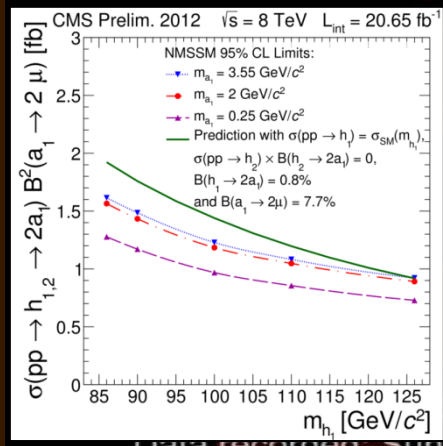
- NMSSM-like scalars and pseudoscalars: Limits ranging from a few to hundreds of fb have been set on sigma x BR of scalars decaying to light pseudoscalars in the context of the NMSSM or DarkSusy models, and a few pb for directly produced pseudoscalars

- Scalars in Fermiophobic and 4th generation: FP Higgs bosons have been excluded for mH>110 GeV and 4th generation Higgs bosons for mH>100 GeV.

- Many other searches for low-mass scalars/pseudoscalars are in progress even with Run 1 data, and more are in preparation for Run 2. We should keep looking!







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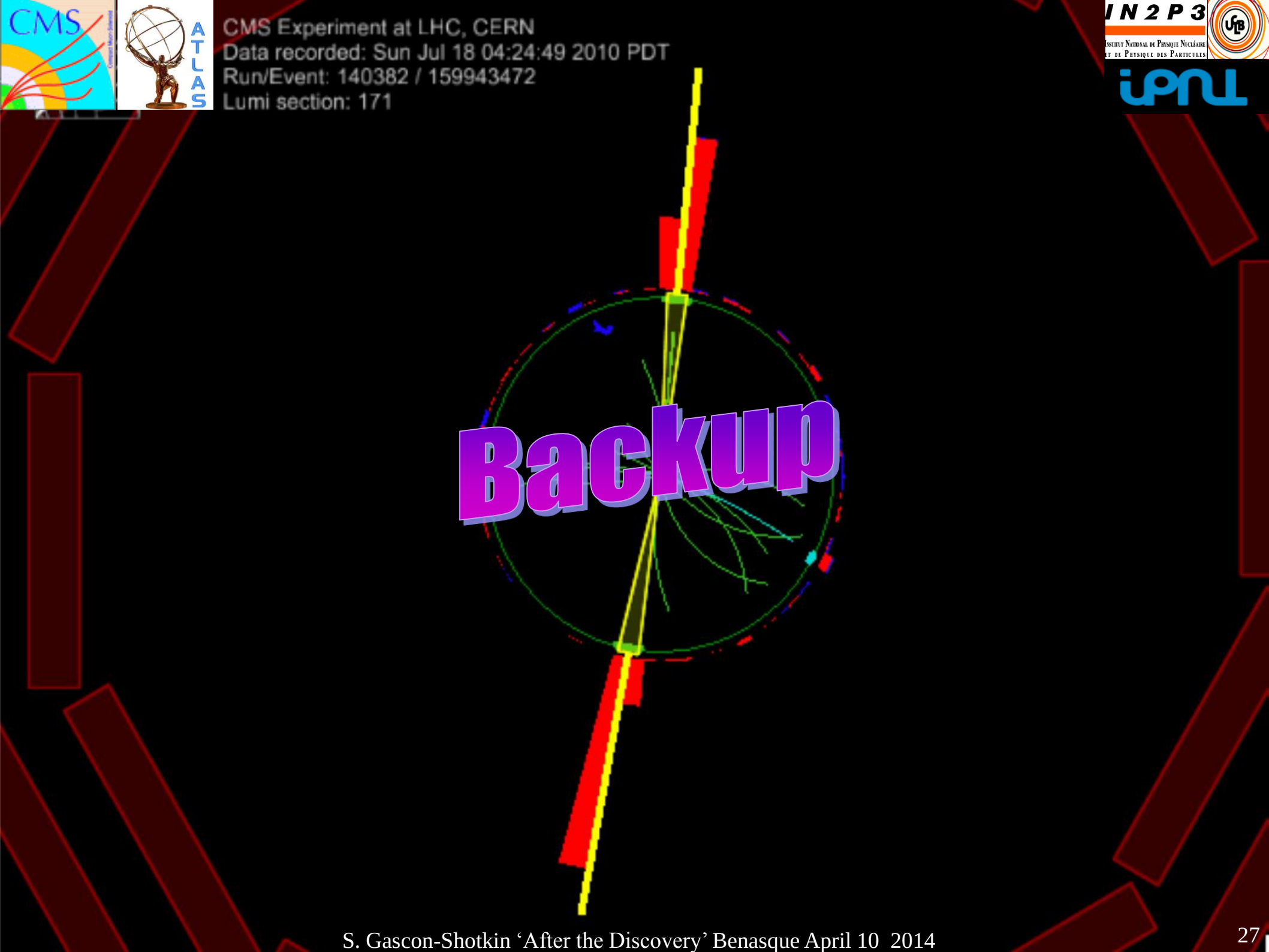
Thank you!


CMS Experiment at LHC, CERN
Data recorded: Sun Jul 18 04:24:49 2010 PDT
Run/Event: 140382 / 159943472
Lumi section: 171
Backup