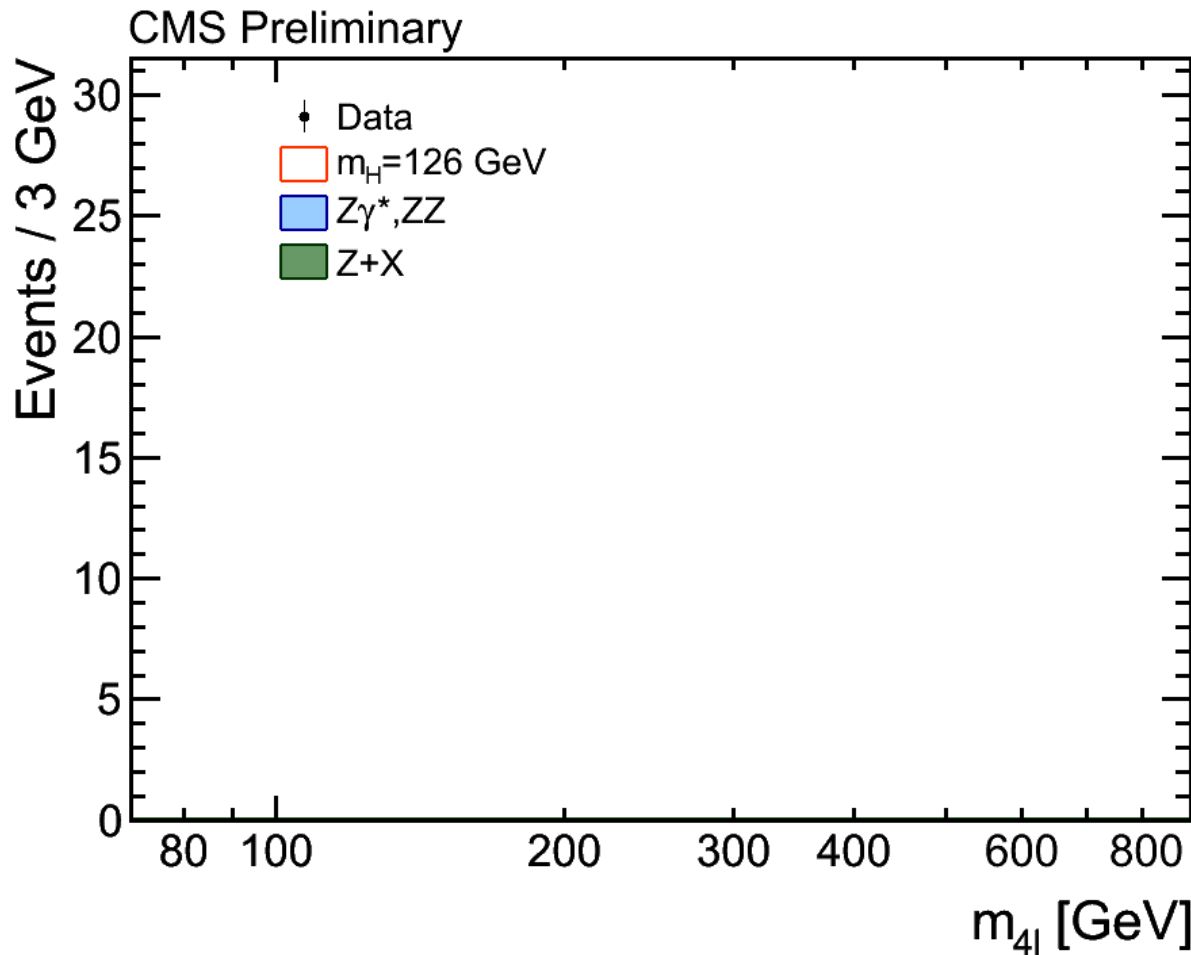


What's Next at LHC apropos Higgs?



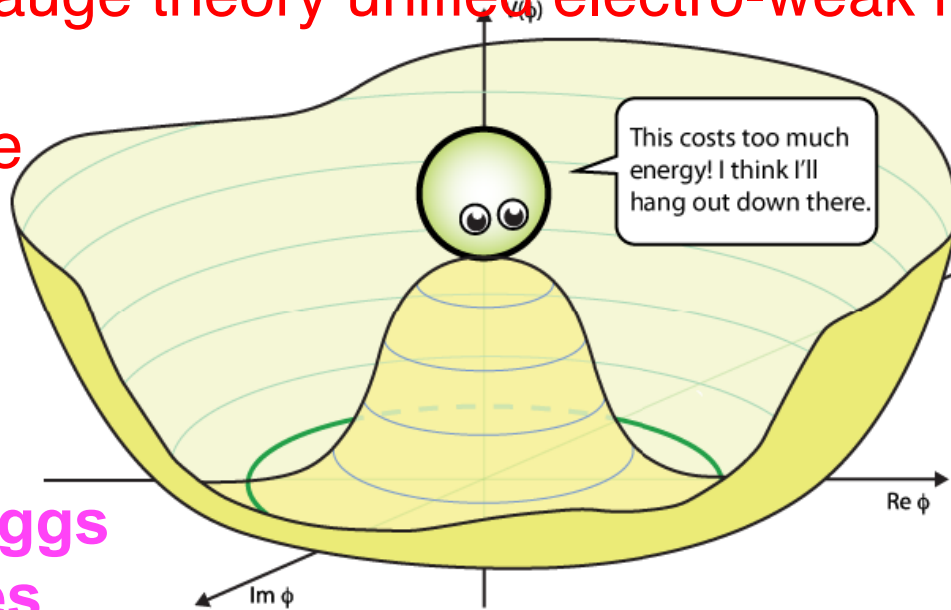
SM Higgs & BSM H Searches & Run-2





Electro-Weak Symmetry Breaking

50 years ago, gauge theory unified electro-weak interactions, but could not accommodate non-zero masses for $W^\pm$ & Z

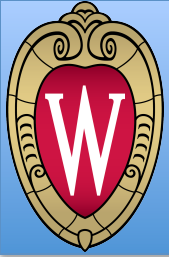


**Predicted
a remnant
scalar
particle!**

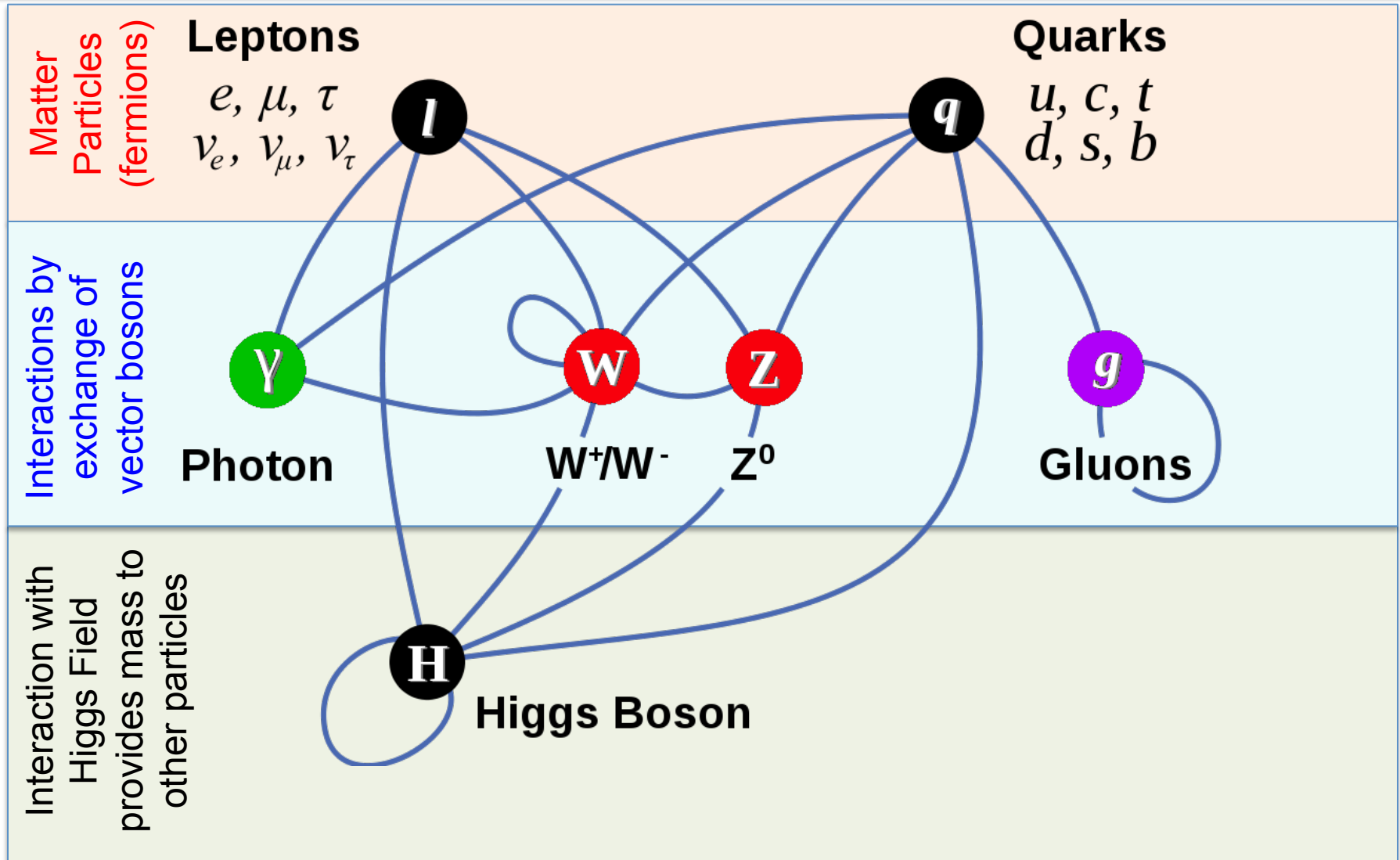
Coupling to Higgs field provides masses to matter particles!!

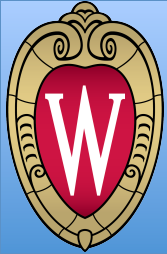
$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2 \Phi^2 - \lambda \Phi^4$$
$$\text{For } \mu^2 < 0, \text{ minimum } v = \sqrt{-\frac{\mu^2}{2\lambda}}$$

Introduction of a doublet of complex scalar fields with peculiar potential provided masses for $W^\pm$ & Z and left γ massless!

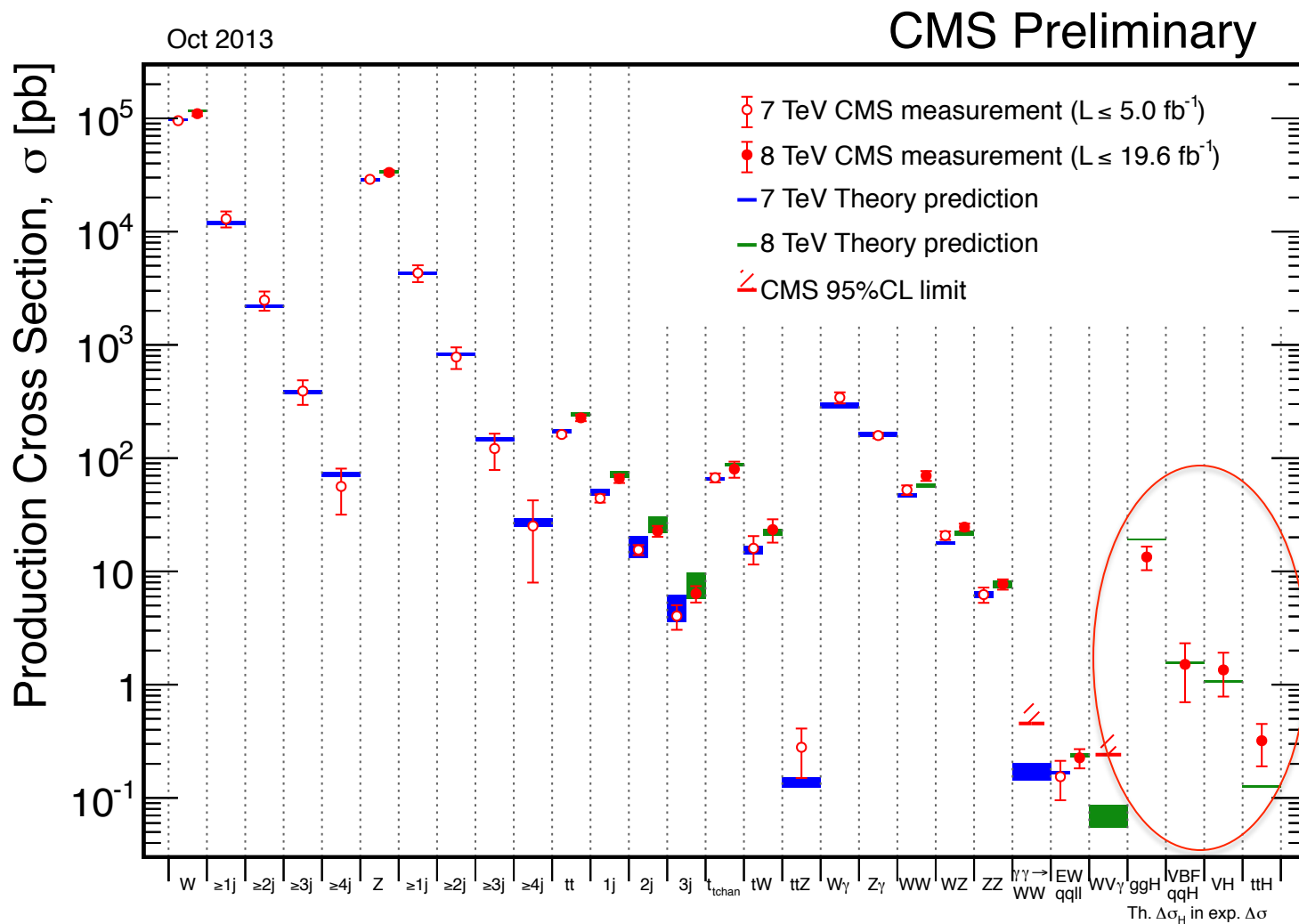


Completion of The Standard Model

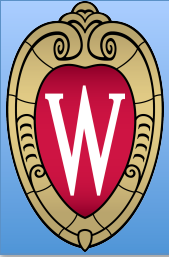




SM @ CMS Summary



Only
New
Kid
on
the
block



Is the New Boson really the SM Higgs?

Is the **signal strength**, where seen, at the correct SM level?

Is this a **scalar**, and not a pseudo-scalar or tensor?

Does it **couple** to the SM particles at appropriate level? t, b, τ, μ

Does it **couple to itself**?

Is this the **only** new non-vector boson, and not one of several?

Fortuitously, its mass of about 125 GeV allows us to answer many of these questions experimentally ☺

- Answers began to emerge by Spring this year (Run-1)
- Others will, circa 2016-2017 (Run-2)
- Self-coupling, direct coupling to muons / charm needs lot of data ☹ → Phase-1 (Run-3) and HL-LHC (Run-4+) 2035



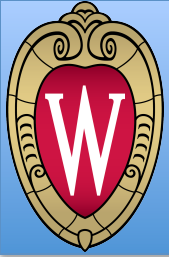
Beyond the Standard Model?

The Standard Model seems to work perfectly well...

...then why do we seek to go beyond the Standard Model?

SM can be convicted for incompleteness!

- No dark matter candidate ☹️
- No explanation for three fermion generations ☹️
- No explanation for hierarchy in fermion masses ☹️
- Inadequate amount of CP violation for baryon formation ☹️
- Strong and electroweak forces are not unified ☹️
- Higgs self energy corrections diverge
 - Various cures require new physics at $\sim$ TeV scale
- Gravity is missing entirely ☹️
 - But, Planck scale is very high compared to EWK

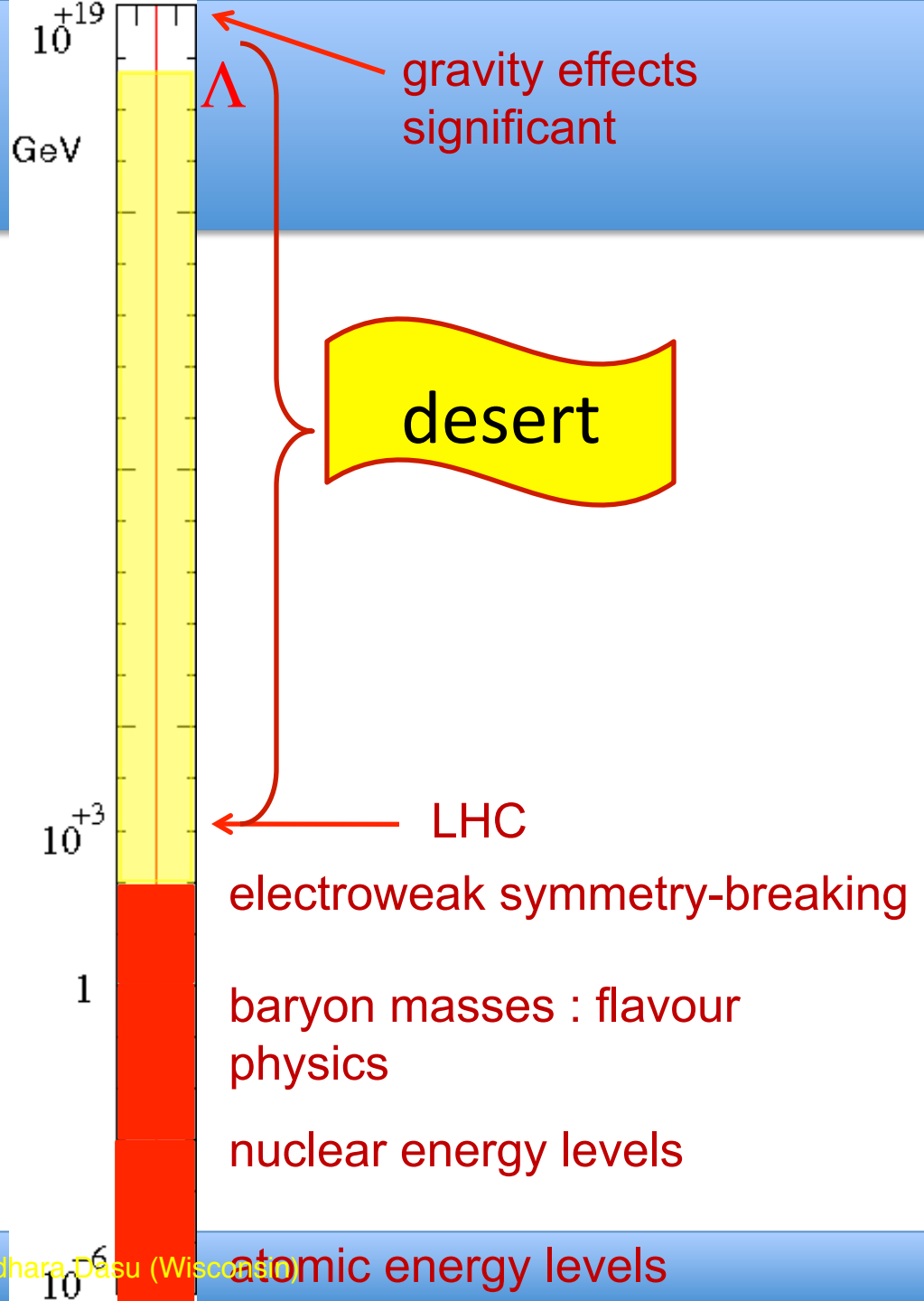


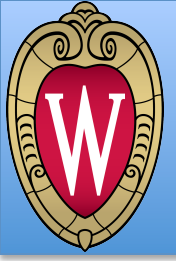
Energy Scales

Proton decay experiments pushed the unification scale of EWK and strong interactions close to Planck scale ☹

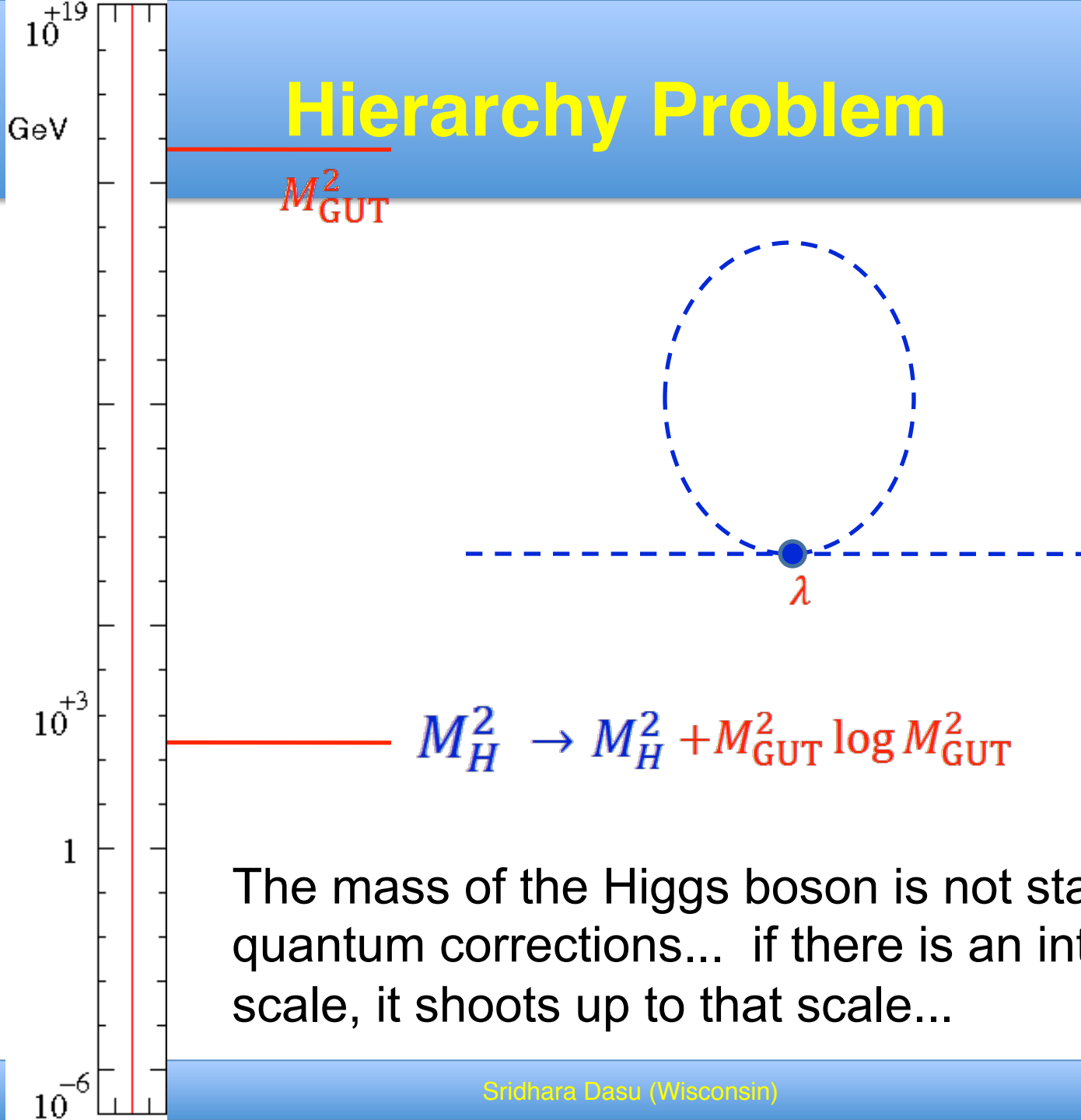
Is there nothing but a desert ahead of us?

From: S. Raychaudhuri, TIFR





Hierarchy Problem





10^{+19}
GeV

Λ

Solutions?

We can solve it by keeping the NP scale high and arranging for cancellation between its contributions to the scalar mass $\Rightarrow$ SUSY @ EWK scale
i.e., Add Particles

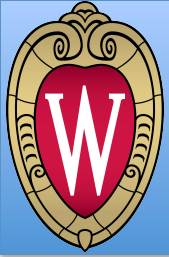
OR

10^{+3}

$$M_H^2 \rightarrow M_H^2 + \lambda \Lambda^2 \log \Lambda^2 - \lambda \Lambda^2 \log \Lambda^2$$

We can solve it by bringing down the NP scale to just above the EW scale $\Rightarrow$ Technicolor, Extra Dim New Forces or New dimensions

Either way, we predict observable effects at LHC



Higgs Mass : Fine Tuning Problem

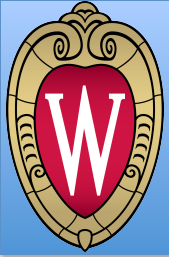
Why is the higgs mass ~ 125 GeV?

- Self-energy corrections should drive it to M_{planck}

$$M_H = \text{[Loop Diagram]} + \text{[Bosons]} - \text{[Fermions]}$$

The diagram shows the Higgs mass M_H as the sum of three terms. The first term is a self-energy loop diagram consisting of a dashed line with a loop attached to it, labeled with a red λ at the vertex. The second term is a dashed line with a blue dotted oval labeled "Bosons" in the middle. The third term is a dashed line with a blue solid oval labeled "Fermions" in the middle, preceded by a minus sign.

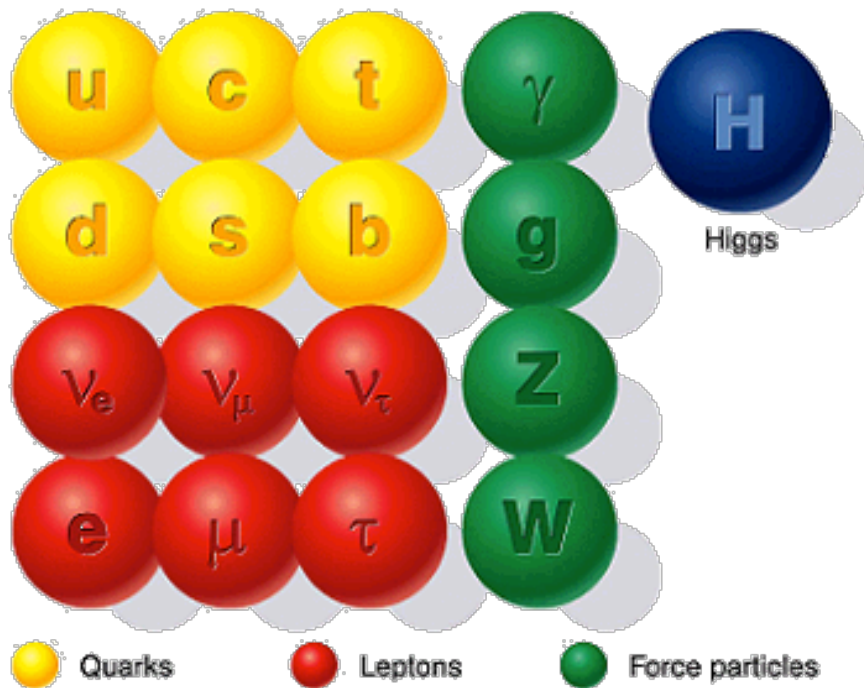
- Fermion and boson contributions should cancel at many significant figures to yield 125 GeV ☹
- Problem is solved “naturally” if there are equal number of bosons and fermions at $\sim \text{TeV}$ scale



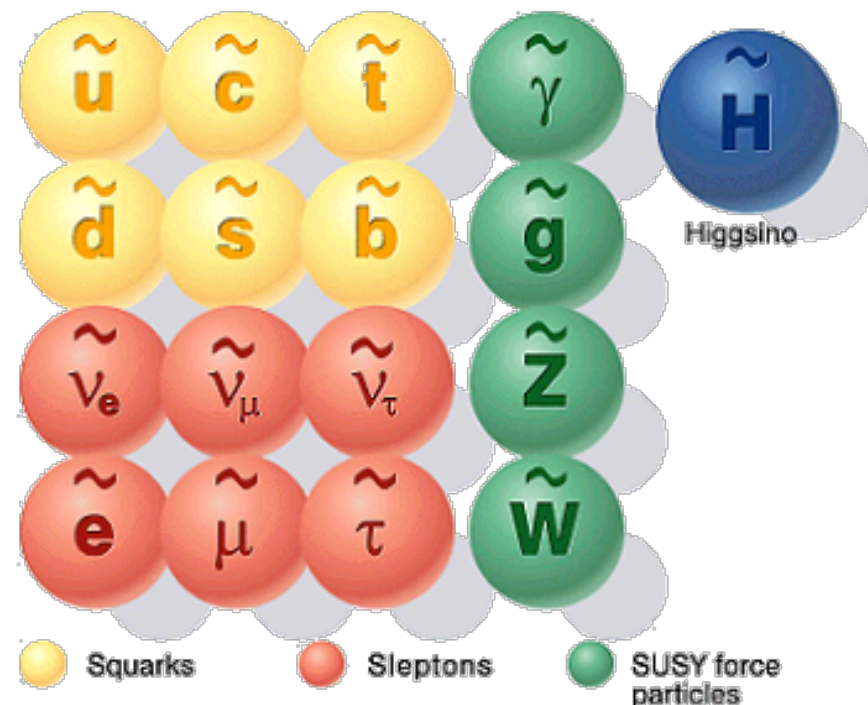
Supersymmetry

A BSM physics theory which doubles known particles again – but the new particles must have large mass

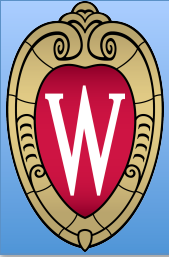
Standard particles



SUSY particles

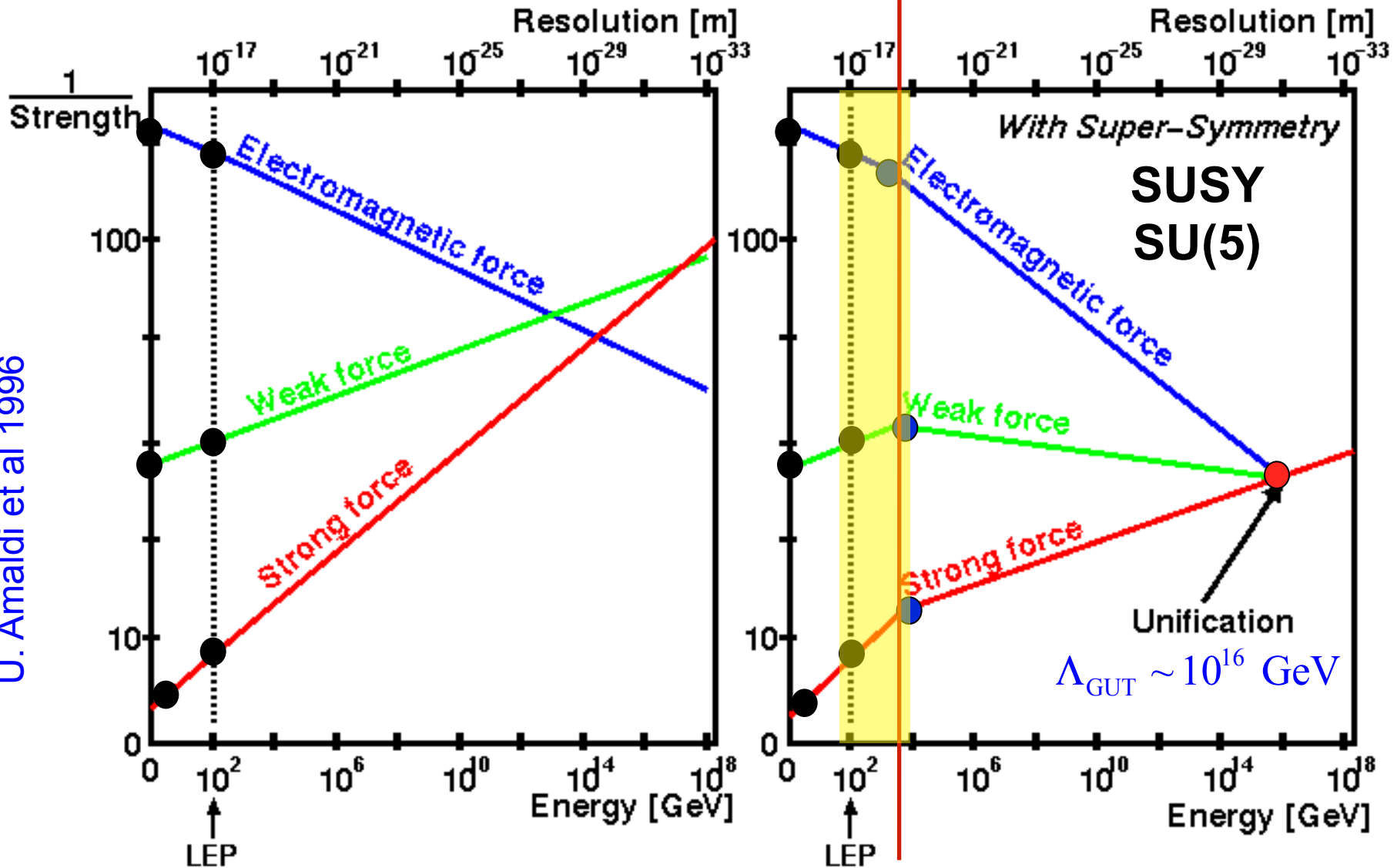


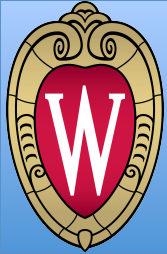
Hope remains that LHC may be able to produce them



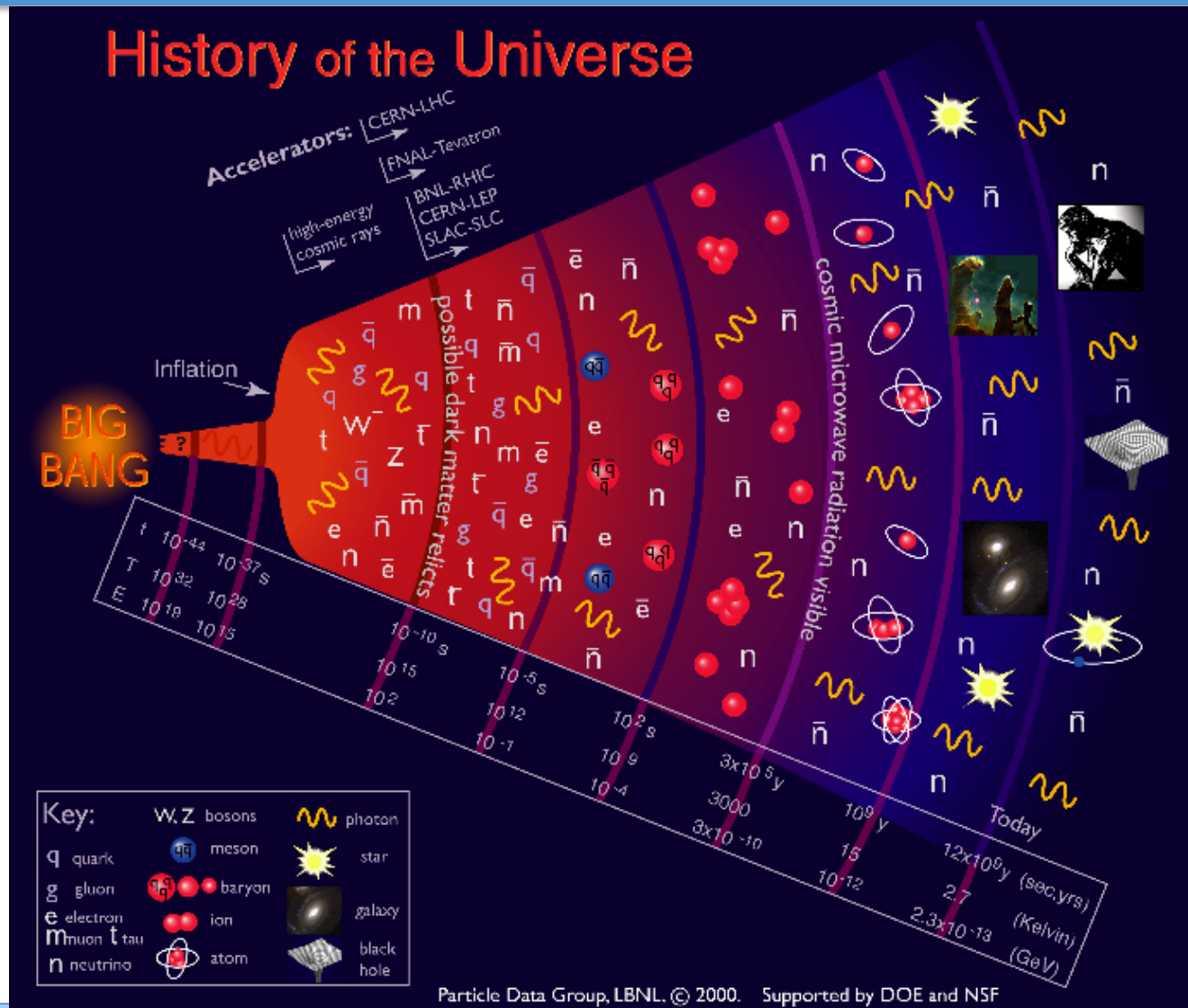
SUSY magically allows for unification

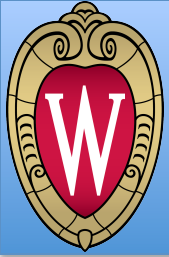
U. Amaldi et al 1996





From Quarks to Cosmos

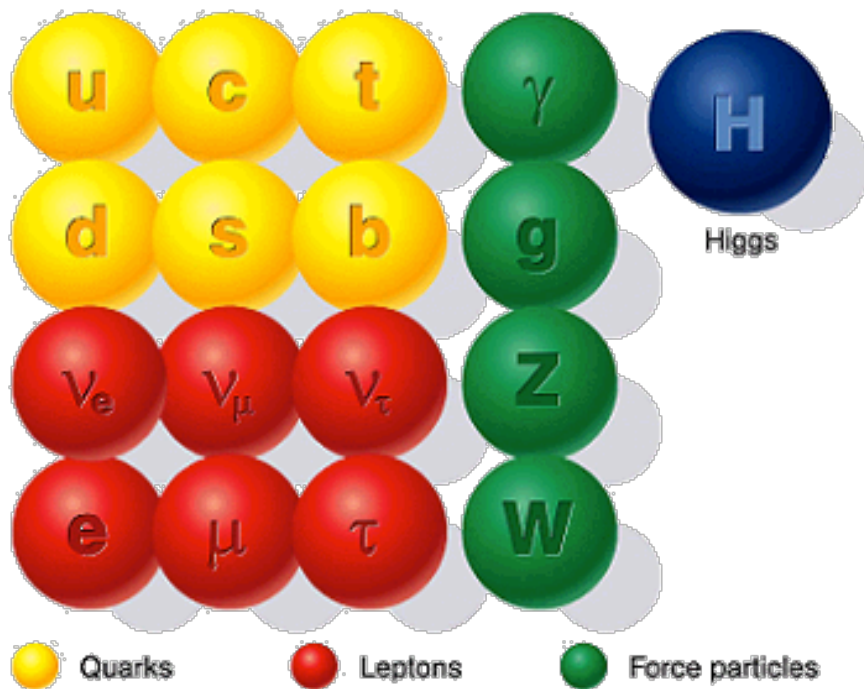




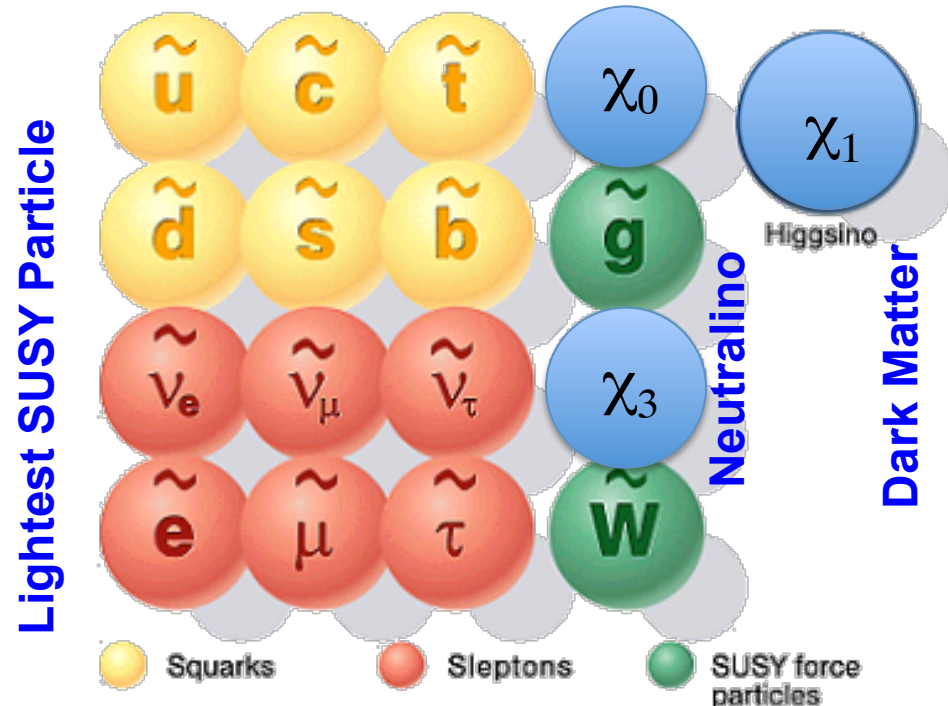
Supersymmetry

A BSM physics theory which doubles known particles again – but the new particles must have large mass

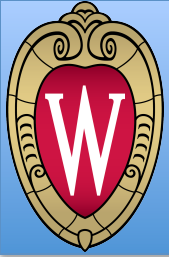
Standard particles



SUSY particles



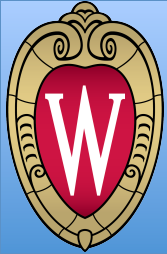
Hope remains that LHC may be able to produce them



MSSM Higgs

Higgs sector in SUSY theory is more complicated

- Need 2 higgs doublets each with 4 degrees of freedom
 - Results in the Standard Model like Higgs (h^0)
 - Plus, two neutral higgs (A^0 , H^0) and charged ($H^\pm$)
 - Only 2 parameters (M_A , $\tan\beta$ – ratio of the two doublets)
 - Masses of higgses and Z related: Search in $(M_A, \tan\beta)$ plane
- Neutral Higgs
 - Look for $\phi=(h^0, A^0, H^0)$ in decays to tau-leptons
- Charged Higgs
 - Look for $H^\pm$ in top decays



MSSM Higgs Characteristics

In supersymmetric theories, there is one Higgs doublet that behaves like the SM one.

$$H_{SM} = H_d \cos \beta + H_u \sin \beta, \quad \tan \beta = v_u/v_d$$

The orthogonal combination may be parametrized as

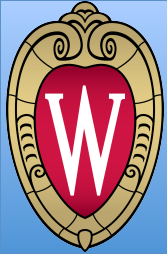
$$H = \begin{pmatrix} H + iA \\ H^\pm \end{pmatrix}$$

where H , $H^\pm$ and A represent physical CP-even, charged and CP-odd scalars (non standard Higgs).

Strictly speaking, the CP-even Higgs modes mix and none behave exactly as the SM one.

$$h = -\sin \alpha \operatorname{Re}(H_d^0) + \cos \alpha \operatorname{Re}(H_u^0)$$

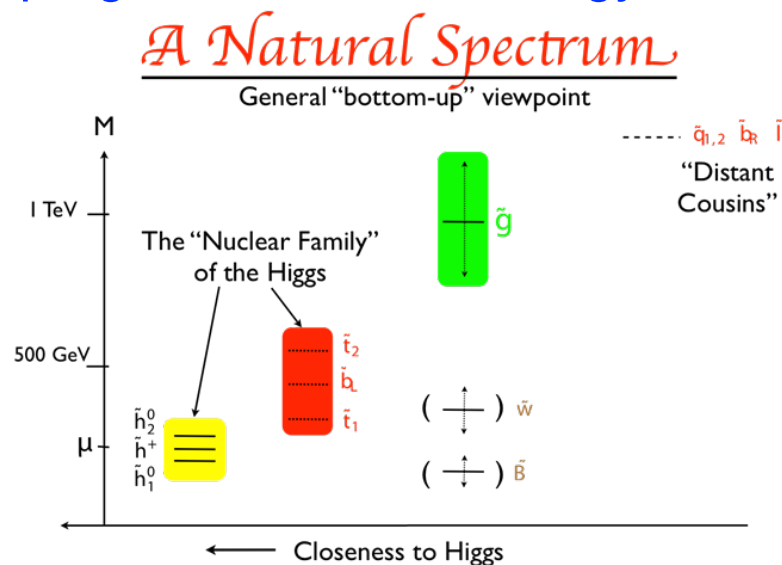
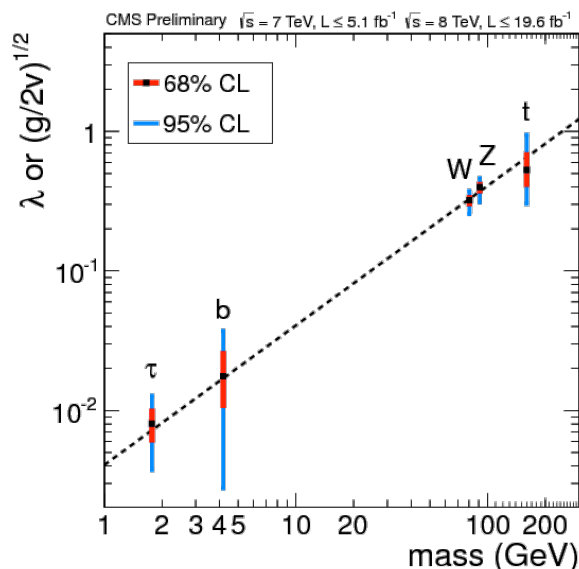
In the so-called decoupling limit, in which the non-standard Higgs bosons are heavy, $\sin \alpha = -\cos \beta$ and one recovers the SM as an effective theory.

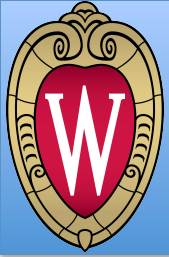


Supernatural SUSY

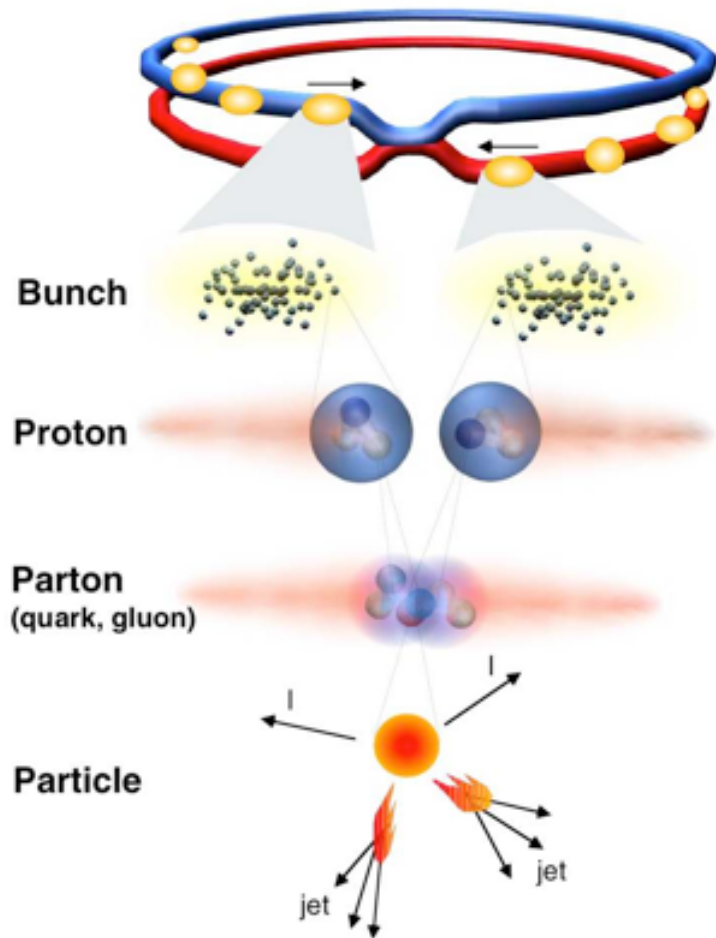
Maximal Higgs-Top coupling $\rightarrow$ Cancel only that $\odot \rightarrow$ All we need is a stop

- Godzilliion parameters, mixing options with all the scalars around $\rightarrow$ people can arrange any spectrum, and they have
- LSP WIMP DM candidate $\rightarrow$ bonus
- If Run-2 $\sim 100 \text{ fb}^{-1}$ doesn't find stop, DM or alternate new physics
- We are at the $\sim$ end of energy frontier at LHC
- HL-LHC $\rightarrow$ Intensity frontier program; VLHC $\rightarrow$ Energy frontier

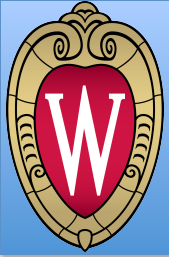




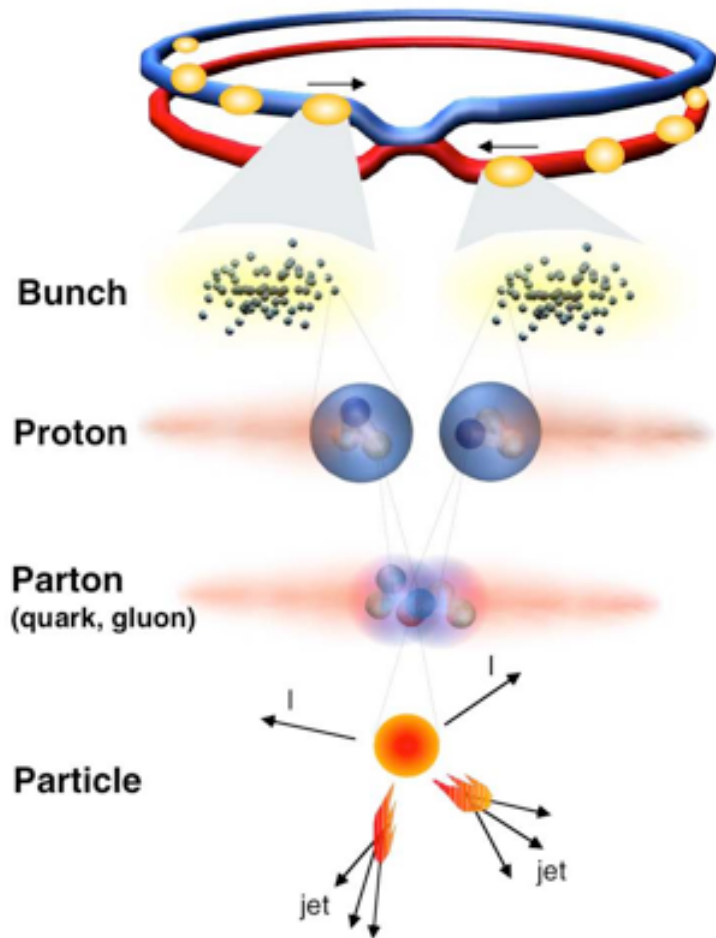
LHC in Run-1



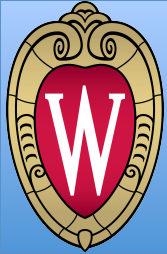
	Design	2011	2012
Beam energy	7 TeV	3.5 TeV	4.0 TeV
Bunches/beam	2835	1380	1380
Protons/bunch	1.15×10^{11}	1.5×10^{11}	2.2×10^{11}
N Collisions Created		2.5×10^{14}	3.5×10^{14}
N Higgs Events		Few hundred	Few hundred



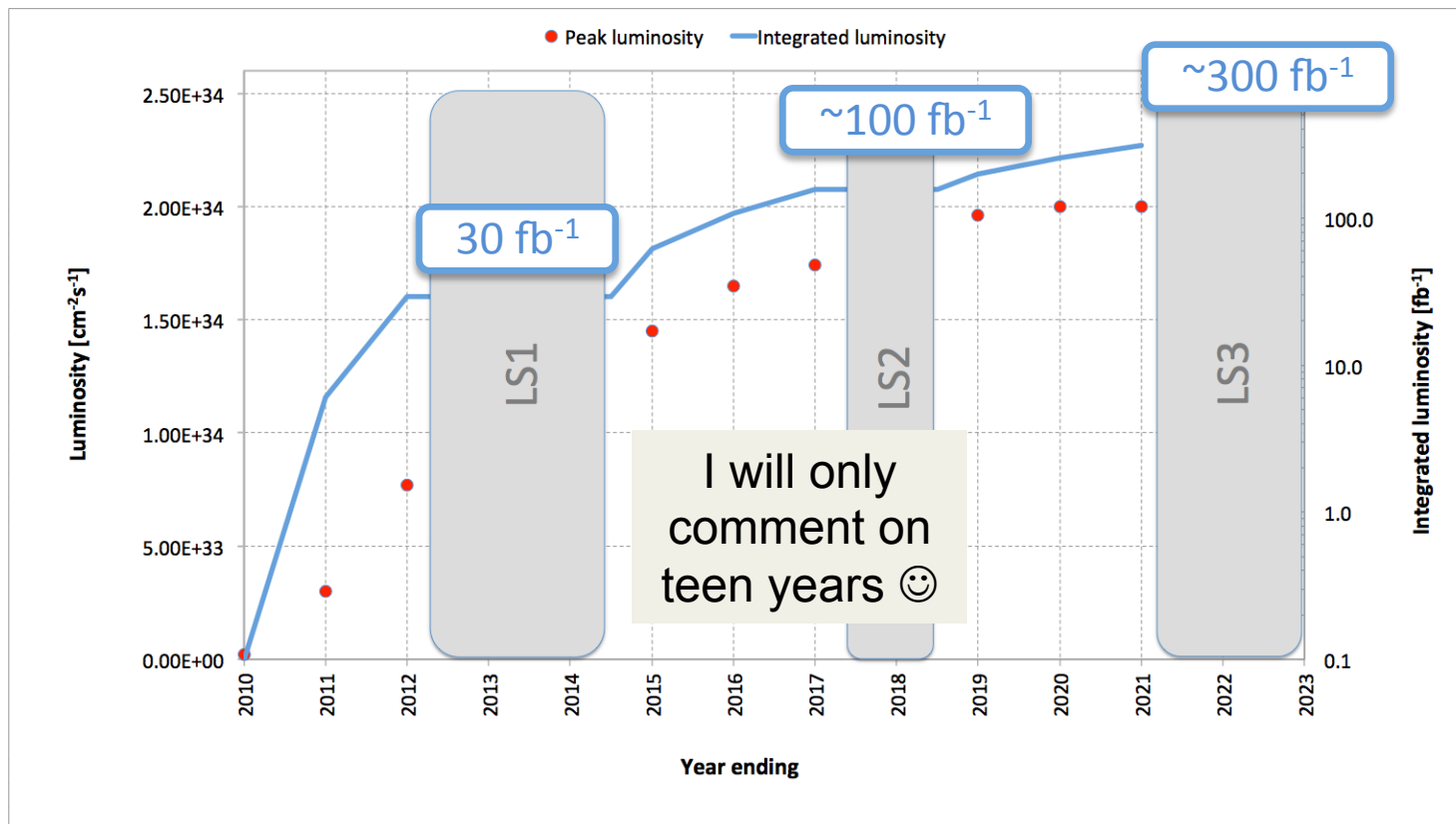
LHC in Run-2



	Design	2012	Run-2
Beam energy	7 TeV	4.0 TeV	6.5 TeV ?
Bunches/ beam	2808	1380	2808 ?
Protons/ bunch	1.15×10^{11}	2.2×10^{11}	2.2×10^{11}
Peak Luminosity	1×10^{34}	7×10^{33}	2.4×10^{34}
N Useful Higgs Events		Few hundred	Few thousand



LHC Schedule



Including energy increase
Run-2 $\sim 10 \times$ Run-1

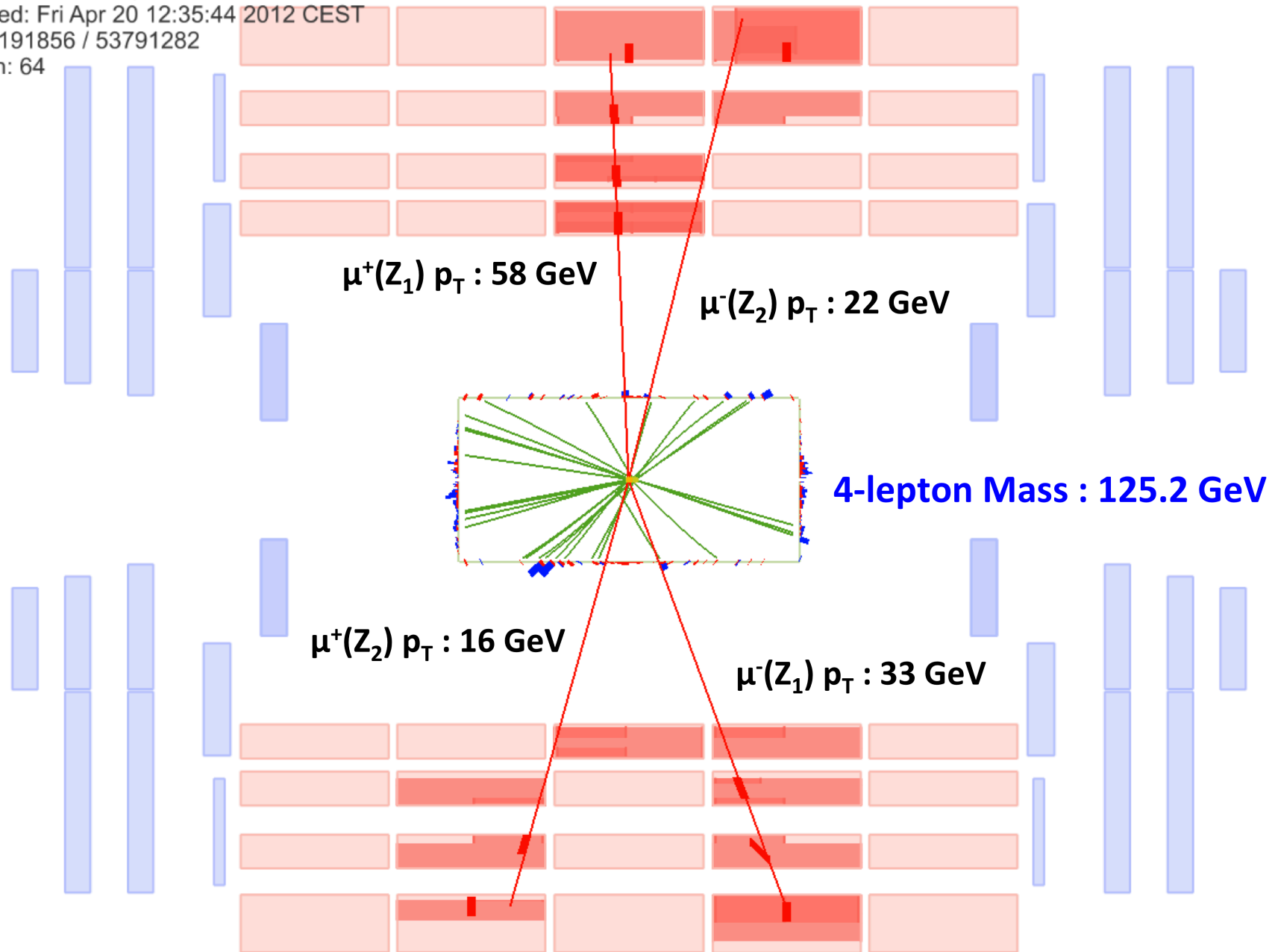
Adults will speak about
HL-LHC, which goes
through 2035 giving 3 ab^{-1}

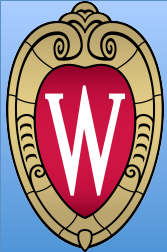
CMS Experiment at LHC, CERN

Data recorded: Fri Apr 20 12:35:44 2012 CEST

Run/Event: 191856 / 53791282

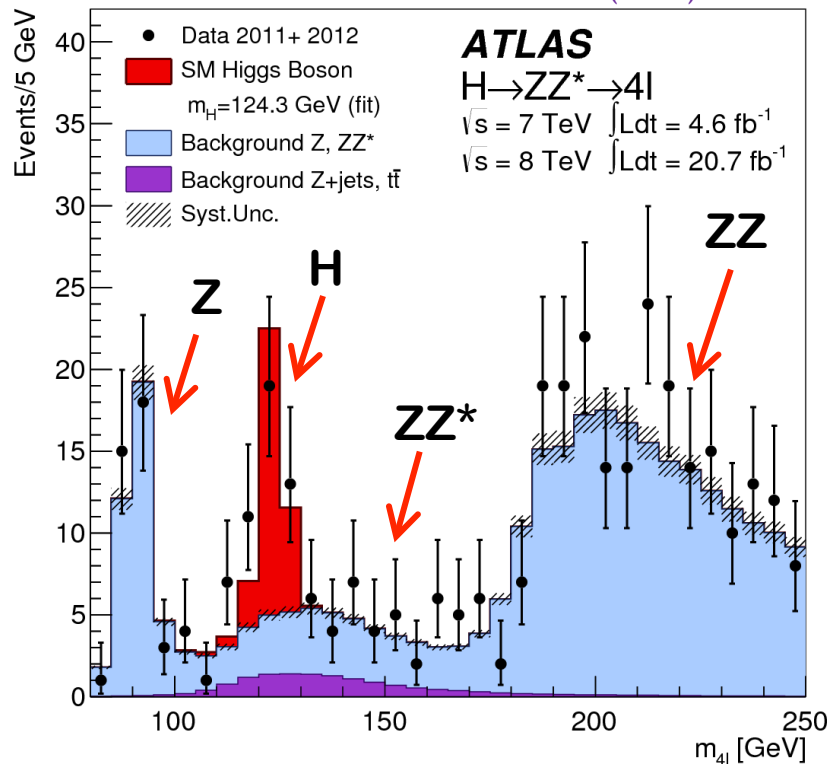
Lumi section: 64



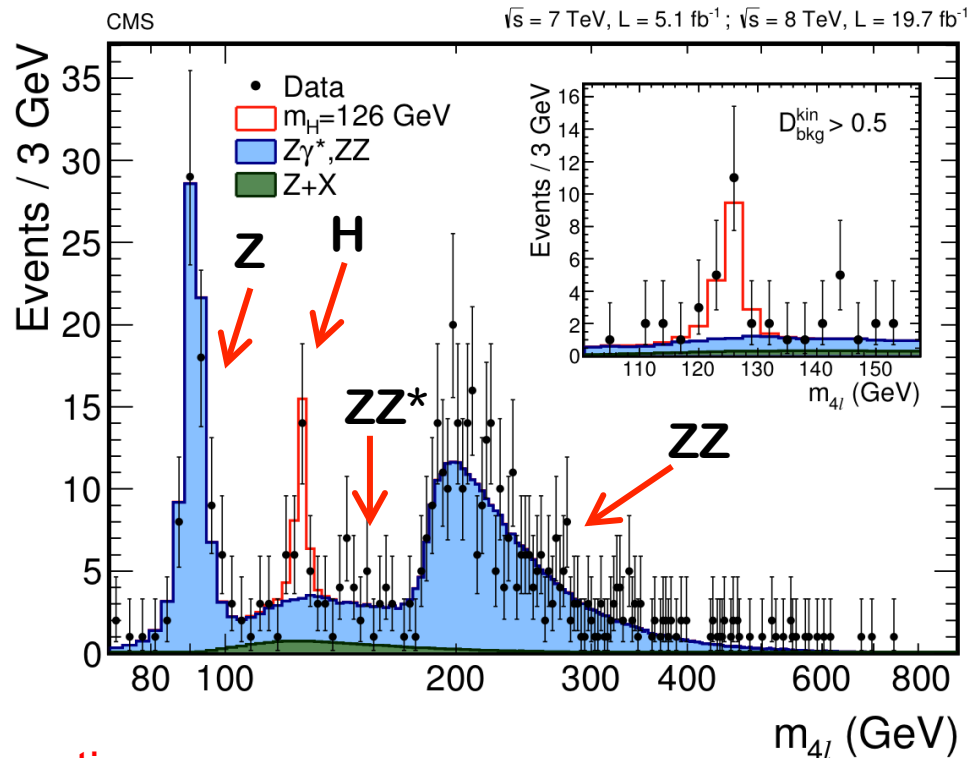


Decays to ZZ^* to 4-light leptons

PLB 726 (2013) 88-119



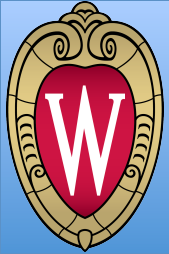
CMS-HIG-13-002 (sub. to JHEP)



Shape vs counting
analysis

Projected

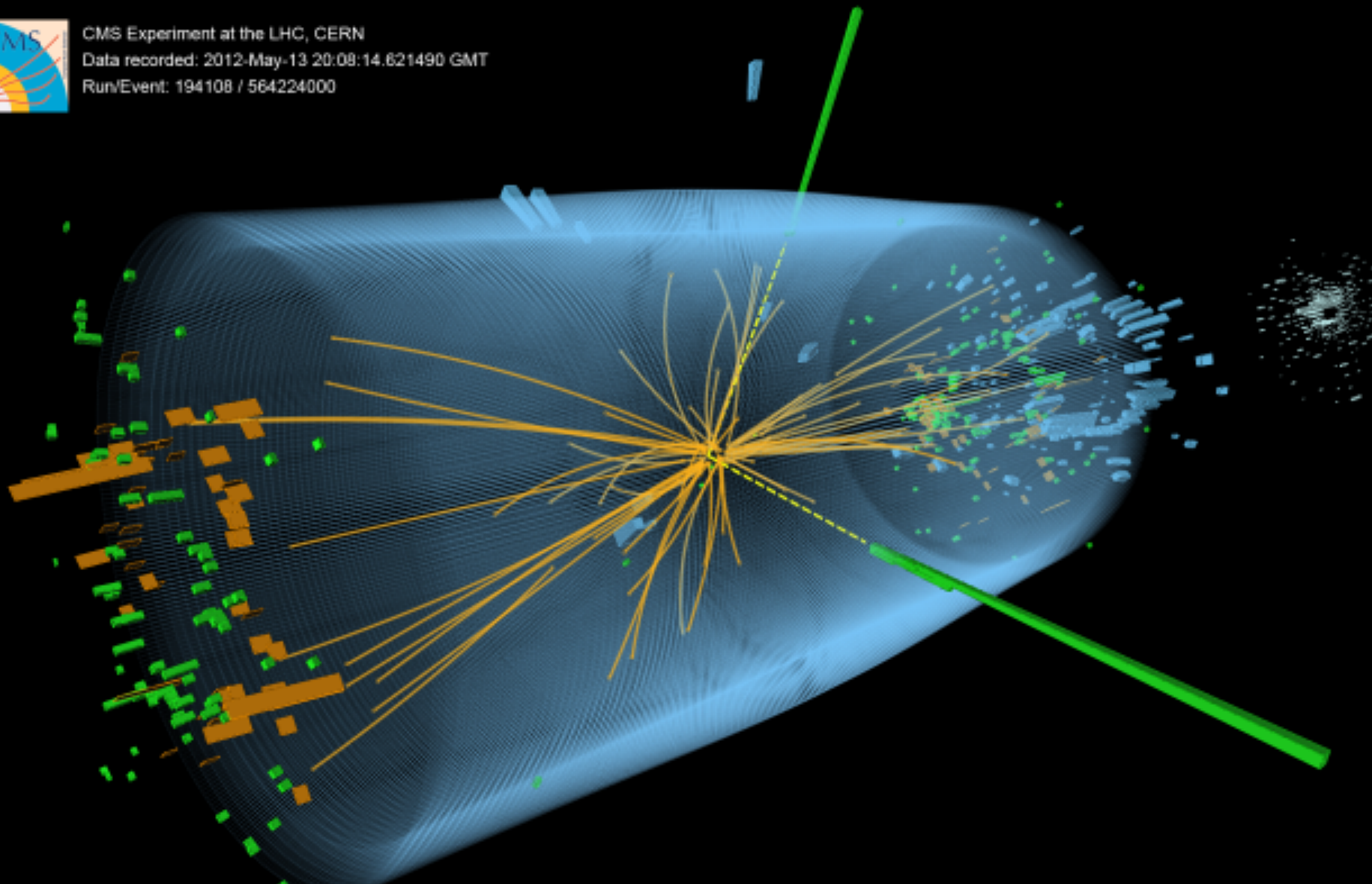
Sample	Signal	BG	Official Sig	Naïve Sig	Signal	Proj BG	Proj Sig	Error
ATLAS:ZZ	27	15	6.6	4	270	150	13	8%
CMS:ZZ	17	3	6.7	4	170	30	12	8%

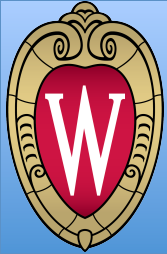


Candidate 2-Photon Event

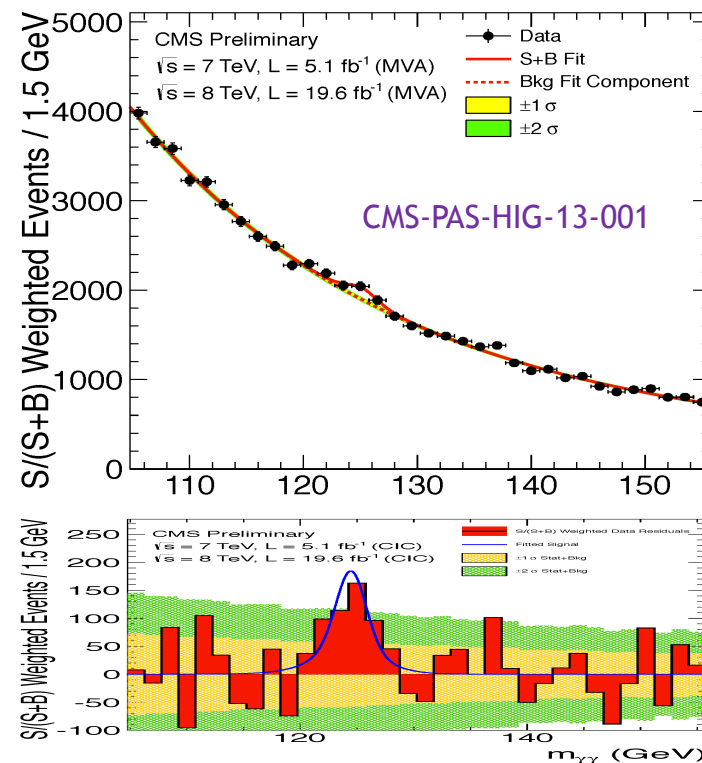
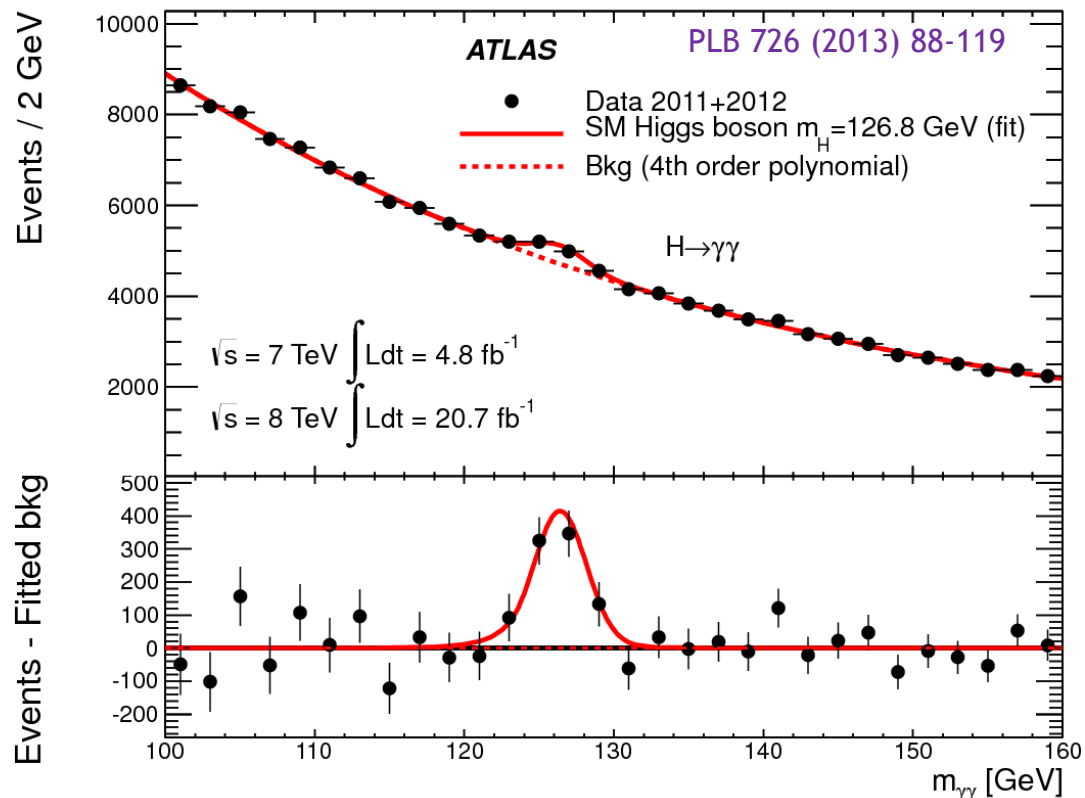


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

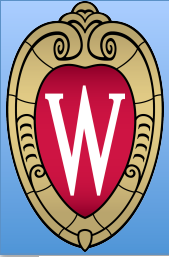




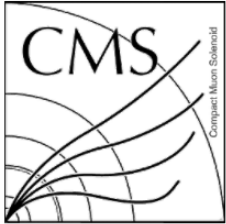
Two Photon Final State



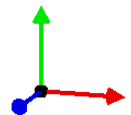
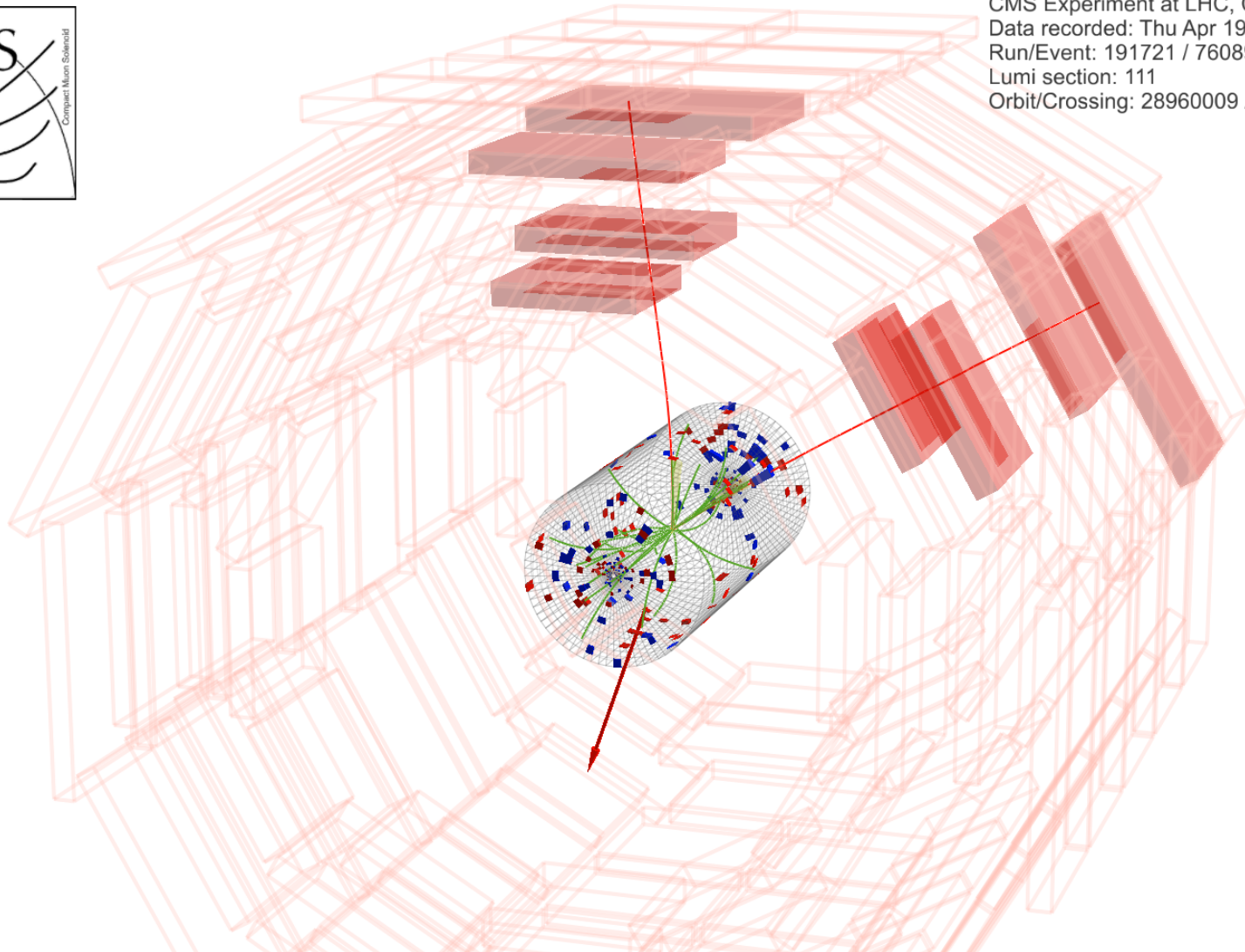
Sample	Signal	Background	Official Significance	Naïve Significance	Projected Signal	Projected Background	Projected Significance	Projected Error
ATLAS: $\gamma\gamma$	700	10000	7.1	7	7000	100000	21	5%
CMS: $\gamma\gamma$	300	6000	3.9	4	3000	60000	12	8%
ATLAS: $\gamma\gamma(\mu=1)$	438	10000	4.1	4	4375	100000	14	7%
CMS: $\gamma\gamma(\mu=1)$	390	6000	4.2	5	3896	60000	15	6%

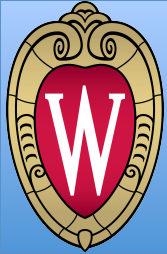


$WW \rightarrow \ell^+ \ell^- \text{ MET}$

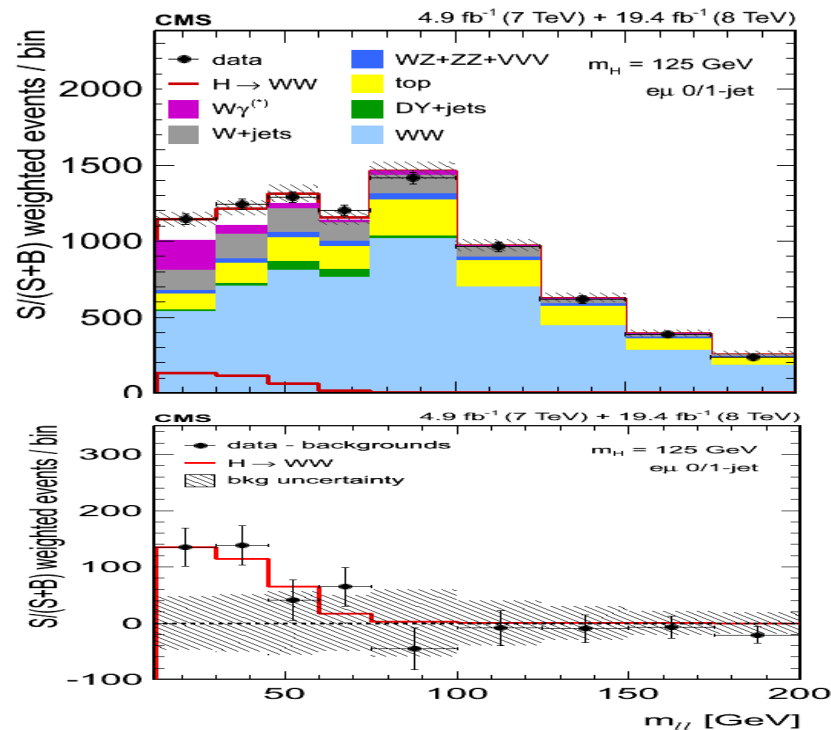
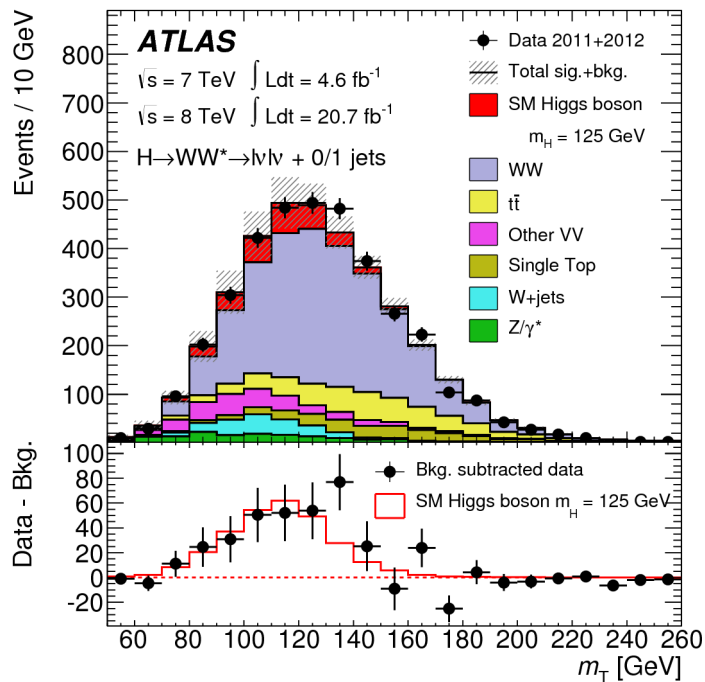


CMS Experiment at LHC, CERN
Data recorded: Thu Apr 19 09:14:14 2012 CEST
Run/Event: 191721 / 76089774
Lumi section: 111
Orbit/Crossing: 28960009 / 815



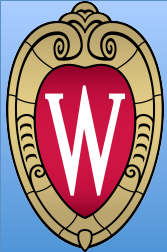


WW $\rightarrow \ell^+ \ell^-$ MET



Sample	Signal	BG	Official Sig	Naïve Sig	Projected Signal	Projected BG	Projected Sig	Error
ATLAS:WW	305	2595	3.8	6	3050	25950	18	6%
CMS:WW	380	4470	3.9	5	3800	44700	17	6%

Ignoring BG
 systematic uncertainty

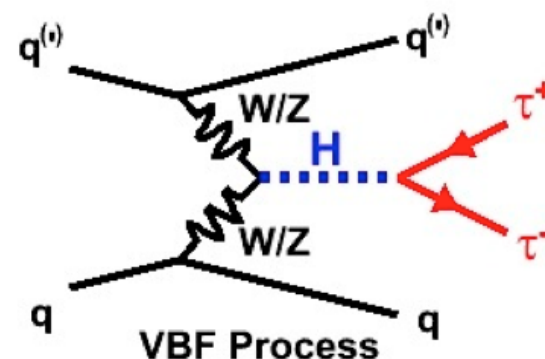
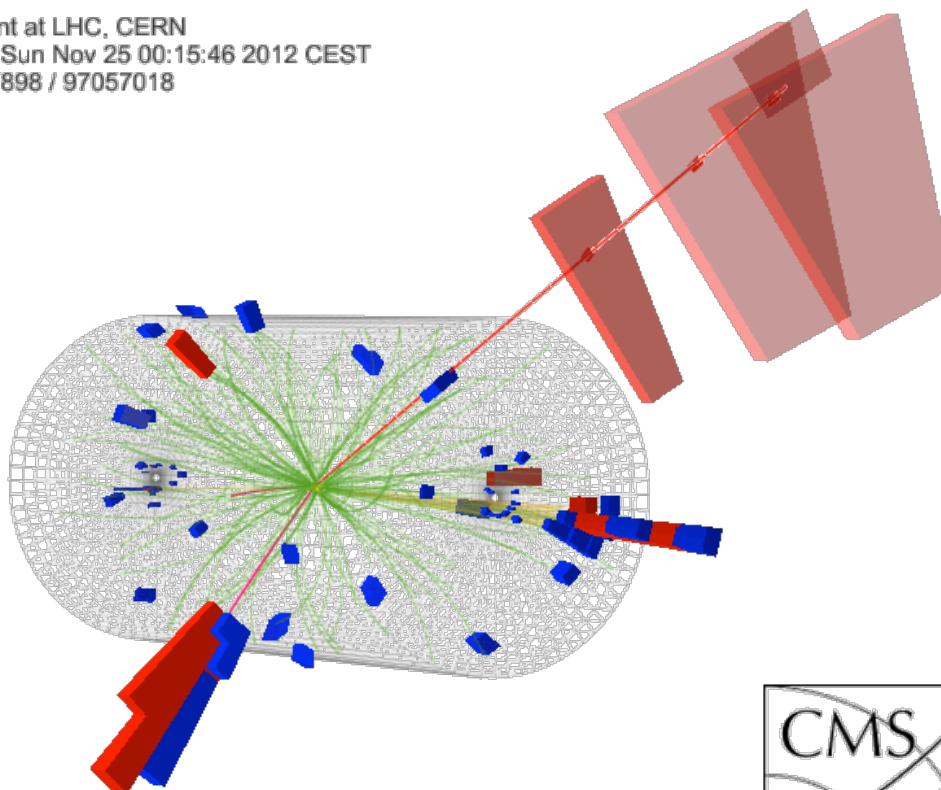


Higgs Decay to Tau Pairs

CMS HIG-13-004

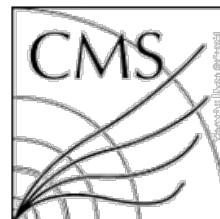
Taus with high branching fraction can probe in all production modes:
W and Z boson fusion; Gluon fusion and W, Z, top associated production

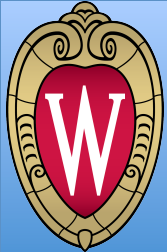
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 25 00:15:46 2012 CEST
Run/Event: 207898 / 97057018



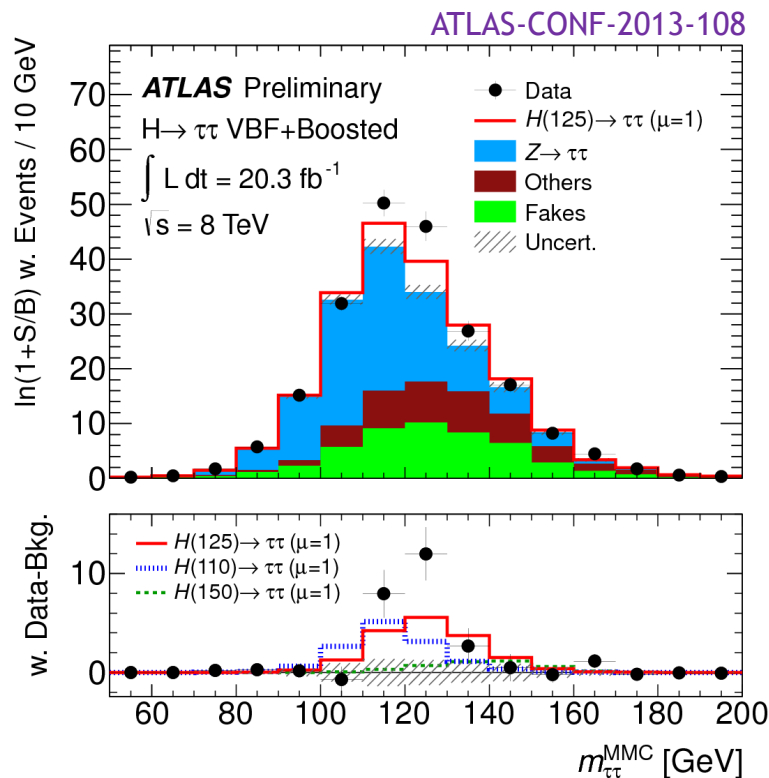
Final states VBF + GF:
 $e\mu$, $\mu\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

Also, VH (WH & ZH)
 $ll\tau_h$, $l\tau_h\tau_h$, $ll\tau_h\tau_h$



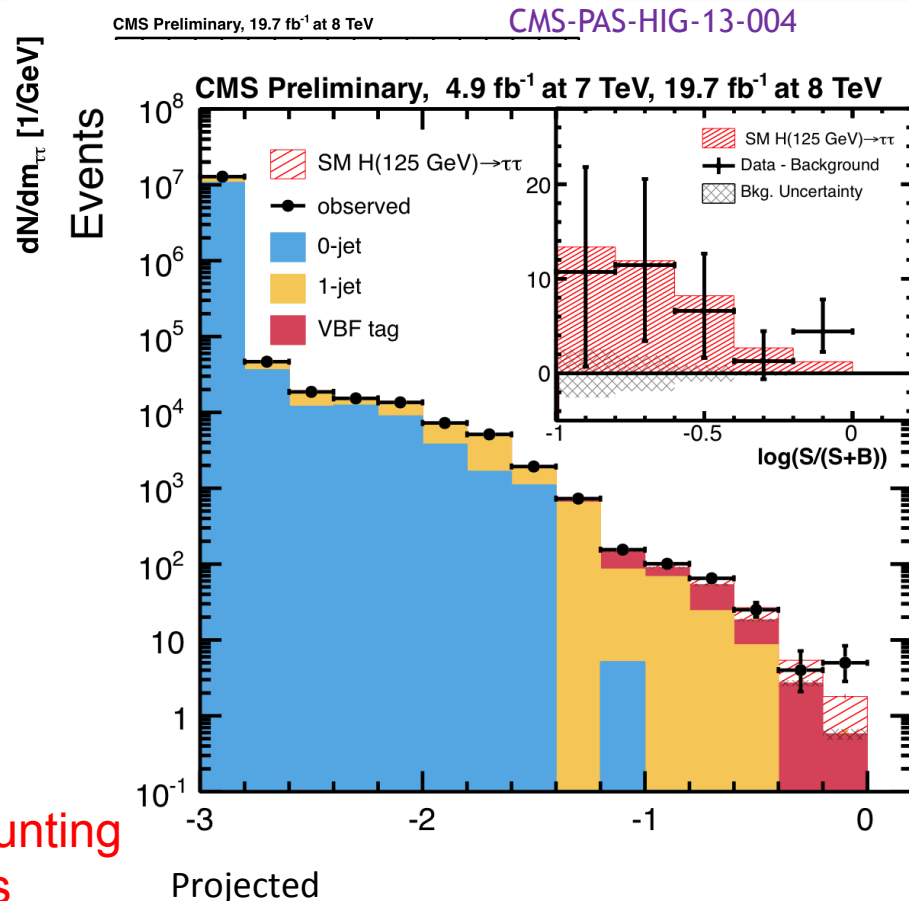


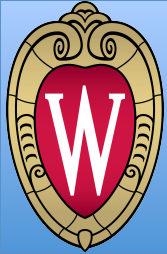
Higgs Decay to Tau Pairs



Shape vs counting
analysis

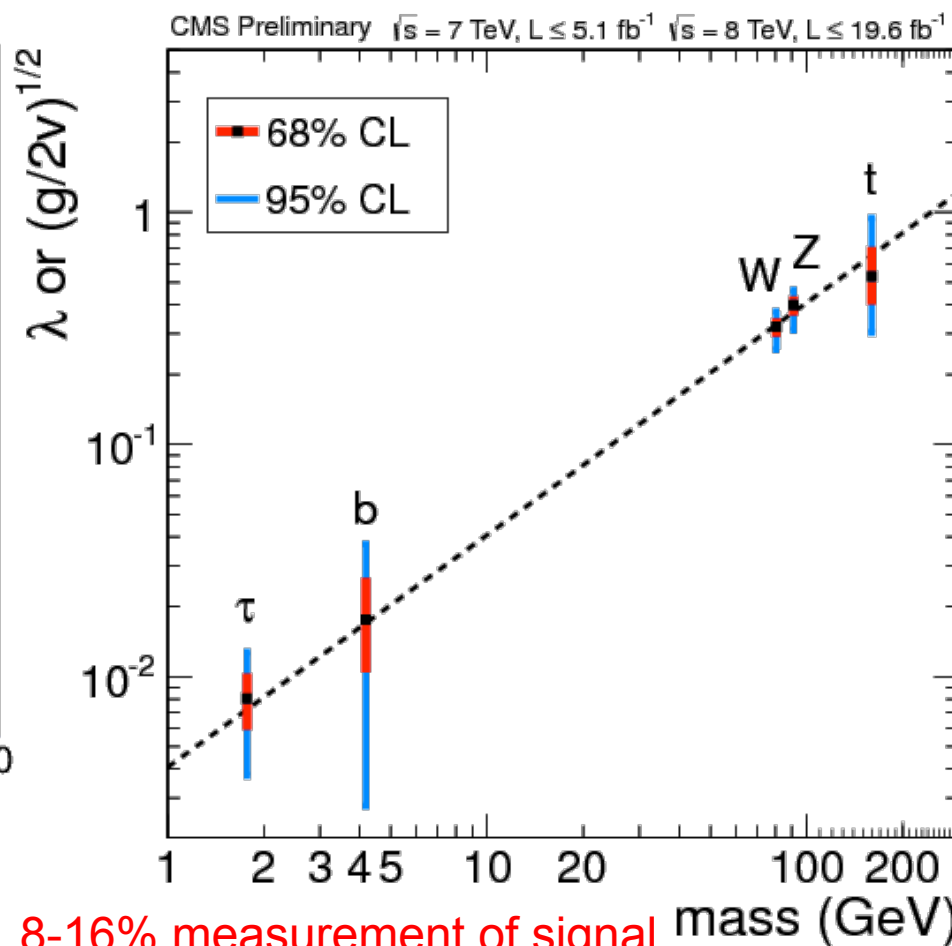
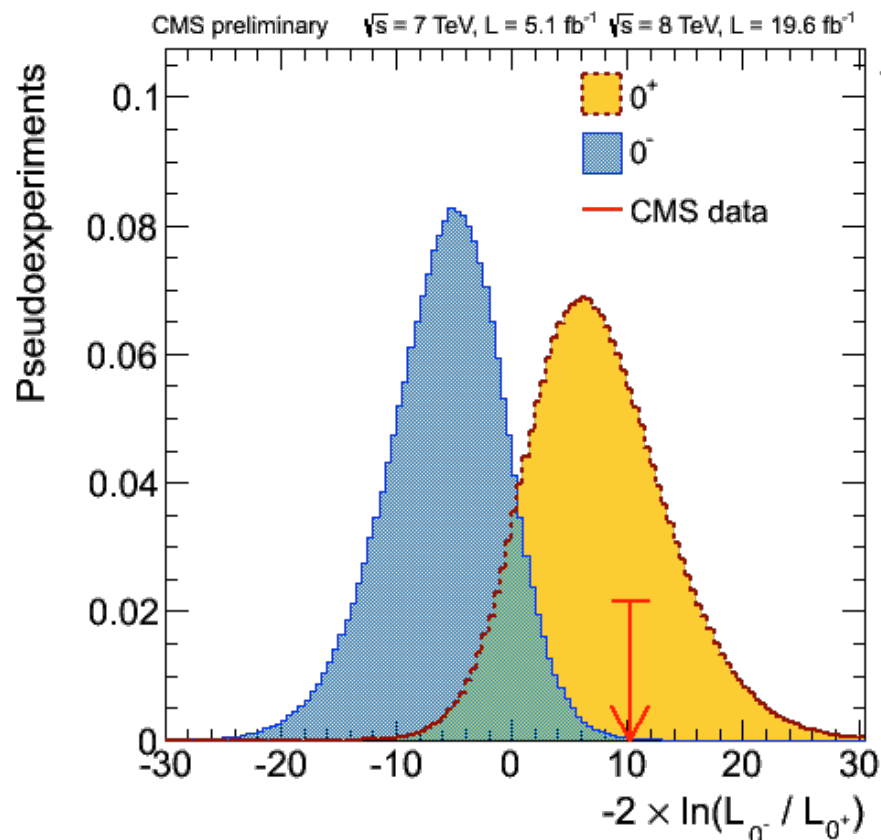
Sample	Signal	BG	Official Sig	Naïve Sig	Projected Signal	Proj BG	Proj Sig	Error
ATLAS: $\tau\tau$	23	121	4.1	2	230	1210	6	16%
CMS-VBF: $\tau\tau$	27	168	3.4	2	270	1675	6	16%





Spin & Couplings

CMS HIG-13-005

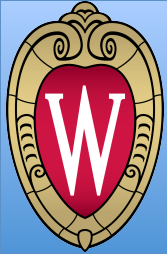


Its spin is like that of SM Higgs (0⁺)

It couples like Higgs

So, is it the SM Higgs?

8-16% measurement of signal strength in τ, W, Z with x10 data

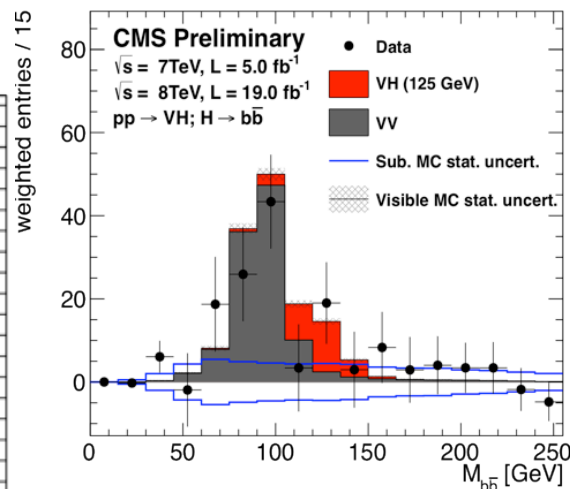
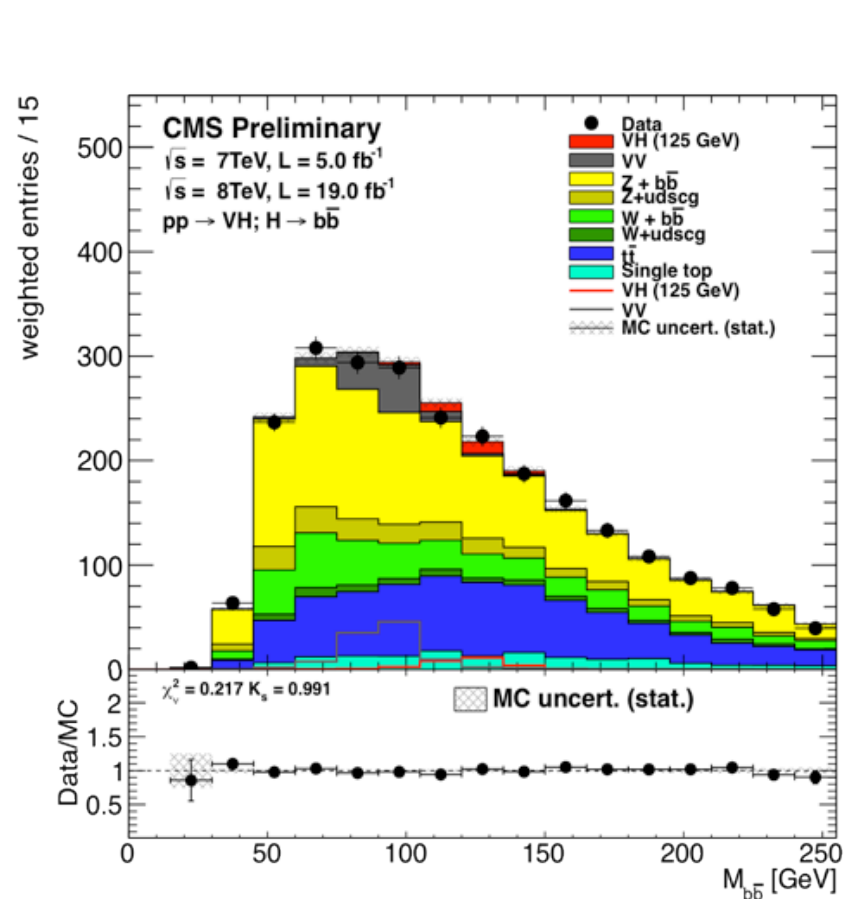


Higgs Decay to Bottom Quarks (VH)

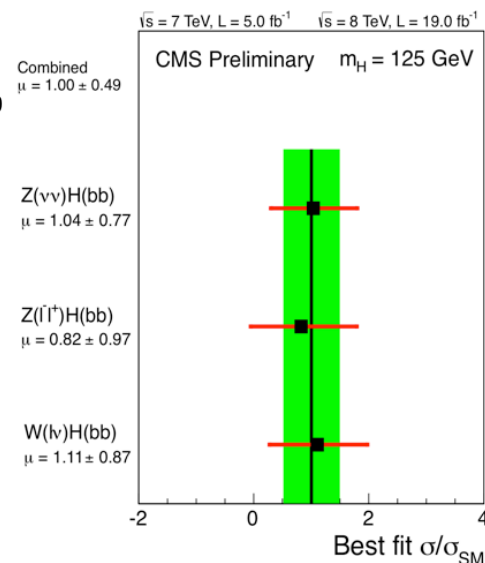
CMS HIG-13-012

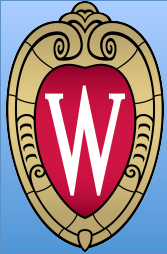
Glueon fusion signal is overwhelmed by QCD

Associated production with W ($l\nu$), Z(ll , $\nu\nu$) probed



A 2.1σ excess seen
(as expected)



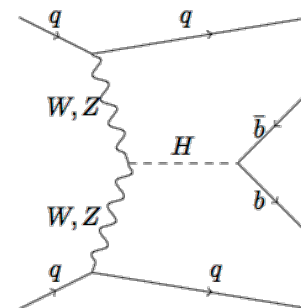


Higgs Decay to Bottom Quarks (VBF)

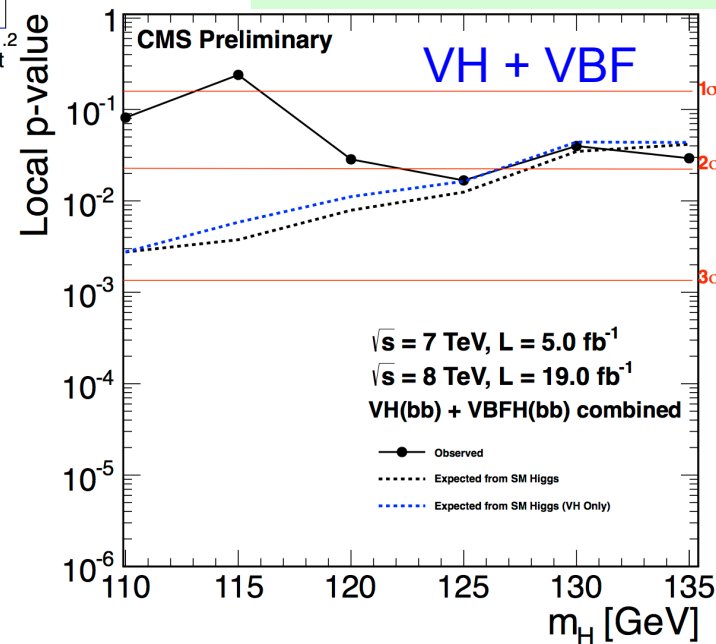
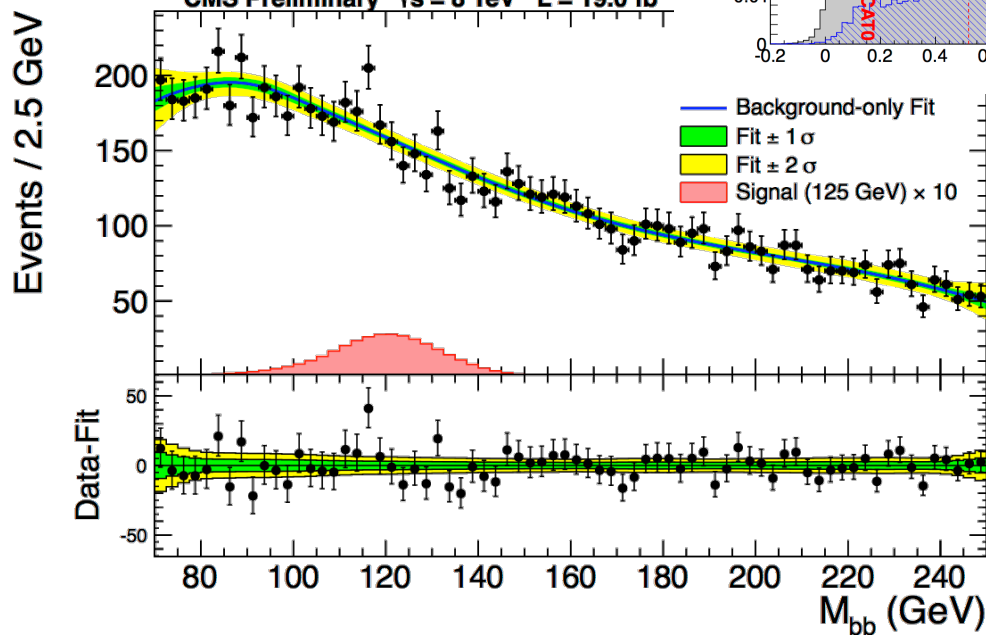
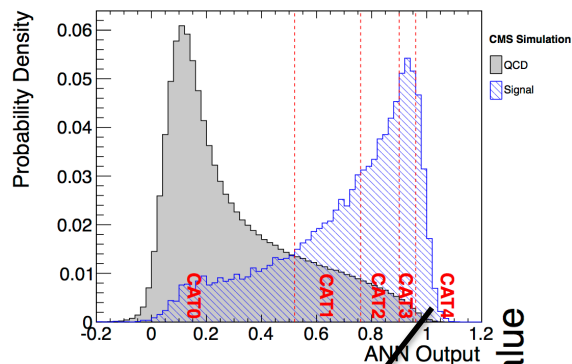
Vector Boson Fusion Production Tagged by Forward Jets
Difficult to trigger – 4 jets (+ 2 b-tags at Higher Levels)

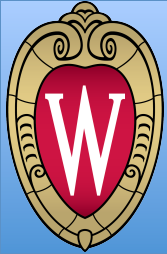
MVA with b-tag sorted jets
kinematics
gluon likelihood

CMS HIG-13-011



CMS HIG-13-011+12



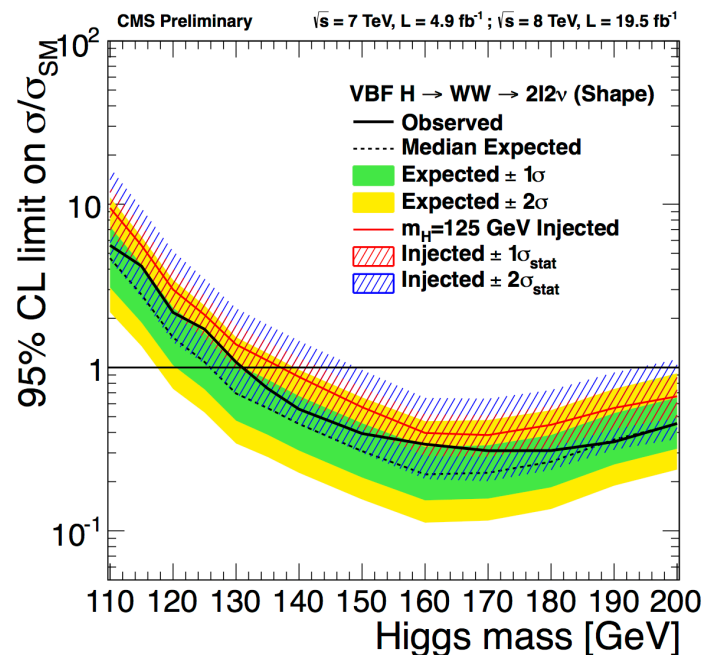
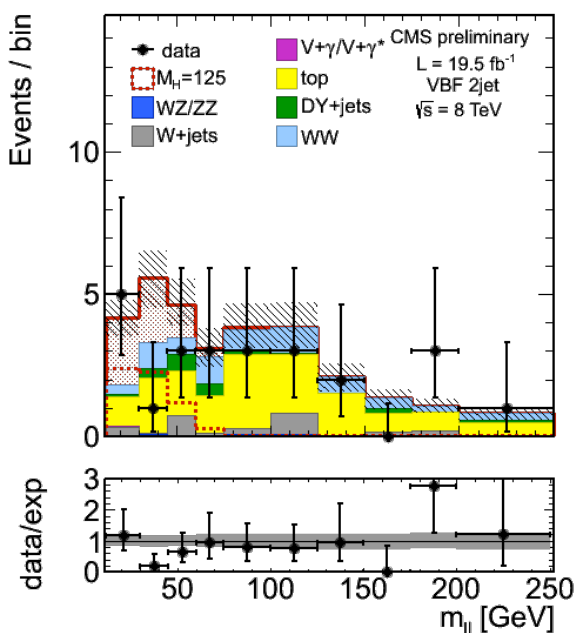
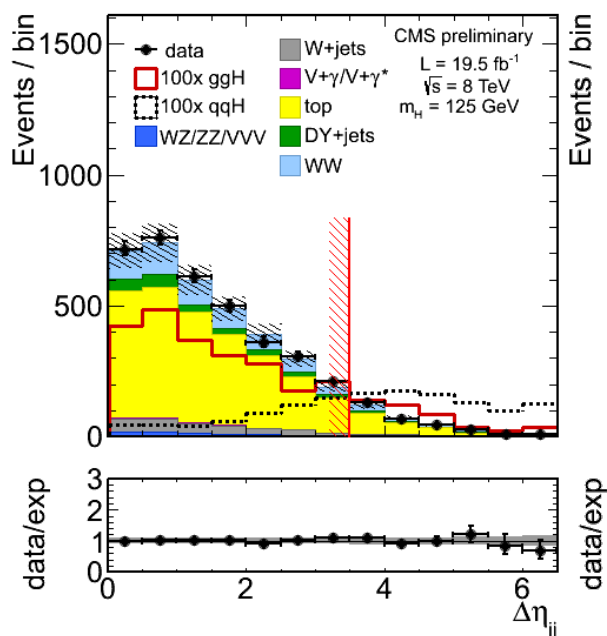
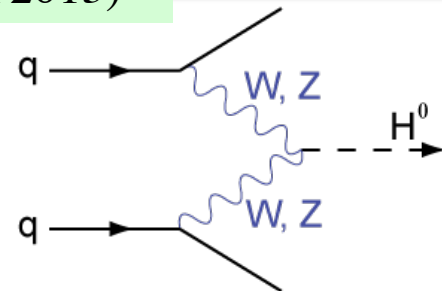


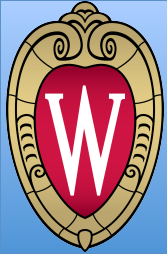
VBF Production: $H \rightarrow WW \rightarrow \ell^+ \ell^- \text{ MET}$

CMS HIG-13-022 (New for SUSY2013)

VBF enhanced by requiring tag jets

- Is the signal due to vector boson fusion?
- Consistent with SM level
- Need $\sim 100 \text{ fb}^{-1}$ at 13 TeV for discovery



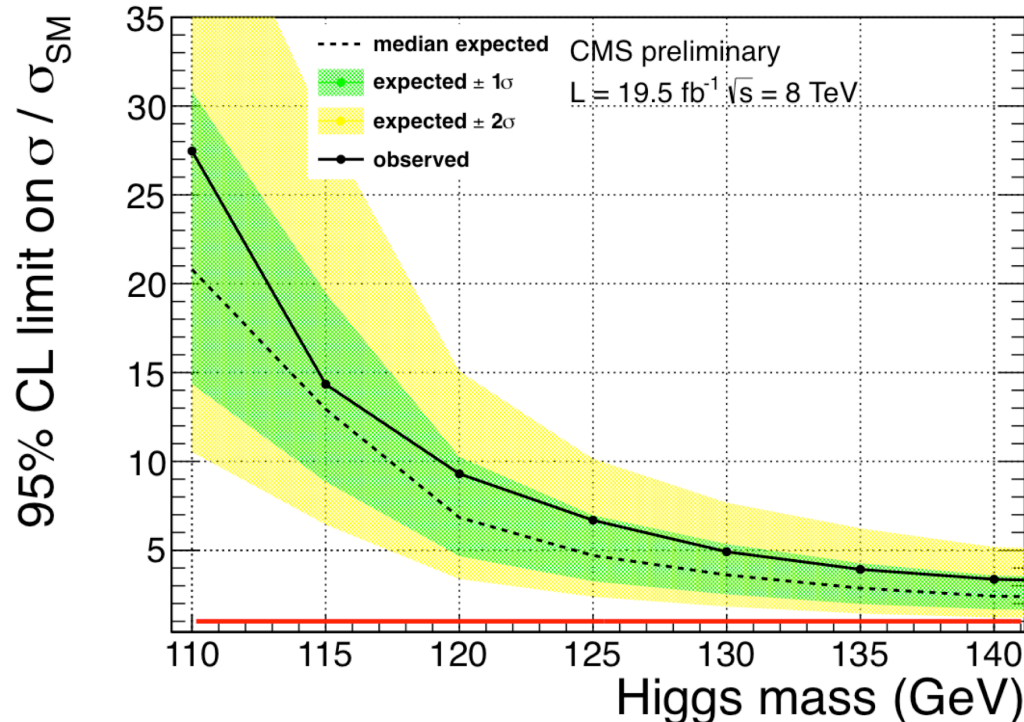
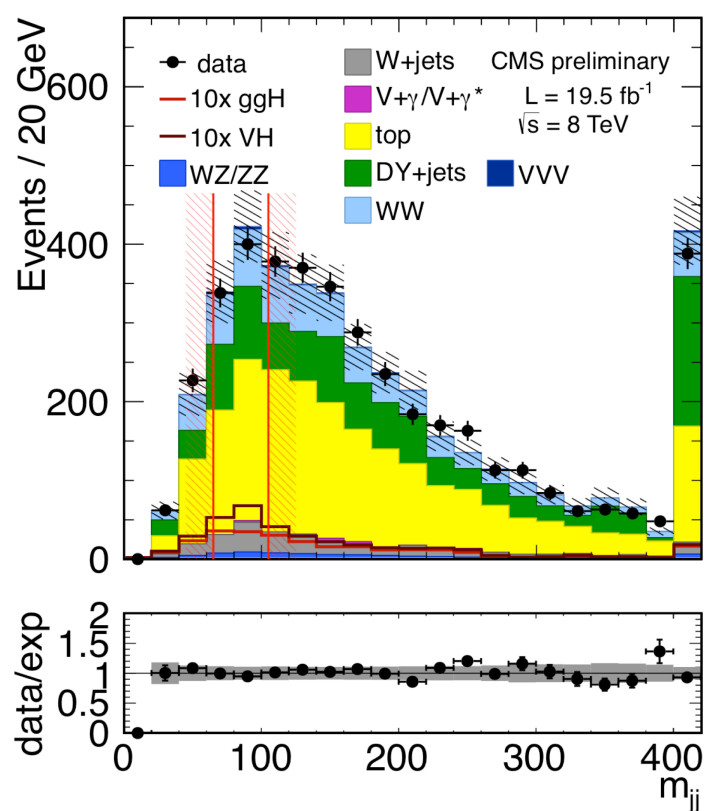


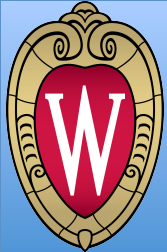
Search for VH , $V \rightarrow jj$ & $H \rightarrow WW \rightarrow \ell^+ \ell^- \text{MET}$

CMS HIG-13-017

Interesting test of production of ggH vs VH

- Not yet sensitive at expected SM level

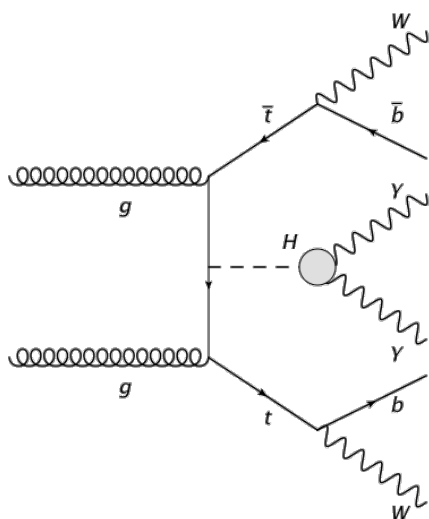




Direct Search for Top Coupling

CMS HIG-13-015

Search for Higgs decay to two photons with top-pair



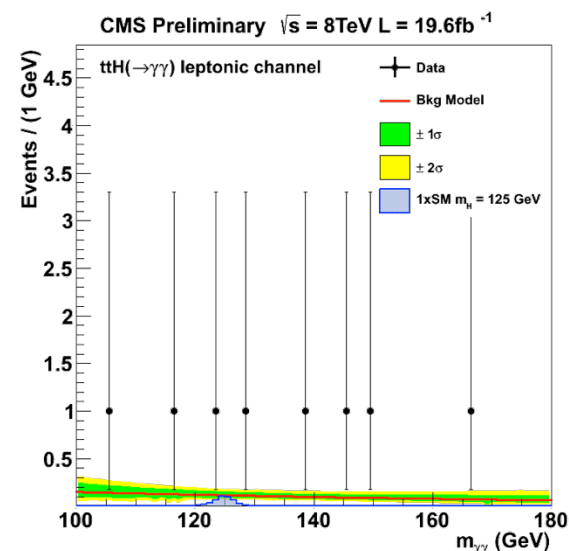
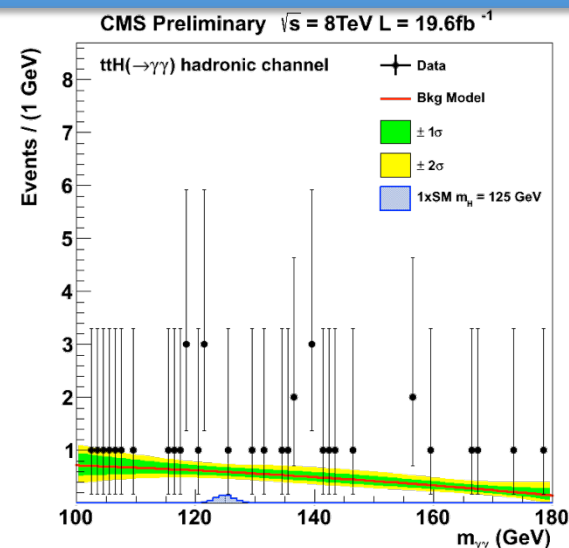
Hadronic:

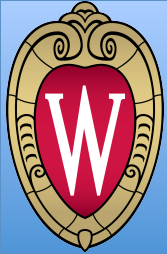
4j, 2b, 2 γ

Leptonic:

2 ℓ , MET, 2 γ

Process	Hadronic Channel	Leptonic Channel
$t\bar{t}H$	0.567 (87%)	0.429 (97%)
$gg \rightarrow H$	0.059 (9%)	0 (0%)
VBF H	0.006 (1%)	0 (0%)
WH/ZH	0.019 (3%)	0.013 (3%)
Total signal	0.65	0.44

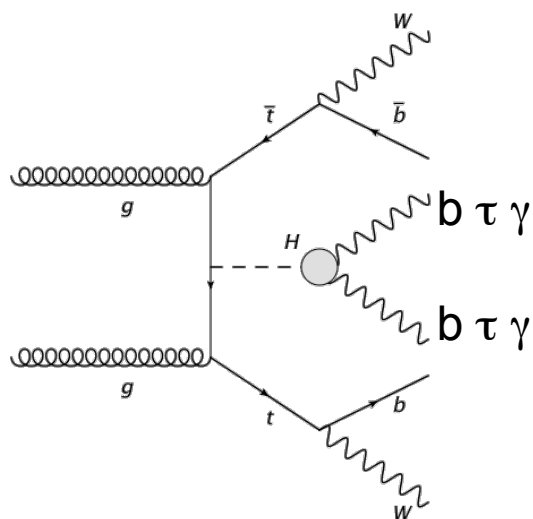




Direct Search for Top Coupling

CMS HIG-13-019

Search for decays to two b-jets, τ -pairs or γ -pairs accompanied with top-pair



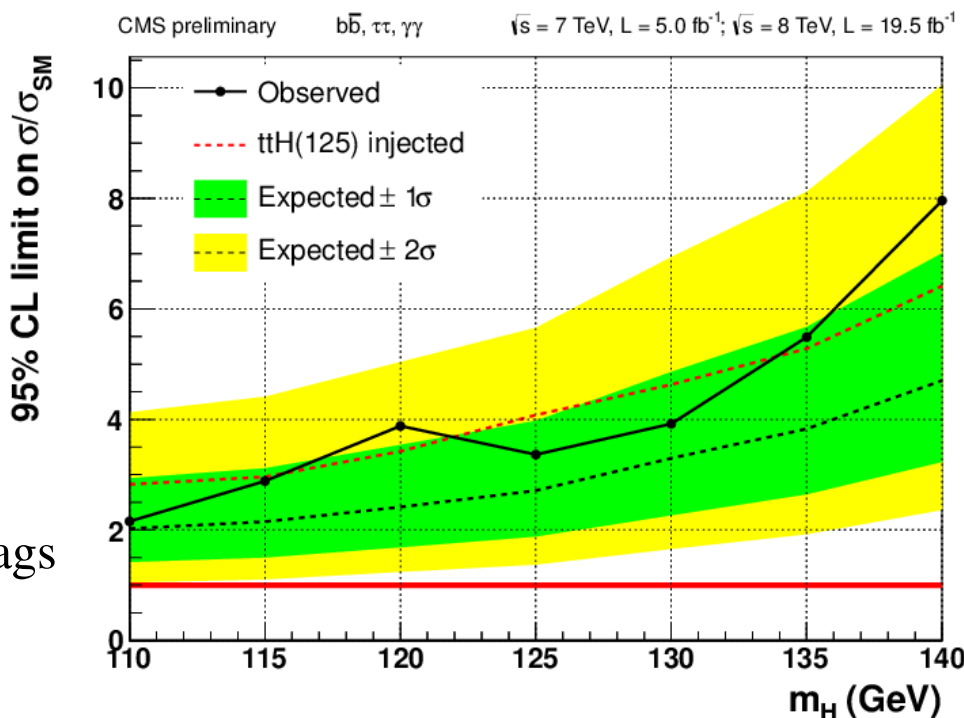
MVA + Classes (lj , $2l$, 2τ) with b-tags

$$ttH(bb) \rightarrow l + 4b + 2j + \nu$$

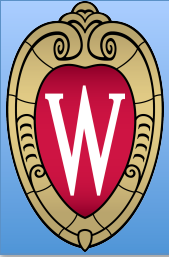
$$ttH(bb) \rightarrow 2l + 4b + 2\nu$$

$$ttH(bb) \rightarrow 2\tau + 4b + 2\nu$$

$$ttH(\tau\tau) \rightarrow 2\tau + 4j + 2b$$

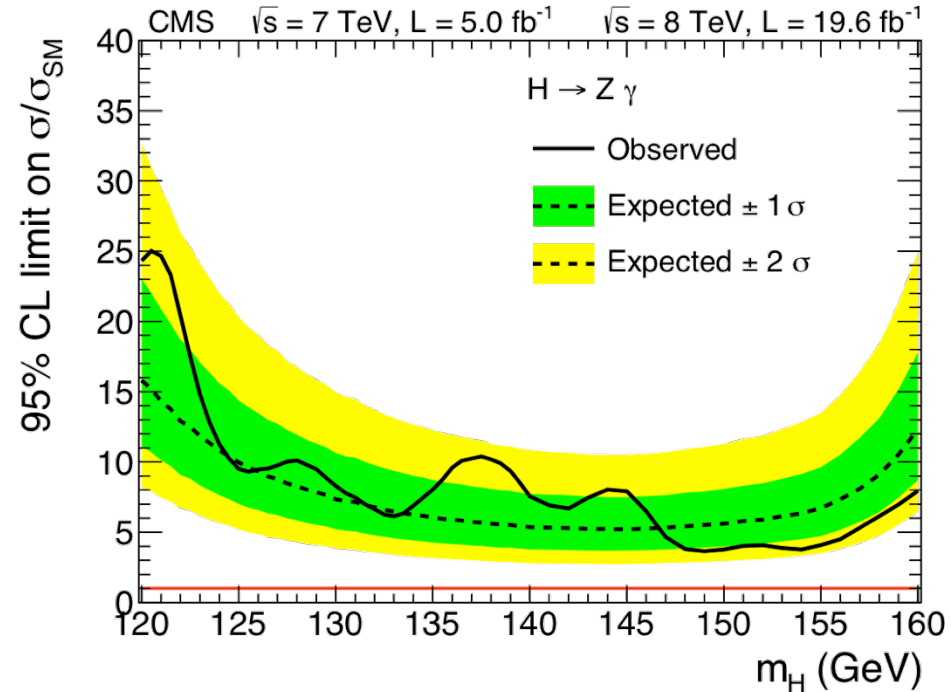
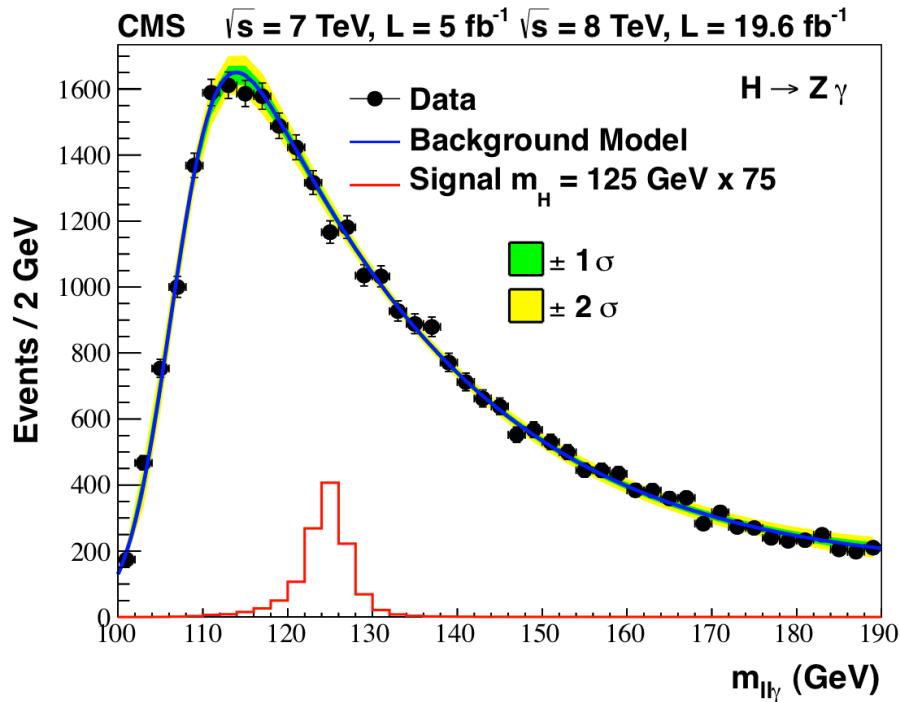


Not at SM sensitivity level yet, but compatible with injected signal of $M_H=125$ GeV



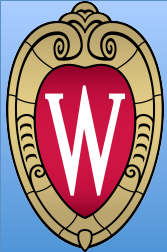
Rare H Decay to $Z\gamma$

CMS HIG-13-006, [arXiv:1307.5515](https://arxiv.org/abs/1307.5515)



Not yet sensitive at SM level

- Search motivated by potential new physics contribution
- Interesting mode for HL-LHC



Dark Matter $\rightarrow$ Source of MET

Higgs decay to dark matter (stable LSP)

LSPs ($\tilde{\chi}$) escape the detector without interacting

$pp \rightarrow ZH \rightarrow l^+l^- \tilde{\chi}\tilde{\chi} \rightarrow \text{Reco-Z} + \text{Missing Energy}$

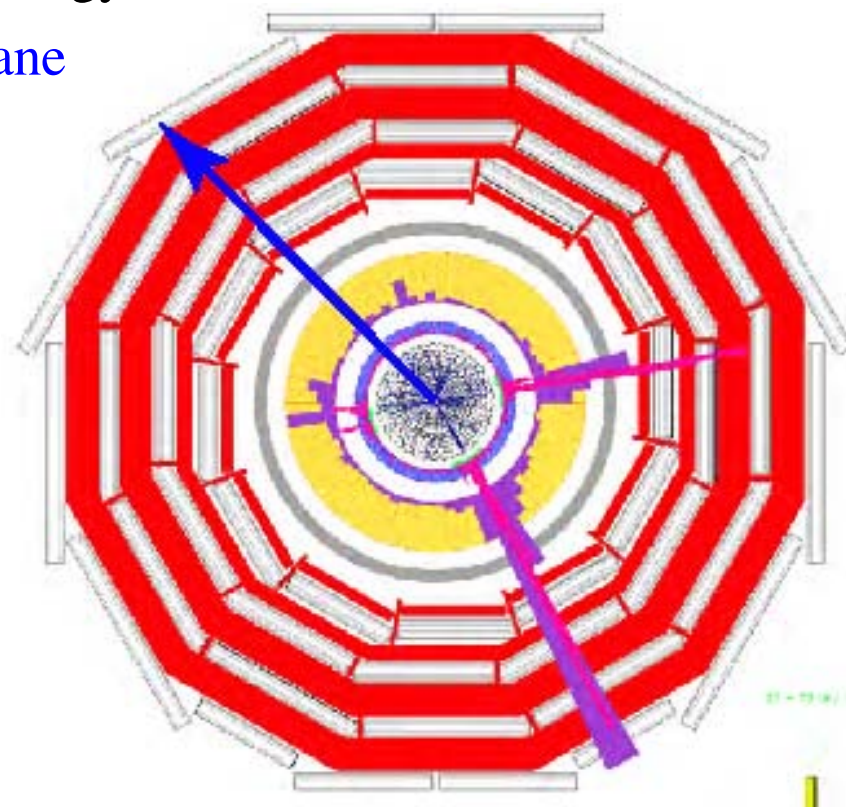
Imbalance of momentum balance in XY-plane

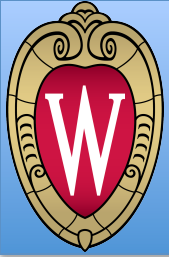
Initial particles (protons) are going in and out of the screen in this picture

Net momentum initially is zero in this XY-plane

Remnants after the collision should also add up to zero momentum

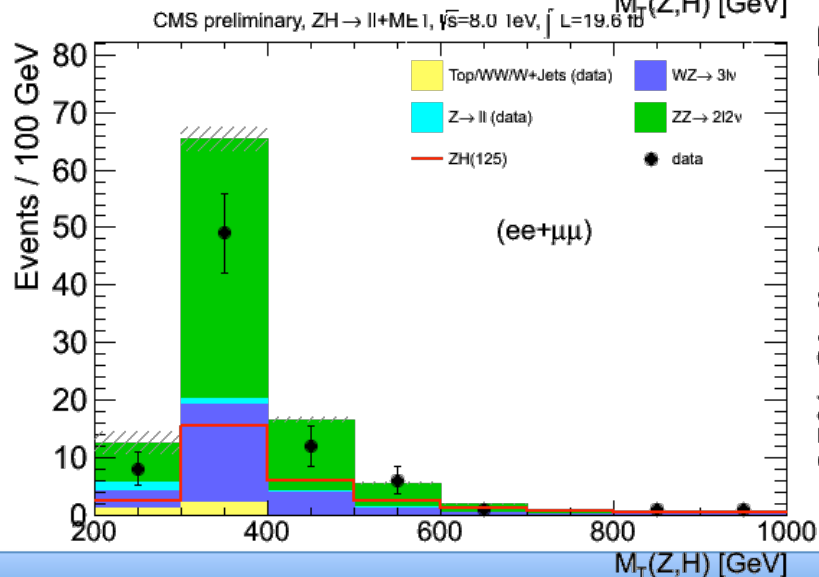
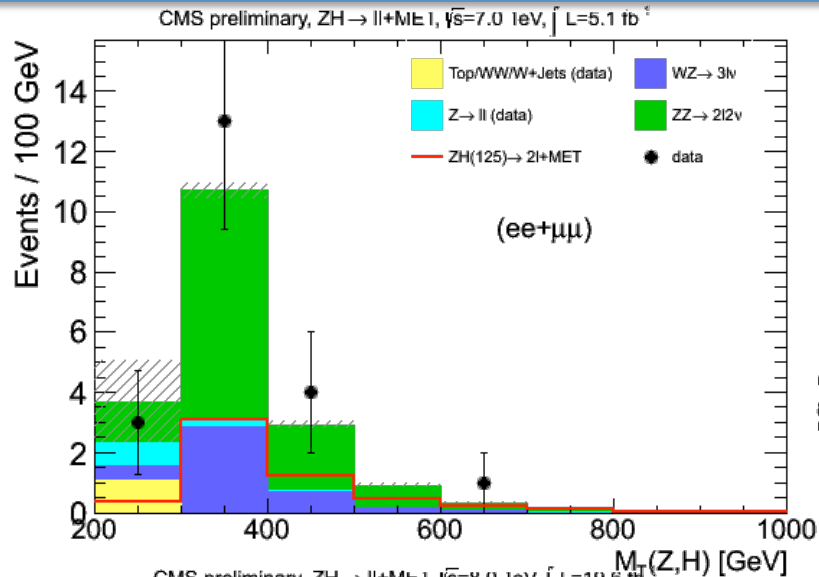
Imbalance seen when there are non-interacting (dark) particles.



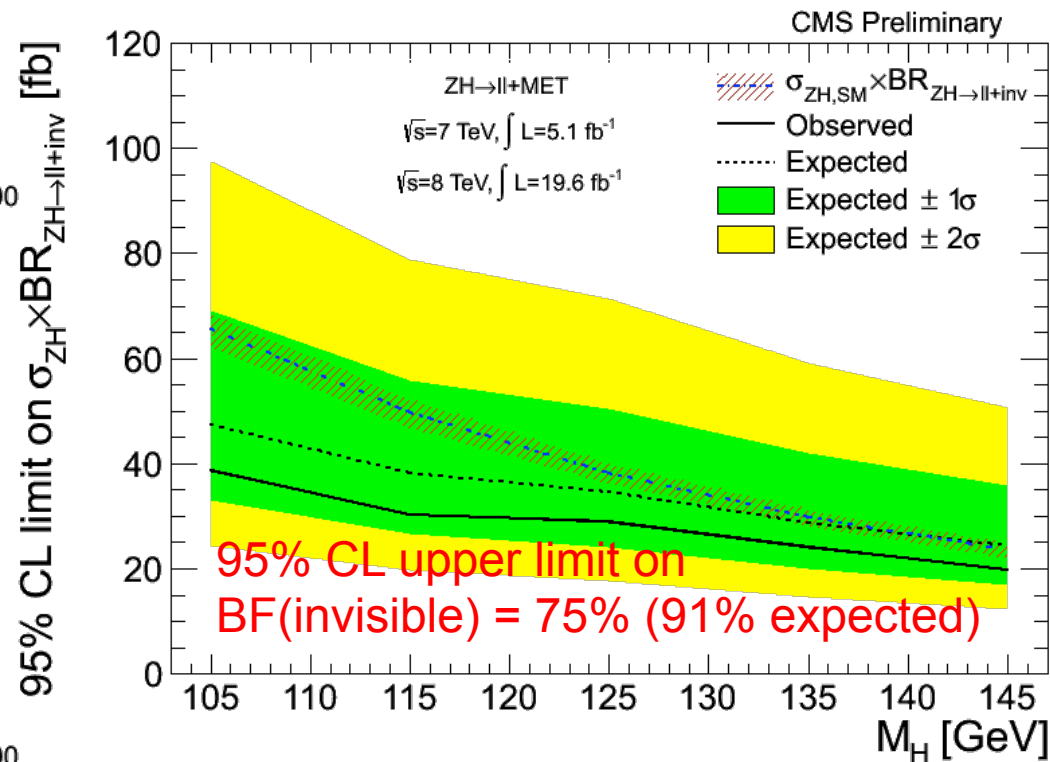


VH: Higgs Decay to Dark Particles

CMS HIG-13-018



H associate production with $Z(\ell\ell)$
 Requiring high reduced E_T^{Miss}
 Balance of P_T^ℓ and recoil
 Jet and additional lepton veto
 Analyze shape of $M_T(Z,H)$

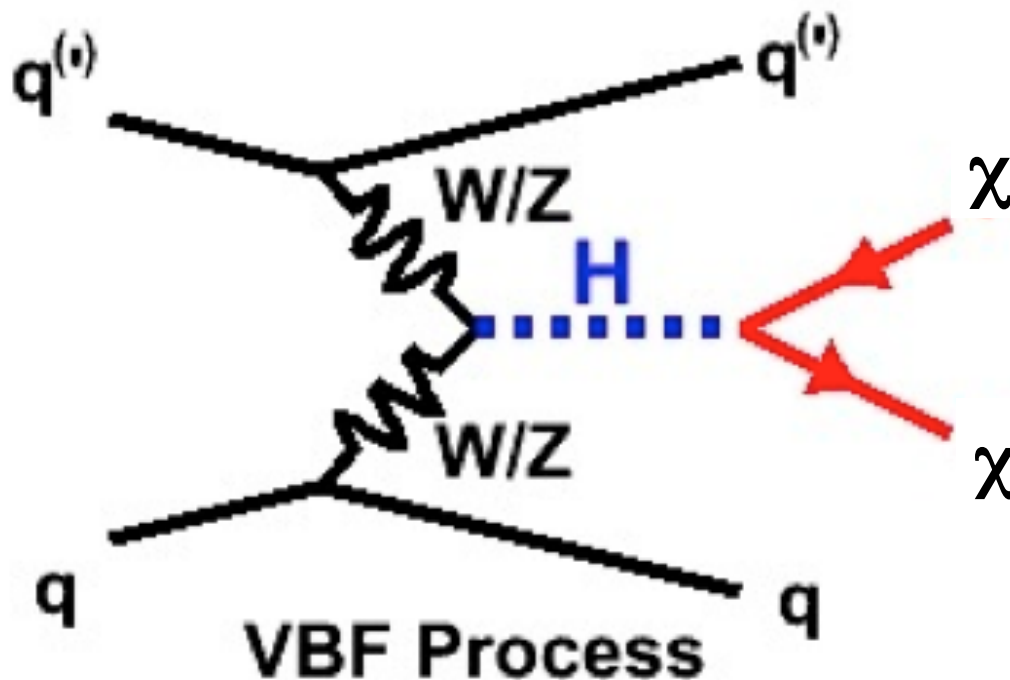


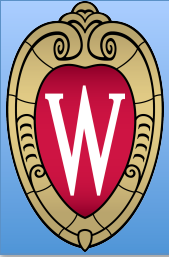


VBF Higgs (Invisible Decay)

Forward jets and nothing else !

- Jets are forward – make large invariant mass
- Large Missing E_T



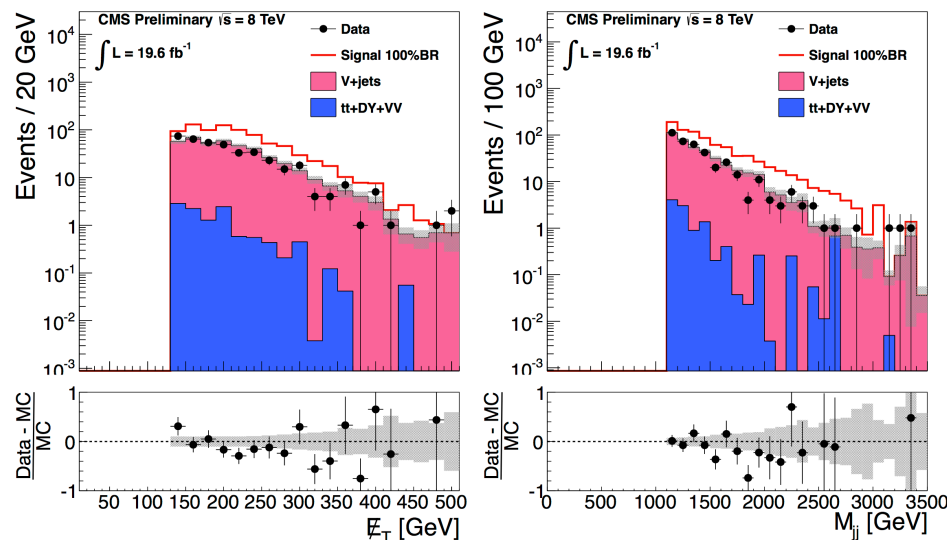


VBF: Higgs Decay to Dark Particles

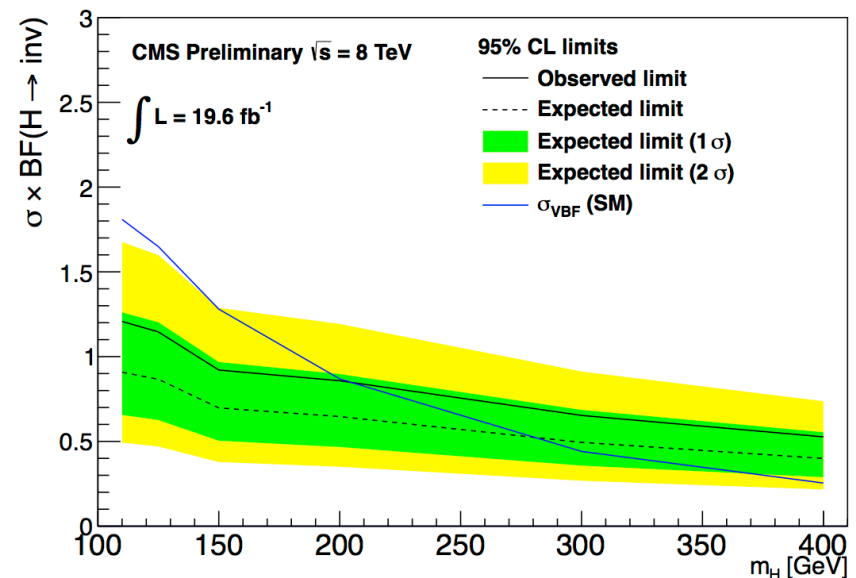
CMS HIG-13-013

VBF associated higgs production

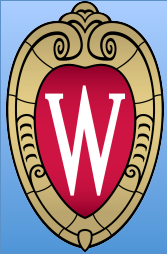
- Special VBF+MET L1&HL triggers & big effort to reduce QCD BG
- $Z(\nu\nu)$ +Jets background predicted using $Z(\mu\mu)$



Data agrees with SM background
dominated by **V+Jets**
Signal histogram plotted is for 100%
Invisible BR



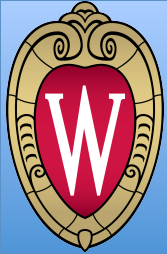
95% CL upper limit at 125 GeV on
 $BF(\text{invisible}) = 69\%$ (53% expected)



Beyond the Standard Model Higgs Sector

There are many possibilities that change the precise predictions of the minimal higgs sector of the Standard Model

- **Fourth (heavy) generation of fermions modify H couplings**
 - Enhanced higgs cross section over SM
 - Measured cross sections agree with SM expectation (earlier slide)
- **Fermiophobic – fermion mass of different origin than higgs**
 - Changes low mass higgs production & decays dramatically
 - Also ruled out for 126 GeV object – in line with SM expectation
- **Beyond minimal higgs doublet field**
 - **Two higgs doublet model (2HDM)**
 - Multiple higgs bosons: 3 neutral and 2 charged
 - Minimal Supersymmetric Model (MSSM) requires 2HDM
 - **NMSSM, triplets ... have even more higgses**
 - Very light pseudoscalar higgs, Doubly charged ...
- **We have been looking for these exotic Higgs bosons**



MSSM Higgs

Higgs sector in SUSY theory is more complicated

- Need 2 higgs doublets each with 4 degrees of freedom
 - Results in the Standard Model like Higgs (h^0)
 - Plus, two neutral higgs (A^0 , H^0) and charged ($H^\pm$)
 - Only 2 parameters (M_A , $\tan\beta$ – ratio of the two doublets)
 - Masses of higgses and Z related: Search in (M_A , $\tan\beta$) plane

– Neutral Higgs

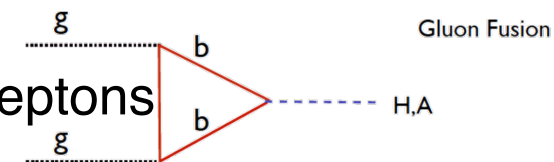
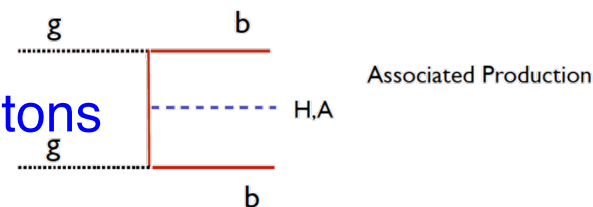
- Look for $\phi=(h^0, A^0, H^0)$ in decays to tau-leptons

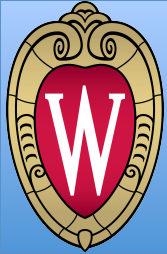
– Charged Higgs

- Look for $H^\pm$ in top decays

Enhanced $\phi=(h^0, A^0, H^0)$ coupling to b-quarks and τ -leptons

- Production rate enhanced $\times \tan^2\beta$
 - Gluon fusion with b,t loops + associated b quark production
- Decays to b-quark and τ -lepton pairs enhanced at all masses

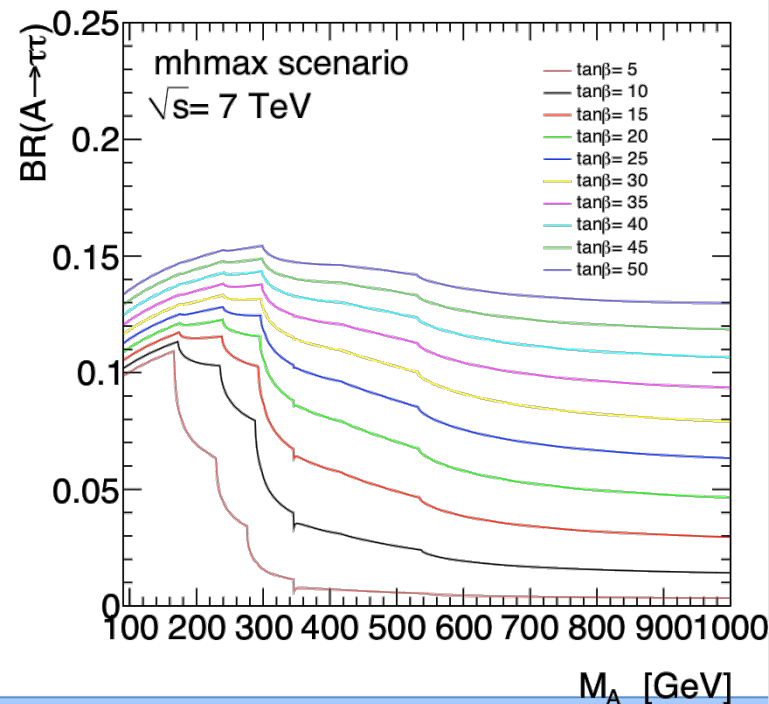
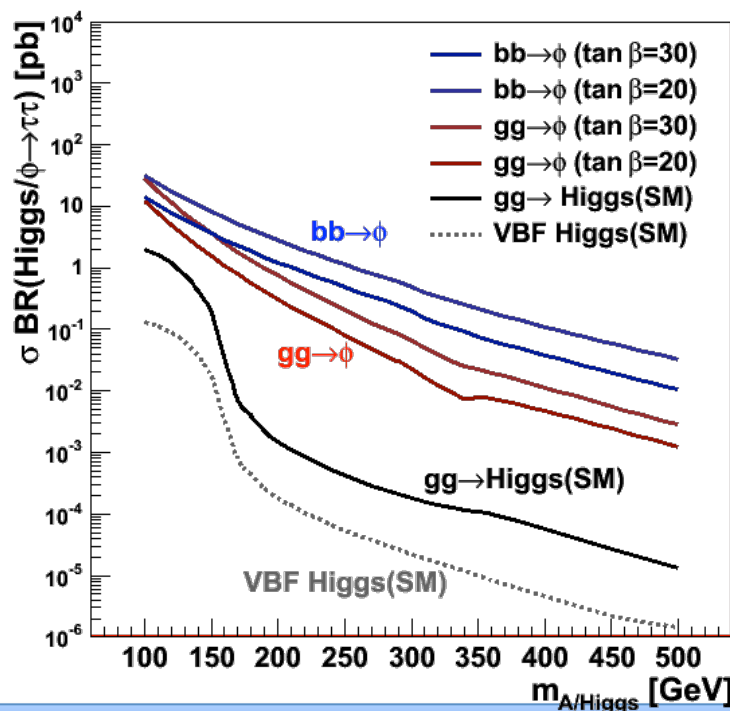
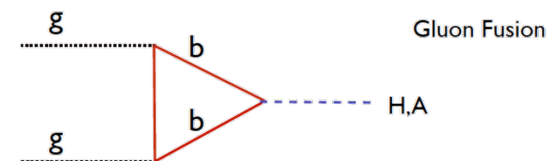
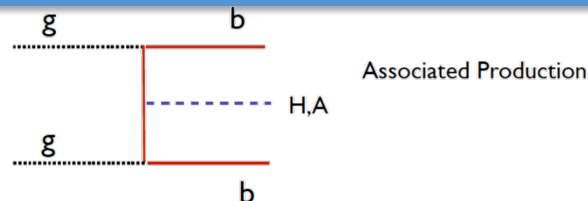


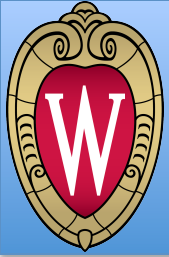


MSSM $\phi(h, H, A)$

Use MHMAX Scenario (TeV Scale SUSY)
Enhanced coupling to b-quarks and τ -leptons

- Production rate enhanced $\times \tan^2\beta$
- Decays to b-quark and τ -lepton pairs enhanced at all masses





MSSM Particle Content

SM particle	SUSY partner	G_{SM} R-Parity, $R = -1^{3B+L+2S}$
R=1	R=-1	
(S = 1/2)	(S = 0)	
$Q = (t, b)_L$	$(\tilde{t}, \tilde{b})_L$	(3,2,1/6)
$L = (\nu, l)_L$	$(\tilde{\nu}, \tilde{l})_L$	(1,2,-1/2)
$U = (t^C)_R$	$\tilde{t}_R^*$	($\bar{3}$,1,-2/3)
$D = (b^C)_R$	$\tilde{b}_R^*$	($\bar{3}$,1,1/3)
$E = (l^C)_R$	$\tilde{l}_R^*$	(1,1,1)
(S = 1)	(S = 1/2)	
B_μ	$\tilde{B}$	(1,1,0)
W_μ	$\tilde{W}$	(1,3,0)
g_μ	$\tilde{g}$	(8,1,0)



MSSM Light Higgs – loop level

Loop corrections dominated by stop – maximal M_h

As is well-known, at tree level the mass of the lightest MSSM Higgs boson, M_h , is bounded from above by the Z -mass. However, loop corrections [4] can raise M_h to the observed value¹ of $M_h = 125.5^{+0.5}_{-0.6}$ GeV as measured by ATLAS [5] and $M_h = 125.7 \pm 0.4$ GeV as measured by CMS [6]. The leading SUSY corrections to M_h arise from stop loops, with the leading component being

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

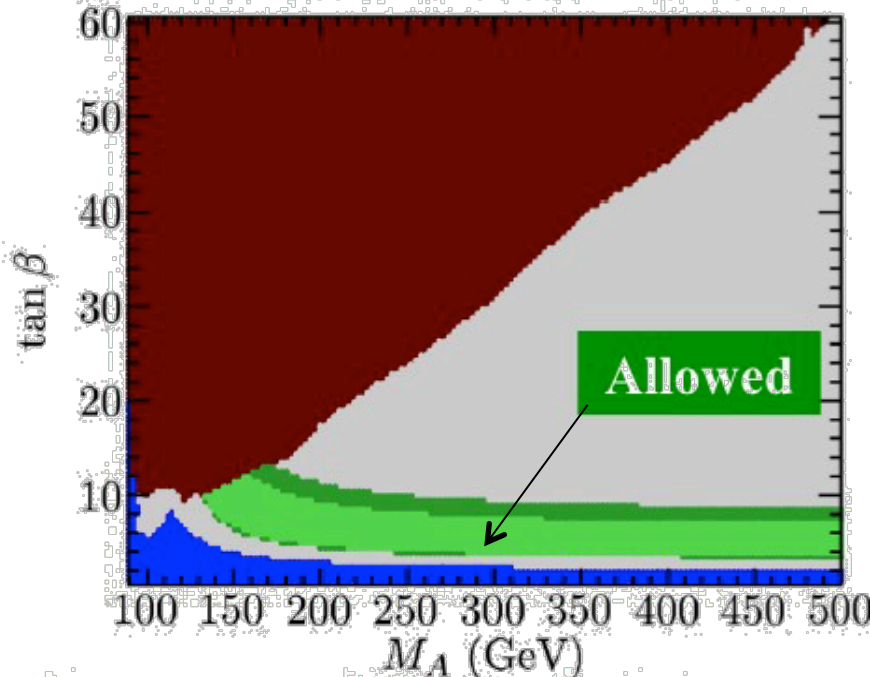
where $\overline{m}_t$ is the running $\overline{\text{MS}}$ top mass, $X_t = A_t - \mu \cot \beta$ is the stop mixing parameter, $M_S = \sqrt{\overline{m}_{\tilde{t}_1} \overline{m}_{\tilde{t}_2}}$ is the geometric mean of the two stop squark masses, and $v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$.

This correction to M_h is maximized when $X_t = \sqrt{6}M_S$. Given the difficulty of obtaining a large Higgs mass with small fine-tuning in the MSSM, this relation was used as a basis for the original m_h^{max} benchmark point [7], with all other SUSY parameters set in the TeV range. However, now that M_h is known, we can see that m_h^{max} actually produces too large a Higgs mass for much of the $M_A - \tan \beta$ plane (with TeV scale stops.) With this in mind, additional new benchmarks have been recently proposed [8].



Implications of SM Like H126 on MHMAX scenario

Phys. Lett. B 710 (2012) 201



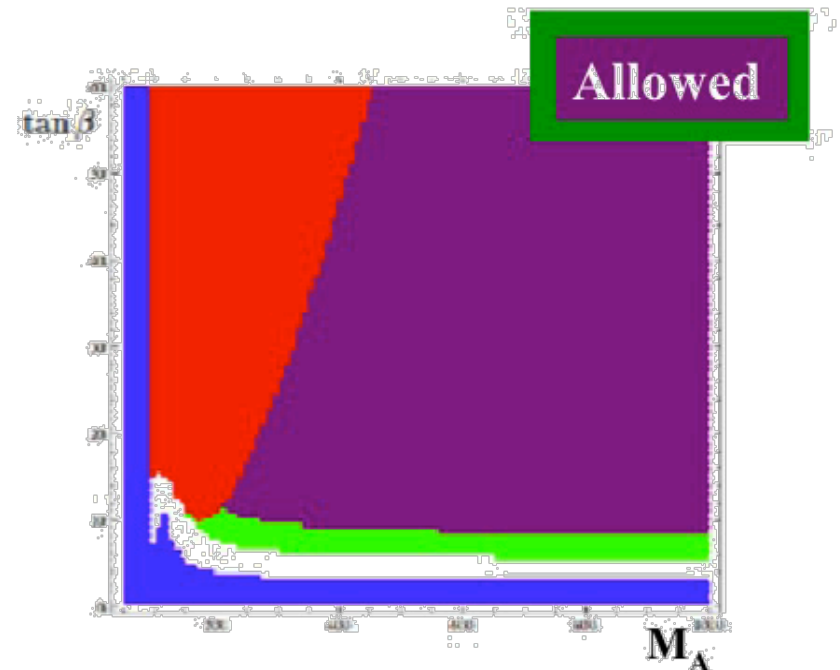
Interpret as CP-even light h with
 $123 < M_h < 127$ GeV

(theoretical uncertainty on $M_h + m_{top}$)

Allowed region strip in M_A - $\tan\beta$

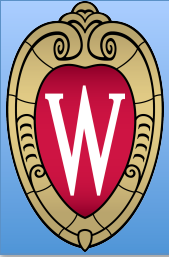
mhmax scenario

Modified $m_{h,max}$ scenario
 $X_t \sim 1300$ GeV



($\square$): $M_h = 125.5 \pm 1$ GeV, ($\square$): $M_h = 125.5 \pm 3$ GeV

X_t : stop mixing parameter



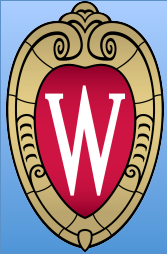
MHMod Scenarios

Playing with stop mixing to ensure $M_h = 126 \pm 3$ GeV

$$m_h^{max}: X_t^{OS} = 2M_{SUSY} \quad X_t^{\overline{MS}} = \sqrt{6}M_{SUSY}$$

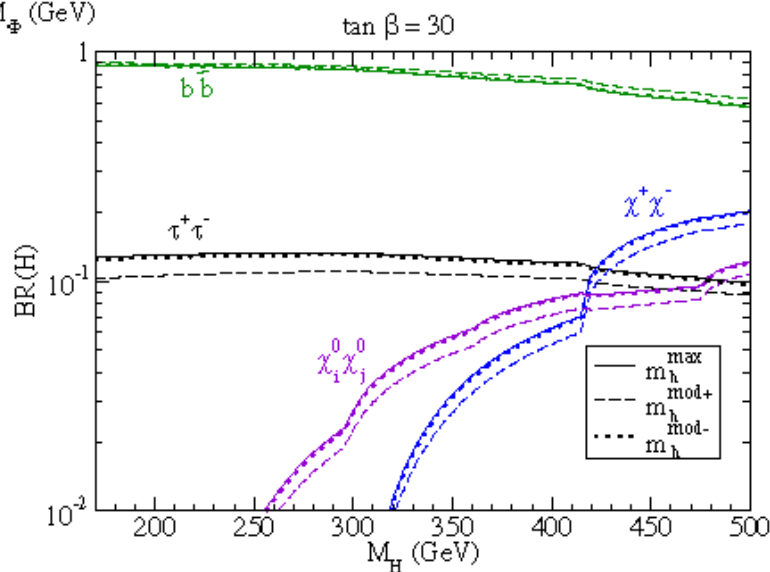
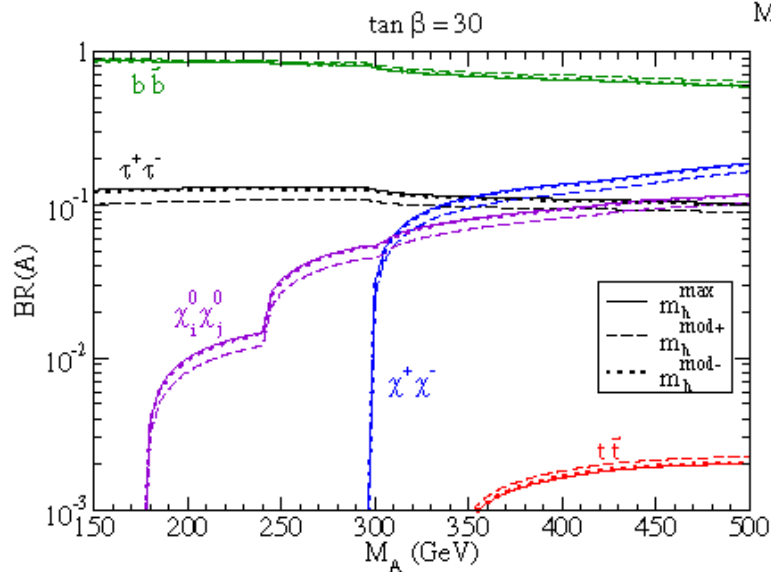
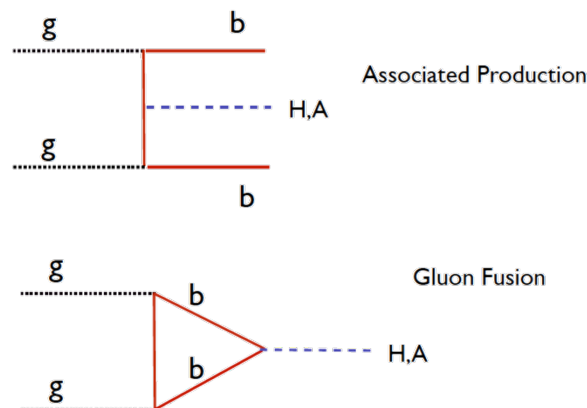
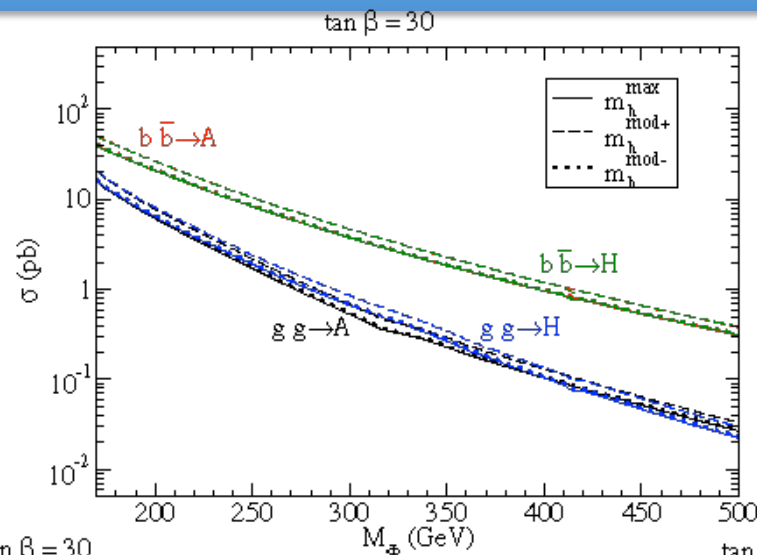
$$m_h^{mod+}: X_t^{OS} = 1.5M_{SUSY} \quad X_t^{\overline{MS}} = 1.6M_{SUSY}$$

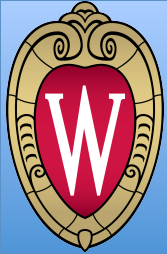
$$m_h^{mod-}: X_t^{OS} = -1.9M_{SUSY} \quad X_t^{\overline{MS}} = -2.2M_{SUSY},$$



MHMod – high $\tan\beta$

Situation with regards to heavy Higgs is essentially the same – only now M_h is ~ 125 GeV

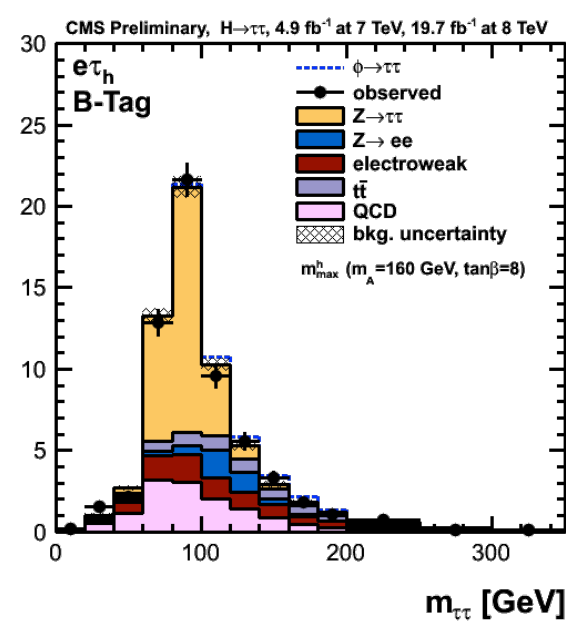
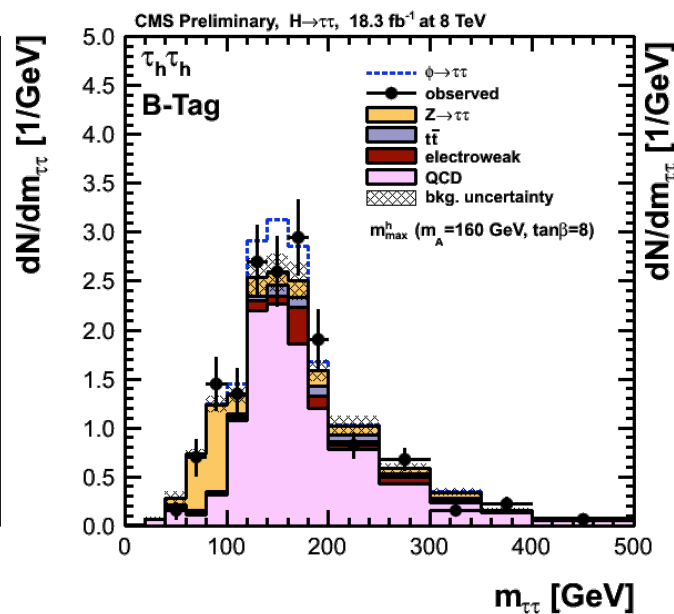
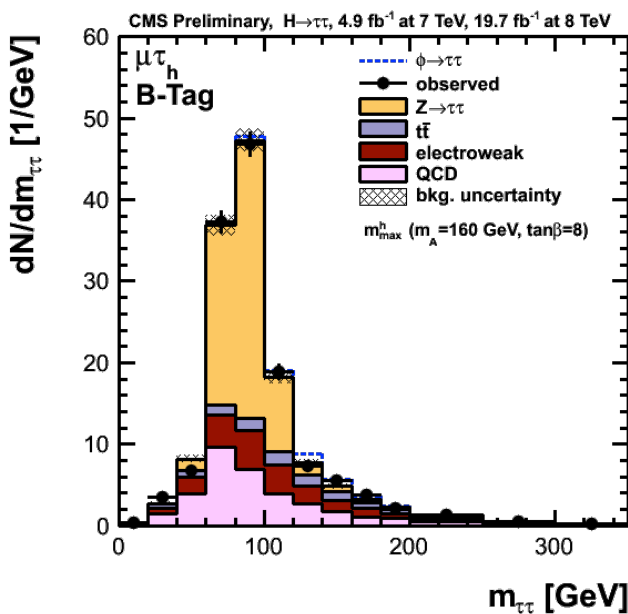


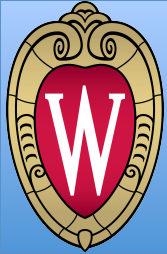


Mass of $\tau\tau$: 17 fb^{-1} Data

CMS HIG-13-021

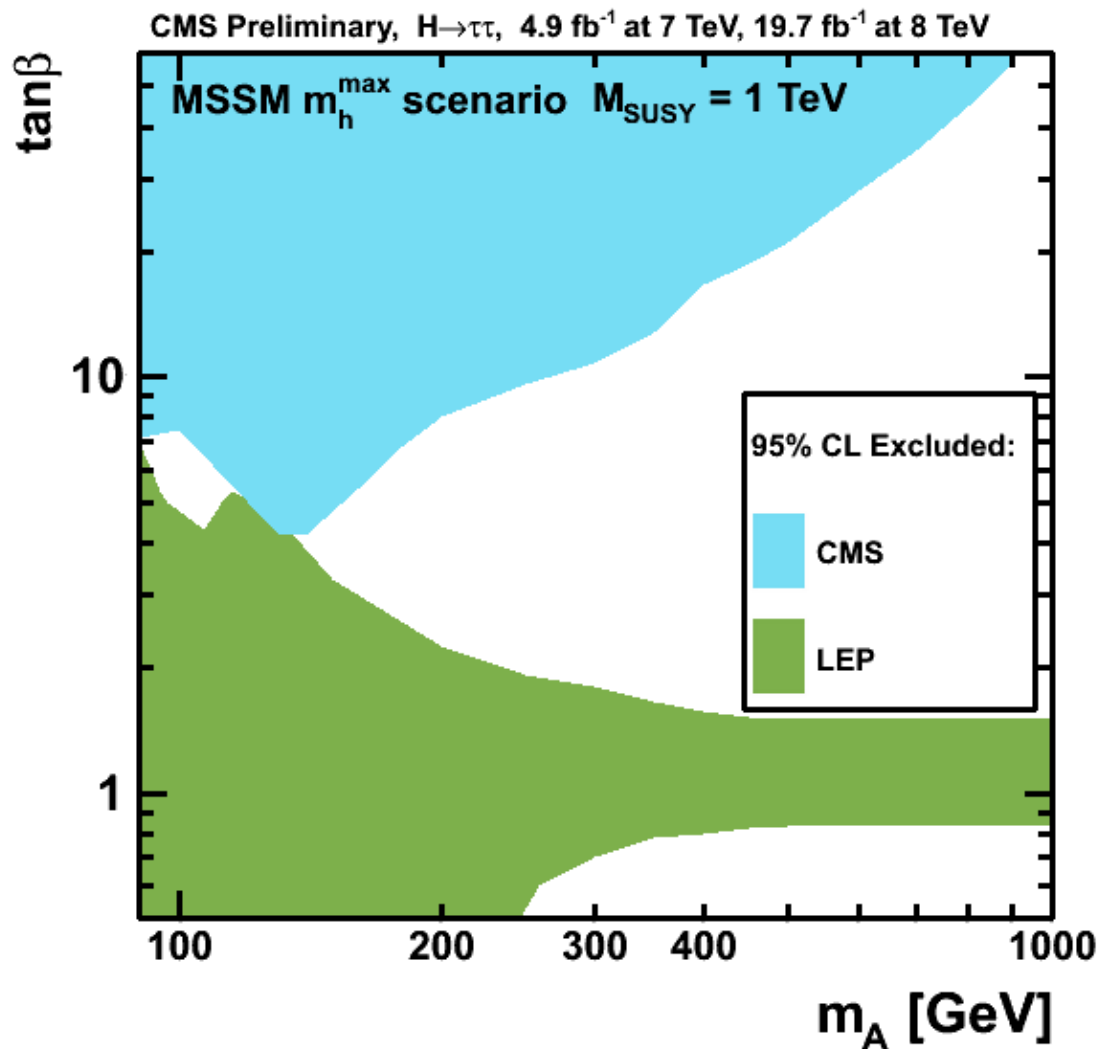
Tau pairs reconstructed in decays to muon + hadrons (1 or 3 prong)
Kinematic fit to obtain tau pair mass – used to search for H to $\tau\tau$ contribution
Two categories: non-b-tagged and b-tagged to enhance $bb\phi$





MSSM Higgs Exclusion

CMS HIG-13-021



Supercedes:

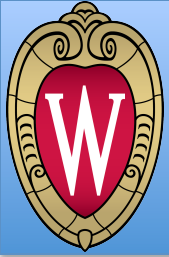
ATLAS CONF 2012-11

CMS PAS HIG-12-033

CMS PAS HIG-11-019

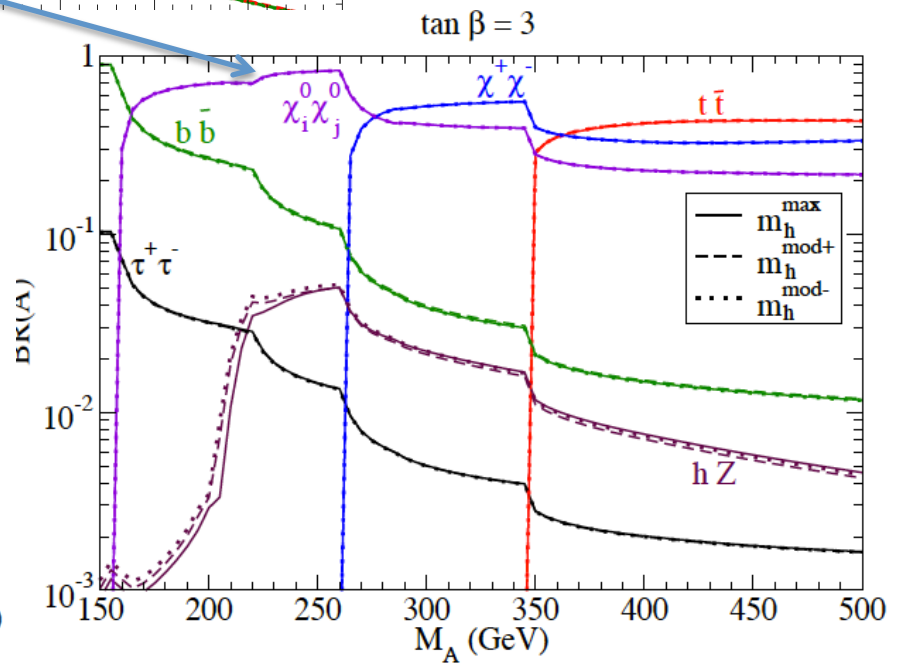
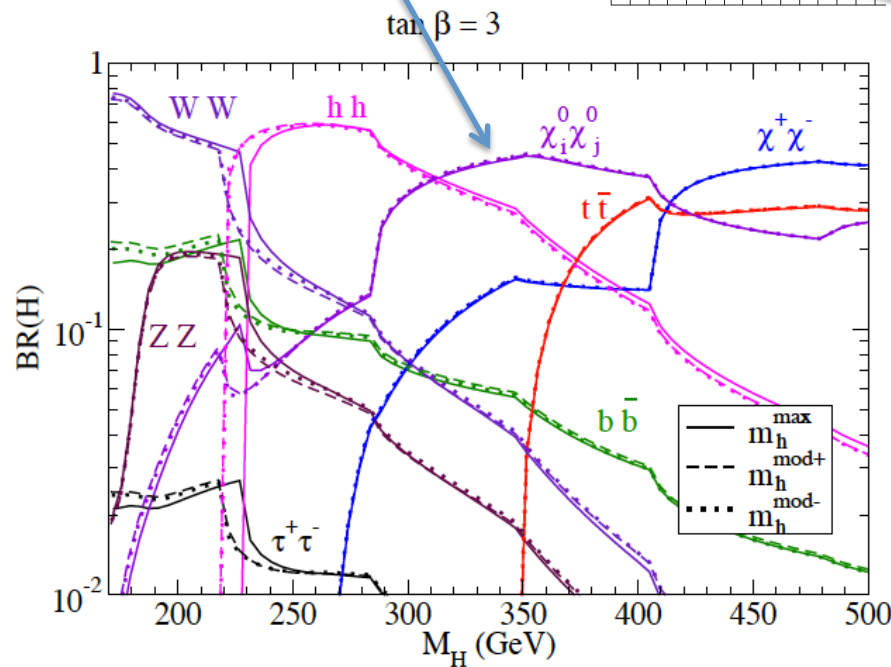
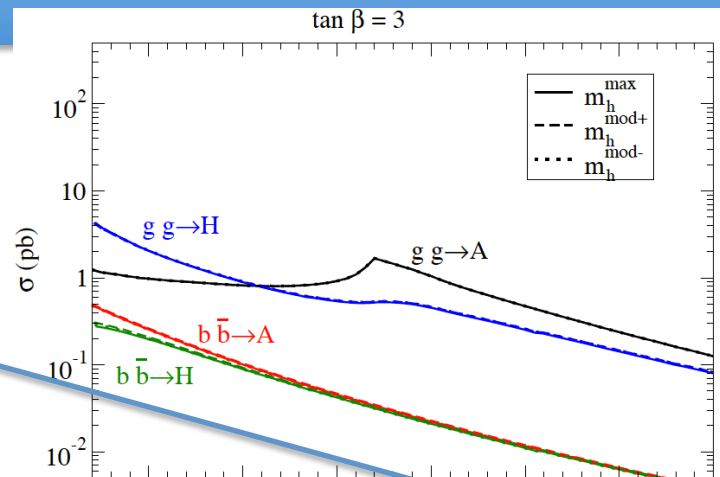
CMS PAS HIG-12-050

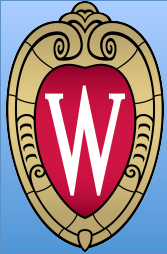
Work on-going
to interpret in
other MSSM
scenarios ...



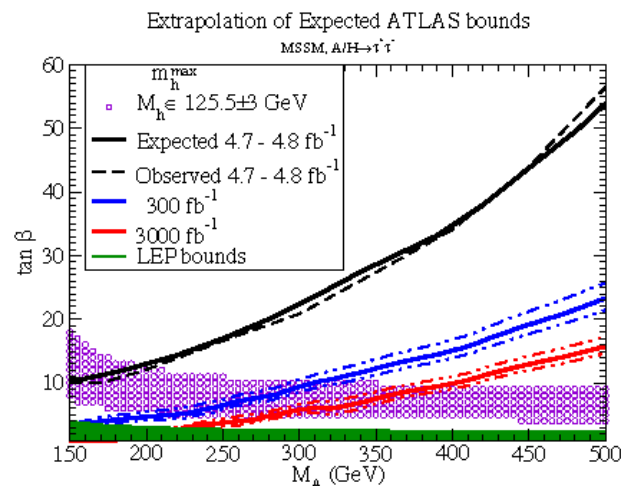
MSSM Higgs Decays : Low $\tan\beta$

Invisible Decays
Decays to Higgses
etc.

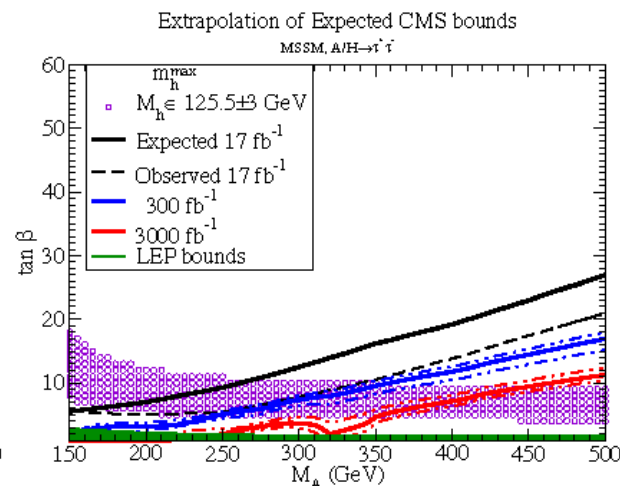




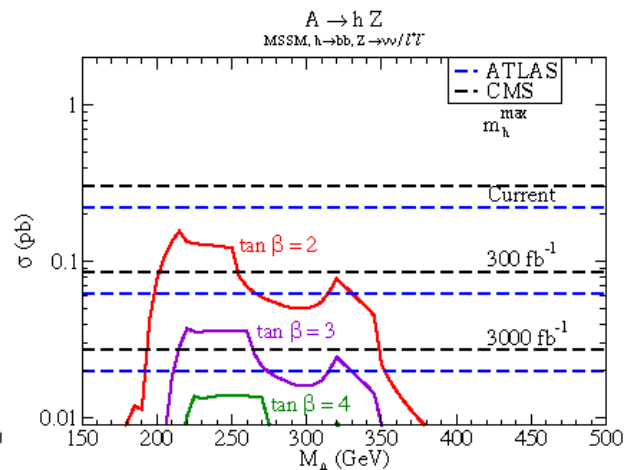
MSSM – Extrapolations



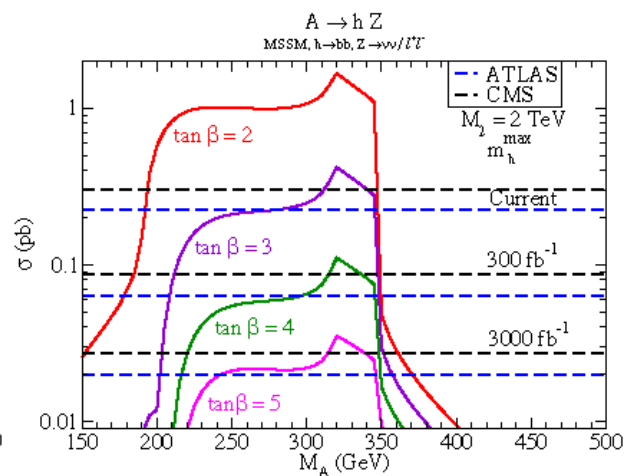
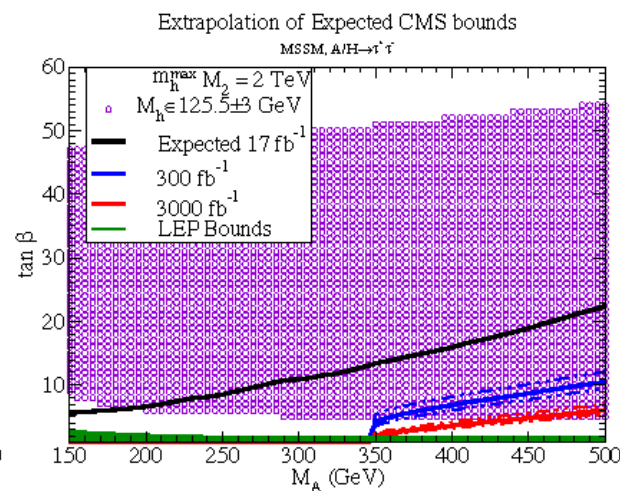
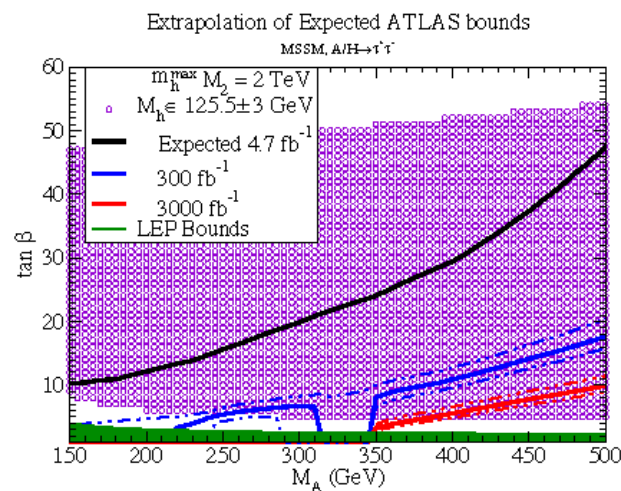
(a)

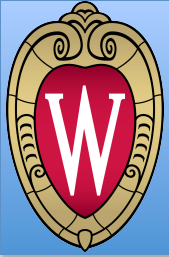


(b)



(c)





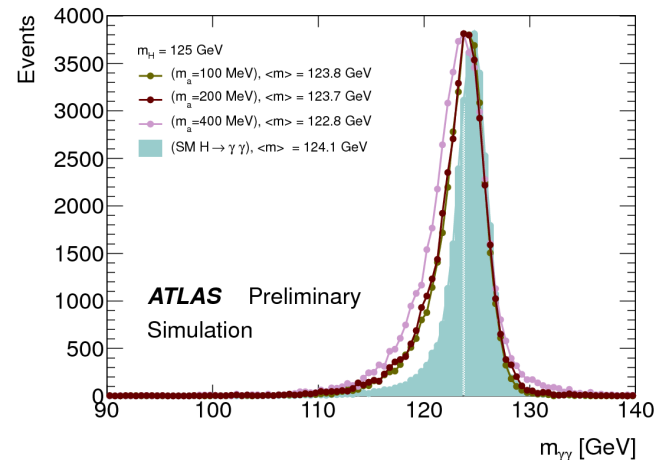
NMSSM: $H \rightarrow aa \rightarrow \gamma\gamma \gamma\gamma$

ATLAS CONF 2012-079

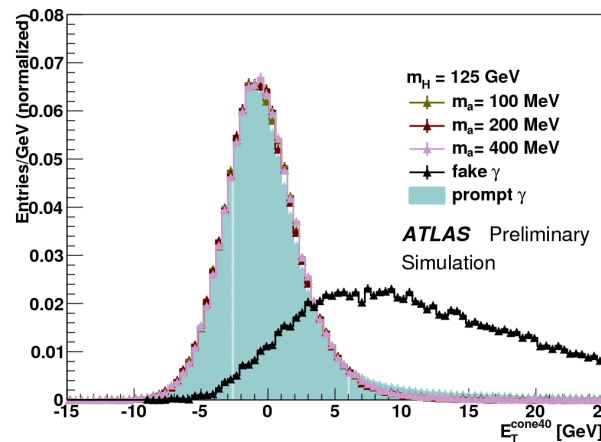
Next-to-Minimal Supersymmetric Standard Model (NMSSM):

Adds singlet scalar field, thereby expanding the Higgs sector to three CP-even (h_1 , h_2 and h_3), two CP-odd (a_1 , a_2) and two charged scalars (H^+ , H^-)

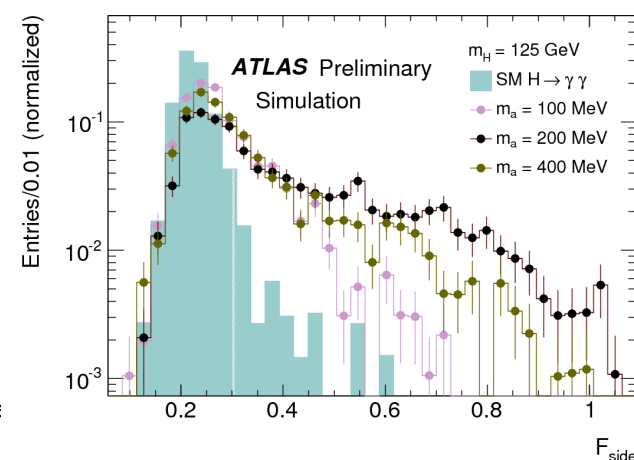
The lightest pseudo-scalar, if less massive than $3M_{\pi^0}$, decays to $\gamma\gamma$
SM like Higgs can decays to four photons via an a -pair



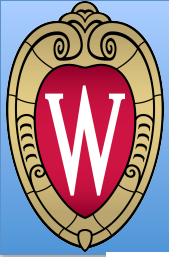
Photon invariant mass
has broader peak than
 $H \rightarrow \gamma\gamma$



Isolation provides
separation from prompt γ
BG

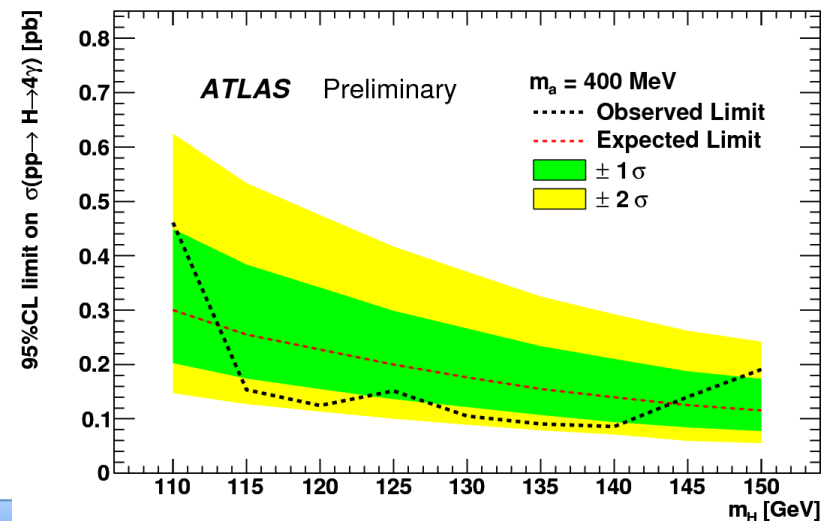
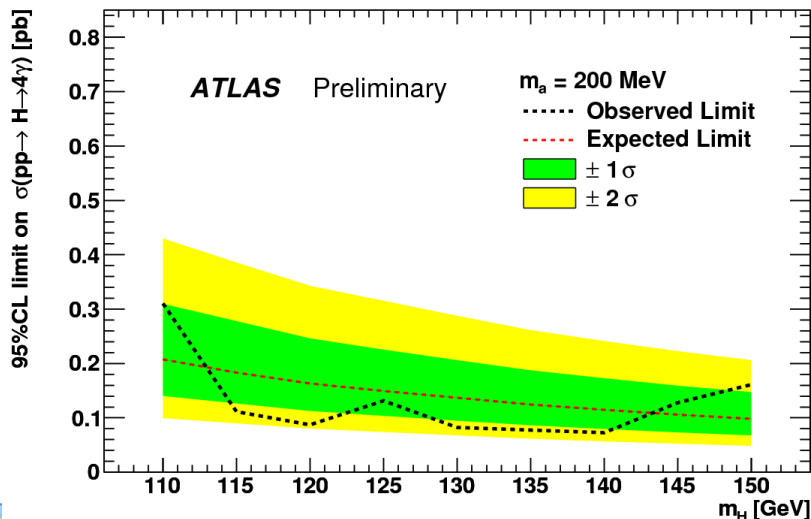
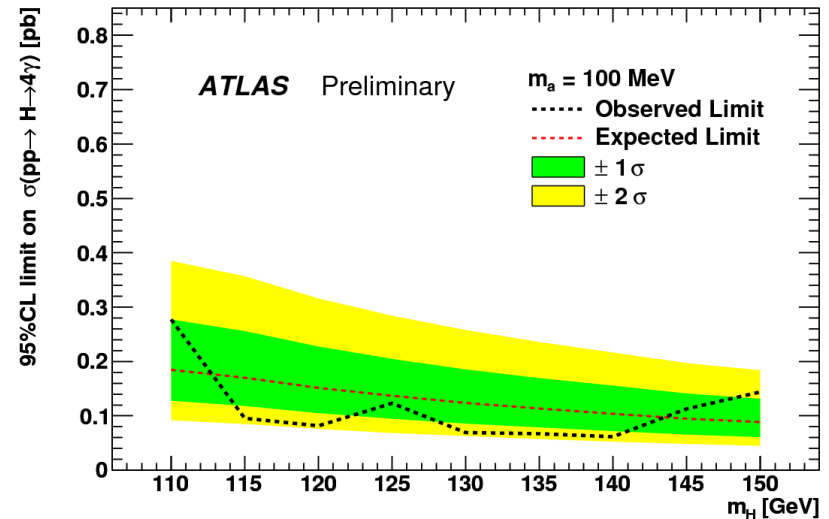
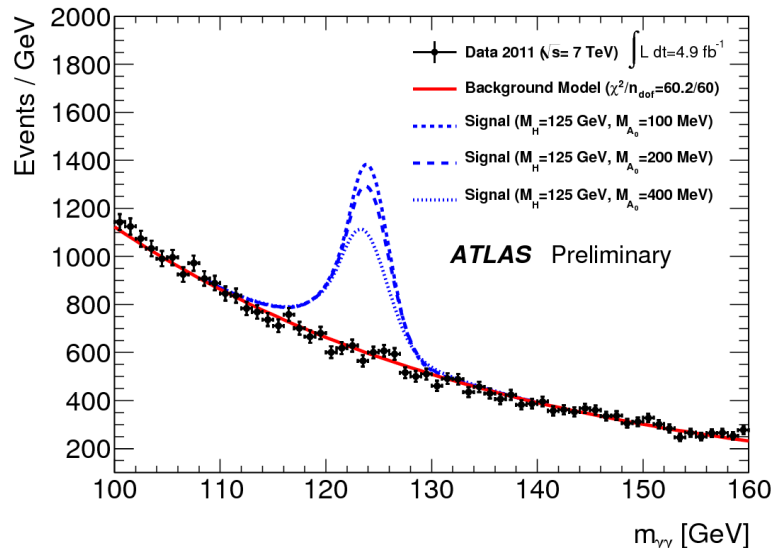


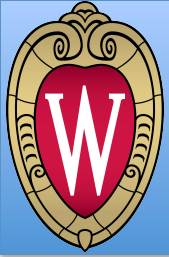
Shower shape
analysis provides
discrimination from SM
 $H \rightarrow \gamma\gamma$



$H \rightarrow aa \rightarrow \gamma\gamma \gamma\gamma$

ATLAS CONF 2012-079





NMSSM: $a_1 \rightarrow \mu^+ \mu^-$

CMS PAS HIG-12-004

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

Adds singlet scalar field, thereby expanding the Higgs sector to three CP-even (h_1, h_2 and h_3), two CP-odd (a_1, a_2) and two charged scalars (H^+, H^-)

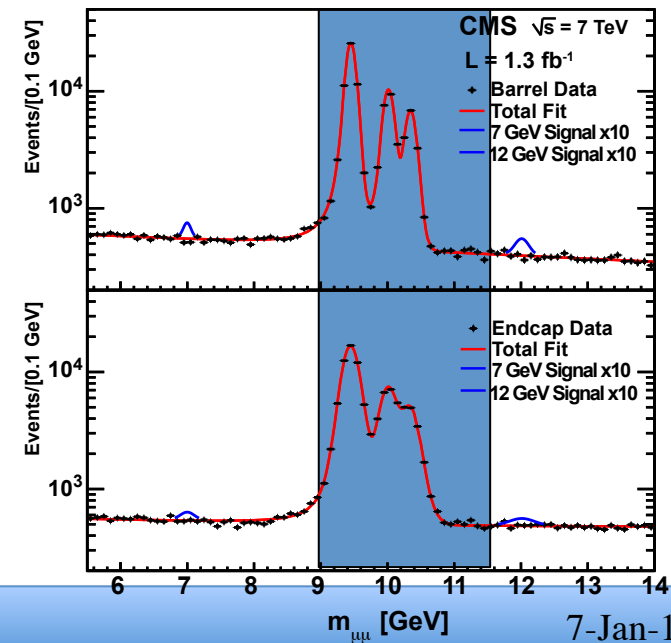
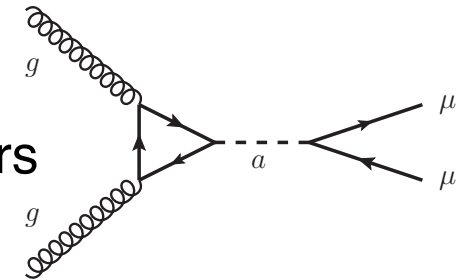
A light (~ 10 GeV) boson produced

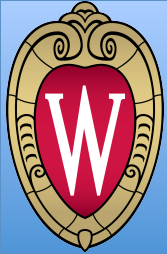
Search for a_1 in its decays to opposite sign di-muon pairs

- Di-tau BR is higher but is deemed impossible

Analysis strategy

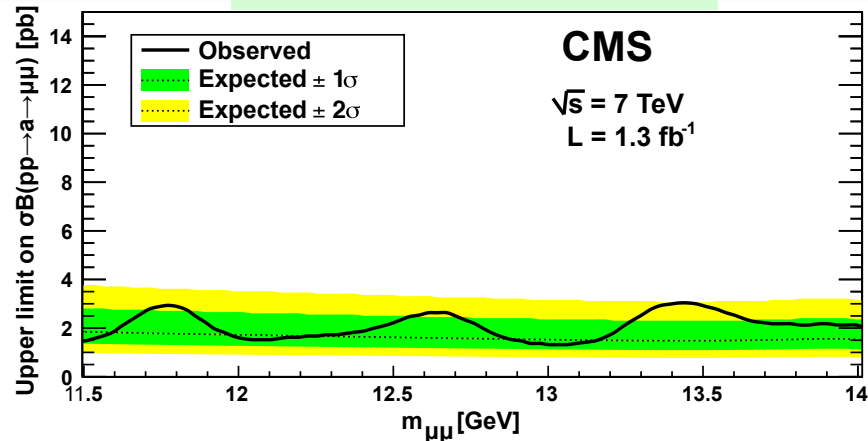
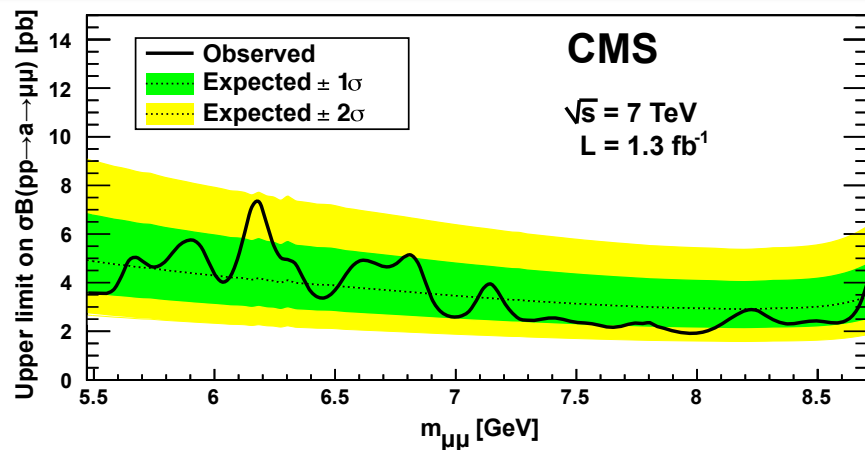
- Chose isolated opposite sign dimuons with
 $p_{T\mu} > 4$ GeV & $p_{T\mu\mu} > 6$ GeV
- Search above/below the epsilon peaks in dimuon invariant mass
 - $5.5 < M_{\mu\mu} < 9$ GeV
 - $11.5 < M_{\mu\mu} < 14$ GeV





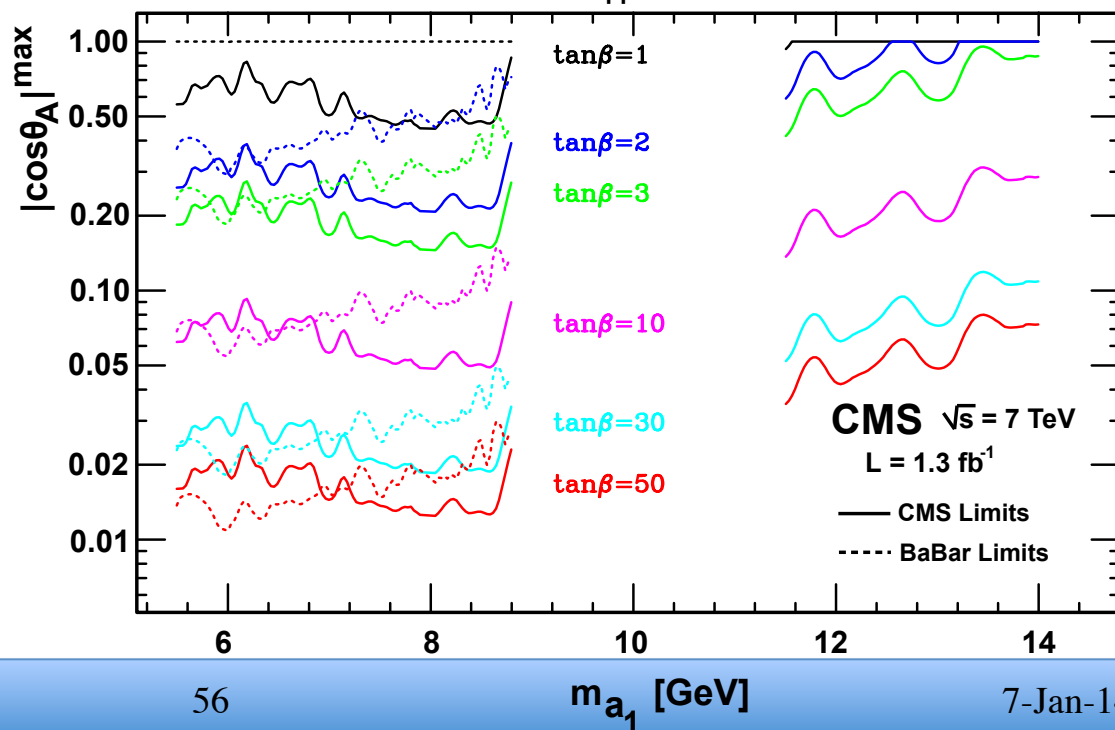
NMSSM: $a_1 \rightarrow \mu^+ \mu^-$ Limits

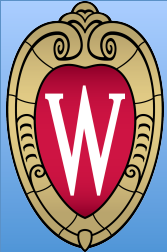
CMS PAS HIG-12-004



Three parameters

$$m_a, \tan \beta, \cos \theta_A$$





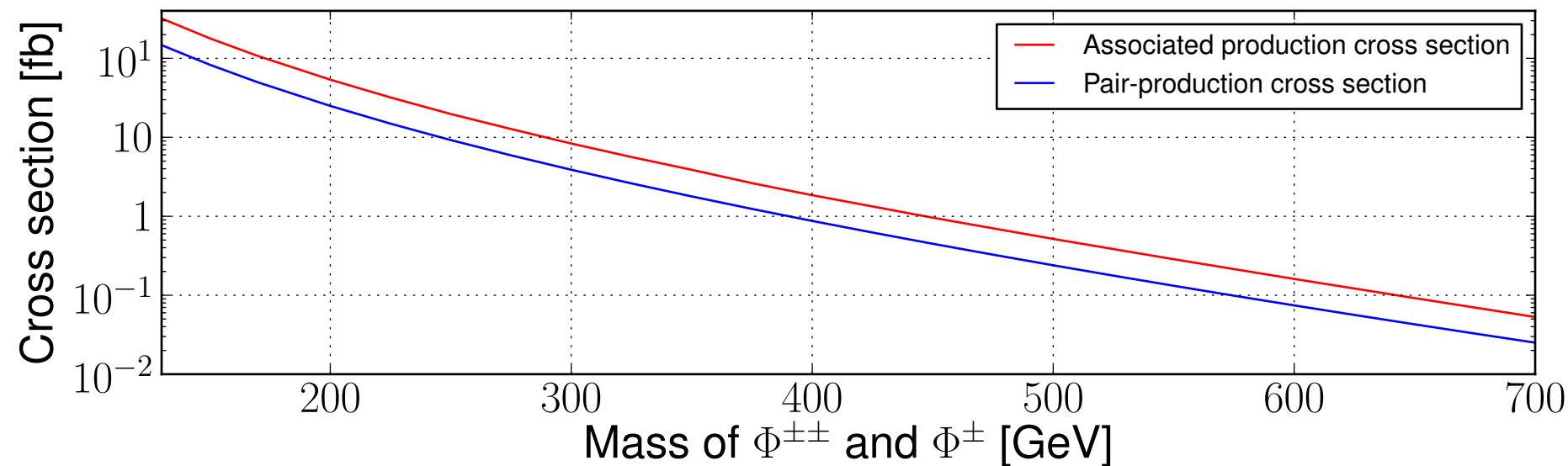
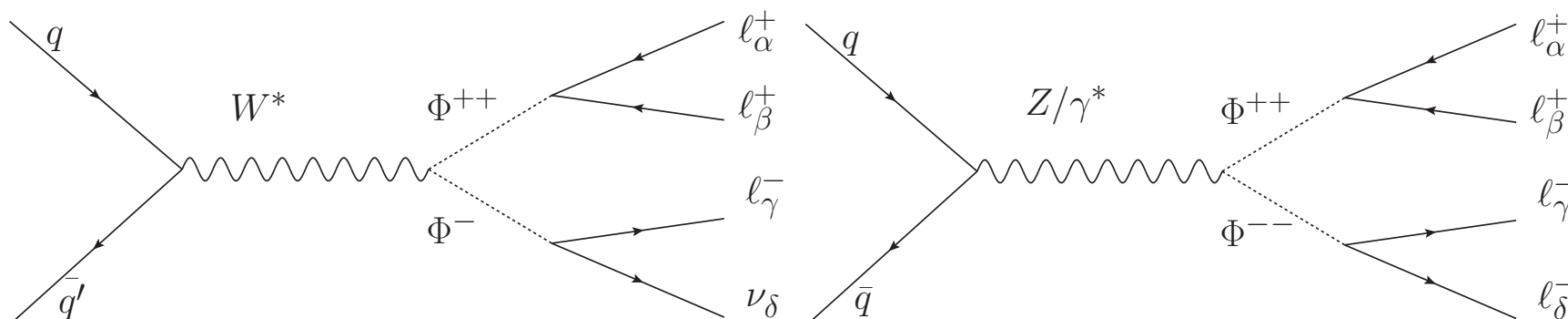
Doubly Charged $\Phi^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$

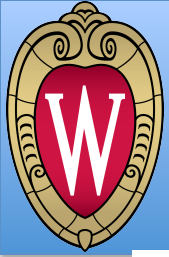
CMS PAS HIG-12-005

Models with triplet of higgs fields, predict doubly charged bosons

- Interestingly triplet models can include fermiophobic neutral higgs

Search for like-sign dilepton production

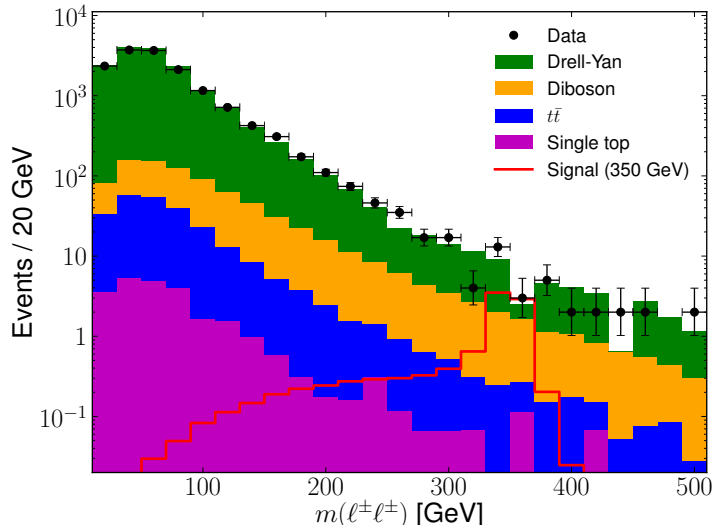




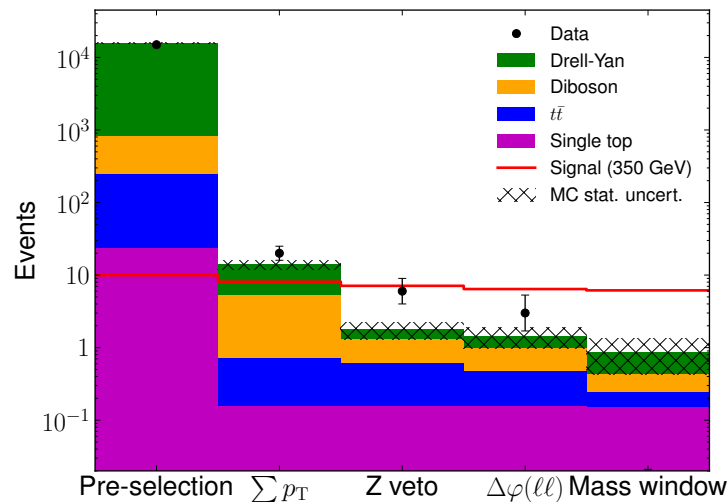
Trilepton & Quadlepton Modes

CMS PAS HIG-12-005

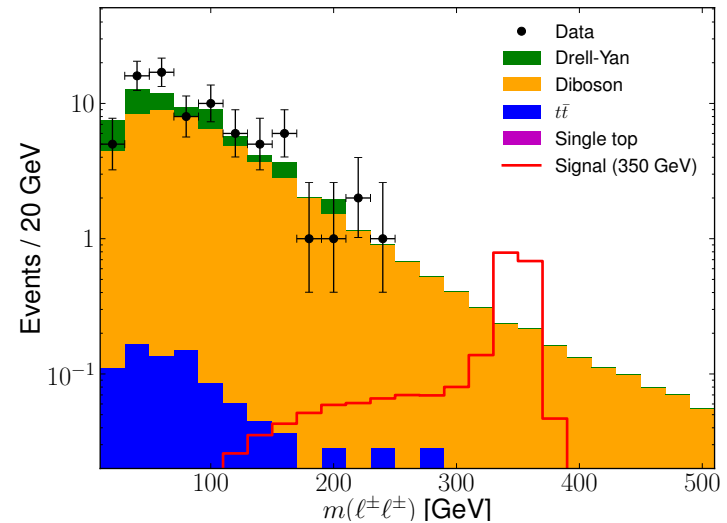
CMS $\sqrt{s} = 7$ TeV, $\int \mathcal{L} dt = 4.9 \text{ fb}^{-1}$



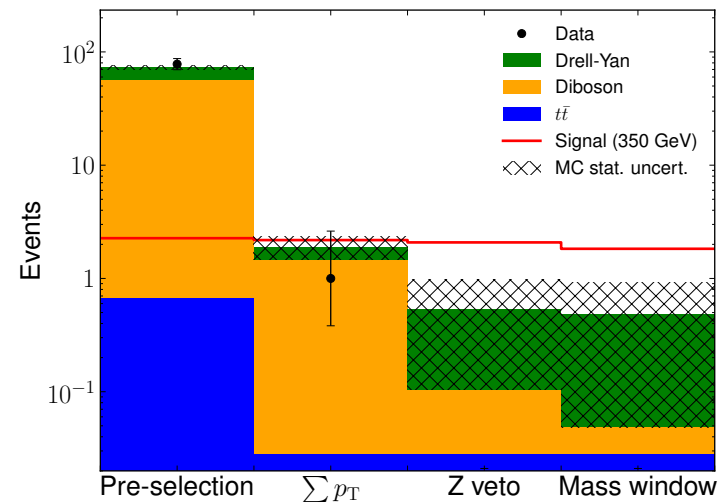
CMS $\sqrt{s} = 7$ TeV, $\int \mathcal{L} dt = 4.9 \text{ fb}^{-1}$

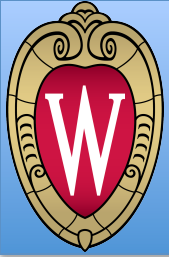


CMS $\sqrt{s} = 7$ TeV, $\int \mathcal{L} dt = 4.9 \text{ fb}^{-1}$



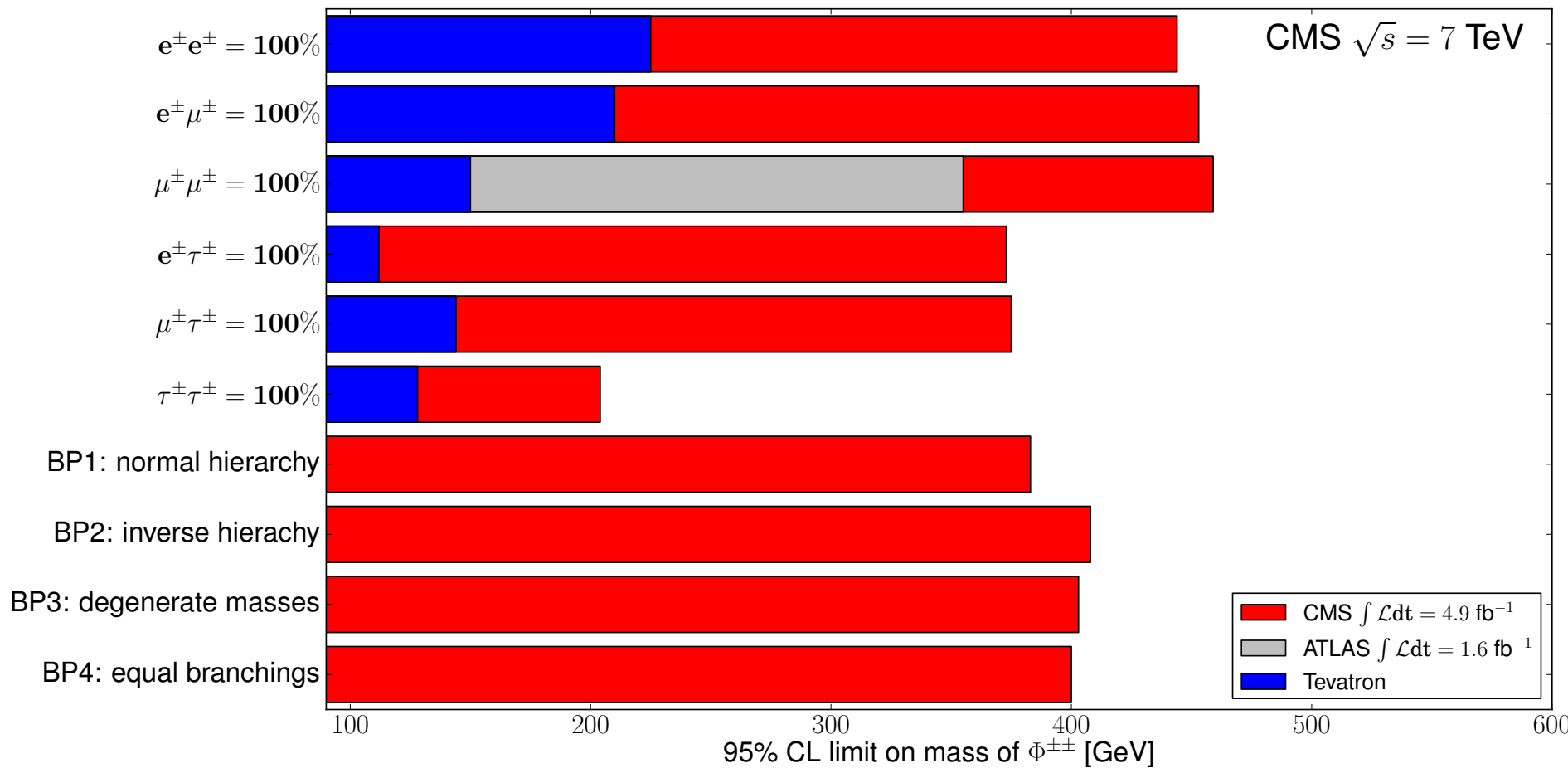
CMS $\sqrt{s} = 7$ TeV, $\int \mathcal{L} dt = 4.9 \text{ fb}^{-1}$

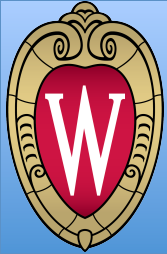




Doubly Charged $\Phi^{\pm\pm} \rightarrow \ell^{\pm}\ell^{\pm}$ Limits

CMS PAS HIG-12-005

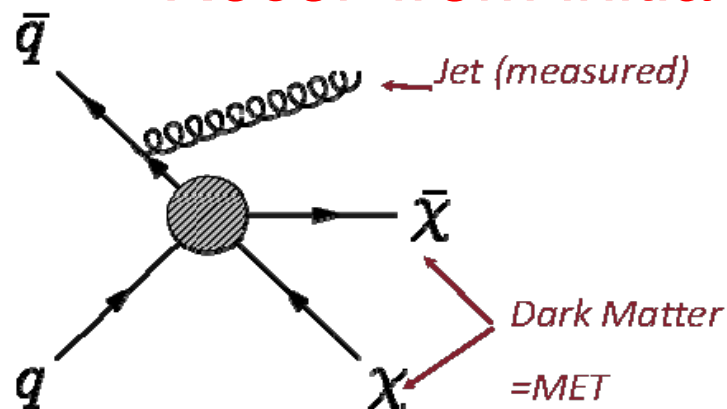




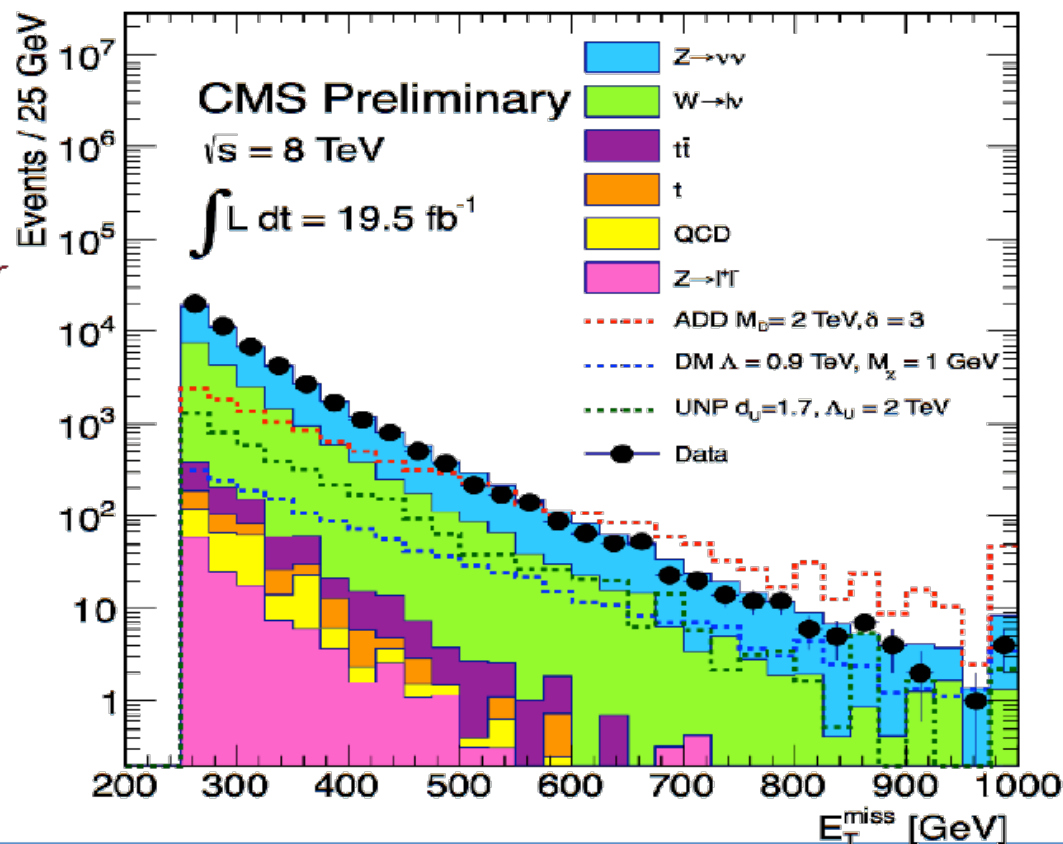
Dark Matter Search

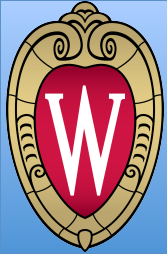
Dark matter particle production by $q\bar{q}$ annihilation

- Recoil from initial-state radiation

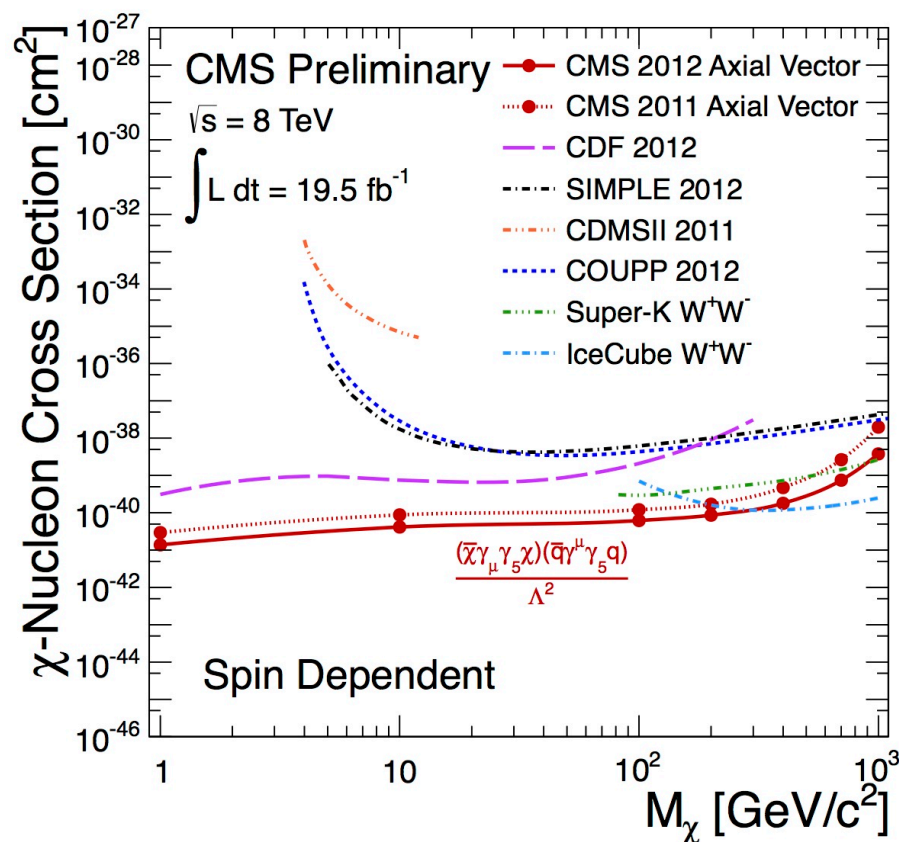
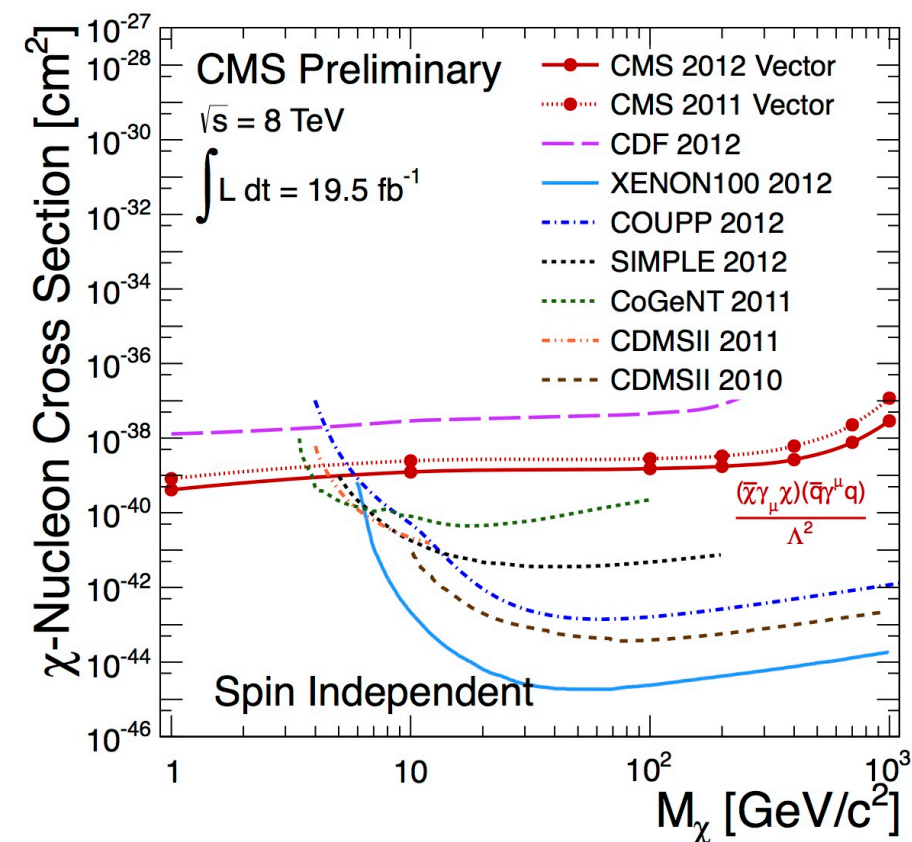


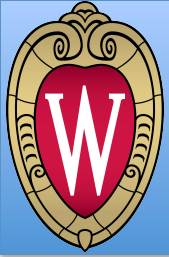
Best limits expected with
 $E_T^{\text{miss}} > 350\text{--}400\text{ GeV}$





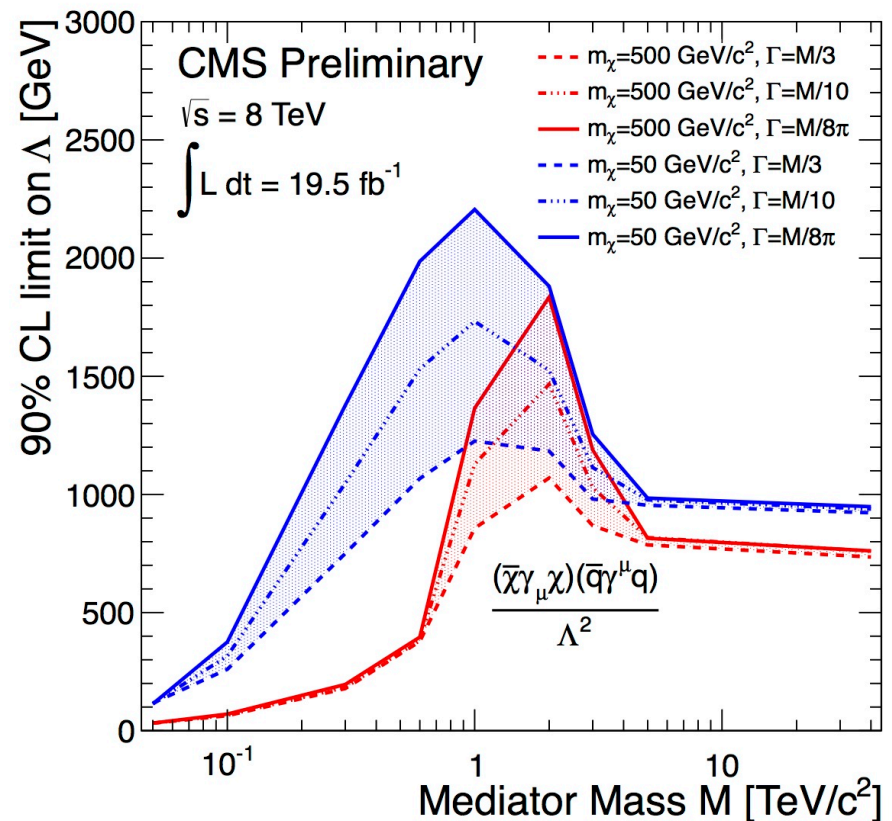
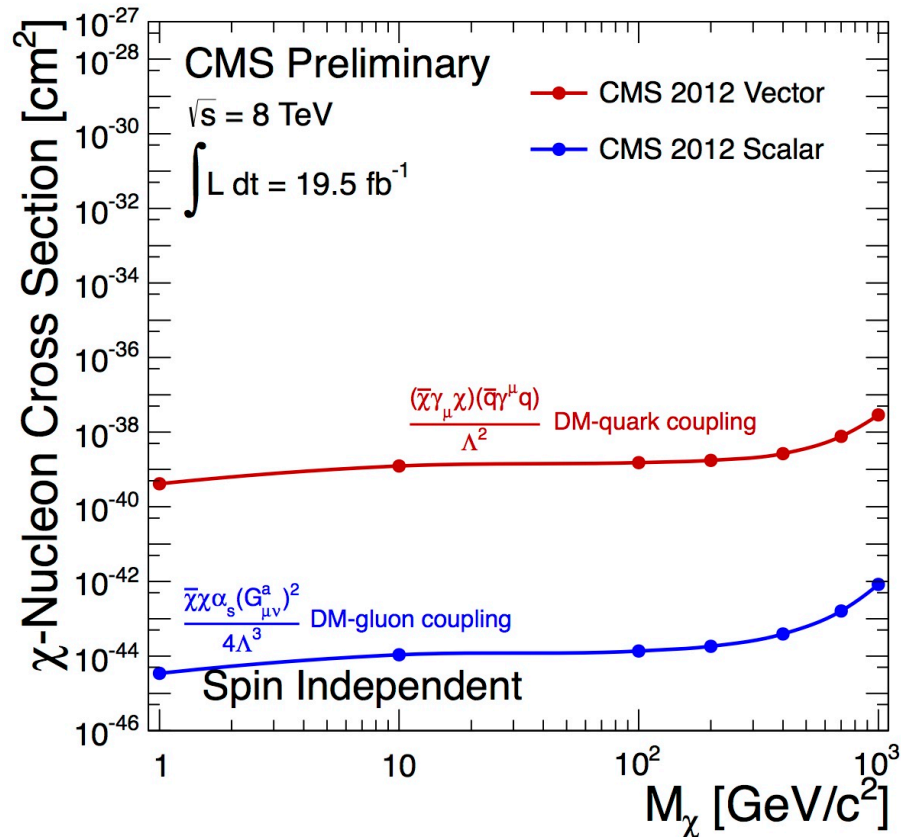
Dark Matter Search

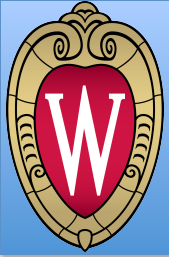




Dark Matter Search

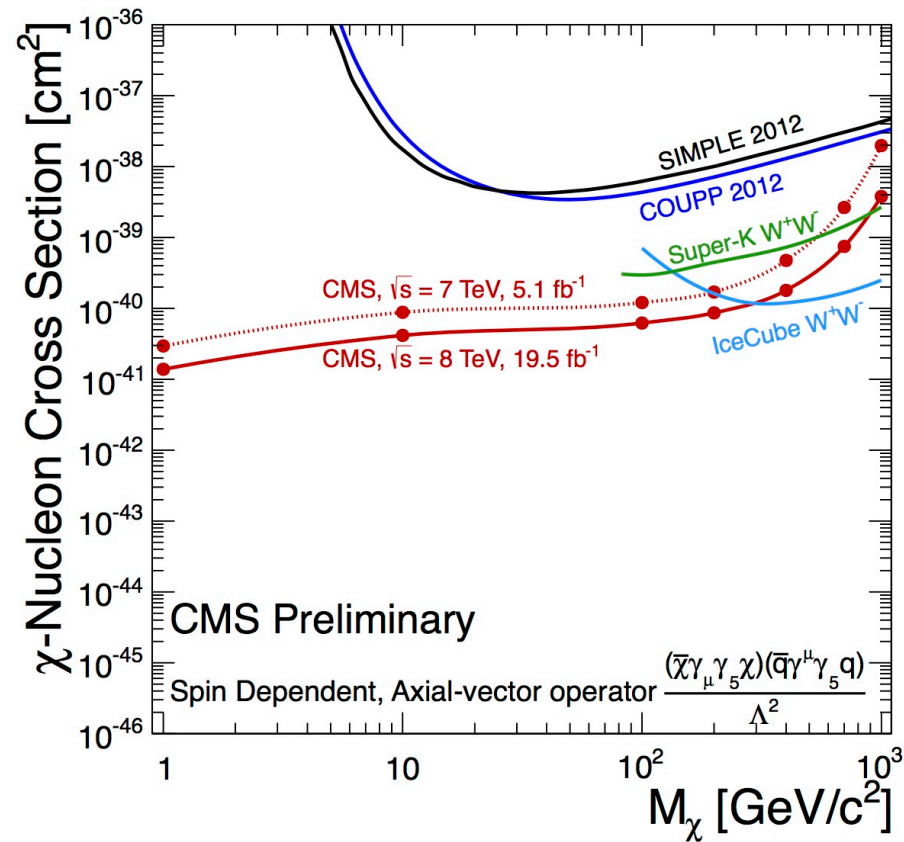
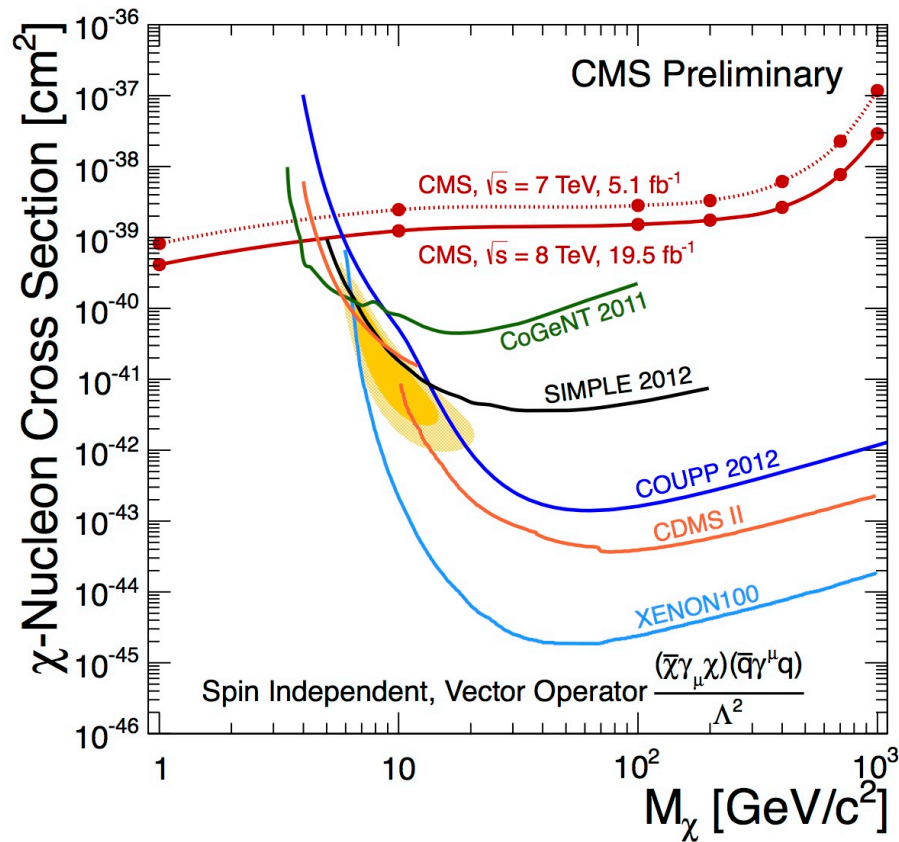
Model dependent: Coupling type, Mediator Mass ...

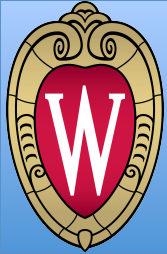




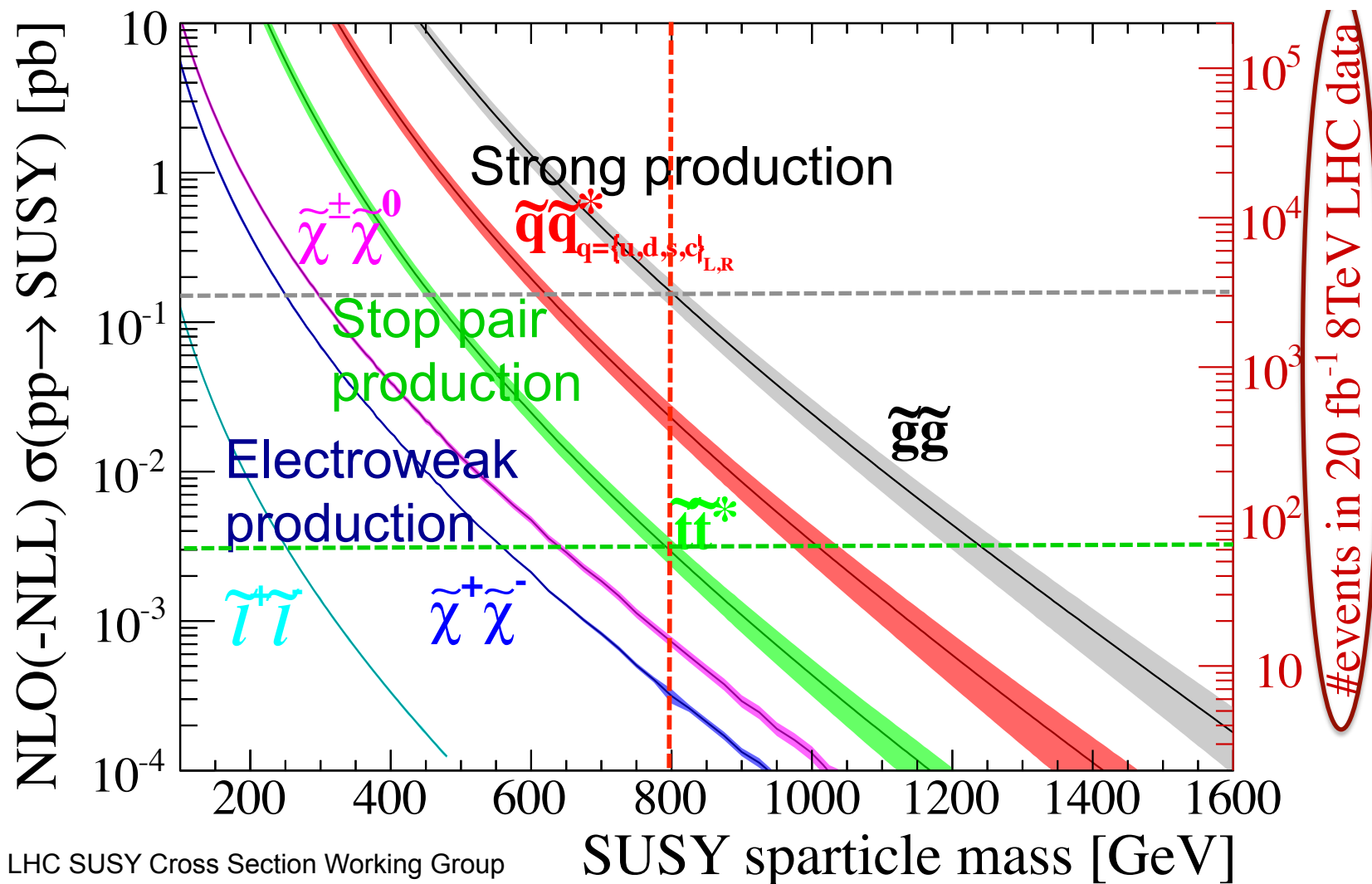
Dark Matter Search

Model dependent: Vector, Axial Vector ...



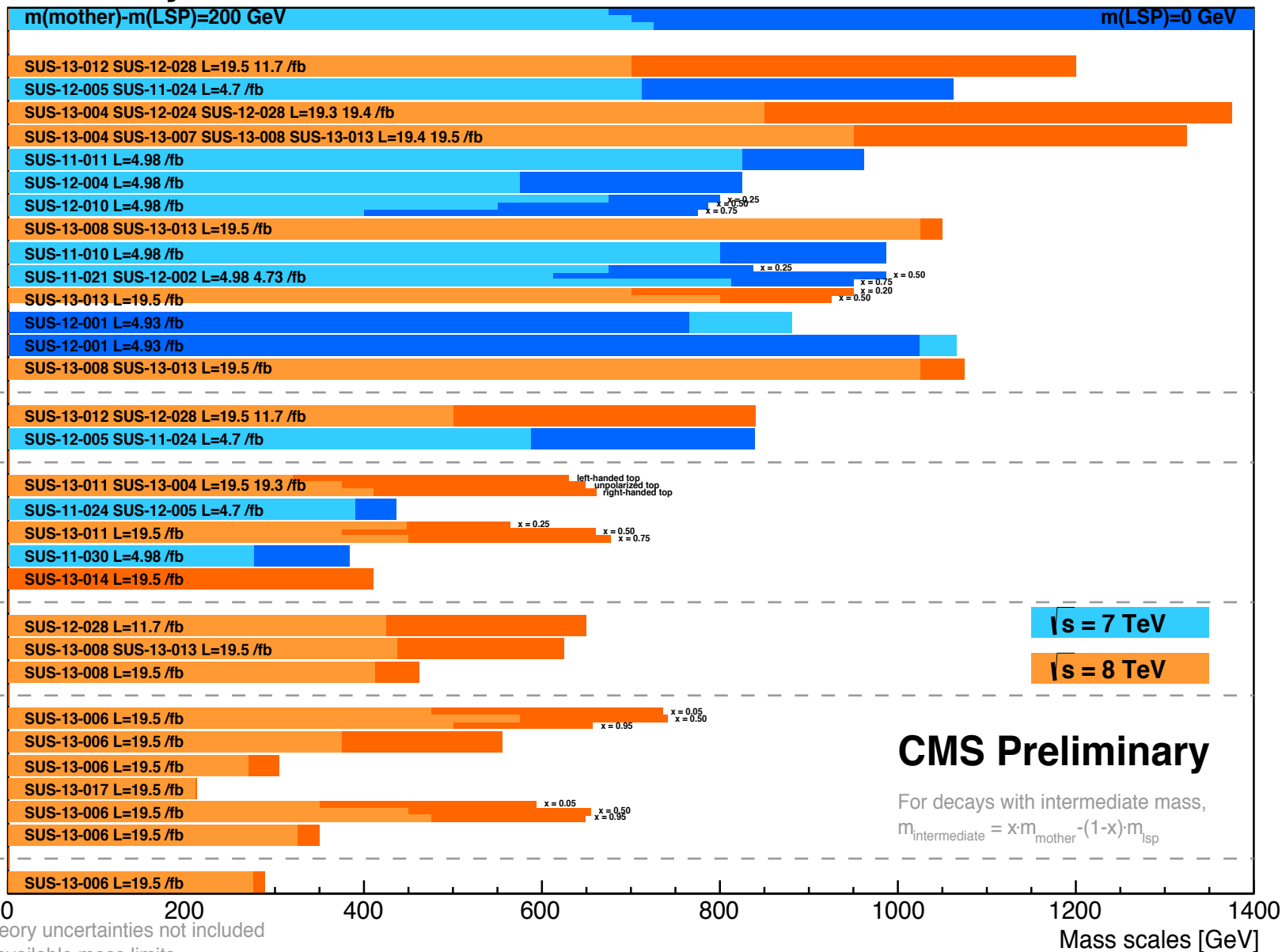


SUSY Cross Sections

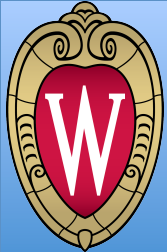


Summary of CMS SUSY Results* in SMS framework

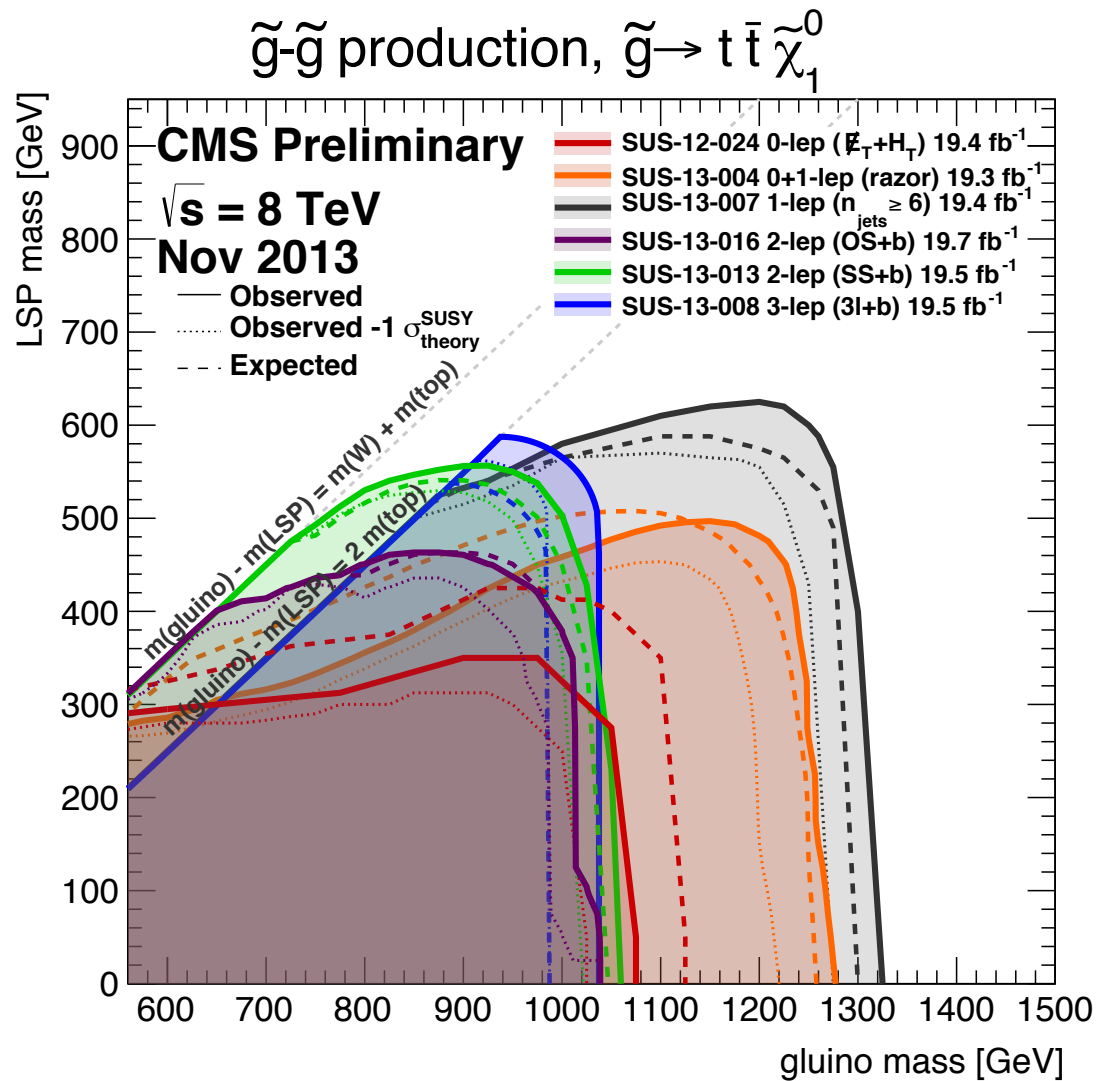
SUSY 2013

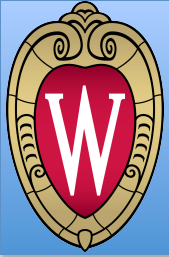


*Observed limits, theory uncertainties not included
 Only a selection of available mass limits
 Probe *up to* the quoted mass limit

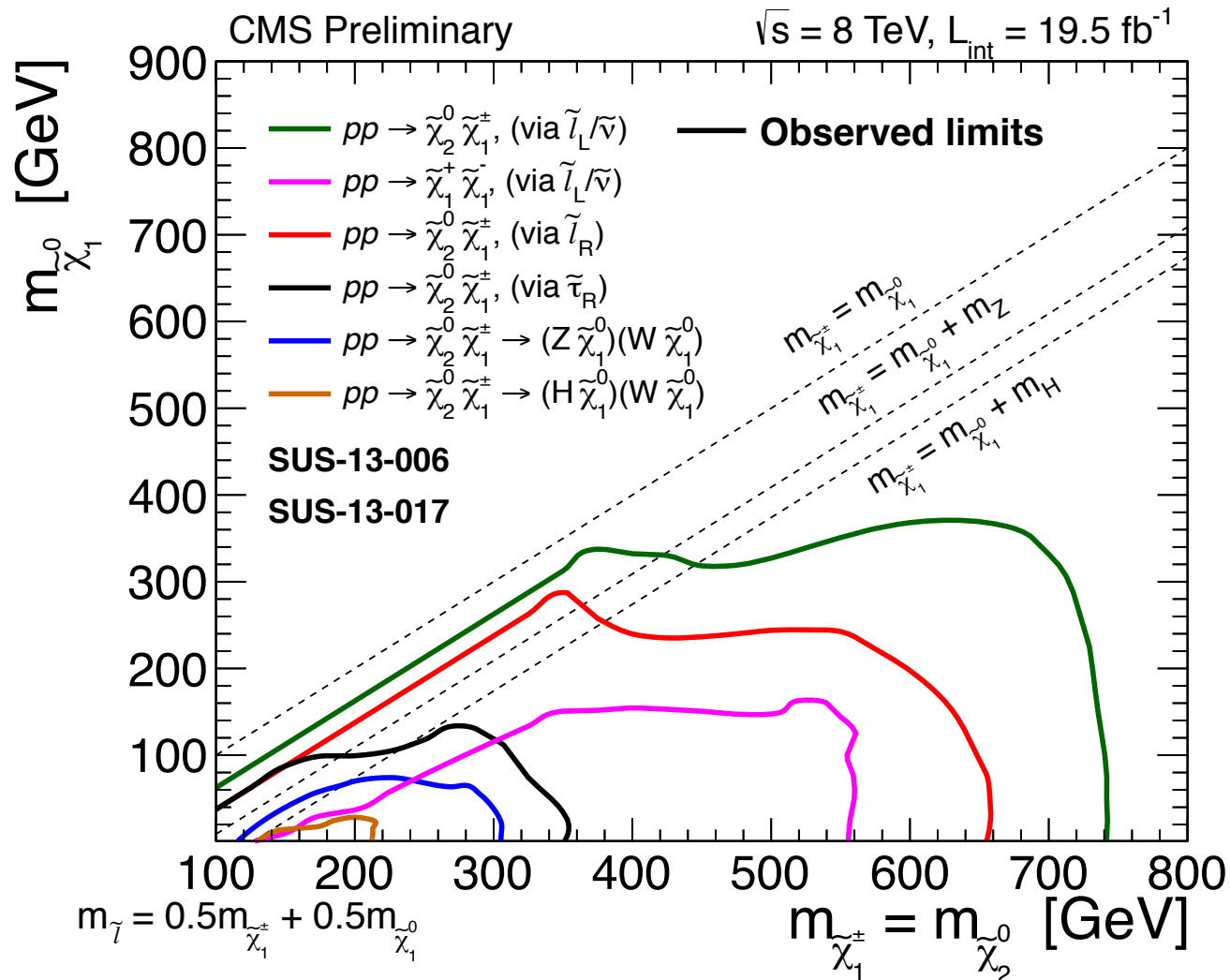


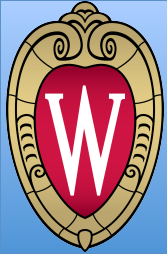
Gluino – LSP Mass Constraints





EWKino – LSP Mass Constraints

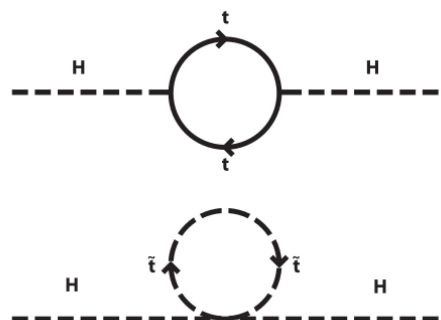




Stop Searches

Stop is important for H mass stabilization

- Perhaps, other SUSY particles are heavier

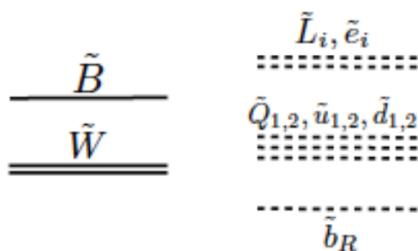


$\tilde{g}$

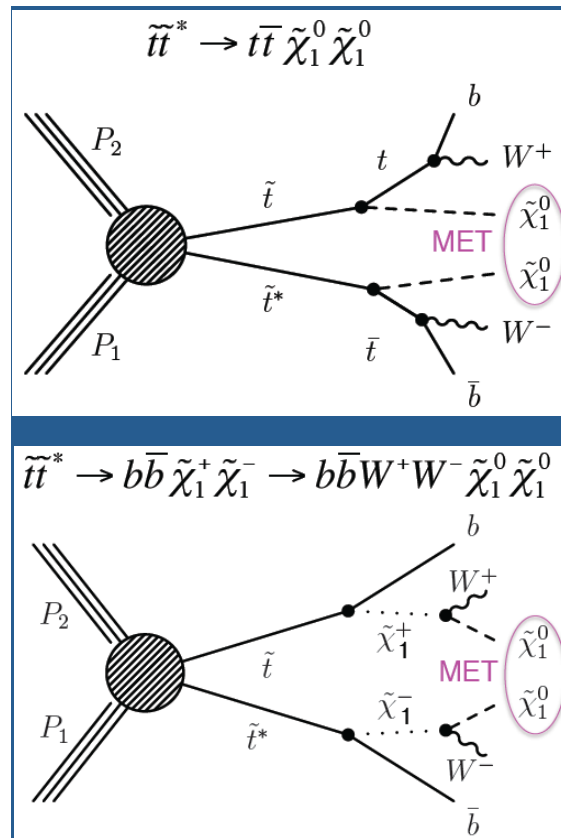
$\tilde{t}_L, \tilde{t}_R$
 $\tilde{b}_L, \tilde{b}_R$

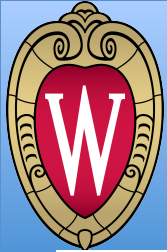
$\tilde{H}$

natural SUSY

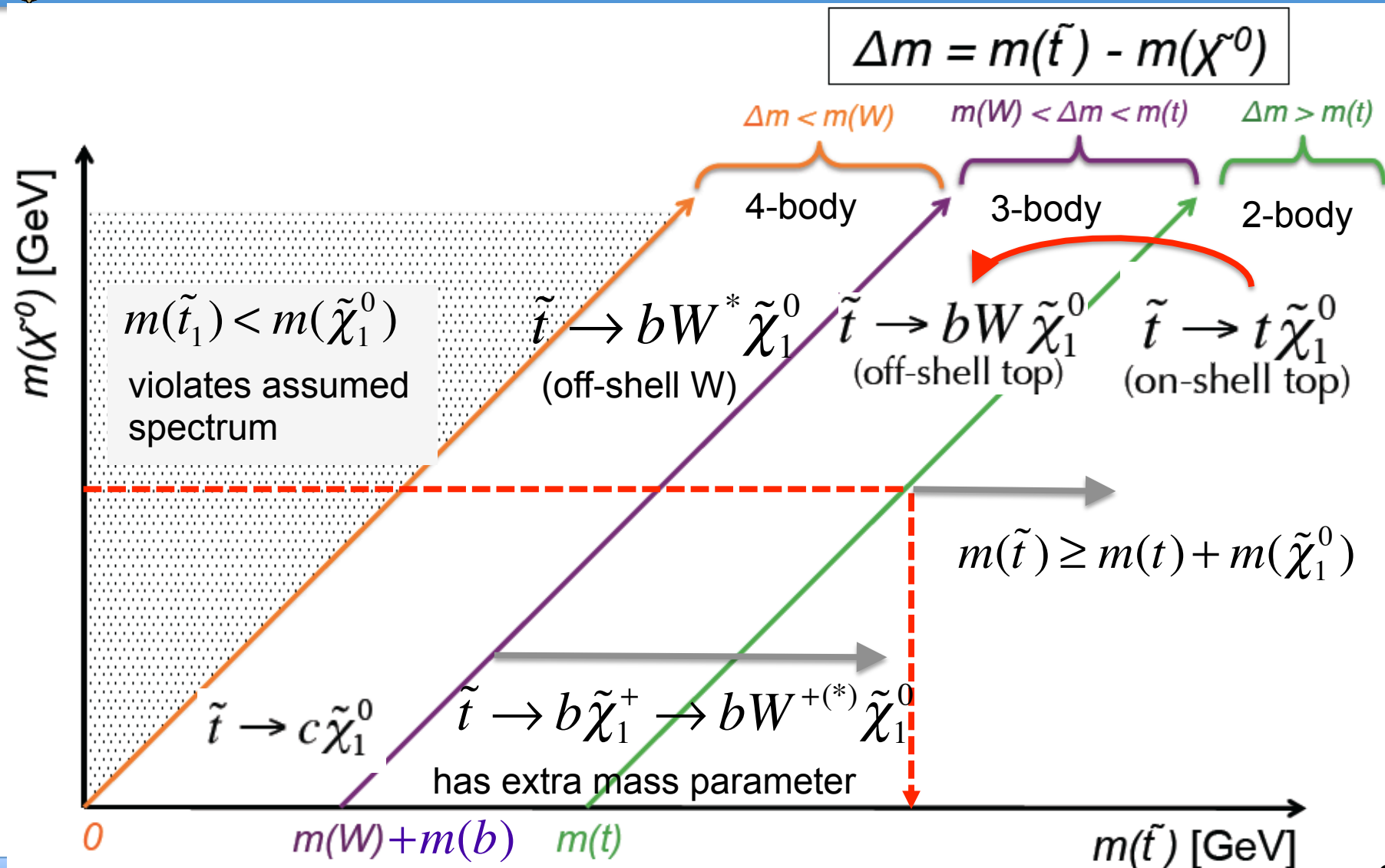


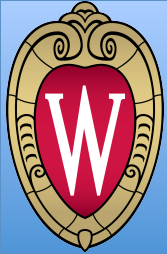
decoupled SUSY





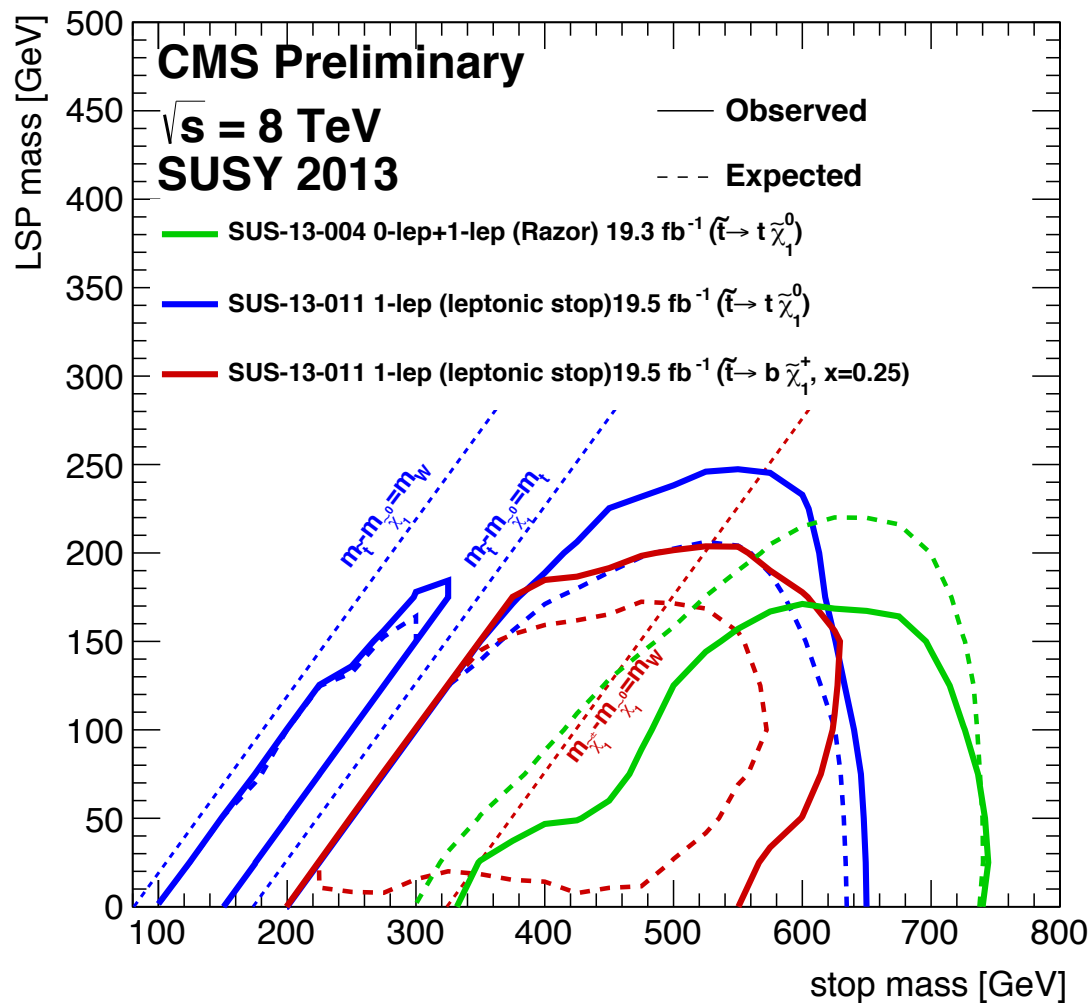
Stop – Neutralino Mass Plane



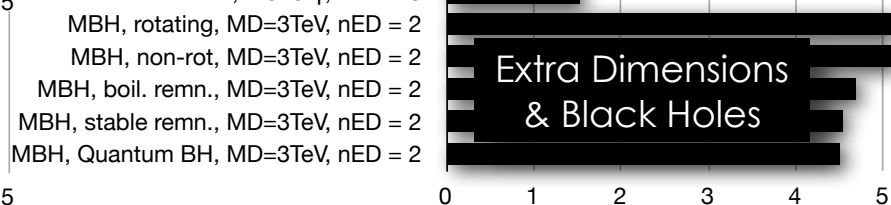
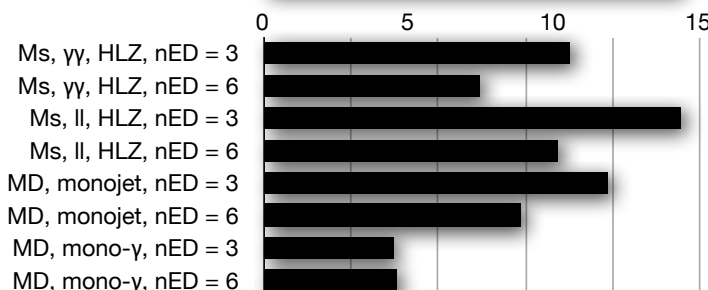
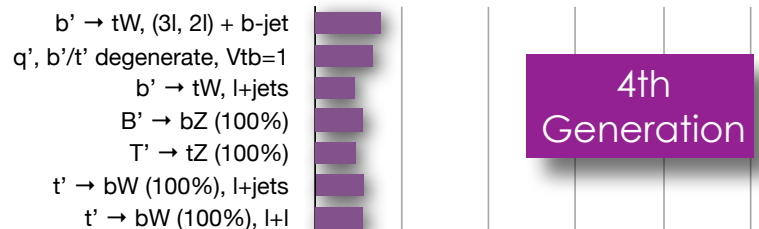
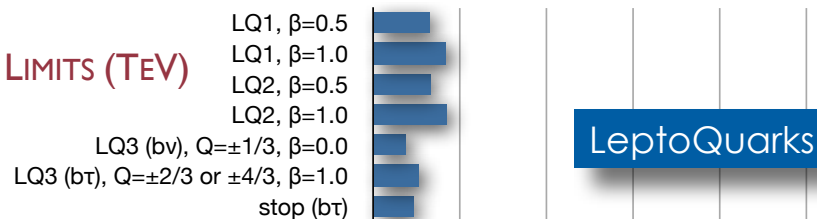
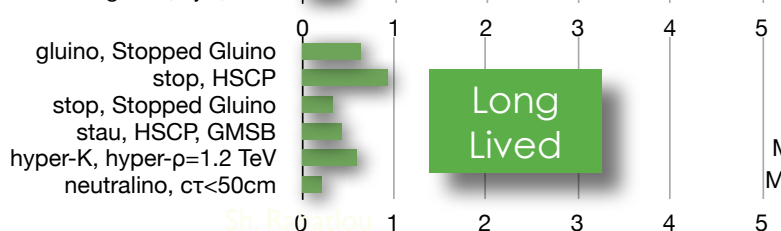
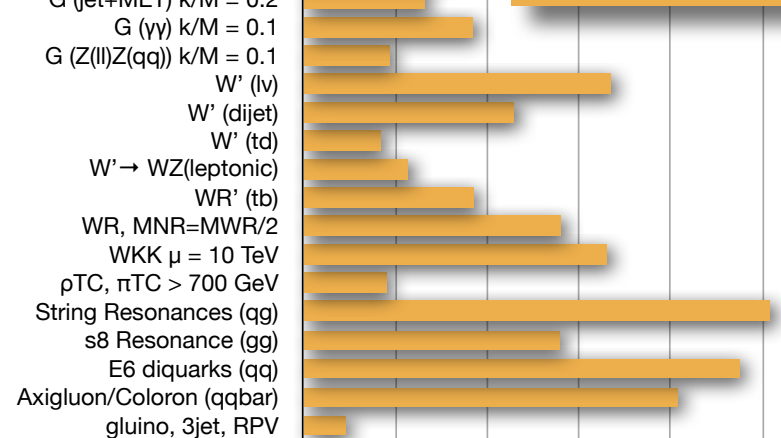
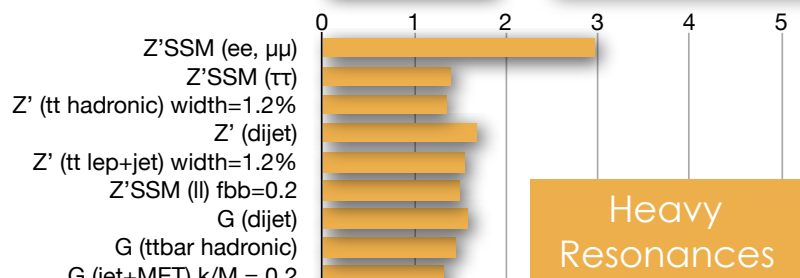
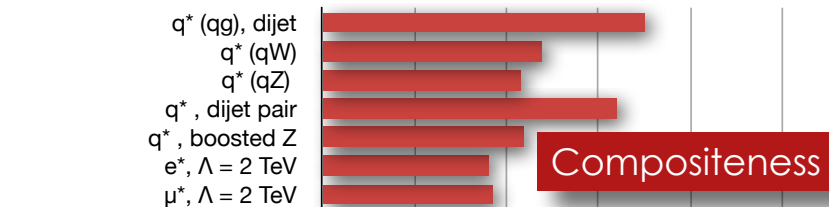


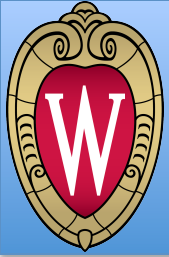
Stop – Neutralino Mass Constraints

$\tilde{t}\text{--}\tilde{t}$ production



CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)





Summary

An SM-like Higgs found

- 8-16% uncertainty on signal strength w/ 100 fb^{-1}
- Searches in rarer modes become sensitive enough for discovery

No BSM in Higgs sector found yet

- Substantial parameter space will be covered

No DM WIMP, SUSY or exotic candidates discovered yet

- 100 fb^{-1} should cover most cases leaving EWK sources

What next?

- There is still a window left for EWK scale SUSY including DM
 - Certainly with “contrived” mass spectra
 - Perhaps, theoretical fine-tuning problem is to be ignored ...
 - Higgs is new portal to BSM, expect much excitement @ LHC!
- The LHC Run 2015-17 @ 13 TeV $\rightarrow 100 \text{ fb}^{-1}$ is critical
- Upgrades to accelerator and detector are underway!