Scalar searches at LHC run-2

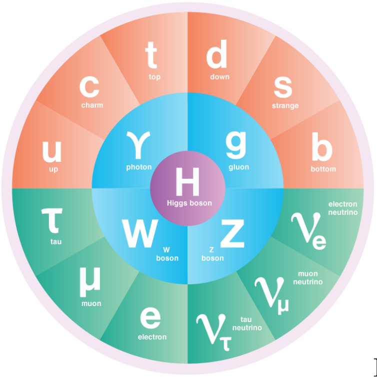
Ushoshi Maitra

TIFR, Mumbai

Outline

1. Standard Model and beyond
2. Observations at LHC
3. BSM

Standard Model

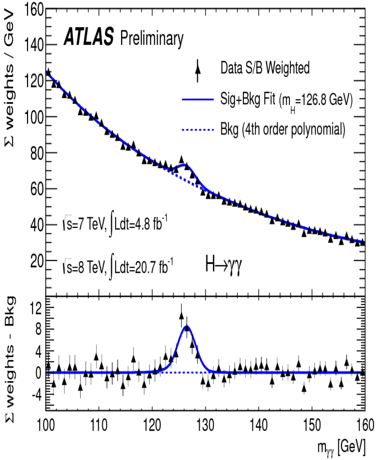


- The standard model is successful in explaining interactions of matter in nature at electroweak scale.
- A simple picture - Gauge bosons mediate the fundamental interactions of matter i.e quarks and leptons.
- To complete the picture, we need SM Higgs to explain mass of the gauge bosons i.e $W,\ Z$.

P.C- http://www.symmetrymagazine.org/standard-model/

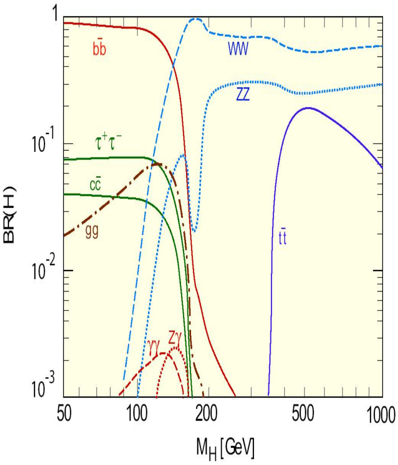
Outline

What did we observe?



- On 4th of July 2012, Large Hadron Collider observed a particle with mass 125 GeV.
- Is this

Higgs boson decay



Dominant decay to $b\bar{b}$ for $M_H \ < \ 130$ GeV.

- In the Standard model, Higgs couples to the gauge bosons via the Kinetic term i.e

$$D_\mu \Phi^\dagger D^\mu \Phi = 2\frac{M_W^2}{v} W^+ W^- + \frac{M_Z^2}{v} Z_\mu Z^\mu$$

where

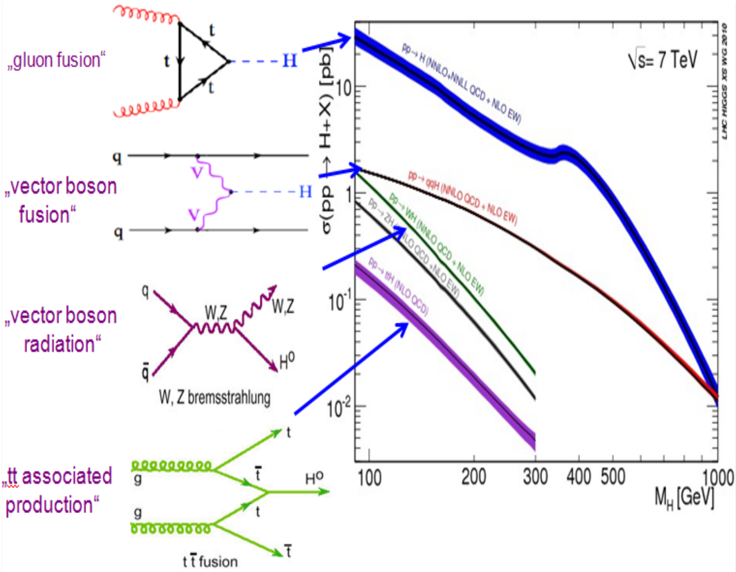
$$D^\mu \Phi = \partial_\mu + igTW_\mu + ig' B_\mu \begin{bmatrix} 0 \\ v + h \end{bmatrix}$$

- Higgs couples to the fermions via the Yukawa term

$$L_{yuk} = y_{ij} \bar{\Psi}^i \Phi \Psi^j = \frac{\sqrt{2} m_f}{v} \bar{\Psi} \Psi$$

- Higgs couples to all particles via its mass

Production at LHC



Observing Higgs@LHC

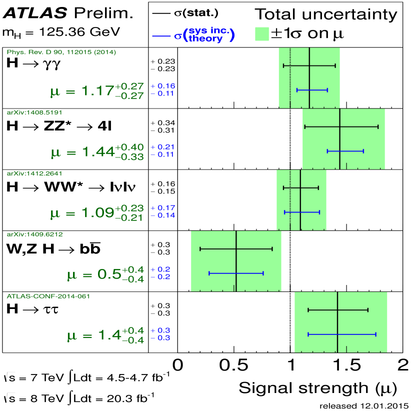
- ggF $\rightarrow \gamma\gamma$
  - low branching ratio but clean environment
  - Possible to reconstruct the Higgs i.e photons 4-vectors are added to reconstruct the invariant mass of the intermediate particle.
- ggF $\rightarrow ZZ^*$
  - Four lepton final states- clean environment and reconstruction
- ggF $\rightarrow WW^*$
  - due to the presence of neutrino, Higgs can not be reconstructed
  - probe electroweak symmetry breaking.
- VH $\rightarrow b\bar{b}$
  - clean signature compared to gluon fusion
  - leptons in the final state kills large multijet background
  - probing quark(down-type) coupling
- VBF $\rightarrow \gamma\gamma, \tau\ \tau, WW^*, ZZ$ and $t\bar{t}h \ \rightarrow \ \gamma\gamma, b\bar{b}$ - can probe electroweak symmetry breaking and Yukawa structure

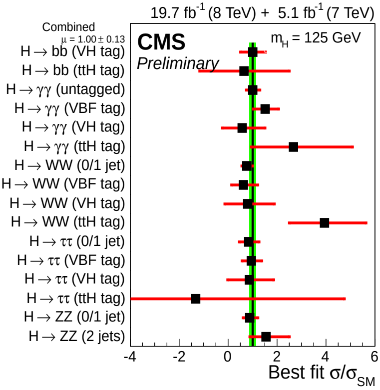
Quantifying our observation

- Signal strength (μ) defined as the ratio of the observed scalar rate to the SM expectation value i.e

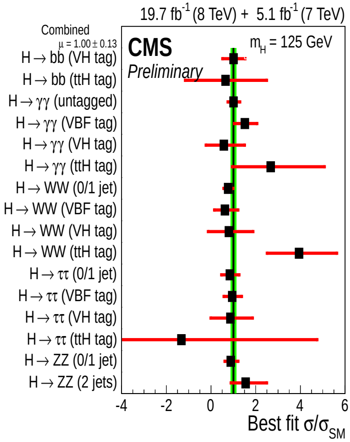
$$\mu = \frac{\sigma(pp \to S \to ab)}{\sigma(pp \to h_{sm} \to ab)}$$

- For a SM Higgs μ should be equal to 1





What did we infer



- The SM predition lies close to the measured value of the signal strength for almost all channels -will improve with more events

- What does it mean?
  - No new physics- The scalar is our 'celebrated' Higgs and μ will become 1 with more events.
  - NEW PHYSICS -Why do we need it??

Outline

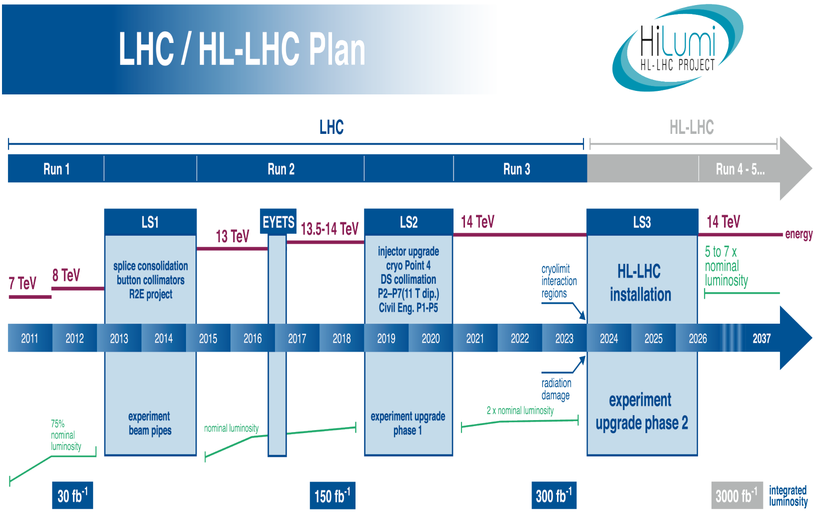
Why beyond Standard model physics?

- There are several drawbacks of the SM such as
  - Naturalness problem - higher order corrections depend on the mass of the heaviest particle in the theory and it is not clear that WHY HIGGS MASS IS $O(100)$ GeV
  - Gravity - What makes gravity so weak
  - Fermion mass hierarchy- no machanism generates mass of the leptons and quarks and THEY APPEAR RANDOM
  - Dark matter -no candidate for dark matter
- To understand these issues we consider that SM is a part of a larger picture -Collectively, termed as beyond Standard model scenarios.

Solutions

- Two extensions of SM are considered
  - Additional dimensions beyond 3+1 space-time -explains weakness of gravity as well as fermion hierarchy
  - Enhanced symmtery -solves naturalness problem, offers a suitable candidate for dark matter
- Low energy measurements are almost conssistent with the Standard model predictions.
- BSM theories predict additional particles and LHC is looking for them.
- Till now no new particle apart from the scalar at 125 GeV has been observed at the LHC - BSM theories are under scrutiny.

Scope at LHC


LHC / HL-LHC Plan
HiLumi
HL-LHC PROJECT
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
13.5-14 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
injector upgrade
cryo Point 4
DS collimation
P2–P7(11 T dip.)
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC
installation
5 to 7 x
nominal
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2011
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2022
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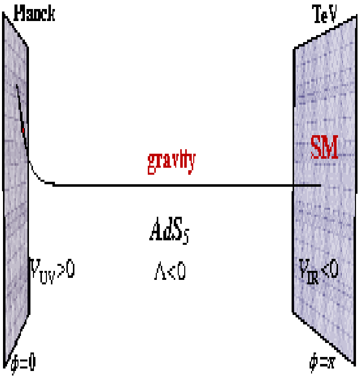
2026
2037
radiation
damage
75%
nominal
luminosity
experiment
beam pipes
nominal luminosity
experiment upgrade
phase 1
2 x nominal luminosity
experiment
upgrade phase 2
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity

Warped Extra dimensional model



- First proposed by L. Randall and R. Sundrum
- Set up - There exist an additional dimension compactified as well as small with two branes and we live in one of the brane
- The five dimensional metric for this configuration is given by

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

- If $kR = 12$, TeV scale can be generated from Planck scale - $m_{phys} = e^{-kR\pi}m_0$..

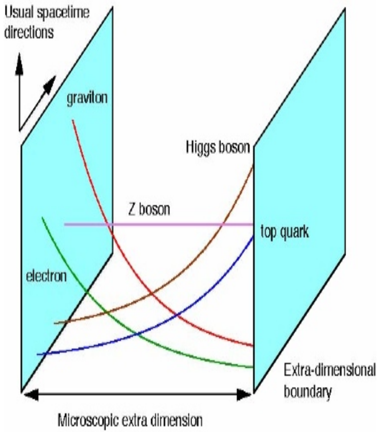
A realistic approach

- All the SM fields Φ can access the bulk - $\Phi(x, y)$
- As y-coordinate is compactified, Fourier expansion of $\Phi(x, y) = \Sigma_n \Phi^n(x) f^n(y)$
- Φ^n are called Kaluza Klein mode (excitation) and zeroth mode is identified with the SM particles.
- The profiles of the SM particles are given by

$$f^s(y) = e^{a_s k y}$$

where $a_0 = 1 + \pm\sqrt{4 + a}$, $a_{1/2} = 1/2 \pm c$, $a_1 = 0$ and $a_2 = -1$

How do they interact with each other??



- Simple picture - Strength of the interaction is given by overlapping integral of their profiles.
- Hierarchy → zeroth mode of Higgs i.e SM Higgs is kept closed to the TeV brane.
- Fermion yukawa → Interaction of the fermion profile with the Higgs profile
- Thus, top quarks are kept close to the TeV brane and light quarks are kept close to the Planck brane.

Kaluza-Klein mode

- The profile $(f(y)$ is given by $f^{(n)} \sim e^{(2-s)ky} J_\alpha(\frac{m_n}{ke^{-ky}})$ where

$$m_n \;=\; (n + \frac{\alpha}{2} - \frac{3}{4}(\frac{1}{4}))\pi k e^{-\pi k R}$$

  for bosons (fermions) and $\alpha^s \;=\; \pm\sqrt{4+a}$,
  $c \;\pm \frac{1}{2},\; 1$ for $s \;=\; 0, 1/2, 1$

- Since $ke^{-\pi kR} \;\sim\; TeV$, masses of the KK particles are $O(TeV)$

- If Randall-Sundrum model exist, then KK particles have to be there and should be observed at LHC.

Tale of two branes

- Two branes are fixed on two points - difficult to imagine
- Instead the relative distance between two branes can be parametrized by a scalar field such that $R \sim < T(x) >$.
- $< T(x) >$ is called the Radion field
- Radion is lighter than other KK modes -Lightest signature - 50 GeV to 1 TeV and beyond

Interaction of Radion

- Radion couples with the trace of energy momentum tensor of the SM $\sim \frac{\varphi}{\Lambda_\varphi} T_\mu^{\mu SM}$
- Trace of energy momentum tensor for the SM particles is given by

$$L_{int} = -\frac{\varphi}{\Lambda_\varphi}(\partial^\mu h \partial_\mu h - 2m_h^2 h^2 + \Sigma_f m_f \bar{f} f$$
$$- \quad 2M_W^2 W_\mu^+ W^{-\mu} - M_Z^2 Z_\mu Z^\mu)$$

- Radion couples to all particles via masses -similar to Higgs

- The running of QCD and QED gauge coupling generates a trace anomaly term via which radion couples to gluon and photon.

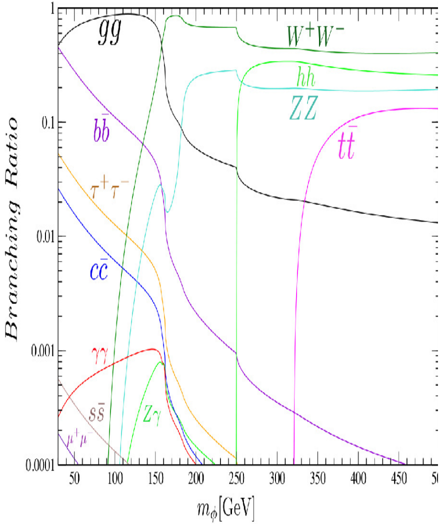
$$T_\mu^\mu{}_{QCD} = \frac{\alpha_s}{8\pi} b_3 G_{\mu\nu a} G^{\mu\nu a}$$

$$T_\mu^\mu{}_{QED} = \frac{\alpha_e}{8\pi} b_Y F_{\mu\nu} F^{\mu\nu}$$

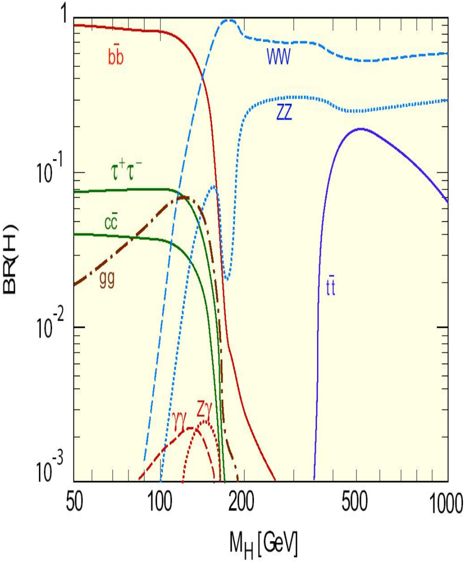
- The radion couples to gluon and photon via trace anomaly term-distinct feature.

Decay of radion compared to Higgs

Radion



Higgs



Radion Higgs mixing

- The mixing between Higgs and radion is described by

$$S_\xi = -\xi \int d^4x \sqrt{-g_{vis}} R(g_{vis}) H^\dagger H$$

$$S_\xi = -6\xi \int d^4x \left[\frac{v}{\Lambda_\varphi} h\Box\varphi + \frac{\gamma^2}{2}\varphi\Box\varphi + h^2 \frac{\Box\varphi}{\Lambda_\varphi} \right]$$

where $\gamma = \frac{v}{\Lambda_\varphi}$.

- On collecting terms with bilinear fields,

$$L_{mix} = -\frac{1}{2}(1+6\gamma^2\xi)\varphi\Box\varphi - \frac{1}{2}\varphi m_\varphi^2 \varphi - \frac{1}{2}h(\Box + m_h^2)h - 6\xi\gamma h\Box\varphi$$

Interactions of physical scalars

- Two physical scalar $(\varphi_1,\ \varphi_2)$

$$\begin{aligned} h = &\quad b\varphi_2 + a\varphi_1 \\ r = &\quad c\varphi_1 + d\varphi_2 \end{aligned}$$

- For the massive gauge bosons and fermions, we have

$$\begin{aligned} L_{int} = &\quad -\tfrac{2M_W^2}{v}(A_{\varphi_1}\varphi_1 + A_{\varphi_2}\varphi_2)W^{+\mu}W^-_\mu \\ &\quad - \tfrac{m_f}{v}(A_{\varphi_1}\varphi_1 + A_{\varphi_2}\varphi_2)\bar{f}f \end{aligned}$$

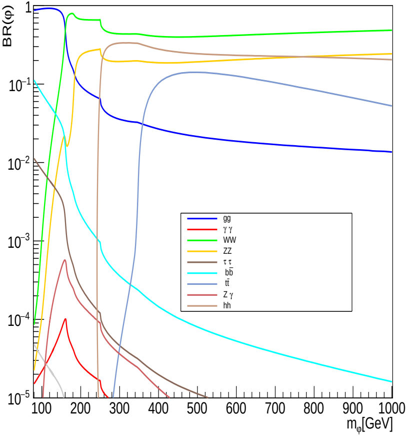
where $A_{\varphi_1} \ = \ a + \gamma c$ and $A_{\varphi_2} \ = \ b + \gamma d$.

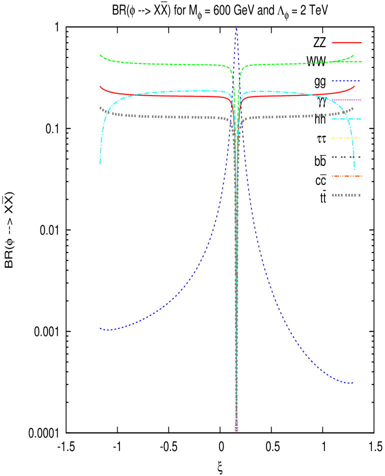
- For the massless gauge bosons

$$\begin{aligned} L_{int}^{\gamma\gamma(gg)} = &\quad -\tfrac{\alpha_e}{8\pi v}\left(\left(\left(\tfrac{4}{3}F_{1/2}(\tau_t) + F_1(\tau_w)\right)A_{\varphi_1} + \tfrac{11}{3}\gamma c\right)\varphi_1\right. \\ + &\quad \left.\left(\left(\tfrac{4}{3}F_{1/2}(\tau_t) + F_1(\tau_w)\right)A_{\varphi_2} + \tfrac{11}{3}\gamma d\right)\varphi_2\right)F^{\mu\nu}F_{\mu\nu} \end{aligned}$$

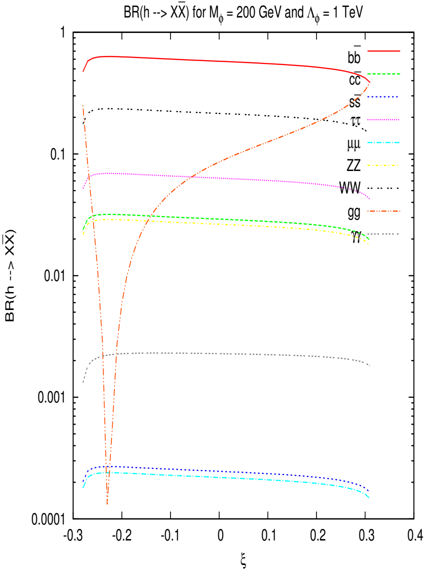
Effect of mixing

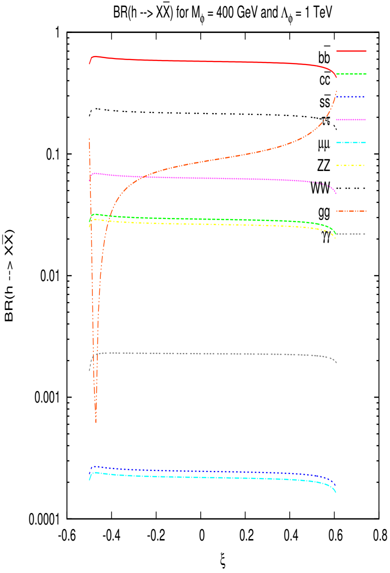
- Due to mixing, both the physical scalars (H, R) have different characteristics which deviates from pure radion or pure Higgs i.e they decay differently





Effect of mixing-Higgs measurement





Signatures of RS model

- If warped extra dimension exist $\rightarrow$ radion must exist and should mix with Higgs.
    - LHC has observed a scalar at 125 GeV -Is the scalar Mixed Higgs? A.Chakraborty, **UM**, S. Raychaidhuri, T. Samui in prepn.
    - Are we going to observe the second scalar i.e Mixed Radion soon? M. Frank, K. Huitu, **UM**, M. Patra, Phys. Rev. D 94, 055016
- Heavy KK state of SM particles should also exist and we must observe them at LHC -Where are they? F. Mahmoudi, **UM**, N. Mangalani, K. Sridhar, JHEP 11 2016(075)

Signal strength measurement as a probe

Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty
		10-parameter fit of μ_F^f and μ_V^f
$\mu_V^{\gamma\gamma}$	$1.05^{+0.44}_{-0.41}$	$^{+0.42}_{-0.38}$
μ_V^{ZZ}	$0.48^{+1.37}_{-0.91}$	$^{+1.16}_{-0.84}$
μ_V^{WW}	$1.38^{+0.41}_{-0.37}$	$^{+0.38}_{-0.35}$
$\mu_V^{\tau\tau}$	$1.12^{+0.37}_{-0.35}$	$^{+0.38}_{-0.36}$
μ_V^{bb}	$0.65^{+0.30}_{-0.29}$	$^{+0.32}_{-0.30}$
$\mu_F^{\gamma\gamma}$	$1.19^{+0.28}_{-0.25}$	$^{+0.25}_{-0.23}$
μ_F^{ZZ}	$1.44^{+0.38}_{-0.34}$	$^{+0.29}_{-0.25}$
μ_F^{WW}	$1.00^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$
$\mu_F^{\tau\tau}$	$1.10^{+0.61}_{-0.58}$	$^{+0.56}_{-0.53}$
μ_F^{bb}	$1.09^{+0.93}_{-0.89}$	$^{+0.91}_{-0.86}$

- Indirect probe - Assuming that the observed scalar is one of physical scalar. The observed signal strength (μ) should be consistent with theoretical prediction.
- Let us assume that the scalar is decaying to diphoton, then

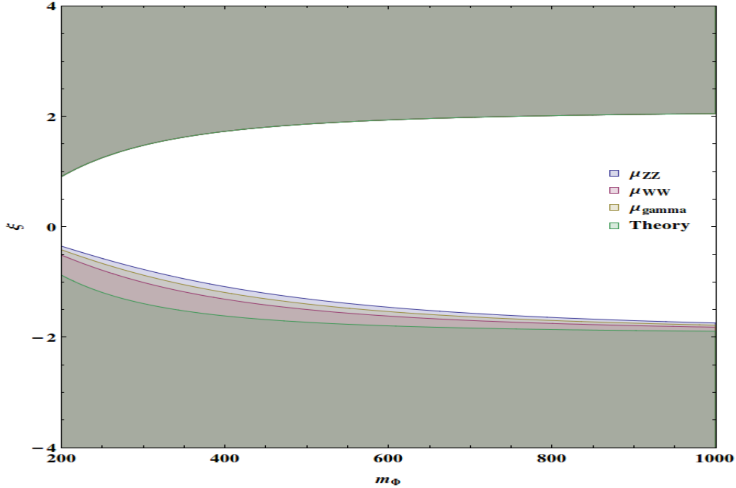
$$\mu_{ggF}^{\gamma\gamma} - \Delta\mu < \frac{\sigma(pp \to H \to \gamma\gamma)}{\sigma(pp \to H_{SM}^{125} \to \gamma\gamma)}$$

$$< \mu_{ggF}^{\gamma\gamma} + \Delta\mu$$

- This will constrain the theoretical space formed by ξ, m_R and Λ_φ.

Constraint from signal strength [shaded regions are excluded]

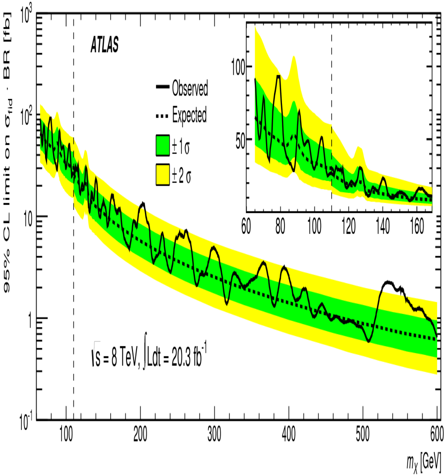
$\Lambda_\varphi = 3$ TeV



Absence of new physics signal

- There exist certain part of theory space where the production cross section of the second scalar is large.
- This implies that till now LHC had sufficient luminosity to observe the scalar.
- Since, no direct evidence of new scalar has been observed at the LHC searches $\rightarrow$ if warped extra dimension exist those points on the theory space are ruled out.

Bounds from null new physics signal

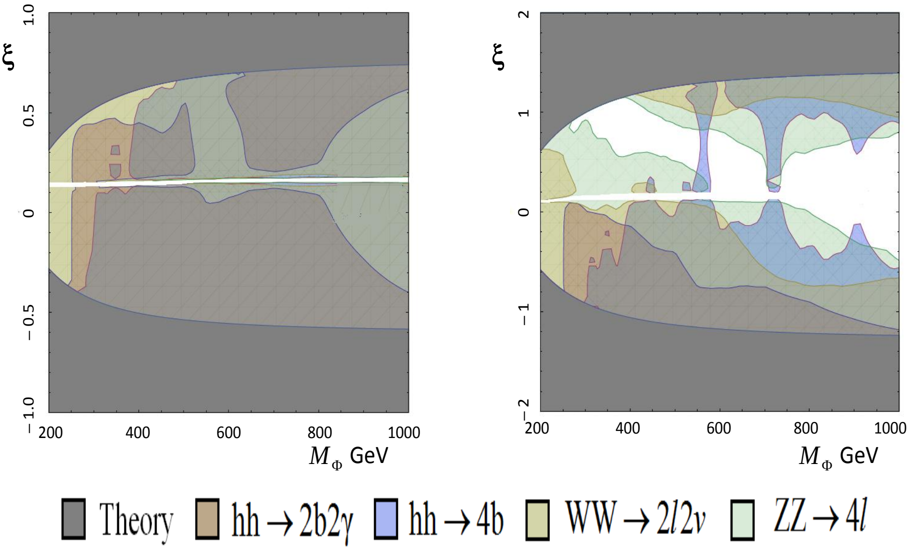


- Let us assume for a given mixing (ξ), vev (Λ_φ) and at a given mass of Mixed radion ($m_R = 300$ GeV (say)), $\sigma(pp > R > \gamma\gamma) \ > \ 10 fb$.

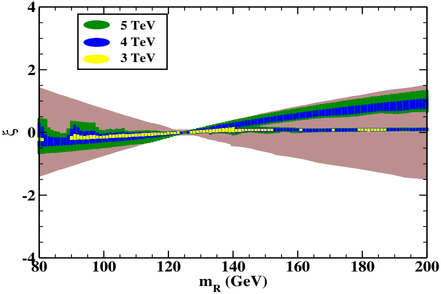
- As 10 fb has already been probed by LHC, if there existed Mixed Radion having 300 GeV mass with that particular ξ and λ_φ, it would have been already observed.

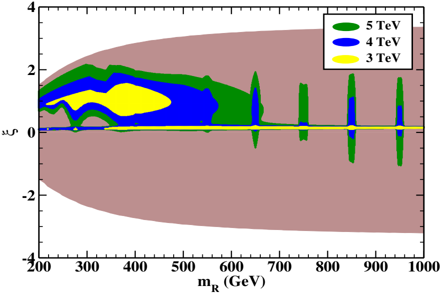
- Null observation implies that $\sigma(pp \ > \ R \ > \ \gamma\gamma/ \ ZZ/ \ WW^*/ \ hh)$ should be less than probed cross sections.

Bounds from heavy Higgs searches



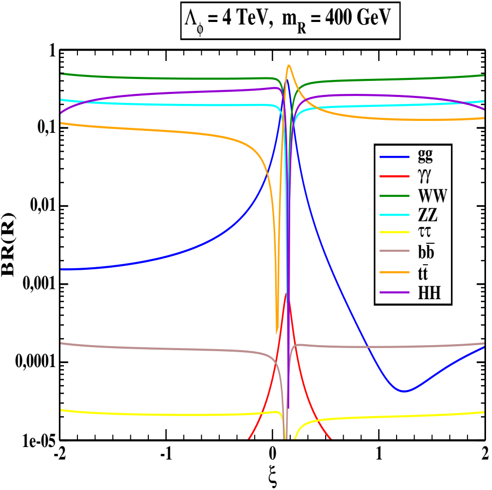
Allowed scenario





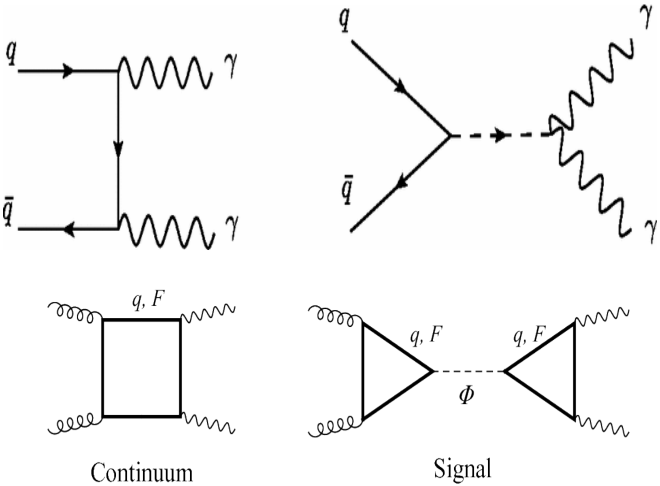
- A narrow strip near $|\xi| \sim 0.16$ is allowed for all values of m_R and all Λ_φ.
- Area of allowed theory space increases with increase in Λ_φ.

Observing the Mixed radion at LHC



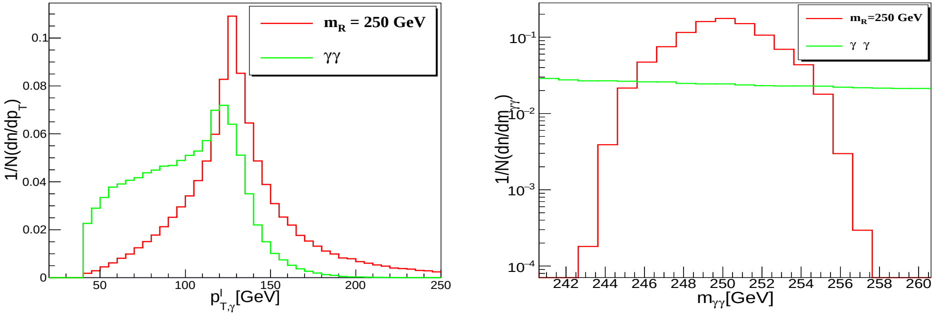
- Coupling of the mixed radion to massive mode vanishes at $|\xi| \sim 0.16$
- If there exist Mixed radion with $\xi = 0.16$, it will be only produced at LHC via gluon fusion and can decay to pair of photons.

Diphoton signal



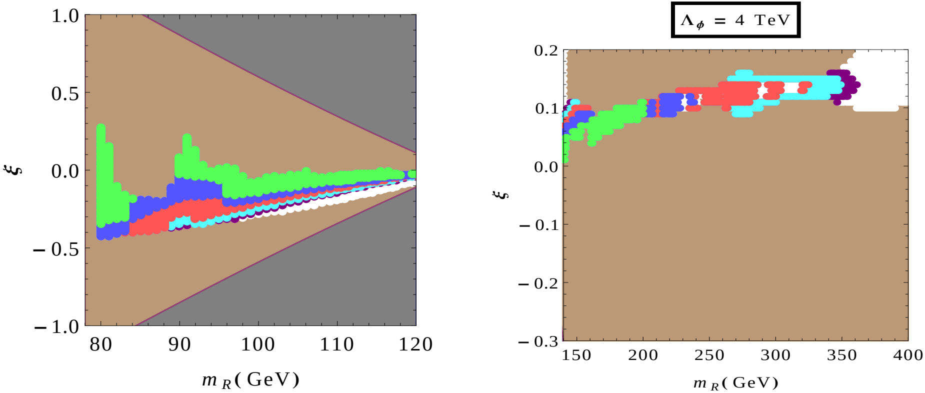
- To observe the signal, it is important to find techniques that will suppress the SM backgrounds.

Signal-Background analysis

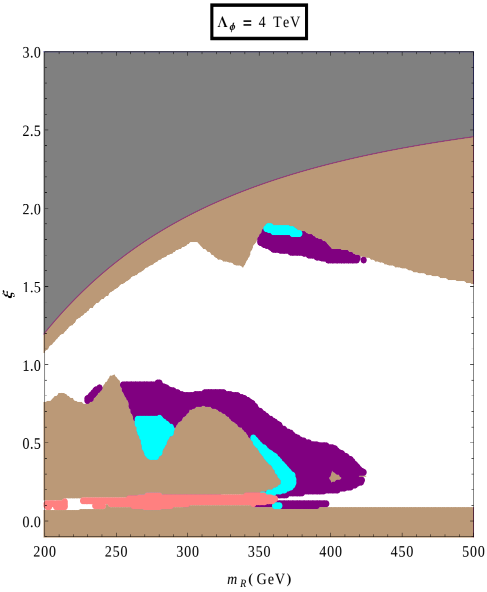


- We found that selecting photons with minimum transverse momentum (p_T) and demanding that they reconstruct the Mixed radion ($m_R - 5.0$ GeV $< \sqrt{(p_1+p_2)^2} < m_R + 5.0$ GeV) will control SM backgrounds.

When can we observe it



- Green region can be observed with 50 fb^{-1} integrated luminosity
- Blue region can be observed with 150 fb^{-1} - by 2017
- Red region can be observed with 300 fb^{-1} - by 2023
- Cyan region can be observed with 1000 fb^{-1} - by 2030
- White region can not be probed, brown region ruled out by 8 TeV and gray region theoretically disallowed.

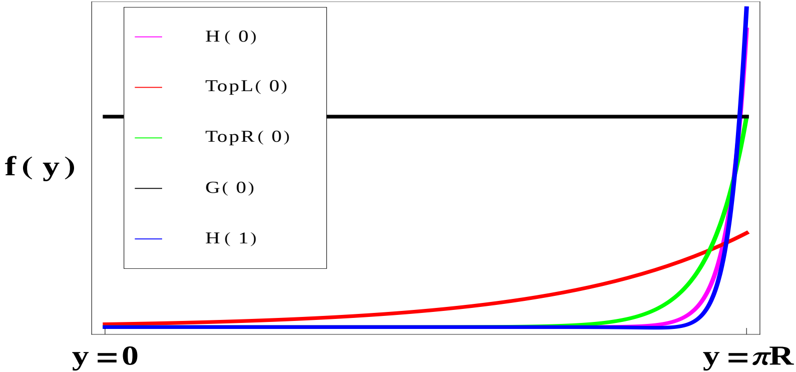


Other channels

- We consider $pp \rightarrow R \rightarrow ZZ$ where Z decays to pair of leptons.
- Cyan region can be observed at 1000 fb^{-1} and Violet region can be observed at 3000 fb^{-1}.
- Beyond 450 GeV, gluon fusion production cross section decreases and LHC looses sensitivity.

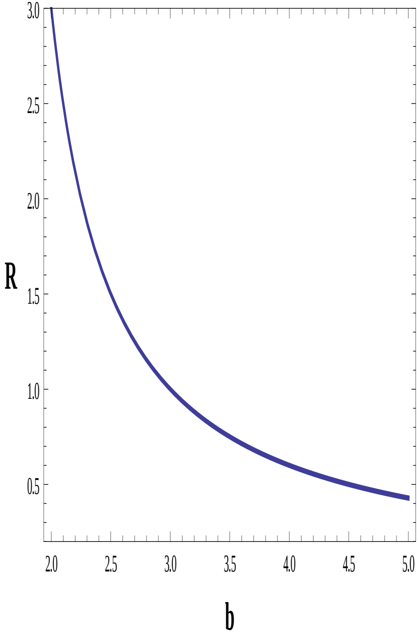
If warped extra dimension exist, then we should also observe
higher Kaluza-Klein mode of SM particle along with the radion

Kaluza Klein mode



- The KK modes have enhanced coupling to SM particles on the TeV brane i.e Top and Higgs.

- The mass of the KK gauge boson is given by $m_n = (n - \frac{1}{4})\pi k e^{-k\pi R} \sim TeV > 3$ TeV - Electroweak precision bound.



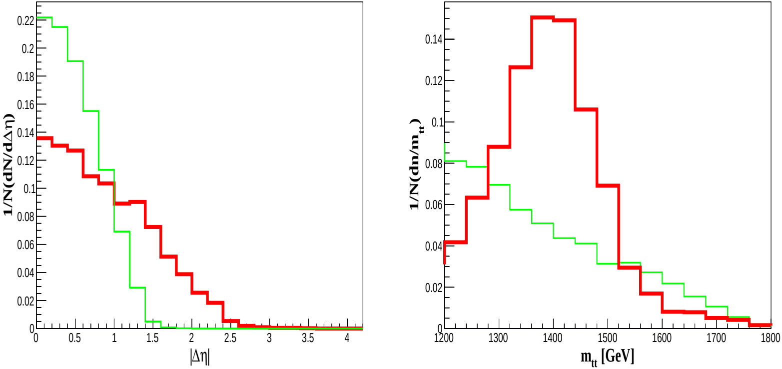
Bulk Higgs

- The mass of the nth KK mode of H is given by $m_n = (n + 2(b-2))\frac{\pi}{4} k e^{-k\pi R}$ where b is the brane mass term.
- When $b \sim 2$, mass of the first KK mode (H_1) lies within 1 - 2 TeV -possible to observe at LHC
- H_1 couples dominantly to pair of top quarks - $f_0^t f_0^t f_1^H \sim 1$
- Due to flat profile of gauge bosons, H_1 decay to VV^* is suppressed - Orthogonality of KK modes

H_1 at LHC

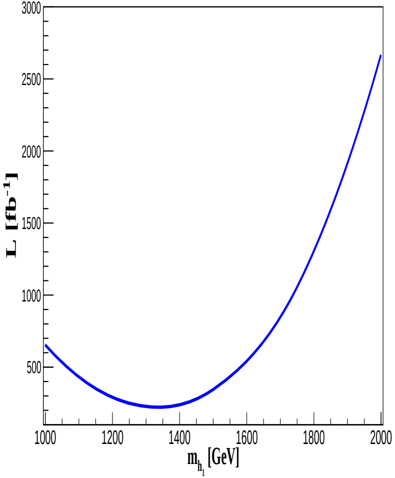
- At LHC, H_1 can be produced via gluon fusion and it will dominantly decay to pair of tops.
- Leptonic decay of top quarks will accompany neutrino and will be difficult to reconstruct.
- We select events with two tops that are reconstructed from hadronic decay of W.
- To suppress SM $t\bar{t}$ background we used further kinematic variables

Selection Criteria



- H_1 is produced at rest, reconstructed tops are separated by large angle $\Delta\eta > 1.2$
- We select events with invariant mass lying within 100 GeV centered around M_{H_1} - few $t\bar{t}$ background survives.

Discovery prospects



- $1.2\ TeV < m_{H1} < 1.6\ TeV$ can be discovered with $300 fb^{-1}$ i.e by 2023
- Beyond 2 TeV, gluon fusion cross section decreases and LHC loses its sensitivity to observe such scalar.

An excess has been seen at $t\bar{t}$ channel -

Does it conclusively imply H_1? ..or hint of warped extra dimension

It can come from supersymmetric (MSSM) or two Higgs doublet model as well

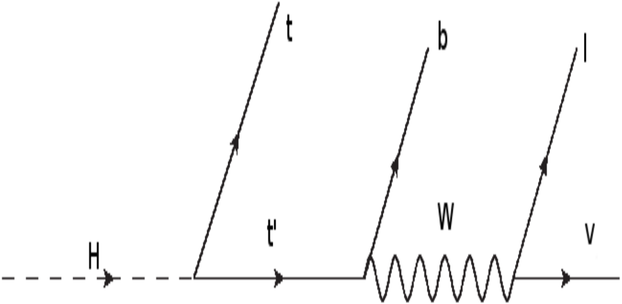
Is there any way to discriminate Kaluza-Klein excitations from a 'non warped-like' scalars??

-UM and A. Iyer, hep-ph-1609.06502

A different approach

- Fermions are present in the bulk and have KK modes
- The $n = 1$ KK top is close to TeV brane and can be lighter than TeV.
- Thus, $H_1 \rightarrow tt_1$ is possible.
- In minimal version of other models, $H_1 \rightarrow tt$ is only possible.
- Segregate models based on presence of just heavy scalar Type A and heavy scalar along with top partner (or a heavy top) Type B.
- How to distinguish Type A from type B?

$H_1 \to tt_2$



- Assume the production of heavy scalar H_1 via gluon fusion and it's decay to t t_2.

- The most general decay of t_2 is
  - BR $(t_2 \to bW) = 50\%$
  - BR $(t_2 \to tZ) = 25\%$
  - BR $(t_2 \to th) = 25\%$

Cascade Topology

The topology can in general be represented by

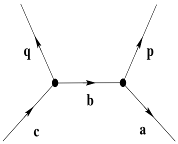
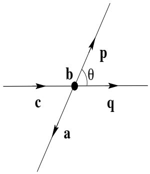


Figure E.1: *Two successive two-body decays are depicted. Arrows indicate particles' directions of motion.*

In the rest frame of b becomes



- In the rest frame of b,

$$\mathbf{P}_a^2 = \lambda[m_a, m_p, m_b]$$

  where $\lambda[x, y, z] \ = \ x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$

- Invariant mass of p-q system is given by

$$m_{pq}^2 = m_p^2 + m_q^2 + 2(E_p E_q - \mathbf{P_p}.\mathbf{P_q} \cos\theta)$$

- $m_{pq,min(max)}$ takes place when $\cos\theta_{pq} \ = \ \pm 1$.

$H_1 \to tt_2 \to tbW$

- The invariant mass of top and bottom is given by

$$m_{tb}^2 = m_t^2 + m_b^2 + 2(E_t E_b - \mathbf{P_t}.\mathbf{P_b})$$

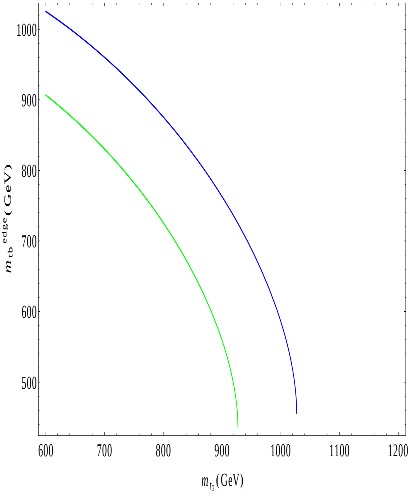
- The magnitude of the transverse momenta of the top quarks in the rest frame of t_2 is given by

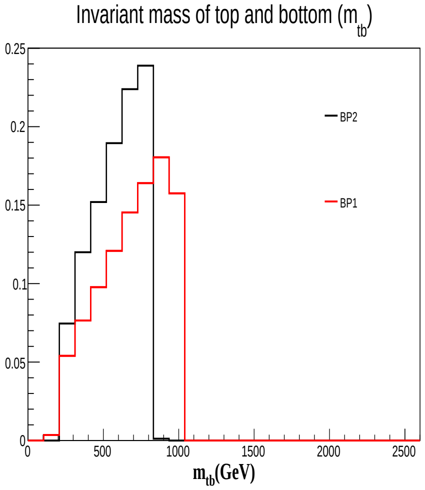
$$p_{t_a}^2 = \frac{m_t^4 + m_{t_2}^4 + m_{H_1}^4 - 2\left(m_t^2 m_{t_2}^2 + m_t^2 m_H^2 + m_{t_2}^2 m_{H_1}^2\right)}{4m_{t_2}^2}$$

$$p_{t_b}^2 = \frac{m_t^4 + m_{t_2}^4 + m_h^4 - 2\left(m_t^2 m_{t_2}^2 + m_t^2 m_h^2 + m_{t_2}^2 m_h^2\right)}{4m_{t_2}^2}$$

where $t_{a,b}$ are the two tops for the event and $E_i^2 = m_i^2 + p_i^2$.

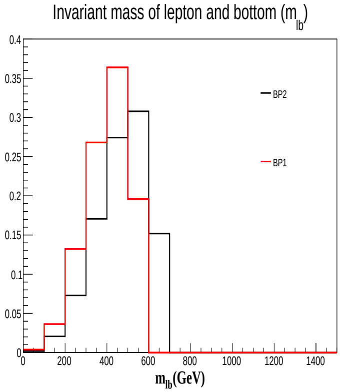
First Kinematic edge





- Maximum of m_{tb} occurs when top and bottom are back to back in the rest frame of t_2-called kinematic edge and is a function of m_{H_1} and m_{t_2}

Second Kinematic edge

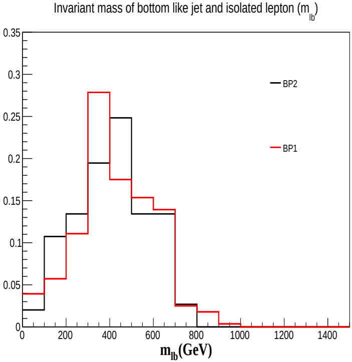


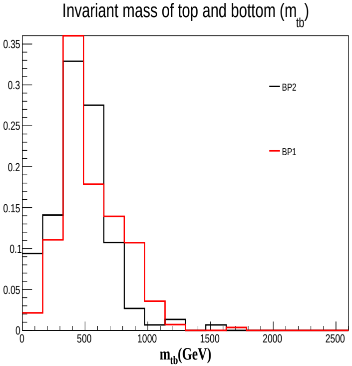
- Maximum of m_{bl} occurs at m_{t_2}.
- Presence of edge in m_{tb} as well as m_{bl} will pin down models consisting heavy scalar along with top partners.
- These kinematic edges will give us an idea of the new physics scale.
- Once an edge has been observed at lower luminosiy, one can follow search strategy to observe these particles.

Benchmark Points

- We are considering two benchmark points,
  - $BP1: \ m_{H_1} \ = \ 1.2 \, TeV, \ m_{t_2} \ = 600$ GeV
  - $BP2: \ m_{H_1} \ = \ 1.1 \, TeV, \ m_{t_2} \ = 700$ GeV.
- Due to s-channel suppression, gluon fusion production cross section decreases as $m_{H_1} \ > \ 1.5 TeV$
- t_2 mass below 600 GeV is ruled out by LHC searches.
- As t_2 mass increases, $BR(H_1 \rightarrow t_2 t)$ gets suppressed.

m_{tb} and m_{bl} edge





	BP1(92 fb)			
BP	Edge^{obs}	Edge$^{exp.}$	Efficiency	Luminosity(fb^{-1})
$1(m_{tb})$	$\sim$1000	1025	0.005	1100
$2(m_{tb})$	$\sim$800	830	0.003	1300

Summary

- Present and future runs of LHC provides immense scope for discovering new particles.
- There are several possible candidates (coming from plethoras of BSM physics) mimicking such discovery.
- It is also important to provide techniques which will lead us towards a particular BSM scenario.
- Edges of invariant mass also gives us an idea of type as well as scale of new physics.
- A Lot Can Happen Over LHC-Stay Tuned!

Future Work

- Probing the existing deviations in a model independent way - Higher dimensional operators
- Searching a light scalar in general two Higgs doublet model
- Charecterizing new physics using leptons along with jets

Thank You