KK Higgs produced in association with a top quark pair in the bulk RS Model

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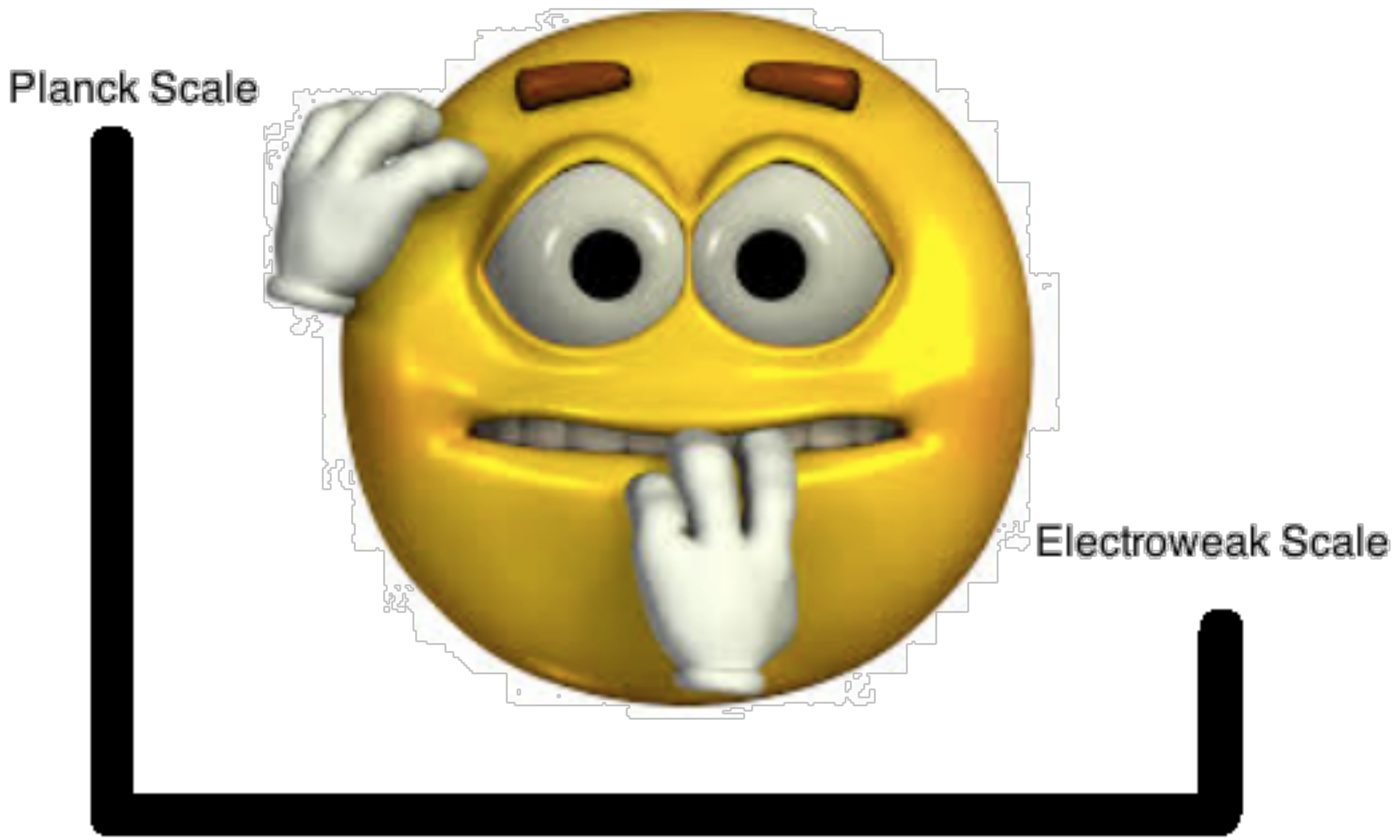
Outline

- Hierarchy problem
- Solution in WED (Warped Extra Dimensions)
- Randall-Sundrum Model
- Bulk Higgs (H1)
- Search for [H1 t t~] channel
- Strategy for detection at the LHC
- Summary

Hierarchy Problem



The huge difference between the Planck Scale (~10^16 TeV) and the Weak Scale (~1 TeV) is one of the ways to express the Hierarchy Problem of the Standard Model.

Randall Sundrum Model

Randall, Sundrum'99

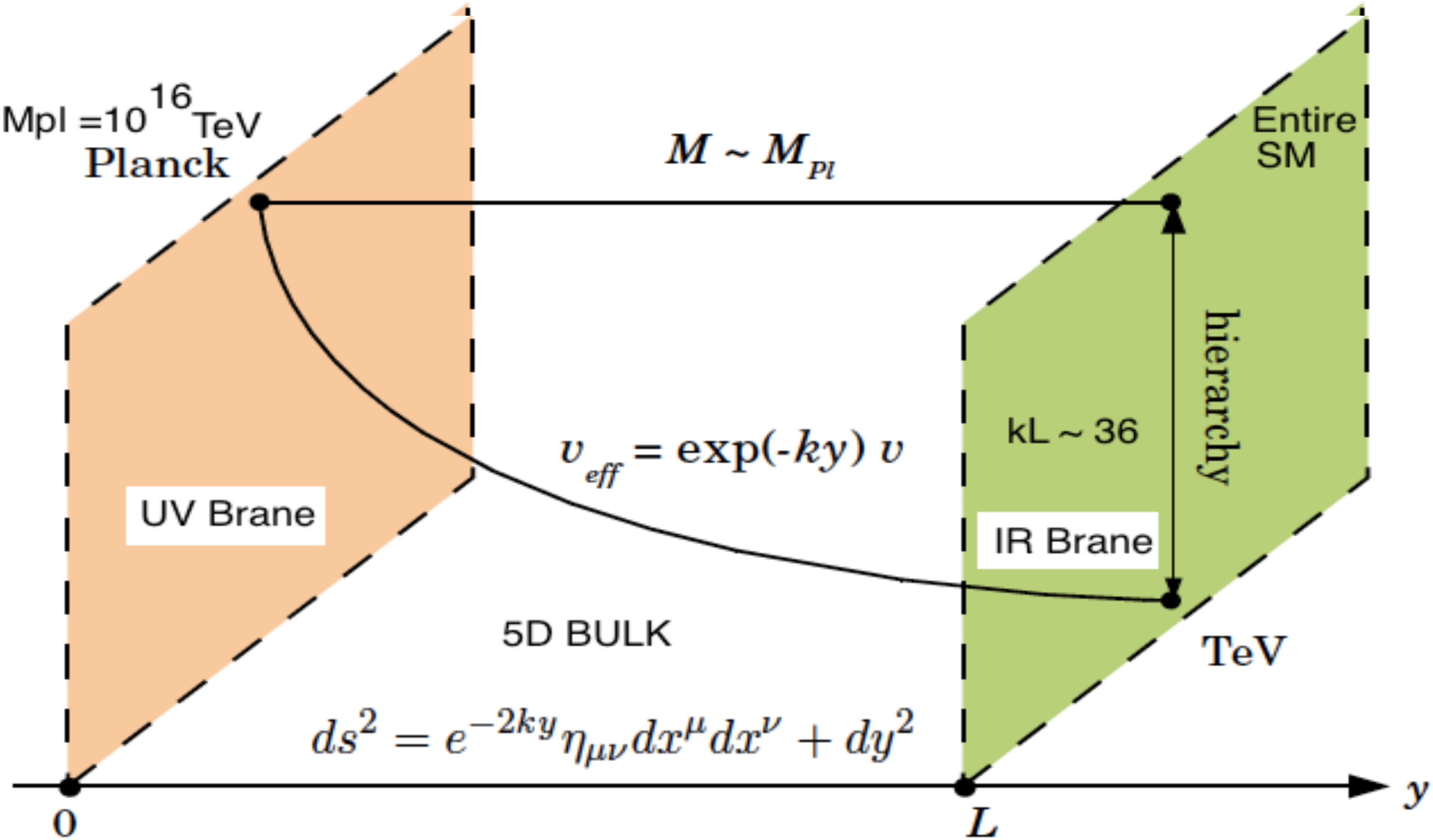


Image @ Gabella'06

Bulk RS Model

Gherghetta'10

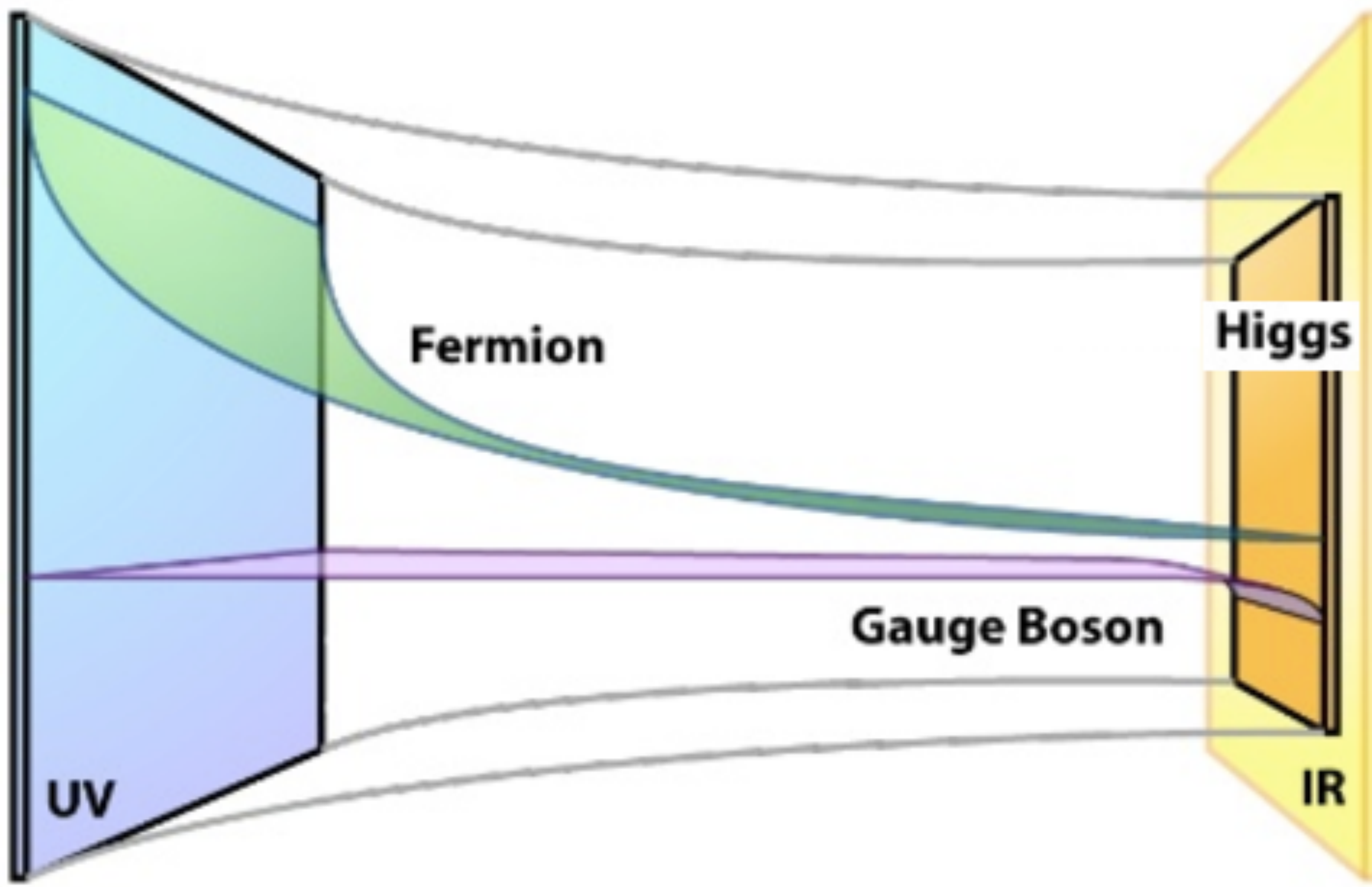


Image @ [EricWilliams]

Bulk RS Models

- With a custodial symmetry

A custodial symmetry (SU(3)xSU(2)L x SU(2)R U(1)y) in the bulk takes care of the T parameter. EW precision constrains yield bounds on lowest KK mass ~ 3TeV

(Agashe, Delgado, May, Sundrum'03)

- With a deformed metric

Introduce an additional scalar field generating a singularity. Due to this warping of the fifth dimension is strongly modified near the IR brane. EW precision constrains yield bounds on lowest KK mass ~ 1TeV

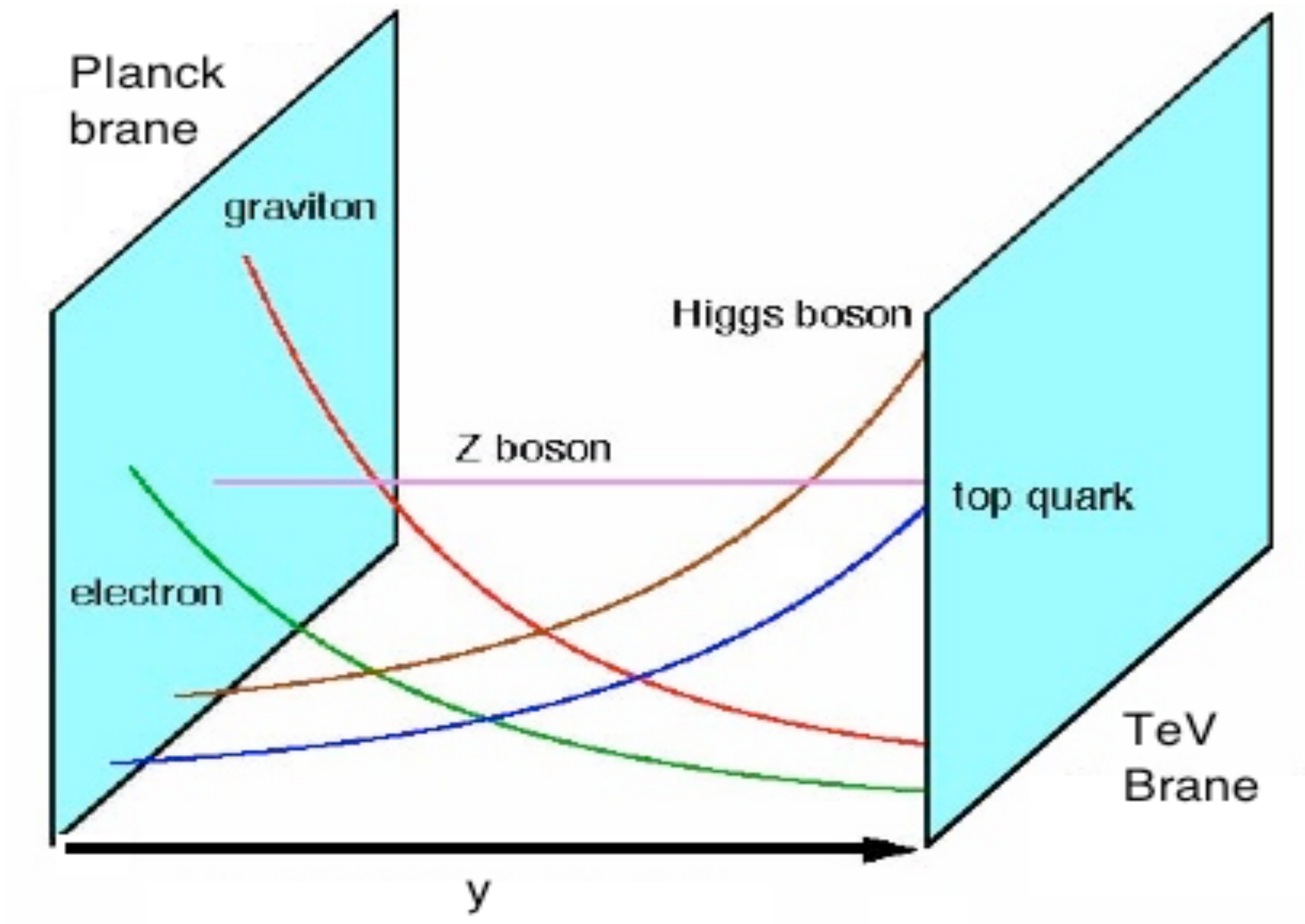
(Cabrer,Gersdorff, Quiros'11)

Why Bulk Higgs ?

Quiros'11;Archer,Carena,Carmona,Neubert'15

- All SM Particles other than Higgs in the Bulk then why not Higgs ?
- Hierarchy problem solution demands b>=2
- Higgs can be inside the bulk very close to IR brane
- Reduces the overlap of KK gauge bosons -> lower Mass scale !
- Relaxes Electroweak Precision constrains
- Offers some explanation to small scale neutrino masses
- Consistent with extensions that include Dark Matter candidate

Bulk RS Model with a Bulk Higgs



Bulk Higgs

Mahmoudi, Maitra, Manglani, Sridhar'16

$$S = \int d^4x dy \sqrt{-g}(D_M \Phi D^M \Phi - m^2 \Phi^\dagger \Phi + 2 \sum_{j=0,1} (-1)^j \lambda^j(\Phi) \delta(y - y_j) + L_{yuk}) \ ,$$

where $y_0 \ = \ 0, \ y_1 \ = \ \pi R,$

$$-\lambda^1(\Phi) = -\frac{M_1}{k}|\Phi^\dagger \Phi| + 2\frac{\gamma}{k^2}|\Phi^\dagger \Phi|^2, \quad \lambda^0 = \frac{M_0}{k}\Phi^\dagger \Phi \text{ and } \ m^2 \ = ak^2.$$

$$\Phi(x,y) = \frac{1}{\sqrt{2\pi R}} \begin{bmatrix} 0 \\ (v_{\rm SM} + h_0(x)) f_0^h(y) + h_n(x) f_n^h(y) \end{bmatrix} \ ,$$

where

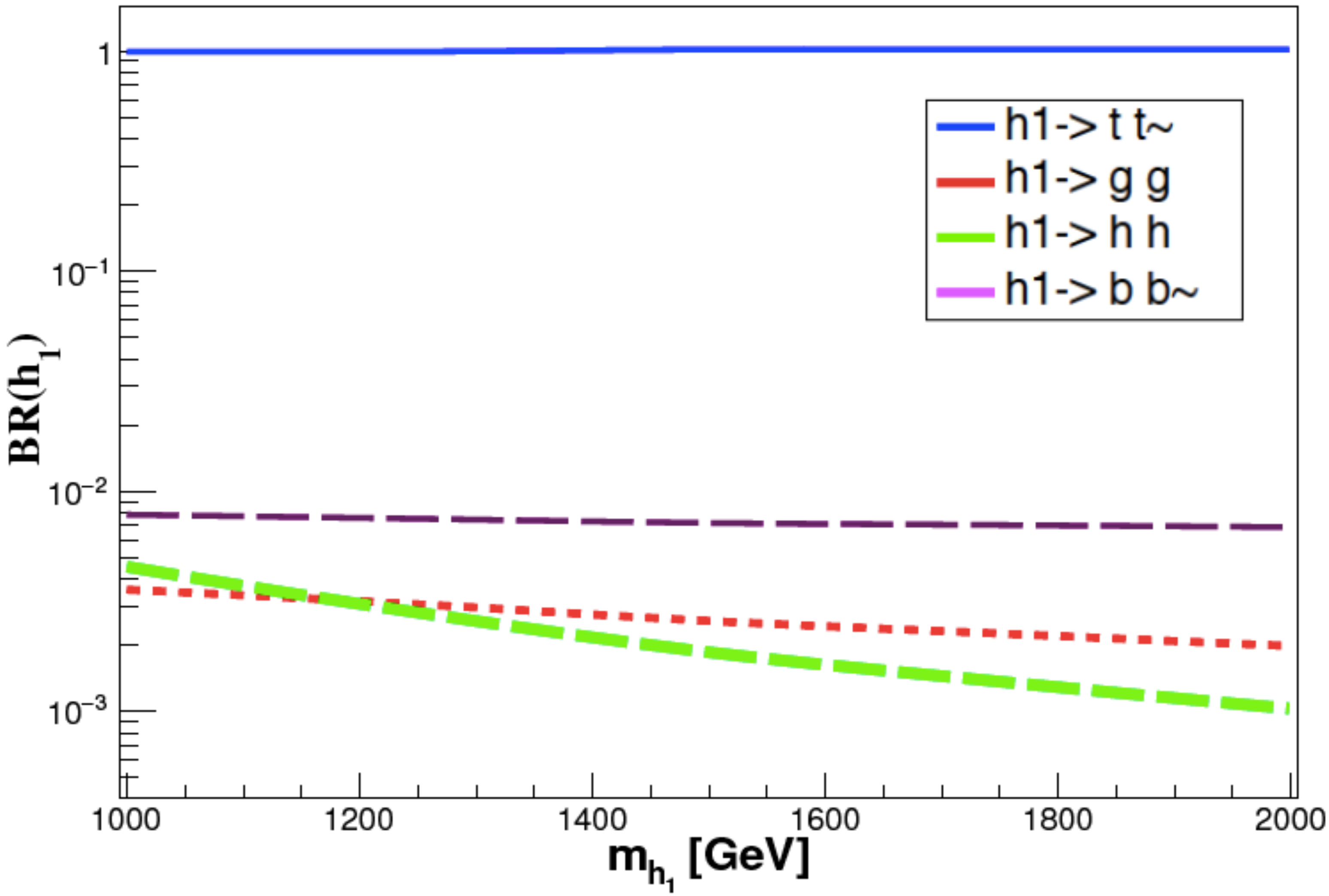
$$f_0^h \ = \ \sqrt{\frac{(2(b-1)k\pi R)}{(e^{2(b-1)kR\pi} - 1)}} e^{(b-1)ky} \text{ and } b \ = \ 2 + \sqrt{4 + a}.$$

Similarly, the bulk equation of motion of h_1 gives us the profile

$$f_1^h \ = \ 1.85\sqrt{kR\pi} e^{-k(R\pi - y)} (J_{b-2}(\frac{m_1 e^{ky}}{k}) + 0.36 Y_{b-2}(\frac{m_1 e^{ky}}{k})) \ ,$$

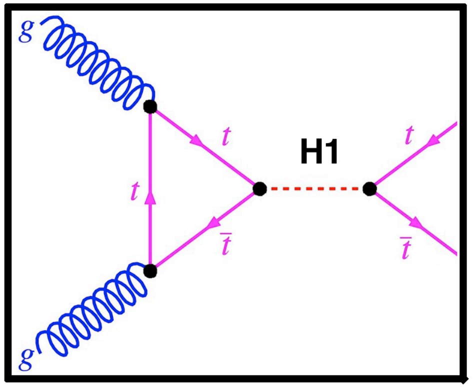
having mass given by $m_1 \ = \ (1 + 2(b-2))\frac{\pi}{4} k e^{-kR\pi}$.

Branching Ratios of h1

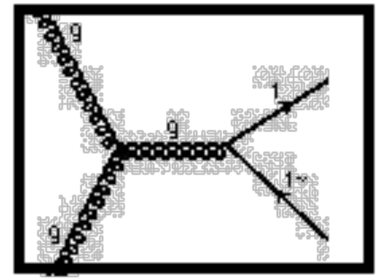


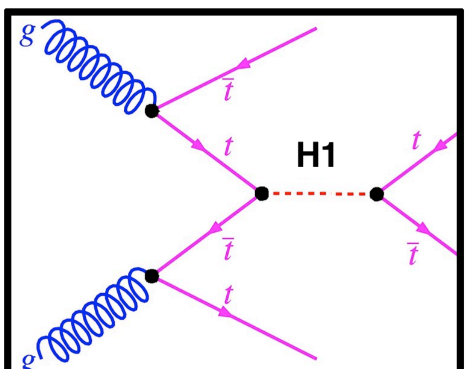
Prominent search channels for H1

M_{H_1} = 1 TeV (@13 TeV)

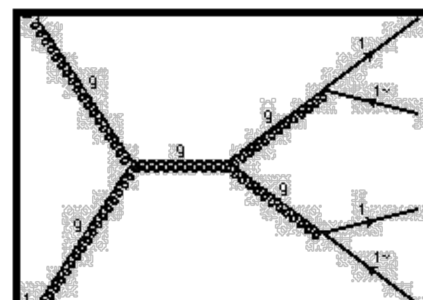


1. Signal
   gg->H1 ~ 0.185 pb
   Background
   SM ttbar ~ 800 pb

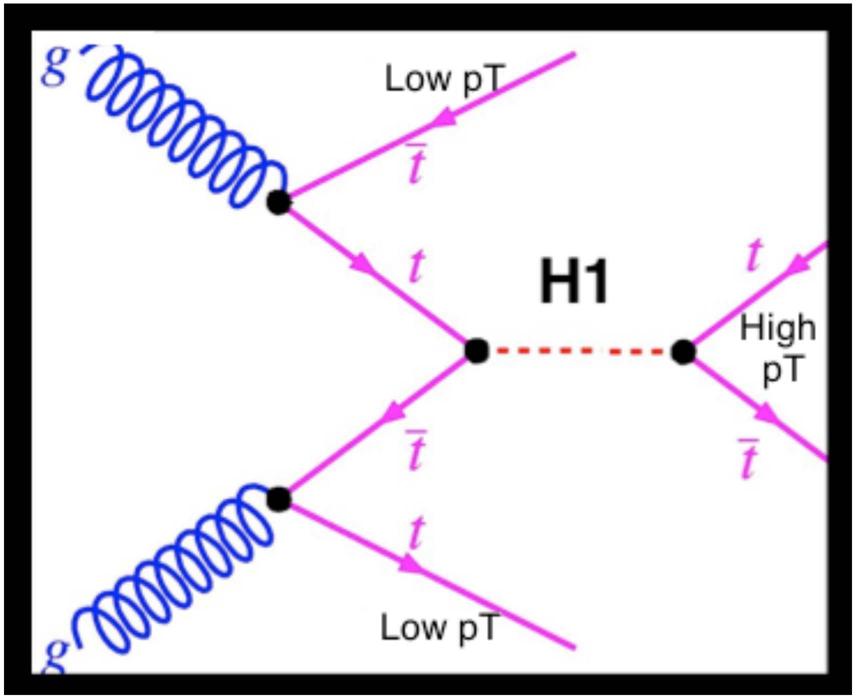




2. Signal
   gg->H1tt ~ 1.26 fb
   Background
   SM four top ~ 10 fb



Strategy for [H1t t~] channel



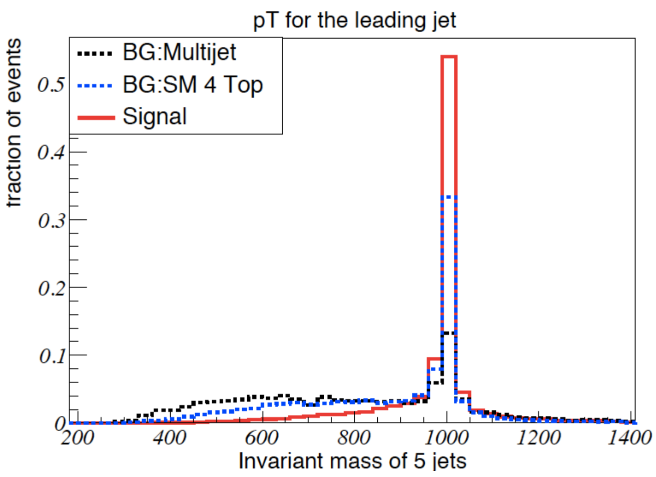
- Hadronic decay of all top quarks (4b + 8n)
  - Our case : Boosted (2b+4n) /(4b+8n)
- One Semileptonic decay (4b+1L+6n+MET)
- Two Semileptonic decay (4b+2L+6n+MET)

Analysis for [H1t t~] channel

Preliminary analysis done for a 1TeV KK Higgs

- We choose 5/6 boosted jets that reconstruct H1 mass.
- Followed by cut on mass window
- Search for isolated leptons(L).
- Cluster remaining particles into jets with lower transverse momentum.

Choice of decay	L /fb 5 sigma	L /fb 3 sigma
L0+2b+4n	2832	1019
L1+2b+2n	1375	495
L2+2b+0n	797	286



Summary

- Bulk RS model with deformed metric predicts bulk

  Higgs mass as low as 800 GeV-1.3 TeV.

- Bulk Higgs has very interesting phenomenology.

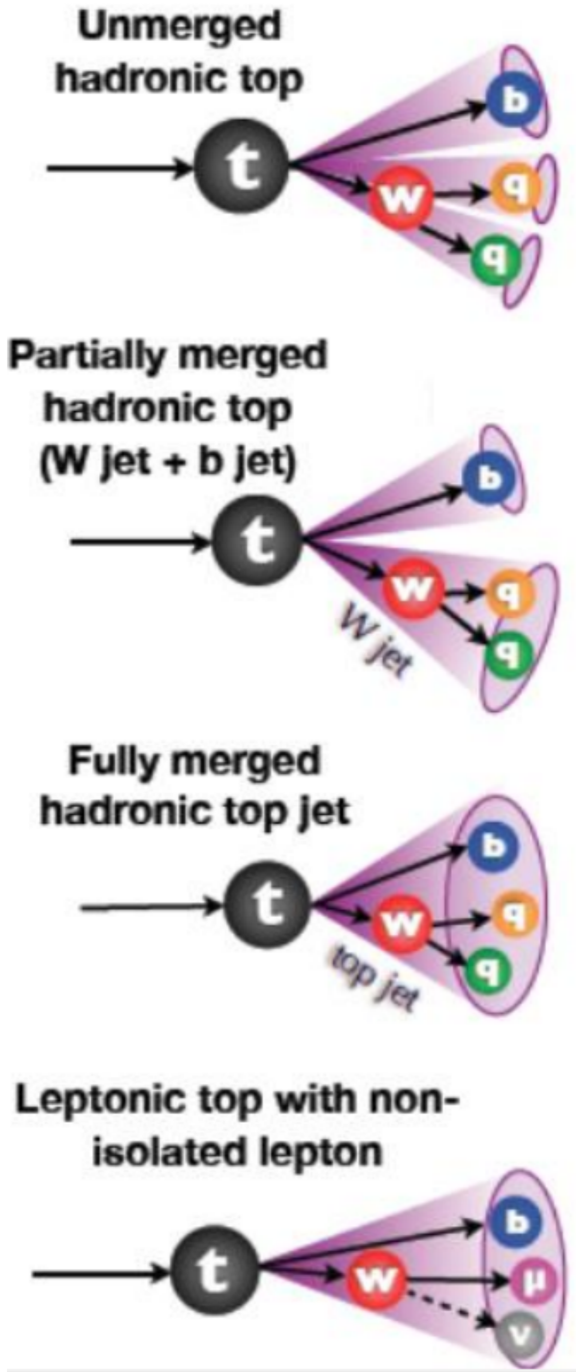
- H_1ttbar has lowest background, interesting to find !

- H_1 can be probed at HL-LHC !

Questions ?

Thank You !

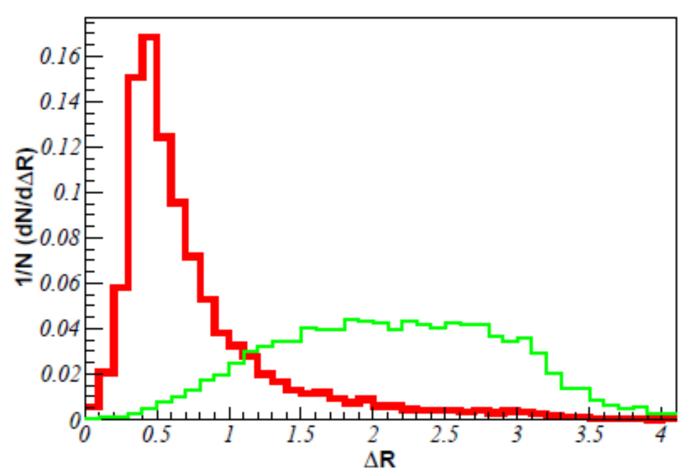
BACK UP SLIDES



Boosted Tops

$$\Delta R = \frac{2\,m}{p_t}$$

- m = mass of decaying particle
- pt = its transverse momentum
- ΔR = separation of its daughters

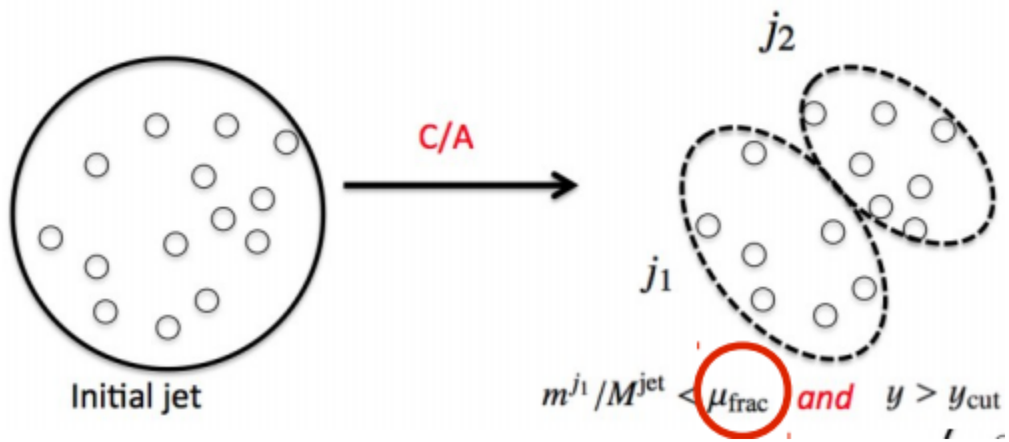


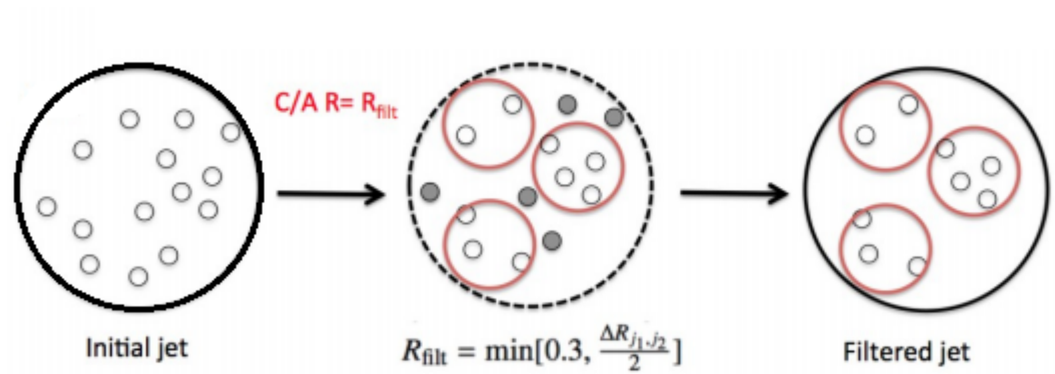
Analysis for [t t~] channel

- Model Files are generated using Feynrules2
- Parton level amplitude using Madgraph5
- Showering is done in Pythia8
- Clustering using CA in Fastjet3
- Signal is enhanced using
  - Using HEPTOPTAGGER
  - cuts on pT of jets
  - Pseudorapidity.

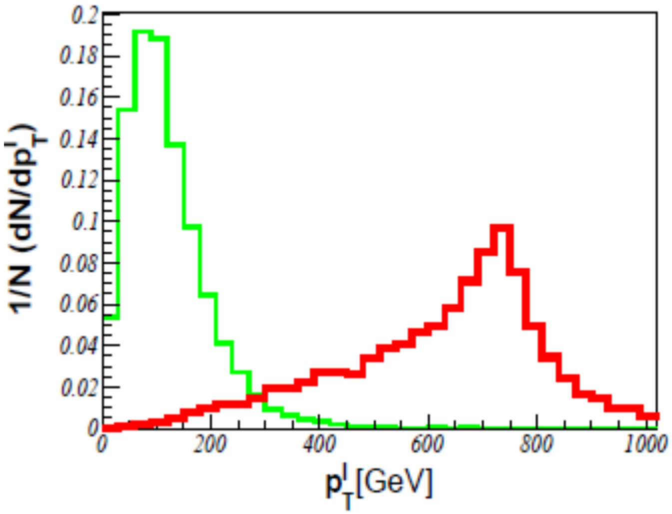
HEPTOPTAGGER

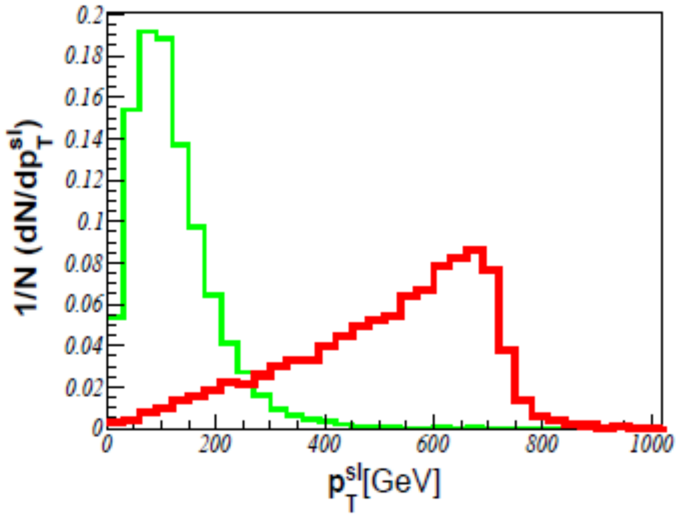
- CA fat jet with R=1.5
- Mass Drop Criterion
  Min mj1 < 0.8 MJ
  Do this till mji< 30GeV
- Filtering
  Three subjets with
  Mj=mt+/- 25
- Top decay kinematics
  Pair wise invariant mass
  Gives W for one pair.

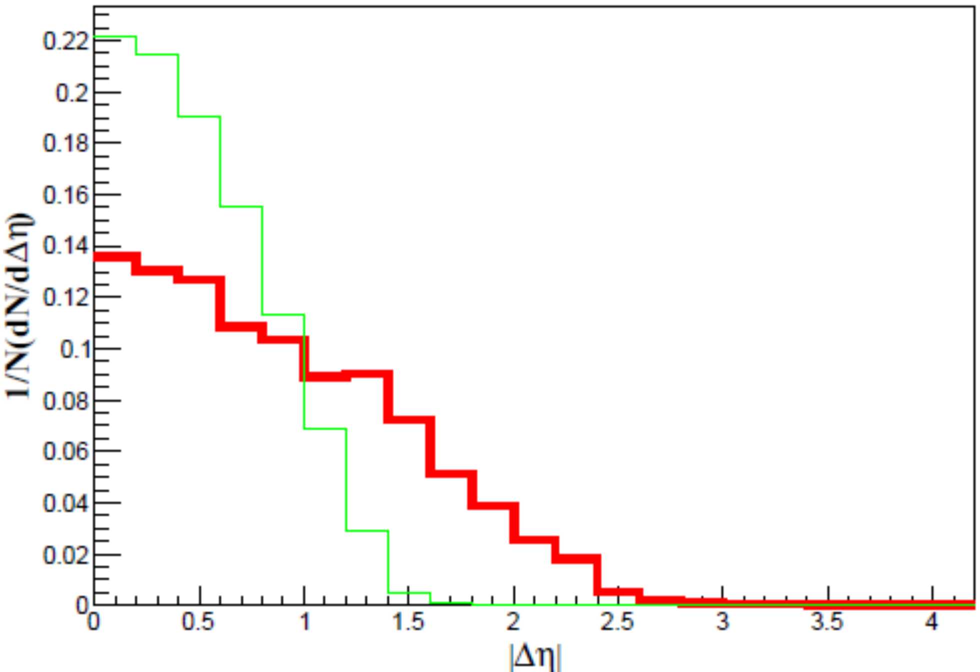




Plots for pT and





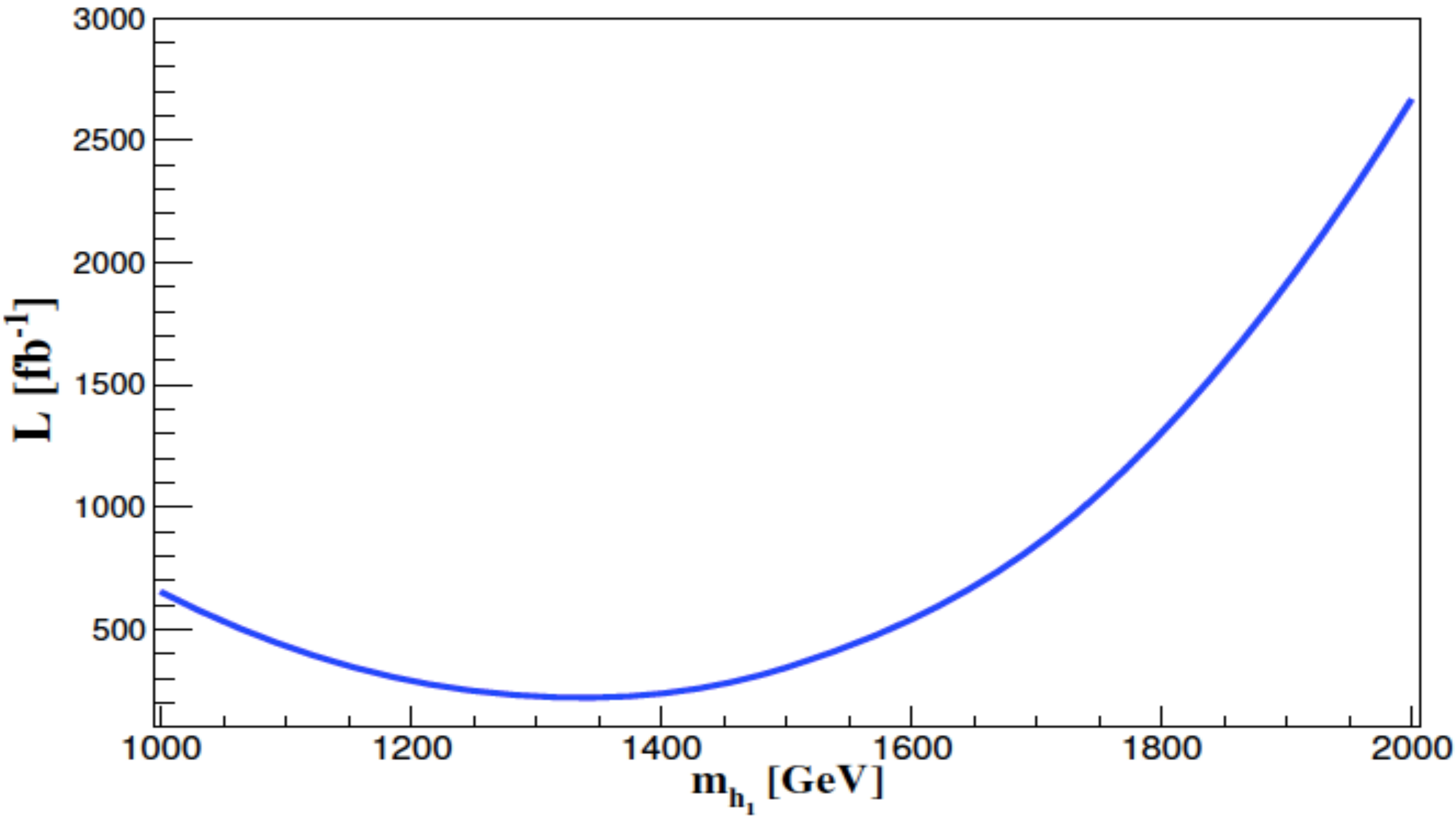


Flow of cuts

Mass (GeV)	Cuts	Signal (fb)	QCD (fb)	$t\bar{t}$ (fb)
1000	2 fat jets ($p_T > 250\,\text{GeV},\ R < 1.5$)	52.36	395183.24	404.80
	2 top-tagged jets	2.64	65.11	27.04
	$p_T^l > 400\,\text{GeV}$ and $p_T^{sl} > 350\,\text{GeV}$	1.43	58.33	26.66
	$\lvert\Delta\eta\rvert > 1.15$	0.063	10.39	1.24
	$900\,\text{GeV} < m_{tt} < 1100\,\text{GeV}$	0.020	–	0.005
1500	2 fat jets ($p_T > 350\,\text{GeV},\ R < 1.5$)	4.05	46390.00	91.50
	2 top-tagged jets	0.24	9.24	5.98
	$\lvert\Delta\eta\rvert > 1.3$	0.06	0.41	0.094
	$1350\,\text{GeV} < m_{tt} < 1550\,\text{GeV}$	0.04	–	0.009

Table 1. Cut flow table for two values of KK Higgs mass.

Results for ttbar channel



Couplings α profile overlaps

5D Field -> Kaluza-Klein tower of 4D fields

$$\Phi(x^\mu, y) = \sum_{n=0}^{\infty} \Phi^{(n)}(x^\mu) f_\Phi^{(n)}(y)$$

Couplings in SM are fit....... $g_4 = g_5 \int_0^{\mathrm{L}} dy \; f_A^{(0)} f_{\mathrm{R}}^{(0)} f_{\mathrm{R}}^{(0)}$

Couplings α Profile overlap $g_{(1)} = g_5 \int_0^{\mathrm{L}} dy \; f_A^{(1)} f_{\mathrm{R}}^{(0)} f_{\mathrm{R}}^{(0)}$

Hierarchy Problem & Extra dimensions

Hierarchy problem of SM

- $M_{Pl}/M_{EWSB} \sim 10^{16}$
- Large difference in scale → high degree of fine-tuning in fermion masses radiative correction (~10^{-34}) to Higgs mass

Large Extra Dimensions, ADD (Arkani-Hamed, Dimopoulos, Dvali) model [*Phys. Lett. B* ***429*** *(1998) 263*].

- SM is constrained in 3+1 dimensions
- Gravity propagates through entire multidimensional space and its strength is diluted -> effective Planck scale is observed

$M_D^{(n_{ED}+2)} \sim \frac{M_{Pl}^2}{R^{n_{ED}}}$, R and n_{ED} is the size and number of ED, respectively

Warped Extra Dimensions, RS (Randall-Sundrum) model [*Phys. Lett.* ***83*** *(1999) 3370 and ibid (1999) 4690*].

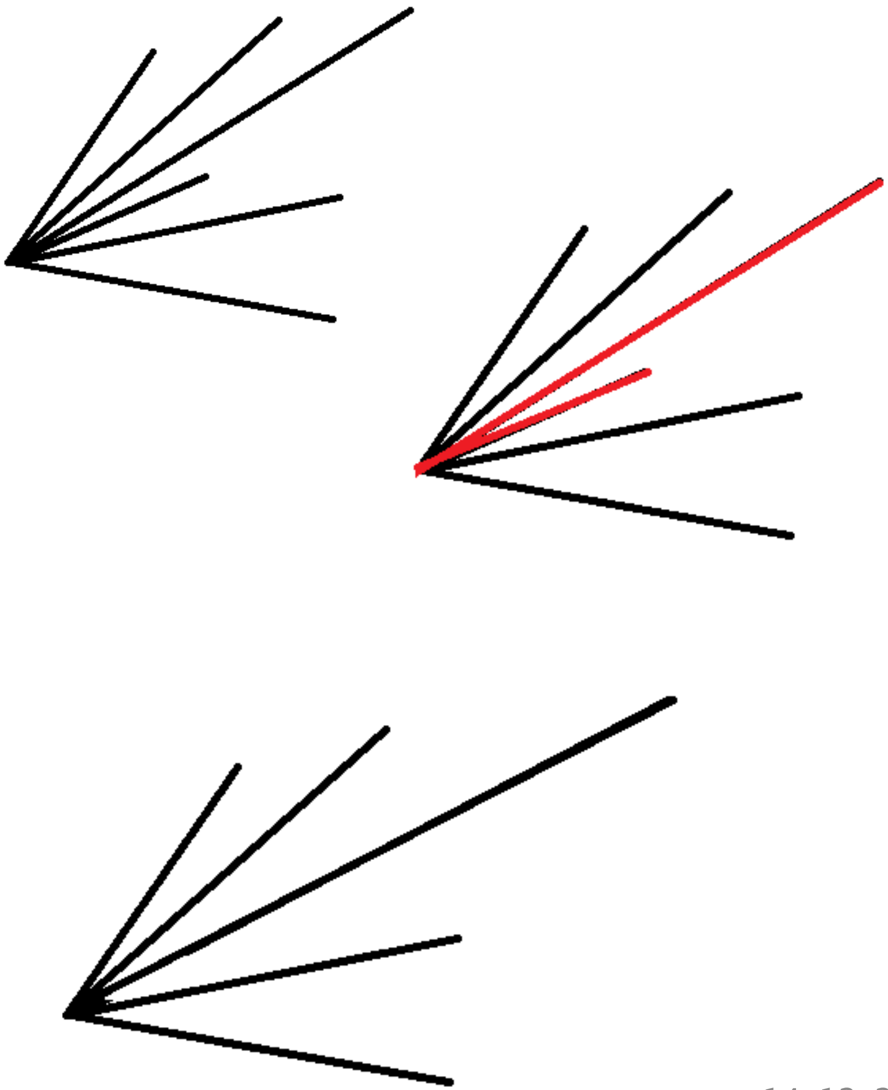
- Extra dimension has finite size with Planck and SM branes at each end
- Gravity is strong at Planck brane but graviton wave function is exponential suppressed when away from Planck brane.
- Effective Planck scale at TeV brane:

$\Lambda_\pi = \overline{M}_{Pl} e^{-kr\pi}$ $\quad kr \sim 10 \rightarrow \Lambda_\pi \sim 1\,TeV$

k: warp factor

r: compactification radius

Sequential Recombination Algorithms



- Find smallest of all dij

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- Recombine and Repeat
- p=1 KT Algorithm
- p=0 Cambridge Aachen
- p=-1 Anti KT Algorithm

Generation of KK modes

scalar field Φ in 5D is

$$S = \int d^5x \, \frac{1}{2}\partial_M \Phi(x^\mu, y)\partial^M \Phi(x^\mu, y).$$

field value is periodic in y coordinates, $\Phi(x^\mu, y + 2\pi R) = \Phi(x^\mu, y)$

Fourier decomposition of Φ along the y direction:

$$\Phi(x^\mu, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=-\infty}^{\infty} \phi^{(n)}(x^\mu) e^{i\frac{n}{R}y}.$$

Reality of Φ implies $\phi^{(-n)} = \phi^{(n)\dagger}$. Plugging the Fourier series expansion into the action,

$$\begin{aligned}
S &= \int d^4x \, dy \, \frac{1}{2\pi R} \sum_{m,n} \left[\frac{1}{2}\partial_\mu \phi^{(m)}(x) e^{i\frac{m}{R}y} \partial^\mu \phi^{(n)} e^{i\frac{n}{R}y} \right. \\
&\qquad \left. - \frac{1}{2}\left(i\frac{m}{R}\right)\phi^{(m)}(x) e^{i\frac{m}{R}y} \left(i\frac{n}{R}\right)\phi^{(n)}(x) e^{i\frac{n}{R}y} \right] \\
&= \int d^4x \sum_{m,n} \left(\int dy \, \frac{1}{2\pi R} e^{i\frac{m+n}{R}y} \right) \frac{1}{2} \left[\partial_\mu \phi^{(m)}(x) \partial^\mu \phi^{(n)}(x) + \frac{mn}{R^2} \phi^{(m)}(x) \phi^{(n)}(x) \right] \\
&= \int d^4x \, \frac{1}{2} \left[\sum_n \partial_\mu \phi^{(-n)} \partial^\mu \phi^{(n)} - \frac{n^2}{R^2} \phi^{(-n)} \phi^{(n)} \right] \\
&= \int d^4x \left\{ \frac{1}{2}\partial_\mu \phi^{(0)} \partial^\mu \phi^{(0)} + \sum_{n=1}^{\infty} \left[\partial_\mu \phi^{(n)\dagger} \partial^\mu \phi^{(n)} - \frac{n^2}{R^2} \phi^{(n)\dagger} \phi^{(n)} \right] \right\}.
\end{aligned}$$

Peskin-Takeuchi parameters S ,T&U.

- vacuum polarization tensors---->

$$\Pi^{\gamma\gamma}_{\mu\nu}(q^2) = -ig_{\mu\nu}q^2 D_{\gamma\gamma}$$
$$\Pi^{\gamma Z}_{\mu\nu}(q^2) = -ig_{\mu\nu}q^2 D_{\gamma Z}$$
$$\Pi^{ZZ}_{\mu\nu}(q^2) = -ig_{\mu\nu}[C_{ZZ} + q^2 D_{ZZ}]$$
$$\Pi^{WW}_{\mu\nu}(q^2) = -ig_{\mu\nu}[C_{WW} + q^2 D_{WW}]$$

- S, T & U

  in terms of

  scalars

(vacuum polarization functions:

the self-energies).

$$S \equiv \frac{4s_W^2 c_W^2}{\alpha}\left(\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2}\right) = \frac{4s_W^2 c_W^2}{\alpha} D_{ZZ}$$

$$T \equiv \frac{1}{\alpha}\left(\frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}\right) = \frac{1}{\alpha}\left(\frac{C_{WW}}{M_W^2} - \frac{C_{ZZ}}{M_Z^2}\right)$$

$$S + U \equiv \frac{4s_W^2}{\alpha}\left(\frac{\Pi_{WW}(M_W^2) - \Pi_{WW}(0)}{M_W^2}\right) = \frac{4s_W^2}{\alpha} D_{WW}$$

Particle Physics of Brane Worlds & Extra Dimensions by Sreerup Raychaudhuri & K. Sridhar