Universal Extra-Dimension at LHC

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Plan

- Hierarchy problem
- Extra-dimensions
  - Flat extra-dimension (ADD and UED model)
  - Warped extra-dimension (RS-model)
- Universal Extra Dimension (UED)
- The Scalar, Fermion, and Gauge particles in the UED model
- Evolution of Gauge Couplings
- Tree level and Radiative Corrected KK-Mass spectra
- Decay modes and Branching ratios of KK-particle
- Collider Signature of UED at LHC
- Conclusion

Standard Model Higgs

SM: $\underbrace{SU(3)_C}_{Strong(g)} \times \underbrace{SU(2)_L \times U(1)_Y}_{E-W(W^{\pm}, Z \text{ and } \gamma)}$

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$$\lambda > 0$$

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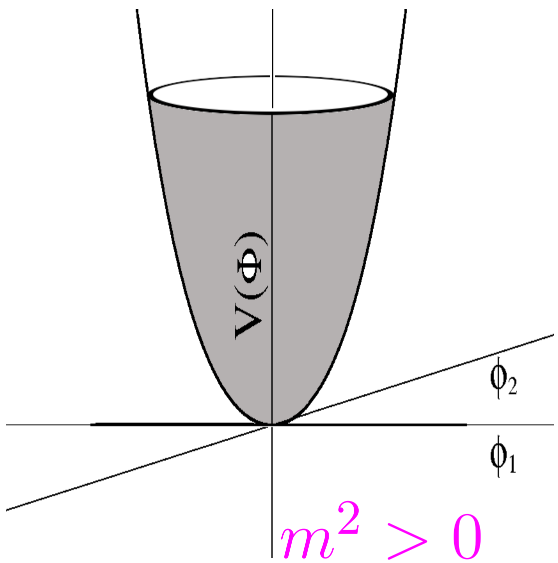

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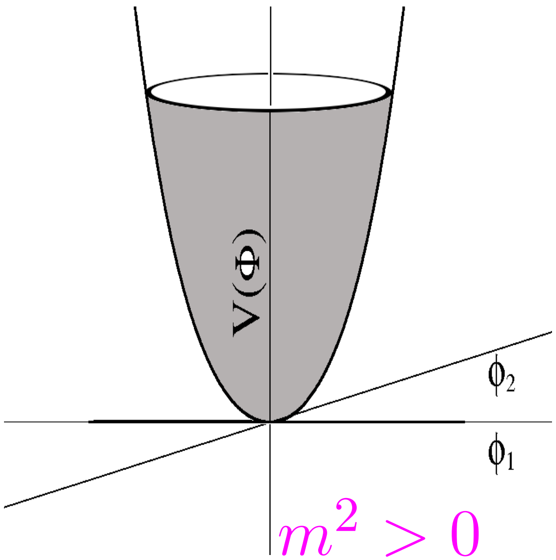

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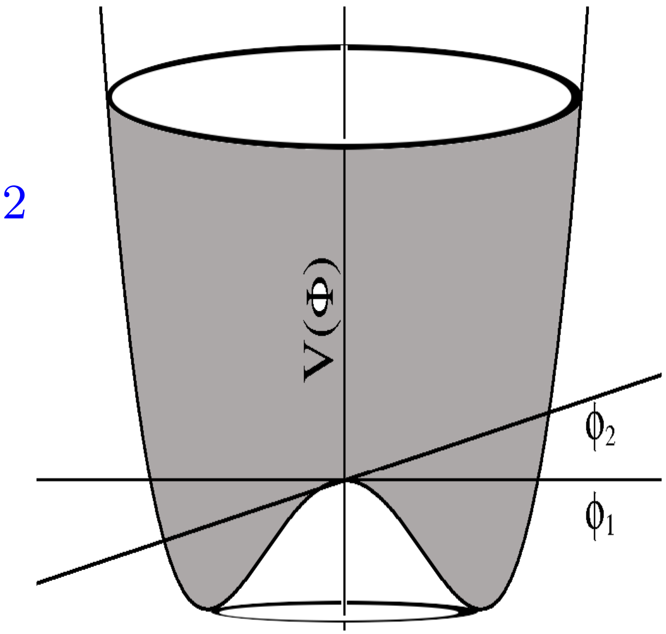
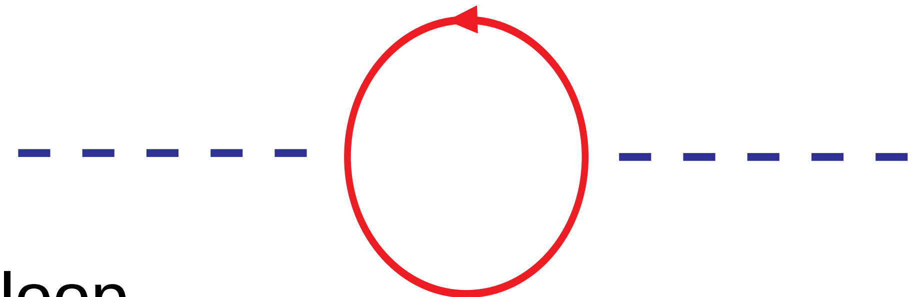


$m^2 < 0 \Rightarrow \langle 0 | \phi^0 | 0 \rangle = v$

$m_H = \sqrt{-2m^2}$, $v = \sqrt{\frac{-m^2}{\lambda}}$ = 246 GeV

Other components of $\Phi \Rightarrow$ *Goldstone bosons*

Hierarchy problem



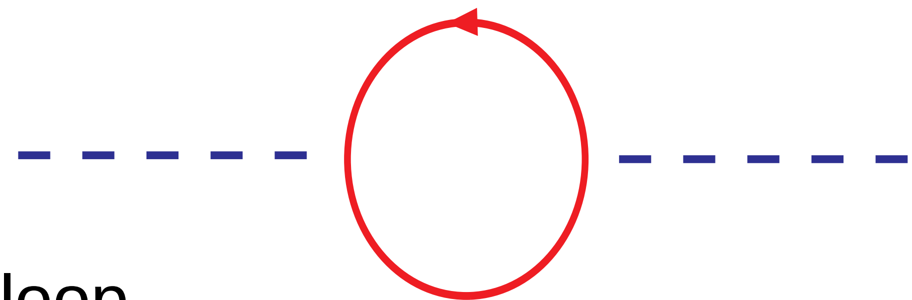
Due to femion loop

$$\Pi_{hh}^{f} = (-1)\int_0^{\Lambda} \frac{d^4k}{(2\pi)^4} Tr\left\{ \left(\frac{-i\lambda_f}{\sqrt{2}}\right) \frac{i}{\not{k}-m_f} \left(\frac{-i\lambda_f}{\sqrt{2}}\right) \frac{i}{\not{p}-\not{k}-m_f} \right\}$$

$$= -\frac{\lambda_f^2}{8\pi^2}\Lambda^2 + \ldots$$

- $m_H^2 = m_{H_0}^2 + \delta m_H^2$
- If $\simeq 10^{16}\ \mathrm{GeV}$, required fine-tuning to 1 part in 10^{26}.

Hierarchy problem and SUSY



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$$= -\frac{\lambda_f^2}{8\pi^2}\Lambda^2 + \ldots$$

- $m_H^2 = m_{H_0}^2 + \delta m_H^2$
- If $\simeq 10^{16}$ GeV, required fine-tuning to 1 part in 10^{26}.
- Due to scalar loop : $\delta \mathrm{m}_H^2 = \frac{\lambda_S}{16\pi^2}\Lambda^2 - \ldots$

$$\boxed{\lambda_S = |\lambda_f|^2} \Rightarrow Supersymmetry$$

Extra Dimensions

- Consider, a massless particle in 5D Cartesian co-ordinate system, and assume that the Lorentz invariance holds.

  $p^2 = 0 = g_{AB}p^A p^B = {p_0}^2 - \vec{p}^2 \pm {p_5}^2$, with $g_{AB} = diag(1, -1-1-1, \pm 1)$

  So, ${p_0}^2 - \vec{p}^2 = p_\mu p^\mu = m^2 = \mp {p_5}^2 \Longrightarrow$ time-like ED: $m^2 = -ve \rightarrow tachyon$

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- free particle moving along x-direction $\Longrightarrow$ *non-compact*

  $\psi = Ae^{ipx} + Be^{-ipx}$, momentum p is not quantized

- particle in a box $\Longrightarrow$ so $V(x) = 0, \; 0 < x < L$

  $=$ infinite elsewhere $\Longrightarrow$ *compact*

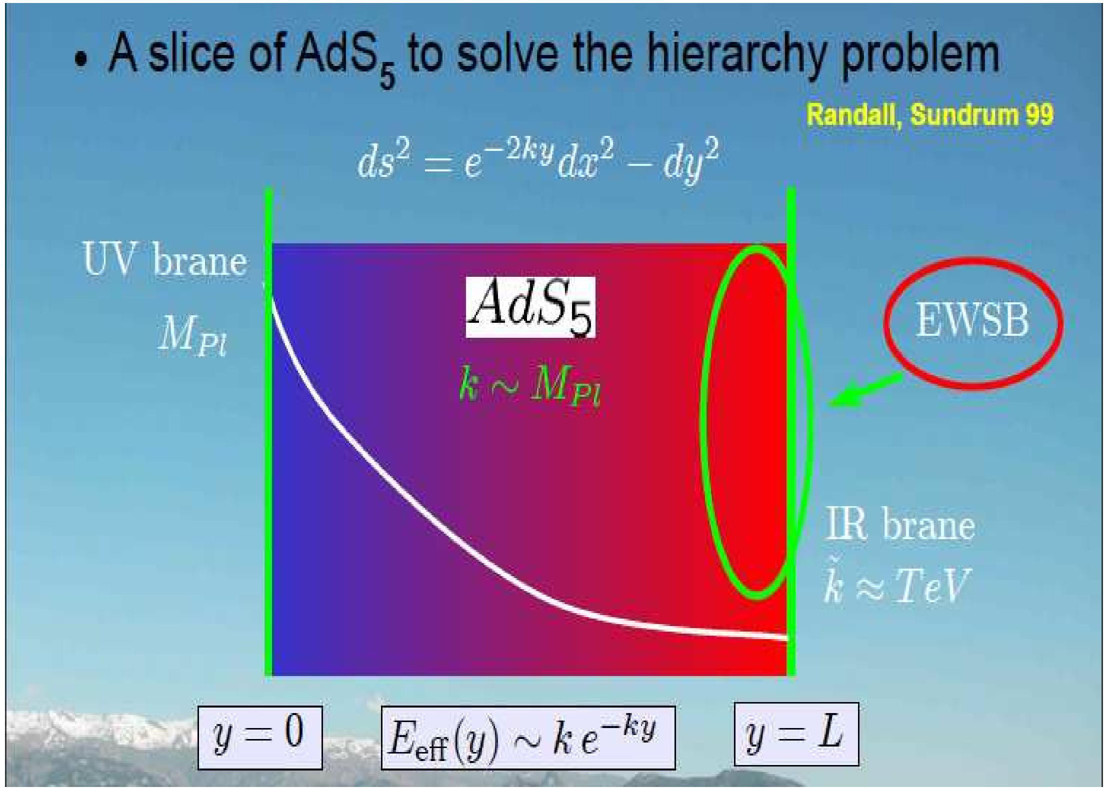
- quantized momenta $p = \frac{n\pi}{L}$

ADD-model

- Consider a D-dimensional spacetime $D = 4 + \delta$
- Space is $factorised$ into $R^4 \times M_\delta$, where M_δ is a δ-dimensional space with volume $V_\delta \sim R^\delta$.
- This implies the four-dimensional effective M_{Pl} is $M_{Pl}^2 = M_{Pl(4+\delta)}^{2+\delta} R^\delta$
- Assuming $M_{Pl(4+\delta)} \sim \mathrm{m}_{EW}$,
  we get $M_{Pl}^2 = \mathrm{m}_{EW}^{2+\delta} R^\delta$
- implies, $R \sim 10^{\frac{30}{\delta}-17} cm \times \left(\frac{1\mathrm{TeV}}{\mathrm{m}_{EW}}\right)^{1+\frac{2}{\delta}}$
- $\delta = 1 \rightarrow R = 10^{13}\mathrm{cm}$ is excluded due to the deviation from Newtonian gravity. But, for $\delta = 2$ it is in the *mm range*.

(N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali)

RS-model



(pic from José Santiago's talk)

- $m_{IR} = m_{UV} exp(-\pi kR)$
- for $kR \sim 12$, a mass $m_{UV} \sim \mathcal{O}(M_{Pl})$ on the UV-brane corresponds to a mass on the IR brane with a value $m_{IR} \sim \mathcal{O}(M_{EW})$. (Randall, Sundrum)

UED at a glance

- In UED model each particle can access all dimensions.

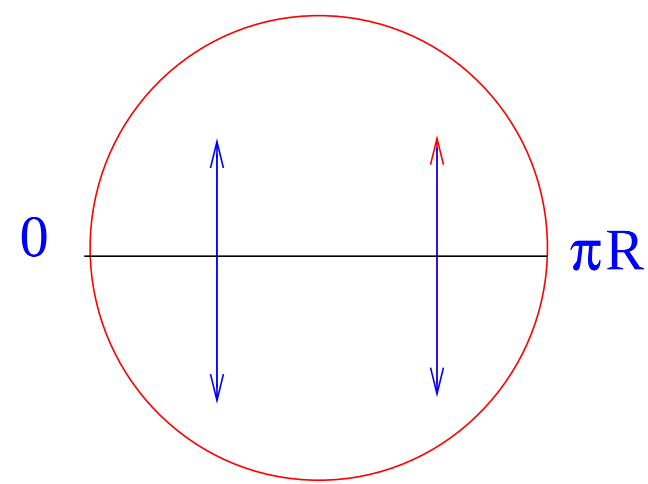
  (Appelquist, Cheng, Deobrescu)

- We consider only ***one space-type extra dimension*** (y)
  So our co-ordinate system : $\{x(t, \vec{x}), y\}$

- Compactification : S^1/Z_2

  Z_2 symmetry : $y \equiv -y$ necessary to get the chiral fermions of the SM

  - Translational symmetry breaks $\Rightarrow p_5$, hence KK number (n) is not conserved.
  - $y \to y + \pi R$ symmetry preserve $\Rightarrow$ KK parity $\equiv (-1)^n$ conserved.



UED at a glance

- $n = 1$ states must be produced in pairs
- Lightest $n = 1$ state is stable $\Rightarrow$ LKP
- All heavier $n = 1$ states finally decay to LKP and corresponding SM (n = 0) states
- Collider signals are soft SM particles plus large $\not{E}$
- Limit on the R^{-1}
  - 250 - 300 GeV from $g_\mu - 2$, $B_0 - \bar{B}_0$ mixing, $Z \to b\bar{b}$ (Agashe, Deshpande, Wu; Chakraverty, Huitu, Kundu; Buras, Spranger, Weiler; Oliver, Papavassiliou, Santamaria)
  - 300 GeV from oblique parameters (Gogoladze, Macesanu)
  - 600 GeV from $b \to s\gamma$ at NLO (Haisch, Weiler)
  - LKP dark matter $\Rightarrow$ Upper bound $\sim$ 1 TeV from overclosure of the universe (Servant, Tait)

Scalar, Fermion, and Gauge boson

Scalar :

$$\phi(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}\phi^{(0)}(x) + \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}\phi^{(n)}(x)\cos\frac{ny}{R}.$$

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Fermions :

$$\mathcal{Q}_i(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}\left[\begin{pmatrix} u_i \\ d_i \end{pmatrix}_L (x) + \sqrt{2}\sum_{n=1}^{\infty}\left[\mathcal{Q}_{iL}^{(n)}(x)\cos\frac{ny}{R} + \mathcal{Q}_{iR}^{(n)}(x)\sin\frac{ny}{R}\right]\right],$$

$$\mathcal{U}_i(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}\left[u_{iR}(x) + \sqrt{2}\sum_{n=1}^{\infty}\left[\mathcal{U}_{iR}^{(n)}(x)\cos\frac{ny}{R} + \mathcal{U}_{iL}^{(n)}(x)\sin\frac{ny}{R}\right]\right],$$

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Gauge boson :

$$A_\mu(x,y) = \frac{\sqrt{2}}{\sqrt{2\pi R}}A_\mu^{(0)}(x) + \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}A_\mu^{(n)}(x)\cos\frac{ny}{R},$$

$$A_5(x,y) = \frac{2}{\sqrt{2\pi R}}\sum_{n=1}^{\infty}A_5^{(n)}(x)\sin\frac{ny}{R}.$$

Effects of KK-modes on RGE

- RGE in SM :

$$16\pi^2 E \frac{dg_i}{dE} = b_i g^3 = \beta_{SM}(g) \quad \Rightarrow \quad \frac{d}{dlnE}\alpha_i{}^{-1}(E) = -\frac{b_i}{2\pi}$$

- Solution :

$$\alpha_i{}^{-1}(E) = \alpha_i{}^{-1}(M_Z) - \frac{b_i}{2\pi} ln \frac{E}{M_Z} \text{ with } \begin{pmatrix} b_Y \\ b_{2L} \\ b_{3C} \end{pmatrix} = \begin{pmatrix} \frac{41}{10} \\ -\frac{19}{6} \\ -7 \end{pmatrix}.$$

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- In UED,

DDG-Nucl.Phys.B537:47-108,1999

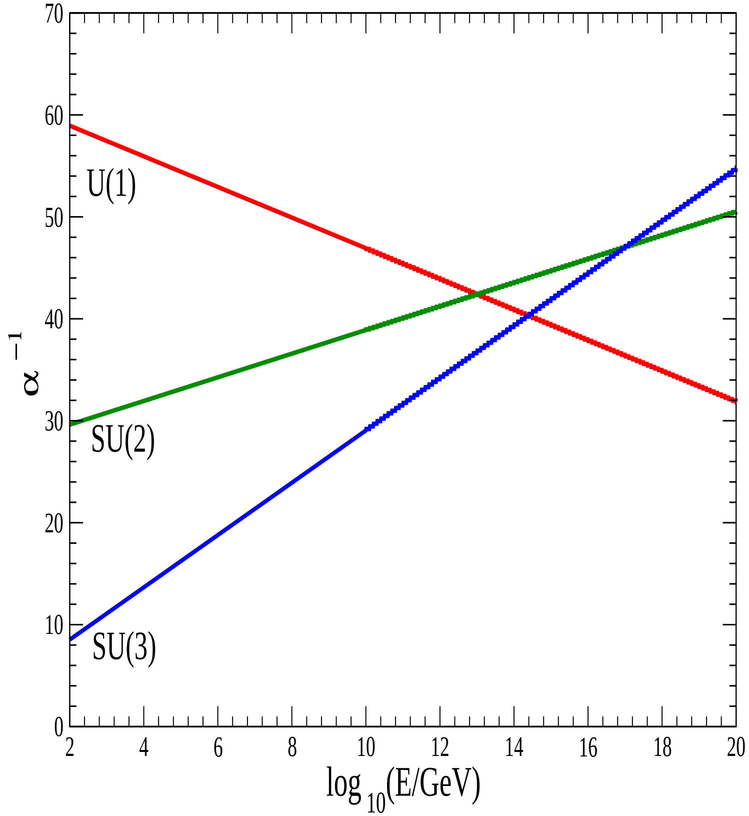
$$16\pi^2 E\frac{dg_i}{dE} = \beta_{SM}(g) + (S-1)\beta_{UED}(g)$$

where, $S = ER$

$$\beta_{UED} = \tilde{b}_i g_i{}^3 \text{ with}$$

$$\begin{pmatrix} \tilde{b}_Y \\ \tilde{b}_{2L} \\ \tilde{b}_{3C} \end{pmatrix} = \begin{pmatrix} \frac{81}{10} \\ \frac{7}{6} \\ \frac{-5}{2} \end{pmatrix}.$$

Gauge Couplings



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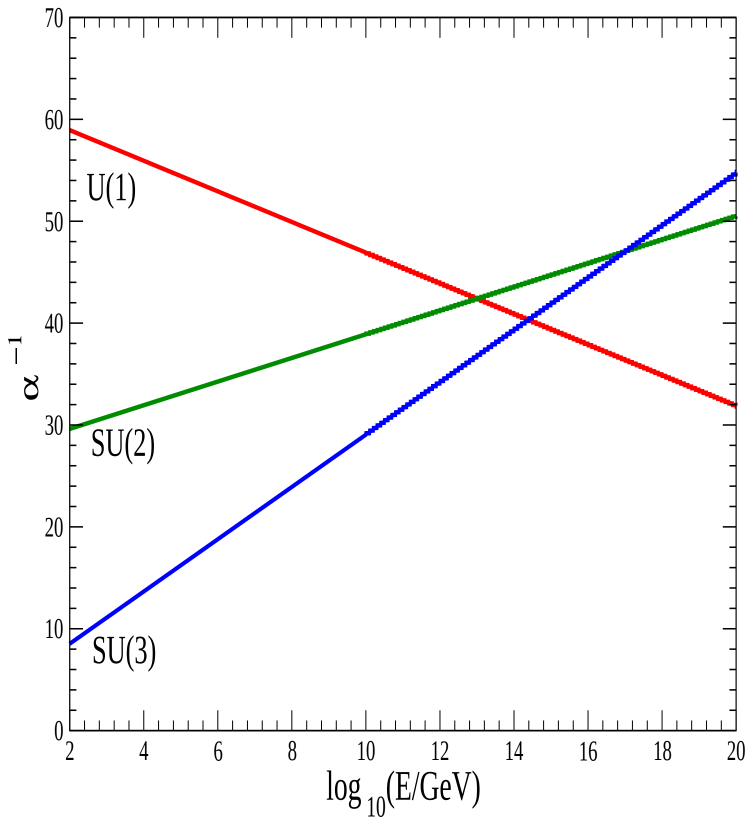
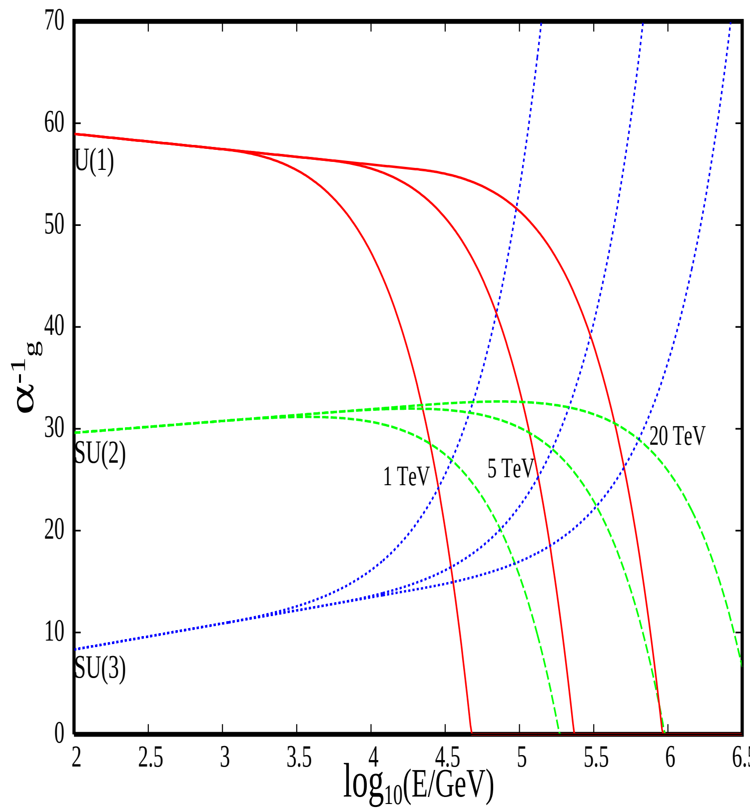




(Bhattacharyya, Datta, Majee, Raychaudhuri)

Radiatvie Corrections

Cheng, Matchev, Schmaltz

Radiative corrections

- Tree level $n-th$ mode KK-mass $m_n = \sqrt{m_0^2 + n^2/R^2}$
- Consider the kinetic term of a scalar field as $L_{\rm kin} = Z\partial_\mu\phi\partial^\mu\phi - Z_5\partial_5\phi\partial^5\phi$,
  - Tree level KK masses originate from the kinetic term in the y-direction.
  - If there is Lorentz invariance, then $Z = Z_5$, there is no correction to those masses.
  - A direction is compactified $\Rightarrow$ Lorentz invariance breaks down.
  - Then, $Z \neq Z_5$, leading to $\Delta m_n \propto (Z - Z_5)$.

Radiative: Bulk Corrections

- These corrections are finite and nonzero only for bosons.
- These corrections, for a given field, are the same for any KK mode.
- For a KK boson mass $m_n(B)$, these corrections are given by

$$\delta\, m_n^2(B) = \kappa \frac{\zeta(3)}{16\pi^4} \left(\frac{1}{R}\right)^2$$

$\kappa = -39 g_1^2/2, -5 g_2^2/2$ and $-3 g_3^2/2$ for B^n, W^n and g^n, respectively.

Radiative: Orbifold Corrections

- Orbifolding additionally breaks translational invariance in the y-direction.
- The corrections to the KK masses arising from interactions localized at the fixed points are logarithmically divergent.

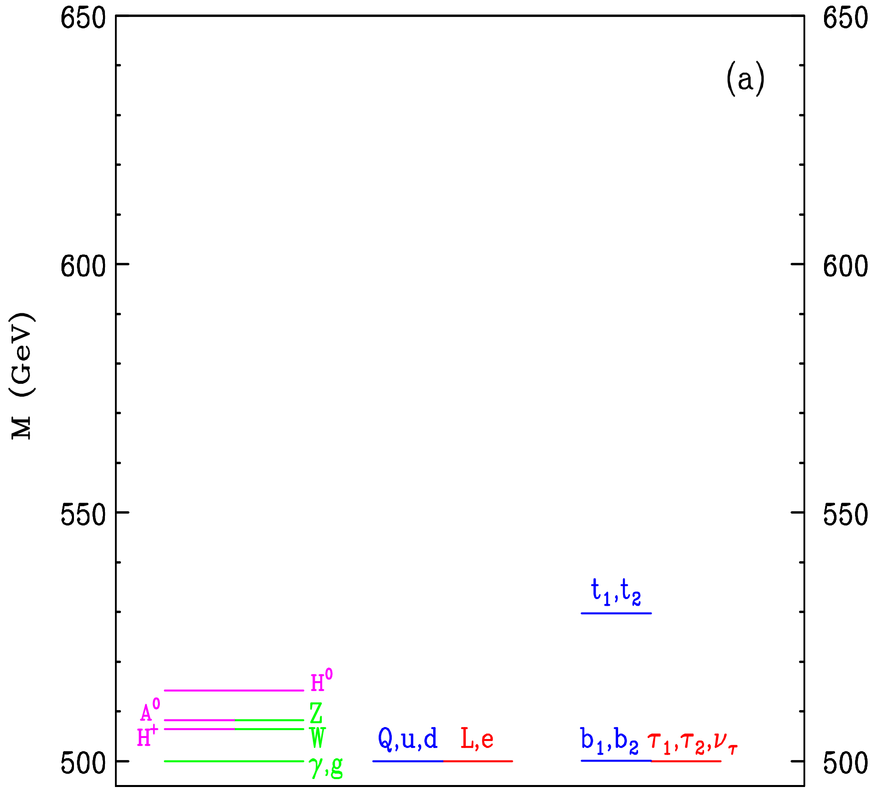
$$\frac{\delta m_n(f)}{m_n(f)} \left(\frac{\delta m_n^2(B)}{m_n^2(B)}\right) = \left(a\,\frac{g_3^2}{16\pi^2} + b\,\frac{g_2^2}{16\pi^2} + c\,\frac{g_1^2}{16\pi^2}\right) \ln\frac{\Lambda^2}{\mu^2},$$

- The mass squared matrix of the neutral KK gauge boson sector in the B_n, W_n^3 basis is given by

$$\begin{pmatrix} \frac{n^2}{R^2} + \hat{\delta} m_{B_n}^2 + \frac{1}{4} g_1^2 v^2 & \frac{1}{4} g_1 g_2 v^2 \\ \frac{1}{4} g_1 g_2 v^2 & \frac{n^2}{R^2} + \hat{\delta} m_{W_n}^2 + \frac{1}{4} g_2^2 v^2 \end{pmatrix}$$

- For $n = 1$ and $R^{-1} = 500$ GeV, it turns out that $\sin^2\theta_W^1 \sim 0.01$ ($<< \sin^2\theta_W \simeq 0.23$), i.e., γ^1 and Z^1 are primarily B^1 and W_3^1, respectively.

Mass Spectra



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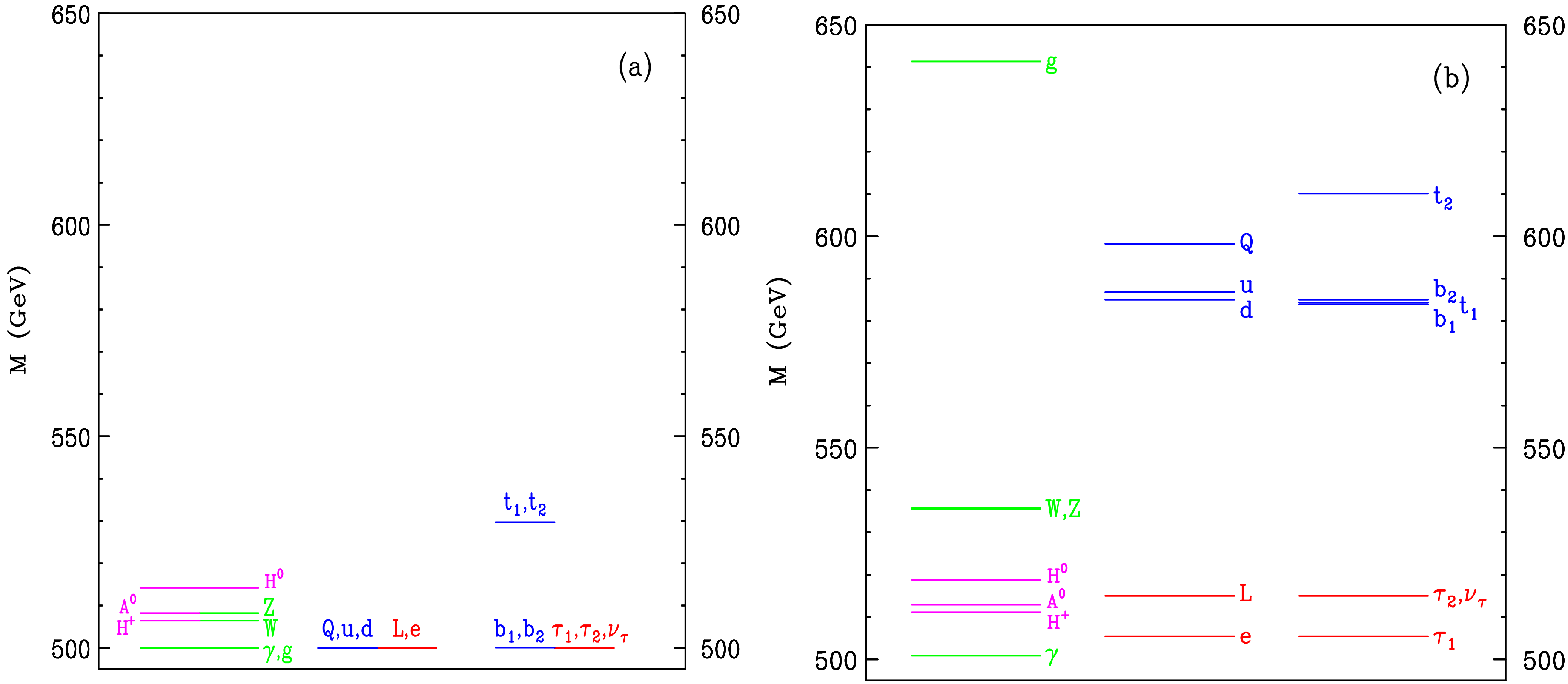
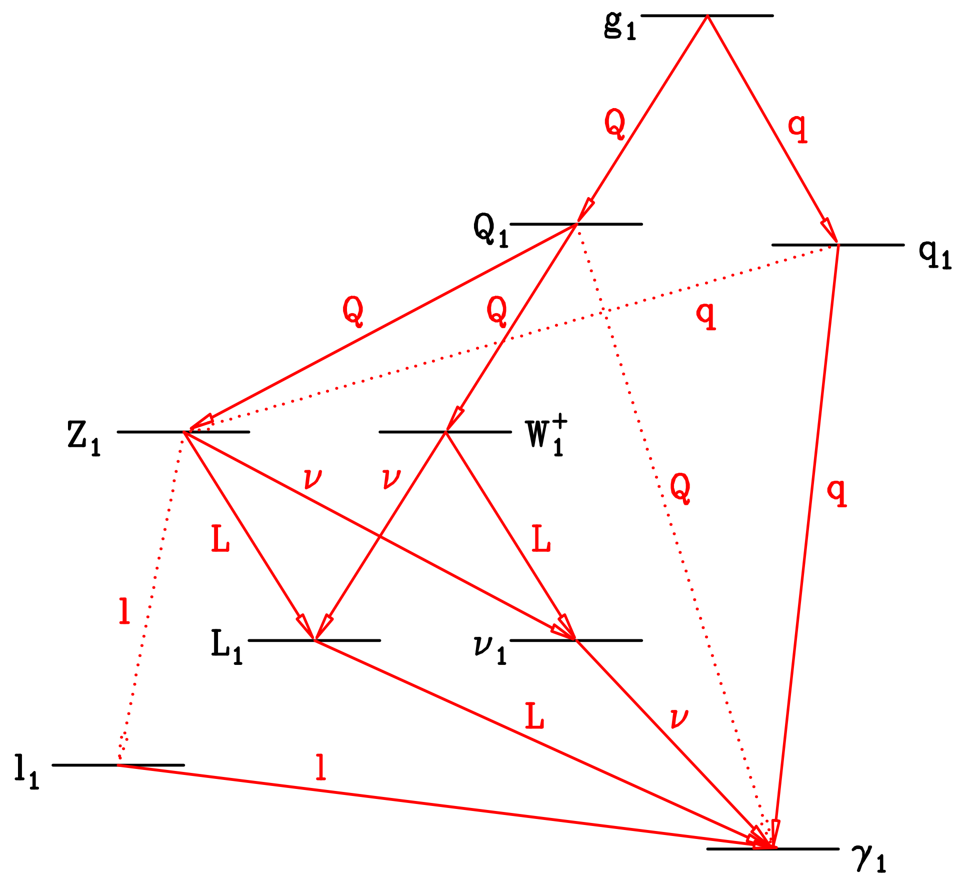


Allowed transitions



Branching ratios

- γ_1 is the LKP. It is neutral and stable.
- KK W- and Z-bosons
  - Hadronic decays closed.
  - Can not decay to their corresponding SM-mode and LKP, as kinematically not allowed.
  - $W_1^{\pm}$ and Z_1 decay democratically to all lepton flavors:
    $B(W_1^{\pm} \to \nu_1 L_0^{\pm}) = B(W_1^{\pm} \to L_1^{\pm} \nu_0) = \frac{1}{6}$
    $B(Z_1 \to \nu_1 \bar{\nu}_0) = B(Z_1 \to L_1^{\pm} L_0^{\mp}) \simeq \frac{1}{6}$
    for each generation.
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KK leptons

- The level 1 KK modes of the charged leptons and neutrinos directly decay to γ_1 and corresponding zero mode states.

Branching ratios

- The heaviest KK particle at the 1st KK-level g_1.
  $B(g_1 \to Q_1 Q_0) \simeq B(g_1 \to q_1 q_0) \simeq 0.5$.

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- KK quarks
  - $SU(2)$-singlet quarks (q_1):
    $B(q_1 \to Z_1 q_0) \simeq \sin^2\theta_1 \sim 10^{-2} - 10^{-3}$
    $B(q_1 \to \gamma_1 q_0) \simeq \cos^2\theta_1 \sim 1$
  - $SU(2)$-doublet quarks (Q_1):
    $SU(2)_W$-symmetry $\Rightarrow$
    $B(Q_1 \to W_1^{\pm} Q_0') \simeq 2B(Q_1 \to Z_1 Q_0)$
    and furthermore for massless Q_0 we have
    $B(Q_1 \to W_1^{\pm} Q_0') \sim 65\%$, $B(Q_1 \to Z_1 Q_0) \sim 33\%$ and
    $B(Q_1 \to \gamma_1 Q_0) \sim 2\%$.

Collider Signature

Bhattacharyya, Datta, Majee, Raychaudhuri

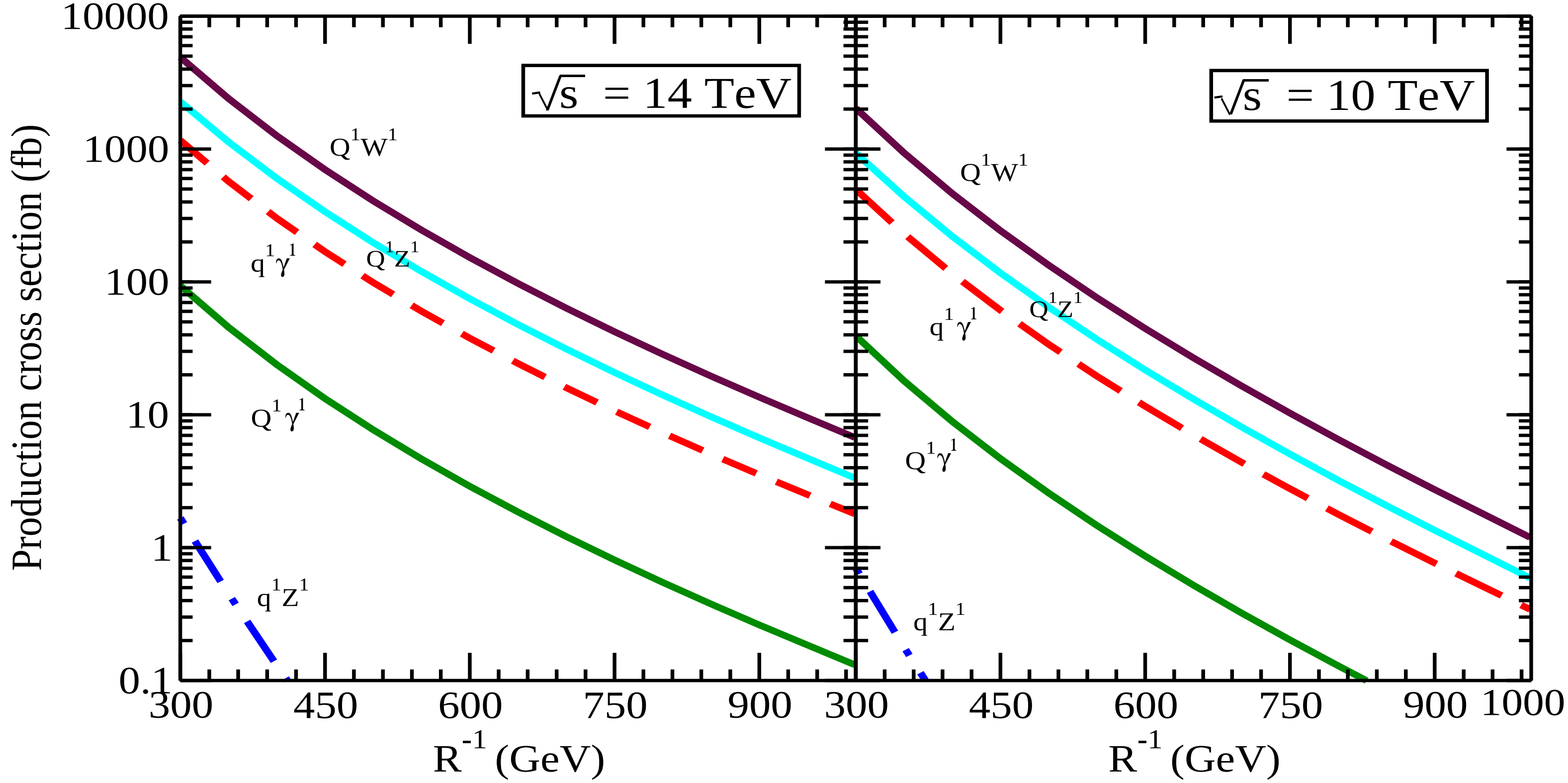
Production

$$|\mathcal{M}\{qg \to \overline{Q}V^1\}|^2 =$$

$$\frac{\pi\alpha_s(\hat{s})(a_L^2 + a_R^2)}{6}\left[\frac{\{-2\hat{s}\hat{t} + 2\hat{s}m_Q^2\}}{\hat{s}^2} + \frac{\{-2\hat{s}\hat{t} - 4\hat{t}m_Q^2 + 2\hat{s}m_Q^2 + 4m_{V^1}^2 m_Q^2\}}{(\hat{t} - m_Q^2)^2}\right.$$
$$\left. + \frac{2\{-2\hat{t}m_Q^2 + 2(\hat{s} + \hat{t})m_{V^1}^2 + 2m_{V^1}^2 m_Q^2 - 2m_{V^1}^4\}}{\hat{s}(\hat{t} - m_Q^2)}\right]$$

Excited quark $\rightarrow$	SU(2) Doublet(Q) ($a_R = 0$)	SU(2) Singlet (q) ($a_L = 0$)
Excited boson $\downarrow$	a_L	a_R
W^1	$\frac{g}{\sqrt{2}}$	0
Z^1	$\frac{g}{2\cos\theta_W^1}\left(T_3 - e_Q \sin^2\theta_W^1\right)$	$-\frac{g}{2\cos\theta_W^1}\left(e_q \sin^2\theta_W^1\right)$
γ^1	$\frac{e_Q}{\cos\theta_W}\cos\theta_W^1$	$\frac{e_q}{\cos\theta_W}\cos\theta_W^1$

Production Crosssection



Basic cuts and n_l crosssection

- basic cuts
  - $p_T^{jet} > 20\text{GeV}$
  - $p_T^{lepton} > 5\text{GeV}$
  - $\not{p}_T^{miss} > 25\text{GeV}$
  - $M_{l_i l_j} > 5GeV$
  - $|\eta| < 2.5$ for all leptons and jet
  - $\text{lepton isolation} : \Delta R > 0.7$, ($n_l \geq 2$ cases)
- crosssection (fb)

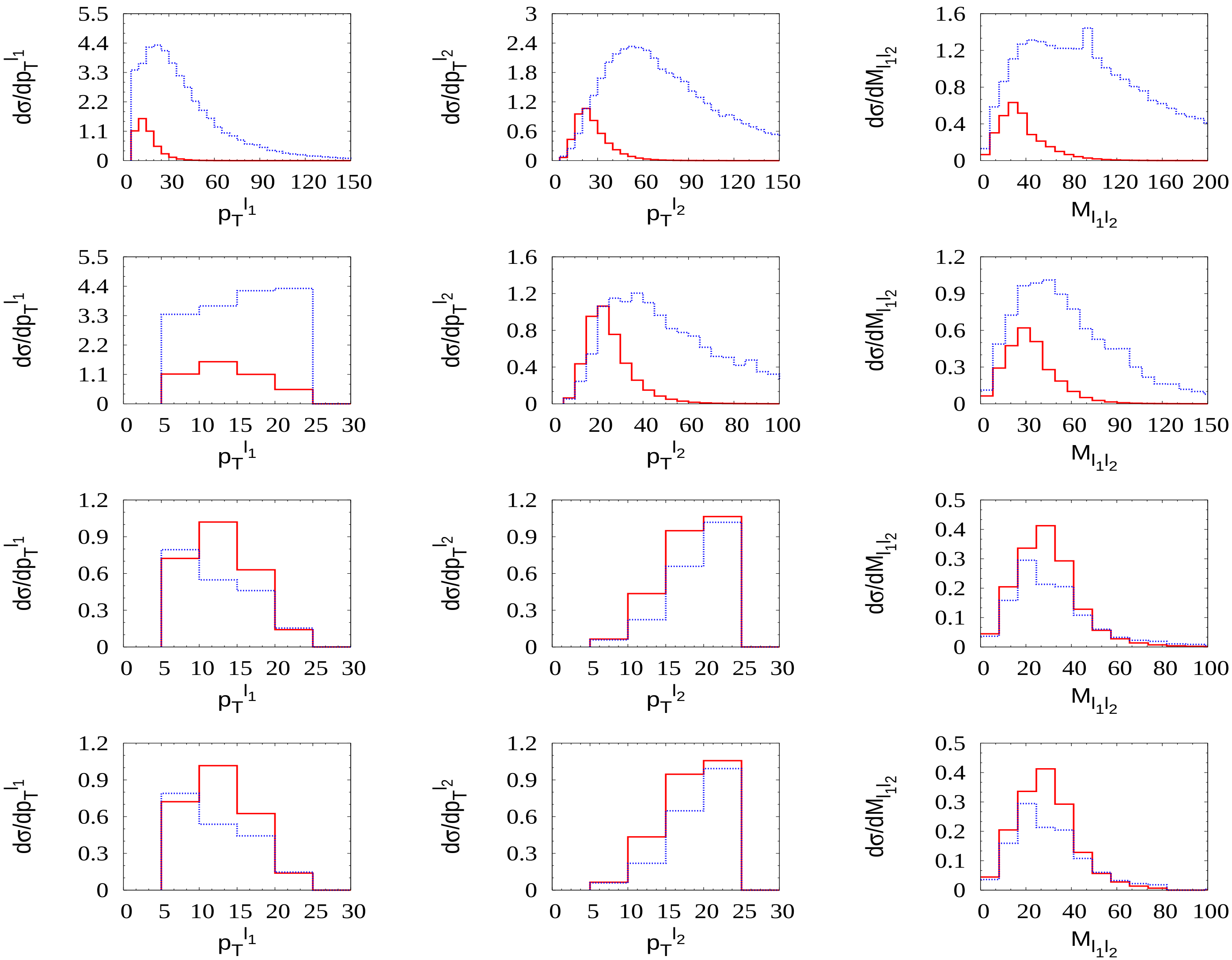
Channel	$0l$	$1l$	$2l$	$3l$	$4l$
Signal (500 GeV)	106.4	17.92	29.58	9.39	1.01
Signal (1 TeV)	2.02	0.35	0.606	0.210	0.025
Background	4.7×10^5	1.3×10^6	8.6×10^4	1183.21	0.13

Two Leptons

- Signal
  - $Q^1 W^1$ production followed by $Q^1 \to Q' W^1$
  - $Q^1 Z^1$ production followed by $Q^1 \to Q Z^1$

    We separately consider ‘like-flavor’, i.e., e^+e^- or $\mu^+\mu^-$, as well as ‘unlike-flavor’, i.e., μ^+e^- + $e^+\mu^-$, in our discussion.
- Background
  - dominanat: $t\bar{t}$ and $b\bar{b}$
  - severely cut down: $p_T^{jet} > 20\mathrm{GeV}$
  - W pair production in association with a jet.
  - Z pair (real or virtual)
  - $Z\gamma^*$
- Additional Cuts:
  - ${p_T}^{l_1} <$ 25 GeV,
  - ${p_T}^{l_2} <$ 25 GeV, and
  - $|M_{l_1 l_2} - M_Z| >$ 10 GeV

Two Leptons



Two Leptons

$\sqrt{s} \quad \rightarrow$	14 TeV		10 TeV	
Cut used $\downarrow$	Signal	Background	Signal	Background
Basic cuts	29.58 (43.10)	8.6$\times 10^4$ (17$\times 10^4$)	10.0 (14.6)	5$\times 10^4$ (9.6$\times 10^4$)
Lepton isolation	24.24 (35.24)	218.38 (429.64)	8.28 (12.06)	108.54 (212.78)
${p_T}^{l_1} < 25$ GeV	21.66 (30.88)	78.67 (154.90)	7.52 (10.74)	41.10 (80.70)
${p_T}^{l_2} < 25$ GeV	12.58 (18.00)	9.44 (18.40)	4.53 (6.52)	5.27 (10.22)
$\lvert M_{l_1 l_2} - M_Z \rvert >$ 10	12.52 (17.88)	9.18 (17.98)	4.51 (6.48)	5.17 (10.08)

Cross section (in fb) at the LHC signal and background for the like-flavour(unlike-flavour) dilepton plus missing p_T plus single jet for $R^{-1} = 500\mathrm{GeV}.$

Three Leptons

- Signal
  - $Q^1 W^1$ production followed by $Q^1 \to Q^0 Z^1$
  - $Q^1 Z^1$ production followed by $Q^1 \to Q'^0 W^1$
- Background $t\bar{t}$ production, WZ or $W\gamma^*$ production in association with a jet.
- Additional Cuts
  - ${p_T}^{l_1} < 25$ GeV,
  - ${p_T}^{l_2} < 25$ GeV, and
  - $|M_{l_1 l_2} - M_Z| > 10$ GeV.

Three Leptons

$\sqrt{s}$ $\rightarrow$	14 TeV		10 TeV	
Cut used $\downarrow$	Signal	Background	Signal	Background
Basic cuts	9.39	1183.21	3.21	555.85
Lepton isolation	6.96	21.69	2.41	10.53
${p_T}^{l_2} < 25$ GeV	5.63	4.09	2.01	1.75
${p_T}^{l_3} < 40$ GeV	5.12	1.31	1.86	0.64
$\lvert M_{l_i l_j} - M_Z \rvert >$ 10 GeV	5.03	1.16	1.82	0.57

Cross section (in fb) at the LHC of signal and background for the trilepton plus one jet and missing p_T channel for R^{-1} = 500 GeV.

Four Leptons

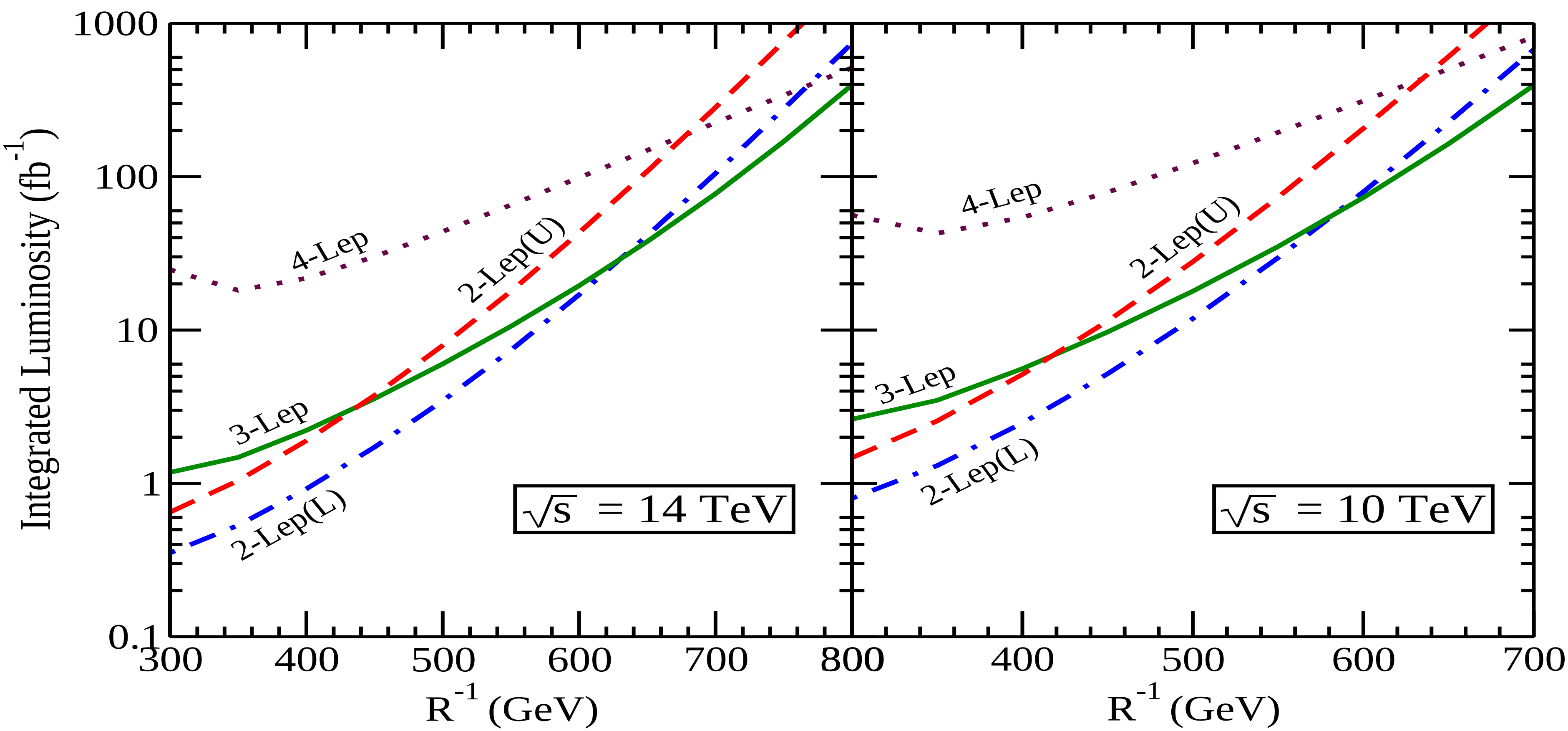
- Signal Q^1Z^1 production followed by $Q^1 \rightarrow Q^0Z^1$

$|M_{l_il_j} - M_Z| >$ 10 GeV for i, j = 1,2,3,4, $i \neq j$.

$\sqrt{s}$ $\rightarrow$	14 TeV		10 TeV	
Cut used $\downarrow$	Signal	Background	Signal	Background
Basic cuts	1.01	0.130	0.350	0.068
Lepton isolation	0.665	0.029	0.233	0.015
$\|M_{l_il_j} - M_Z\| >$ 10 GeV	0.573	0.004	0.206	0.002

Cross section (in fb) at the LHC of signal and background for the tetralepton plus one jet and missing p_T channel for R^{-1} = 500 GeV.

Luminosity plot for a 5σ signal



Conclusions

- we have focussed on the production of the n = 1 excitation of a EW gauge boson along with an n = 1 excited quark.
- First, we imposed some basic cuts to suit LHC observability:
  - the leptons are required to satisfy $p_T > 5$ GeV,
  - the jet must have a p_T not less than 20 GeV,
  - the missing transverse momentum must be more than 25 GeV.
  - $\Delta R > 0.7$
- Single jet $+ \not{p}_T +$ two leptons: Signal: 12.52 fb, Background: 9.18 fb,
- Single jet $+ \not{p}_T +$ three leptons: Signal: 5.00 fb, Background: 1.02 fb,
- Single jet $+ \not{p}_T +$ four leptons: Signal: 0.573 fb, Background: 0.004 fb.
- The analysis performed here is based on a parton-level simulation and is of an exploratory nature.

Thank You !