Beyond Standard Model
(BSM)

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- Lecture I : Effective Field Theory (EFT) Approach
  - Why BSM ?
  - Naive Dimensional Analysis
  - (SM as an) EFT
- Lecture II : BSM w/o Considering Hierarchy Problem
  - Additional Matters: 4th Generation, Additional Scalar (with DM)
  - New Gauge Interactions: Extra U(1), (LR model)
  - Extra Dim (UED)
- Lecture III : BSM Considering Hierarchy Problem
  - SUSY (GUT)
  - Technicolor
  - Large Extra Dim (ADD) and Warped spacetime (RS)

BSM's w/o Considering Hierarchy Problem

- Rule of the model building and General Features
- 4th Generation Fermions (Sequential)
- SM with an extra singlet scalar (+CDM)
- Two-Higgs doublet model
- Extra $U(1)_X$ model
- LR model

Rule of the Model Building

- Specify local gauge symmetry
- Specify the matter contents and their gauge charges (or group representaions)
- Write down all possible operators upto dim-4 (without nonrenormalizable operators)
- Check the anomaly cancellation You could ignore this, assuming there are some other particles around cancelling anomaly. Better to make sure that new particles do not affect what you are interested in
- Include all the minimal ingredients such as renormalizable Yukawa couplings for all the SM fermions
- Special care needed for spin-1 object, since there should be an agency (a new Higgslike field) for the mass of the new spin-1 particle

Simple extensions of the SM

- Extend the matter contents of the SM:
  4th generation (sequential or mirror type), real singlet scalar, real singlet fermion (with extra singlet scalar), more Higgs doublets, vectorlike fermions, and so on
- Extend the gauge group of the SM:
  extra $U(1)$'s, $SU(2)_R$
- Very often one needs to extend the matter contents (fermions) too

4th Generation (Sequential)

[Holdom, Hou, Hurth, Mangano et al, 0904.4698 [hep-ph]]

- Are there extra sequential generation ?
- Asymptotic freedom in QCD if $N_F < 9$

$$\beta_{QCD} \propto (11N_C - 2n_F) = (33 - 2n_F)$$

- $N_\nu = 3$ from $Z^0 \to \nu\bar{\nu}$ does not apply, if $m_{\nu_4} > m_Z/2$ (kinematically not allowed)
- Neutrino oscillation dows not exclude additional hevy neutrinos
- EWPT does not forbid the 4th generation

EWPT

- Folklore “An extra generation of ordinary fermions is excluded at the 6 sigma level on the basis of S parameter alone” is true, only if new families are degenrate
- And the restriction can be relaxed by allowing T to vary as well
- S can be relaxed with heavier Higgs
- A positive contribution to T from mass splitting between heavy doublets

$$S = \frac{2}{3\pi} - \frac{1}{3\pi}\left[\log\frac{m_{t'}}{m_{b'}} - \log\frac{m_{\nu'_\tau}}{m'_\tau}\right]$$

4th Generation (Sequential)

- CKM matrix $\to 4 \times 4$ with 3 CPV phases
$\to$ Much more room for explaining some anomalies in B_s system, which is however getting weaker than before
- Unitarity of CKM:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999 \pm 0.0011 = 1 - |V_{ub'}|^2$$

$\to |V_{ub'}| < 0.04$ which is much weaker than $|V_{ub}| \sim 0.004$

- $|V_{cb'}| > |V_{cb}| \approx 0.04$
- Good target at the LHC and B factory : Phase in $B_s - \overline{B_s}$ mixing and FB Asym in $B \to K^* \mu\mu$
- LHCb data well agrees with the SM predictions, so the room for the 4th generation contributions are getting tight

Collider Search

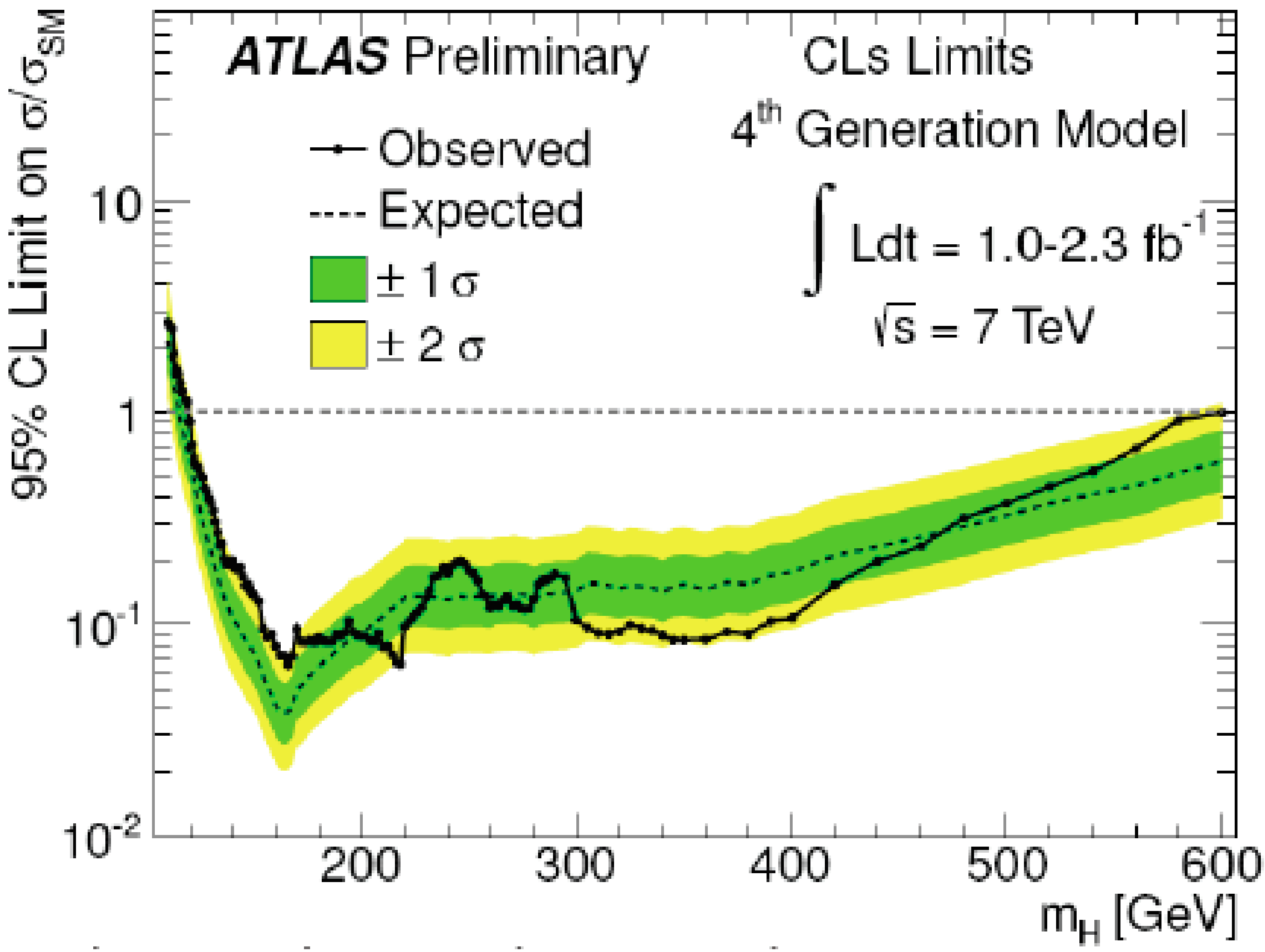
- $m_{t'}, m_{b'} < 1TeV$ from partial wave unitarity
- Nondiscovery could mean full exclusion of the SM4 model, assuming usual decays and mixings
- Dominant decay channel depends on CKM4 mixing and $t - b$ mass splitting
- $t' \to bW$ and $b' \to tW \to bW + W-$
- $b'\bar{b}' \to b\bar{b}W + W - W + W-$ the same sign dilepton or trilepton signals with HT variable
- If $t^{'}$ and $b^{'}$ prefer mixing with the first two generation, one should consider $t^{'}(b^{'}) \to q(jet) + W$
- If $t^{'}$ and $b^{'}$ mass splitting is less than 50 GeV, they are hard to distinguish, and the signal is doubled
- $t^{'}, b^{'}$ 500 GeV can be discovered at 5 sigma level with 400 pb^{-1}

Implications for Higgs search

[Kribs, Plehn, Spannowsky, Tait (2007)]

- Larger cross section for $gg \to H$ due to heavy t' loop
- $Br(H \to \gamma\gamma)$ reduced due to 4th fermion contribution tend to cancel the W loop contribution
- $gg \to H \to WW \to l\nu l\nu$ becomes more important.
- Currently a wide region is excluded
[Check the talks at Lepton Photon 2011]

Higgs limits assuming a 4th generation of quarks and leptons:



Other exotic fermions are still alive and interesting, but the sequential 4th generation is in deep troupble!

SM with extra real singlet scalar

- This is the simplest extension, just one more dof.
- Not solves any problem of the SM, except that
- Model

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 + S + S^3 S^4 - \frac{1}{2} S^2 H^\dagger H \\ &+ \overline{\chi}(i\partial\cdot\gamma - m_\chi + \lambda_S S)\chi\end{aligned}$$

- it might be a messenger for the hidden sector CDM and the SM sector (the 2nd line of the above equation) [See Baek, Ko, Park (2011)]

SM with extra real singlet scalar

- Not strongly constrained by the EWPT, because S is a sinlget
- Mixing between the S and H can dilute the Higgs signatures, such as $H_{1,2} \to WW^{(*)}, ZZ^{(*)}$, $b\bar{b}$
- Invisible Higgs decays possible, if kinmatically allowed

$$H_{1,2} \to \overline{\chi}\chi$$

- If we impose Z_2 symmetry $S \to -S$, then S itself can be a CDM (the simplest CDM model)
- Stronger 1st order phase transition possible
$\to$ Better for EW baryogenesis ?

Singlet + CDM

- S, T parameters independent of DM sector
- Direct detection and relic density depend on DM sector
- $\sigma(H_i)Br(H_i \to WW^*)$ depend on DM sector

$$\xi_i \equiv \frac{\sigma(H_i)Br(H_i \to WW^*)}{\sigma(H_{\rm SM})Br(H_{\rm SM} \to WW^*)}$$

- The ratios ξ_i's will be smaller than "1" in general, whether or not $H_i \to \overline{\chi}\chi$ is open
  cf. This is a main difference between this model and the real singlet scalar dark matter with Z_2 symmetry (which is much more studied in the literature), where there is only one SM Higgs boson
- Both Higgs bosons can have $\xi_i < 1$, because of $h - s$ mixing and $H_i \to \overline{\chi}\chi$

Two-Higgs doublet model (2HDM)

- Add one more Higgs doublet
- Considered as a possible source of CP violation observed in $K_L \to \pi\pi$ ($\epsilon_K \approx 10^{-3}$) (T.D.Lee) using spontaneous CP violation (relative CP phase between v_1 and v_2)
- Tree level contribution to the ρ parameter is zero
- Generally relax the EWPT constraints, and Higgs boson could be heavier
- However, generic 2HDM has neutral Higgs mediated FCNC problem:
  Mass matrices and Yukawa couplings can not be diagonalzied simultaneously in general

Natural Flavor Conservation (NFC)

- A Way Out : Natural Flavor Conservation by Glashow and Weinberg Fermions with a given electric charge couples only to one Higgs doublet
- This could be realized by assigning a Z_2 symmetry

$$H_1 \to +H_1, \quad H_2 \to -H_2$$

- This Z_2 sym should be broken softly:

$$-m_{12}^2 H_1 H_2^* + h.c.$$

  in order that we can have massive pseudoscalar A^0
- It may look *ad hoc* to introduce Z_2 and then break it softly
- Or, one could introduce $U(1)_H$, where H_1 and H_2 have different charges, and assign some $U(1)_H$ charges to the SM fermions in order to reproduce Type I,II,IV etc. (see Ko, Omura, Yu, 2011)

Some popular Z_2 assignments

Type	H_1	H_2	U_R	D_R	E_R	N_R	Q_L, L
I	$+$	$-$	$+$	$+$	$+$	$+$	$+$
II	$+$	$-$	$+$	$-$	$-$	$+$	$+$
X	$+$	$-$	$+$	$+$	$-$	$-$	$+$
Y	$+$	$-$	$+$	$-$	$+$	$-$	$+$

- Type I : SM fermions get masses from H_1 only, H_2 is a spectator and could be a CDM if its VEV is zero (Inert Higgs DM)
- Type II : Up type (down type) fermions get masses from $H_1(H_2)$
- Type III : General 2 HDM

V precision tests (Kanemura, Okada et al 2011)

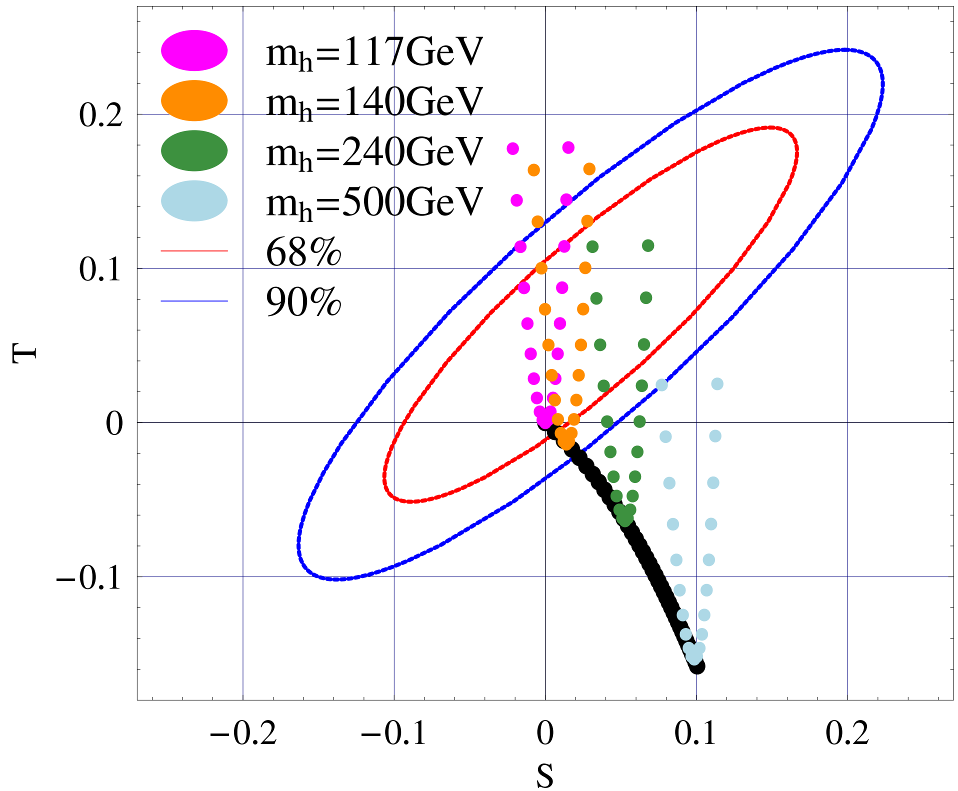


Figure 1: The χ^2 analysis in the (S, T) plane is shown in the THDM where the SM-like Higgs boson is taken to be $117, 140, 240$ and 500 GeV, with the SM-like limit $\sin(\beta - \alpha) = 1$ and $m_{H^\pm} = 300$ GeV. The mass of heavy neutral Higgs bosons $m_A = m_H$ is varied from 200 GeV to 400 GeV by the 10 GeV

A new resolution of FCNC with extra $U(1)_H$

- Softly broken Z_2 is somewhat ad hoc in 2HDM
- Let us implement Z_2 to local $U(1)_H$ symmetry, assuming H_1 and H_2 carry different $U(1)_H$ charges
  $\rightarrow$ Higgs flavor quantum number
- No massless pseudoscalar, because it is eaten by new Z_H boson
- Z_H can be very light if g_H coupling is small enough
  $\rightarrow$ Natural candidate for U boson by Pierre Fayet
- $U(1)_H$ charges of the SM are controlled by phenomenologically acceptable Yukawa couplings and anomaly cancellation
- Opens a new window for 2HDM model building
- See the new paper by Ko, Omura, Yu (2011) for more details

- For example, consider Type-I where

U_R	D_R	Q_L	L	E_R	N_R	H_1	Type
u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$	
0	0	0	0	0	0	0	$h_2 \neq$
$1/3$	$1/3$	$1/3$	-1	-1	-1	0	$U(1)_{B}$
1	-1	0	0	-1	1	1	$U(1)$
$2/3$	$-1/3$	$1/6$	$-1/2$	-1	0	$1/2$	$U(1)_Y$

- Conditions for the Type-I Yukawa interactions:

$$u - q - h_1 = d - q + h_1 = e - l + h_1 = n - l - h_1 = 0$$

MSSM Higgs sector

- MSSM has two Higgs doublet with opposite Y charges
  – Supersym sector: Type-II Higgs doublet model
  – Soft SUSY breaking sector : Type-III Higgs doublet model
- Therefore, the MSSM Higgs sector becomes Type III after all
  $\rightarrow$ Large FCNC through neutral Higgs bosons becomes possible for large $\tan\beta$
- Most prominent example is $B_s \rightarrow \mu^+\mu^-$

Extra $U(1)_X$ model

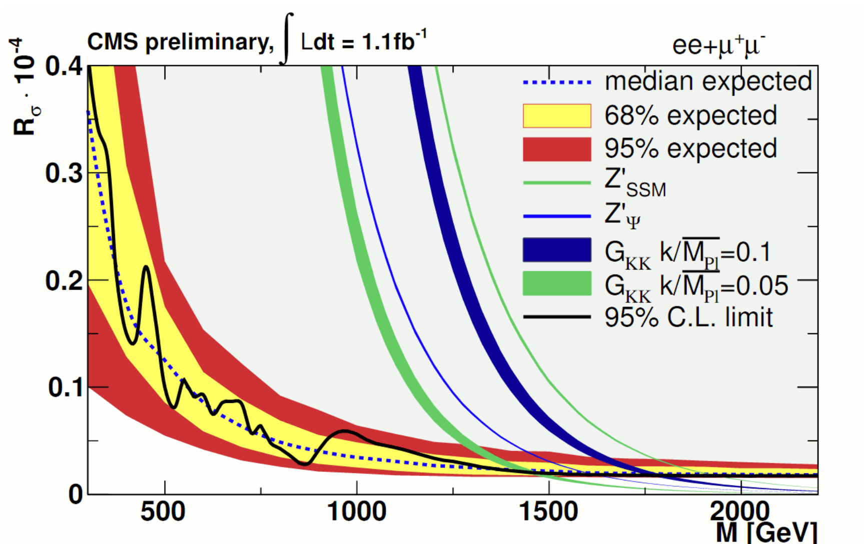
- The simplest gauge extension of the SM
- Very easy to search at colliders, if $U(1)_X$ gauge boson couples to leptons (and quarks)
- GUT or string inspired models have a number of new $U(1)$'s
- Very strong bound on extra Z' from LEP(2), Tevatron and LHC
- Leptophobic Z' can be significantly lighter, however
- $U(1)_B$ and/or $U(1)_L$ might be a reason behind the stability or longetivity of proton
- $U(1)_{B-L}$ is popular
  $-$ it is one of the anomaly free subgroup of the SM gauge group
  $\to$ can gauge it without additional fermions
  $-$ it could be a part of $SO(10)$

Search for Heavy Resonance: dilepton channel

- Randall-Sundrum KK graviton excitation
- Neutral heavy gauge boson
- Technihadron

Sequential SM:
m(Z') > 1.9 TeV at 95% C.L.

RS graviton (k/M_{Pl} = 0.1):
m(G) > 1.8 TeV at 95% C.L.



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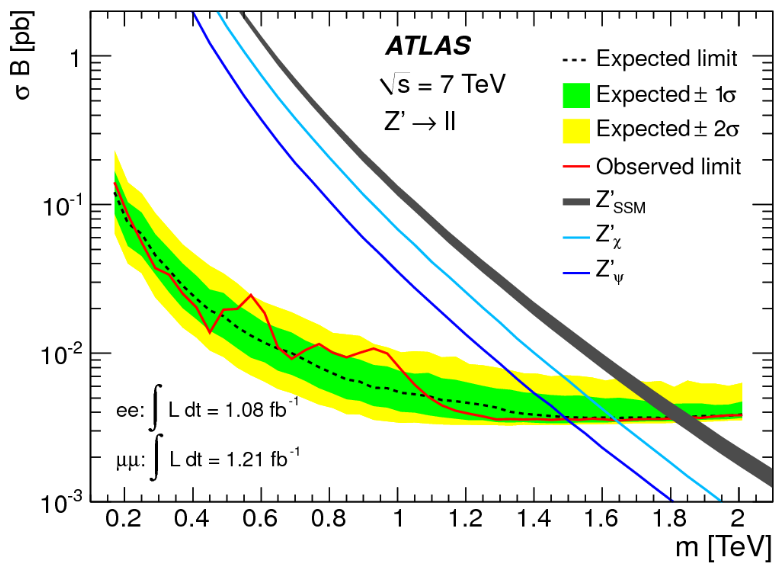
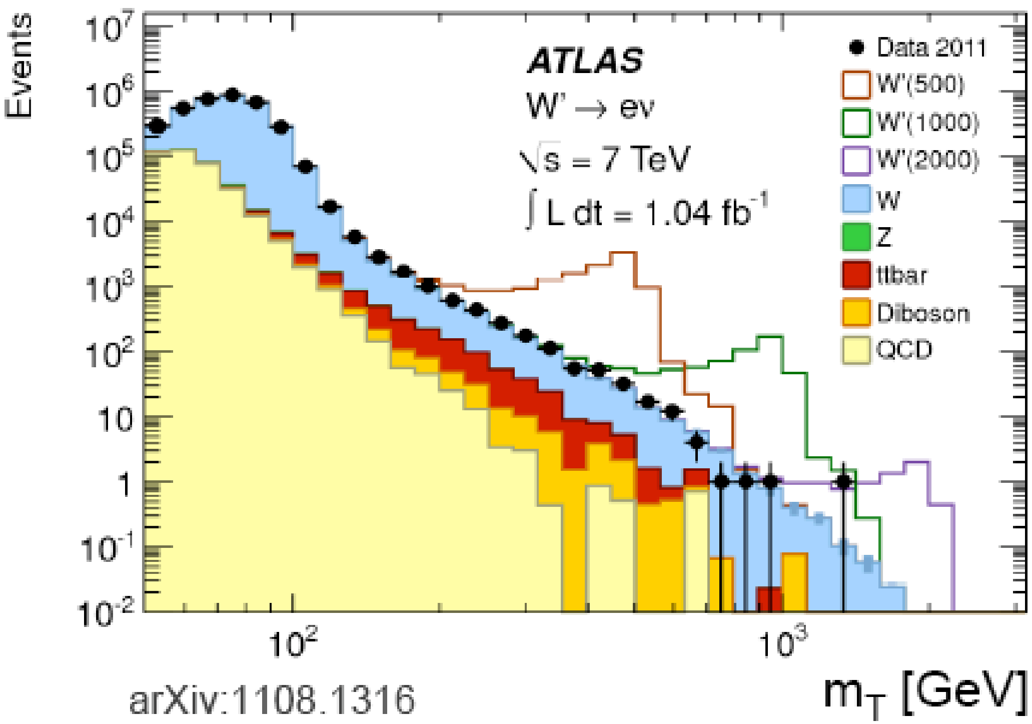
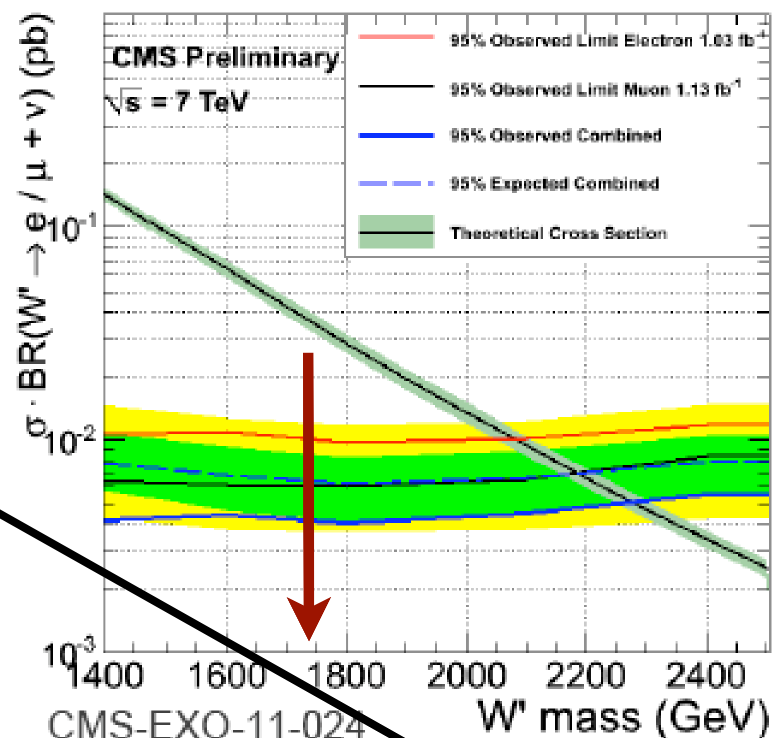


arXiv:1108.1582

current limits on W’
(caution: the analysis is for sequential W)





Leptophobic Z': (Rosner, 1996)

- Consider E_6 model with rank 6, with two extra $U(1)$'s with

$$\begin{aligned} E_6 &\rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R \\ &\rightarrow SU(3)_C \times SU(2)_L \times U(1)_L \times SU(2)_R \times U(1)_R \end{aligned}$$

- EM charge operator is given by

$$Q = I_{3L} + \frac{Y_W}{2} \equiv I_{3L} + I_{3R} + \frac{Y_L + Y_R}{2}$$

- Define three other $U(1)$ charges associated with $U(1)_\chi$, $U(1)_\psi$ and $U(1)_\eta$:

$$\begin{aligned} Q_\chi &= 4I_{3R} - 3(Y_L + Y_R) \\ Q_\psi &= 3(Y_R - Y_L) \\ Q_\eta &= 3I_{3R} - 6Y_L + \frac{3}{2}Y_R \end{aligned}$$

Leptophobic Z'

- These $U(1)$'s are identified as

$$E_6 \to SO(10) \times U(1)_\psi \to [SU(5) \times U(1)_\chi] \times U(1)_\psi$$

- $U(1)_\eta$ is a linear combination of $U(1)_\psi$ and $U(1)_\chi$
- Leptophobic $U(1)'$:

$$Q^{'} = (Q_\eta + Y_W)/5 = I_{3R} - Y_L + \frac{1}{2} Y_R$$

- This was proposed as a solution to R_b problem on Z^0 pole in mid 90's
- Z' has zero couplings to the SM leptons, but has a large couplings to exotic leptons

	Q_η	State	Q	I_{3L}	I_{3R}	Y_L	Y_R	Q'
(16, 5*)	1	d^c	1/3	0	1/2	0	$-1/3$	1/3
		e^-	-1	$-1/2$	0	$-1/3$	$-2/3$	0
		ν_e	0	1/2	0	$-1/3$	$-2/3$	0
(16, 10)	-2	u	2/3	1/2	0	1/3	0	$-1/3$
		d	$-1/3$	1/2	0	1/3	0	$-1/3$
		u^c	$-2/3$	0	$-1/2$	0	$-1/3$	$-2/3$
		e^+	1	0	1/2	2/3	1/3	0
(16, 1)	-5	N_e^c	0	0	$-1/2$	2/3	1/3	-1
(10, 5*)	1	h^c	1/3	0	0	0	2/3	1/3
		E^-	-1	$-1/2$	$-1/2$	$-1/3$	1/3	0
		ν_E	0	1/2	$-1/2$	$-1/3$	1/3	0
(10, 5)	4	h	$-1/3$	0	0	$-2/3$	0	2/3
		E^+	1	1/2	1/2	$-1/3$	1/3	1
		ν_E^c	0	$-1/2$	1/2	$-1/3$	1/3	1
(1, 1)	-5	n	0	0	0	2/3	$-2/3$	-1

Z' Br and FB Asym

$$A_{FB} = \frac{3}{4} \frac{[Q(u)^2 - Q(u^c)^2][Q(f)^2 - Q(f^c)^2]}{[Q(u)^2 + Q(u^c)^2][Q(f)^2 + Q(f^c)^2]}$$

State f	Squared charge	Branching ratio	Branching ratio/3 (%)	$A_{FB}(u\bar{u} \to Z' \to f\bar{f})$
d	$(1+1)/3$	1/12	2.8	0
u	$(1+4)/3$	5/24	6.9	0.27
N_e^c	1	1/8	4.2	0.45
h	$(4+1)/3$	5/24	6.9	-0.27
E	$0+1$	1/8	4.2	0.45
ν_E	$0+1$	1/8	4.2	0.45
n	1	1/8	4.2	-0.45
Total	8	1	33.3	

LR model

- Introduce $SU(2)_R$ acting on the RH fermions, just like the $SU(2)_L$ of the SM
- Motivated in order to havr RH and LH particles on the equal footing
- However RH and LH particles are completely different objects in the massless limit (namely, before EWSB), and no strong reason these two sectors follow the same type of physical laws in principle
- One can have either $g_L = g_R$ or $g_L \neq g_R$
- $g_L = g_R$ case is strongly constrained by flavor physics and collider searches
- $W_R^{\pm}$ search has a strong bound on M_{W_R}
- Mixing among 3 neutral gauge bosons B_μ, W_L^3 and W_R^3
- Neutrino physics could be interesting in the LR model

Extra Dimension Scenarios

- Why Extra Dim ?
- Universal Extra Dim (UED)
- Large Extra Dim (ADD)
- Warped Extra Dim (RS)

Why Extra Dim ?

- We are living in (3+1)-dim spacetime
- Kaluza-Klein theory: 5-dim General Relativity includes 4-dim Gravity + Electromagnetism (with extra dim size of $1/M_{Pl}$)
- However there could be very tiny extra dim's, or we could live in Alice's flat wonderland in extra dim's
- New ways of symmetry breaking (both gauge sym and supersymmetry) and solving fine tuning probelm (Gauge-Higgs Unification)
- Superstring theory, the only consistent quantum gravity as of today, is defined only in higher dimensions
- Some of the extra dim scenarios have observable consequences at LHC and other collider experiments
- Existence of extra dim should be an experimental question

Generic Features of Extra Dim

- Exrta dim appears as a tower of new massive particles. Consider a wave equation in $4+1$ dim with coordinate (x^μ, y):

$$(\partial^2 + \partial_y^2)\phi(x,y) = 0$$

  with $0 \leq y \leq L$

- Consider a plane wave solution:

$$\phi \sim e^{ip\cdot x + ik\cdot y}$$

- Then one has $p^2 - k^2 = 0$ so that

$$p^2 = k^2 \neq 0 = m^2$$

- Momentum in the extra dim looks like “mass” in 4-dim spacetime
- Infinite tower of massive states:

Universal Extra Dim (UED)

- Consider UED where all the SM fields live in extra dim
- Does not solve the hierrchy problem
- CDM: usually B_1, the 1st KK mode of $U(1)_Y$ gauge bosons
- Popular for collider phenomenology and CDM
- Similar event topology to the SUSY case, but the CDM carries spin-1, not spin-1/2
- Good benchmark model to be compared with better studied SUSY models
- Considerable study on how to reconstruct the mass of CDM and its parent particles both in SUSY and UED using various kinematic variables such as M_{T2}

Large extra dim (ADD)

- Larger extra dim implies lighter new states
- ADD (Arkani-Hamed, Dimopoulos, Dvali) say that one can solve the hierarchy problem, if only gravity propagates in extra dim
- Gravity flux propagates in higher dim than em field flux
  That's why gravity is much weaker than gauge forces
- KK gravitons are finely spaces, almost continuum in mass with $1/M_{\mathrm{Planck}}$ suppressed couplings to the SM fields

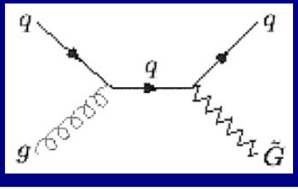
Virtual KK gravitons in ADD scenario

- Real emission of G_{KK} leads to missing E_T (or p_T) signatures at colliders:

$$e^+e^- \to \gamma G_{KK}, \; q\bar{q} \to g G_{KK}, \; qg \to q g_{KK}$$

- Monojet (or single photon) + missing E_T Signature
- Virtual graviton exchanges can modify 4-fermion processes, for example
- After summing over the infinite tower of KK gravitons, the effective couplings to the SM particles become $1/TeV$ suppressed, not $1/M_{\text{Planck}}$ suppressed
- Large degeneracy compensates the suppression factor, leading to observable consequences at colliders
- $gg \to \gamma\gamma$ at tree level, in sharp contrast to the SM case (one loop involving quarks)
- Care needed, since the interaction is

Search for Monojets



- Large Extra-D (ADD):
  - → Brings the Plank scale down to the TeV scale:

$$M_{Pl}{}^2 \sim M_D{}^{2+n} R^n$$

  - → Graviton escapes detector
- Also Split SUSY
- Look for a jet and ~ nothing else
- Challenge:
  - → Instrumental background
  - → Understanding Z(→ νν) + jets

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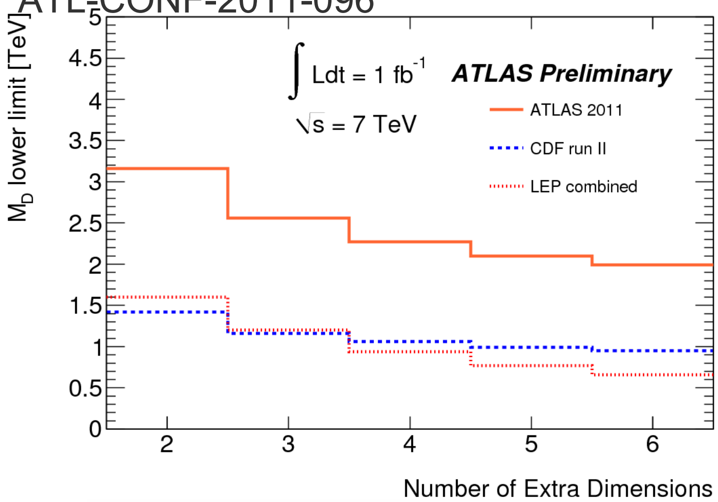

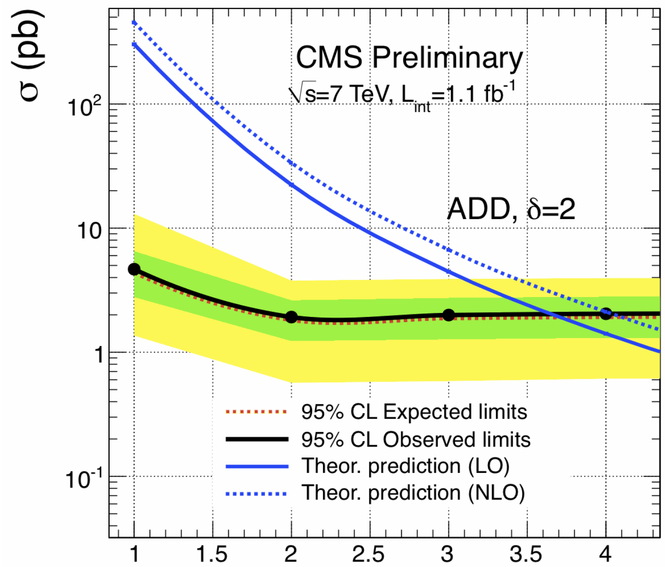

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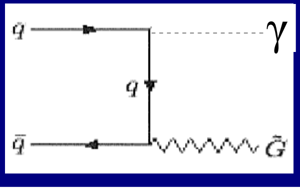
Search for Monophoton

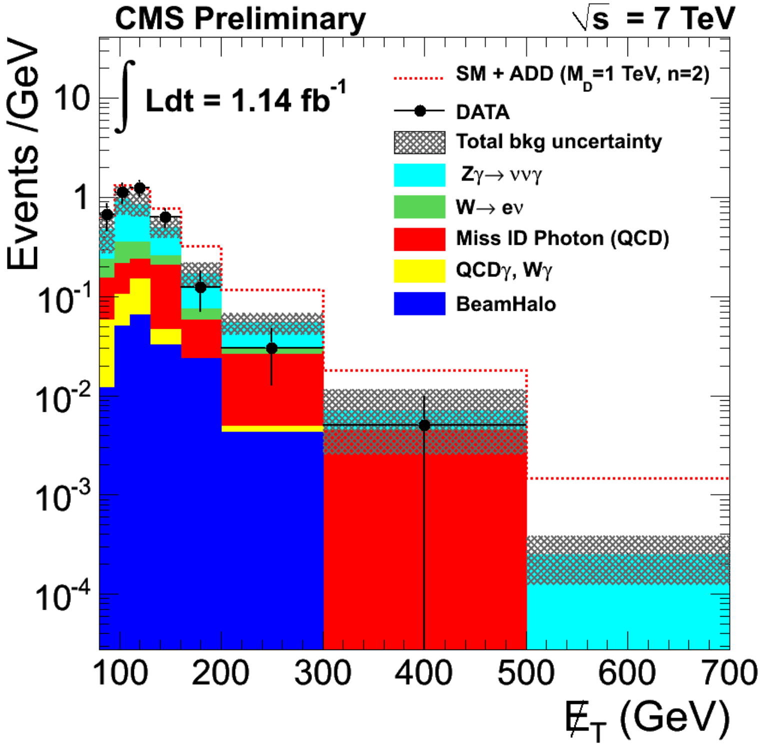


- Large Extra-D (ADD):
  - → Graviton escape detector
- Similarly to monojet:

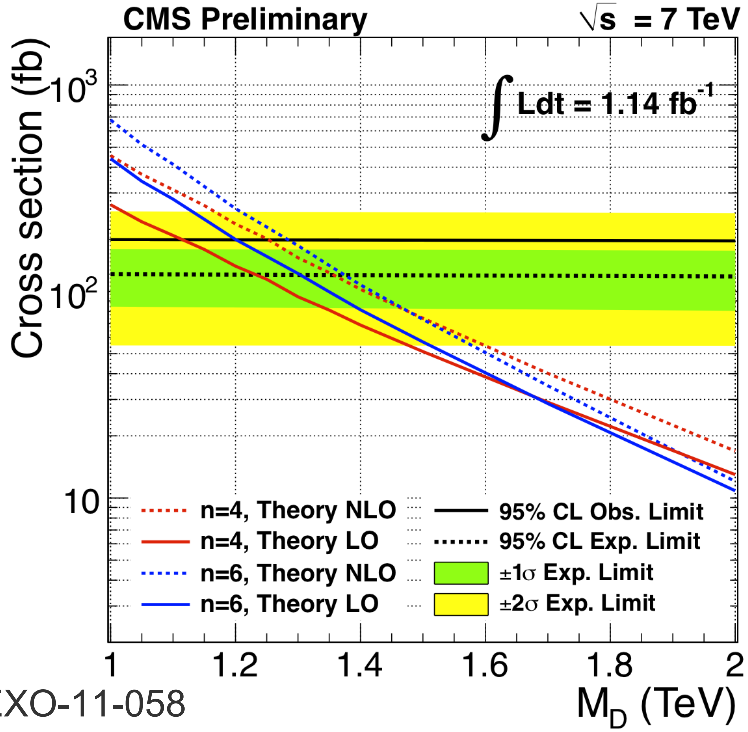
  Look for a photon and ~ nothing else

For n = 2-6:

M_D > 1.25 − 1.31 TeV



NEW!



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Search for deviation in dilepton/diphoton spectrum

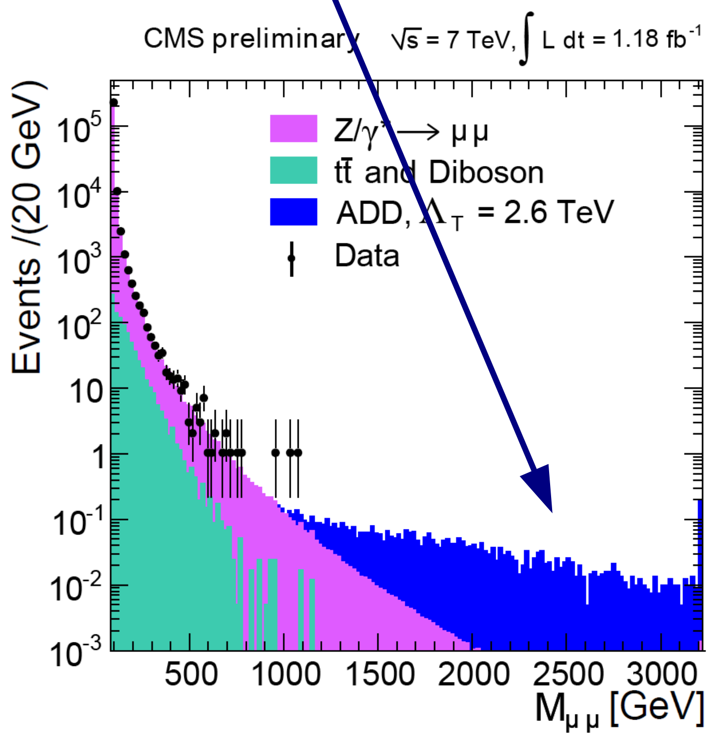
- Large Extra-D (ADD):
  - → KK graviton tower with Δm << detector resolution

Dimuon, n = 3: M_S > 3.2 TeV

Diphoton:

CMS-EXO-11-038

K factor	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
1.0	3.2	3.4	2.8	2.6	2.4	2.2
1.6	3.5	3.7	3.1	2.8	2.6	2.4



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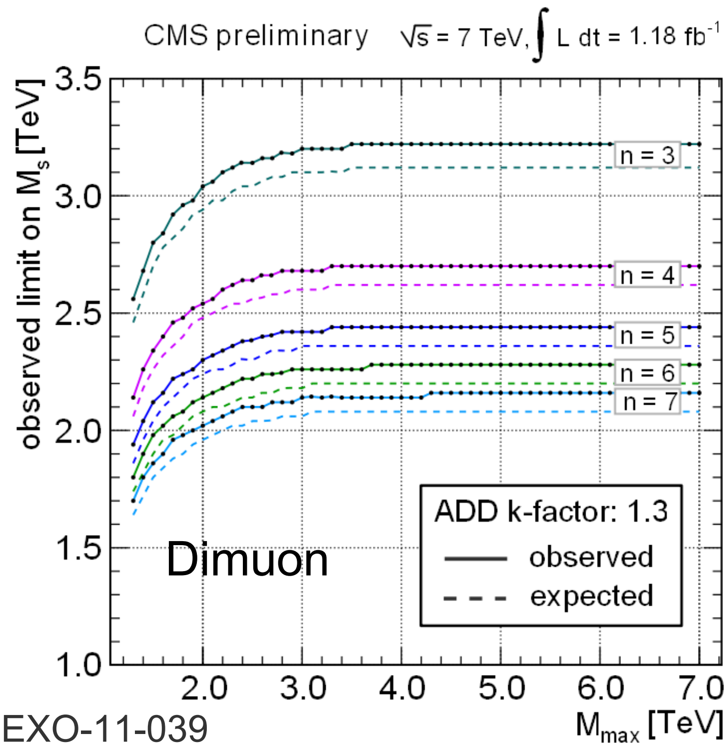

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Warped Spacetime : Randall-Sundrum (RS)

- If Higgs lives in the TeV brane, one can understand the hierarchy problem from a warp factor $e^{-kR} \sim 10^{16}$ with $kR \sim 33$
- Gauge coupling unification possible, if all the matters and gauge fields live in the bulk
- CDM candidate
- KK states of the gauge bosons and the SM fermions
- Couplings are determined by the wavefunctino profiles of the KK modes in the extra dim
- Details depend on the models (many works during the past 10 years or so)

Randall-Sundrum Scenario

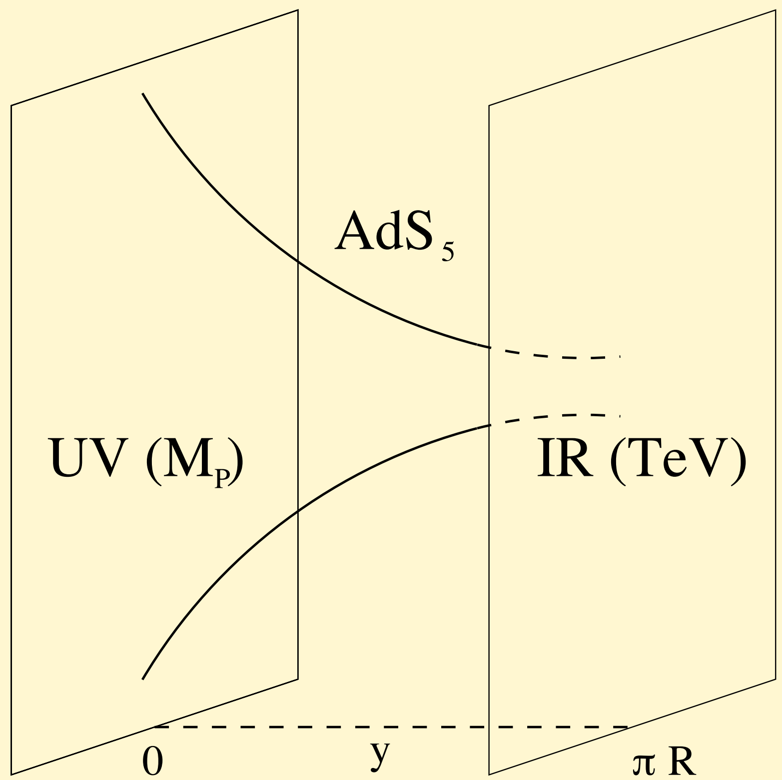


Figure 1: *A slice of* AdS_5*: The Randall-Sundrum scenario.*

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \equiv g_{MN}dx^M dx^N,$$

$$m_H^2|H|^2 \to (m_H e^{-\pi kR})^2|H|^2$$

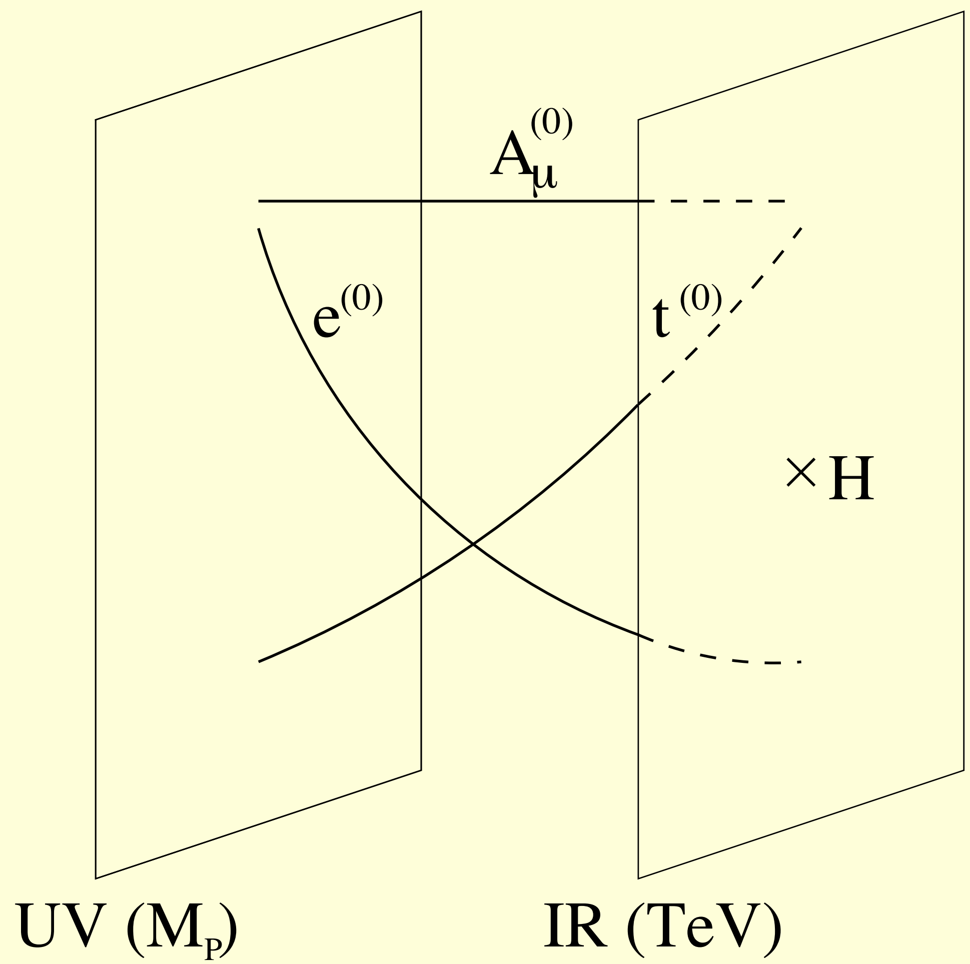


Figure 2: *The Standard Model in the warped five-dimensional bulk.*

OR, only gravity in the bulk and all the SM fields on the IR brane

Scores of some models

	SM	SUSY	RS-I
Quad Div.	Problem	Yes(SUSY)	Yes (warp factor)
$M_W << M_{Pl}$	Problem	Mu problem	Yes (warp factor)
G.C.U.	No	Yes	Yes
Cold DM	No (axion ?)	Neutralino, gravitino, axion ?	Yes

SM in the bulk

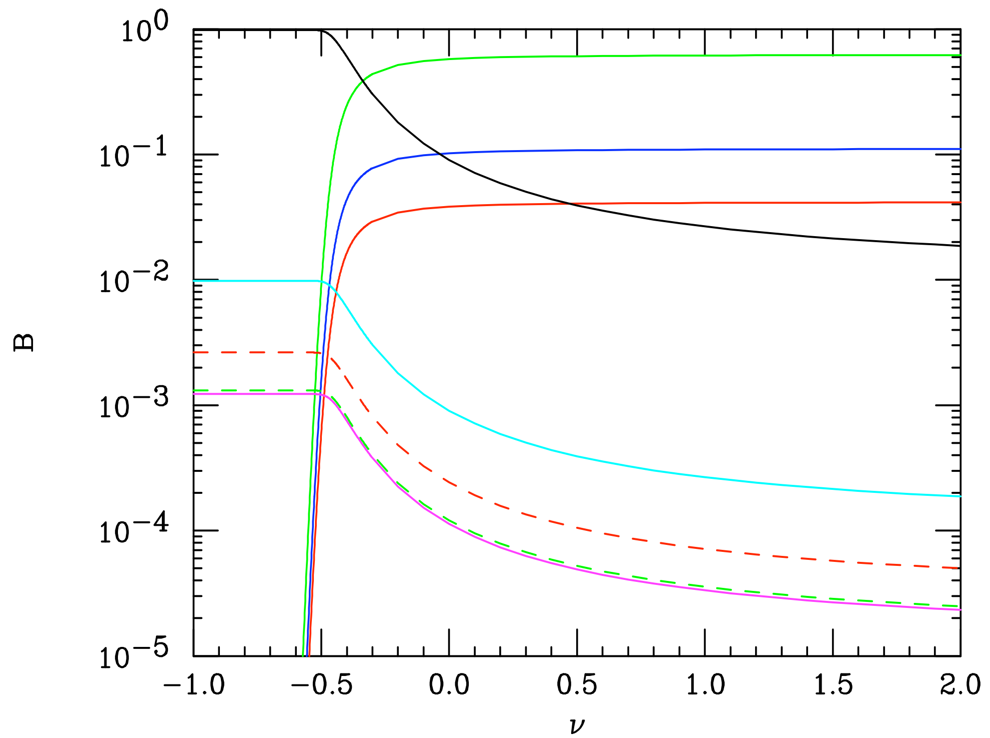


Figure 6: Branching fractions for two-body decays of the first KK graviton excitation with a mass of 1 TeV as a function of ν. The final states are, from top to bottom on the right-hand side of the figure, pairs of light quarks, tops, leptons, higgs, gluons, W's, Z's and photons. The Higgs mass is assumed to be 120 GeV.

SM on the TeV brane

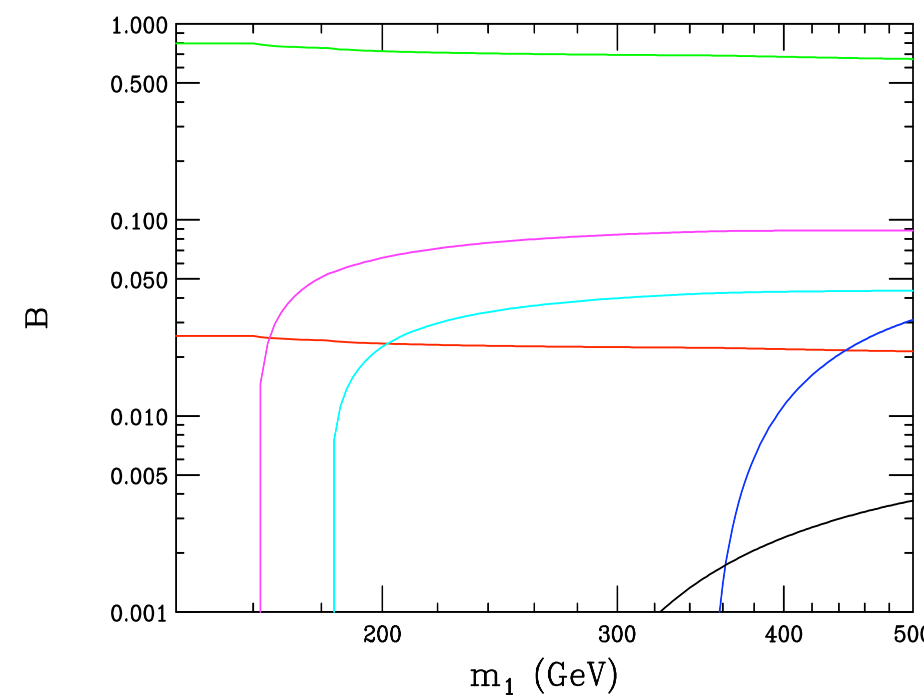


Figure 14: Mass dependencies of the two-body branching fractions for the first graviton KK state in the case where the SM fields are on the wall. From top to bottom on the right side of the figure the curves are for dijets, W's, Z's, tops, dileptons and Higgs pairs assuming a Higgs mass of 120 GeV.

$$
\begin{aligned}
G_1 &\rightarrow l^+l^- \quad \text{OR} \\
&\rightarrow ZZ \rightarrow 4\mu \\
&\rightarrow WW \rightarrow 3\mu + \nu
\end{aligned}
$$

depending on the mass and other parameters

Davoudiasl, Hewett, Rizzo (2000)

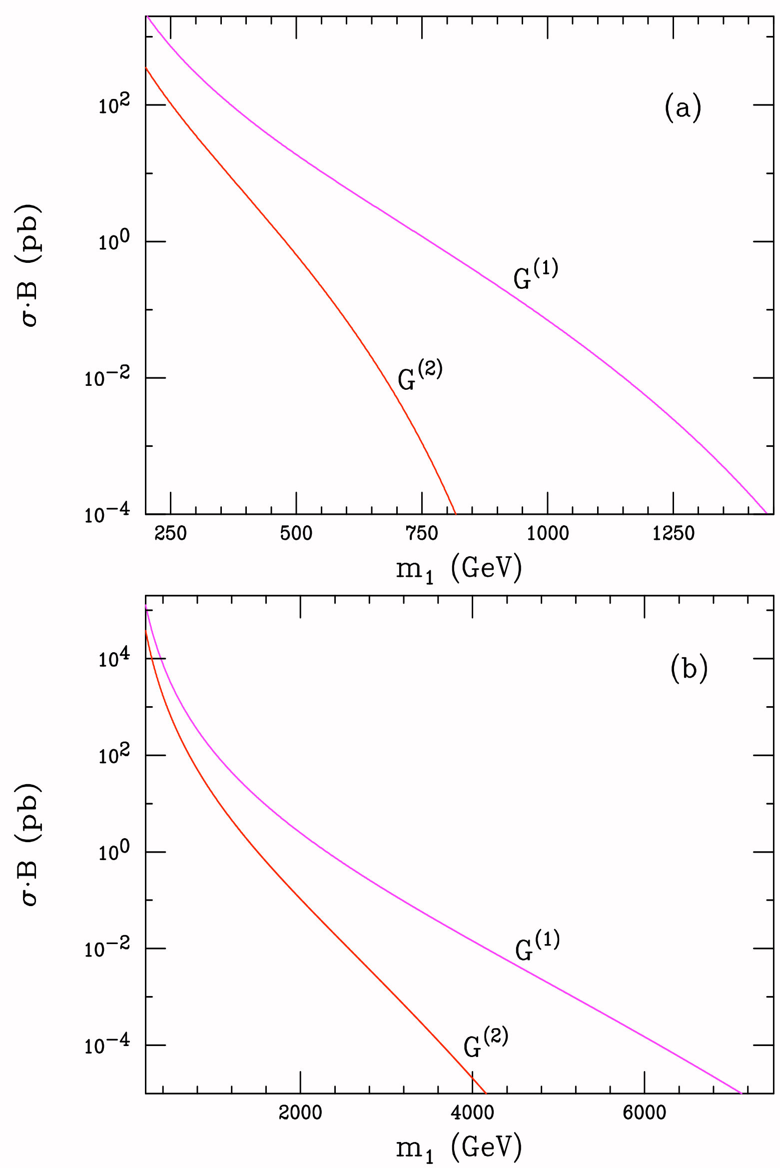


Figure 18: Cross sections for Drell-Yan production at the (a) Tevatron and (b) LHC of the first two graviton KK states coupling to the SM on the wall as a function of m_1. The upper (lower) curve in each case is for the first (second) KK state. Here, we have set $k/\overline{M}_{Pl} = 0.1$.

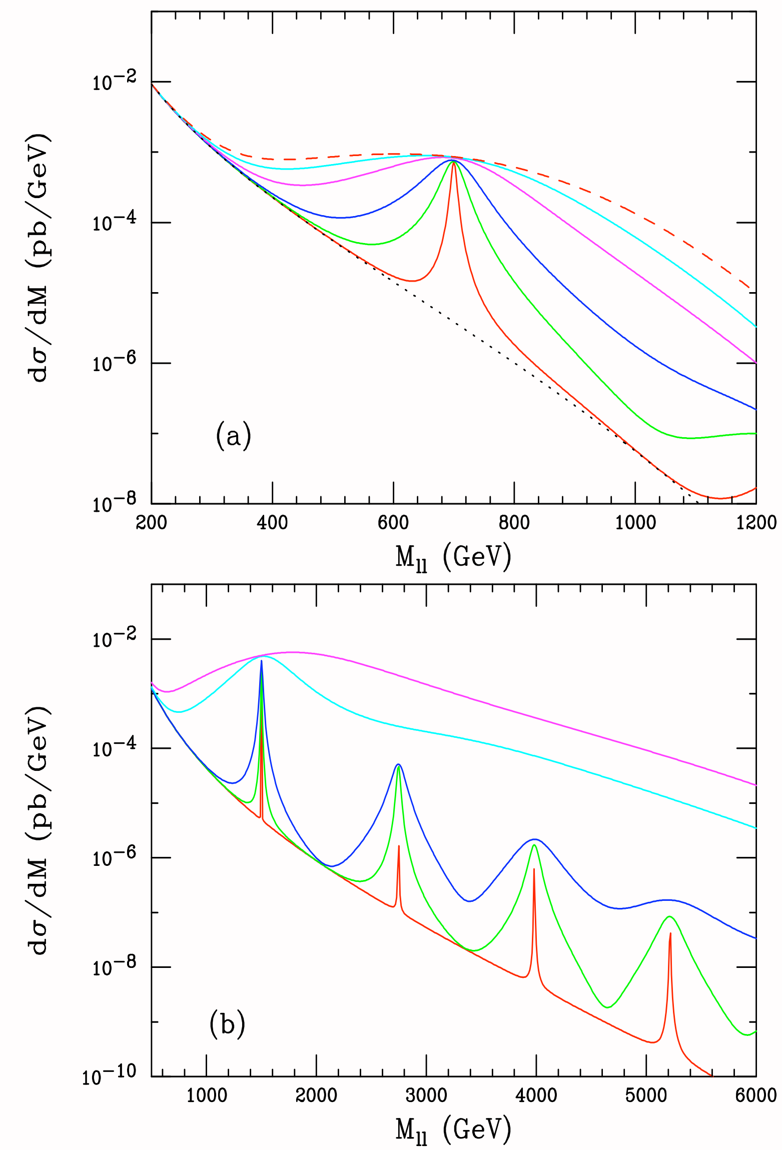


Figure 17: Drell-Yan production of a (a) 700 GeV KK graviton at the Tevatron with $k/\overline{M}_{Pl} =$ 1, 0.7, 0.5, 0.3, 0.2, and 0.1, respectively, from top to bottom; (b) 1500 GeV KK graviton and its subsequent tower states at the LHC. From top to bottom, the curves are for $k/\overline{M}_{Pl} =$ 1, 0.5, 0.1, 0.05, and 0.01, respectively.

Spin Determination from angular distribution

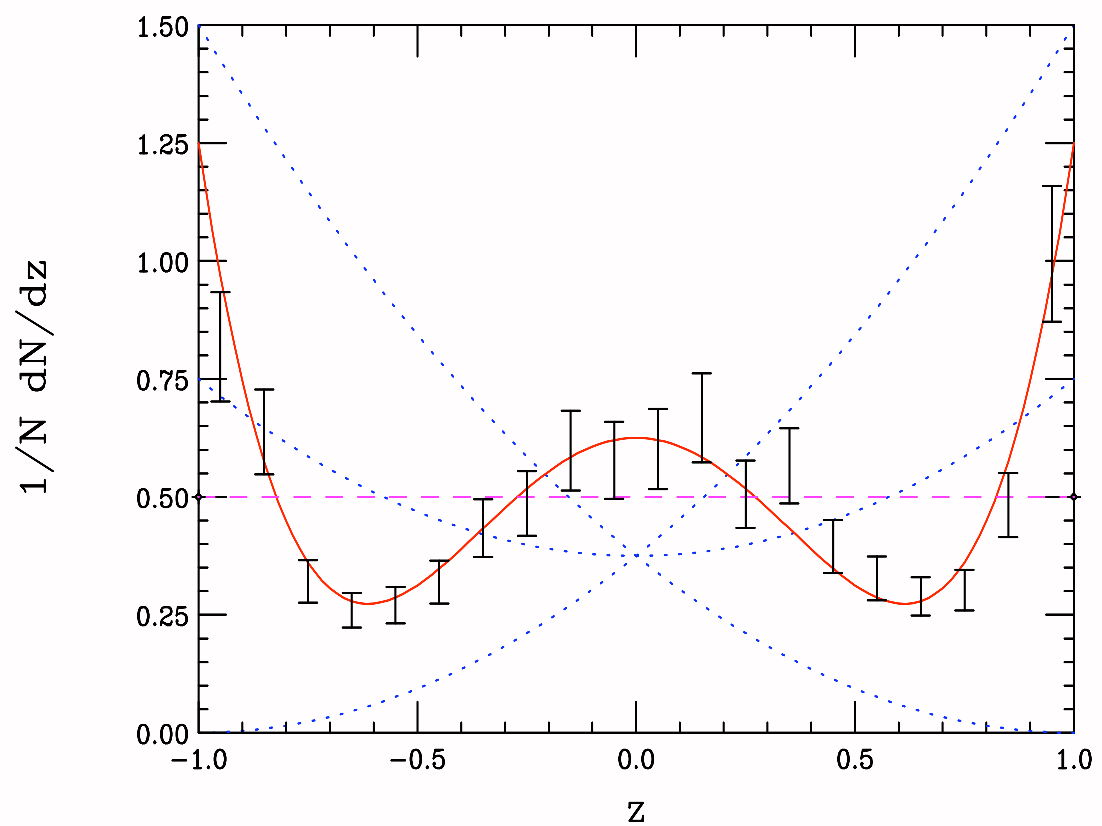


Figure 19: Normalized angular distribution ($z = \cos\theta$) for the decay of a spin-2 graviton into fermion pairs (the 'w'-shaped curve) in comparison to similar decays by either spin-0 (dashed) or spin-1 (dotted) particles. The data with errors show the result from a typical sample of 1000 events.

RS: Radion

- How to stabilize the extra dim in RS ? (Goldberger and Wise)
- Radion ϕ: scalar dof associated with fluctuation of the two branes
- Radion couplings to the SM:

$$\mathcal{L} = \frac{1}{\Lambda_\phi} \phi T^\mu_\mu (\mathrm{SM})$$

- Simialr to the Higgs coupling to the SM fields, upto v/Λ_ϕ scaling
- Radion phenomenology is very similar to the Higgs phenomenology for $\xi = 0$, except that $\phi - g - g$ coupling is enhanced due to the anomaly (Ko et al.)
- Higgs-radion mixing from $\xi R H^\dagger H$ term : (Giudice, Rattazzi, Wells)

EWSB by New Strong Interaction

- Technicolor
- EWSB w/o Higgs boson in Extra Dim

Technicolor (TC)

- Dynamical generation of EWSB
- Enough to have three NG bosons for W_L and Z_L
- Similar to the chiral symmetry breaking of QCD in the SM with three NG bosons: $\pi^\pm, \pi^0$
- Consider new strong force (called TC, local $SU(N_{TC})$ gauge group) with flavors with $SU(2)_L \times SU(2)_R$ global chiral symmetry :

$$\begin{pmatrix} U_L \\ D_L \end{pmatrix}, \begin{pmatrix} U_R \\ D_R \end{pmatrix}$$

  with $\alpha = 1, 2, ..N_{TC}$
- Assume $SU(2)_L \times SU(2)_R \to SU(2)_V$ for two-flavor TC theory
- We get exactly 3 NG bosons necessary for $W_L^\pm$ and Z_L

Collider Signatures for TC

- TC is nonperturbative and very difficult to calculate many observables
- The scaled-up version of TC is strongly disfavored by EWPT (Peskin and Takeuchi's S, T, U parameters)
- Can consider different versions of TC
- Typical signatures of TC : π_{TC}, ρ_{TC}, ω_{TC}, $a_{1,TC}$, σ_{TC}, etc.
- Eichten, Lane, Martin interprete the CDF Wjj excess in terms of production and decays of TC particles (2011):

$$p\bar{p} \to \rho_{TC} \to \pi_{TC} W \to (jj)(l\nu)$$

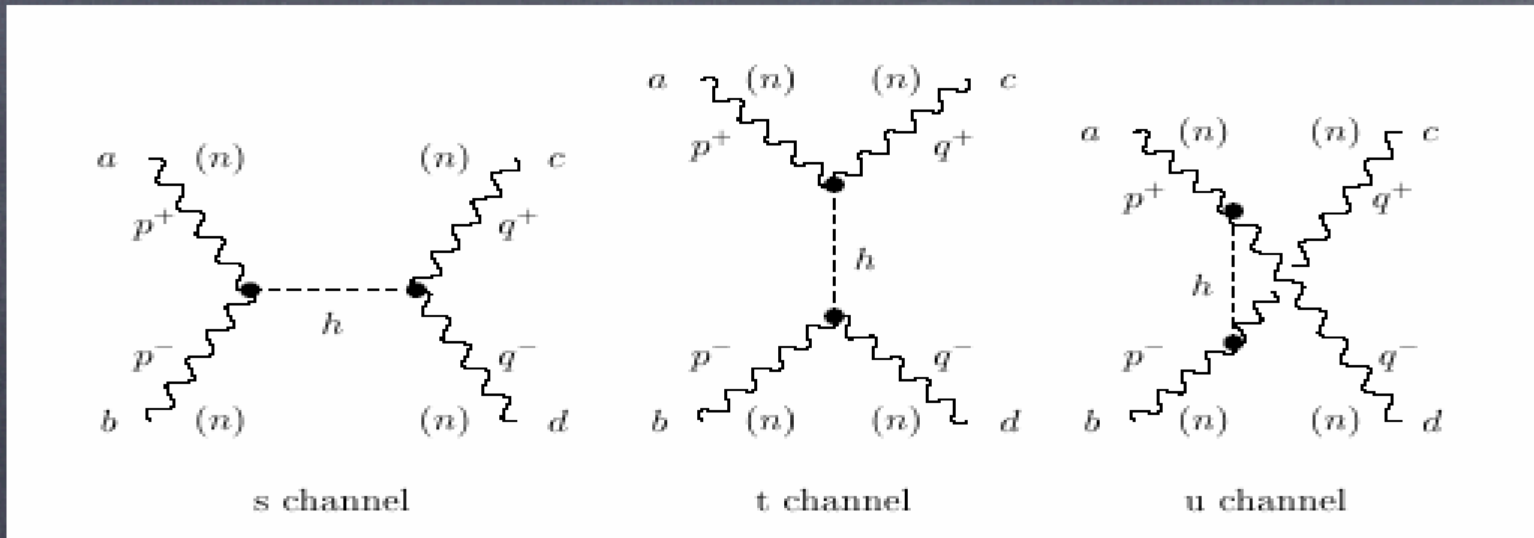
Higgsless EWSB in extra dim

- Lee, Quigg, Thacker tell us that Higgs boson unitarizes $W_L W_L$ scattering
- One can give W mass by a suitable boundary conidition in extra dim
- What happens to the perturbative unitarity in $W_L W_L$ scattering ?
- Unitarity is acheived when we add up the conitrubutions of infinite tower of KK states, due to the sumrules that are dervied from 5-dim gauge symmetry
- Interesting predictions for a resonance in $W_L Z_L$ channel
- Fermion setor is too complicated to be described here in brief

Higgsless EWSB and New Gauge Bosons

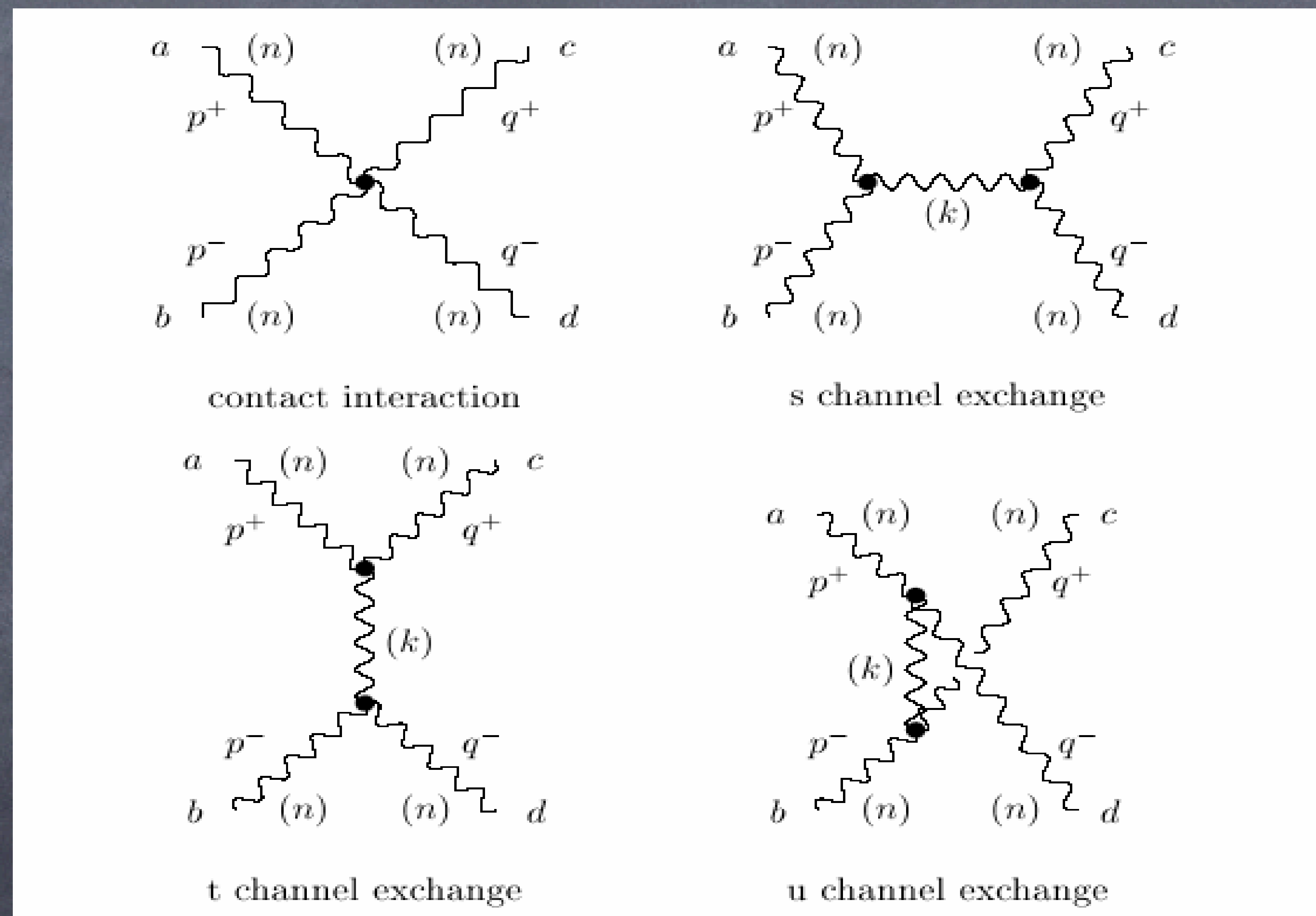
EWSB by Boundary Conditions

- WW scattering violates unitarity
- New physics scale around $\Lambda \sim 4\pi M_W/g \sim 1.8\mathrm{TeV}$
- Too low & in conflict with EW precision test
- Folklore : Tree level unitarity of WL WL elastic scattering is achieved by Higgs boson (B.W.Lee, C. Quigg and H.B.Thacker, 1977)
- True in 4-dim w/ finite number of particles



(in 4 dim)

VS.



(in 5 dim)

Sumrules from higher dim gauge invariance

$$A = A^{(4)} \frac{E^4}{M_n^4} + A^{(2)} \frac{E^2}{M_n^2} + A^{(0)} + \mathcal{O}\left(\frac{M_n^2}{E^2}\right).$$

$$A^{(4)} = i\left(g_{nnnn}^2 - \sum_k g_{nnk}^2\right)\left(f^{abe} f^{cde}(3 + 6\cos\theta - \cos^2\theta) + 2(3 - \cos^2\theta) f^{ace} f^{bde}\right)$$

$$A^{(2)} = \frac{i}{M_n^2}\left(4 g_{nnnn} M_n^2 - 3\sum_k g_{nnk}^2 M_k^2\right)\left(f^{ace} f^{bde} - \sin^2\frac{\theta}{2}\, f^{abe} f^{cde}\right)$$

$$g_{nnnn}^2 = \sum_k g_{nnk}^2.$$

$$4 g_{nnnn}^2 M_n^2 = 3\sum_k g_{nnk}^2 M_k^2.$$

- So, the folklore is evaded if there are infinite number of KK states, and the sumrules are satisfied (Csaki, Grojean, Murayama, Pilo and Terning (2003))

- Realistic model : Csaki, Grojean, Terning et al. by adjusting fermion structures

- $$\boxed{\Lambda \sim \frac{3\pi^4}{g}\frac{M_W^2}{M_1^2} \sim 5 - 10\mathrm{TeV}}$$

- W, Z : the 1st KK modes of gauge fields in the bulk, the 0th modes are projected out by suitable boundary conditions

- Similar to closed vs. open pipe air column, fixed vs.

Saturation Limit : The 1st KK mode almost saturates the sum rules

" Small Coupling to SM gauge bosons "

$$g^{(1)}_{WZV} \lesssim \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_1^{\pm} M_W} \approx 0.04 \quad \text{for } M_1^{\pm} = 700\text{GeV}$$

" Very Narrow Vector Resonance "

$$\Gamma(V_1^{\pm} \to W^{\pm} Z) \approx \frac{\alpha (M_1^{\pm})^3}{144 \sin^2\theta_W M_W^2}$$

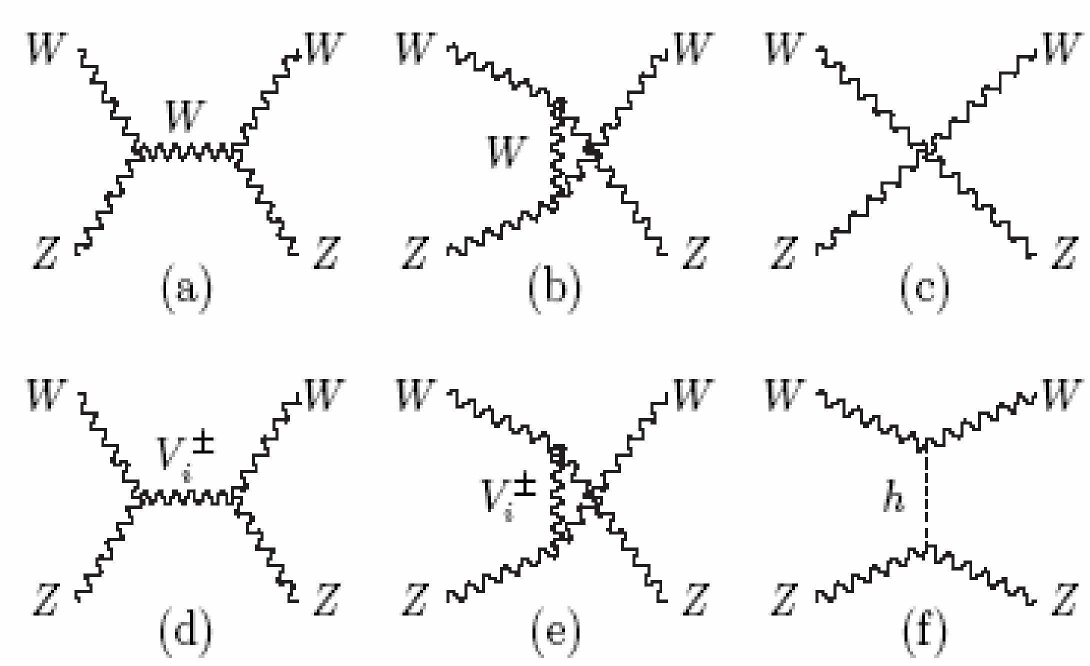


FIG. 1. Diagrams contributing to the $W^{\pm}Z \to W^{\pm}Z$ scattering process: (a), (b) and (c) appear both in the SM and in Higgsless models, (d) and (e) only appear in Higgsless models, while (f) only appears in the SM.

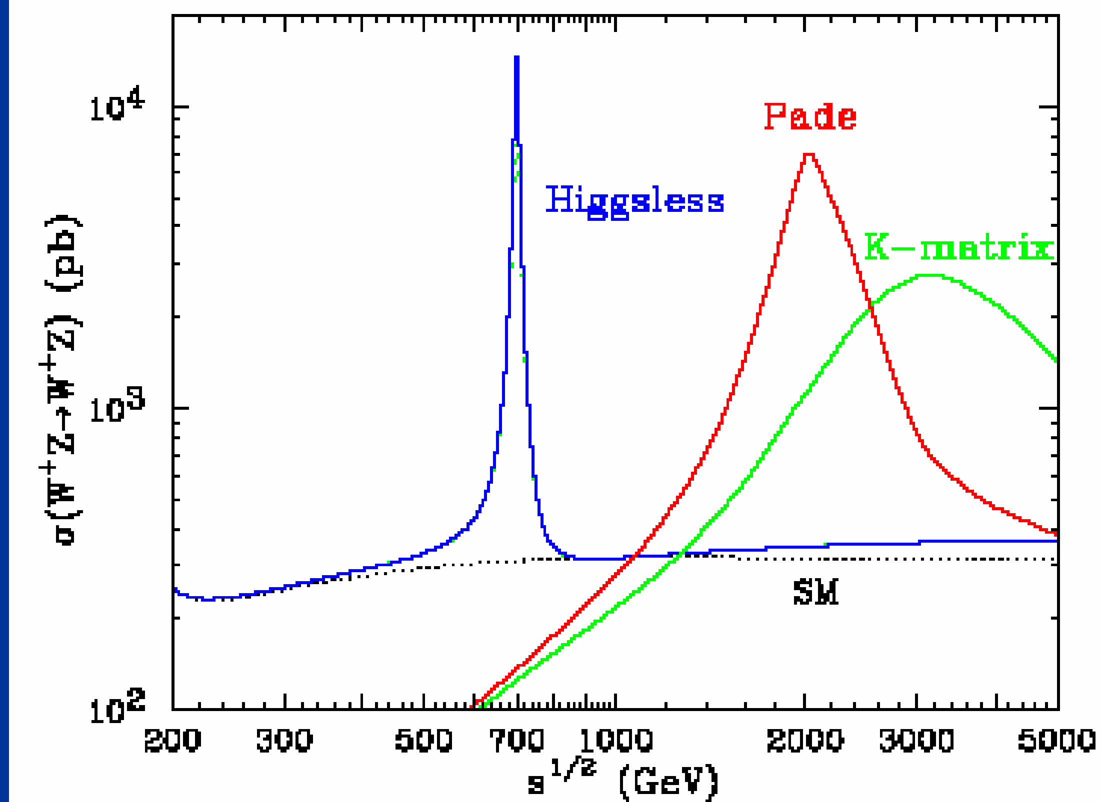


FIG. 2. WZ elastic scattering cross-sections in the SM (dotted), the Higgsless model (blue), and two "unitarization" models: Padé (red) and K-matrix (green).

Birkedal, Matchev, Perelstein (2005) PRL

Resonance in the WZ channel is a unique feature of this scenario !!

"Multi muons"

Comparison of WW and WZ elastic scatterings

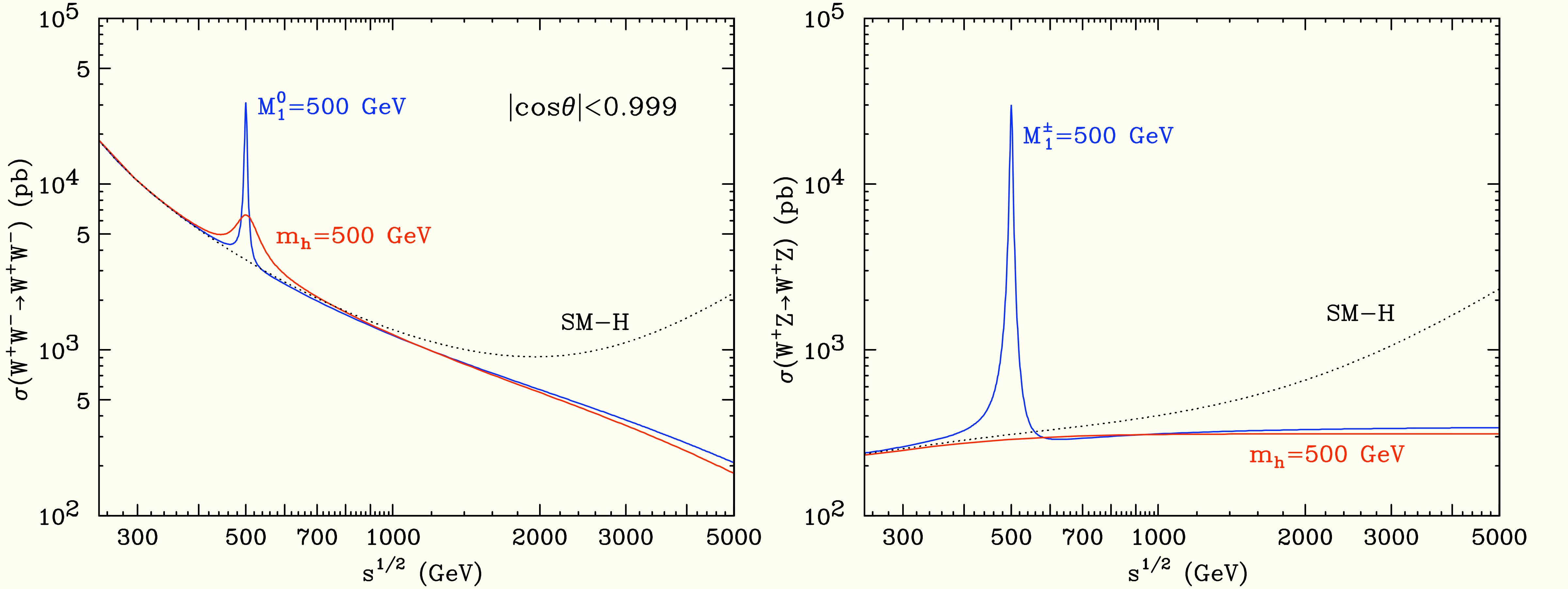


Figure 3: Elastic scattering cross-sections for $WW \to WW$ (left) and $WZ \to WZ$ (right) in the SM without a Higgs boson (SM-H) (dotted), the SM with a 500 GeV Higgs boson (red) and the Higgsless model with a 500 GeV MVB (blue).

Model	$WW \to WW$	$WZ \to WZ$	$WW \to ZZ$
SM	Yes	No	Yes
Higgsless	Yes	Yes	No

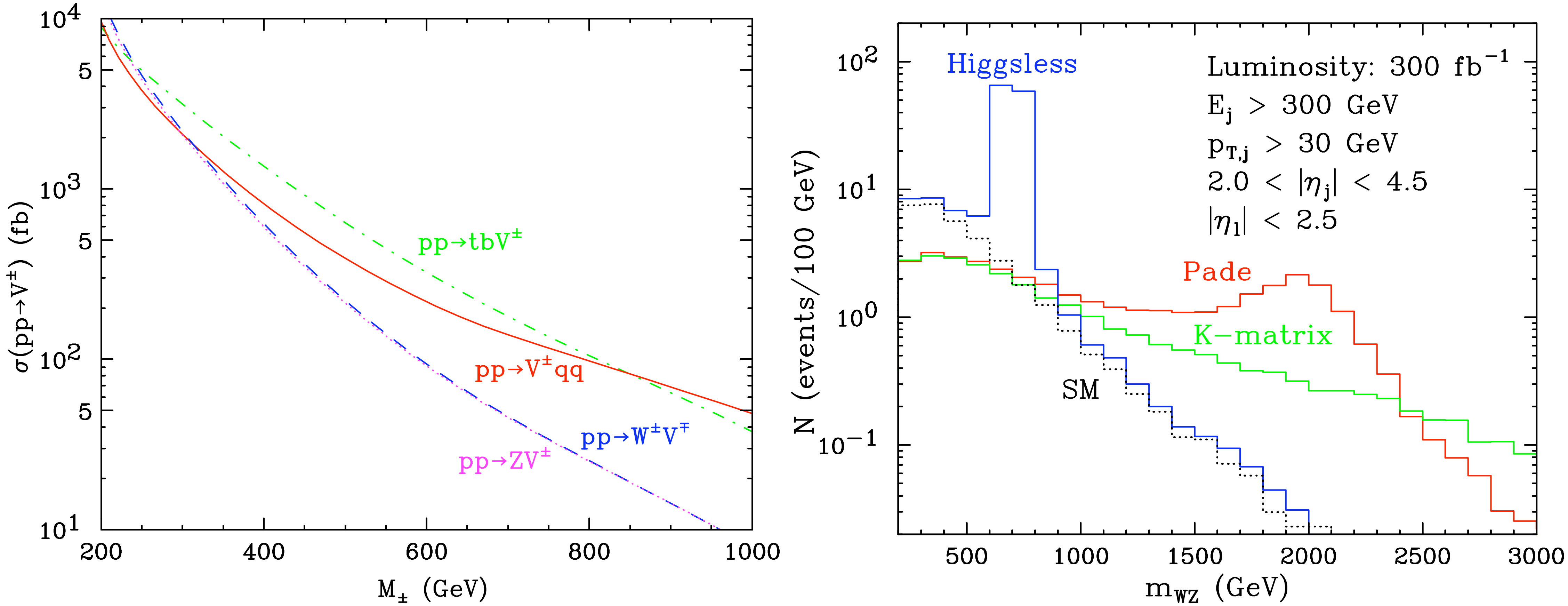


Figure 4: Left: Production cross-sections of $V^\pm$ at the LHC. Here $tbV^\pm$ production assumes SM-like couplings to third generation quarks. Right: The number of events per 100 GeV bin in the $2j + 3\ell + \nu$ channel at the LHC with an integrated luminosity of 300 fb^{-1} and cuts as indicated in the figure. Results are shown for the SM (dotted), the Higgsless model with $M_1^\pm = 700$ GeV (blue), and two "unitarization" models: Padé (red) and K-matrix (green) [16].

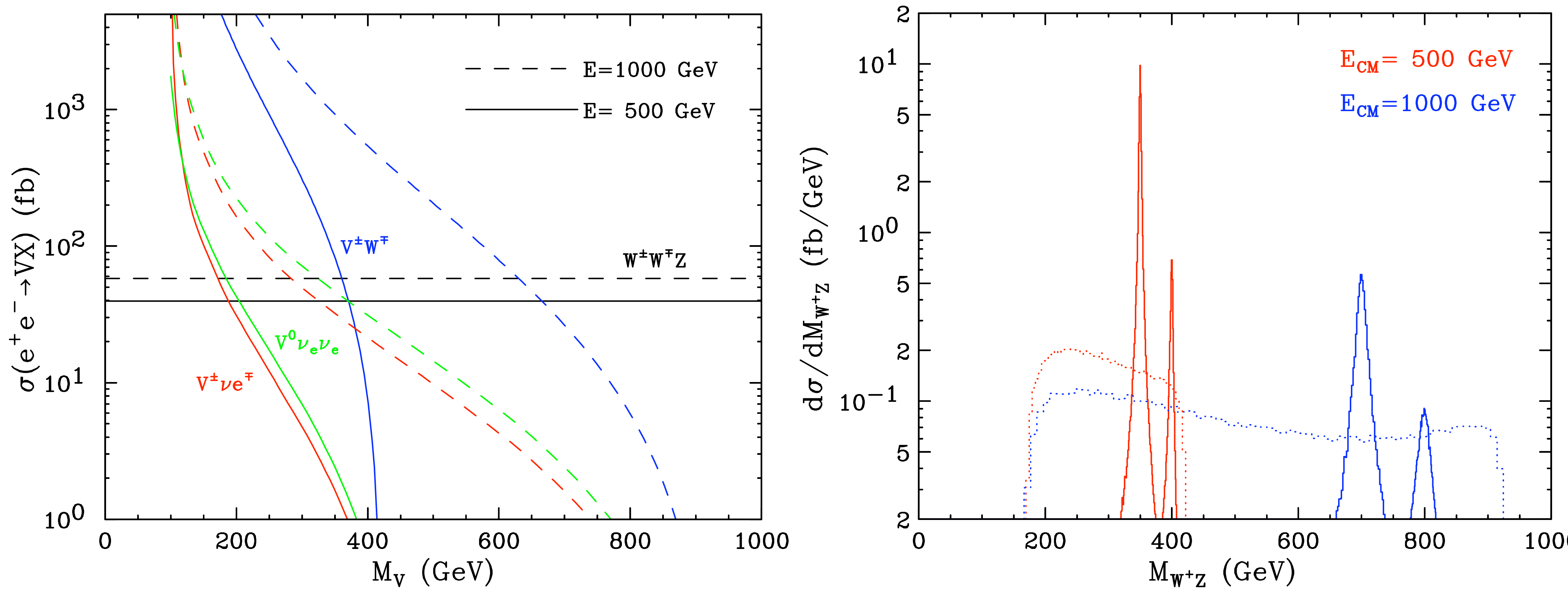


Figure 5: Left: V_1 production cross-sections and the continuum SM background at an e^+e^- lepton collider of center of mass energy 500 GeV (solid) or 1 TeV (dashed). Right: WZ invariant mass distribution for Higgsless signals (solid) and SM background (dotted), at $E_{CM} = 500$ GeV (red, $M^{\pm} = 350, 400$ GeV) and $E_{CM} = 1$ TeV (blue, $M^{\pm} = 700, 800$ GeV).