Radiative Corrections and Universal Extra Dimensions

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University of Pittsburgh
@Brookhaven Forum 2017

Fig.1 A multi-loop correction to a tree

with Ayres Freitas and Kyoungchul Kong

The Why, the What and the How

the Why

- Universal Extra Dimensions (UED) is an attractive new physics model
- **KK-Parity** leads to stable dark matter candidate

the What

Radiative corrections: [1)]

- Split the heavily degenerate **mass spectrum**/open up decay channels (leading Log not sufficient)
- Induce **KK-Number violating couplings** (old and new)

the How

- Sum over the an **infinite tower** of states for mass corrections
- The induced couplings do not require resummation but a cutoff

[1)] H. Cheng, K. Matchev, M. Schmaltz hep-ph/1702.00401

Universal Extra Dimensions (UED)

Universal Extra Dimensions:

- Assume five-dimensional spacetime manifold
- To explain four-dimensional world impose boundary conditions (Kaluza Klein Compactification/**Orbifolding**)

$$\Psi(x^\mu, y) = \Psi(x^\mu, y + 2\pi R)$$

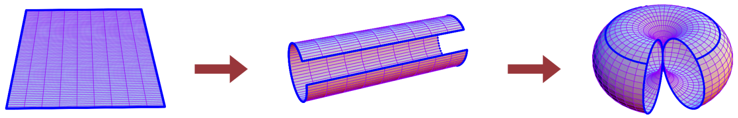
(Current Limit: $M = \frac{1}{R} \geq 1400\text{GeV}$ with $\Lambda R \sim 10$[1,2,3] @LO)

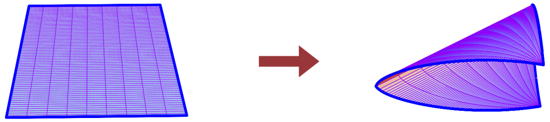
$$\Psi(x^\mu, y) = \Psi(x^\mu, -y)$$

- Fields $\Psi(x^\mu, y)$ propagating can be decomposed into Fourier modes

$$\Psi(x^\mu, y) = \frac{1}{\sqrt{\pi R}}\psi_0(x) + \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty}\psi_n(x)\cos\frac{ny}{R}$$

- ψ_0 are the standard model modes, ψ_n a tower of additional (heavy) excitations of mass $M = \frac{n}{R}$





[1] N. Deutschmann, T.Flacke, J. Kim hep-ph/1702.00401

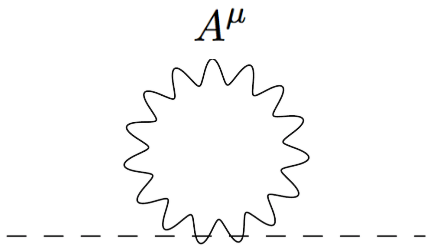
[2] K. Matchev, A.Datta et al hep-ph/1702.00413

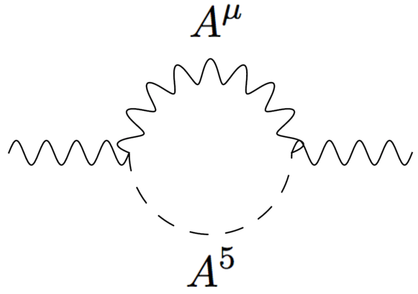
[3] ATLAS hep-ex/1501.03555

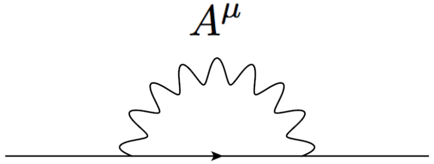
Instead of calculating 5D self-energies – try something different…

Mass Corrections (I)

…Using 4D EFT and **Poisson summation identity**:







$$\underbrace{\sum_{n=-\infty}^{\infty} \Sigma_n}_{\text{Sum over KK-modes}} = \underbrace{\sum_{k=-\infty}^{\infty} \mathcal{F}\left(\Sigma_k \right)}_{\text{Sum over winding numbers (formaly infinite)}}$$

$$\mathcal{F}\{f\}(k) = \int dx f(x) e^{-2\pi i k x}$$

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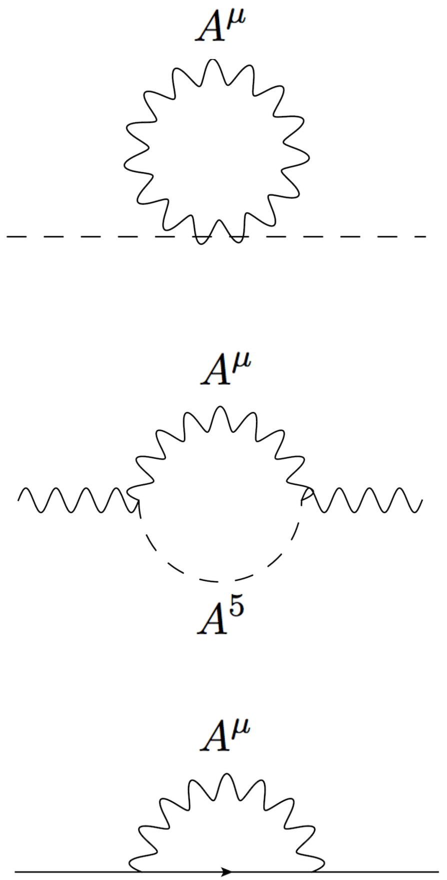

$$\underbrace{\sum_{n=-\infty}^{\infty} \text{—}\!\!\left(\Sigma_n\right)\!\!\text{—}}_{\text{Sum over KK-modes}} = \underbrace{\sum_{k=-\infty}^{\infty} \mathcal{F}\left(\text{—}\!\!\left(\Sigma_k\right)\!\!\text{—} \right)}_{\text{Sum over winding numbers (formaly infinite)}}$$

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Sum over KK-modes

Sum over winding numbers (formaly infinite)

Regularize by dropping the zero winding number, e.g.:

$$\sum_{n=0}^{\infty} A_o[n^2 M] = \frac{M^2}{2} \sum_{k=-\infty}^{\infty} \left[-\frac{\delta^2(k)}{4\pi^2} \left(\frac{1}{\varepsilon} + 1 - \log \frac{M^2}{\mu^2} \right) - \frac{1}{2\pi^2 |k|^3} \right]$$

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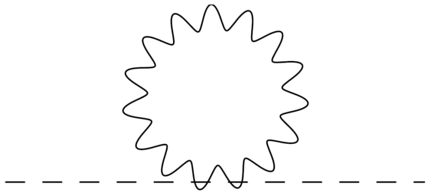

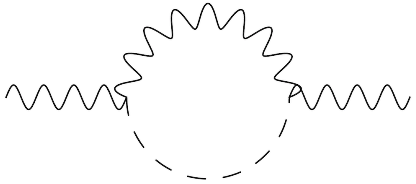

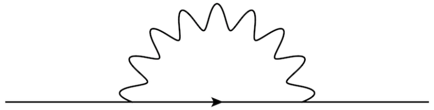

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which is contributing to the Bulk corrections.

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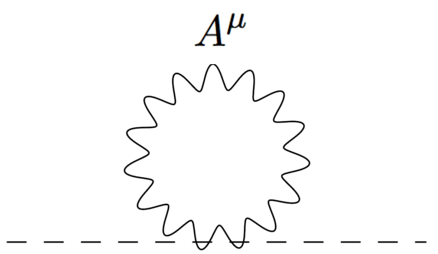

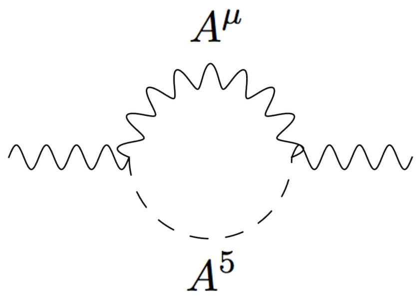

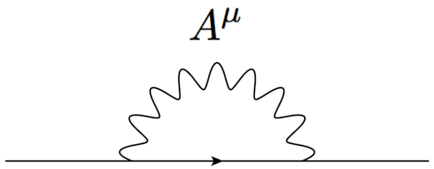

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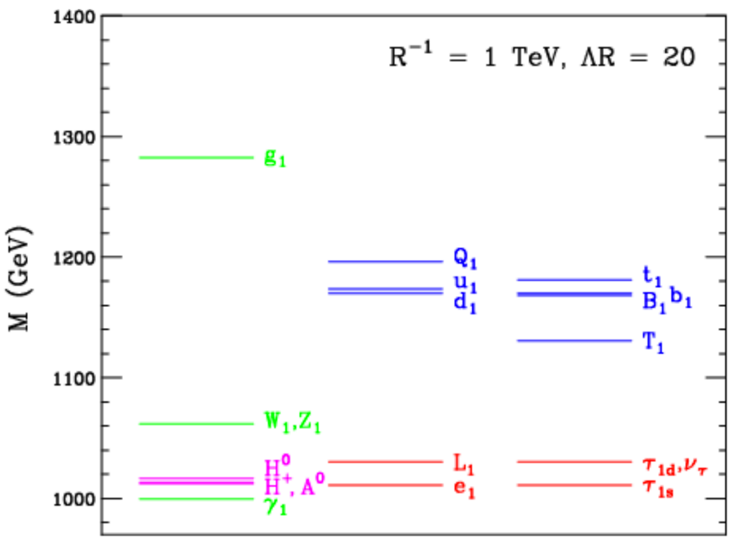
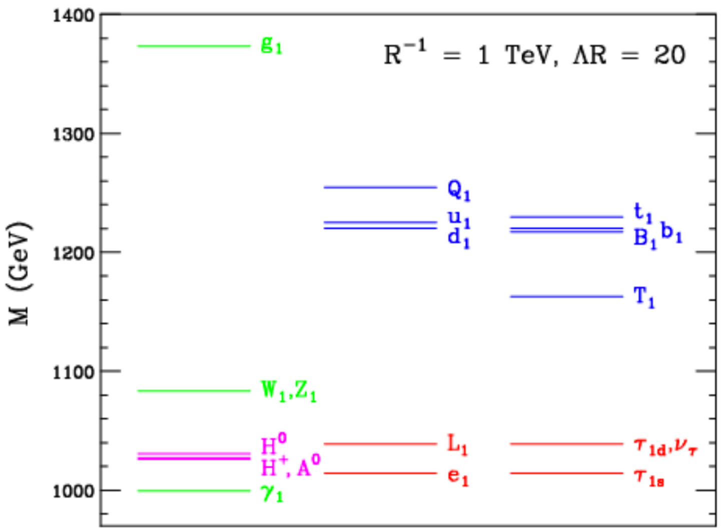
The Brane corrections still require a $\overline{MS}$/EFT counterterm $\sim \frac{1}{\varepsilon} + \log\frac{\Lambda^2}{\mu^2}$ ← Cutoff scale

Mass Corrections (II)

Fig.2 n=1 mass spectrum leading log (left) vs full one loop (right)





$$\delta M^2_{S_n} = Re[\Sigma^S_n(p^2)]\Big|_{p^2=M_n^2}$$

$$\delta M^2_{V_n} = -Re[\Sigma^T_n(p^2)]\Big|_{p^2=M_n^2}$$

$$\delta M_{F_n} = \frac{M_n}{2} Re\begin{bmatrix}\Sigma^L_n(M_n^2) + \Sigma^R_n(M_n^2) \\ +2\Sigma^s_n(M_n^2)\end{bmatrix}$$

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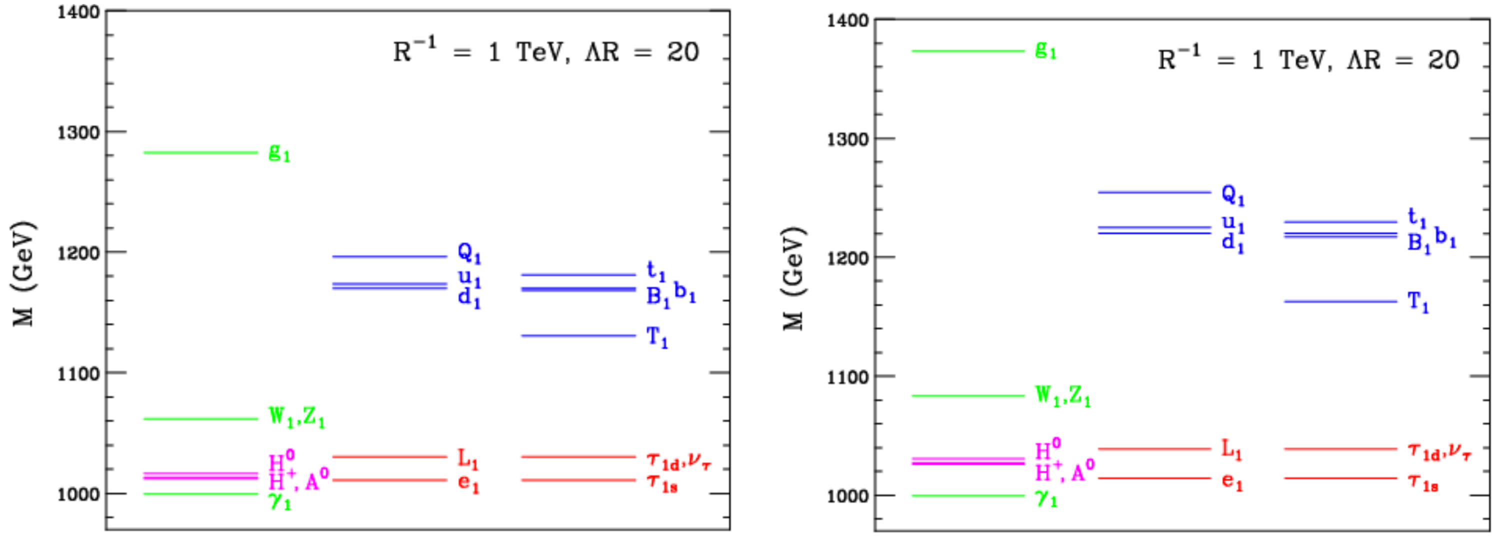

$$\delta M_{S_n}^2 = Re[\Sigma_n^S(p^2)]\Big|_{p^2=M_n^2}$$

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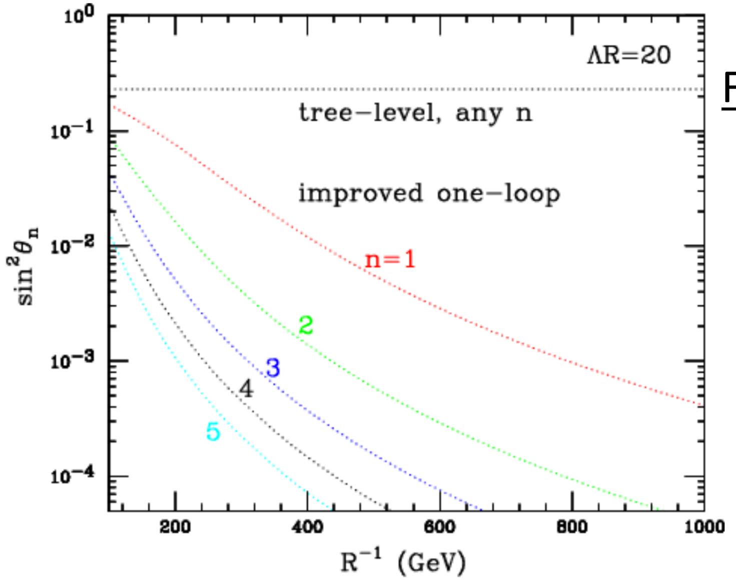


Fig.3 Weinberg mixing angle for higher modes

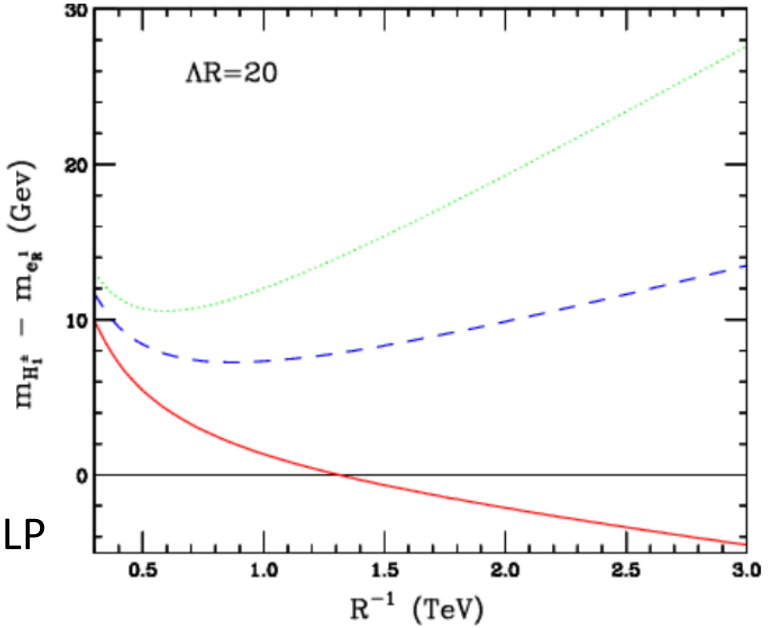
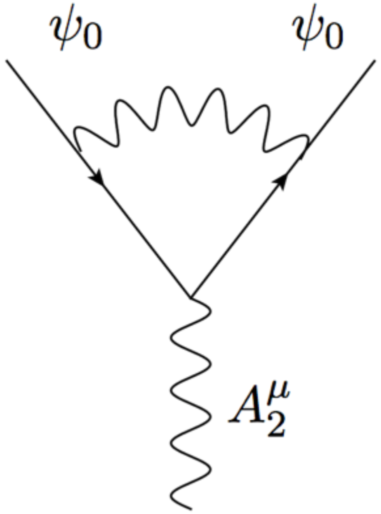


Fig.4 Higgs vs Lepton NLP

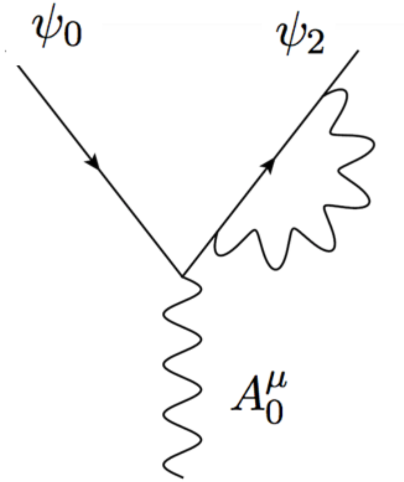
Vertex Corrections (I)

Old Couplings improved



$\log \Lambda^2 R^2$-dependence ~ finite stuff!

$$\mathcal{L}_F \supset -igC_{200}\overline{\psi_0}\gamma^\mu T^a\,\psi_0 A^a_{2\mu}$$



$$\mathcal{L}_{FD} \supset \underbrace{-igC_{020}\overline{\psi_2}\gamma^\mu T^a\,\psi_0}_{\text{Vector}} A^a_{0\mu} \underbrace{-\,igD_{020}\overline{\psi_2}\sigma^{\mu\nu}T^a}_{\text{Dipole}}\,\psi_0 F^a_{0\mu\nu}\text{+h.c.}$$

Vertex Corrections (I)

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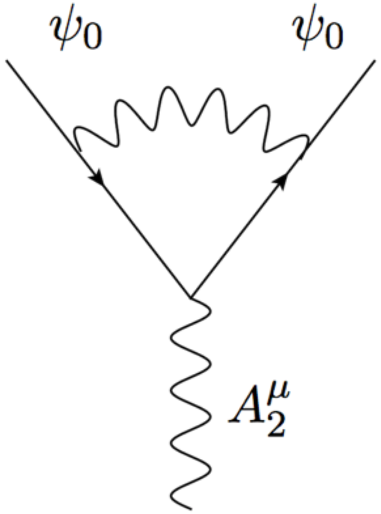

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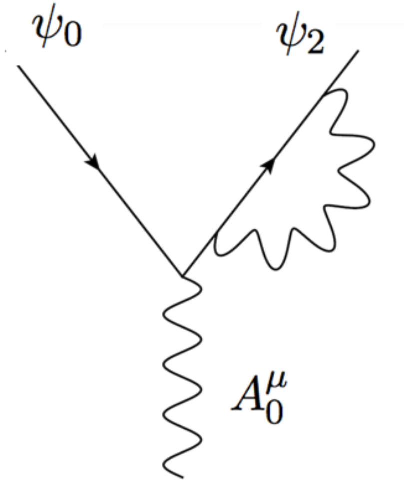

NO $\log \Lambda^2 R^2$-dependence!

$$\mathcal{L}_{FD} \supset -igC_{020}\overline{\psi_2}\gamma^\mu T^a \psi_0 A^a_{0\mu} - igD_{020}\overline{\psi_2}\sigma^{\mu\nu} T^a \psi_0 F^a_{0\mu\nu} + \text{h.c.}$$

Vector (Previously thought to be zero)

Dipole

Vertex Corrections (I)

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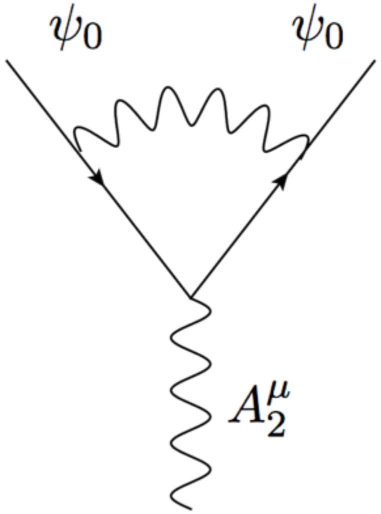

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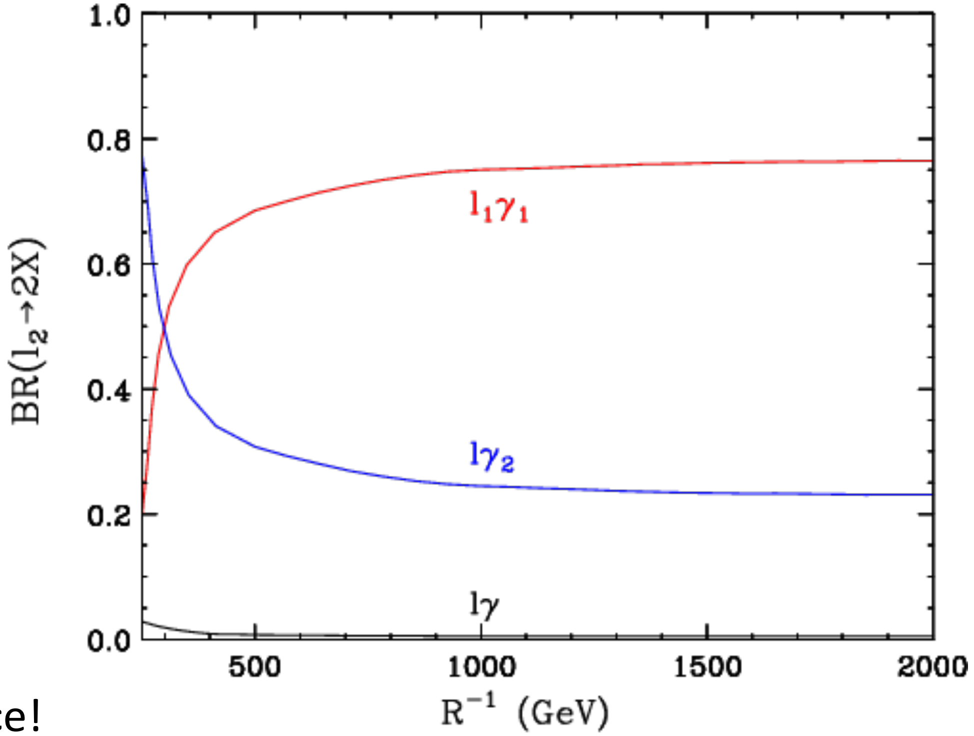
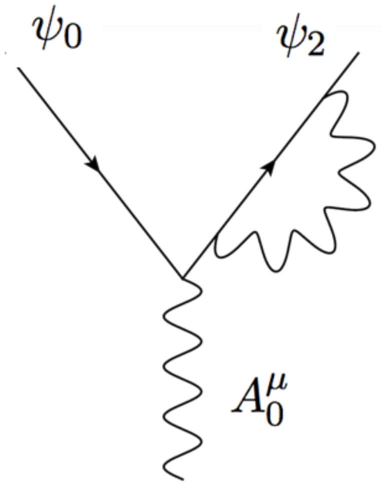


Fig.5 Lepton/NLKP decay width



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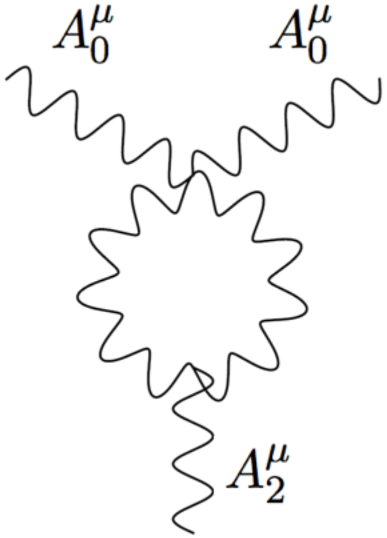
Vector — Dipole

Previously thought to be zero

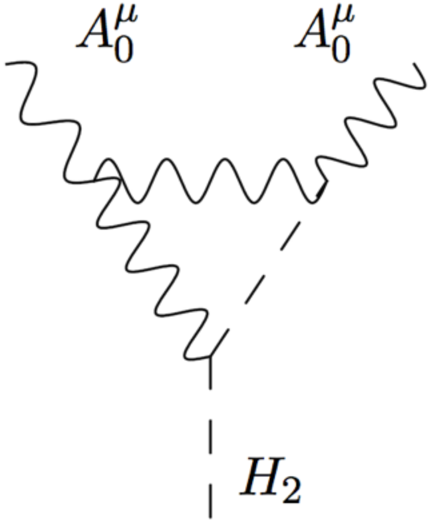
Vertex Corrections (II)

New couplings induced



$$\mathcal{L}_{3V} \supset \frac{\sqrt{2}C_{ijk}f^{abc}}{64\pi^2}\left[\left(\partial_\mu V_\nu^{a,i} - \partial_\nu V_\mu^{a,i}\right)V^{\mu,b,j}V^{\nu,c,k}\right]$$

→ C_{ijk} is not cyclically symmetric! Non-Log terms violate **5D gauge invariance**



$$\mathcal{L}_{HVV} \supset \frac{iv\sqrt{2}C_{ij}}{64\pi^2 M^2} H_2 F_{\mu\nu}^i F^{i,\mu\nu}$$

→ No coupling to SM gluons for **CP-even** Higgs
→ **CP-odd** Higgs does

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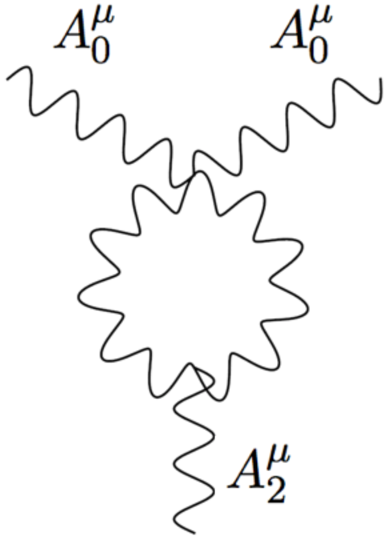

$$\mathcal{L}_{3V} \supset \frac{\sqrt{2}C_{ijk}f^{abc}}{64\pi^2}\left[\left(\partial_\mu V_\nu^{a,i} - \partial_\nu V_\mu^{a,i}\right)V^{\mu,b,j}V^{\nu,c,k}\right]$$

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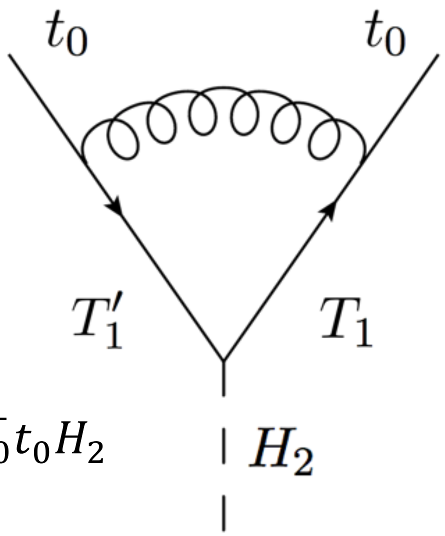
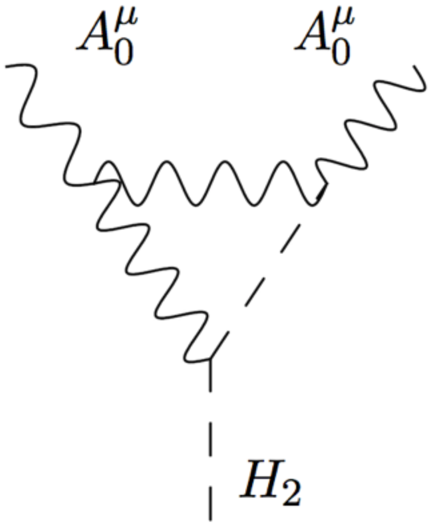


$$\mathcal{L}_{HVV} \supset \frac{\sqrt{2}C_{ttH}}{64\pi^2}\bar{t_0}t_0H_2$$

$C_{ttH} \sim \mathcal{O}(\alpha_s)$!



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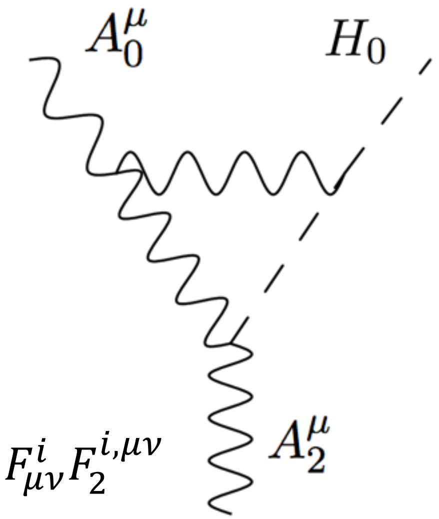

$$\mathcal{L}_{VHV} \supset \frac{iv\sqrt{2}G_{ij}}{64\pi^2M^2}H_0F_{\mu\nu}^iF_2^{i,\mu\nu}$$

Decay Widths and Branching Ratios

<u>A selection:</u>

$\frac{1}{R} = 1$ TeV $\quad \Lambda R = 20$

	$g_0 g_0$	$q_0 q_0$	$\bar{t}_0 t_0$	$Q_1 Q_1$
Gluon_2	56%	34%	6%	4%

Tree-level decays

	$t_0 g_0$	$t_0 \gamma_0$	$\mathrm{t}_1 \gamma_1$	$\mathrm{b}_0 W_0^+$
Top_2	78%	8%	12%	2%

	$\gamma_0 \gamma_0$	$\gamma_0 Z_0$	$Z_0 Z_0$	$W_0^+ W_0^-$	$\bar{t}_o t_o$
Higgs_2	2%	<1%	13%	24%	61%

(*Fine print: The branching rations only contain a selection of decay channels so far!)

…and now what?

What we have:

- A fully **one-loop corrected mass spectrum** telling us which decay channels are open!

- A comprehensive collection **of n=2 KK-number violating Wilson coefficients** implemented in `CalcHep`

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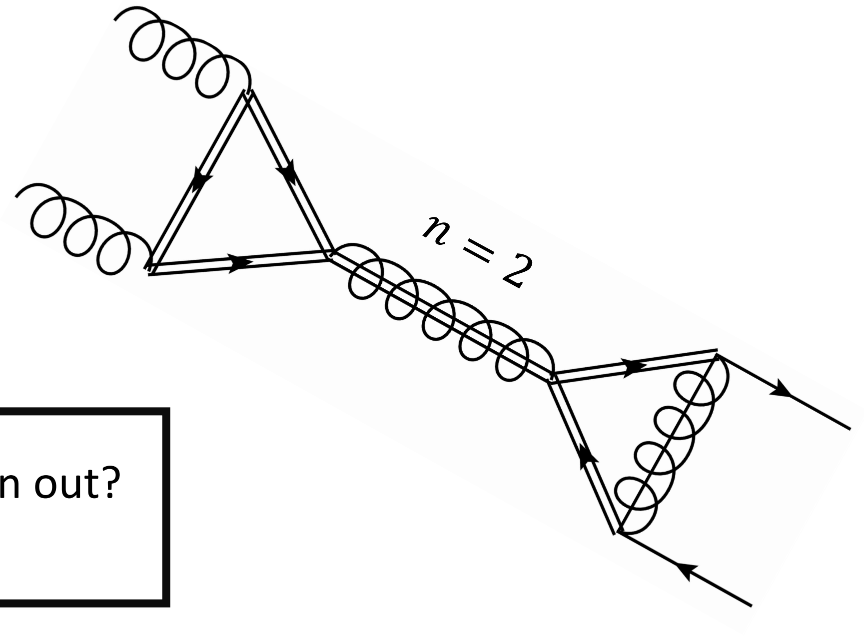
Follow-up/Work in Progress:

- How about Collider signatures/limits?

- Implications for/from relic abundance?



How are Λ and R going to turn out?
Stay tuned!

Thanks!