SUSY 2019
Theoretical and experimental considerations of a multi-brane world

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Based on:

- Agashe, Collins, Du, Hong, Kim, RKM, JHEP 1705 (2017) 078,
- Agashe, Collins, Du, Hong, Kim, RKM, Phys.Rev. D99 (2019) no.7, 075016,
- Agashe, Collins, Du, Hong, Kim, RKM, JHEP 1811 (2018) 027
- Csaki, Du, Hong, RKM, Telem, *in preparation*
- Contino, Max, RKM *in preparation*

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UNIVERSITY OF MARYLAND 1856

General Motivation: Away from the first attempts

- Naturalness as a guiding principle is under question. Many of the favorite BSM frameworks are increasingly fine-tuned.
- Are there plausible extensions of BSM scenarios that are consistent with observations and still meaningful phenomenologically?

RS models

Focus on this specific framework, but many considerations are model independent.

Flavor + CP + EWPT

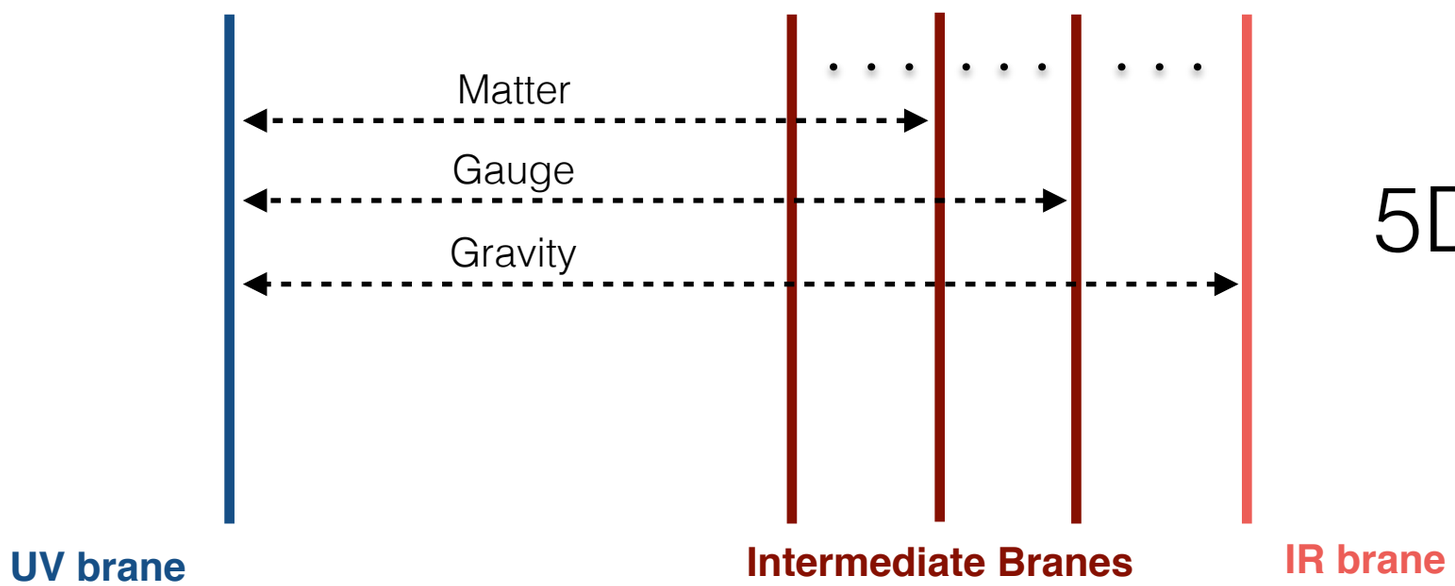
$$m_{\rm KK} \gtrsim 20 \text{ TeV}$$

Little hierarchy problem is not so little anymore.

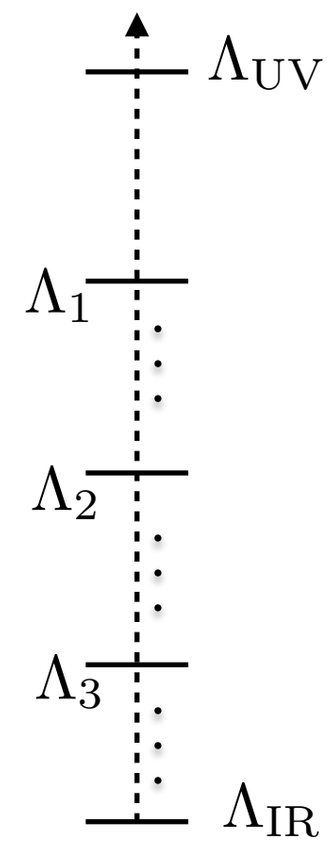
Extended RS

Agashe, Du, Hong, Sundrum JHEP 1701 (2017) 016

- General Framework: the IR structure not modeled by just one IR brane. There can be more than one brane in the IR.
- Bulk fields can propagate different amounts in the bulk.



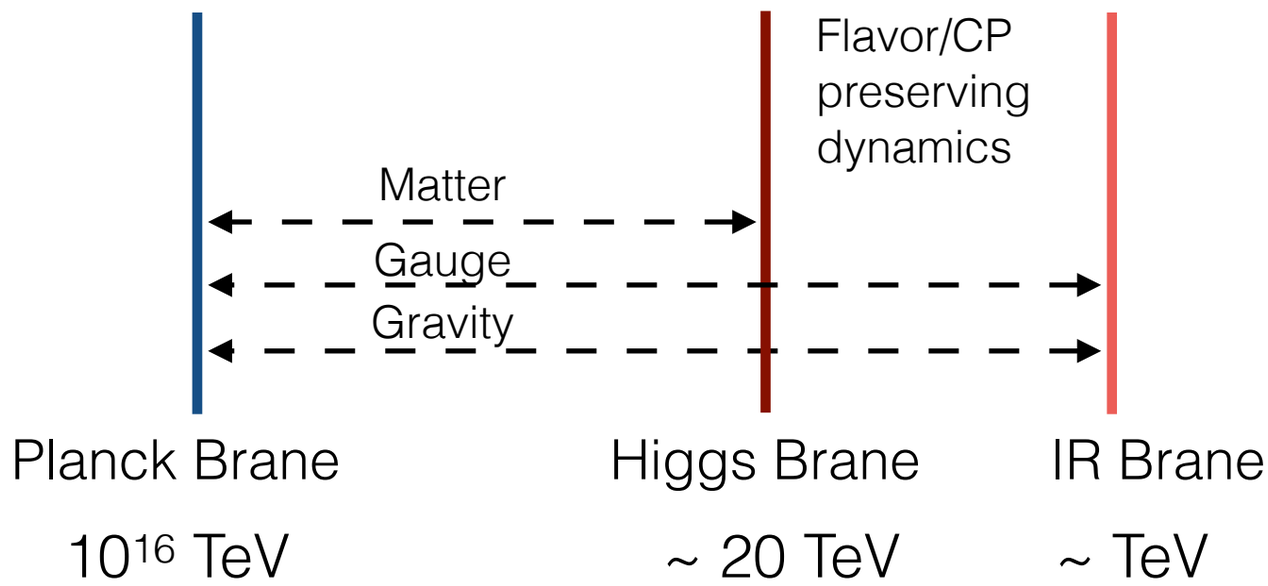
5D ⟷ 4D

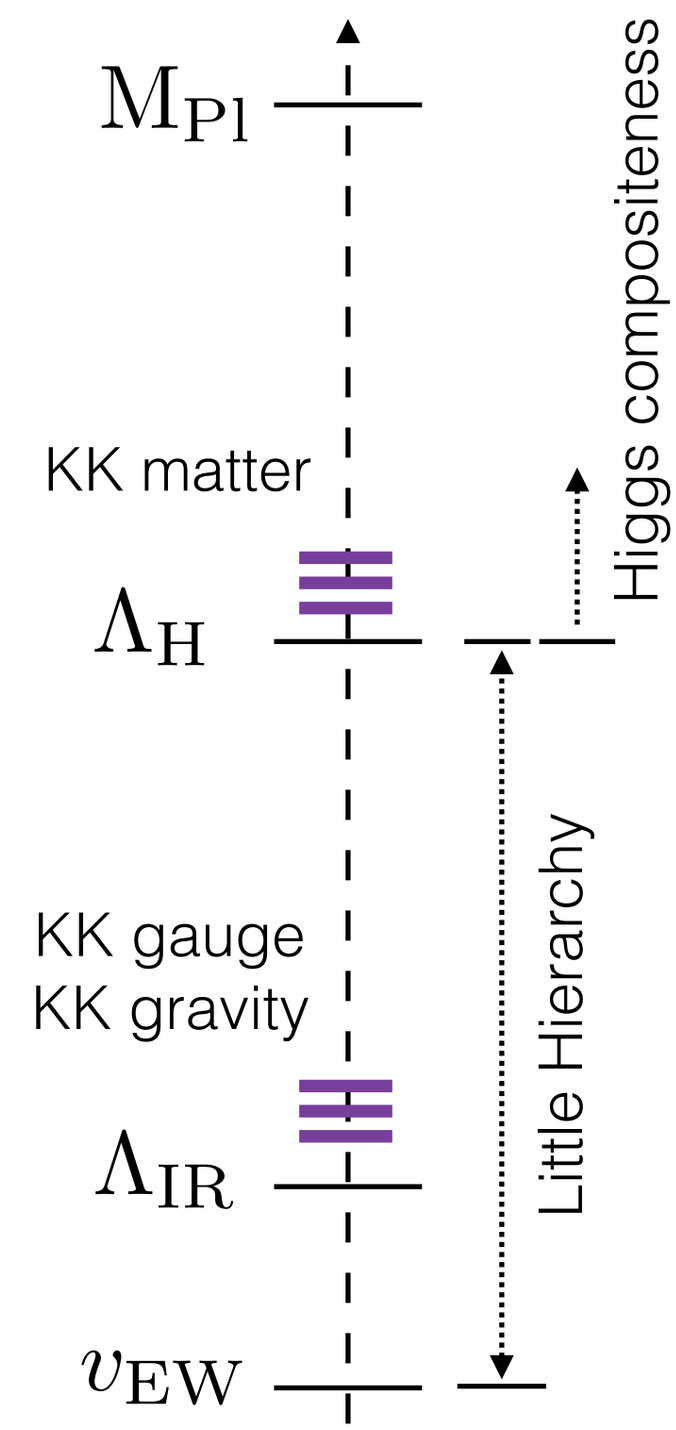


Guiding principle

- Gravity as a fluctuation of entire spacetime
- Matter can radiate gauge bosons

Simplest possibility: 1 intermediate brane (RS_3)



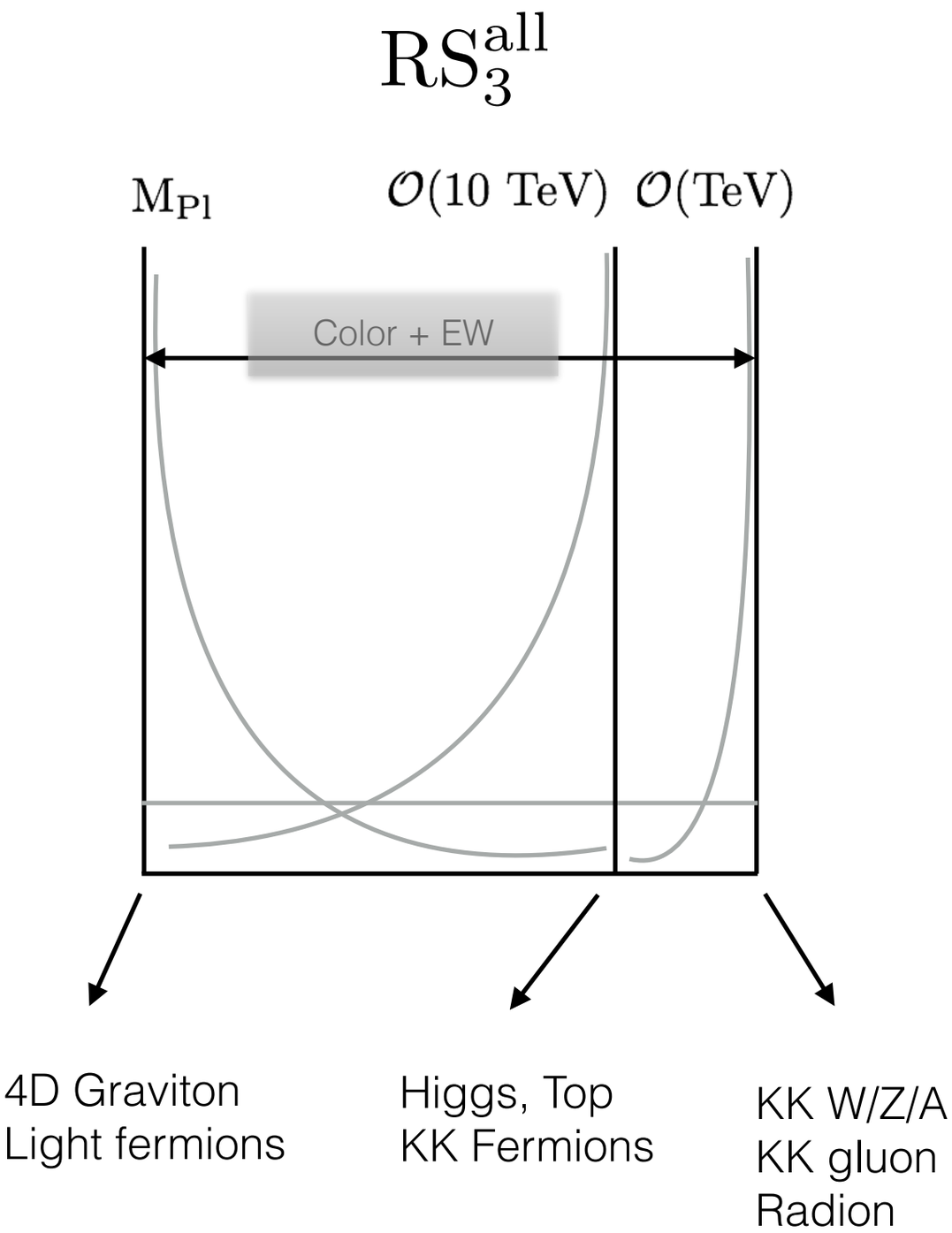


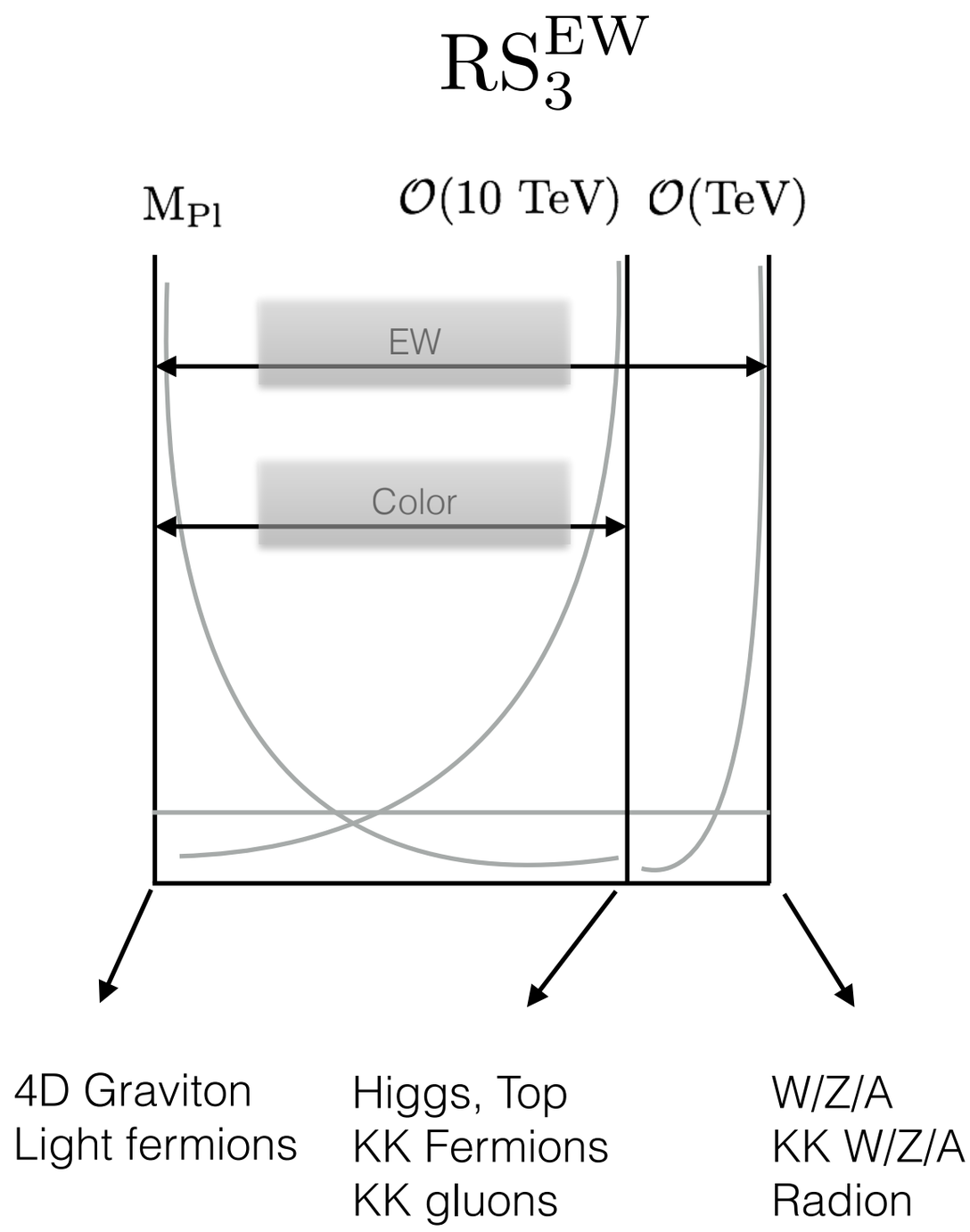
Still many possibilities!

(will need varying levels of sophistication)

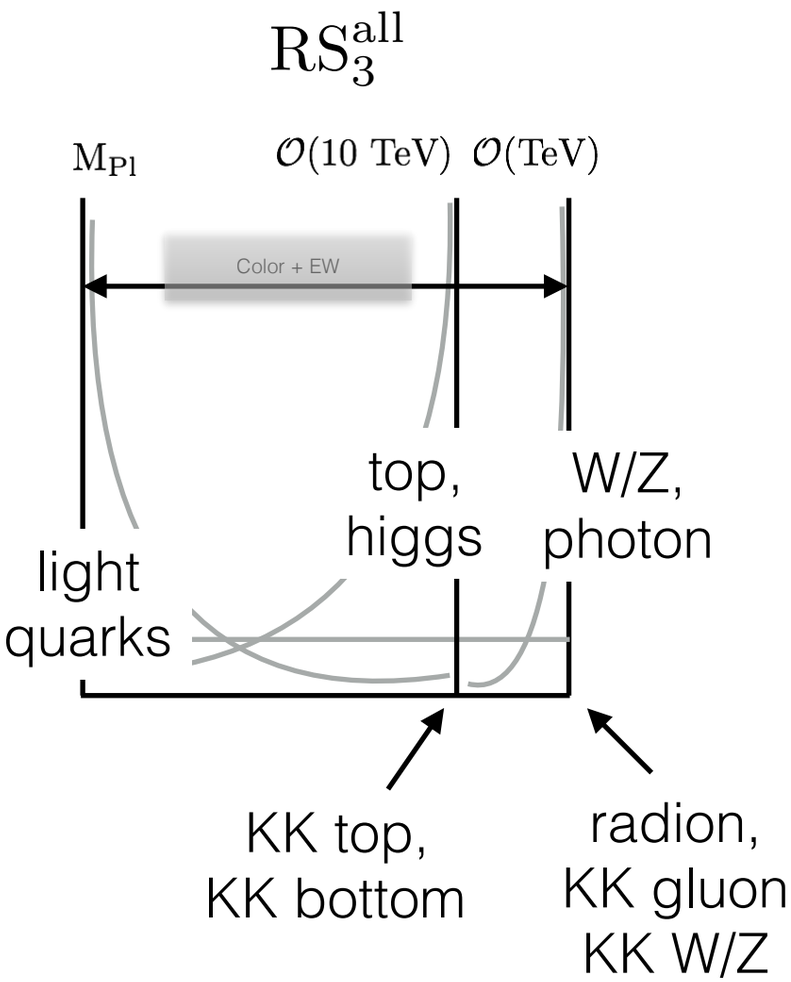
- **Agashe, Collins, Du, Hong, Kim, RKM, JHEP 1705 (2017) 078,**
- **Agashe, Collins, Du, Hong, Kim, RKM, Phys.Rev. D99 (2019) no.7, 075016,**
- **Agashe, Collins, Du, Hong, Kim, RKM, JHEP 1811 (2018) 027**

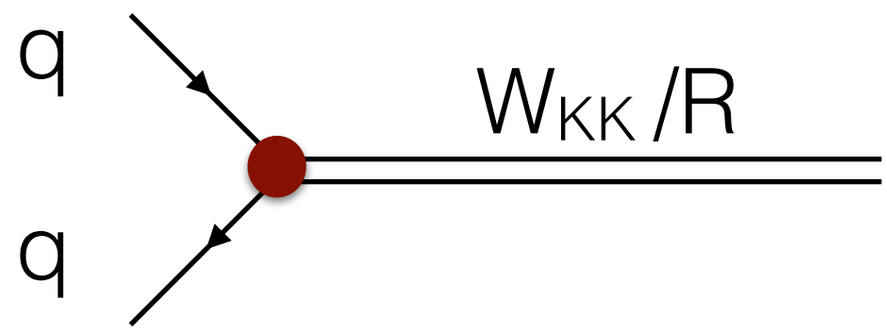
Two models


$\mathrm{RS}_3^{\mathrm{all}}$
$\mathrm{M_{Pl}}$
$\mathcal{O}(10\ \mathrm{TeV})$
$\mathcal{O}(\mathrm{TeV})$
Color + EW
4D Graviton
Light fermions
Higgs, Top
KK Fermions
KK W/Z/A
KK gluon
Radion

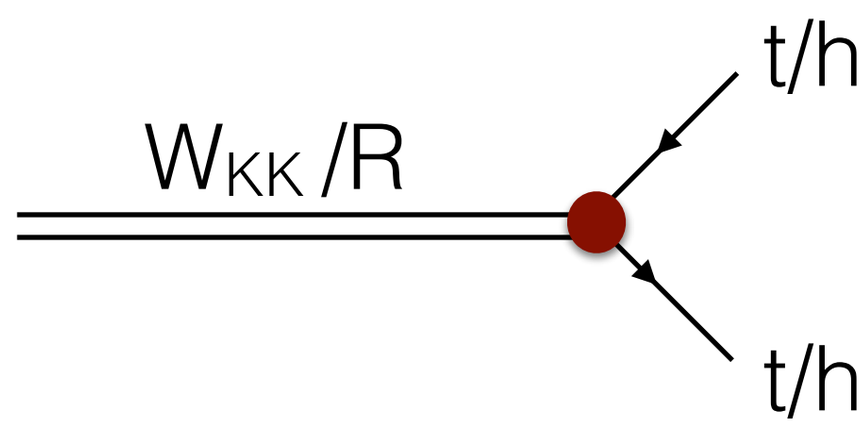

$\mathrm{RS}_3^{\mathrm{EW}}$
$\mathrm{M_{Pl}}$
$\mathcal{O}(10\ \mathrm{TeV})$
$\mathcal{O}(\mathrm{TeV})$
EW
Color
4D Graviton
Light fermions
Higgs, Top
KK Fermions
KK gluons
W/Z/A
KK W/Z/A
Radion

What changes from the standard RS scenario?



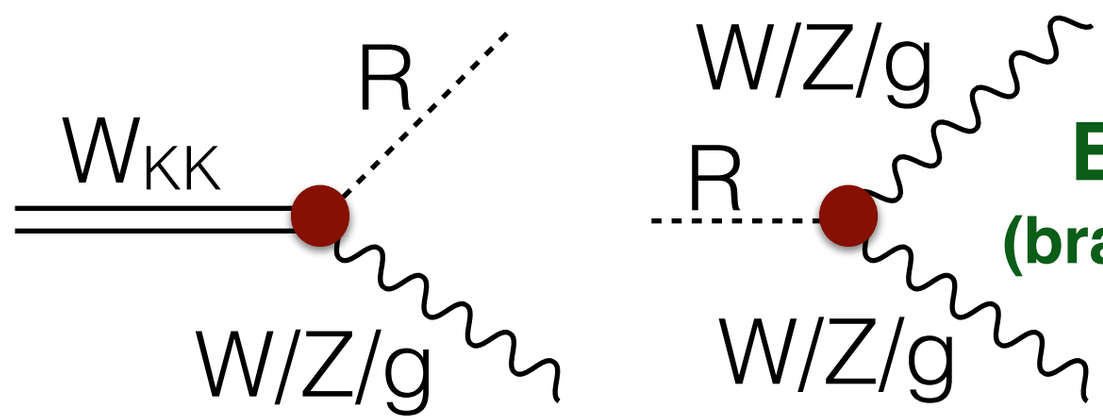


Unchanged



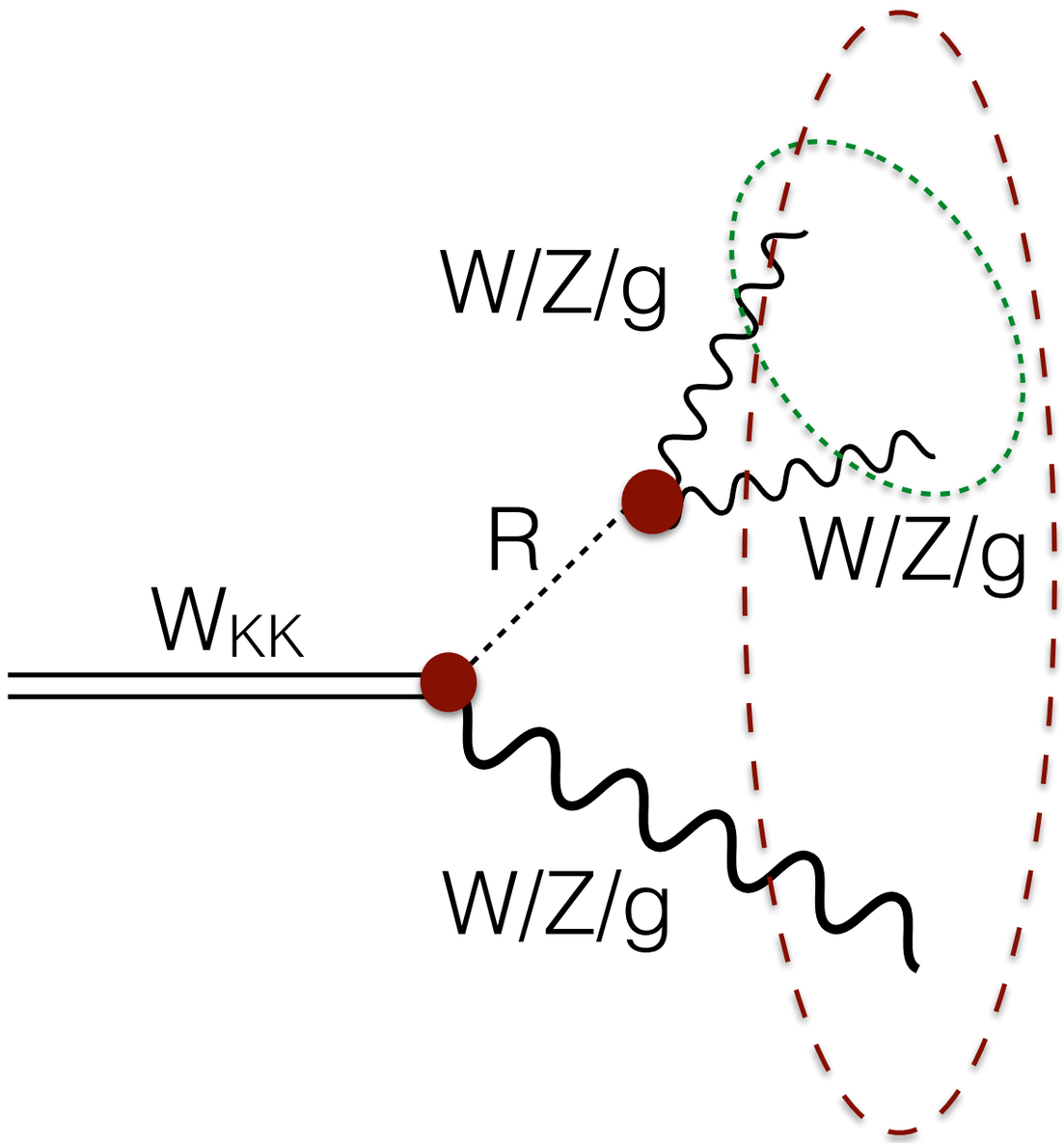
Reduced

- Matter propagates till ~20 TeV brane
- Gauge fields and gravity propagate till ~ TeV brane



Enhanced
(branching ratio)

Novel kinematic features: Cascade Decay



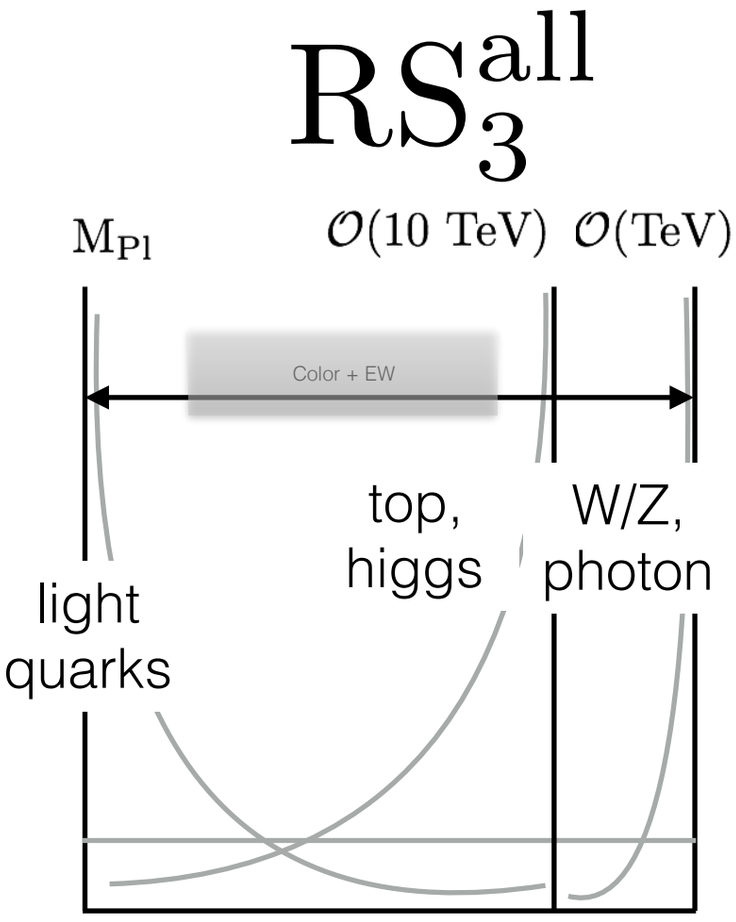
Novelty:

- Usual theoretically appealing features of RS models : HP, fermion mass hierarchy, flavor etc. But, naturalness probed indirectly.
- 2 and 3 body resonant structure.

Challenges:

- Kinematic Ambiguity in the signal.
- Non-standard topology of detector objects. Fat Jets with varying radii. Merged leptons, non isolated photons, etc…

An indirect effect of the naturalizing new physics



All gauge bosons propagate in the entire bulk

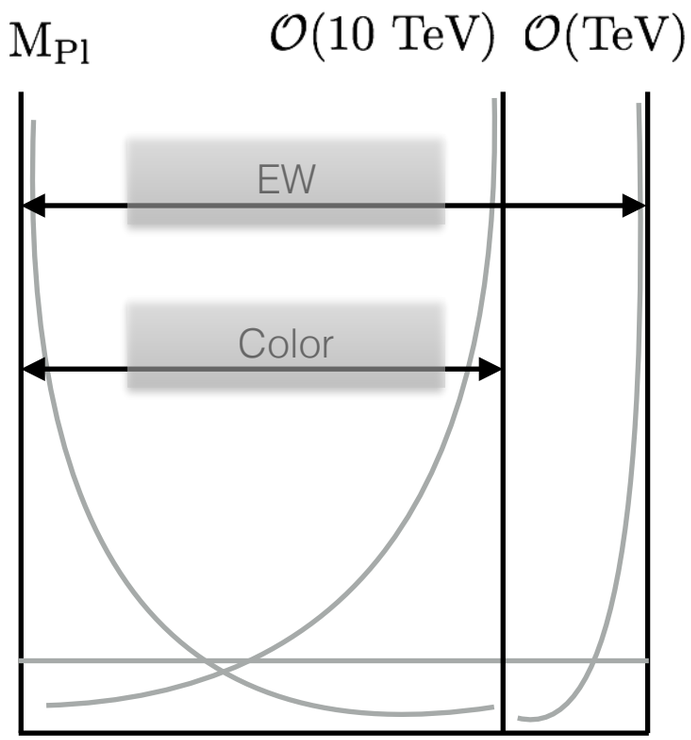
Tri-boson signals of various kinds.

- tri-jet
- jet + di-boson
- jet + di-photon
- tri-boson
- boson + di-photon
- tri-photon

JHEP 1705 (2017) 078

- **Studied two benchmark points: (m_{KK} = 3 TeV, m_{rad} = 1 TeV and 1.5 TeV).**
- **Most promising channels are tri-jet and jet + di-photons, where 300/fb is enough to get close to discovery reach of 3 sigma.**

$\mathrm{RS}_3^{\mathrm{EW}}$



Only EW gauge bosons propagate in the entire bulk

Tri-boson signals of various kinds.

- tri-jet
- jet + di-boson
- jet + di-photon
- tri-boson
- boson + di-photon
- tri-photon

Two differences compared to the earlier case:

- Rates for final states with jets are suppressed. Tri-bosons become genuinely the dominant signal.
- Radion production cross-section also suppressed: can have a **light** radion, which leads to very boosted objects at detectors.

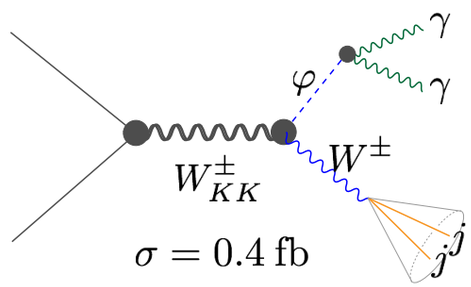
$\mathrm{RS}_3^{\mathrm{EW}}$

Heavy Radion ~ 1.5 TeV **Only EW gauge bosons propagate in the entire bulk**

Phys.Rev. D99 (2019) no.7, 075016

Focus on hadronic W channels:

W+di-photon

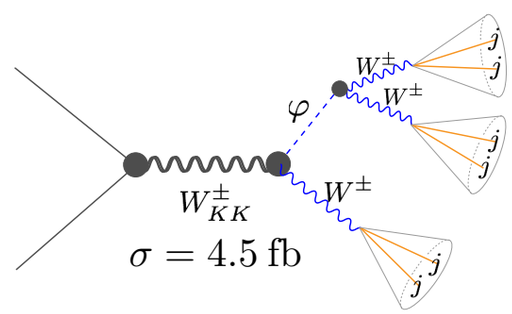


A simple cut and count strategy suffices.

5 sigma at 300/fb.

Strong discriminants: W-tagging, invariant mass of two photons. pT of photons

Tri-boson

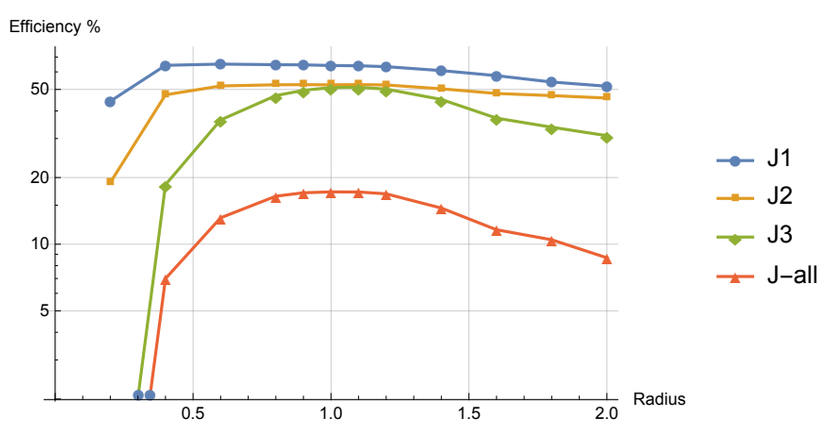


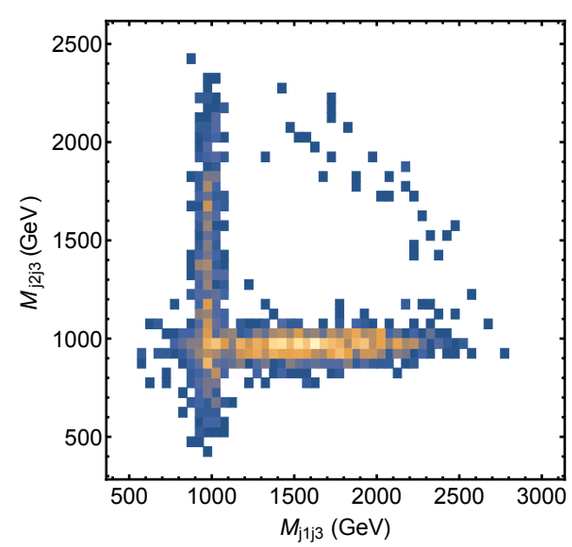
Needs more than just cut and count

3 sigma at 300/fb.

Optimizations: Optimal radius for the jet.

Kinematical ambiguity in the invariant mass construction.





$\mathrm{RS}_3^{\mathrm{EW}}$

Light Radion ~ 200 GeV

Only EW gauge bosons propagate in the entire bulk

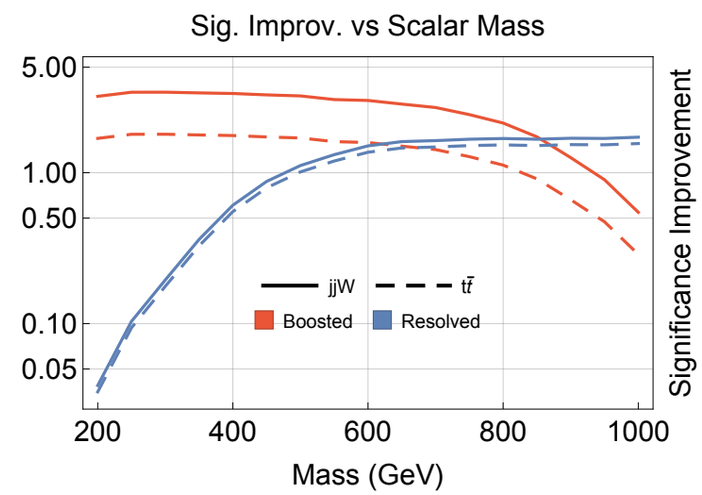
Phys.Rev. D99 (2019) no.7, 075016

Light scalars expected in many BSM models.

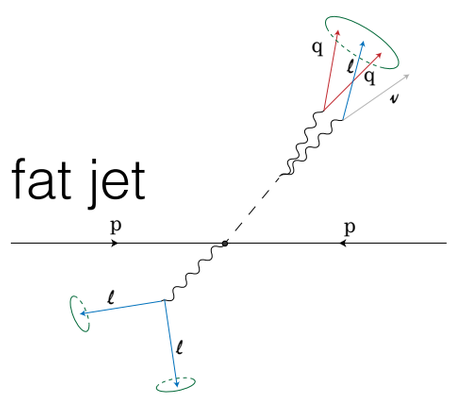
(composite Higgs model, Models with extended 4D gauge sectors,…)

The detector level objects are different

- Four pronged jets.
- Leptons buried inside jets.



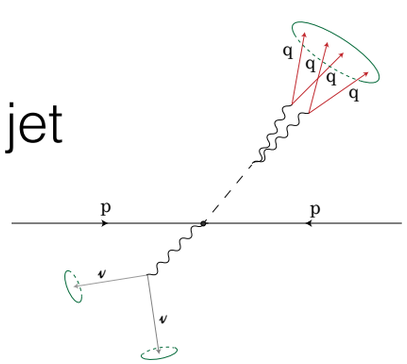
Lepton inside a fat jet



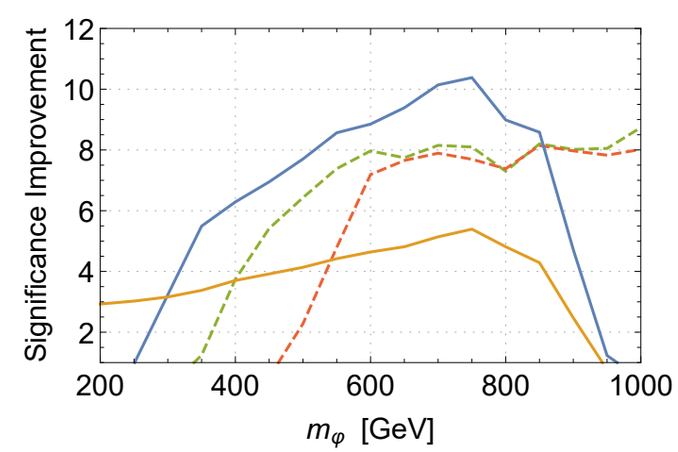
Cluster jet into n sub-jets

$$\mathrm{LSF_n} = \max_{\text{all leptons}} \frac{p_{T_{\ell_k}}}{p_{T_{s_j}}}$$

4-pronged fat jet



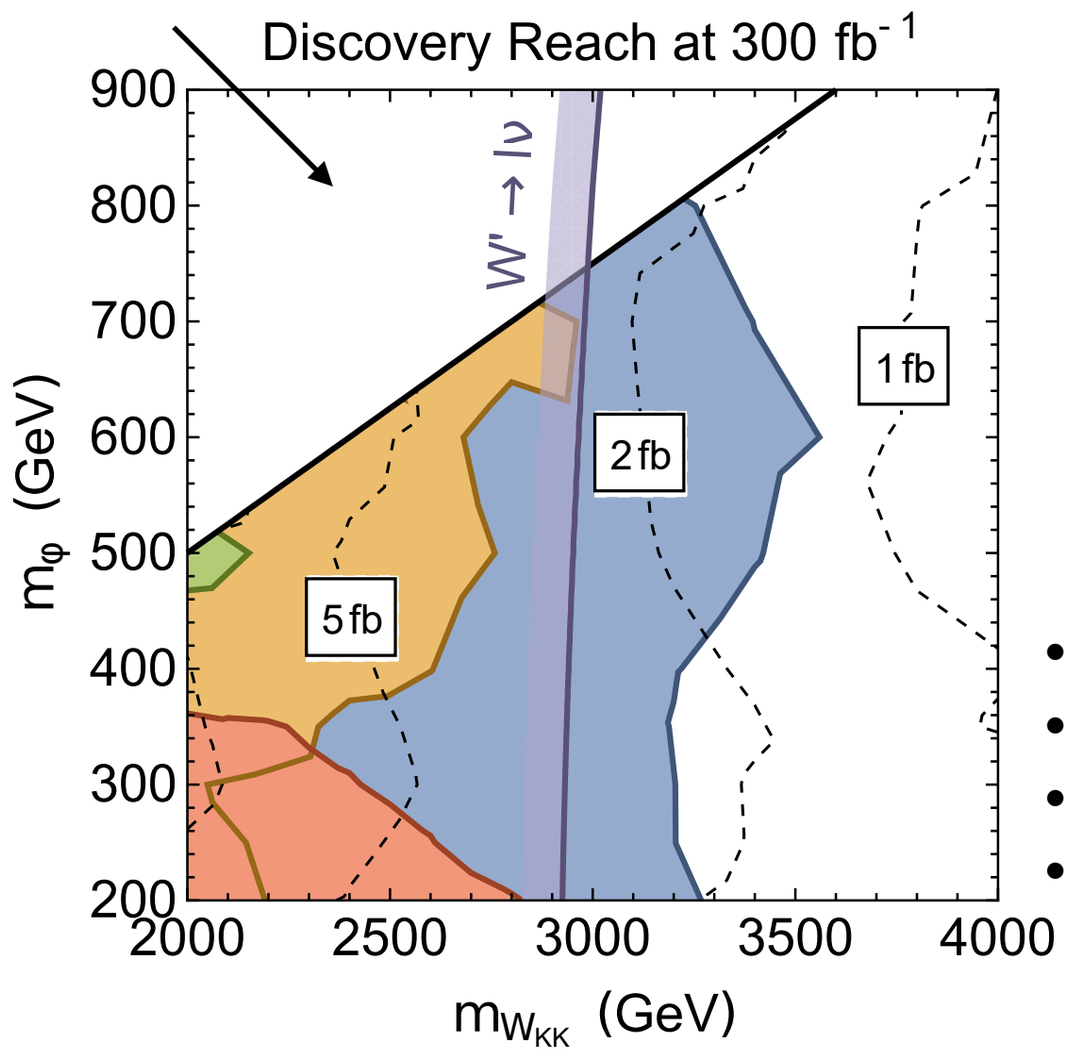
Clustering sequence vs Decay sequence



Application to the explicit 3-brane RS model

with only EW in the bulk

Decay products well resolved



M_{WKK} heavier than few TeV from leptonic decay

- Yellow: l nu (qqqq)
- Green: qq (qqqq)
- Red: qq (l nu qq)
- Blue: combined

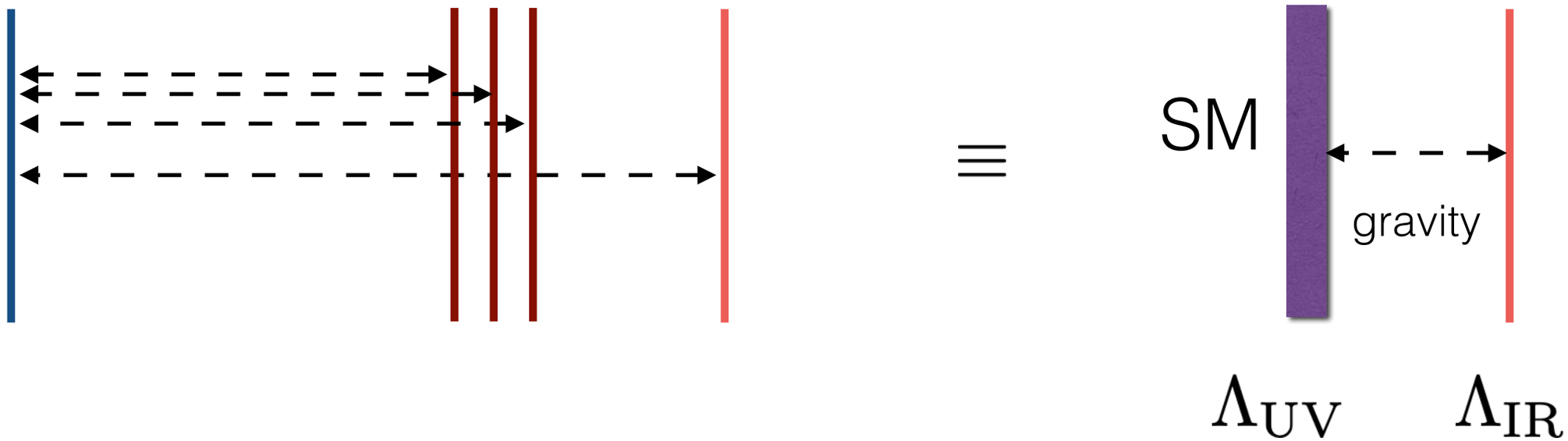
Hadronic Tagger

Leptonic Tagger

Such signals can be buried in data very easily.

Only gravity in the extended bulk: Dark Sectors

Contino, Max, RKM *in preparation*



Like RS_2, except there is a second IR brane, and the UV brane is not at Planck/GUT scale.

Motivates considering non-gravitational portals to dark sectors.

What is the minimal structure of a dark sector?

- (assume) a local QFT $\mathrm{T}_{\mu\nu}$
- (require) a hierarchy of scale $\Lambda_{\mathrm{IR}} \ll \Lambda_{\mathrm{UV}}$

Can be achieved by a strongly coupled approximate CFT

Two operators of low scaling dimensions. All other operators have heavier scaling dimensions.

$$\mathrm{T}^{\mathrm{CFT}}_{\mu\nu} \quad \text{and} \quad \mathcal{O}_\Delta, \ \Delta \lesssim 4$$

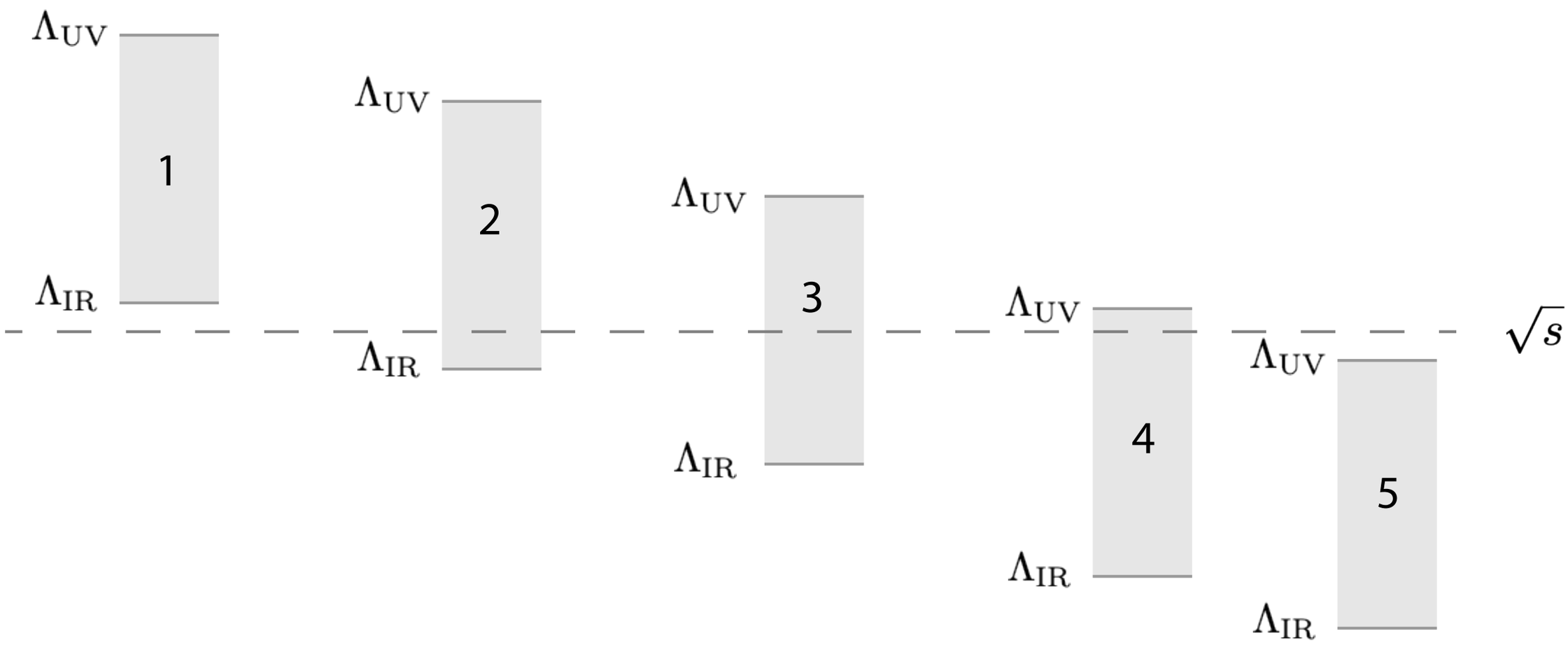
Interactions with SM:

$$\frac{1}{\Lambda_{\mathrm{UV}}^4} \mathrm{T}^{\mathrm{CFT}}_{\mu\nu} \mathrm{T}^{\mu\nu}_{\mathrm{SM}}$$

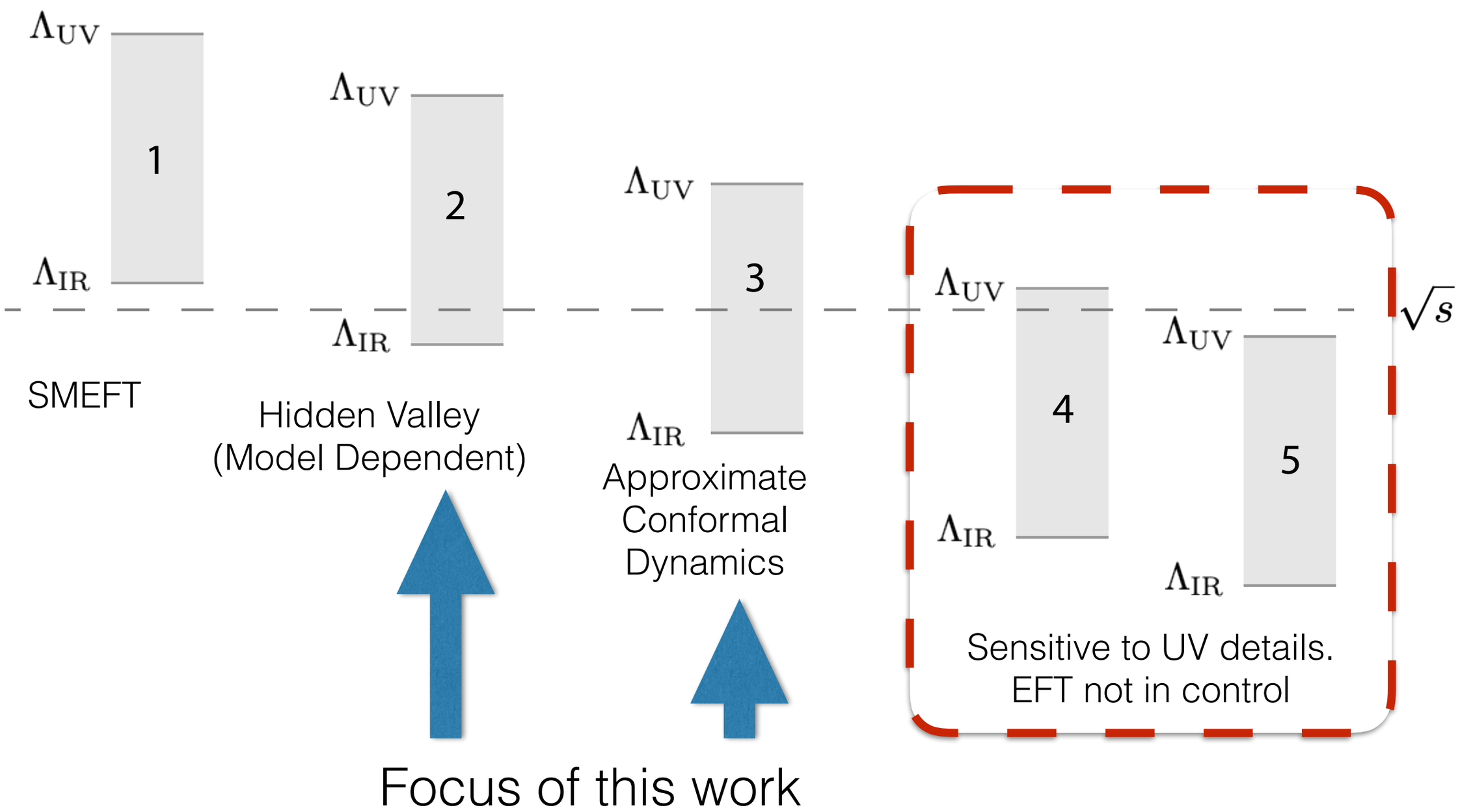
$$\frac{1}{\Lambda_{\mathrm{UV}}^{\Delta-2}} \mathcal{O} H^\dagger H$$

Mediators responsible for these interactions also generate other interactions, which have to be included for self consistency

Experimental probes of the dark sector



Experimental probes of the dark sector



A plethora of collider, low energy and cosmological bounds apply.

Processes/Considerations

- Colliders (LHC and LEP):
  - Missing energy signals (with some SM final state)

- Cosmology:
  - Decay of the lightest state and its presence at various times in the history of the universe

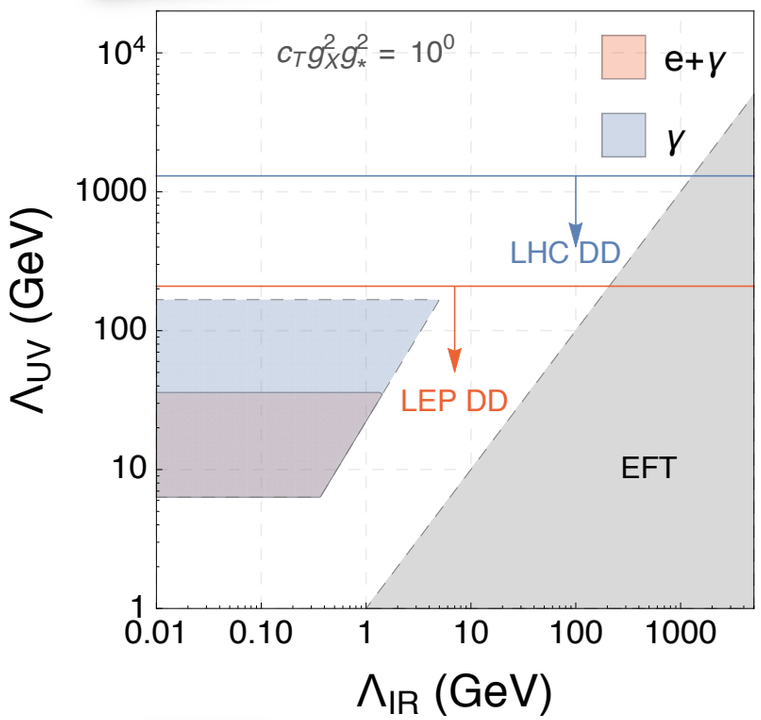
Steps/Assumptions

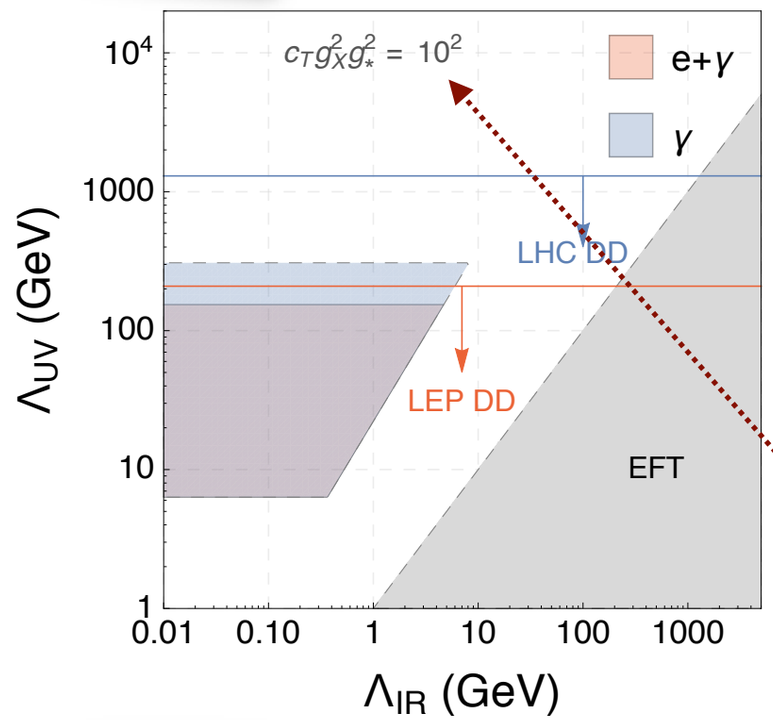
- Colliders:
  - Use data in bins where EFT makes sense.
  - Use optical theorem for inclusive matrix elements.

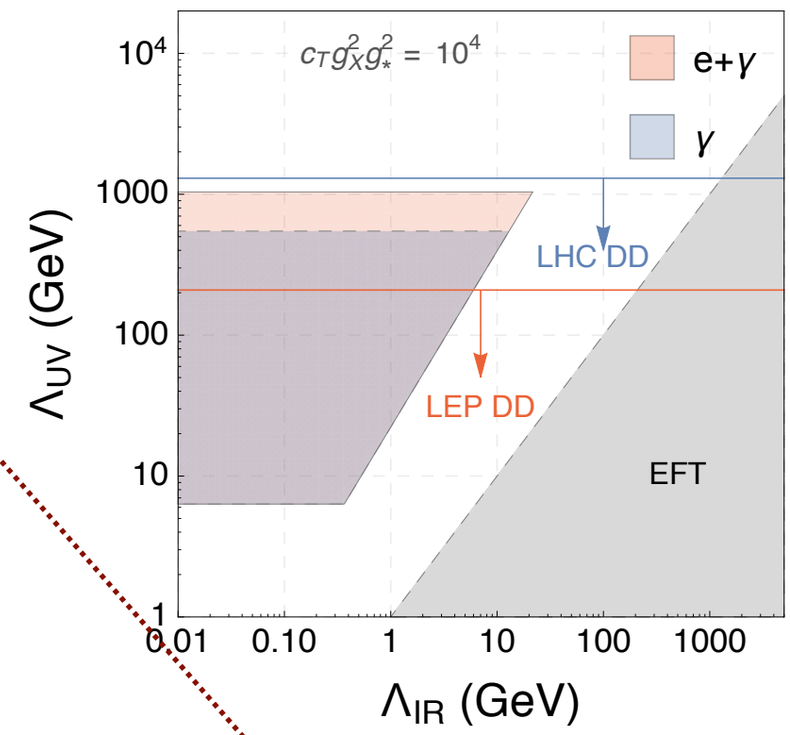
- Cosmology:
  - Assume the two sectors to be in kinetic equilibrium after reheating.
  - Dark sector confines at $\Lambda_{\rm IR}$, and sets the mass of the lightest stable state.

Collider bounds (LEP)

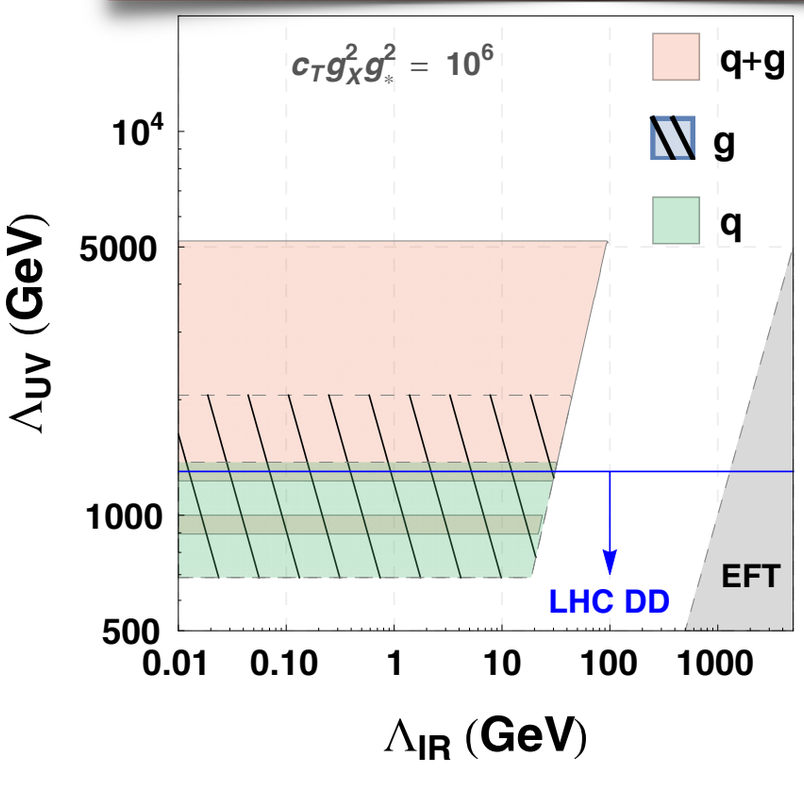
Preliminary

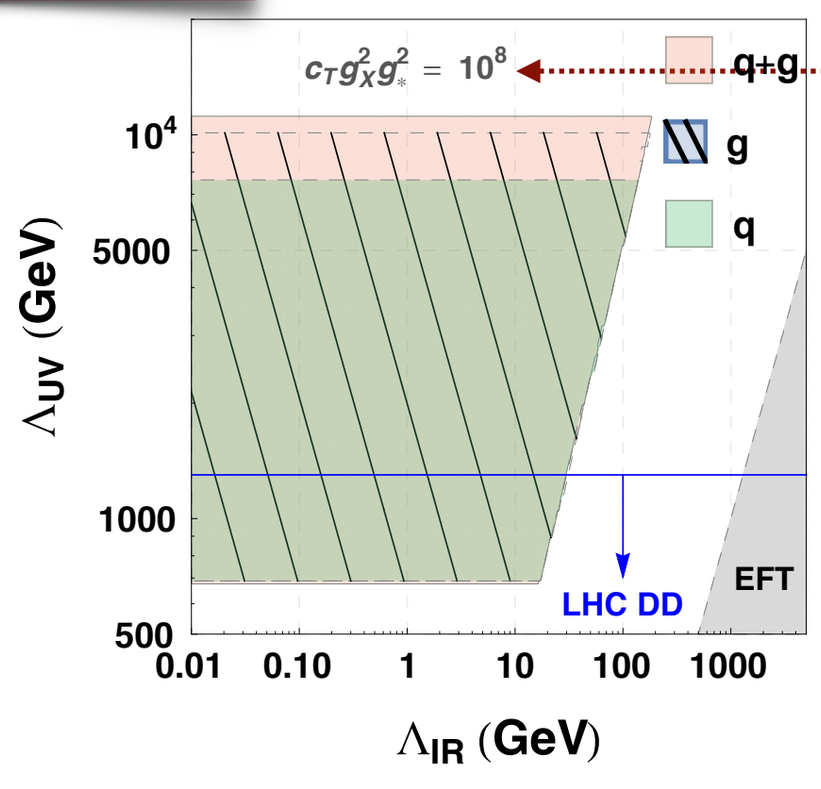






Collider bounds (LHC)





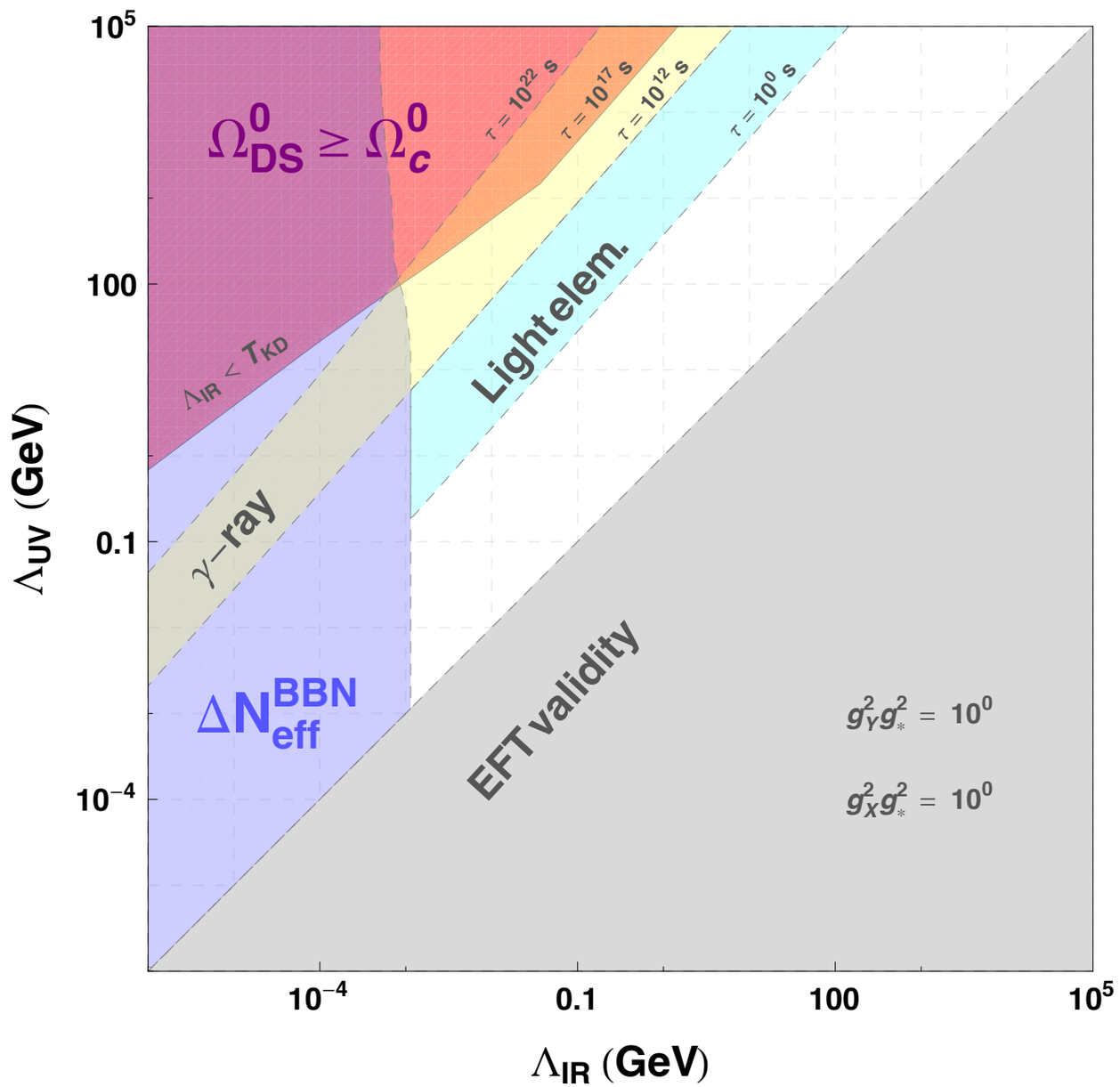
Reach very sensitive to c_T, and better for higher values

Excluded regions cut off at lower values of UV scale due to EFT considerations

Cosmology bounds

Preliminary

Constraints from long lived lightest state

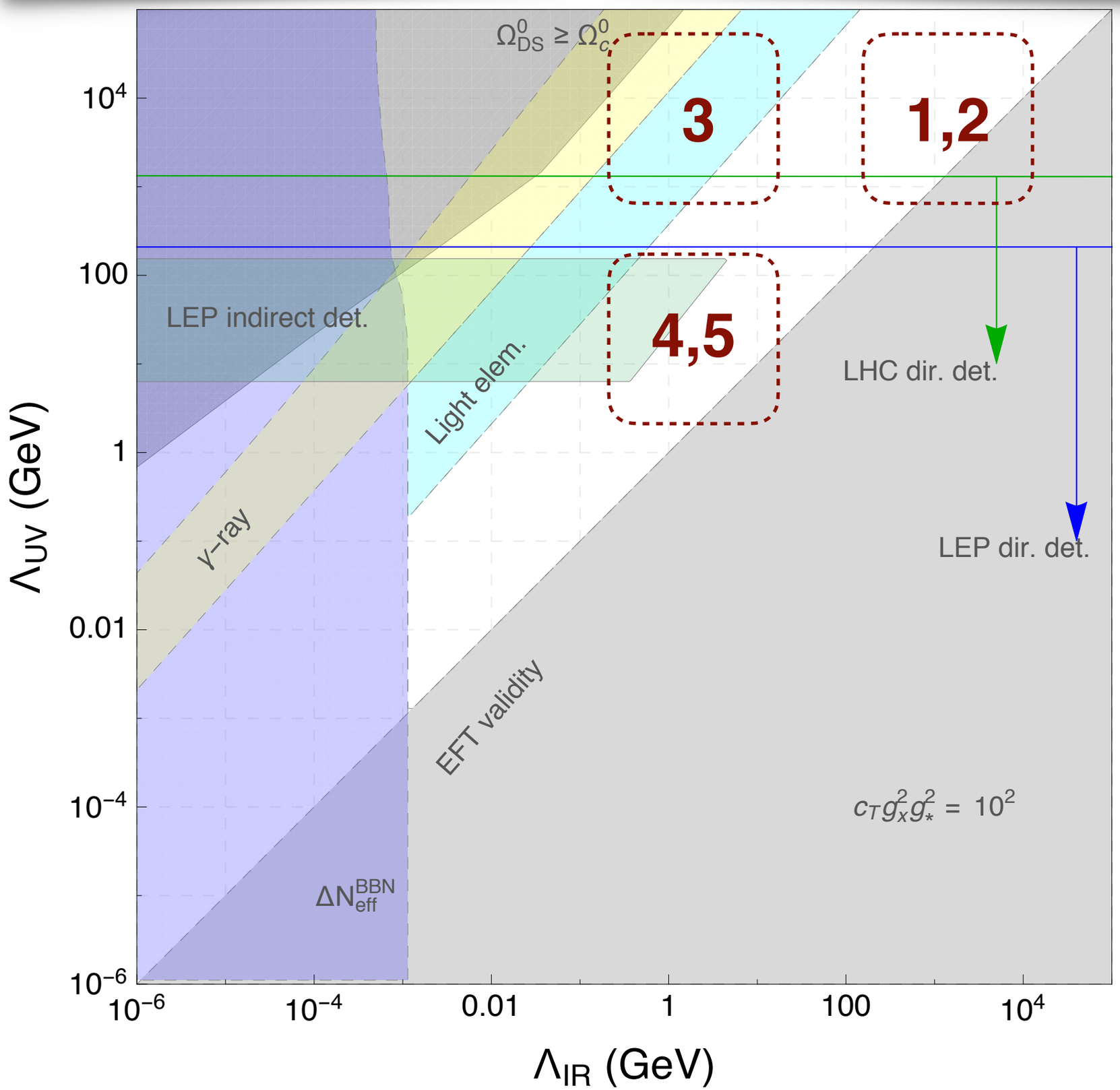


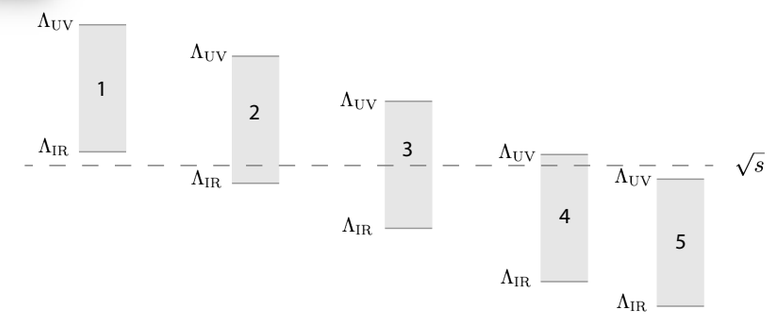
- Assume the two sectors to be in kinetic equilibrium right after reheating.
- Dark sector confines at IR scale
- Lightest state has mass $\Lambda_{\rm IR}$

- Relic density of the lightest state today is bounded.
- Life time bound by Light elements and by gamma-ray constraints.
- Relativistic degrees of freedom at BBN and CMB constrained
- Lightest state should be cold at structure formation

Putting it all together

Preliminary





Preliminary

Other bounds

- Low energy experiments
  - Hydrogen energy level shifts
  - Fifth force
  - g-2 of electron
  - Beam Dump NA62

→ **Only relevant for very low values of IR scale**

- Supernova constraints
- Indirect measurements: not-useful at LHC due to EFT. There is a search at LEP which gives a bound.
- Bounds from Higgs invisible width and modifications to its couplings.

What have we learnt about allowed dark sectors, under these assumptions?

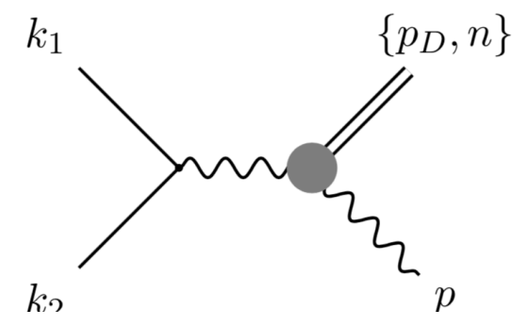
- Colliders do not impose strong constraints, if want to be model independent.
- Standard cosmological picture imposes strong constraints.
- The lightest state can't be the main component of DM. Need a heavier state with some accidental stability.

To summarise

- Important to explore corners of theory space and confront them with data.
- New model considered, and model-independent lessons learnt from them: Signal can hide in data, dedicated searches are needed.
- Dark sectors arise naturally in this construction. The bounds on the minimal structure are not enough to give a DM candidate.

BACK UP SLIDES

Inclusive matrix elements from optical theorem



Matrix element

$$\mathcal{M}(k_1, k_2, p, p_D, n) = \mathcal{M}_{\mu\nu}(k_1, k_2, p) \int d^4x \, e^{i\,x\cdot(p-k_1-k_2)} \, \langle p_D, n| \, \mathrm{T}^{\mathrm{CFT}}_{\mu\nu}(x) \, |\Omega\rangle$$

$$\int d\Pi_D \, |\mathcal{M}|^2 \; = 2 \, \mathrm{Im} \, \langle\Omega| \, \mathrm{T}^{\mathrm{CFT}}_{\alpha\beta}(p - k_1 - k_2) \mathrm{T}^{\mathrm{CFT}}_{\mu\nu}(k_1 - k_2 - p) \, |\Omega\rangle \; \mathcal{M}_{\mu\nu}\mathcal{M}^*_{\alpha\beta}$$

2 point function stress-energy tensor known from symmetry.

Dependence on central charge c_T

EFT consistency when using data to place bounds

For massless particles, in 2->2 process $\quad p^2_{\mathrm{dark}} = s - 2\sqrt{s}\, p_{\,\mathrm{final}}$

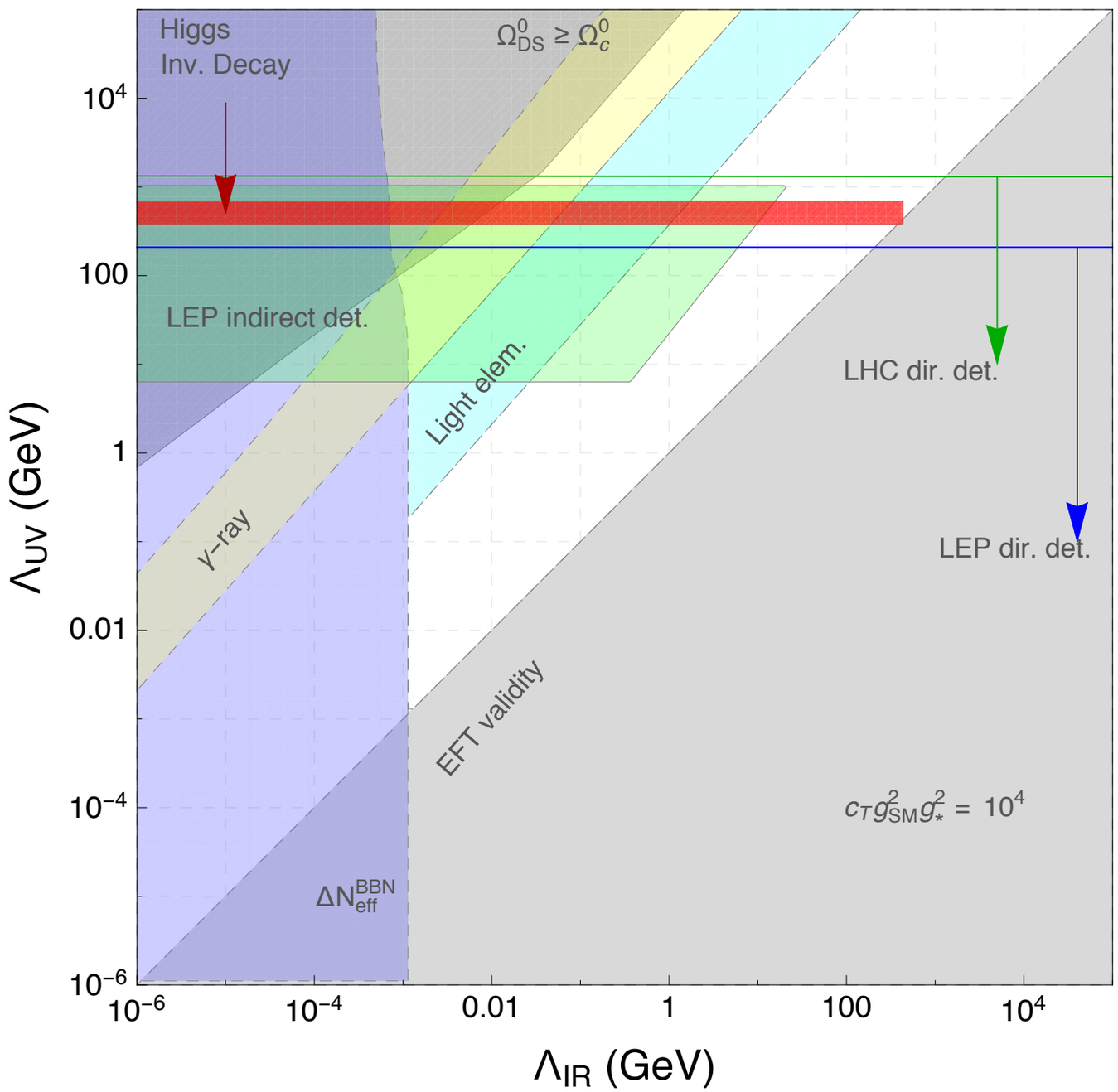
Restrict to bins with lower values of momentum flowing into the dark sector, allows UV scale to be lower.

Perform an optimization of this procedure

Backup: Low energy bounds

Experiment	Lower bound on $\Lambda_{\rm UV}$	Applicable if $\Lambda_{\rm IR}$
Hydrogen	$7.84\ \text{MeV}\left\{c_T\, g_{\rm X}^{ee}\, g_{\rm X}^{pp}\, g_*^2\right\}^{1/8}$	$\lesssim 3.7$ keV
$(g-2)_e$	$1.25\ \text{GeV}\sqrt{c_T\,(g_{\rm X}^{ee}\, g_*)^2}$	$\lesssim 511$ keV
o-Ps	$5.51\ \text{MeV}\, c_T^{1/8} g_*^{1/2} \times \left[\left(g_{\rm X}^{ee}\right)^4 + \frac{1}{3}\left(g_{\rm X}^{\gamma\gamma}\right)^4 - \frac{47}{45}\left(g_{\rm X}^{ee} g_{\rm X}^{\gamma\gamma}\right)^2\right]^{1/8}$	$\lesssim 1.8$ keV
SN1978A	$750\ \text{MeV}\left\{c_T\,(g_{\rm X}^{nn}\, g_*)^2\right\}^{1/8}$	$< 17.3\ \text{MeV}(g_{\rm X}^{nn}\, g_*)^{-1/5}\left[\frac{\Lambda_{\rm UV}}{1\ \text{GeV}}\right]^{4/5}$
LEP-2 Z'	$410\ \text{GeV}\sqrt{\frac{\Lambda_{\rm IR}}{209\ \text{GeV}}}\left\{c_T\,(g_{\rm X}\, g_*)^2\right\}^{1/4}$	$\gtrsim 209$ GeV

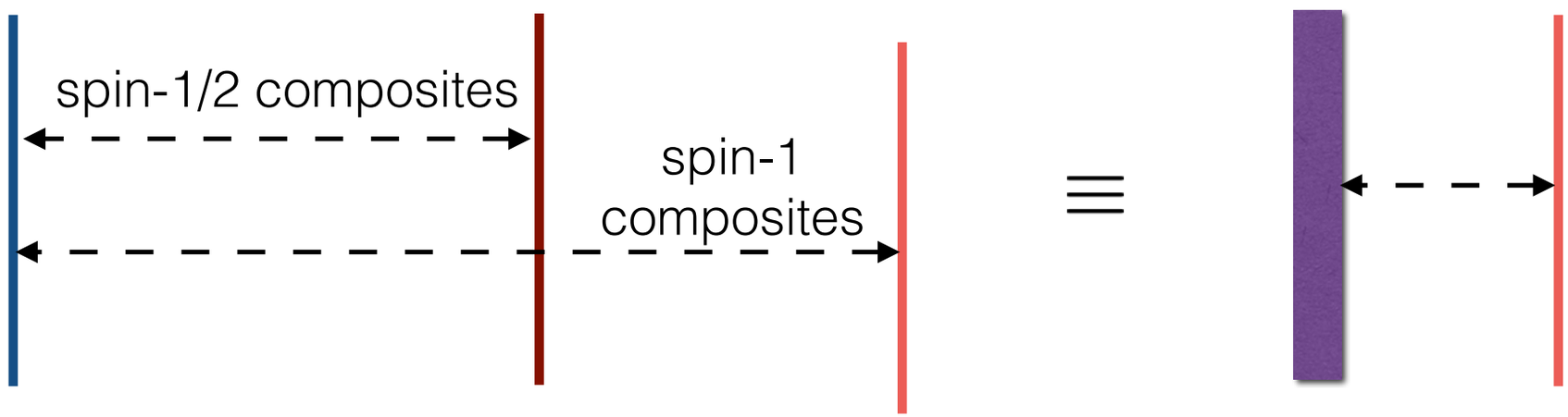
Backup: Higgs couplings modification



Backup: IR CFT interactions

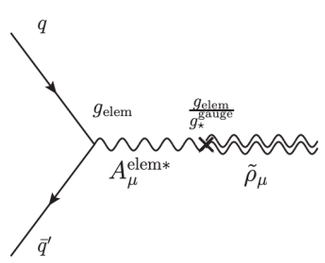
For a fixed value of Higgs scale, IR scale is only probed by direct production

Two contributions: UV CFT and IR CFT

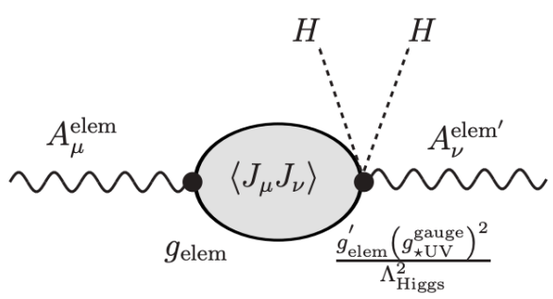


$$A_\mu^{elem} J^\mu_{CFT,IR}$$

$$\frac{J^\mu_{CFT,IR} J^{UV}_\mu}{\Lambda_H^2}$$



photon-rho mixing



S-parameter

$$J^\mu_{\text{strong IR}} \sim \frac{\Lambda^2_{\rm IR}}{g_\star^{\rm gauge}} \rho^\mu_{\rm IR}.$$

$$T^{\text{strong IR}}_{\mu\nu} \sim \frac{\Lambda^3_{\rm IR}}{g_{\star\,\rm IR}^{\rm grav}} H_{\mu\nu}.$$

$$\delta\mathcal{L}\left(\Lambda_{\rm Higgs}\right) \sim \frac{\left(g_{\star\,\rm UV}^{\rm gauge}\right)^2}{\Lambda^2_{\rm Higgs}} J^\mu_{\text{strong IR}} \left(\bar{t}\gamma_\mu t + H^\dagger D_\mu H\right)$$

$$\delta\mathcal{L}\left(\Lambda_{\rm Higgs}\right) \sim \frac{\left(g_{\star\,\rm UV}^{\rm grav}\right)^2}{\Lambda^4_{\rm Higgs}} T^{\mu\nu\,(t/H)} T^{(\text{strong IR})}_{\mu\nu}$$