Three-boson signals of a three-brane world

Rashmish K. Mishra

SNS Pisa and INFN Pisa

Based on:
JHEP 1701 (2017) 016, JHEP 1705 (2017) 078, PRD 99 (2019) 7, 075016, JHEP 1811 (2018) 027, 1906.xxxxx
Collaboration with:
Kaustubh Agashe, Jack Collins, Roberto Contino, Peizhi Du, Sungwoo Hong, Doojin Kim, Kevin Max

31st Rencontres de Blois, 2019

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

↓

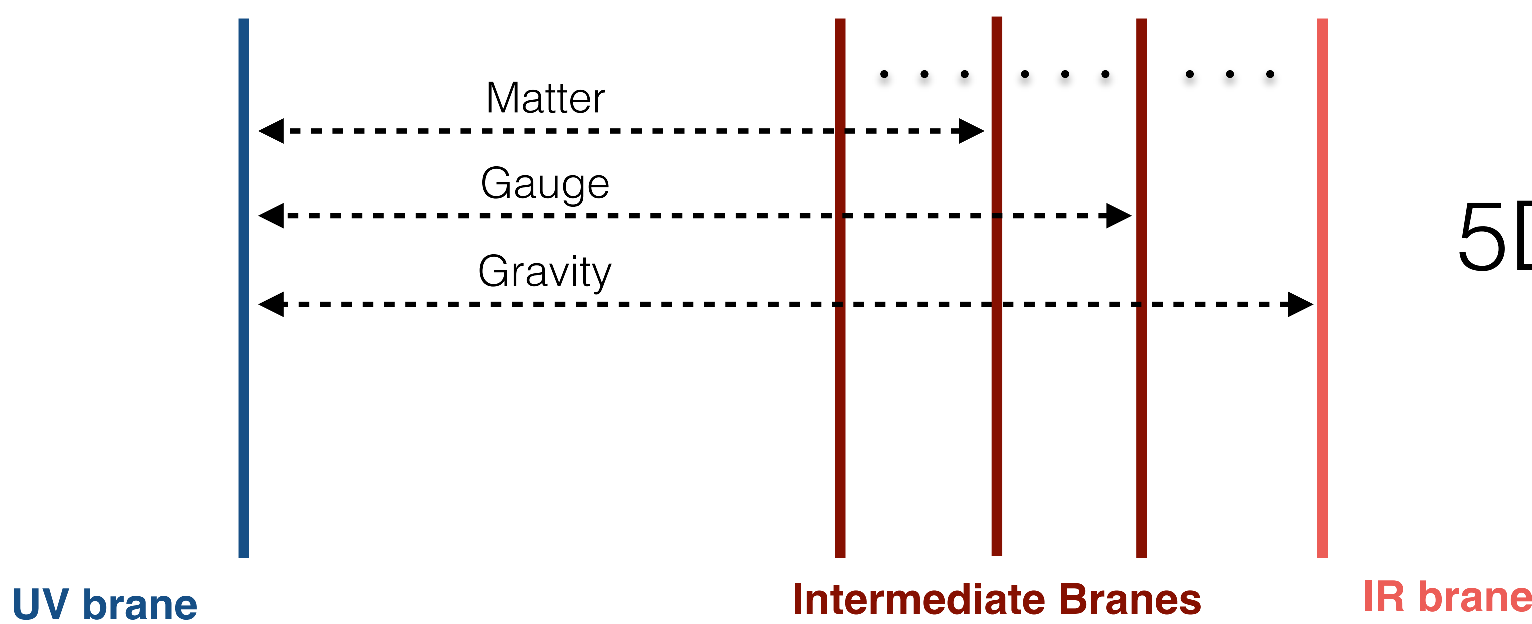
$$m_{\rm KK} \gtrsim 20\ {\rm TeV}$$

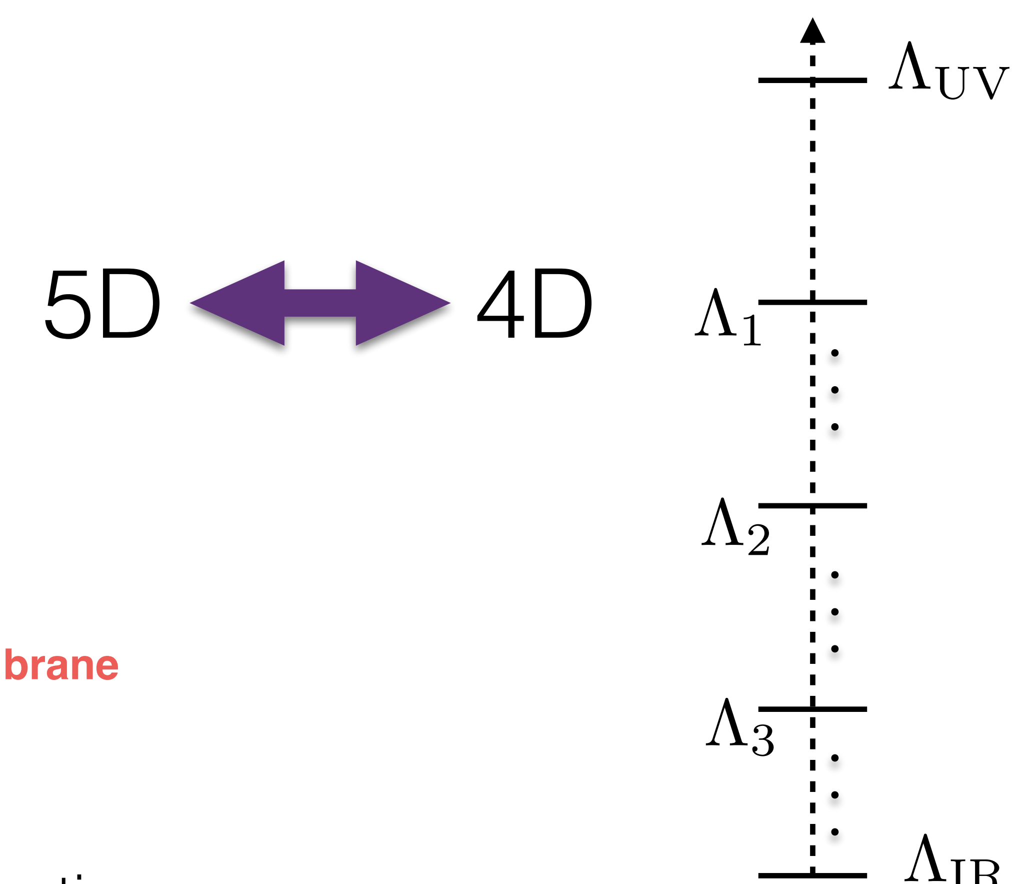
Little hierarchy problem is not so little anymore.

Extended RS

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

- General Framework: the IR structure modeled by multiple IR branes.
- Bulk fields can propagate different amounts in the bulk.

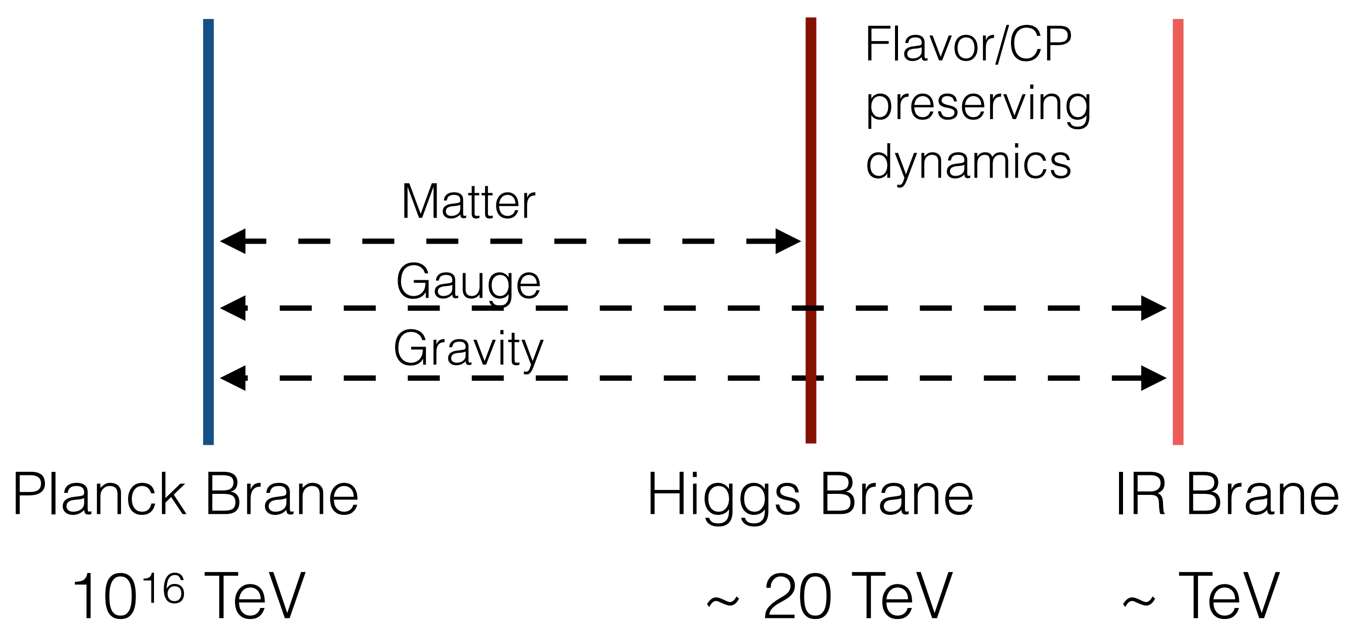


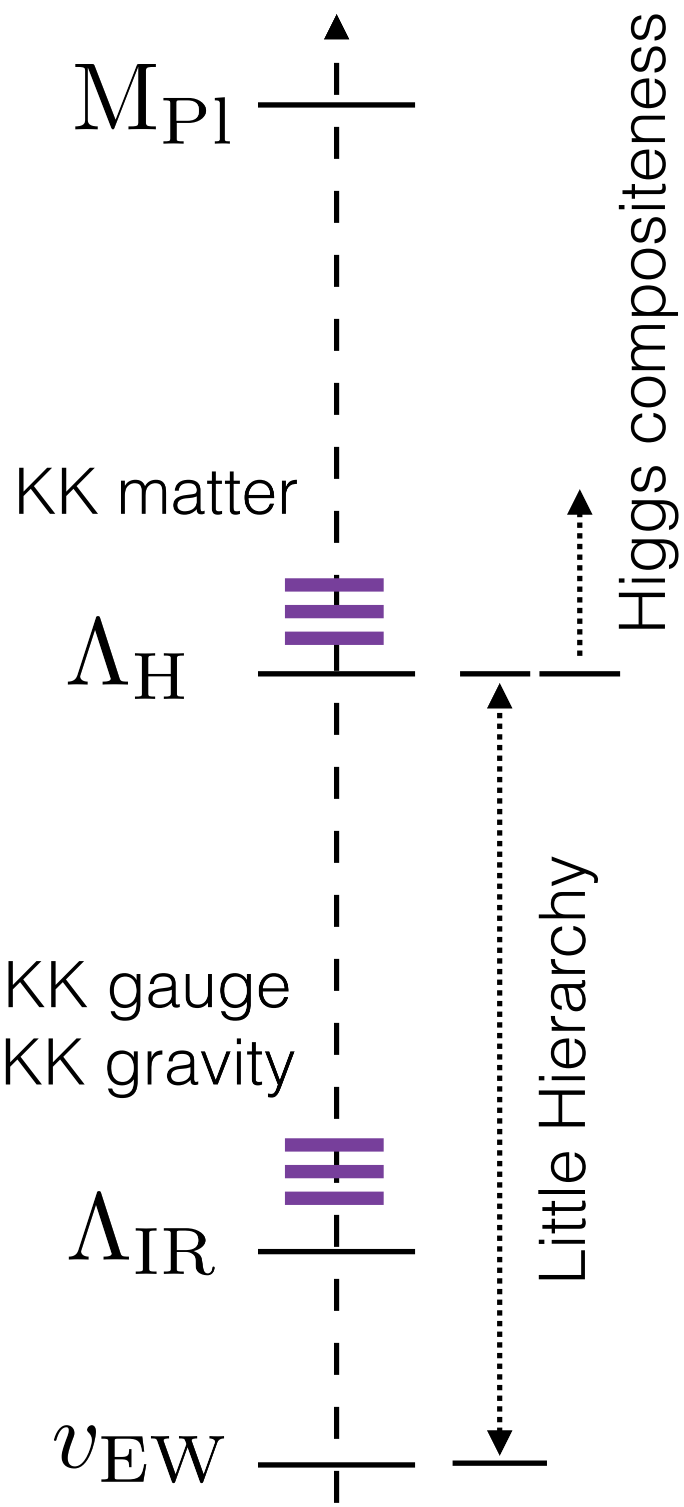


Guiding principle

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

Simplest scenario: 1 intermediate brane



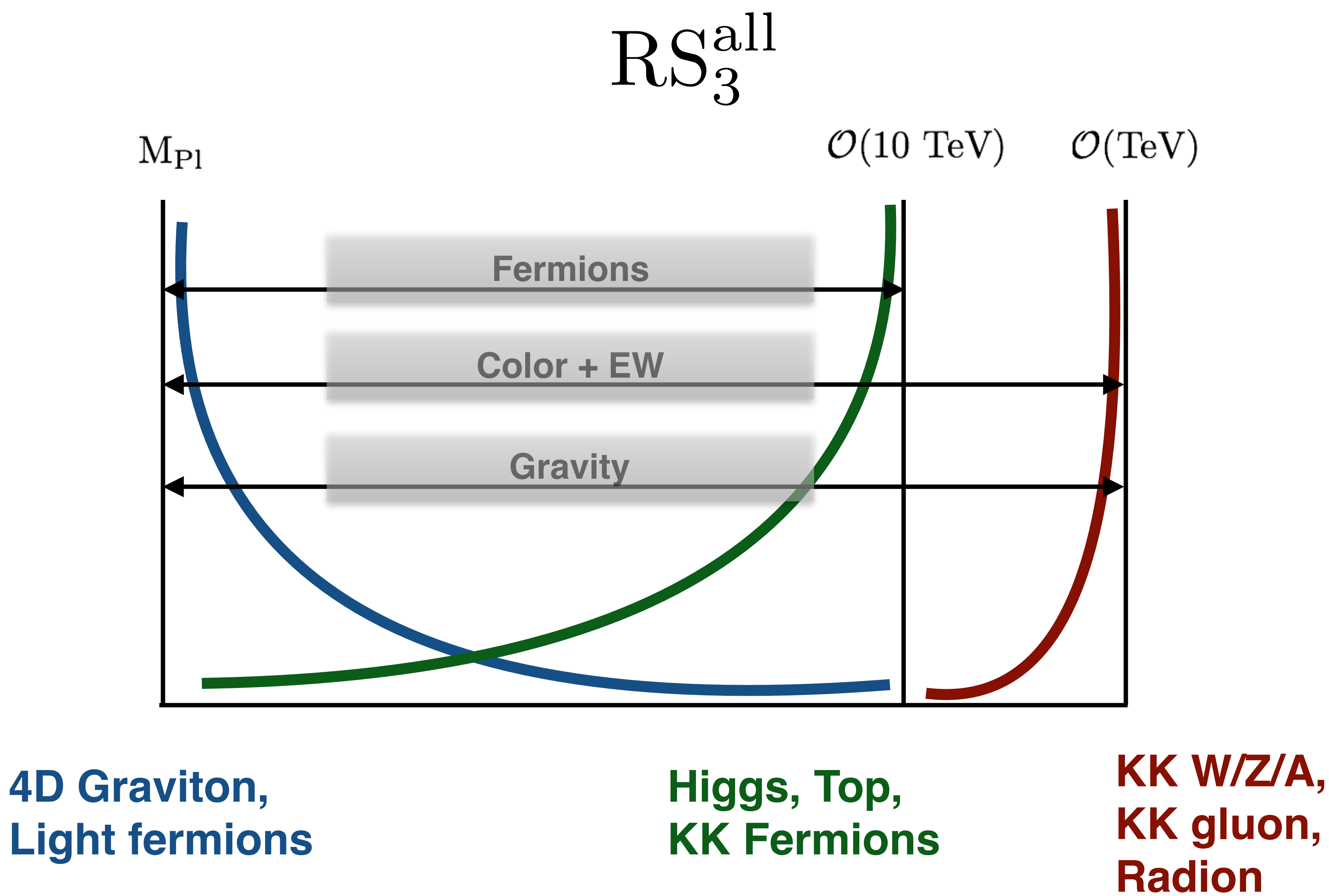


Still many possibilities!

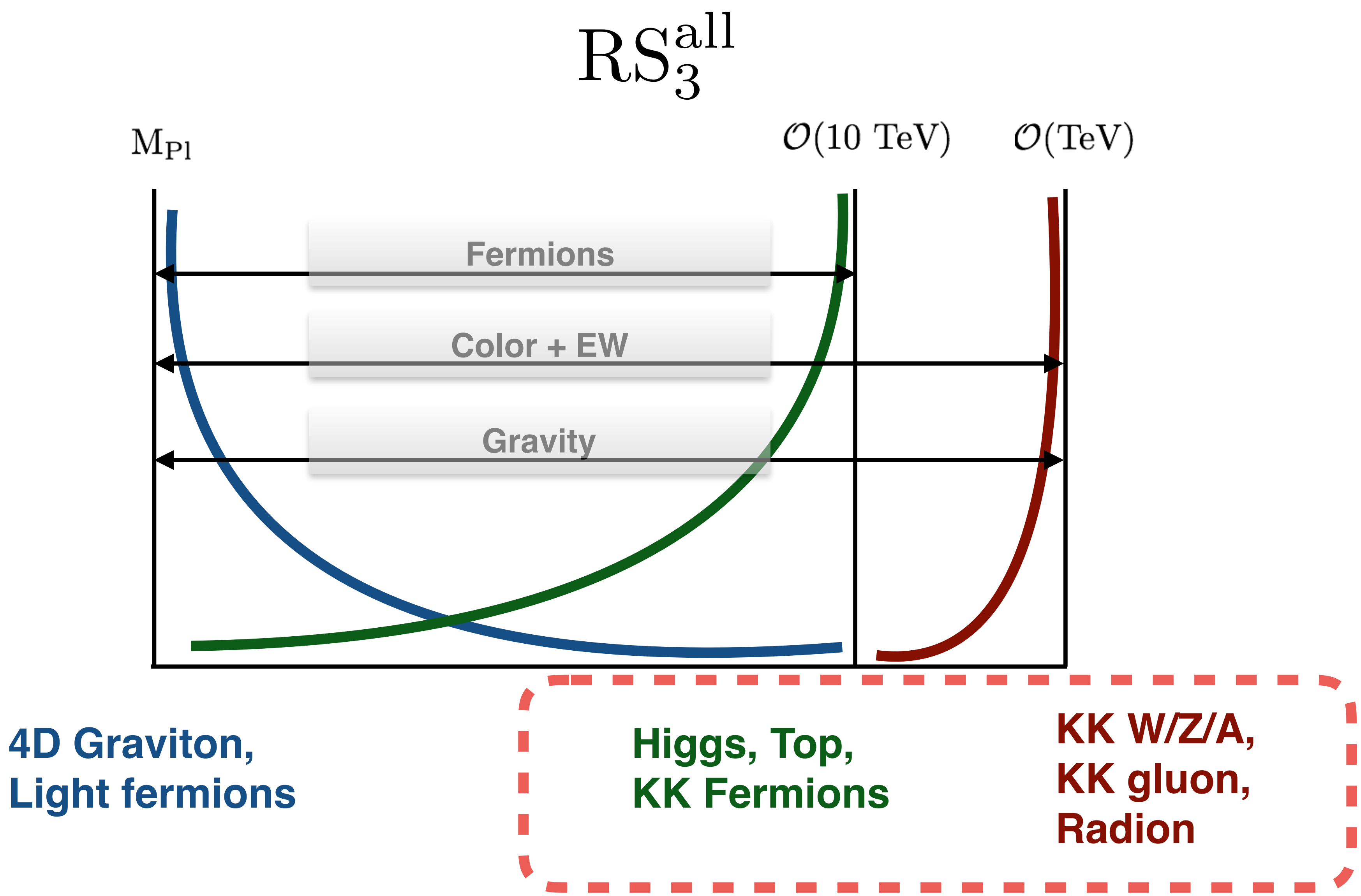
(will need varying levels of sophistication)

- 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

RS models with 3 branes: RS_3

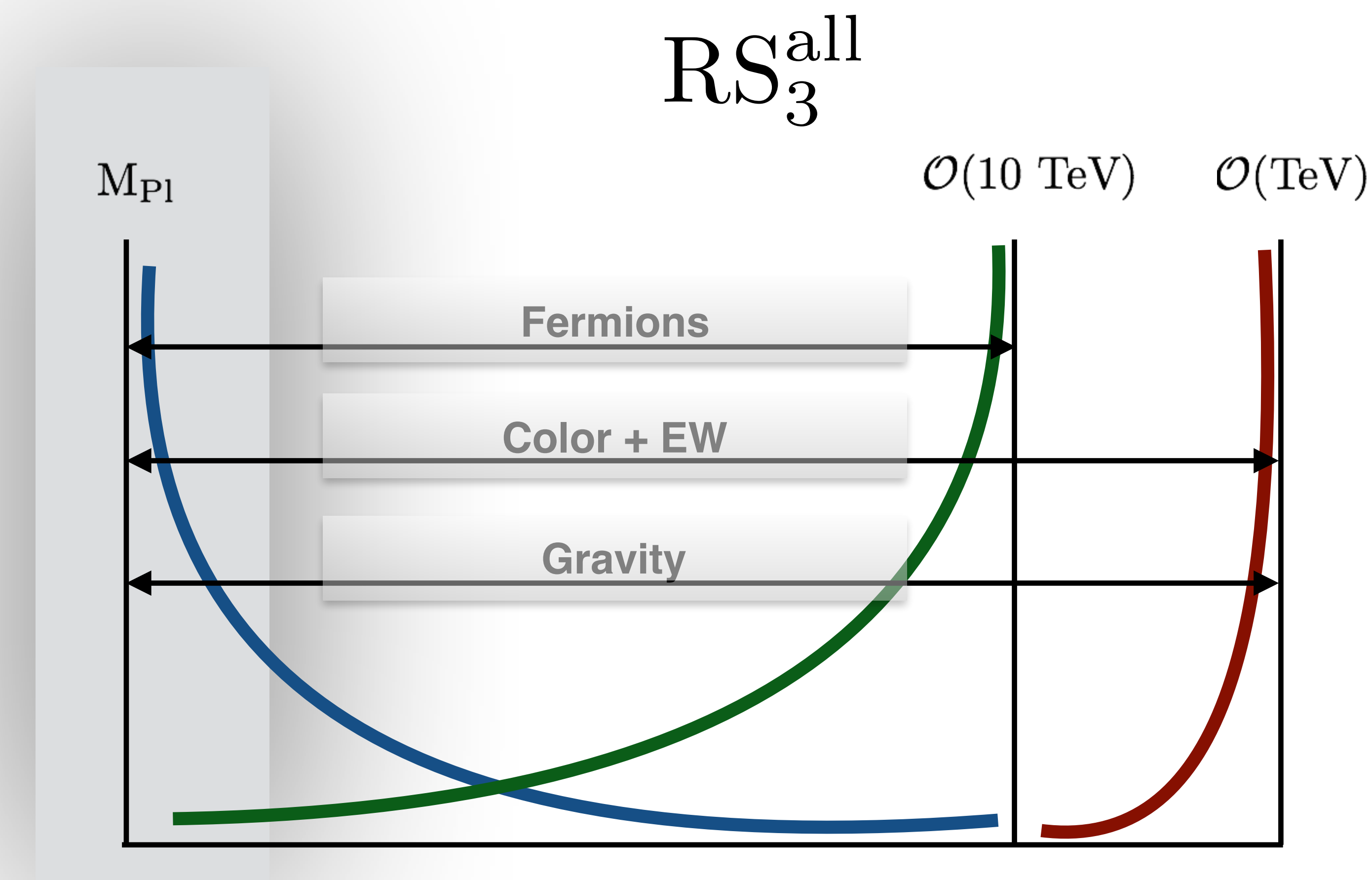


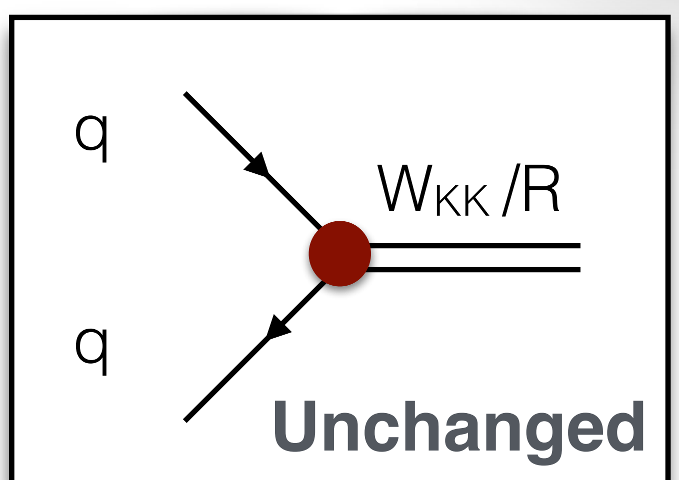
RS models with 3 branes: RS_3



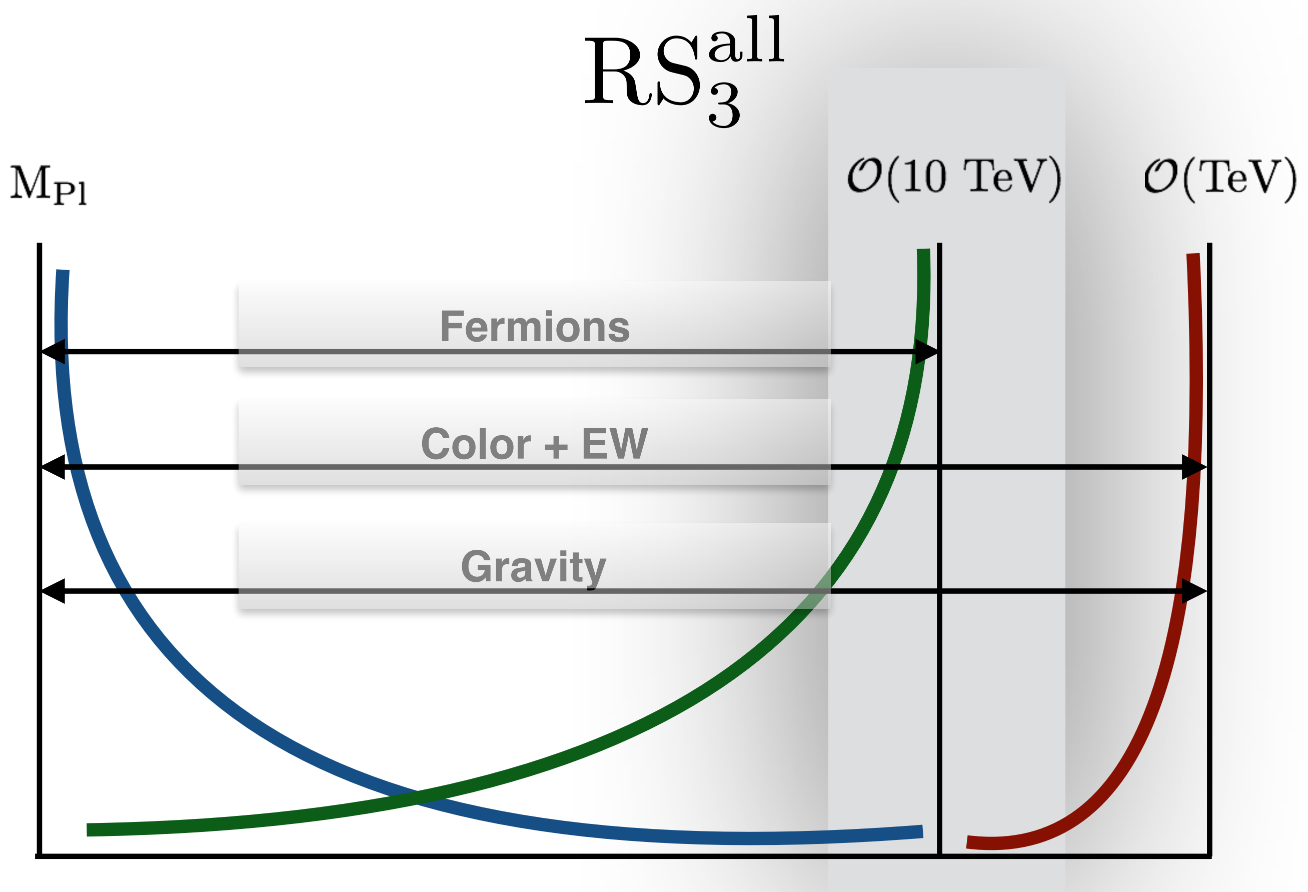
Overlap in original RS construction

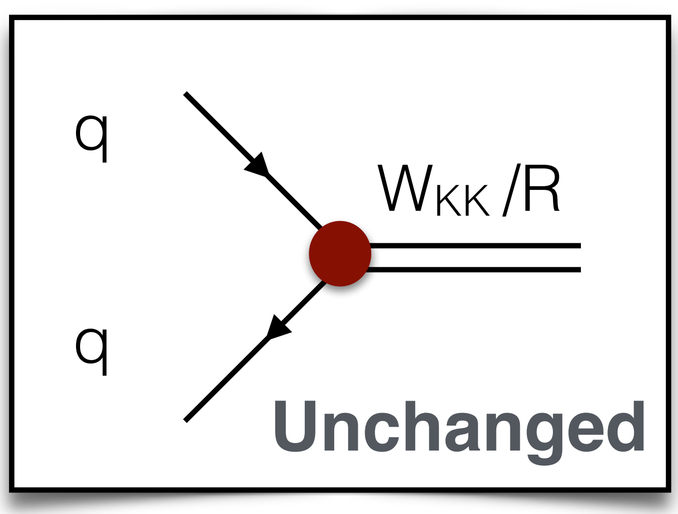
RS models with 3 branes: RS_3

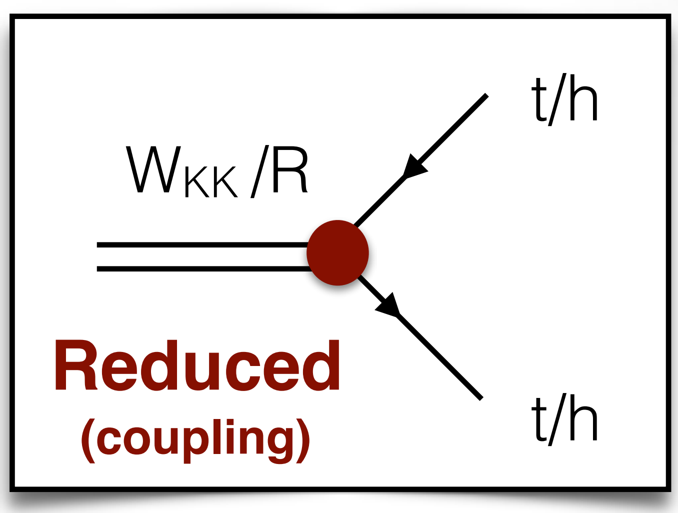




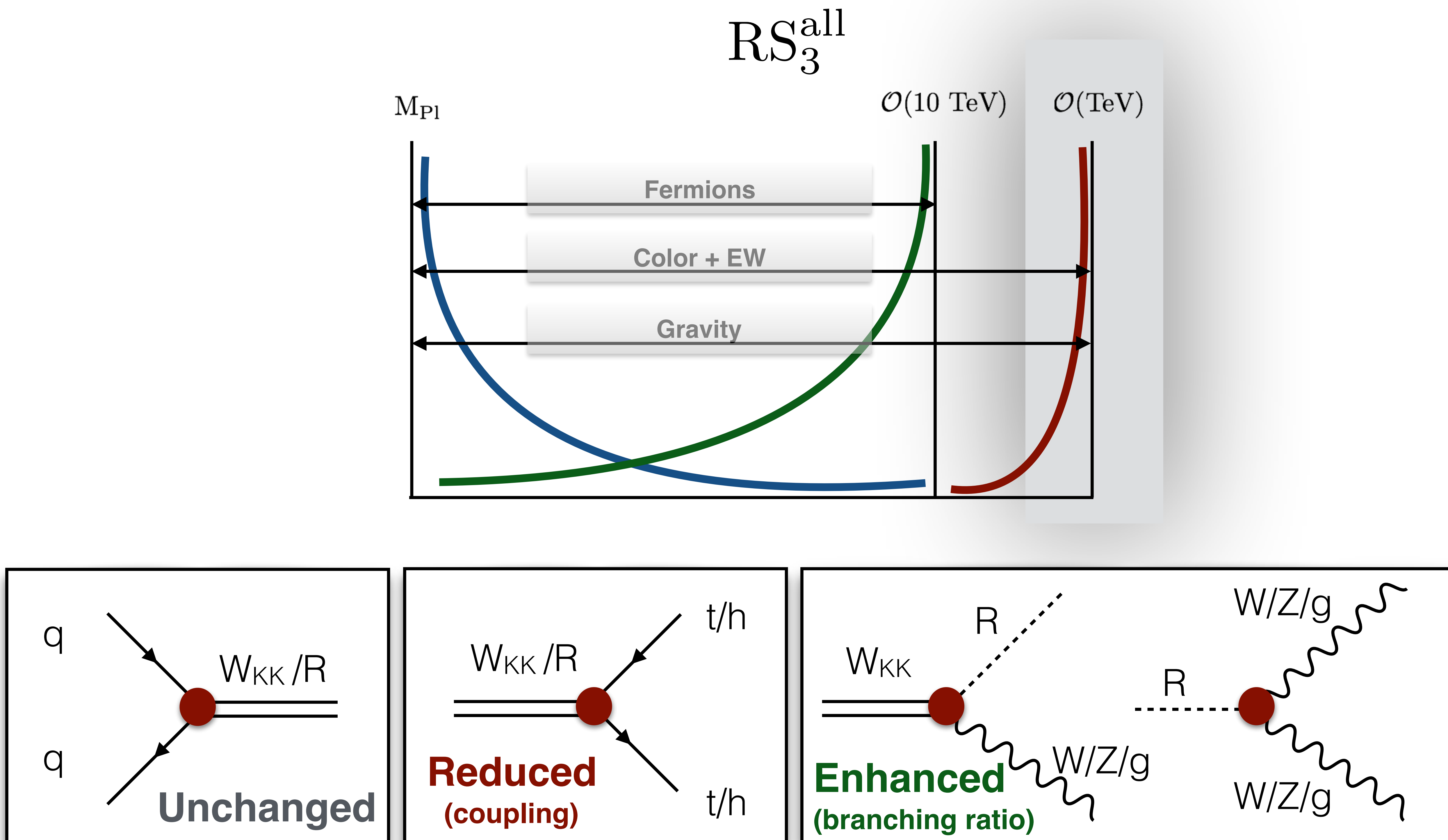
RS models with 3 branes: RS_3



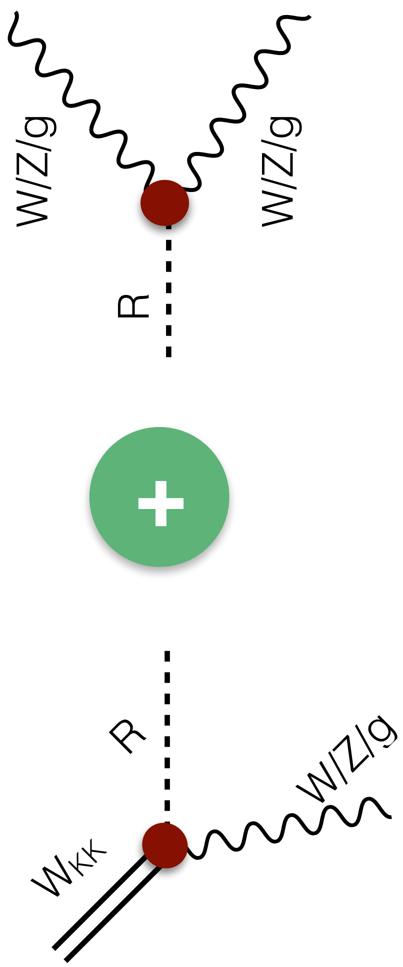


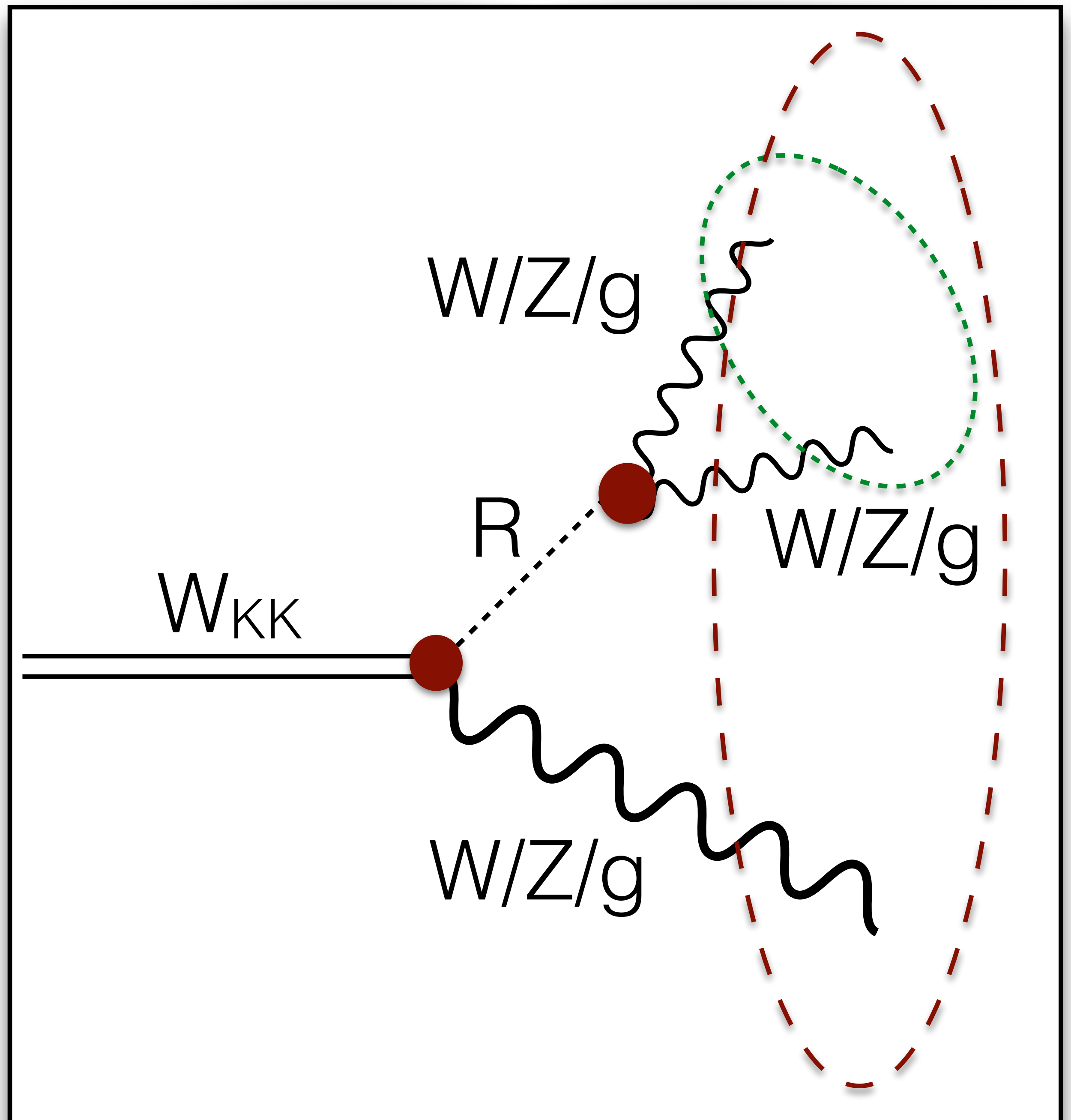


RS models with 3 branes: RS_3



Novel kinematic features: Cascade Decay

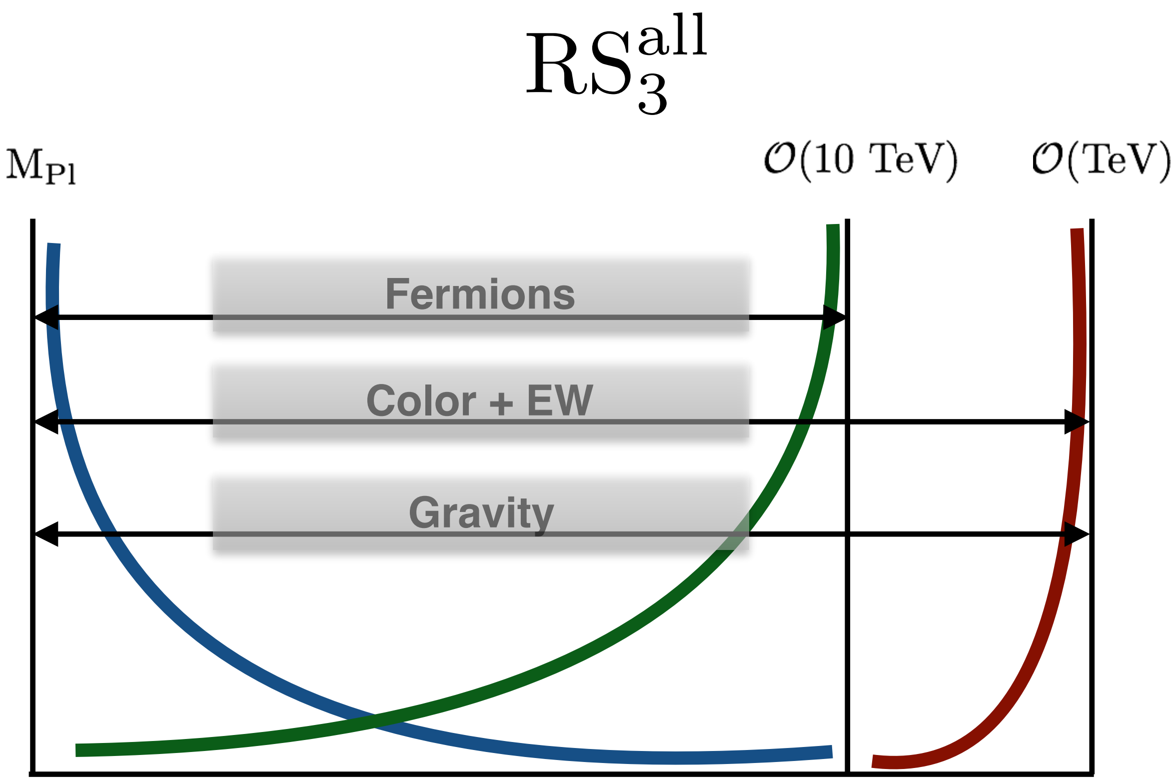




Challenges:

- Kinematic ambiguity.
- Non-standard topology: fat jets with varying radii, merged leptons, non isolated photons, …

"Tri" signals of various kinds.



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

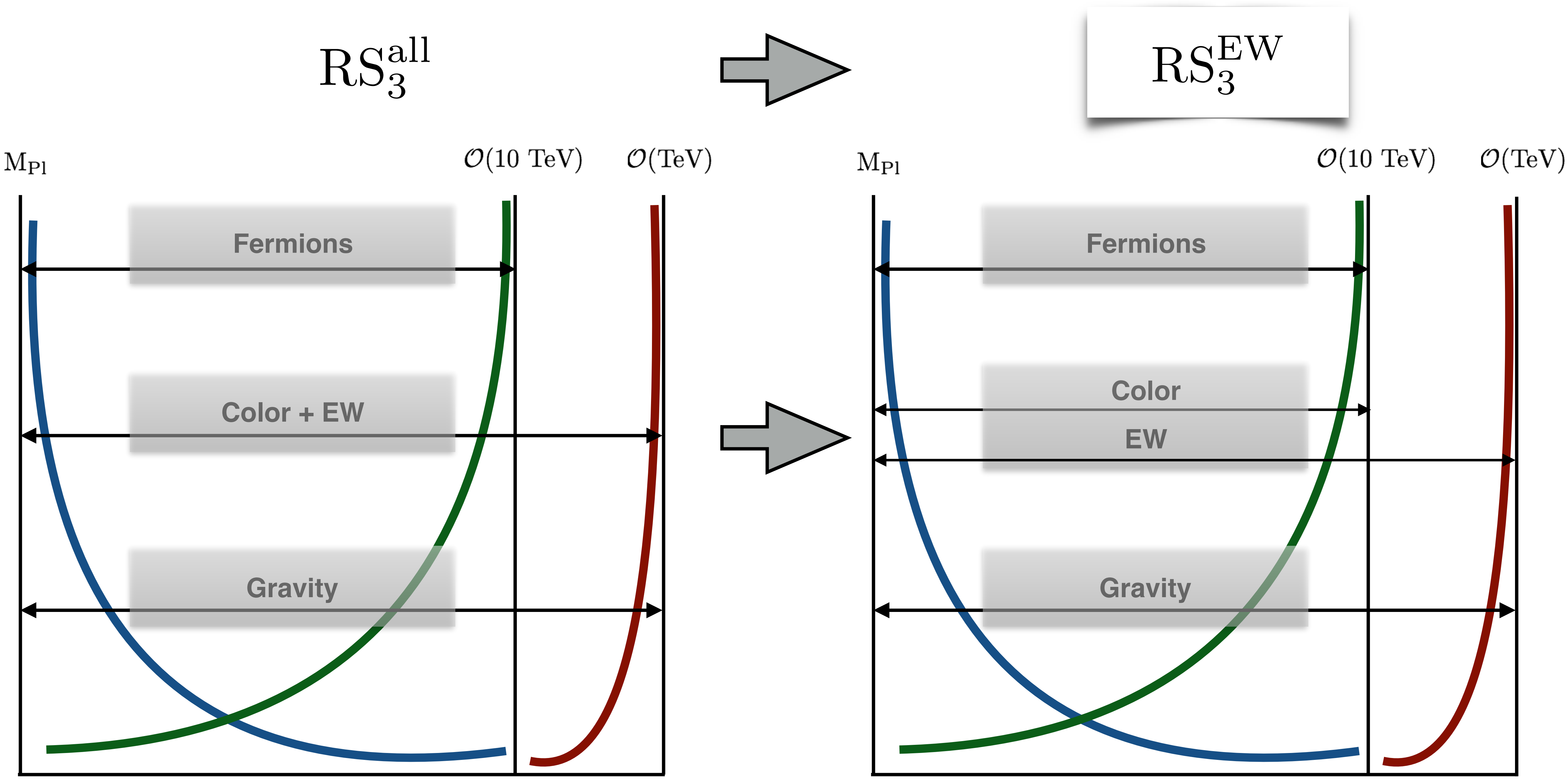
JHEP 1705 (2017) 078

- **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.**

Decouples gluons and its partners as well.

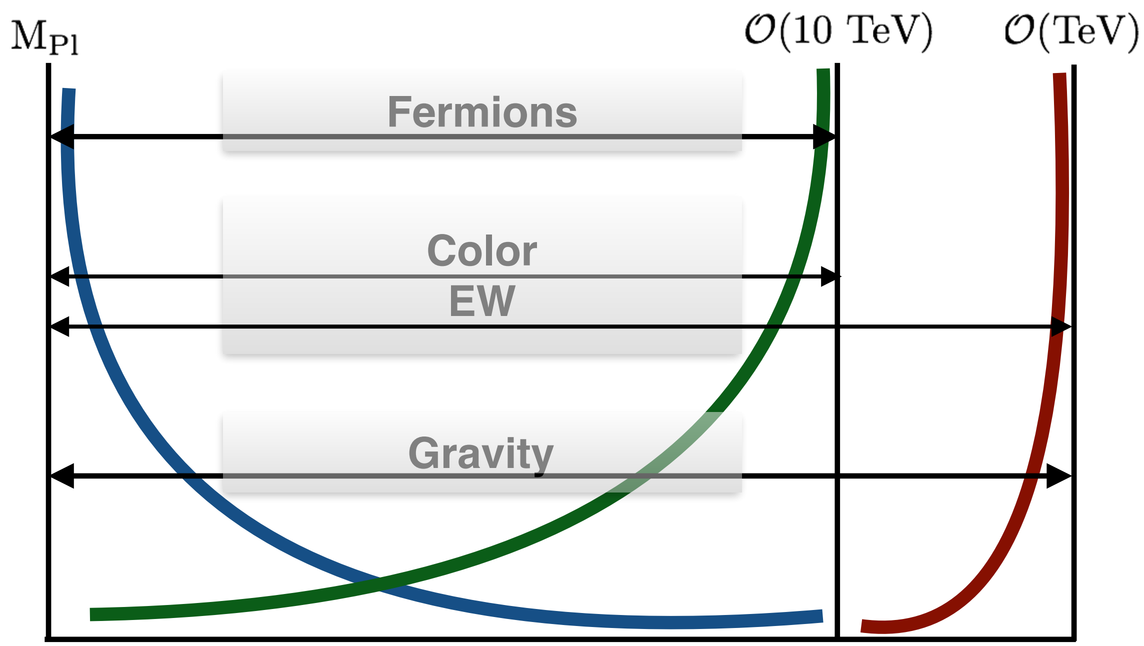
$\mathrm{RS}_3^{\mathrm{all}}$ ⇒ $\mathrm{RS}_3^{\mathrm{EW}}$

An alternative: Decouples gluons (+ partners)



RS_3^{EW}

Boosted Regime and Jet free signals



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

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

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.

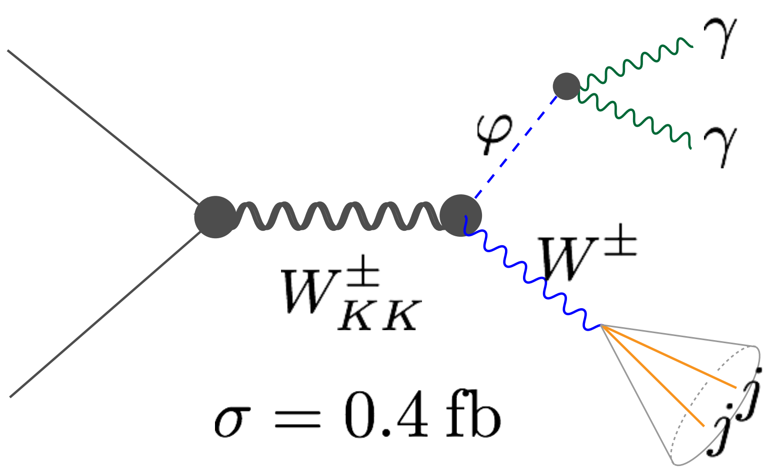
RS_3^{EW}

Non-boosted regime:Tri-boson Signals

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

Focus on hadronic W channels:

- **W + di-photon**
- Three W



- W tagging: $65 < M_J < 105$ GeV, $\tau_{21} < 0.75$ with **60**% efficiency.
- Primary background: $j\gamma\gamma$, $jj\gamma$ (jet faking photon)
- Signal discriminants: high pT jet/photons, clean 2 body inv. mass in photons
- Additionally: Three body inv. mass peak - crucial for KK gauge boson discovery
- **Achieved significance** $\sim 5\sigma$ @ $300/fb$, LHC14

A simple cut and count strategy suffices.

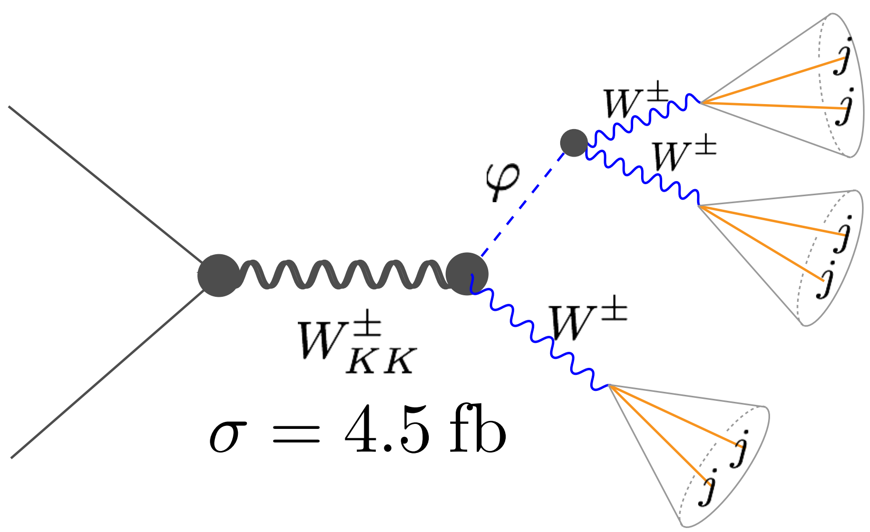
Discovery channel for Radion: Significance with existing di-photon searches is ~1.5 sigma for 1 TeV radion.

RS_3^{EW}

Non-boosted regime:Tri-boson Signals

Focus on hadronic W channels:

- W + di-photon
- Three W



Two complications:

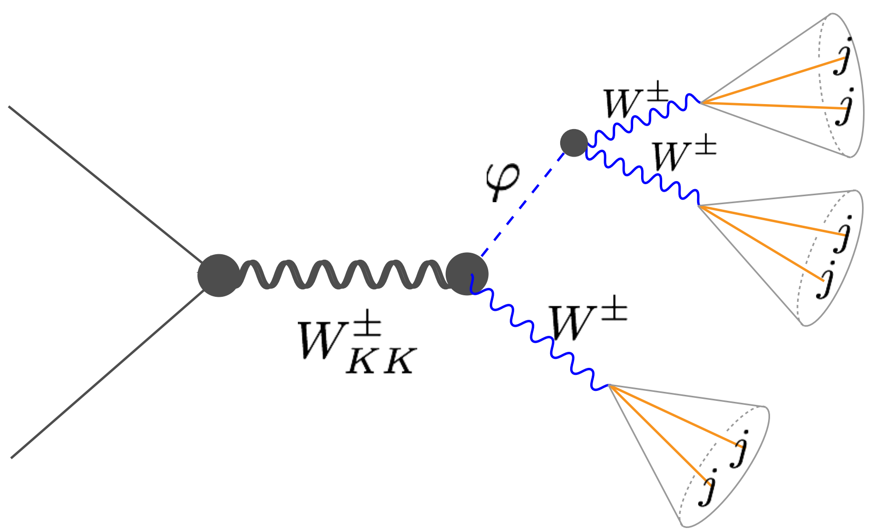
- Fat jets expected, with varying optimal radius.
- Combinatorial ambiguity affects the 2-body invariant mass cuts.

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

Non-boosted regime:Tri-boson Signals

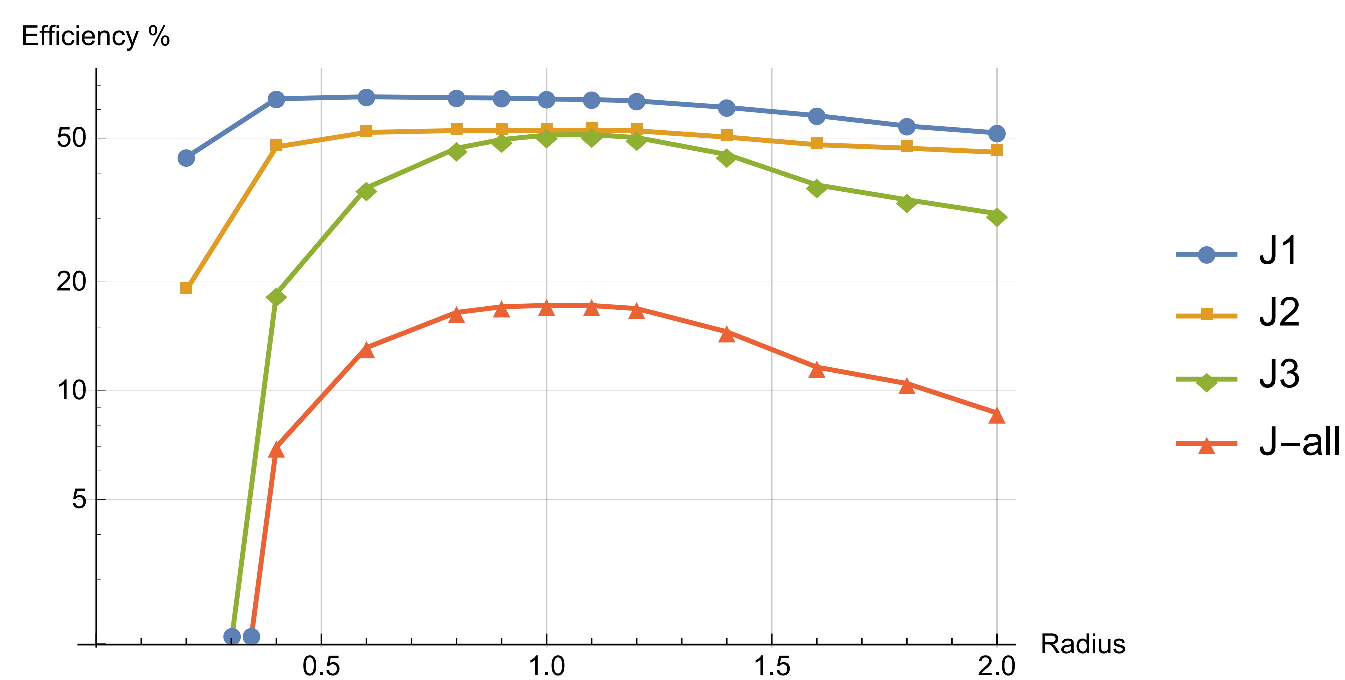
Focus on hadronic W channels:

- W + di-photon
- Three W



Two complications:

- Fat jets expected, with varying optimal radius.
- Combinatorial ambiguity affects the 2-body invariant mass cuts.



Optimal R = 1 gives ~ 18% overall tagging efficiency.

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

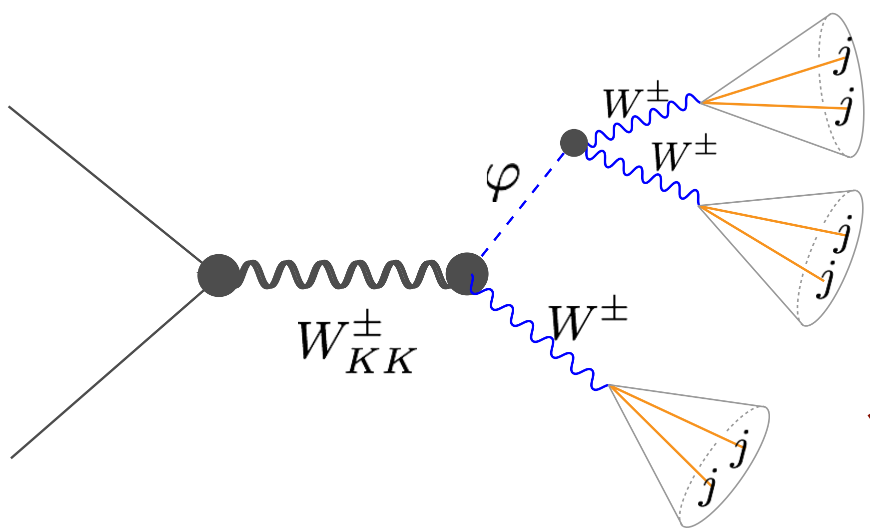
Non-boosted regime:Tri-boson Signals

Focus on hadronic W channels:

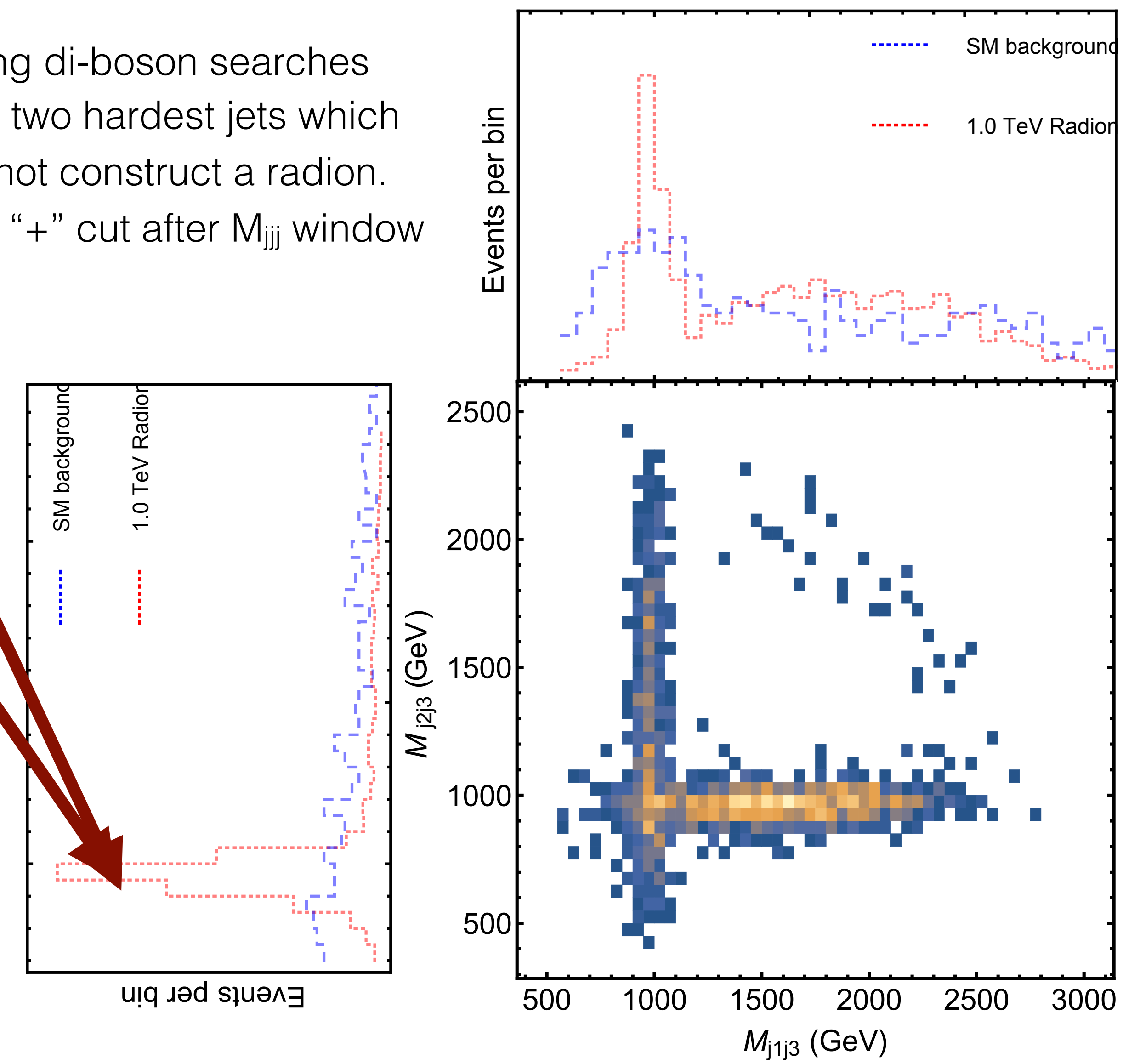
- W + di-photon
- Three W

Two complications:

- Fat jets expected, with varying optimal radius.
- Combinatorial ambiguity affects the 2-body invariant mass cuts.



Existing di-boson searches select two hardest jets which does not construct a radion. Use a “+” cut after M_{jjj} window cut.



Using optimal jet radius and the “+” cut, can get disc. sig. of ~3 at 300/fb at LHC 14.
Further improvements possible: new variables - product of p_T, product of tau_{21} . Requires background modeling so needs a more careful analysis.

RS_3^{EW}

Boosted regime: non-standard jets

JHEP 1811 (2018) 027

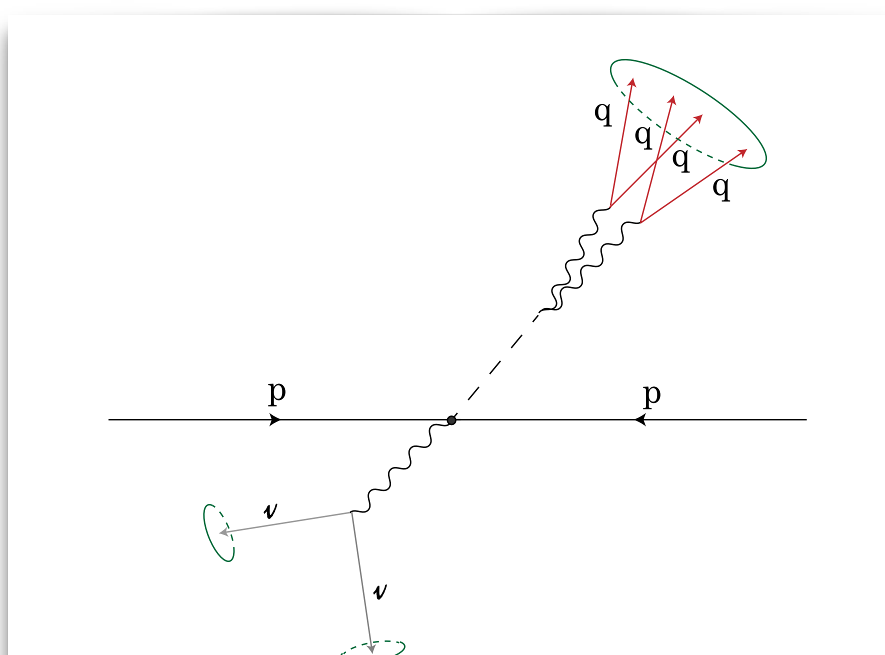
Light scalars expected in many BSM models.

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

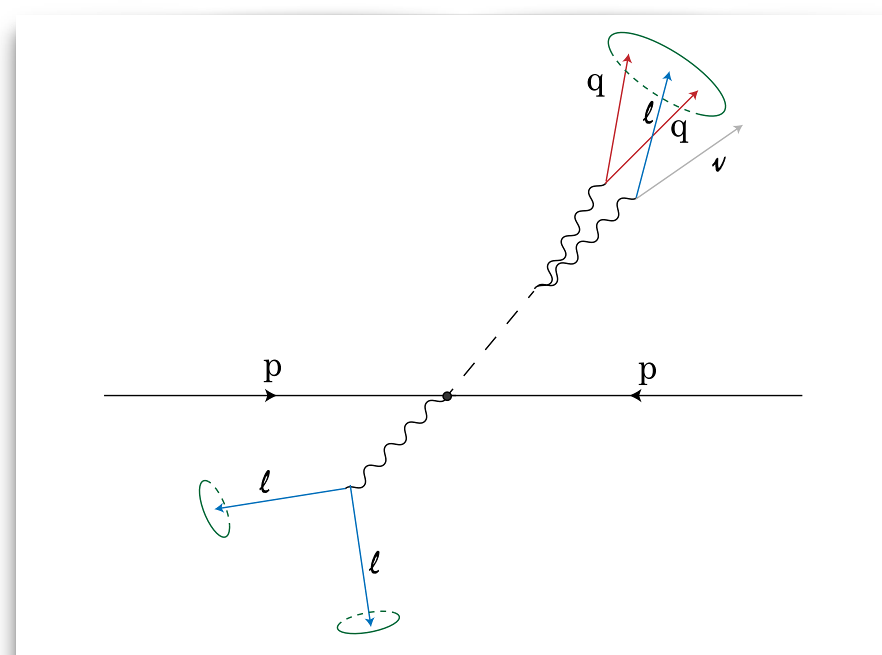
At this point, what’s the novelty?

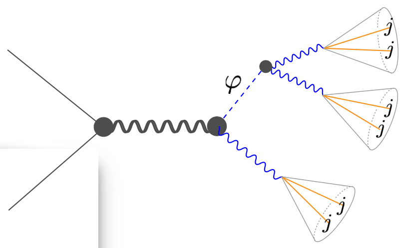
The detector level objects are completely different

4-pronged jets



Leptons inside jets





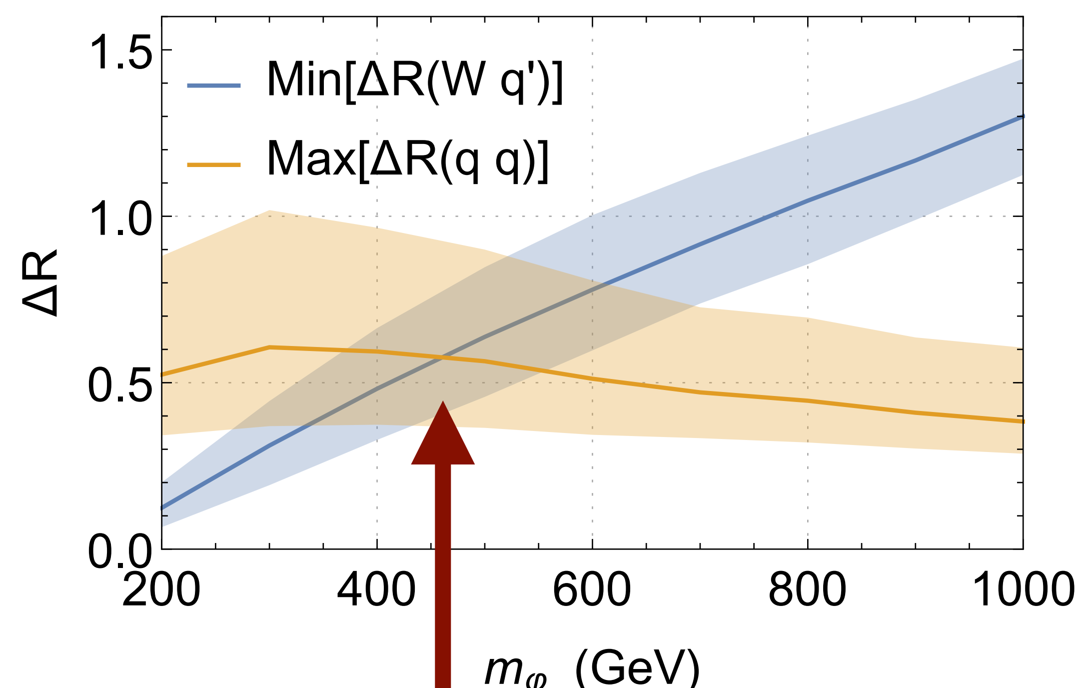
$\mathrm{RS}_3^{\mathrm{EW}}$

Light Radion ~ 200 GeV

Interplay of two relevant angles

$$\Delta R_{WW} \simeq \frac{2\sqrt{m_\varphi^2 - 4m_W^2}}{pT_\varphi}$$

$$\Delta R_{qq/\ell\nu} \simeq \frac{2m_W}{pT_W} \simeq \frac{4m_W}{pT_\varphi}$$

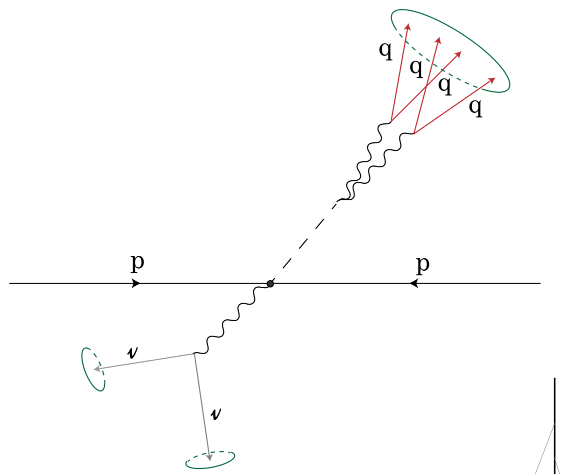


Decay products from different W start to overlap

Decay products from different W are separate

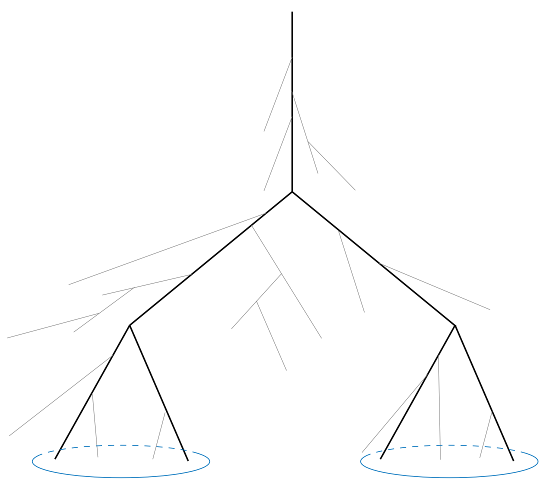
Desirable to identify the two W separately.

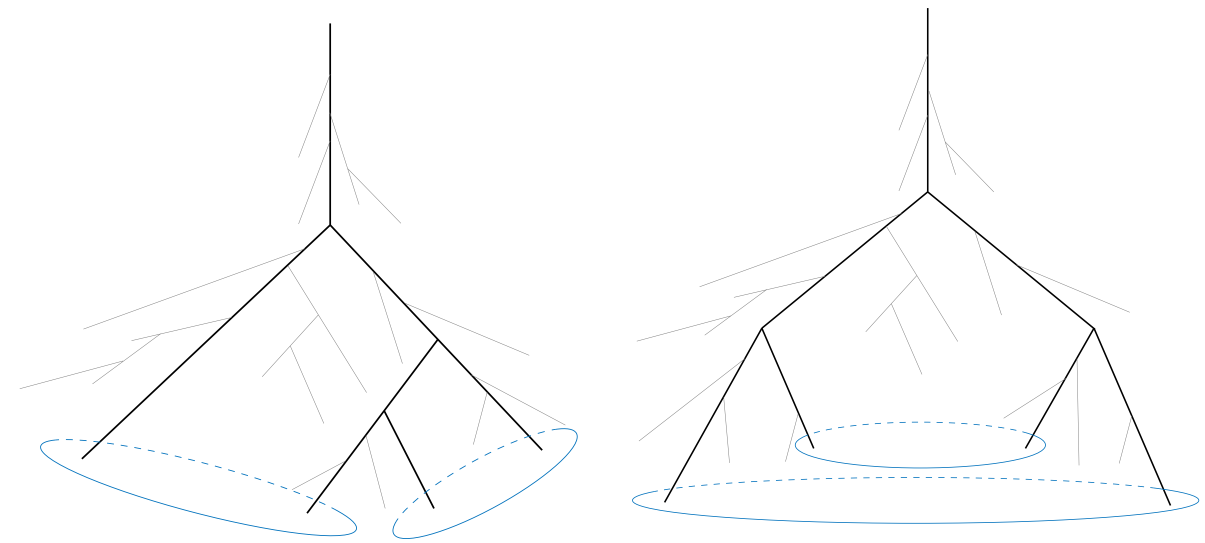
- **For fully hadronic decay, just identifying sub-jets from W is not enough (for low masses).**
- **For semi-leptonic decay, no such ambiguity.**



Fully hadronic

Cluster sequences vs Decay sequence.



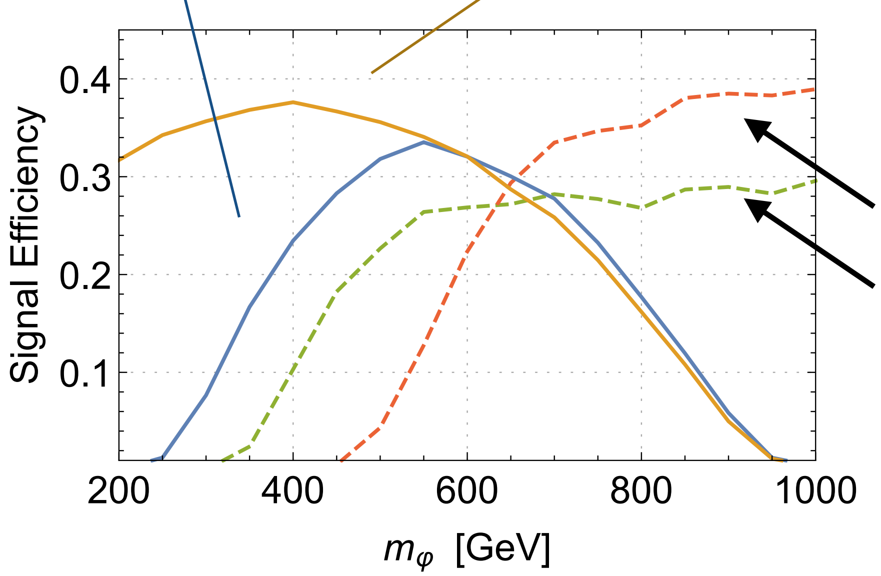


Intermediate masses
Cluster sequences matches decay sequence

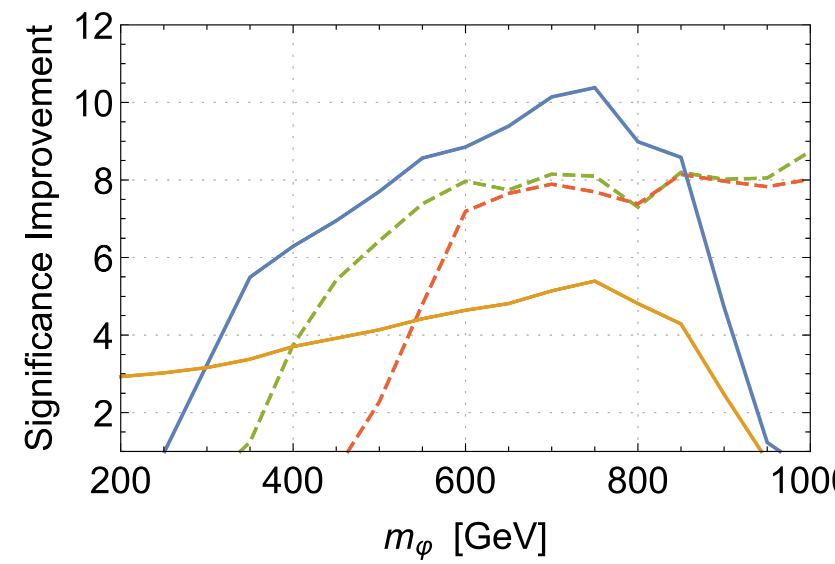
Lower masses
Cluster sequences does not match decay sequence

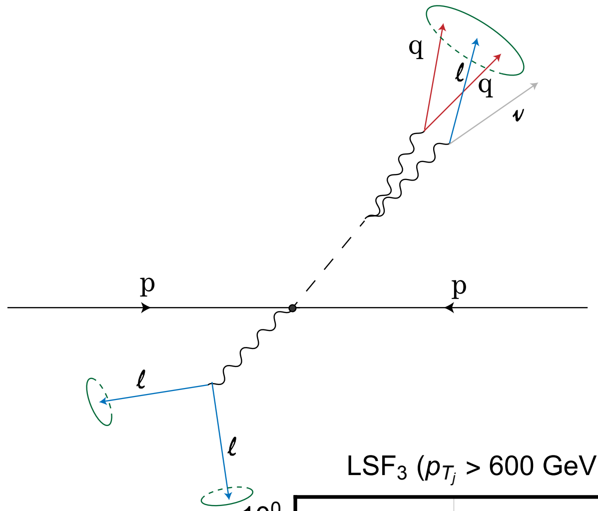
- Cluster using CA algorithm
- Identify hard splittings using soft drop condition

Relevant backgrounds - Z + jet



Resolved Tagger:
R = 0.8 (red)
R = 0.5 (green)





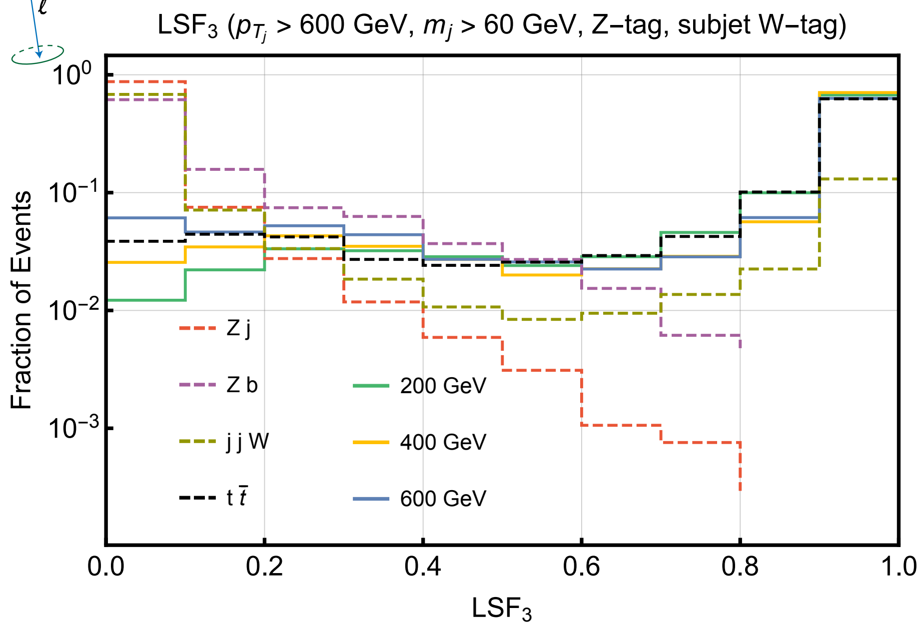
Semi-Leptonic

Lepton Subjet Fraction (LSF_n)

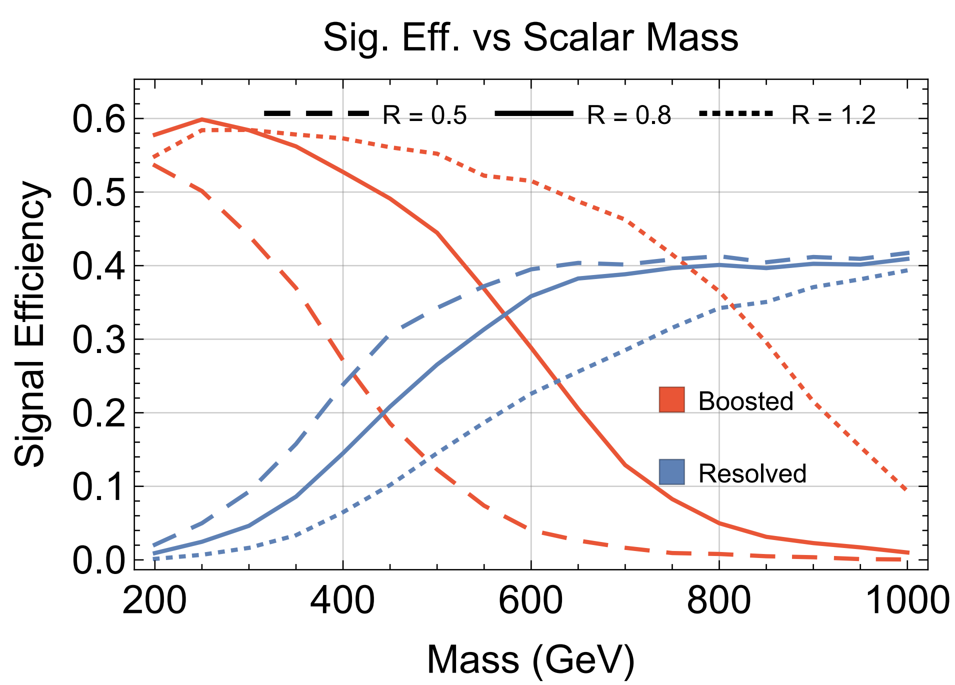
Cluster jet into n sub-jets

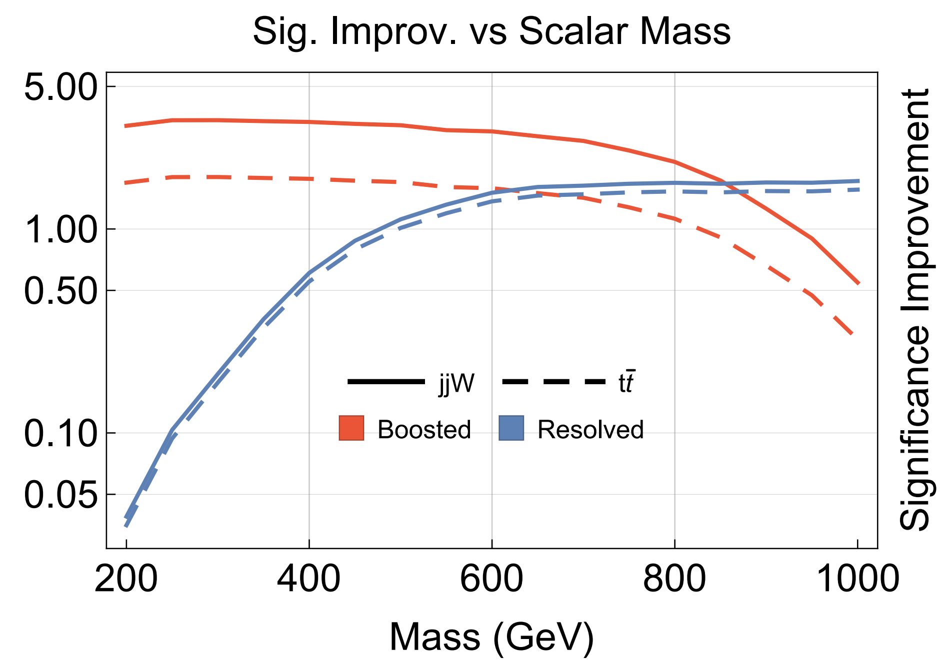
$$\mathrm{LSF_n} = \max_{\text{all leptons}} \frac{p_{T_{\ell_k}}}{p_{T_{s_j}}}$$

l_k is the transverse momentum of k^{th} lepton in subject s_j

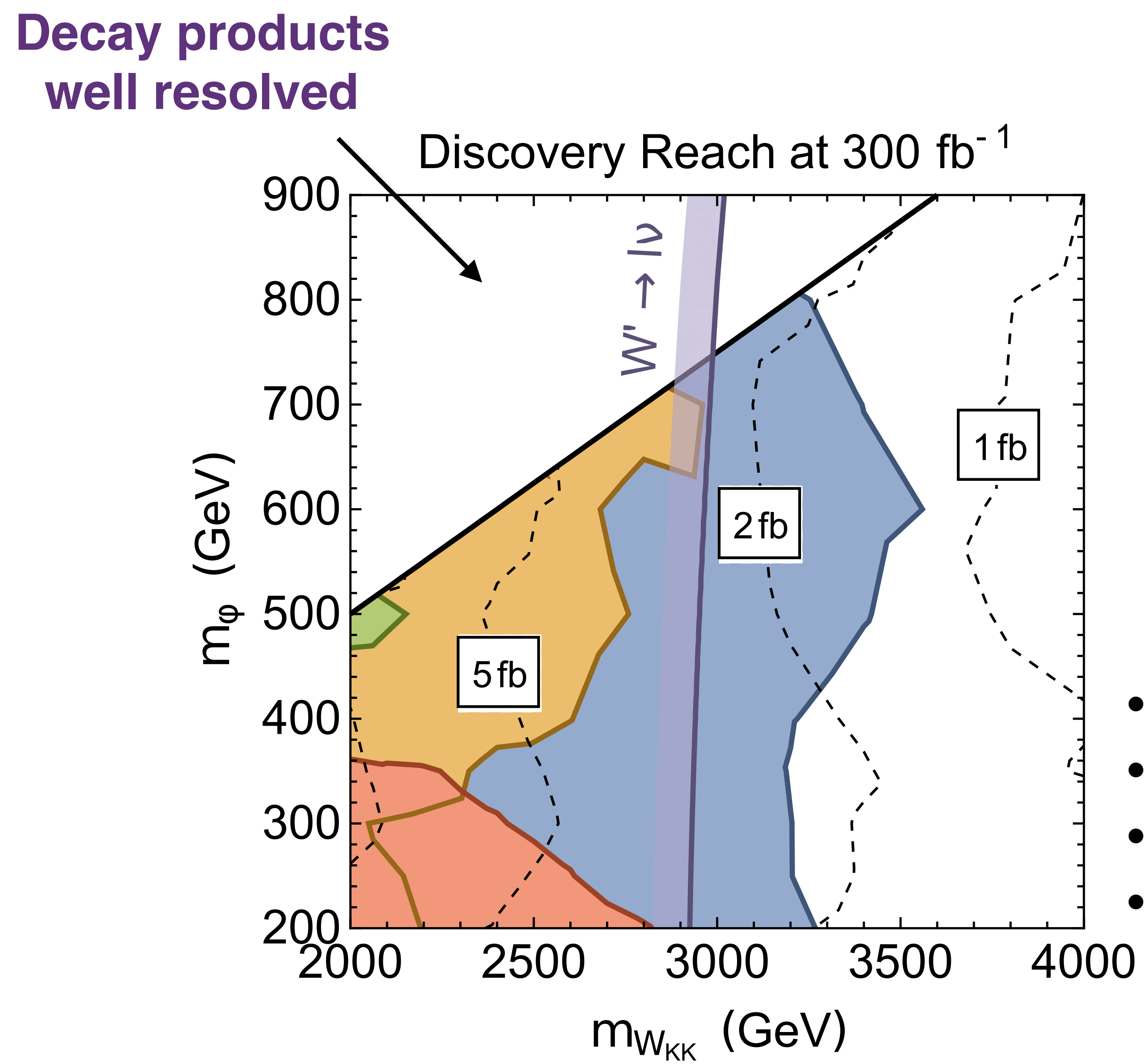


Several relevant backgrounds - Zj, Zb, jjW, tt-bar.
The variable selects the signal like backgrounds.





Application of all of this to the explicit 3-brane RS model with only EW in the bulk



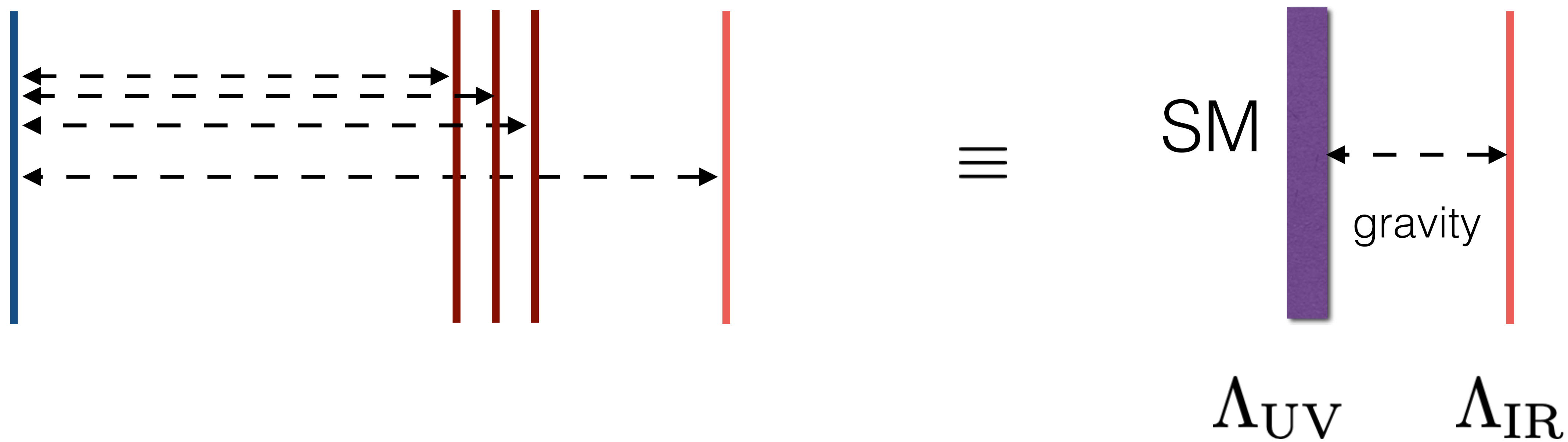
M_{WKK} heavier than few TeV from leptonic decay

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

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.

See the talk "General bounds on Conformal Dark Sectors" by K. Max Wednesday at 15:00

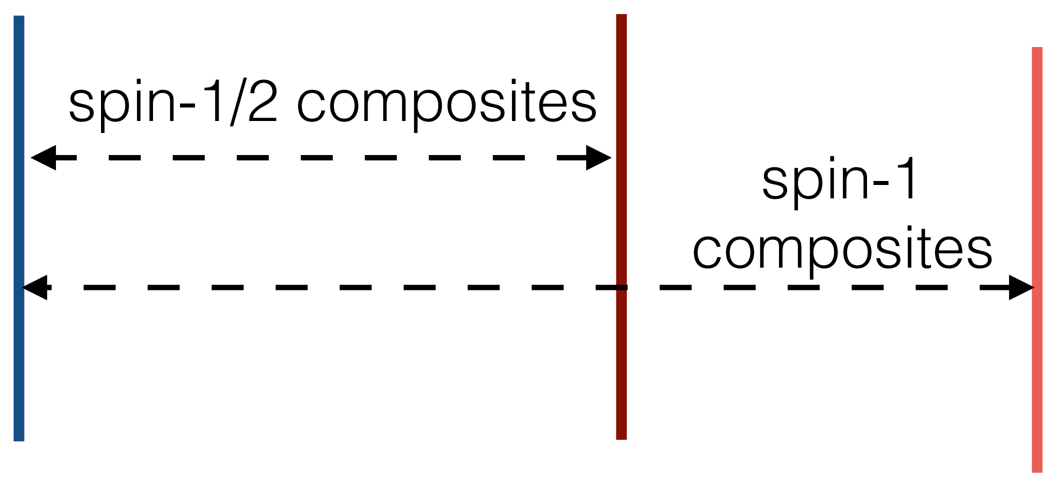
To summarise

- 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.

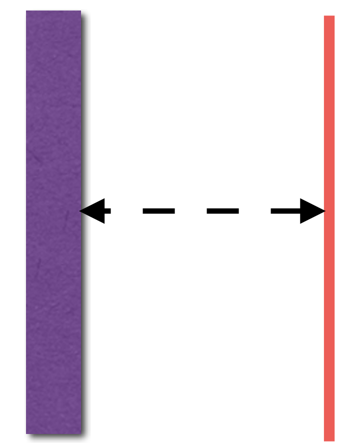
Backup: IR CFT interactions

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

Two contributions: UV CFT and IR CFT

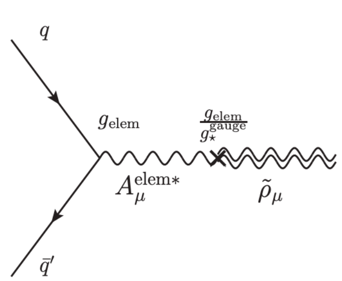


$\equiv$

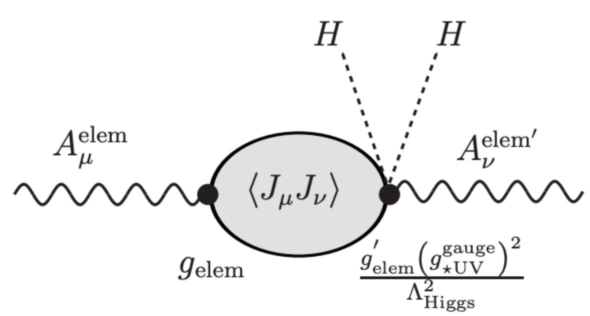


$$A_\mu^{elem} J^\mu_{CFT,IR}$$

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



photon-rho mixing



S-parameter

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

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

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

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

Backup: tri-jet and jet+di-photon cut flow

JHEP 1705 (2017) 078

Cuts	g-ggg-BP1	g-ggg-BP2	jjj
No cuts	29.33	46.60	(7.7×10^7)
$N_j \geq 3$ with pre-selection cuts	23.23	40.05	1.9×10^6
$M_{jjj} \in [2500, 3100]$ GeV	12.20	–	7.9×10^4
$M_{j_1 j_2} \in [1700, 2900]$ GeV	11.12	–	3.9×10^4
$M_{j_1 j_3} \in [850, 2100]$ GeV	9.96	–	1.9×10^4
$M_{j_2 j_3} \in [800, 1050]$ GeV	5.12	–	2015.28
$p_{T,j_1} \geq 1100$ GeV	2.73	–	266.41
$M_{all} \leq 3300$ GeV	1.98	–	94.53
$M_{jjj} \in [2400, 3100]$ GeV	–	22.31	1.0×10^5
$M_{j_1 j_2} \in [1300, 2400]$ GeV	–	19.57	4.8×10^4
$M_{j_1 j_3} \in [1100, 1700]$ GeV	–	13.82	1.0×10^4
$M_{j_2 j_3} \in [900, 1550]$ GeV	–	8.81	1564
$p_{T,j_1} \geq 900$ GeV	–	6.79	807.83
$p_{T,j_2} \geq 600$ GeV	–	6.20	644.54
$p_{T,j_3} \geq 300$ GeV	–	5.44	464.07
$M_{all} \in [2800, 3300]$ GeV	–	3.43	124.61
S/B	0.02	0.03	–
$S/\sqrt{B}$ ($\mathcal{L} = 300$ fb^{-1})	3.49	5.25	–
$S/\sqrt{B}$ ($\mathcal{L} = 3000$ fb^{-1})	11.03	16.60	–

Table 6. Cut flows for signal and major background events in terms of their cross sections (in fb). The number in the parentheses for jjj is obtained with basic cuts ($p_{T,j} > 20$ GeV, $p_{T,\gamma} > 10$ GeV, $|\eta_j| < 5$, $|\eta_\gamma| < 2.5$, $\Delta R_{jj} > 0.4$, $\Delta R_{j\gamma} > 0.4$, $\Delta R_{\gamma\gamma} > 0.4$) at the generation level to avoid divergence. The pre-selection cuts ($p_{T,j} > 150$ GeV, $M_{jj} > 300$ GeV) are imposed at the parton level as well to generate events in the relevant phase space, and are reimposed at the detector level.

Cuts	g-$g\gamma\gamma$-BP1	g-$g\gamma\gamma$-BP2	$j\gamma\gamma$	$jj\gamma$
No cuts	0.17	0.19	(1.07×10^5)	(8.7×10^7)
$N_{j(\gamma)} \geq 1\,(2)$ with pre-selection cuts	0.10	0.13	1.35	1.60
$M_{\gamma\gamma} \in [950, 1350]$ GeV	0.10	–	0.2	0.13
$M_{j\gamma\gamma} \in [2100, 3200]$ GeV	0.09	–	0.02	0.02
$M_{\gamma\gamma} \in [1450, 1550]$ GeV	–	0.12	0.04	0.04
$M_{j\gamma\gamma} \in [2500, 3150]$ GeV	–	0.11	0.005	0.006
$S/\sum B$	2.25	10.0	–	–
$S/\sqrt{S+\sum B}$ ($\mathcal{L} = 300$ fb^{-1})	4.3	5.4	–	–
$S/\sqrt{S+\sum B}$ ($\mathcal{L} = 3000$ fb^{-1})	13.6	17.1	–	–

Table 7. Cut flows for signal and major background events in terms of their cross sections (in fb). The numbers in the parentheses for $j\gamma\gamma$ and $jj\gamma$ are obtained with basic cuts ($p_{T,j} > 20$ GeV, $p_{T,\gamma} > 10$ GeV, $|\eta_j| < 5$, $|\eta_\gamma| < 2.5$, $\Delta R_{jj} > 0.4$, $\Delta R_{j\gamma} > 0.4$, $\Delta R_{\gamma\gamma} > 0.4$) at the generation level to avoid divergence. The pre-selection cuts ($p_{T,j} > 200$ GeV, $p_{T,\gamma} > 200$ GeV, $M_{\gamma\gamma} > 750$ GeV) are imposed at the parton level to generate events in the relevant phase space, and are reimposed at the detector level.

Backup: ATLAS 1903.10415

- Analysis focuses on at least two neutrinos in the final state: to allow two leptons which reduces background.
- Invariant mass cuts are not imposed with this topology in mind.

Evidence for the production of three massive vector bosons with the ATLAS detector

The ATLAS Collaboration

A search for the production of three massive vector bosons in proton–proton collisions is performed using data at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider in the years 2015–2017, corresponding to an integrated luminosity of 79.8 fb^{-1}. Events with two same-sign leptons ℓ (electrons or muons) and at least two reconstructed jets are selected to search for $WWW \to \ell\nu\ell\nu qq$. Events with three leptons without any same-flavour opposite-sign lepton pairs are used to search for $WWW \to \ell\nu\ell\nu\ell\nu$, while events with three leptons and at least one same-flavour opposite-sign lepton pair and one or more reconstructed jets are used to search for $WWZ \to \ell\nu qq\ell\ell$. Finally, events with four leptons are analysed to search for $WWZ \to \ell\nu\ell\nu\ell\ell$ and $WZZ \to qq\ell\ell\ell\ell$. Evidence for the joint production of three massive vector bosons is observed with a significance of 4.0 standard deviations, where the expectation is 3.1 standard deviations.