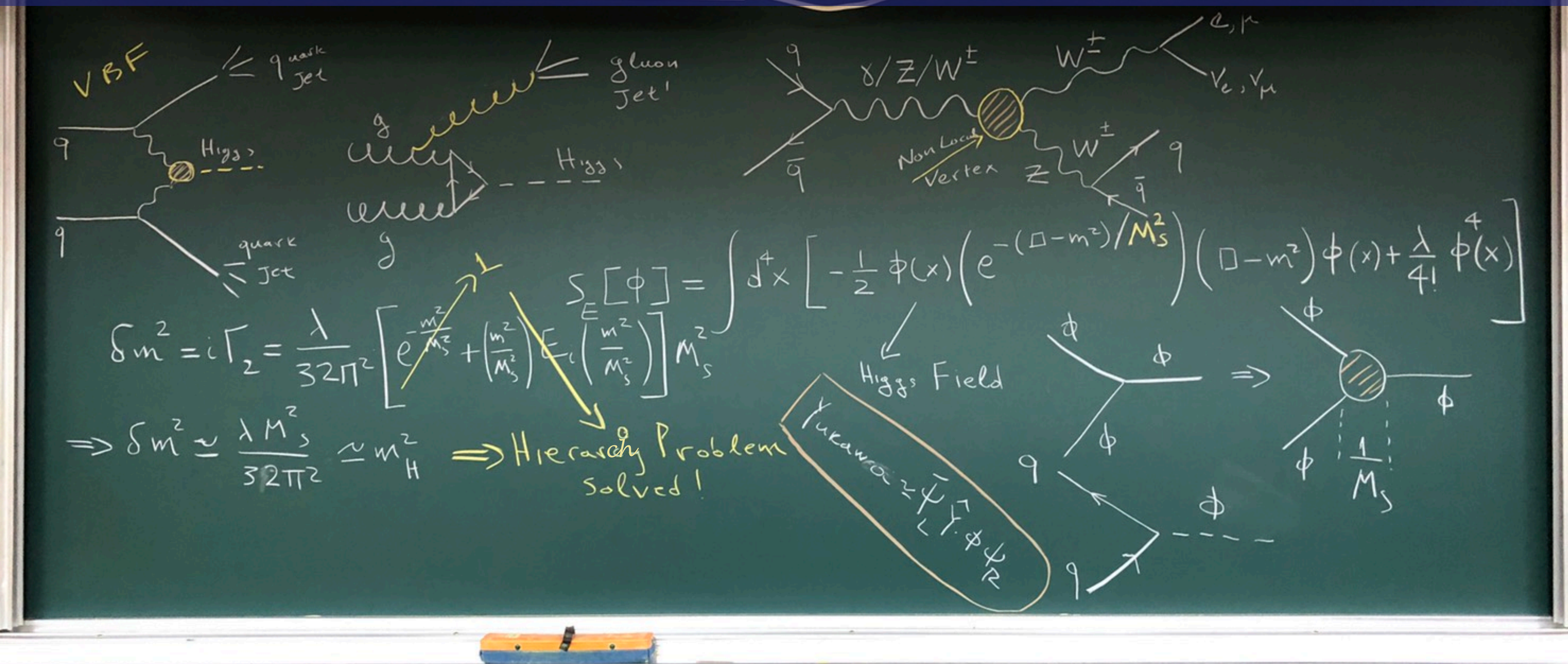
High P_T Higgs excess as a signal of non-local QFT at the LHC



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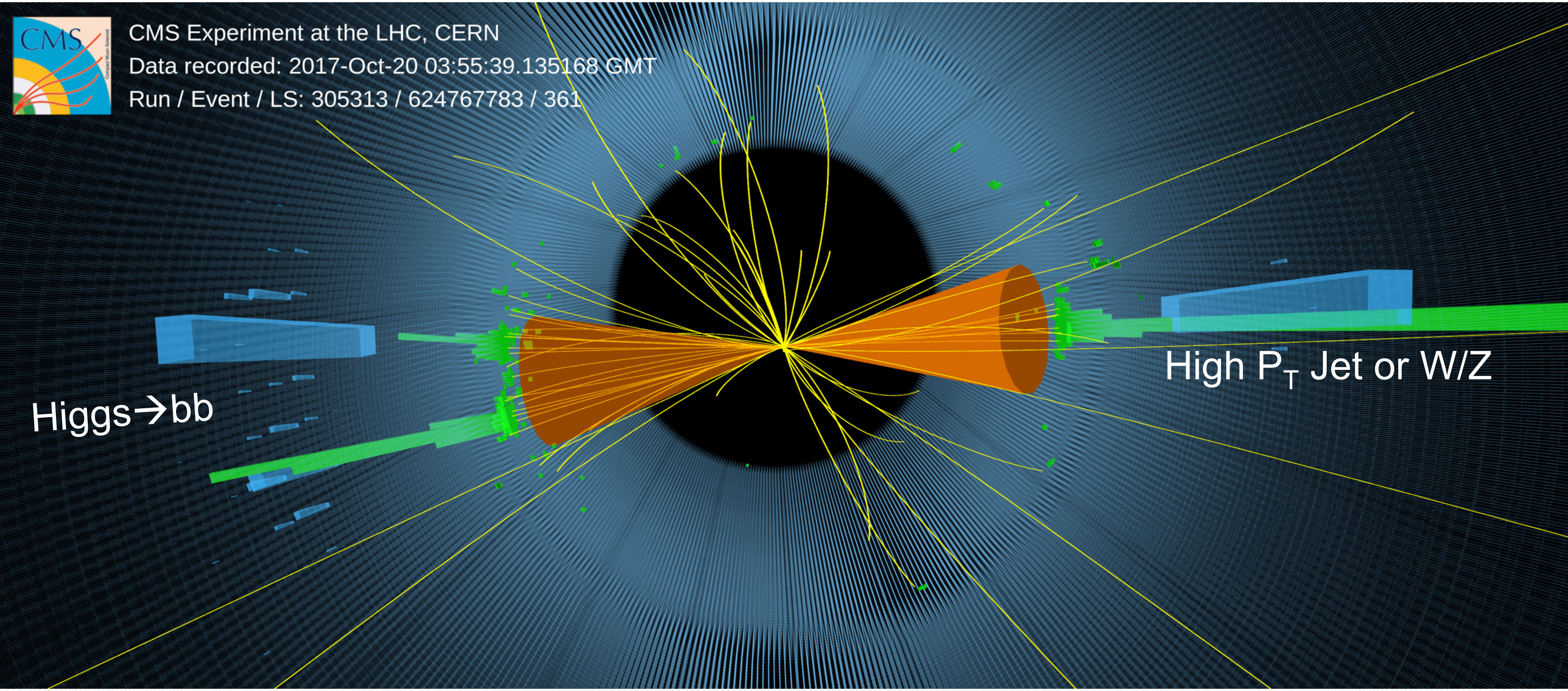
Offshell-2021, 6-9 July 2021

Introduction

- Phenomenological aspects of a “non-local” SM extension are studied.
- Non-locality is introduced by inserting infinite-term polynomials of derivatives in the Lagrangian kinetic or interaction terms
  - Inspired by String Field Theory (late 60’s!)
  - Equivalent to introducing exponential form factors in SM vertices.
  - NL theory is UV finite with no new DOFs or ghosts.
- In this type of extensions the presence of Regge-like trajectories/poles are strongly motivated.
  - J=1 meson poles correspond to W′ and Z′, close to the NL scale.
  - **Lineshapes and cross sections modified by the form factors.**
- Heavy Vectors give anomalous high-Pt Higgs yields.
- In this work, we explore the NL-SM discovery potential in LHC.

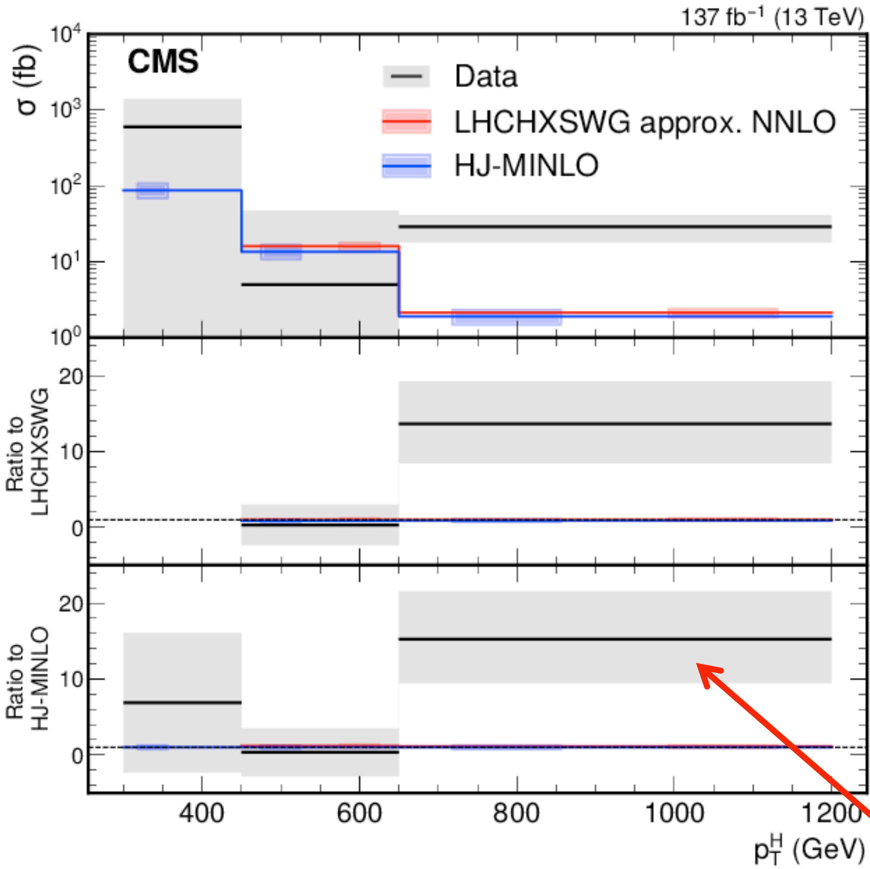
Boosted Higgs: gateway to New Physics?

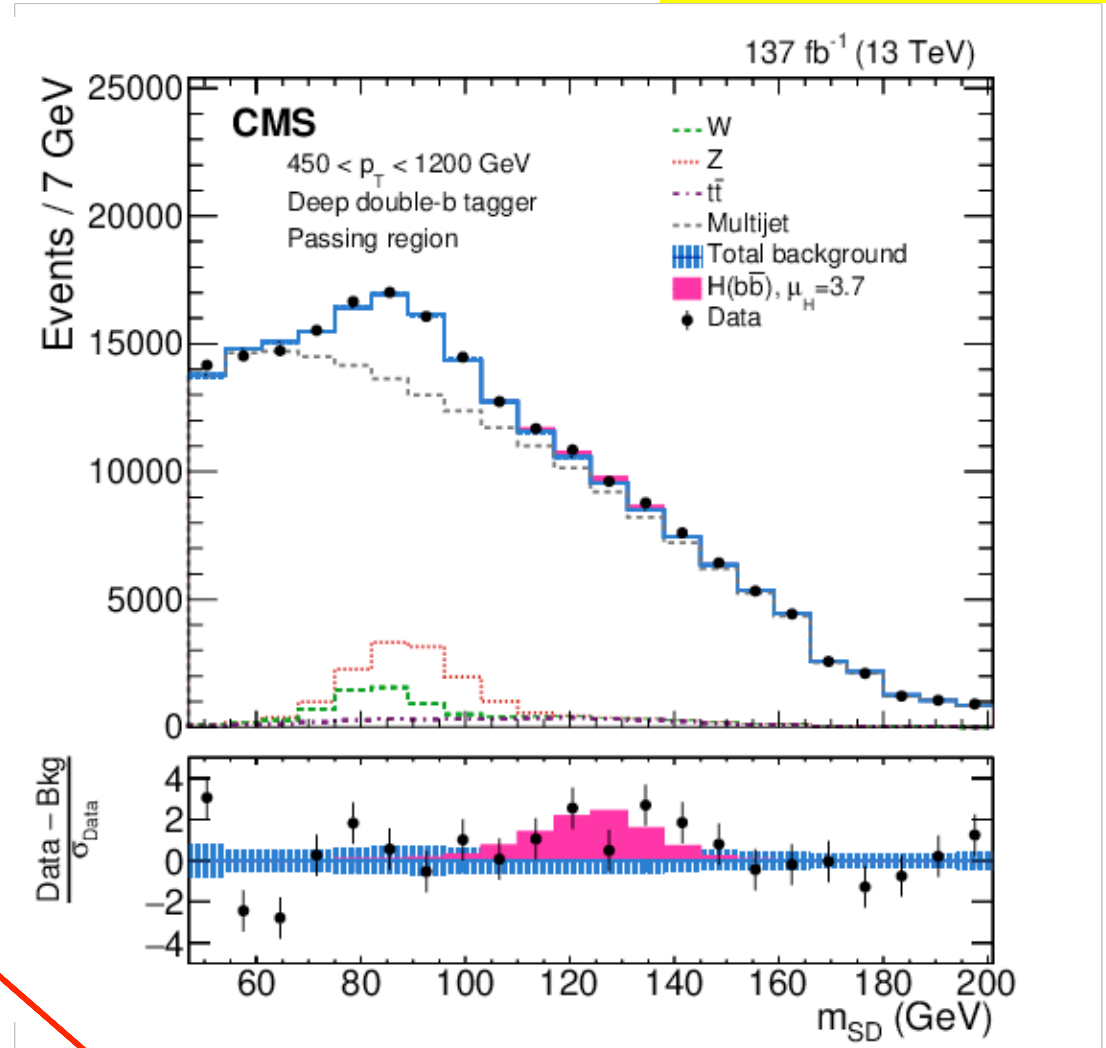


Spectacular events events with Higgs decaying into two small angle objects (bb here) and recoiling against a hadronic object (or even lepton, dilepton).

CMS High P_T H→bb (137 fb^{-1})

JHEP 12 (2020) 085

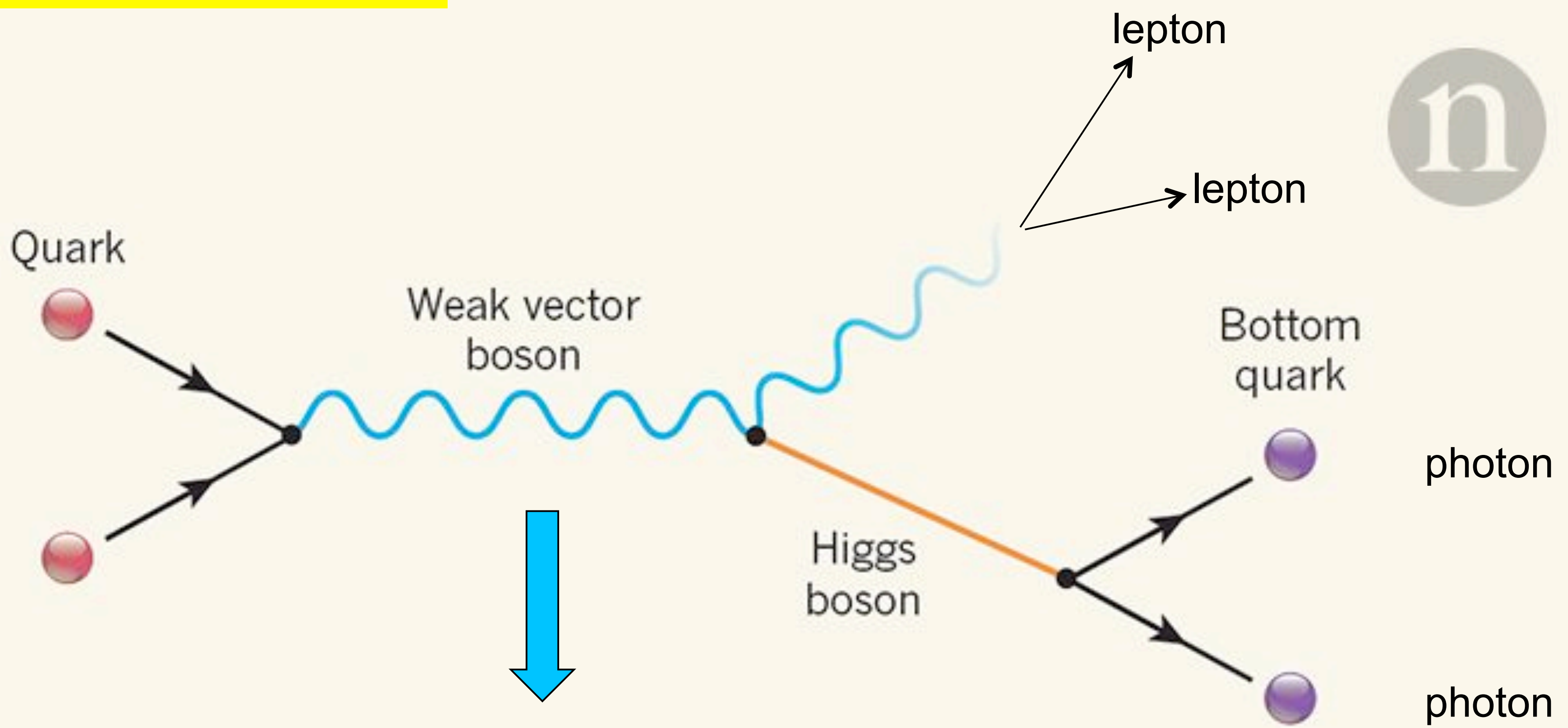




In 2020, CMS reports a small excess for P_T>650GeV: 2.6 σ
(Excess not seen in the Z→bb).

Anomalous boosted H production?

Nature NEWS AND VIEWS 19 Nov 2018



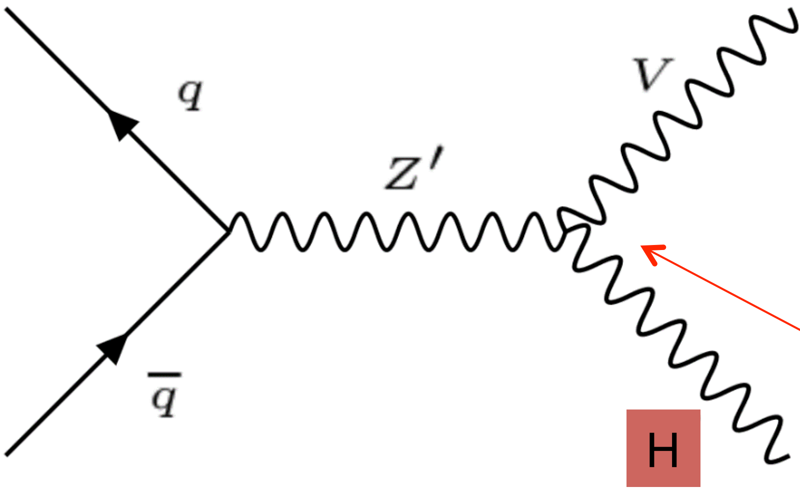
Heavy Exotic Vector(s):

- Predicted by many BSM models
- In composite theories naturally expected as poles in Regge trajectories (J=1 poles), but may not be narrow!

Problem: a visible Higgs excess would require larger cross sections from currently assumed generic models (like HVT, used by ATLAS/CMS)

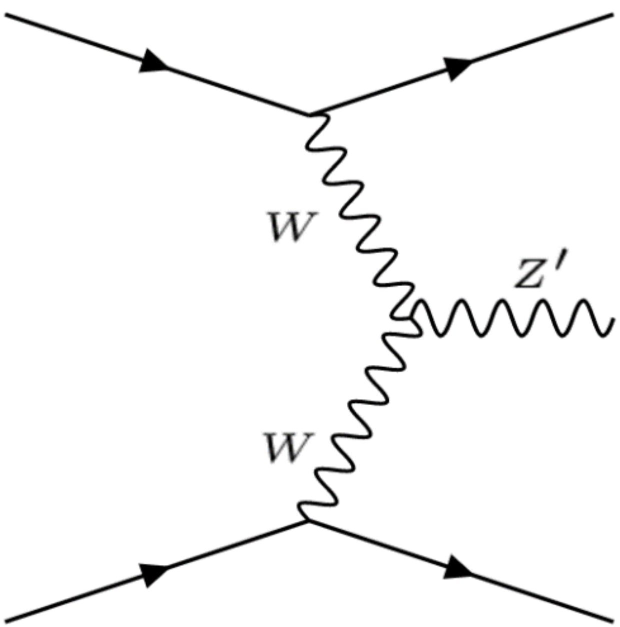
A bit of history: VV/VH dominance

Hoffmann, Kaminska, Nicolaidou, SP, EPJC74 (2014) 3181



Drell-Yan production (dominant)

Larger gV coupling? Form Factor.
NP effects studied in: **JHEP 1803 (2018) 159**



Vector Boson Fusion (VBF)

Li, Nicolaidou, SP, EPJC, arXiv:1904.03995 (2019)

(used VH/VZ → V+bb)

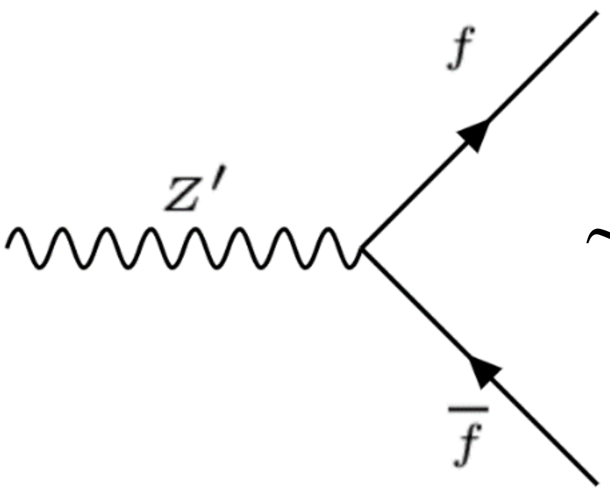
A model for BSM spin-1 resonances

HVT Model

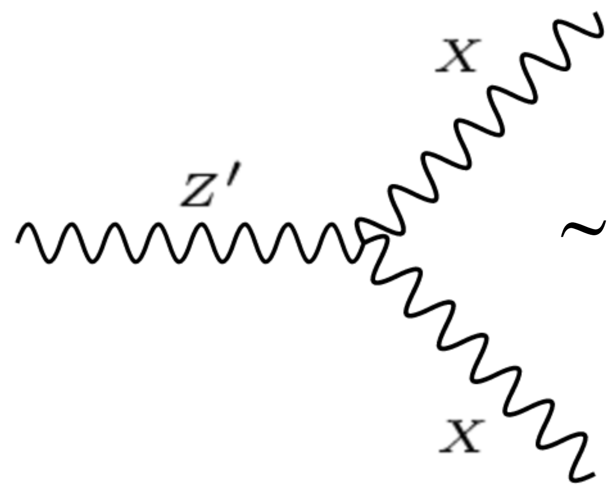
23. D. Pappadopoulo, A. Thamm, R. Torre and A. Wulzer, Heavy Vector Triplets: Bridging Theory and Data, JHEP 09 (2014) 060.

Coupling of resonance to SM fermions through mixing with the Eweak bosons.

Coupling of resonance to weak boson through effective coupling gV.



$$\sim \frac{g^2}{g_V} c_F$$



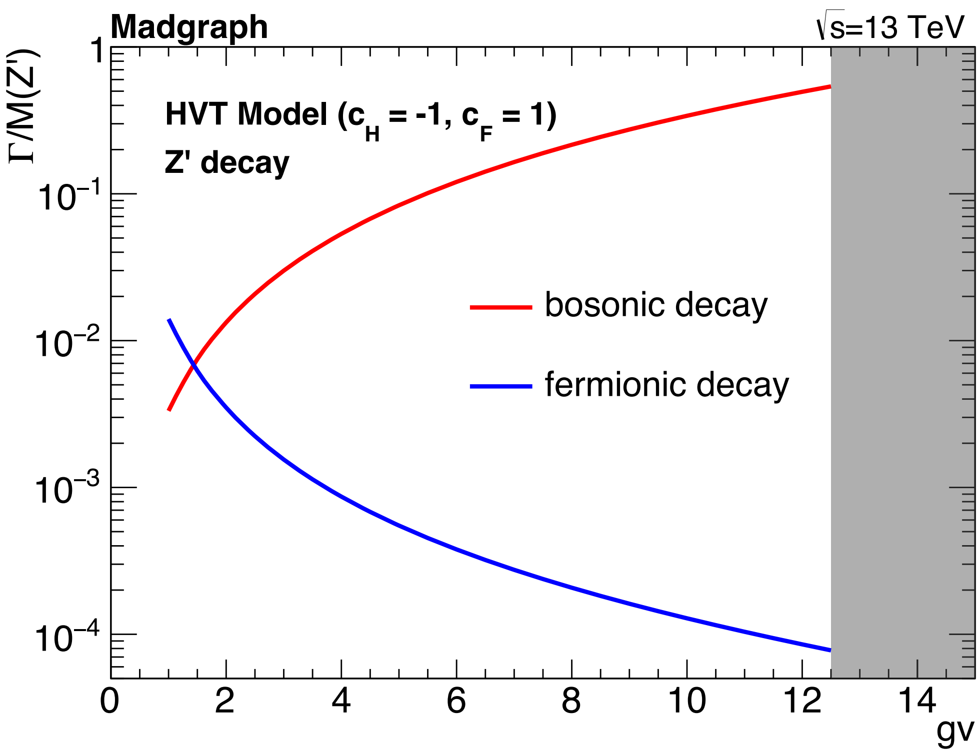
$$\sim g_V c_H$$

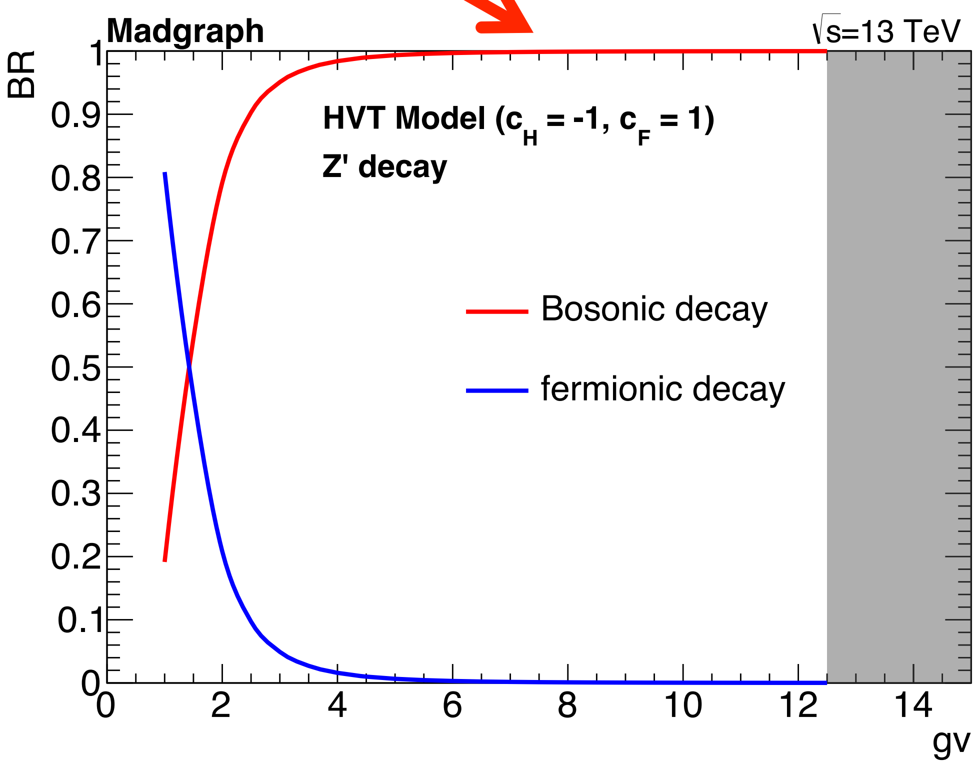
Additional weight to the coupling to add flexibility

Additional weight to the coupling to add flexibility

V′ decays to VV, VH dominant

Large g_V





For large g_V the BR to fermions goes to 0.

Large g_V also means larger width (>5%). Only close to NP regime width very large.

Can we increase HVT xsections?

- Non-local modification of the SM, may affect couplings: cross sections modified
- Several SM extensions fall in this effective description.
- The new Physics scale Λ_{NL} should be at a few TeV.

Non-Local QFT

Smearing a delta function using exp(p^2) gives a Gaussian: smearing of a point.

$$e^{\alpha^2 \partial_x^2}\delta(x) = e^{\frac{\partial_x^2}{\Lambda^2}}\delta(x) = \frac{1}{\alpha\sqrt{2}}e^{-\frac{x^2}{4\alpha^2}}$$

Smearing effects become important at scale $\Lambda \sim 1/\alpha$

The coefficient α has dimension of $1/P^2$: this is the non-locality scale squared

String Field Theory

Non-locality enters through infinite derivatives which give form factors.

Infinite derivative operators well known in String Theory:

$$\boxed{V \sim e^{c\frac{\Box}{M_s^2}}}$$

Amplitudes proportional to exp(cα′□)

String Tension (used in ST vertices)
Scale of non-locality

$$a' = \frac{1}{M_s^2}$$

Universal Regge Slope
(back in the 60's!)

EPJ A 48, 127 (2012)

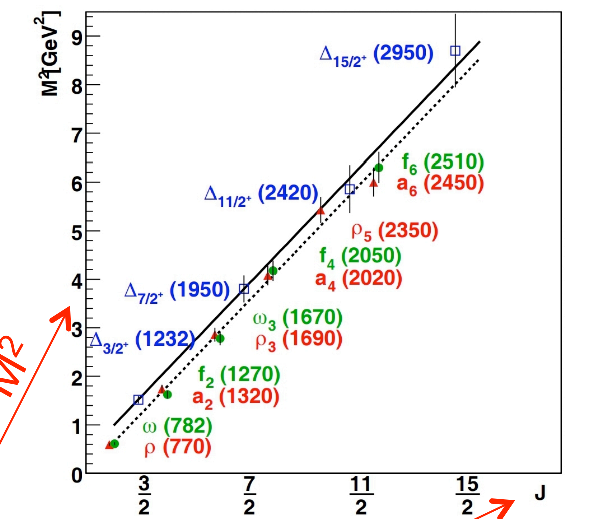


Fig. 1. The leading Regge trajectory: Δ resonances with maximal J in a given mass range. Also shown is the Regge trajectory for mesons with $J = L + S$.

Reminder: Regge trajectory $\quad a'E_N^2 = N\hbar$

For QCD strings $a' = \left(10^{-15}\ \mathrm{m}\right)^2$ for superstrings $a' = \left(10^{-33}\ \mathrm{m}\right)^2$

The non-local QFT prescription

PRD 101 (2020) 8, 084019

Start with a real scalar $\phi(x)$ and write down the action:

$$S = \frac{1}{2}\int d^4x d^4y \phi(x)\mathcal{K}(x-y)\phi(y) - \int d^4x V(\phi(x)),$$

Operator that makes explicit the non-local dependence.

Fourier Transform

$$\begin{aligned} S_{\mathcal{K}} &= \frac{1}{2}\int d^4x d^4y \phi(x)\mathcal{K}(x-y)\phi(y) \\ &= \frac{1}{2}\int d^4x d^4y \phi(x) \boxed{\int \frac{d^4k}{(2\pi)^4} F(-k^2) e^{ik\cdot(x-y)}} \phi(y) \\ &= \frac{1}{2}\int d^4x d^4y \phi(x) F(\Box) \int \frac{d^4k}{(2\pi)^4} e^{ik\cdot(x-y)} \phi(y) \\ &= \frac{1}{2}\int d^4x \phi(x) F(\Box) \phi(x), \end{aligned}$$

$$\int \frac{d^4k}{(2\pi)^4} e^{ik\cdot(x-y)} = \delta^{(4)}(x-y)$$

Use the the integral representation of the Dirac δ

$$\mathcal{K}(x-y) = F(\Box)\delta^{(4)}(x-y).$$

Strictly speaking it should be dimensionless: $\dfrac{\Box}{\Lambda^2_{NL}}$

Choice of F(□)

PRD 101 (2020) 8, 084019

$$F(\Box) = e^{-f(\Box)} \prod_{i=1}^{N} (\Box - m_i^2),$$

If we require F(□) to be an *entire analytic function*. We use the Weierstrass factorization theorem.

Its inverse is the propagator

$$\Pi(k) = e^{f(-k^2)} \prod_{i=1}^{N} \frac{-i}{k^2 + m_i^2}.$$

2N is the number of poles in the propagator

For N>1 there are ghost DOF. So, selecting N=1.

$$\boxed{F(\Box) = e^{\frac{(-\Box + m^2)^n}{M_s^{2n}}} (\Box - m^2),}$$

Polynomial functions of □ is std choice for f(□)

(*) EAF: c-valued function that is holomorphic at all finite points in the whole complex plane.

Non-Locality is in the Interaction!

$$\tilde{\phi}(x) = e^{-\frac{1}{2}f(\Box)}\phi(x) = \int d^4y\mathcal{F}(x-y)\phi(y),$$

After a field redefinition …

where $\mathcal{F}(x-y) := e^{-\frac{1}{2}f(\Box)}\delta^{(4)}(x-y)$

$$S = \frac{1}{2}\int d^4x\tilde{\phi}(x)(\Box - m^2)\tilde{\phi}(x) - \int d^4xV\left(e^{\frac{1}{2}f(\Box)}\tilde{\phi}(x)\right)$$

The NL operator appears in the interaction term

$$e^{-f(\Box)}(\Box - m^2)\phi(x) = \frac{\partial V(\phi)}{\partial\phi(x)},$$

Field Equations have a new term: the NL operator.

for a delta source: $\delta^{(4)}(x-y) = \delta(x^0-y^0)\delta^{(3)}(\vec{x}-\vec{y})$

$$e^{-f(\Box_x)}(\Box_x - m^2)\Pi(x-y) = i\delta^{(4)}(x-y)$$

The solution is:

$$\Pi(x-y) = \int\frac{d^4k}{(2\pi)^4}\frac{-ie^{f(-k^2)}}{k^2+m^2-i\epsilon}e^{ik\cdot(x-y)}$$

Or in momentum space:

$$\boxed{\Pi(k) = -\frac{ie^{f(-k^2)}}{k^2+m^2-i\epsilon}}$$

Usual propagator now carries the NL operator

NL non-abelian gauge theories

Goshal, Mazumdar, Okada, Villalba, arXiv:2010.15919, 2020

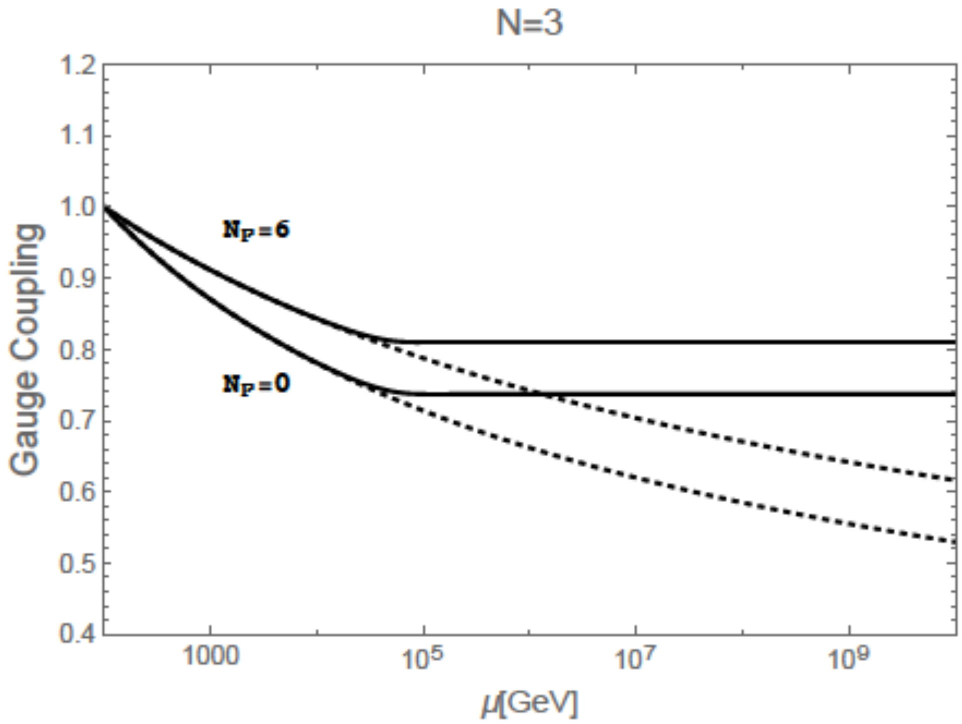


Figure 1. The SU(3) gauge coupling running with $N_F = 6$ & $N_F = 0$, shown in solid (dashed) black lines for the non-local (local) theories. Here, we have set $M = 10^5$ GeV.

Theory is not scale invariant at the IR, but it becomes invariant at the UV, beyond the non-locality scale.

In the Higgs sector, the Hierarchy problem is ameliorated.

No ghosts and and no new degrees of freedom.

One may ask: does this mean the spacetime is discrete?

Discrete or not discrete spacetime?

We can think of non-locality in different ways:

i. Discretization of spacetime: a minimal length scale exists (usually Planck~$1/M_p$)

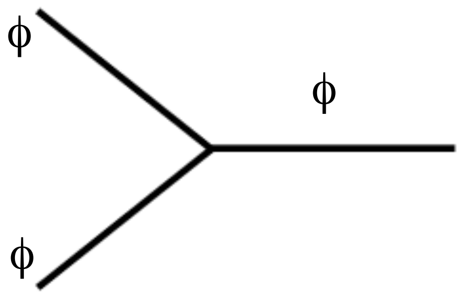
ii. Related to interactions in **continuous spacetime**: free theory is unaffected by non-locality. Switching on interactions at some scale Λ_{NP} non-locality is then associated with this scale.

Here we use (ii) and introduce the non-locality via form factors applied on kinetic operators or equivalently interaction terms in the Lagrangian.

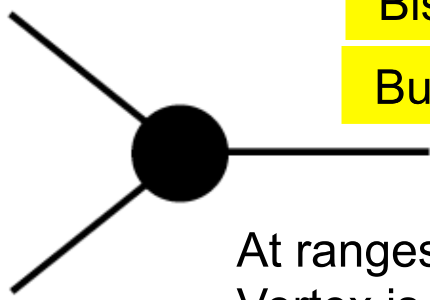
Non-Local SM

Biswas, Okada: NPB 898 (2015) 113-131

Buoninfante et.al. PRD 101 (2020) 8, 084019



Local vertex



Nonlocal vertex

At ranges R < 1/M
Vertex is smeared by infinite derivative operator

$$S_E[\phi] = \int d^4x \left(-\frac{1}{2}\phi(x) e^{-(\Box - m^2)/M_s^2} (\Box - m^2)\phi(x) + \frac{\lambda}{4!}\phi^4(x) \right)$$

$$\delta m^2 = i\Gamma_2 = \frac{\lambda}{32\pi^2}\left[\cancelto{1}{e^{-\frac{m^2}{M^2}}} + \cancelto{0}{\left(\frac{m^2}{M^2}\right) Ei\left(-\frac{m^2}{M^2}\right)} \right] M^2$$

Hierarchy problems are reduced

- For $k^2 << M^2$ vertices look point-like → SM effective theory.
- For $k^2 > M^2$ couplings scale → theory is conformal.
- No problems with vacuum stability.
- Theory is UV finite.

Non-locality at the SM (TeV) scales?

Similarity to string potential,
Veneziano amplitude

$$\sigma_{NL-SM} = e^{a\frac{s}{\Lambda_{NL}^{2}}} \times \sigma_{SM}$$

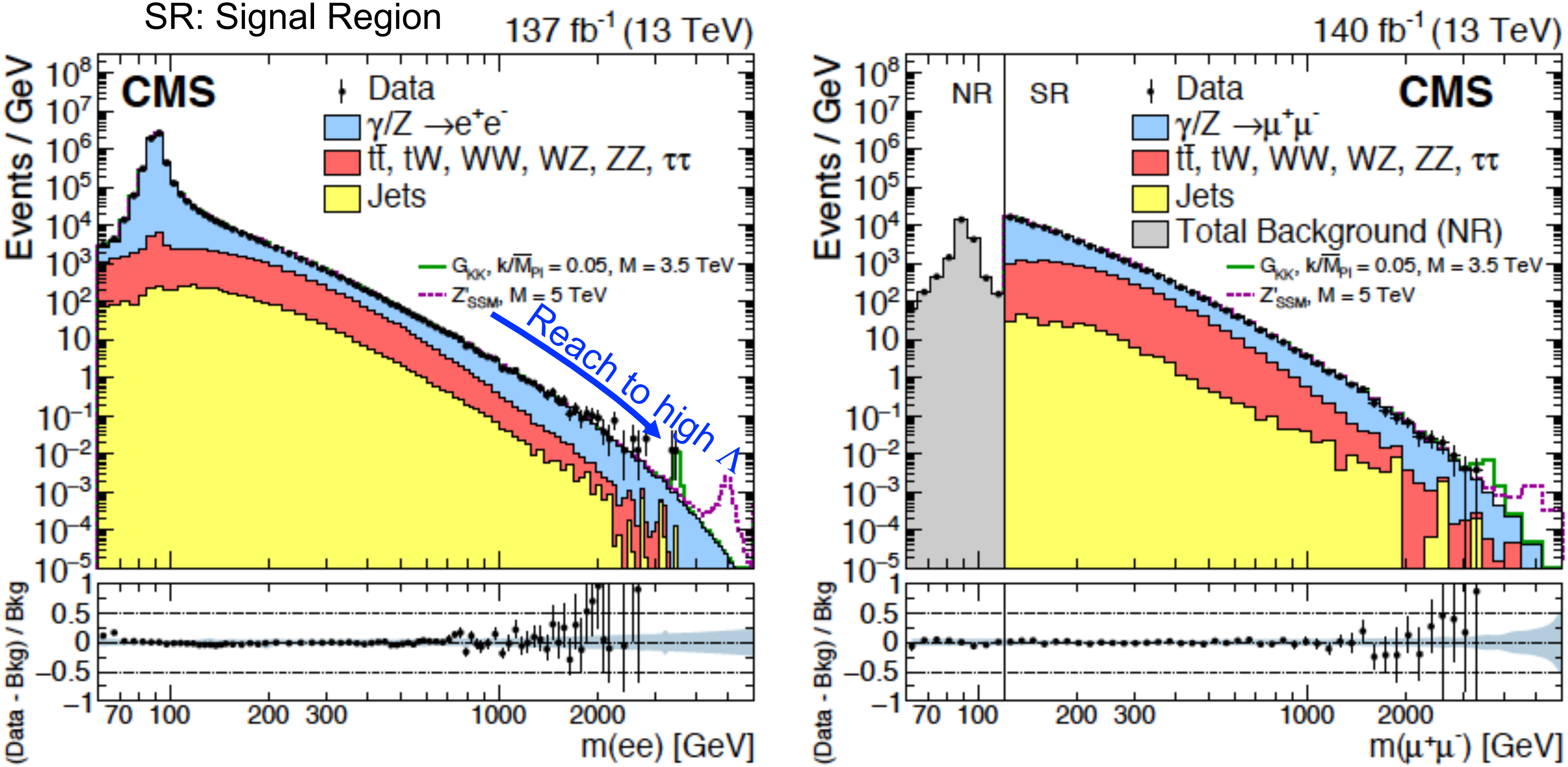
s = q^2 : momentum transfer square

We need LHC observables that have s ~ Λ^2 ~ multi-TeV

High mass DY: affected by NL

arXiv:2103.02708

NR: Normalization Region
SR: Signal Region



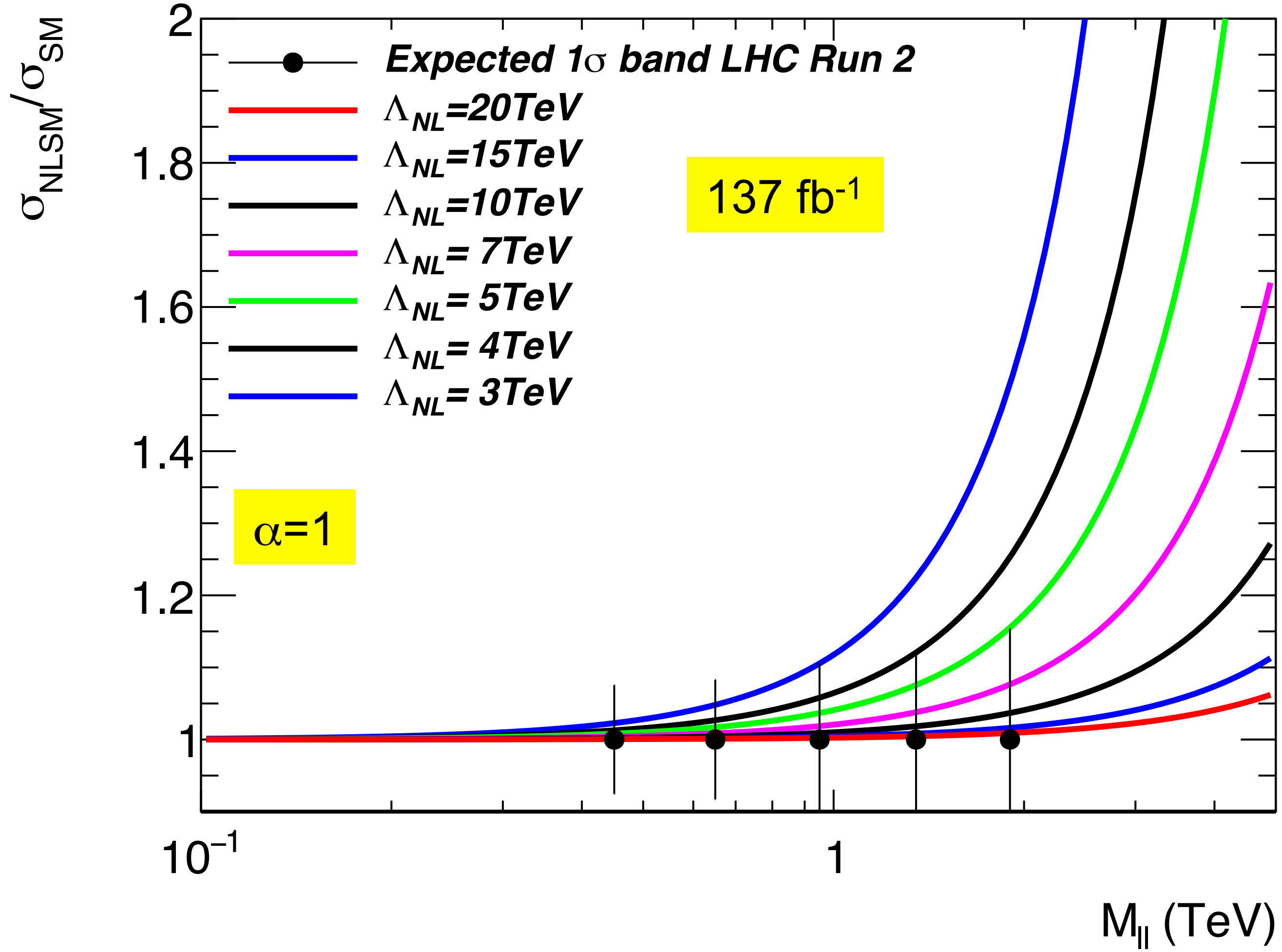
electrons

muons

Deviations (up or down) are expected for Non-Locality effects

High mass DY: constrain the Λ_{NL}

Use the CMS published 1-σ uncertainties to get an idea of the expected limits.
We leave the extracted (observed) limits to the experiments.



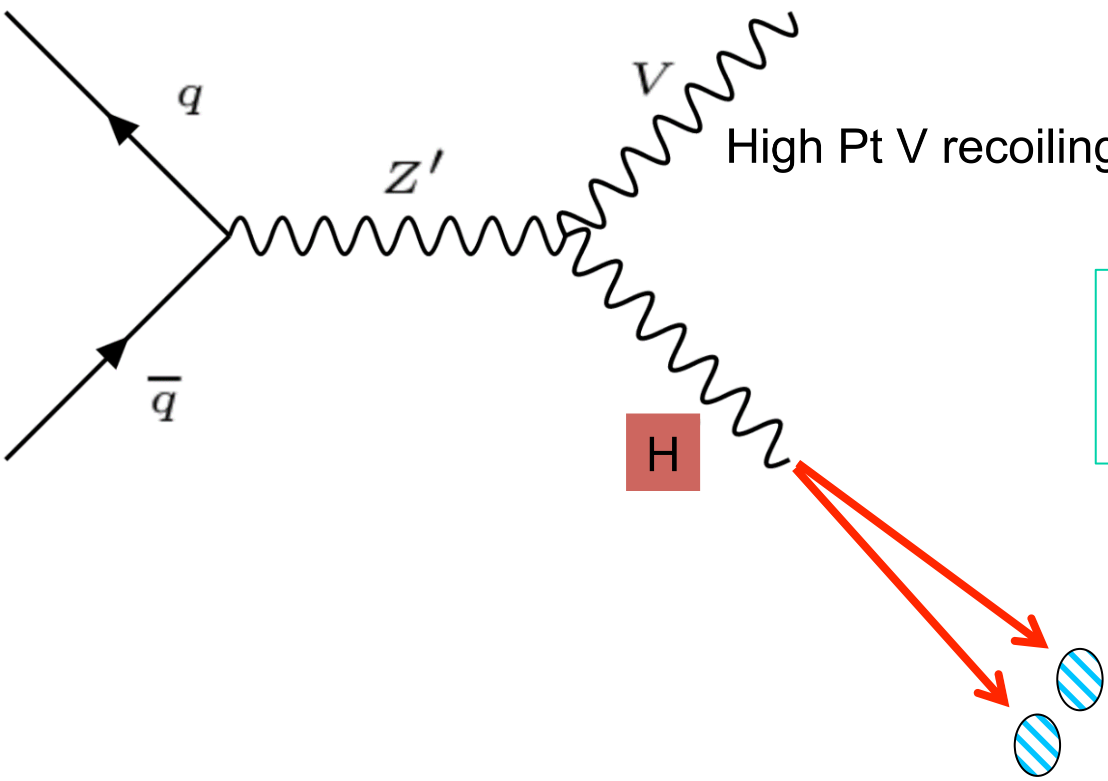
In this work we consider only α>0 (positive deviations).
A few TeV limit can already be set by DY!

Non-Local QFT at the LHC

NL effects can lead to diboson excess (only in the s-channel production)

We want to look in a region of phase space with very small background.

Look for VH→γγ events with "collinear" photons. (V→leptonic for now)

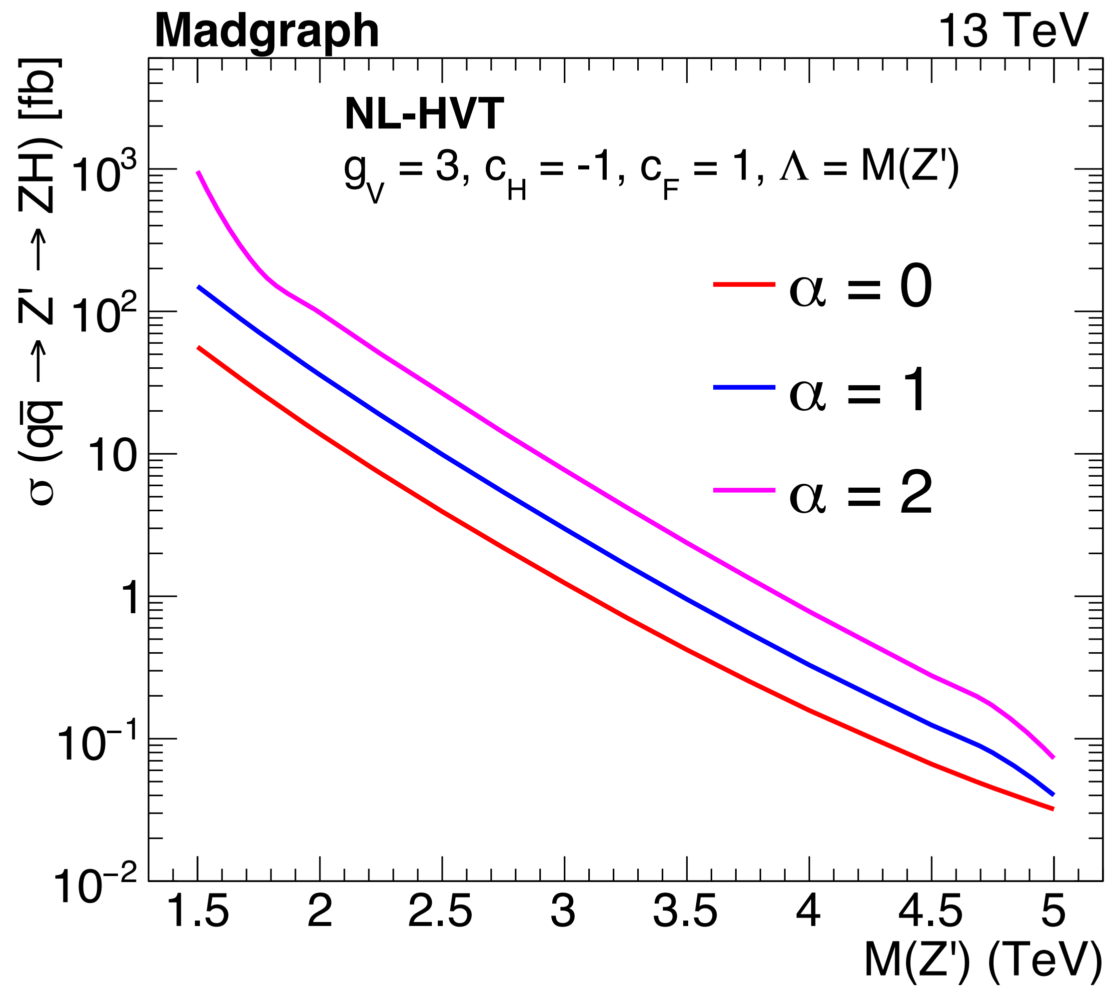


High Pt V recoiling off Higgs

We have been calculating the feasibility of this idea for Run3 and HL-LHC with sub-fb sensitivity out to 4-5TeV.

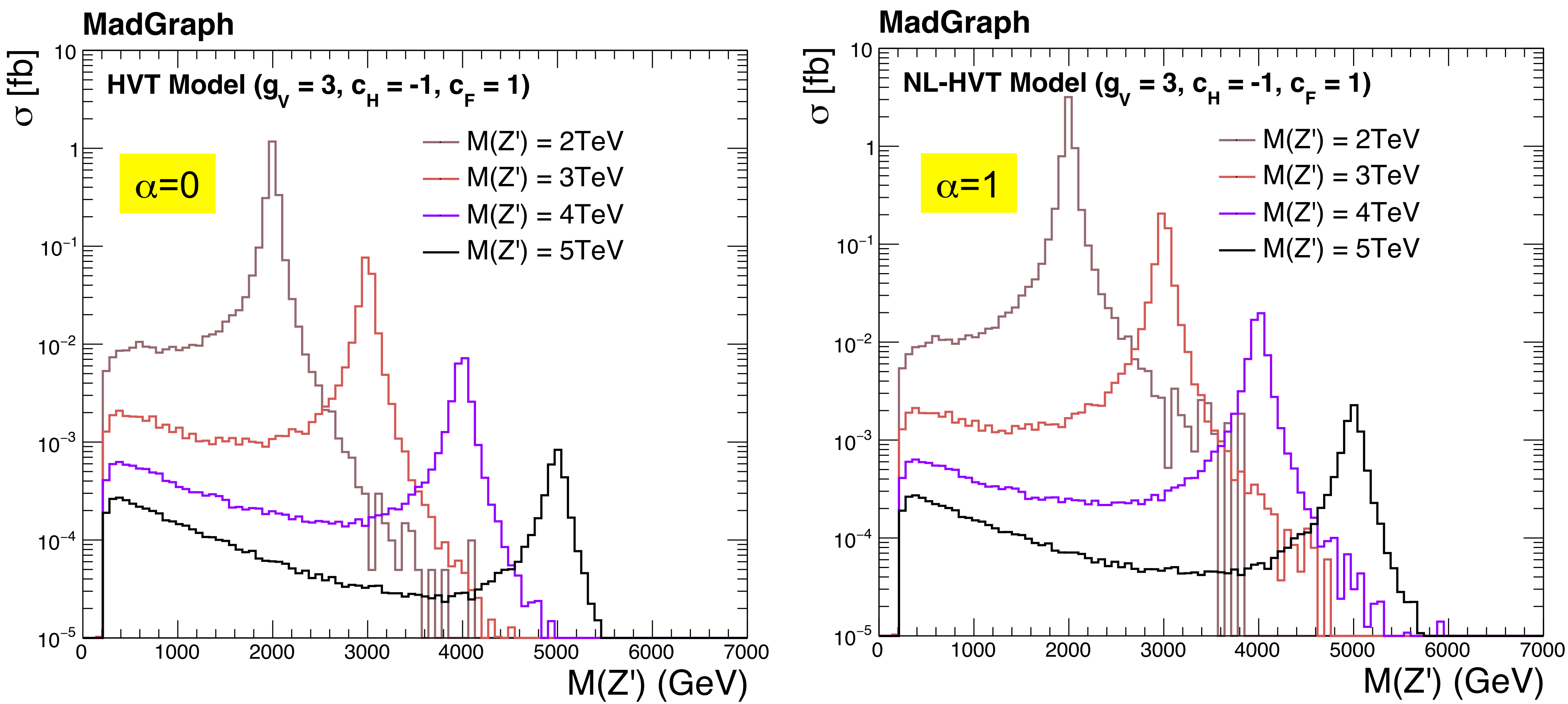
Almost Collinear Photons!

pp→Z′ cross section at 13TeV



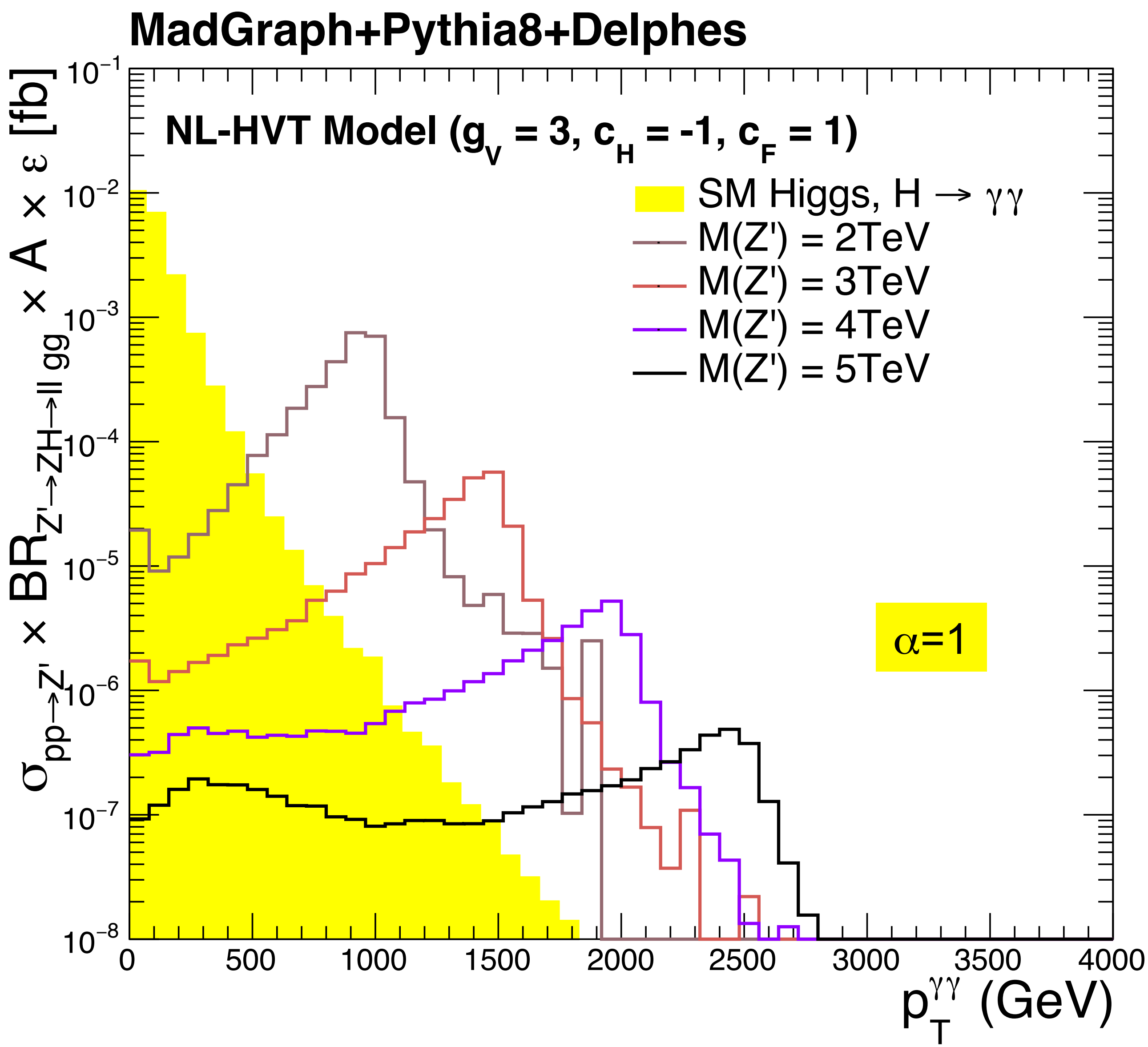
The above is LO calculation ➔ **No narrow VH, VV (HVT) resonances seen at LHC.**
For α>0 not only cross sections but also lineshapes are modified (see next).

Z′ xsection: non-local modifications



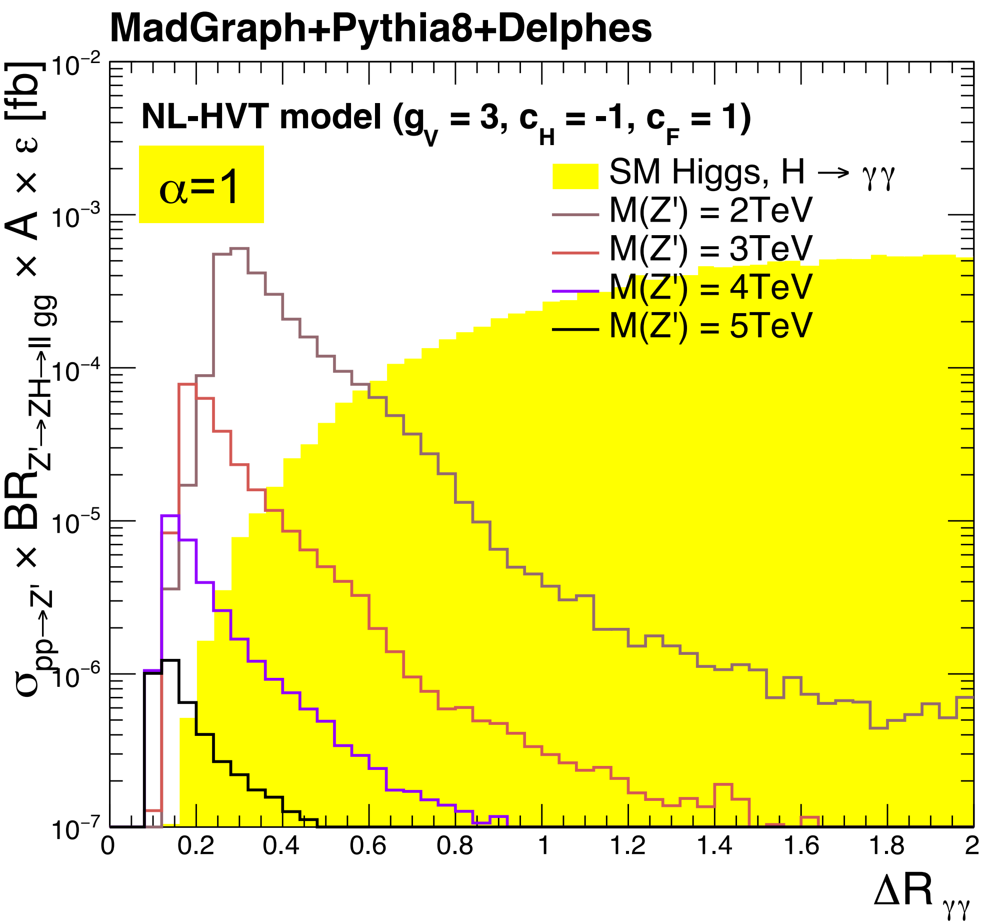
Non-locality effects can lead to significant increases in the cross section

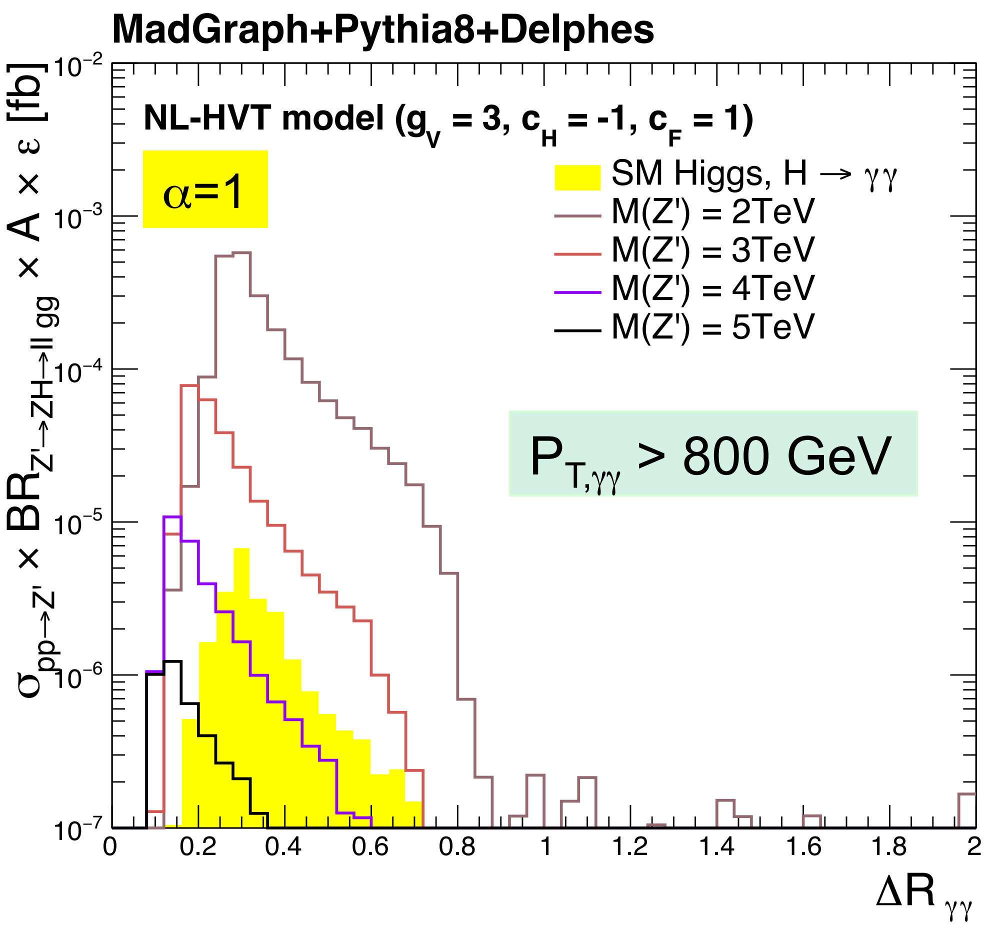
Higgs yields vs diphoton P_T



The non-local signal is significantly boosted wrt the SM Higgs (mostly VH)

Higgs yields vs diphoton ΔR





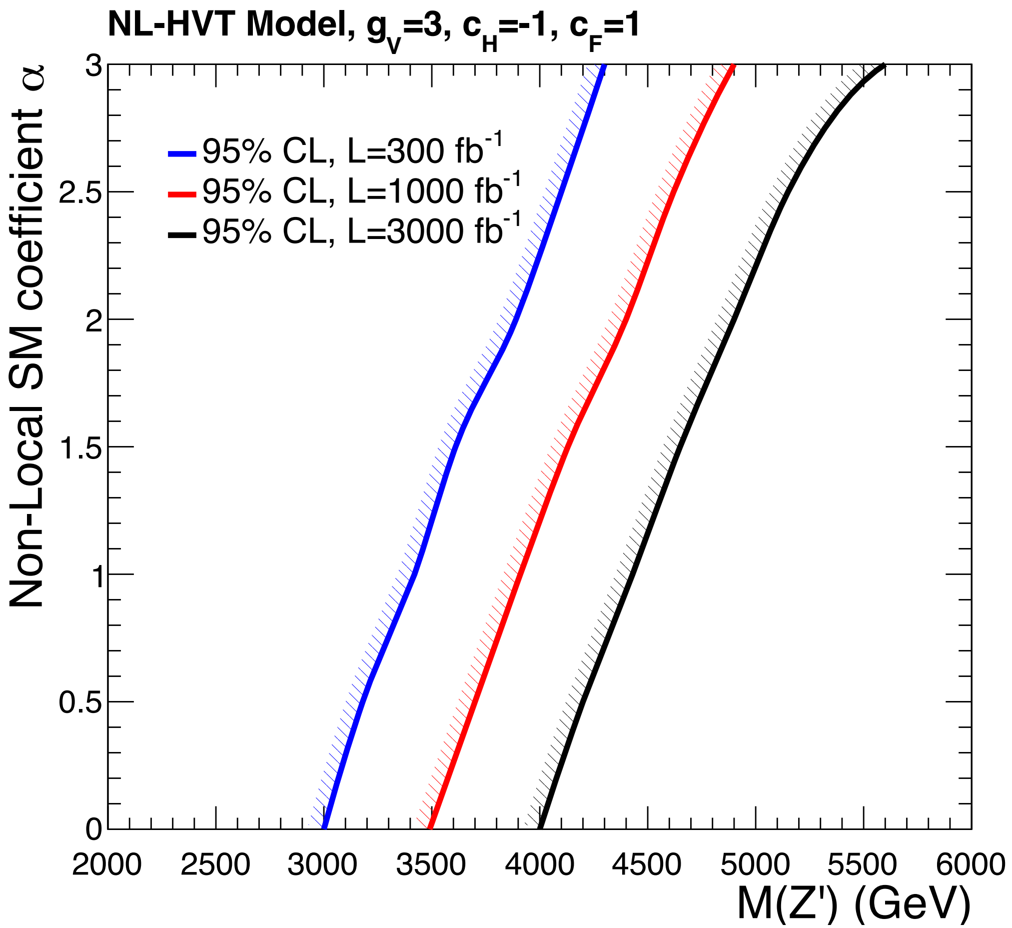
Effect of a cut on the diphoton Pt > 800 GeV

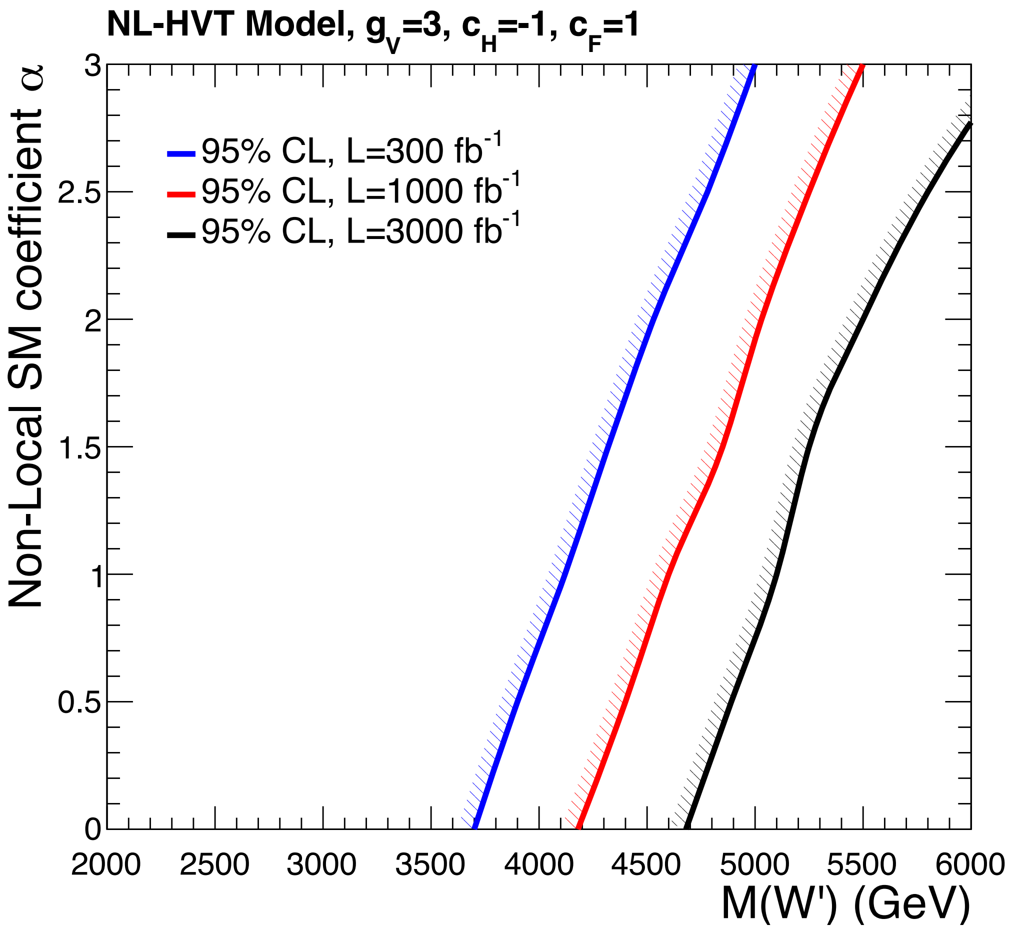
Anomalous Higgs yields

Process $qq \to V' \to \gamma\gamma$	$\sigma \times BR$ [fb]	A$\times\epsilon$ [%]	Yield ($P_T^{\gamma\gamma} > M_{V'}/3$) [fb]	$M_{V'}$ [TeV]
$Z' \to ZH \to \ell\ell\gamma\gamma$ (2 TeV)	1.90×10^{-3}	40.8	6.8×10^{-4}	2
$Z' \to ZH \to \ell\ell\gamma\gamma$ (3 TeV)	1.97×10^{-4}	34.4	5.3×10^{-5}	3
$Z' \to ZH \to \ell\ell\gamma\gamma$ (4 TeV)	2.99×10^{-5}	29.9	5.1×10^{-6}	4
$Z' \to ZH \to \ell\ell\gamma\gamma$ (5 TeV)	6.36×10^{-6}	29.4	3.8×10^{-7}	5
$W' \to WH \to \ell\nu\gamma\gamma$ (2 TeV)	1.26×10^{-2}	54.1	6.0×10^{-3}	2
$W' \to WH \to \ell\nu\gamma\gamma$ (3 TeV)	1.33×10^{-3}	46.7	4.8×10^{-4}	3
$W' \to WH \to \ell\nu\gamma\gamma$ (4 TeV)	1.99×10^{-4}	42.3	4.8×10^{-5}	4
$W' \to WH \to \ell\nu\gamma\gamma$ (5 TeV)	4.20×10^{-5}	43.8	5.4×10^{-6}	5
SM $ZH \to \ell\ell\gamma\gamma$	0.20	13.3	3.8×10^{-5}	2
SM $ZH \to \ell\ell\gamma\gamma$	0.20	13.3	3.4×10^{-6}	3
SM $ZH \to \ell\ell\gamma\gamma$	0.20	13.3	5.1×10^{-7}	4
SM $ZH \to \ell\ell\gamma\gamma$	0.20	13.3	7.0×10^{-8}	5
SM $WH \to \ell\nu\gamma\gamma$	1.01	35.2	2.7×10^{-4}	2
SM $WH \to \ell\nu\gamma\gamma$	1.01	35.2	2.5×10^{-5}	3
SM $WH \to \ell\nu\gamma\gamma$	1.01	35.2	3.3×10^{-6}	4
SM $WH \to \ell\nu\gamma\gamma$	1.01	35.2	3.7×10^{-7}	5
SM Continuum $\ell\ell\gamma\gamma$	638.2	0.21	2.7×10^{-4}	2
SM Continuum $\ell\ell\gamma\gamma$	638.2	0.21	1.6×10^{-5}	3
SM Continuum $\ell\ell\gamma\gamma$	638.2	0.21	2.8×10^{-6}	4
SM Continuum $\ell\ell\gamma\gamma$	638.2	0.21	5.6×10^{-8}	5
SM Continuum $\ell\nu\gamma\gamma$	654.4	2.9	5.2×10^{-4}	2
SM Continuum $\ell\nu\gamma\gamma$	654.4	2.9	4.1×10^{-5}	3
SM Continuum $\ell\nu\gamma\gamma$	654.4	2.9	3.4×10^{-6}	4
SM Continuum $\ell\nu\gamma\gamma$	654.4	2.9	1.6×10^{-7}	5

Order of magnitude

VH→γγ 95% CL contours vs Luminosity





In LHC Phase 2 the sensitivity to non-local effects reaches the scale of ~5 TeV.

Summary

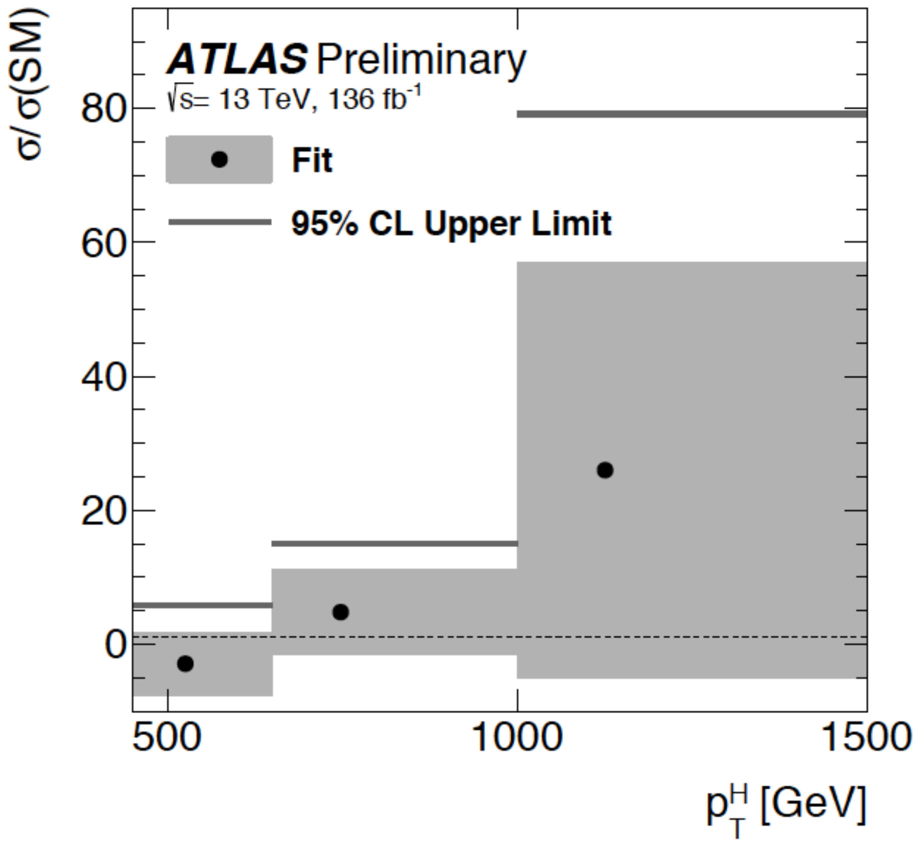
- A “non-local” SM extension was presented and its potential signals were discussed.
- Non-Locality is implemented through form factors smearing interaction vertices.
  - This is the effective description of many BSM models.
- DY measurements can put constraints in NL scales.
- Hypothetical new heavy states or continuum associated with the BSM physics can lead to anomalous boosted Higgs production.
- Analyses optimized for boosted Higgs can be ideal for early signs of new physics.

Extra Slides

ATLAS High P_T $H \rightarrow bb$ (136 fb^{-1})

ATLAS-CONF-2021-010

p_T^H [GeV]	μ_H Exp.	μ_H Obs.
300–450	1 ± 18	-7 ± 17
450–650	1.0 ± 3.3	-2.9 ± 4.7
>650	1.0 ± 6.3	4.8 ± 6.4



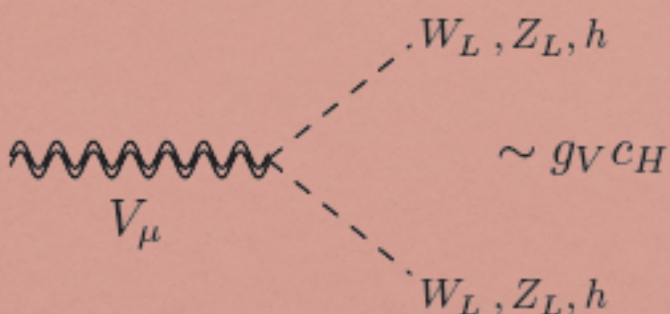
Large uncertainties in ATLAS results. Need more luminosity.

Heavy Vector Triplet simplified model

Pappadopulo et al

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\,a} \qquad V = (V^+, V^-, V^0)$$
$$+ i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^{\mu\,a}_F$$
$$+ \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V^a_\mu V^b_\nu D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V^a_\mu V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\nu\,a} V^b_\mu V^c_\nu$$

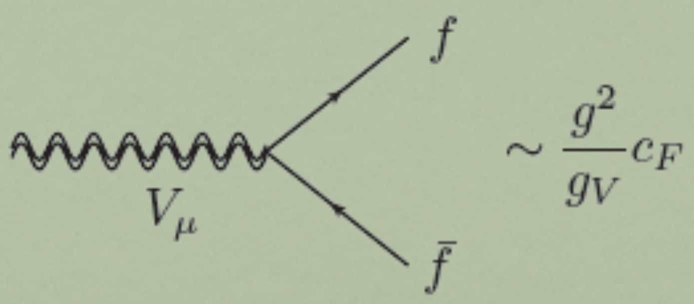
Coupling to SM Vectors



$\sim g_V c_H$

Coupling to SM fermions

$J^{\mu\,a}_F = \sum_f \bar{f}_L \gamma^\mu \tau^a f_L$



$\sim \frac{g^2}{g_V} c_F$

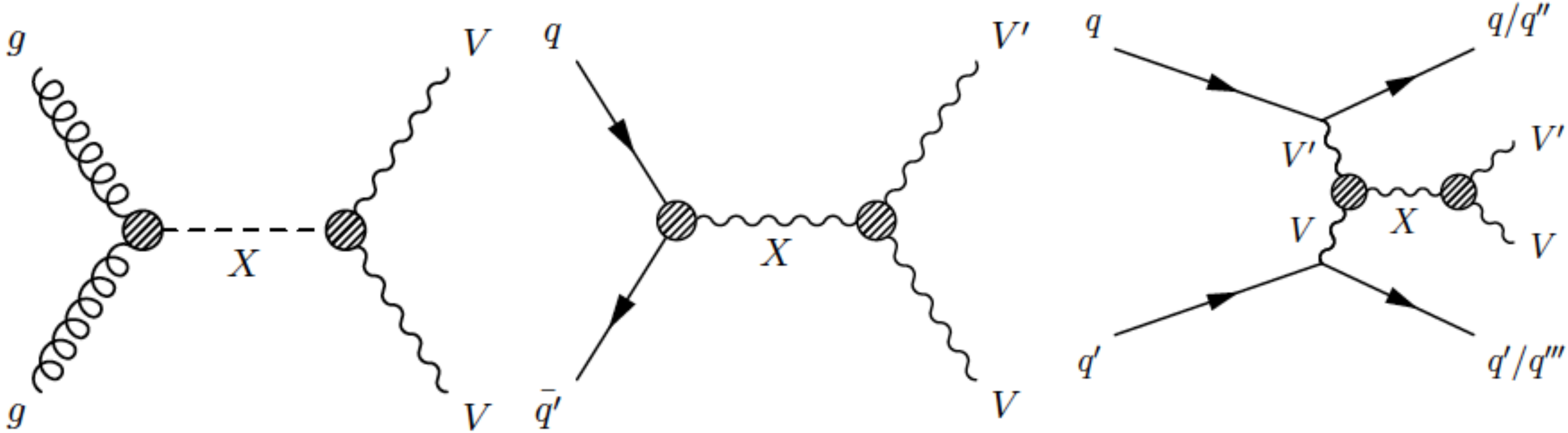
$c_F V \cdot J_F \;\rightarrow\; c_l V \cdot J_l + c_q V \cdot J_q + c_3 V \cdot J_3$

Put this is in Madgraph5 (LO) and send it through detectors

X→VV search in ATLAS

2004.14636 [hep-ex]

Full LHC Lumi: 139/fb

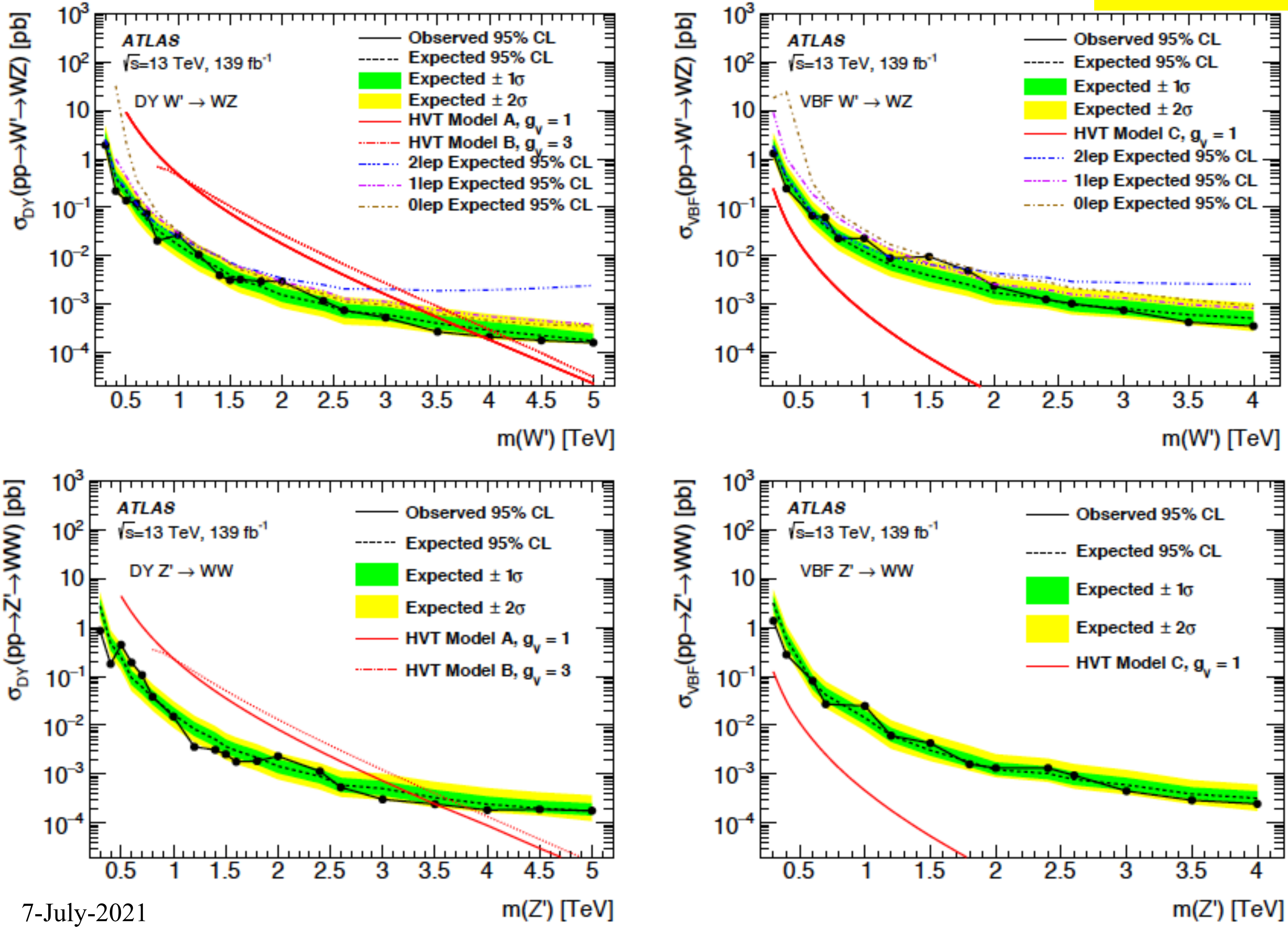


V→lep
V'→had

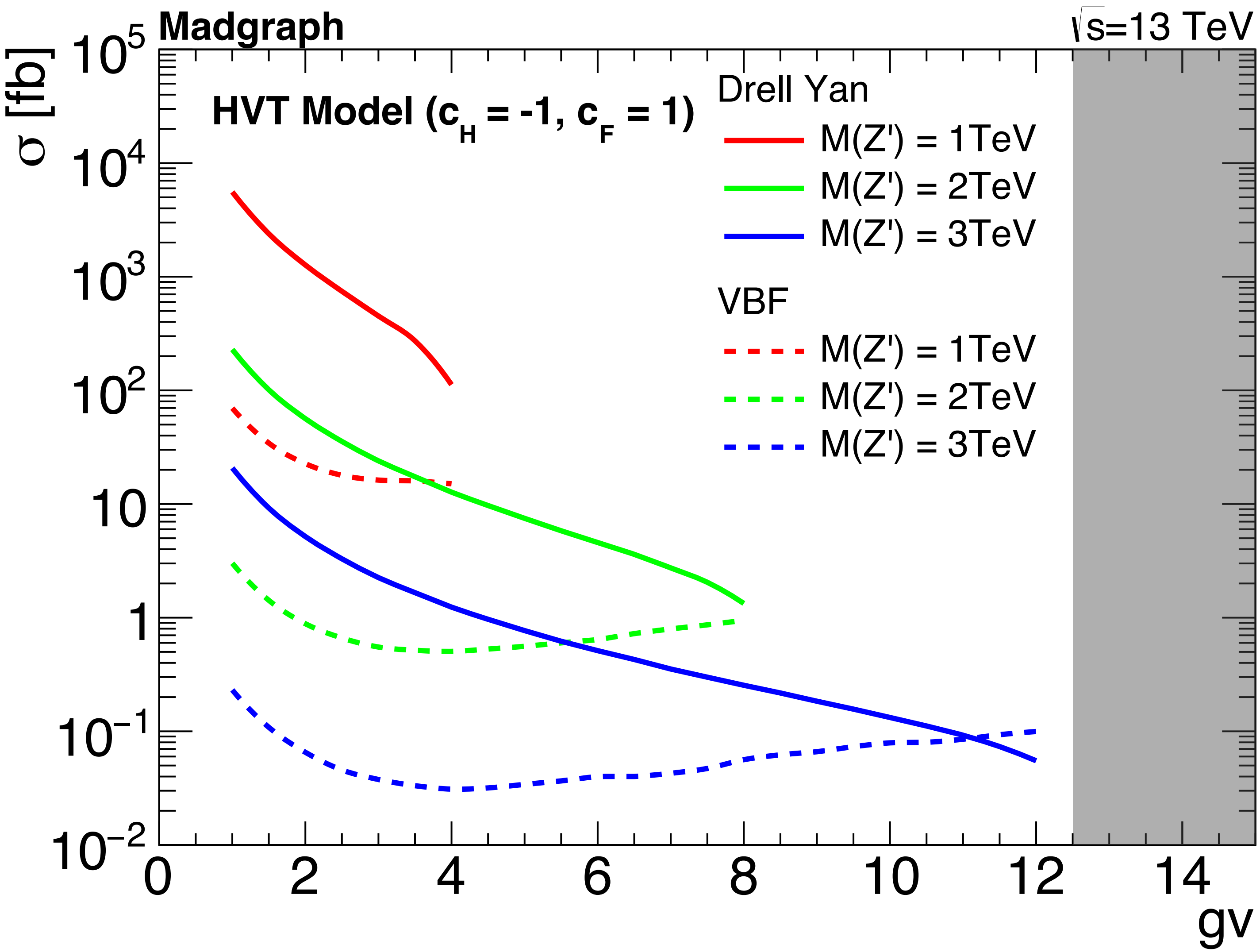
Again, in many BSM scenarios states X are predicted to preserve Unitarity.
Caution: they don't have to be a single state nor narrow states!

X→VV search in ATLAS

2004.14636 [hep-ex]



pp→Z' xsection at 13TeV



The above is LO calculation ➔ **No narrow VH, VV (HVT) resonances seen at LHC**
Are there extra BSM contributions that can change the xsections & lineshapes?