Vector boson fusion production of new heavy physics at the LHC and future colliders

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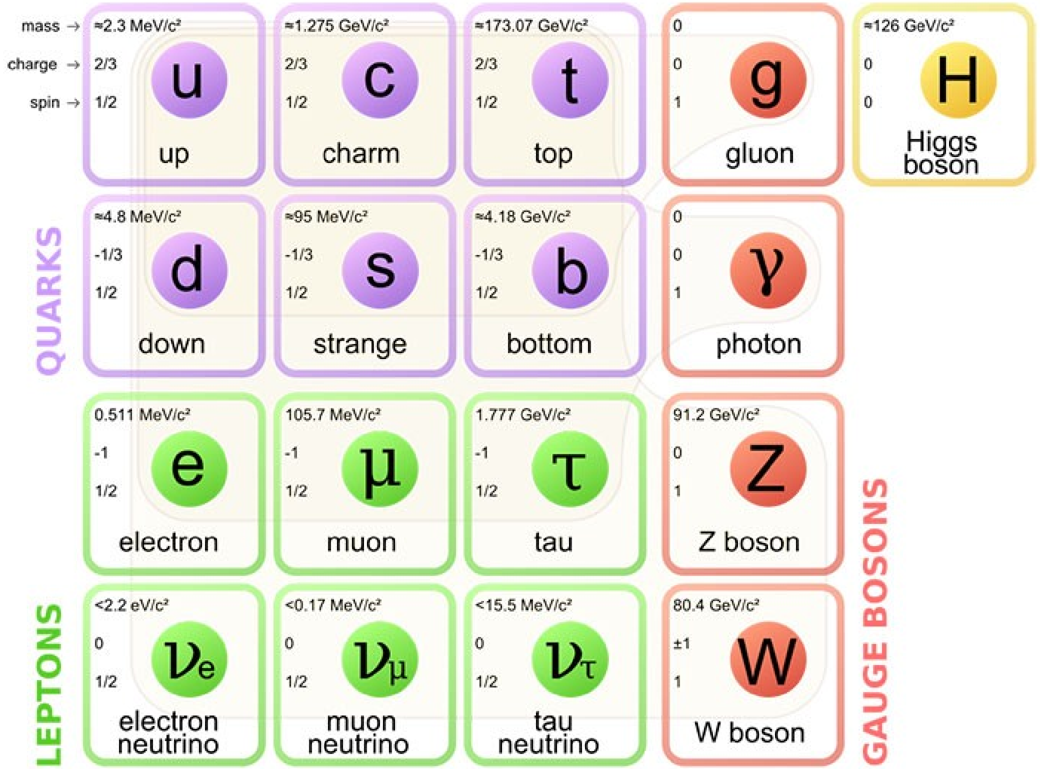
The University of Melbourne

In collaboration with Michael J. Baker, Andrea Thamm, and Riccardo Torre

THE UNIVERSITY OF MELBOURNE

The Standard Model



Comprises all observed fundamental particles:

<u>Fermions</u> (spin-1/2)
- Quarks – up and down type
- Leptons – charged and neutrinos

<u>Scalar bosons</u> (spin-0)
- Higgs only known scalar

<u>Vector bosons</u> (spin-1)
- Gluons mediate strong interactions
- Photon mediates electromagnetism
- W and Z mediate weak interactions

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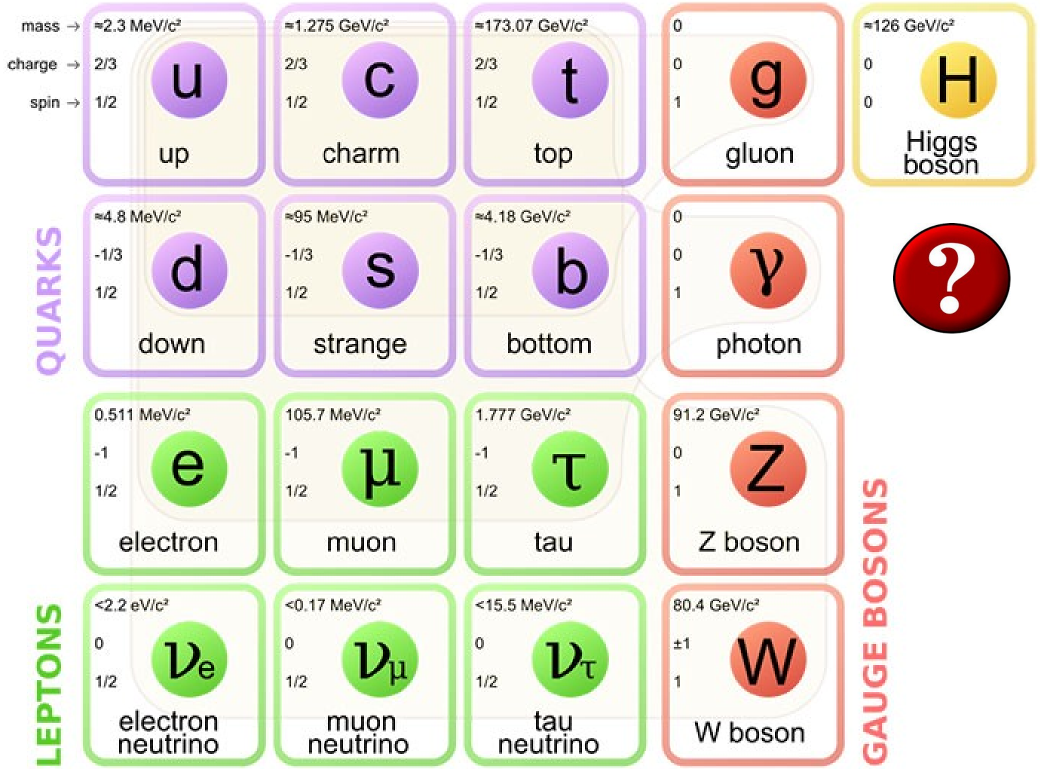

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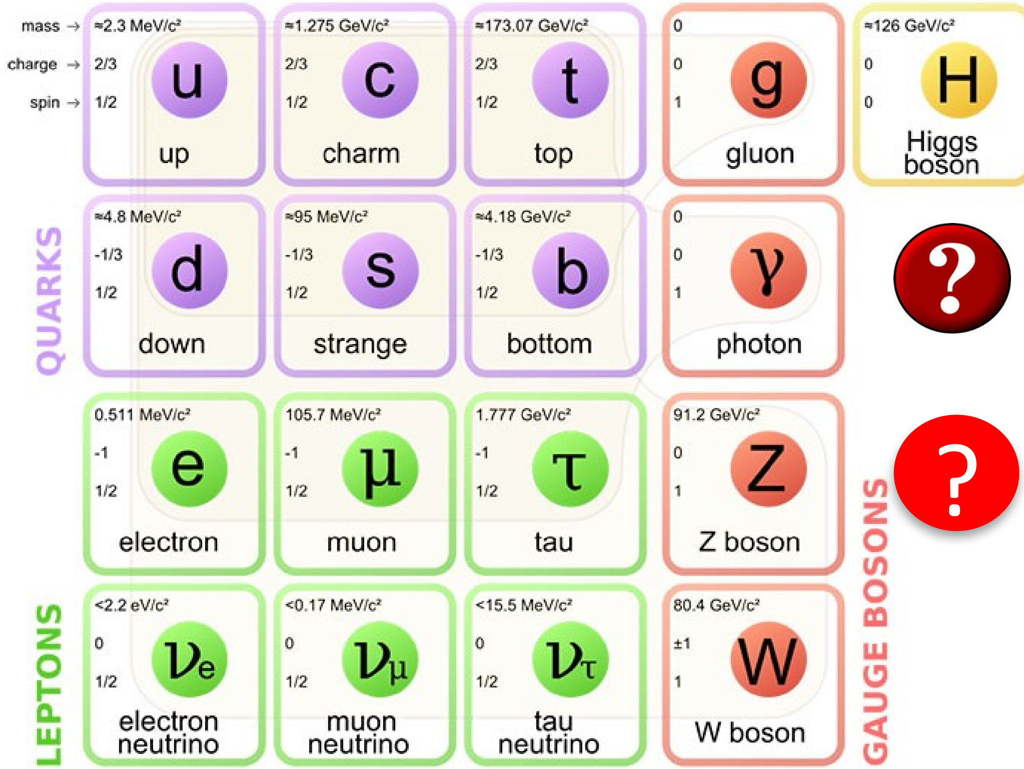

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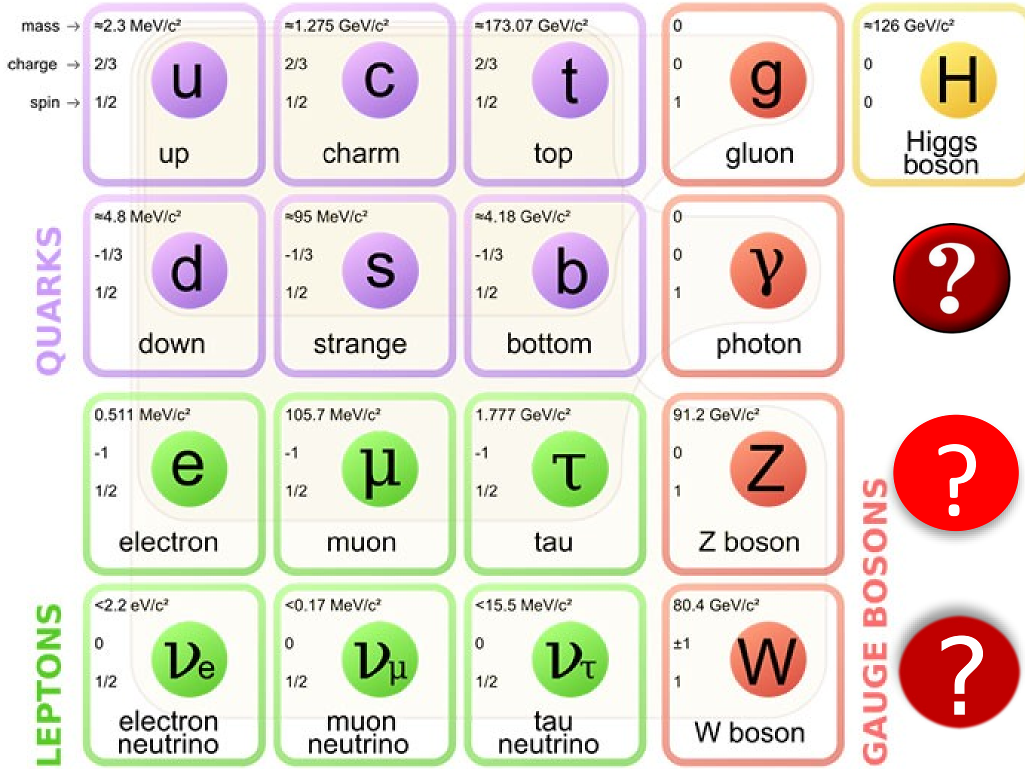

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- 27km ring of superconducting magnets
- Oppositely-travelling proton beams collide at 0.99999999c
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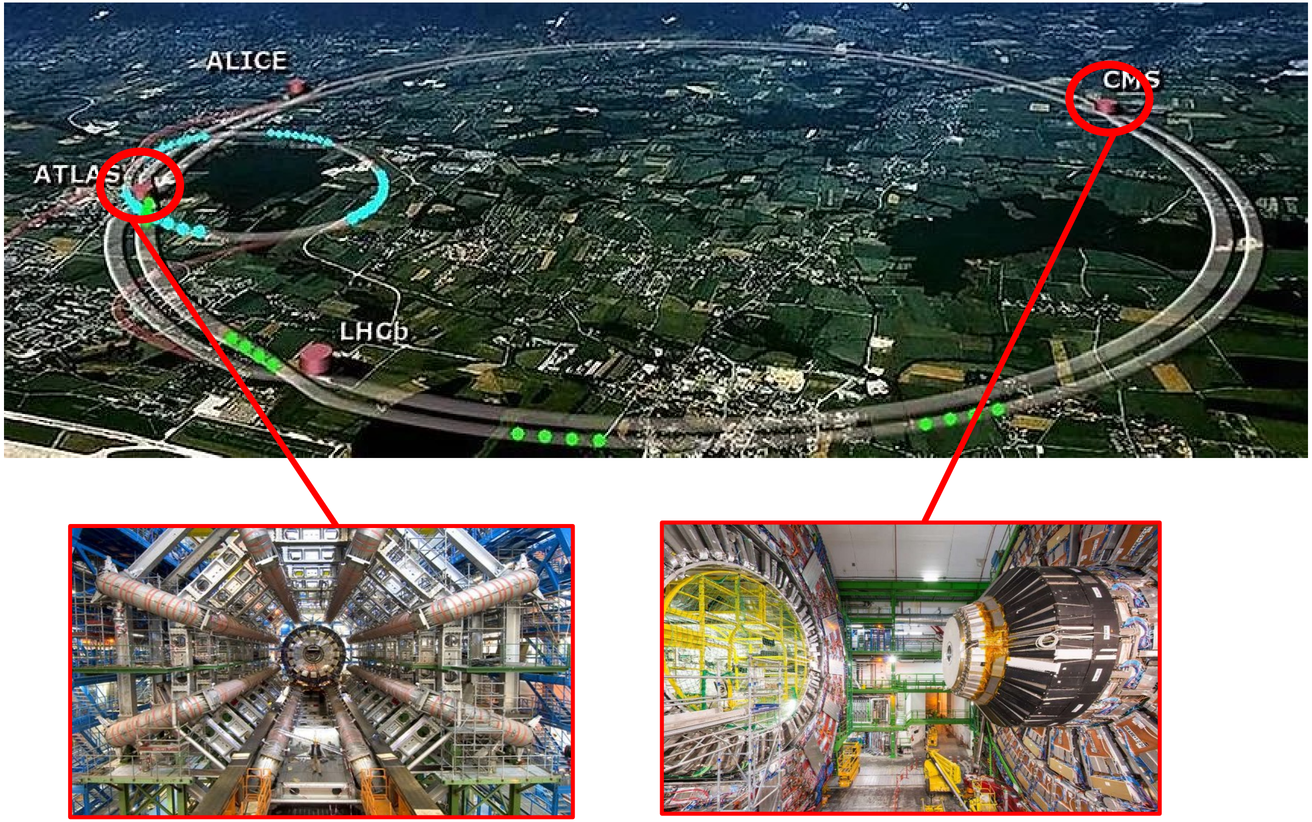

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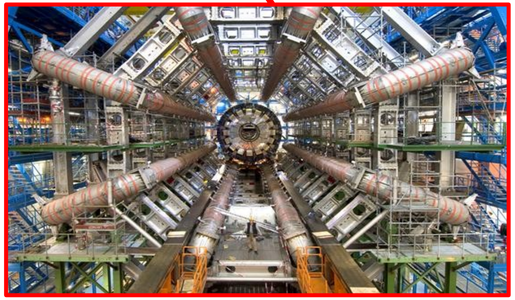

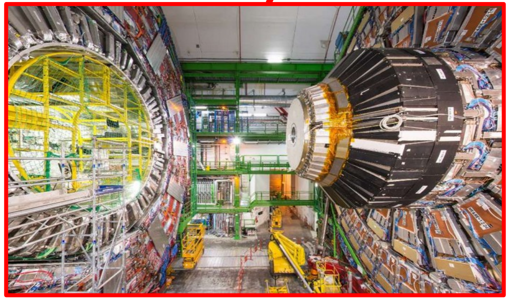

ATLAS and CMS produce an enormous amount of data (over 90 petabytes) per year

The LHC: Beyond the Standard Model

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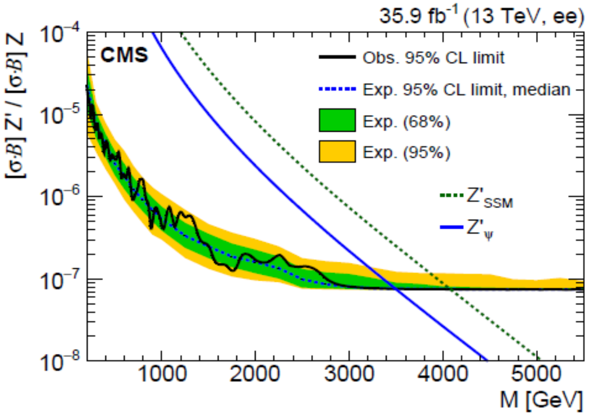

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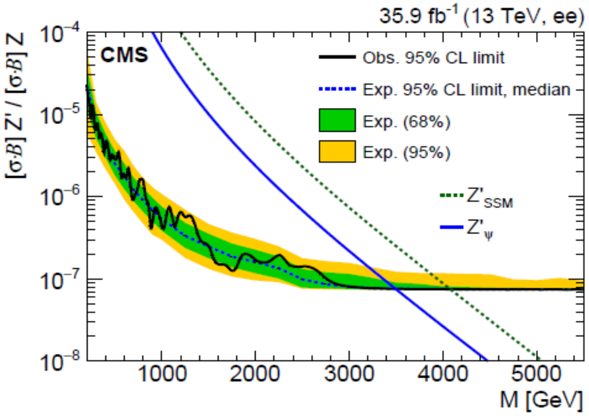

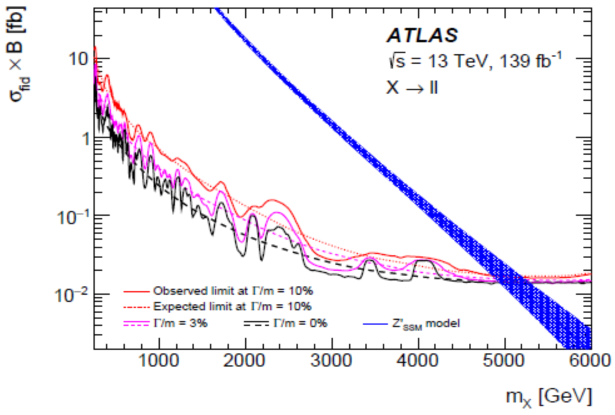

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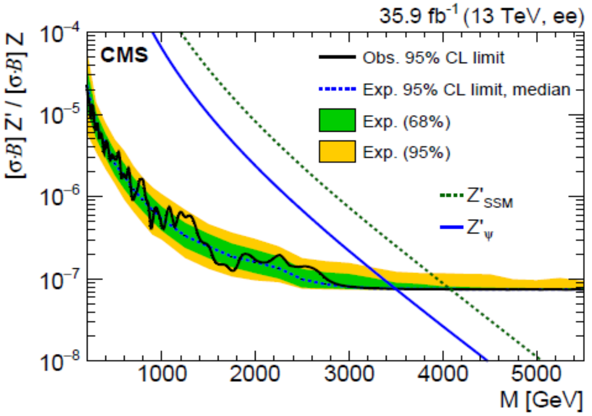

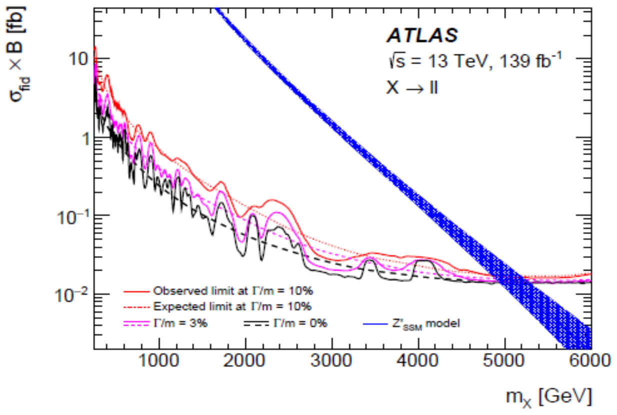

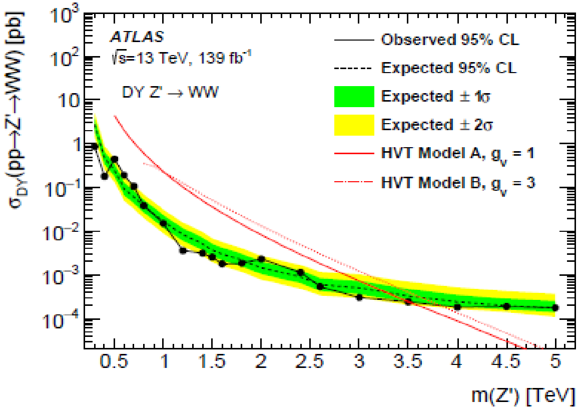

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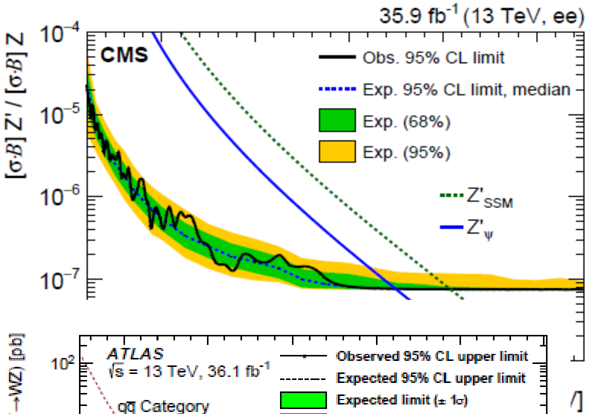

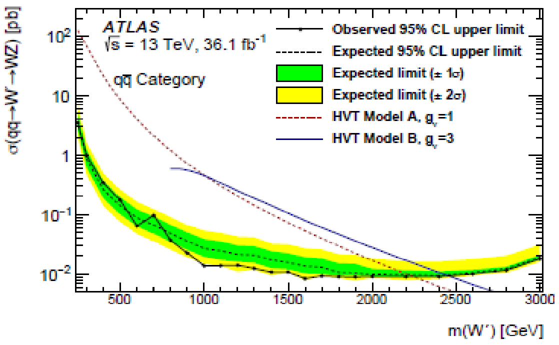

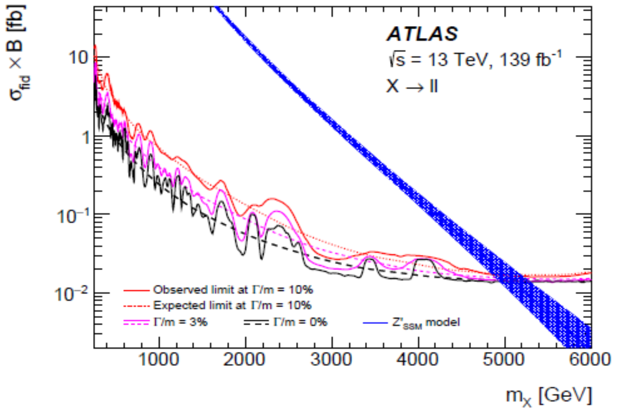

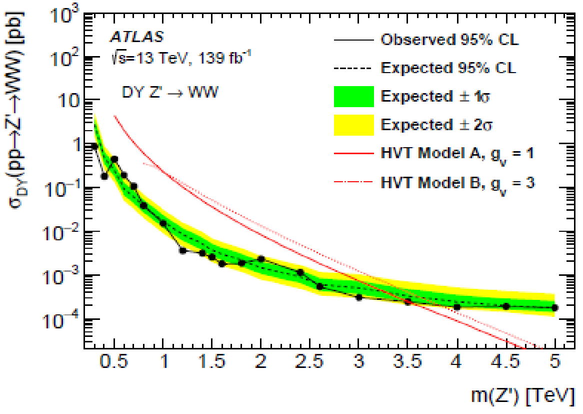

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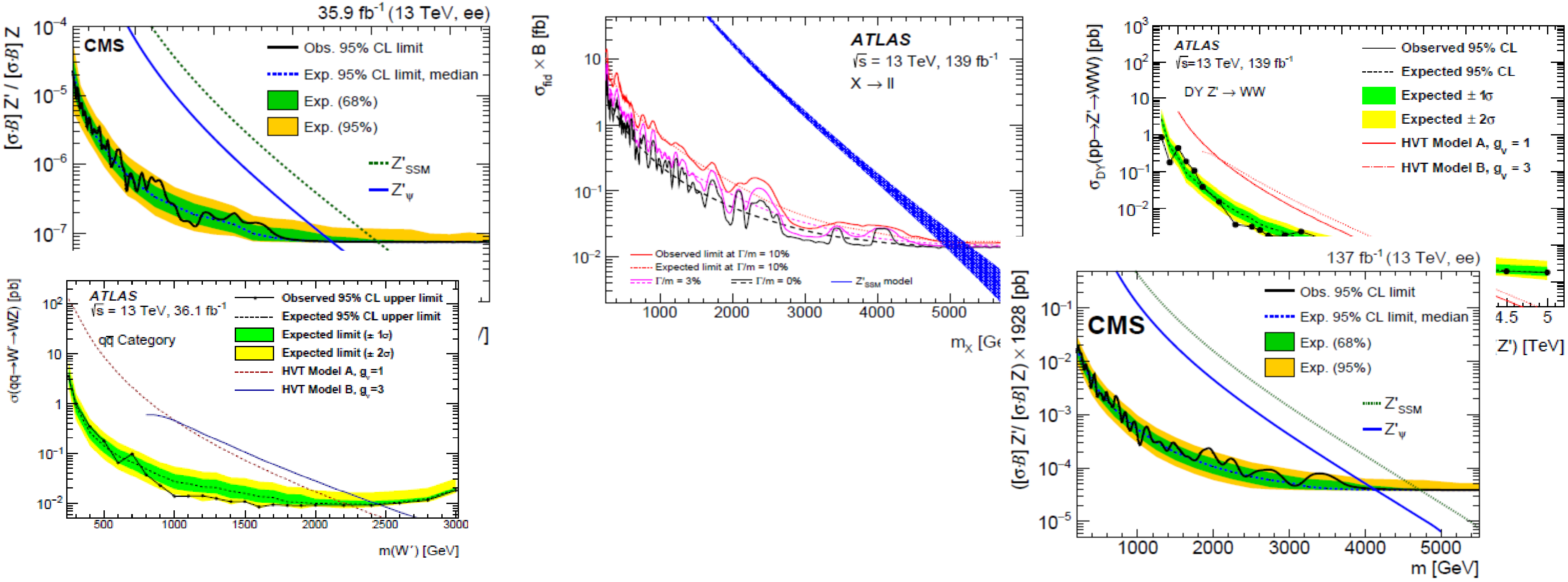

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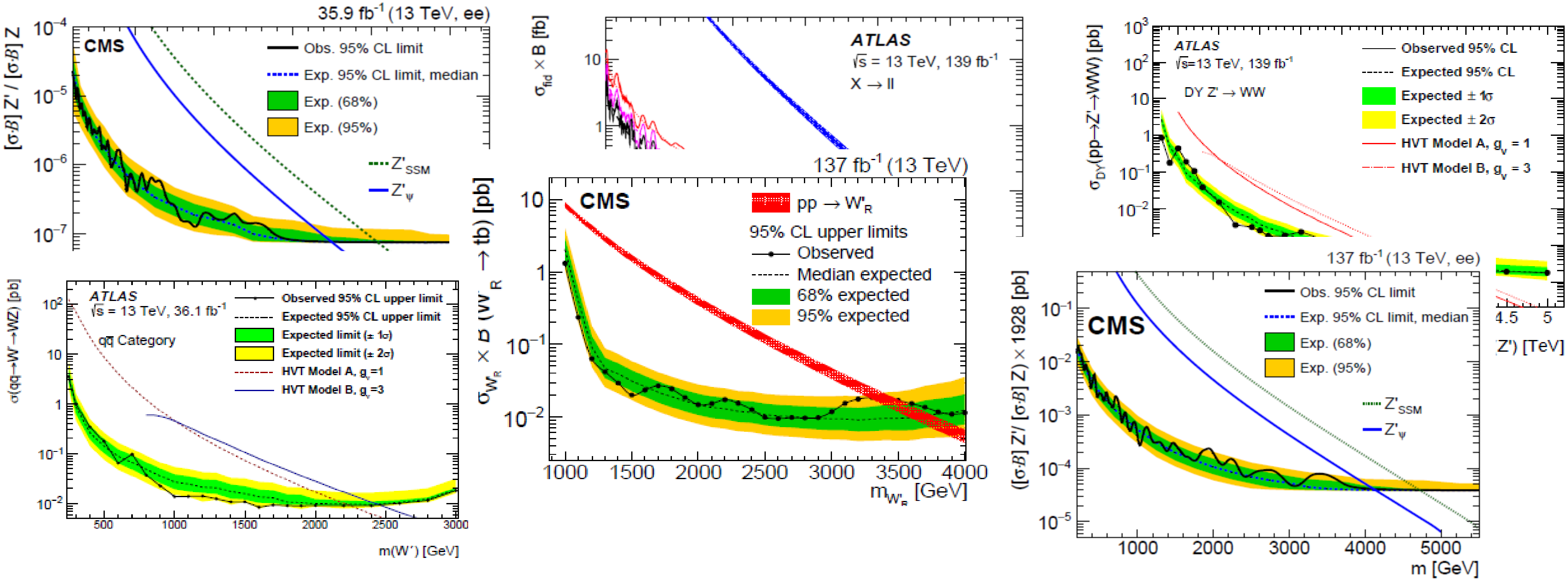

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Models with heavy vectors are ubiquitous in BSM theories

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Standard Model Higgs H_L	Higgs H_R breaks symmetry
Mass states W and Z	Mass states W' and Z'

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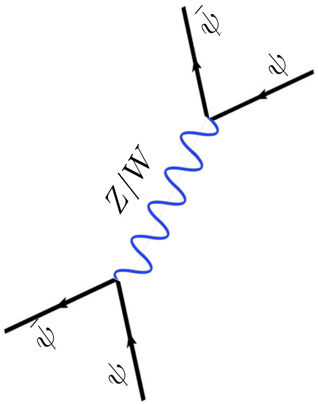

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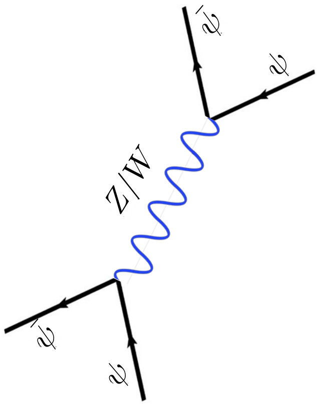

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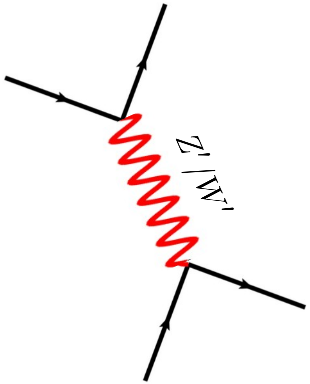
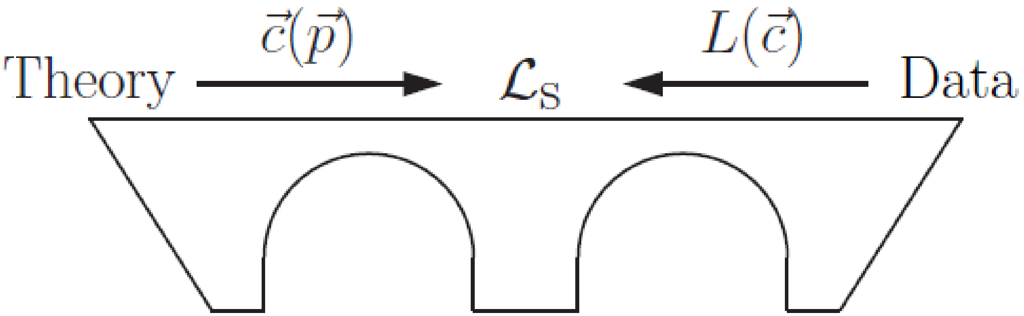


Simplified models



arxiv.org/abs/1402.4431

- Model-independent framework
- Only considers a few new particles/interactions

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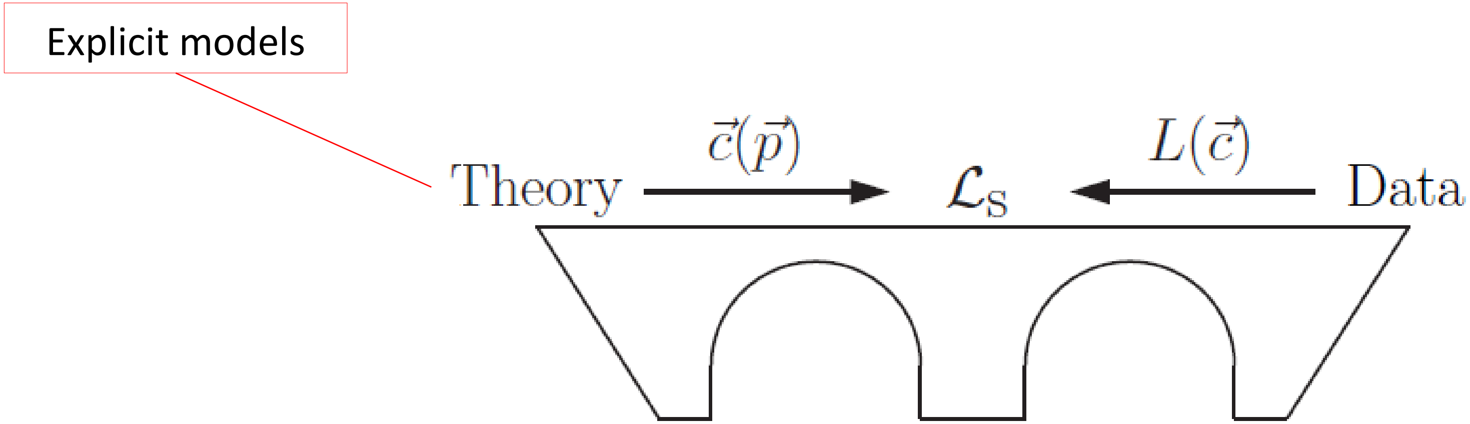

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Explicit models

Resonance searches
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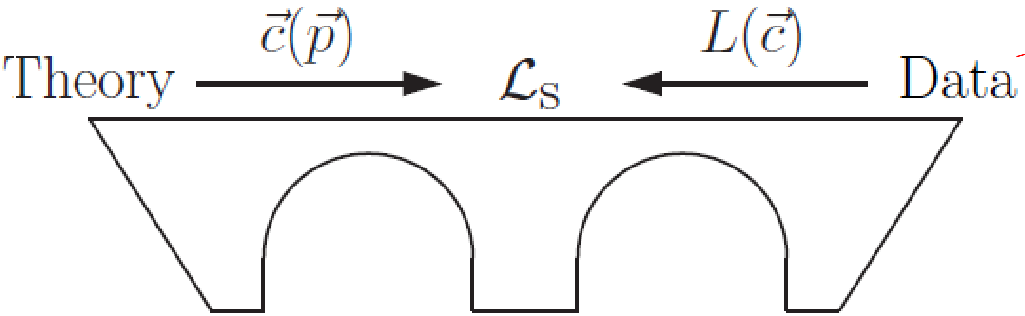

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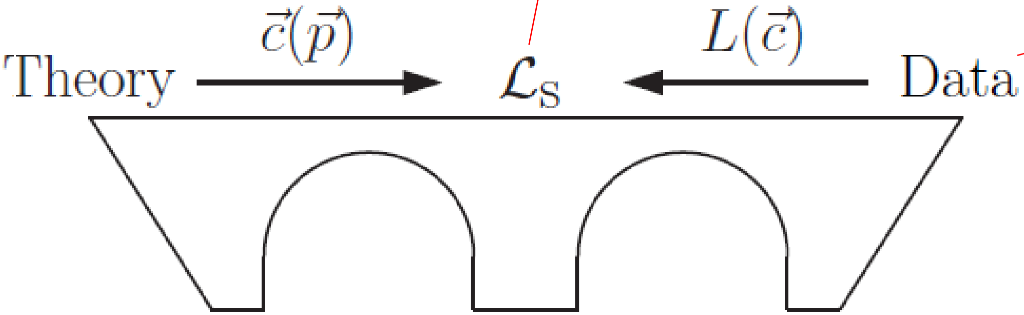

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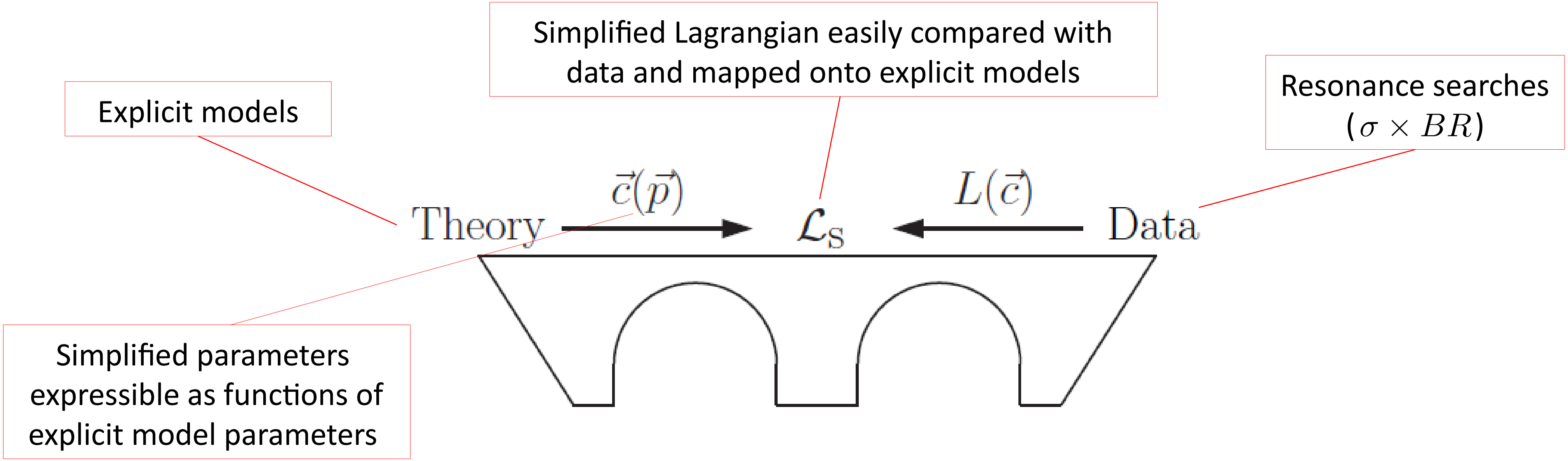

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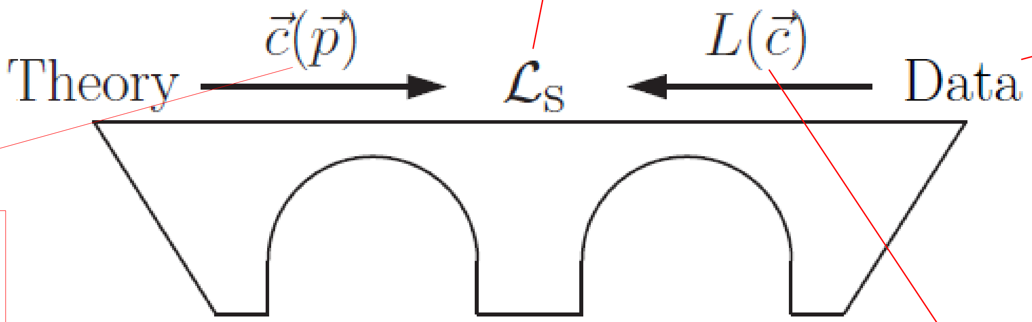

Simplified parameters expressible as functions of explicit model parameters

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Experimental limits converted into limits on simplified parameters

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Summary so far

Theory	Experiment
There exists a multitude of theories beyond the SM • Many theories that solve different problems • Many different theories that solve the same problem • Not possible for one experiment to test all the parameters of all the models separately	ATLAS & CMS produce enormous amounts of data • Search results are generic, result of statistical analysis of data • Many searches for the same resonance in different channels • Too many theories and too many experiments, with no way of knowing which theory is worth examining

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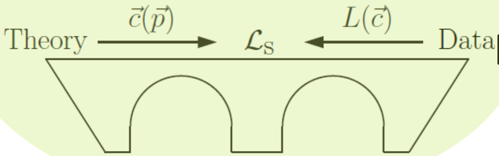

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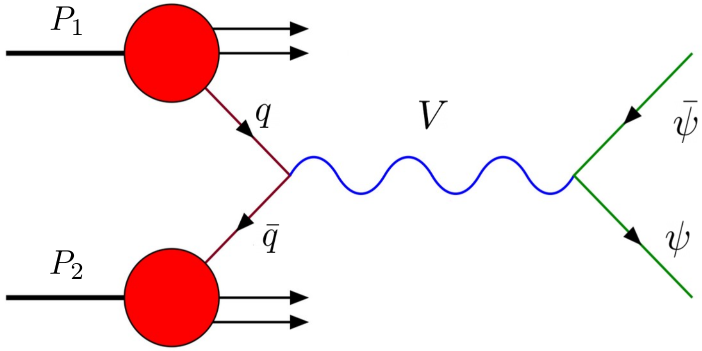
- Drell-Yan (DY)



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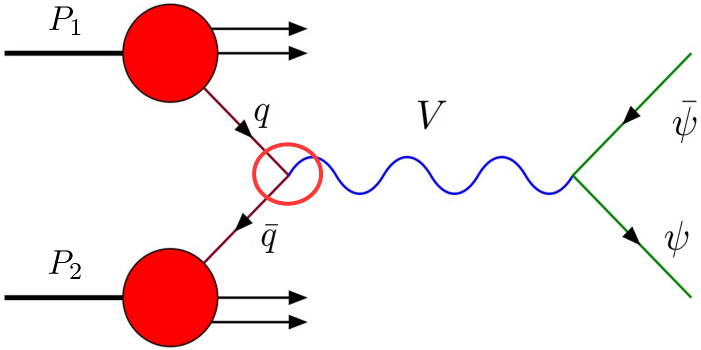

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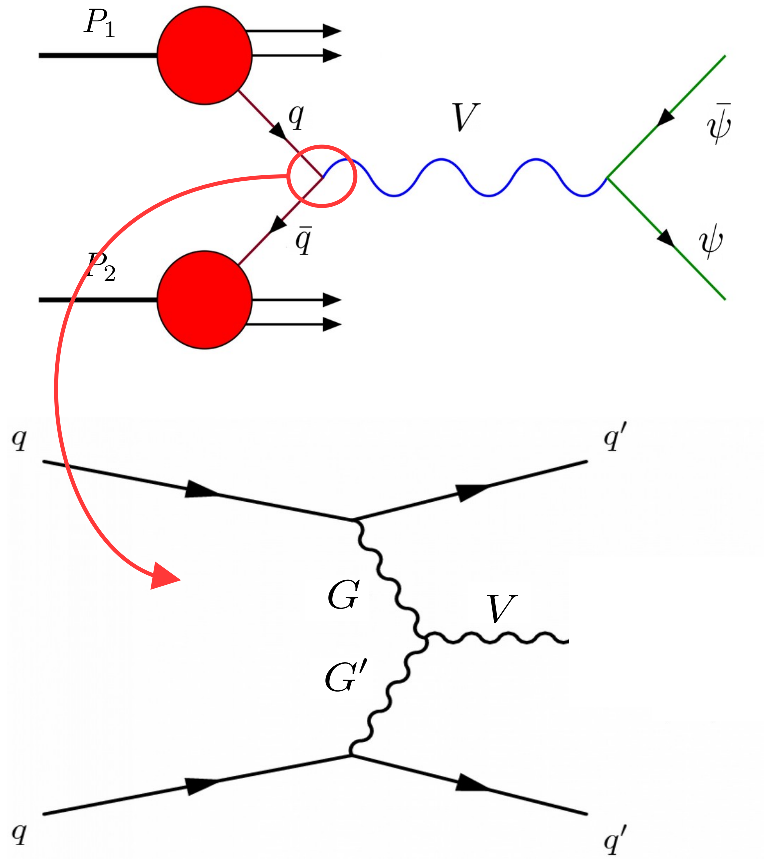

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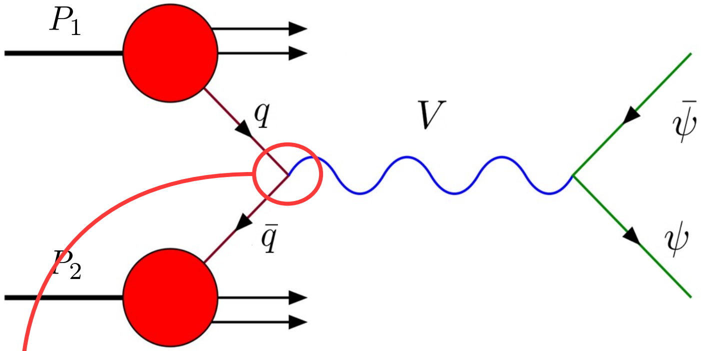
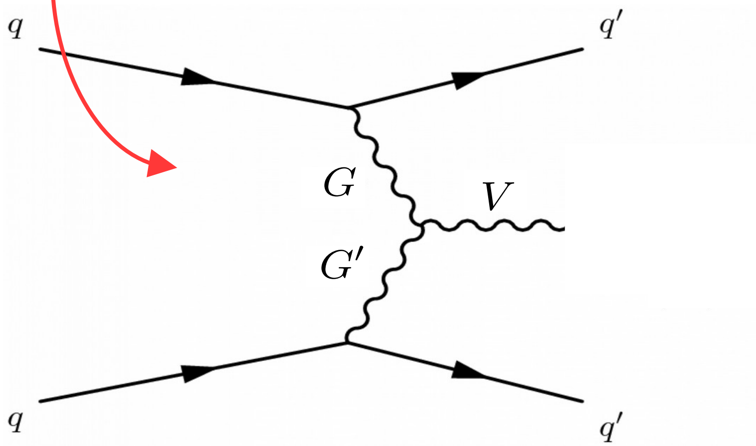
–– Parton luminosity
–– Parton-level cross section





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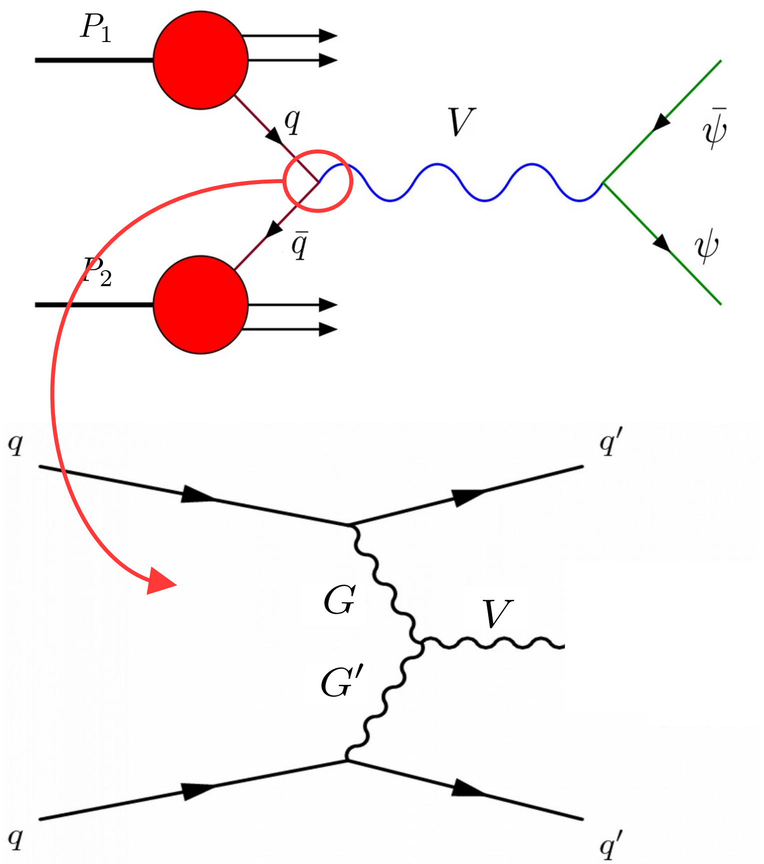

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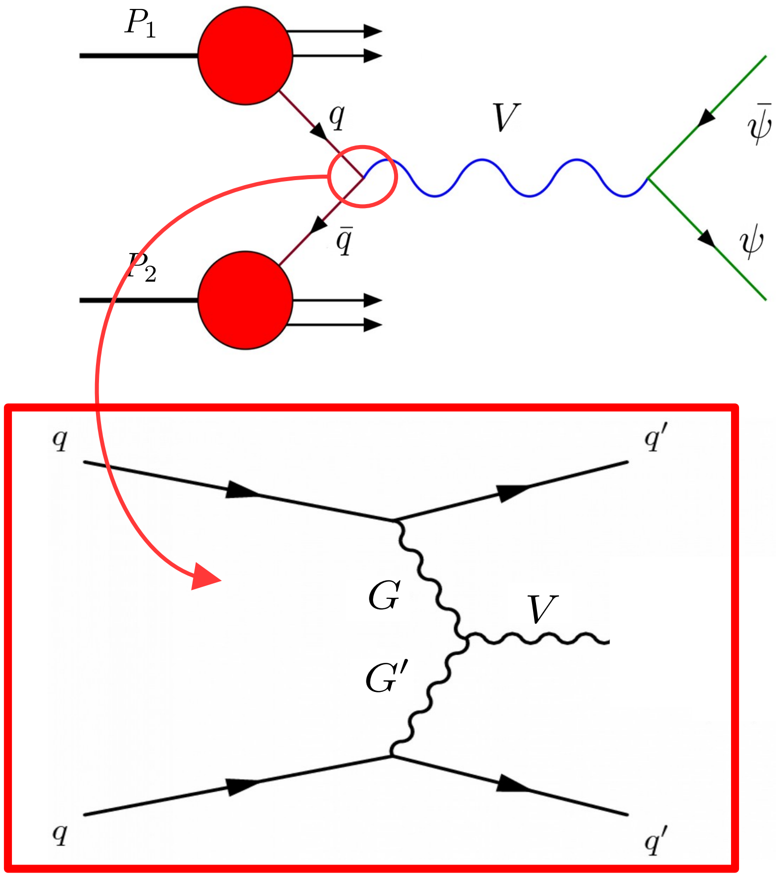

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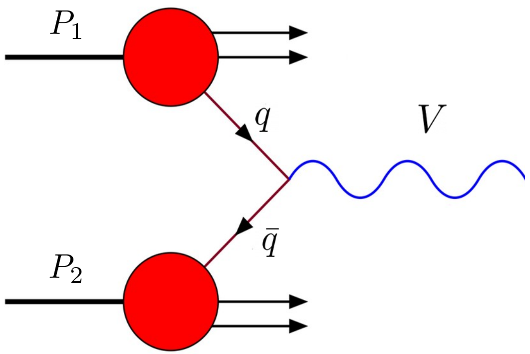

Cross section looks like

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu^2), Q^2/\mu^2)$$

So the parton luminosity function can be written

$$\hat{s}\frac{dL_{ij}}{d\hat{s}} = \frac{1}{1+\delta_{ij}} \int_0^1 dx_1 dx_2 [(f_i(x_1, \mu^2) x_2 f_j(x_2, \mu^2)) + (1 \leftrightarrow 2)] \delta(\hat{s}/s x_1 - x_2).$$

CoM energies at or above 13 TeV → consider all valence and sea quark combinations,
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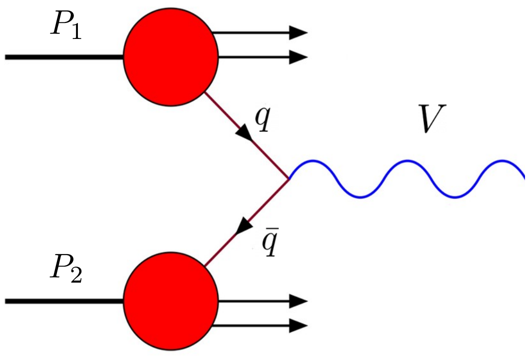

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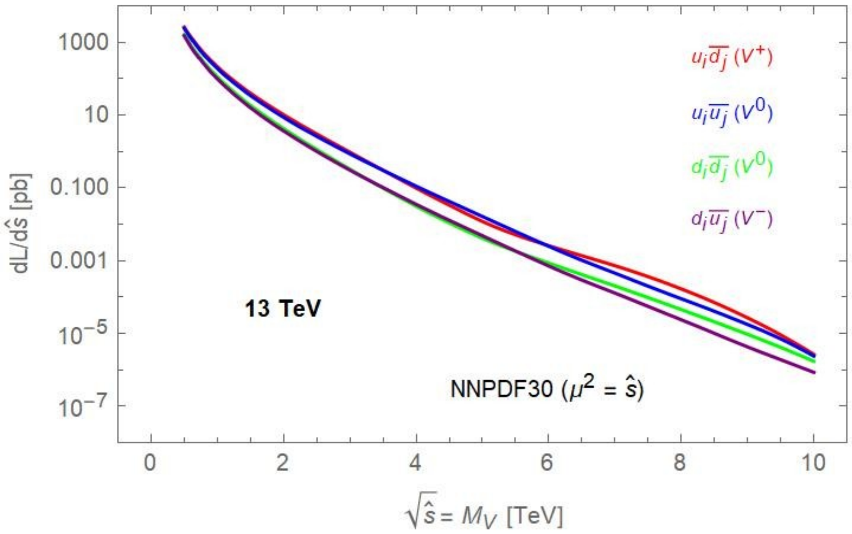
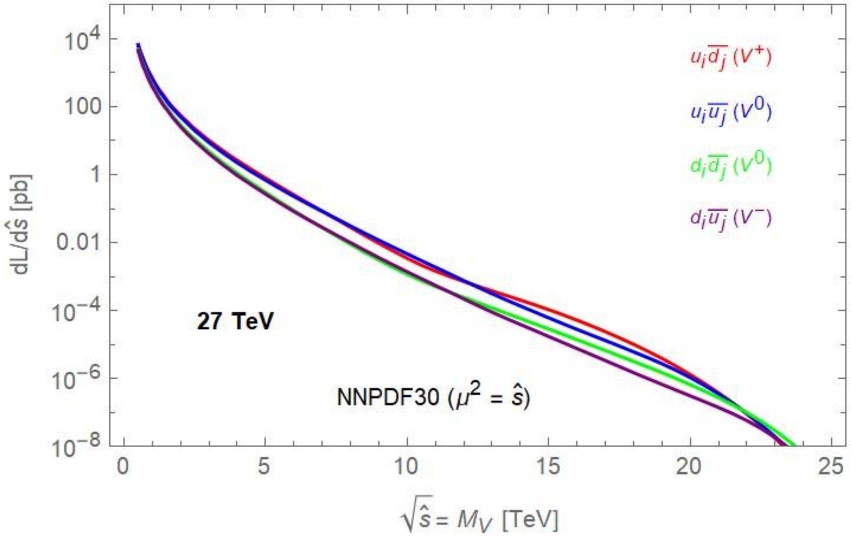
Easy to compute, given knowledge of PDFs

DY – parton luminosities





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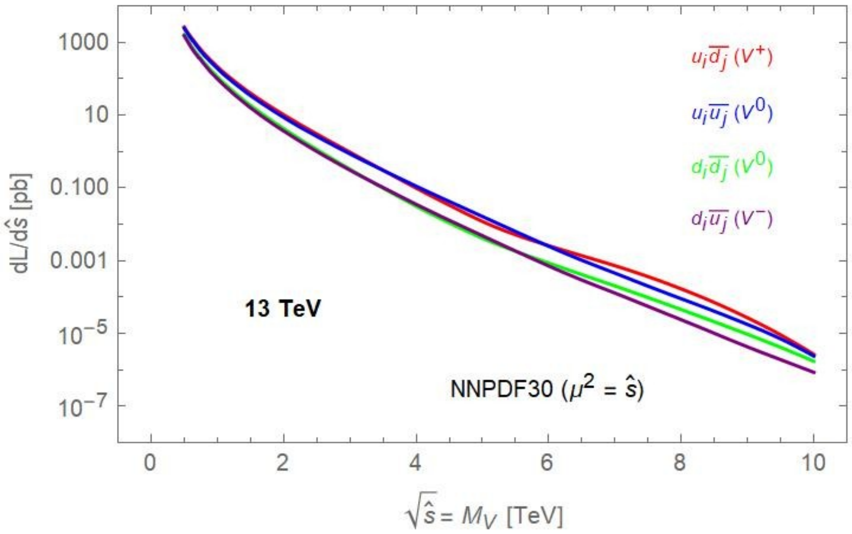
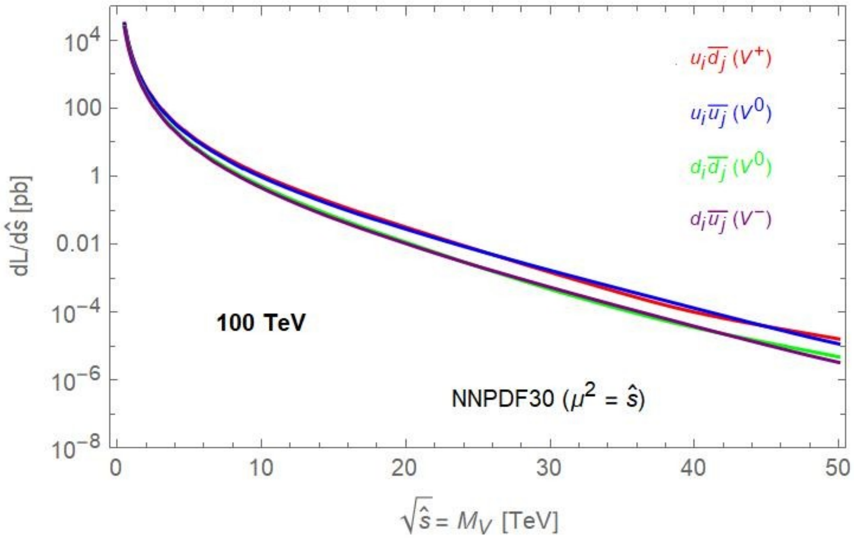
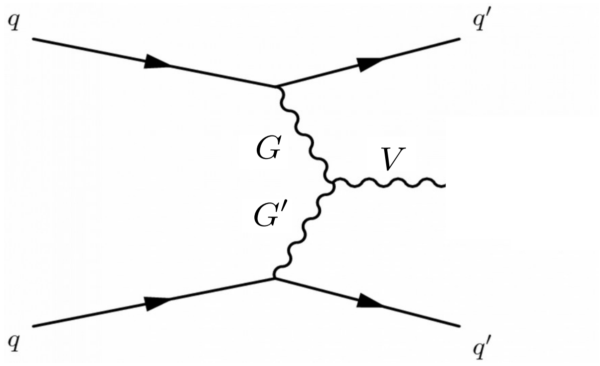




Vector boson fusion production



Parton luminosity calculation more involved. Introduce electroweak splitting functions for longitudinally polarised gauge bosons only*:

$$f_{q/W_L^{\pm}}(x) = \frac{\alpha}{4\pi \sin^2\theta_W}\frac{1-x}{x}$$

$$f_{u/Z_L}(x) = \frac{\alpha}{16\pi\cos^2\theta_W \sin^2\theta_W}\frac{1-x}{x}(2-\frac{16}{3}\sin^2\theta_W + \frac{64}{9}\sin^4\theta_W)$$

$$f_{d/Z_L}(x) = \frac{\alpha}{16\pi\cos^2\theta_W \sin^2\theta_W}\frac{1-x}{x}(2-\frac{8}{3}\sin^2\theta_W + \frac{16}{9}\sin^4\theta_W)$$

We can then define an *effective* luminosity for the emission of two longitudinally polarised gauge bosons from the quarks q_i and q_j:

$$\frac{dL}{d\xi}\Big|_{q_i q_j/G_L G'_L}\left(\xi = \frac{z}{y}\right) = \int_\xi^1 \frac{dx'}{x'} f_{q_i/G_L}(x') f_{q_j/G'_L}\left(\frac{\xi}{x'}\right)$$

Vector boson fusion production

Putting it all together, the VBF parton luminosity is

$$\frac{dL}{dz}\Big|_{pp/G_L G'_L} = \sum_{i,j} \int_z^1 \frac{dy}{y} \int_x^1 \frac{dx}{x} [f_{q_i}(x,\mu^2) + f_{\bar{q}_i}(x,\mu^2)][f_{q_j}(\frac{y}{x},\mu^2) + f_{\bar{q}_j}(\frac{y}{x},\mu^2)] \frac{dL}{d\xi}\Big|_{q_i q_j/G_L G'_L} \left(\xi = \frac{z}{y}\right)$$

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Effective luminosity contains terms $\propto \alpha_{\mathrm{EW}}^2$, leading to overall suppression with respect to DY.

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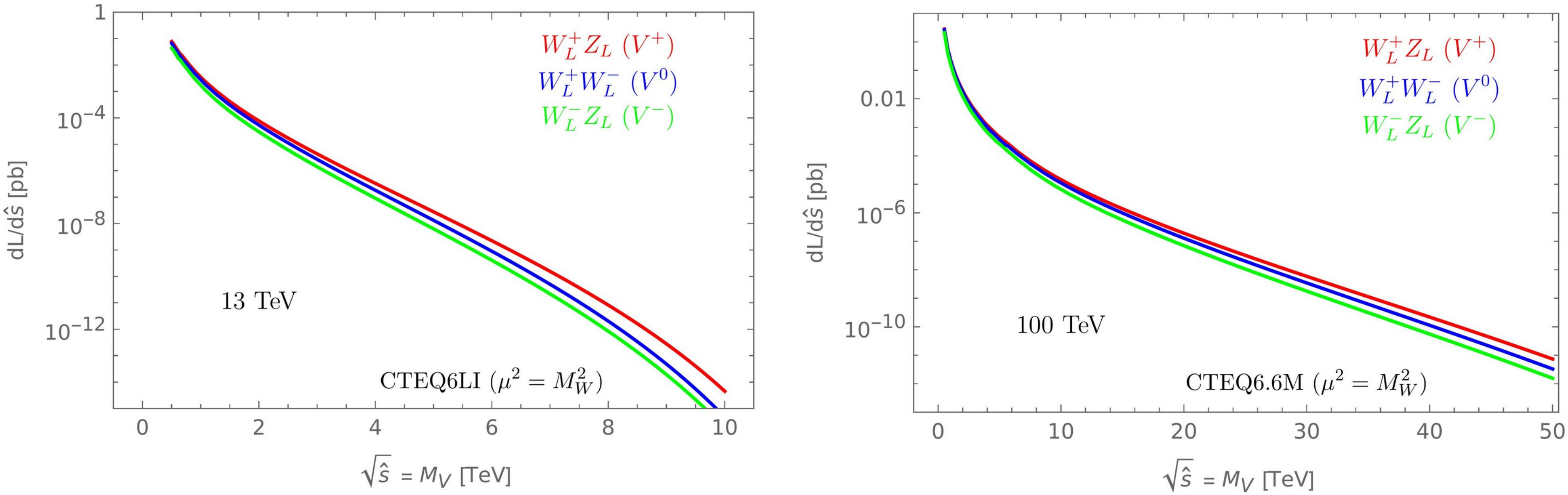
Total cross section is then

$$\sigma^{pp \to G_L G'_L qq \to V qq}(s) = \int_{\frac{2M_V^2}{s}}^1 dz \left.\frac{dL}{dz}\right|_{pp/G_L G'_L} \sigma^{G_L G'_L \to V}(zs)$$

VBF – parton luminosities



Summary of vector producion

Production of (colourless) heavy vector bosons can occur in a pp collision via two channels:

1) Drell-Yan

- Quark-quark production
- Parton luminosity easy to compute, given knowledge of PDFs

2) Vector boson fusion

- Both quarks split off a (longitudinally polarised) gauge boson
- Gauge boson annihilation produces new vector V
- Parton luminosity suppressed by factors of α_{EW}, due to the gauge boson splitting functions

Vector boson fusion has been explored far less than Drell-Yan for this reason. Can it be a viable search channel for higher energy/luminosity colliders?

VBF production of heavy vector triplets

Michael J. Baker, Timothy Martonhelyi, Andrea Thamm, Riccardo Torre
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The role of vector boson fusion in the production of heavy vector triplets at the LHC and HL-LHC

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Abstract: We clarify the role of vector boson fusion (VBF) in the production of heavy vector triplets at the LHC and the HL-LHC. We point out that the presence of VBF production leads to an unavoidable rate of Drell-Yan (DY) production and highlight the subtle interplay between the falling parton luminosities and the increasing importance of VBF production as the heavy vector mass increases. We discuss current LHC searches and HL-LHC projections in di-boson and di-lepton final states and demonstrate that VBF production outperforms DY production for resonance masses above 1 TeV in certain regions of the parameter space. We define two benchmark parameter points which provide competitive production rates in vector boson fusion.

We focused on a simplified model of heavy vectors that transform as triplets under $SU(2)_L$

- What are the phenomenological features of the cross section that determine the rate of DY production relative to VBF?
- Is there a region of the parameter space for which VBF is the dominant production mode?
- Is the LHC and HL-LHC well-placed to leverage this production mode?

Why triplets?

First consider how SM fields transform under the SM gauge group:

$$L \sim (\mathbf{1},\mathbf{2})_{-\frac{1}{2}}, \qquad E \sim (\mathbf{1},\mathbf{1})_{-1},$$
$$Q \sim (\mathbf{3},\mathbf{2})_{\frac{1}{6}}, \qquad D \sim (\mathbf{3},\mathbf{1})_{\frac{-1}{3}}, \qquad U \sim (\mathbf{3},\mathbf{1})_{\frac{2}{3}},$$
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Vector	$\mathcal{V}_\mu^0$	$\mathcal{V}_\mu^1$	$\mathcal{W}_\mu^0$	$\mathcal{W}_\mu^1$	$\mathcal{G}_\mu^0$	$\mathcal{G}_\mu^1$	$\mathcal{H}_\mu$	$\mathcal{L}_\mu$
Irrep	$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{1},\mathbf{1})_1$	$(\mathbf{1},\mathbf{3})_0$	$(\mathbf{1},\mathbf{3})_1$	$(\mathbf{8},\mathbf{1})_0$	$(\mathbf{8},\mathbf{1})_1$	$(\mathbf{8},\mathbf{3})_0$	$(\mathbf{1},\mathbf{2})_{-\frac{3}{2}}$
Vector	$\mathcal{U}_\mu^2$	$\mathcal{U}_\mu^5$	$\mathcal{Q}_\mu^1$	$\mathcal{Q}_\mu^5$	$\mathcal{X}_\mu$	$\mathcal{Y}_\mu^1$	$\mathcal{Y}_\mu^5$	
Irrep	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\mathbf{3},\mathbf{1})_{\frac{5}{3}}$	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$	$(\bar{\mathbf{6}},\mathbf{2})_{\frac{1}{6}}$	$(\bar{\mathbf{6}},\mathbf{2})_{-\frac{5}{6}}$	

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Channel	$V^0 \in (\mathbf{1},\mathbf{3})_0$	$V^+ \in (\mathbf{1},\mathbf{3})_0$
ll	✓	✗
$l\nu$	✗	✓
$l\nu_R$	✗	✗
jj	✓	✓
tb	✗	✓
tt	✓	✗
WW	✓	✗
ZZ	✗	✗
WZ	✗	✓
Zh	✓	✗
Wh	✗	✓
$W\gamma$	✗	✓
hh	✗	✗

Heavy vector triplets: A simplified model

Consider a simplified model of a heavy vector, in addition to the particle content of the SM, that transforms under $SU(3)_c \times SU(2)_L \times U(1)_Y$ as

$$V^a \sim (\mathbf{1}, \mathbf{3}, 0),\ \ a = 1,\ 2,\ 3$$

Have the familiar relations: $$V^\pm_\mu = \frac{V^1_\mu \mp i V^2_\mu}{\sqrt{2}}, \quad V^0_\mu = V^3_\mu$$

Full Lagrangian:

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

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$$\sigma \times BR \propto c^2_{q,H} \times c^2_{q,H,\ell}$$

The production cross section

What are the ingredients that enter into a comparison between HVT production via DY and VBF? We look at the cross section:

$$\sigma(pp \to V + X) \quad = N_{\mathrm{DY}} \sum_{q,\bar{q}' \in p} \frac{\Gamma_{V \to q\bar{q}'}}{M_V} \frac{dL_{q\bar{q}'}}{d\hat{s}}\bigg|_{\hat{s}=M_V^2} + N_{\mathrm{VBF}} \sum_{G,G' \in p} \frac{\Gamma_{V \to GG'}}{M_V} \frac{dL_{GG'}}{d\hat{s}}\bigg|_{\hat{s}=M_V^2}$$

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Process-dependent constant – Favours VBF by a factor of 36

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Differential parton luminosities – Favours DY due to α_{EW} suppression in the gauge boson splitting functions

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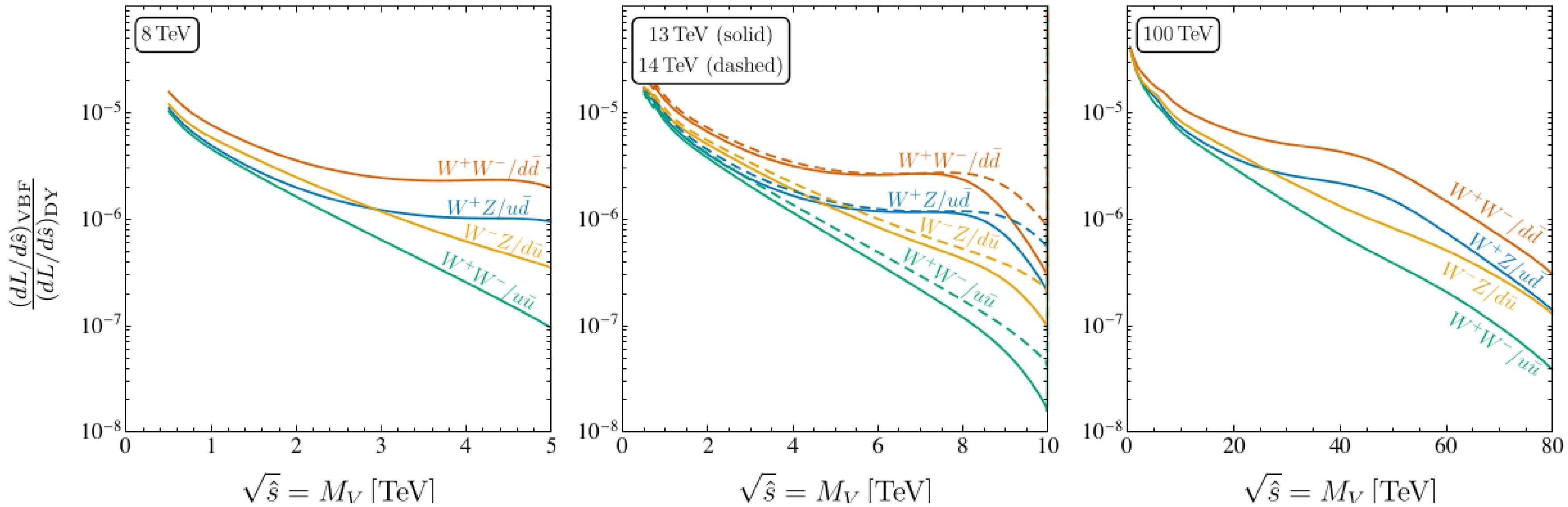

- VBF suppressed with respect to DY by a factor between 10^{-5} and 10^{-7}, depending on resonance production channel, mass, and collider energy
- Significantly outweighs VBF enhancement from numerical factors $N_{DY/VBF}$

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Order one for $g_V \sim c_H \sim c_q \sim 1$

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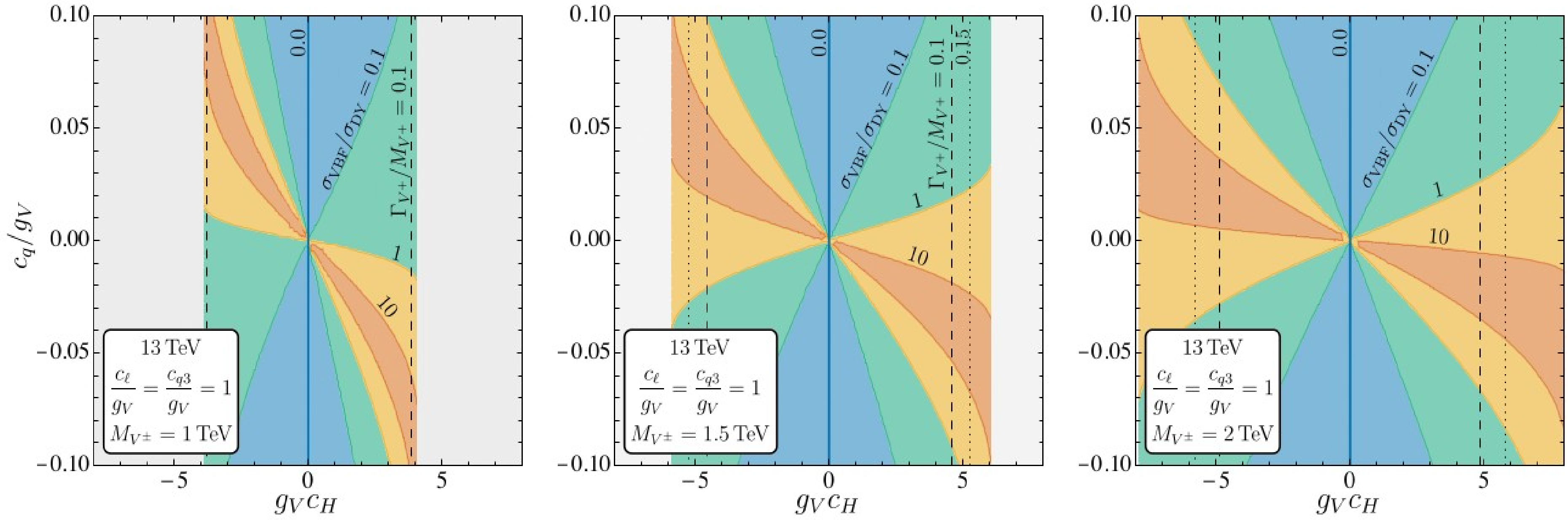
Grows faster with mass than the reduction given by parton luminosities – VBF increasingly important for larger resonance masses!

Putting it all together

For very small c_q, we can identify regions of the parameter space where the VBF cross section dominates.
See that for larger resonance masses, the VBF-dominant areas increase.



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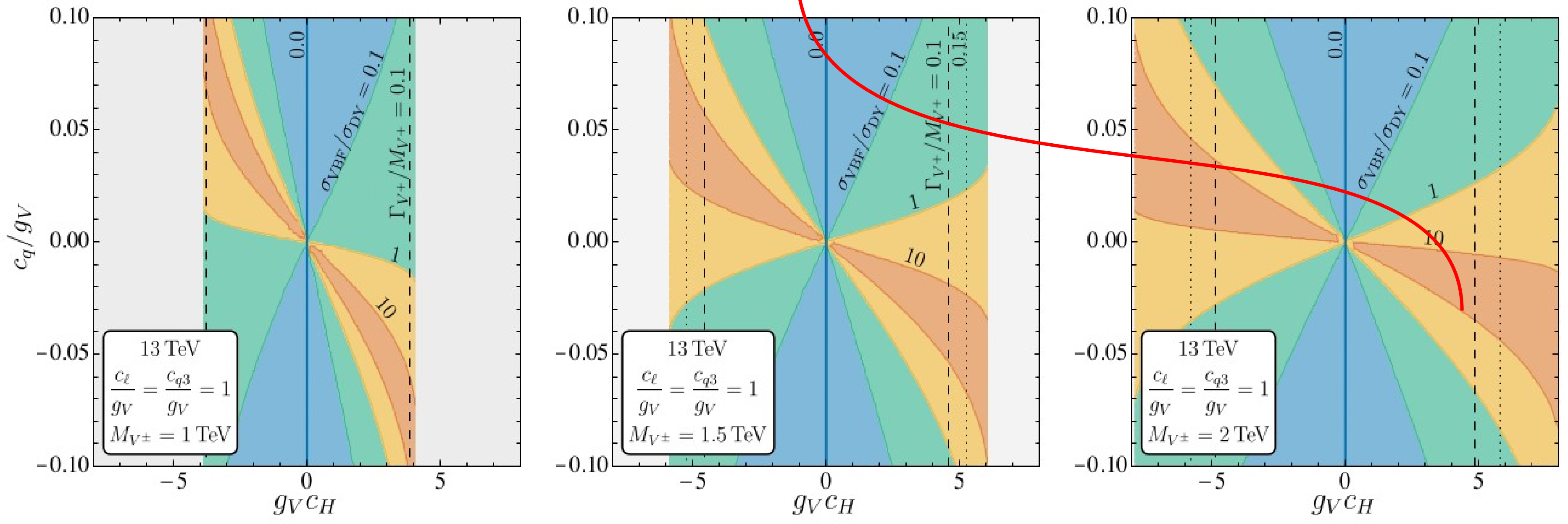
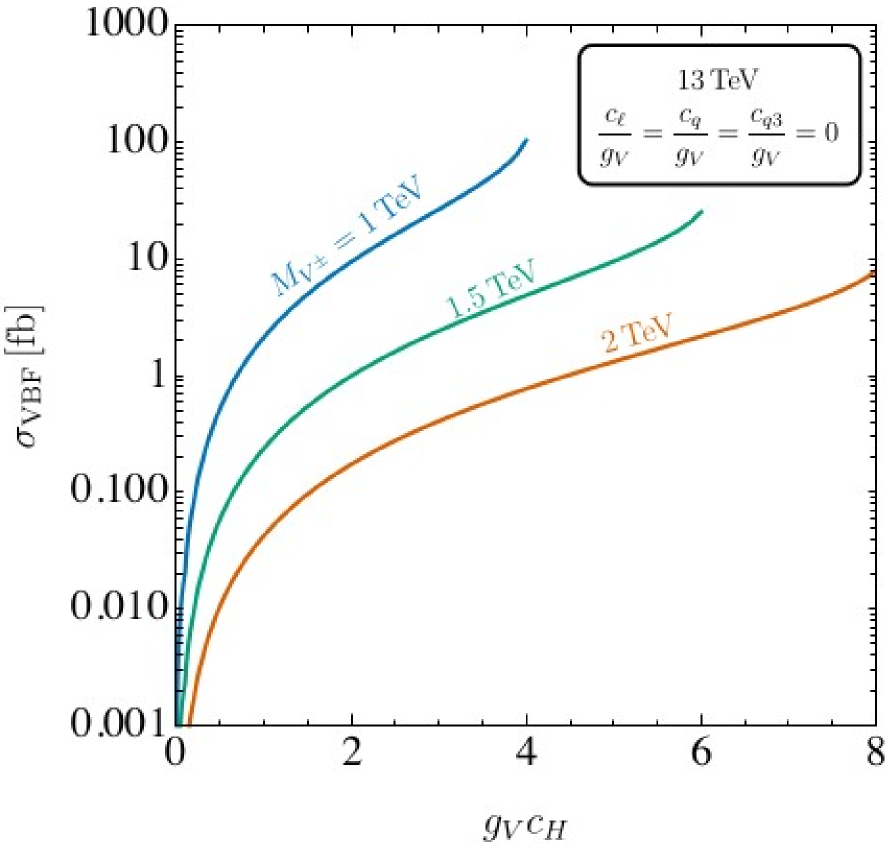


Higher masses

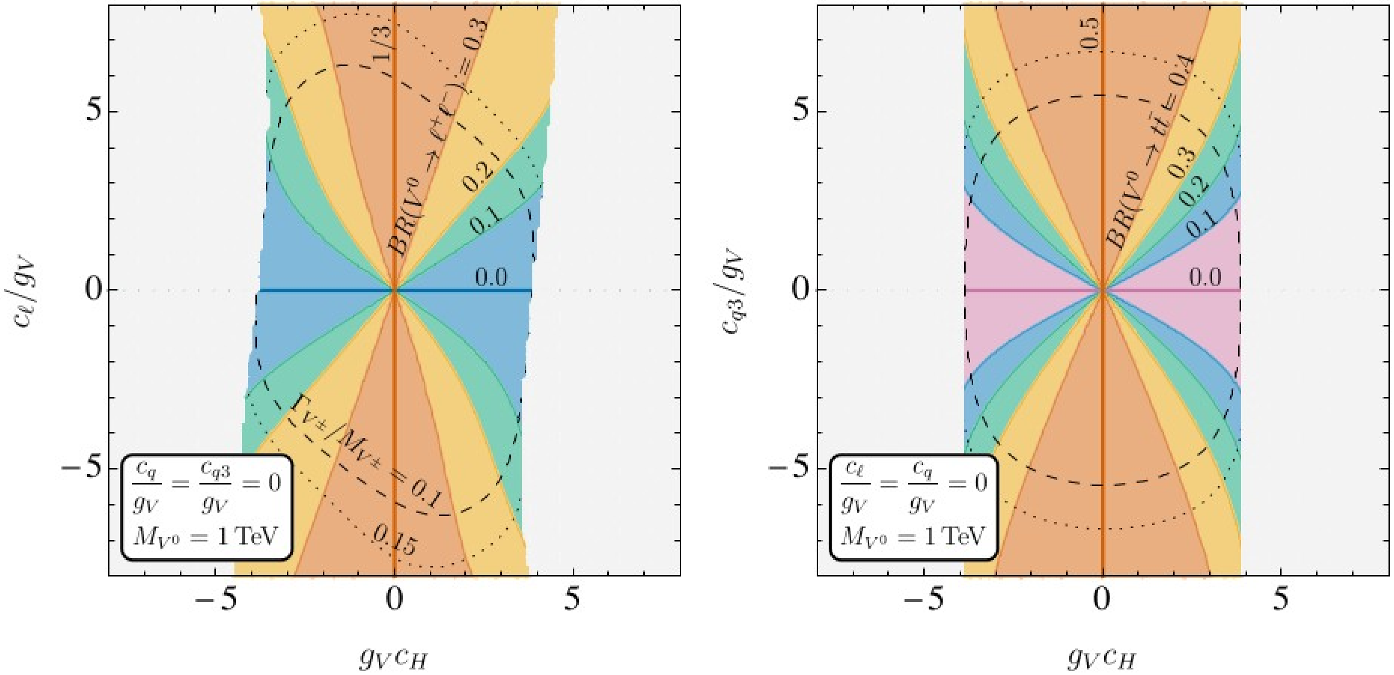


The area for which $\sigma_{VBF}/\sigma_{DY} > 1$ increases with resonance mass, but σ_{VBF} also decreases

- Parton luminosities decrease rapidly
- VBF searches will eventually lose sensitivity
- $g_V c_H \ll 1$ also difficult to probe

Two-body final states

Now that we know the relevant region of our simplified parameter space, what is the relative importance of each decay channel?



- Decays into di-jets generally irrelevant for VBF studies
- c_{q3} can be different to light quark couplings
- Di-lepton/ heavy di-quark decays can dominate over di-boson in certain regions of parameter space

Current results from ATLAS and CMS

Various VBF-specific searches have been done in run II of the LHC, particularly in the di-bosonic and di-leptonic final state.

Channel	Theoretical benchmark
$ZW \to \ell\nu\ell'\ell'$	**VBF-DB (di-boson):**
$Zh \to$ leptons hadrons	$g_V c_H = 4$
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Dominant VBF-production above 1 TeV, almost total decay to di-bosons

Reasonable decay to di-leptons. Only theoretically consistent above 0.8 TeV

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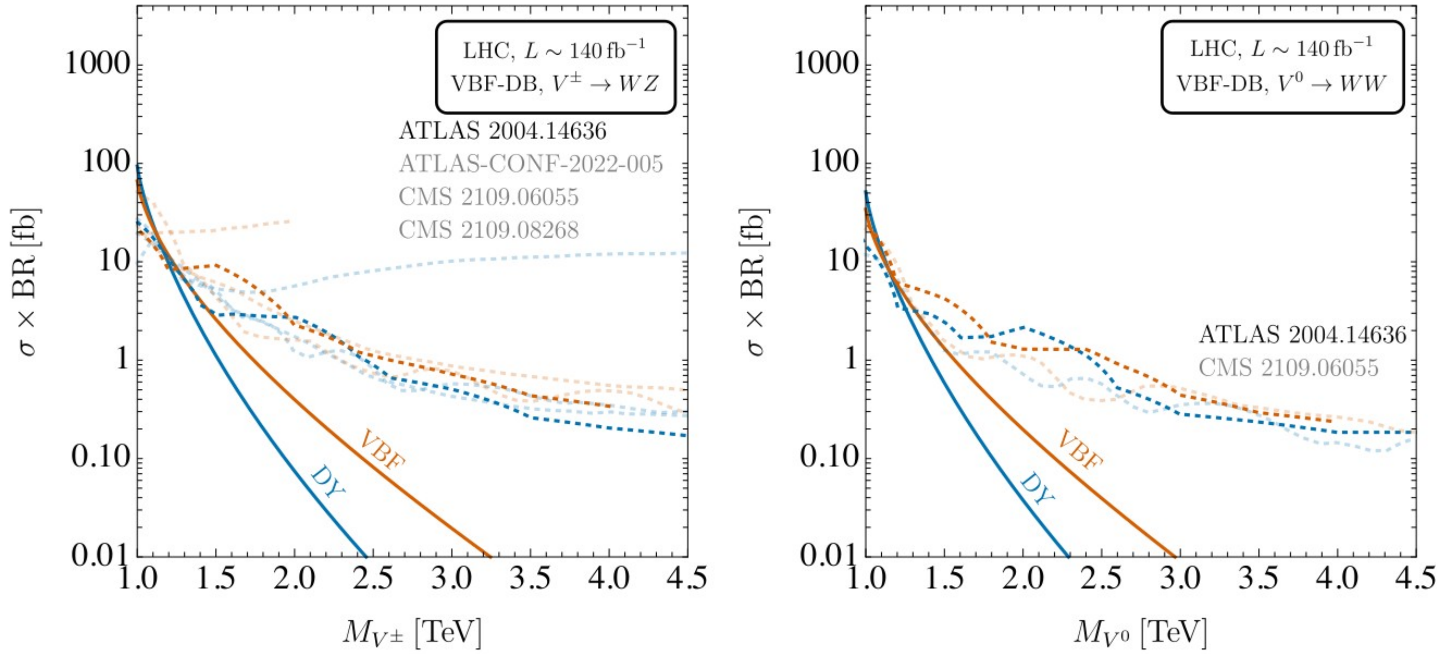

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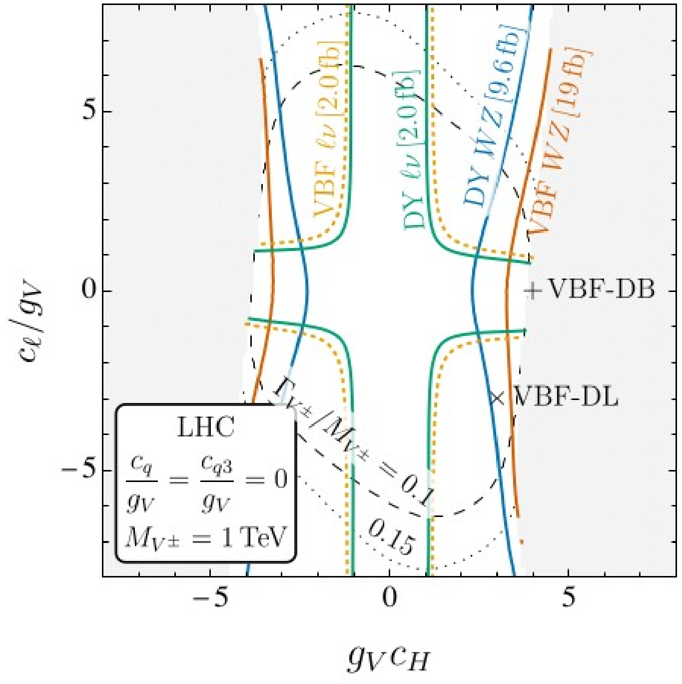

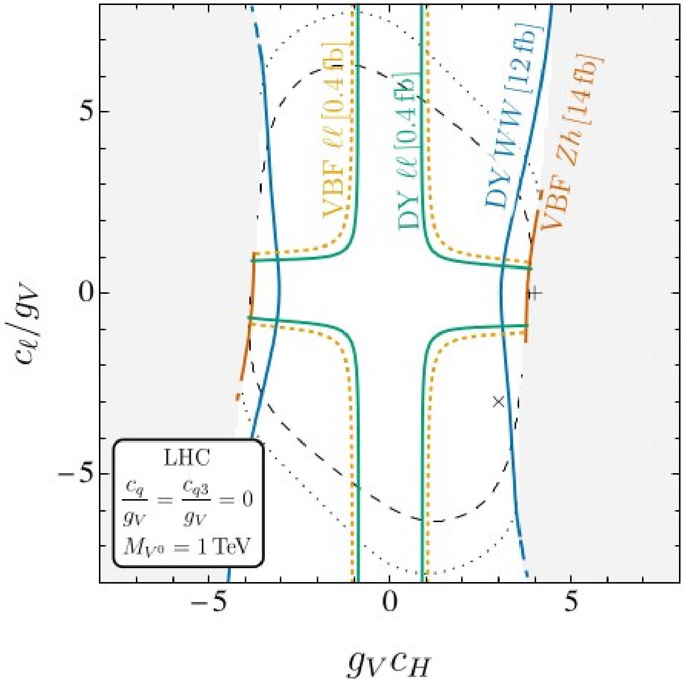

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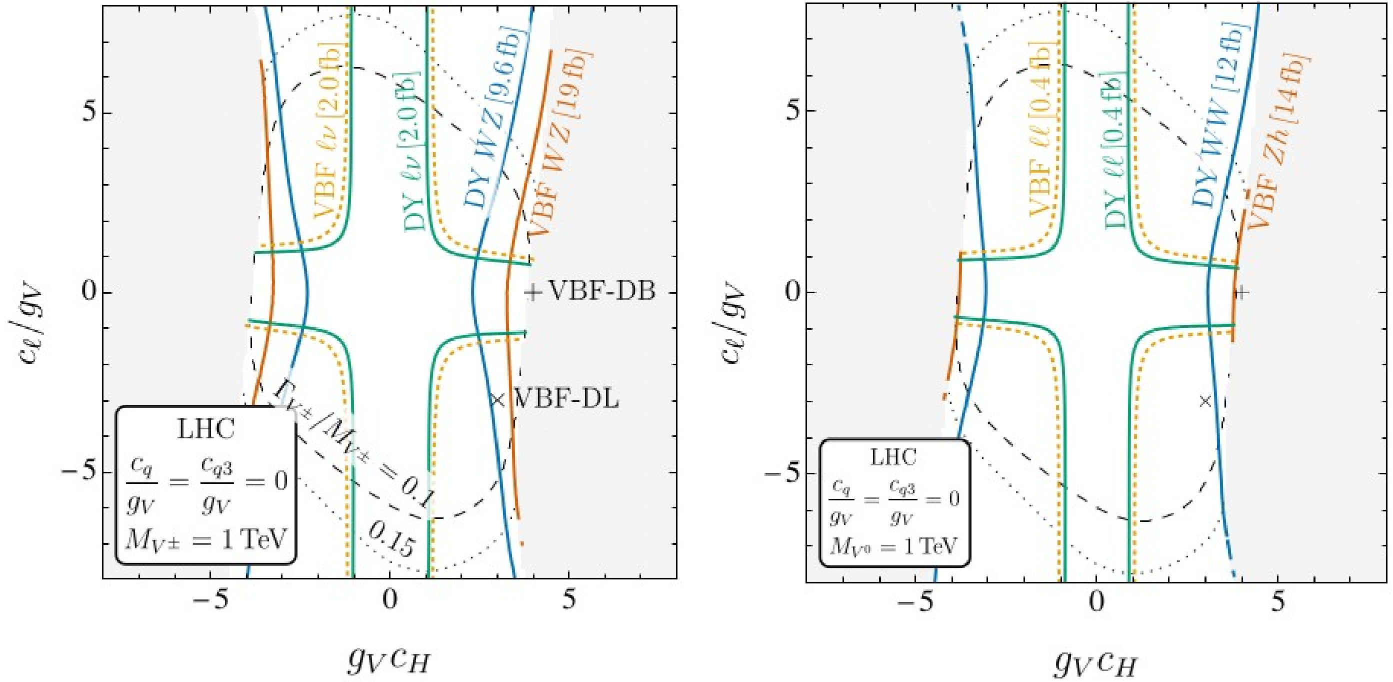

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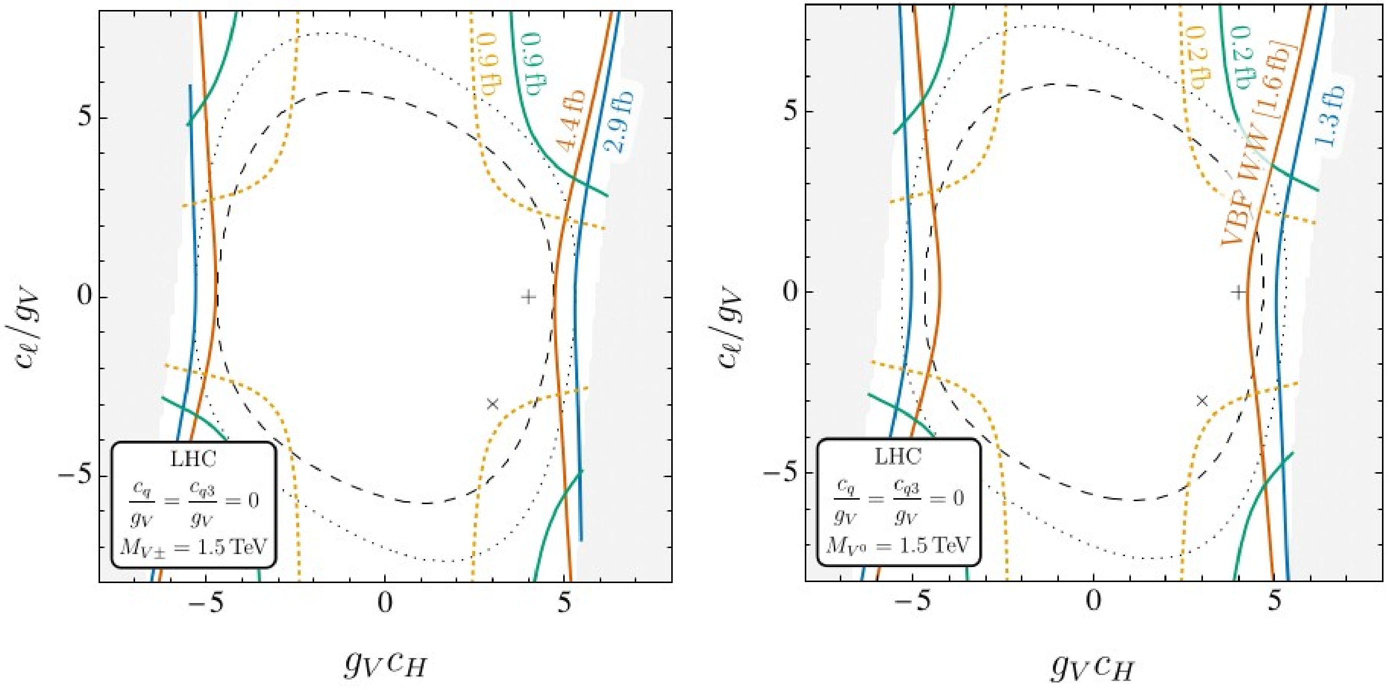

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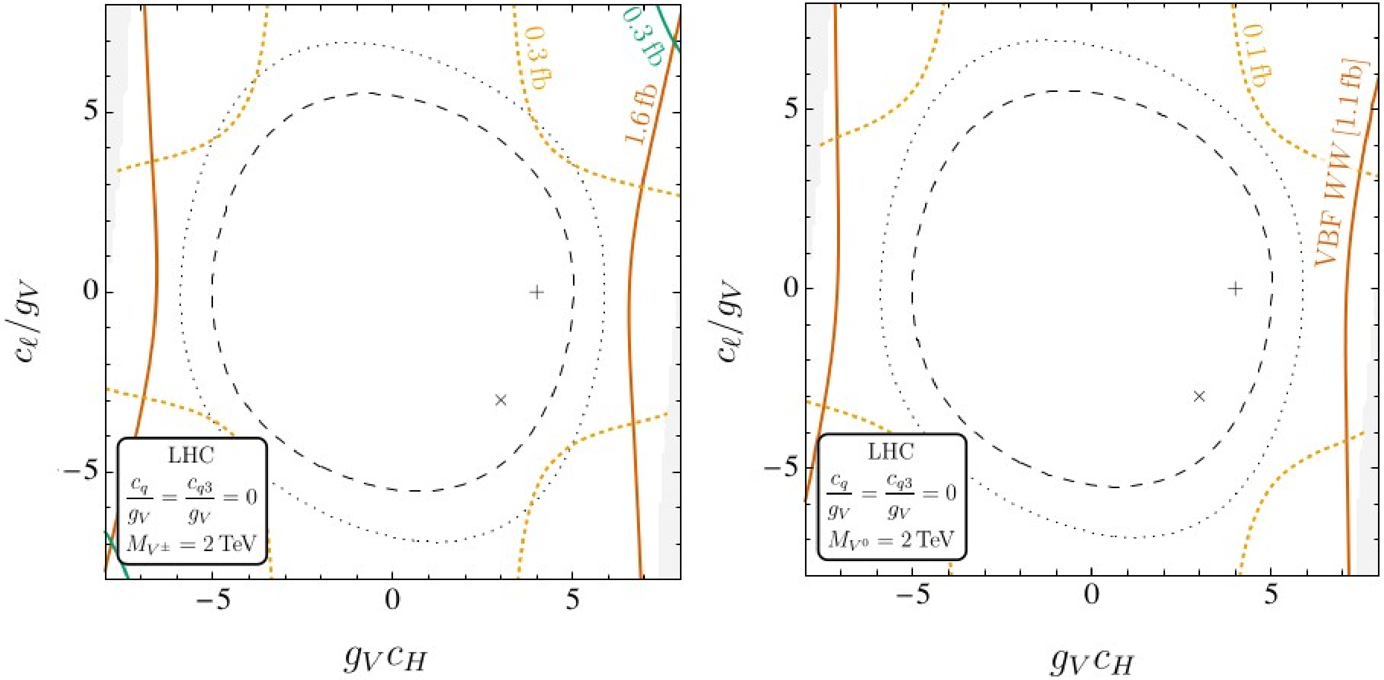

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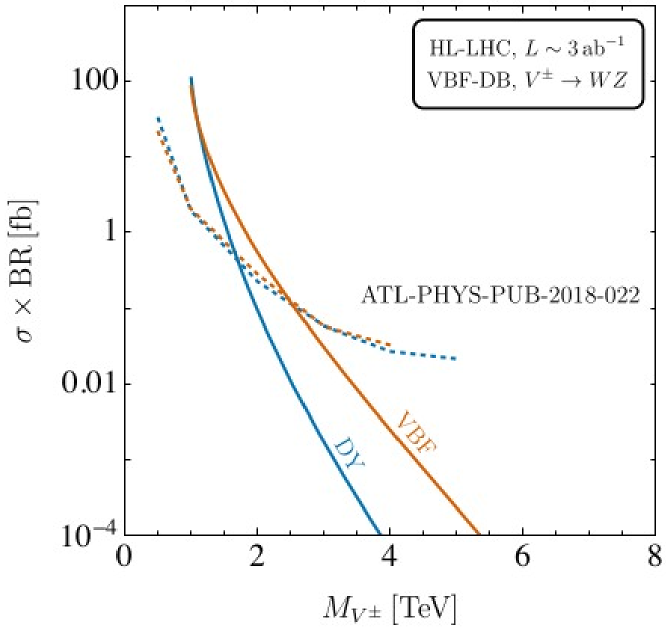
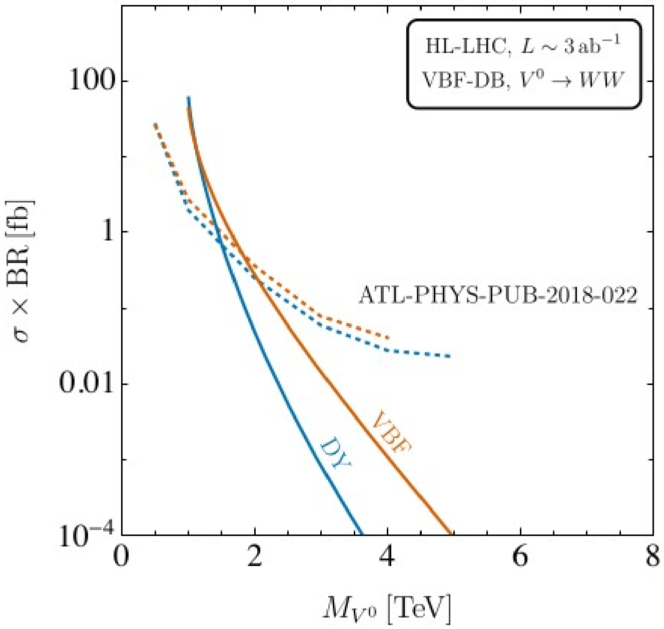
DY drops off, and VBF is best

HL-LHC: Projected limits

In the future, the LHC is well-placed to further leverage the dominant VBF production mode present in certain regions of the HVT parameter space. We look to the HL-LHC:





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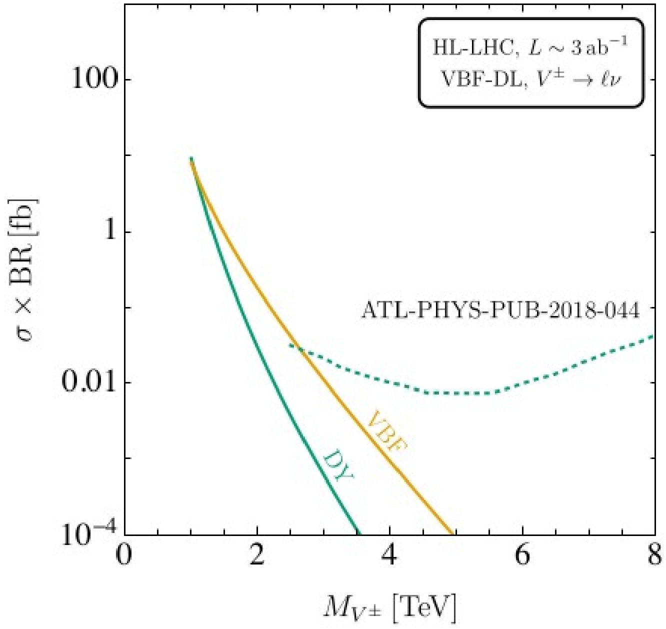

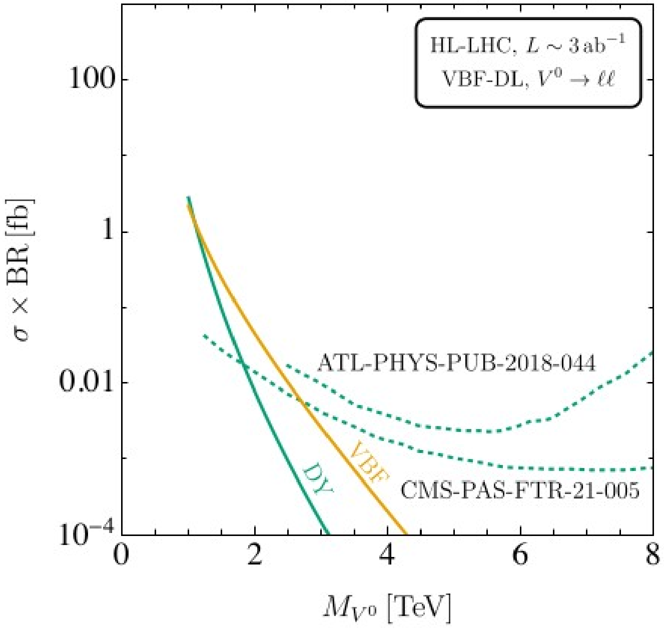

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No VBF di-lepton projections yet, but similar bound expected

Next steps: Extrapolation of results

- Dedicated extrapolation procedure for DY production to future colliders already exists

- For a given resonance mass, experimental limit depends exclusively on the number of background events

$$B(s, L, M_V) = B(s_0, L_0, M_V^0)$$

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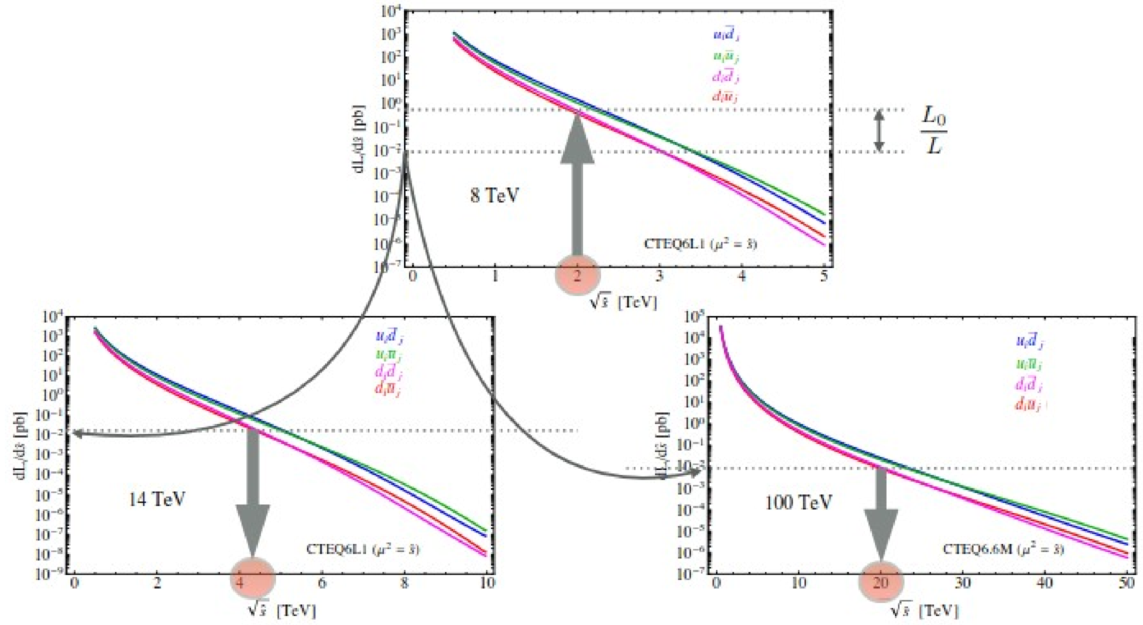

arXiv:1502.01701

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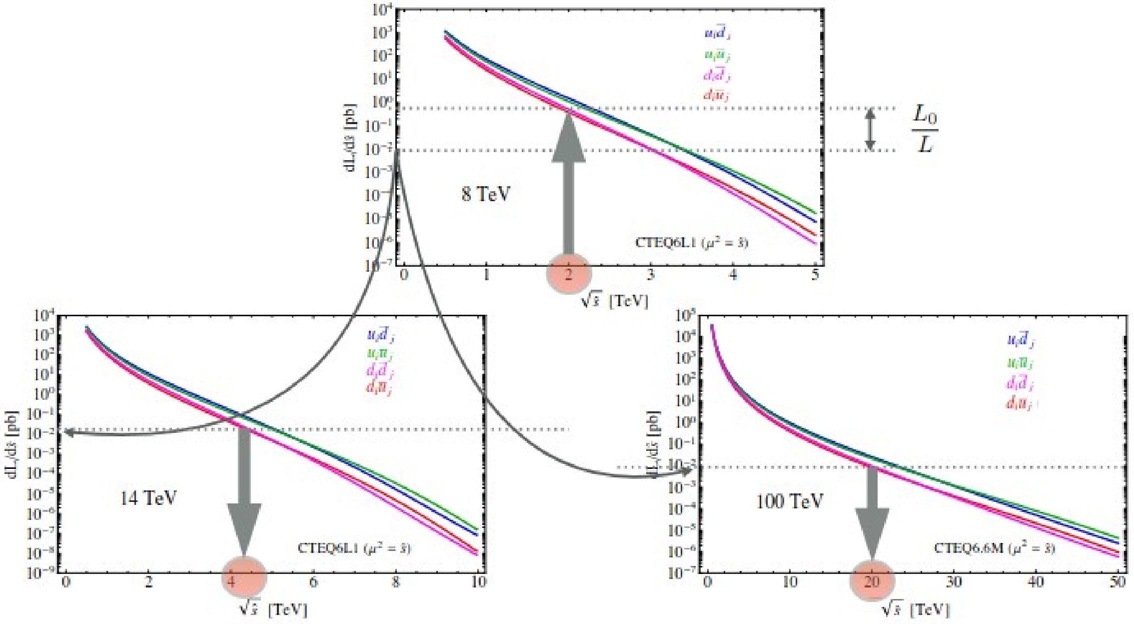

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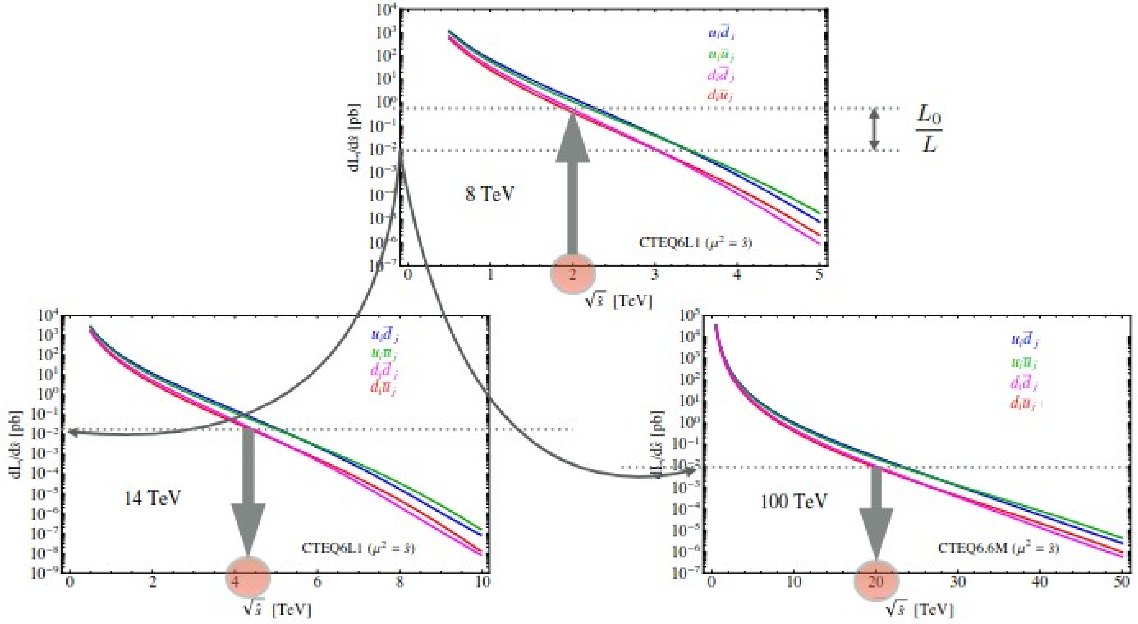

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Can this procedure be applied to VBF?

Summary

Vector boson fusion is, as of yet, an under-utilised production mode in searches at ATLAS and CMS. Current experimental capabilities place it as a competitive production mode, as shown by using a simplified model of heavy vector triplets.

- Simplified models are incredibly useful for collider phenomenology, as our results may be mapped onto a wide class of explicit models

- Vector boson fusion may be the dominant production mode in those models whose light quark couplings are very small

- In this region of parameter space, LHC searches in the VBF channel have a higher mass reach than those of DY for resonance masses above 1 TeV

- HL-LHC VBF searches have an even higher mass reach

- Dedicated extrapolation procedure would show how VBF production would fare at the HE-LHC and 100 TeV FCC

Thank you

THE UNIVERSITY OF MELBOURNE