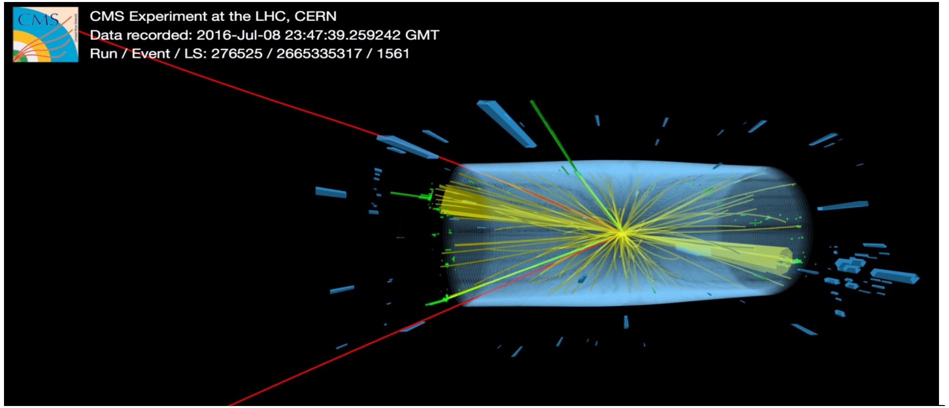
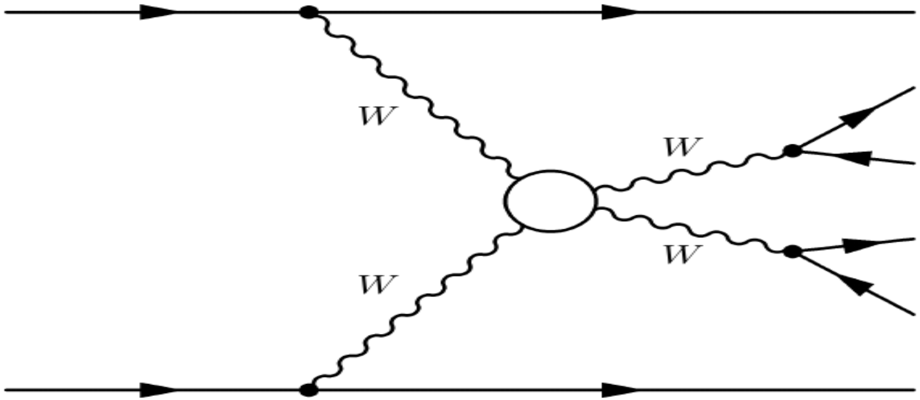
Search for anomalous couplings in the hadronic decay channel of Vector Boson Scattering at CMS

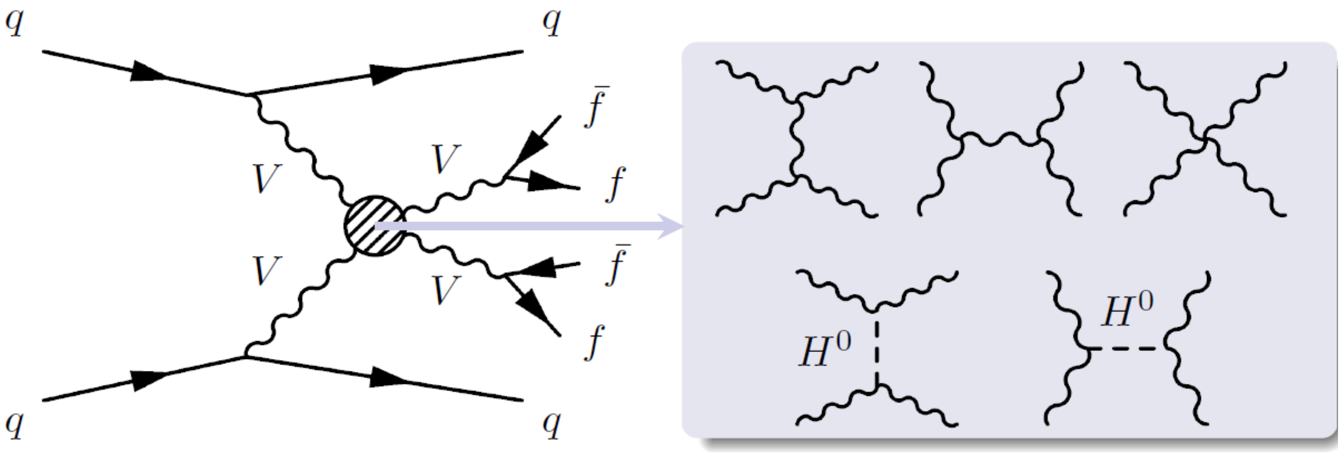
KSETA workshop, Durbach 2022

Max Neukum



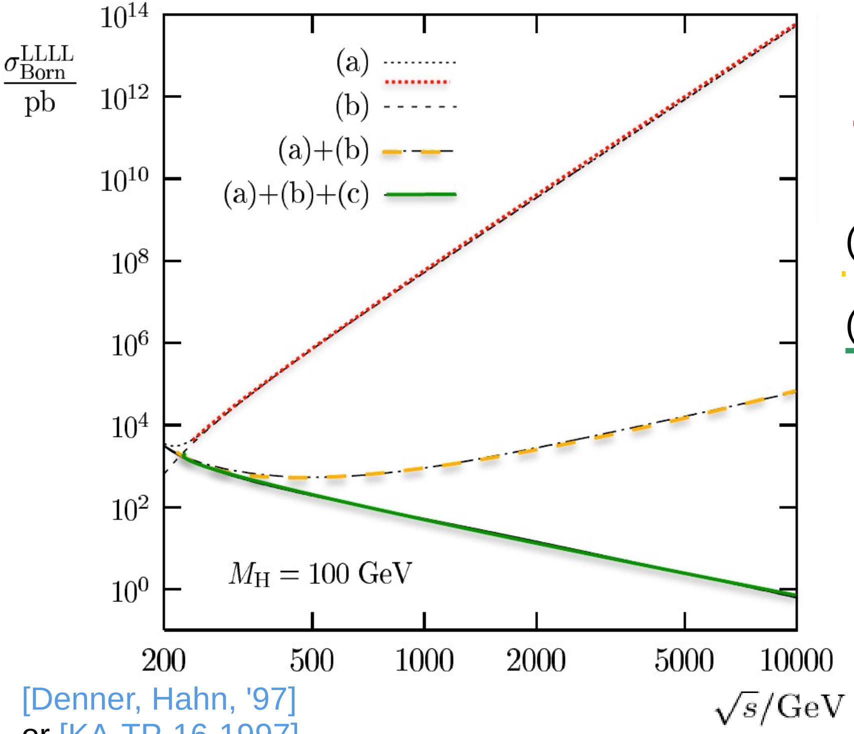


Vector Boson Scattering at the LHC



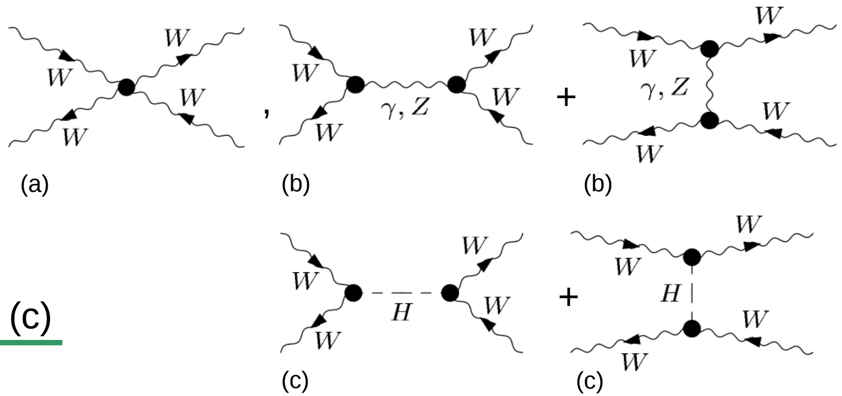
- VVjj final state with V=W,Z
- Contains triple and quartic gauge couplings (QGC)
- Leading Order: EW ($\alpha_{EW}{}^{6}$), QCD ($\alpha_{EW}{}^{4}\alpha_{S}{}^{2}$), and inteference ($\alpha_{EW}{}^{5}\alpha_{S}$)

Theoretical motivation



[Denner, Hahn, '97]
or [KA-TP-16-1997]

(a),(b)



(a) + (b)

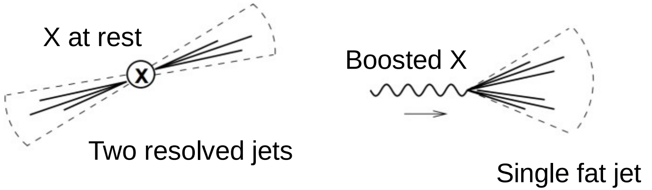
(a) + (b) + (c)

"No-lose theorem" of LHC:

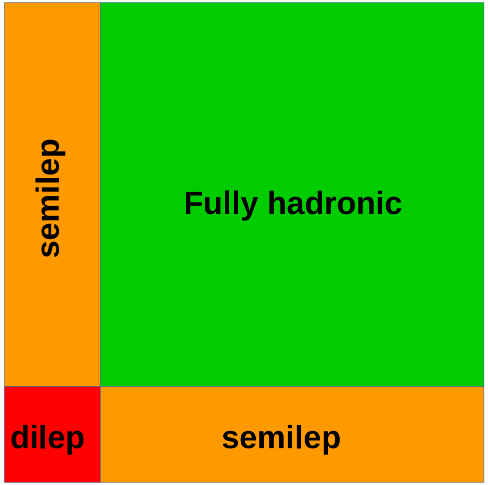
- Violation of Unitarity without Higgs (~1.2 TeV)
- Either Higgs or something else

Hadronic decay channel

- Hadronic decays of V=W,Z have the largest Branching Ratio
- The final state is fully reconstructable, since there are no neutrinos
- Boosted regime:



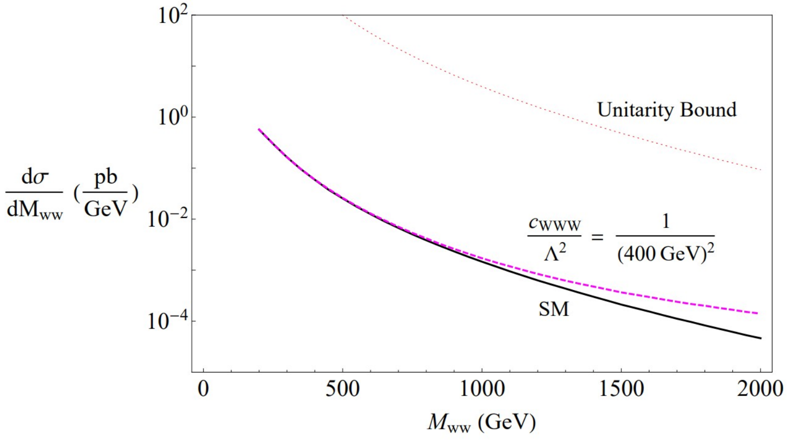
- No neutrinos, no charged leptons
- <u>Main challenges:</u>
  - Very large QCD multijet background
  - Small cross-section compared to background processes



Effective Field Theory approach

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \ldots$$

- Include higher (mass-) dimension operators
- Integrate out higher energy effects → truncate series
- Theory invalid beyond Λ
- aTGC: mostly dim-6
- aQGC: dim-8



Effective Field Theory approach

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{f_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

- Currently implemented: only dim-6 or dim-8
- aQGC: dim-8

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$, $\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

[O. Éboli et al.]

Effective Field Theory approach

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{f_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

- aTGC: mostly dim-6
- Recent study suggests 15 dim-6 operators for VBS
  [VBSCAN-PUB-05-21]
- For now: focus on 3 operators, that only affect vector bosons
- Warsaw basis

$$Q_{Hl}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_p) \qquad Q_{Hl}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{l}_p \sigma^i \gamma^\mu l_p)$$

$$Q_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_p) \qquad Q_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{q}_p \sigma^i \gamma^\mu q_p)$$

$$Q_{ll} = (\bar{l}_p \gamma_\mu l_p)(\bar{l}_r \gamma^\mu l_r) \qquad Q_{ll}^{(1)} = (\bar{l}_p \gamma_\mu l_r)(\bar{l}_r \gamma^\mu l_p)$$

$$Q_{qq}^{(1)} = (\bar{q}_p \gamma_\mu q_p)(\bar{q}_r \gamma^\mu q_r) \qquad Q_{qq}^{(1,1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_r \gamma^\mu q_p)$$

$$Q_{qq}^{(3)} = (\bar{q}_p \gamma_\mu \sigma^i q_p)(\bar{q}_r \gamma^\mu \sigma^i q_r) \qquad Q_{qq}^{(3,1)} = (\bar{q}_p \gamma_\mu \sigma^i q_r)(\bar{q}_r \gamma^\mu \sigma^i q_p)$$

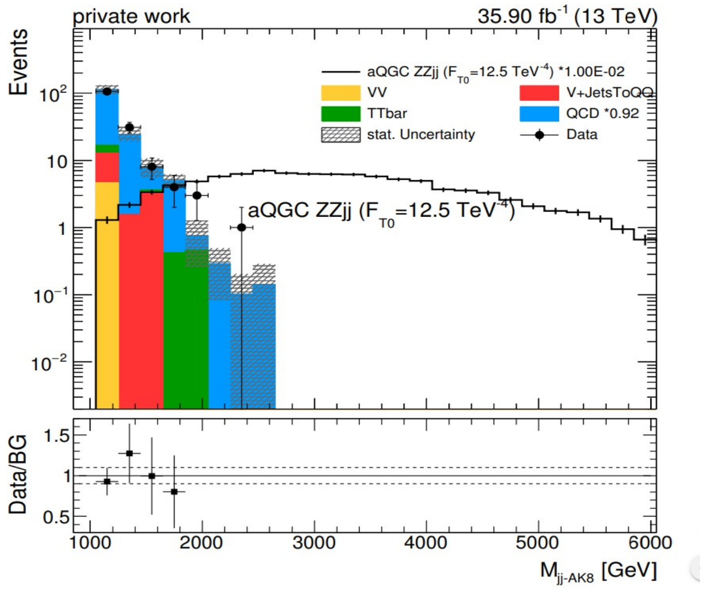
$$Q_{HD} = (H^\dagger D_\mu H)(H^\dagger D^\mu H) \qquad Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

$$Q_{HWB} = (H^\dagger \sigma^i H) W_{\mu\nu}^i B^{\mu\nu} \qquad Q_{HW} = (H^\dagger H) W_{\mu\nu}^i W^{i\mu\nu}$$

$$Q_W = \varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$$

Summary of a previous study

- QCD Fit in control region, with transfer function: $\left(p_0 / \left(x/\sqrt{s}\right)^{p_1}\right)$
- For dim-8 operators only: comparable limits with 2016 data



observed asymptotic 95% CL_s exclusion limits [TeV^{-4}]

aQGC parameter	literature limits	VV
f_{S0}/Λ^{-4}	$(-2.7, 2.7)$	$-16, 18$
f_{S1}/Λ^{-4}	$(-3.4, 3.4)$	$-30, 30$
f_{M0}/Λ^{-4}	$(-0.69, 0.7)$	$-3, 3$
f_{M1}/Λ^{-4}	$(-2.0, 2.1)$	$-3.7, 3.7$
f_{M2}/Λ^{-4}	$(-8.2, 8.0)$	$-5, 5$
f_{M3}/Λ^{-4}	$(-21, 21)$	$-8, 8$
f_{M4}/Λ^{-4}	$(-15, 16)$	$-8, 8$
f_{M5}/Λ^{-4}	$(-25, 24)$	$-13, 13$
f_{M6}/Λ^{-4}	$(-1.3, 1.3)$	$-6, 6$
f_{M7}/Λ^{-4}	$(-3.4, 3.4)$	$-6.4, 6.4$
f_{T0}/Λ^{-4}	$(-0.12, 0.11)$	$-0.2, 0.2$
f_{T1}/Λ^{-4}	$(-0.12, 0.13)$	$-0.18, 0.18$
f_{T2}/Λ^{-4}	$(-0.28, 0.28)$	$-0.43, 0.43$
f_{T5}/Λ^{-4}	$(-0.70, 0.74)$	$-0.7, 0.7$
f_{T6}/Λ^{-4}	$(-1.6, 1.7)$	$-0.91, 0.91$
f_{T7}/Λ^{-4}	$(-2.6, 2.8)$	$-1.5, 1.5$
f_{T8}/Λ^{-4}	$(-0.47, 0.47)$	$-0.73, 0.73$
f_{T9}/Λ^{-4}	$(-1.3, 1.3)$	$-1.6, 1.6$

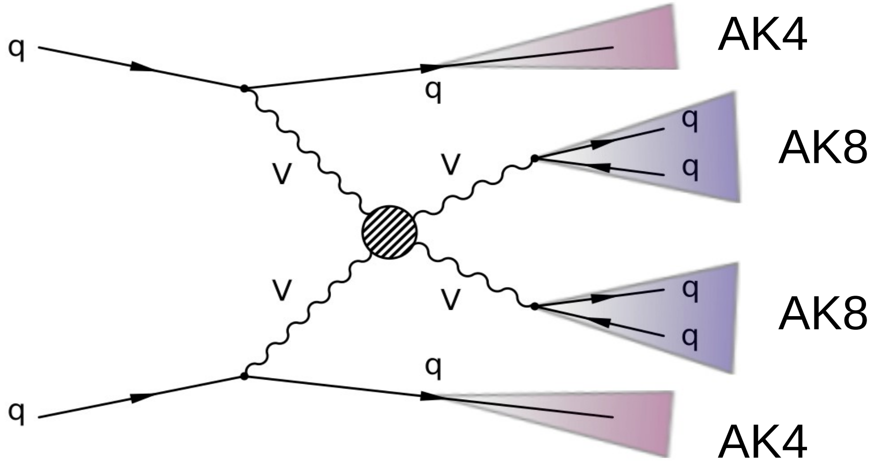
Signal Topology

VV Selection: AK8

- $p_T \geq 200$ GeV, $|\eta| < 2.5$
- 60 GeV $< m_V <$ 215 GeV
- DNN based boosted jet tagger

VBS Selection: AK4

- $p_T \geq 50$ GeV
- $\Delta\eta(j_1,j_2) > 3.0$
- $m(j_1,j_2) \geq 500$ GeV



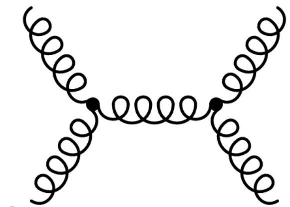
→ Control Region: fail VBS Selection

→ Data taken in 2016 - 2018 (“full Run-2”)

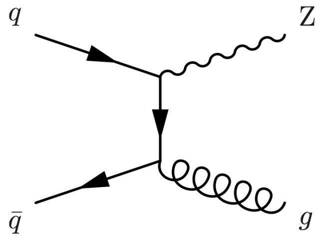
Backgrounds

QCD multijets

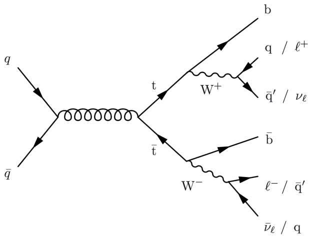
- Overwhelming background
- Not resonant in M_V



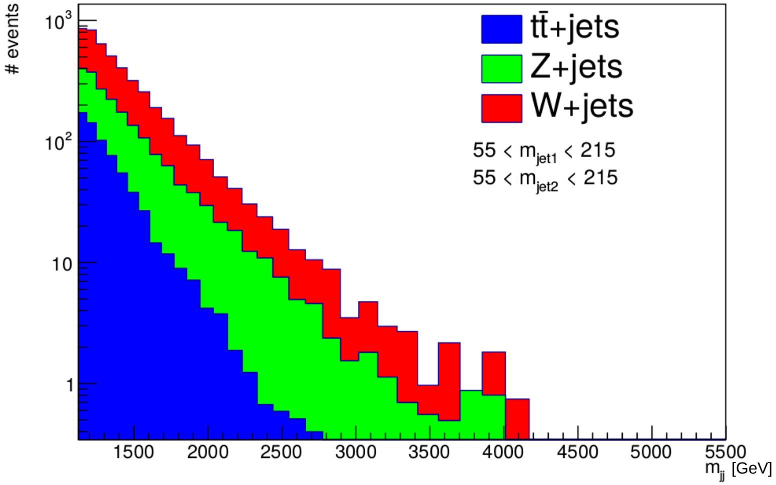
V+jets



ttbar

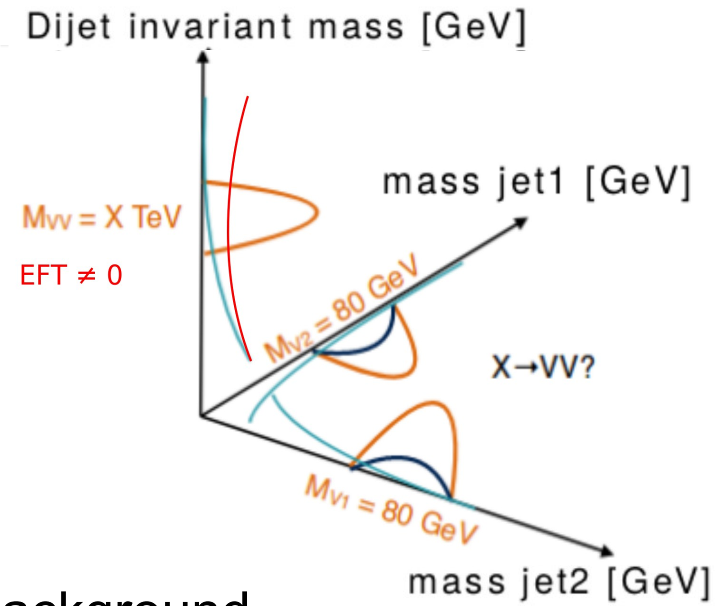


- Smaller backgrounds: VV, VVV, single top, tt+X



Analysis strategy

- 3D Fit in M_{V1}, M_{V2}, M_{VV}
  - M_{VV}: very sensitive to EFT
  - M_V: QCD background not resonant
- Follow fit strategy of resonance search (~30% improvement compared to 1D)
- Fit to data via morphing between shapes
- Differences to resonance searches:
  - VBS topology: tagging jets reduce background
  - EFT signal not resonant in M_{VV}, but changes the slope



à la CMS-B2G-18-002

Signal modeling

$$N \propto |A| = |A_{SM}|^2 + \sum_{\alpha} \frac{c_\alpha}{\Lambda^2} \cdot 2\,\Re\left(A_{SM} A^{\dagger}_{Q_\alpha}\right) + \sum_{\alpha\beta} \frac{c_\alpha c_\beta}{\Lambda^4} \cdot \left(A_{Q_\alpha} A^{\dagger}_{Q_\beta}\right)$$

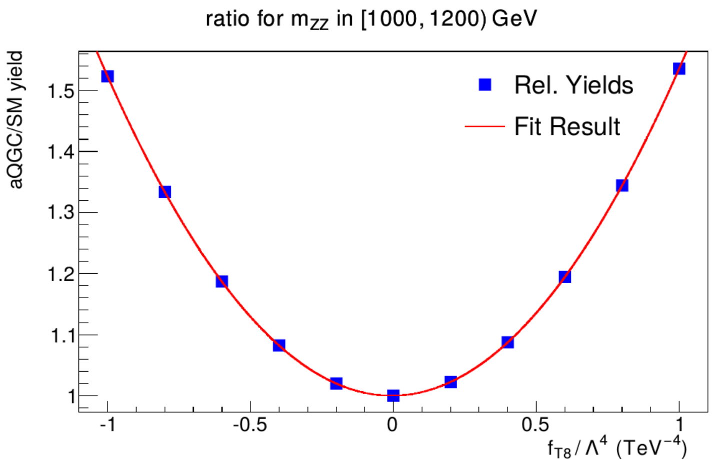
Interference SM-EFT

Pure EFT (quadratic)

- UFO models as input to MadGraph:
  - Dim6: SMEFTsim Implements the Warsaw basis
  - Dim8: "Eboli model" includes some operators
- SM yield is scaled with a 2nd degree polynomial
- Quadratic fit describes signal scaling perfectly
- Scaling is more dominant in higher mass bins

arXiv:1709.06492

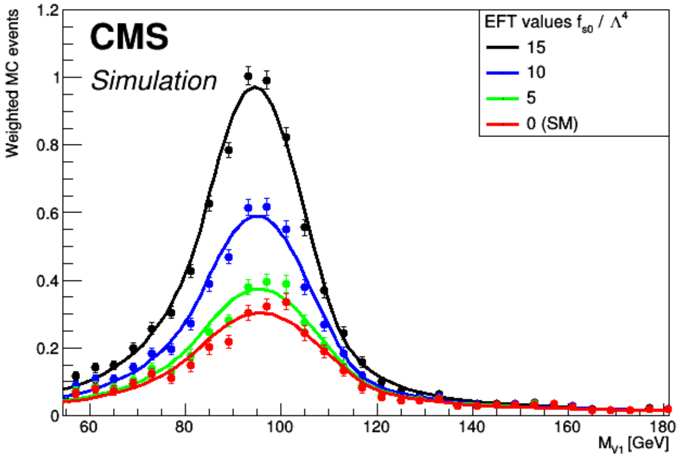
arXiv:2004.05174

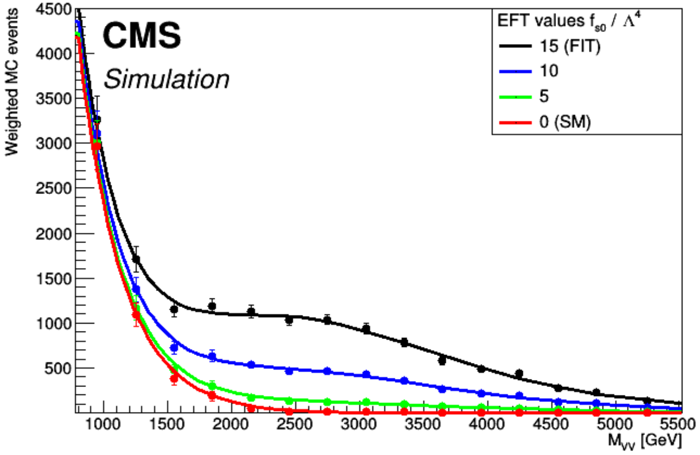


Signal parametrization

- Parametrize m_{V1}, m_{V2} with a **double-sided Crystal Ball** function
- For m_{VV} use the envelope of $SM^2 + aQGC^2 + 2 * SM * aQGC$

$$F_{VV} = N_{SM}\left(e^{a_0 M_{VV}} + e^{a_{corr} M_{VV}}\right) + N_{Int} \cdot f_i^2 \cdot e^{a_1} \frac{1 + Erf\left(\left(M_{VV} - a_{0,1}\right)/a_w\right)}{2} + N_{quadr} \cdot f_i^2 \cdot e^{a_2 M_{VV}}$$

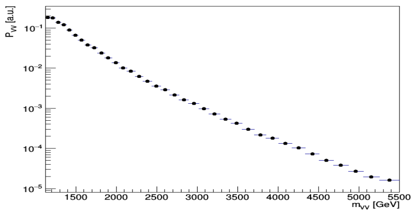


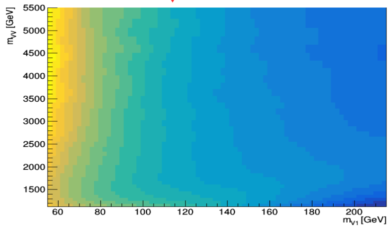


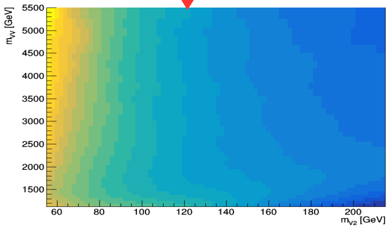
Modeling the QCD background

- Derive 3D templates from MC
- Take correlations ($m_{V1,2}$ | m_{VV}) into account
- Calculate detector response for $m_{V1,2}$ and m_{VV} → scale and resolution
- Each event contributes with the 1D/2D gaussian kernel

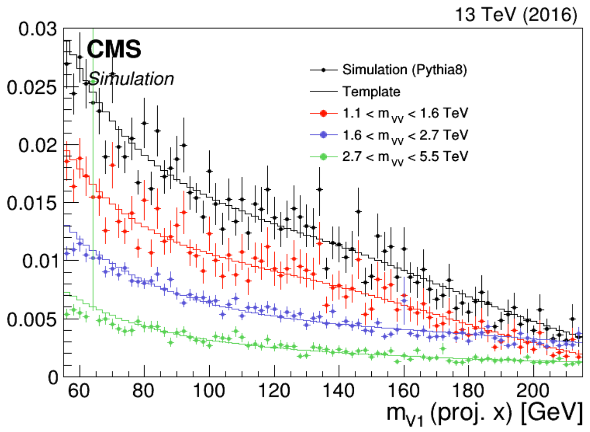
$$P(m_{VV}, m_{V1}, m_{V2}) = P_{VV}(m_{VV}) \times P_{cond,1}(m_{V1}|m_{VV}) \times P_{cond,2}(m_{V2}|m_{VV})$$

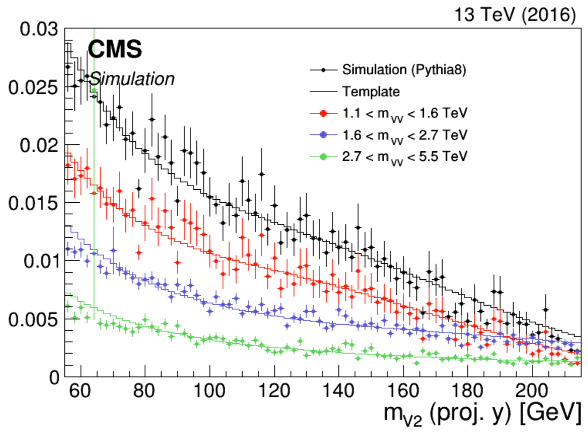


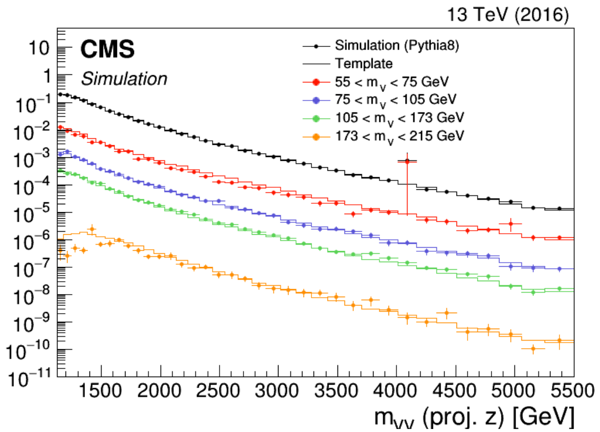




Nonresonant projections

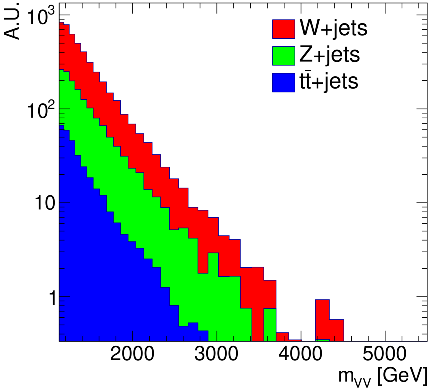


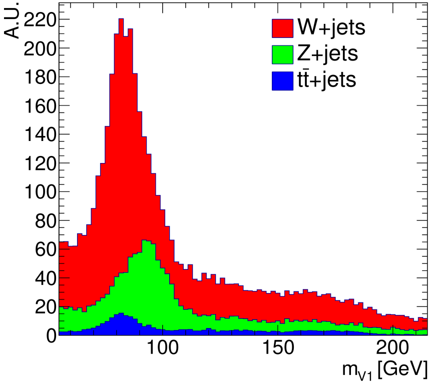


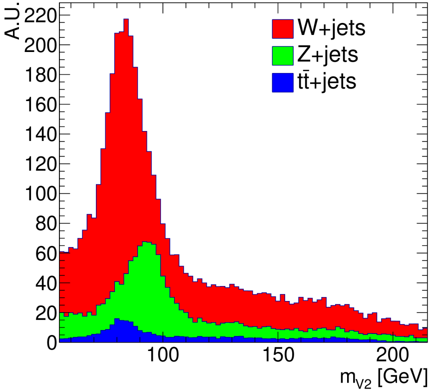


- Projections of 3D template on each axis
- Similarly: conditional PDFs for resonant backgrounds
- Further major backgrounds are: V+jets, ttbar, single top and VV production

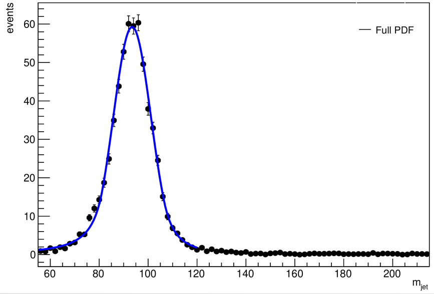
Resonant background





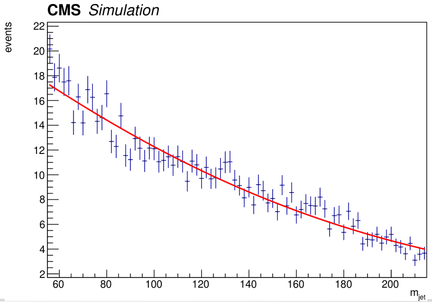


$$P_{V+jets}(m_{V1}, m_{V1}, m_{VV}|\bar{\theta}) = 0.5\left(P_{VV}(m_{VV}|\bar{\theta}_1)\, P_{res}(m_{V1}|\bar{\theta}_2)\, P_{non-res}(m_{V2}|\bar{\theta}_3)\right)$$
$$+0.5\left(P_{VV}(m_{VV}|\bar{\theta}_1)\, P_{res}(m_{V2}|\bar{\theta}_2)\, P_{non-res}(m_{V1}|\bar{\theta}_3)\right)$$



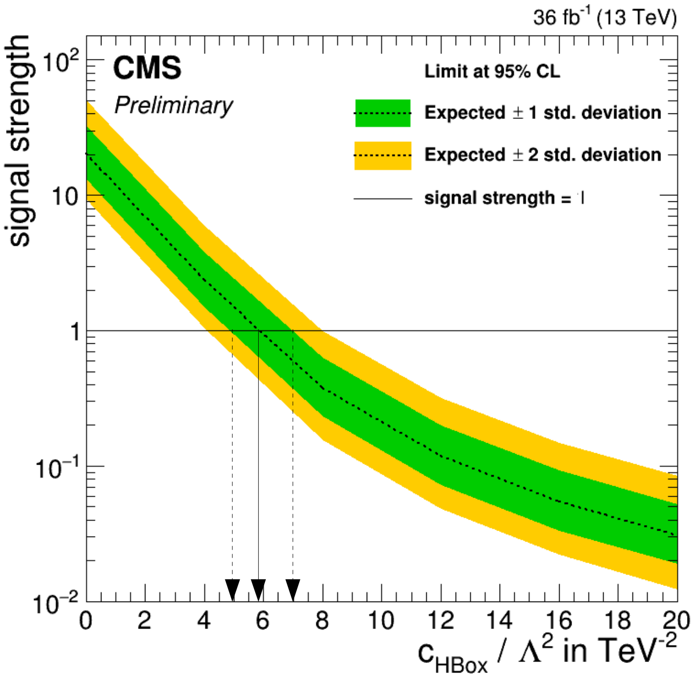
P_{res} : double-sided Crystal Ball

$P_{non-res}$: gaussian



First fit results

- Expected CL_s limits for different values of the EFT parameter
- Shown are limits at 95% CL
- Values below the horizontal line can be excluded
- 95% CL limit on c_{HBox}: [-5.92, 5.83]
- Next steps:
  - repeat for other operators and expand to full Run2
  - Include all systematic uncertainties



Summary

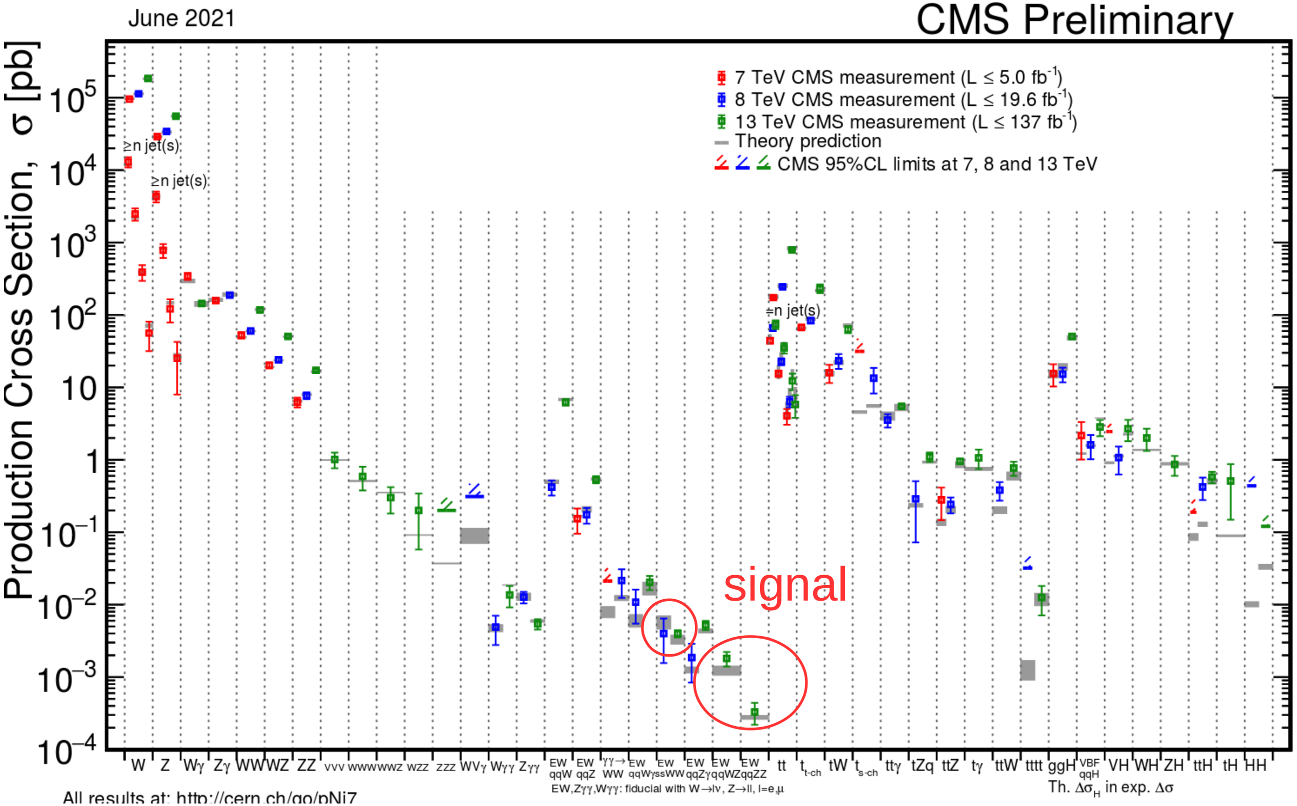
- Search for anomalous couplings in hadronic decay channel of VBS
- Large branching ratio but also large background
- Simultaneous Fit of backgrounds and signal in 3D
  → suppress large QCD background

Outlook

- Final Fit shows already comparable limits to existing analyses
- Include full Run2 (2016 – 2018) statistics
- Full systematics will be included
- 2D limits, Unitarity restoration

Backup

CMS: production cross sections



EFT Operators

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \quad (5)$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \quad (6)$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad (8)$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \quad (9)$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad (10)$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \quad (11)$$

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \quad (12)$$

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \quad (13)$$

$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \quad (14)$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right] \quad (15)$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \quad (16)$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \quad (17)$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \quad (18)$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \quad (19)$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \quad (20)$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \quad (21)$$

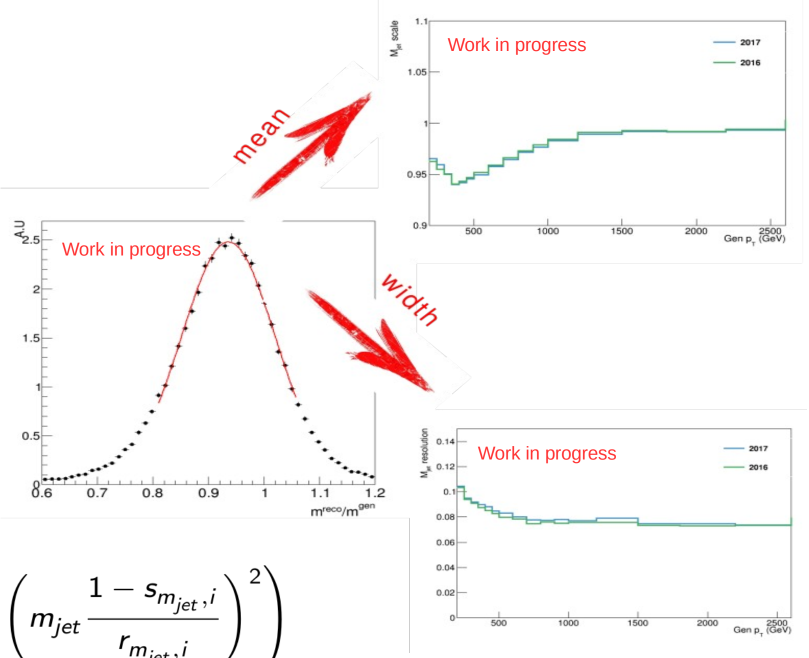
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \quad (22)$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \quad (23)$$

[O. Eboli et al]

Detector response: Gaussian kernels

- For each bin in generated p_T: derive jet mass scale and resolution as $m_{jet}^{reco} / m_{jet}^{gen}$
- Same for dijet mass
- Instead of an event, fill full 1D/2D gaussian kernel

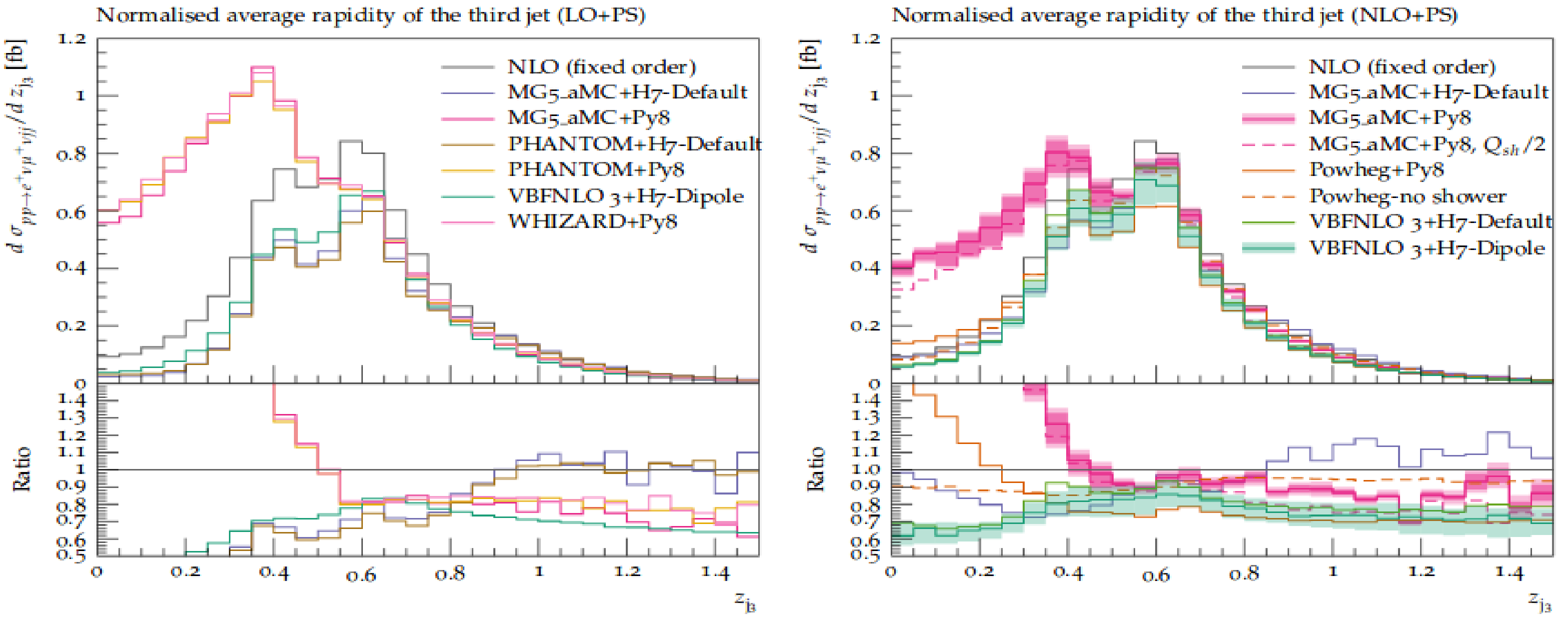


$$k(m_{jet}, m_{jj}) = \frac{w_i}{2\pi r_{m_{jet},i} \cdot r_{m_{jj},i}} \exp\left(-\frac{1}{2}\left(m_{jj}\frac{1-s_{m_{jj},i}}{r_{m_{jj},i}}\right)^2 - \frac{1}{2}\left(m_{jet}\frac{1-s_{m_{jet},i}}{r_{m_{jet},i}}\right)^2\right)$$

Central Jets and PS

Karlsruhe Institute of Technology

- In VBS reduced central jet activity



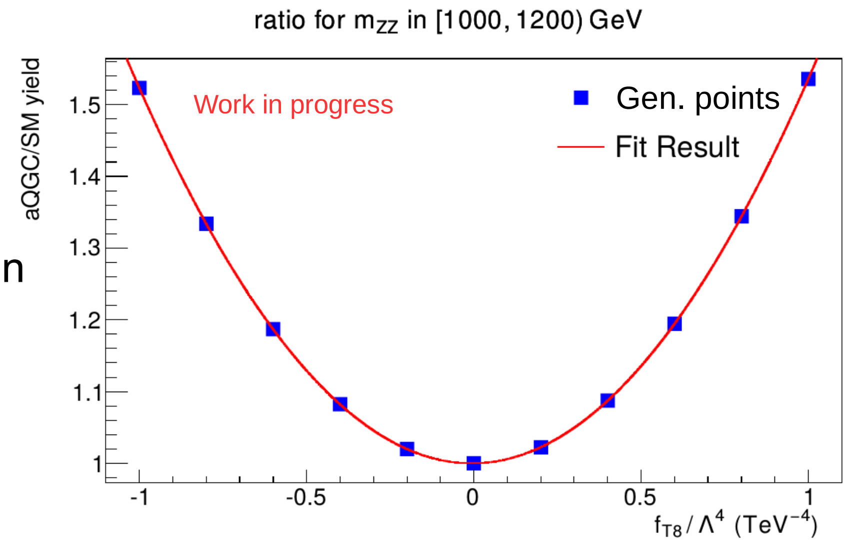
[Ballestrero et al.]

Signal modeling

$$N \propto |\mathcal{A}|^2 = |\mathcal{A}_{\rm SM}|^2 + \sum_\alpha \frac{c_\alpha}{\Lambda^2} \cdot 2\Re(\mathcal{A}_{\rm SM}\mathcal{A}^\dagger_{Q_\alpha}) + \sum_{\alpha,\beta} \frac{c_\alpha c_\beta}{\Lambda^4} \cdot (\mathcal{A}_{Q_\alpha}\mathcal{A}^\dagger_{Q_\beta})$$

Interference SM-EFT Pure EFT (quadratic)

- MadGraph5 + UFO model + reweighting
- SMEFTsim Implements the Warsaw basis in MadGraph
- SM yield is scaled with a 2nd degree polynomial in each m_{VV} bin
- Quadratic fit describes signal scaling perfectly
- Scaling is more dominant in higher mass bins



Signal modeling (II)

- Signal modelling uses MadGraph LO Reweigthing

$$W^{new} = \frac{|M_{new}|^2}{|M_{orig}|^2} W_{orig}$$

- Start with f_i = 0 except one parameter. Starting with non-SM scenario enhances statistics
- Use MadGraph reweighting to apply a weight along f_i-axis for every event
- For 2D limits, this has to be a 2D-grid.