Electroweak diboson: LHC measurements and theory

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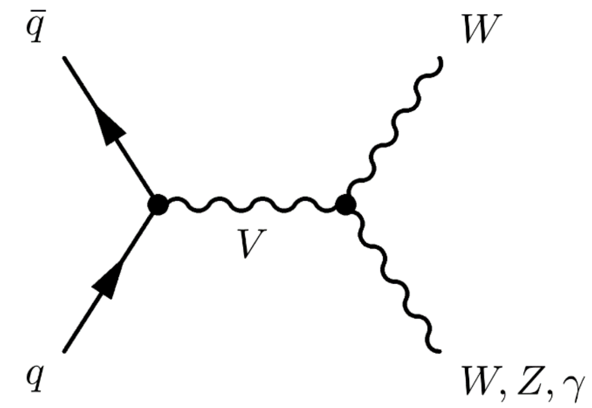
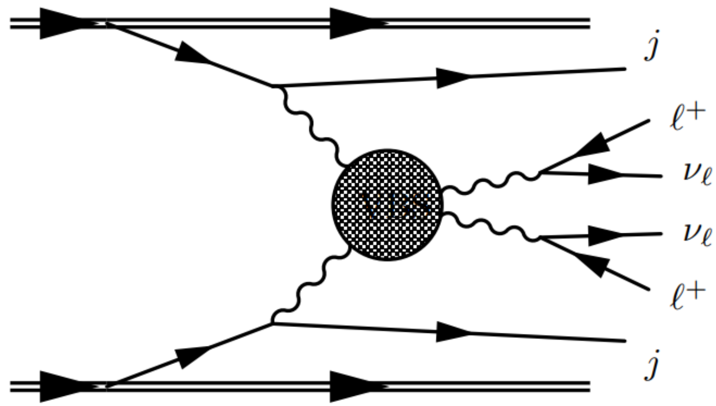
Diboson processes at the LHC

- **Vector boson pair production**
  - Basic process: qbar q → VV
  - Order α^2: large cross section
  - Sensitive to triple gauge couplings (TGC)
- **Vector boson scattering (VBS)**
  - Basic process: VV→VV
  - accompanied by 2 quark jets
    = tagging jets
  - Order α^4: suppressed cross section
  - Sensitive to quartic gauge couplings (QGC)



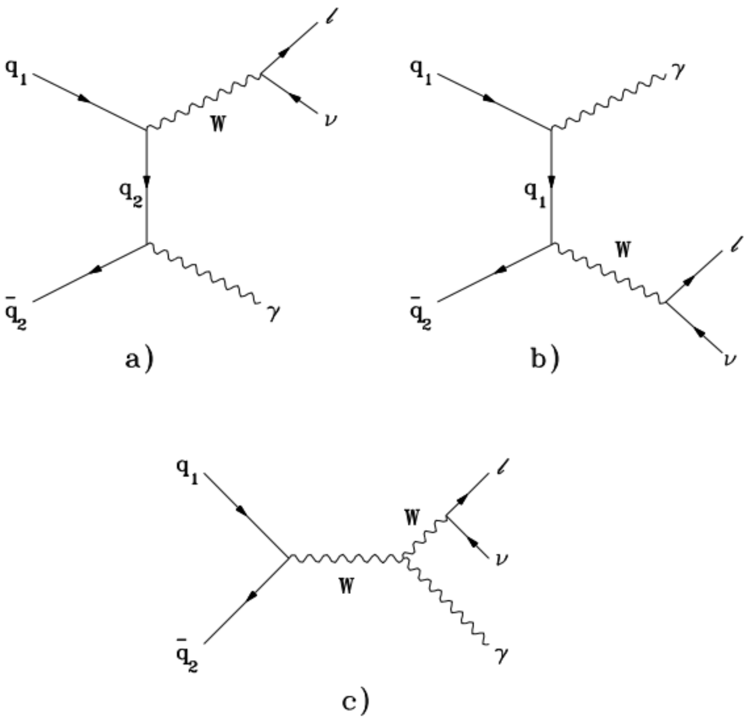


Observe decay leptons of weak bosons (or hadronic V decay)

Outline of talk:

- Pair production in quark annihilation
- QCD corrections
- Observations at the LHC
- Measurement of anomalous TGC (aTGC)
- Effective Lagrangian for VBS
- Unitarization for off-shell VV→VV
- LHC measurements
- Conclusions

EW boson pair production: $q\bar{q} \rightarrow W^+W^-$, $W\gamma$ etc.



- Test non-abelian structure of SM
- Repeat studies of $e^+e^- \rightarrow W^+W^-$ and $q\bar{q} \rightarrow V_1V_2$ of LEP and Tevatron

Parameterize WWV couplings by effective Lagrangian

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i g_1^V \left(W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu}\right) + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda}$$

Deviations from SM values (anomalous triple gauge couplings, aTGC)

$$\Delta g_1^V = g_1^V - 1\,, \quad \Delta\kappa_V = g_1^V - 1\,, \quad \lambda_V$$

must be form factors to preserve unitarity at high energy, $\sqrt{\hat{s}}$

Connection to gauge invariant EFT parameterization

- Linear realization of EW symmetry breaking: $\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$
- Three C,P even operators at dimension 6 level

$$\mathcal{L}_{eff}^{tri} = \mathcal{L}_{SM}^{tri} + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_{WWW}}{\Lambda^2}\mathcal{O}_{WWW}$$

- with

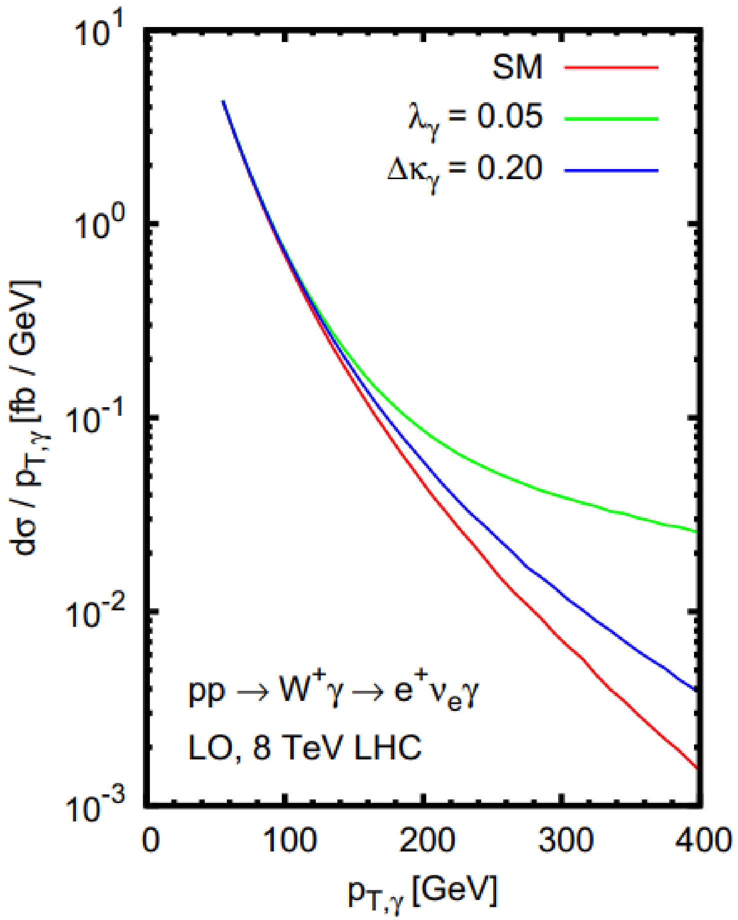
$$\begin{aligned} \mathcal{O}_{WWW} &= \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_{\rho}^{\mu}] \\ \mathcal{O}_W &= (D_\mu\Phi)^\dagger \hat{W}_{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger \hat{B}_{\mu\nu}(D_\nu\Phi) \end{aligned}$$

leads to

$$\begin{aligned} g_1^Z &= 1 + f_W \frac{m_Z^2}{2\Lambda^2}\,, \\ \kappa_Z &= 1 + [f_W - s^2(f_B + f_W)]\,\frac{m_Z^2}{2\Lambda^2}\,, \\ \kappa_\gamma &= 1 + (f_B + f_W)\,\frac{m_W^2}{2\Lambda^2}\,, \\ \lambda_\gamma = \lambda_Z &= \frac{3m_W^2 g^2}{2\Lambda^2}\, f_{WWW} = \lambda\,, \end{aligned}$$

- Relations spoiled at dimension 8 level and beyond

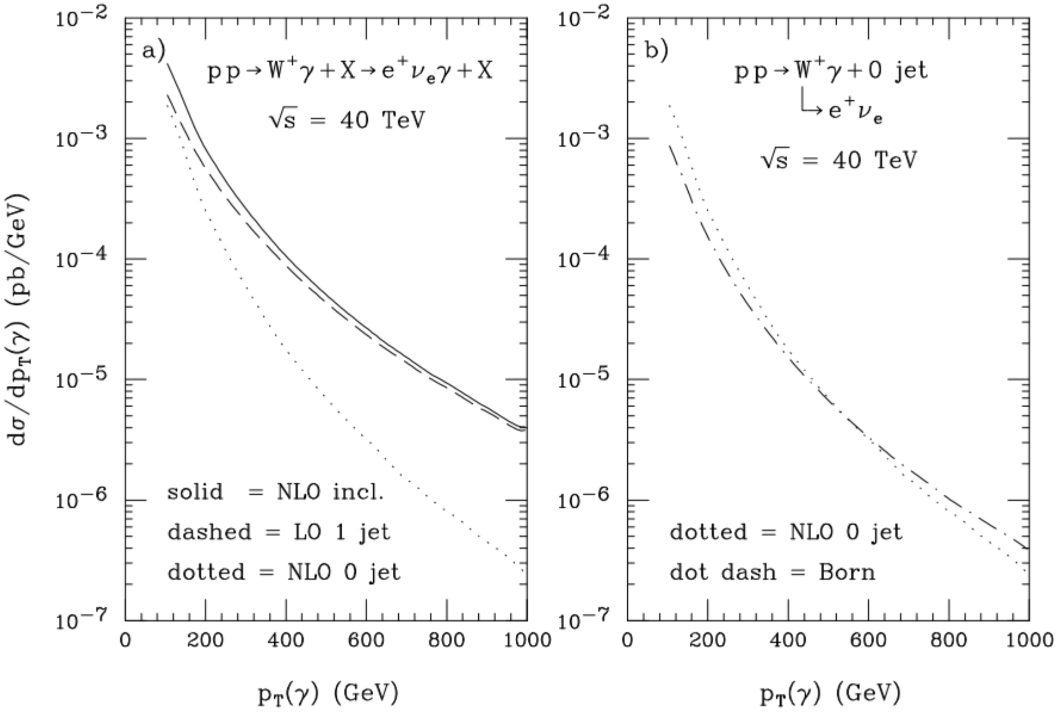
Effects of anomalous couplings



- Anomalous couplings lead to enhanced production of hard events with $J = 1$
  $\Longrightarrow$ mostly central events
- Anomalous couplings are produced by loop-effects of heavy particles with new interactions
  $\Longrightarrow$ form-factor effects
- $\sqrt{\hat{s}}$-dependence of form factors unknown
  $\Longrightarrow$ shape of $\sqrt{\hat{s}}$- or p_T-distributions is ambiguous
- loop effects typically produce small to modest deviations
  $\Longrightarrow$ form-factor effects expected to strongly reduce enhancements at high p_T

Effects of NLO QCD corrections

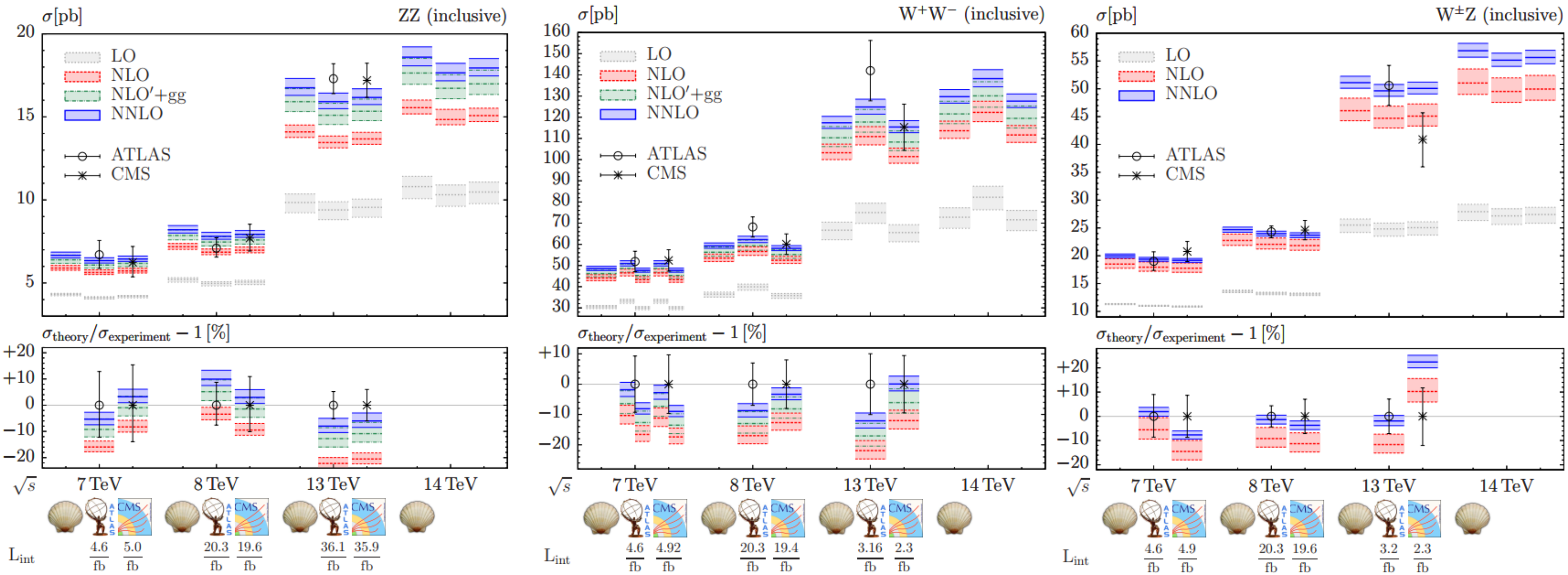
Baur, Han, Ohnemus (1993)



Central jet veto against radiation: Baur (1993)

- Anomalous couplings and QCD corrections lead to enhanced production of hard events
- Hard QCD jets recoil against photon: hard γj event with soft W radiation
- Jet veto (no jet with $p_T(j) > 50$ GeV in event) restores LO expectations

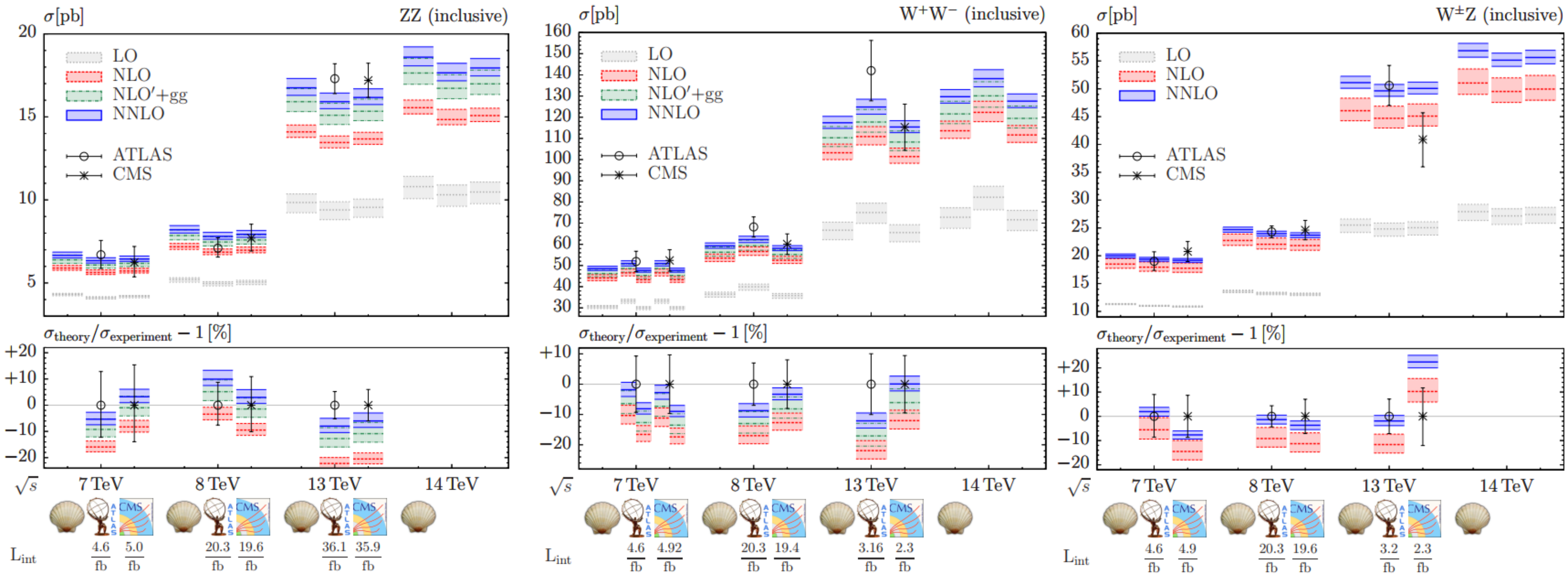
QCD corrections: up to NNLO (Grazzini, Kallweit, Wiesemann 2017)



Excellent agreement of off-shell fiducial cross sections at NNLO

$\sqrt{s}$	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]	σ_{CMS} [pb]
7	$10.902(7)^{+0.5\%}_{-1.2\%}$	$17.72(1)^{+5.3\%}_{-4.1\%}$	$19.18(3)^{+1.7\%}_{-1.8\%}$	$20.76\,^{+1.32}_{-1.32}(\mathrm{stat})^{+1.13}_{-1.13}(\mathrm{syst})^{+0.46}_{-0.46}(\mathrm{lumi})$
8	$13.115(9)^{+1.3\%}_{-2.1\%}$	$21.80(2)^{+5.1\%}_{-3.9\%}$	$23.68(3)^{+1.8\%}_{-1.8\%}$	$24.61\,^{+0.76}_{-0.76}(\mathrm{stat})^{+1.13}_{-1.13}(\mathrm{syst})^{+1.08}_{-1.08}(\mathrm{lumi})$
13	$25.04(2)\ ^{+4.3\%}_{-5.3\%}$	$45.09(3)^{+4.9\%}_{-3.9\%}$	$49.98(6)^{+2.2\%}_{-2.0\%}$	$40.9\ ^{+3.4}_{-3.4}(\mathrm{stat})^{+3.1}_{-3.3}(\mathrm{syst})^{+1.3}_{-1.3}(\mathrm{lumi})^{+0.4}_{-0.4}(\mathrm{th})$
14	$27.39(2)\ ^{+4.7\%}_{-5.7\%}$	$49.91(4)^{+4.9\%}_{-4.0\%}$	$55.60(7)^{+2.3\%}_{-2.0\%}$	

QCD corrections: up to NNLO (Grazzini, Kallweit, Wiesemann 2017)



Excellent agreement of off-shell fiducial cross sections at NNLO with new data

$\sqrt{s}$	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]	$\sigma_{\rm NNLO}$ [pb]	$\sigma_{\rm CMS}$ [pb]
7	$10.902(7)^{+0.5\%}_{-1.2\%}$	$17.72(1)^{+5.3\%}_{-4.1\%}$	$19.18(3)^{+1.7\%}_{-1.8\%}$	$20.76\,^{+1.32}_{-1.32}(\text{stat})^{+1.13}_{-1.13}(\text{syst})^{+0.46}_{-0.46}(\text{lumi})$
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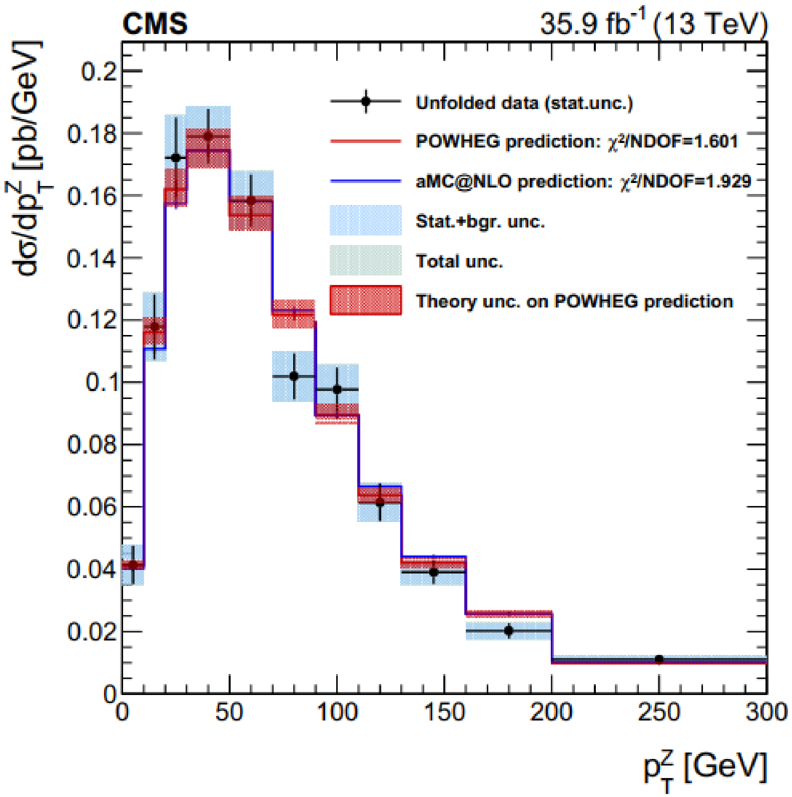
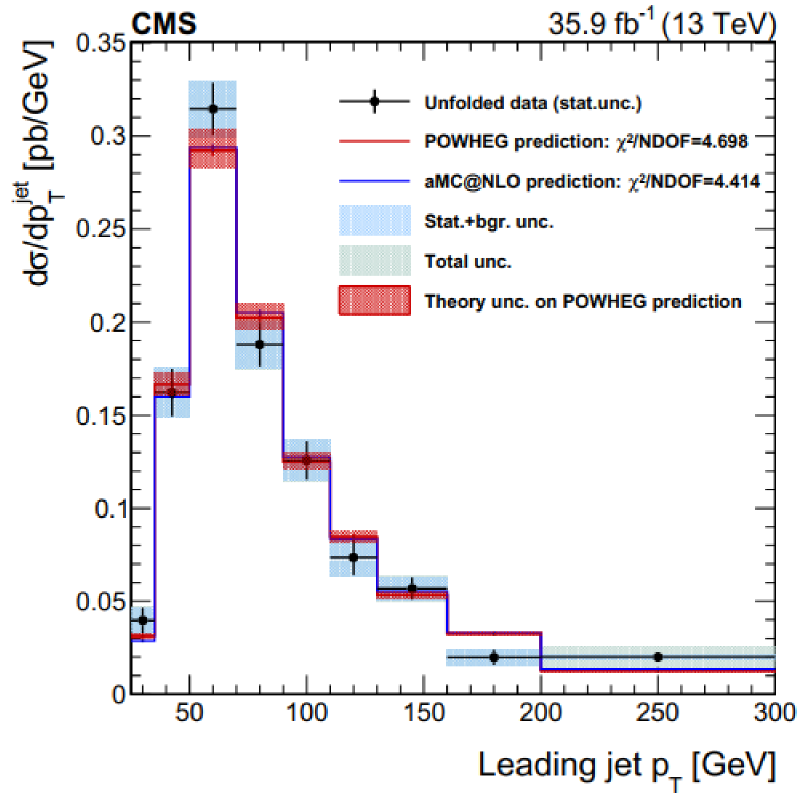
13	$25.04(2)\ ^{+4.3\%}_{-5.3\%}$	$45.09(3)^{+4.9\%}_{-3.9\%}$	$49.98(6)^{+2.2\%}_{-2.0\%}$	$48.09^{+1.00}_{-0.96}\,(\text{stat})^{+0.44}_{-0.37}\,(\text{theo})^{+2.39}_{-2.17}\,(\text{syst}) \pm 1.39\,(\text{lumi})$
14	$27.39(2)\ ^{+4.7\%}_{-5.7\%}$	$49.91(4)^{+4.9\%}_{-4.0\%}$	$55.60(7)^{+2.3\%}_{-2.0\%}$	

More information from distributions…..

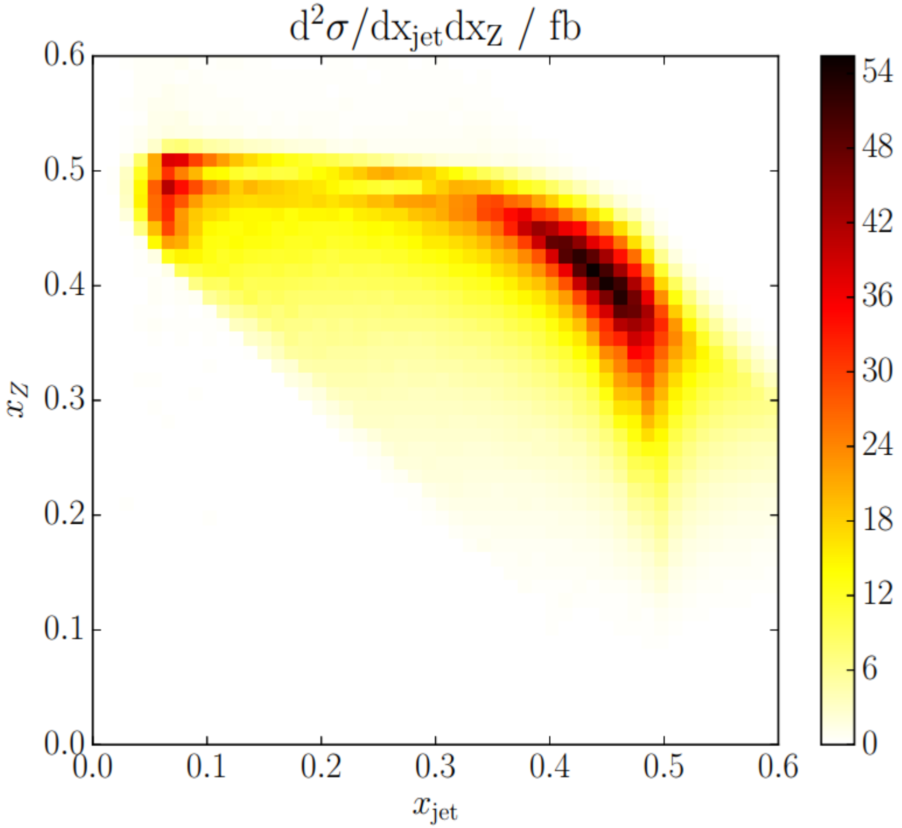
pT of Z or accompanying jet in WZ events compared to NLO QCD prediction



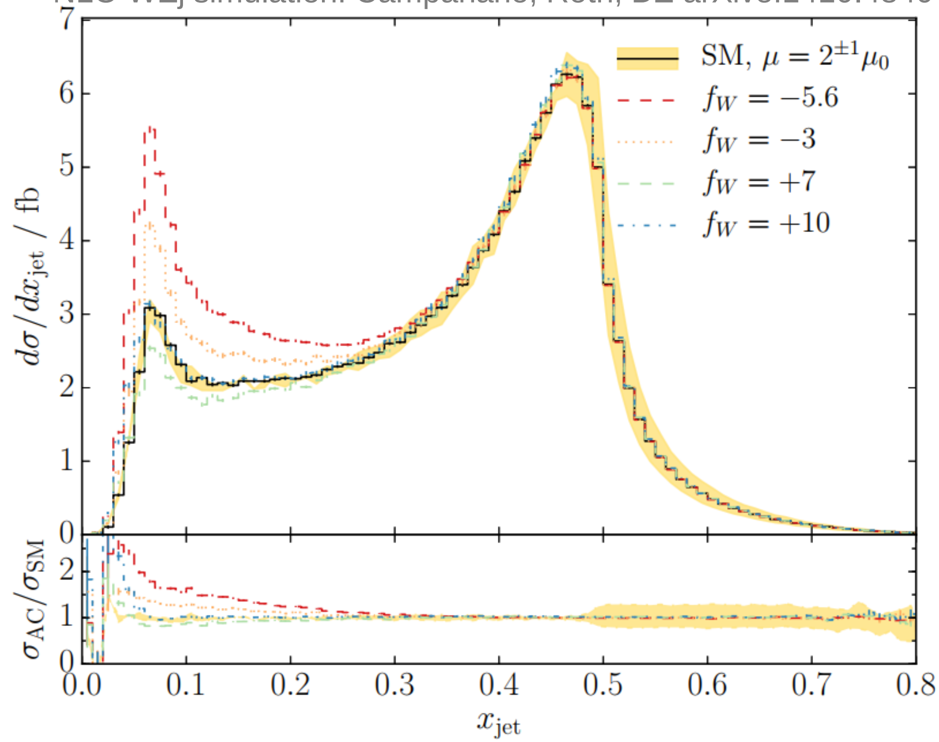


High pT jet is at least as common as high pT Z (similar expectation for W pT)

High pT bosons and jets at NLO (pT(Z) > 200 GeV sample)



NLO WZj simulation: Campanario, Roth, DZ arXive:1410.4840

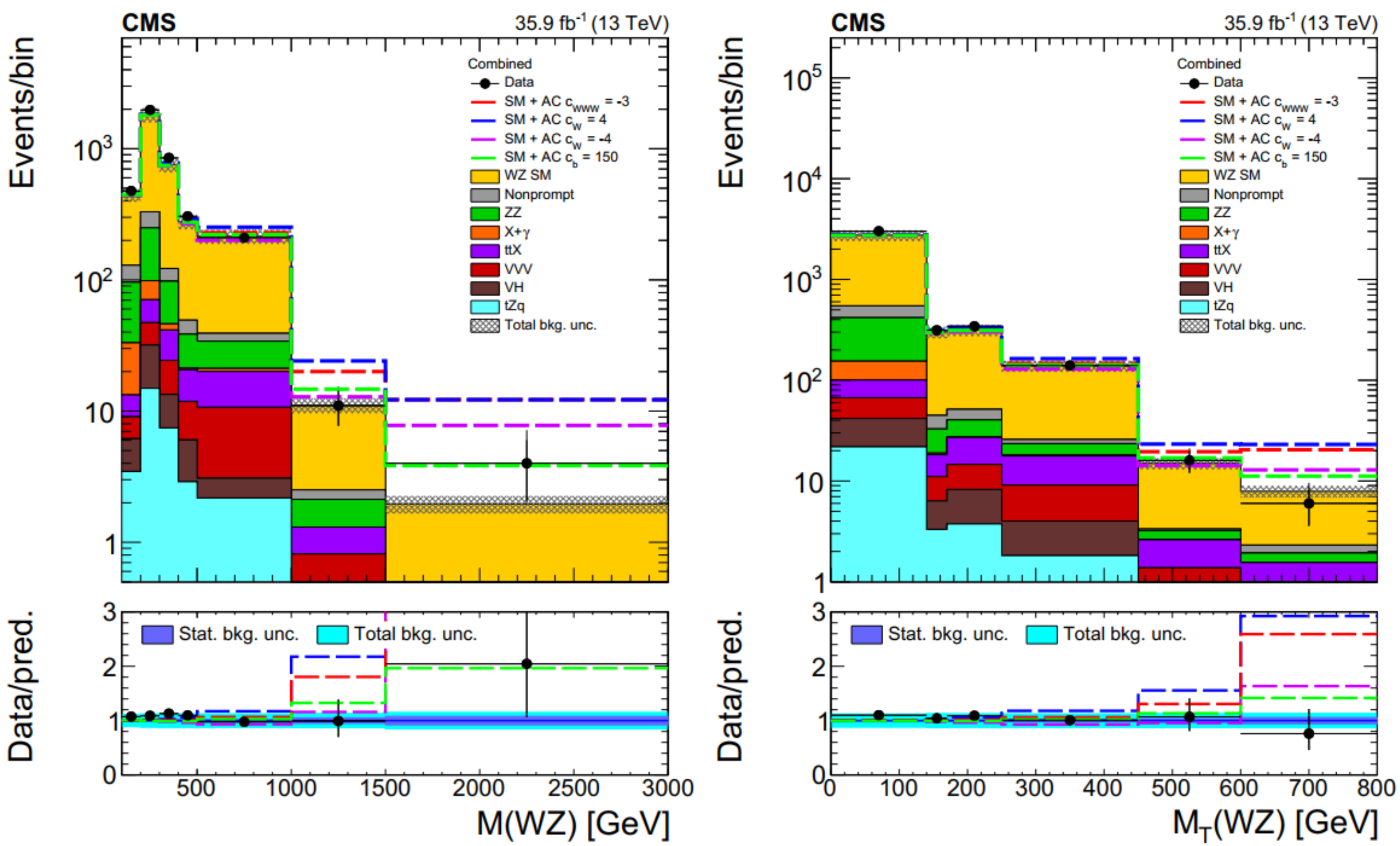


Measure for pT balance of W,Z,jet

$$x_V = \frac{E_{TV}}{\sum_{\text{jets}} \mathrm{E}_{\mathrm{T},i} + \sum_{W,Z/H} \mathrm{E}_{\mathrm{T},i}}$$

- large fraction of events with Z recoil against jet, not W
- Sensitivity to aTGC only for low jet pT
- Dynamical jet veto improves sensitivity to anomalous TGC

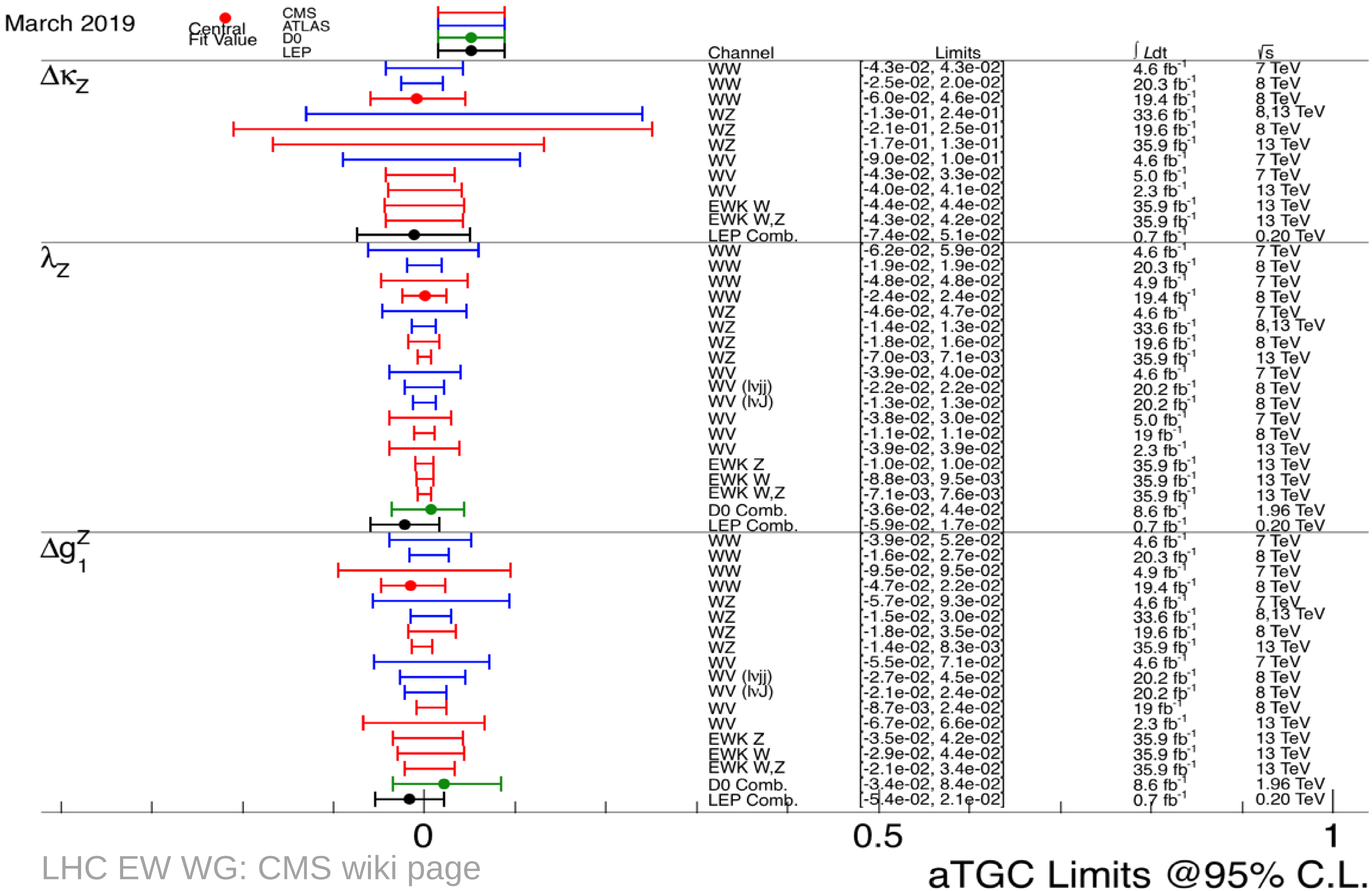
Constraining aTGC with LHC data: WZ example



Anomalous couplings with negligible form factor effect (i.e. pure dimension 6 EFT) lead to strong enhancement at high WZ mass

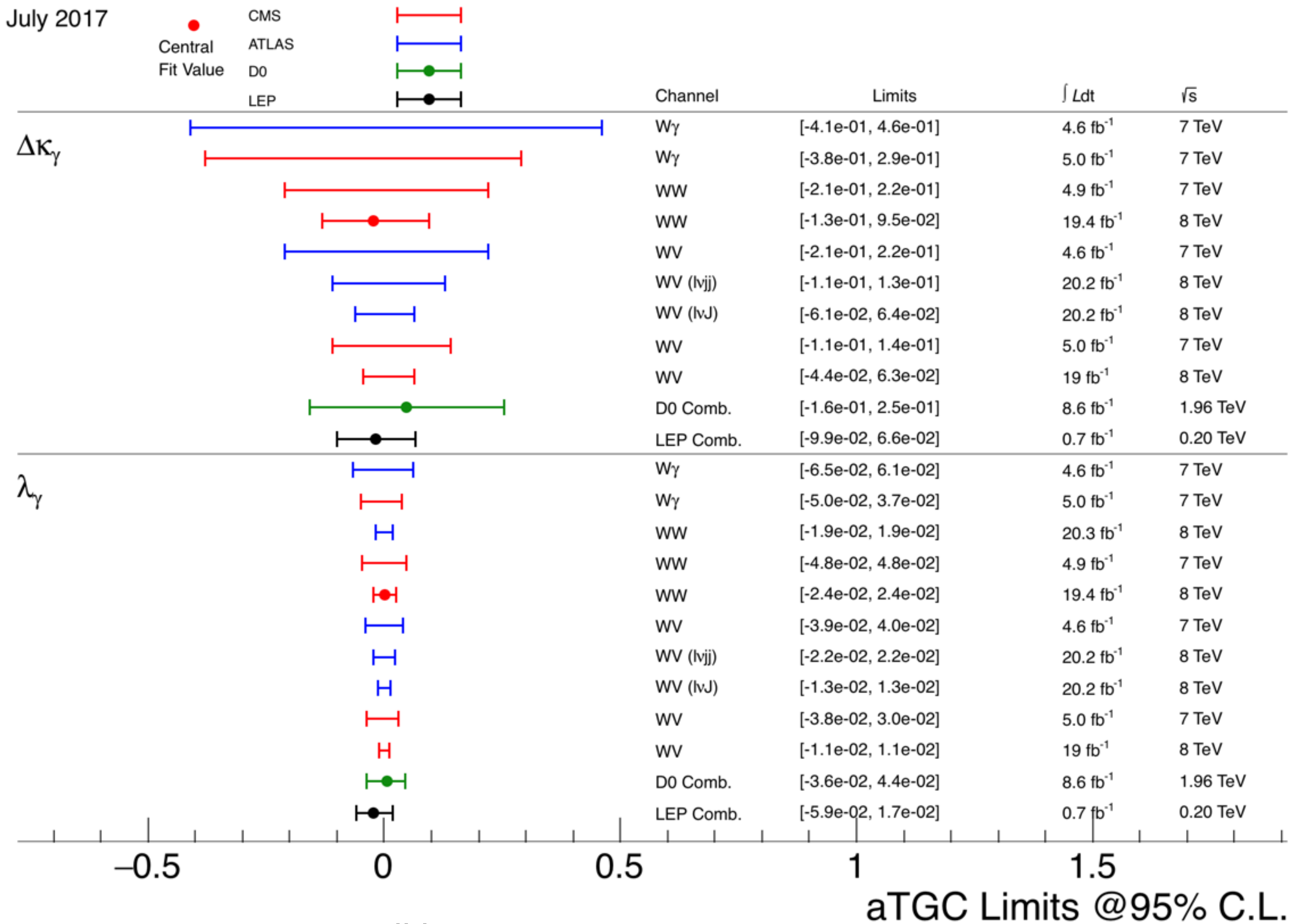
➔ Nonobservation provides stringent bounds on Wilson coefficients

Limits on anomalous WWZ couplings



LHC EW WG: CMS wiki page

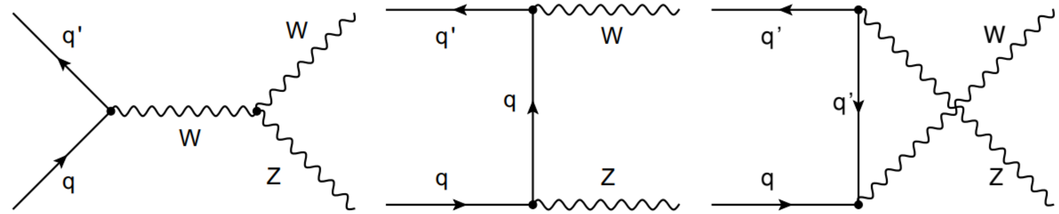
Limits on anomalous WWγ couplings



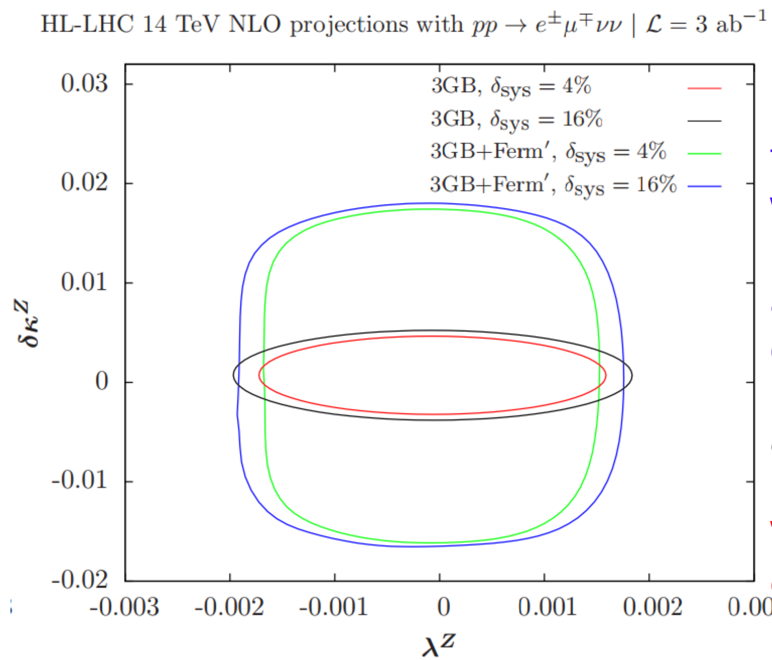
LHC EW WG: CMS wiki page

aTGC vs. anomalous Zff or Wff couplings

- Anomalous couplings spoil subtle cancellations between contributing Feynman graphs
- Would enhanced rate point to larger WWZ coupling or smaller Zff coupling (or vice versa)?



- LEP precision data on Zff couplings puts blame for increased cross sections on aTGC for now…
- Per Mil level measurements of aTGC require simultaneous fits for aTGC and Vff couplings



Reach of HL-LHC to aTGC with / without taking into account anomalous Vff couplings (Dawson et al., arXive:1902.04070)

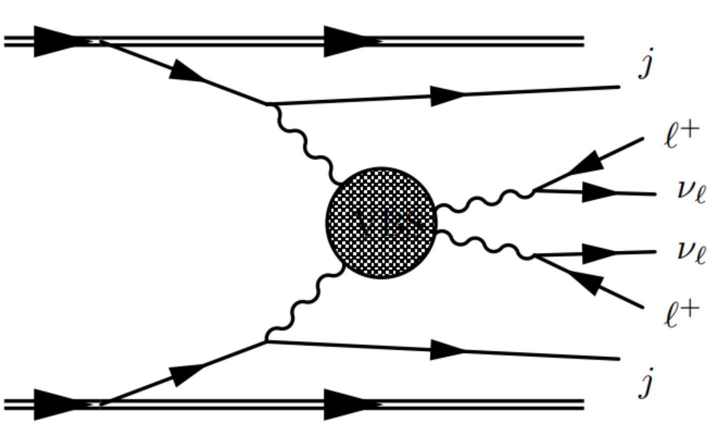
W+W- production only

- ➔ Need multi-parameter fits of diverse EFT coefficients and multiple processes when probing TeV region for EFT scale Λ
- Need to measure interference effects with SM amplitude

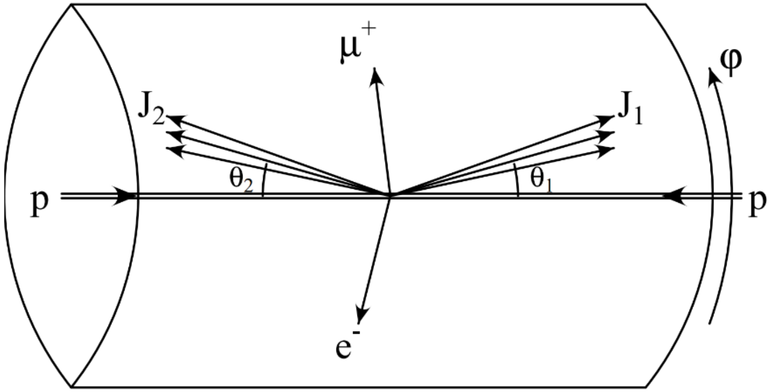
Vector boson scattering (VBS)

Karlsruher Institut für Technologie

- Vector boson scattering
  - Basic process: VV→VV
  - accompanied by 2 quark jets = tagging jets
  - Order α^4: suppressed cross section
  - Sensitive to quartic gauge couplings



- Characteristics (→VBS cuts)
  - Large rapidity separation of jets
  - Large dijet invariant mass
  - Decay leptons between tag jets



Need EFT with dimension 8 operators for aQGC parameterization

Going beyond dimension 6

Reason for dimension 8 operators like

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{M,1} = \text{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{T,1} = \text{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \text{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

- Dimension 6 operators only do not allow to parameterize $VVVV$ vertex with arbitrary helicities of the four gauge bosons

For example: $\mathcal{L}_{S,0}$ is needed to describe $V_L V_L \to V_L V_L$ scattering

- New physics may appear at 1-loop level for dimension 6 operators but at tree level for some dimension 8 operators

Building blocks: $D_\mu\Phi \equiv \left(\partial_\mu + i\frac{g'}{2}B_\mu + igW_\mu^i\frac{\tau^i}{2}\right)\Phi$ with $\Phi = \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix}.$

$$W_{\mu\nu} = \frac{i}{2}g\tau^I(\partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g\epsilon_{ijk}W_\mu^j W_\nu^k)\,,$$
$$B_{\mu\nu} = \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu)\,.$$

Full set of dimension 8 operators (Eboli et al.)

- Distinguish by dominant set of vector boson helicities
- Longitudinal operators: derivatives of Higgs doublet field

$$\mathcal{O}_{S_0} = \left[\left(D_\mu \Phi \right)^\dagger D_\nu \Phi \right] \times \left[\left(D^\mu \Phi \right)^\dagger D^\nu \Phi \right]$$
$$\mathcal{O}_{S_1} = \left[\left(D_\mu \Phi \right)^\dagger D^\mu \Phi \right] \times \left[\left(D_\nu \Phi \right)^\dagger D^\nu \Phi \right]$$
$$\mathcal{O}_{S_2} = \left[\left(D_\mu \Phi \right)^\dagger D_\nu \Phi \right] \times \left[\left(D^\nu \Phi \right)^\dagger D^\mu \Phi \right]$$

Field strength ←→ transverse polarizations

Transverse operators

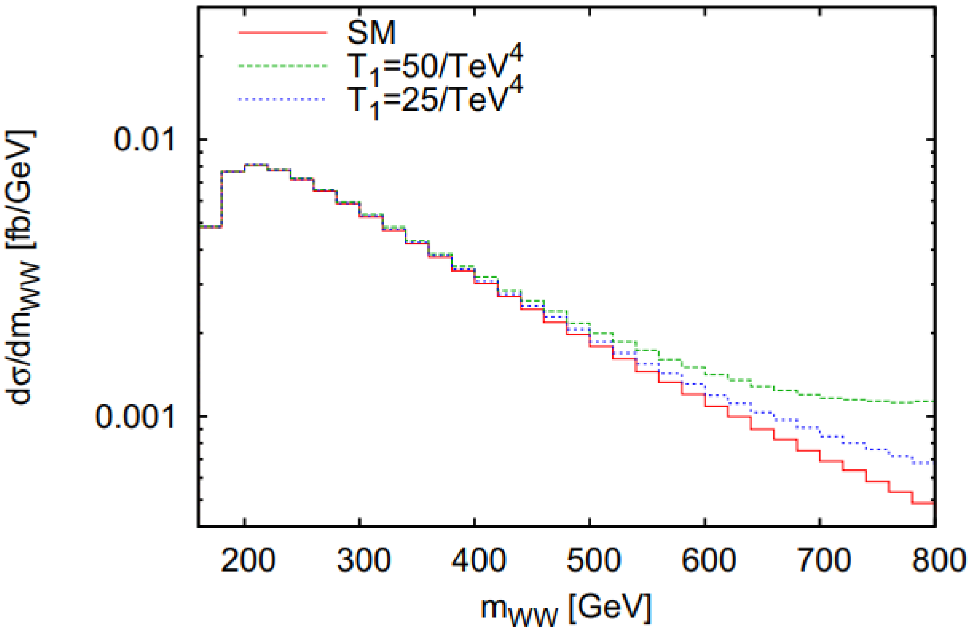
$$\mathcal{O}_{T_0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$
$$\mathcal{O}_{T_1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]$$
$$\mathcal{O}_{T_2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right]$$
$$\mathcal{O}_{T_5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta},$$
$$\mathcal{O}_{T_6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu},$$
$$\mathcal{O}_{T_7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha},$$
$$\mathcal{O}_{T_8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta},$$
$$\mathcal{O}_{T_9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}.$$

Mixed: transverse-longitudinal

$$\mathcal{O}_{M_0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\beta\Phi\right],$$
$$\mathcal{O}_{M_1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\mu\Phi\right],$$
$$\mathcal{O}_{M_2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\beta\Phi\right],$$
$$\mathcal{O}_{M_3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[\left(D_\beta\Phi\right)^\dagger D^\mu\Phi\right],$$
$$\mathcal{O}_{M_4} = \left[\left(D_\mu\Phi\right)^\dagger W_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu},$$
$$\mathcal{O}_{M_5} = \left[\left(D_\mu\Phi\right)^\dagger W_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu},$$
$$\mathcal{O}_{M_7} = \left[\left(D_\mu\Phi\right)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right].$$

$VV \to W^+W^-$ with dimension 8 operators

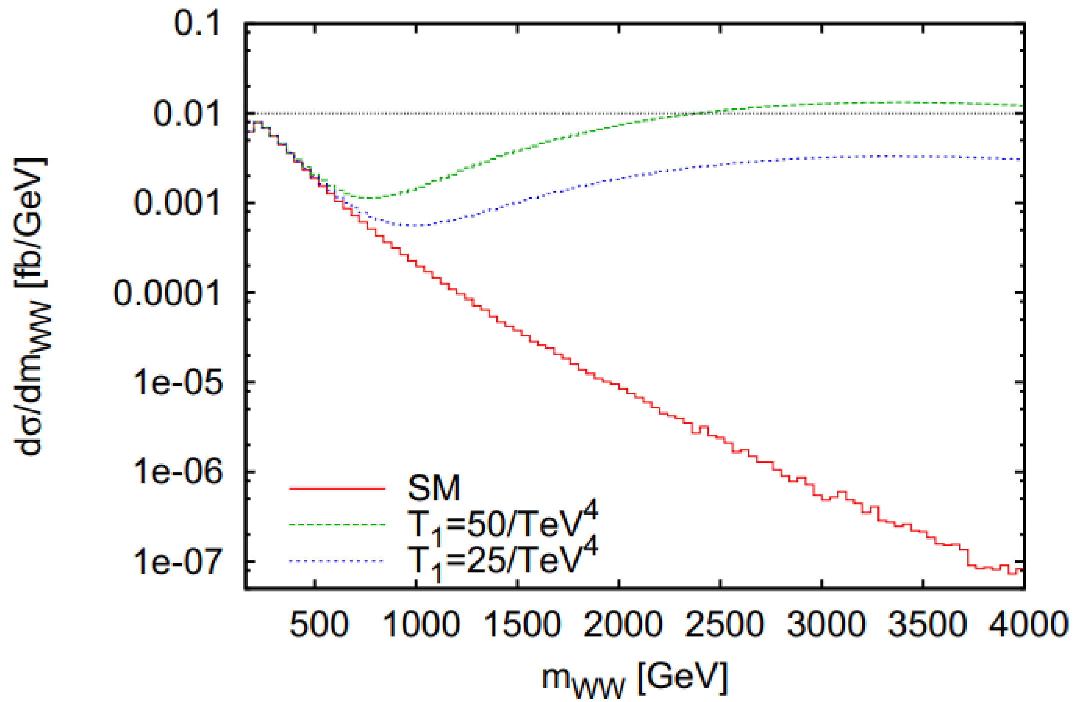
Effect of $\mathcal{L}_{eff} = \frac{f_{T_1}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$
with $T_1 = \frac{f_{T_1}}{\Lambda^4}$ constant on $pp \to W^+W^- jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- Small increase in cross section at high WW invariant mass??

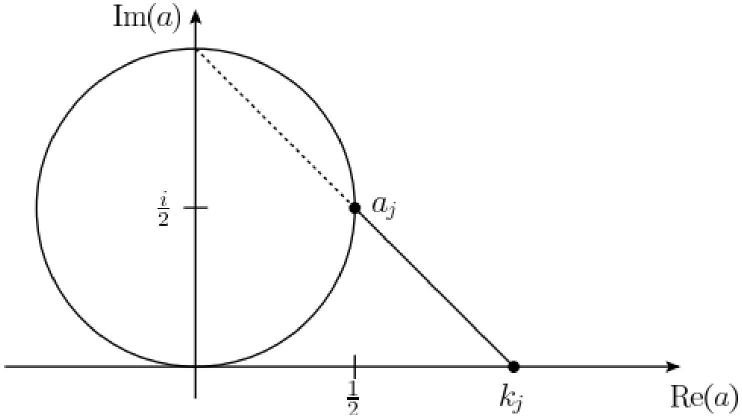
$VV \to W^+W^-$ with dimension 8 operators

Effect of constant $T_1 = \frac{f_{T_1}}{\Lambda^4}$ on $pp \to W^+W^- jj \to e^+\nu_e\mu^-\bar{\nu}_\mu jj$



- Huge increase in cross section at high m_{WW} is completely unphysical
- Need form factor for analysis or some other unitarization procedure

K matrix unitarization

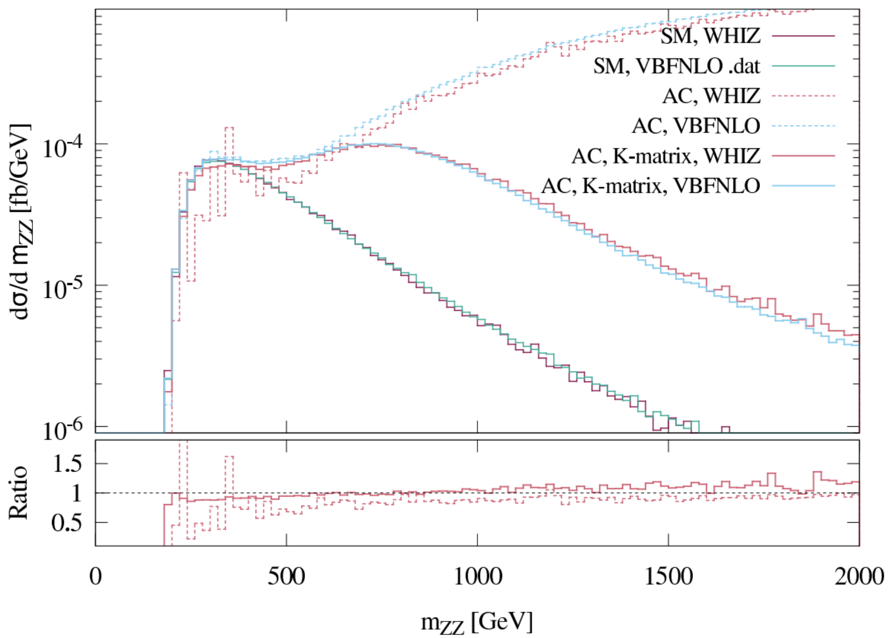


Project amplitude k_j, which exceeds (tree-level) unitarity, back onto Argand circle
→ K matrix unitarized amplitude a_j

[VBFNLO implementation: Löschner, Perez;

following: Alboteanu, Kilian, Reuter]

Comparison with Whizard, which has this method already implemented: [Kilian, Ohl, Reuter, Sekulla, et al.]



Example: VBF-ZZ (e+e-μ+μ-)
good agreement between both codes
for longitudinal ops. at LO

→ can now generate distributions
also at NLO via VBFNLO

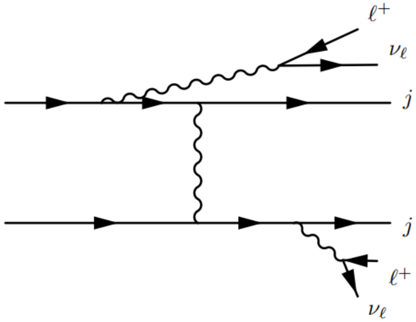
Extension to mixed and transverse operators via numerical partial wave unitarization: work with Genessis Perez, Marco Sekulla (1807.02707) and Heiko Schäfer-Siebert

Off-shell VBS amplitude

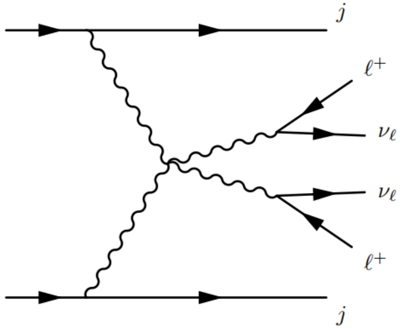
- Assume new physics in VV→VV only

$$\mathcal{M}_{pp\to 4fjj} = \mathcal{M}^{\mathrm{SM}}_{pp\to 4fjj} + \mathcal{M}^{\mathrm{BSM}}_{pp\to 4fjj}$$

- SM part alone has vector boson emission, triple gauge couplingsH etc. which interfere destructively
  → SM piece is unitary and small



(a) Vector boson emission



(b) Quartic gauge interaction.

- → unitarize BSM piece only

$$\begin{aligned}\mathcal{M}^{\mathrm{BSM}}_{pp\to 4fjj} =& J^{\mu}_{p_1\to jV_1}\ J^{\nu}_{p_2\to jV_2}\ D^{V_1}_{\mu\alpha}(q_1)\ D^{V_2}_{\nu\beta}(q_2)\\ &\times \mathbf{M}^{\alpha\beta\gamma\delta}_{V_1V_2\to V_3V_4}\ D^{V_3}_{\gamma\rho}(q_3)\ D^{V_4}_{\delta\sigma}(q_4)\\ &\times J^{\rho}_{V_3\to\bar{f}f}\ J^{\sigma}_{V_4\to\bar{f}f}\end{aligned}$$

- V-propagators decompose into polarization sums

$$\begin{aligned}D^{\mu\nu}_V(q) &= \frac{-\mathrm{i}}{q^2 - m_V^2 + i\,m_V\,\Gamma_V}\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)\\ &\equiv \frac{-\mathrm{i}}{q^2 - m_V^2 + i\,m_V\,\Gamma_V}\sum_\lambda \epsilon^{*\mu}_{J}(q,\lambda)\epsilon^{\nu}_{\mathcal{M}}(q,\lambda)\end{aligned}$$

- Defines $\mathcal{M}^{VBS}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_1,q_2;q_3,q_4) = \epsilon_{\mathcal{M},\alpha}(q_1,\lambda_1)\epsilon_{\mathcal{M},\beta}(q_2,\lambda_2)\,\mathbf{M}^{\alpha\beta\gamma\delta}_{V_1V_2\to V_3V_4}\,\epsilon^*_{\mathcal{M},\gamma}(q_3,\lambda_3)\epsilon^*_{\mathcal{M},\delta}(q_4,\lambda_4)$

Unitarization of tree level amplitude: $T_0 \rightarrow T_u$

- K-matrix (also called T-matrix) procedure for on-shell hermitian T_0

$$\mathbf{T}_L = \left(\mathbb{1} - \frac{\mathrm{i}}{2}\mathbf{T}_0^\dagger\right)^{-1} \frac{1}{2}\left(\mathbf{T}_0 + \mathbf{T}_0^\dagger\right) = \left(\mathbb{1} + \frac{1}{4}\mathbf{T}_0\mathbf{T}_0\right)^{-1} \left(\mathbf{T}_0 + \frac{\mathrm{i}}{2}\mathbf{T}_0\mathbf{T}_0\right)$$

- General virtualities → T_0 not normal for off-shell VV→VV

  Must distinguish

$$\mathbf{A}_{t\leftarrow s} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_3, q_4; q_1, q_2)$$
$$\mathbf{A}_{s\leftarrow t} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(k_3, k_4; k_1, k_2)$$
$$\mathbf{A}_{t\leftarrow t} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_3, q_4; k_1, k_2)$$

- Use

$$\mathbf{A}^{\mathrm{unit}}_{t\leftarrow s} = \left(\mathbb{1} + \frac{1}{4}\mathbf{A}_{t\leftarrow s}\mathbf{A}_{s\leftarrow t}\right)^{-1} \left(\mathbf{A}_{t\leftarrow s} + \frac{\mathrm{i}}{2}\mathbf{A}_{t\leftarrow t}\mathbf{A}_{t\leftarrow s}\right)$$

- Alignment problems avoided by using largest eigenvalue of denominator

$$\mathbf{A}^{\mathrm{unit}}_{t\leftarrow s} = \left(\mathbb{1} + \frac{1}{4}a^2_{\max}\right)^{-1} \left(\mathbf{A}_{t\leftarrow s} + \frac{\mathrm{i}}{2}\mathbf{A}_{t\leftarrow t}\mathbf{A}_{t\leftarrow s}\right)$$

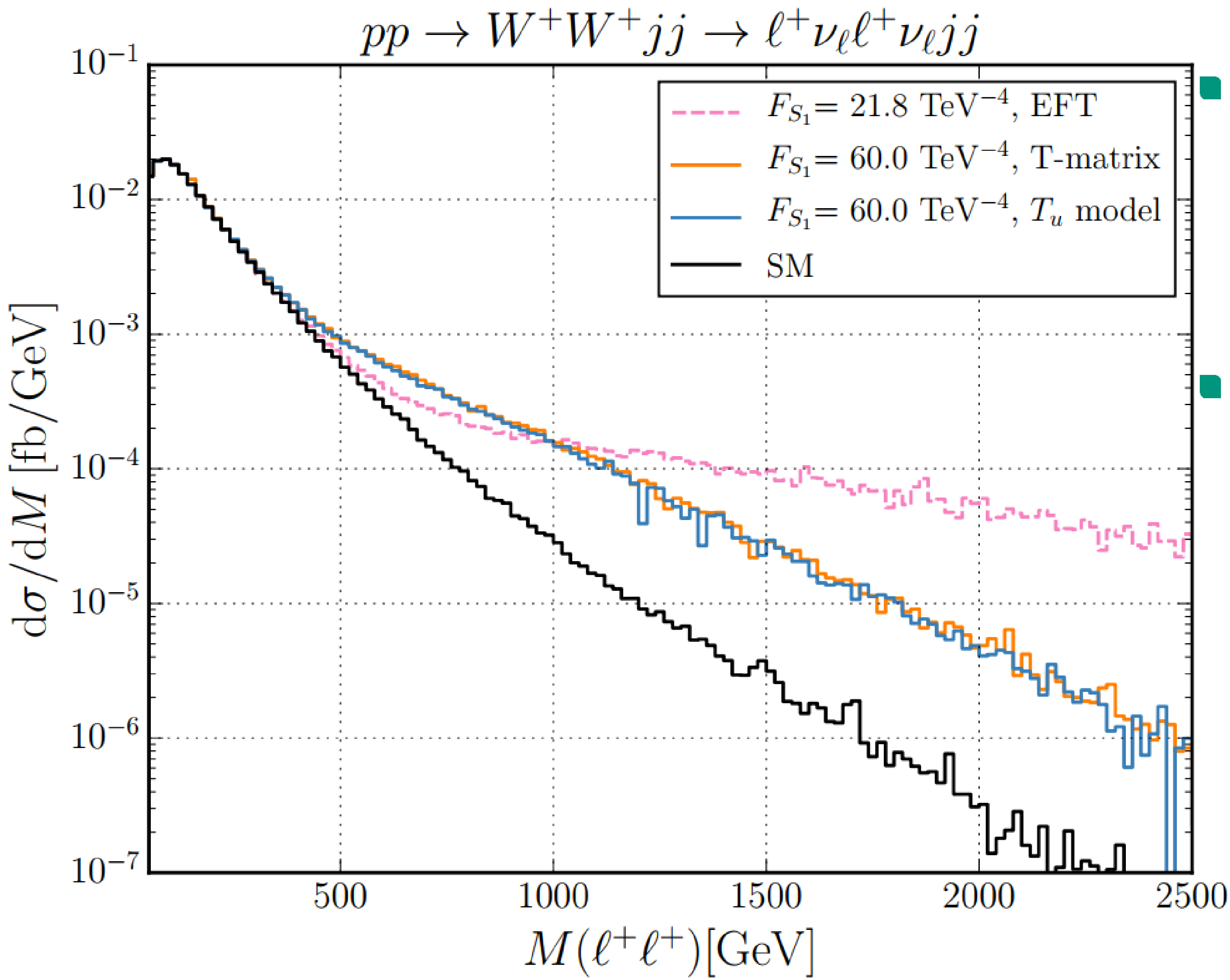
Example: same sign WW production in VBS

- Definition of fiducial phase space region

$$
\begin{array}{lll}
m_{\ell\ell} > 20\,\mathrm{GeV}, & m_{jj} > 500\,\mathrm{GeV}, & \\
p_T^{\ell} > 20\,\mathrm{GeV}, & p_T^{j} > 30\,\mathrm{GeV}, & p_T^{\mathrm{miss}} > 30\,\mathrm{GeV} \\
|\eta_\ell| < 2.5, & |\eta_j| < 5, & \Delta\eta_{jj} > 2.5\,.
\end{array}
$$

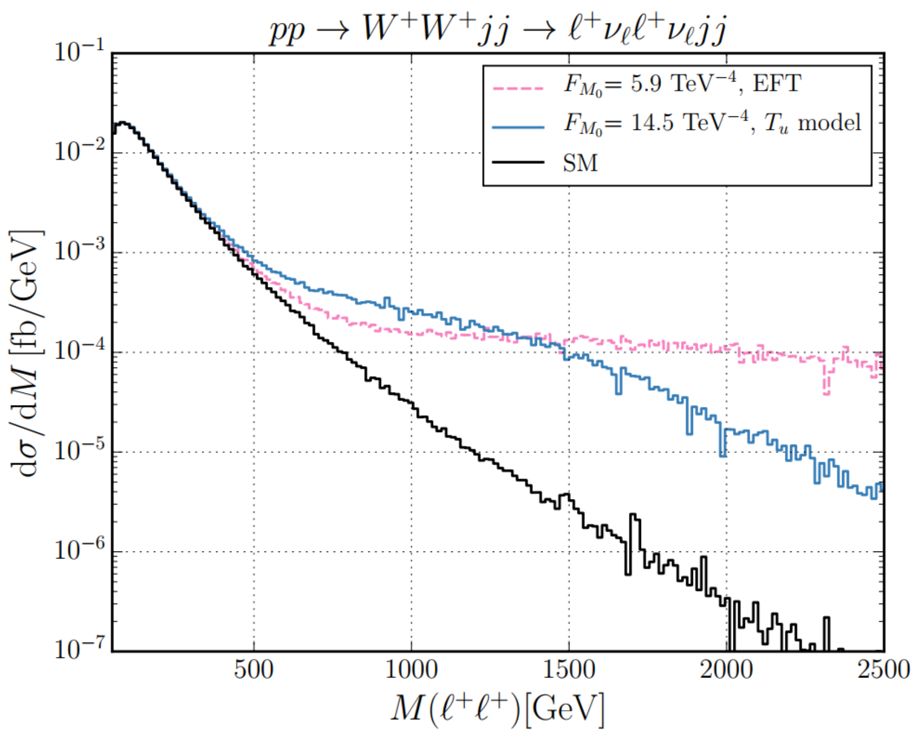
- Jets defined with anti-kT clustering and R=0.4

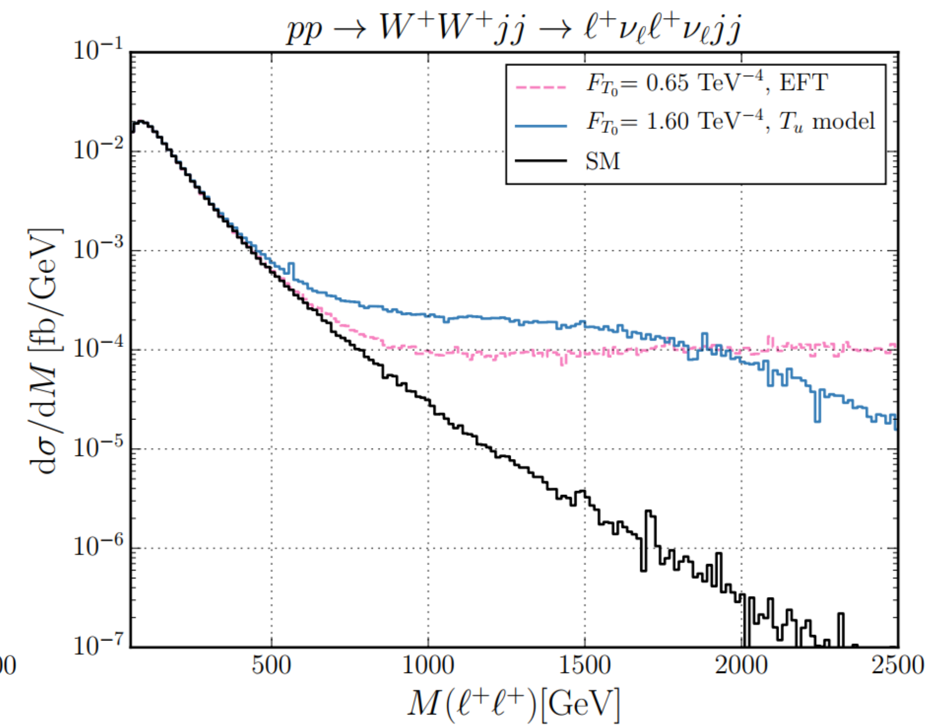
Comparison to K-matrix



- Excellent agreement between different unitarization methods
- $F_{S_1} = f_{S_1}/\Lambda^4$ coefficients adjusted for unitarized models to reproduce pure EFT cross section ←→ CMS limits on F from ssWW analysis

Mixed and transverse operators

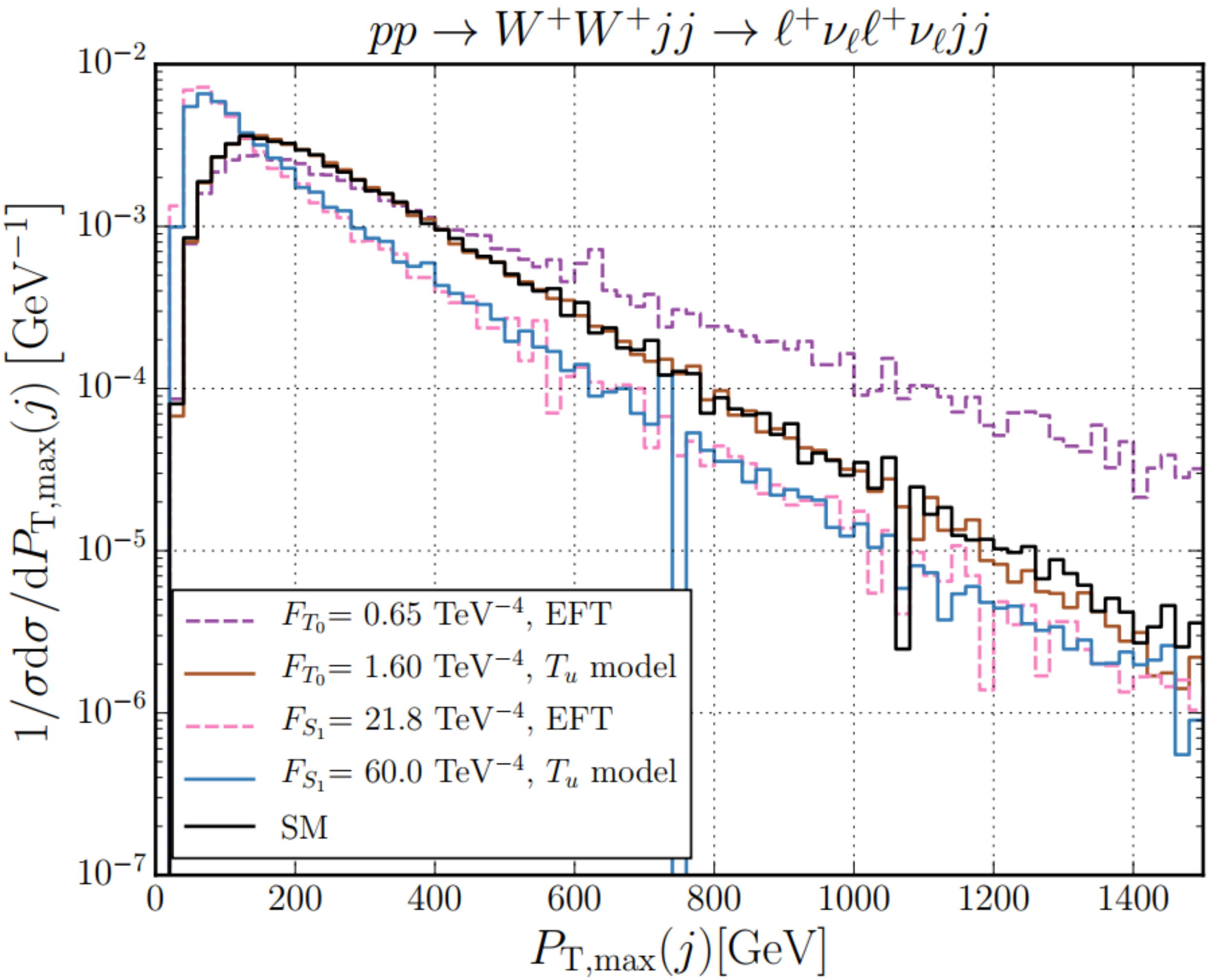




Unitarity bound depends on whether j=0,1, or 2 partial waves dominate

Larger deviations allowed for transverse than for longitudinal operators

Incident W polarization: pT(j,max)



- Typical off-shell behavior

$M \sim [s^2 + (q_1^2 + q_2^2 - q_3^2 - q_4^2)\, s]/\Lambda^4$

- Unitarization suppresses large incident virtualities → pT(j,max) shapes depend on polarization only

- Enhancement at small pT(j,max) is sign for predominant longitudinal scattering

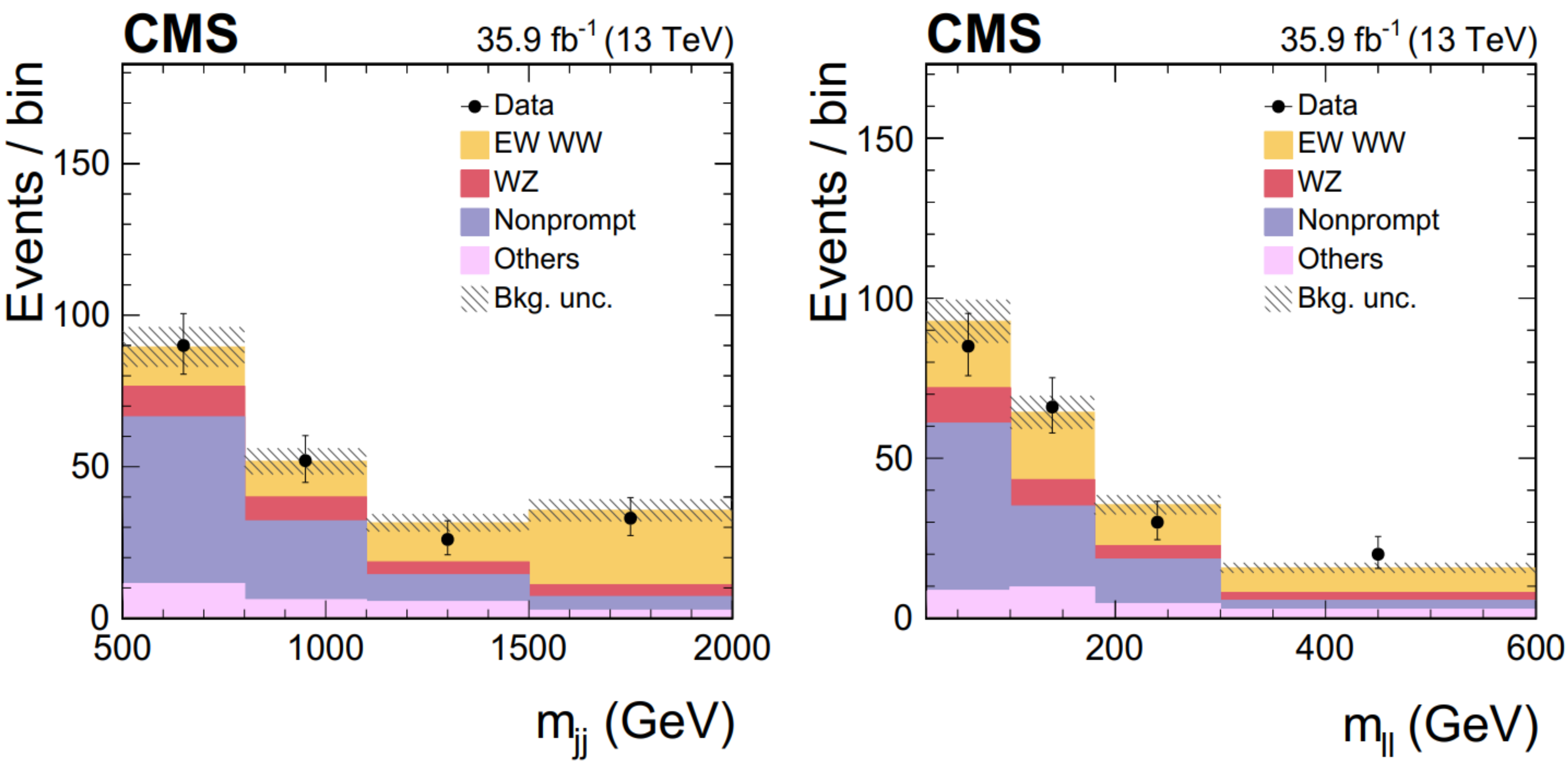
Comments

- Unitarization changes shapes of distributions
- Our T_u model supresses high VV invariant mass and large incident virtualities: similar to what one expects from loop functions
- Unitarization is not unique → additional model dependence

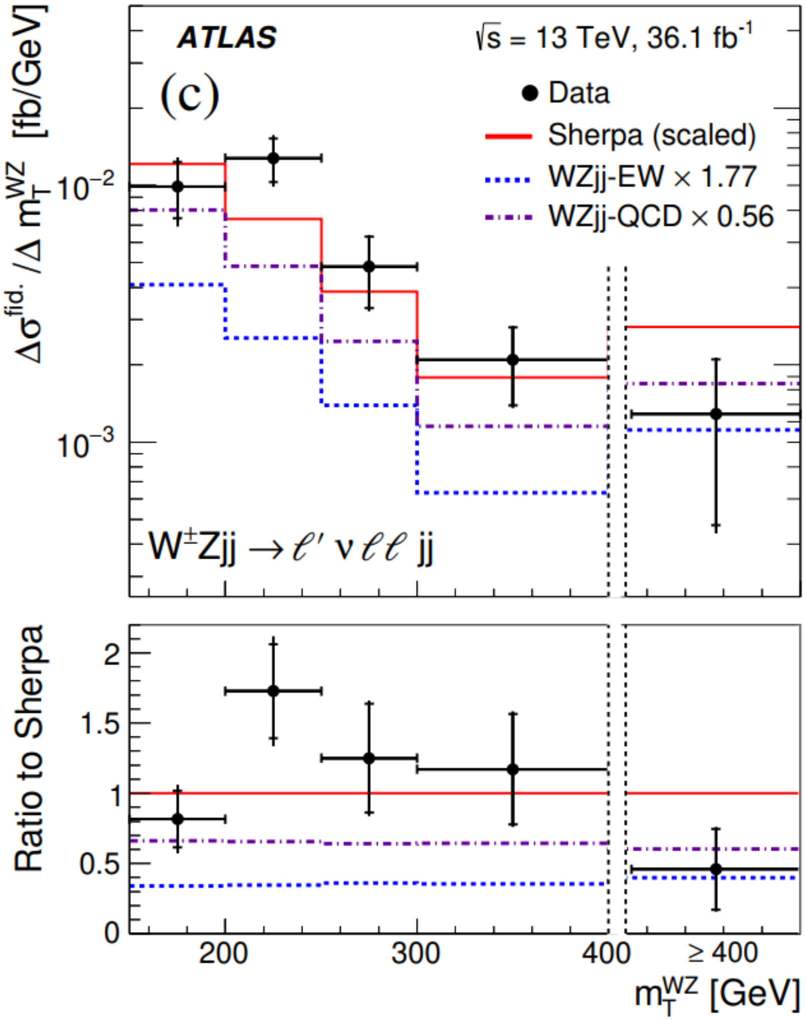
- Some form of unitarization (or form factors which avoid tree level unitarity violation) should be included in experimental anlysis of EFT coefficients

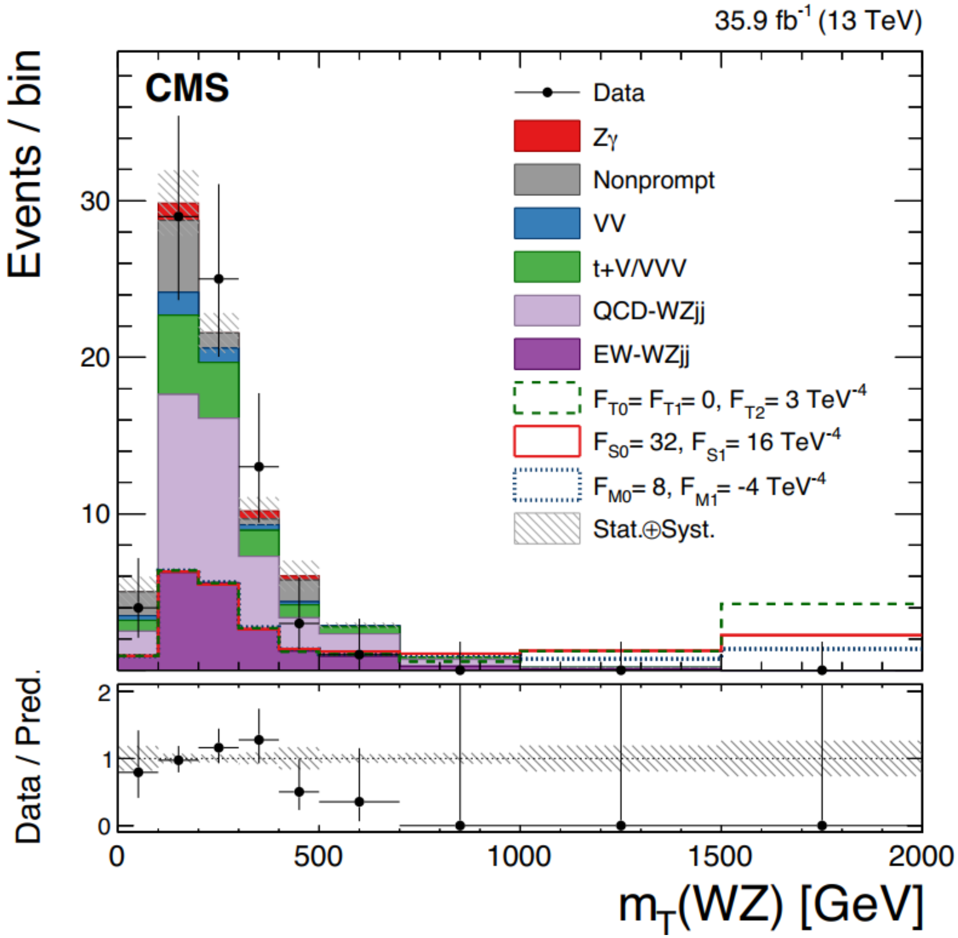
LHC data on same sign W scattering

- Observed (with modest background) by ATLAS and CMS
- Useful bounds on Wilson coefficients of dim-8 operators

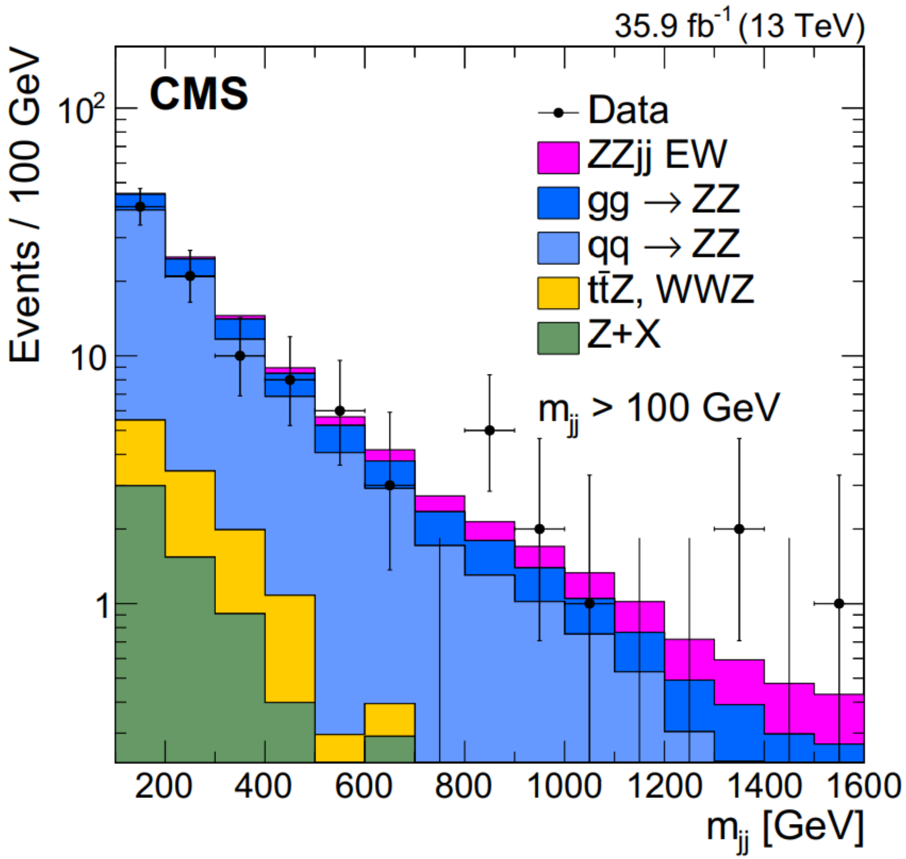


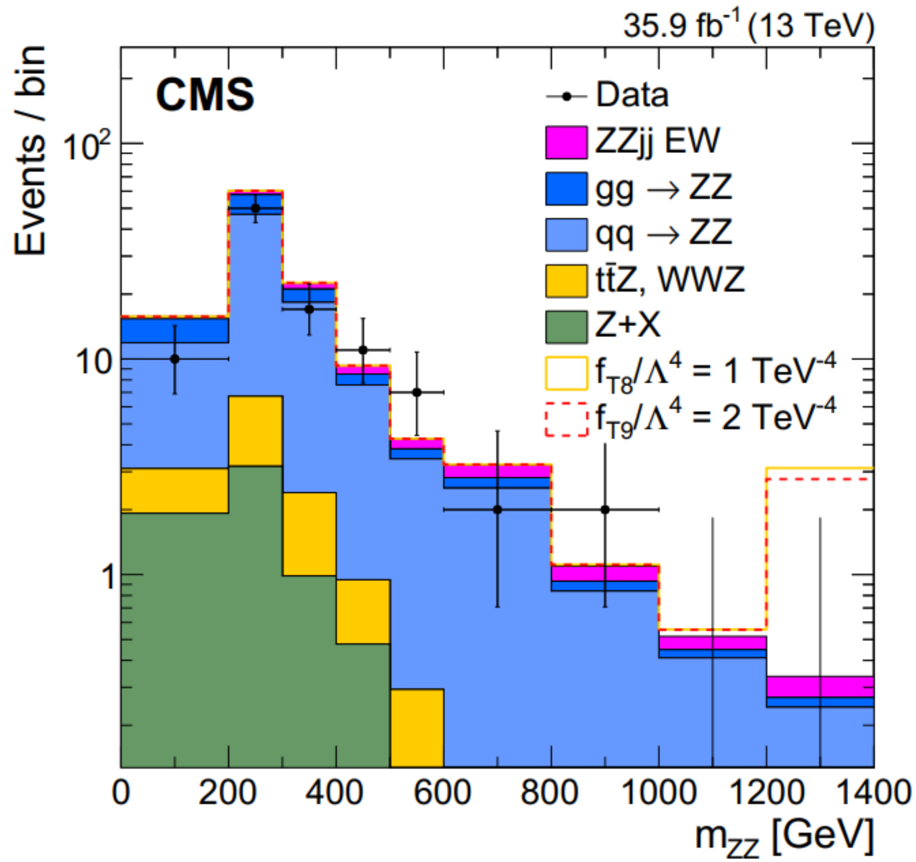
WZ scattering: 3 lepton + pTmiss + 2jet signal





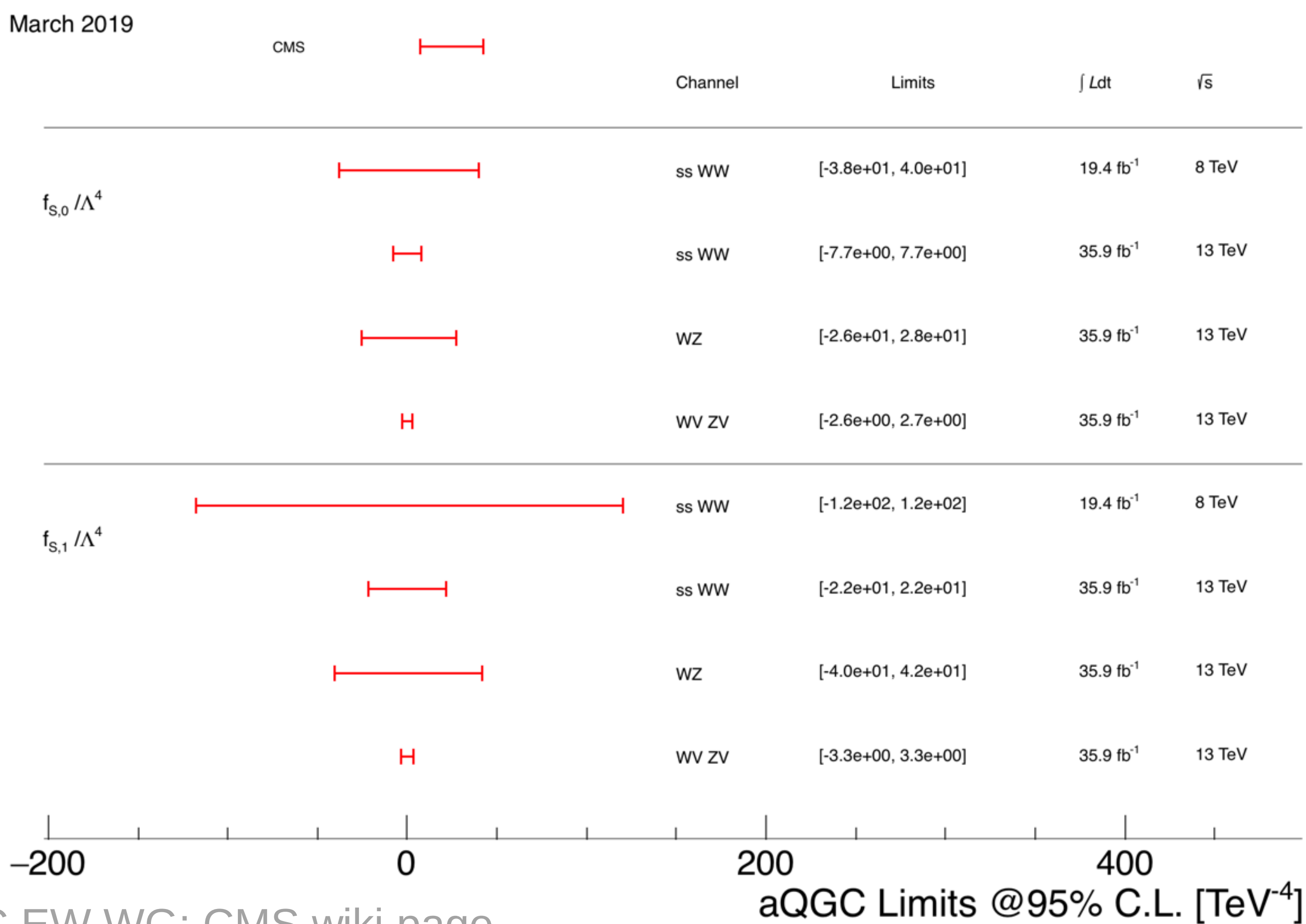
ZZjj production in VBS: 4-lepton signal





Limits on aQGC from LHC data up to 13 TeV:

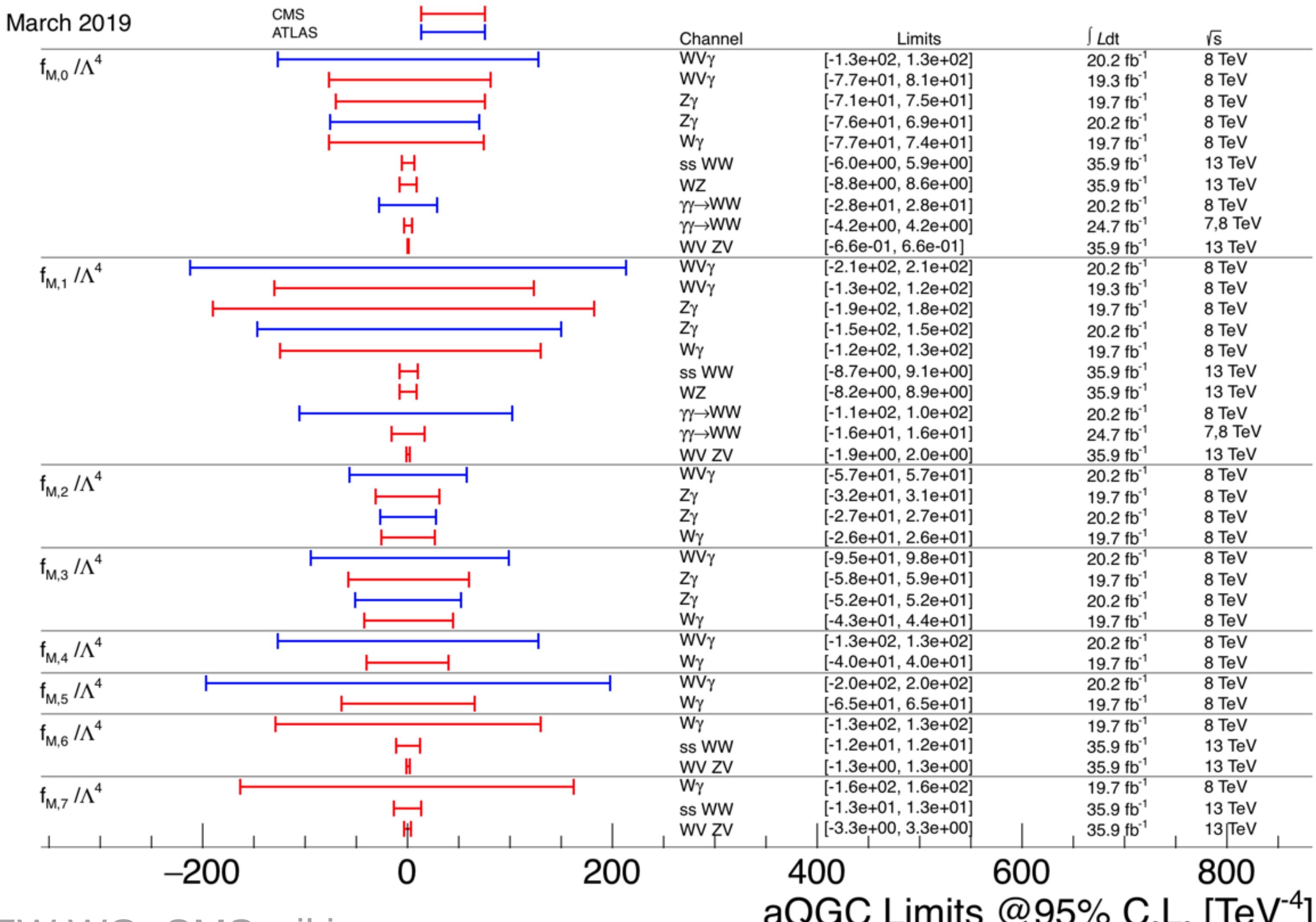
f_S – affecting purely longitudinal scattering



LHC EW WG: CMS wiki page

Limits on aQGC from LHC data up to 13 TeV:

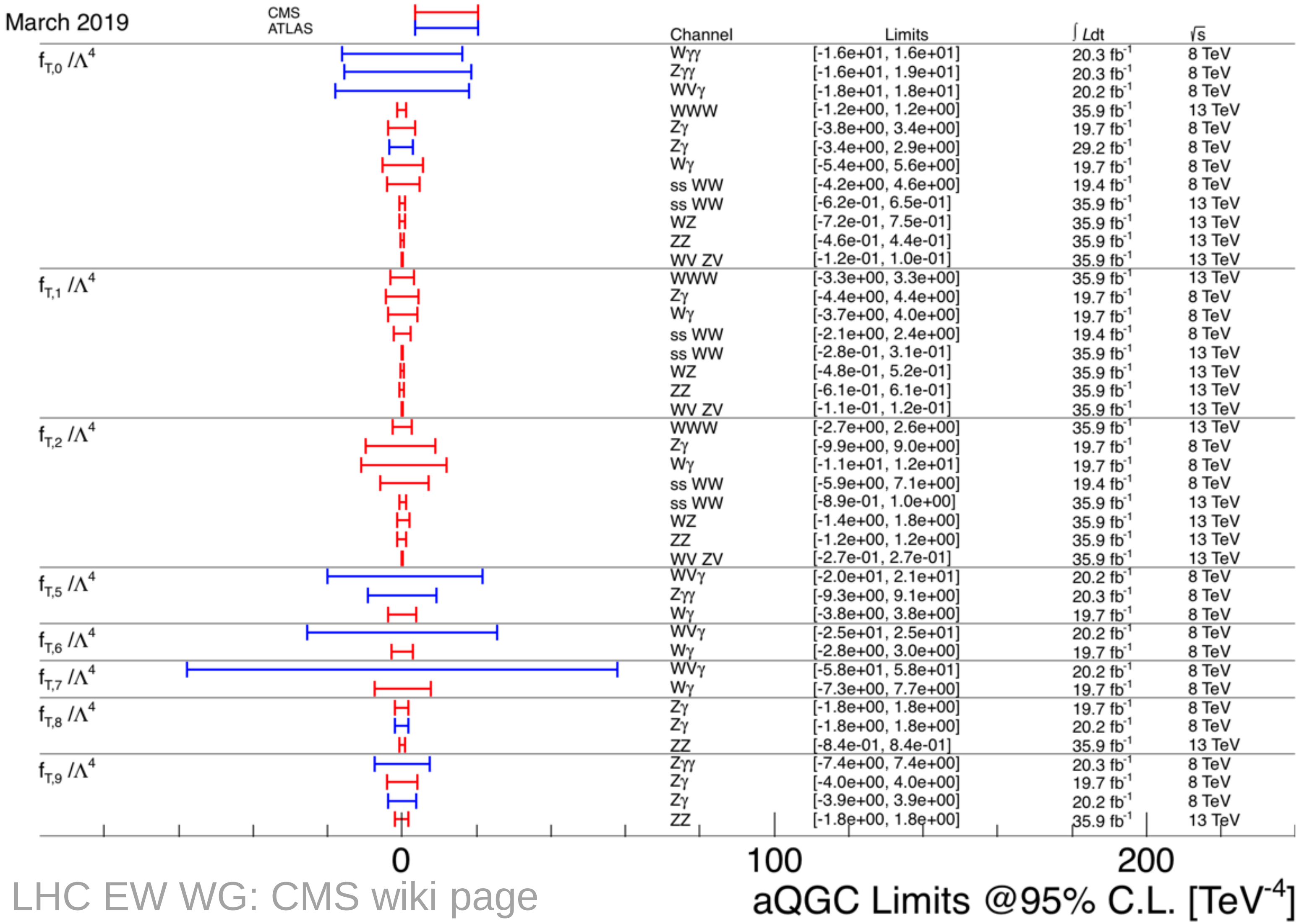
f_M – mixed longitudinal/transverse scattering



LHC EW WG: CMS wiki page

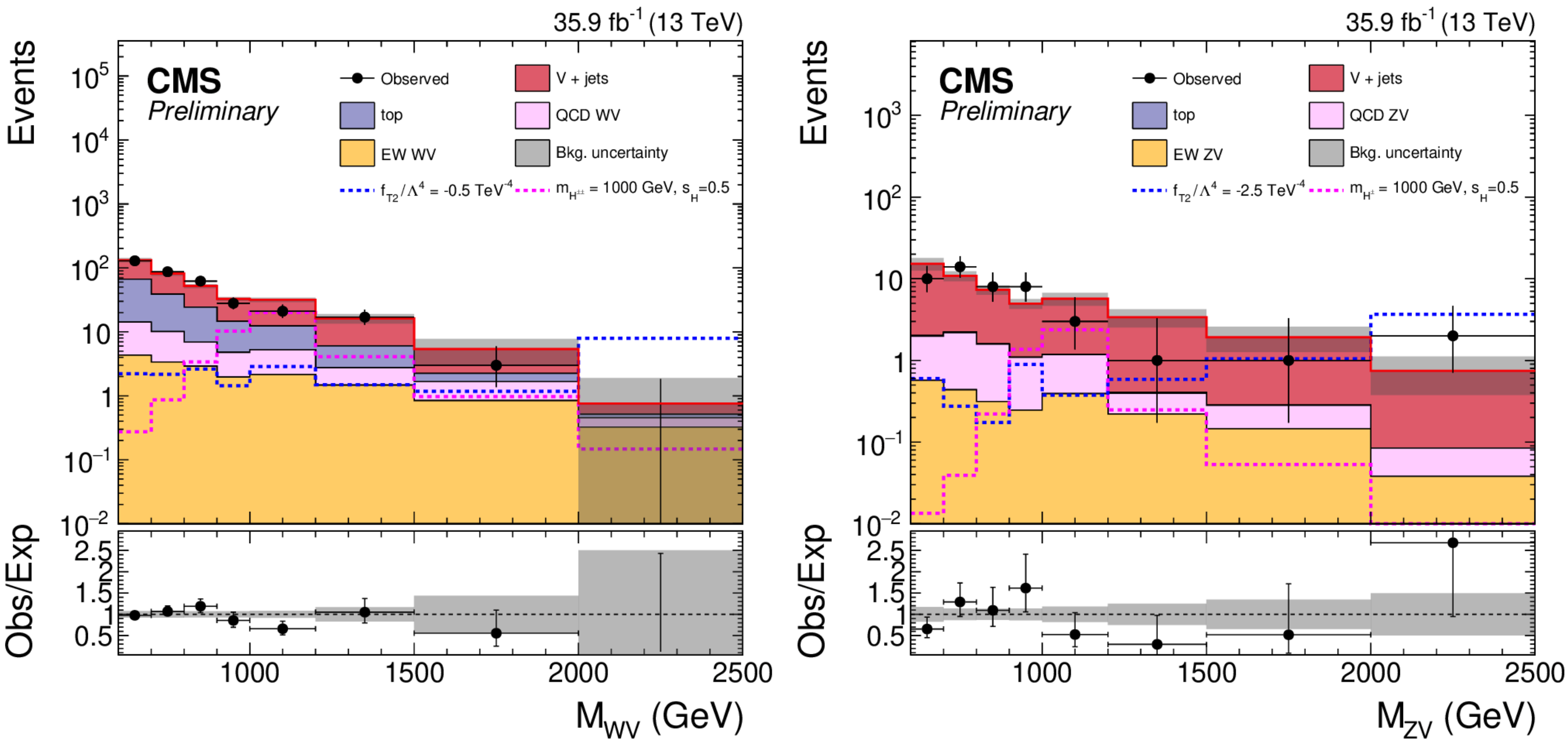
Limits on aQGC from LHC data up to 13 TeV:

f_T – affecting purely transverse scattering



LHC EW WG: CMS wiki page

WV/ZV signatures: W/Z-leptons, V → hadrons (fat jet)



Limits from CMS WV/ZV VBS search at 13 TeV

	Observed (WV) (TeV^{-4})	Expected (WV) (TeV^{-4})	Observed (ZV) (TeV^{-4})	Expected (ZV) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{S0}/Λ^4	$[-2.6, 2.7]$	$[-4.0, 4.0]$	$[-37, 37]$	$[-29, 29]$	$[-2.6, 2.7]$	$[-4.0, 4.0]$
f_{S1}/Λ^4	$[-3.2, 3.3]$	$[-4.9, 4.9]$	$[-30, 30]$	$[-23, 23]$	$[-3.3, 3.3]$	$[-4.9, 4.9]$
f_{M0}/Λ^4	$[-0.66, 0.66]$	$[-0.95, 0.95]$	$[-6.9, 6.9]$	$[-5.1, 5.1]$	$[-0.66, 0.66]$	$[-0.95, 0.95]$
f_{M1}/Λ^4	$[-1.9, 2.0]$	$[-2.8, 2.8]$	$[-21, 21]$	$[-15, 15]$	$[-1.9, 2.0]$	$[-2.8, 2.8]$
f_{M6}/Λ^4	$[-1.3, 1.3]$	$[-1.9, 1.9]$	$[-14, 14]$	$[-10, 10]$	$[-1.3, 1.3]$	$[-1.9, 1.9]$
f_{M7}/Λ^4	$[-3.3, 3.2]$	$[-4.8, 4.8]$	$[-33, 33]$	$[-24, 24]$	$[-3.3, 3.3]$	$[-4.8, 4.8]$
f_{T0}/Λ^4	$[-0.11, 0.10]$	$[-0.16, 0.15]$	$[-1.3, 1.3]$	$[-0.95, 0.95]$	$[-0.12, 0.10]$	$[-0.16, 0.15]$
f_{T1}/Λ^4	$[-0.11, 0.12]$	$[-0.17, 0.17]$	$[-1.4, 1.4]$	$[-0.98, 0.99]$	$[-0.11, 0.12]$	$[-0.17, 0.17]$
f_{T2}/Λ^4	$[-0.27, 0.27]$	$[-0.38, 0.38]$	$[-3.1, 3.2]$	$[-2.3, 2.3]$	$[-0.27, 0.27]$	$[-0.38, 0.38]$

Caveats:

- CMS analysis does not take into account form-factors/unitarization
  $\frac{f}{\Lambda^4}$ bounds expected to weaken by factor 2 to 3 (from ssWW experience)
- Normalization of T operators does not include expected loop suppression
  factor $\frac{g^4}{16\pi^2} = \frac{\alpha^2}{\sin^4\theta_W} \approx 10^{-3}$
- Only large enhancements at high WV/ZV invariant mass is probed

Still: Impressive progress on aQGC measurements

Conclusions

- Diboson pair production at LHC provides powerful tests of electroweak symmetry breaking
- Large cross sections for qbar q→VV, NNLO QCD corrections known, precise measurements from ATLAS/CMS ➔precise aTGC measurements
- Even stronger gauge theory cancellations for VBS
- Pure EFT approach to parameterization of BSM effects is insufficient due to large energy reach of LHC and breakdown of unitarity at tree level. Effect most pronounced for VBS and dimension 8 operators
- Unitarization models provide improved tools for describing BSM VV scattering
- Impressive measurements of VBS processes already, from ATLAS and CMS. More to come from 2017 and 2018 data!

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Thanks for listening!

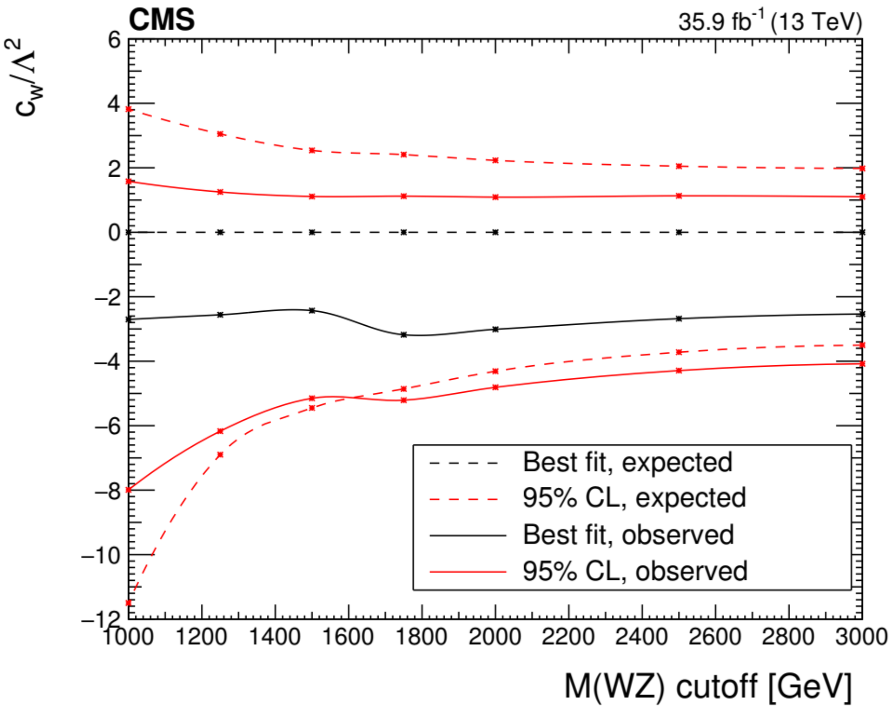
Backup

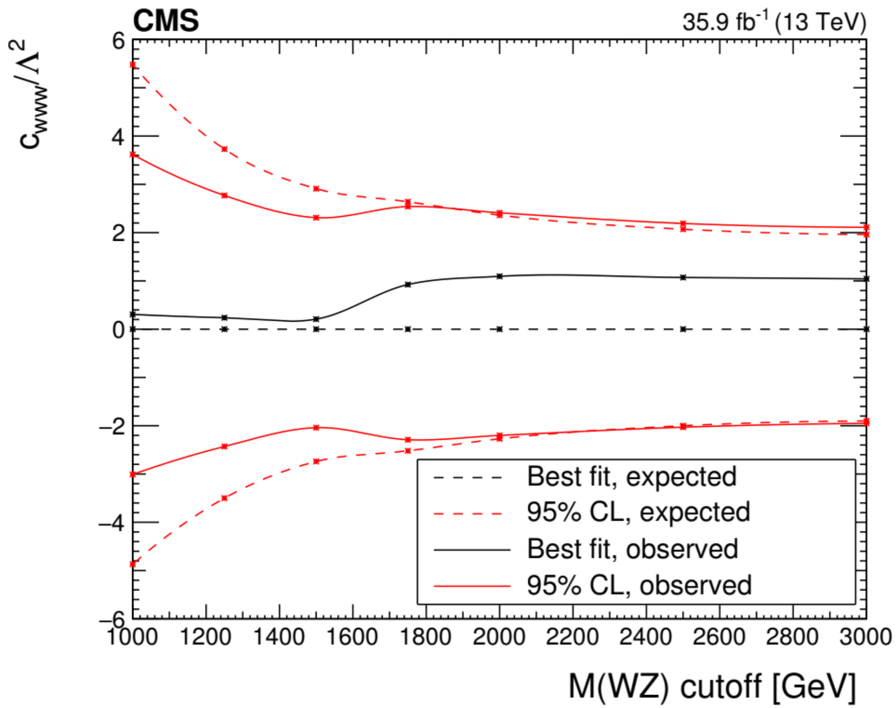
Process (${process_id})	σ_{LO}	σ_{NLO}	σ_{loop} ($\sigma_{loop}/\Delta\sigma^{ext}_{NNLO}$)	$\sigma^{r_{cut}}_{NNLO}$	$\sigma^{extrapolated}_{NNLO}$	K_{NLO} (%)	K_{NNLO} (%)
$pp \to e^-\bar{\nu}_e\gamma$ (ppenexa03)	$726.1(1)^{+11\%}_{-12\%}$ fb	$1850(1)^{+6.6\%}_{-5.3\%}$ fb	–	$2286(1)^{+4.0\%}_{-3.7\%}$ fb	$2256(15)^{+3.7\%}_{-3.5\%}$ fb	+155	+22.0
$pp \to e^+\nu_e\gamma$ (ppexnea03)	$861.7(1)^{+10\%}_{-11\%}$ fb	$2187(1)^{+6.6\%}_{-5.3\%}$ fb	–	$2707(3)^{+4.1\%}_{-3.8\%}$ fb	$2671(35)^{+3.8\%}_{-3.6\%}$ fb	+154	+22.1
$pp \to ZZ$ (ppzz02)	$9.845(1)^{+5.2\%}_{-6.3\%}$ pb	$14.10(0)^{+2.9\%}_{-2.4\%}$ pb	$1.361(1)^{+25\%}_{-19\%}$ pb (52.9%)	$16.68(1)^{+3.2\%}_{-2.6\%}$ pb	$16.67(1)^{+3.2\%}_{-2.6\%}$ pb	+43.3	+18.2
$pp \to W^+W^-$ (ppwxw02)	$66.64(1)^{+5.7\%}_{-6.7\%}$ pb	$103.2(0)^{+3.9\%}_{-3.1\%}$ pb	$4.091(3)^{+27\%}_{-19\%}$ pb (29.5%)	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	$117.1(1)^{+2.5\%}_{-2.2\%}$ pb	+54.9	+13.4
$pp \to e^-\mu^-e^+\mu^+$ (ppemexmx04)	$11.34(0)^{+6.3\%}_{-7.3\%}$ fb	$16.87(0)^{+3.0\%}_{-2.5\%}$ fb	$1.971(1)^{+25\%}_{-18\%}$ fb (57.6%)	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	$20.30(1)^{+3.5\%}_{-2.9\%}$ fb	+48.8	+20.3
$pp \to e^-e^-e^+e^+$ (ppeeexex04)	$5.781(1)^{+6.3\%}_{-7.4\%}$ fb	$8.623(3)^{+3.1\%}_{-2.5\%}$ fb	$0.9941(4)^{+25\%}_{-18\%}$ fb (56.9%)	$10.37(1)^{+3.5\%}_{-3.0\%}$ fb	$10.37(1)^{+3.5\%}_{-3.0\%}$ fb	+49.2	+20.2
$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$ (ppeexnmnmx04)	$22.34(0)^{+5.3\%}_{-6.4\%}$ fb	$33.90(1)^{+3.3\%}_{-2.7\%}$ fb	$3.212(1)^{+25\%}_{-19\%}$ fb (49.6%)	$40.39(2)^{+3.5\%}_{-2.8\%}$ fb	$40.38(2)^{+3.5\%}_{-2.8\%}$ fb	+51.7	+19.1
$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$ (ppemxnmnex04)	$232.9(0)^{+6.6\%}_{-7.6\%}$ fb	$236.1(1)^{+2.8\%}_{-2.4\%}$ fb	$26.93(1)^{+27\%}_{-19\%}$ fb (94.3%)	$264.7(1)^{+2.2\%}_{-1.4\%}$ fb	$264.6(2)^{+2.2\%}_{-1.4\%}$ fb	+1.34	+12.1
$pp \to e^-e^+\nu_e\bar{\nu}_e$ (ppeexnenex04)	$115.0(0)^{+6.3\%}_{-7.3\%}$ fb	$203.4(1)^{+4.7\%}_{-3.8\%}$ fb	$12.62(1)^{+26\%}_{-19\%}$ fb (33.8%)	$240.8(1)^{+3.4\%}_{-3.0\%}$ fb	$240.7(1)^{+3.4\%}_{-3.0\%}$ fb	+76.9	+18.4
$pp \to e^-\mu^-e^+\bar{\nu}_\mu$ (ppemexnmx04)	$11.50(0)^{+5.7\%}_{-6.8\%}$ fb	$23.55(1)^{+5.5\%}_{-4.5\%}$ fb	–	$26.17(1)^{+2.2\%}_{-2.1\%}$ fb	$26.17(2)^{+2.2\%}_{-2.1\%}$ fb	+105	+11.1
$pp \to e^-e^-e^+\bar{\nu}_e$ (ppeeexnex04)	$11.53(0)^{+5.7\%}_{-6.8\%}$ fb	$23.63(1)^{+5.5\%}_{-4.5\%}$ fb	–	$26.27(1)^{+2.3\%}_{-2.1\%}$ fb	$26.25(2)^{+2.3\%}_{-2.1\%}$ fb	+105	+11.1

Integrated cross sections for MATRIX VV production processes (from Grazzini, Kallweit, Wiesemann, EPJC)

Form factor dependence for aTGC measurement?

- Limiting M(WZ) range for bounding aTGC: CMS measurement





- Also interesting: M(WZ) cutoff below 1 TeV would exhibit sensitivity to „small“ deviations e.g. from BSM loop effects and interference with SM contributions

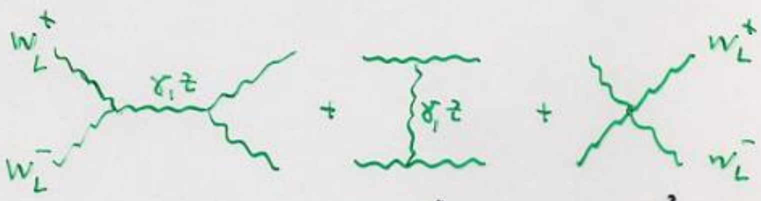
WW scattering and unitarity

Consider longitudinal W's

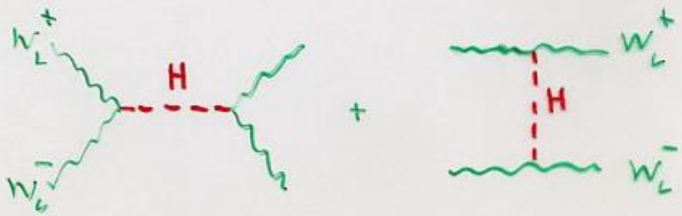
$$W_L^+ W_L^- \to W_L^+ W_L^-$$

Polarisation vector

$$\varepsilon_L^\mu = \frac{p^\mu}{m_W} + \mathcal{O}\left(\frac{m_W}{E}\right) \sim \frac{\sqrt{s}}{m_W}$$



$$\mathcal{M} \sim \underbrace{\frac{s^2}{m_W^4} \qquad \frac{s^2}{m_W^4} \qquad \frac{s^2}{m_W^4}}_{s/m_W^2}$$



$$\frac{s}{m_W^2} \qquad \frac{s}{m_W^2}$$

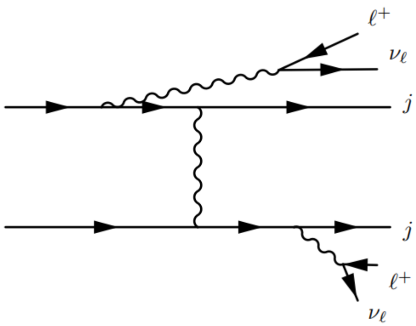
sum $\sim s^0$ for $s \gg m_H^2$

Off-shell VBS amplitude

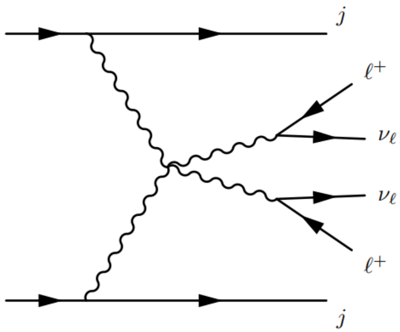
- Assume new physics in VV→VV only

$$\mathcal{M}_{pp\to 4fjj} = \mathcal{M}^{\rm SM}_{pp\to 4fjj} + \mathcal{M}^{\rm BSM}_{pp\to 4fjj}$$

- SM part alone has vector boson emission, triple gauge couplingsH etc. which interfere destructively
  → SM piece is unitary and small



(a) Vector boson emission



(b) Quartic gauge interaction.

- → unitarize BSM piece only

$$\mathcal{M}^{\rm BSM}_{pp\to 4fjj} = J^\mu_{p_1\to jV_1}\ J^\nu_{p_2\to jV_2}\ D^{V_1}_{\mu\alpha}(q_1)\ D^{V_2}_{\nu\beta}(q_2) \times \mathbf{M}^{\alpha\beta\gamma\delta}_{V_1V_2\to V_3V_4}\ D^{V_3}_{\gamma\rho}(q_3)\ D^{V_4}_{\delta\sigma}(q_4) \times J^\rho_{V_3\to \bar f f}\ J^\sigma_{V_4\to \bar f f}$$

- V-propagators decompose into polarization sums

$$D^{\mu\nu}_V(q) = \frac{-\mathrm{i}}{q^2 - m_V^2 + i\, m_V\, \Gamma_V}\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right) \equiv \frac{-\mathrm{i}}{q^2 - m_V^2 + i\, m_V\, \Gamma_V}\sum_\lambda \epsilon^{*\mu}_J(q,\lambda)\epsilon^\nu_{\mathcal{M}}(q,\lambda)$$

- Defines $\mathcal{M}^{VBS}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_1,q_2;q_3,q_4) = \epsilon_{\mathcal{M},\alpha}(q_1,\lambda_1)\epsilon_{\mathcal{M},\beta}(q_2,\lambda_2)\,\mathbf{M}^{\alpha\beta\gamma\delta}_{V_1V_2\to V_3V_4}\,\epsilon^*_{\mathcal{M},\gamma}(q_3,\lambda_3)\epsilon^*_{\mathcal{M},\delta}(q_4,\lambda_4)$

Partial wave decomposition and unitarity relation

- S-matrix unitarity

$$\mathbf{S} = 1 + \mathrm{i}\mathbf{T}\,, \qquad \mathbf{T}_{fi} = (2\pi)^4 \delta(P_f - P_i)\, \mathcal{T}_{fi}$$

$$2\mathrm{Im}\mathbf{T} = -\mathrm{i}\left(\mathbf{T} - \mathbf{T}^\dagger\right) = \mathbf{T}^\dagger \mathbf{T} = \mathbf{T}\mathbf{T}^\dagger$$

- Implication for helicity amplitudes

$\mathcal{M}_{\lambda_3\lambda_4 \leftarrow \lambda_1\lambda_2} = \mathcal{T}_{fi}$

$$\mathcal{T}_{fi} - \mathcal{T}^*_{if} = \mathrm{i} \sum_n \int \underbrace{\frac{d^3\mathbf{q}_{n,3} d^3\mathbf{q}_{n,4}}{(2\pi)^3 2q^0_{n,3} (2\pi)^3 2q^0_{n,4}} (2\pi)^4 \delta(P_i - q_{n,3} - q_{n,4})}_{\frac{\lambda^{1/2}(s, q^2_{n,3}, q^2_{n,4})}{8s(2\pi)^2} d\Omega} S_n\, \mathcal{T}^*_{nf} \mathcal{T}_{ni}$$

- Projection onto j<=2 partial waves

$$\mathcal{M}_{\lambda_3\lambda_4 \leftarrow \lambda_1\lambda_2}(\Theta, \varphi) = 8\pi \mathcal{N}_{fi} \sum_{j=\max(|\lambda_{12}|,|\lambda_{34}|)}^{J_{\max}} (2j+1) \mathcal{A}^j_{\lambda_3\lambda_4 \leftarrow \lambda_1\lambda_2} d^j_{\lambda_{12}\lambda_{34}}(\Theta)\, e^{\mathrm{i}\lambda_{34}\varphi}$$

- Partial wave unitarity relation

$$2\mathrm{Im}(\mathcal{A}^j_{\lambda_3\lambda_4 \leftarrow \lambda_1\lambda_2}) = \sum_n \frac{\mathcal{N}_{ni}\mathcal{N}_{nf}}{\mathcal{N}_{fi}} \frac{\lambda^{1/2}(s, q^2_{n,3}, q^2_{n,4})}{s} S_n \sum_{\lambda'_1,\lambda'_2} {\mathcal{A}^j}^*_{\lambda'_1\lambda'_2 \leftarrow \lambda_3\lambda_4} \mathcal{A}^j_{\lambda'_1\lambda'_2 \leftarrow \lambda_1\lambda_2}$$

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Unitarization of tree level amplitude: $T_0 \rightarrow T_u$

- K-matrix (also called T-matrix) procedure for on-shell hermitian T_0

$$\mathbf{T}_L = \left(\mathbb{1} - \frac{\mathrm{i}}{2}\mathbf{T}_0^\dagger\right)^{-1} \frac{1}{2}\left(\mathbf{T}_0 + \mathbf{T}_0^\dagger\right) = \left(\mathbb{1} + \frac{1}{4}\mathbf{T}_0\mathbf{T}_0\right)^{-1} \left(\mathbf{T}_0 + \frac{\mathrm{i}}{2}\mathbf{T}_0\mathbf{T}_0\right)$$

- General virtualities → T_0 not normal for off-shell VV→VV

  Must distinguish

$$\mathbf{A}_{t\leftarrow s} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_3, q_4; q_1, q_2)$$
$$\mathbf{A}_{s\leftarrow t} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(k_3, k_4; k_1, k_2)$$
$$\mathbf{A}_{t\leftarrow t} = \mathcal{M}_{\lambda_3,\lambda_4;\lambda_1,\lambda_2}(q_3, q_4; k_1, k_2)$$

- Use

$$\mathbf{A}^{\mathrm{unit}}_{t\leftarrow s} = \left(\mathbb{1} + \frac{1}{4}\mathbf{A}_{t\leftarrow s}\mathbf{A}_{s\leftarrow t}\right)^{-1} \left(\mathbf{A}_{t\leftarrow s} + \frac{\mathrm{i}}{2}\mathbf{A}_{t\leftarrow t}\mathbf{A}_{t\leftarrow s}\right)$$

- Alignment problems avoided by using largest eigenvalue of denominator

$$\mathbf{A}^{\mathrm{unit}}_{t\leftarrow s} = \left(\mathbb{1} + \frac{1}{4}a^2_{\mathrm{max}}\right)^{-1} \left(\mathbf{A}_{t\leftarrow s} + \frac{\mathrm{i}}{2}\mathbf{A}_{t\leftarrow t}\mathbf{A}_{t\leftarrow s}\right)$$

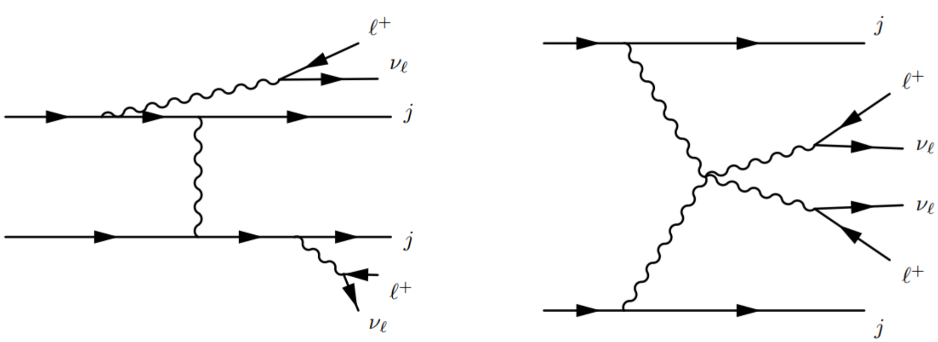
Projection on V helicities

- Decompose all final V-propagators and initial V propagators for VBS graphs into polarization sums
- For helicity projection, delete all unwanted terms in helicity sum

$$D_V^{\mu\nu}(q) = \frac{-\mathrm{i}}{q^2 - m_V^2 + i\, m_V\, \Gamma_V} \left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right)$$

$$\equiv \frac{-\mathrm{i}}{q^2 - m_V^2 + i\, m_V\, \Gamma_V} \sum_\lambda \epsilon_J^{*\mu}(q,\lambda) \epsilon_{\mathcal{M}}^\nu(q,\lambda)$$

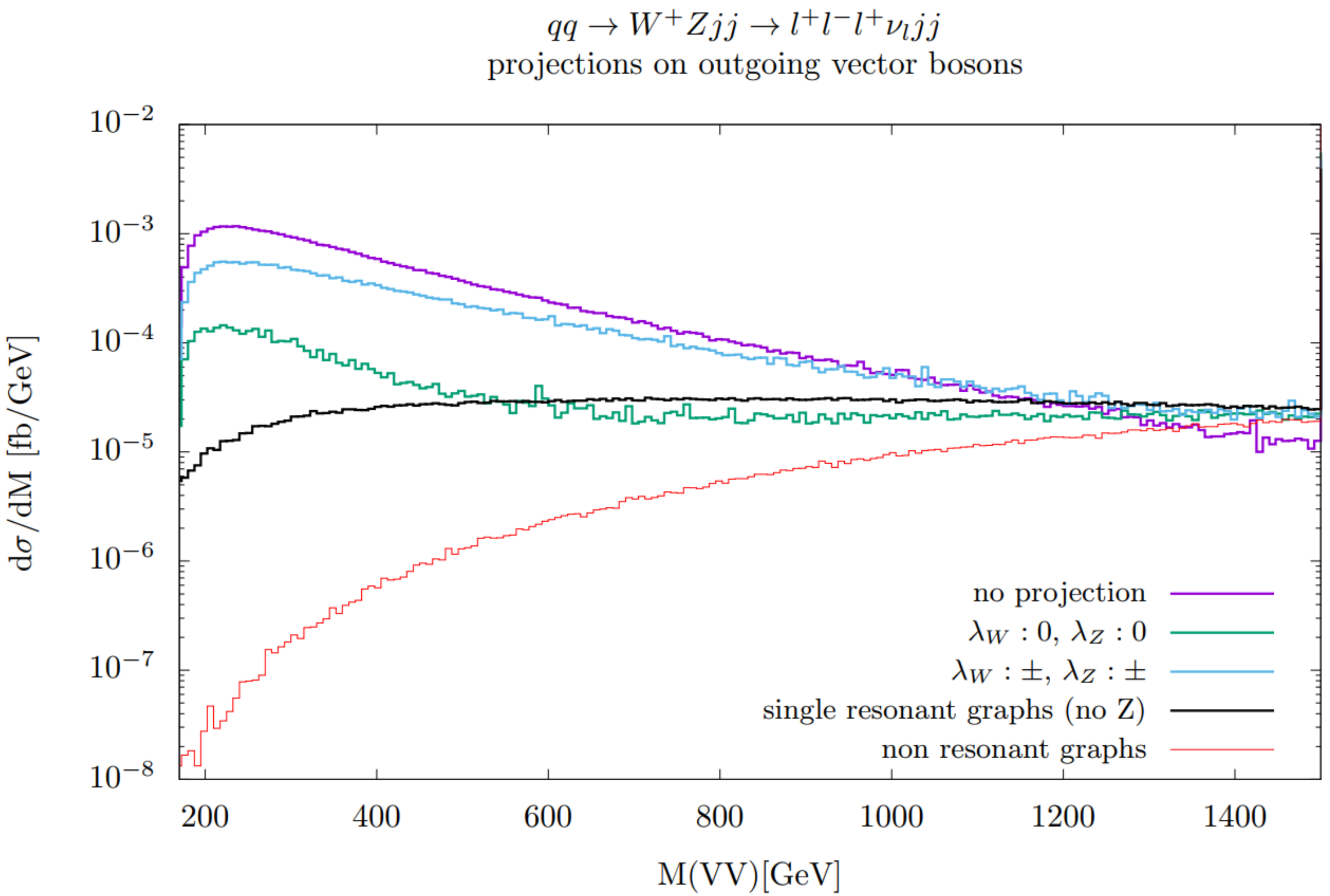
- For final V, projection is possible for most graphs
- Problem for initial V: not defined for V emission off quark lines



(a) Vector boson emission (b) Quartic gauge interaction.

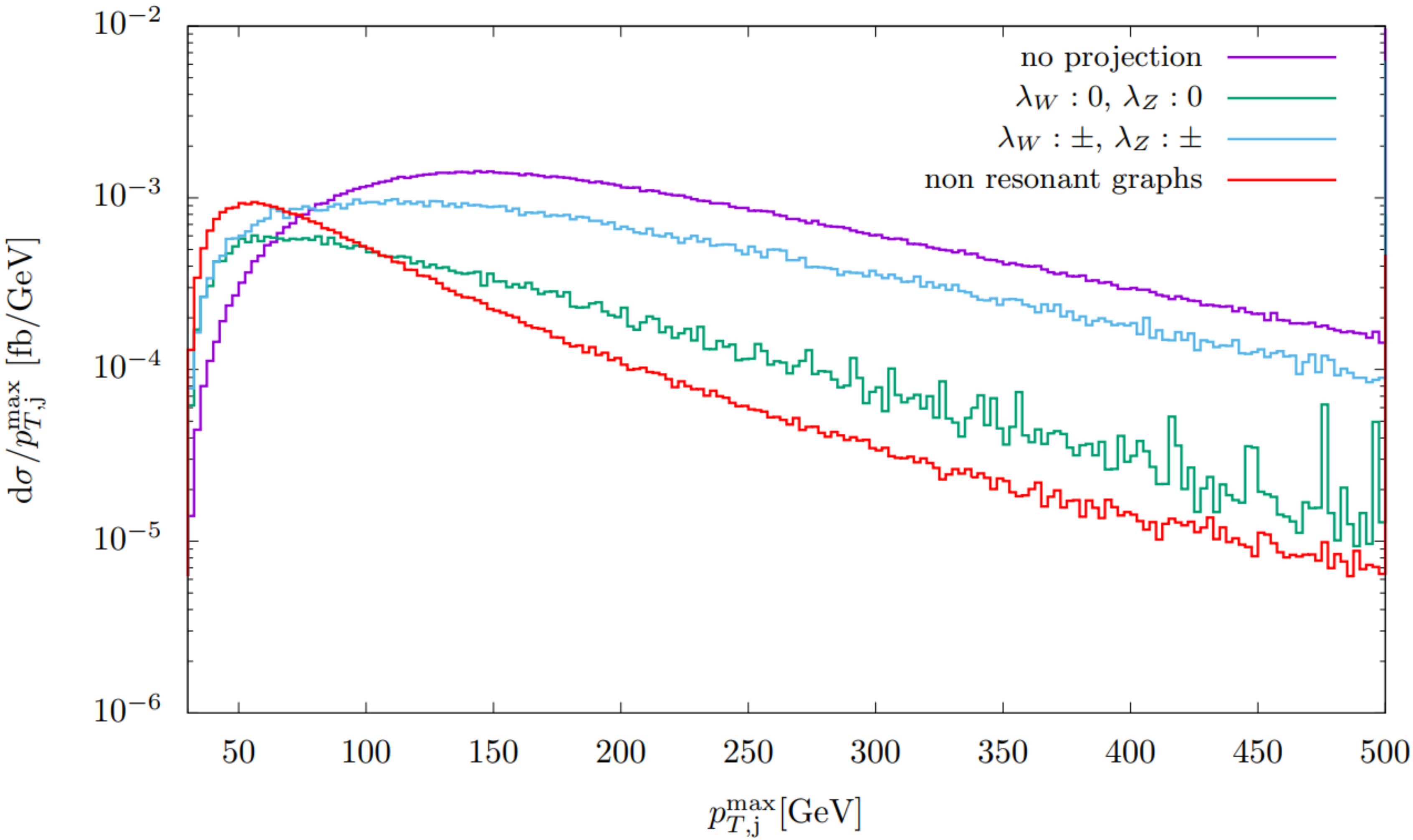
Consider helicity projections in VV c.m. frame for SM case in the following
Work by Heiko Schäfer-Siebert

Helicity projection of final bosons

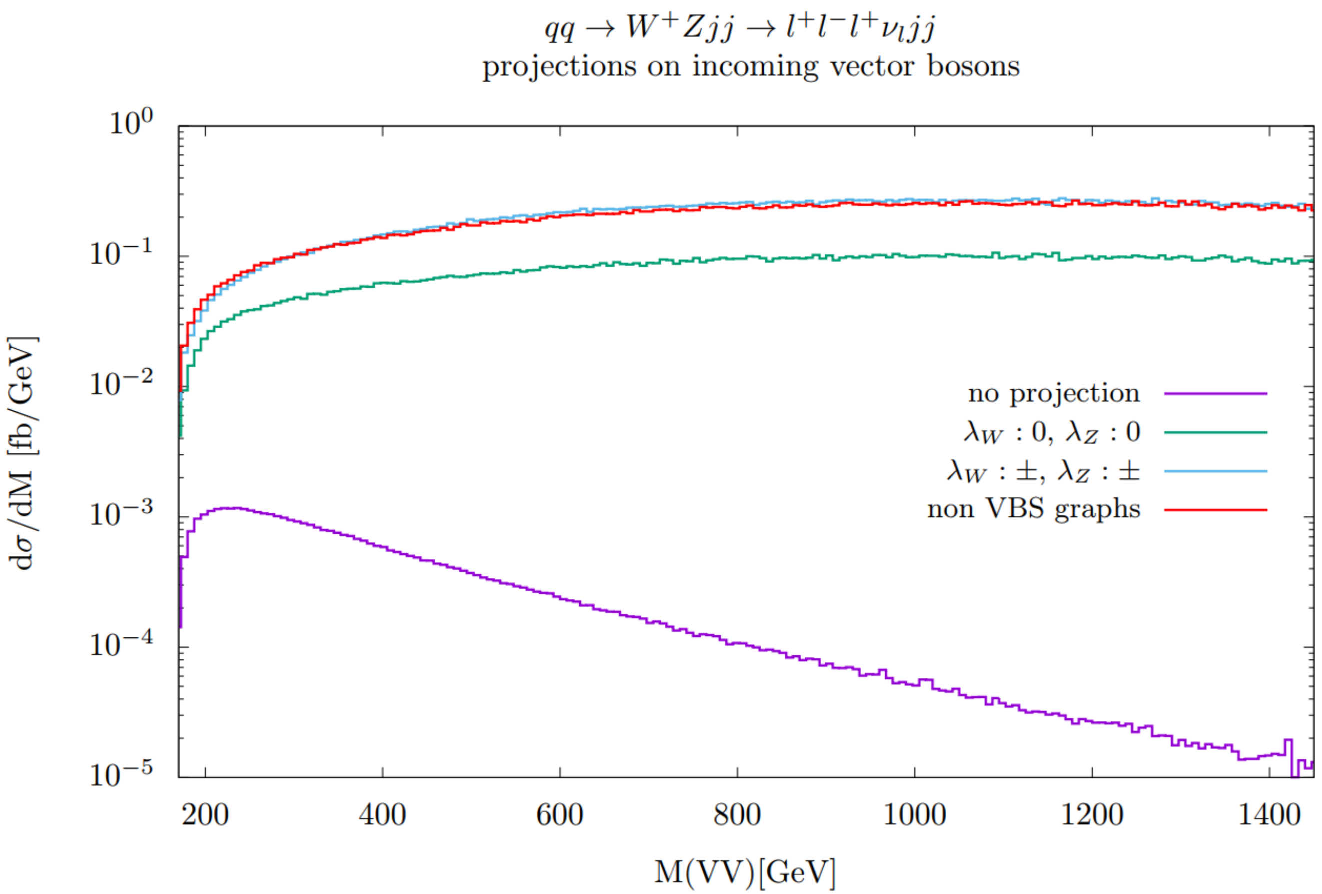


Caution at high WZ invariant mass

Distributions suffer from helicity projection



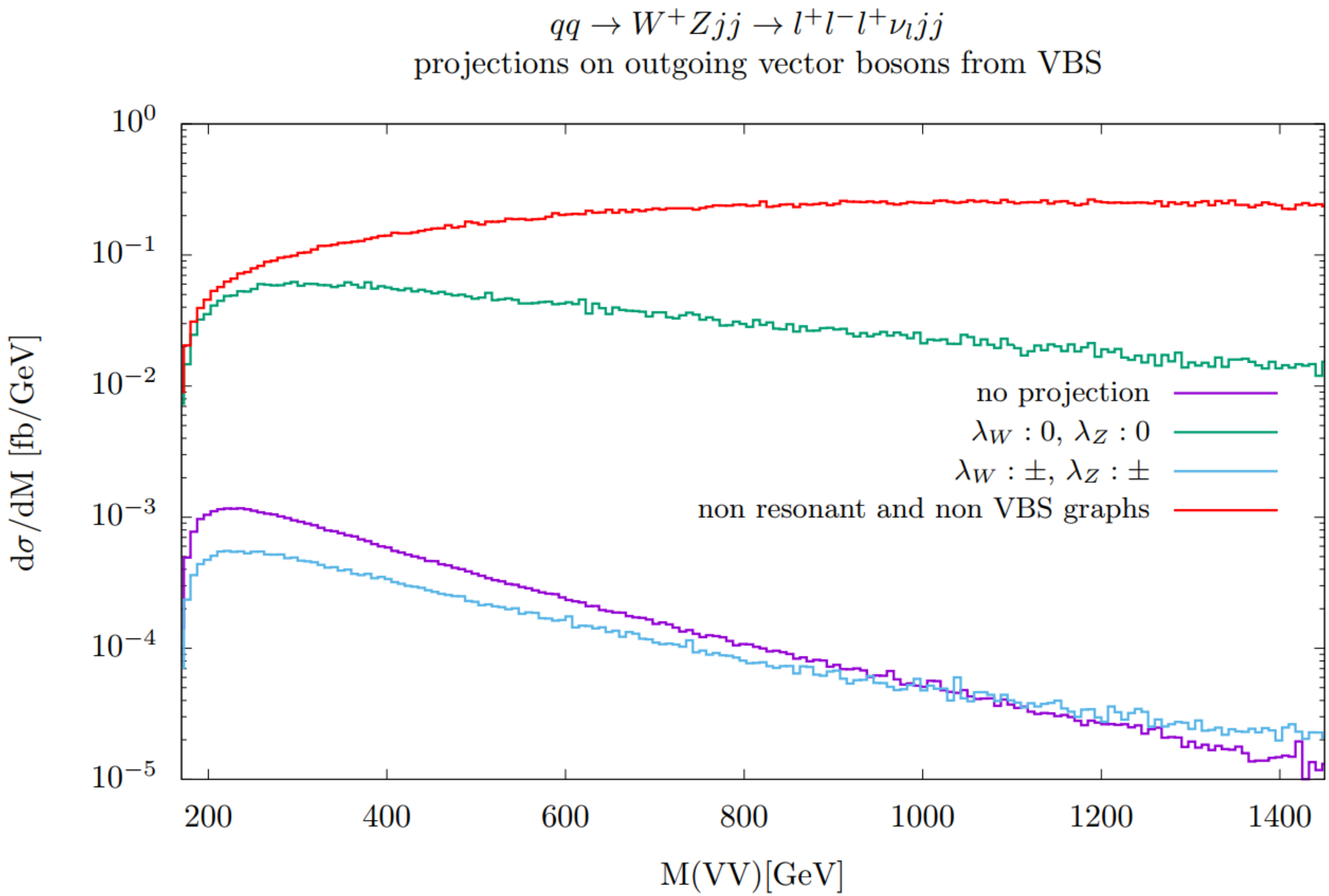
Huge interference effects for initial boson helicities



Interference with non-VBS graphs is huge! Projection on initial helicities spoils cancellations

Precludes definition of polarized cross sections for incoming space-like VV in full qq→qqVV process

Projection of final V in ALL graphs is crucial



Some conclusions on polarization

- Huge gauge theory cancellations between VBS graphs and V-emission off quark lines appears to preclude definition of polarized cross sections for inital V in VBS for the SM contribution
- Projection onto specific helicities of final state VV is viable, at least for modest VV invariant masses
- Above m(WZ)=600 GeV interference of graphs without Z-propagator becomes problematic for definition of $W_L Z_L$ production
- Results not trustworthy above m(WZ)= 1.2 TeV
- SM result is smaller than sum of „*polarized cross sections*“ in important regions of phase space, presumably due to excess events above 1.2 TeV

Define polarized cross sections by appropriate projection of angular distributions of decay products?

Much more data still to be analyzed…

Results shown were based on data taken up to 2016