Unitarization effects in EFT predictions of VBS @LHC

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COMPOSE-IT: Unitarity for composite models and beyond in the HL-LHC era

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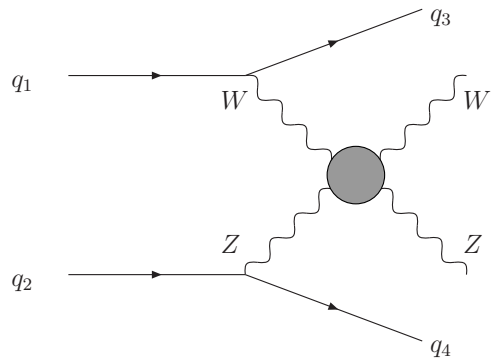
Based on Phys. Rev. **D100** (2019) 096003 [1907.06668]

$pp \to WZj_1j_2$

by $WZ \to WZ$ scattering



Outline

- Introduction: linear vs. non-linear EFT's
- The Electroweak Chiral Lagrangian (EChL)
- Aspects and implications of unitarity violation
- Restoring unitarity in WZ scattering at the LHC
- Parameter determination uncertainties
- Conclusions

The (EW) Chiral symmetry in the SM and BSM

The Spontaneously Breaking Sector (SBS) of the SM can be written as

$$\mathcal{L}_{SBS} = \frac{1}{4}\langle \partial_\mu M^\dagger \partial^\mu M \rangle - \frac{\lambda}{4}\left(\frac{1}{2}\langle M^\dagger M\rangle + \frac{\mu^2}{\lambda}\right)^2$$

where $M = \sqrt{2}\begin{pmatrix} \phi_0^* & \phi^+ \\ -\phi^- & \phi_0 \end{pmatrix}$ and the Φ doublet is $\begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix}$.

$\Rightarrow$ the $\mathcal{L}_{SBS}$ is manifestly invariant under the global transformation:

$$M \to M' = g_L M g_R^\dagger \quad \text{with } g_L \subset SU(2)_L \text{ and } g_R \subset SU(2)_R$$

This global $SU(2)_L \times SU(2)_R$ is called the EW Chiral symmetry.
It is spontaneously broken down to the diagonal subgroup

$$SU(2)_L \times SU(2)_R \to SU(2)_{L+R} \equiv SU(2)_{Custodial}$$

Gauge interactions ($g' \neq 0$) and different fermion masses (in the same doublet) explicitly break the Chiral and Custodial symmetries.

Main implication of Custodial symmetry: ρ parameter value is close to 1!

Linear approach to BSM: SMEFT

- The Higgs and the Goldstone bosons (GBs) form a left $SU(2)$ doublet. In particular, the Higgs always appears in the combination $H + v$.
- The GBs **transform linearly** under the Chiral symmetry.
- Based on a **cutoff Λ expansion** (canonical dimension):

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

- SMEFT typically emerges from **weakly interacting** UV theory.
- Typical situation when H is a fundamental field.

Our approach to BSM: the non-linear EChL or HEFT

- The Goldstone bosons π^a are independent from the Higgs boson.
  In particular, the Higgs is a $SU(2)$ singlet.
- The π^a **transform non-linearly** under the Chiral symmetry.
- Based on a **derivative expansion** $\leftrightarrow$ Chiral expansion (powers of p).
  Derivates and masses are soft scales of the EFT with power counting
  $\mathcal{O}(p) \Rightarrow$ the $\mathcal{L}$ is organized in terms of operators $\mathcal{O}(p^2)$, $\mathcal{O}(p^4)$, ...
- Associated to **strongly interacting** UV theory.
  Natural scenario to generate dynamically resonances.
- Appropriate for composite models of the EWSB (H as a pseudo GB).
- Non-trivial relation between linear and non-linear representations!
  Some higher order operators, that were dim-8 in the linear representation, can contribute to a lower order in the non-linear one (dim-4 in the Chiral expansion).

The Electroweak Chiral Lagrangian (EChL)

- Symmetries are Lorentz, CP, EW gauge $SU(2)_L \times U(1)_Y$ and Chiral $SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$. Based on ChPT of QCD.
- Light degrees of freedom and building blocks are:

  Higgs boson as a singlet $\Rightarrow \mathcal{F}(H) = 1 + 2a\frac{H}{v} + b\left(\frac{H}{v}\right)^2 + \ldots$

  EW gauge bosons $\Rightarrow \hat{W}_\mu = gW_\mu^a\tau^a/2,\ \hat{B}_\mu = g'\,B_\mu\tau^3/2,\ \hat{W}_{\mu\nu},\ \hat{B}_{\mu\nu}$.

  EW GBs in $U = \exp\left(\frac{i\pi^a\tau^a}{v}\right)$ that transforms linearly $U \to g_L U g_R^\dagger$

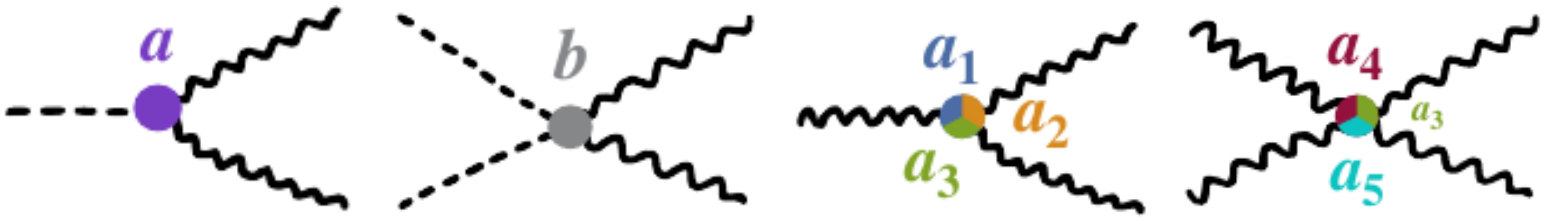
  $\Rightarrow D_\mu U = \partial_\mu U + i\hat{W}_\mu U - iU\hat{B}_\mu$ and $\mathcal{V}_\mu = (D_\mu U)U^\dagger$.

  Our assumptions: fermion ints as in SM. Custodial sym preserved.

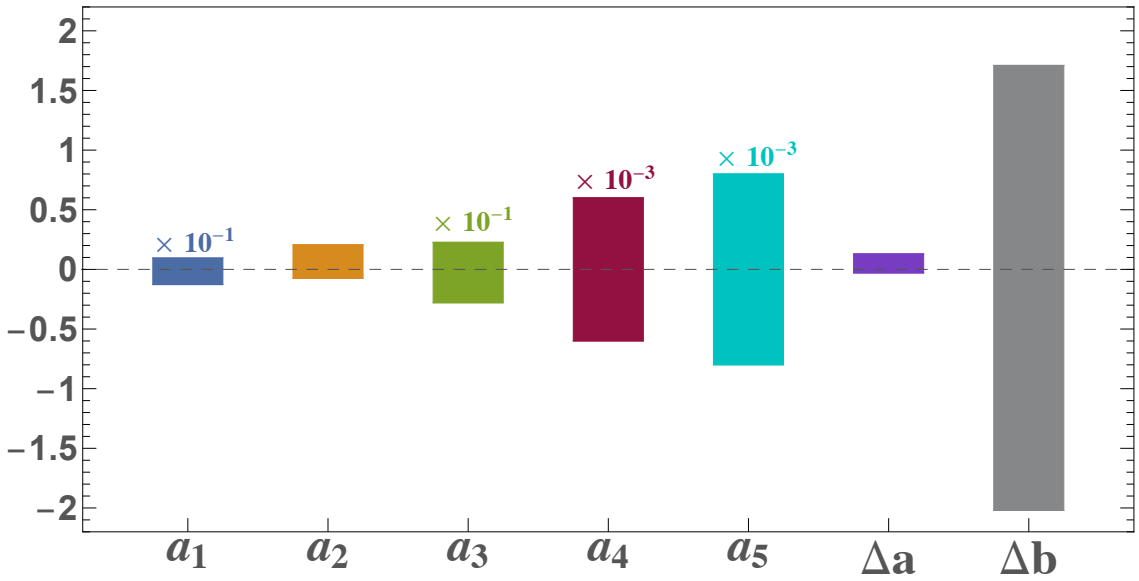
$\mathcal{L}_{EChL} = \mathcal{L}_2 + \mathcal{L}_4$ (relevant for VBS)

$$\mathcal{L}_2 = -\frac{1}{2g'}\langle\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\rangle - \frac{1}{2g}\langle\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\rangle + \frac{1}{2}\partial_\mu H\partial^\mu H - V(H)$$
$$+ \frac{v^2}{4}\mathcal{F}(H)\langle D_\mu U^\dagger D^\mu U\rangle$$
$$\mathcal{L}_4 = a_1\langle U\hat{B}_{\mu\nu}U^\dagger\hat{W}^{\mu\nu}\rangle + ia_2\langle U\hat{B}_{\mu\nu}U^\dagger[\mathcal{V}^\mu,\mathcal{V}^\nu]\rangle - ia_3\langle\hat{W}_{\mu\nu}[\mathcal{V}^\mu,\mathcal{V}^\nu]\rangle$$
$$+ a_4\langle\mathcal{V}_\mu\mathcal{V}_\nu\rangle\langle\mathcal{V}^\mu\mathcal{V}^\nu\rangle + a_5\langle\mathcal{V}_\mu\mathcal{V}^\mu\rangle\langle\mathcal{V}_\nu\mathcal{V}^\nu\rangle$$

EChL parameters and interactions



- SM predictions recovered for $\Delta a = a - 1 = 0$, $\Delta b = b - 1 = 0$ and $a_i = 0$.
- Only a, b, a_4 and a_5 survive *switching off* gauge interactions (limit $g, g' \to 0$). Relevant parameters applying Equivalence Theorem (ET): $A(V_L V_L \to V_L V_L) \simeq A(\pi\pi \to \pi\pi)$
- Exp. bounds derived from
  [Pyhs. Rev. **D98** (2018) 030001 (PDG)
  Pyhs. Rev. **D99** (2019) 033001 (ATLAS)
  Phys. Lett. B 798 (2019)134985 (CMS)
  Phys. Rev. **D101** 012002 (ATLAS)
  ATLAS-CONF-2019-030 (2001.05178)]



Implications of unitarity violation in VBS

- VBS is a powerful observable to look for New Physics: extremely sensitive to SM deviations introduced by EChL operators.
  Quasi-direct access to Goldstone dynamics through the longitudinal components (Equivalence Theorem).
- In the EChL context, interactions among gauge bosons scale with the external momenta $\Rightarrow$ pathological predictions when energy increases $\Rightarrow$ violation of unitarity of the S matrix!
- Unitarity requires on each J^{th} partial wave of $A(V_{\lambda_1}V_{\lambda_2} \to V_{\lambda_3}V_{\lambda_4})$

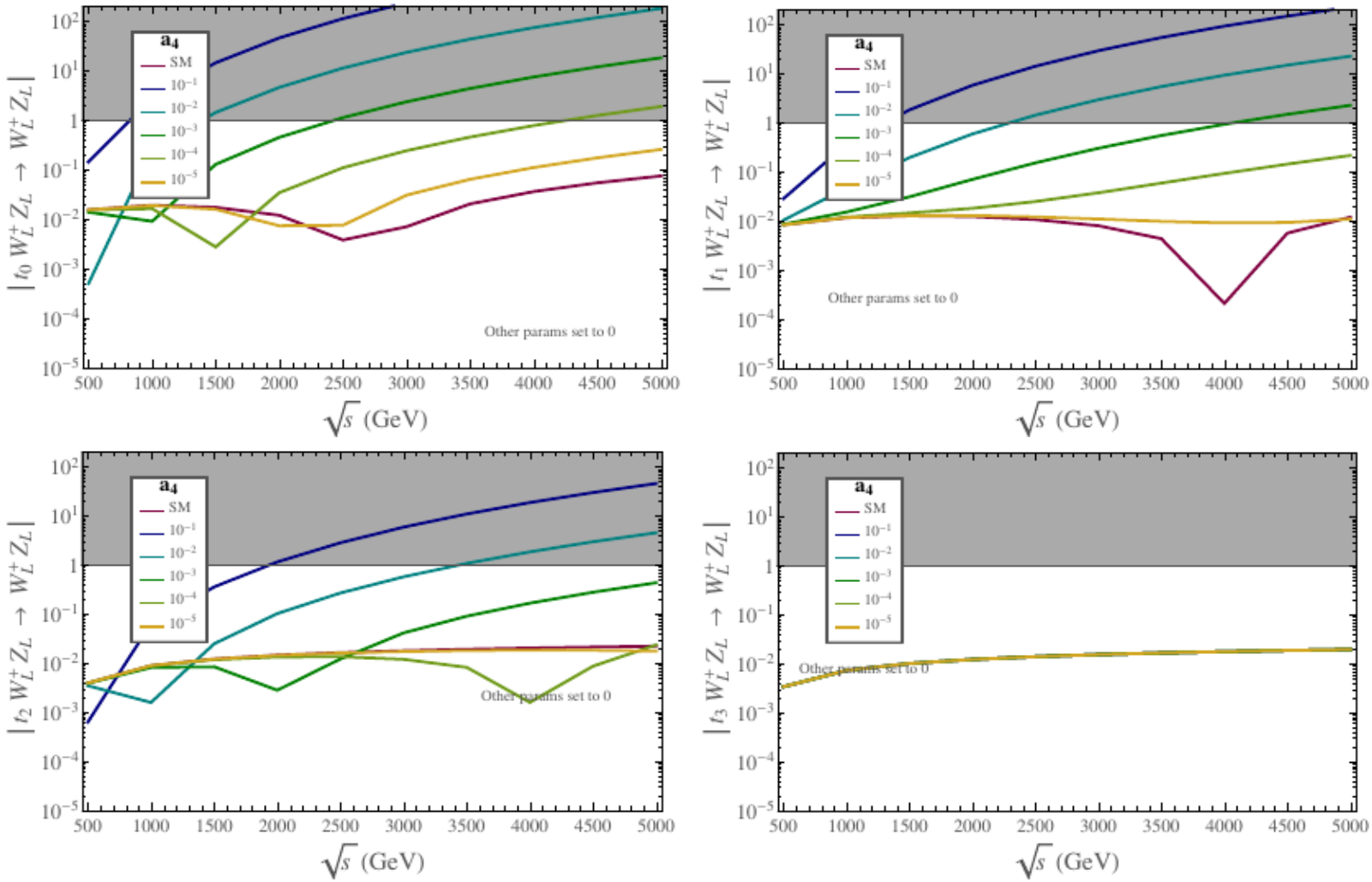
$$\mathrm{Im}[a^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s)] = \sum_{\lambda_a,\lambda_b} [a^J_{\lambda_1\lambda_2\lambda_a\lambda_b}(s)][a^J_{\lambda_a\lambda_b\lambda_3\lambda_4}(s)]^*$$

  It is a **coupled system** among all helicity states!
- Unitarity condition can be rewritten as $|a^J(s)| \leq 1$ and defines the unitary violation energy scale. This scale depends on EChL parameters.
- As in the ChPT, unitarity condition is fulfiled perturbatively

$$\mathrm{Im}[a^J_{\mathcal{O}(p^4)}(s)] = |a^J_{\mathcal{O}(p^2)}(s)|^2$$

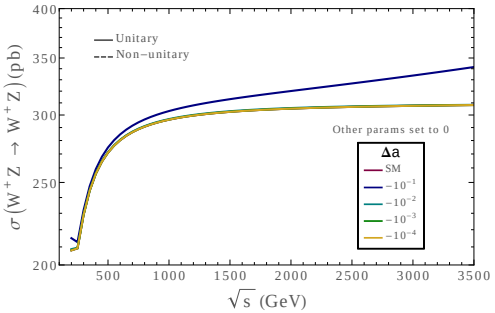
Unitarity violation in WZ scattering at partial wave level

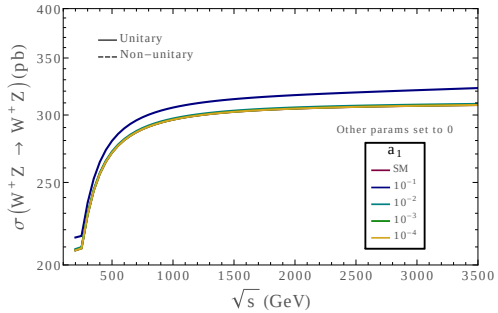
As an example, consider the helicity state $LL \to LL$ and study the effect of a_4 in the partial wave amplitudes t_J corresponding to $J = 0, 1, 2, 3$.

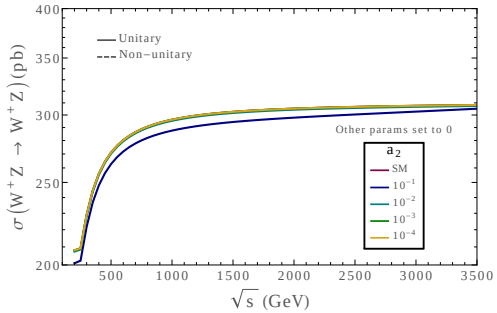


Next, consider the total cross section $\sigma(W^+Z \to W^+Z)$

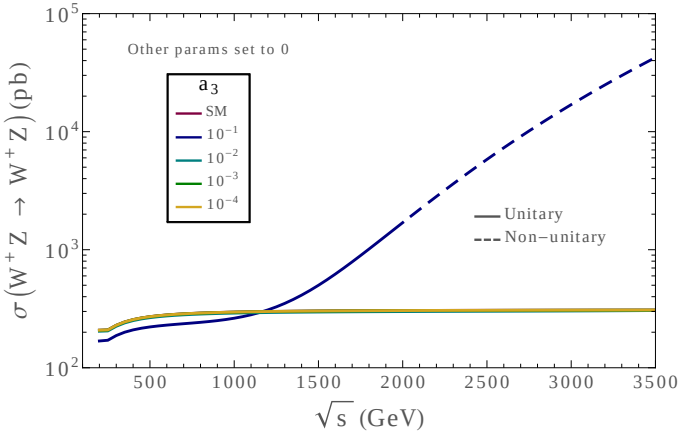
Unitarity violation in WZ scattering at subprocess level



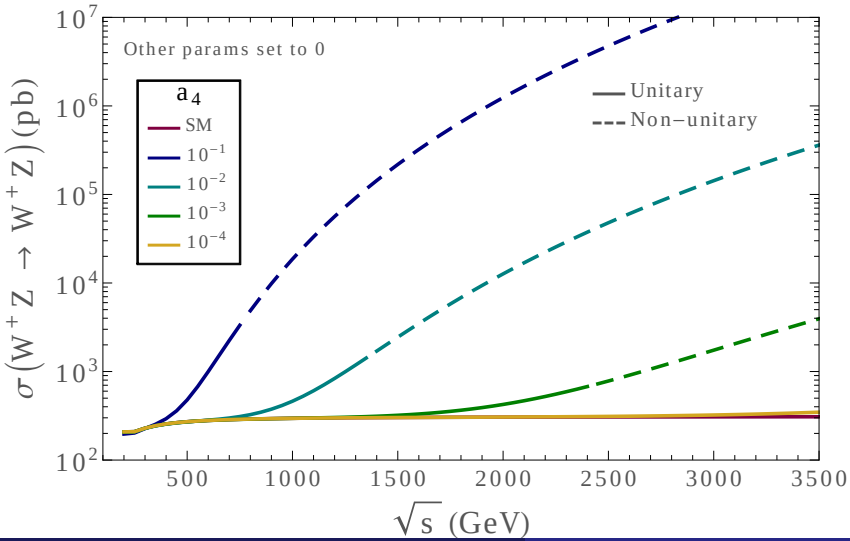


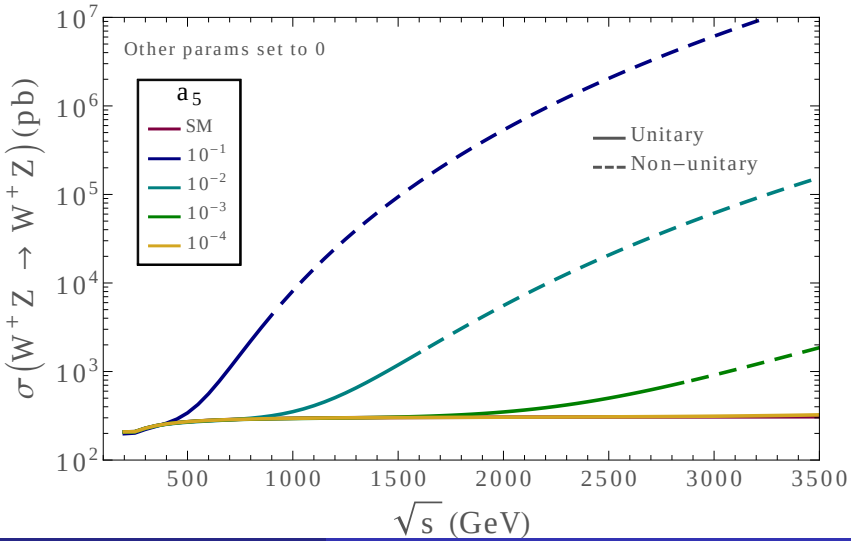


a_4 and a_5 are the most relevant parameters to unitarity violation!



$a_{LLLL}^{J=0}(s)$ is the dominant contribution to unitarity violation!

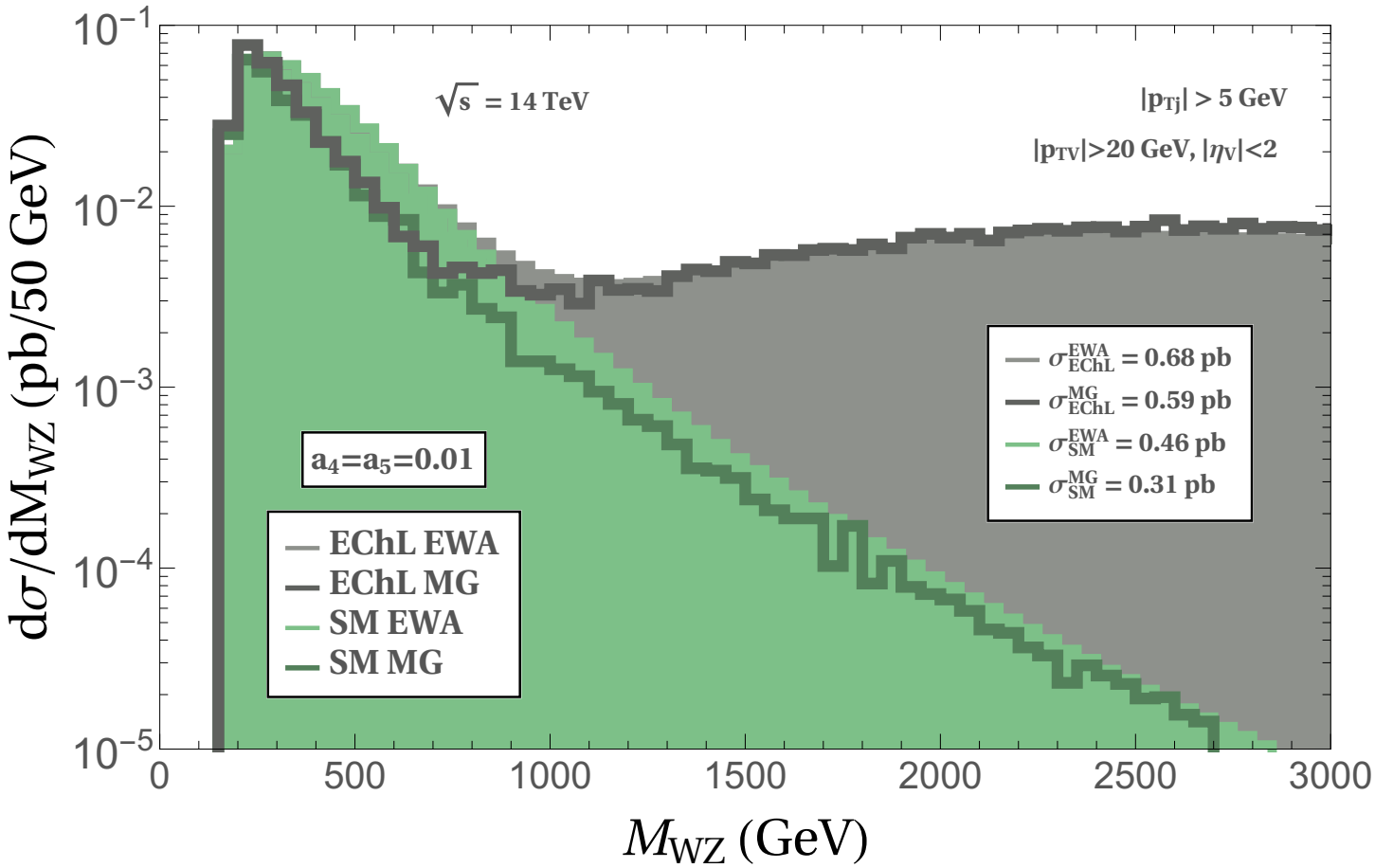




Unitarity violation in WZ scattering at the LHC

Extrapolating this prediction at subprocess level in the prediction at the LHC process $pp \to WZ + jj$

For example in the differential cross section: what happens above 1.5 TeV?



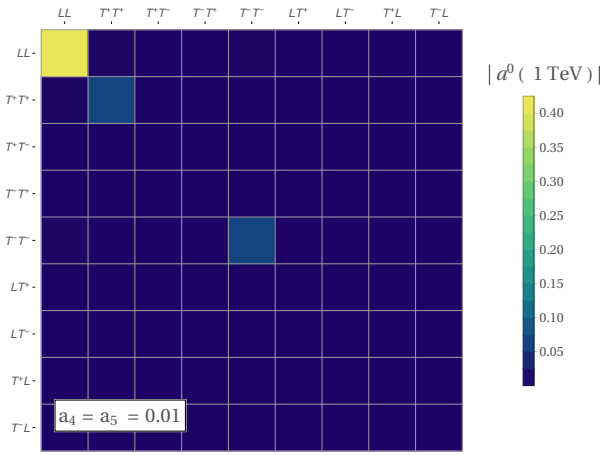
$\Rightarrow$ **unitarization for realistic predictions is mandatory!**

Coupled helicities system

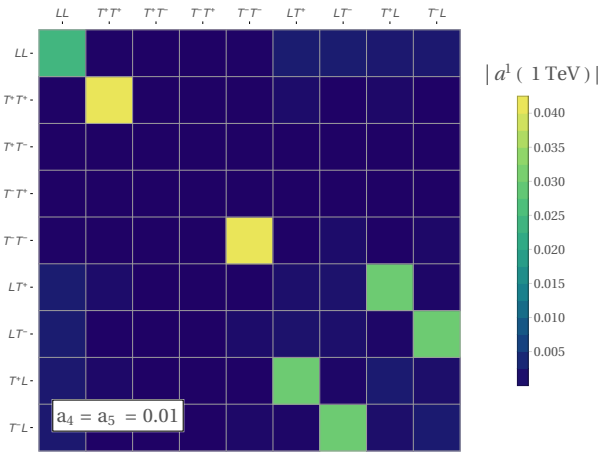
Looking at the partial wave amplitudes in order to fulfil unitarity condition:

- All the helicities channels $(9 \times 9 = 81)$ have to be considered consistently.

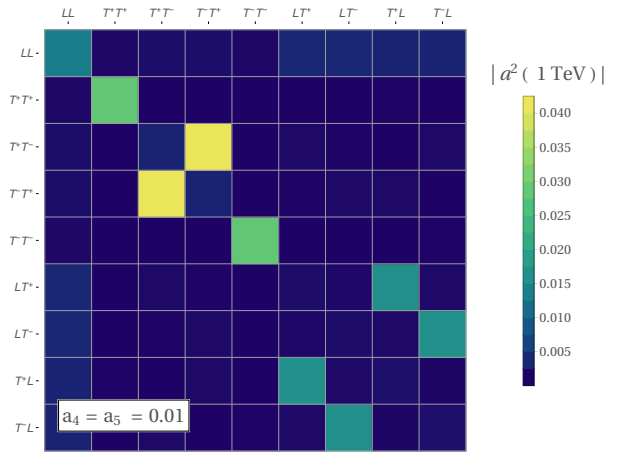
$J = 0$



$J = 1$



$J = 2$



- The i^{th} helicity amplitude grows with the CM energy like $A_i \sim s^{\xi_i}$ $\Rightarrow$ eventually reach the unitarity limit $|a_i^J| = 1$ at some scale $s = \Lambda_i$.
- Longitudinal modes only dominant for some J's or (a_4, a_5) values. In particular, $\xi_{LLLL} = 2$ can be understood through the ET.

Unitarization methods applied to the total amplitude

In order to provide unitary amplitude $\hat{A}$, several methods are implemented.

If we suppress *by hand* the pathological behaviour in the total amplitude:

- **Cut-Off**: limit the validity range of the EFT up to the minimal unitarity violation scale Λ

$$\hat{A}(WZ \to WZ) = A(WZ \to WZ) \quad \text{for } s \leq \Lambda^2$$

- **Form Factor (FF)**: suppress the pathological behaviour via multiplying the amplitude by a smooth, continuous function

$$\hat{A}(WZ \to WZ) = A(WZ \to WZ) f^{\mathrm{FF}} \quad \text{with } f^{\mathrm{FF}} = (1 + s/\Lambda^2)^{-\xi}$$

- **Kink**: now the suppression is not smooth, but through a step function

$$f^{\mathrm{Kink}} = \begin{cases} 1 & \text{if } s \leq \Lambda^2 \\ (s/\Lambda^2)^{-\xi} & \text{if } s > \Lambda^2 \end{cases}$$

Unitarization methods applied to the partial waves

In the other two methods, unitarity is recovered from partial waves directly.
Our proposal:

$$\hat{A}_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,\cos\theta) = A_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,\cos\theta) + 16\pi\sum_{J=0}^{2}(2J+1)\,d^J_{\lambda,\lambda'}(\cos\theta)\left(\hat{\mathbf{a}}^J_{[\lambda_1\lambda_2\lambda_3\lambda_4]}(s) - a^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s)\right)$$

- **K-matrix**: an imaginary part is added such that the unitarity limit is saturated. The 9×9 matrix $\mathbf{a}$ containing the whole coupled helicity system is reconstructed as

$$\hat{\mathbf{a}}^J = \mathbf{a}^J \cdot [\mathbf{1} - i\,\mathbf{a}^J]^{-1}$$

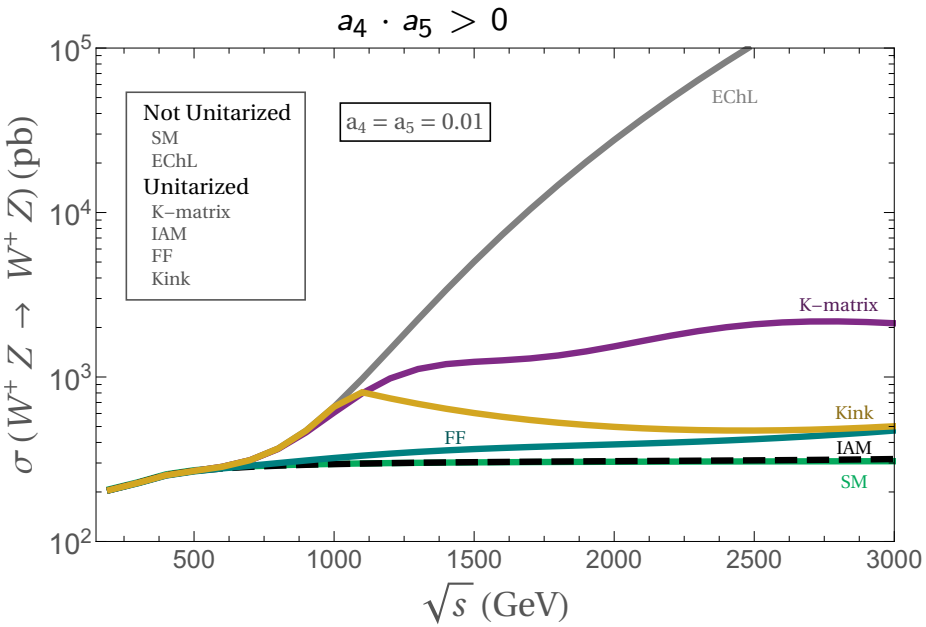
- **Inverse Amplitude Method (IAM)**: from the contributions of $\mathcal{O}(p^2)$ and $\mathcal{O}(p^4)$ in the chiral expansion, the partial wave matrix amplitude is reconstructed as

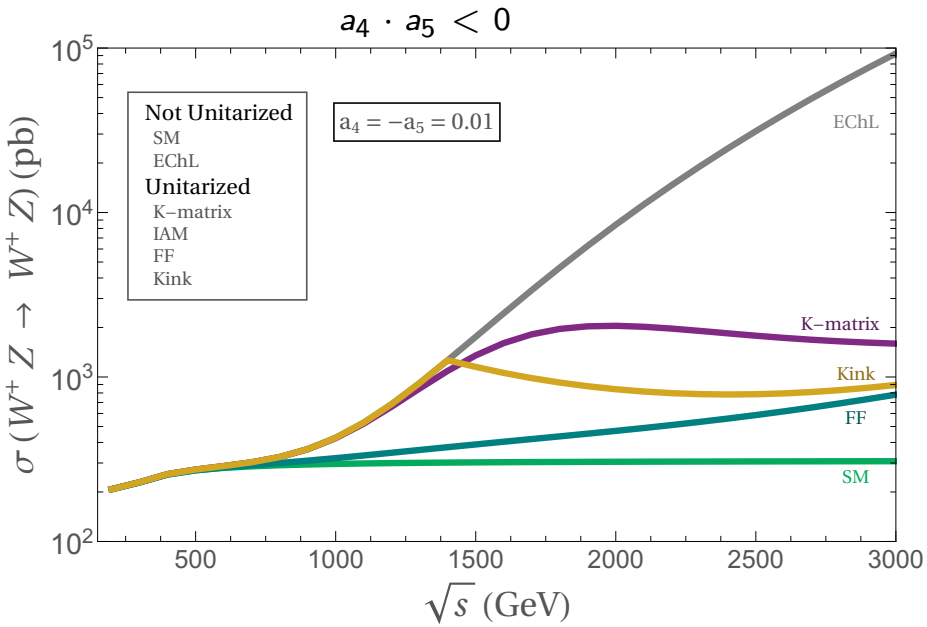
$$\hat{\mathbf{a}}^J = \mathbf{a}^{(2)\,J} \cdot [\mathbf{a}^{(2)\,J} - \mathbf{a}^{(4)\,J}]^{-1} \cdot \mathbf{a}^{(2)\,J}$$

A priori, no preferred unitarization method, but in this case:
Not only unitary predictions arise, but also the appropriate analytical structure $\Rightarrow$ dynamically generated resonances can be accommodated with this procedure (as in ChPT for pion-pion scattering).

Implications of unitarity at subprocess level

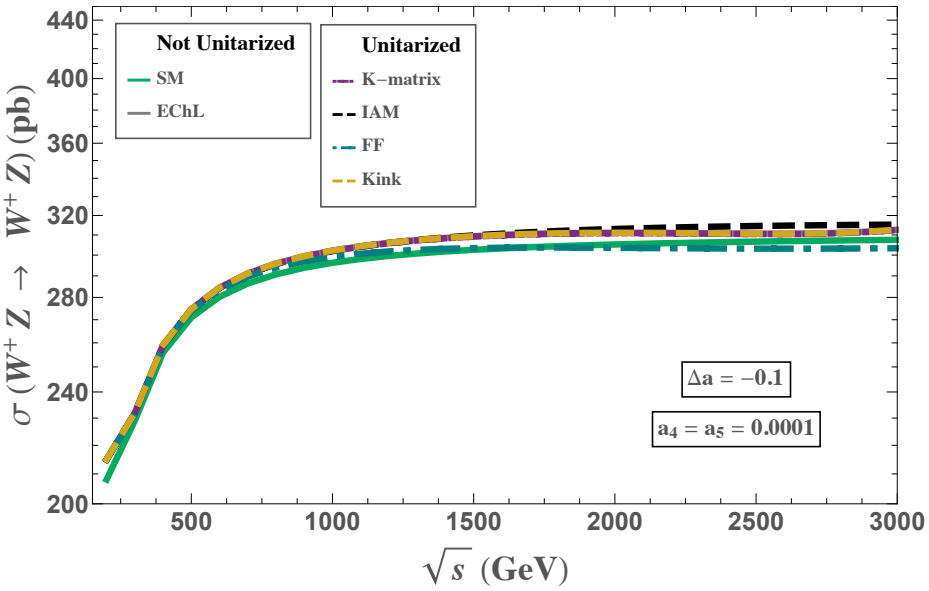
Applying the unitarization procedures to the $WZ \to WZ$ total cross section Very different predictions using different methods! $\Rightarrow$ the experimental constraints interpreted using one method or another will be different.

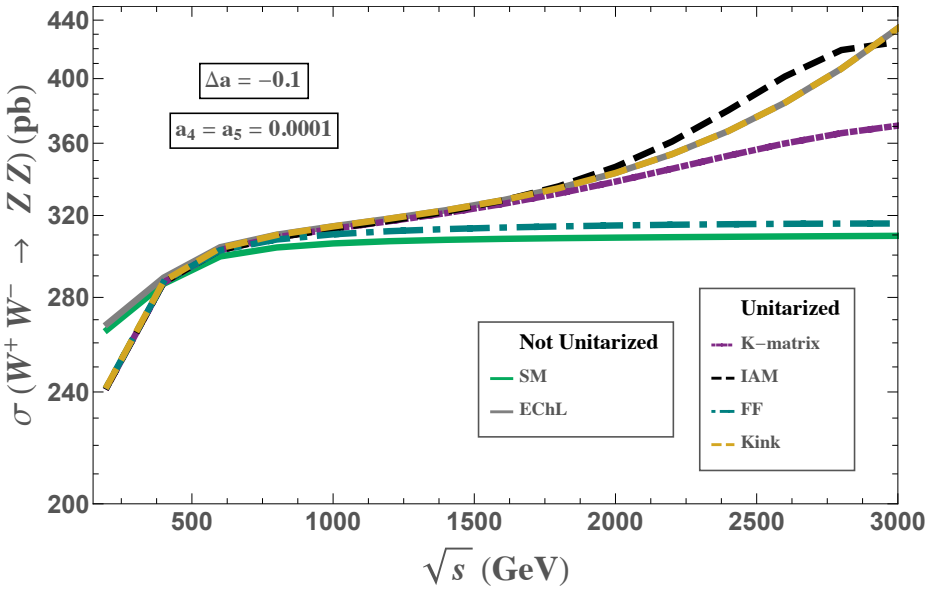


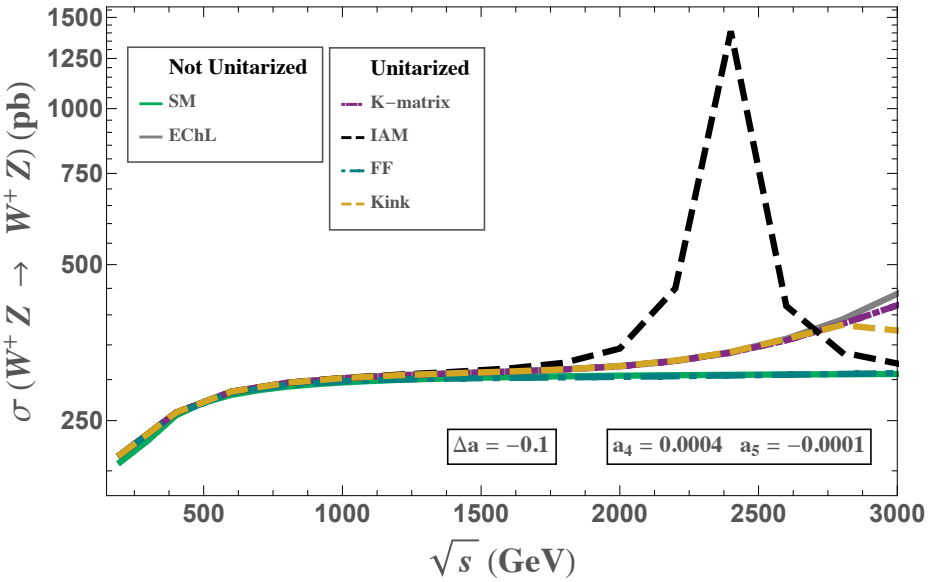


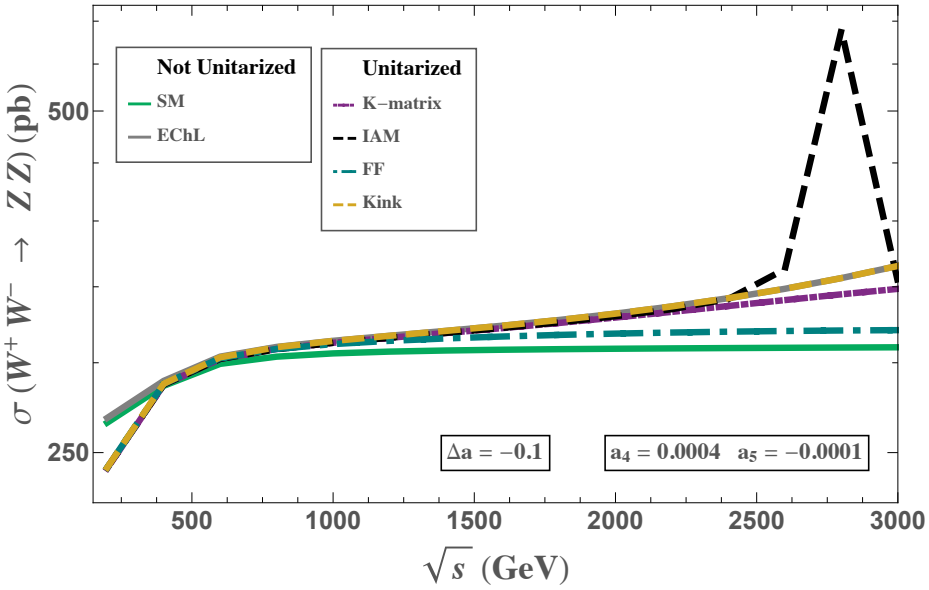
Then our aim is to give an estimate of the theoretical uncertainty in the experimental determination of a_4 and a_5 due to the unitarization scheme choice.

More benchmark points: dynamical resonances in the IAM









We work here with non-resonant scenarios below $4\pi v \sim 3$ TeV.

Present experimental constraints: no consensus yet

Current bounds are given using one method at a time or no method at all.

- Some ATLAS analyses:
  [Phys. Rev. **D95** (2017) 032001]

  use K-matrix

  for $a_{4(5)} = \alpha_{4(5)}$

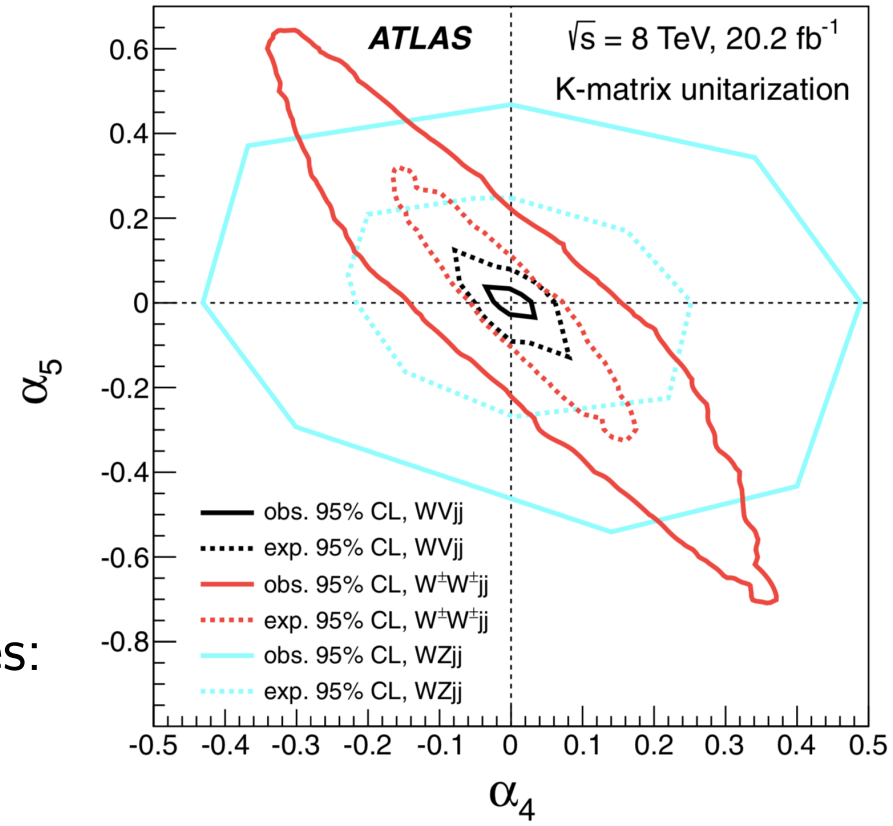
  light blue contour at 95% C.L.

  Our work focused in this Run 1

  aQGC in VBS with final state
  $W(l\nu)V(qq') + jj$

- Other ATLAS and CMS analyses:
  no unitarization method applied

  $a_{4(5)} = \frac{v^4}{16}\frac{f_{S0(S1)}}{\Lambda^4}$



	Expected (WV) (TeV^{-4})	Observed (ZV) (TeV^{-4})	Expected (ZV) (TeV^{-4})
f_{S0}/Λ^4	$[-4.2, 4.2]$	$[-40, 40]$	$[-31, 31]$
f_{S1}/Λ^4	$[-5.2, 5.2]$	$[-32, 32]$	$[-24, 24]$

95% C.L. limits for $\sqrt{s} = 13$ TeV, 35.9 fb^{-1}

[Phys. Lett. B 798 (2019)134985 (CMS)]

- Other searches: Cut-Off used.

Our computation of unitarity effects at pp collisions

1.- Unitarization applied to VBS subprocess amplitude $\Rightarrow \sigma(pp \to WZjj)$ computed with a Python code using the Effective W Approximation

That is by means of a factorization connecting the subprocess with the process.

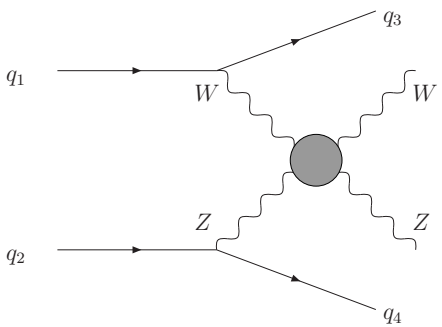
2.- Then we check the goodness of the EWA by comparing with full MG5 $pp \to WZjj$ events (VBS+others). Both in SM and EChL.

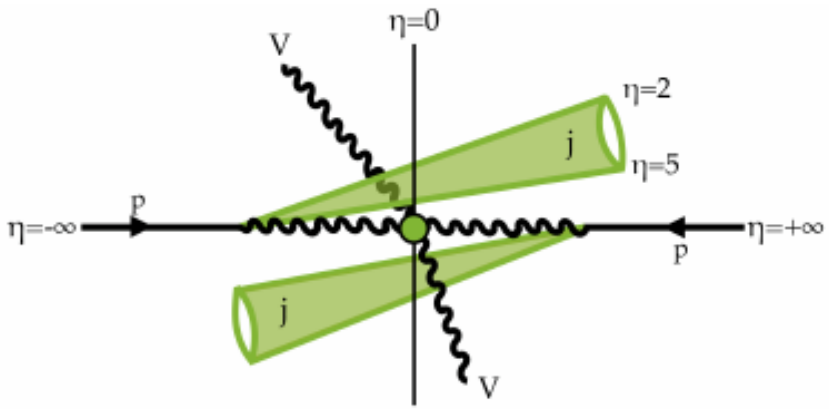
3.- We compare our predicted $\sigma^{\mathrm{EWA}}(pp \to WZjj)$ for a given unitarization method with LHC data in the (a_4, a_5) plane.

4.- VBS events usually selected by specific VBS-cuts: large pseudorapidity gap and large invariant mass (like $\Delta\eta_{jj} > 4$ and $M_{jj} > 500$ GeV).

$pp \to WZj_1j_2$

by $WZ \to WZ$ scattering





Effective W Approximation (EWA)

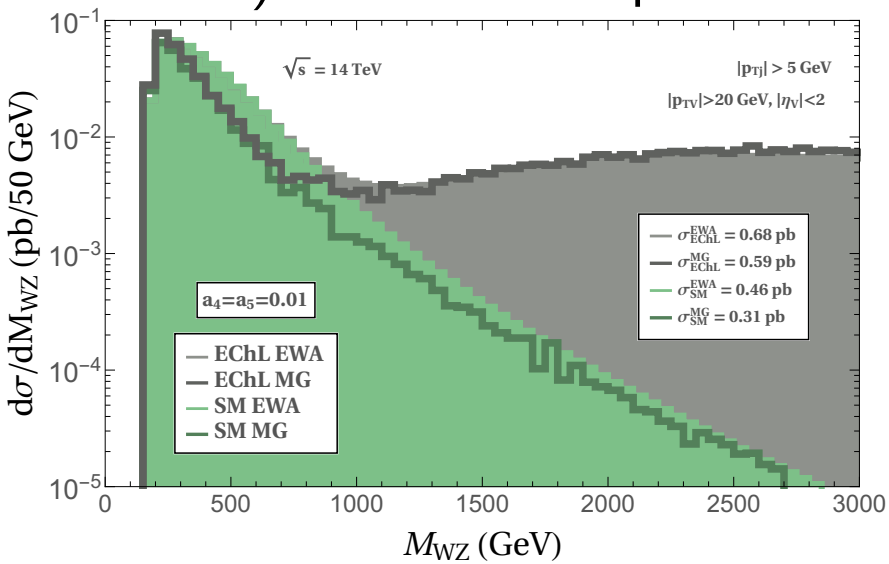
- W's and Z's considered as partons inside the proton.

  Generalization of the Weiszäcker-Williams approximation for photons.
- They are emitted collinearly from the fermions (quarks) with probability functions $f_V(\hat{x})$ and then scatter on-shell.
- Factorization using a sort of PDFs

$$\sigma(pp \to (V_1 V_2 \to V_3 V_4) + X) =$$
$$\sum_{i,j} \int\int dx_1 dx_2 f_{q_i}(x_1) f_{q_j}(x_2) \int\int d\hat{x}_1 d\hat{x}_2 f_{V_1}(\hat{x}_1) f_{V_2}(\hat{x}_2) \hat{\sigma}(V_1 V_2 \to V_3 V_4)$$

- We have tested with MG5 the accuracy of various probability functions (SM and EChL): Dawson's Improved formulas work best!

[Nucl. Phys. **B249** (1985) 42]



More about the EWA

The most accurate EWA expression in our setup is the Dawson's Improved

$$f_{V_T}^{Improved}(\hat{x}) = \frac{C_V^2 + C_A^2}{8\pi^2 \hat{x}} \eta \left[\frac{-\hat{x}^2}{1 + M_V^2/(4E^2(1-\hat{x}))} + \frac{2\hat{x}^2(1-\hat{x})}{M_V^2/E^2 - \hat{x}^2} + \left\{ \hat{x}^2 + \frac{\hat{x}^4(1-\hat{x})}{(M_V^2/E^2 - \hat{x}^2)^2} \left(2 + \frac{M_V^2}{E^2(1-\hat{x})} \right) - \frac{\hat{x}^2}{(M_V^2/E^2 - \hat{x}^2)^2} \frac{M_V^4}{2E^4} \right\} \log \left(1 + \frac{4E^2(1-\hat{x})}{M_V^2} \right) + \hat{x}^4 \left(\frac{2-\hat{x}}{M_V^2/E^2 - \hat{x}^2} \right)^2 \log \frac{\hat{x}}{2-\hat{x}} \right]$$

with $C_{V(A)}$ the vector(axial) couplings Vqq, $\hat{x}$ the fraction of quark energy $E = \frac{\sqrt{s_{qq}}}{2}$ carried by V and $\eta \equiv \left(1 - \frac{M_V^2}{\hat{x}^2 E^2}\right)^{1/2}$

In the limit $M_V \ll E$ (LLA) $\Rightarrow$

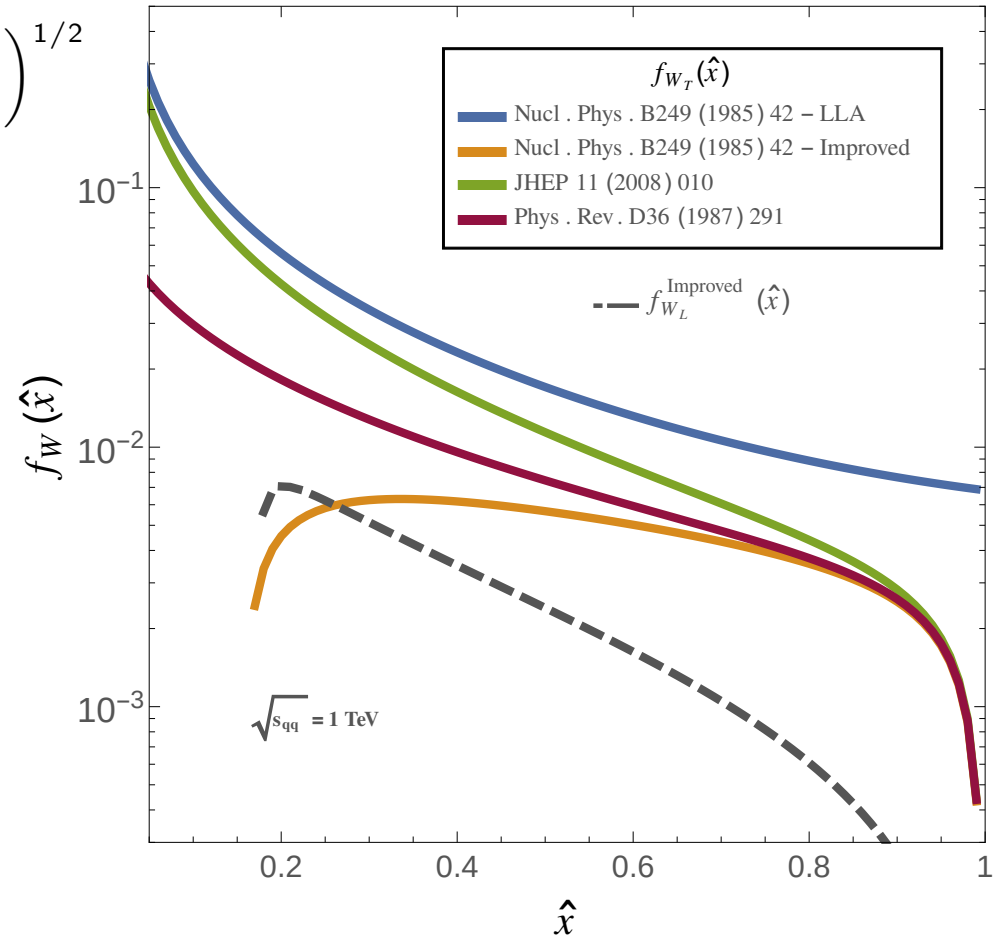
$$f_{V_T}^{LLA}(\hat{x}) = \frac{C_V^2 + C_A^2}{8\pi^2 \hat{x}} \left[\hat{x}^2 + 2(1-\hat{x}) \right] \log \left(\frac{4E^2}{M_V^2} \right)$$

Among different f_V

In the high $\hat{x}$ region: similar results.

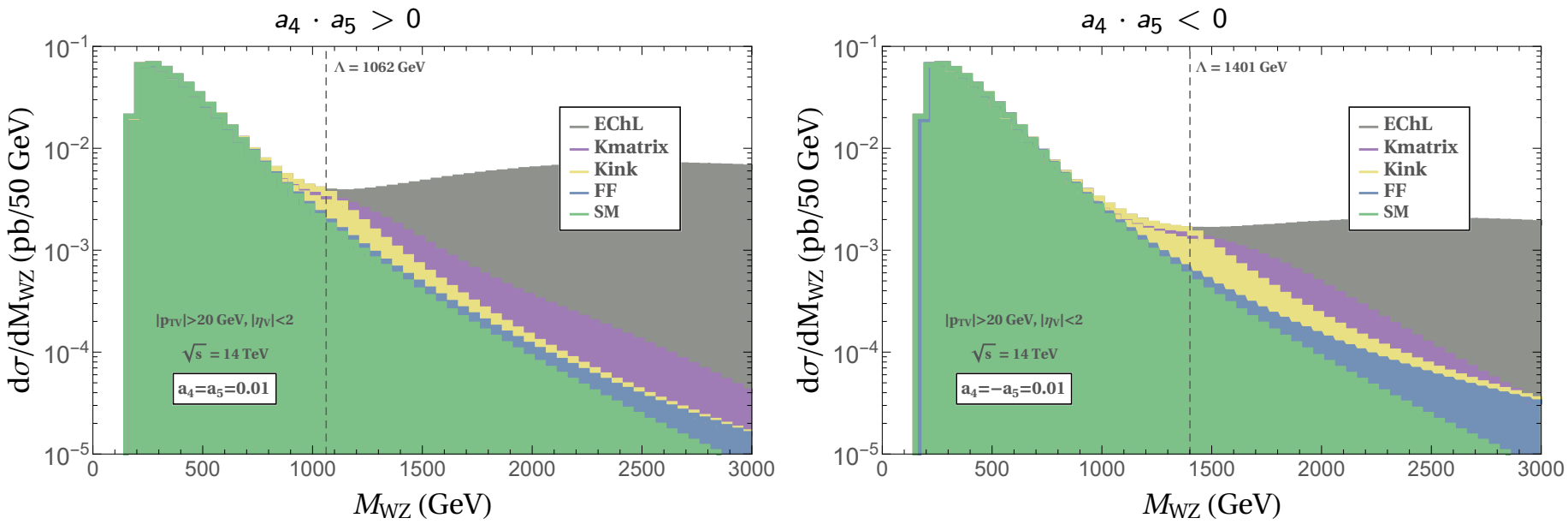
In the low $\hat{x}$ region: differ quite a lot.

Dawson's Improved gets correct $\sigma(pp \to WZ + jj)$ in low M_{WZ} region (most events here).



Predictions with different unitarization methods at LHC

- Different results depending on unitarization method also at the LHC.
- Both distributions and cross sections result to be different.

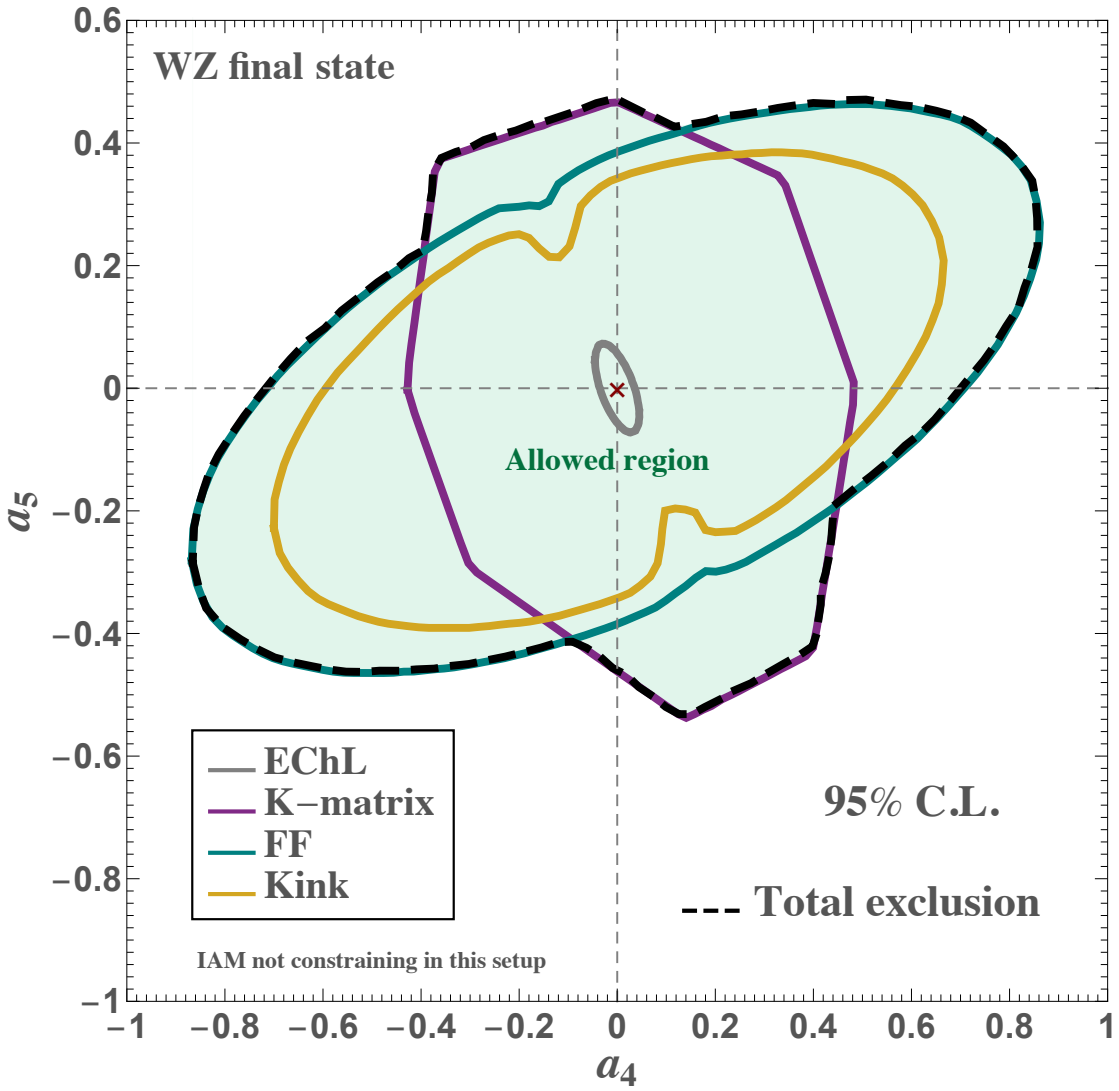


Low M_{WZ} region: all procedures give very similar predictions (ChPT).
Non-unitarized EChL: SS a_4 and a_5 is more constrained than OS.
Form Factor and Kink: OS a_4 and a_5 is more constrained than SS.
Cut-Off scale is lower in the SS case.
In both SS and OS: $\sigma_{\mathrm{EChL}} > \sigma_{\text{K-matrix}} > \sigma_{\mathrm{Kink}} > \sigma_{\mathrm{FF}}$

Our results: parameter uncertainty in (a_4, a_5) plane

- We focus on WZ Run 1 ATLAS analysis ($\sqrt{s} = 8$ TeV and $\mathcal{L} = 20.2\,\mathrm{fb}^{-1}$)
- From the ATLAS 'ellipse' (contour at 95% C.L.) for K-matrix we extract our equivalent cross section.

- For the other unitarization methods, we construct the contours at 95% C.L.
  Main assumption: selection cuts affect equaly all predictions.
- Non-unitarized gives strong constraints (small ellipse).
  $a_4.a_5 > 0$ more constrained.
- Overlap corresponds to the uncertainty in (a_4, a_5)
- Same game for linear EFTs.
- Shape and orientation change from one method to another. Size enhances by ~ 10 the uncertainty respect to the non-unitarized constraints.



Conclusions

- EFT is a powerful tool to study New Physics in a model-independent way.
- EChL is the most general EFT suitable for strongly interacting scenarios of EWSB. This EFT approach might lead to event predictions that violate unitarity.
- VBS is the key observable of this kind of physics.
- Unitarization methods must be applied in order to provide unitary predictions:
  $\Rightarrow$ different unitarization procedures lead to different predictions for VBS.
  $\Rightarrow$ a theoretical uncertainty is associated with this ambiguity.
- We provide a first approximation to quantify this uncertainty in the experimental determination of (a_4, a_5) due to the unitarization scheme choice through the elastic WZ scattering at the LHC.

$\Rightarrow$ this theoretical uncertainty can be large and
it must be taken into account in the interpretation of the
experimental data.

Thank you!

Backup slides

Transformations under $SU(2)_L \times SU(2)_R$

The rotations under $SU(2)_L$ and $SU(2)_R$ correspond to

$$g_L = e^{i\vec{\tau}\cdot\vec{\alpha}_L/2} \quad \text{and} \quad g_R = e^{i\vec{\tau}\cdot\vec{\alpha}_R/2}$$

Then building blocks transform under the global $SU(2)_L \times SU(2)_R$ as

$$U \mapsto U' = g_L\, U\, g_R^\dagger \qquad \text{with chiral dim.} = 0$$

$$\hat{B}_\mu \mapsto \hat{B}'_\mu = \hat{B}_\mu \qquad \text{with chiral dim.} = 1$$

$$\hat{W}_\mu \mapsto \hat{W}'_\mu = g_L\, \hat{W}_\mu\, g_L^\dagger \qquad \text{with chiral dim.} = 1$$

$$D_\mu U \mapsto (D_\mu U)' = g_L\, D_\mu U\, g_R^\dagger \qquad \text{with chiral dim.} = 1$$

$$\hat{B}_{\mu\nu} \mapsto \hat{B}'_{\mu\nu} = \hat{B}_{\mu\nu} \qquad \text{with chiral dim.} = 2$$

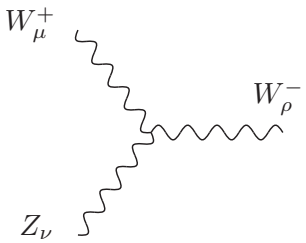
$$\hat{W}_{\mu\nu} \mapsto \hat{W}'_{\mu\nu} = g_L\, \hat{W}_{\mu\nu}\, g_L^\dagger \qquad \text{with chiral dim.} = 2$$

For the EW gauge symmetry $SU(2)_L \times U(1)_Y \subset SU(2)_L \times SU(2)_R$, the association of the generator of $U(1)_Y$ as the third one of the $SU(2)_R$ and the generator of $U(1)_{EM}$ as the third one of the $SU(2)_{L+R}$:

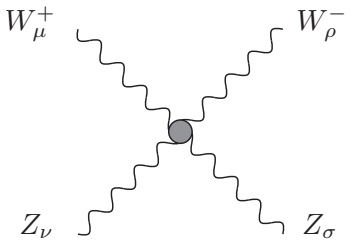
$$Y \leftrightarrow X_R^3 \;\text{ and }\; Q \leftrightarrow X_{L+R}^3 = T^3 + Y$$

Relevant Feynman rules for $A(WZ \to WZ)^{\mathrm{EChL}}$

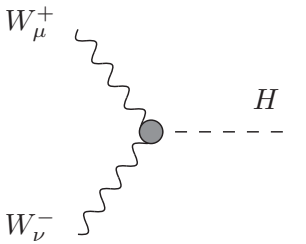
Simplified scenario: only effects of a, a_4 and a_5



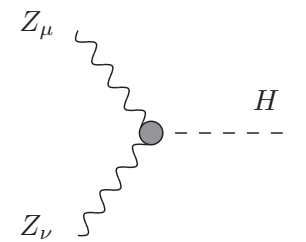
$$V^{EChL}_{W_\mu^+ W_\rho^- Z_\nu} = V^{SM}_{W_\mu^+ W_\rho^- Z_\nu}$$



$$V^{EChL}_{W_\mu^+ W_\rho^- Z_\nu Z_\sigma} = ig^2 c_{\mathrm{w}}^2 \Big[g_{\mu\nu} g_{\rho\sigma} + g_{\mu\sigma} g_{\nu\rho} - 2 g_{\mu\rho} g_{\nu\sigma} \Big] + \frac{ig^4}{c_{\mathrm{w}}^2} \Big[a_4 \big(g_{\mu\nu} g_{\rho\sigma} + g_{\mu\sigma} g_{\nu\rho} \big) + 2\, a_5 \big(g_{\mu\rho} g_{\nu\sigma} \big) \Big]$$



$$V^{EChL}_{W_\mu^+ W_\nu^- H} = igM_W g_{\mu\nu} + igM_W (a-1)\, g_{\mu\nu}$$



$$V^{EChL}_{Z_\mu Z_\nu H} = \frac{igM_Z}{c_{\mathrm{w}}} g_{\mu\nu} + \frac{igM_Z}{c_{\mathrm{w}}} (a-1)\, g_{\mu\nu}$$

Experimental searches for the ECHL parameters (95% C. L.)

- a_1: EW precision measurements (S parameter) [Pyhs. Rev. **D98** (2018) 030001 (PDG)]

$$-0.12 < S^{obs} = -4\pi a_1 < 0.16$$

- a_2 and a_3: ATLAS global-fit in the search with $\sqrt{s} = 13$ TeV and $\mathcal{L} = 36$ fb^{-1} looking for W^+W^- and $W^\pm Z$ (full leptonic decays) via VBF [Pyhs. Rev. **D99** (2019) 033001 (ATLAS)] $\Rightarrow$ aTGC (γW^+W^- and ZW^+W^-)

$$-8.3 < \frac{f_B}{\Lambda^2} = \frac{8(a_2 - a_1)}{v^2} < 26 \text{ and } -3 < \frac{f_W}{\Lambda^2} = -\frac{8a_3}{v^2} < 3.7$$

- a_4 and a_5: CMS search for anomalous EW production of W^+W^-, $W^\pm Z$ and ZZ plus 2 jets with $\sqrt{s} = 13$ TeV and $\mathcal{L} = 36$ fb^{-1} [Phys. Lett. B 798 (2019)134985 (CMS)] $\Rightarrow$ aQGC ($W^+W^-W^+W^-$ and ZZW^+W^-)

$$-2.7 < \frac{f_{S0}}{\Lambda^4} = \frac{16a_4}{v^4} < 2.7 \text{ and } -3.4 < \frac{f_{S1}}{\Lambda^4} = -\frac{16a_5}{v^4} < 3.4$$

- Δa: ATLAS combined measurements of all Higgs production and decay modes with $\sqrt{s} = 13$ TeV and $\mathcal{L} = 80$ fb^{-1} [Phys. Rev. **D101** 012002 (ATLAS)]

$$0.94 < \kappa_V = 1 + \Delta a < 1.14$$

- Δb: ATLAS search for $HH \to b\bar{b}b\bar{b}$ via VBF with $\sqrt{s} = 13$ TeV and $\mathcal{L} = 126$ fb^{-1} [ATLAS-CONF-2019-030 (2001.05178)]

$$-0.56 < \kappa_{2V} = 1 + \Delta b < 2.89$$

Unitarized amplitudes

The partial wave decomposition is

$$a^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s) = \frac{1}{32\pi}\int_{-1}^{1} d\cos\theta\ A(V_{\lambda_1}V_{\lambda_2}\to V_{\lambda_3}V_{\lambda_4})(s,\cos\theta)\, d^J_{\lambda,\lambda'}(\cos\theta)$$

where J is the total angular momentum of the system, $\lambda = \lambda_1 - \lambda_2$, $\lambda' = \lambda_3 - \lambda_4$, being λ_i the helicity states of the external gauge bosons, and where $d^J_{\lambda,\lambda'}(\cos\theta)$ are the Wigner functions.

For the K-matrix and IAM methods, the unitarized amplitude is reconstructed from the corresponding unitarized partial wave and the non-unitary amplitudes following:

$$\begin{aligned}\hat{A}_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,\cos\theta) = A_{\lambda_1\lambda_2\lambda_3\lambda_4}(s,\cos\theta)&\\ - 16\pi\sum_{J=0}^{2}(2J+1)\, d^J_{\lambda,\lambda'}(\cos\theta)\, a^J_{\lambda_1\lambda_2\lambda_3\lambda_4}(s)&\\ + 16\pi\sum_{J=0}^{2}(2J+1)\, d^J_{\lambda,\lambda'}(\cos\theta)\, \hat{\mathbf{a}}^J_{[\lambda_1\lambda_2\lambda_3\lambda_4]}(s)&\end{aligned}$$

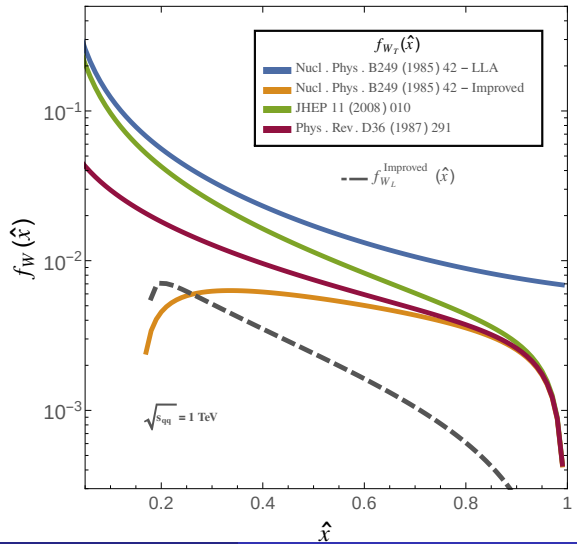
More about the EWA

The most accurate EWA expression in our setup is the Dawson's Improved

$$f_{V_T}^{Improved}(x) = \frac{C_V^2+C_A^2}{8\pi^2 x}\left[\frac{-x^2}{1+M_V^2/(4E^2(1-x))}+\frac{2x^2(1-x)}{M_V^2/E^2-x^2}+\left\{x^2+\frac{x^4(1-x)}{(M_V^2/E^2-x^2)^2}\left(2+\frac{M_V^2}{E^2(1-x)}\right)-\frac{x^2}{(M_V^2/E^2-x^2)^2}\frac{M_V^4}{2E^4}\right\}\log\left(1+\frac{4E^2(1-x)}{M_V^2}\right)+x^4\left(\frac{2-x}{M_V^2/E^2-x^2}\right)^2\log\frac{x}{2-x}\right]\eta$$

$$f_{V_L}^{Improved}(x) = \frac{C_V^2+C_A^2}{\pi^2}\frac{1-x}{x}\frac{\eta}{(1+\eta)^2}\left\{\frac{1-x-M_V^2/(8E^2)}{1-x+M_V^2/(4E^2)}-\frac{M_V^2}{4E^2}\frac{1+2(1-x)^2}{1-x+M_V^2/(4E^2)}\frac{1}{M_V^2/E^2-x^2}\right.$$
$$-\frac{M_V^2}{4E^2}\frac{x^2}{2(1-x)(x^2-M_V^2/E^2)^2}\left[(2-x)^2\log\frac{x}{2-x}-\left(\left(x-\frac{M_V^2}{E^2x}\right)^2-(2(1-x)+x^2)\right)\log\left(1+\frac{4E^2(1-x)}{M_V^2}\right)\right]$$
$$\left.-\frac{M_V^2}{8E^2}\frac{x}{\sqrt{x^2-M_V^2/E^2}}\left[\frac{2}{x^2-M_V^2/E^2}+\frac{1}{1-x}\right]\left[\log\frac{2-x-\sqrt{x^2-M_V^2/E^2}}{2-x+\sqrt{x^2-M_V^2/E^2}}-\log\frac{x-\sqrt{x^2-M_V^2/E^2}}{x+\sqrt{x^2-M_V^2/E^2}}\right]\right\}$$

with $C_{V(A)}$ the vector(axial) couplings Vqq, x the fraction of quark energy $E=\frac{\sqrt{s_{qq}}}{2}$ carried by V and $\eta \equiv \left(1-\frac{M_V^2}{x^2E^2}\right)^{1/2}$



In the limit $M_V \ll E$ (LLA) $\Rightarrow$

$$f_{V_T}^{LLA}(x) = \frac{C_V^2+C_A^2}{8\pi^2 x}\left[x^2+2(1-x)\right]\log\left(\frac{4E^2}{M_V^2}\right)$$

$$f_{V_L}^{LLA}(x) = \frac{C_V^2+C_A^2}{\pi^2}\frac{1-x}{x}$$