[Jenny, Maas and BR **PRD** 105 (2022), **arXiv: 2204.02756**]

Vector boson scattering from augmented perturbation theory

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FWF Der Wissenschaftsfonds.
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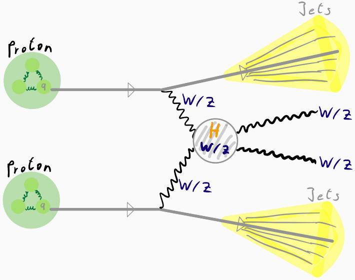
Vector boson scattering

- Very important process of electroweak physics
- Heavily studied in experiments
- Especially for BSM searches



- **This talk**: Pathway to measuring finite extent of “Higgs”
- Why bother?
- Necessary for scenarios where Higgs is composite
  - E.g. in BSM: composite Higgs, Technicolor, ...
  - Maybe additional background from within the SM?

Scattering processes

[Sakurai, Napolitano **Modern Quantum Mechanics** (2020)]

- **Experiment**: cross-sections in specified decay channel
- **Theory**: cross-sections from fundamental theory

$$\frac{d\sigma}{d\Omega} \propto |\mathcal{M}|^2 \qquad \mathcal{M} \ldots \text{Transition matrix}$$

- Specify channel e.g. Higgs: $J^P_{\mathcal{C}} = 0^+_0 \leftrightarrow$ needs a partial wave analysis

$$\mathcal{M} \propto \sum_J (2J+1) \underbrace{e^{i\delta_J} \sin(\delta_J)}_{f_J \ldots \text{partial transition amplitude}} P_J(\cos\theta)$$

- Phase shift δ_J contains full scattering information

How is δ_J modified for intermediate states with finite radius?

Including finite size contribution

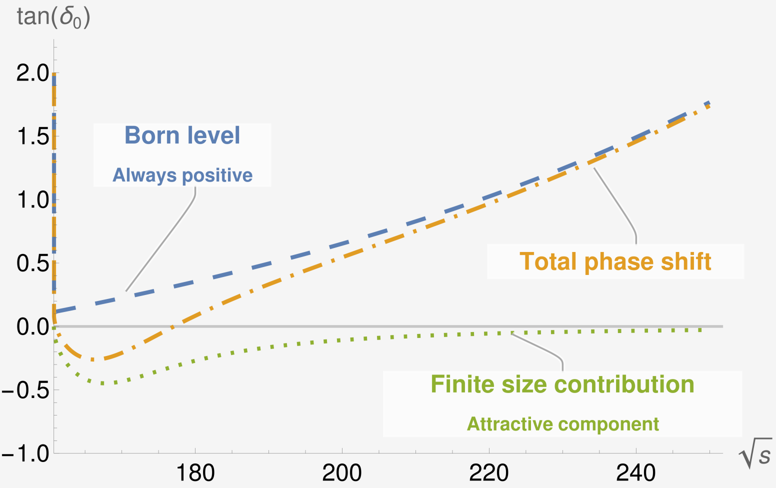
[Sakurai, Napolitano **Modern Quantum Mechanics** (2020) / Jenny, Maas and BR **PRD** 105 (2022), **arXiv: 2204.02756**]

- Focus on process: $W^{\pm}W^{\mp}/ZZ \to W^{\pm}W^{\mp}/ZZ$
- Close to elastic threshold additional attractive component
- Can be described by the scattering length a_0

$$\tan(\delta_J) \approx \frac{\sqrt{s-4m_W^2}}{a_0^{-1}} \qquad \text{@ elastic threshold}$$

- **Negative** scattering length $\leftrightarrow$ **Bound state** of some size
- Inside the elastic region $\to$ contribution becomes small
- Modification of perturbative approximation:

$$\tan(\delta_J) \to \tan(\delta_{J,\mathrm{PT}}) - \Delta f(a_0, s)$$



Mock-up: **Phase shift** modification for Higgs with $m_H = 125$ GeV and $a_0^{-1} \approx 40$ GeV.

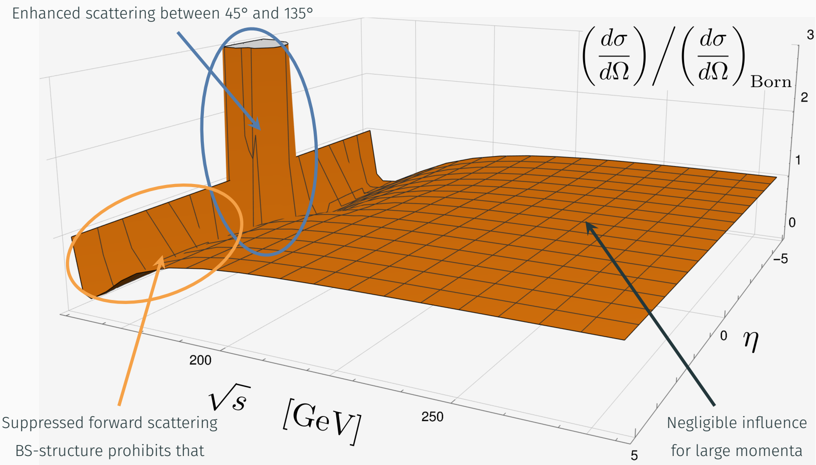
- Modification of $\tan(\delta_J)$ $\leftrightarrow$ direct impact on cross-section
- Ratio of modified differential cross-sections to usual PT

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{mod.}} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{\text{PT}} = \left|1 - \frac{2\mathcal{M}_{\Delta f}}{\mathcal{M}_{\text{PT}}}\left(1 - \frac{\mathcal{M}_{\Delta f}}{2\mathcal{M}_{\text{PT}}}\right)\right|$$

- Deviations expected only for $\mathcal{M}_{\Delta f} \gg \mathcal{M}_{\text{PT}}$
  - for $\sqrt{s}$ close to elastic threshold E_{th}
  - requires $E_{th} \lessapprox m_H + \left|a_0^{-1}\right|$

What do these deviations look like?

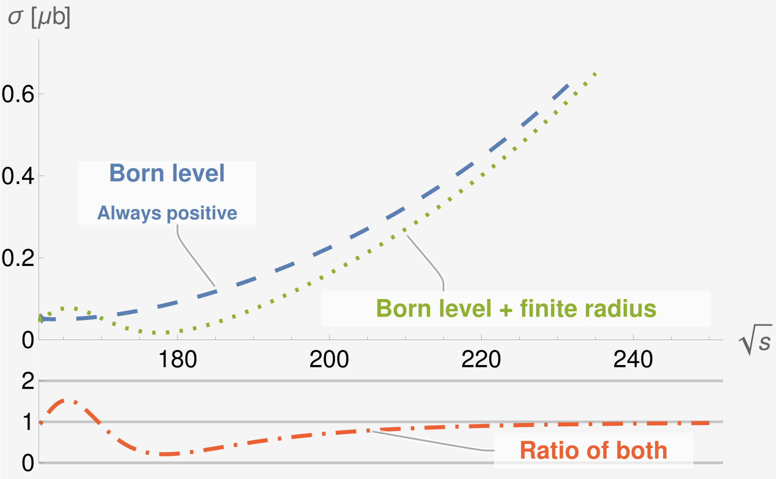
Including finite size contribution



Mock-up: **Differential cross-section** modification for Higgs with $m_H = 125$ GeV and $a_0^{-1} \approx 40$ GeV.

Including finite size contribution

[Jenny, Maas and BR **PRD** 105 (2022), **arXiv: 2204.02756**]



Mock-up: **Integrated cross-section** modification for Higgs with $m_H = 125$ GeV and $a_0^{-1} \approx 40$ GeV.

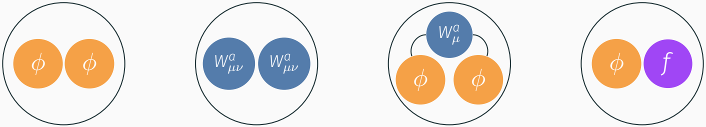
[Fröhlich et al., PL **B97** (1980) and NP **B190** (1981) / **REVIEW:** Maas **PPNP** 106 (2019), **arXiv: 1712.04721**]

There are still two open questions in this talk:

1. Why are there SM-like Higgs masses used in mock-ups?
2. What does "augmented perturbation theory" refer to?

Field theory **requires** physical states to be gauge-invariant

$\rightarrow$ All weakly interacting particles are bound states



Usual point-like assumption is not valid $\rightarrow$ finite radius

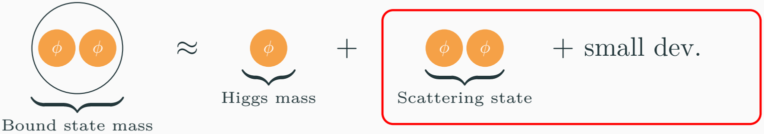
A possible SM-background?

[Fröhlich et al., PL **B97** (1980) and NP **B190** (1981) / **REVIEW:** Maas **PPNP** 106 (2019), **arXiv: 1712.04721**]

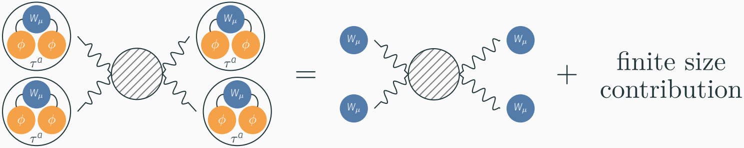
- "Augmented perturbation theory" (APT)

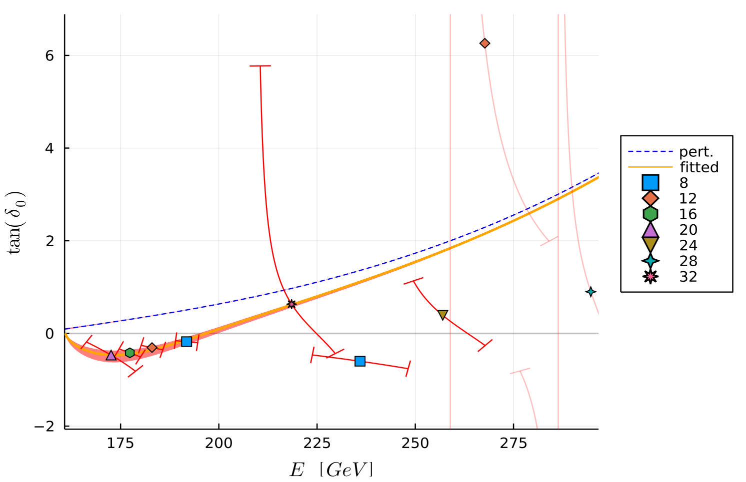
  Maps: **bound state** correlators ↔ **perturbative** correlators
- Masses are unaffected by finite size

  [Maas and Sondenheimer **PRD** 102 (2020) / Dudal et al. **EPJ** C81 (2021)]



- Scattering processes are sensitive to the change





Tangent of phase shift: **Lattice result (w. statistical errors) + Born-level PT + finite size contribution**

$E_{th} \approx 160$ GeV; $m_H \approx 148$ GeV; $\alpha_{W,200\text{ GeV}} = 0.492$; $a_0^{-1} \approx -39$ GeV

[Jenny, Maas and BR **PRD** 105 (2022), **arXiv:** **2204.02756**
REVIEW: Maas **PPNP** 106 (2019), **arXiv:** **1712.04721**]

- VBS process allows to probe "composite-ness" of the Higgs
  - → from SM
  - → from BSM
- Can be identified from modifications of the cross-section close to threshold
- Field theory **requires unaccounted-for SM background**
- Either way guarantees a discovery of ...
  - → a subtle SM-effect
  - → something new

[Jenny, Maas and BR **PRD** 105 (2022), **arXiv: 2204.02756**]

Thank you!

Der Wissenschaftsfonds.

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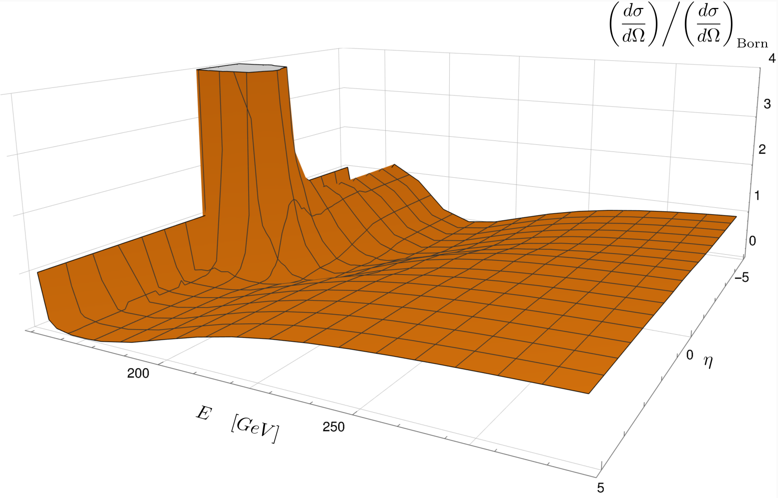
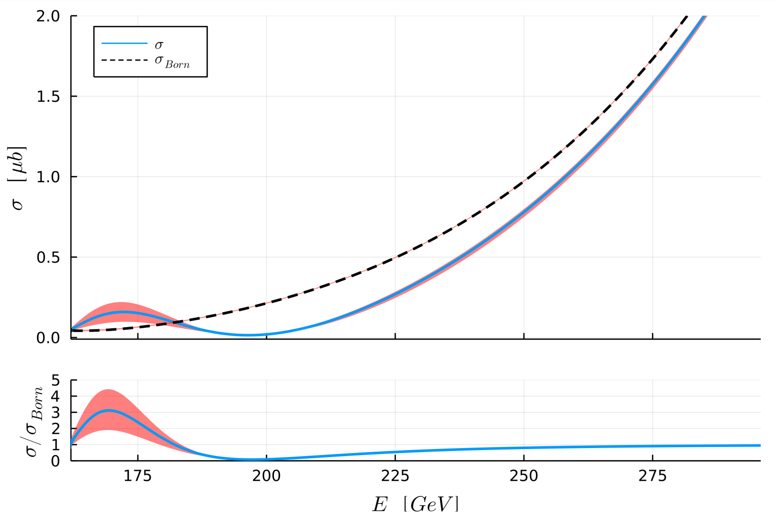
Reduced SM with large α_W



Modification of differential cross-section: $E_{th} \approx 160$ GeV; $m_H \approx 148$ GeV; $a_0^{-1} \approx -39$ GeV

Reduced SM with large α_W

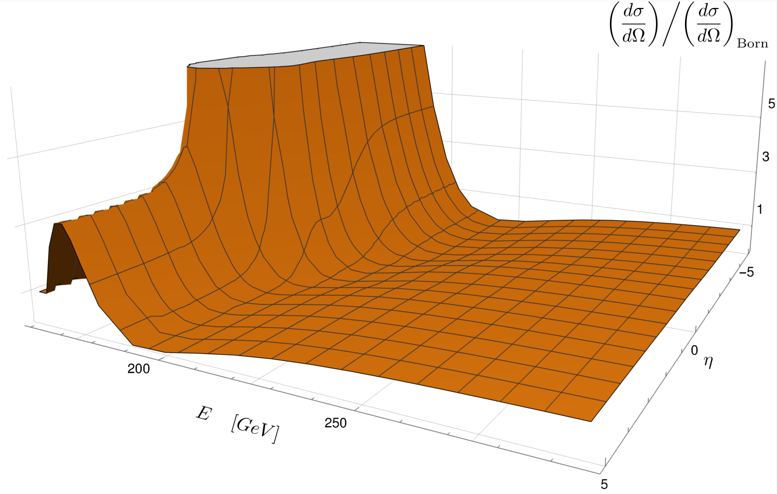
[Jenny, Maas and BR **PRD** 105 (2022), **arXiv: 2204.02756**]



Integrated cross-sections (top) and ratio of these (bottom)

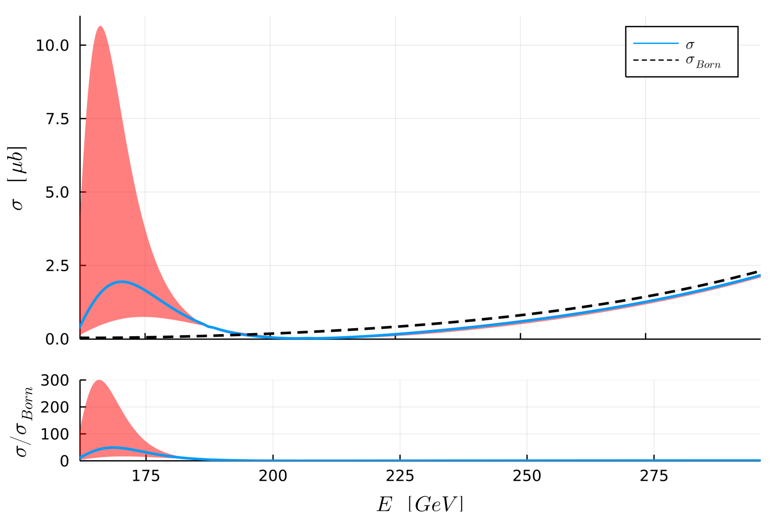
Reduced SM with large α_W

[Jenny, Maas and BR **PRD** 105 (2022), **arXiv: 2204.02756**]



Modification of differential cross-section: $E_{th} \approx$ 160 GeV; $m_H \approx$ 149 GeV; $a_0^{-1} \approx -12$ GeV

Reduced SM with large α_W



Integrated cross-sections (top) and ratio of these (bottom)

Augmented Perturbation Theory (Masses)

[Fröhlich et al., PL **B97** (1980) and NP **B190** (1981) / Maas, PPNP **106** (2019), **arXiv: 1712.04721**]

1. Formulate gauge-invariant operator and correlator e.g.:

$$0^+ \text{ singlet:} \quad H(x) = \left(\phi_i^\dagger \phi_i\right)(x)$$

$$\langle H(x)H(y)\rangle = \left\langle \left(\phi_i^\dagger \phi_i\right)(x)\left(\phi_j^\dagger \phi_j\right)(y)\right\rangle$$

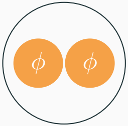
2. Expand Higgs field in fixed gauge $\phi_i = vn_i + h_i$

$$\left\langle \left(\phi_i^\dagger \phi_i\right)(x)\left(\phi_j^\dagger \phi_j\right)(y)\right\rangle = dv^4 + 4v^2 \left\langle \Re\left[n_i^\dagger h_i\right]^\dagger(x)\Re\left[n_j^\dagger h_j\right](y)\right\rangle +$$
$$+2v\left\{\left\langle \left(h_i^\dagger h_i\right)(x)\Re\left[n_j^\dagger h_j\right](y)\right\rangle + (x \leftrightarrow y)\right\} + \left\langle \left(h_i^\dagger h_i\right)(x)\left(h_j^\dagger h_j\right)(y)\right\rangle$$

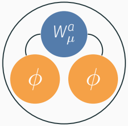
3. Perform standard Perturbation Theory

$$\left\langle \left(\phi_i^\dagger \phi_i\right)(x)\left(\phi_j^\dagger \phi_j\right)(y)\right\rangle = d'v^4 + 4v^2 \left\langle \Re\left[n_i^\dagger h_i\right]^\dagger(x)\Re\left[n_j^\dagger h_j\right](y)\right\rangle_{\text{tl}} +$$
$$+ \left\langle \Re\left[n_i^\dagger h_i\right]^\dagger(x)\Re\left[n_j^\dagger h_j\right](y)\right\rangle_{\text{tl}}^2 + \mathcal{O}(g^2, \lambda)$$

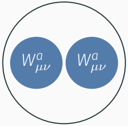
Gauge invariant weakly interacting particles

Physical Higgs: $\mathcal{O}^{0^+_0} =$ 

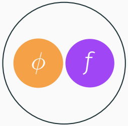
$= \phi^\dagger\phi = \frac{1}{2}\,\mathrm{tr}\left\{\Phi^\dagger\Phi\right\}$

Physical W^a_μ: $\mathcal{O}^{1^-_1\,a}_\mu =$ 

$= \mathrm{tr}\left\{\tau^a\Phi^\dagger D_\mu\Phi\right\}$

W-Ball: $\mathcal{O}^{0^+_0} =$ 

$= 1 - W^a_{\mu\nu}W^{\mu\nu\,a}$

Physical fermion: $\mathcal{O}^F =$ 

$= \Phi\begin{pmatrix}\nu^L\\ e^L\end{pmatrix}$

Modified cross-section

[**Reunitarization:** Killian et. al. PRD **91** (2015), **arXiv: 1408.6207**]

- Assuming: phaseshift δ_J can be obtained from PT
- Reunitarized partial transition amplitude:

$$F_J = 1/\operatorname{Re}(1/f_J) \to F_J = \tan(\delta_J)/(1 - \mathrm{i}\tan(\delta_J))$$

- Adding finite size contribution: $\tan(\delta_J) \to \tan(\delta_J) - \Delta f_J$

$$\Rightarrow F_J \to F_J - \frac{\Delta f_J}{(\Delta f_J - \mathrm{i} - \tan(\delta_J))(\mathrm{i} + \tan(\delta_J))} = F_J - \Delta F_J$$

$$\mathcal{M}_{\mathsf{PT}} \propto \sum_J (2J+1) F_J P_J(\cos\theta) \quad \mathcal{M}_{\Delta f} \propto \sum_J (2J+1) \Delta F_J P_J(\cos\theta)$$

$$\mathcal{M}_{\mathsf{mod.}} = \mathcal{M}_{\mathsf{PT}} - \mathcal{M}_{\Delta f}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathsf{mod.}} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{\mathsf{PT}} = \frac{\left|\mathcal{M}_{\mathsf{PT}} - \mathcal{M}_{\Delta f}\right|^2}{\left|\mathcal{M}_{\mathsf{PT}}\right|^2} = \left|\frac{\left(\mathcal{M}_{\mathsf{PT}} - \mathcal{M}_{\Delta f}\right)^2}{\mathcal{M}_{\mathsf{PT}}^2}\right|$$

$$= \left|1 - \frac{2\mathcal{M}_{\Delta f}}{\mathcal{M}_{\mathsf{PT}}}\left(1 - \frac{\mathcal{M}_{\Delta f}}{2\mathcal{M}_{\mathsf{PT}}}\right)\right|$$