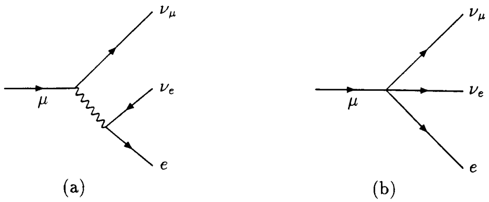
SPRACE

Higgs Worshop

São Paulo Research and Analysis Center

EFT - What is it?

Let us look at the muon decay:

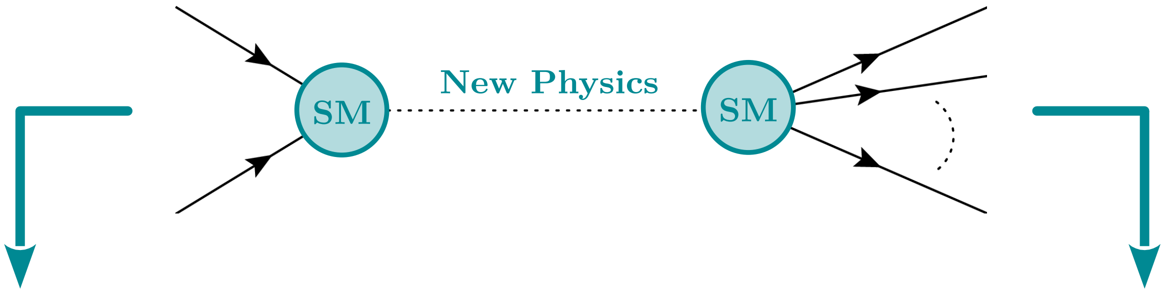


$$\mathcal{M} = \frac{g^2}{8}\bar{u}(P_e)\gamma^\mu(1-\gamma_5)v(P_{\bar{\nu}_e})\left(\frac{-g_{\mu\nu}+\frac{k_\mu k_\nu}{M_W^2}}{k^2-M_W^2}\right)\bar{u}(P_{\nu_\mu})\gamma^\nu(1-\gamma_5)u(P_\mu)$$

From an effective field theory (Four Fermion Interaction):

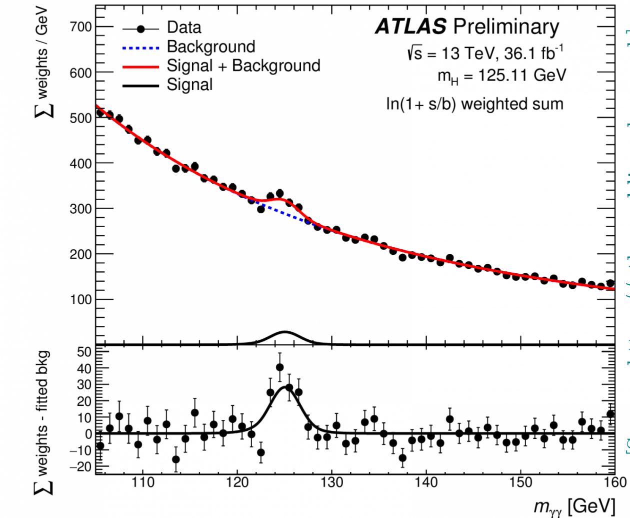
$$\mathcal{L}_{eff} = \sum_\alpha \frac{G_i}{\sqrt{2}}\bar{\psi}_e O_i \psi_{\nu_e}\psi_{\nu_\mu} O^i \psi_\mu$$

BSM Searches at Present and Future Colliders



Ideal case, detect new particles directly ...

... like the Higgs.



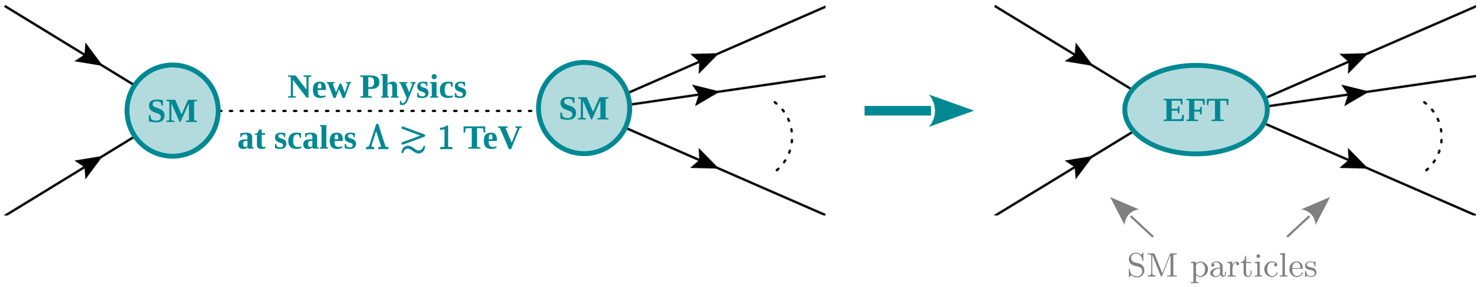
[Source: https://atlas-public.web.cern.ch]

Otherwise detect "heavy" new physics indirectly ...

... through small deviations in couplings, shapes of distributions, ...

... but indirect measurements are not model independent!

Effective Theories (EFT) as Tools for BSM Searches



- EFT's can be a great tool to parametrize such heavy effects systematically → in the following Standard Model Effective Theory (SMEFT)

Wilson coefficients that depend on unknown UV model parameters

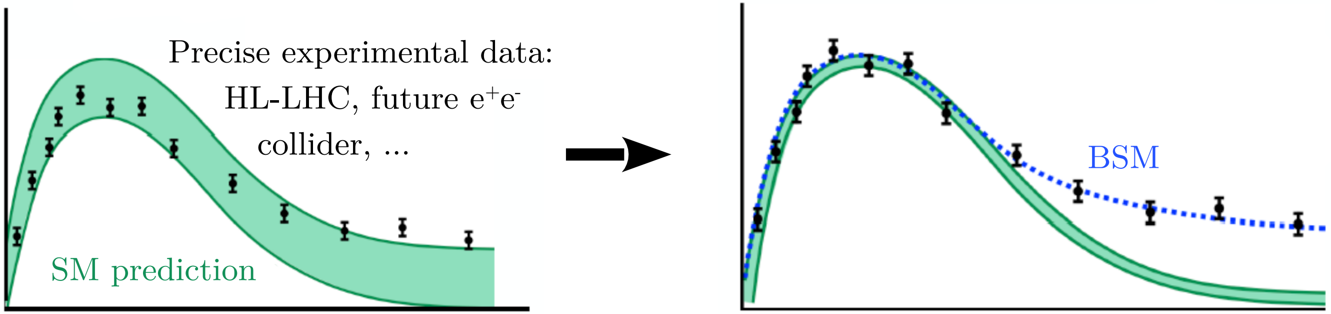
Effective operators for SM particles

$$L_{\text{SMEFT}} = L_{\text{SM}} + \sum_i \frac{C_i^6 O_i^6}{\Lambda^2} + \sum_i \frac{C_i^8 O_i^8}{\Lambda^4} + \dots$$

Scale of new physics

- Only assumptions in SMEFT: *i)* new operators respect SM gauge symmetries, and *ii)* no new light particles → renormalizable order-by-order in scale of new physics $1/\Lambda$

Precise Measurements ⇔ Precise Predictions



[Giulia Zanderighi]

- Precise measurement can be an important source of information on New Physics
- In SMEFT, BSM contributions need to be fitted

$$A \sim A_{\mathrm{SM}} + \boxed{A^{6,i}_{\mathrm{SMEFT}}} \frac{C_{6,i}}{\Lambda^2} + \boxed{A^{8,ij}_{\mathrm{SMEFT}}} \frac{C_{6,i}C_{6,j}}{\Lambda^4} + \boxed{A^{8,i}_{\mathrm{SMEFT}}} \frac{C_{8,i}}{\Lambda^4} + \dots$$

computed perturbatively

- Higher orders in the perturbative expansion might allow …

… the study of operators **not present** at LO
… more reliable bounds on operators **present** at LO

Is EFT renormalisable?

- A theory with operators of higher order is non renormalisable.
- In what sense we can compute higher order terms?
- Toy model:

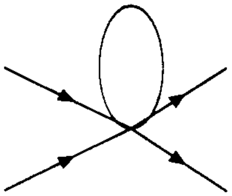
$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi \partial^\mu \phi - m^2 \phi^2) + \frac{\lambda}{4!}\phi^4$$

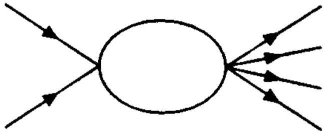
Non-renormalizable terms

Higher orders terms

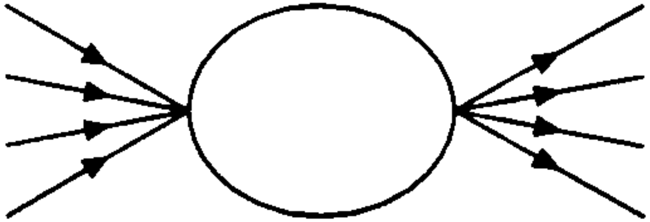
$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi \partial^\mu \phi - m^2 \phi^2) + \frac{\lambda}{4!}\phi^4 + \frac{\alpha}{6!\Lambda^2}\phi^6$$

If we keep up to order α





However, going to second order:



We need the 8 point function to renormalize it!

EFT pathway to new physics

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$ → Processes and observables

→ Sensitivity → Measurements

→ $$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2} \sum_i c_i^6(\mu) a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$ → Constraints on WC

→ UV physics

Huge effort to improve each one of these steps!

Future of global fits

How can we improve fits?

More observables:

- Particle level observables
- New final states
- Better description: EFT in backgrounds

More/less/different operators:

- Different flavour assumptions
- UV inspired scenarios

Better EFT predictions

Higher Orders in $1/\Lambda^4$

- squared dim-6 contributions
- double insertions of dim-6
- dim-8 contributions

Higher Orders in QCD and EW

EFT is a QFT, renormalisable order-by order in $1/\Lambda^2$

$$\mathcal{O}(\alpha_s, \alpha_{ew}) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_{ew}}{\Lambda^2}\right)$$

EFT Truncation

The Problem

- EFT $=$ low energy expansion

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{BSM}}$$

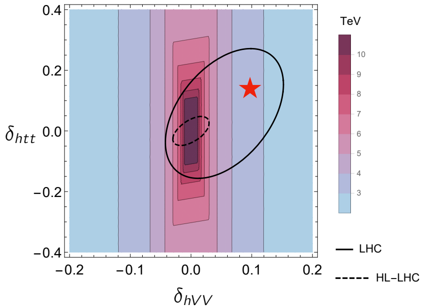
$$\mathcal{M}_{\text{BSM}} = \mathcal{M}_6 + \mathcal{M}_8 + \cdots \qquad \mathcal{M}_n \sim \frac{E^n}{\Lambda^n}$$

- $\mathcal{M}_{\text{BSM}}$ grows with energy

  $\Rightarrow$ signals at high energy

  $\Rightarrow$ EFT breaks down at high energy

- No guaranteed scale separation at LHC



Abu-Ajamieh, Chang, Chen, ML (2020)

Statement of Principles

- Constraining coefficients in a truncated expansion requires assumptior about the size of neglected terms

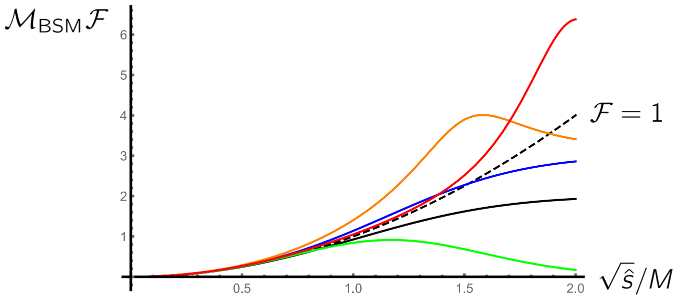
- Priors should be explicit and have a clear physical meaning

- Truncation error is a theory uncertainty that should be treated quantitatively

Form Factors

EFT model must make predictions for $\hat{s} > M$

$$\mathcal{M}_{\text{BSM}}(\hat{s}, \hat{t}) \to \mathcal{M}_{\text{BSM}}(\hat{s}, \hat{t})\mathcal{F}(x, y) \qquad x = \frac{\hat{s}}{M^2} \quad y = \frac{\hat{t}}{M^2} \quad z = \frac{\hat{u}}{M^2}$$



Note: events can be generated by reweighting

- $x, y, z \ll 1$: descendants

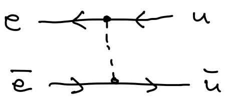
  $\mathcal{F}(x, y) = 1 + c_1 x + c_2 y + c_3 xy + \cdots$

- $x, y, z \sim 1$: general behavior

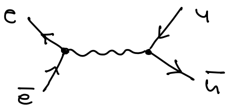
- $x, y, z \gg 1$: $\mathcal{M}_{\text{BSM}}\mathcal{F} \to$ constant (scale invariant)

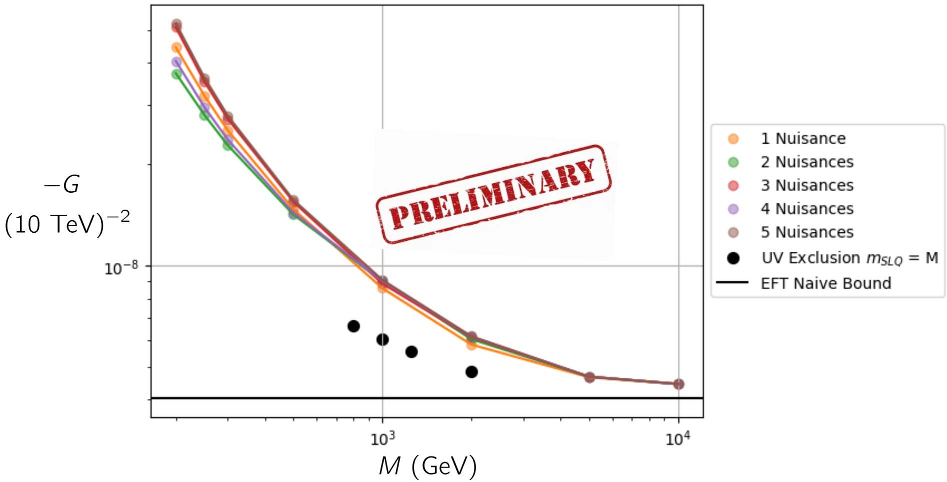
Comparison with UV Models

Scalar leptoquark model:



Z' model:





- Naive EFT bound is *stronger* than bound for leptoquark model (predicts high energy growth for $\hat{s} \gtrsim m_{\mathrm{SLQ}}^2$)
- EFT with theory errors is more conservative approaches UV model bound for $M = m_{\mathrm{SLQ}} \to \infty$

Matching (Guillermo)

Travelling through the SMEFT

Data points to IR pattern

Which UV models?

Which low-energy pheno?

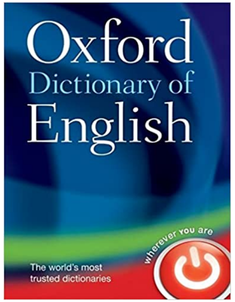
From the EFT

To the UV

And back

Bottom-up approach: UV/IR dictionaries

$$\mathcal{L}_{\mathrm{UV}}$$



$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{\mathcal{L}_6}{\Lambda^2}$$

- What is the data telling us?
- UV/IR dictionaries tell us ***all*** SM extensions which can contribute to a particular experimental observable (at a given order in the EFT expansion)

Dictionary at tree-level

- Tree-level dictionary to the SMEFT @ dim-6 already exists, with ***all*** possible extensions which can generate WCs and their explicity contribution.
- Some operators can be generated at one-loop
  - Considering weakly coupled renormalizable UV

C. Arzt, M. B. Einhorn, and J. Wudka, hep-ph/9405214
Craig, Jiang, Li, Sutherland 2001.00017

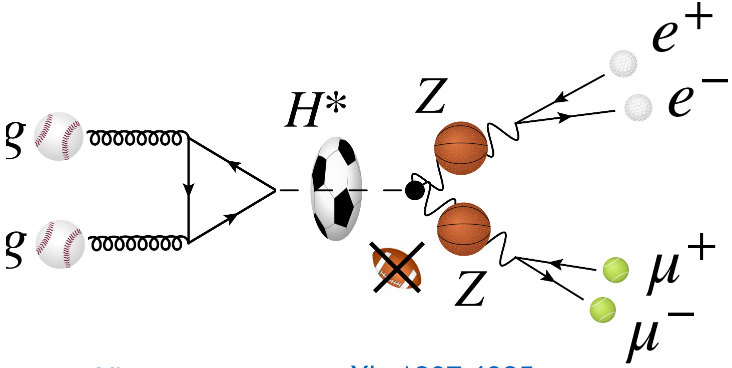
$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Ω_1	Ω_2	Ω_4	Υ	Φ			
$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

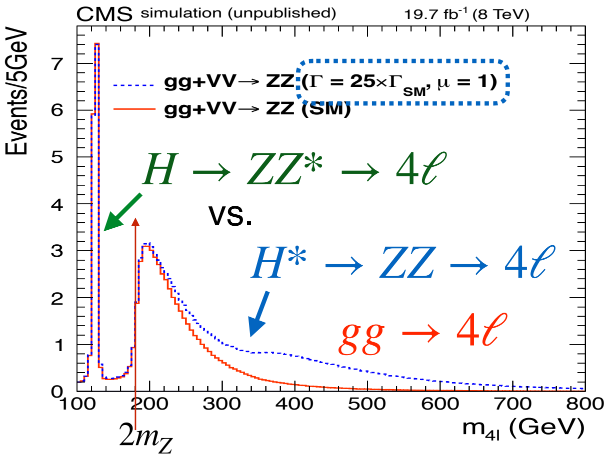
N	E	Δ_1	Δ_3	Σ	Σ_1	
$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
U	D	Q_1	Q_5	Q_7	T_1	T_2
$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

De Blas, Criado, Perez-Victoria, Santiago, 1711.10391

Off-shell Higgs boson data



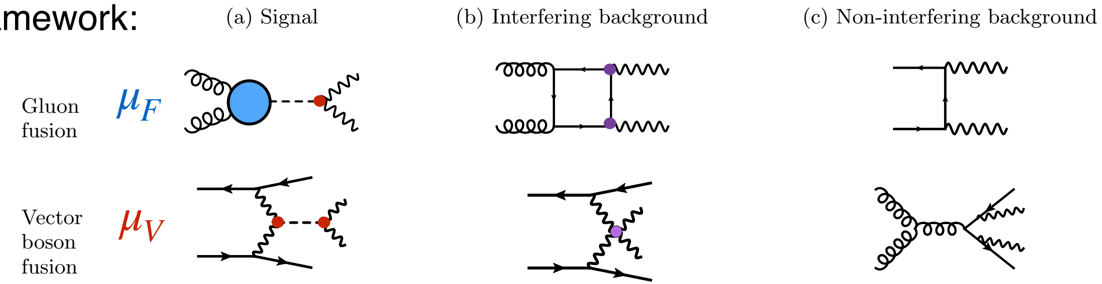


arXiv:1206.4803 arXiv:1307.4935

$$10 \sim \frac{\sigma_{\text{onhell}}}{\sigma_{\text{offshell}}} \propto \frac{1}{\Gamma_{\text{tot}}}$$

CMS Run1: arXiv:1405.3455: $\Gamma_H = 1.8^{+7.7}_{-1.8} \times 10^{-3}\,\text{GeV}$

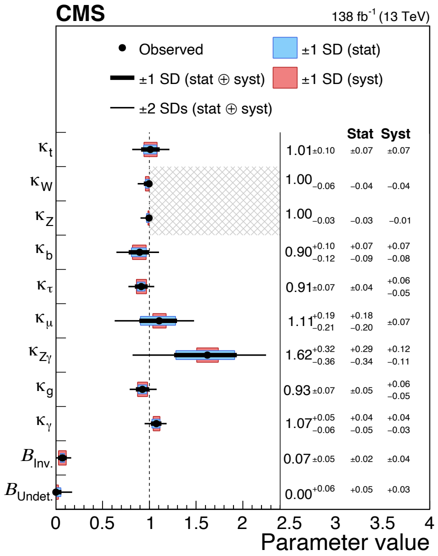
- μ framework:



tools MCFM+JHUGen: arXiv:2002.09888

Summary / Conclusion

- Test off-shell H^* in new regime: both CMS and ATLAS observe $\sim 4\sigma$ in Run-2
  — best direct constraint on Γ_H from H line shape across wide energy range
- Introduce off-shell H^* in κ framework (for Run-2 combination)
  — κ_Q model any heavy particles in the loop in addition to κ_t, κ_b (κ_Q equivalent to κ_g)
  — κ_Z, κ_W model HVV couplings
  — application to CMS data: Γ_H stable results



- Introduce off-shell H^* in EFT fits (Run-2 & 3)
  — naturally a part of VBS process
  — CMS data: $(\delta c_z, c_{z\Box}, c_{zz}, \tilde{c}_{zz})$ with Γ_H stable results
  — expand to CP-odd and CP-even operators
  — more details: talk at the 20th Workshop of the LHC Higgs Working Group (2023)

Introduction

- Focus on Higgs boson produced at high invariant masses $p_H^2 \gg m_H^2$
- E.g: $gg \to H \to VV$:

  10% of events above the $2\, m_V$ threshold. [Kauer, Passarino '12]
- Large offshell rates also in EW production. [Campbell, Ellis '15; Gritsan *et al.* '20]

- Contrary to expectations from narrow width approximation:

$$\frac{\Gamma_H}{m_H} \simeq \frac{4\ \text{MeV}}{125\ \text{GeV}} \sim 10^{-5}$$

  → Expect a very narrow resonance and hence offshell cross section highly suppressed.

- Due to Higgs boson restoring unitarity in massive scattering amplitudes

  ➡ offshell Higgs production allows us to probe unitarization behavior.

- ✓ Indirect constraints on Higgs width by comparing onshell and offshell Higgs rates. [Caola, Melnikov (2013)]

  $\sigma_{\text{on}} \propto g_i^2 g_f^2 / \Gamma_H \qquad \sigma_{\text{off}} \propto g_i^2 g_f^2$
- ✓ Probe Higgs in a different kinematic regime.

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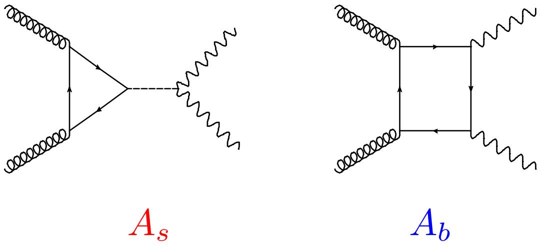
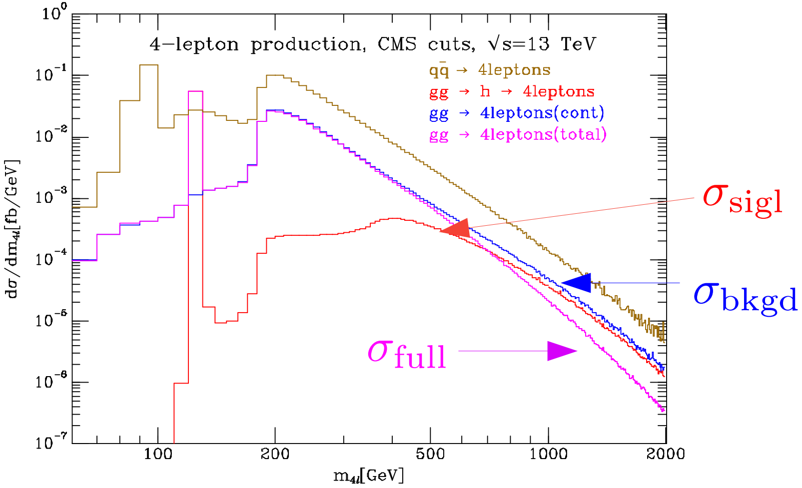
- Need to consider:
  - Signal
  - Background
  - Interference
  - Full (physical) result SBI



$$|A_{ZZ}|^2 = |A_s|^2 + |A_b|^2 + 2\mathrm{Re}[A_s A_b^*] \quad \to \sigma_{\rm full} = \sigma_{\rm sigl} + \sigma_{\rm bkgd} + \sigma_{\rm intf}$$



Large destructive interference at high energies – sign of Higgs unitarizing massive scattering amplitudes.

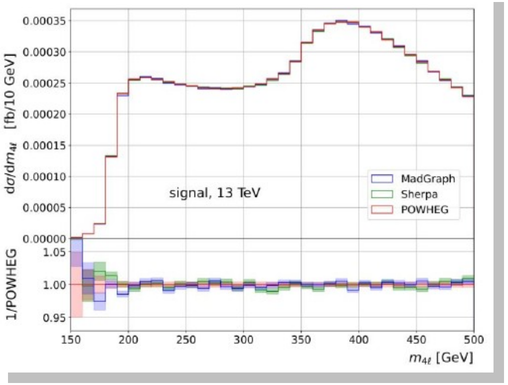
[Campbell, Ellis, Williams (2013)]

Modelling additional radiation

- Going beyond NLO is very demanding → include additional radiation through parton showers.
- Combine with fixed-order either through merging or jet matching.

➡ Tuned comparison of merged NLO+PS (POWHEG) vs. LO 0+1 jet matching (MadGraph and Sherpa).

Compare results at LO (no PS) to tune parameters: any difference beyond LO due to additional QCD radiation.



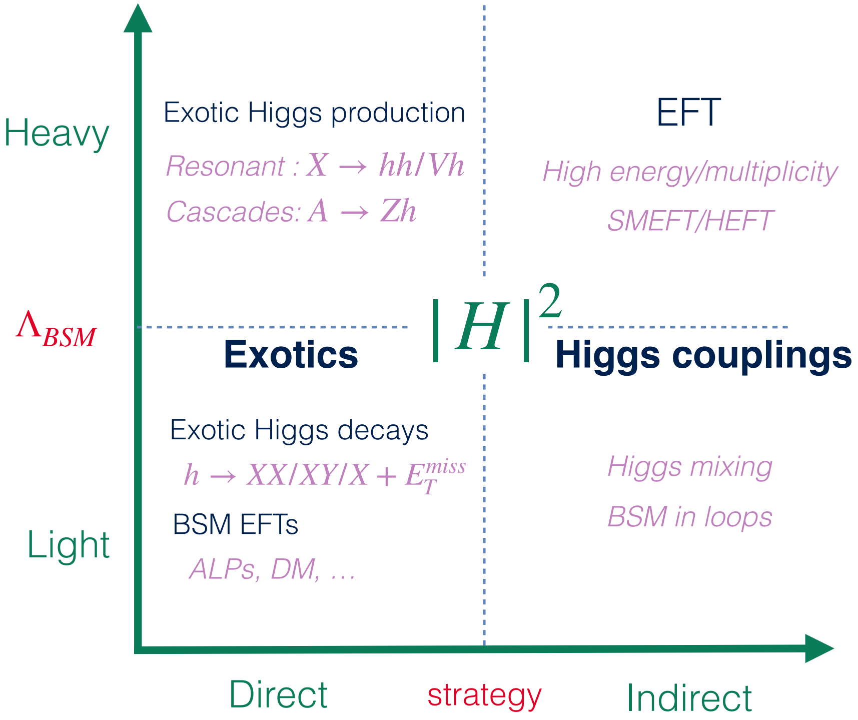
σ_{LO} [fb]	POWHEG	MADGRAPH	SHERPA
signal	0.08745(5)	0.08742(1)	0.08741(5)
bkgd	2.725(1)	2.724(1)	2.726(1)
full	2.617(1)	2.617(1)	2.616(1)

Talk by Matteo Lazzeretti

See also [Li et al (2020)]

BSM & EFT (Ken)

Higgs gateway to BSM



Effective Field Theory for Beyond the Standard Model

- Lack of experimental evidence of new physics indicate a mass gap between SM and BSM scales
- BSM physics influencing the Higgs sector, two common EFTs: SMEFT and HEFT
- SMEFT Lagrangian

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i>4} \sum_{k} \frac{C_k^{(i)}}{\Lambda^{i-4}} \mathcal{O}_k^{(i)}$$

- In HEFT, Electroweak-symmetry is non-linearly realized; the Higgs and the three electroweak Goldstone bosons (GBs) are considered independent and not part of a SU(2) doublet.

Akanksha