Multiple production of weak bosons in e^+e^- collisions

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Indirect Search for BSM

Focus of current and collider analyses and studies:

- Higgs interactions

  = trilinear interactions of H with heavy quarks, heavy leptons, massive bosons

- Top-quark threshold, top-quark continuuum, $t\bar{t}H$

  = trilinear interactions of $t\bar{t}$

- Global EW fit

  = all trilinear interactions of the SM

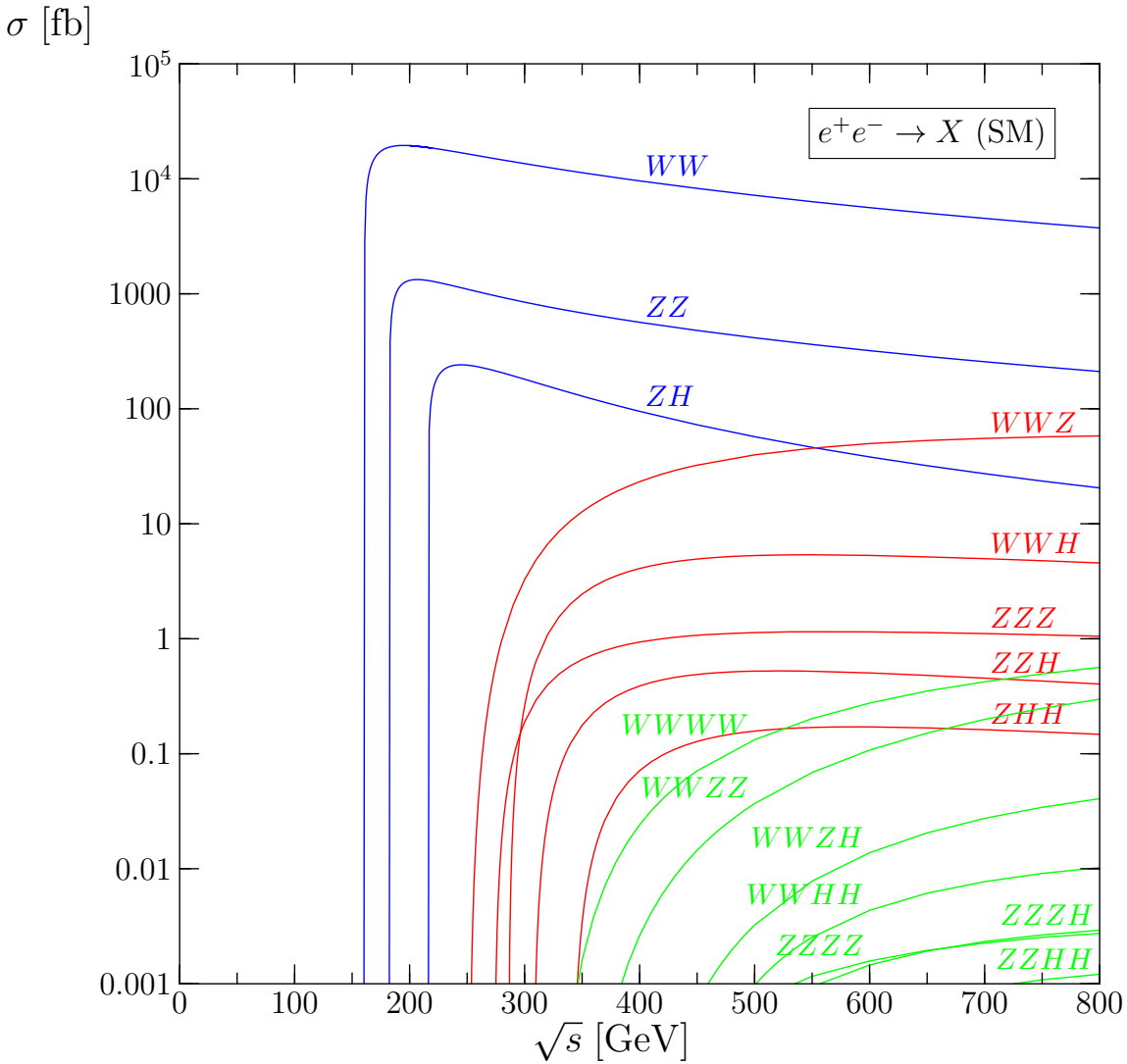
Standard Framework: truncated SMEFT (D=6)

This talk:

An overview of the phenomenology of multi-boson production

$\Rightarrow$ trilinear and quartic interactions and beyond

The Threshold Range



	thr [GeV]	max [GeV]
WW	160.8	195
ZZ	182.4	200
ZH	216.3	240
WWZ	252.0	950
ZZZ	273.6	550
WWH	285.9	550
ZZH	307.5	520
ZHH	341.4	590
WWWW	321.5	3000
WWZZ	343.1	4000
WWZH	377.0	2000
WWHH	410.9	1400

Multi-boson physics: Experimental Prospects

LC case

Final states (6 fermions, 8 fermions) can be studied trigger-less and fully exclusive in all observables.

Main issues:

- Separate Z from W (and H) in fully hadronic decay mode
- Jet charge (W^+ vs W^-)
- Combinatorics
- Invisible decays (minor fraction)

In any case:

Low Rates in clean environment

$\Rightarrow$ Many measurements will be statistics-dominated.

Multi-boson physics: SM Theory

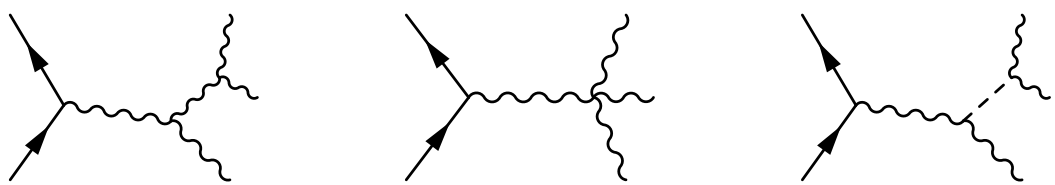
Calculation: Baseline

All parameters are known, so all cross sections and distributions can be accurately computed and compared to experiment (in principle)

SM is weakly interacting

$\Rightarrow$ Add gauge-boson, Higgs, and contact terms coherently:

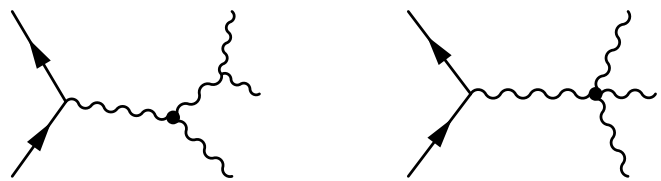
$$\mathcal{M} \sim E^n/v^n \quad \overset{\text{SM gauge cancellations}}{\Longrightarrow} \quad \mathcal{M} \sim g^n E^0$$



Multi-boson physics: Standard BSM Theory

Framework for deviations: SMEFT (D=6 truncated)

$\Rightarrow$ Gauge cancellations broken in a controlled way:



$$\delta\mathcal{M} \sim E^n/v^n \qquad \overset{D=6 \text{ gauge c.}}{\Longrightarrow} \qquad \delta\mathcal{M} \sim g^{n-2} c_i E^2$$

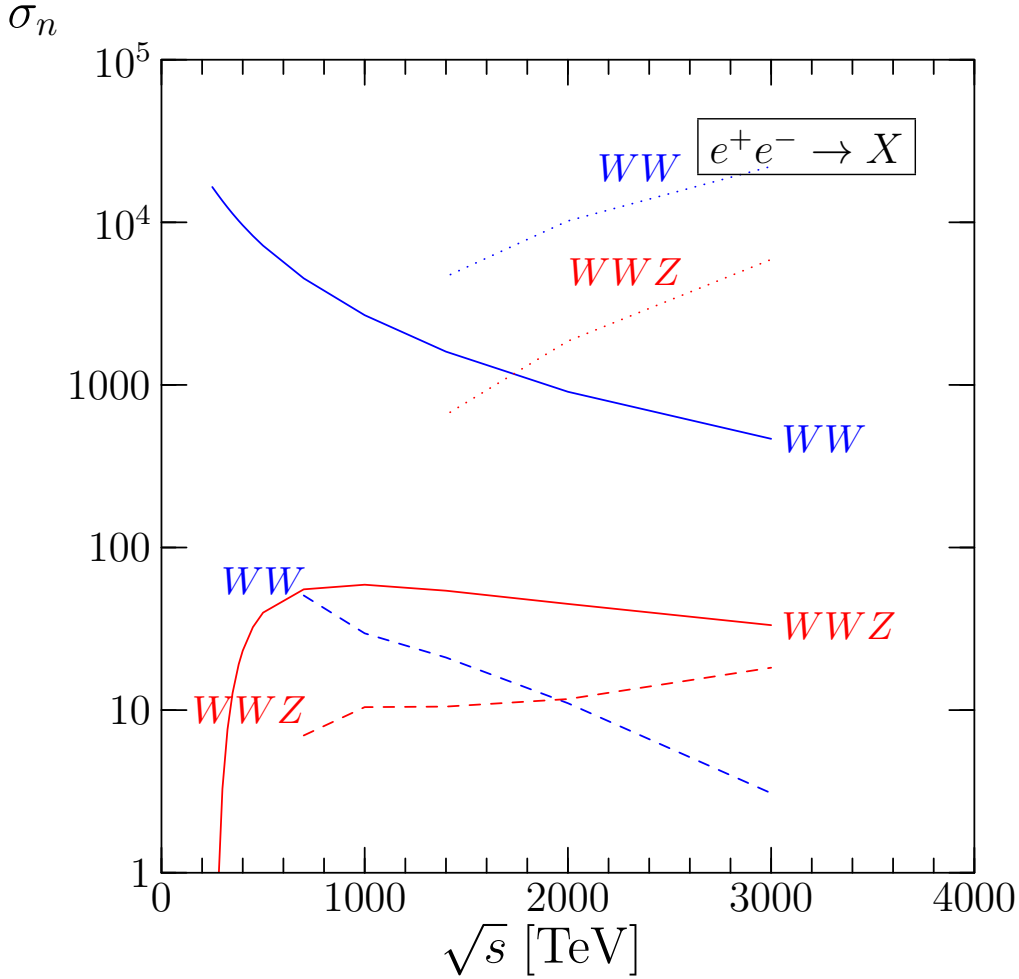
EFT parameters from global fit (decays / diboson @LHC @LC)

$\Rightarrow$ All quartic couplings predicted by SMEFT?

Combined Fit?

Triboson W^+W^-Z vs Diboson W^+W^-: $D = 6$ coupling c_W

- interference (dashed)
- quadratic (dots)



$\Rightarrow$ Improved fit for $D = 6$ SMEFT model

Multi-boson physics: Model-Independent Analysis

- SMEFT = calculational tool
  - gauge invariance controls impact of lower-order data
    on higher-order processes
    and renormalization of loop corrections

  $\Rightarrow$ Power counting in terms of E^2/Λ^2, iterative: $D = 6, 8, 10, \ldots$

- Problems: proliferation of parameters, varying level of precision on basis, unitarity in production processes

$\Rightarrow$ Truncated SMEFT is a model with limitations and shortcomings
which becomes unsuitable for higher-order processes

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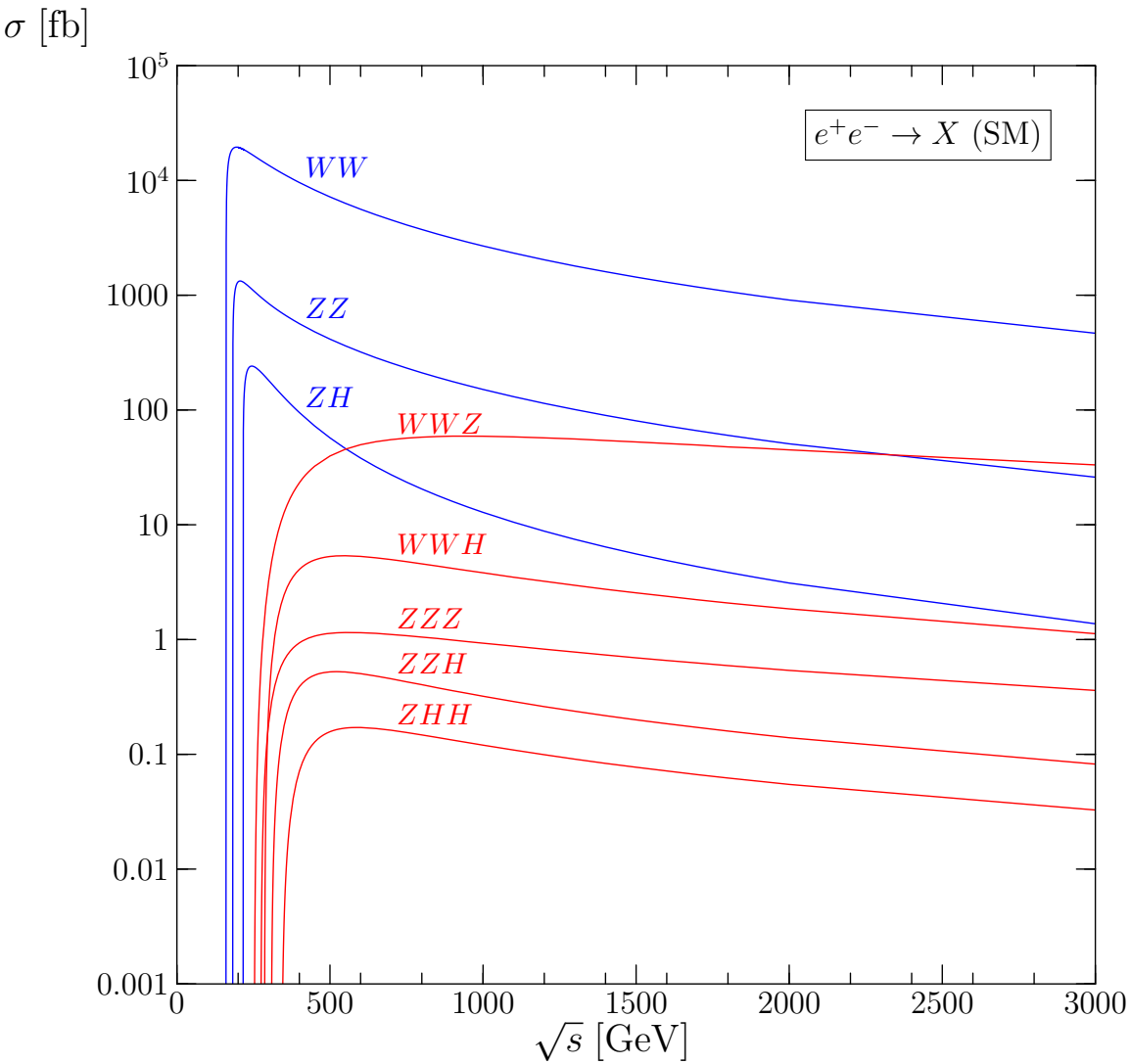
- Multiboson Analysis beyond SMEFT:
  - $\Rightarrow$ Observables = process-specific energy-dependent form factors

    after fitting and subtracting $D = 6$ (lower-order) terms

Processes at high energy

Some Observations:

- *WWZ* important
- *WWH* vs *ZH*
- Neutral final states suppressed



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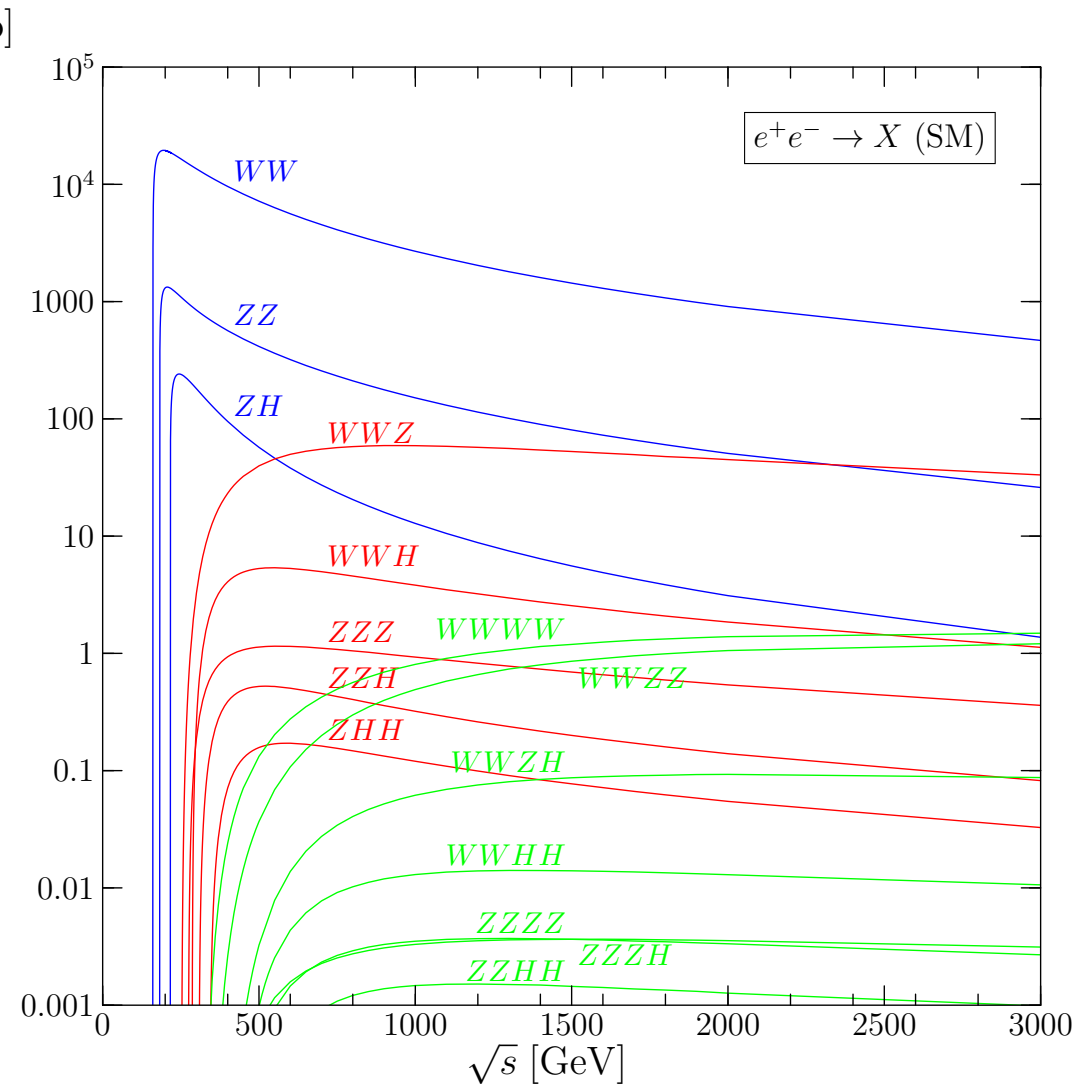

Processes at high energy

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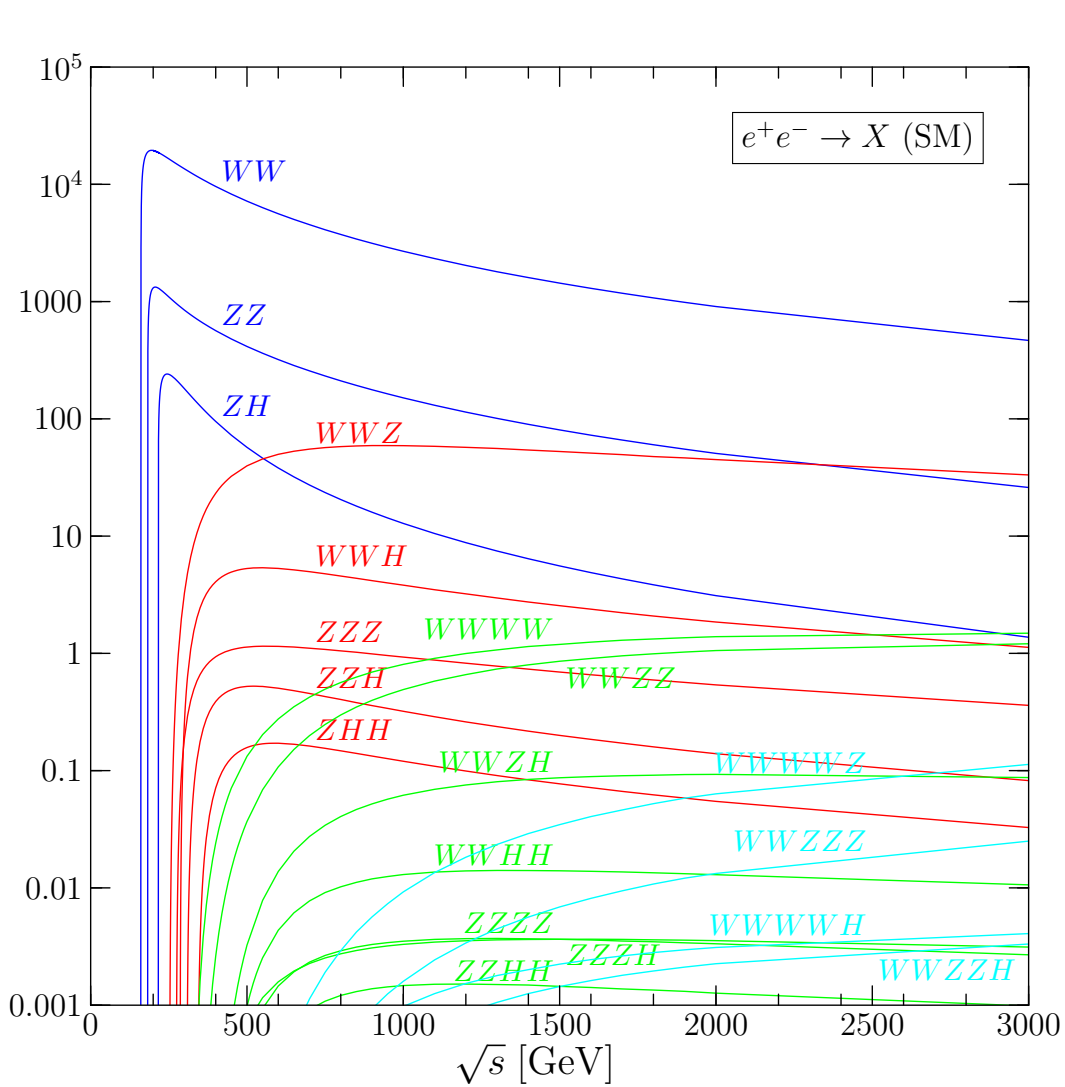
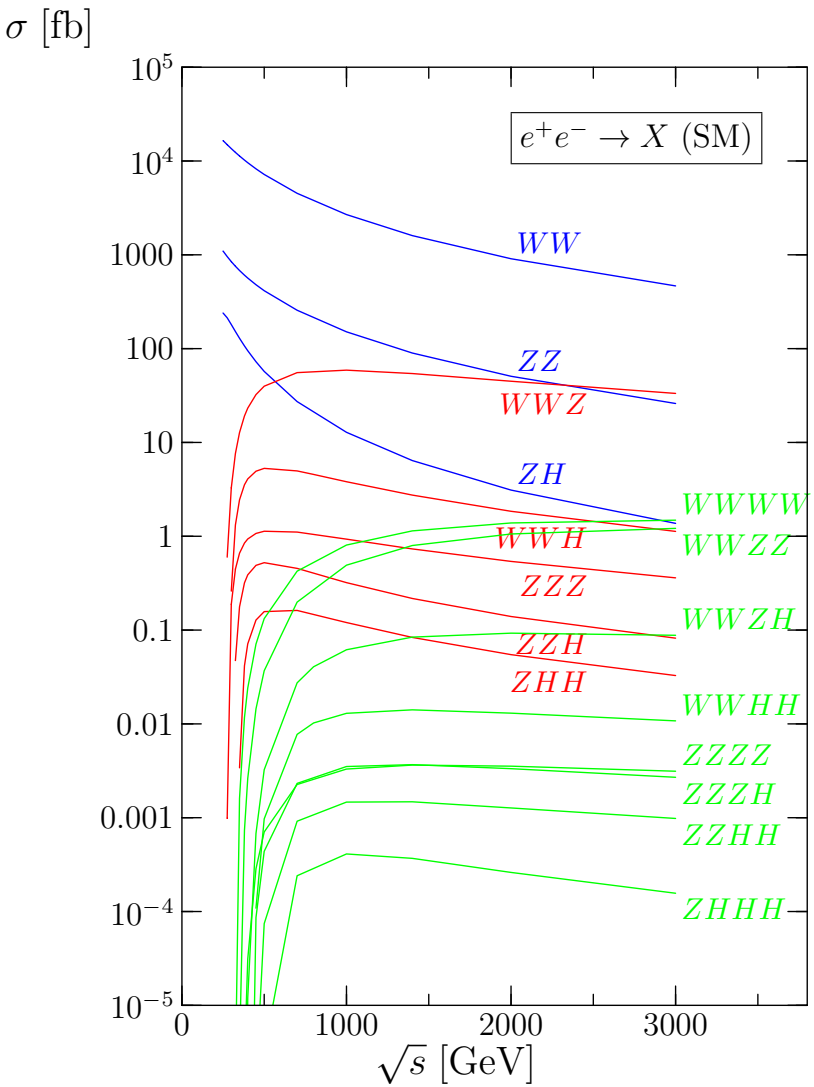
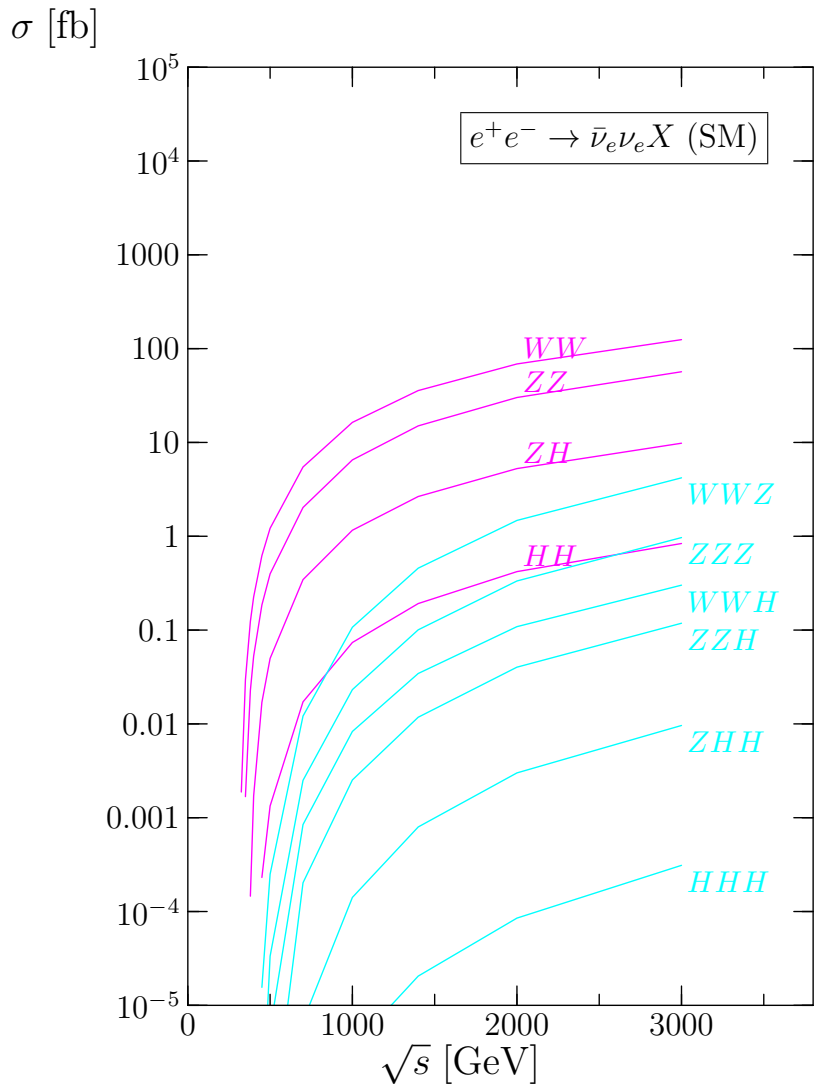
- $6j$, $8j$, $10j$ as background and signal



The Rise of VBS





arXiv:1812.02093

Unitarity Limits?

Unitarity

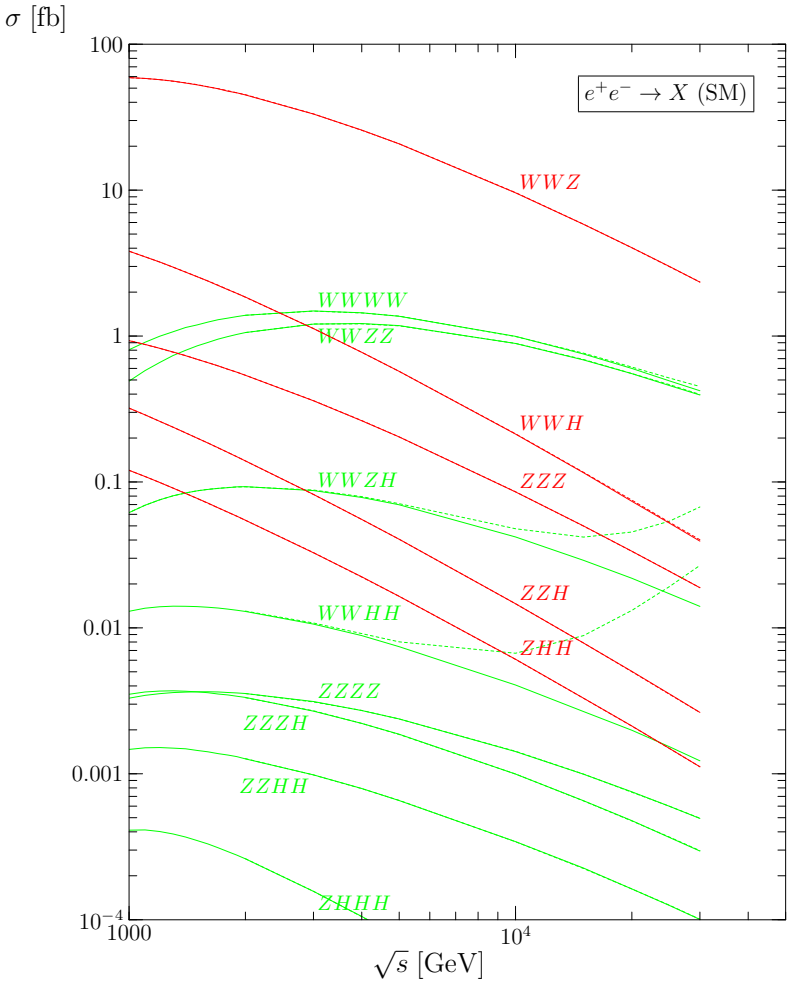
- Diboson and quasi-elastic VBS:
  weak $\rightarrow$ strong
  - $\Rightarrow$ Interference (linear in SMEFT)
  - $\Rightarrow$ Limit $\sim$ factor 10 (elastic rescattering)

- Multiboson and inelastic VBS:
  weak $\rightarrow$ strong
  - $\Rightarrow$ Quadratic terms and beyond
  - $\Rightarrow$ Limit $\sim$ factor 10^x (inelastic $\lesssim$ elastic)
  - $\Rightarrow$ Resonances / strongly interacting Higgs (portal) sector

  Perturbative operator expansion $\Rightarrow$ form-factor parameterization

Fun with Asymptotics

Gauge invariance!



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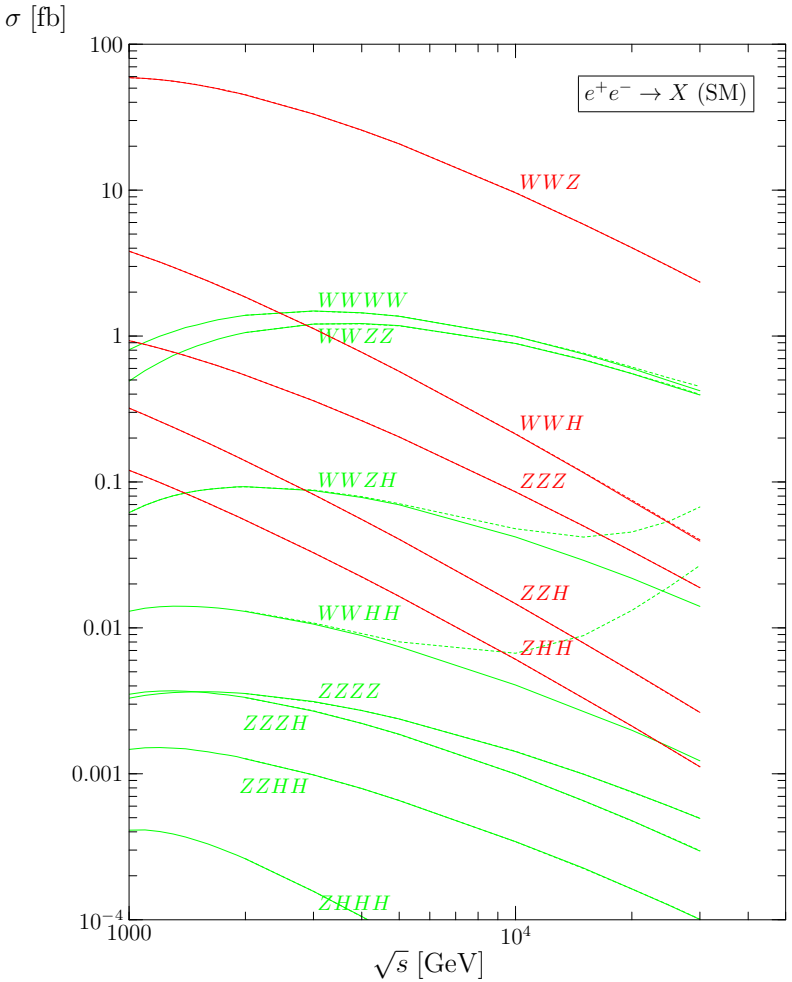

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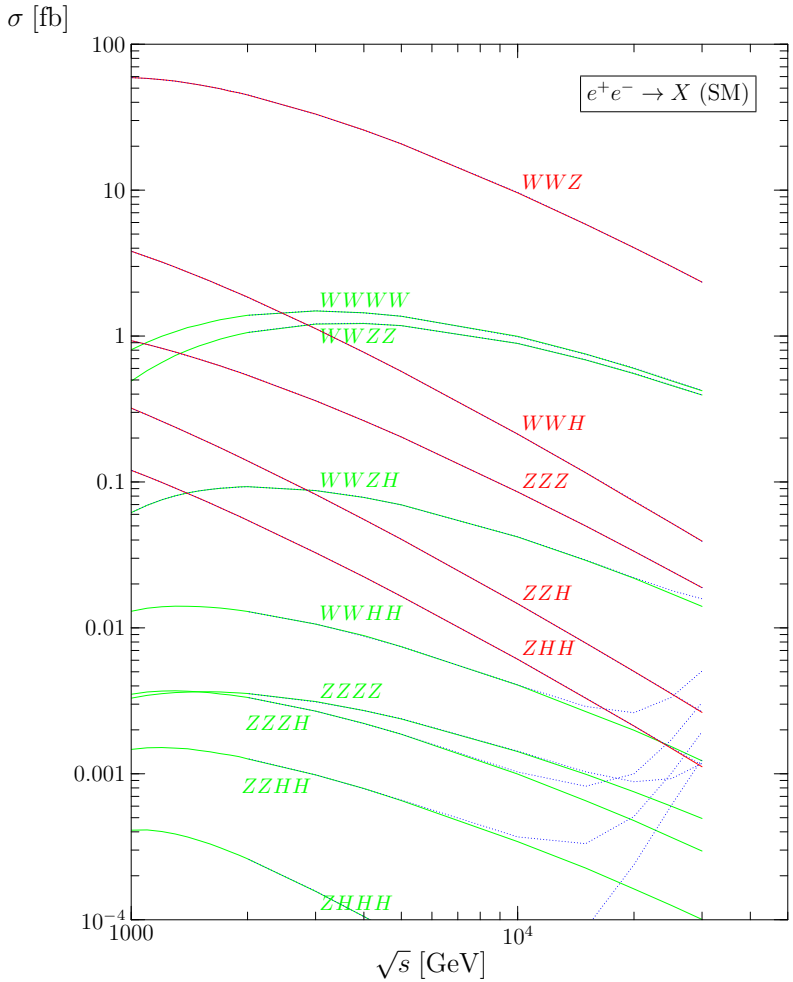

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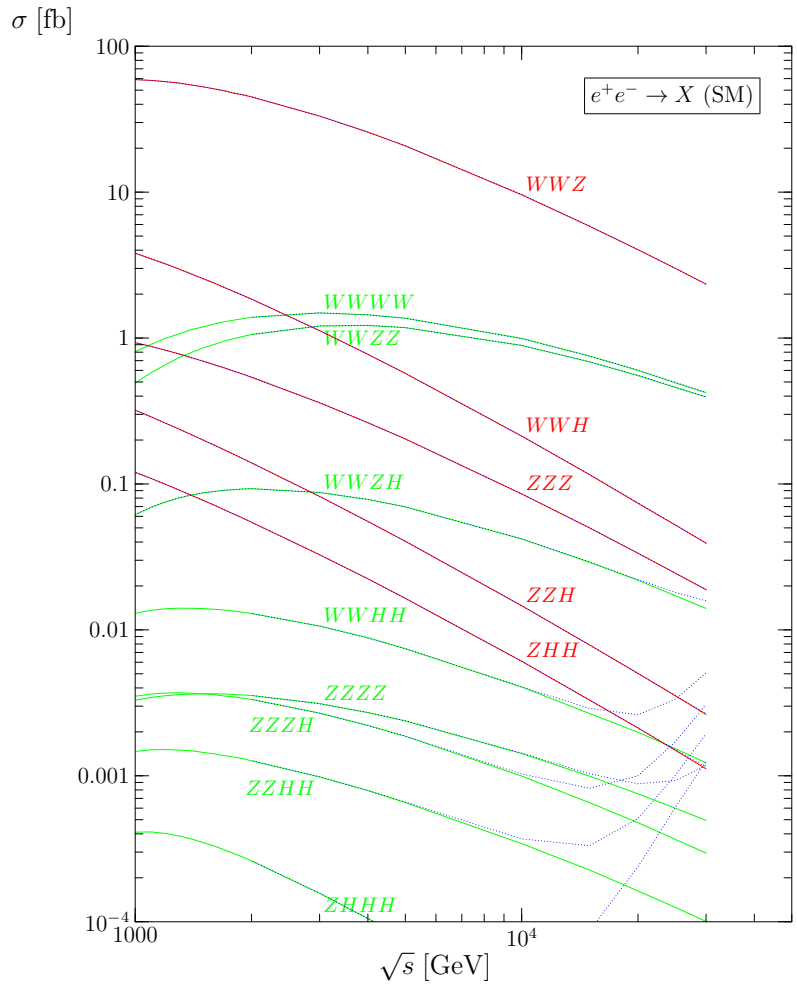

Hee coupling – do we really know the Higgs mechanism that shapes our universe?

Summary

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2. Adds to precision measurements within truncated SMEFT

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3. Potential for direct observation of new physics (EW, Higgs)

   . . . any EW-BSM effect will likely affect some multiboson processes

   (enhancement by orders of magnitude is allowed)

Read More:

- The CLIC Potential for New Physics
  (CERN Yellow Report, arXiv:1812.02093)

- Brass, Kilian, Reuter, et.al.: W.I.P.