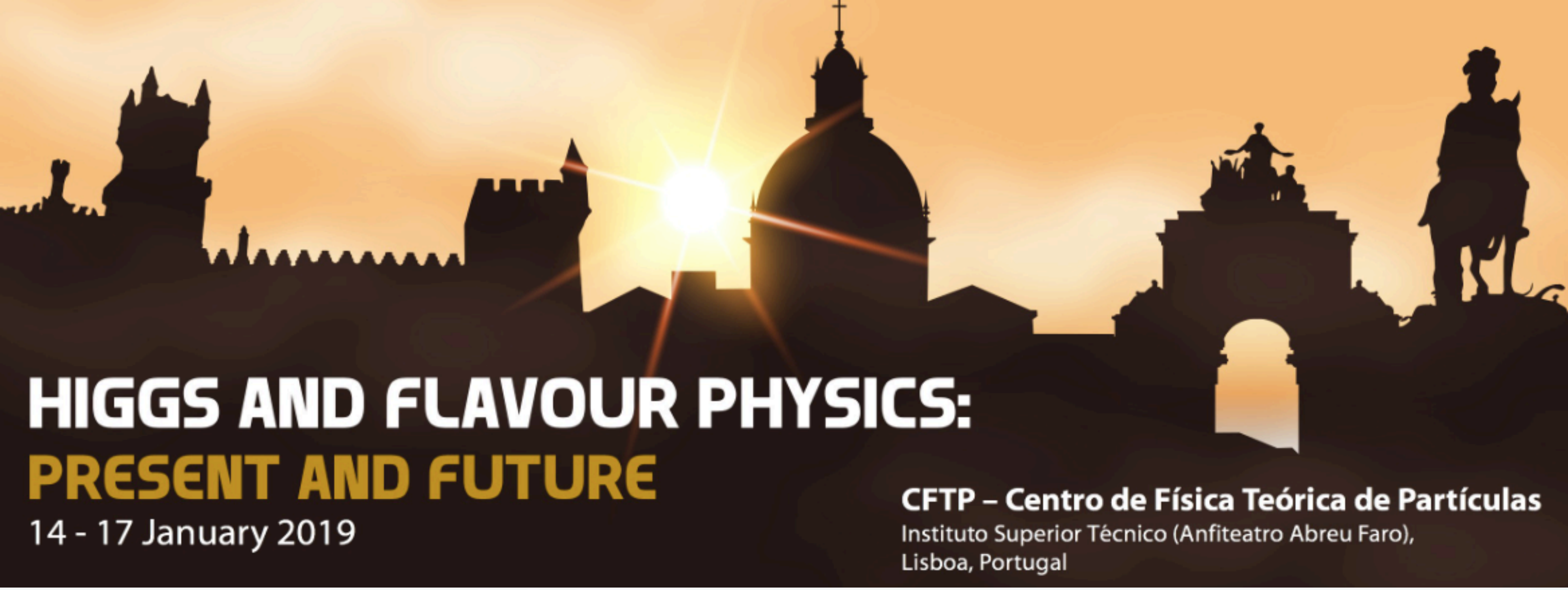


WW scattering: a window beyond the Standard Model

Jan Kalinowski

University of Warsaw

Why have we built the LHC?

to study VV scattering!

Massive W^+, W^- , Z have 3 polarizations thanks to Goldstone modes

Lee, Quigg and Thacker '77:
scattering of EW Goldstones not consistent above ~1 TeV

NO-LOSE theorem

➔ either we see restoration of unitarity (Higgs, new resonances?)
or see something completely new (substructure, strong interaction!)

The Brout-Englert-Higgs mechanism

In the simplest model proposed in 1964, the gauge symmetry is broken by a complex scalar field with a ”Mexican-shaped” potential.

Gauge invariance

Massless $W^{\pm}, Z$ (spin 1)

3×2 **polarizations** $= 6$

$+$

3 Goldstones $\varphi_i(x)$

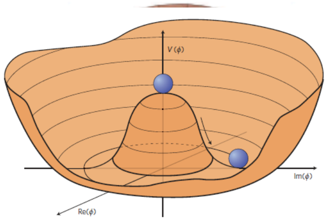
SSB $\downarrow$

Massive $W^{\pm}, Z$

3×3 **polarizations** $= 9$

Spontaneous Symmetry Breaking

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda \, (\Phi^\dagger \Phi)^2$$



$\mu^2 < 0$

$$\Phi(x) \; = \; \exp\left\{ i\,\vec{\sigma} \cdot \frac{\vec{\varphi}(x)}{v} \right\} \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v + H(x) \end{bmatrix}$$

$$D_\mu \Phi = (\partial_\mu + \tfrac{i}{2}\, g\, \vec{\sigma} \cdot \vec{W}_\mu + \tfrac{i}{2}\, g'\, B_\mu)\, \Phi \quad ; \quad v^2 = -\mu^2/\lambda$$

$$(D_\mu \Phi)^\dagger D^\mu \Phi \;\to\; M_W^2\, W_\mu^\dagger W^\mu + \frac{M_Z^2}{2}\, Z_\mu Z^\mu$$
$$\times \left(1 + \tfrac{H}{v}\right)^2$$

$$\mathbf{M_W} = \mathbf{M_Z} \cos\theta_W = \tfrac{1}{2}\, \mathbf{g\, v}$$

Goldstones responsible for V masses

$$\mathcal{L}_\Phi = (D_\mu\Phi)^\dagger D^\mu\Phi - \lambda\left(|\Phi|^2 - \frac{v^2}{2}\right)^2$$
$$= \frac{1}{2}\mathrm{Tr}\left[(D^\mu\Sigma)^\dagger D_\mu\Sigma\right] - \frac{\lambda}{4}\left(\mathrm{Tr}\left[\Sigma^\dagger\Sigma\right] - v^2\right)^2$$
$$= \frac{v^2}{4}\mathrm{Tr}\left[(D^\mu U)^\dagger D_\mu U\right] + O(H/v)$$

custodial symmetry

$$\Sigma \to g_L\,\Sigma\,g_R^\dagger$$

$$g_{L,R} \in SU(2)_{L,R}$$

$$\Sigma \equiv (\Phi^c, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^+ \\ -\Phi^- & \Phi^0 \end{pmatrix} \equiv \frac{1}{\sqrt{2}}(v + H)\,U(\vec{\varphi})$$

$$U(\vec{\varphi}) \equiv \exp\left\{i\,\vec{\sigma}\cdot\frac{\vec{\varphi}}{v}\right\}$$

$$\mathcal{L}_2 = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu U^\dagger D^\mu U\right) \xrightarrow{U=1} \mathcal{L}_2 = M_W^2\, W_\mu^\dagger W^\mu + \frac{1}{2}M_Z^2\, Z_\mu Z^\mu$$

$$\mathbf{M_W = M_Z \cos\theta_W = \frac{1}{2} g\, v}$$

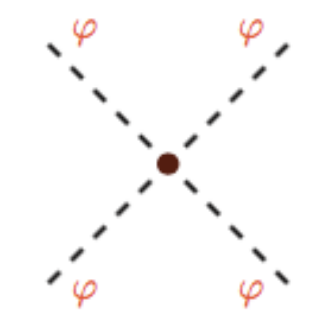
Goldstone dynamics determined by the symmetry

$$\boxed{\mathcal{L}_2 = \frac{f^2}{4}\,\mathrm{Tr}\left(\partial_\mu U^\dagger \partial^\mu U\right)}$$

become free at zero momenta

$$\begin{aligned}
\frac{v^2}{4}\langle\partial_\mu U^\dagger \partial^\mu U\rangle &= \partial_\mu\varphi^-\partial^\mu\varphi^+ + \frac{1}{2}\partial_\mu\varphi^0\partial^\mu\varphi^0 \\
&+ \frac{1}{6v^2}\left\{\left(\varphi^+\overleftrightarrow{\partial}_\mu\varphi^-\right)\left(\varphi^+\overleftrightarrow{\partial}^\mu\varphi^-\right) + 2\left(\varphi^0\overleftrightarrow{\partial}_\mu\varphi^+\right)\left(\varphi^-\overleftrightarrow{\partial}^\mu\varphi^0\right)\right\} \\
&+ O\left(\varphi^6/v^4\right)
\end{aligned}$$

therefore



$$T\left(\varphi^+\varphi^- \to \varphi^+\varphi^-\right) = \frac{s+t}{v^2}$$

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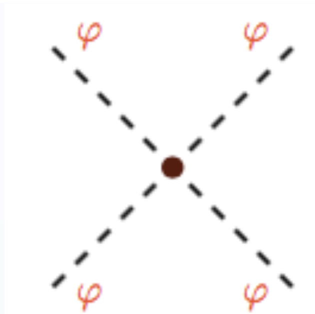
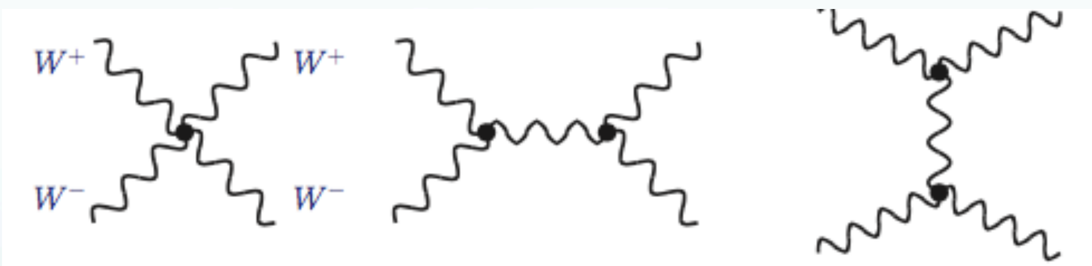


$$T\left(\varphi^+\varphi^- \to \varphi^+\varphi^-\right) = \frac{s+t}{v^2}$$

Equivalence theorem

Cornwall-Levin-Tiktopoulos, Lee-Quigg-Thacker



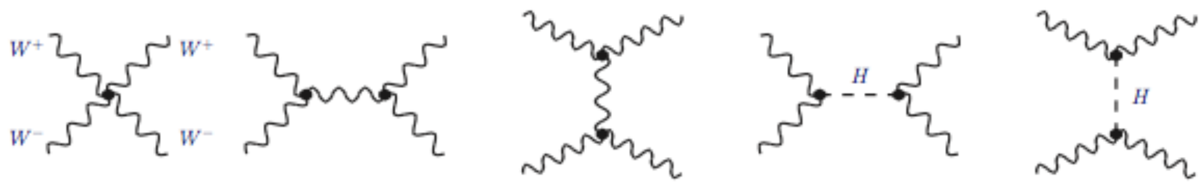
strong gauge cancellations

$$\boxed{\begin{aligned} T(W_L^+W_L^- \to W_L^+W_L^-) &= \frac{s+t}{v^2} + O\left(\frac{M_W}{\sqrt{s}}\right) \\ &= T(\varphi^+\varphi^- \to \varphi^+\varphi^-) + O\left(\frac{M_W}{\sqrt{s}}\right) \end{aligned}}$$

violates unitarity at ~1 TeV

Restoration of unitarity and calculability

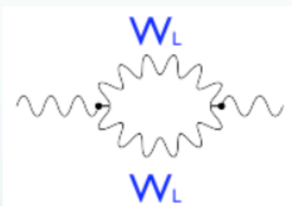
$W_L^+ W_L^- \to W_L^+ W_L^-$:

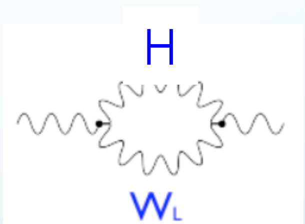


$$T_{SM} = \frac{1}{v^2}\left\{s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2}\right\} = -\frac{M_H^2}{v^2}\left\{\frac{s}{s - M_H^2} + \frac{t}{t - M_H^2}\right\}$$

Higgs exchange exactly cancells the O(s,t) terms

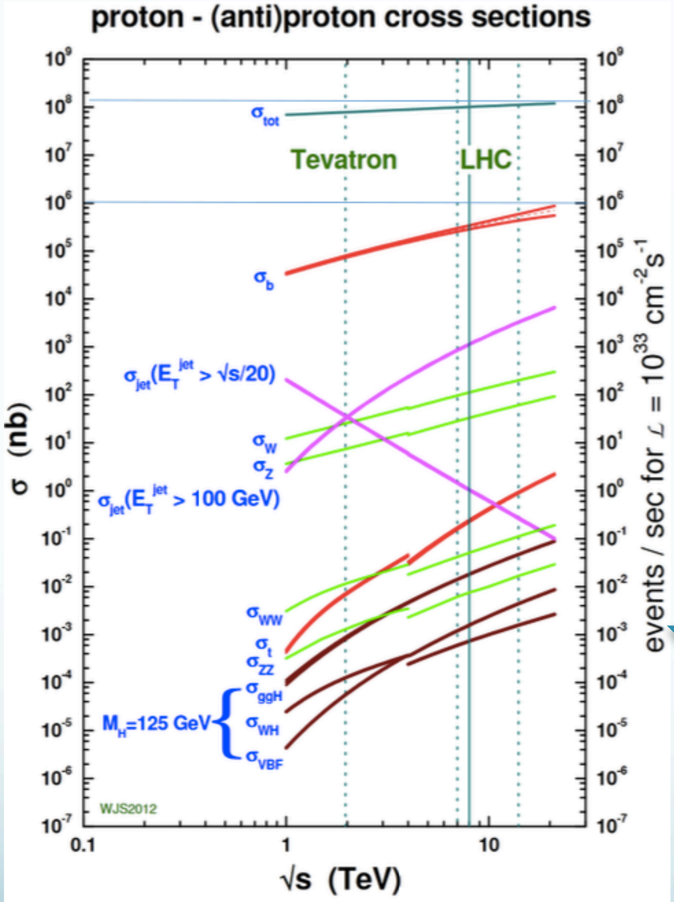
Higgs also neded to make loops finite

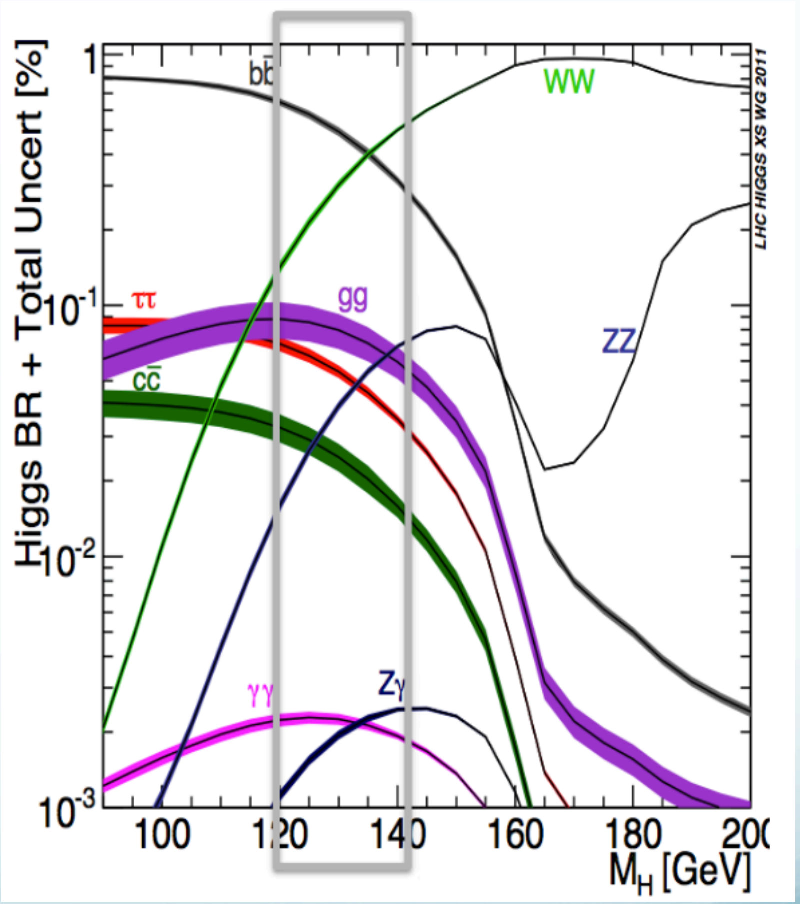




Hunting the Higgs difficult

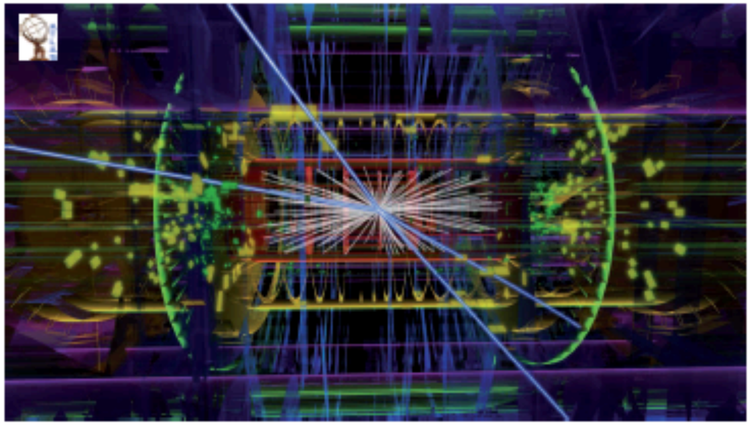
- extremely small production cross sections,
- processes involving Higgs resemble other SM processes,
- dominant decay mode extremely hard experimentally

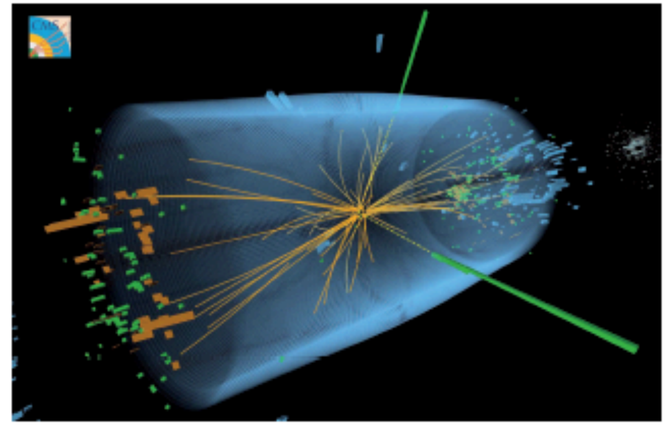


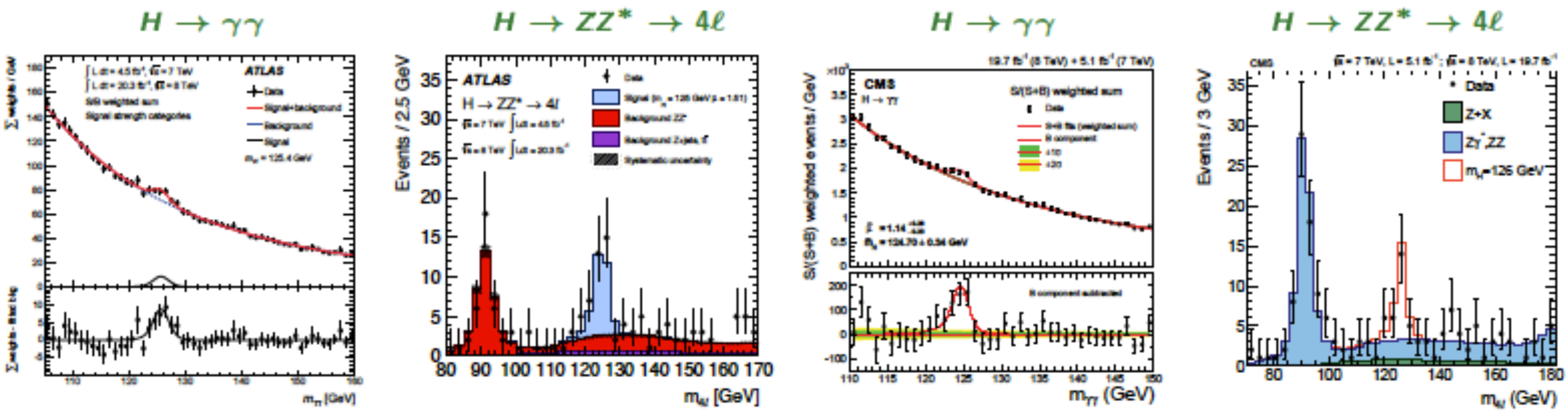


the LHC was needed with ATLAS and CMS detectors

And the Higgs has been found ! 4 July 2012







$$M_H = (125.09 \pm 0.21 \pm 0.11)\ \text{GeV}$$

Once the mass is known, the SM is complete and predictive

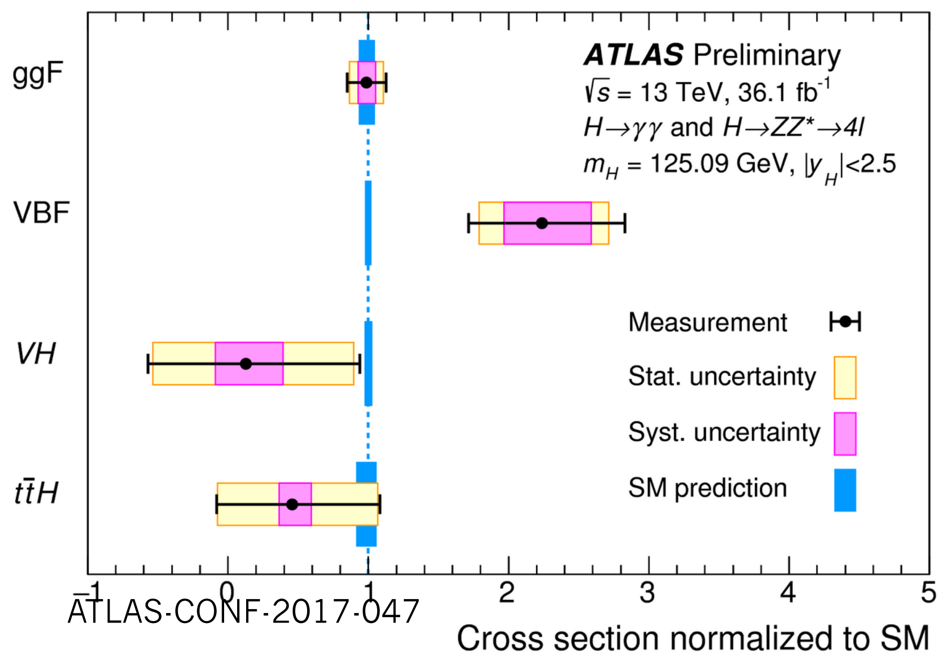
$$M_H \Rightarrow \lambda = \frac{M_H^2}{2v^2} = 0.13$$

great triumpf of weakly coupled SM

Entering era of precision measurements

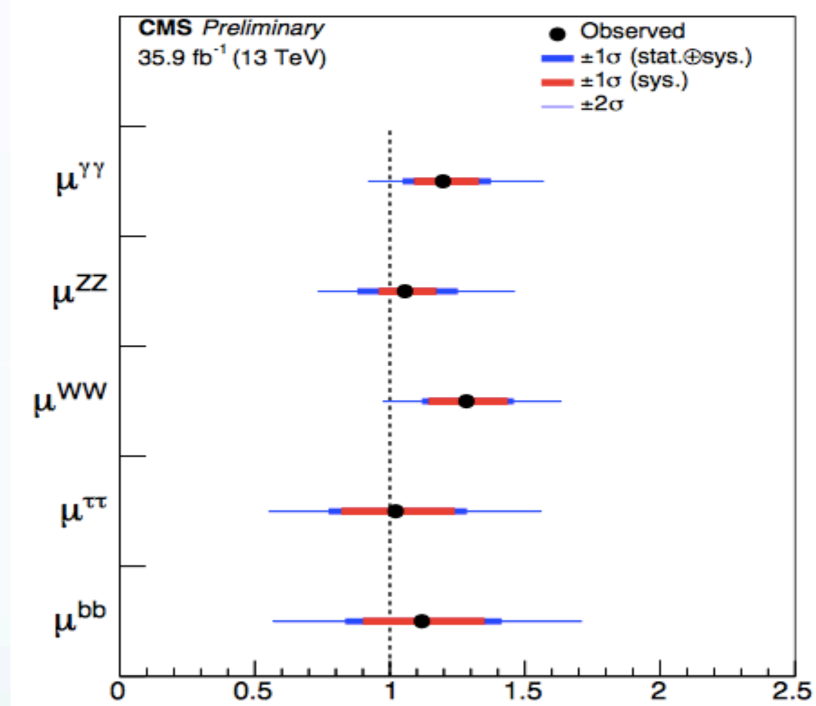
signal strengths:

per production mode



ATLAS-CONF-2017-047

per decay mode



CMS-PAS-Hig-17-031

Entering era of precision measurements

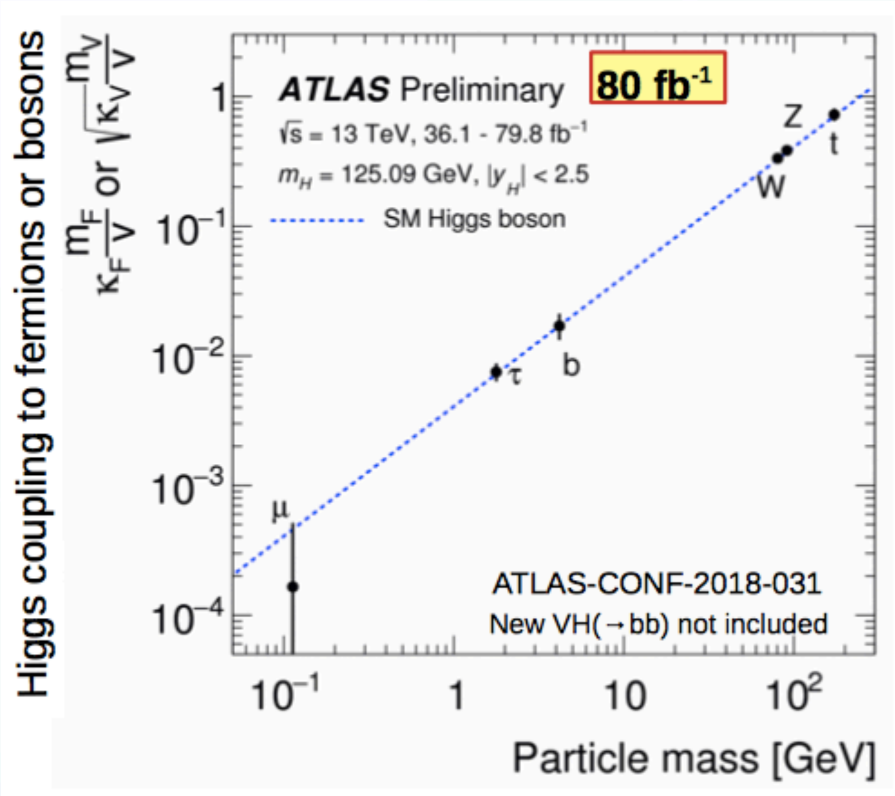
With the Higgs boson we are probing physics which is very different from the one we are doing with the gauge bosons and fermions

- the Higgs couples to mass

  e.g. no fermion universality!

- large variations

- this is the signature of being the Higgs



Physics after Higgs

The Standard Model is seemingly complete

Physics after Higgs

The Standard Model is seemingly complete

“This could be the discovery of the century. Depending, of course, on how far down it goes.”

Physics after Higgs

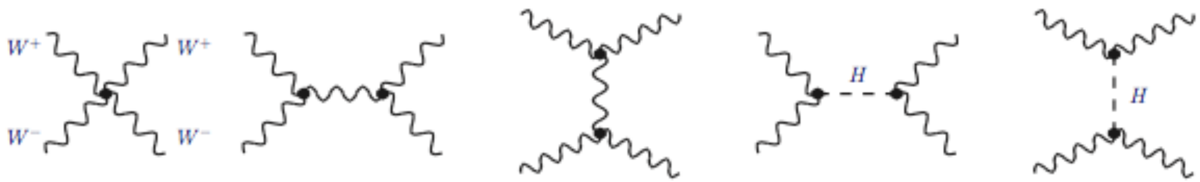
The Standard Model is seemingly complete, but

many open questions about the Higgs:

- is it the SM Higgs?
- is it the only one scalar state?
- is it an elementary/composite?
- is it natural?
- is it the first sign of supersymmetry?
- is it really responsible for masses of all elementary particles?
- is it a portal to a hidden world?
- is it at the origin of baryon asymmetry?
- is it responsible for early inflationary expansion of the Universe?
- ….
-

Restoration of unitarity and calculability

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



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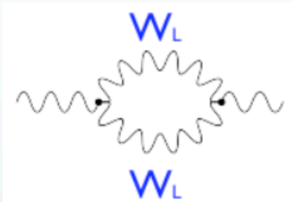
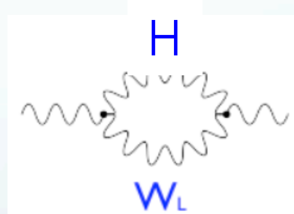
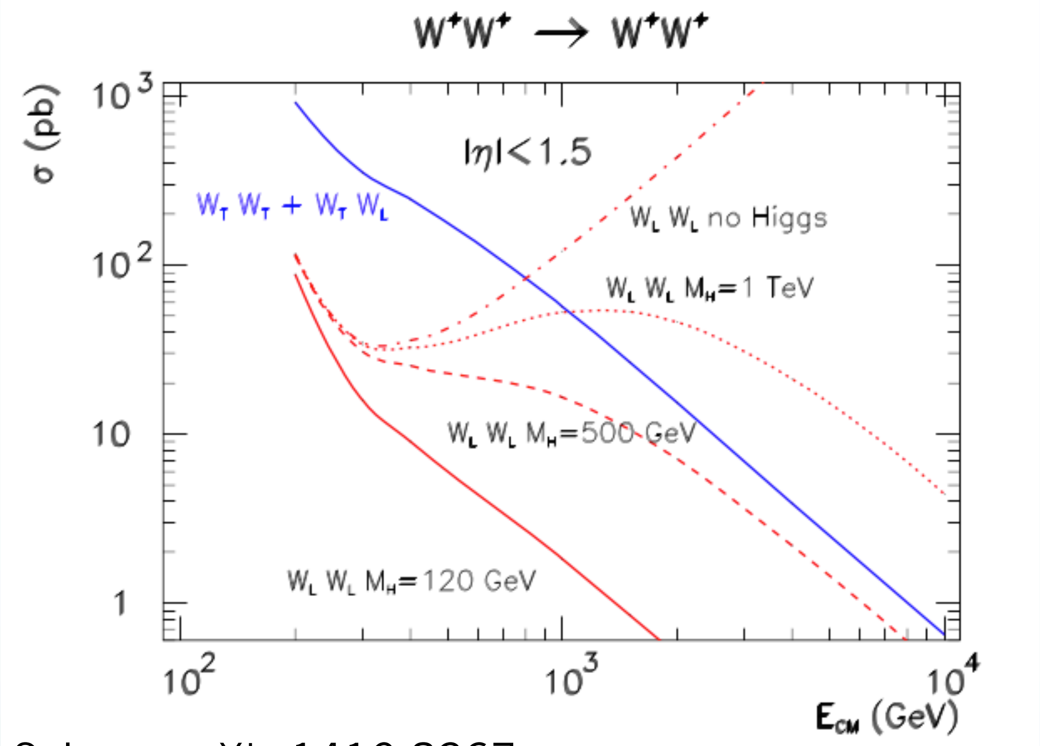




However, deviations from the SM Higgs couplings spoil the delicate cancellation

Difficult to see experimentally



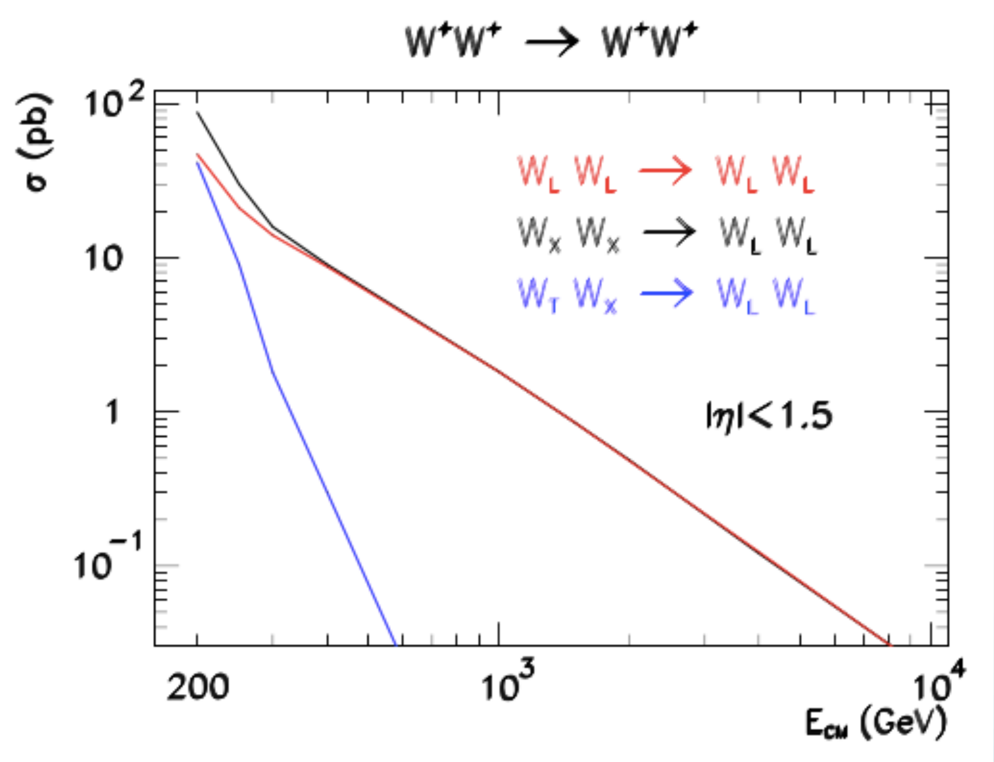
Szleper arXiv:1412.8367

- large background from W_T
- not easy to measure W polarization

Why pp-> jj W^+W^+ ?

- no cross-talk amplitudes:

$$W_T W_X \to W_L W_L, \;\; W_L W_L \to W_T W_X$$



Doroba, JK, Kuczmarski, Pokorski, Rosiek, Szleper: Phys.Rev.D86 [arXiv:1201.2768]

Why pp–> jj W⁺W⁺ ?

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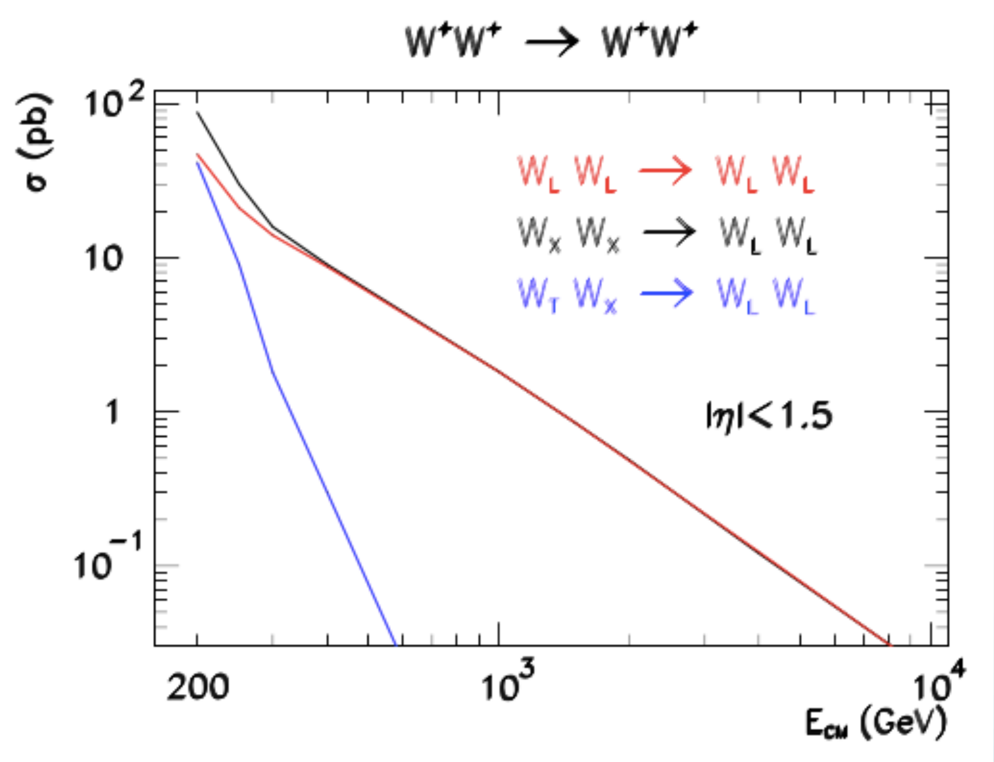
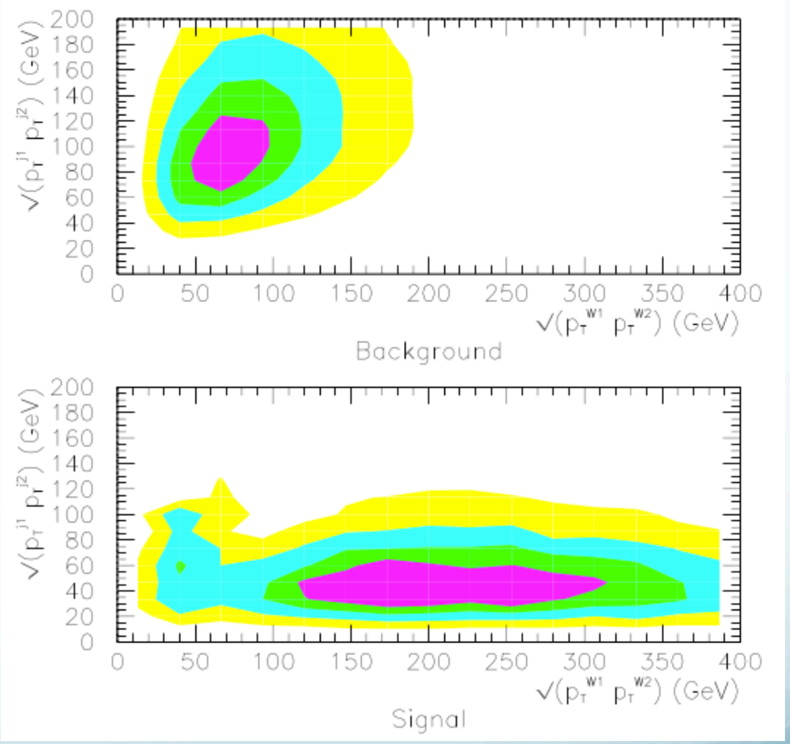


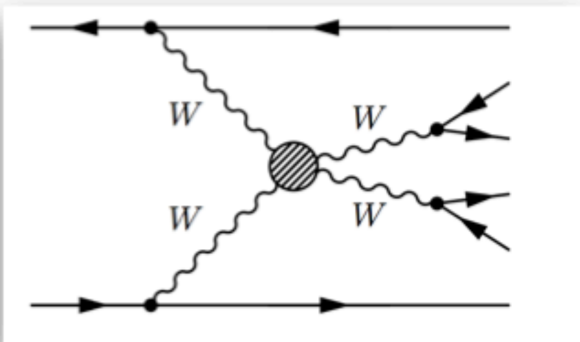
- W's emitted by colliding quarks: their polarization encoded in kinematics of outgoing jets

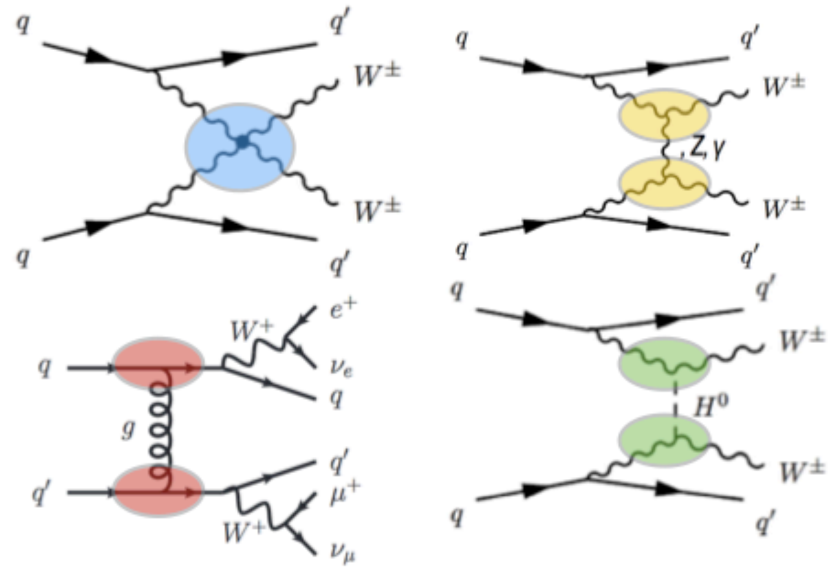


$R_{p_T} \equiv p_T^{l1} p_T^{l2} / (p_T^{j1} p_T^{j2}$ helps to separate L from T

Electroweak Diboson Production

- LHC can probe W and Z quartic couplings in Standard Model for the first time (massive bosons)





- At LO production cross section is sum of terms also involving strong coupling constant

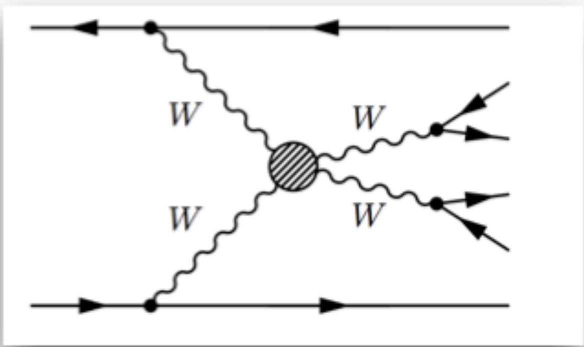
- $\frac{\sigma_{EW}(VV+jj)}{\sigma_{QCD}(VV+jj)}$ largest for W±W± production

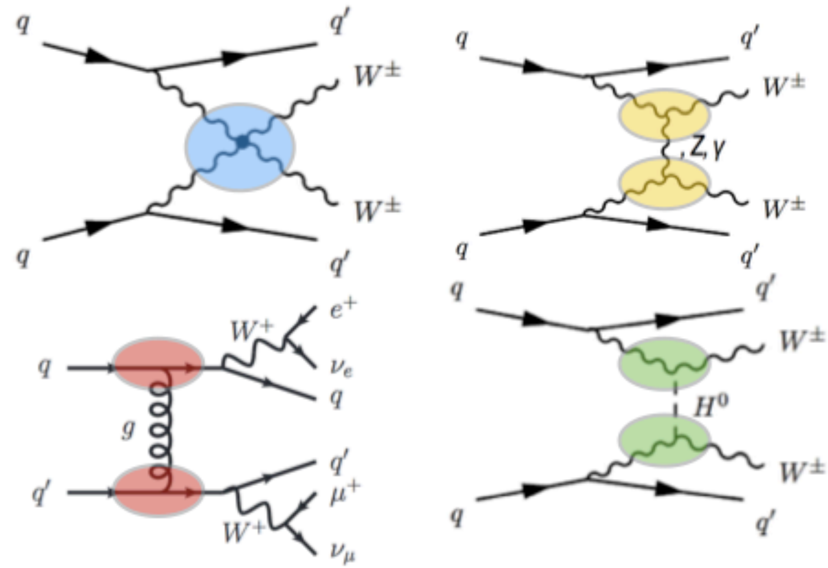
$\sigma_{EW} \propto \mathcal{O}(\alpha_{EW}^6)$	$\sigma_{EW \times QCD} \propto \mathcal{O}(\alpha_{EW}^5 \alpha_S)$	$\sigma_{QCD} \propto \mathcal{O}(\alpha_{EW}^4 \alpha_S^2)$
EW Signal	Interference, uncertainty or added to background, usually O(1%)	Background (QCD induced)

  - most sensitive to probe quartic gauge coupling

Electroweak Diboson Production

- **LHC can probe W and Z quartic couplings in Standard Model for the first time (massive bosons)**





- **At LO production cross section is sum of terms also involving strong coupling constant**

- $\dfrac{\sigma_{EW}(VV+jj)}{\sigma_{QCD}(VV+jj)}$ **largest for W±W± production**
  - **most sensitive to probe quartic gauge coupling**

$\sigma_{EW} \propto \mathcal{O}(\alpha_{EW}^6)$	$\sigma_{EW\times QCD} \propto \mathcal{O}(\alpha_{EW}^5 \alpha_S)$	$\sigma_{QCD} \propto \mathcal{O}(\alpha_{EW}^4 \alpha_S^2)$
EW Signal	Interference, uncertainty or added to background, usually O(1%)	Background (QCD induced)

$W^{\pm}W^{\pm}$ VBS (Observation 13 TeV)

- **Measurement performed inclusively in ee, eμ, μμ channel, two same-sign leptons**
  - **Major backgrounds estimated from the data: Fake leptons (60%), WZ (QCD+EW), charge flip (for electrons (sub) per mille level)**
  - **Major syst. unc.: jet energy scale, fake background**
  - **fiducial volume lepton: $|\eta| < 2.5$, $p_T > 20$ GeV, jets $|\eta| < 5$, $p_T > 30$ GeV, $m_{JJ} > 500$ GeV, $|\Delta\eta_{JJ}| > 2.5$**
- **Fit performed in 2 dimensions (m_{JJ} vs m_{ll}) to extract best-fit signal strength modifier**

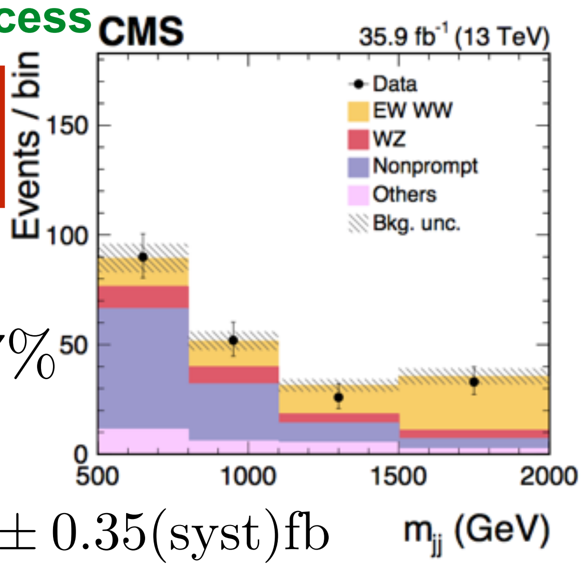
PRL 120, 081801

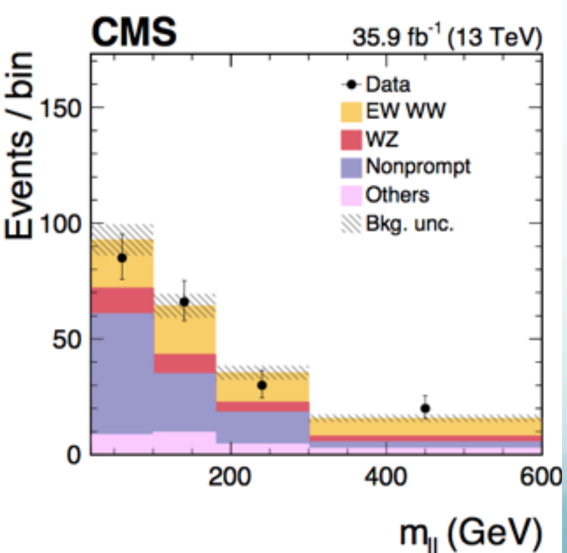
First observation of VBS process

5.5 (5.7) observed
(expected) significance

$$\sigma_{LO}^{EW} = 4.25 \pm 0.27\text{fb}$$

$$\sigma_{NLO-EW} \approx \sigma_{LO} - 17\%$$





$$\sigma^{\text{meas.}} = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst})\text{fb}$$

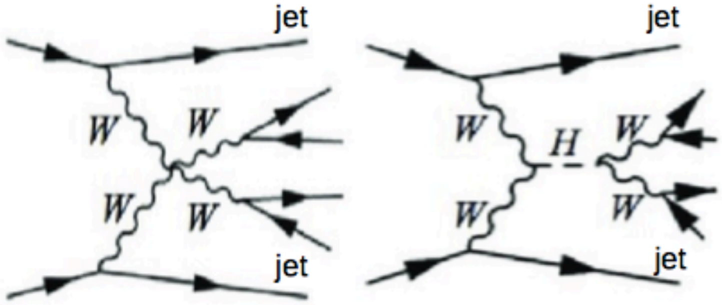
Observation of same-sign WWjj

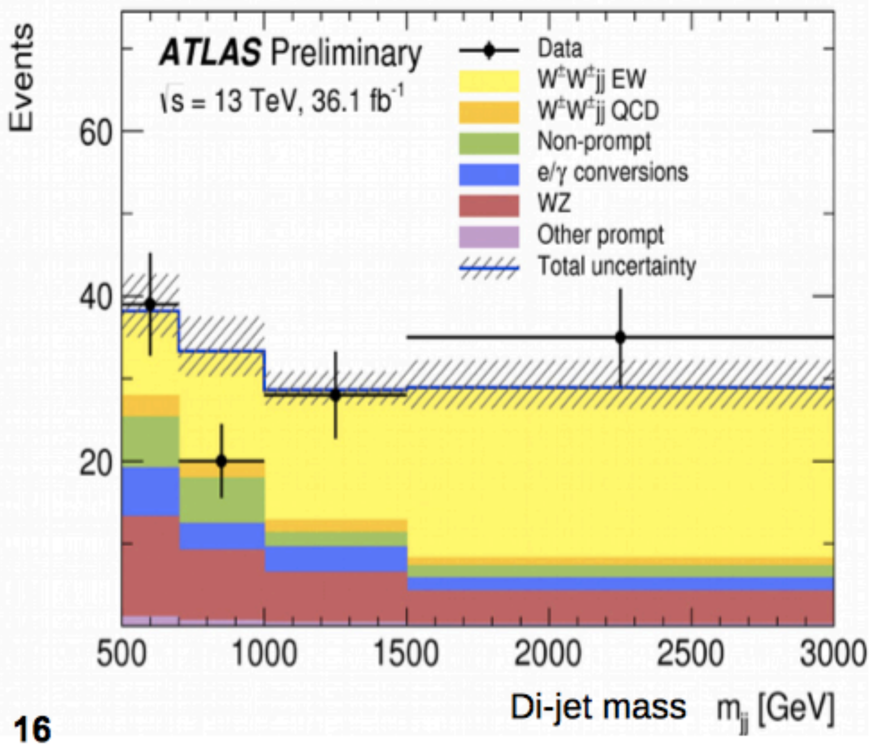
New

ATLAS-CONF-2018-030

Higgs boson needed to restore unitarity of the WW scattering cross-section.
→ Higgs boson leads to strong suppression via gauge cancellation of individual EW diagrams.
→ Part of electroweak symmetry breaking studies.

pp → $W^{+/-}$ $W^{+/-}$ jet jet process:
-Large electroweak cross-section fraction (σ_{EW}/σ_{QCD}).
and a strong background suppression.





Significance:
6.9σ (4.6σ) obs (exp)

Fiducial cross-

$$\sigma_{\rm fid} = 2.91^{+0.51}_{-0.47}(\text{stat.}) \pm 0.27(\text{syst.})\text{ fb}$$

$$\sigma^{\rm Sherpa}_{\rm fid} = 2.01^{+0.33}_{-0.23}\text{ fb}$$

$$\sigma^{\rm Powheg}_{\rm fid} = 3.08^{+0.45}_{-0.46}\text{ fb}$$

pp-> jj W^+W^+ beyond the SM

Assumption:

measurements of VBS at the LHC reveal disagreement with SM predictions, but no new states are seen directly

Goals of our studies:

- learn as much as possible about the origin of the effect from a VBS analysis carried within the framework of the EFT
- discuss issues related to the proper use of the EFT
- propose strategies for future data analyses

JK, Kozów, Pokorski, Rosiek, Szleper, Tkaczyk: EPJC78(2018)403,

Look at physics beyond the SM

- The SM may be considered as a low-energy effective theory (EFT) of a more fundamental one at some high scale Λ
- At current energies $E \ll \Lambda$ the high mass states can appear as highly off-shell or in loops
- In the Lagrangian language – they can be integrated out giving rise to higher–dimension operators

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{C_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)} + \Sigma_i \frac{C_i^{(8)}}{\Lambda_i^4} \mathcal{O}_i^{(8)} + \ldots$$

$\mathcal{O}_i^{(d)}$ dimension–d operators built from SM fields and respecting SM gauge symmetry

$$f_i^{(6)} = \frac{C_i^{(6)}}{\Lambda^2}, \qquad f_i^{(8)} = \frac{C_i^{(8)}}{\Lambda^4}, \ldots.$$

Prime example: Fermi theory of weak interactions

Alternatives: anomalous couplings

- Lagrangian approach (for TGC, also for QGC)

$$
\begin{aligned}
\mathcal{L} \;=\; & i g_{WWV} \Big(g_1^V (W_{\mu\nu}^+ W^{-\mu} - W^{+\mu} W_{\mu\nu}^-) V^\nu + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W_\mu^{\nu+} W_\nu^{-\rho} V_\rho^\mu \\
& + i g_4^V W_\mu^+ W_\nu^- (\partial^\mu V^\nu + \partial^\nu V^\mu) - i g_5^V \epsilon^{\mu\nu\rho\sigma} (W_\mu^+ \partial_\rho W_\nu^- - \partial_\rho W_\mu^+ W_\nu^-) V_\sigma \\
& + \tilde{\kappa}_V W_\mu^+ W_\nu^- \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W_\mu^{\nu+} W_\nu^{-\rho} \tilde{V}_\rho^\mu \Big)
\end{aligned}
$$

  - not necessarily gauge invariant, need to impose it
  - additional terms can be generated by adding derivatives --> $1/M_W$

- Vertex function approach (momentum space analog)

$$
\begin{aligned}
\Gamma_V^{\alpha\beta\mu} \;=\; & f_1^V (q-\bar{q})^\mu g^{\alpha\beta} - \frac{f_2^V}{M_W^2} (q-\bar{q})^\mu P^\alpha P^\beta + f_3^V (P^\alpha g^{\mu\beta} - P^\beta g^{\mu\alpha}) \\
& + i f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + i f_5^V \epsilon^{\mu\alpha\beta\rho} (q-\bar{q})_\rho \\
& - f_6^V \epsilon^{\mu\alpha\beta\rho} P_\rho - \frac{f_7^V}{m_W^2} (q-\bar{q})^\mu \epsilon^{\alpha\beta\rho\sigma} P_\rho (q-\bar{q})_\sigma
\end{aligned}
$$

  - coefficients are formfactors (momentum dependent), but arbitrary
  - W charge and gauge invariance: constraints on formfactors

- In such approaches: no relations between TGCs and QGCs

Look at physics beyond the SM

EFT: $$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i \frac{C_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)} + \Sigma_i \frac{C_i^{(8)}}{\Lambda_i^4} \mathcal{O}_i^{(8)} + \ldots$$

Questions:

- Is it really model independent?
- How useful is it to describe future VBS data at the LHC?
- How to proceed to to keep proper physics interpretation of EFT parameters?
- Can we go beyond setting limits?

EFT facts

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i f_i^{(6)} \mathcal{O}_i^{(6)} + \Sigma_i f_i^{(8)} \mathcal{O}_i^{(8)} + ...$$

- In principle a model independent tool for BSM physics below Λ
- An infinite expansion – no unitarity violation, but infinite number of parameters
- For practical reasons, one needs a choice
- Which operators dominant, which can be neglected?
  Not obvious!
  (see. e.g. Contino ea. 1604.06444, Azatov ea, 1607.05236, Franceschini ea, 1712.01310, Falkowski ea, 1609.06312, ...)
- Once the choice made, the model-independence lost, unitarity may be violated
- Common practice: take just one or a few operators ➔ an "EFT model" defined by chosen operators $\mathcal{O}_i$ and values of Wilson coefficients f_i

"EFT model" --- the usage and limitations

- Validity of an "EFT model": for WW it can be valid up to an invariant mass M

$$M < \Lambda \leq M^U(f_i)$$

  where $M^U(f_i)$ is fixed by partial wave unitarity constraint

- The same M applies to all amplitudes affected by the considered operator, even if they are still far from their own unitarity limits

- Different processes may define different maximum allowed value for the same set of higher dimension operators

- It may also happen that Λ is much lower than any unitarity bound (lesson learned from the Higgs boson!)

- We do not know what lies behind M. We may try to guess it within some (reasonable?) speculations based on general physics principles

Measured quantities never violate unitarity

Dimension 8 operators: relevant for ssWW

$$\mathcal{O}_{S0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right],$$

$$\mathcal{O}_{S1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right],$$

$$\mathcal{O}_{M0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right],$$

$$\mathcal{O}_{M1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right],$$

$$\mathcal{O}_{M6} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} W^{\beta\nu} D^\mu \Phi \right],$$

$$\mathcal{O}_{M7} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi \right],$$

$$\mathcal{O}_{T0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right],$$

$$\mathcal{O}_{T1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right],$$

$$\mathcal{O}_{T2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha} \right].$$

$$D_\mu \equiv \partial_\mu + i\frac{g'}{2}B_\mu + igW^i_\mu \frac{\tau^i}{2}$$

$$W_{\mu\nu} = \frac{i}{2} g \tau^i (\partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g\epsilon_{ijk} W^j_\mu W^k_\nu)$$

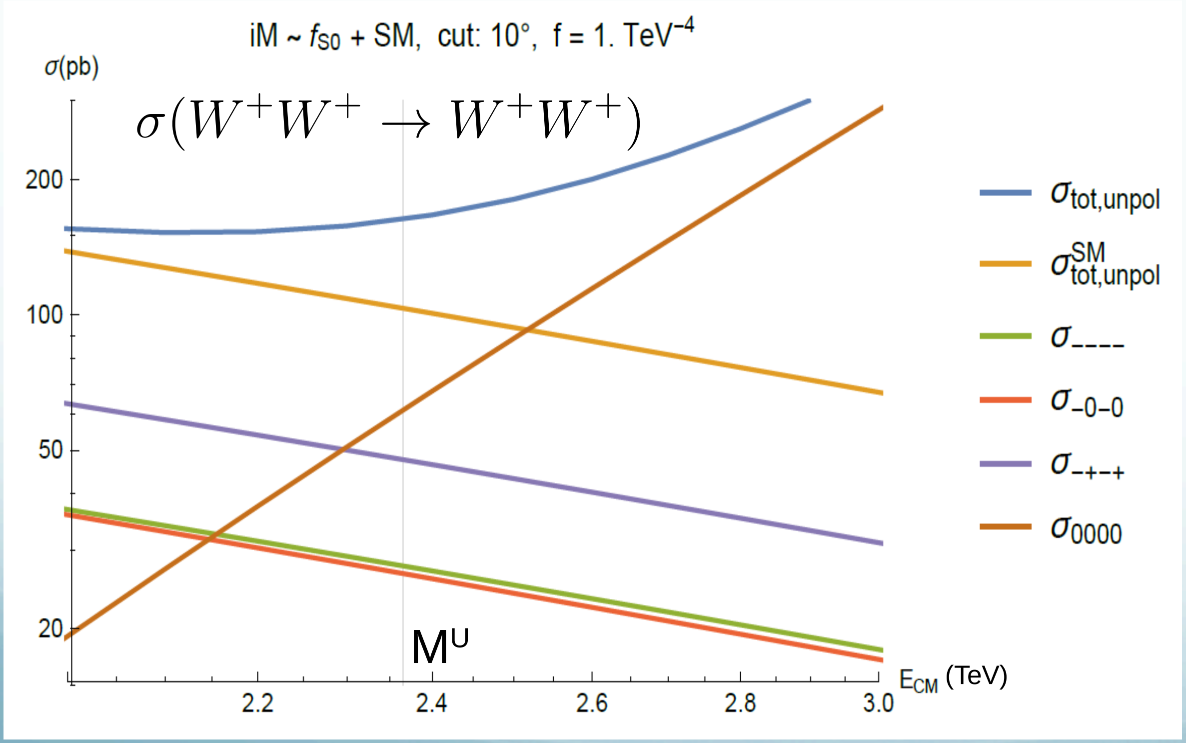
$$\hat{W}_{\mu\nu} = \tfrac{1}{ig} W_{\mu\nu}$$

they do not affect triple vector boson couplings

Helicities and unitarity limits

an easy case: $\mathcal{O}_{S0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]$

BSM mainly in one helicity amplitude



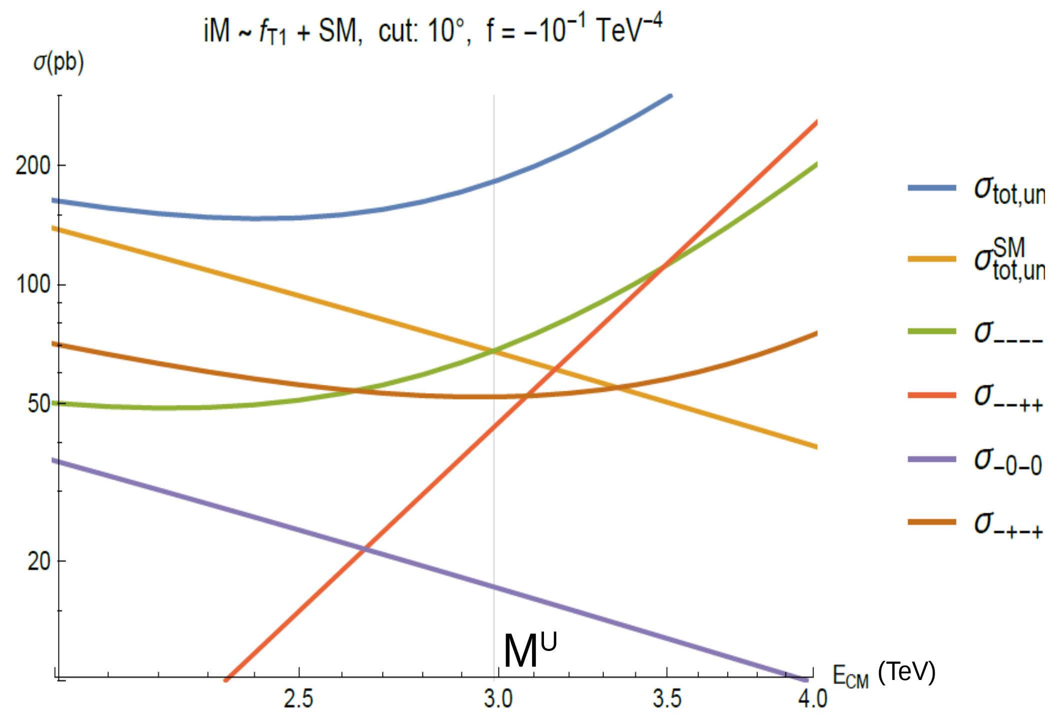
unitarity limits (in TeV)
for individual amplitudes

Hel. \ f_{S0} =	0.01	0.1	1.	10.
−−−−	x	x	x	x
−−−0	x	x	x	x
−−−+	x	x	x	x
−−00	440.	140.	44.	14.
−−0+	x	x	x	x
−−++	x	x	x	x
−0−0	x	x	x	x
−0−+	x	x	x	x
−000	x	x	x	x
−00+	x	x	x	x
−+−+	x	x	x	x
−+00	x	x	x	x
0000	7.5	4.2	2.4	1.3

Helicities and unitarity limits

a non-trivial case: $\mathcal{O}_{T1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$

BSM affects many helicity amplitudes



unitarity limits (in TeV)
for individual amplitudes

Hel. \ f_{T1} =	−0.01	−0.1	−1.	−10.
−−−−	5.3	3.0	1.7	0.96
−−−0	7.5×10^7	7.5×10^6	7.5×10^5	7.5×10^4
−−−+	1.7×10^3	530.	170.	53.
−−00	440.	140.	44.	14.
−−0+	74.	34.	16.	7.4
−−++	5.5	3.1	1.7	0.99
−0−0	2.5×10^3	800.	250.	80.
−0−+	69.	32.	15.	6.9
−000	3.7×10^7	3.7×10^6	3.7×10^5	3.7×10^4
−00+	2.3×10^3	740.	230.	74.
−+−+	10.	5.6	3.2	1.8
−+00	1.7×10^3	530.	170.	53.
0000	x	x	x	x

pp-> jj W^+W^+ -> jj $\mu^+\mu^+\nu\nu$ at the HL-LHC

- In the ssWW the invariant WW mass is not experimentally accessible,
  ➔ we do not know which part of the measured distribution comes from the EFT-controlled range
- Define the BSM signal as $S = \mathcal{D}_i^{model} - \mathcal{D}_i^{SM}$

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- The EFT-controlled signal is given by

$$\mathcal{D}_i^{model} = \underbrace{\int_{2M_W}^{\Lambda} \frac{d\sigma}{dM}|_{model}\, dM}_{\text{EFT in its range of validity}} + \underbrace{\int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM}|_{SM}\, dM}_{\text{only SM contribution}}$$

- The EFT can be applied to describe the full measured distribution provided the region $M > \Lambda$ does not significantly distort it

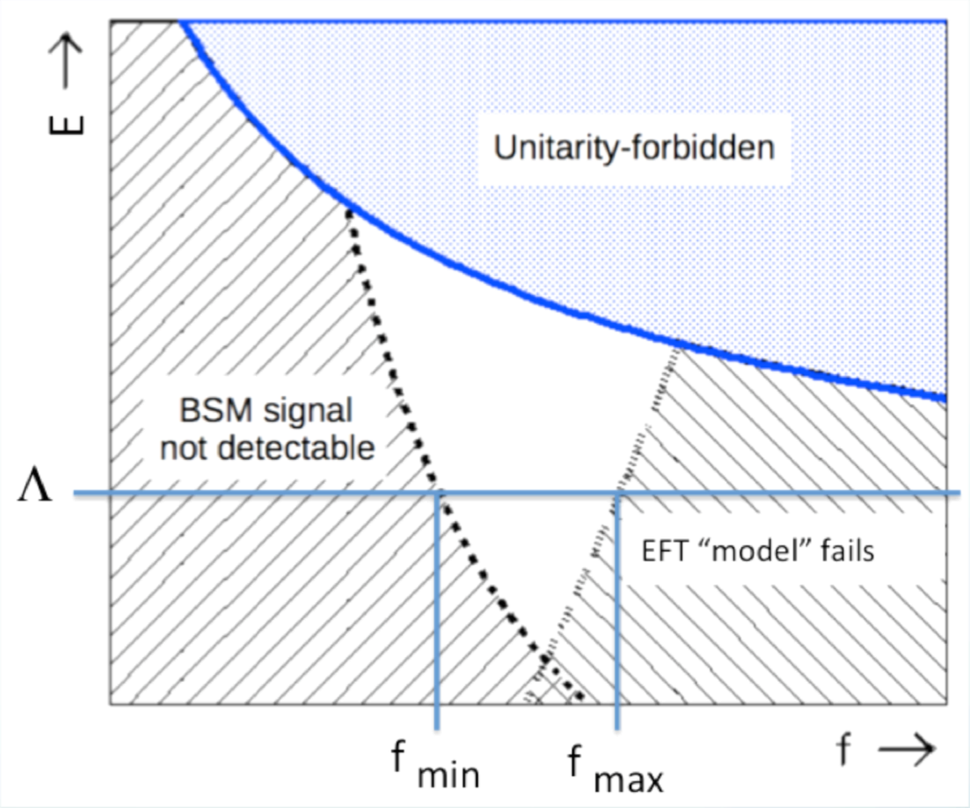
- It puts constraints in the (f, Λ) plane

Cartoon plot

for given Λ :

a) $f > f_{min}$ to see BSM effect

b) $f < f_{max}$ the effect not dominated by $M > \Lambda$



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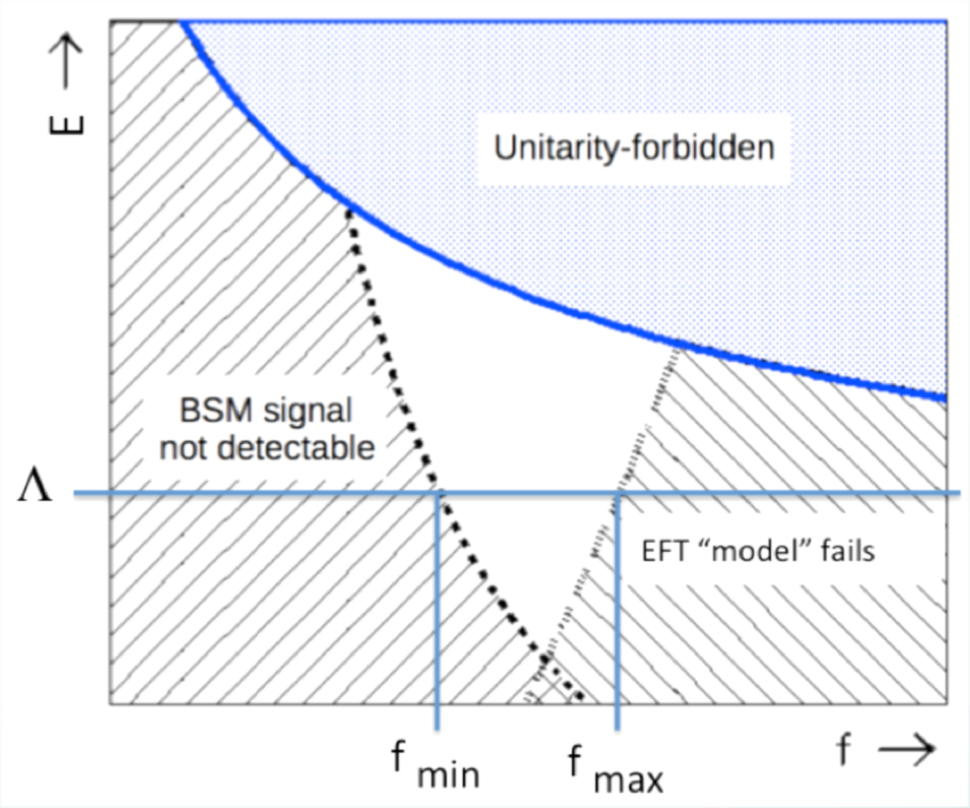
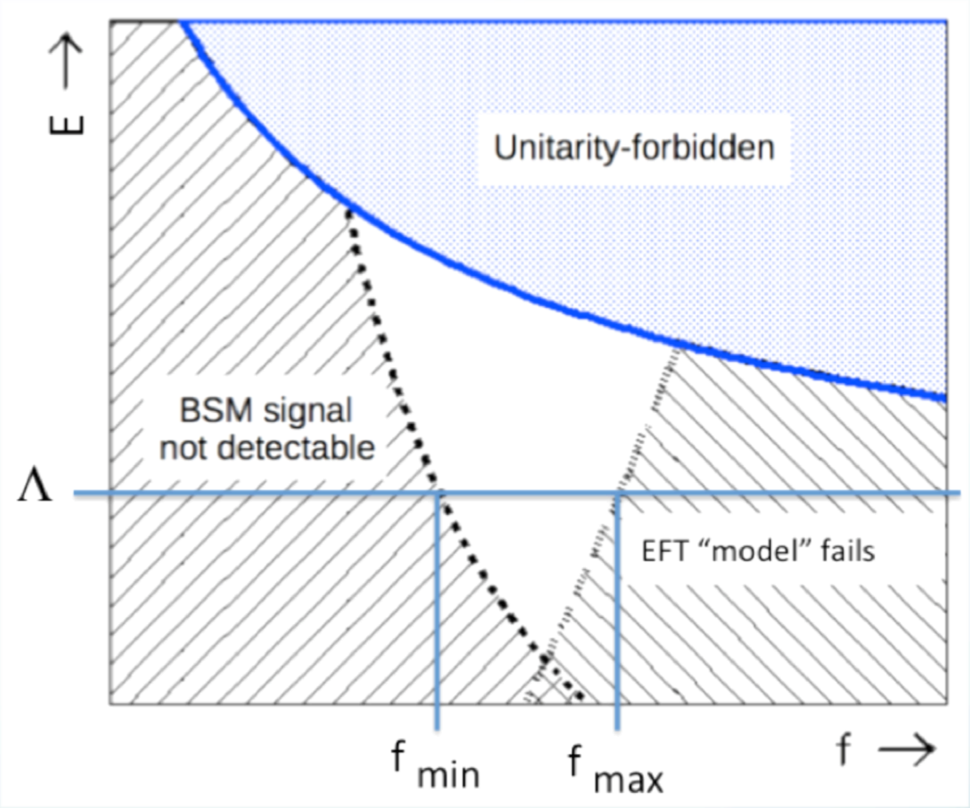


Need a reasonable estimate what happens above Λ in accordance with all physics principles

Estimating the signal above Λ

Above Λ expect the total cross section ~ 1/s

We assume that all amplitudes remain constant at their values they reach at Λ, even for those which are still far from their respective unitarity limit



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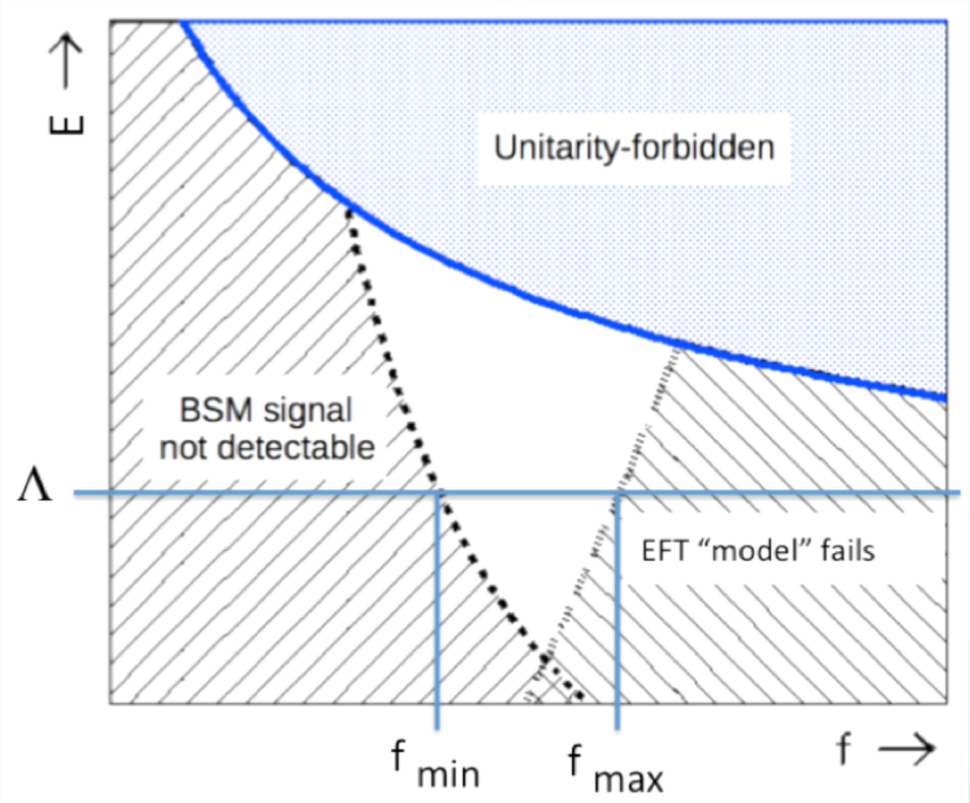


Our proposal:

$$\mathcal{D}_i^{model} = \int_{2M_W}^{\Lambda} \frac{d\sigma}{dM}|_{model}\, dM + \int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM}|_{A=const}\, dM$$

EFT in its range of validity

physicall plausible contribution

Proposed procedure

- Our proposal:

$$\mathcal{D}_i^{model} = \int_{2M_W}^{\Lambda} \frac{d\sigma}{dM}|_{model}\, dM + \int_{\Lambda}^{M_{max}} \frac{d\sigma}{dM}|_{A=const}\, dM$$

EFT in its range of validity   physicall plausible contribution

+ requirement that the signal is driven by the EFT--controlled region

i.e. as long as the measured signal is not too sensitive to details above Λ

Practical criterion: signals calculated with and without M>Λ should be statistically consistent (e.g. within 2 sigma)

Proposed procedure

- Measure the most sensitive distributions
- Fit (f, Λ) using simulated distributions including BSM contributions from the region M>Λ
- Using the fitted values (f, Λ) recalculate simulated distributions removing the BSM contribution from M>Λ
- Check the statistical consistency between the the original simulated distributions and recalculated ones
- Obtained values of (f, Λ) make sense if such consistency is found, i.e. the “EFT triangle” is not empty
- Otherwise description of data in terms of a studied “EFT–model” is not possible
- Stability of the result against different regularization methods would provide a measure of uncertainty

Simulation work – proof of the procedure

Private MG5+Pythia simulated samples of ~1M events for the process

$pp \to jj\, \mu^+\mu^+\nu\nu$ at 14 TeV for each dim-8 operator separately

Tails for $M>\Lambda$ modeled by applying additional weights $(\Lambda/M)^4$

Signal significances calculated from different differential distributions

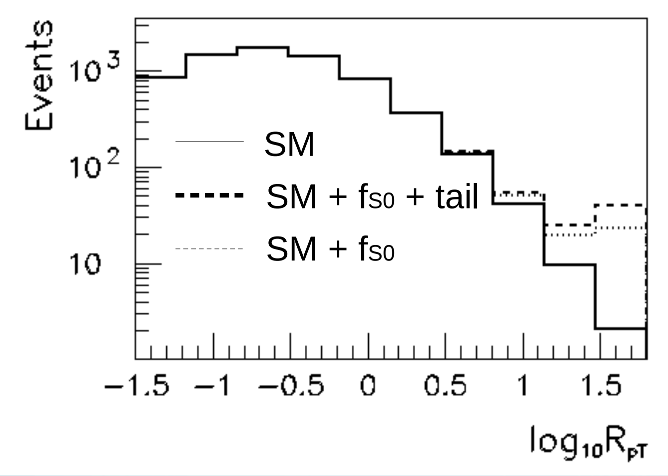
assuming HL-LHC luminosity of 3/ab

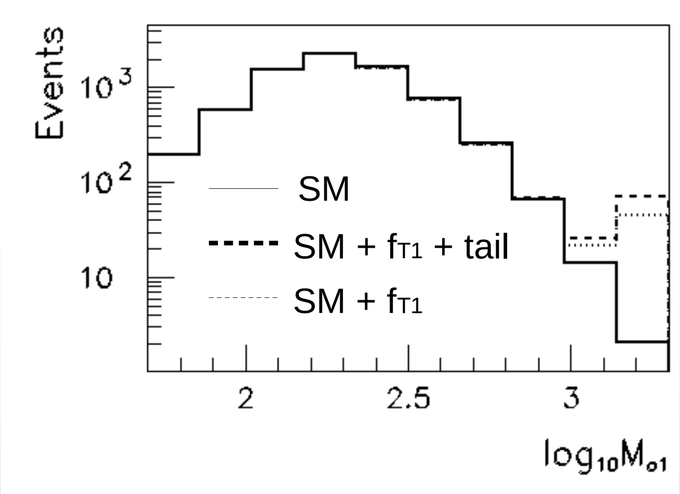
Simulation work – proof of the procedure

Most sensitive variables:

for S0 and S1 operators $R_{p_T} \equiv p_T^{l1} p_T^{l2} / (p_T^{j1} p_T^{j2})$

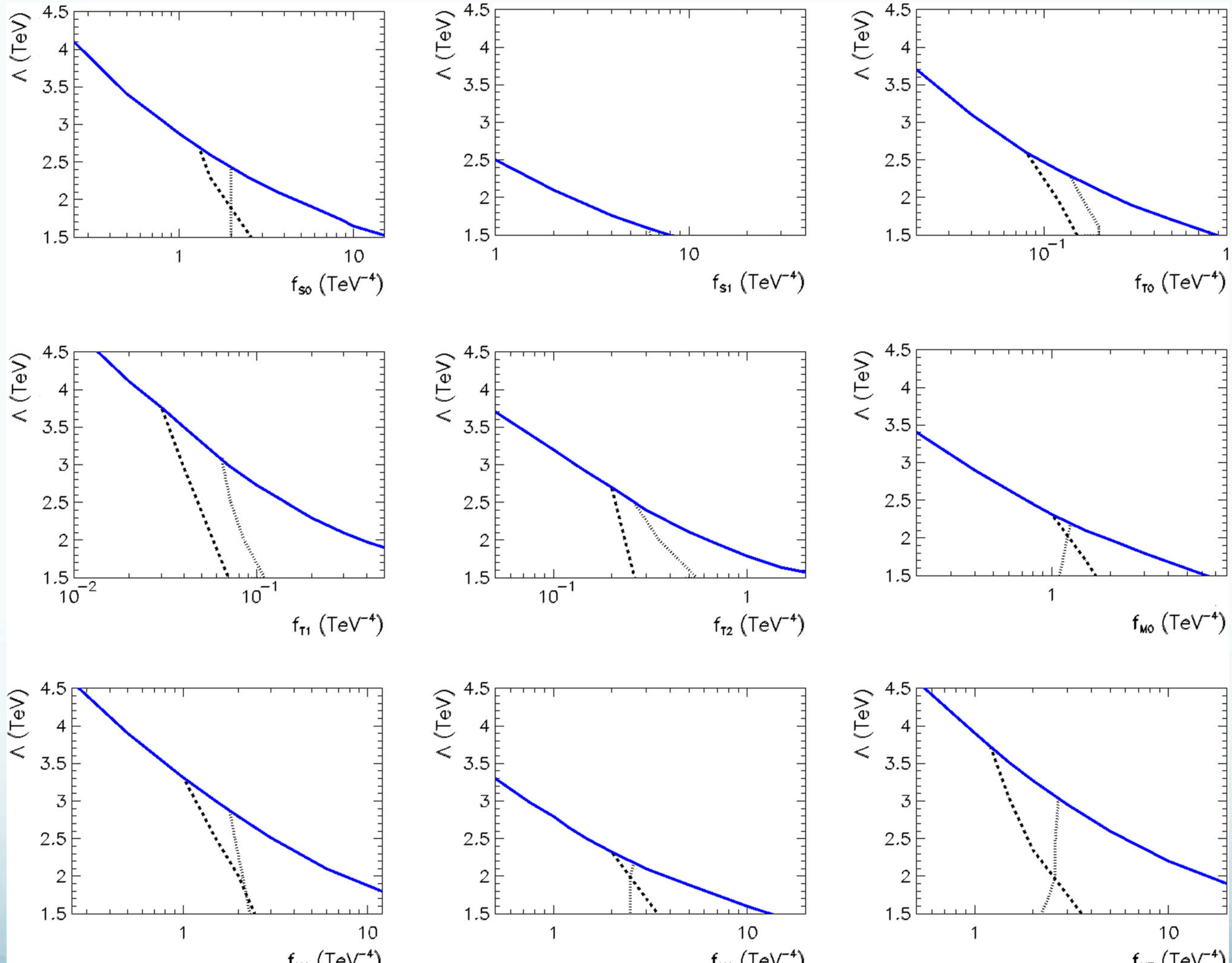
for others $M_{o1} \equiv \sqrt{(|\vec{p}_T^{\,l1}| + |\vec{p}_T^{\,l2}| + |\vec{p}_T^{\,miss}|)^2 - (\vec{p}_T^{\,l1} + \vec{p}_T^{\,l2} + \vec{p}_T^{\,miss})^2}$



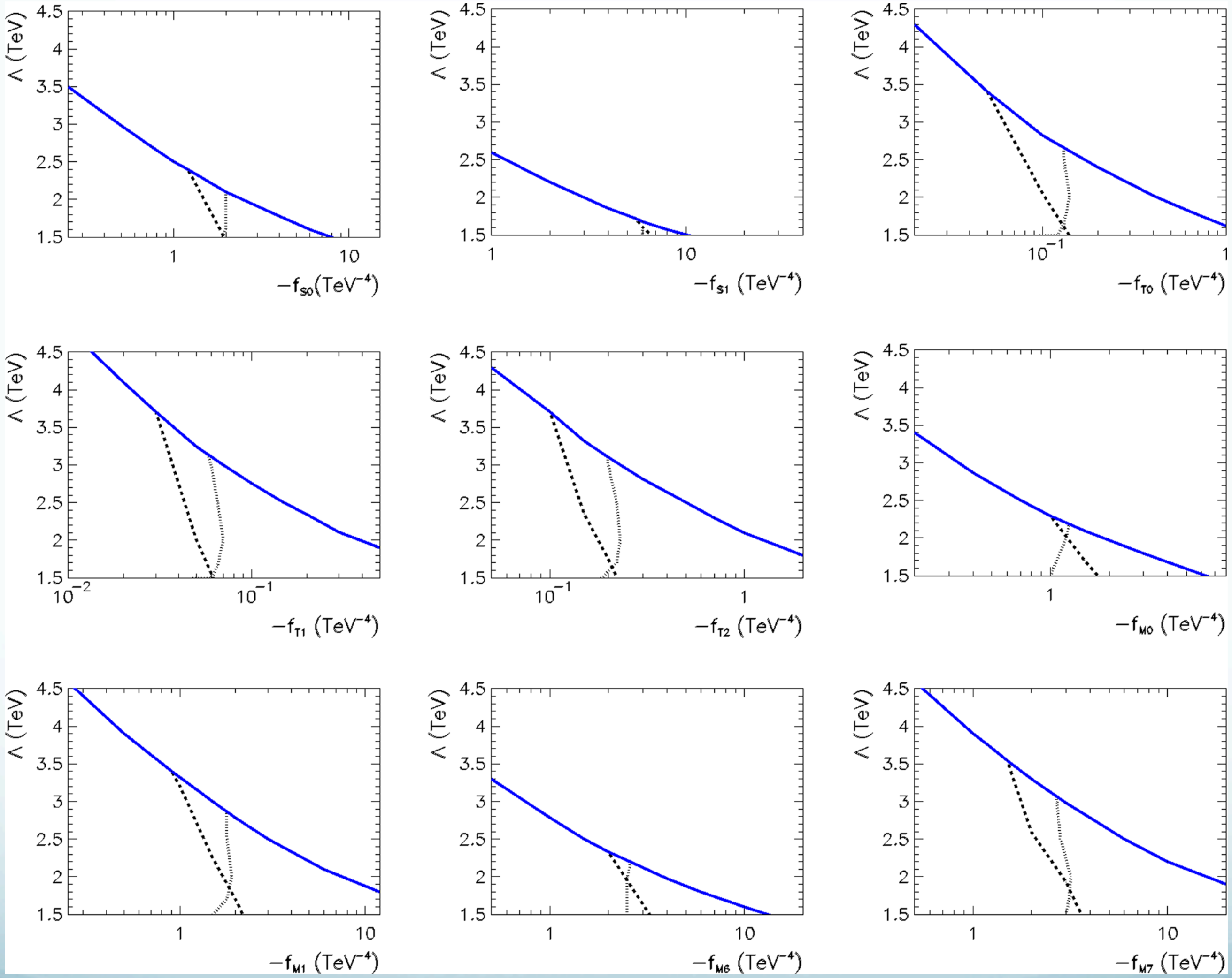


$f_{T1} = 0.1/TeV^4$

Examples of “EFT triangles”



Examples of "EFT triangles"



Examples of “EFT triangles”

Caution: no detector simulation in this study, just a demo of the method

All triangles rather small, but not empty (S1 most problematic)

for most operators (S and M) we can probe theories with Λ>2 TeV and near the strong coupling limit

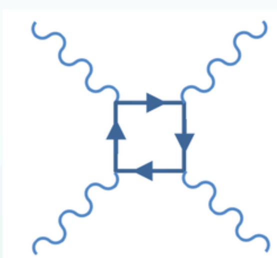
for T operators a wider range is open

A hint on BSM couplings

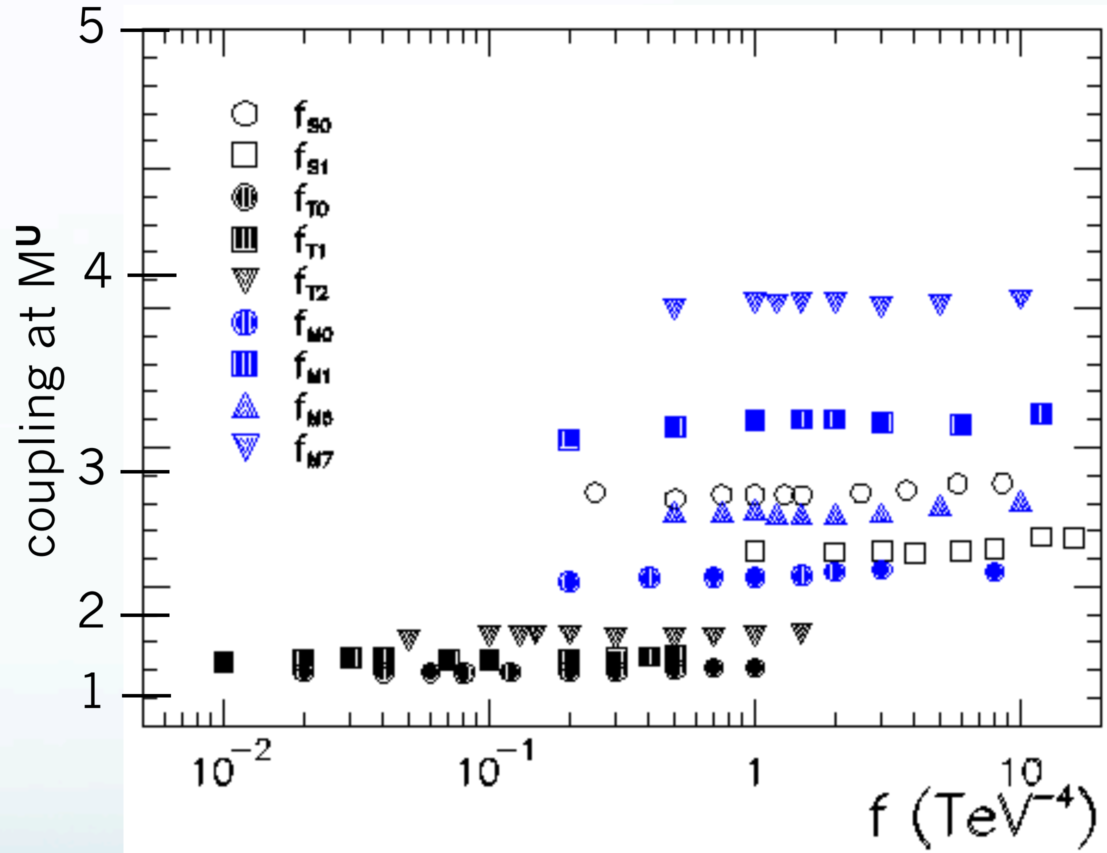
for dim-8 operators

$$C_i^{(8)} = f_i^{(8)} \Lambda^4$$

assuming the dim-8 operator
to be loop--induced



$$C_i^{(8)} \sim g_*^4$$



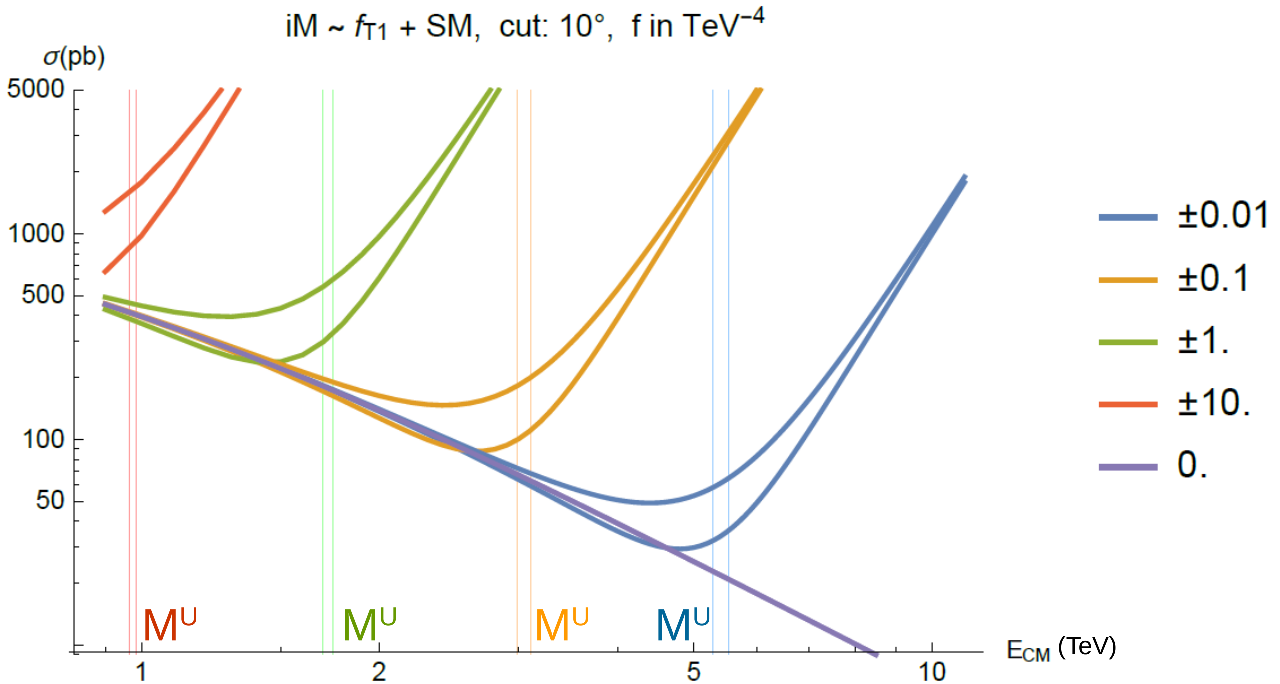
for every dim-8 operator the maximum value of g_* occurs when Λ=M^U

Conclusions and outlook

- WW scattering is becoming one of the most studied process at the LHC
- Since new physics seems to be pushed further away than expected, the EFT framework can be used to explore BSM
- Features and limitations of the EFT framework discussed
- A concept of and "EFT model" introduced
- A new data analysis strategy proposed
- We find for all dim-8 operaters that affect the quartic WWWW coupling regions where 5σ BSM signal can be observed at HL-LHC
- We attempted to extract the strength of plausible underlying physics
- Other VBS processes and W decay channels may improve the situation

Justification of high M tail modeling

- Asymptotically, every dim-8 operator produces a divergence ~s^3 in the total cross section.
- After regularization expected behavior ~$1/s$ → reweight like $1/s^4$, i.e., $(\Lambda/M)^8$

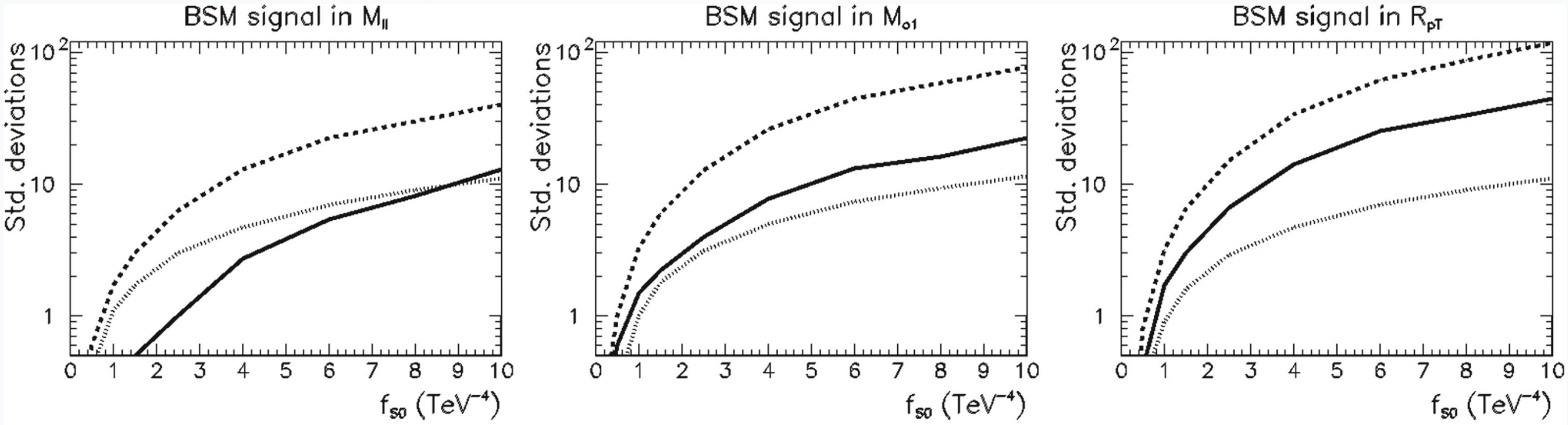


Total $W^+W^+ \to W^+W^+$ cross section for different f_{T1}

- But we are mostly interested in the region just above $\Lambda \sim M^U$
- Around unitarity limit:
  - the highest power term is not dominant yet,
  - the fastest growing amplitude is not dominant yet.
- Hence the overall energy dependence is much less steep.

- Of the simple power law scalings, $(\Lambda/M)^4$ fits best to the overall energy dependence around M^U.

signal significance



$$\chi^2 = \sum_i (N_i^{BSM} - N_i^{SM})^2 / N_i^{SM}$$

$$\chi^2_{add} = \sum_i (N_i^{EFT} - N_i^{BSM})^2 / N_i^{BSM}$$