WW scattering: a window beyond the Standard Model

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Why have we built the LHC?

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to study VV scattering!

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

Lee, Quigg and Thacker '77:
scattering of EW Goldstones violates unitarity above ~1 TeV

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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

Gauge invariance

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

3×2 polarizations $=$ 6

$+$

3 Goldstones $\varphi_i(x)$

SSB $\Big\downarrow$

Massive $W^{\pm}$, Z

3×3 polarizations $=$ 9

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

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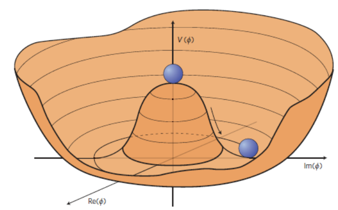
Spontaneous Symmetry Breaking

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



$\mu^2 < 0$

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

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

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

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

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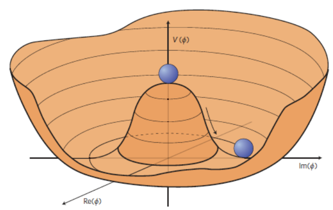

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when the gauge symmetry is spontaneously broken, the would-be Goldstone mode becomes a third component of the vector field and thus makes it massive.

Goldstones responsible for V masses

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

custodial symmetry

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

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

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

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

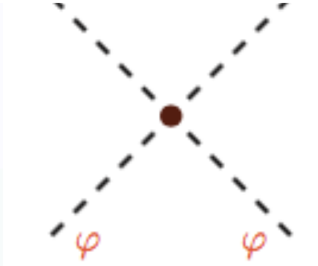
$$\mathcal{L}_2 = \frac{v^2}{4}\,\mathrm{Tr}\left(D_\mu U^\dagger D^\mu U\right) \xrightarrow{U=1} \mathcal{L}_2 = M_W^2\,W_\mu^\dagger W^\mu + \frac{1}{2}M_Z^2\,Z_\mu Z^\mu$$

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

Goldstone dynamics determined by symmetry

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

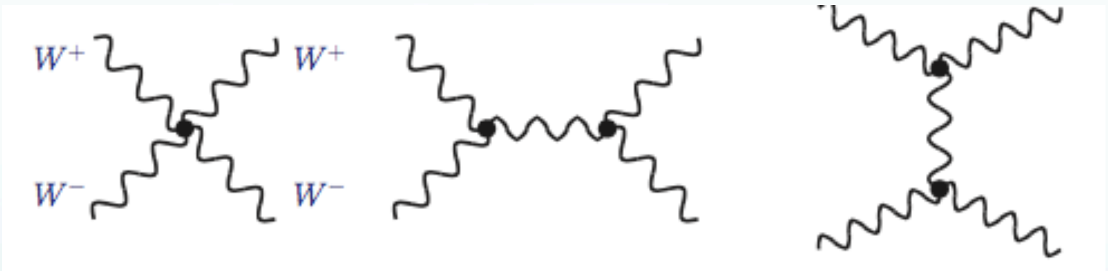
become free at zero momenta



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

Equivalence theorem

Cornwall-Levin-Tiktopoulos, Lee-Quigg-Thacker



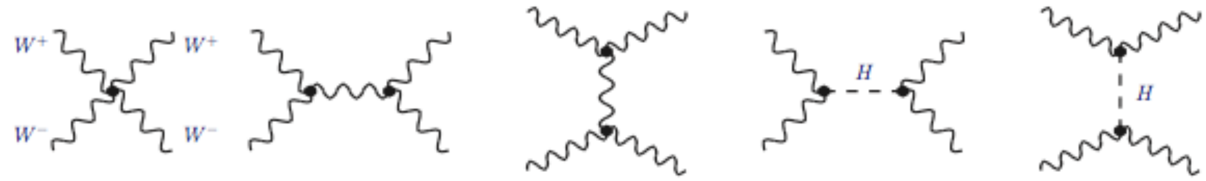
strong gauge cancellations

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

violates unitarity at ~1 TeV

Restoration of unitarity and calculability

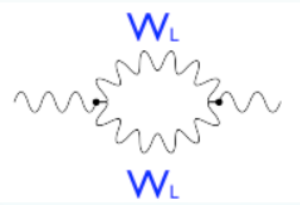
$W_L^+ W_L^- \rightarrow W_L^+ W_L^-$:

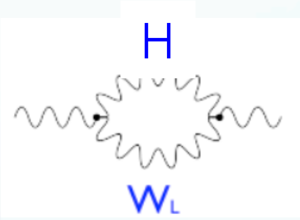


$$T_{SM} = \frac{1}{v^2}\left\{s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2}\right\} = -\frac{M_H^2}{v^2}\left\{\frac{s}{s - M_H^2} + \frac{t}{t - M_H^2}\right\}$$

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

Higgs also neded to make loops finite





Studying VBS → direct probe of EWSB

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- Either elementary scalar is found
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    - Necessary to develop techniques to observe $W_L W_L$ scattering

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PHYSICAL REVIEW D **86,** 036011 (2012)

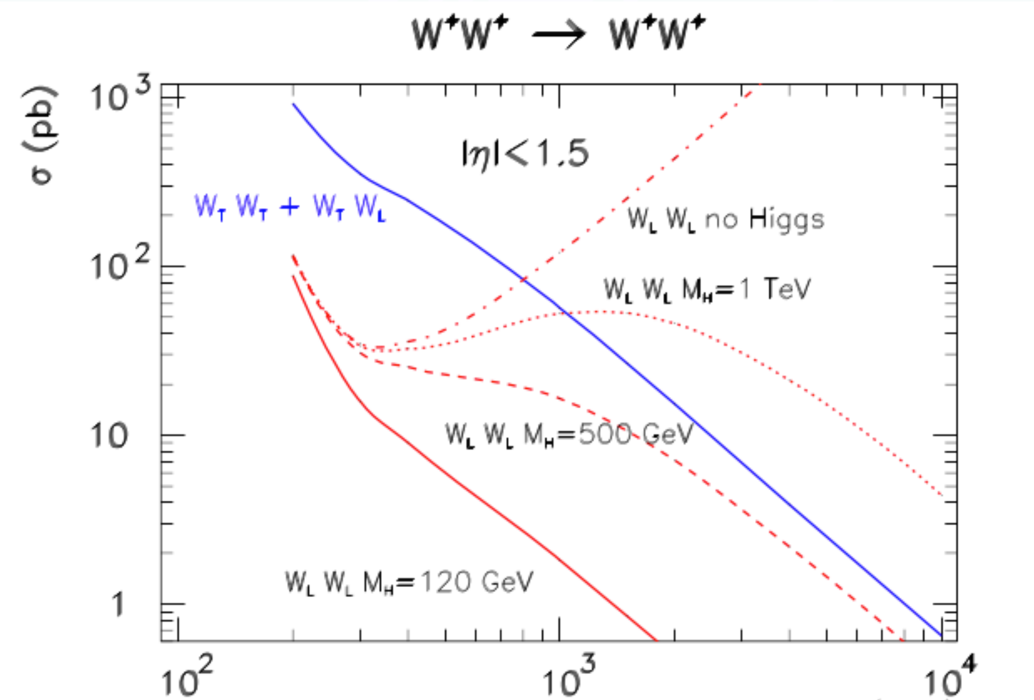
$W_L W_L$ scattering at the LHC: Improving the selection criteria

Krzysztof Doroba,[1] Jan Kalinowski,[1,2] Jakub Kuczmarski,[1] Stefan Pokorski,[1] Janusz Rosiek,[1] Michał Szleper,[3] and Sławomir Tkaczyk[4]

$W_L W_L$ scattering difficult to detect

for $m_V^2 \ll s \ll M^2$

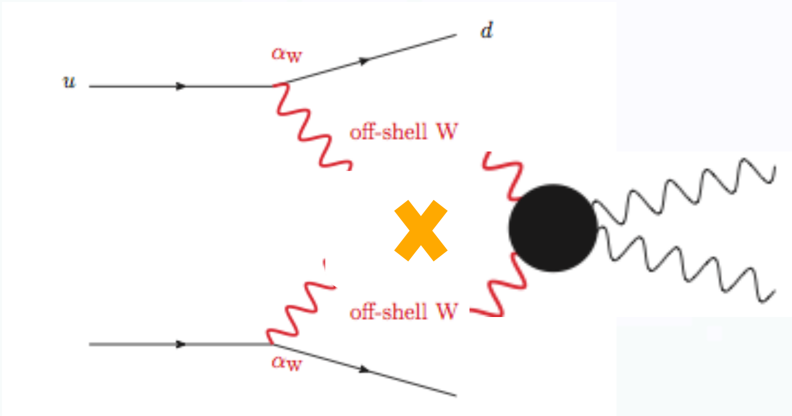
$$\begin{cases} \mathcal{A}_T = \mathcal{A}(V_T V_T \to V_T V_T) \sim \mathcal{O}(1) \\ \mathcal{A}_L = \mathcal{A}(V_L V_L \to V_L V_L) \sim s/m_V^2 \end{cases}$$



Szleper arXiv:1412.8367

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

WW scattering in pp collisions



$$\sigma \sim \int ds \;\; \mathcal{L}_{WW}(s) \;\; \frac{d\sigma(WW \to WW)}{ds}$$

- W radiation from the initial quark
  - for transverse $f_-(x, p_\perp) = \frac{1}{x} \frac{p_\perp^3}{(m^2(1-x)+p_\perp^2)^2}$,
  - for longitudinal $f_0(x, p_\perp) = \frac{(1-x)^2}{x} \frac{2m^2 p_\perp}{(m^2(1-x)+p_\perp^2)^2}$

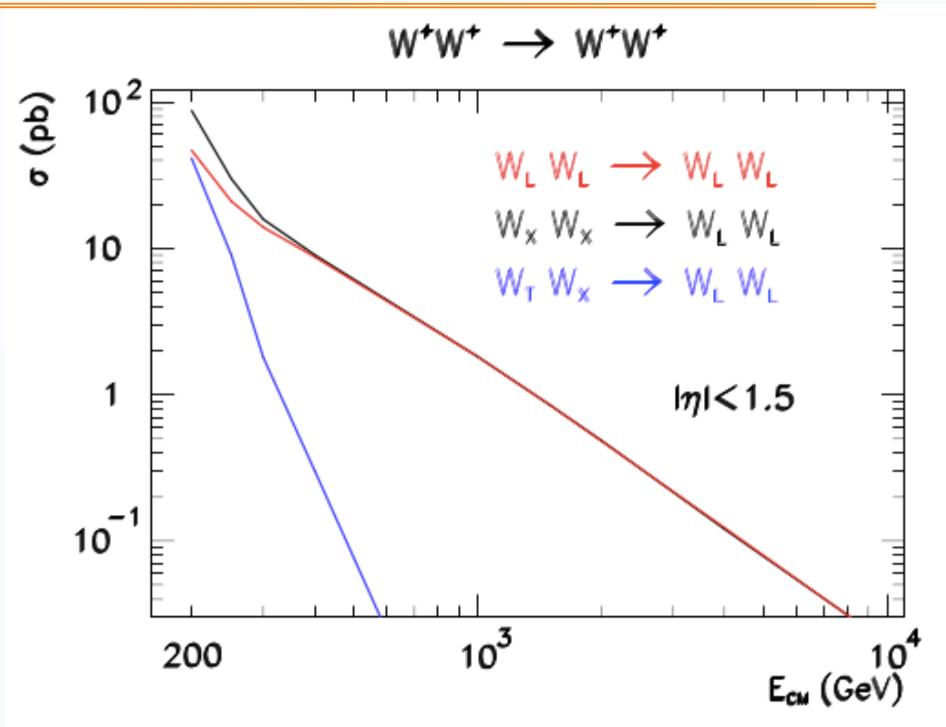
➔ tagging jets with small p_T should enrich W_L content

- W_L should scatter at large angles, so leptons from W_L decays should have large p_T
- in addition irreducible and reducible background

Why pp-> jj W⁺W⁺ ?

➢ no cross-talk amplitudes:

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



Why pp-> jj W⁺W⁺ ?

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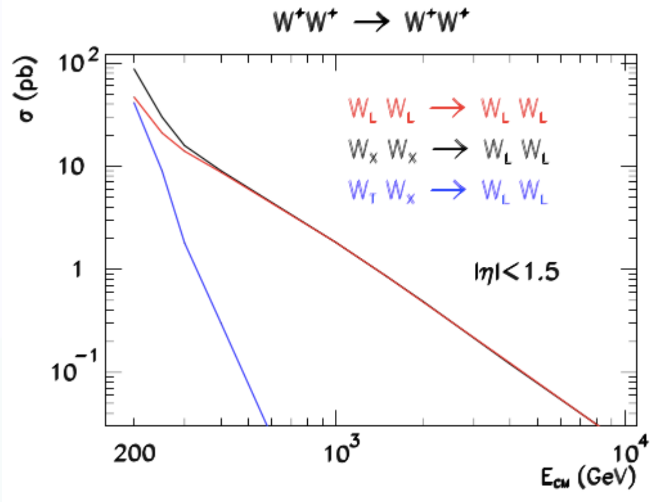
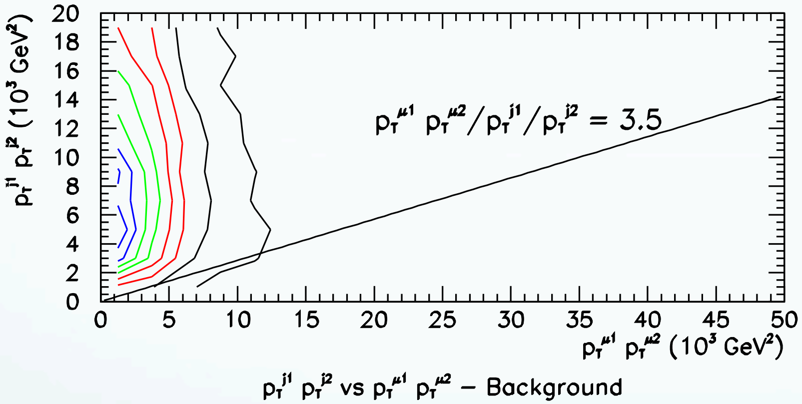
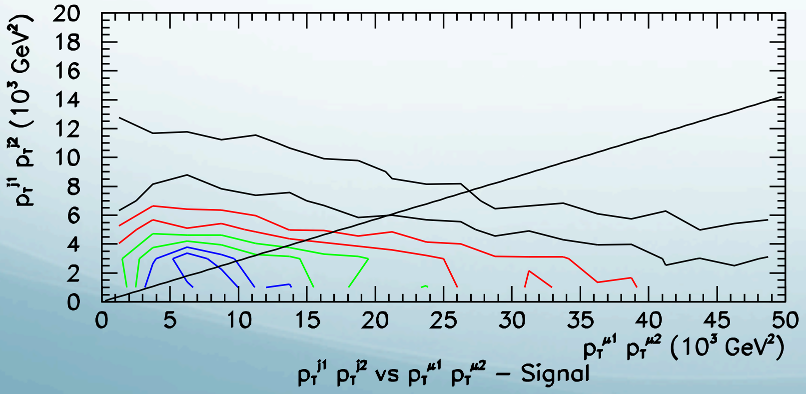
$$W_T W_X \to W_L W_L, \quad W_L W_L \to W_T W_X$$







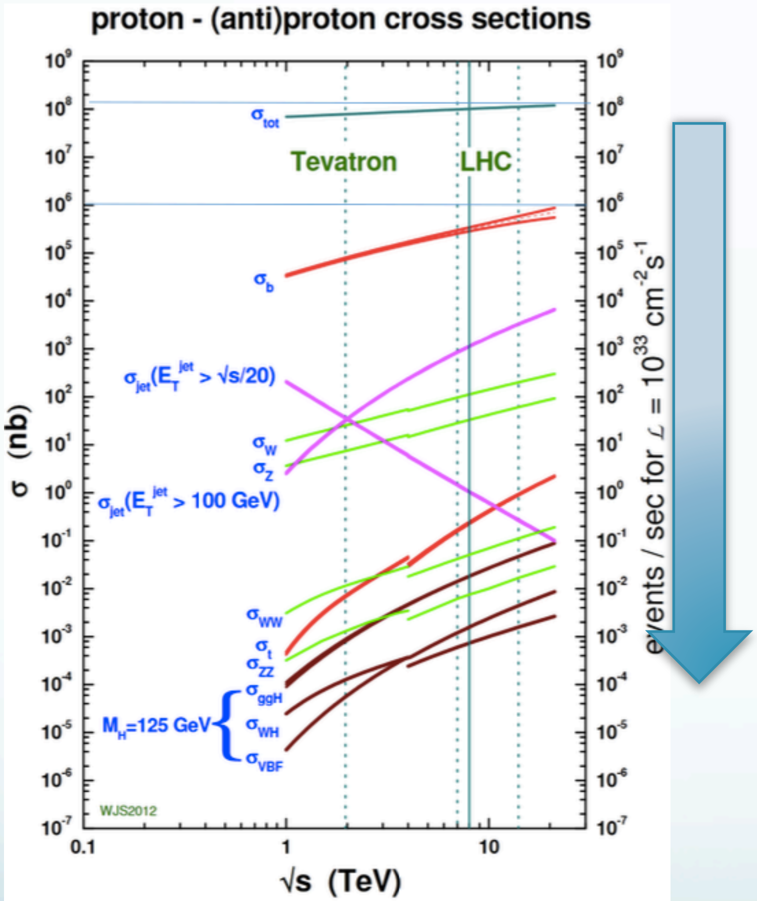
- W's emitted by colliding quarks: their polarization encoded in kinematics of outgoing jets

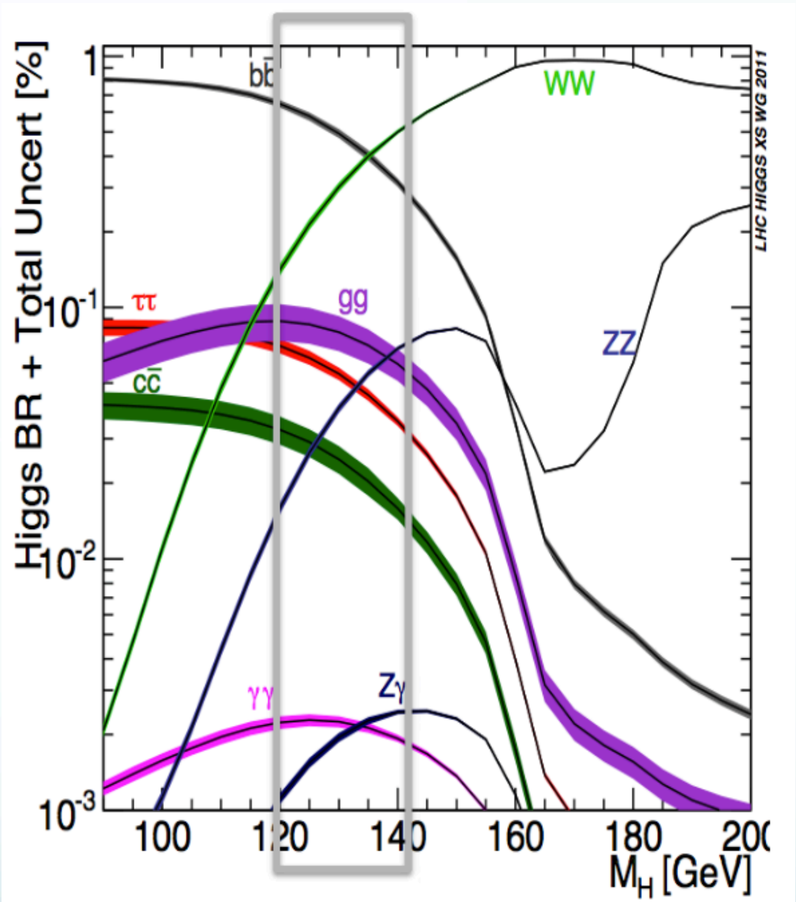
- Our proposal: use a new quantity

$$R_{p_T} = p_T^{l_1} p_T^{l_2} / (p_T^{j_1} p_T^{j_2})$$

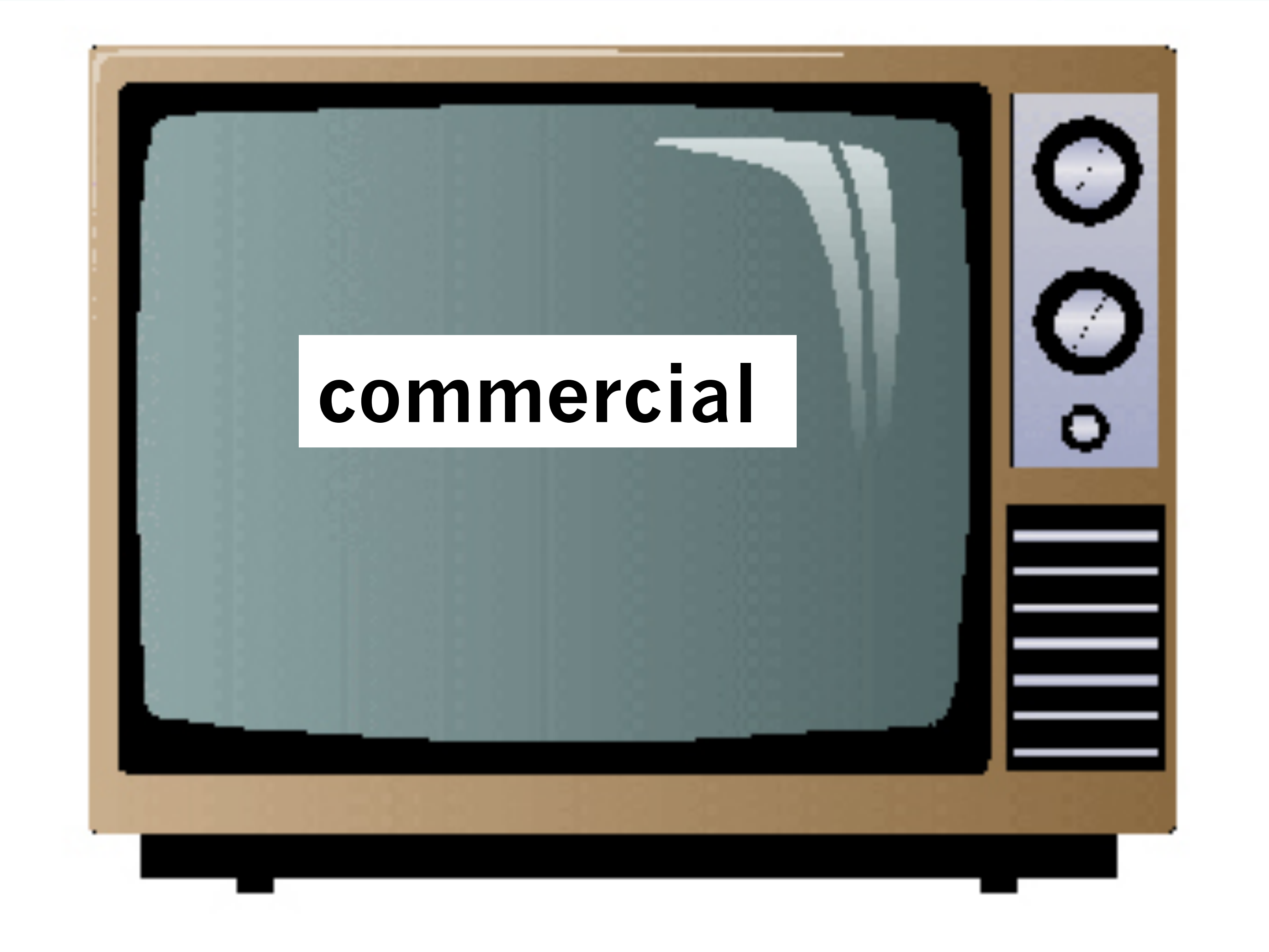
that helps to separate L from T

In 2012 a new particle has been found





consistent with the SM Higgs boson properties time for

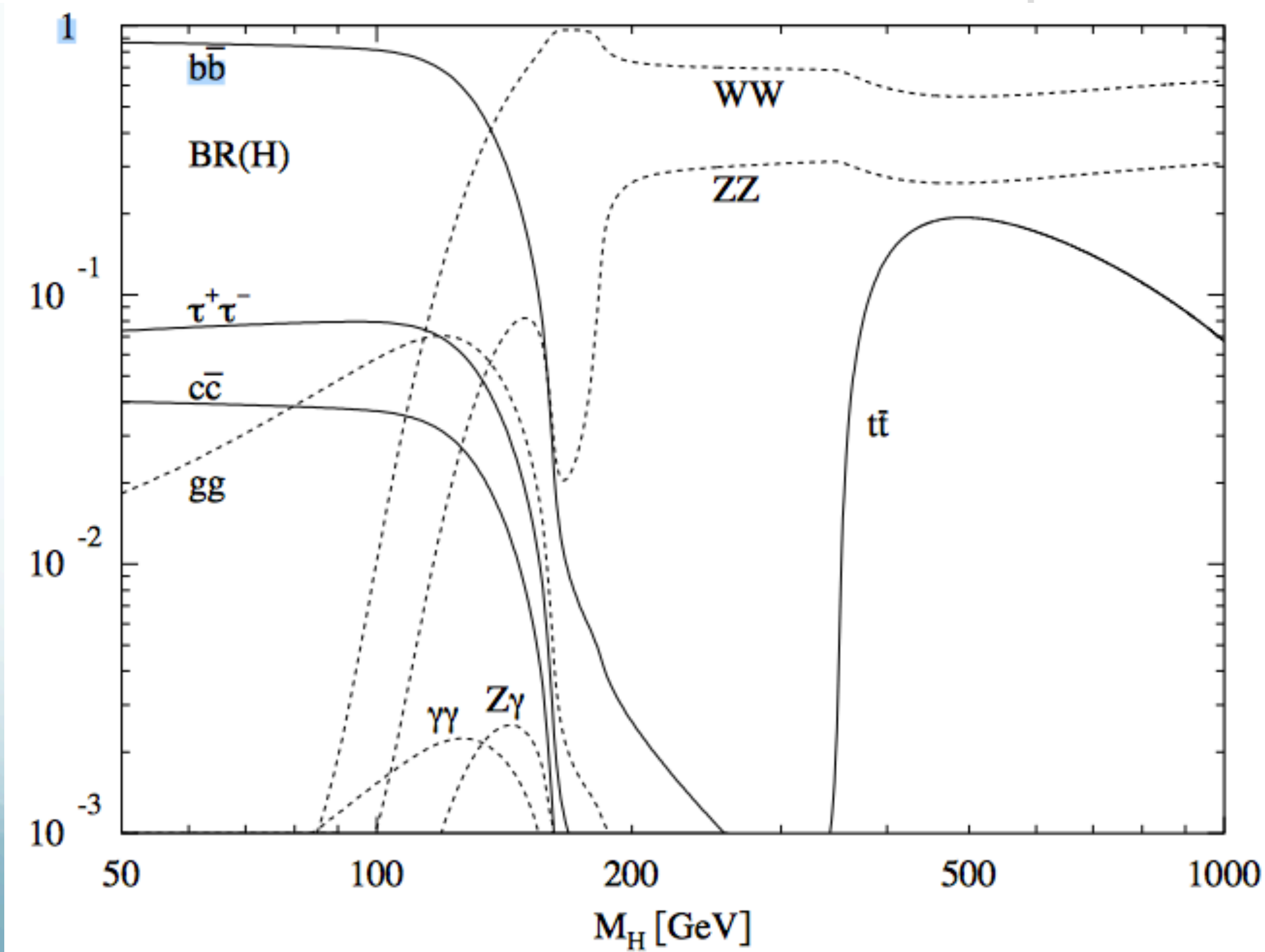


High Energy Physics – Phenomenology

HDECAY: a Program for Higgs Boson Decays in the Standard Model and its Supersymmetric Extension

A. Djouadi, J. Kalinowski, M. Spira

(Submitted on 30 Apr 1997)



Computer Physics Communications

CPC 108 (1998) 56

almost 2000 citations

High Energy Physics – Phenomenology

[Submitted on 29 Jan 2018]

HDECAY: Twenty++ Years After

Abdelhak Djouadi, Jan Kalinowski, Margarete Muehlleitner, Michael Spira

The program HDECAY determines the partial decay widths and branching ratios of the Higgs bosons within the Standard Model with three and four generations of fermions, including the case when the Higgs couplings are rescaled, a general two––Higgs doublet model where the Higgs sector is extended and incorporates five physical states and its most studied incarnation, the minimal supersymmetric Standard Model (MSSM). The program addresses all decay channels including the dominant higher–order effects such as radiative corrections and multi–body channels. Since the first launch of the program, more than twenty years ago, important aspects and new ingredients have been incorporated. In this update of the program description, some of the developments are summarized while others are discussed in some detail.

Comments: LaTeX, 41 pages
Subjects: High Energy Physics – Phenomenology (hep-ph)
DOI: 10.1016/j.cpc.2018.12.010
Report number: CERN–TH–2017–262, LPT–Orsay–18–04, KA–TP–03–2018, PSI–PR–18–02
Cite as: arXiv:1801.09506 [hep-ph]
(or arXiv:1801.09506v1 [hep-ph] for this version)

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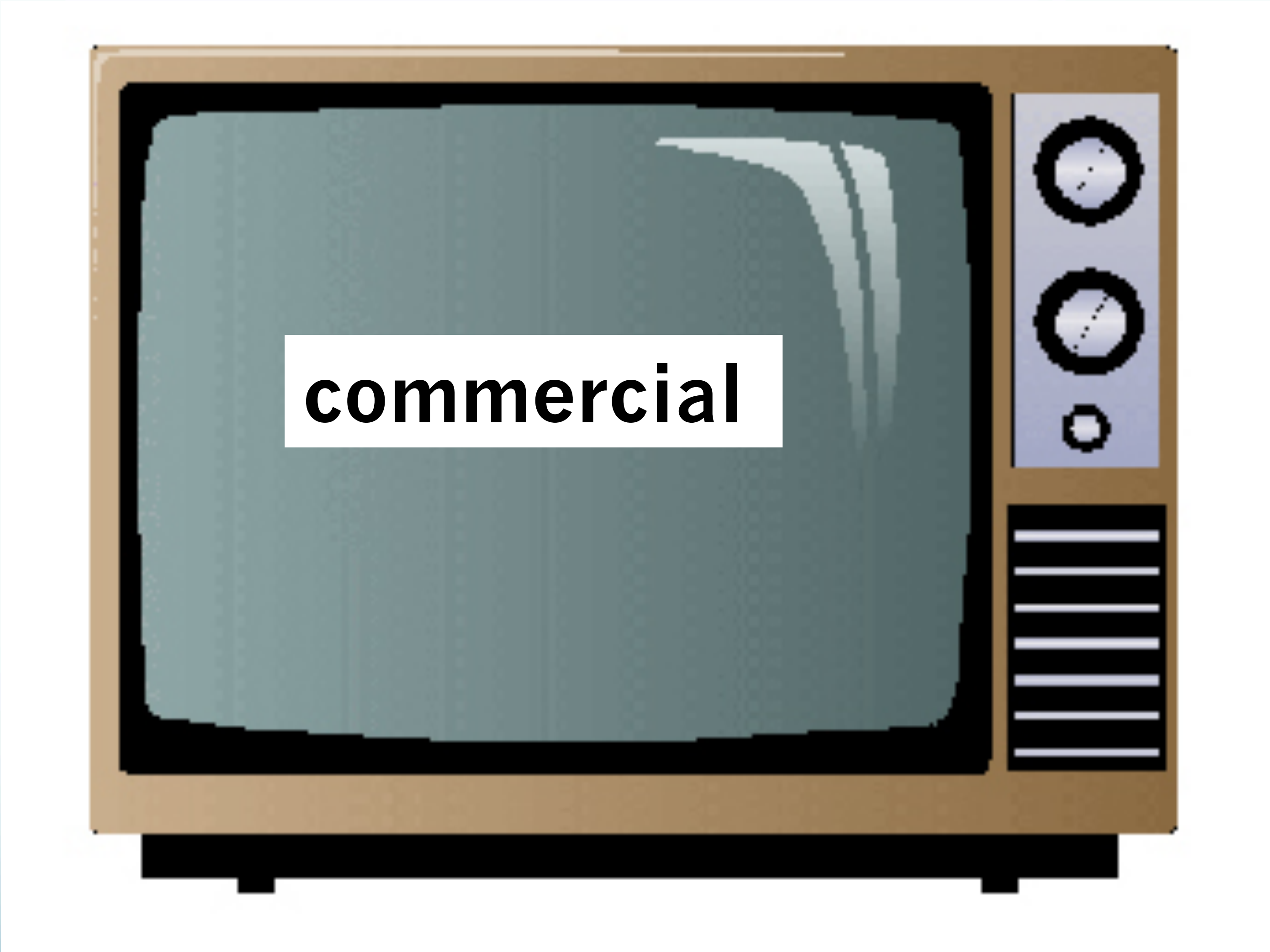
Computer Physics Communications

CPC 238 (2019) 214

CPC 50th anniversary article

end of



SM: before the Higgs

we had a quantum field theory with guaranteed discoveries:

with no-lose theorems:

beyond the Fermi theory (the W boson)

beyond the strange and K mesons (the charm)

beyond the bottom and tau (the top and tau-neutrino)

beyond the electroweak theory (the Higgs)

scattering amplitudes grow with energy
without W, top, Higgs….

SM: after the Higgs

we have a consistent and renormalizable theory that

- does not predict anything else
- but leaves many unanswered questions
  - the Higgs sector of the SM quite arbitrary
  - where and how does the SM break down?
  - hierarchy problem: why the weak scale << M_{Pl}
  - which machine(s), experiment(s) will reveal cracks in the SM?
  - are the B--anomalies the first signs?
  - or the anomalous muon g-2 moment?

Is there physics after Higgs?

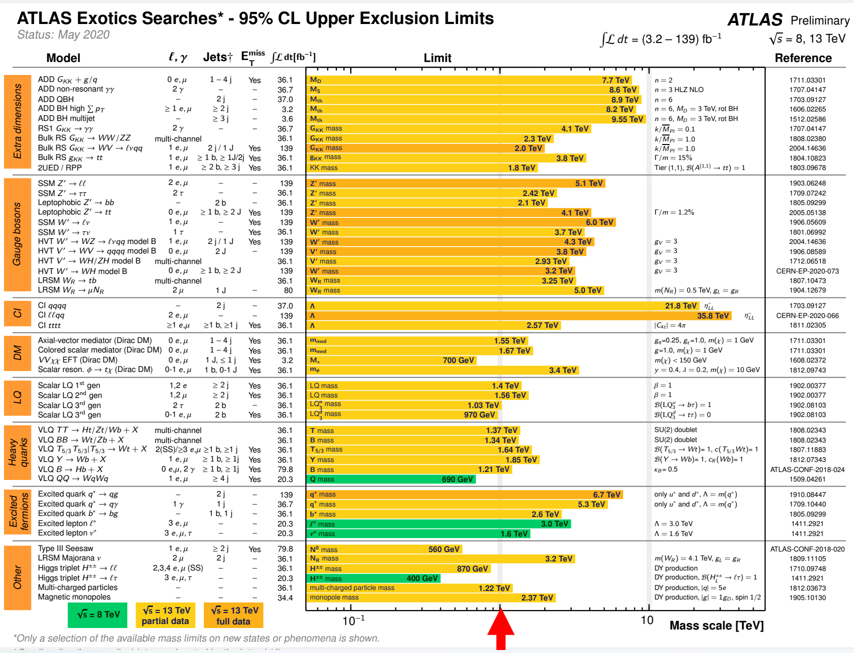
Foreword

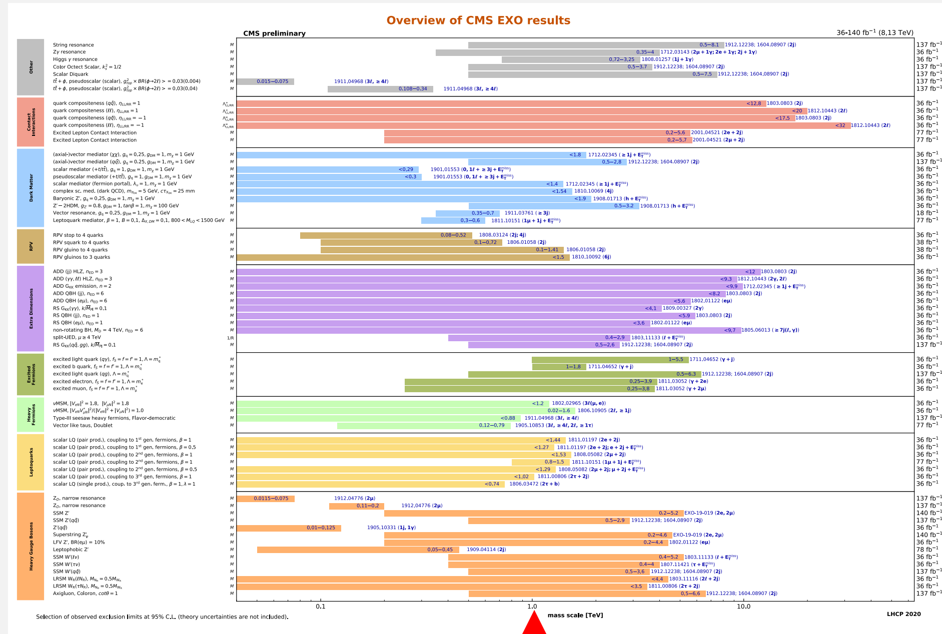
the discussion of the **future** in HEP must start from the understanding that there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which can ***guarantee discoveries*** beyond the SM, and ***answers*** to the big questions of the field:

M. Mangano, Plenary ECFA Nov.2015

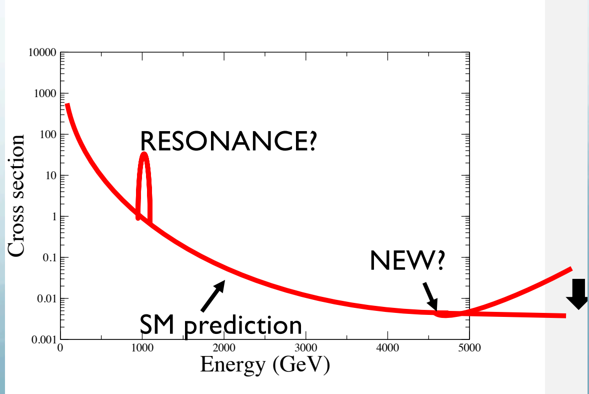
With no new particles in sight

Current limits in the 1 – 10 TeV range





- ➢ precision measurements of Higgs properties
- ➢ look for new physics in tails of distributions



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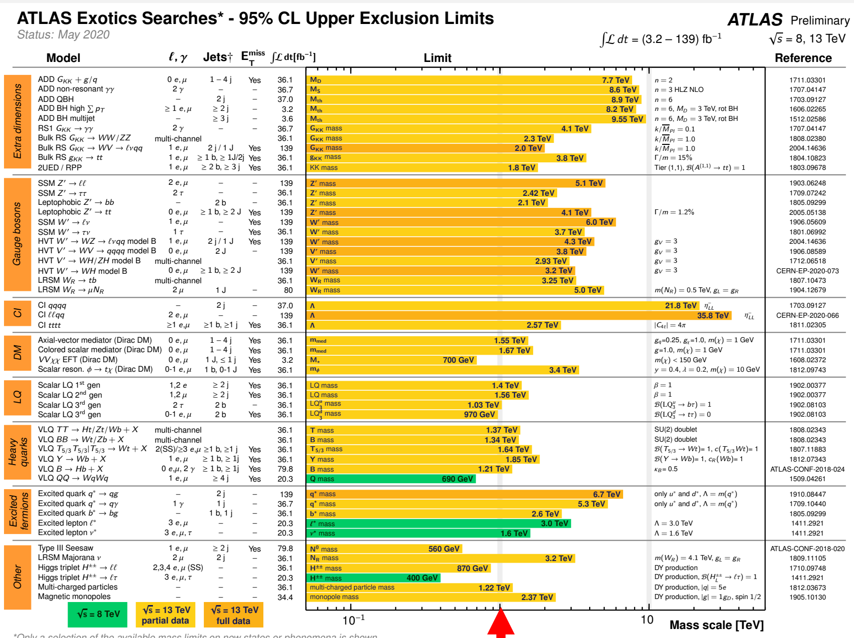

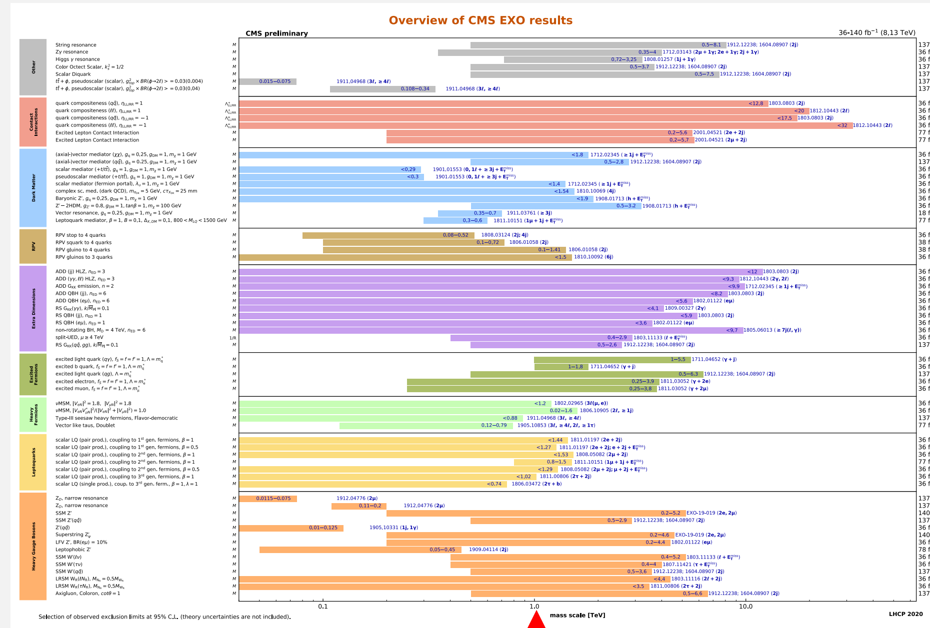

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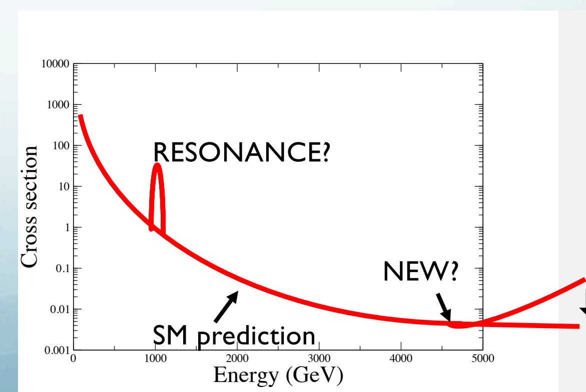
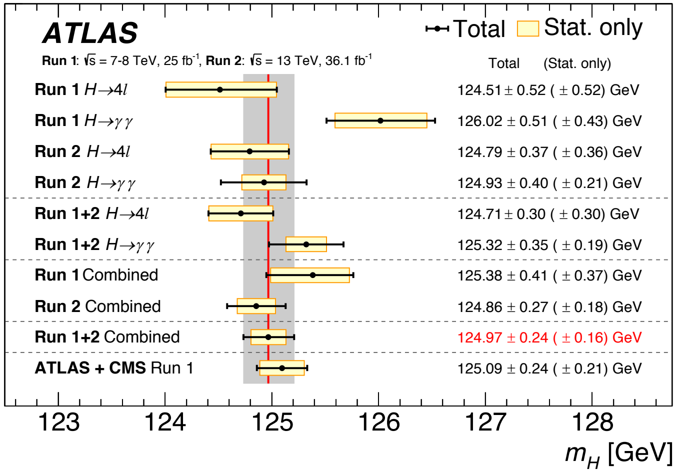
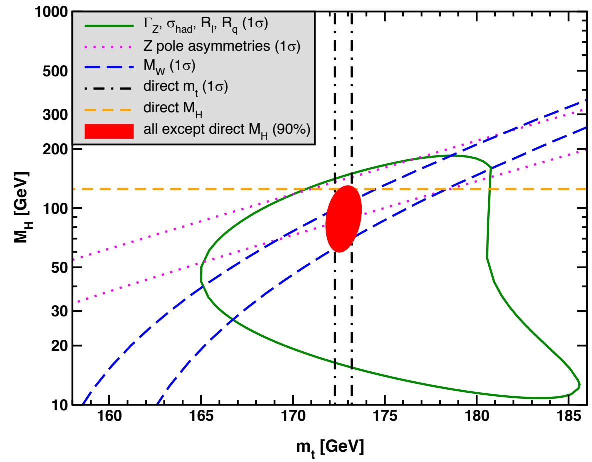
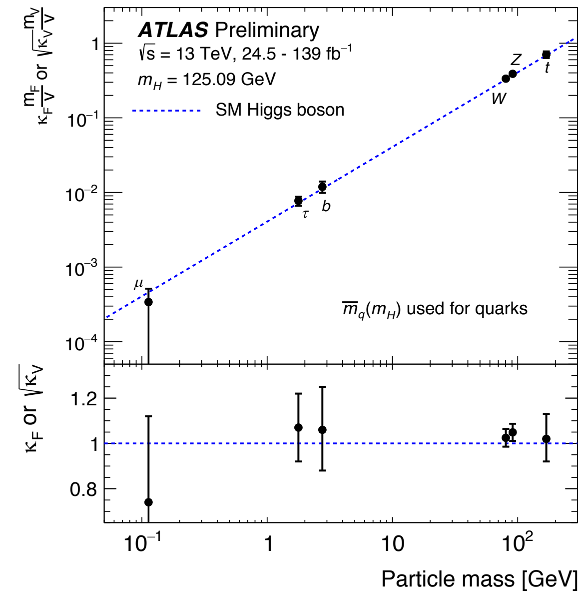
this is much harder than looking for resonances



Era of precision measurements







- Higgs mass is precision observable
- SM predicts relation between M_t, M_W and M_H
- couplings to fermions and gauge bosons fixed in SM

➔ consistent picture but room for new physics

No resonances? Hierarchy of scales?

$\Lambda >> M_W$ where complete model exists

- any new particles or symmetries at high scale
- expect effects of heavy particles suppressed at low scales

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Model independent parametrization: Effective field theory

- only SM particles in theory at low scales with SM-like Higgs
- treat SU(3)xSU(2)xU(1) as good symmetry with doublet Higgs
- \+ remnants of high scale model described by effective field theory

Prime example: Fermi theory of weak interactions

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

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

Eur. Phys. J. C (2018) 78:403
https://doi.org/10.1140/epjc/s10052-018-5885-y

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Theoretical Physics

Same-sign WW scattering at the LHC: can we discover BSM effects before discovering new states?

Jan Kalinowski[1,2], Paweł Kozów[1], Stefan Pokorski[1], Janusz Rosiek[1], Michał Szleper[3,a], Sławomir Tkaczyk[4]

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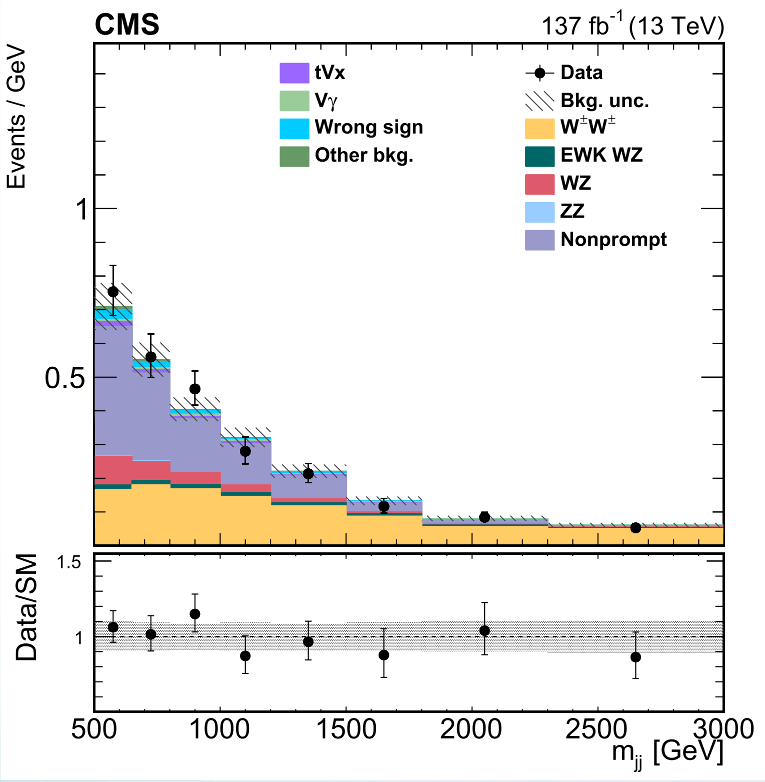
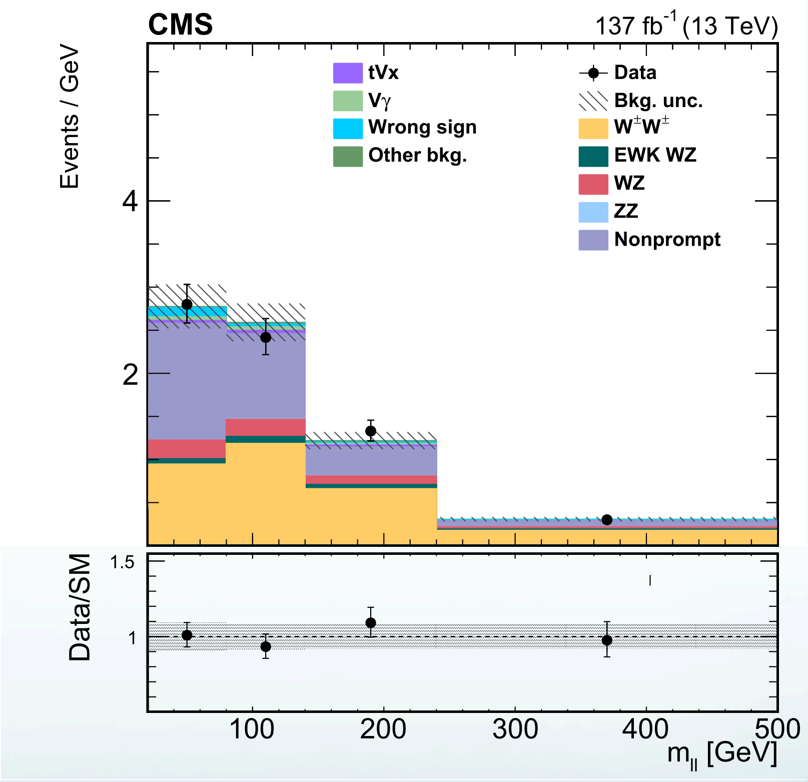
Goals of our study:

- 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

Electroweak diboson production

has been observed





CMS Phys.Lett.B 809 (2020) 135710

EFT parametrization

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

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

- 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" --- 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

Dim 8 operators: relevant for ssWW

$$\mathcal{O}_{S0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right],$$
$$\mathcal{O}_{S1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right],$$
$$\mathcal{O}_{M0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right],$$
$$\mathcal{O}_{M1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right],$$
$$\mathcal{O}_{M6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right],$$
$$\mathcal{O}_{M7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^\nu\Phi\right],$$
$$\mathcal{O}_{T0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right],$$
$$\mathcal{O}_{T1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right],$$
$$\mathcal{O}_{T2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right].$$

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

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

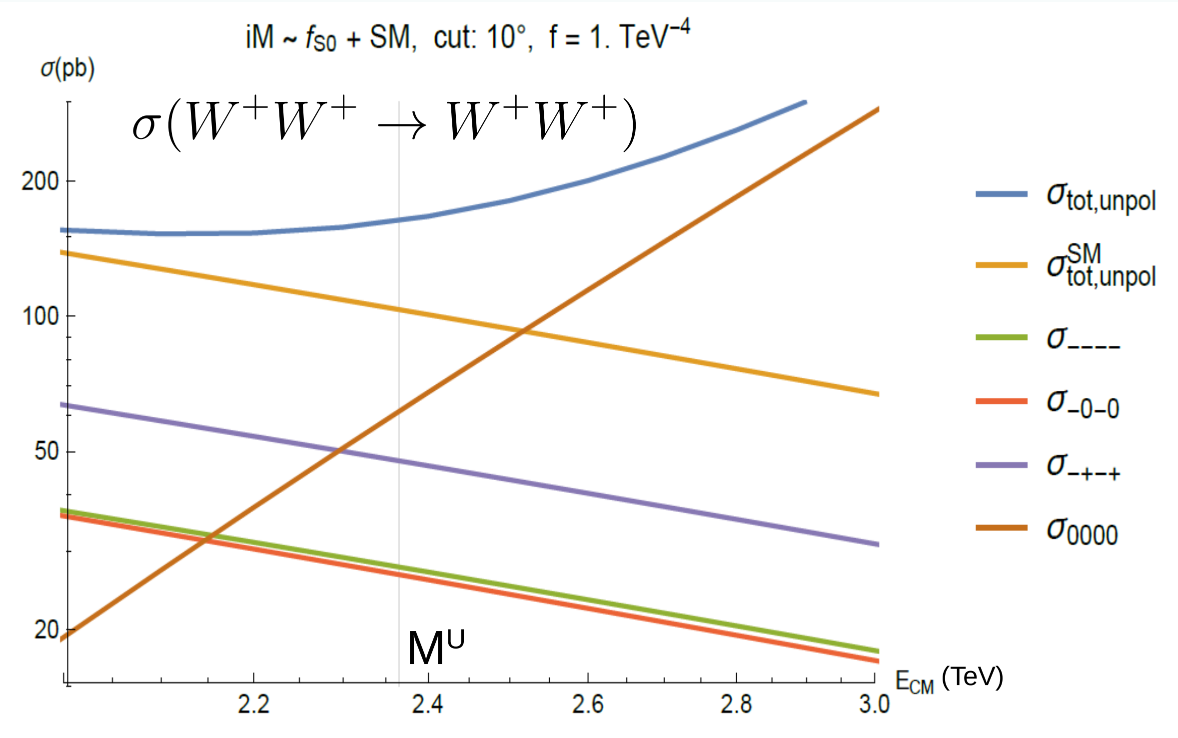
$$\hat{W}_{\mu\nu} = \frac{1}{ig}W_{\mu\nu}$$

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



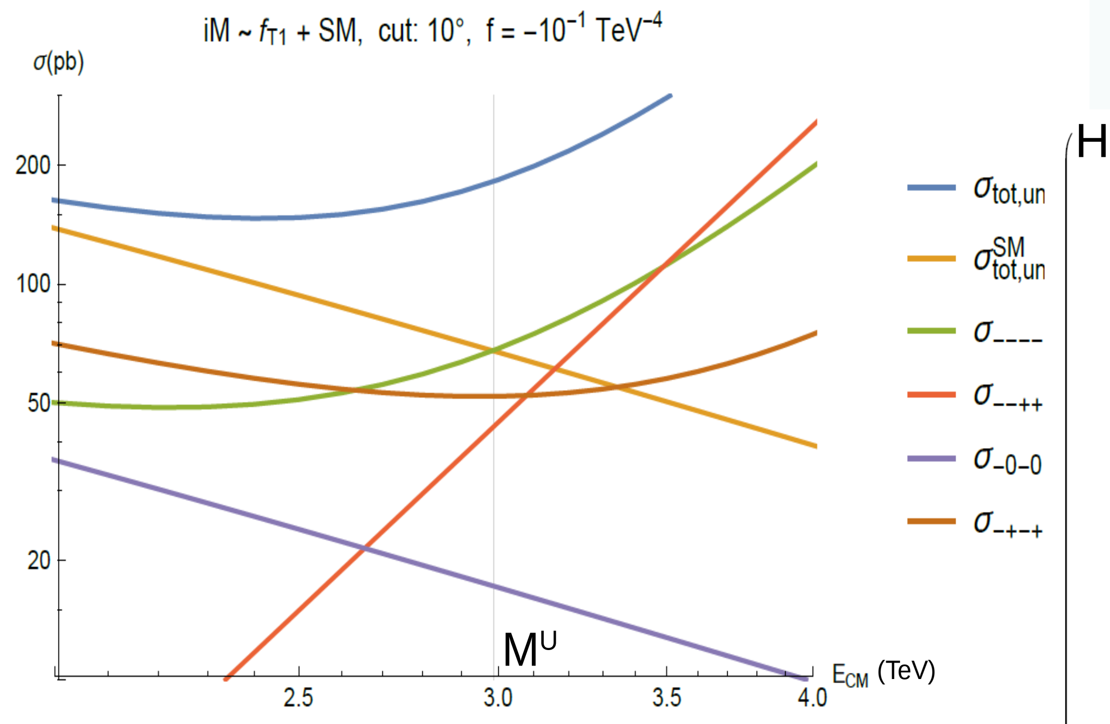
unitarity limits (in TeV)
for individual amplitudes

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 $\mu^+\mu^+\nu\nu$ 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 $S = \mathcal{D}_i^{model} - \mathcal{D}_i^{SM}$

pp -> 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 $S = \mathcal{D}_i^{model} - \mathcal{D}_i^{SM}$

- The EFT-controlled signal is given by

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

EFT in its range of validity

only SM contribution

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

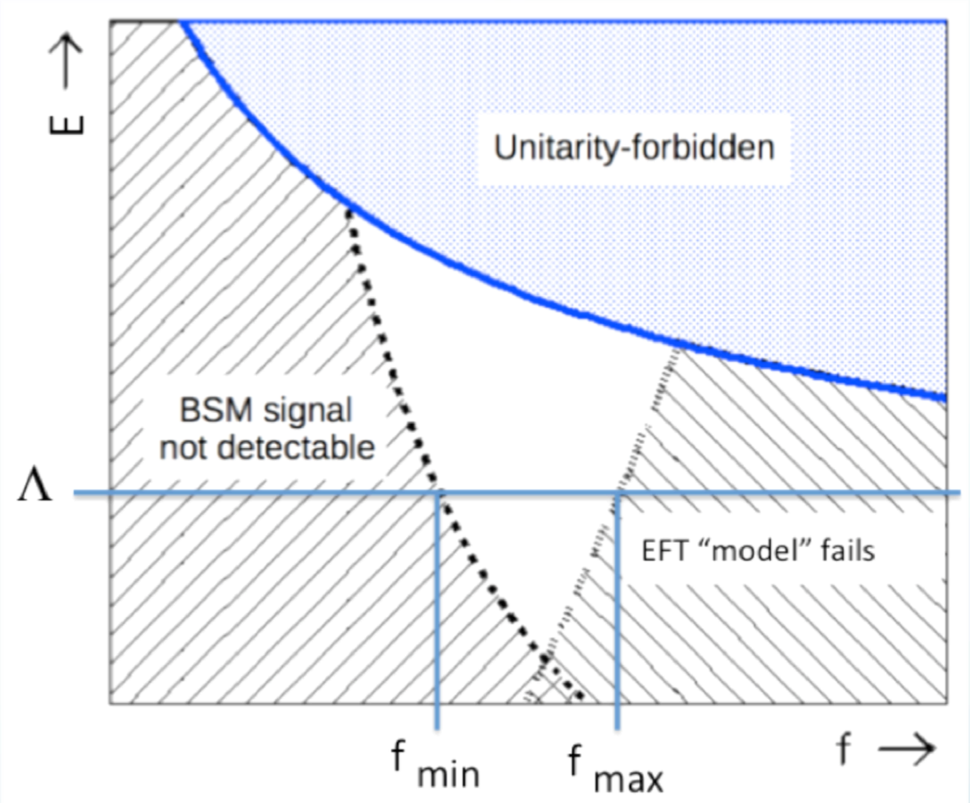
- It puts constraints in the (f, Λ) plane

Cartoon plot

for given Λ :

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

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



Cartoon plot

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

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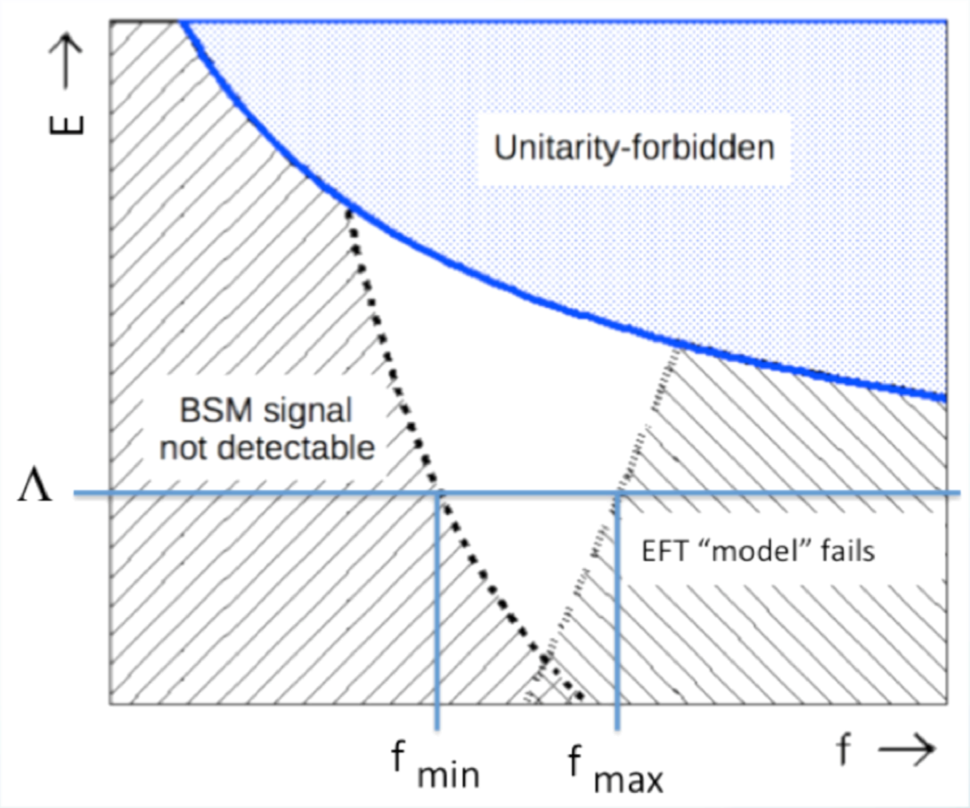
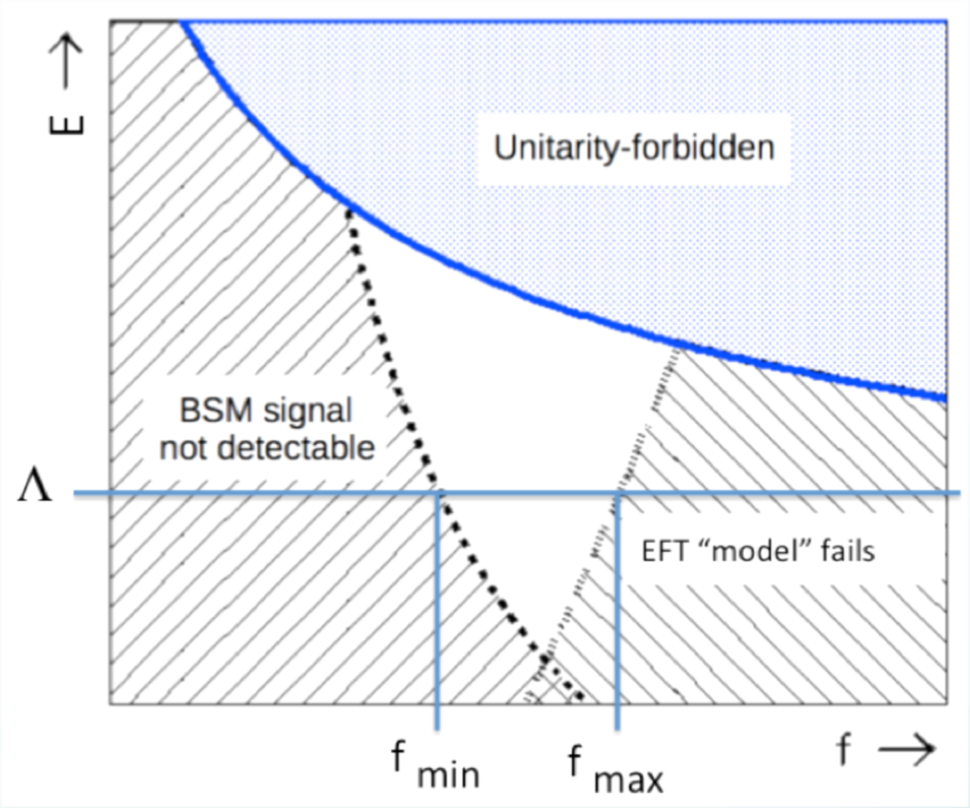


Need a reasonable estimate what happens above Λ in accordance with all physics principles

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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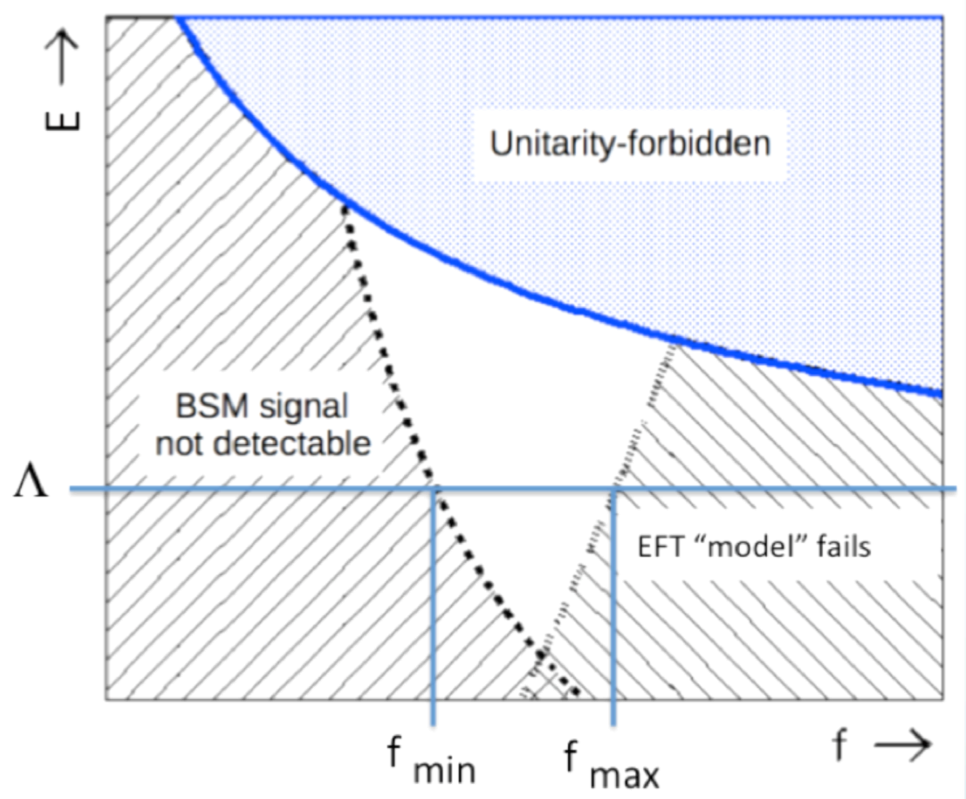


Our proposal:

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

EFT in its range of validity physically plausible contribution

Proposed procedure

- Our proposal:

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

EFT in its range of validity   physically 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 $M>\Lambda$ 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 – 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

- Typical VBS-like selection
  $$M_{jj} > 500\ GeV, \quad p_T^j > 30\ GeV, \quad p_T^l > 25\ GeV,$$
  $$\Delta\eta_{jj} > 2.5, \quad |\eta_j| < 5, \quad |\eta_l| < 2.5,$$

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

- Signal significances calculated from different differential distributions

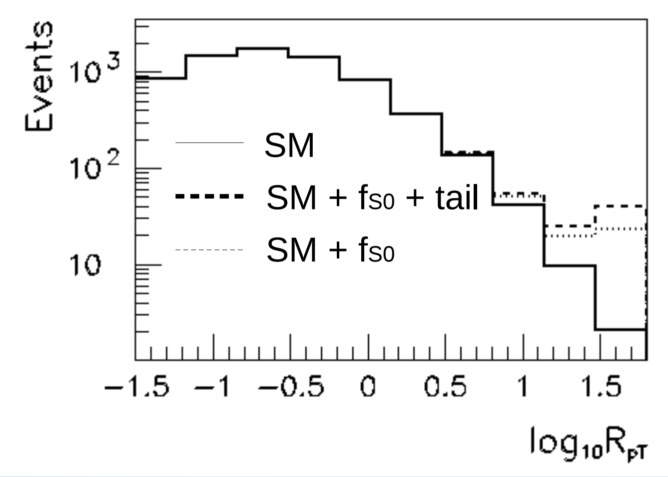
  assuming HL-LHC luminosity of 3/ab

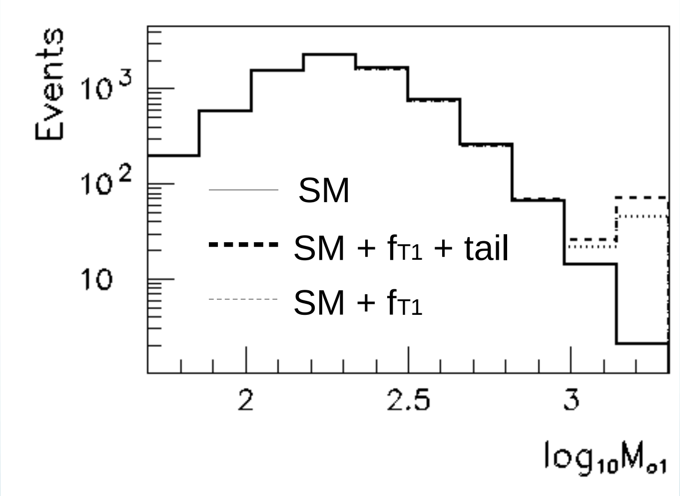
Simulation – proof of the procedure

Most sensitive variables:

for S0 and S1 operators $R_{p_T} = p_T^{l_1} p_T^{l_2} / (p_T^{j_1} p_T^{j_2})$

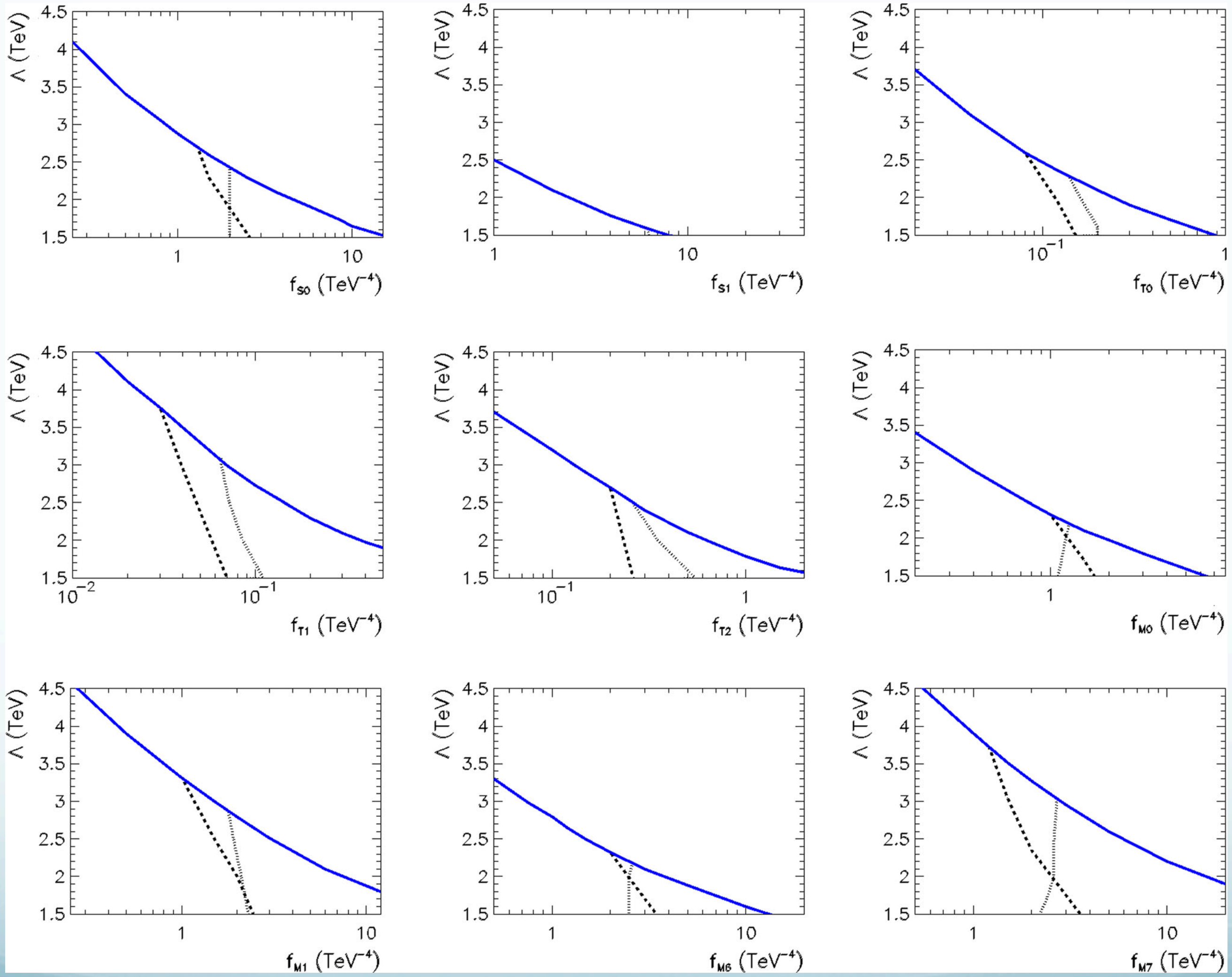
for others $M_{o1} \equiv \sqrt{(|\vec{p}_T^{\,l1}| + |\vec{p}_T^{\,l2}| + |\vec{p}_T^{\,miss}|)^2 - (\vec{p}_T^{\,l1} + \vec{p}_T^{\,l2} + \vec{p}_T^{\,miss})^2}$



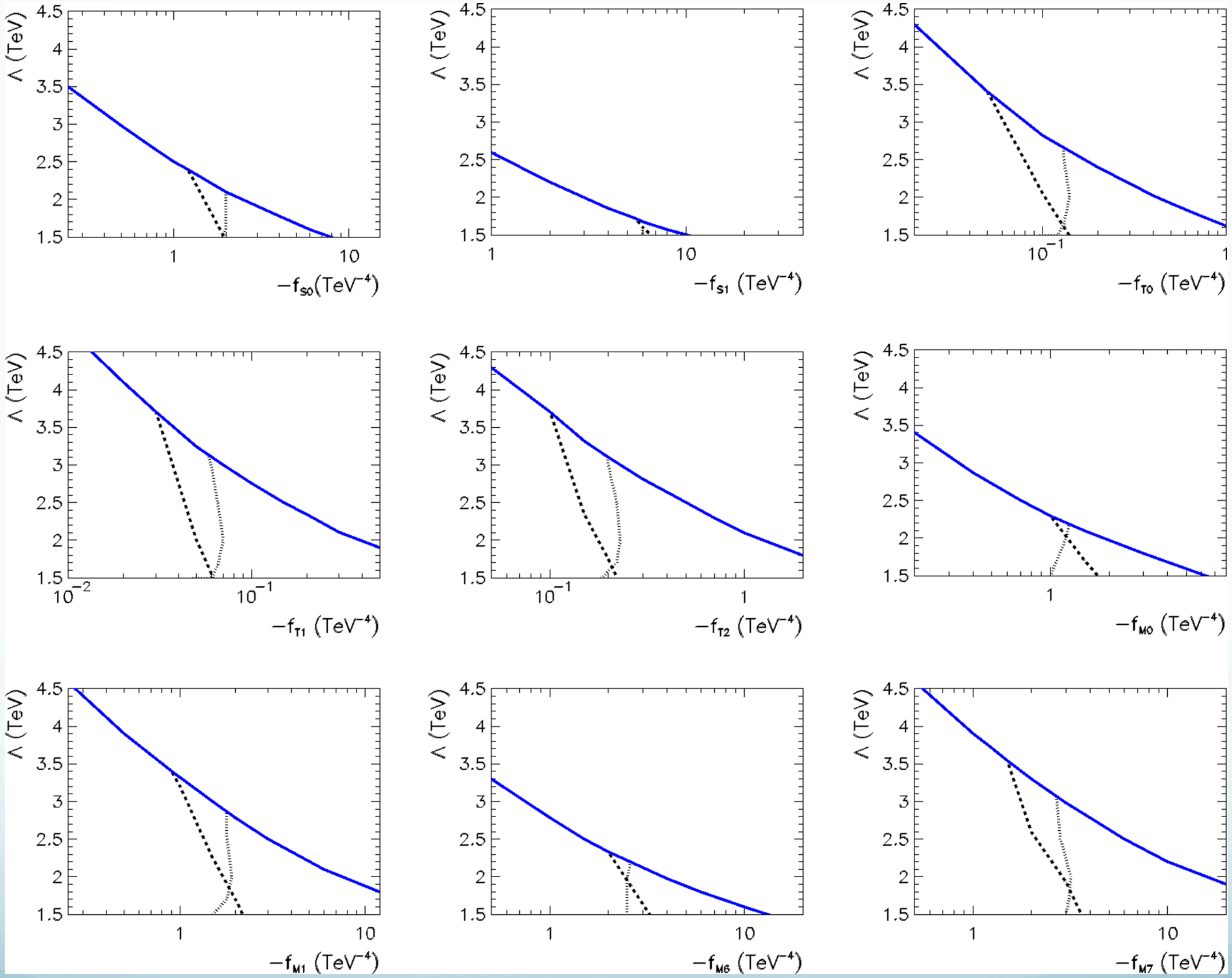


$f_{T1} = 0.1/TeV^4$

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

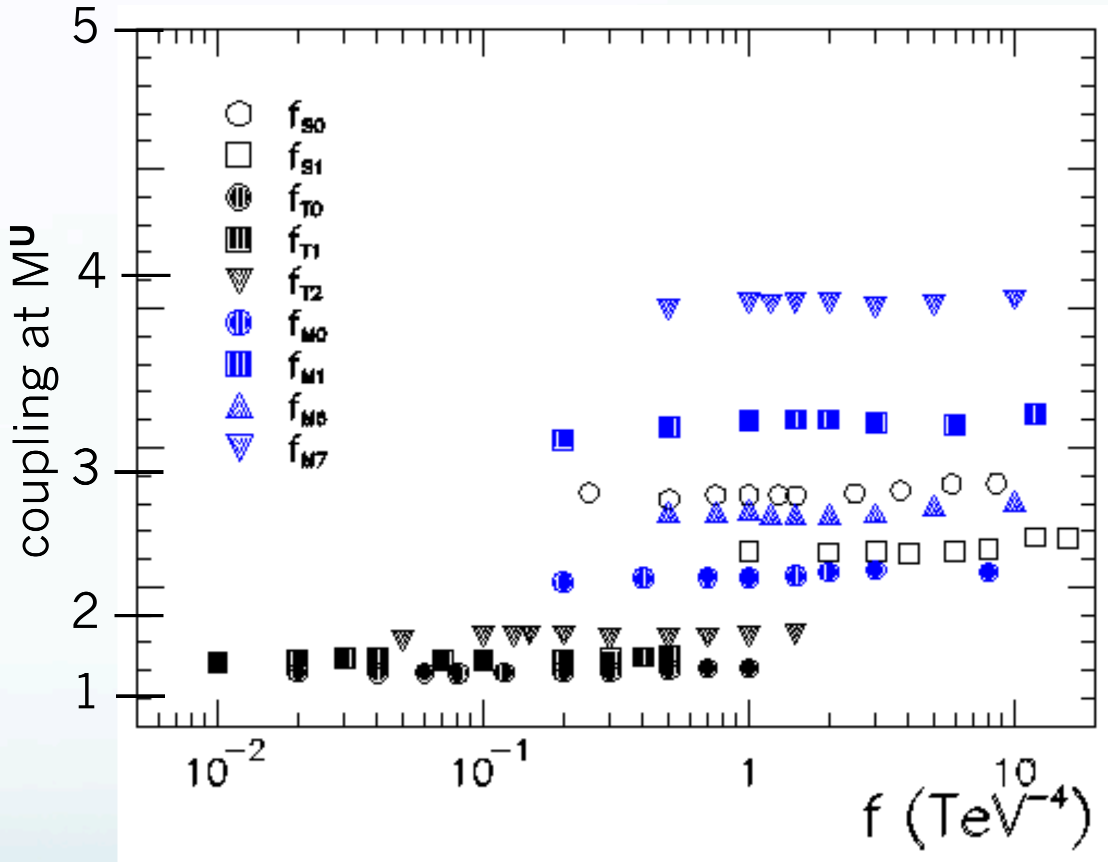
for T operators a wider range is open

A hint on BSM couplings ?

for dim-8 operators

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

$$M_{WW} < \Lambda < M^U$$



our EFT-respecting procedure puts non-trivial bounds on cut-off Λ

given range of cut-off Λ corresponds to a range of couplings C_i

From HL-LHC to HE-LHC

Chaudhary, JK, Kaur, Kozow, Sandeep, Szleper, Tkaczyk EPJC 80(2020)181

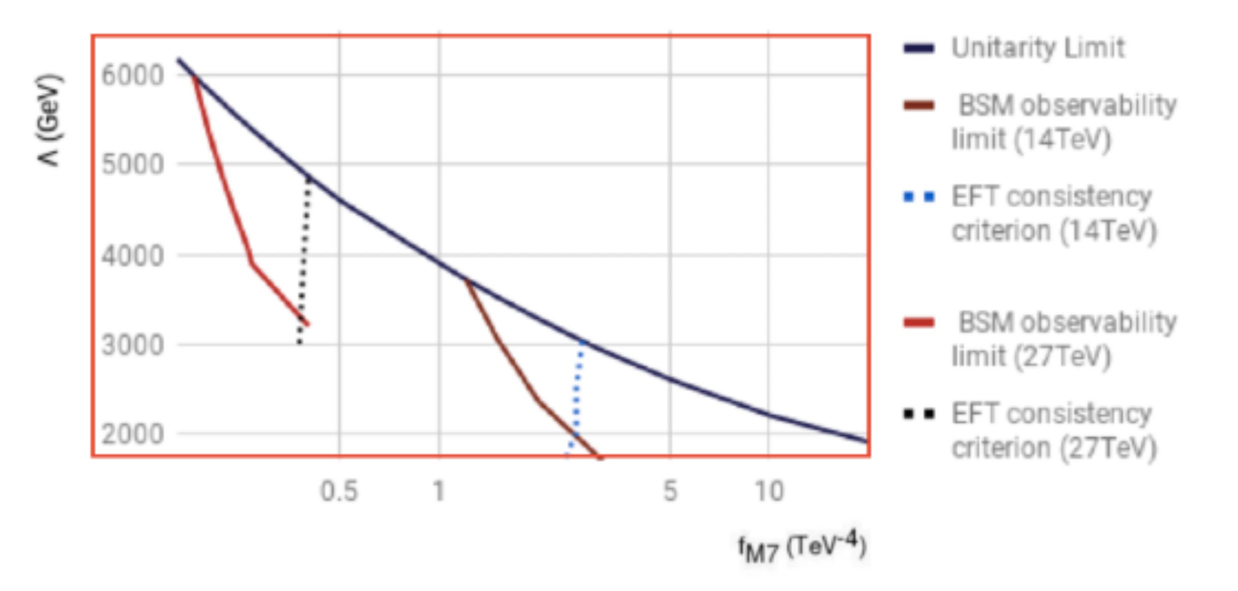
Question:

will the increased energy range to 27 TeV

and integrated luminosity of 15/ab

translate into larger EFT triangles?

example:



EFT trangles shift to lower *f* values but areas do not change significanlty

Finally coming to real data

Chaudhary, JK, Kaur, Kozow, Pokorski, Sandeep, Szleper, Tkaczyk PoS(LHCP2020)023

taking data from CMS Coll. Phys.Lett.B 809 (2020) 135710

	$W^\pm W^\pm$ Not clipped (TeV^{-4})	WZ Not clipped (TeV^{-4})	Combined Not clipped (TeV^{-4})	$W^\pm W^\pm$ Clipped (TeV^{-4})	WZ Clipped (TeV^{-4})	Combined Clipped (TeV^{-4})
f_{T0}	[-0.28, 0.31]	[-0.62, 0.65]	[-0.25, 0.28]	[-1.5, 2.3]	[-1.6, 1.9]	[-1.1, 1.6]
f_{T1}	[-0.12, 0.15]	[-0.37, 0.41]	[-0.12, 0.14]	[-0.81, 1.2]	[-1.3, 1.5]	[-0.69, 0.97]
f_{T2}	[-0.38, 0.50]	[-1.0, 1.3]	[-0.35, 0.48]	[-2.1, 4.4]	[-2.7, 3.4]	[-1.69, 3.1]
f_{M0}	[-3.0, 3.2]	[-5.8, 5.8]	[-2.7, 2.9]	[-13, 16]	[-16, 16]	[-11, 12]
f_{M1}	[-4.7, 4.7]	[-8.2, 8.3]	[-4.1, 4.2]	[-20, 19]	[-19, 20]	[-15, 14]
f_{M7}	[-6.7, 7.0]	[-10, 10]	[-5.7, 6.0]	[-22, 24]	[-22, 22]	[-16, 18]
f_{S0}	[-6.0, 6.4]	[-19, 19]	[-5.7, 6.1]	[-35, 36]	[-83, 85]	[-34, 35]
f_{S1}	[-18, 19]	[-30, 30]	[-16, 17]	[-100, 120]	[-110, 110]	[-86, 99]

Caution

- We have only considered single dimension-8 operators at a time.
- Non-zero values of more than one f provides much more flexibility
- In particular, for those operators whose individual unitarity limits are driven by helicity combinations which contribute little to the total cross section.
- Consequently, regions of BSM observability and EFT consistency can only be larger than what we found here.
- Study of VBS processes in the EFT language can be the right way to look for new physics and should gain special attention in case the LHC fails to observe new physics states

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

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Same-sign WW scattering at the LHC: can we discover BSM effects before discovering new states?
Eur. Phys. J. C 78 (2018) 403 [arXiv:1802.02366 [hep-ph]].

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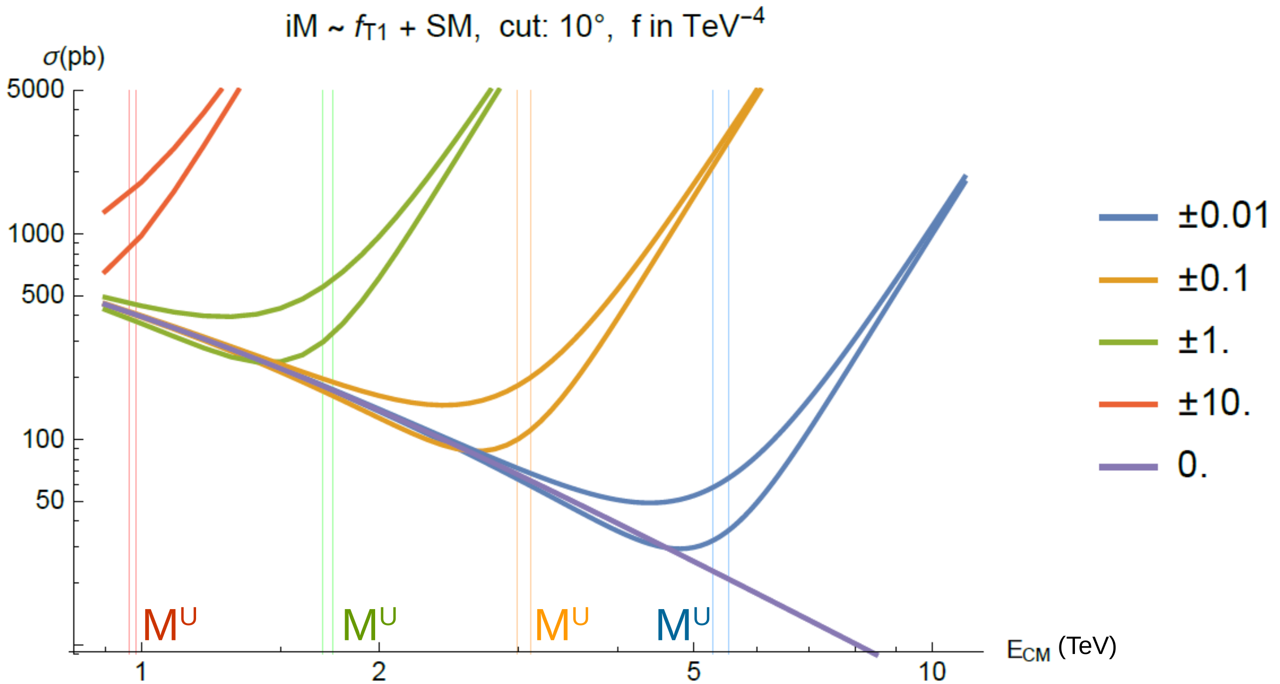
M. Szleper, G. Chaudhary, J. Kalinowski, M. Kaur, P. Kozów, S. Pokorski. K. Sandeep, S. Tkaczyk,
EFT validity issues in Vector Boson Scattering processes
Pos LHCP2020 (2021) 023

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., $(\Lambda/M)^8$

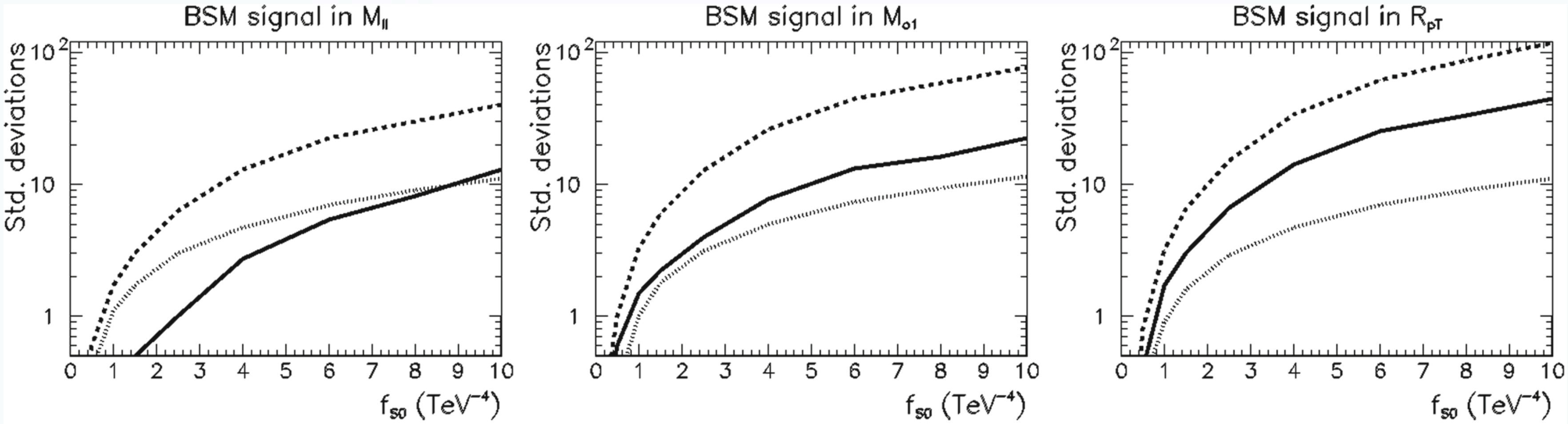


Total $W^+W^+ \rightarrow W^+W^+$ cross section for different f_{T1}

- 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



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

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

on-shell vs off-shell WW scattering

$$
\begin{aligned}
\epsilon_-^\mu &= \tfrac{1}{\sqrt{2}}(0, +1 - i, 0) && \text{(left)},\\
\epsilon_+^\mu &= \tfrac{1}{\sqrt{2}}(0, -1 - i, 0) && \text{(right)},\\
\epsilon_0^\mu &= (k, 0, 0, E)/\sqrt{k^2} && \text{(longitudinal)},\\
\epsilon_A^\mu &= (E, 0, 0, k)/\sqrt{\tfrac{k^2 - M_W^2}{k^2 M_W^2}} && \text{(auxiliary)},
\end{aligned}
$$

$$
\frac{-i \sum_{\lambda=1}^{4} \epsilon_\lambda^\mu \left(\epsilon_\lambda^\nu\right)^*}{k^2 - M_W^2}.
$$

$$
M \equiv \frac{\sum_{\lambda_1\lambda_2\lambda_3\lambda_4} M_{\lambda_1}^{q1} M_{\lambda_2}^{q2} M_{\lambda_1\lambda_2\lambda_3\lambda_4}^{WW} M_{\lambda_3}^{l1} M_{\lambda_4}^{l2}}{(k_1^2 - M_W^2)(k_2^2 - M_W^2)(k_3^2 - M_W^2)(k_4^2 - M_W^2)},
$$

$$
\lambda_i \in \{\epsilon_-, \epsilon_+, \epsilon_0, \epsilon_A\}.
$$

the scattered vector bosons must be fast, $|\mathbf{k_i}| \sim E_i >> M_W$,