Introduction and motivation for Effective Field Theories in high energy physics
Experimental view

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Outline

- **Quest for Beyond Standard Model: where do we stand**
  (gauge bosons, top, Higgs sector and new particles)

- **Why we have not (yet) found New Physics** (“anomalies” exist)

- **How can we use LHC data in the best way**

- **What is an Effective Field Theory (EFT)**

- **Example of EFT: Fermi theory of weak interactions**
  Multipole expansion
  (SM) EFT fit @ LHC
  (important to know well the SM)

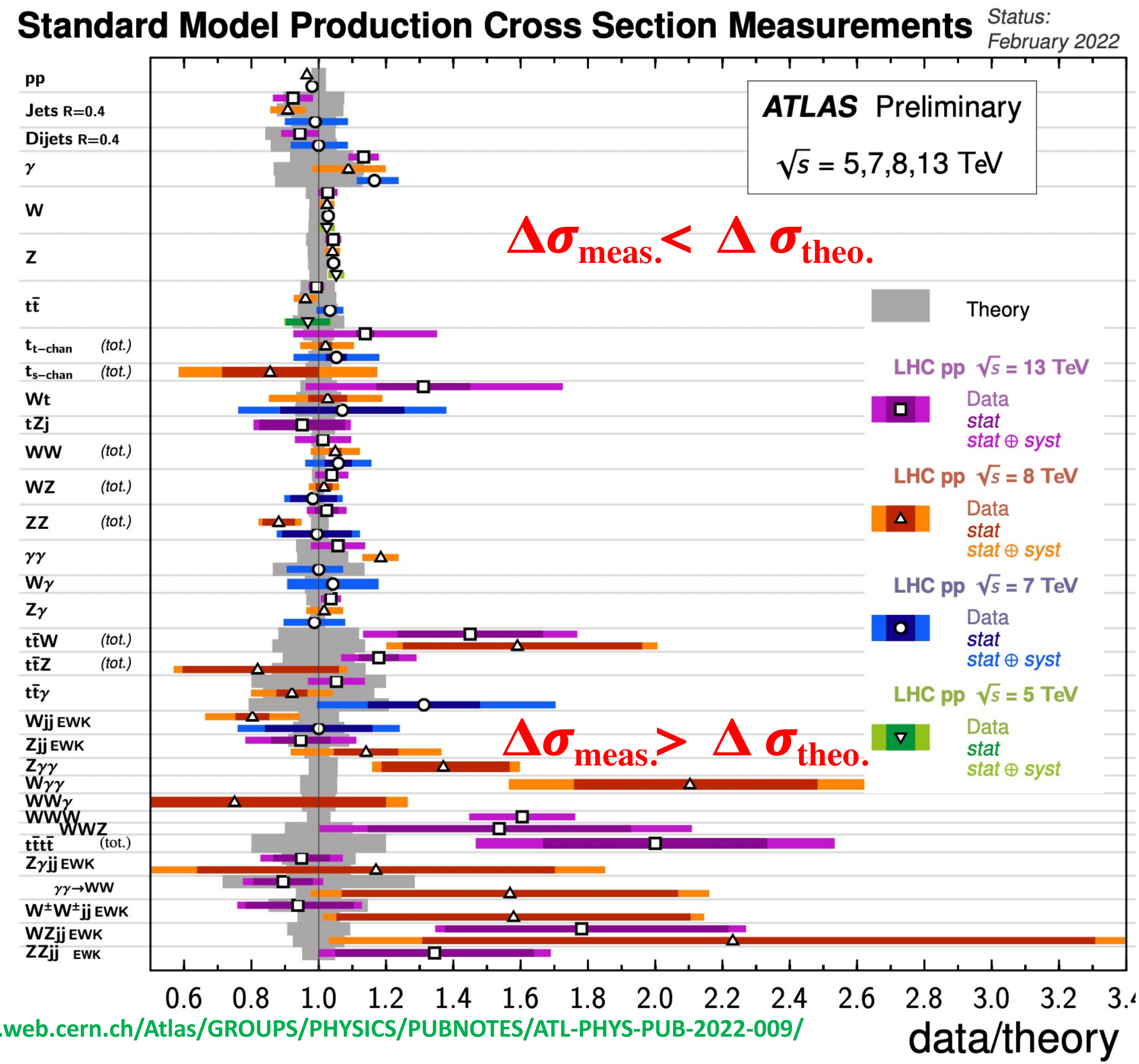
- **Summary**

Quest for Beyond Standard Model: where do we stand ?

Gauge bosons and top quark

- Comparison data/theory over many orders of magnitudes ($\sim 10^{11}$pb→ $\sim 10^{-3}$ pb)

- No significant deviations so far



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/

Higgs sector

- **No significant deviations**
- **Spin and Parity:**
  Results consistent with SM predictions
  (SM Higgs $J^{PC} = 0^{++}$)

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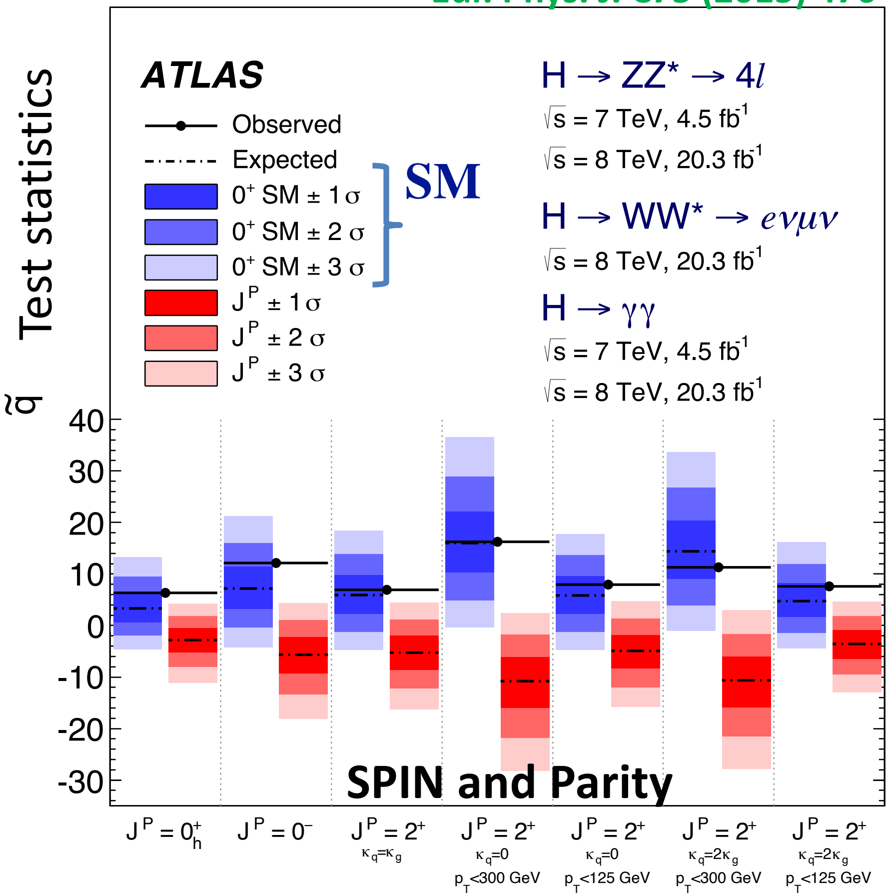
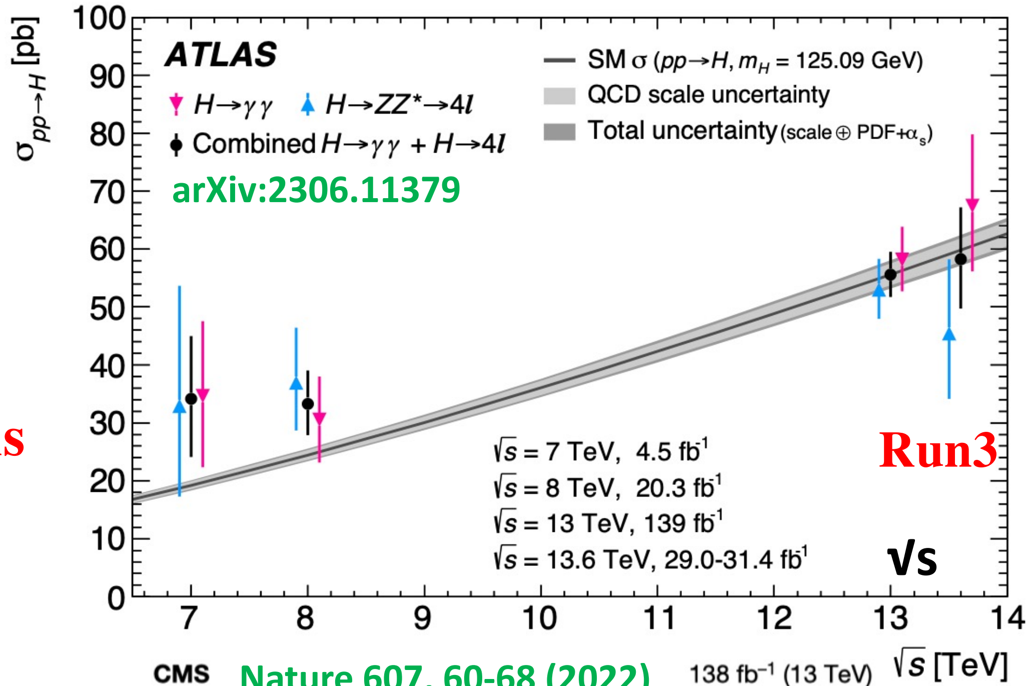
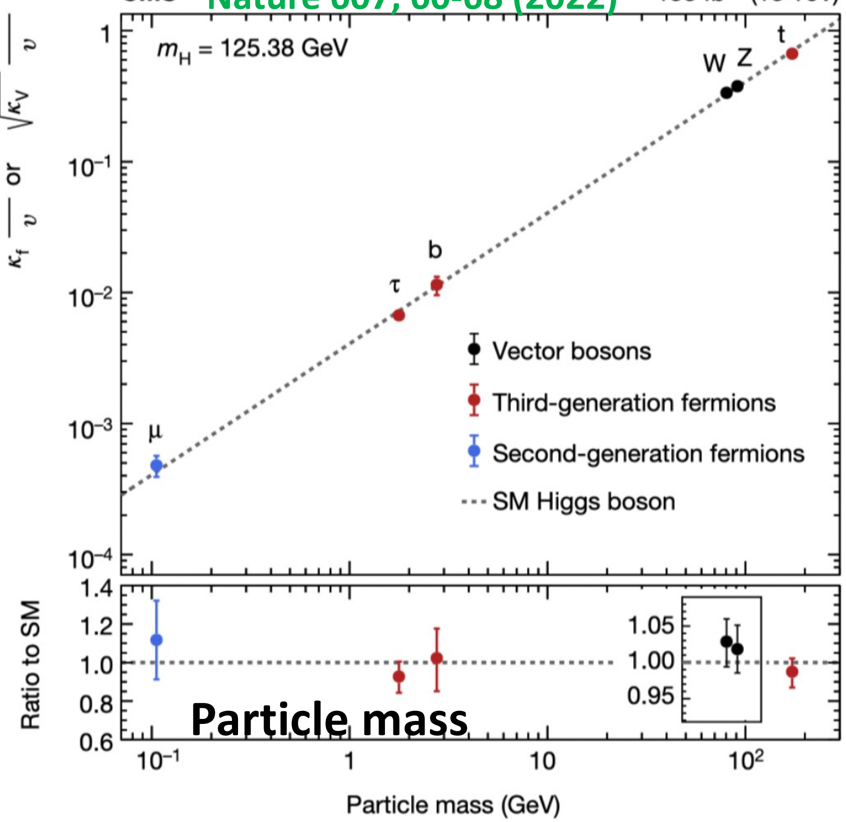


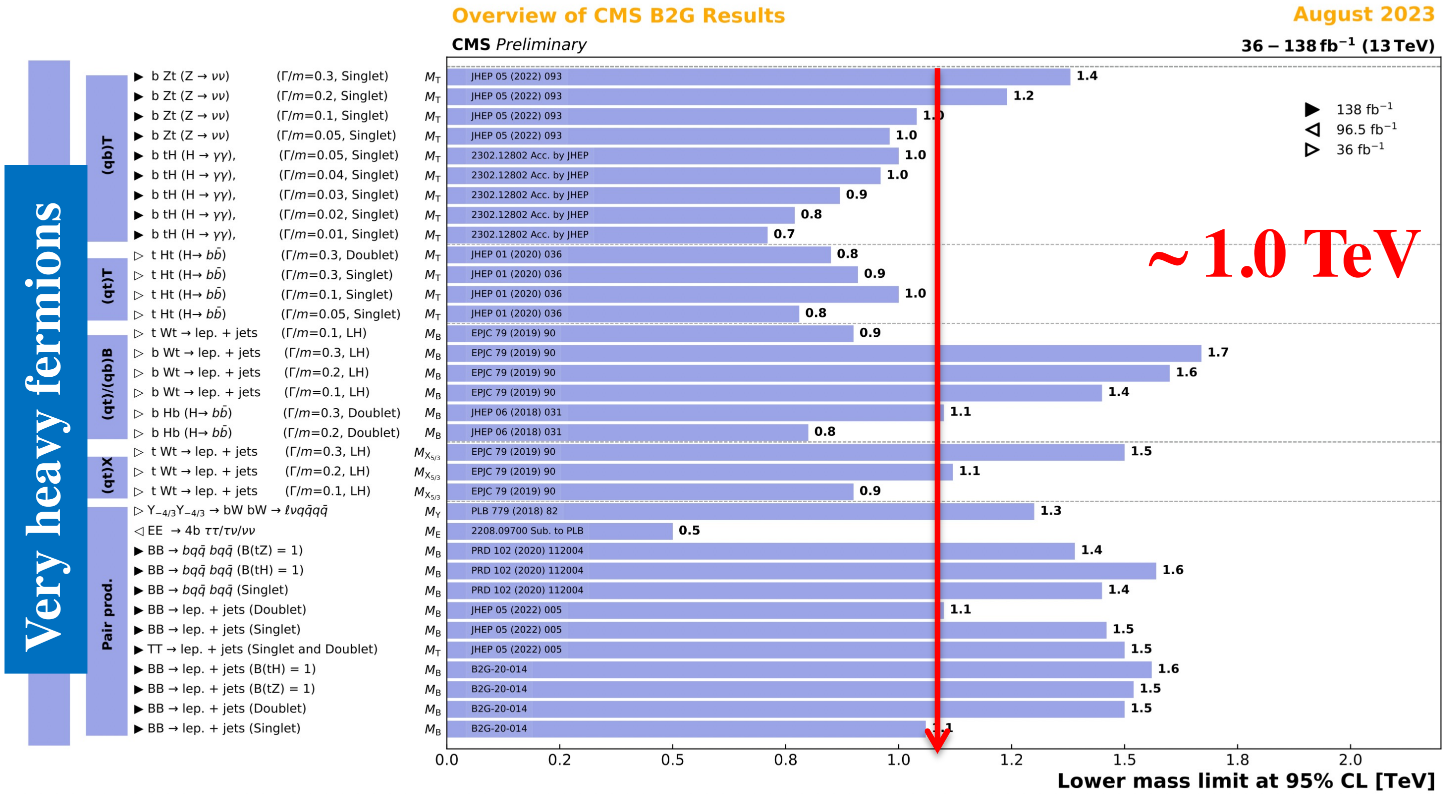


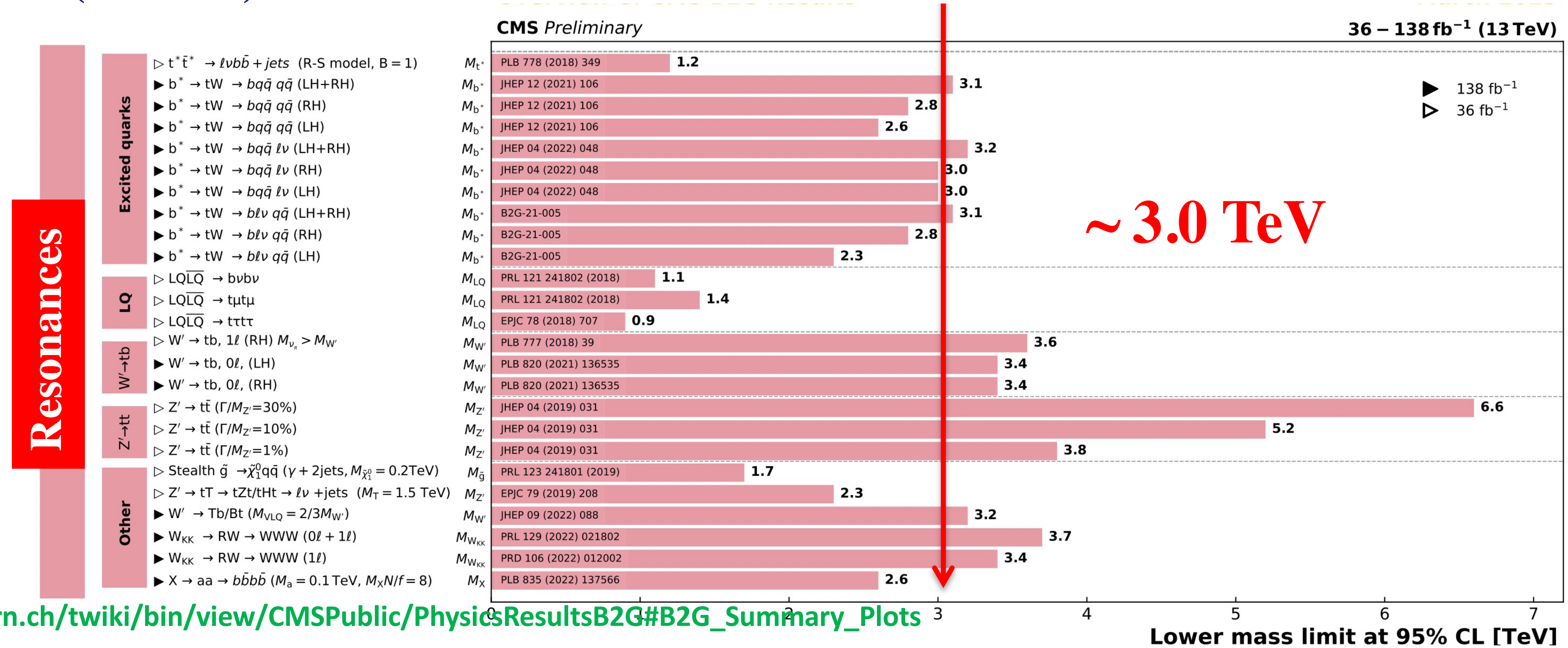


New particles

- Many direct searches (too many to display in one page)
- No new particles

→ Set lower mass limit @ 95%CL up to ≈ 6.6 TeV (Z'→tt)





https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G#B2G_Summary_Plots

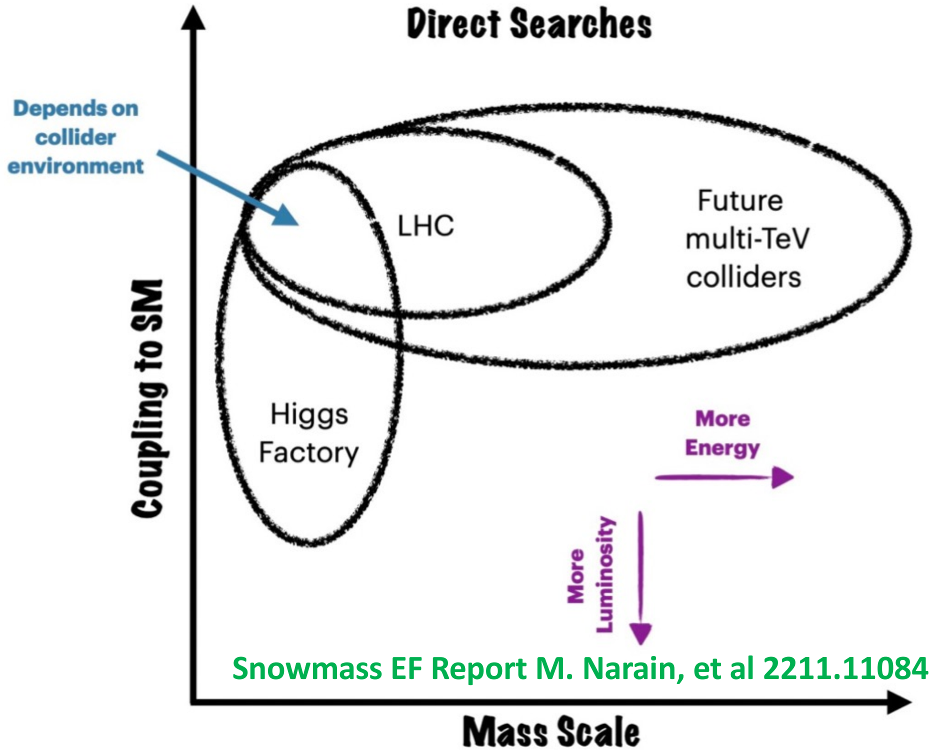
Why we have not (yet) found new physics (wrt SM) (*)?

(*) Few anomalies exist

1. New physics is buried in the backgrounds

2. New physics is weakly coupled

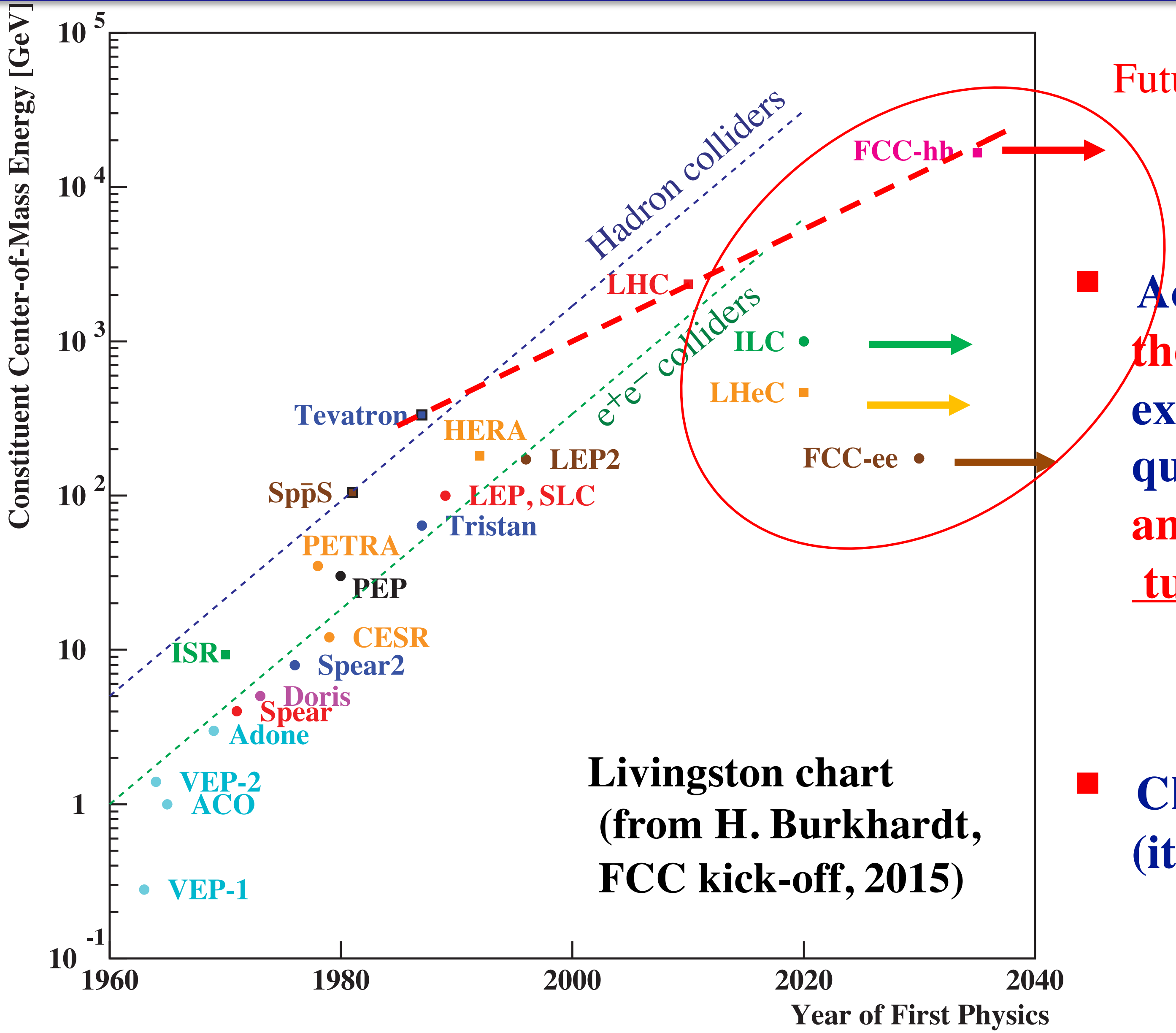
Improve: trigger (TLA) analysis methods (ML), theory prediction of bkg and/or more luminosity



- Direct searches of new states:
  $\sqrt{s'} > M_x$
  Need a machine with enough energy
  - Search for a peak (often) in the invariant mass of the decay products or in the production cross section (ex. LEP)
  - In most cases, direct searches motivated by a 'descriptive' theory (ex. SUSY)

3. A gap exists between the reached energy and new physics

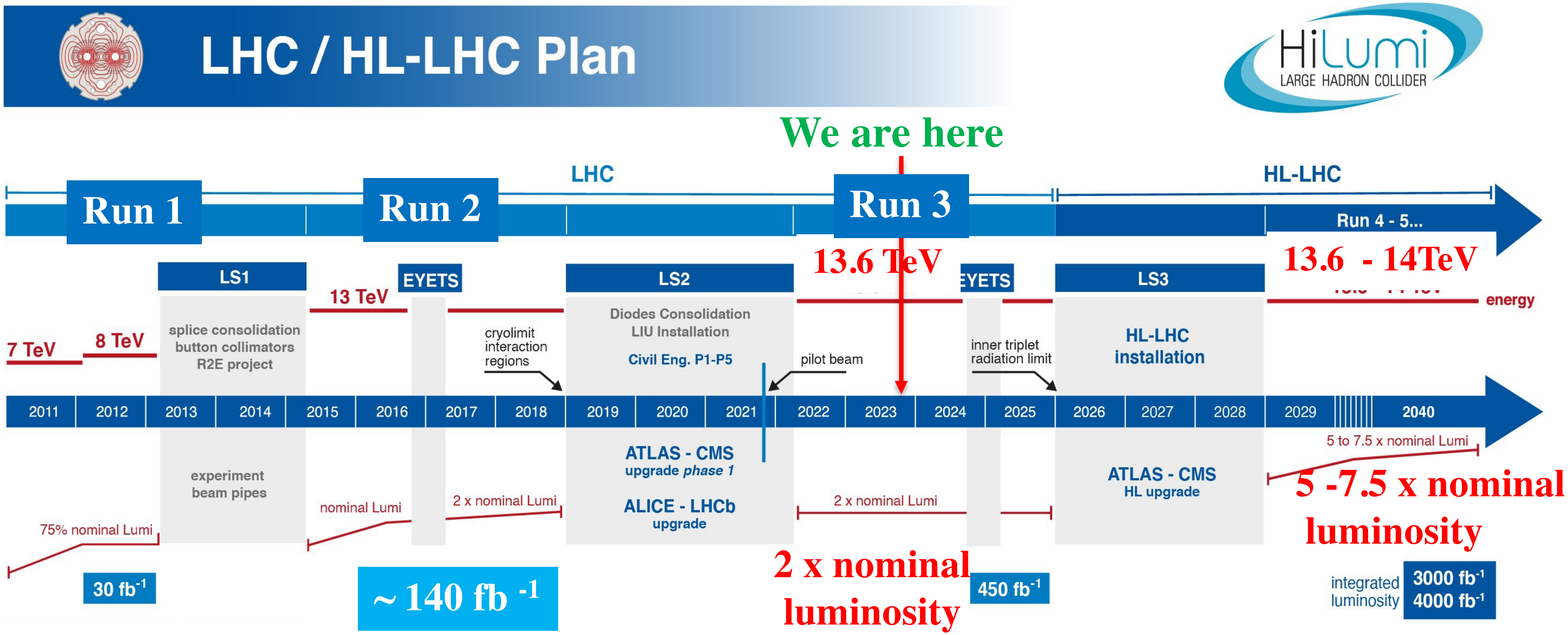
A gap between the reached energy and new physics
→ Increase the energy in the center of mass ($\sqrt{s'} > M_X$) ?



- **Accelerator Physics offers the unique opportunity to explore many fundamental questions at high intensity and energy <u>with known, tunable initial conditions</u>**

- **Change in slope:**
  (it takes time and money)

(HL-)LHC: a powerful tool already NOW
How can we use it in the best way ?



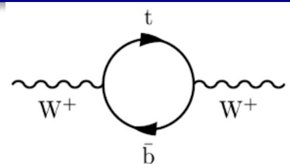
- Energy ~ constant (since 2015)
- Significant luminosity increase (@HL-LHC ~ 15 times the present data sample)

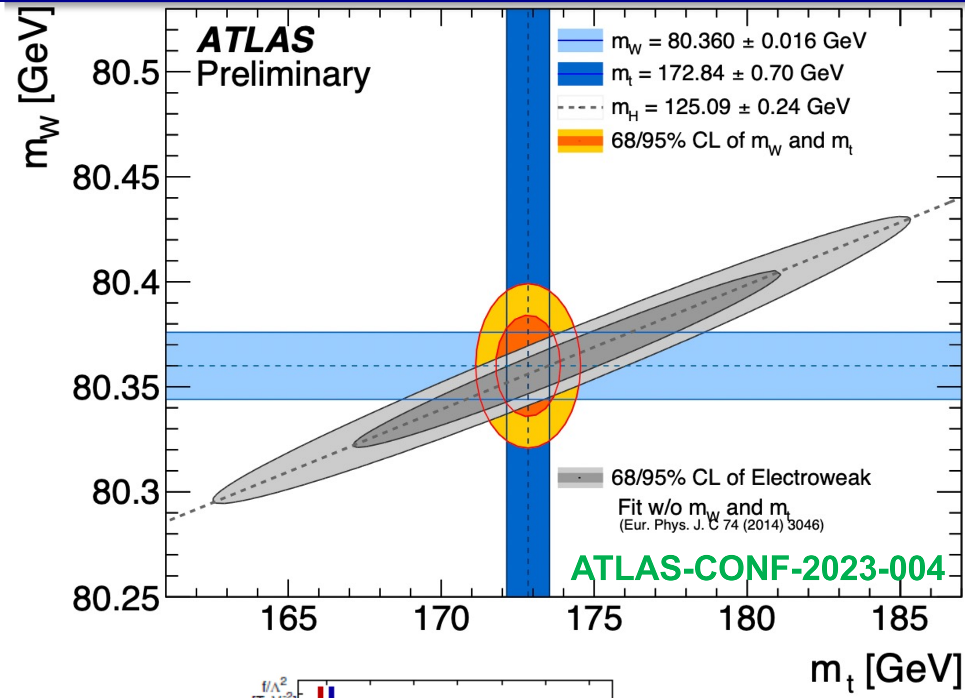
Complementary search scenarios wrt direct searches

- **Search for new physics by measuring very precisely key SM observables (EWPO)**

Expansion in coupling strength

Any significant inconsistency wrt SM
→existence of New Physics

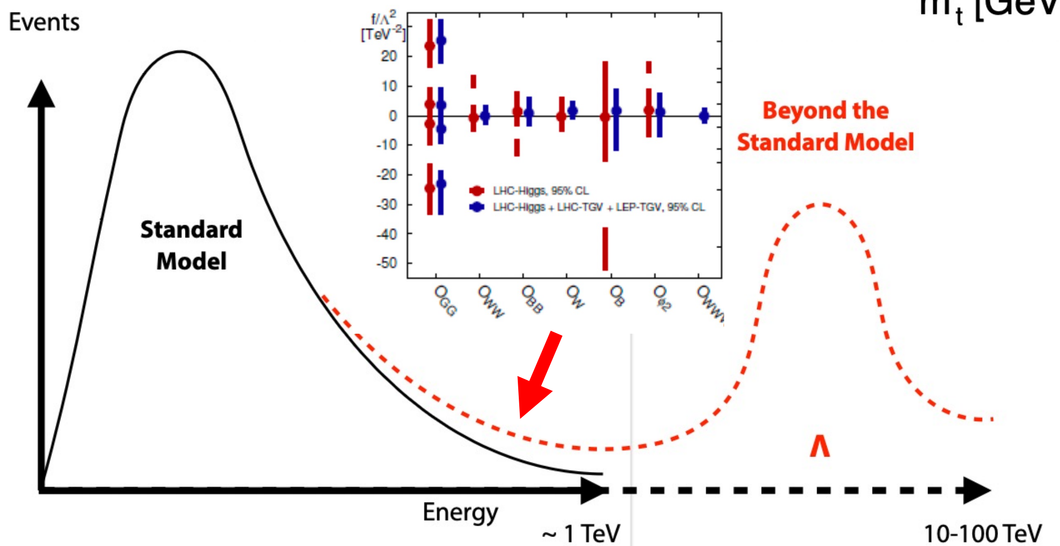




- **Search for deviations from SM in high energy regions (often tails)**

Use an Effective Field Theory to interpret the data
Expansion in scale ratios

→ In both cases probe energy scales beyond the direct kinematic reach



What is an EFT ?

- It's a quantum field theory describing the behaviour of an underlying unknown physical theory ("UV complete") in some limited regime ("IR limit").

- In an EFT, the details of (new) Physics are irrelevant @ $E \ll \Lambda$

→ EFT use degrees of freedom relevant to the IR regime (simplification)

Λ is a scale (energy or inverse of a distance):

- @ $E \ll \Lambda$ (new) Physics effects are described by local, analytic operators with $1/\Lambda^n$ suppressions
- possible divergences @ $E \sim \Lambda$ and above, can be neglected

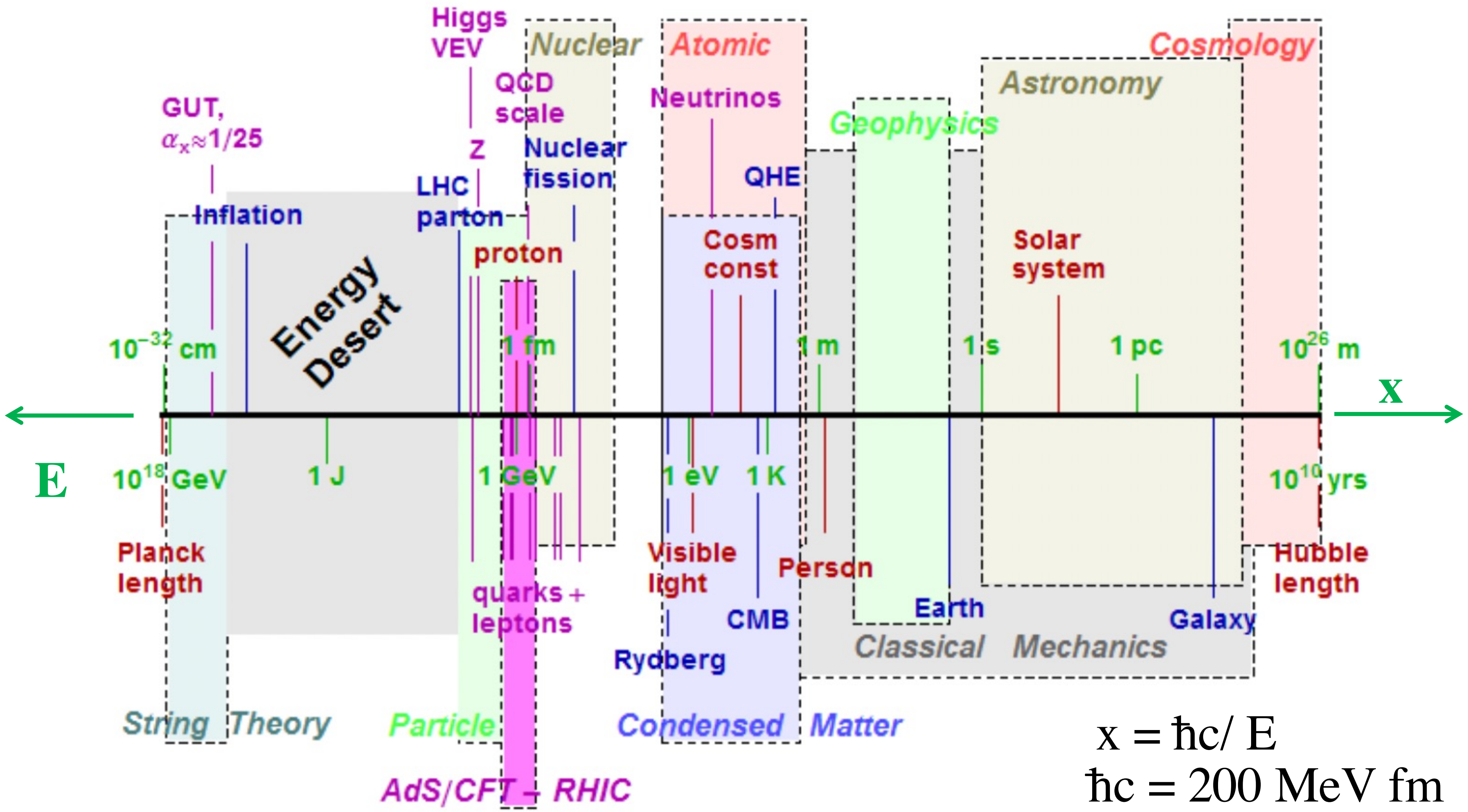
In practice: Taylor expansion of the Lagrangian in powers of E/Λ

$$\mathscr{L}_{\mathrm{EFT}} = \sum_{\mathscr{D}>0,i} \frac{c_i^{(\mathscr{D})} O_i^{(\mathscr{D})}}{\Lambda^{\mathscr{D}-d}}$$

d = space-time dimensions
c_i = Wilson coefficients
O_i = allowed operators
$\mathscr{D}$ = operator dimension

- New physics expressed in terms of coefficients of higher dimension operators including constraints of locality, gauge and Lorentz invariance

Nature has naturally many scales (“divide et impera”)



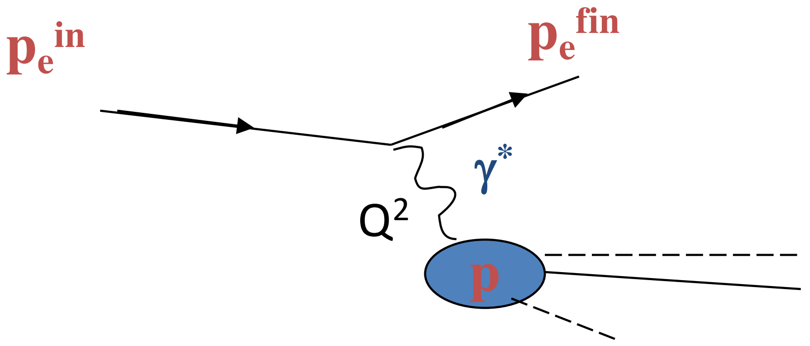
$x = \hbar c / E$

$\hbar c = 200$ MeV fm

https://phy.princeton.edu/research/high-energy-theory/gubser-group/outreach/energy-scales-in-physics

Nature has naturally many scales (“divide et impera”)

Electron scattering on a proton

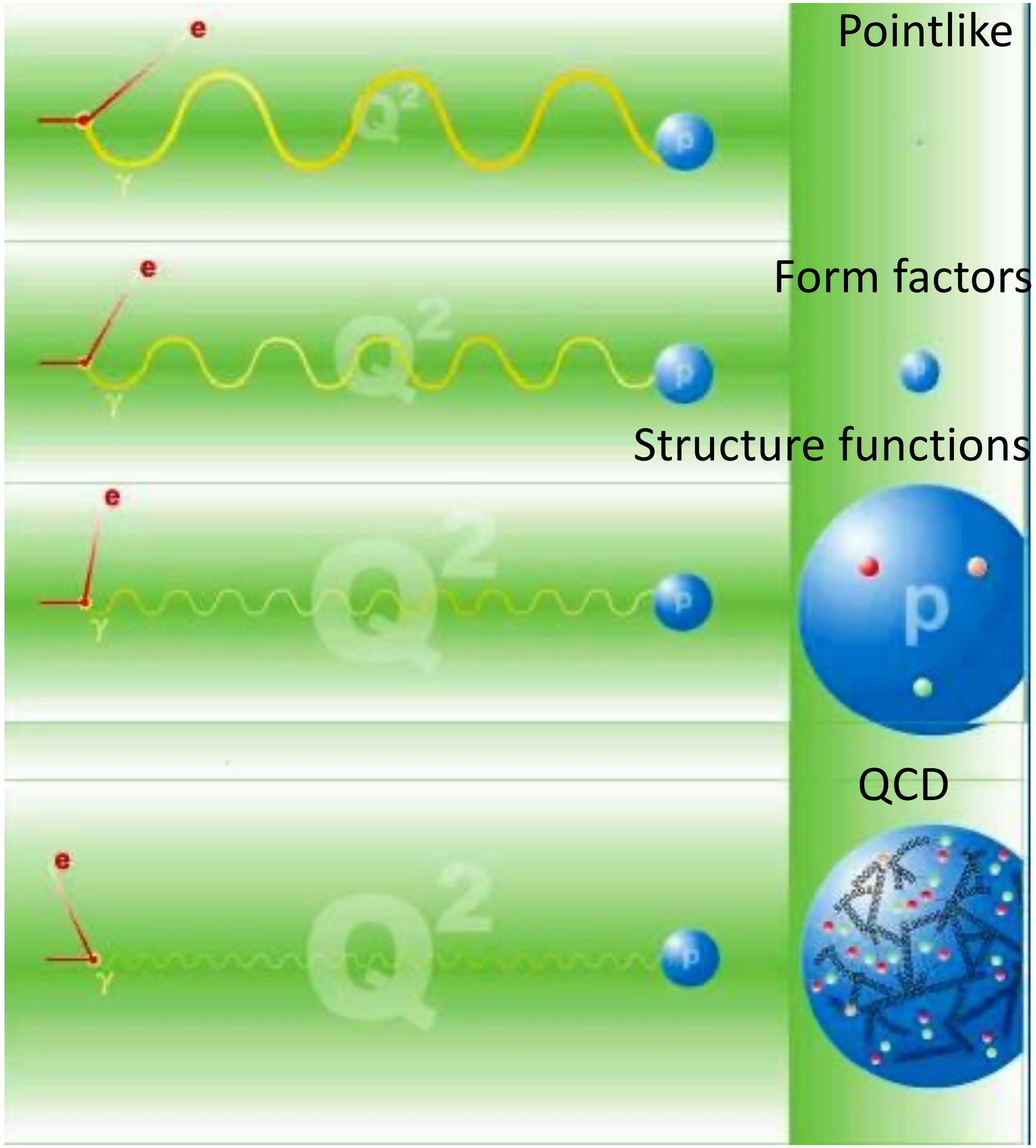


$$Q^2 = (p_e^{in} - p_e^{fin})^2$$

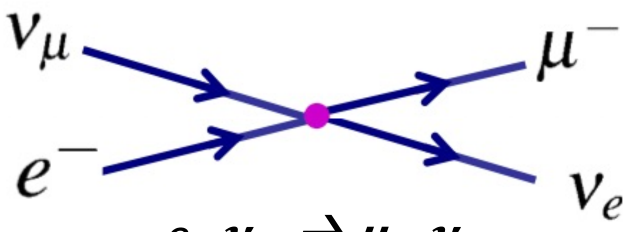
@ Higher and higher Q^2
(= smaller and smaller λ)
new physics regime

$\Lambda \sim \sqrt{Q^2}$ or $\Lambda \sim 1/\lambda$

Q^2



Successful example of EFT: Fermi theory of weak interactions



$e^- \nu_\mu \to \mu^- \nu_e$

Current-current 'universal'* interaction

'Contact interaction'

* Same coupling constant for all weak interactions

$$M_{fi} = \frac{G_F}{\sqrt{2}} g_{\mu\nu} [\overline{\psi}\gamma^\mu (1-\gamma^5)\psi][\overline{\psi}\gamma^\nu (1-\gamma^5)\psi]$$

- **Neglecting the lepton masses ($m_e \sim m_\mu \ll E_\nu$):**

$$\sigma_{\nu_\mu e^-} = \frac{G_F^2 s}{\pi}$$

s = energy^2 in the center of mass = $2\, m_e E_\nu$

G_F = Fermi constant measured in the μ decay (@ a scale $\Lambda \sim m_\mu$) = $1.16 \cdot 10^{-5}$ GeV^{-2}

- **The cross section cannot be higher than the value corresponding to the max of the scattering probability ('unitarity violation')** $\sigma^{elastic}_{max}$

$$\sigma^{elastic}_{max} = (2l+1)16\,\pi/s$$

From partial wave analysis neglecting spins

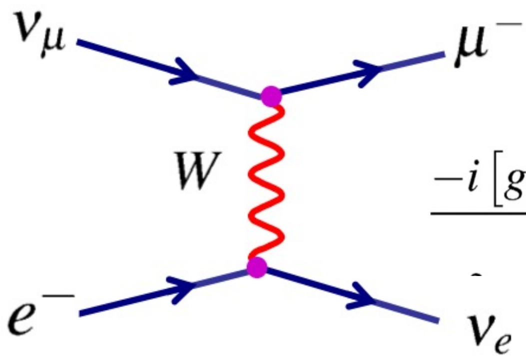
l = angular momentum

- **The Fermi cross section violates unitarity $\sqrt{s} \approx \sqrt{G_F} \approx$ 300 GeV**

Successful example of EFT: Fermi theory of weak interactions

$e^- \nu_\mu \rightarrow \mu^- \nu_e$

- **The divergent behaviour is 'cured' by introducing an 'intermediate' massive boson of Spin 1 as propagator**



$$M_{fi} = [\tfrac{g_W}{\sqrt{2}} \overline{\psi} \tfrac{1}{2} \gamma^\mu (1-\gamma^5)\psi] \frac{g_{\mu\nu} - q_\mu q_\nu / m_W^2}{q^2 - m_W^2} [\tfrac{g_W}{\sqrt{2}} \overline{\psi} \tfrac{1}{2} \gamma^\nu (1-\gamma^5)\psi]$$

$q^2 = (p_e^{in} - p_{\nu e}^{fin})^2$

For $q^2 \ll m_W^2$ **one obtains back the contact interaction** $(\Lambda \sim m_W)$

Expansion in $\delta = q / M_W$

$$\frac{1}{q^2 - M_W^2} = -\frac{1}{M_W^2}\left(1 + \frac{q^2}{M_W^2} + \frac{q^4}{M_W^4} + \ldots\right)$$

$$M_{fi} = \frac{i}{M_W^2}\left(\frac{-ig_W}{2\sqrt{2}}\right)^2 (\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e} \gamma^\mu P_L \nu_e)_{,\,\nu_\ell}) + \mathcal{O}\left(\frac{1}{M_W^4}\right)$$

$$\frac{G_F}{\sqrt{2}} \equiv \frac{g_W^2}{8 M_W^2}$$

Great success

Intermediate Energy Cross Sections:
Eν ~ 0.1 – 100 GeV

Quasi-elastic scattering: $\nu_\mu n \rightarrow \mu^- p$

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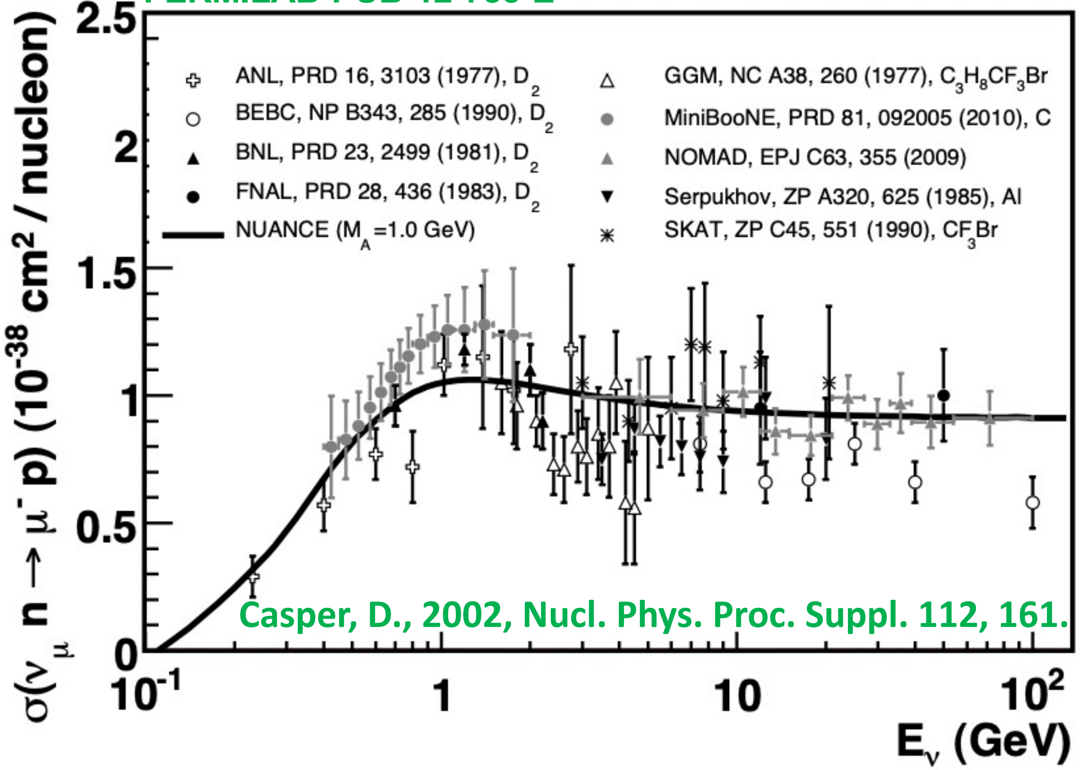
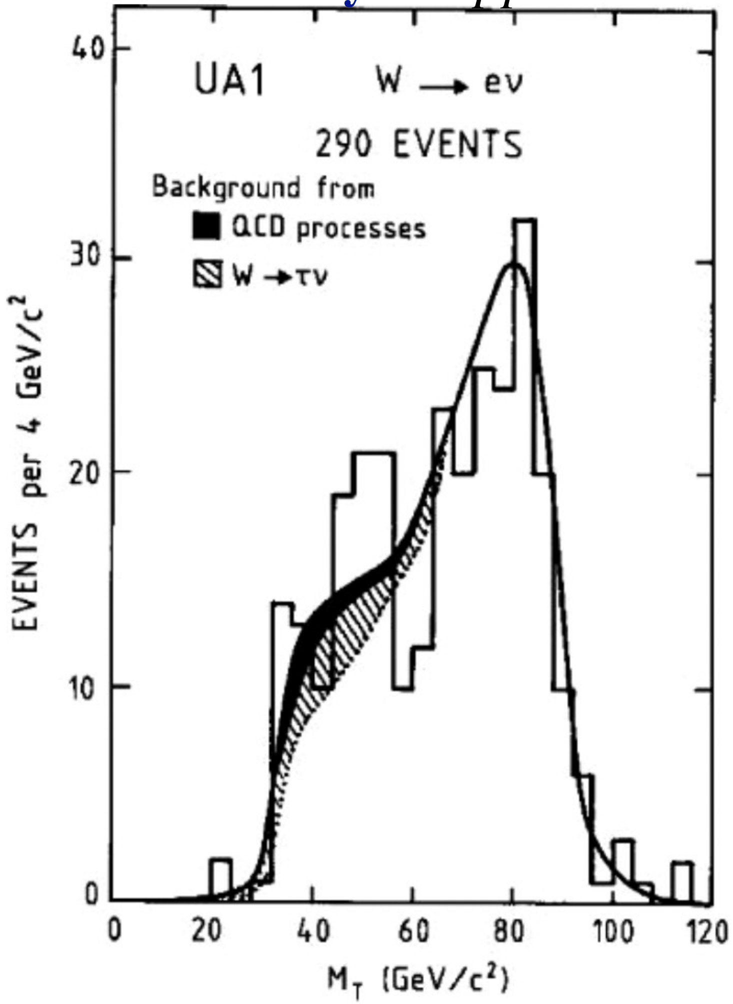


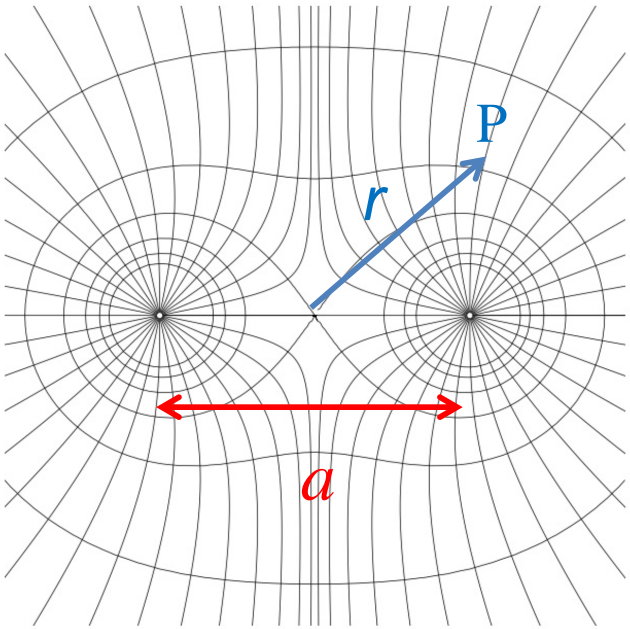
Casper, D., 2002, Nucl. Phys. Proc. Suppl. 112, 161.

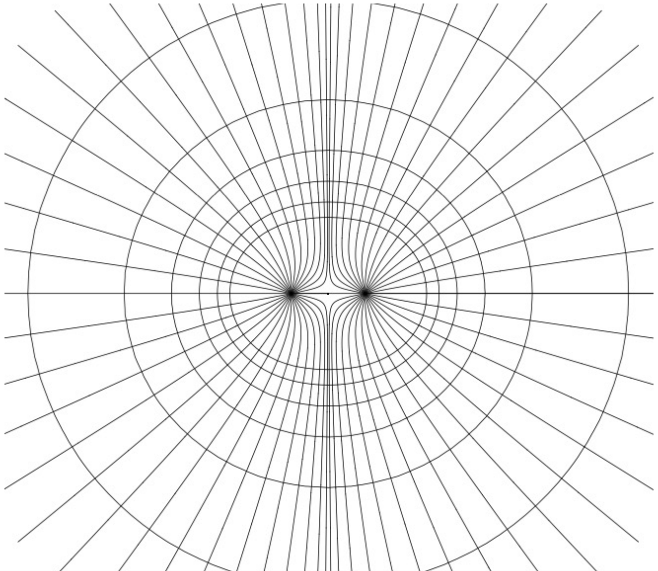
1983: W discovery: $p\bar{p} \rightarrow W\ X$



C. Albajar et al., (UA1 Collaboration), Z. Phys. C 44, 15 (1989)

Another example of EFT : multipole expansion





- **Potential from point-like charges (sources)**

$$V(\mathbf{r}) = \frac{1}{r}\sum_{l,m} b_{lm}\frac{1}{r^l}Y_{lm}(\Omega) \qquad b_{lm} \equiv c_{lm}a^l$$

c_{lm} **dimensionless coefficient**

a **short distance (high energy scale)** $\Lambda \sim 1/a,$

$$V(\mathbf{r}) = \frac{1}{r}\sum_{l,m} c_{lm}\left(\frac{a}{r}\right)^l Y_{lm}(\Omega)$$

Expansion in *l*

$$\delta = a/r$$

- **Simplification if** $a << r$ **(far)**

- **The field far away from the sources looks like a point-like charge (truncation to small *l*)**

Other examples of EFT

- **HQET Heavy quark effective theories**

  Low-energy dynamics of hadrons containing a heavy quark.

  Expansion parameter: $\Lambda_{\mathrm{QCD}}/m_Q$

- **Chiral Perturbation Theory**

  Interactions of pions and nucleons at low momentum transfer. Expansion parameter: p/Λ_χ

  $\Lambda_\chi \sim 1$ Gev

- **Soft-collinear effective theory SCET**

  Energetic QCD processes, the final states (jets) with small invariant mass M_J wrt to the center-of-mass energy of the collision (Q). Expansion parameter: M_J/Q

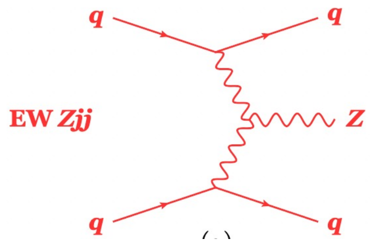
- **SMEFT** describes deviations from the SM. Expansion parameter: $1/\Lambda$

- **SM is itself an effective theory valid at our accessible energies**

EFT methods allow us to separate scales in a multi-scale problem, and organize the calculation in a systematic way

Example of (SM)EFT fit @ LHC

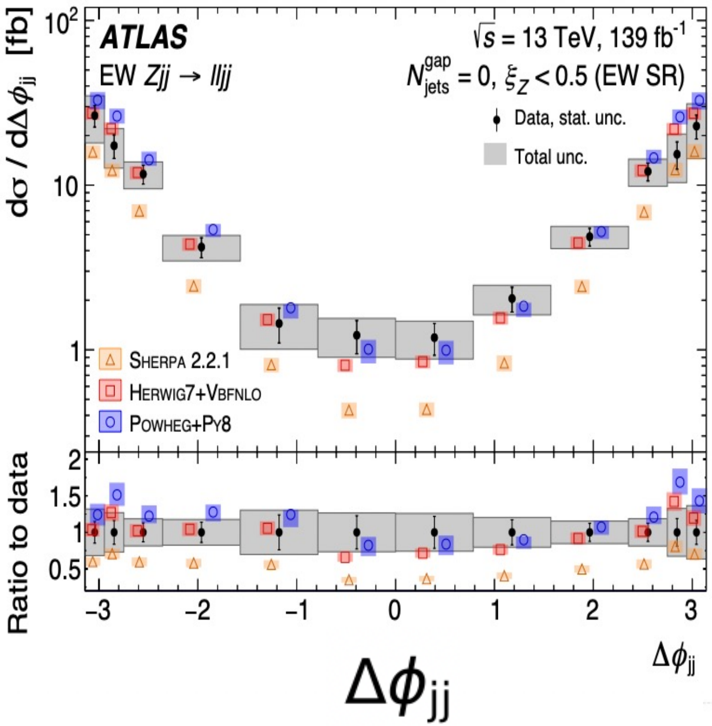
- **Vector Boson Fusion (VBF) Differential cross section**



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

$c_i = c_W$

$O_i = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$



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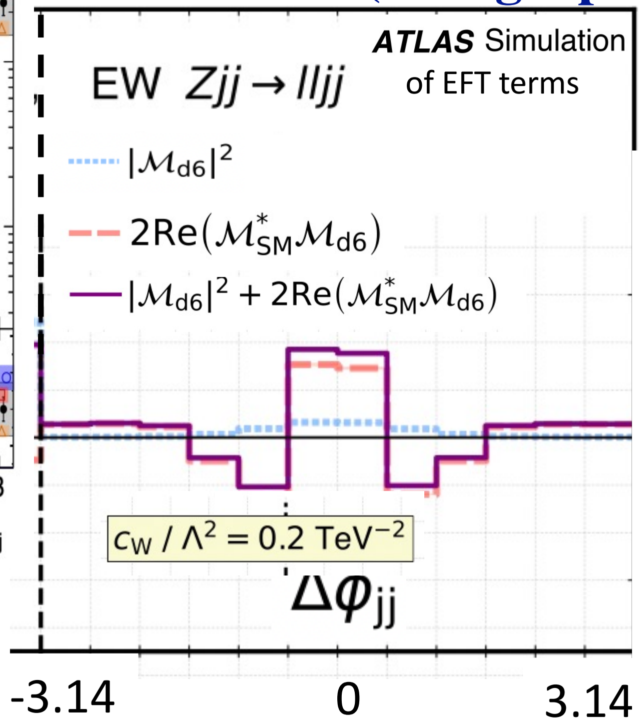
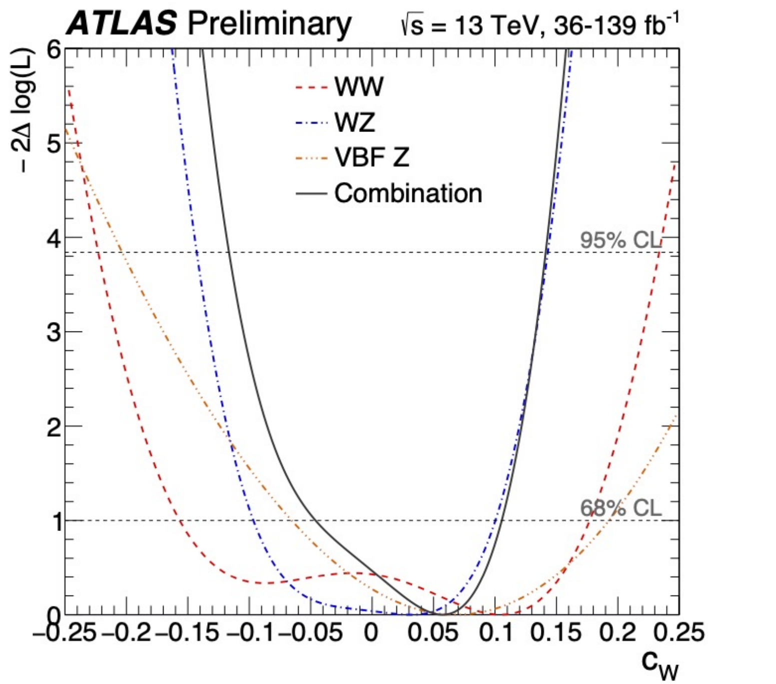
Ratio to SM (Madgraph)



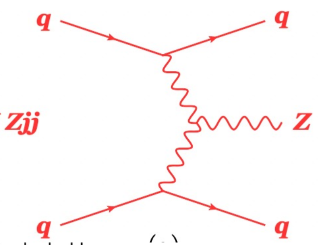
One-dimensional confidence level intervals

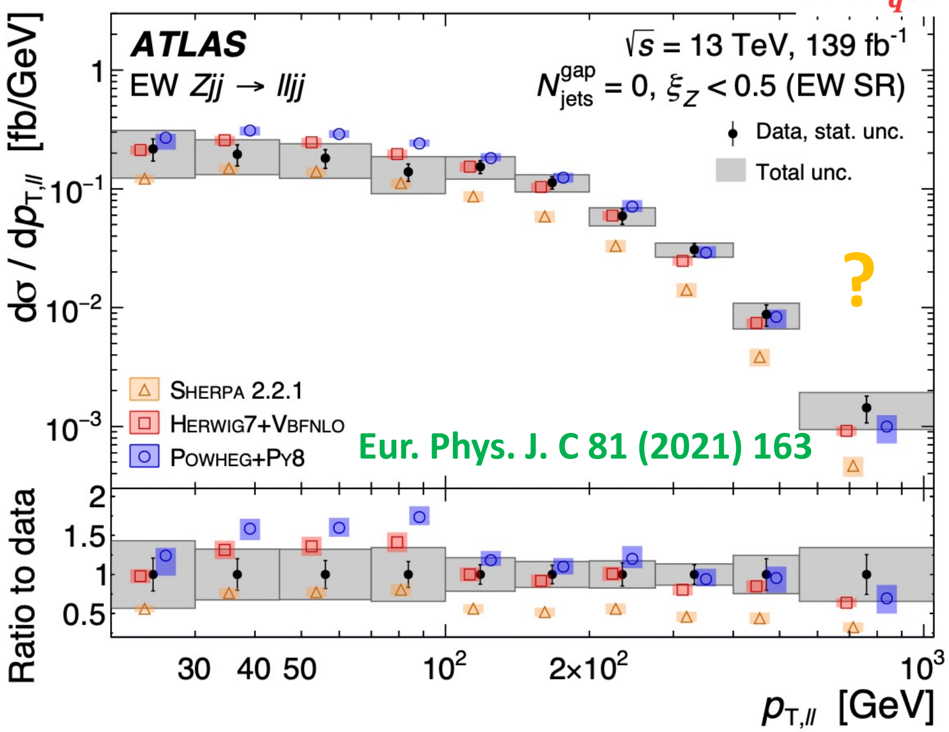


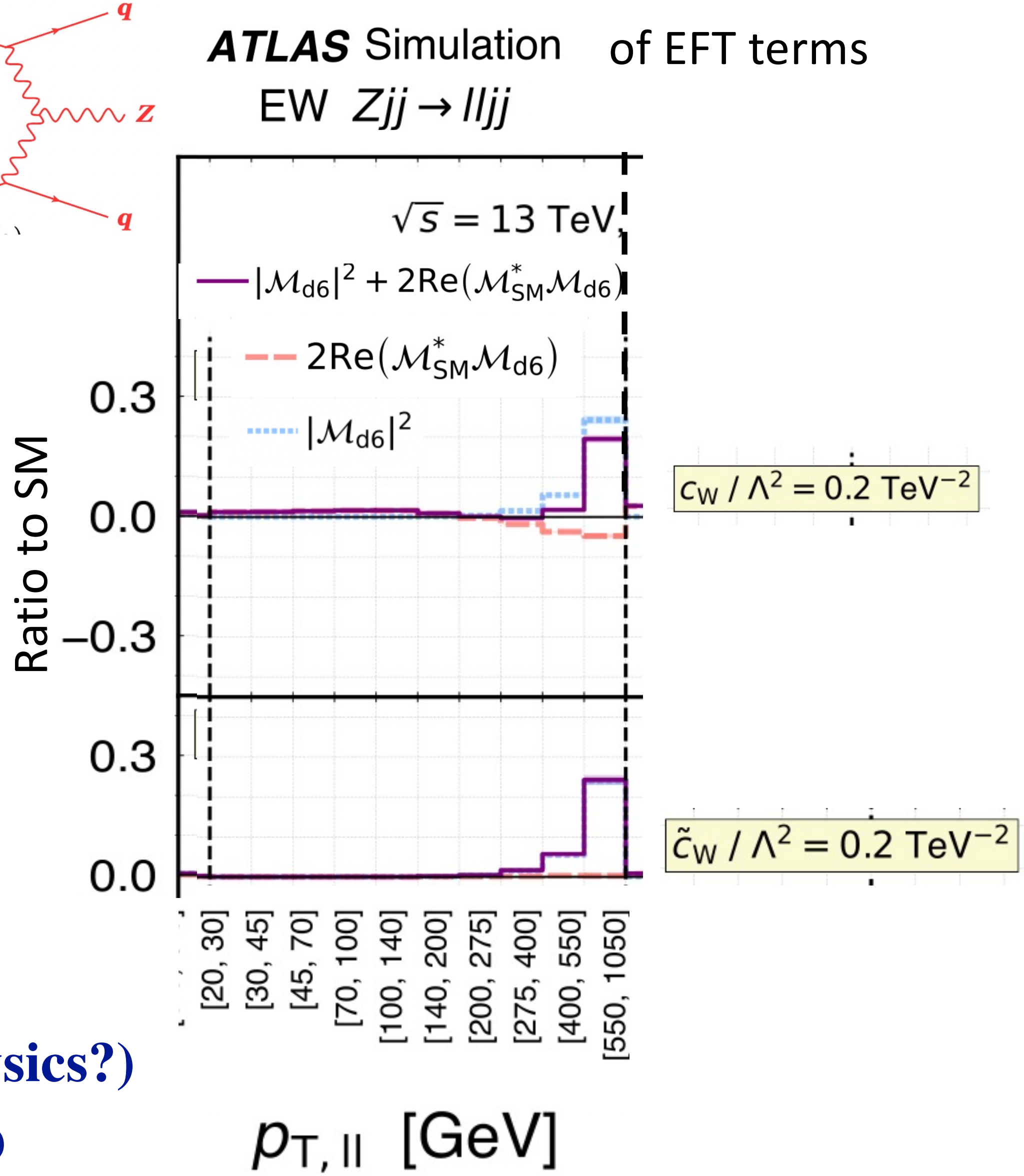
- **EFT quantify degree of compatibility wrt SM in a theoretically and statistically well sounded way in many distributions, comparison and combinations among experiments**

Important to know well the SM

- **Vector Boson Fusion (BVF) Differential cross section**







- **Understand the predictions (Sherpa has less tail or it is New physics?)**
- **Know higher orders in QCD & QED**

Summary
Motivations for EFT mainly from an experimental point of view

- It takes time to build higher energy machines

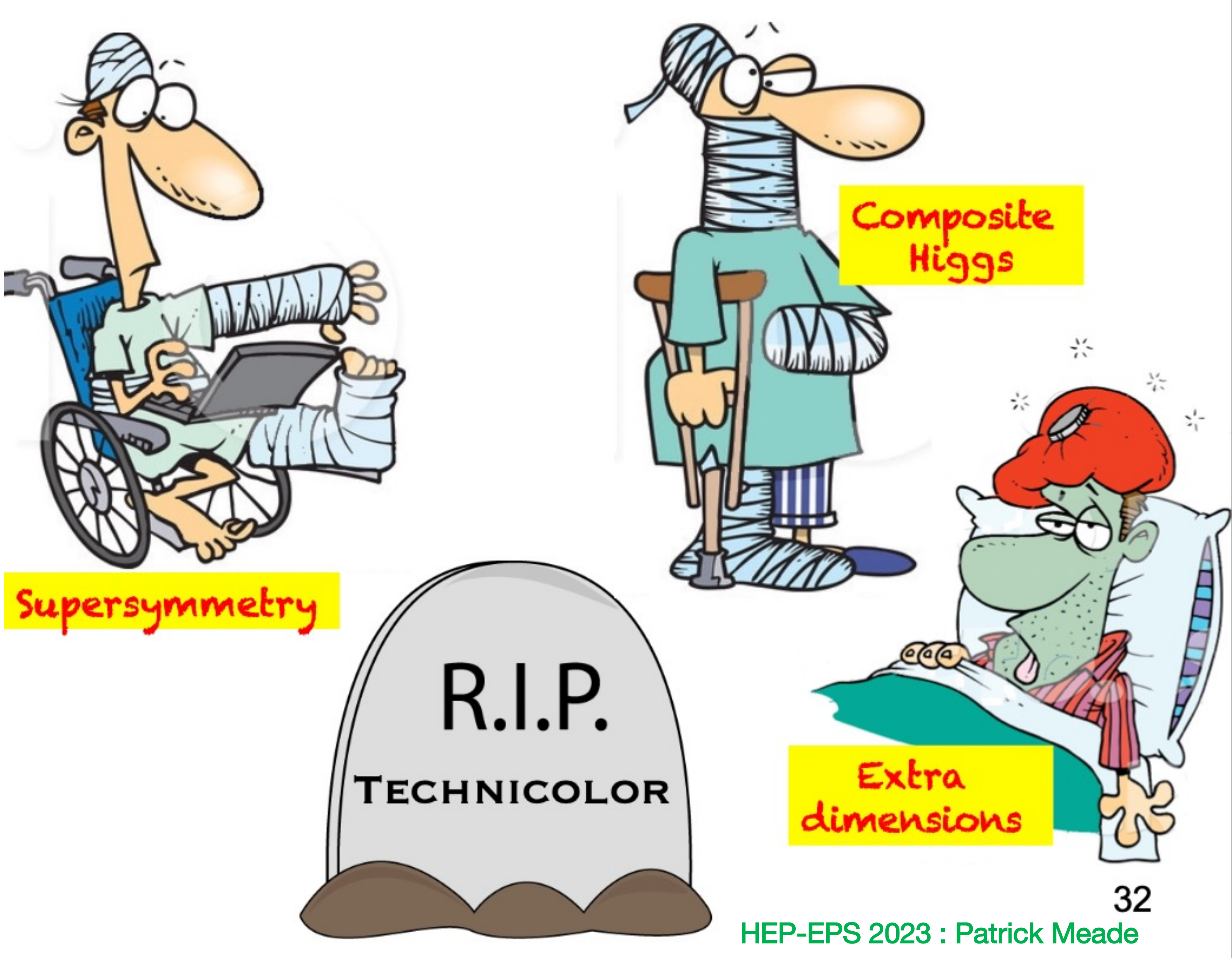
- Nature has naturally many scales ("divide et impera")

- Few examples from the past show that the EFT approach was successful

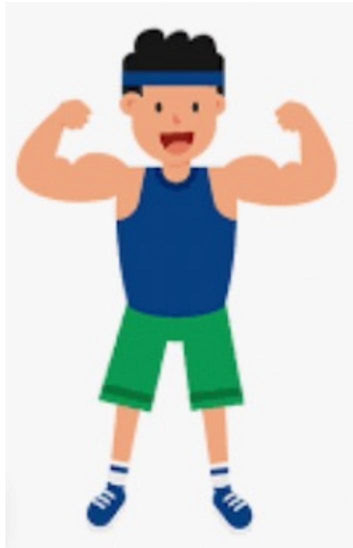
- EFT allow to quantify small deviations or the degree of compatibility wrt SM in a theoretically and statistically sounded way in many distributions, comparisons and combinations among experiments

- Reduced model dependence wrt direct searches

Introduction and experimental motivation: End



EFT



(.. " but it is not as easy as it seems " ..)

Additional references

Aneesh V. Manohar, Introduction to Effective Field Theories : arXiv:1804.05863v1

https://www.hep.phy.cam.ac.uk/~thomson/lectures/partIIIparticles/Handout10_2009.pdf
Mark Thomson lectures