Theory perspective on LHC Run 3 and beyond

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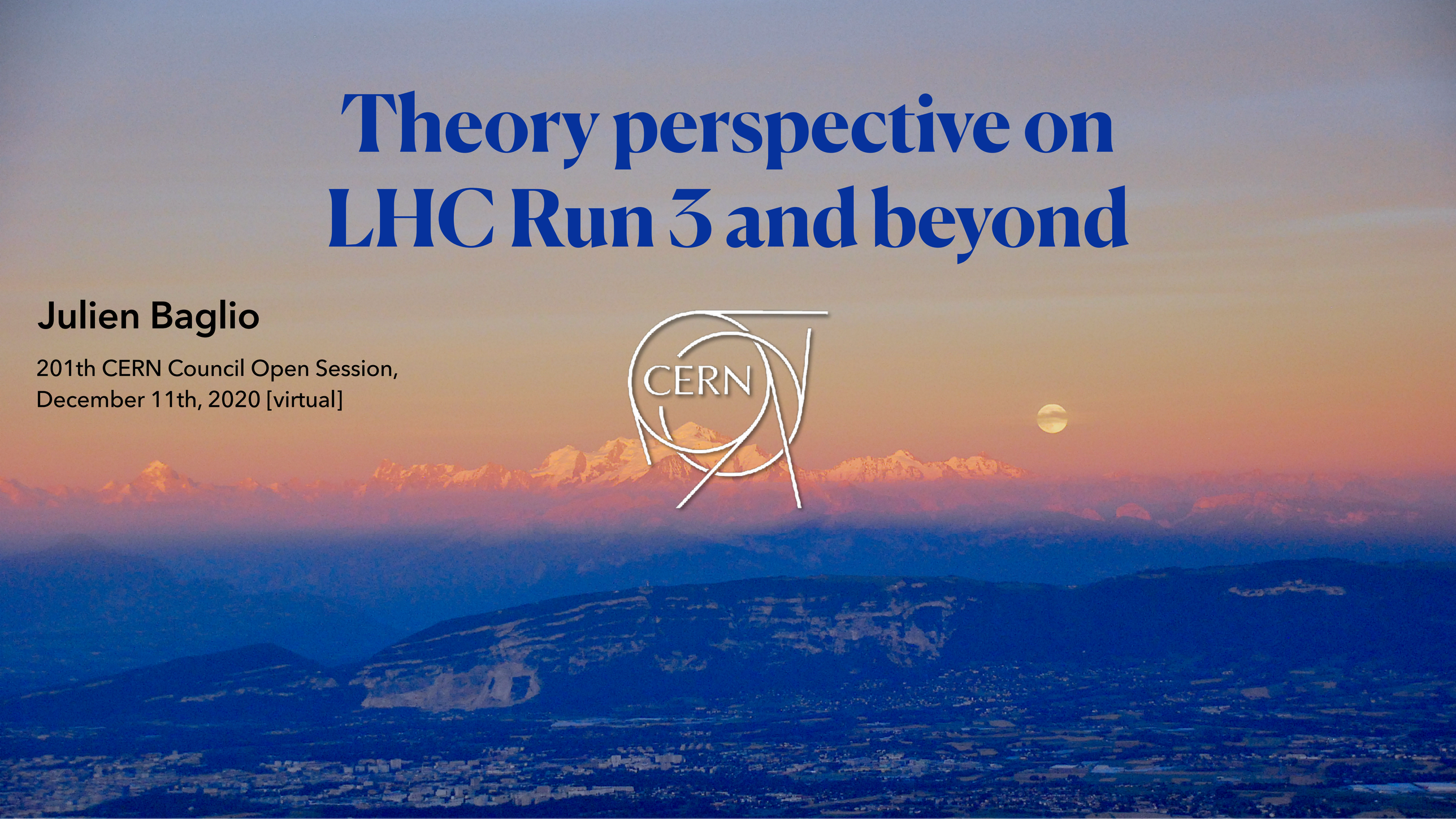
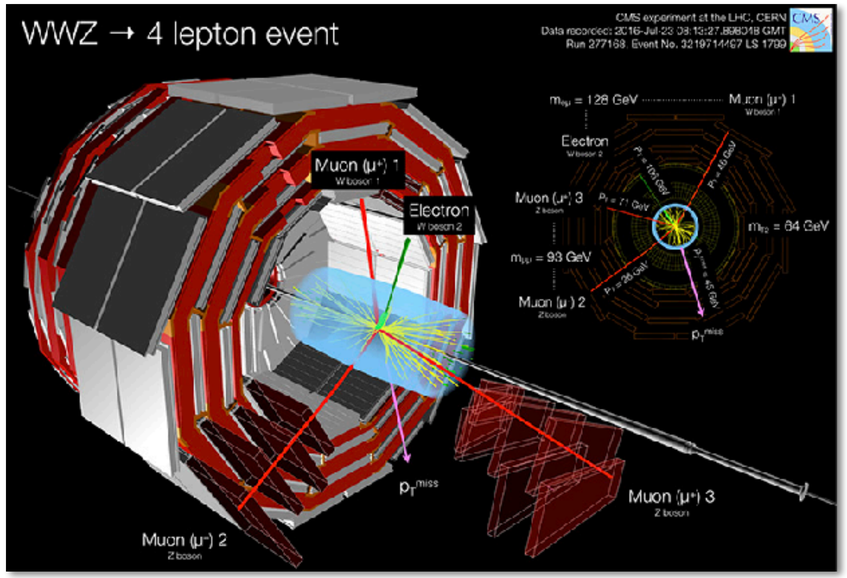
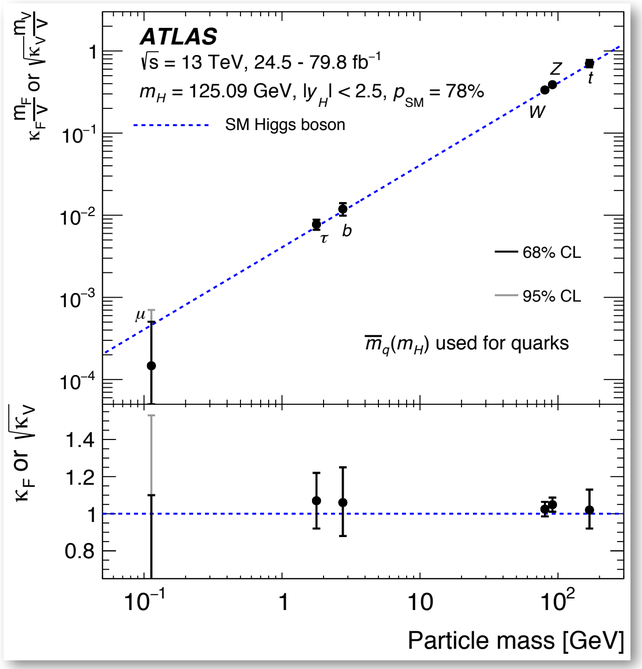
201th CERN Council Open Session,
December 11th, 2020 [virtual]



LHC Run 1 and Run 2 are a big success!



[Phys.Rev.Lett. 125 (2020) 151802]



[Phys.Rev.D 101 (2020) 012002]

- **2012: Discovery** of a **spin-0 particle** with **Higgs-like properties** (ATLAS, CMS)

The first elementary scalar observed in Nature

- **2014: Discovery** of a **collective-like (flow) behavior** in multi-hadron *p-p* and *p-Pb* collisions (ALICE, CMS)
- **2015:** First **observation** of the rare $B_s^0 \to \mu^+\mu^-$ **decay** (LHCb, CMS)
- **2018:** Direct **measurement** of **top-Higgs Yukawa coupling** in $t\bar{t}H$ production; **bottom-Higgs Yukawa coupling** in $VH, H \to b\bar{b}$ (ATLAS, CMS)
- **2020:** First **observation** of **VVV production** and **VV scattering** (CMS); first **observation** of **time-dependent CP violation** in B_s systems (LHCb)

The Big Questions

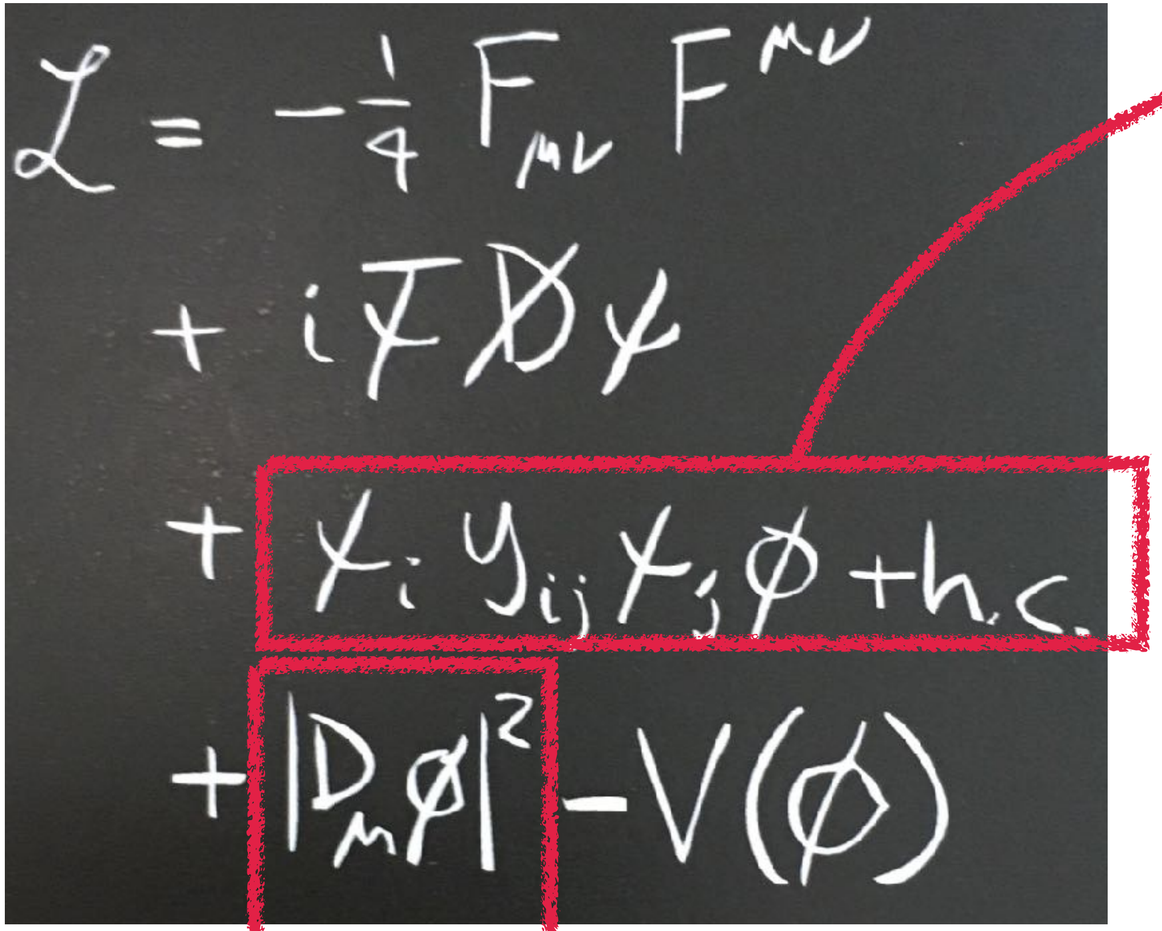
- **What is the nature of electroweak symmetry breaking (EWSB)?**
- **What is the nature of Dark Matter?** Dark Energy?
- What is the mechanism behind the generation of neutrino masses?
- How to explain the matter/antimatter asymmetry of the Universe?

  Where are the additional sources of CP violation?
- etc.

Disclaimer: Focus on the first two questions for the remaining (impossible to cover everything)

We have observed a Higgs boson...

Really?



Yukawa interaction: measured and compatible with the Standard Model (SM) for the 3rd generation...

Gauge-Higgs interaction: measured and compatible with the SM...

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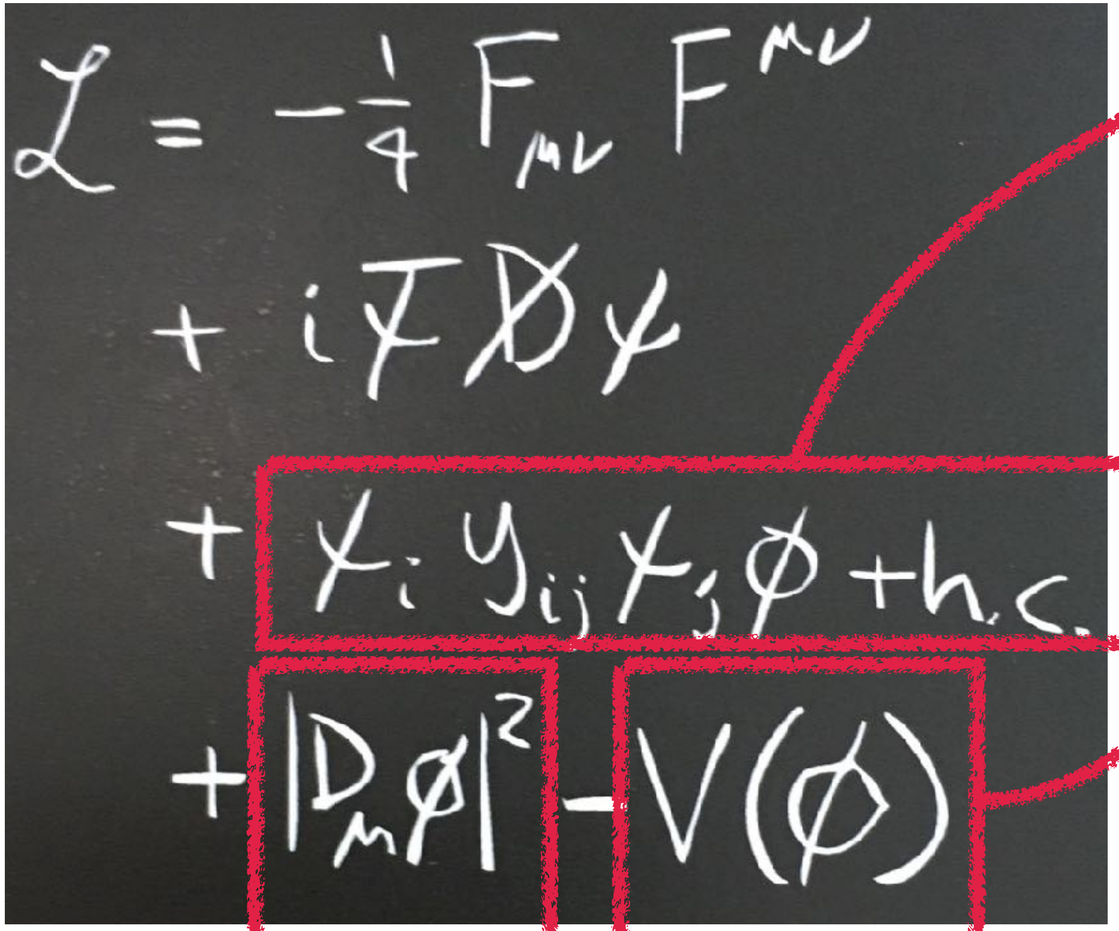
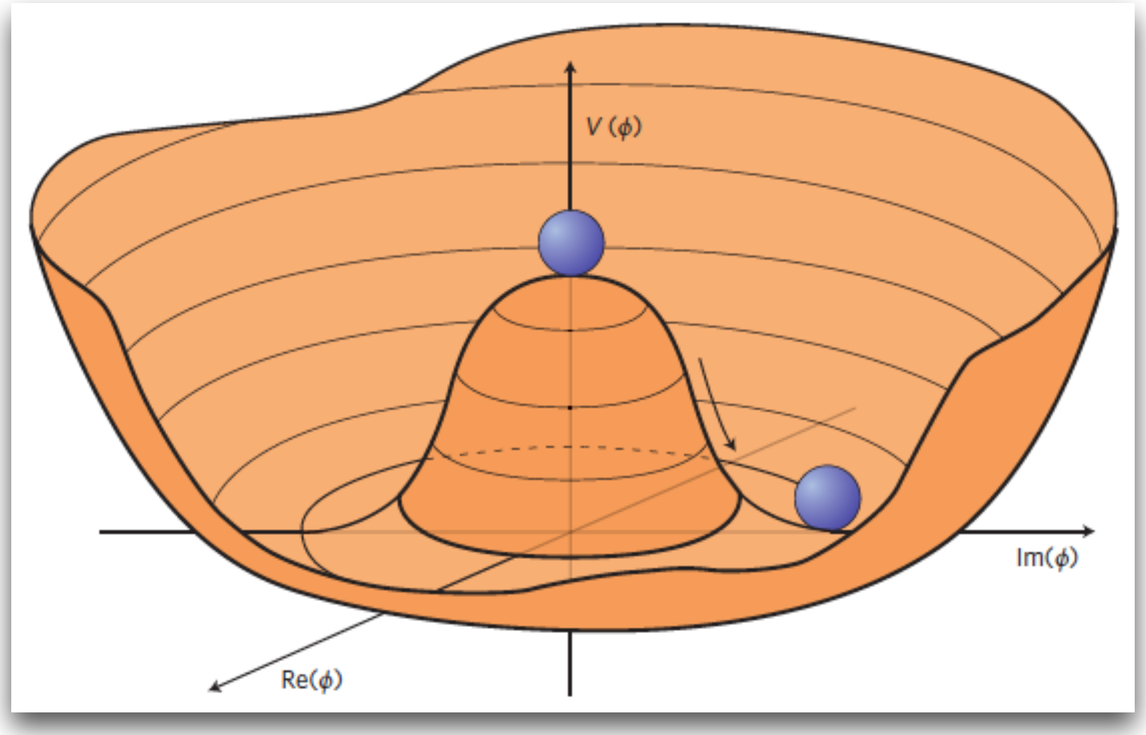


Yukawa interaction: measured and compatible with the Standard Model (SM) for the 3rd generation…

The core of EWSB: the scalar potential, not yet measured! Its shape dictates the fate of our vacuum!

Gauge-Higgs interaction: measured and compatible with the SM…

Higgs self-interactions: cornerstone of the SM



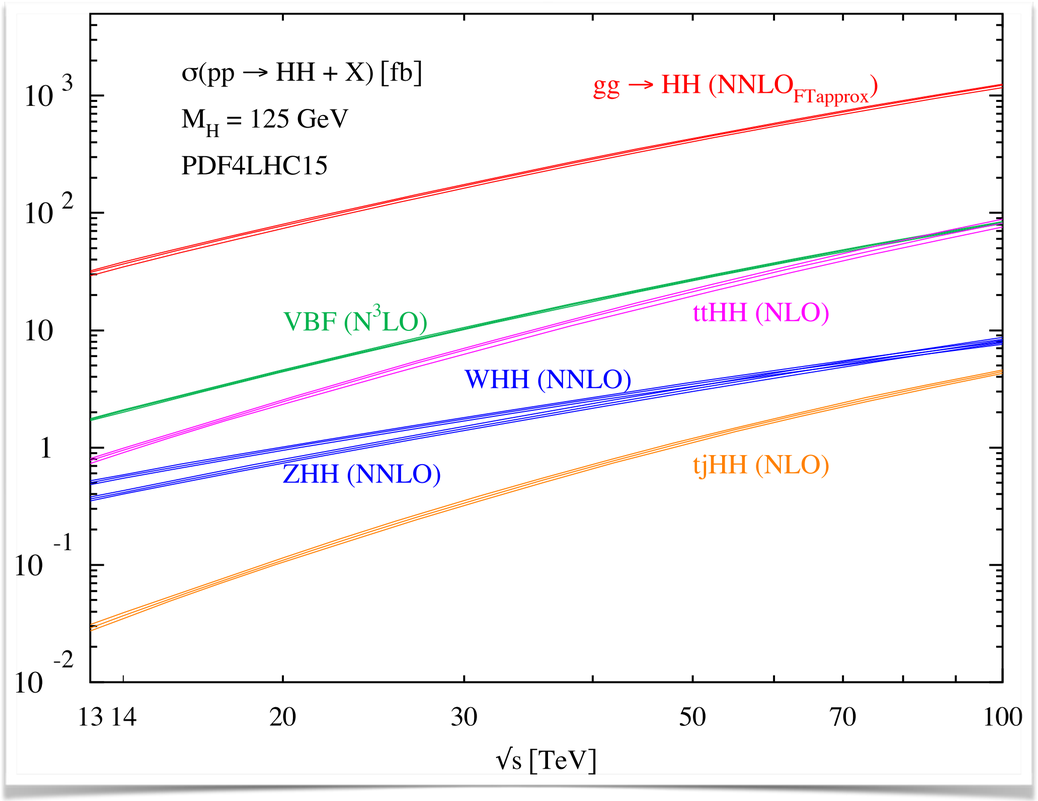
After EWSB, with ***H*** **the Higgs *boson*:**

$$V(H) = \frac{1}{2}M_H^2 H^2 + v\lambda_{H^3} H^3 + \frac{1}{4}\lambda_{H^4} H^4 + \text{constant}$$

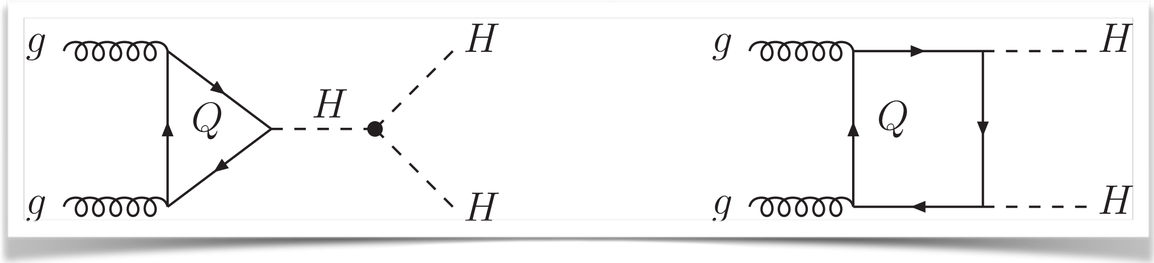
SM predicts $\lambda_{H^3} = \lambda_{H^4} = \dfrac{M_H^2}{2v^2}$

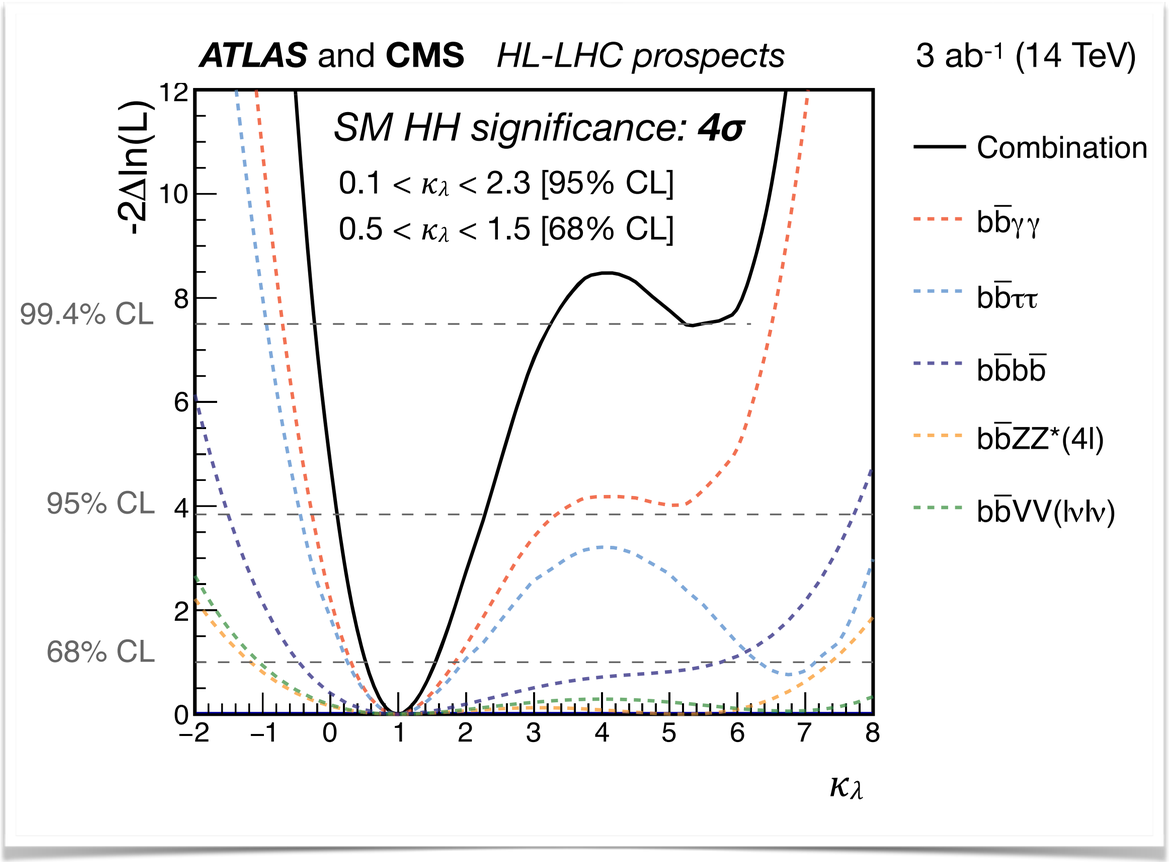
Establishing non-zero Higgs-self interactions = start accessing the shape of the potential! Key goal of Run 3 and HL-LHC

Direct access to the self-couplings: Higgs pair production



[Rev.Phys. 5 (2020) 100045]





[CERN Yellow Rep. Monogr.7 (2019)]

Small probability to produce Higgs pairs:

- **Lots of data needed: HL-LHC!**
- **Precise predictions needed to reduce the uncertainties**

Higgs and SM program: keep probing couplings

- **1st- and 2nd-generation Yukawa couplings**: lots of room for **new physics** here
- **Triple-Higgs coupling**: shape of the scalar potential, may give indications on the dynamics behind EWSB (still unknown!)
- If new physics is heavy: **effective field theory** a very powerful tool to probe it

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_i \frac{d_i}{\Lambda^4}\mathcal{O}_i^{d=8} + \dots$$

scale of new physics

HL-LHC EFT prospects:

δg_{HZZ}	3.6 %
δg_{HWW}	3.2 %
δg_{Hbb}	5.3 %
$\delta g_{H\tau\tau}$	3.4 %
$\delta g_{H\mu\mu}$	5.5 %
δg_{Htt}	3.5 %
δg_{Hgg}	2.3 %
…	

[CERN Yellow Rep. Monogr.7 (2019)]

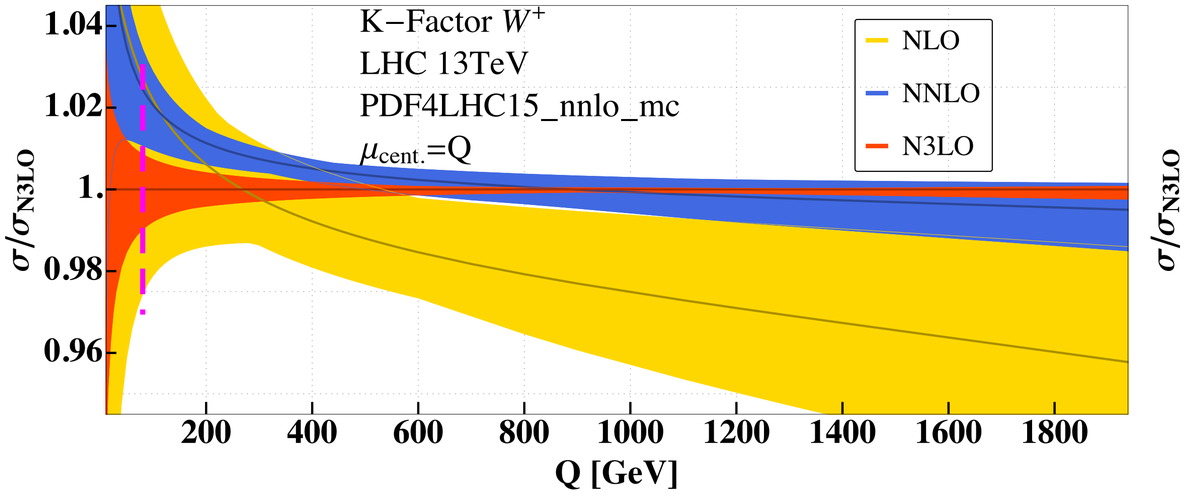
Higgs and SM program: keep probing couplings

To search for indirect evidence of new physics in experimental data:

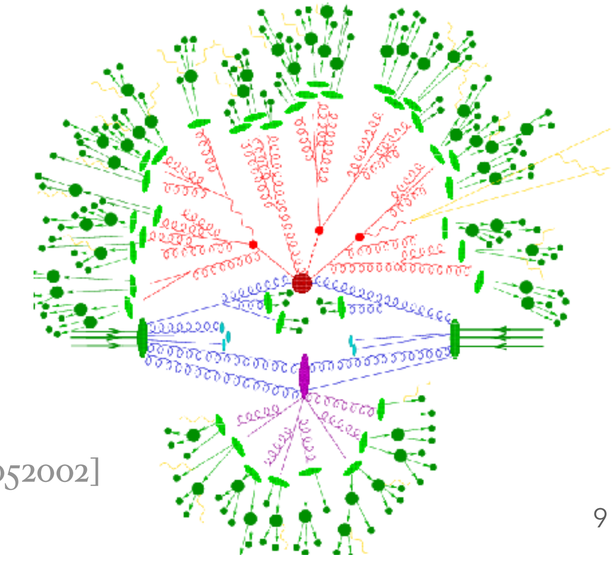
requires high-precision theoretical predictions!

Push QCD and electroweak higher-order calculations

Develop new tools to describe soft radiation even more accurately



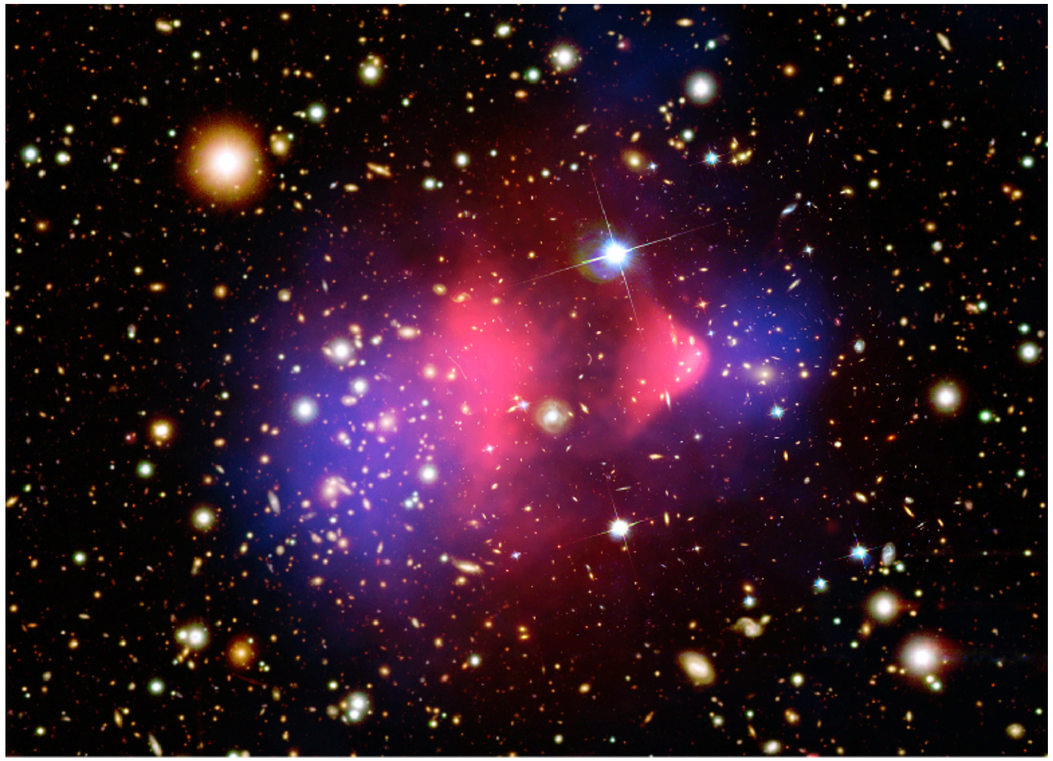
[JHEP 11 (2020) 143]



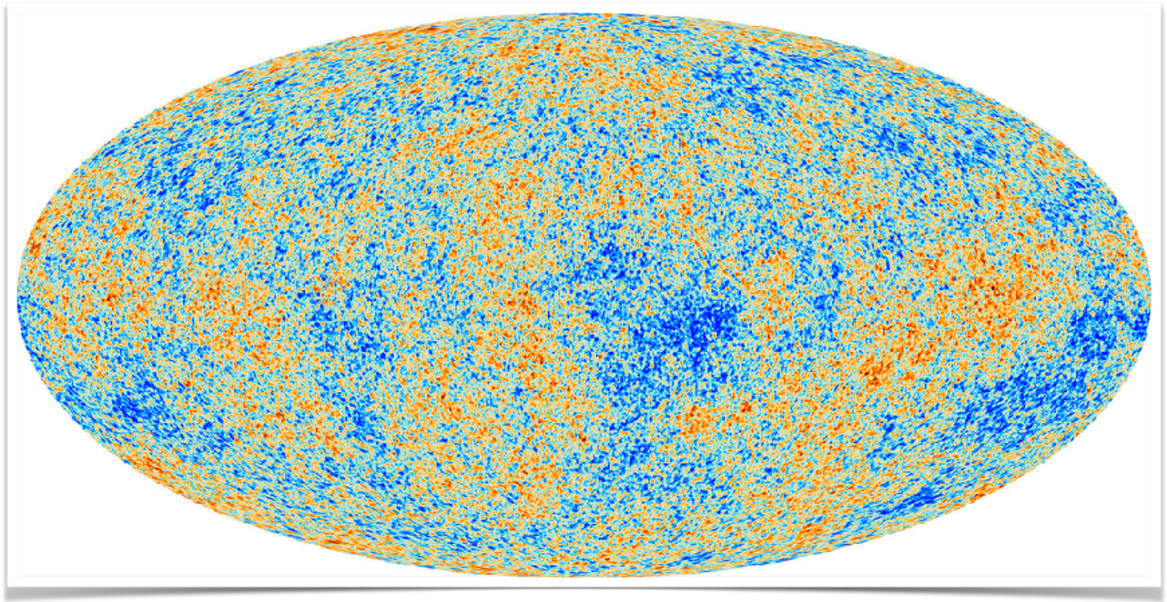
[see for example Phys.Rev.Lett. 125 (2020) 052002]

We have observational evidences of Dark Matter...

[Astrophys. J. 604 (2003) 596–603]



Stars (optics) / Gas (X-rays) / Dark Matter (DM)



[A&A 571 (2014) A12]

Baryonic density $\Omega_b h^2 = 0.0224 \pm 0.0001$

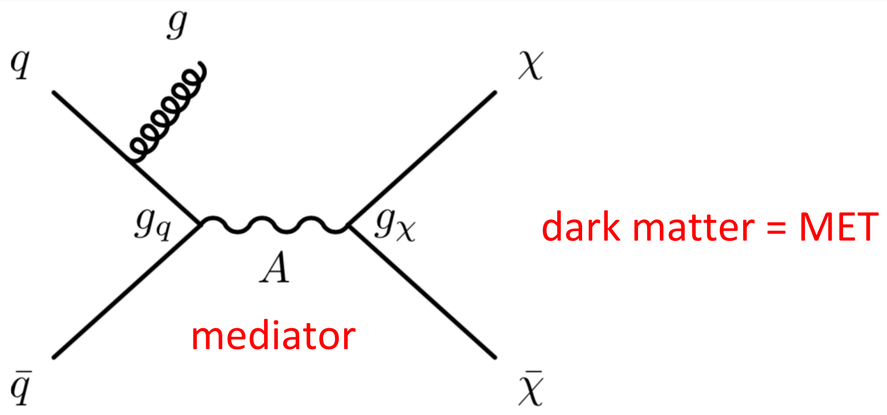
Dark Matter (DM) density $\Omega_c h^2 = 0.120 \pm 0.001$

[A&A 641 (2020 A6]

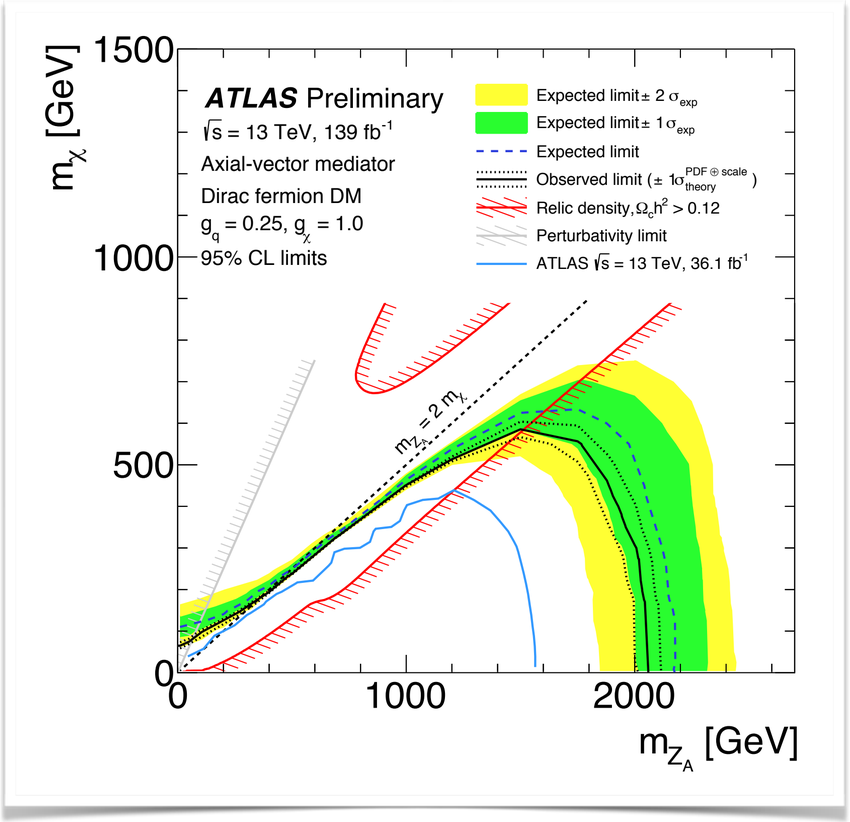
But what is it really? Weakly interactive massive particle(s) (WIMPs)? Something else?

WIMPs are still looked for

DM stable and neutral: missing energy in detectors!



Still no excess: exclusion limit strongly model-dependent



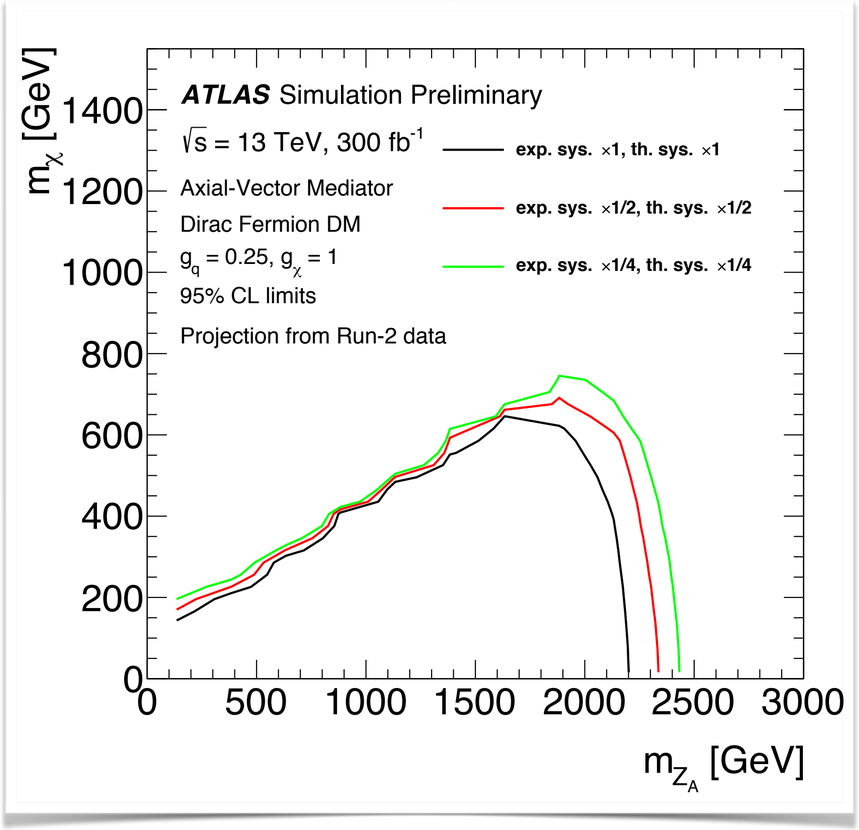
[ATLAS-CONF-2020-048]

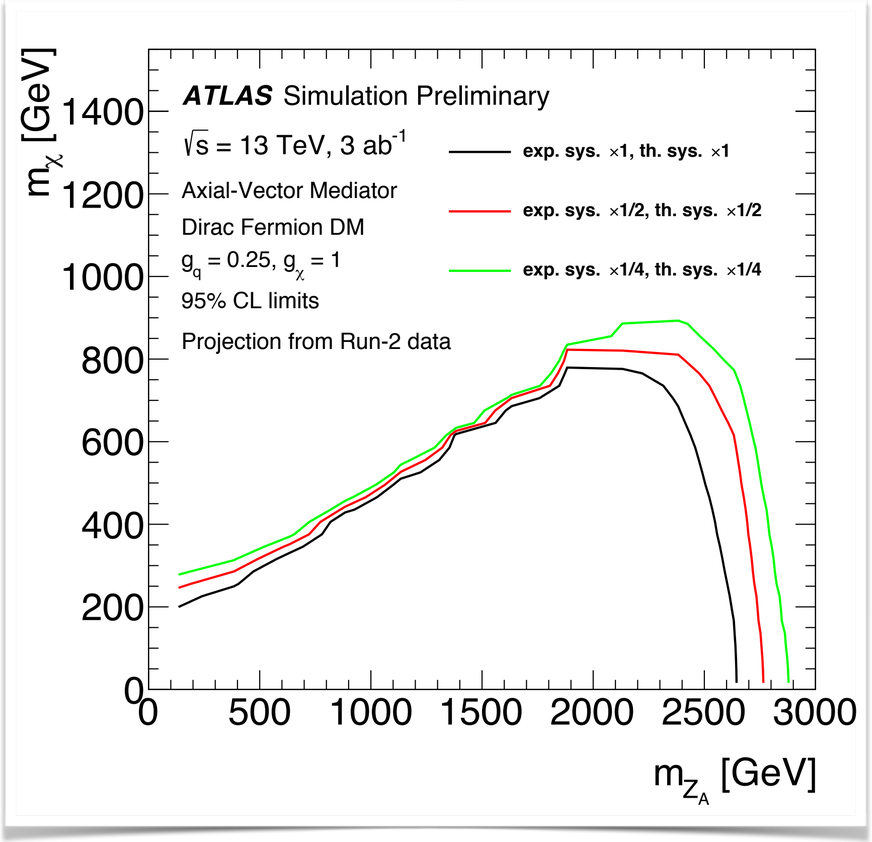
- Mono-X search: X tagging missing energy from DM χ
- Mediator A can be anything (Higgs portal? Gauge portal? Supersymmetric models? Exotic?)

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{2} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} m_{Z_A}^2 Z'_\mu Z'^\mu + \bar{\chi}(i\gamma^\mu \partial_\mu + g_\chi(1+\gamma^5)\gamma^\mu Z'_\mu - m_\chi)\chi + g_q \bar{q}\gamma^\mu Z'_\mu q$$

WIMPs are still looked for

Higher luminosity = more data = higher reach in the tails

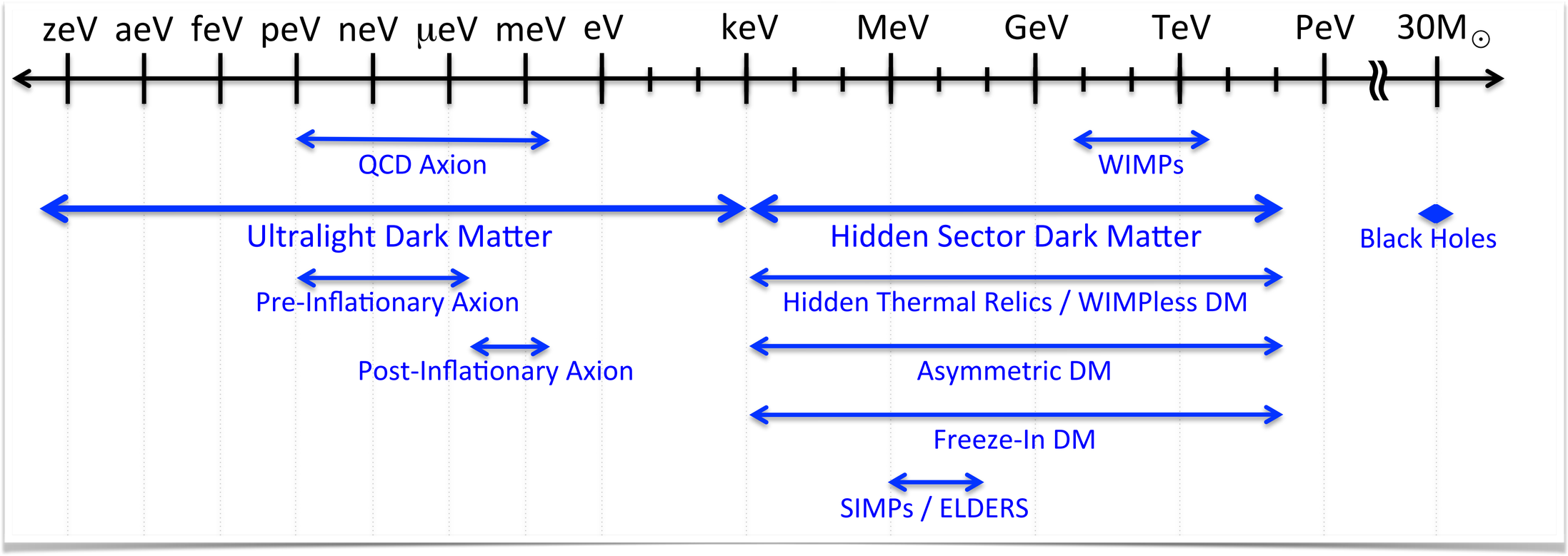




[ATL-PHYS-PUB-2018-043]

Exciting new directions beyond WIMP

Plethora of ideas and models beyond WIMPs: strong interacting massive particles (SIMPs), axions and axion-like particles (ALPs), feebly-interacting (massive) particles (FI(M)Ps), etc.



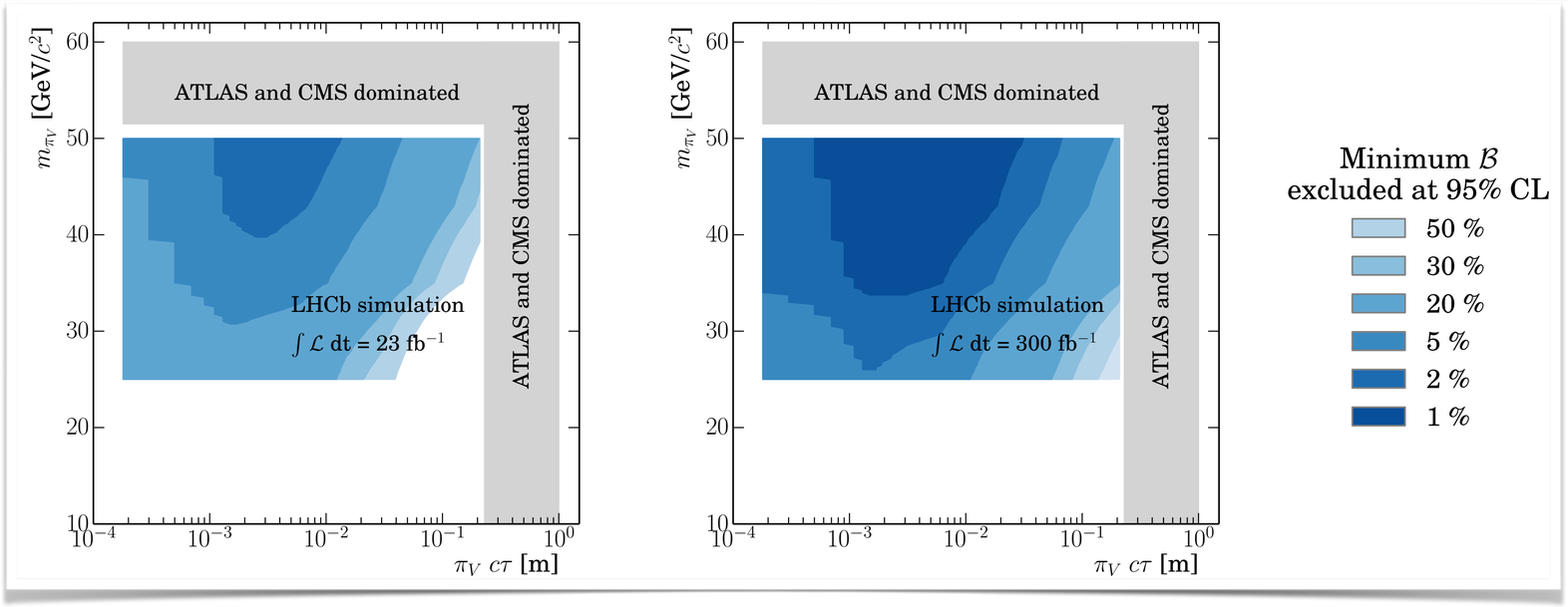
[arXiv:1707.04591]

Exciting new directions beyond WIMP

Plethora of ideas and models beyond WIMPs: strong interacting massive particles (SIMPs), axions and axion-like particles (ALPs), feebly-interacting massive particles (FIMPs), etc.

Most are long-lived particles (LLPs): small couplings, or very heavy mediator, or very small mass difference with the mediator ⇒ **look for disappearing tracks or displaced vertices**

Exemple with LHCb searches for hidden-valley pions π_v, via $H \to \pi_v\pi_v$, $\pi_v \to$ hadrons:



[arXiv:1808.08865]

[see also Phys.Rev. D97 (2018) 095033]

Outlook

We have a bright future ahead!

- **Precision measurements**: Rich program with lots of room for **new physics** here
- **Electroweak symmetry breaking mechanism**: HL-LHC will allow for probing a crucial part of the SM still un-tested yet!
- **The nature of Dark Matter**: Lots of new results to come, will explore new corners in the theory space beyond the WIMP paradigm

Thanks for your attention!