Stress-testing the Standard Model at ATLAS: a theorist viewpoint

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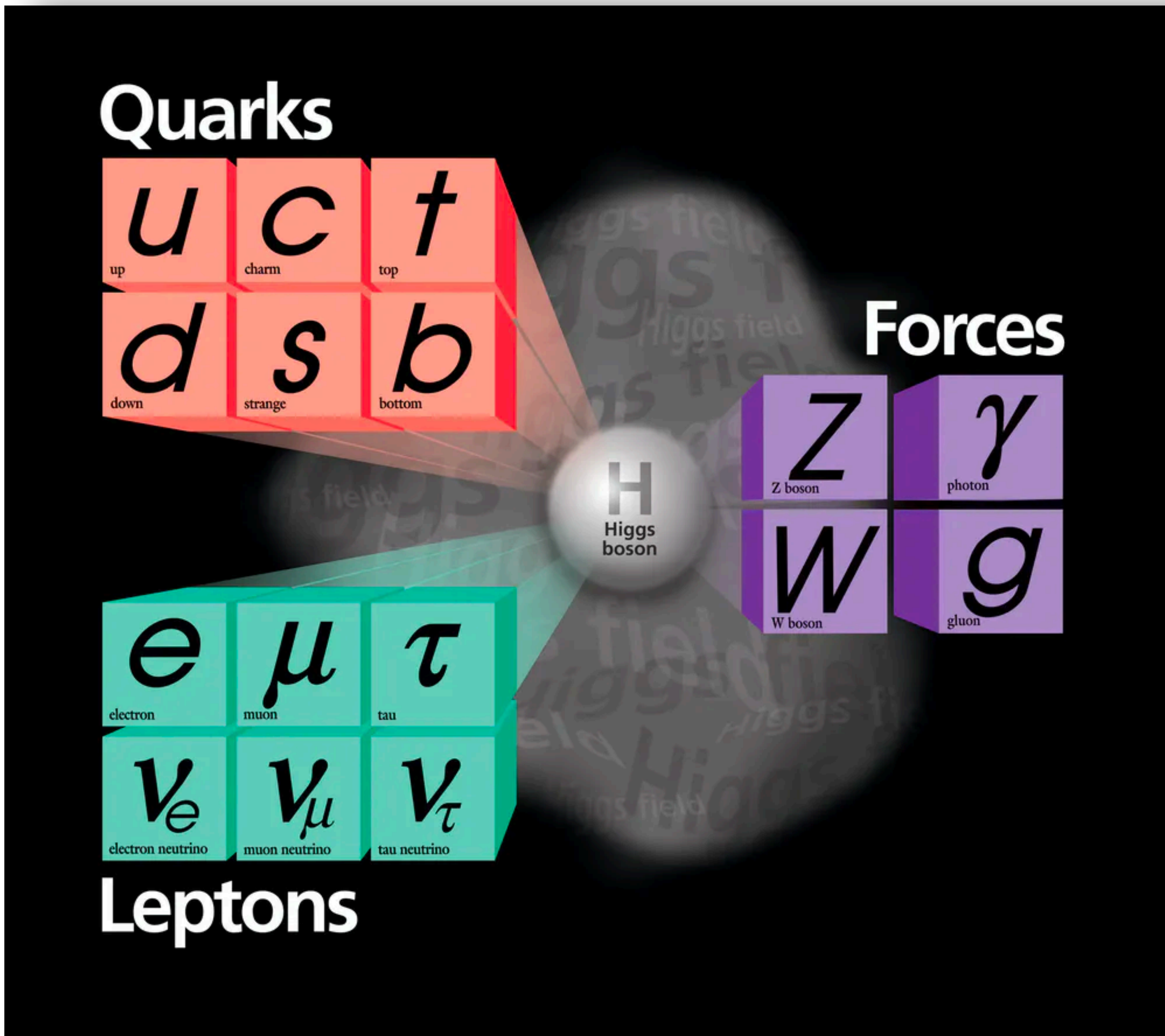
Nikhef Topical Lectures:
Physics at the LHC
Amsterdam, 5th June 2023

The Standard Model at the cross-roads

The Standard Model

Standard Model of particle physics: hugely succesful, powerful framework describing **elementary particles** and their **interactions**



matter particles

- 6 quarks *(fractional charge)*
- 3 charged leptons (*e.g. electron*)
- 3 neutrinos *(only weak charge)*
- Organised in **3 generations:** identical (?) except for mass

force carriers

- photon (*electromagnetism*)
- gluon (*strong nuclear force*)
- weak bosons (*weak nuclear force*)

Higgs boson

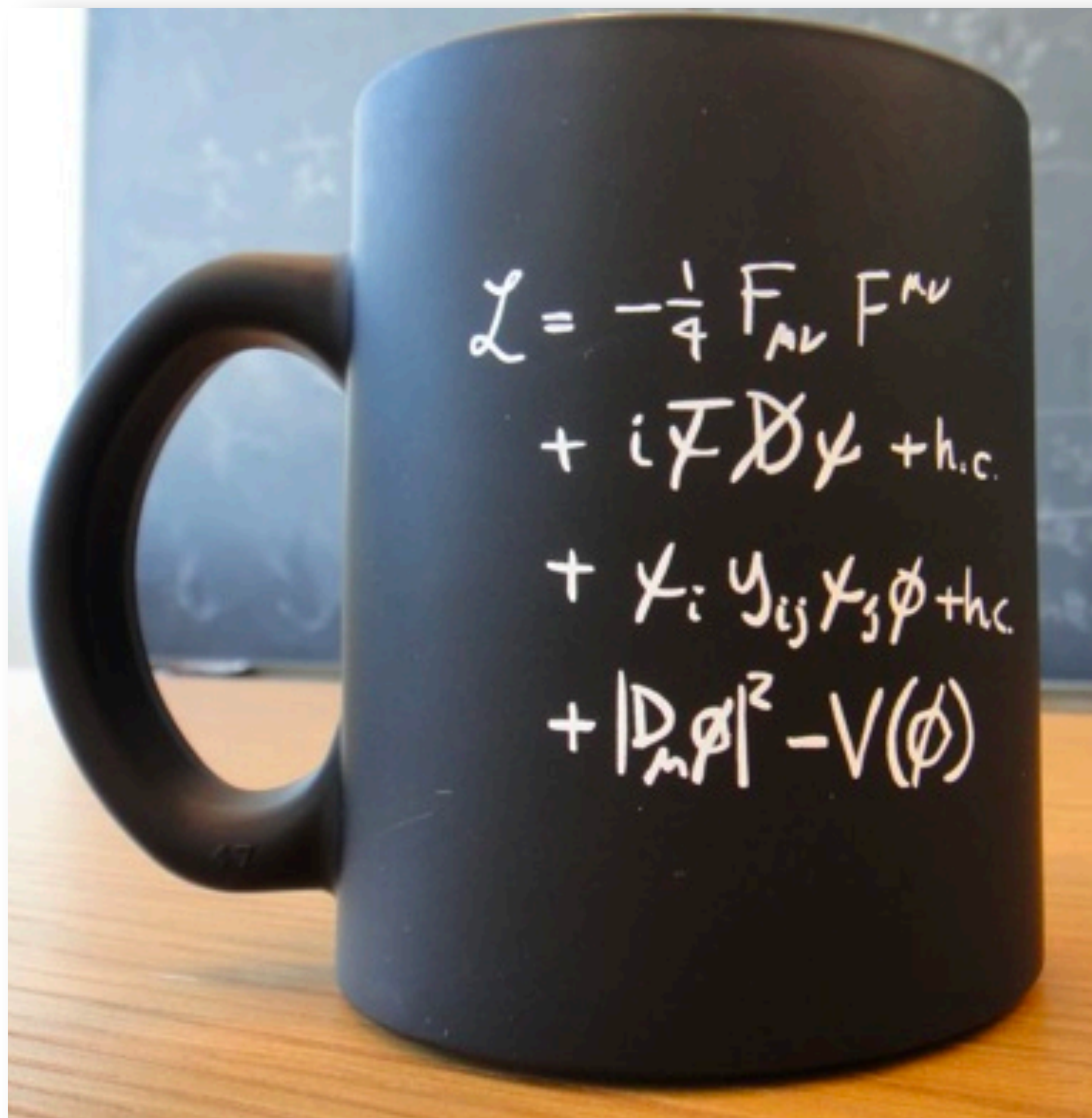
both matter particle and force carrier

The (incomplete) Standard Model

Standard Model of particle physics: hugely succesful, but leaves many foundational questions unanswered

Origin of particle masses and Higgs force?

Where is all the missing Antimatter?



What is Dark Matter?

Quantum Gravity? Inflation?

requires new particles and interactions beyond the Standard Model

Higgs Discovery

The Higgs boson is nowadays textbook material, but before its discovery in 2012 **its existence was far from obvious**

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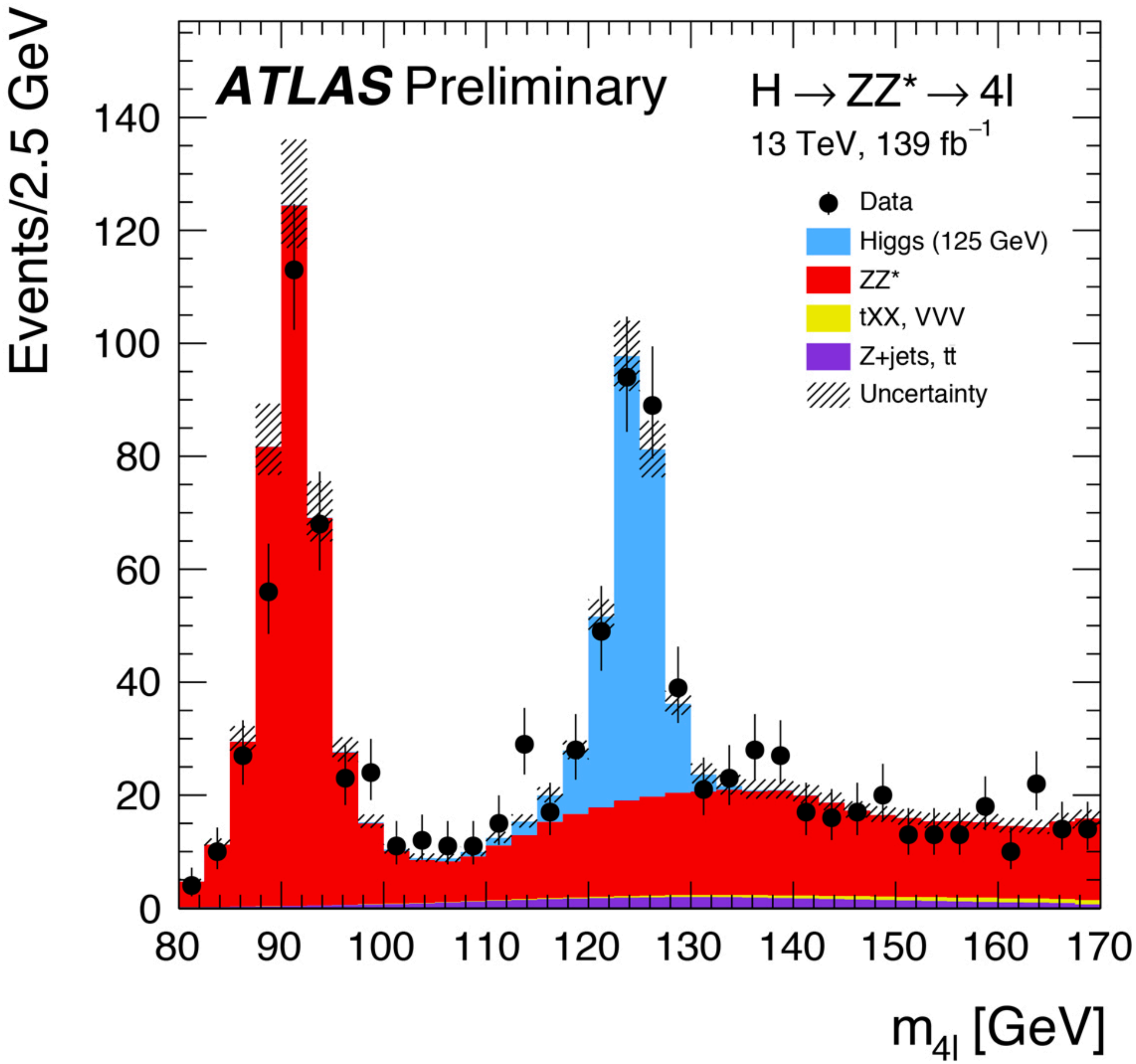
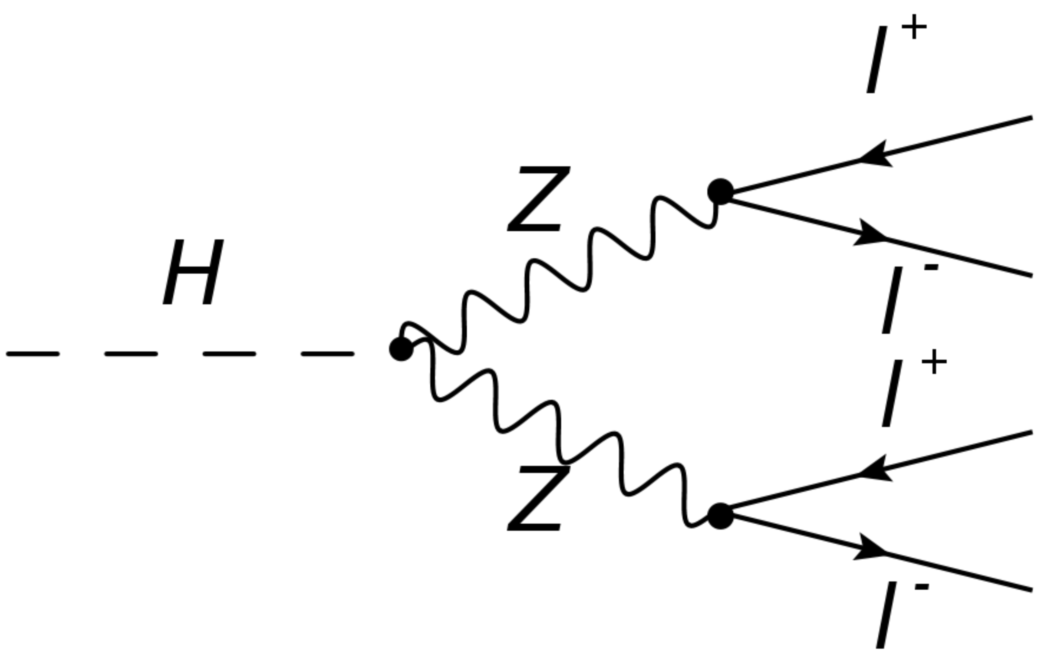




extremely clean signal in the four-lepton golden channel (background-free)

still a lot we don't know about the Higgs!

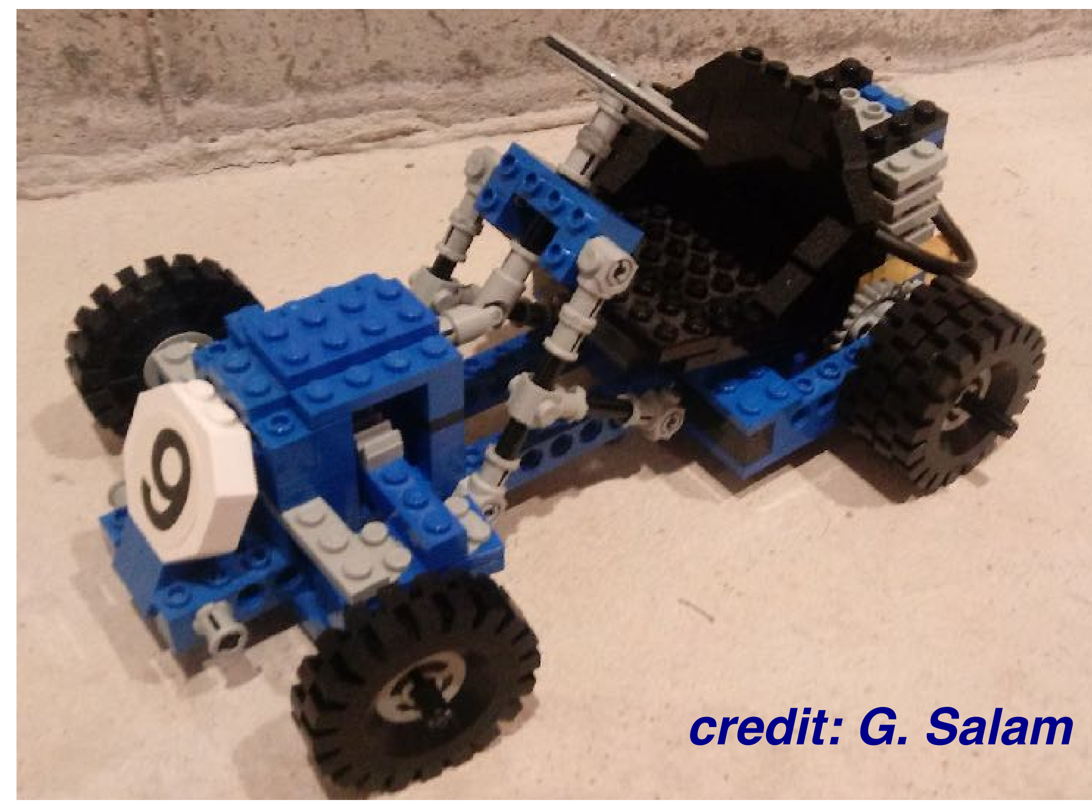
Fingerprinting the Higgs

The fact that we have observed **all SM particles** does not mean that we are done: **we still need to discover & validate** many of the **SM interactions!**

particles

https://www.piqsels.com/en/public-domain-photo-fqrgz

particles + interactions



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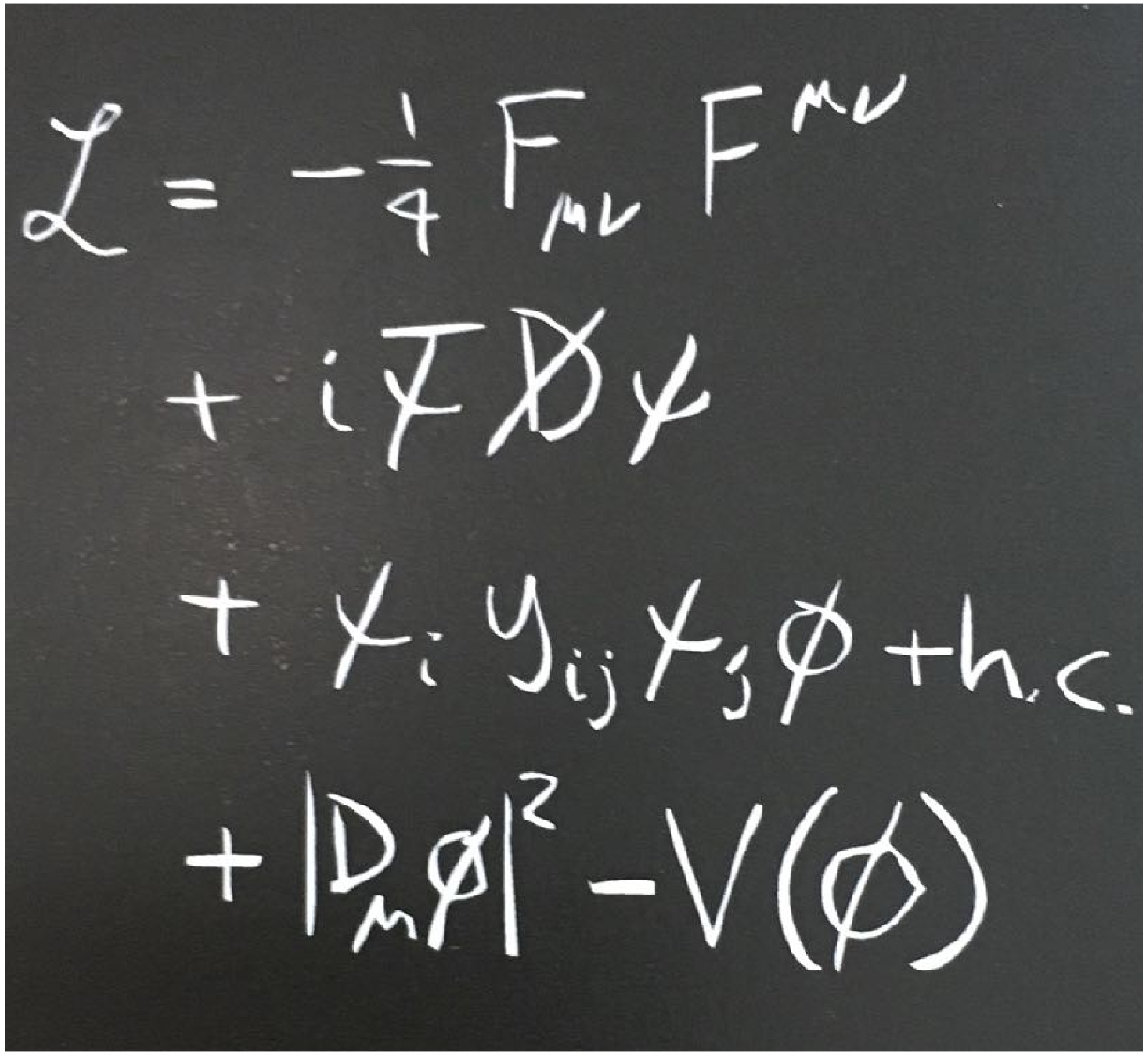
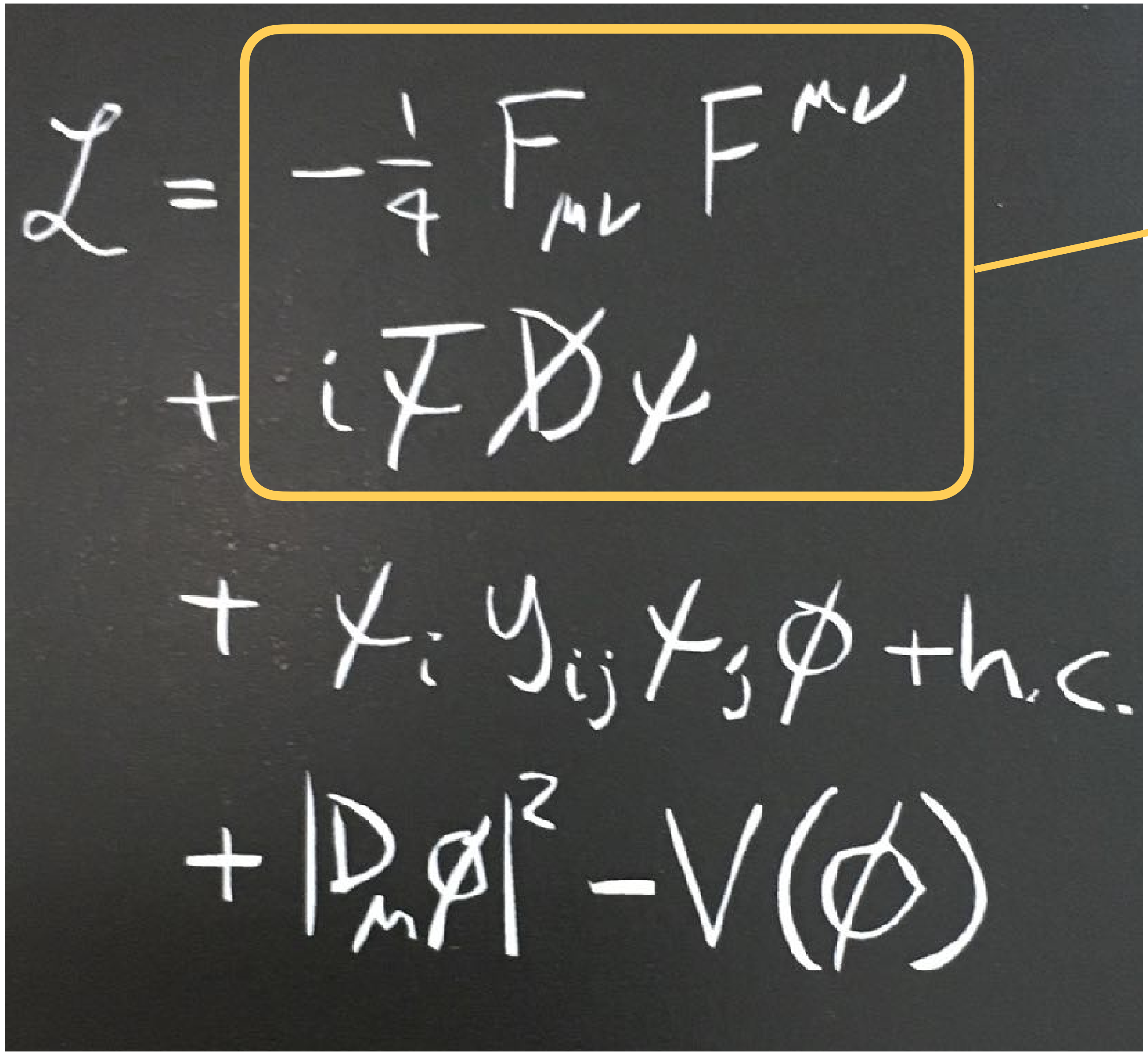
Fingerprinting the Higgs



credit: G. Salam

Fingerprinting the Higgs



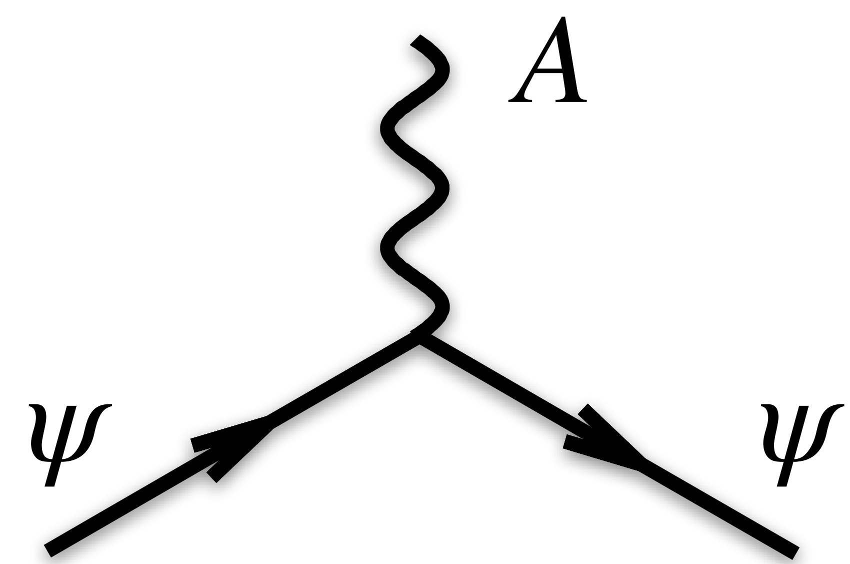
credit: G. Salam

Gauge sector:

Electromagnetism, QED,

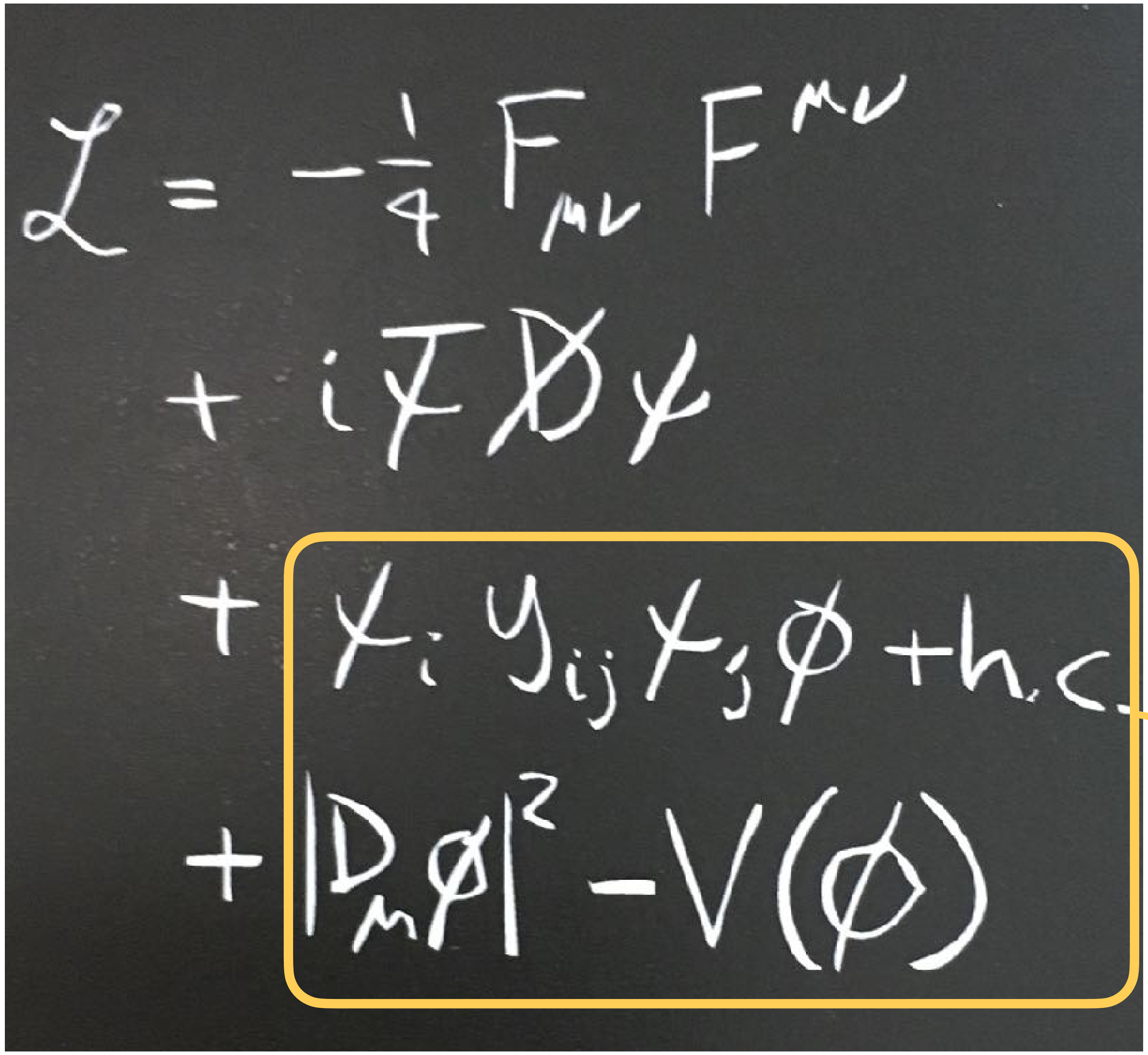
weak interactions

well understood, high-precision tests
(e.g. anomalous magnetic moment electron)



basic ideas already present in
Maxwell's electromagnetism

Fingerprinting the Higgs



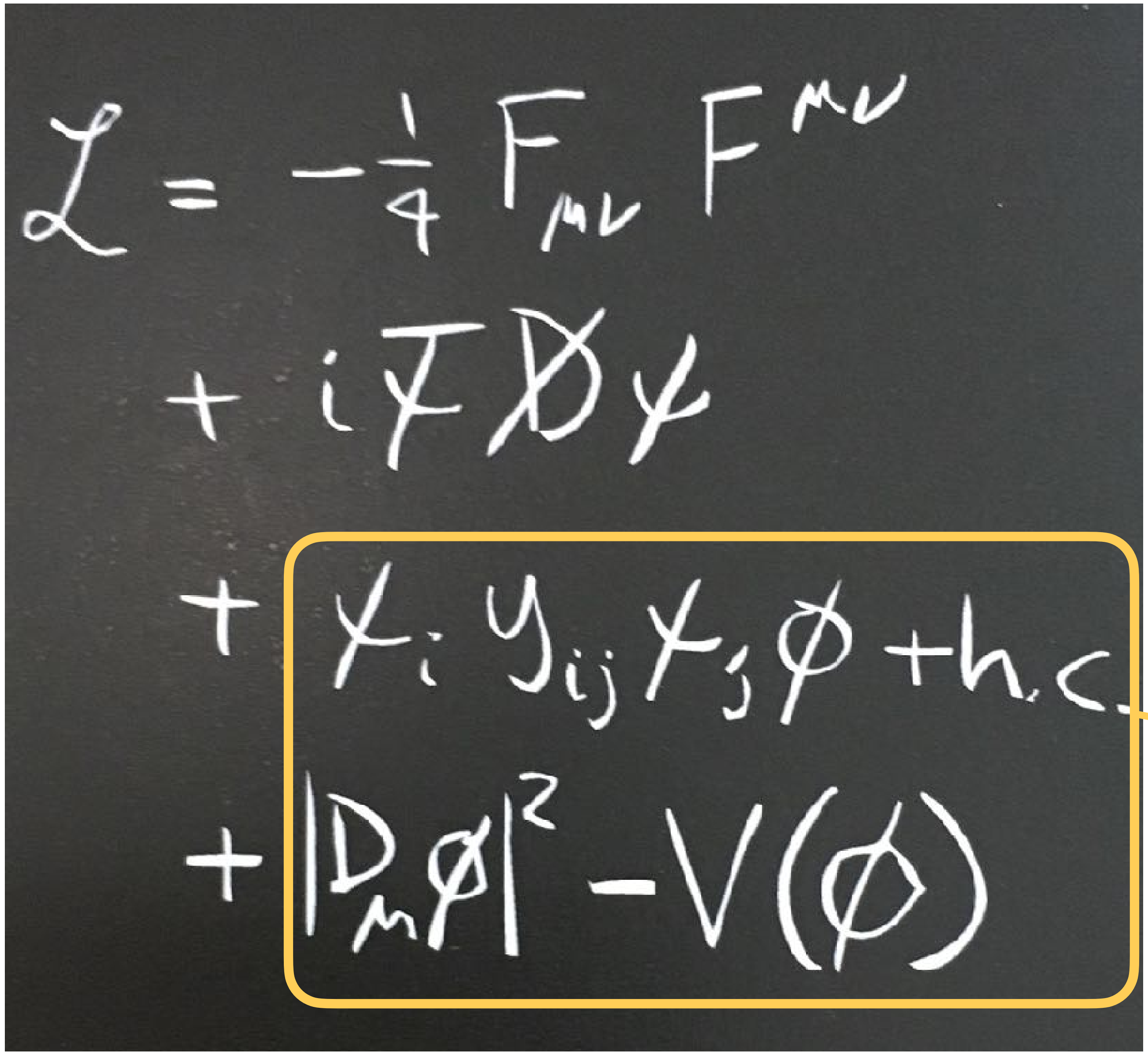
credit: G. Salam

Higgs sector & Yukawa interactions: became available with Higgs discovery

the majority of free parameters in the SM appear in the Yukawa sector

- Initial constraints on **second-generation couplings**
- **First-generation** Yukawa forces never probed
- Limited information on **Higgs self-interactions**

Fingerprinting the Higgs



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Nature

Yukawa forces are unique: first fundamental quantum interaction where **interaction strength is not quantised**

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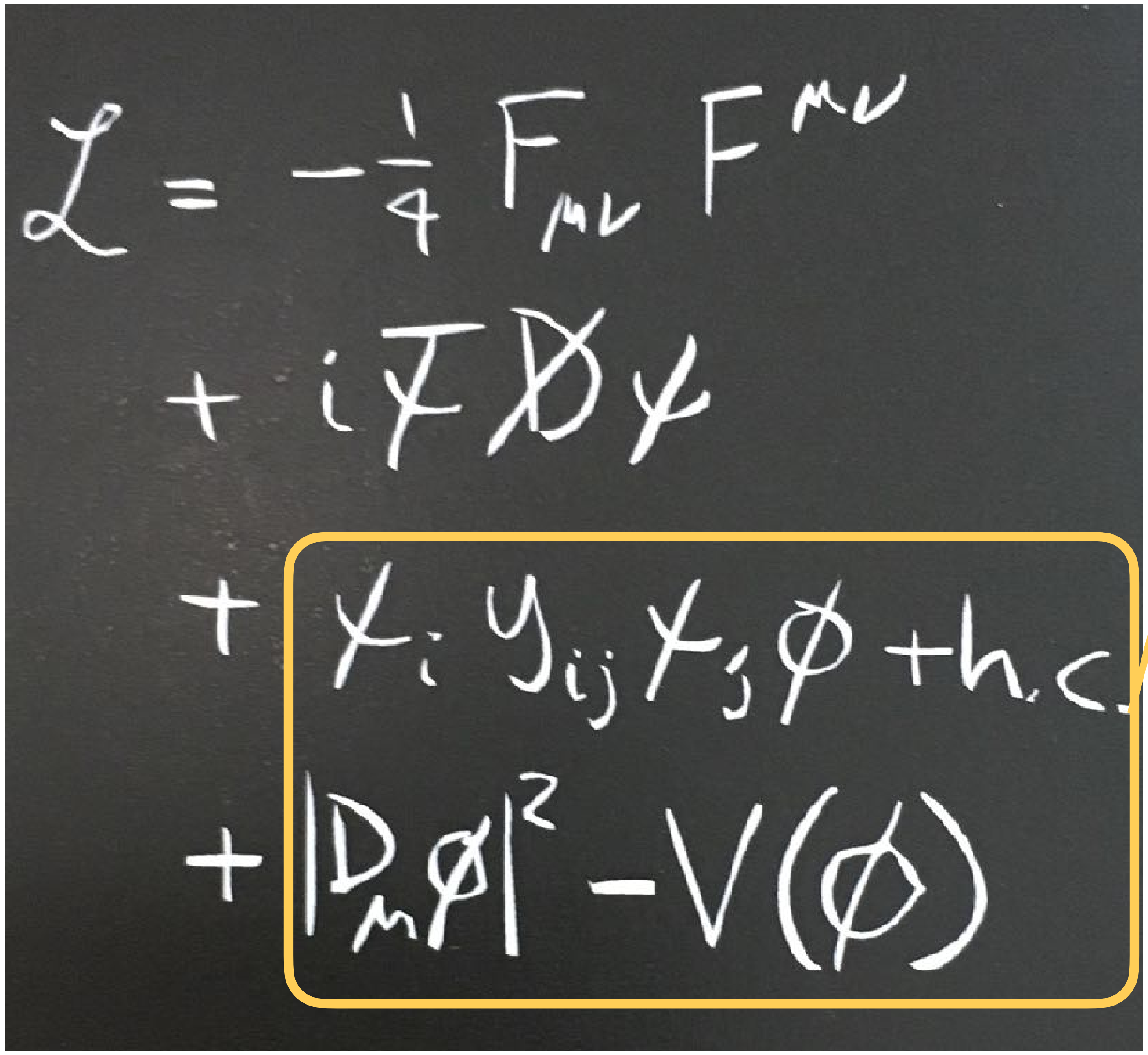
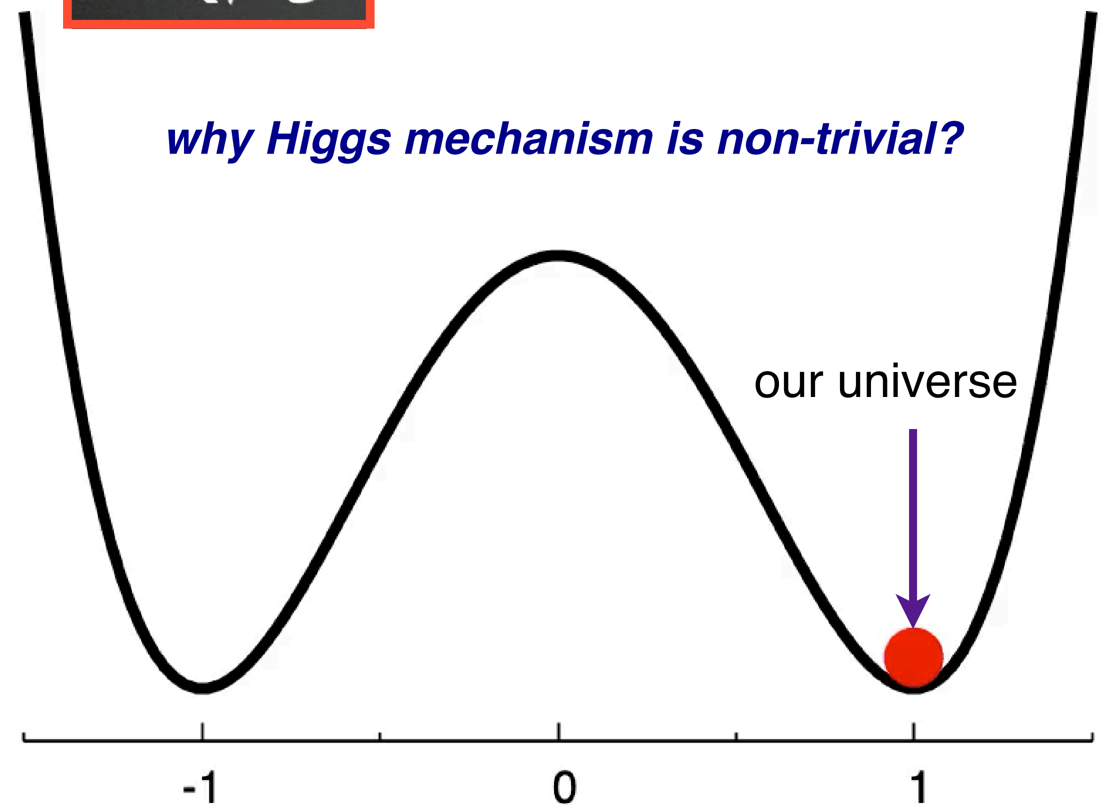
Fingerprinting the Higgs

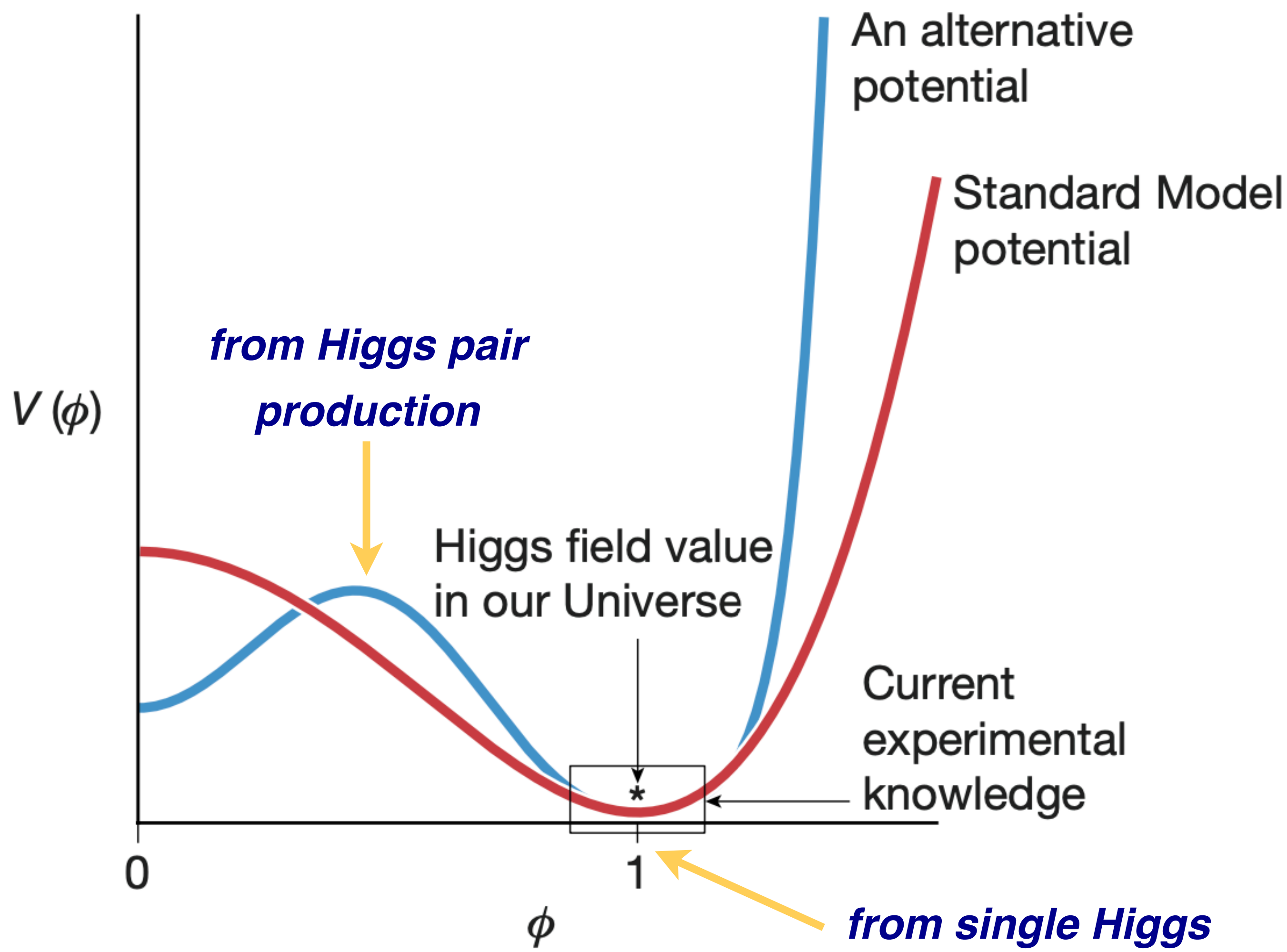


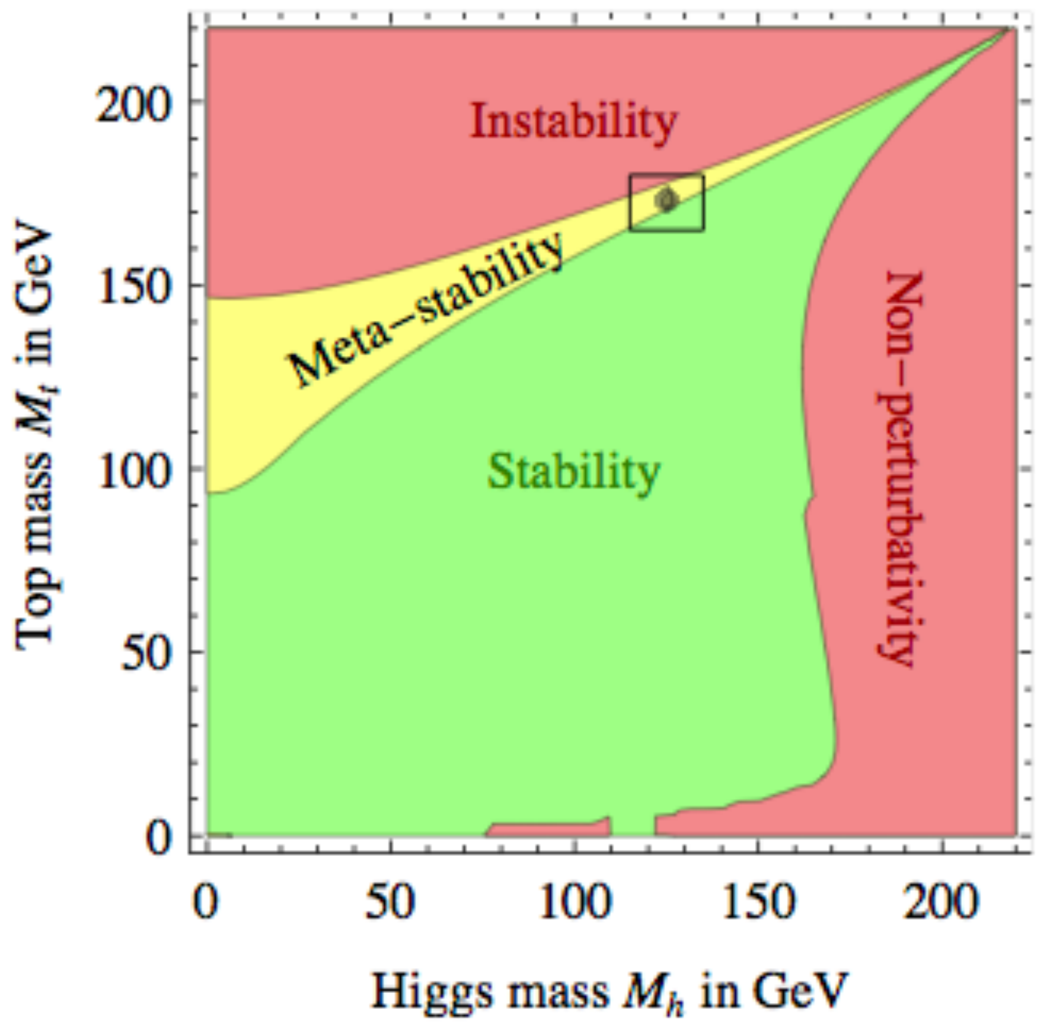
$$\boxed{V(\phi)} = -\mu^2\phi^2 + \lambda\phi^4$$



- Only know **elementary scalar particle**
- A **field permitting all space** and spontaneously breaking EW symmetry
- Different interactions of this field with **each of the matter particles**

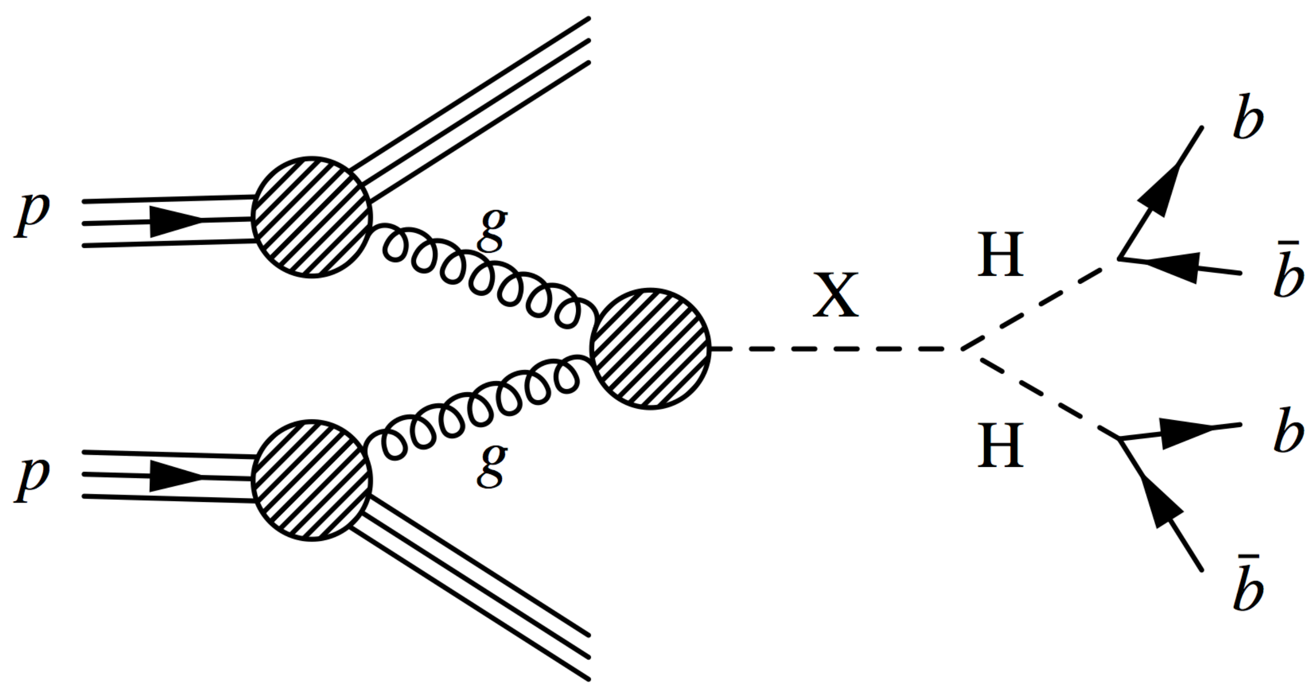
The Higgs potential





- Single Higgs measurements can only probe **local potential close to minimum**
- Alternative potentials would have dramatic implications for **cosmology, baryon asymmetry, stability the Universe**
- Can be probed directly with **Higgs pair production**

(also from single Higgs via quantum corrections)



Towards a New Standard Model

conceptual limitations & unexplained particle physics / astronomical / cosmological data

theory bottlenecks

- Why 3 generations? Universality?
- Origin of particle masses, couplings, electroweak scale?
- Higgs mechanism elementary?
- Stability of Universe's vacuum?
- Quantum gravity?

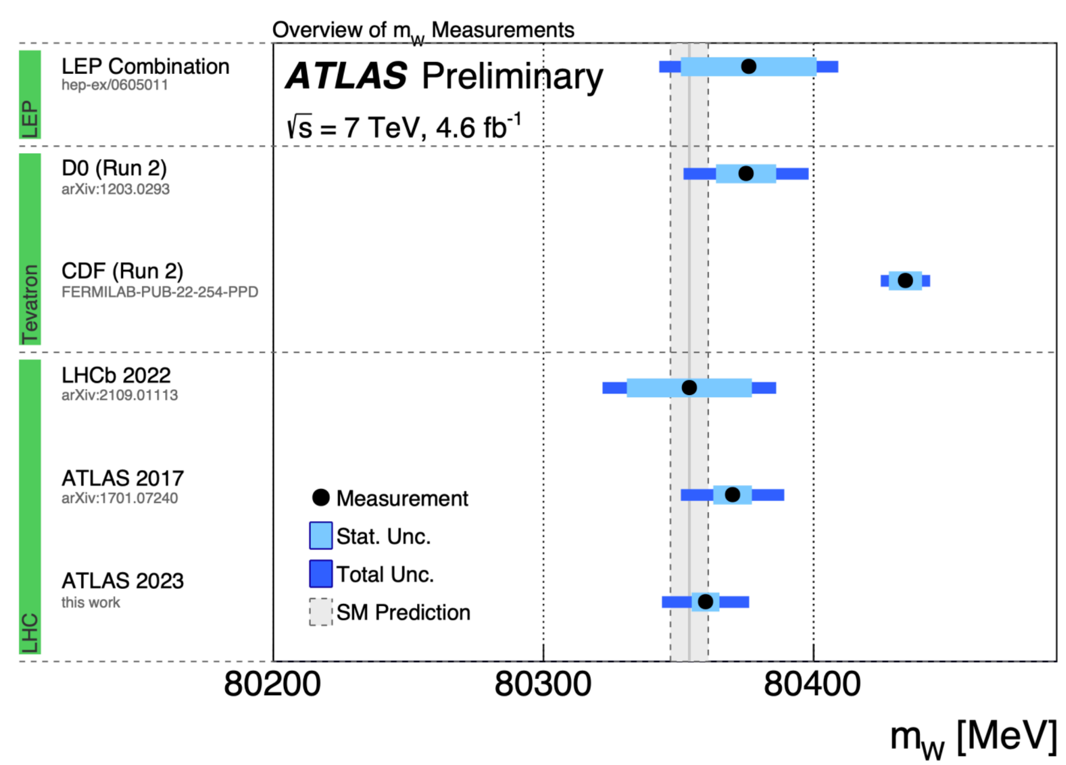
HEP anomalies

- Lepton-flavour universality?
- Muon anomalous magnetic moment?
- *W*-mass?

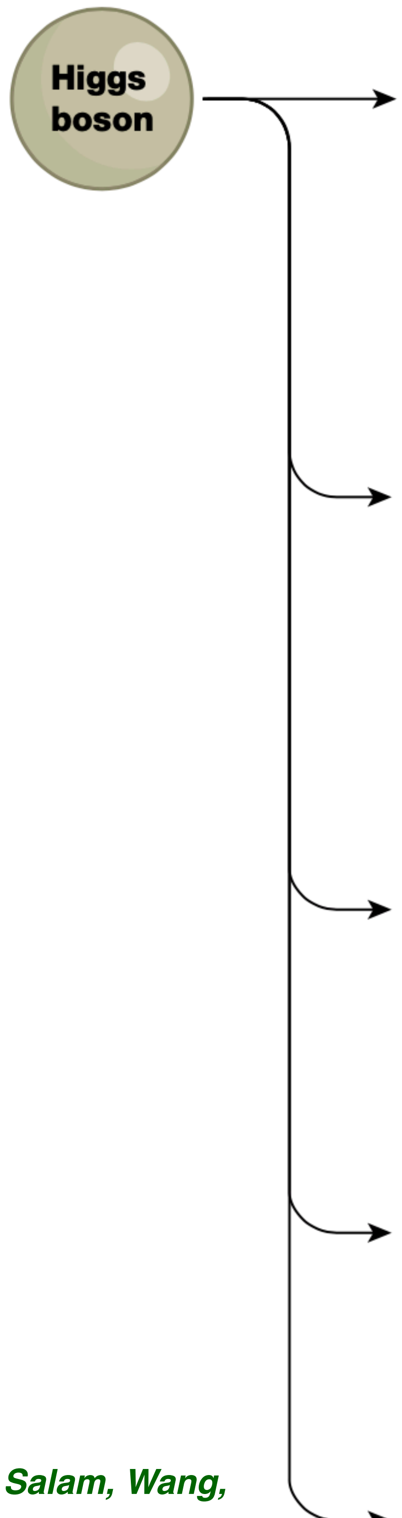
astro/cosmo conundrums

- (Particle) Dark Matter?
- Matter-antimatter asymmetry?
- Inflation?
- Strong gravity, deviations from general relativity?

demands multi-pronged, diverse, **theory & experimental programs** to pin down the features of the **new Standard Model**



Higgs as a probe and portal for New Physics



Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the W and Z bosons?

Why is there more matter than antimatter in the Universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?

What is dark matter?

- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

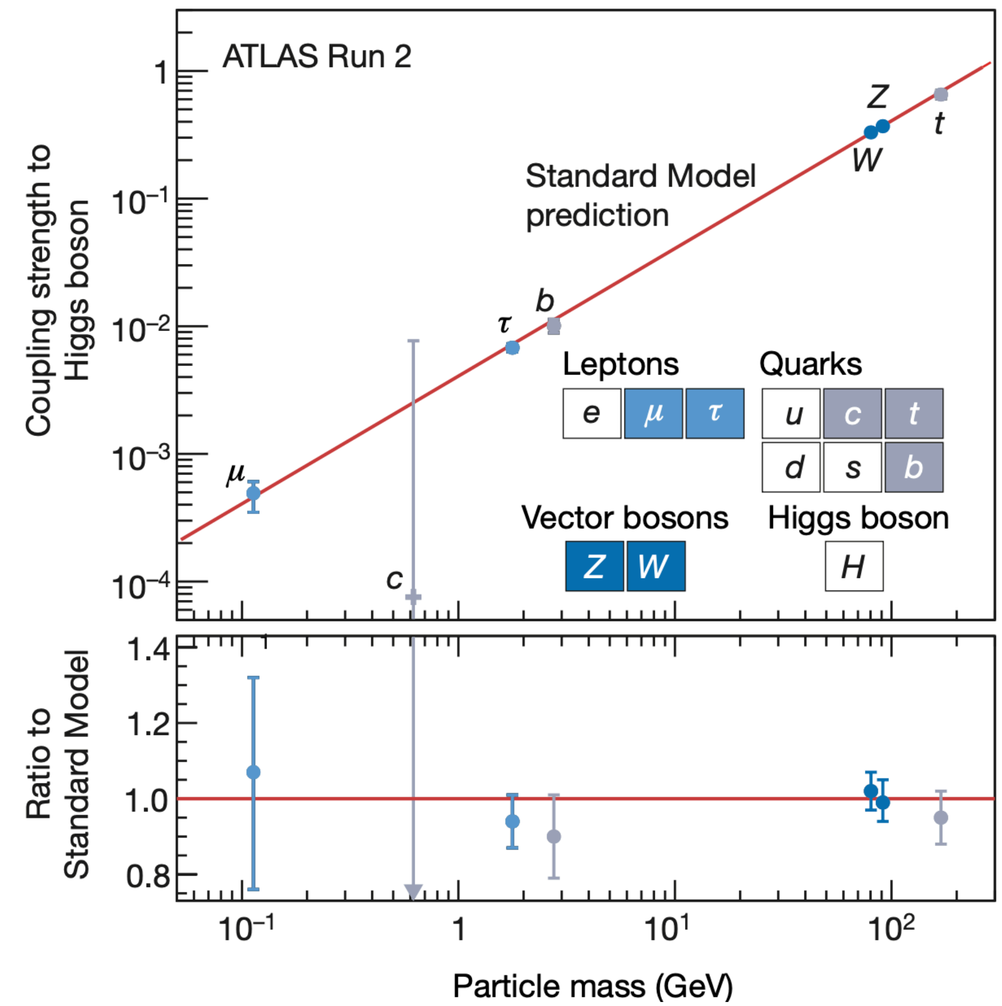
What is the origin of the vast range of quark and lepton masses in the Standard Model?

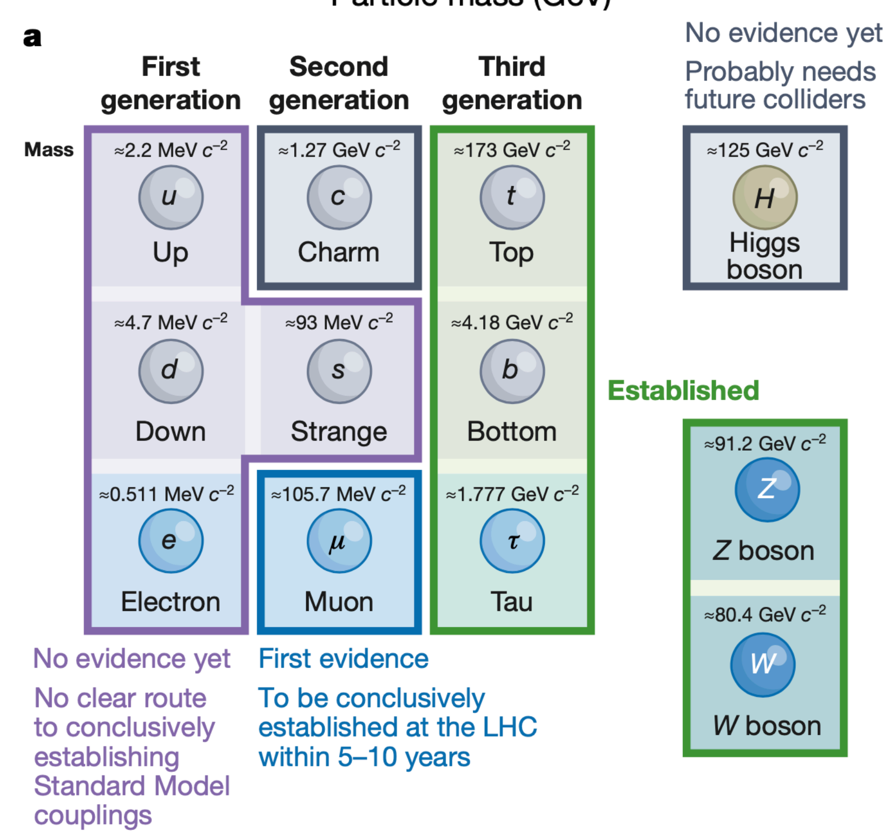
- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \to \mu^+\tau^-$)?

What is the origin of the early Universe inflation?

- Any imprint in cosmological observations?

Salam, Wang, Zanderighi, Nature 2022



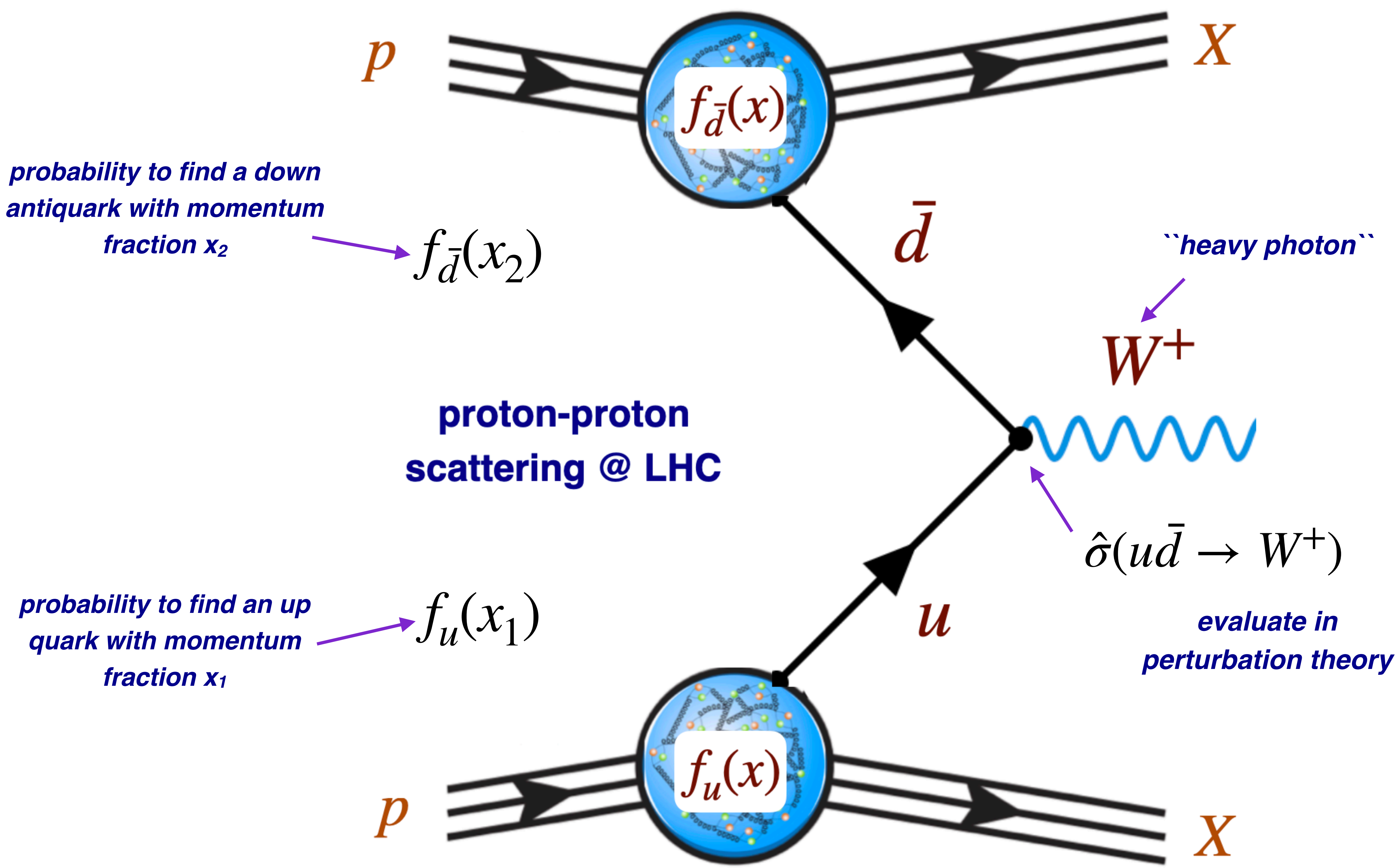


Key ATLAS physics targets

Proton structure constraints

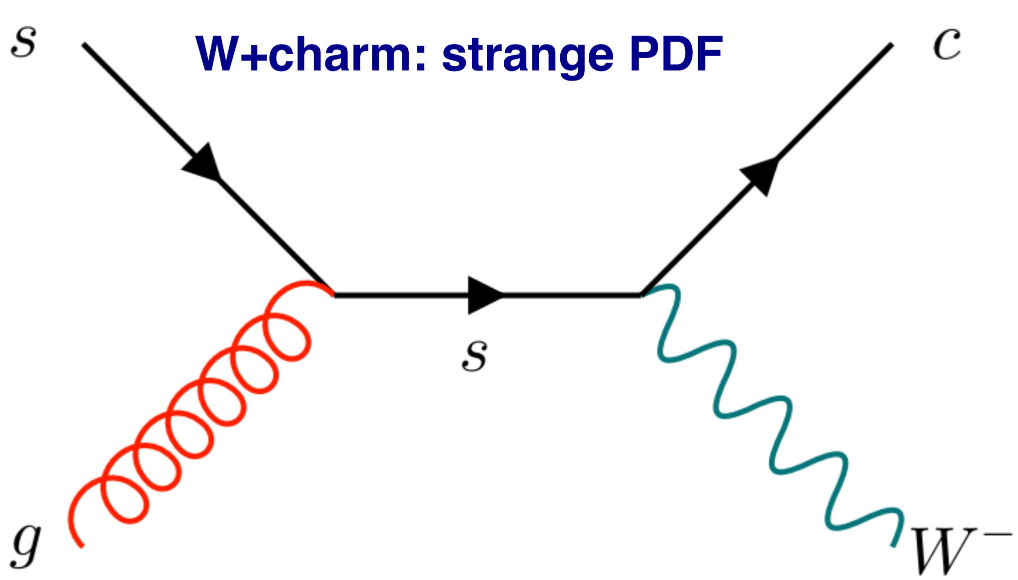
probability of producing a W+ boson

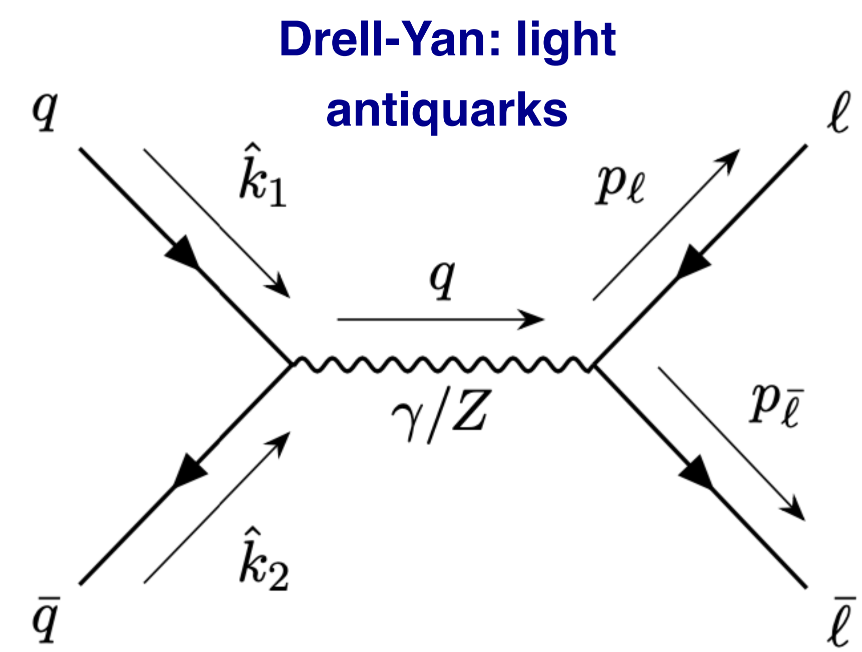
$$\sigma(pp \to W^+) \propto f_u(x_1) \otimes f_{\bar{d}}(x_2) \otimes \hat{\sigma}(u\bar{d} \to W^+)$$

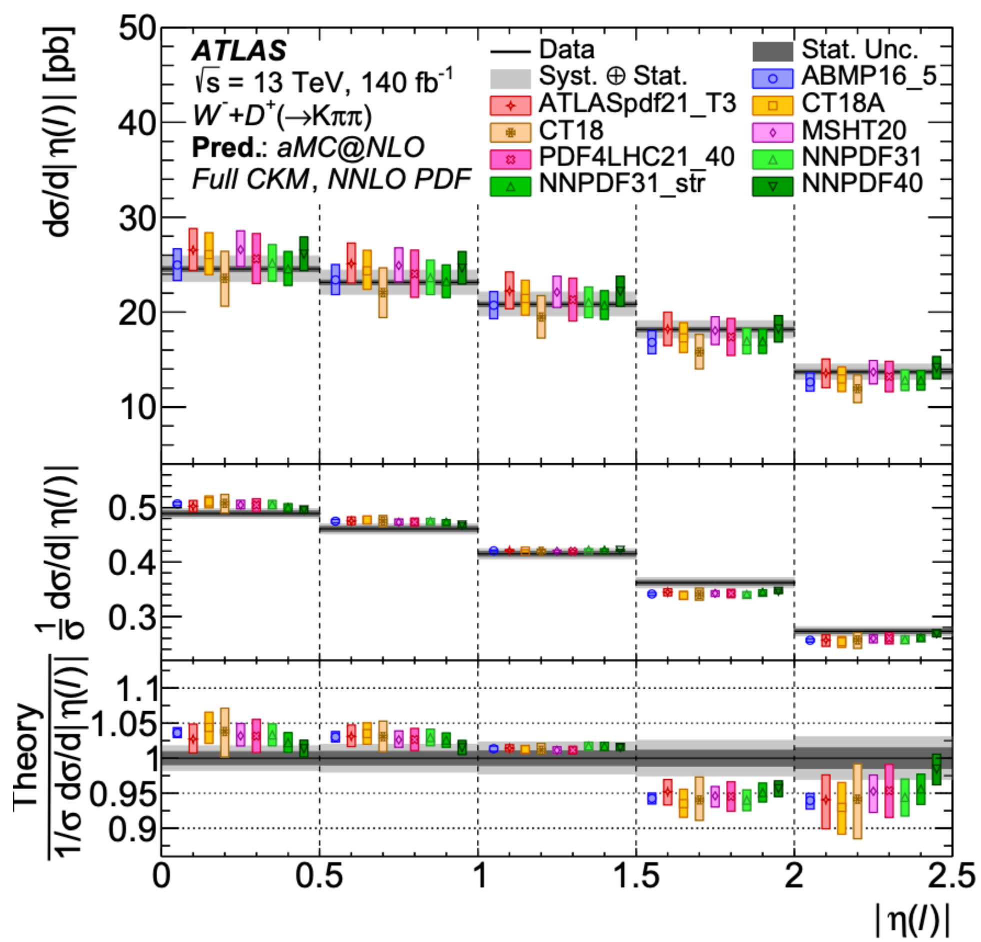


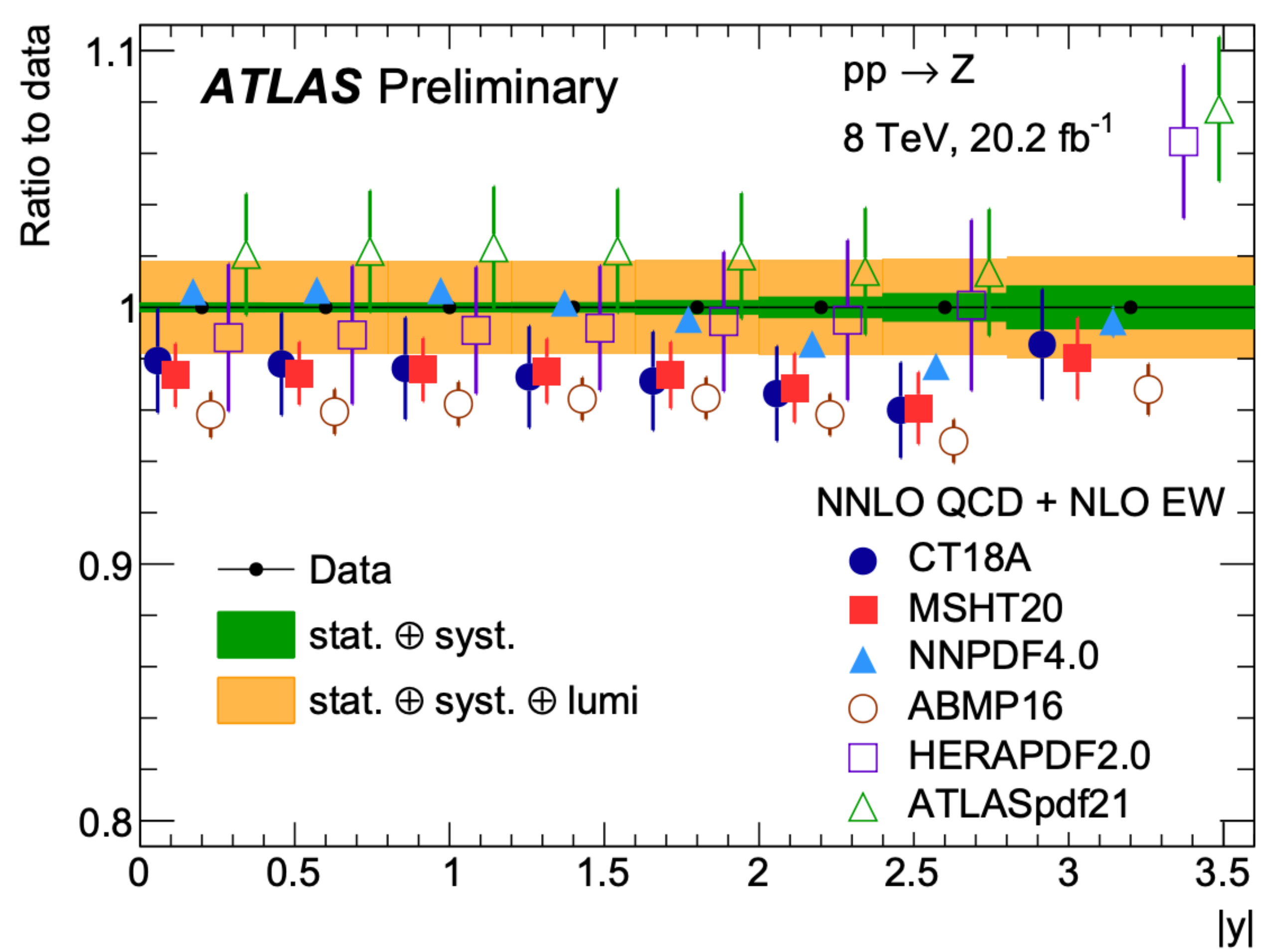
Proton structure constraints

ATLAS measurements enable improved modelling of **proton substructure**







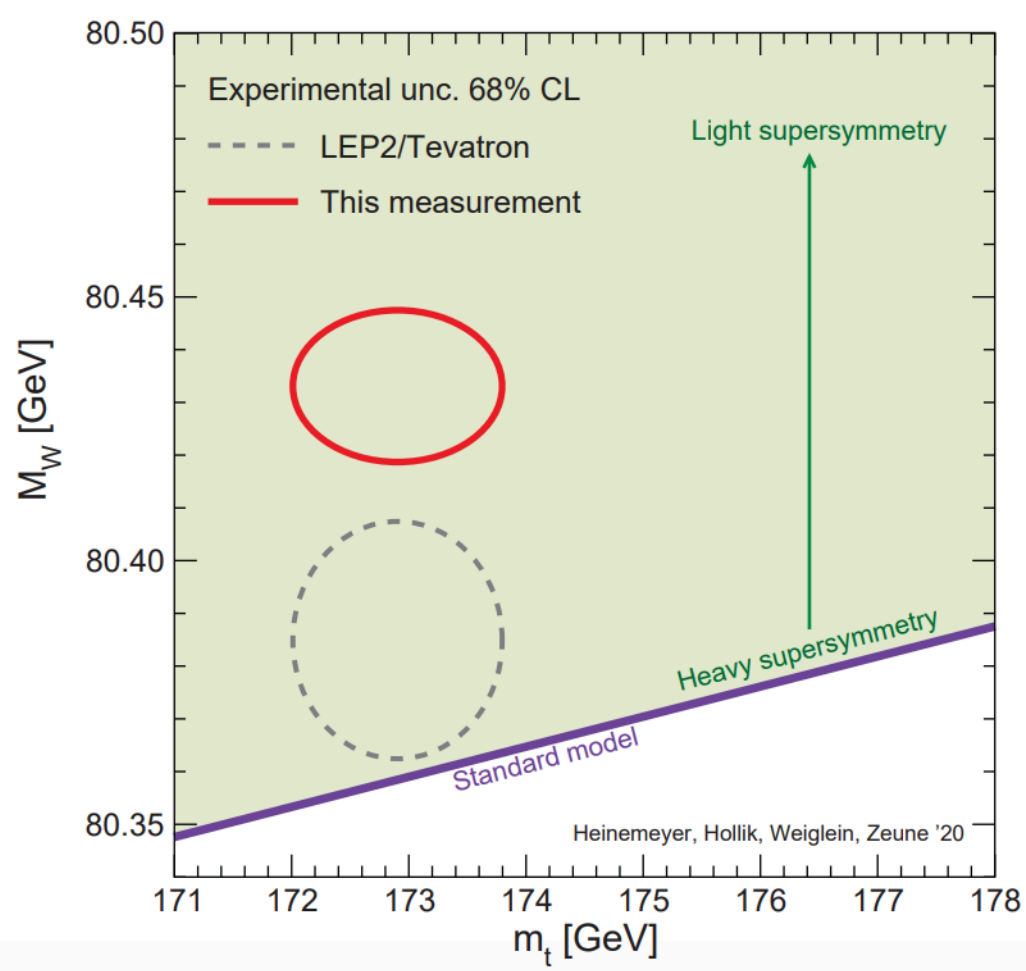


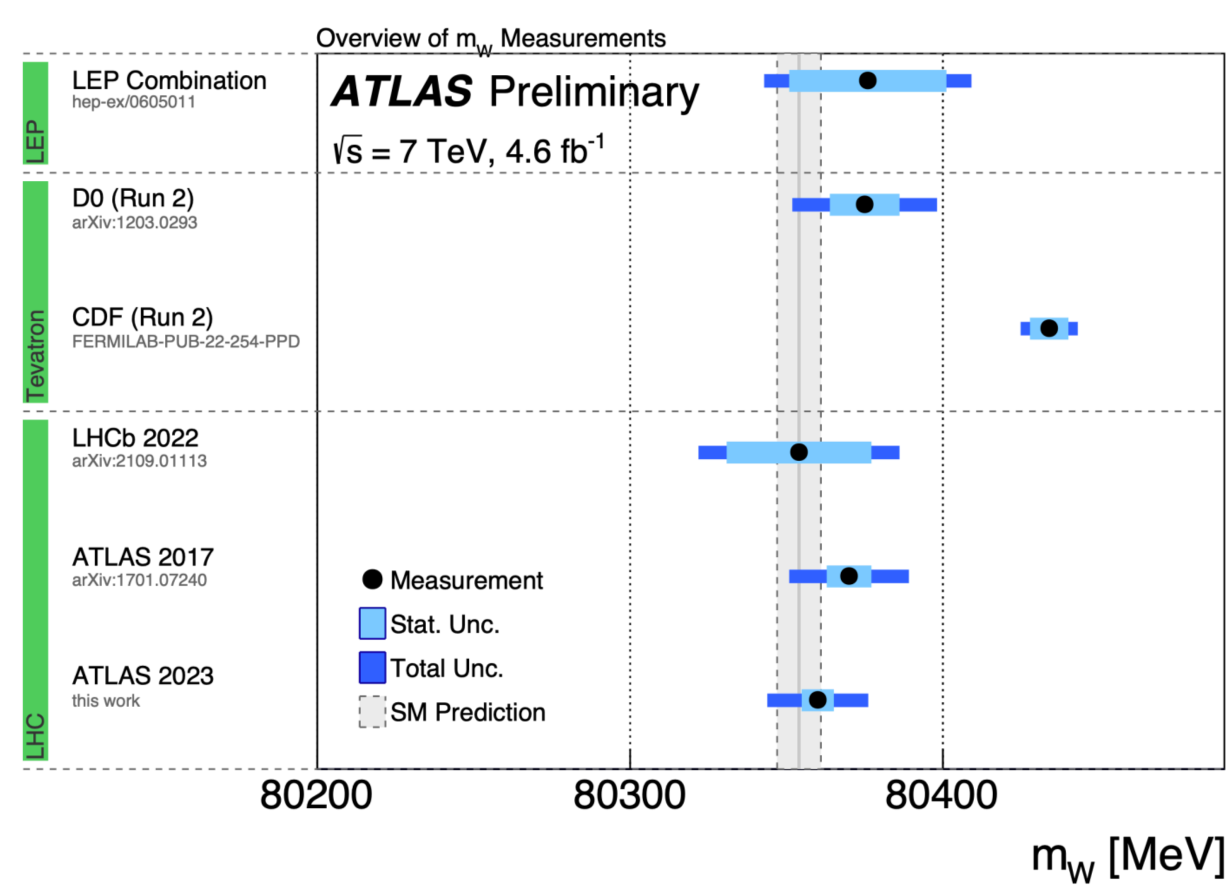
Precision determination of SM parameters

The SM contains **18 free parameters** which have to be constrained by experimental data. ATLAS can provide stringent constraints for many of them

W mass

- Hadron colliders outperform LEP due to unprecedented statistics
- Challenging measurement, requires controlling **shape of distributions** (template fits) at **per-mille level**
- Tension between ATLAS (favour SM) and CDF measurements (favours supersymmetry)



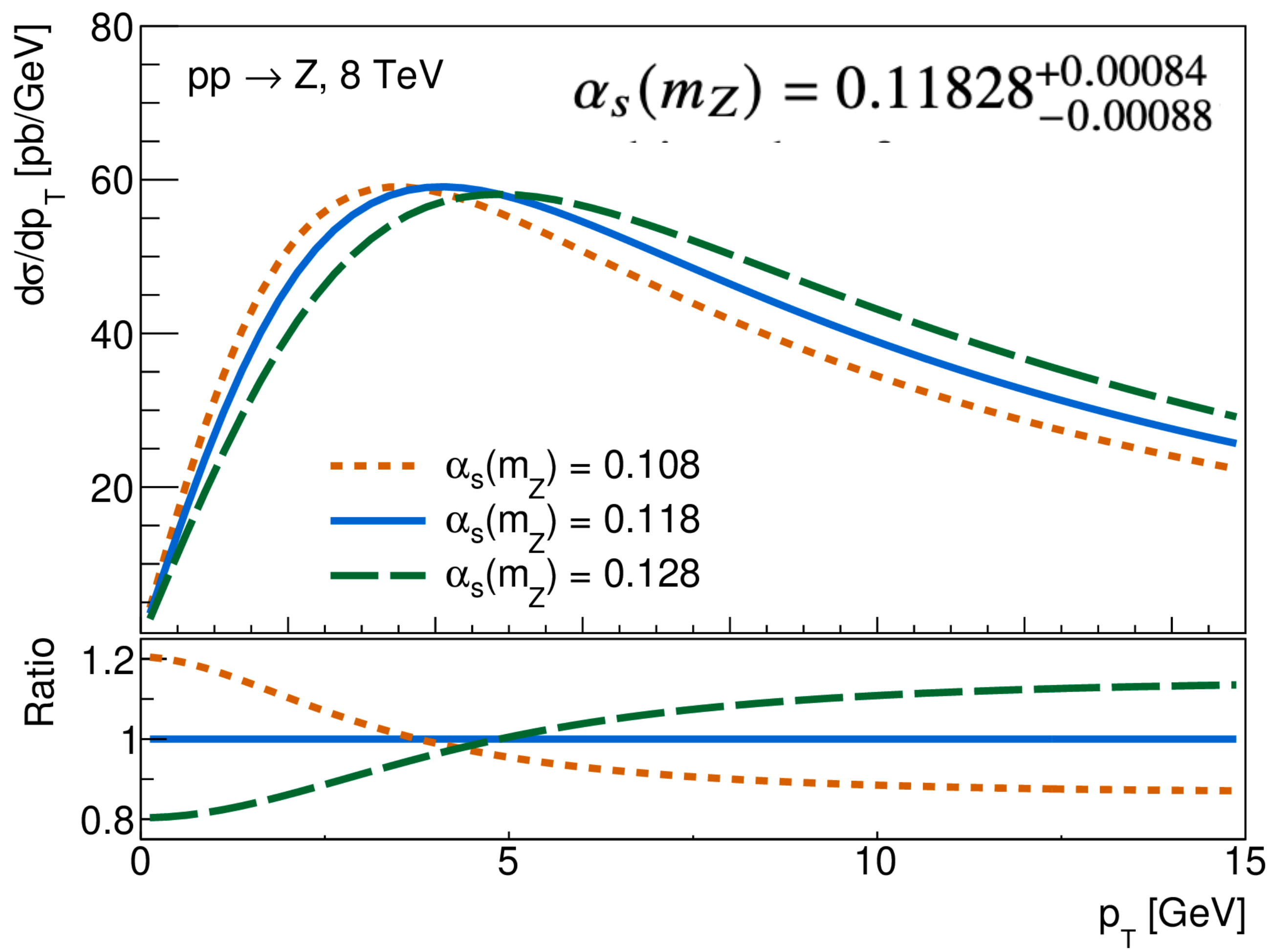


Precision determination of SM parameters

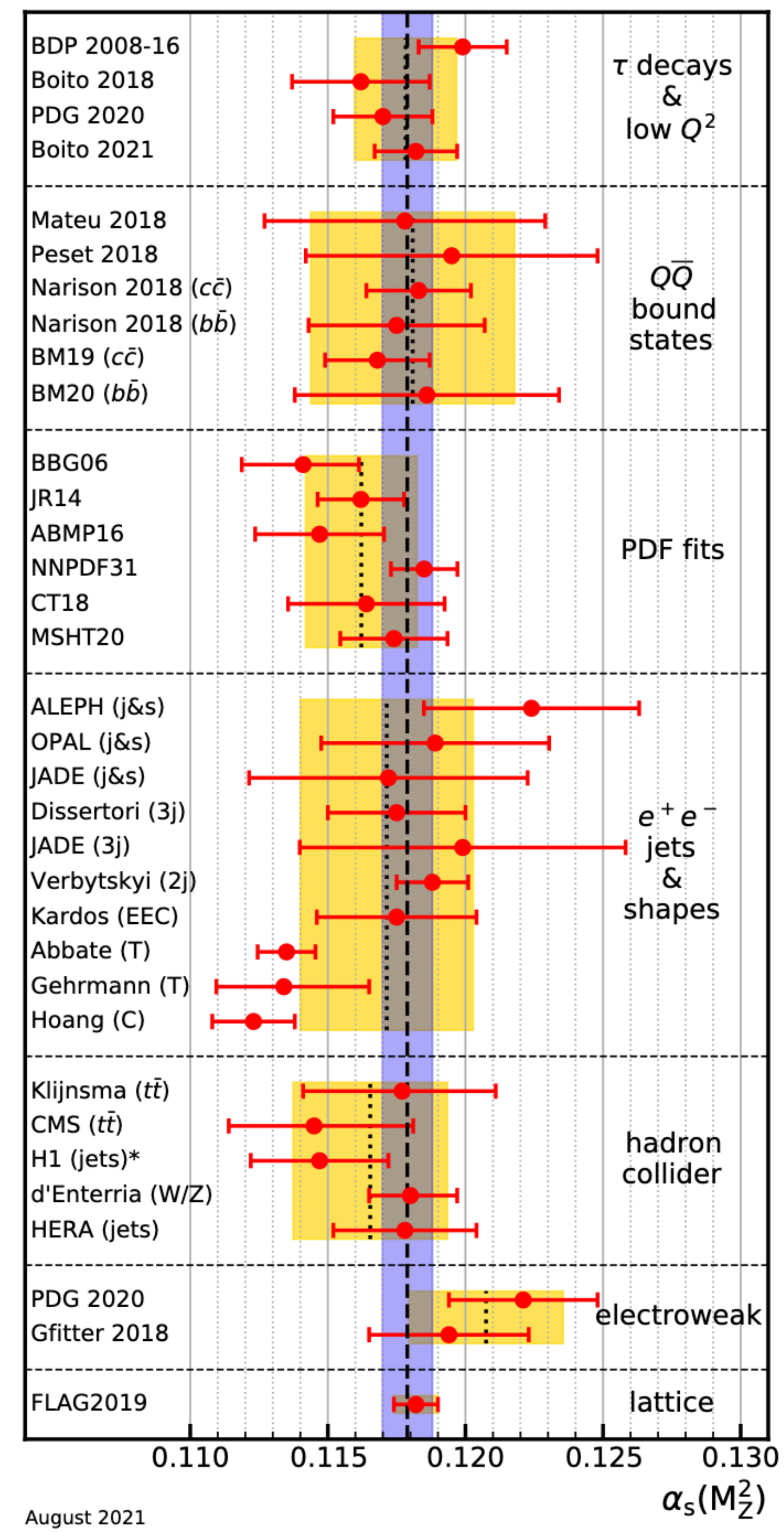
The SM contains **18 free parameters** which have to be constrained by experimental data. ATLAS can provide stringent constraints for many of them

strong coupling

- Large statistics, gluon-initiated processes: strong coupling at LHC
- Main bottleneck: **theory errors** from PDFs and higher-order QCD
- Recent extraction from Z p_T: **highest single-measurement precision**

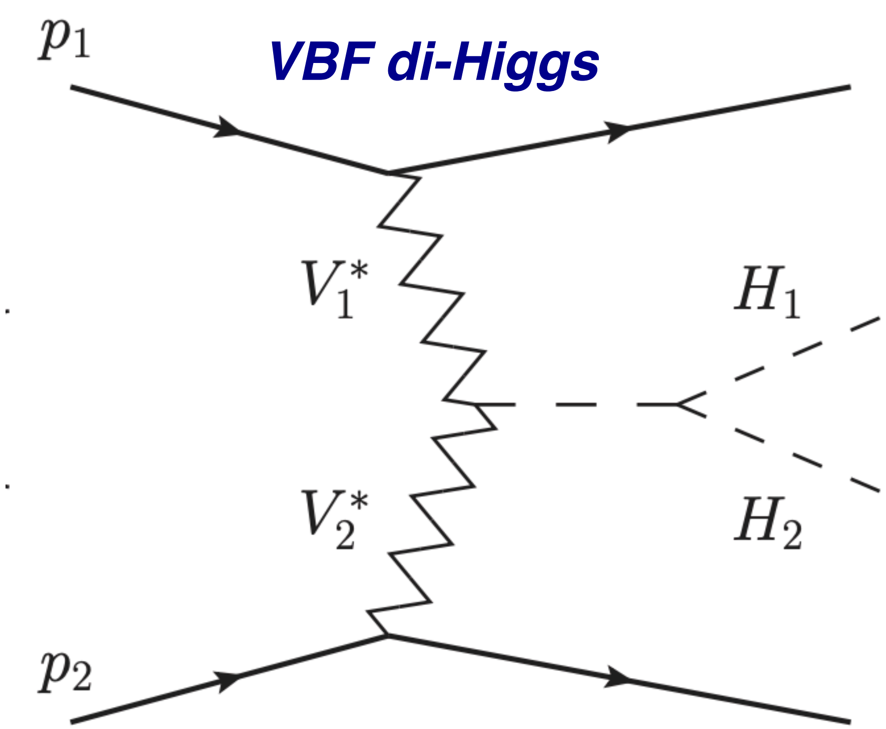


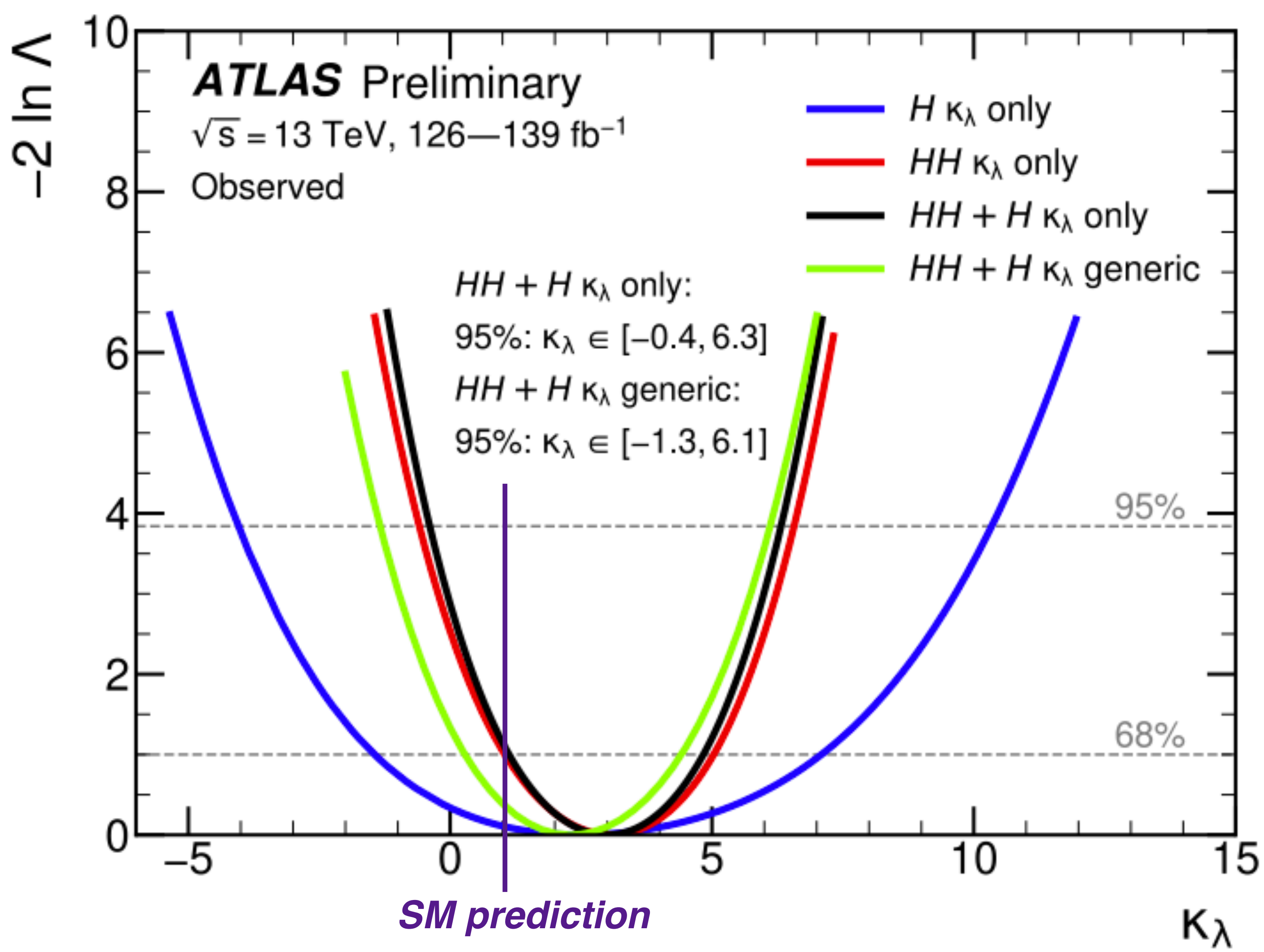
LHC

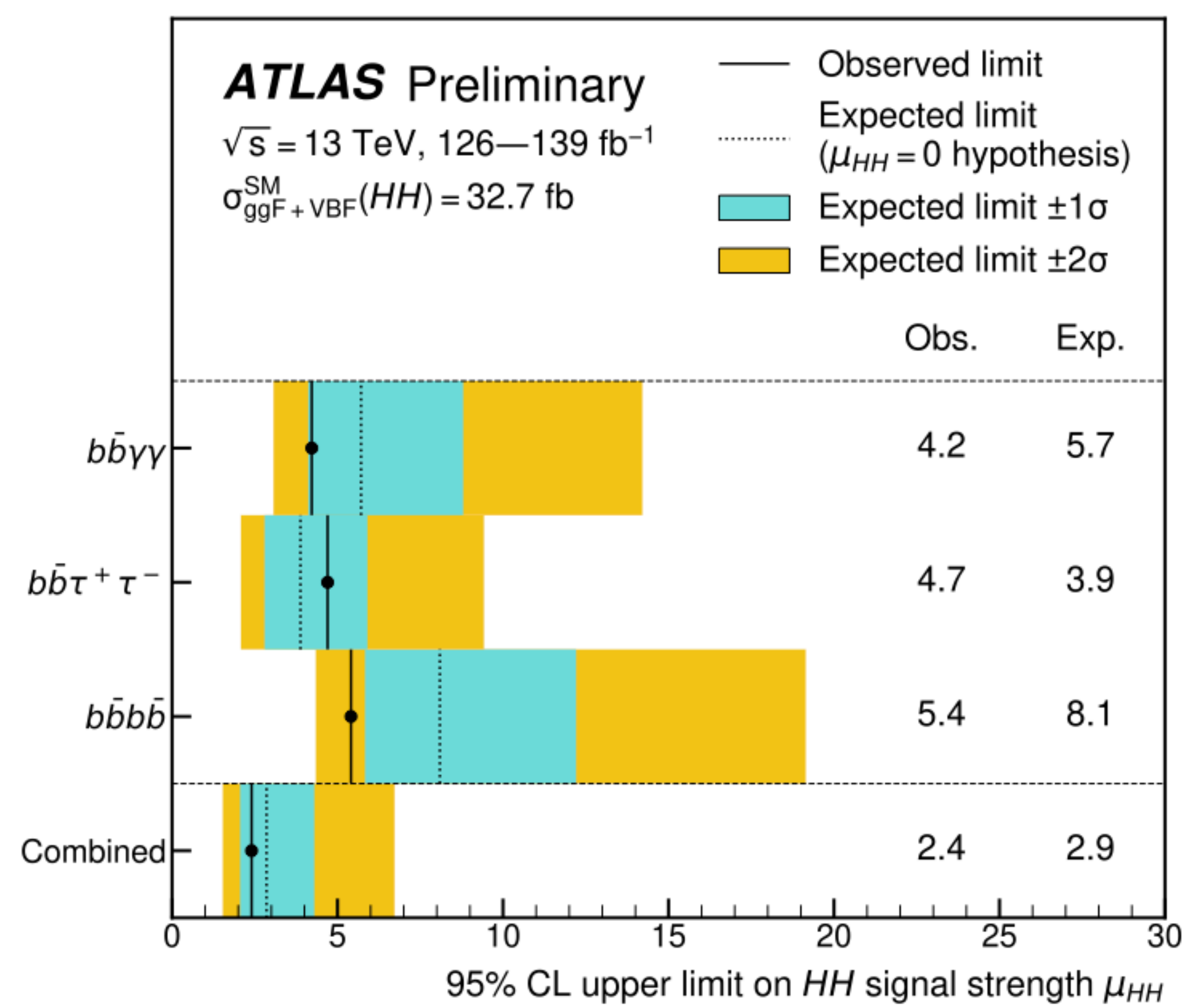


Reconstructing the Higgs potential

- Constrain **Higgs self-interactions** with both di-Higgs (gluon fusion and VBF) and single-Higgs (via quantum loops)
- Sensitive to deviations in **SM Higgs potential**
- HL-LHC to establish Higgs self-interactions (in the SM)





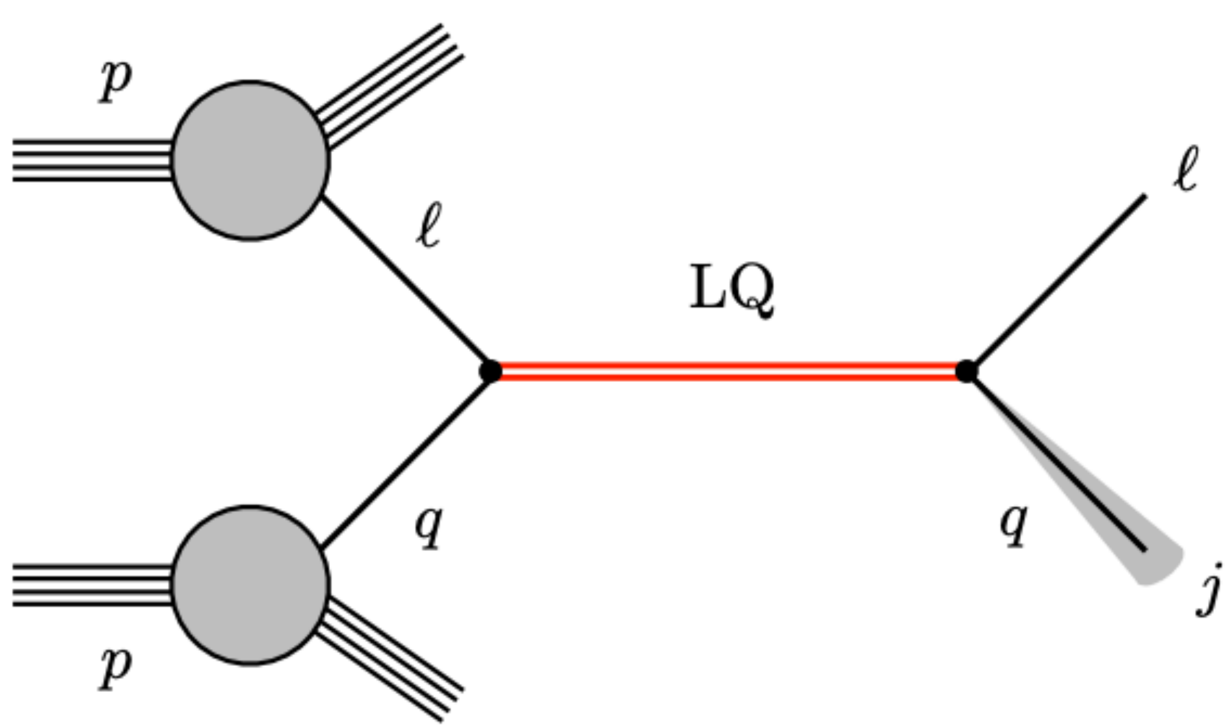


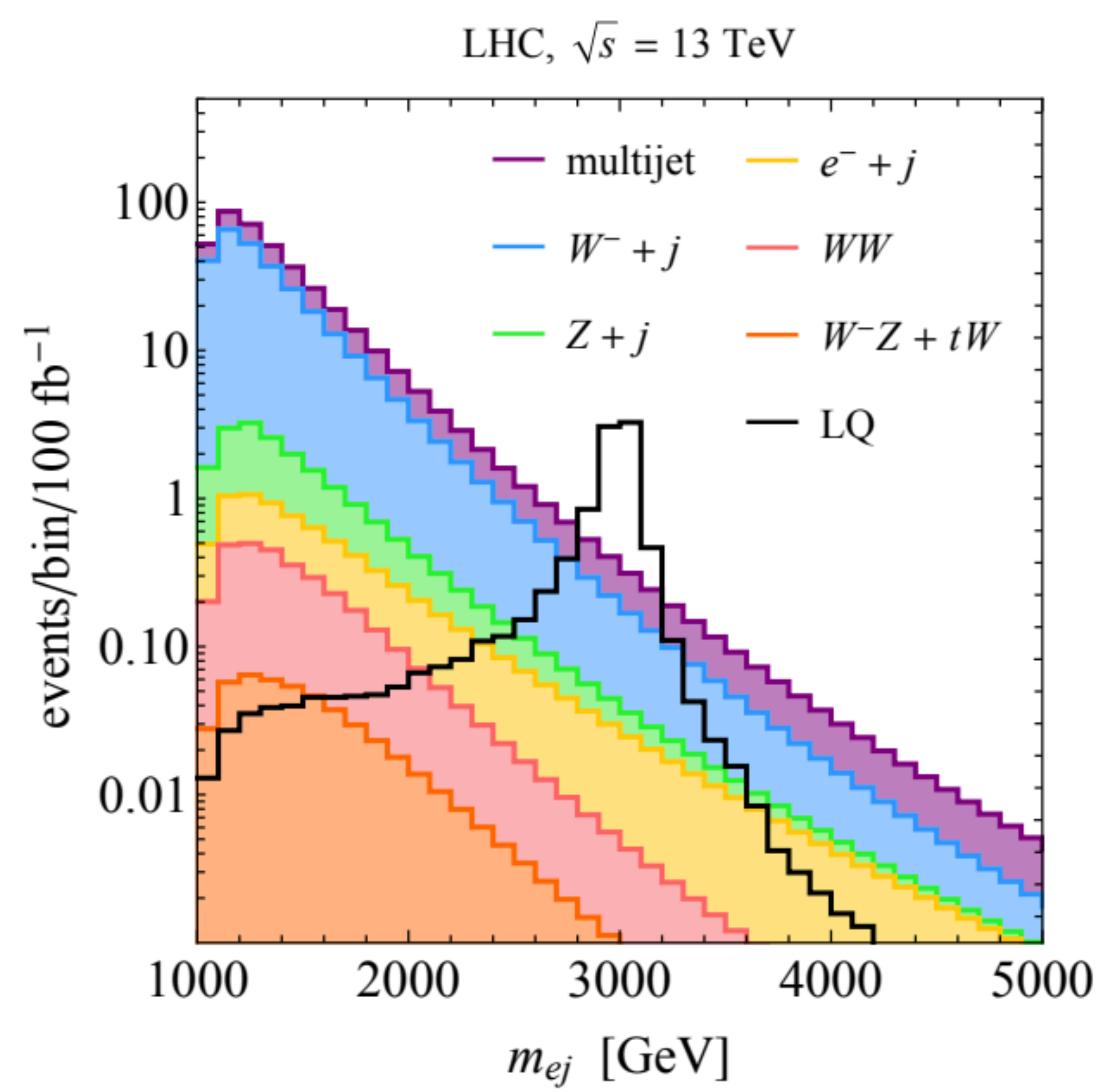
Searches for new phenomena

- Beyond traditional BSM production benchmarks (e.g. supersymmetry), new ideas being proposed to e**xploit LHC sensitivity to new massive particles**

- Leptoquarks (coupling leptons with quarks) could be resonantly produced once we account for the **lepton content of the proton** (lepton PDFs generated by QED DGLAP evolution)

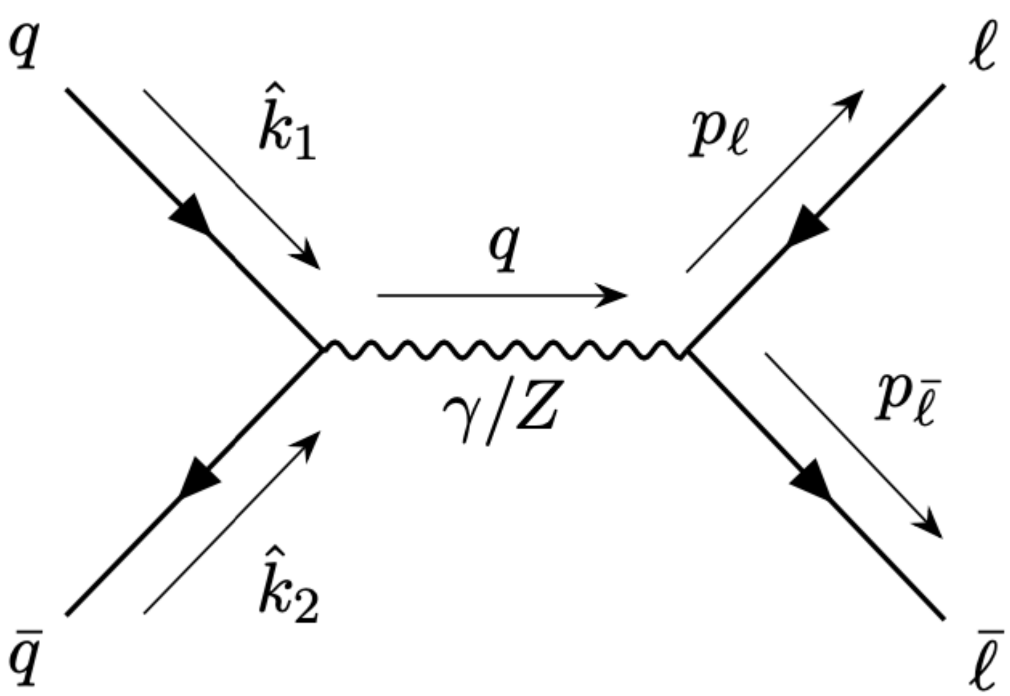
- Opportunities to connect **flavour physics** (tomorrow's lectures) with **high-p_T physics**





Searches for new phenomena

Searches for New Physics rely on a **robust understanding of SM processes**



Forward-backward asymmetry in high-mass Drell-Yan

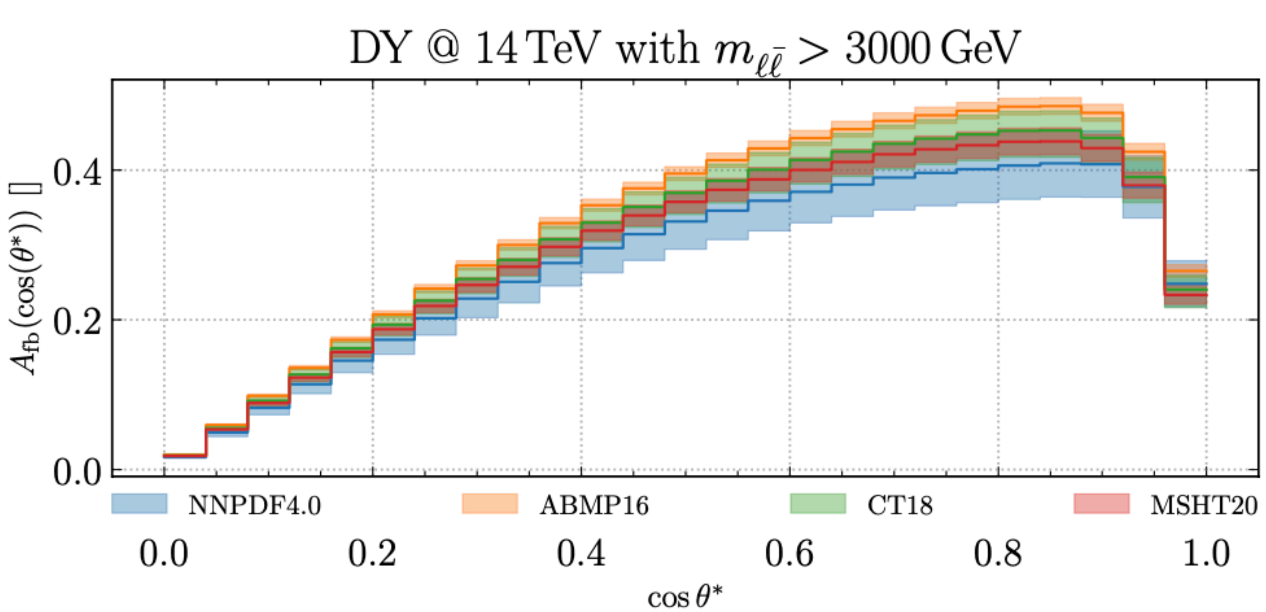
$$\left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\mathrm{FB}} = \left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\cos\theta^*} - \left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{-\cos\theta^*}$$

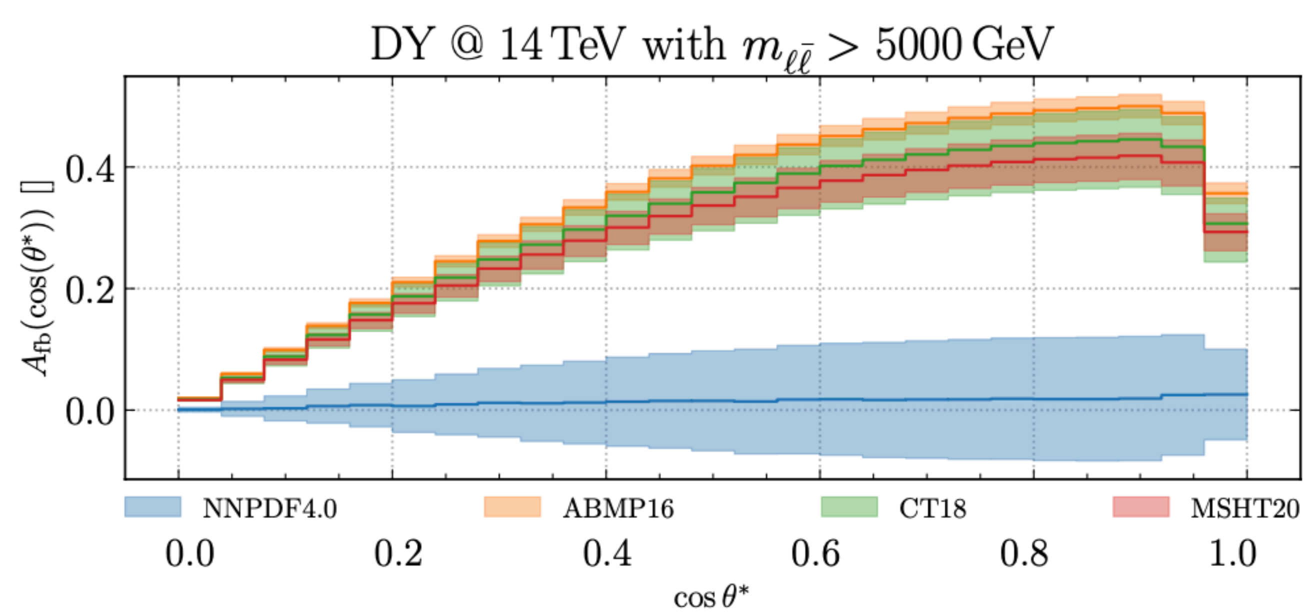
Is a negative FB asymmetry evidence for **BSM physics**? Or can it also be explained by **QCD?**

$$A_{\mathrm{FB}}^{(\mathrm{LO})} \propto f_q(x_2) f_{\bar{q}}(x_2)\left[\frac{f_q(x_1)}{f_q(x_2)} - \frac{f_{\bar{q}}(x_1)}{f_{\bar{q}}(x_2)}\right]$$

fall-off rate quarks | **fall-off rate anti-quarks**

ATLAS data can also **calibrate its own ``backgrounds"** by means of improved proton structure analyses





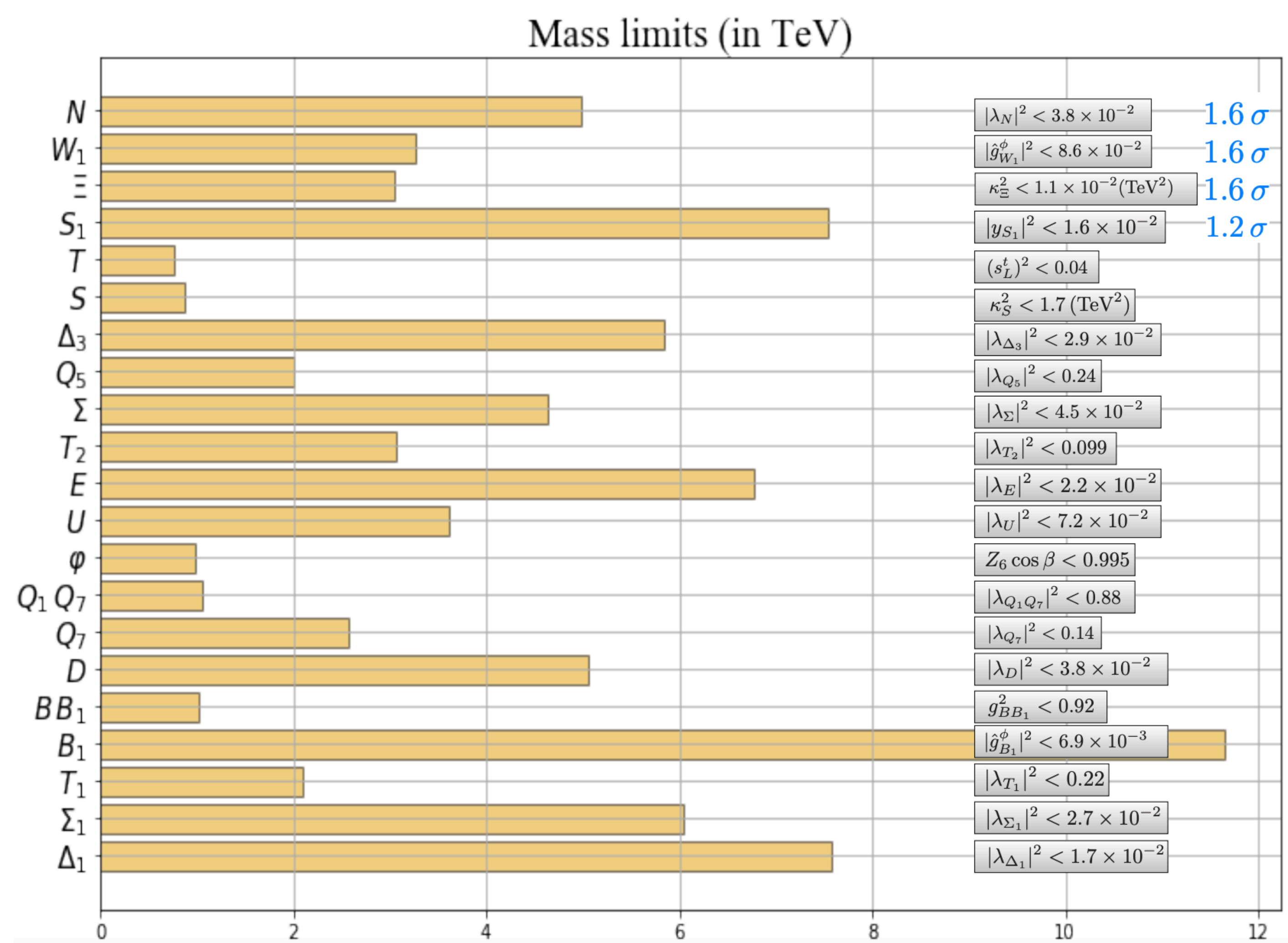
The Standard Model as an EFT

$$\mathcal{L}_{\mathsf{SMEFT}}(\{c_i\},\Lambda) = \mathcal{L}_{\mathsf{SM}} + \sum_{d=5}^{\infty}\sum_{i=1}^{N_d} c_i^{(d)} \frac{\mathcal{O}_i^{(d)}}{\Lambda^{d-4}}$$

- ☑ **Low-energy limit** of generic UV-complete theories with linearly realised EWSB
- ☑ **Complete basis** at any given mass-dimension: systematic parametrisation of BSM effects
- ☑ **Fully renormalizable**, full-fledged QFT: compute higher orders in QCD and EW

Exploit the full power of **SM measurements** for model-independent BSM searches: constrain large classes of BSM scenarios matched to the SMEFT

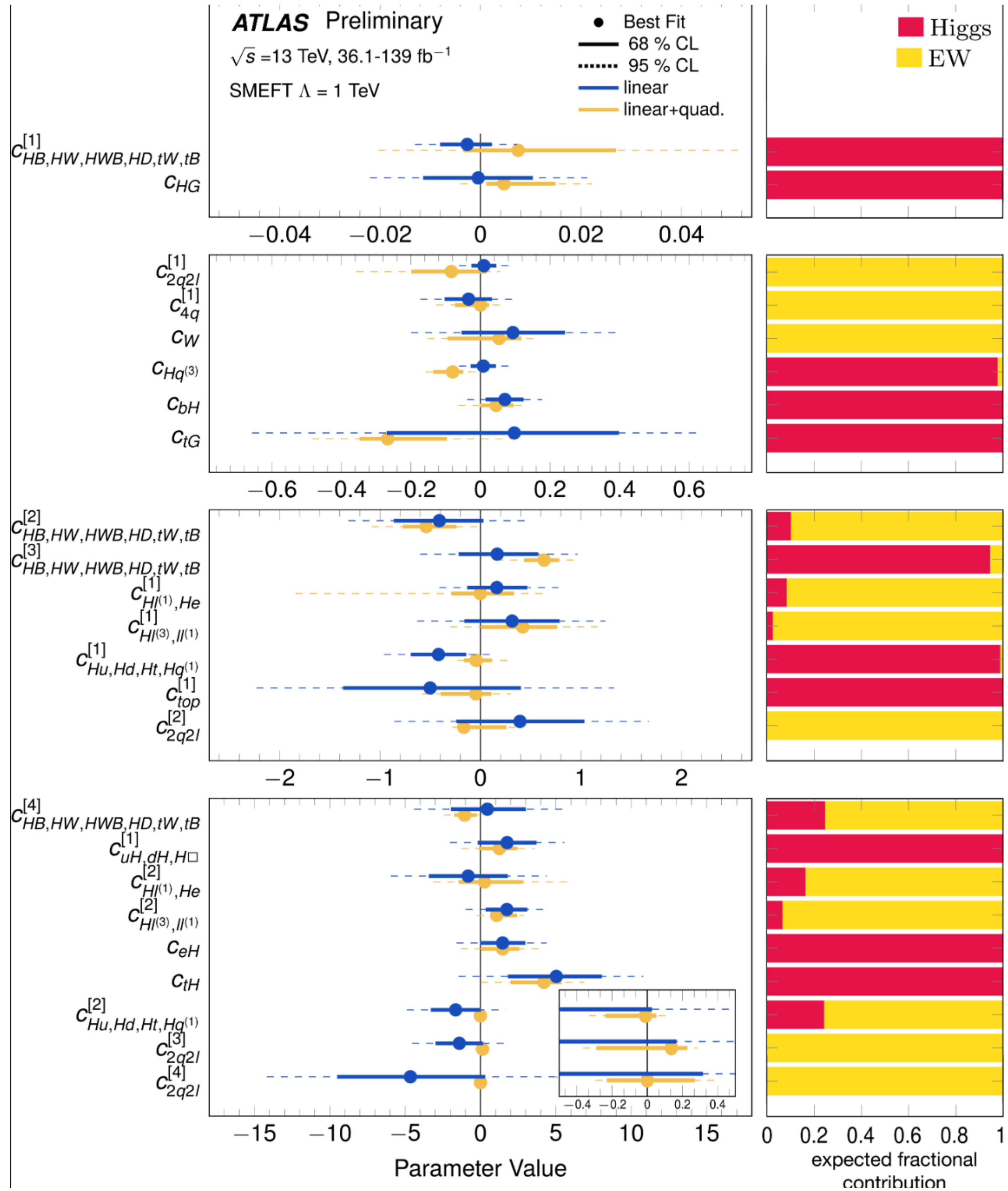
tree-level, single-field extensions of the SM
FitMaker, Ellis et al 2020



SMEFT at ATLAS

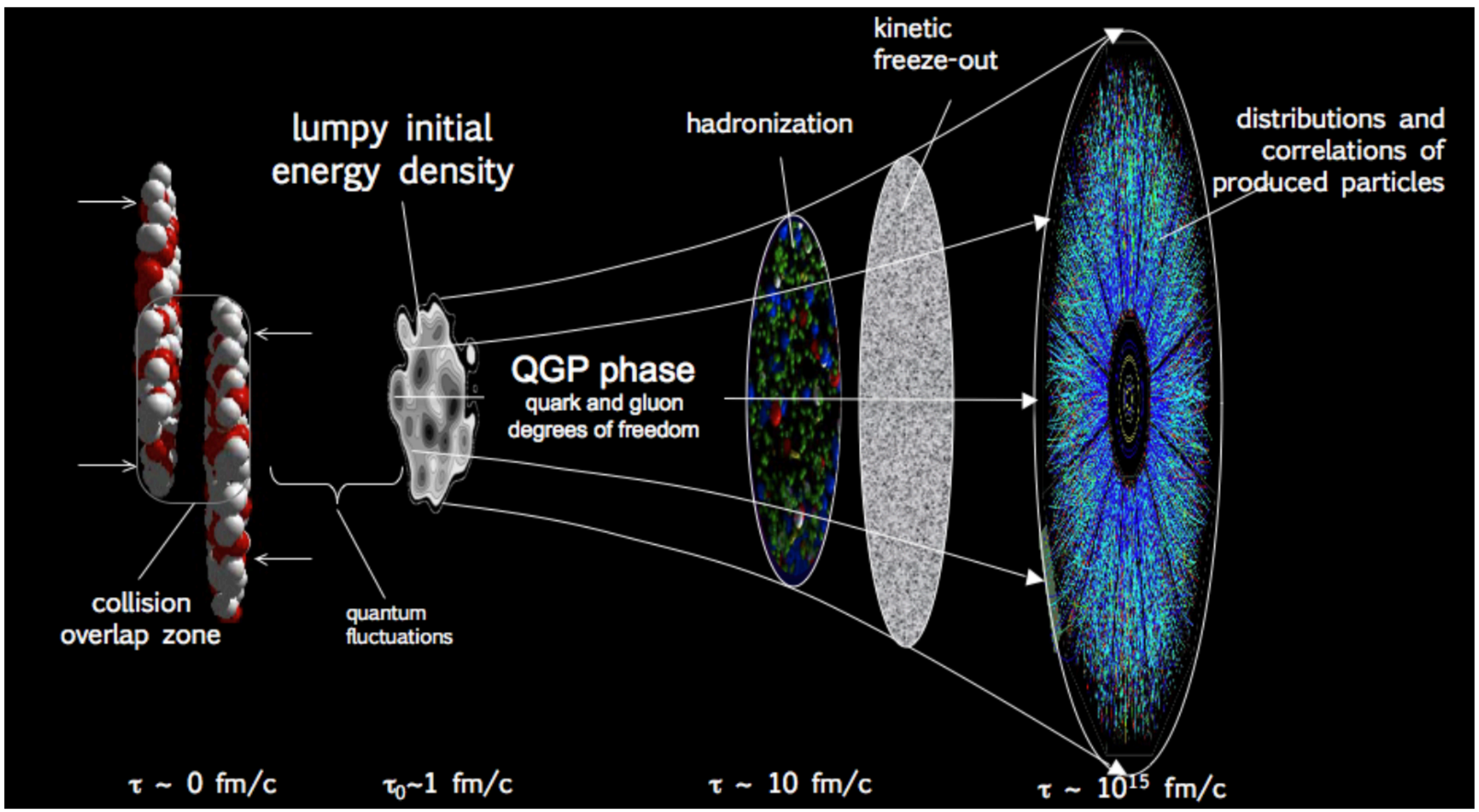
- SMEFT interpretation of ATLAS **Higgs** and **electroweak data**
- Constraints **24 independent DoFs** in the SMEFT parameter space
- Input for **global EFT fits** accounting for also top and/or flavour data

Process	Details
$pp \to h \to \gamma\gamma$	ggF, VBF, Wh, Zh, $t\bar{t}h$, th
$pp \to h \to ZZ^*$	ggF, VBF, Wh, Zh, $t\bar{t}h(4\ell)$
$pp \to h \to WW^*$	ggF, VBF
$pp \to h \to \tau\tau$	ggF, VBF, Wh, Zh, $t\bar{t}h(\tau_{\text{had}}\tau_{\text{had}})$
	Wh, Zh
$pp \to h \to b\bar{b}$	VBF
	$t\bar{t}h$
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$p_T^{\text{lead. lep.}}$ $\left(m_{\ell\ell} > 55\,\text{GeV}\,, p_T^{\text{jet}} < 35\,\text{GeV}\right)$
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	m_T^{WZ} $(m_{\ell\ell} \in (81, 101)$ GeV$)$
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	m_{ZZ} $(m_{4\ell} > 180\,\text{GeV})$
$pp \to \ell^{+}\ell^{-}jj$	$\Delta\Phi_{jj}$ $(m_{jj} > 1000\,\text{GeV}\,, m_{\ell\ell} \in (81, 101)$ GeV$)$



Heavy Ion Collisions @ ATLAS

- ATLAS also has a rich program in proton-ion and ion-ion collisions: connection with **Quark Gluon Plasma** (Wednesday lectures)
- High-pT physics and QGP physics connected by **hard probes** in proton-lead and lead-lead collisions
- Proton-lead collisions determine the initial state of lead-lead collisions: **disentangle cold from hot nuclear matter effects**



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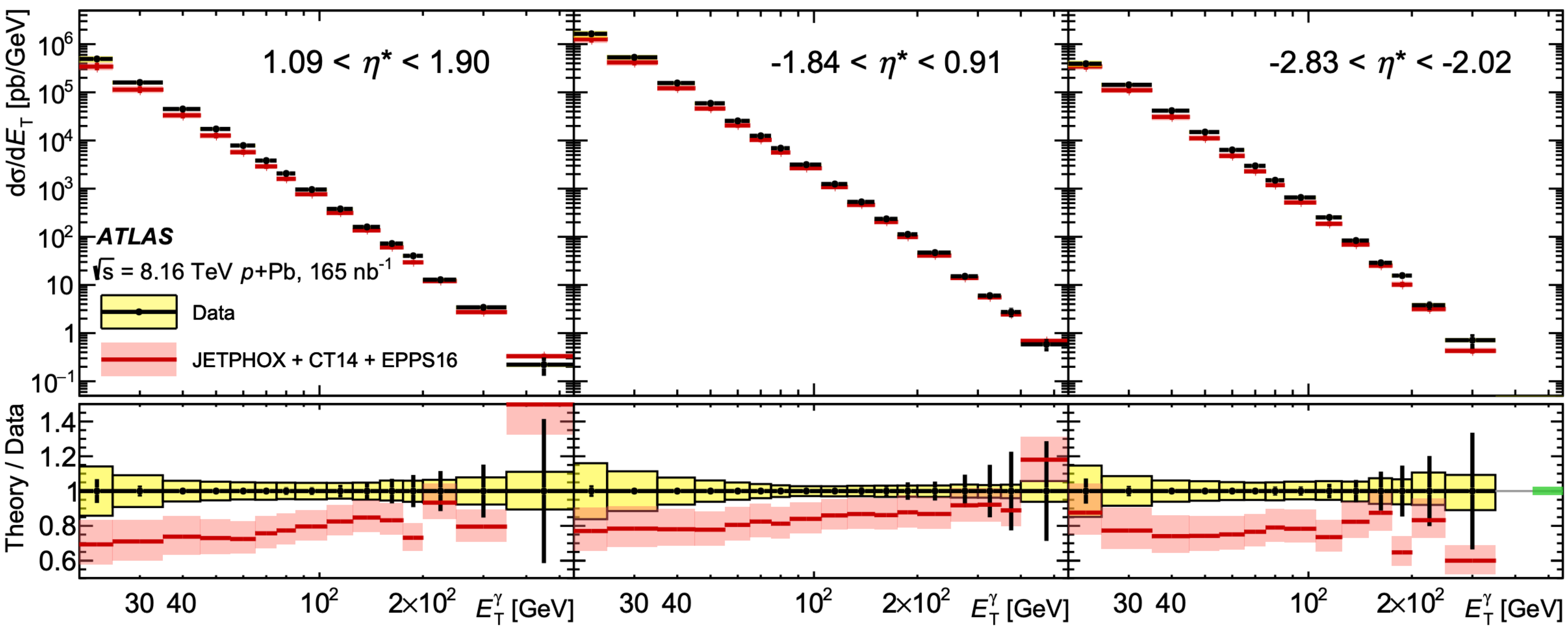

Photons not affected by QGP, but still modified in p+Pb vs p+p from **cold nuclear matter effects**

Summary and outlook

- A general-purpose detector such as ATLAS offers excellent opportunities to **stress-test the Standard Model at the high-energy frontier**

- **Fingerprinting the Higgs particle** (2nd gen couplings, self-interactions, new EFT interactions) remains a key goal of the ALTAS program including the HL phase

- Precision **measurements of SM parameters** and of hadron structure provide a complementary approach to direct new physics searches

- A lot of connections (in many cases unexploited!) between the ATLAS program and those of **LHCb** (flavour physics, Tuesday) and **ALICE** (Quark-Gluon Plasma, Wednesday)