Latest findings from the LHC, in perspective

Michelangelo L. Mangano
CERN, Theory Department

on the nature of EW symmetry breaking

- EW and strong interactions have free parameters (the symmetry groups, the strength of couplings, the charges of elementary particles). But at least we do have a deep understanding of their dynamical nature, namely the gauge principle. This allows us to speculate about an even deeper origin, e.g. from string theory or higher-dimensional Kaluza-Klein theories

- The Higgs mechanism relies of the quartic Higgs potential, in particular on the negative sign of its quadratic component. But we have no clue as to what is its dynamical origin, independently of whether we look at it with a SM or BSM perspective …

- Understanding the origin of the Higgs potential and the nature of Higgs interactions is a paramount puzzle of modern physics, regardless of whether they eventually match the SM assumption or require new physics

- Having established the existence of the Higgs is similar to having established inflation, through cosmological observations. The real question (for both Higgs and inflation) is now "**where does it come from?**"

a historical example: superconductivity

- The relation between the Higgs phenomenon and the SM is similar to the relation between superconductivity and the Landau-Ginzburg theory of phase transitions: a quartic potential for a bosonic order parameter, with negative quadratic term, and the ensuing symmetry breaking. If superconductivity had been discovered after Landau-Ginzburg, we would be in a similar situations as we are in today: an experimentally proven phenomenological model. But we would still lack a deep understanding of the relevant dynamics.

- For superconductivity, this came later, with the identification of e^-e^- Cooper pairs as the underlying order parameter, and BCS theory. In particle physics, we still don't know whether the Higgs is built out of some sort of Cooper pairs (composite Higgs) or whether it is elementary, and in both cases we have no clue as to what is the dynamics that generates the Higgs potential. With Cooper pairs it turned out to be just EM and phonon interactions. With the Higgs, none of the SM interactions can do this, and we must look beyond.

- The hierarchy problem, and the search for a ***natural*** explanation of the separation between the EW and Planck scales, provided so far an obvious setting for the exploration of the dynamics underlying the Higgs phenomenon. Lack of evidence for a straightforward answer to naturalness (eg SUSY), forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties

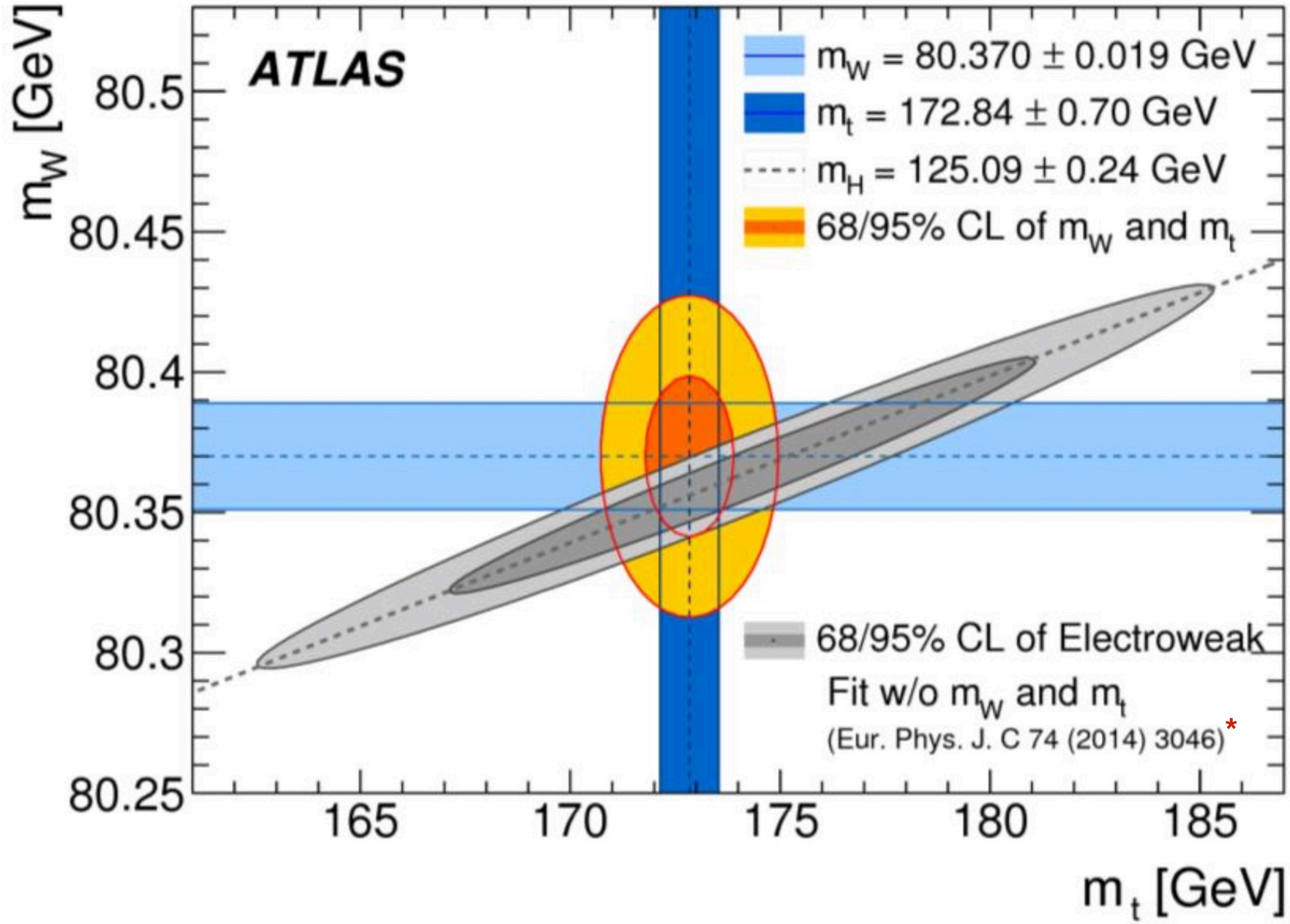
- We often ask "is the Higgs like in SM?" ….The right way to set the issue is rather, more humbly, **"what is the Higgs?"** …

- The programme:
    - quantum-level properties of EW interactions
    - the properties of the Higgs
        - couplings to EW gauge bosons and selfcouplings
        - couplings to fermions
    - the properties of the top quark

Probes of the quantum structure of EW interactions

ATLAS arXiv:1701.07240

$m_W = 80.370 \pm 0.019$ GeV
[± 7 MeV (stat.) ± 11 MeV (syst.) ± 14 MeV (modelling)]

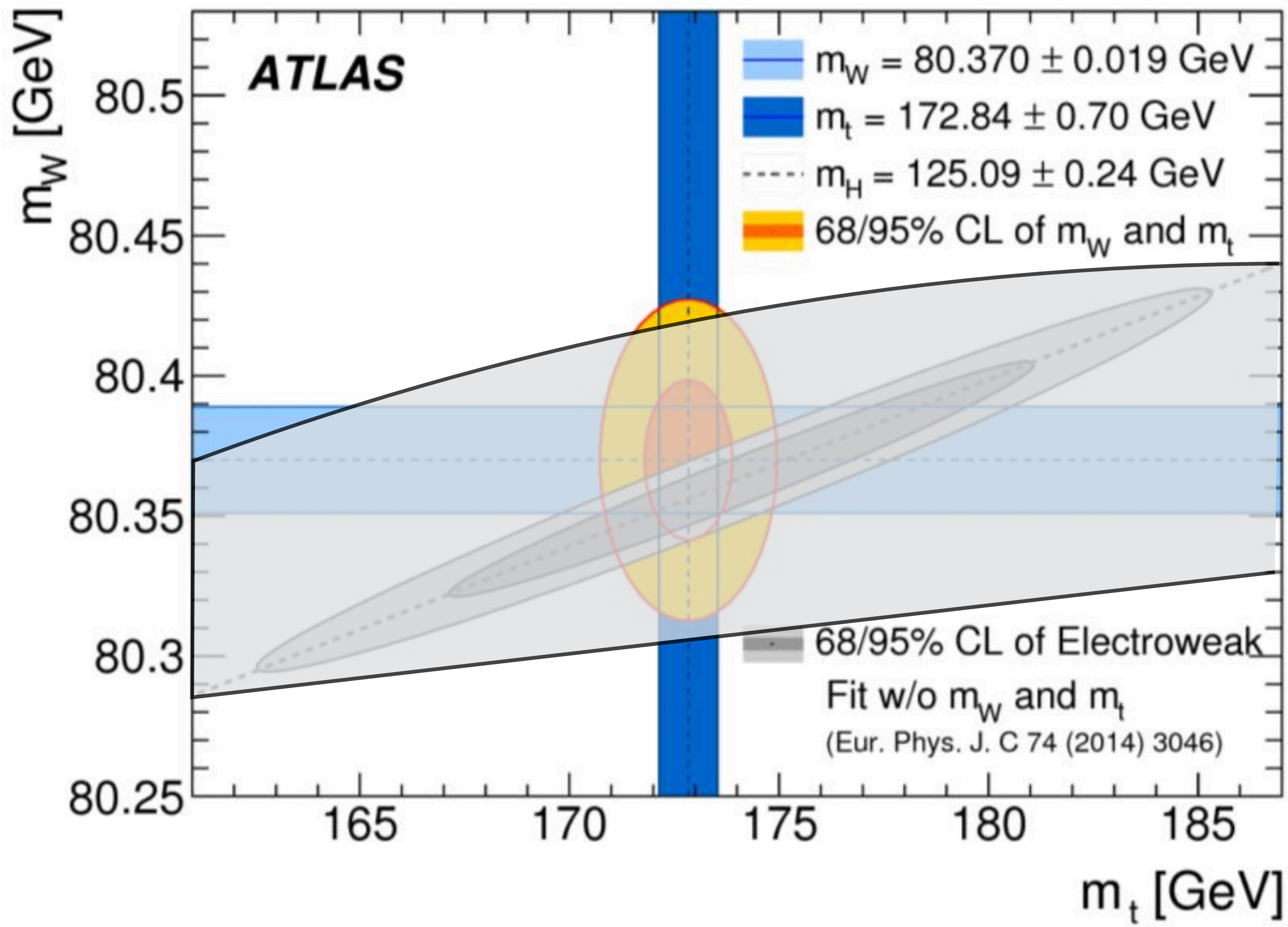


Fit, from EW precision data, for m_W vs m_{top} (linearized around 173 Gev)

$$m_W^{EW\text{-}fit}\,(\text{MeV}) = 80370 + 6.11\times10^{-3}\,(m_{top} - 172840) \pm 15_{fit@95\%}$$

* Baak et al, EPJC 74 (2014) 3046

before the Higgs discovery and m_H=125 constraint:



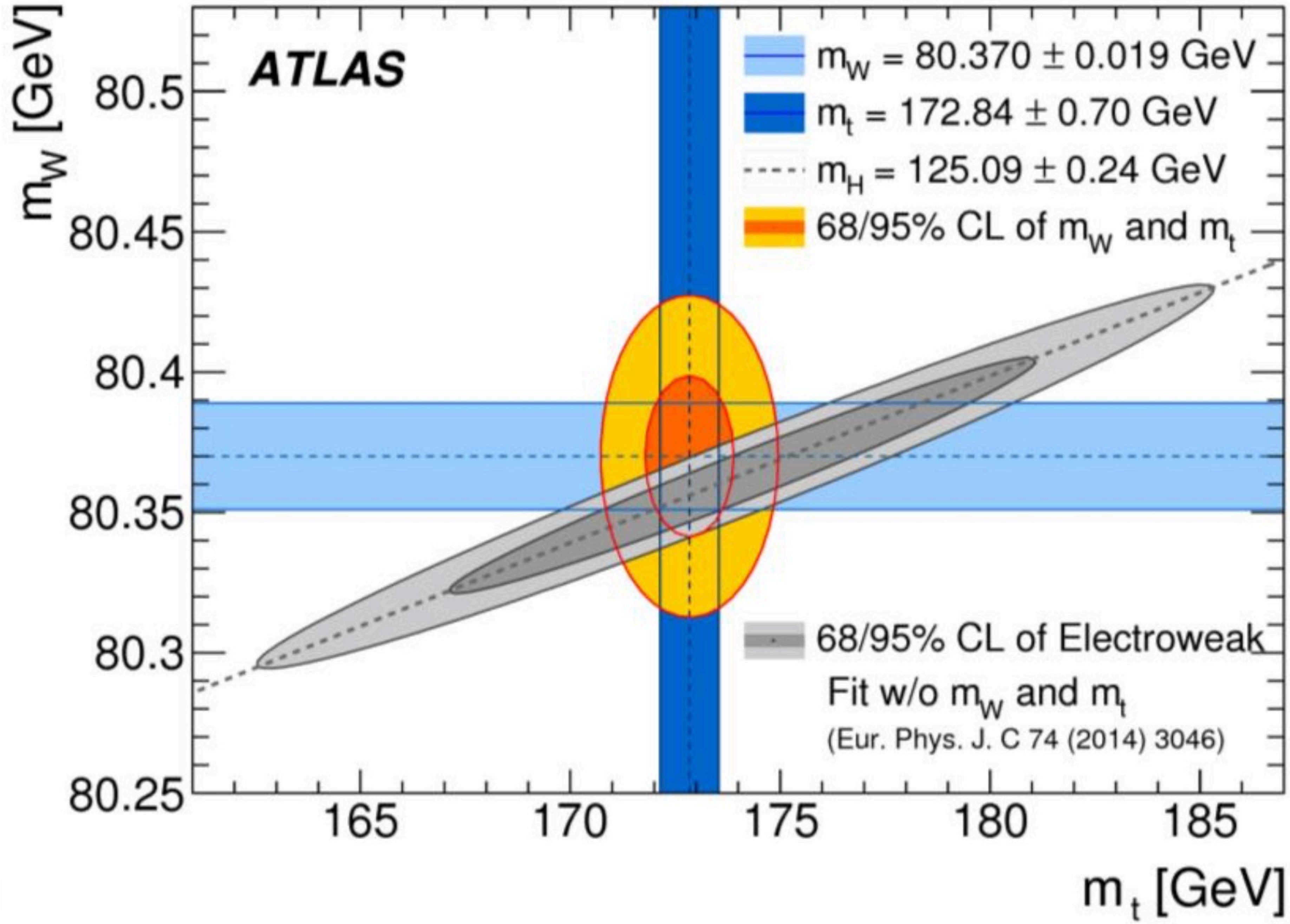
Fit, from EW precision data, for m_W vs m_{top} (linearized around 173 Gev)

$m_W^{EW\text{-}fit}$ (MeV) = ... ± $55_{fit@95\%}$

the Higgs observation redefines the needs and precision targets for m_W !!

ATLAS <u>arXiv:1701.07240</u>

m_W = 80.370 ± 0.019 GeV
[± 7 MeV (stat.) ± 11 MeV (syst.) ± 14 MeV (modelling)]



Fit, from EW precision data, for m_W vs m_{top} (linearized around 173 Gev)

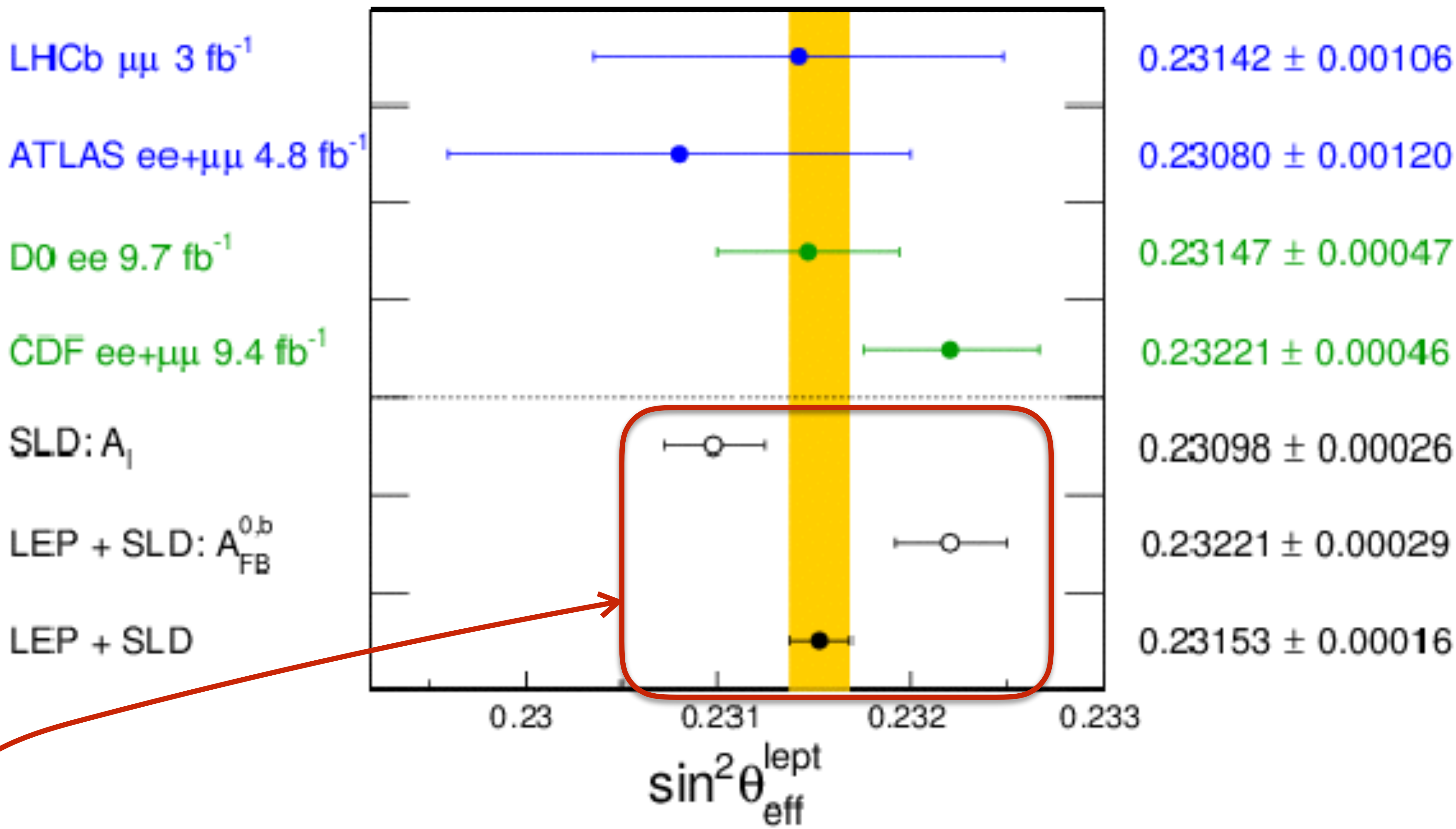
$$m_W^{EW\text{-}fit}\,(\text{MeV}) = 80370 + 6.11\times10^{-3}\,(m_{top} - 172840) \quad \pm 15_{fit@95\%}$$

NB: Δm_{top} = 1 GeV ⇒ $\Delta m_W^{EW\text{-}fit}$ ~ 6 MeV

Message:

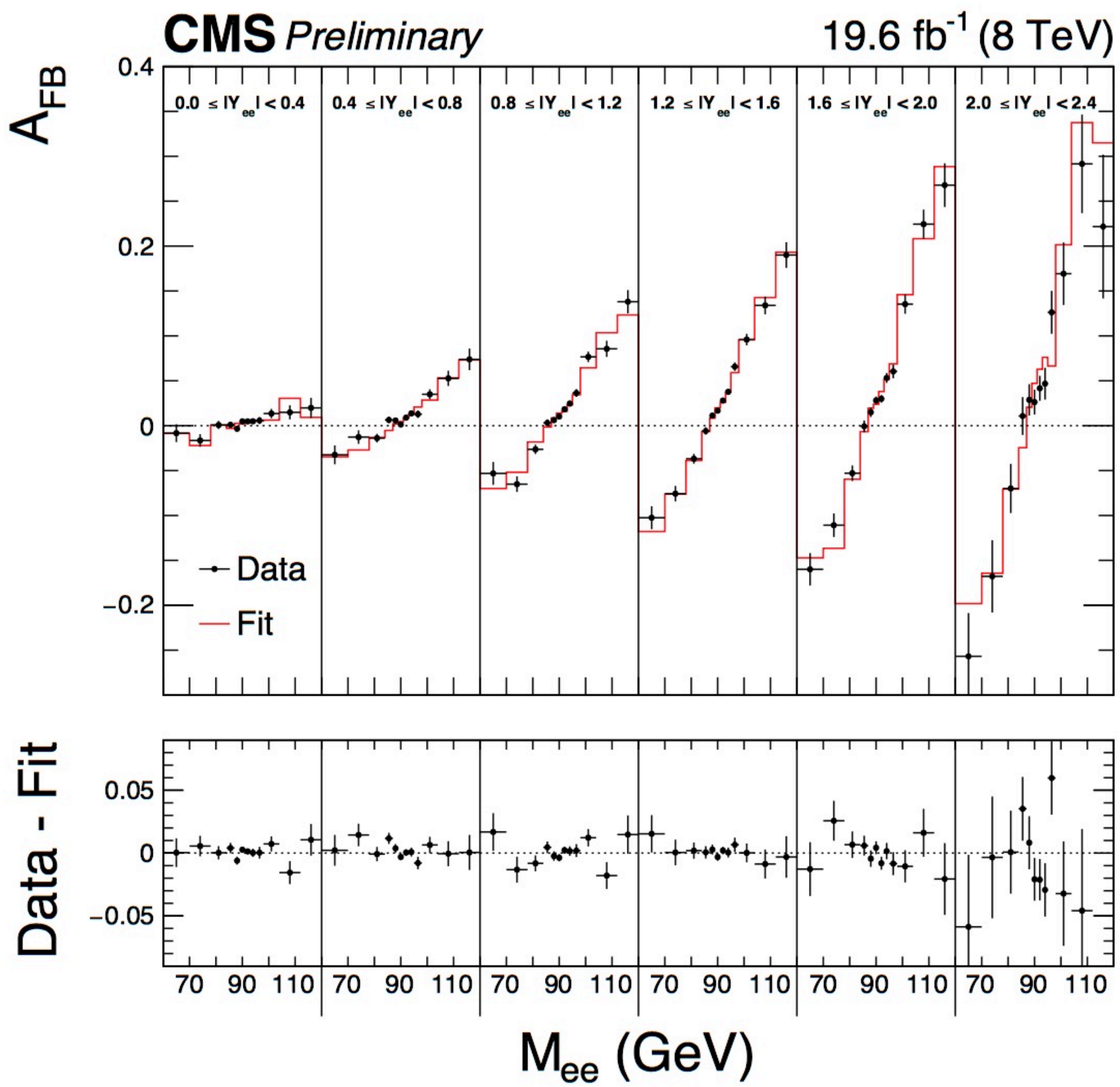
- These results don't emerge overnight ….
- … 20 years of precision measurements of m_W and m_{top} at the Tevatron and, now, LHC, have been crucial to be able, **today**, to discuss and quantitatively test the consistency of SM radiative corrections in view of the Higgs discovery
- There is still need, and room, for further improvements

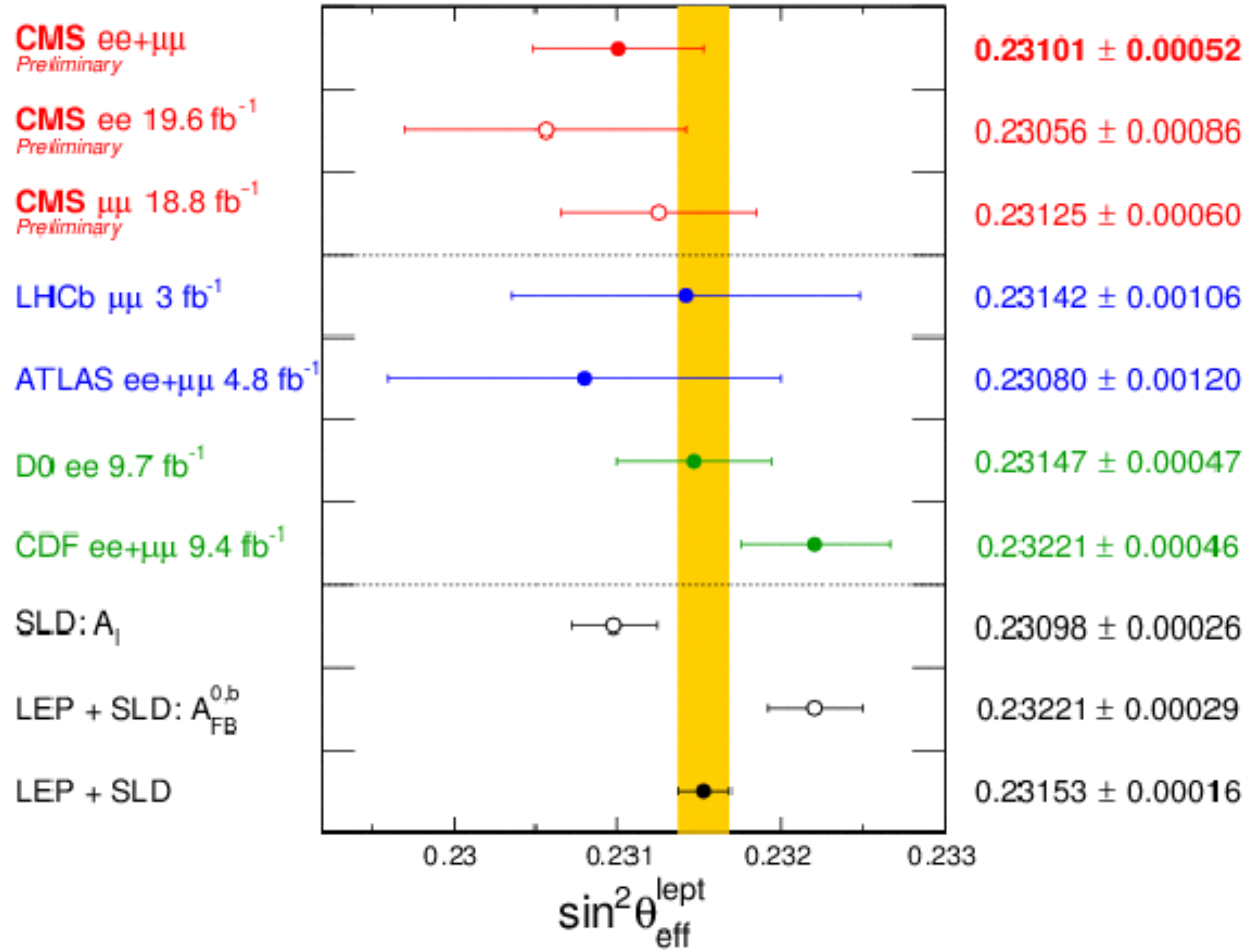
$\sin^2\theta_W$



A leading puzzle left open by LEP/SLD, and a major source of systematics in EW precision tests

CMS 2017





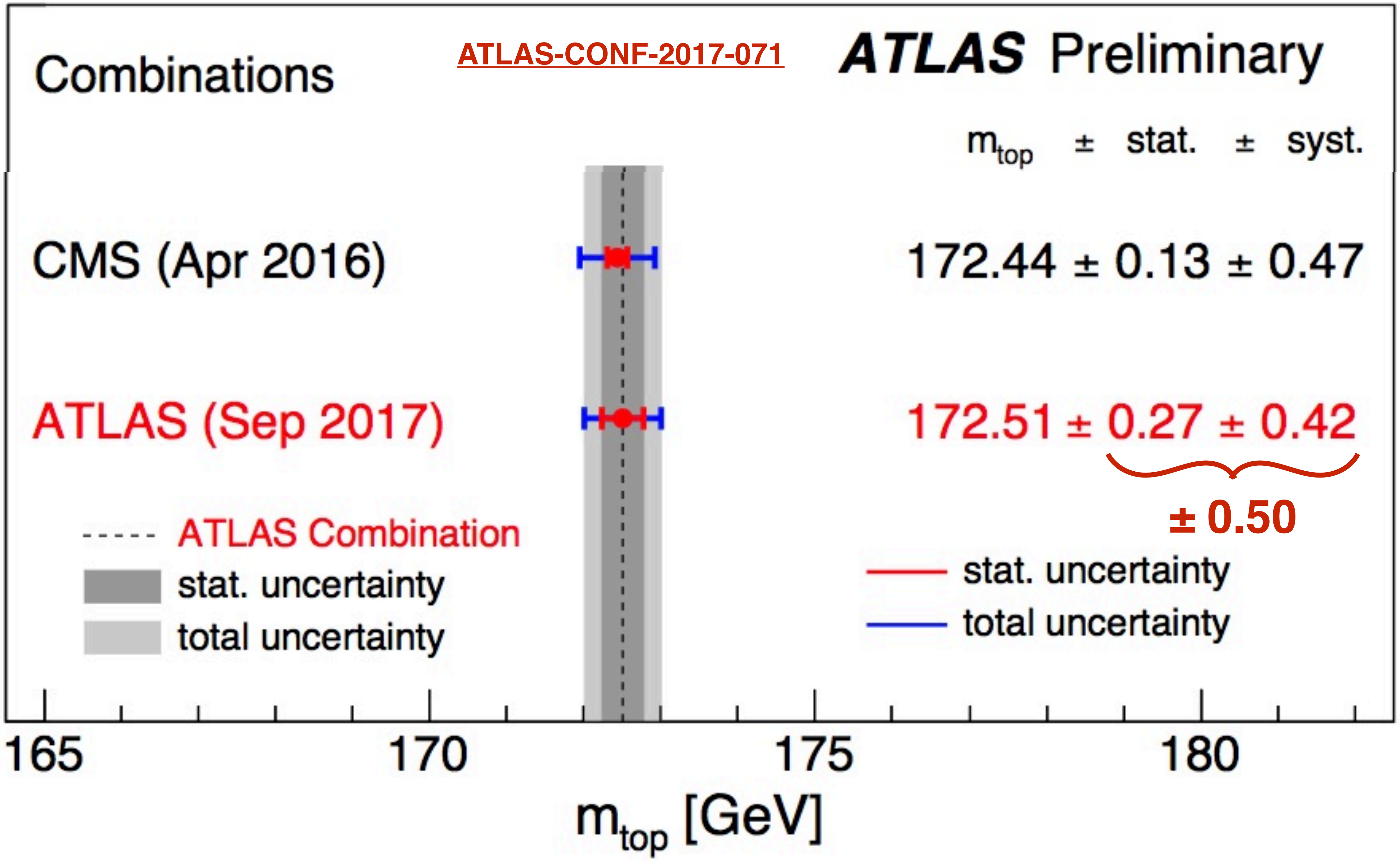
CMS-PAS-SMP-16-007

$$\sin^2\,\theta_{\rm eff}^{\rm lept} = 0.23101 \pm 0.00036_{\rm stat} \pm 0.00018_{\rm syst} \pm 0.00016_{\rm TH} \pm 0.00030_{\rm PDF} = 0.23101 \pm 0.00052$$

Most systematics are statistics driven ⇒

Total uncertainty to be reduced to current WA level with future data

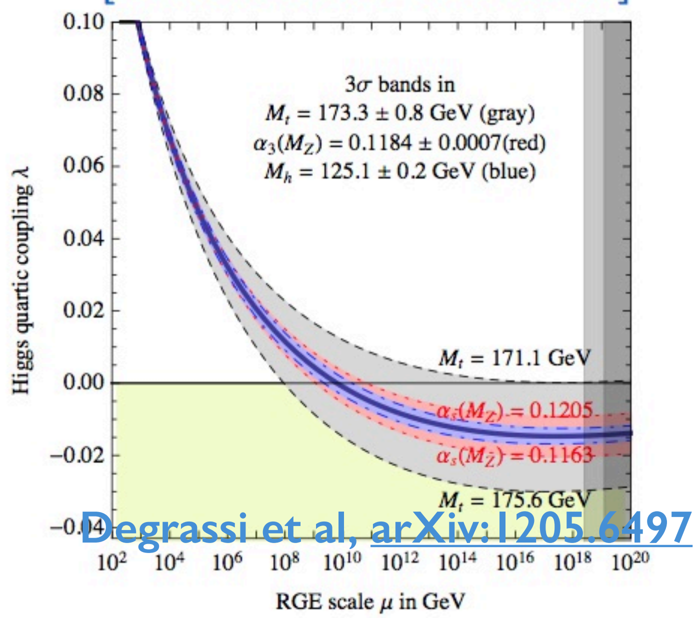
δm_{top} to 500 MeV



- **Current limiting systematics: TH**
  - production, decay and hadronization modeling, to be improved with ongoing calculations and more data (⇒MC validation and tuning)
  - m_{pole} vs m_{EW} conversion: renormalon syst now down to ~150 MeV

Fate of the vacuum

[Buttazzo et al. 1307.3536]

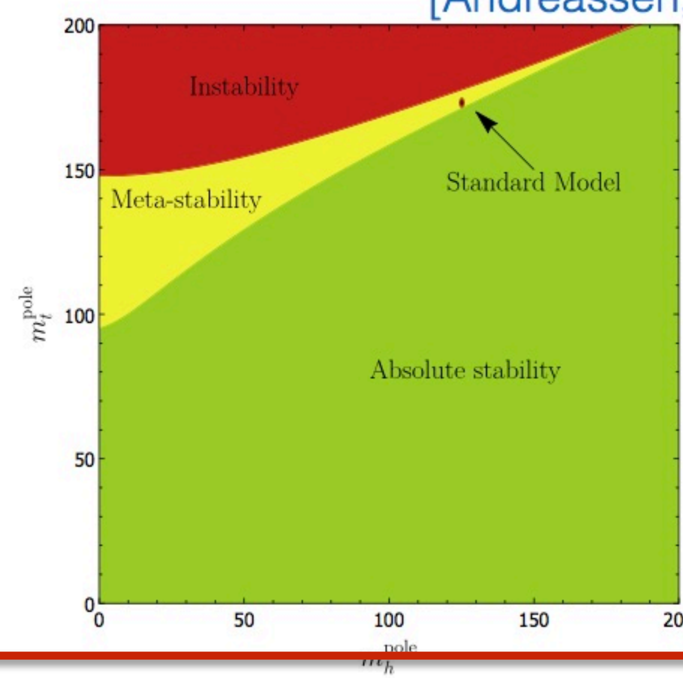


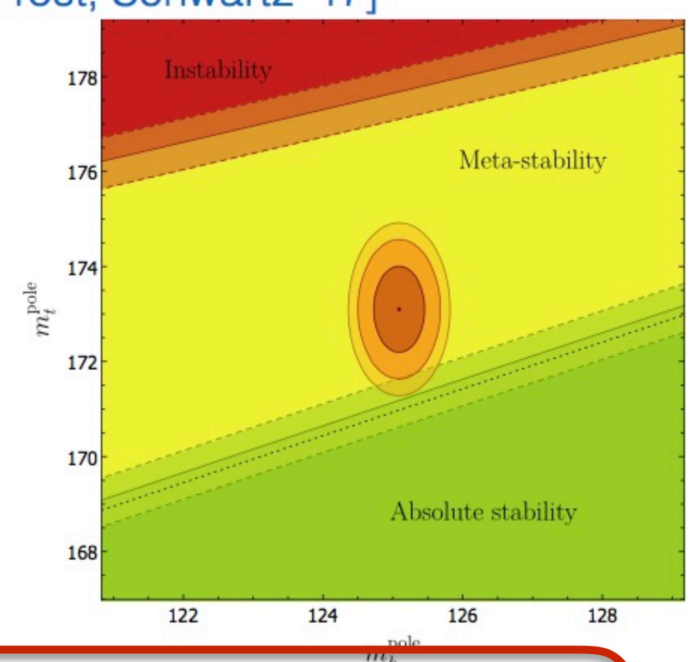
SM Higgs quartic runs negative in UV, implying metastability/instability

[Cabibbo, Maiani, Parisi, Petronzio, '79; Hung '79; Lindner 86; Sher '89; …]

$$\beta_\lambda = \frac{1}{16\pi^2}\left(24\lambda^2 + 12y_t^2\lambda - 6y_t^4 + \dots\right)$$

[Andreassen, Frost, Schwartz '17]





State of the art: [Andreassen, Frost, Schwartz '17]

$$\tau_{SM} = \left(\frac{\Gamma}{V}\right)^{-1/4} = 10^{139^{+102}_{-51}} \text{ years}$$

Uncertainty equal parts m_t, α_s, threshold corrections

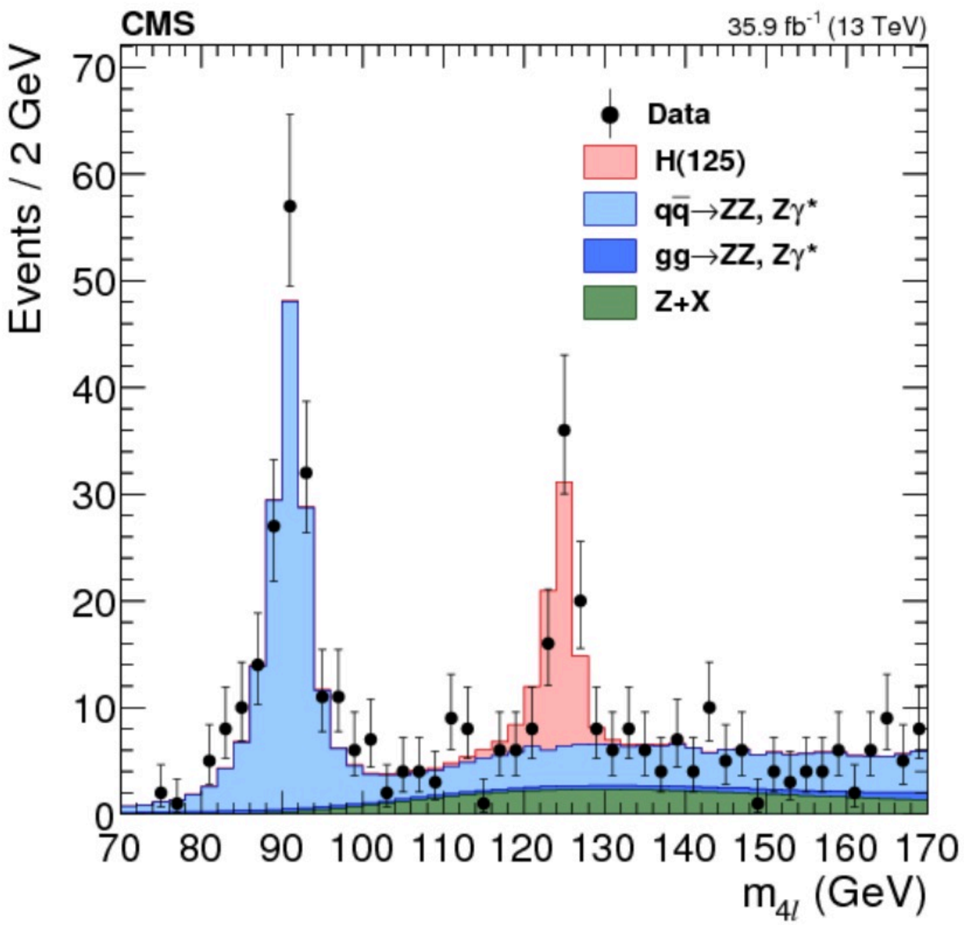
(To rule out absolute stability: reduce top quark mass uncertainty below 250 MeV)

Not an issue of concern for the human race…. but the closeness of mtop to the critical value where the Higgs selfcoupling becomes 0 at M_{Planck} (namely 171.3 GeV) might be telling us fundamental about the origin of EWSB

Higgs properties

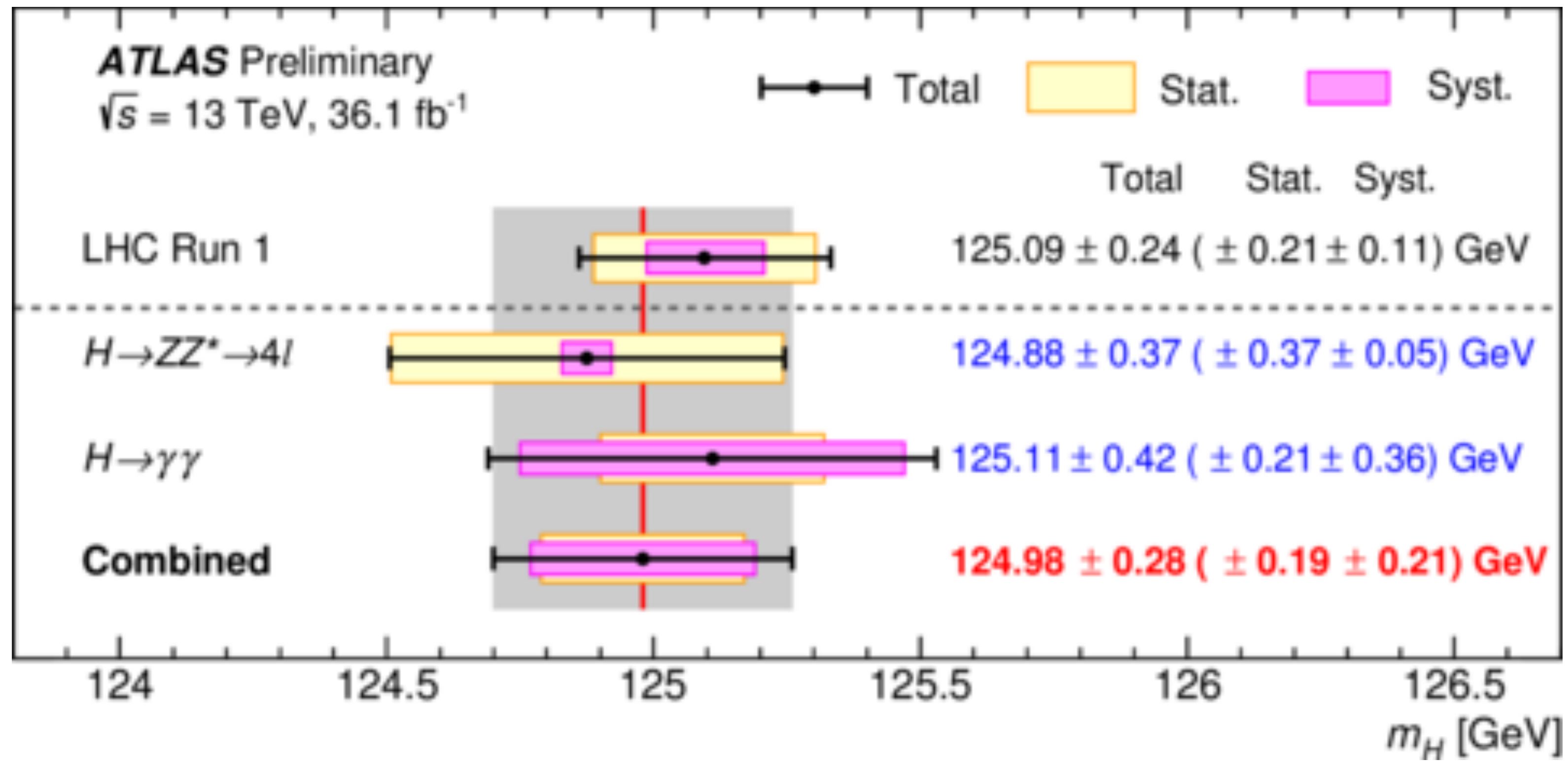
Higgs mass, 2017

CMS



arXiv:1706.09936

ATLAS



ATLAS-CONF-2017-046

3D likelihood fit (m_{4l}, ZZ bg, δm) ⇒

$m_H = 125.26 \pm 0.20_{stat} \pm 0.08_{syst}$ GeV

= 125.26 ± 0.22 GeV

γγ and 4ℓ combination, run 1+2 ⇒

$m_H = 124.98 \pm 0.19_{stat} \pm 0.21_{syst}$ GeV

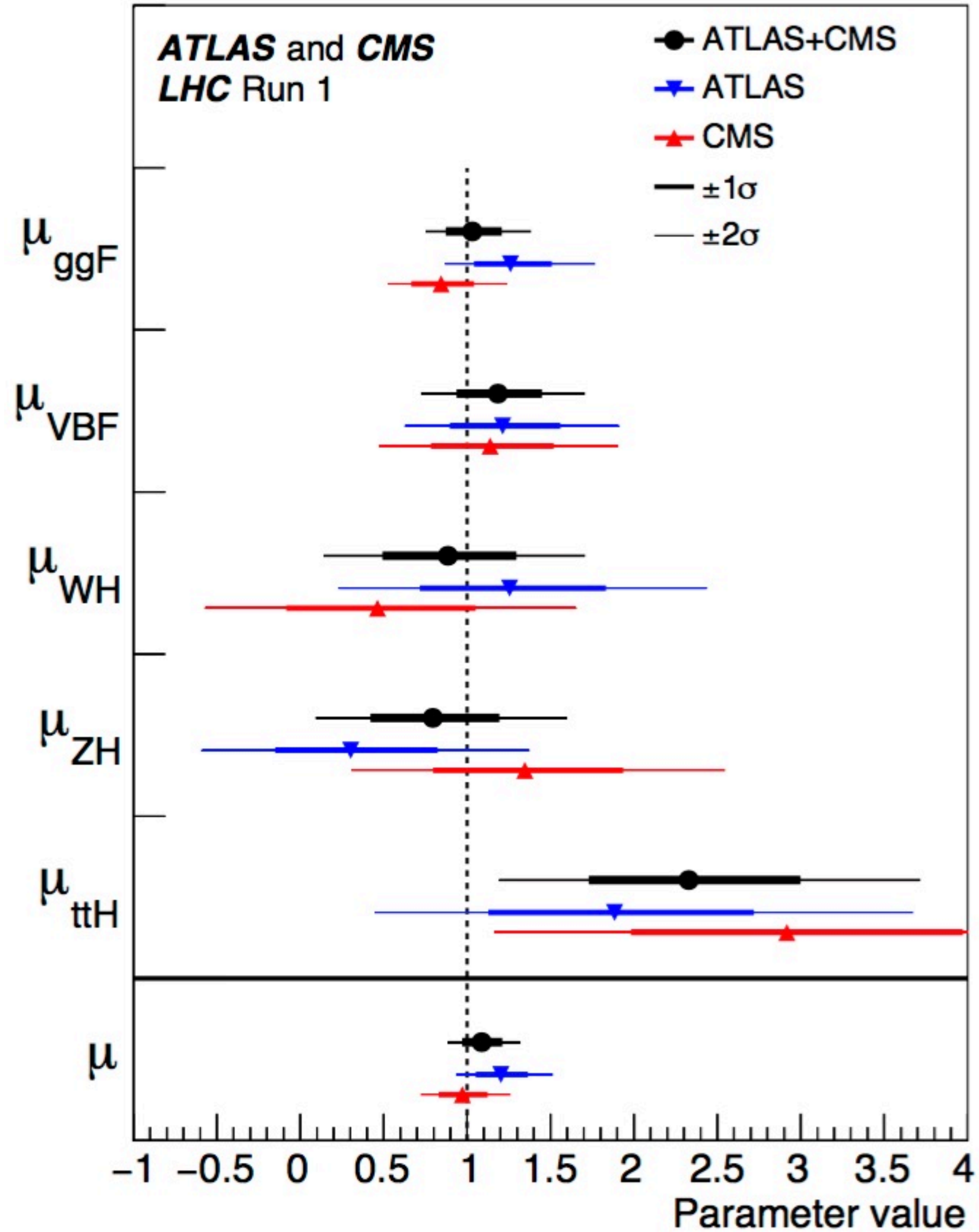
= 124.98 ± 0.26 GeV

⇒ 2 x 10^{-3} precision ….

it took over 6 years from 1983 discovery to get below 5 x 10^{-3} on m_Z (1989: CDF, SLC, LEP)

Higgs couplings: global fit of run 1 data

$\mu = \sigma x BR / [\sigma x BR]_{SM}$
assuming SM BR's in data



ATLAS+CMS
JHEP 1608 (2016) 045

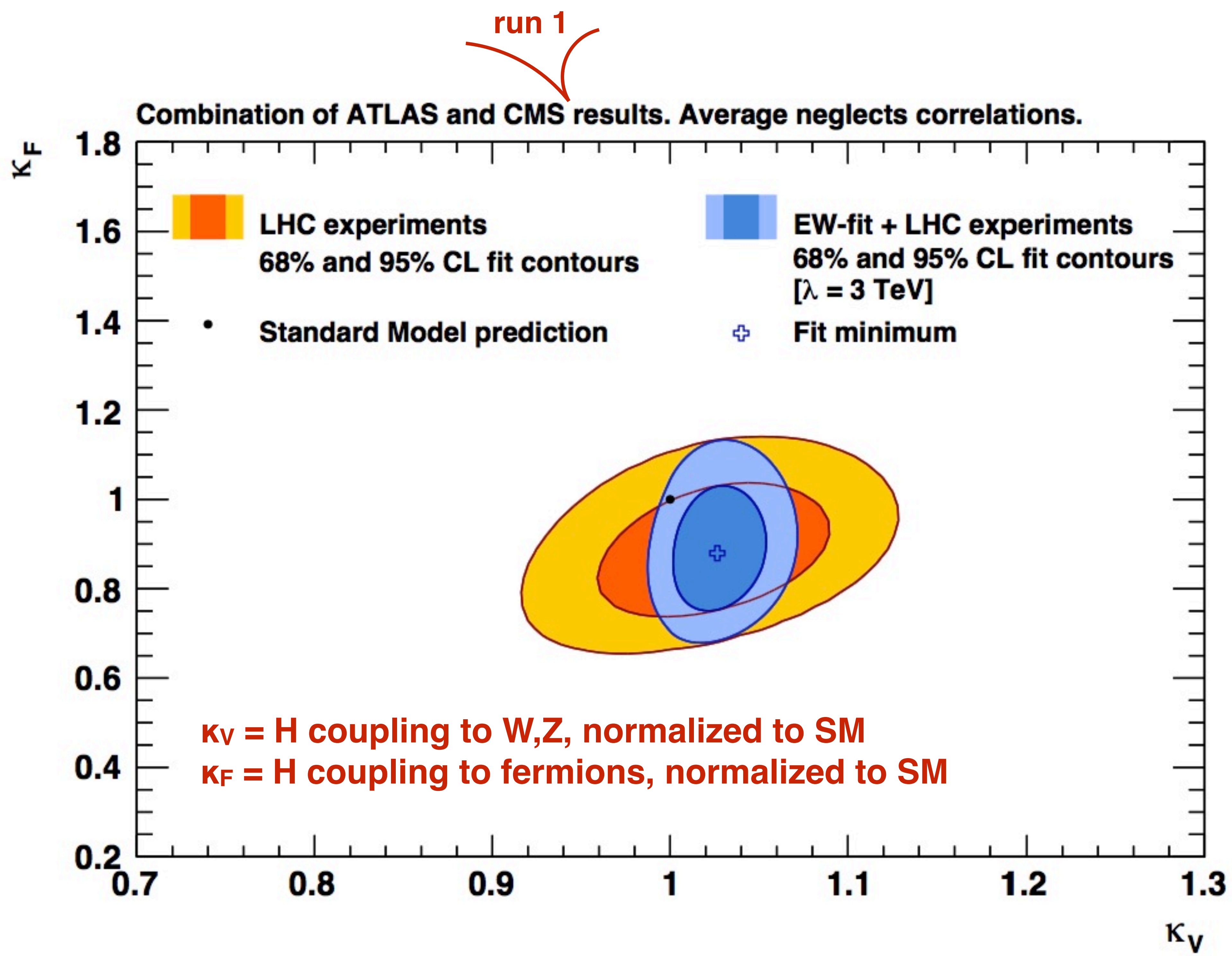
$\mu = 1.09 \pm 0.11$

- combination of different production and decay channels, explicit constraints on individual couplings are much less precise than 10% !!

- essential to establish couplings individually, through combinations of different production and decay channels

… keeping in mind the overall picture:

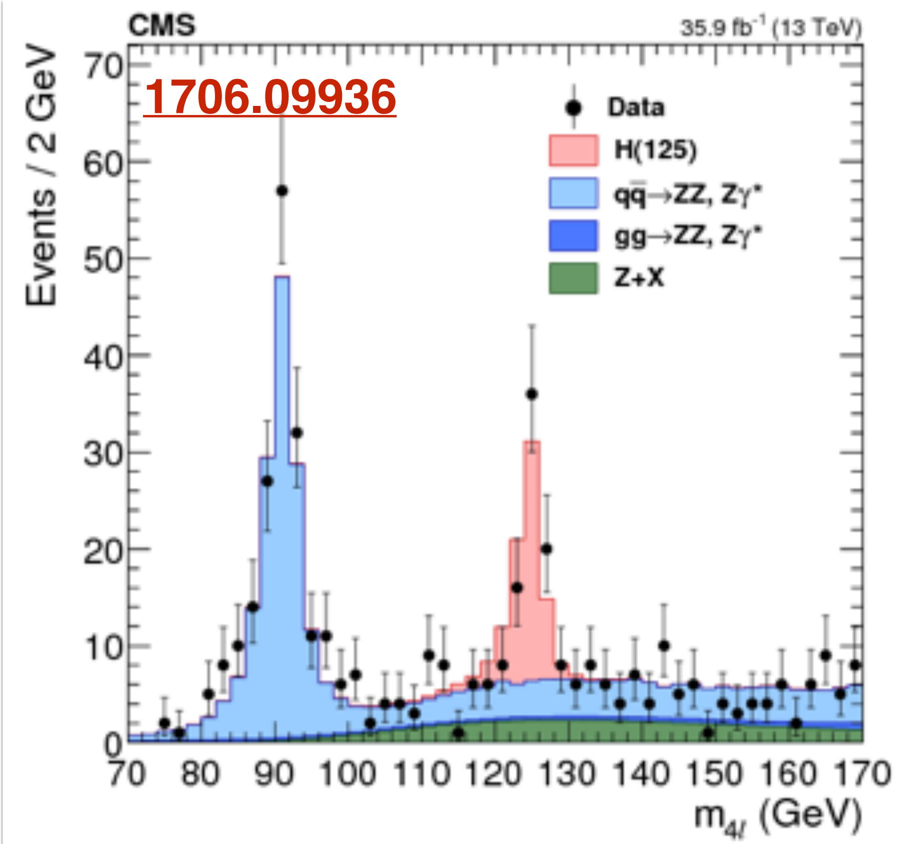
EW constraints are still ~more powerful than direct Higgs properties



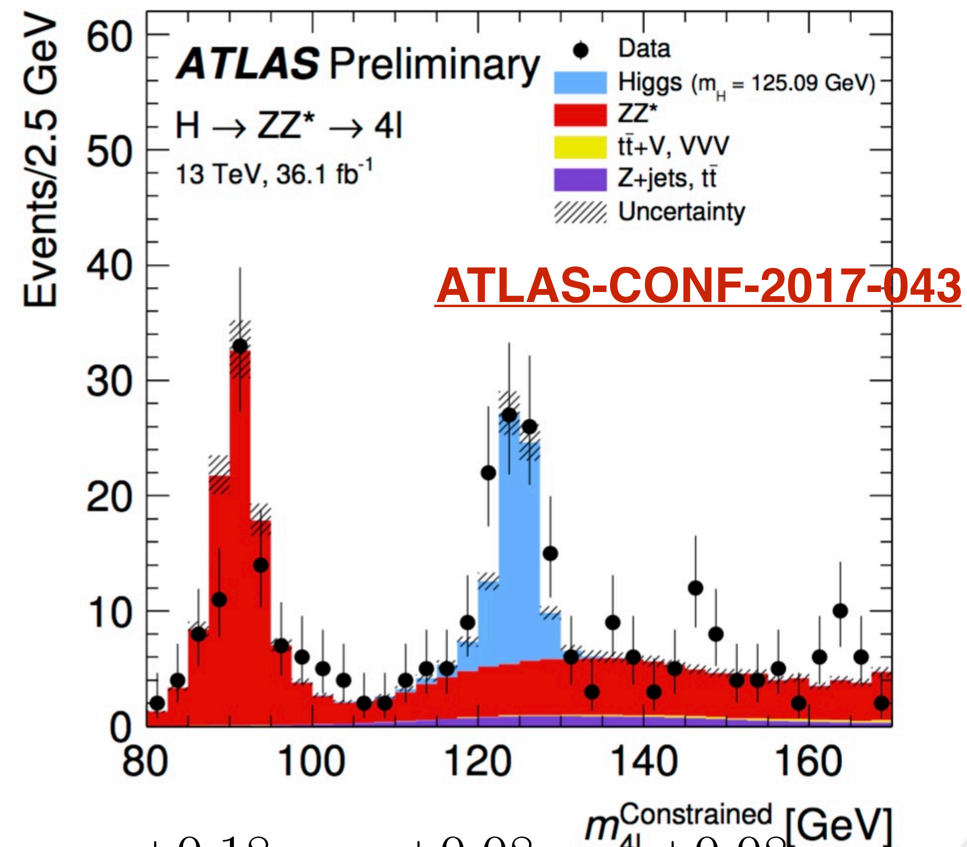
* Baak et al, EPJC 74 (2014) 3046

μ=(obs rate)/(SM rate), 2017

pp→H→4ℓ

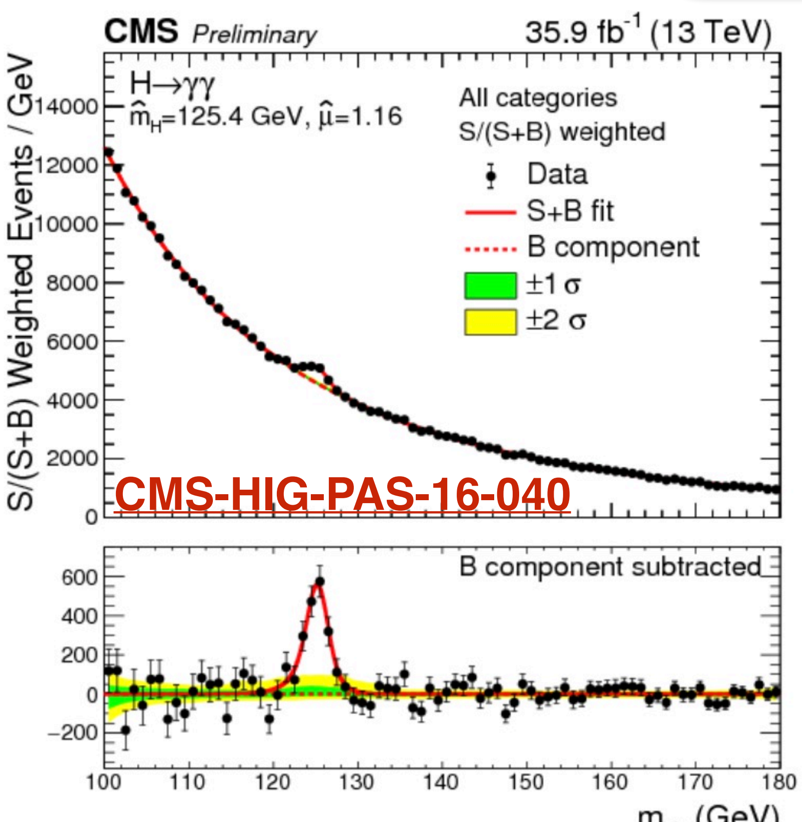


$$\mu = 1.05\,^{+0.15}_{-0.14}\,{}_{(stat)}\,^{+0.11}_{-0.09}\,{}_{(syst)} = 1.05\,^{+0.19}_{-0.17}$$

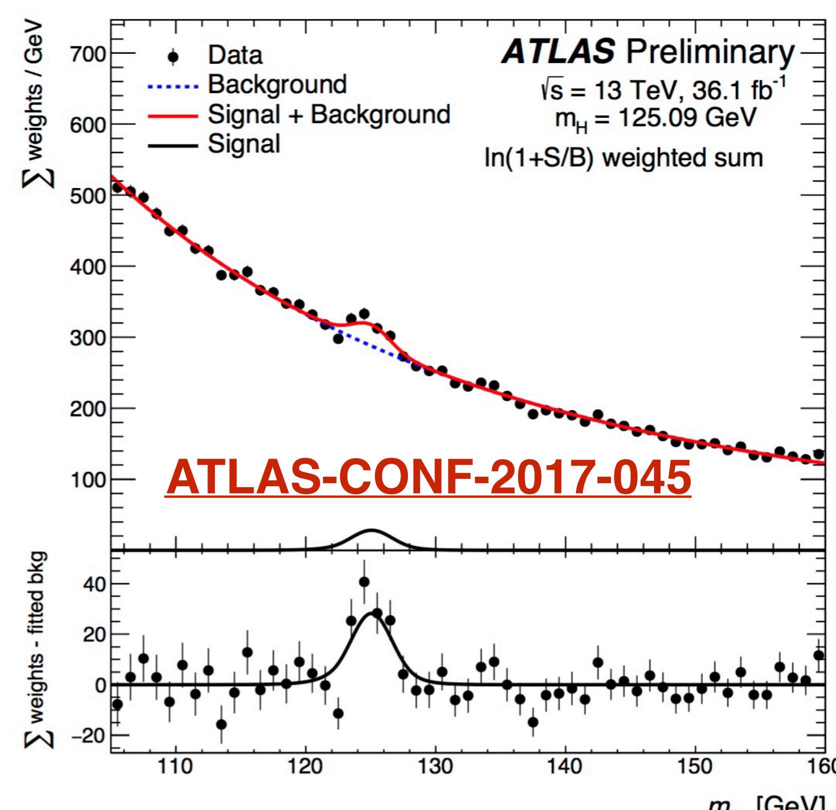


$$\mu = 1.28\,^{+0.18}_{-0.17}\,{}_{(stat)}\,^{+0.08}_{-0.06}\,{}_{(exp)}\,^{+0.08}_{-0.06}\,{}_{(TH)} = 1.28\,^{+0.21}_{-0.19}$$

pp→H→γγ



$$\mu = 1.16\,^{+0.11}_{-0.10}\,{}_{(stat)}\,^{+0.09}_{-0.08}\,{}_{(exp)}\,^{+0.06}_{-0.05}\,{}_{(TH)} = 1.16\,^{+0.15}_{-0.14}$$



$$\mu = 0.99\,^{+0.12}_{-0.11}\,{}_{(stat)}\,^{+0.06}_{-0.05}\,{}_{(exp)}\,^{+0.06}_{-0.05}\,{}_{(TH)} = 0.99 \pm 0.14$$

… by the end of run 2:

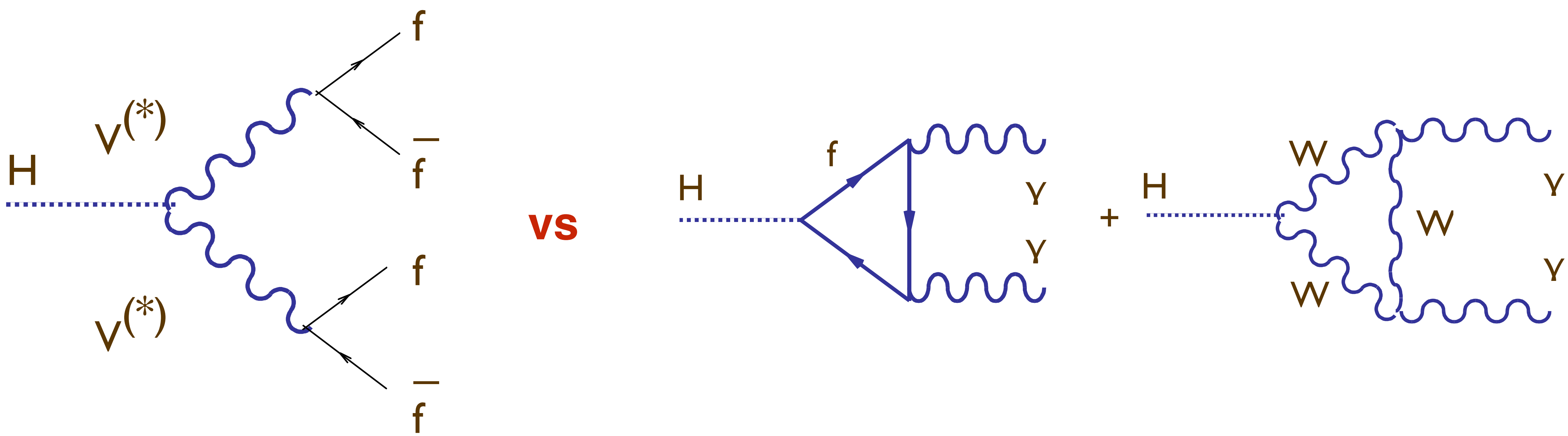
35 fb^{-1} → O(120) fb^{-1} ⇒ δ_{stat} → δ_{stat} / 2 ⇒δ_{stat} ~ O(δ_{syst}) ~ 10%

beyond run 2:

- Explore lower-rate but lower-syst measurements:
  - VH and VBF production channels (δ_{TH} ~ %)
  - "cleaner" kinematical configurations (eg high-p_T H production), possibly more sensitive to BSM effects
- Focus on ratios (removes several δ_{syst} , like δ_{lumi}~O(2%), $\delta_{TH\ xs}$~O(4%), …)

NB

- Ratios contain rich information, which new physics corrections cannot easily hide from
- Eg (pp→H→4ℓ) / (pp→H→γγ) probes loop vs tree-level couplings: a modification of the former affects the latter in a totally different way, and vice versa

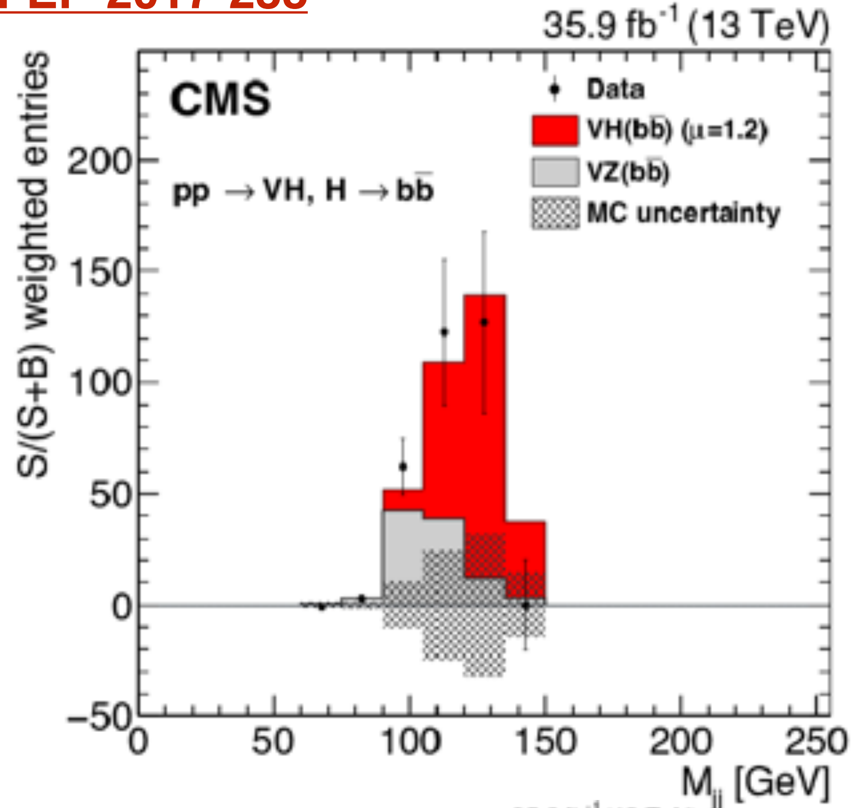


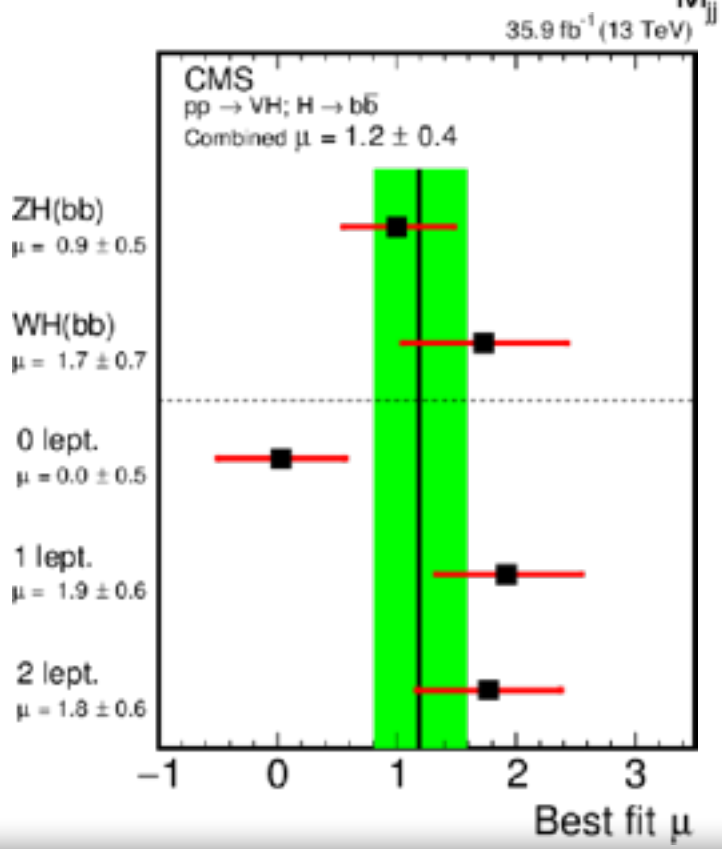
- Precise ratio measurements can be much more sensitive to new physics than individual absolute measurements

Direct evidence for Hbb coupling in pp→VH(→bb)

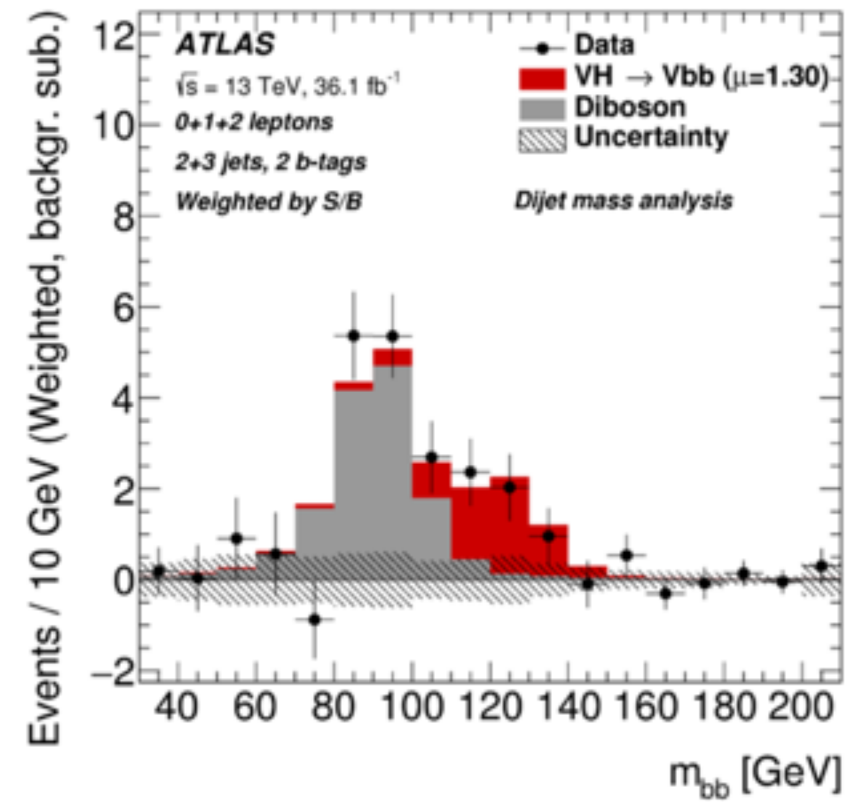
See also recent 5σ Hττ coupling results from CMS, CERN-EP-2017-181

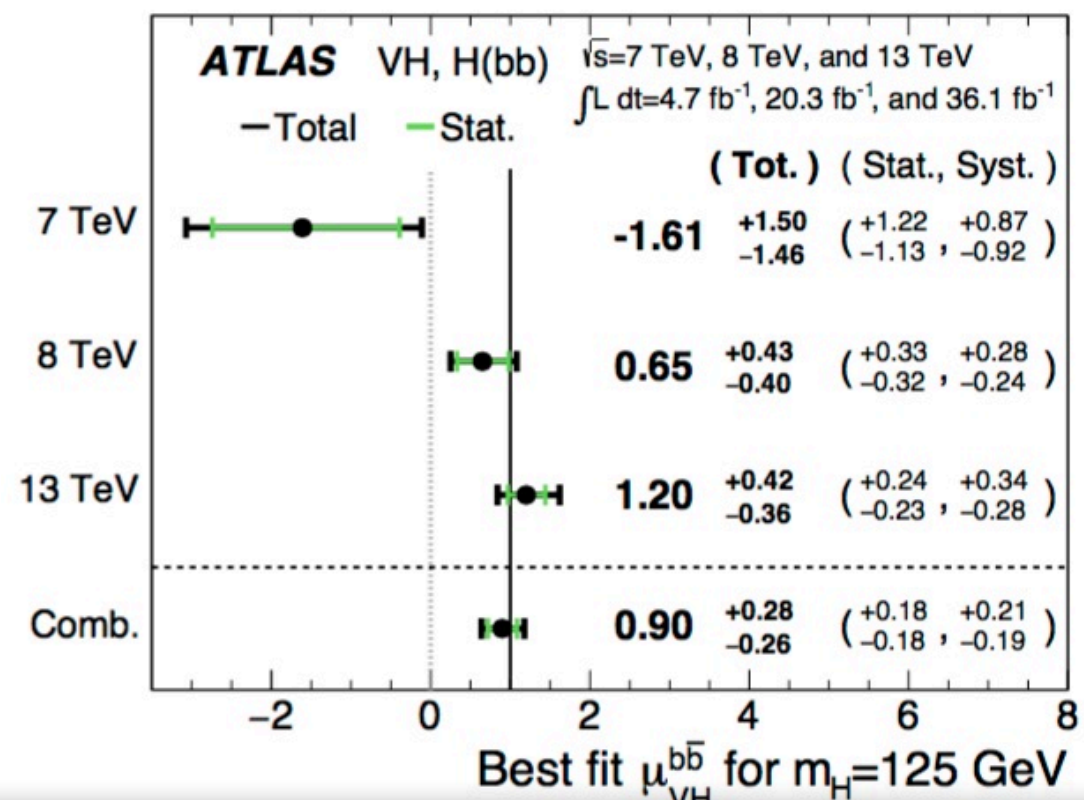
CMS, CERN-EP-2017-233





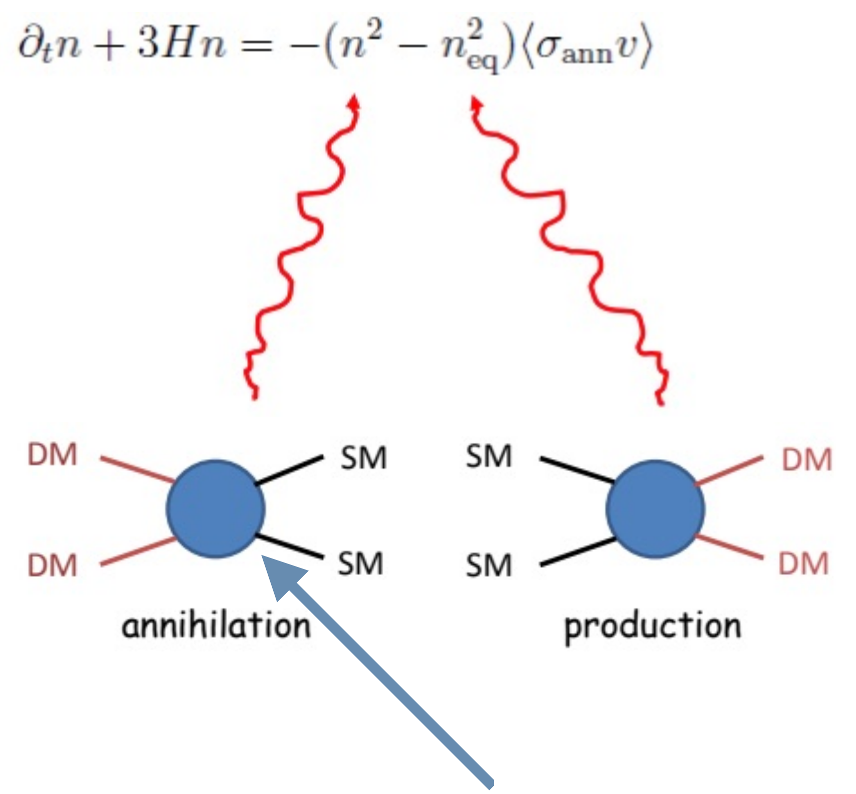
ATLAS, CERN-EP-2017-175

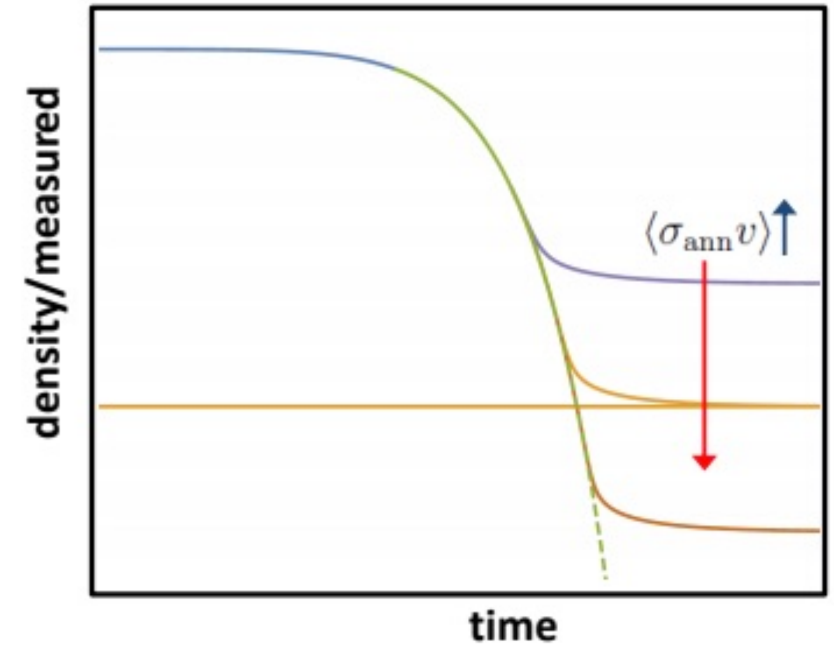




Run 1+2 $\mu=1.06^{+0.31}_{-0.29}$ ⇒ 3.8σ (3.8 exp'd) $\mu=0.90^{+0.28}_{-0.26}$ ⇒ 3.6σ (4.0 exp'd)

BSM searches: wimp DM as an example

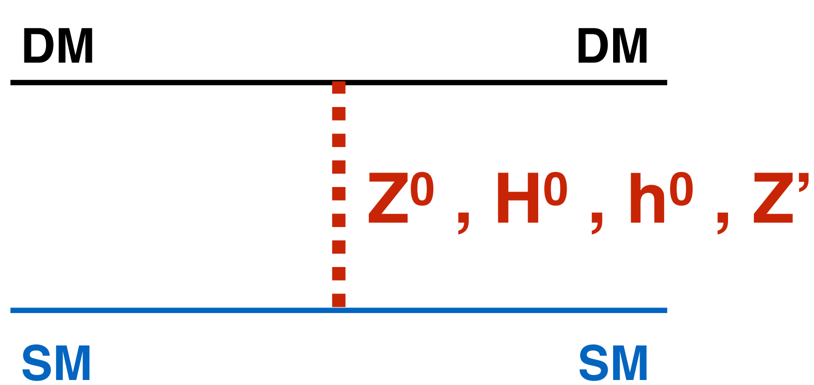


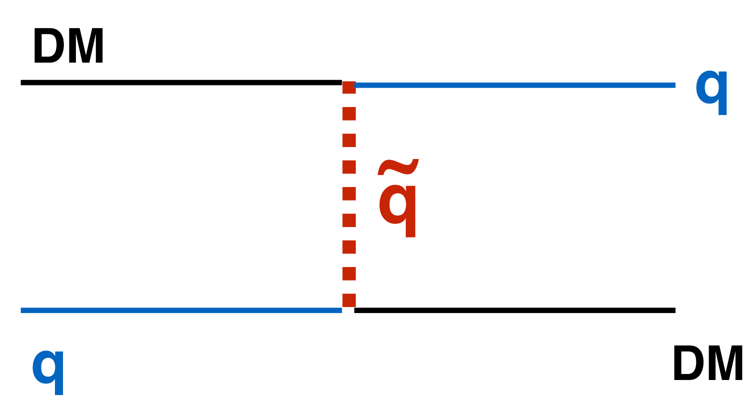


What's inside these blobs? SM particles (eg W/Z bosons) or other mediators?

What would be responsible for the interaction of DM with a "direct detection" detector?

E.g.:

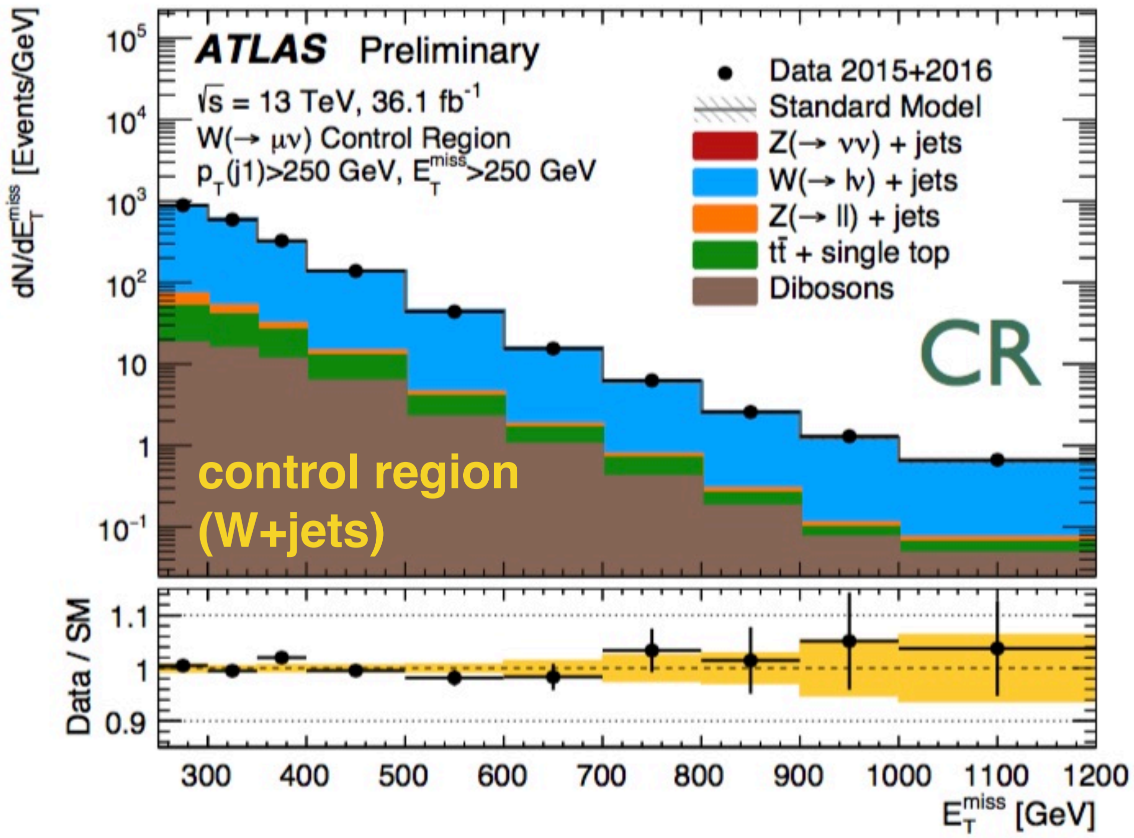


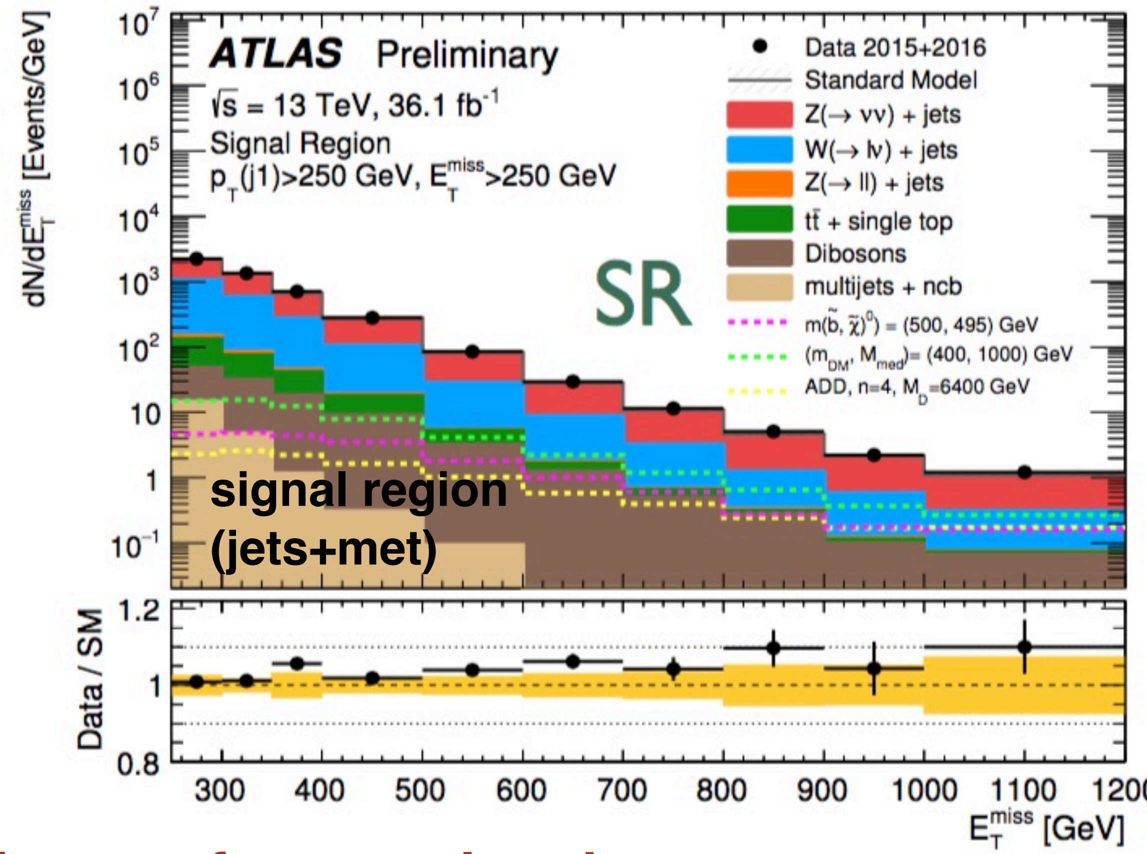


The LHC programme addresses both aspects of the problem, the search for a missing-E_T signal, and the search for potential mediators

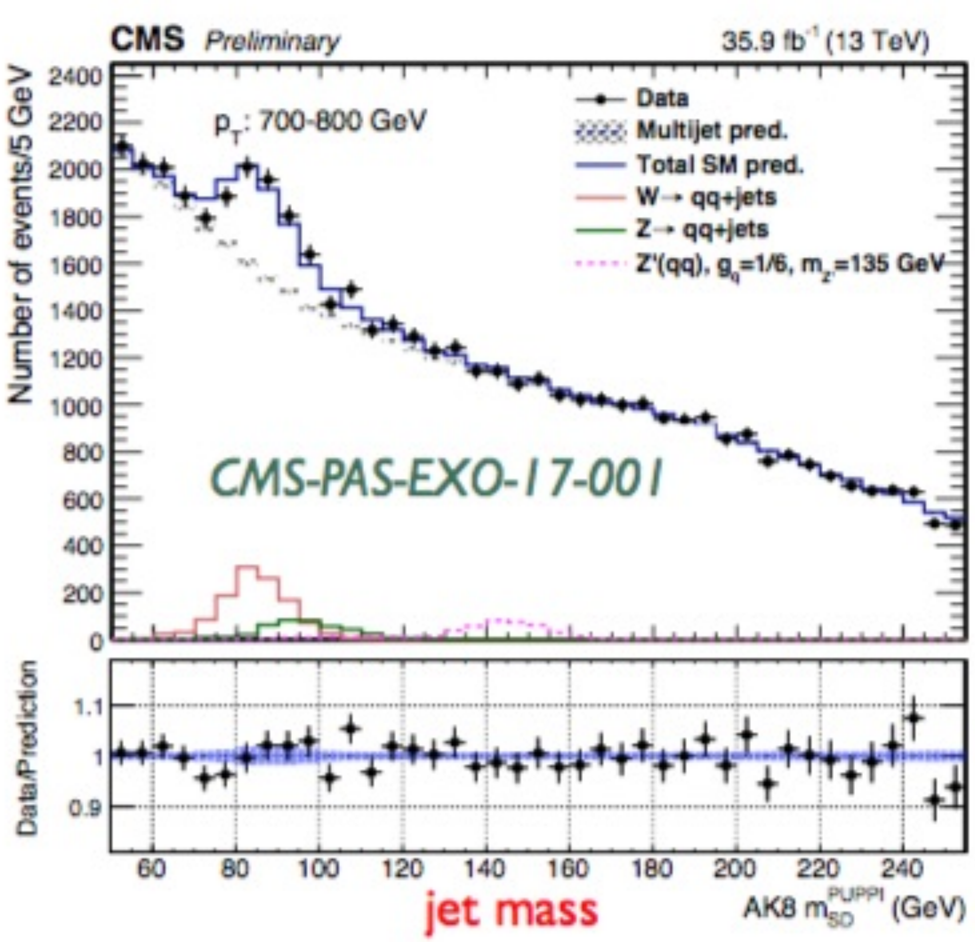
Superb control of the missE$_T$ signatures (few % syst's)

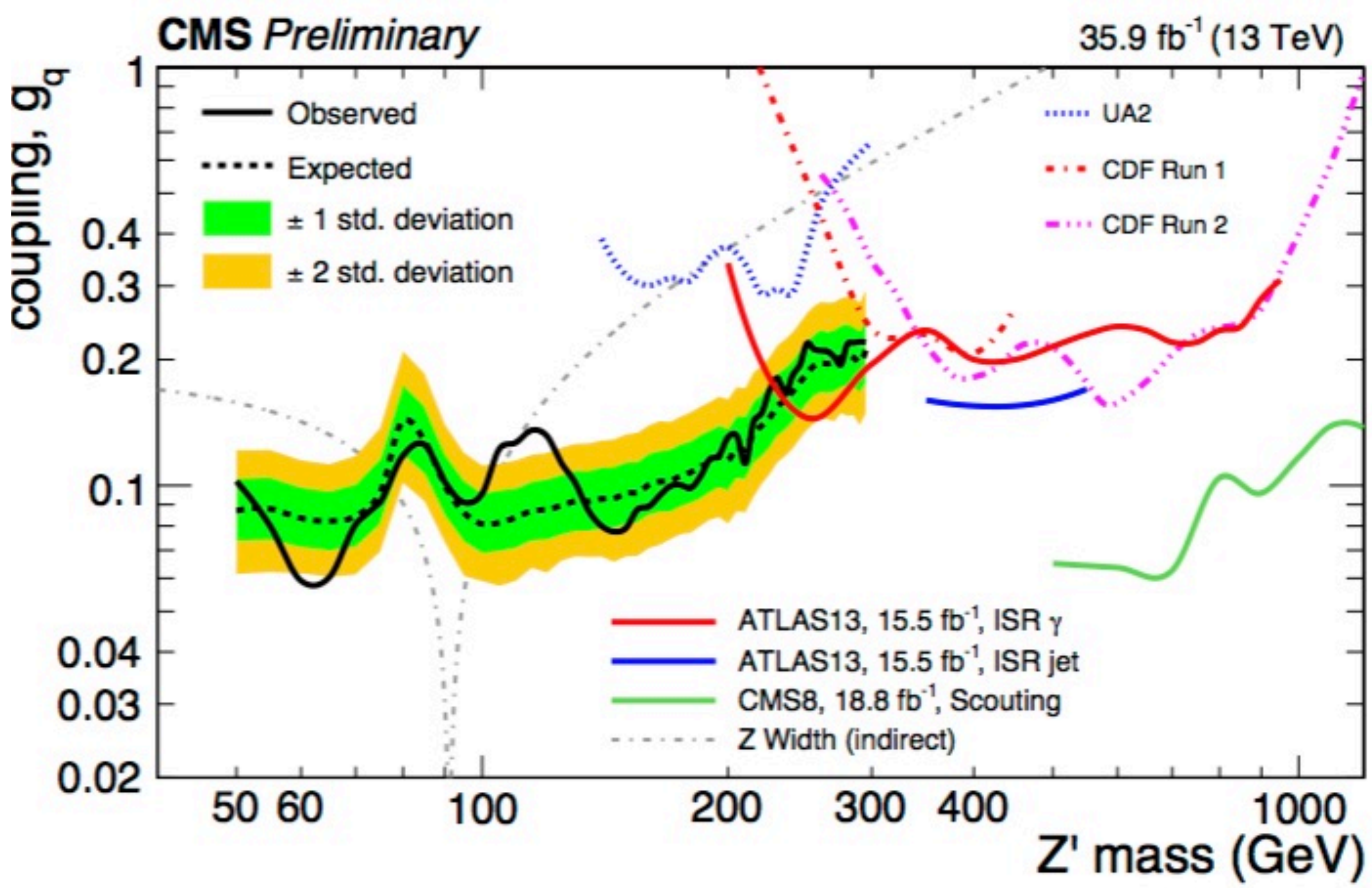
ATLAS-CONF-2017-060





Sensitivity to potential mediators in low-mass regions so-far unexplored





no signal so far of DM, or of other new particles ….

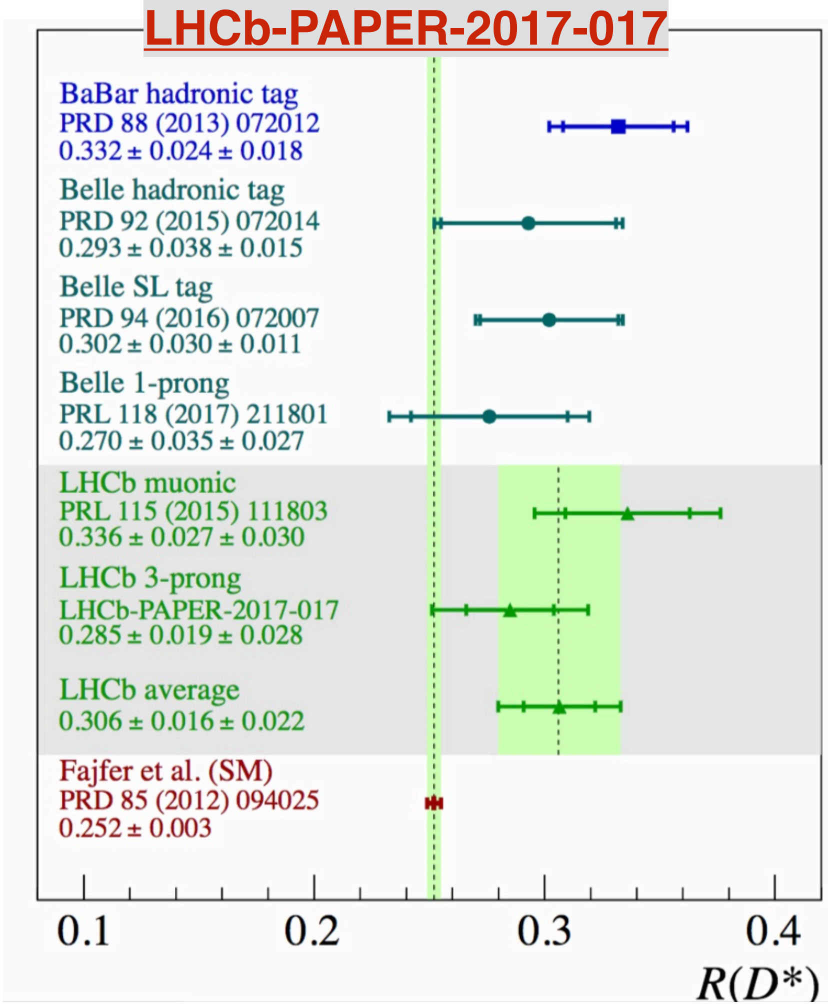
⇒ lack of evidence for new physics from LHC??

… not quite:

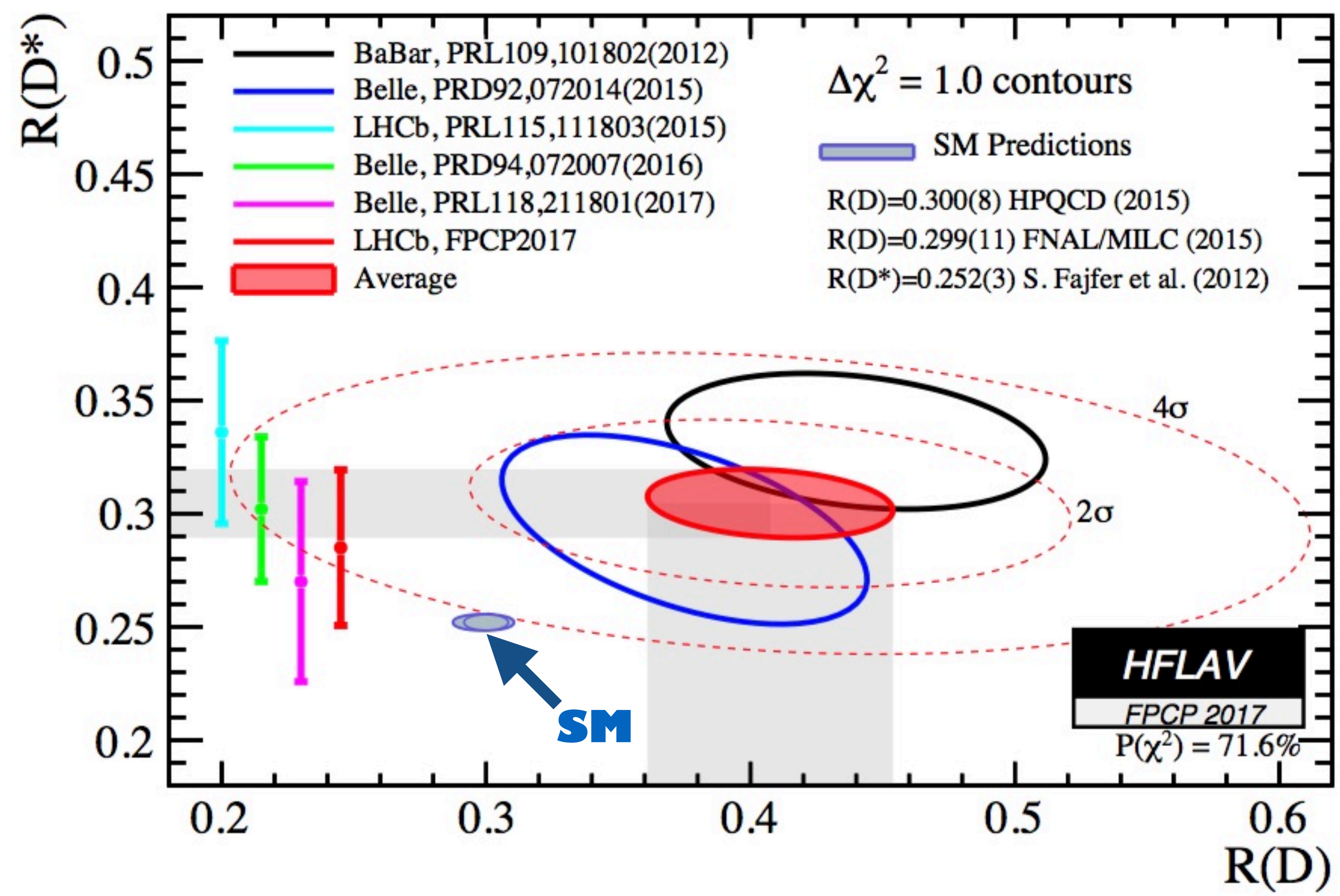
FLAVOUR ANOMALIES

b→cℓν

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\mu\nu)}$$



Overall combination of R(D) and R(D*) is 4.1σ from SM



b→sℓℓ

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

m_{ll} [mass range]	SM	Exp.
$R_K^{[1-6]}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*}^{[1.1-6]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.069} \pm 0.047$
$R_{K^*}^{[0.045,1.1]}$	0.91 ± 0.03	$0.660^{+0.110}_{-0.070} \pm 0.024$

LHCb, PRL 113 (2014) 151601 , arXiv:1705.05802

Remarks

The above observables are theoretically robust: small and reliable uncertainties

Other anomalies at the 2-3σ level exist, but subject to less robust estimates of QCD uncertainties

Statistics still plays a dominant role (esp for R_K). More data will also allow use of new final states with independent exptl systematics … eg

LHCb-PAPER-2017-035, to appear

$$R_{J/\psi} = \frac{BR(B_c \to J/\psi \tau \nu)}{BR(B_c \to J/\psi \mu \nu)}$$

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

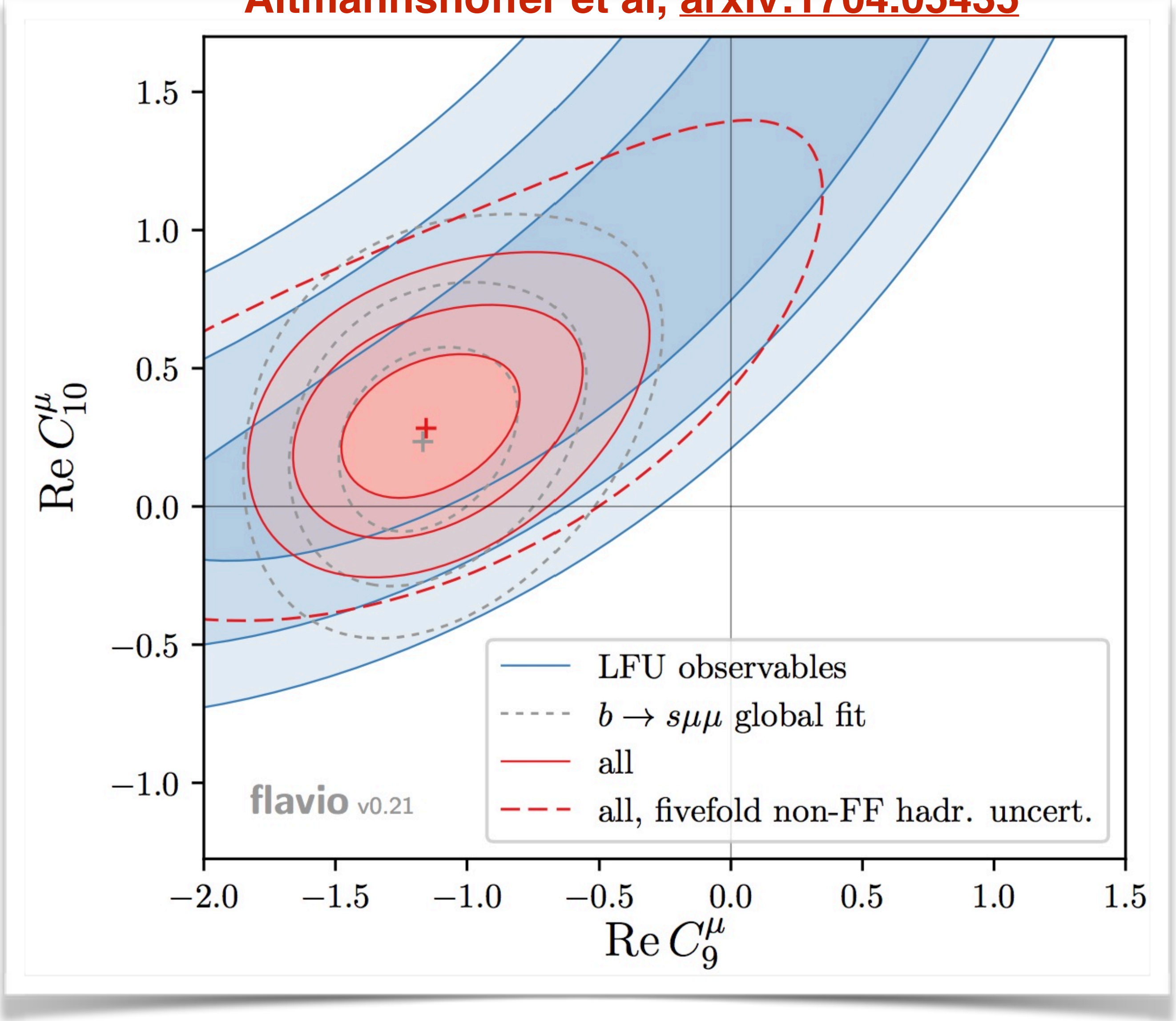
(about 2 σ from SM)

The fact that SM deviations of this type, variety and size are phenomenologically acceptable, gives a sign of how little we still know about "what's out there" at the TeV scale, and our openness towards surprises (see also the story of the 750 GeV γγ resonance)

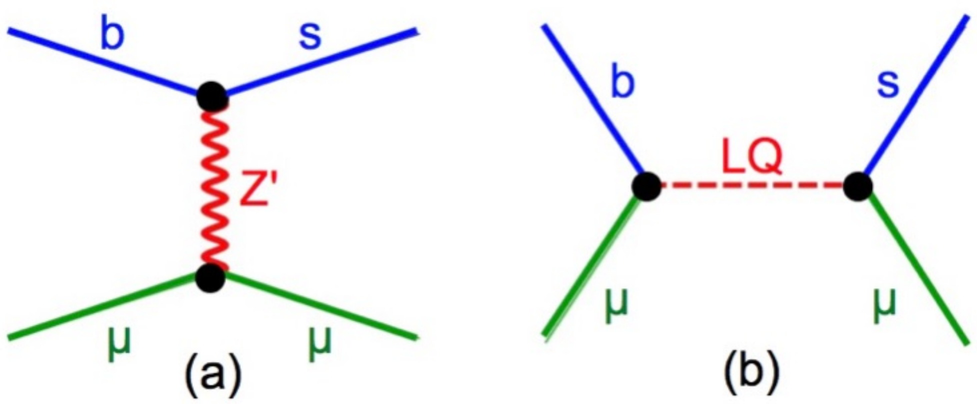
Example of EFT interpretation of R_K

$$O_9^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

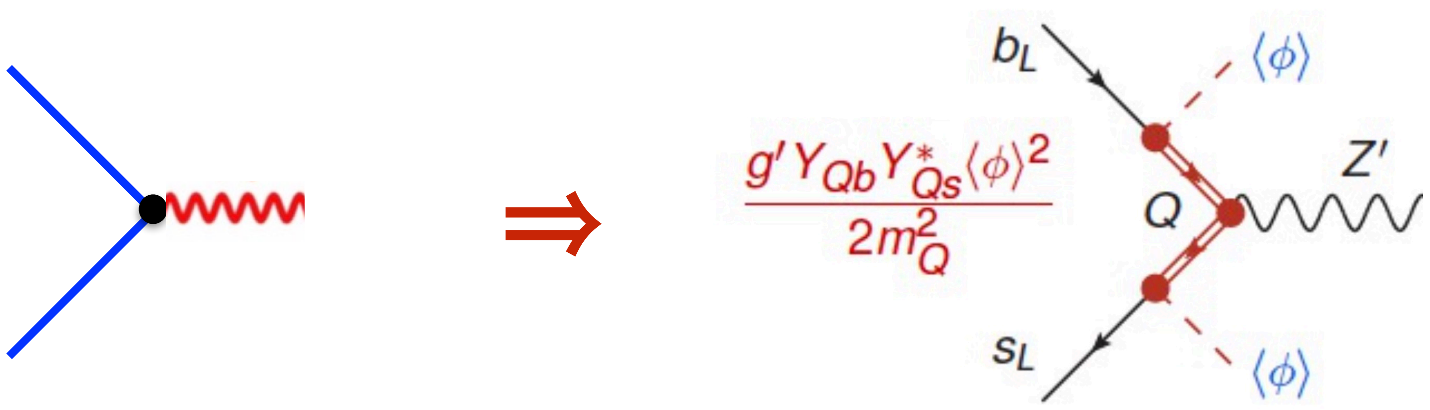
Altmannshoffer et al, arxiv:1704.05435



Possible explicit realizations:



where, e.g. ,



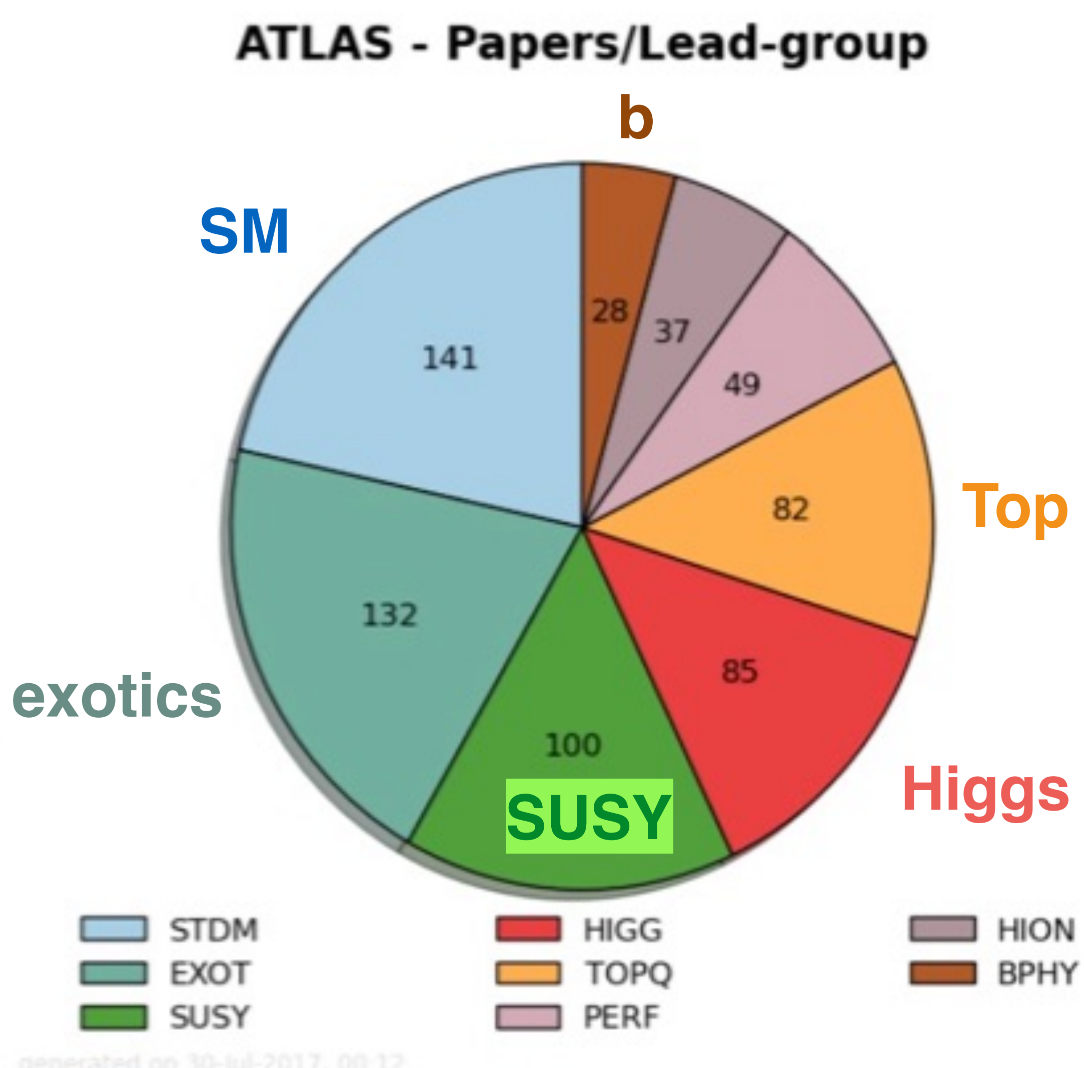
Upper limits on Z' and Leptoquark masses are model-dependent, and constrained also by other low-energy flavour pheonmenology, but typically lie in the range of 1→few TeV

LHC scientific production (ATLAS, CMS, LHCb)

Papers published/submitted to refereed journals

ATLAS	670
CMS	650
LHCb	396

Programme diversity (ATLAS example, similar stats for the others)



65% of the papers on measurements (ie on “the real world”)

35% on searches

Remarks

- These 1700 papers reflect the underlying existence, at the LHC, of 100's of scientifically "independent" experiments, which historically would have required different detectors and facilities, built and operated by different communities
- On each of these topics the LHC expts are advancing the knowledge previously acquired by dedicated facilities
  - HERA→PDFs, B-factories→flavour, RHIC→HIs, LEP/SLC→EWPT, etc
- Even in the perspective of new dedicated facilities, LHC maintains a key role of complementarity (see eg $B_{(s)} \to \mu\mu$ etc)

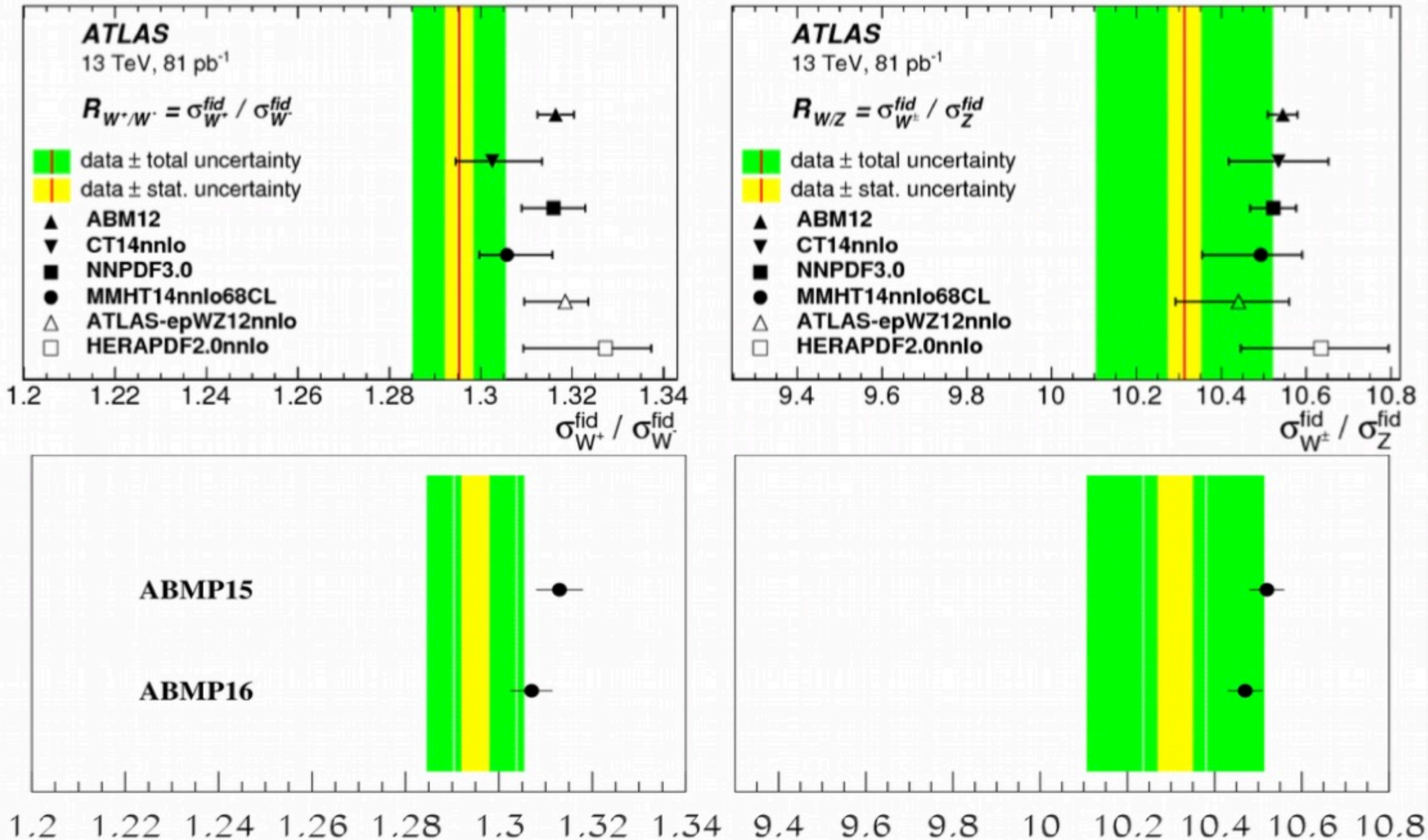
Not covered for lack of time

- **Extensive programme of searches for BSM**
- **Rich flavour physics programme**
  - precise measurements of CKM from charm/b decays
  - rare processes ($B_{d,s} \to \mu\mu$ decays, …)
- **Thorough and extensive studies of QCD dynamics in non-perturbative regimes**
  - total, elastic and diffractive cross sections
  - PDF determinations via precise XS measurements (W/Z, jets, hvq's)
  - exotic hadrons: tetra- and pentaquark spectroscopy, glueball searches via exclusive diffractive pp reactions, …
  - hadron production in the fwd region (implications for modeling of cosmic-ray showers in the atmosphere)
  - collective phenomena in pp, pA and AA collisions (the "ridge" effect)
  - nuclear PDF determinations with the pA programme
  - heavy ion collisions, QGP

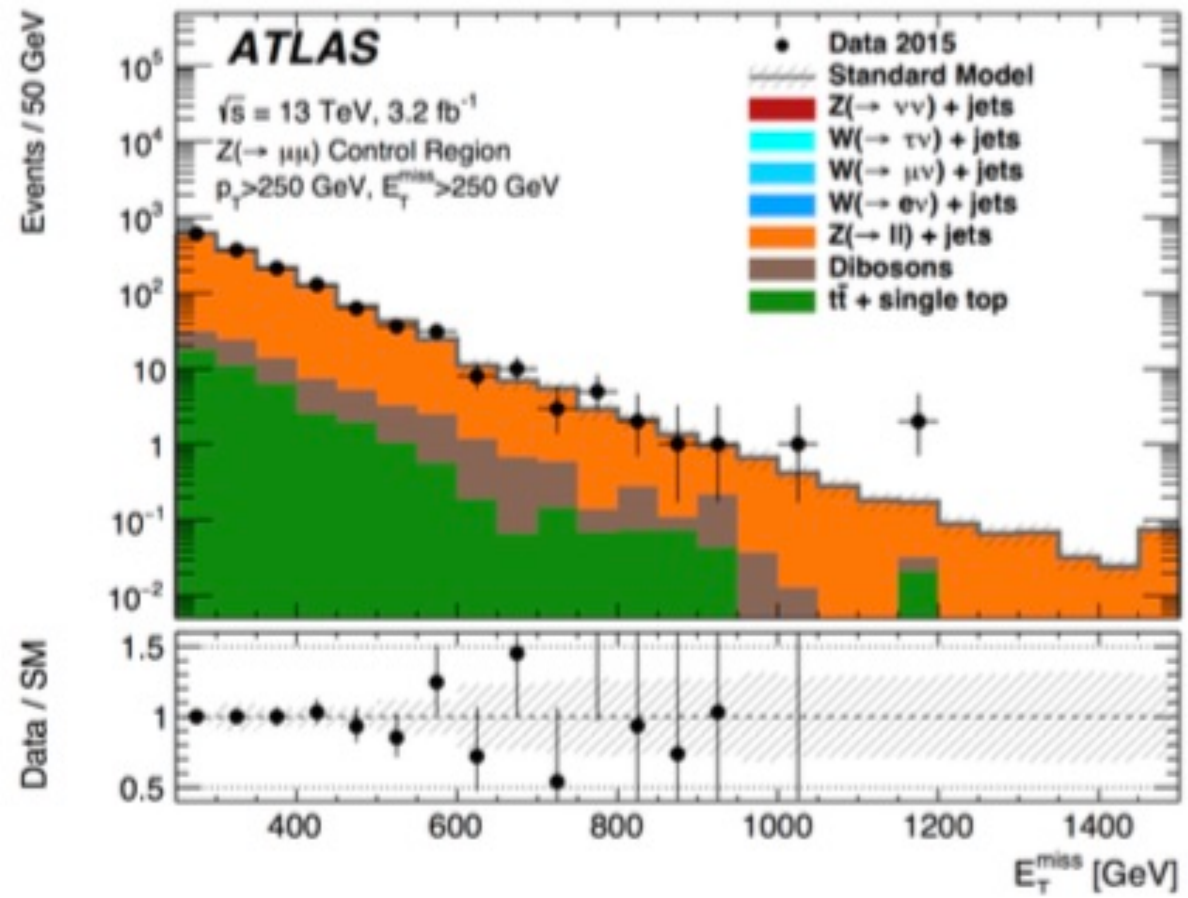
Some examples

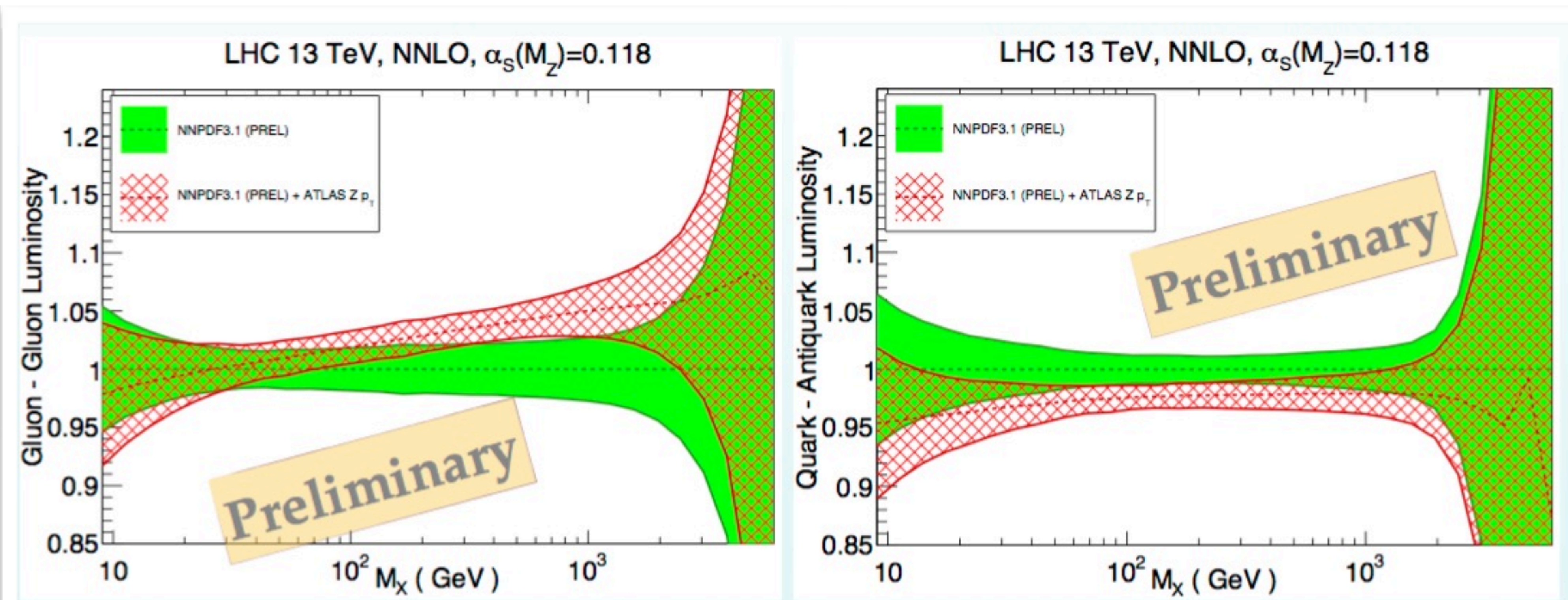
ATLAS W&Z at 13 TeV

ATLAS, hep-ex/1603.09222



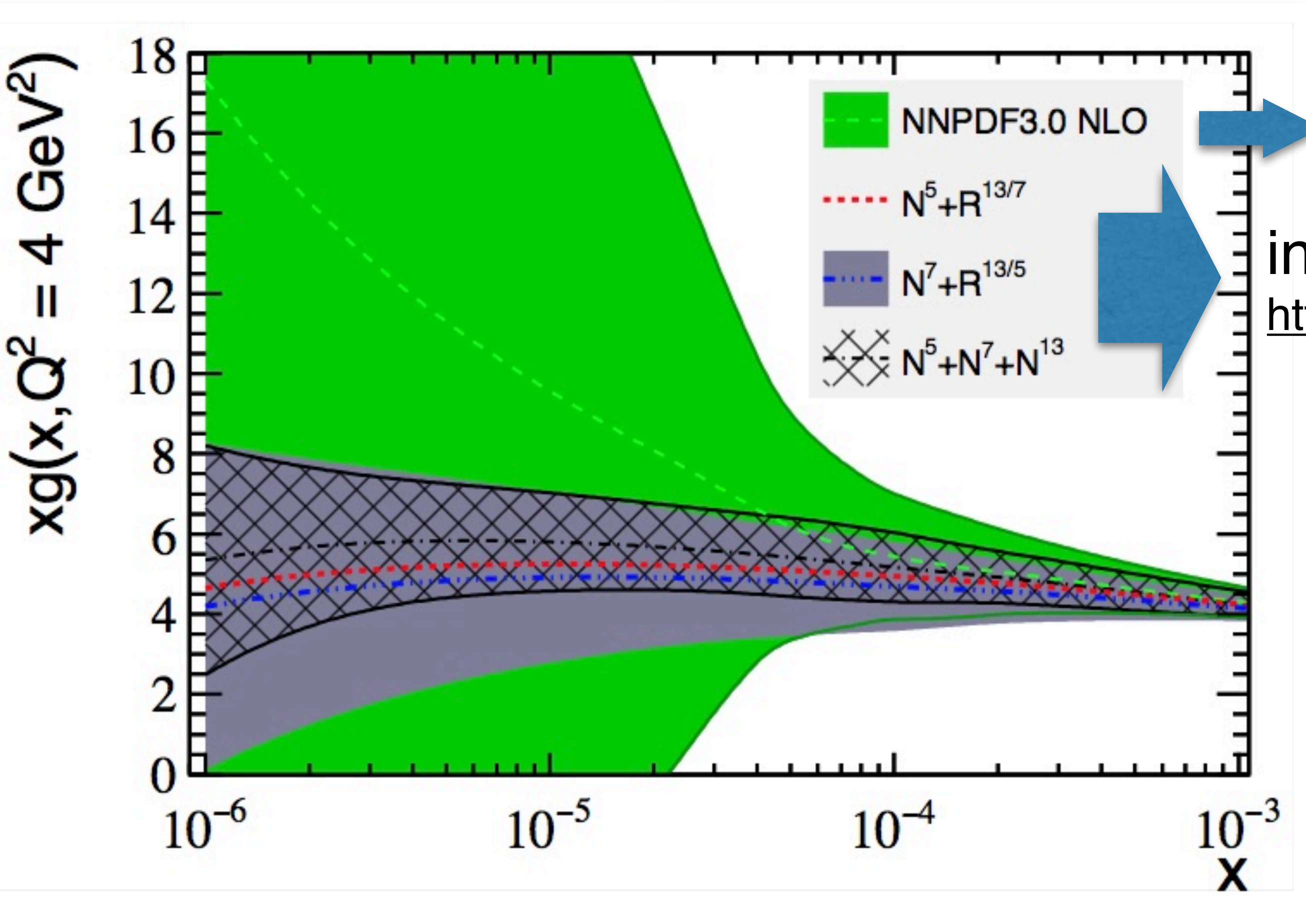
Impact of Z p_T spectrum on PDF fits





Preliminary NNPDF3.1 NNLO fits suggest a **sizeable impact** of the **LHC Z p_T data** on the PDFs

Forward charm production at LHCb, implications for cosmic ray physics



Gauld, Rojo: http://arxiv.org/abs/arXiv:1610.09373

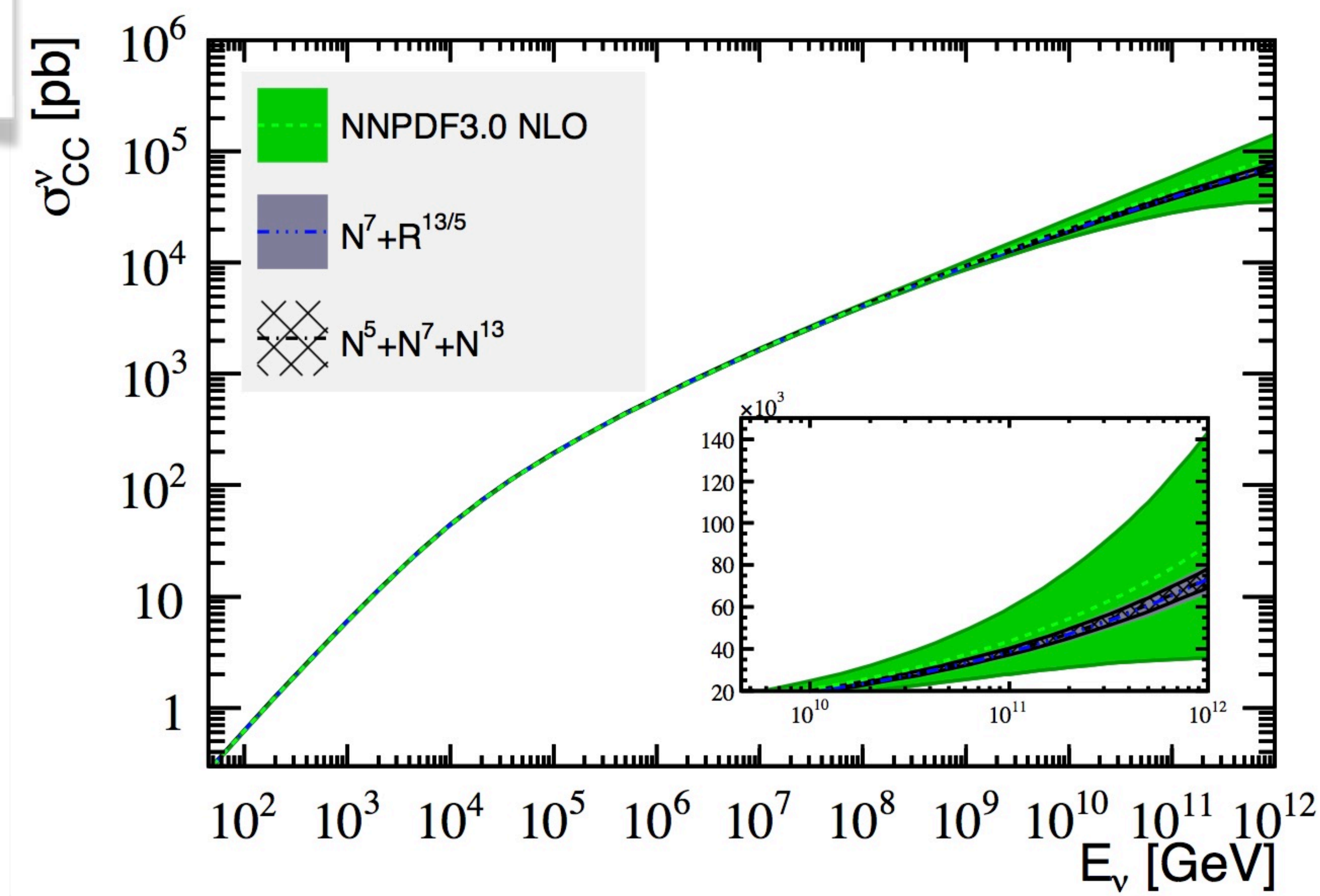
→ only HERA small-x data

→ inclusion of LHCb charm data in the fits
http://arxiv.org/abs/arXiv:1610.02230

$$N_X^{ij} = \frac{d^2\sigma(\text{X TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\text{X TeV})}{dy_{\text{ref}}^D d(p_T^D)_j} ,$$

$$R_{13/X}^{ij} = \frac{d^2\sigma(\text{13 TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\text{X TeV})}{dy_i^D d(p_T^D)_j} ,$$

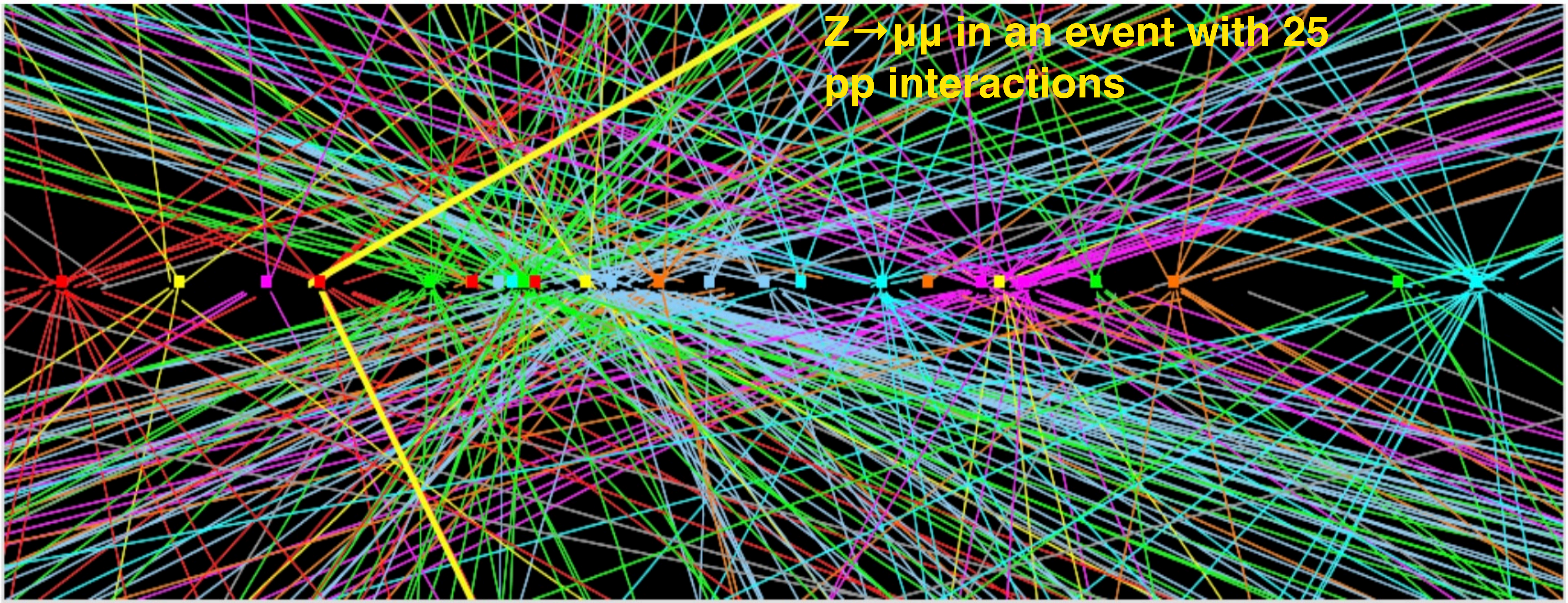
The reduction in small-x gluon PDF uncertainty leads to a reduction in systematics for the calculation of the cross sections of cosmic high-energy neutrinos



Final remarks

- LHC results are having a profound impact on HEP
- The thoroughness, and inconclusiveness, of **direct** BSM searches, redefines our expectations on physics at the TeV-scale, and forces us to review in detail even the most basic assumptions and theoretical biases (naturalness, charged-lepton universality, wimp miracle, …)
- The LHC surprises us each day with its versatility and precision: it is redefining the physics landscape in several areas within, and well beyond, its initial scopes and ambitions
- More than ever, and independently of whether new discoveries will emerge soon, it appears to be the right machine to exhaustively explore and settle the understanding of physics at the TeV scale

O(5-10cm)



currently at ⟨pileup⟩>30, increasing to 150-200 from 2026 …. like doing optical astronomy with a telescope mounted in Times Square, instead of on top of Mt Palomar