Higgs and Fundamental Interactions at High Precision

Results with DESY scientists' leading contributions

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Hamburg, 02.12.2024

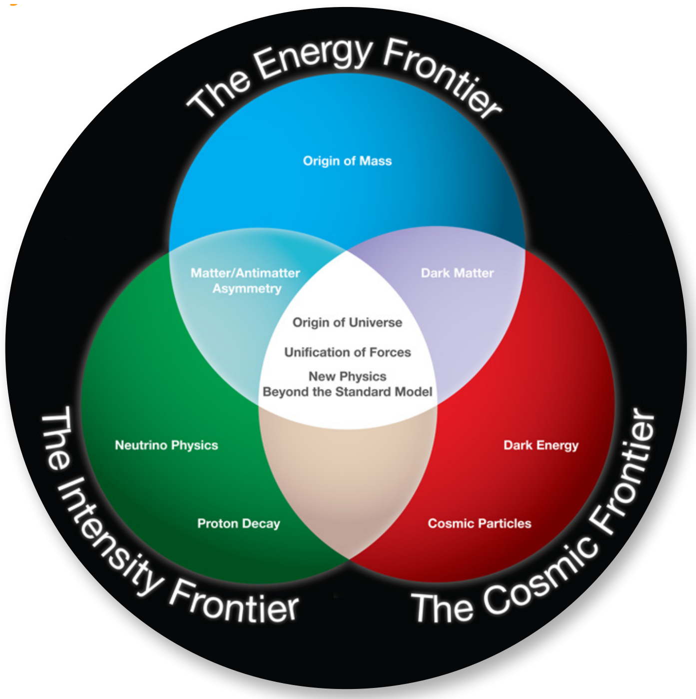
Stringent test of the standard model

Has been tested by many experiments since its formulation

Perform measurements across a broad range of observables and compare them to SM predictions.

The intensity frontier

- High-flux beams colliding at low energies
- Uncover new particles indirectly
    - E.g. could alter the lepton flavour universality



The energy frontier

- Particle beams colliding at high energies
- Direct production of new particles
    - E.g. is the Higgs boson at 125 GeV the SM Higgs?

Significant deviations from the SM predictions can indicate the presence of physics beyond the SM.

ATLAS, CMS and Belle II

Main players at DESY

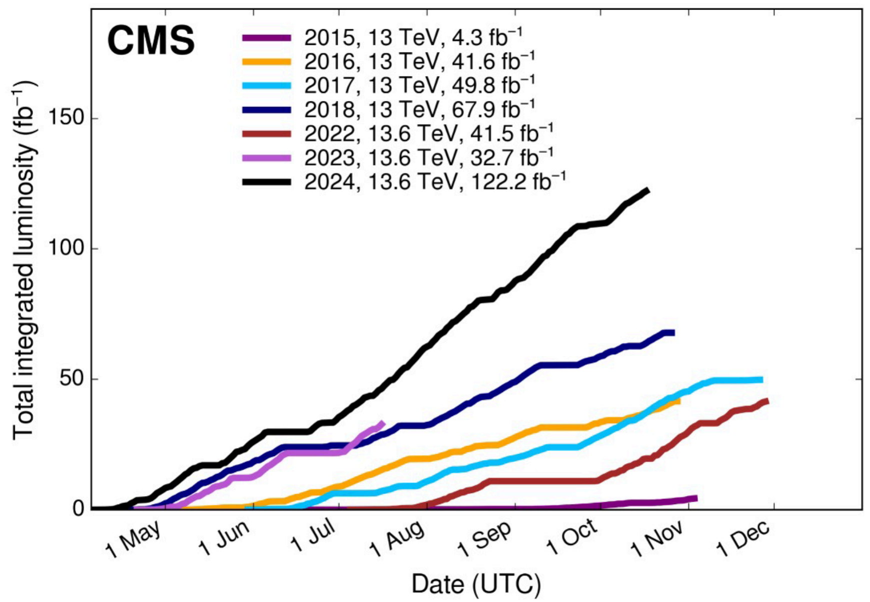
Rich harvest of data:

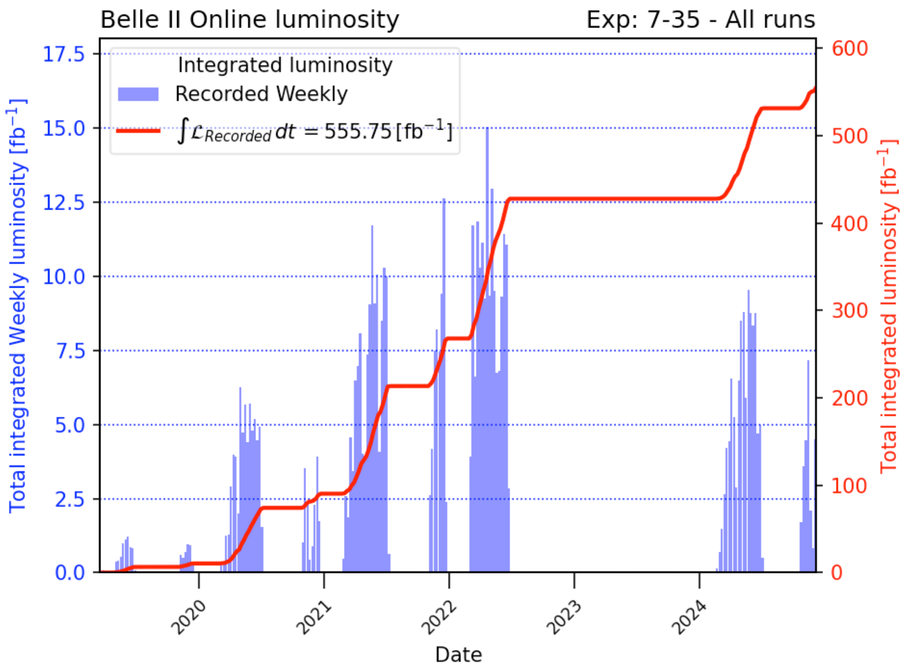
- LHC delivered $140\ \mathrm{fb}^{-1}$ at Run2, and already $196\ \mathrm{fb}^{-1}$ in Run3
- Belle II collected same amount of data as the first generation B-factories

Key contributions to operations and calibration.

Examples:

- Alignment of CMS and Belle II detectors with Millipede II (program developed by UHH and DESY scientists)
- Unprecedented precision of luminosity measurement (ATLAS 0.83% full Run 2, CMS 1.2% in 2016)
- Neutral and charged particle reconstructions at Belle II (DESY scientists holding leading positions)





Higgs boson couplings to bosons and fermions

ATLAS: Nature 607 52 (2022)
CMS: Nature 607 60 (2022)

Only interaction that distinguishes the generations of fermions

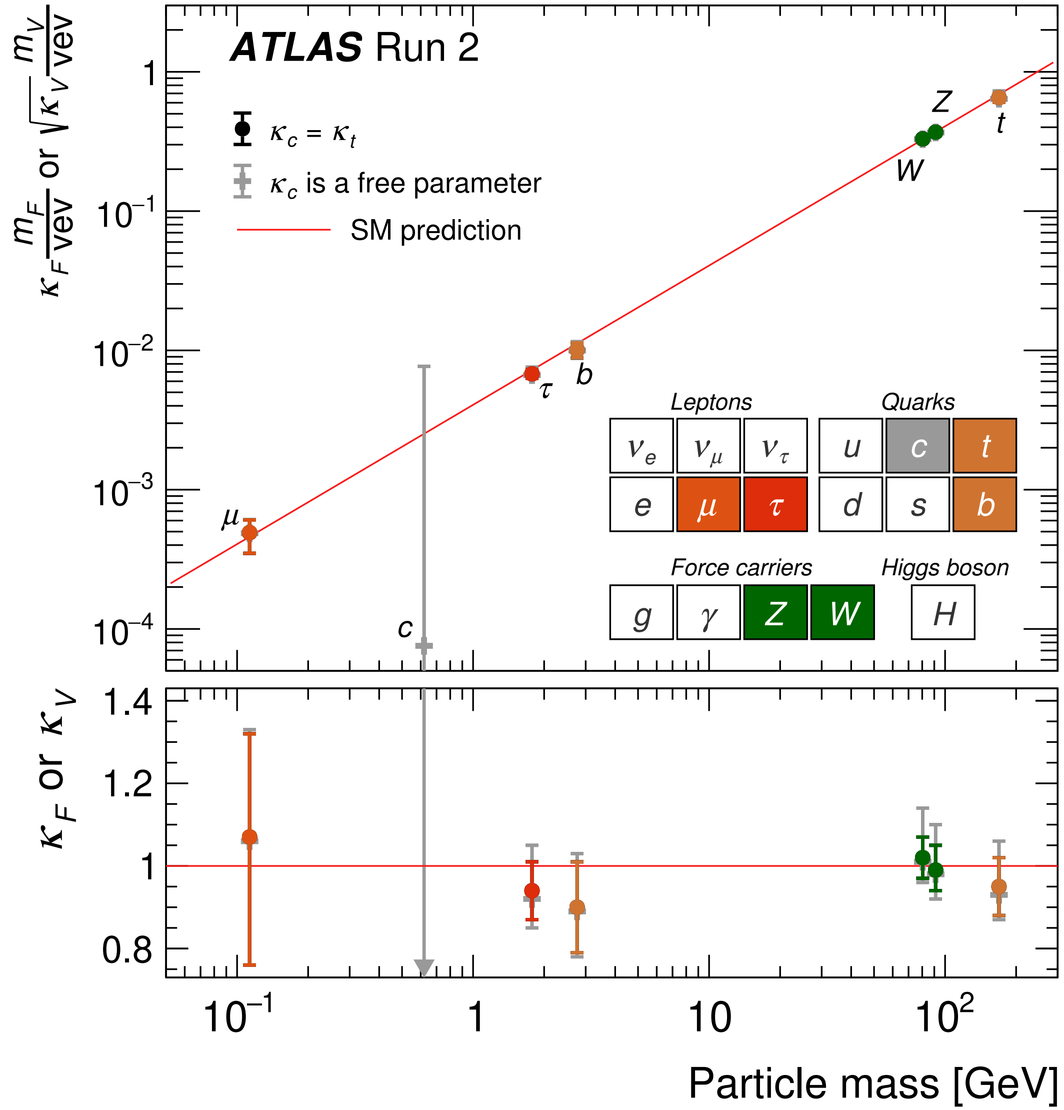
Kunlin Ran,
Tina Ojeda,
Birgit Stapf,
Petar Bokan

Detailed portrait of the Higgs boson from ATLAS and CMS 10 years after its discovery

- Statistical combination of a large range of measurements of different Higgs boson production and decay channels using LHC Run 2 data
- The measurements are interpreted in the κ-framework
  - κ is multiplicative modifier of SM Higgs coupling

Couplings to the Higgs boson scale with the particle mass

- Precision of 6-8% on couplings to bosons and 7-12% on couplings to third-generation fermions



Characterising the Higgs boson production

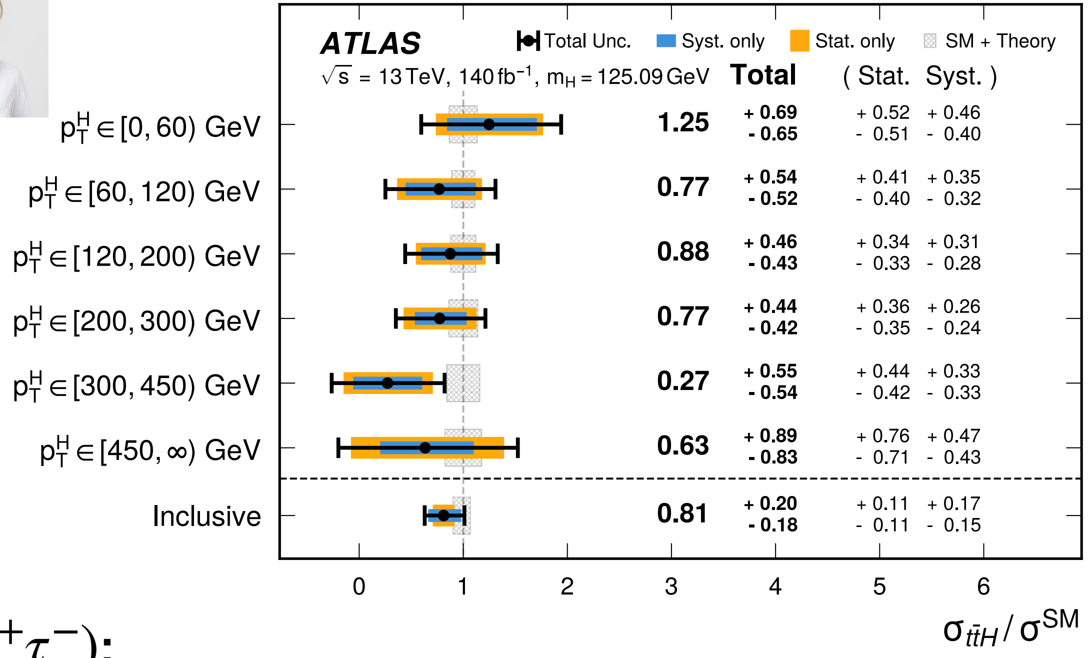
ATLAS: arXiv:2407.10904
CMS: EPJ C83 (2023) 562
STXS: arXiv:1906.02754

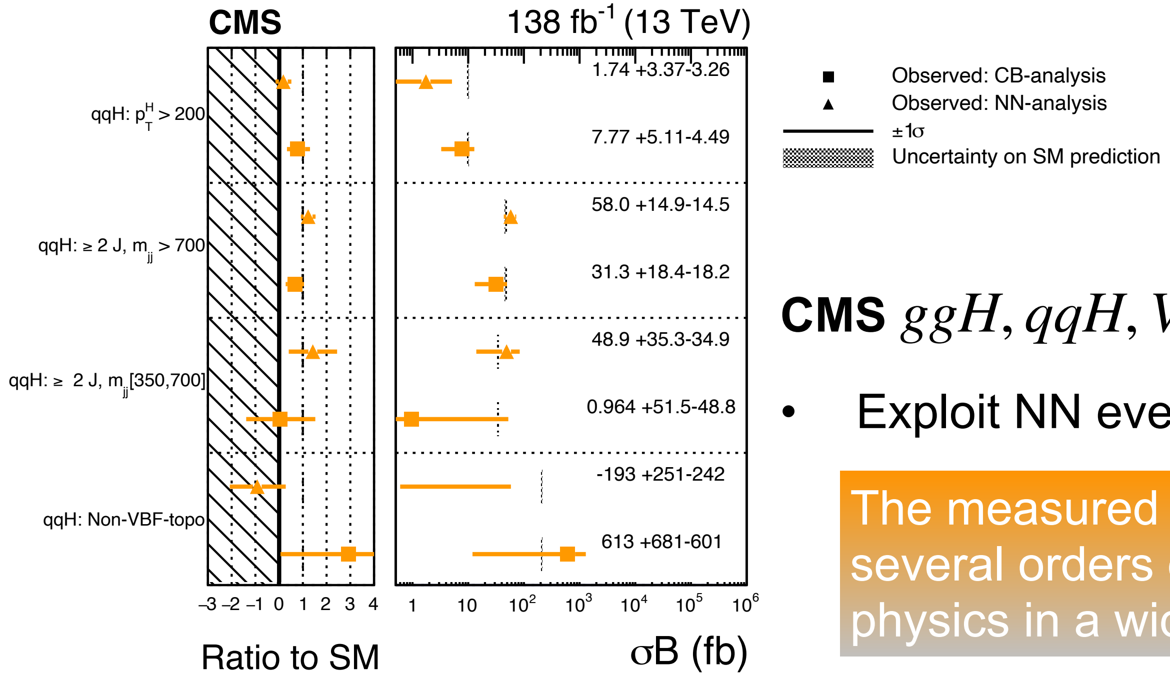
Studying the kinematics for individual production processes

ATLAS: $t\bar{t}H(\rightarrow b\bar{b})$:

- Most precise single-channel inclusive and differential cross section

Best sensitivity to the high p_T region, particularly sensitive to BSM physics





CMS $ggH, qqH, VH(H \rightarrow \tau^+\tau^-)$:

- Exploit NN event selection, enhancing the precision of differential results

The measured differential cross sections span several orders of magnitude, probing the BSM physics in a wide range.

Higgs total and differential cross sections

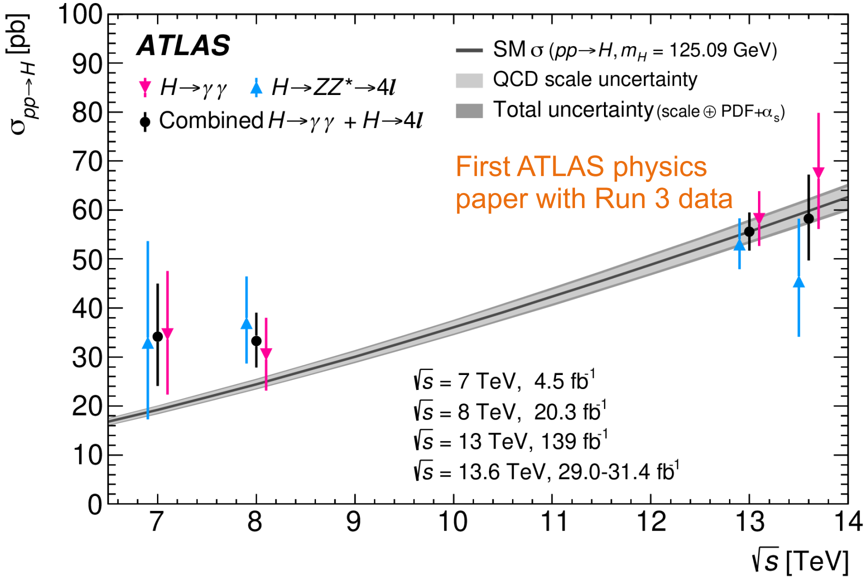
ATLAS: JHEP 05 (2023) 028
EPJ. C 84 (2024) 78
Theory: PRL 127 (2021) 7

Excellent resolution channels H→γγ and H→ZZ*→4l

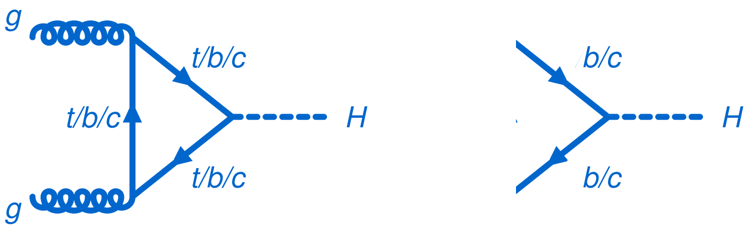
Unprecedented precision of 7%, comparable to that of the SM (5%).

$$\sigma_{pp\to H} = 55.5^{+4.0}_{-3.8}\ \text{pb} \qquad \sigma^{SM}_{pp\to H} = 55.6 \pm 2.5\ \text{pb}$$

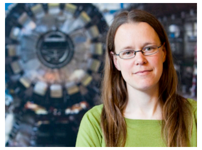
13 TeV



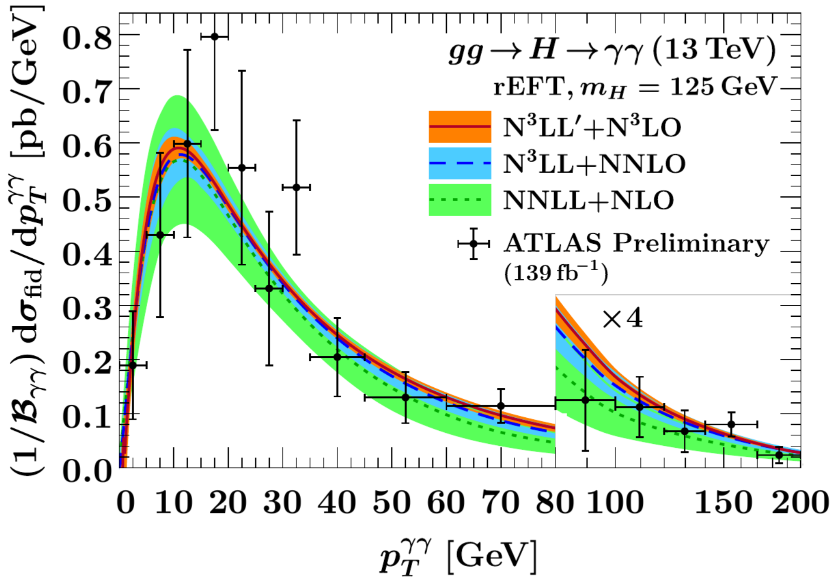
The differential cross-section affected by the modifications of the coupling strength to b- and c-quarks



- Constraint on charm Yukawa coupling from p_T

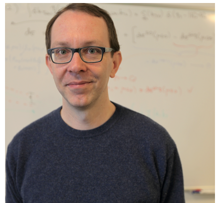


$\kappa_c \subset$ [-2.27,2.27] at 95% CL using DESY gluon fusion theory predictions



First N³LL' +N³LO theory calculation for total and differential cross section in gluon fusion, including also fiducial region for H→γγ

- Highest order prediction achieved at a hadron collider



CMS: JHEP 06 (2022) 012
Theory: EPJ C82 (2022) 604

The CP properties of Higgs boson

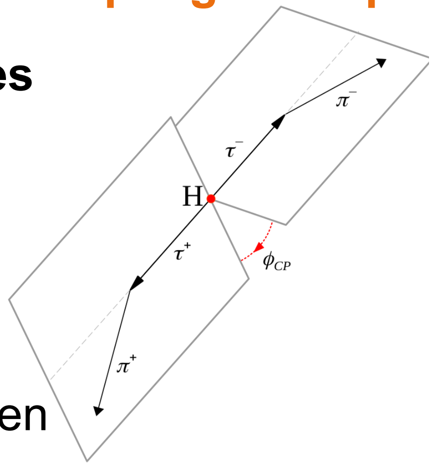
First measurement of the CP structure of the Higgs coupling to τ leptons

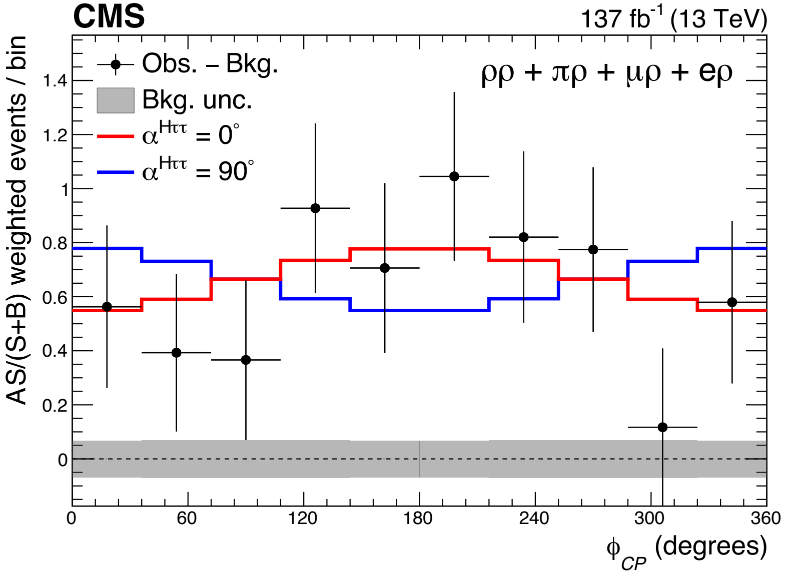
Exploit the angular correlations between decay planes of the τ leptons

- a phase shift between different mixing scenarios

The pure CP-odd state is disfavoured at 3 s. d.

- Constraints on the ratio of the CP-odd and the CP-even components

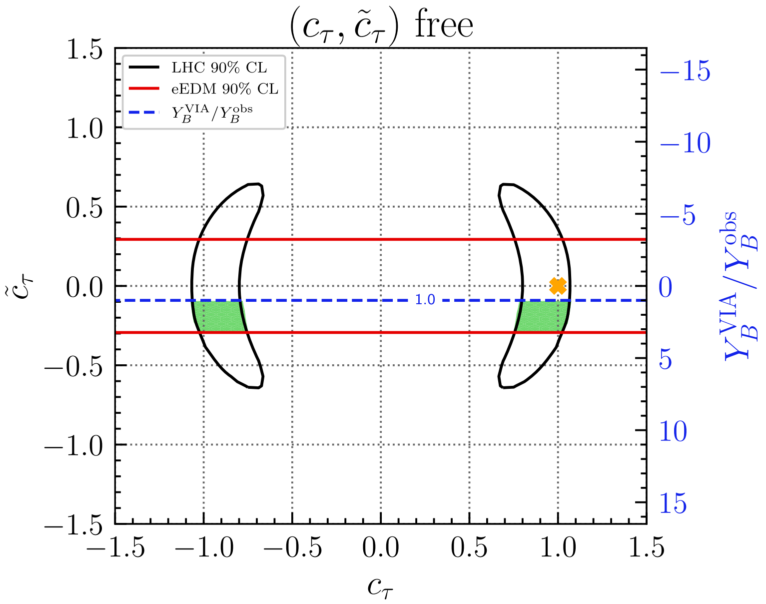




Global analysis of the CP structure - joint activity theory/experiment:

- Combine $H\tau\tau$ coupling and CP measurements, with constraints from electron dipole moment measurements

Current limits of CP violation in $H \to \tau\tau$ is sufficient to explain the baryon asymmetry in the universe

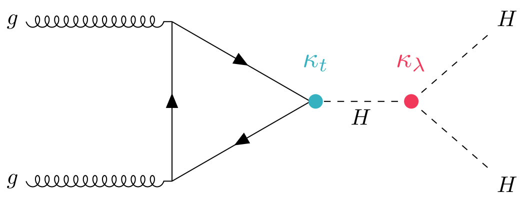


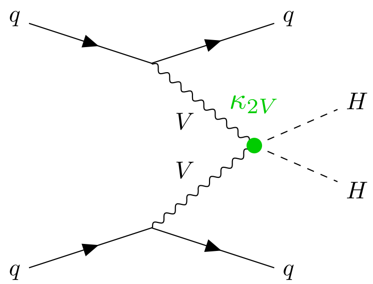
ATLAS: PRL 133, 101801 (2024)
Theory: PRL 129, 231802 (2022)

Higgs self coupling

Important for the understanding of the evolution of the universe

The most sensitive test of Higgs boson self-interaction from di-Higgs production





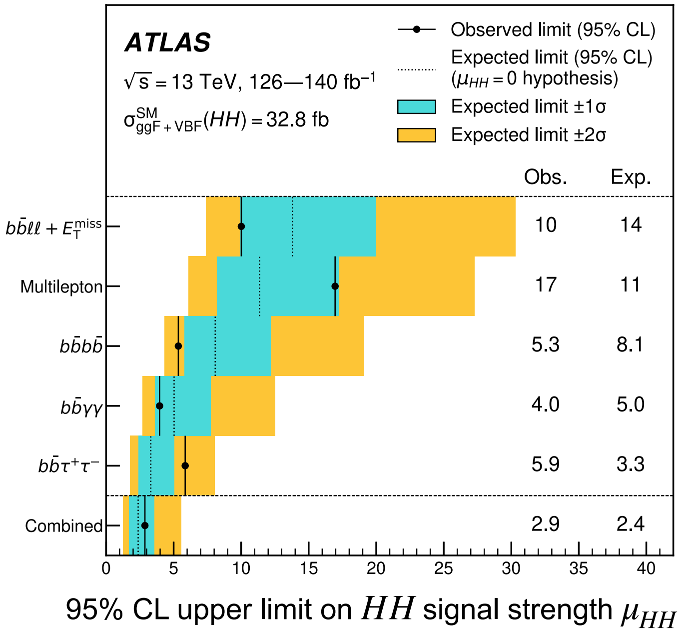
- Direct probe of trilinear self-coupling and quartic coupling between two Higgs bosons and two vector bosons

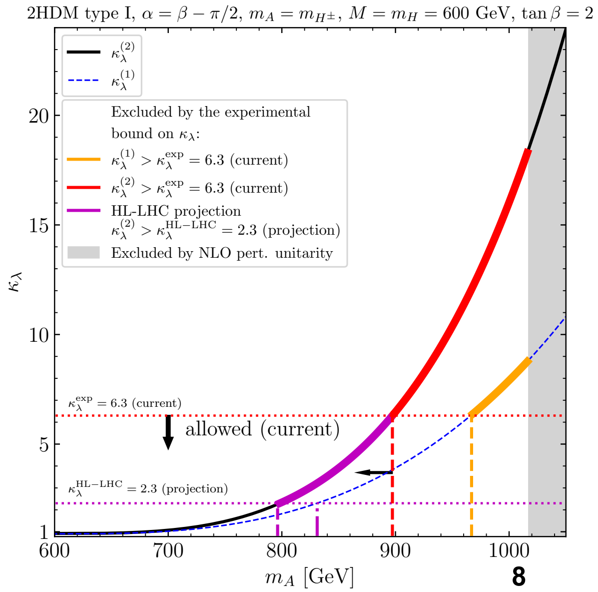
Data constrains:

$$-1.2 < \kappa_\lambda < 7.2 \text{ and } 0.57 < \kappa_{2V} < 1.48$$

Probe the extensions of the SM

- Example: the two Higgs doublets model in so far unconstrained parameter regions

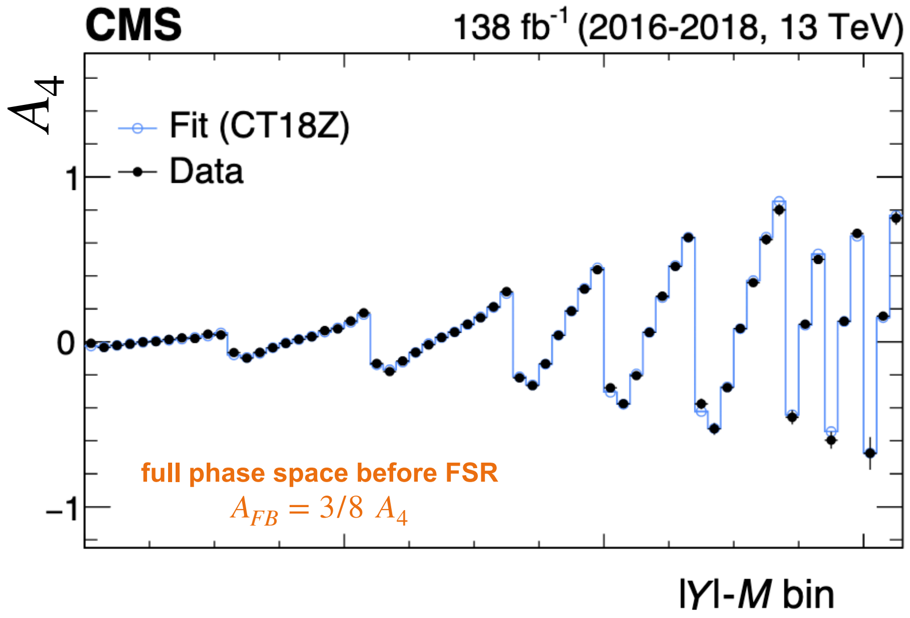




Effective electroweak mixing angle $\sin^2\theta_{\text{eff}}$

CMS: arXiv:2408.07622

Drives the strength of the neutral component of the weak interaction.



$\sin^2\theta_{\text{eff}}$ **is measured from the forward-backward asymmetry of μ^+ or e^+ ($q\bar{q} \to Z/\gamma \to \ell^+\ell^-$) with respect to the direction of Z boson motion**

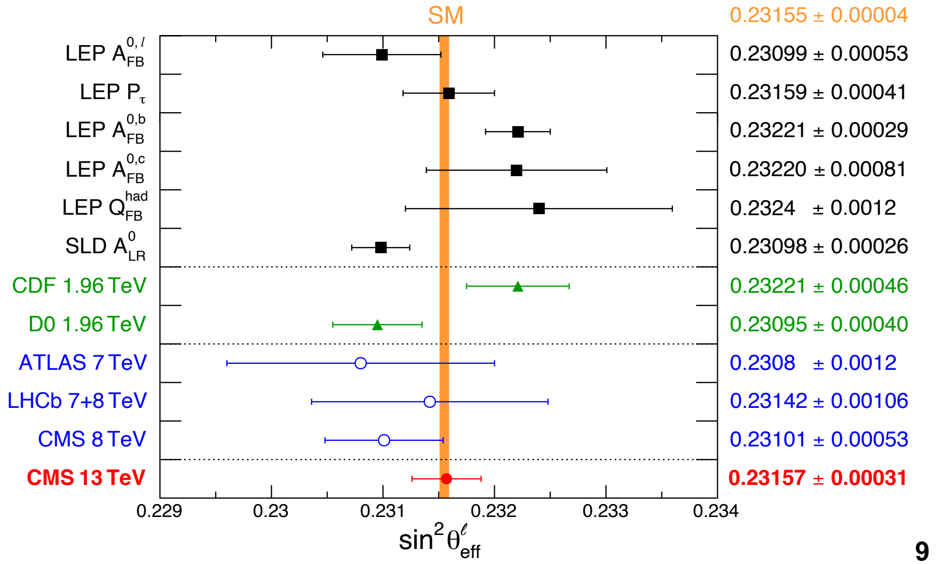
$$A_{FB} = (N_F - N_B)/(N_F + N_B)$$

- Unfolded as an angular coefficient A_4

Most precise measurement at hadron colliders:

$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23157 \pm 0.00010(stat) \pm 0.00015(exp) \pm 0.00009(theo) \pm 0.00027(PDF)$$

- Result in perfect agreement with SM prediction



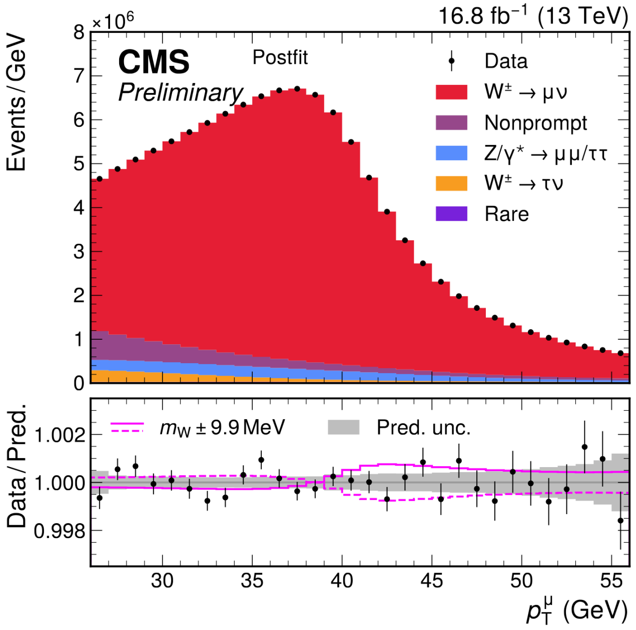
W boson mass

CMS: Submitted to Nature
ATLAS: Submitted to EPJC

Drives the strength of the charged component of the weak interaction

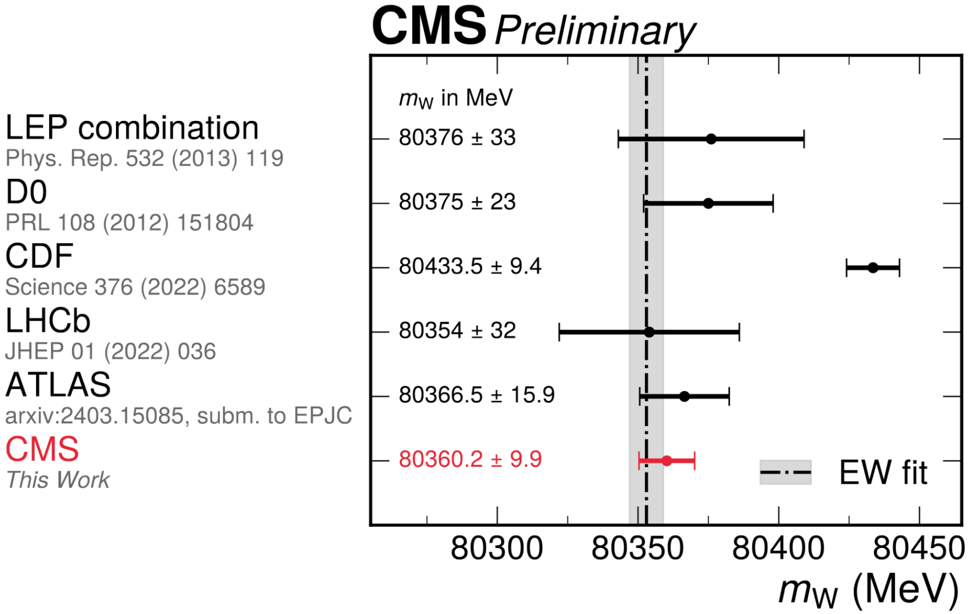
$W \to \mu\nu$:

- m_W is directly sensitive to p_T distribution of the muon but strongly dependent on the theoretical modelling
- State-of-the-art theory predictions at N3LL+NNLO with novel "theory nuisance parameters" approach developed by DESY theory group



Most precise measurement at the LHC:
$m_W = 80360.2 \pm 9.9$ MeV

- Agreement with the expectation from the SM
- Precision approaching the one of the Z boson mass



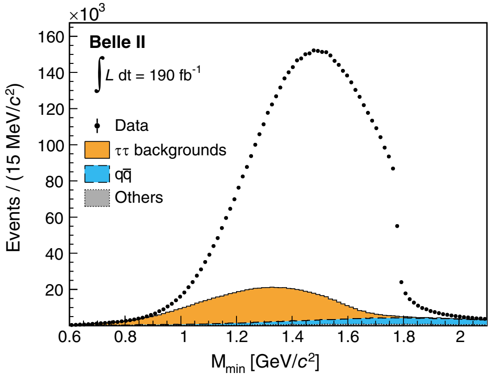
τ-lepton mass measurement

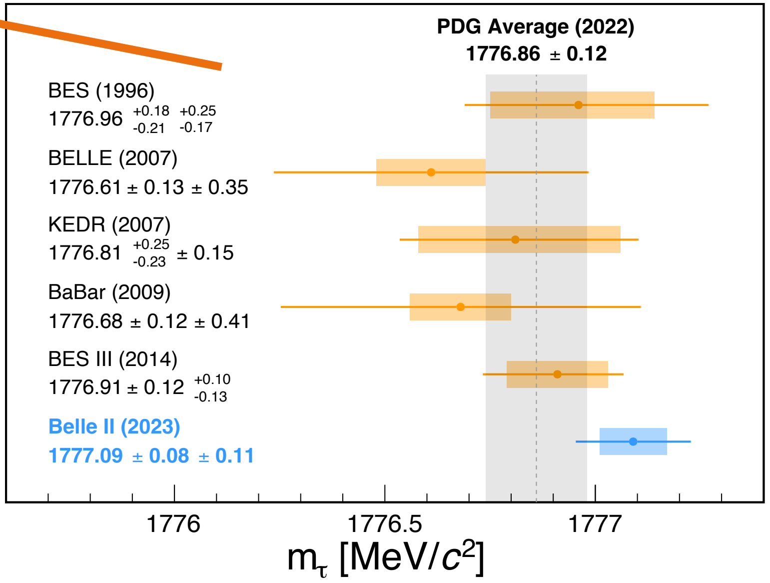
Fundamental parameter of SM

Belle II: PRD 108 (2023) 032006

The tau lepton mass is known with the least precision compared to other leptons.

- Exploit the sharp threshold behaviour in the region close to the nominal value of the τ mass





World's most precise measurement to date

$$m_\tau = 1777.09 \pm 0.14\ \text{MeV}/c^2$$

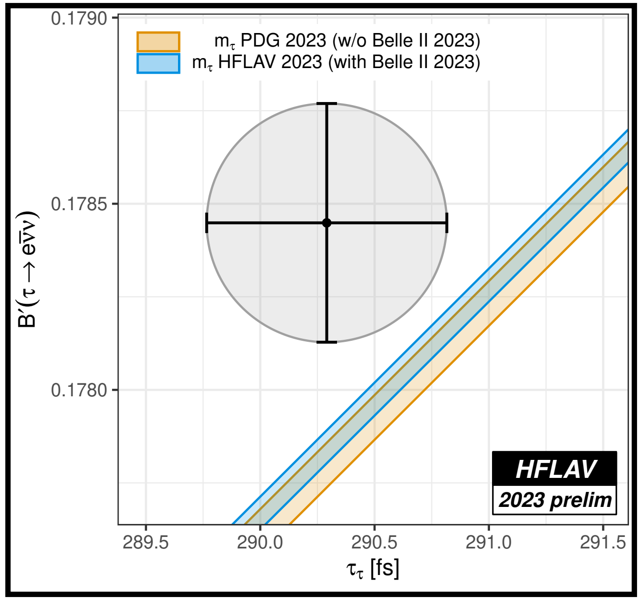
- Slightly higher world average value including Belle II recent measurement

Important input to lepton-flavour-universality tests

- The relation between $B'(\tau \to e\nu\bar{\nu})$ and the lifetime τ_τ very sensitive to the value of the τ mass
- Slight tension decreased further

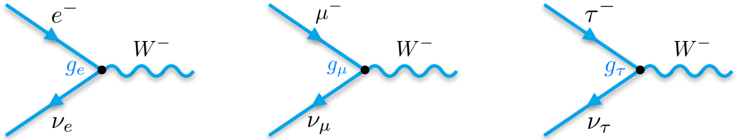
$$B' \propto B_{\mu e} \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5}$$

$B'(\tau \to e\nu\bar{\nu})$ represents the average of $\mathscr{B}(\tau \to e\nu\bar{\nu})$ and the value predicted from $\mathscr{B}(\tau \to \mu\nu\bar{\nu})$ assuming lepton universality



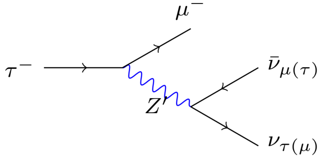
Test of lepton flavour universality in τ decays

The coupling of leptons to W bosons is flavour-independent



Test of $\mu - e$ universality by measuring g_μ / g_e

- BSM physics could enter in a variety of ways

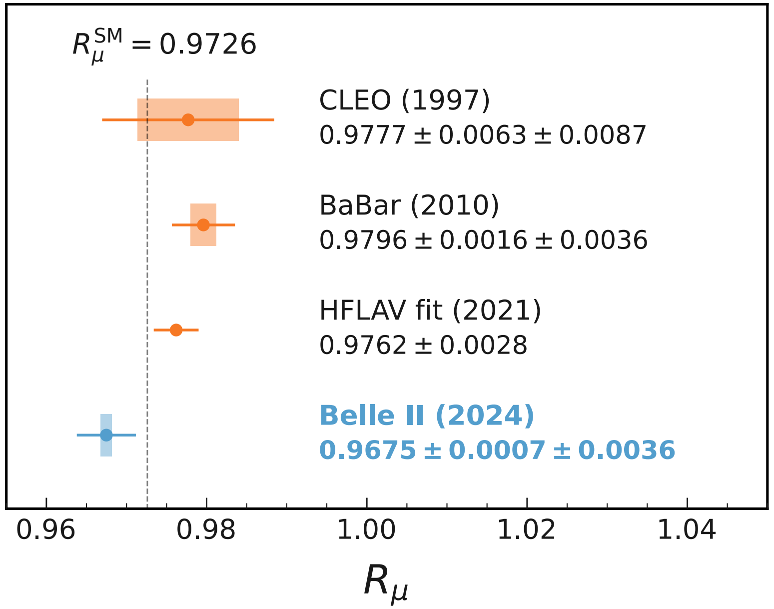


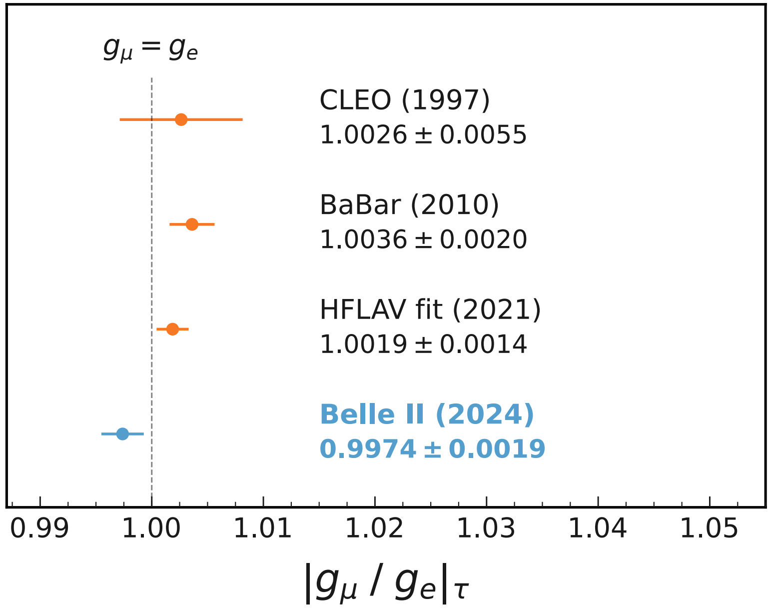
- Measured from the leptonic branching fraction ratio

$$R_\mu = \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \overset{SM}{=} 0.9726 \qquad \left(\frac{g_\mu}{g_e}\right)^2_\tau \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \overset{SM}{=} 1$$

Most precise test of $\mu - e$ universality in τ decays from a single measurement

- Consistent with SM expectation at the level of 1.4σ

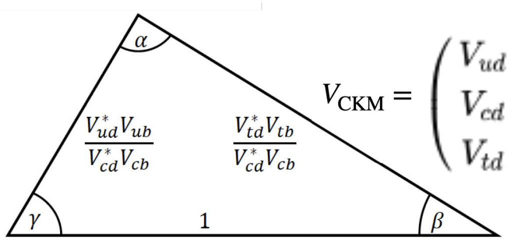




Long-standing "V_{ub}-puzzle"

Important probe of the CKM matrix elements

Belle: PRL 131, 211801 (2023)



$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{\mathrm{CKM}} V_{\mathrm{CKM}}^{\dagger} = \mathbf{1}$$

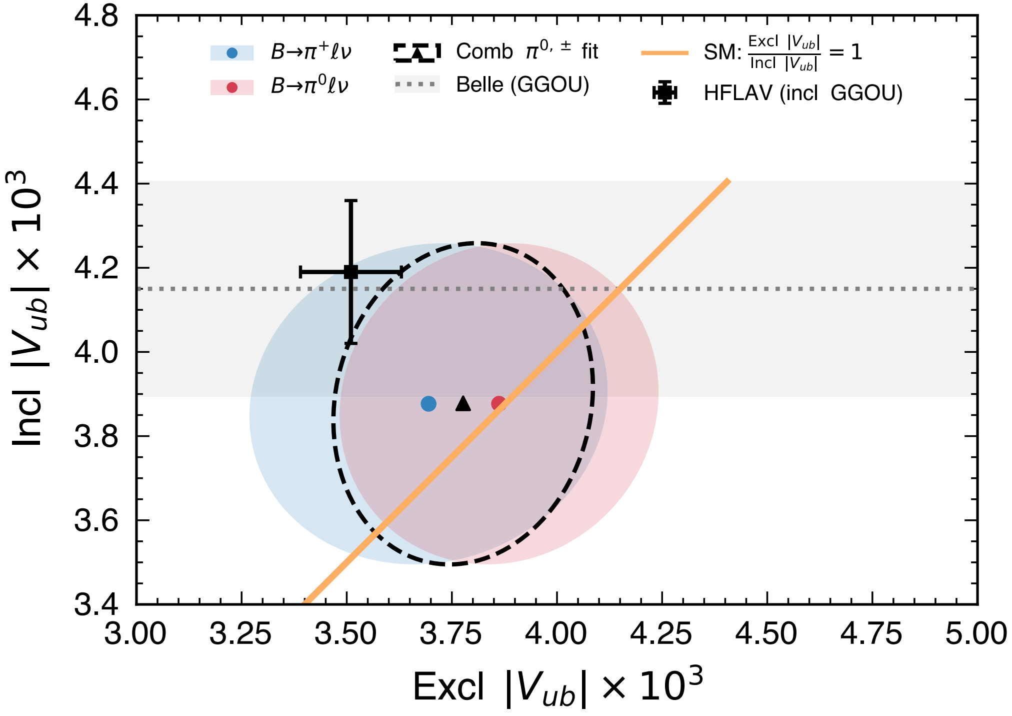
Constraint on unitarity triangle from V_{ub} measurements

- Discrepancy between exclusive and inclusive determinations with 3.7 standard deviations from unity
  - Exclusive: $B \to \pi \ell \nu, B \to \rho \ell \nu,$ etc
  - Inclusive: $B \to X_u \ell \nu$

First simultaneous determination of inclusive & exclusive $|V_{ub}|$
$V_{ub}^{\mathrm{excl}} / V_{ub}^{\mathrm{incl}} = 0.97 \pm 0.12$ compatible with SM

$$|V_{ub}^{\mathrm{excl}}| = (3.78 \pm 0.23 \pm 0.16 \pm 0.14) \times 10^{-3}$$

$$|V_{ub}^{\mathrm{incl}}| = (3.88 \pm 0.20 \pm 0.31 \pm 0.09) \times 10^{-3}$$



Top physics

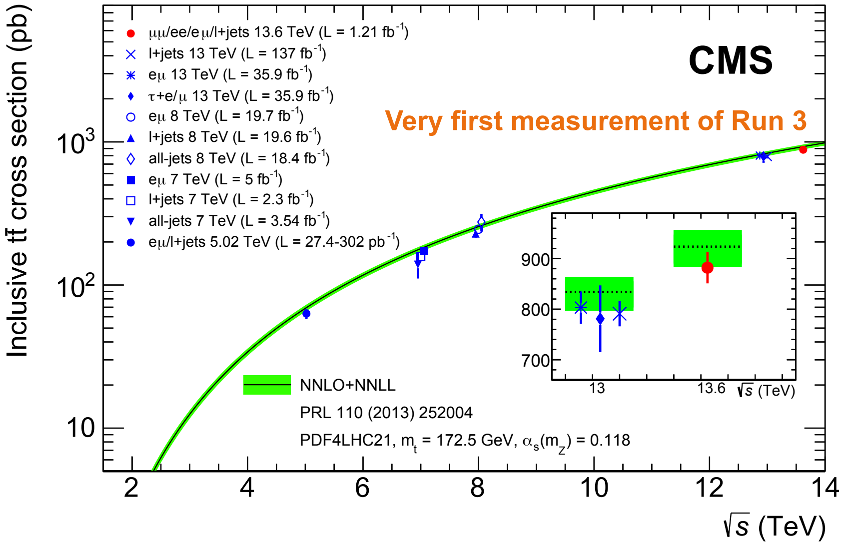
Selected highlights of a huge program

CMS: JHEP 08 (2023) 204
PLB 844 (2023) 138076

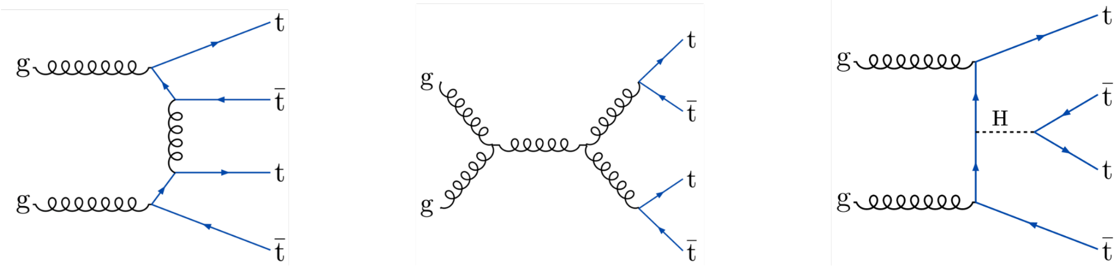
Cross section of top-quark pair production

- Provide important checks of perturbative QCD

The inclusive $t\bar{t}$ production cross section scale with the centre-of-mass energy as expected

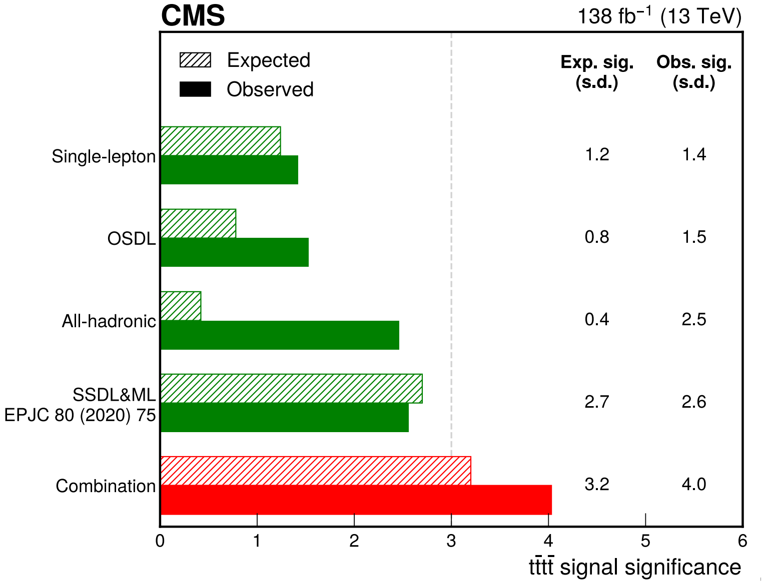


Production of four top quarks



- Constrain the top quark Yukawa coupling, CP-related parameters, and effective field theory operators

Achieved a significance of 4.0 standard deviations

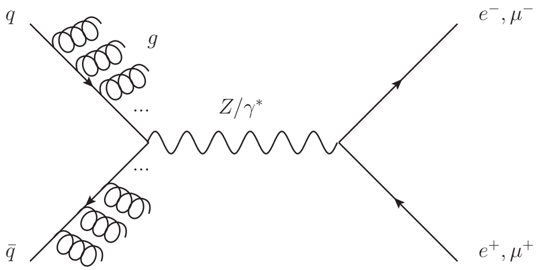


The strong coupling constant α_s

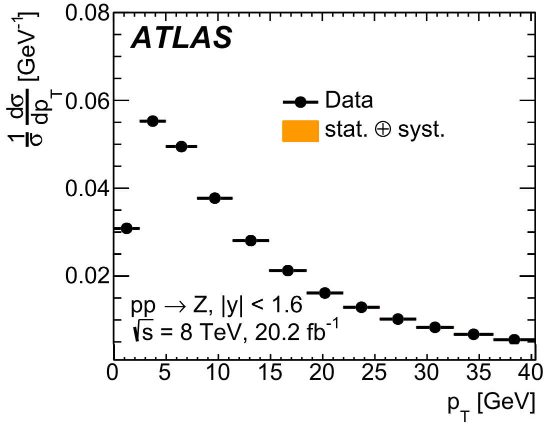
ATLAS: EPJ C 84 (2024) 315
arXiv:2309.12986
CMS: JHEP 02 (2022) 142

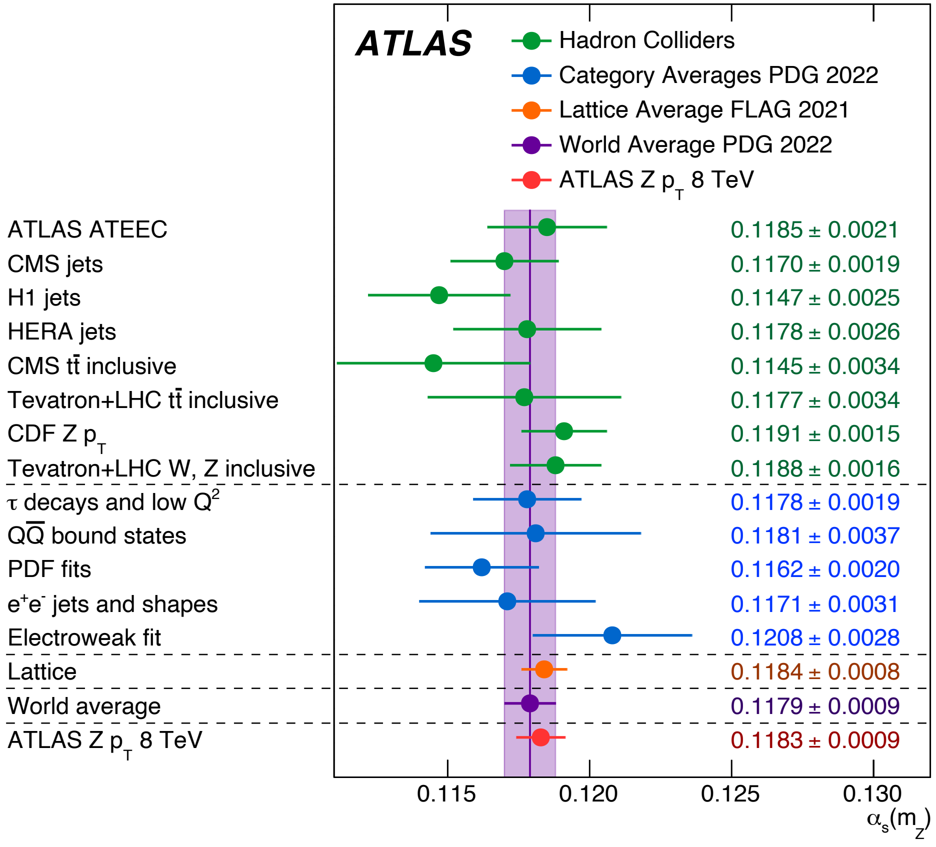
The least precisely determined coupling among the fundamental couplings in nature

New experimental methodology to extract DY cross section



- First $p_T(Z)$ cross section measured in full-lepton phase space
  - ‰ level precision in the central region, sub-% uncertainties up to |y| < 3.6
  - exceptional possibilities for phenomenological interpretations





$\alpha_s(m_Z)$ measurement with % level accuracy !

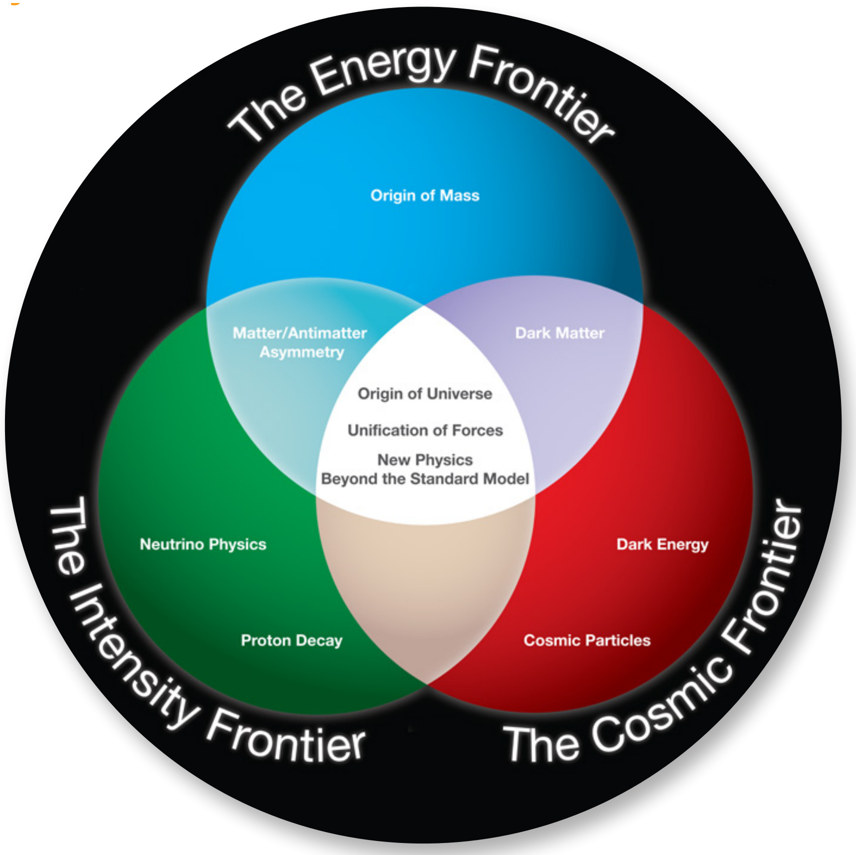
Outlook

Very interesting times ahead!

- **DESY groups** of ATLAS, CMS and Belle II lead a variety of analysis from very high precision measurements to first observations of rare standard model processes

- Close collaboration with theory groups ensures accurate comparisons with standard model predictions and provides guidance for interpreting results

- The standard model holds up to tests, but theoretical and experimental uncertainties still leave room for potential physics beyond the standard model



Goal for the next decade: enhance the precision further!

Thank you

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