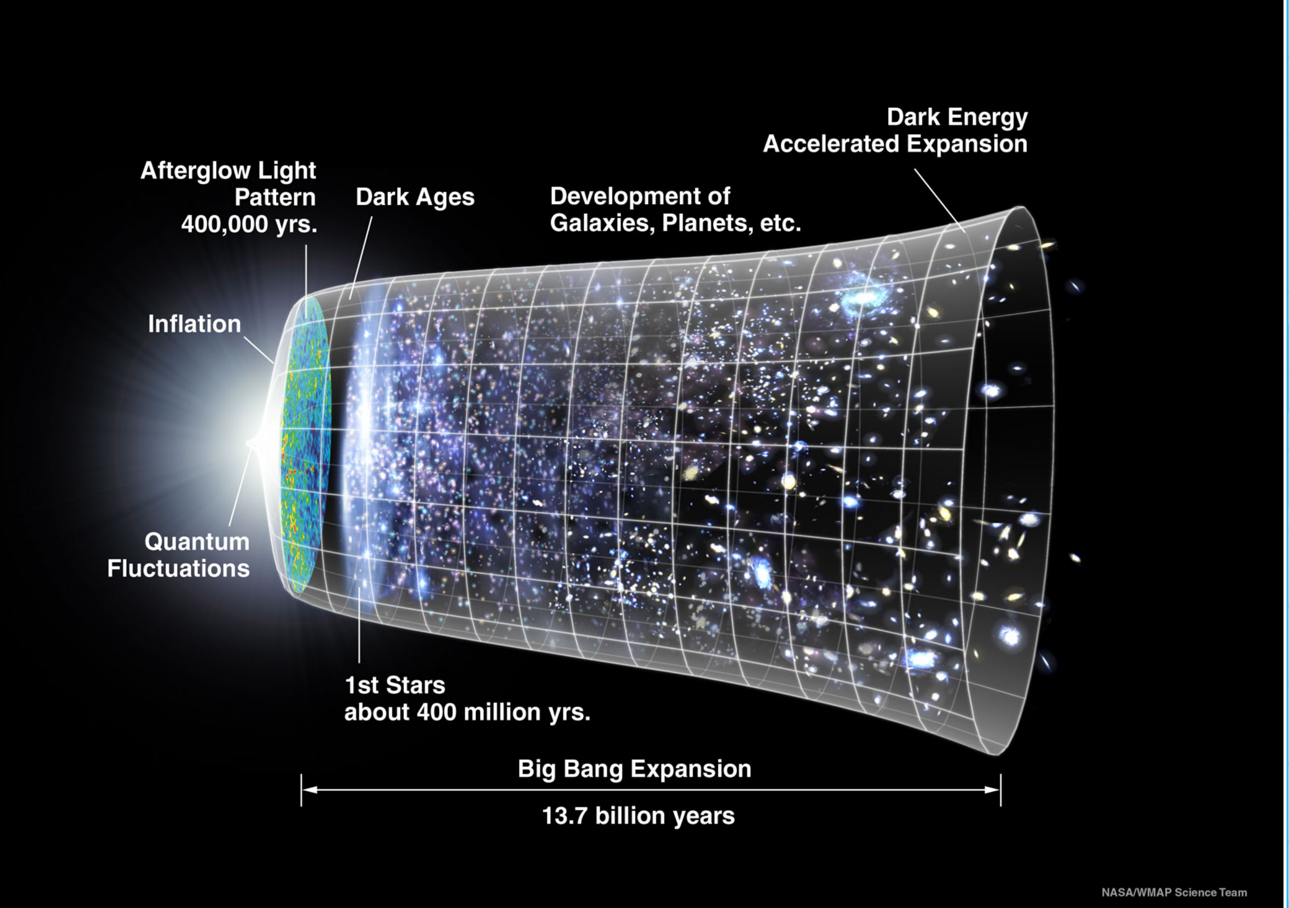
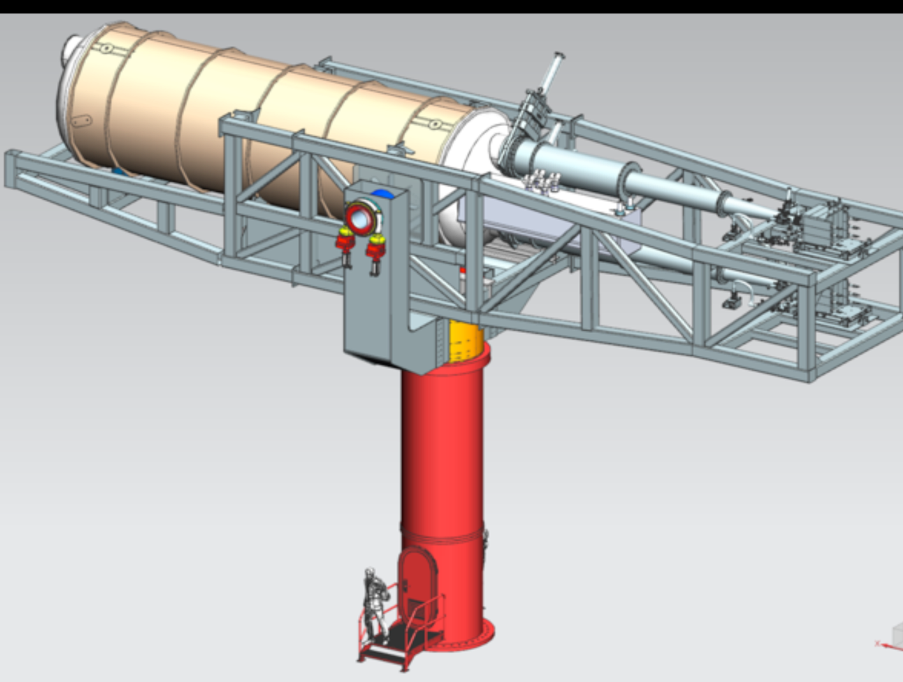
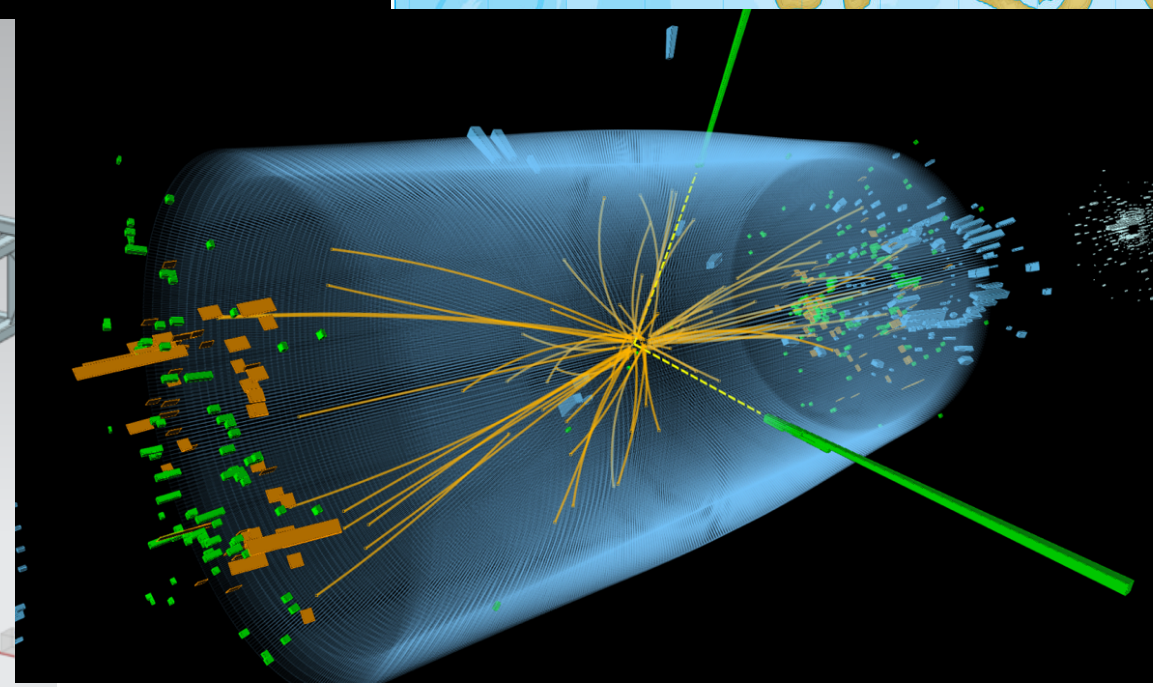






Fundamental Particles and Forces — Overview

Georg Weiglein, DESY

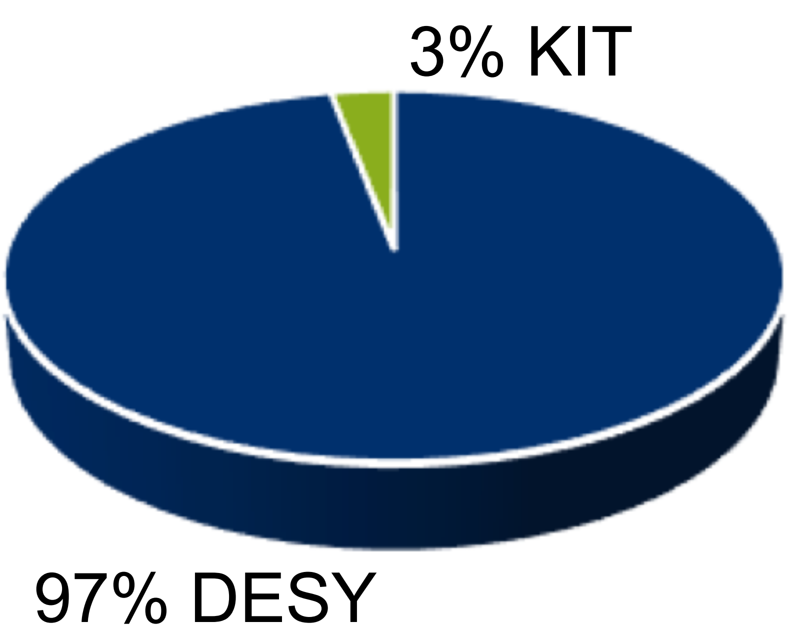
11 / 2021

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE
DESY.

Topic: Fundamental Particles and Forces (FPF)

MATTER AND THE UNIVERSE

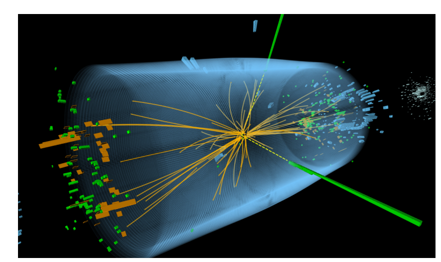
Theory + Experiments | Theory



Two Helmholtz Centres at three locations

Present situation (in a nutshell):

The Higgs-boson discovery at the LHC in 2012 has established a non-trivial structure of the vacuum, i.e. of the lowest-energy state in our universe



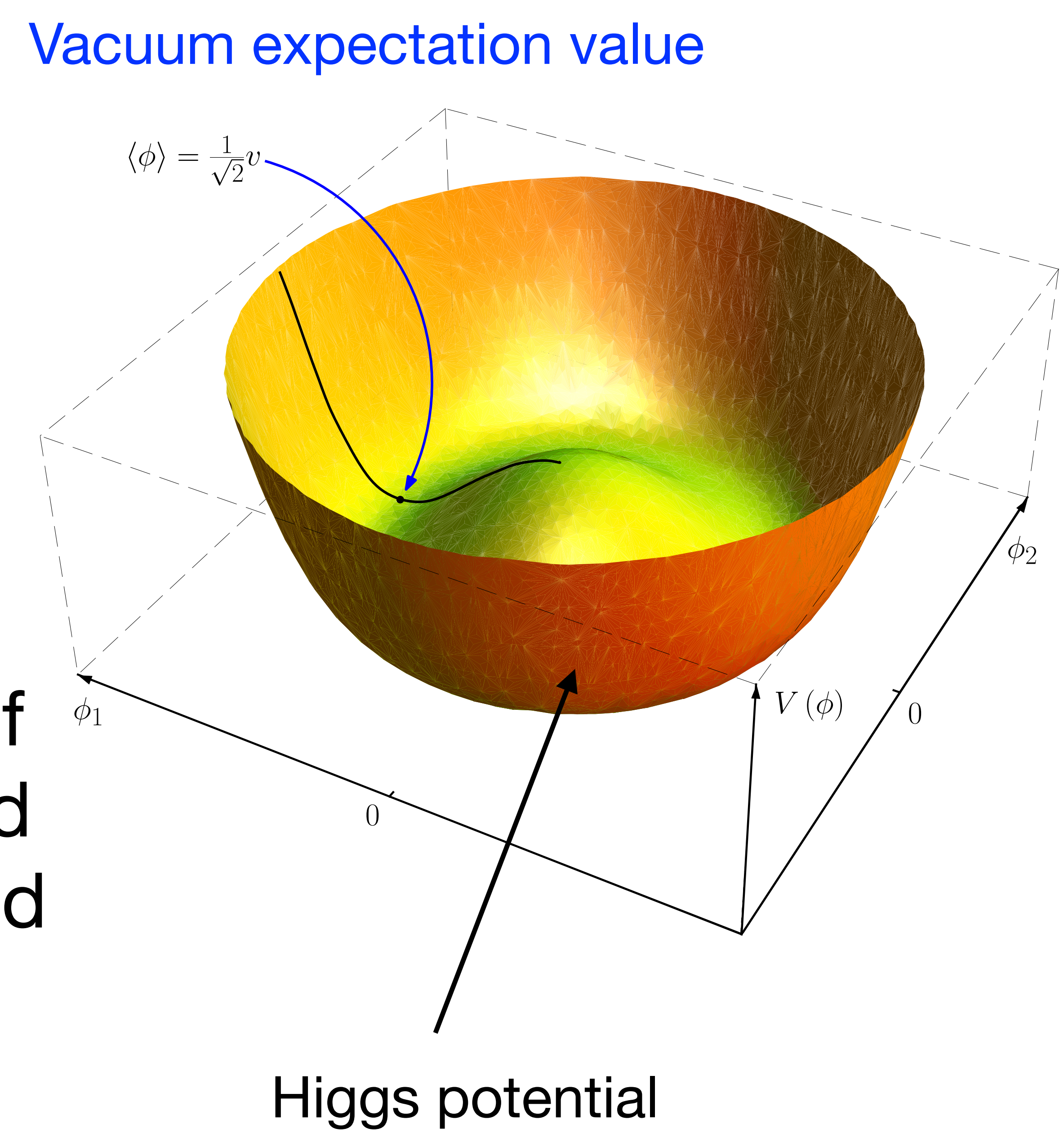
Nobel Prize 2013

The origin of mass of elementary particles is related to this structure: mass arises from the interaction with the Higgs field

FPF: present situation and open questions

The vacuum structure is caused by the Higgs field through the Higgs potential. We lack a deeper understanding of this!

We do not know where the Higgs potential that causes the structure of the vacuum actually comes from and which form of the potential is realised in nature. Experimental input is needed to clarify this!



Higgs physics: status

The Standard Model of particle physics uses a ``minimal” form of the Higgs potential with a single Higgs boson that is an elementary particle.

The LHC results on the discovered Higgs boson within the current uncertainties are compatible with the predictions of the Standard Model, but also with a wide variety of other possibilities, corresponding to very different underlying physics.

Thus, we have discovered a new particle, but we do not know yet the physics that is associated with it. We have a description of the known particles and their interactions, but we do not know the underlying dynamics.

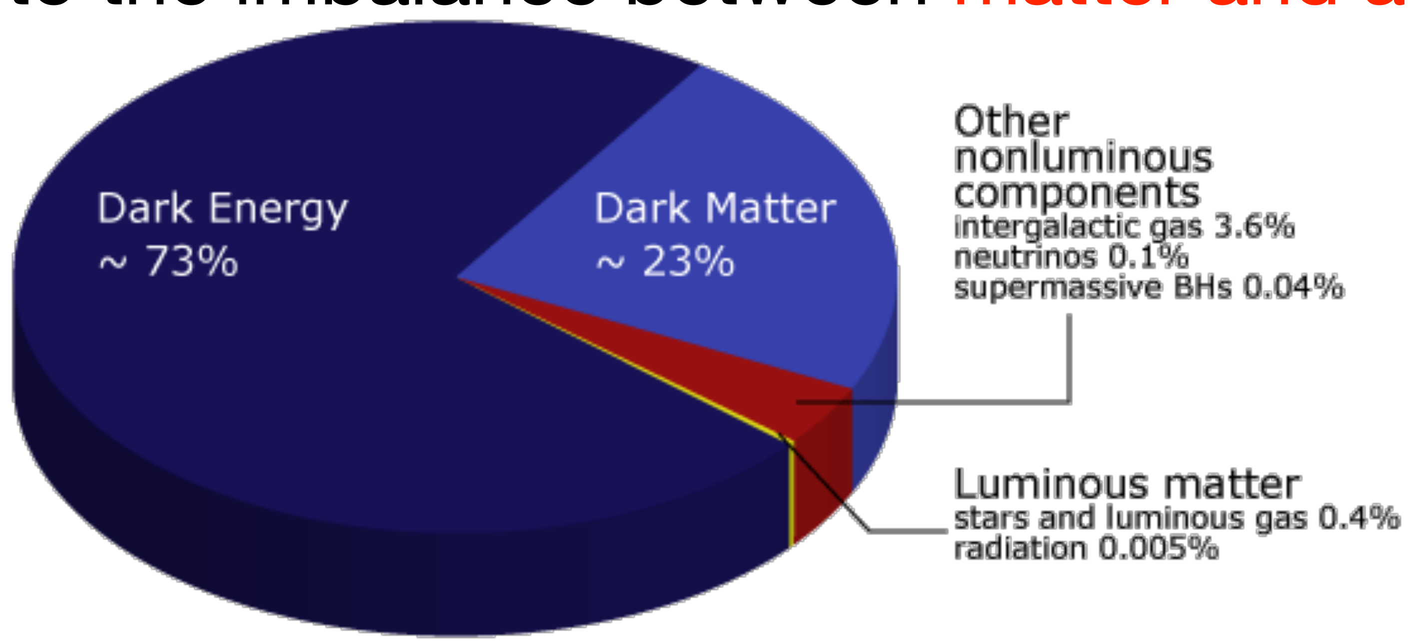
The puzzle of the Higgs mass: $M_H \approx 125$ GeV
All other elementary particle masses are ``protected” from physics at much higher scales (gravity, …) by known symmetries. But what protects M_H?

FPF: some of our main goals

Determine the underlying dynamics of electroweak symmetry breaking: single doublet or extended Higgs sector (new symmetry?), fundamental scalar or compositeness (new interaction?), …
Find out what protects the Higgs mass from physics at high scales

⇒ *Precision measurements of Higgs properties (mass, couplings, CP properties, …) and comparison to precise theory predictions*

Get access to the dark sector of the universe (dark matter and dark energy) and to the imbalance between matter and anti-matter



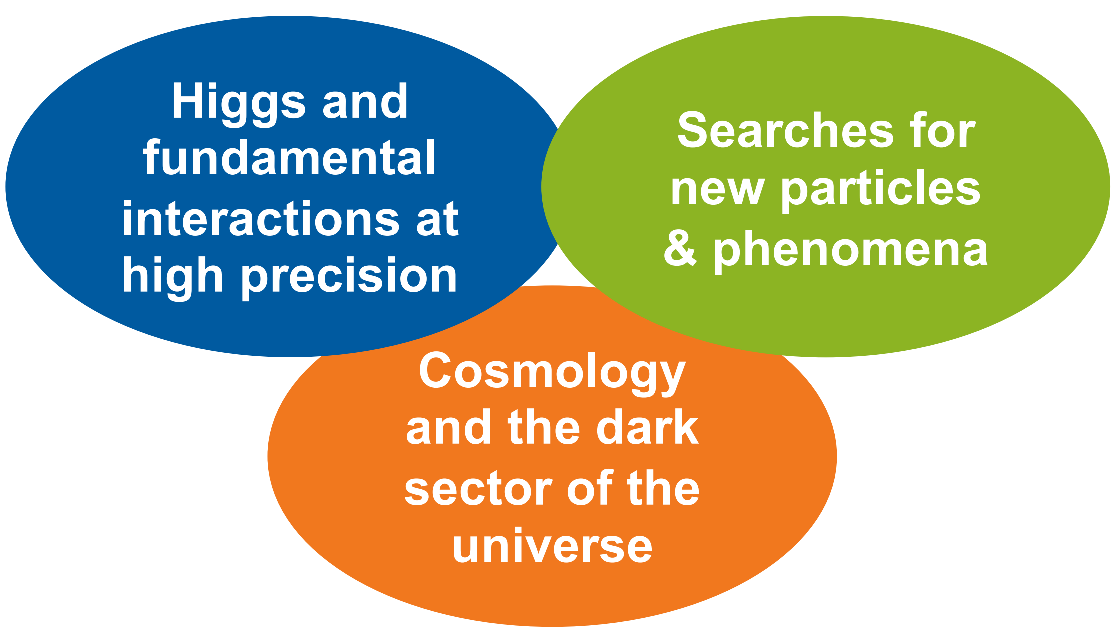
Guiding themes for PoF IV

Mission and Strategy

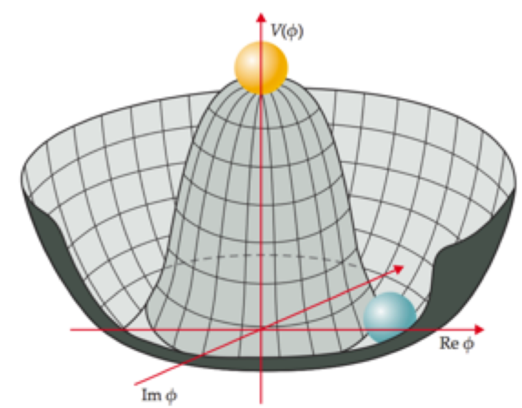
MATTER AND THE UNIVERSE

Our mission: Study the fundamental laws of Nature in our universe, governed by quantum physics and the dynamics of space-time

Guiding themes for PoF IV

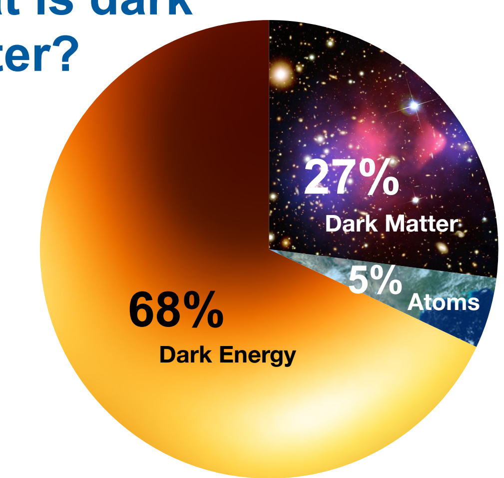


Science drivers

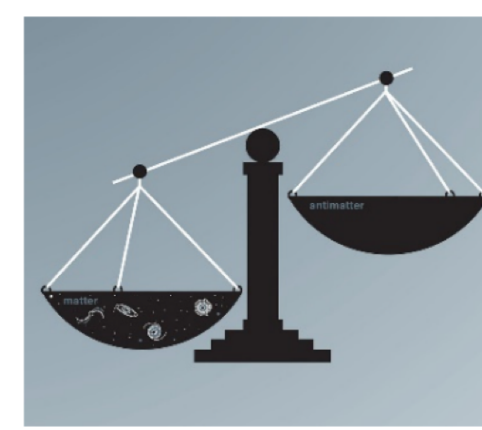


What is the structure of the vacuum?

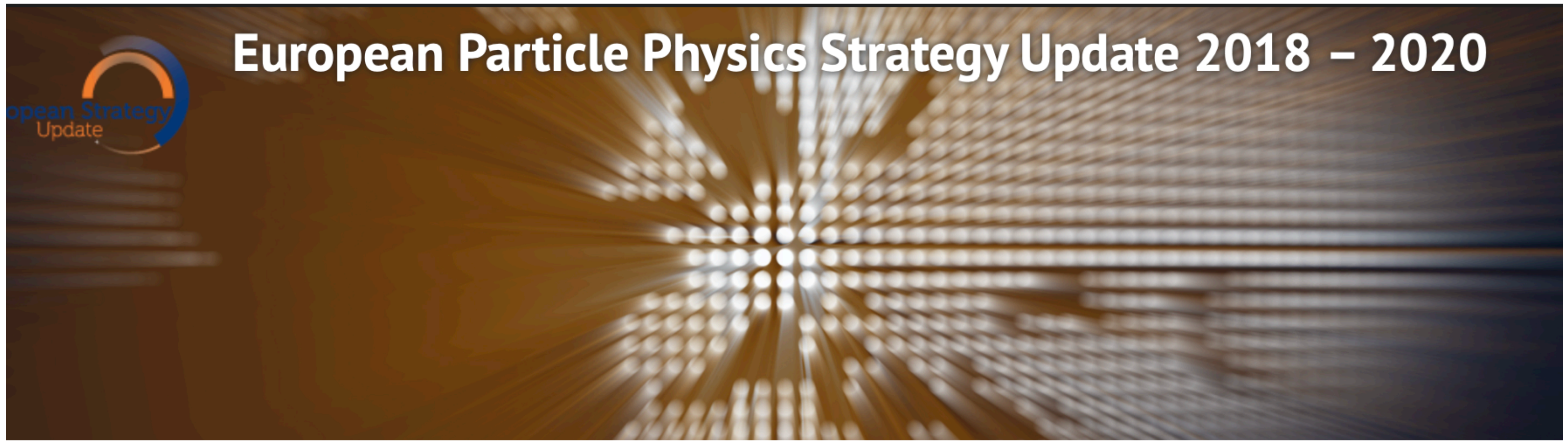
What is dark matter?



Where did the anti-matter go?



Update of the European Strategy for Particle Physics



Future Projects:

3. High-priority future initiatives

a) An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

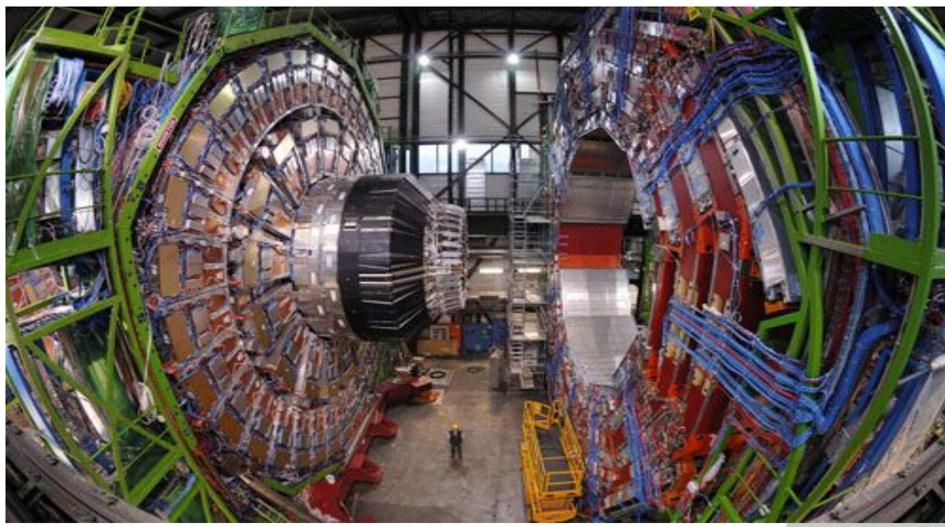
- *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

Programme

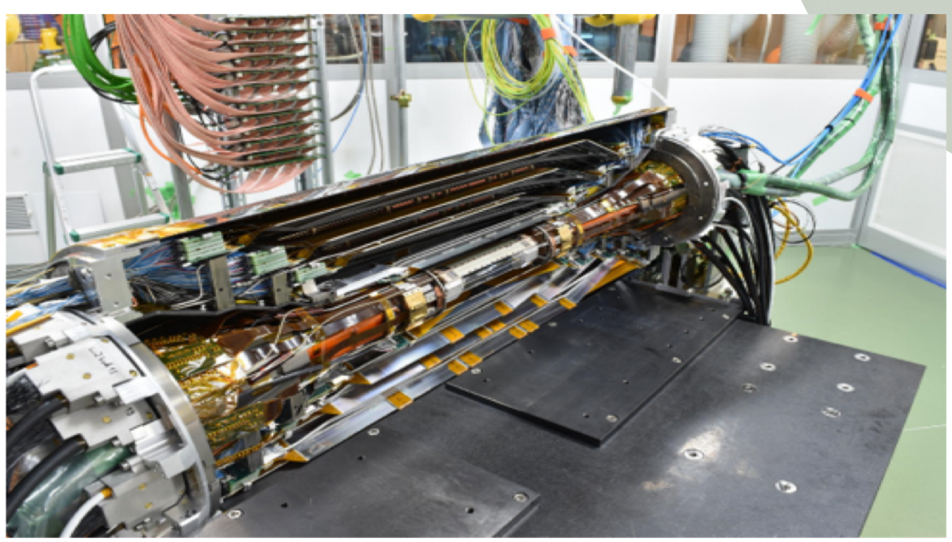
Program Pillars: Experiments and Theory

LHC experiments @ CERN



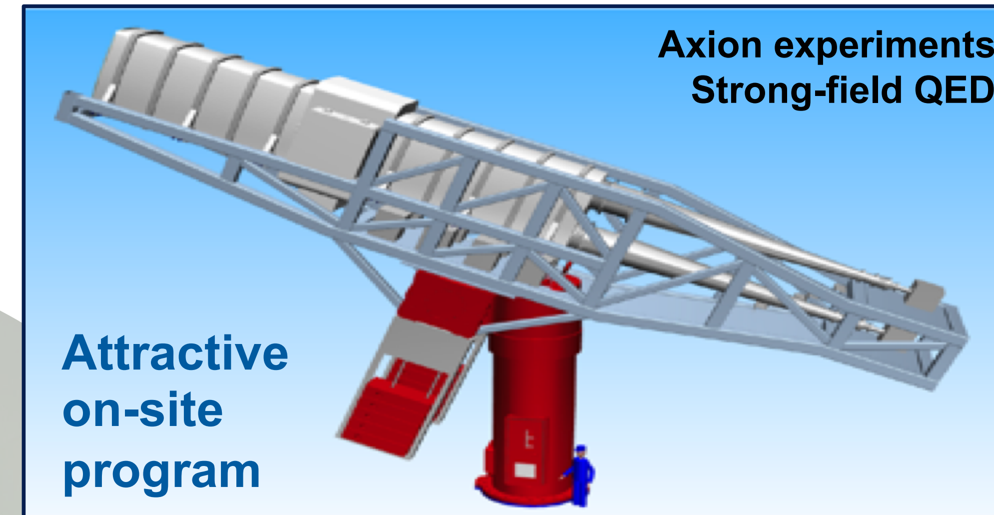
Leading contributions to global collider projects (CERN, KEK)

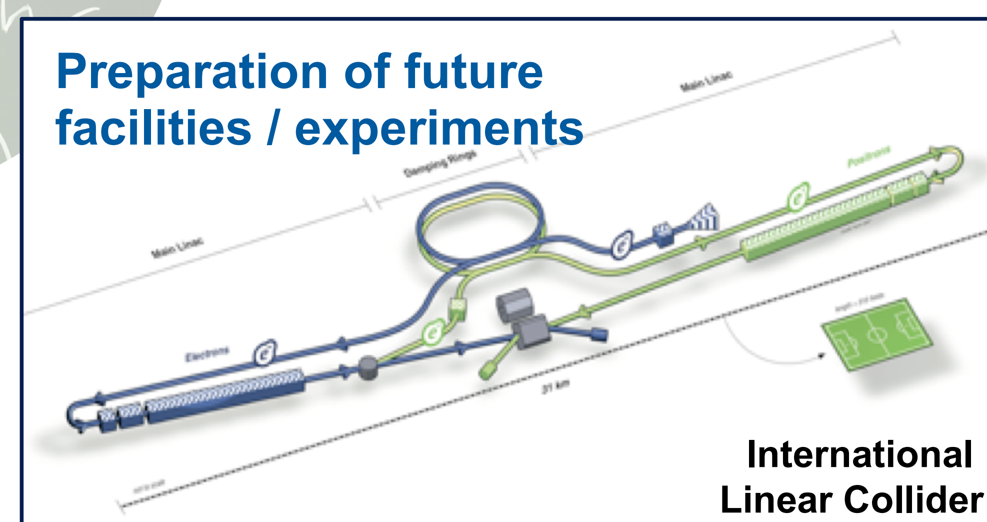
Belle II @ KEK (Japan)



Broad theory portfolio

Collider Physics
Particle Cosmology
Lattice Gauge Theory
String Theory

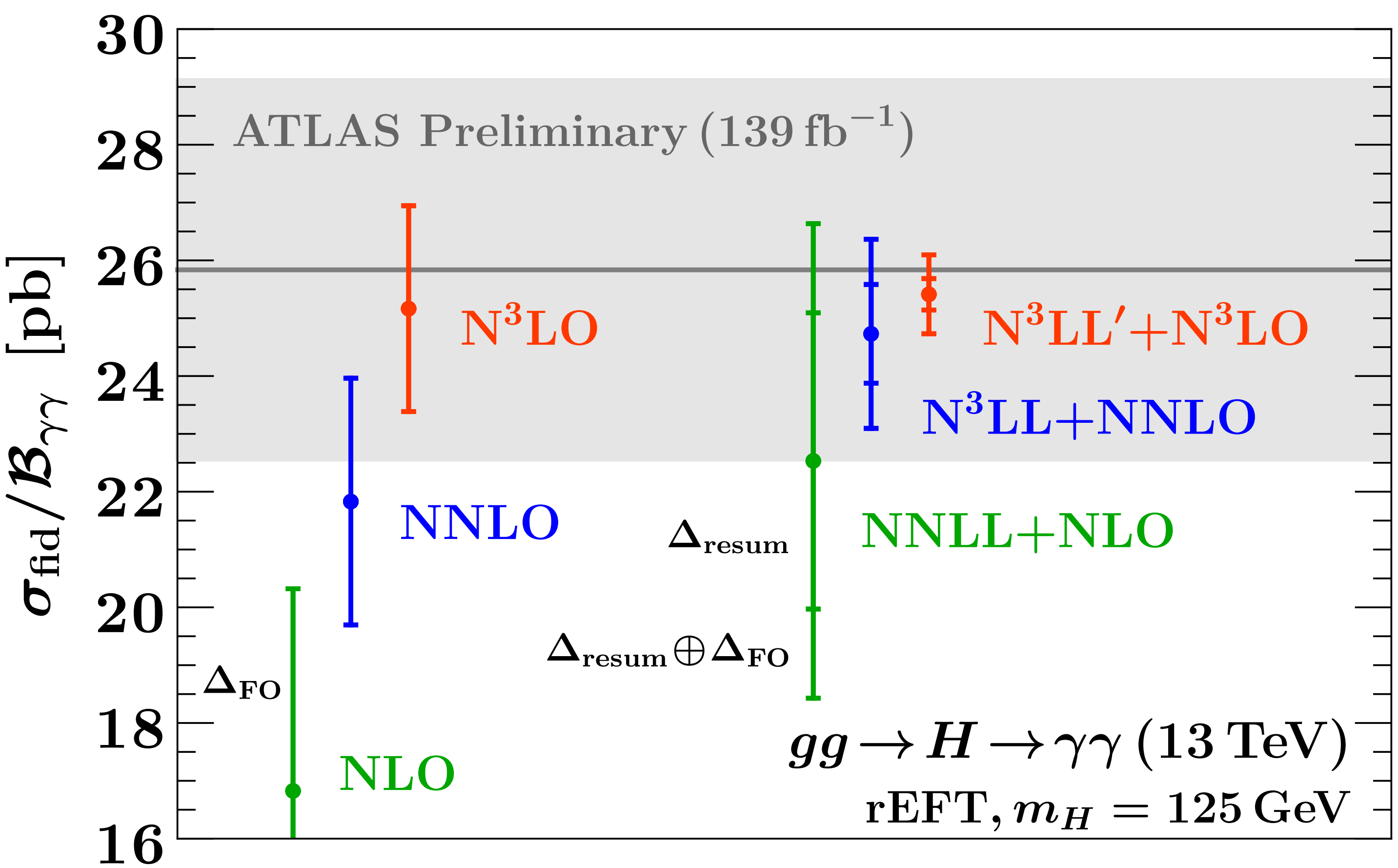




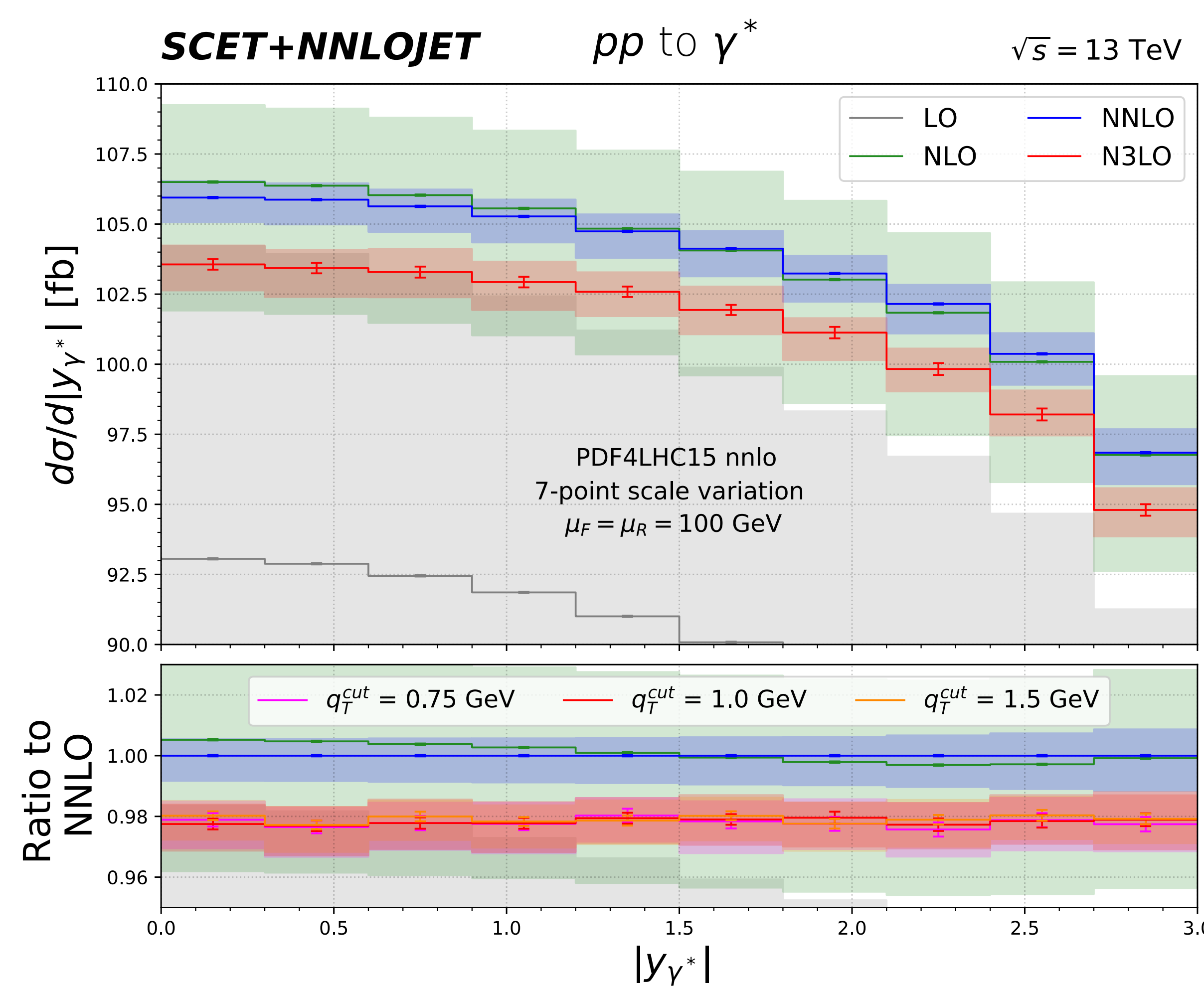
Some examples of recent results

High-precision predictions for:

Higgs production at the LHC in comparison with the ATLAS measurement: gg → H → $\gamma\gamma$



Drell-Yan production at the LHC: di-lepton rapidity distribution



[see flash talk by X. Chen]

LHC (CMS): Higgs CP properties

Final states with tau leptons

HIG-20-006, arXiv:2110.04836 (sub. to JHEP)

- The $\mathrm{H} \to \tau\tau$ decay is a powerful probe of CP violating effects in the Higgs sector
- Generalized $\mathrm{H}\tau\tau$ Yukawa interaction:

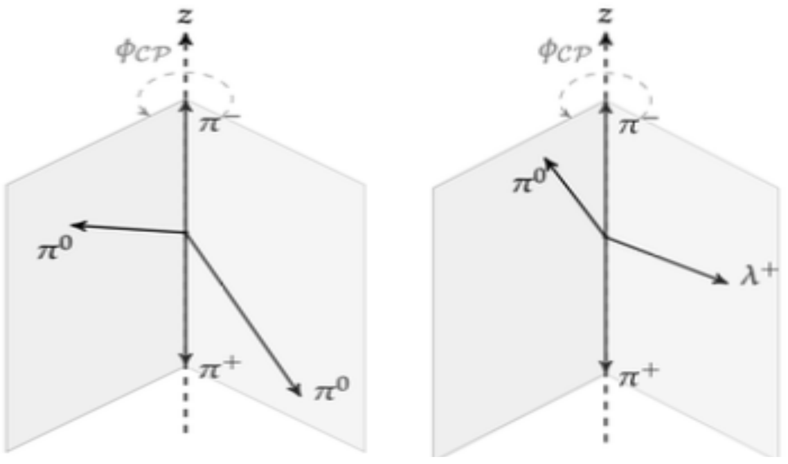
$$L_Y = \frac{m_\tau}{v}\mathrm{H}(\kappa_\tau\,\bar{\tau}\tau + \tilde{\kappa}_\tau\bar{\tau}i\gamma_5\tau)$$

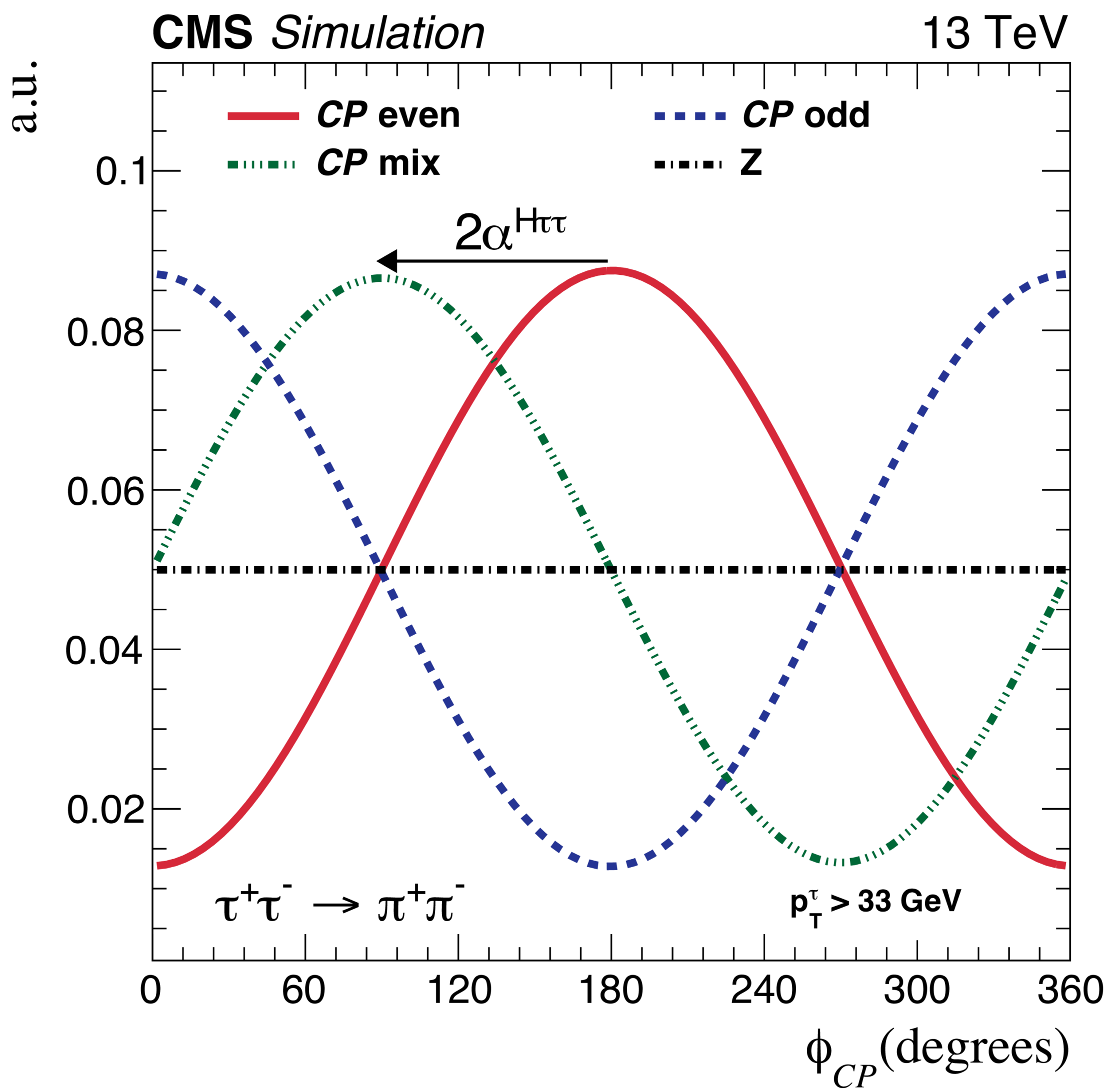
- CP mixing angle:

$$\tan\alpha^{H\tau\tau} = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

  - measured by studying distribution of angle between τ decay planes (Φ_{CP})

- Analysis performed on full Run 2 dataset ($137\ \mathrm{fb}^{-1}$) in most sensitive final states: $\tau_h\tau_h,\ \tau_\mu\tau_h,\ \tau_e\tau_h$





LHC (CMS): Higgs CP properties (II)

Final states with tau leptons

HIG-20-006, arXiv:2110.04836 (sub. to JHEP)

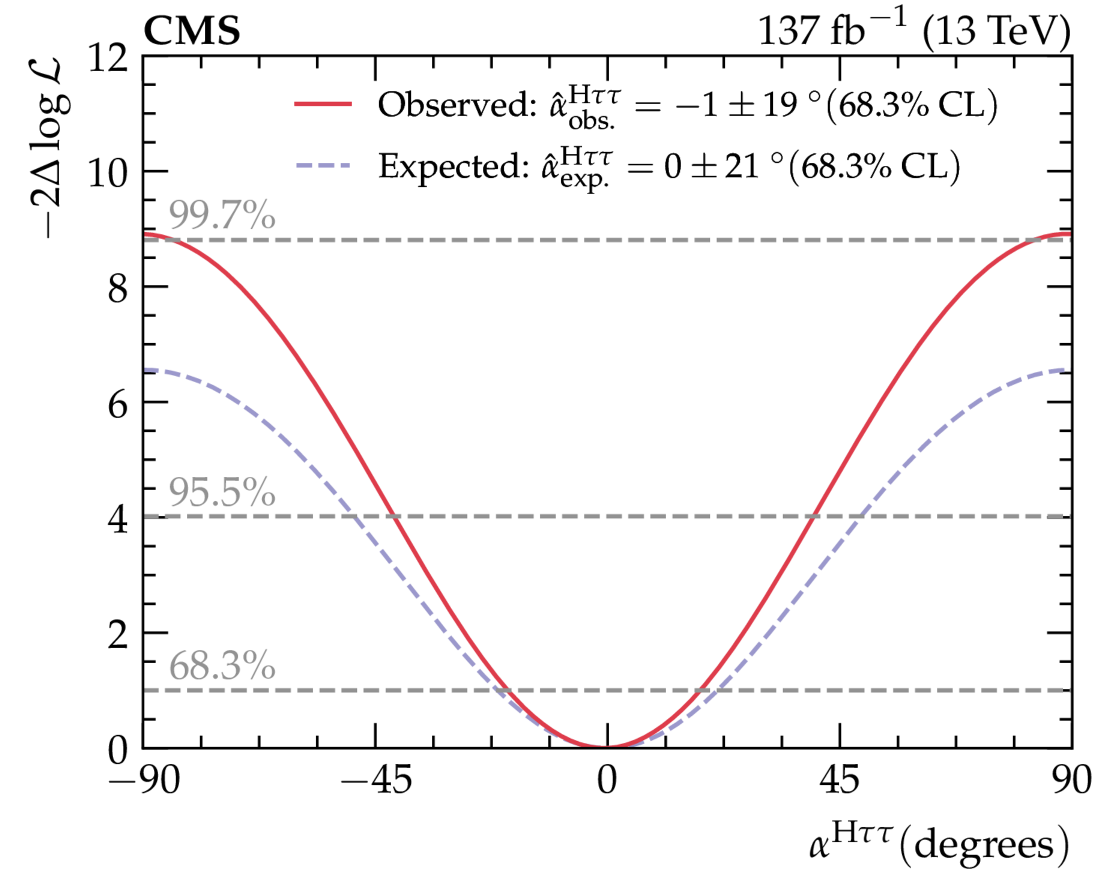
- Measured value of CP mixing angle $\alpha^{H\tau\tau} = (-1 \pm 19)^o$

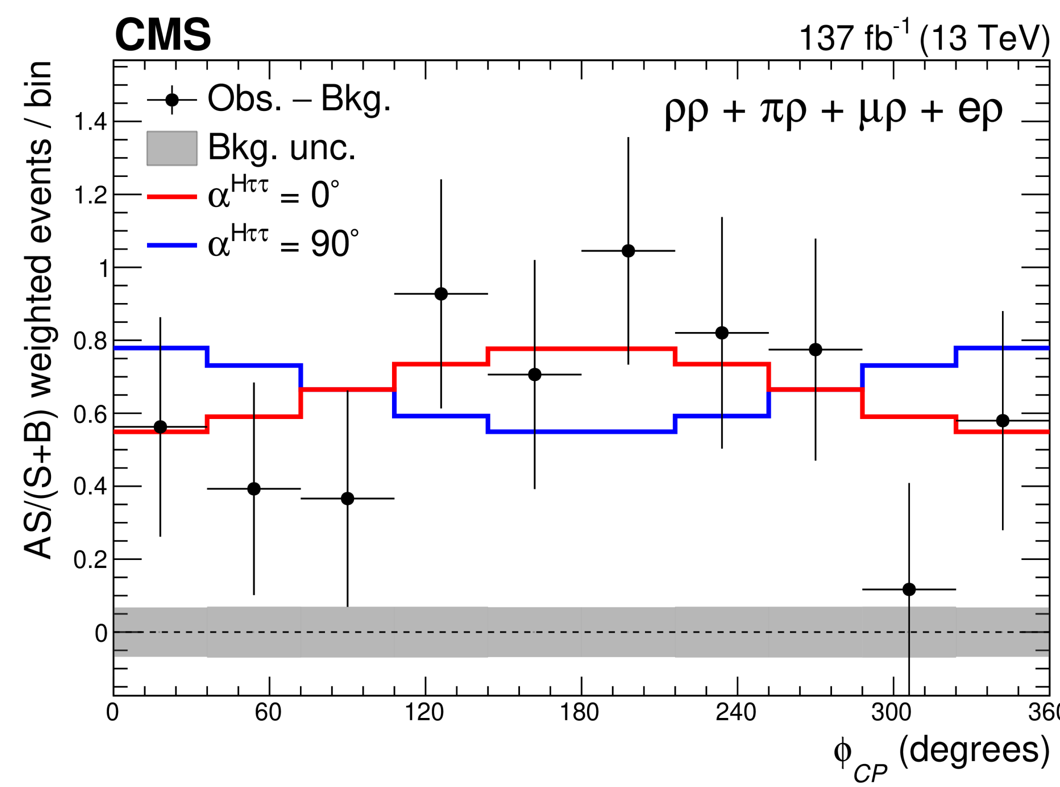
  ➔ consistent with SM prediction

➔ Hypothesis of pure CP-odd coupling is rejected at $3\ \sigma$ level

➔ First measurement ever of the CP structure of the $H\tau\tau$ Yukawa coupling

- DESY contribution:
  - analysis of $e\tau_h$ and $\mu\tau_h$ final states
  - participation in statistical combination





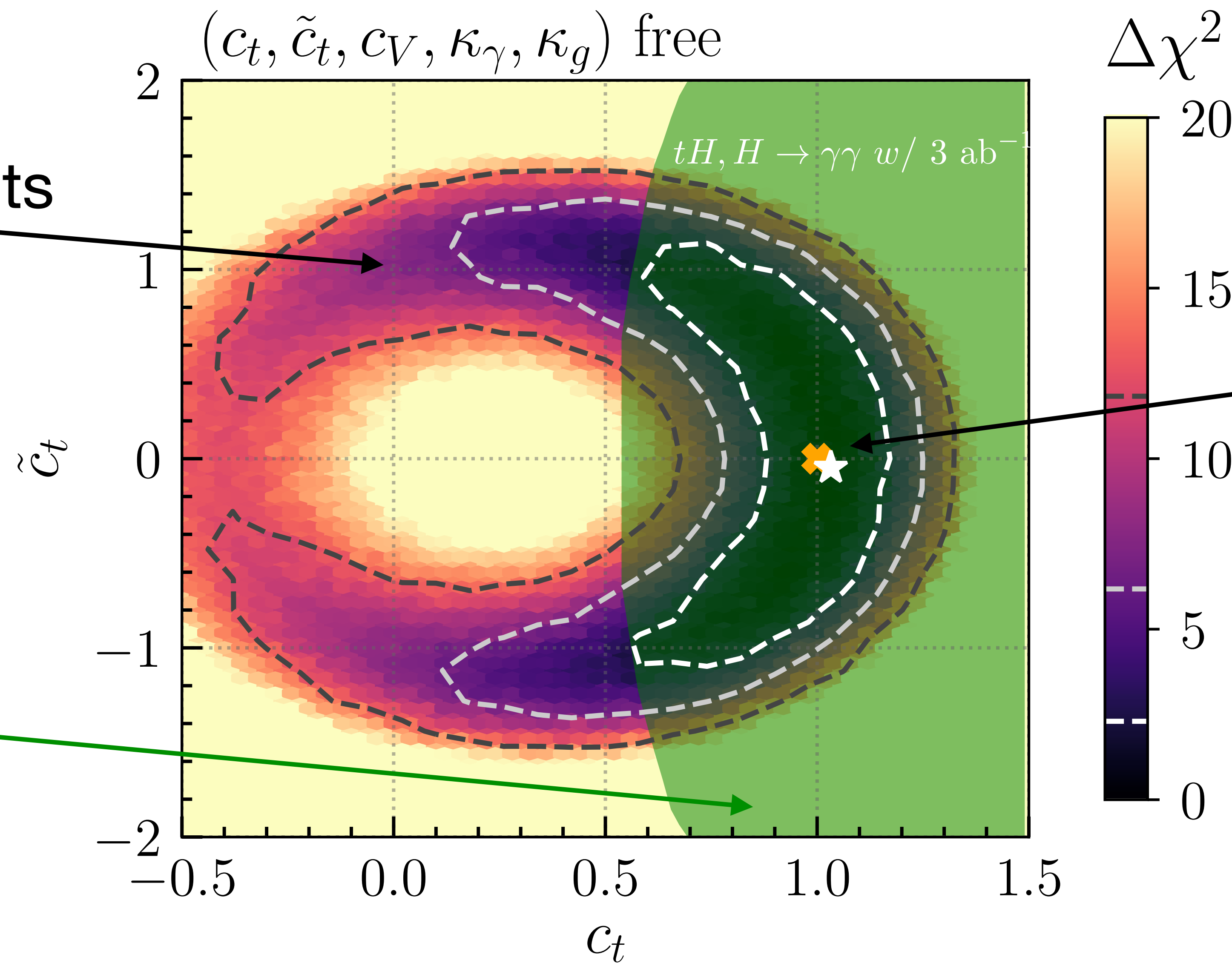
CP structure of the top Yukawa coupling: current constraints and HL-LHC prospects

[experiment + theory joint effort]

Global fit to LHC inclusive and differential signal rates

$$\mathcal{L}_{\rm yuk} = -\frac{y_t^{\rm SM}}{\sqrt{2}}\bar{t}\,(c_t + i\gamma_5\tilde{c}_t)\,tH$$

current constraints



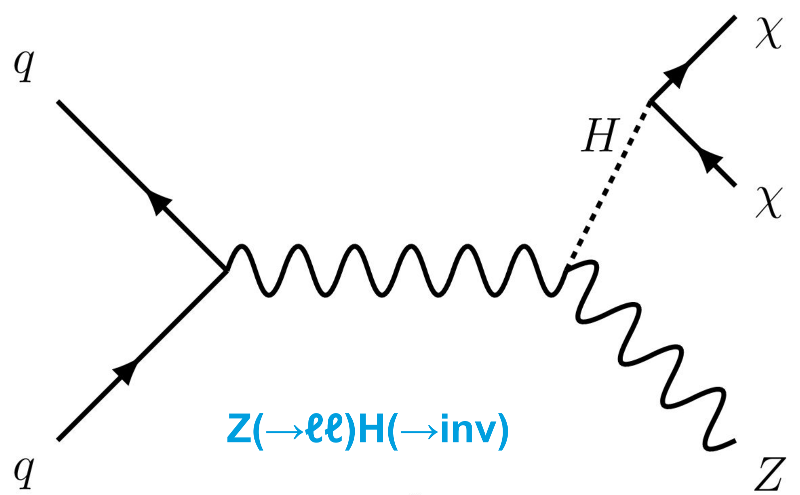
SM value

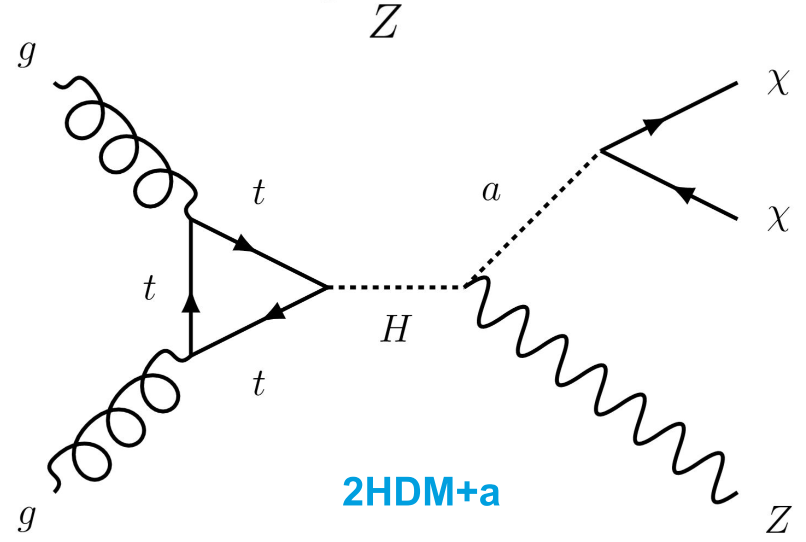
impact of measurement of *tH* production at the HL-LHC

⇒ Only mild constraints on the CP structure at LHC and HL-LHC

ATLAS: search for invisible Higgs decays and dark matter

Final state: Z → leptons + missing energy





Complementary sensitivity to search for dark matter

- Dark matter can be produced in invisible decays of the Higgs boson in the right mass range, Z(→ll)H(→ inv)
  - Absence of significant excess allows us to constrain H→ invisible
- Consider simplified dark matter model and two-Higgs-Doublet models plus an additional pseudoscalar mediator a (2HDM+a), Z(→ll)+Dark Matter

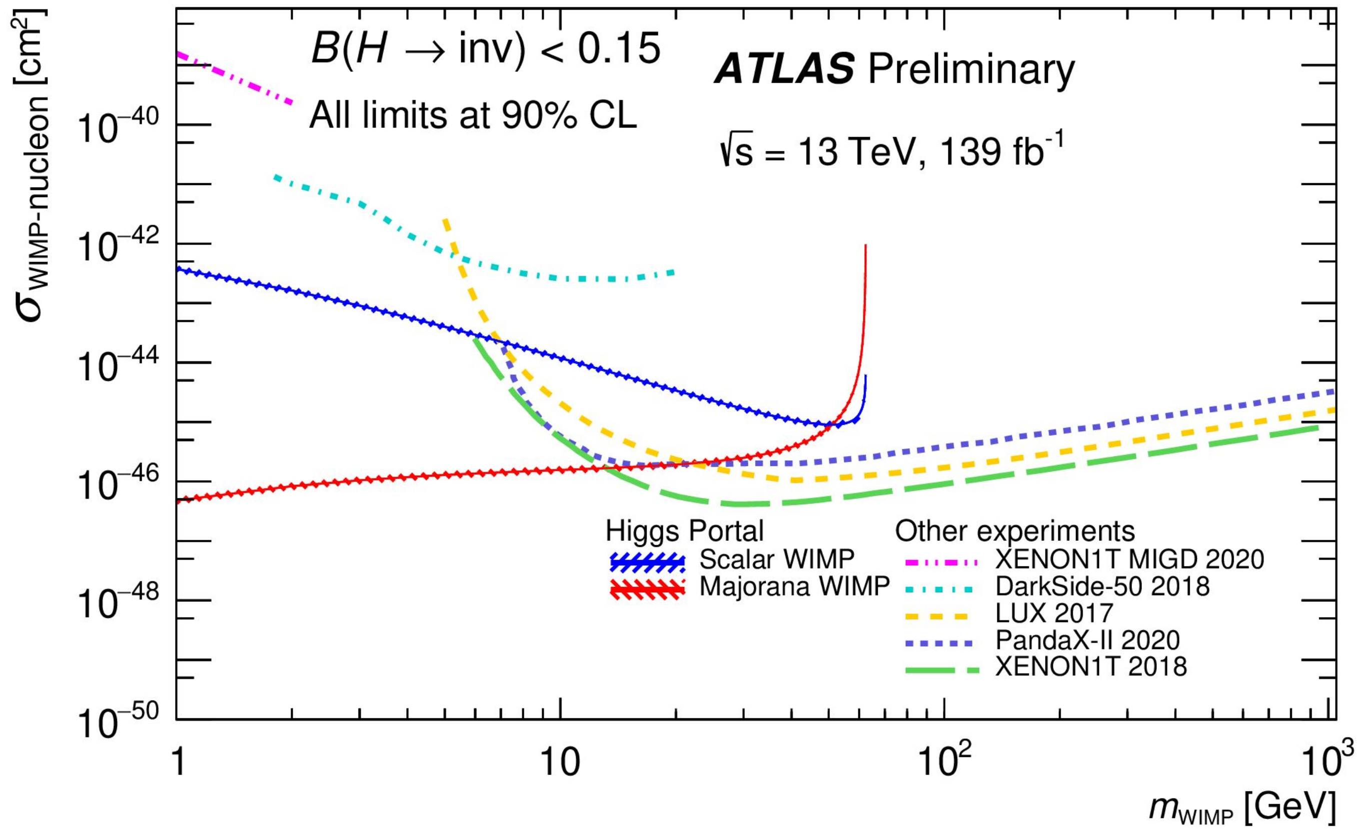
Distinct signature in final states with Z→ℓℓ and missing transverse momentum

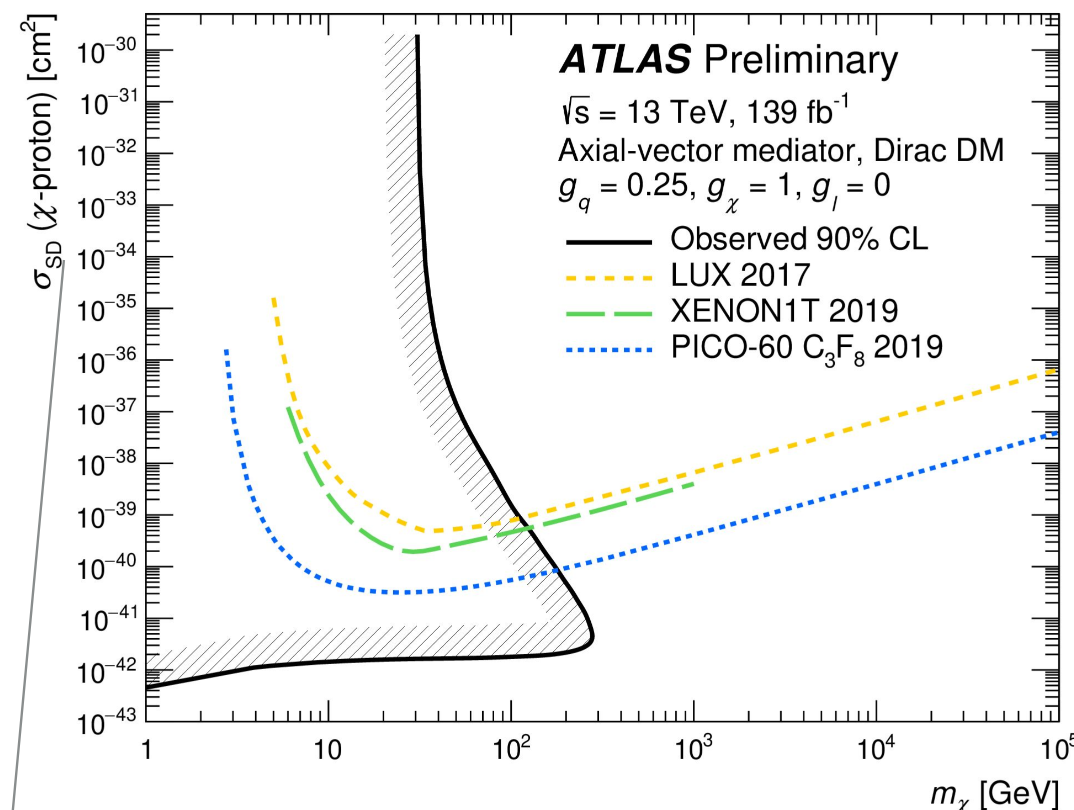
ATLAS: search for invisible Higgs decays and dark matter

ATLAS-CONF-2021-029

No significant excess over SM is observed (limited by the ZZ modelling uncertainties/Jet, MET description)

- $Z(\to ll)H(\to \text{inv})$ Branching ratio limit: < 0.18 (0.18) observed (expected) @ 95% C.L.
- Complementary sensitivity at low dark matter/WIMP masses compared to direct searches





Reinterpretation in Higgs portal model, comparison to direct detection limits

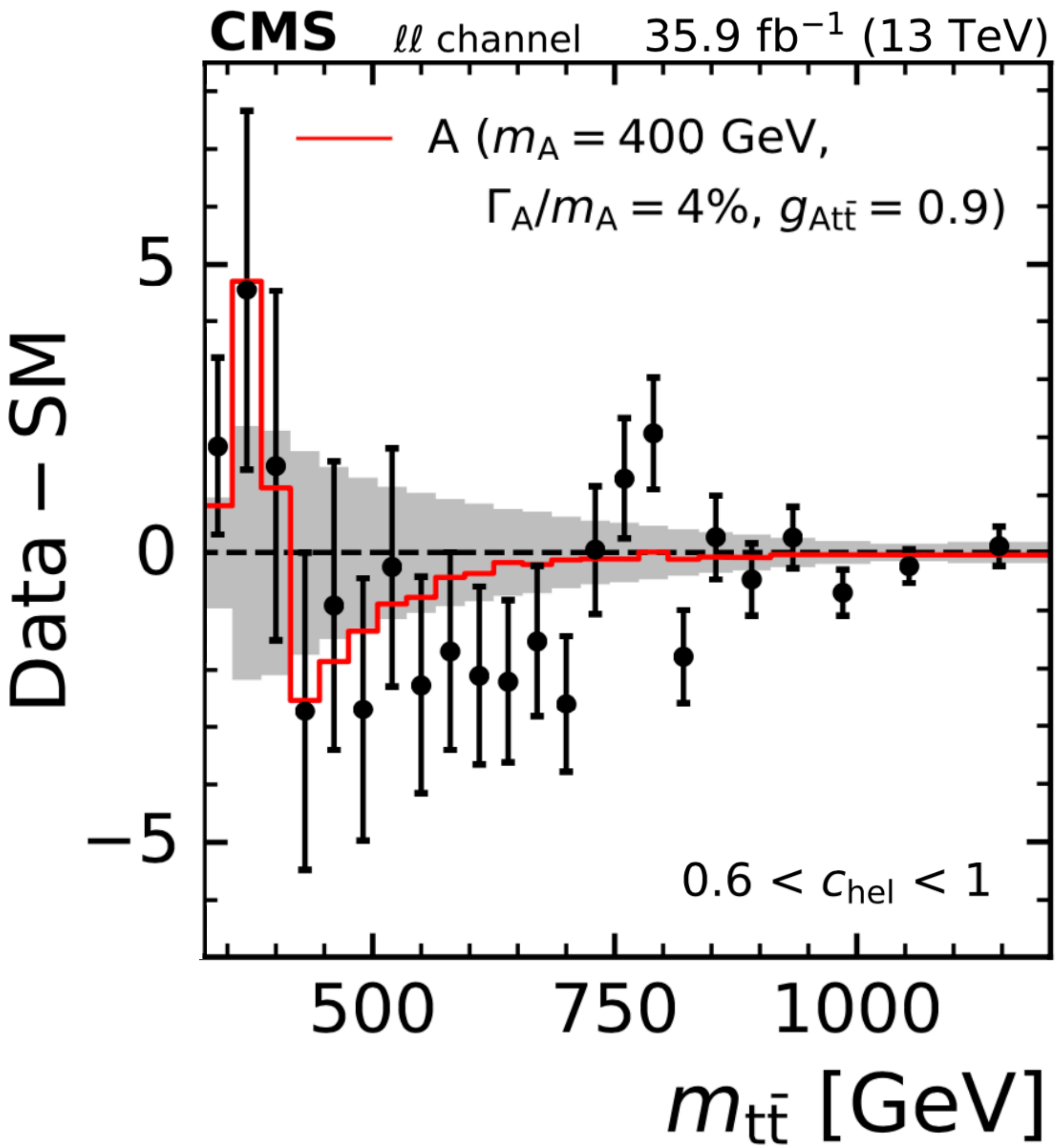
Reinterpretation in dark matter simplified model, comparison to direct detection limits

Axial vector mediator couples to the nucleon spin, Spin Dependent (SD)
Vector mediator coupling increases with nucleon mass, Spin Independent (SI)

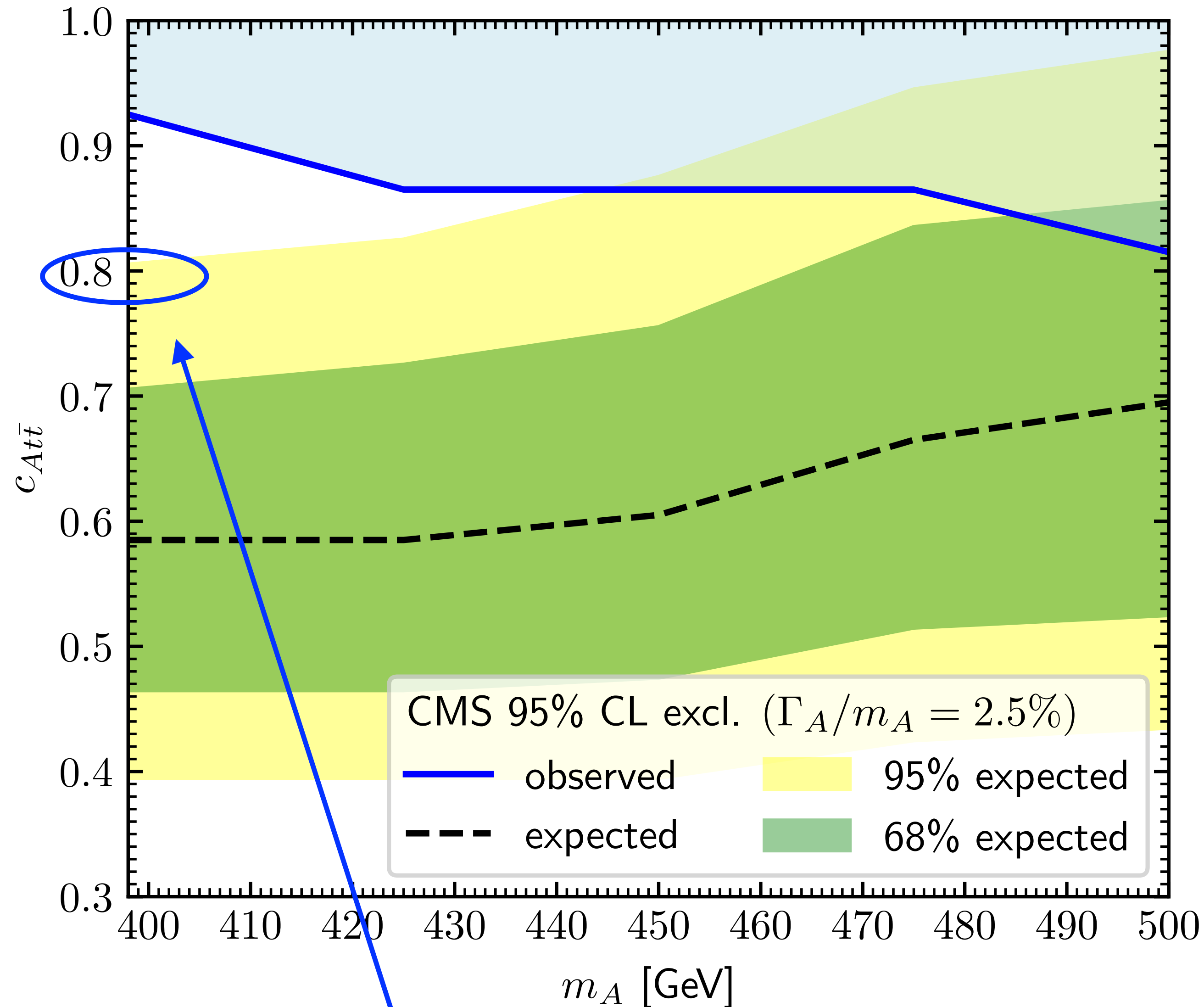
⇒Complementary to dark matter direct detection searches

Search for additional Higgs bosons: H, A → tt

Slight excess in CMS search at about 400 GeV:



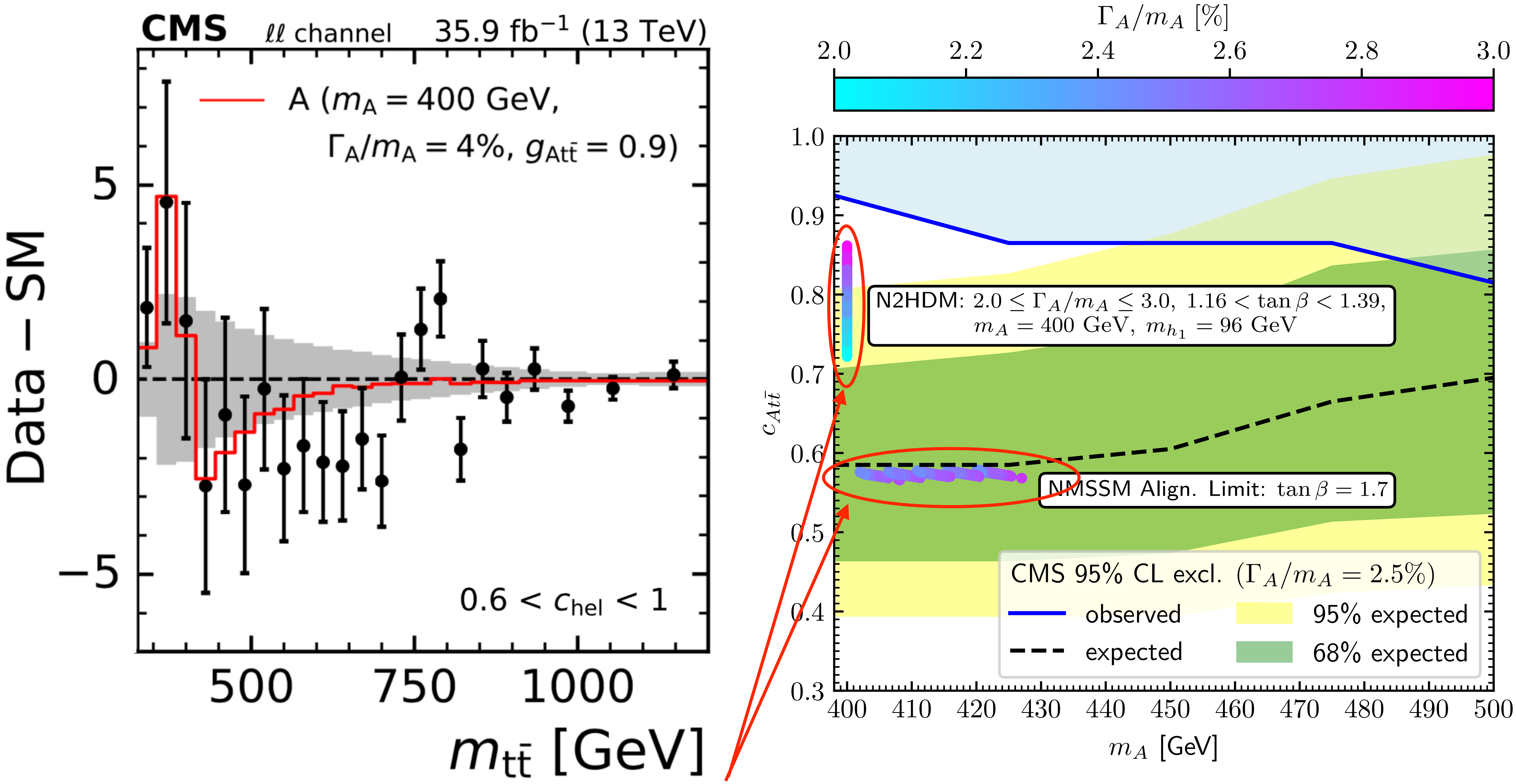
[see flash talk by A. Anuar]



CMS, best fit value for $\Gamma_A/m_A = 2.5\%$

Search for additional Higgs bosons: H, A → tt

Slight excess in CMS search at about 400 GeV:

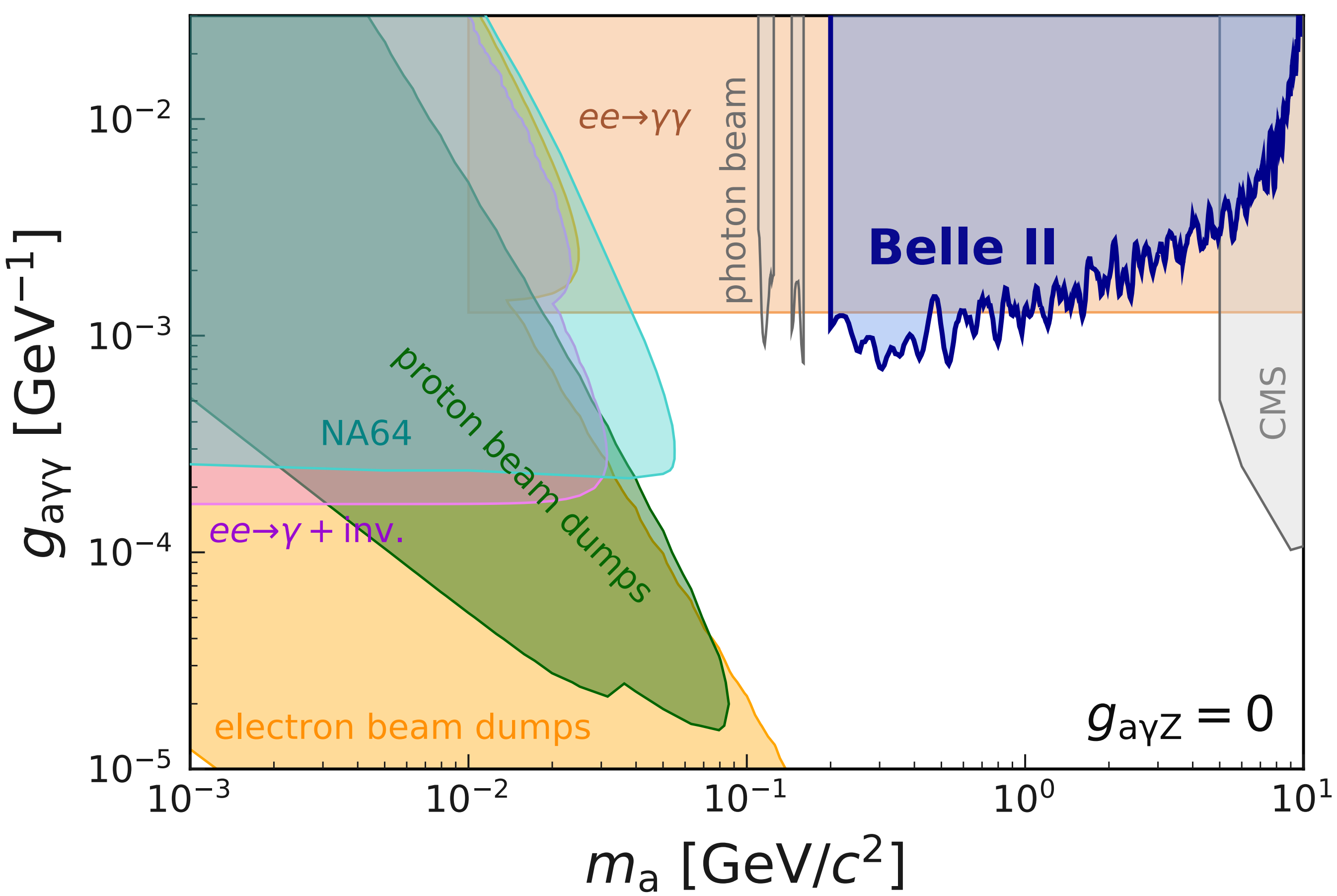


⇒ Good description of the A → tt excess at 400 GeV in models with extended Higgs sectors (N2HDM, NMSSM) *[experiment + theory joint effort]*

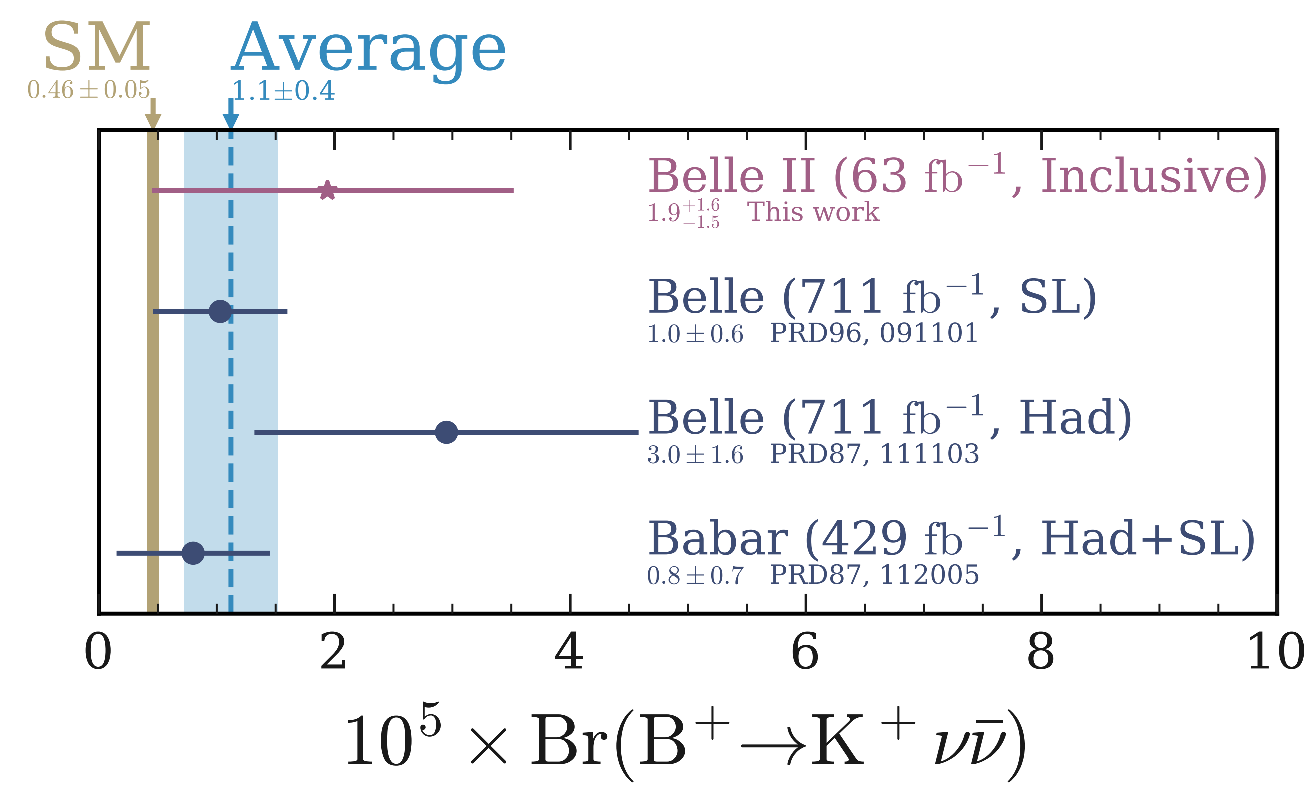
Important DESY contributions to first Belle II publications

[see flash talk by A. Martini]

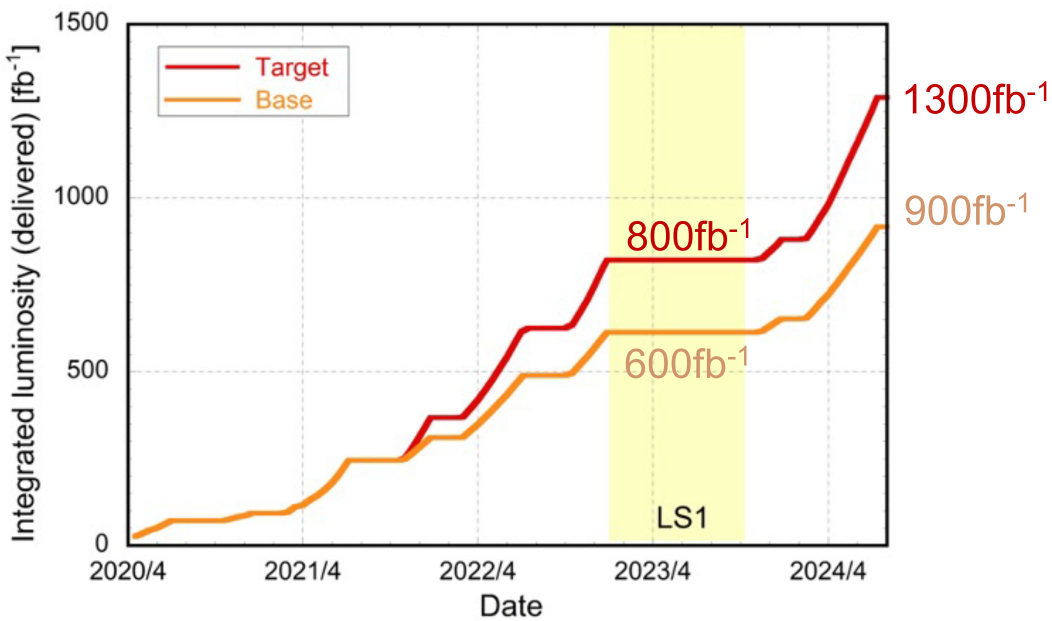
Axion-like particle searches:



Rare decay:



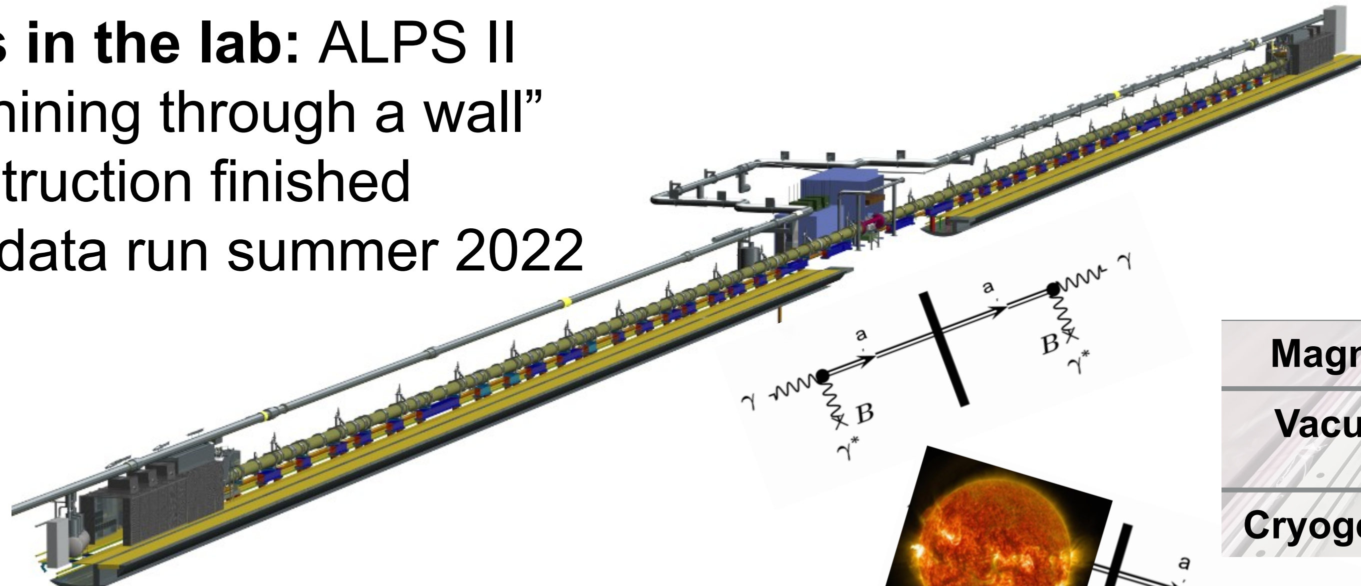
Large improvements expected from much more data during the next years

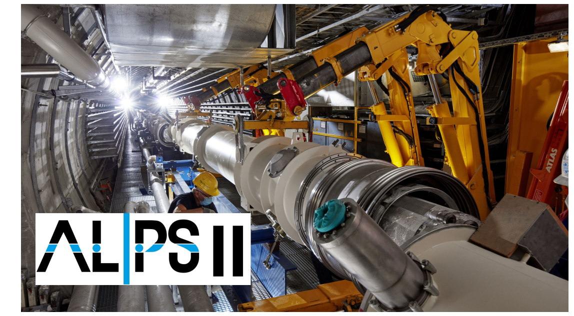


Plans and opportunities for on-site experiments

Search for ALPS (axion-like particles, very weakly interacting), non-linear QED

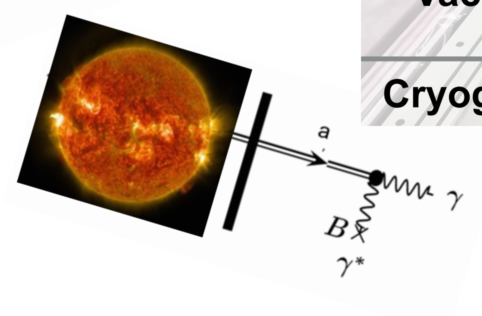
Axions in the lab: ALPS II
“light shining through a wall”
- Construction finished
- First data run summer 2022



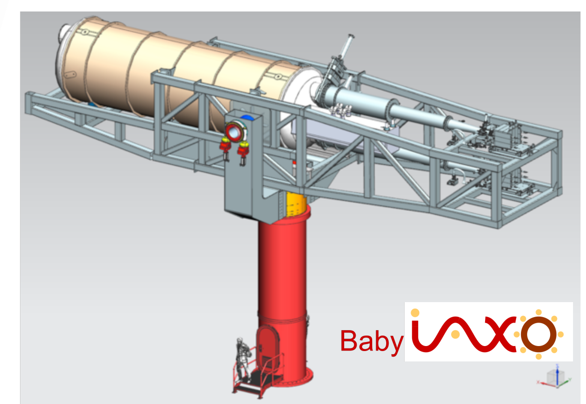


Magnets	24 / 24 dipoles straightened, installed, and aligned
Vacuum	installed and tested, including central vacuum tank and in-vacuum optomechanical components
Cryogenics	installed and ready for TÜV pressure tests

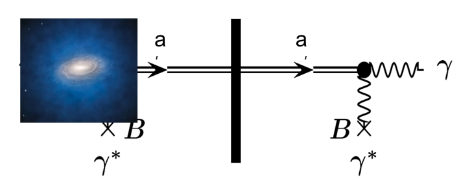
[see flash talk by K. Karan]

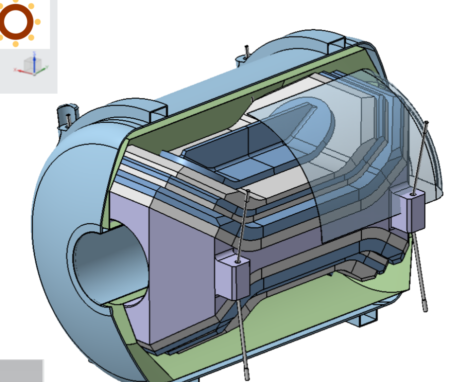


Axions from the sun: BabyIAXO
- Design ongoing
- Start construction 2022

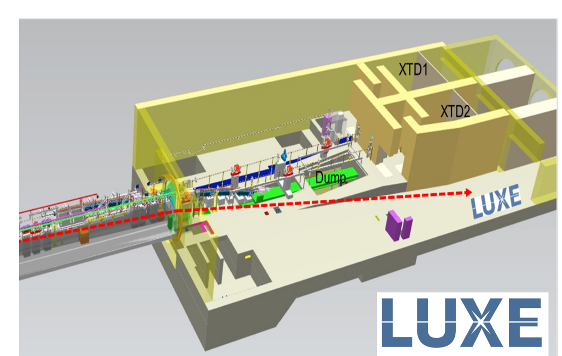


Local dark matter Axions: MADMAX
- CERN experiment followed by DESY experiment?





Non-linear QED, light Axions: LUXE
- Utilise E-XFEL beam and strong laser
- Conceptual design report released *https://arxiv.org/abs/2102.02032*



Future Collider Forum

Support activities in Germany related to future colliders

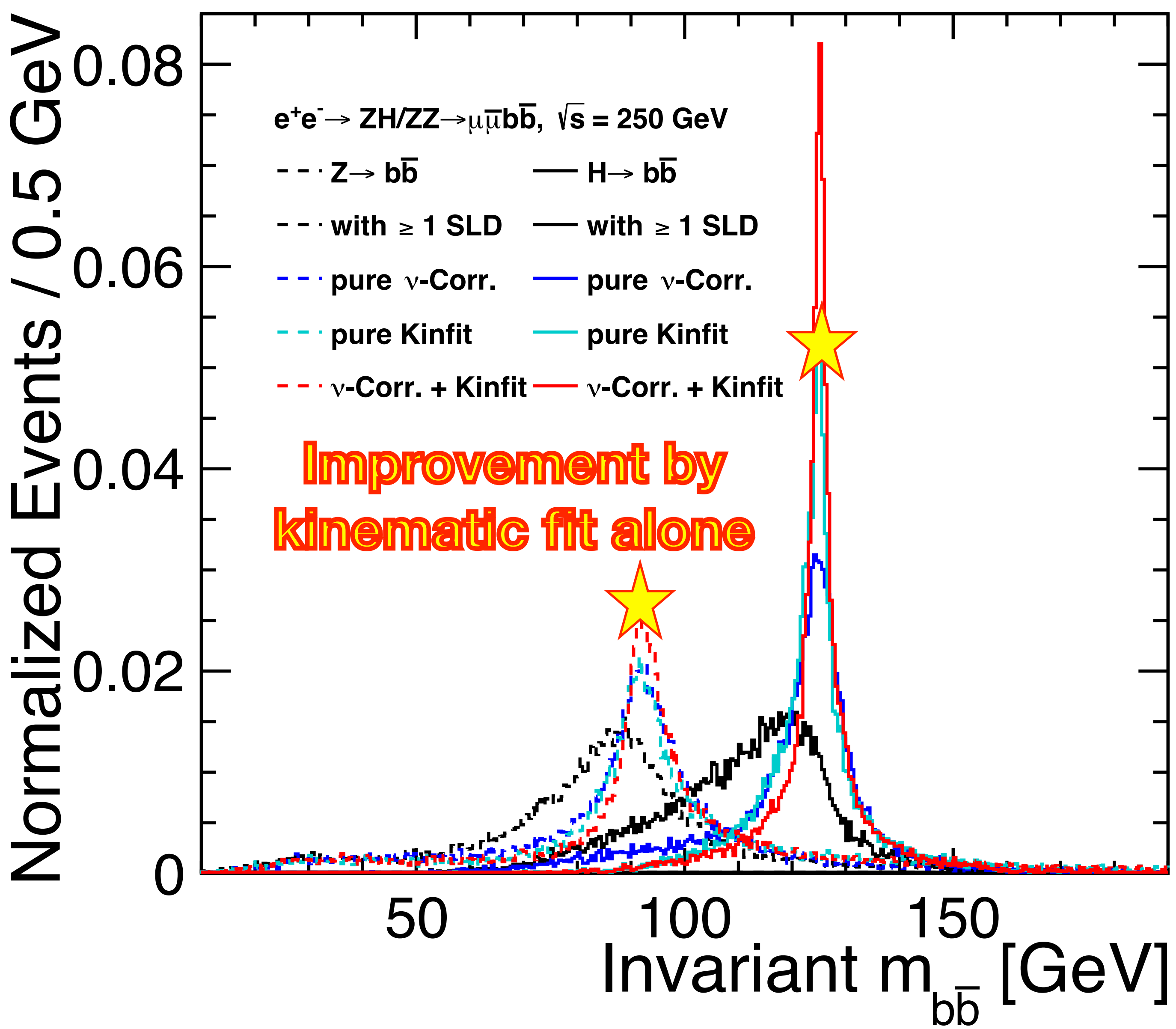
- Forum for all projects: Compact Linear Collider (CLIC), Future Circular Collider (FCCee/eh/hh), International Linear Collider (ILC), Muon Collider, …
- Foster the interaction between physics studies (experiment and theory) and activities on the detector and accelerator side
- Identify and exploit synergies between the activities on the different future projects
- Reduce the threshold for contributions in individual groups, enable exchange at the ``working level”
- Allow to reach critical mass also with smaller contributions
- ``Community Meeting”, increase of visibility, especially for younger researchers

Kick-off meeting: April 2021, first Workshop: October 2021

Higgs factory: invariant mass reconstruction in $H \to bb$ / cc

arXiv:2110.13731

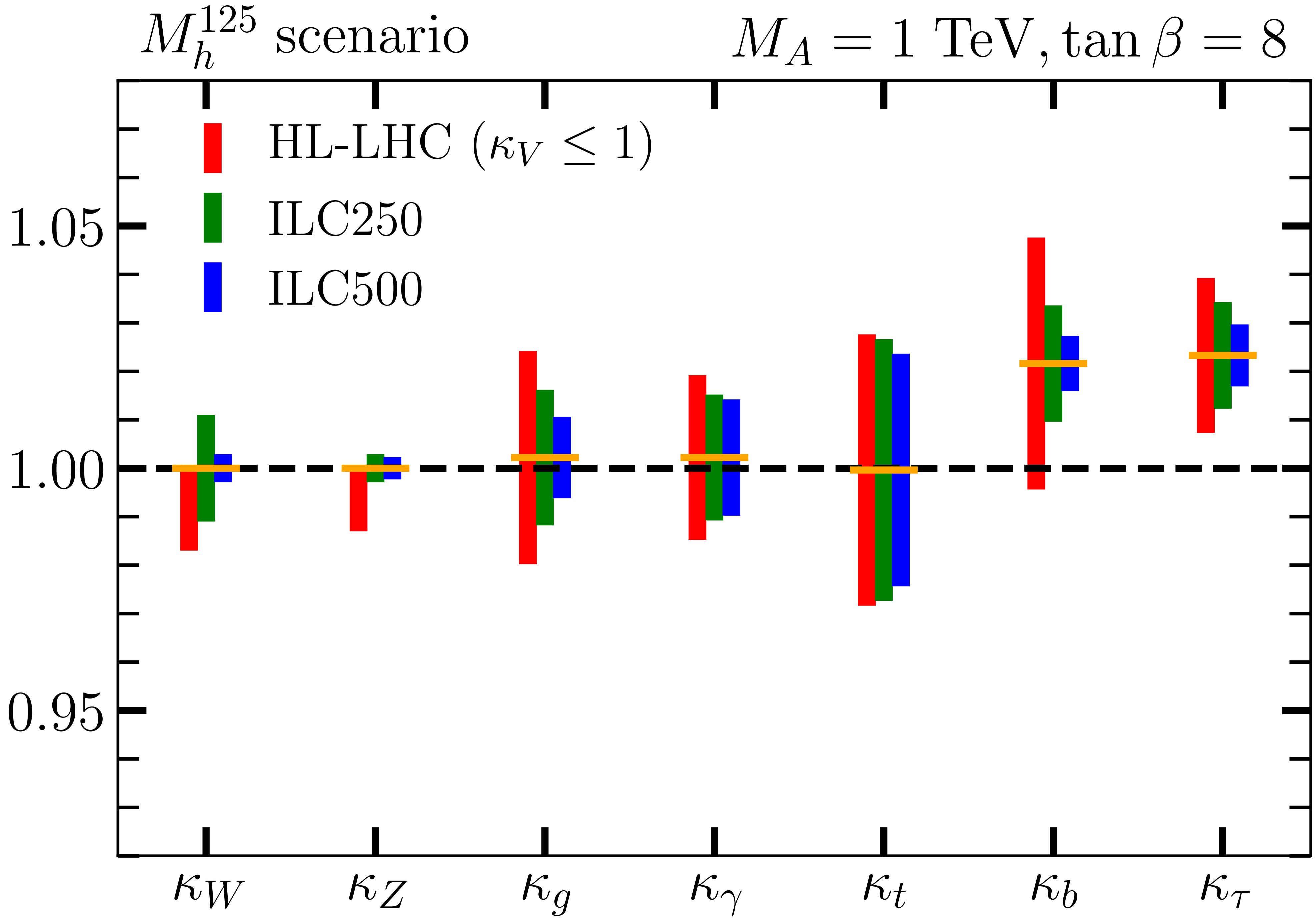
- At a future e^+e^- collider, reconstruction of $H \to bb$ / cc is important for many Higgs measurements
- invariant mass of reconstructed jets suffers from semi-leptonic b/c decays (SLD):
  - shift of peak position
  - long tail to lower masses
  - **ZH / ZZ not very cleanly separated (black histo)**
    => this is what enters projections so far!
- **kinematic fit with ParticleFlow-based error parametrisation for each jet (cyan histo & stars)** sharpens mass peaks **drastically**
- **adding an explicit correction for neutrinos from semi-leptonic decays could offer even further improvement (red histos)**



Impact expected on many Higgs and top projections, incl Higgs BRs, Higgs self-coupling, top electroweak couplings, …

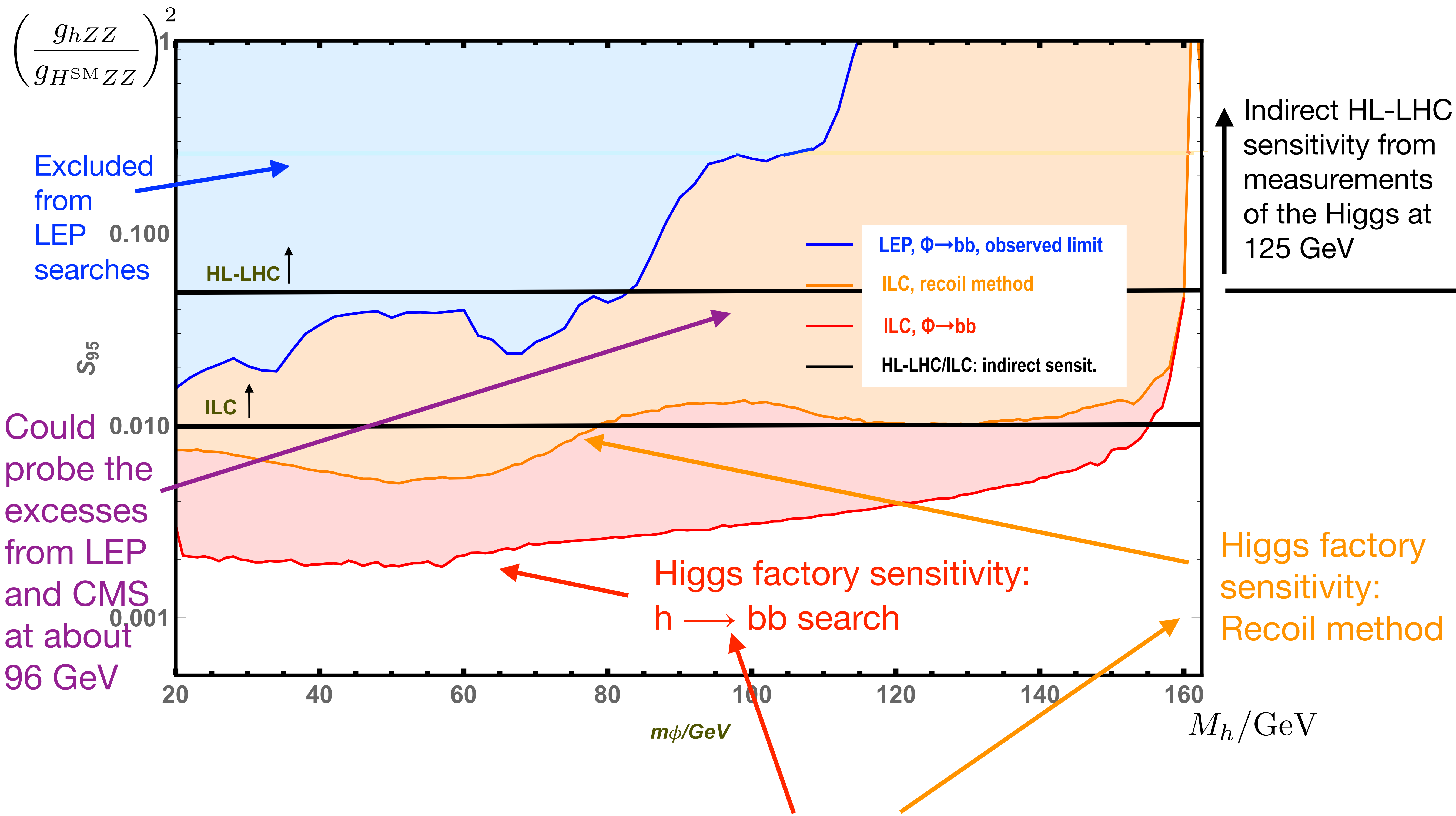
Higgs couplings: HL-LHC vs. Higgs factory

Example: heavy SUSY scenario



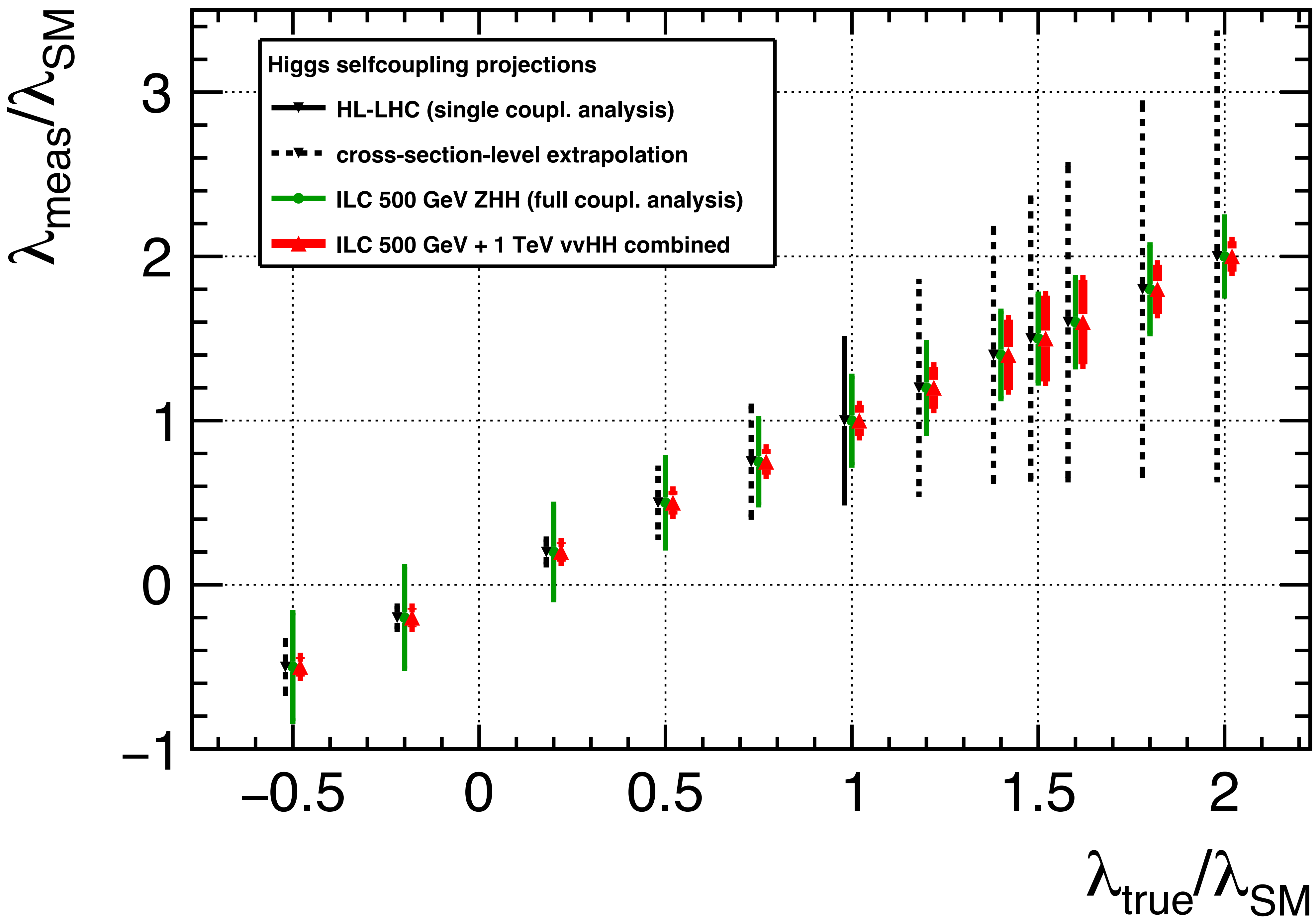
⇒ Precision at 1% level provides large sensitivity for discriminating between different realisations of underlying physics

Higgs factory discovery potential for new light states: Sensitivity at 250 GeV with 500 fb^{-1} to a new light Higgs



⇒ Higgs factory at 250 GeV will explore a large untested region!

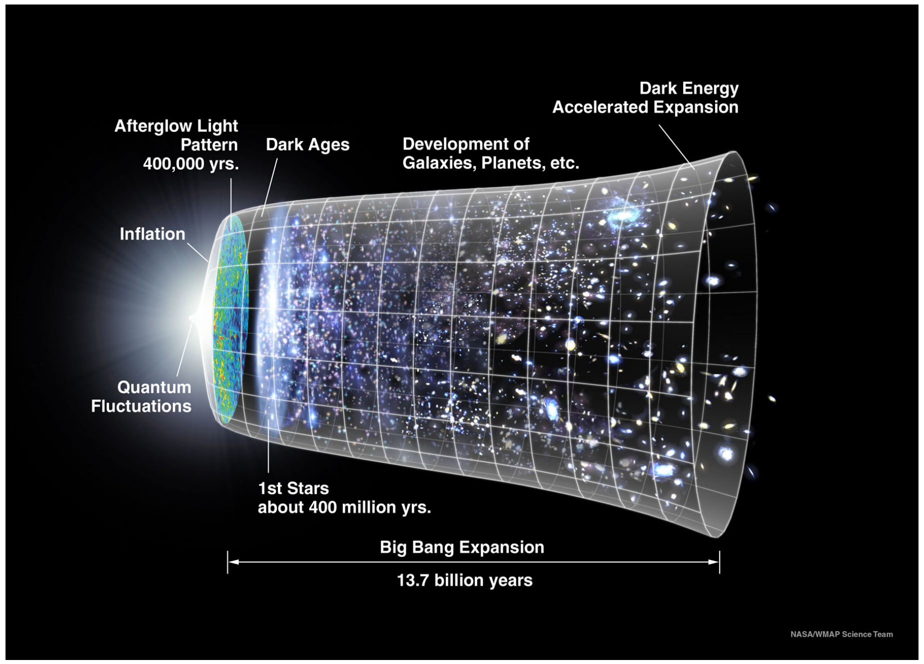
Higgs self-coupling sensitivity: ILC vs. HL-LHC

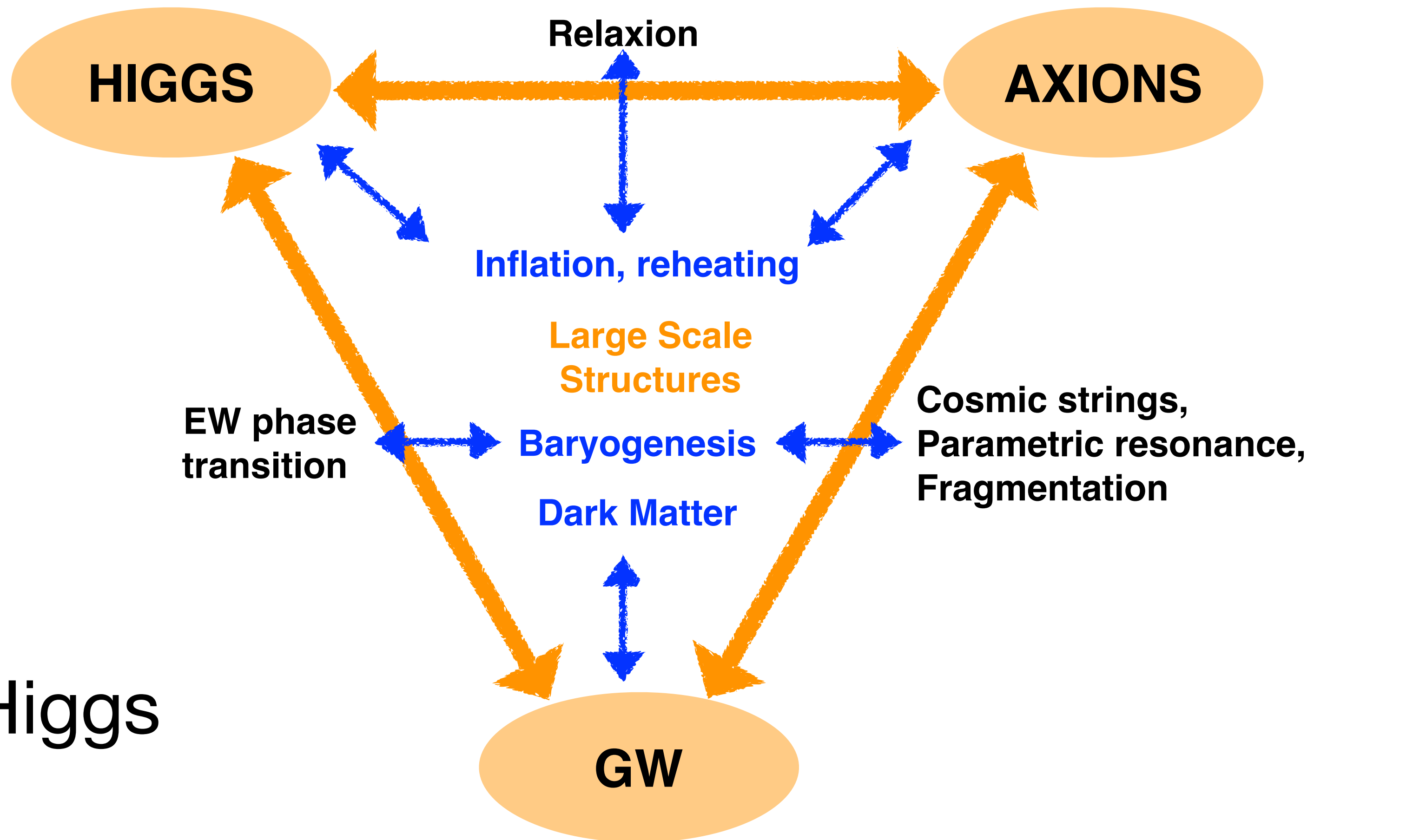


⇒ Capabilities of the facilities depend on the actual value of λ!

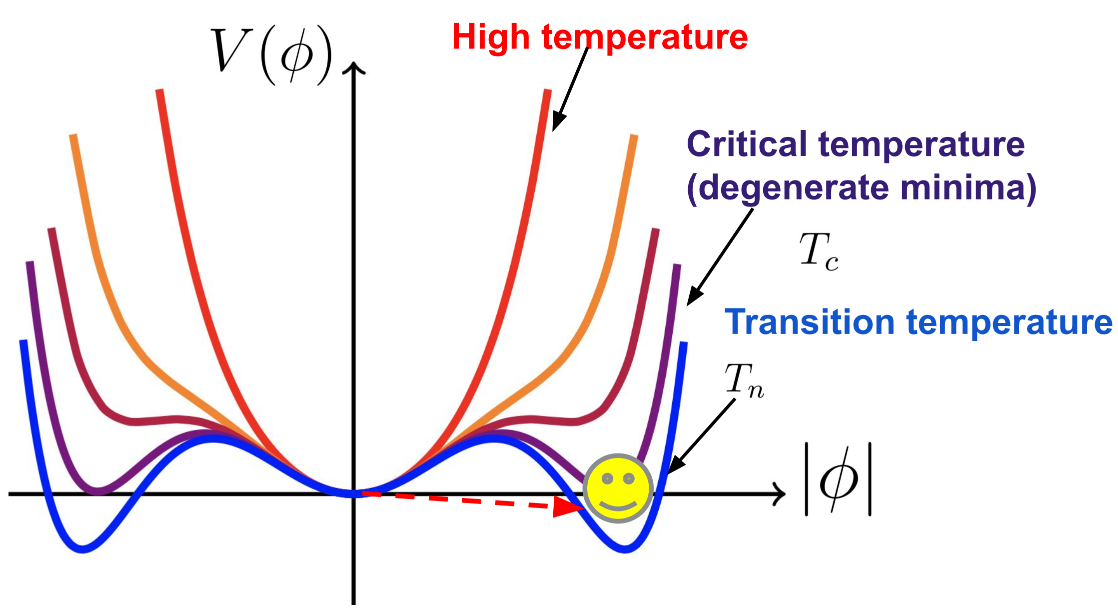
ILC: 10-15% precision on λ or better with ZHH (500 GeV) + $\nu\nu$HH (1 TeV)

Interplay between collider physics and cosmology





Temperature evolution of the Higgs potential in the early universe:



Baryogenesis: creation of the asymmetry between matter and anti-matter in the universe requires a first-order EW phase transition (FOEWPT)

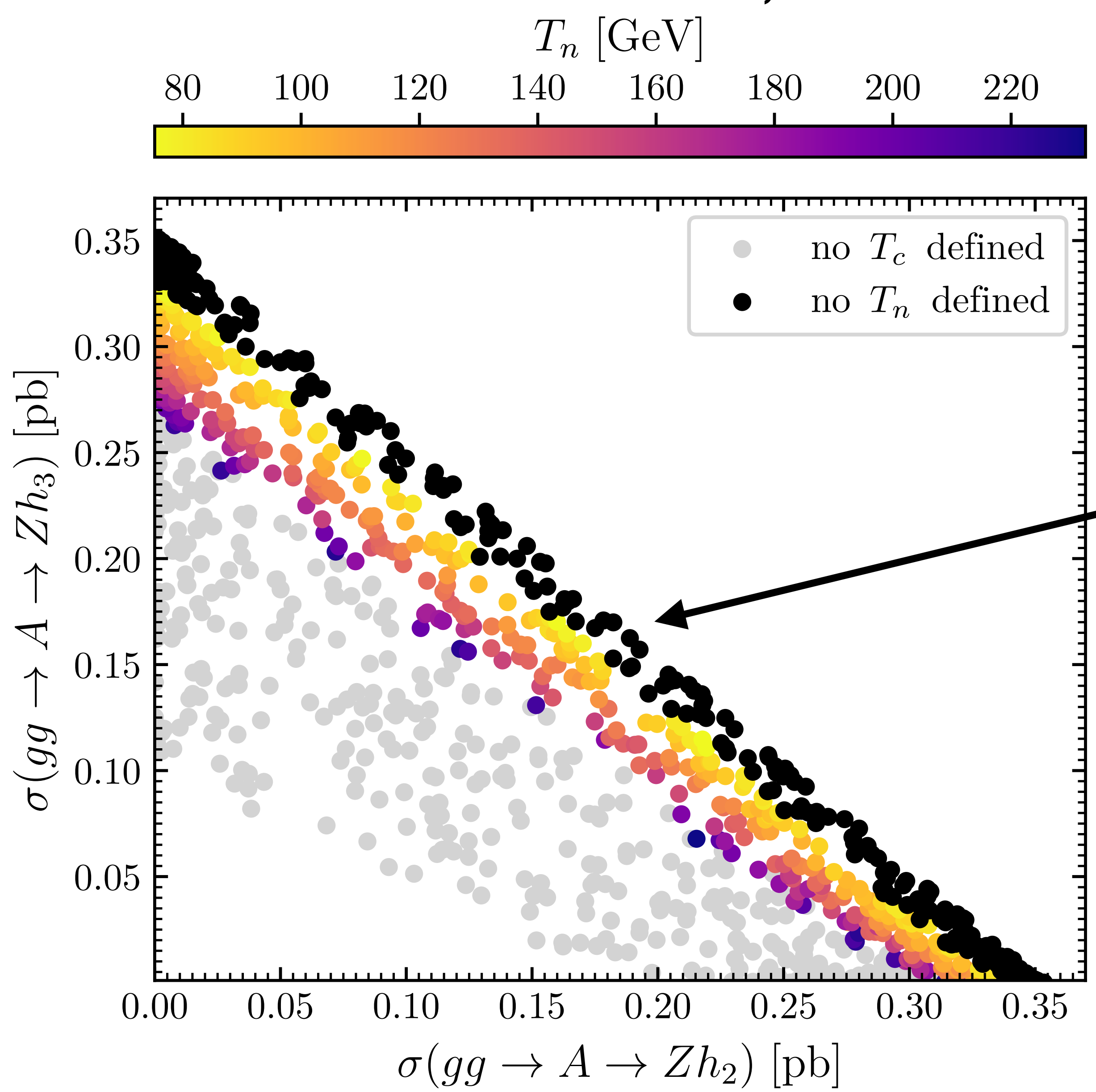
Does not work in the SM, can be realised in extended Higgs sectors

FOEWPT: N2HDM (two doublets + real singlet)

[see flash talk by M. O. Olea]

``Smoking gun" collider signature: A → Z h_2, A → Z h_3

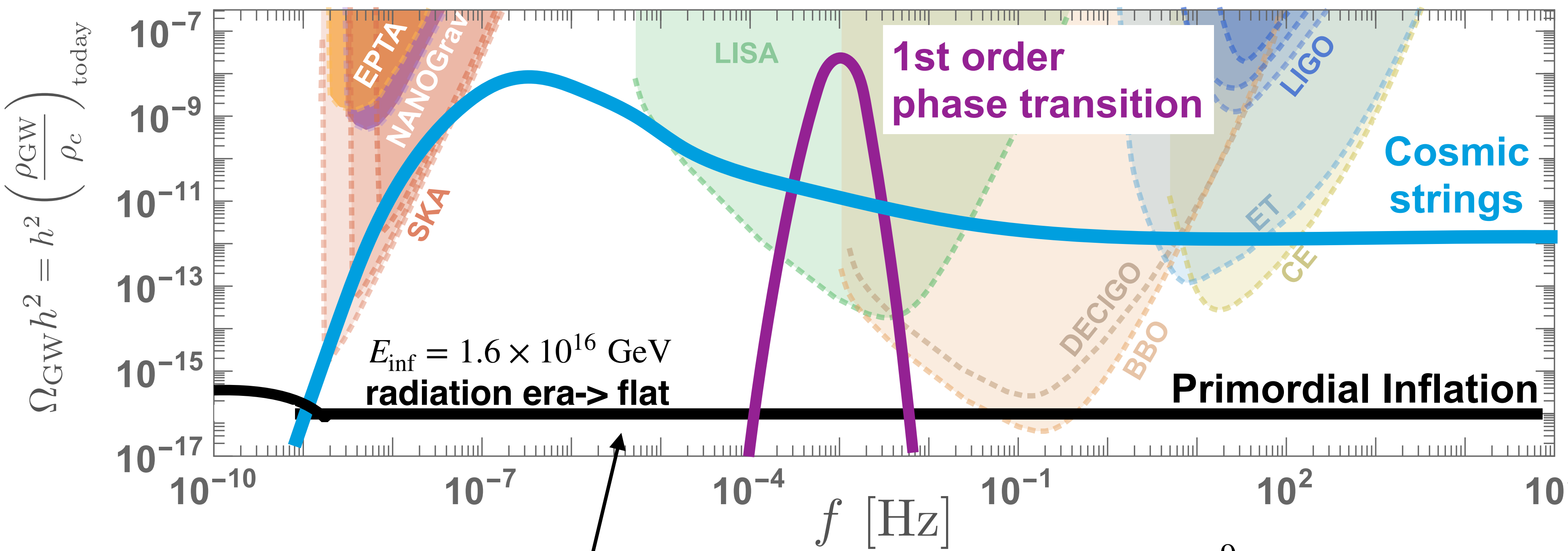
Nucleation temperature for the FOEWPT, N2HDM scan:



No FOEWPT; universe is trapped in a ``false" vacuum

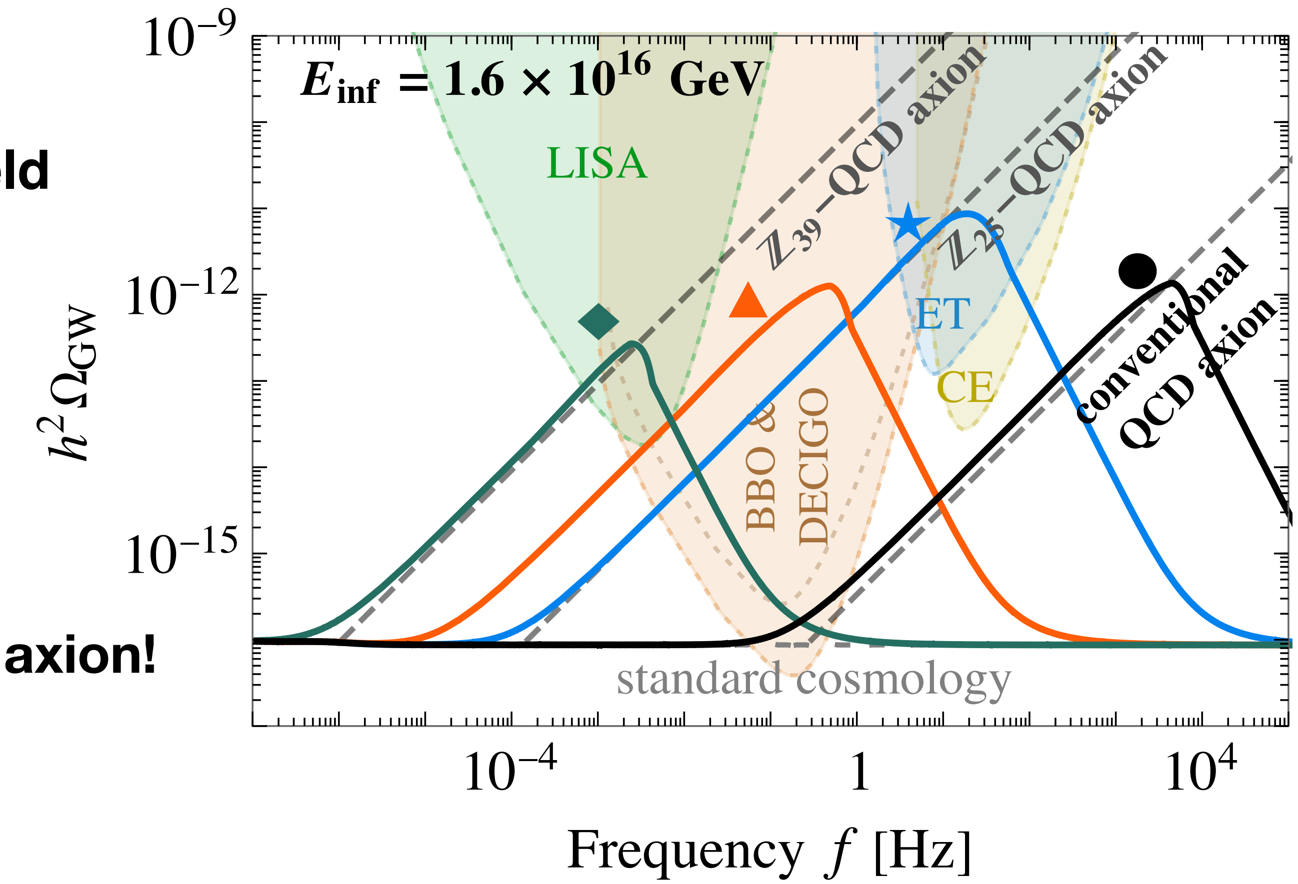
⇒ Lower nucleation temperatures, i.e. stronger FOEWPTs, are correlated with larger signal rates at the LHC!

Gravitational waves as a probe of the early universe



Irreducible GW background from amplification of initial quantum fluctuations of the gravitational field during inflation

Primordial GW enhanced by an early spinning axion!

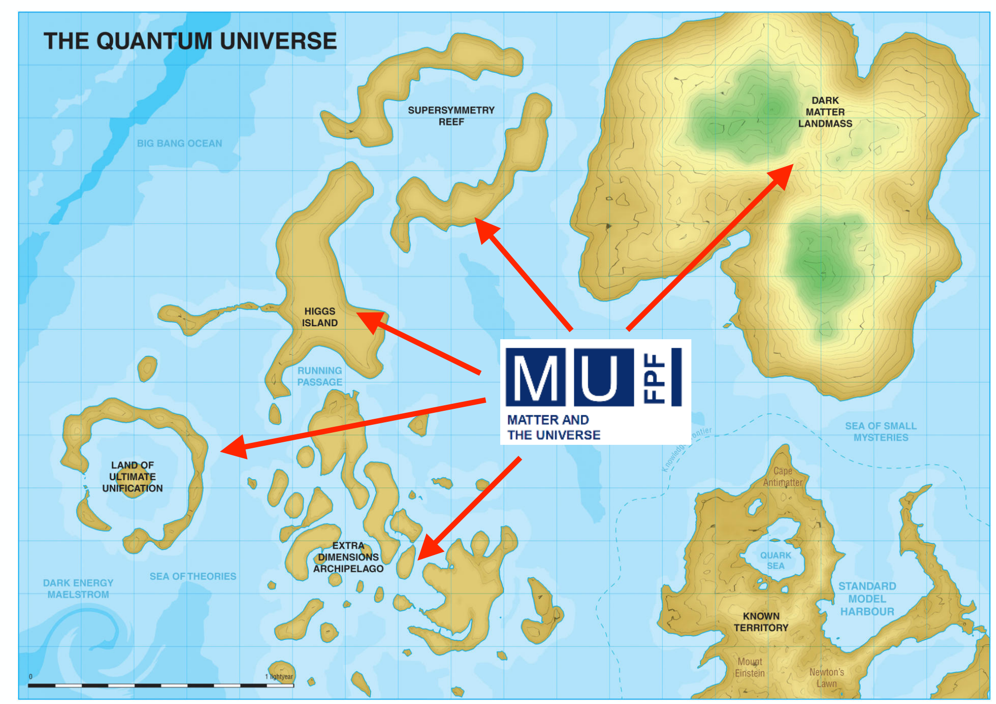


Conclusions: FPF, present and future

[See the ``Outlook" talk by Priscilla Pani!]

FPF: exploration of the fundamental laws of nature provides a window to the evolution of the early universe and may reveal a connection to the dark sector

Goal: find our way on the ``Quantum Universe map"



Role as a leading partner and national lab:

- Indispensable partner for German universities in int'l endeavours
- World-leading infrastructures, experience and expertise
- On-site experiments with unique discovery potential
- Facilitate decisive German contribution to next int'l collider project

Backup

Are there additional sources for CP violation in the Higgs sector?

The amount of CP violation in the SM (induced by the CKM phase) is not sufficient to explain the observed asymmetry between matter and anti-matter in the universe

$\Rightarrow$ Search for additional sources of CP violation

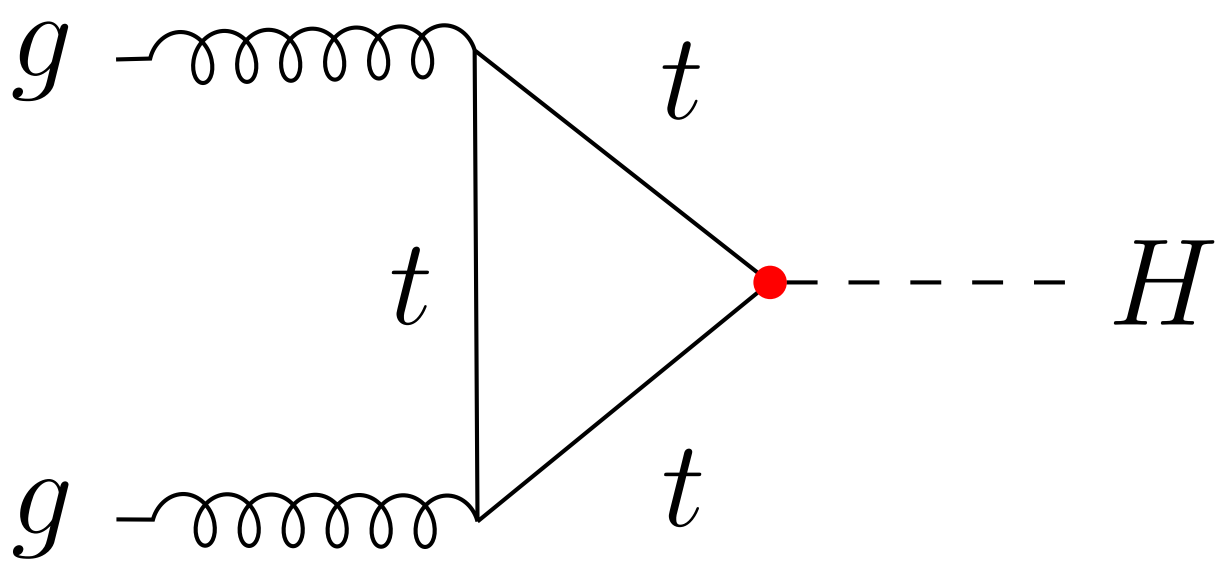
Baryogenesis: creation of the asymmetry between matter and anti-matter in the universe requires a first-order electroweak phase transition (FOEWPT)
Does not work in the SM, can be realised in extended Higgs sectors

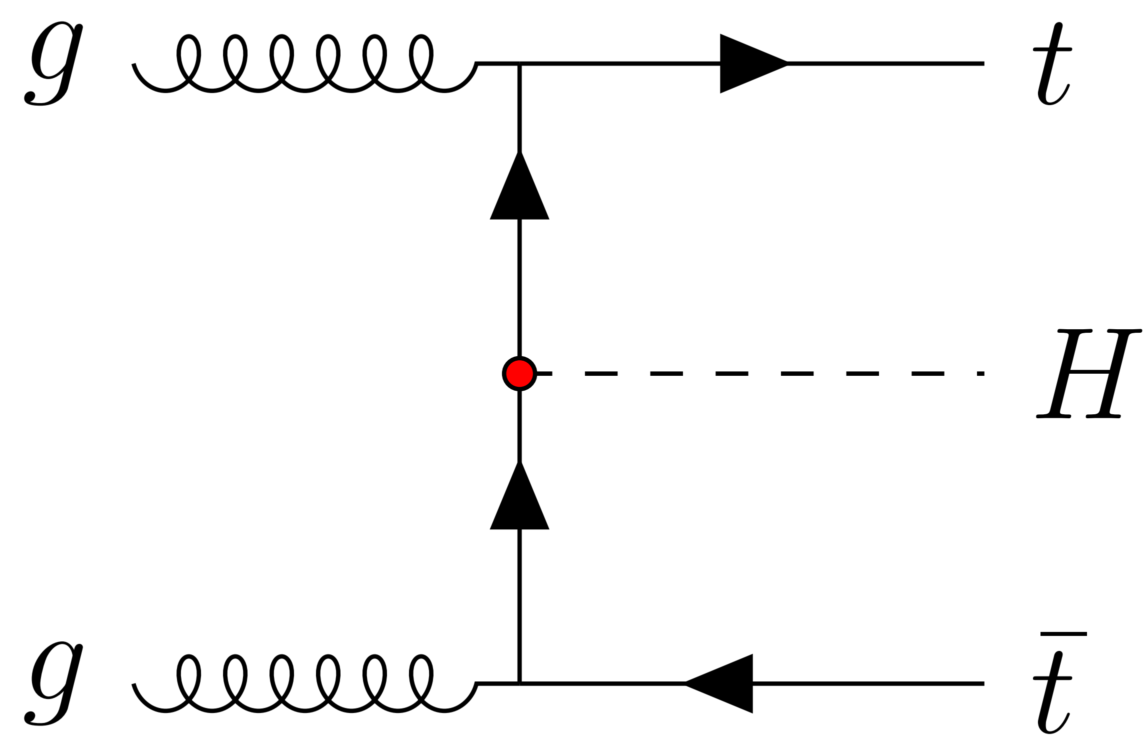
But: strong experimental constraints from limits on electric dipole moments (EDMs)

CP properties of h125

It has been experimentally verified that h125 is not a pure CP-odd state, but it is by no means clear that it is a pure CP-even state

The main testing ground are processes involving only Higgs couplings to fermions





with H → $\tau\tau$, bb, …

Composite Higgs

Approaches to address the question how a scalar particle can be light, $M \sim 125$ GeV:

- SUSY: elementary scalars related via SUSY to elementary fermionic superpartners, which naturally have a small mass (weakly broken chiral symmetries)

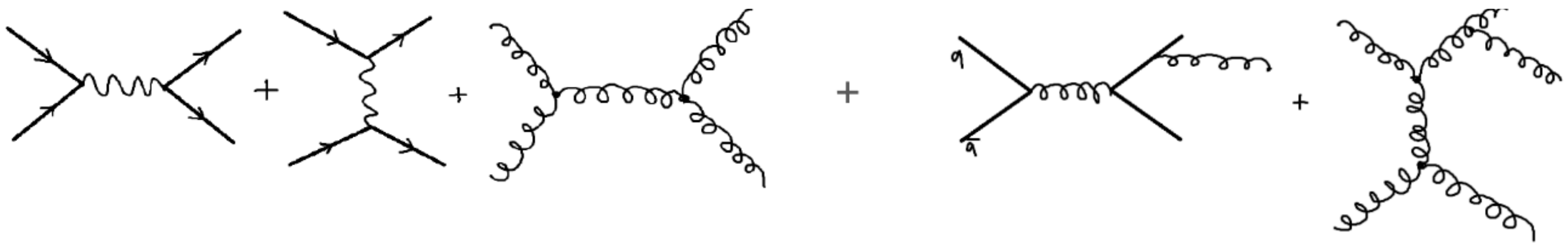
- Spontaneous breaking of a continuous global symmetry:
  ⇒ massless Goldstone boson

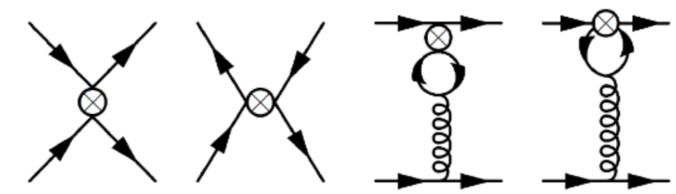
  Explicit breaking of global symmetry
  ⇒ pseudo-Goldstone boson (PGB)

  Mass of the PGB is proportional to the strength of the symmetry breaking

Simultaneous constraints on QCD and BSM

SMEFT interpretation of the inclusive jet production in pp collisions at 13 TeV



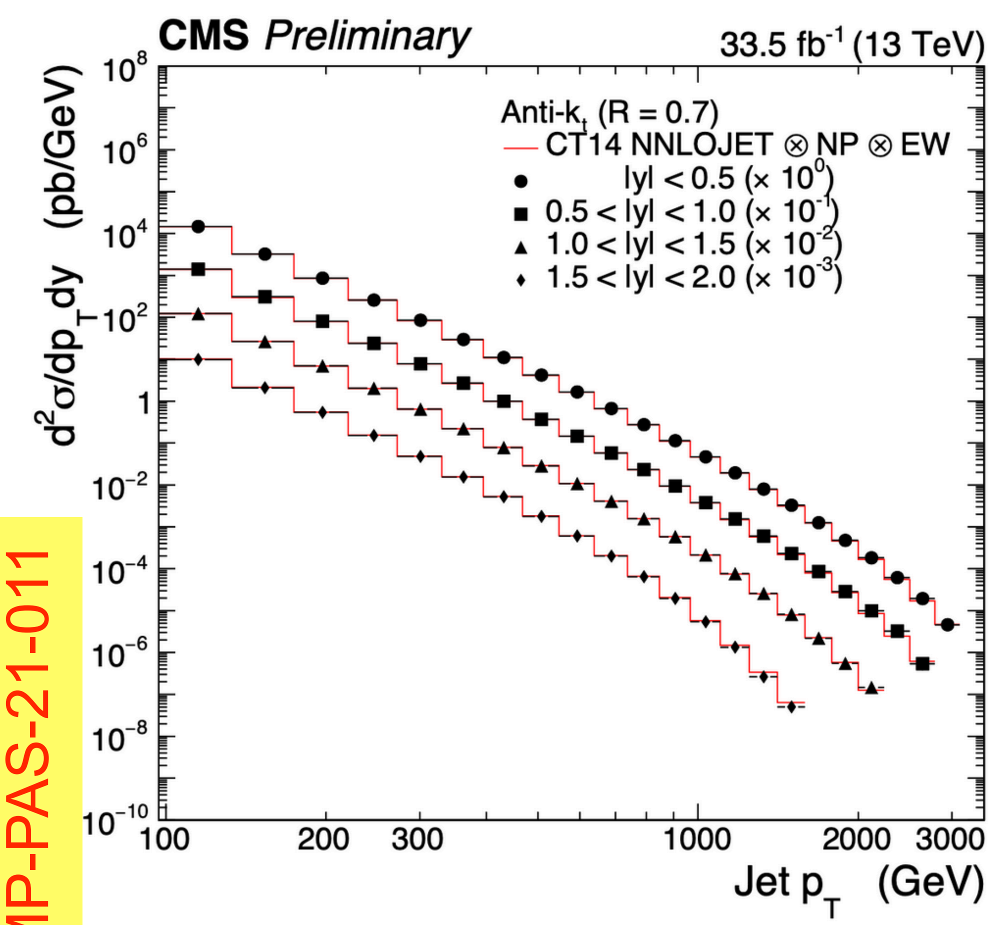


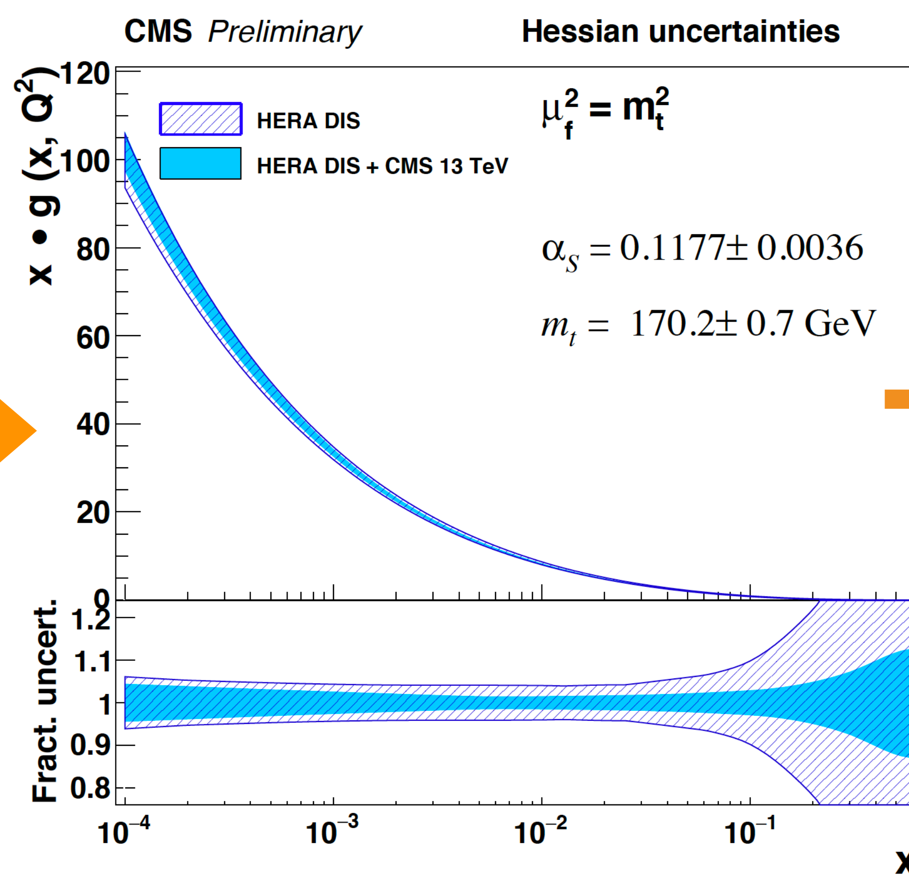
direct probe of gluon and strong coupling constant

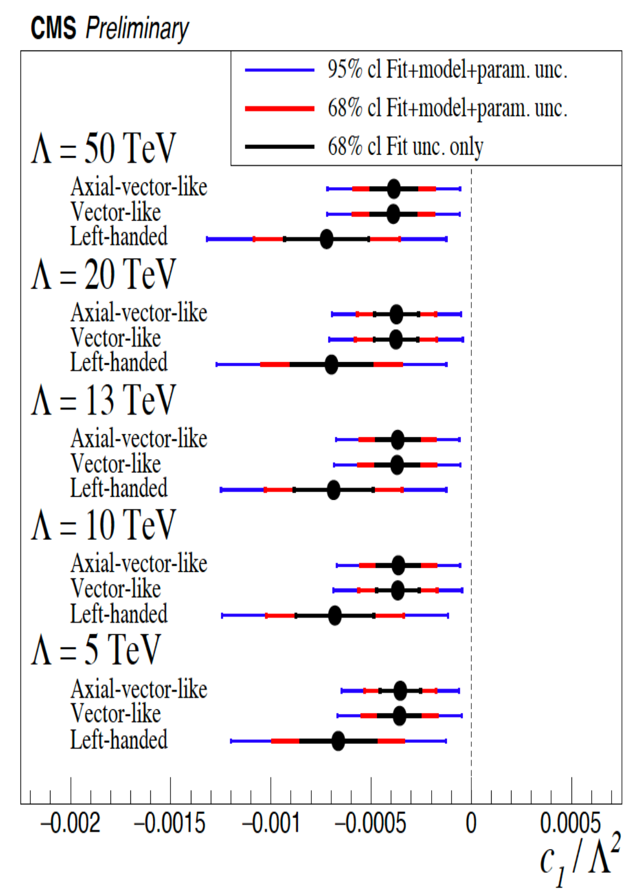
contact interactions

New CMS data used in QCD+CI fit at NLO with DIS (EPJC 75 (15)12) and CMS ttbar (EPJC 80 (2020) 7)

CMS-SMP-PAS-21-011







- Improvement in PDF accuracy at high x
- Simultaneous extraction of QCD and BSM parameters
- No risk of absorbing BSM into PDFs

95% CL exclusion for Λ ($c_1 = -1$):

Left-handed : $\Lambda > 24$TeV

Vector-like: $\Lambda > 32$TeV

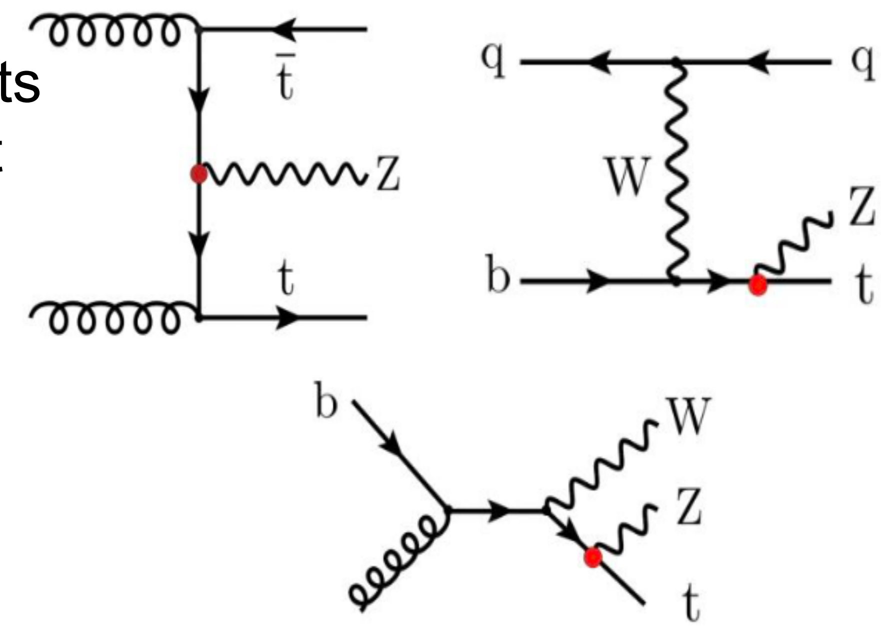
Axial-vector like $\Lambda > 31$TeV

Probing t-Z couplings with EFT and ML

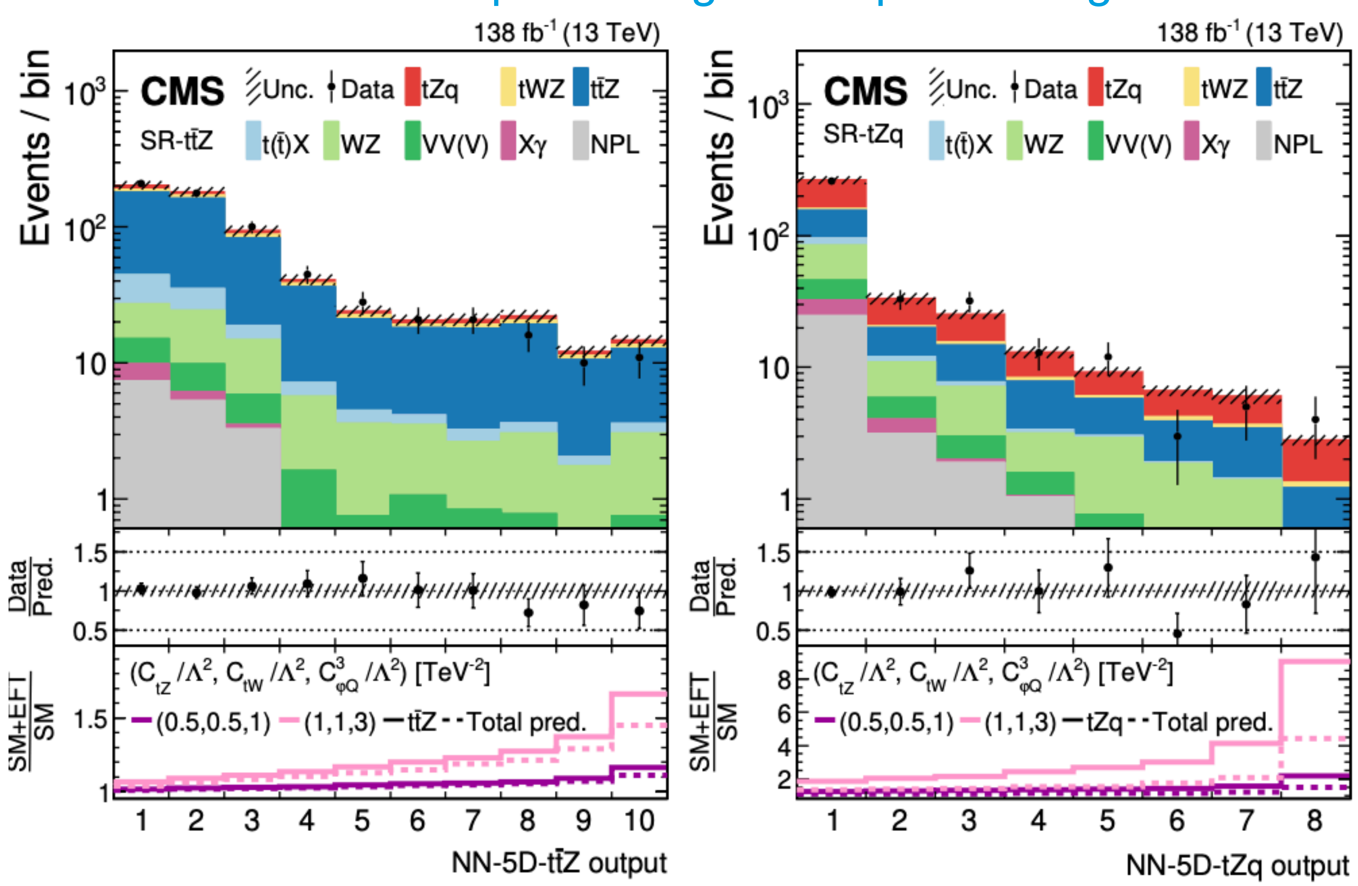
Featured on last CERN Courier

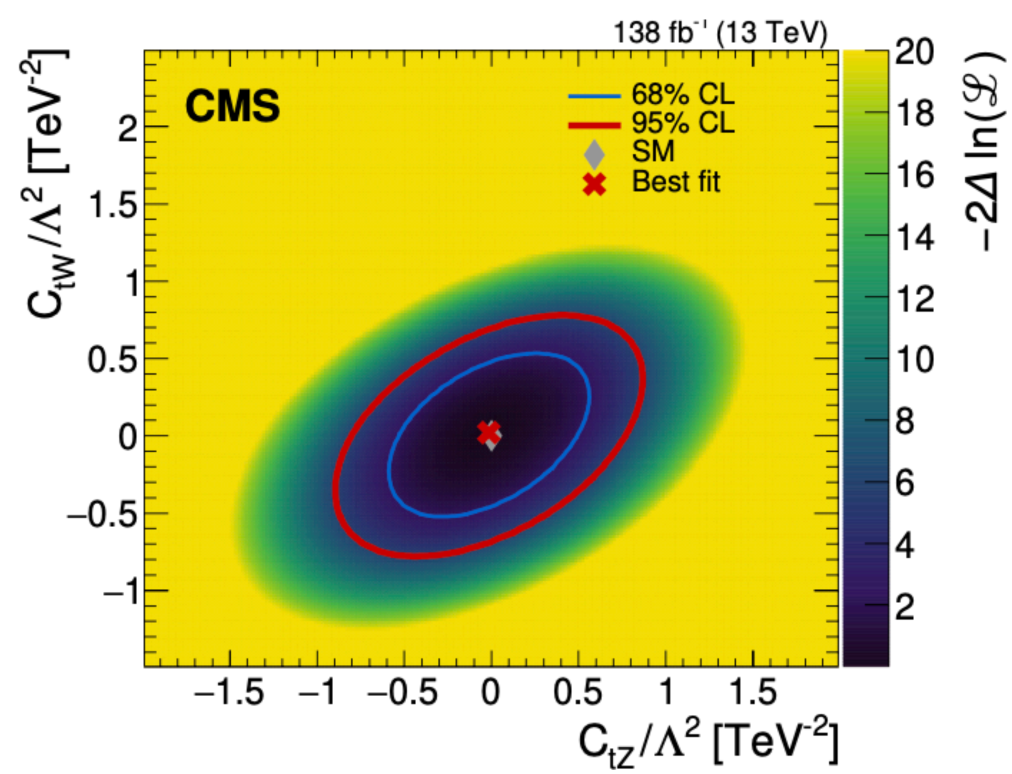
CERNCOURIER
VOLUME 61 NUMBER 5 SEPTEMBER/OCTOBER 2021

- t-Z coupling modified by various BSM scenarios
- EFT framework: interpret deviations in precision measurements as signs for new physics at higher energy, model-independent
- **Novel approach:** constrain several t-Z EFT operators in a simultaneous analysis of ttZ, tWZ, & tZq events:
  - Consider up to 5 EFT operators simultaneously
  - Pioneer use of Deep Learning techniques to target EFT effects



TOP-21-001, arXiv:2107.13896 (sub. to JHEP)

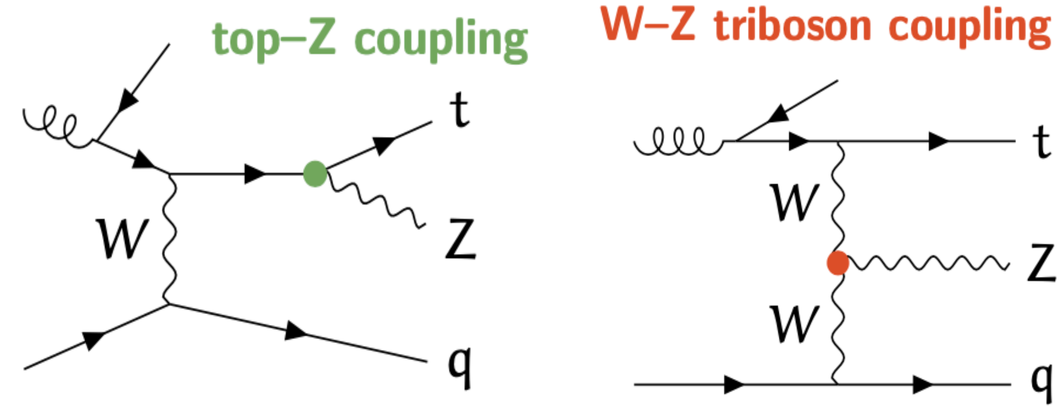




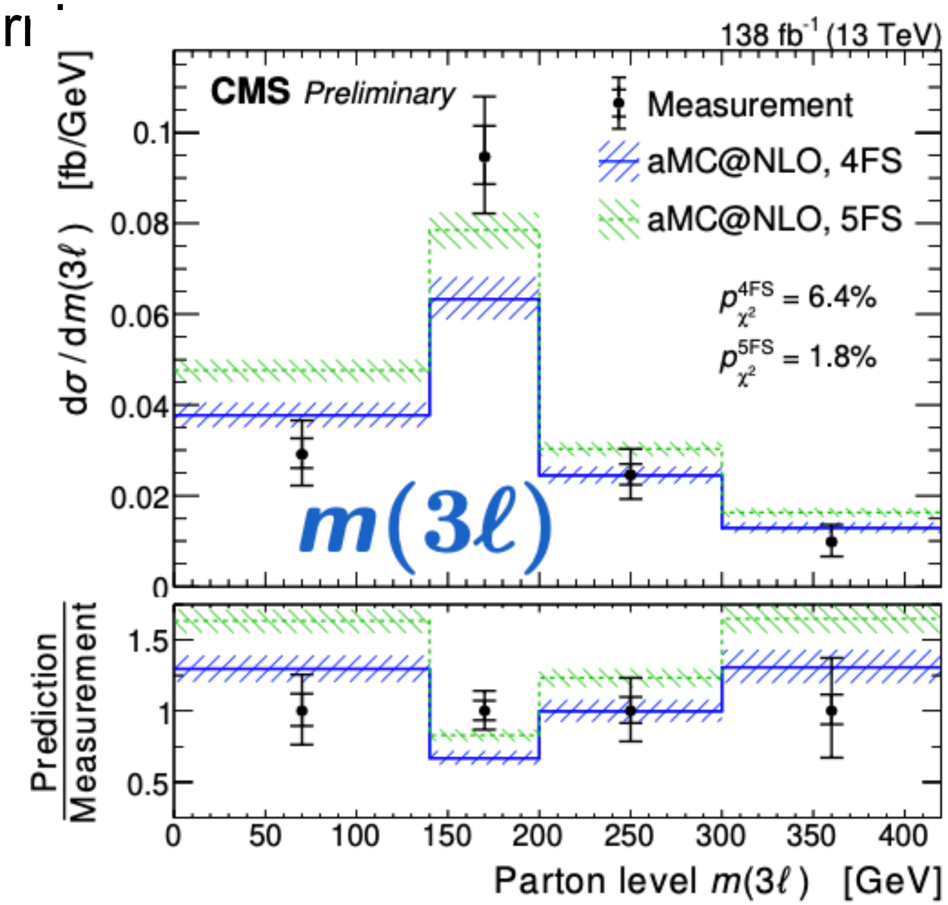
tZq production in final states with 3 leptons

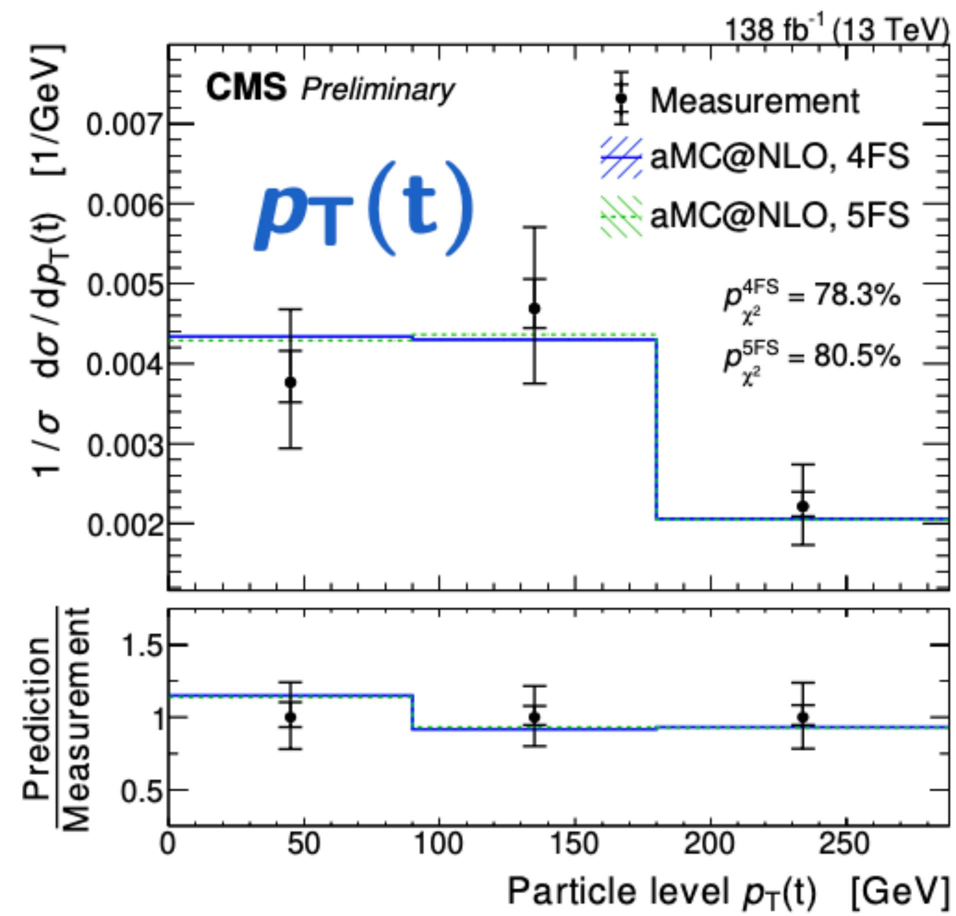
Rare process, connects top with EWK sector

- EWK production → polarized top
- Sensitive to many EFT operators



- First ever tZq differential measurements of top & Z observables, top-Z system, leptons
- First ever measurement of top spin asymmetry in tZq (proportional to polarization)
- Exploit machine lear
techniques (DNN)
to enhance
sensitivity
to tZq signal



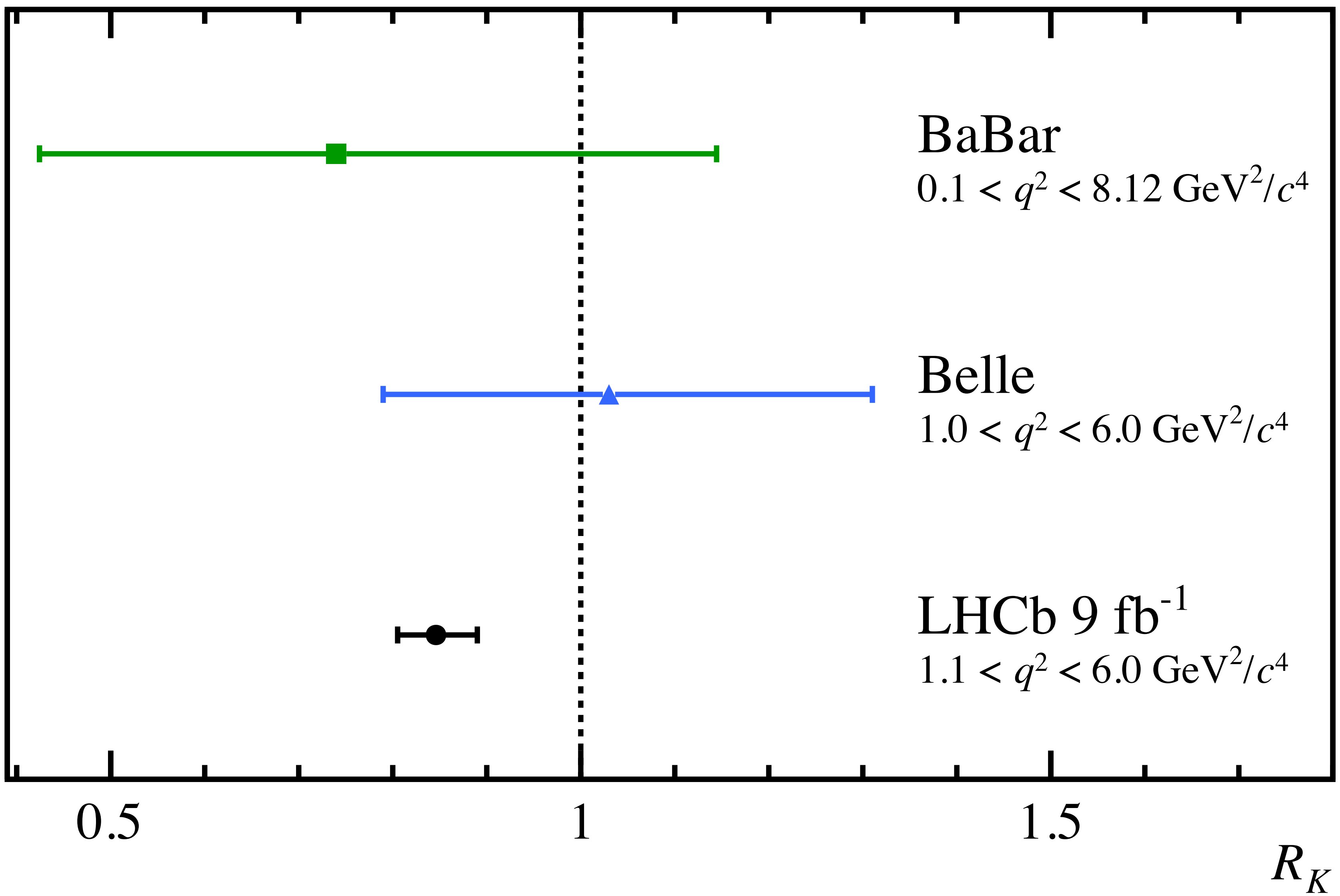


CMS-PAS-TOP-20-010

Flavour physics anomalies

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to \mu^+\mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to e^+e^-)K^+)}$$

https://arxiv.org/abs/2103.11769

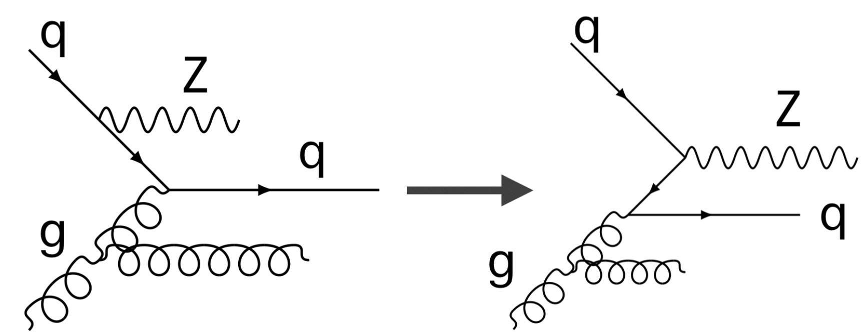


Could the underlying physics of flavour be accessible at the TeV scale?

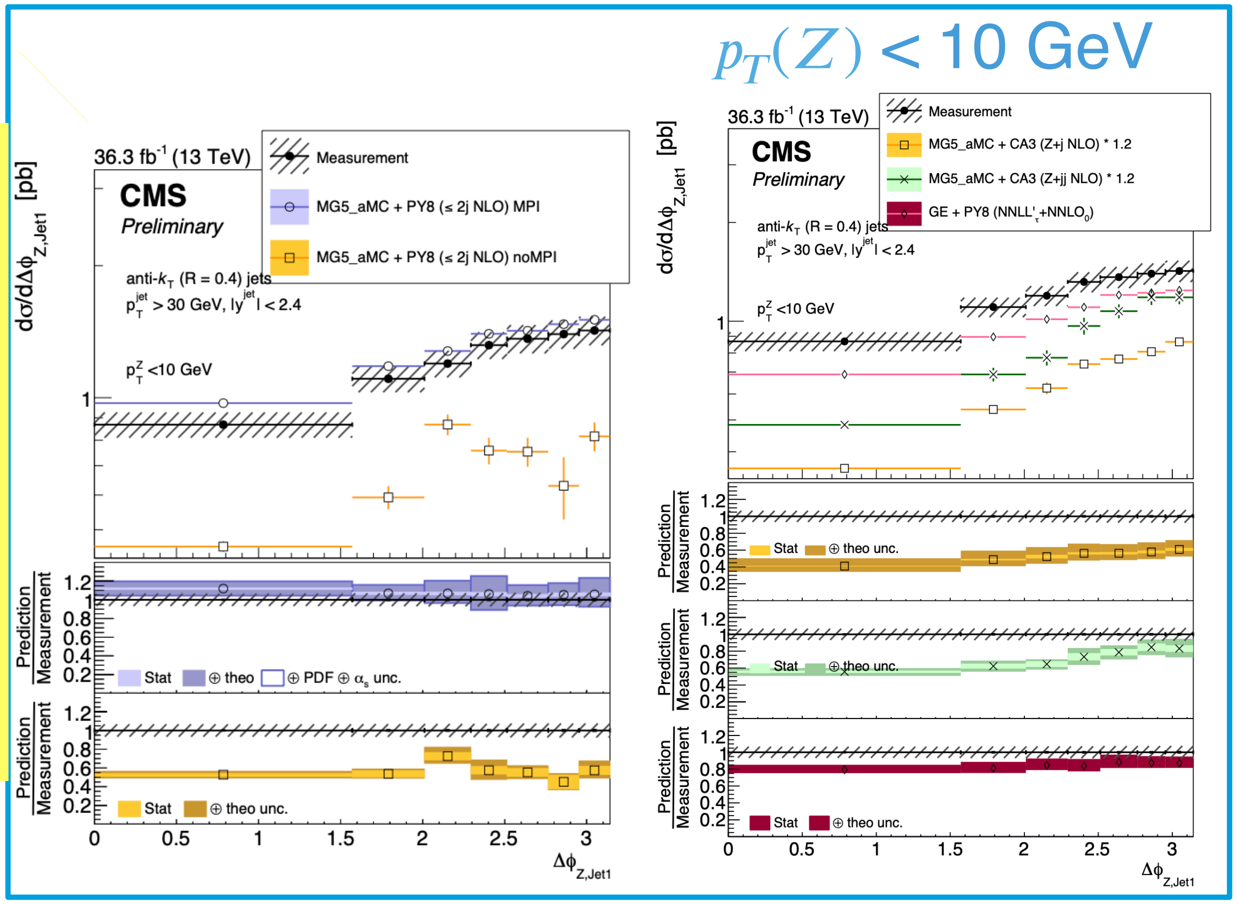
Azimuthal correlations in Z+jets events

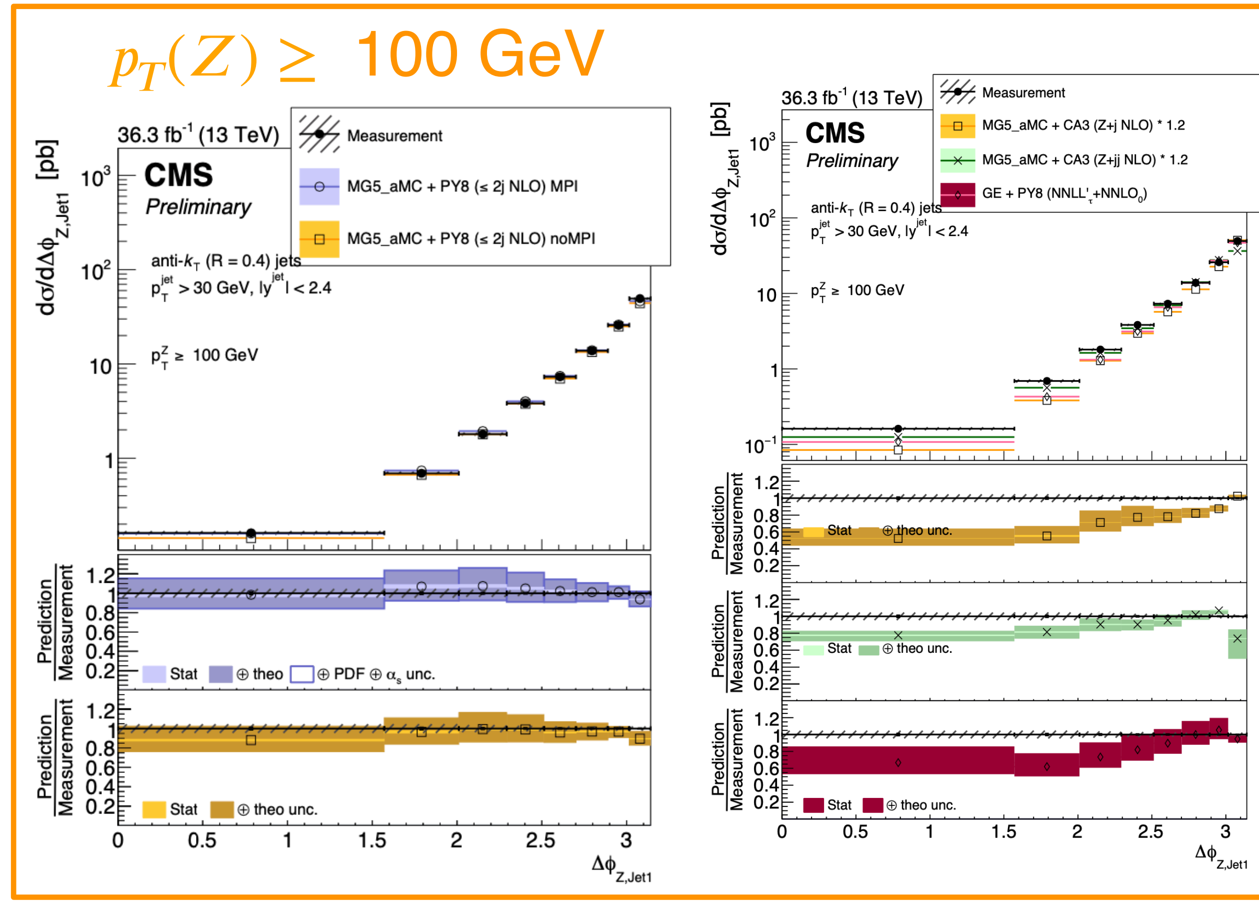
Particular interest in Parton Branching (PB) predictions

- **Small** $p_T(Z)$: soft-gluon resummation and non-perturbative contributions essential
- **High** $p_T(Z)$: Z+jet production dominant, significant corrections from QCD processes



CMS-SMP-PAS-21-003





Tested predictions: Madgraph5 NLO with / without MPI, GENEVA (NNLO + NNLL resummation)
MCatNLO-CA3 (Z+j) NLO PB , MCatNLO-CA3 (Z+2j) NLO PB

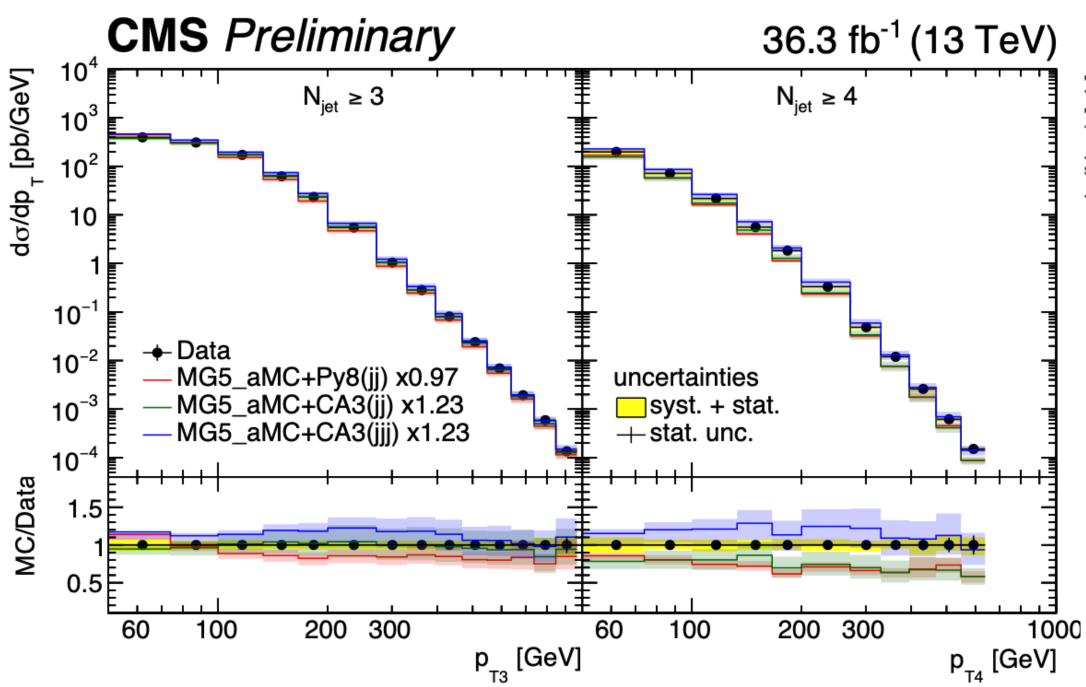
- **Z + jet measurements challenge theoretical predictions**
- **Good agreement achieved incl. contr. of multiparton interactions, parton shower, PB**

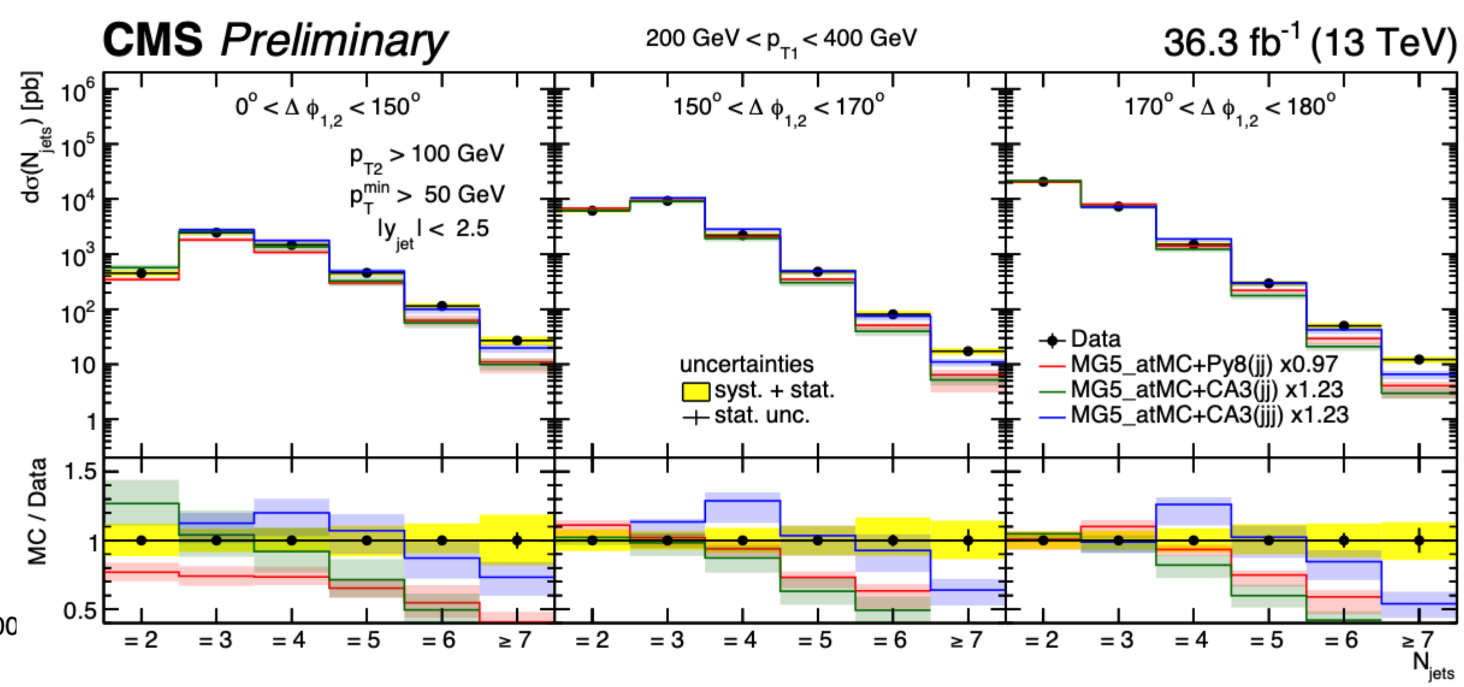
Insight into the structure of higher-order corrections

Data compared to MG5_atMC NLO predictions interfaced with Pythia8 and CASCADE3

- For the first time measured jet multiplicity in bins of the leading jet p_T & azimuthal angle between leading jets $\Delta\phi_{1,2}$
- Up to seven jets are measurable
- Cross section of the four leading jets measured up to the TeV scale:
  - **Benchmark for Standard Model multi-jet cross section calculations**
  - **Test simulations including parton showers for higher jet multiplicity**

CMS-SMP-PAS-21-006



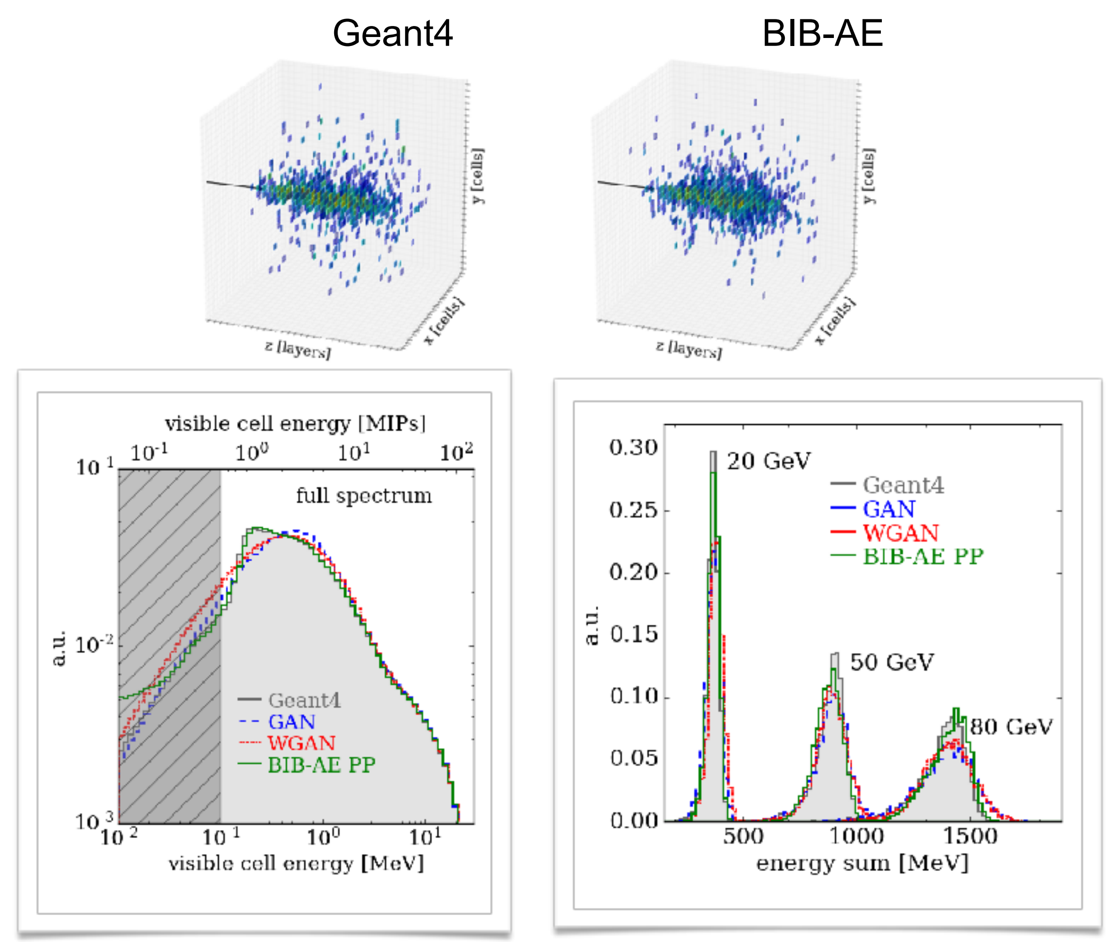


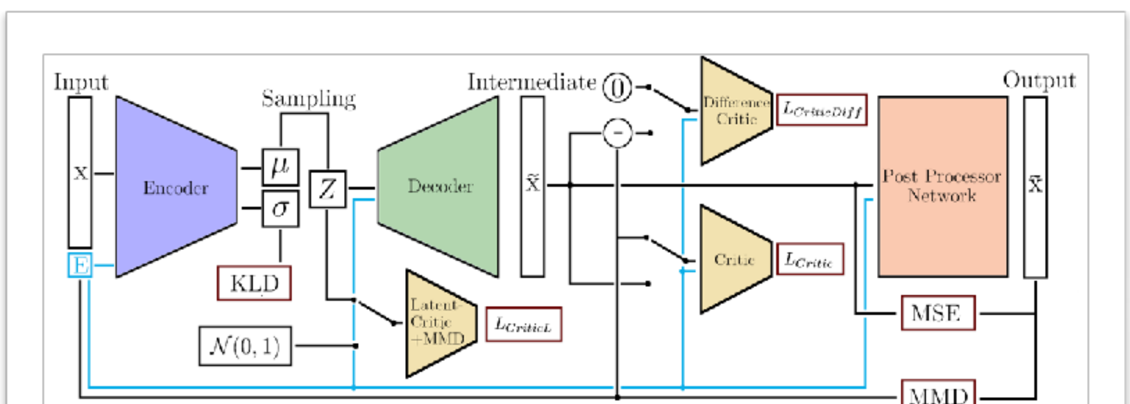
- **Measurements compared to LO (MadGraph, Pythia8, Herwig++)**
- **Comparison to NLO (MADGRAPH5_MC@NLO) with Pythia8 and CASCADE3 predictions**
- **For high jet multiplicities the lack of higher order contributions can be observed**

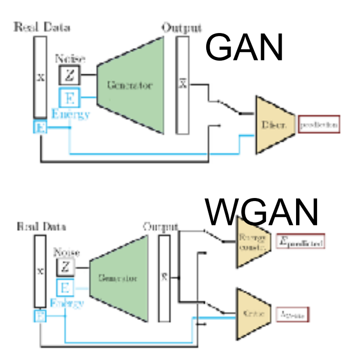
Machine learning for calorimeter simulation

high fidelity simulation of photons in highly granular ILD-ECal

- project carried out with UHH in **QU Excellence Cluster**
- **fast ML based shower simulation**
- use sample of photons at 90 deg impact angle in ILD Ecal (5x mm^2, SiW) w/ uniform energies 10-100 GeV
- achieve **high fidelity** in distributions of relevant physical variables
- using Bounded-Information-Bottleneck Auto Encoder (BIB-AE) w/ post-processing
- also compared to GAN and WGAN



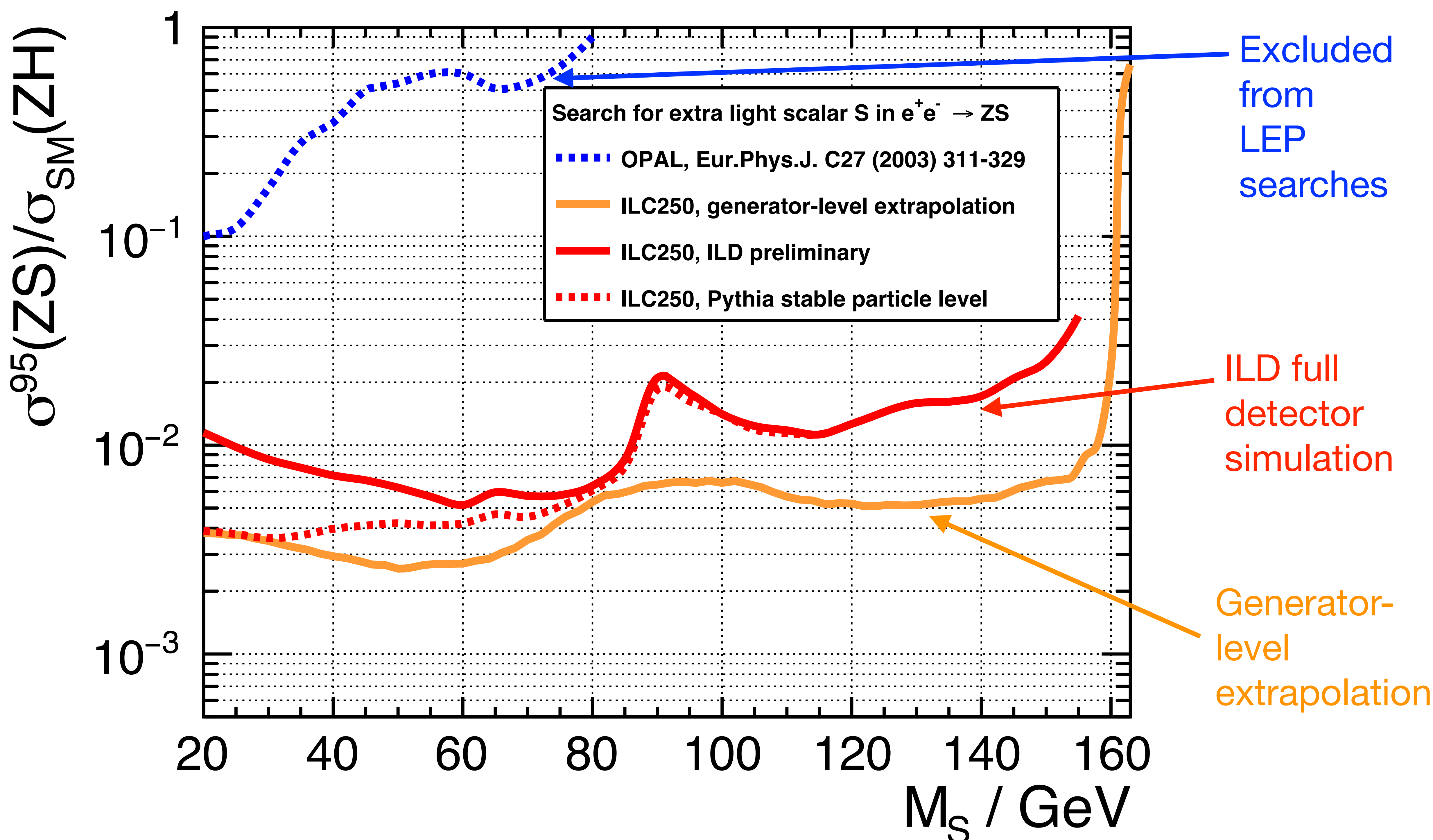




Bounded-**I**nformation-**B**ottleneck **A**uto **E**ncoder with Post Processing

Getting High: High Fidelity Simulation of High Granularity Calorimeters with High Speed, Erik Buhmann (Hamburg U.) Sascha Diefenbacher (Hamburg U.), Engin Eren (DESY), Frank Gaede (DESY), Gregor Kasieczka (Hamburg U.), Katja Krüger (DESY) et al. (May 11, 2020), e-print: 2005.05334 to be published in Computing and Software for Big Science

e^+e^- collider at 250 GeV with 2 ab^{-1}, recoil method: generator-level extrapol. + ILD full detector simulation



⇒ Higgs factory at 250 GeV will explore a large untested region!

Outlook

Future developments for the future

- DESY particle physics will contribute significantly to the recently started ECFA study on e+e- Higgs/Top/EW factories
- Software & High-level reconstruction algorithm developments for e+e- Higgs factories
  - Key4HEP
  - kinematic fitting => exploit highly-granular particle flow detector for detailed error analysis
  - charged hadron ID with time-of-flight and specific energy loss measurements => detector optimisation
  - machine learning in simulation and
- Apply these to Higgs & BSM physics - implications on detector concept design?