European Strategy for Particle Physics

Opening Session

Outstanding questions in particle physics

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23-27 JUNE 2025 Lido di Venezia

This talk

My goals:

- To remind ourselves of the wonderful physics we are dealing with
  - Unavoidably incomplete and biased!

My hope:

- To provide a modicum of inspiration as we enter our deliberations this week

Much thanks to C. Marinissen, J. ter Hoeve, J. Rojo, G. Giudice, C. Grojean, M. Merk, N. Tuning, P. Decowski, M. van Beekveld, C. Weniger, V. Plakkot, M. van Leeuwen, S. Badger, J. de Vries, W. Verkerke

Amsterdam and Venice

✓ Canals & Boats

✓ Many, many tourists

- Amsterdam: “Venice of the North”. Only approximate symmetry

City inspiration

Amsterdam

- Amsterdam has a negative groundstate: -1 to -4 meters below sea level
- We live behind a domain wall
- In a meta stable local universe

Venice

- Altitude is fine tuned to just above sea level: 0 to +1 meters.
- By negative corrections from sea water rise, positive from flood barriers

Very inspiring: Lido!

- With one-loop correction for precision

City inspiration

Amsterdam

- Amsterda
- We live be
- In a meta

Venice

- Altitude is
- By negativ

Very inspiring

- With one-

ESPP 2020 - Theory

*Europe should continue to vigorously **support a broad programme of theoretical research** covering the full spectrum of particle physics from abstract to phenomenological topics. The pursuit of new research directions should be encouraged and **links with fields such as cosmology, astroparticle physics, and nuclear physics fostered**. Both **exploratory research and theoretical research with direct impact on experiments** should be supported, including **recognition for the activity of providing and developing computational tools**.*

Europe, and CERN, has continued to provide support for a broad theory programme

- With natural national variations

Connections with cosmology, astroparticle and nuclear physics are natural and strong

- Very much intertwined in everyday research.
- EUCAPT center [@ CERN Theory Group] coordinates PP, AP, Cosmo theory efforts

Lots of efforts on tools for experiments (Monte Carlo's, fixed order calculations, EFTs etc), and for other theorists (loop methods etc)

- The importance of this is broadly recognized

All will also be important for the next update period!

Where are we are and where are we going?

We have found all particles of the Standard Model.

But we have not measured all interactions and parameters!

- Higgs self interactions, Yukawa's, neutrino masses etc!

Doing this is, and should be, a central goal of our field.

More generally, we should resolve to explore, to gather knowledge, about the physics of the Standard Model, and beyond.

Doing this is very hard. We need a broad approach, with insights from the HL-LHC, a new flagship collider, enormous neutrino detectors, hypersensitive Dark Matter detectors, equisitely sensitive smaller experiments etc.

Likewise, we need theory predictions much more precise that hitherto. And we need ideas, in many directions, for explanations, guidance, new connections etc.

And we need the talent to do all this!

Higgs mechanism

The Standard Model contains 4 scalar fields

$$\Phi(x) = \begin{pmatrix} \phi_1(x) + i\,\phi_2(x) \\ \phi_3(x) + i\,\phi_4(x) \end{pmatrix} = \exp\left[i\,U(x)\right] \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

- Three of these scalars we “saw” in the early 1980’s, as part of the W and Z boson masses
- $h(x)$ finally observed in 2012

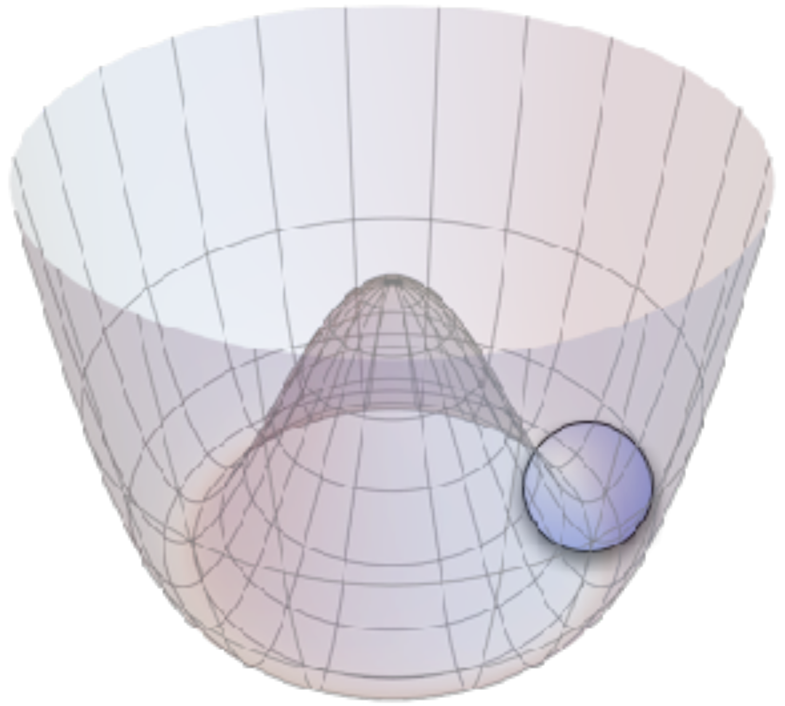
The Higgs mechanism

- Provides masses for the W and Z bosons
- Provides fermion mass terms through Yukawa interactions - standard mass terms are forbidden by the SM structure

Brout-Englert-Higgs

The (BE) Higgs field and its potential sit at the center of the Standard Model:

- We assume the potential



$$V(\Phi) = \mu^2\, \Phi^\dagger \Phi + \lambda_4 \left(\Phi^\dagger \Phi\right)^2$$

- with $\mu^2 < 0$, so groundstate is not fully invariant under SU(2)xU(1). Is this weird?
- Not for condensed matter colleagues. They deal with
  - Ferromagnet, Bose-Einstein condensation of Cooper pairs in superconductors, …

But we deal with the whole Universe!

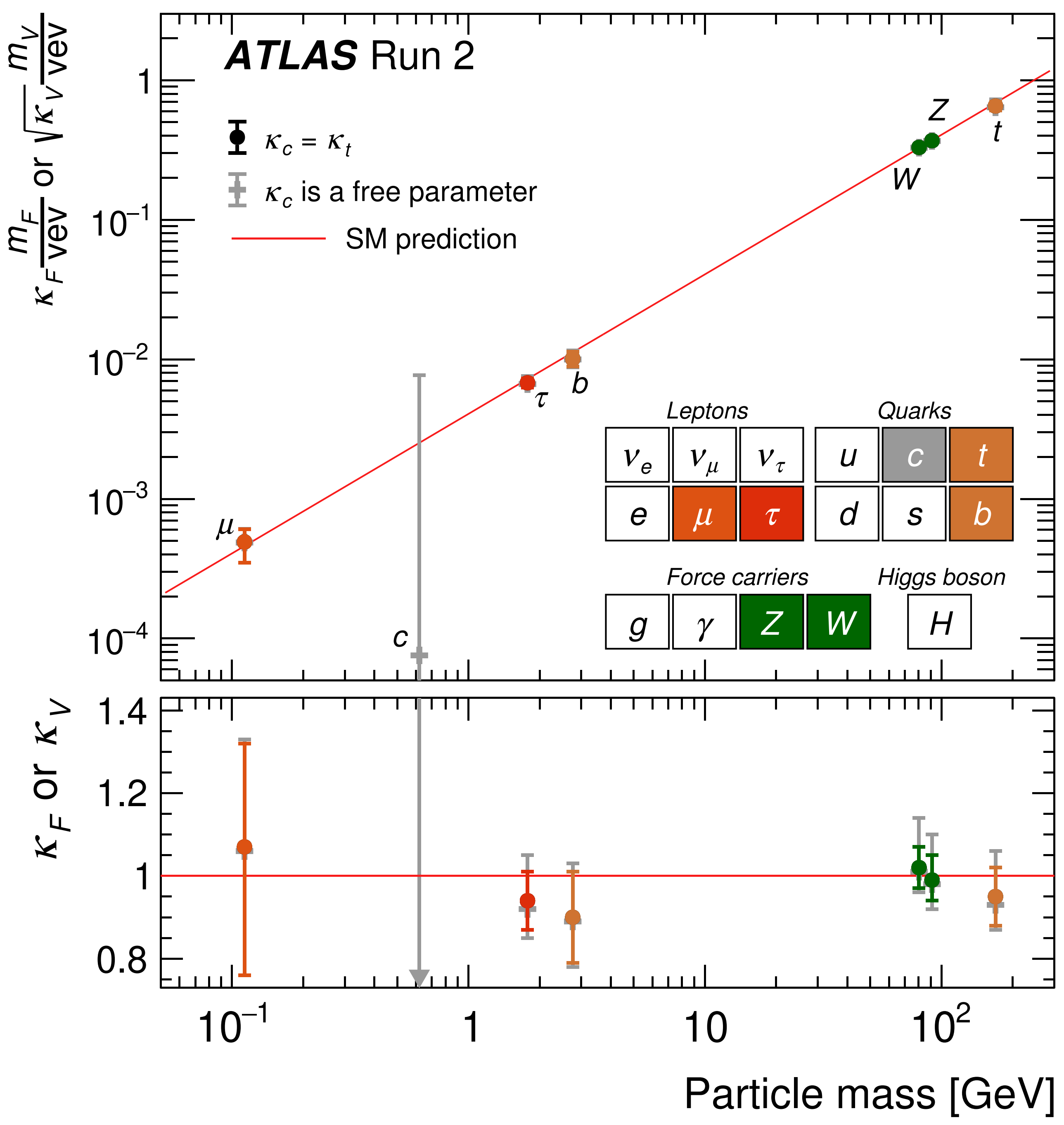
$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \boxed{h(x)} \end{pmatrix}$$

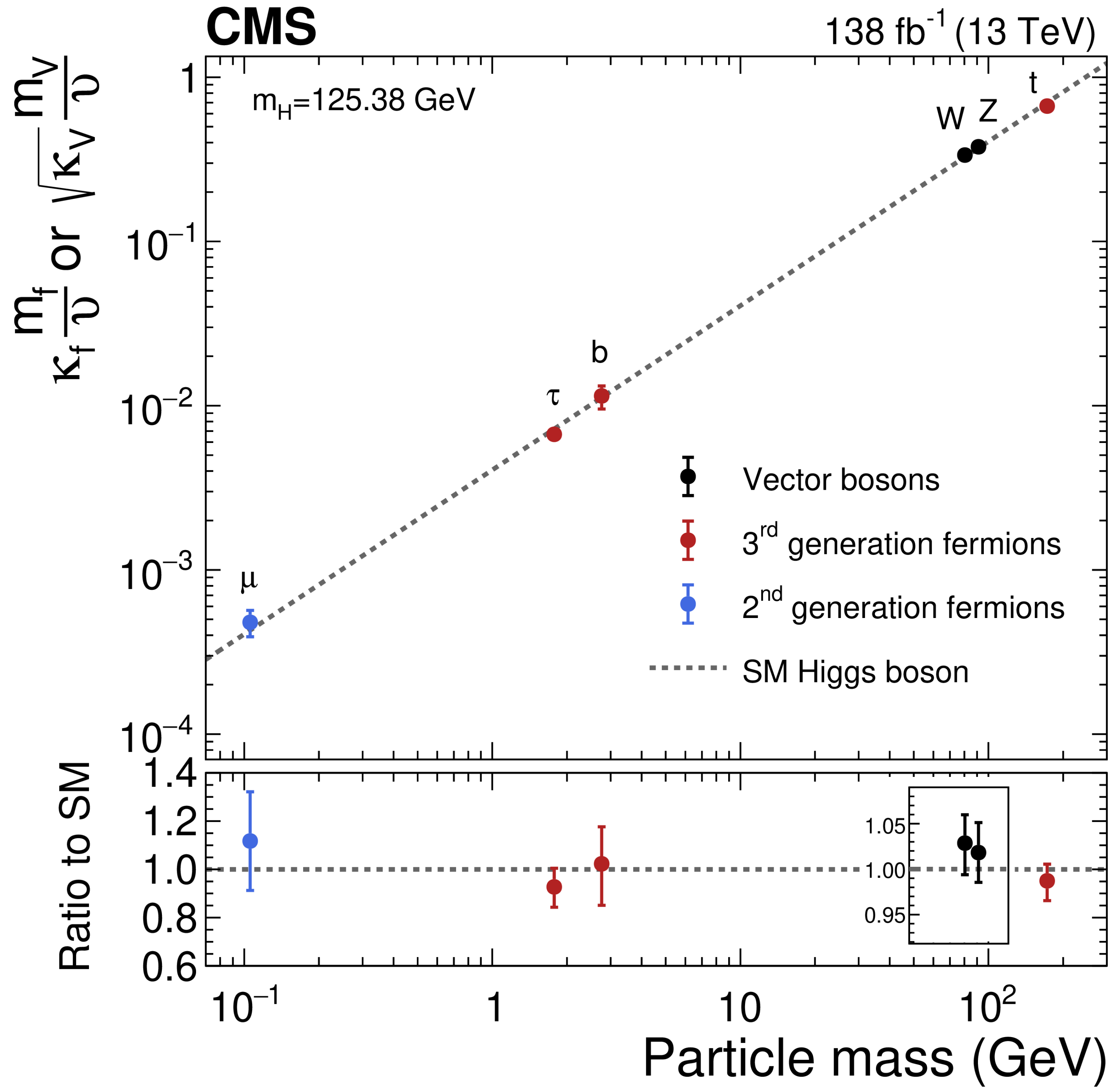
Let's appreciate: the Higgs boson is a nugget of vacuum!

Particle masses

The Higgs mechanism in the Standard Model predicts $m_i = g_i v$

- In impressive agreement with experiment





- After Newton and Einstein, we have established a new concept of “mass”!

Stress testing Higgs physics and SM

Our ambition:

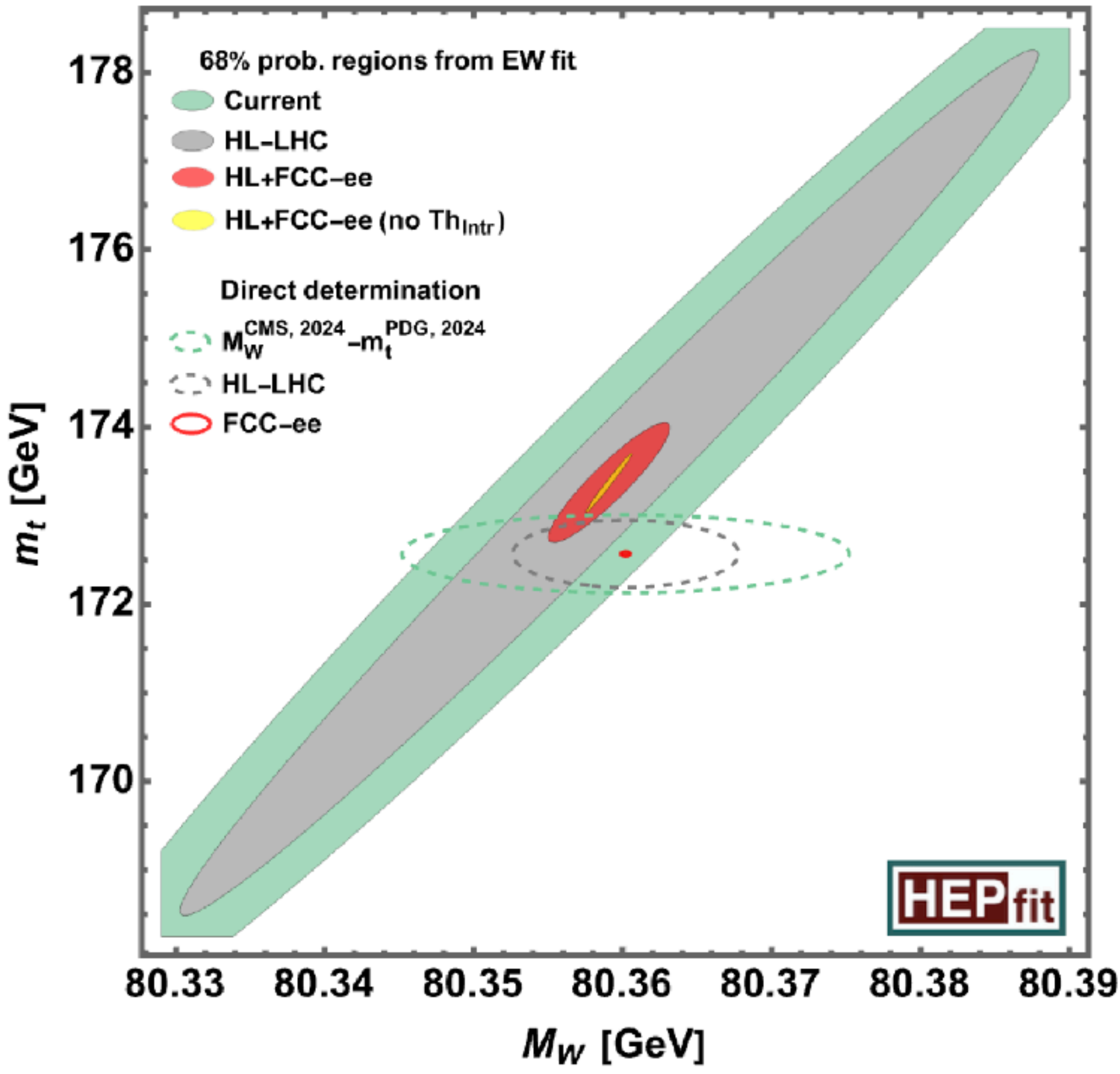
- make huge numbers of Higgs bosons, to scrutinize its properties and interactions.
- stress test the Standard Model in many ways.

Classic example: "closure test" of SM at FCC-ee

$$m_W = f(m_t, m_h, G_F, \alpha, \ldots)$$

m_W and m_t uncertainties 50x smaller

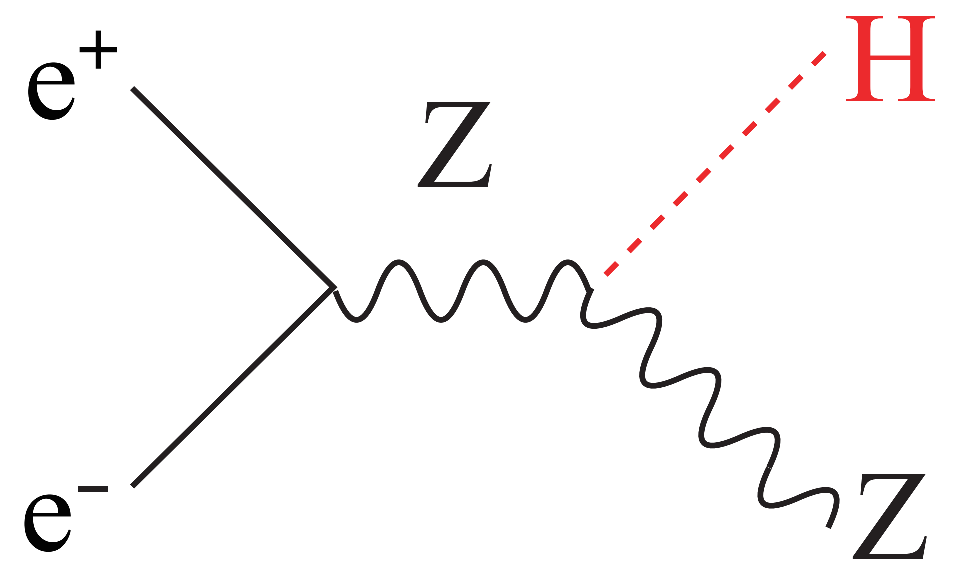
- By scanning WW and $t\bar{t}$ thresholds, using excellent knowledge of beam energy
  - Top quark mass extraction requires significant theory input



Higgs mass, width and couplings

Main process: radiation off a Z-boson

- Reconstruct the Z-boson from leptons -> 4-vector for Higgs boson -> mass peak
  - Current mass: 125.11 +- 0.11 GeV
  - Expected FCC-ee precision: 4 MeV (mostly statistical)
- Leads also to the total ZH cross section
- Leads to Higgs width, using again Z-recoil, to per cent level accuracy
  - Only 4 MeV in SM



With a Higgs factory we will improve our knowledge about the Higgs boson and its couplings tremendously.

- By order of magnitude w.r.t HL-LHC
- Other EW parameters will be known much better too

Atomic size

There is hope that FCC-ee can determine whether the electron mass is indeed due to the Higgs mechanism

- Run a number of years at the H-pole: $e^+e^- \to H$ to determine electon Yukawa
  - Serious $e^+e^- \to q\bar{q}$ background
- Experimentally very difficult: needs e.g. large reduction of Beam Energy Spread

We would then understand the size of atoms!

Bohr radius $$a_0 = \frac{\hbar}{m_e c \alpha}$$

Higgs self coupling

Higgs potential in unitary gauge
after expanding around minimum

$$V(h) = \frac{1}{2} m_H^2 h^2 + \boxed{\lambda_3 v\, h^3} + \frac{1}{4} h^4$$

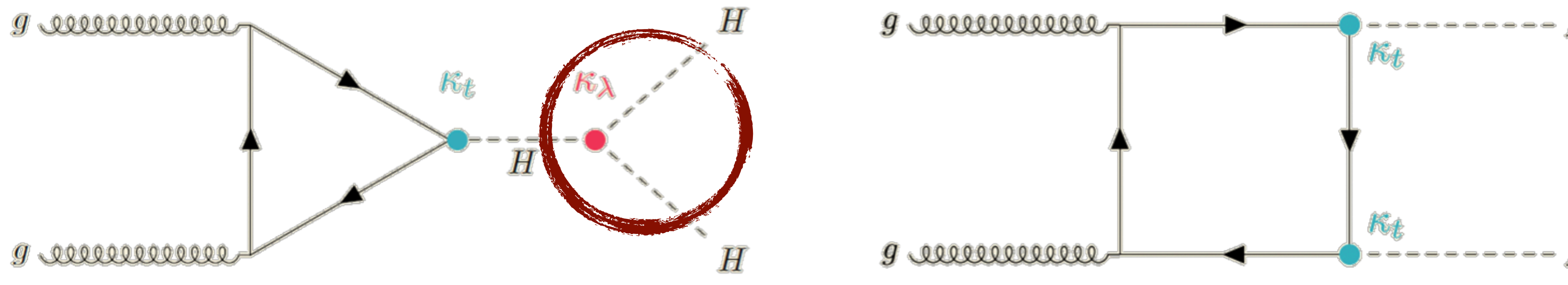
The HL-LHC can do better here than previously thought, through di-Higgs production

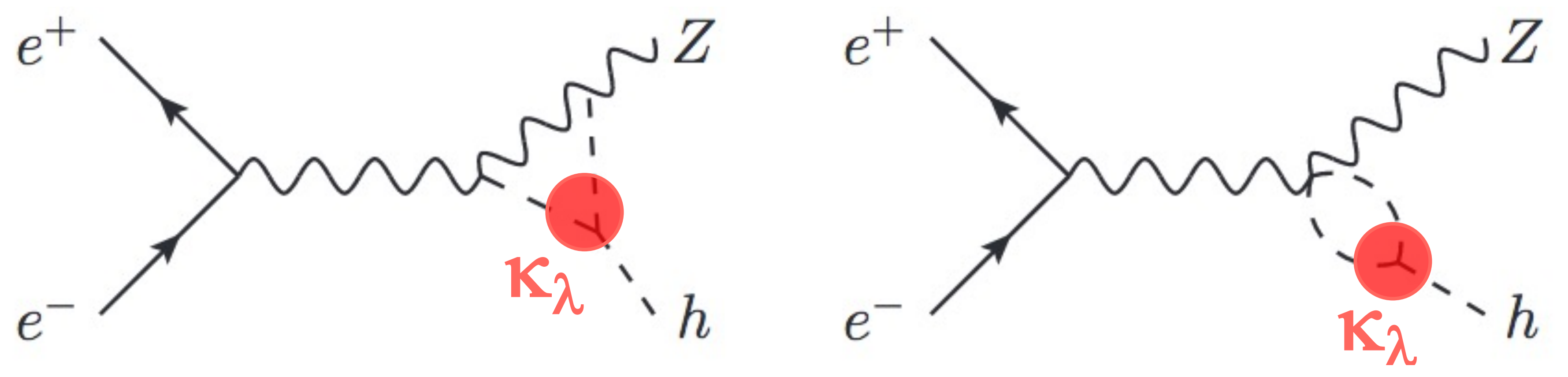
Expect 7σ observation of process by ATLAS+CMS

- Determination of tri-Higgs coupling to 30%

What could FCC do?

- FCC-ee: only via loop effects
  - But can still help constrain to about 20%
- FCC-hh: percent level accuracy

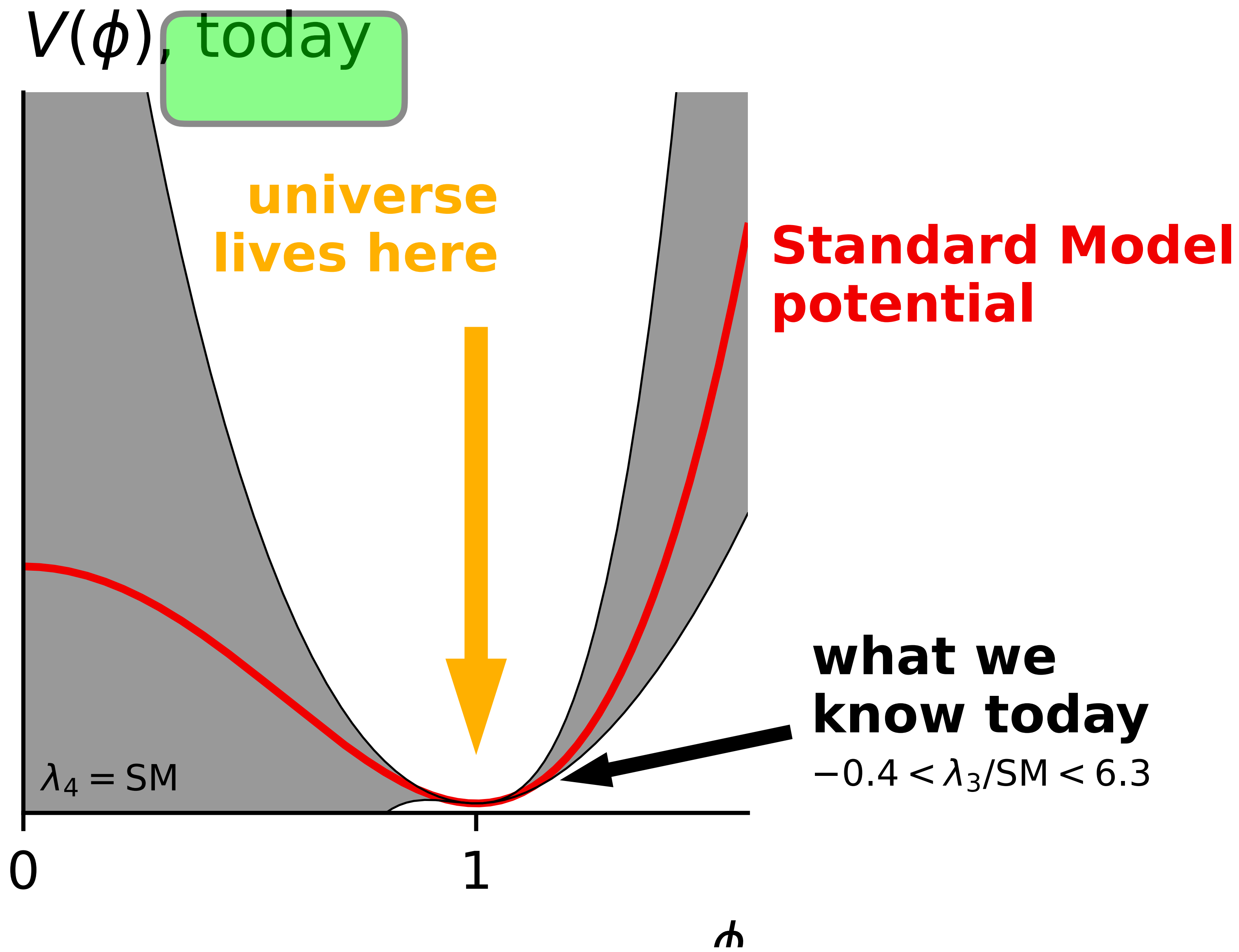


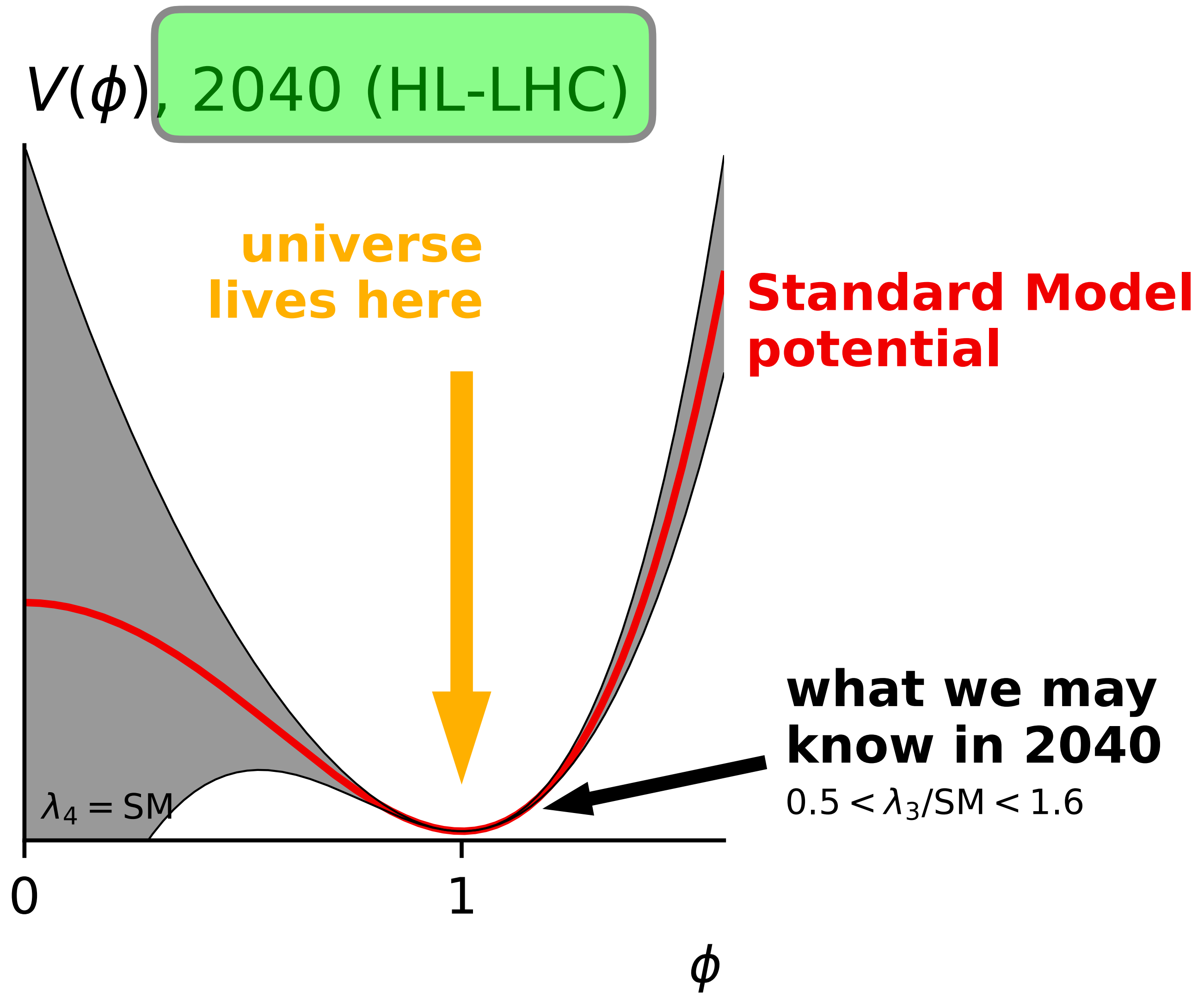


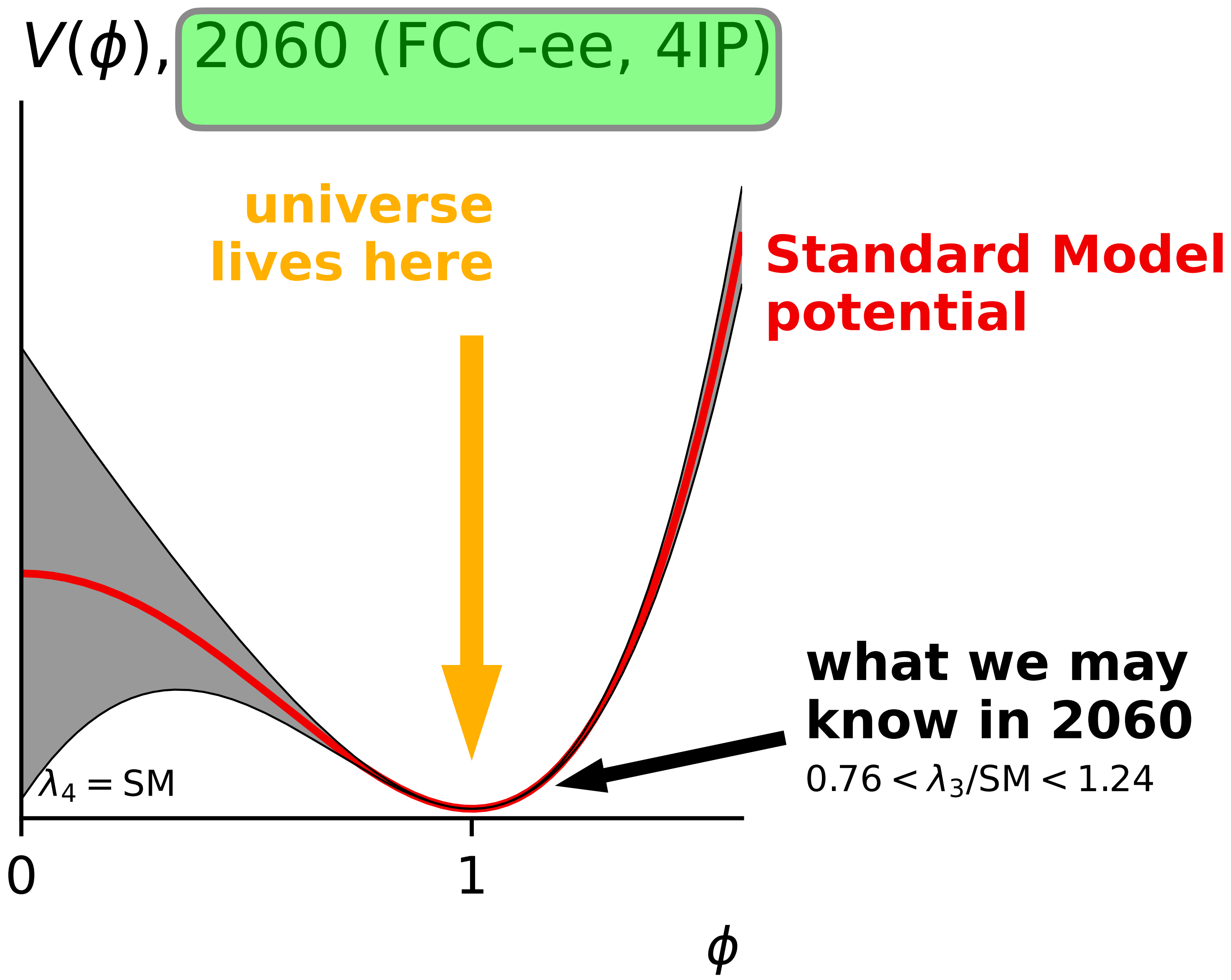
Note: triple and quartic (pseudo) scalar couplings are “established” in meson scattering

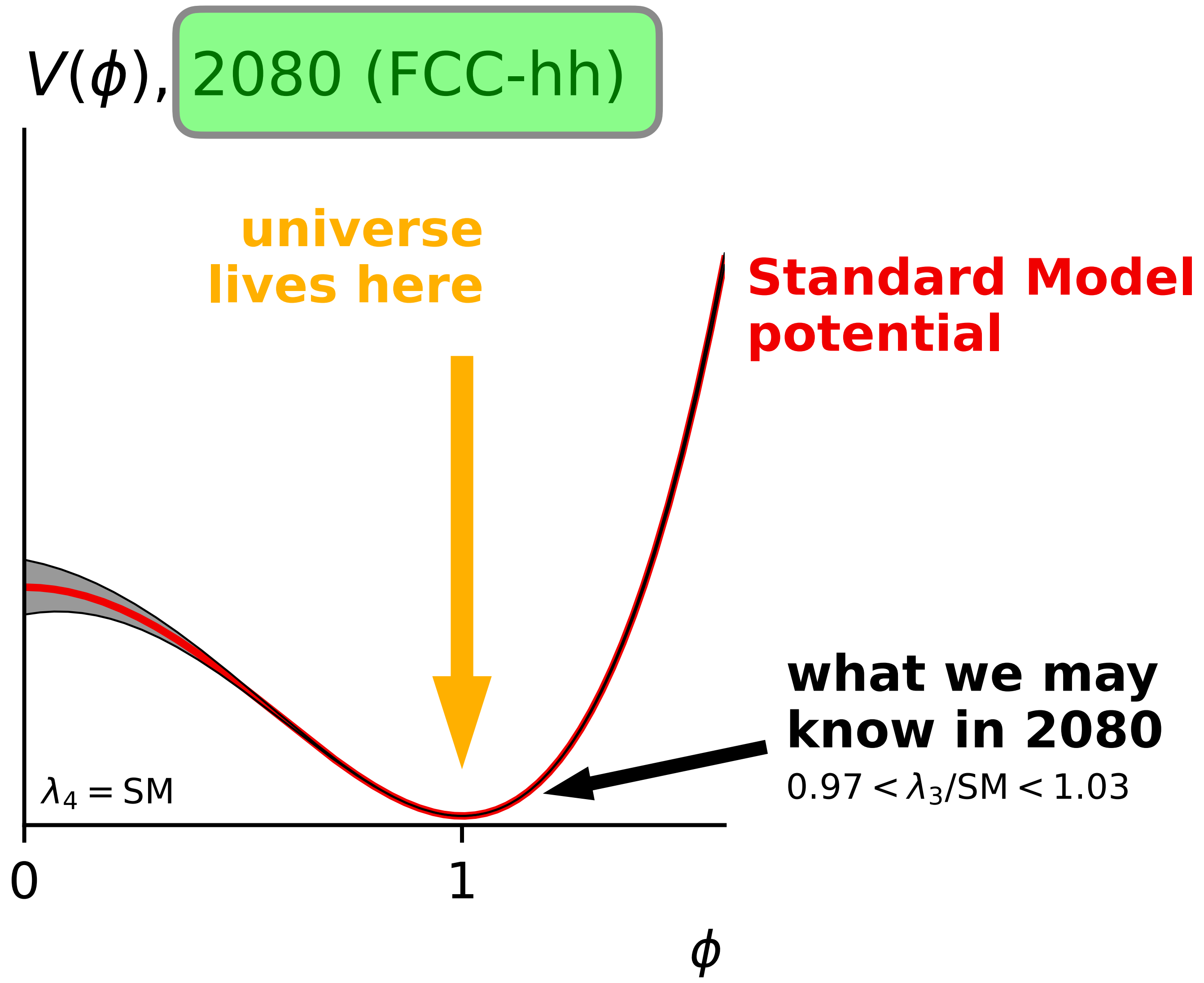
Knowledge of Higgs potential

G. Salam









New physics sensitivities, via EFT

Many BSM models have been formulated and tested in decades past.

One often parametrizes New Physics, agnostically, via Effective Field Theory

$$\mathcal{L}_{\mathrm{BSM}} = \mathcal{L}_{\mathrm{SM}} + \sum_j \frac{C_j^{(5)}}{\Lambda} \mathcal{O}_j^{(5)} + \sum_j \frac{C_j^{(6)}}{\Lambda^2} \mathcal{O}_j^{(6)} + \ldots$$

- With SM fields and symmetries: “SMEFT”
- Idea: comparing data with this EFT may reveal that some of the Wilson coefficients are non-zero. Would focus the hunt for the right model
  - Results are sometimes also expressed through “effective couplings” $(g^{\mathrm{eff}}_{HX})^2 \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\mathrm{SM}}_{H\to X}}$

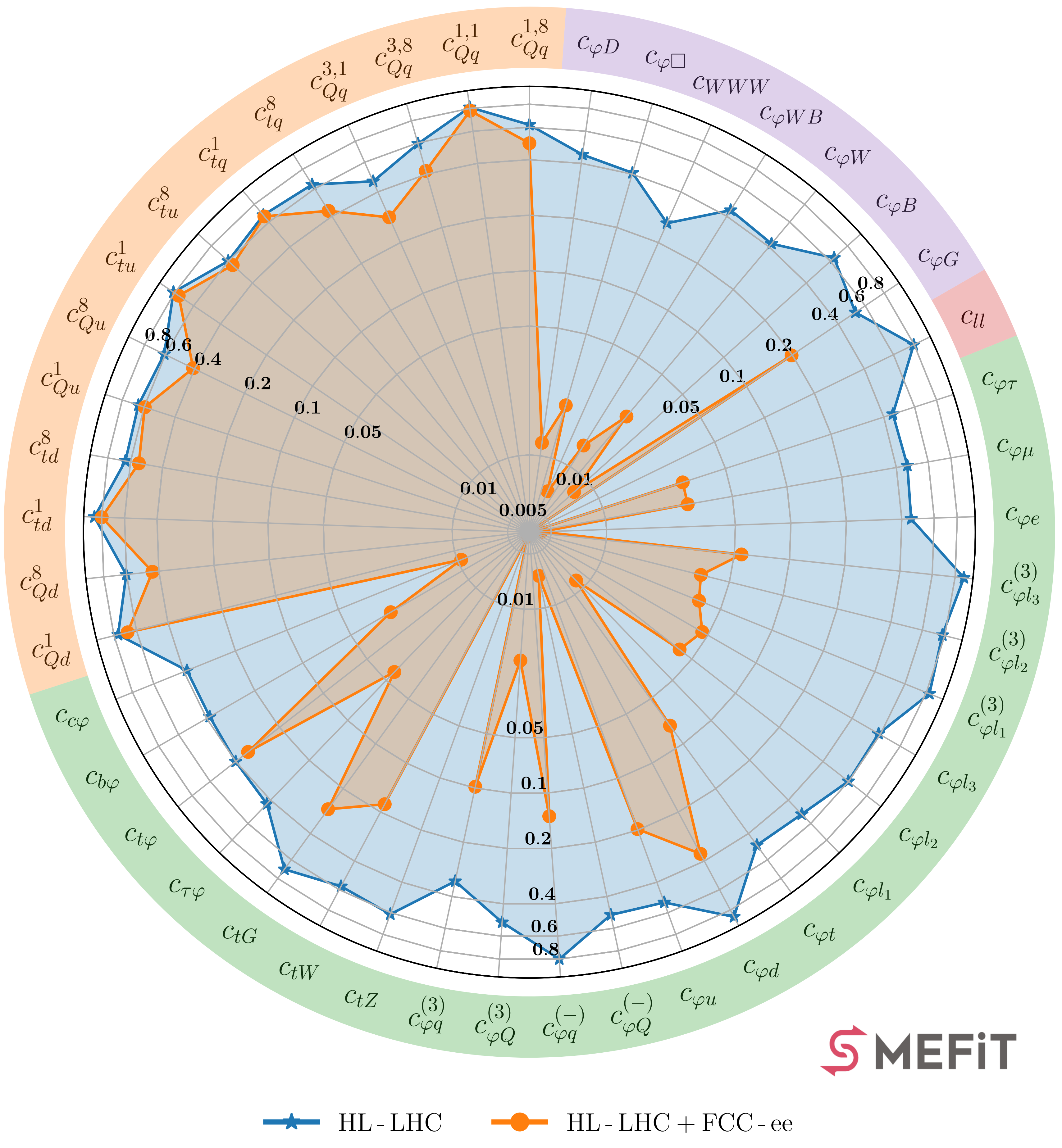
Powerful framework, also integrated into or interfaced with event generators..

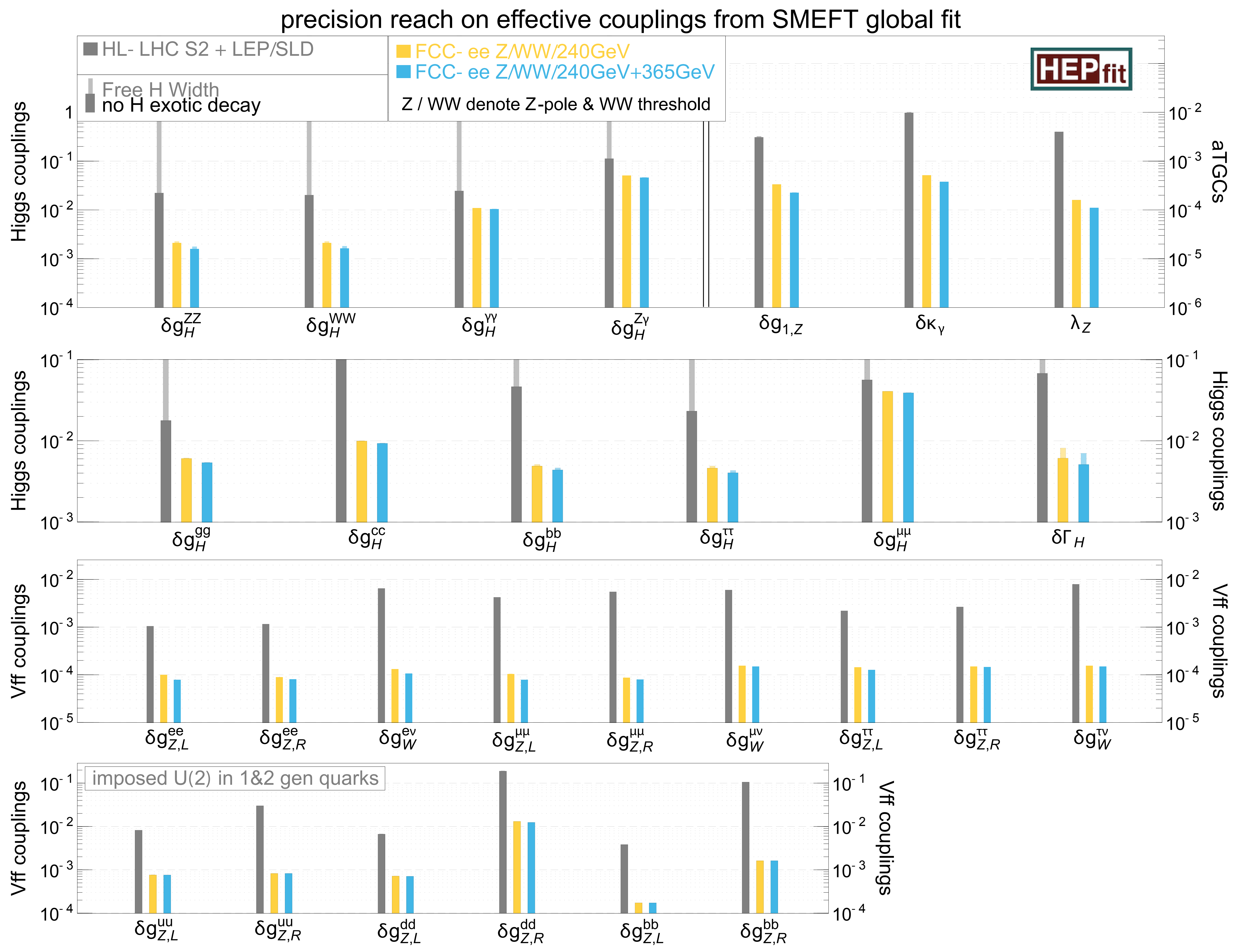
- And into experimental analyses

MadGraph5_aMC@NLO, Pythia8, Herwig, Sherpa

SMEFT global fit

Ratio of confidence intervals, linear fit





Global SMEFT fit, showing substantial impact of HL-LHC and FCC-ee on EFT parameters

EFT and discoveries?

Can one make discoveries in EFT approach? It can certainly help, but depends on the "prior" assumptions about the BSM model

- E.g. assuming a composite Higgs boson corresponds to activation of certain operators

Directions for EFT

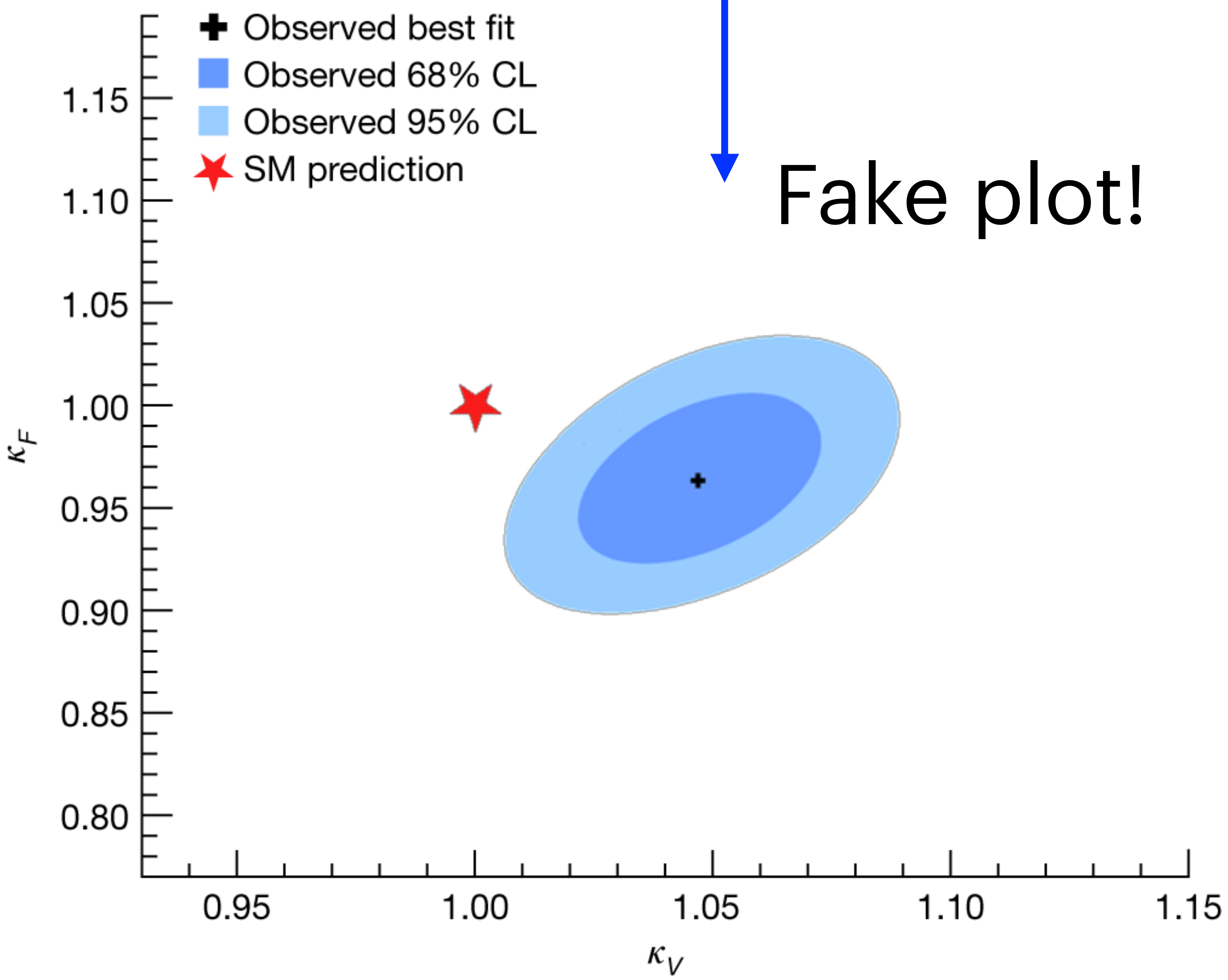
- Stronger connection of experiments with EFT analyses?
- More cross talk with model builders community?

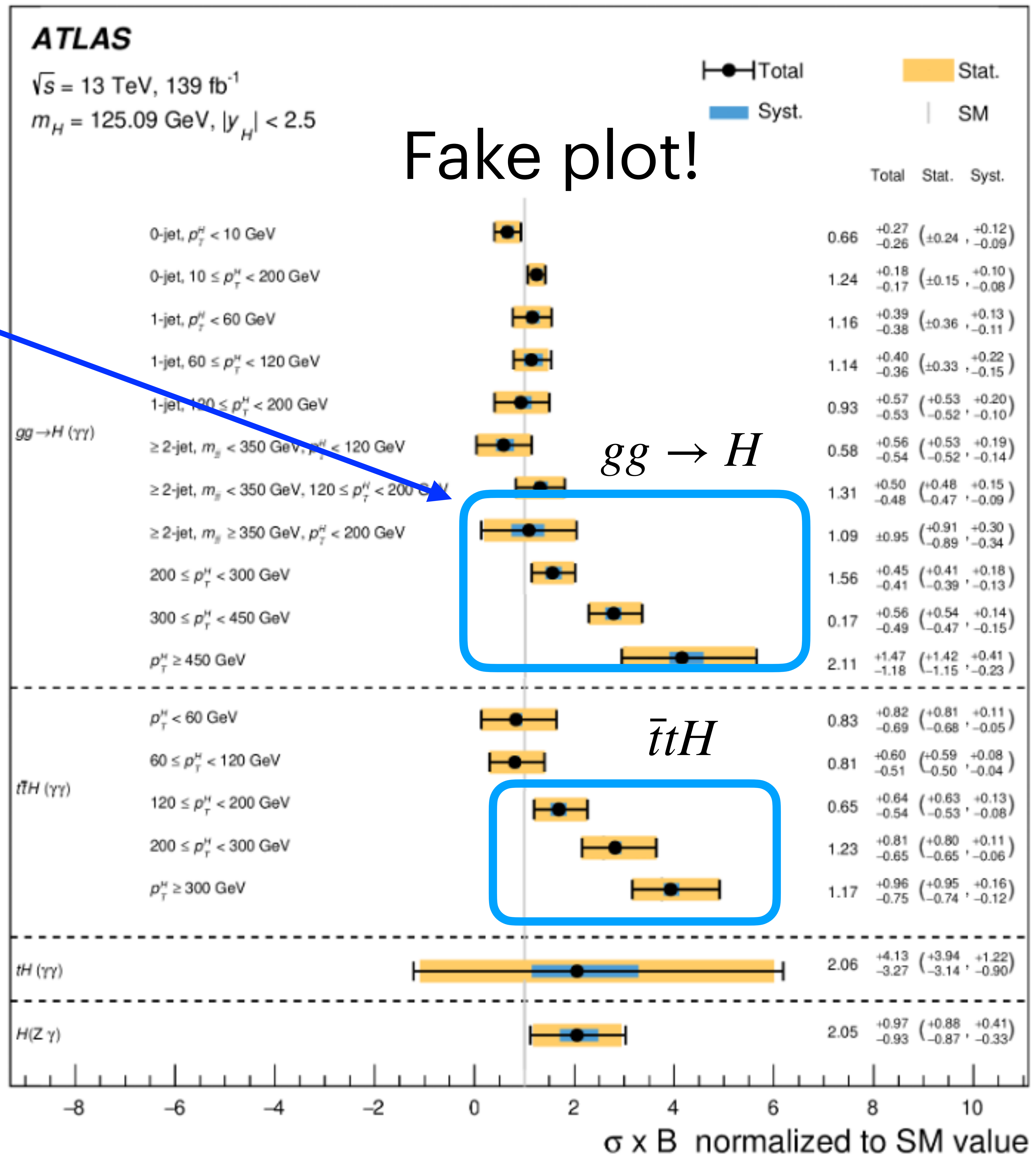
Don't rely only on EFT's, think also of the physics, ideas/knowledge they represent!

What new physics may look like (I)

Heavy BSM physics could show up at high pT in Higgs cross sections

Or in deviations of vector boson couplings





What new physics may look like (II)

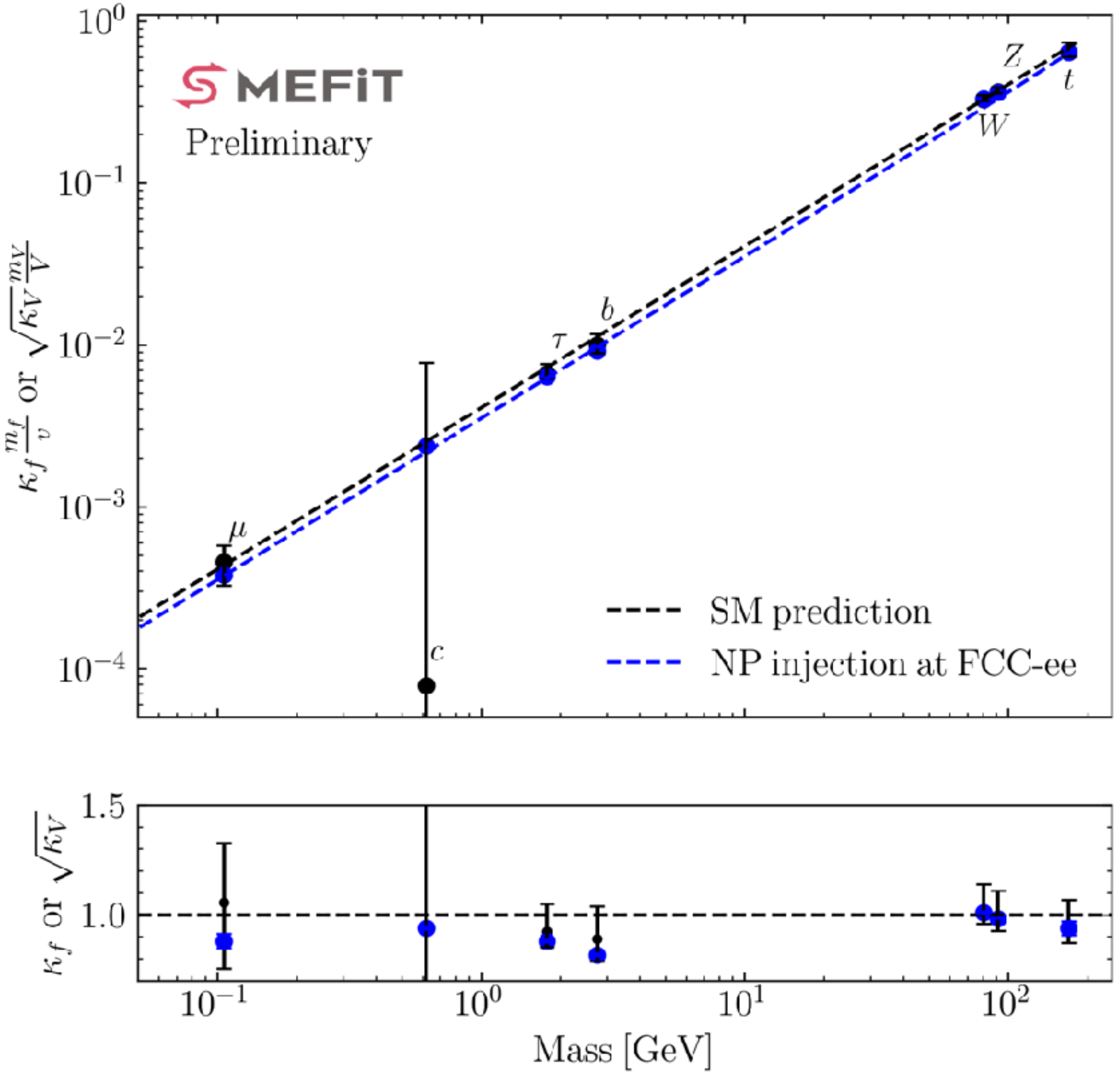
J. ter Hoeve

Example: UV model injection, via SMEFiT

- 2 extra fermions $(3,2)_{1/6,7/6}$
- 1 extra heavy vector boson $(1,3)_0$

Relations between couplings and mass now more complicated

- Deviations from straight line



Strong CP problem

We can add to the QCD Lagrangian the term $\theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} G^a_{\rho\sigma} \varepsilon^{\mu\nu\rho\sigma}$

- It violates P,T and therefore CP, due to $\varepsilon^{\mu\nu\rho\sigma}$

One can generate such a term also when performing a chiral rotation on quark fields ("anomaly")

- Seen as integration variables in a path integral

$$\psi \to \exp(i\alpha\gamma_5)\,\psi$$

- θ only meaningful without massless quarks

It is actually a topological term, and represents the $\theta-$vacuum

$$|\theta\rangle = \sum_n \exp(in\theta)\,|n\rangle$$

- A sum over gluon configurations with different "winding number"

If we can probe θ , we again learn more about the vacuum of the Universe!

Strong CP problem

A non-zero θ induces a non-zero Electric Dipole Moment of the neutron.

Now: $d_n < 1.8 \cdot 10^{-26}\ e\,cm$ from nEDM, so that. $\theta < 10^{-10}$.

Why so small? <u>This is the Strong CP problem</u>

Some upcoming nEDM experiments and their target sensitivity in $e\,cm$

- n2EDM (PSI) - $1 \cdot 10^{-27}$ [start data taking after summer]
- PanEDM (ILL) - $1 \cdot 10^{-27}$ [commissioning]
- More @Triumph, LANL, J-Parc...

Possible explanations for zero θ

1) θ is really zero, because one of the quarks is precisely massless

- Ruled out by lattice results for the up quark mass

2) θ is really zero because parity is actually conserved in the UV complete theory

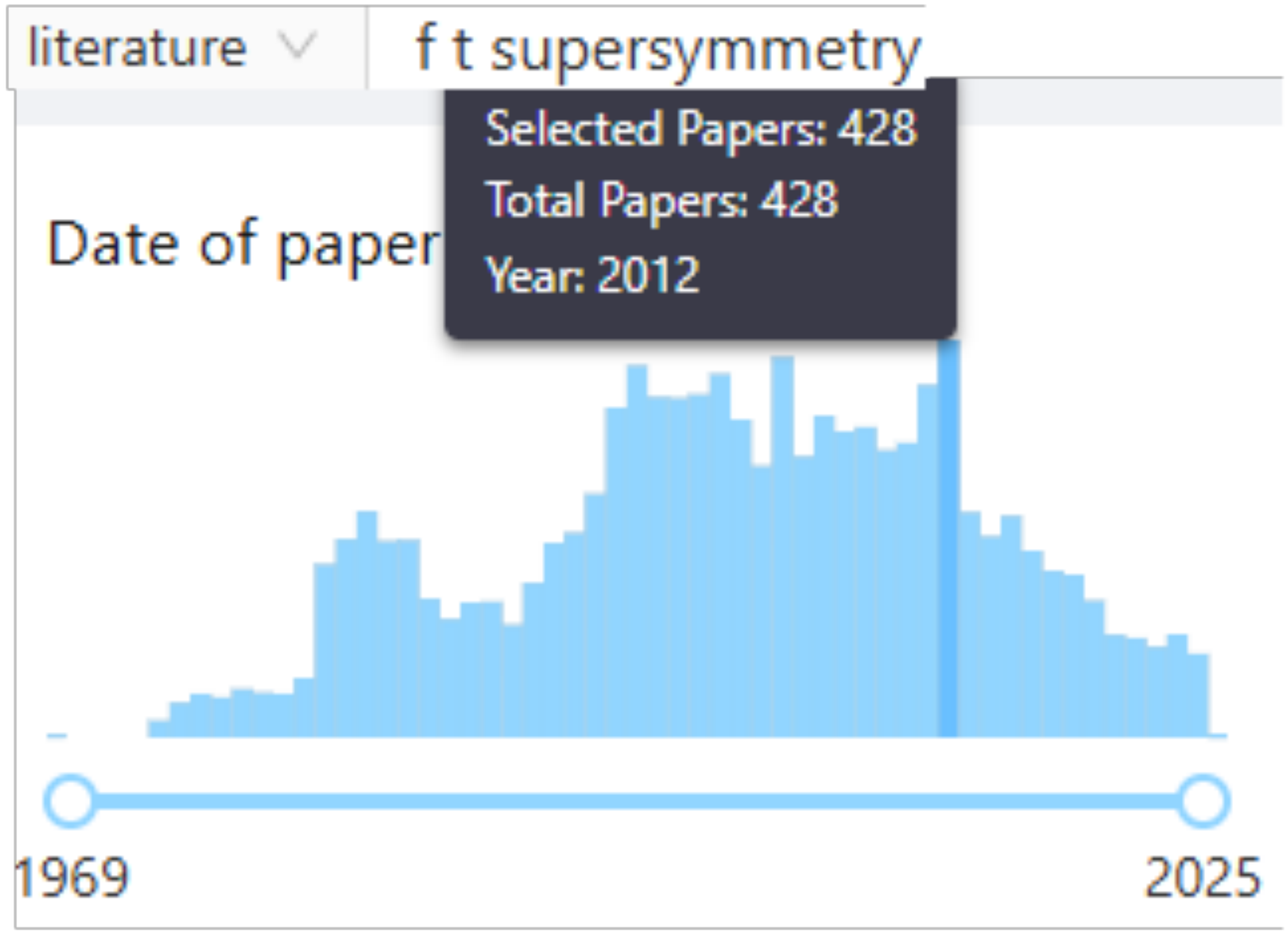
- Difficult: at some point CP is broken to ensure CP violation in the weak sector

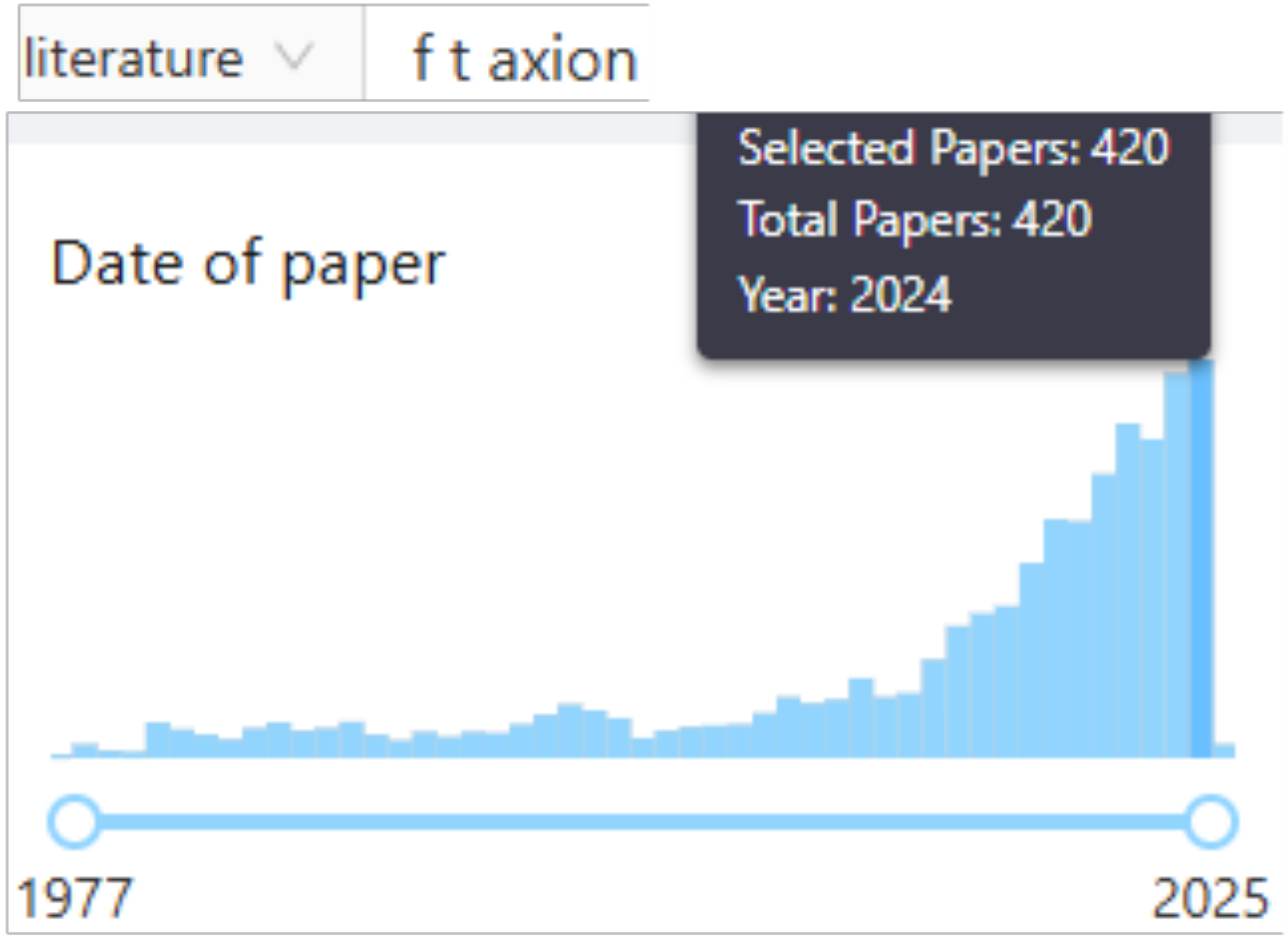
3) θ is really zero, because it is part of a new field, whose groundstate relaxes to zero

Peccei, Quinn

- Pseudoscalar $a(x)$: Goldstone boson of new (PQ) global symmetry: **the axion**!

Axions





Axion physics is a beautiful combination of cosmology, particle, nuclear and astroparticle physics, with experiments large and small

Axion model

Kim, Shifman, Vainshtein, Zakharov

One realization of axion model* (KSVZ):

- Extend SM with fermion "χ" that is coloured, but SU(2)xU(1) singlet, plus SM complex scalar singlet "Φ"
- $U(1)_{PQ}$ symmetry

$$\Phi \to e^{i\alpha}\Phi \qquad \chi_L \to e^{i\alpha/2}\chi_L \qquad \chi_R \to e^{-i\alpha/2}\chi_R$$

- A new Yukawa term $y_\Phi \, \bar{\chi}_L \chi_R \Phi \; + hc$ is invariant. Assume Higgs-like potential

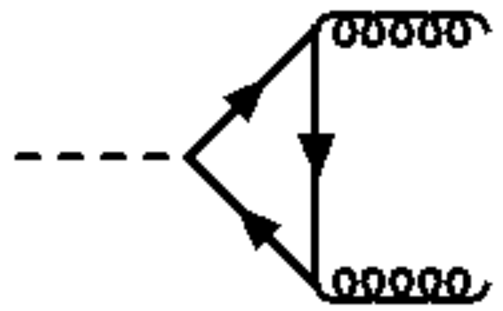
$$V(\Phi) = \lambda_\Phi \left(|\Phi|^2 - \tfrac{1}{2} v_a^2\right) \longrightarrow \Phi(x) = \frac{1}{\sqrt{2}}(v_a + \rho_a(x))\, e^{ia(x)/v_a}$$

- $a(x)$ is massless, while χ gets a heavy mass $m_\chi = y_\Phi v_a/\sqrt{2}$

*) Other model: DFSZ [Dine, Fischer, Srednicki, Zhitnitsky]

Axion CP solution and couplings

Axion couples via χ loop to gluons like θ term:



$$\frac{g_s^2}{32\pi^2}\frac{a}{v_a}G^a_{\mu\nu}G^a_{\rho\sigma}\varepsilon^{\mu\nu\rho\sigma}$$

Combined

$$\frac{g_s^2}{32\pi^2}\left(\theta+\frac{a}{v_a}\right)G^a_{\mu\nu}G^a_{\rho\sigma}\varepsilon^{\mu\nu\rho\sigma}$$

Lowest energy when the coefficient is zero → Strong CP problem is “washed out”!

Because the PQ symmetry is anomalous, the axion is a “pseudo” Goldstone bosons

- → mass!
    - Issue: PQ “quality problem”, how to keep PQ symmetry “good enough” , i.e. without serious explicit breaking due to quantum gravity e.g.

Axion mass and potential

The axion potential can be computed using QCD. At small a it reads

$$E(a,\theta) = -m_\pi^2 f_\pi^2 \cos\left(\theta + \frac{a(x)}{v_a}\right) \longrightarrow m_a \simeq 5.7 \left(\frac{10^{12}\,\mathrm{GeV}}{v_a}\right) \mu\mathrm{eV}$$

- In chiral EFT, on lattice, or using instantons
- Currently "allowed" range for QCD axions: $10^{-12}\,\mathrm{eV} < m_a < 0.01\,\mathrm{eV}$

In a more general approach the axion couples to other SM fields

- Axion - photon: $\sim g_{a\gamma} a\, F_{\mu\nu} F_{\rho\sigma}\, \epsilon^{\mu\nu\rho\sigma} \sim g_{a\gamma} a\, \vec{E} \cdot \vec{B}$
- Axion - electron $\sim g_{ae} (\partial_\mu a)\, \bar{e} \gamma^\mu \gamma_5 e$

Axions as Dark Matter

Preskill, Wise, Wilczek; Abbott, Sikivie; Dine, Fischler

Axions can be (part of) Dark Matter, via misalignment mechanism

- Break PQ symmetry in early universe
  - Massless axion field takes different values in different Hubble patches

$$a_i = \theta_i \, v_a$$

- Values not in minima: "misaligned"
- Rolling towards minimum leads to coherently oscillating axion field

$$a(t) = A(t)\,\cos(m_a t)$$

- Oscillation would even now affect electron mass and fine-structure constant
  - For very light ALPs, can check this with atomic clocks!

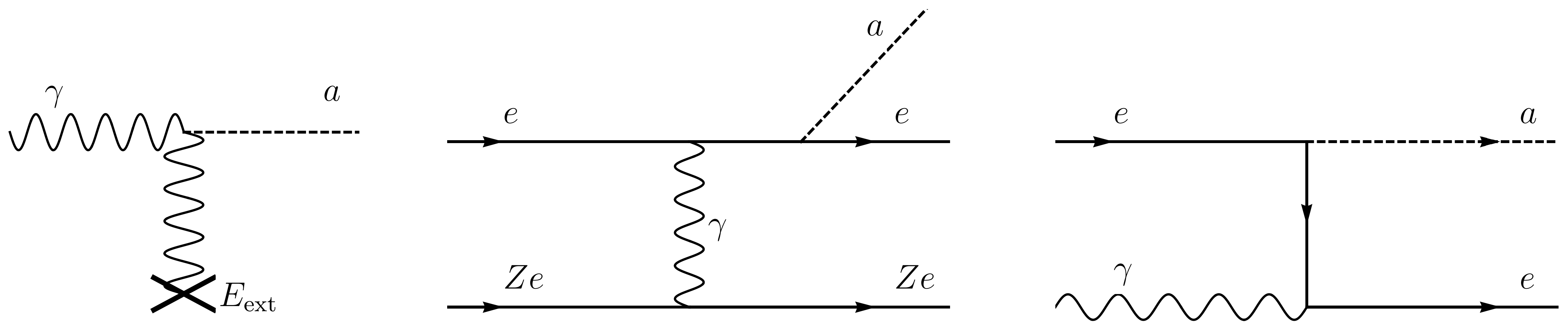
Dark matter mass range for QCD axion $10^{-6} - 10^{-3}\,\mathrm{eV} \quad \rightarrow \quad 100\,\mathrm{MHz} - 10\,\mathrm{GHz}$

Axion detection

Axions should be copiously produced in stars, affecting stellar evolution → bounds on couplings

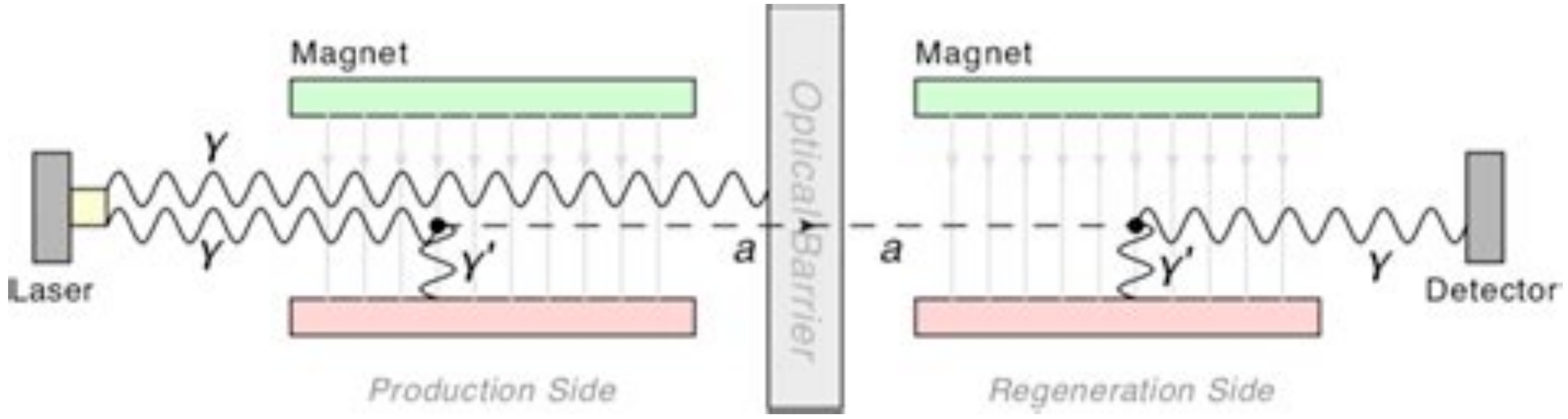
Important is (inverse) Primakoff process, via $g_{a\gamma}\, a\, \vec{E} \cdot \vec{B}$ interaction

Sikivie



Light shining through walls:

- ALPSII, OSQAR



Primakoff process also key for helioscopes, haloscopes and beam dump experiments

- CAST (best so far) (@CERN), (Baby)IAXO (@DESY), ADMX, CAPP, RADES .. SHiP

Naturalness

Some quantities are "unnaturally" small

$$m_{\rm H}/m_{\rm Pl} \simeq 10^{-17} \qquad \theta < 10^{-10} \qquad \rho_\Lambda \simeq (10^{50} - 10^{120}) \times \rho_{\rm Obs}$$

Is this (still) a useful guide to New Physics?

Naturalness varieties:

- Technical: small parameter gets small corrections (e.g. θ)
- 't Hooft: a parameter is naturally small if, when set to zero, more symmetry emerges
  - Setting a fermion mass to zero leads to extra chiral symmetry

Past Naturalness succes

Weisskopf

$\delta m_e \sim m_e \Lambda$ $\qquad$ $\delta m_e \sim -m_e \Lambda$

Successful guide:

- Electron self energy
  - Leading contributions from electron and positron in old-fashioned perturbation theory cancel.

$$\delta m_e \sim m_e \ln(\Lambda/m_e)$$

  - ’t Hooft natural. Not true for scalars: $\delta m_s \sim \Lambda^2$
- Pion mass difference
  - EM self-energy corrections to $m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{4\pi}\Lambda^2$. Fit: $\Lambda \sim 800$, the ρ mass!
- Charm quark from GIM mechanism
  - These were postdictions. Without charm $m_{K_L^0} - m_{K_S^0} \simeq C\Lambda^2$, implying $\Lambda < 3$ GeV.

Gaillard, Lee

  - Adding the charm quark eliminates the divergence, and predicts $m_c \simeq 1.5\,\mathrm{GeV}$

Naturalness and θ

θ is technically natural

- Not 't Hooft natural: there is also CP violation when $\theta = 0$

Is it still a good principle?

- Anthropic solution is not convincing: $\theta \lesssim 0.1$ is allowed by cosmology

Note: the axion solution

- Does not require large cancellations
- Rather, the effective θ "relaxes" to zero dynamically

Naturalness and the Higgs mass

Corrections to scalar mass not "protected". From SM at one loop:

$$\mu^2 = \mu^2_{\text{bare}} - \underbrace{\frac{3y_t^2}{8\pi^2}\Lambda^2}_{\text{top}} + \underbrace{\frac{3\lambda}{8\pi^2}\Lambda^2}_{\text{Higgs}} + \underbrace{\frac{9\alpha_w + 3\alpha'}{16\pi}\Lambda^2}_{\text{electroweak}}$$

How to interpret Λ? Planck scale? Scale of new degrees of freedom?

If Naturalness still "functions", new particles in loops should mitigate e.g. the top quark divergence:

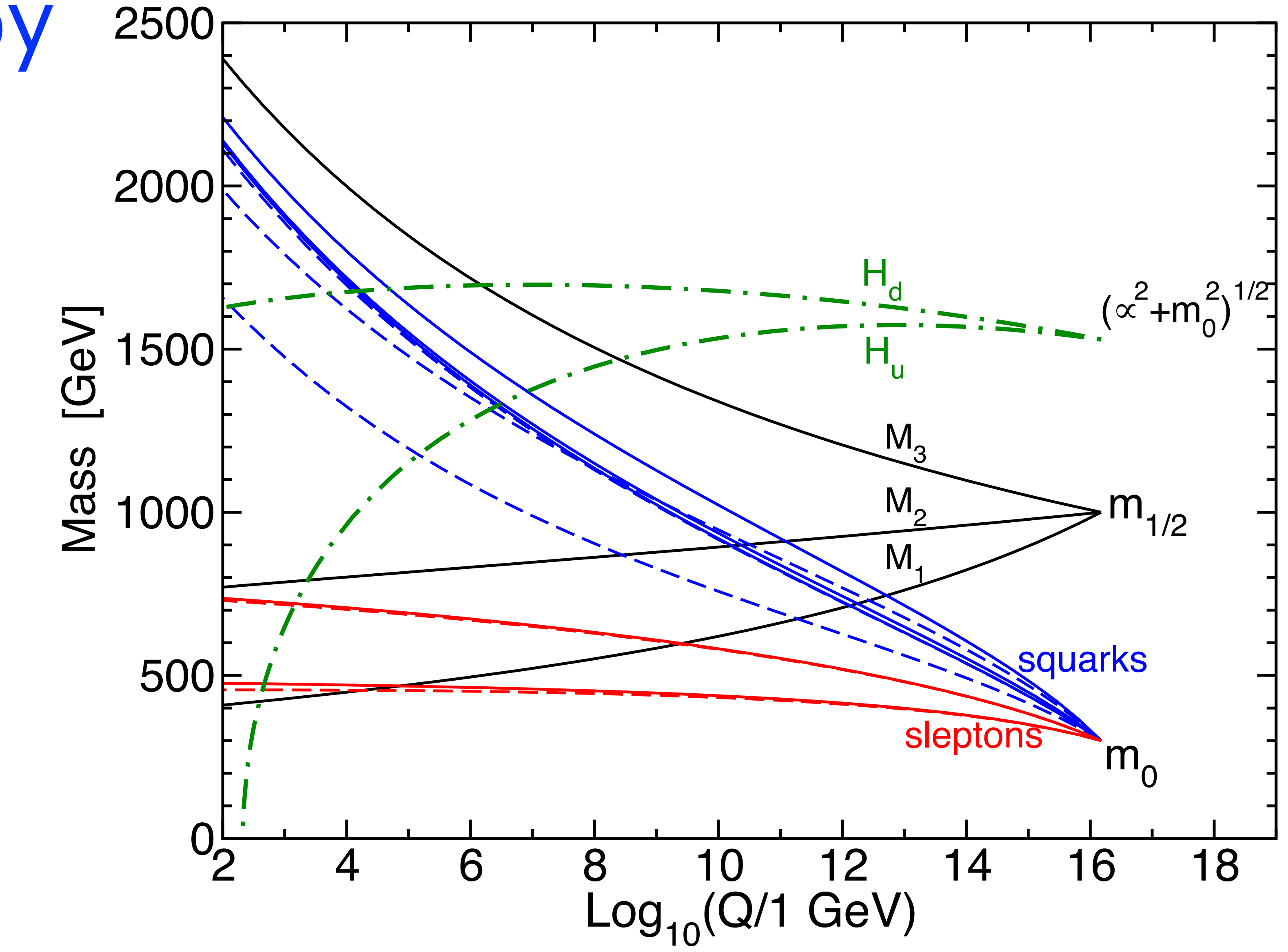
- Supersymmetry: "stops" (scalar top partners)
- Little Higgs theories: non-chiral new "T" quarks,
  - Higgs as a Goldstone Boson

Naturalness / Hierarchy problem

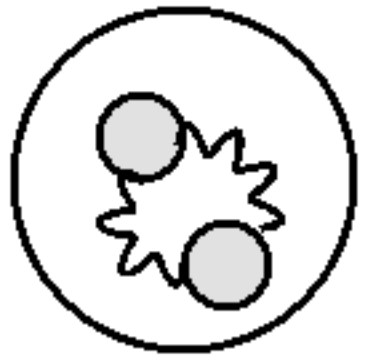
Can we explain the negative mass term in the Higgs potential "$-|\mu^2|\Phi^\dagger\Phi$"?

- Supersymmetry has "radiative EW symmetry breaking" , through RG evolution of soft susy breaking terms, driven by top loops

Ibañez, Ross



- Can we think of other mechanisms?



Other ideas

- Higgs is not fundamental, but a bound state of strongly interacting fermions
- Relaxion: can the Higgs mass "relax" to its value, just like θ ?

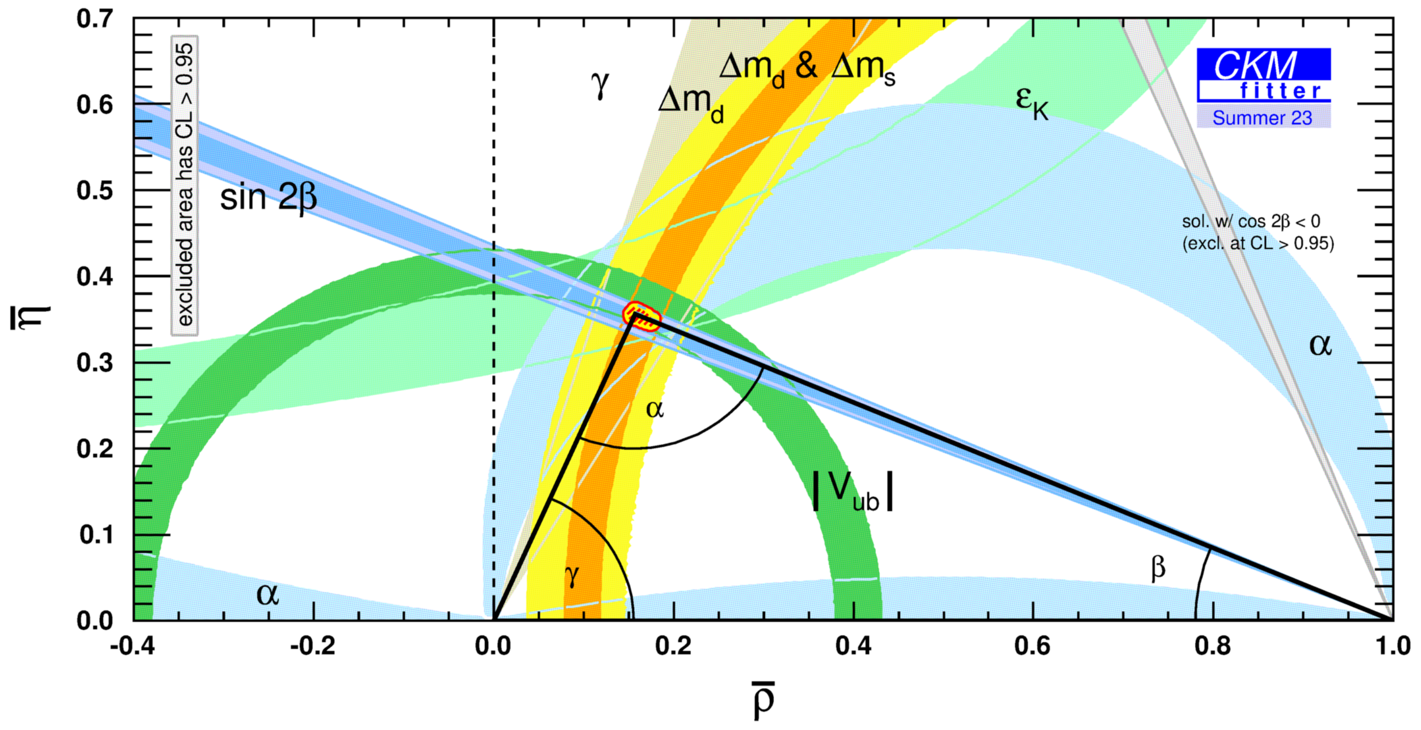
Is Naturalness still a guide? Time will tell..

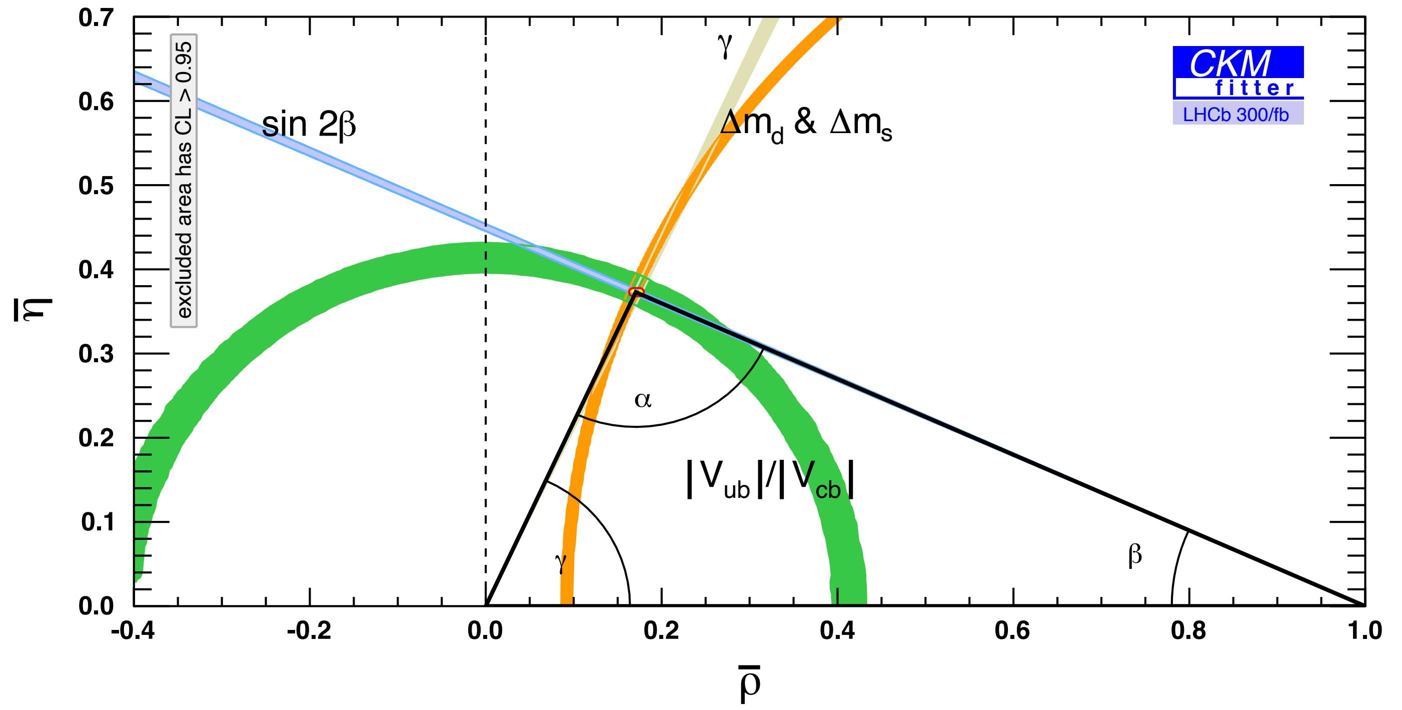
Flavour

With flavour physics we can look in detail far beyond collider limits.

Ever more severe stress-tests of the SM coming:

- By determining CKM parameters up to 10x better than now!
  - e.g. angle γ
- Through (new) CP violating observables, e.g.
  - Charm sector: up-type quark! CKM suppressed→ opportunity
  - Increased focus on loop-dominated processes (penguins)

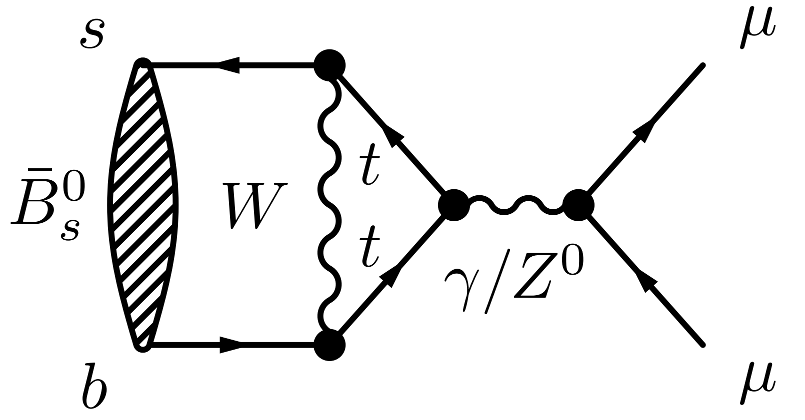


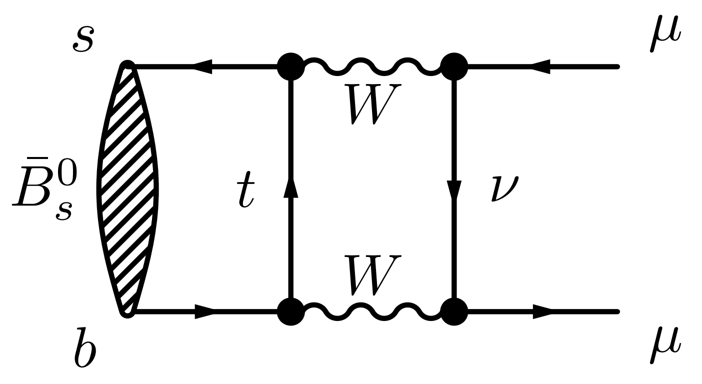


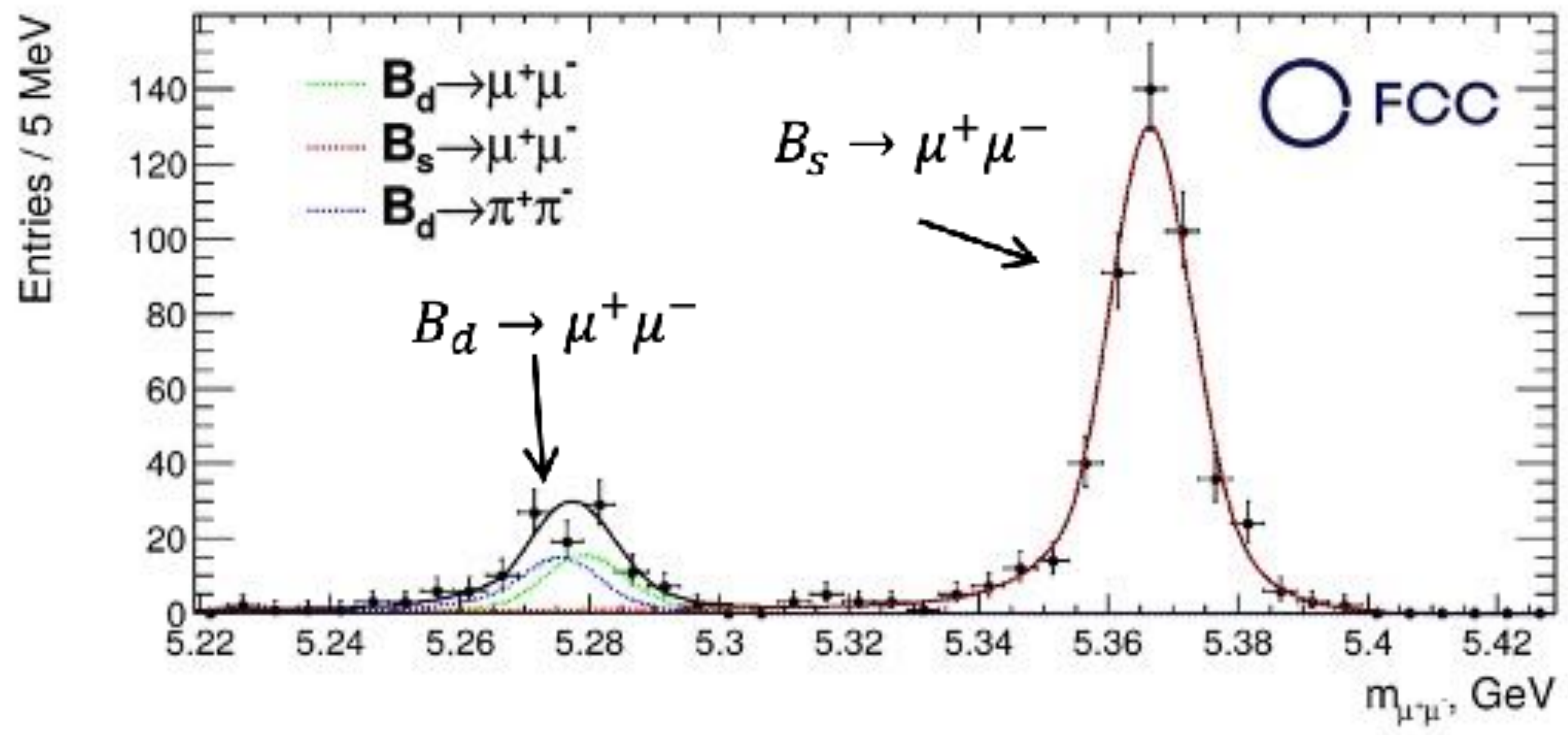
Rare decays

Rare decays as delicate detectors of heavy particles in loops, e.g.

- $B^0_{d,s} \to \mu^+\mu^-$
- $K^+ \to \pi^+\nu\bar{\nu}$ [NA62]





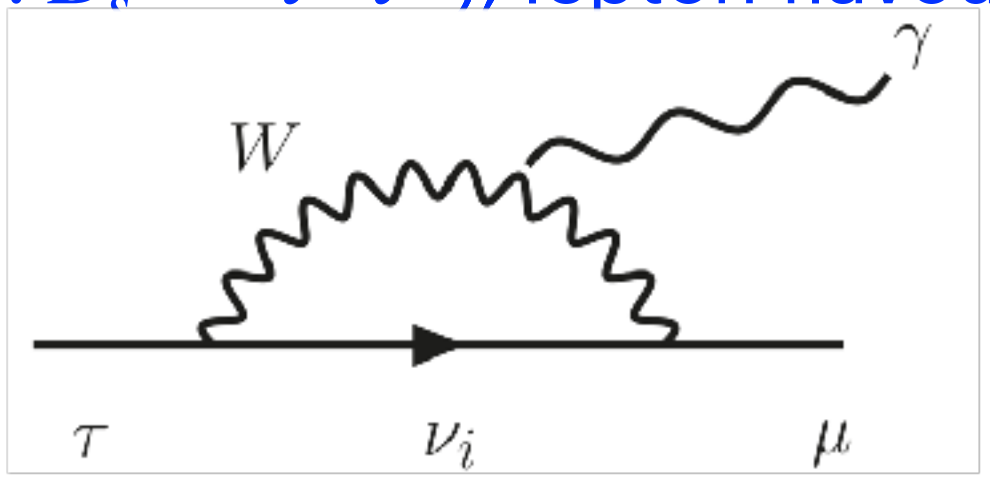


Major benefits for precision expected from lattice calculations of form factors and hadronic matrix elements, to per cent accuracy.

Important: completion of the HL-LHC programme.

At Higgs factory, flavour physics happens mostly at the Z-pole.

- Difficult to compete in statistics with LHCb
- But still significant flavour programme: decays with missing energy (e.g. $B_s \to \tau^+\tau^-$), lepton flavour violation in τ decays, etc.

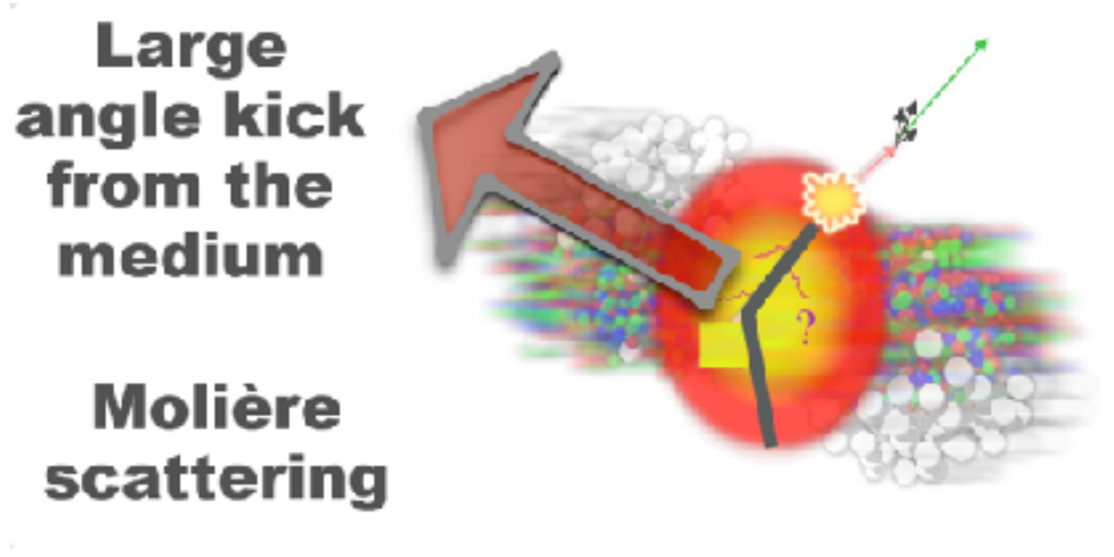


Heavy Ions

Many ideas to test! A selection:

When does the Quark Gluon Plasma change from liquid to (quasi)-particles?

- Scattering with quasiparticle can lead to large angle scattering
- Test through jet substructure: see clearly separated subjet

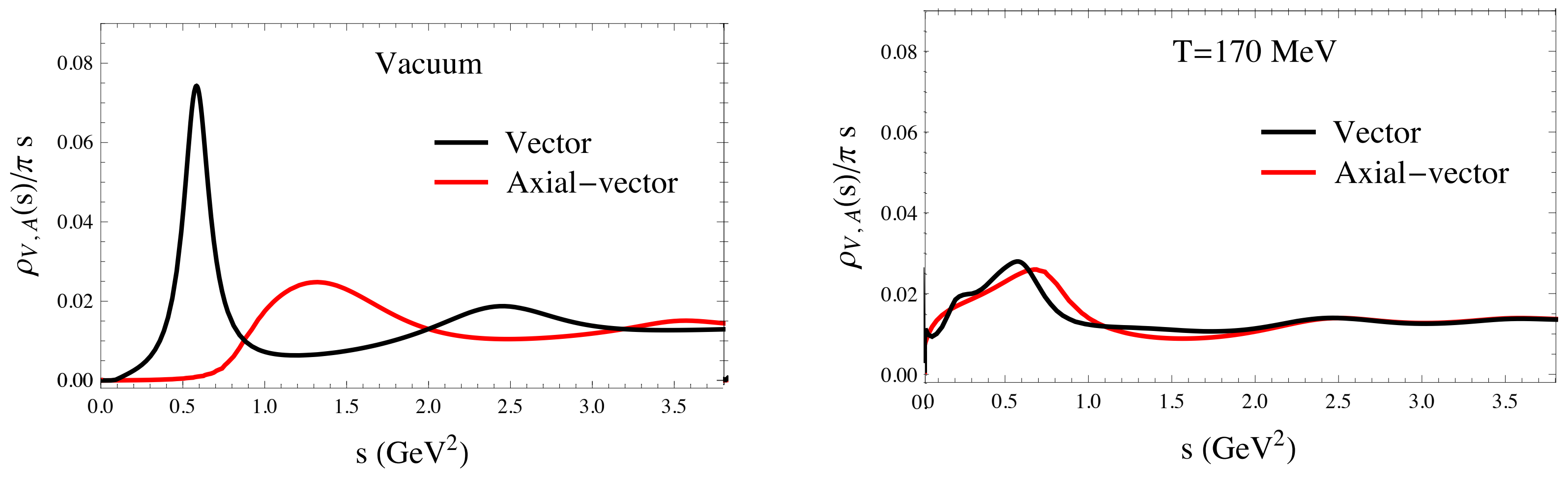


ALICE, RHIC

Can we see chiral symmetry being restored, i.e. $\langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \to 0$, above the critical temperature?

- Vacuum engineering!
- Mass peak of ρ melts, and mixes with a_1 meson. Test through dilepton spectrum

Hohler, Rapp



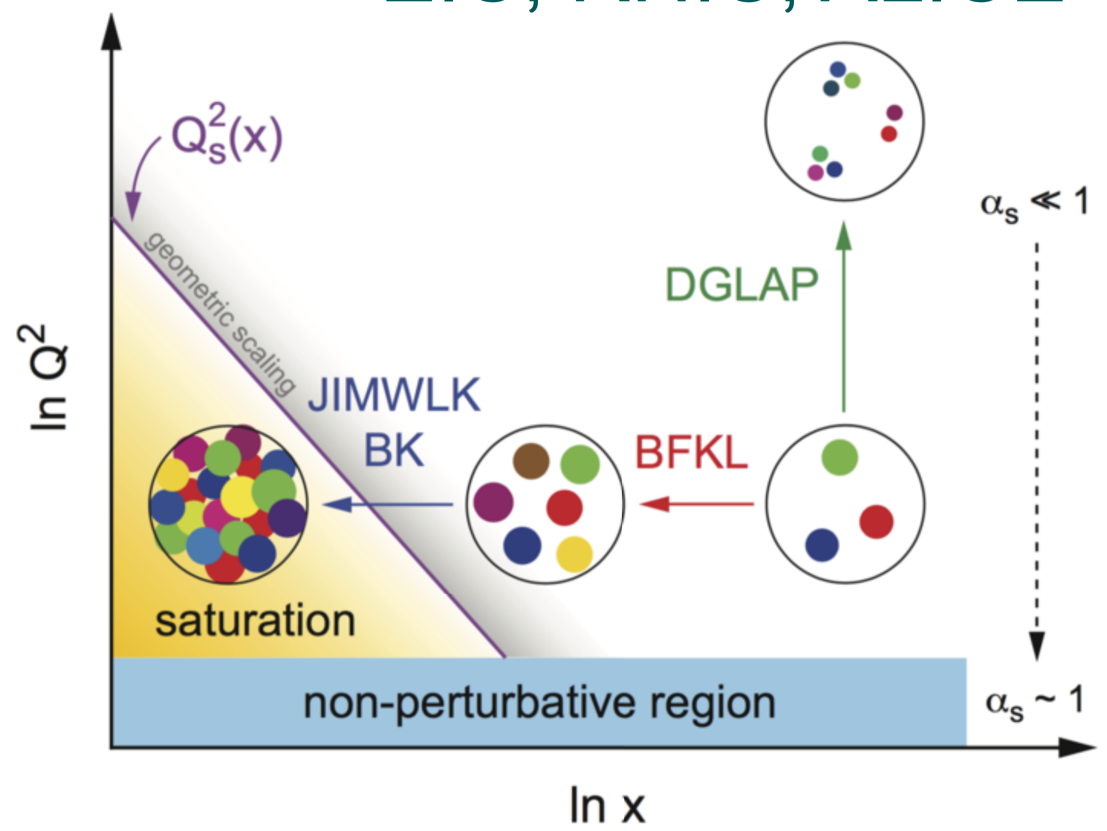
ρ and a_1 spectral function

ALICE, NA60+?

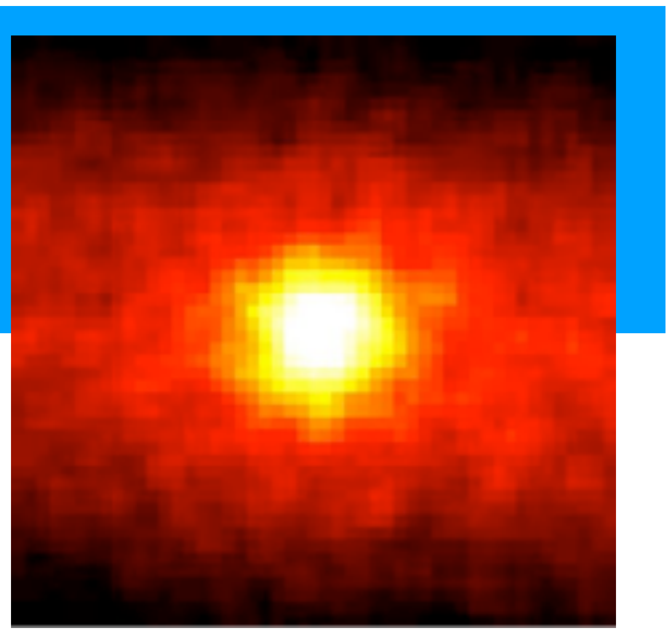
Can we see clear signs of parton saturation?

- Partons merging due to dense packing at high energy
- Look for deviations of DGLAP scaling at small x, due to non-linear evolution

EIC, RHIC, ALICE



Neutrino's



PMNS mixing matrix

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\rm CP}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,c_{23} \end{pmatrix}$$

So many fascinating questions. Major ones:

What is their flavour structure, mass hierarchy (normal or inverted)?

- Via KM3NeT-ORCA, T2K, HyperK, DUNE, JUNO,..
- All parameters to be measured/constrained

Is there CP violation in the lepton sector?

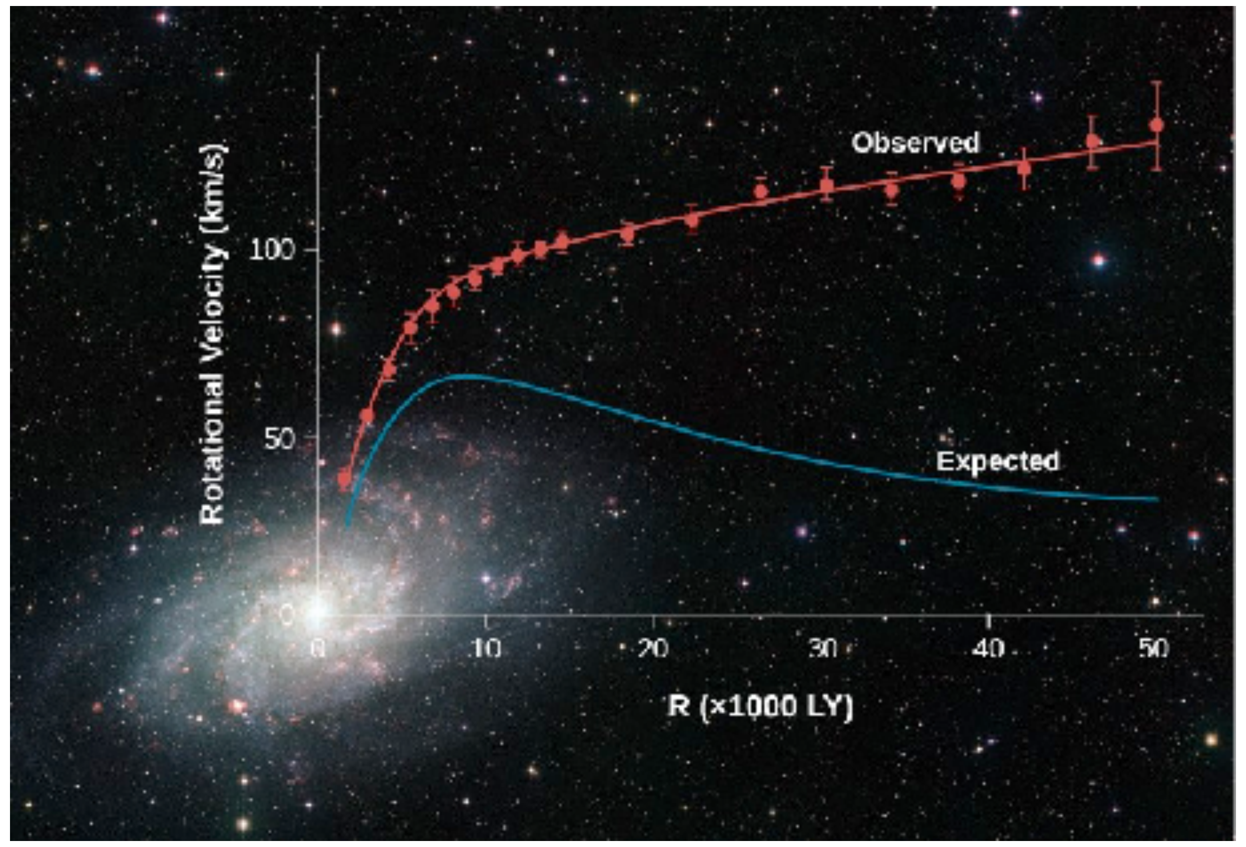
- DUNE and Hyper-K can measure δ_{CP} well by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu - \bar{\nu}_e$
  - MSW matter effect important

Are neutrinos their own anti-particle (Majorana)?

- Many searches for neutrino-less double beta-decay underway

Dark Matter

Dark Matter is indirectly observed, but we don't know its nature:



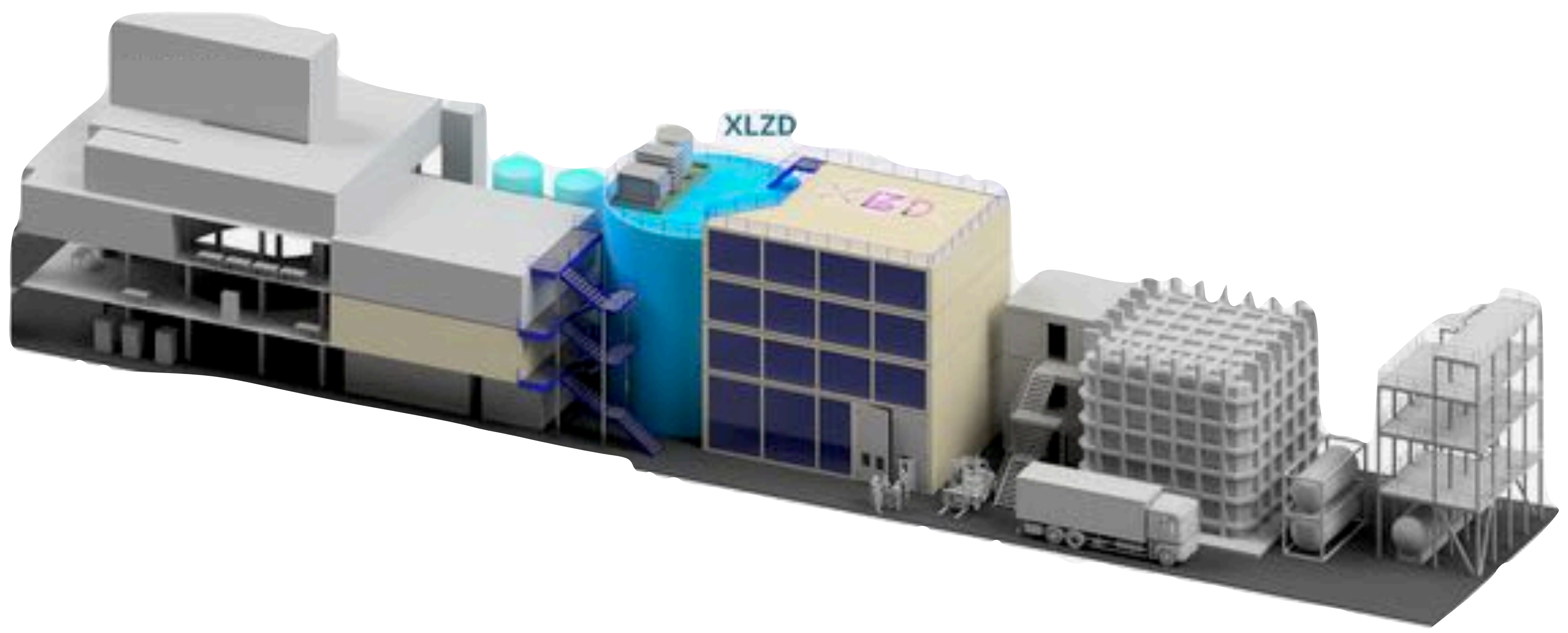
What could be DM → What could DM be?

- Weakly Interacting Massive Particles (WIMPs) [GeV - TeV]
  - Neutralino (supersymmetry), or Kaluza Klein particle (extra dimensions)
- Axions or Axion-Like-Particles (ALP's) [nev - meV]
  - From SM extensions, string theory
- Sterile Neutrinos [kev-TeV]
  - Active-sterile neutrino mixing, νMSM

Possible future of Direct Detection: XLZD Observatory*)

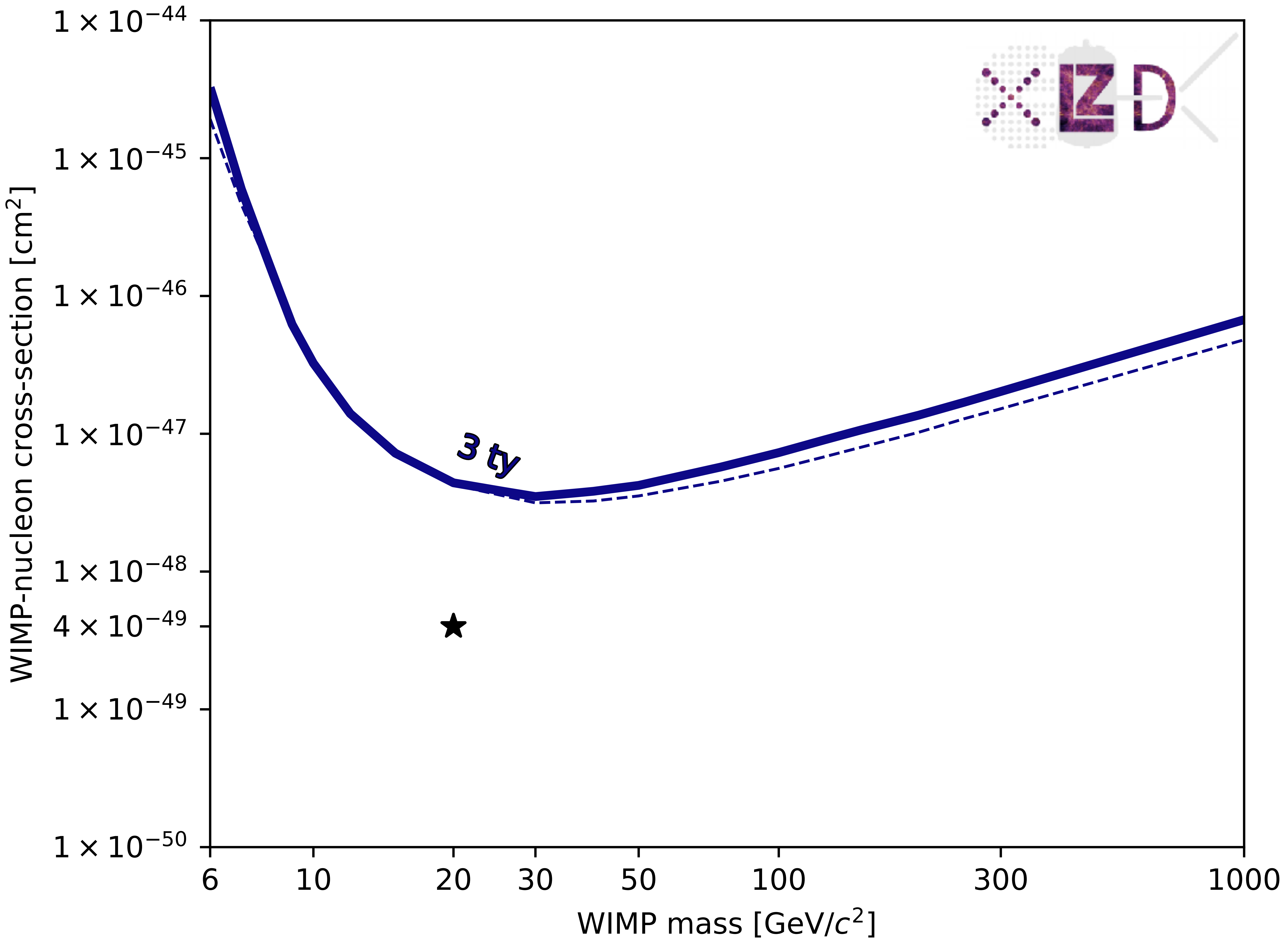
- Planned Liquid Xenon dual-phase TPC. 60 tons active target

Xenon, Lux-Zeppelin, Darwin



What would discovery look like (III)?

A discovery of a 20 GeV WIMP with σ = 4 × 10^{-49} cm^2



XLZD results of toy-experiments for different exposures in ton-years

If discovery sensitivity > 3σ a closed contour is drawn, an upper limit line is drawn otherwise.

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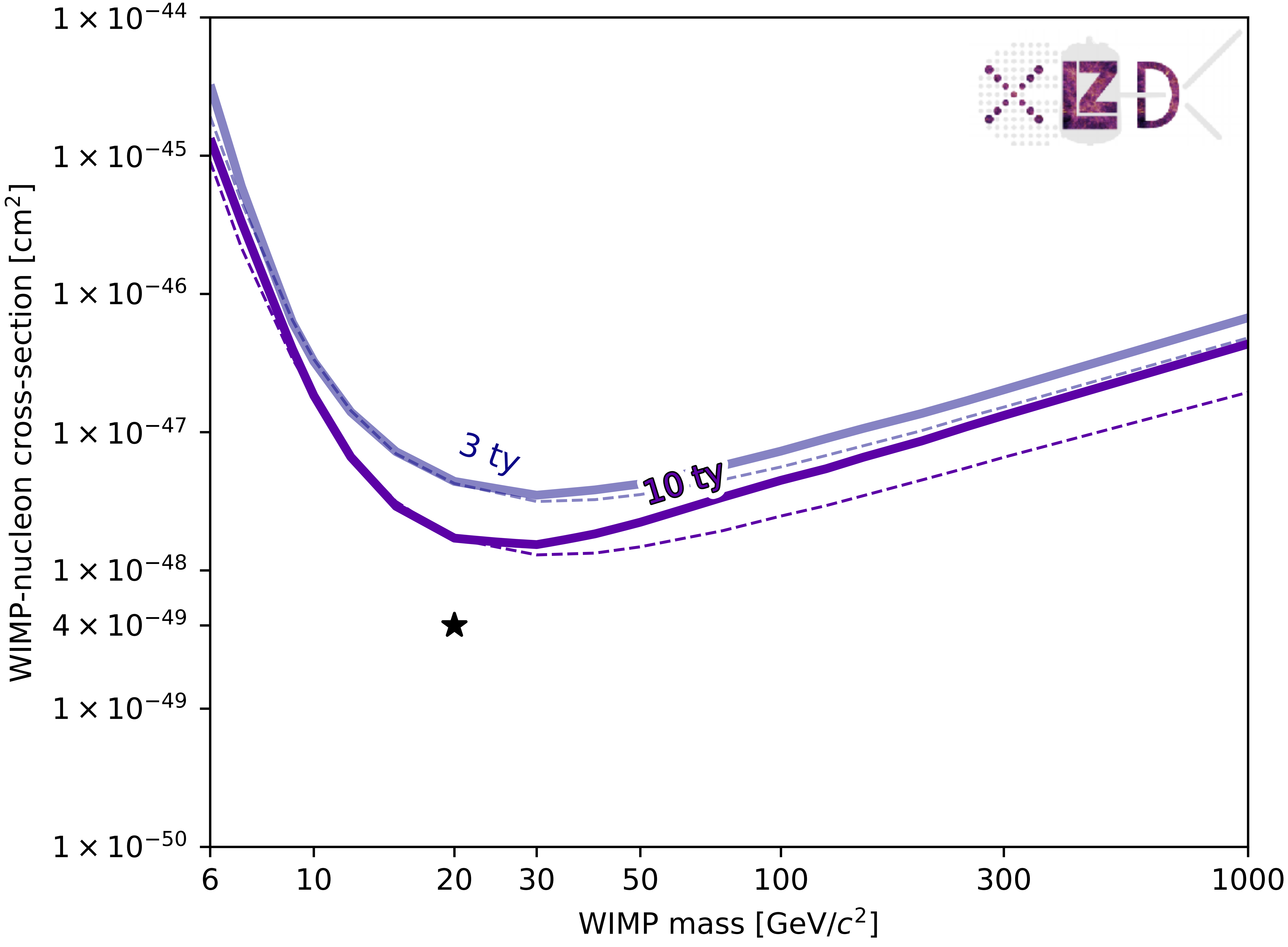

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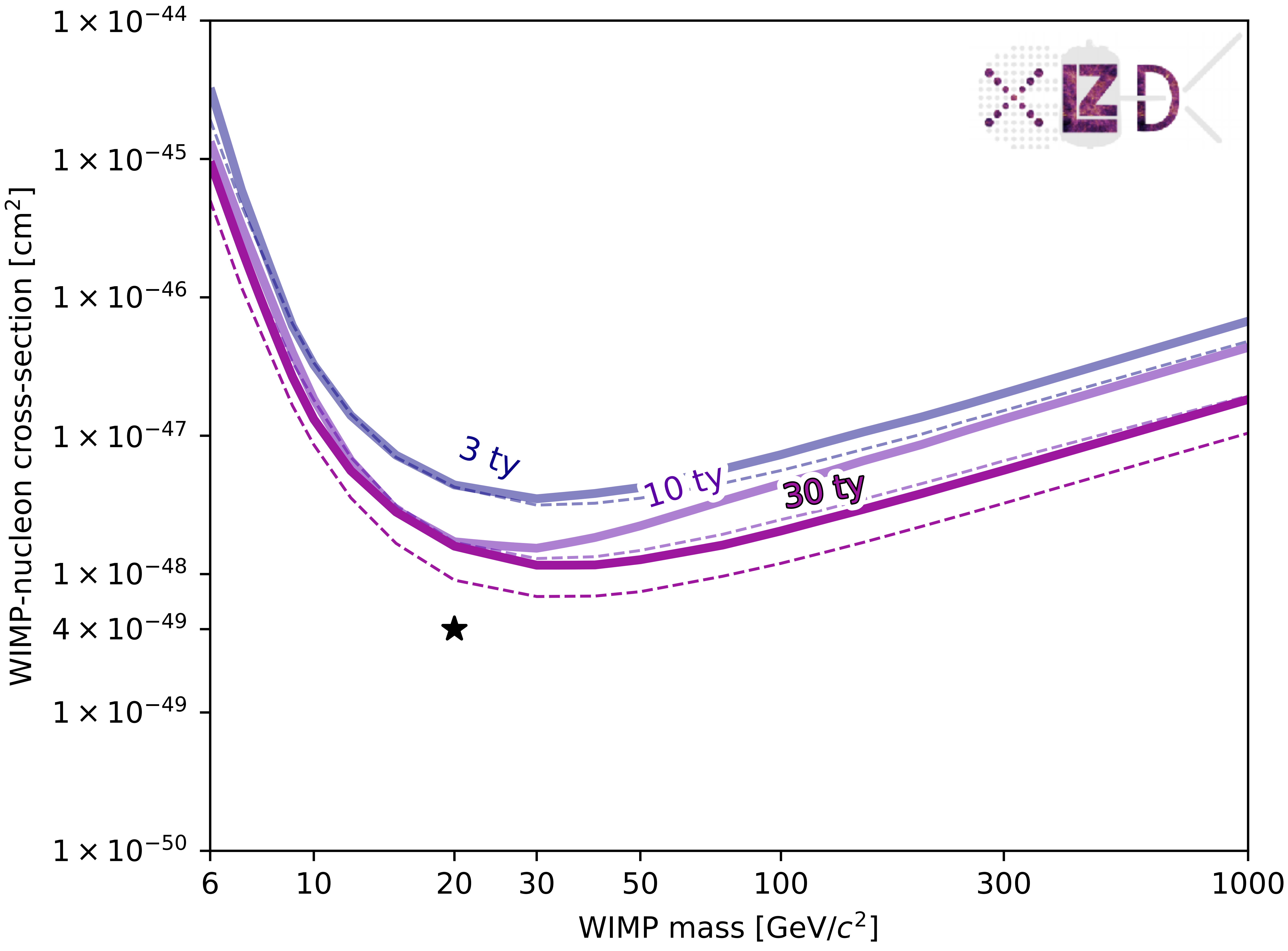

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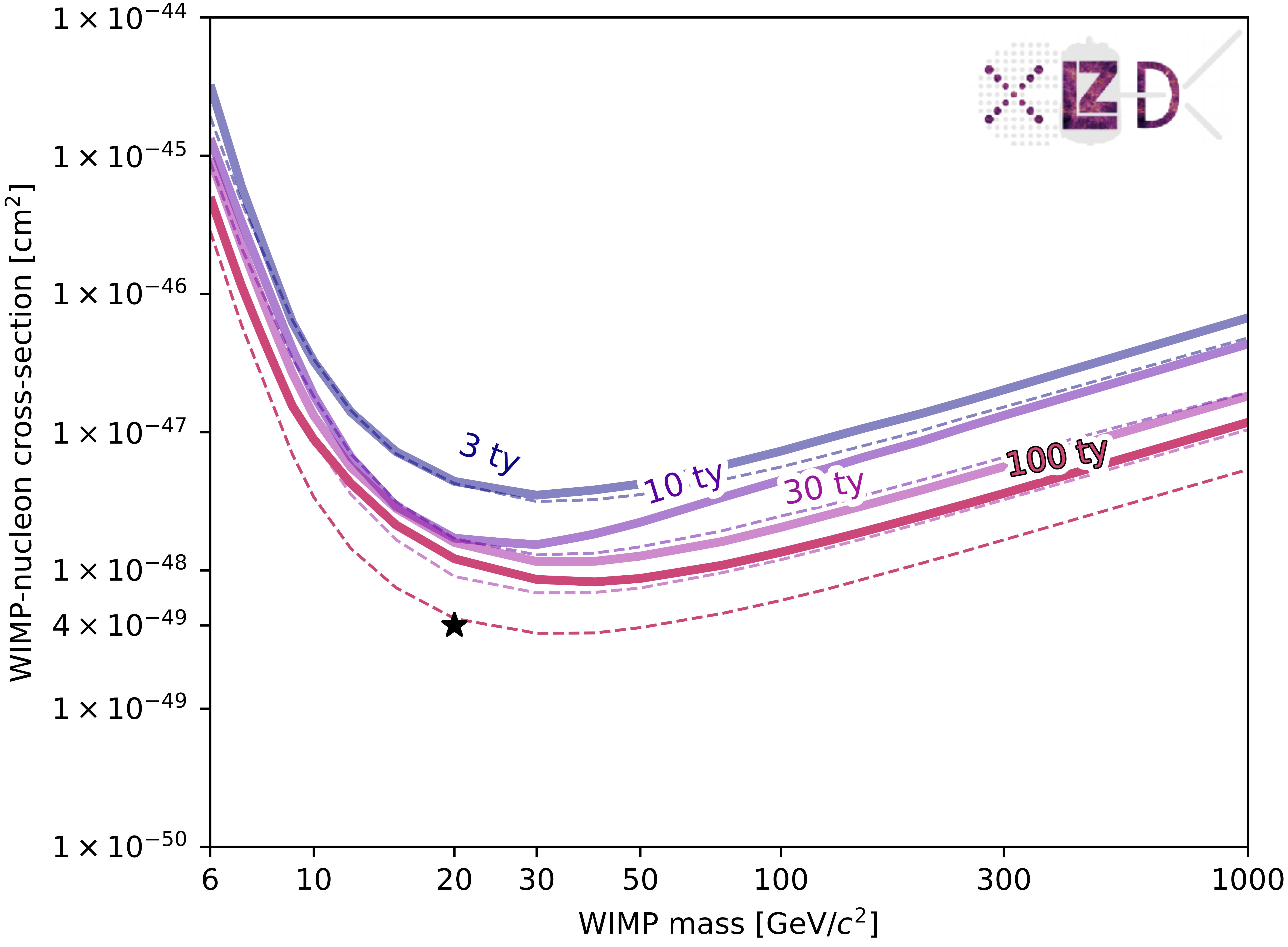

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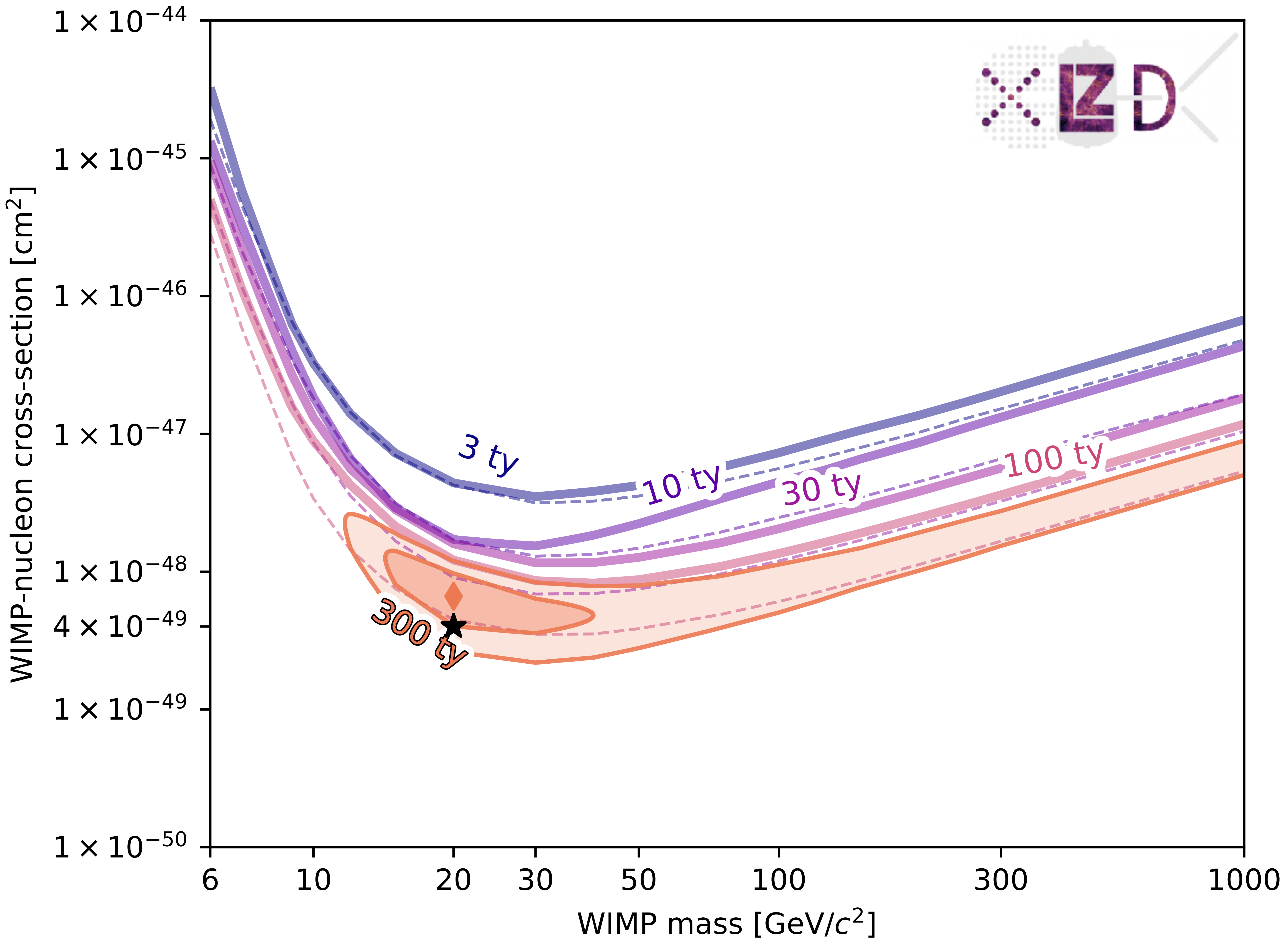

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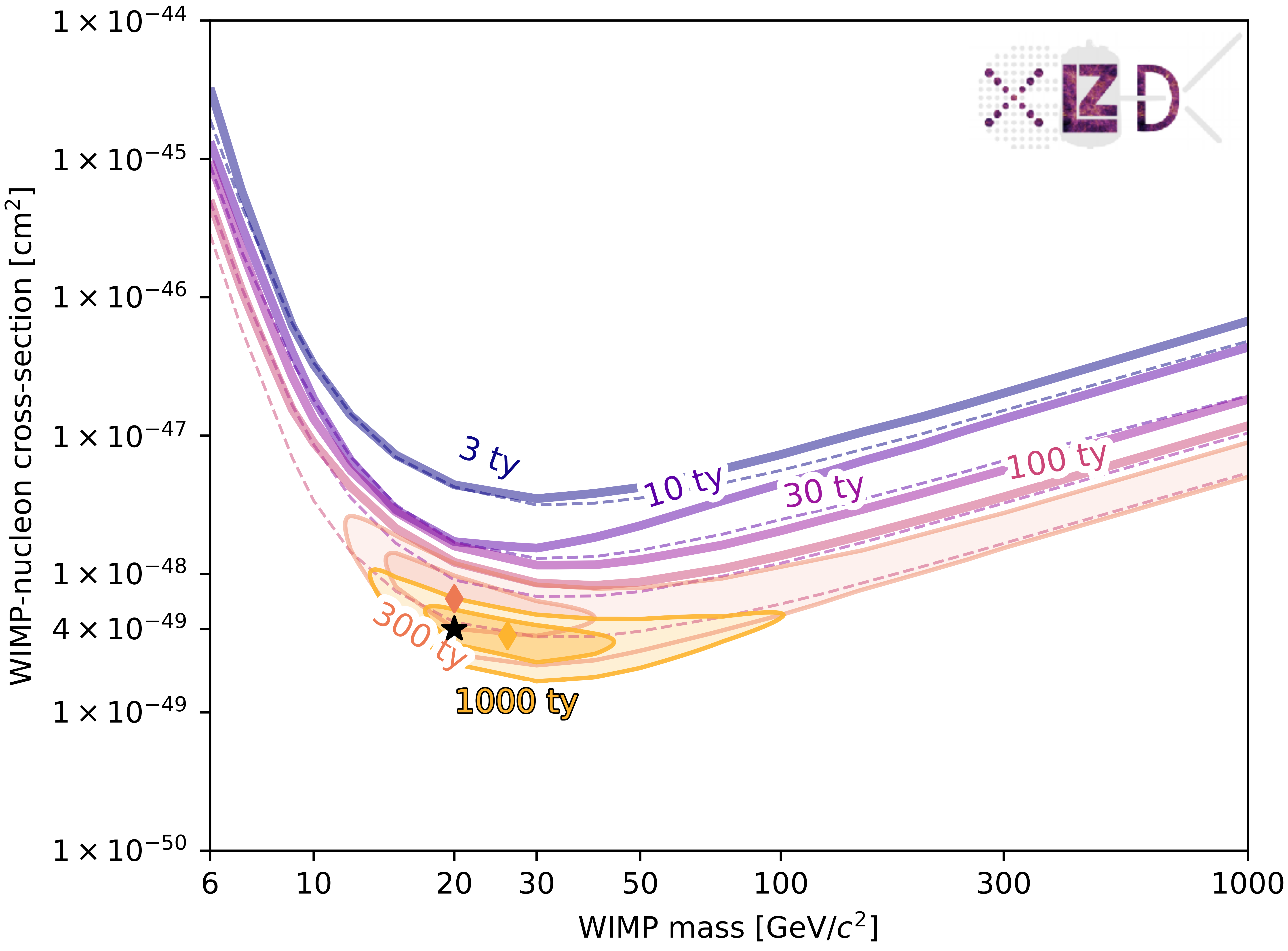

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Theoretical Precision

"Look deep into nature, and then you will understand everything better."
Attributed to Einstein

The great increase in precision from upcoming measurements must be matched by theory:

- Need percent-level accuracy for HL-LHC predictions. For some FCC/LC/etc predictions need per-mille level.

In recent years enormous progress, due to new inventions, computing power.

- Numerical, and computer algebra (Mathematica, FORM,..)

Mathematics has been a source of outstanding ideas

Loops and number theory

In higher order calculations one encounters families of loop integrals, e.g.

$$I(a_1, a_2) = \int \frac{d^d k}{i\pi^{d/2}} \frac{1}{[k^2]^{a_1} \, [(k-p)^2 - m^2]^{a_2}} = \int \frac{d^d k}{i\pi^{d/2}} \frac{1}{D_1^{a_1} D_2^{a_2}}$$

Many can be related through Integration By Parts (IBP) identities

$$0 = \int \frac{d^d k}{i\pi^{d/2}} \frac{\partial}{\partial k^\mu} \left[v^\mu \cdot \frac{1}{D_1^{a_1} D_2^{a_2}} \right], \quad v^\mu = \{k^\mu, p^\mu\} \longrightarrow \sum_j R_{ij}(d, s, m^2) \cdot I_j = 0,$$

- Yields a smaller, finite set: Master Integrals

Can have millions of integrals and relations, with rational functions of $d, s, m, \ldots$ as coefficients.

Von Manteuffel, Schabinger; Peraro

Clever method: use "Finite Field arithmetic" $\mathbb{F}_p = \{0,1,2,\ldots,p-1\}$

- Evaluate $d, s, m, \ldots$ at some integer values modulo p (large prime) → R_{ij} as numbers mod p
- Solve for linear system mod p, for various p
- Reconstruct coefficients symbolically, using Chinese Remainder Theorem and rational reconstruction!
  - Implemented in various software packages [KIRA, FIRE,…]

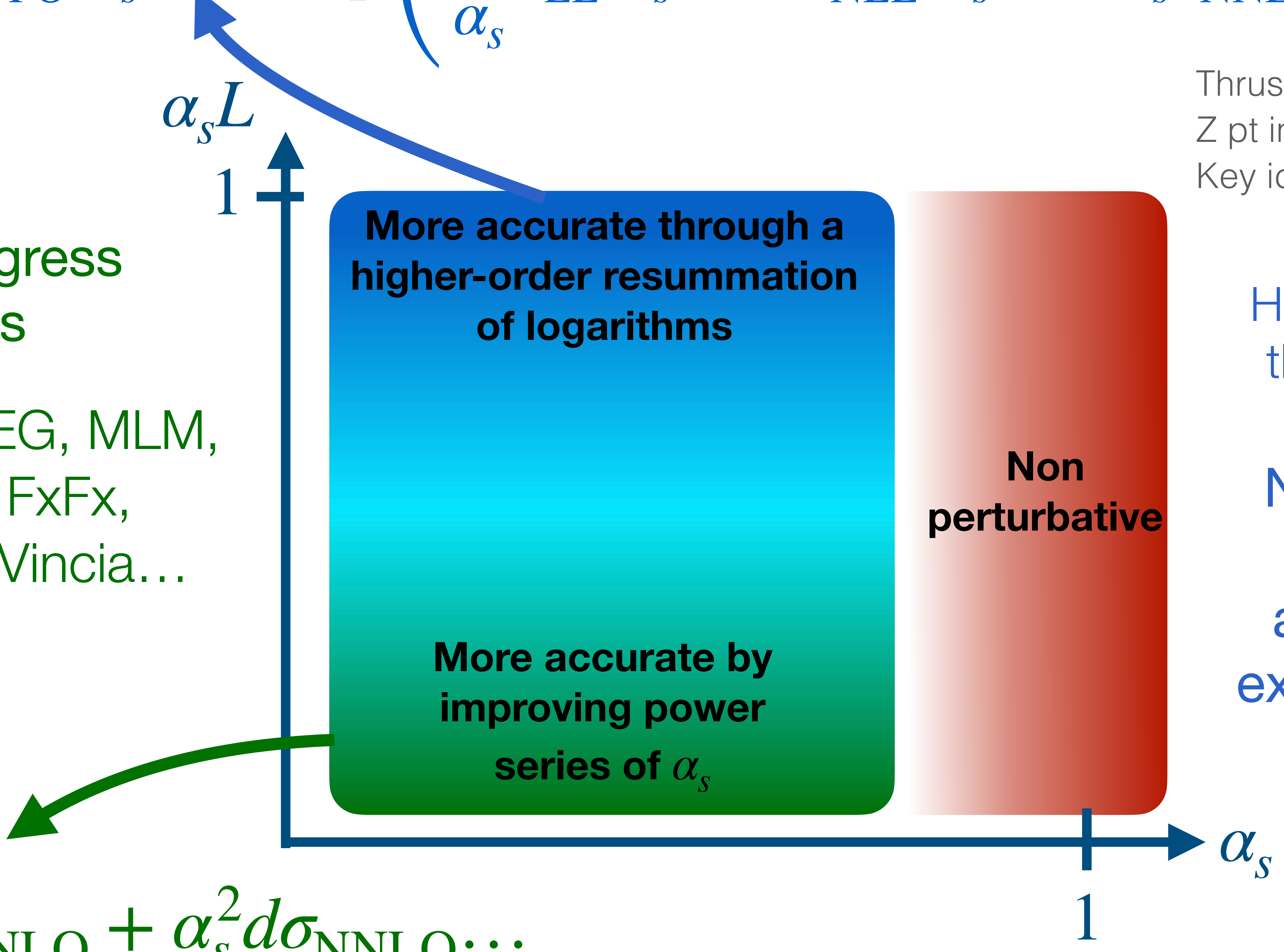
Precision with event generators

$$d\sigma \sim d\sigma_{\rm FO}(\alpha_s, L) \times \exp\left(\frac{1}{\alpha_s} g_{\rm LL}(\alpha_s L) + g_{\rm NLL}(\alpha_s L) + \alpha_s g_{\rm NNLL}(\alpha_s L) + \ldots\right)$$

Thrust, C-parameter
Z pt in hadronic collisons, jet vetoes
Key idea: treat recoil correctly

Has seen enormous progress over the last 20 years

i.e. MC@NLO, POWHEG, MLM, CKKW, MIN(N)LO, FxFx, Geneva, UNNLOPS, Vincia…



High accuracy now explored by the parton shower community

NLL is becoming the new standard, but NNLL accuracy is necessary to exploit full physics potential

$$d\sigma \sim d\sigma_{\rm LO} + \alpha_s d\sigma_{\rm NLO} + \alpha_s^2 d\sigma_{\rm NNLO} \cdots$$

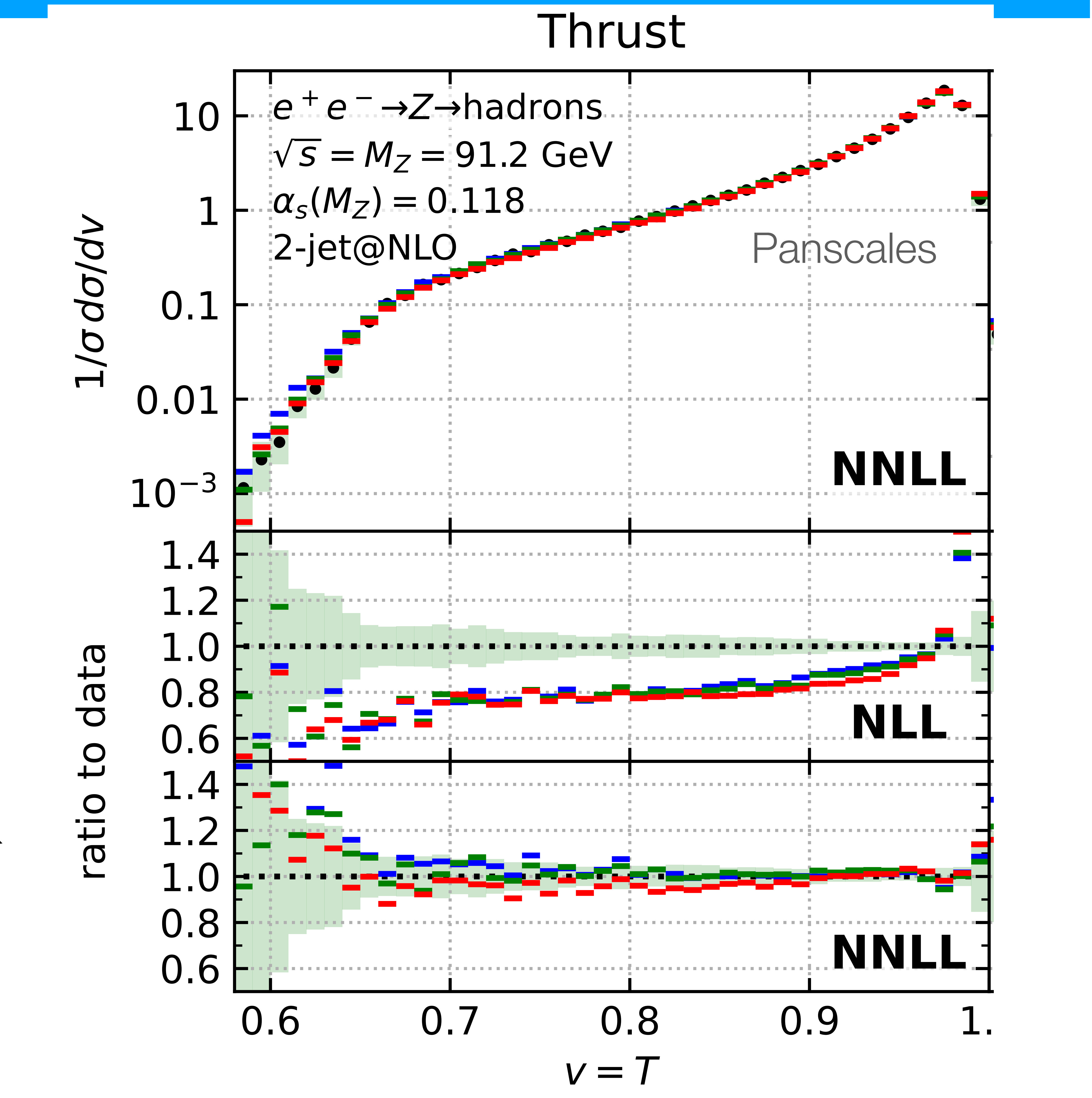
PanScales, Herwig, Sherpa.

Improved parton shower

Longstanding discrepancy between true value of $\alpha_s(M_z) = 0.118$ and that needed to describe LEP data: $\alpha_s(M_z) = 0.1365$

Not observed for every LL shower

NNLL showers obviate need for large α_s value to match LEP data



Artificial Intelligence

2024 Physics Nobel Prize to G. Hinton and J. Hopfield

- Used statistical physics ideas to enable machine learning and neural networks

Classification, pattern recognition etc crucial for modern particle physics

- → improved di-Higgs expectations, parton distribution functions (NNPDF)

Generative AI and LLM's

- Great help with coding, writing, research -> productivity boost
  - LLMs can already solve problems in Quantum Field Theory textbooks e.g. [but beware hallucination!]
- Can we soon add thousands of smart virtual AI agents to our teams?
- Do we need "Large Physics Models"?

AI queries have a significantly larger CO_2 footprint!!

- 1 ChatGPT question = 15x Google query

Summary

There are outstanding ideas in all areas of particle physics!

To explore these and gather knowledge we need a broad diverse programme

Need input from HL-LHC, a new flagship collider, a wide variety of other experiments, and neighbouring fields.

From theory we need many ideas and methods to explore new regimes.

A bright future is possible. Let us realize it!

Open Symposium Preview

Open Symposium Preview

Open Symposium Preview

I wish us all an inspired and fruitful symposium!