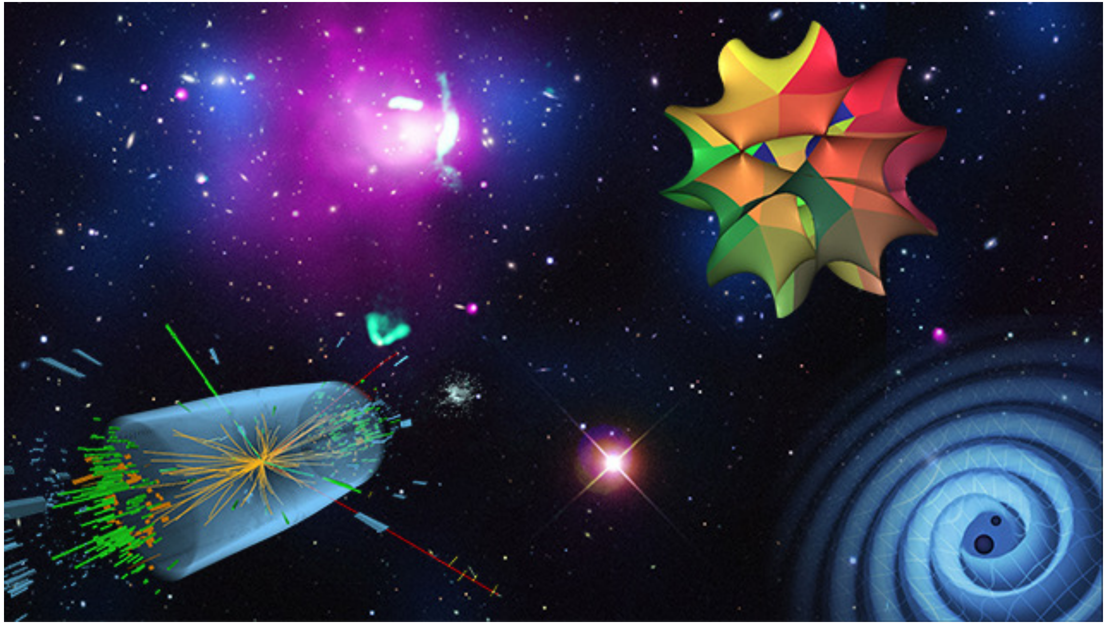
Understanding the Quantum Universe: particle physics status and plans

Beate Heinemann

DESY and Hamburg Univrsity

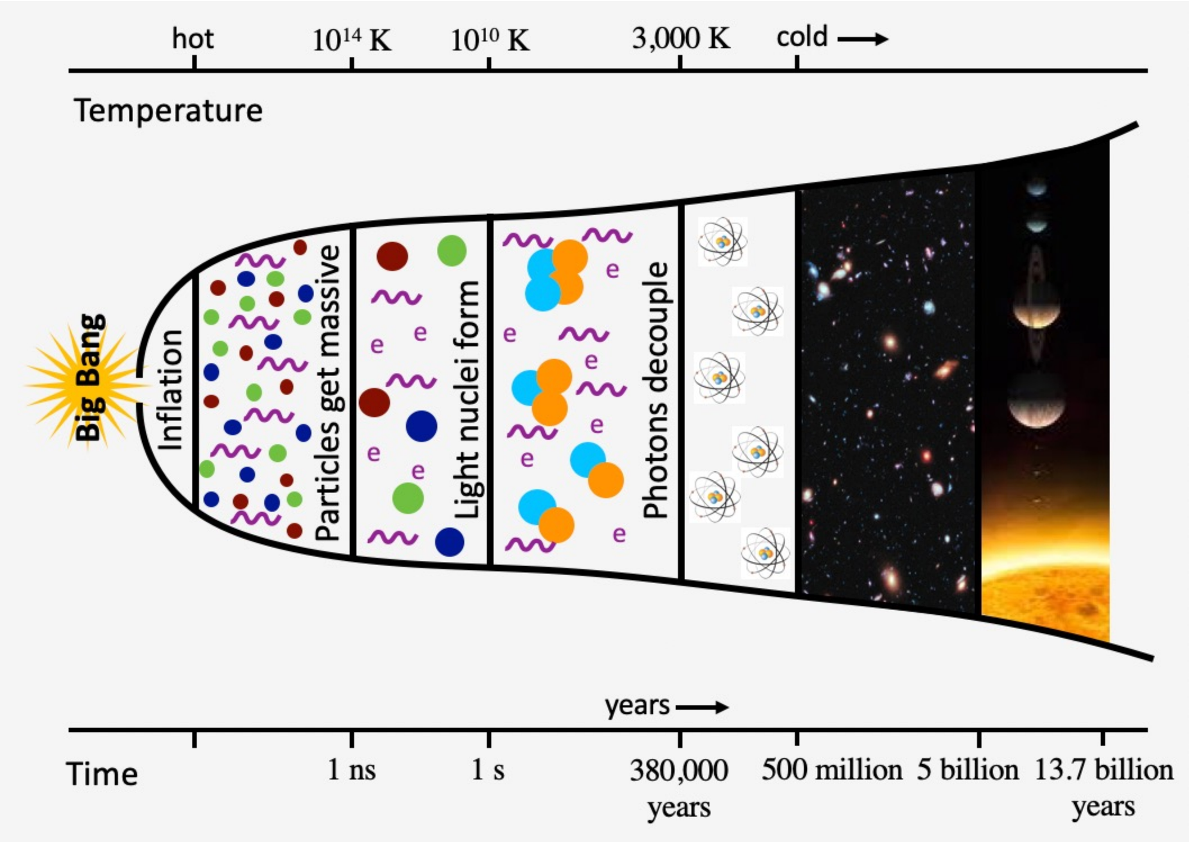


HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

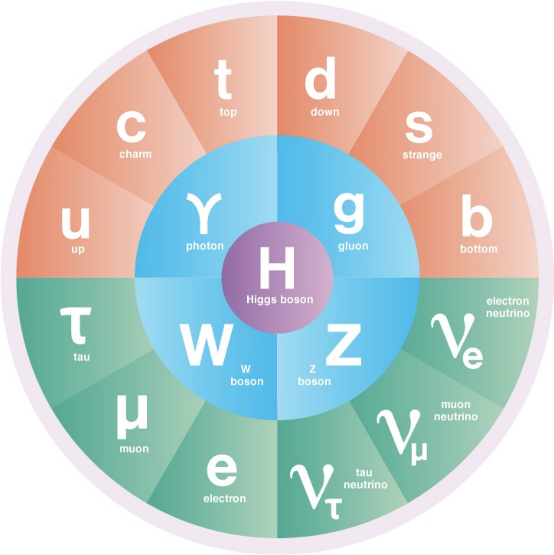
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

20/10/2023

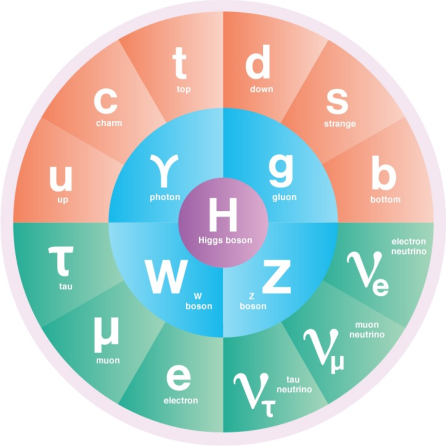
Our Universe



from Selya Ipek



The Standard Model Lagrangian



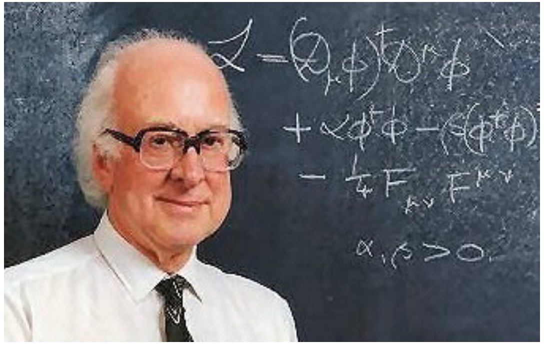
$$\begin{aligned}\mathcal{L} \;=\; & -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\psi \\ & + \psi_i\lambda_{ij}\psi_j h + \text{h.c.} \\ & + |D_\mu h|^2 - V(h) \\ & + \frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j\end{aligned}$$

gauge sector

flavour sector

Higgs sector

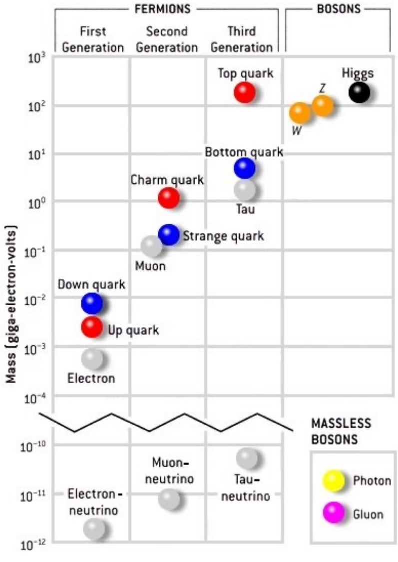
ν mass sector

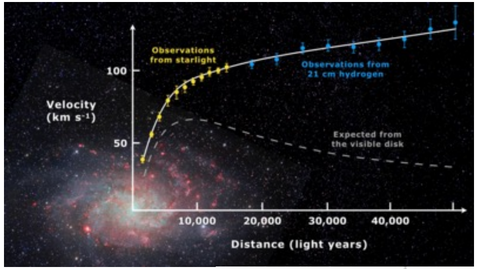


+ are there new particles and forces (that solve some of the mysteries)?

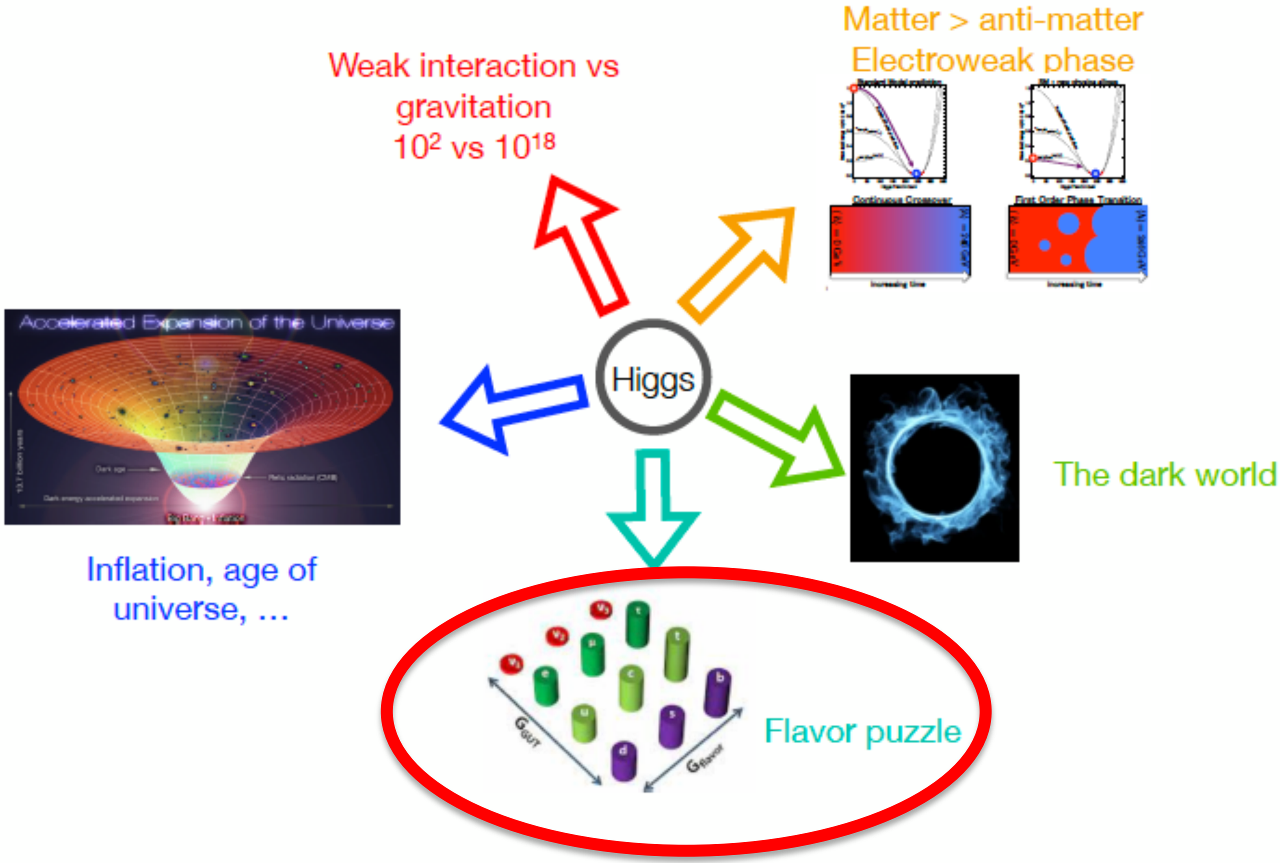
(Some) interesting questions for particle physics

- **What is the origin of flavour?**
  - Why is the mixing matrix so different in quark and neutrino sector?
  - Are there flavour changing neutral currents?
- **Why is there any matter left in our Universe?**
  - Which mechanisms exist to fulfill the three Sakharov's conditions?
  - How did electroweak phase transition occur?
  - Is there CP violation in the neutrino sector?
- **Is Dark Matter a particle?**
  - Can we produce it from known matter?
  - Is there a dark world?
  - And… what is Dark Energy?
- **Is the Universe natural?**
  - Why is the Higgs mass so low?
  - Are there new symmetries in Nature?
- …





Big Questions and the Higgs Boson



Weak interaction vs
gravitation
10^2 vs 10^{18}

Matter > anti-matter
Electroweak phase

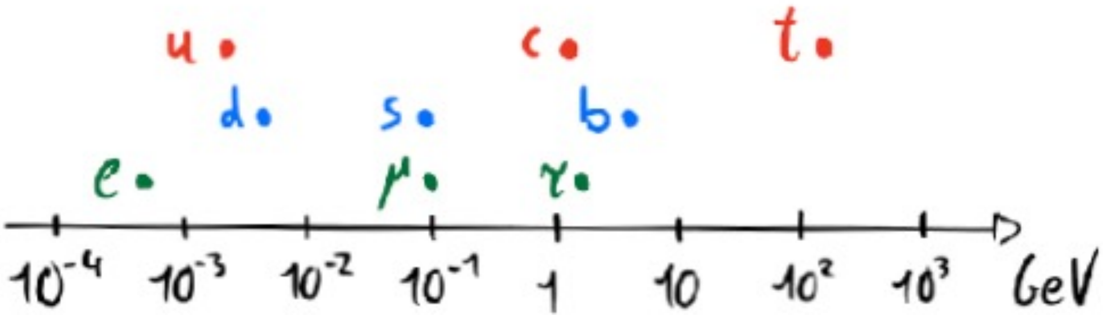
Higgs

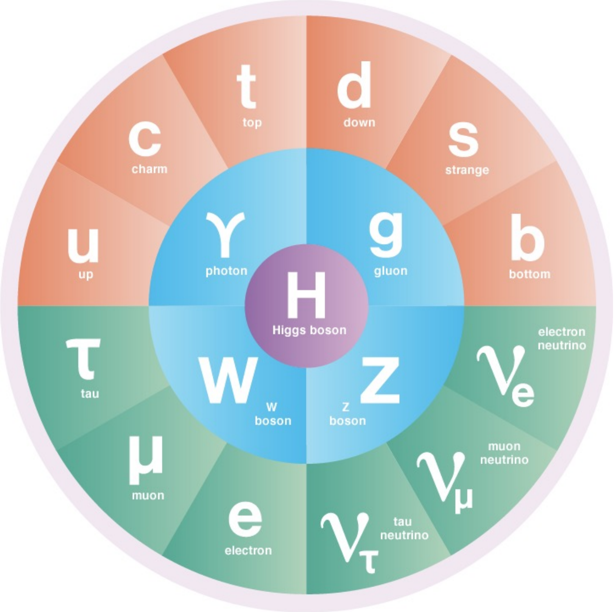
Inflation, age of
universe, …

The dark world

Flavor puzzle

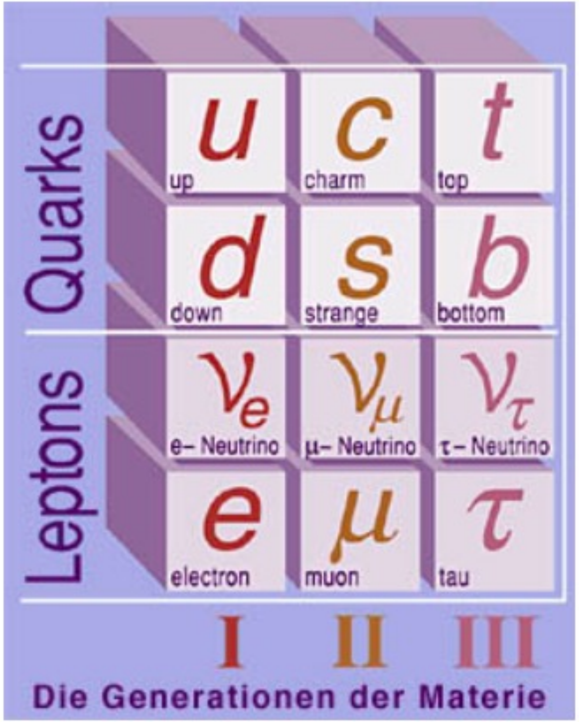
The Flavour Puzzle



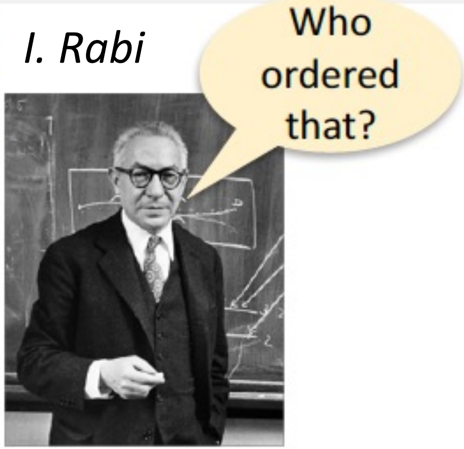


Higgs is the only SM boson that distinguishes flavour

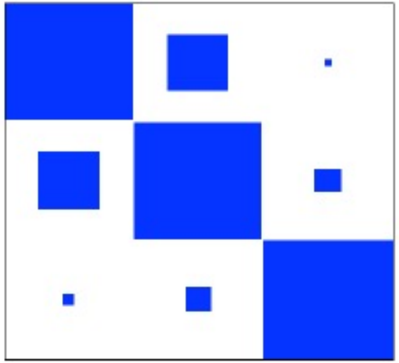
The Flavour Puzzle



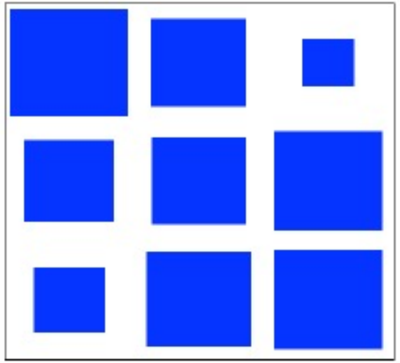
I. Rabi



Quark mixing



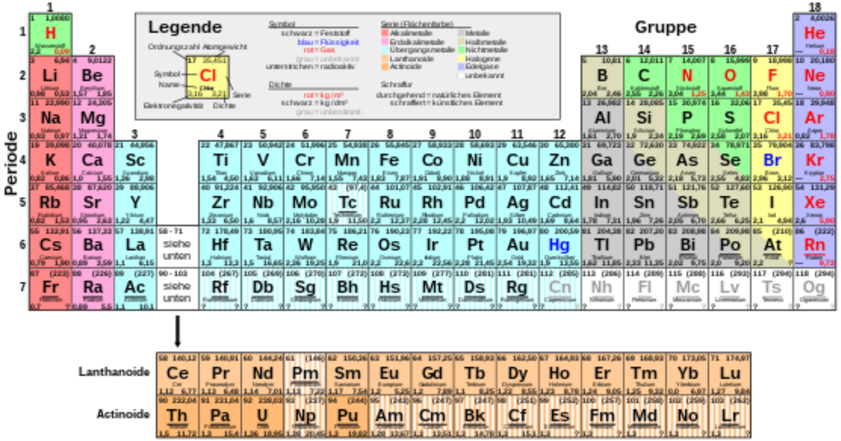
Neutrino mixing



- Flavour puzzle today *(adapted from Y. Nir):*
  - Why is there so much structure in the quark sector?
  - Why is there no structure in the neutrino sector?
  - Why are there no flavor-changing neutral currents?
- What is source of CP violation explaining lack of anti-matter?
- Flavour is also excellent probe of high-scale physics
  - New physics tends to break accidental symmetries of SM

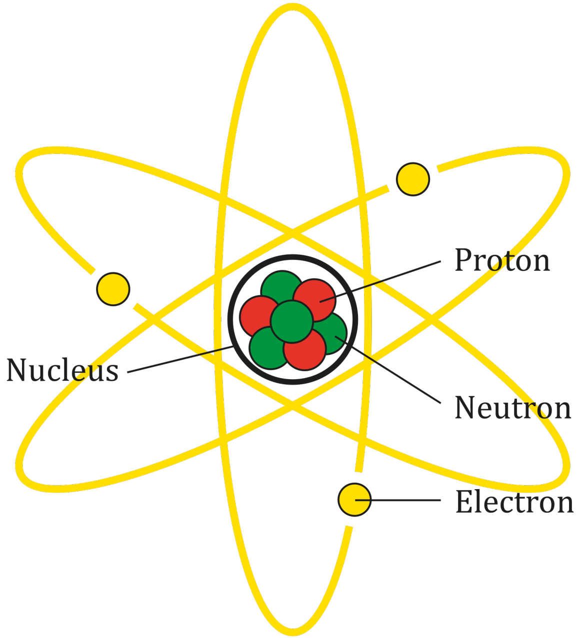
Why is there Flavour?

Is it like a periodic table?



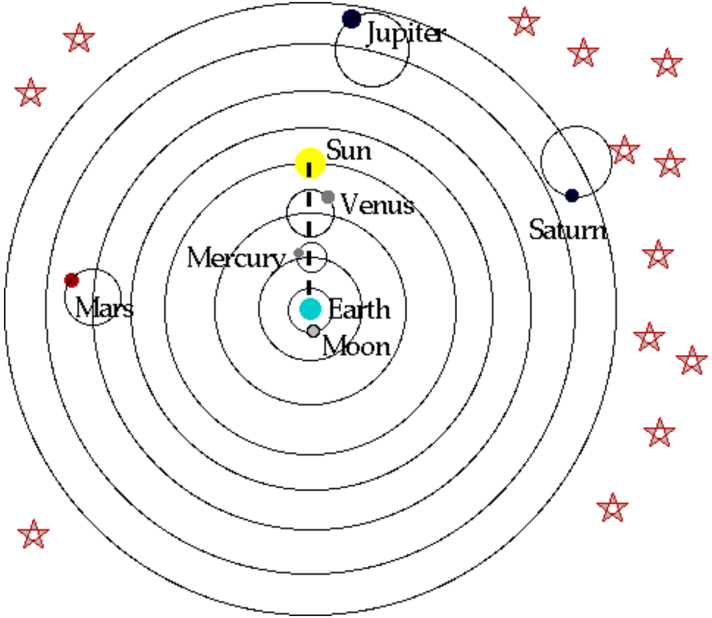
Periode	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H																		He
2	Li	Be												B	C	N	O	F	Ne
3	Na	Mg												Al	Si	P	S	Cl	Ar
4	K	Ca	Sc		Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y		Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La	58 - 71 siehe unten	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac	90 - 103 siehe unten	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

Lanthanoide	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinoide	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

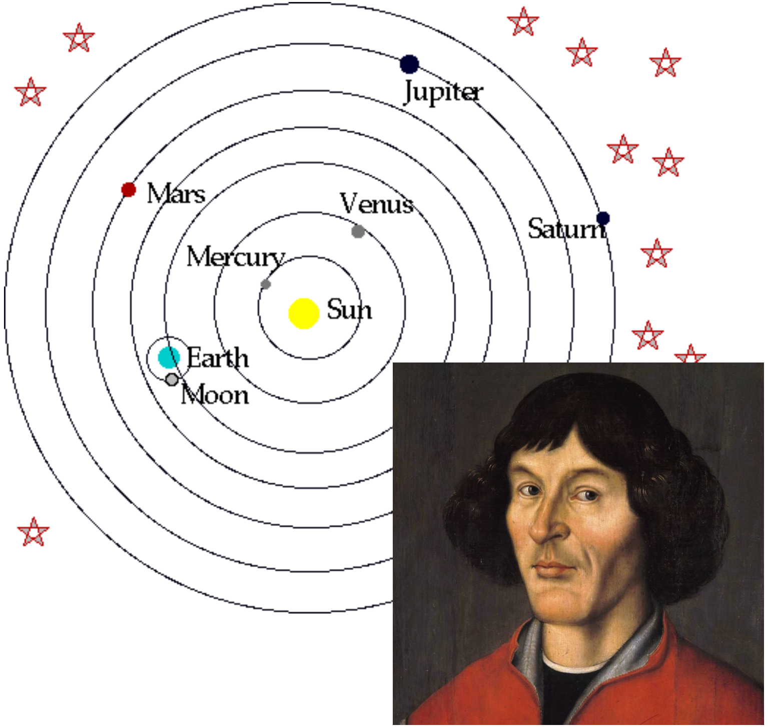


Why is there Flavour?

Do we have a completely wrong perspective?



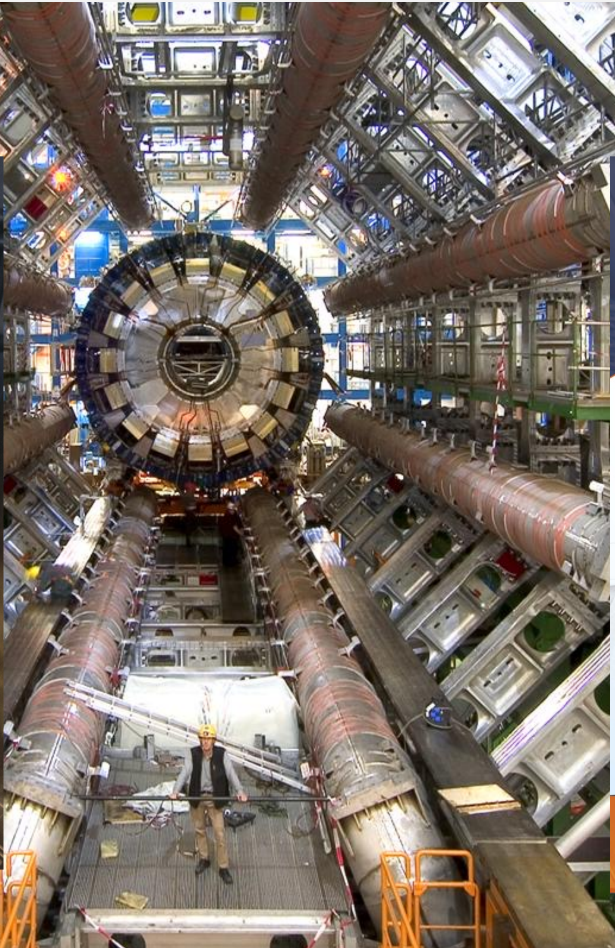
Epicycles

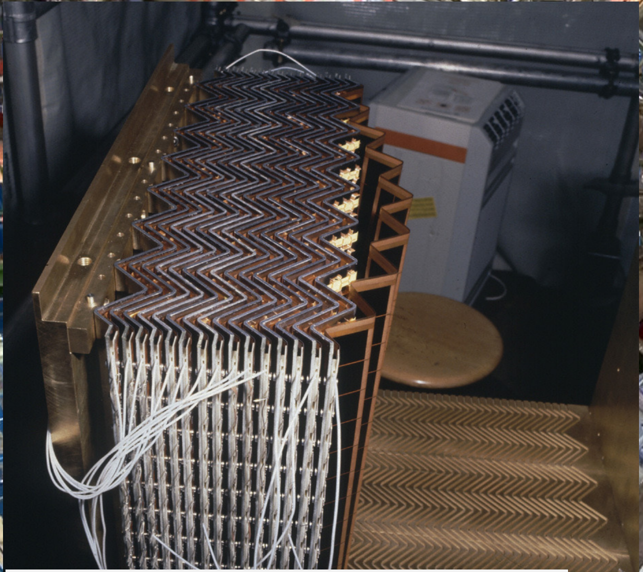


Circumference: 27 km

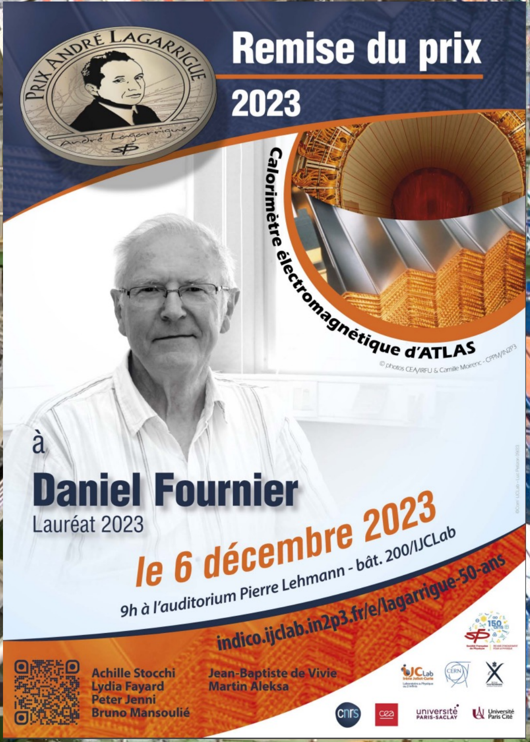
Energy = 13.6 TeV (Run 3)

The ATLAS detector





1st prototype of ATLAS LAr calorimeter barrel 1990



PRIX ANDRÉ LAGARRIGUE

Remise du prix 2023

Calorimètre électromagnétique d'ATLAS

© photos CEA/IRFU & Camille Moirenc - CPPM/IN2P3

à

Daniel Fournier

Lauréat 2023

le 6 décembre 2023

9h à l'auditorium Pierre Lehmann - bât. 200/IJCLab

indico.ijclab.in2p3.fr/e/lagarrigue-50-ans

Achille Stocchi
Lydia Fayard
Peter Jenni
Bruno Mansoulié

Jean-Baptiste de Vivie
Martin Aleksa

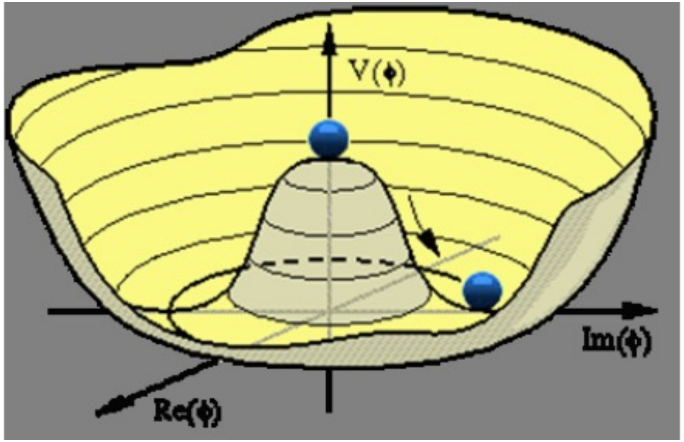
©Com IJCLab – Luc Petizon 09/23

The Higgs Mechanism

- 1964
  - P. Higgs, R. Brout, F. Englert
- New scalar self-interacting field with 4 d.o.f.:

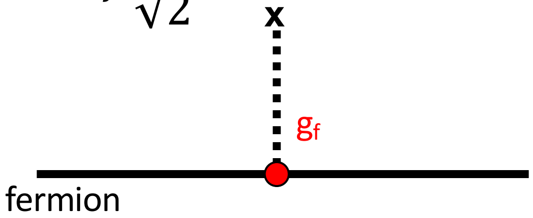
$$V(\Phi) = \frac{\lambda}{4}(\Phi^\dagger\Phi - \tfrac{1}{2}v^2)^2$$

- Ground state: non-zero-value breaks electroweak symmetry generating
  - 3 Goldstone bosons: $W^\pm_L$,Z_L
  - 1 neutral Higgs boson
- Masses of fermions m_f proportional to unknown Yukawa couplings g_f

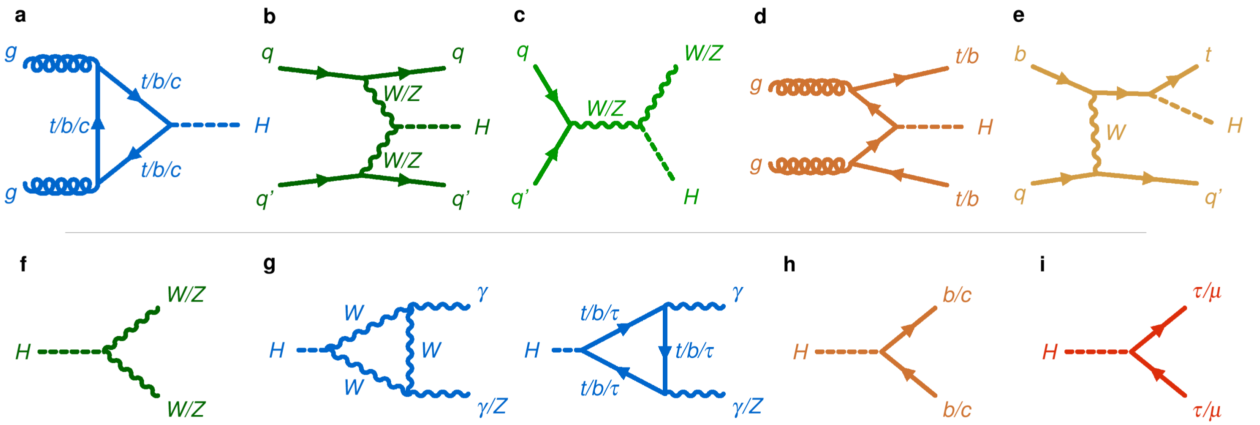


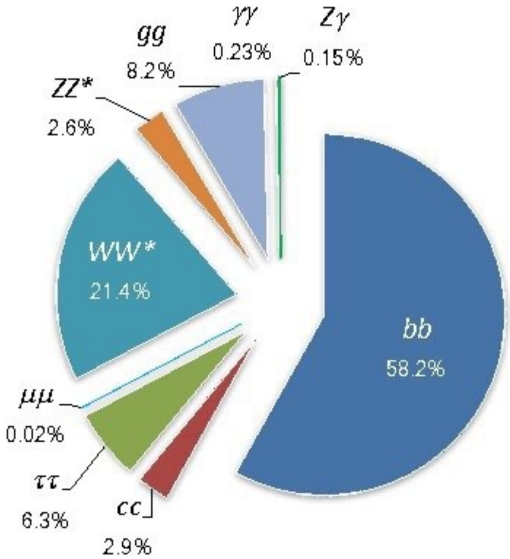
$\langle\Phi^0\rangle = v/\sqrt{2}$, where $v = 246$ GeV.

$$m_f = g_f\frac{v}{\sqrt{2}}$$



Higgs Boson production & decay

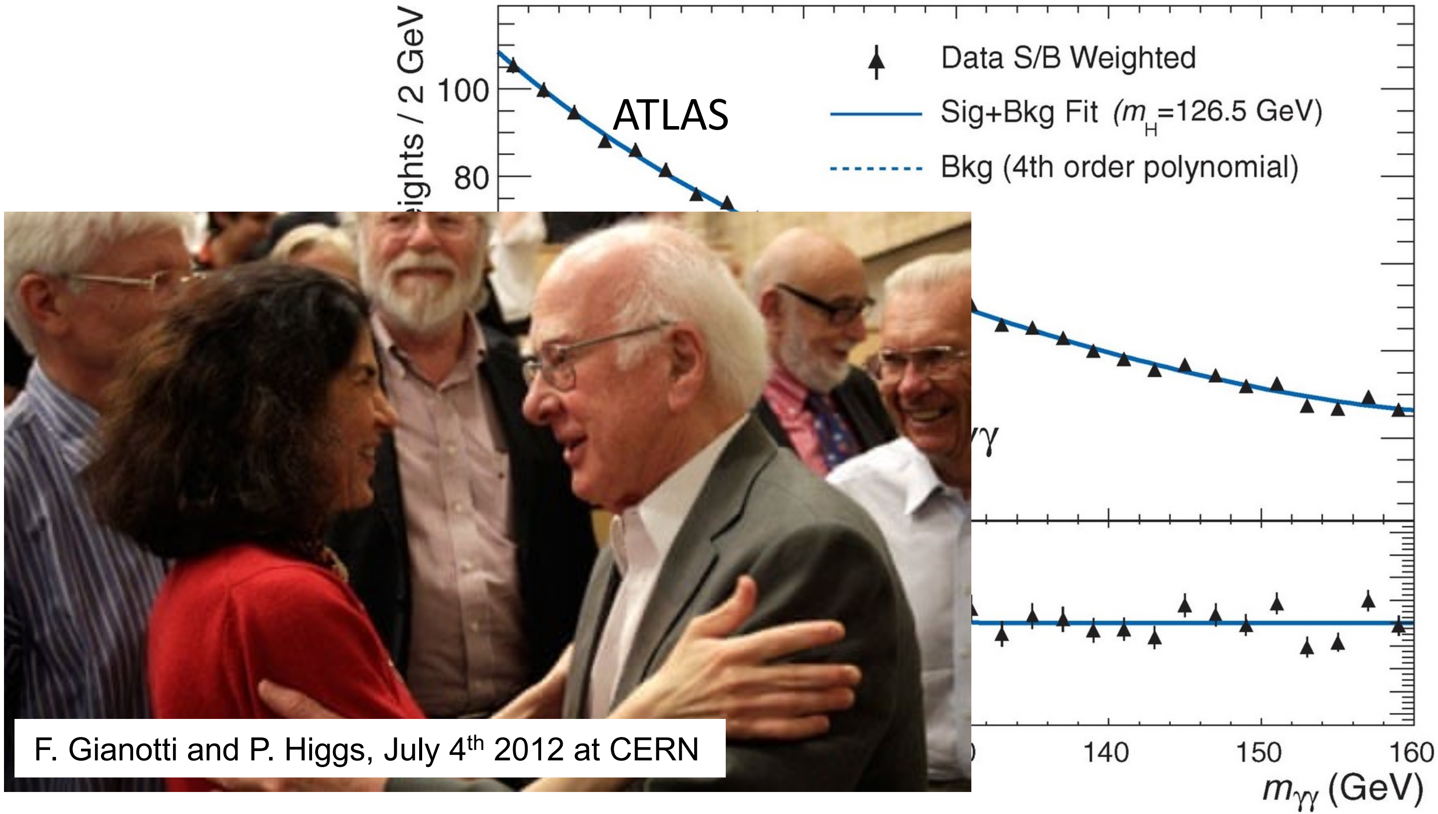




Higgs boson production and decay
complex and through many signatures

Higgs Boson production & decay

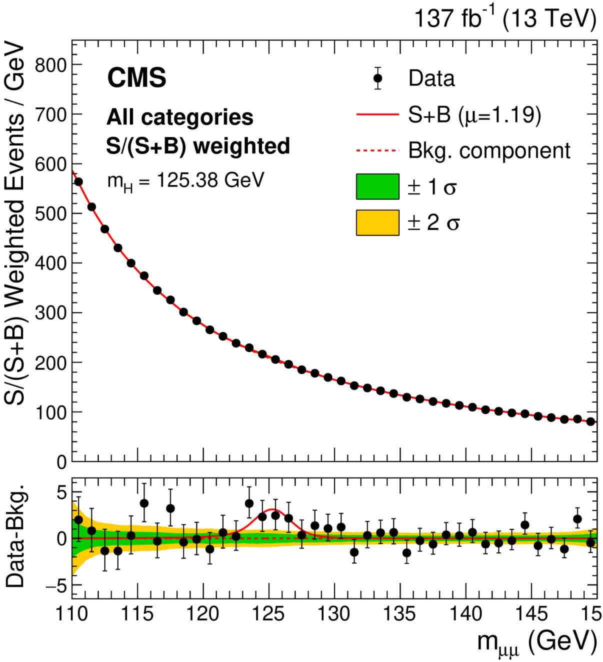
Initial observation: decays to $\gamma\gamma, ZZ, WW$

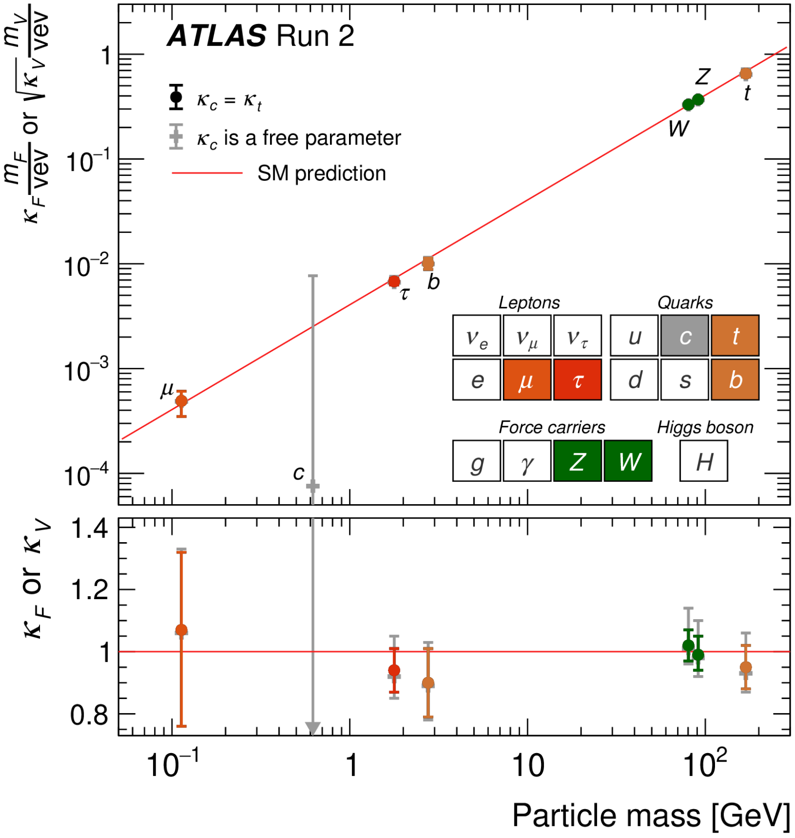


F. Gianotti and P. Higgs, July 4th 2012 at CERN

Higgs boson couplings

- Fermion coupling to top, b, tau and muon seen
- All agree with expectation





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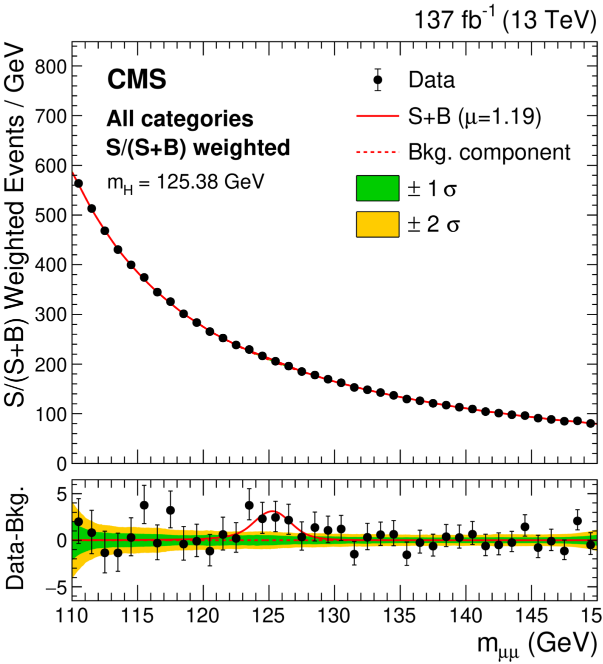
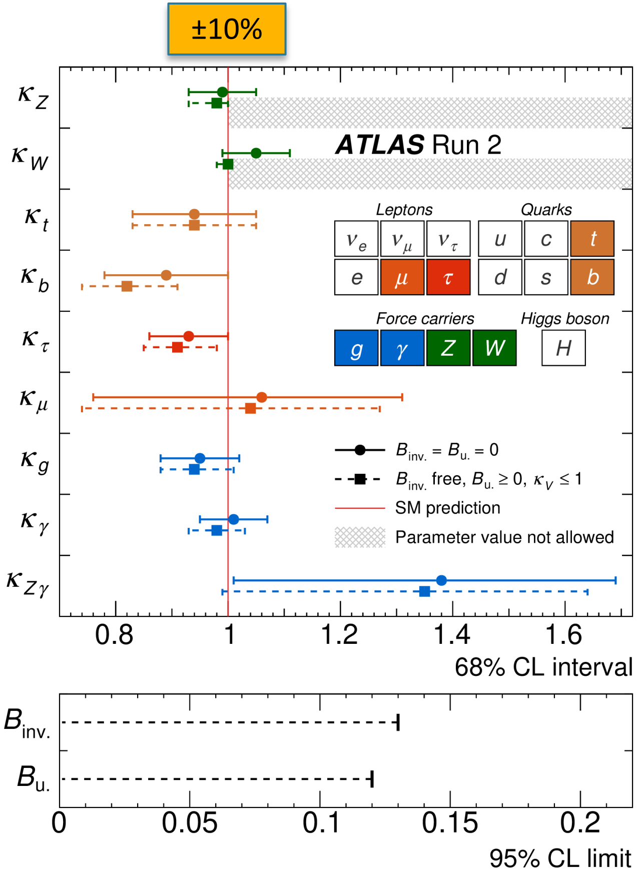
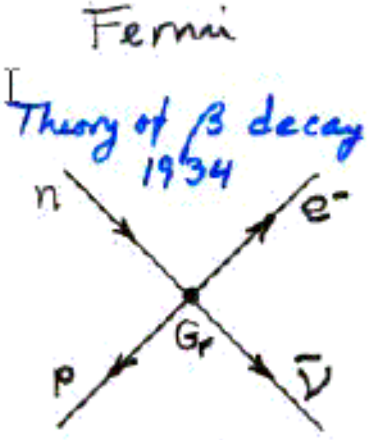




Why measure couplings with precision?

Reminder: beta-decay



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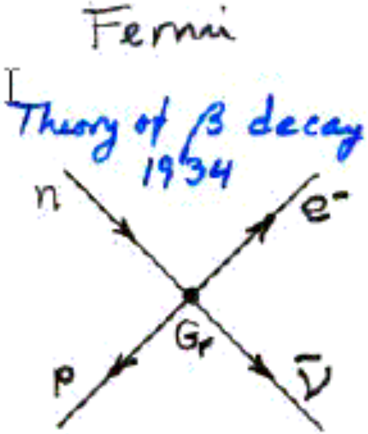
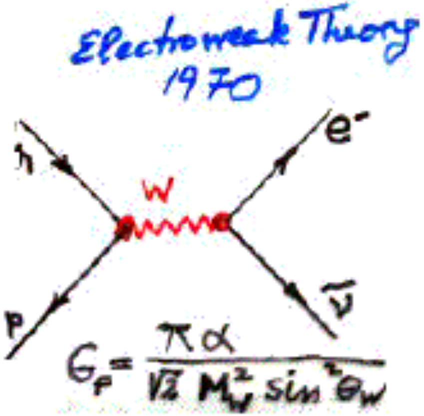
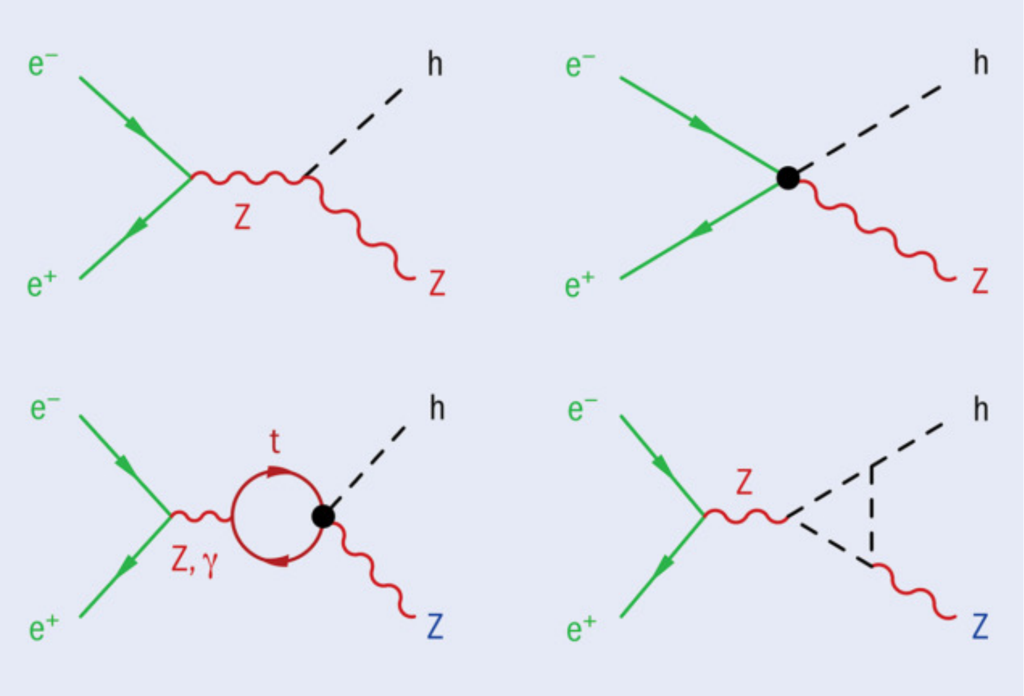




Precise measurement of process at low energy probes mass scales at high energies

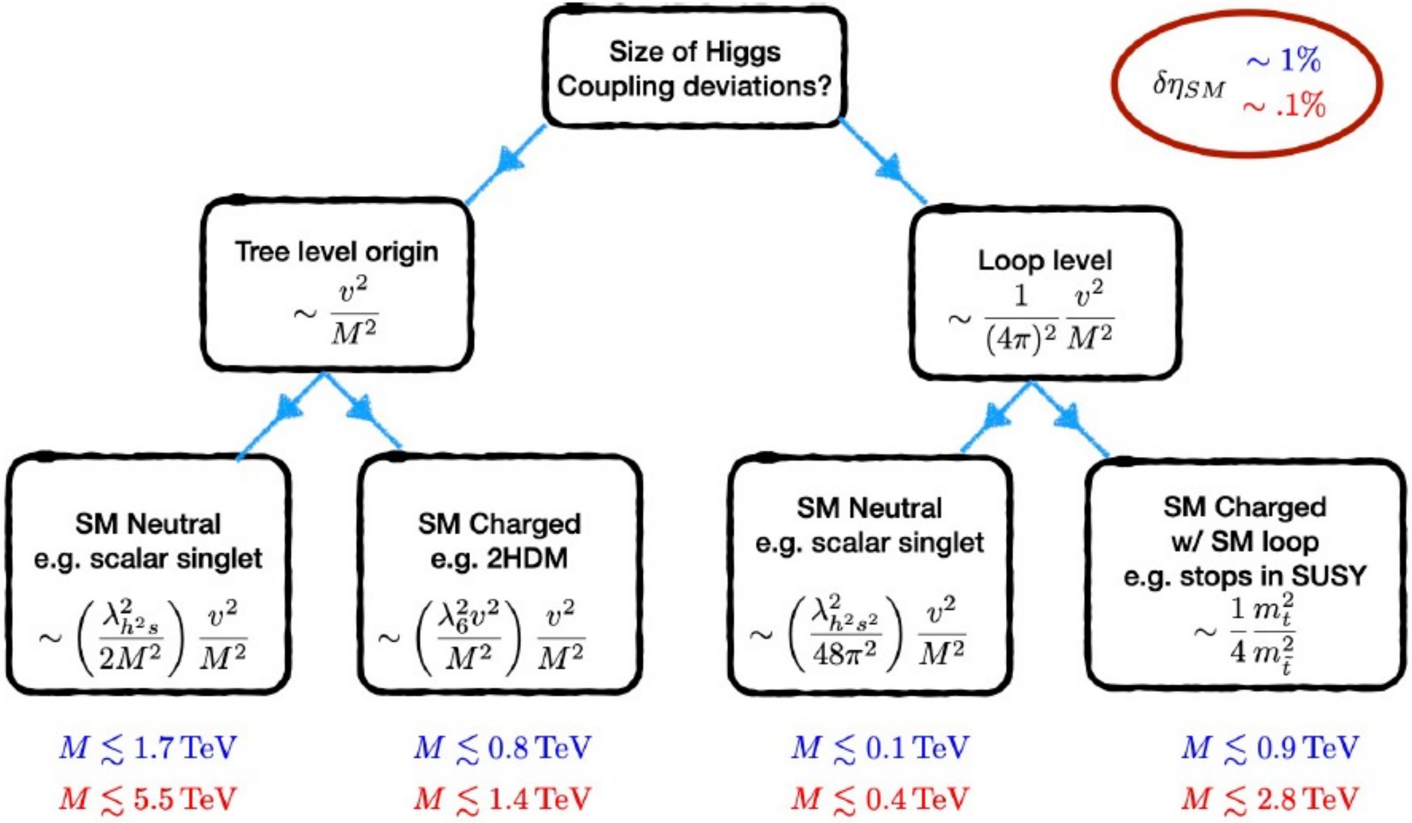
Why measure Higgs couplings with precision?



● Does not exist in SM

Can teach us about new interactions

Why measure Higgs couplings with precision?



Size of Higgs Coupling deviations?

$\delta\eta_{SM}$ $\sim 1\%$ $\sim .1\%$

Tree level origin $\sim \frac{v^2}{M^2}$

Loop level $\sim \frac{1}{(4\pi)^2}\frac{v^2}{M^2}$

SM Neutral e.g. scalar singlet $\sim \left(\frac{\lambda^2_{h^2 s}}{2M^2}\right)\frac{v^2}{M^2}$

SM Charged e.g. 2HDM $\sim \left(\frac{\lambda_6^2 v^2}{M^2}\right)\frac{v^2}{M^2}$

SM Neutral e.g. scalar singlet $\sim \left(\frac{\lambda^2_{h^2 s^2}}{48\pi^2}\right)\frac{v^2}{M^2}$

SM Charged w/ SM loop e.g. stops in SUSY $\sim \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}}^2}$

$M \lesssim 1.7\,\mathrm{TeV}$ $M \lesssim 5.5\,\mathrm{TeV}$

$M \lesssim 0.8\,\mathrm{TeV}$ $M \lesssim 1.4\,\mathrm{TeV}$

$M \lesssim 0.1\,\mathrm{TeV}$ $M \lesssim 0.4\,\mathrm{TeV}$

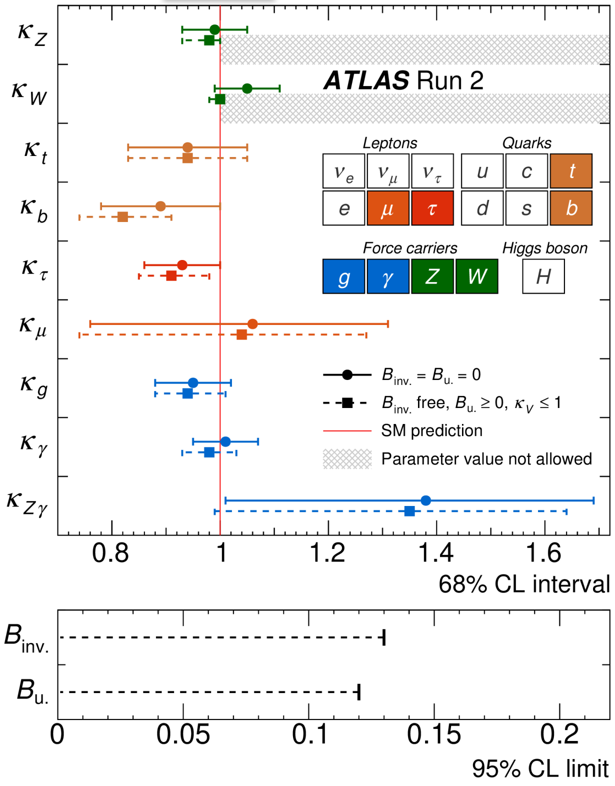
$M \lesssim 0.9\,\mathrm{TeV}$ $M \lesssim 2.8\,\mathrm{TeV}$

Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

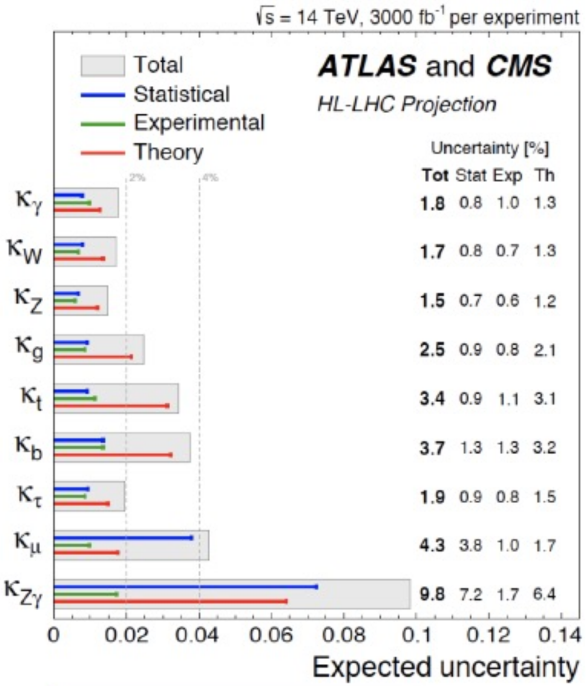
33

Future Higgs Prospects

±10%



High Luminosity LHC (HL-LHC)

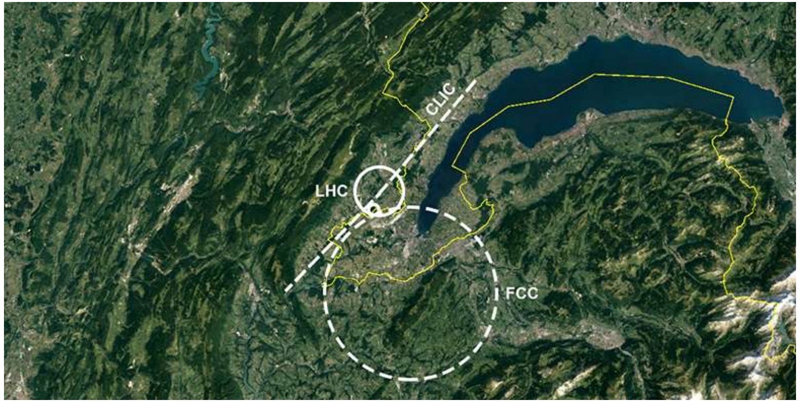


Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

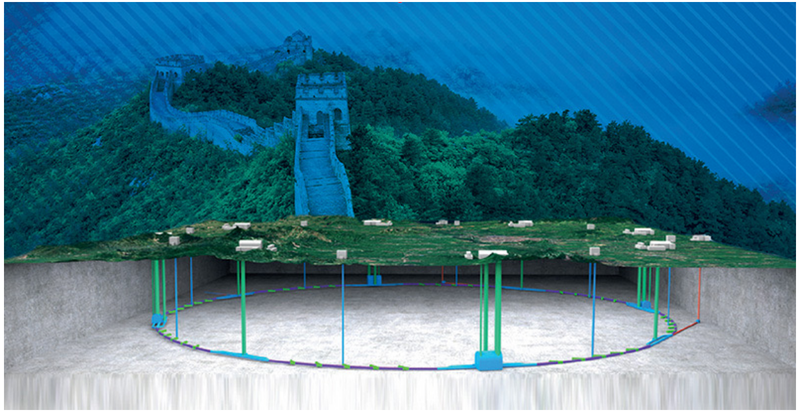
10%

Future Colliders



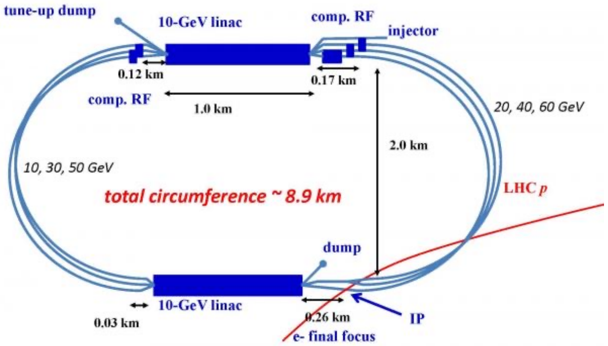
Proposed colliders:

- Linear e+e-: ILC, CLIC
- Circular e+e-: FCC-ee, CePC
- pp: HE-LHC, FCC-hh, SppC
- ep: LHeC, FCC-eh

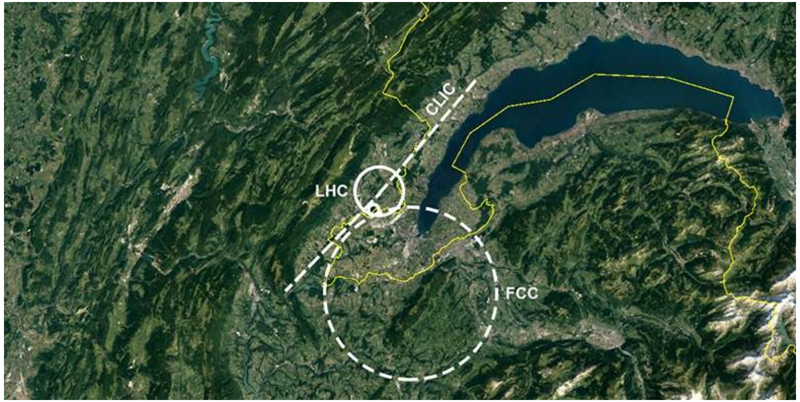


Planned location and artist's rendering of ILC

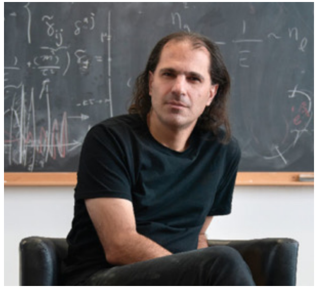
Artist's rendering provided by the Linear Collider Collaboration

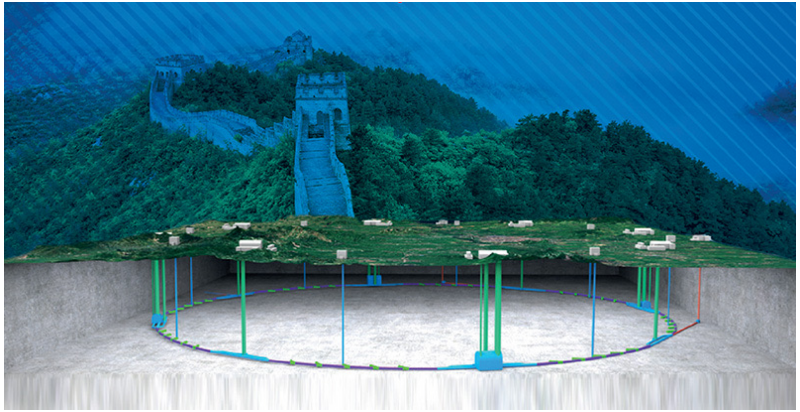


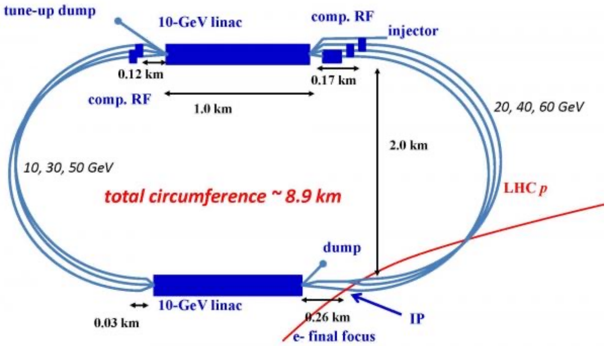
Future Colliders



“Higgs is the most important actor … the reason for building the next colliders is to study the Higgs boson to death, full stop”
(Nima Arkani-Hamed)

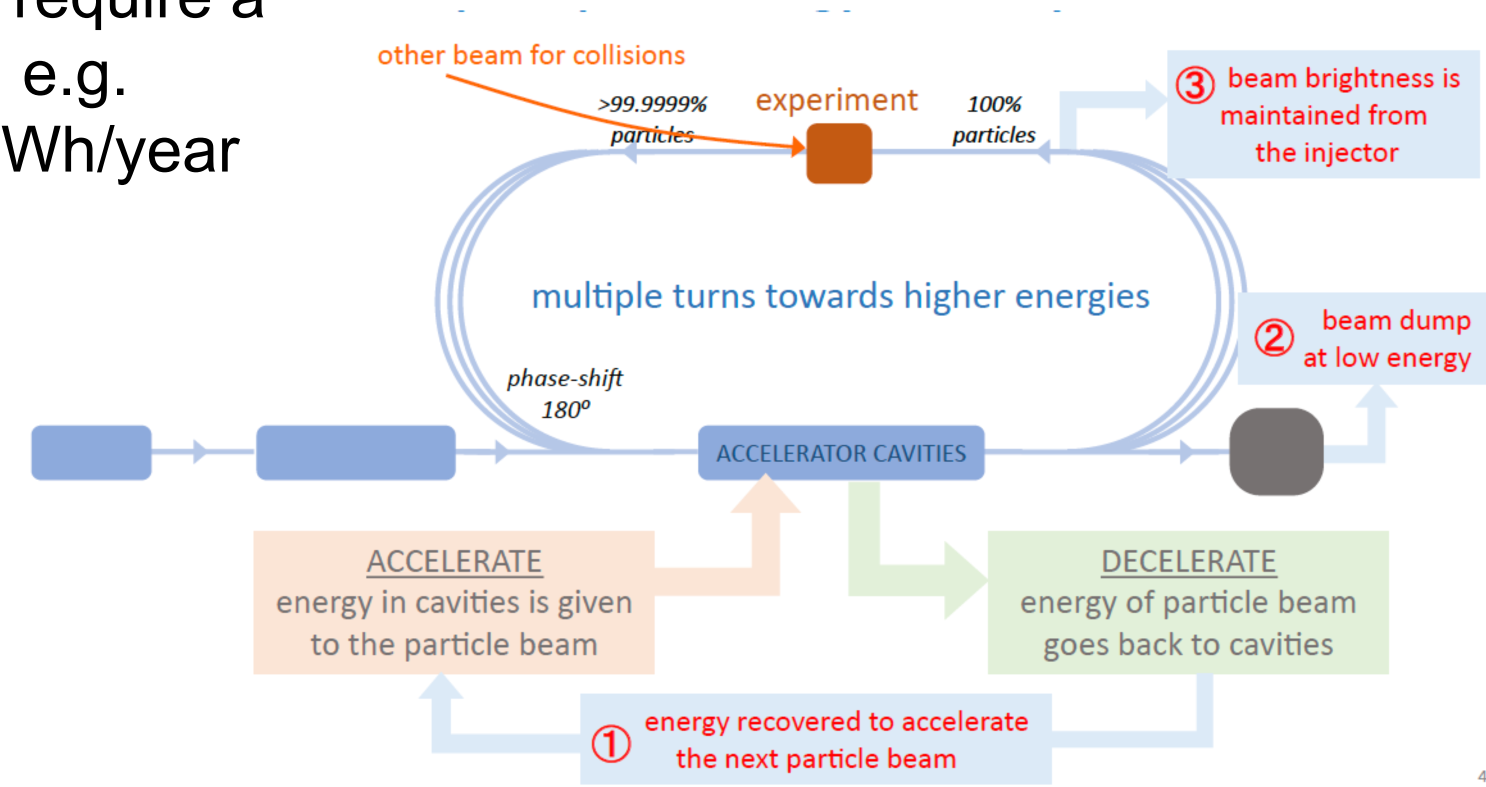






Energy Consumption / Recovery

Accelerators require a lot of energy, e.g. CERN: 1.3 TWh/year



other beam for collisions

>99.9999% particles

experiment

100% particles

③ beam brightness is maintained from the injector

multiple turns towards higher energies

② beam dump at low energy

phase-shift 180º

ACCELERATOR CAVITIES

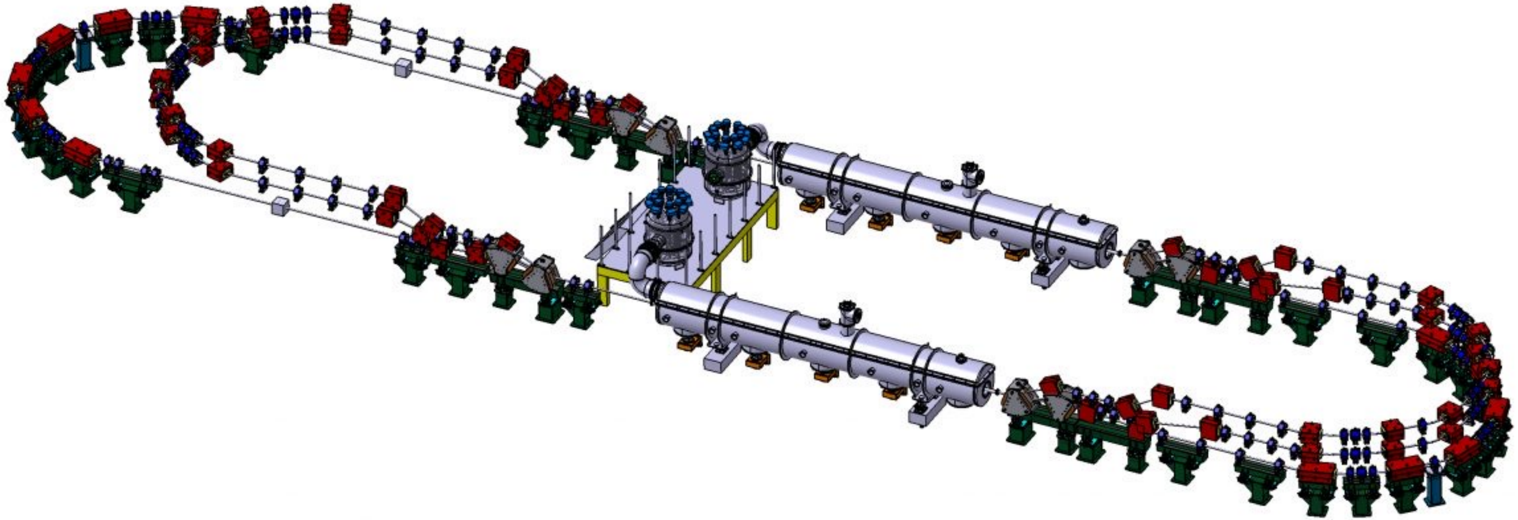
ACCELERATE
energy in cavities is given to the particle beam

DECELERATE
energy of particle beam goes back to cavities

① energy recovered to accelerate the next particle beam

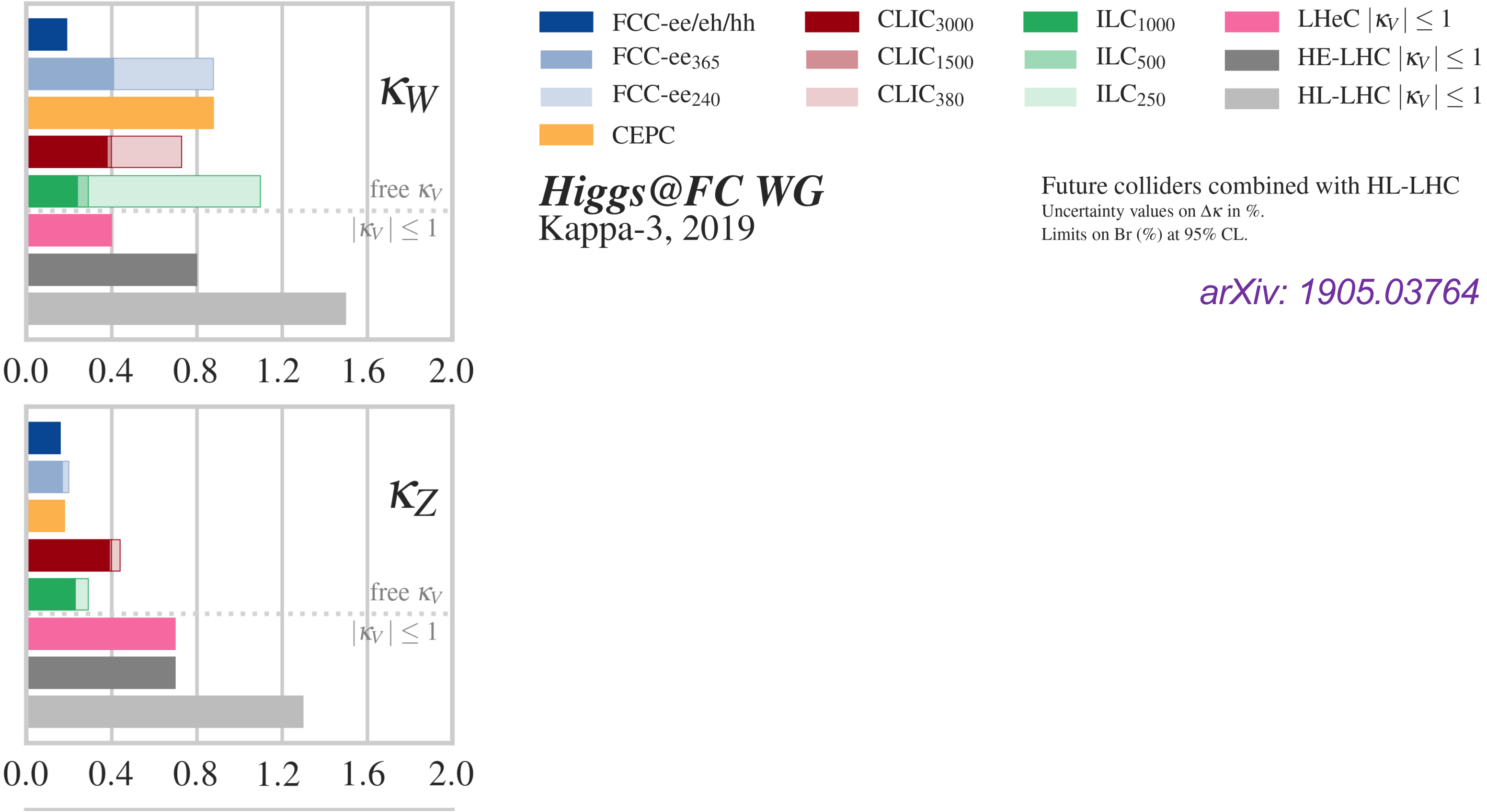
PERLE at IJClab

Proto-type for LHeC with 250 MeV electrons and interesting use for nuclear physics



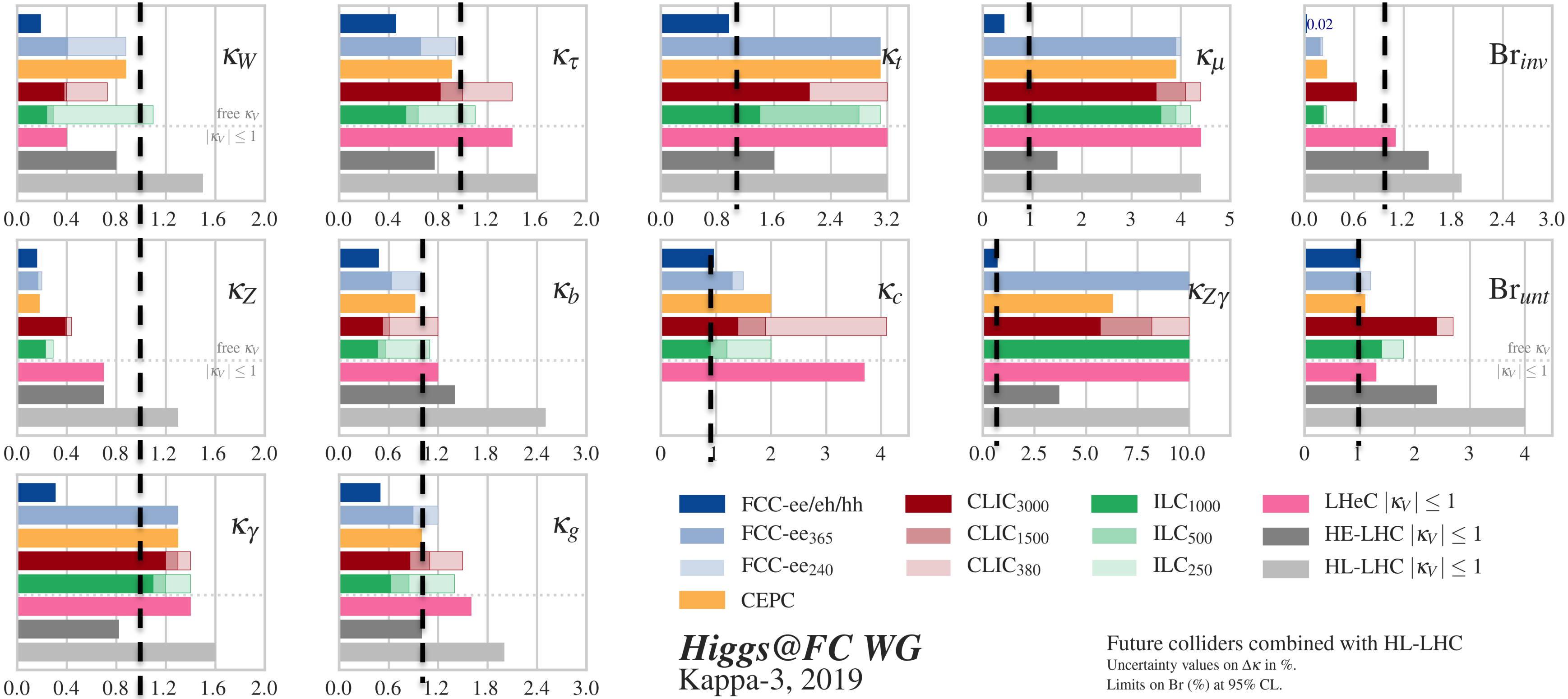
Conceptional Design Report: https://arxiv.org/pdf/1705.08783.pdf

Higgs: Coupling Constraints: Future Colliders



arXiv: 1905.03764

Higgs: Coupling Constraints: Future Colliders

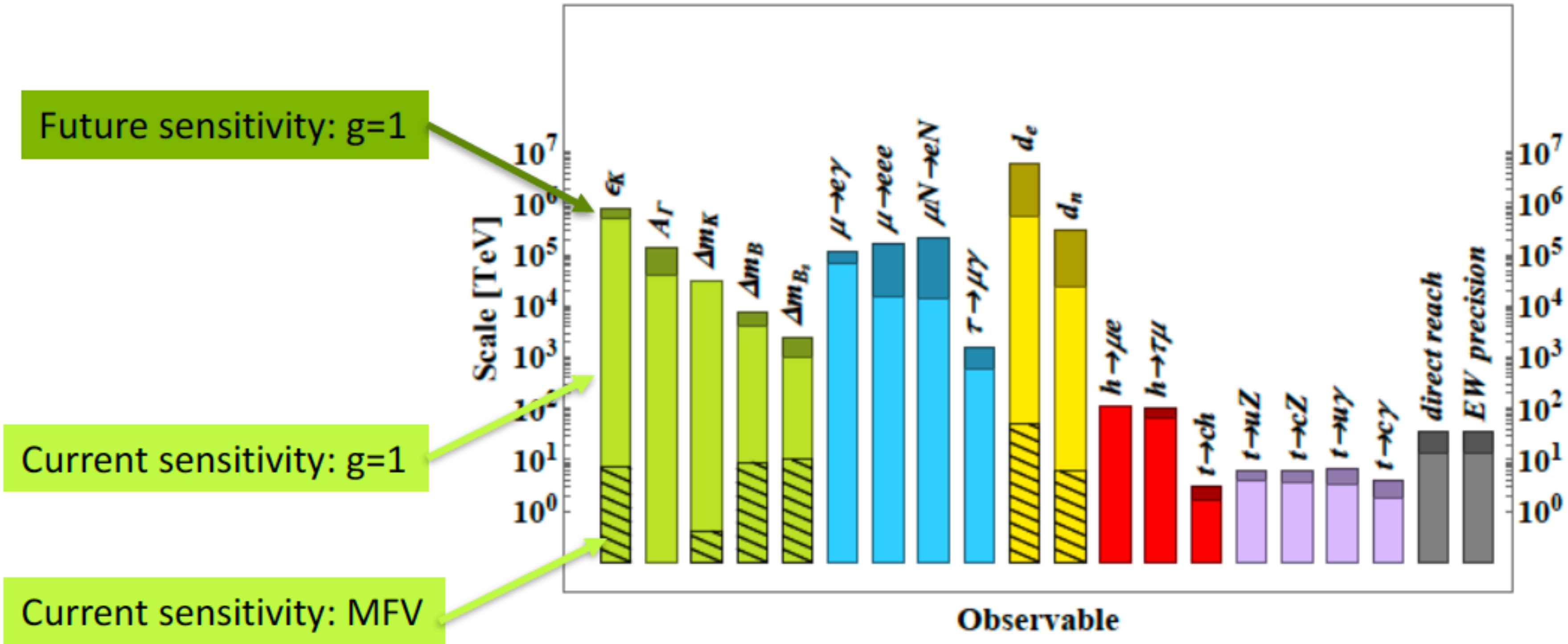


Higgs@FC WG
Kappa-3, 2019

Future colliders combined with HL-LHC
Uncertainty values on $\Delta\kappa$ in %.
Limits on Br (%) at 95% CL.

arXiv: 1905.03764

Many different probes of flavour

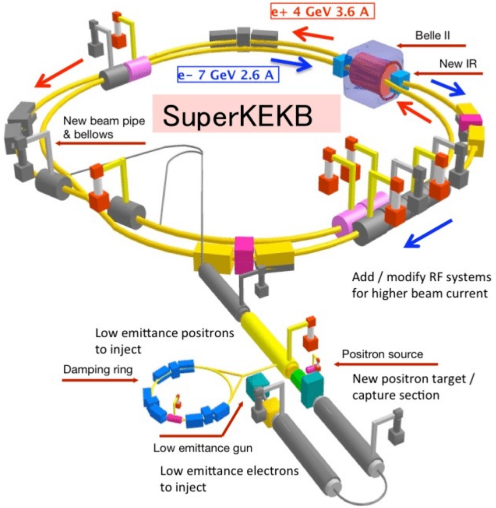

Future sensitivity: g=1

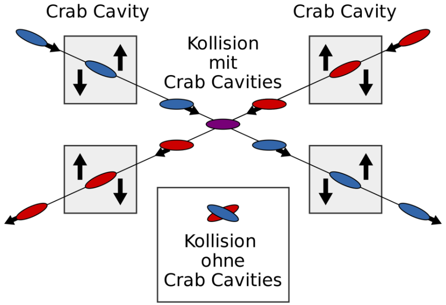
Current sensitivity: g=1

Current sensitivity: MFV

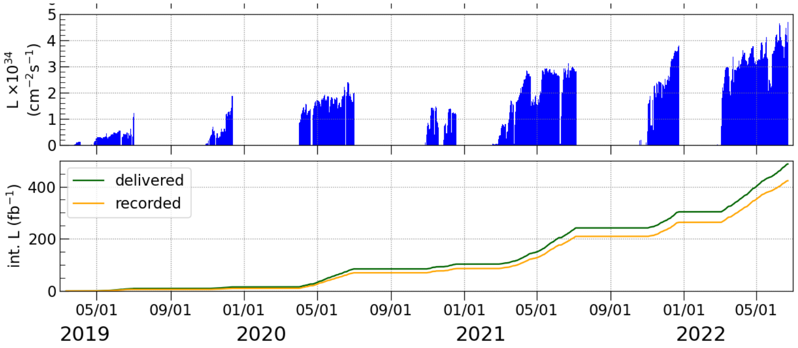
Rare processes at B- and Kaon and Muon factories can probe higher scales than the LHC direct searches!

Belle II and LHCb

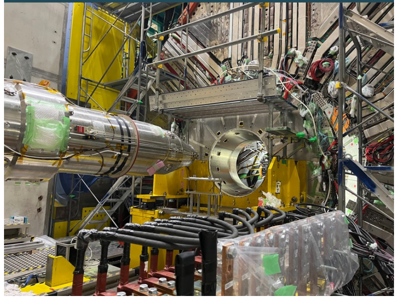




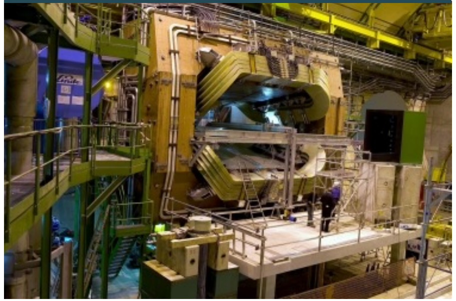
$$L_{peak} = 4.65 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$$



Belle II at SuperKEKB/KEK



LHCb at LHC/CERN

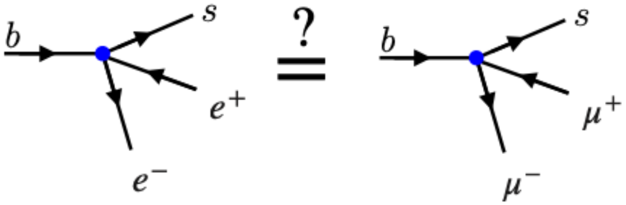


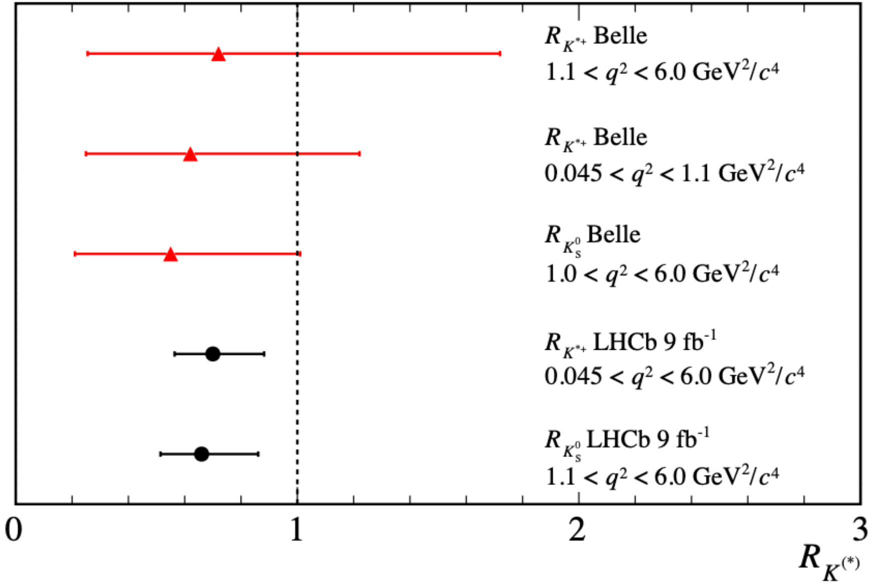
Anomalies in Flavour Physics

Lepton universality

Status 2019

- Flavour physics can probe physics at much higher energy
- Test universality of such interactions

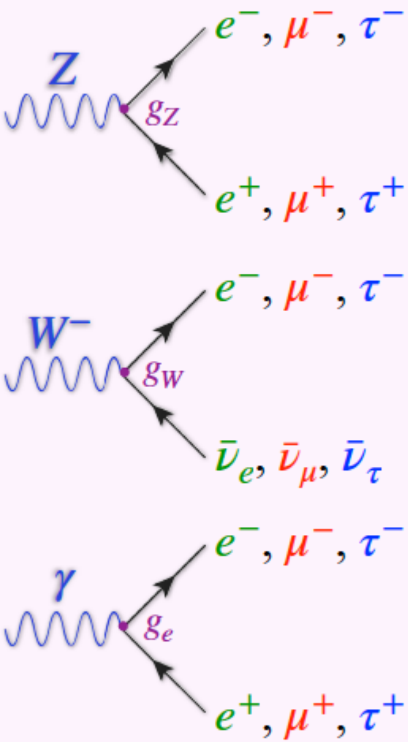




$$R^{-1}_{K^{(*)}} = \frac{\mathcal{B}(B\to K^{(*)}e^+e^-)}{\mathcal{B}(B\to J/\psi\,(e^+e^-)\,K^{(*)})} \Big/ \frac{\mathcal{B}(B\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B\to J/\psi\,(\mu^+\mu^-)\,K^{(*)})}$$

Lepton Flavour Universality Tests: 2022

SM: same electroweak couplings to all lepton gen.



LFU tests

To **0.28%** in Z decays

$$\frac{\Gamma_{Z\to\mu\mu}}{\Gamma_{Z\to ee}} = 1.0009 \pm 0.0028$$

LEP, Phys. Rept. 427 (2006) 257

$$\frac{\Gamma_{Z\to\tau\tau}}{\Gamma_{Z\to ee}} = 1.0019 \pm 0.0032$$

LEP, Phys. Rept. 427 (2006) 257

To **0.8%** in W decays

$$\frac{\mathcal{B}(W \to e\nu)}{\mathcal{B}(W \to \mu\nu)} = 1.004 \pm 0.008$$

CDF + LHC, JPG: NPP, 46, 2 (2019)

$$\frac{\Gamma_{W\to\tau\nu}}{\Gamma_{W\to\mu\nu}} = 1.070 \pm 0.026$$

LEP, Phys. Rept. 532, 119 (2013)

2.6σ tension

$$\frac{\Gamma_{J/\psi\to\mu\mu}}{\Gamma_{J/\psi\to ee}} = 1.0016 \pm 0.0031$$

PDG (BESIII), RPP, Chin. Phys. C40 (2016) 100001

$$\frac{\Gamma_{D_s\to\tau\nu}}{\Gamma_{D_s\to\mu\nu}} = 9.95 \pm 0.61$$

HFLAV, Eur. Phys. J. C77 (2017) 895

To **0.2%** in meson decays

$$\frac{\Gamma_{\pi\to e\nu}}{\Gamma_{\pi\to\mu\nu}} = (1.234 \pm 0.003) \times 10^{-4}$$

PiENu, Phys. Rev. Lett. 115, 071801 (2015)

3.1σ tension

$$\frac{\Gamma^{1.1-6}_{B\to K^+\mu\mu}}{\Gamma^{1.1-6}_{B\to K^+ee}} = R_K = 0.846^{+0.043}_{-0.040}$$

LHCb, Nature Phys. 18, 3 (2022)

$$\mathcal{R}(D) = 0.357 \pm 0.029$$

HFLAV, Summer 2023

$$\mathcal{R}(D^*) = 0.284 \pm 0.012$$

3.3σ tension

To **0.14%** in $\tau \to \ell\nu\nu$

$$g_\mu/g_e = 1.0018 \pm 0.0014$$

PDG, A. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

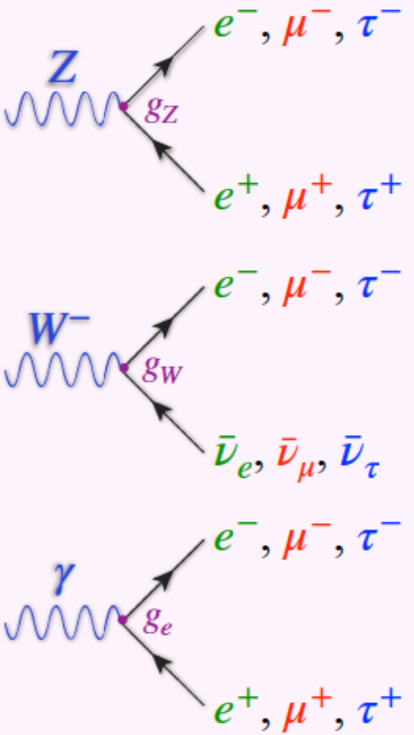
$$g_\tau/g_\mu = 1.0030 \pm 0.0015$$

PDG, S. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

M. F. Sevilla, EPS ‘23

Lepton Flavour Universality Tests: 2023

SM: same electroweak couplings to all lepton gen.



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LEP, Phys. Rept. 427 (2006) 257

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CDF + LHC, JPG: NPP, 46, 2 (2019)

$$\frac{\Gamma_{W\to\tau\nu}}{\Gamma_{W\to\mu\nu}} = 0.992 \pm 0.013$$

ATLAS, Nature 17, 813 (2021)

To **0.2%** in meson decays

$$\frac{\Gamma_{J/\psi\to\mu\mu}}{\Gamma_{J/\psi\to ee}} = 1.0016 \pm 0.0031$$

PDG (BESIII), RPP, Chin. Phys. C40 (2016) 100001

$$\frac{\Gamma_{D_s\to\tau\nu}}{\Gamma_{D_s\to\mu\nu}} = 9.95 \pm 0.61$$

HFLAV, Eur. Phys. J. C77 (2017) 895

$$\frac{\Gamma_{\pi\to e\nu}}{\Gamma_{\pi\to\mu\nu}} = (1.234 \pm 0.003) \times 10^{-4}$$

PiENu, Phys. Rev. Lett. 115, 071801 (2015)

$$\frac{\Gamma^{1.1-6}_{B\to K^+\mu\mu}}{\Gamma^{1.1-6}_{B\to K^+ee}} = R_K = 0.95 \pm 0.05$$

LHCb, PRL 131, 051803 (2023)

$$\mathcal{R}(D) = 0.357 \pm 0.029$$

HFLAV, Summer 2023

$$\mathcal{R}(D^*) = 0.284 \pm 0.012$$

3.3σ tension

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PDG, A. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

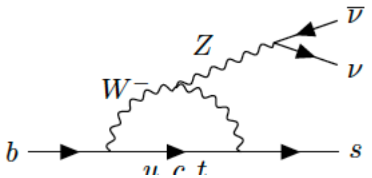
$$g_\tau/g_\mu = 1.0030 \pm 0.0015$$

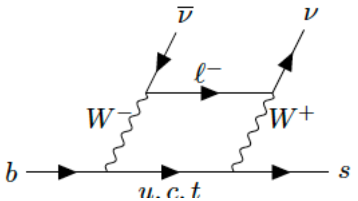
PDG, S. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

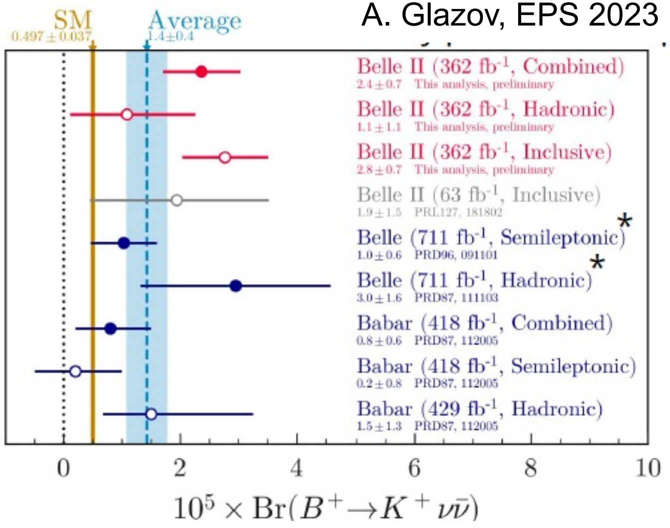
M. F. Sevilla, EPS '23

New from Belle II: $B^{\pm} \to K^{\pm}\nu\bar{\nu}$

The decay $B^+ \to K^+\nu\bar{\nu}$







A. Glazov, EPS 2023

Complimentary probe of BSM scenarios

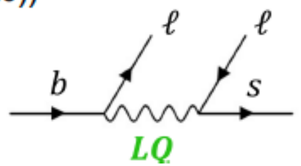
Many BSM models can be constrained like:

Dark Matter (PRD 98 055003 (2018)),

Leptoquarks (PRD 102, 015023 (2020)),

Axions (PRD 101, 095006 (2020))

Z’ (JHEP 1411 (2014) 121)



e.g. Leptoquark

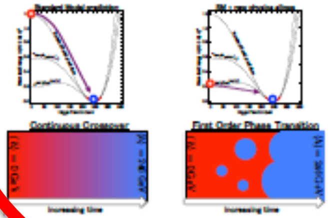
New result:

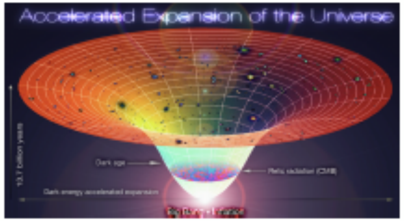
- 3.6σ evidence
- 2.8σ higher than prediction

Big Questions and the Higgs Boson

Weak interaction vs
gravitation
10^2 vs 10^{18}

Matter > anti-matter
Electroweak phase

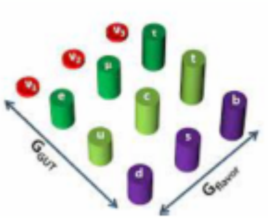




Inflation, age of
universe, ...

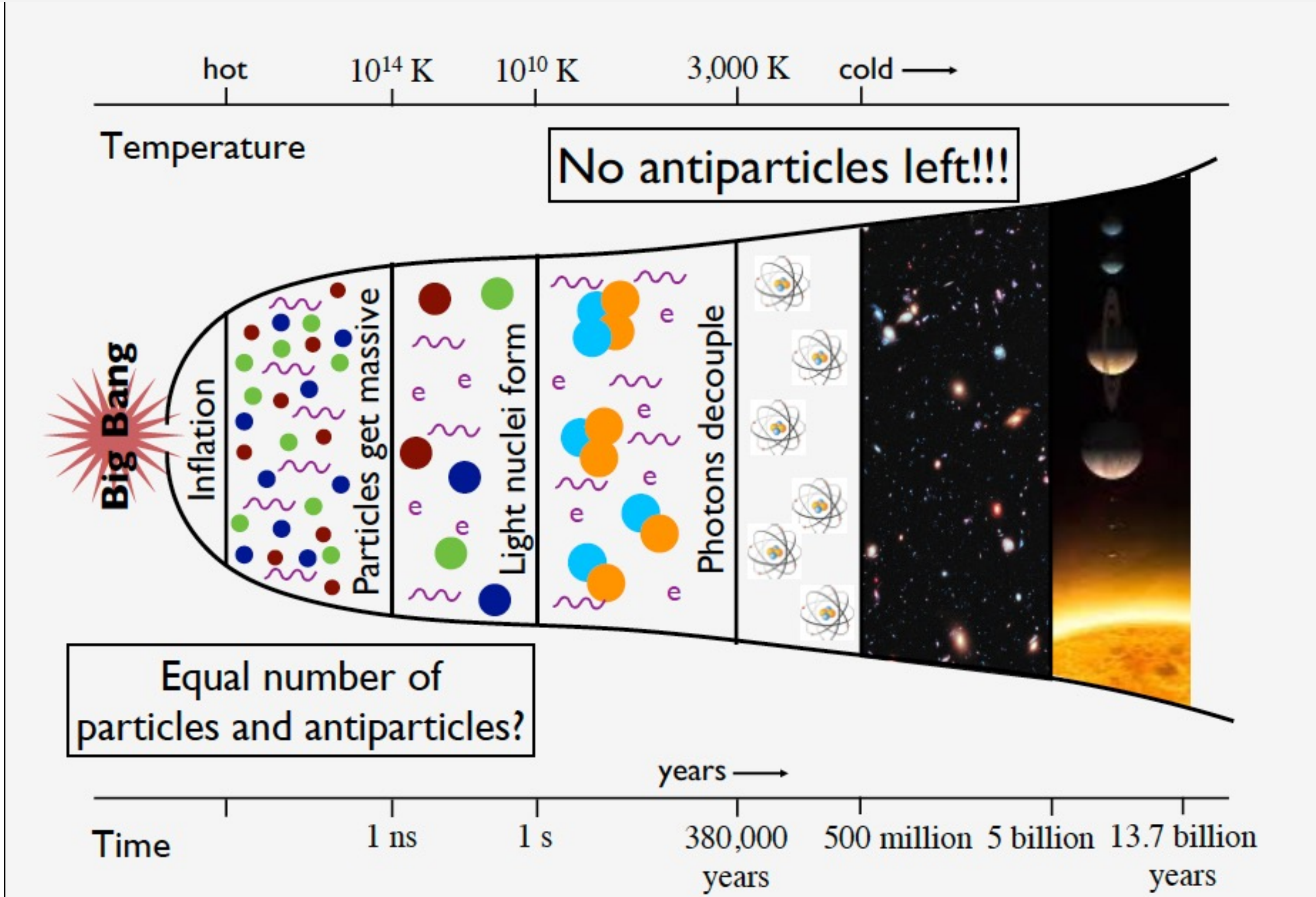
Higgs

The dark world

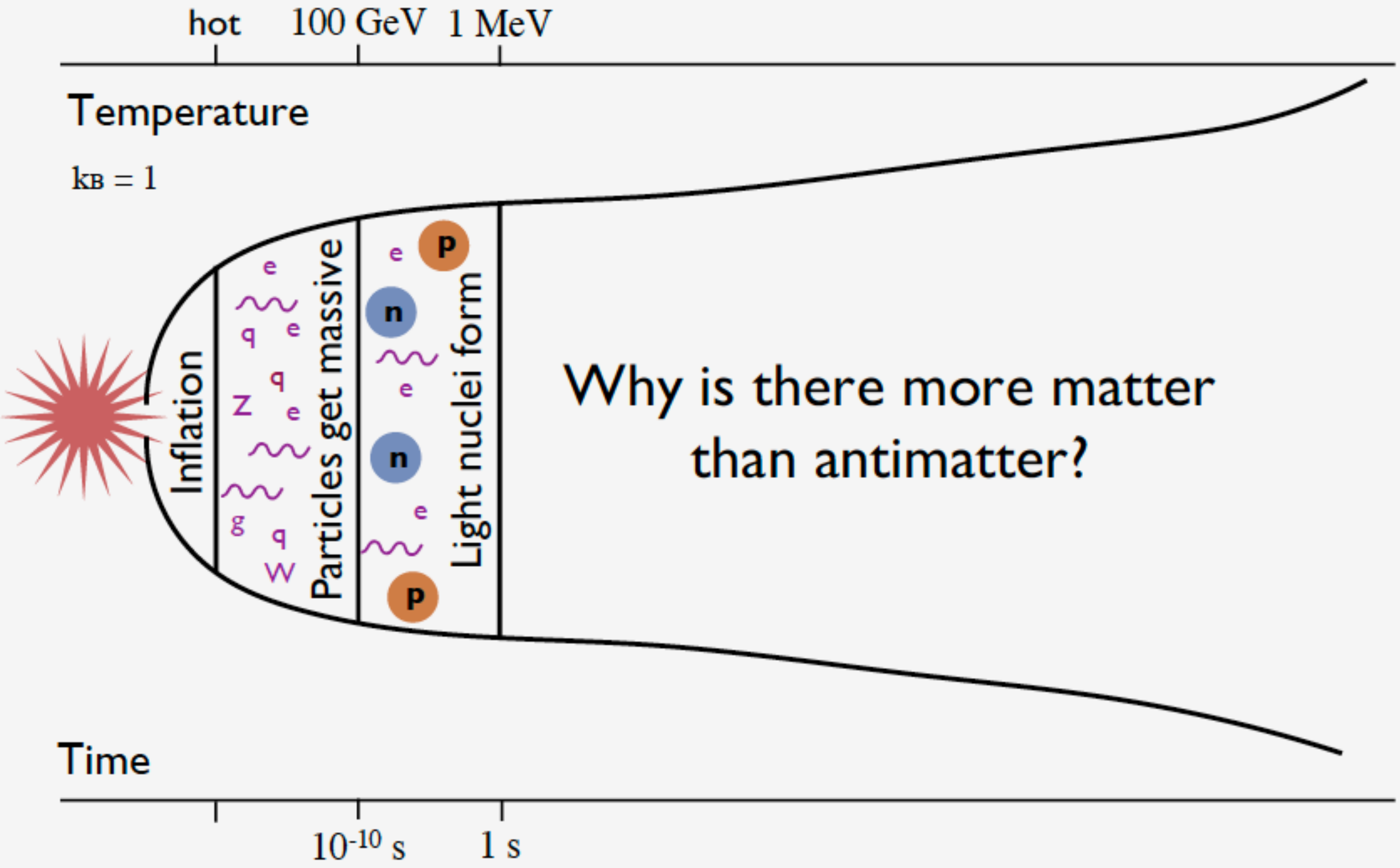


Flavor puzzle

A brief history of the Universe



A brief history of the (very early!) Universe



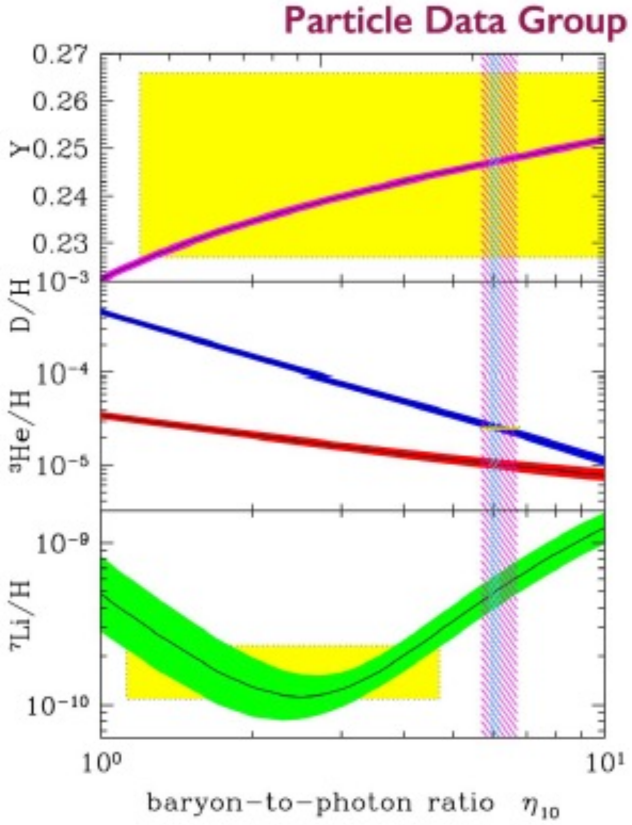
Why is there more matter than antimatter?

How much matter and anti-matter?

Today: per litre in Universe:

- 550000 photons
- 0.001 baryons
- 0 antibaryons

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$



baryons = protons, neutrons,…

Matter-Antimatter Asymmetry

During very early Universe

10.000.000.001

Matter

10.000.000.000

Antimatter

?

Materie-Antimaterie Asymmetry

Now

1

●

Matter

0

Antimatter

The three conditions of Andrei Sakharov

Three conditions have to be fulfilled simultaneously:

1. No thermal equilibrium
2. Violation of C and CP
3. Baryon number not conserved

A. Sakharov, 1921-1989

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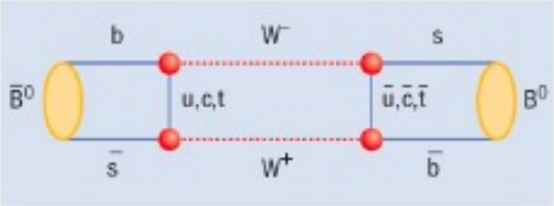
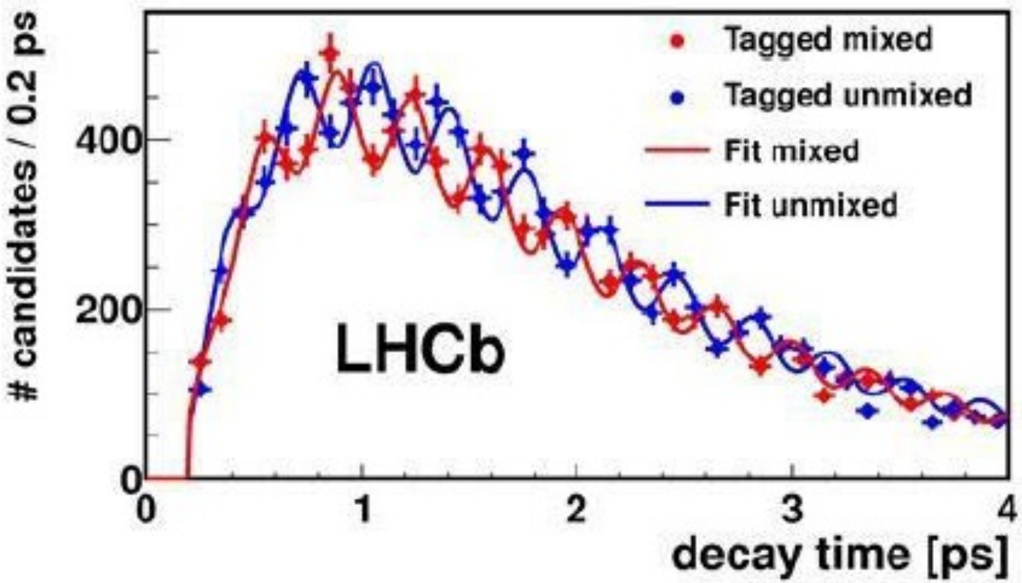
Matter antimatter oscillations: CP violation

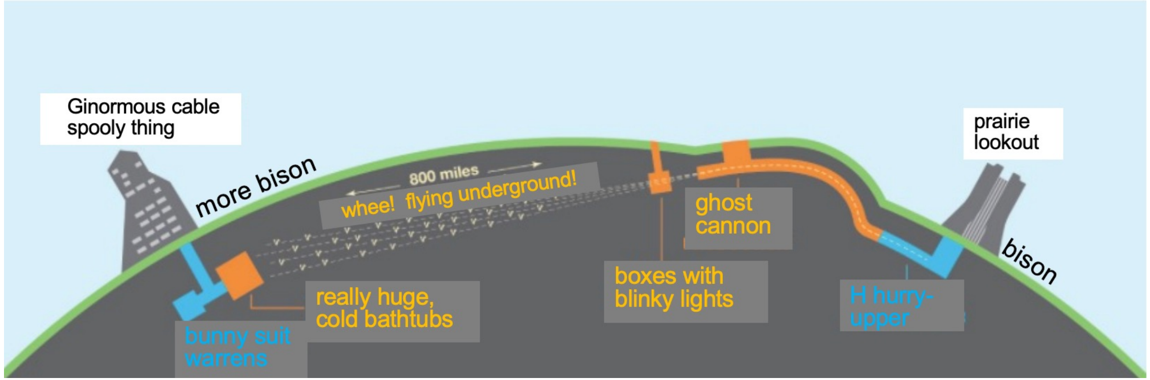




Matter-antimatter oscillations occur in the quark sector:

- E.g. 4 billion times per second for B_s meson
- Rate not sufficient to explain asymmetry in Universe

Is there CP violation in the neutrino sector?



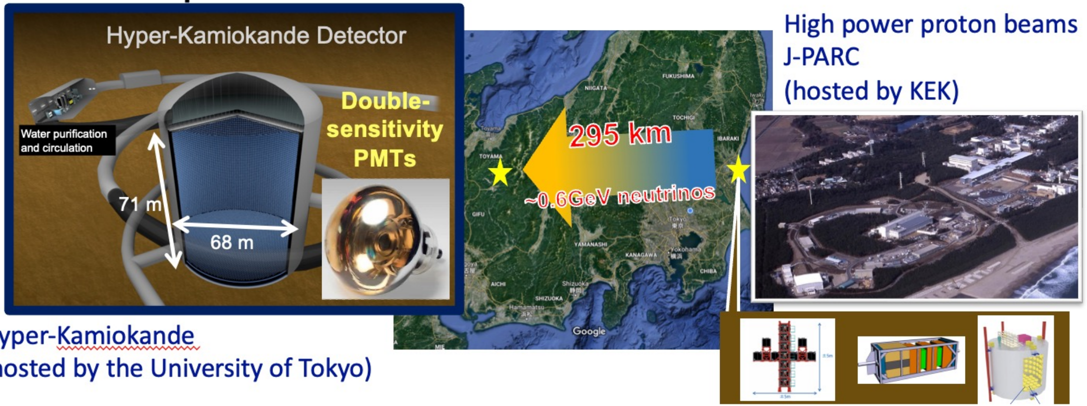
LBNF/DUNE (2029+)

- Phase 1: 1.2 MW beam
- Phase 2: 2 MW beam

J-PARC/Hyperkamiokande (2027+)

1.3 MW beam

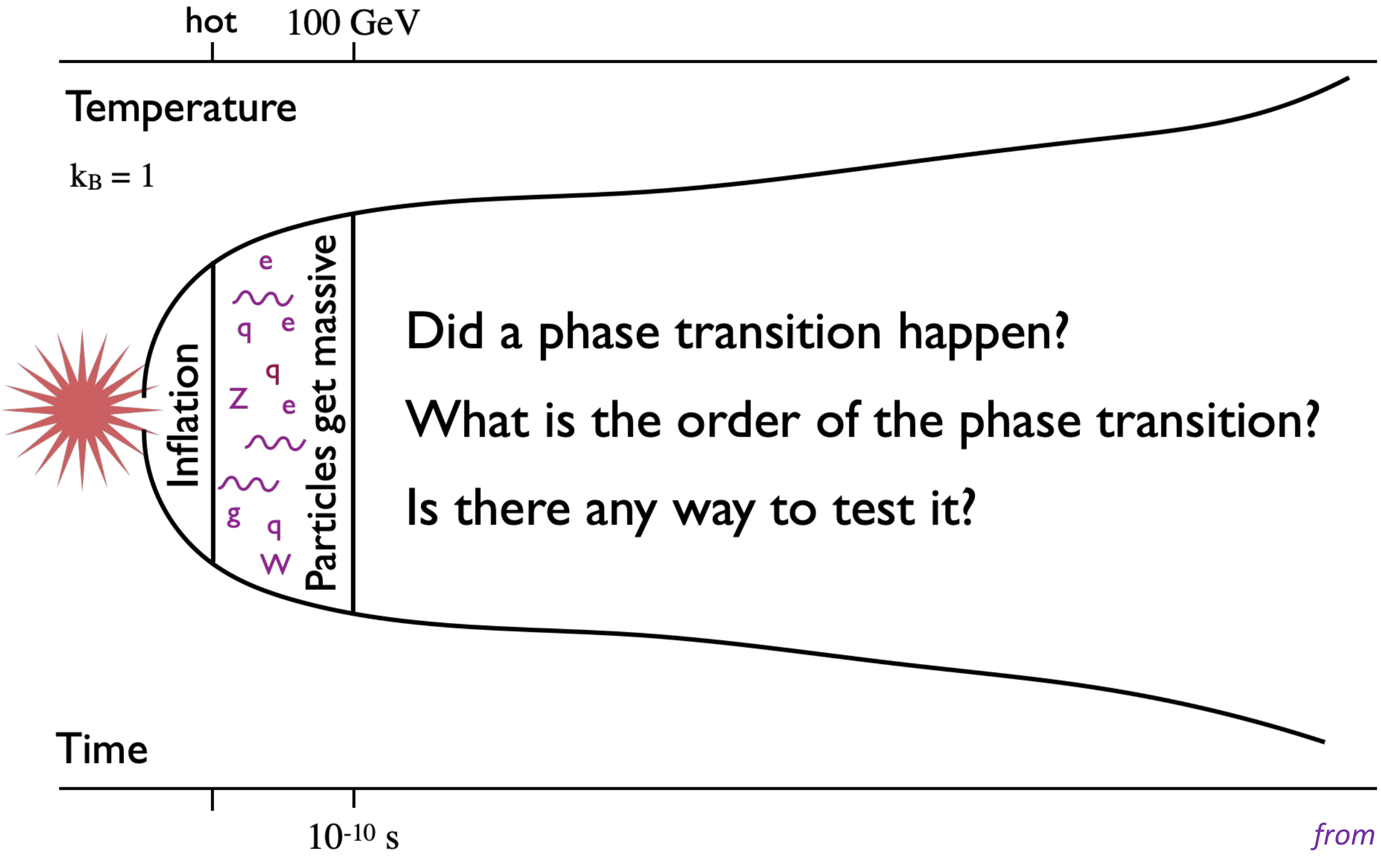
Operation start in 2027 For Accelerator/Atmospheric/Solar/ Supernova neutrinos, and proton decays



High power proton beams
J-PARC
(hosted by KEK)

Hyper-Kamiokande
(hosted by the University of Tokyo)

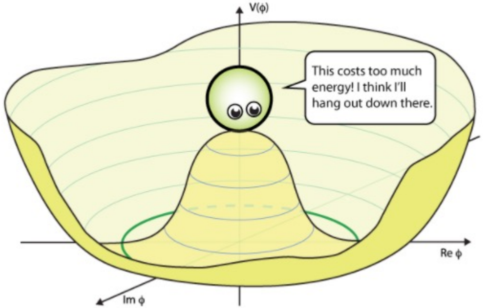
The electroweak phase transition



Did a phase transition happen?

What is the order of the phase transition?

Is there any way to test it?



from Selya Ipek

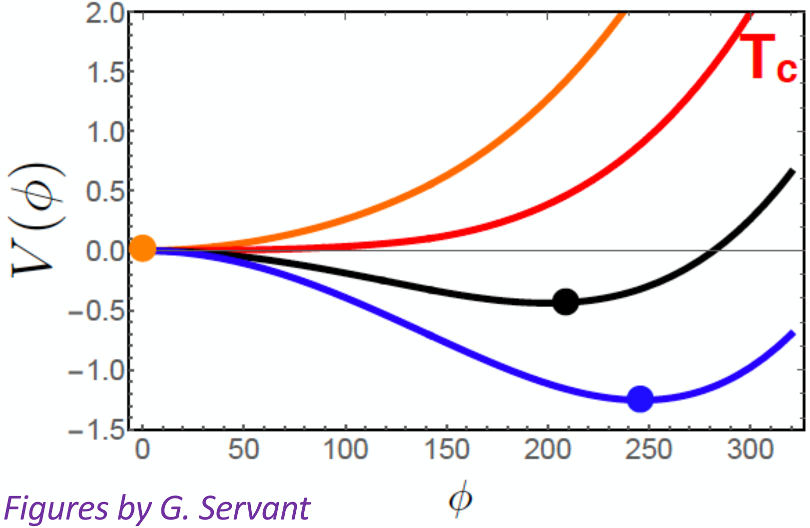
Electroweak potential

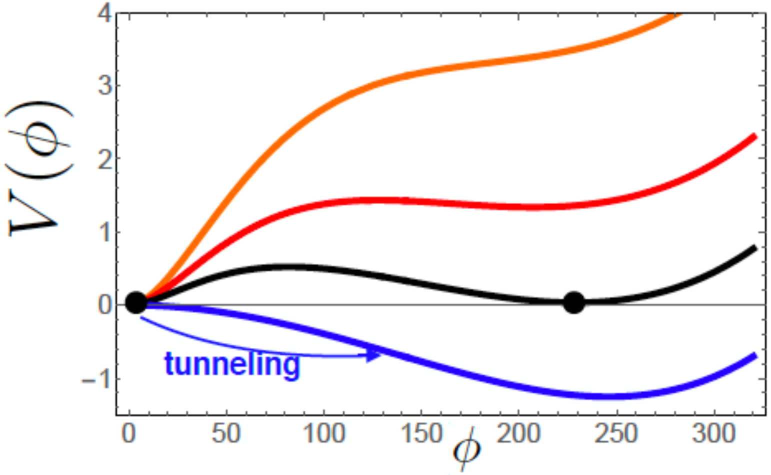
Standard Model

- Electroweak phase transition (EWPT) is a "smooth crossover"
- Electroweak symmetry restored for $T \geq T_C = 130$ GeV

Alternative idea

- Electroweak phase transition via tunneling: 1st order transition
  - Two phases co-exist
- Electroweak baryogenesis possible if strong 1st order transition





Figures by G. Servant

Electroweak potential

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Alternative idea

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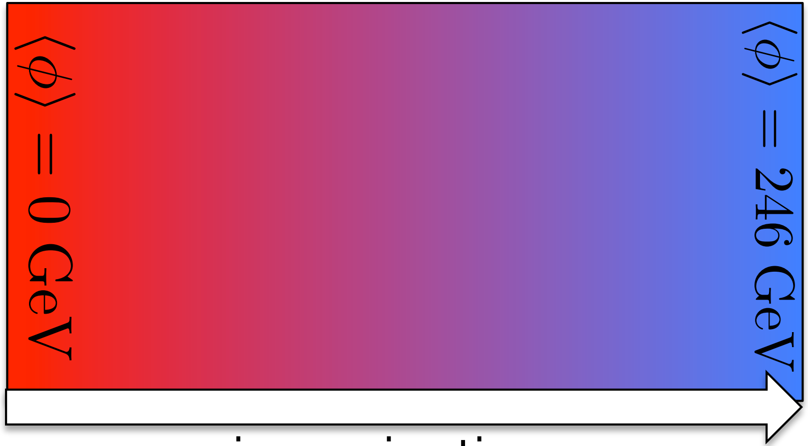
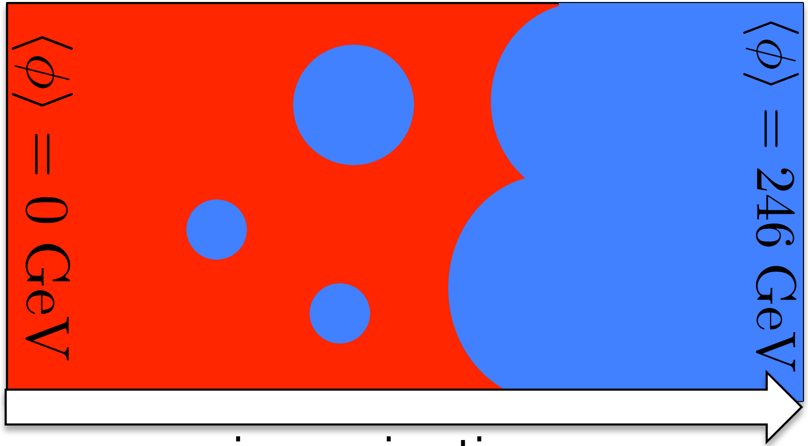
  - Two phases co-exist
- Electroweak baryogenesis possible if strong 1st order transition $\frac{v(T_{\rm pt})}{T_{\rm pt}} \gtrsim 1.0$

Continuous Crossover



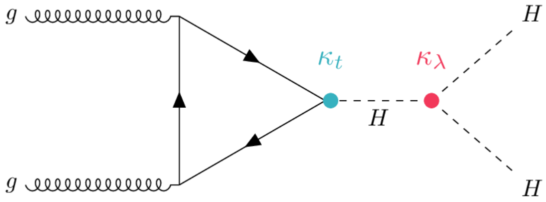
increasing time

First Order Phase Transition

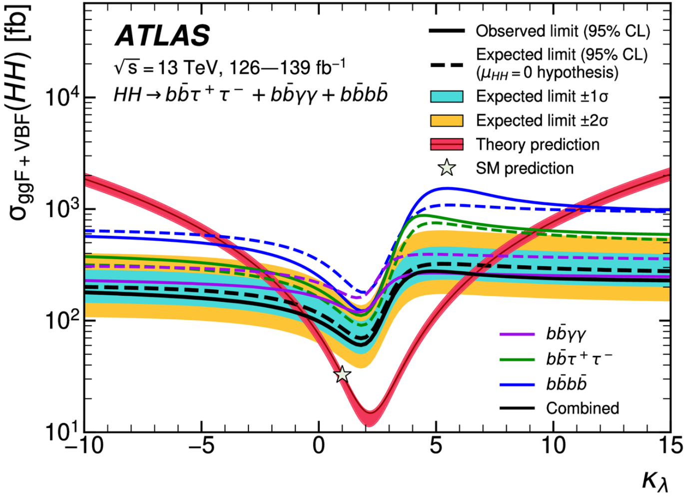


increasing time

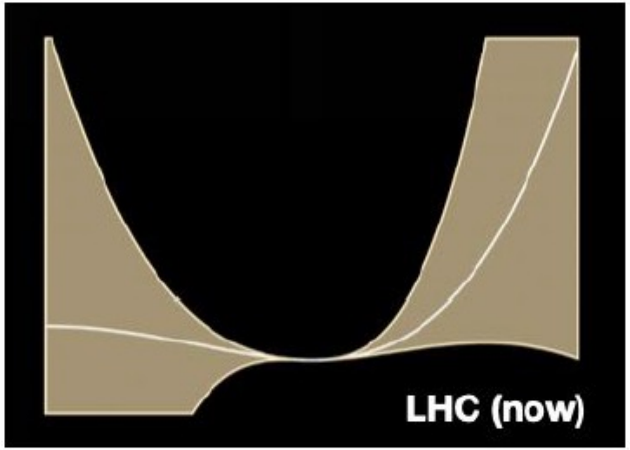
Di-Higgs Production: LHC result



$$\sigma_{HH} \sim \frac{\sigma_H}{1000}$$



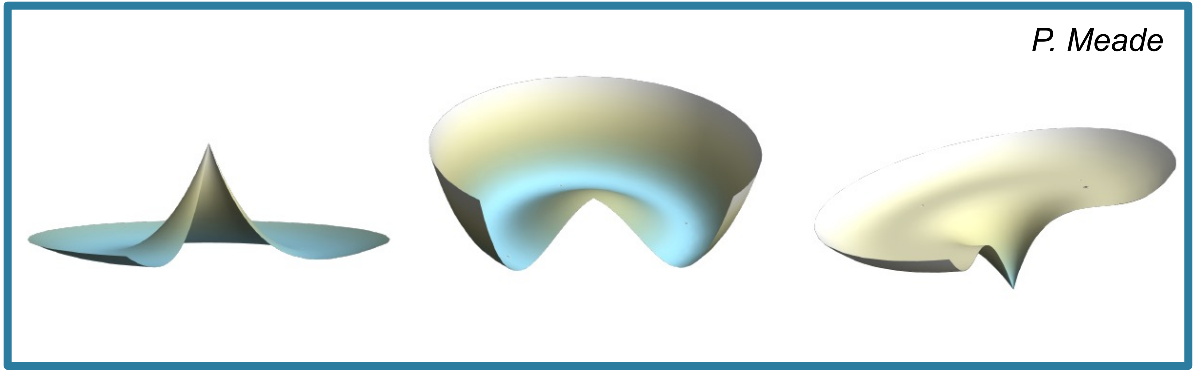
$$\kappa_\lambda = {}^{\lambda}/_{\lambda_{SM}}$$



Nathanial Craig

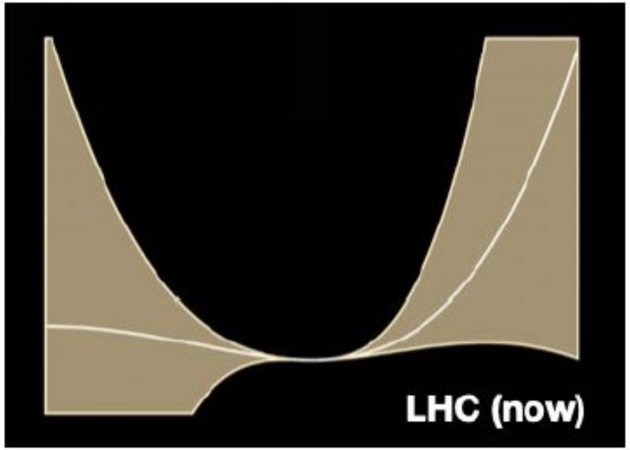
Constraints on κ_λ :
-0.4<κ_λ<6.3 at 95% CL

Di-Higgs Production: LHC result



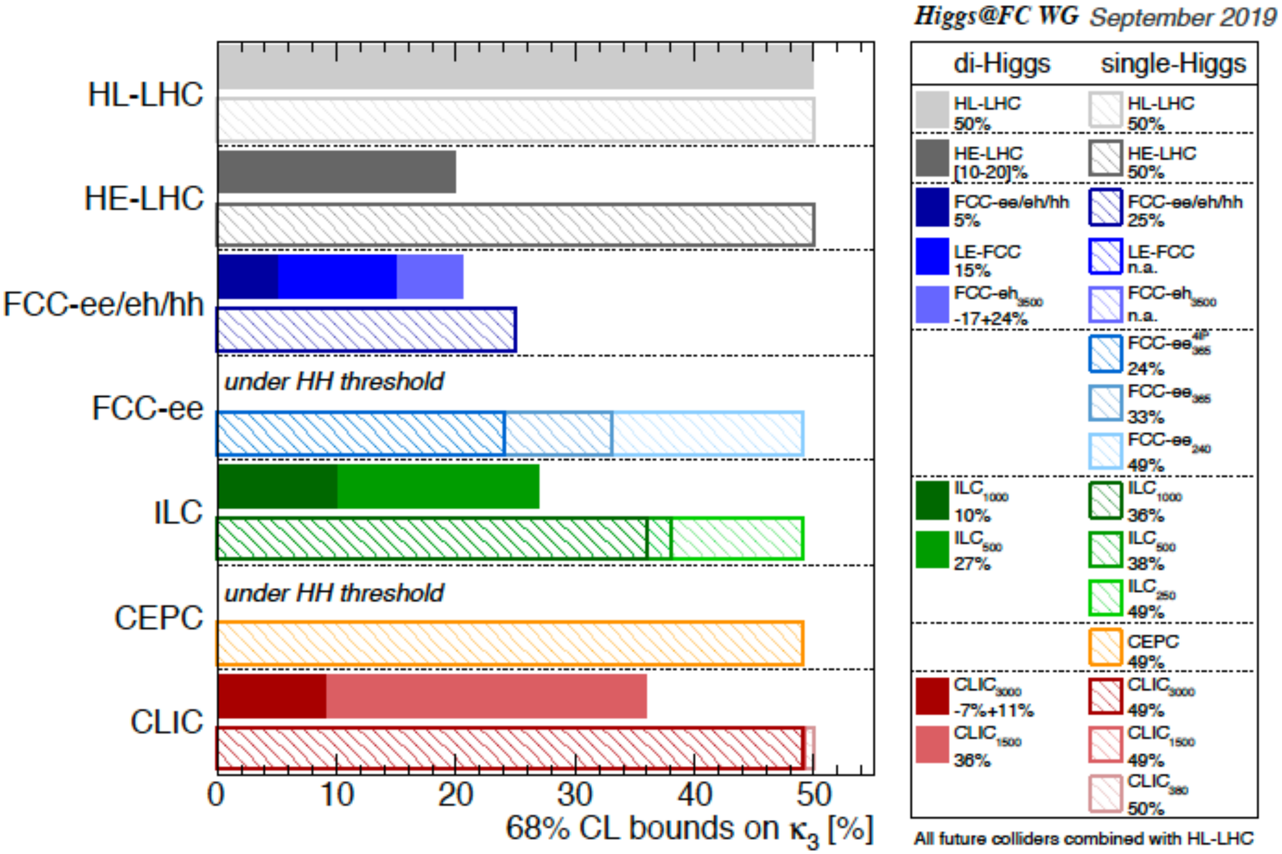
P. Meade

Nature could have any of these!!

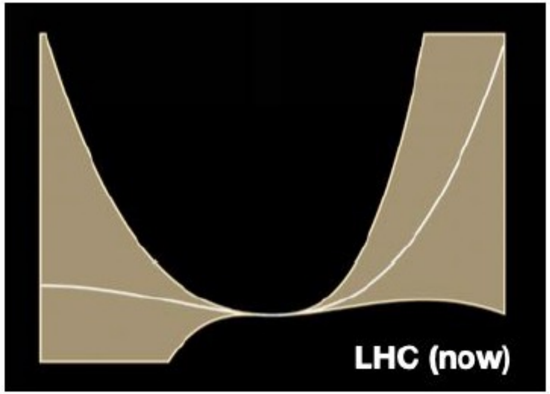


Nathanial Craig

Sensitivity to κ_λ: future colliders

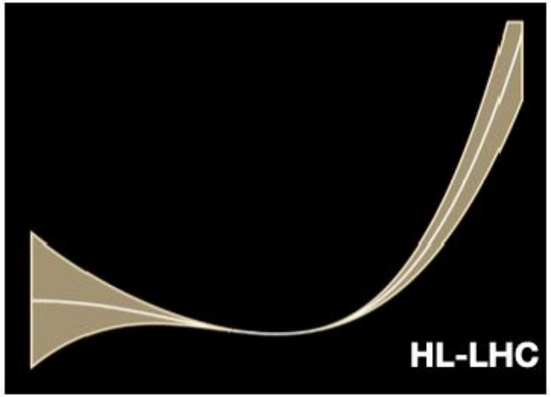


What might we learn about the H potential?

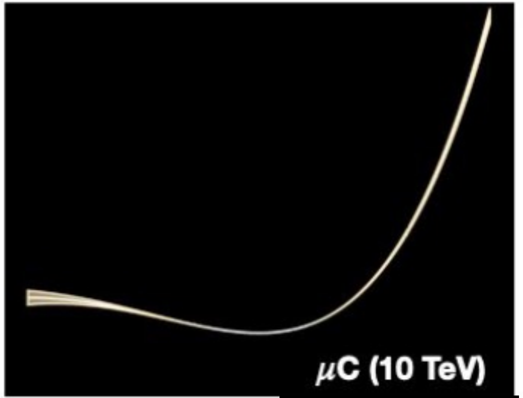


Nathanial Craig

$\Delta\kappa < 50\%$

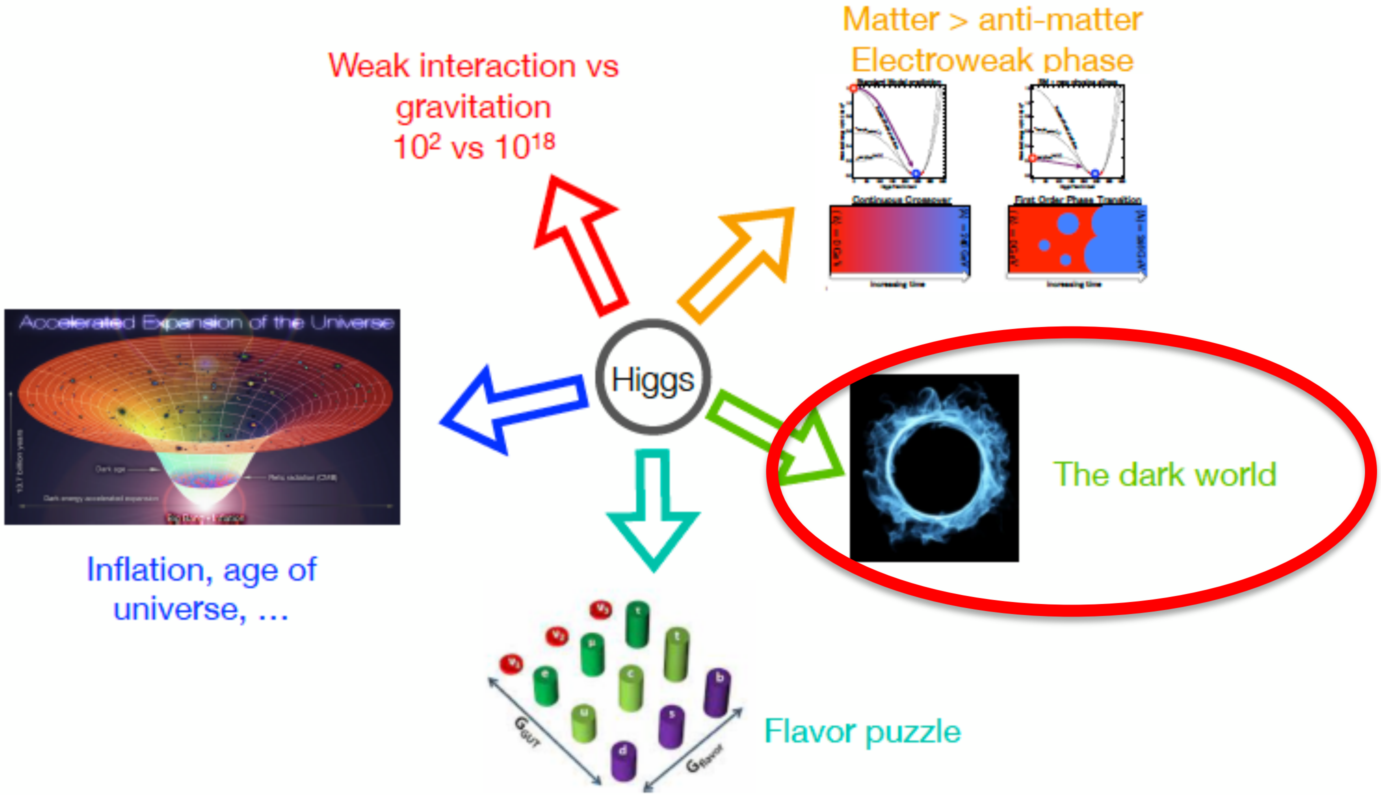


$\Delta\kappa < 5\%$



(or FCC-hh)

Big Questions and the Higgs Boson



Weak interaction vs gravitation
10^2 vs 10^{18}

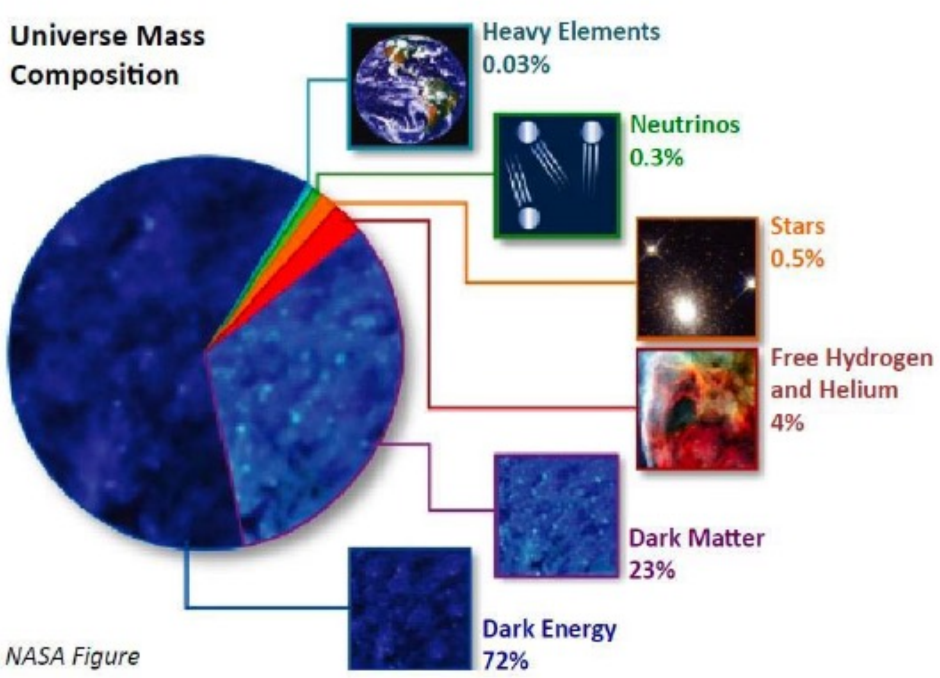
Matter > anti-matter
Electroweak phase

Inflation, age of universe, ...

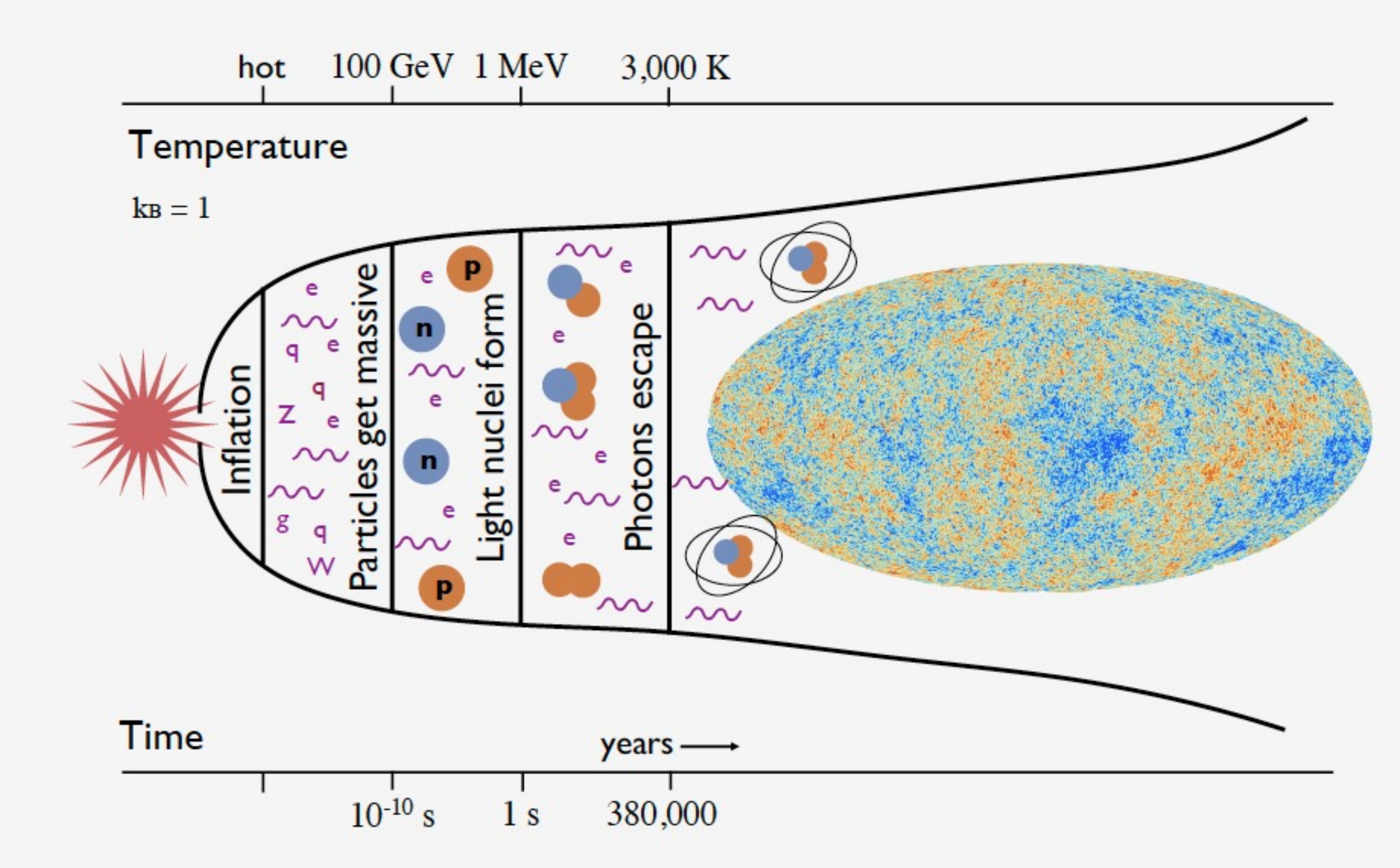
The dark world

Flavor puzzle

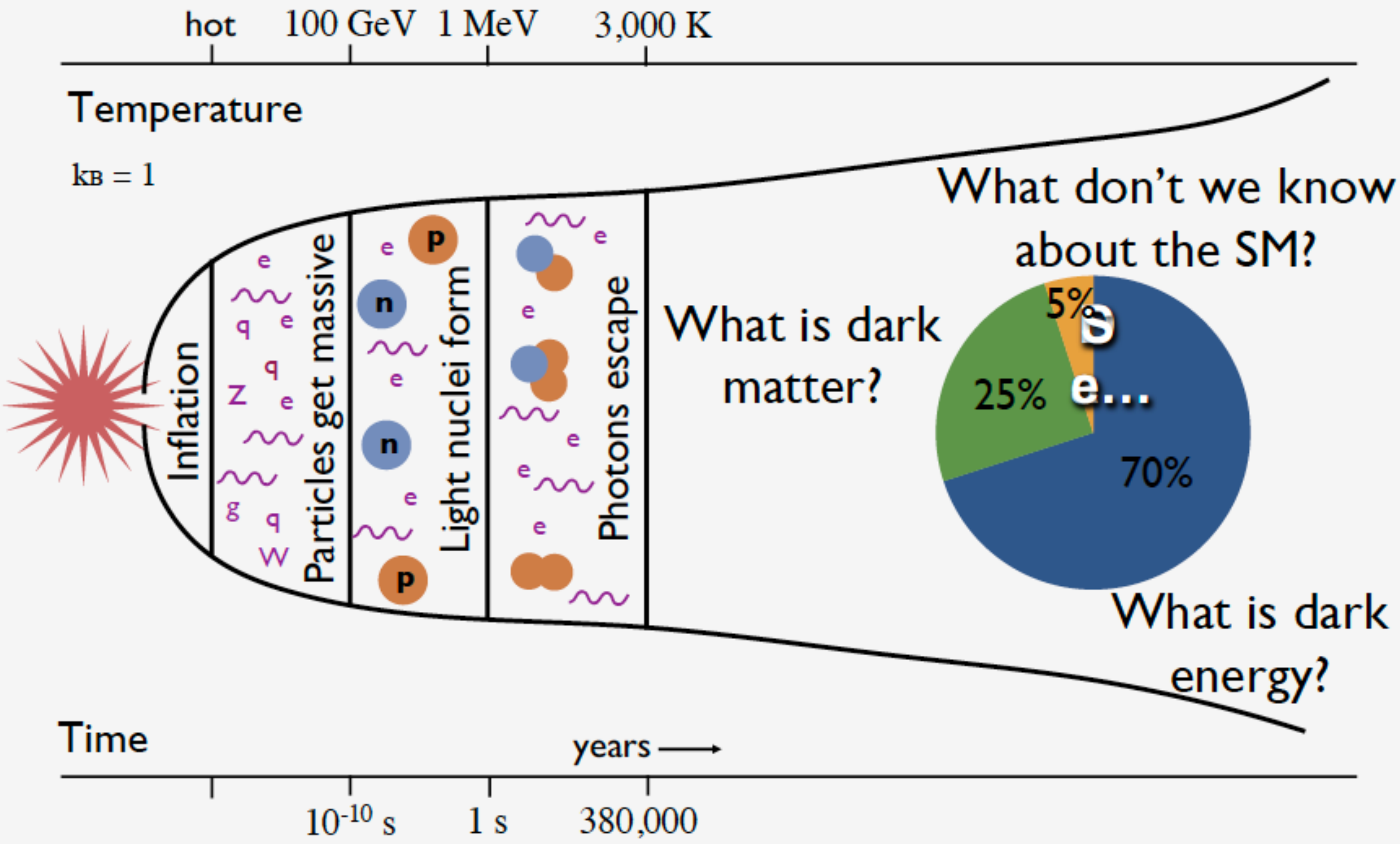
Composition or the Universe



A brief history of the (very early!) Universe



A brief history of the (very early!) Universe

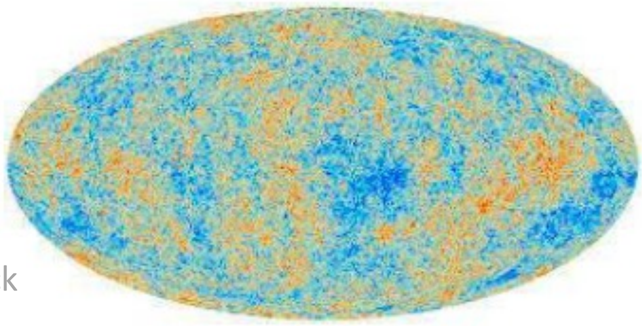


What don't we know about the SM?

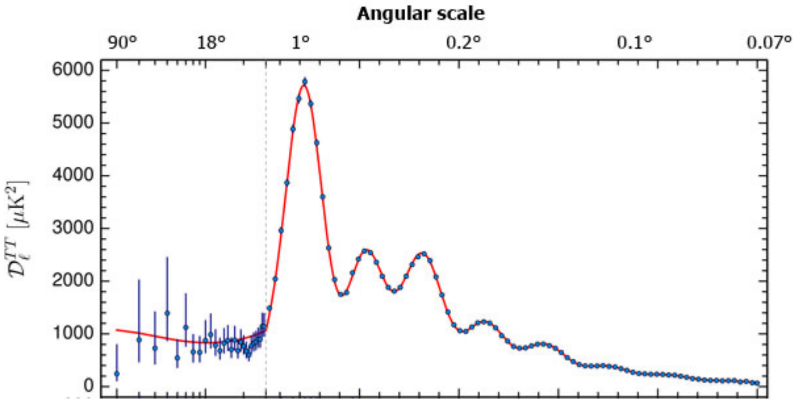
What is dark matter?

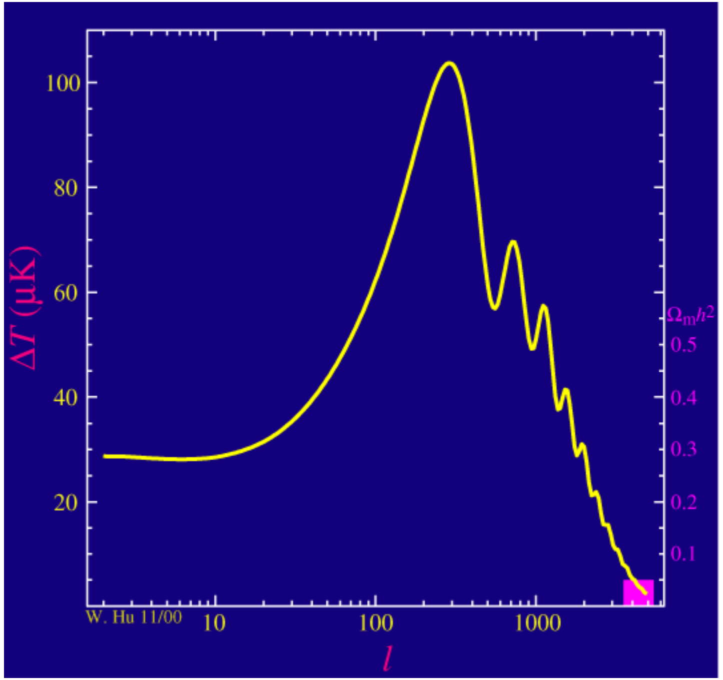
What is dark energy?

85% of the matter in the Universe is invisible!



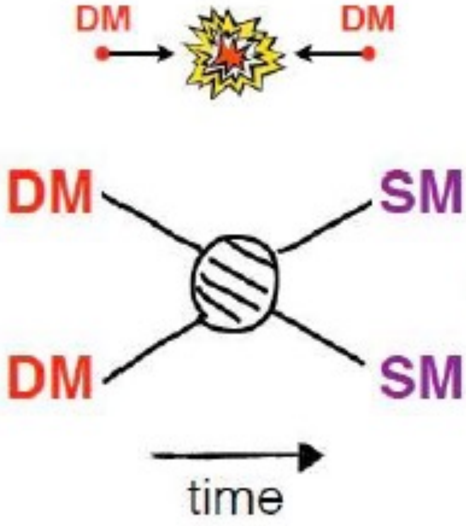
©Planck

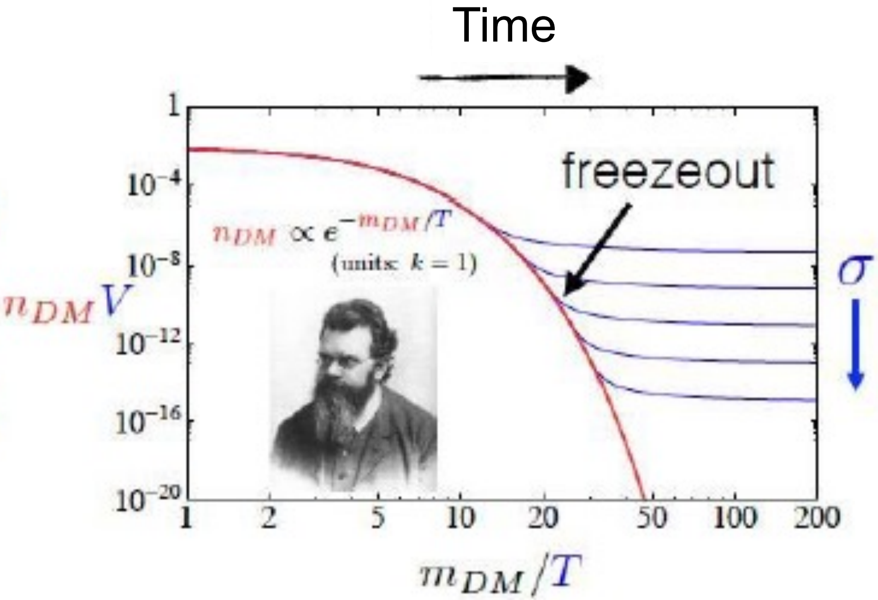




Dark matter only known through gravitational interactions

Dark Matter: annihilation in the early Universe

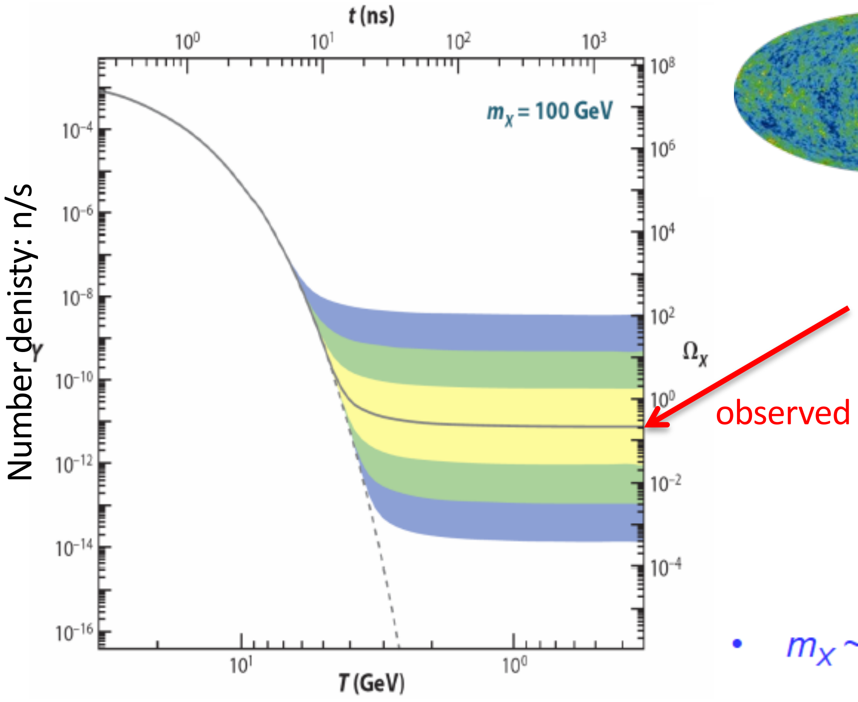


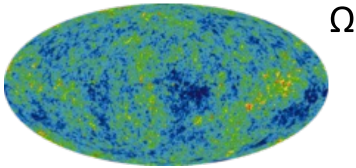


- Lee, Weinberg, Phys. Rev. Lett. **39**, 165 (1977).

The WIMP(*)-Miracle

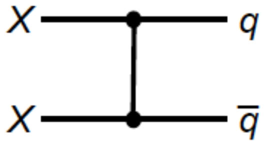
(*) WIMP=Weakly Interacting Massive Particle





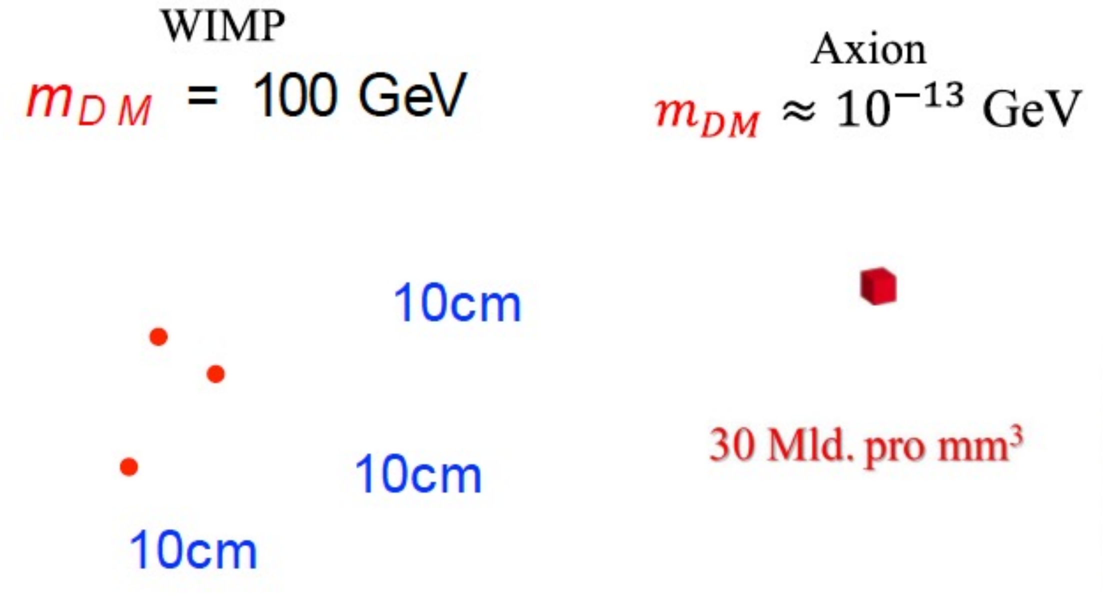
$\Omega_X h^2 = 0.1188 \pm 0.0010$
$= 5.32 \times \Omega_b h^2$

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



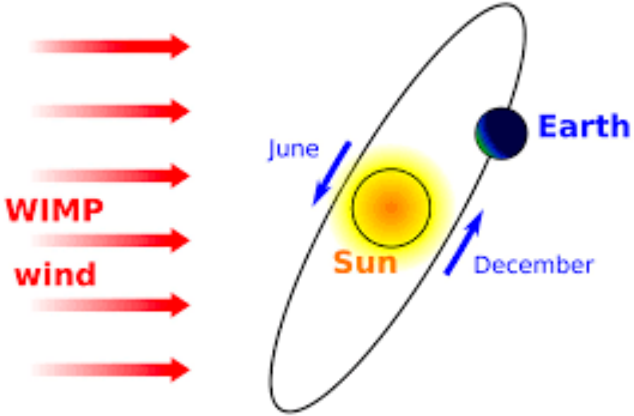
- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

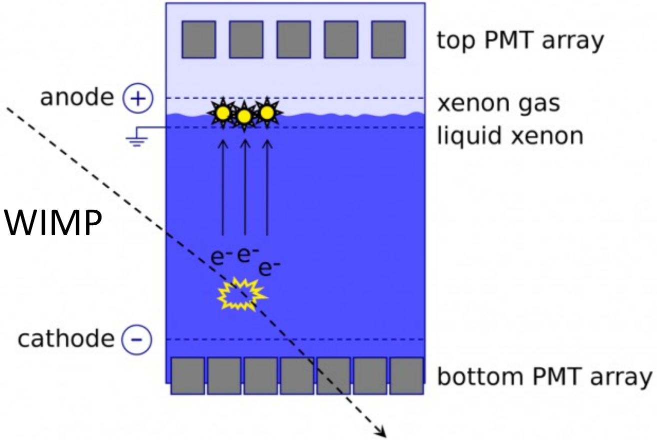
Dark Matter candidates: WIMPs or axions?

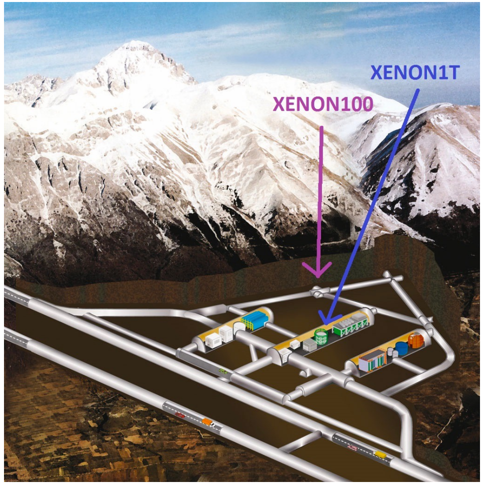


Dark matter density today: 300 GeV/liter

Direct Searches for WIMPs



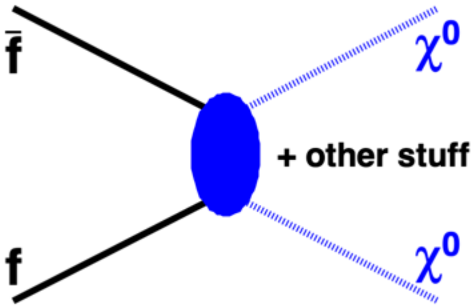




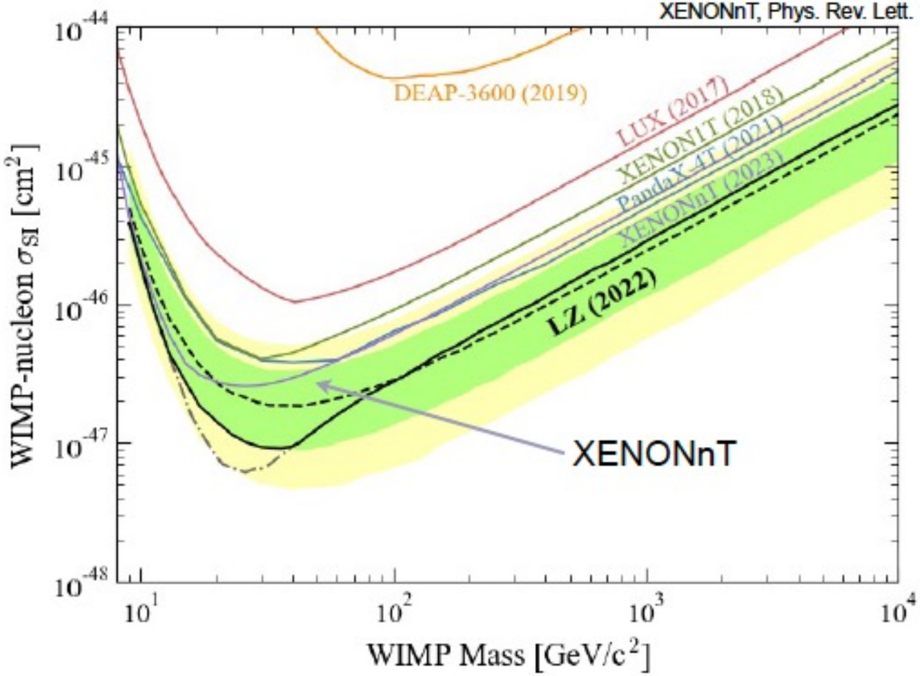
Gran Sasso, Italy

Ca. 1400m below surface

Searches for WIMP Dark Matter



Underground direct detection experiments: XENON1T and LZ



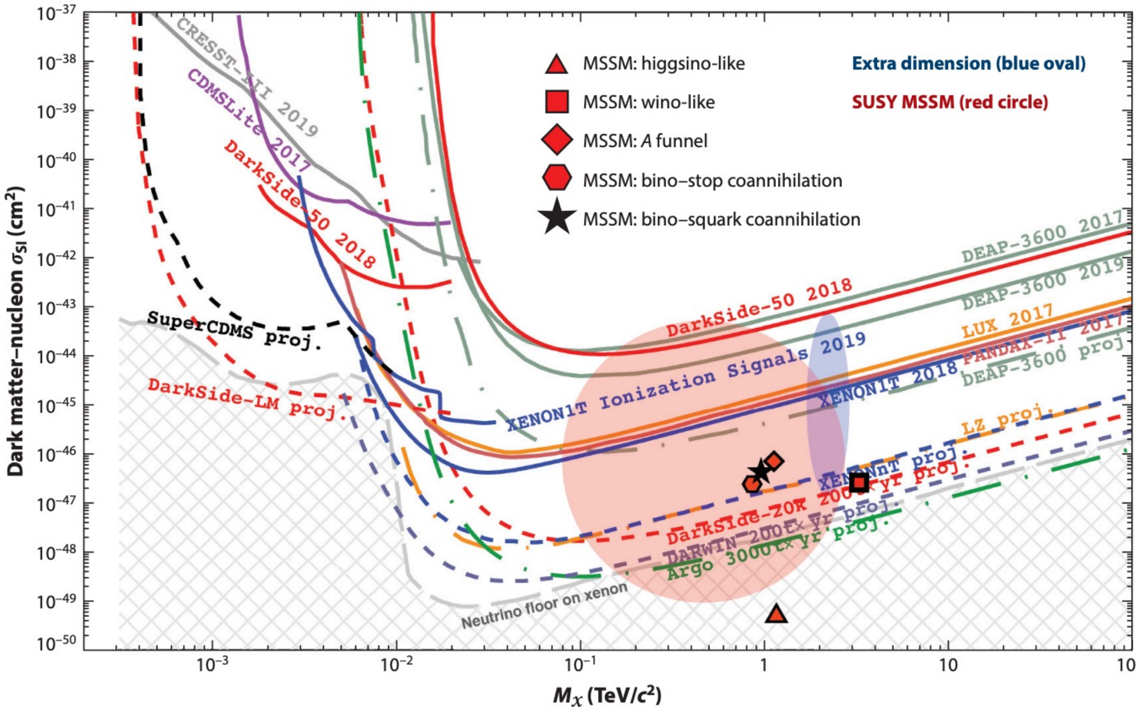
LZ, Phys. Rev. Lett. 131, 041002 (2023)
XENONnT, Phys. Rev. Lett. 131, 041003 (2023)

WIMP Dark Matter: next generation

3rd generation noble liquid tank WIMP searches planned:

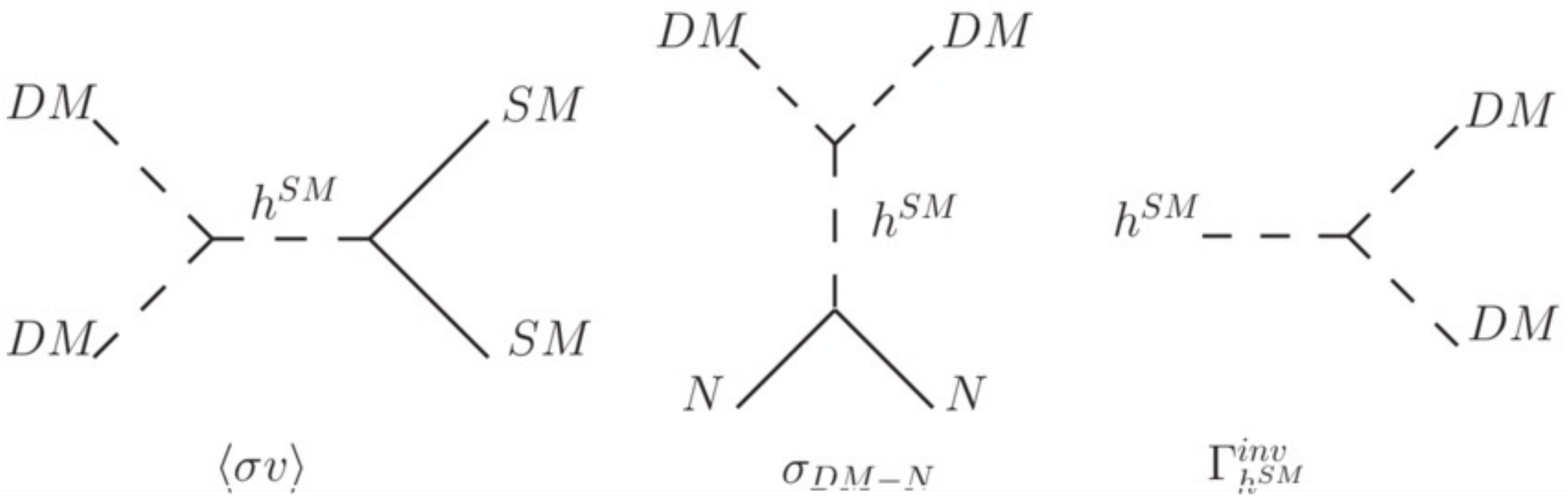
- DARWIN/XLZD: Liquid Xe
- ARGO: Liquid Ar

Will test much of parameter space of supersymmetry



Simplest supersymmetry scenarios predict “Wino” or “Higgsino” with masses > 1 TeV => difficult (but possible) to test

Does Higgs couple to Dark Matter?



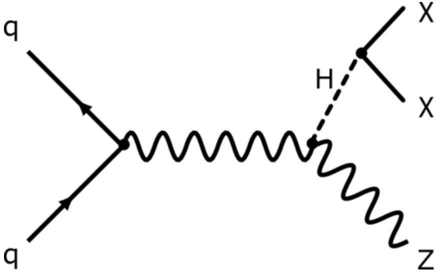
DM annihilation
early Universe &
satellites

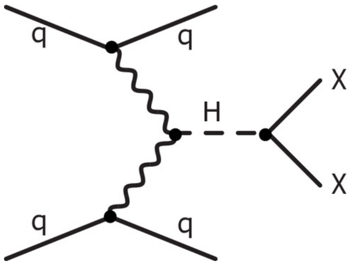
DM-N Scattering
(XENON1T etc.)

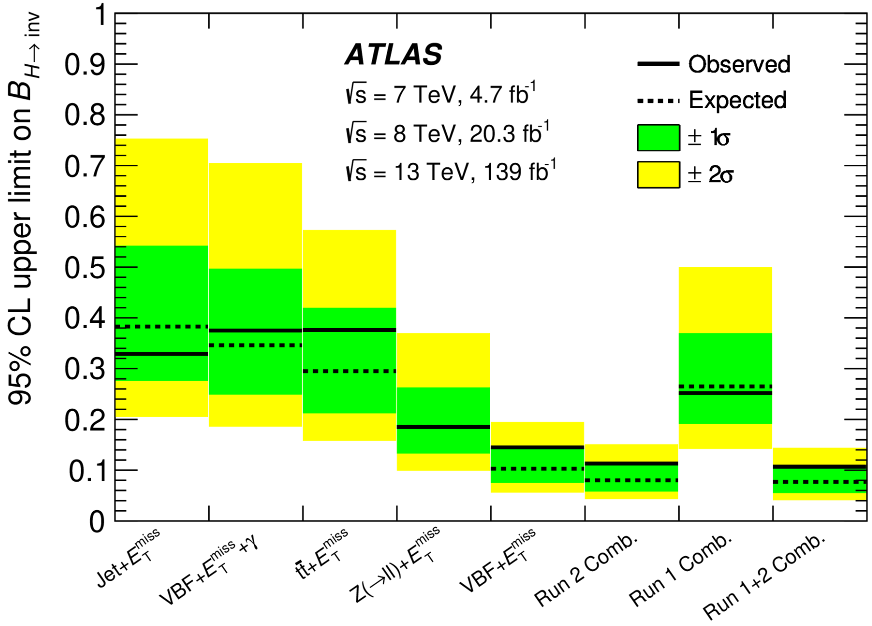
DM production
early Universe &
LHC

“Invisible” Higgs decays?

- Higgs can decay to dark matter candidates if $m_H > 2\ m_\chi$
- Current limit: BR<10.7%







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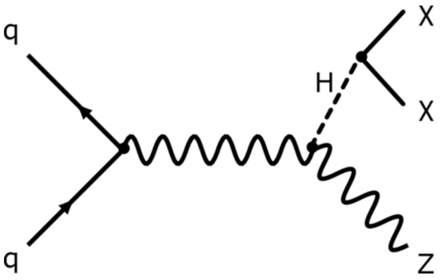
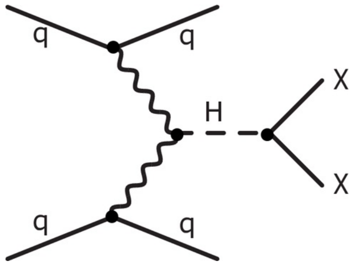
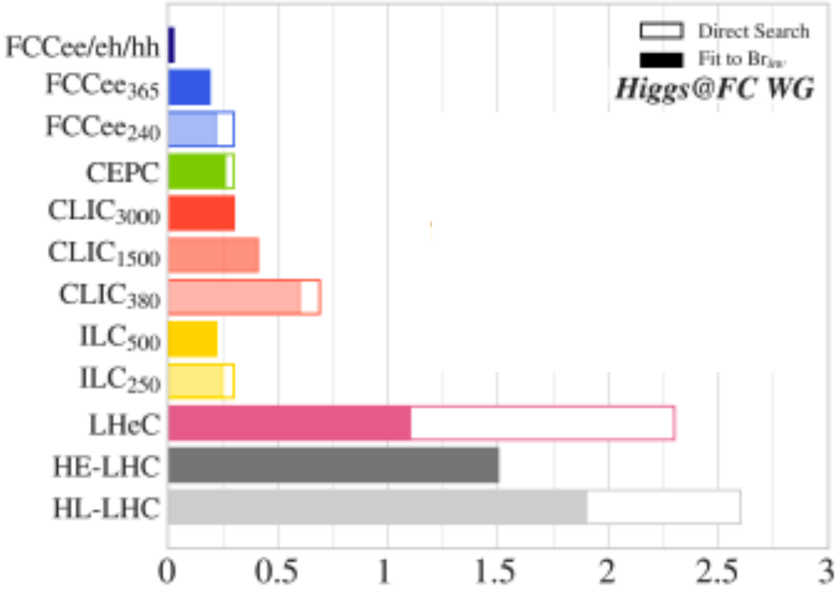






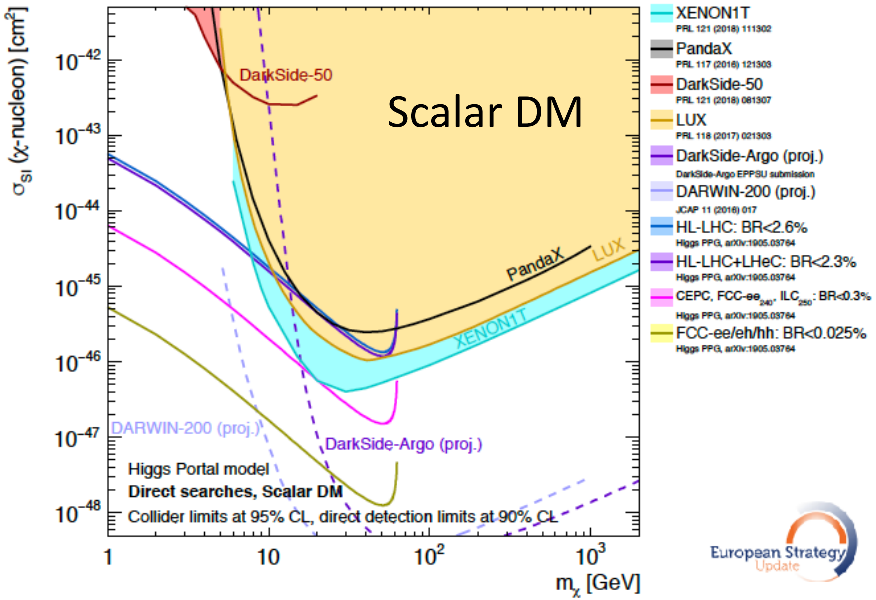
- HL-LHC will improve by factor 10 compared to now
- Future ee colliders gain another factor ~10
- And… FCC-hh yet another factor 10!

Comparing direct detection and Higgs constraints

Dark Matter can be scalar, vector or fermion:

$$\boxed{\mathrm{BR}_\chi^{\mathrm{inv}} \equiv \frac{\Gamma(H\to\chi\chi)}{\Gamma_H^{\mathrm{SM}}+\Gamma(H\to\chi\chi)} = \frac{\sigma_{\chi p}^{\mathrm{SI}}}{\Gamma_H^{\mathrm{SM}}/r_\chi+\sigma_{\chi p}^{\mathrm{SI}}}}$$

$$\text{with} \quad r_\chi = \Gamma(H\to\chi\chi)/\sigma_{\chi p}^{\mathrm{SI}}$$

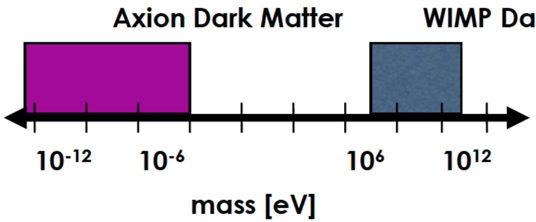


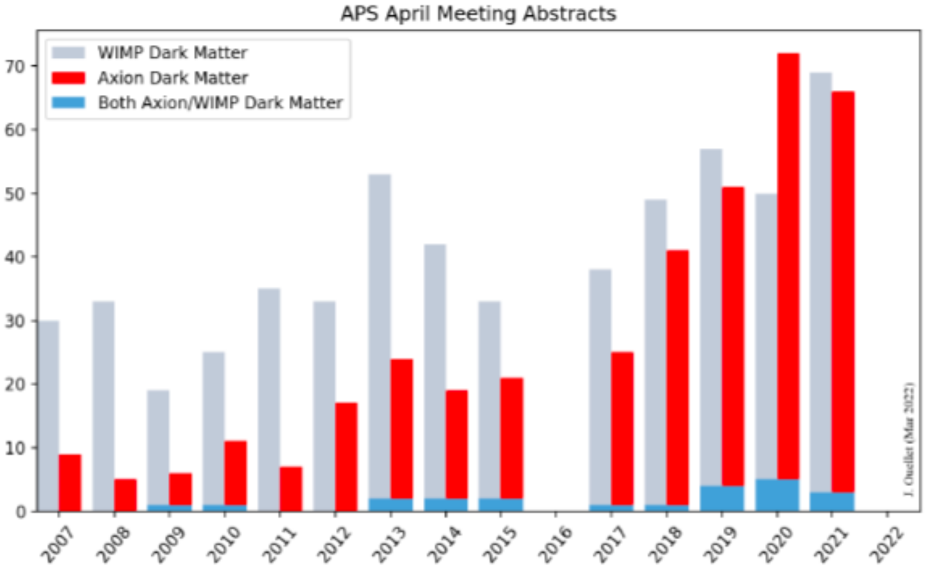
arXiv:1910.11775

- Approaches are complementary
  - Higgs more sensitive at low mass, direct detection more sensitive at high mass
- Comparison is model-dependent
  - This is good: if we see signal we will learn physics from it!

Dark Matter

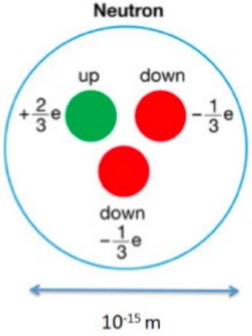
WIMPs and/or axions





J. Ouellet

- Traditionally strong focus on WIMPs but interest in axions is growing
- QCD axion is the *only* solution to strong CP problem



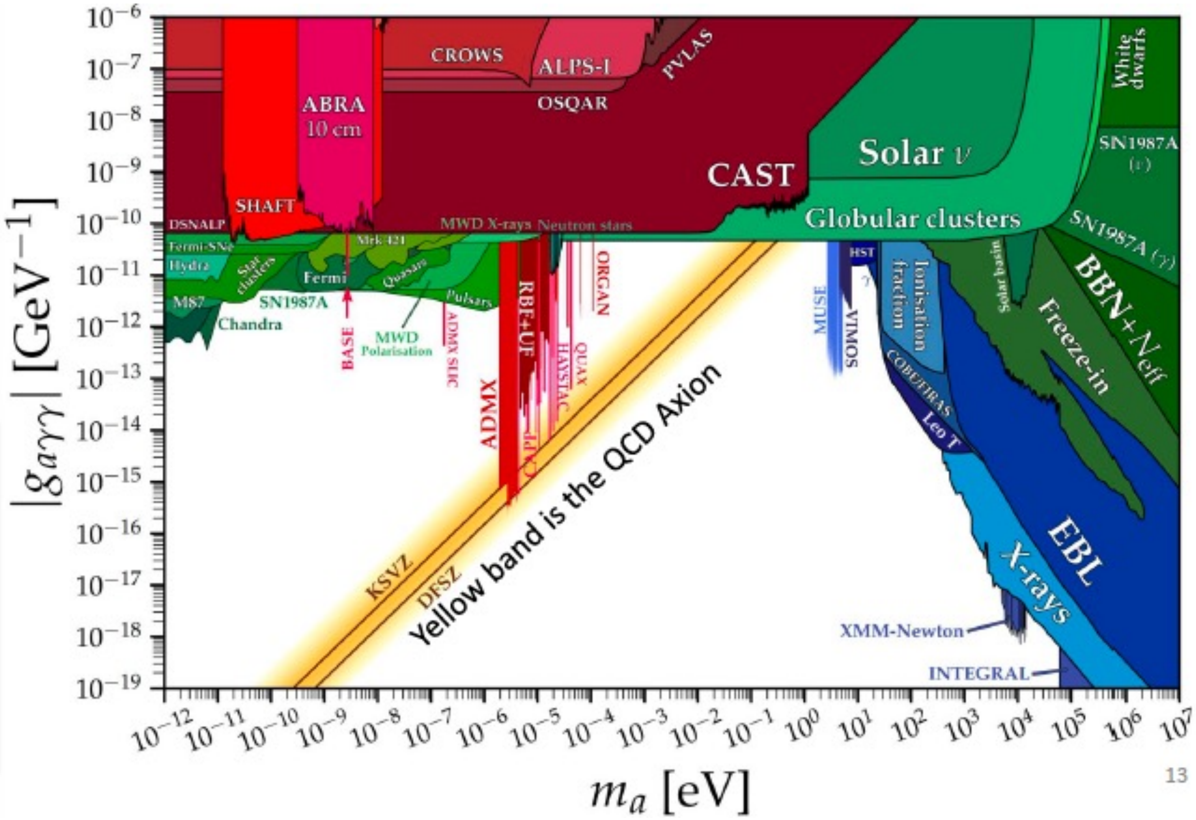
d = ~~10^{-16} e cm~~
< 3×10^{-26} e cm

Axion Status

Current constraints

Theory expectation for axion as dark matter (in simple models)

$$10^{-6} < m_{axion} < 10^{-2}\ eV$$



Axion Status

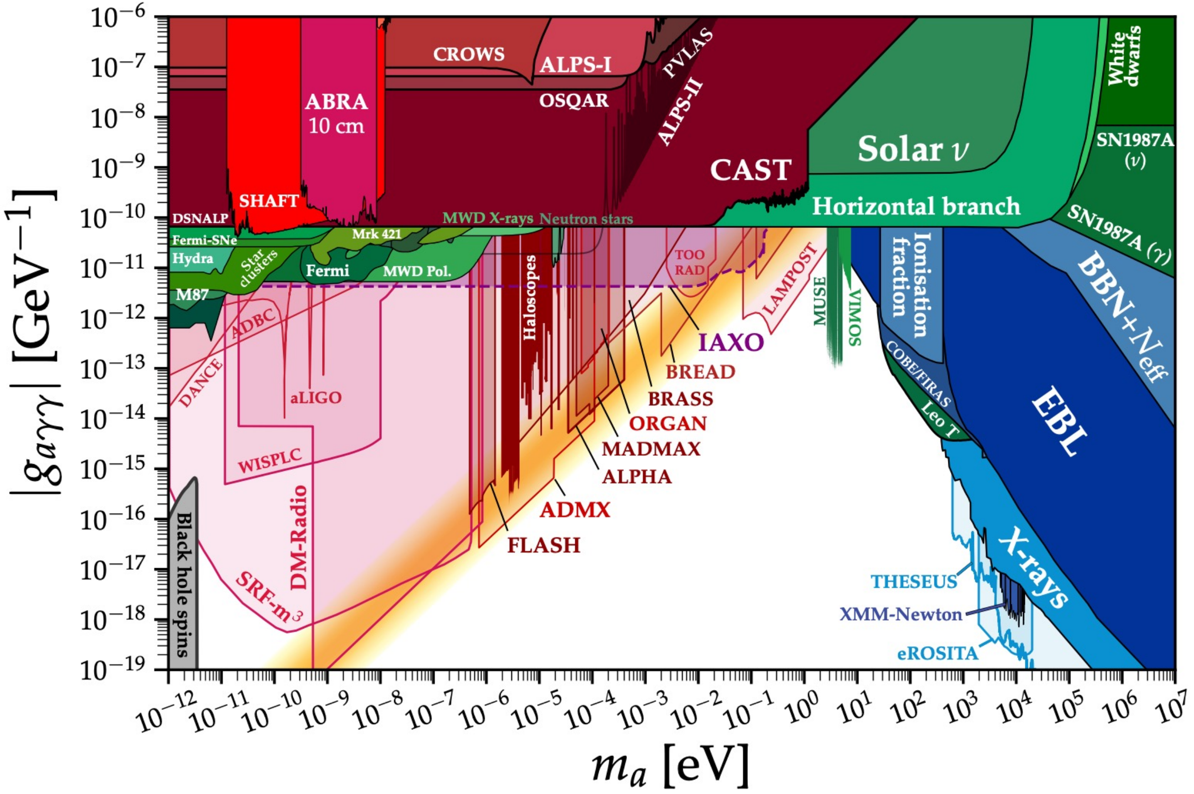
Future experiments

Theory expectation for axion as dark matter (in simple models)

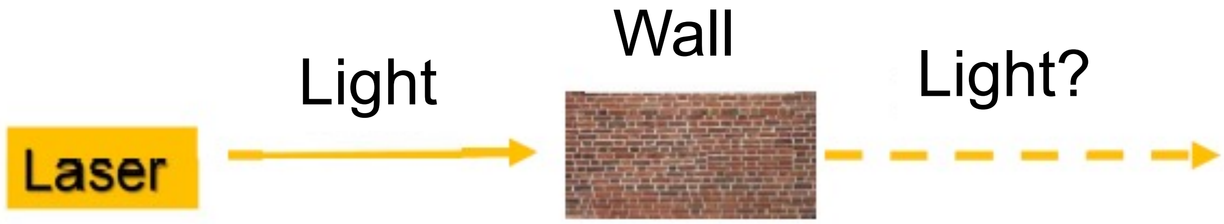
$$10^{-6} < m_{axion} < 10^{-2}\ eV$$

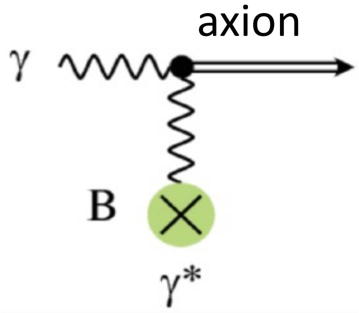
Will cover entire mass range down to 10^{-9} eV in the next decade or so!

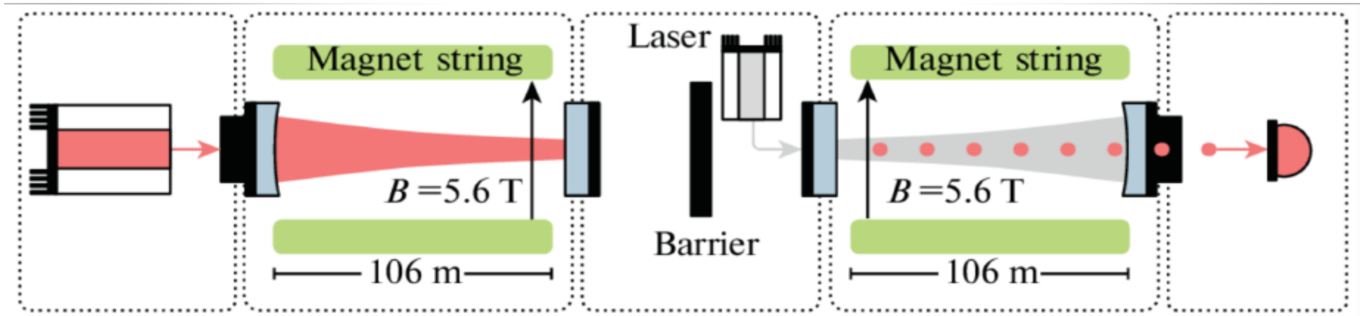
Very dynamic area!



Search for Axion-like particles at DESY, ALPS II: Can light travel through a wall?

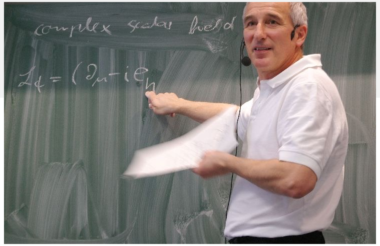


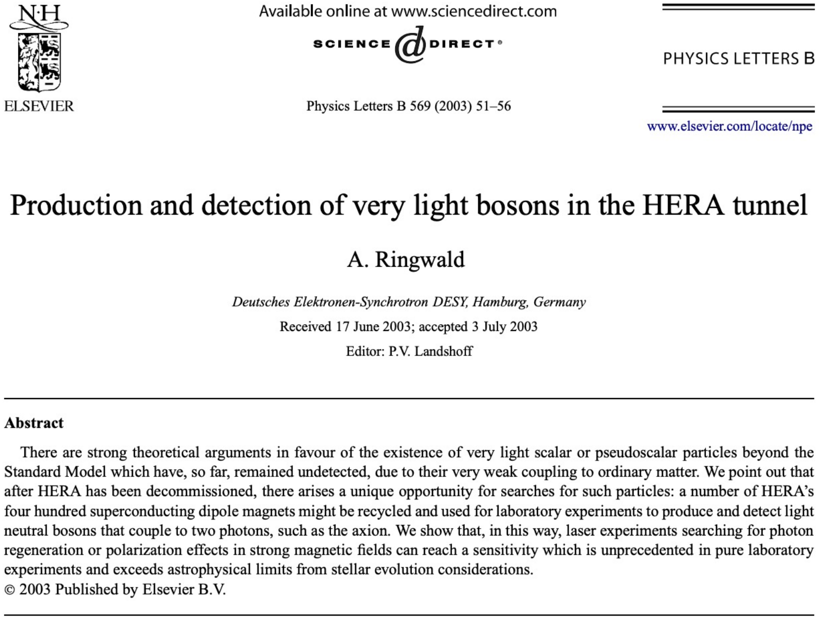




Any Light Particle Search II

20 years in the making…





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Production and detection of very light bosons in the HERA tunnel

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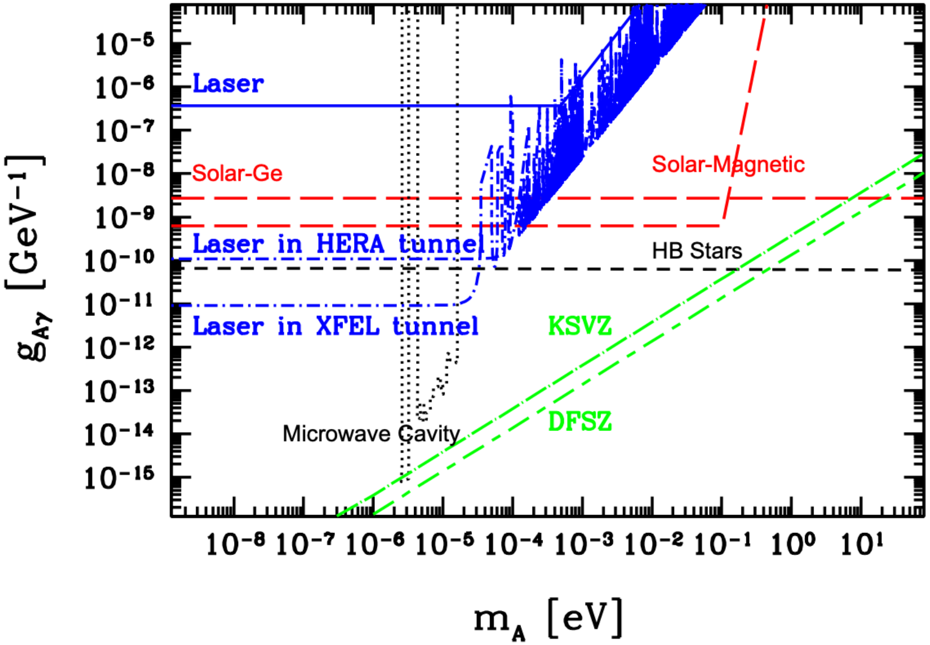
Received 17 June 2003; accepted 3 July 2003

Editor: P.V. Landshoff

Abstract

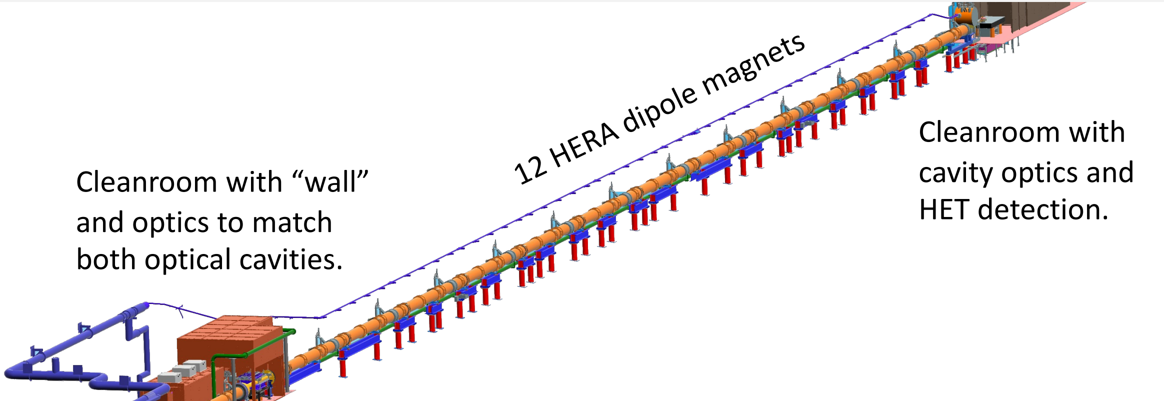
There are strong theoretical arguments in favour of the existence of very light scalar or pseudoscalar particles beyond the Standard Model which have, so far, remained undetected, due to their very weak coupling to ordinary matter. We point out that after HERA has been decommissioned, there arises a unique opportunity for searches for such particles: a number of HERA's four hundred superconducting dipole magnets might be recycled and used for laboratory experiments to produce and detect light neutral bosons that couple to two photons, such as the axion. We show that, in this way, laser experiments searching for photon regeneration or polarization effects in strong magnetic fields can reach a sensitivity which is unprecedented in pure laboratory experiments and exceeds astrophysical limits from stellar evolution considerations.



Any Light Particle Search II

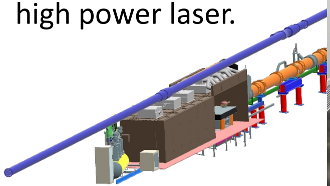
Recent achievements
- 12/2021: magnet string at T=4 K.
- 06/2022: world-record cavity storage time: 6.75 ms.
- 11/2022: observe first calibration signal
- May 24th: first science run

7 coll. institutions



Cleanroom with “wall” and optics to match both optical cavities.

Cleanroom with cavity optics and HET detection.



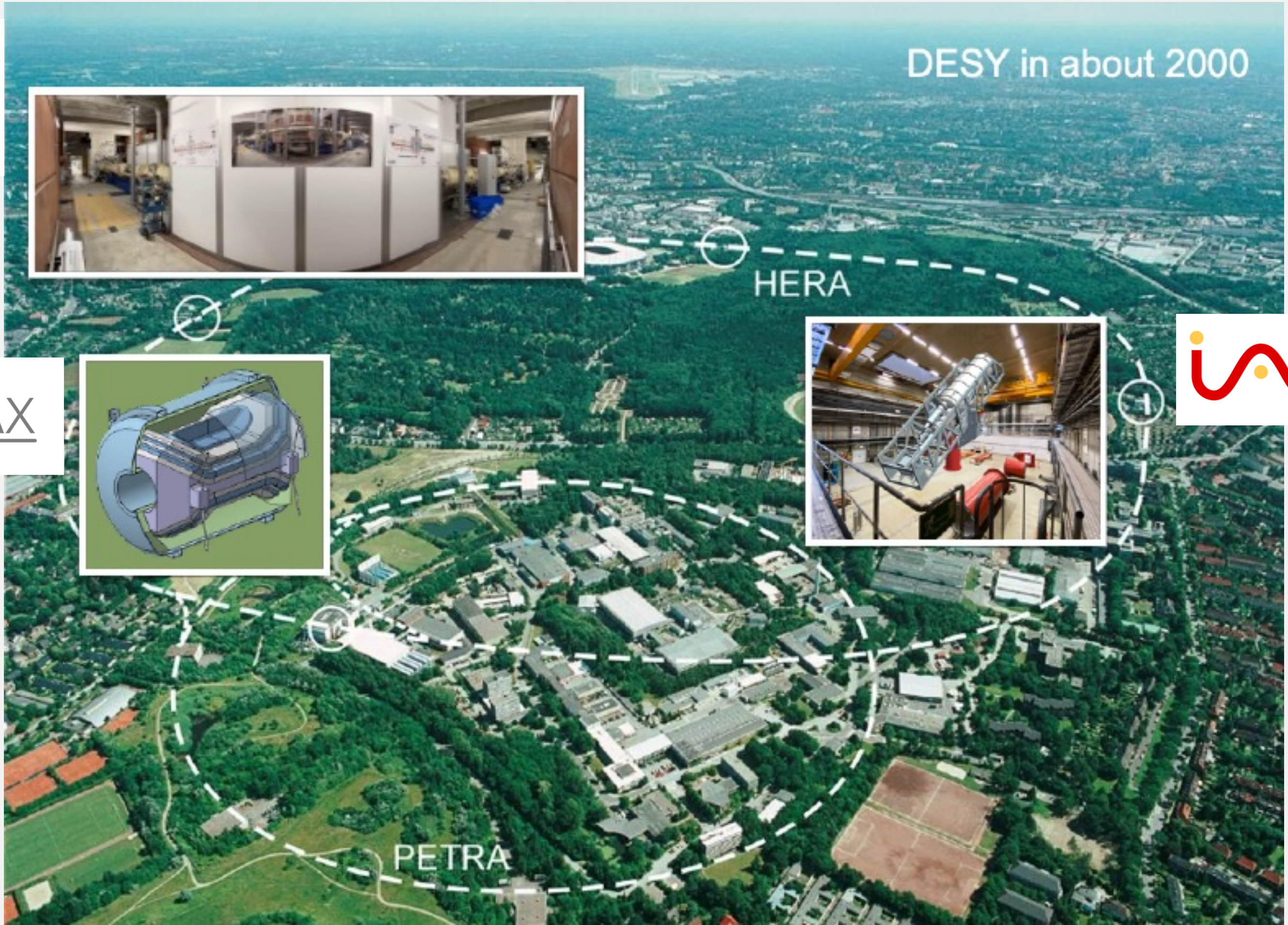
Cleanroom with high power laser.

Current and Future Axion Experiments at DESY

ALPS

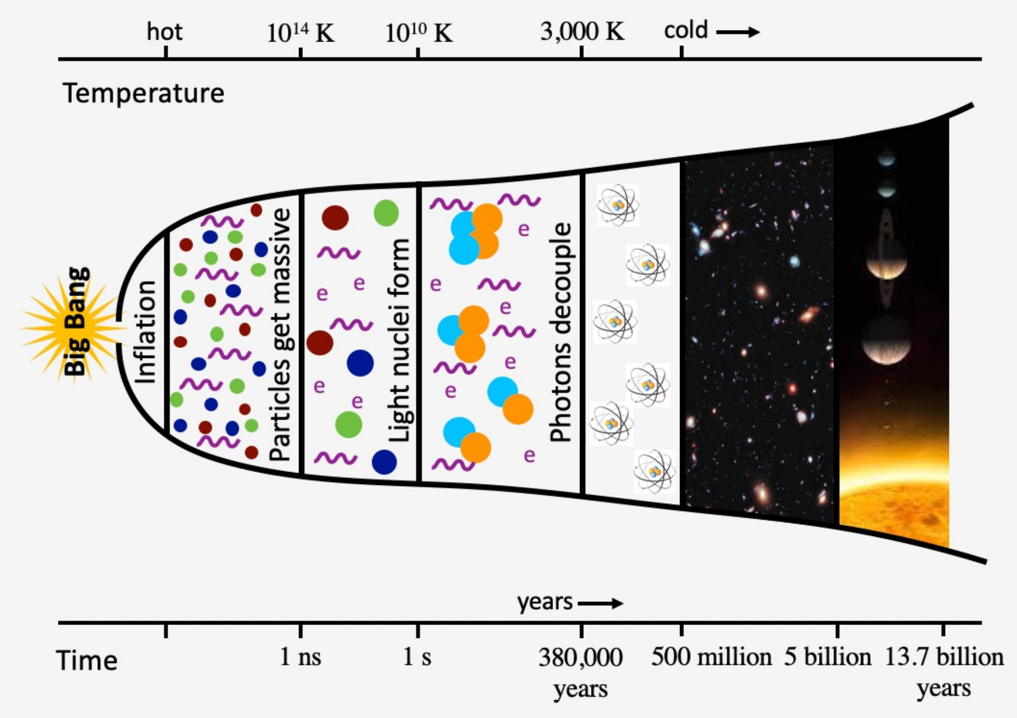
MADMAX

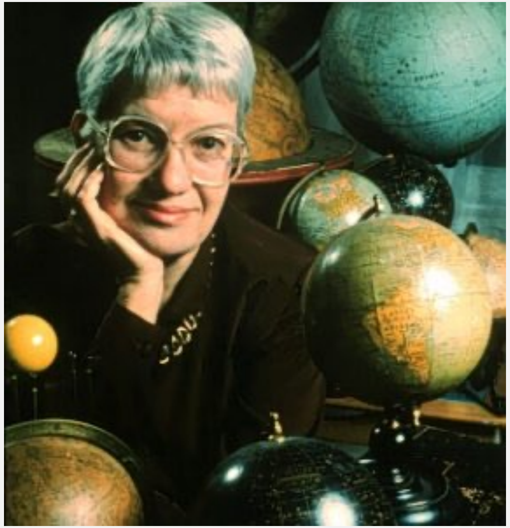
IAXO



Conclusions

Particle physics plans a balanced portfolio of complementary experiments to understand the quantum Universe





V. Rubin: *"Science progresses best when observations alter our preconceptions"*