Beyond Collider Physics

Hyung Do Kim
(Seoul National University &
PI of CERN-Korea Theory Collaboration)

KPS pioneer session
2023. 10. 26

Contents

- Collider Physics
- FCC vs muon collider
- Example1 : Naturalness (dark radiation and CMB S4)
- Example 2 : Weak scale as a trigger (very light scalars)
- New Korean Projects at CERN (SND, Isolde, gbar)
- CERN Korea Summer Student Program

Theoretical Physics

- New physics at the weak scale
- No observation of new physics at the LHC
- No definite prediction on new physics scale
- No definite new physics scenario
- No definite future (?)

- The era of precision physics
- Theory driven progress is hard to achieve
- Dilutions in all possible directions

Future Direction

- Energy frontier
- Intensity frontier
- Rare process
- The chance for the big discovery was 1/3 for each (Freeman Dyson, personal science history study)
- Too much emphasis on energy frontier in 21st century

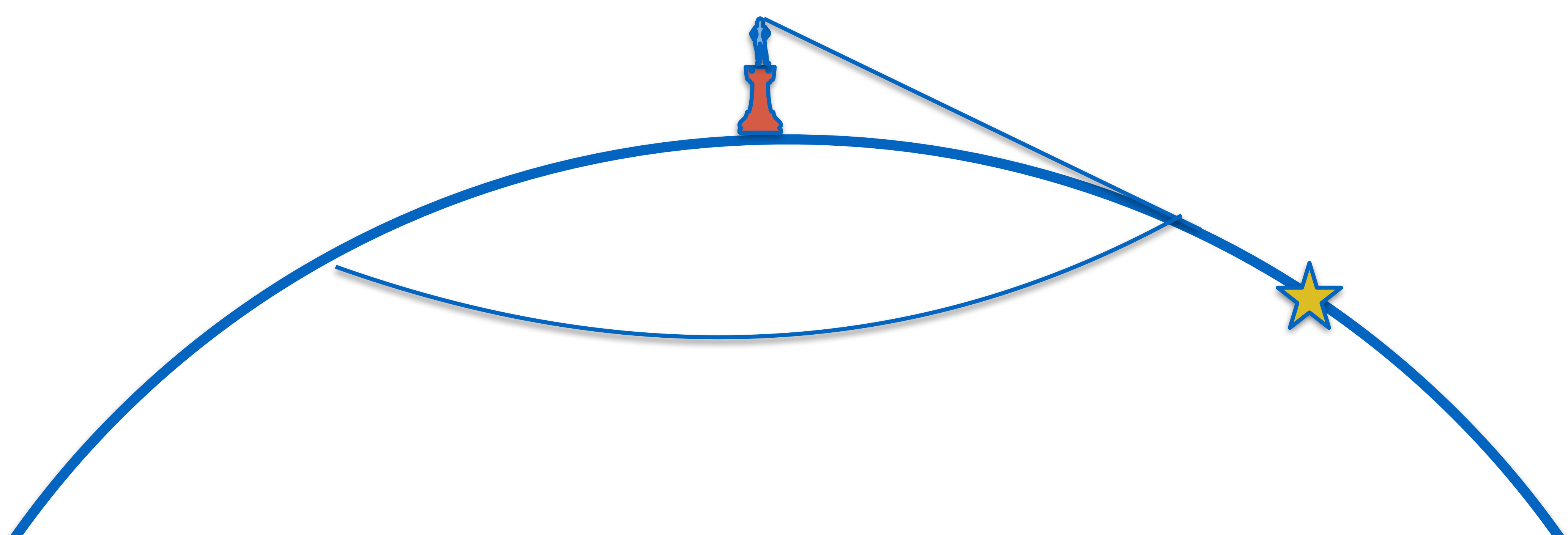
Future of collider physics

- FCC vs muon colliders
- 25 years for FCC_ee
- 50 years for FCC_pp
- 25 ~ 35 years for muon colliders

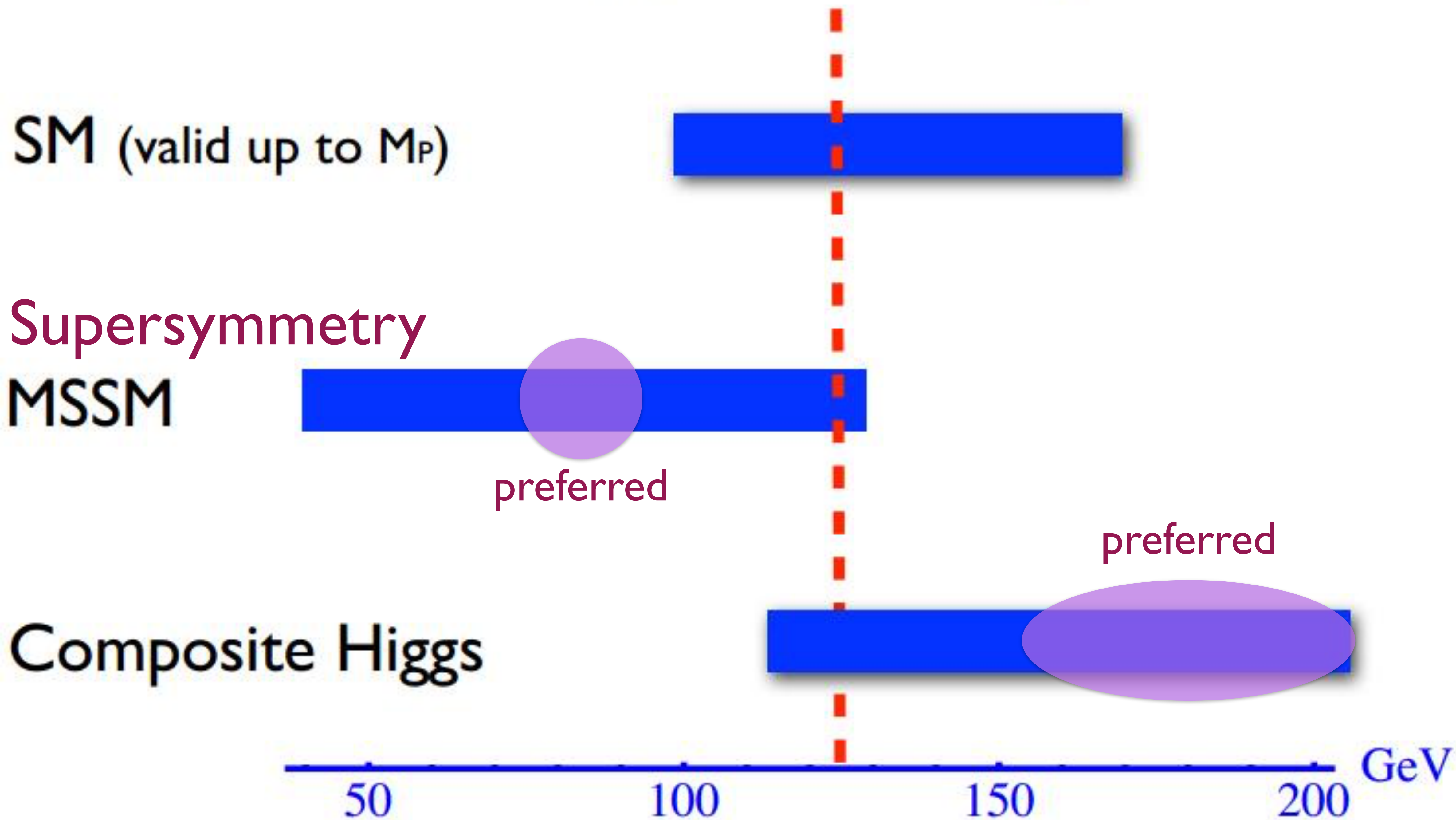
My belief on new physics

- Weak scale supersymmetry at multi-TeV (suggested by Higgs mass)

- It is beyond the horizon we can see now and we need a taller tower to extend the horizon



Higgs mass range



From the talk of Alex Pomarol

Giudice Strumia (2011)

$(\frac{v}{M})^2 \sim 10^{-2}$

$$\left(\frac{v}{M}\right)^2 = 10^{-2}$$

$$\left(\frac{v}{M}\right)^2 \sim 10^{-16}$$

10 TeV

within 50 years

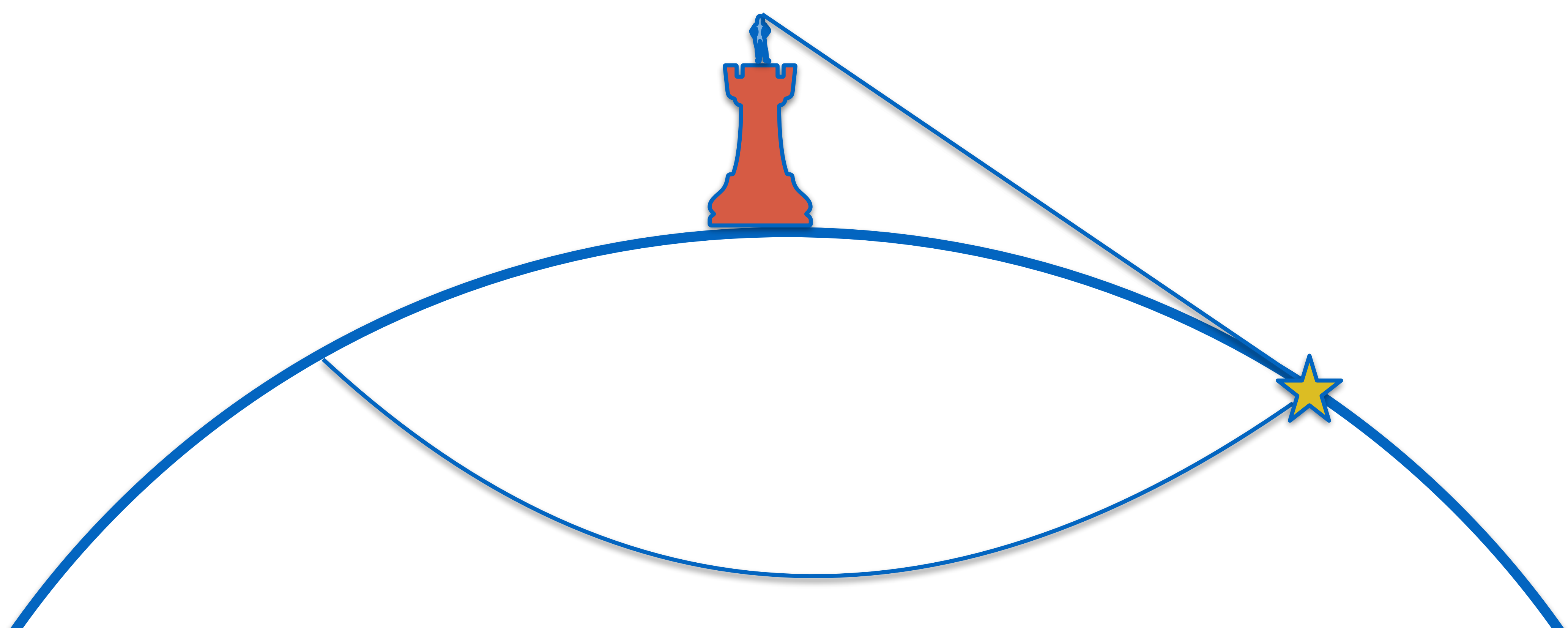
100 TeV

100 years(?)

My belief on new physics

- Weak scale supersymmetry at multi-TeV (suggested by Higgs mass)

- Tall tower? bending light? mirror?



Higgs mass

$$V = m_H^2 |H|^2 + \lambda |H|^4 + \cdots$$ irrelevant operators!

relevant operator! marginal operator!

$\mu \gg m$ $[m_H^2] = 2$ $[\lambda] = 0$

$\mu \sim m$

$\mu \ll m$

relevant operators
are important

cosmological constant

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\rm Pl}^2}{2} R - \Lambda_{\rm cc} \right]$$

relevant operator!

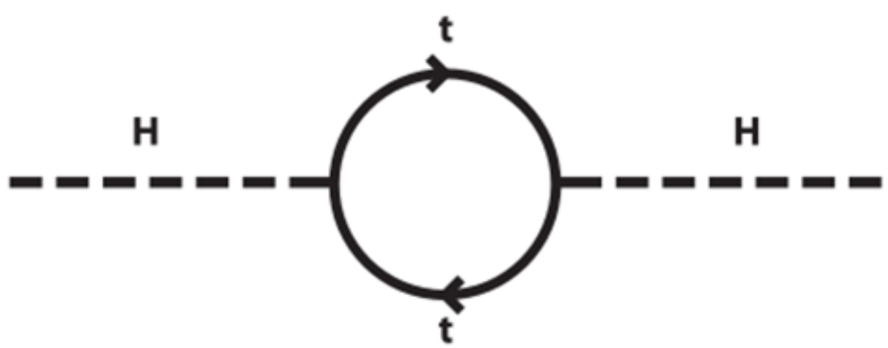
$[\Lambda_{\rm cc}] = 4$

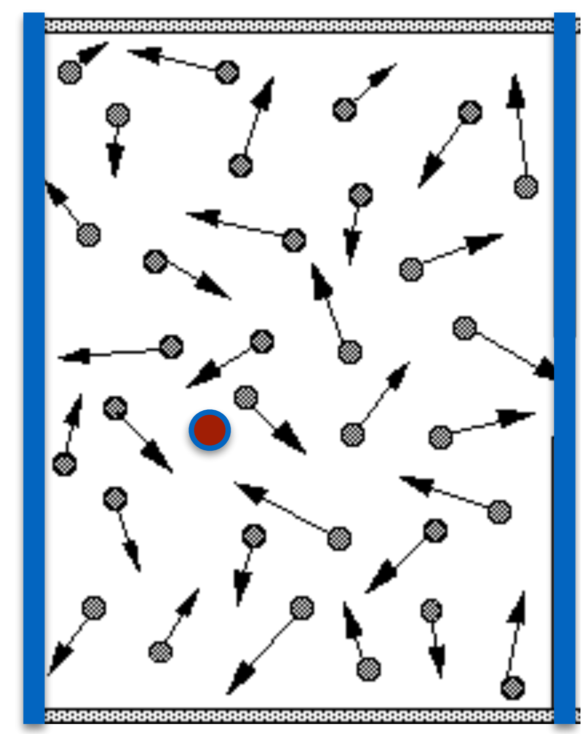
The most notorious problems in fundamental physics

$$\frac{m_h^2}{M_{\rm Pl}^2} \sim 10^{-32}$$

$$\frac{\Lambda_{\rm cc}}{M_{\rm Pl}^4} \sim 10^{-123}$$

Higgs mechanism





$$T_{\text{red}} = 10^{-32}\ T_{\text{grey}}$$

Shielding

$$\delta m_h^2 = \frac{3\, m_t^2}{2\pi^2 v^2}\, \Lambda^2$$

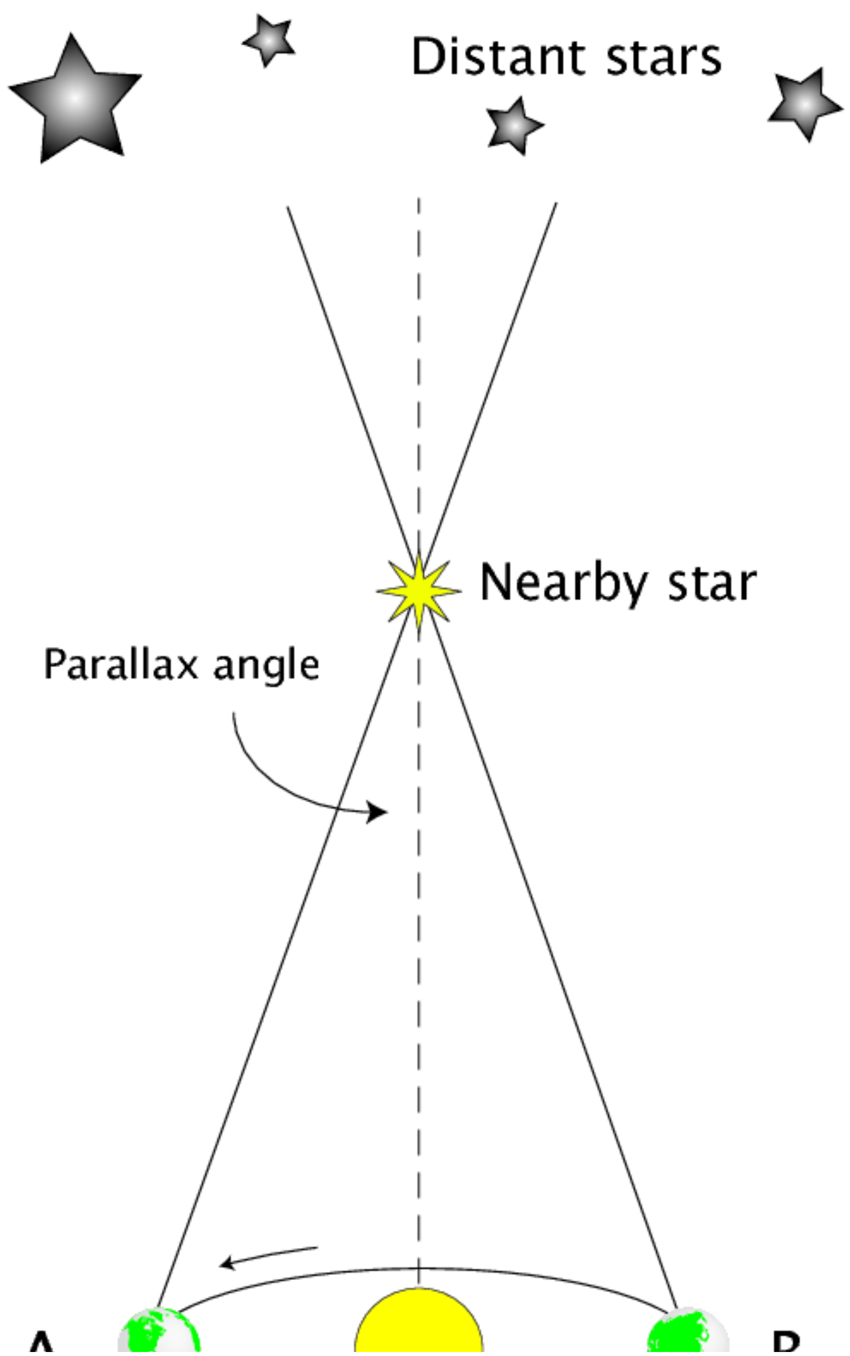
$$m_h^2 = m_{h0}^2 + \delta m_h^2$$

It is unnatural to have $m_h^2 \ll \Lambda^2$

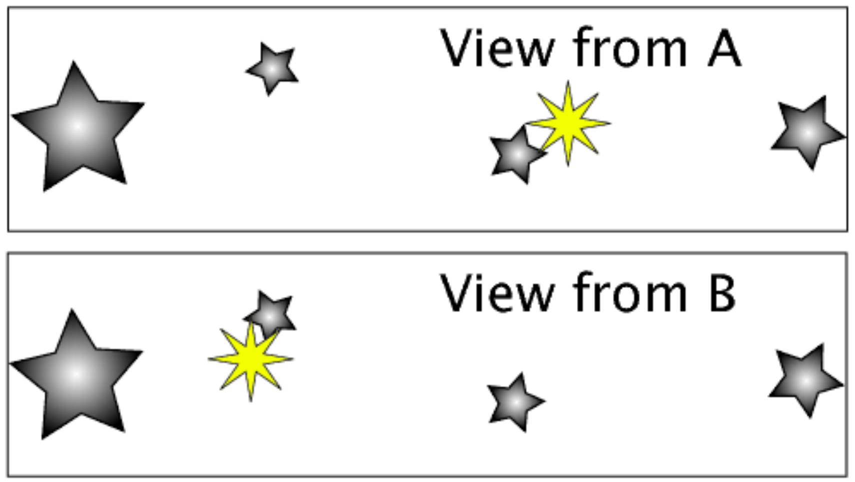
It implies new effective theory at TeV scale

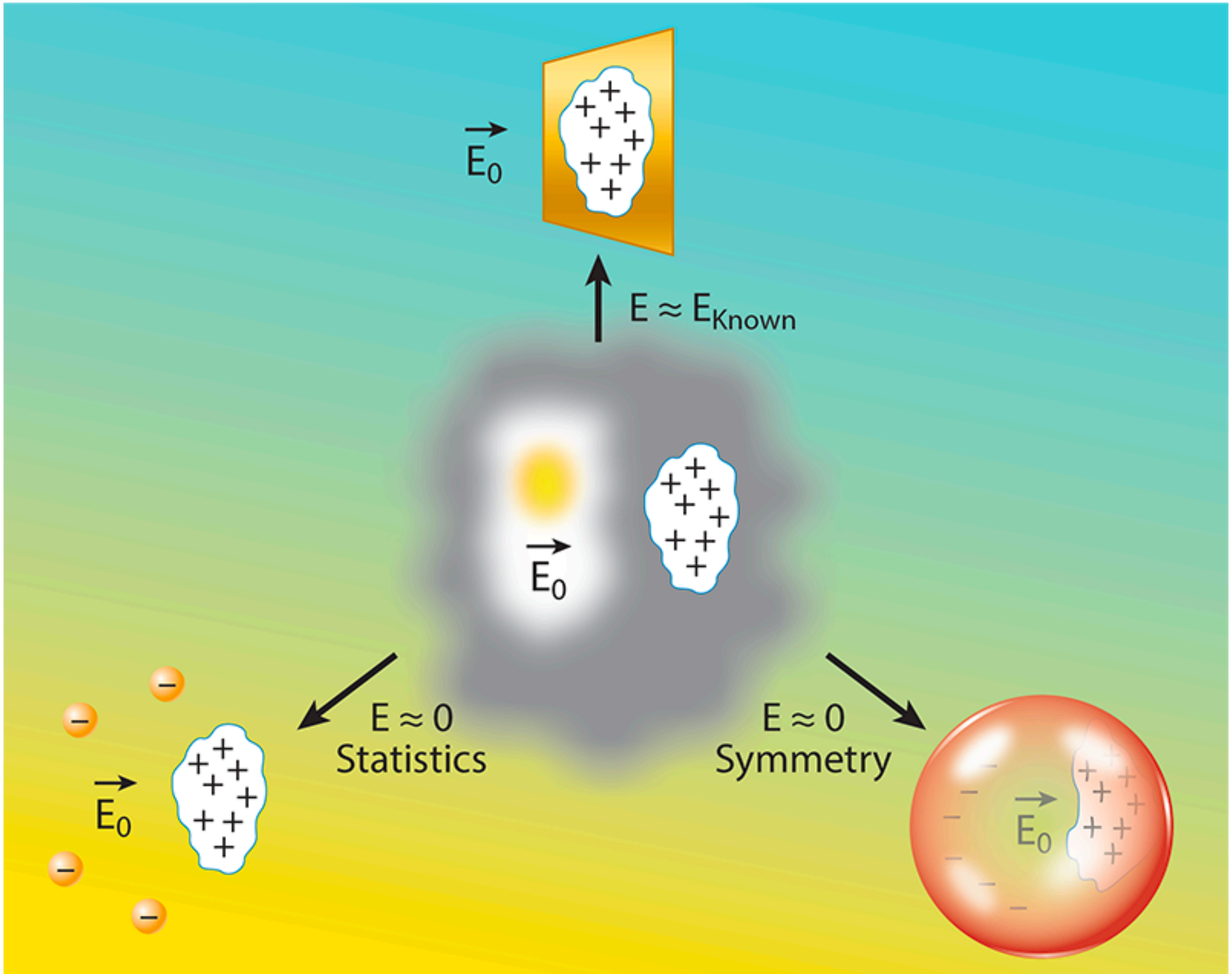
supersymmetry, composite Higgs, technicolor, etc.

Example on (un)naturalness



두번째 가까운 별
4.22광년
20,000 AU




$\vec{E}_0$
$E \approx E_{Known}$
$\vec{E}_0$
$E \approx 0$
Statistics
$E \approx 0$
Symmetry
$\vec{E}_0$
$\vec{E}_0$

Beyond Collider Physics :1st example

- Nnaturalness: N copies of the Standard Model with varying Higgs masses
- Predicts deviation in standard cosmology: dark radiation ($\Delta N_{\rm eff}$), dark disc, matter power spectrum
- No new particles at the LHC

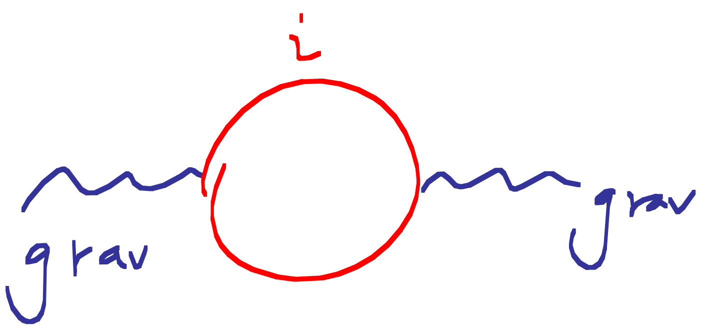
Dvali Redi PRD (2009)

Arkani-Hamed Cohen D'agnolo Hook HDK Pinner, PRL (2016)

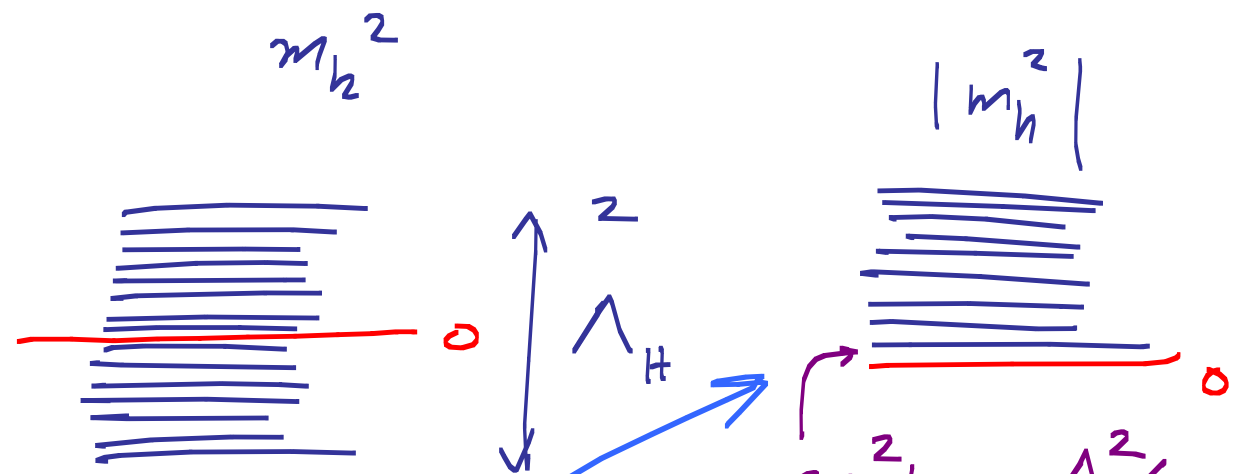
$N = 10^{32}$

$\Lambda_* = 100$ GeV

N copies of (MS) SM



$M_{pl}^2 \sim N \Lambda_*^2$



$|m^2_{min}| \sim \Lambda^2/N$

enormous reduction of dof

if reheaton is a pNGB

Cosmology Dominantly Reheats Bottom of Spectrum

scenario I

$N = 10^{16}$

$\Lambda_* = \Lambda_H = 10^{10}$ GeV

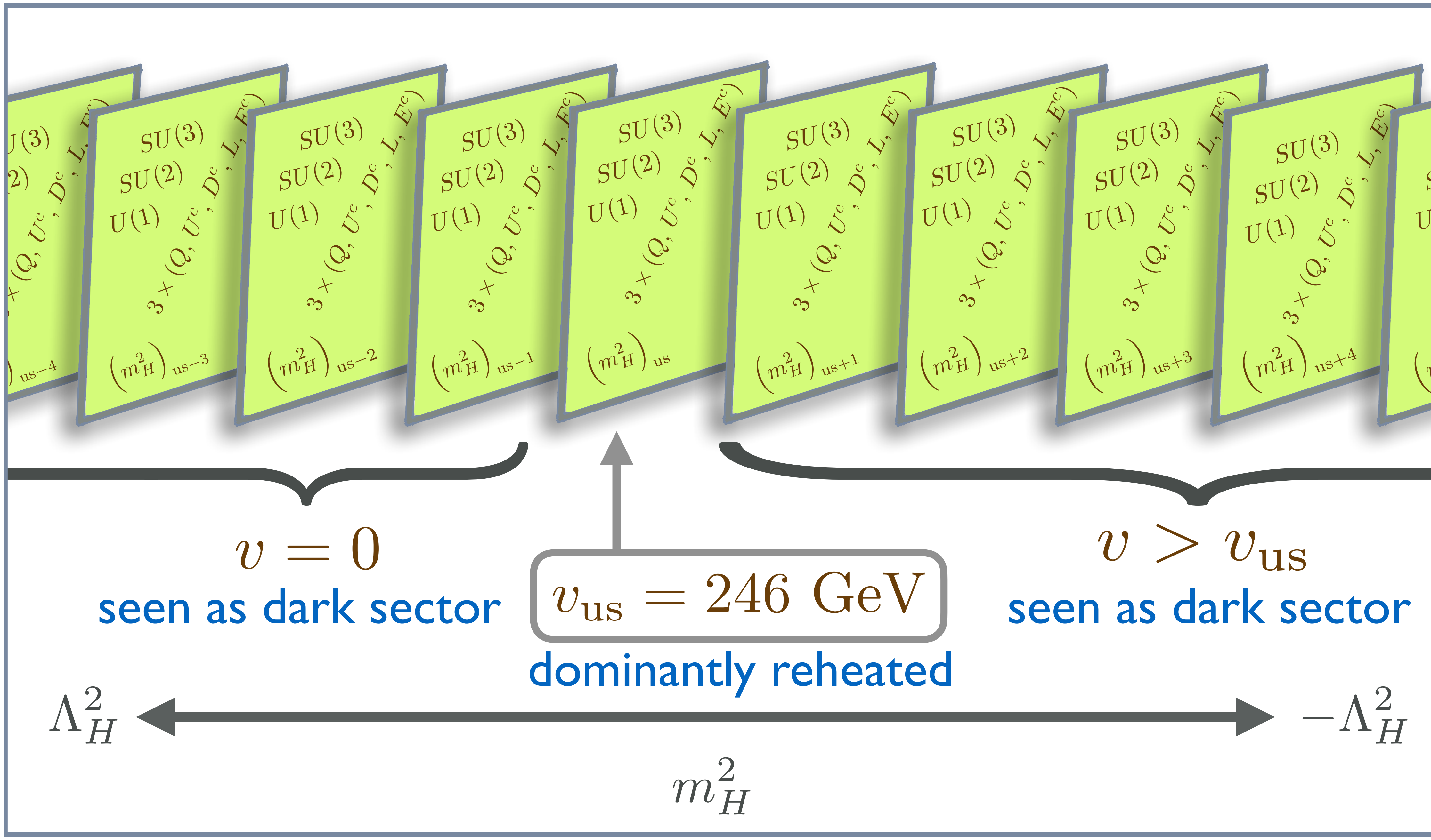
scenario II

$N = 10^4$

$\Lambda_* = 10^{16}$ GeV

$\Lambda_H = 10$ TeV

by N Arkani-Hamed



$$\left(m_H^2\right)_i = -\frac{\Lambda_H^2}{N}\left(2\,i + r\right), \qquad -\frac{N}{2} \leq i \leq \frac{N}{2}$$

Arkani-Hamed Cohen D'agnolo
Hook HDK Pinner, PRL (2016)

Arkani-Hamed Cohen D'agnolo Hook HDK Pinner, PRL (2016)

scalar reheat

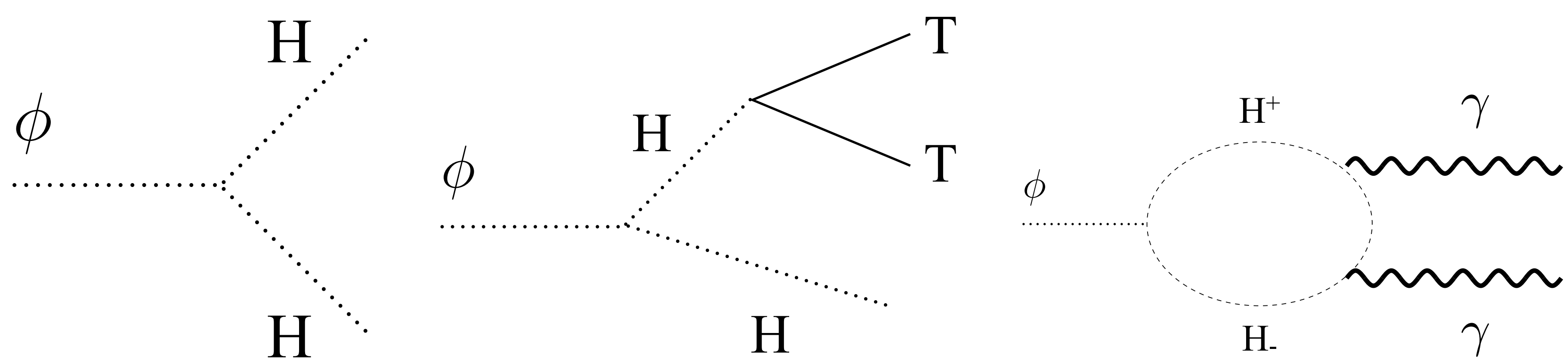
$A\phi H^\dagger H$

fermion reheat

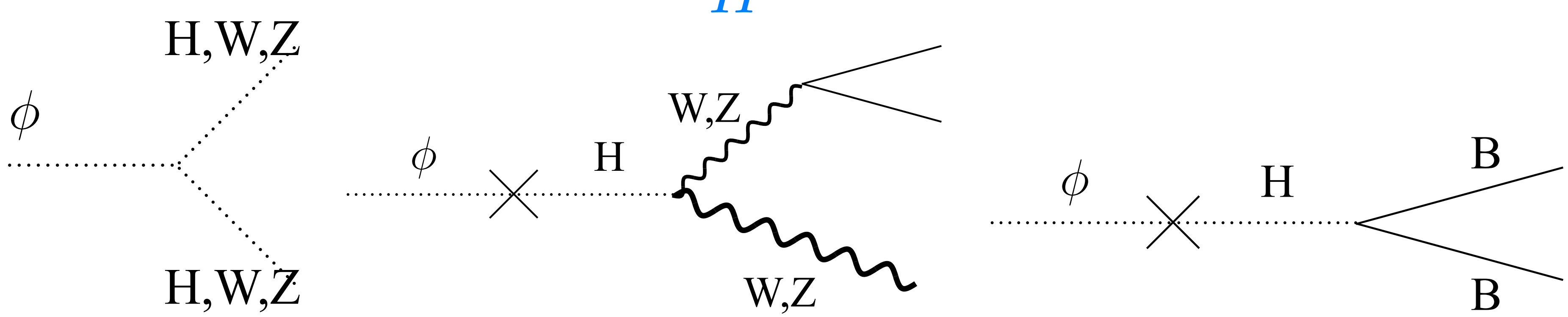
$\lambda S L H$

population of the sectors

$m_H^2 > 0$



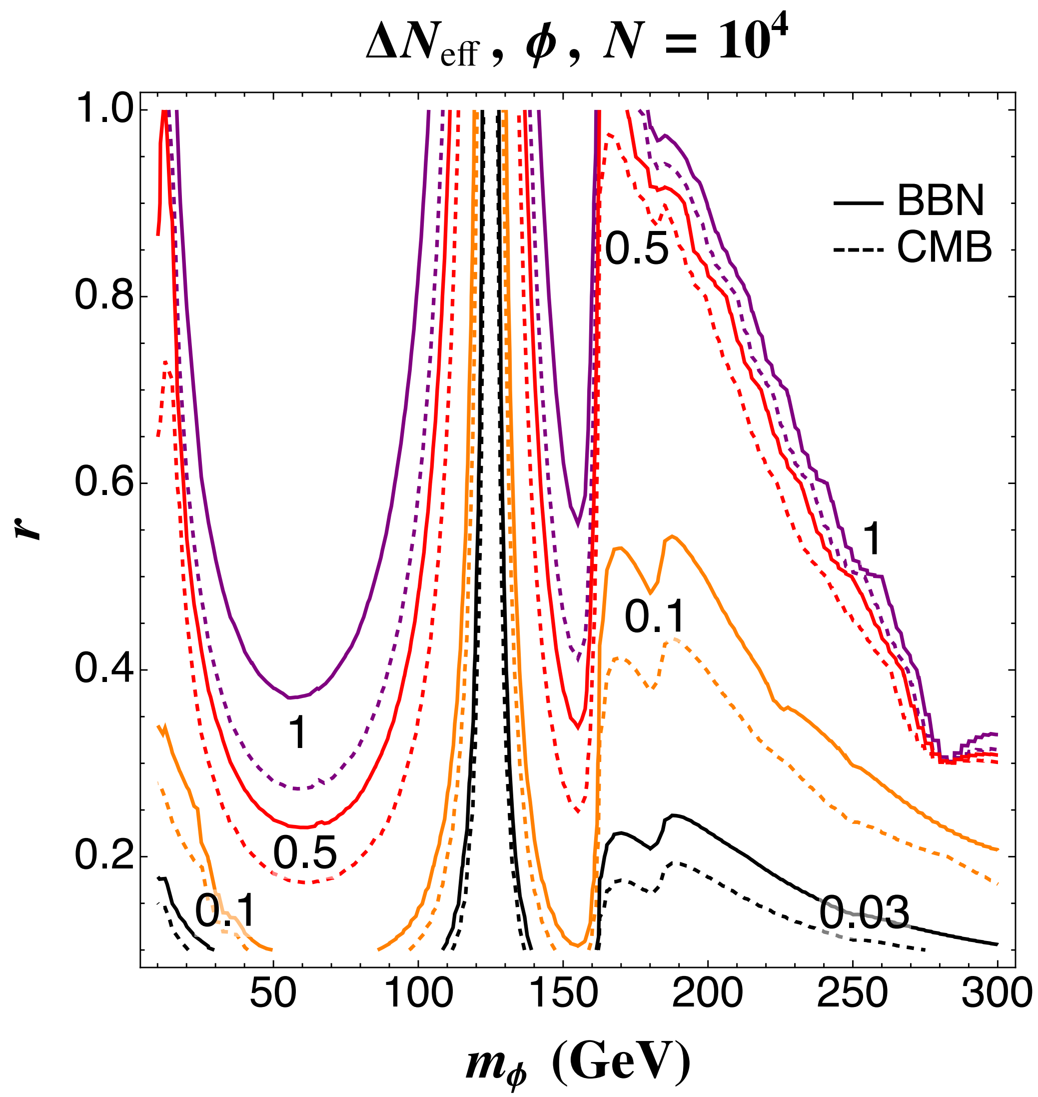
$m_H^2 < 0$

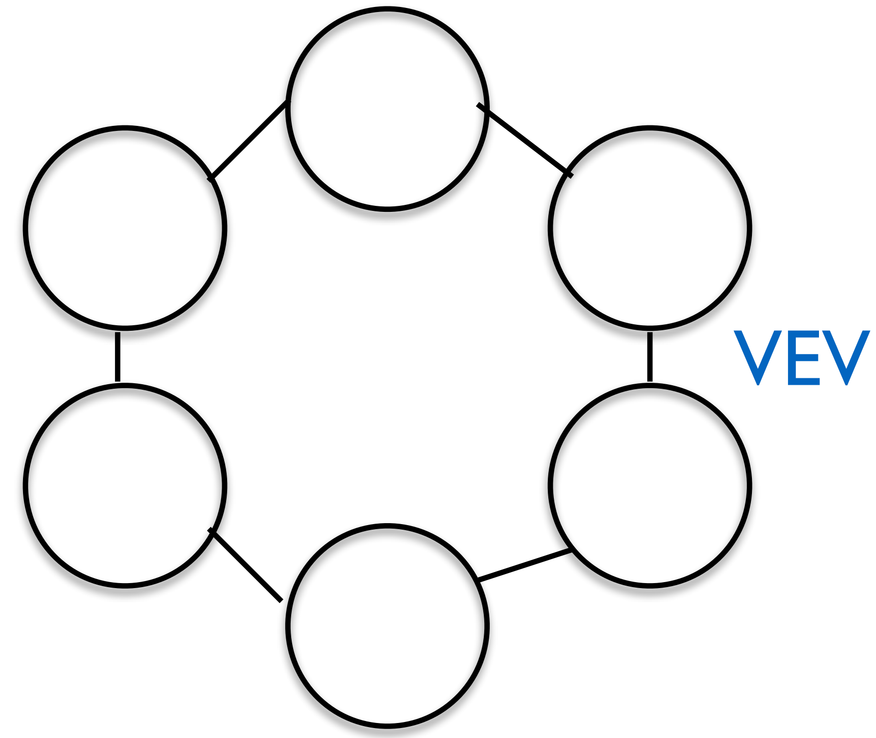


$$\mathcal{L}_\phi^{\langle H \rangle \neq 0} \supset \mathcal{C}_1^\phi \, a \, y_q \frac{v}{m_h^2} \phi \, q \, q^c \, ;$$

$$\mathcal{L}_\phi^{\langle H \rangle = 0} \supset \mathcal{C}_3^\phi \, a \, \frac{g^2}{16\,\pi^2} \frac{1}{m_H^2} \, \phi \, W_{\mu\nu} W^{\mu\nu} \, ,$$

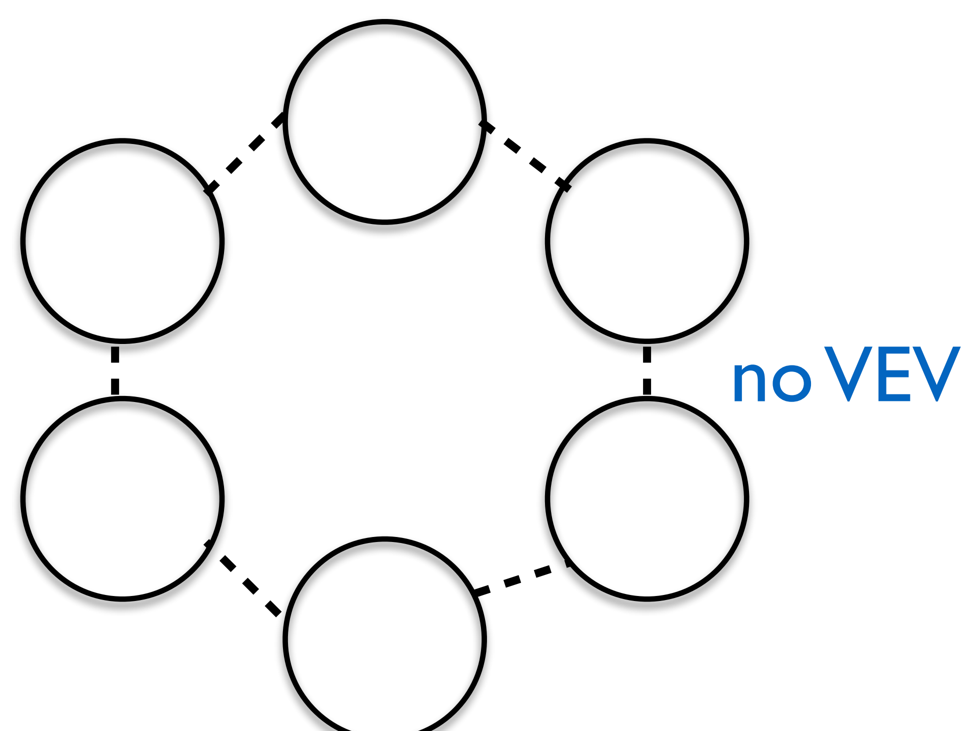
different phase of deconstruction





phase A : extra dimension

phase B : Nnaturalness



dark radiation $4.4 + 3 = 7.4$

photon neutrino

Br(i=2)~ 0.1

generic prediction $\Delta N_{\rm eff} \sim \mathcal{O}(1)$

Arkani-Hamed Cohen D'agnolo Hook HDK Pinner, PRL (2016)

Beyond Collider Physics :2nd example

- Weak scale as a trigger
- Predicts an additional Higgs at the weak scale
- Extremely light scalar particles are present
- No new fermions at the weak scale

PHYSICAL REVIEW D **104,** 095014 (2021)

Editors' Suggestion Featured in Physics

Weak scale as a trigger

Nima Arkani-Hamed,[1] Raffaele Tito D'Agnolo,[2] and Hyung Do Kim[3]

[1] *School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*
[2] *Université Paris-Saclay, CNRS, CEA, Institut de physique théorique, 91191, Gif-sur-Yvette, France*
[3] *Department of Physics and Astronomy and Center for Theoretical Physics, Seoul National University, Seoul 08826, Korea*

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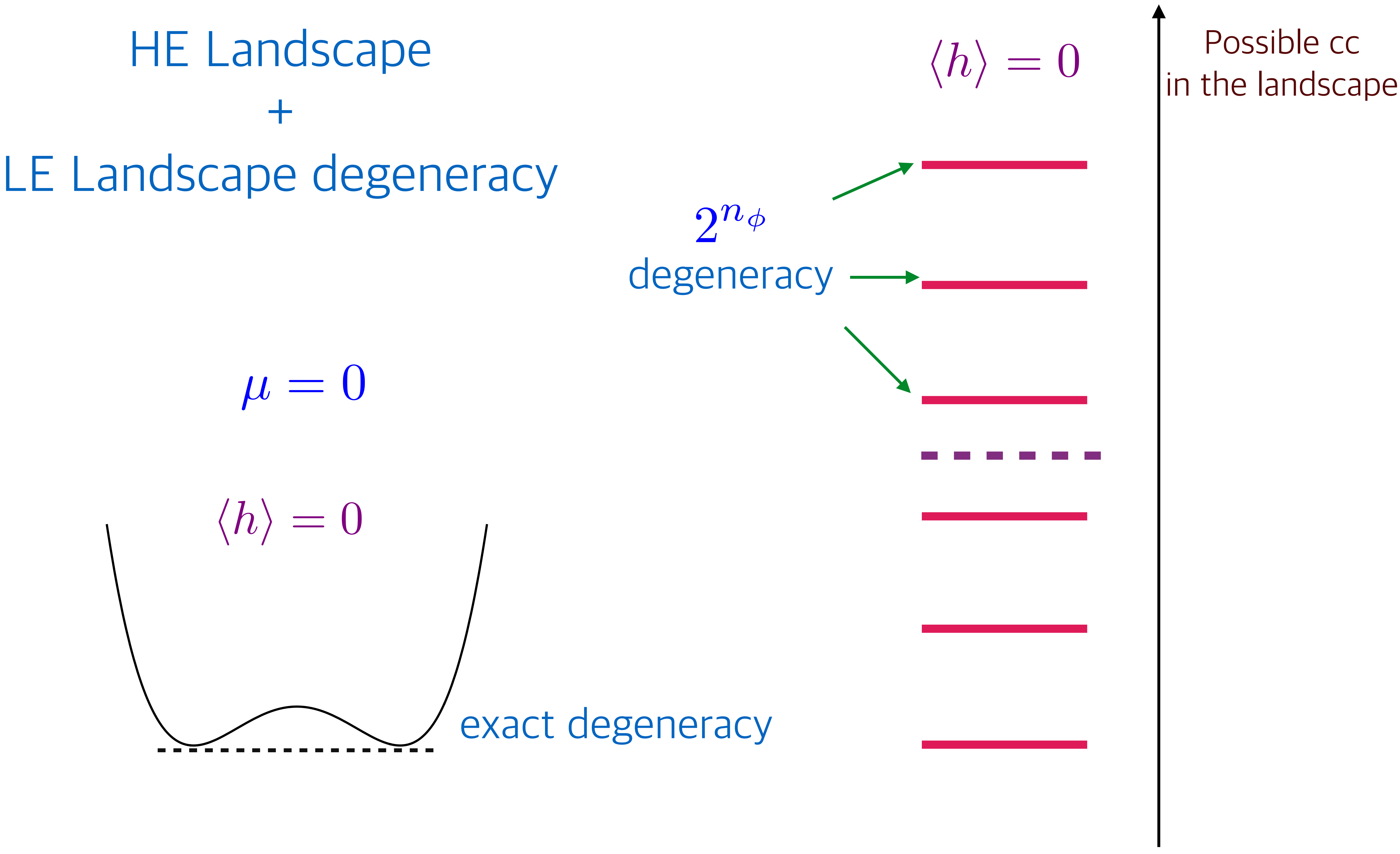
Does the value of the Higgs mass parameter affect the expectation value of local operators in the Standard Model? For essentially all local operators the answer to this question is "no", and this is one of the avatars of the hierarchy problem: Nothing is "triggered" when the Higgs mass parameter crosses zero. In this article, we explore settings in which Higgs mass parameters *can* act as a "trigger" for some local operators $\mathcal{O}_T$. In the Standard Model, this happens for $\mathcal{O}_T = \mathrm{Tr}(G\tilde{G})$. We also introduce a "type-0" two Higgs doublet model, with a Z_4 symmetry, for which $\mathcal{O}_T = H_1 H_2$ is triggered by the Higgs masses, demanding the existence of new Higgs states necessarily comparable to or lighter than the weak scale, with no wiggle room to decouple them whatsoever. Surprisingly, this model is not yet entirely excluded by collider searches, and will be incisively probed by the high-luminosity run of the LHC, as well as future Higgs factories. We also discuss a possibility for using this trigger to explain the origin of the weak scale, invoking a landscape of extremely light, weakly interacting scalars ϕ_i, with a coupling to $\mathcal{O}_T$ needed to make it possible to find vacua with small enough cosmological constant. The weak scale trigger links the tuning of the Higgs mass to that of the cosmological constant, while coherent oscillations of the ϕ_i can constitute dark matter.


HE Landscape
+
LE Landscape degeneracy
$\mu = 0$
$\langle h \rangle = 0$
exact degeneracy
2^{n_ϕ}
degeneracy
$\langle h \rangle = 0$
Possible cc
in the landscape

HE Landscape

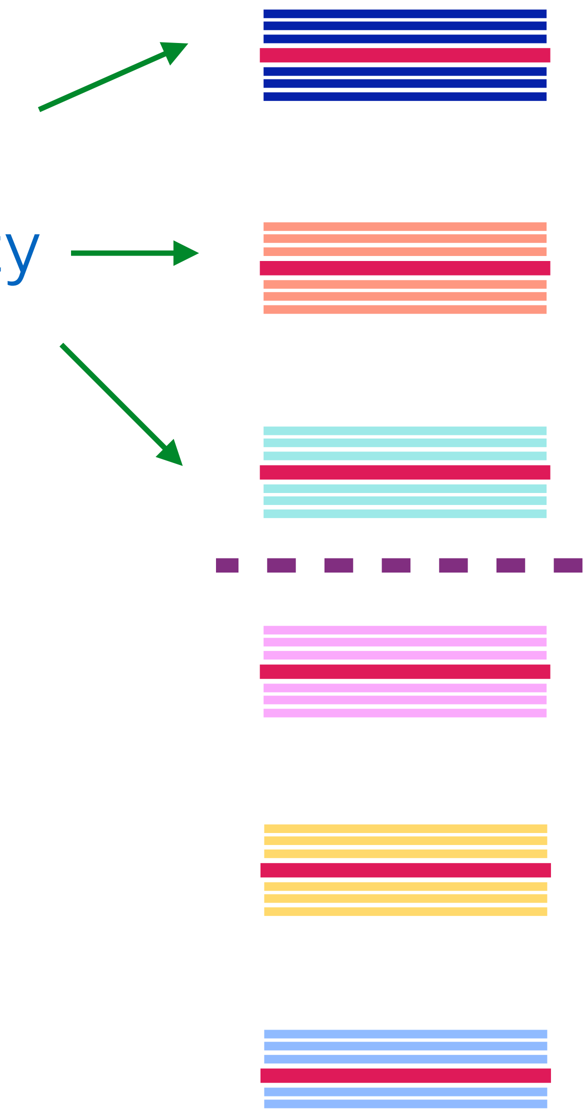
+

LE Landscape degeneracy lifted

$\langle h \rangle < \mu_S$

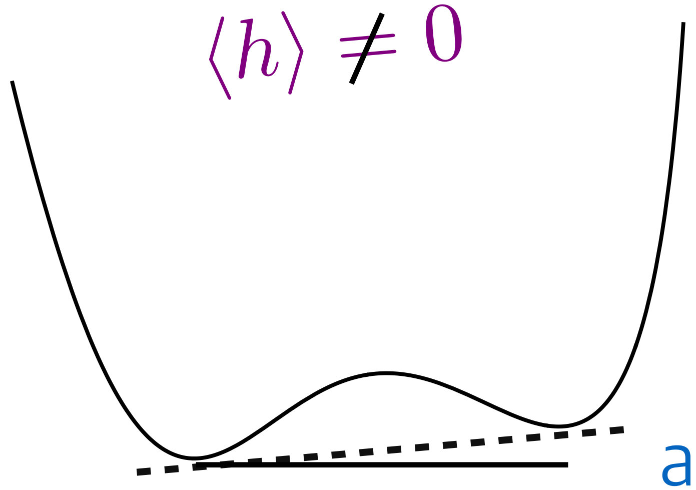
2^{n_ϕ}

degeneracy



$\mu \leq \mu_S$

$\langle h \rangle \neq 0$



approximate degeneracy

HE Landscape

+

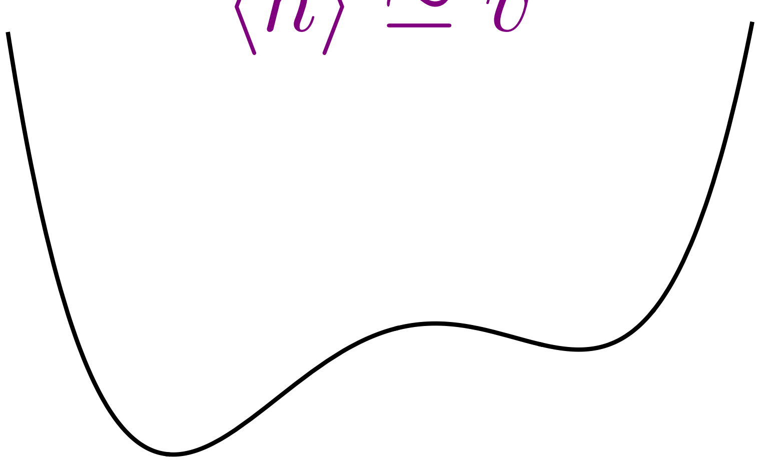
LE Landscape degeneracy lifted

fill up the gap of the HE landscape

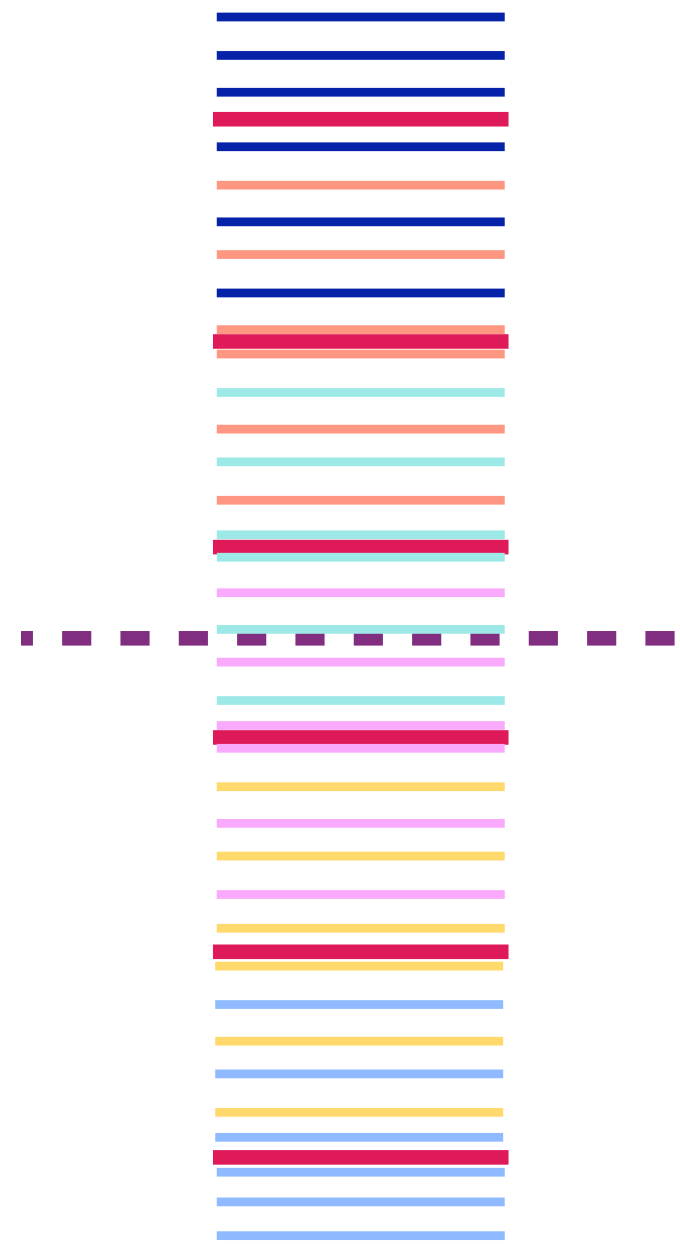
no distinction between HE and LE landscape

$$\mu_S \leq \mu \leq \mu_B$$

$$\langle h \rangle \simeq v$$



$$\mu_S \lesssim \langle h \rangle \lesssim \mu_B$$



HE Landscape

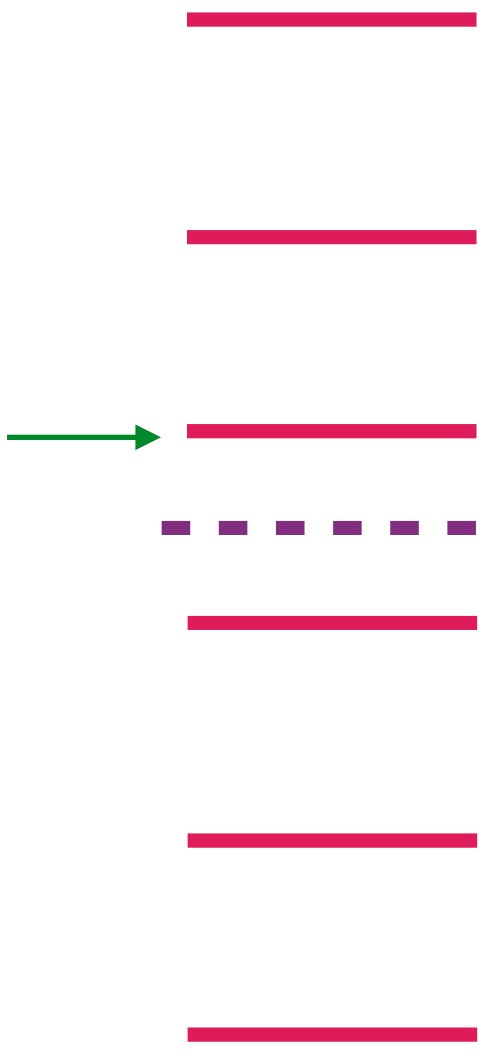
+

LE Landscape degeneracy lifted

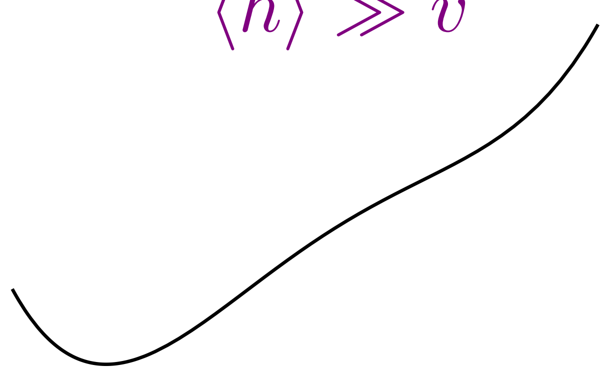
$\langle h \rangle \gg \mu_B$

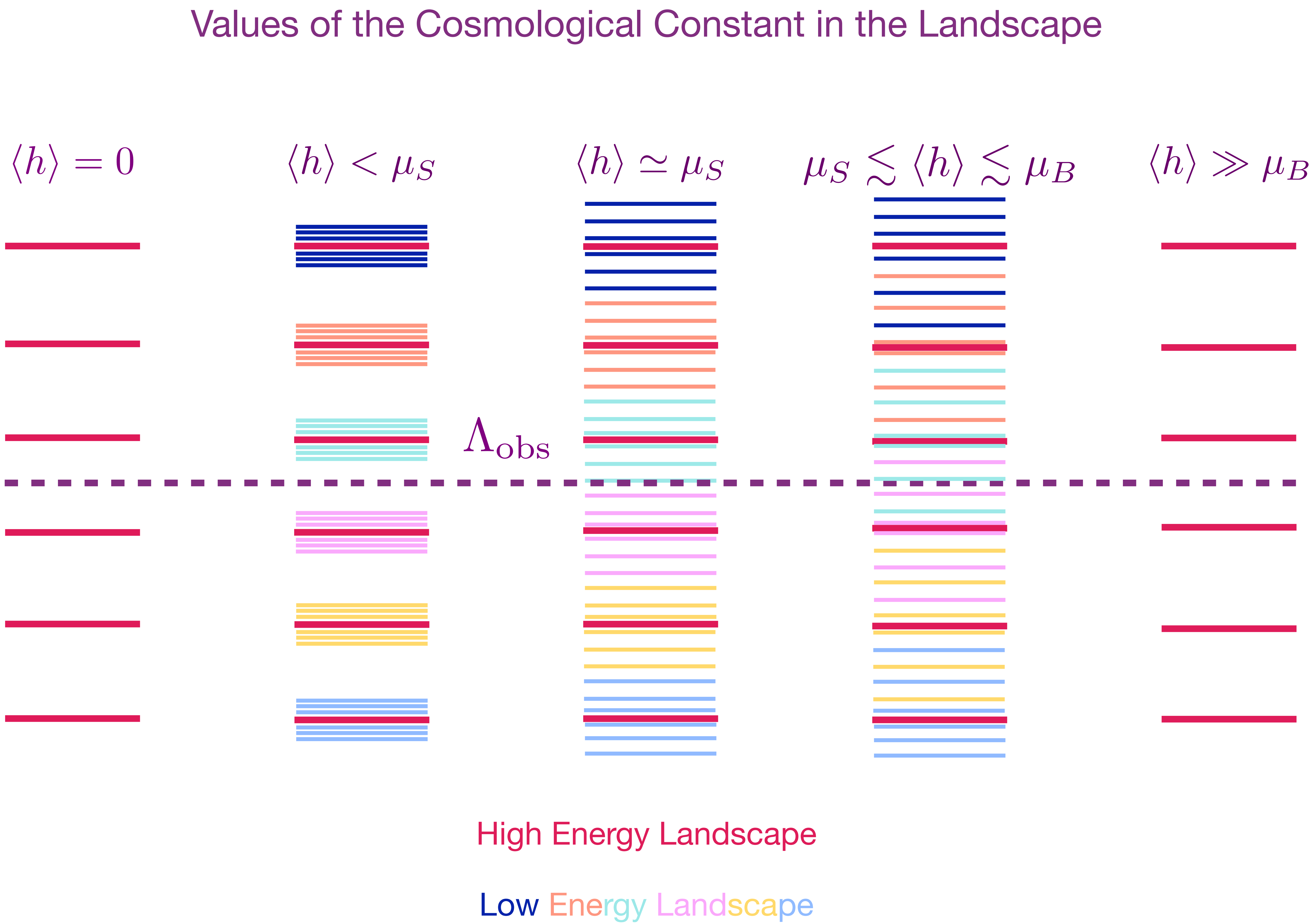
$\mu \geq \mu_B$

no degeneracy

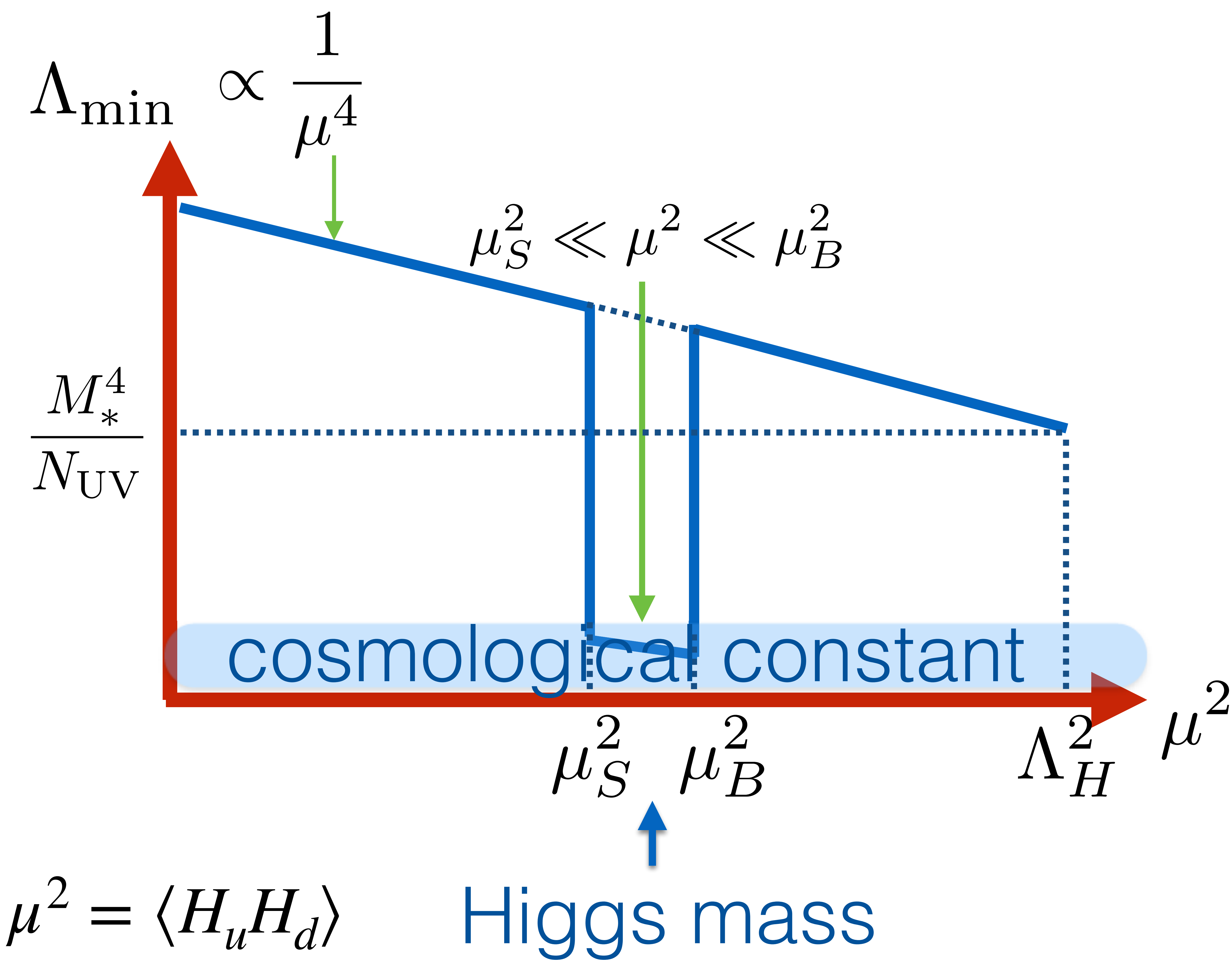


$\langle h \rangle \gg v$





Values of the Cosmological Constant in the Landscape
$\langle h \rangle = 0$
$\langle h \rangle < \mu_S$
$\langle h \rangle \simeq \mu_S$
$\mu_S \lesssim \langle h \rangle \lesssim \mu_B$
$\langle h \rangle \gg \mu_B$
$\Lambda_{\rm obs}$
High Energy Landscape
Low Energy Landscape



$\Lambda_{\rm min} \propto \frac{1}{\mu^4}$
$\mu_S^2 \ll \mu^2 \ll \mu_B^2$
$\frac{M_*^4}{N_{\rm UV}}$
cosmological constant
μ^2
μ_S^2
μ_B^2
Λ_H^2
Higgs mass
$\mu^2 = \langle H_u H_d \rangle$

Lessons

- Forward detector
- Fixed target experiments
- Anti-matter experiments
- Neutrino experiments
- All of these experiments might be important

Physics Beyond Colliders Study Group (2016–)

Develop ideas to renew CERN's fixed-target program

Charge: Explore the opportunities offered by CERN's unique accelerator complex, its scientific and technical infrastructure, and its know-how in accelerator and detector science and technology, to address today's outstanding questions in particle physics through initiatives that complement the goals of the main experiments of the Laboratory's collider programme.

Primarily investigate, and, where appropriate, provide support to, projects expected to be sited at CERN. May also examine ideas and provide initial support for contributions to projects external to CERN.

Create a central forum for exchanges between the PBC experimental community and theorists for assessment of the physics reach of the proposed projects in a global landscape.

From the talk of Chris Quigg

Example Physics Objectives

- Dedicated experiments for studies of rare processes and searches for feebly interacting particles
- Projects aimed at addressing fundamental particle physics questions using the experimental techniques of nuclear, atomic, and astroparticle physics
- Emerging technologies such as quantum sensors, that would benefit from the contribution of CERN competences and expertise
- Respond to community initiatives outside the current CERN program

Diversity and Scale Diversity

From the talk of Chris Quigg

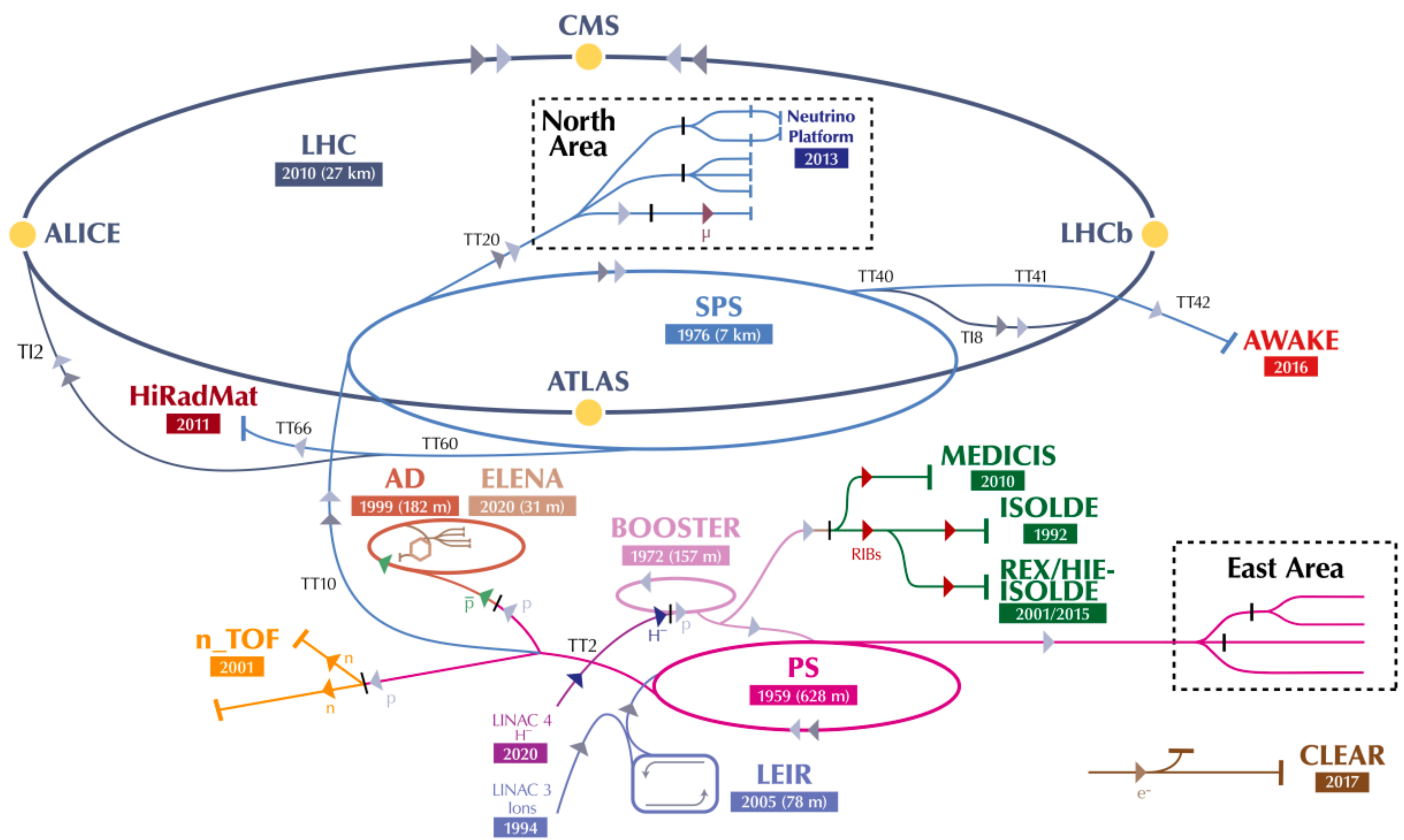
Current PBC Organization

Coordinators

Gianluigi Arduini (CERN), ACC
Jörg Jaeckel (Heidelberg), TH
Claude Vallée (Marseille), EXP

2019 Summary Report
arXiv:1902.00260
$\rightsquigarrow$ Eurostrategy Update

The CERN accelerator complex
Complexe des accélérateurs du CERN



H⁻ (hydrogen anions) p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons) μ (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

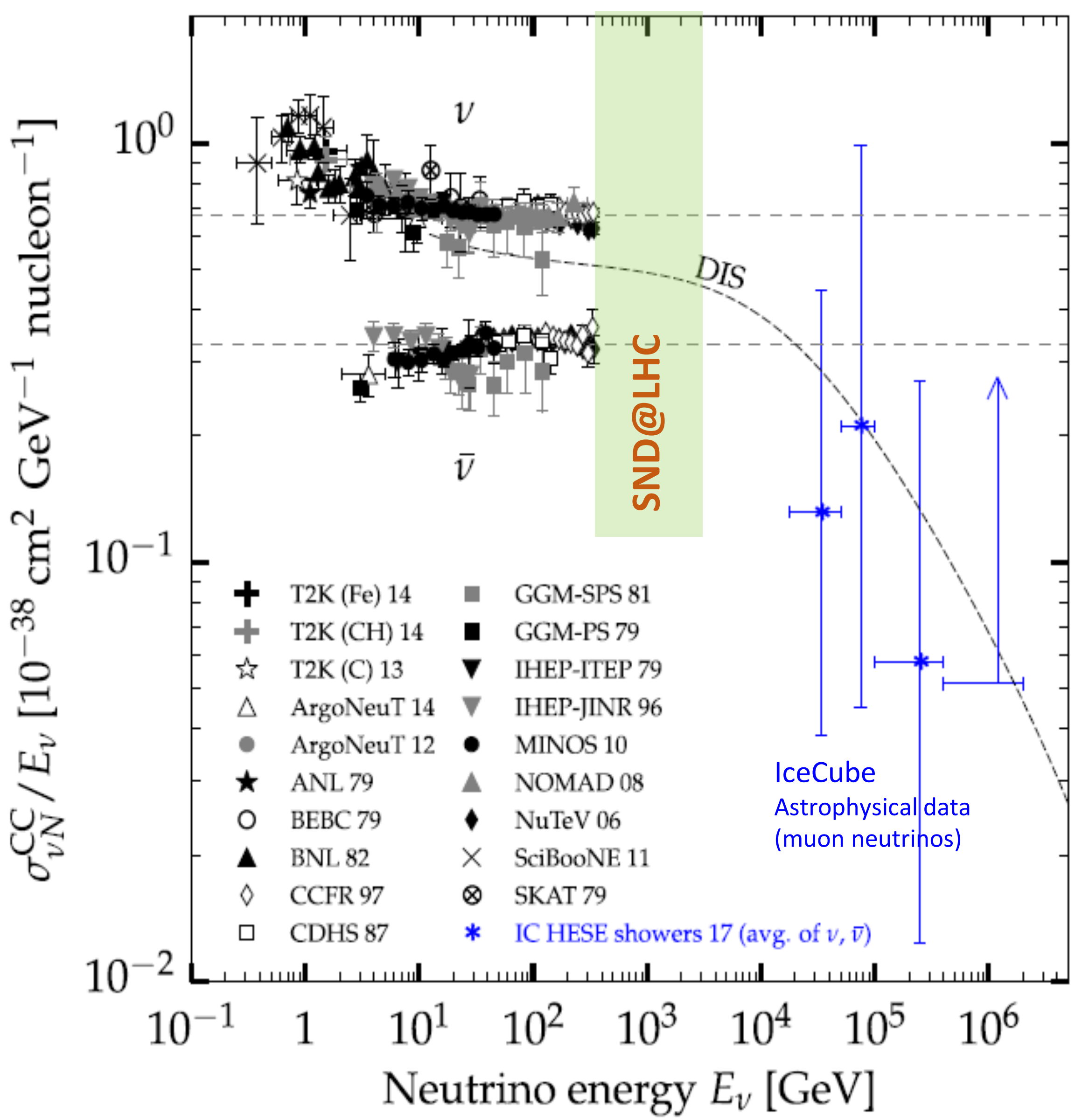
SND @ LHC

Scattering and Neutrino Detector at LHC

From the talk of CS Yoon

Motivation

Study of **High-energy neutrinos** in unexplored energy region
& Search for **Feebly interacting particles (FIPs)**



Neutrino interactions

- LHC can create huge numbers of high-energy neutrinos in the **forward directon**.
- Measure ν interactions in unexplored energy range (~TeV) and unexplored pseudo-rapidity region
  SND@LHC : $7.2 < \eta < 8.4$ (off-axis)
  FASERν : $\eta > 8.8$ (on-axis).
- Detection of all three types of neutrinos
  → Test of lepton flavour universality
- Neutrino is a good prove for heavy flavors
  → Measure Neutrino induced forward charm production

Search for FIPs

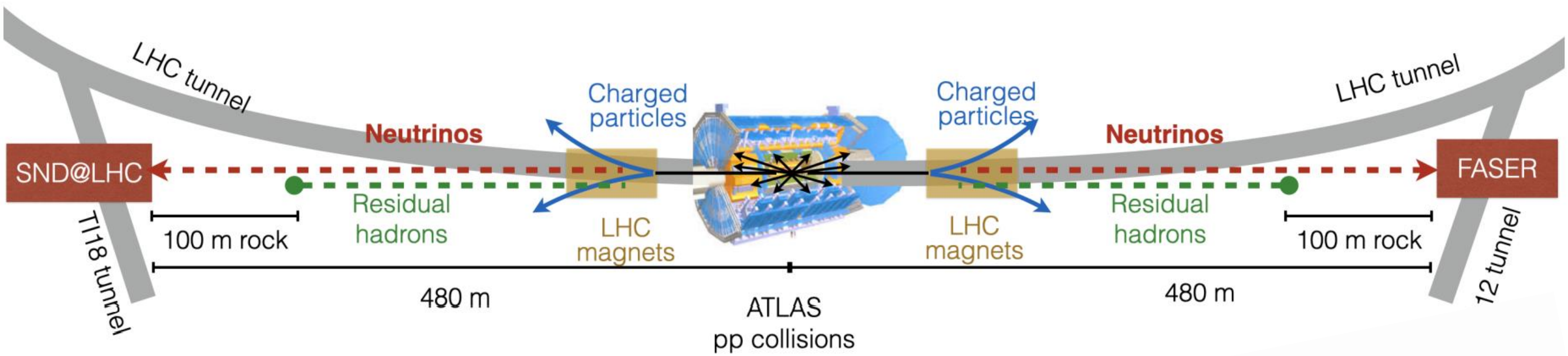
- Search for the Feebly interacting particles **decaying** within the detector or **scattering** off the target.

SND@LHC and FASER

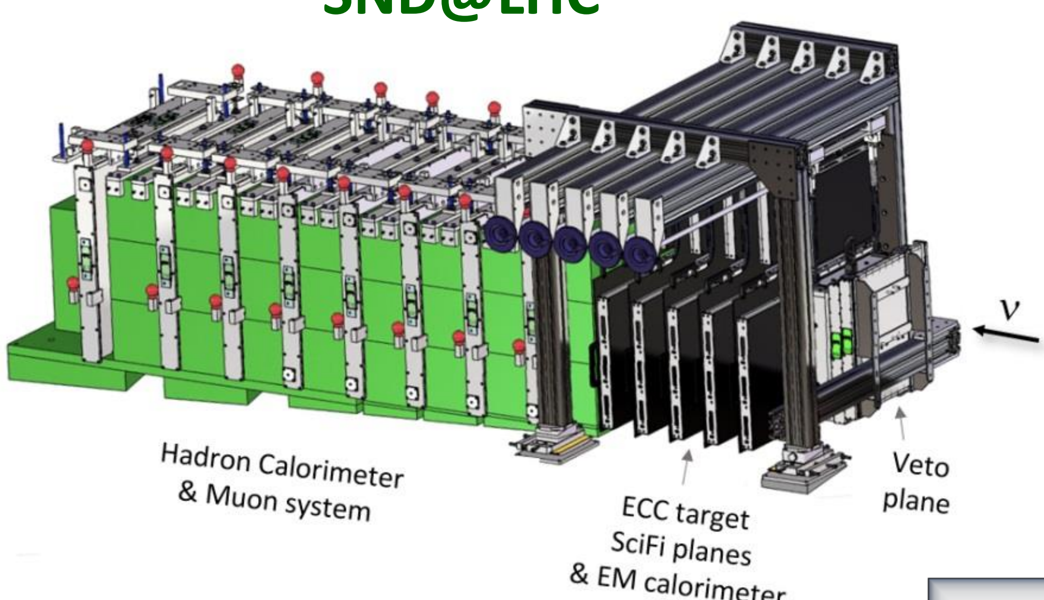
From the talk of CS Yoon

Symmetric - 480 m away from ATLAS IP
Complementarity - different η range

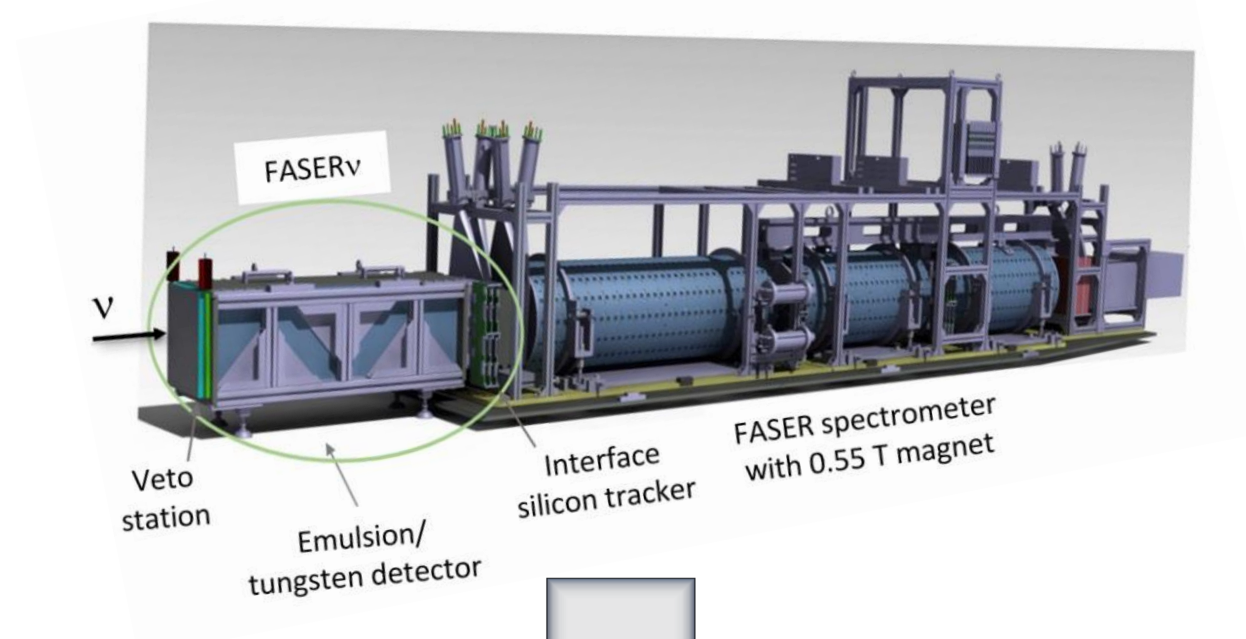
Suitable experimental environment
LHC magnet - deflect charged particles
100 m rock - absorb residual hadrons



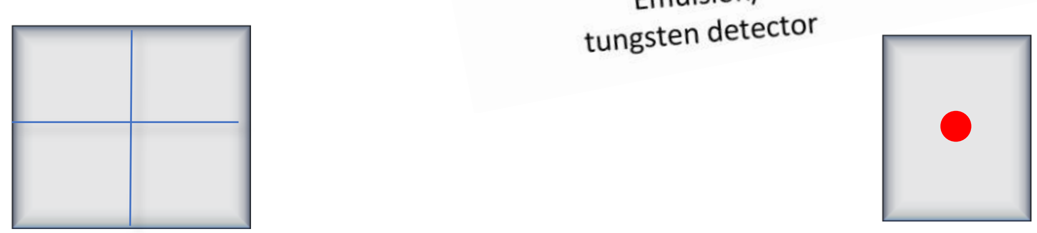
SND@LHC



FASER & FASERν



$7.2 < \eta < 8.4$
off-axis



● Beam collision axis

$\eta > 8.8$
on-axis

From the talk of CS Yoon

Physics result (2022 run) – only by electronic detector

The first observation of Collider Neutrinos: 8 ν_μ CC events

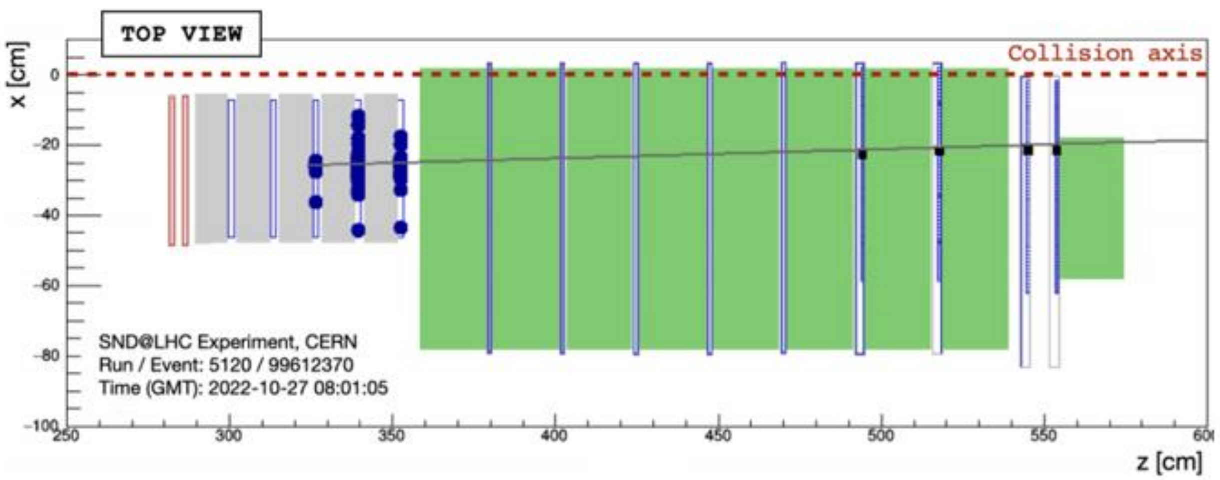
Estimated background : 0.086 events

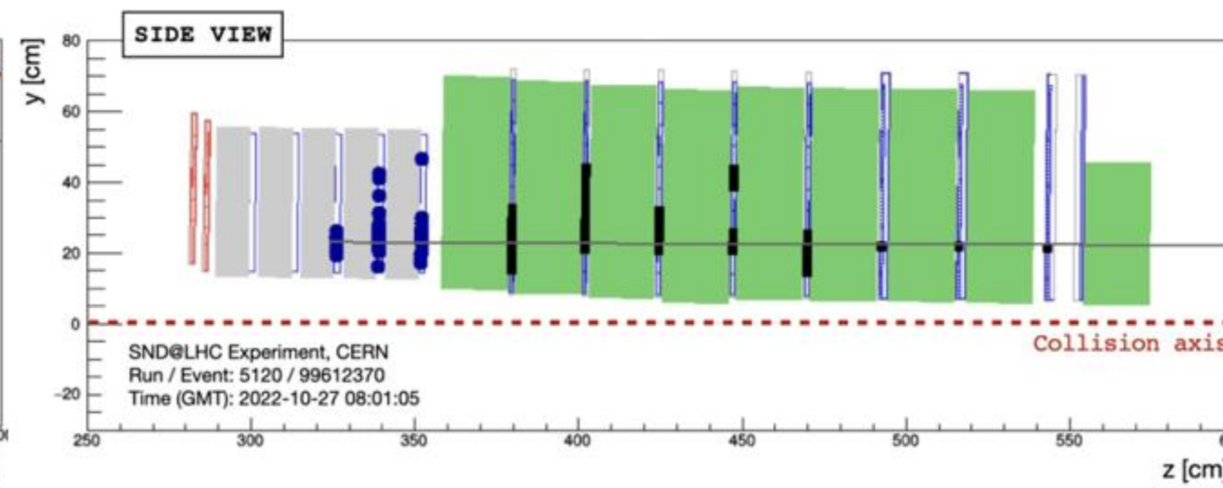
Significance : 6.8 σ

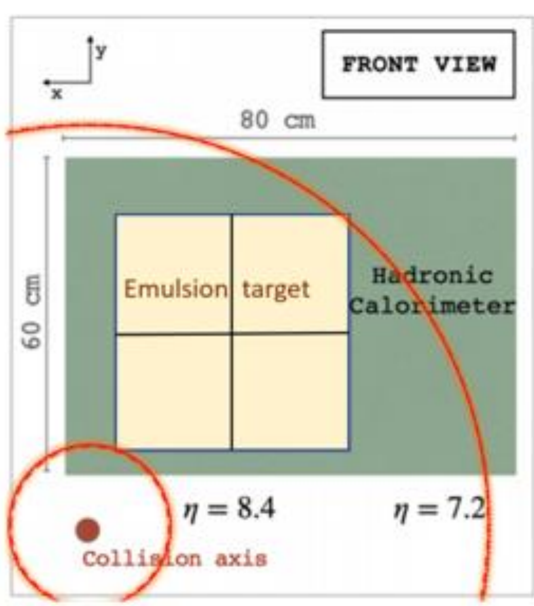
PRL 131, 031802 (2023)

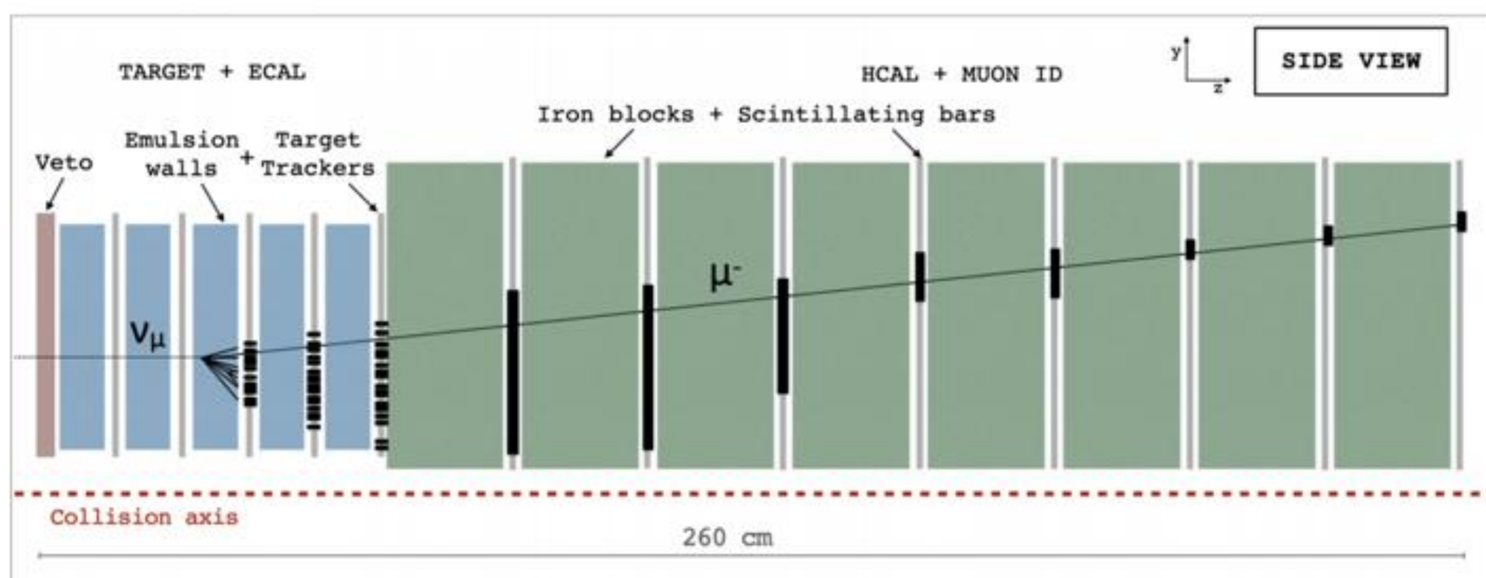
$\sqrt{s}$ = 13.6 TeV

36.8 fb^{-1}









SND@LHC Collaboration

- Bulgaria
- Denmark
- Germany
- Italy
- Japan
- Korea
- Russia
- Switzerland
- Turkey
- United Kingdom
- Portugal
- Chile
- Brazil
- CERN

180 members, 24 institutes
13 countries & CERN

(Korean group: 4 institutes, 8 members)

From the talk of CS Yoon

Korean group member (SND@LHC & SHiP)

Gyeongsang National University (GNU)

S. H. Kim, K. Y. Lee, B. D. Park, J. Y. Sohn, C. S. Yoon

Korea University (KU)

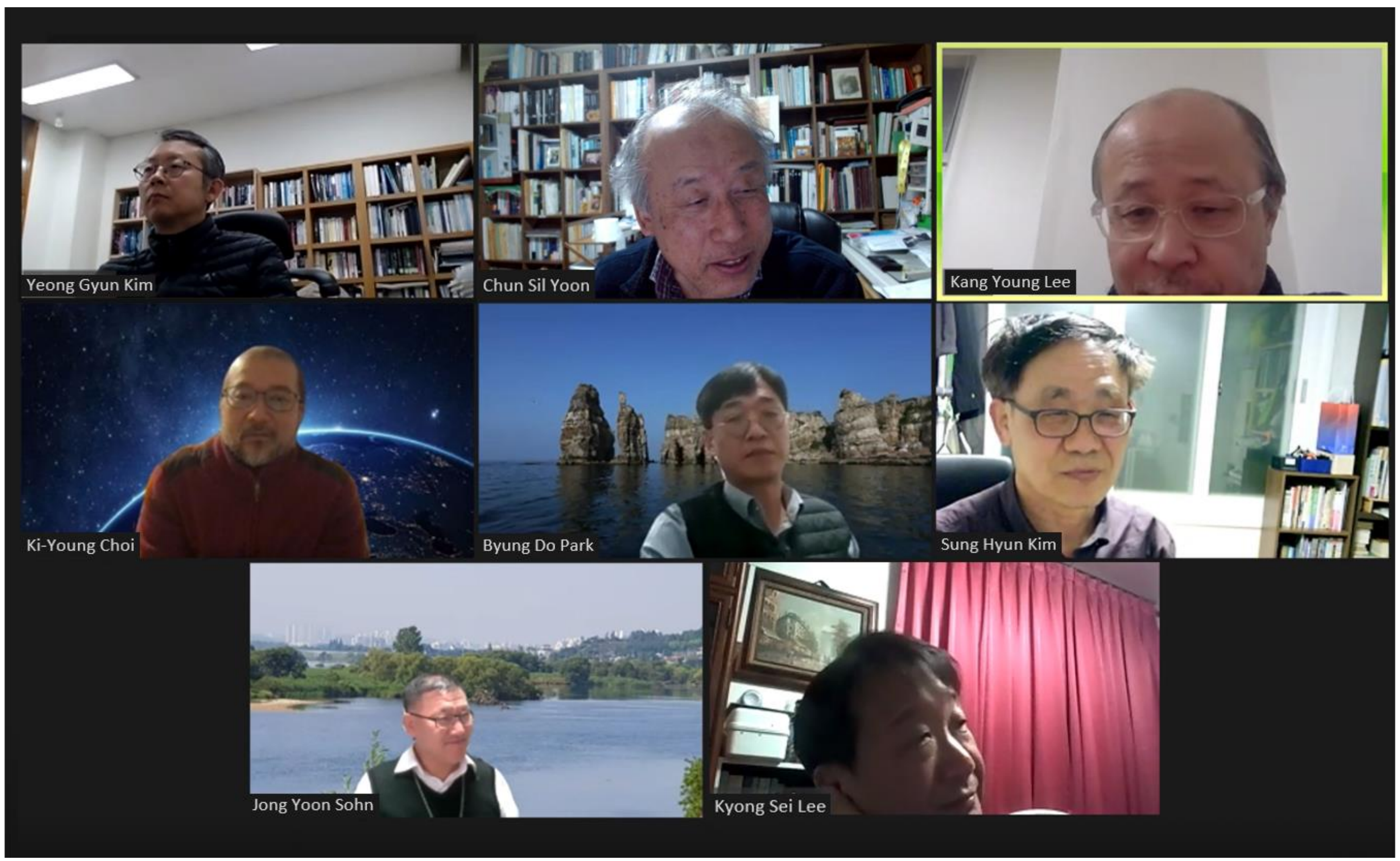
K. S. Lee

Gwangju National University of Education (GNUE)

Y. G. Kim

Sungkyunkwan University (SKKU)

K.-Y. Choi



From the talk of CS Yoon

KSND @ LHC (?)

(similar to KCMS and KoAlice)

From the talk of CS Yoon

SHiP experiment

- Search for Hidden Particles -

A general-purpose intensity-frontier experiment operating in beam-dump mode at the **CERN SPS ECN3** to perform measurements in Neutrino physics and to search for Feebly interacting long-lived particles (GeV-scale) such as heavy neutral lepton (HNL), dark photon, dark scalar, axion-like particle and light dark matter etc.

Using High-intensity 400 GeV proton beam
6 x 10^{20} pot, 15 years run

Hidden sector models	Final states
Neutrino portal, SUSY neutralino	$\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}$
Vector, scalar, axion portals, SUSY sgoldstino	$e^+e^-, \mu^+\mu^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-, K^+K^-$
Neutrino portal ,SUSY neutralino, axino	$\ell^+\ell^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

$\mu^-\pi^+$

Many Vee decay modes

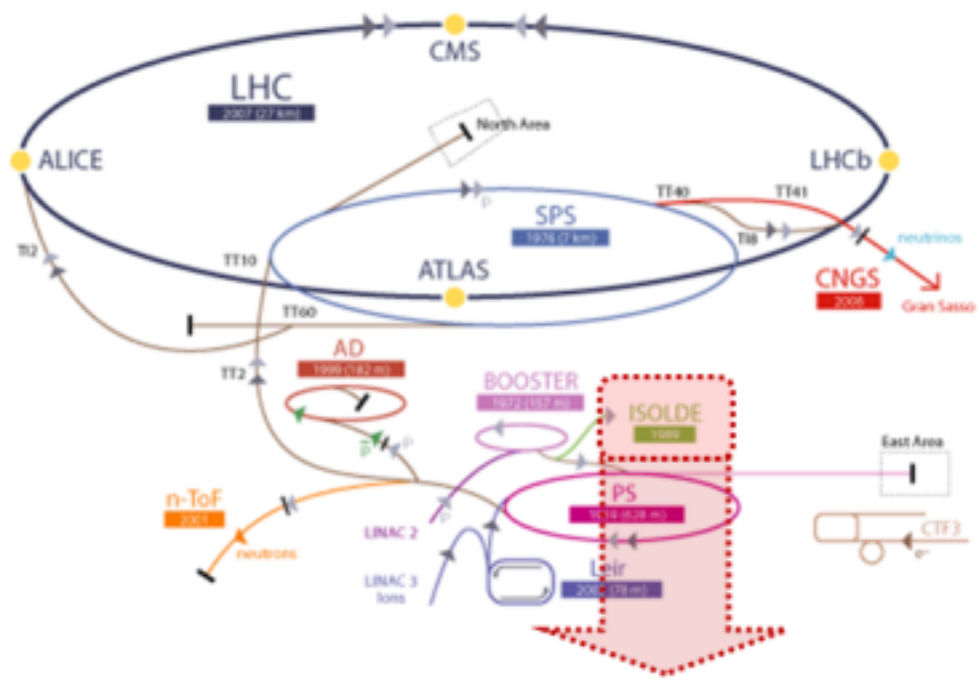
→ ***Particle ID and Full reconstruction are essential to minimize model dependence.***

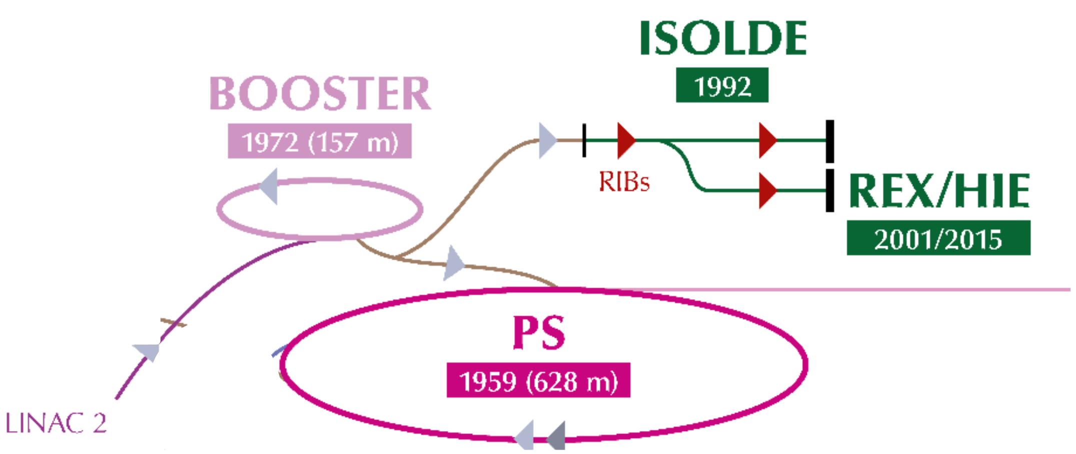
Isolde (CERN)

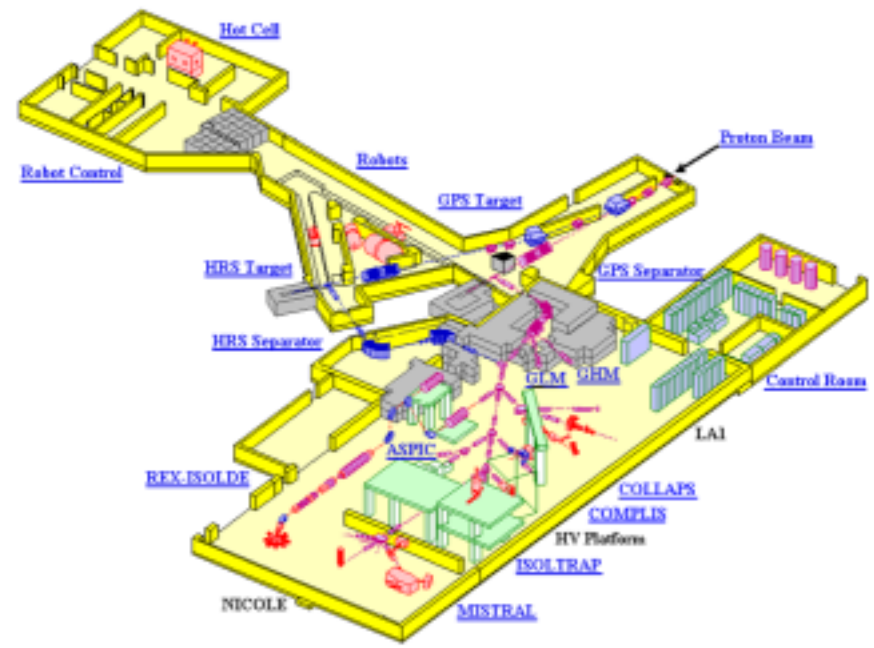
&

Isol (RAON@IRIS/IBS)

Isotope **s**eparation **o**n **l**ine







Isolde (CERN)

Isotope **s**eparation **o**n **l**ine **de**vice

Isolde@CERN

&

Isol@IRIS/IBS

=>

K-Isolde(?)

(similar to KCMS and KoAlice)

CERN Korea
Theory Collaboration

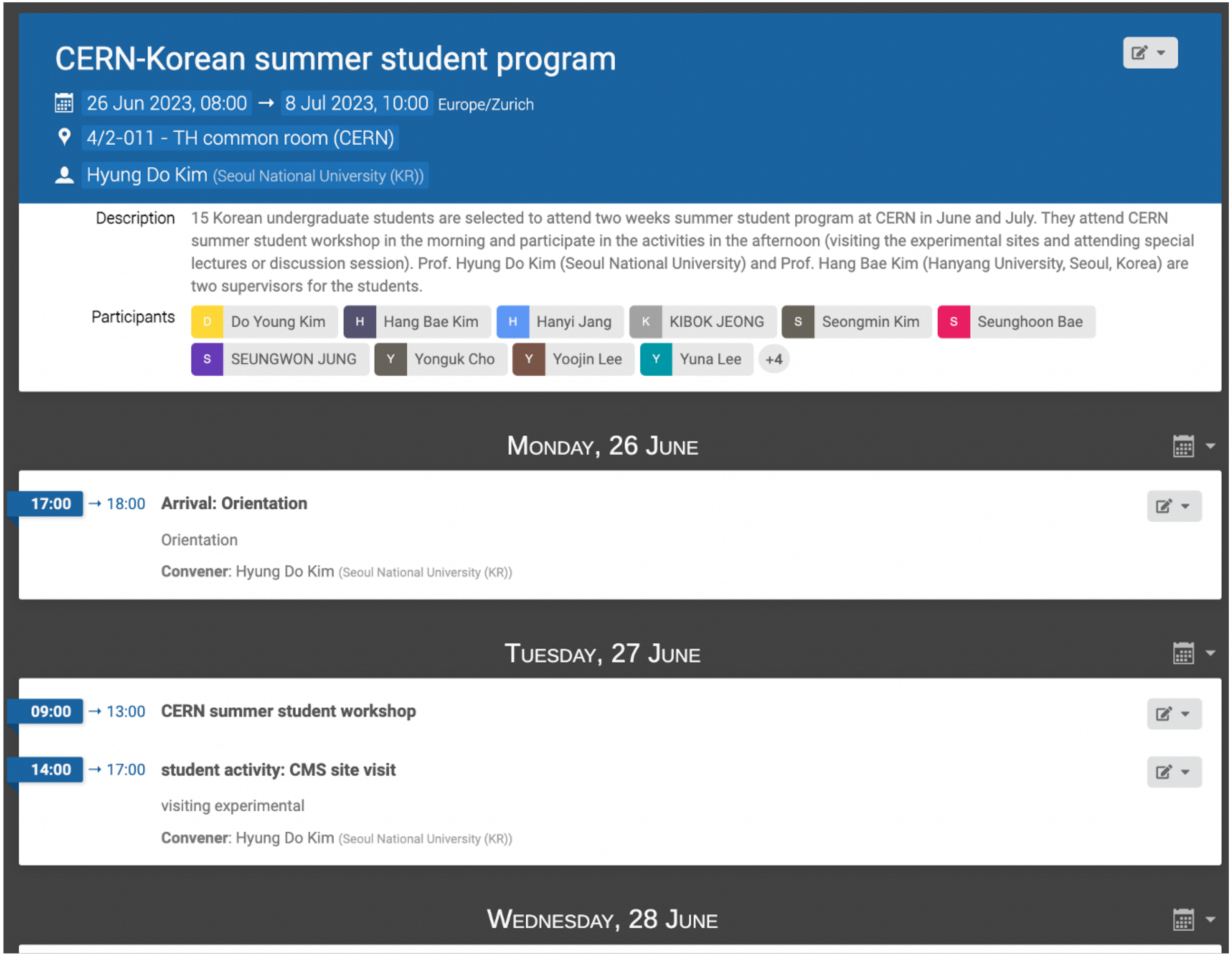
since 2009

CERN fellows alumni

Name	Period	Position	Current Position
Hyun Min Lee	2010. 1 ~ 2012. 5	Fellow	Chung-Ang (Faculty) ★
Chul Kim	2010. 2 ~ 2011. 1	Fellow	Seoultech (Faculty) ★
Jin Ouk Gong	2010.10 ~ 2012. 9	Fellow	Ewha Womans U (Faculty) ★
Myeonghun Park	2011.10 ~ 2013. 9	Fellow	Seoultech (Faculty) ★
Chan Beom Park	2012.10 ~ 2014. 9	Fellow	Chonnam Nat'l U (Faculty) ★
Ian-Woo Kim	2013. 9 ~ 2015. 8	Fellow	UpHere, Inc. (Founder)
Hye-Sung Lee	2014. 8 ~ 2015. 7	Fellow	KAIST (Faculty) ★
Ji-Haeng Huh	2015.10~ 2017. 9	Fellow	
Hee Seok Chung	2016.04 ~ 2017. 8	Fellow	Humbolt Fellow (Munich)
Doojin Kim	2016.09 ~ 2018. 8	Fellow	Arizona U (Postdoc)
Seung-Joo Lee	2017.09 ~ 2020. 4	Fellow	IBS (Faculty) ★
Yu-Seon Jeong	2018.09 ~ 2020. 9	Fellow	Chung-Ang U (Researcher)
Sohyun Park	2019.09 ~ 2022. 8	Fellow	
Jinsu Kim	2020.09 ~ 2022. 8	Fellow	Tongji U (Faculty) ★
Gongjun Choi	2021.09 ~ 2023. 8	Fellow	Minnesota U (Postdoc)
Saebyeok Jeong	2022.09 ~ 2025.08	Fellow	CERN
Jihwan Oh	2023.09 ~ 2025.08	Fellow	CERN

8 out of 15 fellows became faculties

CERN Korea summer student program from 2023



CERN-Korean summer student program

26 Jun 2023, 08:00 → 8 Jul 2023, 10:00 Europe/Zurich

4/2-011 - TH common room (CERN)

Hyung Do Kim (Seoul National University (KR))

Description: 15 Korean undergraduate students are selected to attend two weeks summer student program at CERN in June and July. They attend CERN summer student workshop in the morning and participate in the activities in the afternoon (visiting the experimental sites and attending special lectures or discussion session). Prof. Hyung Do Kim (Seoul National University) and Prof. Hang Bae Kim (Hanyang University, Seoul, Korea) are two supervisors for the students.

Participants: D Do Young Kim, H Hang Bae Kim, H Hanyi Jang, K KIBOK JEONG, S Seongmin Kim, S Seunghoon Bae, S SEUNGWON JUNG, Y Yonguk Cho, Y Yoojin Lee, Y Yuna Lee, +4

Monday, 26 June

17:00 → 18:00 **Arrival: Orientation**

Orientation

Convener: Hyung Do Kim (Seoul National University (KR))

Tuesday, 27 June

09:00 → 13:00 **CERN summer student workshop**

14:00 → 17:00 **student activity: CMS site visit**

visiting experimental

Convener: Hyung Do Kim (Seoul National University (KR))

Wednesday, 28 June

Morning : CERN summer student program lectures

Afternoon : visiting facilities and special lectures for 2 weeks

(CMS, ALICE, DATA CENTER, GBAR, PS, PROTO-DUNE, …)

June 10 to June 28, 2024

(Big) TH Institute on BSM at CERN

list of organizers

Tim Cohen (CERN/EPFL)

Gilly Elor (Mainz Univ.)

Gian Giudice (CERN)

Sungwoo Hong (KAIST)

Hyung Do Kim (SNU)

Matthew McCullough (CERN)

Minho Son (KAIST)