

Theory Vision

Why we need a Higgs factory

Hitoshi Murayama (Berkeley/Kavli IPMU)
CEPC Workshop, Oct 24, 2022

Local Organizing Committee

Shan Jin (Chair)
Yaquan Fang
Xingtao Huang
Yongsheng Huang
Gang Li
Shu Li
Yuhui Li
Ming Qi
Manqi Ruan

NJU
IHEP
SDU
SYSU
IHEP
TDLI/SJTU
IHEP
NJU
IHEP

Xiaolong Wang
Yuehong Xie
Zhenwei Yang
Chunxu Yu
Lei Zhang
Liming Zhang
Yunlong Zhang
Hongbo Zhu
Huaxing Zhu

FDU
CCNU
PKU
NKU
NJU
THU
USTC
ZJU
ZJU

Secretary

Sicheng Zhou
Hongjuan Xu
Yan Wu

NJU
IHEP
IHEP

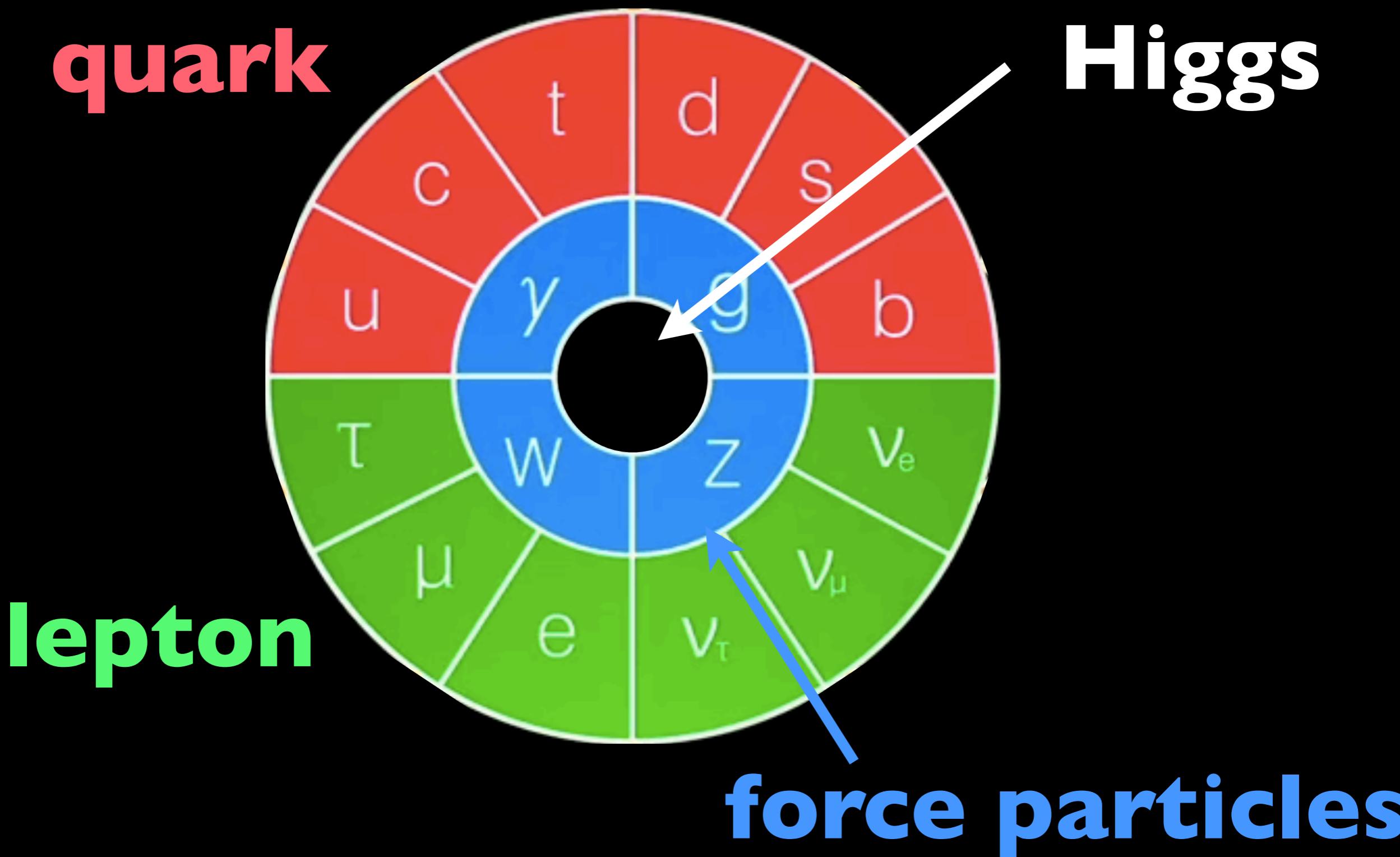
<https://indico.ihep.ac.cn/event/17020/>
Contact: cepews2022@ihep.ac.cn
Tel: +86 18951633979





July 4, 2012

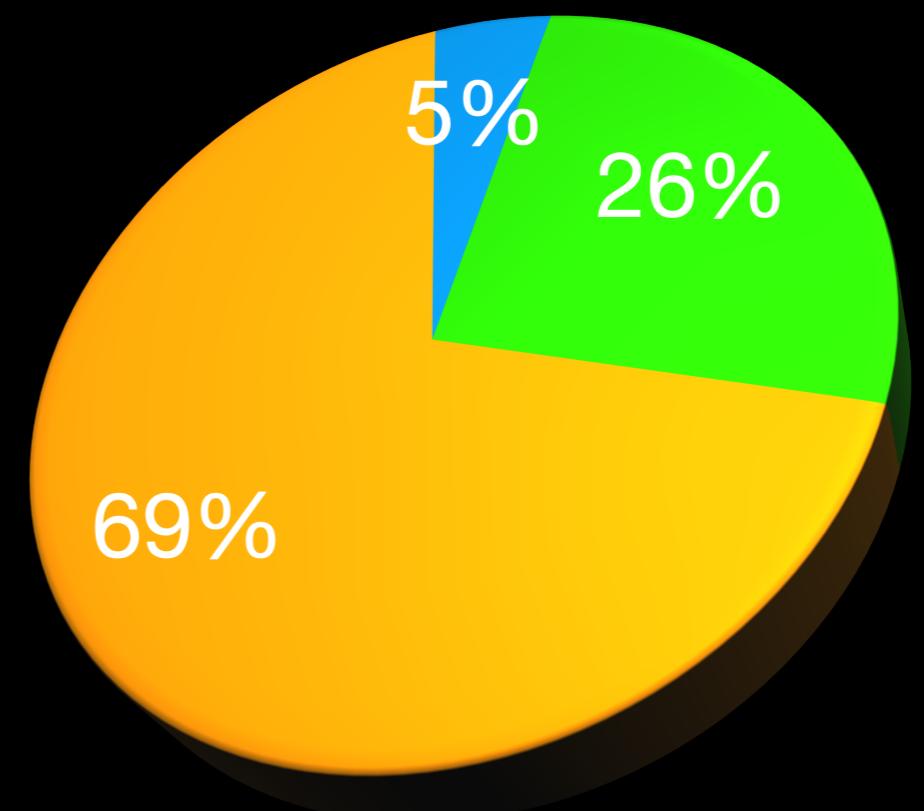
Standard Model



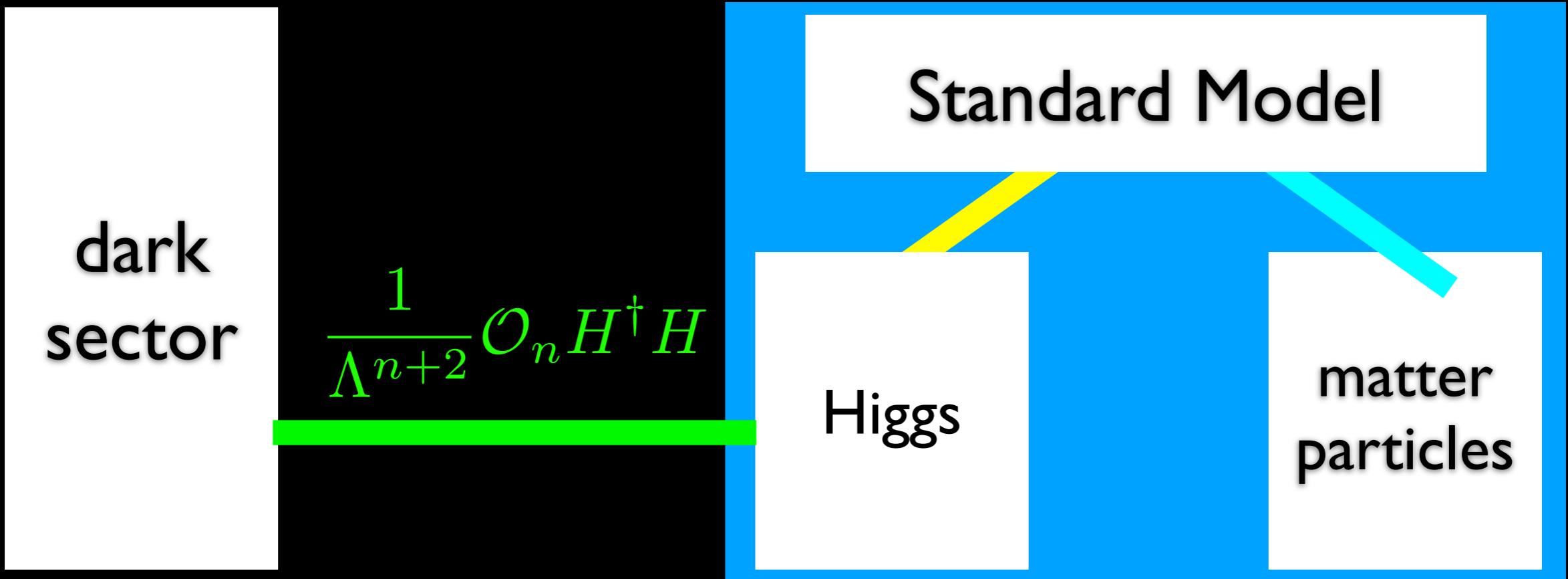
Beyond SM?

- We cannot explain
 - neutrino mass (1998)
 - dark matter (2003)
 - dark energy (1998)
 - inflation (2013)
 - baryon asymmetry (2013)
- theoretical expectation:
 - Higgs is the portal

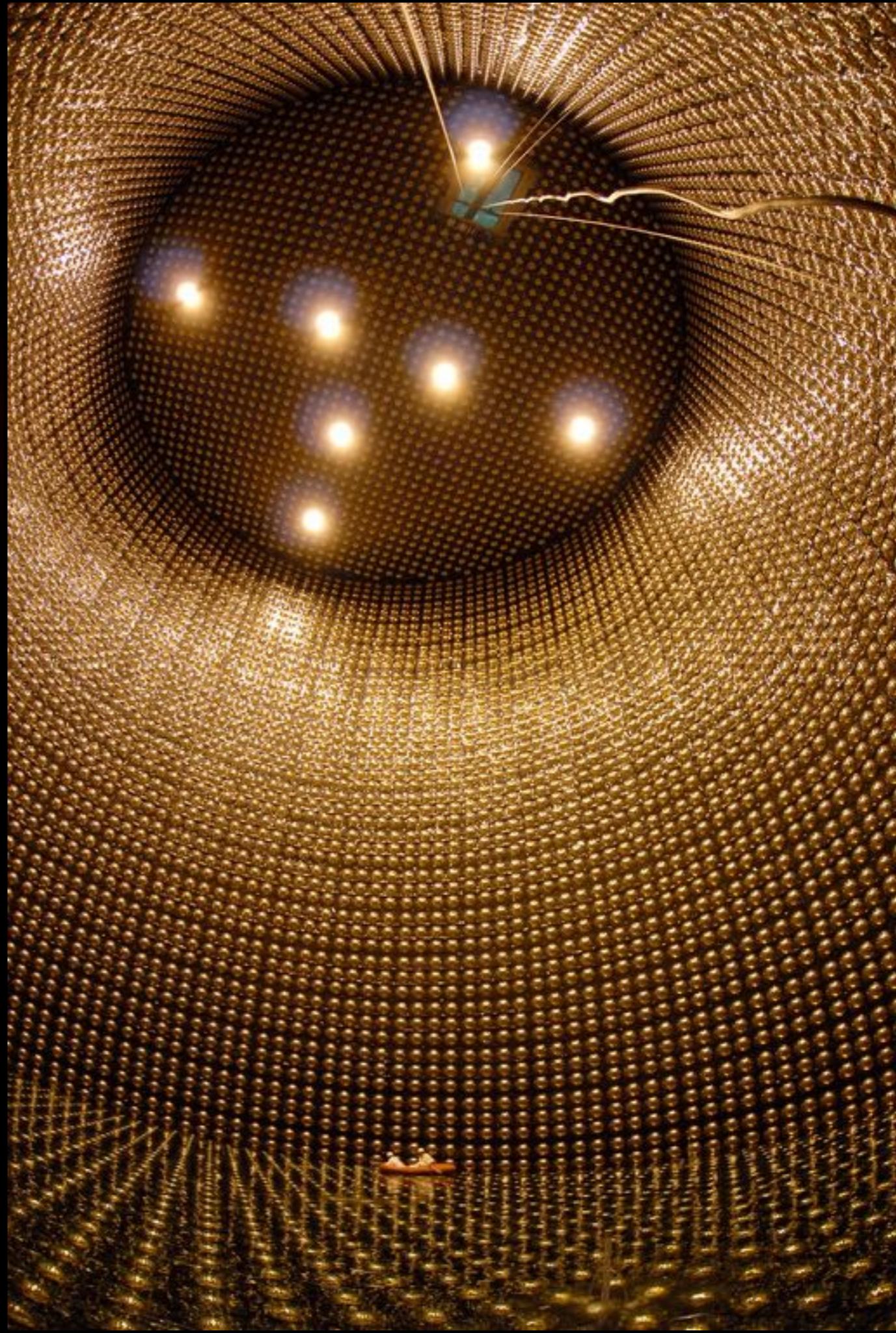
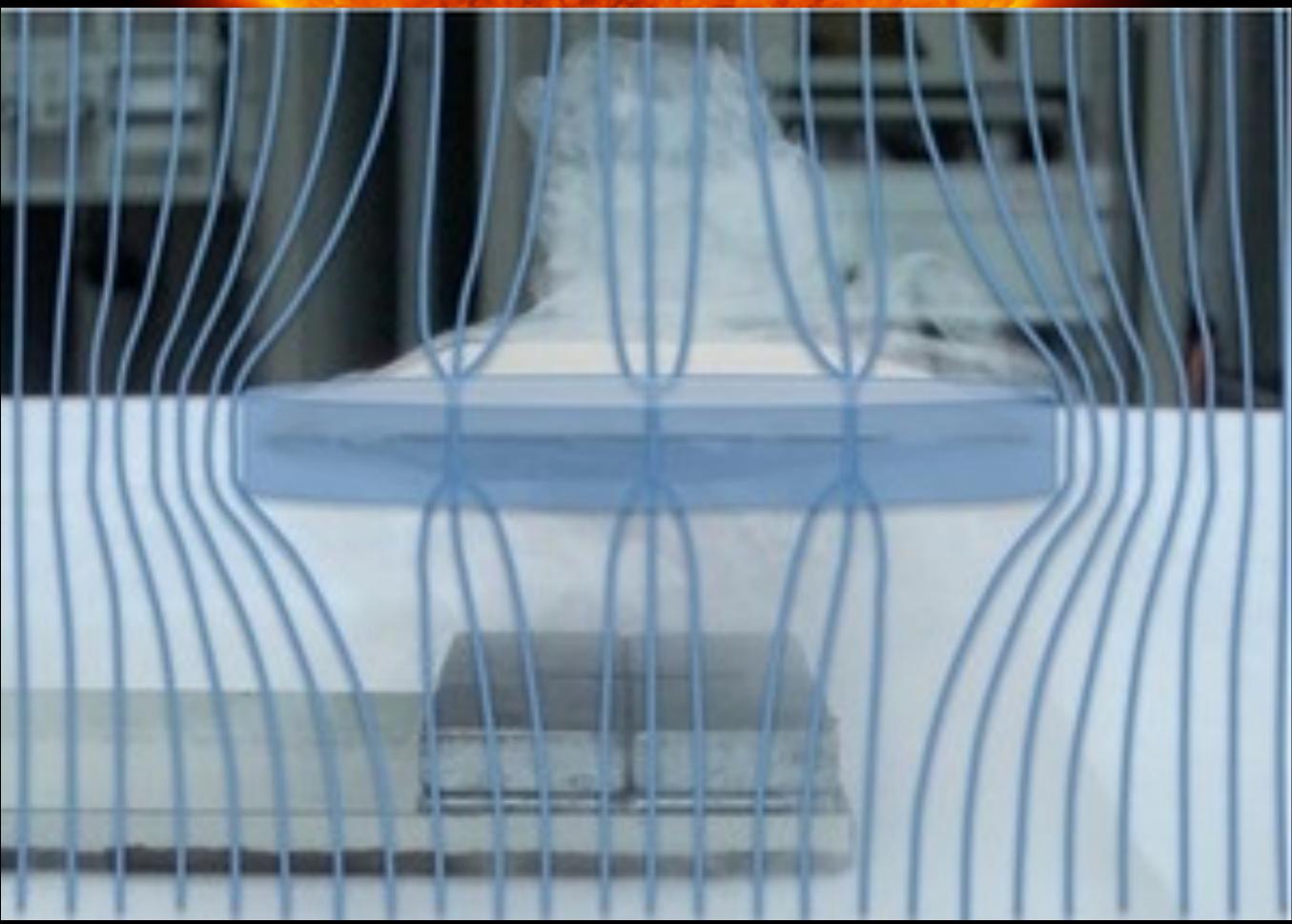
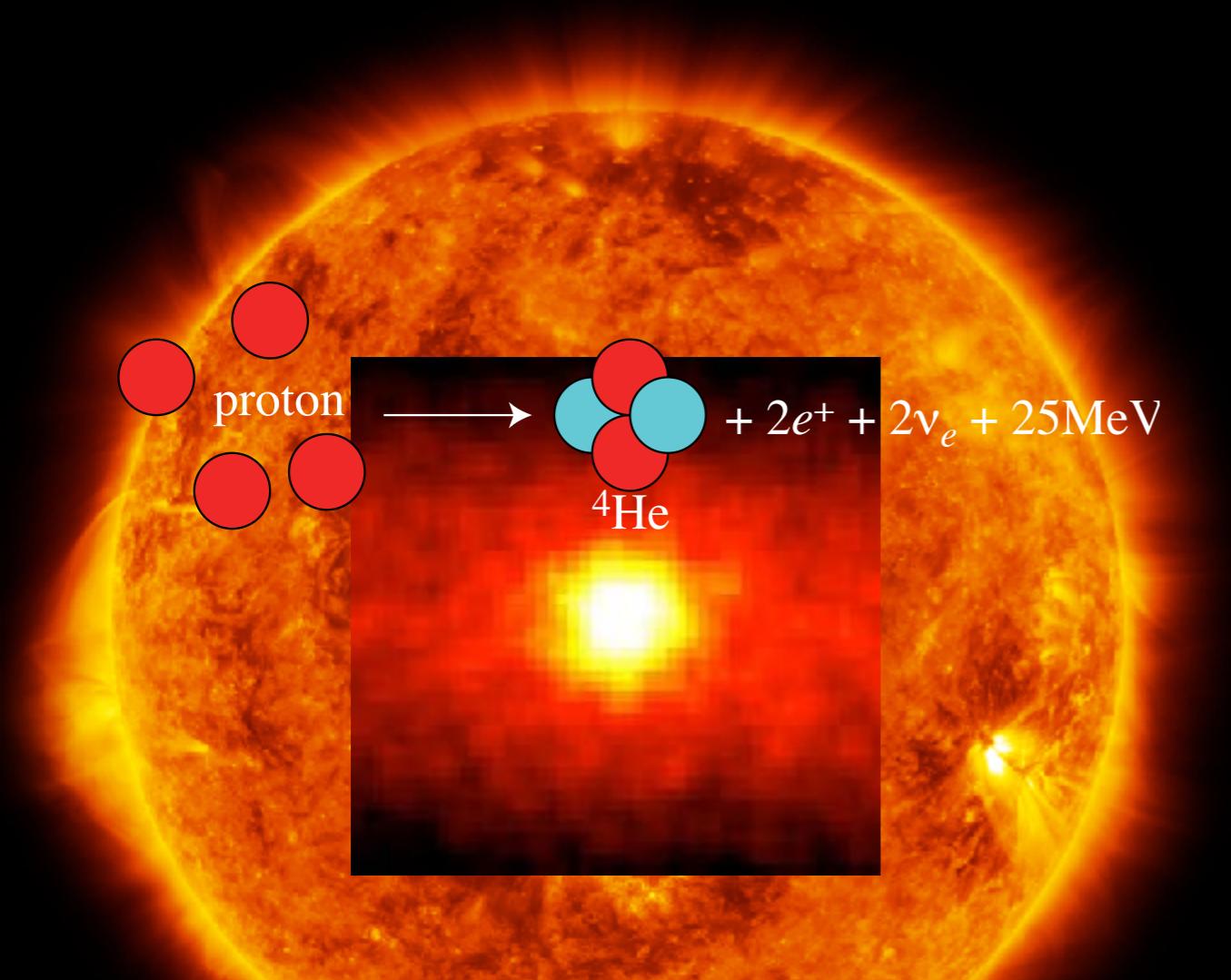
- atoms
- dark matter
- dark energy



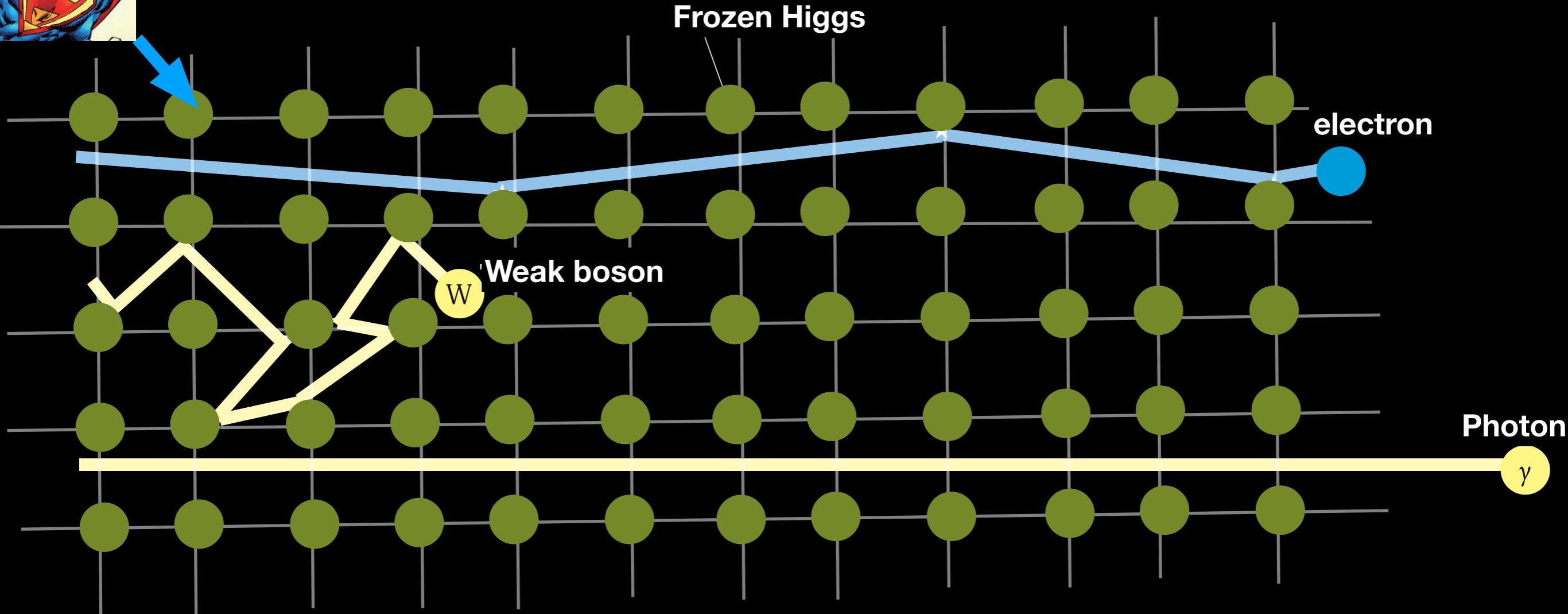
portal



cf. $\frac{1}{\Lambda^{n+4}} \mathcal{O}_n F_{\mu\nu} F^{\mu\nu}$

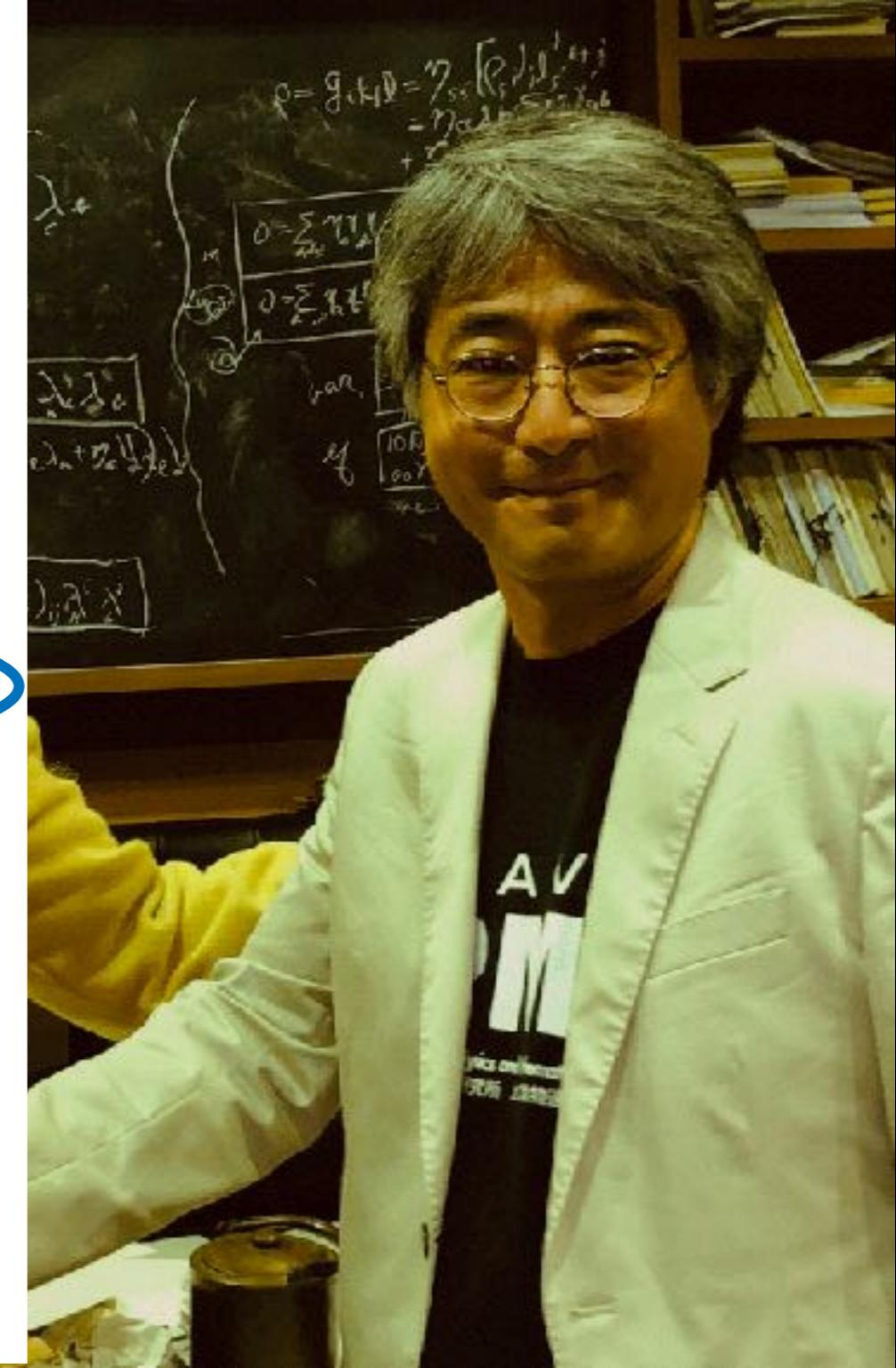
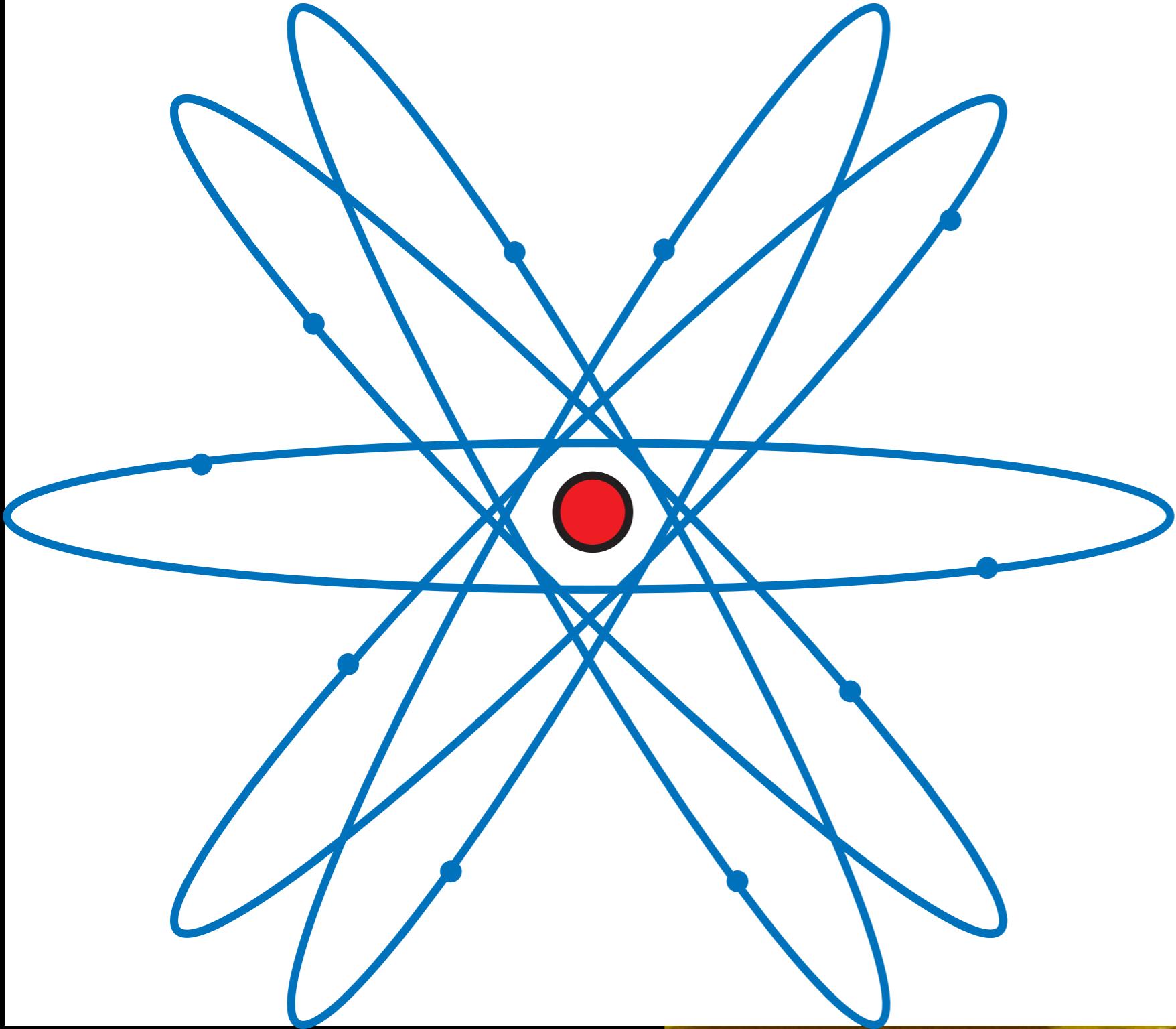


Higgs boson frozen in the Universe



Credit: Newton Japan

Just the right amount of Higgs boson for us to exist!





**Who is he keeping us
from falling apart?**

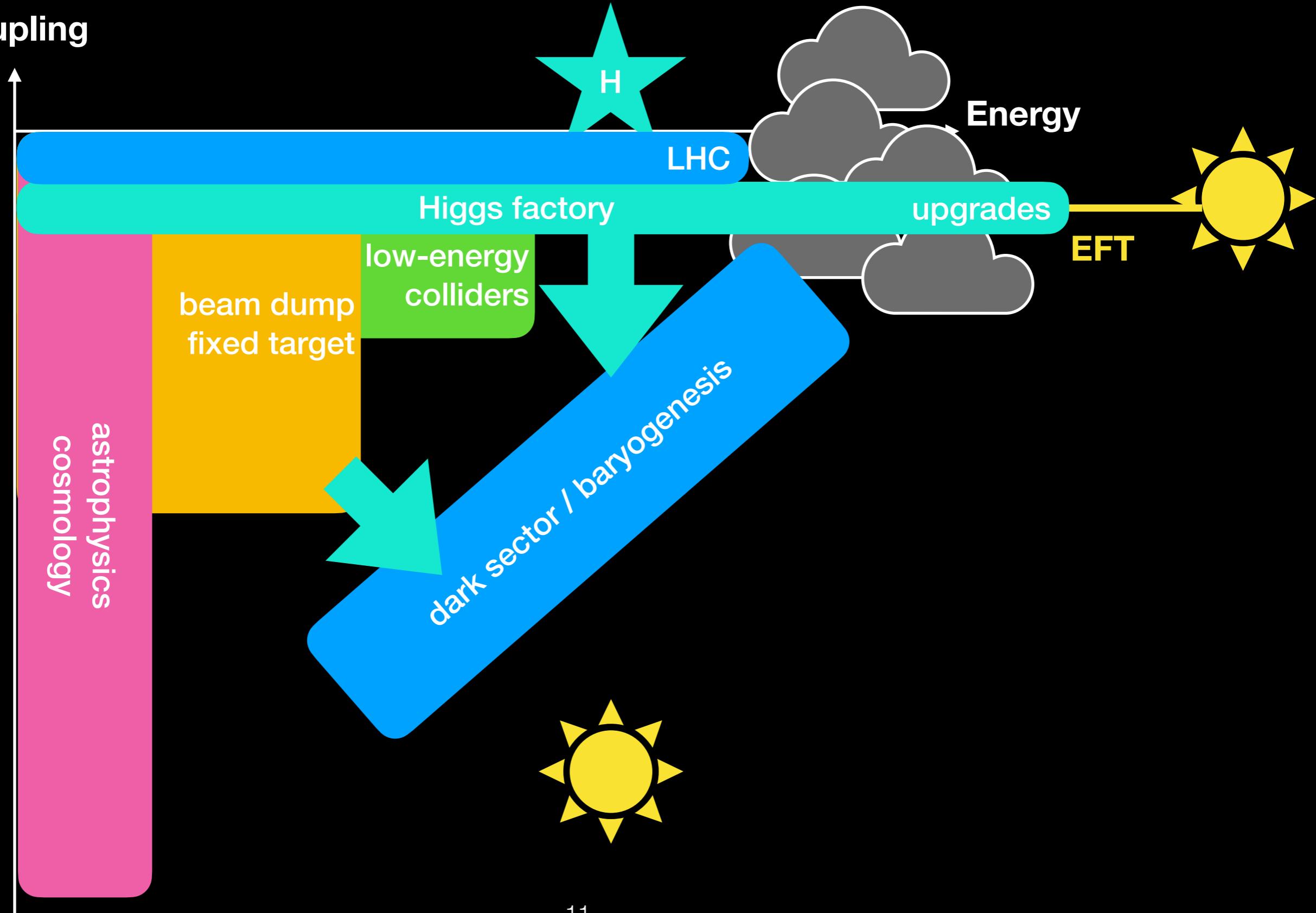
History of Colliders

lepton vs hadron

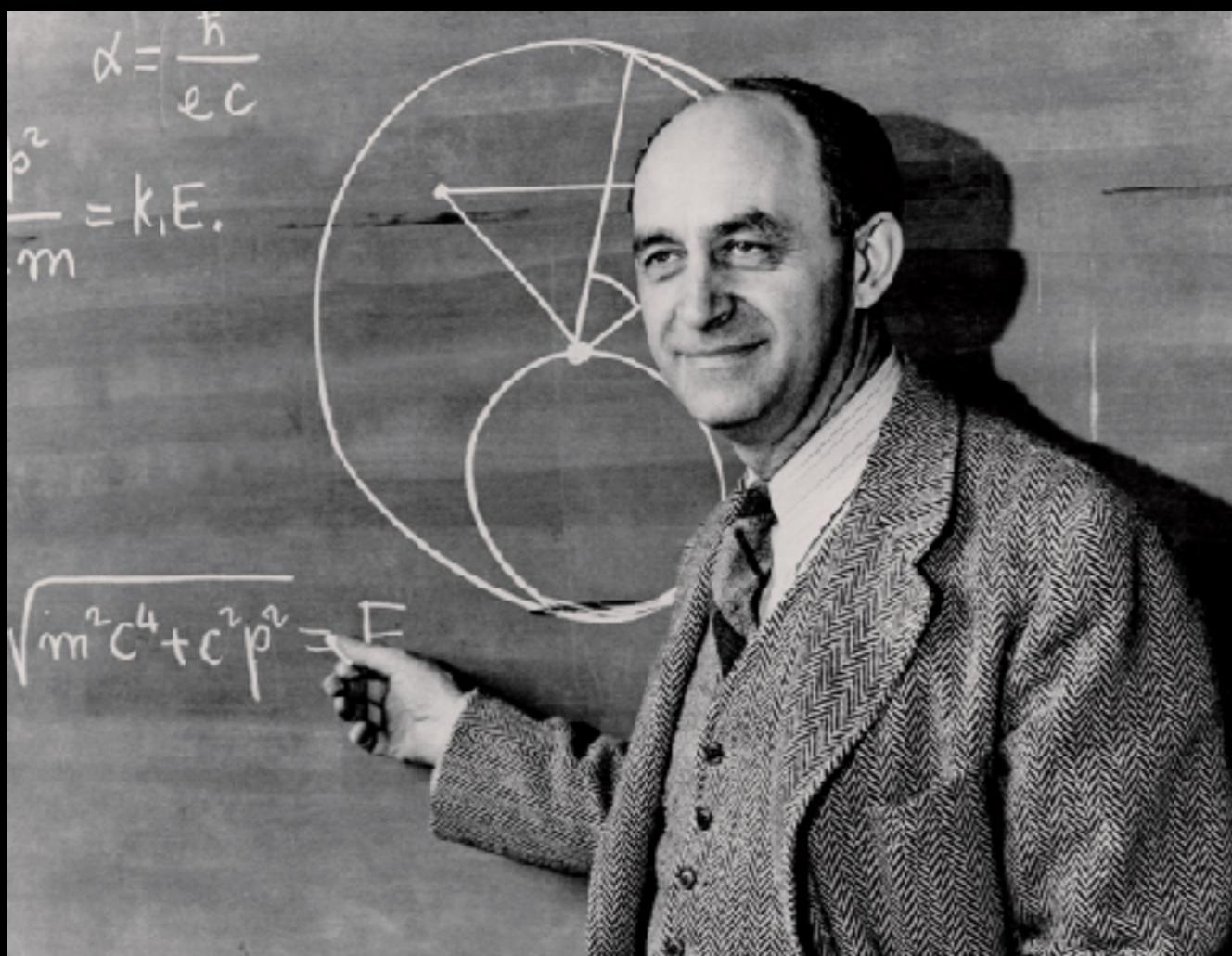
1. precision measurements of neutral current
(i.e. polarized $e+d$) predicted m_W, m_Z
 2. UA1/UA2 discovered W/Z particles
 3. LEP/SLC *nailed* the gauge sector
-
1. precision measurements of W and Z (i.e. LEP + Tevatron)
predicted m_t and m_H
 2. Tevatron discovered top, LHC discovered a Higgs particle
 3. Higgs factory *nails* the Higgs & top sector
-
1. precision measurements at Higgs factory predicts ???

Vision

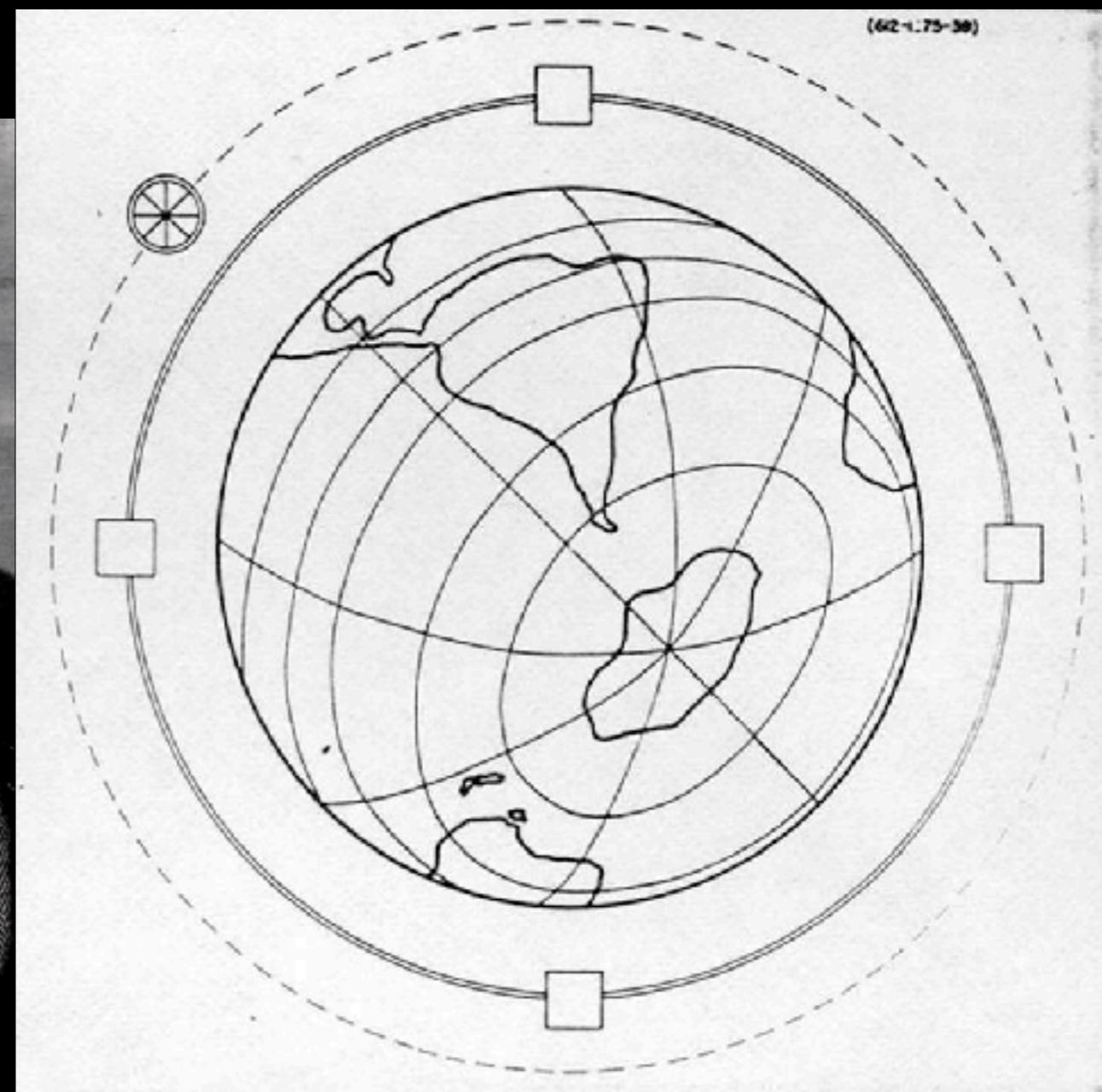
Coupling



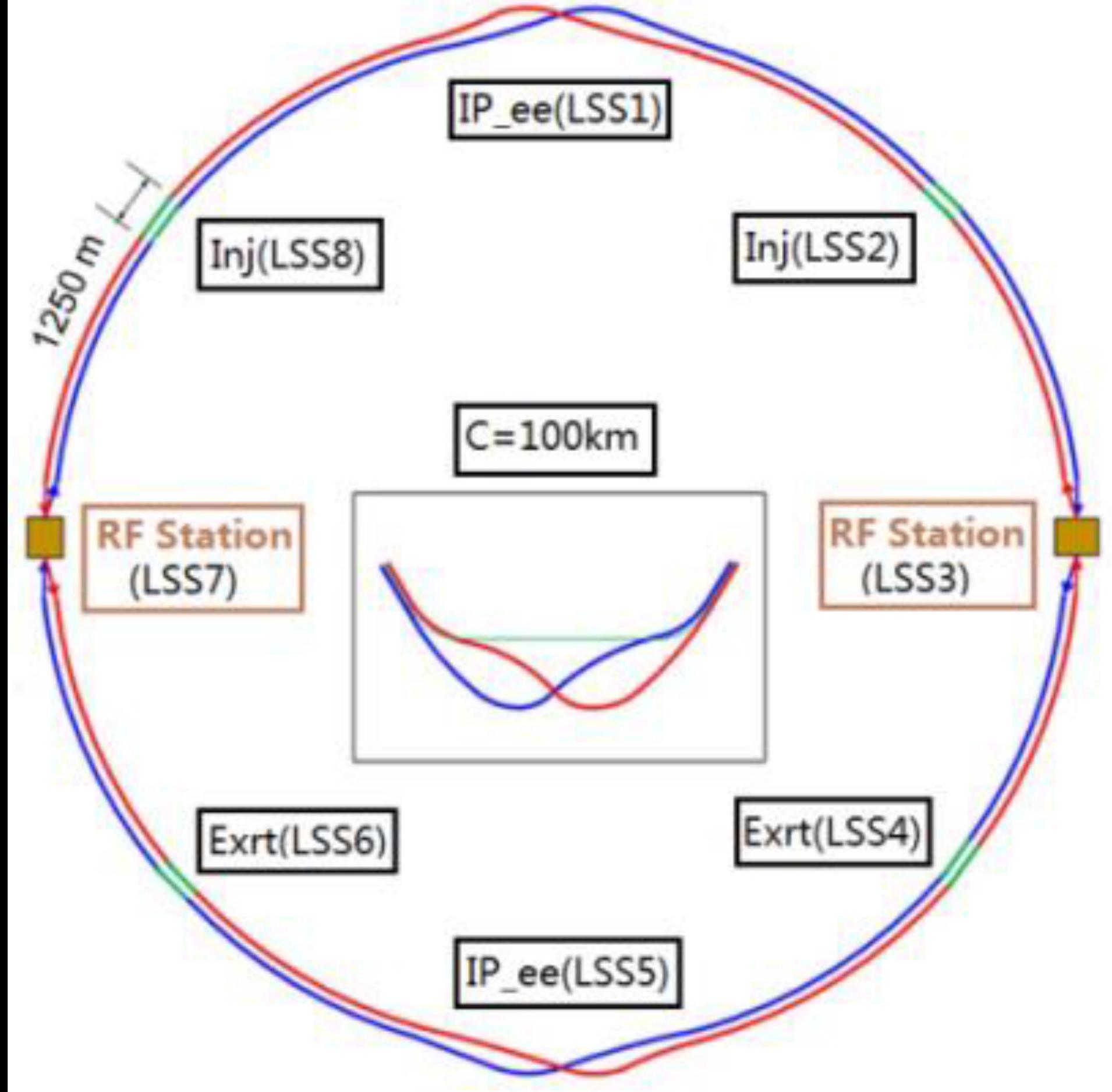
Globatron



Enrico Fermi



E_{CM}=3 TeV p p fixed target experiment

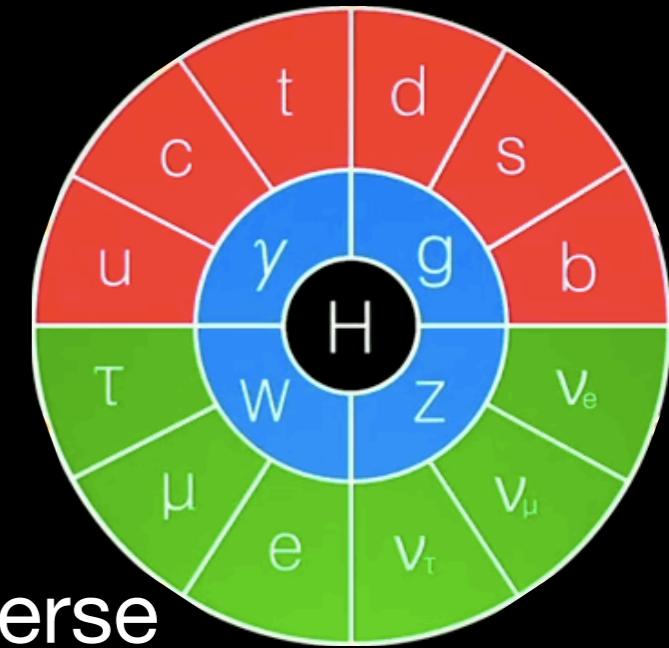


e⁺e⁻ collider experiment *as small as* 100 km

Higgs as central theme

- Higgs is at the **center** of the Standard Model
- the only particle that **talks to everybody**
- the only particle that **doesn't spin**
- the only particle that is **condensed** in the universe
- the **source of all masses** of elementary particles
- We **don't know why** it is the case for any of the points above
- the **lowest order coupling** to new physics

unbelievably important & special particle!





I hated it!

- Higgs boson is the *only spin 0 particle* in the standard model
 - we have never seen one before
 - faceless particle!
 - one of its kind, no context
 - but does the most important job
- The theory **looks very artificial**
- we still don't know *dynamics* behind the Higgs condensate
- *Higgsless theories*: now dead



Context for Scalar Bosons?

Supersymmetry

- Higgs just one of *many* scalar bosons
- SUSY loops make m_h^2 negative
- superpartners

composite

- spins cancel among constituents
- condensate by a strong attractive force, holography
- top partner, pNGBs, vector-like quarks

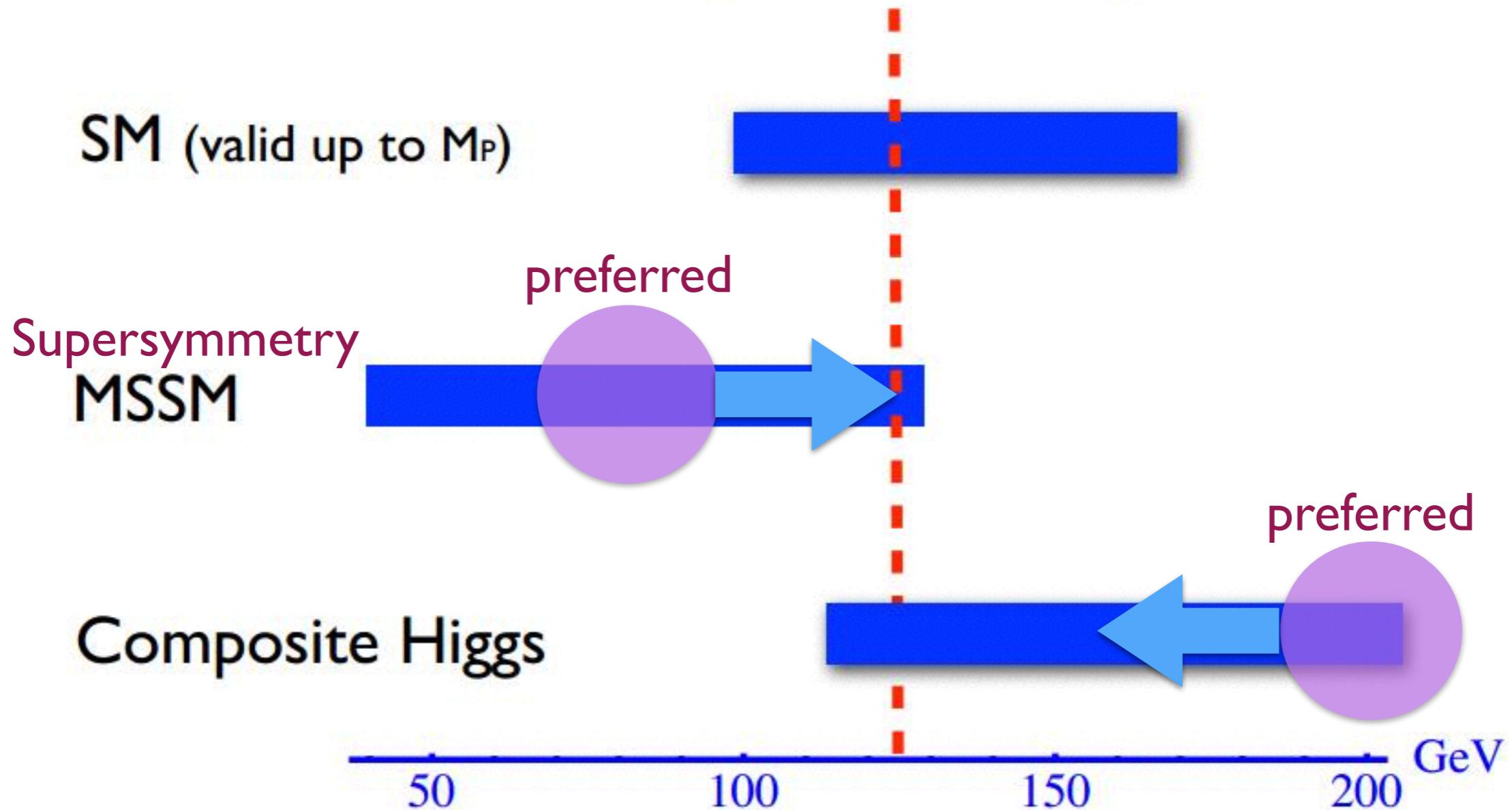
Extra dimension

- Higgs spinning in extra dimensions
- new forces from particles running in extra D
- KK particles

a different “naturalness” argument

Higgs boson must know something about them

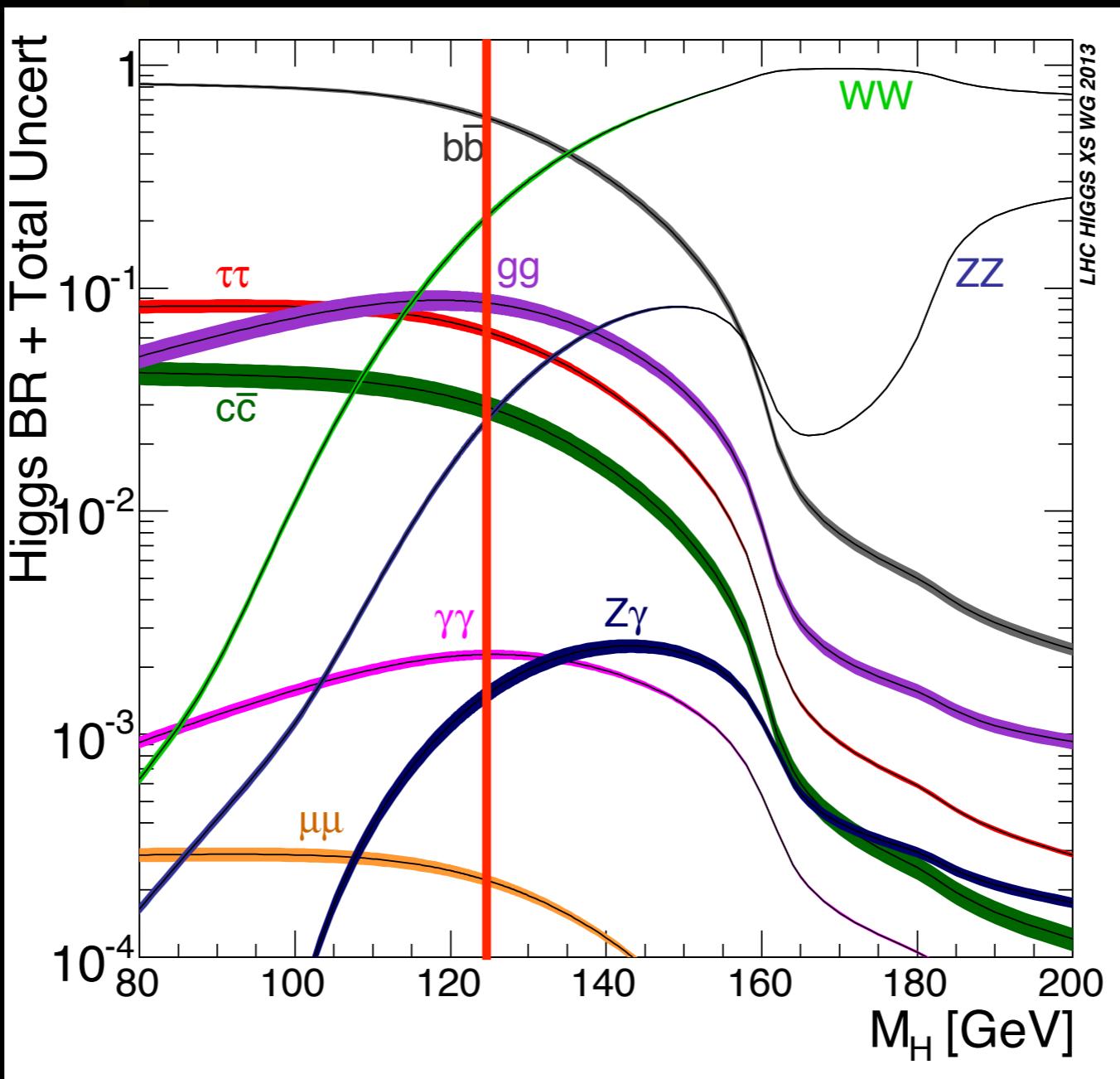
Higgs mass range



By A Pomarol

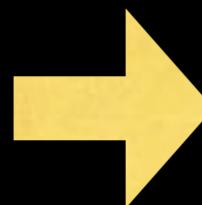
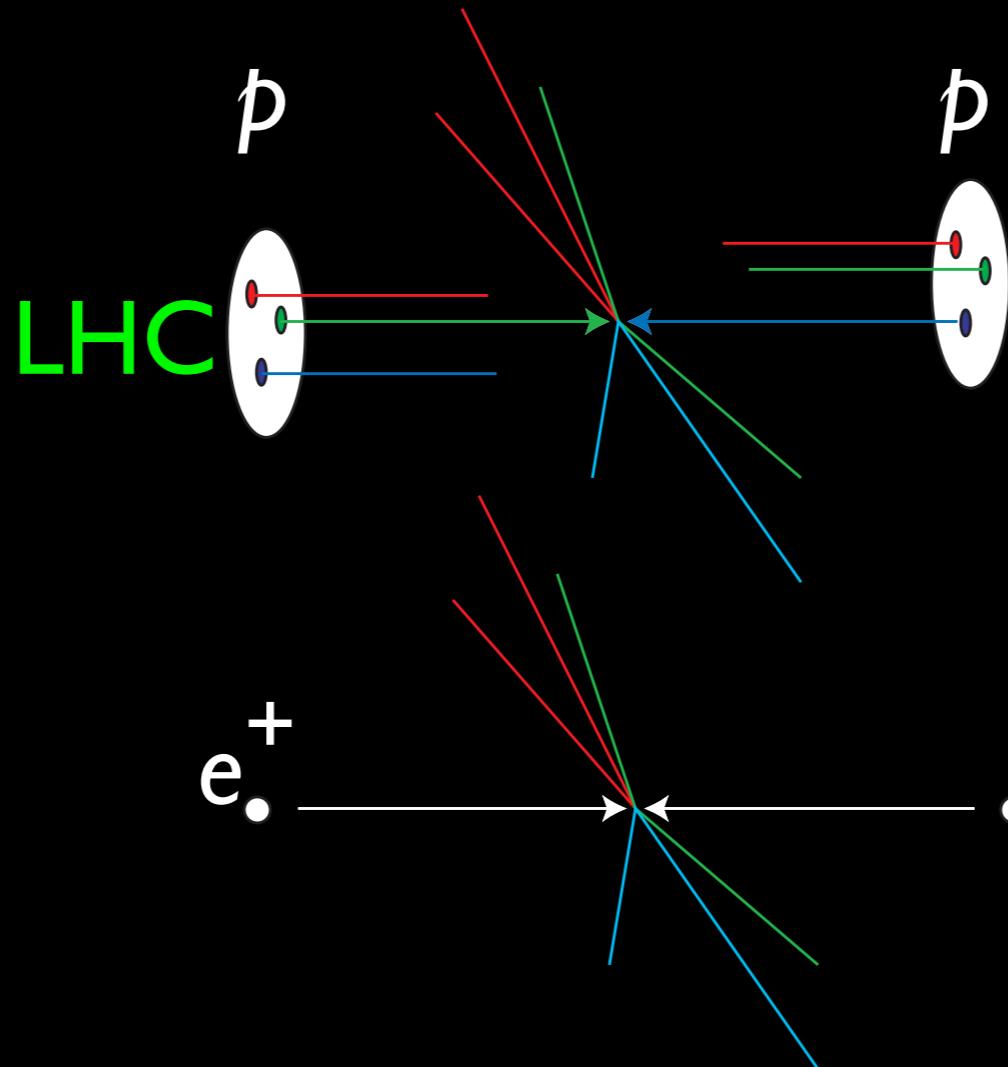
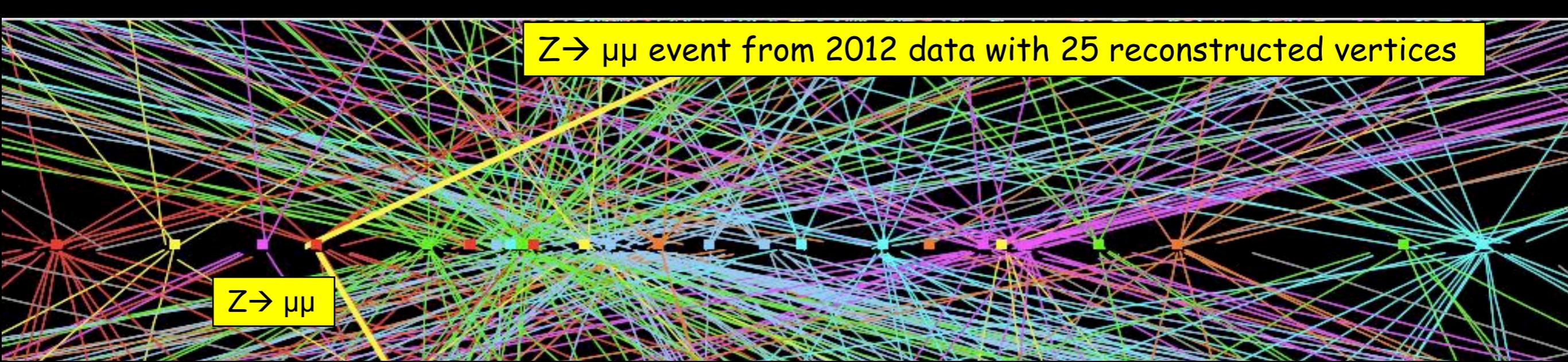


dream case for experiments



stupid not to do this!

$Z \rightarrow \mu\mu$ event from 2012 data with 25 reconstructed vertices



What you can't
see at LHC

LHC vs e^+e^-

More crisp images



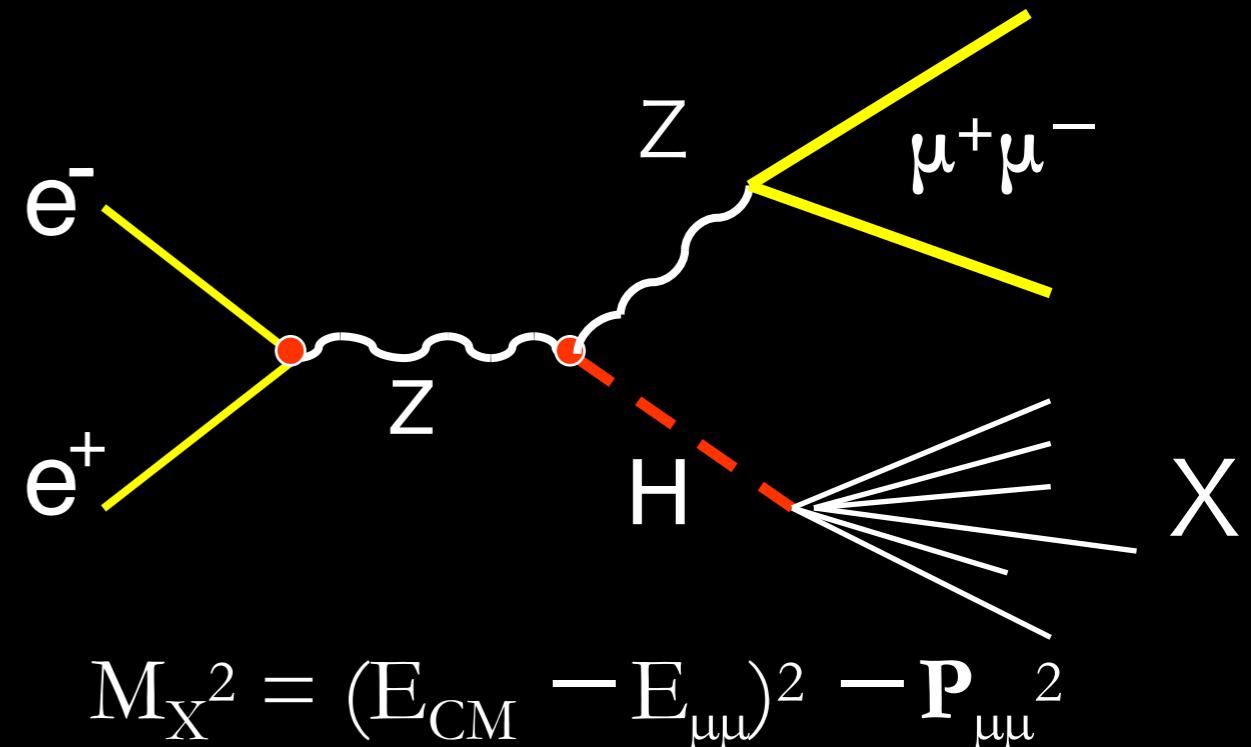
LHC



e^+e^-

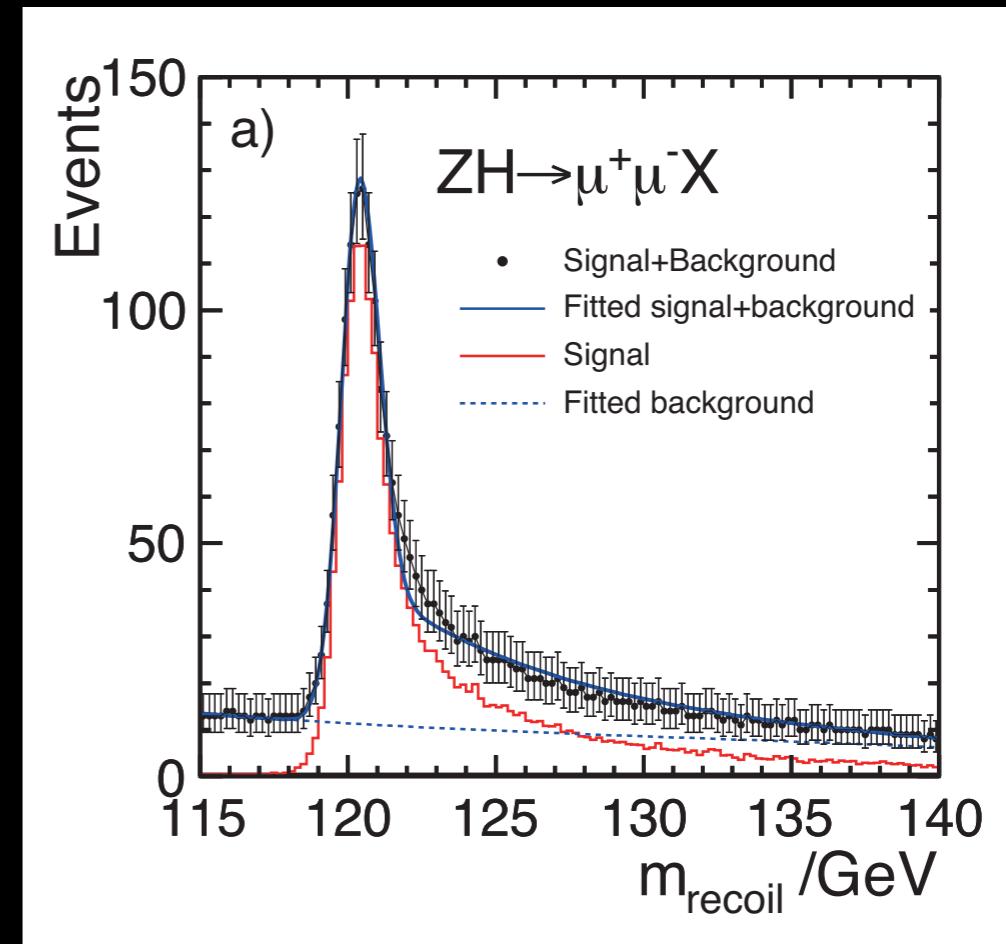
e^+e^-

- simple kinematics
- no loss of the longitudinal momentum (modulo photon emission)
- can make use of all final states
 - not just easily identifiable particles (i.e. leptons@LHC)
- capture all information for a given event



$$M_X^2 = (E_{CM} - E_{\mu\mu})^2 - \mathbf{P}_{\mu\mu}^2$$

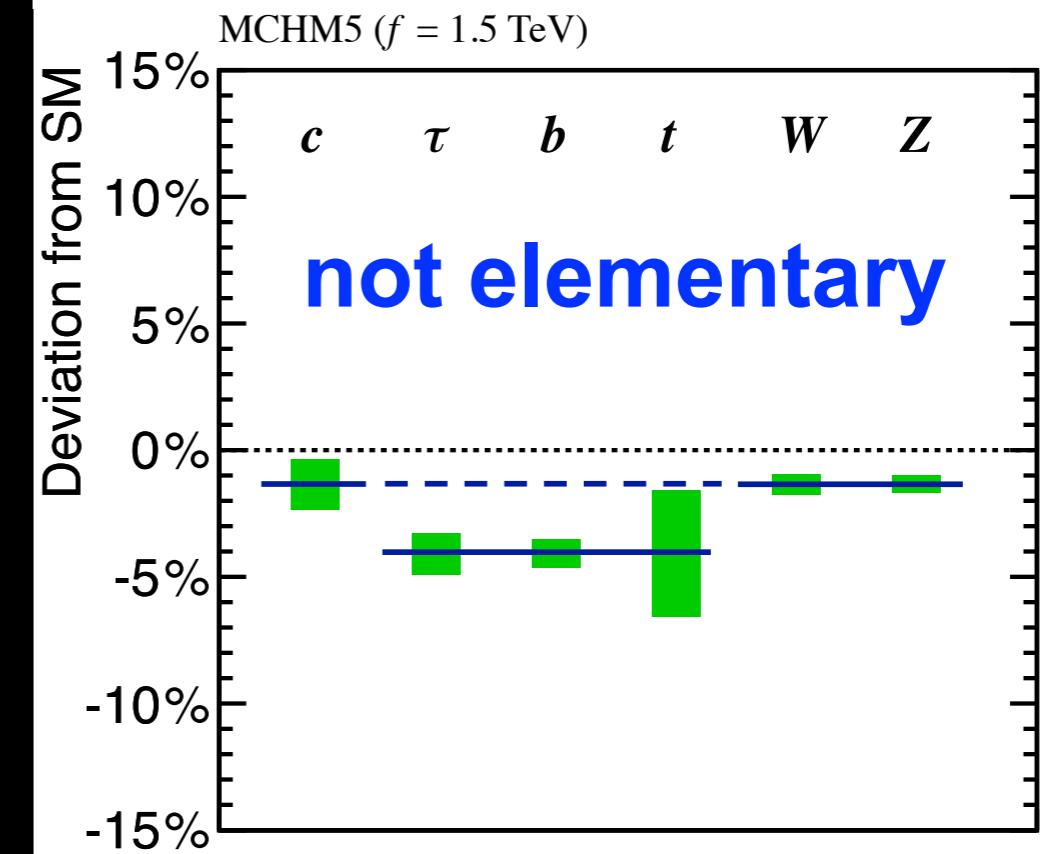
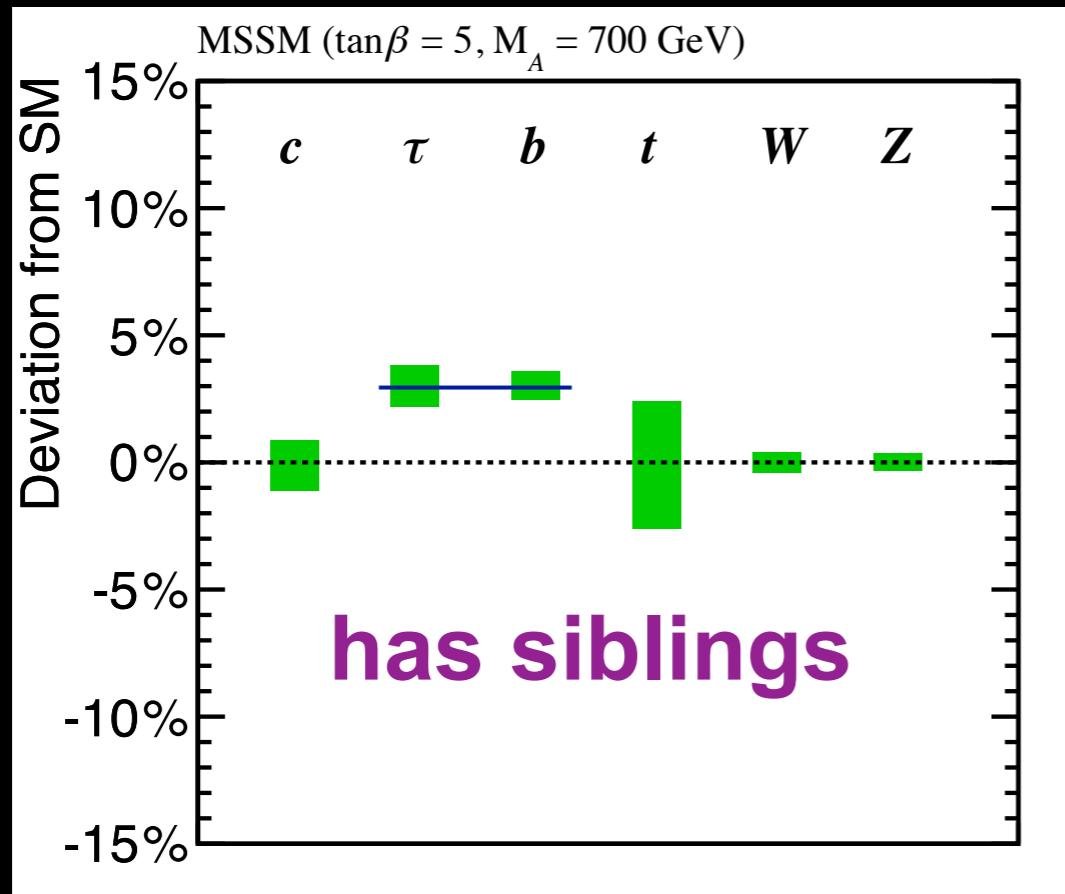
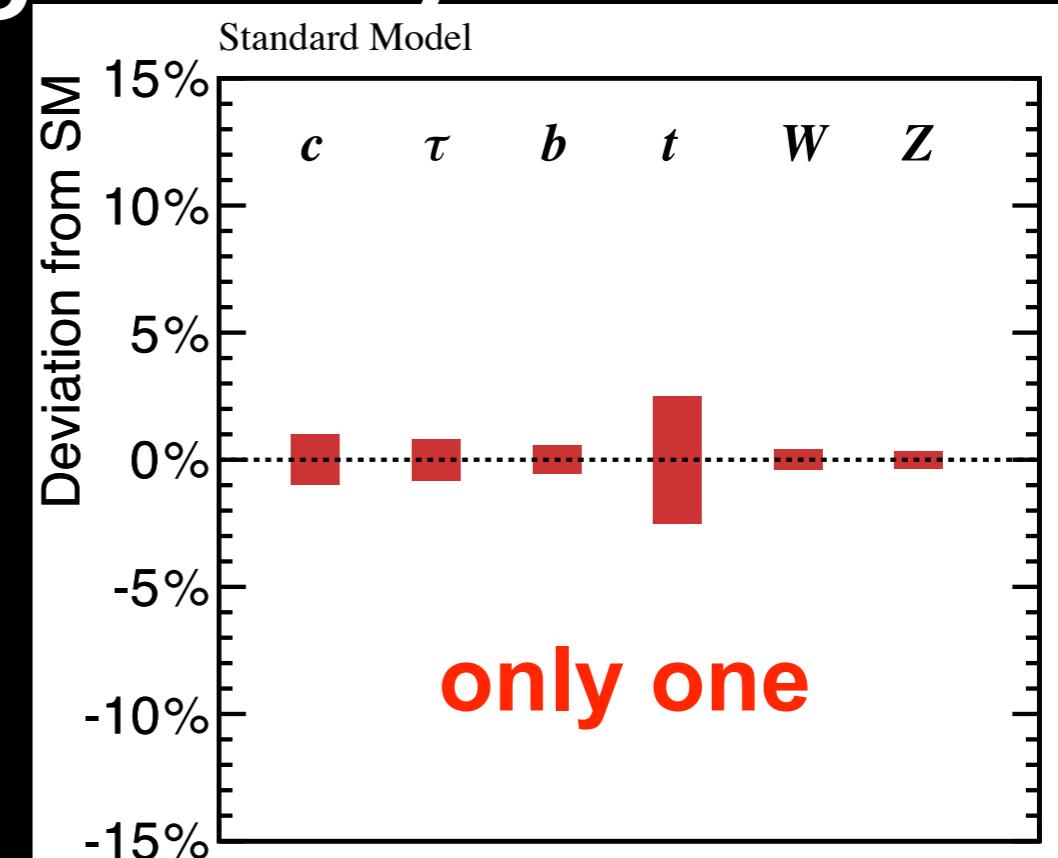
$$m_{\text{recoil}}^2 = m_Z^2 + s - 2\sqrt{s}E_Z$$



What is Higgs really?

Only one? (SM)
has siblings? (2DHM)
not elementary?

Lumi 1920 fb-1, $\text{sqrt}(s) = 250 \text{ GeV}$
Lumi 2670 fb-1, $\text{sqrt}(s) = 500 \text{ GeV}$



HEPfit

HL-LHC

HL+HELHC

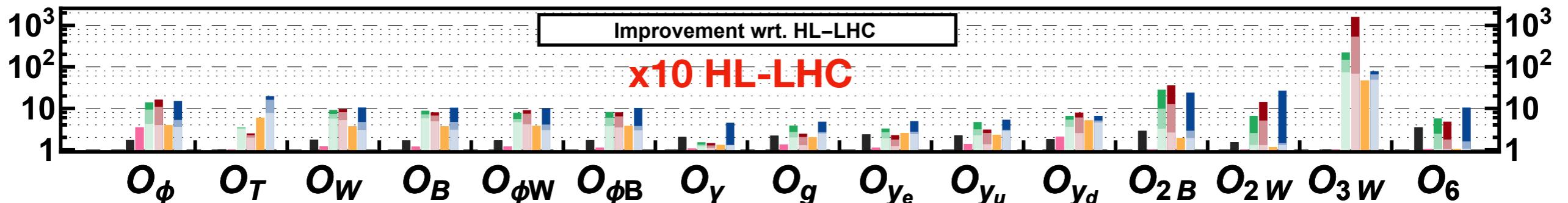
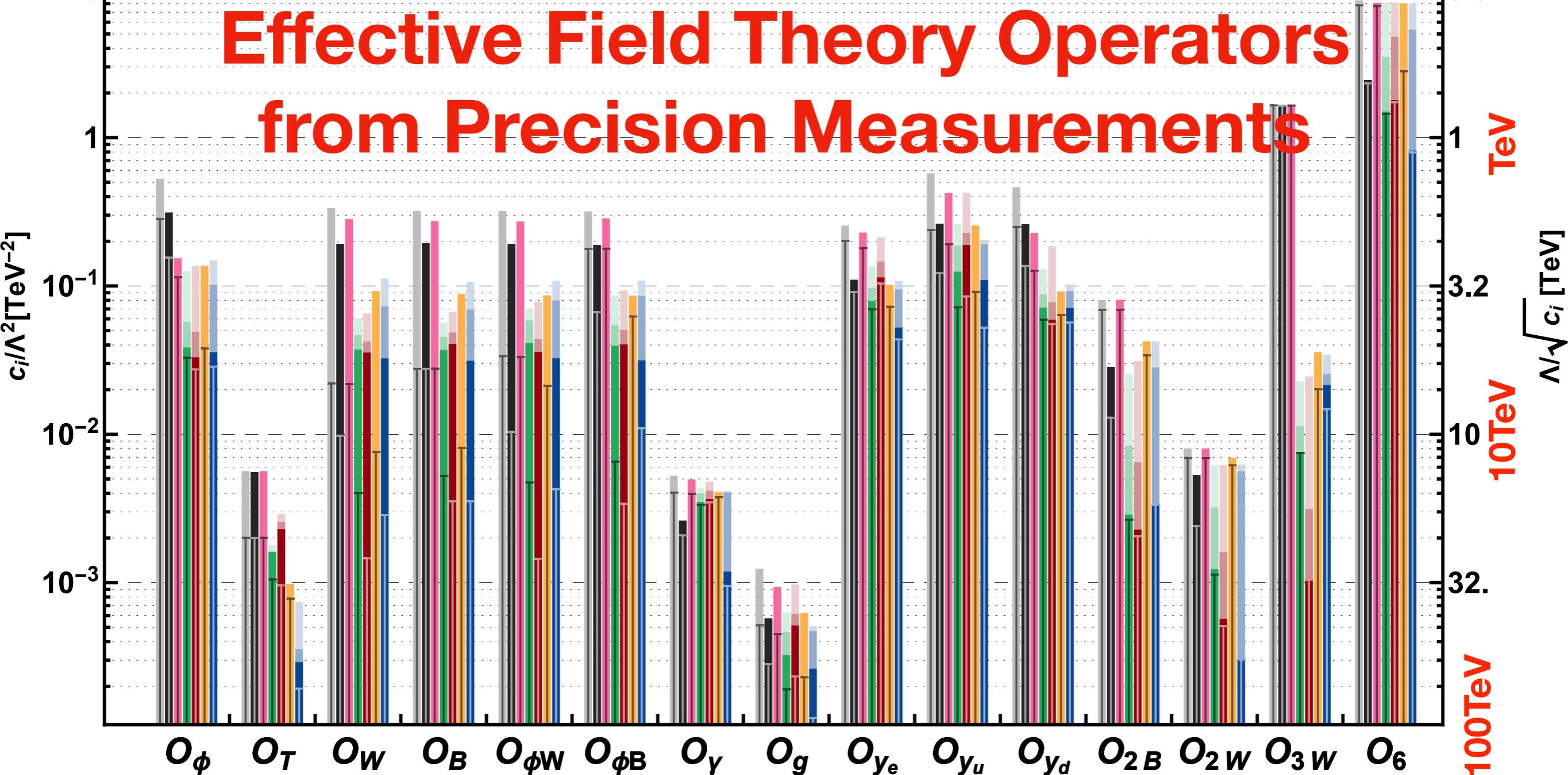
HL+LHeC

HL+ILC₂₅₀HL+CLIC₃₈₀
HL+CLIC₁₅₀₀
HL+CLIC₃₀₀₀

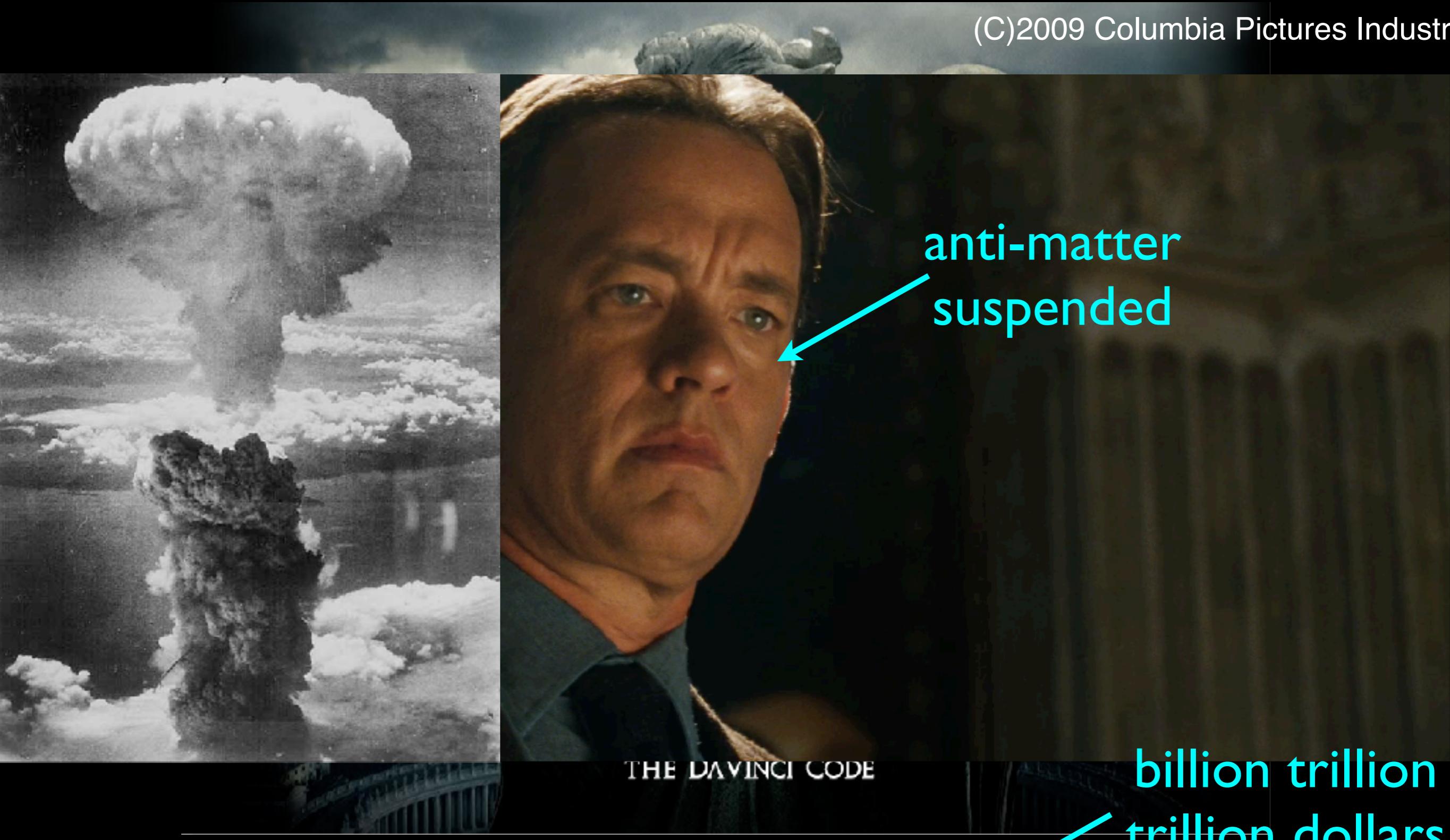
HL+CEPC

HL+FCC_{ee240}
HL+FCC_{ee}
HL+FCC_{ee/eh/hh}Higgs@FC WG
September 2019

T Single operator fit

Global fit to $\mathcal{L}_{\text{SILH}}$ 

(C)2009 Columbia Pictures Indust



A scientist at CERN produced a quarter gram of anti-matter
without the knowledge of the Director General
falls into wrong hands!

anti-matter
suspended

billion trillion
trillion dollars

Beginning of Universe

1,000,000,001

1,000,000,001

matter

anti-matter

Complete Annihilation

matter

anti-matter

Beginning of Universe

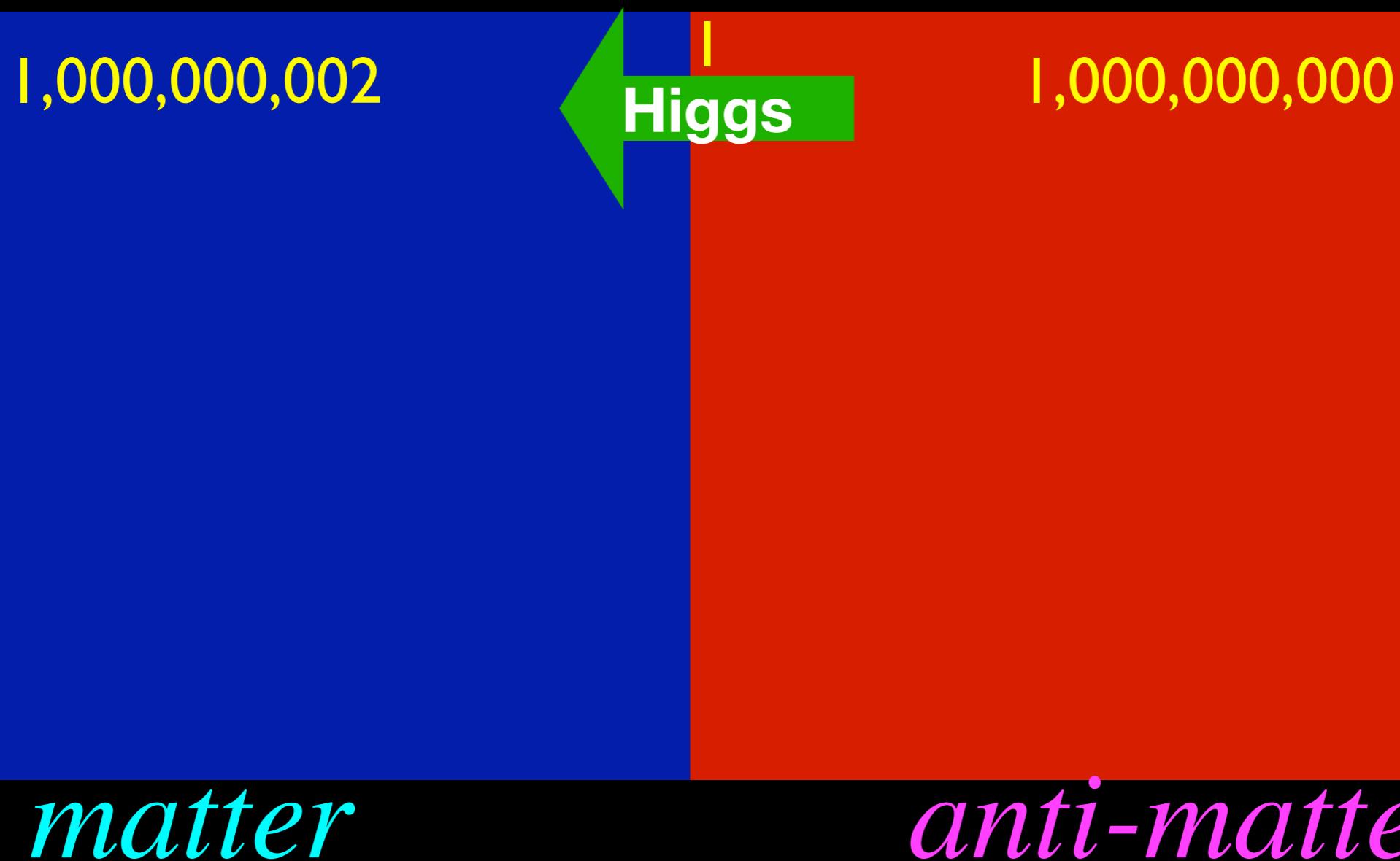
1,000,000,001

1,000,000,001

matter

anti-matter

When Higgs froze



How we were saved

2
us

matter

anti-matter



**Did he save us from
a complete annihilation?**

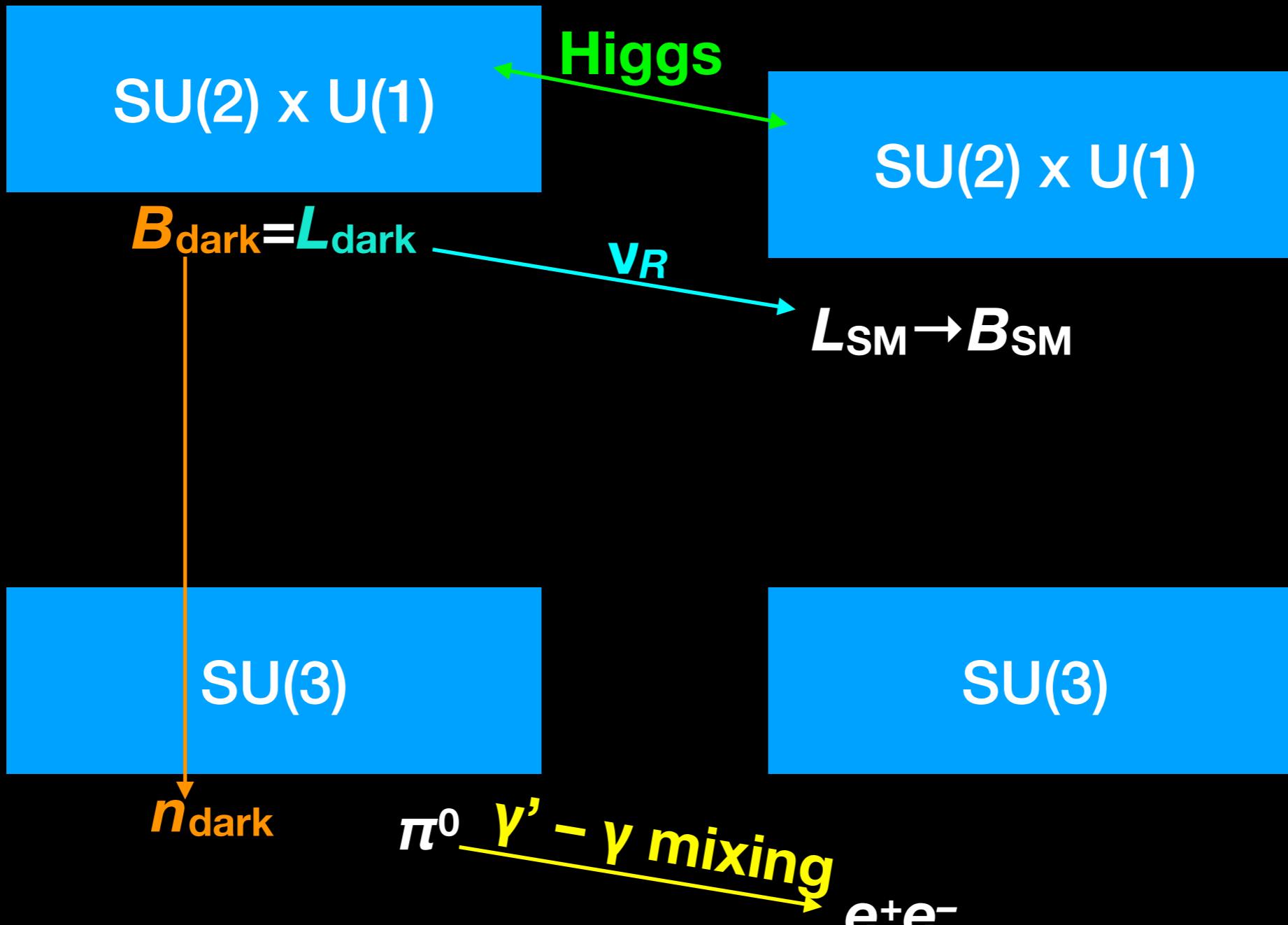
**Who is he keeping us
from falling apart?**

©Warner Bro

baryogenesis + DM

dark sector

SM



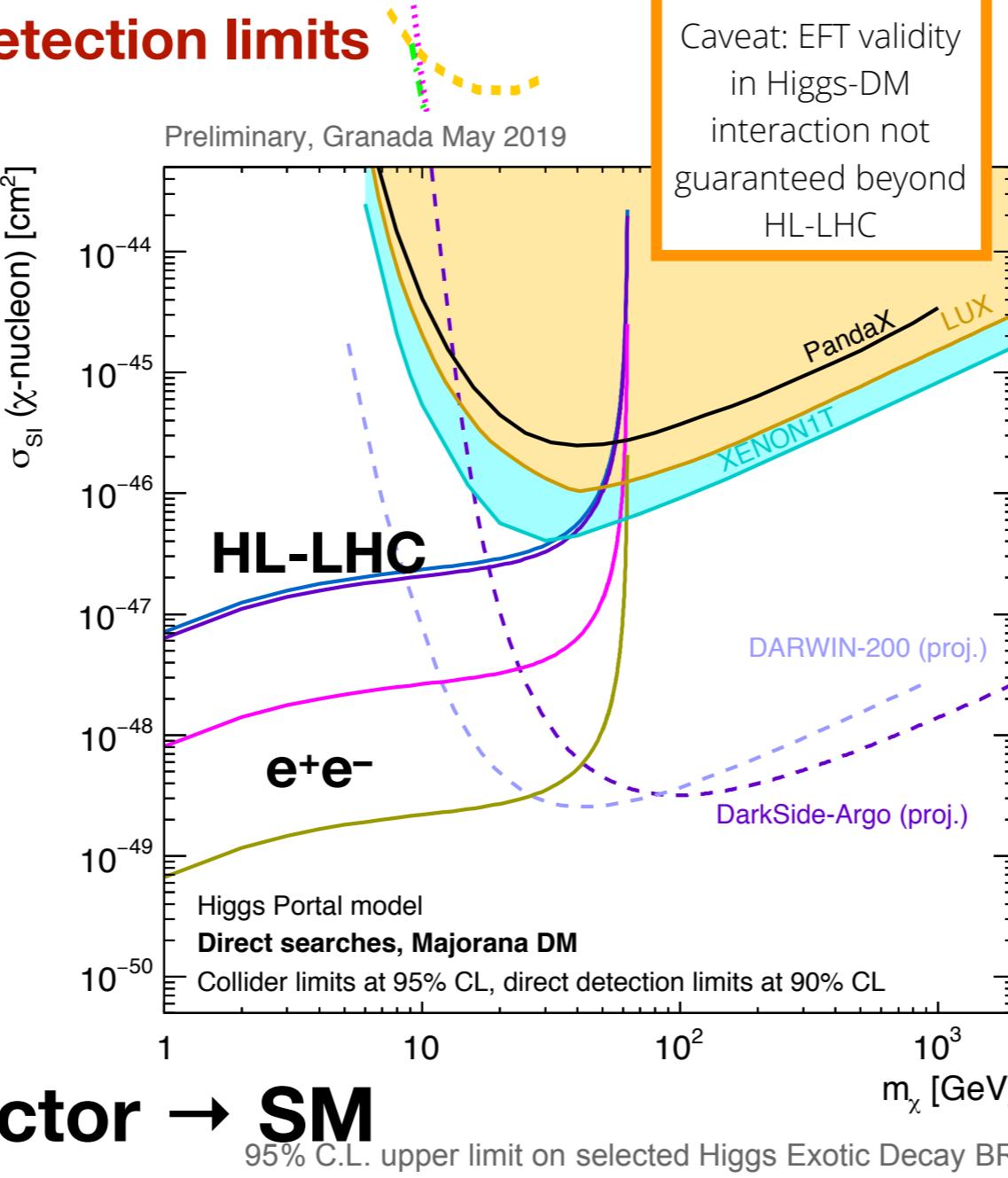
Why dark matter and baryon differ only by ~5?

Eleanor Hall, Thomas Konstandin, Robert McGehee, HM,
Géraldine Servant, Bethany Suter. arXiv:1910.08068. 1911.12342. 2107.03398

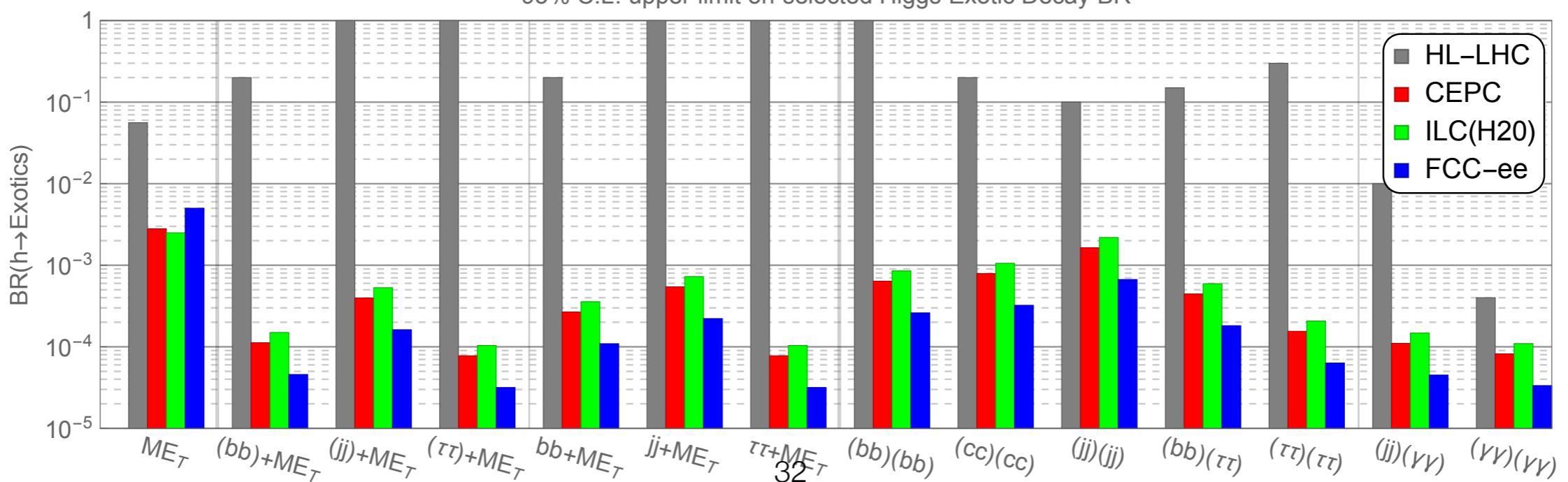
direct detection limits

Higgs decay to dark matter

x10 HL-LHC

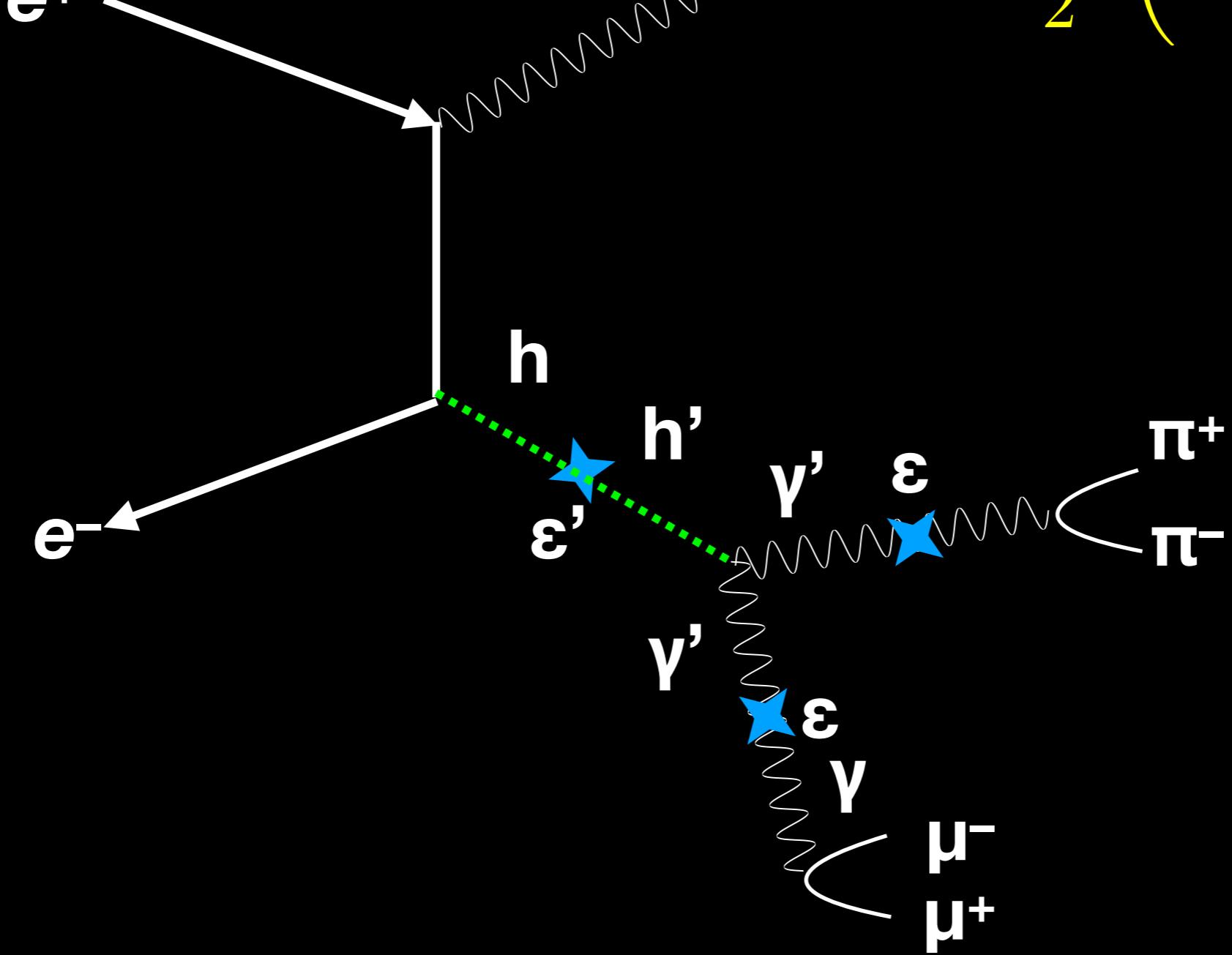


x1000–10000 HL-LHC
exotic Higgs decays

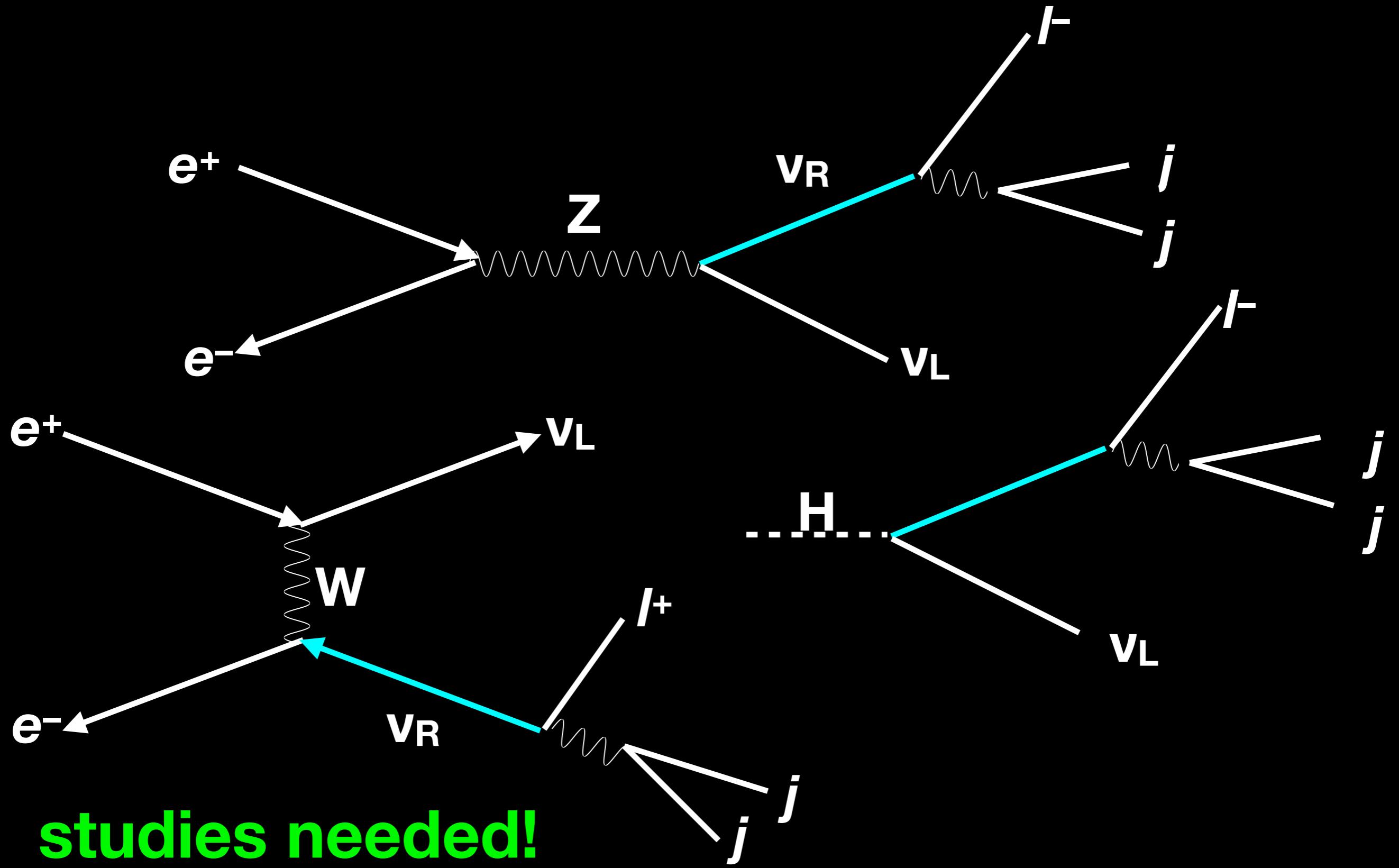


Higgs portal

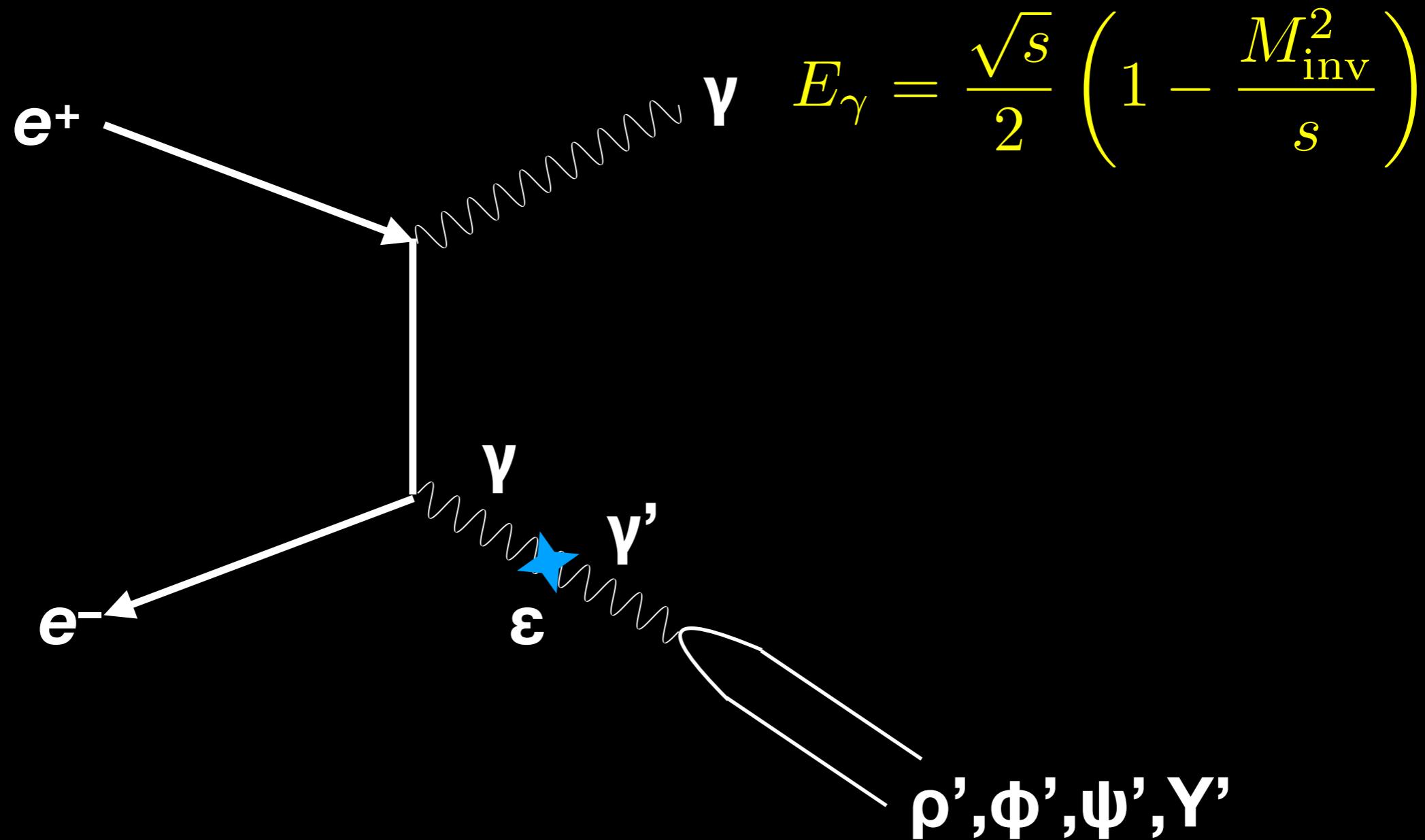
$$e^+ \text{---} \begin{array}{c} \nearrow \\ \text{Z} \end{array} E_Z = \frac{\sqrt{s}}{2} \left(1 + \frac{m_Z^2}{s} - \frac{M_h^2}{s} \right)$$



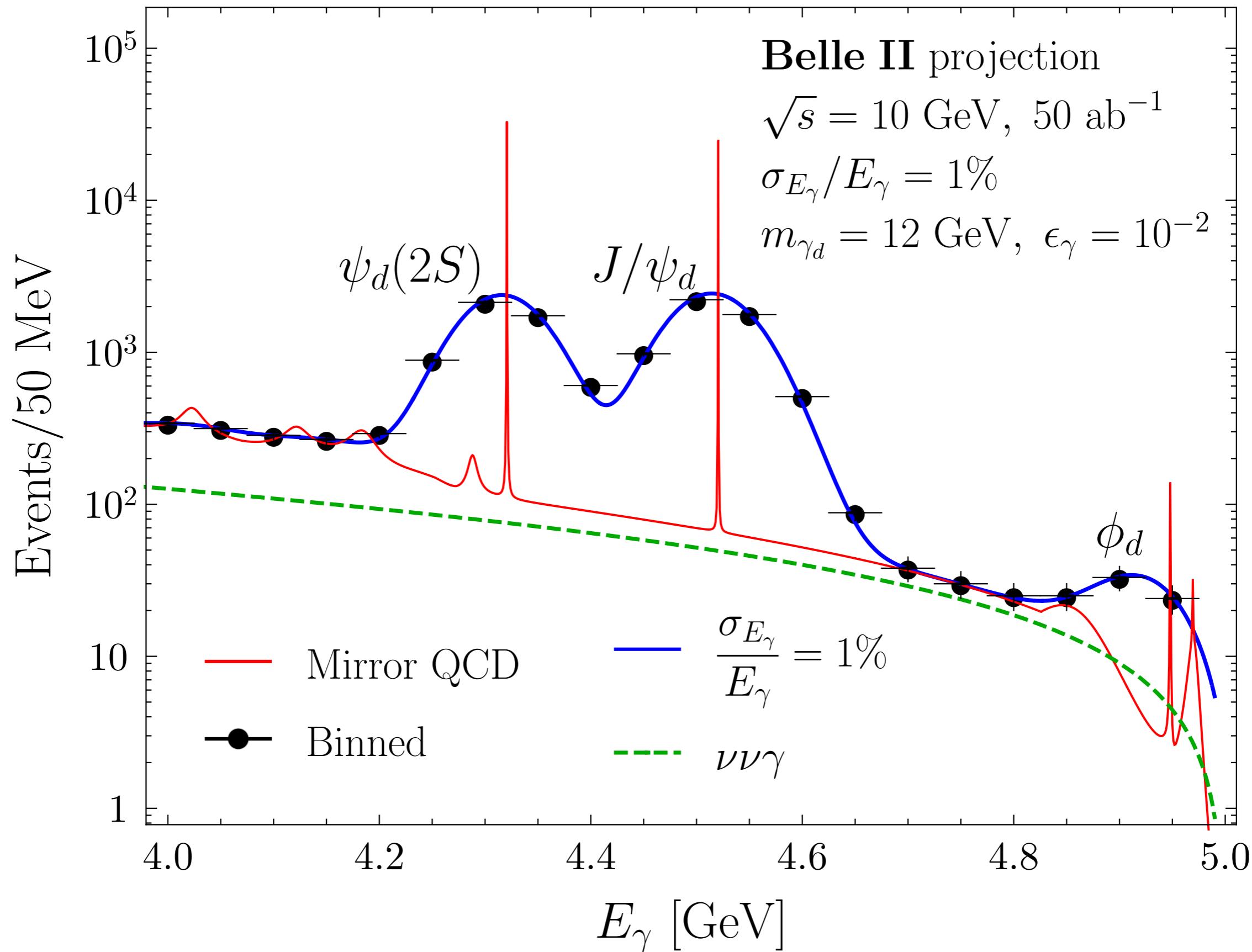
neutrino & Higgs portal



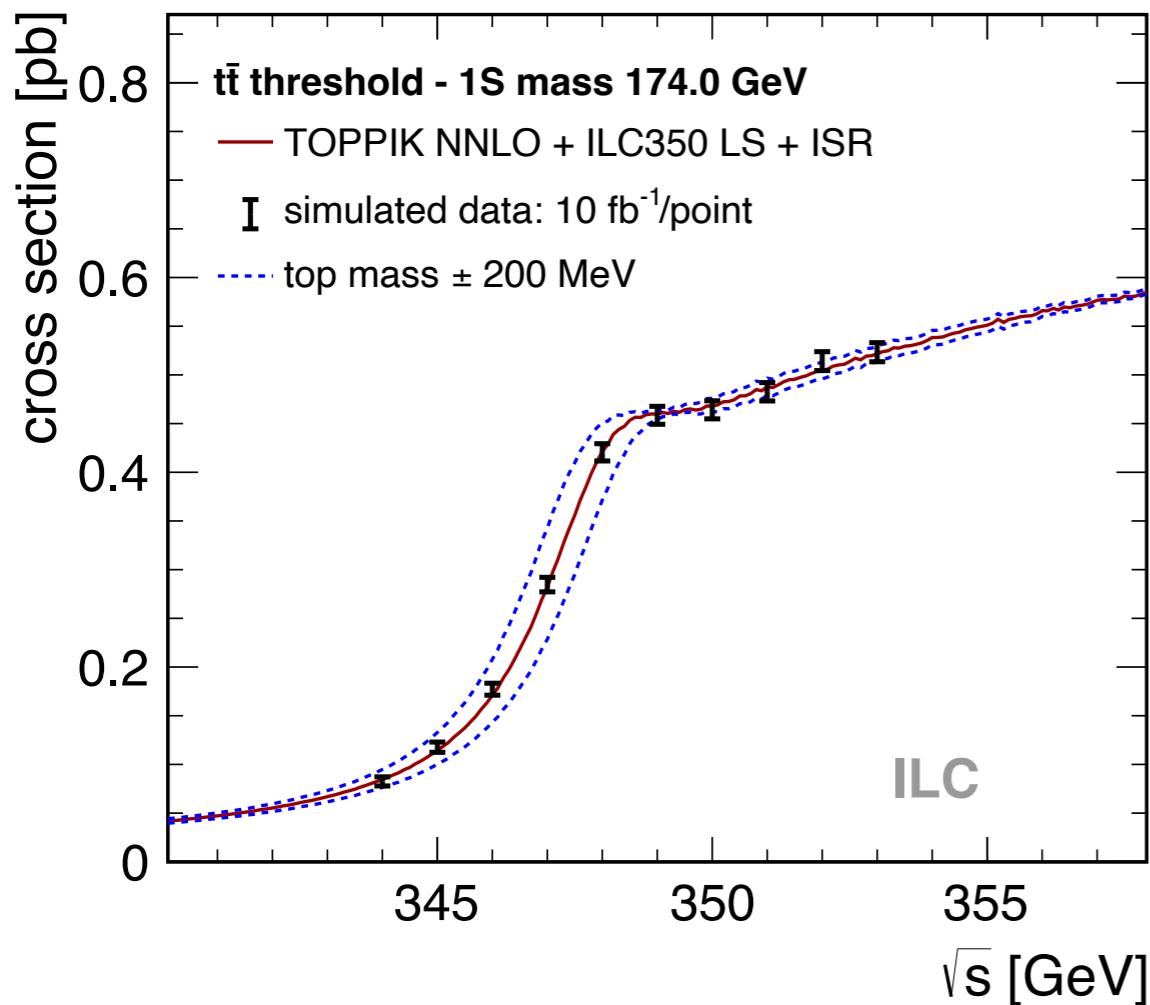
Dark Spectroscopy



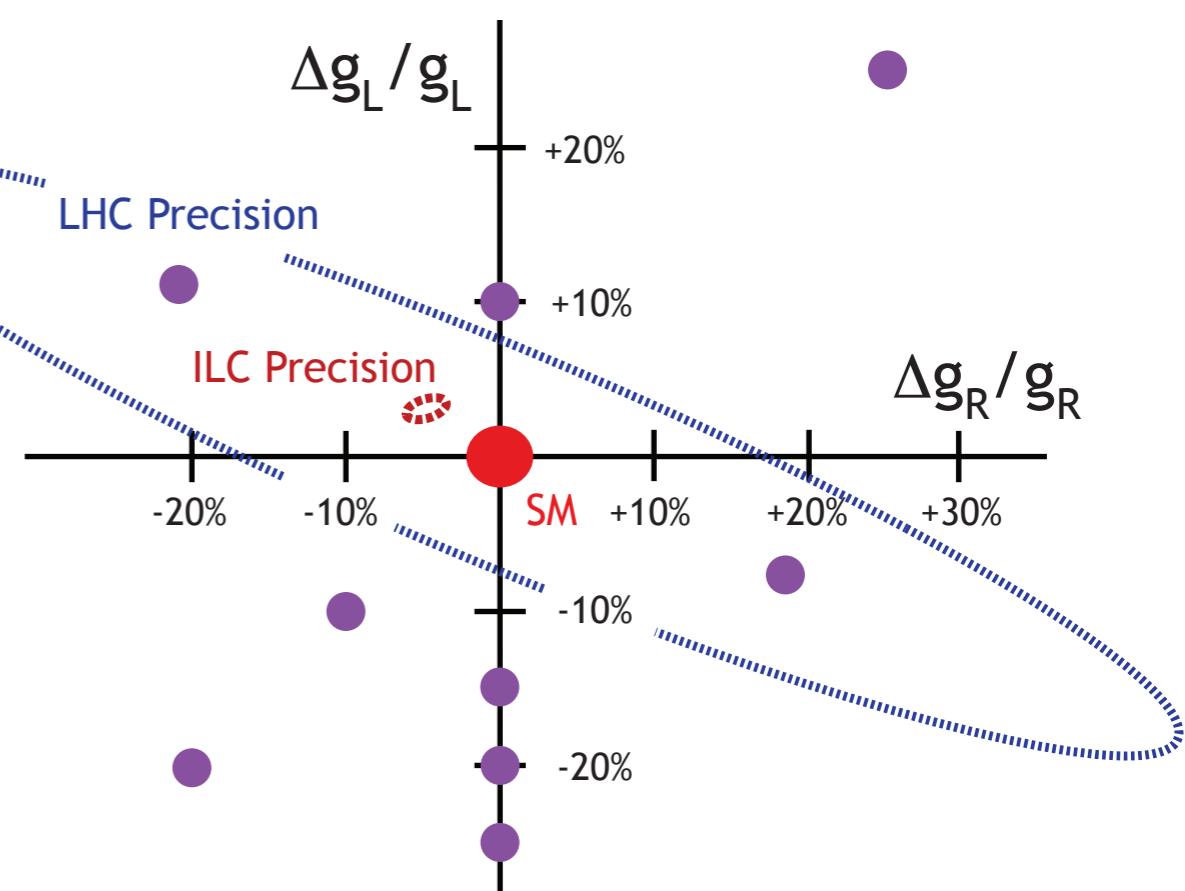
Dark Spectroscopy



top quark



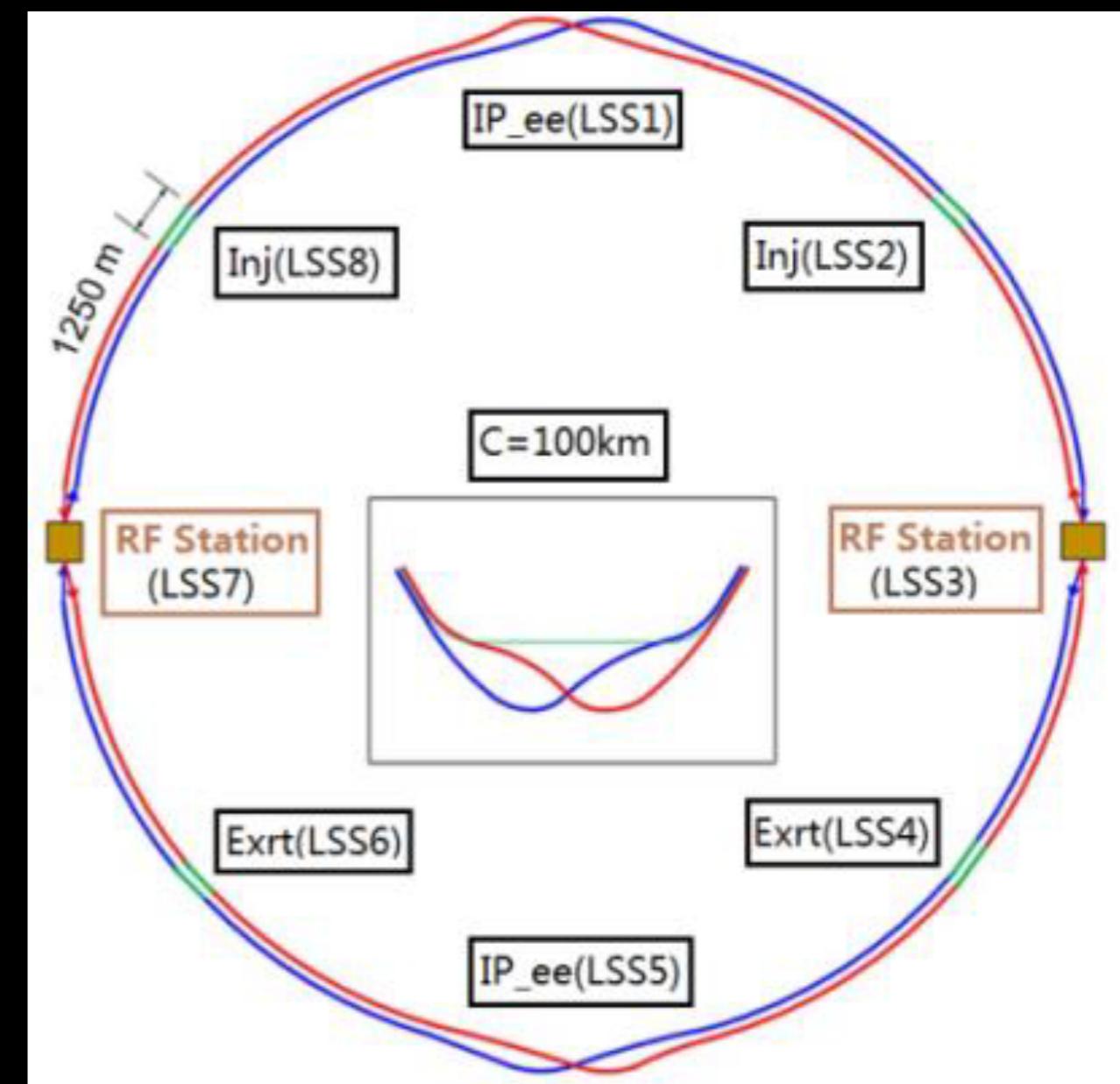
fate of the Universe



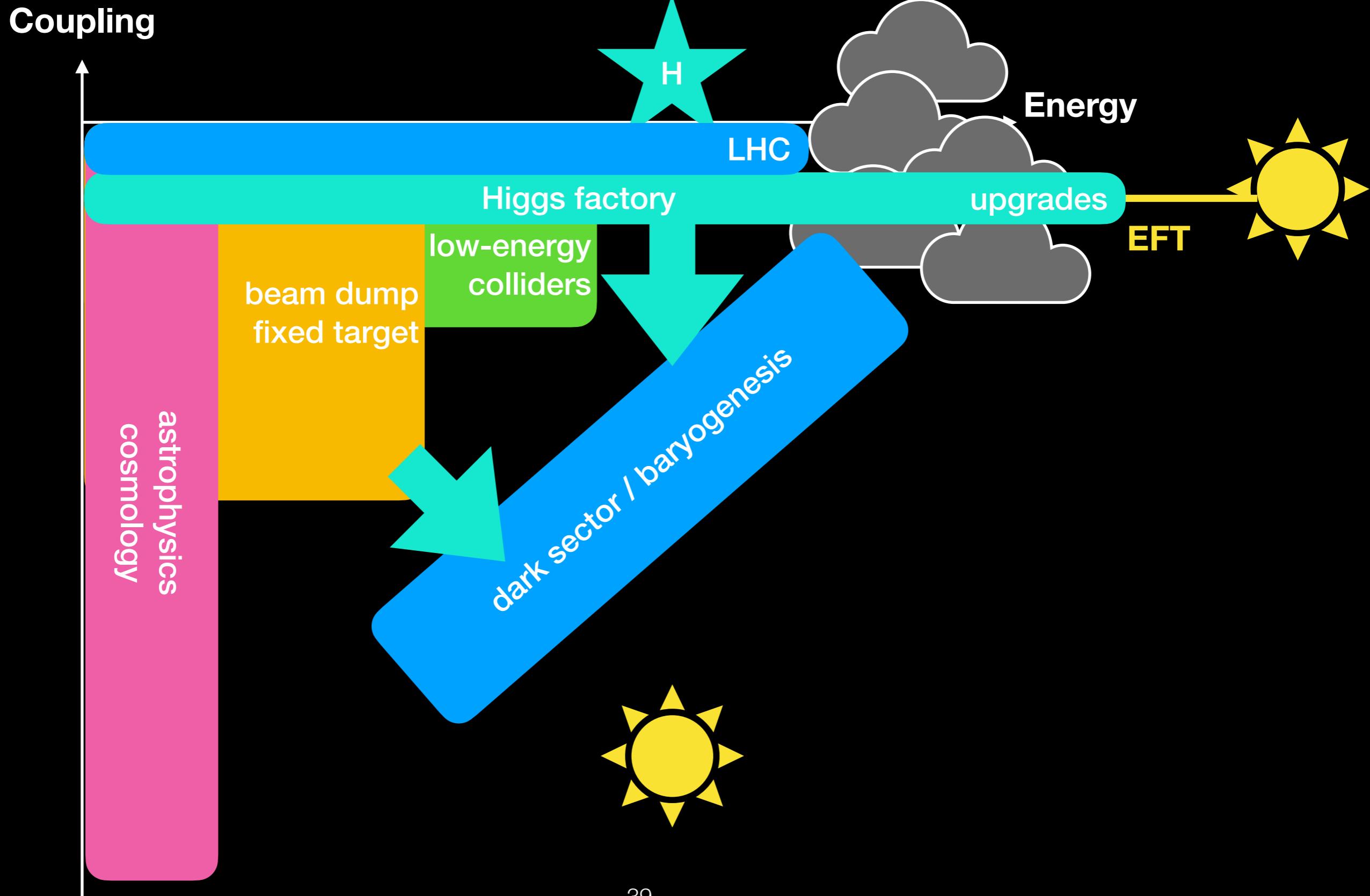
composite top+Higgs?

CEPC advantages

- 100km vs 91 km (FCC)
- Tera Z vs Giga Z (ILC)
- Potentially early realization
- Iron-based superconductor for SPPC



Vision





CHARLES M. SCHLEICH

**I WANT YOU
FOR HIGGS FACTORY
NEAREST RECRUITING STATION**