Vision of Particle Physics

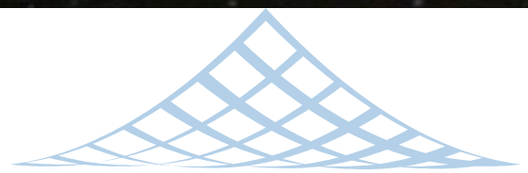
–with emphasis on colliders–

Hitoshi Murayama (Berkeley & Kavli IPMU)

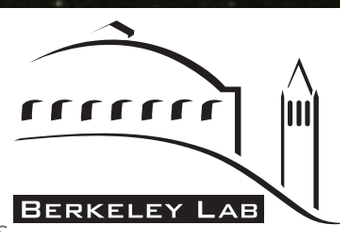
KAIST-TAIX Workshop for Future Particle Accelerators

July 8, 2019

東京大学
THE UNIVERSITY OF TOKYO



BERKELEY CENTER FOR THEORETICAL PHYSICS

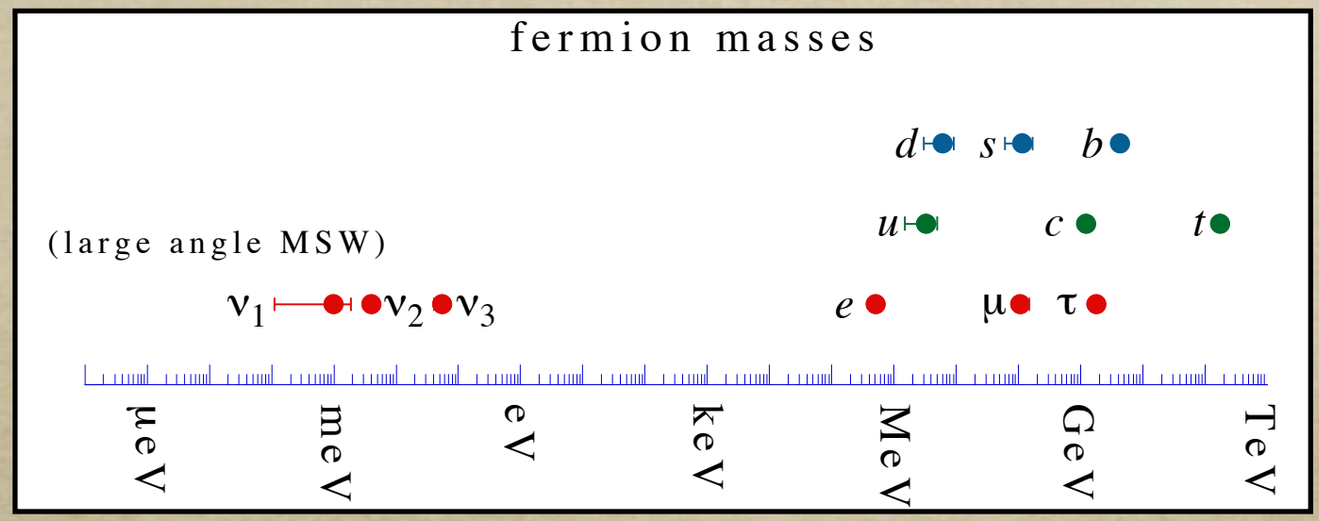


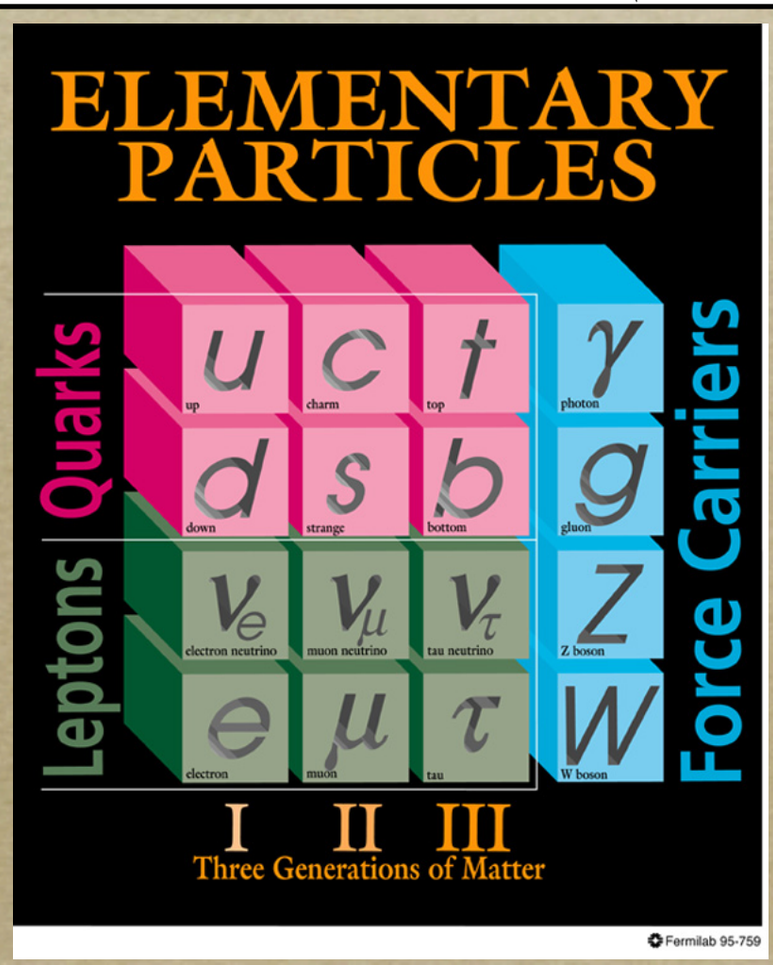
BERKELEY LAB

KAVLI IPMU

Big Questions –Horizontal–

- *Why are there three generations?*
- *What physics determines the pattern of masses and mixings?*
- *Why do neutrinos have mass yet so light?*
- *What is the origin of CP violation?*
- *What is the origin of matter anti-matter asymmetry in Universe?*

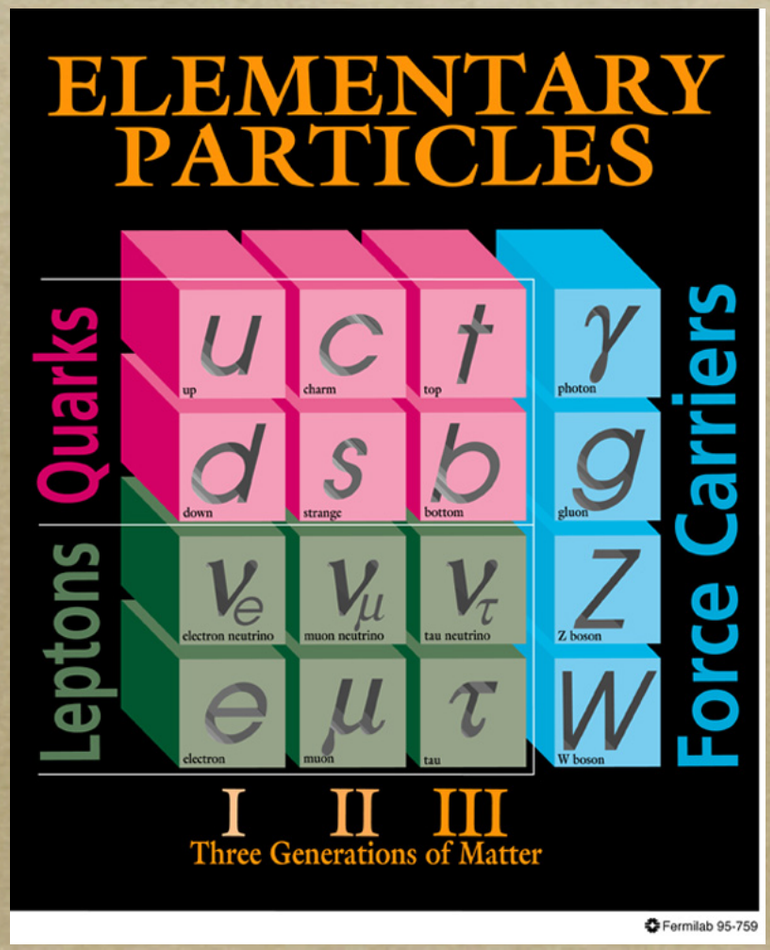




Big Questions
–Vertical–

- *Why are there three unrelated gauge forces?*
- *Why is strong interaction strong?*
- *Charge quantization*
- *anomaly cancellation*
- *quantum numbers*
- *Is there a unified description of all forces?*
- *Why is* $m_W \ll M_{Pl}$ *?* *(Hierarchy Problem)*

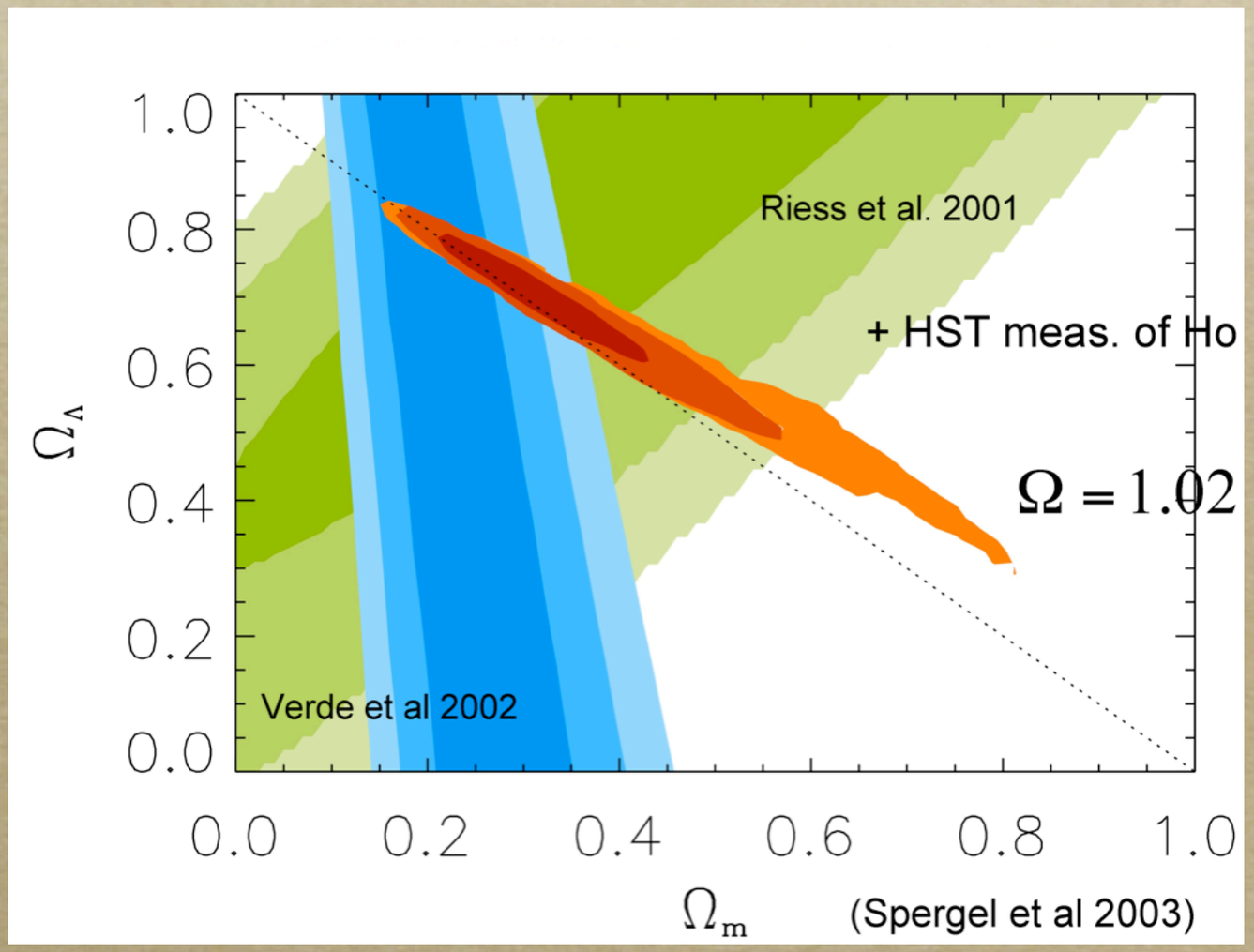
$$Q(\mathbf{3},\mathbf{2},+\frac{1}{6}),\quad u(\mathbf{3},\mathbf{1},+\frac{2}{3}),\quad d(\mathbf{3},\mathbf{1},-\frac{1}{3}),$$
$$L(\mathbf{1},\mathbf{2},-\frac{1}{2}),\quad e(\mathbf{1},\mathbf{1},-1)$$



HM, *Outlook*, Lepton Photon 2003

Big Questions
–From the Heaven–

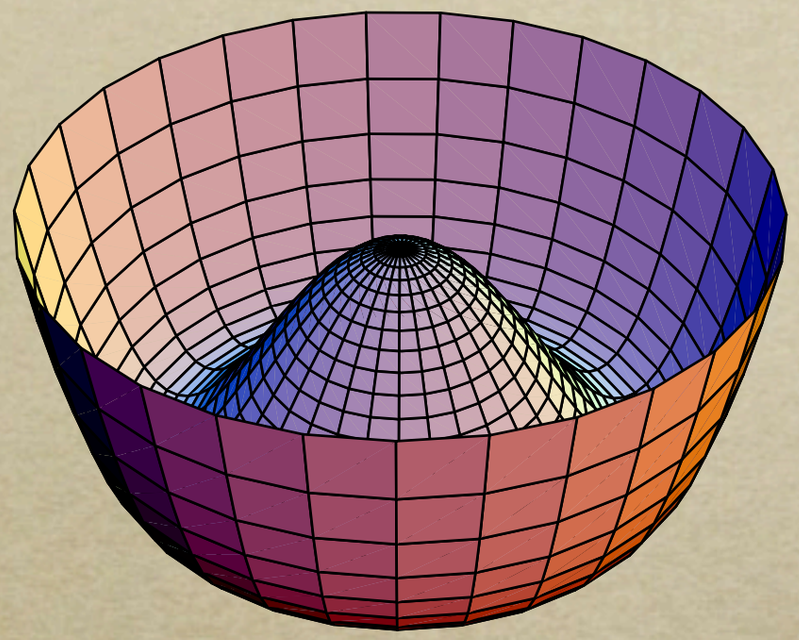
- *What is Dark Matter?*
- *What is Dark Energy?*
- *Why now? (Cosmic coincidence problem)*
- *What was Big Bang?*
- *Why is Universe so big? (flatness problem, horizon problem)*
- *How were galaxies and stars created?*

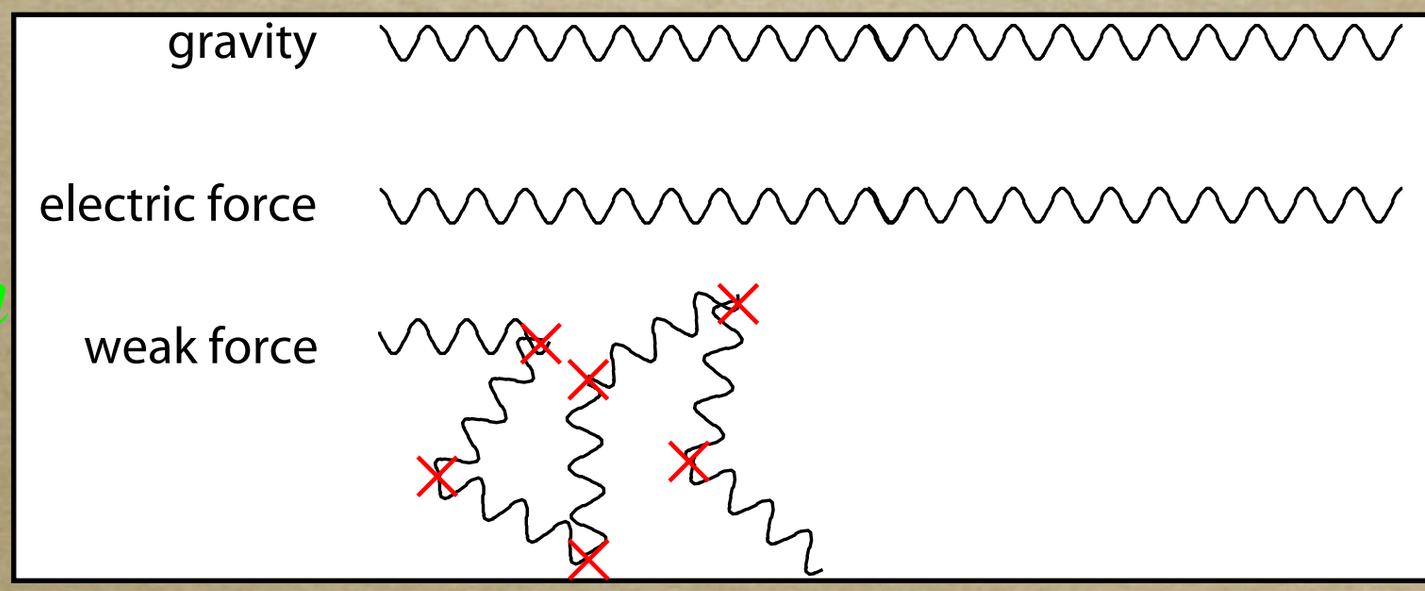


HM, *Outlook*, Lepton Photon 2003

Big Questions
–From the Hell–

- *What is the Higg boson?*
- *Why does it have negative mass-squared?*
- *Why is there only one scalar particle in the Standard Model?*
- *Is it elementary or composite?*
- *Is it really condensed in our Universe?*





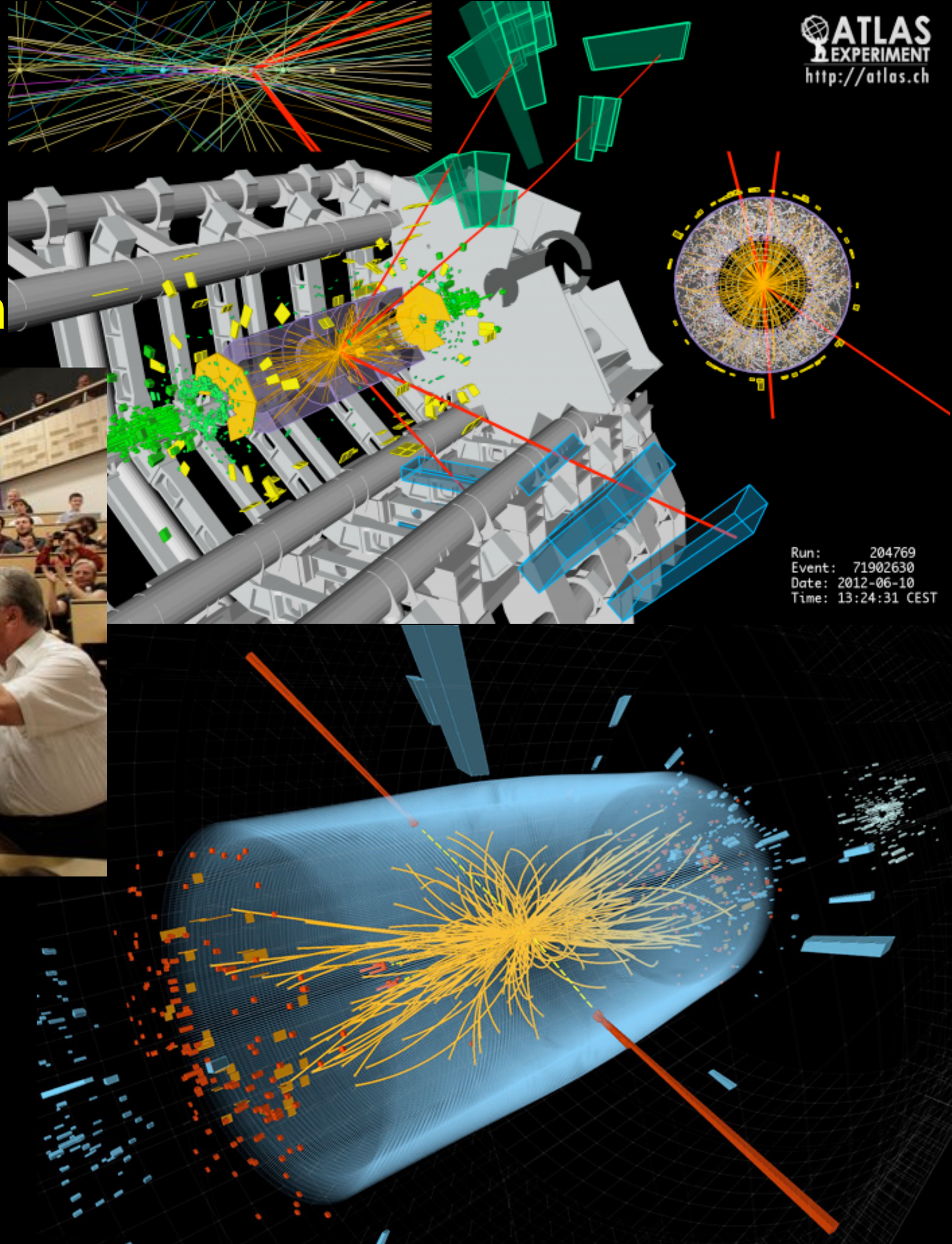
2012.7.4

discovery of Higgs boson

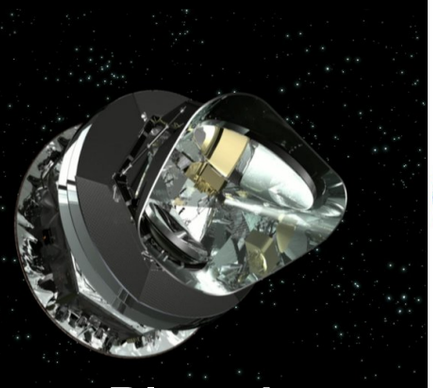
theory：1964

design：1984

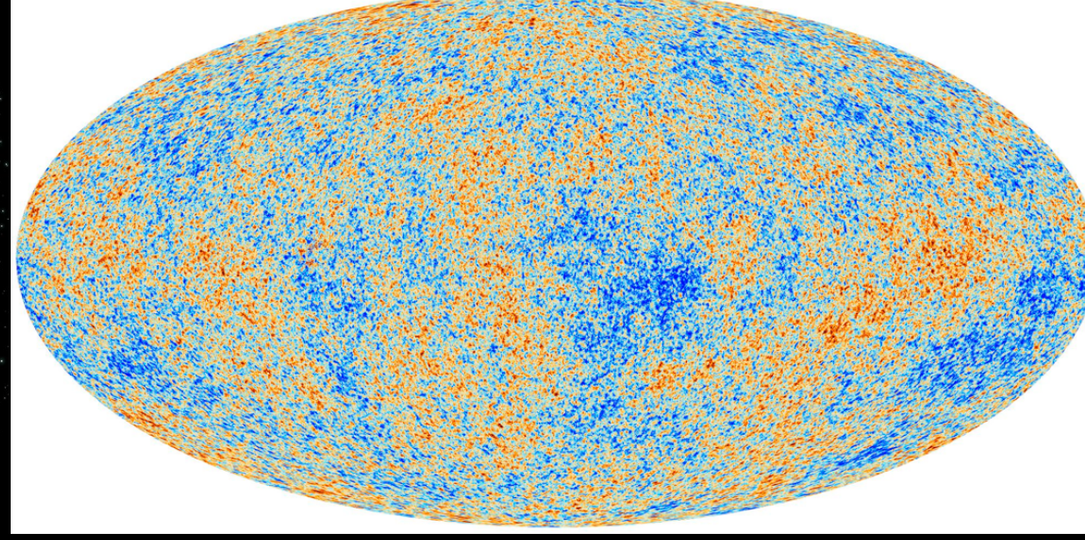
construction：1998



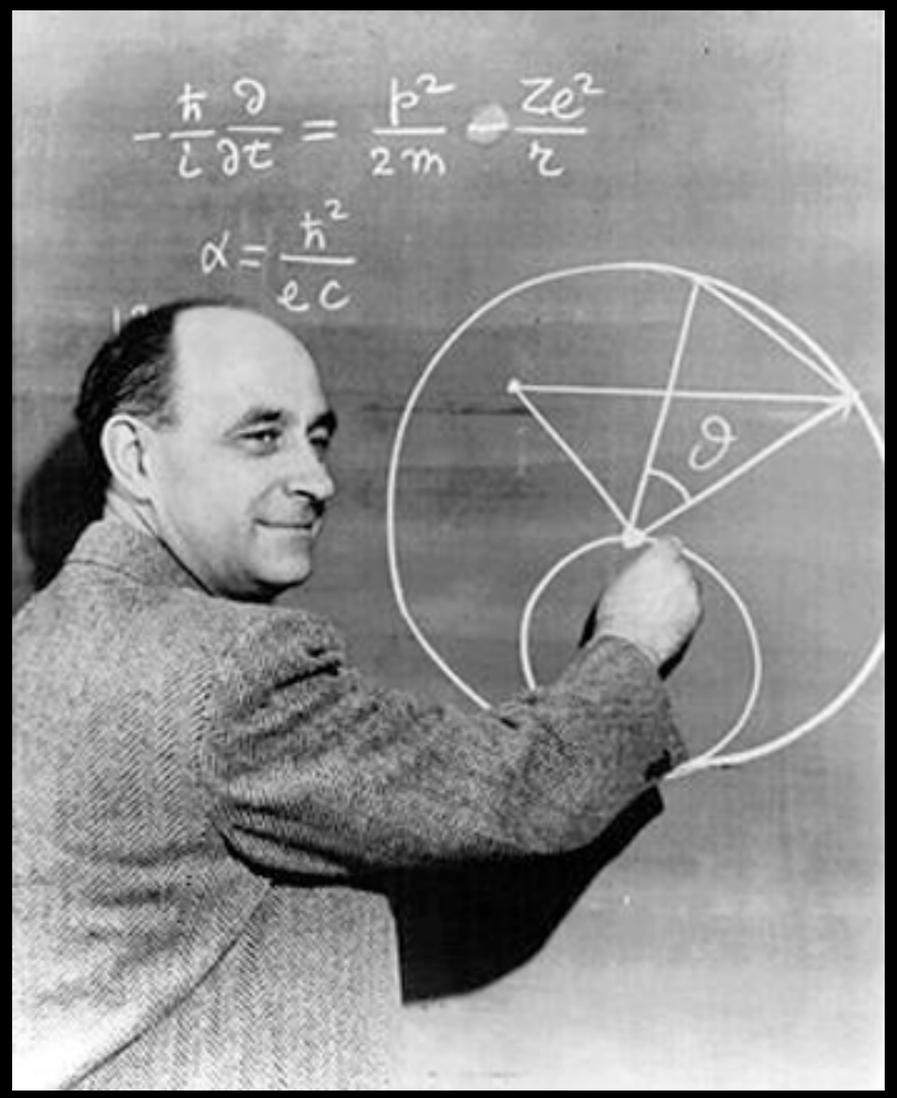
Minimal



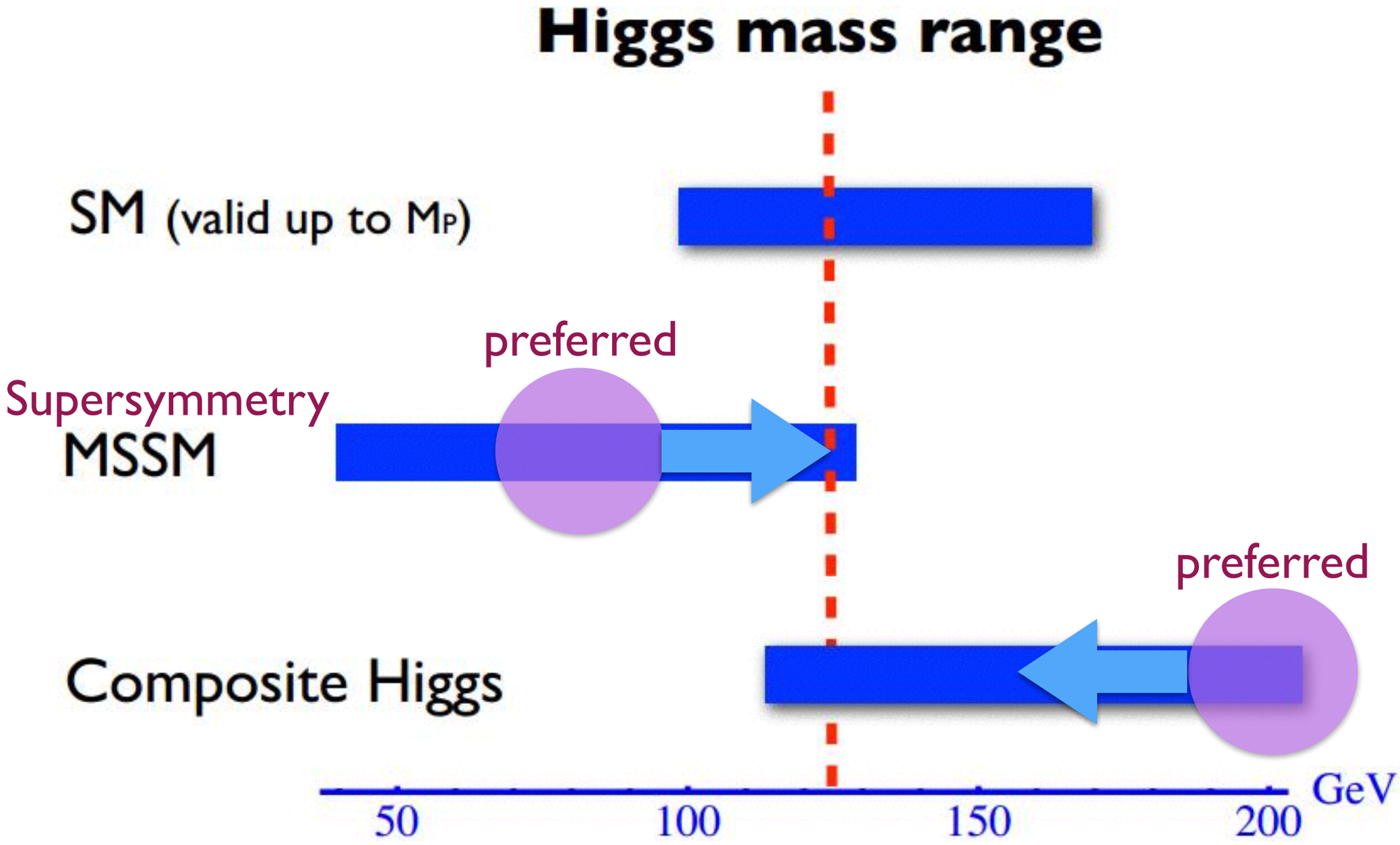
Planck



- It looks very much like *the* Standard Model Higgs boson
- We've known the energy scale to probe since 1933
- now a UV complete theory of strong, weak, EM forces possibly valid up to even M_{Pl}
- cosmology also looks minimal single-field inflation (Planck)



Where do we go next?

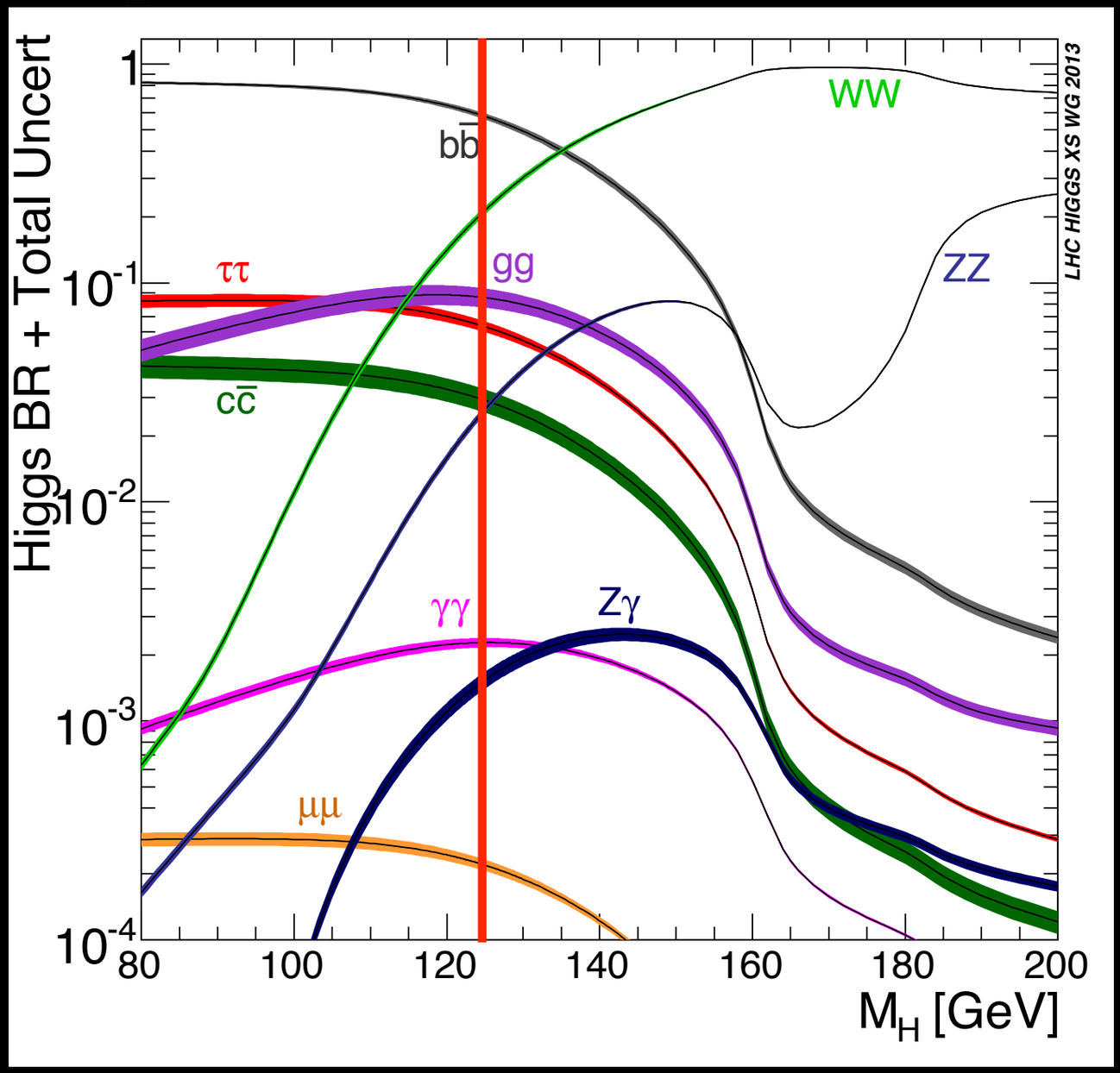

Higgs mass range
SM (valid up to MP)
preferred
Supersymmetry
MSSM
preferred
Composite Higgs
50
100
150
200
GeV

By A Pomarol

Nima's anguish

m_H=125 GeV seems almost maliciously designed to prolong the agony of BSM theorists….

dream case for experiments

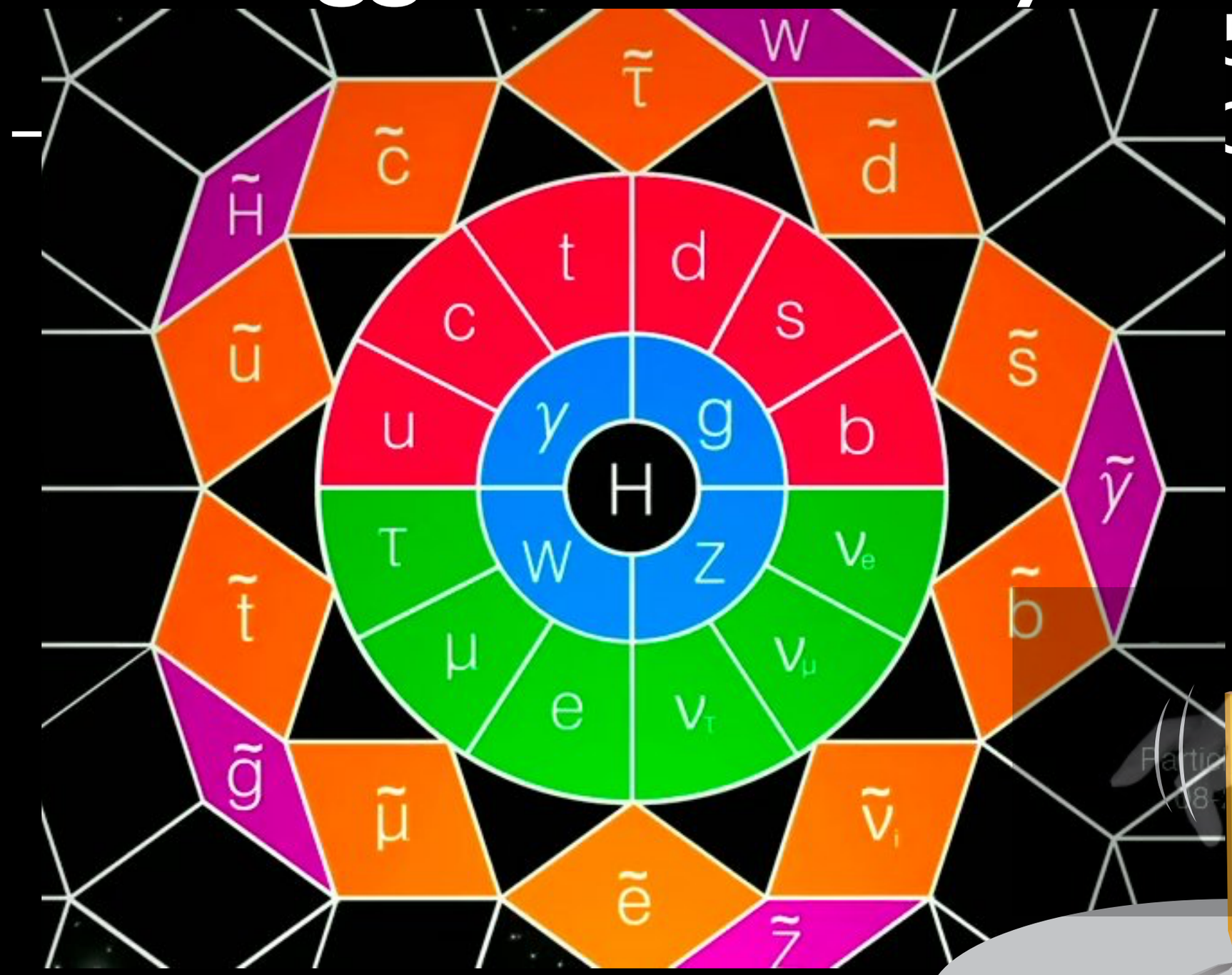


stupid not to do this!

Scalar

- every elementary particles have spin
- electrons, photons, quarks, ...
- only Higgs boson doesn't spin
- Faceless! A *spooky particle*
- I had proposed "Higgsless theories"
- *Is it the only one?*
- *does it have siblings? relatives?*
- *Maybe it's spinning in extra dimensions?*
- *maybe composite?*
- *why did it freeze in?*

Higgs is too testy



503
378
125

supersymmetry

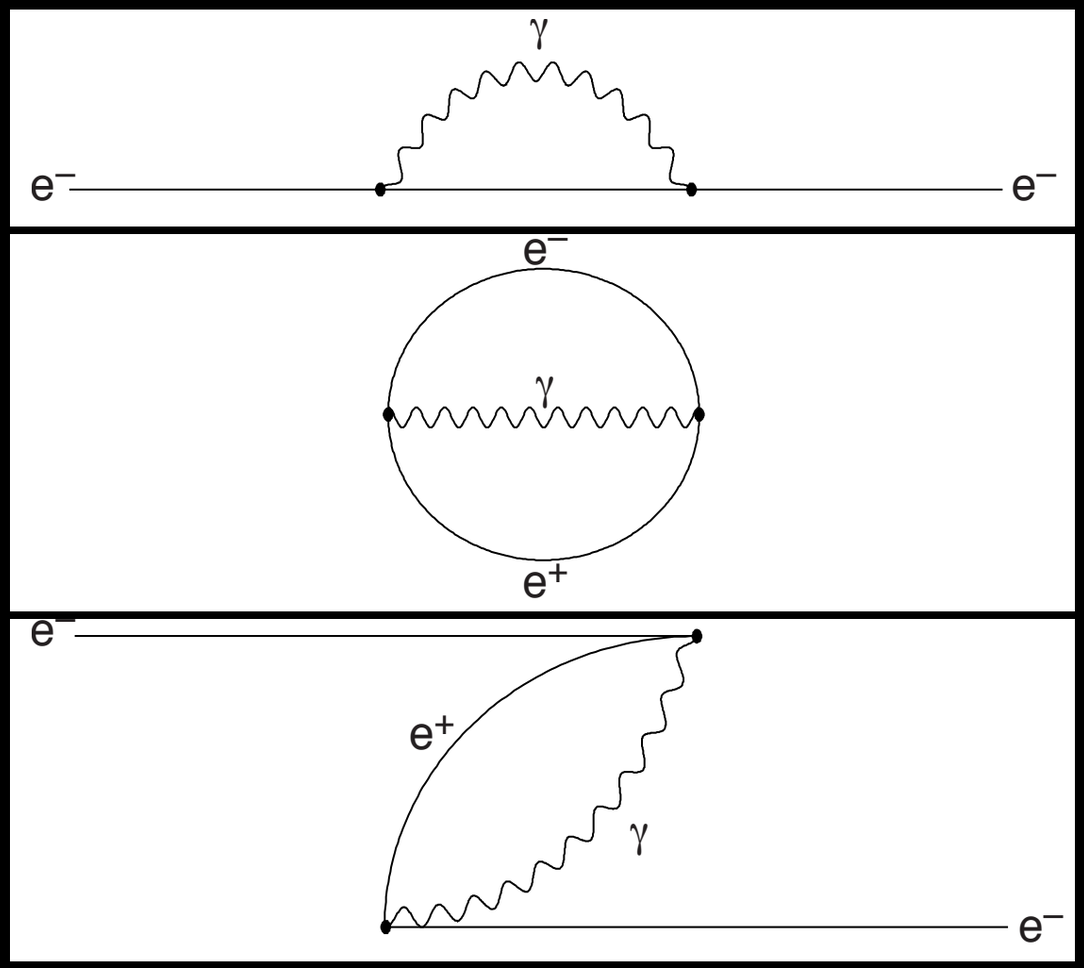
Electron mass is natural by doubling #particles

- Electron creates a force to repel itself

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

- quantum mechanics and anti-matter

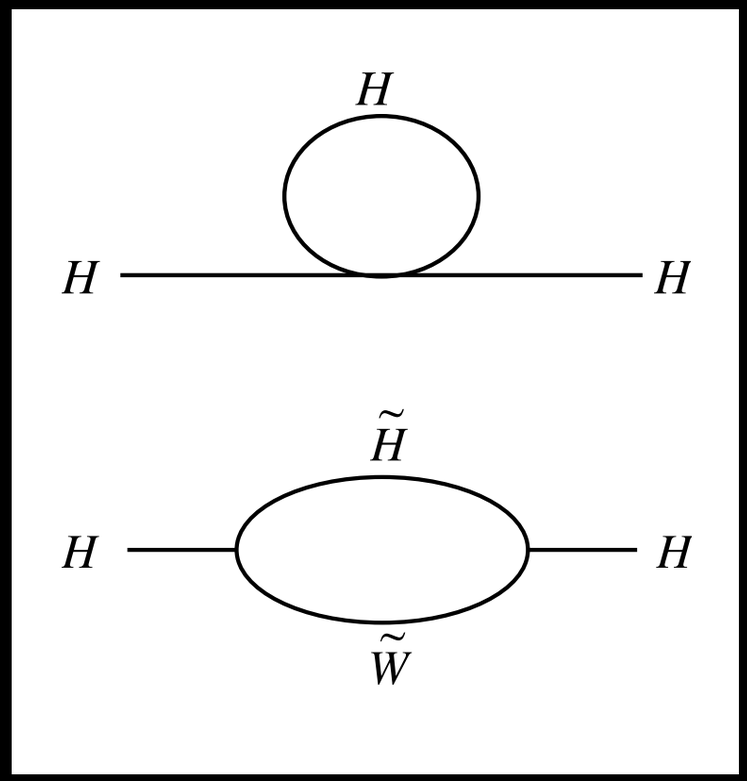
⇒ only 10% of mass even for Planck-size $r_e \sim 10^{-33}$cm



$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

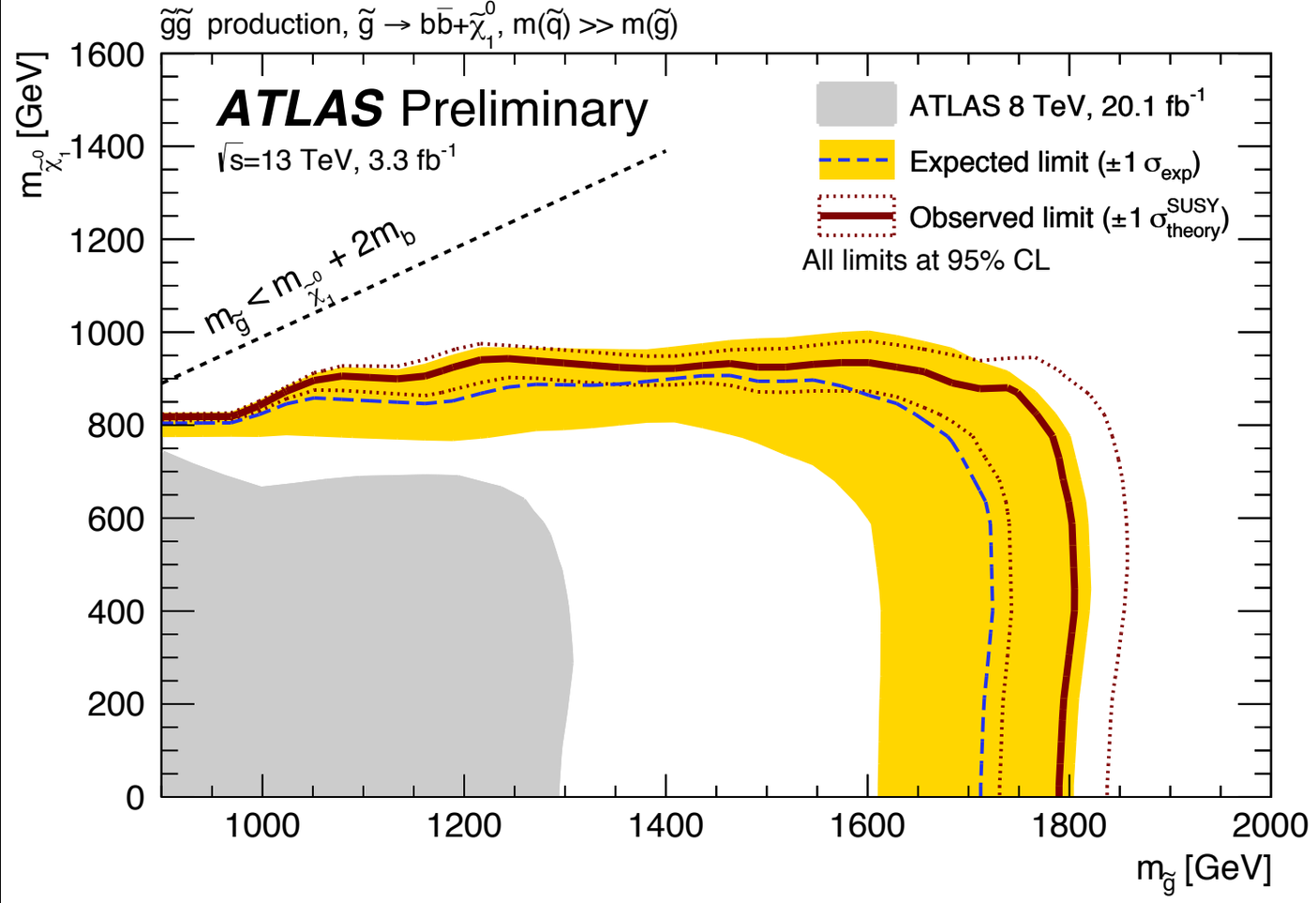
Higgs mass is natural by doubling #particles?

- Higgs also repels itself
- Double #particles again
  ⇒ superpartners
- only log sensitivity to UV
- Standard Model made consistent up to higher energies

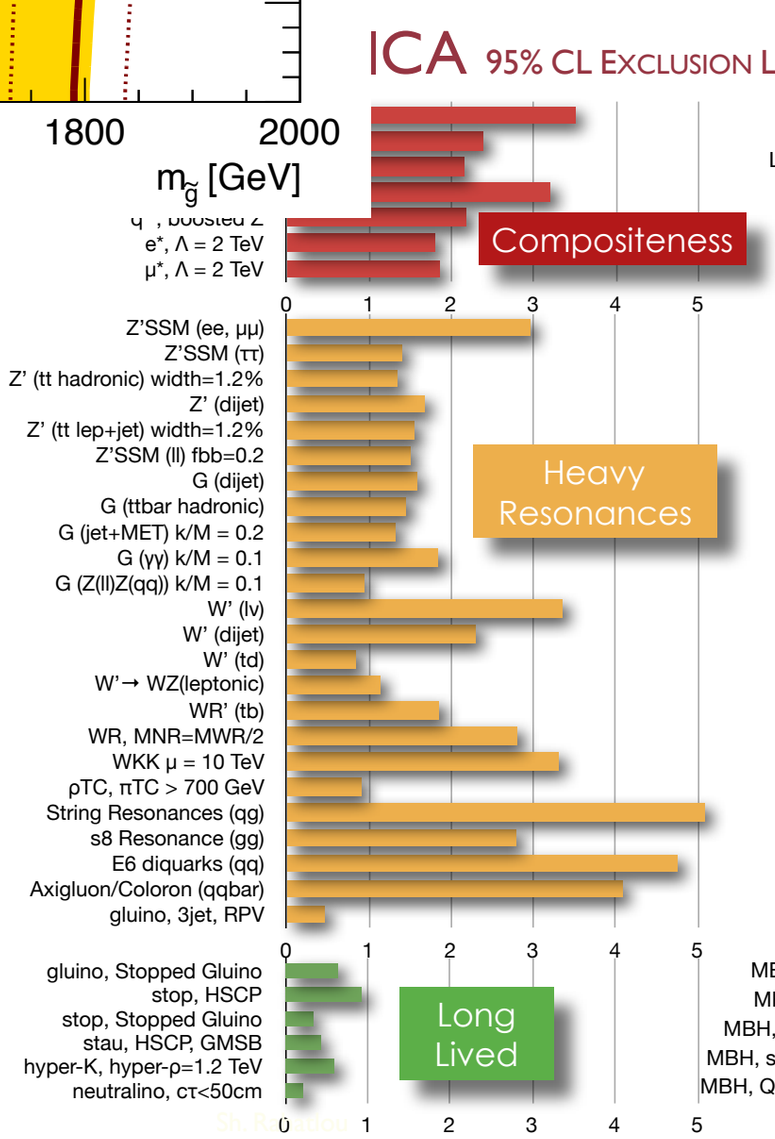


$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

⇒ I still take it seriously



no sign of
new physics
that explains Higgs!



LHC score card

- origin of EWSB
  - Higgs discovered: but only a partial answer
- naturalness
  - None
- dark matter
  - None
- EW baryogenesis
  - No new CP violation
- unexpected
  - Perhaps??? 750 GeV diphoton???

Supersymmetry

ENGINEERING
Machines That Change Shape

MEDICINE
An Off Switch for Cancer

NEUROSCIENCE
How to Reach "Vegetative" Patients

SCIENTIFIC AMERICAN

ScientificAmerican.com

A CRISIS IN PHYSICS?

IF SUPERSYMMETRY DOESN'T PAN OUT, SCIENTISTS NEED A NEW WAY TO EXPLAIN THE UNIVERSE

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MAY 2014

KAVLI IPMU

been there before

The New York Times

Science

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ENVIRONMENT

315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE

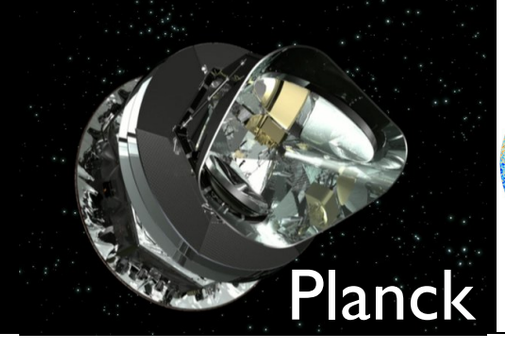
Published: January 5, 1993

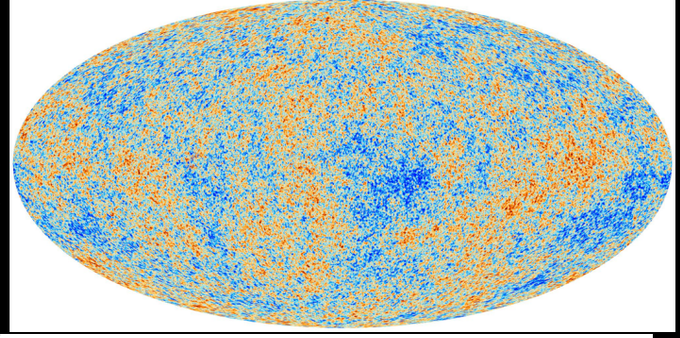
Three hundred and fifteen physicists worked on the experiment.

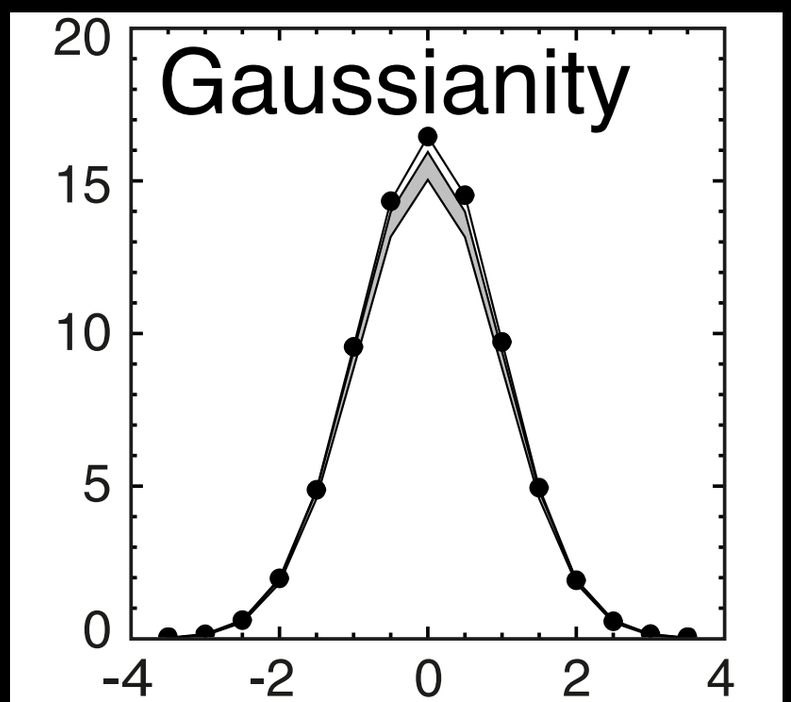
Their apparatus included the Tevatron, the world's most powerful

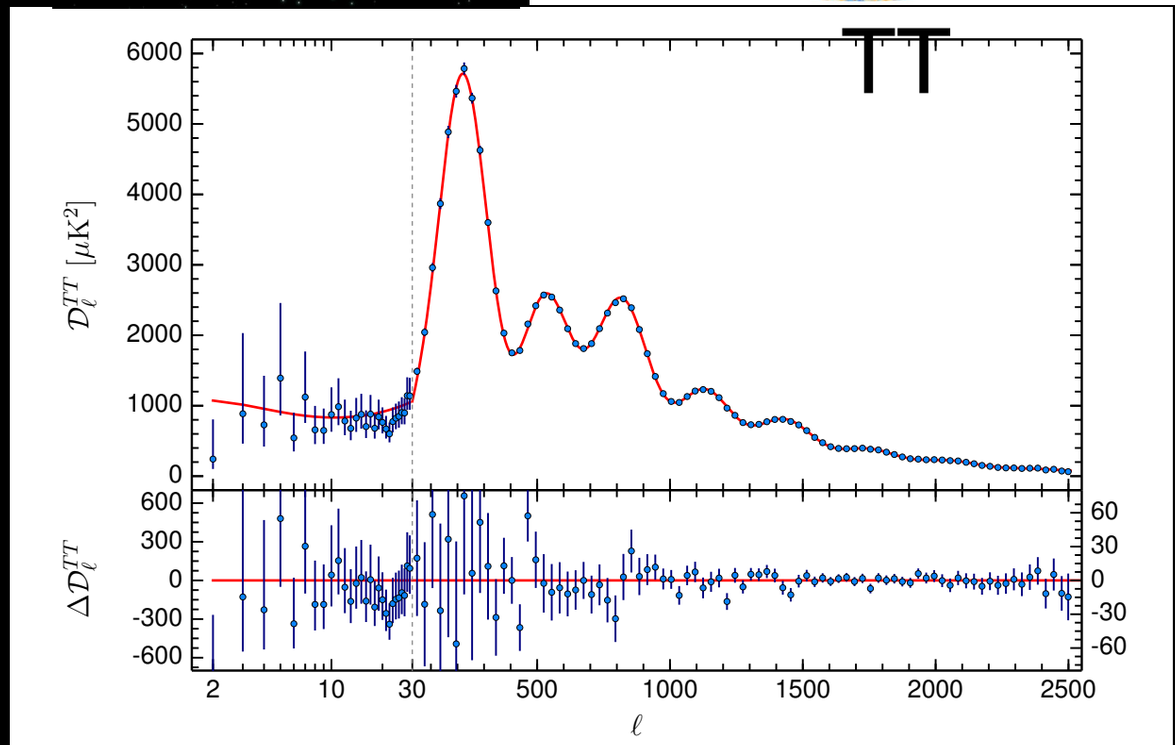
Naturalness works!

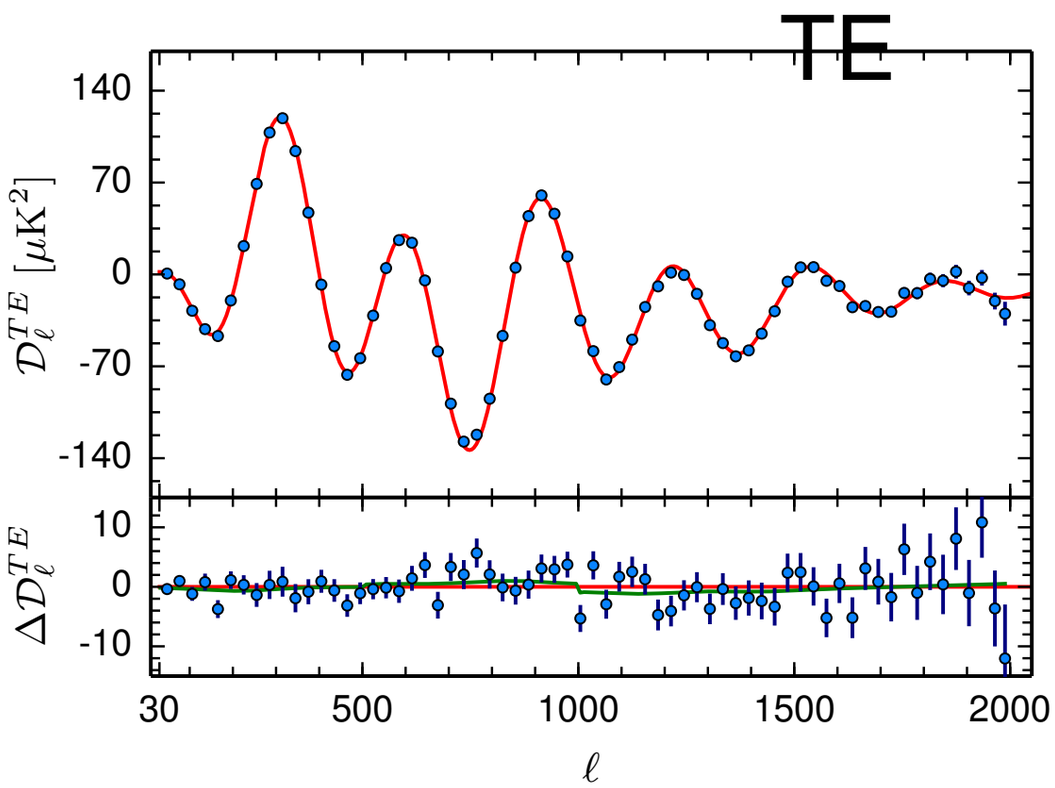
- Why is the Universe big?
- Inflation
  - horizon problem
  - flatness problem
- large entropy







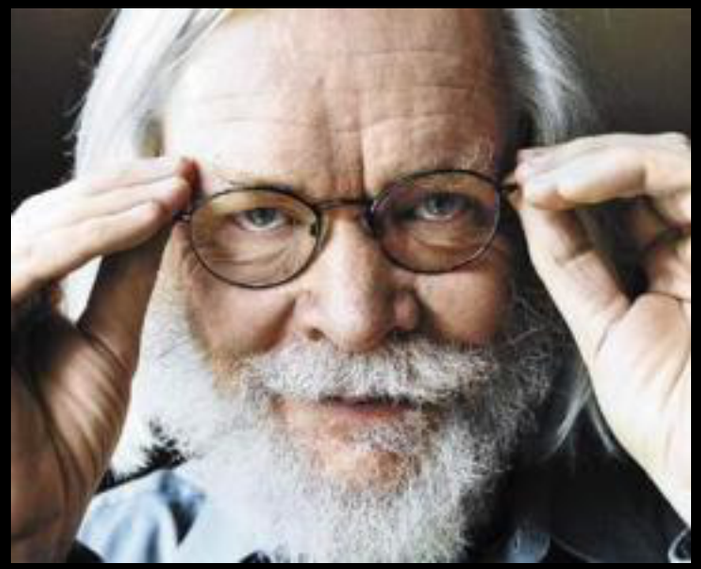




scalar top mass ≥ 10 TeV preferred

Giudice and Strumia, arXiv:1108.6077

assumption: MSSM

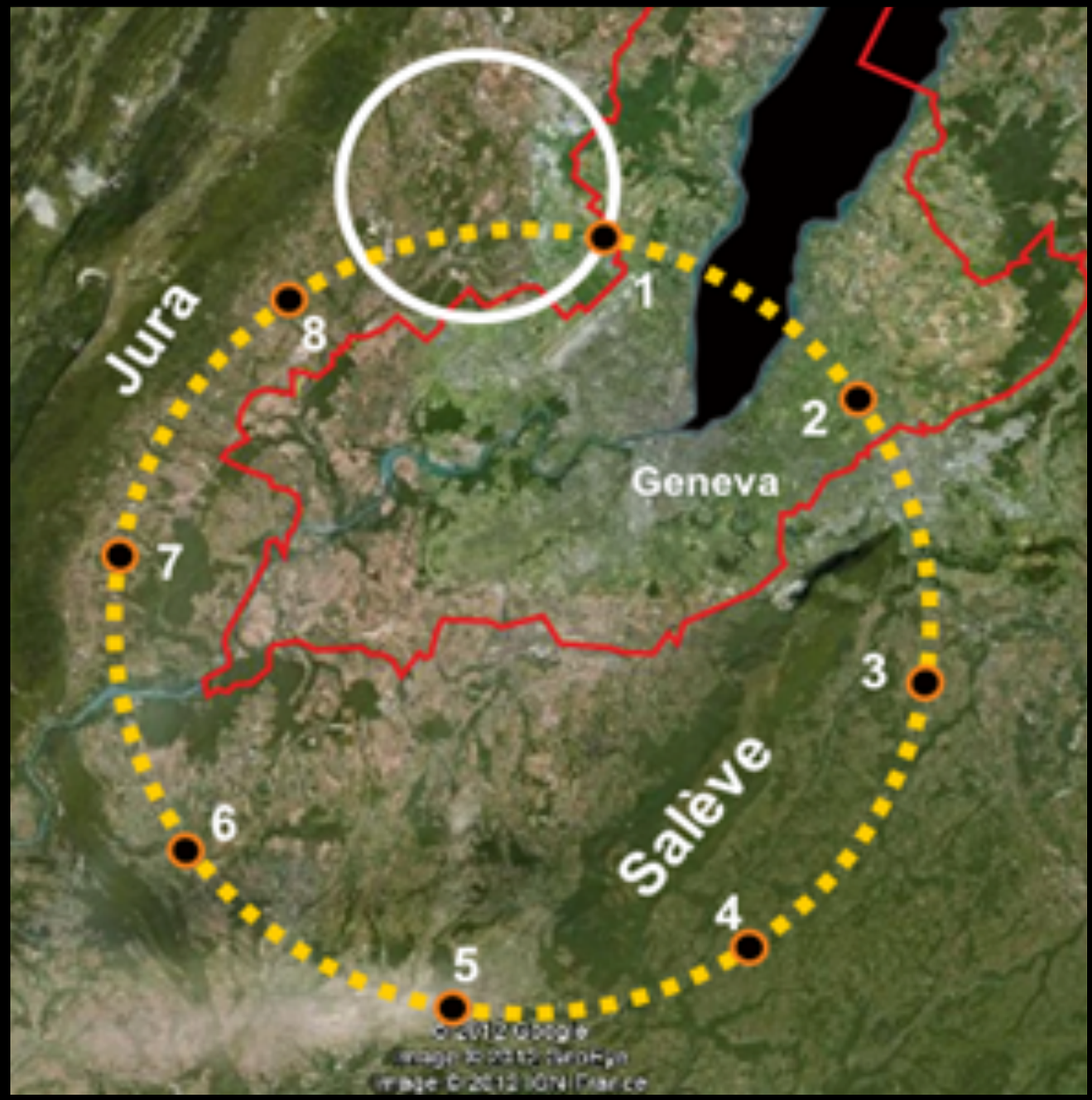


Better Late Than Never

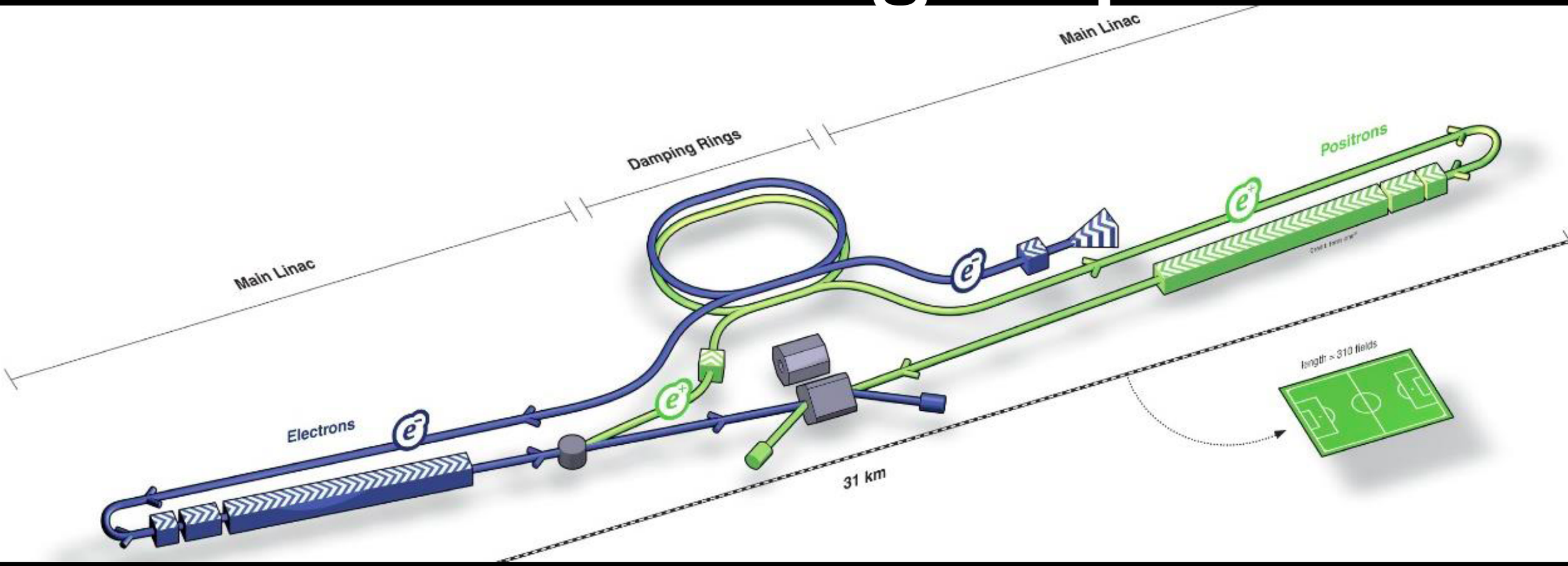
Even $m_{SUSY} \sim 10$ TeV ameliorates fine-tuning from 10^{-36} to 10^{-4}

higher energies?

- Need to explore
- HL-LHC boosts reach
- We believe we should keep aiming at higher energies
- HE-LHC?
- *100 TeV pp would be great!*
- Need to continue magnet R&D
- Possible first stage: FCCee from m_Z upto 365 GeV



Another staged path

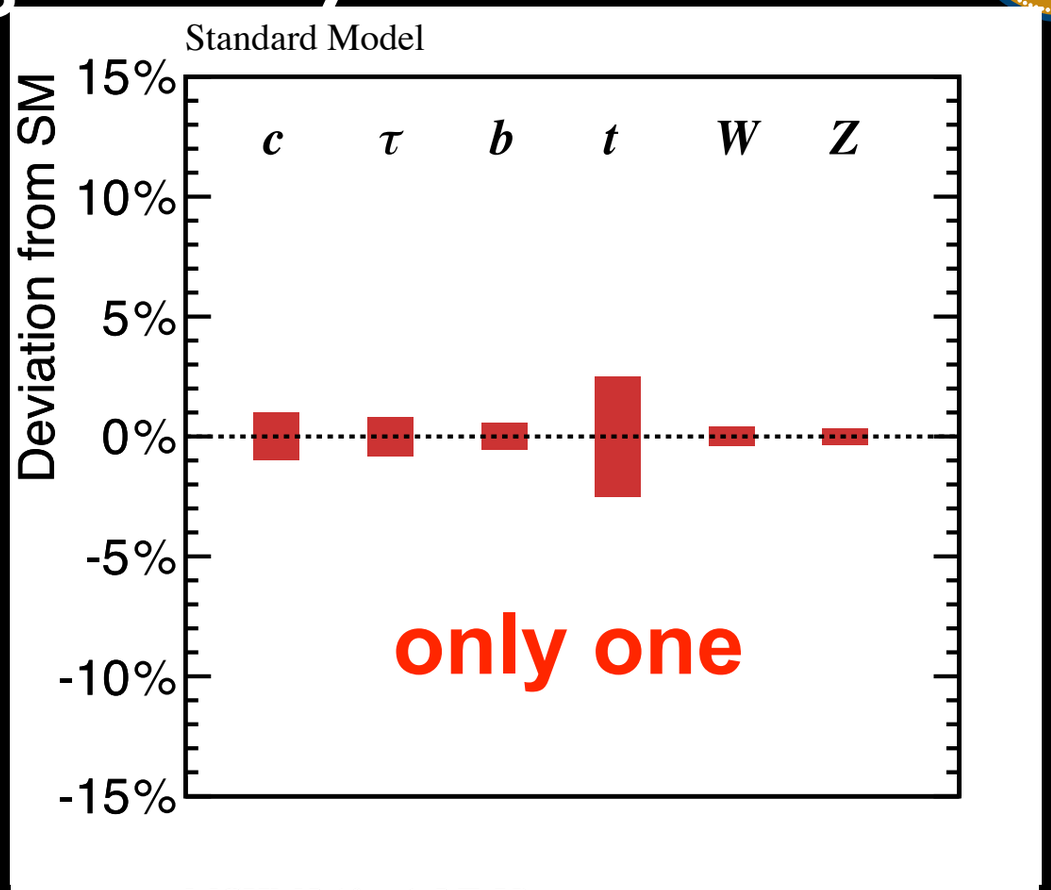


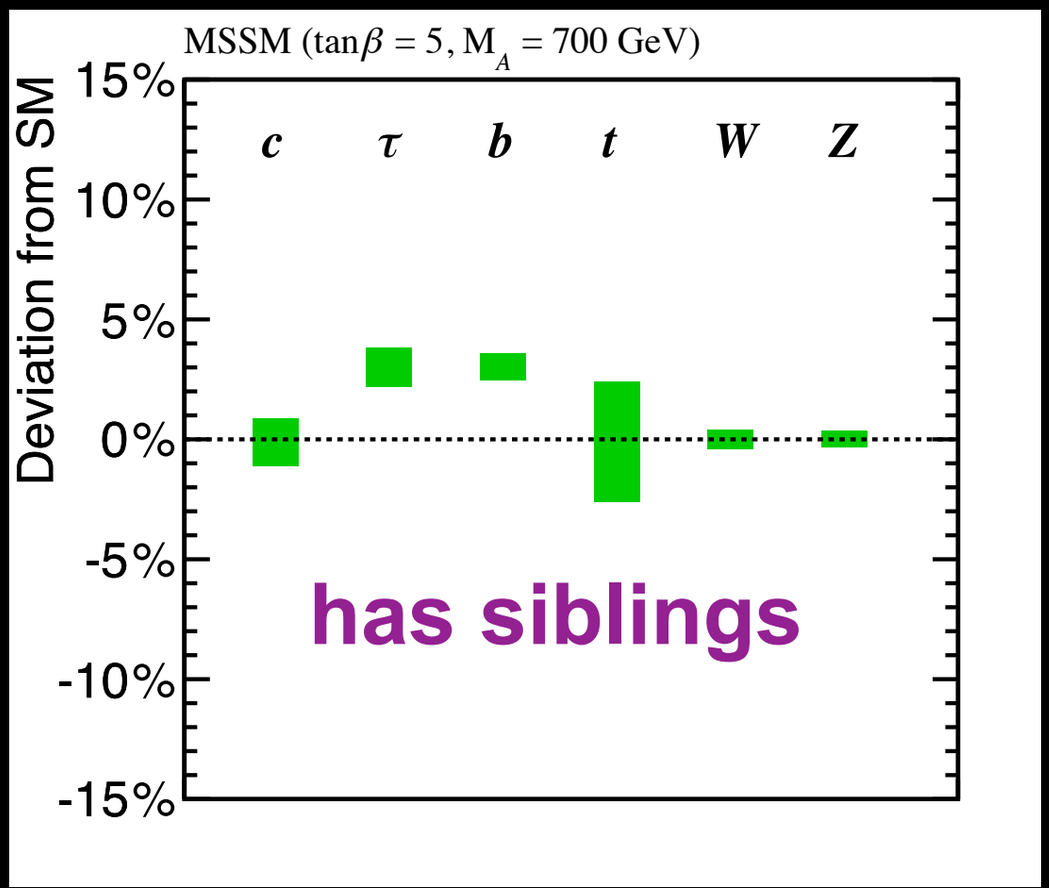
- Start with 250 GeV
- guaranteed precision Higgs and top physics
- extendable 500 GeV to 1 TeV
- TDR exists

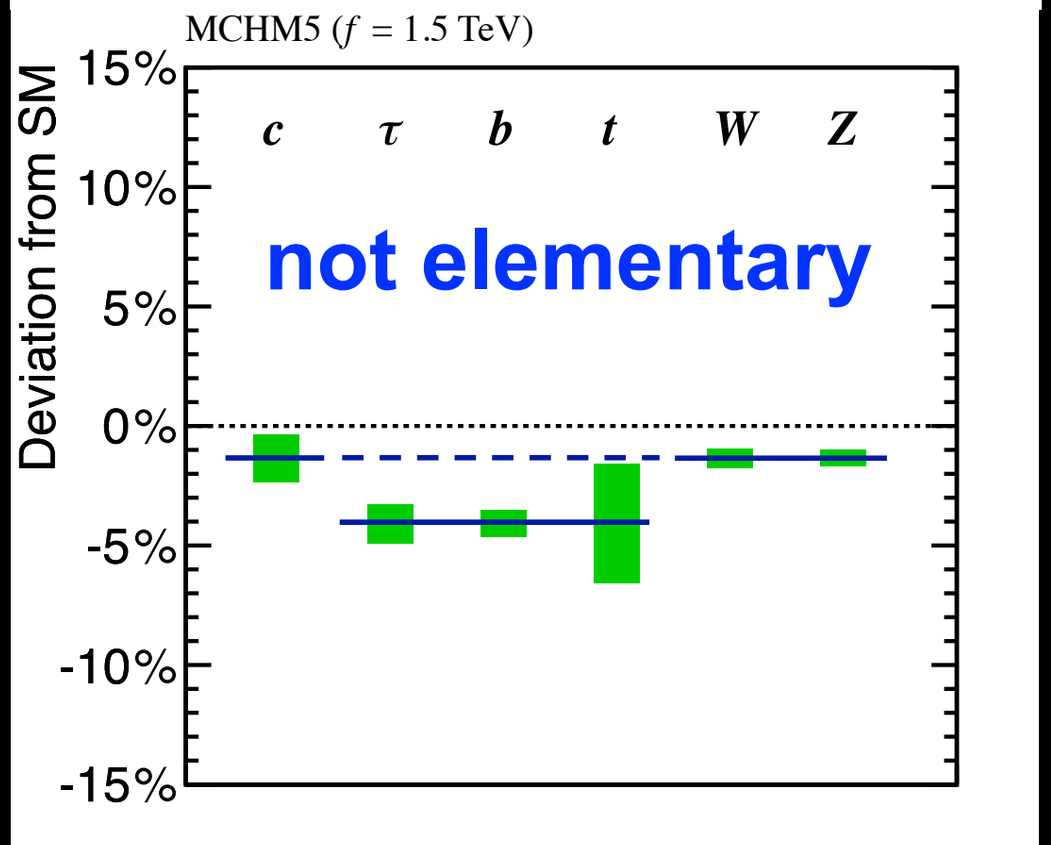
What is Higgs really?

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

Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV

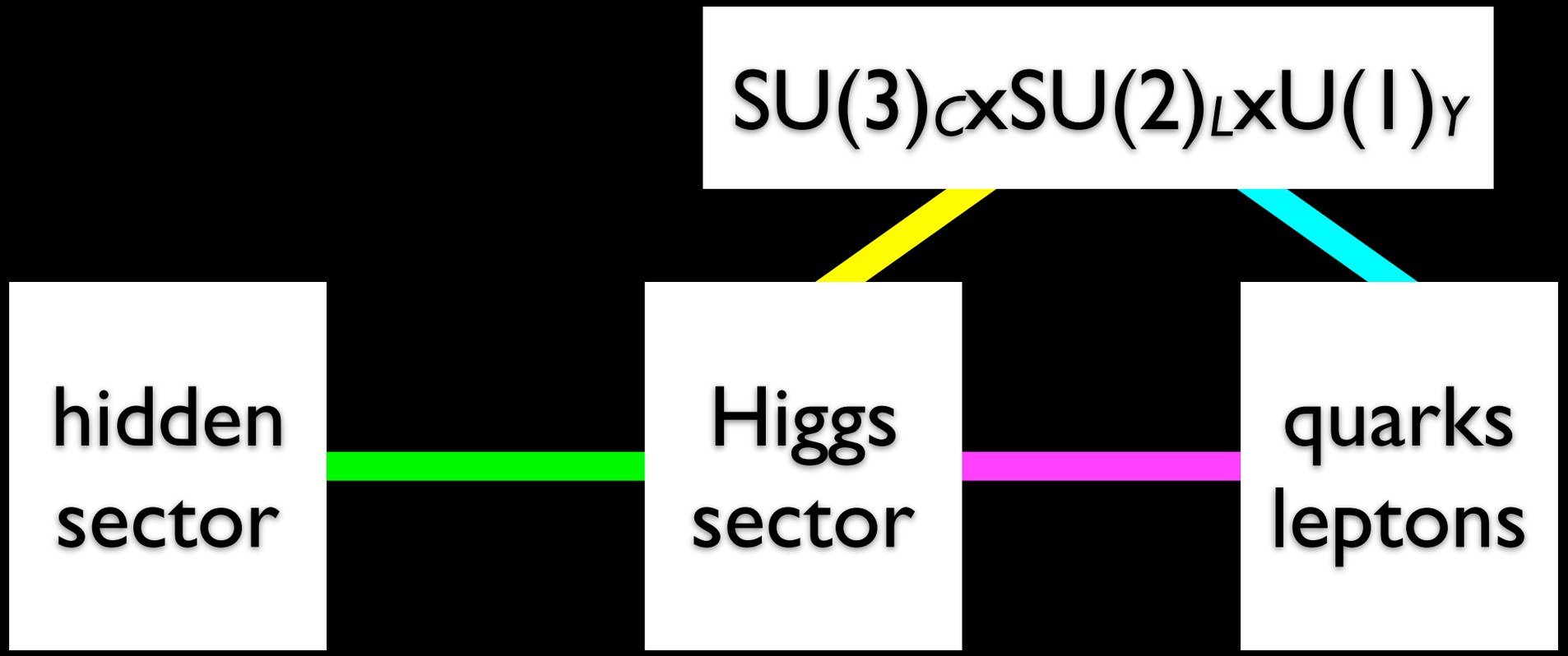






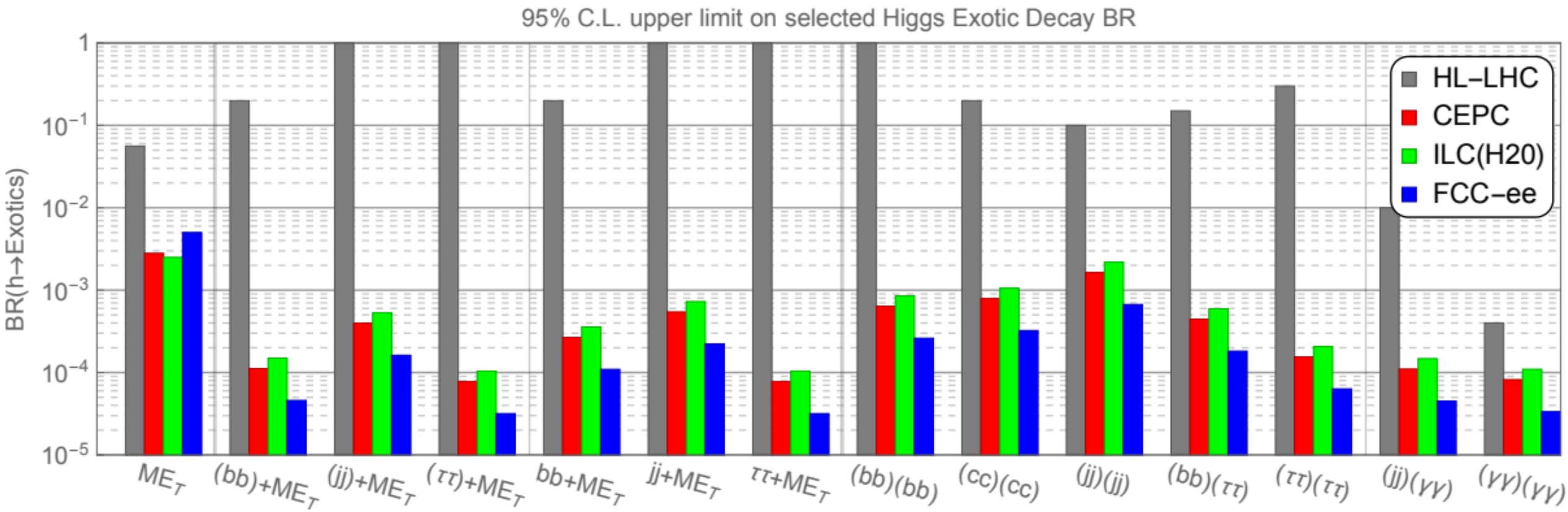
Higgs as a portal

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other "sectors"



$$\mathcal{L} = \mathcal{O}_{hidden} H^\dagger H$$

Higgs exotic decay



Complementary to hadron collider searches

Liantao Wang, GRC 2019

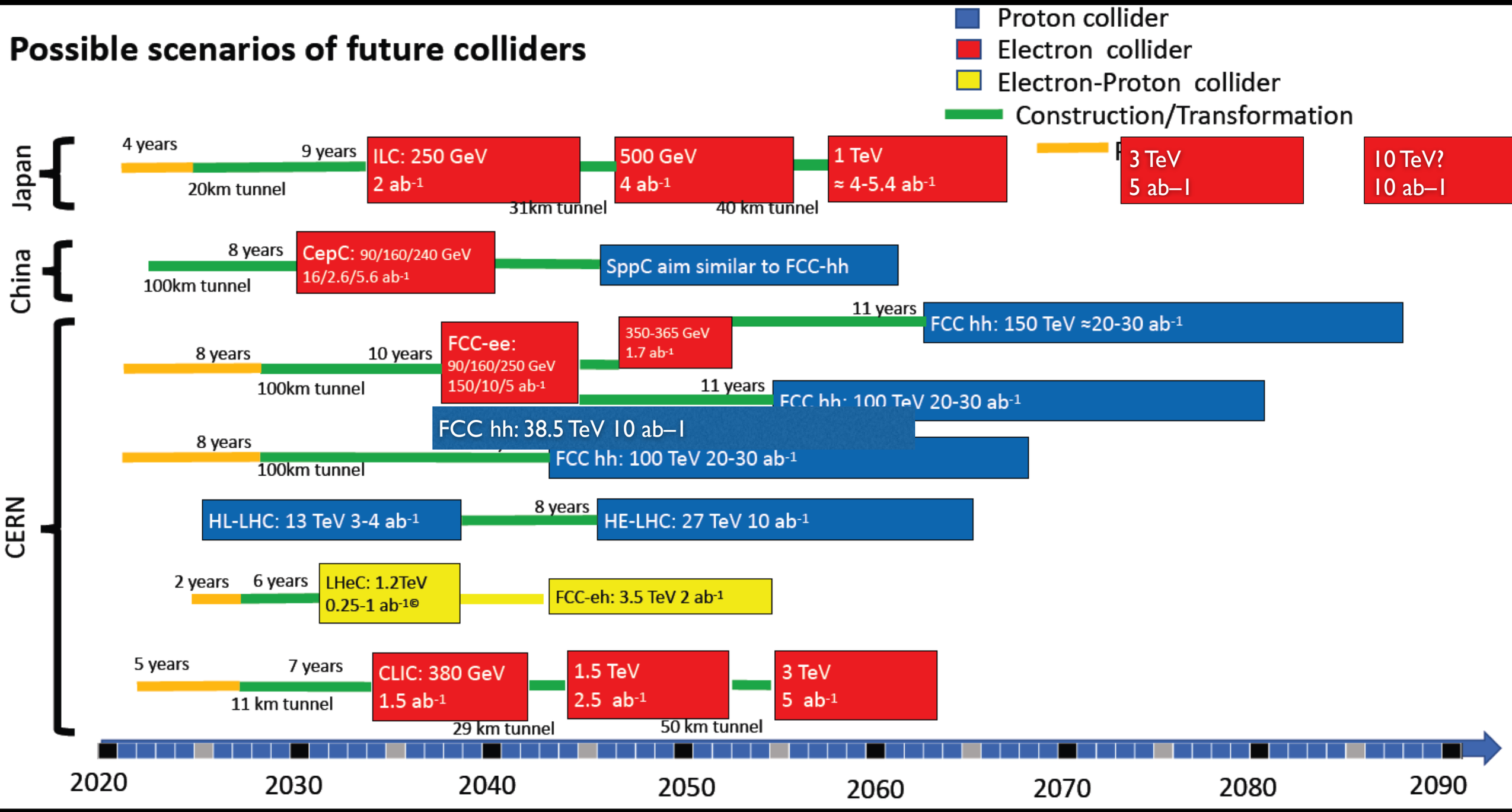
Timelines

Akira Yamamoto
@ Granada

Personal View on Relative Timelines

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	**Construction**		**Operation**		**Upgrade**	
NRF—LC	Proto/pre-series	**Construction**		**Operation**		**Upgrade**	
Hadron Collier (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	**Construction**		**Operation**			**Upgrade**
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		**Construction**		**Operation**	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series		**Construction**		

Possible scenarios of future colliders

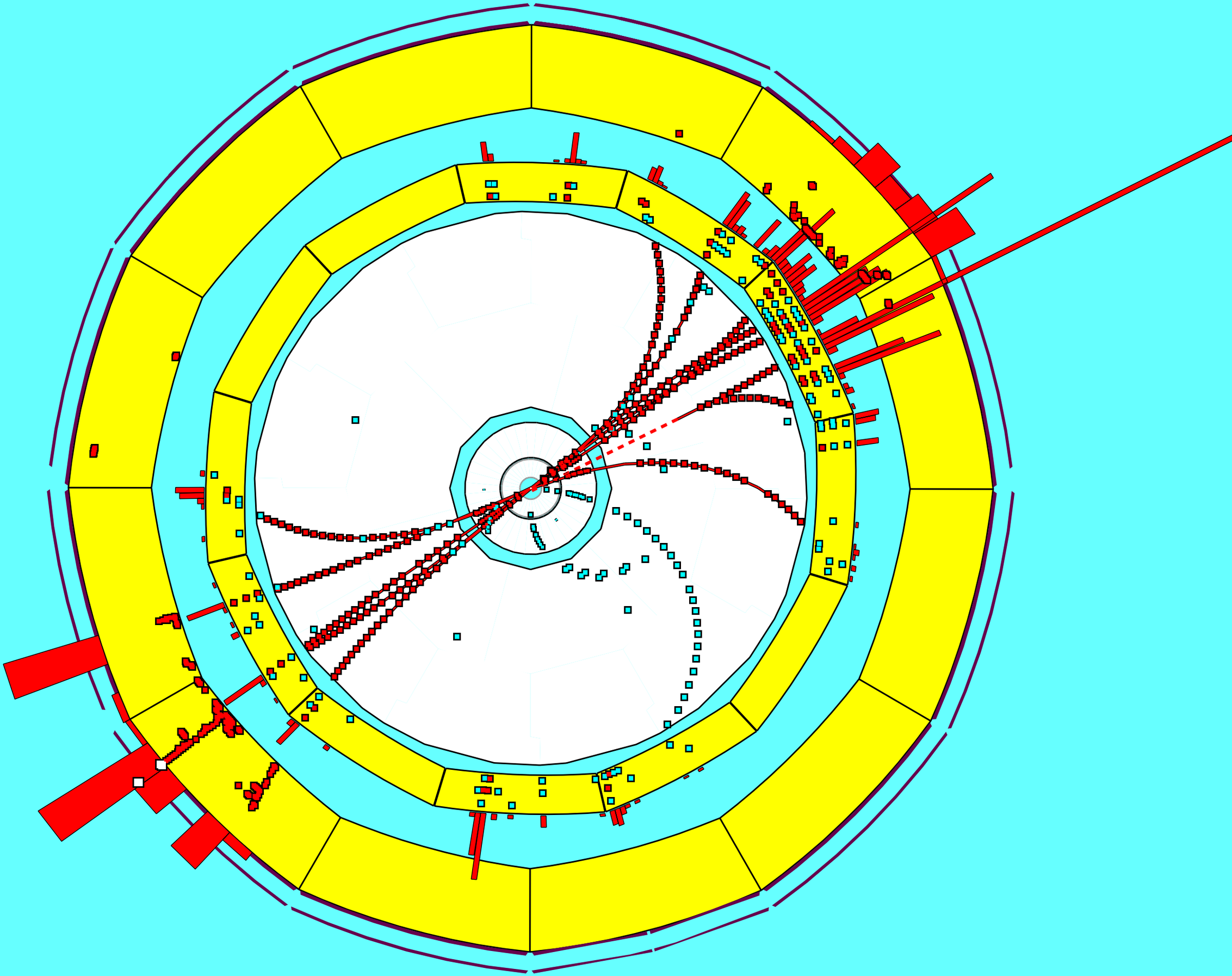


Ursula Bassler @ Granada

History of Colliders

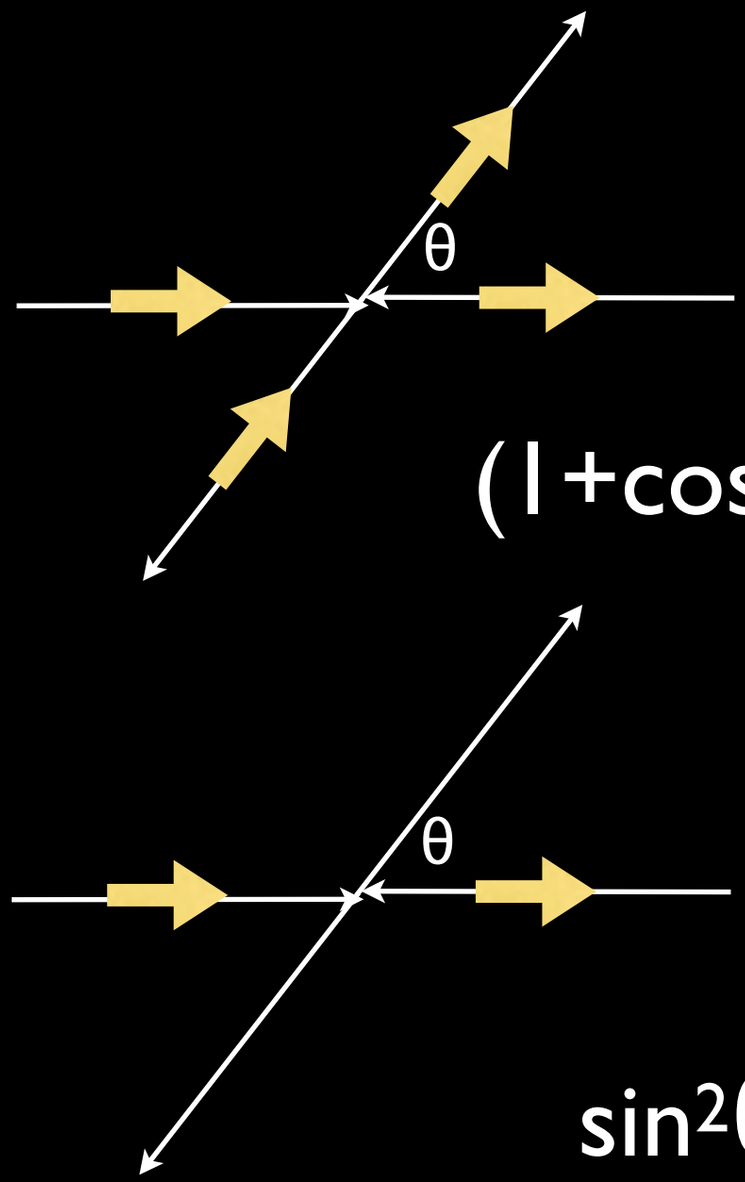
1. precision measurements of neutral current (*i.e.* polarized *e*+*d*) predicted m_W, m_Z
2. UA1/UA2 discovered W/Z particles
3. LEP *nailed* the gauge sector
1. precision measurements of W and Z (*i.e.* LEP + Tevatron) predicted m_H
2. LHC discovered *a Higgs particle*
3. LC *nails* the Higgs sector?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

ALEPH DALI Run=15768 Evt=5906



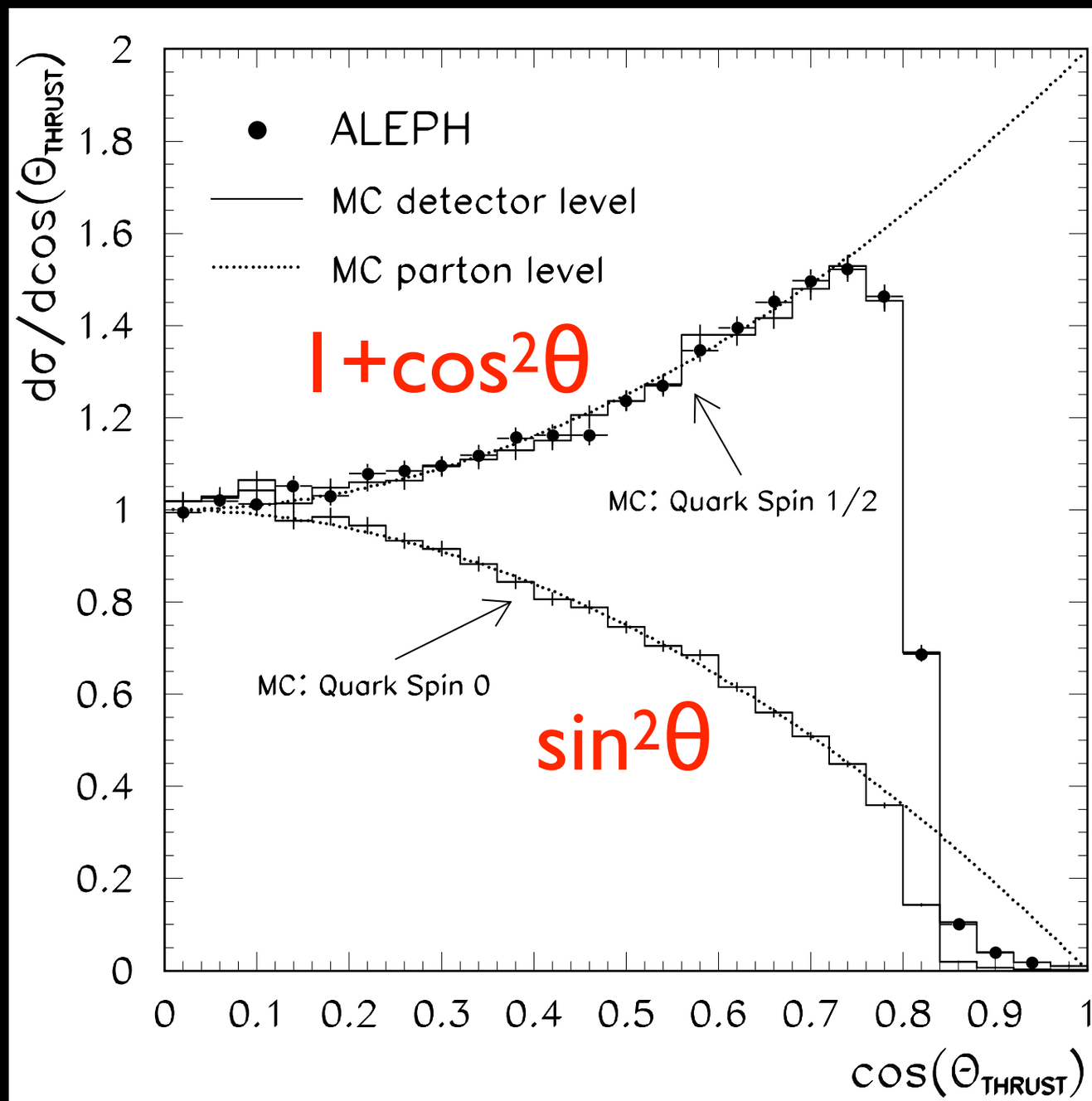
“New particle” has spin 1/2

quark

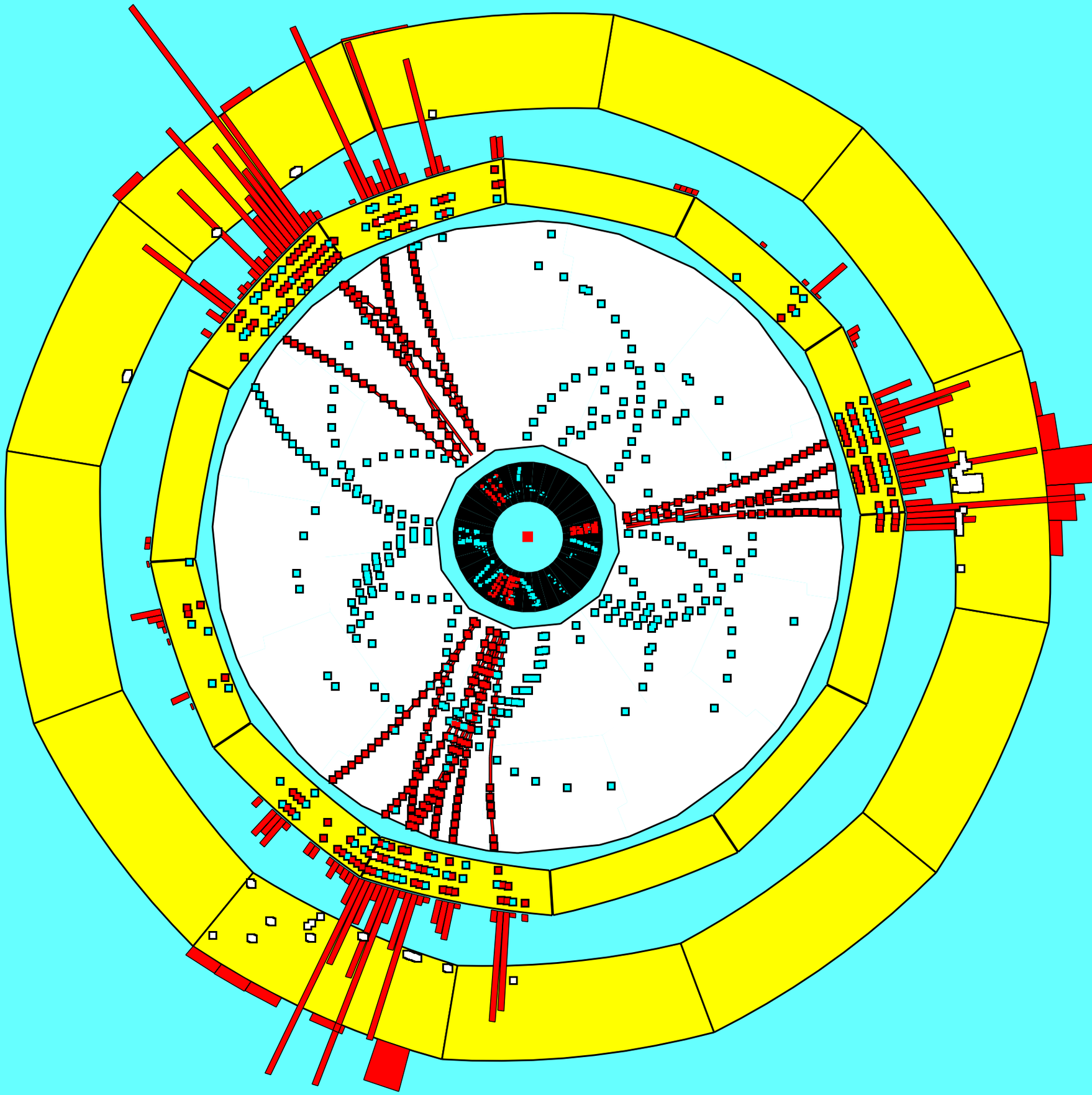


$(1+\cos\theta)^2$

$\sin^2\theta$

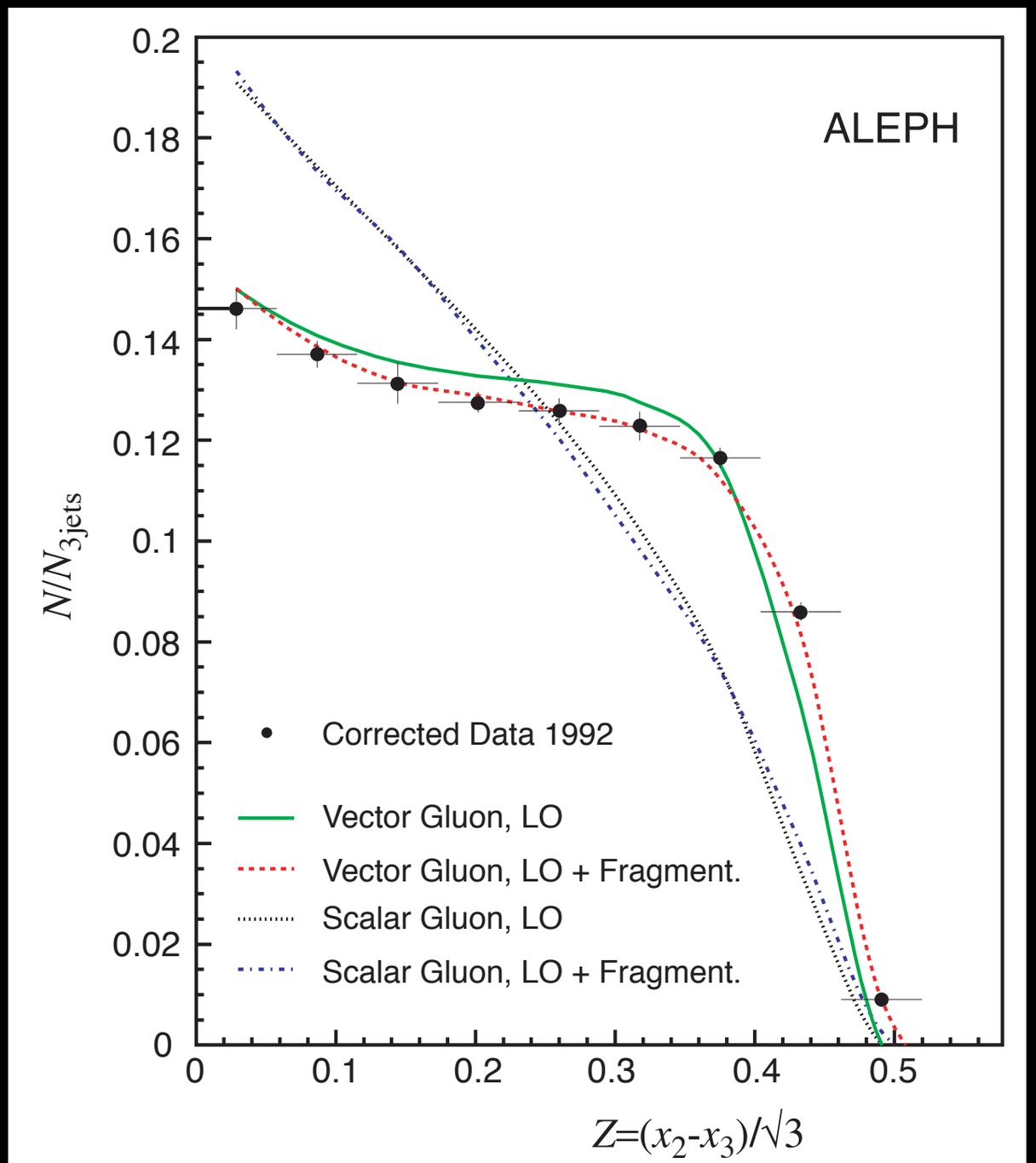


ALEPH DALI Run=9063 Evt=7848

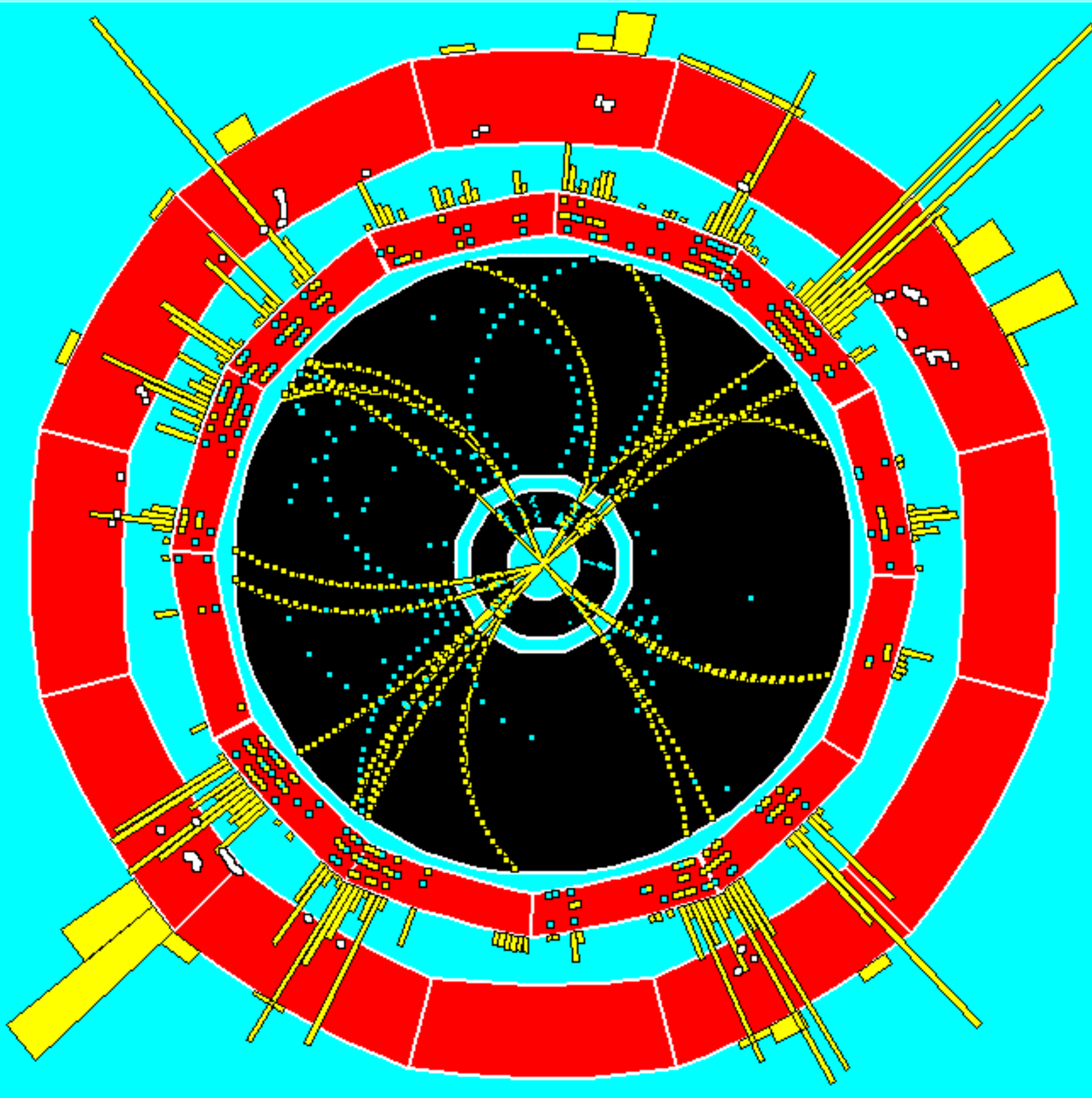


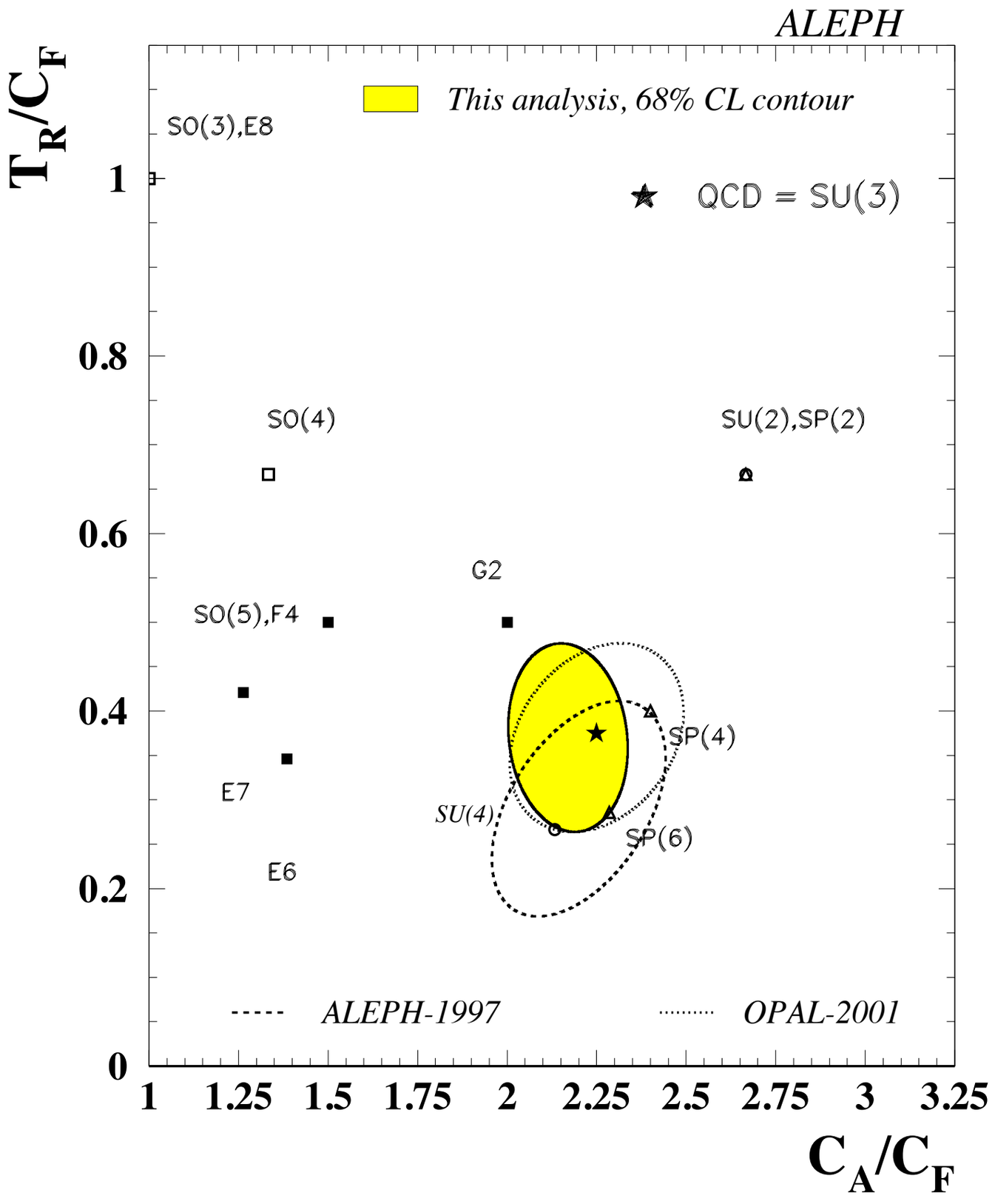
“New particle” has spin 1

gluon

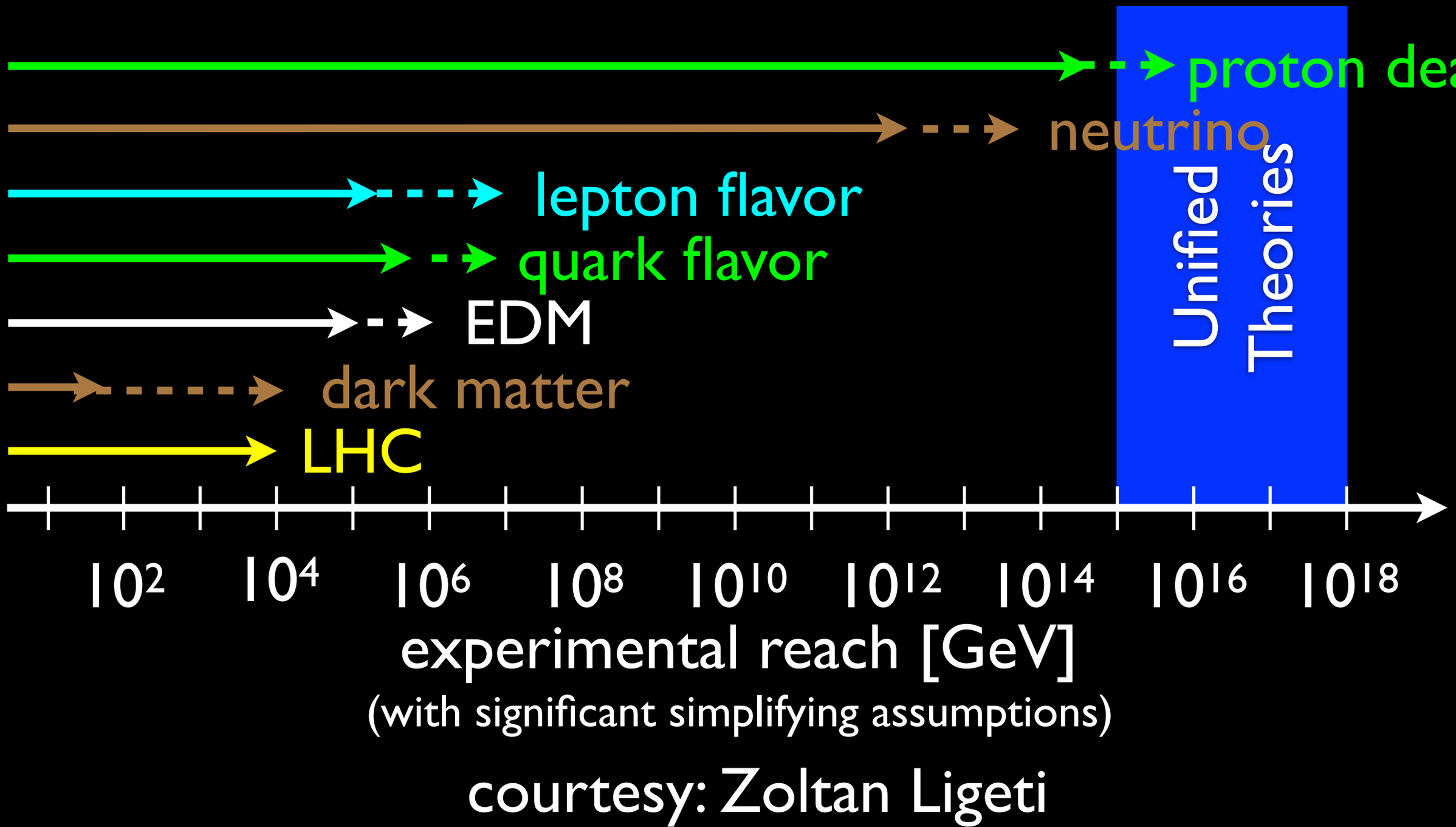


ALEPH DALI Run=9095 Evt=8852




ALEPH
T_R/C_F
This analysis, 68% CL contour
SO(3),E8
QCD = SU(3)
SO(4)
SU(2),SP(2)
G2
SO(5),F4
SP(4)
E7
SU(4)
SP(6)
E6
ALEPH-1997
OPAL-2001
0
0.2
0.4
0.6
0.8
1
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
3.25
C_A/C_F

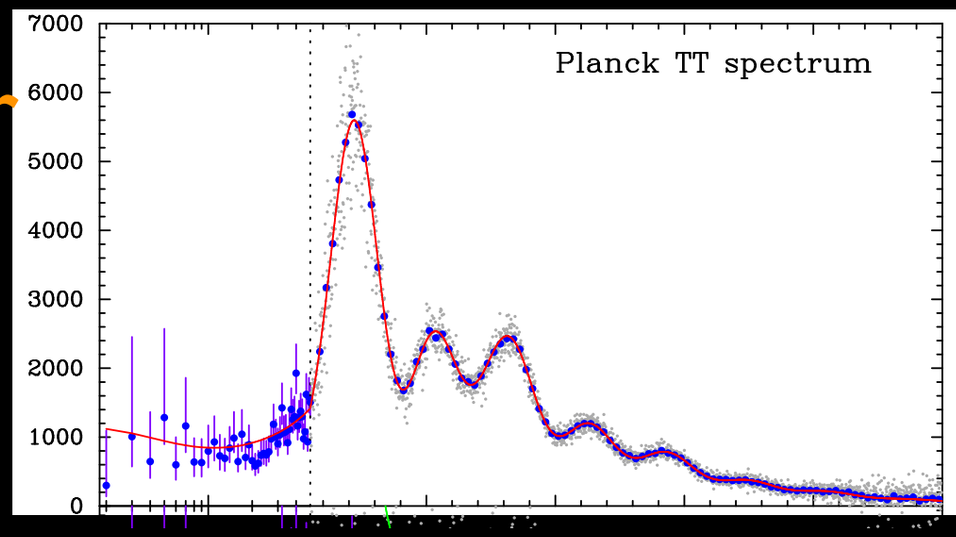
Power of Expedition



courtesy: Zoltan Ligeti

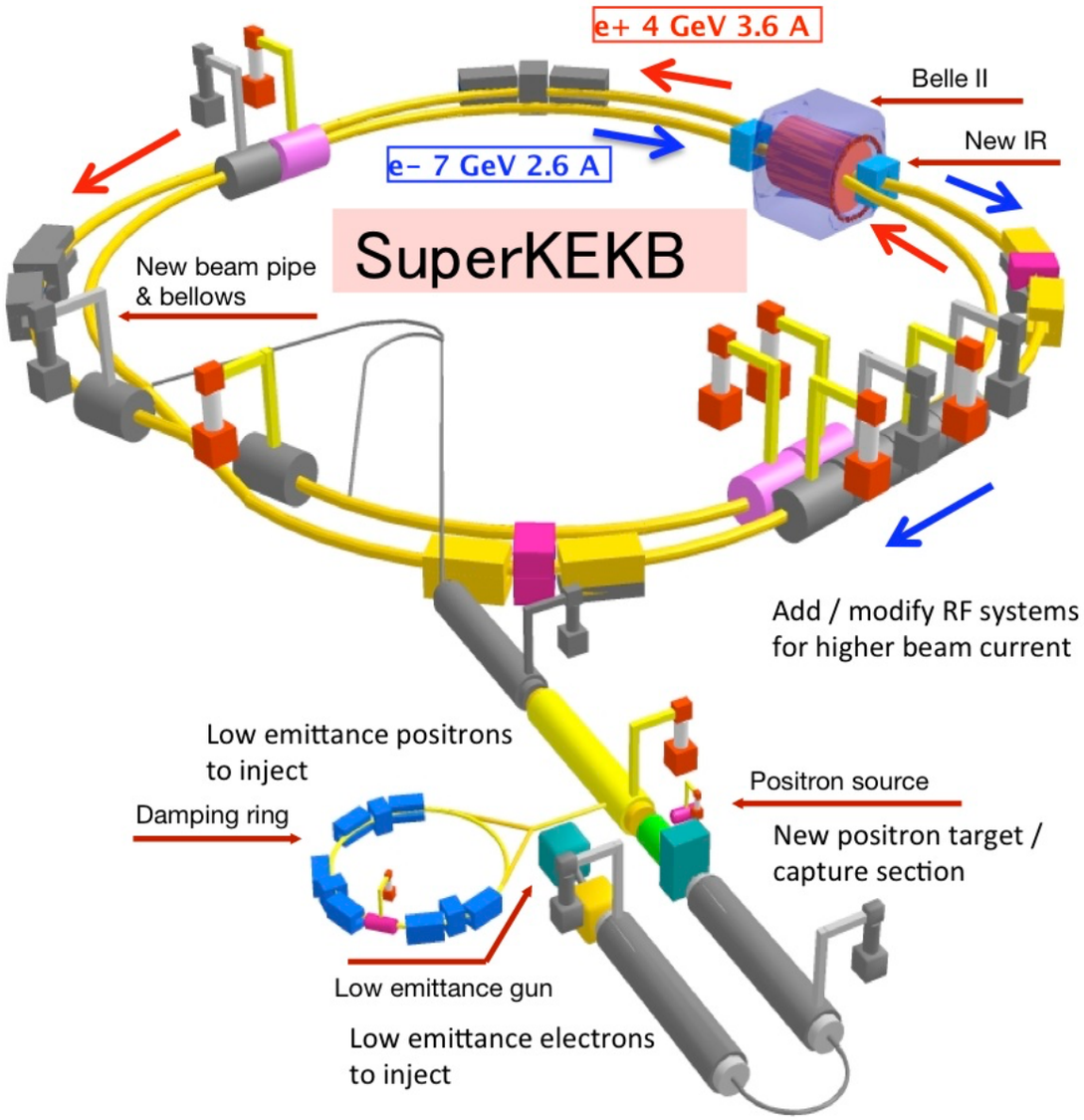
Five evidences for physics beyond SM

- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry

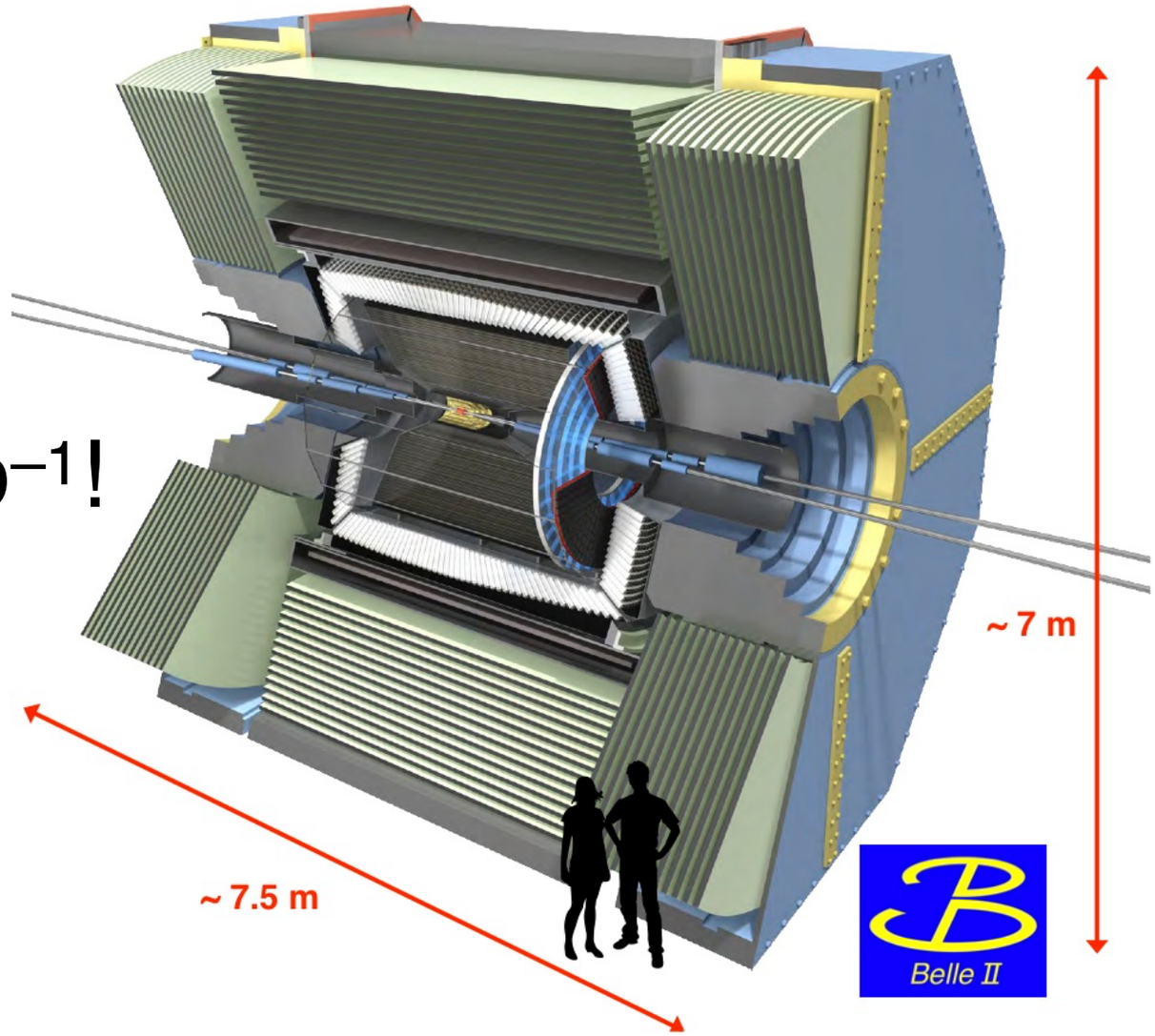


We don't really know their energy scales...

Super KEK B & Belle II

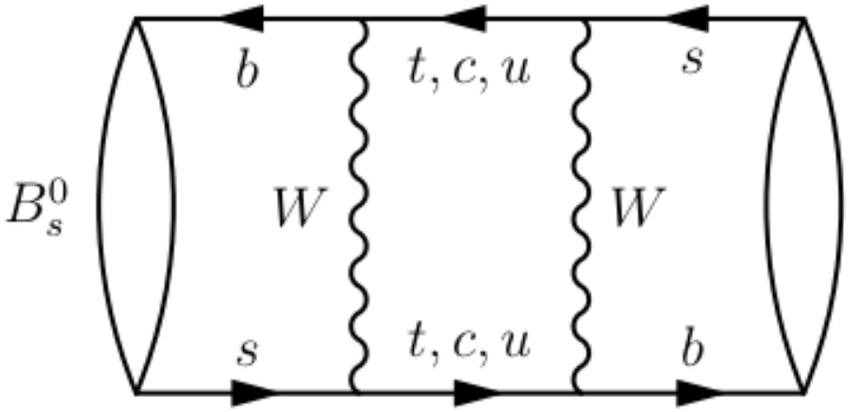


50 ab^{-1}!



B_s: Strangely Beautiful

- ν_μ and ν_τ mix a lot
- (ν_μ, s_R), (ν_τ, b_R) under GUT
- Perhaps big mixing between s_R and b_R?
- I had predicted O(1) effects of new physics on B_s



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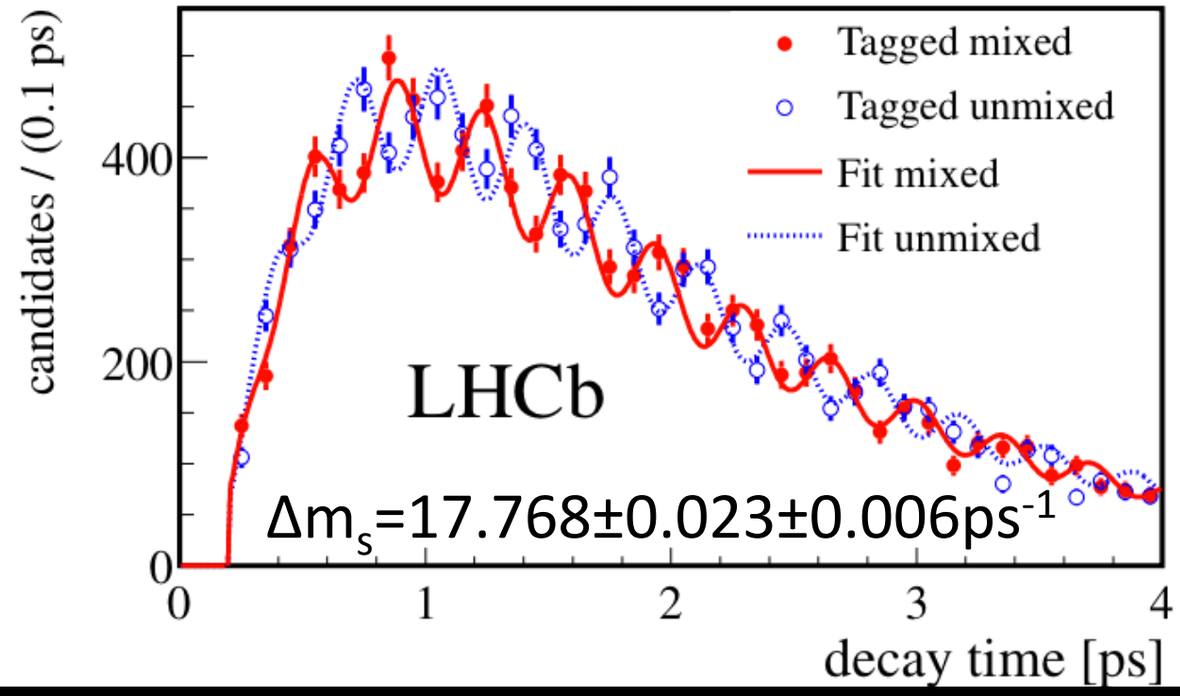


b to s transitions still very interesting!

Excitement

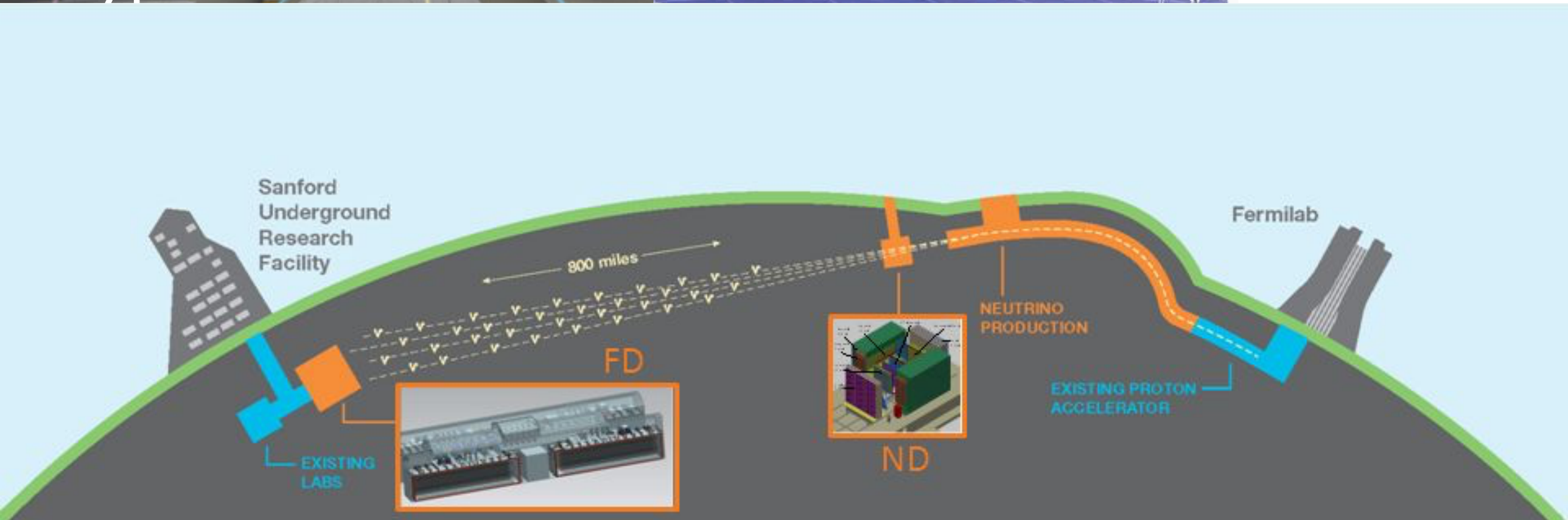
- CP violation in neutrino sector may be observable with conventional technique

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\frac{\Delta m^2_{12} L}{4E} - \sin\frac{\Delta m^2_{13} L}{4E} - \sin\frac{\Delta m^2_{23} L}{4E} -$$

2002
KamLAND
SNO

2012
Daya Bay
RENO

1998
Super-K



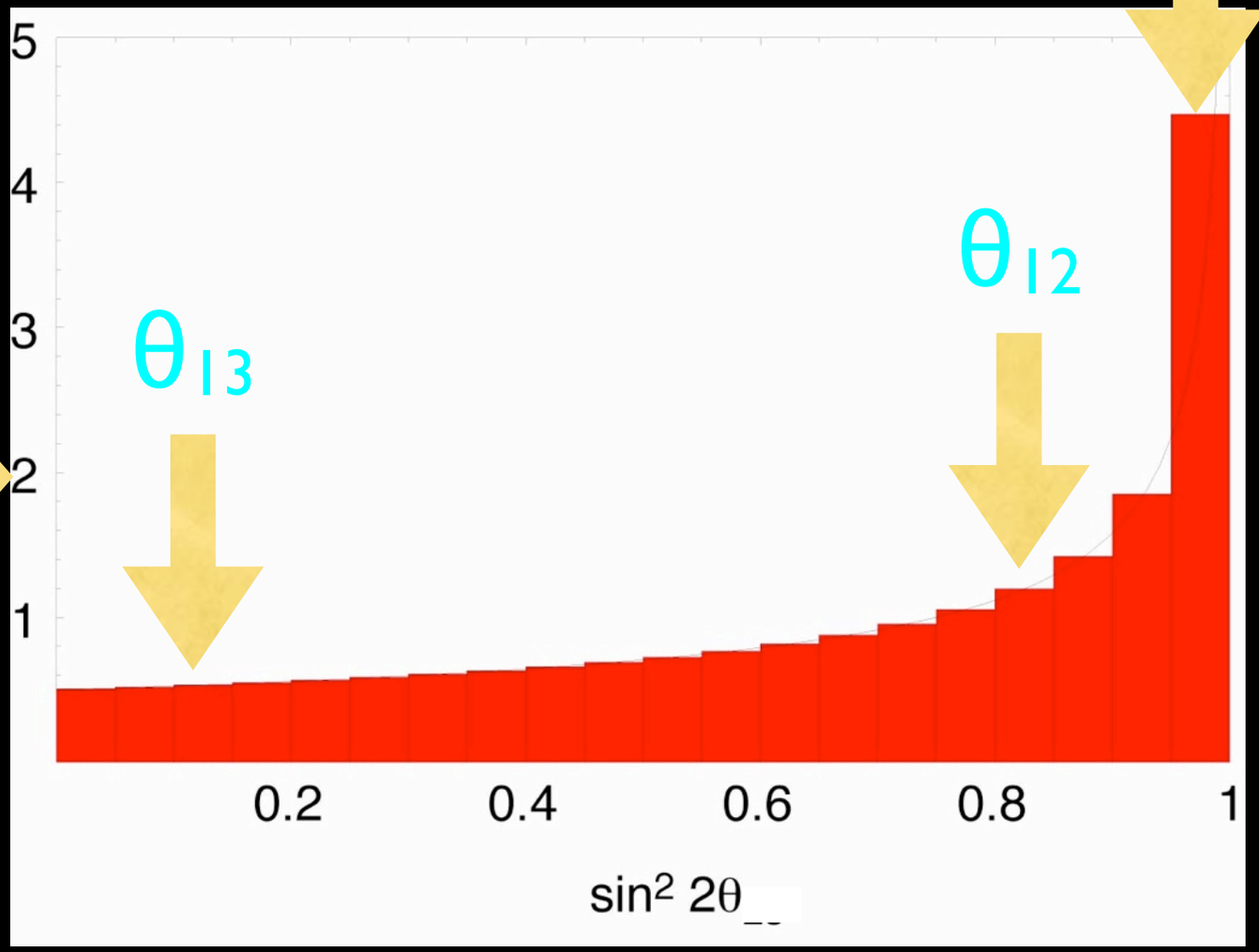
anarchy

Miriam-Webster: "*A utopian society of individuals who enjoy complete freedom without government*"

neutrinos

large mixing

symmetry



Kolmogorov-Smirnov test (de Gouvêa, HM)

nature has 47% chance to choose this kind of numbers

KAVLI IPMU

10^{-30} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 10^{30} 10^{40} 10^{50} mass [GeV]

to fluffy

preheating

Q-balls

mirolensing etc

10^{-10} 10^{0} 10^{6} mass [GeV]

moduli w/ vector mediation

QCD axion

sterile neutrino

gravitino

SIMP

asymmetric DM

WIMP

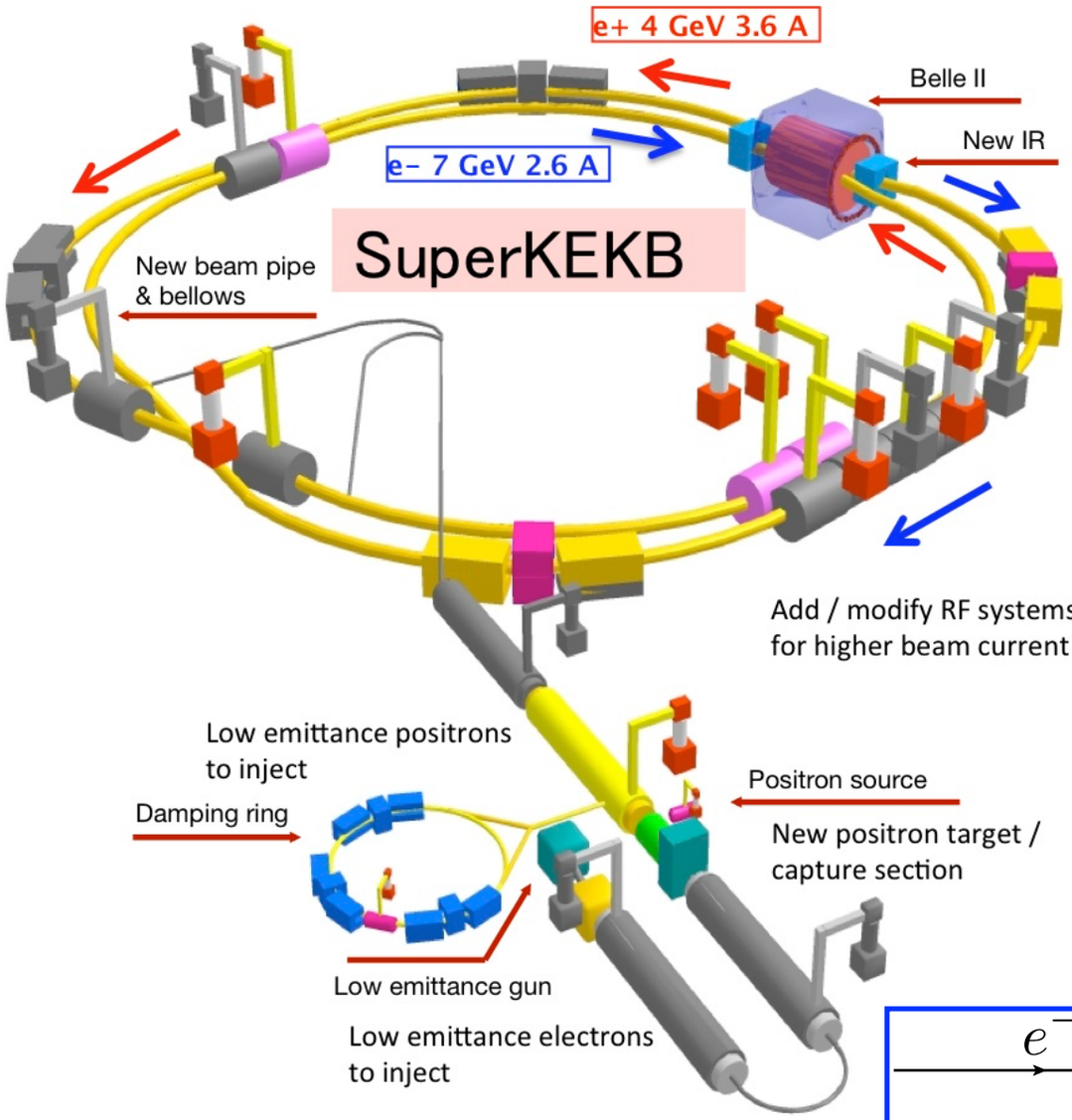
non-thermal

defects

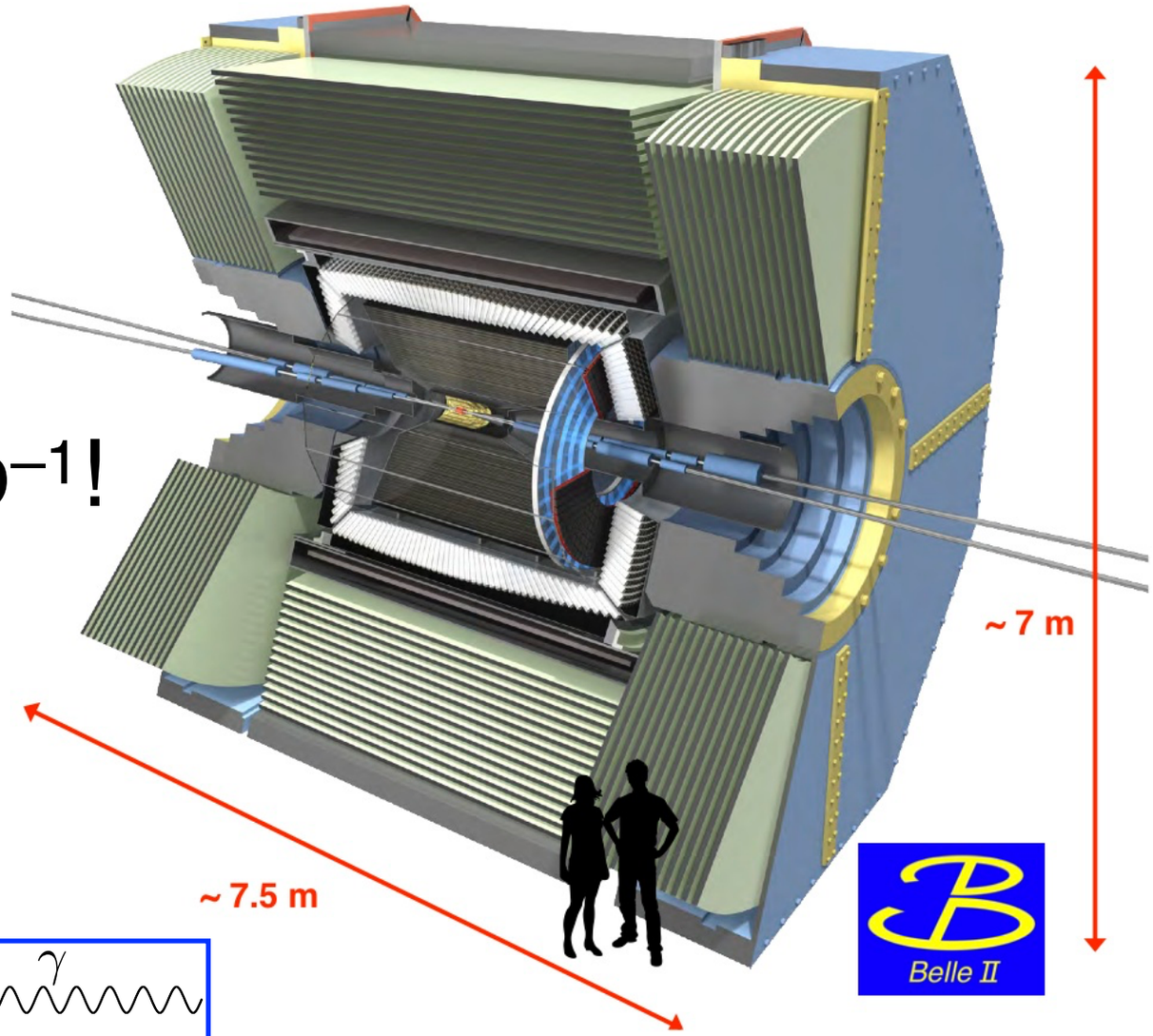
SIMP: dark hadrons

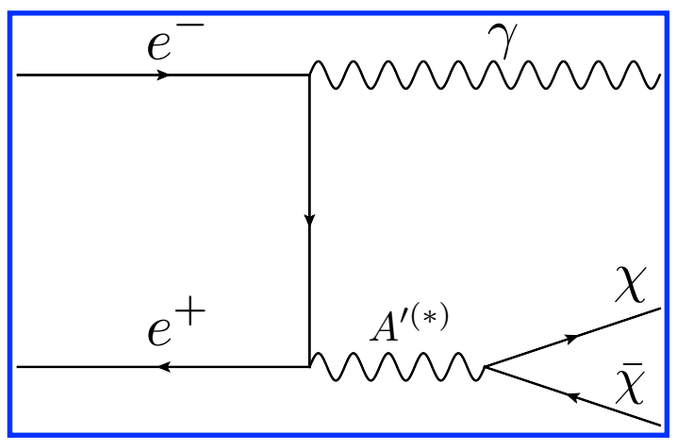
m~0.3GeV, $\sigma \sim 10^{-24}\mathrm{cm}^2$

Super KEK B & Belle II



50 ab^{-1}!





$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\text{inv}}^2}{s}\right)$$

BES III projection

$\sqrt{s} = 4$ GeV, 100 fb^{-1}

$\sigma_{E_\gamma}/E_\gamma = 2\%$

$m_{\gamma_d} = 3$ GeV, $\epsilon_\gamma = 8 \times 10^{-4}$

Dark sector

Binned

$\frac{\sigma_{E_\gamma}}{E_\gamma} = 2\%$

$\nu\nu\gamma$

Events/40 MeV

E_γ [GeV]

Belle II projection

$\sqrt{s} = 10$ GeV, 50 ab^{-1}

$\sigma_{E_\gamma}/E_\gamma = 1\%$

$m_{\gamma_d} = 12$ GeV, $\epsilon_\gamma = 10^{-2}$

$\psi_d(2S)$

J/ψ_d

ϕ_d

Mirror QCD

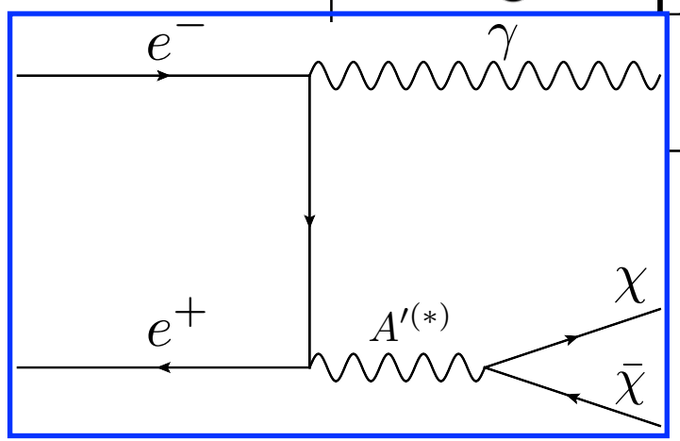
Binned

$\frac{\sigma_{E_\gamma}}{E_\gamma} = 1\%$

$\nu\nu\gamma$

Events/50 MeV

E_γ [GeV]



Yonit Hochberg, Eric Kuflik, HM

new ideas

- heavy ion produces axion ~ Z^4
- neutrino beams can be used for search for dark matter and light feebly coupled particles
- atomic clocks, interferometers for dark matter searches
- growing connection to astrophysics

Conclusions

- Particle Physics: exciting as ever!
- Higgs: need to understand it better
  - HL-LHC, ILC, CEPC, FCCee
- naturalness: higher energies, precision
  - HE-LHC, FCChh, CLIC, PWFA
  - flavor physics, EDM, 0νββ, p-decay
- baryogenesis:
  - *B*, *K*, LFV, neutrino oscillation
- dark matter: open mind, broad search
  - cosmology, direct, indirect, collider

theorist

experiments

healthy field!