素粒子物理とコライダー

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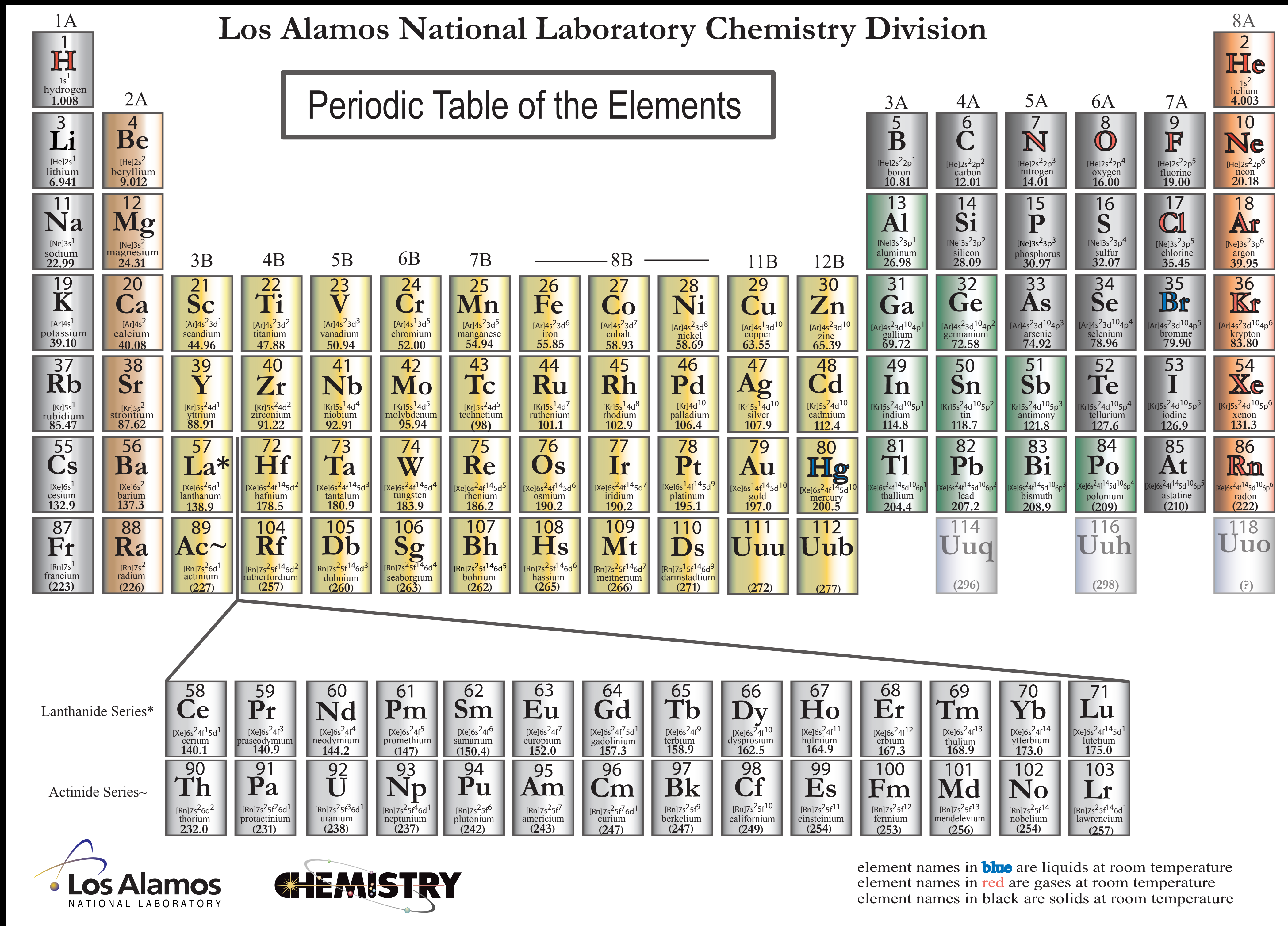
将来電子・陽電子コライダーの物理と技術

東京大学 THE UNIVERSITY OF TOKYO
BERKELEY CENTER FOR THEORETICAL PHYSICS
BERKELEY LAB
KAVLI IPMU

Why accelerators?

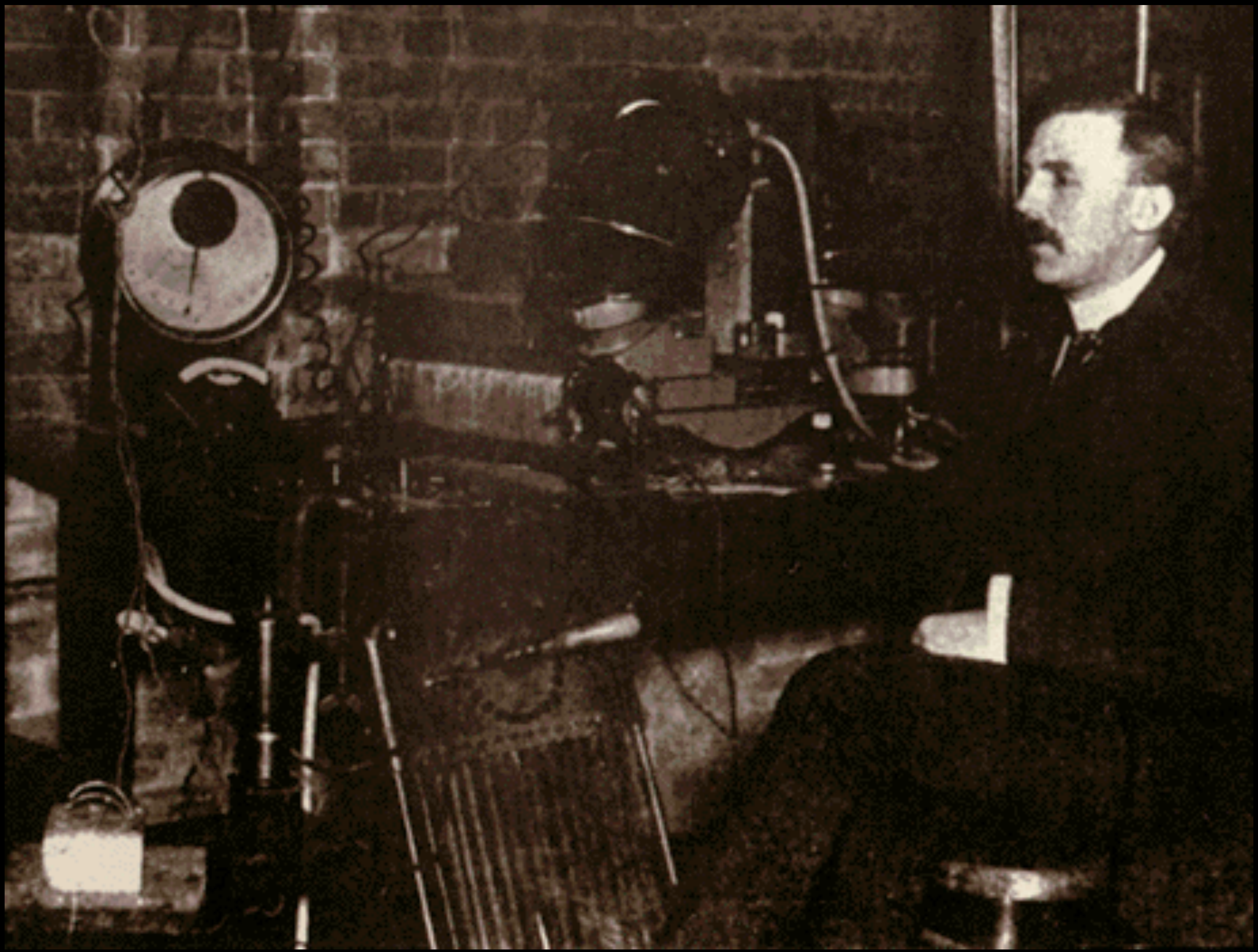
Ancient Greeks: Elements

Periodic Table

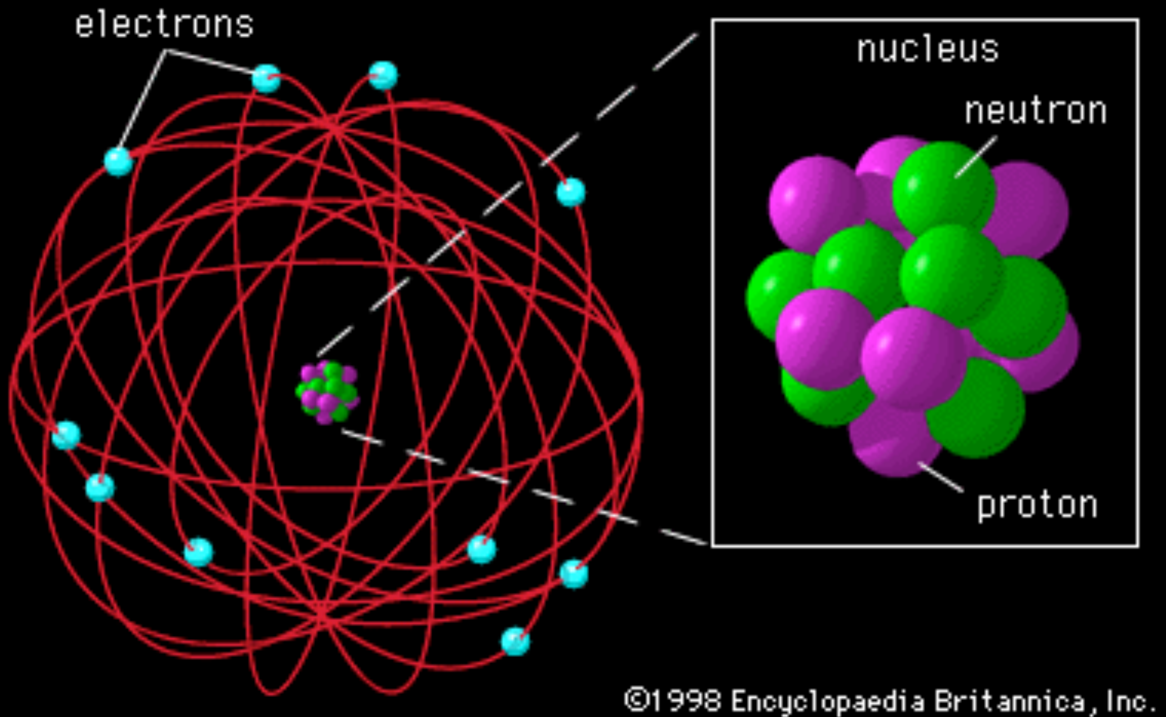


So many *flavors* of atoms?

Rutherford



all chemical elements



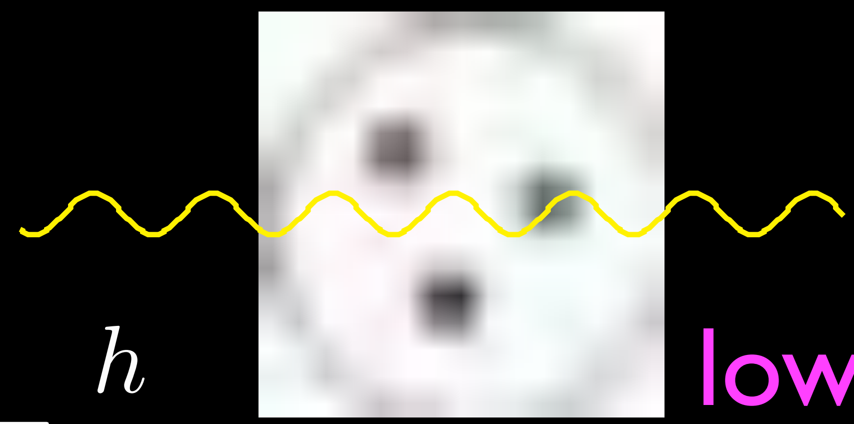
resolution=energy

- Quantum Mechanics:
  particle=wave

- higher energy
  = shorter wavelength
  = better resolution

$$E = cp$$

$$\Delta x \approx \lambda = \frac{h}{p}$$



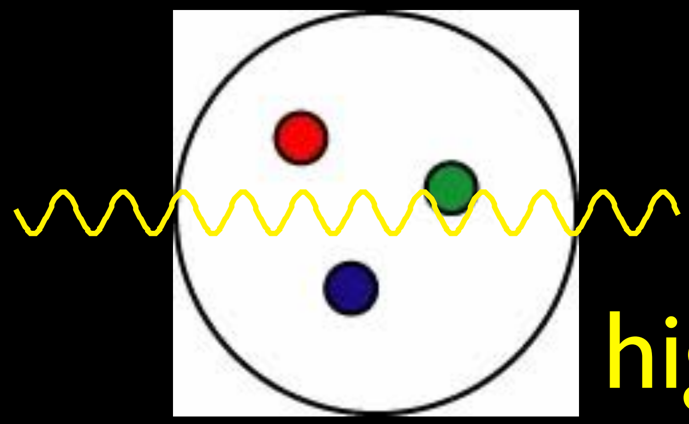
low energy

- Rutherford scattering:

$$E = 8.3 \text{ MeV}$$

$$m = 3.7 \text{ GeV}$$

$$\lambda = \frac{hc}{E} = 5.0 \text{ fm}$$



high energy

deeper into the heart of the matter (literally)

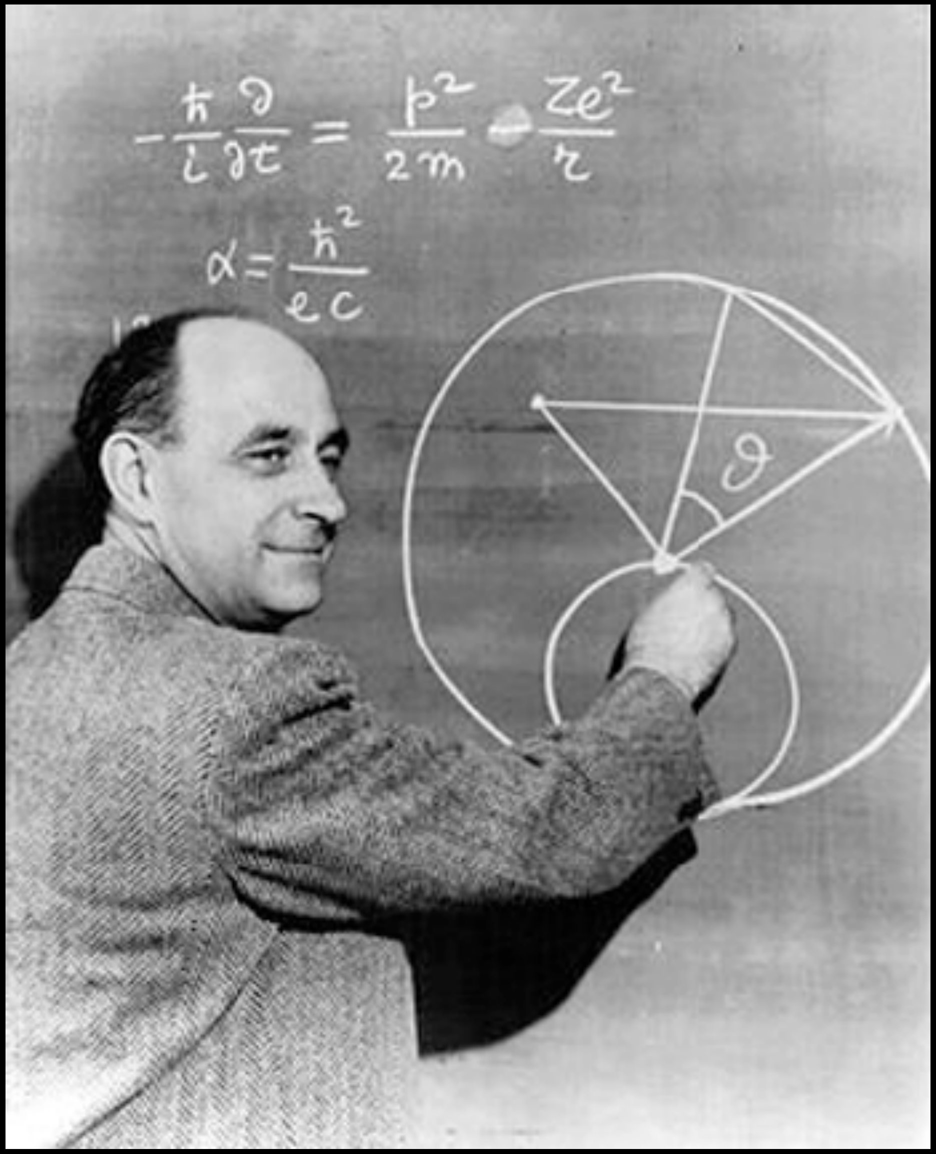
increase resolution

Einstein?

My son on Halloween!

Fermi's dream era

- Fermi formulated the first theory of the weak force (1932)
- *The required energy scale to study the problem known since then:* ~TeV
- We are finally got there with LHC!



Ernest Orlando Lawrence

early cyclotron

Why colliders?

fixed target

- fixed target experiment:

$$\sqrt{s} = \sqrt{2E_{\rm beam}M_{\rm target}}$$

$$\simeq {\rm GeV}\left(\frac{E_{\rm beam}}{\rm GeV}\right)^{1/2}$$

$$\sqrt{s} \simeq 14\ {\rm TeV}$$

$$\Rightarrow E_{\rm beam} \simeq 100,000{\rm TeV}$$

- need R~400,000km
- collider: R=27km

$$\sqrt{s} = 2E_{\rm beam} = 2 \times 7\ {\rm TeV}$$

$$2\pi R = \frac{E}{eBc} = 18{\rm km}\frac{8\ {\rm T}}{B}\frac{E}{7\ {\rm TeV}}$$

challenges

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8 \text{ fb}}{s/\text{TeV}^2}$$

- unitarity: $\sigma \propto E^{-2}$
  - higher current = higher power
- beam is a “gas” of particles
  - pretty sparse
  - need to squeeze the beam to tiny size
- need to avoid synchrotron radiation
  - energy loss per time
  - can’t scale LEP

$$\mathcal{L} = \frac{N_1 N_2}{4\pi\sigma_x\sigma_y} f_{\text{collision}}$$

$$\Delta E_{SR} = \frac{1}{3\epsilon_0}\frac{e^2\beta^3E^4}{Rm^4}$$

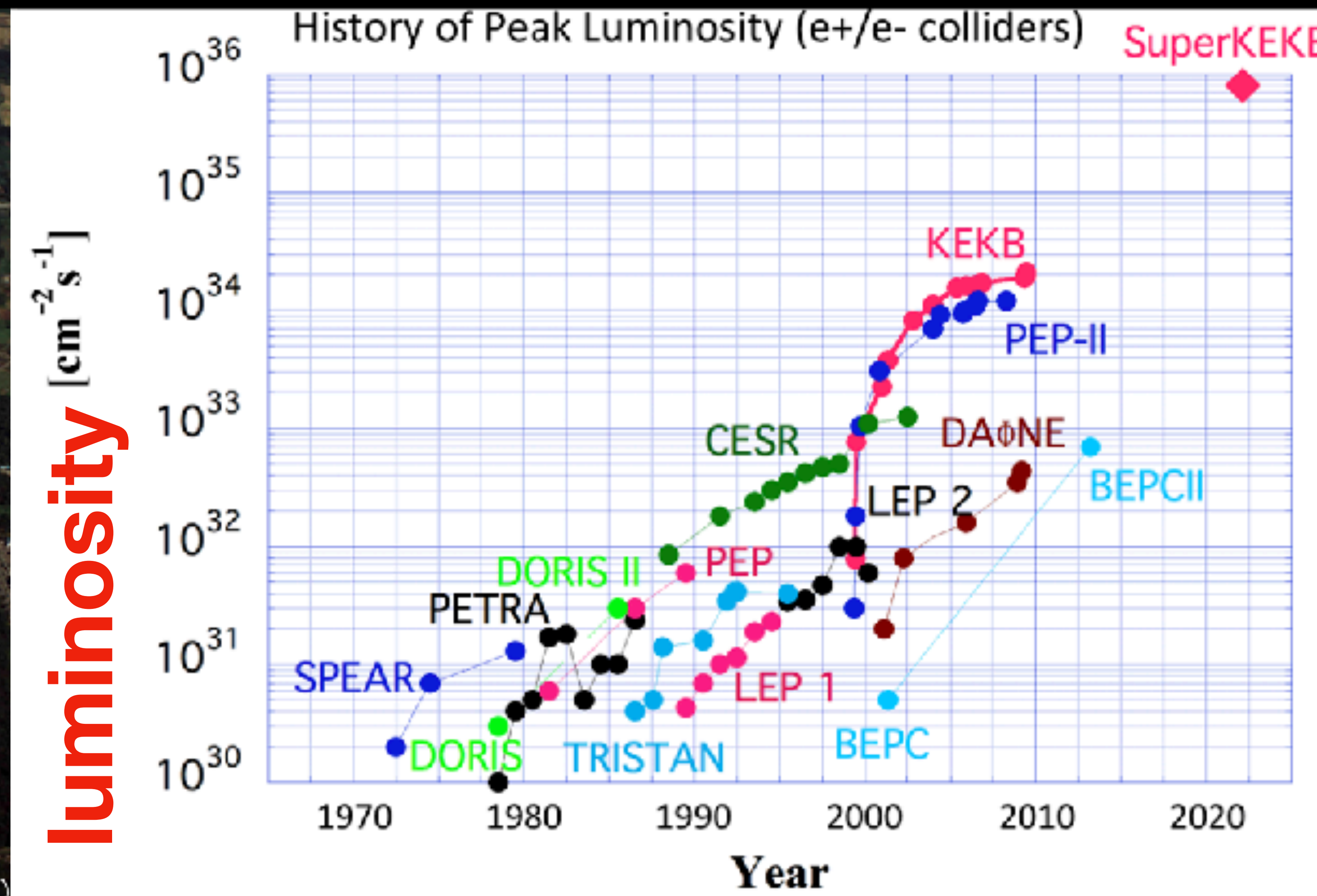
$$P_{\text{synchrotoron}} \propto \frac{1}{R^2}\left(\frac{E}{m}\right)^4$$

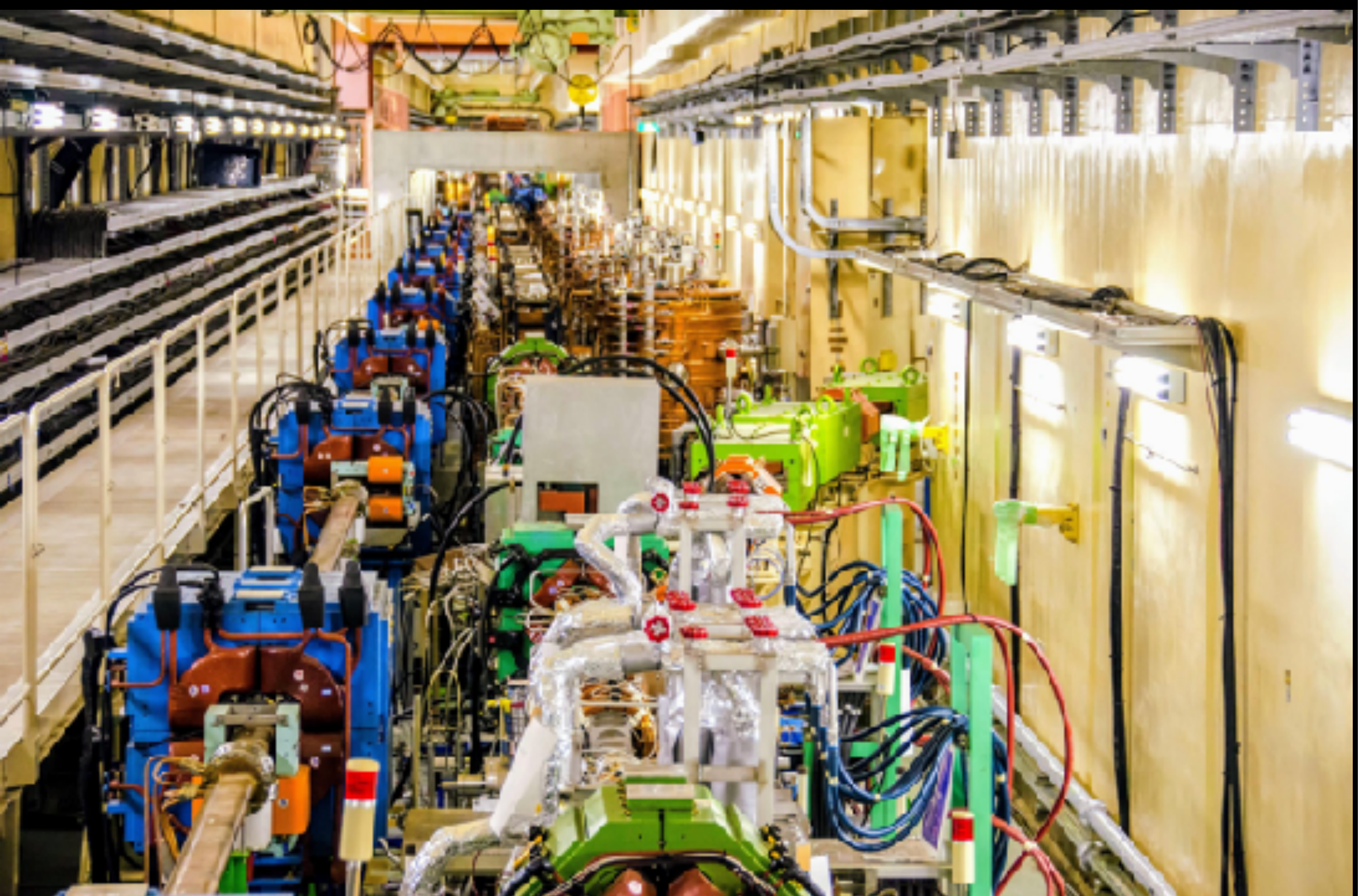
$$\frac{(200 \text{ GeV})^2}{27 \text{ km}} = \frac{(1 \text{ TeV})^2}{675 \text{ km}}$$

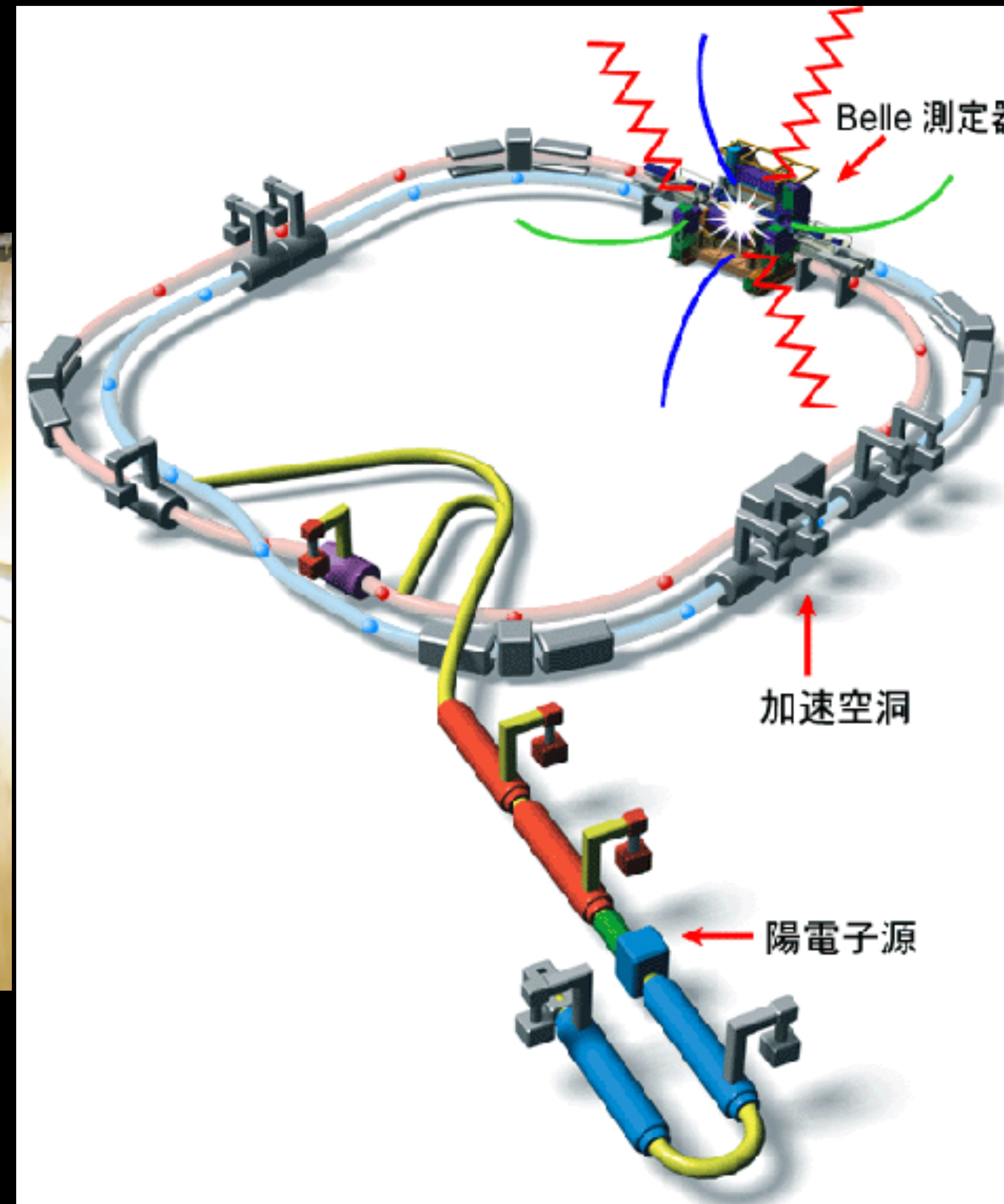
muon collider: $\frac{(1 \text{ TeV})^2}{16 \text{ m}}$

still need magnets: >km

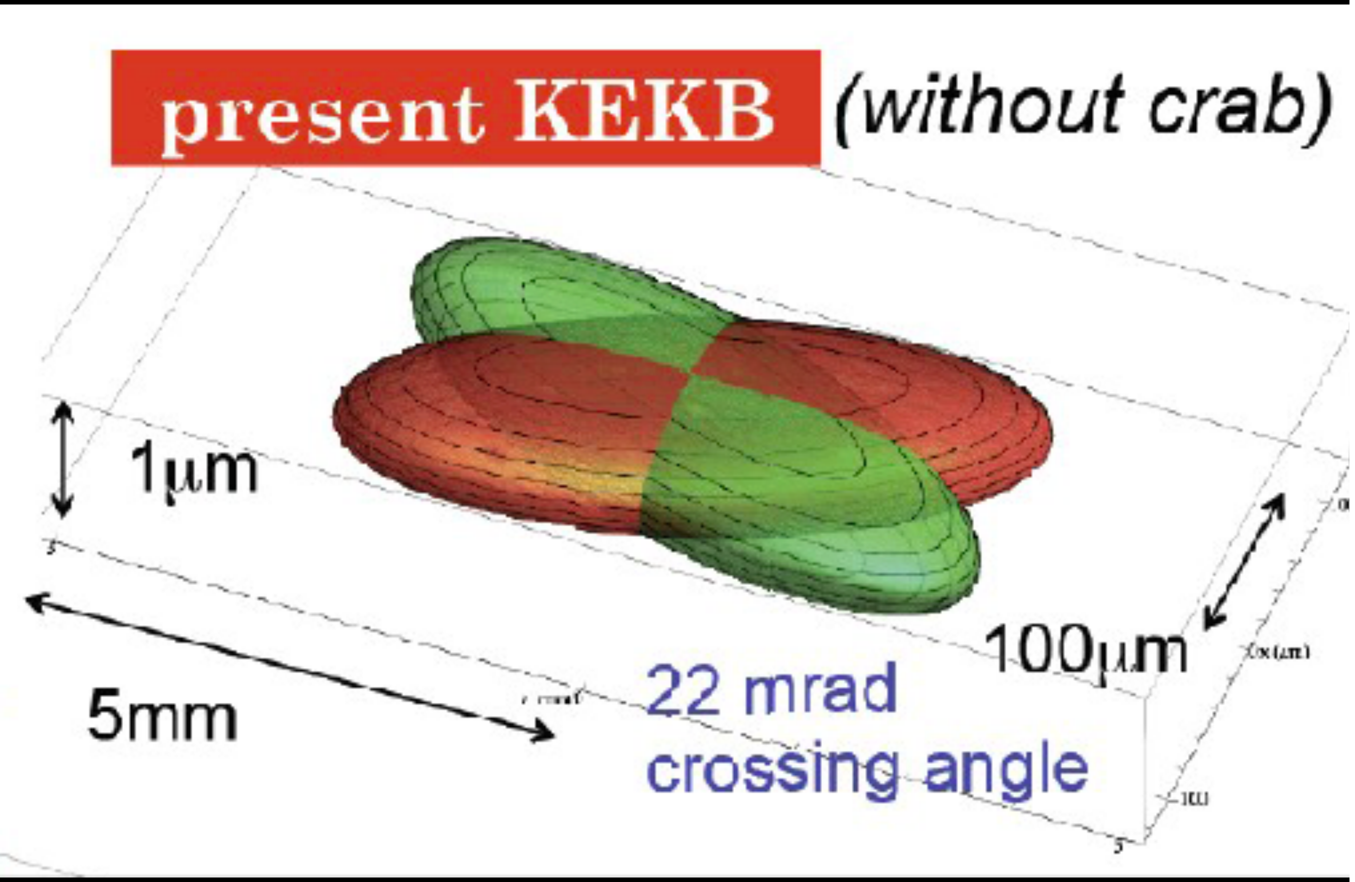
Japan is a leader

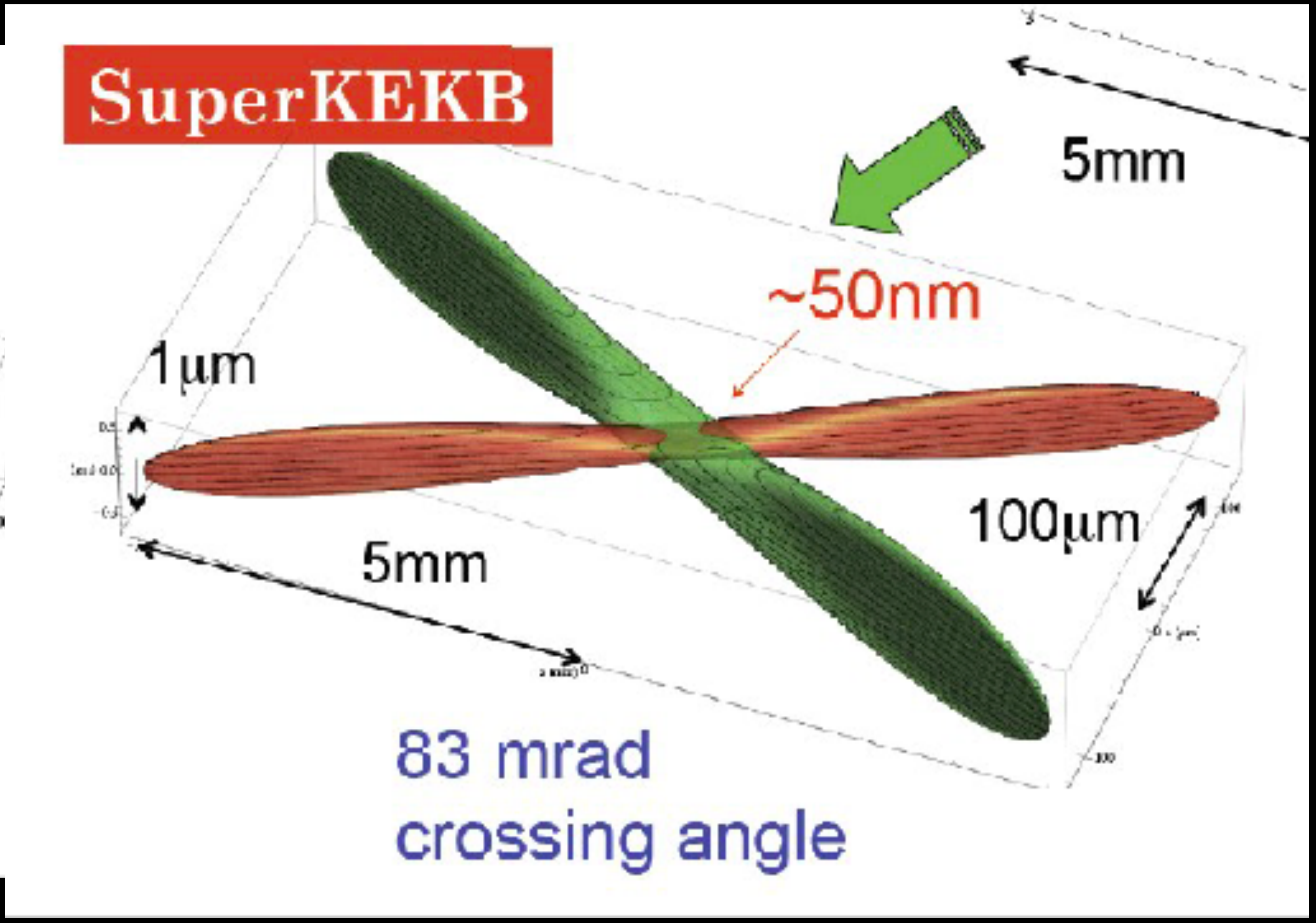





Belle 測定器
加速空洞
陽電子源

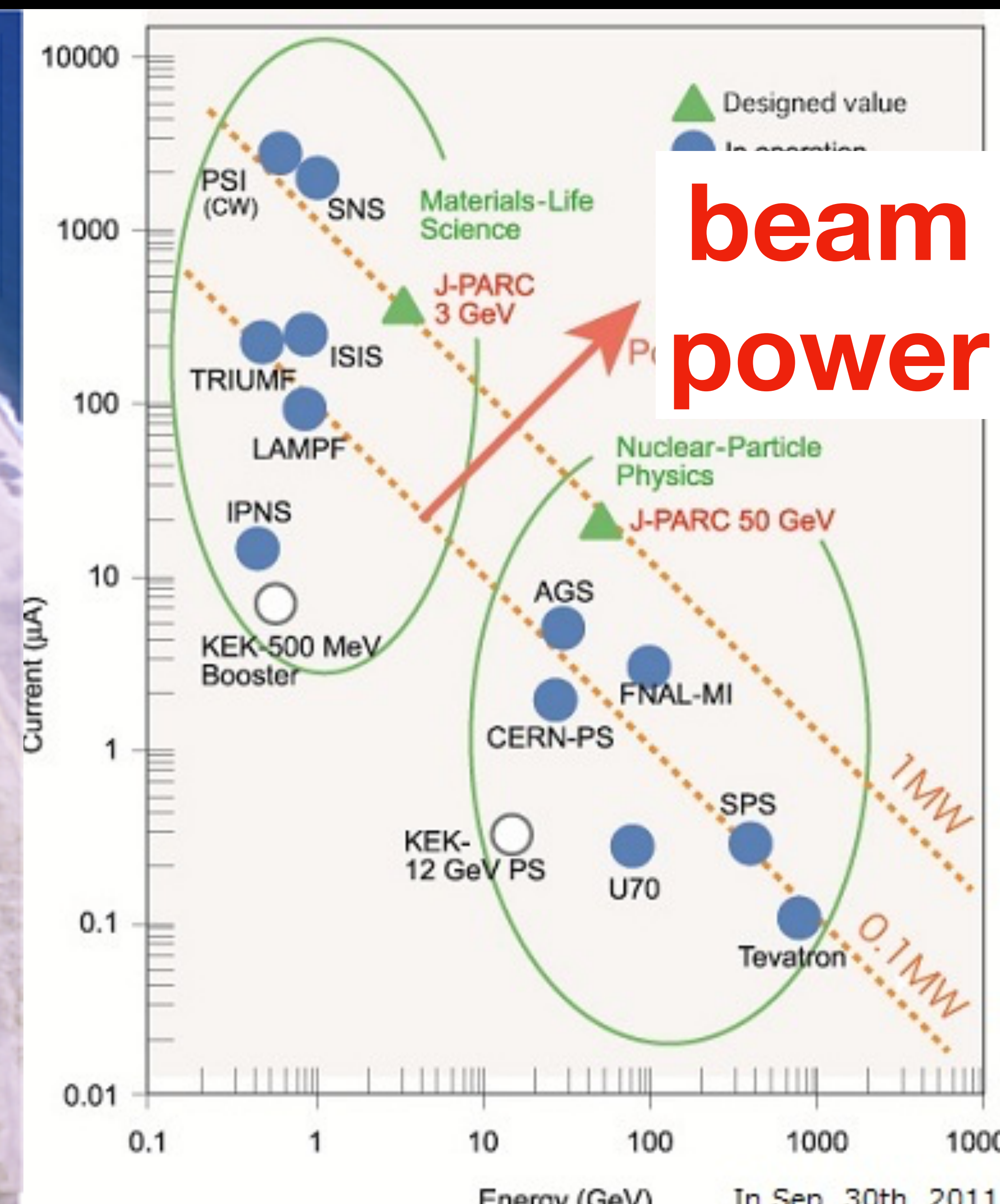
nano beam





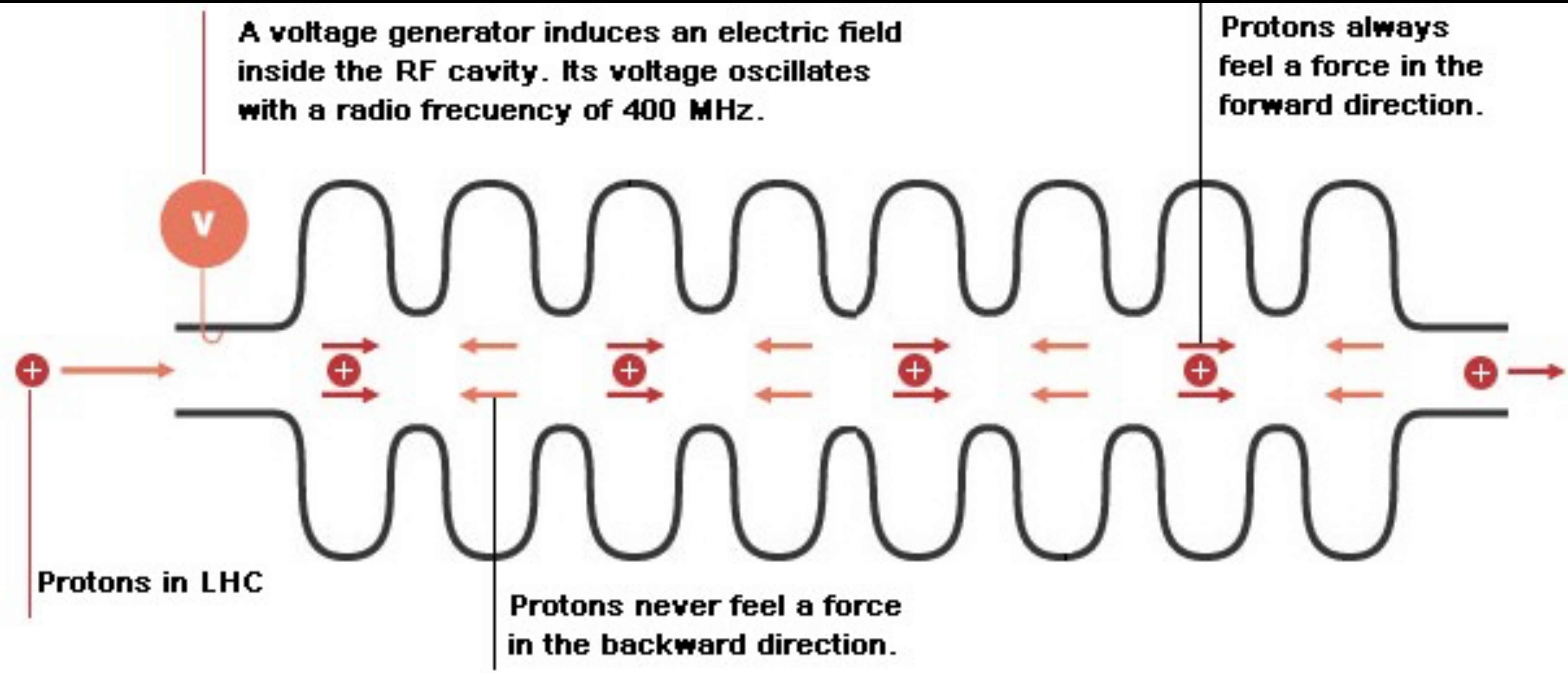
ILC beam is only 7nm high

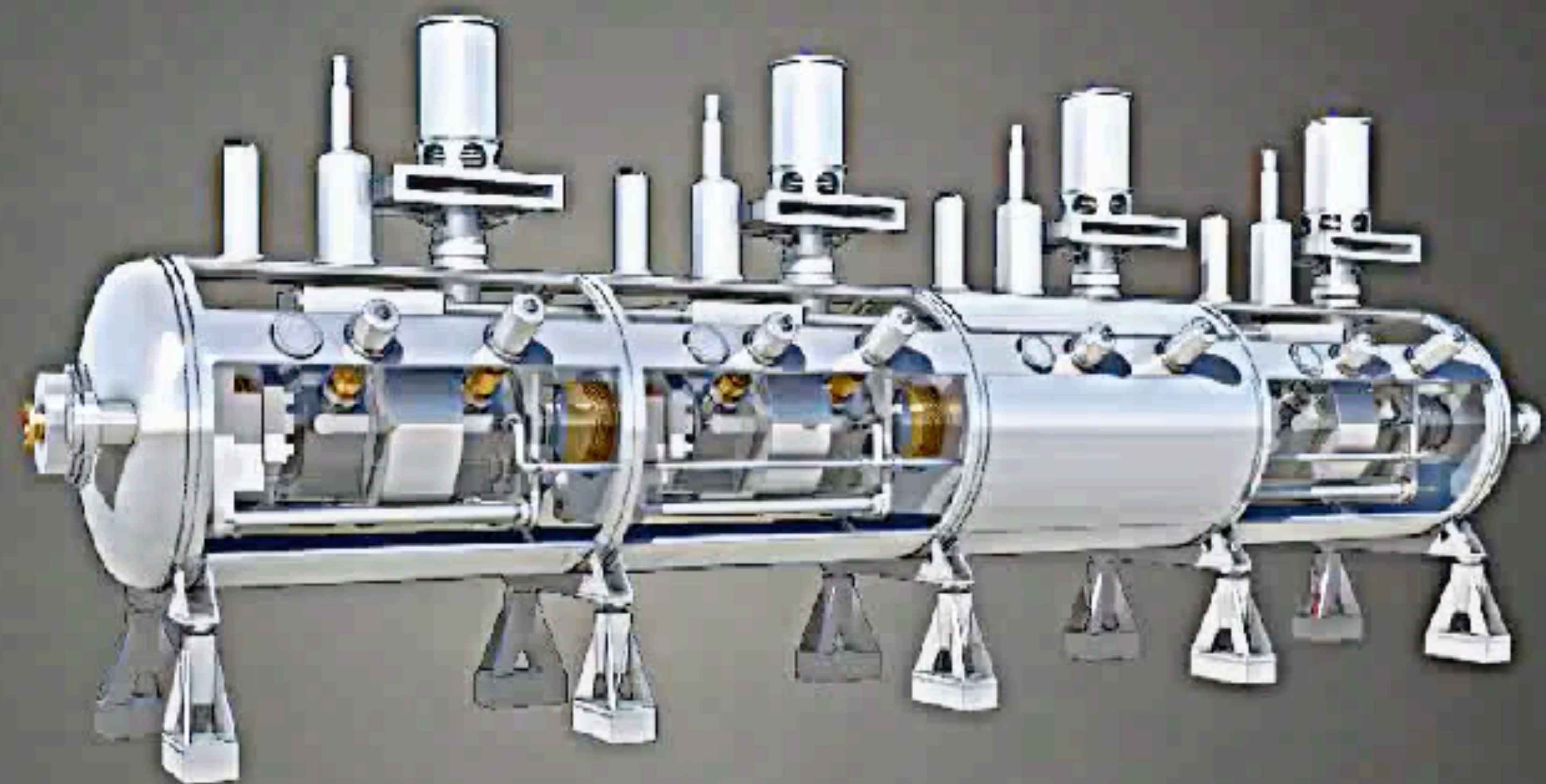
Japan is a leader



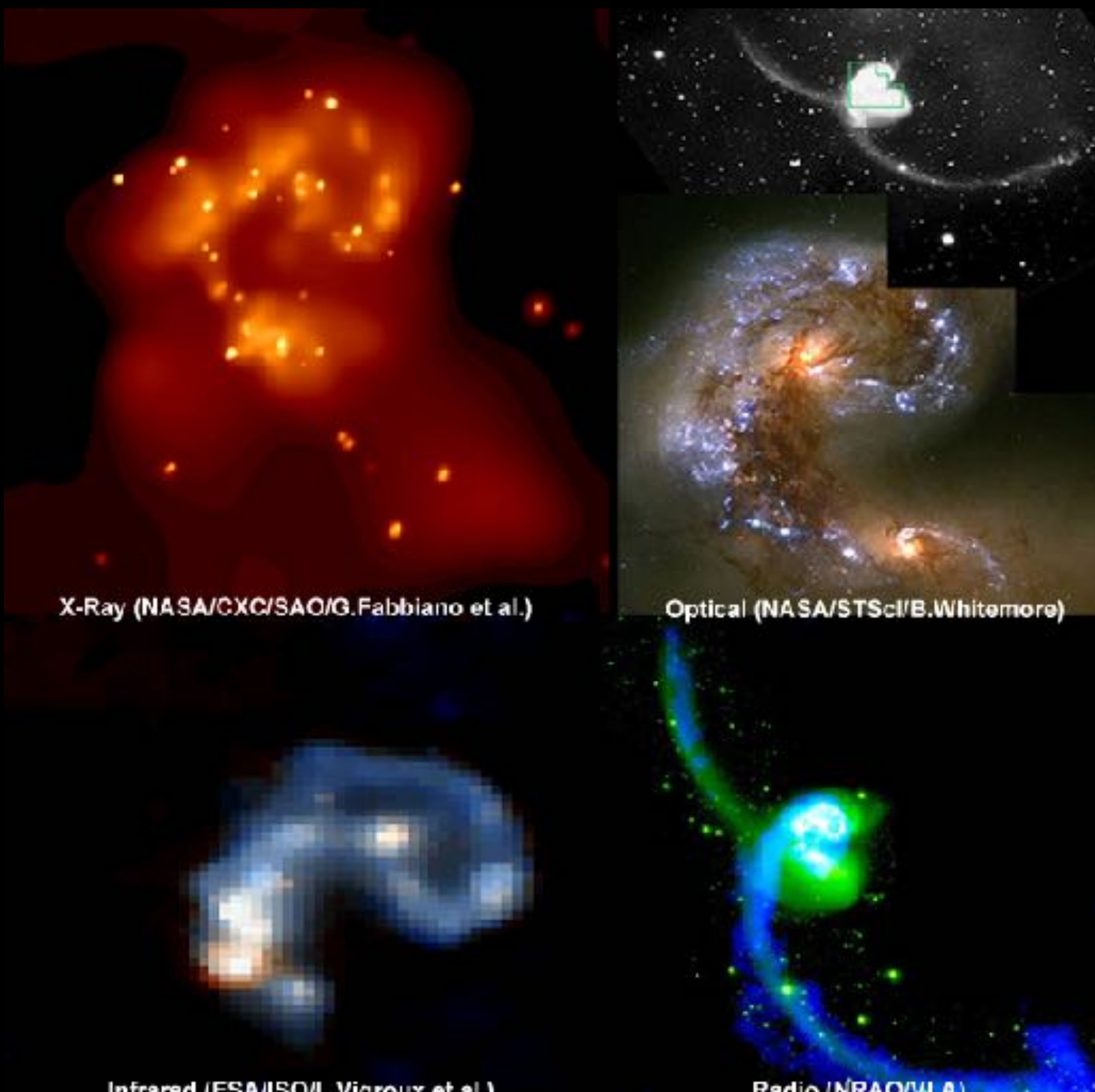

B
E

RF cavity


A voltage generator induces an electric field
inside the RF cavity. Its voltage oscillates
with a radio frecuency of 400 MHz.
Protons always
feel a force in the
forward direction.
V
Protons in LHC
Protons never feel a force
in the backward direction.



Multiple Wavebands in Astronomy



Telescopes vs Accelerators

aim	necessity	telescopes	accelerators
better image	better resolution	bigger mirrors, site, AO	higher energy better detector
probe deeper	better exposure	larger telescopes, more time	more powerful beams (luminosity)
full understanding	multiple probes	OIR, radio, X-ray, UV, γ, GW, CR	protons, electrons, neutrinos
PI mode	different science	time share instruments	facility share detectors
survey mode	large statistics	dedicated survey	collider




had predicted
three for each type

top 1995

tau 1975

bottom 1978

muon

strange

charm 1974

electron

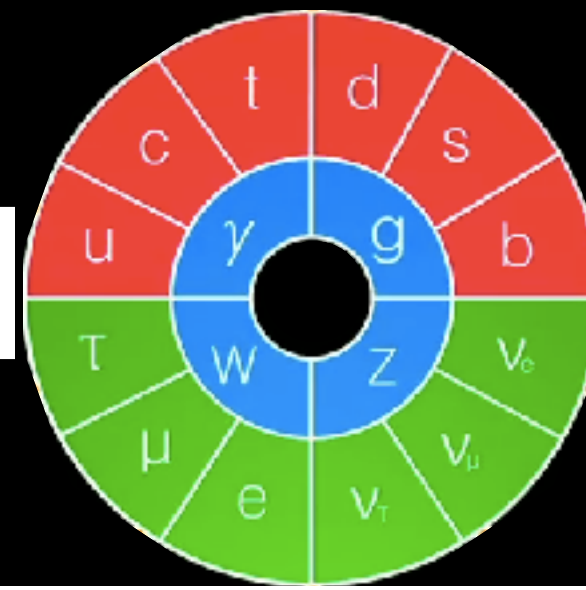
down

up

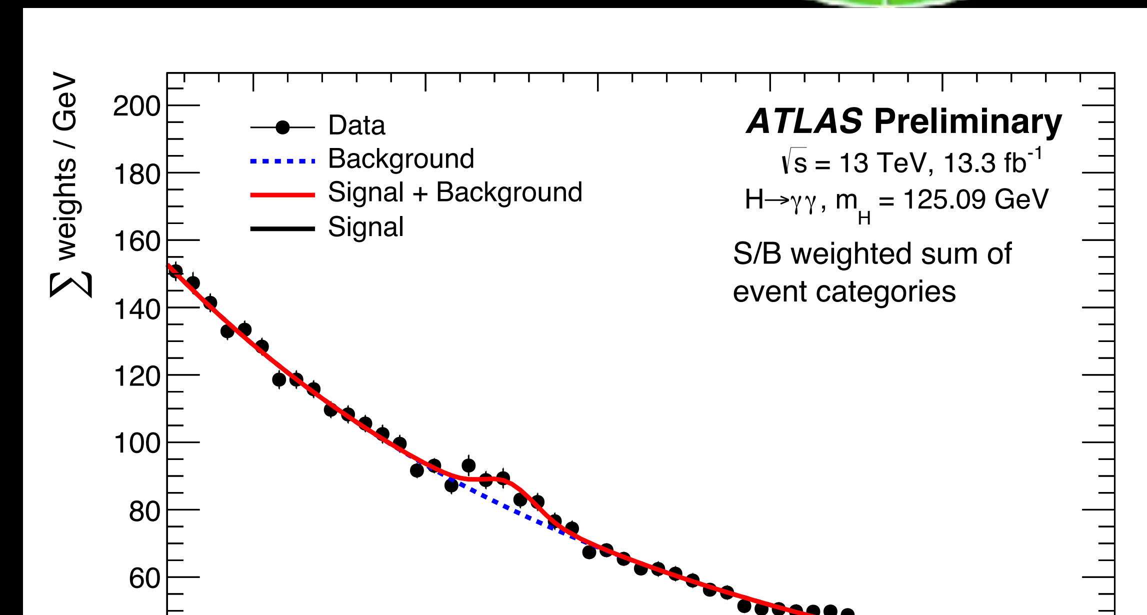
All you need
to build atoms

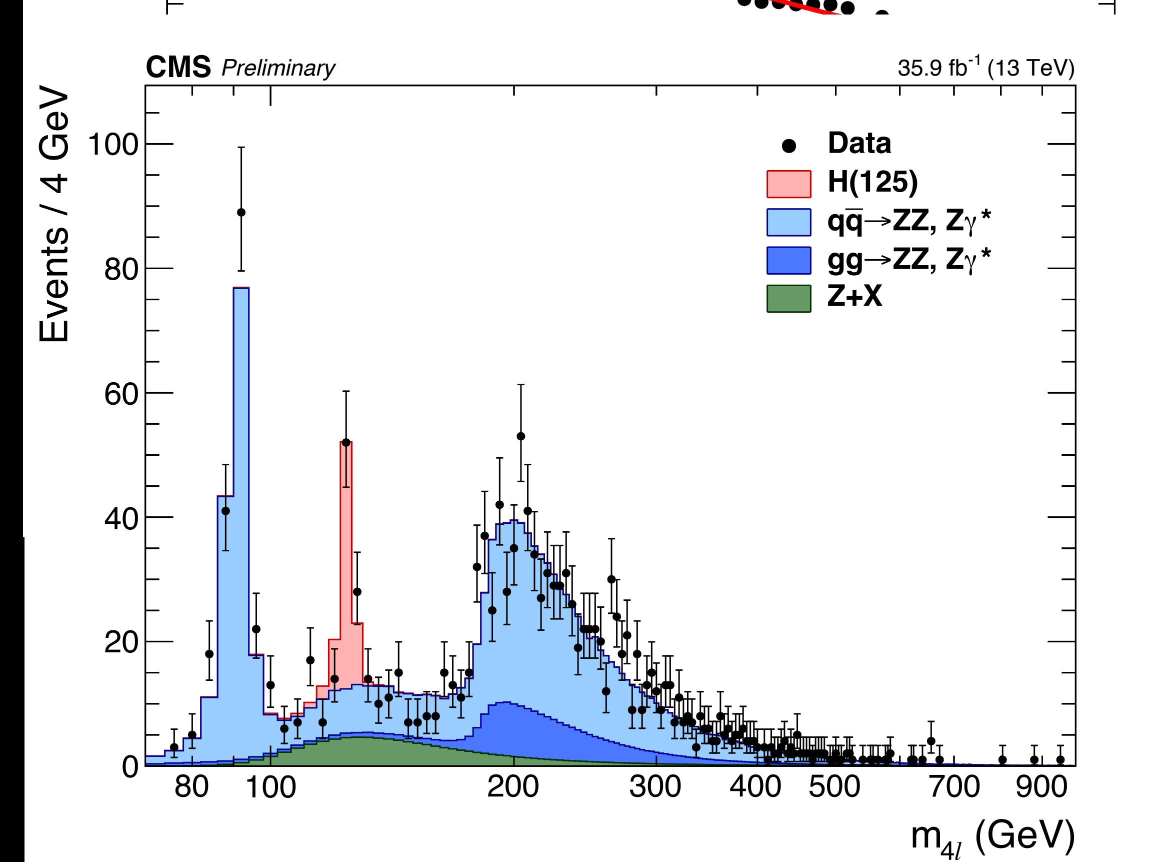
What next?

Standard Model



- *triumph of 20th century physics*
- most successful physical theory ever
- describes three forces:
  - electromagnetism
  - strong
  - weak
- Particle Data Group complies more than 24,000 measurements, all agree with the SM except for a few
- some predictions (electron magnetic moment) are test at the level of 10^{-12}!
- but we see problems in the 21st century

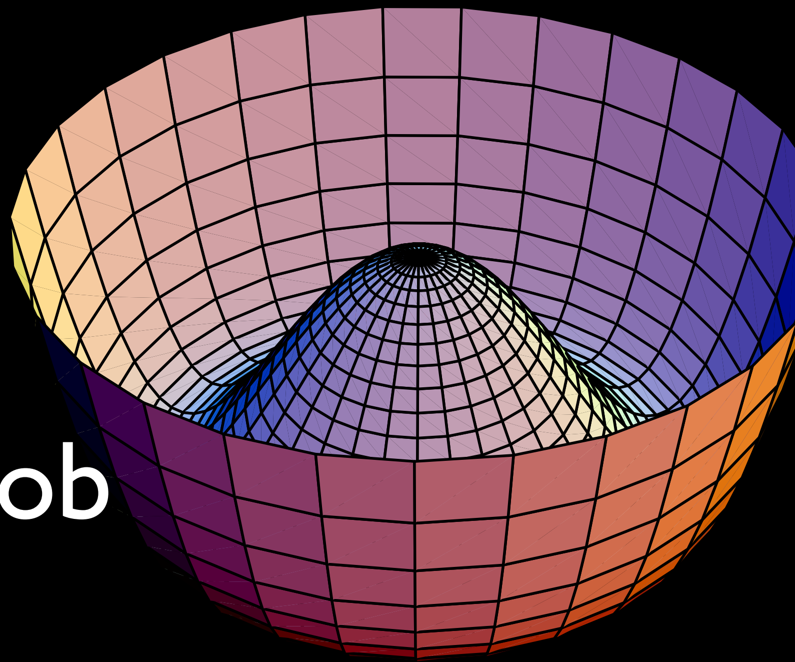




Pressing

What is Higgs?
Is it alone?
Any siblings?
Any relatives?
Why frozen?

- Higgs boson is the *only spin 0 particle* in the standard model
  - it is *faceless*
  - one of its kind, no context
  - but does the most important job
- 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

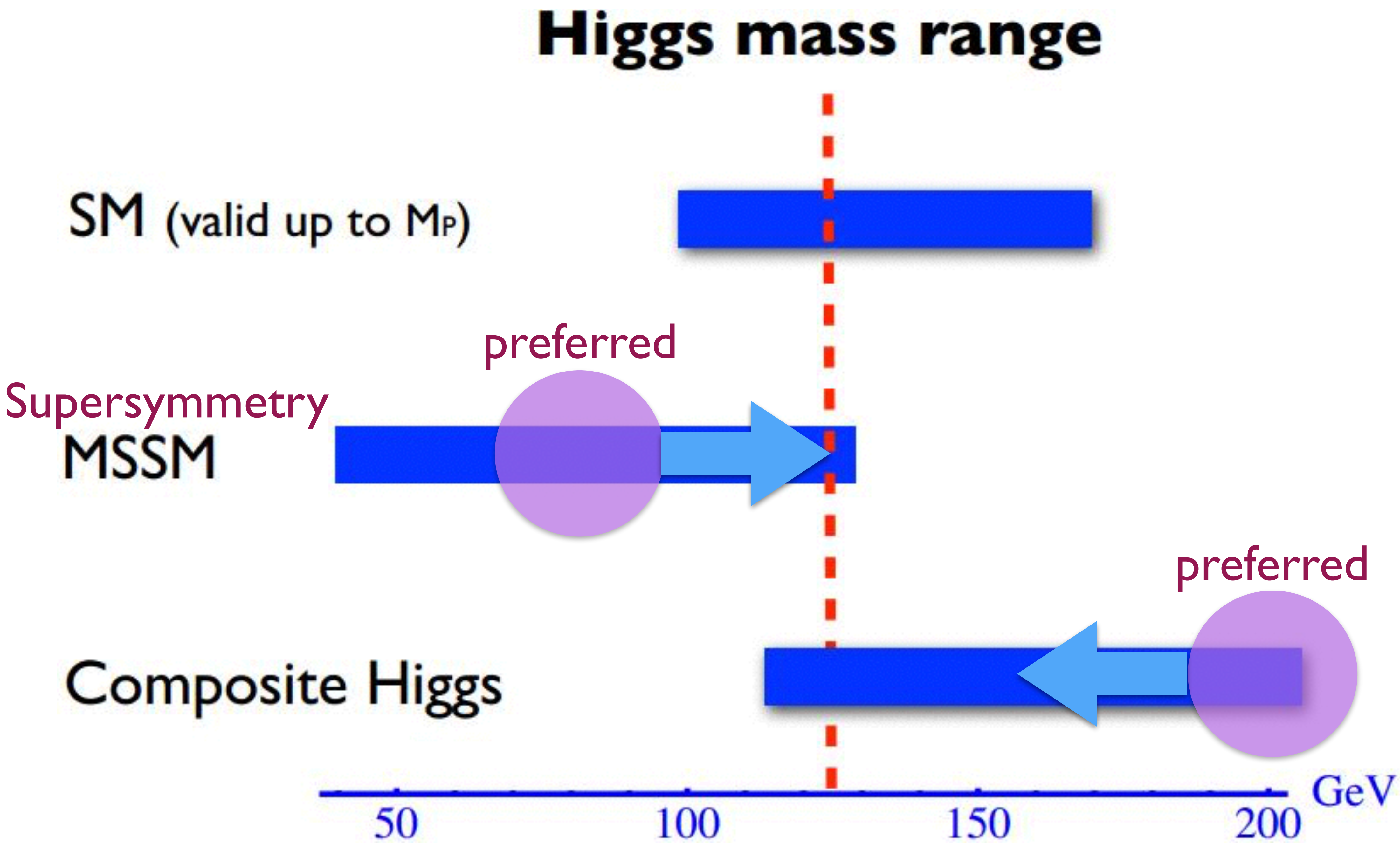
Extra dimension

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

a different "naturalness" argument

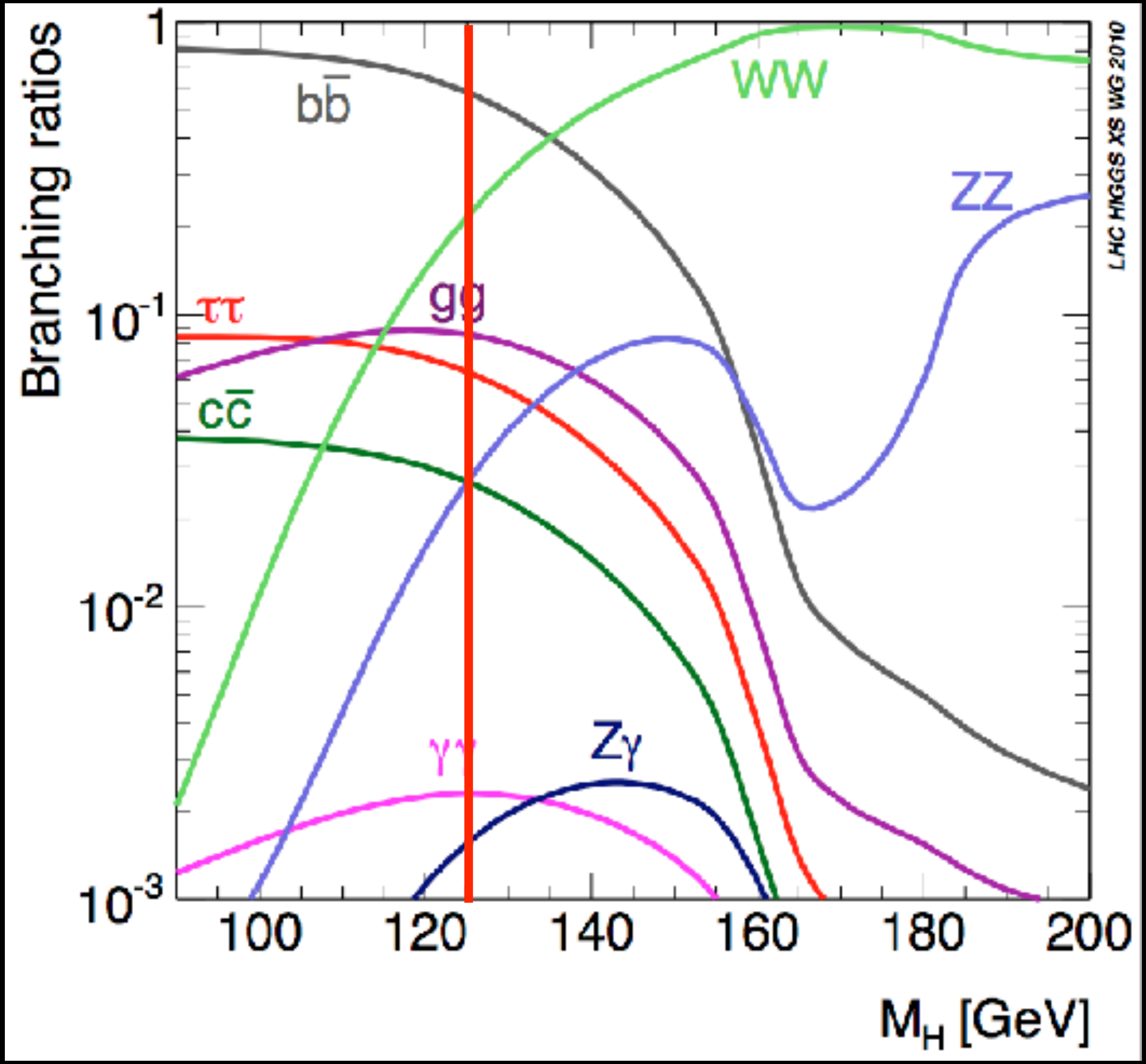
Nima's anguish

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


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

By A Pomarol

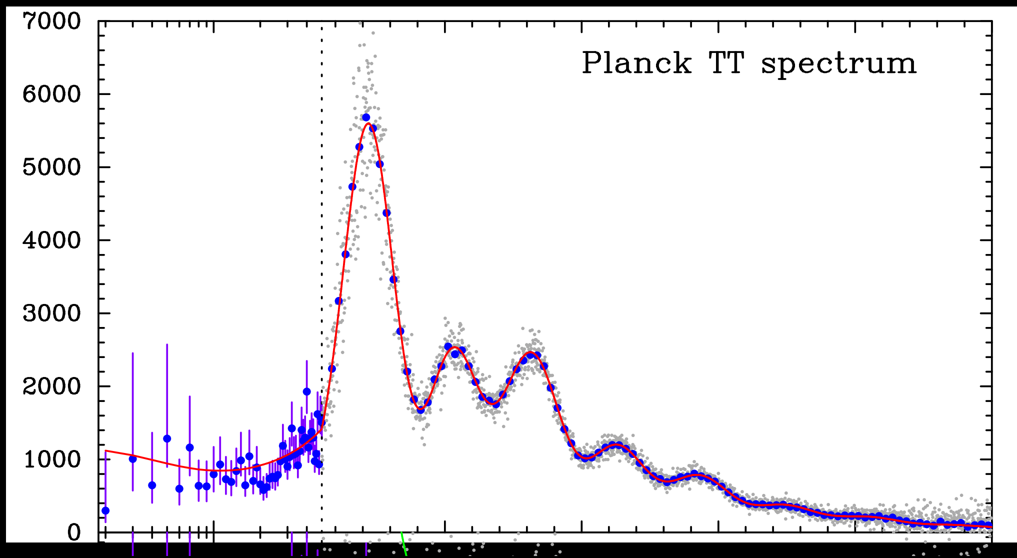
dream case for experiments



can measure them all!

Five evidences for physics beyond SM

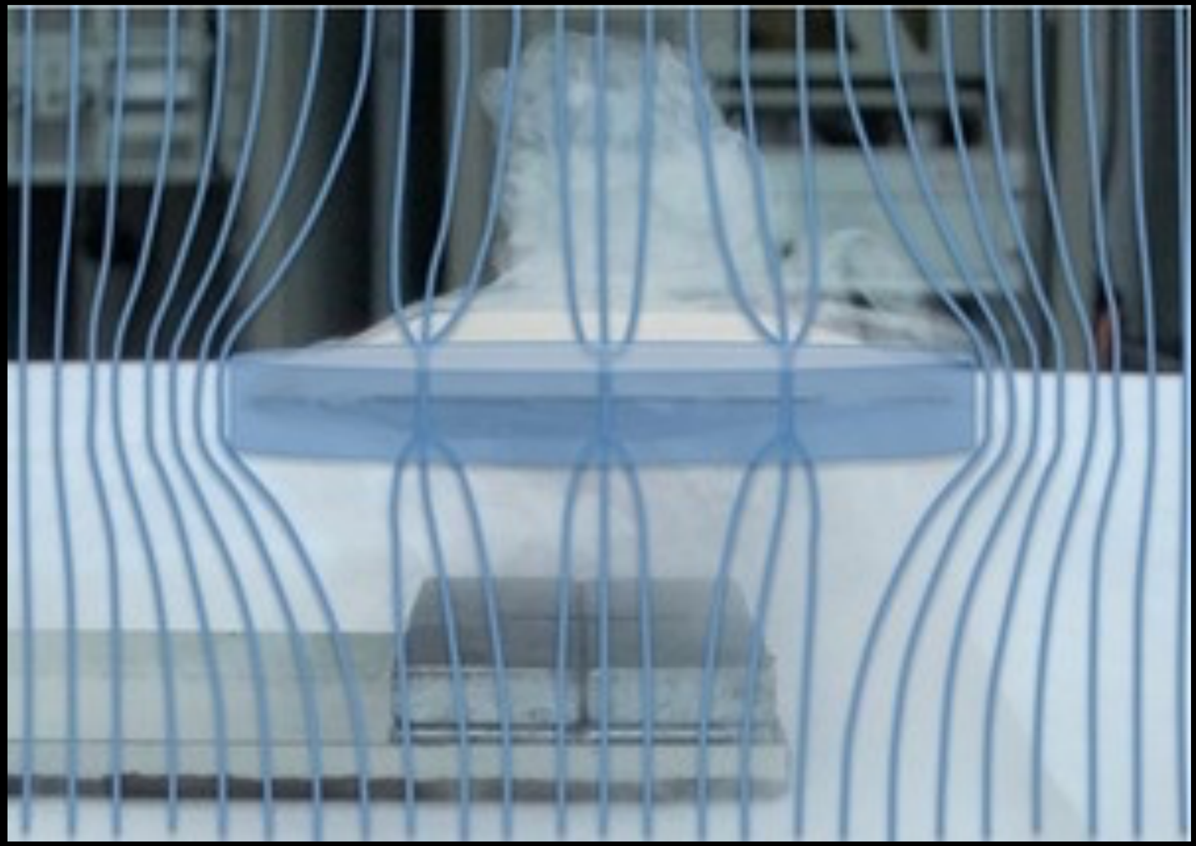
- Since 1998, it became clear that there are at least five missing pieces in the SM
  - dark matter (2003)
  - neutrino mass (1998)
  - dark energy (1998)
  - acausal density fluctuations (2003)
  - baryon asymmetry (2003)

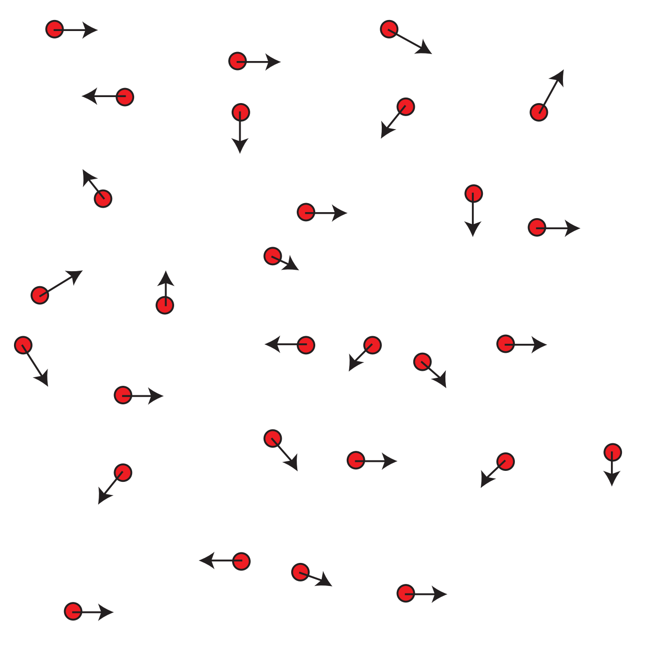


Early Universe = laboratory of particle physics

Mystery

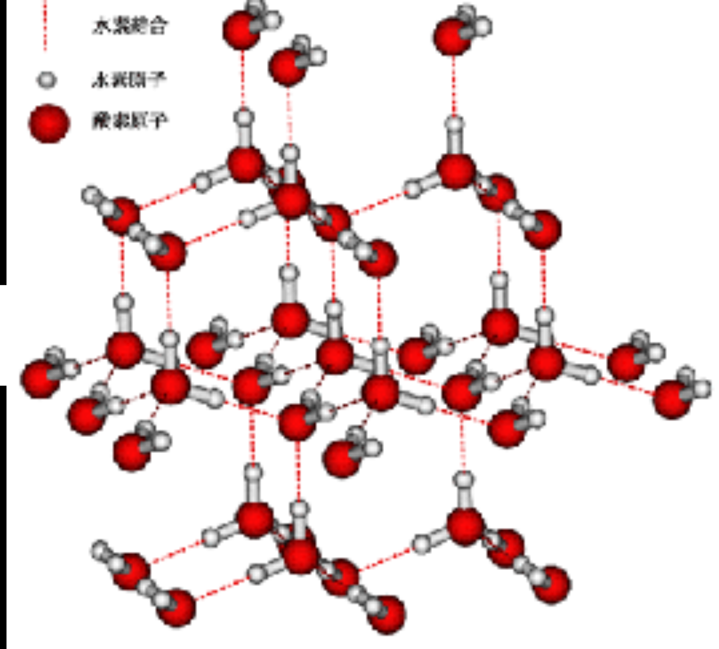
- Weak force is basically the same kind as the electromagnetism
- But then why is its range much shorter than the size of nuclei?
- the range 10^{-16} cm is *just right*!





verse got colder

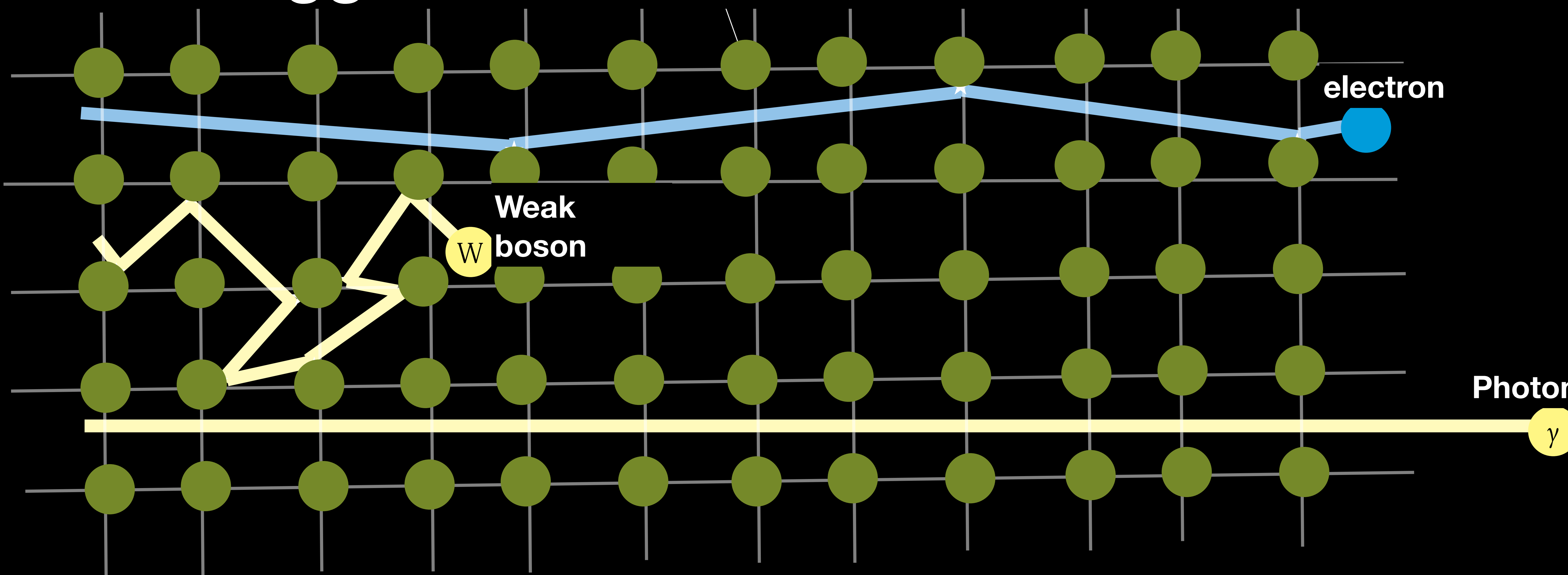
4×10^{15} °K



symmetry gets broken

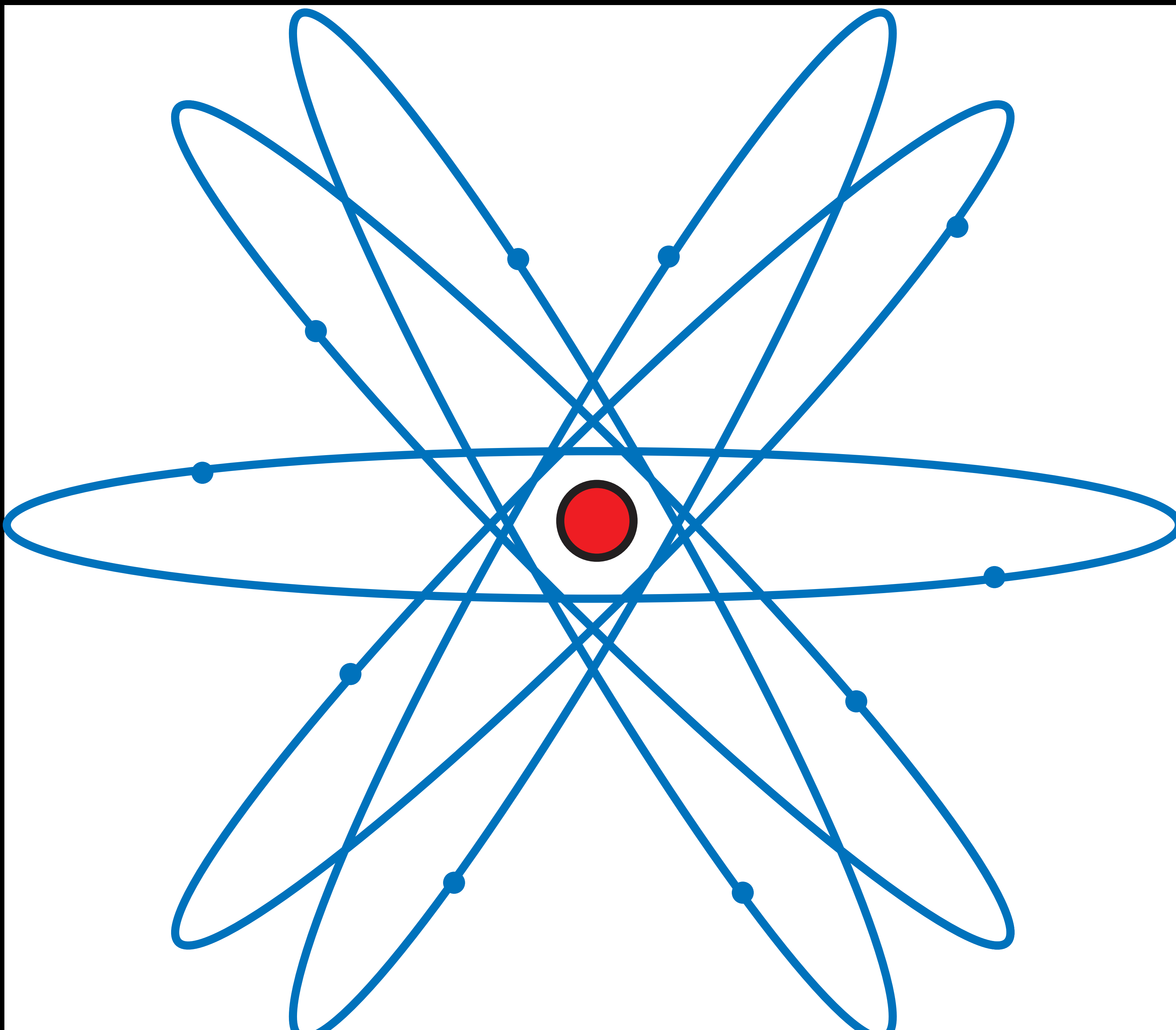
disorder ⇒ order

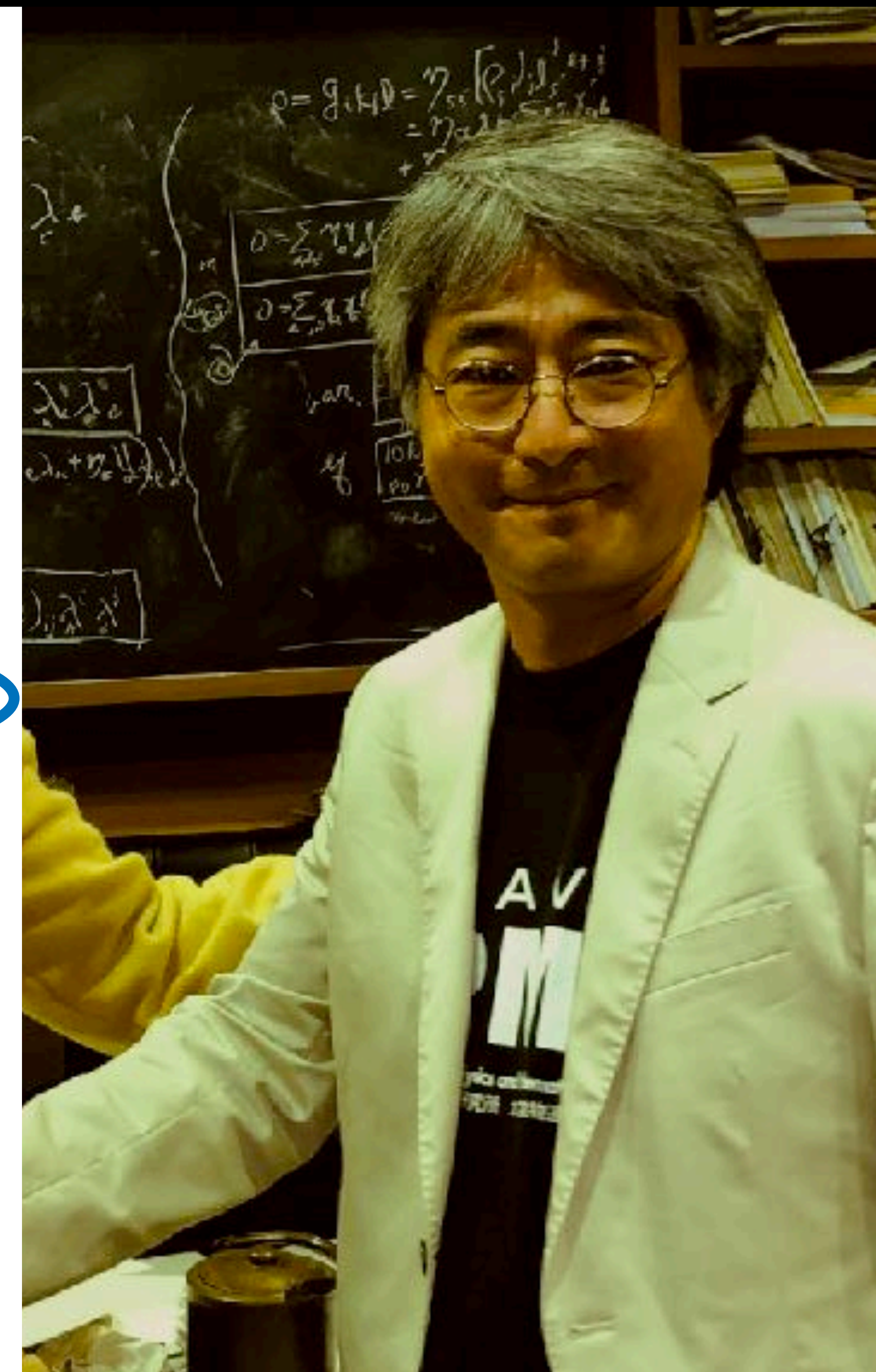
Higgs boson frozen in the Universe



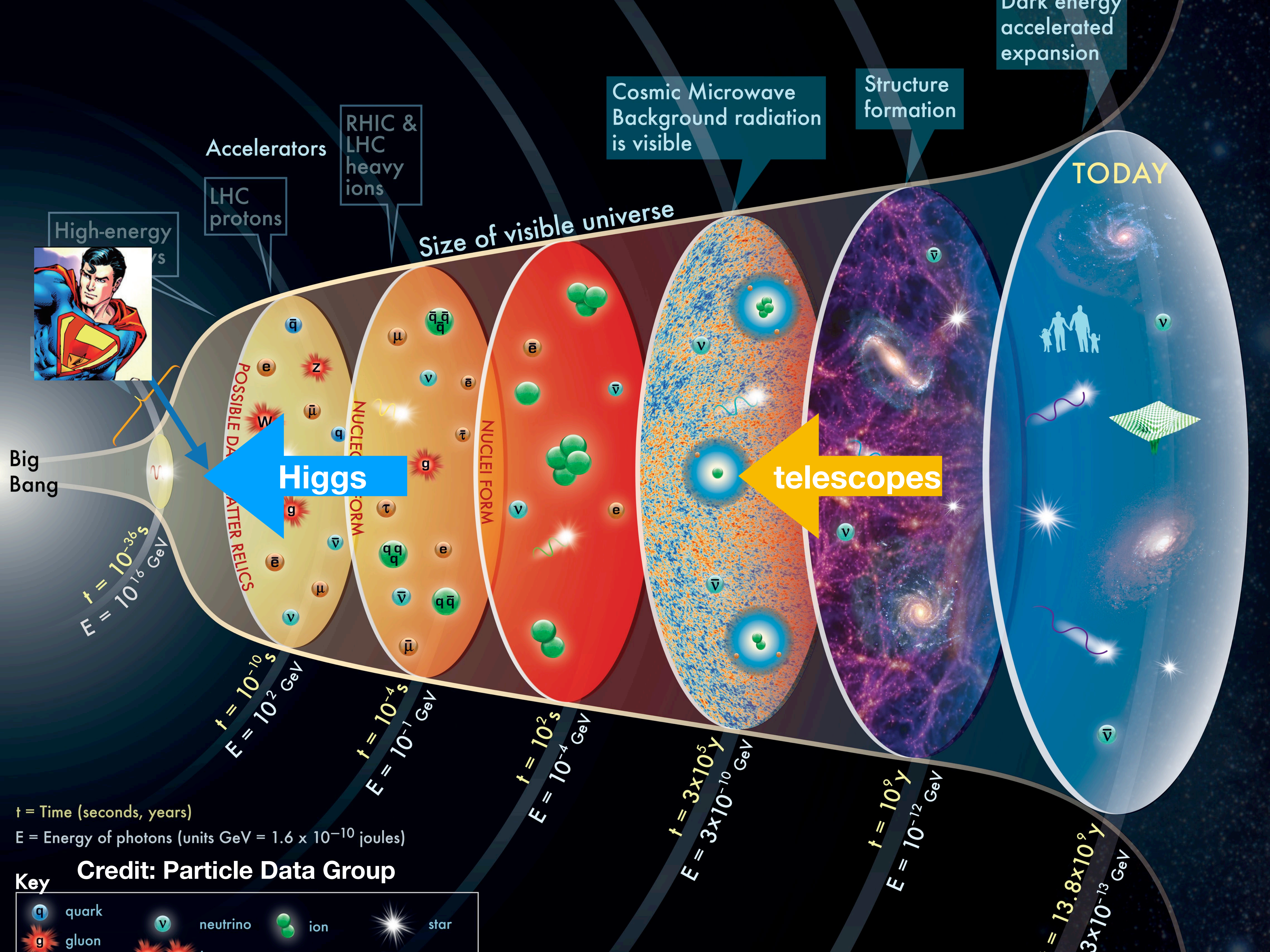
Just the right amount of Higgs boson for us to exist!

Credit: Newton Japa






Who is he?
Why is he frozen?
Why do we exist?



Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy
TODAY
Size of visible universe
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
Higgs
telescopes
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Credit: Particle Data Group
Key
quark
gluon
neutrino
ion
star

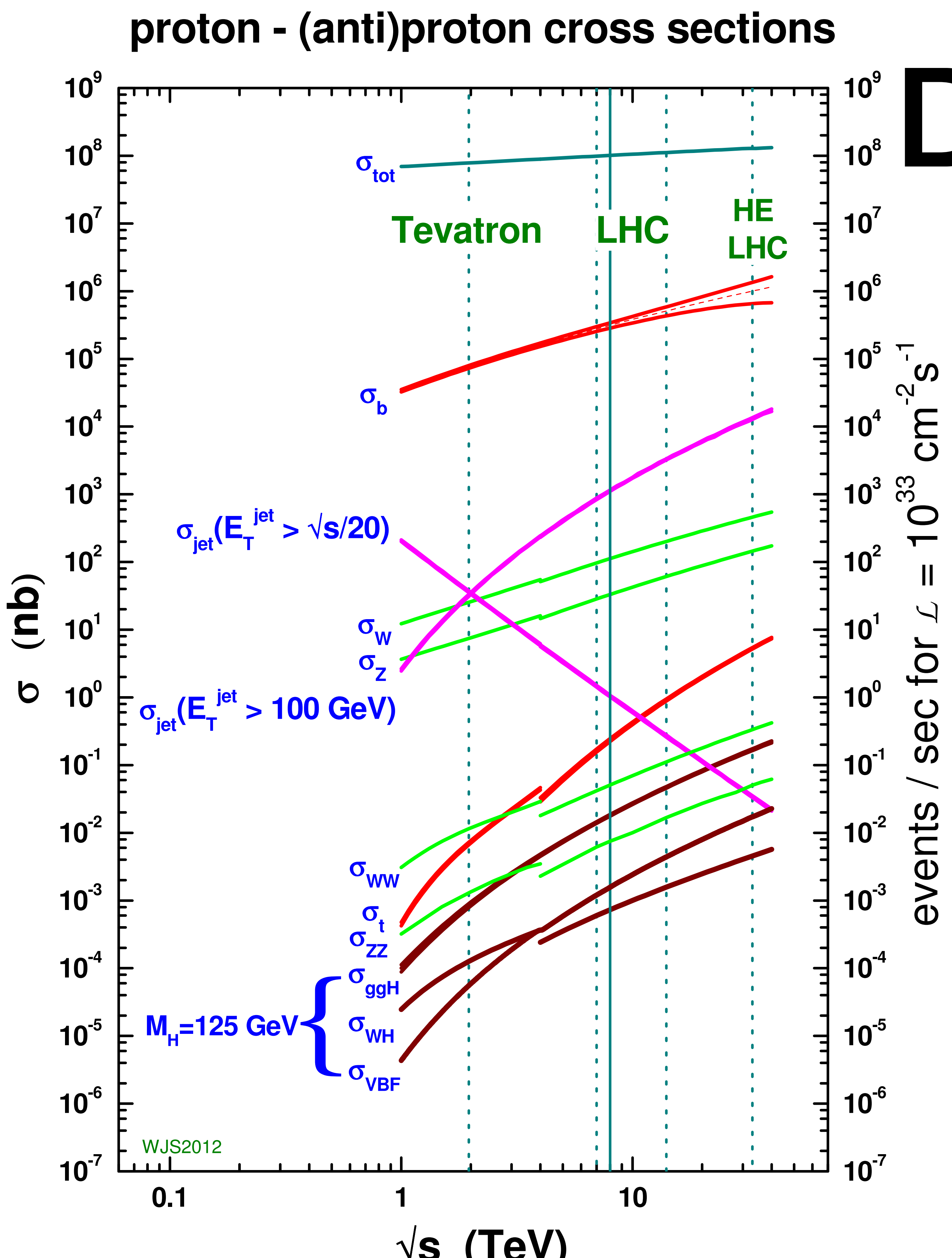
Cold Atom Laboratory (CAL) on ISS

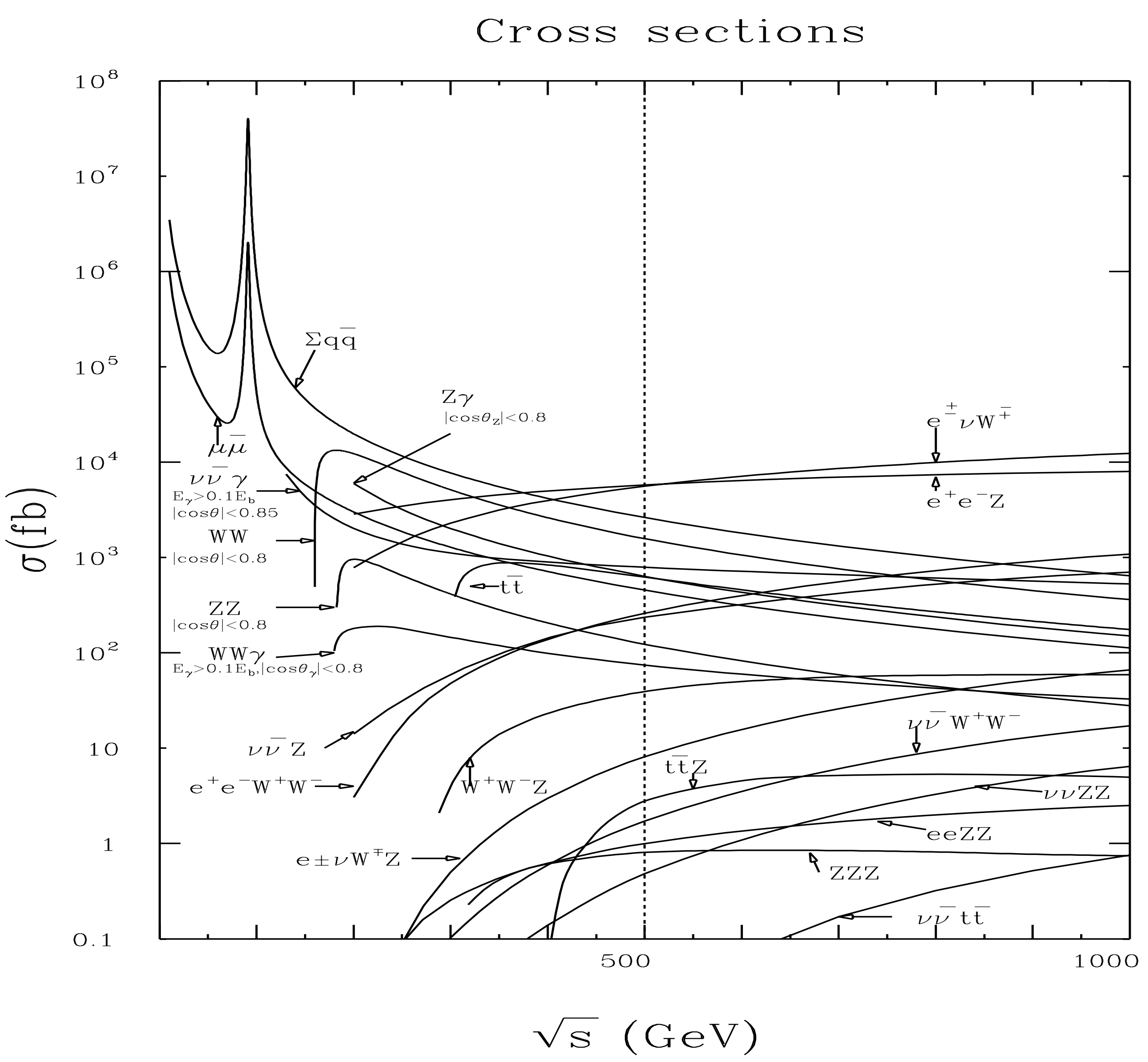
https://en.wikipedia.org/wiki/File:Bose-Einstein_Condensation.ogv

Why e^+e^-?

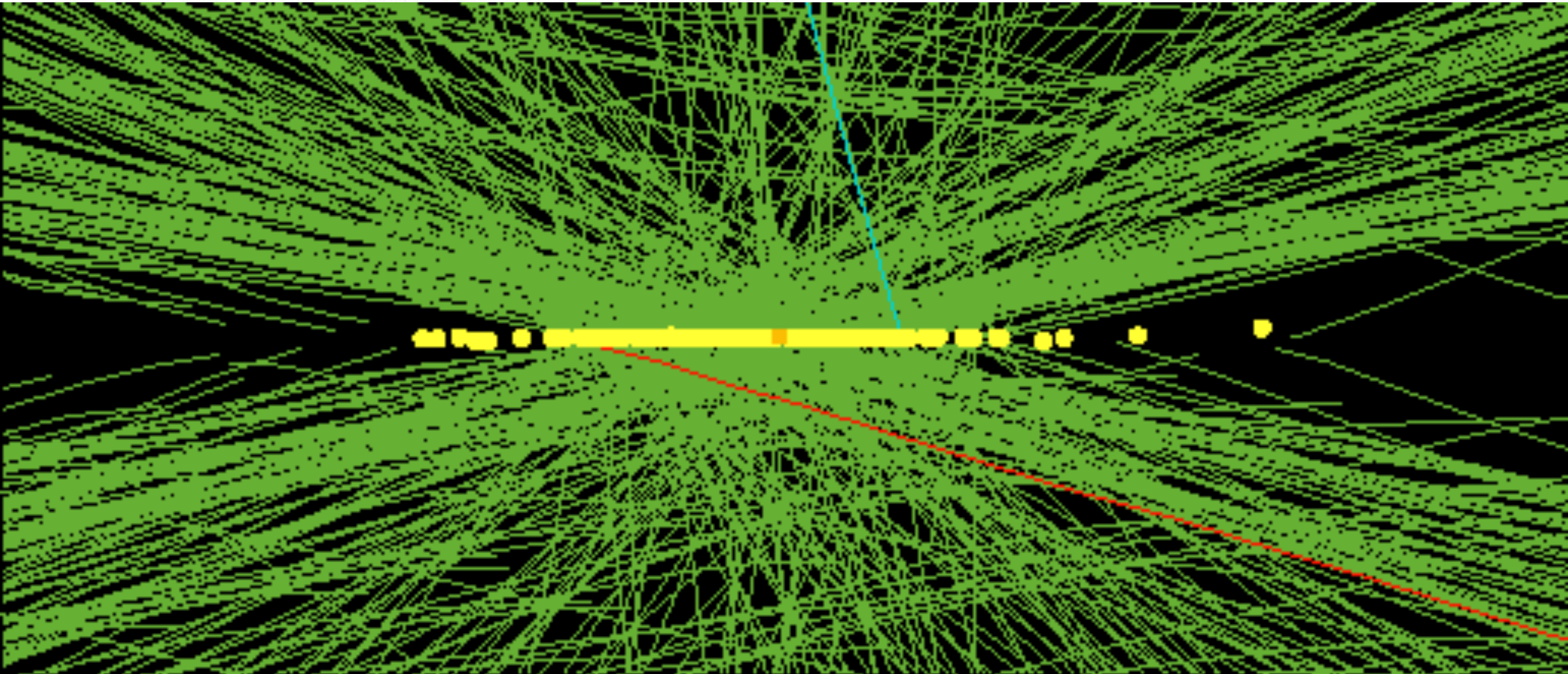
- Democratic
- Clear
- Holistic

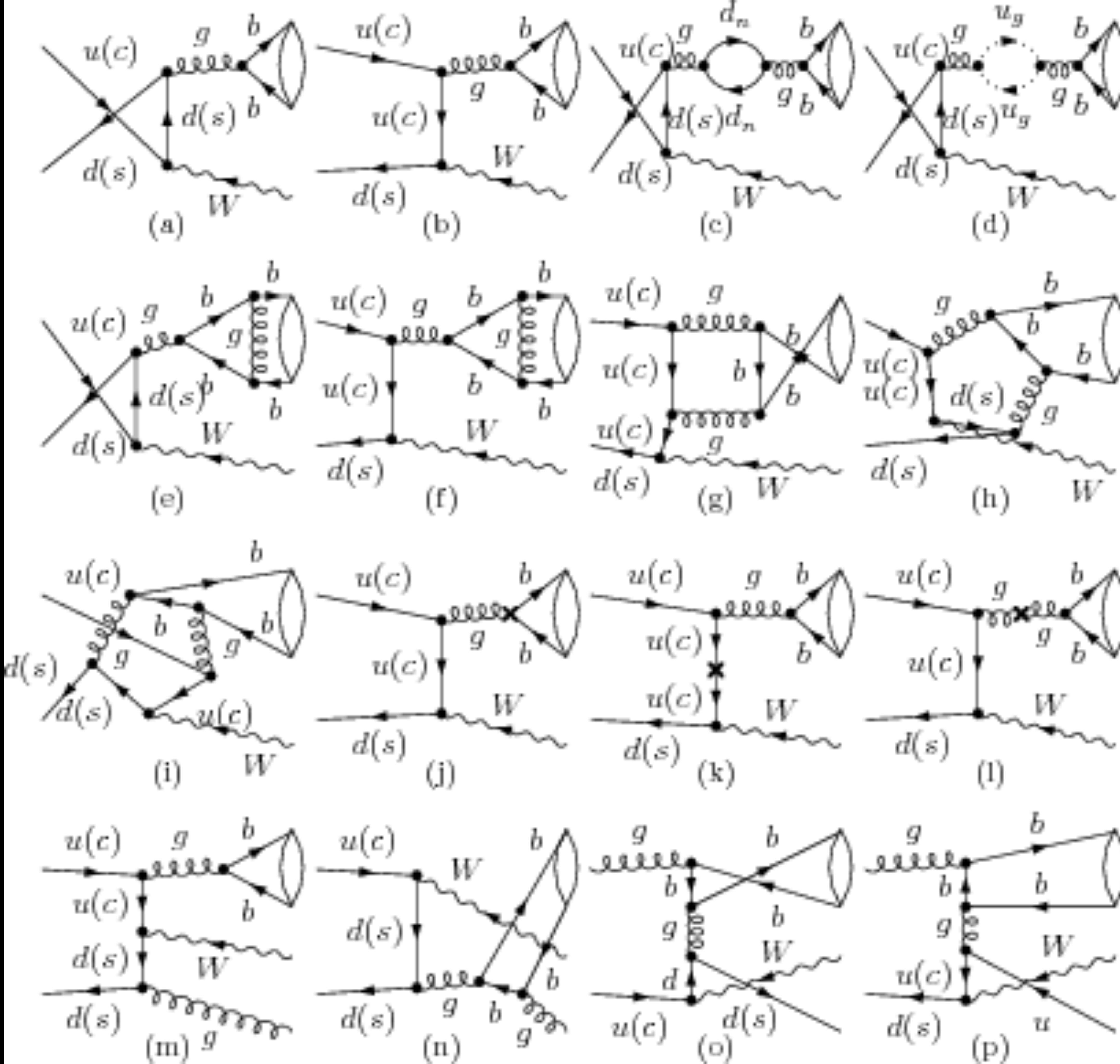
Democratic


proton - (anti)proton cross sections
σ (nb)
events / sec for ℒ = 10^33 cm^-2 s^-1
√s (TeV)
0.1
1
10
Tevatron
LHC
HE LHC
σ_tot
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_WW
σ_t
σ_ZZ
σ_ggH
σ_WH
σ_VBF
M_H=125 GeV
WJS2012


Cross sections
σ(fb)
√s (GeV)
500
1000
Σqq̄
μμ̄
Zγ
νν̄γ
WW
ZZ
WWγ
tt̄
e±νW∓
e+e−Z
νν̄Z
e+e−W+W−
W+W−Z
tt̄Z
νν̄W+W−
ννZZ
eeZZ
ZZZ
e±νW∓Z
νν̄tt̄

Parameter	2012	Nominal	HL-LHC (25 ns)	HL-LHC (50 ns)
C.O.M Energy	8 TeV	13-14 TeV	14 TeV	14 TeV
N_p	$1.2\ 10^{11}$	$1.15\ 10^{11}$	$2.0\ 10^{11}$	$3.3\ 10^{11}$
Bunch spacing / k	50 ns /1380	25 ns /2808	25 ns /2808	50ns /1404
ε (mm rad)	2.5	3.75	2.5	3.0
β* (m)	0.6	0.55	0.15	0.15
L ($cm^{-2}s^{-1}$)	$\sim 7\times10^{33}$	10^{34}	$7.4\ 10^{34}$	$8.4\ 10^{34}$
Pile up	~25	~20	~140	~260





u(c)
g
b
d(s)
b
d(s)
W
(a)
u(c)
b
g
u(c)
b
W
d(s)
(b)
u(c)
g
d_n
b
d(s)
d_n
g
b
d(s)
W
(c)
u(c)
g
u_g
b
d(s)
u_g
g
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(d)
u(c)
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d(s)
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b
d(s)
W
(e)
u(c)
g
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b
g
u(c)
b
b
W
d(s)
(f)
u(c)
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u(c)
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u(c)
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d(s)
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(g)
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u(c)
b
u(c)
d(s)
g
d(s)
W
(h)
u(c)
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d(s)
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d(s)
u(c)
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(i)
u(c)
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u(c)
W
d(s)
(j)
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g
(n)
g
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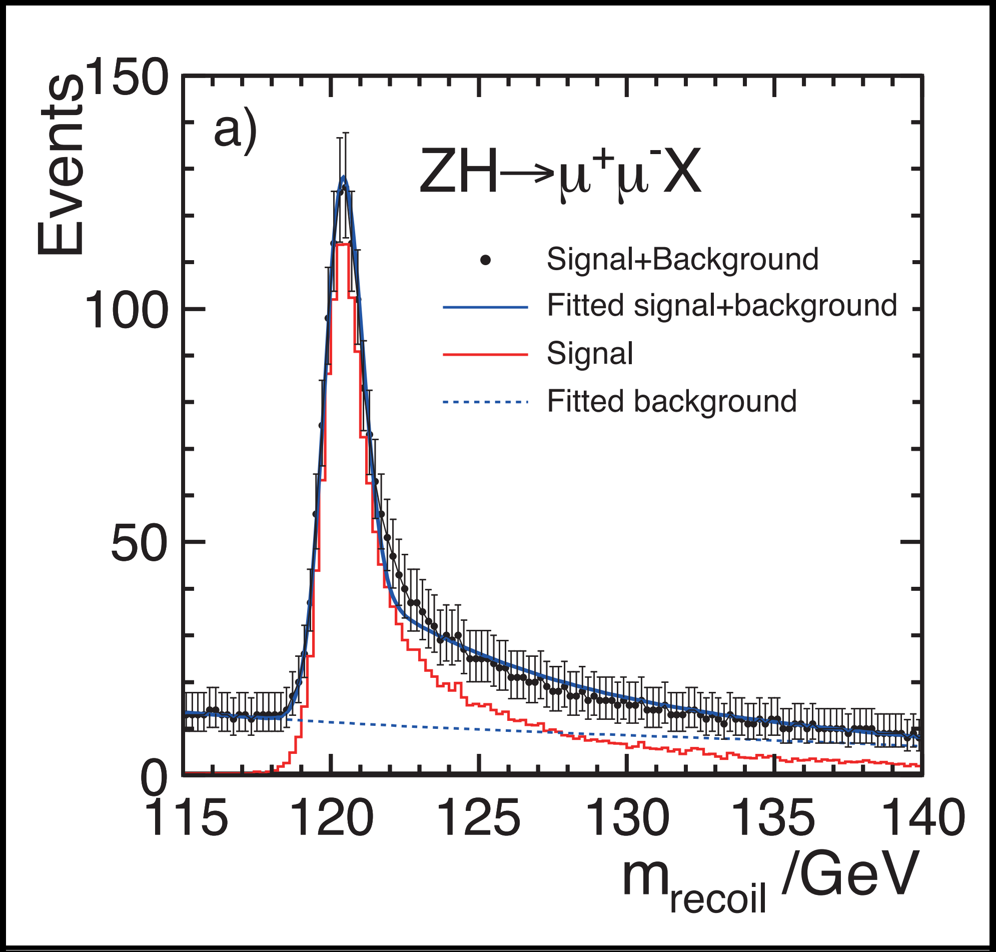
d
u(c)
d(s)
(o)
g
b
b
b
g
W
u(c)
d(s)
u
(p)

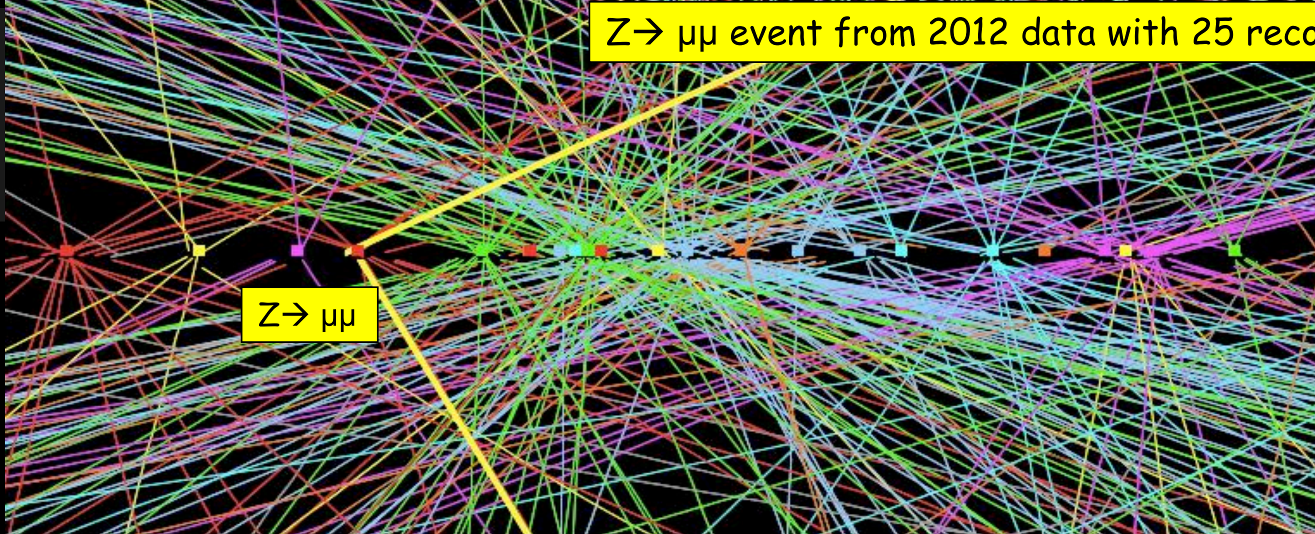
Holistic

- simple kinematics

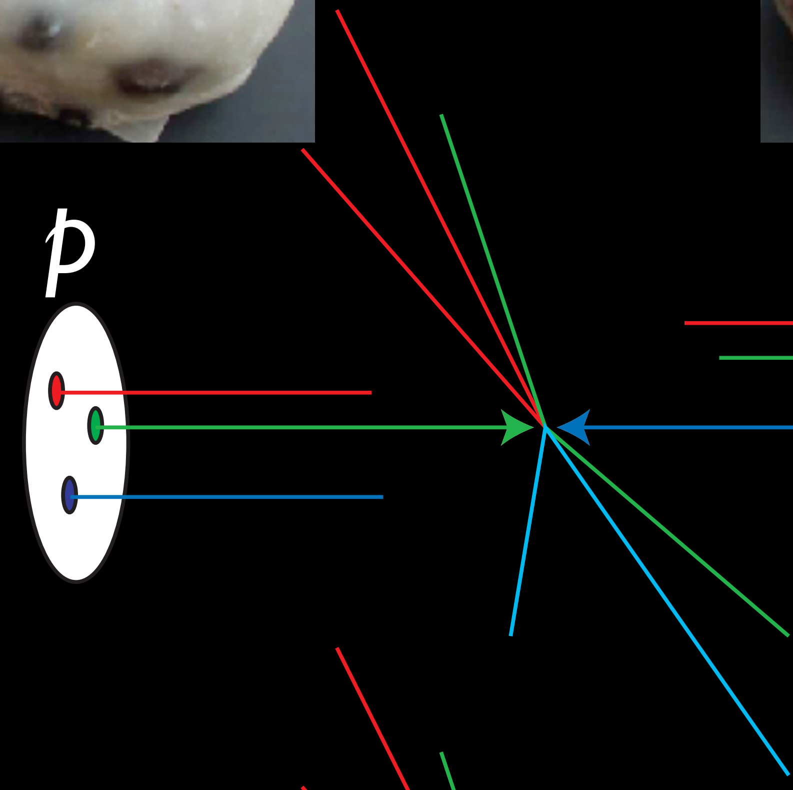
$$m_{\mathrm{recoil}}^2 = m_Z^2 + s - 2\sqrt{s}E_Z$$

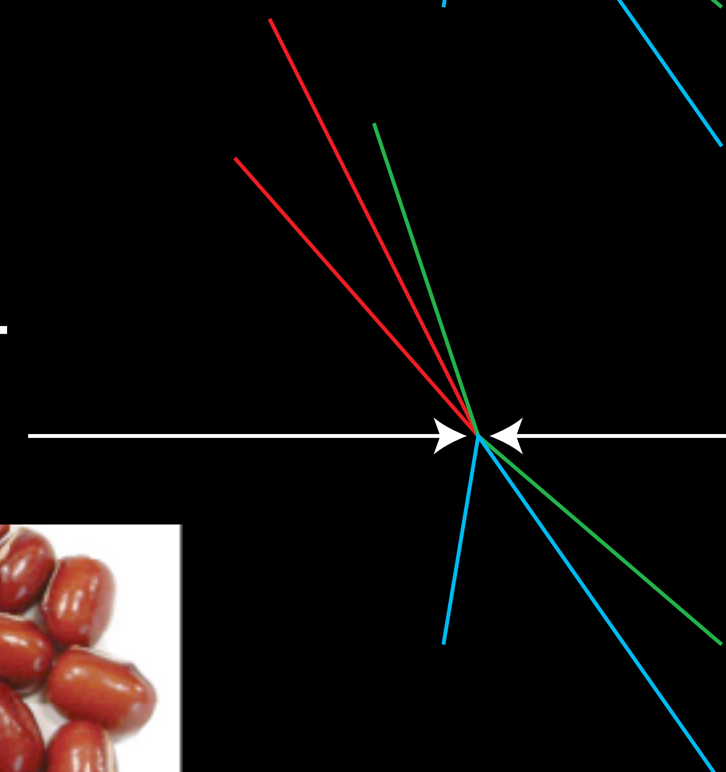
- no loss of the longitudinal momentum (modulo photon emission)
- can make use of all final states
  - not just easily identifiable particles (i.e. leptons@LHC)
- capture all information for a given event





- e^-, e^+ are elementary
- collision energy is fixed and known
- entire CM energy can be used for producing particles
- can make particles democratically
- can capture whole information

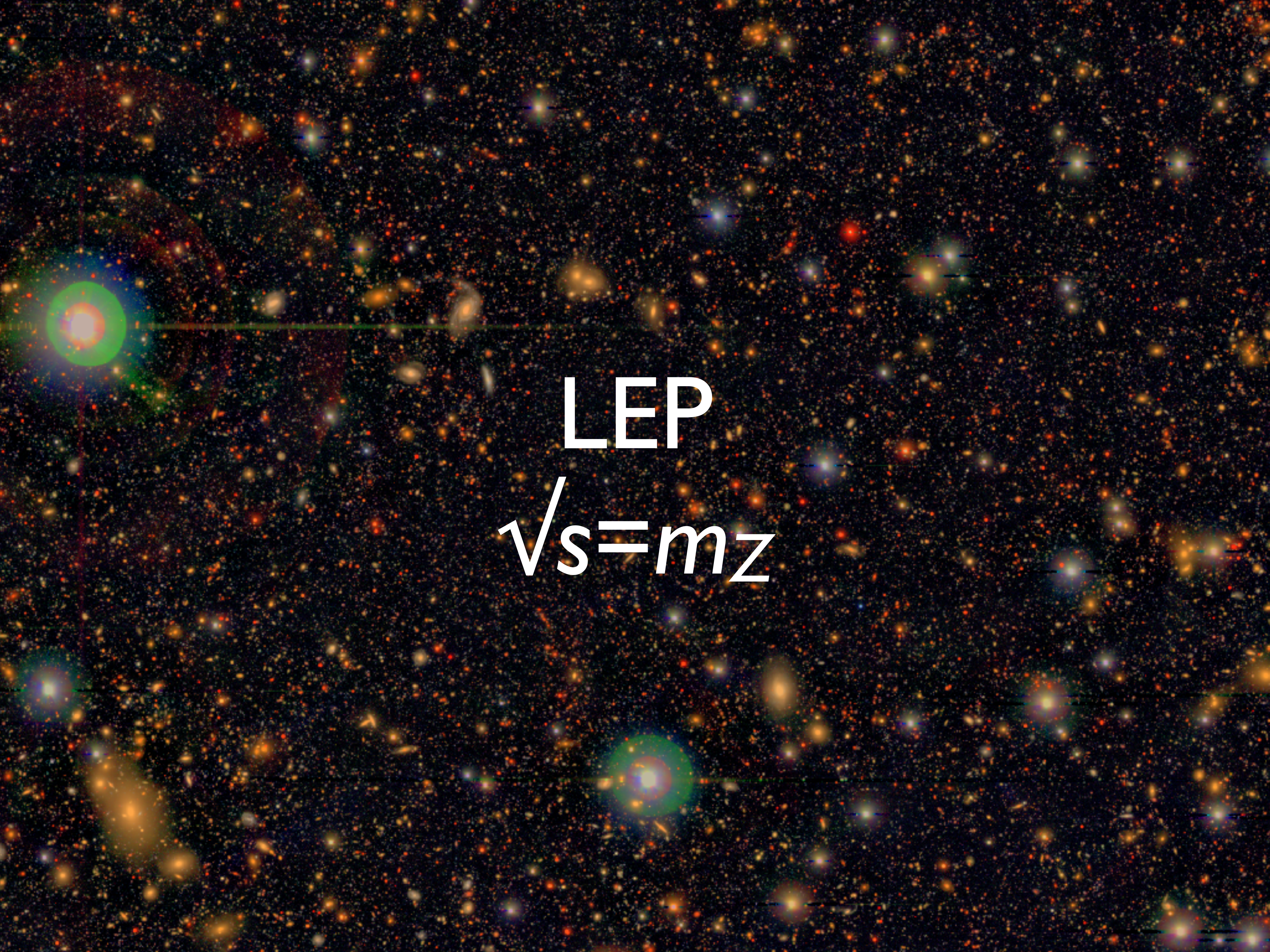


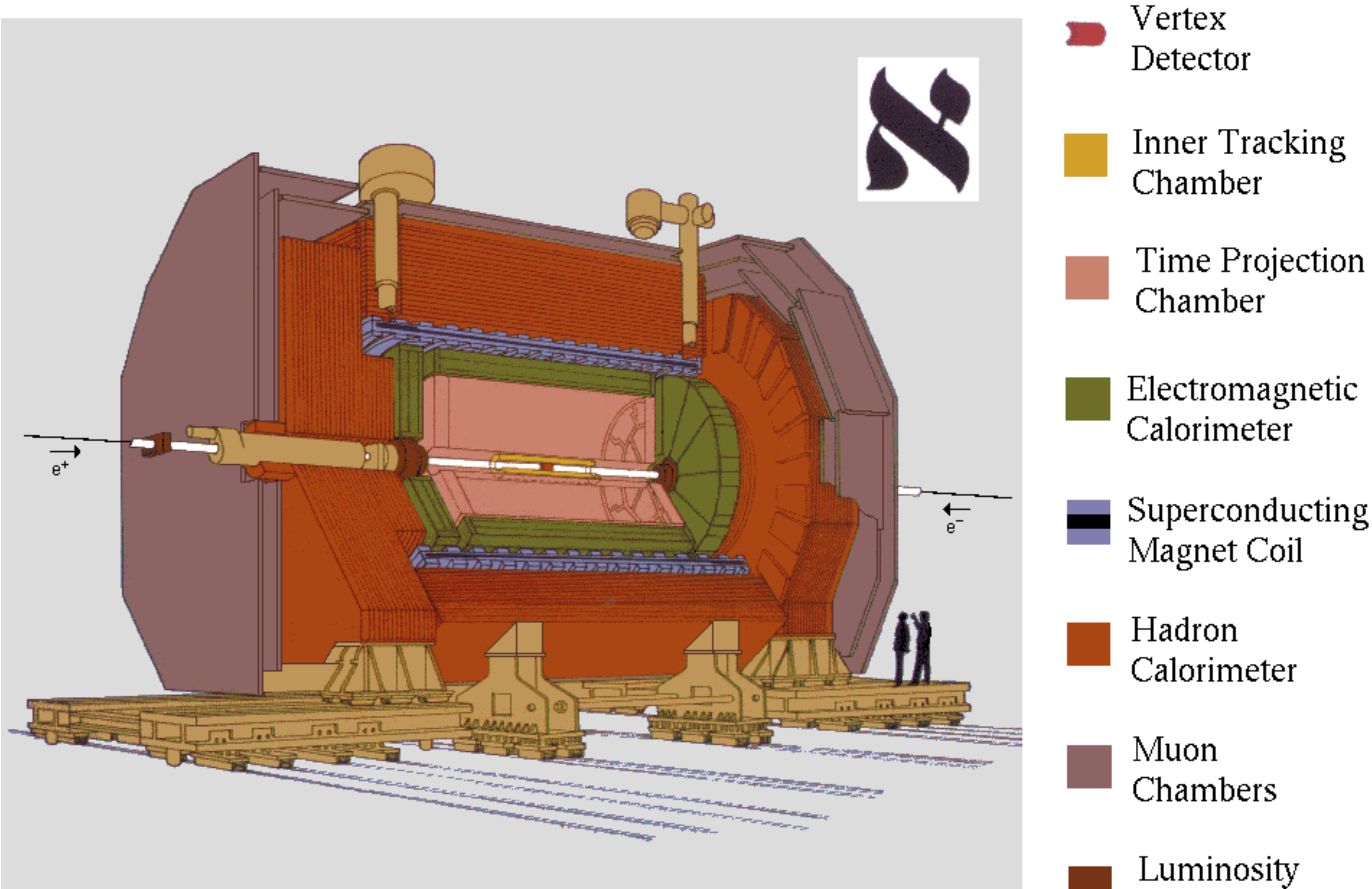


⇒ precision Higgs measurements
phenomena not seen at LHC

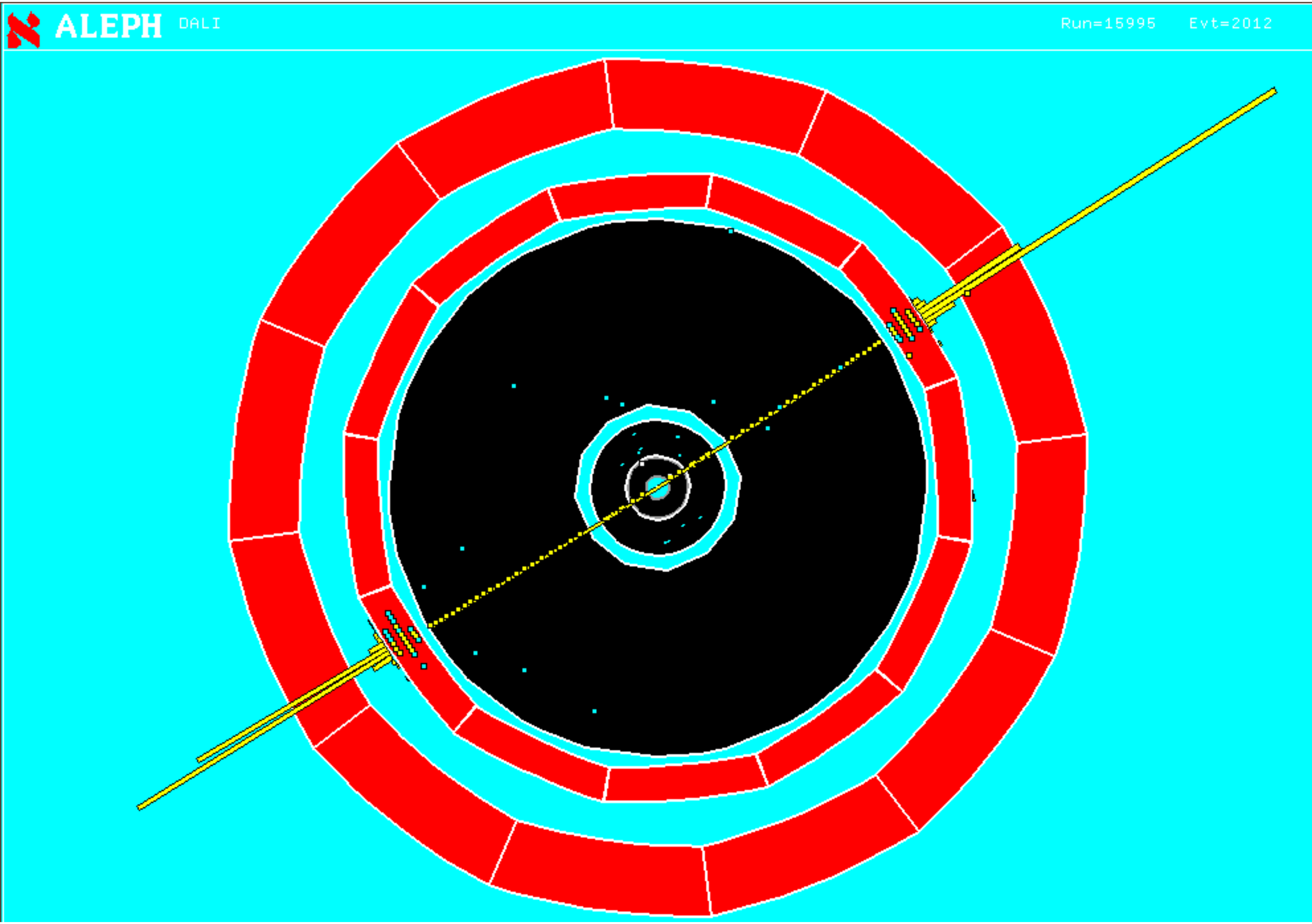
History of Colliders

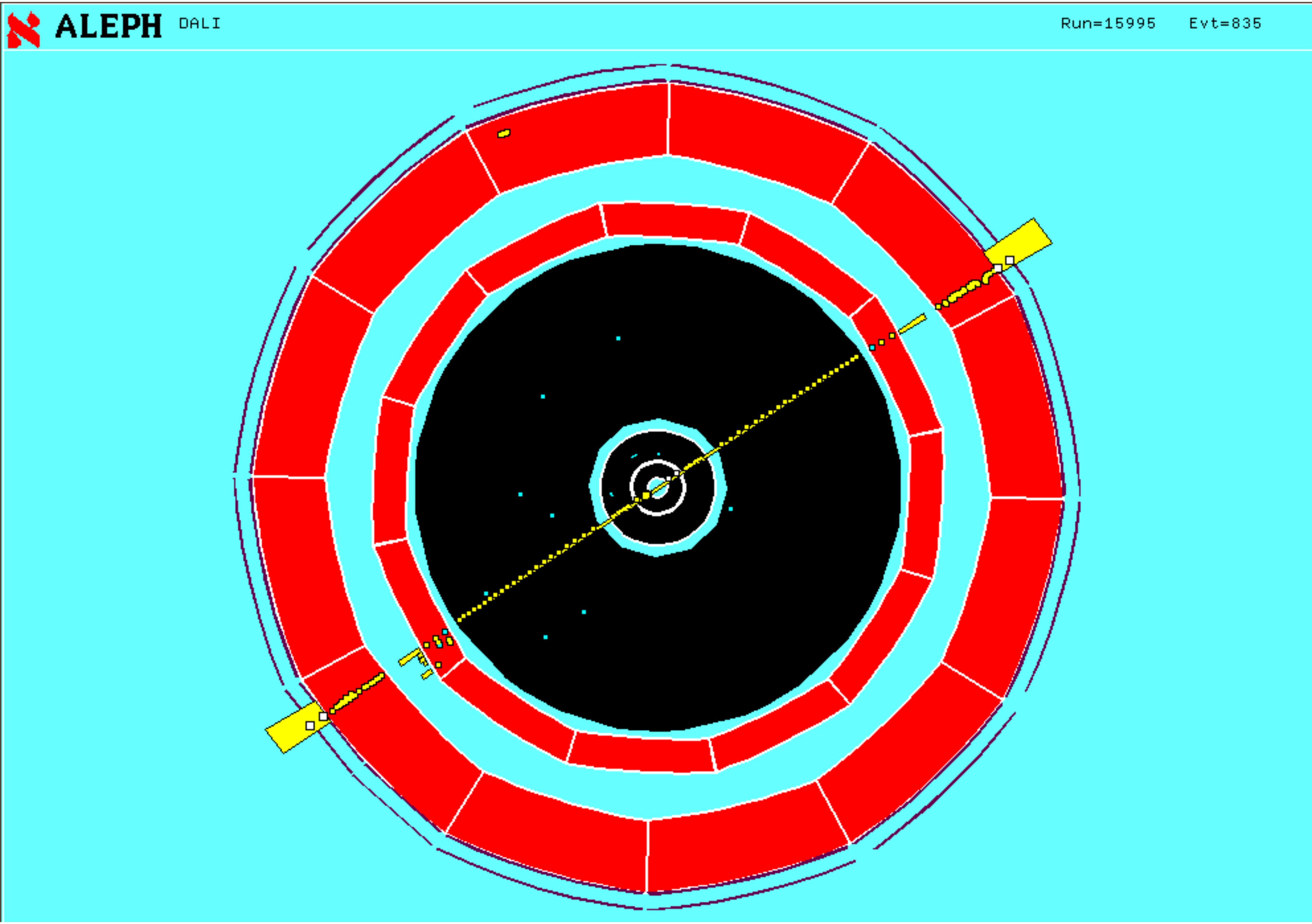
1. precision measurements of neutral current (*i.e.* polarized *e*+*d*) predicted m_W, m_Z
2. UA1/UA2 discovered *W*/*Z* particles
3. LEP *nailed* the gauge sector
1. precision measurements of *W* and *Z* (*i.e.* LEP + Tevatron) predicted m_H
2. LHC discovered *a Higgs particle*
3. LC *nails* the Higgs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

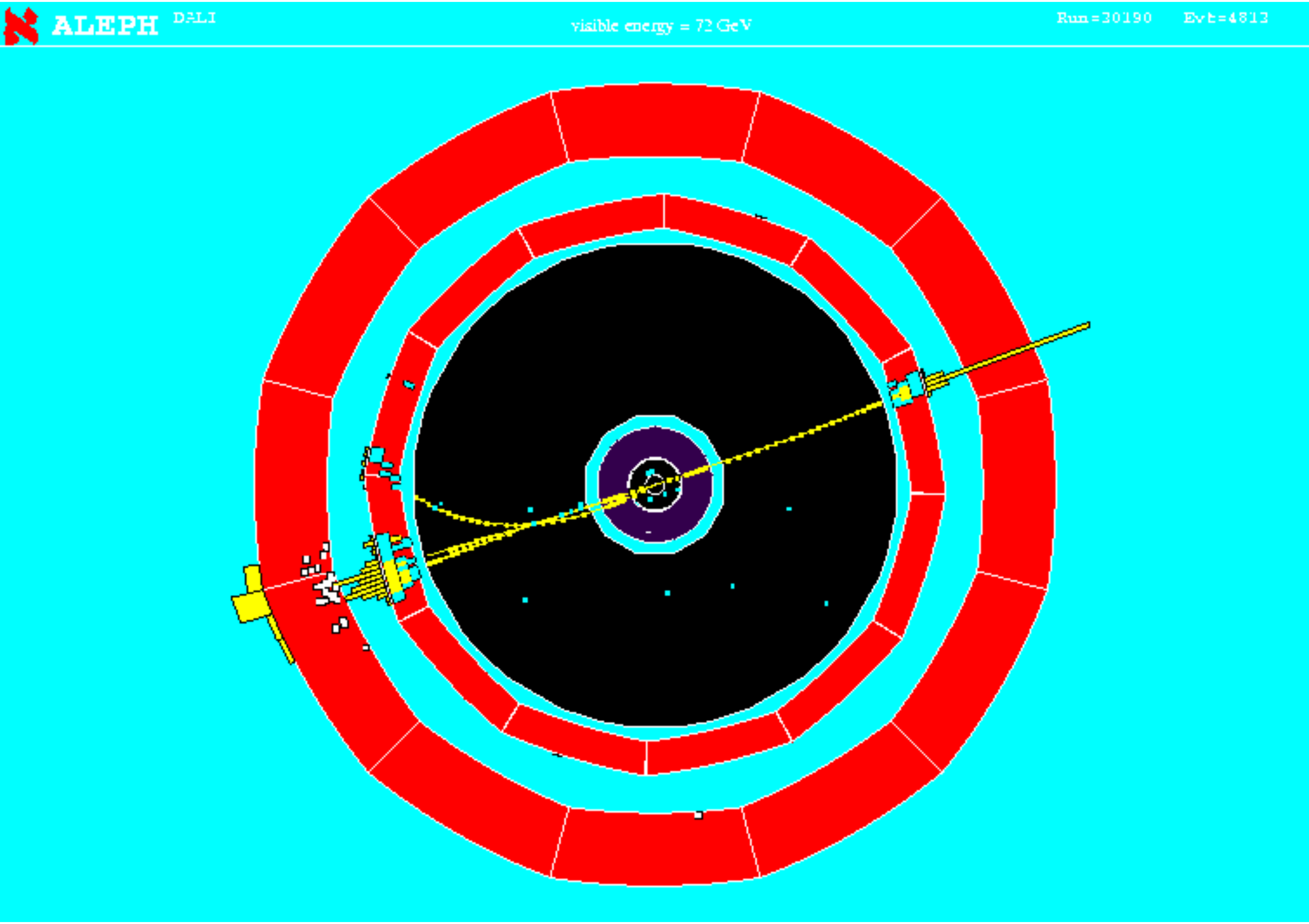

LEP
$\sqrt{s}=m_Z$

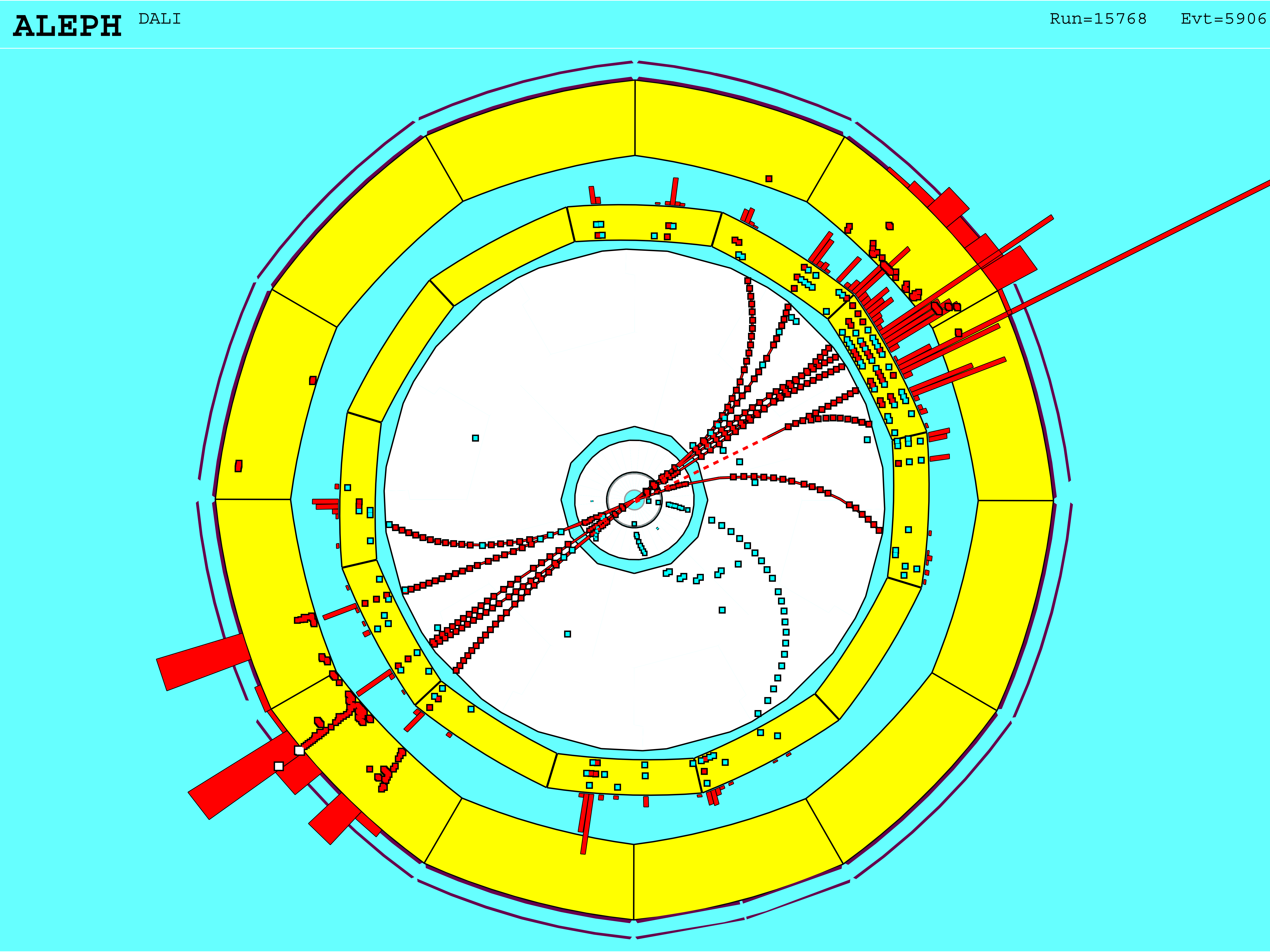


The ALEPH Detector


ALEPH
DALI
Run=15995
Evt=2012

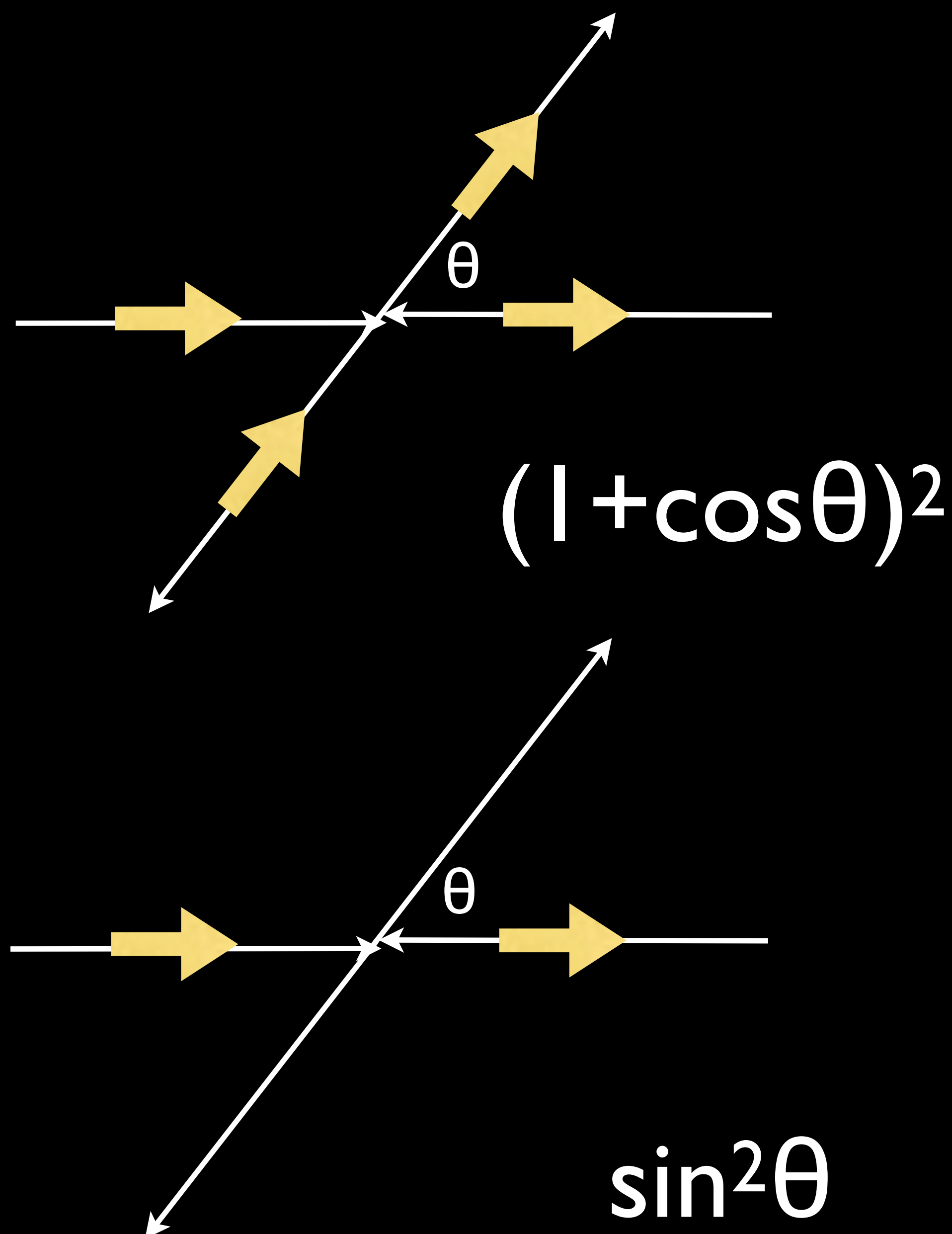

ALEPH
DALI
Run=15995
Evt=835

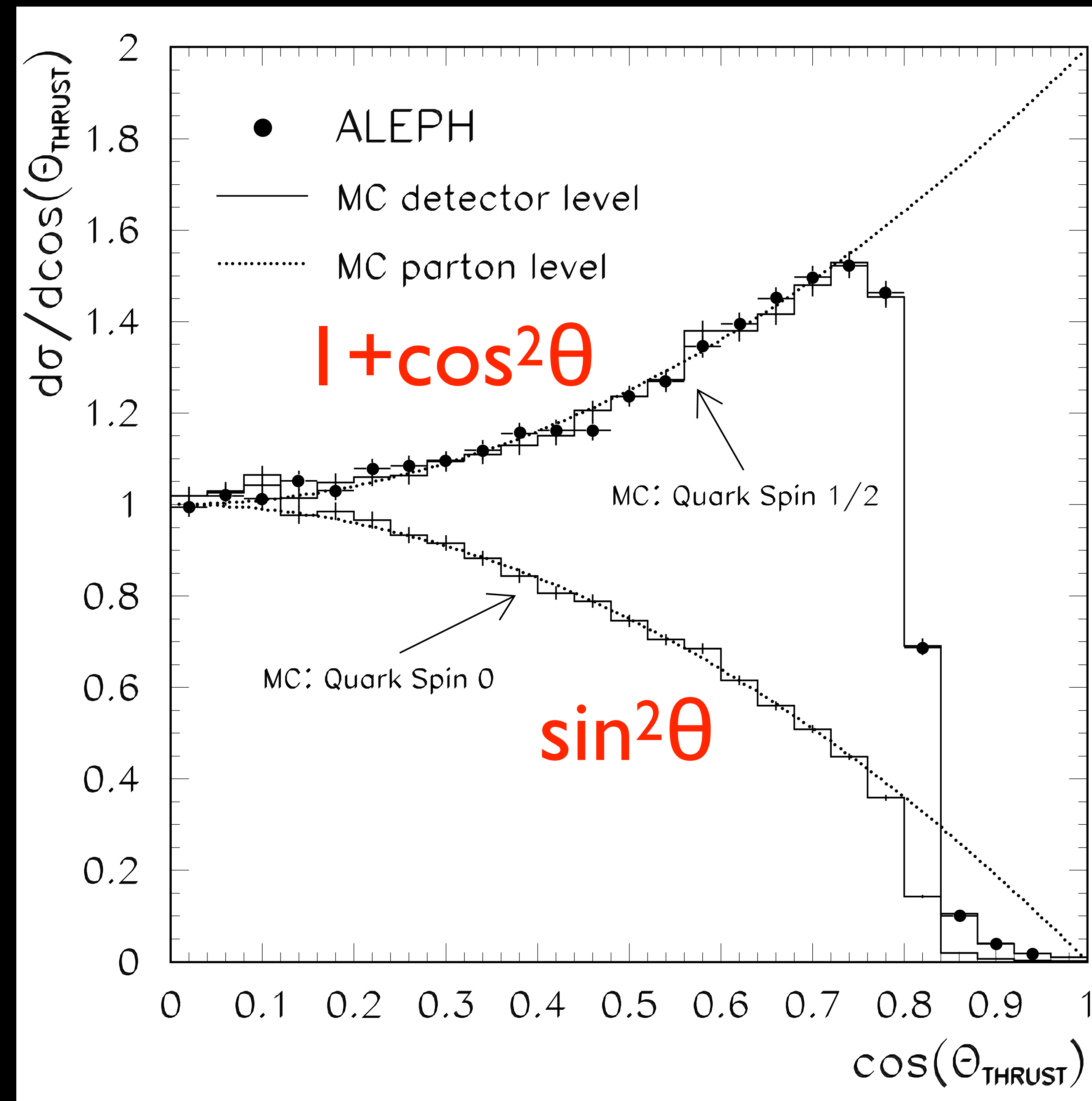

ALEPH
DALI
visible energy = 72 GeV
Run=30190
Evt=4813

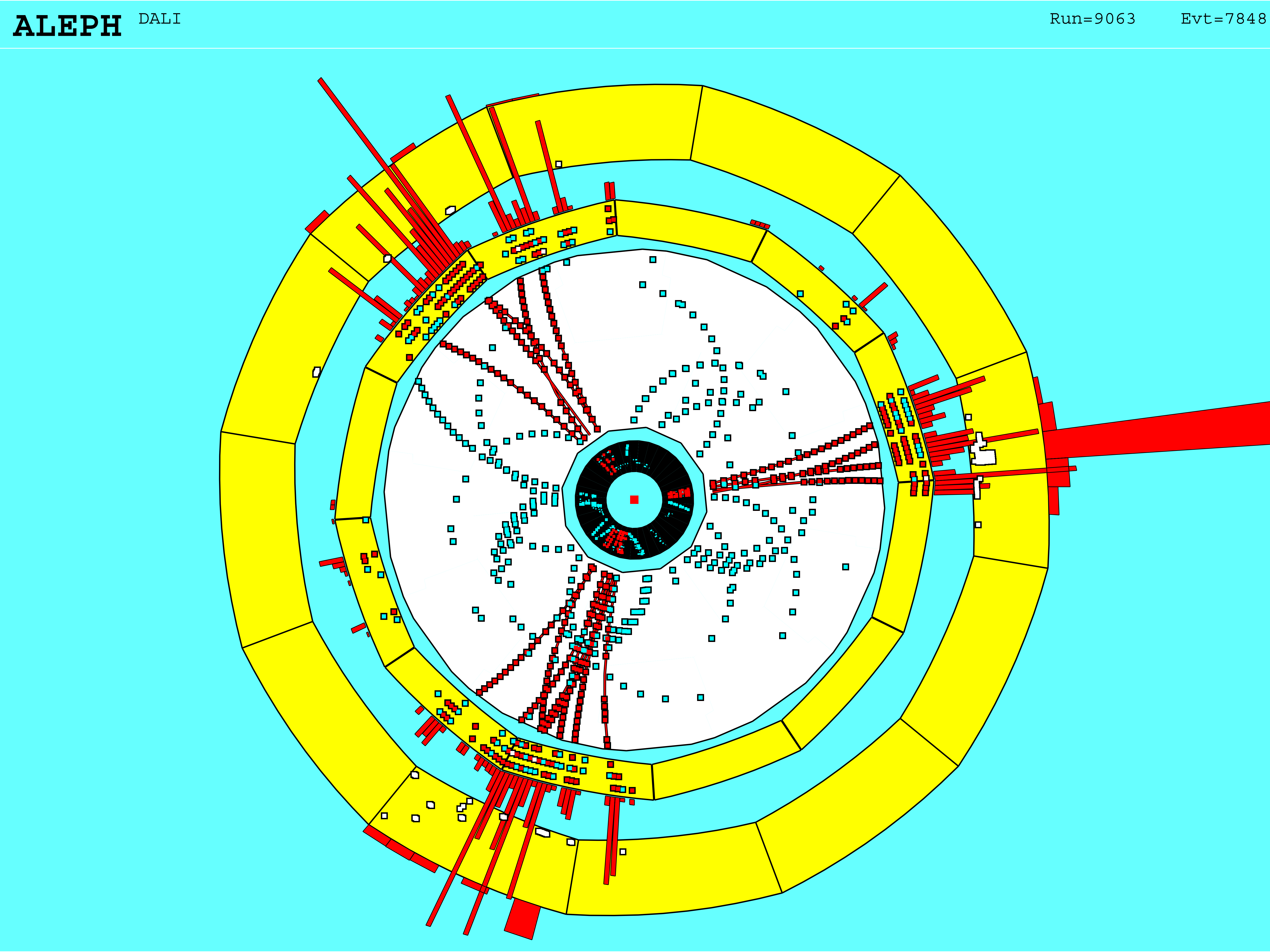

ALEPH
DALI
Run=15768
Evt=5906

"New particle" has spin 1/2

quark

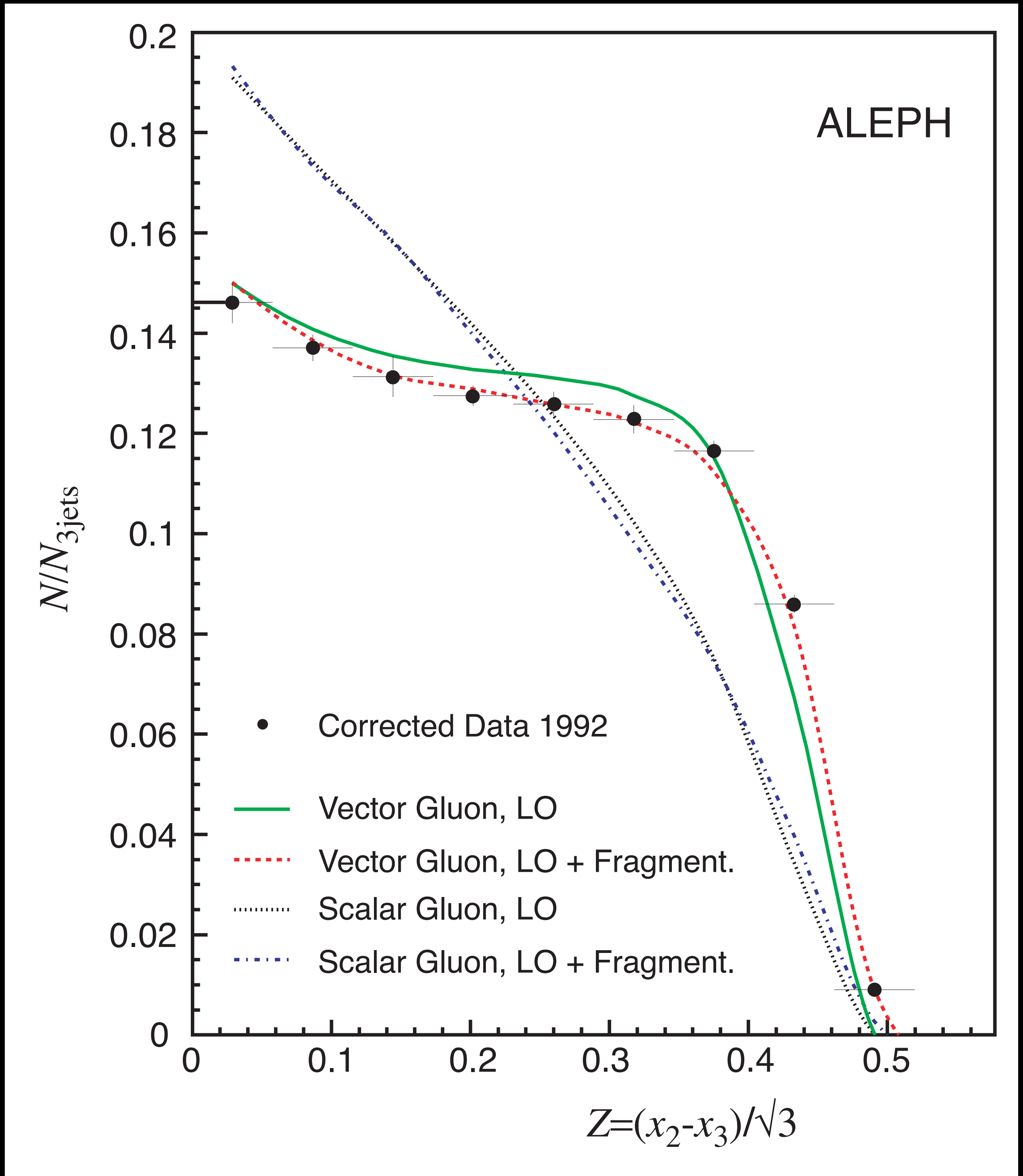


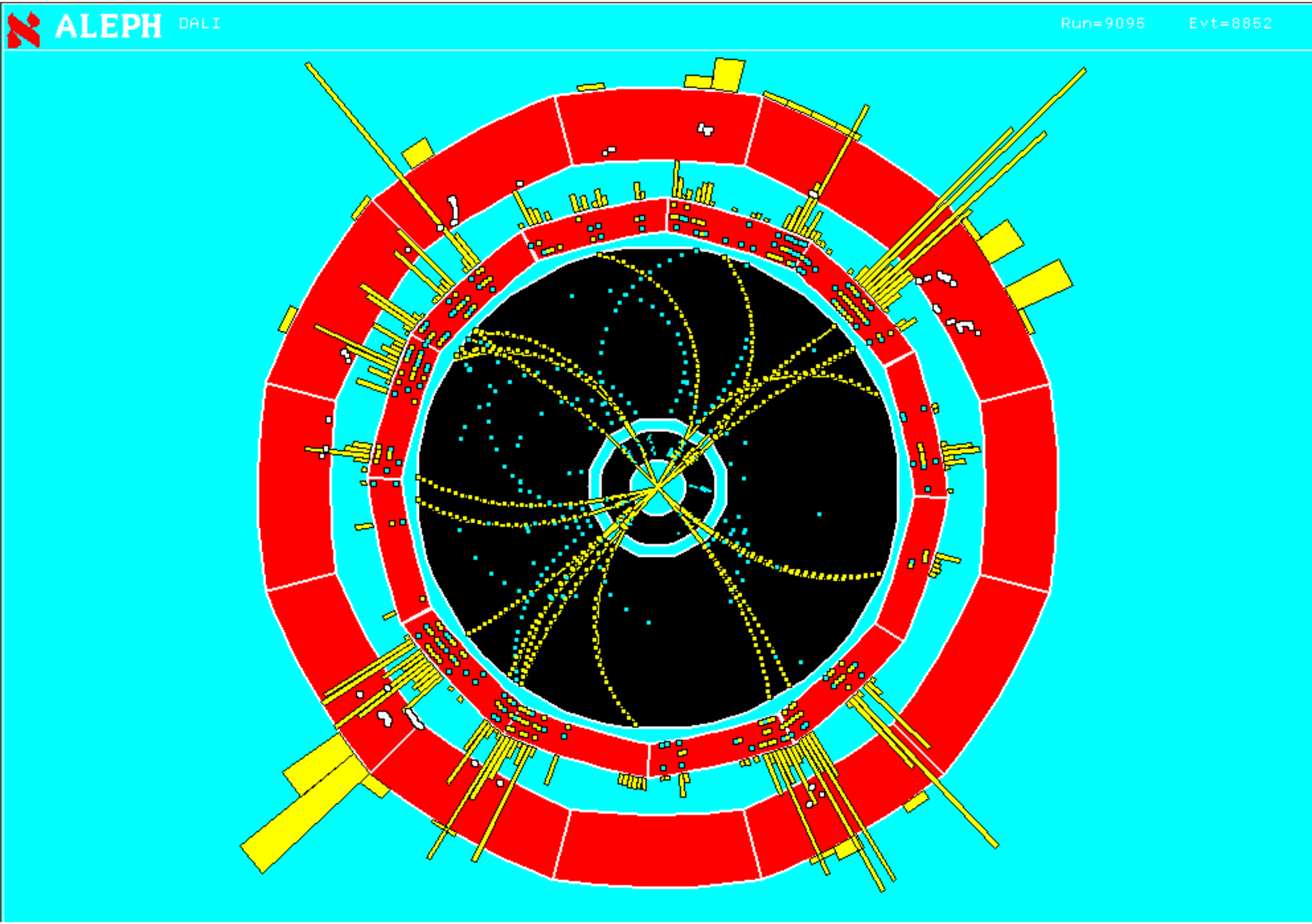


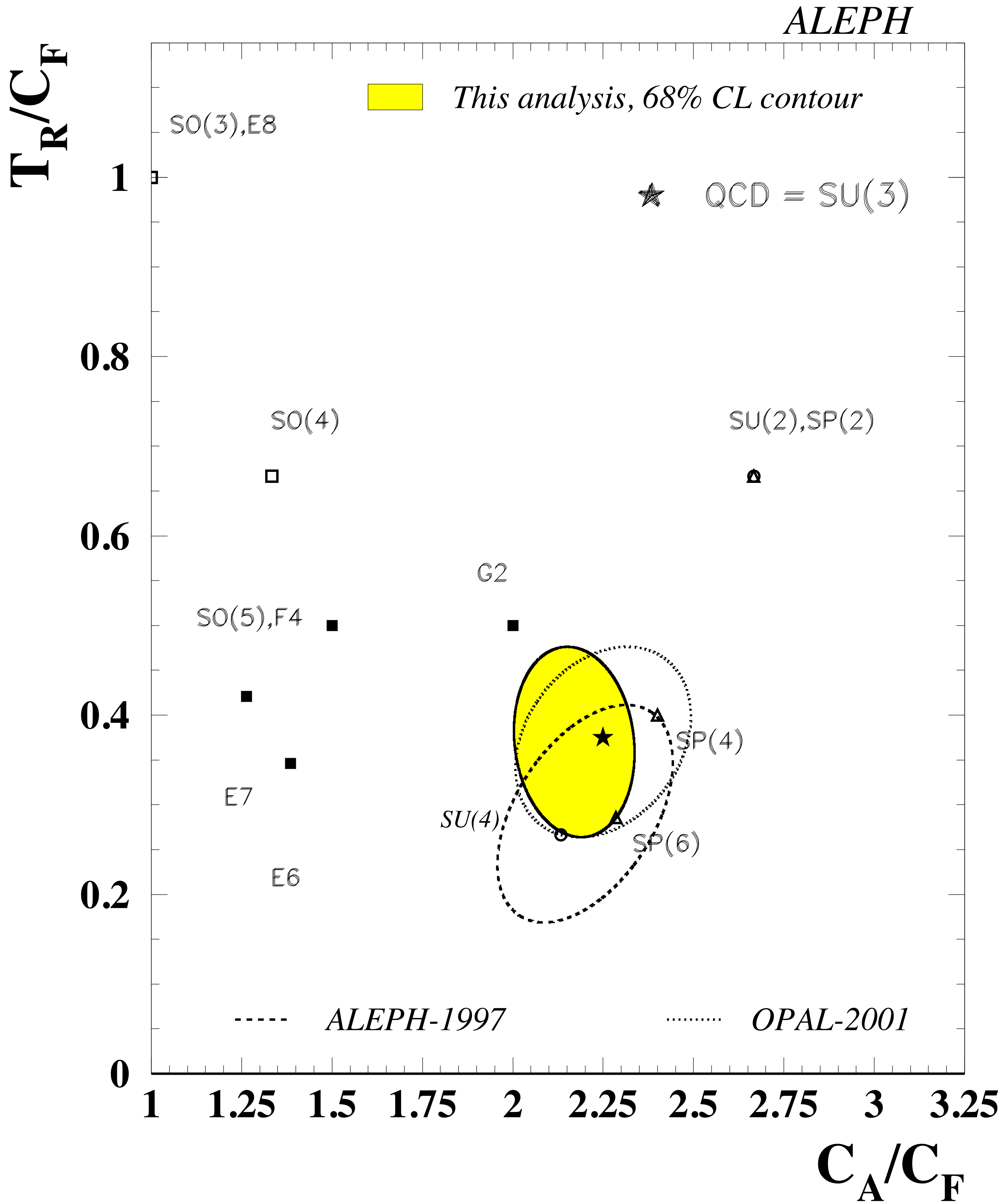

ALEPH
DALI
Run=9063
Evt=7848

“New particle” has spin 1

gluon



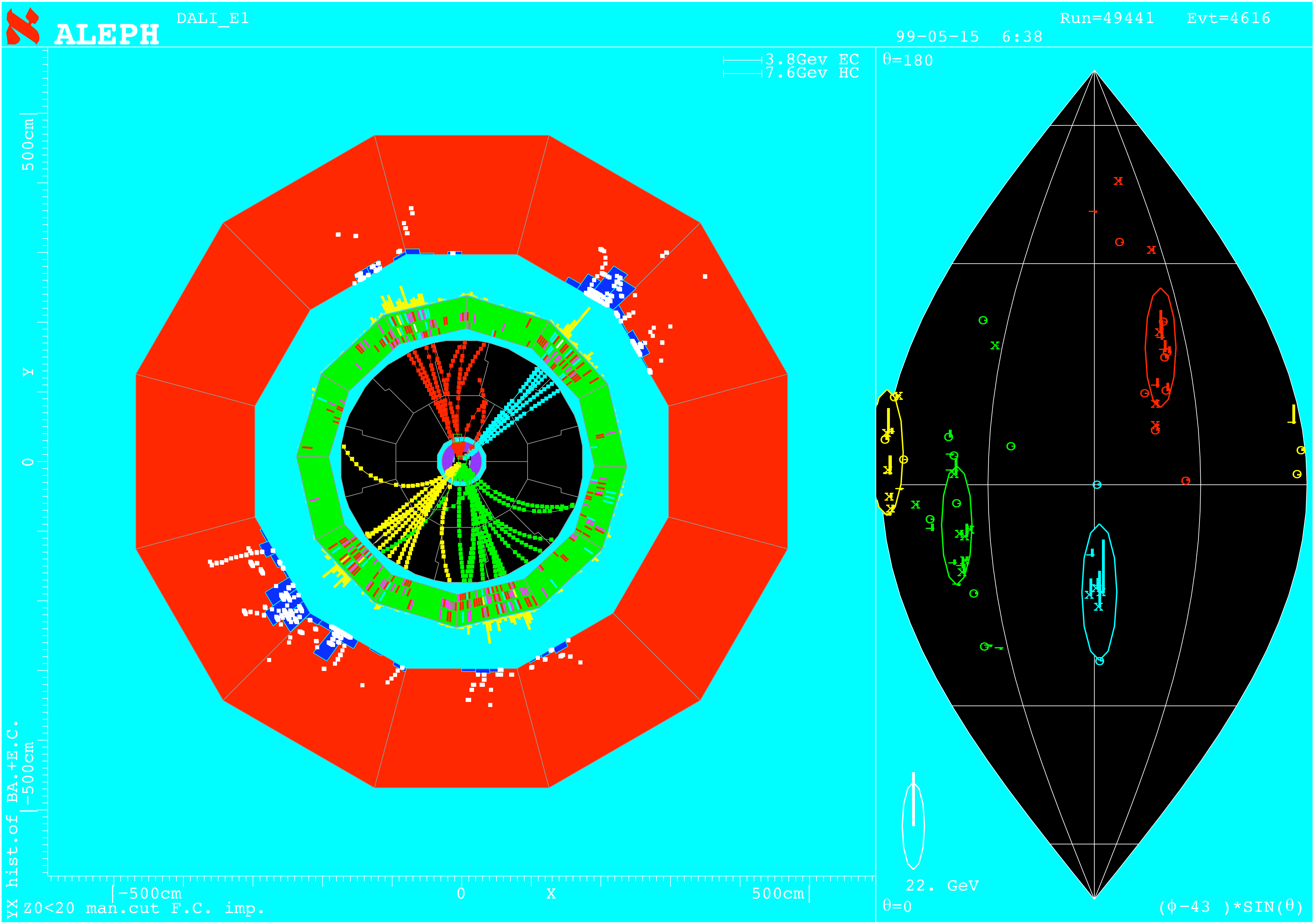


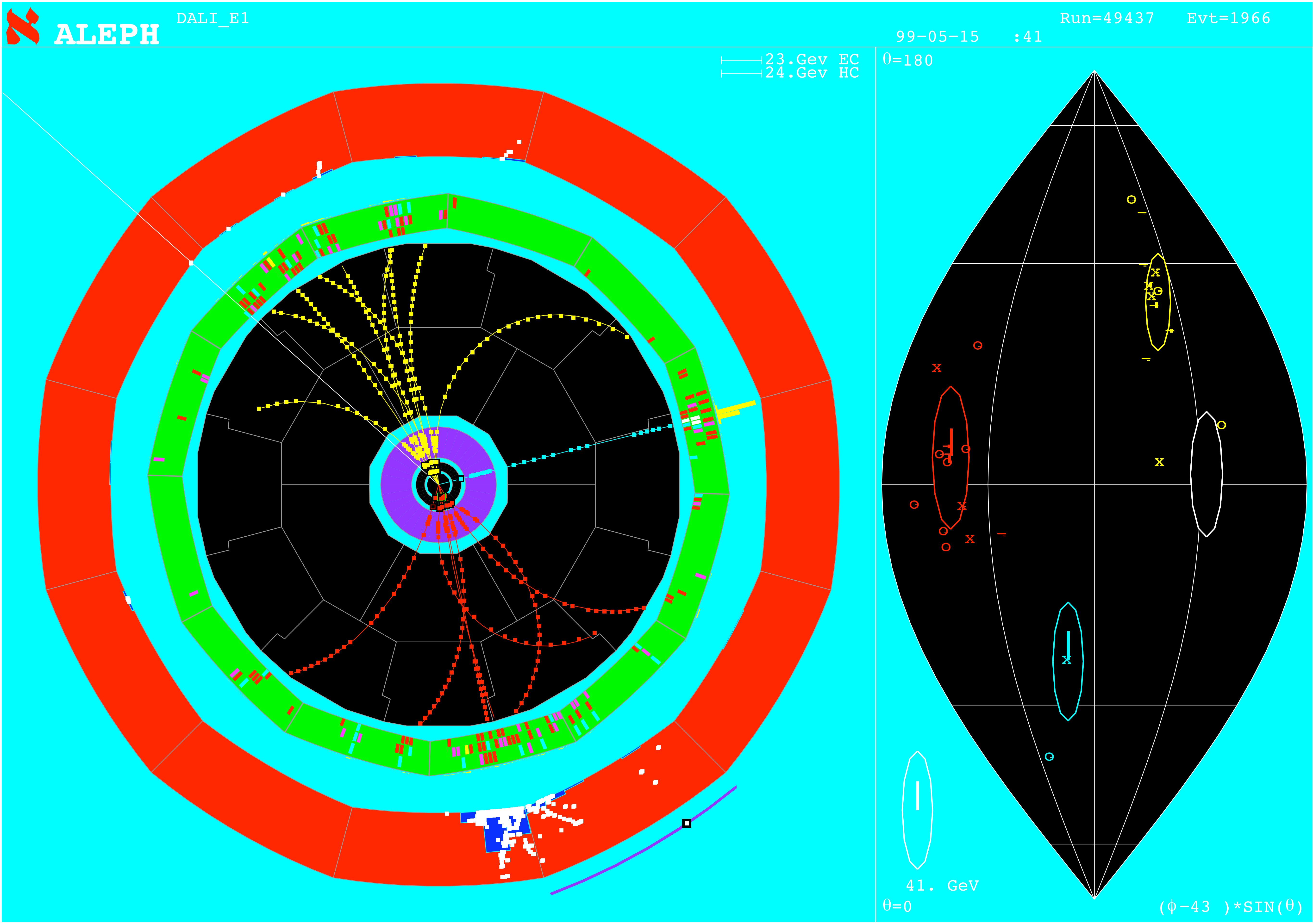


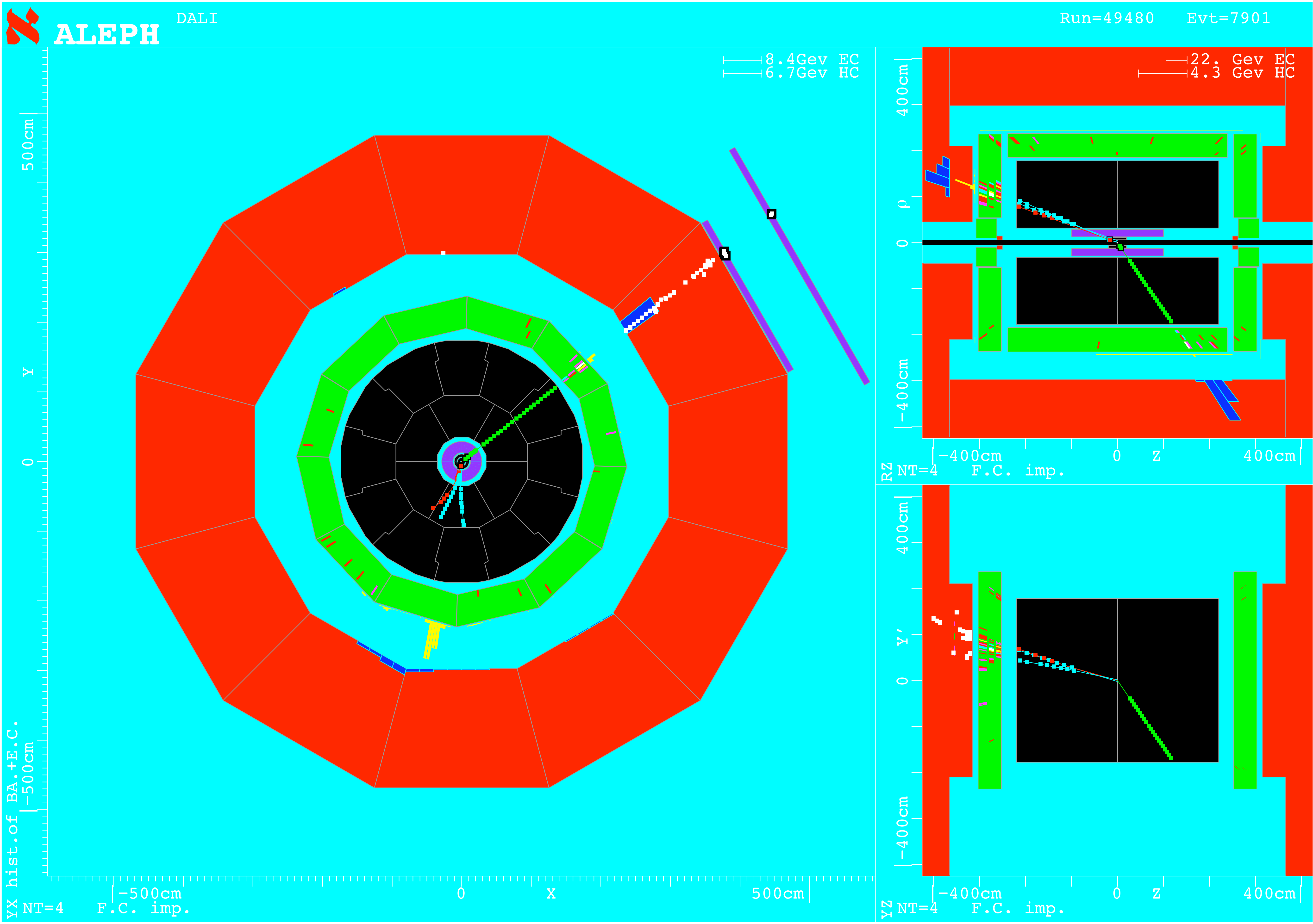
ALEPH
This analysis, 68% CL contour
QCD = SU(3)
SO(3),E8
SO(4)
SU(2),SP(2)
G2
SO(5),F4
SP(4)
E7
SU(4)
SP(6)
E6
ALEPH-1997
OPAL-2001
T_R/C_F
C_A/C_F
0
0.2
0.4
0.6
0.8
1
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
3.25

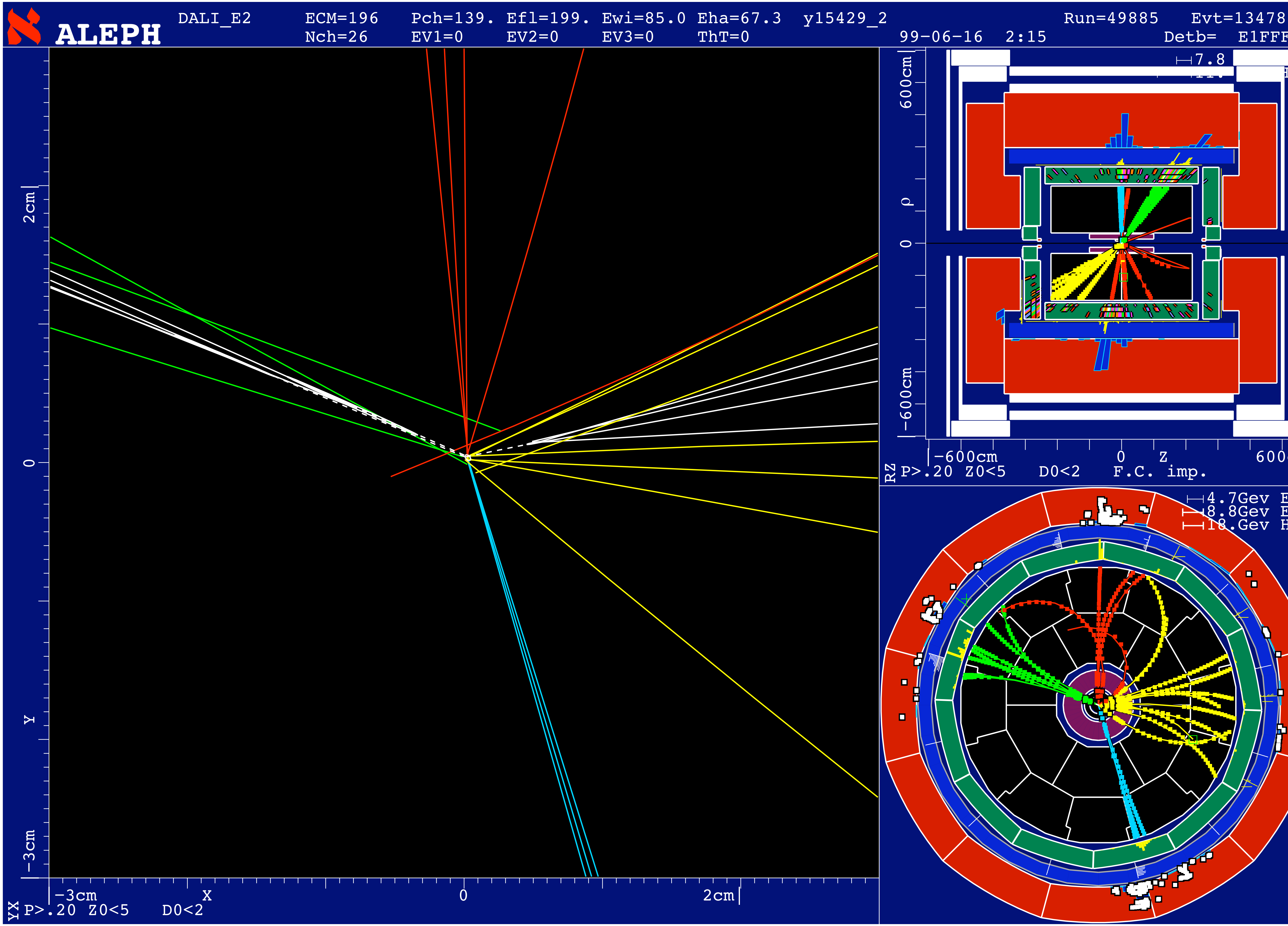
LEP-II

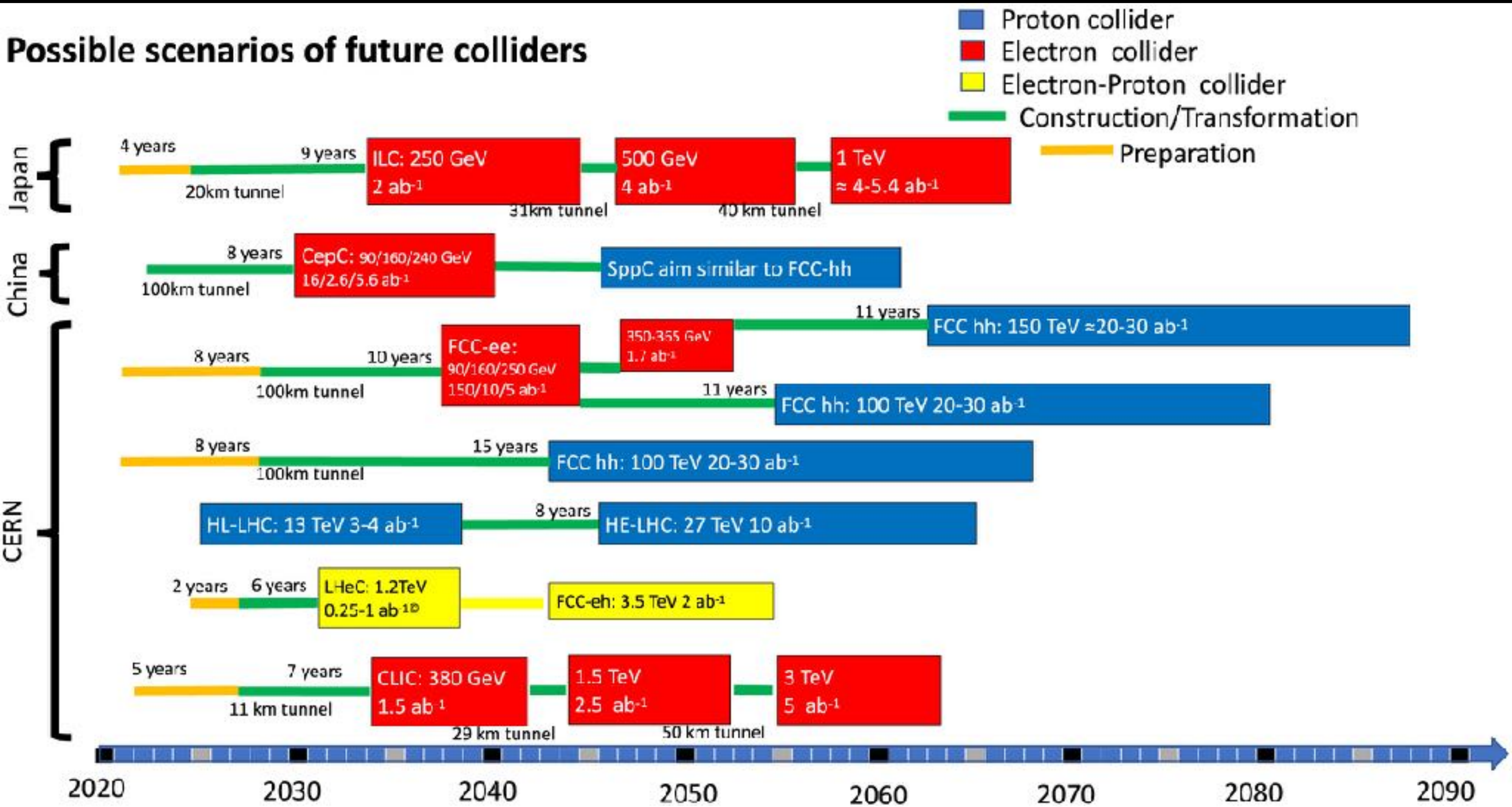
$\sqrt{s}$=200GeV


ALEPH
DALI_E1
Run=49441 Evt=4616
99-05-15 6:38
3.8Gev EC
7.6Gev HC
θ=180
500cm
Y
0
-500cm
YX hist.of BA.+E.C.
-500cm
0
X
500cm
Z0<20 man.cut F.C. imp.
22. GeV
θ=0
(φ-43)*SIN(θ)

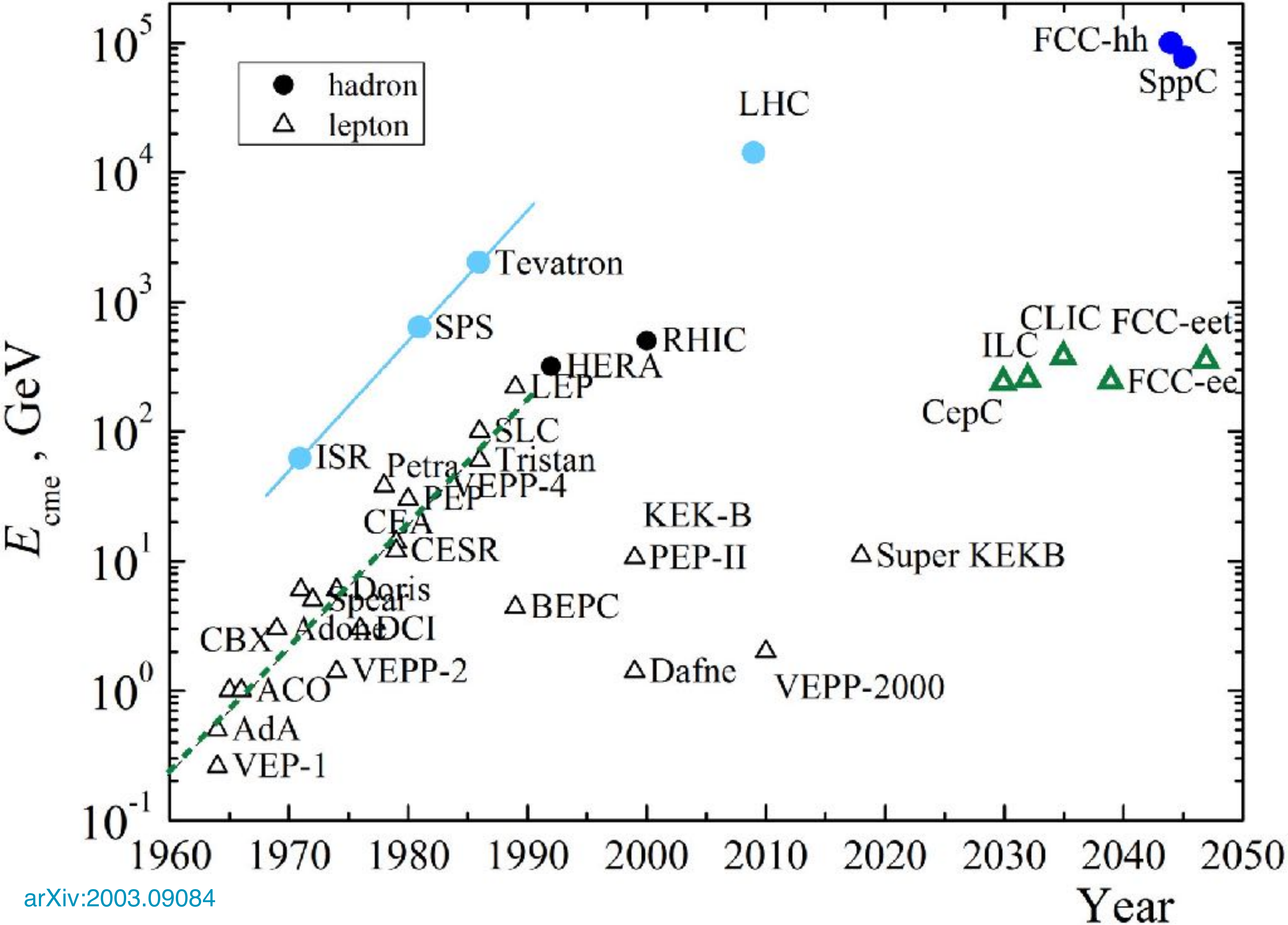

ALEPH
DALI_E1
Run=49437 Evt=1966
99-05-15 :41
23.Gev EC
24.Gev HC
θ=180
41. GeV
θ=0
(ϕ-43)*SIN(θ)


ALEPH
DALI
Run=49480 Evt=7901
8.4Gev EC
6.7Gev HC
500cm
Y
0
-500cm
YX hist.of BA.+E.C.
NT=4 F.C. imp.
-500cm
0
X
500cm
22. Gev EC
4.3 Gev HC
400cm
ρ
0
-400cm
-400cm
0
Z
400cm
RZ NT=4 F.C. imp.
400cm
Y'
0
-400cm
-400cm
0
Z
400cm
YZ NT=4 F.C. imp.


ALEPH
DALI_E2
ECM=196
Nch=26
Pch=139.
EV1=0
Efl=199.
EV2=0
Ewi=85.0
EV3=0
Eha=67.3
ThT=0
y15429_2
99-06-16 2:15
Run=49885
Evt=13478
Detb= E1FFF
2cm
0
Y
-3cm
-3cm
X
0
2cm
YX P>.20 Z0<5 D0<2
600cm
ρ
0
-600cm
7.8
-600cm
0
Z
600
RZ P>.20 Z0<5 D0<2 F.C. imp.
4.7Gev
8.8Gev
18.Gev



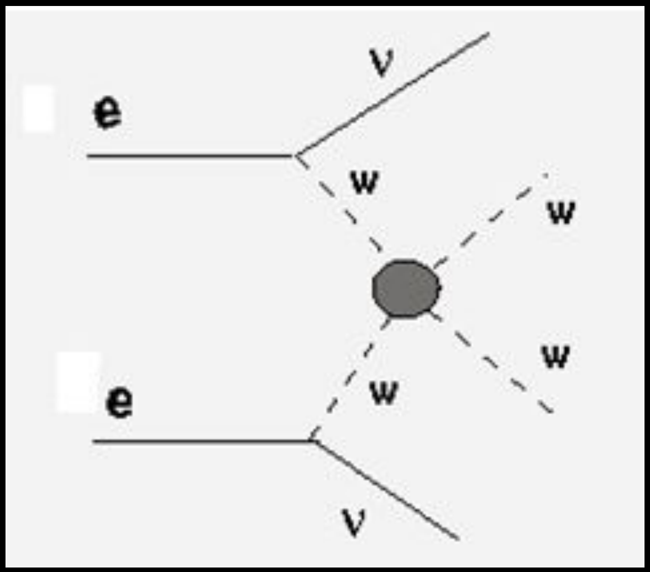
U. Bassler, CERN Council Meeting, 2019

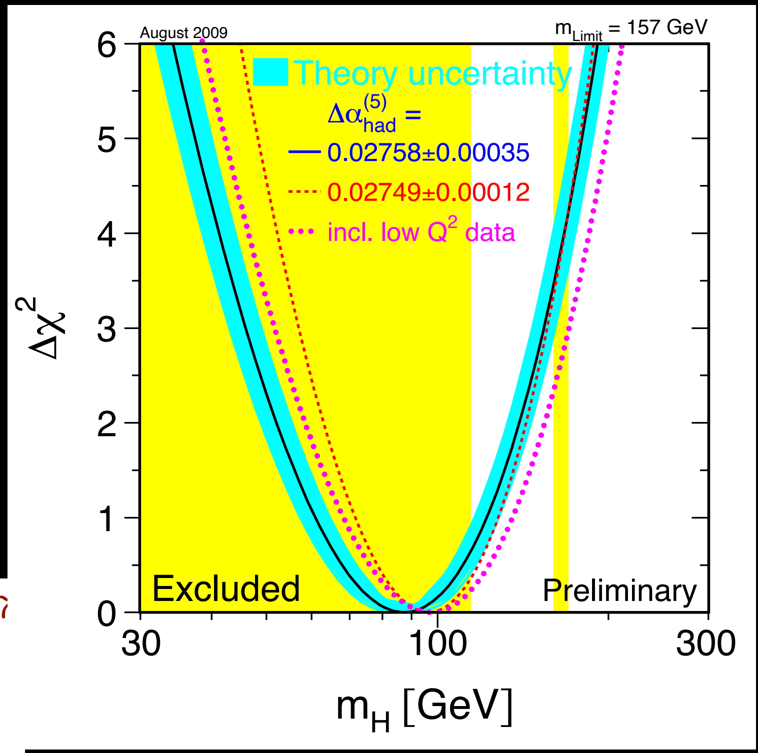


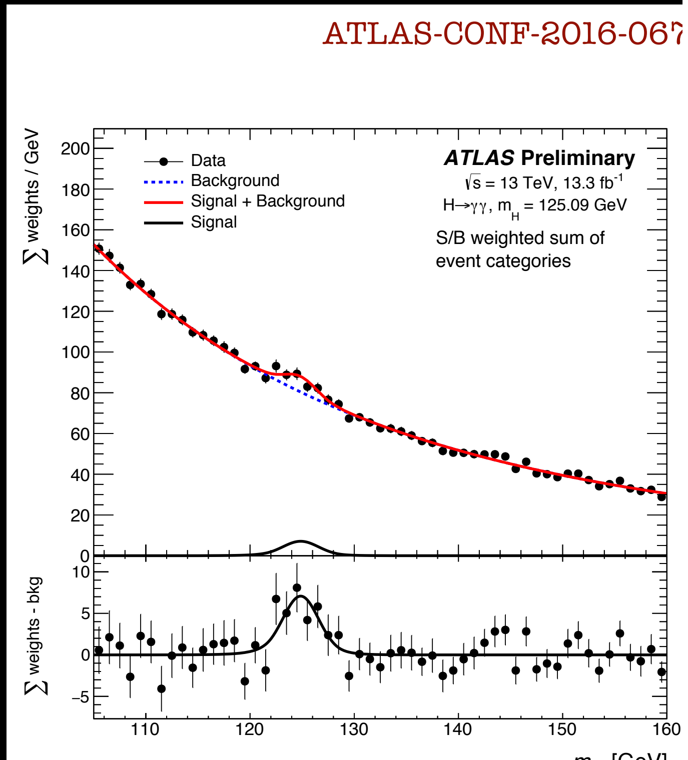
arXiv:2003.09084

Why 250 GeV?

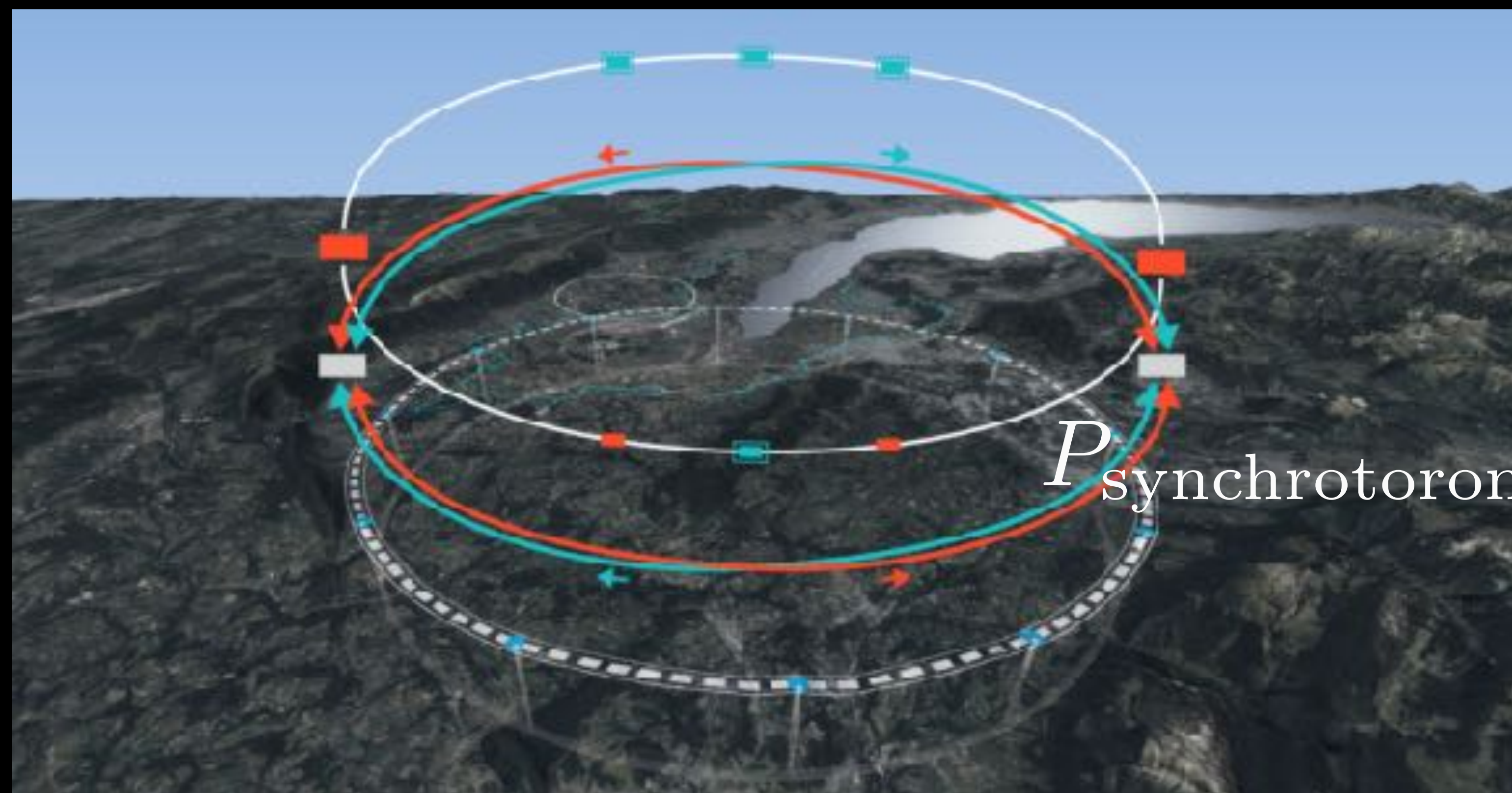
- 1980's: 1.5 TeV minimum
  - we didn't know whether EWSB was strongly or weakly coupled
- 2000's: 500 GeV
  - LEP told us it is likely to have a Higgs boson <250 GeV
- 2012: 250 GeV
  - m_H=125 GeV, *ZH* production possible at 250 GeV
  - 350 GeV also allows for t tbar production



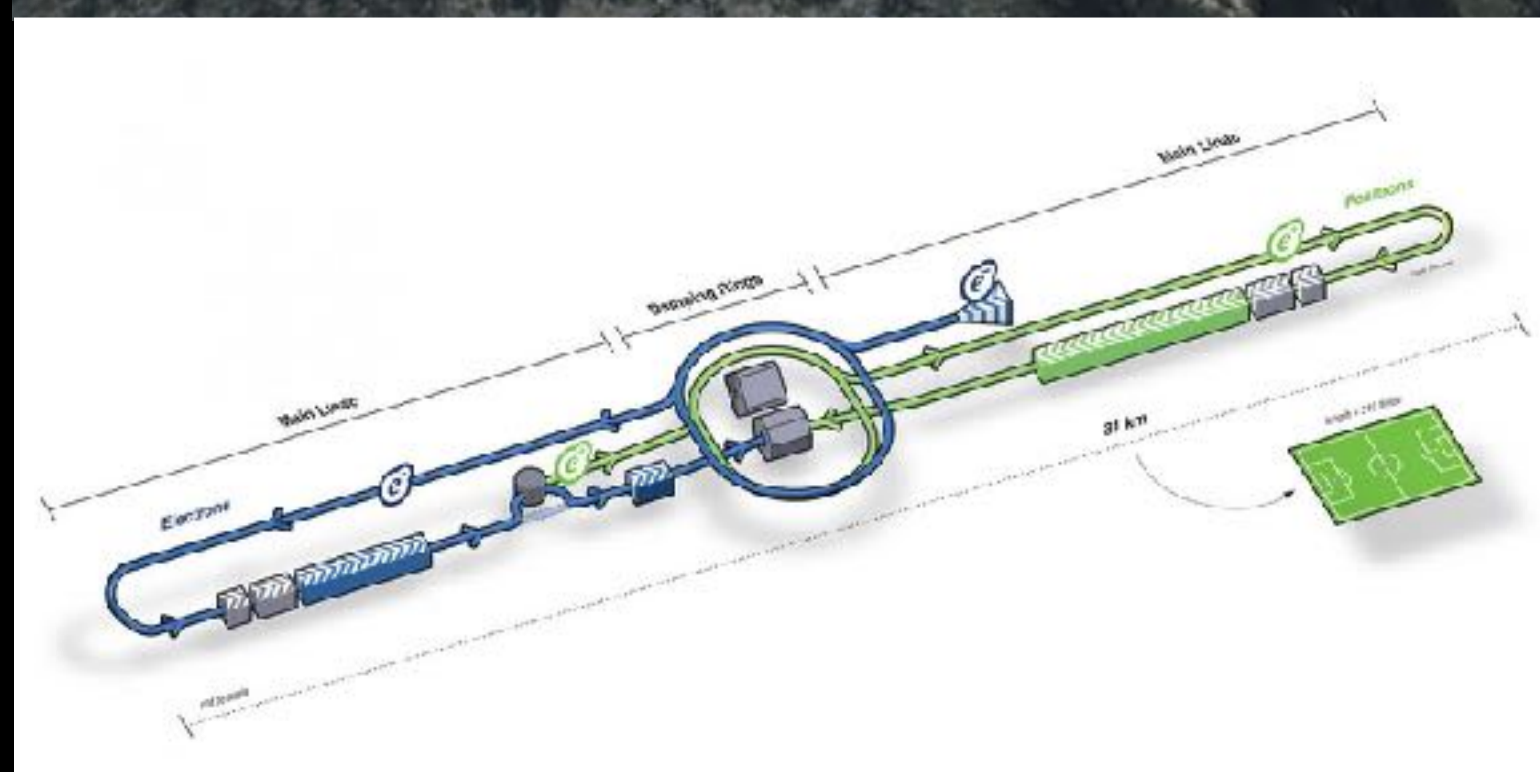




Future of colliders



$$P_{\text{synchrotoron}} \propto \frac{1}{R^2}\left(\frac{E}{m}\right)^4$$

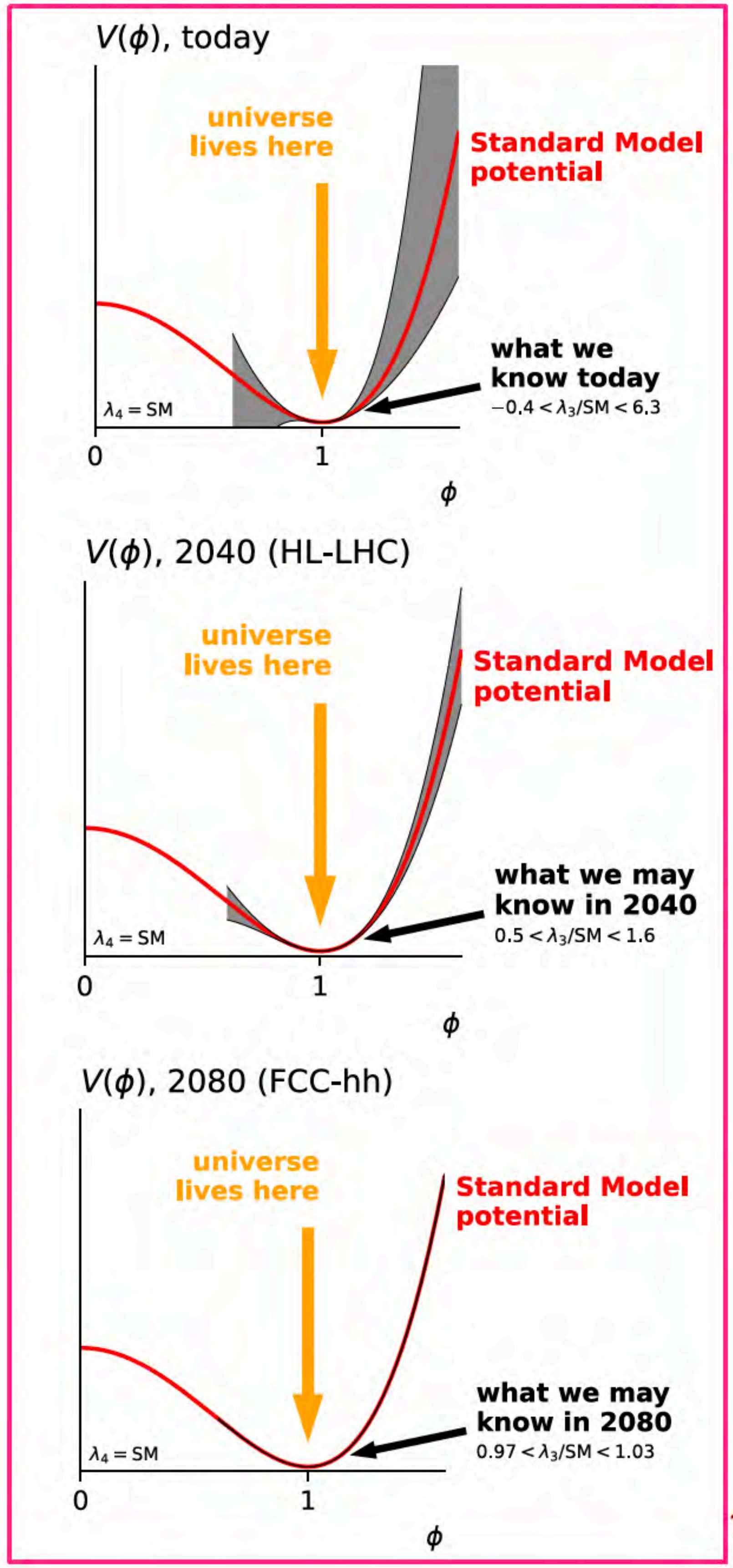


Towards 10 TeV pCM

- Ultimate direct discovery reach of TeV scale phenomena
- Possible with hadron (FCC-hh @ 100 TeV) or muon colliders, but R&D is needed

- Higgs physics:
  - Probe the electroweak phase transition; Higgs self coupling measurements to 5% precision

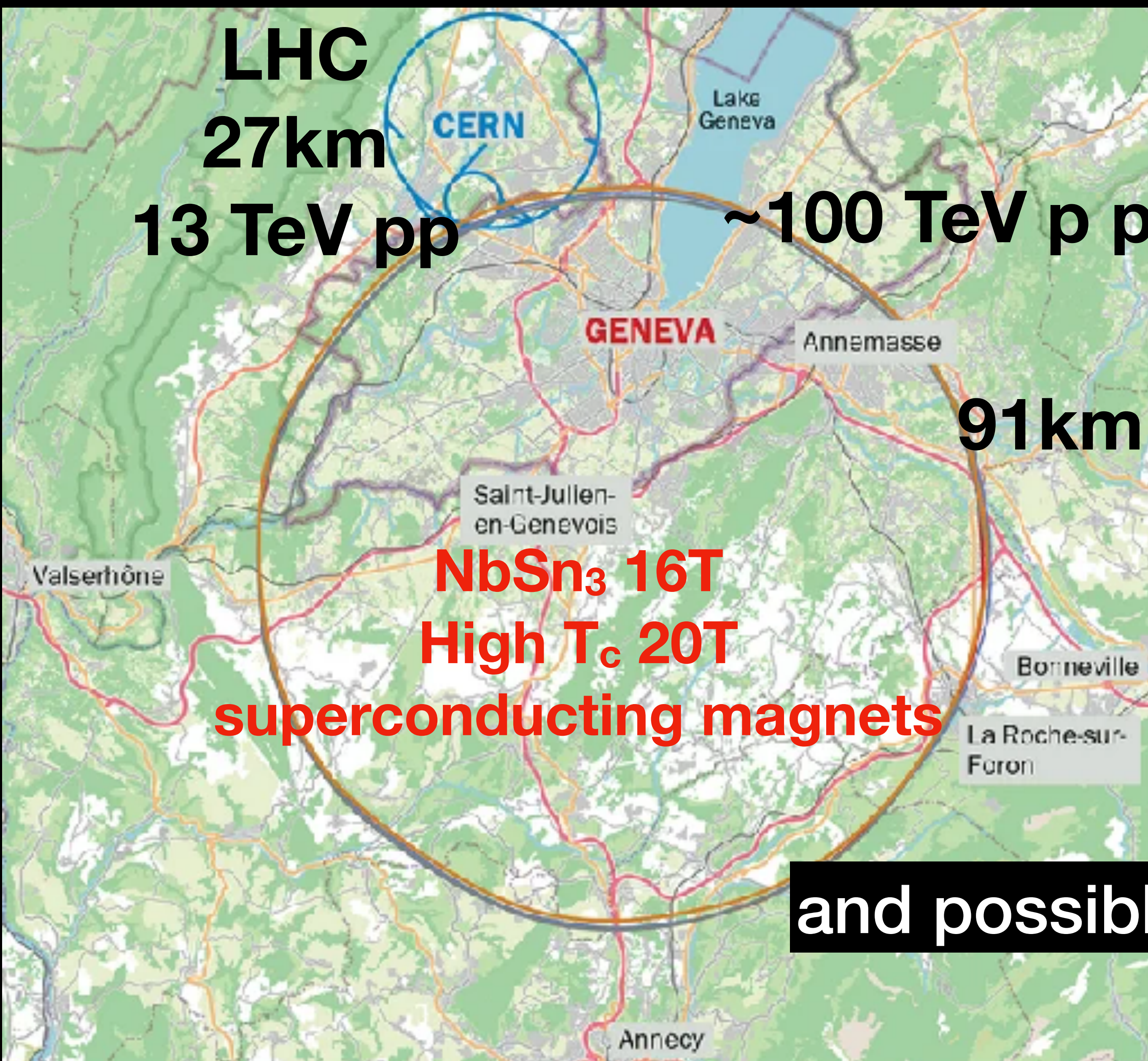
- Direct beyond the SM searches:
  - Direct discovery of the particles responsible for any deviations observed in Higgs factory
  - Dark matter: “reach the thermal WIMP target for minimal WIMP candidates”



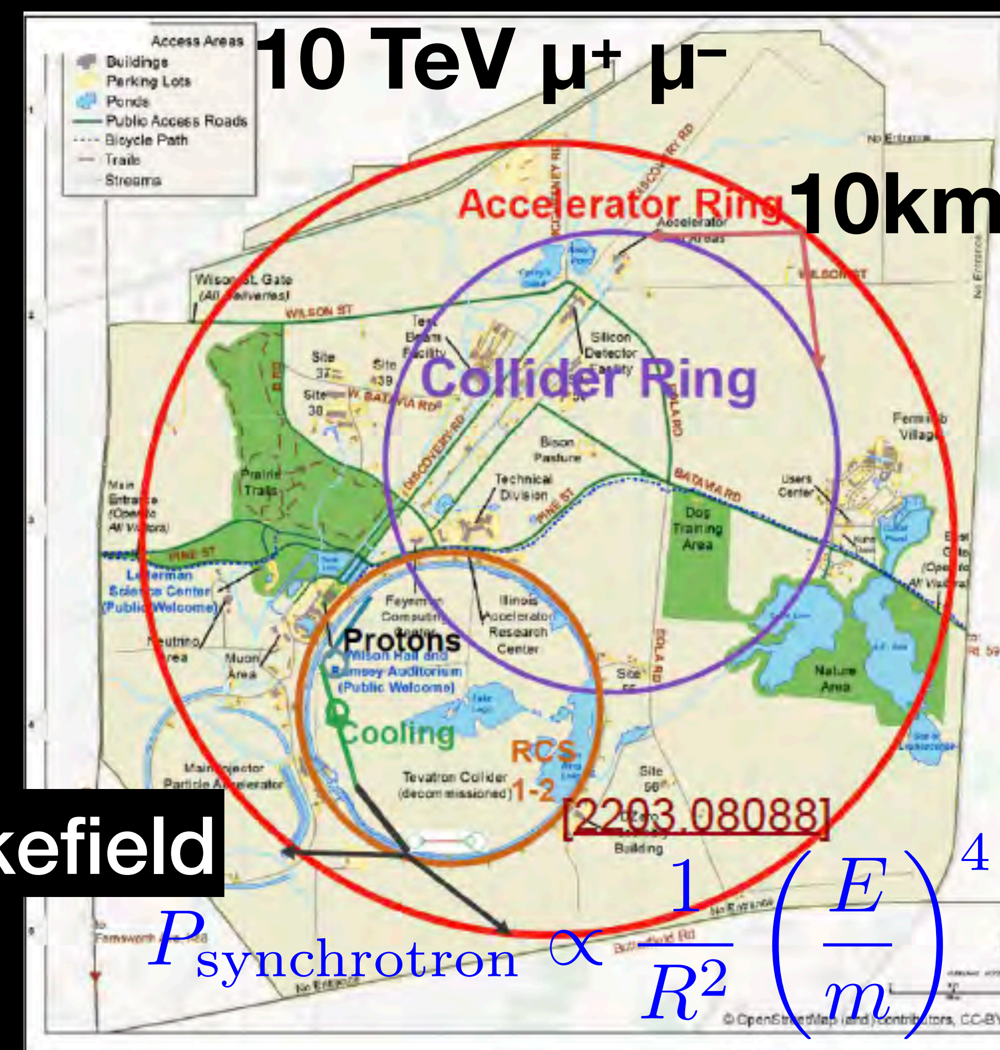
New enabling technologies

5% measurement of Higgs self coupling

Energy 10xLHC
Size 1/3 x LHC
Fits inside the Fermilab site



and possibly wakefield



Muon production and cooling

素粒子物理とコライダー

Hitoshi Murayama (Berkeley, Kavli IPMU Tokyo)

Pre-LCWS2024 School July 7, 2024

将来電子・陽電子コライダーの物理と技術

東京大学 THE UNIVERSITY OF TOKYO

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

KAVLI IPMU