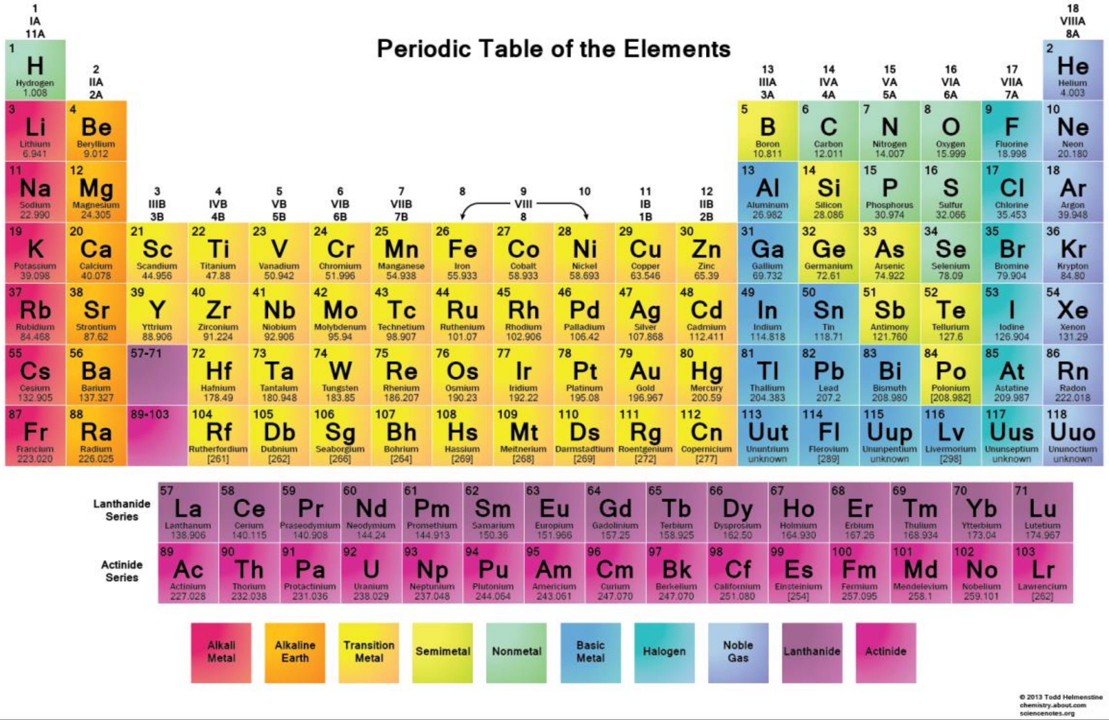
À la chasse de la
MATIÈRE NOIRE
au grand collisionneur du CERN

Anna Sfyrla

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Section de physique

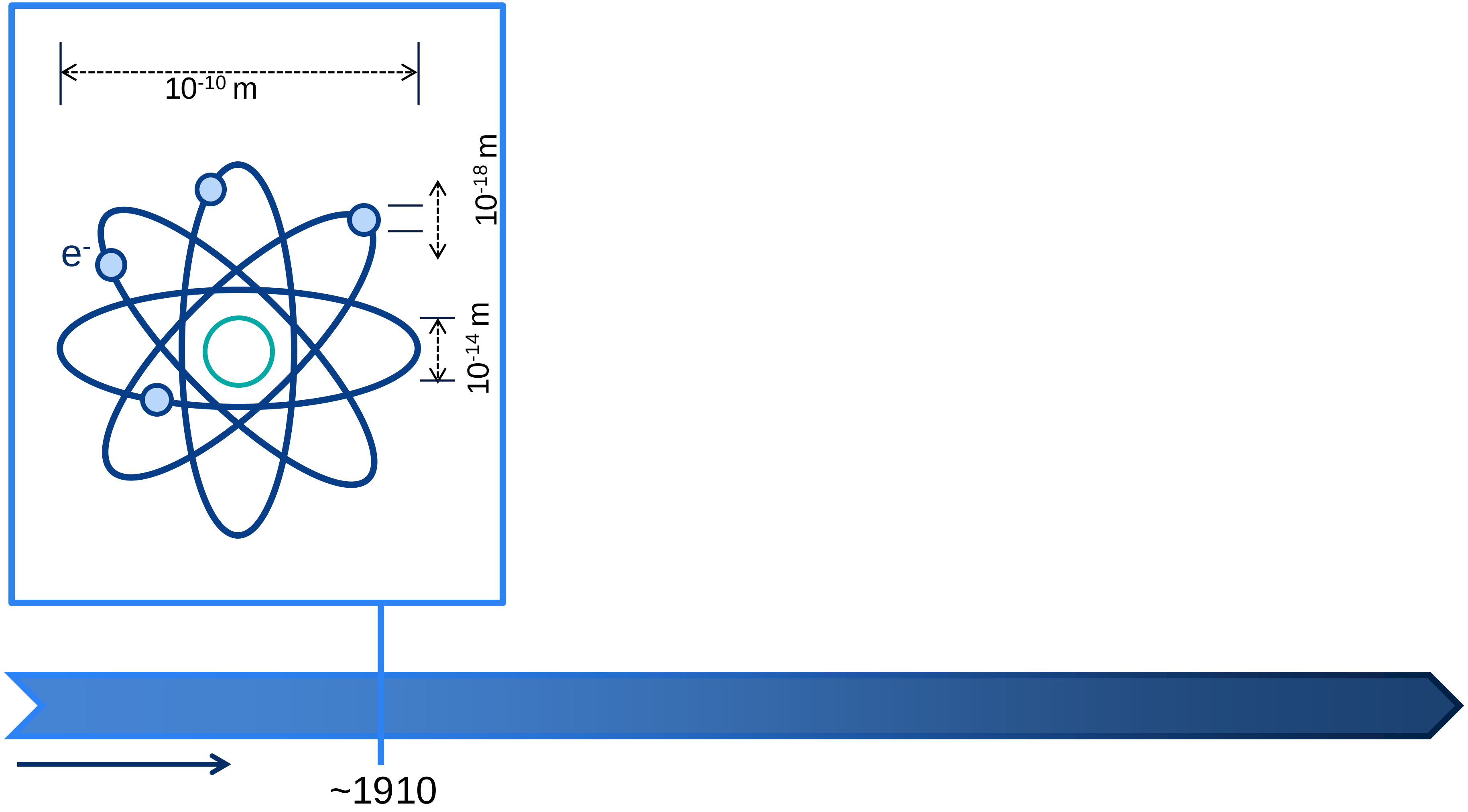
ATLAS EXPERIMENT
FASER

MATTER

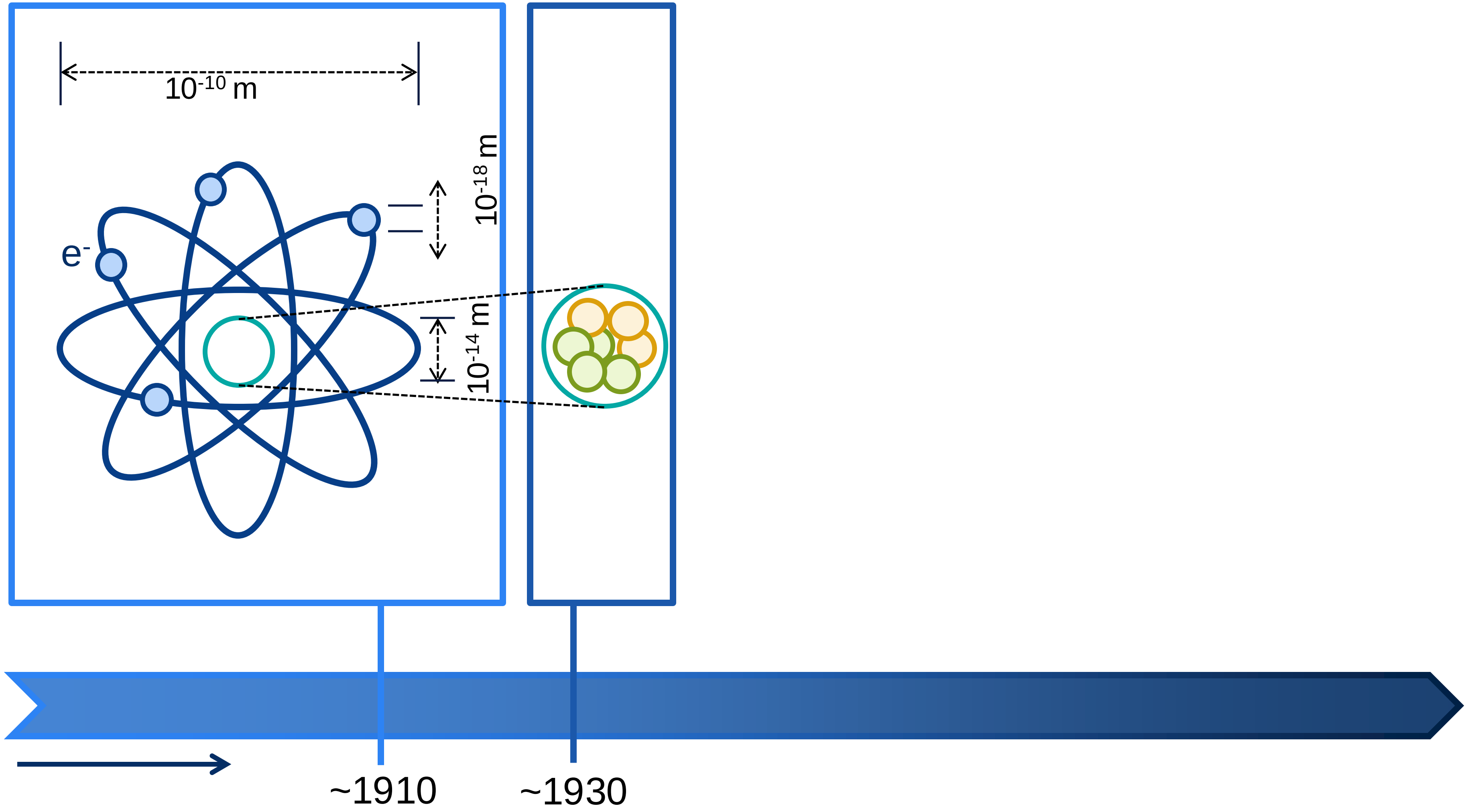


~400 BC 0 AC ~1870

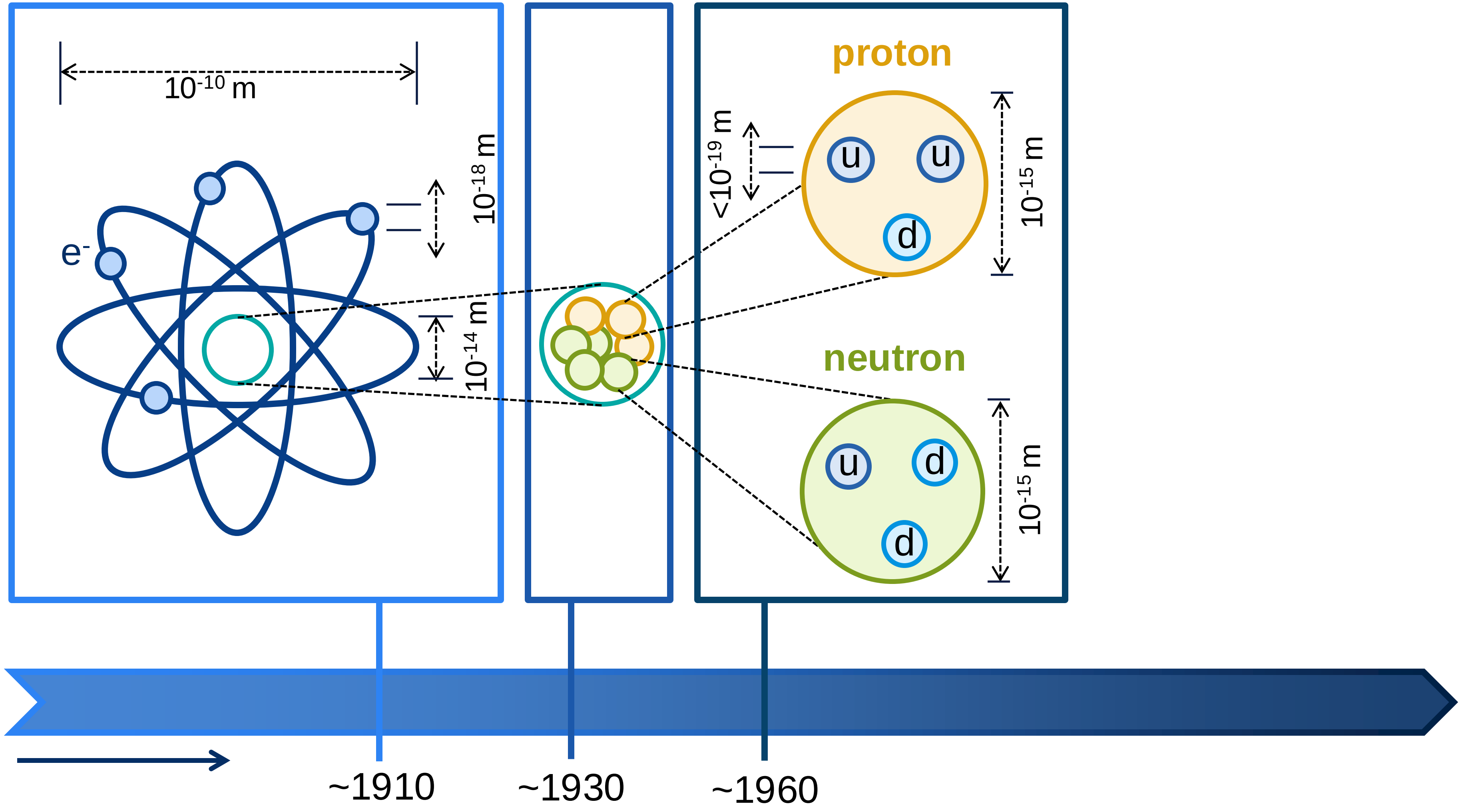
MATTER



MATTER

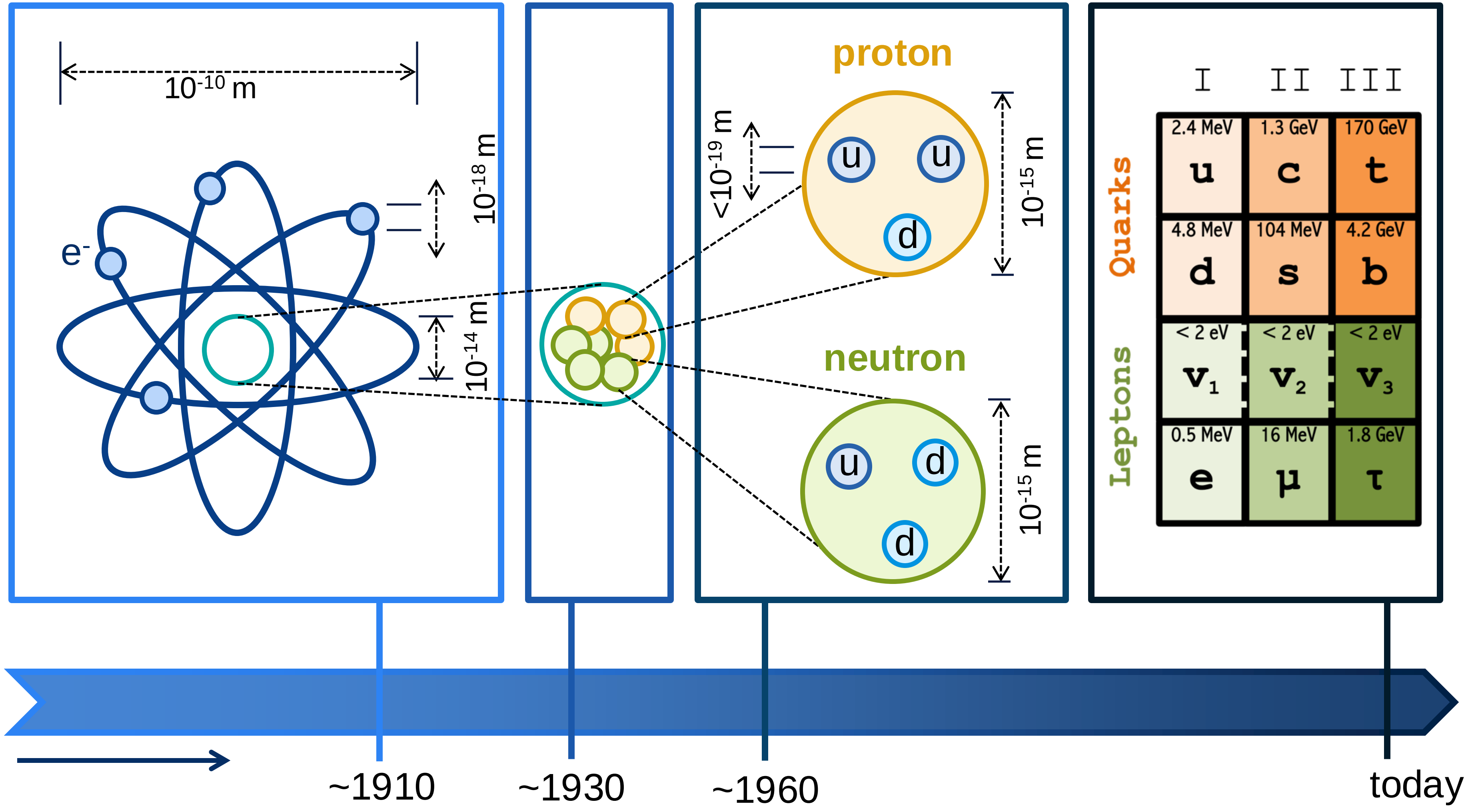


MATTER



10^-10 m
e-
10^-18 m
10^-14 m
<10^-19 m
proton
u
u
d
10^-15 m
neutron
u
d
d
10^-15 m
~1910
~1930
~1960

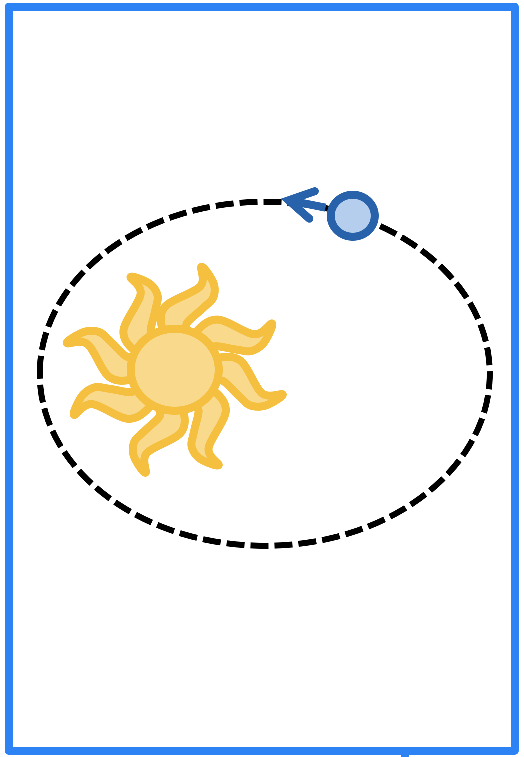
MATTER

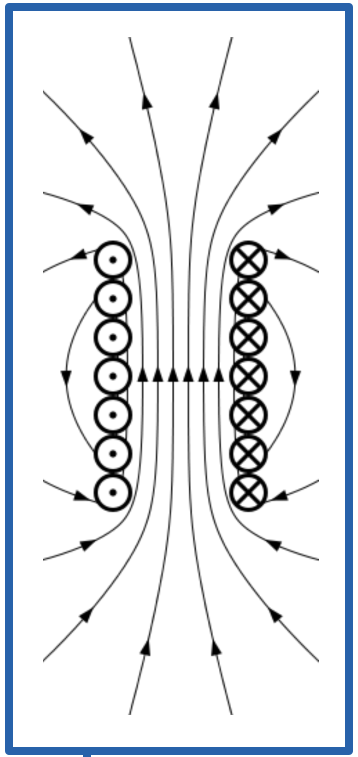


10^{-10} m
e-
10^{-18} m
10^{-14} m
$<10^{-19}$ m
proton
u
u
d
10^{-15} m
neutron
u
d
d
10^{-15} m
I
II
III
Quarks
Leptons
2.4 MeV
u
1.3 GeV
c
170 GeV
t
4.8 MeV
d
104 MeV
s
4.2 GeV
b
< 2 eV
ν_1
< 2 eV
ν_2
< 2 eV
ν_3
0.5 MeV
e
16 MeV
μ
1.8 GeV
τ
~1910
~1930
~1960
today

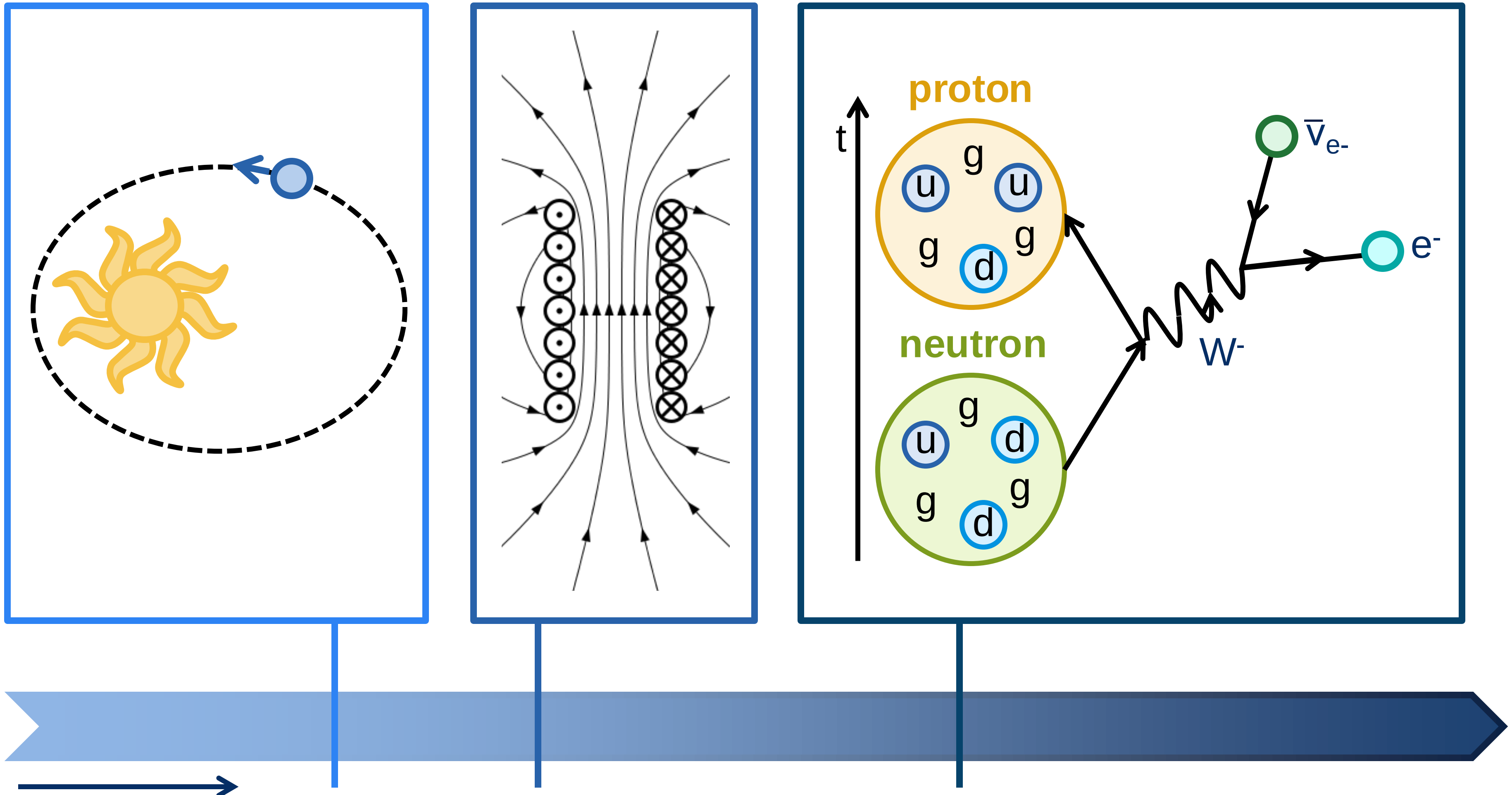
FORCES

FORCES



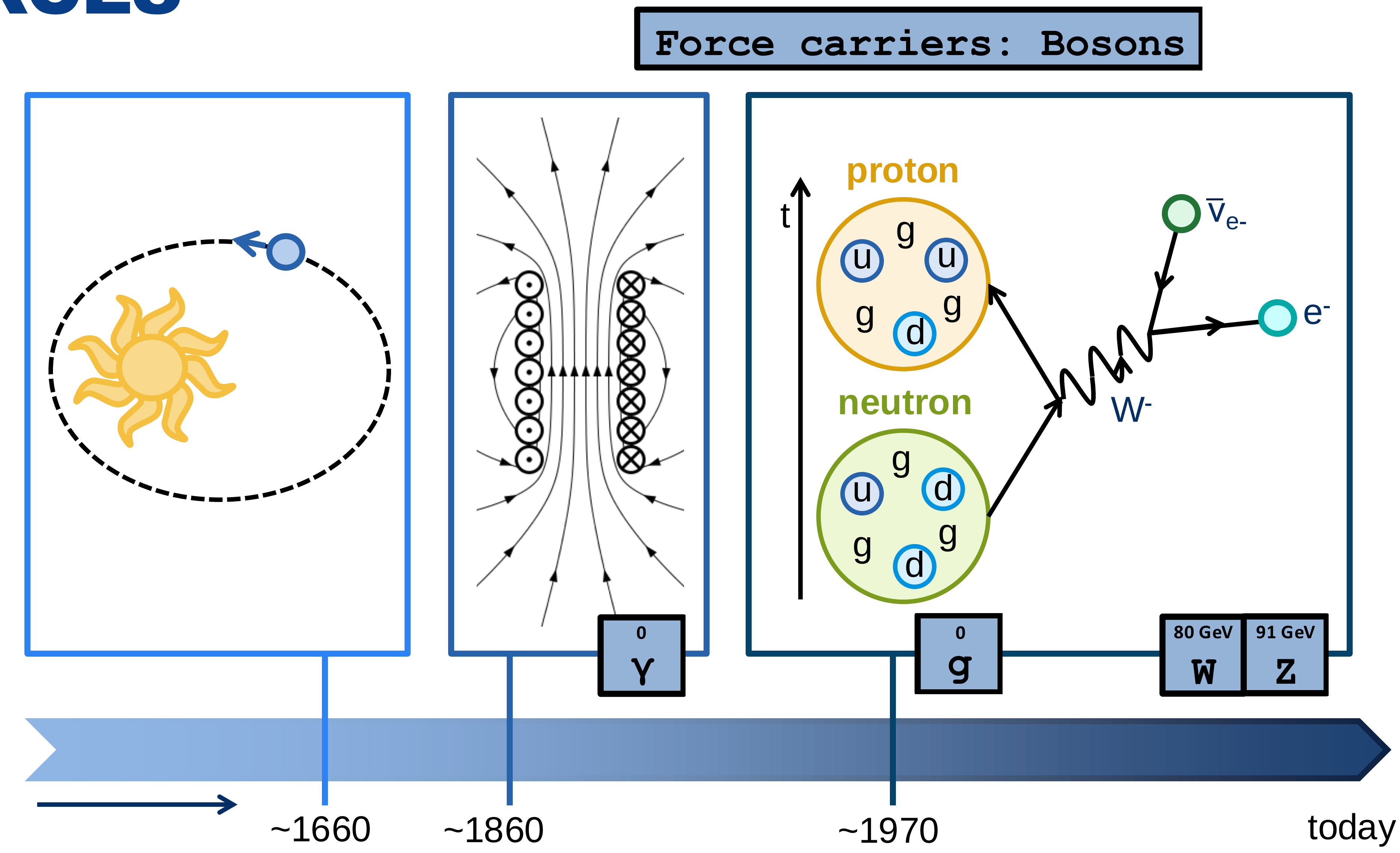


FORCES



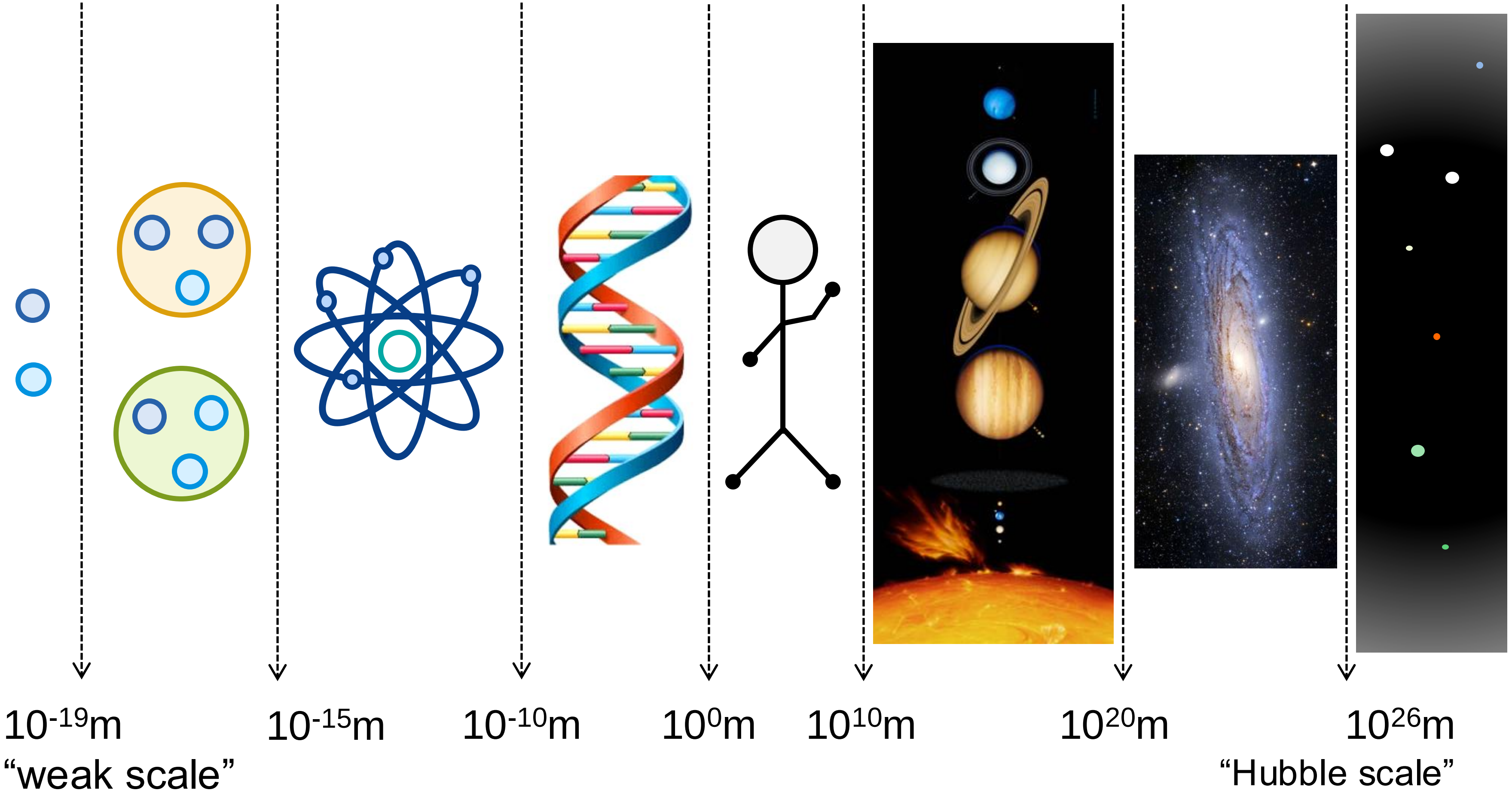
~1660 ~1860 ~1970 today

FORCES



Force carriers: Bosons
t
proton
u
g
u
g
g
d
neutron
u
g
d
g
g
d
$\bar{\nu}_{e-}$
e^-
W^-
0
γ
0
g
80 GeV
W
91 GeV
Z
~1660
~1860
~1970
today

RANGE OF FORCES

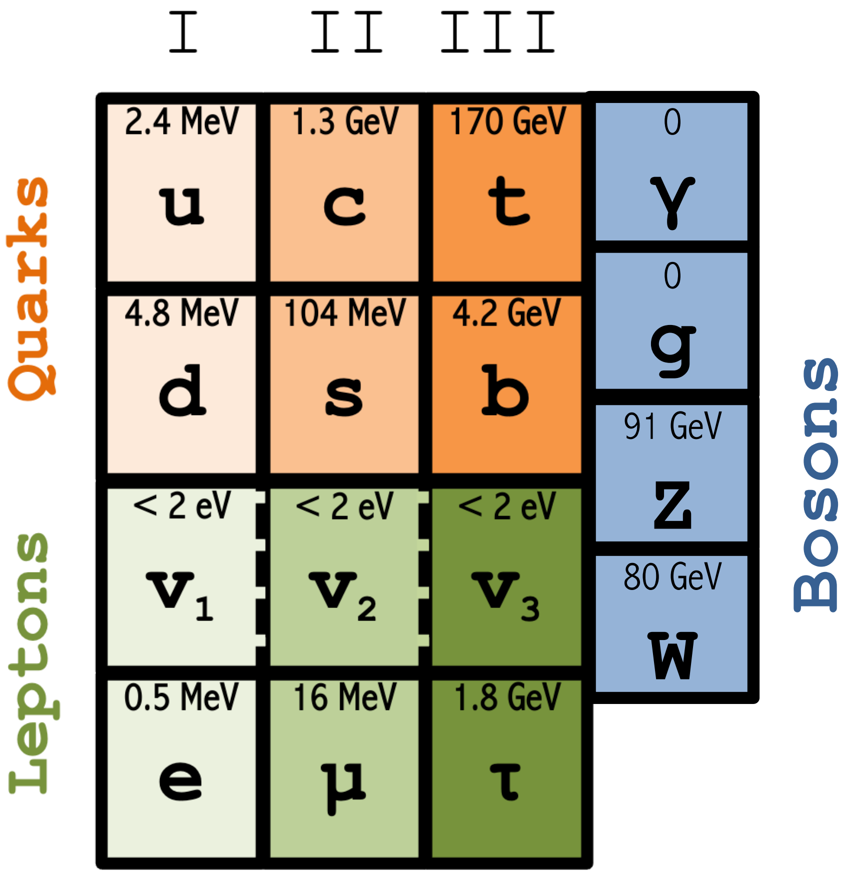


THE STANDARD MODEL

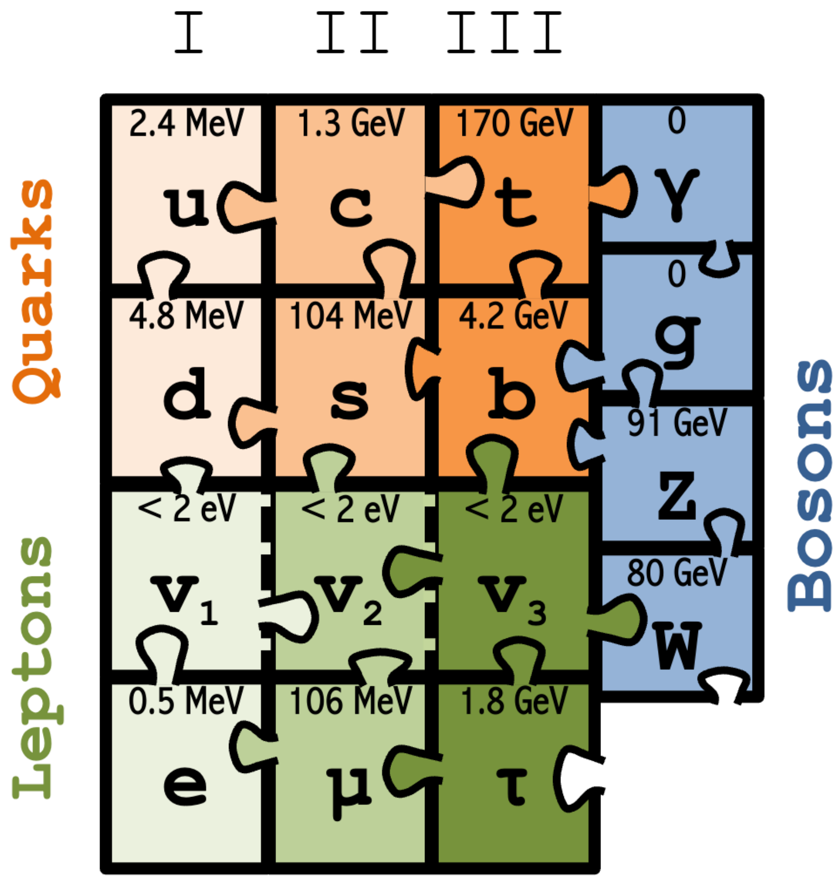
THE STANDARD MODEL

	I	II	III
Quarks	2.4 MeV u	1.3 GeV c	170 GeV t
	4.8 MeV d	104 MeV s	4.2 GeV b
Leptons	< 2 eV v_1	< 2 eV v_2	< 2 eV v_3
	0.5 MeV e	16 MeV μ	1.8 GeV τ

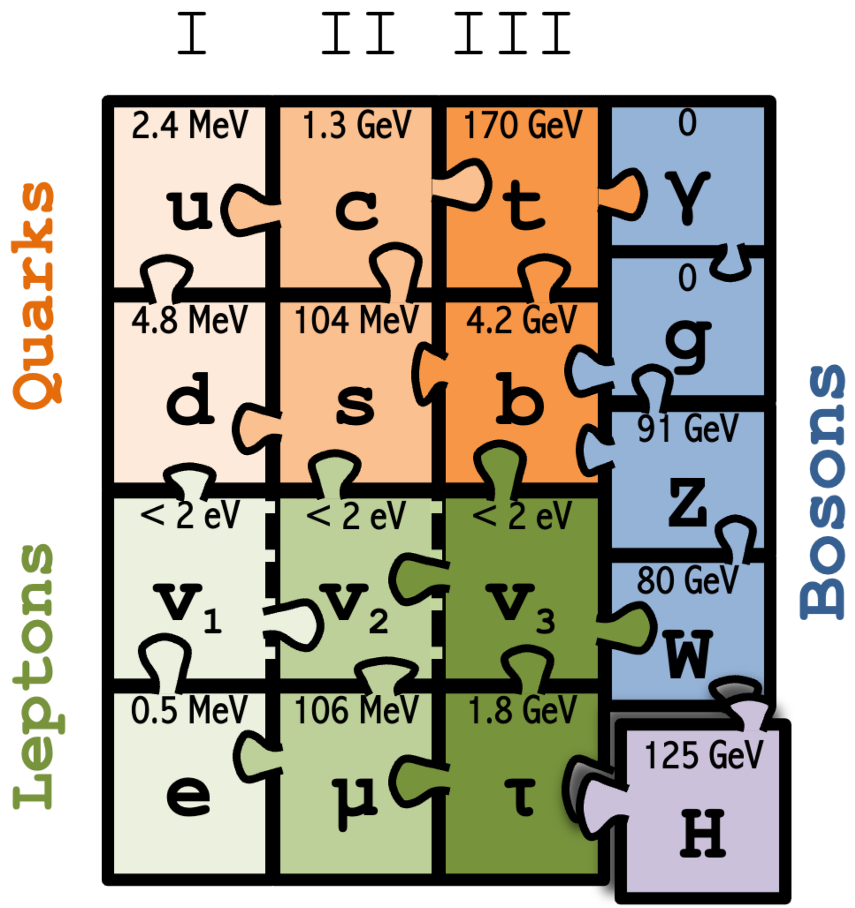
THE STANDARD MODEL

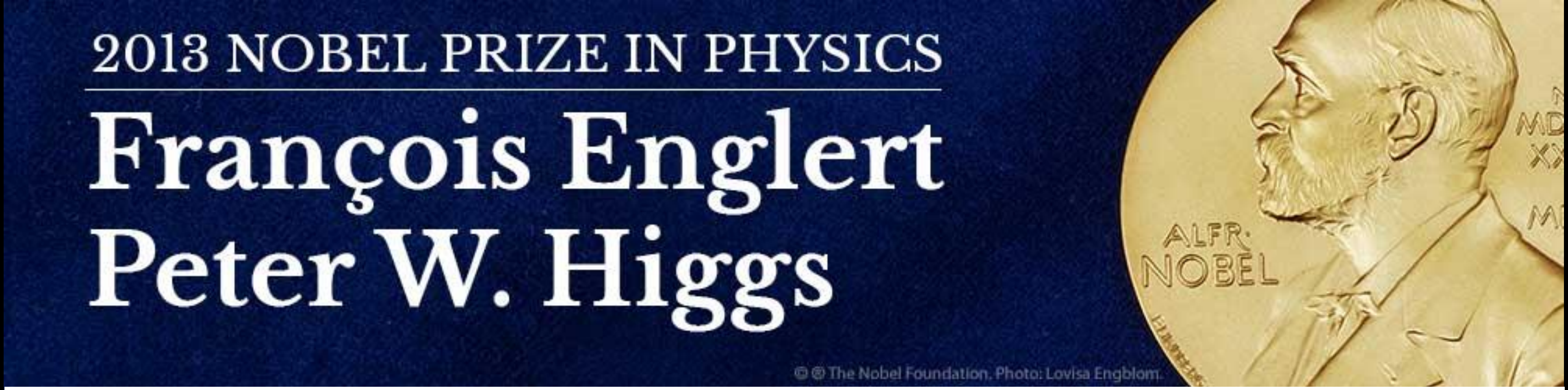


THE STANDARD MODEL



THE STANDARD MODEL

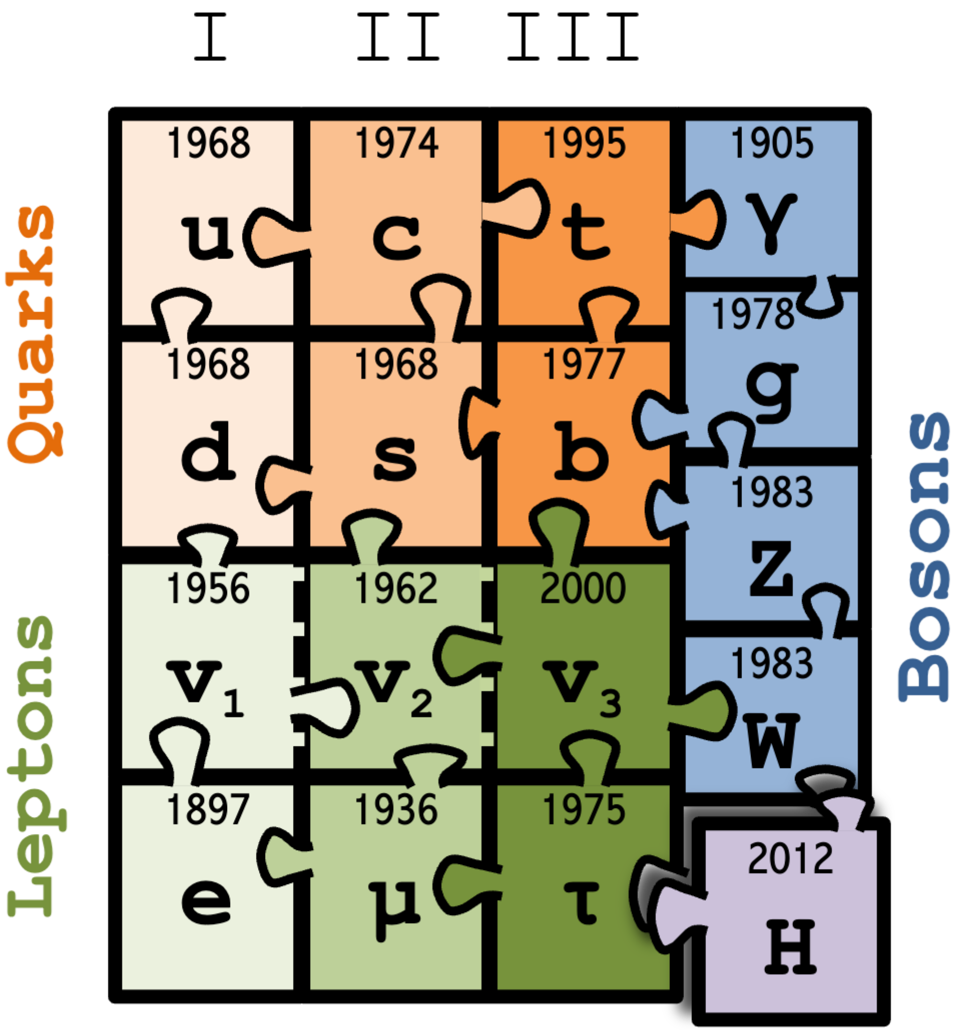




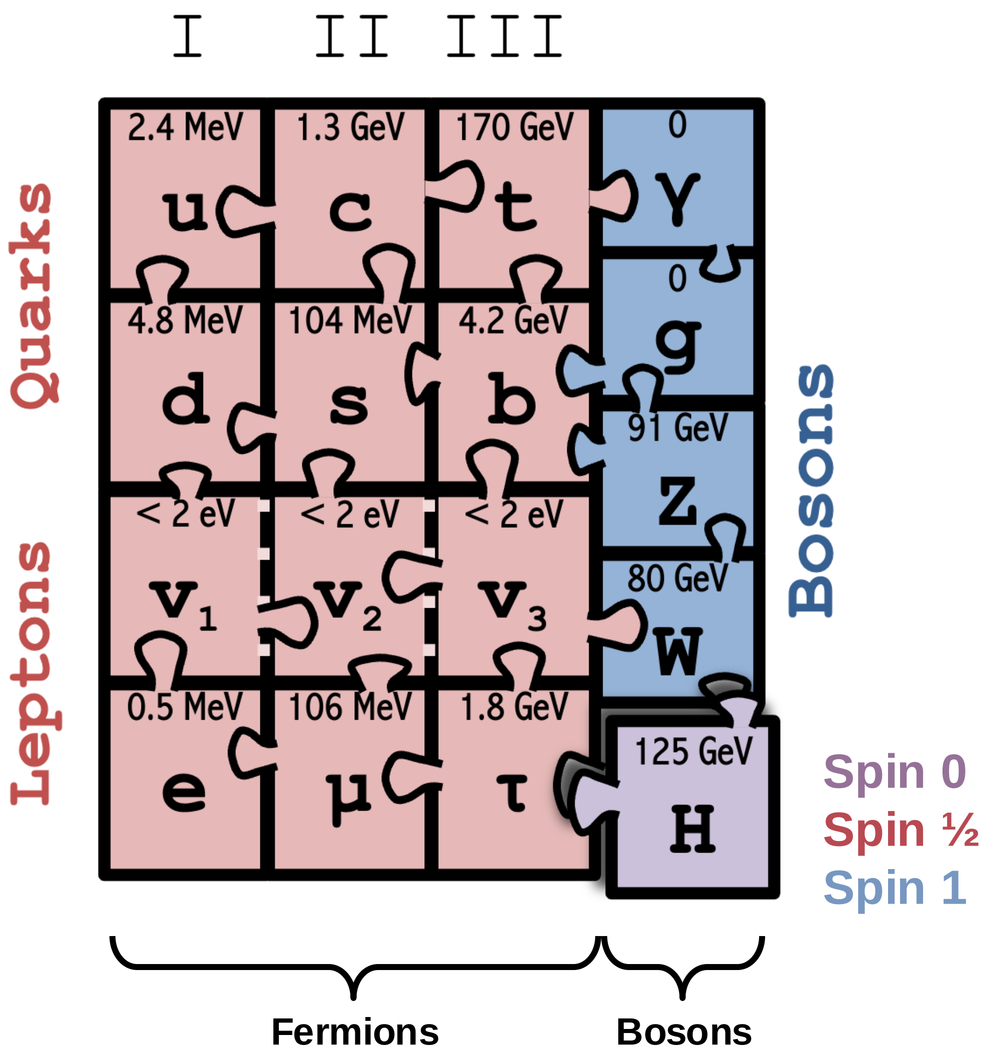
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider”

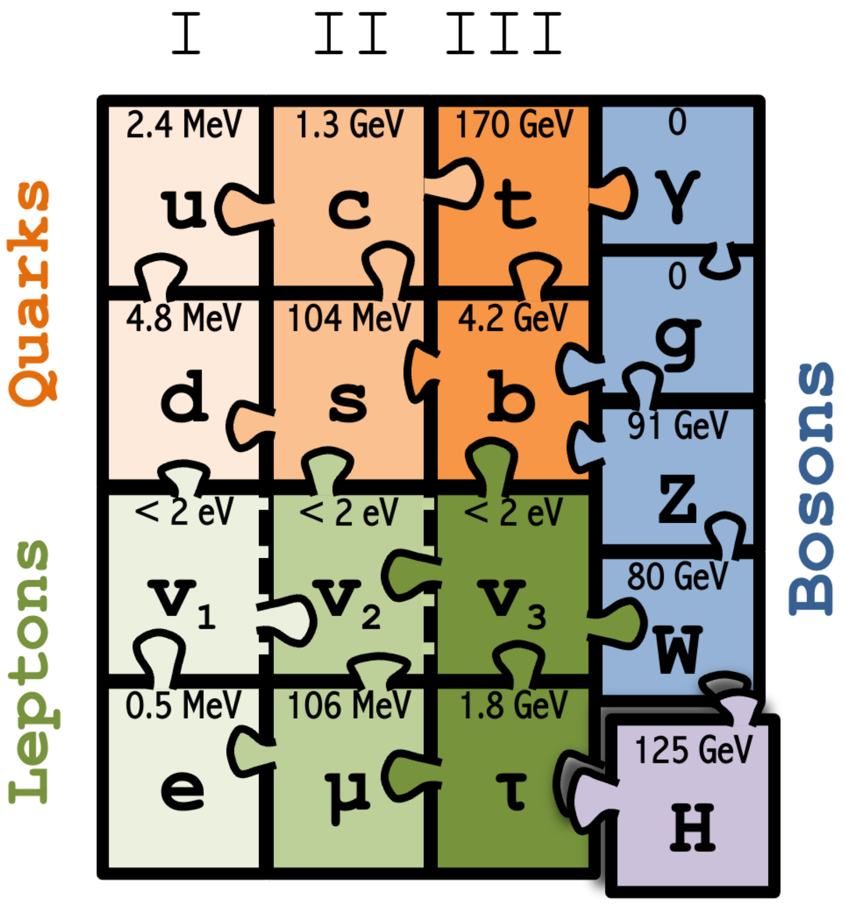
THE STANDARD MODEL



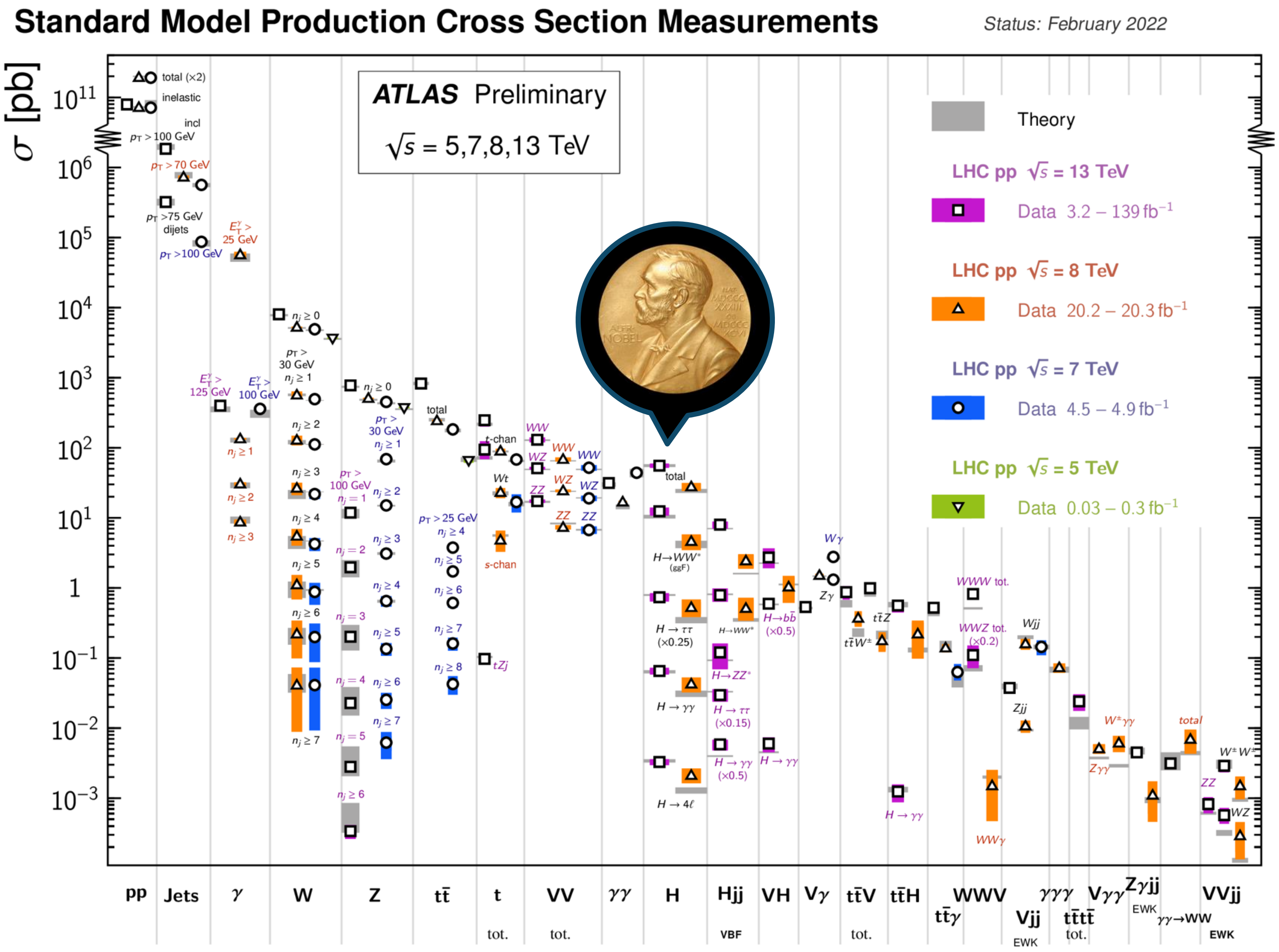
THE STANDARD MODEL



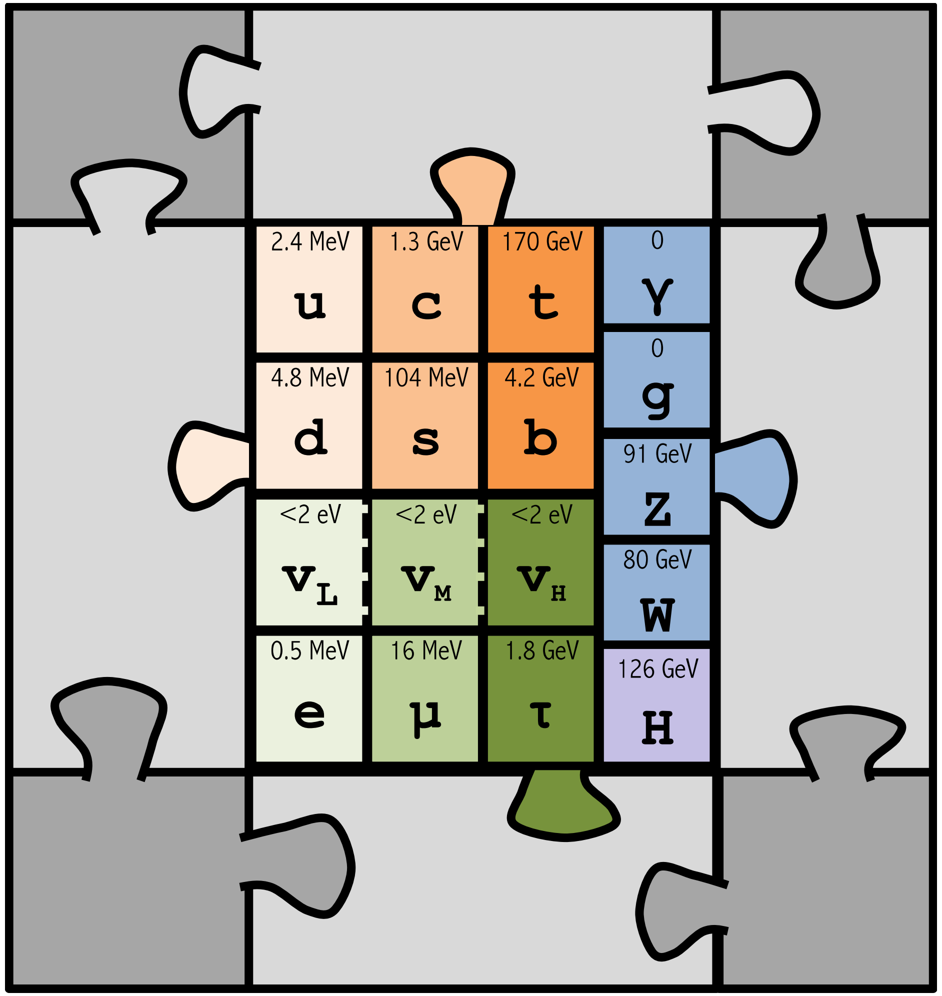
THE STANDARD MODEL

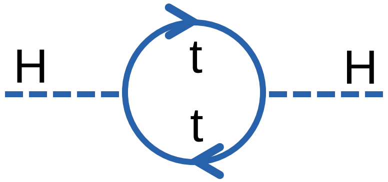


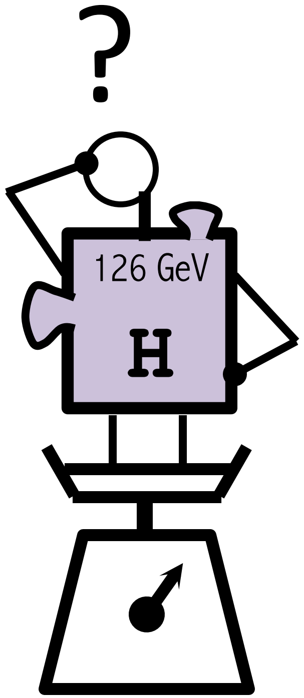
THE STANDARD MODEL STUDIED IN DETAIL



...ONE PIECE IN THE PUZZLE



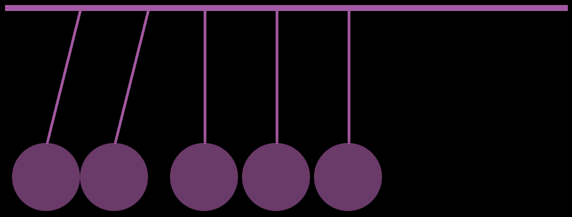


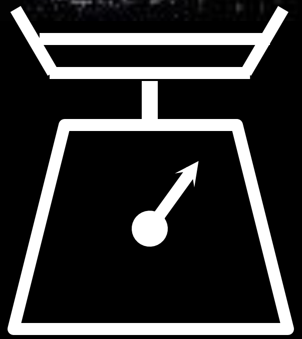


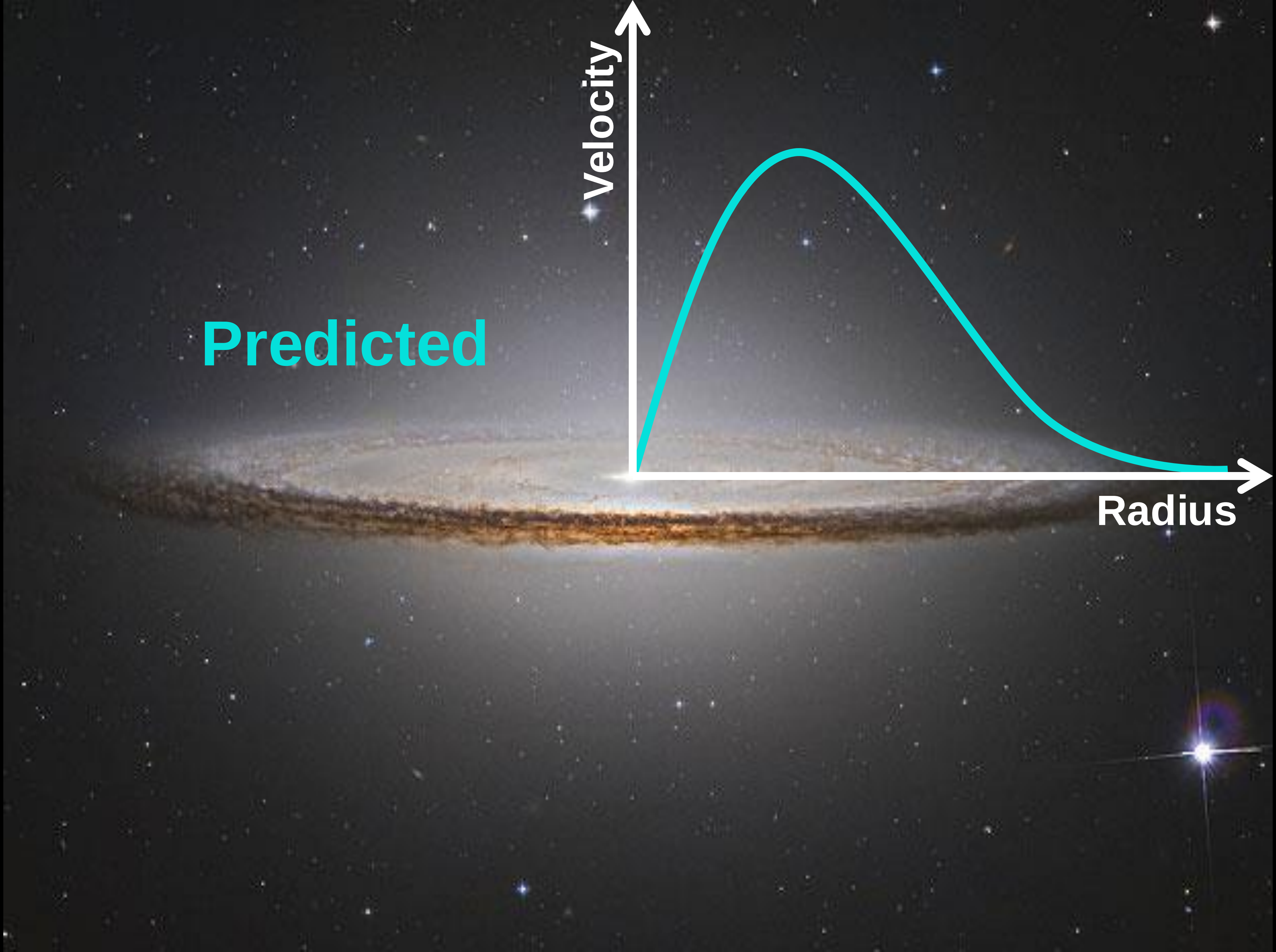
$$m_H^{SM} = m_0 + \alpha + \beta + \ldots \gg 126\mathrm{GeV}$$

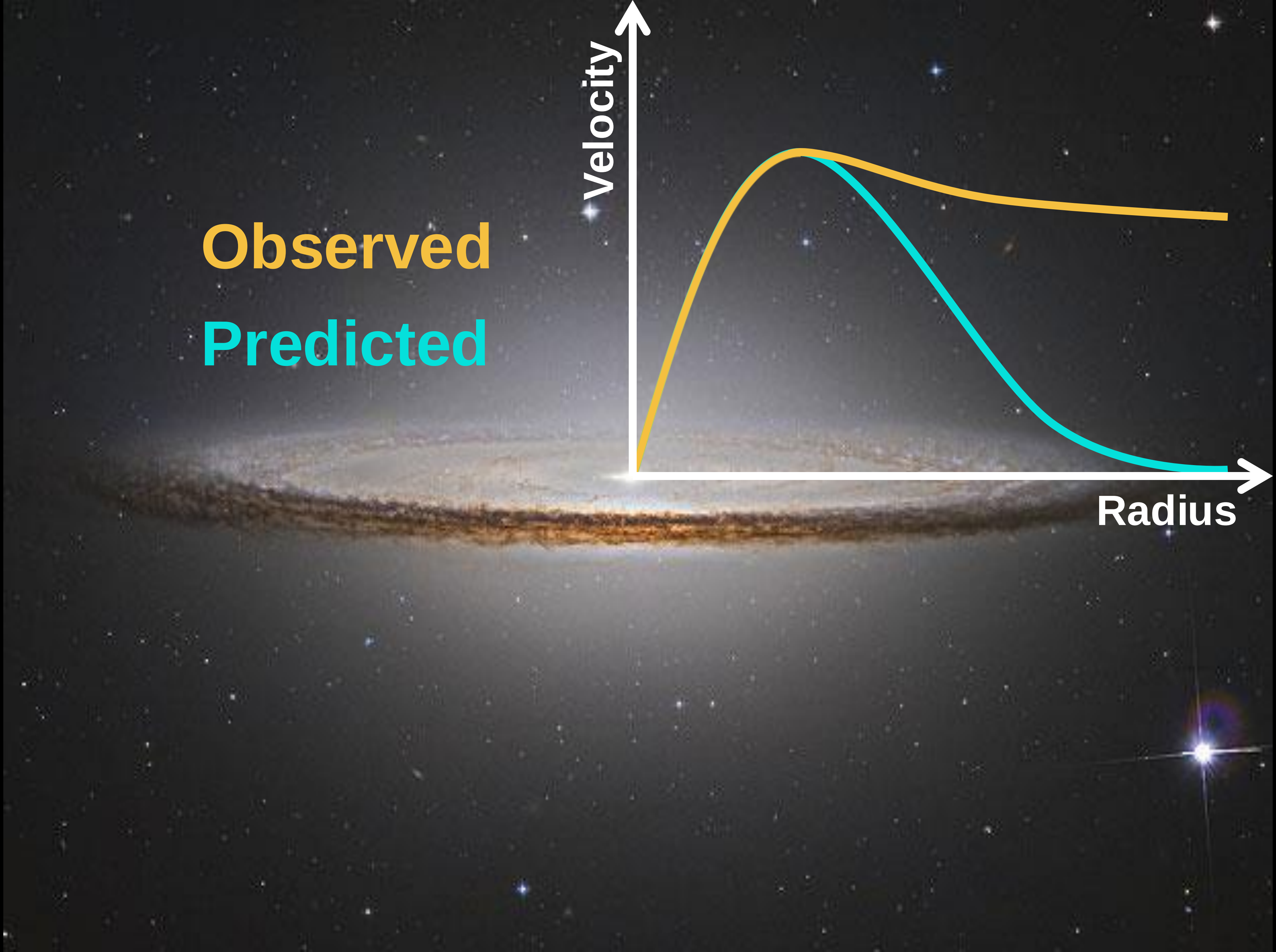
Theory of Gravity

Laws of Motion



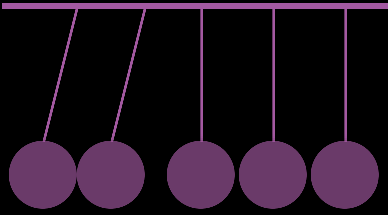



Predicted
Velocity
Radius


Observed
Predicted
Velocity
Radius

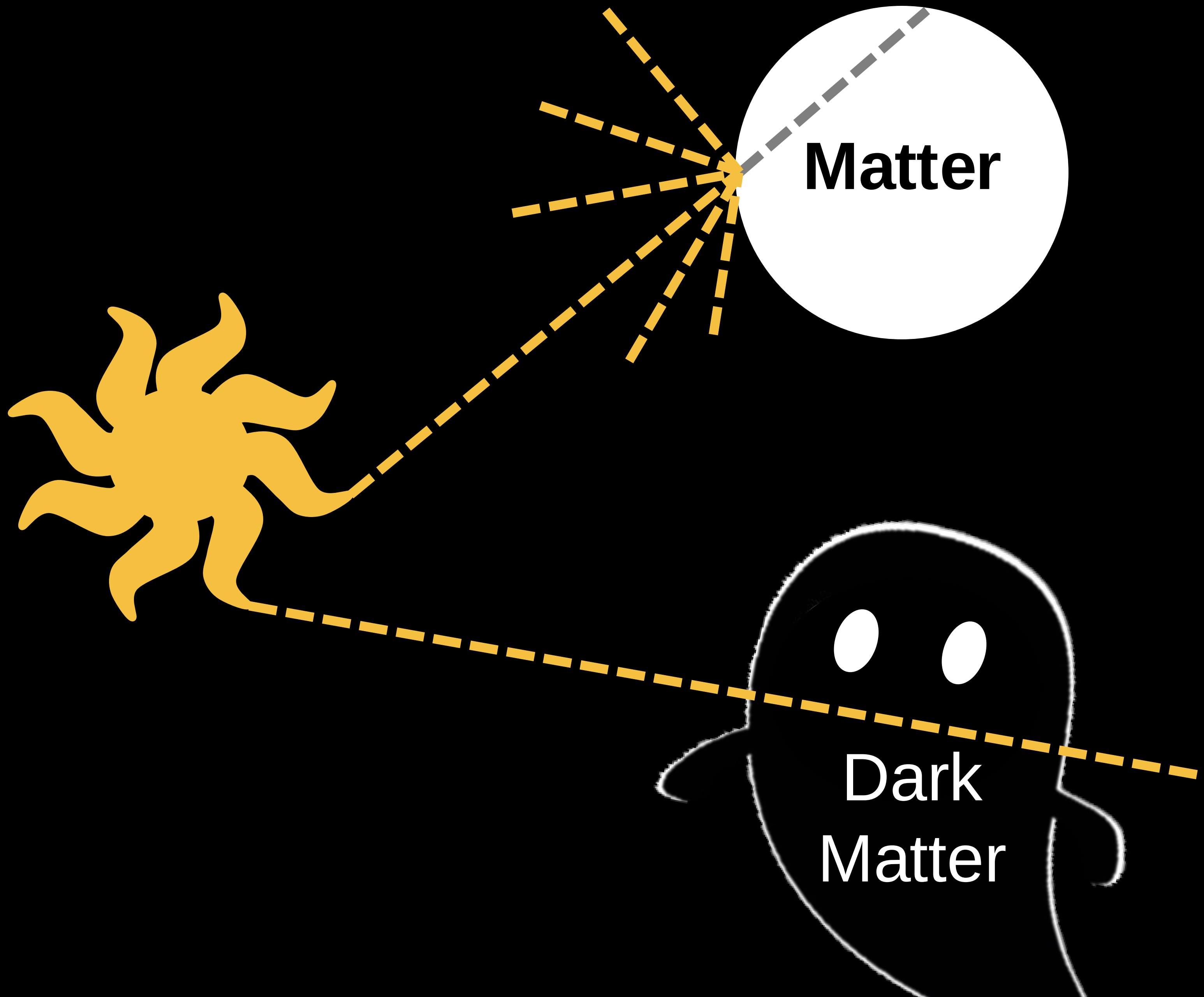
Theory of Gravity

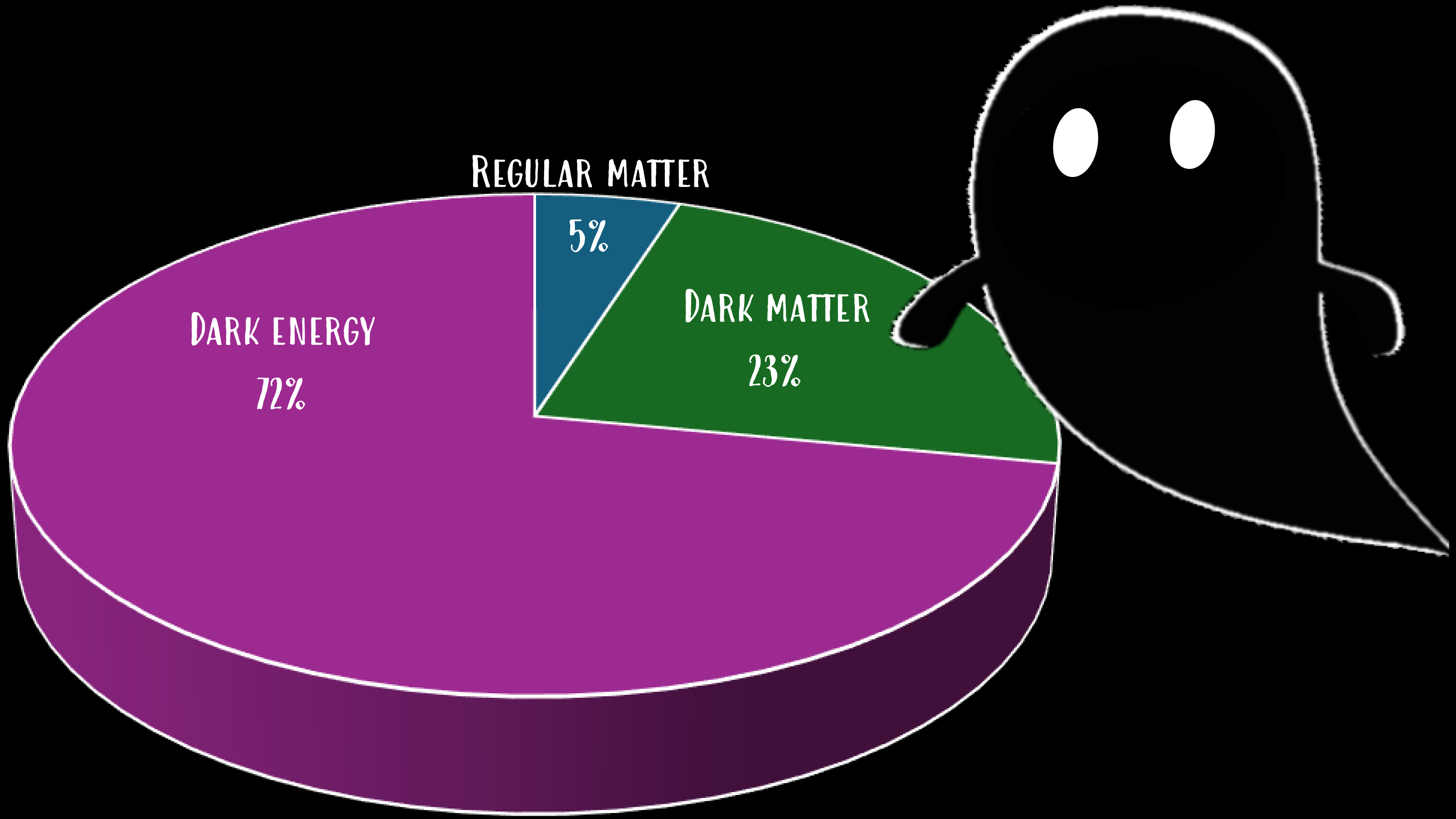
Laws of Motion

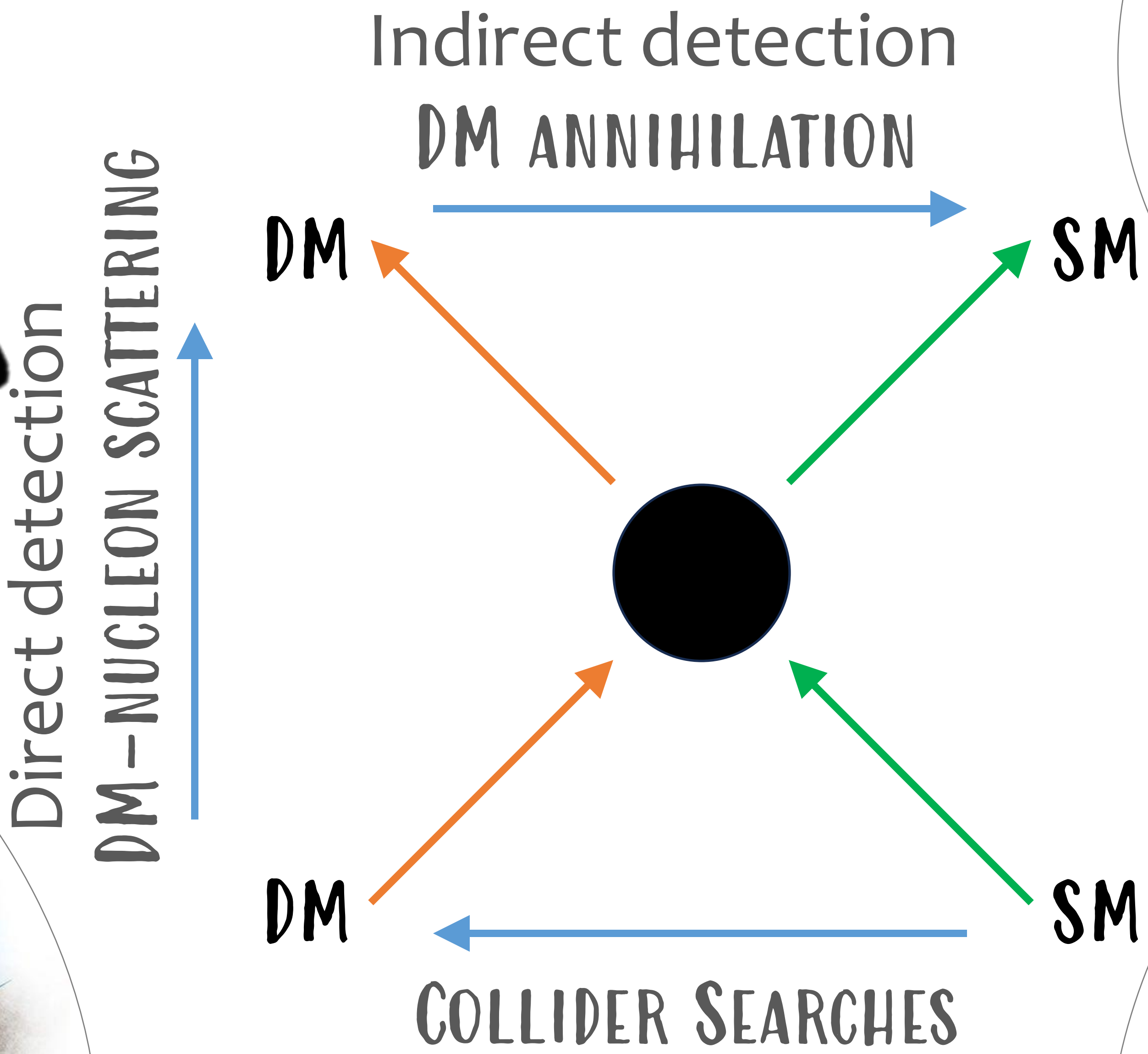


?

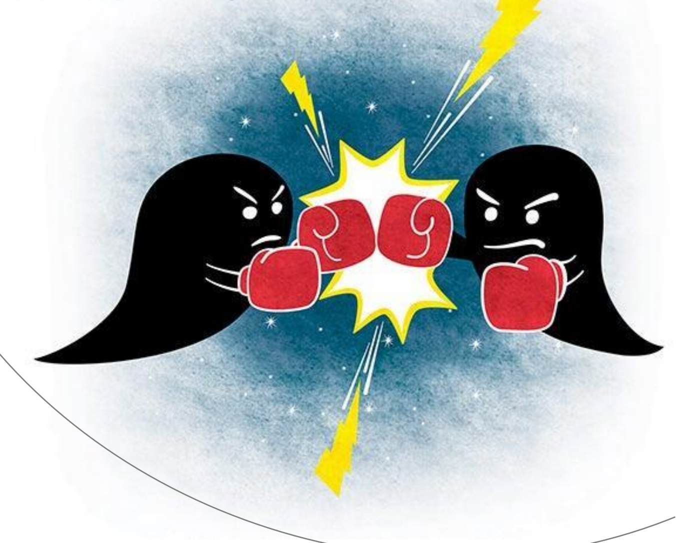

Dark
Matter

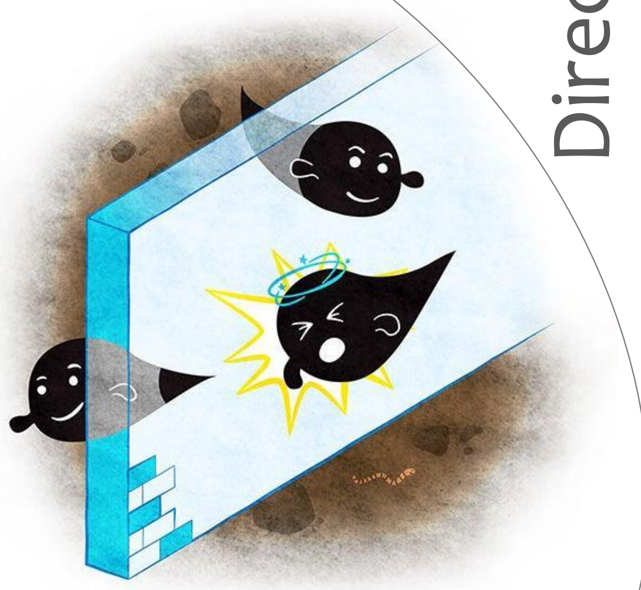

Matter
Dark
Matter


Regular matter
5%
Dark matter
23%
Dark energy
72%

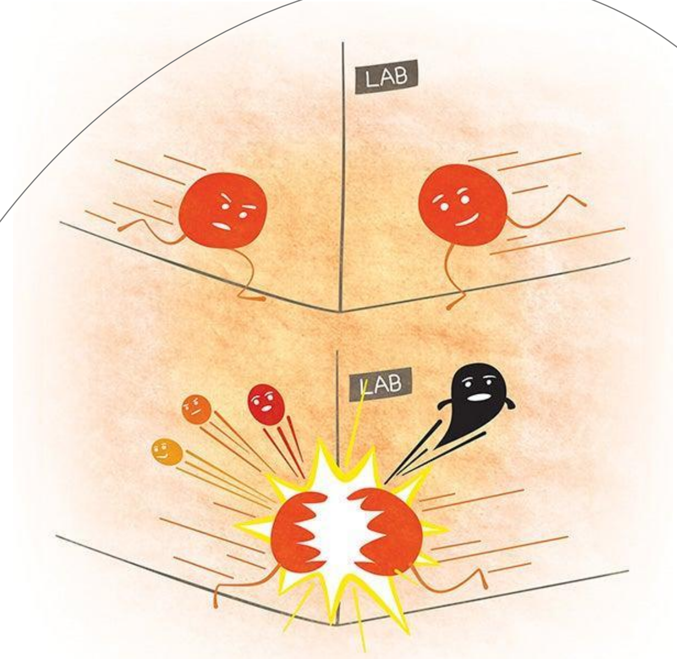


Indirect detection



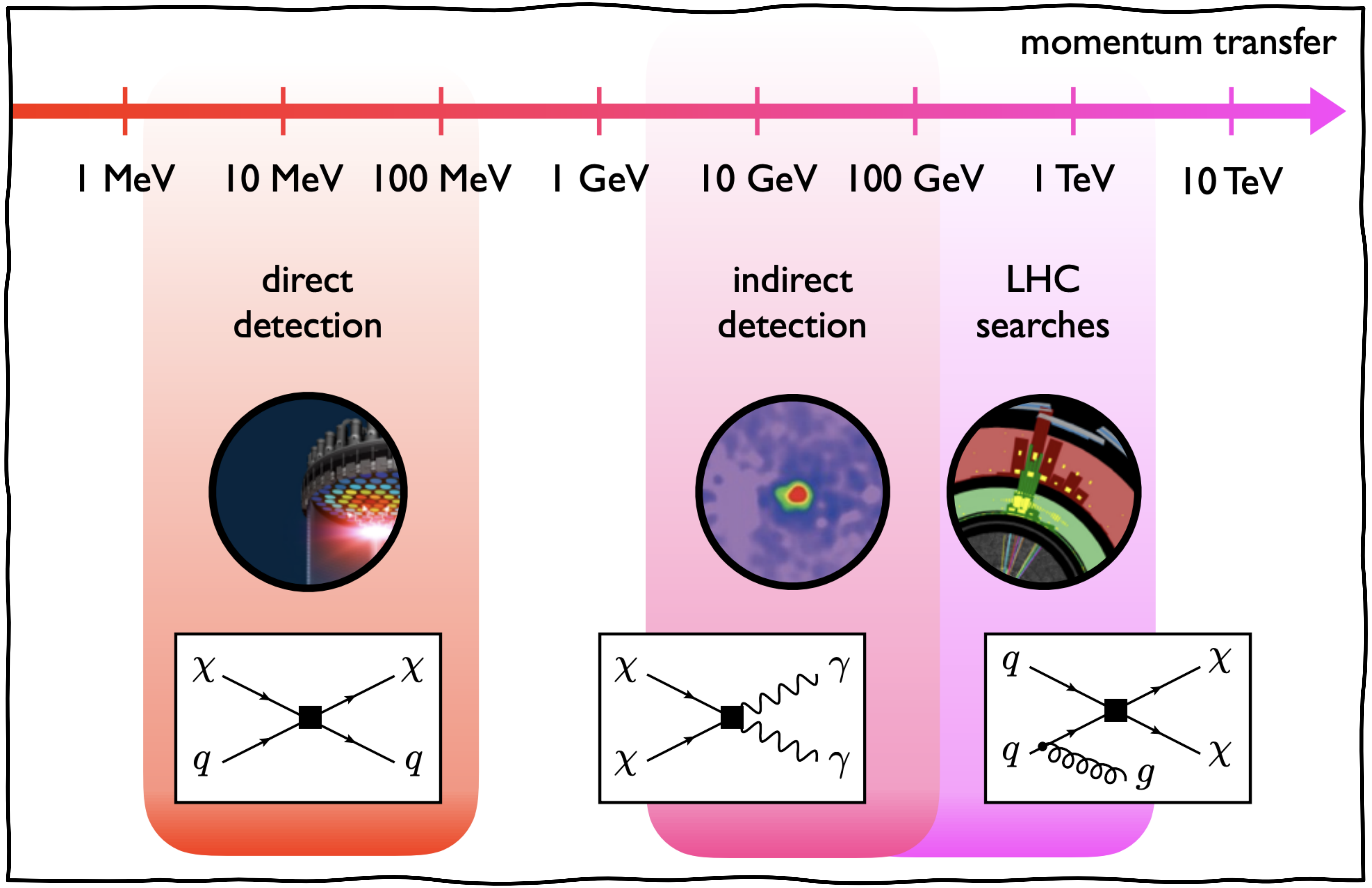


Direct detection



Collider searches

Drawings from
https://www6.slac.stanford.edu/news/2016-02-08-three-ways-bust-ghostly-dark-matter



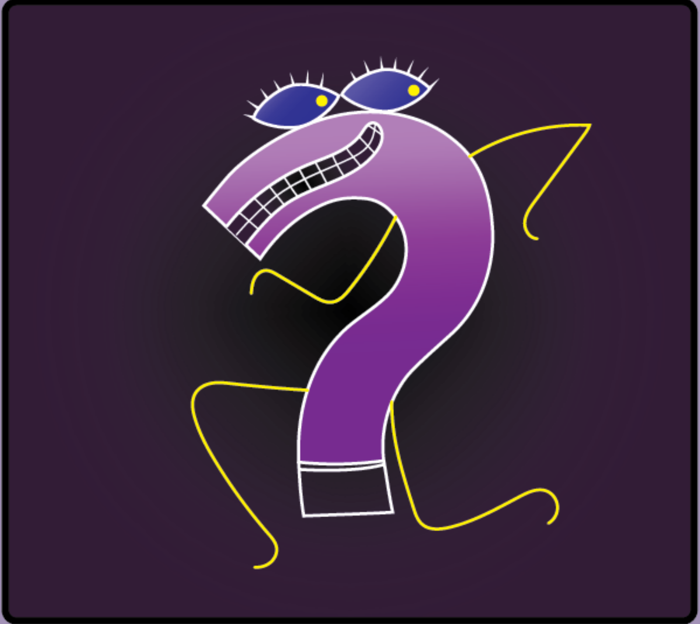
https://arxiv.org/pdf/1810.09420.pdf

TYPE : ?

PARTICULE X ?

Masse ?

eV KeV MeV GeV TeV



POUVOIR SPECIAL

Particule hypothétique qui constitue la **MATIERE NOIRE**, une sorte de matière qui semble dominer notre Univers.

Charge -1 0 +1

Particule non découverte

PROPRIETES EXPERTES

Spin ?

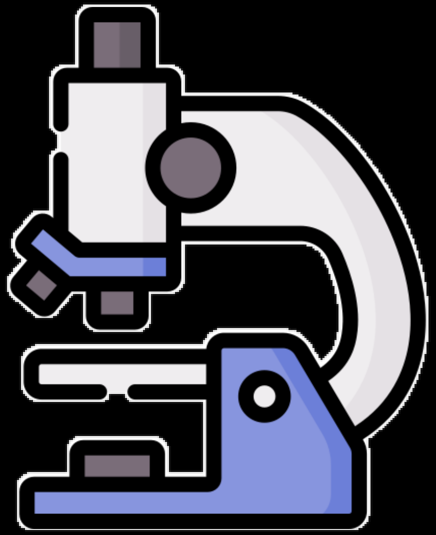
Particule stable

UNIVERSITÉ DE GENÈVE

INSTRUMENTS!

How do we "see" the smallest particles?

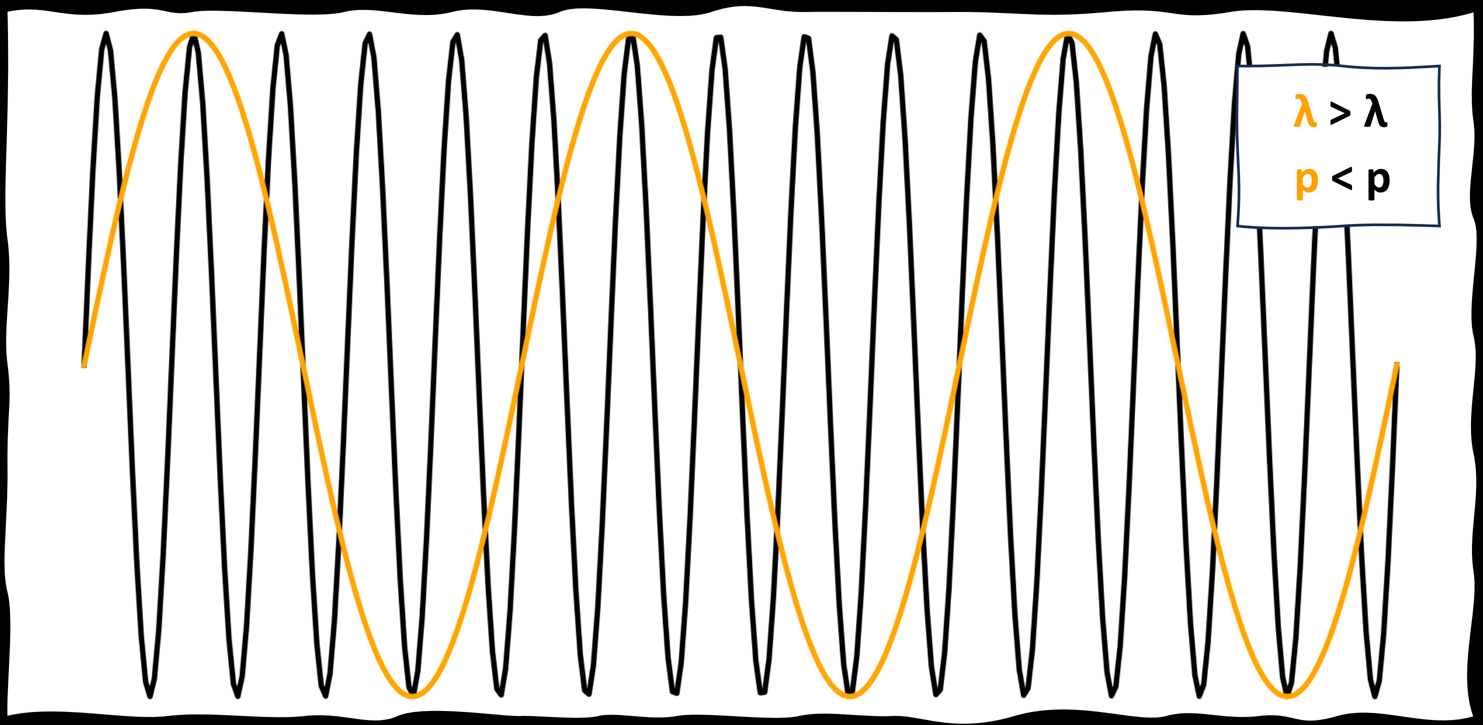
- **Atoms** are about **10^{-10} meters** in size
- **Protons** are around **10^{-15} meters**
- **Elementary particles** (like quarks and electrons) are even smaller — possibly **point-like**, with sizes **below 10^{-18} meters**.



We don't "see" them directly — instead, we **infer** their size and structure through **high-energy particle collisions** and **scattering experiments.**

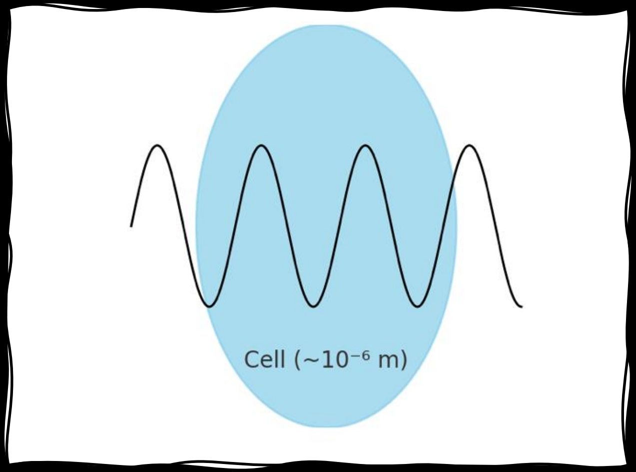
Small distance <=> High energy

Wavelength λ associated with a particle of momentum p: $\lambda = \frac{constant}{p}$



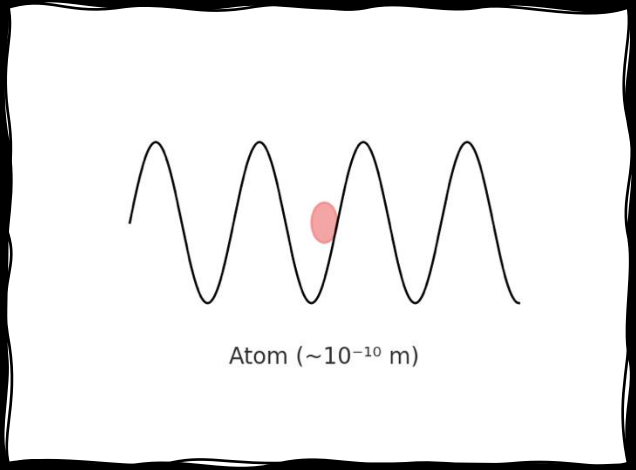
Small distance <=> High energy

Wavelength λ associated with a particle of momentum p: $\lambda = \frac{constant}{p}$



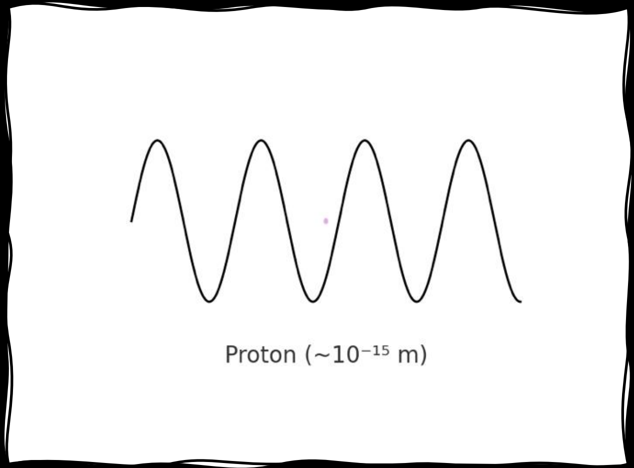
Small distance <=> High energy

Wavelength λ associated with a particle of momentum p: $\lambda = \dfrac{constant}{p}$



Small distance <=> High energy

Wavelength λ associated with a particle of momentum p: $\lambda = \dfrac{constant}{p}$

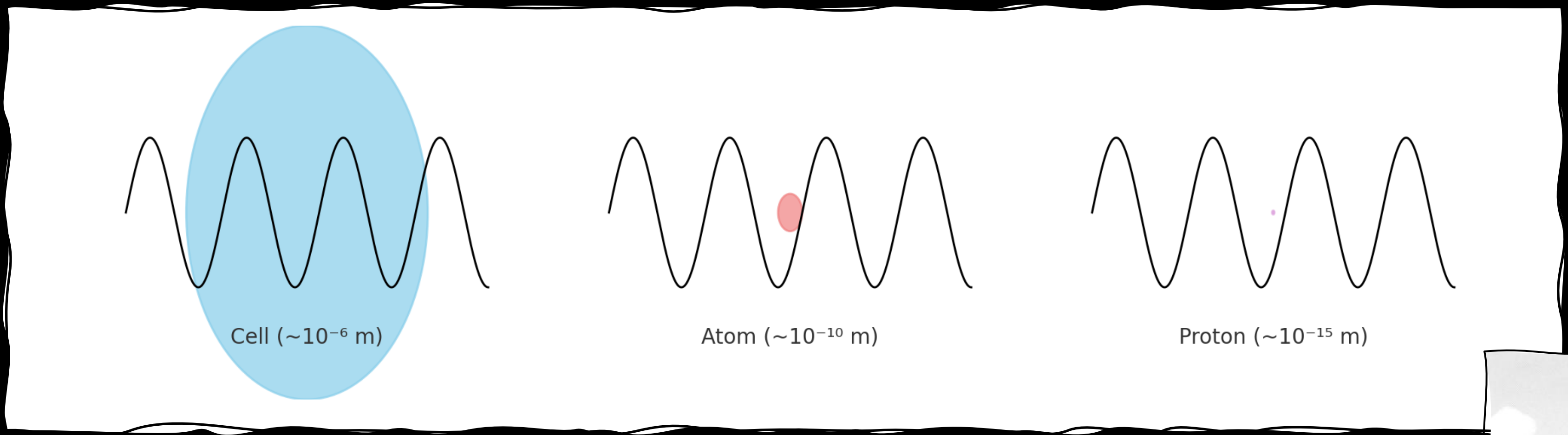


<u>Rule of thumb</u>: You can't see things smaller than the wavelength of the probe you're using.

To detect **smaller things**, you need **shorter wavelengths**, which means **higher momentum and energy**!

Small distance <=> High energy

Wavelength λ associated with a particle of momentum p: $\lambda = \frac{constant}{p}$



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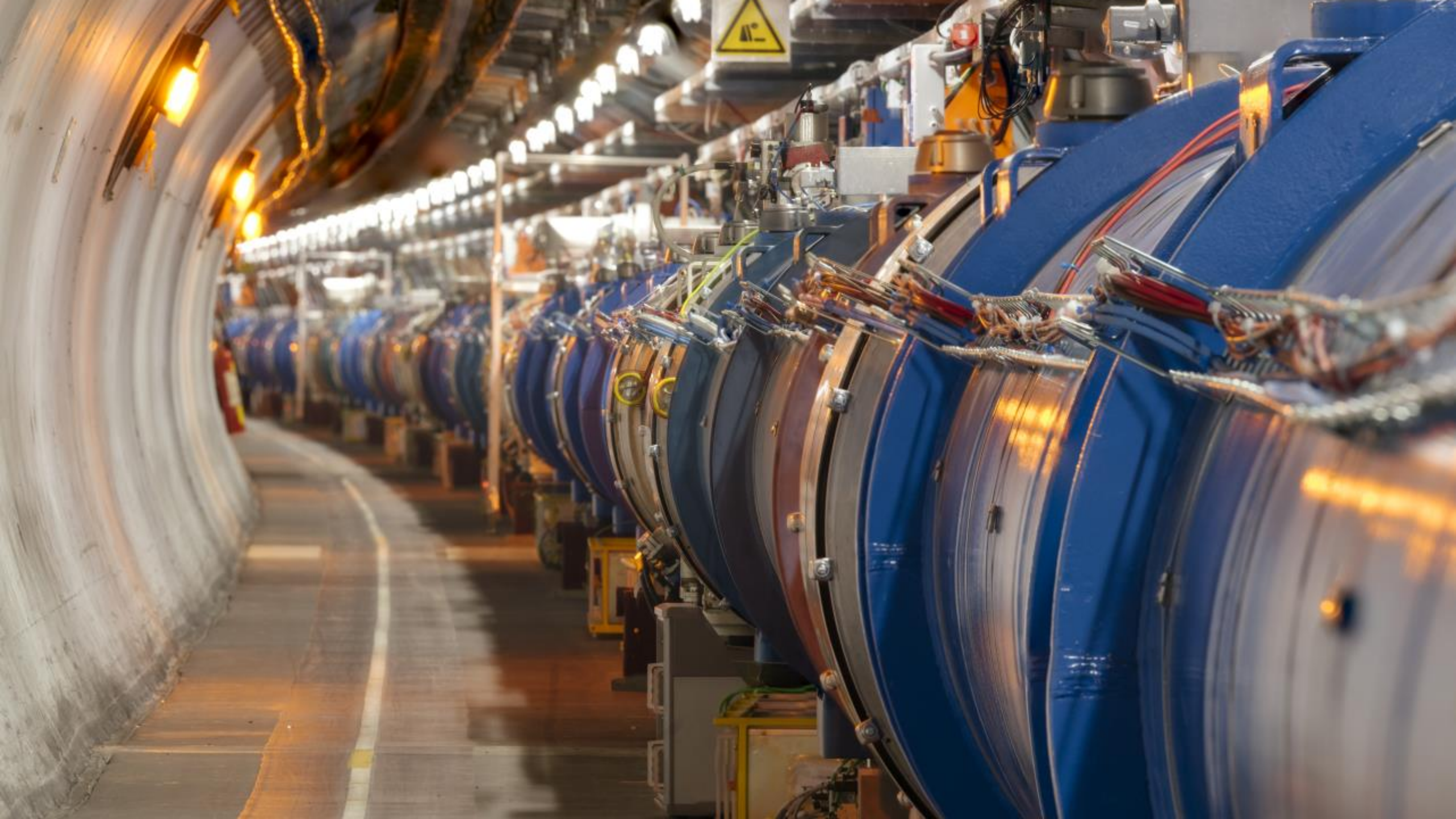
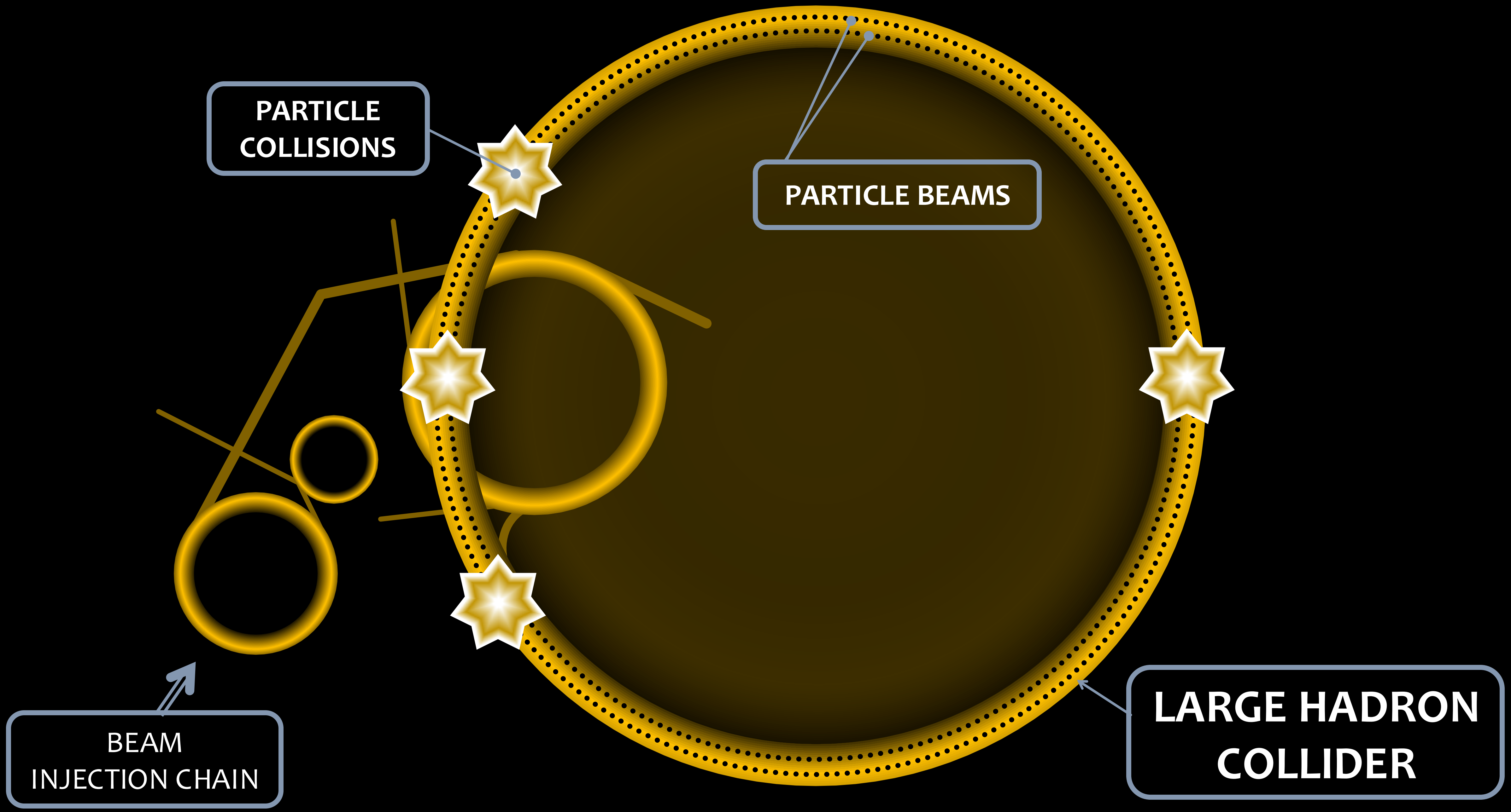
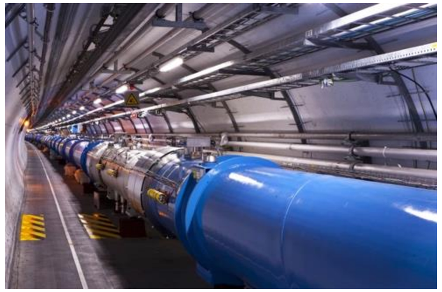



PARTICLE COLLISIONS
PARTICLE BEAMS
BEAM INJECTION CHAIN
LARGE HADRON COLLIDER

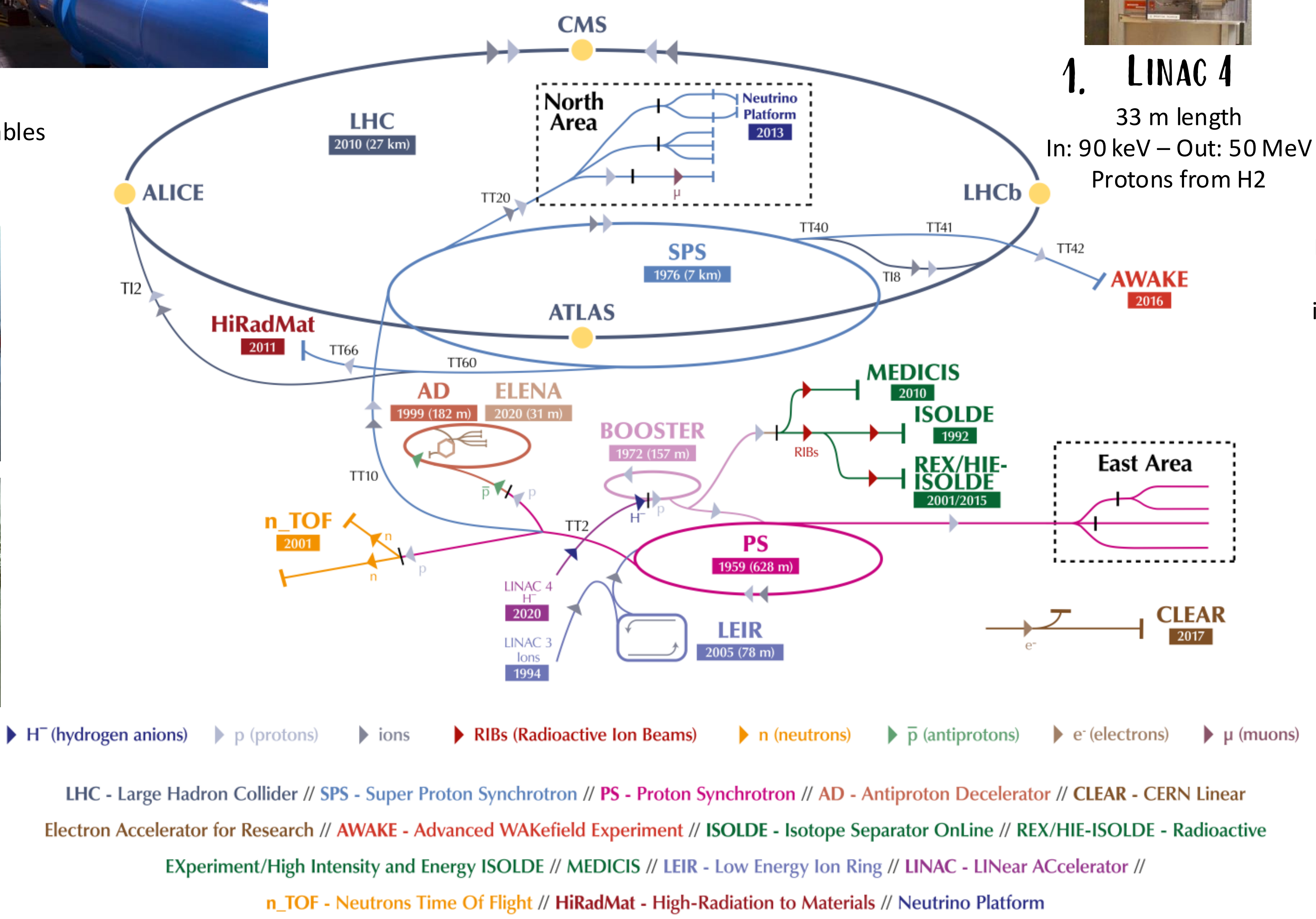


5. LHC

26.7 km circ.
In: 450 GeV – Out: ~7 TeV
Magnets with superconducting cables
12'000 A → 8.33 Tesla
Temperature: 1.9 K

4. SPS

6.9 km circ.
In: 26 GeV – Out: 450 GeV
First underground machine



1. LINAC 4

33 m length
In: 90 keV – Out: 50 MeV
Protons from H2

BOOSTER 2.

157 m circ. – 4 rings
In: 50 MeV – Out: 1.4 GeV
N: up to 3.4×10^{13} protons per pulse
Defines brightness,
i.e. number of protons per bunch in transverse dimension

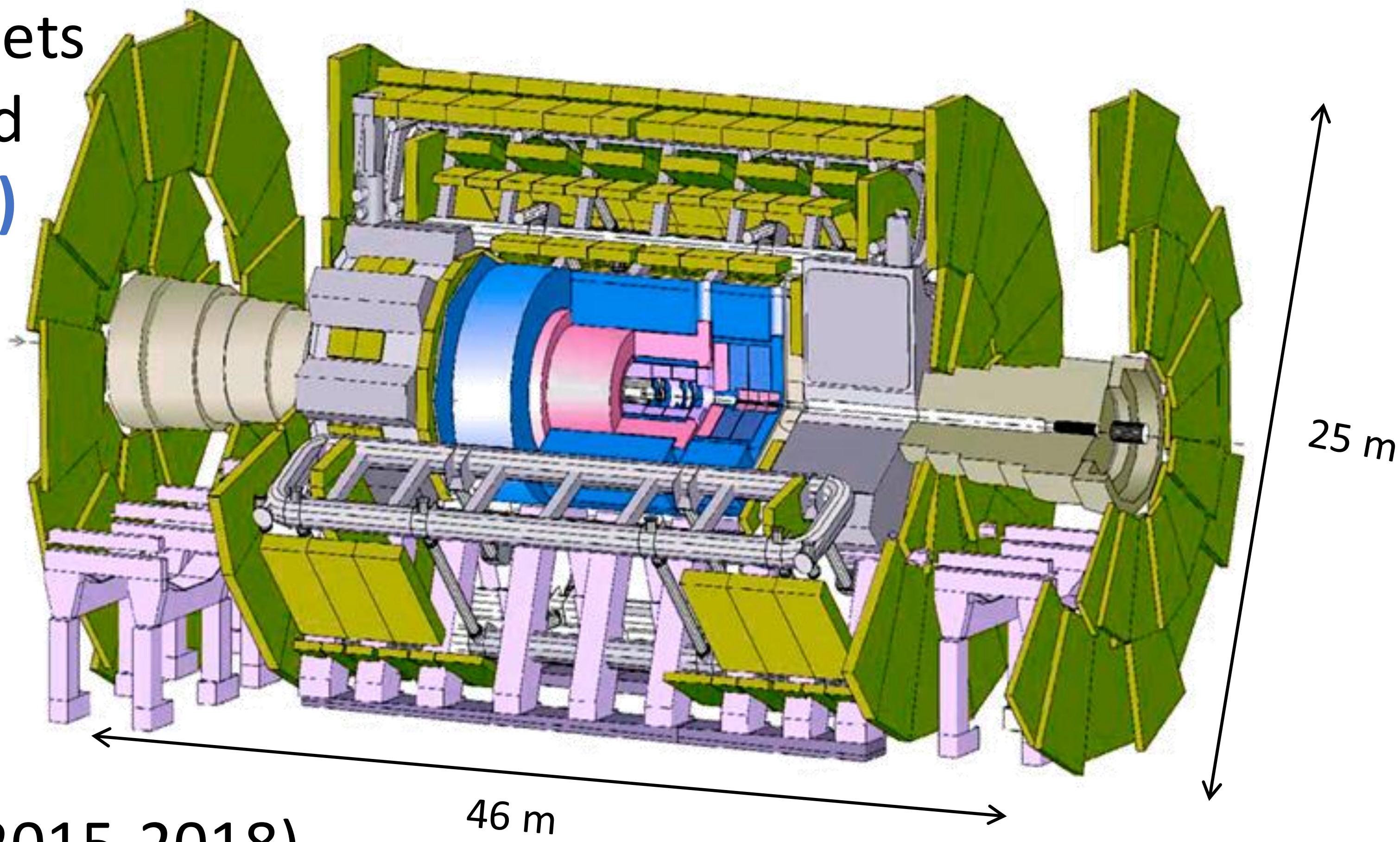
PS 3.

628 m circ.
In: 1.4 GeV – Out: 26 GeV
N: up to 3.3×10^{13} protons
Defines beam time structure

Example: The ATLAS detector in numbers

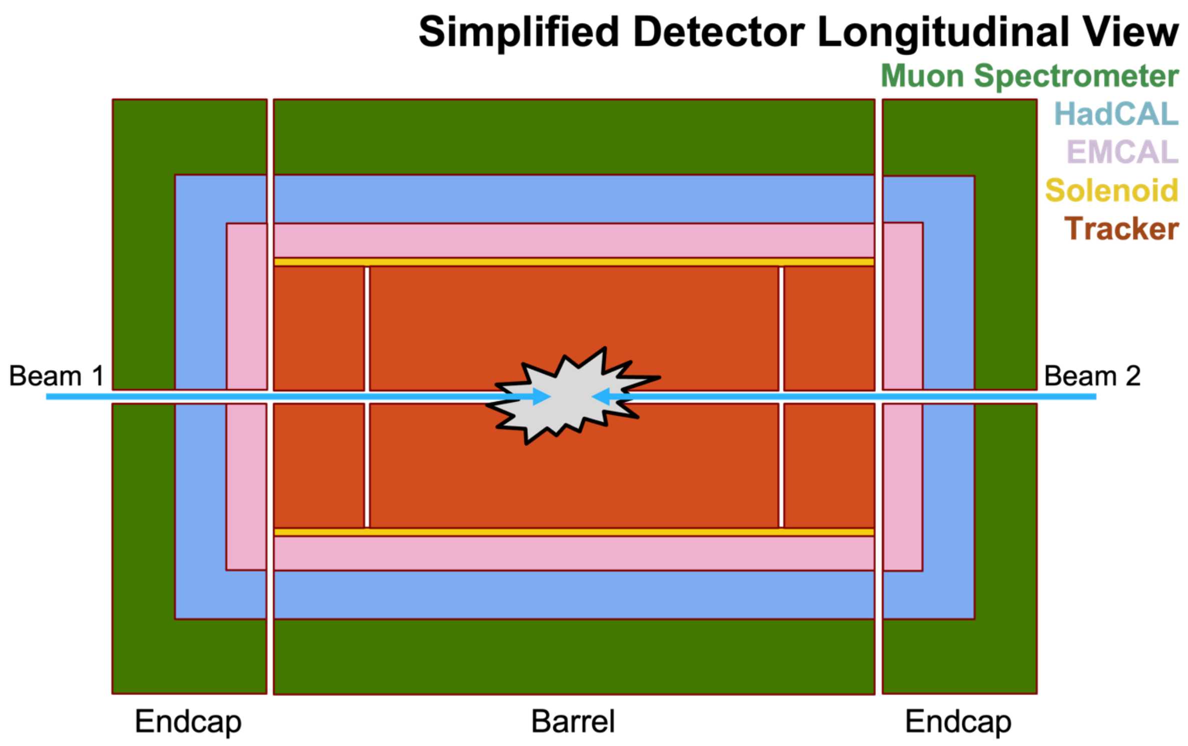
- ✓ Weights **7 ktonnes** ()
- ✓ **2-4 T** superconducting magnets
- ✓ Position of particles recorded with an accuracy of **O(10 µm)**
- ✓ **100 M** channels

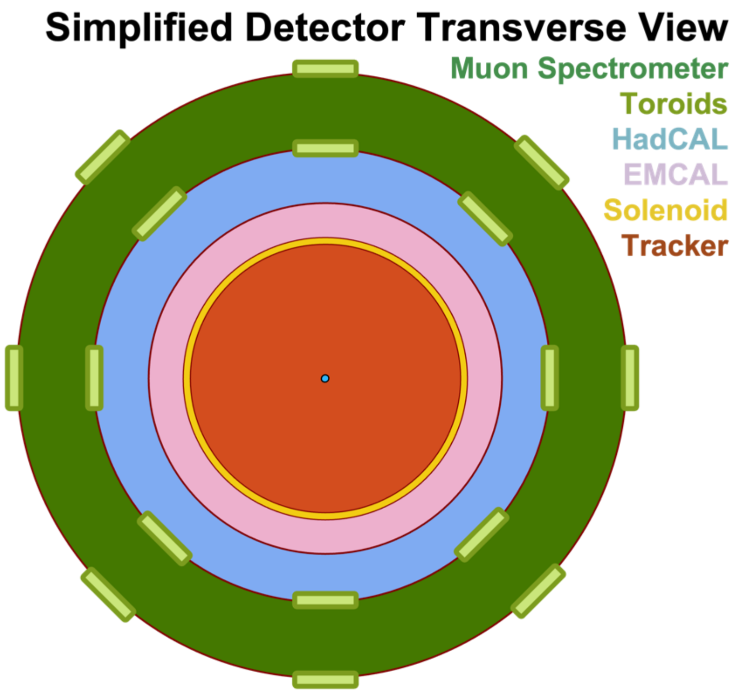
- ✓ **1 Giga** collisions/second
- ✓ **1000** events/second stored
- ✓ **500 PB** data on disk & tape
- ✓ **0.5 M** CPU cores used 24/7



- ✓ **20 billion** events collected (2015-2018)

General purpose detectors at the LHC

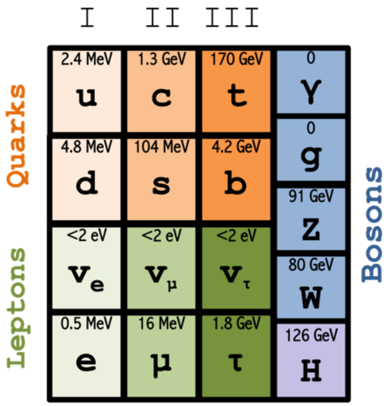


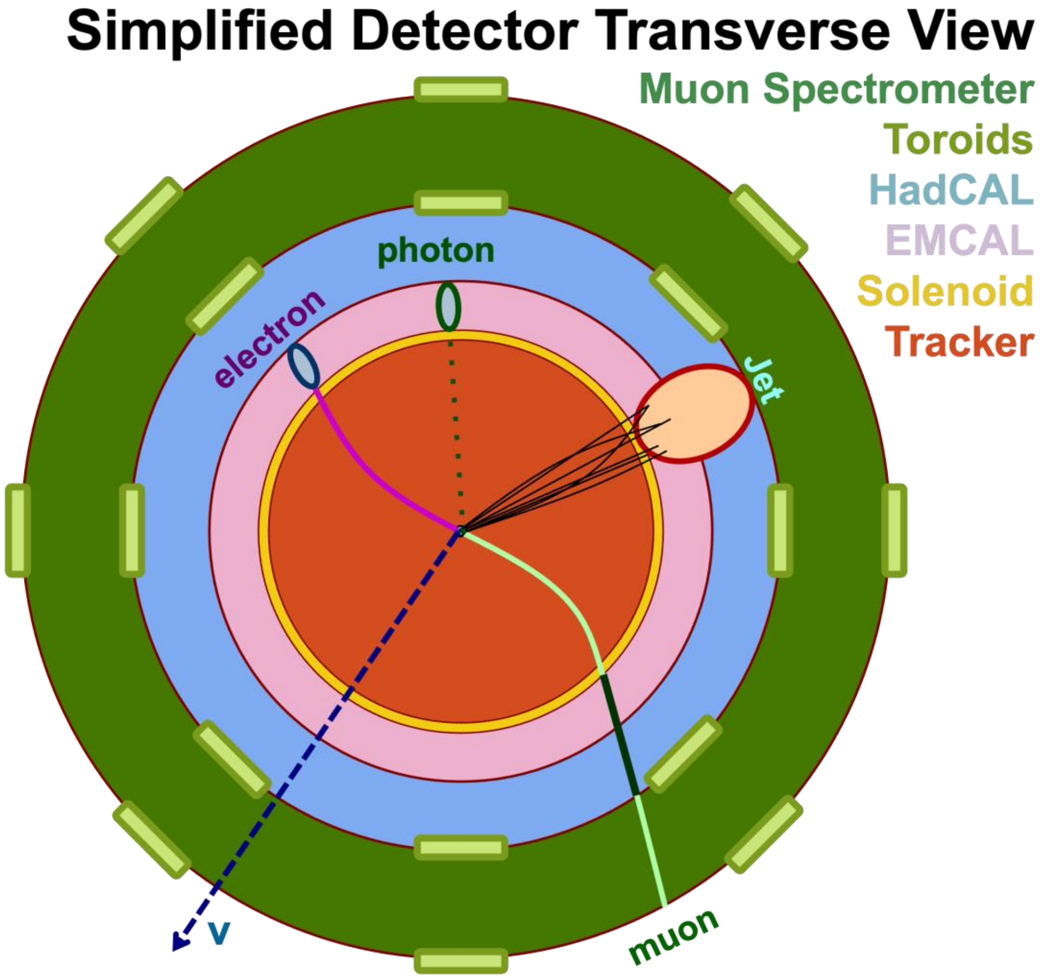


What do we reconstruct?

- Tracks and clusters

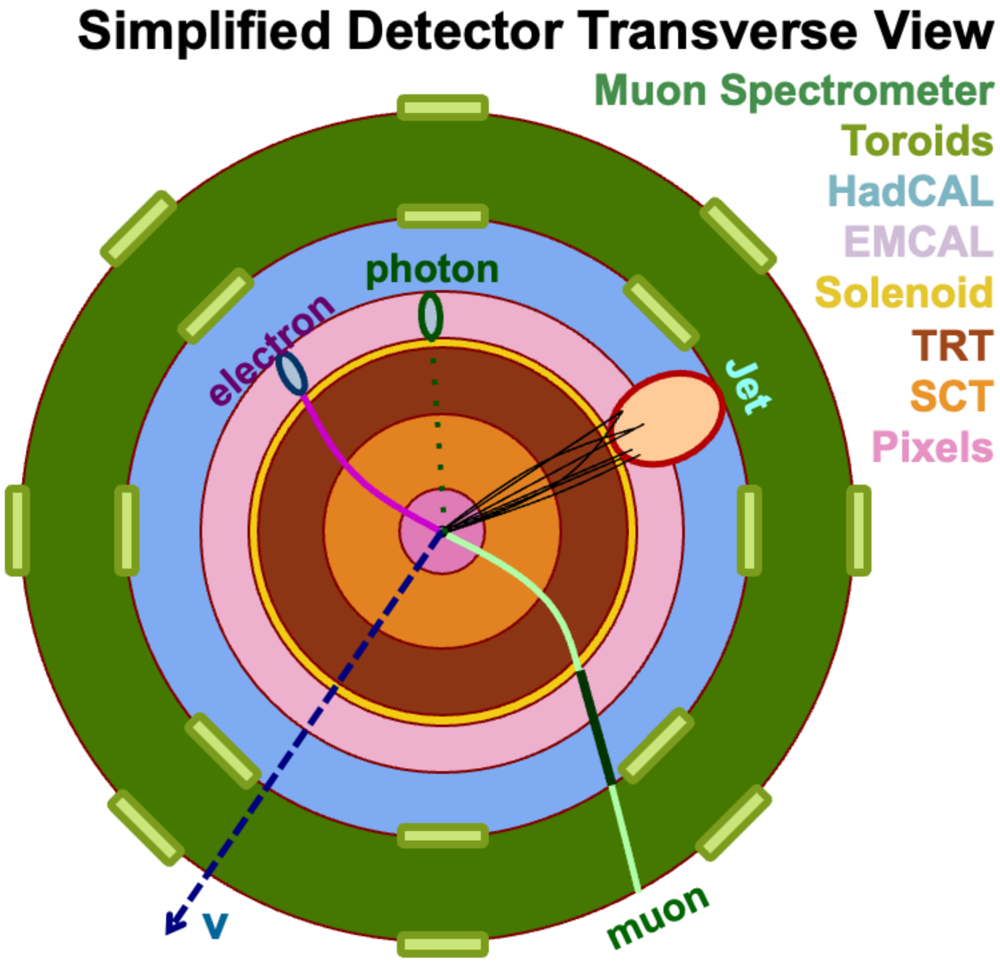
- Combining those:
    - "objects", i.e. "particles"





Missing Transverse Momentum – ME_T

	I	II	III	Bosons
Quarks	2.4 MeV u	1.3 GeV c	170 GeV t	0 γ
	4.8 MeV d	104 MeV s	4.2 GeV b	0 g
				91 GeV Z
Leptons	<2 eV ν_e	<2 eV ν_μ	<2 eV ν_τ	80 GeV W
	0.5 MeV e	16 MeV μ	1.8 GeV τ	126 GeV H



In the transverse plane:

$$\Sigma_i \vec{p}_{T,i} = 0$$

So for what we can't directly measure (e.g. neutrinos)

$$E_{\mathrm{T}}^{\mathrm{miss}} = -\Sigma_i \vec{p}_{T,i}$$

Missing Transverse Momentum – ME_T

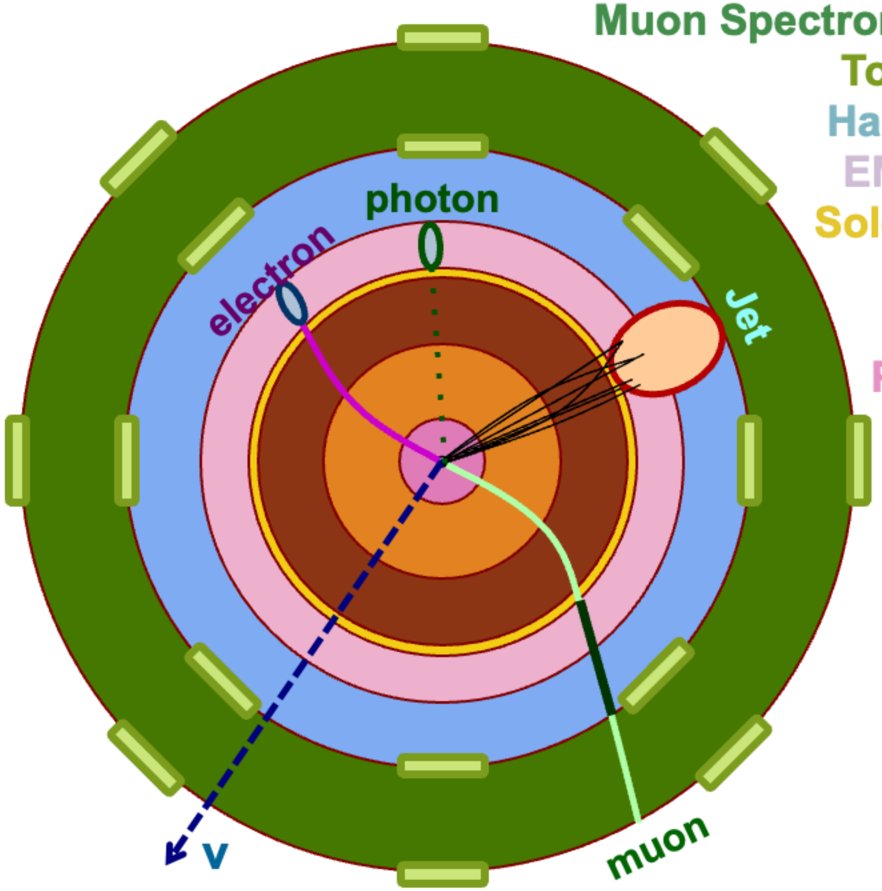
In the transverse plane:

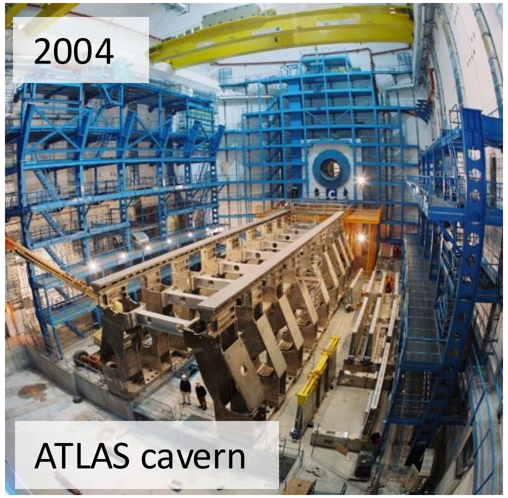
$$\Sigma_i \vec{p}_{T,i} = 0$$

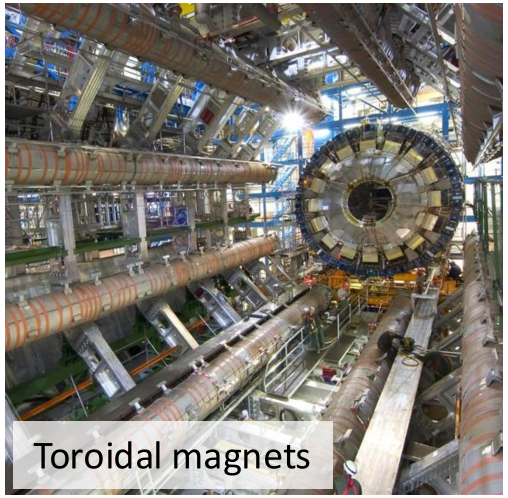
Or dark matter candidates!

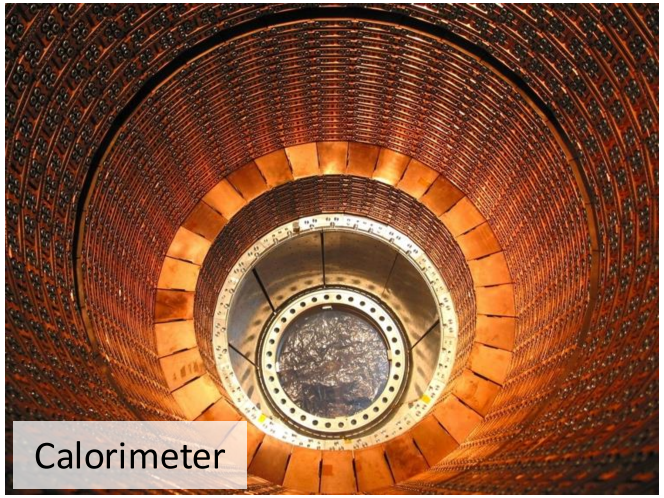
So for what we can't directly measure (e.g. neutrinos)

$$E_{\mathrm{T}}^{\mathrm{miss}} = -\Sigma_i \vec{p}_{T,i}$$

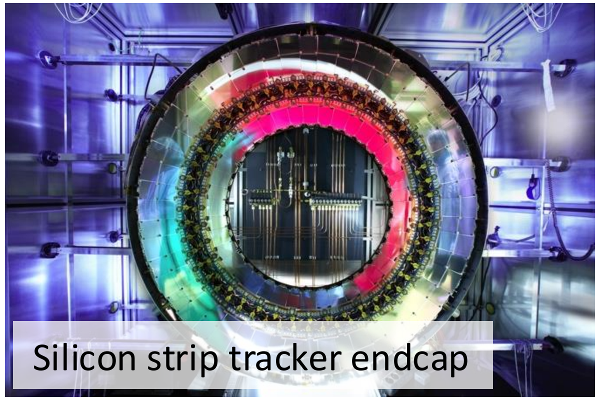


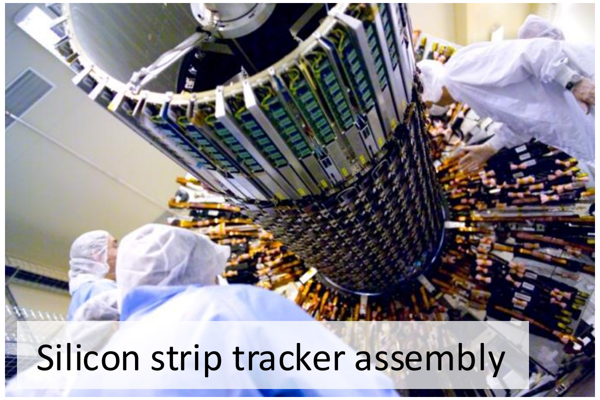

2004
ATLAS cavern

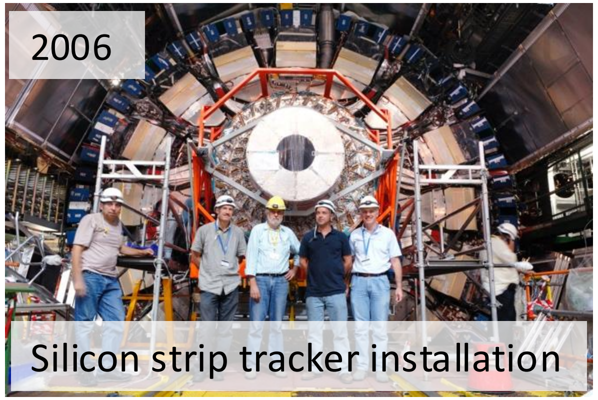

Toroidal magnets


Calorimeter


Pixel tracker

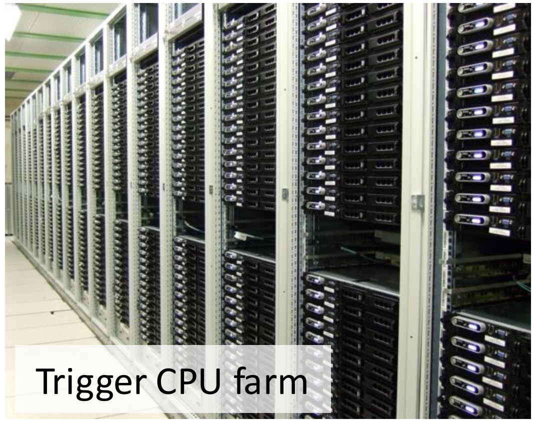

Silicon strip tracker endcap


Silicon strip tracker assembly


2006
Silicon strip tracker installation

ATLAS
EXPERIMENT

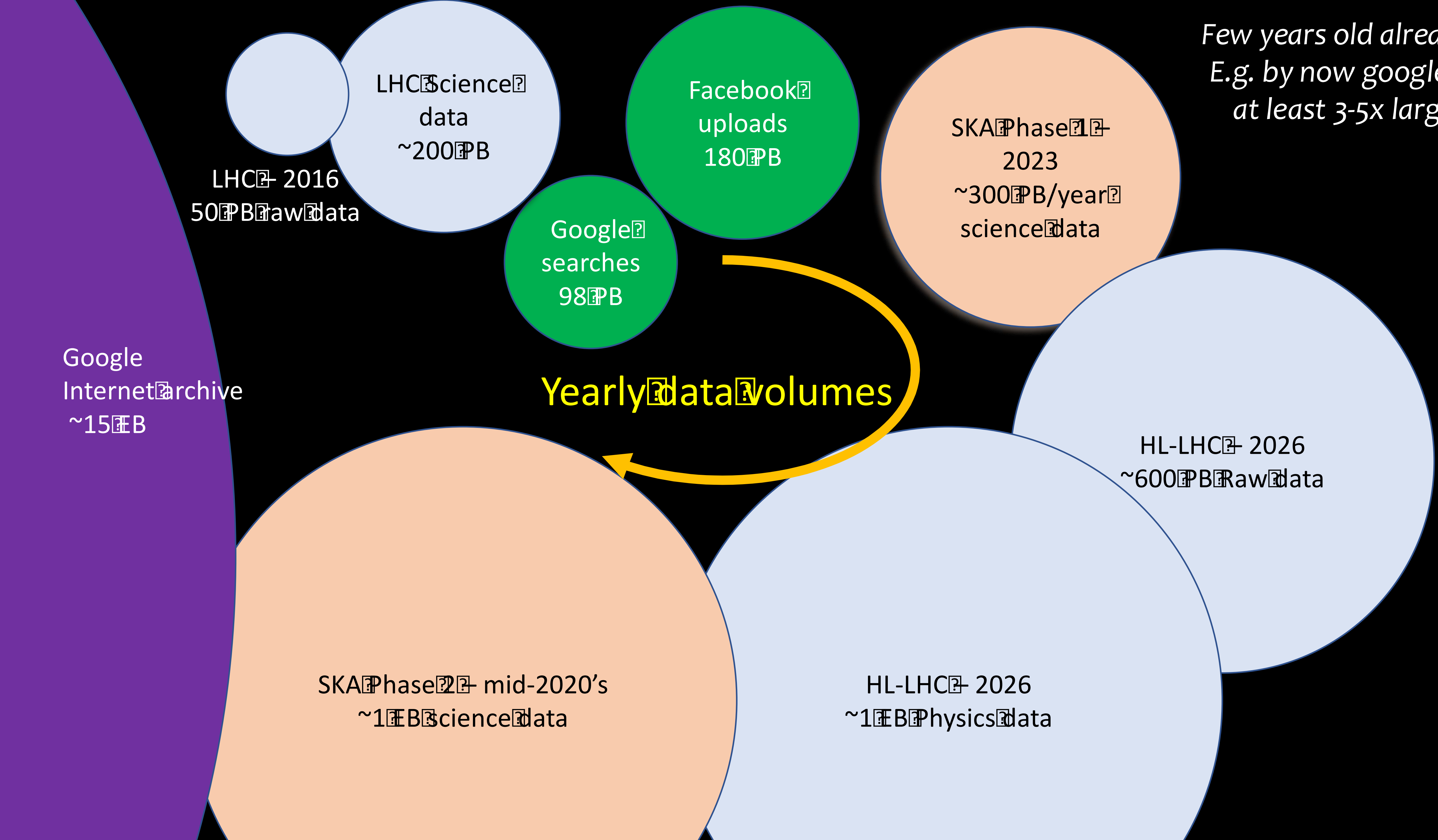

2014
Innermost pixel tracker installation


Trigger CPU farm

(Aspects relevant for all LHC detectors)

- Fast and radiation hard sensors
- Stability and accuracy of constructed structures
- Extremely fast readout systems for low latency processing
- Computing infrastructure to process enormous amounts of data

Few years old already
E.g. by now google is at least 3-5x larger!



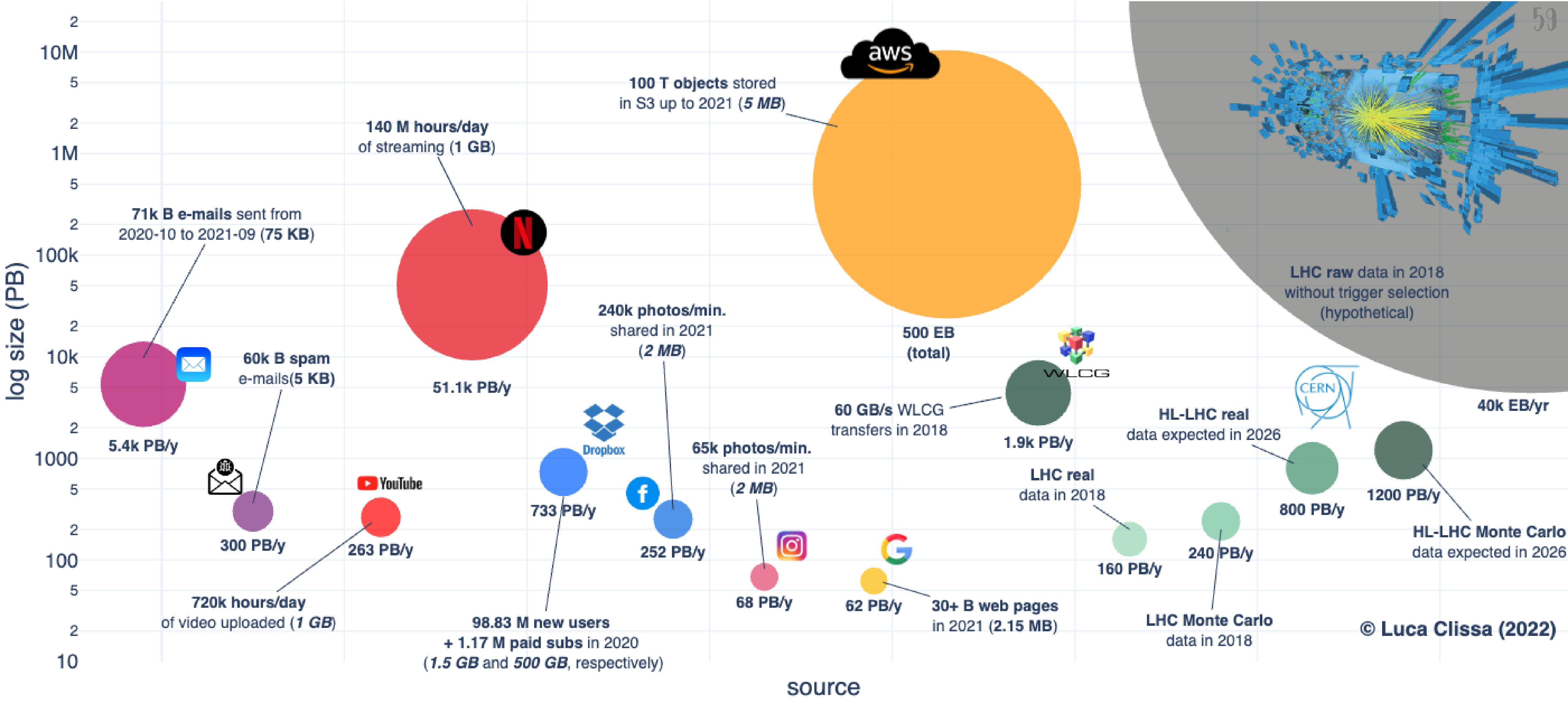


Figure 2.3: **Big Data sizes.** Bubble plot of the orders of magnitude of data produced by important big data players. The balloon areas illustrate the amount of data and the text annotations highlight the key factors considered in the estimates. Average per-unit sizes are reported in parentheses, where italic indicates measures reconstructed based on likely assumptions because no references were found.

https://clissa.github.io/BigData2021/BigData2021.html

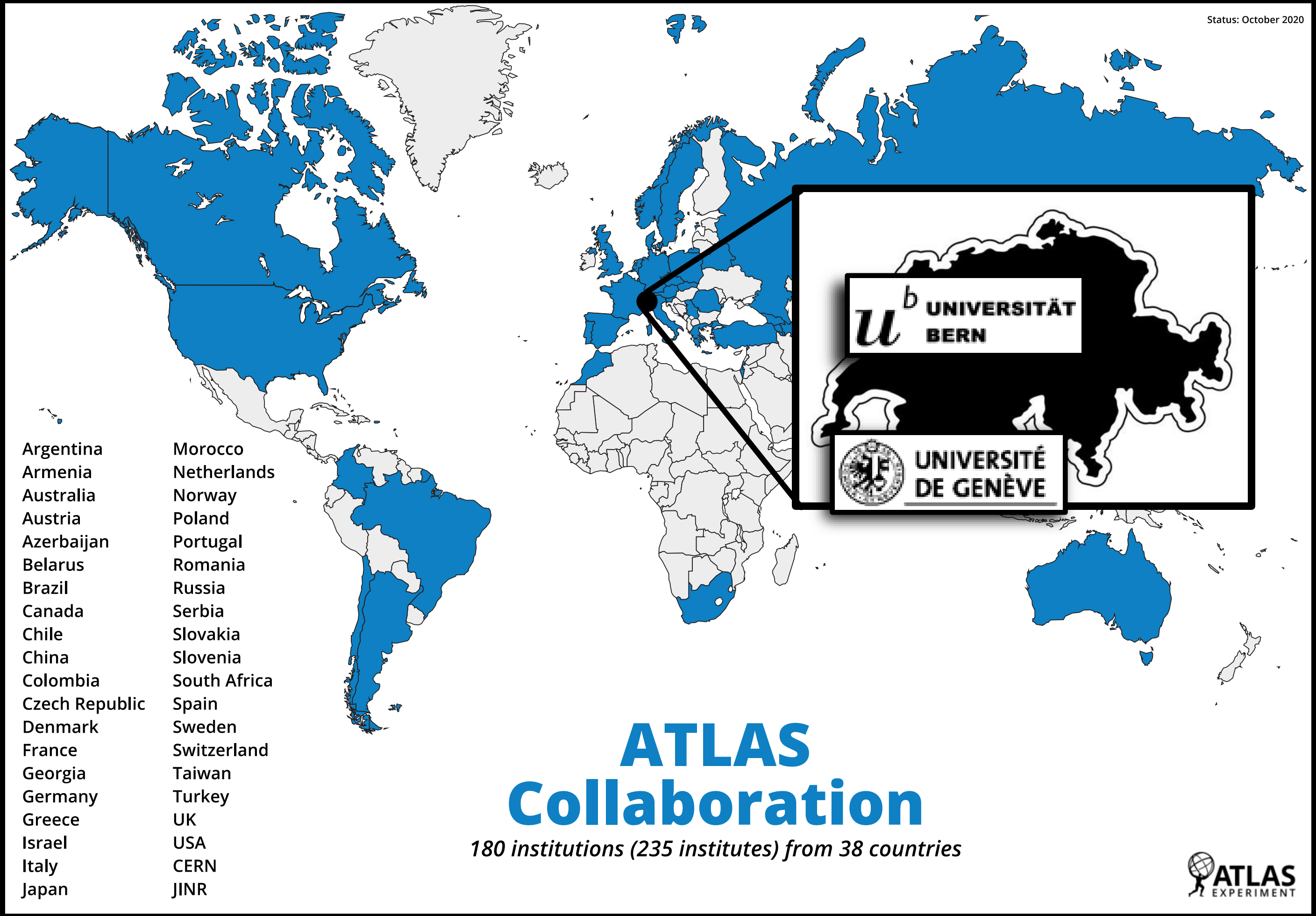
The ATLAS Collaboration

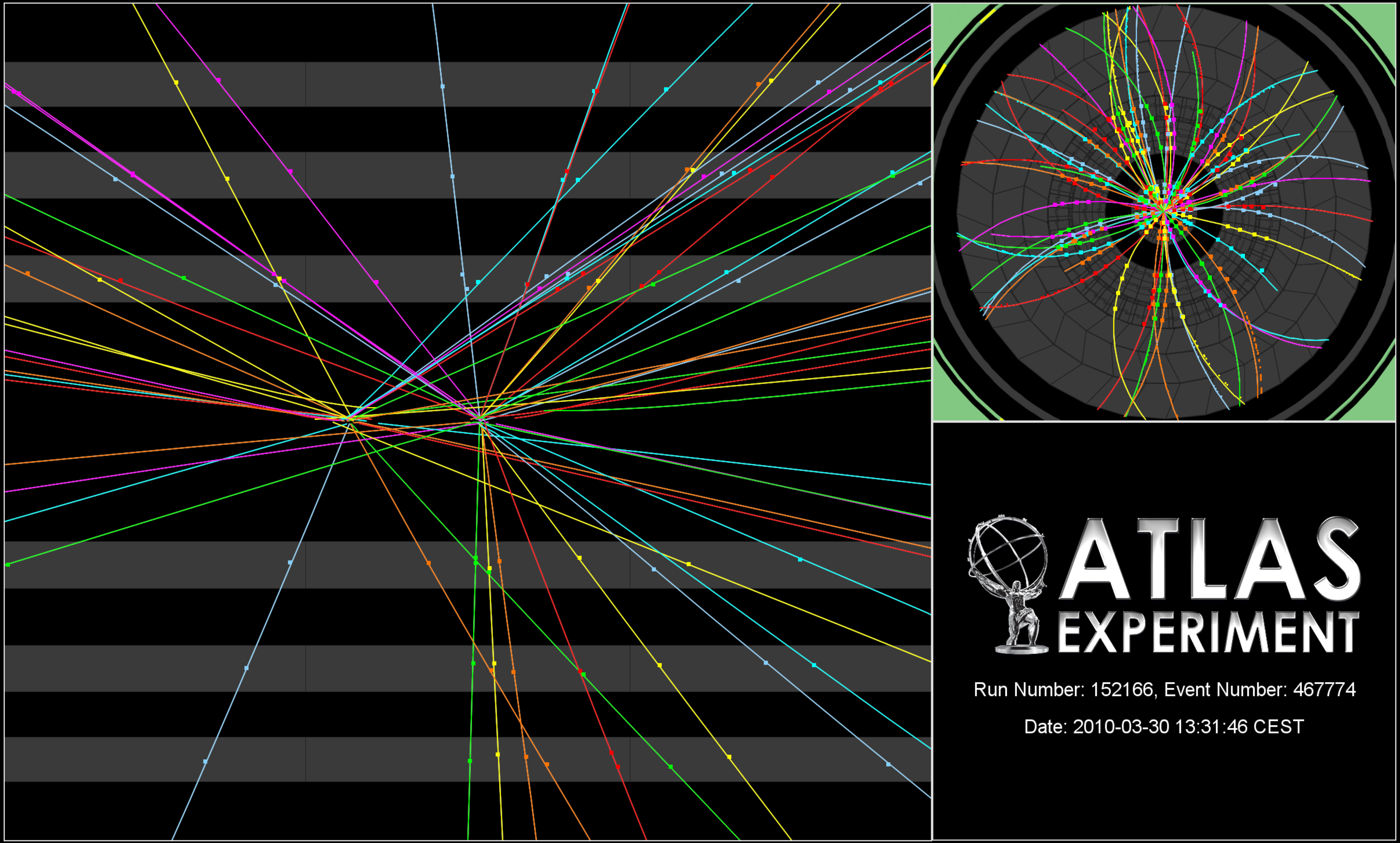
3000
Scientific authors

38
Countries

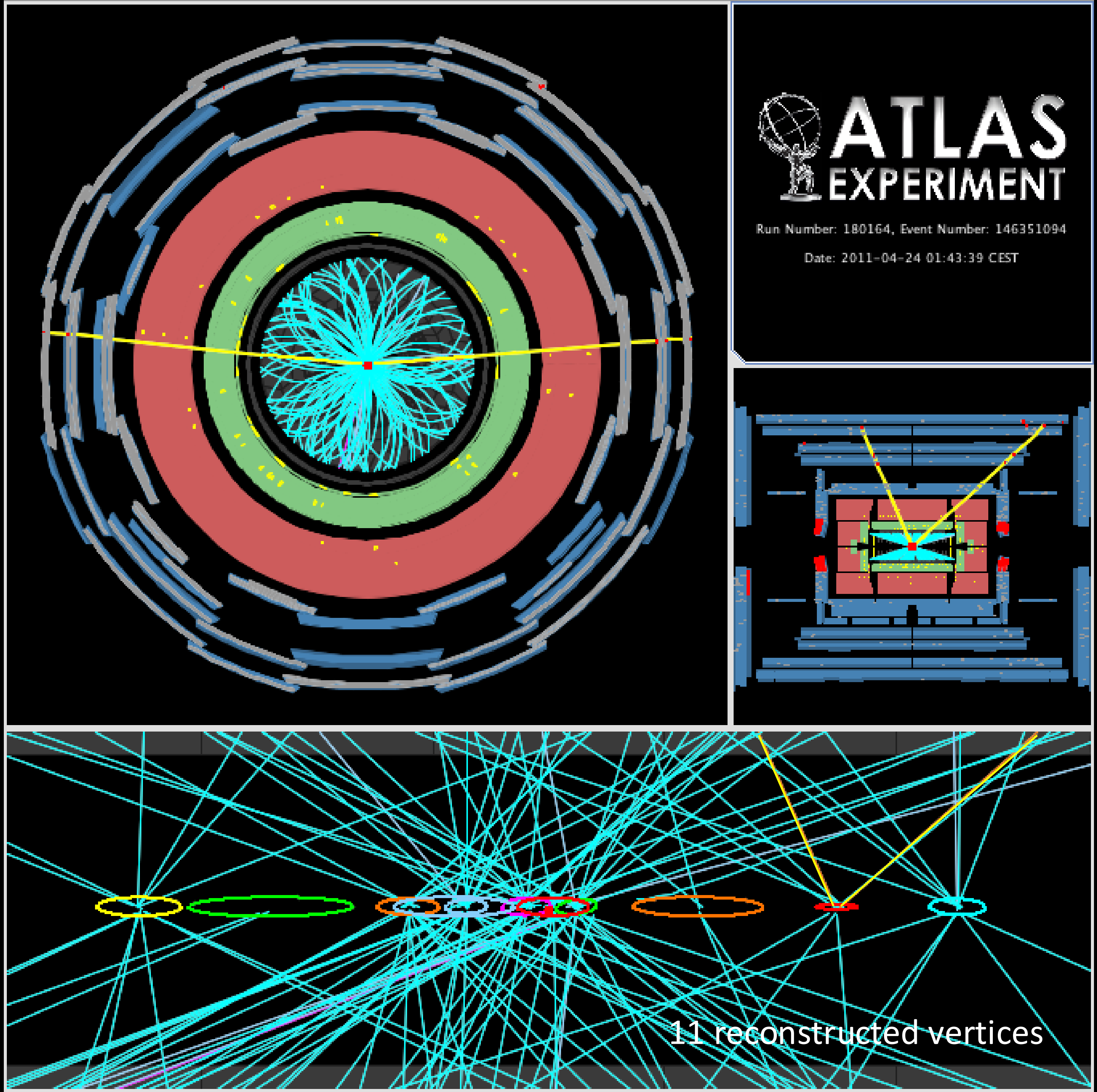
180
Institutions

1200
Doctoral students



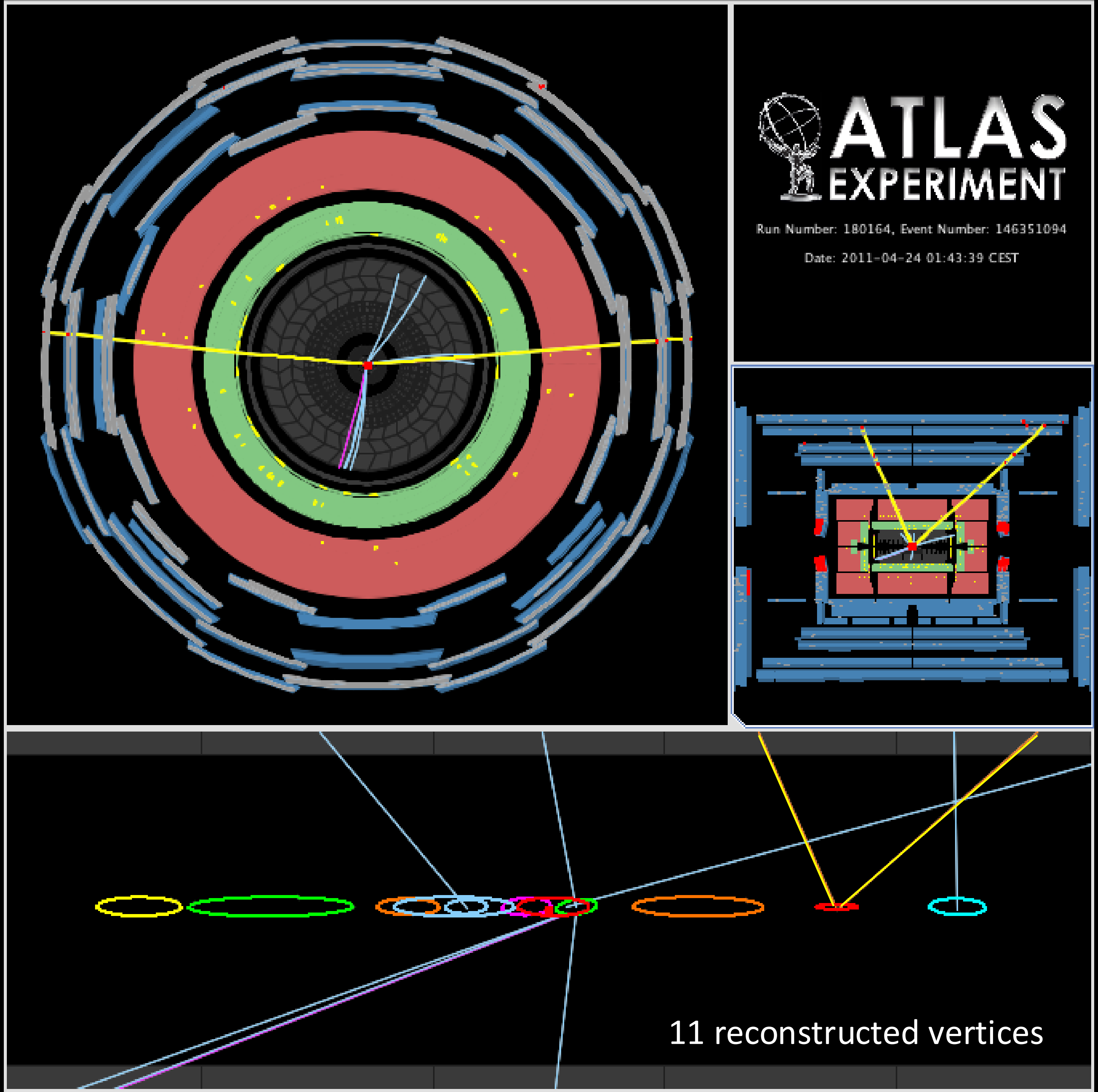


http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html



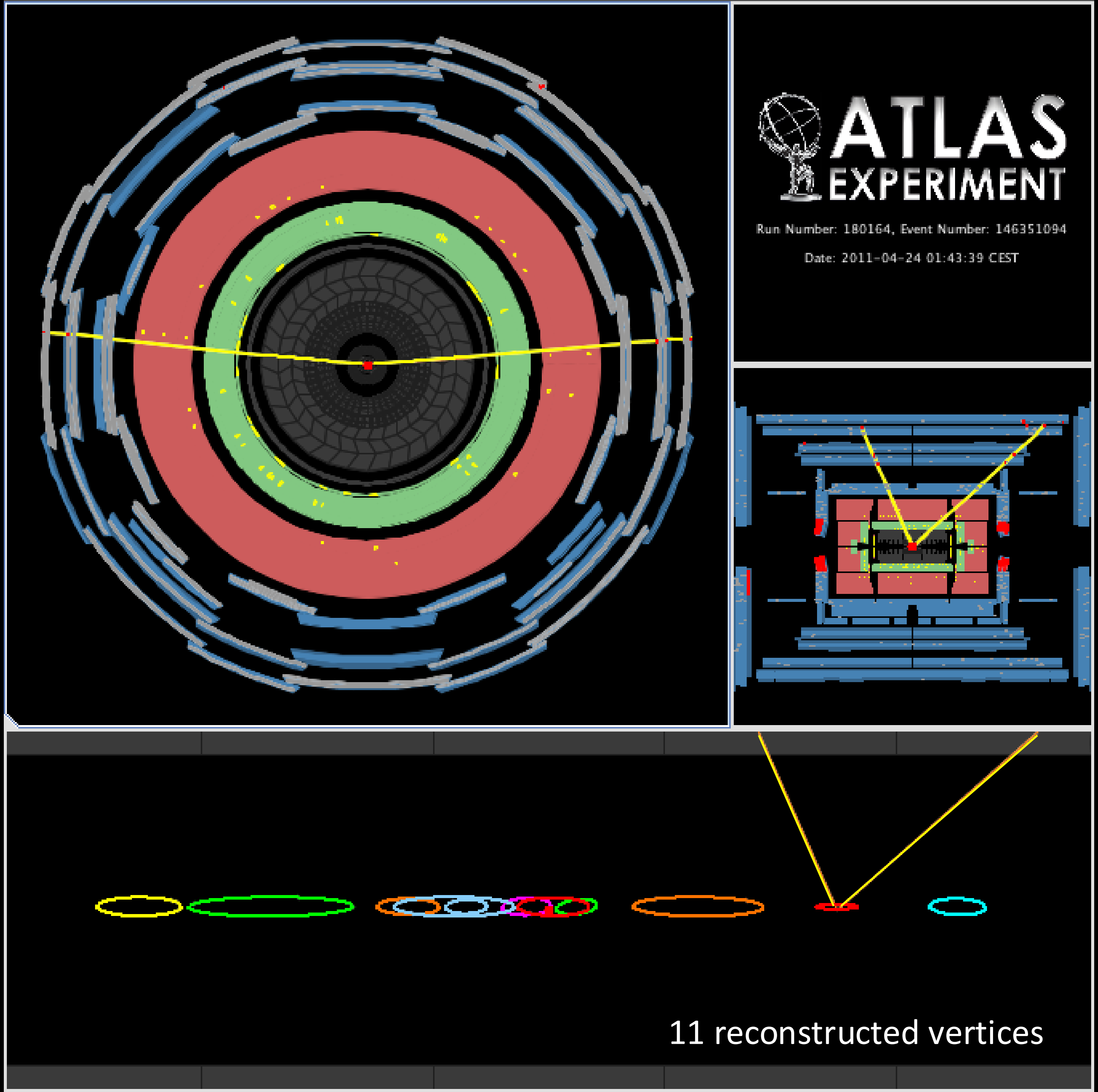
Z->μμ event;
2011 data.

Track pT > 0.5 GeV



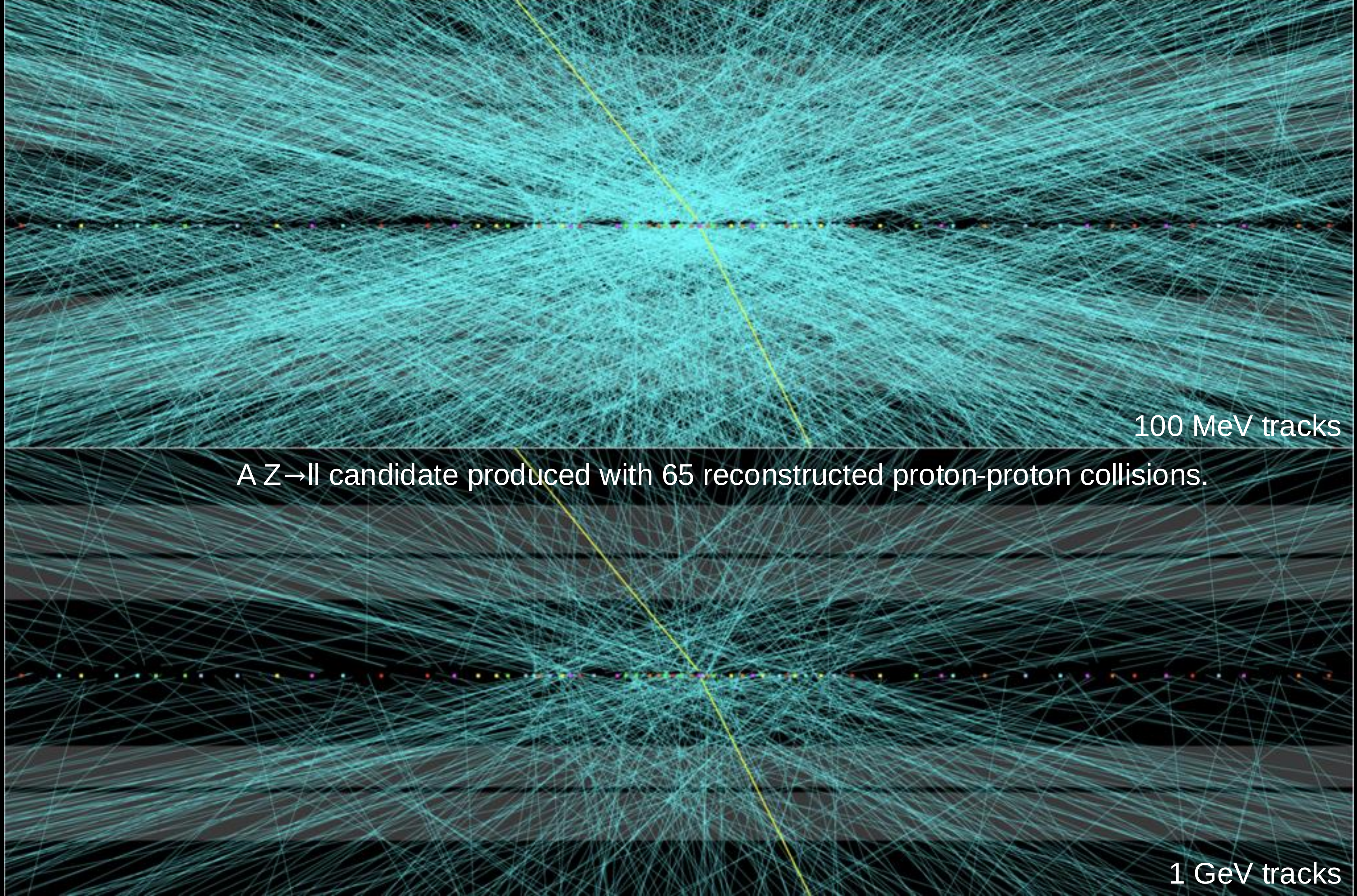
Z->μμ event;
2011 data.

Track pT > 2 GeV

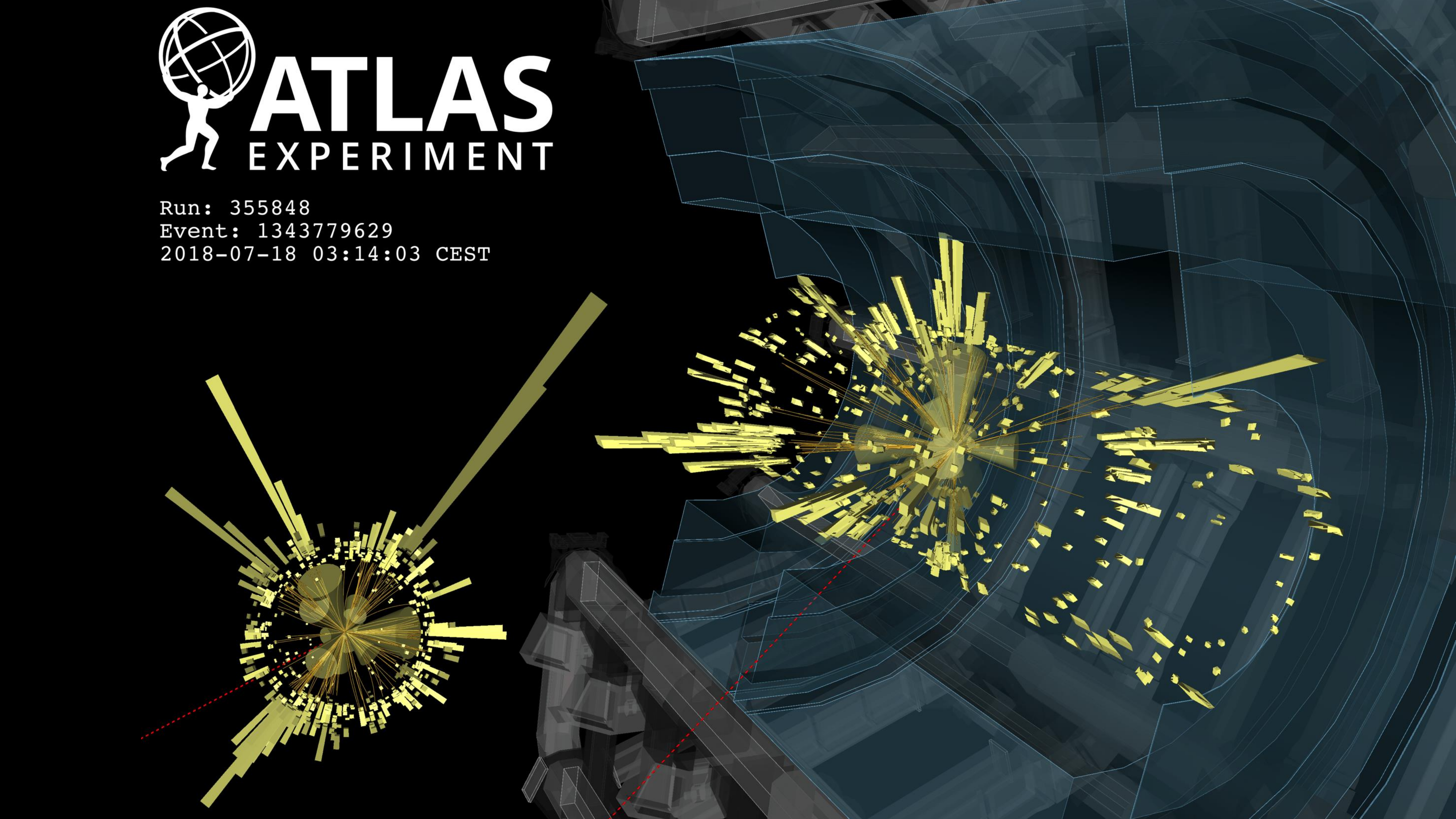


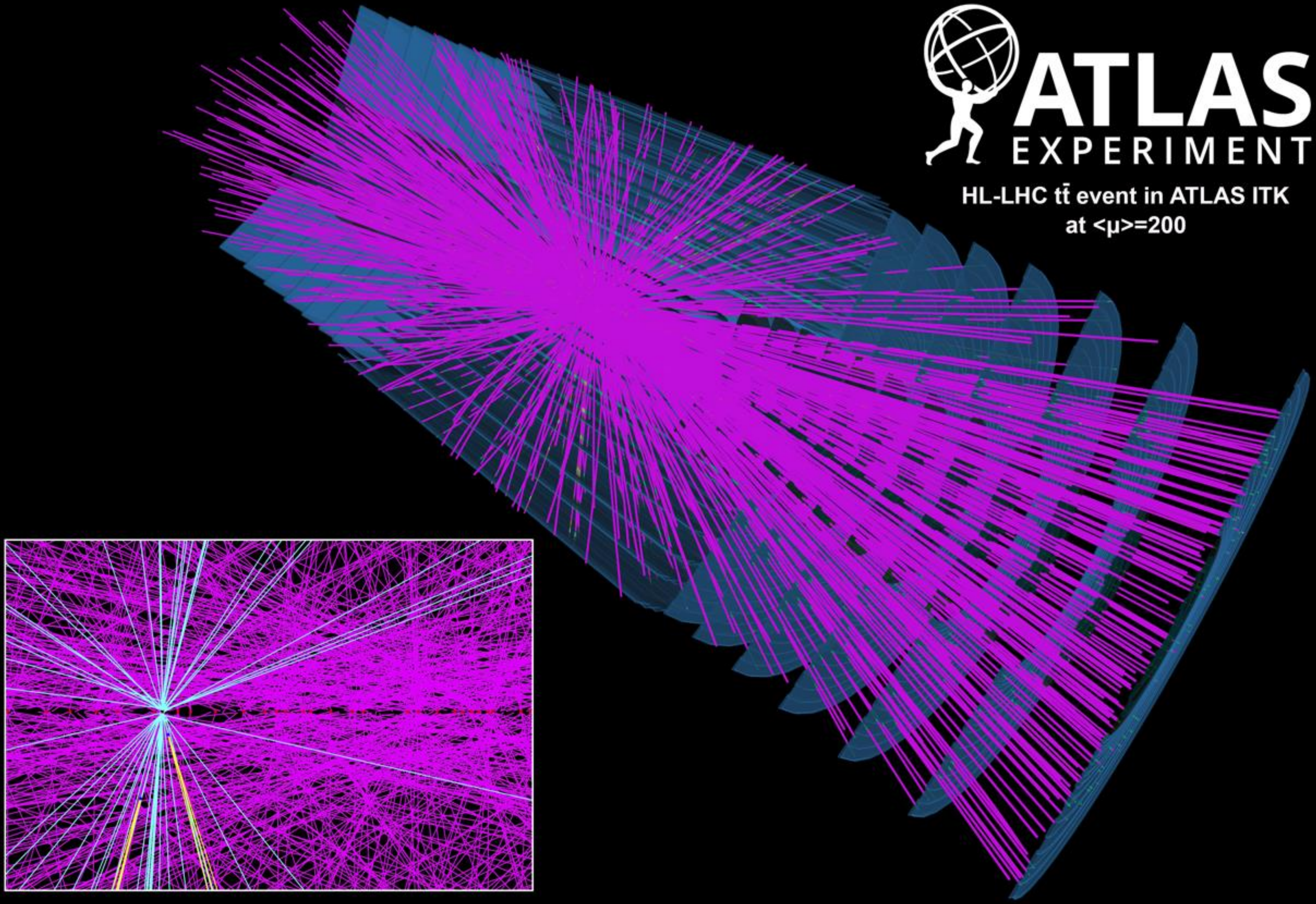
Z->μμ event;
2011 data.

Track pT > 10 GeV



A Z→ll candidate produced with 65 reconstructed proton-proton collisions.


ATLAS
EXPERIMENT
Run: 355848
Event: 1343779629
2018-07-18 03:14:03 CEST



HL-LHC $t\bar{t}$ event in ATLAS ITK
at $\langle\mu\rangle=200$

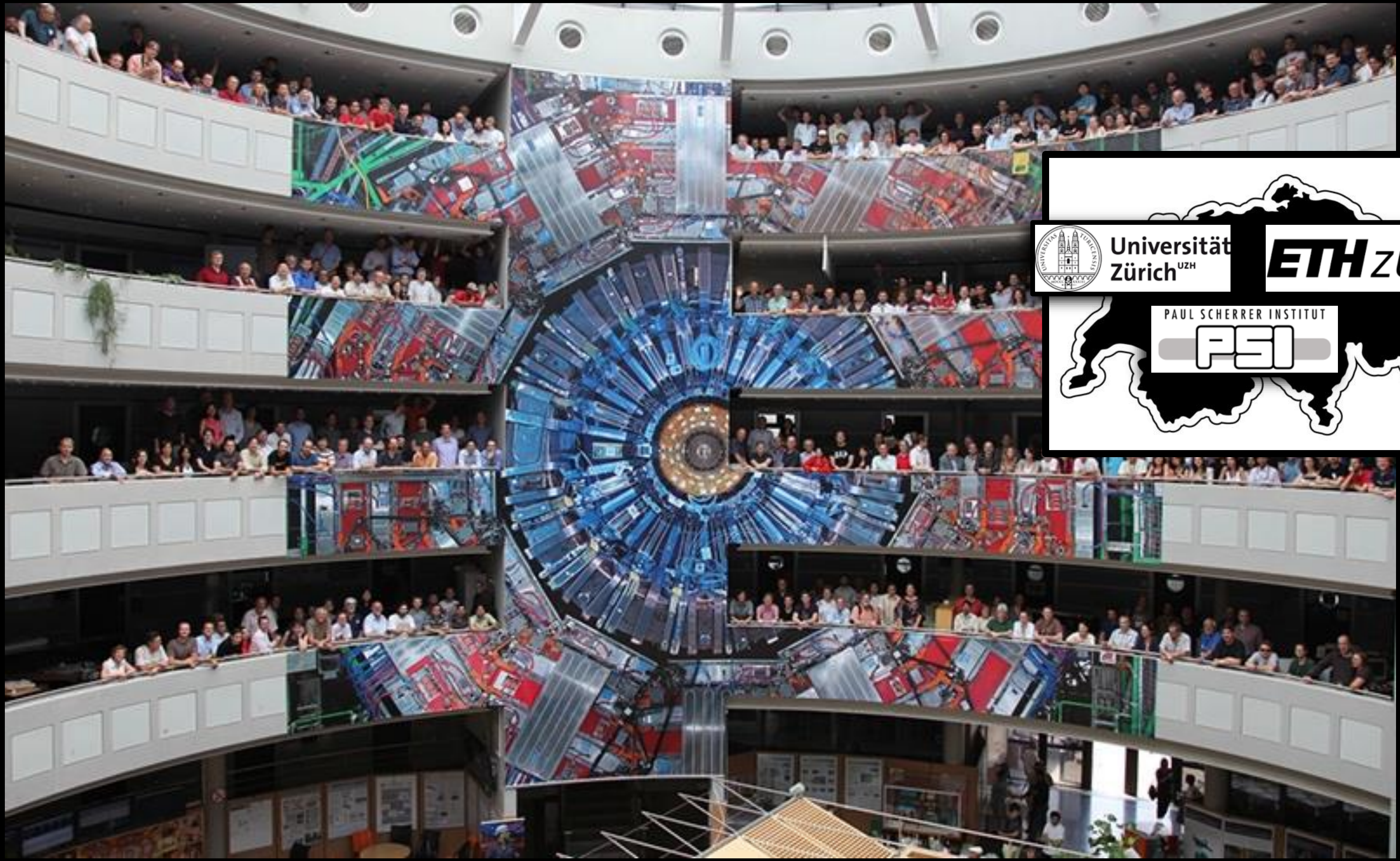
The CMS Collaboration

2100
Scientific authors

51
Countries

229
Institutions

1100
Doctoral students



The LHCb Collaboration

1500
Members

19
Countries

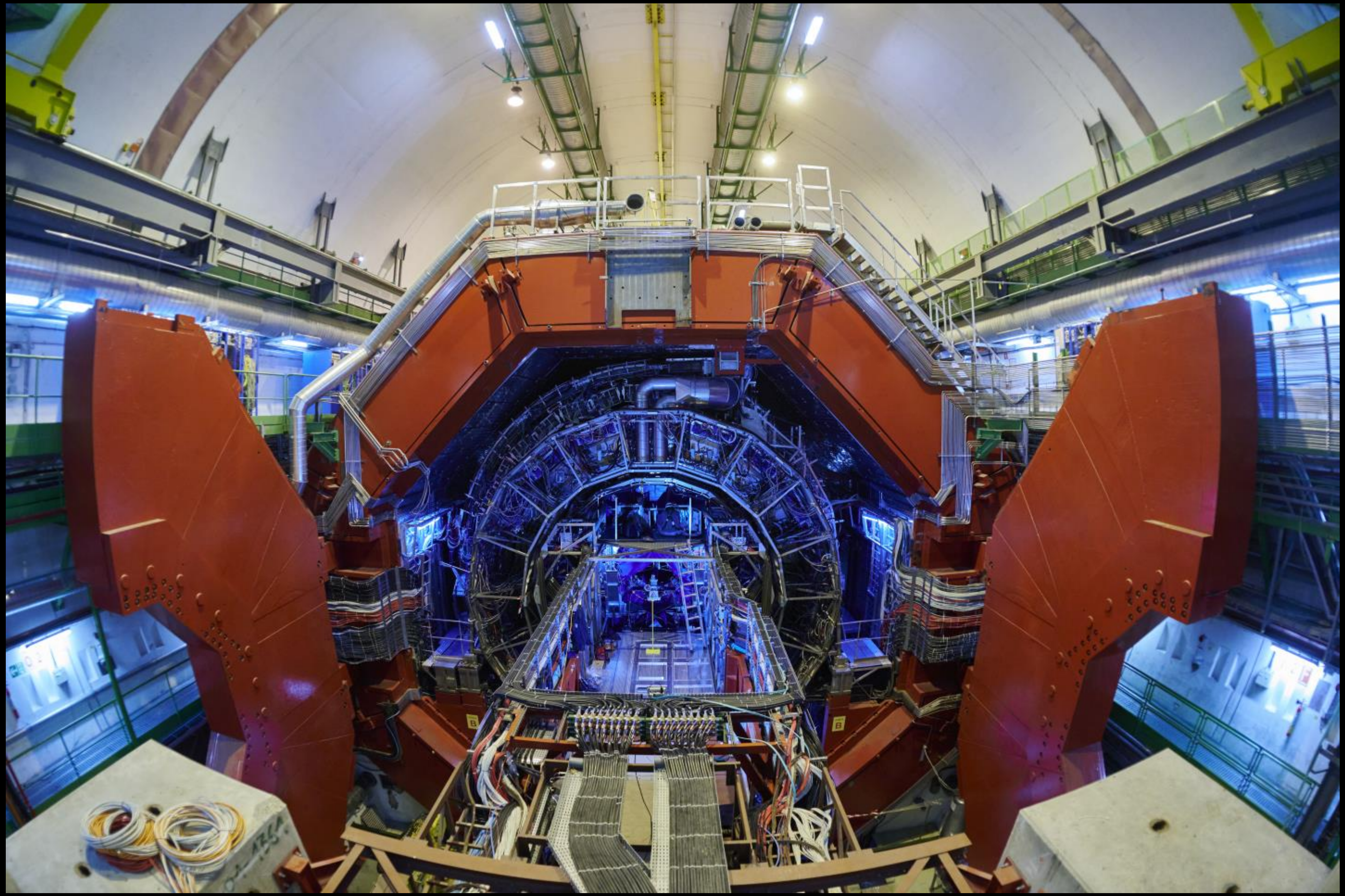
87
Institutions

The ALICE Collaboration

1990
Members

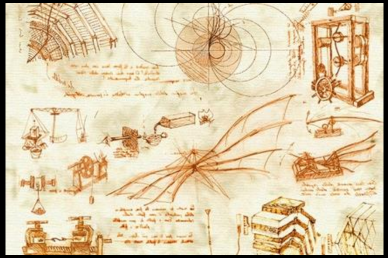
40
Countries

172
Institutions



A bit of LHC history
using CMS as an example

1993



Approval of project

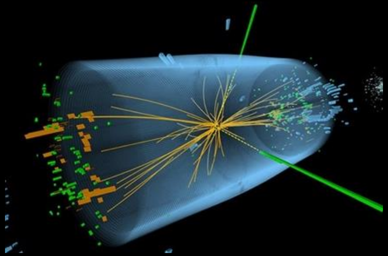
1993 – 2005

R&D

2010

First physics data

2012



Higgs Discovery

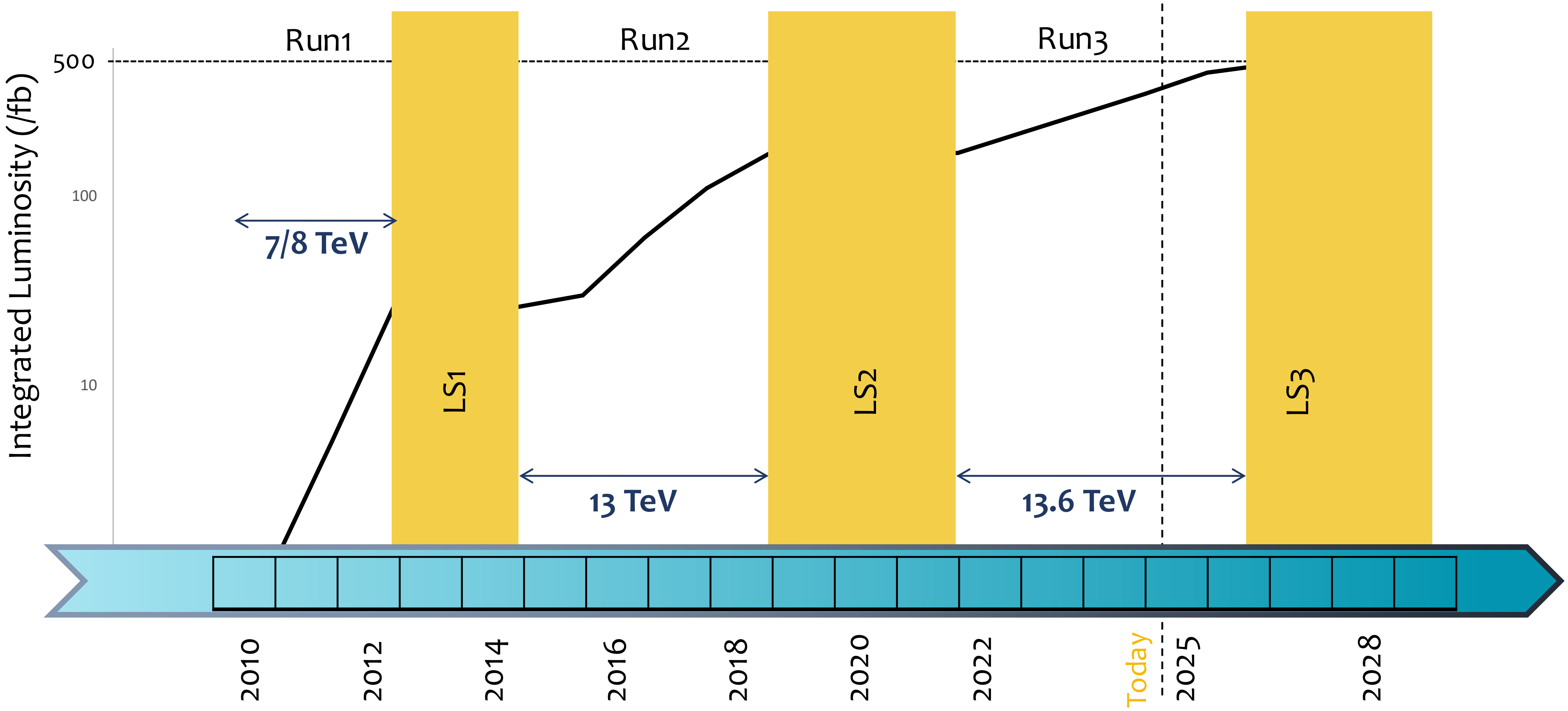
2013

Nobel Prize

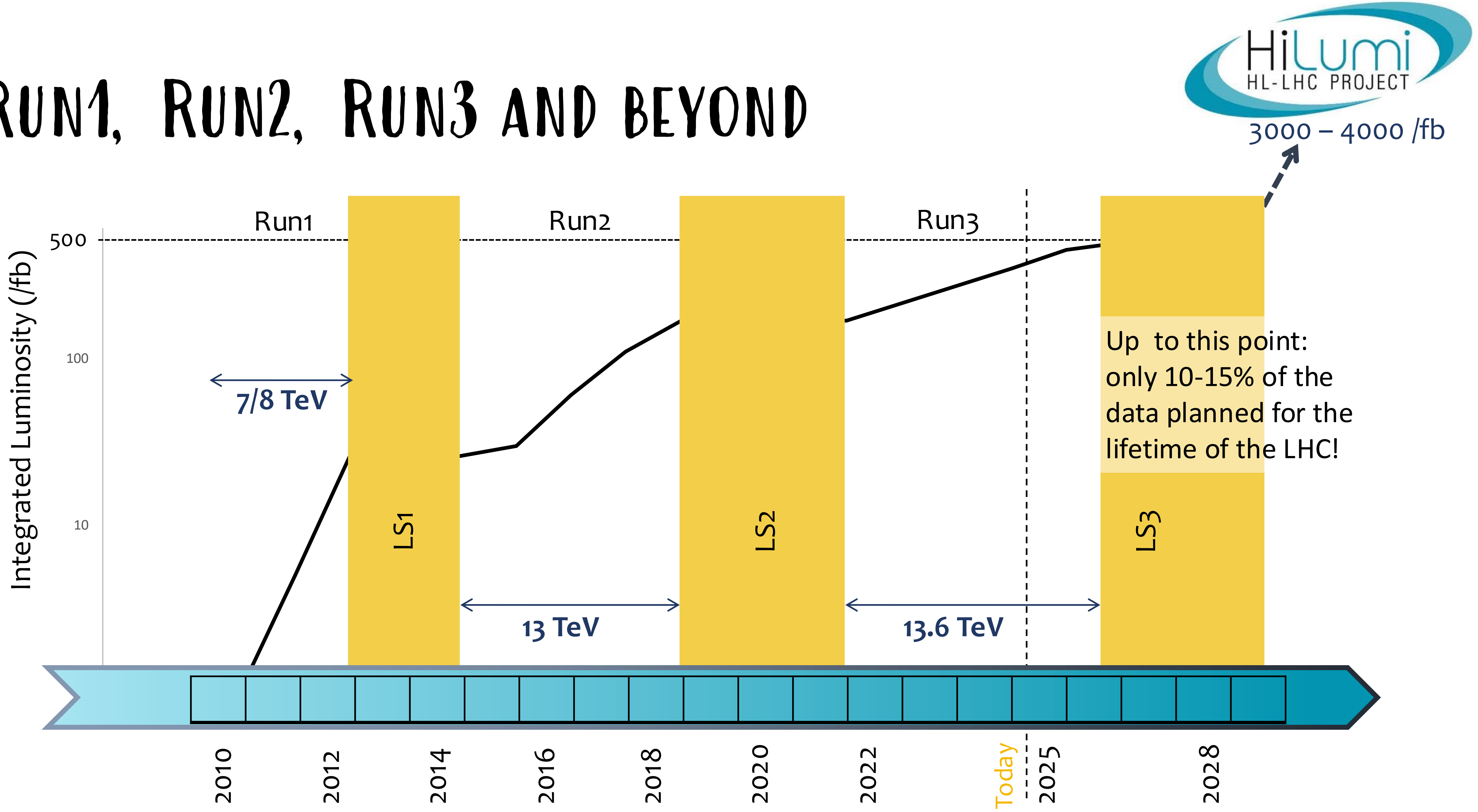
Since then

More data
to probe rare phenomena
& unravel
nature's secrets

Run1, Run2, Run3 ...

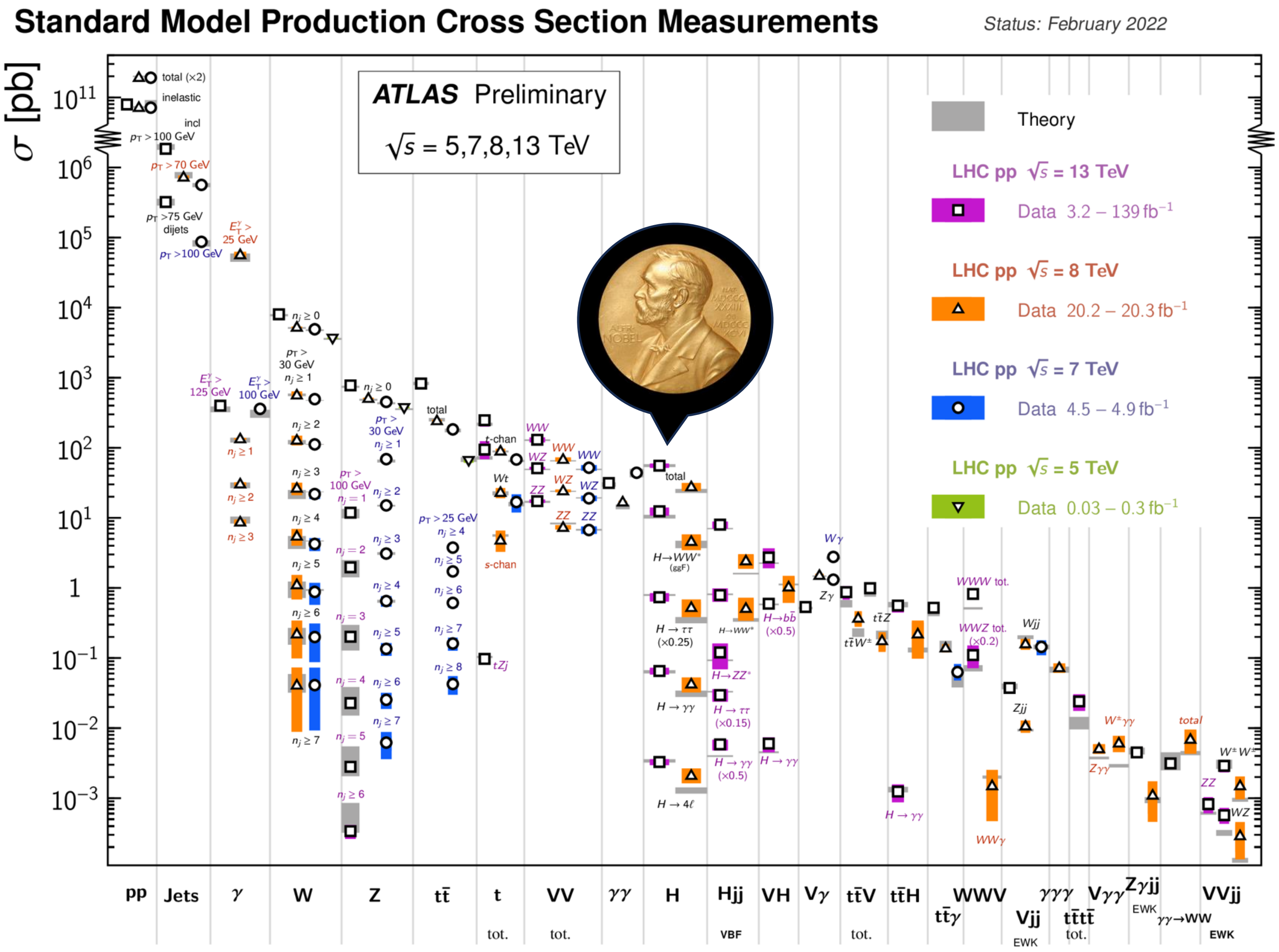


Run1, Run2, Run3 and beyond



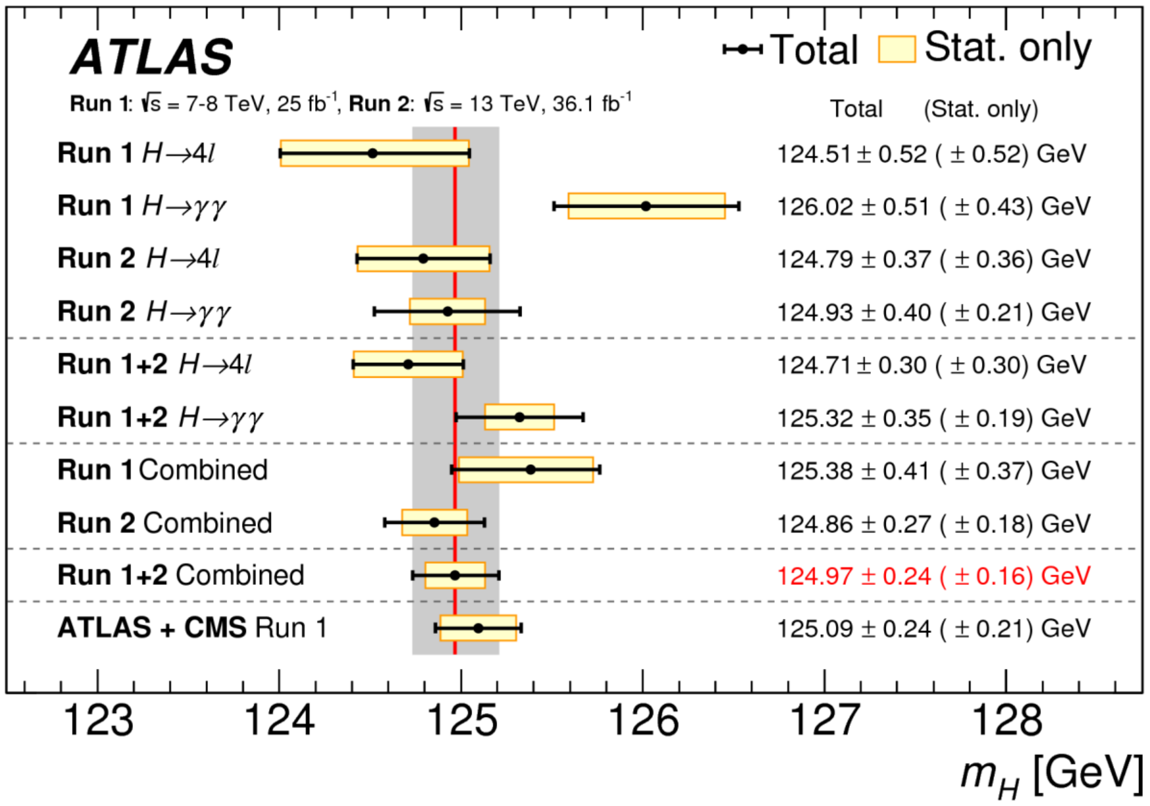
The Landscape of Particles

The Standard Model studied in detail

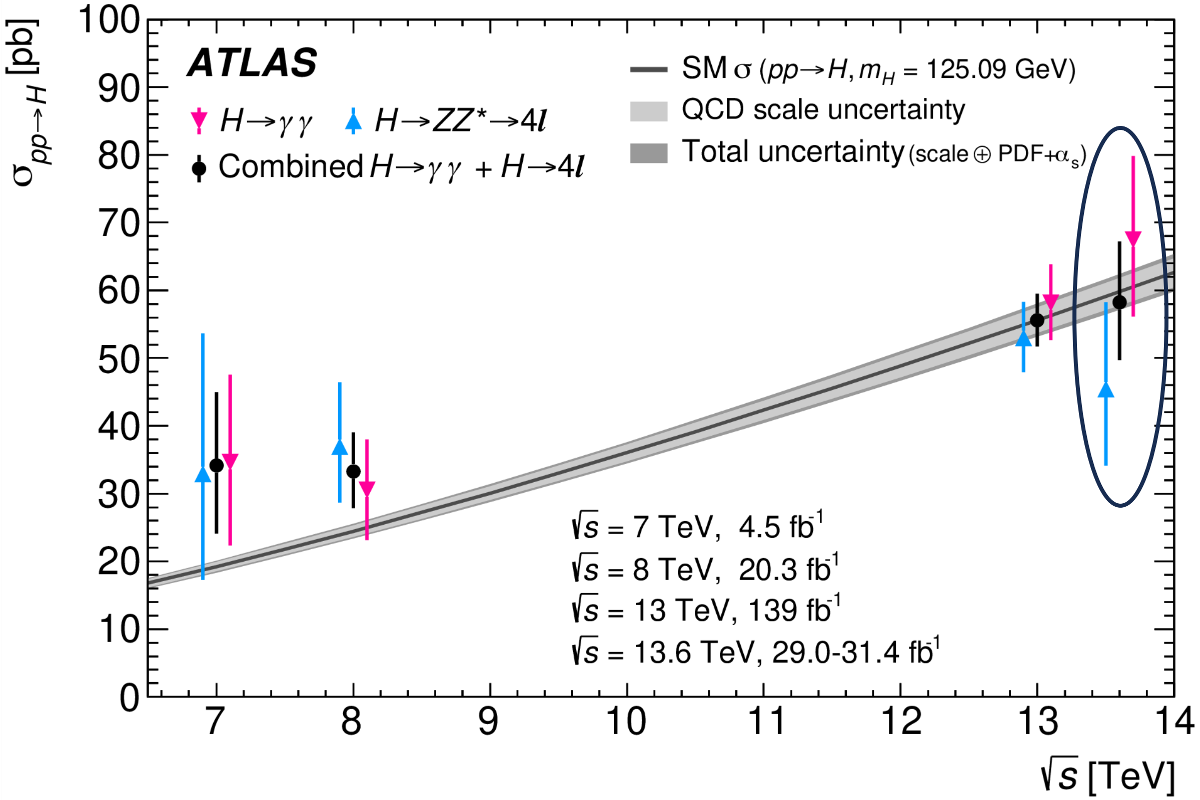


The Higgs Boson

Intense efforts to asses its properties with high precision



Mass

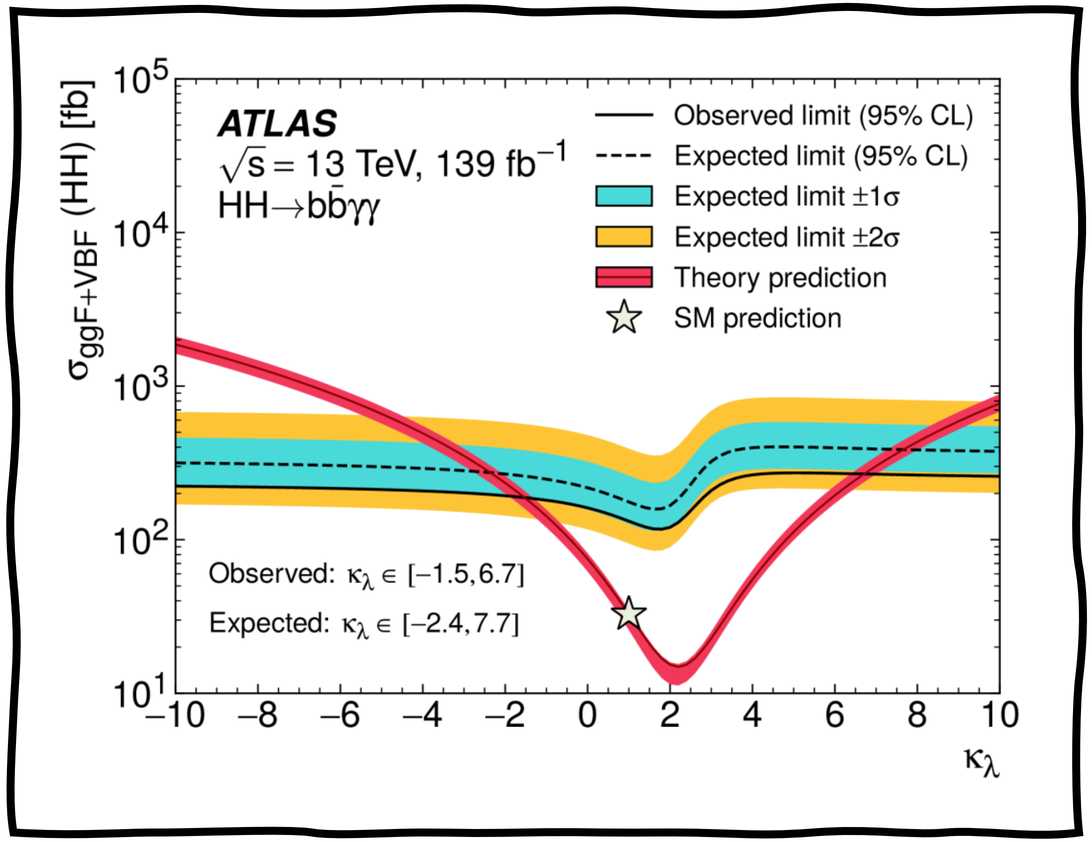


Production cross-section

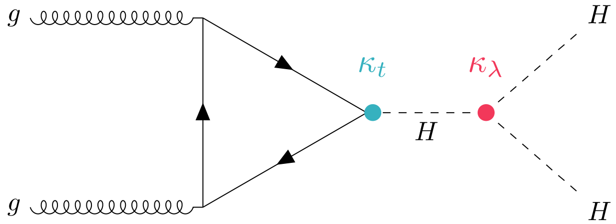
Searches

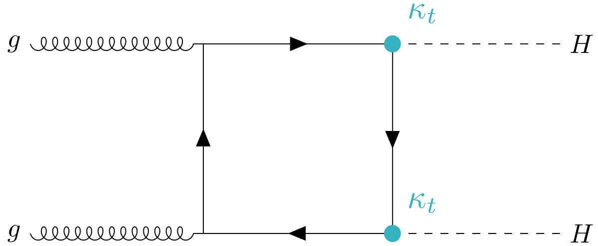
Higgs searches: Processes not yet observed

- There are still SM processes that have not been observed
  - Eg. HH production
  - We don't know if it occurs in rates as the SM predicts

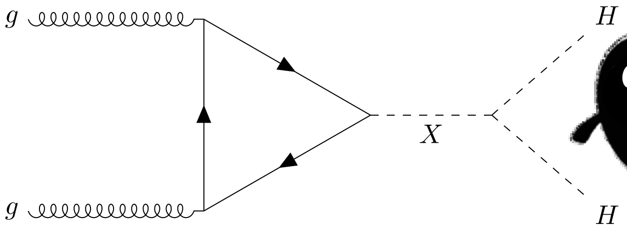


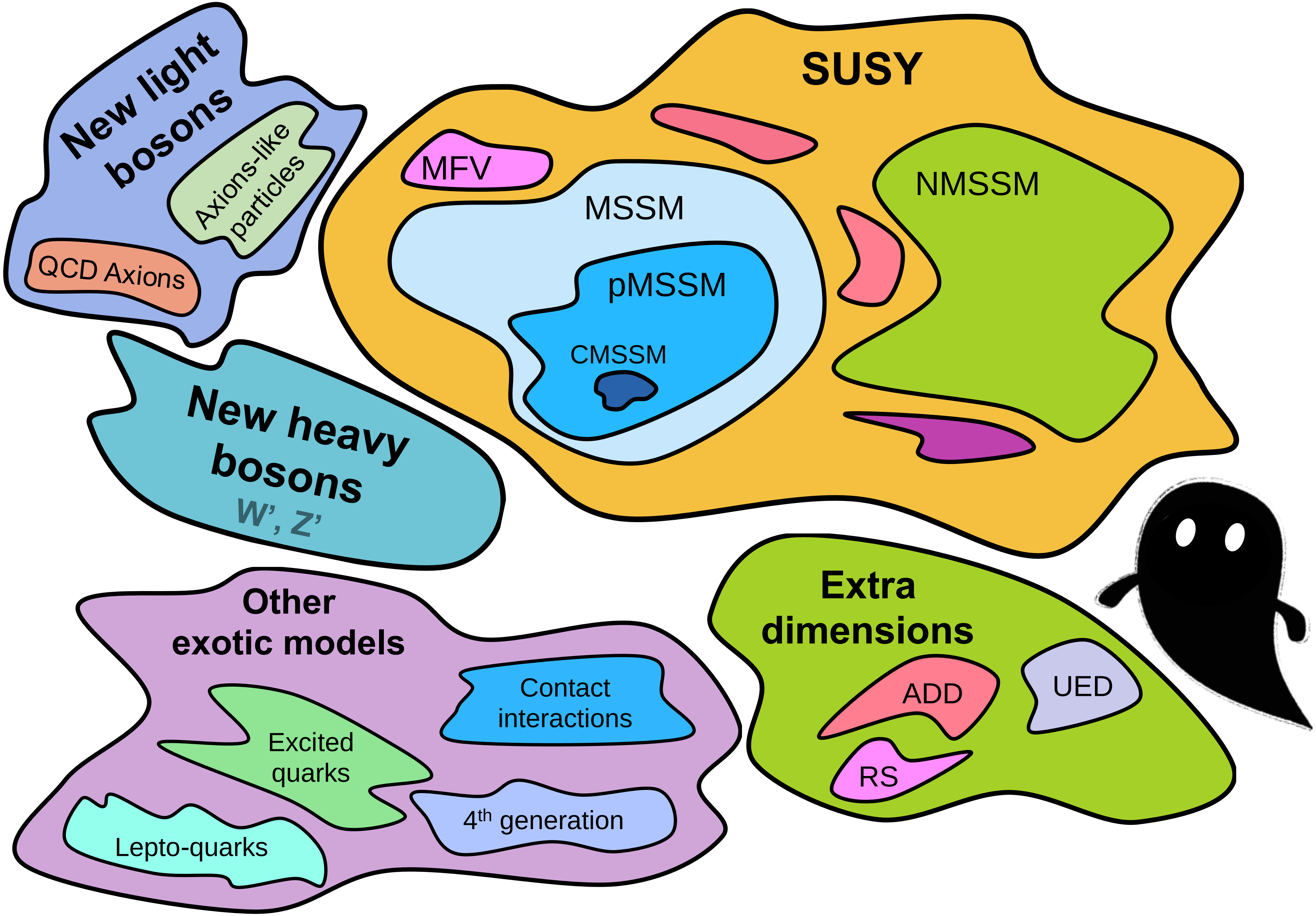
Recent HH->bbγγ results





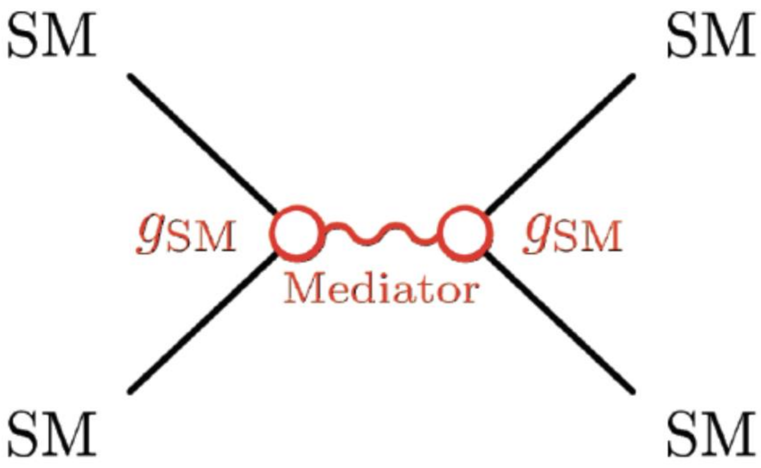
Sensitivity to new physics!



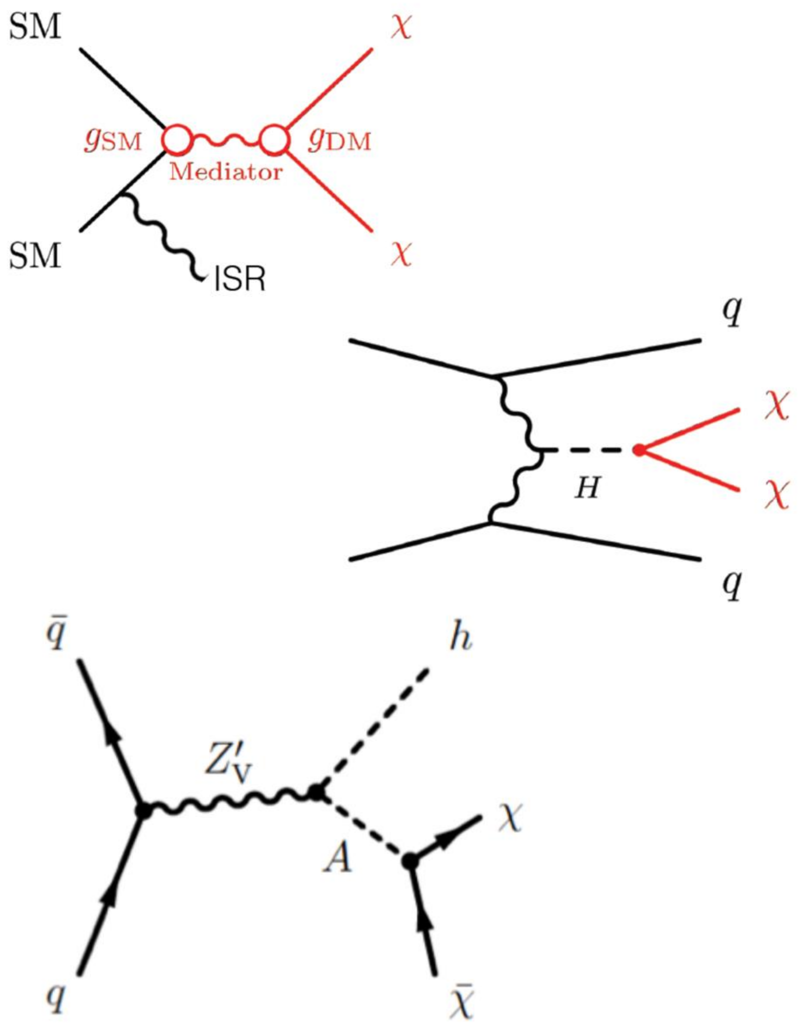

New light bosons
Axions-like particles
QCD Axions
SUSY
MFV
MSSM
pMSSM
CMSSM
NMSSM
New heavy bosons
W', Z'
Other exotic models
Contact interactions
Excited quarks
4th generation
Lepto-quarks
Extra dimensions
ADD
UED
RS

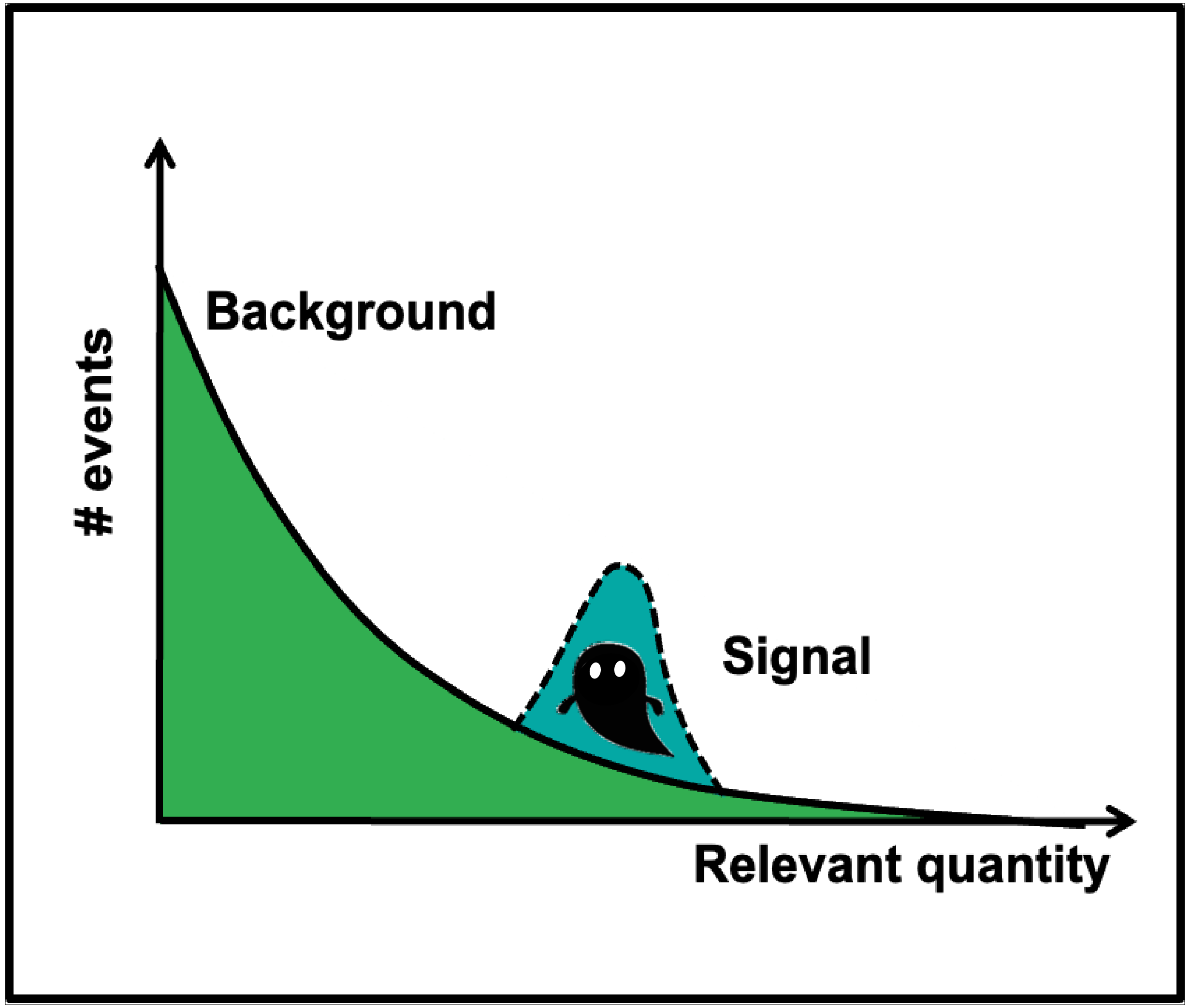
Dark Matter Searches

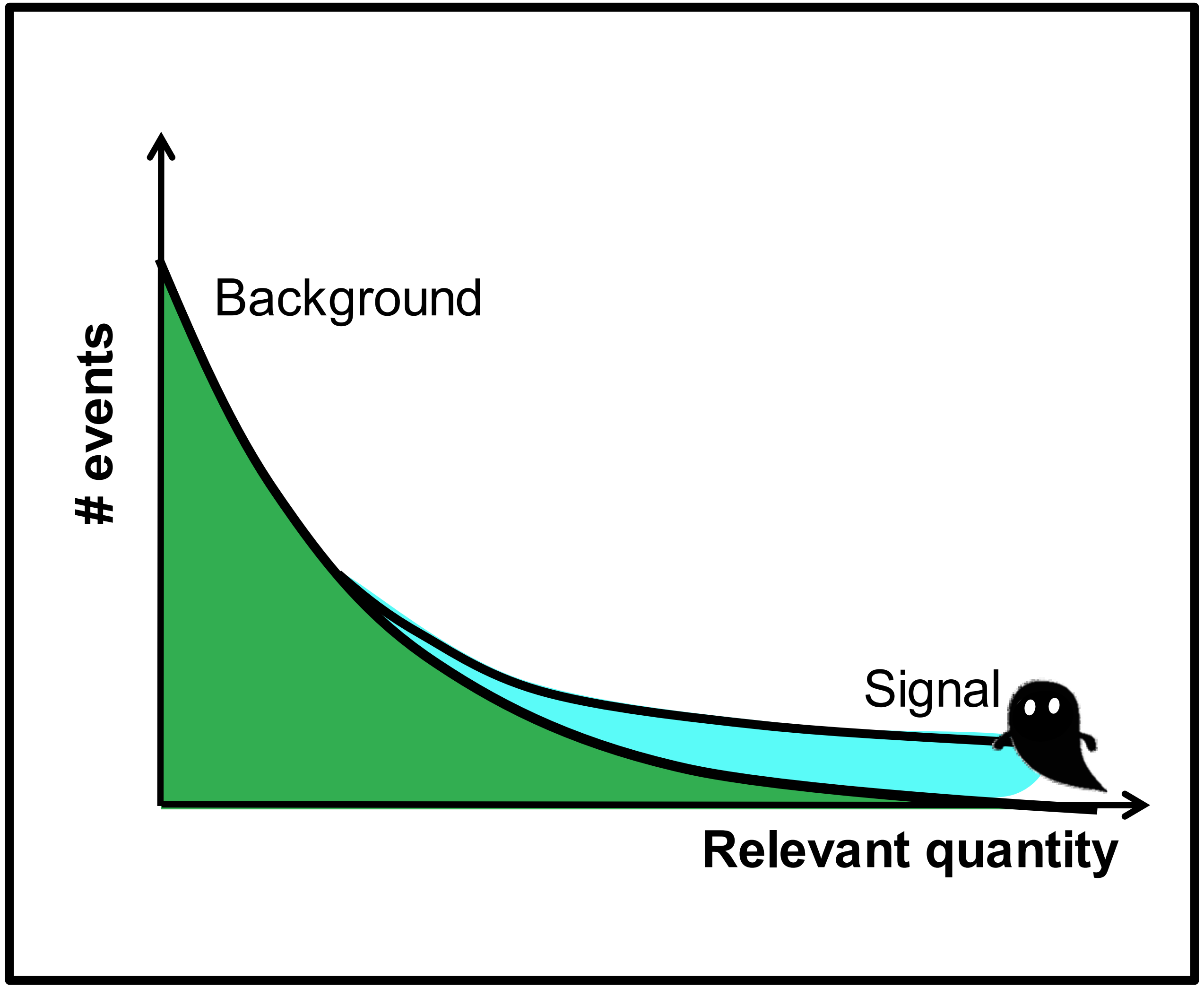
Mediator searches

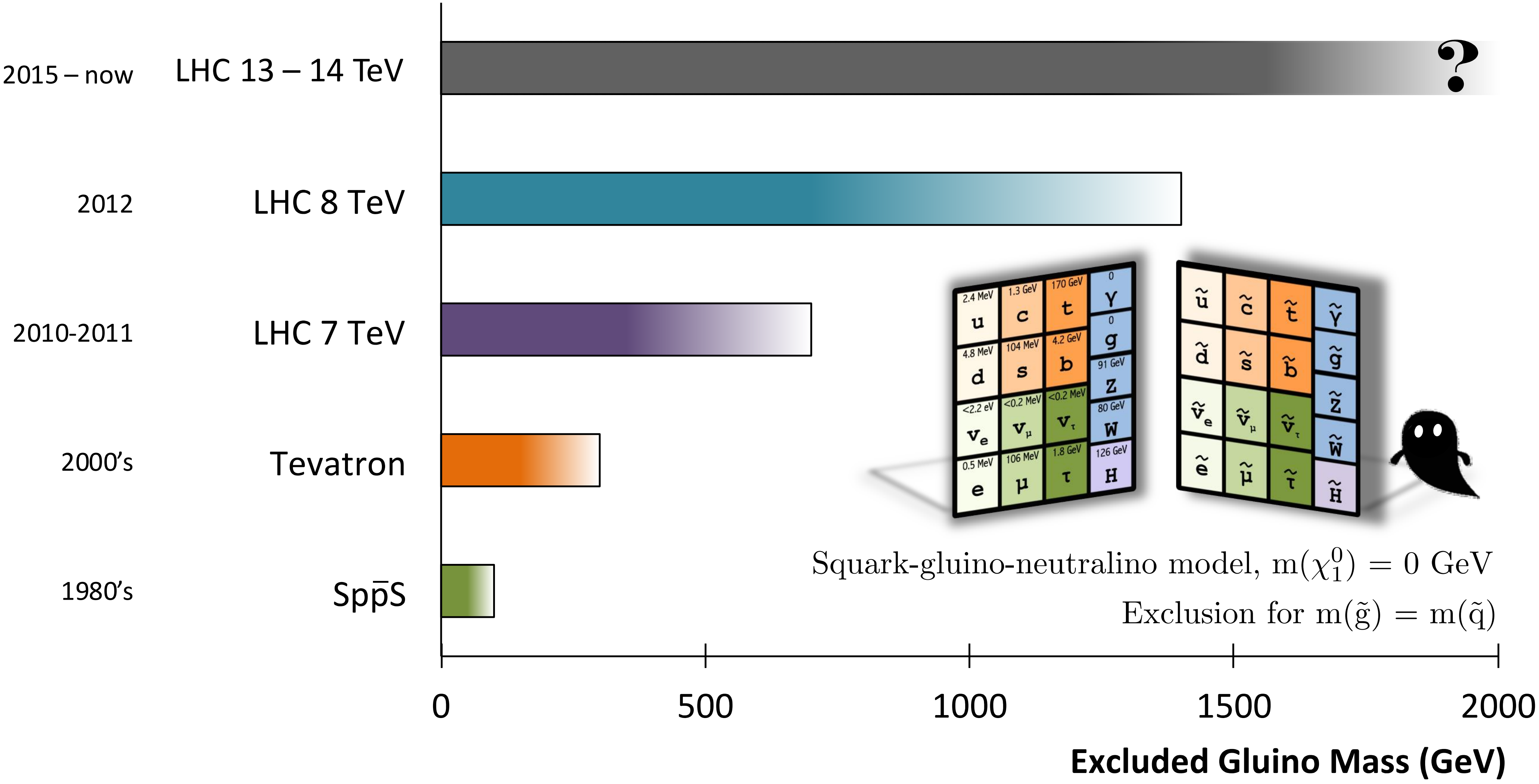


Direct searches

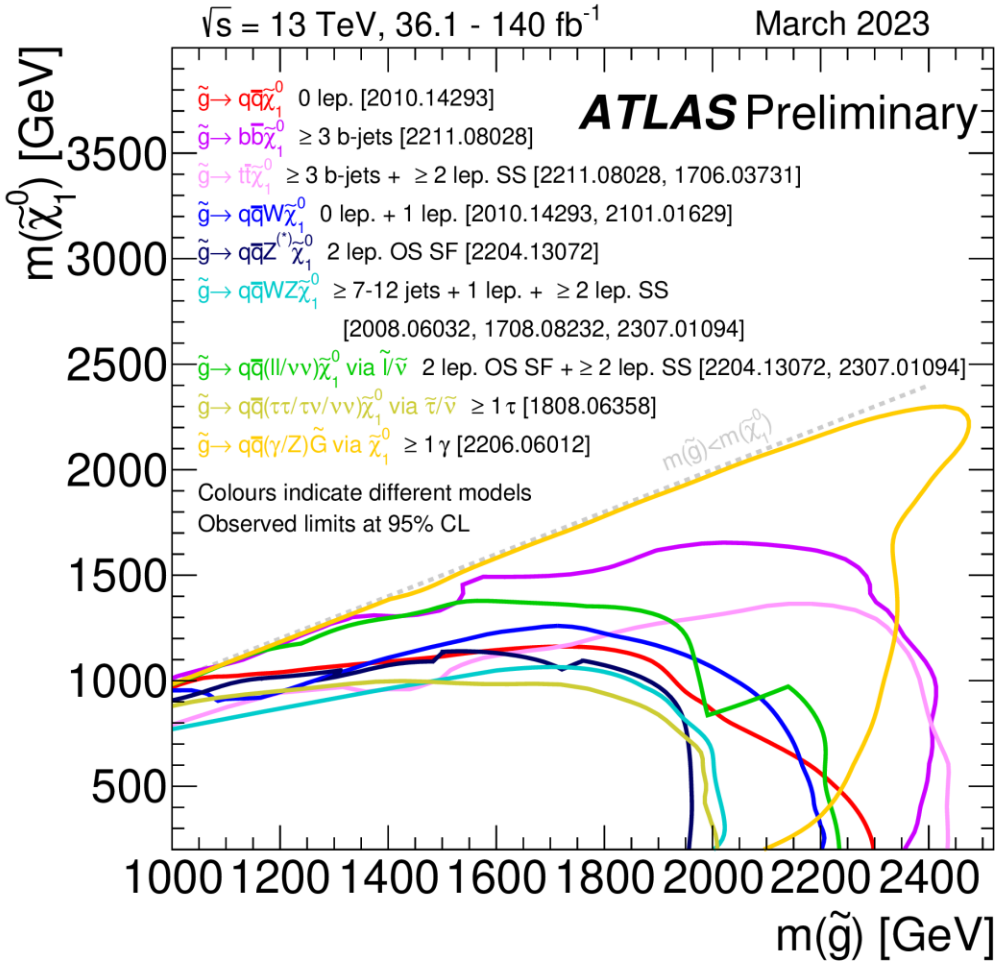


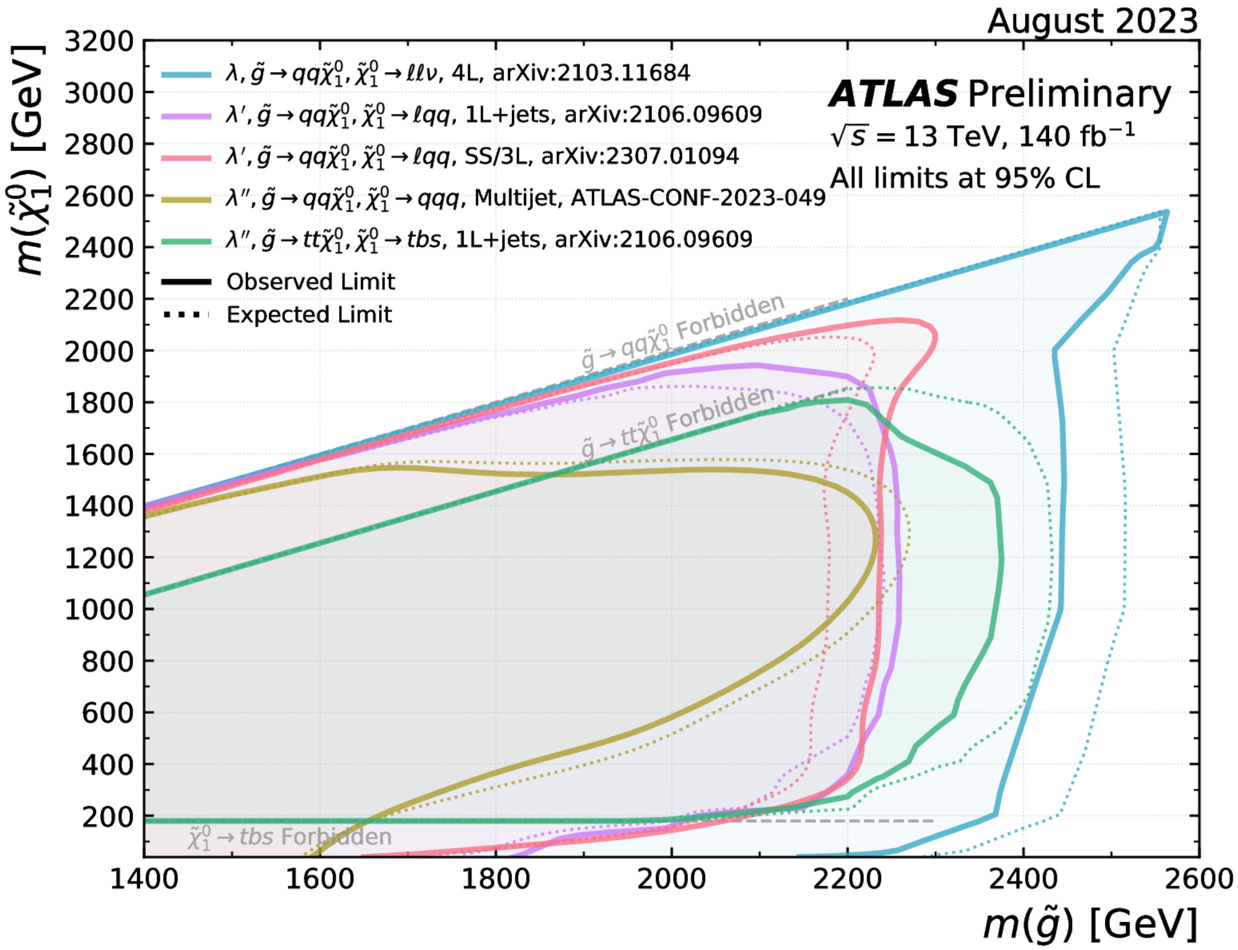

Background
Signal
events
Relevant quantity


Background
Signal
events
Relevant quantity


2015 – now
LHC 13 – 14 TeV
?
2012
LHC 8 TeV
2010-2011
LHC 7 TeV
2000's
Tevatron
1980's
Sp$\bar{p}$S
Squark-gluino-neutralino model, $m(\chi_1^0) = 0$ GeV
Exclusion for $m(\tilde{g}) = m(\tilde{q})$
0
500
1000
1500
2000
Excluded Gluino Mass (GeV)

SUSY SEARCHES: A PLETHORA OF RESULTS





Many other searches...

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2022

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.6 - 139)\ \text{fb}^{-1}$ $\sqrt{s} = 8,\ 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH multijet	–	≥3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW \to \ell\nu qq$	$1\ e, \mu$	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1\ e, \mu$	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$0\ e, \mu$	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	139	W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ \to \ell\nu qq$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\ell'\ell'$ model C	$3\ e, \mu$	2 j (VBF)	Yes	139	W' mass 340 GeV	$g_V c_H = 1$, $g_f = 0$	ATLAS-CONF-2022-005
	HVT $W' \to WH$ model B	$0\ e, \mu$	≥1 b, ≥2 J		139	W' mass 3.2 TeV	$g_V = 3$	2007.05293
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η^-_{LL}		1703.09127
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	139	Λ 35.8 TeV	η^-_{LL}	2006.12946
	CI $eebs$	$2\ e$	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	$2\ \mu$	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	$\geq 1\ e,\mu$	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	m_{med} 2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	$0\ e, \mu$	2 b	Yes	139	m_{med} 3.1 TeV	tanβ=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med} 560 GeV	tanβ=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	$2\ e$	≥2 j	Yes	139	LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	$2\ \mu$	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ^u_3 mass 1.2 TeV	$\mathcal{B}(LQ^u_3 \to b\tau) = 1$	2108.07665
	Scalar LQ 3rd gen	$0\ e, \mu$	≥2 j, ≥2 b	Yes	139	LQ^u_3 mass 1.24 TeV	$\mathcal{B}(LQ^u_3 \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	$\geq 2\ e, \mu, \geq 1\ \tau$	≥1 j, ≥1 b	–	139	LQ^d_3 mass 1.43 TeV	$\mathcal{B}(LQ^d_3 \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	$0\ e, \mu, \geq 1\ \tau$	0 – 2 j, 2 b	Yes	139	LQ^d_3 mass 1.26 TeV	$\mathcal{B}(LQ^d_3 \to b\nu) = 1$	2101.12527
	Vector LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ^V_3 mass 1.77 TeV	$\mathcal{B}(LQ^V_3 \to b\tau) = 0.5$, Y-M coupl.	2108.07665
Heavy quarks	VLQ $TT \to Zt + X$	$2e/2\mu/\geq 3e,\mu$	≥1 b, ≥1 j	–	139	T mass 1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	$1\ e, \mu$	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	$1\ e, \mu$	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	$0\ e,\mu$	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	$2,3,4\ e, \mu$	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	$2,3,4\ e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2,3,4\ e, \mu$ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H^{\pm\pm}_L \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q \rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1905.10130

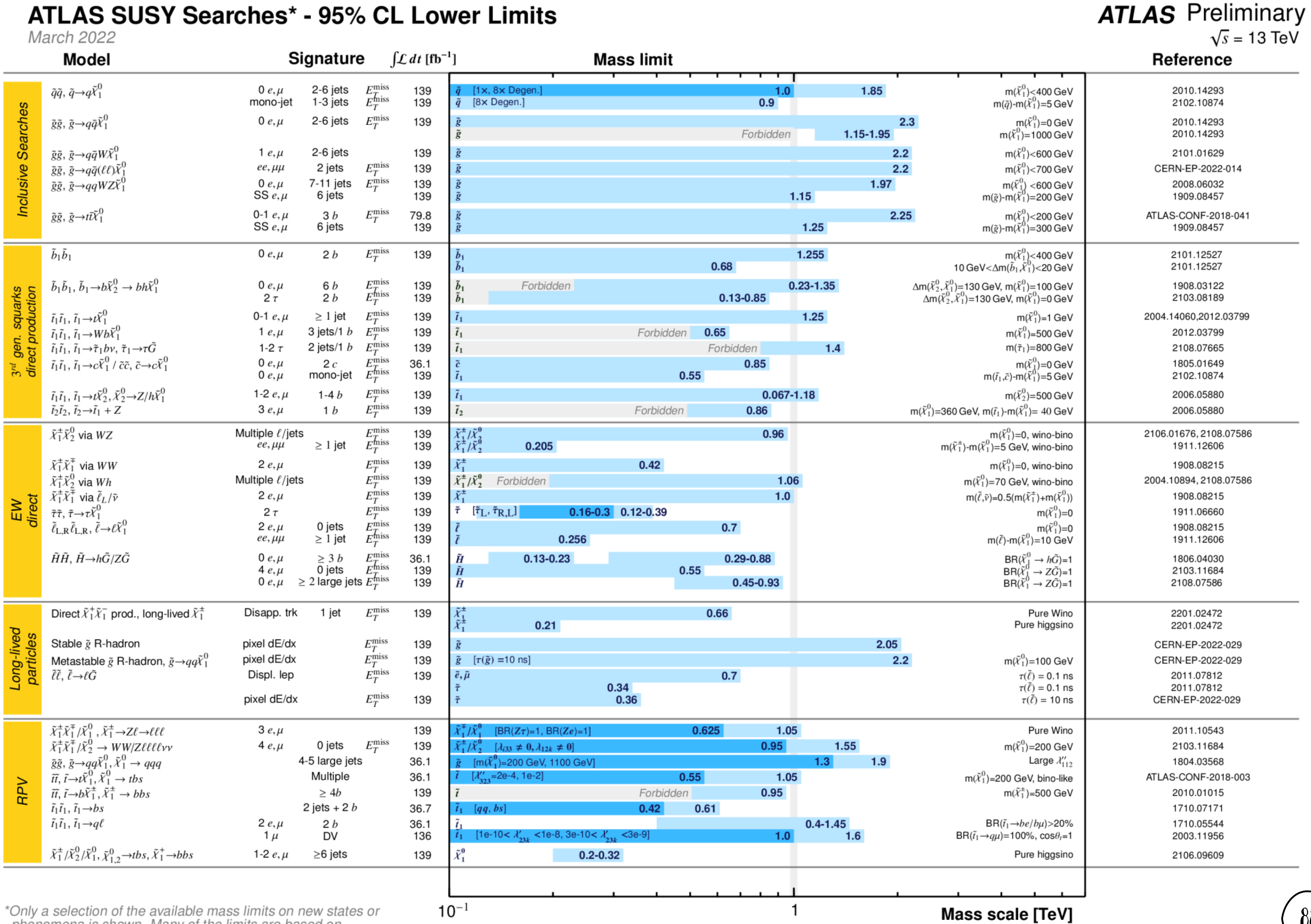
$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

10^{-1} 1 10 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

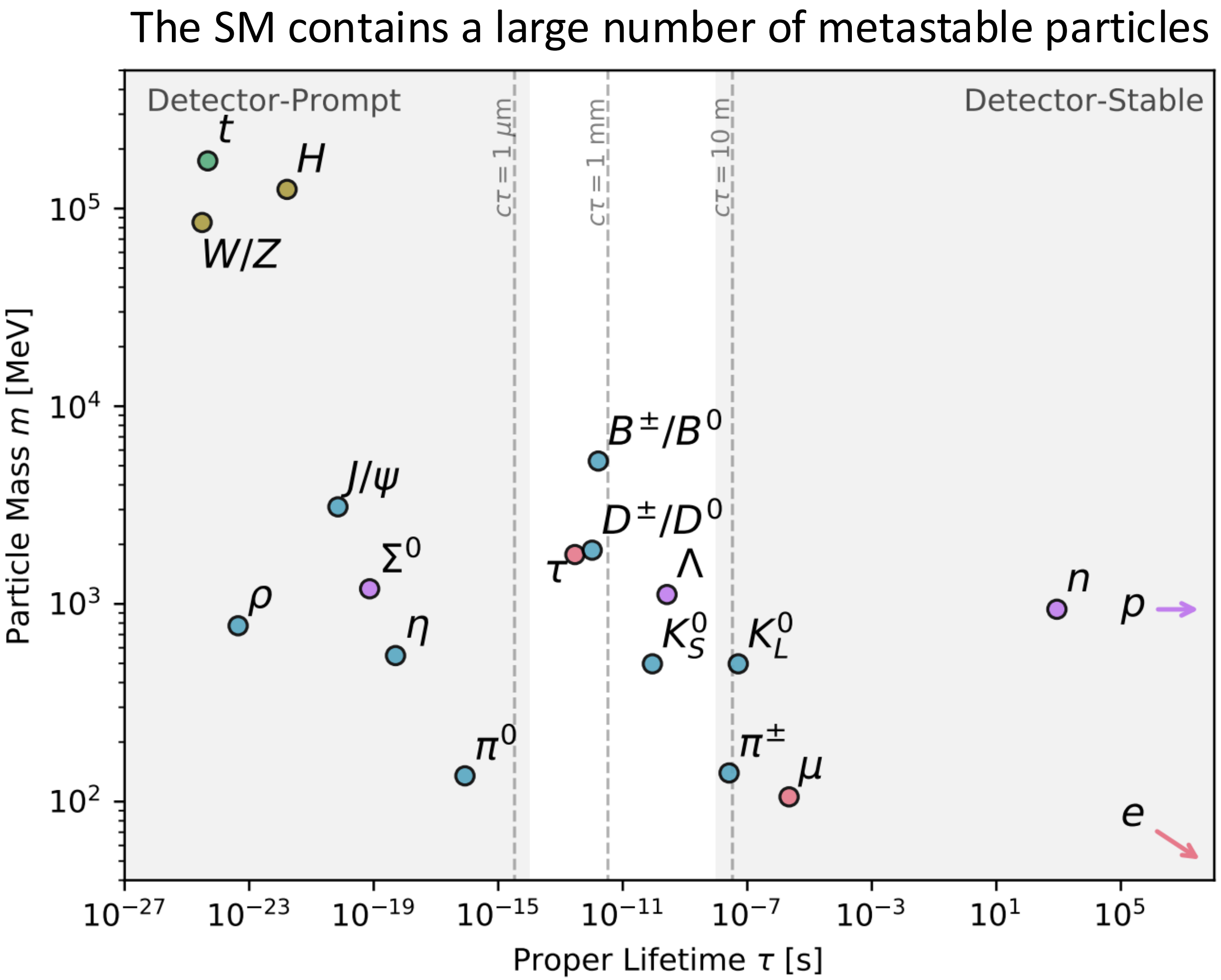
Many other searches...



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

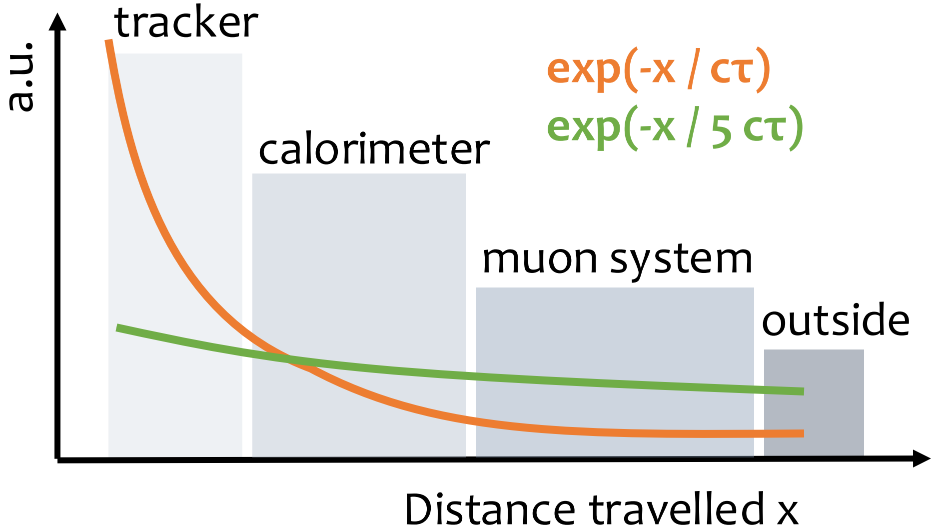
Searches for exotic signatures

Non-conventional Signatures
e.g. Signatures of long-lived particles

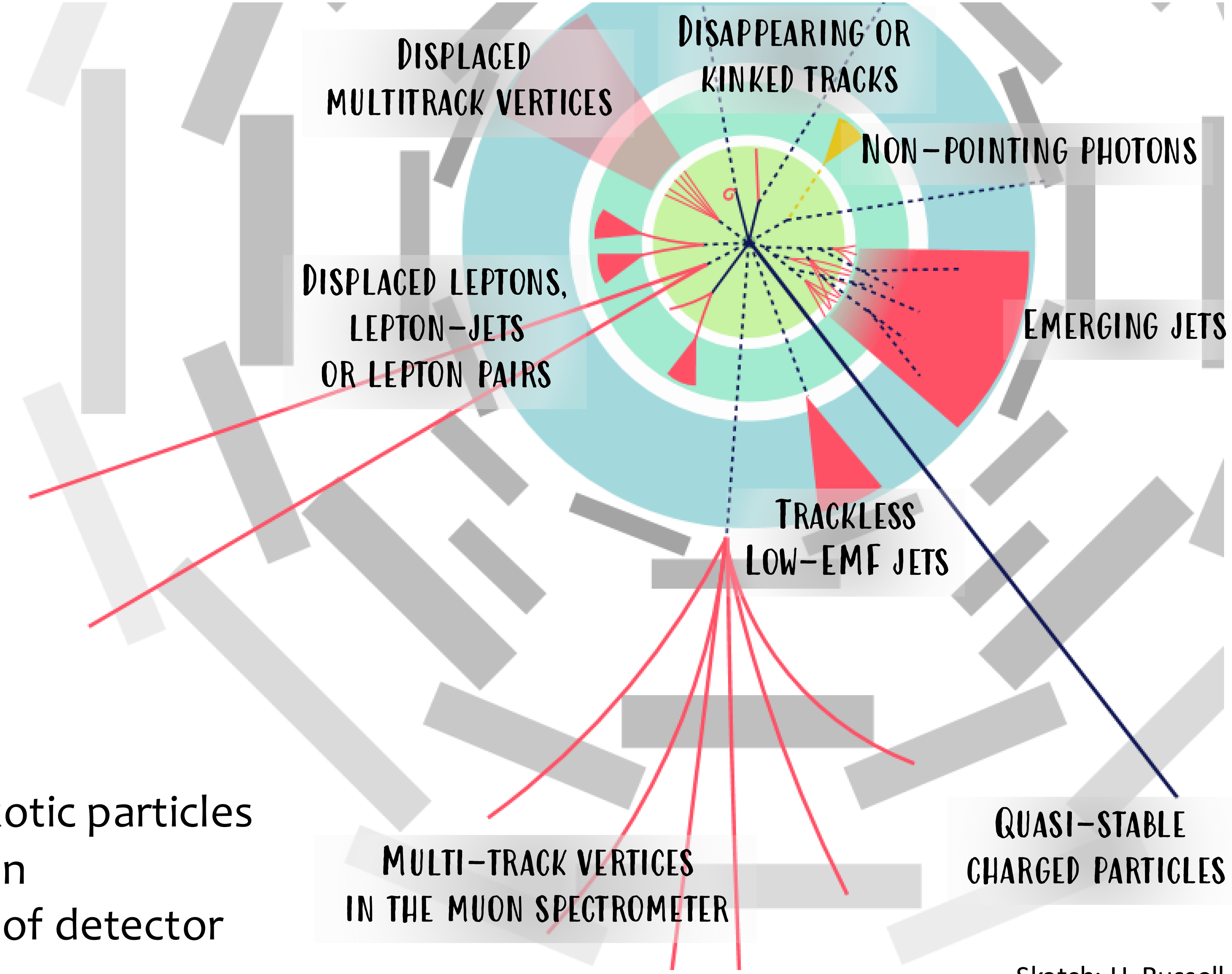


$$\frac{dN}{dt} = -\frac{N}{\tau}$$

$$\Rightarrow N(t) = N_0 e^{(-t/\tau)}$$



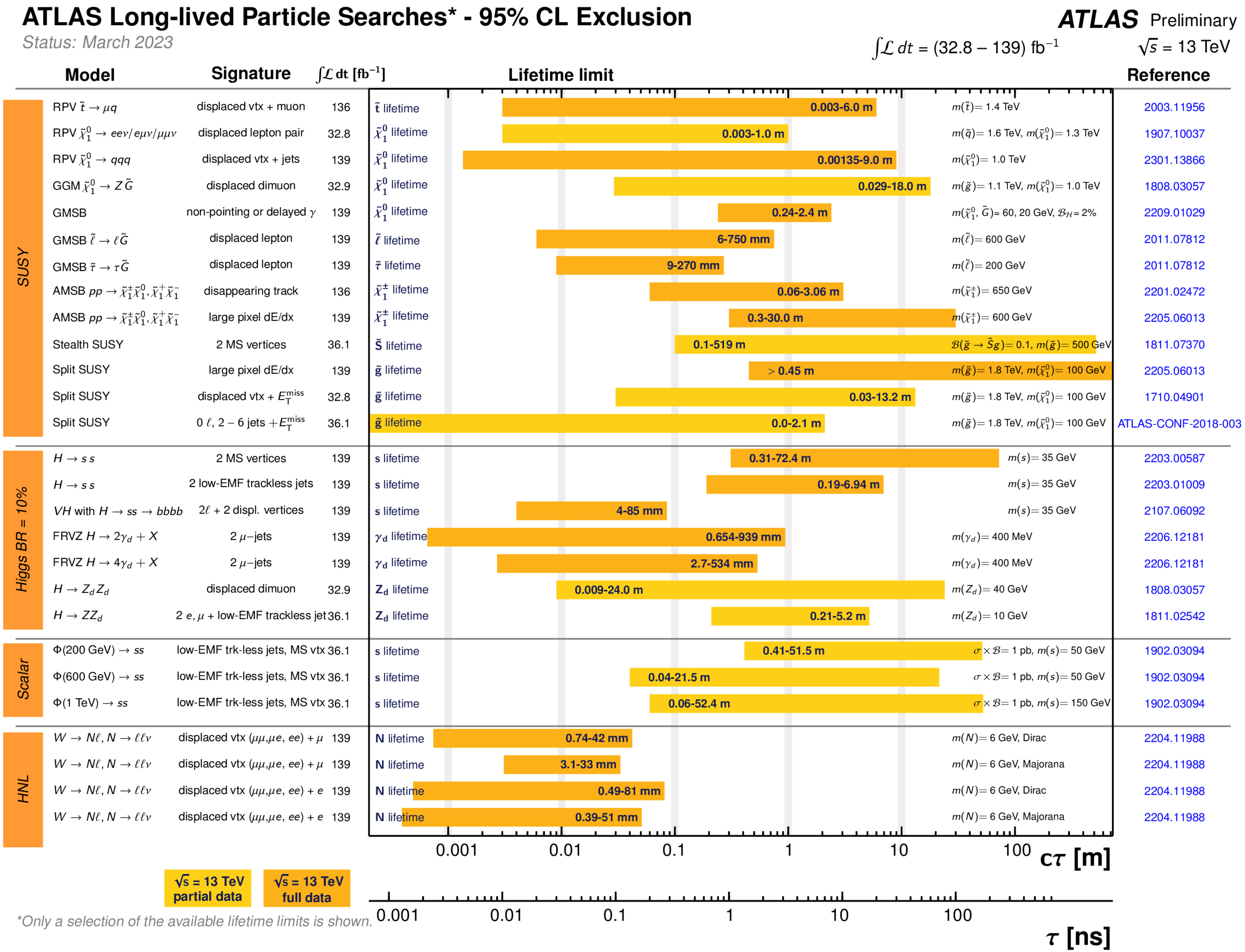
Non-conventional Signatures

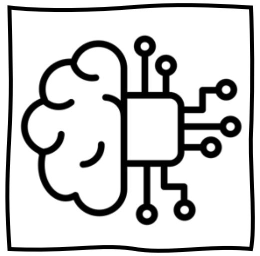
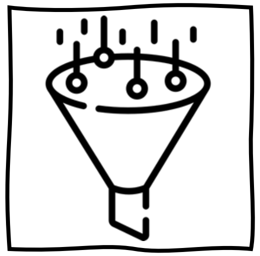
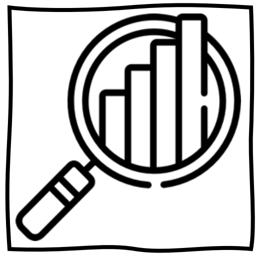
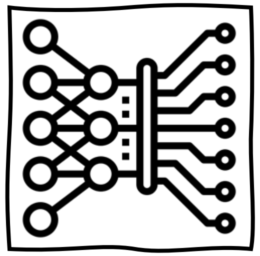


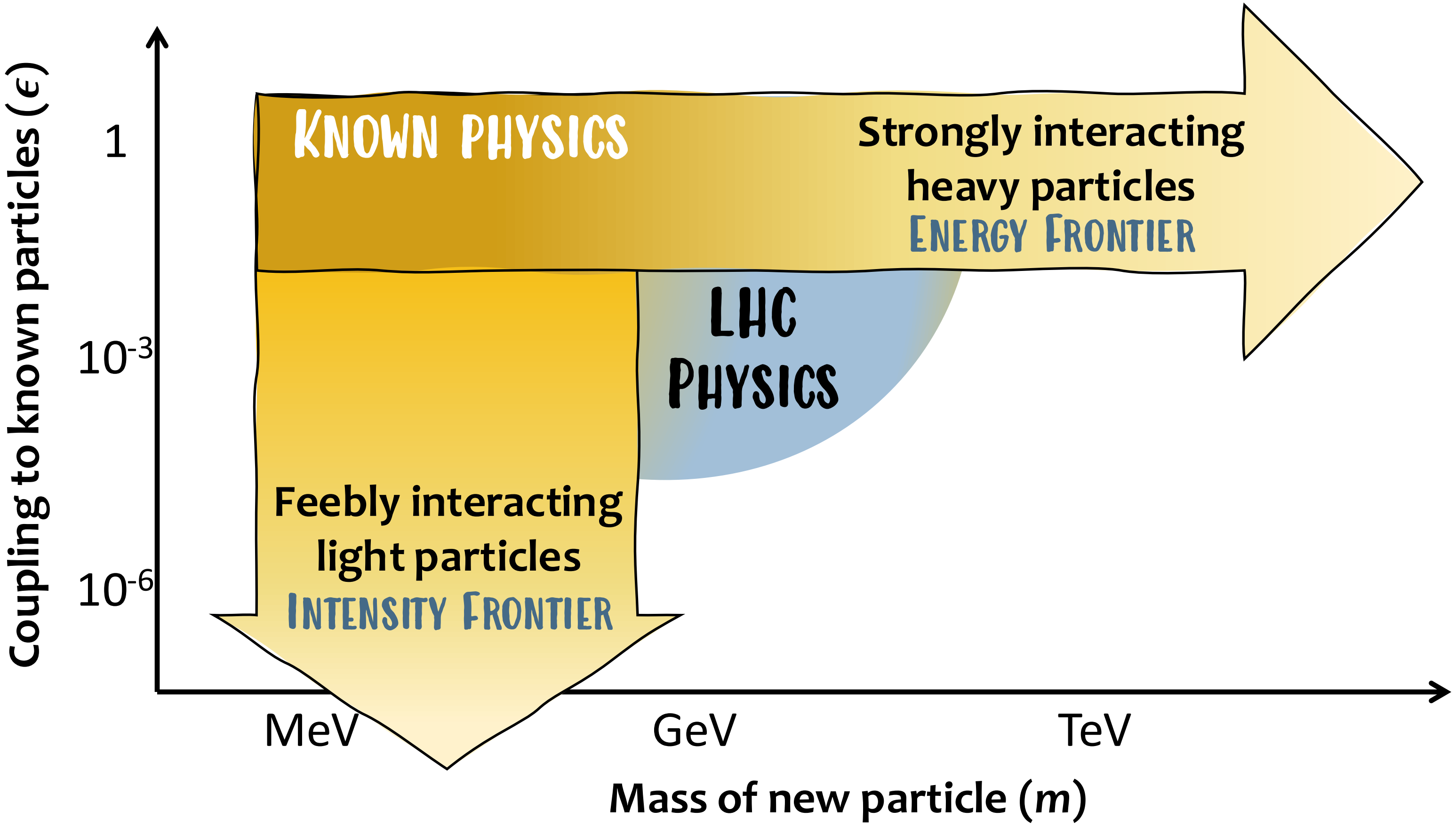
- Many interesting possibilities of exotic particles
- Unique challenges in reconstruction
- Possible with good understanding of detector

Sketch: H. Russell

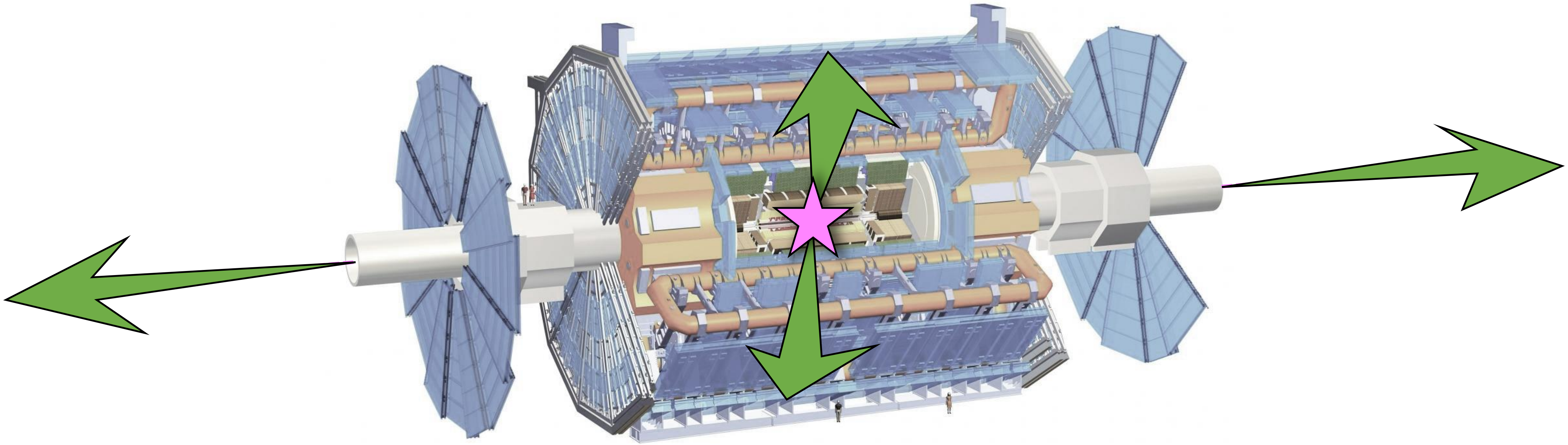
MANY OTHER SEARCHES...



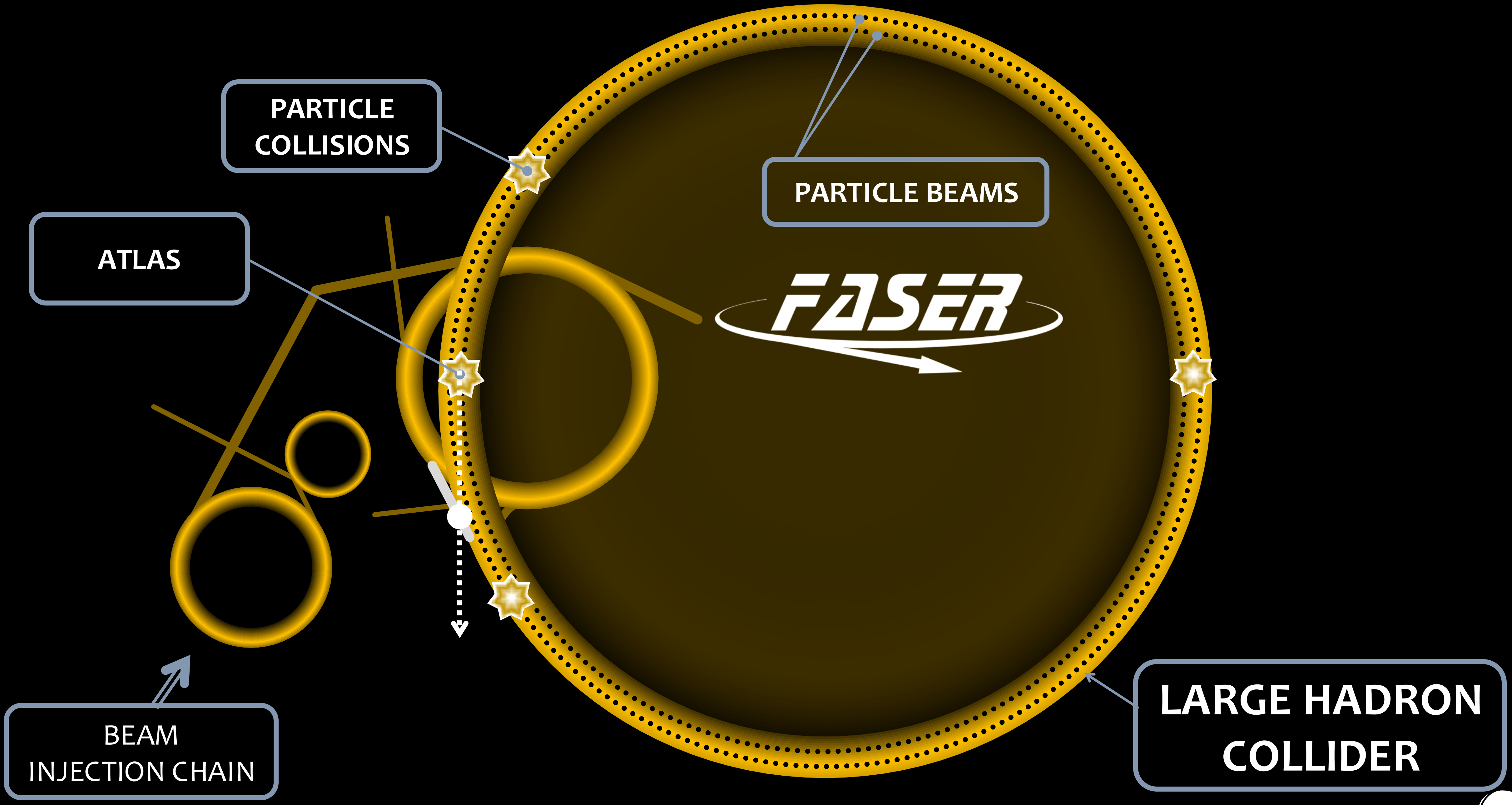







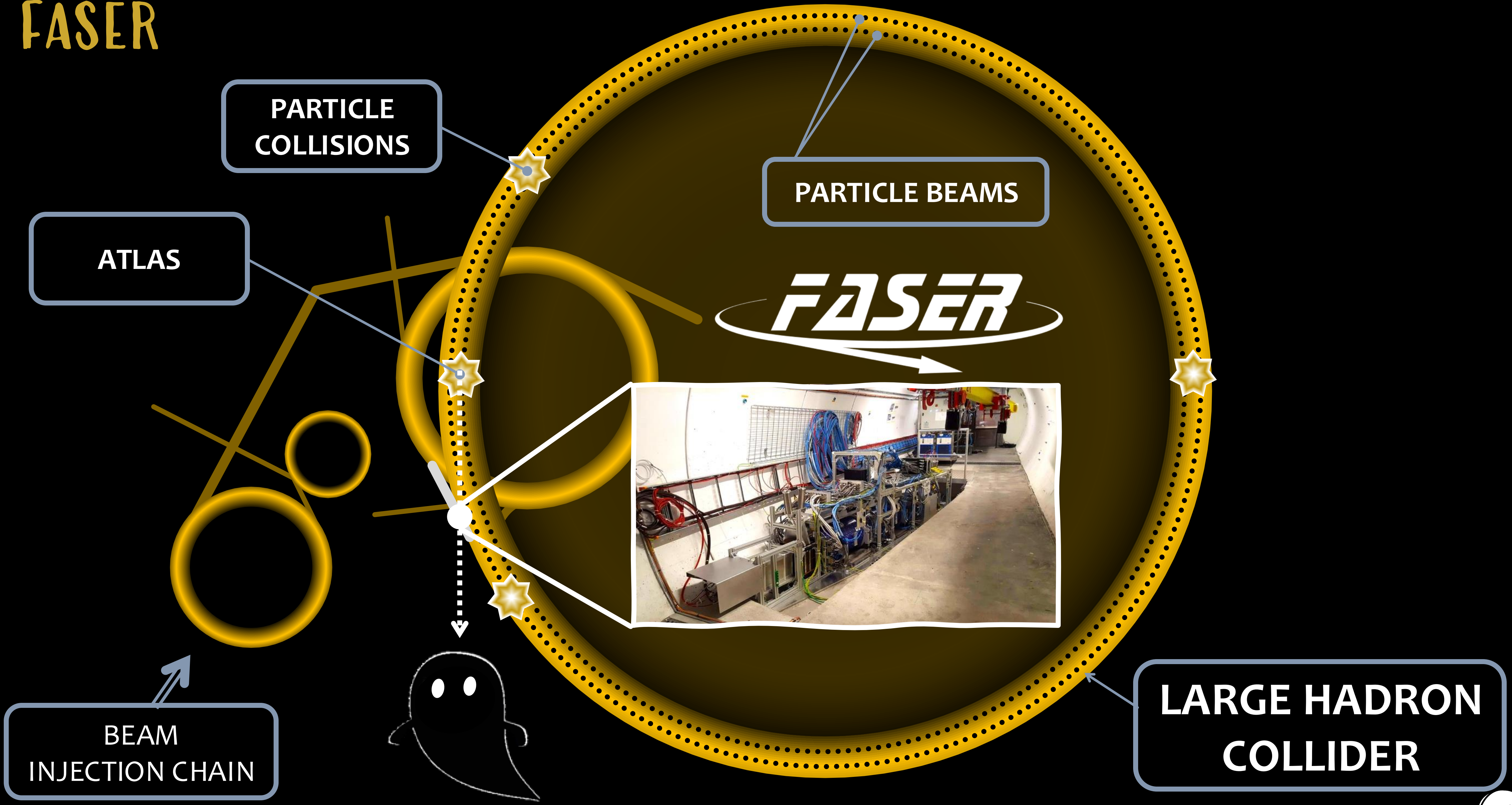
- Improve instrumentation / diversify experimental methods
- Get more data
- Look at higher energies



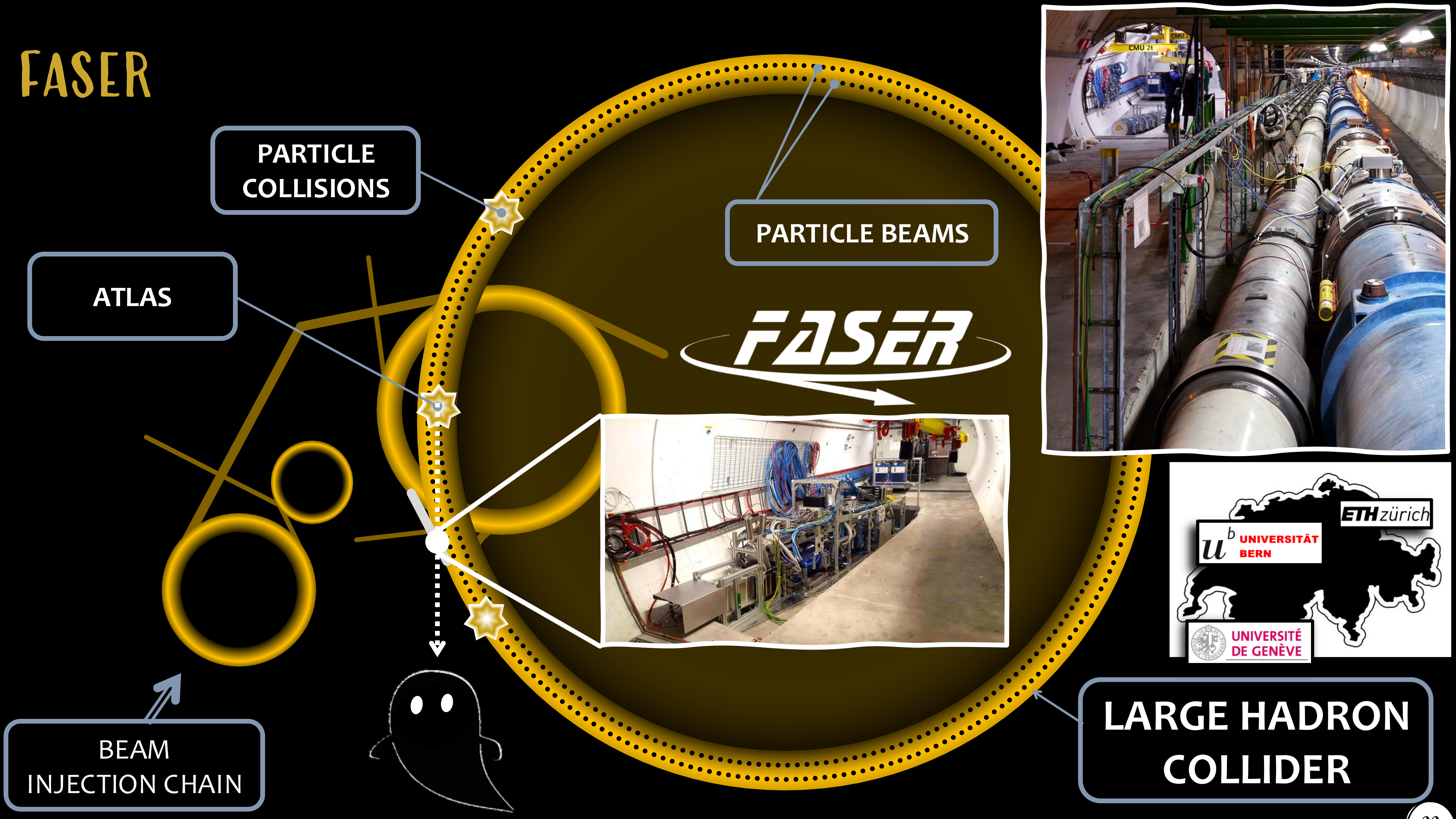
Very Forward experiments at the LHC


PARTICLE COLLISIONS
ATLAS
PARTICLE BEAMS
FASER
BEAM INJECTION CHAIN
LARGE HADRON COLLIDER

FASER


PARTICLE COLLISIONS
ATLAS
PARTICLE BEAMS
FASER
BEAM INJECTION CHAIN
LARGE HADRON COLLIDER

FASER

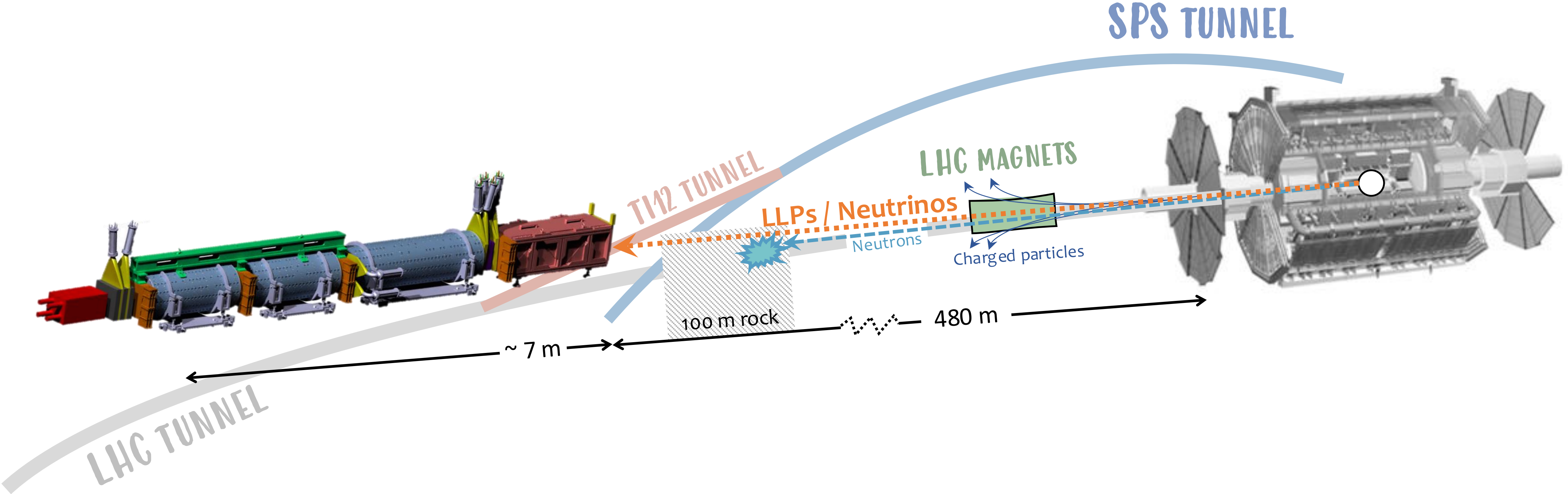

PARTICLE COLLISIONS
ATLAS
PARTICLE BEAMS
FASER
BEAM INJECTION CHAIN
LARGE HADRON COLLIDER
ETH zürich
UNIVERSITÄT BERN
UNIVERSITÉ DE GENÈVE

CMU 2t
CMU 2t
ATTENTION
TENSION
DANGER
FASER
FASER

Forward Search Experiment at the LHC

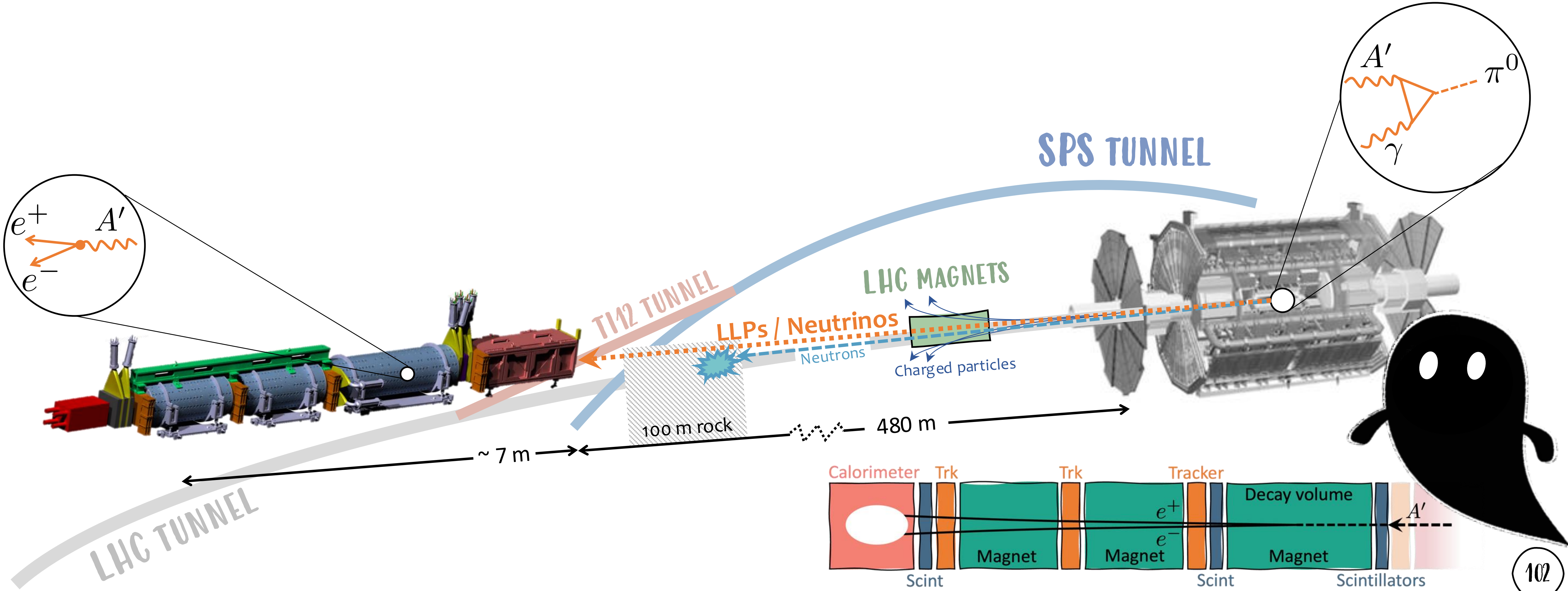
FASER

Primary goal: Searches for new weakly interacting light particles, coupling to SM via mixing with SM “portal” operator

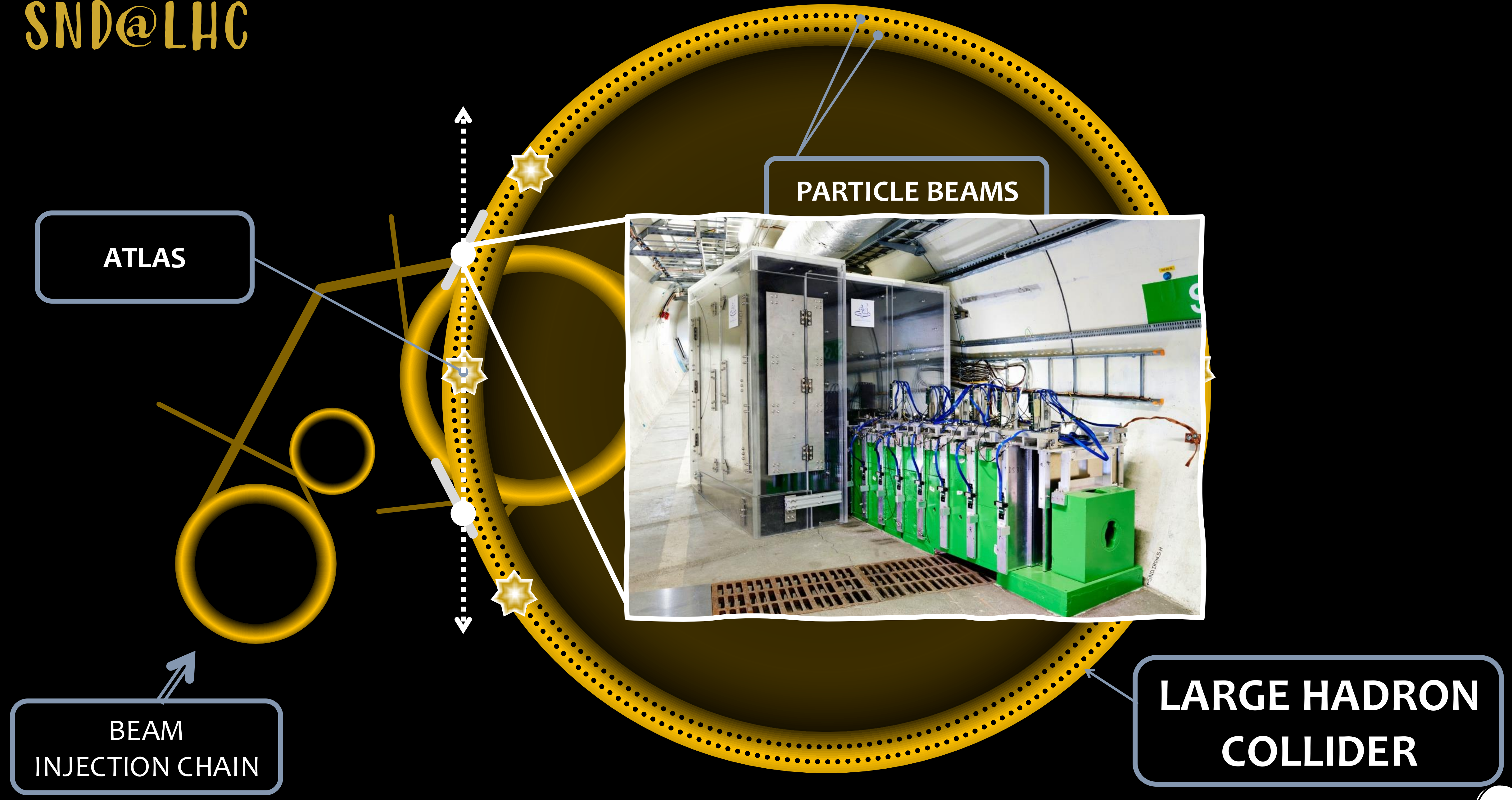


Forward Search Experiment at the LHC

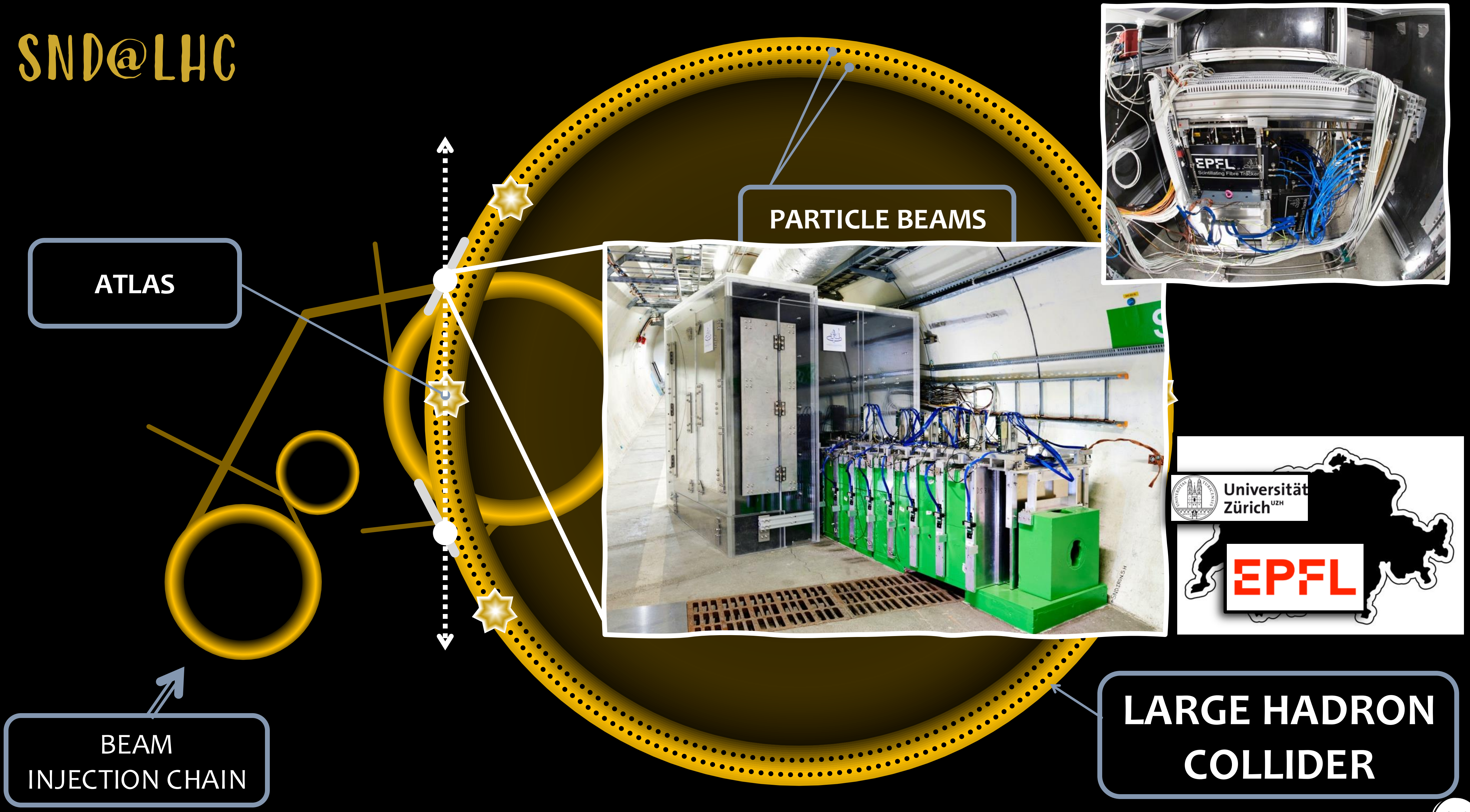
Primary goal: Searches for new weakly interacting light particles, coupling to SM via mixing with SM "portal" operator



SND@LHC

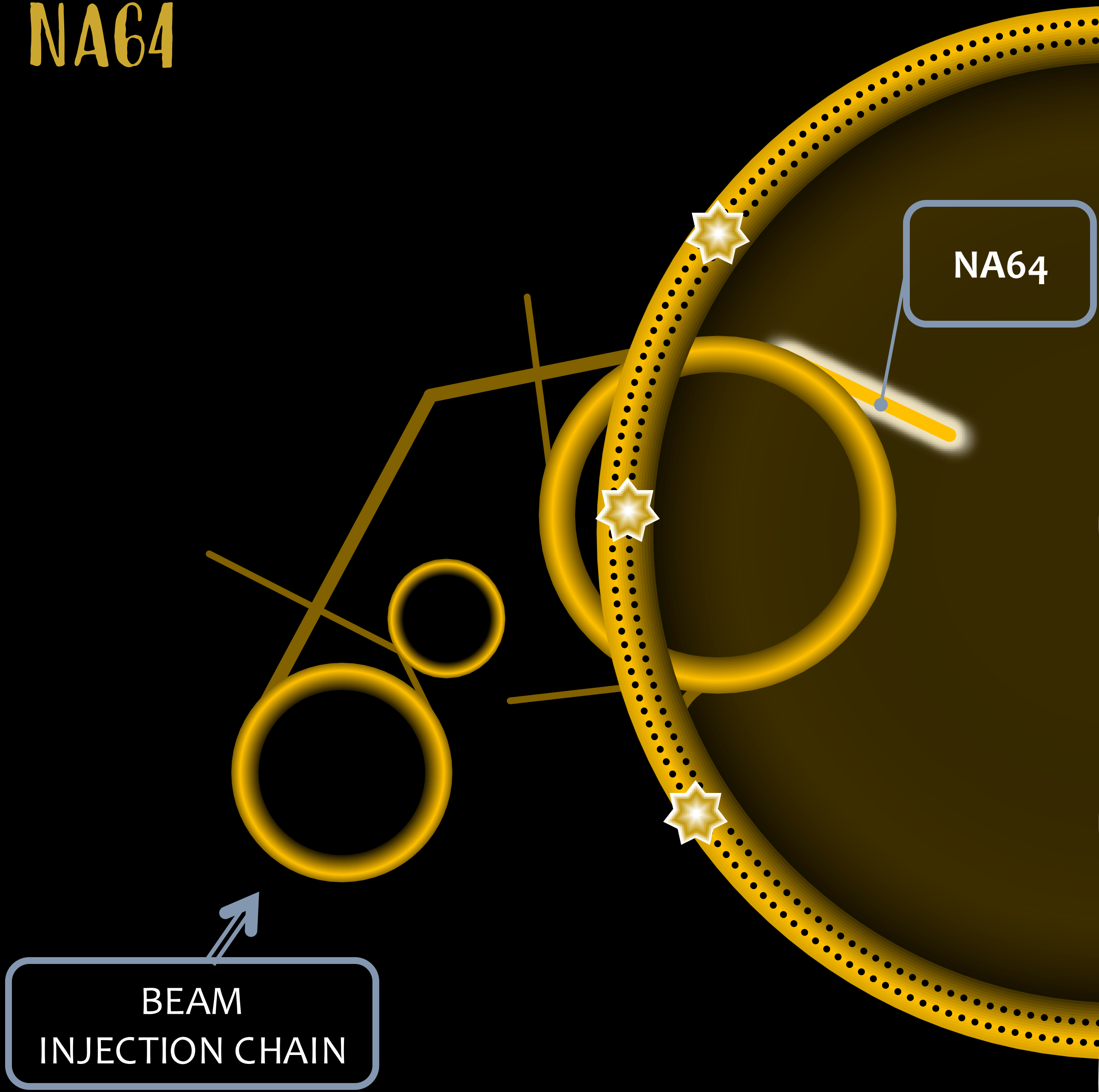

ATLAS
PARTICLE BEAMS
BEAM
INJECTION CHAIN
LARGE HADRON
COLLIDER

SND@LHC

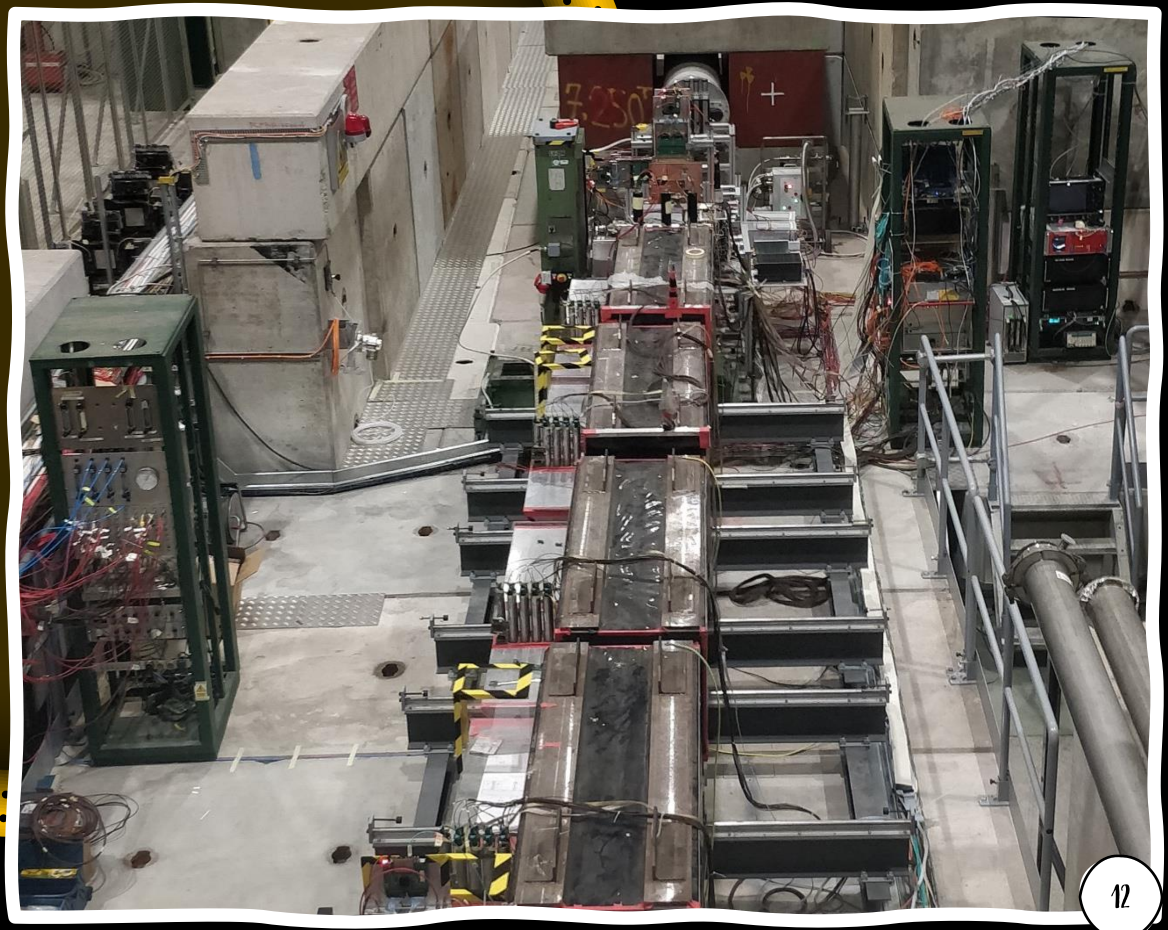

ATLAS
PARTICLE BEAMS
BEAM
INJECTION CHAIN
LARGE HADRON
COLLIDER
EPFL
Scintillating Fibre Tracker
Universität
Zürich UZH
EPFL

Experiments in the "North Area"

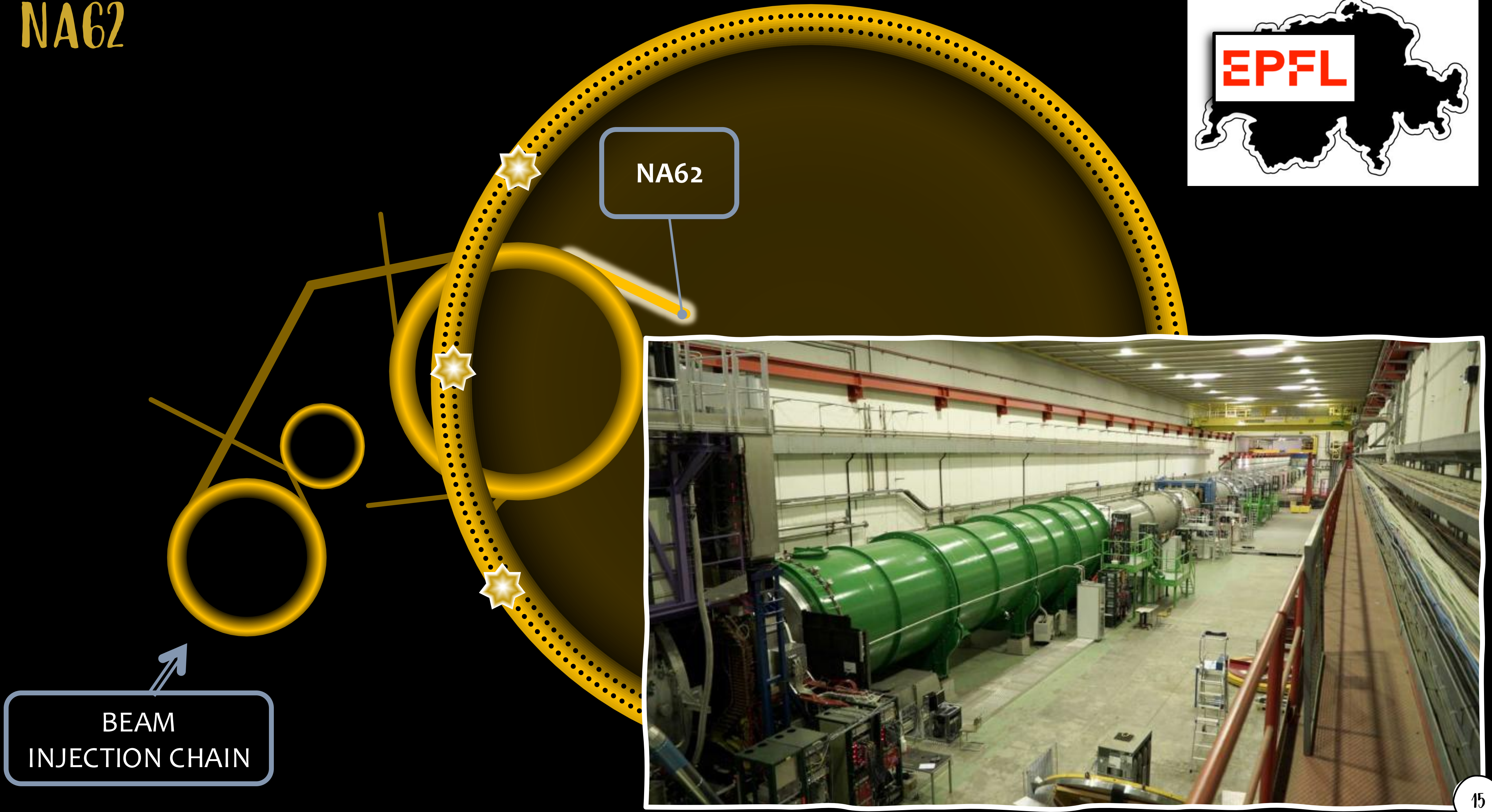
NA64

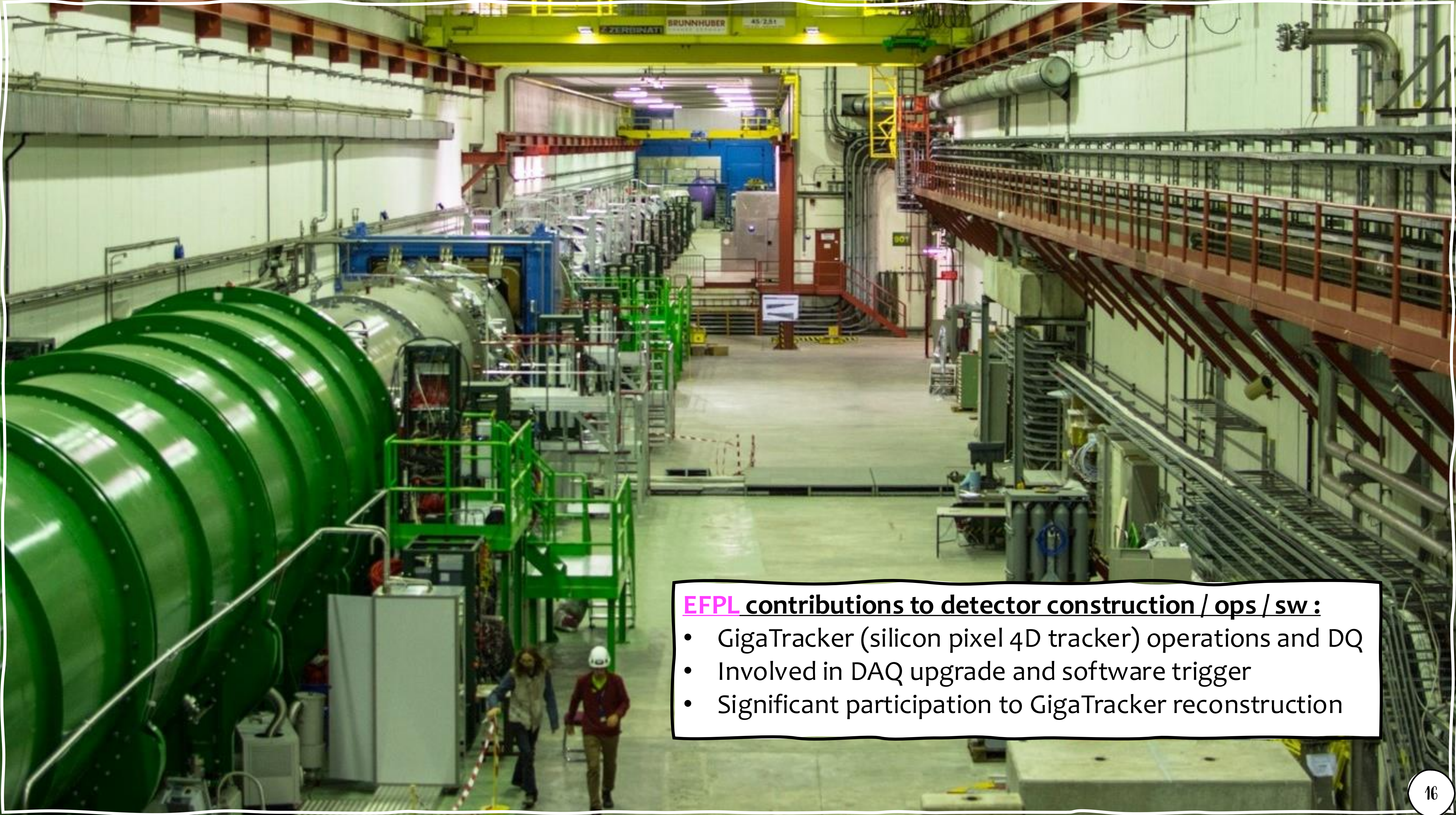


New area dedicated to NA64 prepared by CERN during LS2



NA62

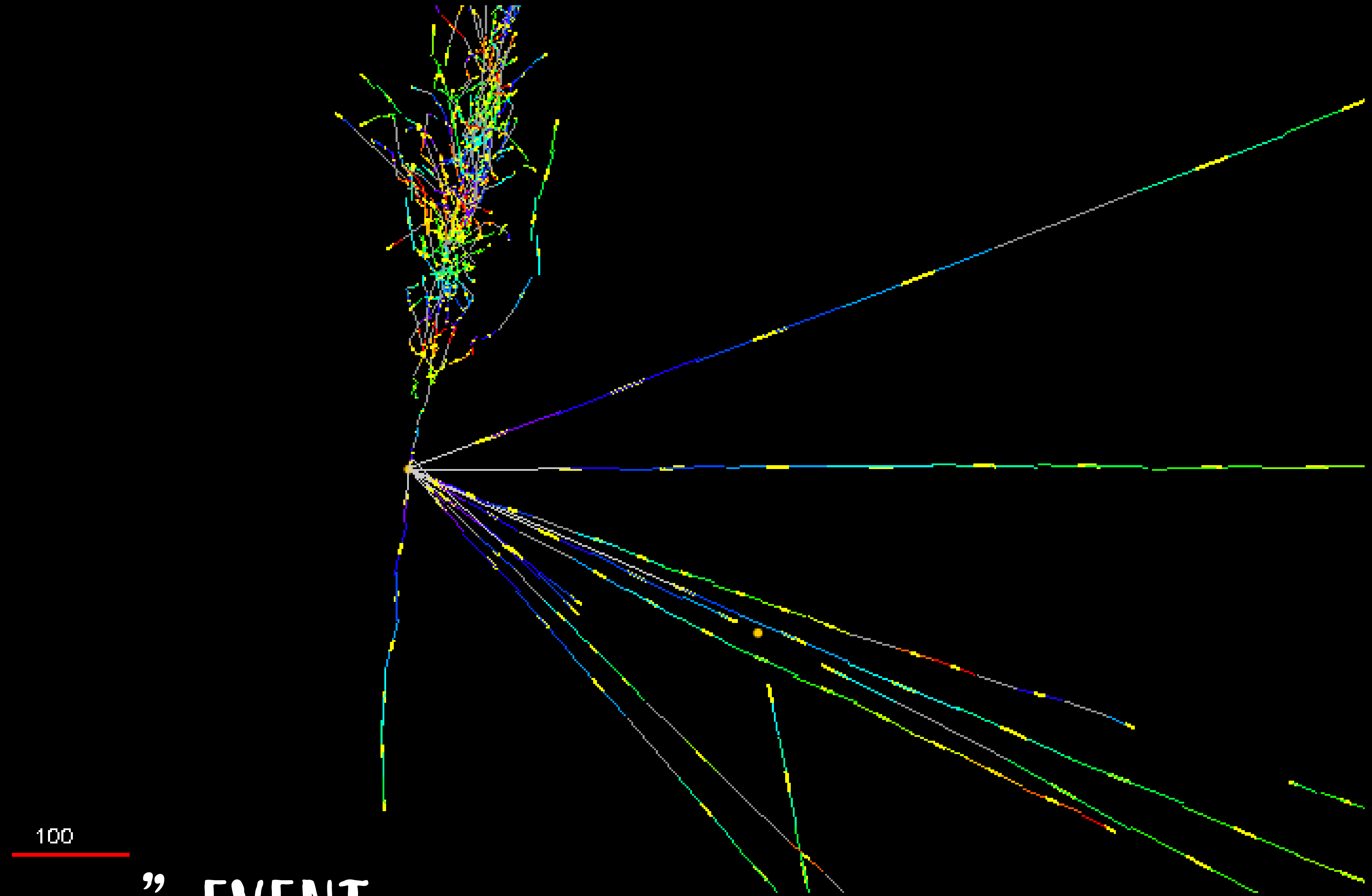




<u>EFPL contributions to detector construction / ops / sw :</u>

- GigaTracker (silicon pixel 4D tracker) operations and DQ
- Involved in DAQ upgrade and software trigger
- Significant participation to GigaTracker reconstruction

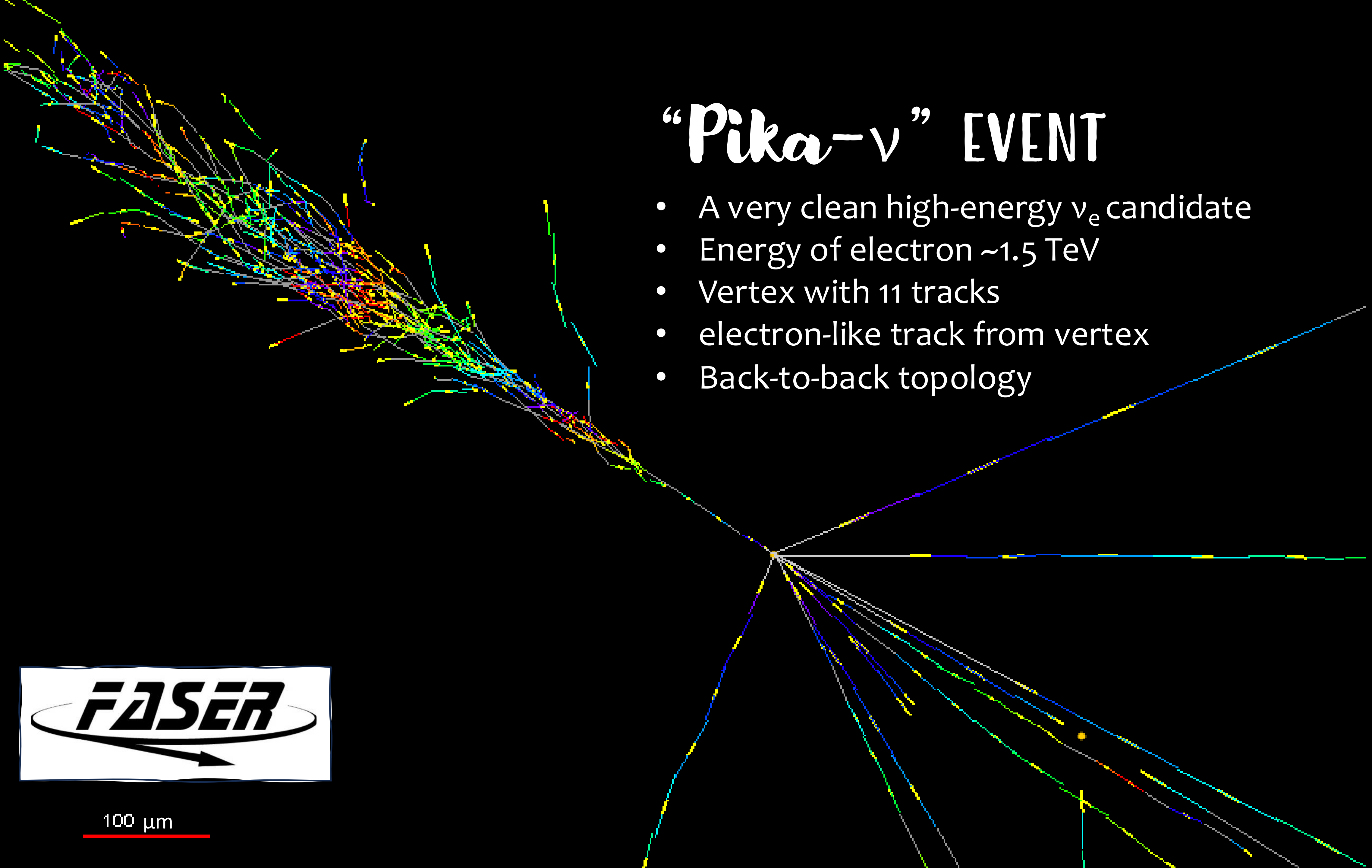
Highlights from recent results



"Pika-ν" EVENT

"Pika-ν" EVENT

- A very clean high-energy ν_e candidate
- Energy of electron ~1.5 TeV
- Vertex with 11 tracks
- electron-like track from vertex
- Back-to-back topology



FASER

Searches for Dark Photons

NA64

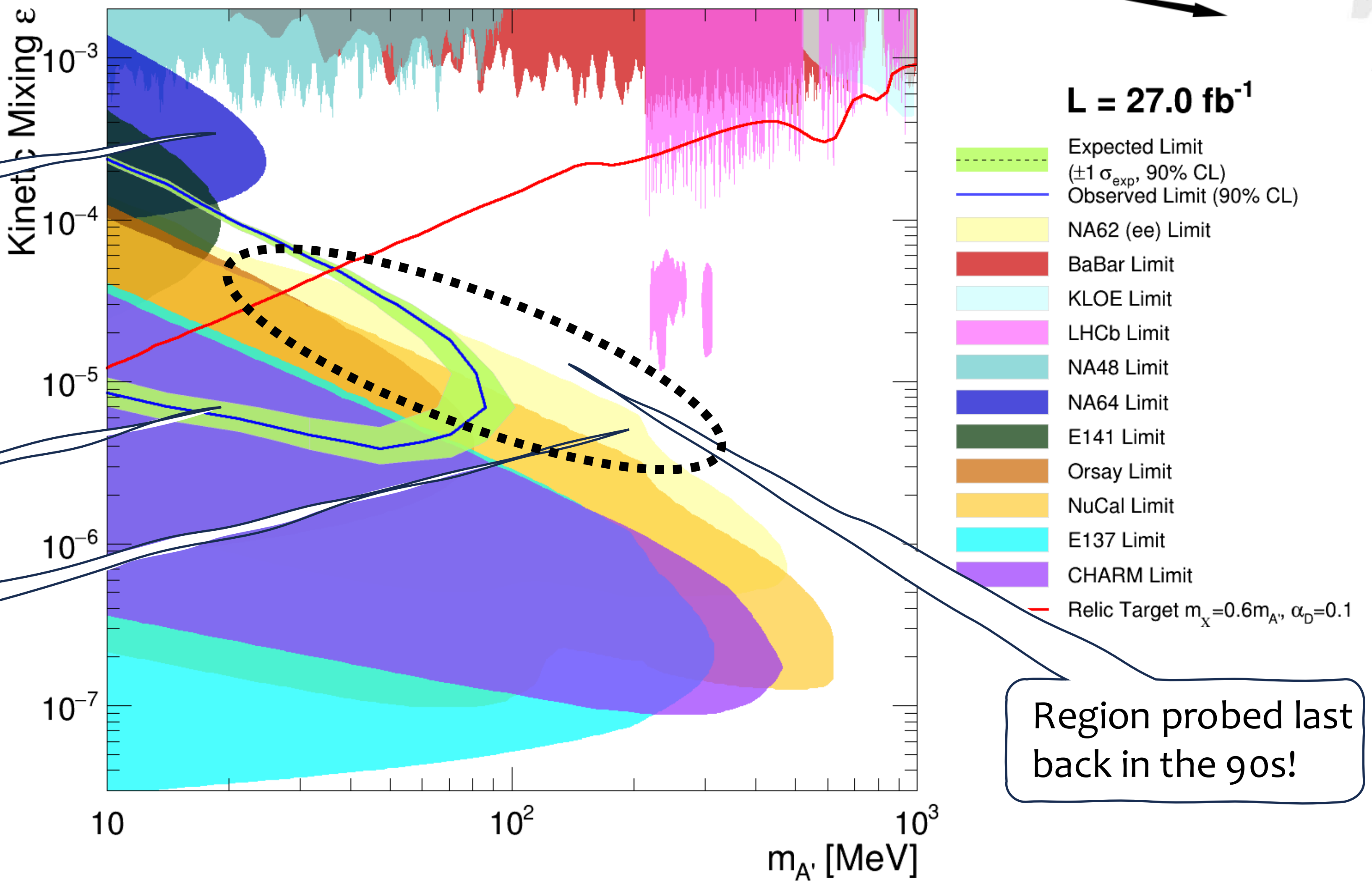
Phys.Rev.D 101 (2020) 7, 071101

FASER

Phys. Lett. B 848 (2024) 138378

NA62

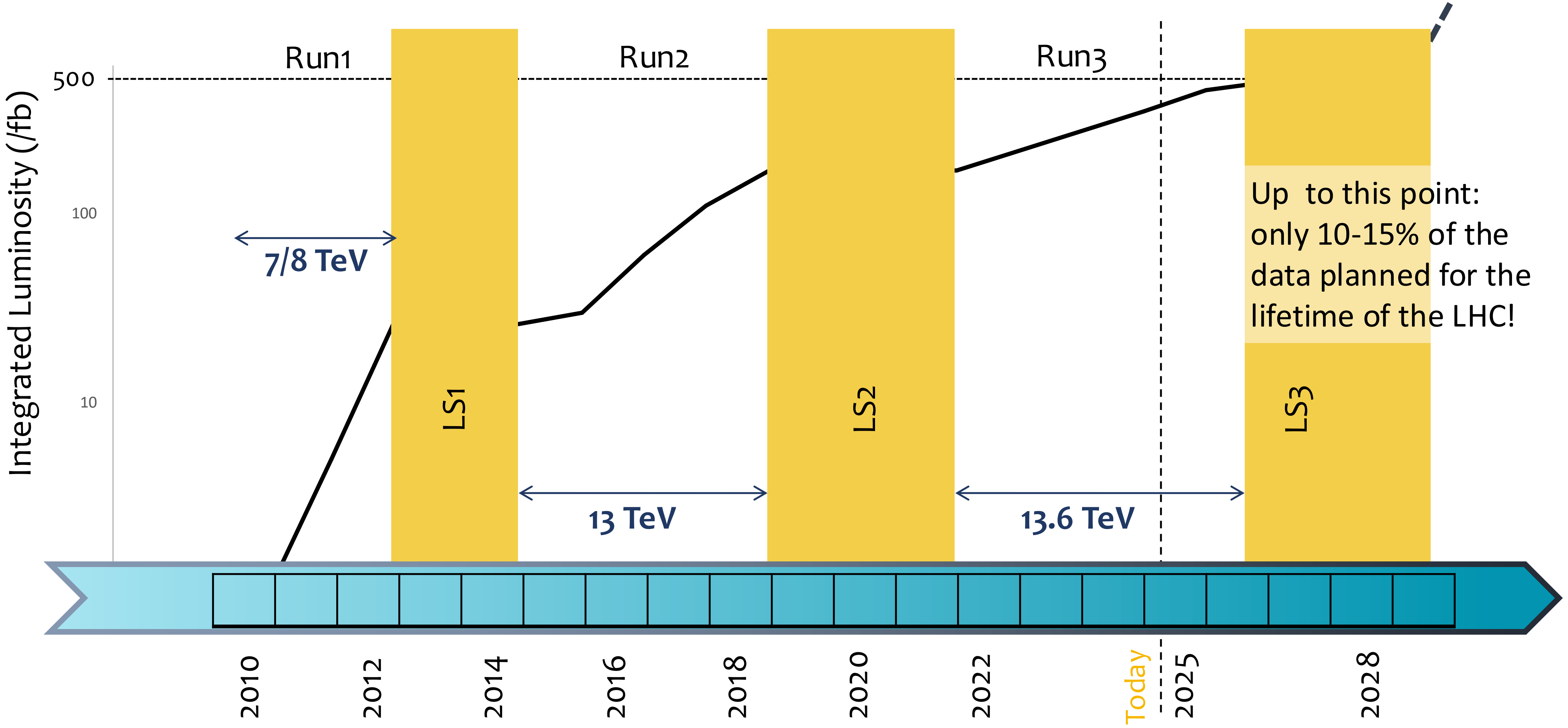
Phys. Rev. Lett. 133 (2024) 111802



Region probed last back in the 90s!

WHAT'S BEYOND LHC RUN3 ?

Run1, Run2, Run3 and beyond



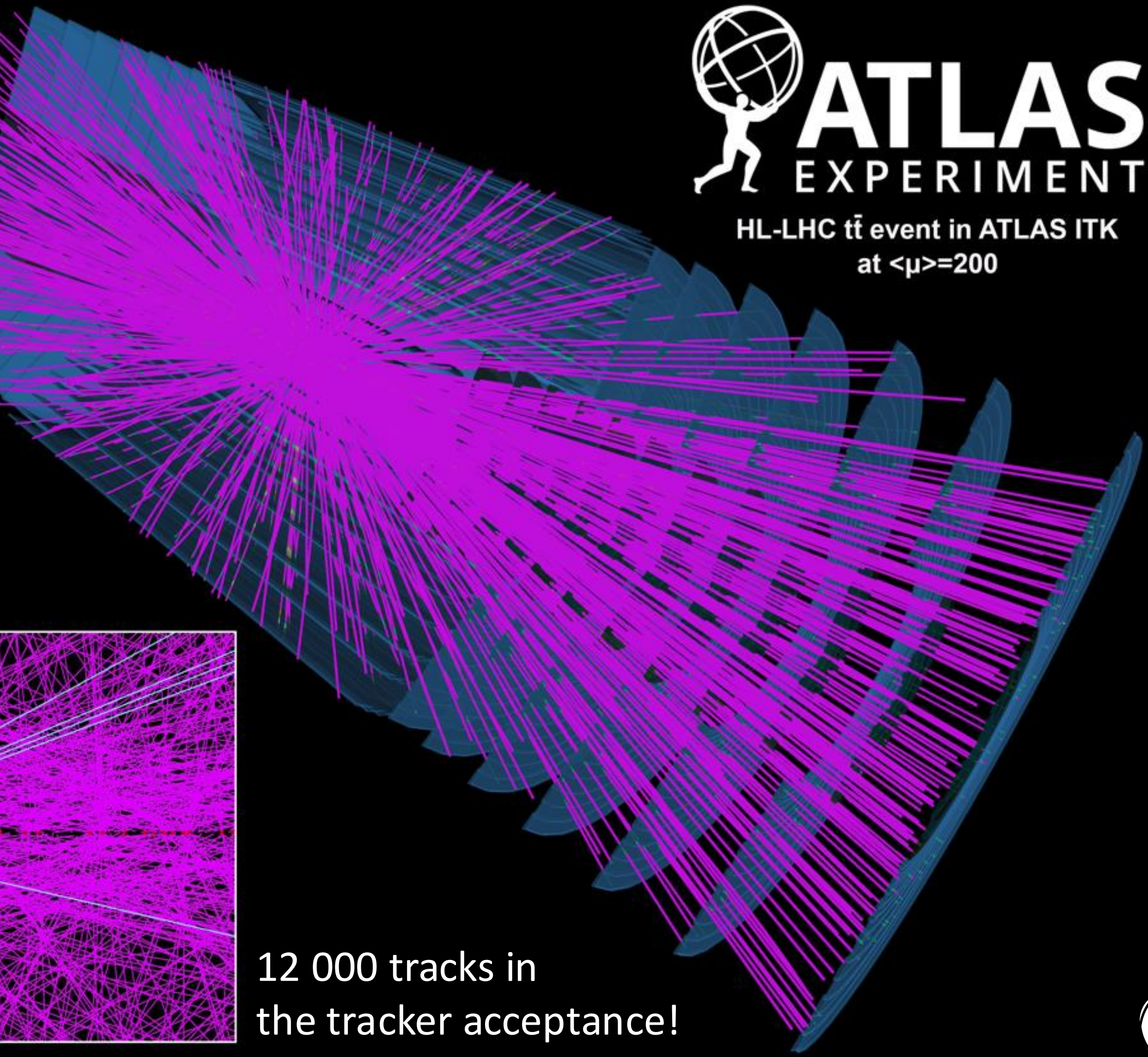
Required HL-LHC detector upgrades

Unprecedented challenges :

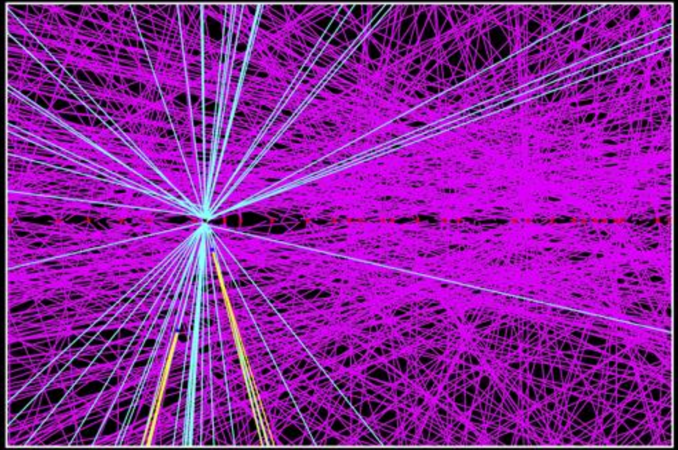
- amounts of radiation (~ $2x10^{16}$ n_{eq}/cm^2)
- data rates (> 5 GHz p–p collisions)
- data volume (~ 350 PB of RAW data / year)

Development of :

- radiation hard detectors
- fast electronics
- new detection methods, e.g. use of timing
- new software & computing approaches



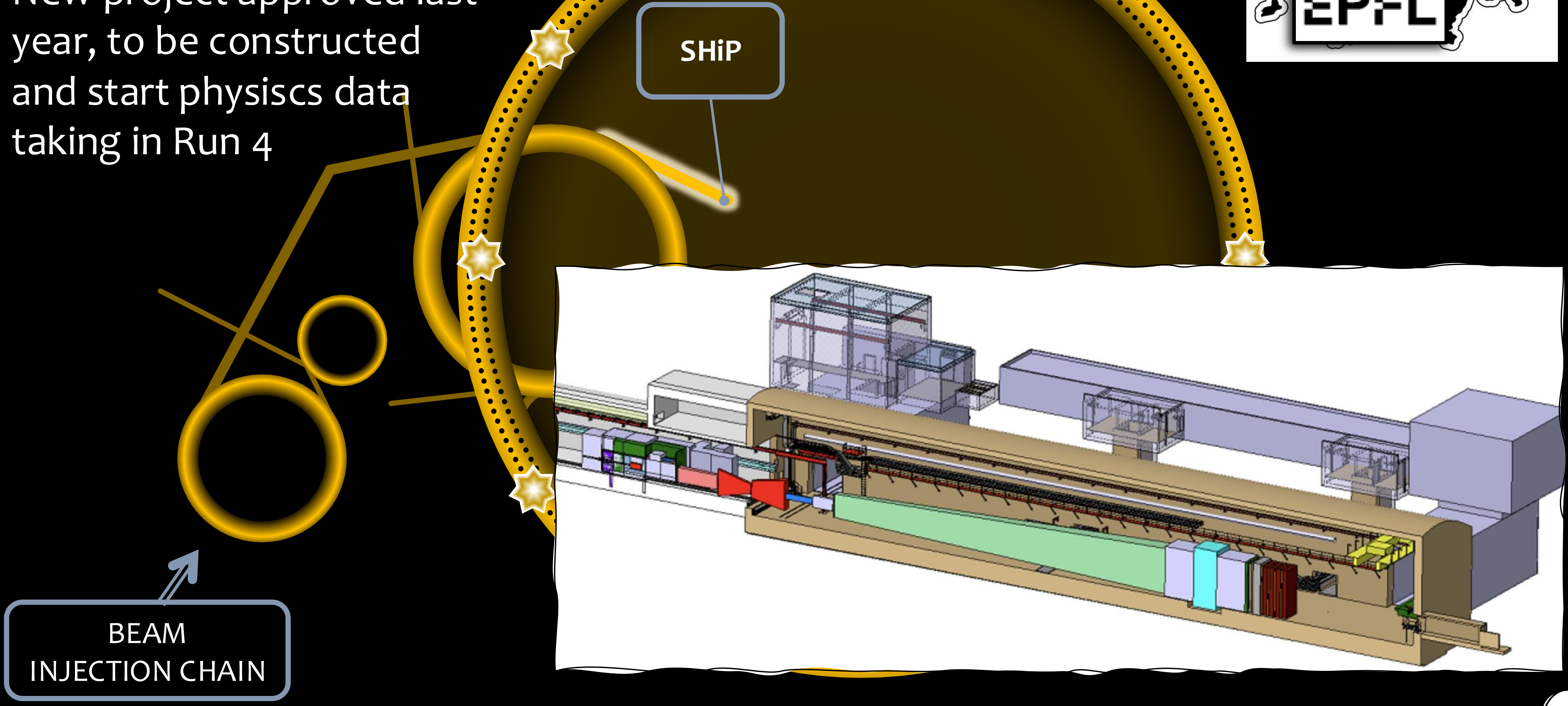
HL-LHC $t\bar{t}$ event in ATLAS ITK at <μ>=200



12 000 tracks in the tracker acceptance!

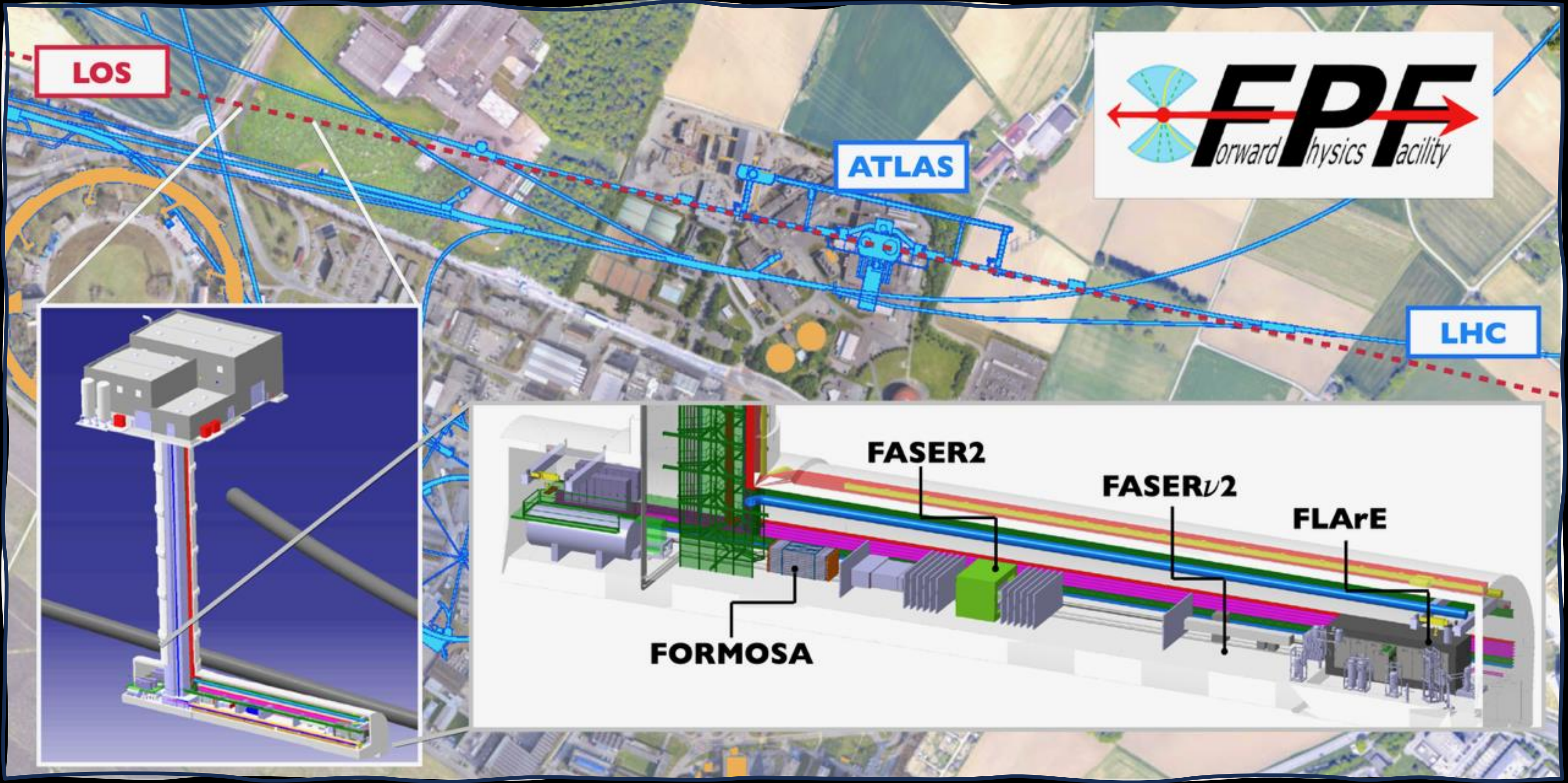
SHiP

New project approved last year, to be constructed and start physiscs data taking in Run 4



A TEASER FOR THE PROPOSED FORWARD PHYSICS FACILITY

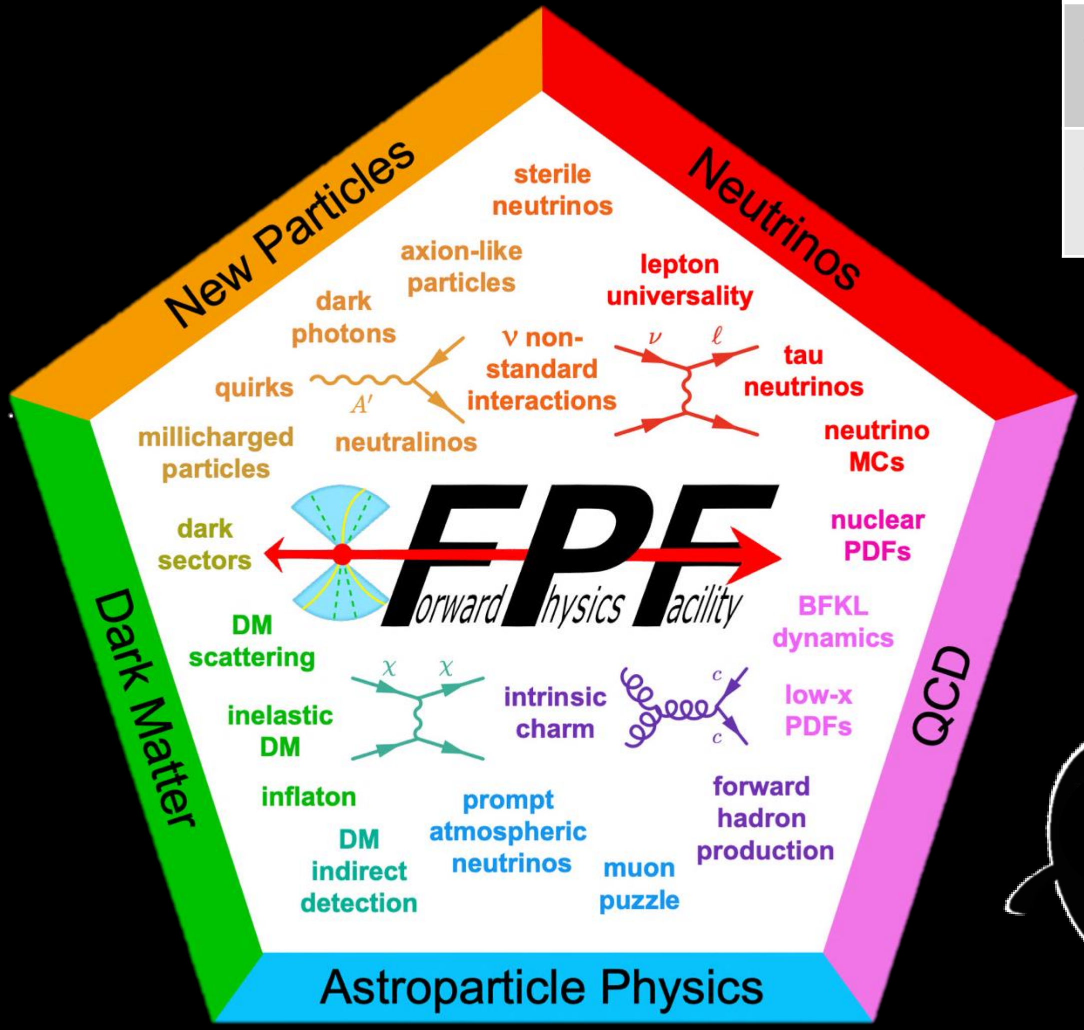
The rich physics program in the far-forward region strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era



Document to be submitted to european strategy

LoI for SNOWMASS-2021
arXiv:2203.05090
FPF – Kickoff workshop
FPF – 5th workshop
FPF – 6th workshop
FPF – 7th workshop in February 2024

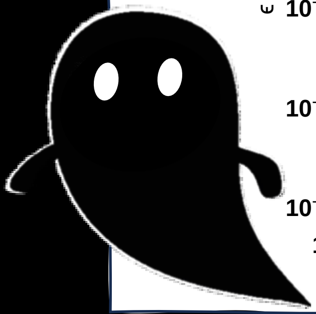
The physics programme of FPF

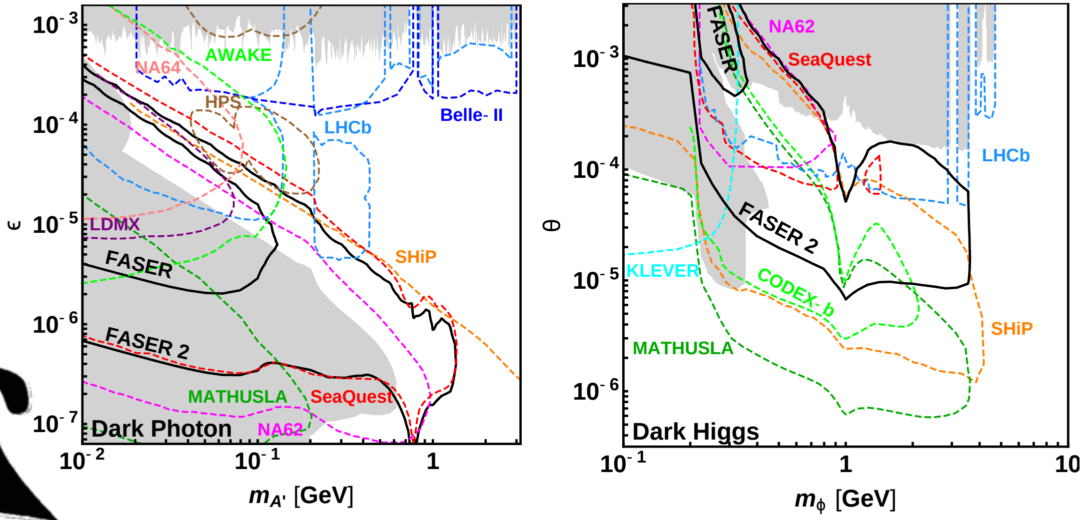


	Available lumi	Mass of ν detector	ν_e	ν_μ	ν_τ
# interacting in **FASERν**	150 / fb	1 tn Tungsten	~1000	~20000	~10
# interacting in **FASERν2**	3000 / fb	**10 tn** Tungsten	$\sim 10^5$	$\sim 10^6$	$\sim 10^4$

Unprecedented numbers of detectable neutrinos, at energy ranges where there is **currently no available data**!

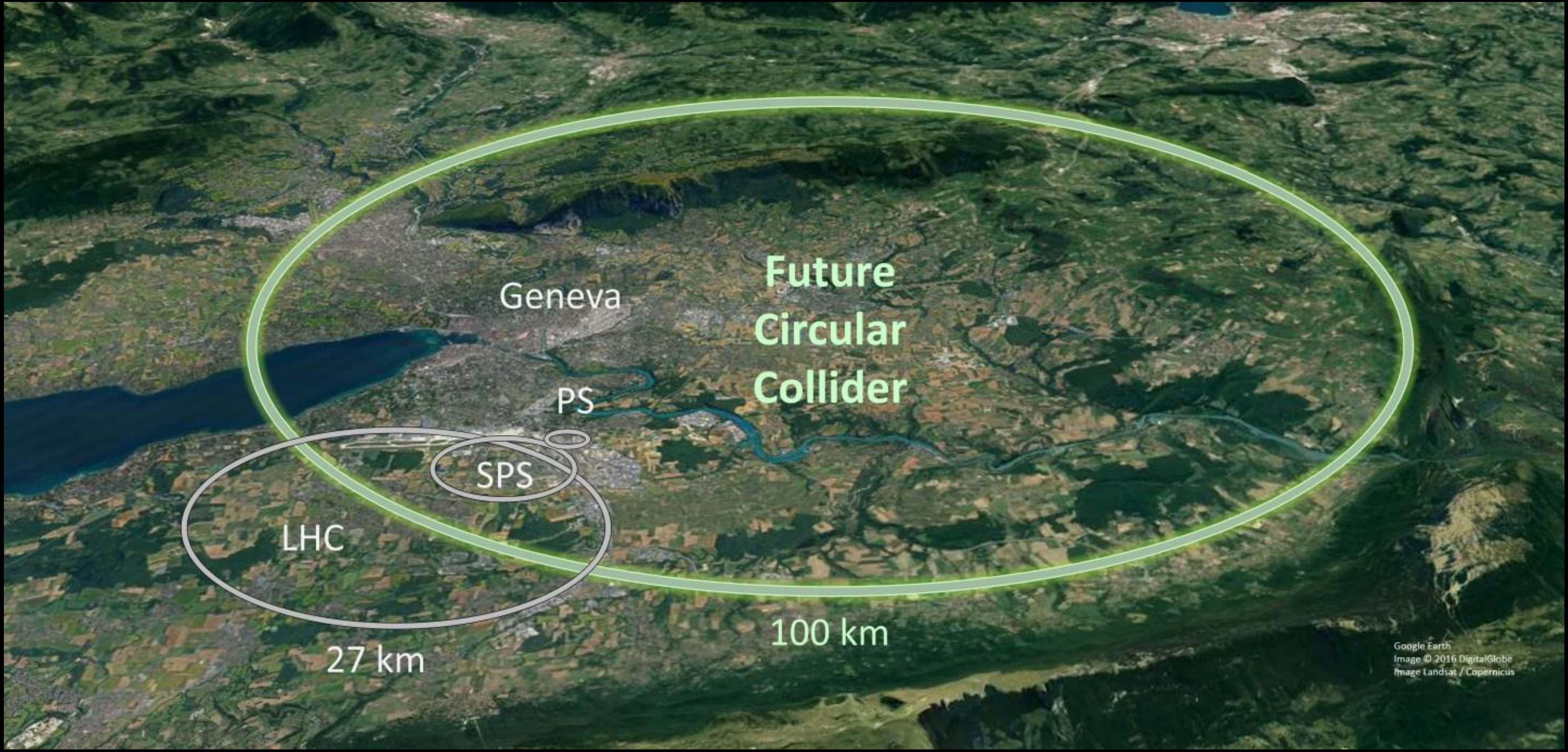
Increased BSM physics case **beyond** just increased luminosity





From https://pbc.web.cern.ch/sites/default/files/2023-04/FPFSummary_final.pdf

WHAT'S BEYOND HL-LHC ?


Future
Circular
Collider
Geneva
PS
SPS
LHC
100 km
27 km
Google Earth
Image © 2016 DigitalGlobe
Image Landsat / Copernicus

The FCC project

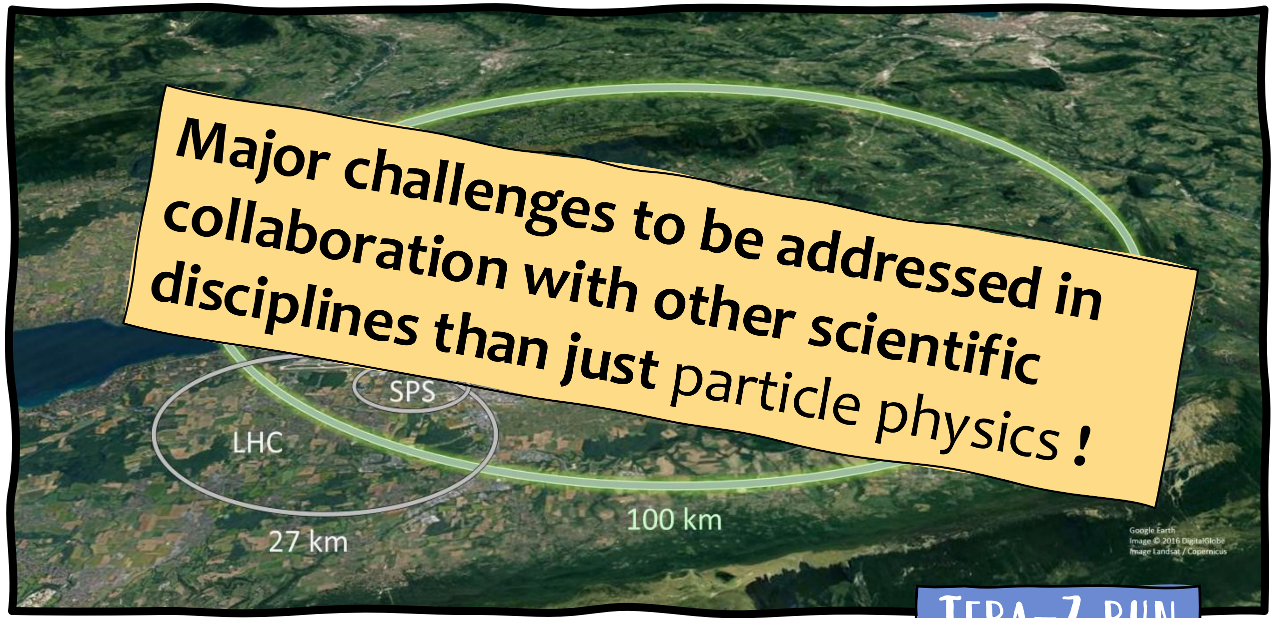
2020 European Strategy Update

An **electron-positron Higgs factory is the highest-priority next collider**. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.

https://europeanstrategy.cern/european-strategy-for-particle-physics

Aims at pushing both **energy** and **intensity frontiers** of particle colliders

- Conceptual design report (2020)
- Technical and financial feasibility study due for next EU strategy update (2027)



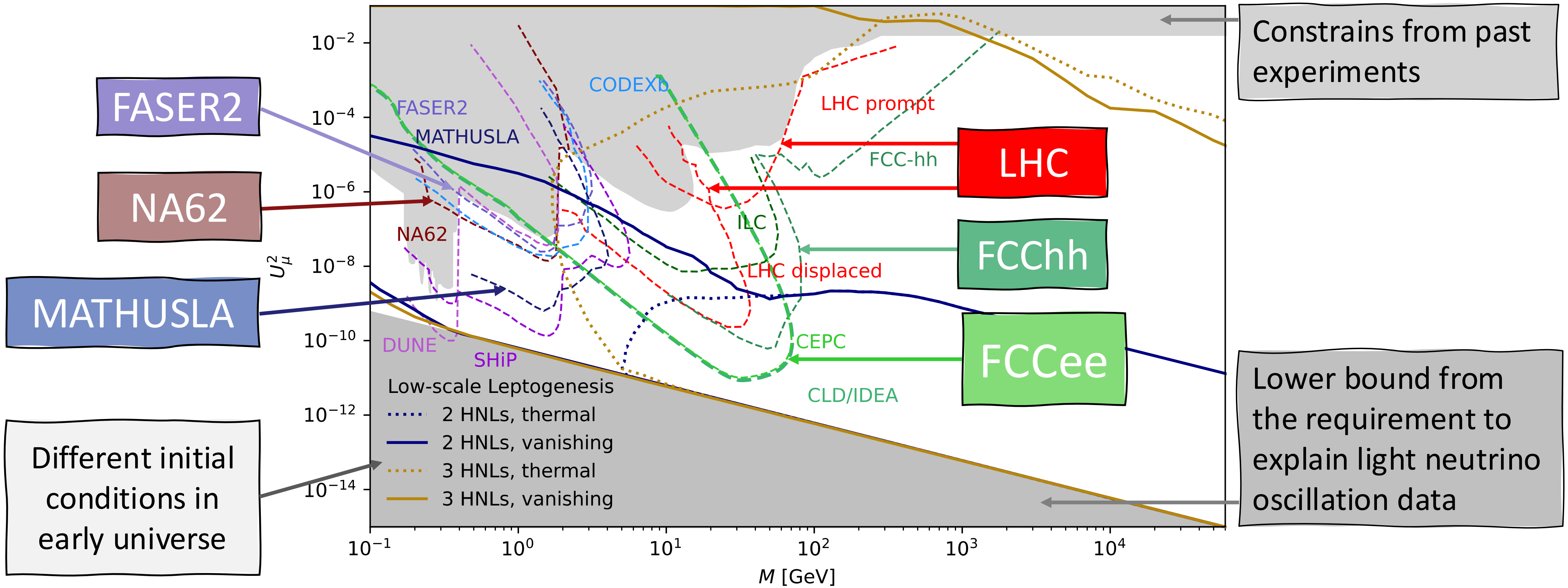
TERA-Z RUN

Stage	Collisions	CME	L (ab^{-1})	N events
FCC-ee	e^+e^-	90 GeV (Z-pole)	150	**5×10^{12}** Z
		160 GeV (WW)	10	10^8 WW
		240 GeV (HZ)	5	10^6 HZ
		365 GeV (tt)	1.5	10^6 tt
FCC-hh	pp	100 TeV	30	2×10^{10} H 3×10^7 HH
FCC-eh	ep	3.5 TeV		

Runs with heavy ions not included

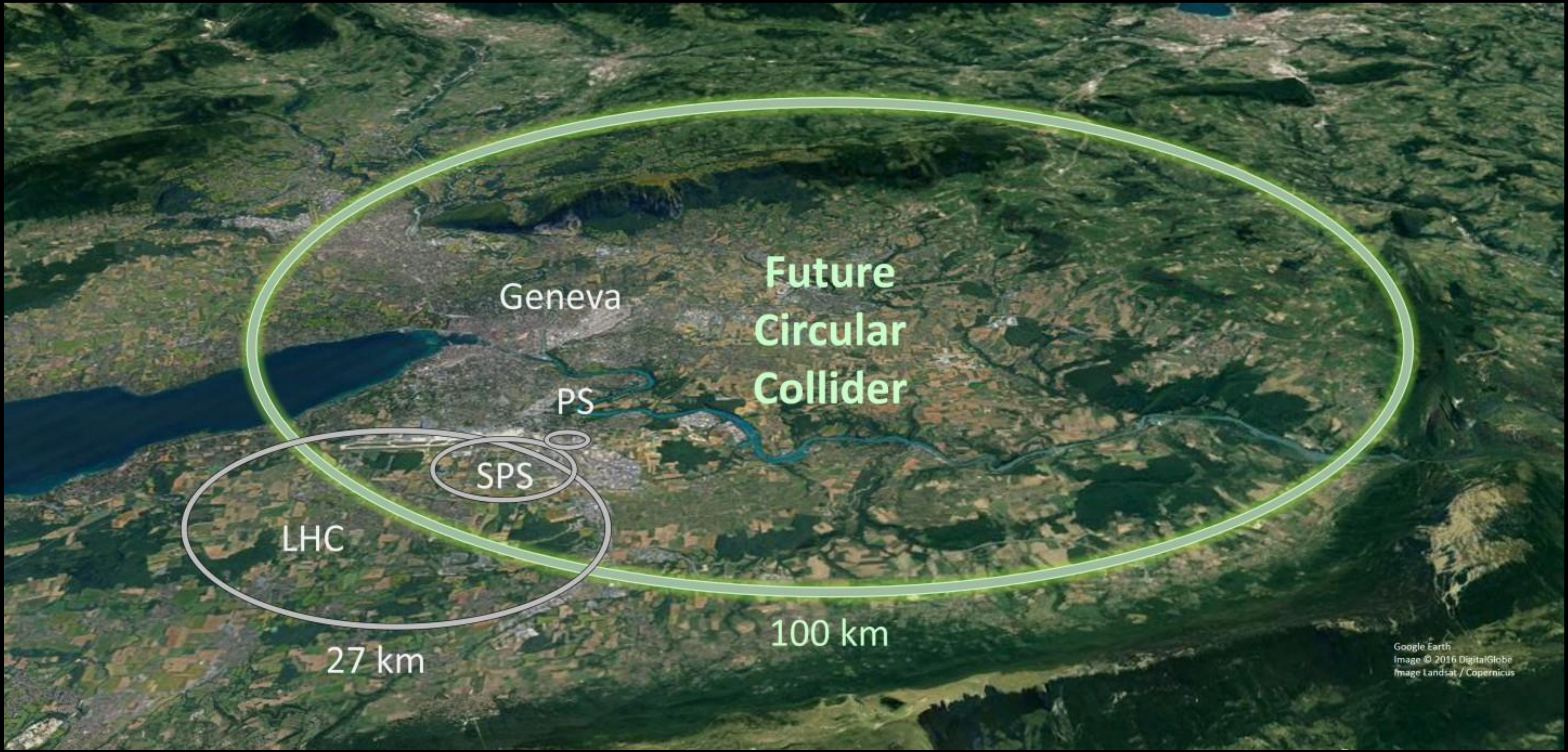
Recent review – input to Snowmass – arXiv:2203.06520

Reach for heavy Neutral Leptons in future experiments



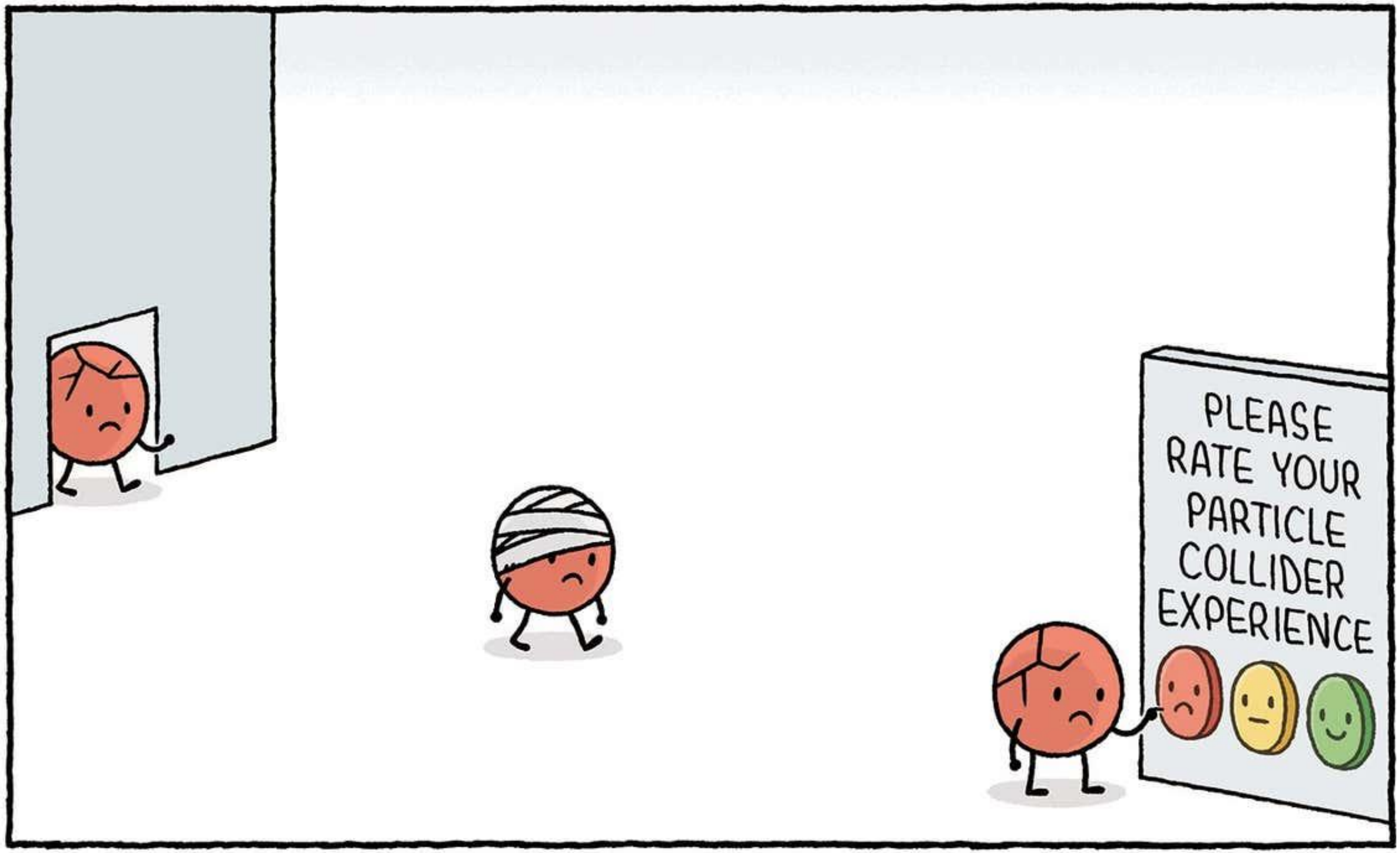
FCC-ee running at the Z-pole has the potential to exclude the region of masses and couplings down to the see-saw limit

LLPs at FCC – 2203.05502


Future
Circular
Collider
Geneva
PS
SPS
LHC
27 km
100 km
Google Earth
Image © 2016 DigitalGlobe
Image Landsat / Copernicus

In Brief:
Searching for Dark Matter at CERN

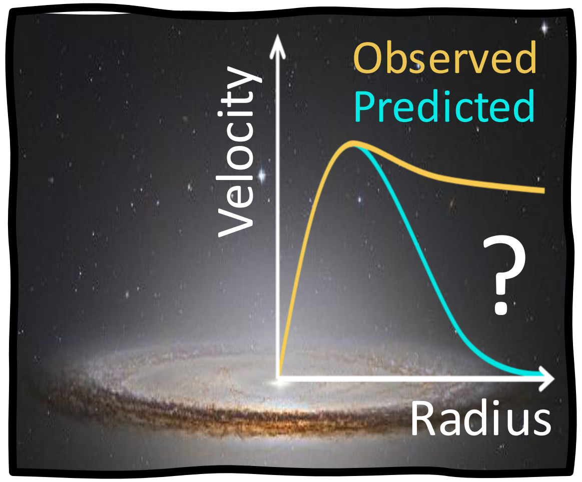
- The **Standard Model** is a brilliant framework that explains much of the known universe — but **it's incomplete**.
- One of its biggest mysteries: **What is dark matter?**
- To explore the **smallest building blocks of nature**, we need to reach **higher and higher energies**, which we do through **powerful particle collisions**.
- These collisions may create **dark matter candidates**, and **CERN experiments are actively searching** for them.
- The next breakthrough in physics could be **just around the corner** — we must be ready to recognize it!
- Along the way, we drive **cutting-edge technological innovation** with impacts far beyond particle physics.



TOM GAULD for NEW SCIENTIST

Extras

The landscape of new particles @ colliders



- Simple mechanism for DM evolution: "freeze out"