DARK MATTER SEARCHES

at colliders

For questions, don’t hesitate to get in touch:
anna.sfyrla@unige.ch

Indirect detection

DM ANNIHILATION

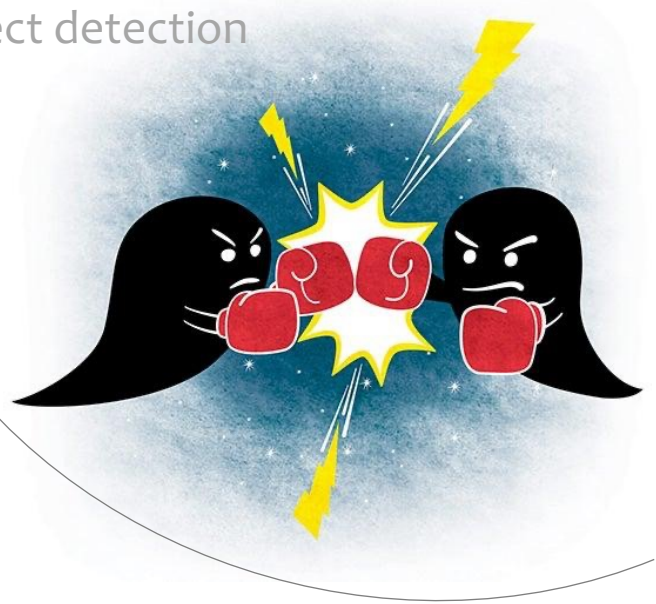
DM → SM

Direct detection

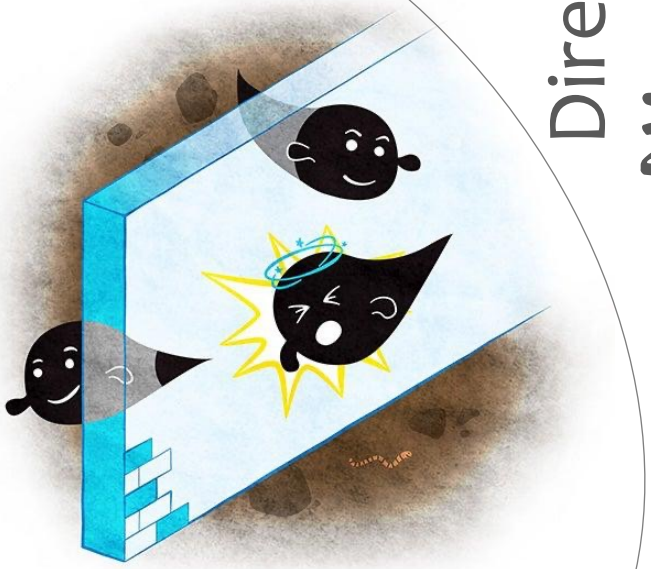
DM–NUCLEON SCATTERING

SM → DM

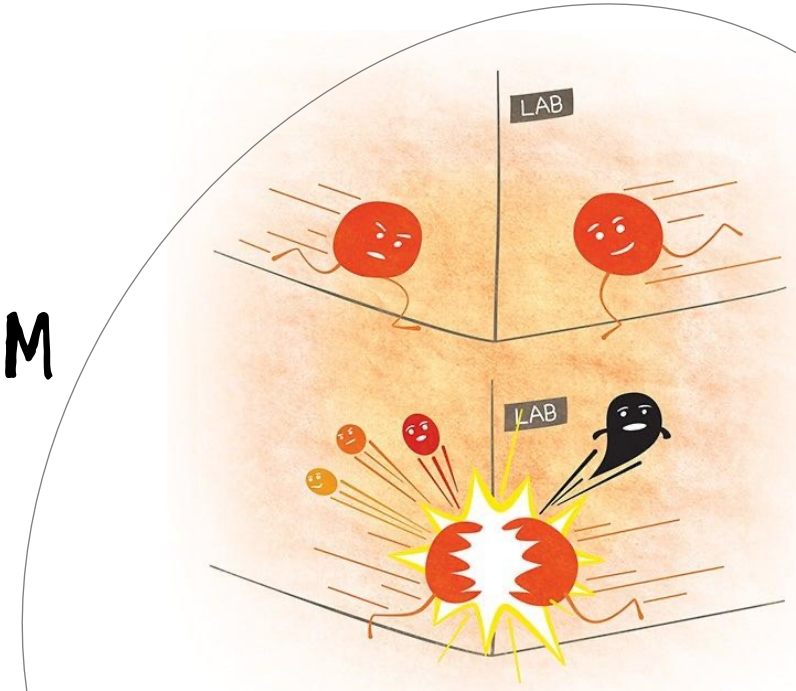
COLLIDER SEARCHES



Indirect detection

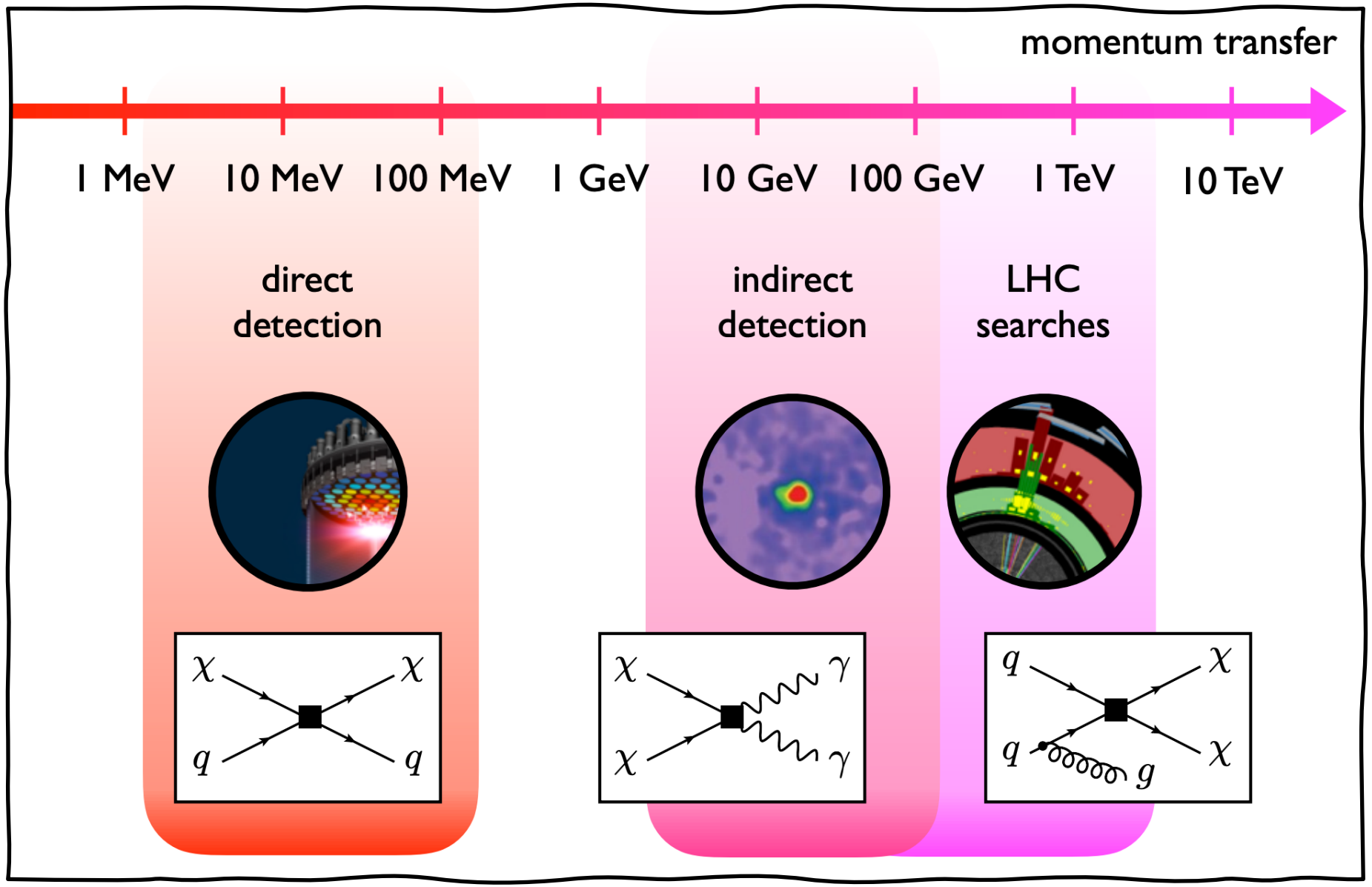


Direct detection

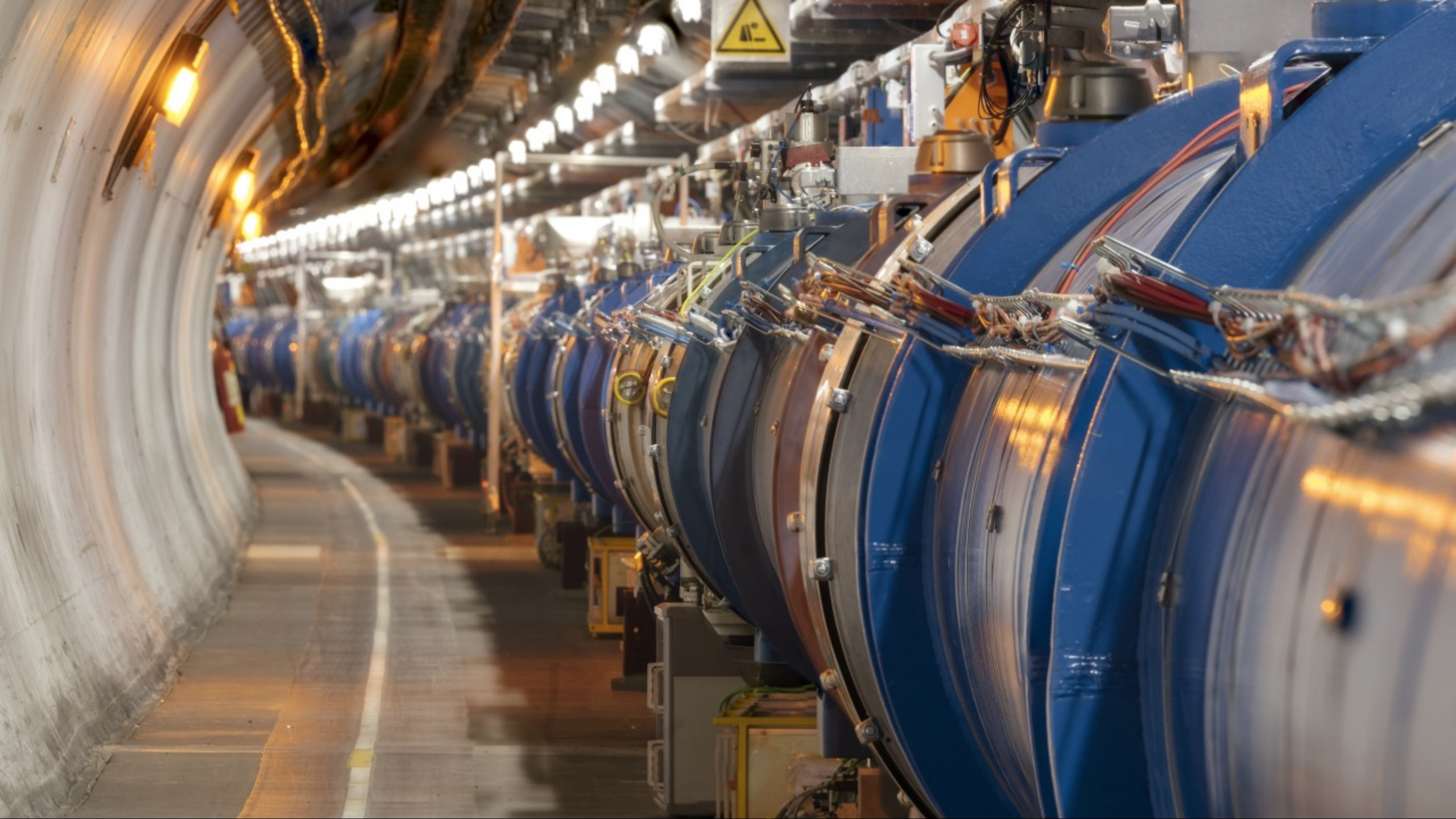


Collider searches

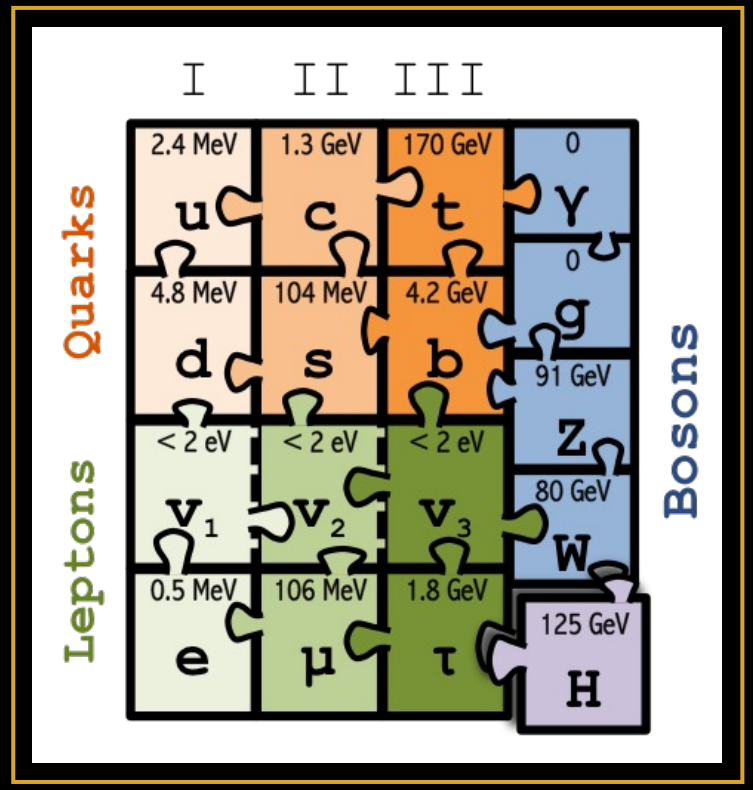
Drawings from
https://www6.slac.stanford.edu/news/2016-02-08-three-ways-bust-ghostly-dark-matter



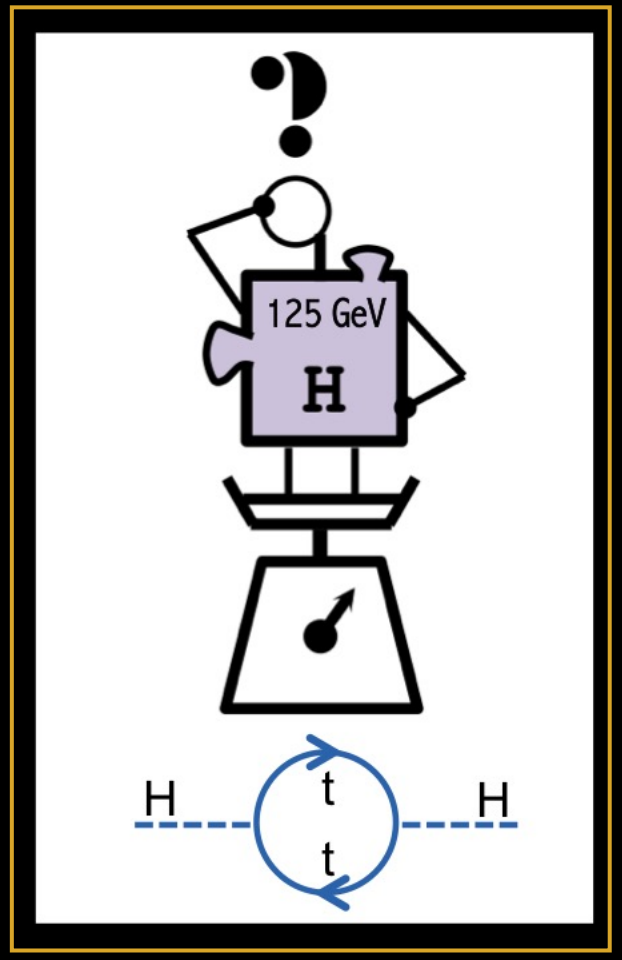
https://arxiv.org/pdf/1810.09420.pdf

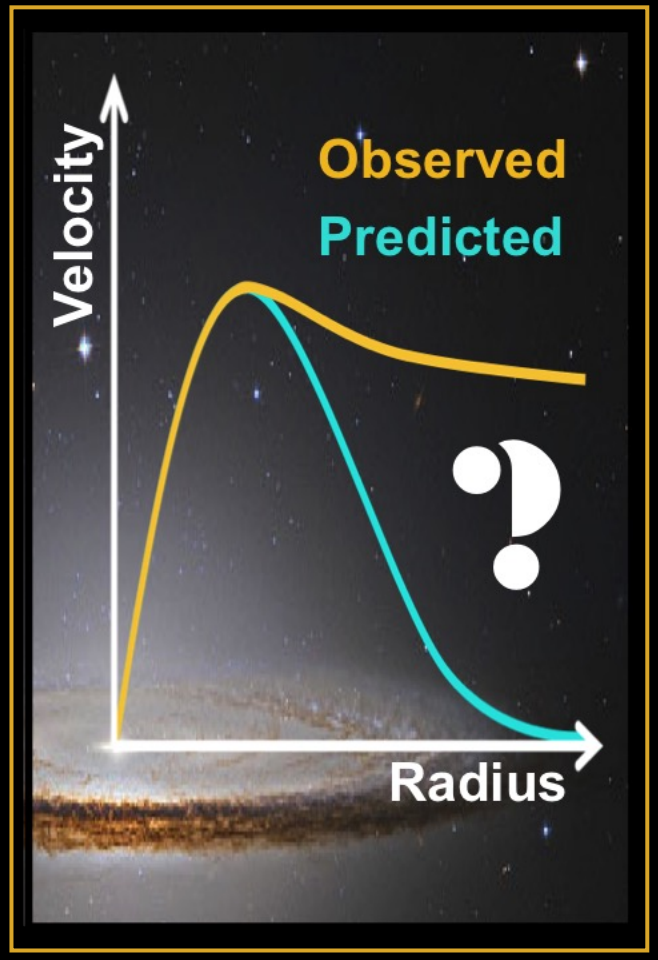


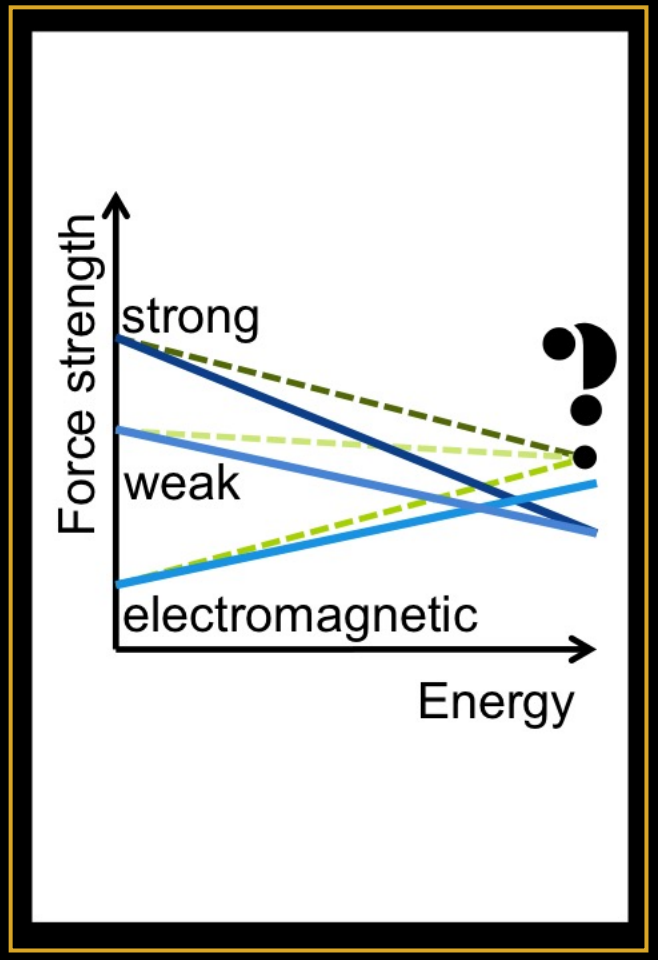
The Standard Model



...its Biggest Questions...







...AND ITS MORE SUBTLE ONES!

The “strong CP problem”: Why does QCD preserve CP symmetry?

Within the SM, the QCD vacuum structure introduces a CP violating term in the Lagrangian:

$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

while measurements require that the vacuum angle θ is tiny!

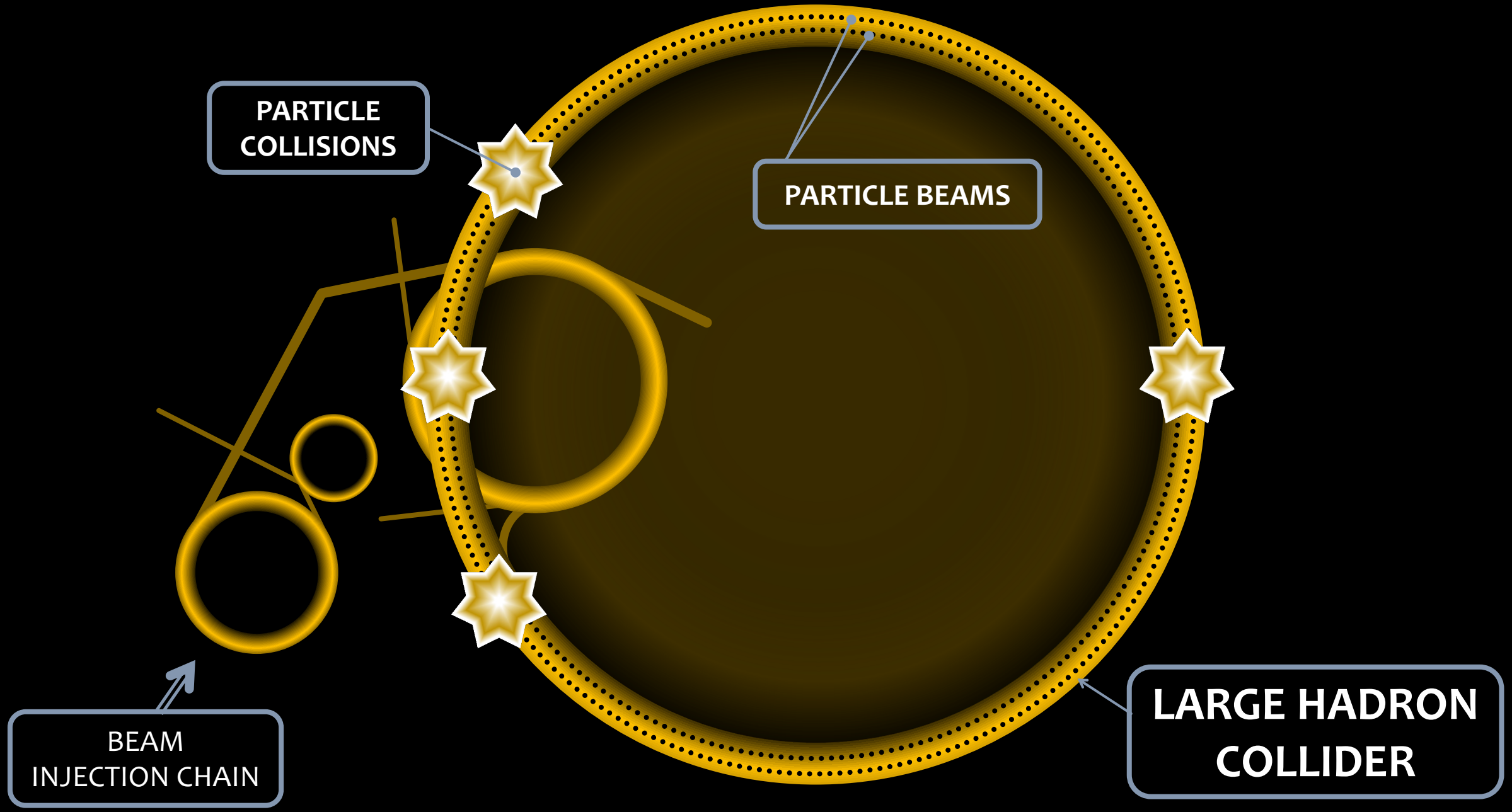
The non-zero angle θ implies non-zero neutron electric dipole moment (EDM)
The angle is stringently constrained by neutron EDM measurements

Most sensitive measurement on the neutron EDM to date achieved by the **PSI** experiment **nEDM**:

$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}$ e·cm.

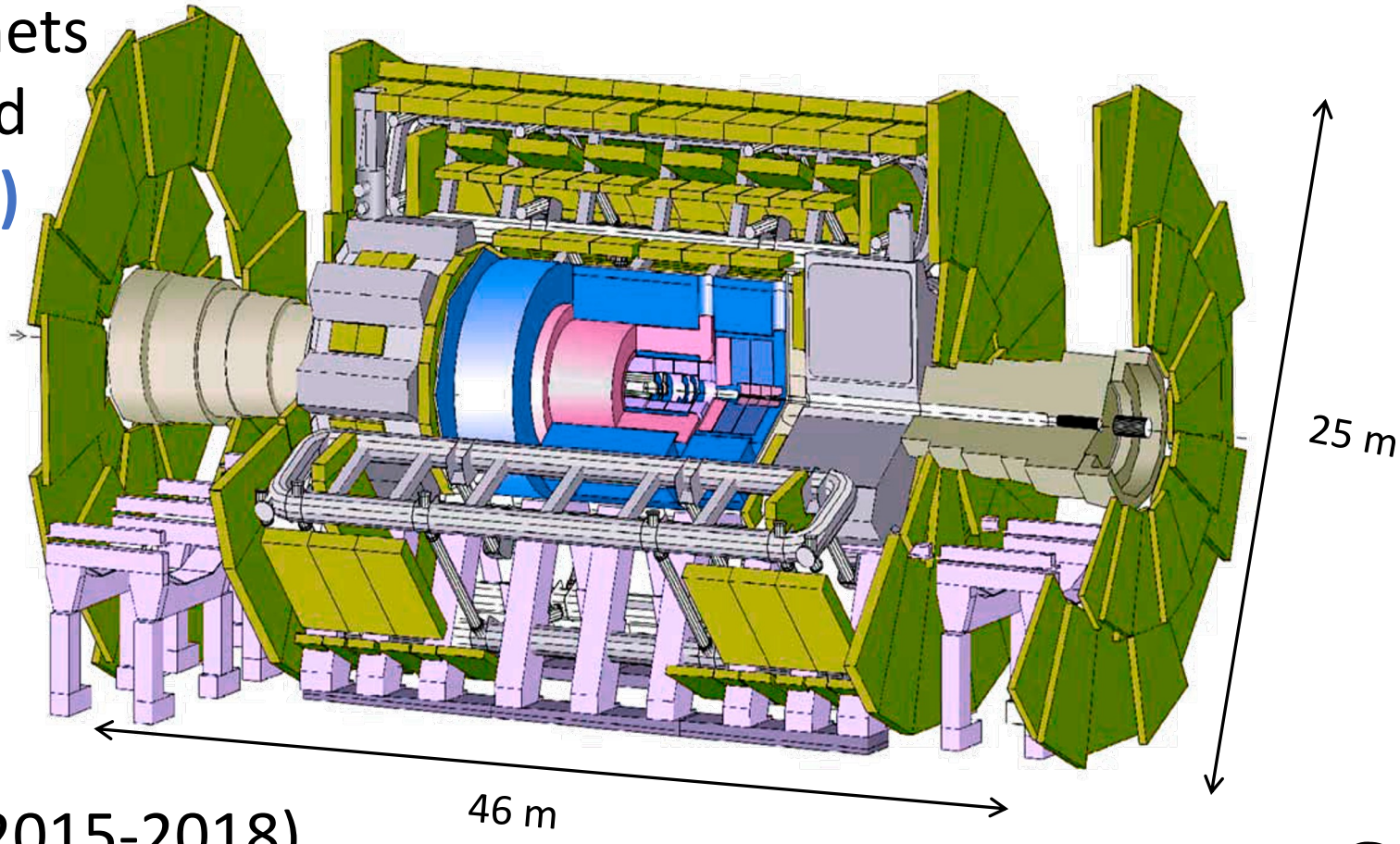
In other words,

The “strong CP problem”: Why no measurable neutron EDM?


PARTICLE COLLISIONS
PARTICLE BEAMS
BEAM INJECTION CHAIN
LARGE HADRON COLLIDER

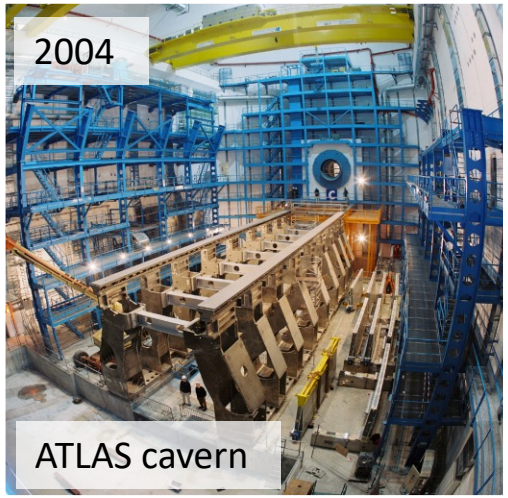
Example: The ATLAS detector in numbers

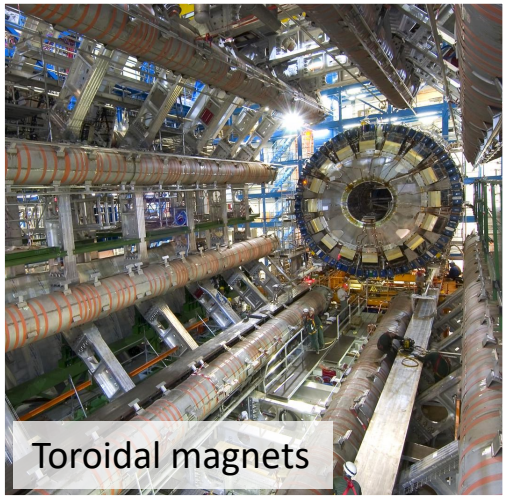
- ✓ Weights **7 ktonnes** ()
- ✓ **2-4 T** superconducting magnets
- ✓ Position of particles recorded with an accuracy of **O(10 µm)**
- ✓ **100 M** channels

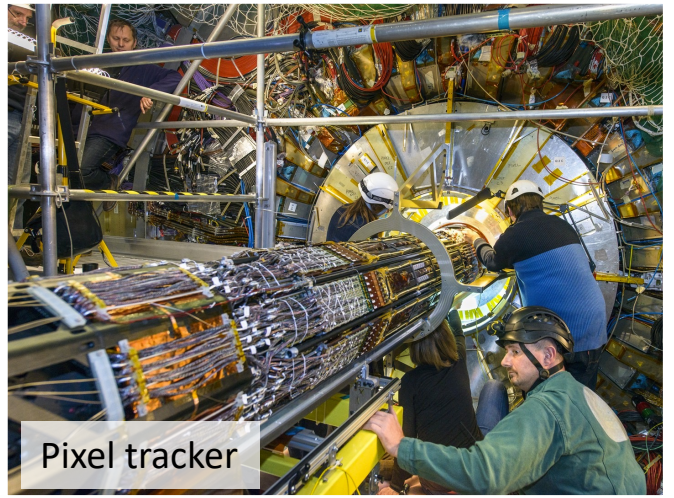


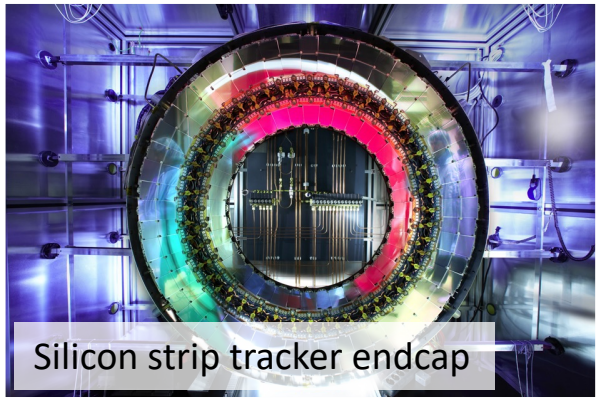
- ✓ **1 Giga** collisions/second
- ✓ **1000** events/second stored
- ✓ **500 PB** data on disk & tape
- ✓ **0.5 M** CPU cores used 24/7

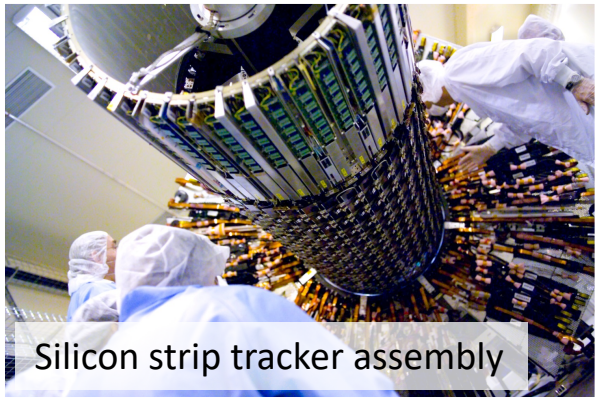
- ✓ **20 billion** events collected (2015-2018)

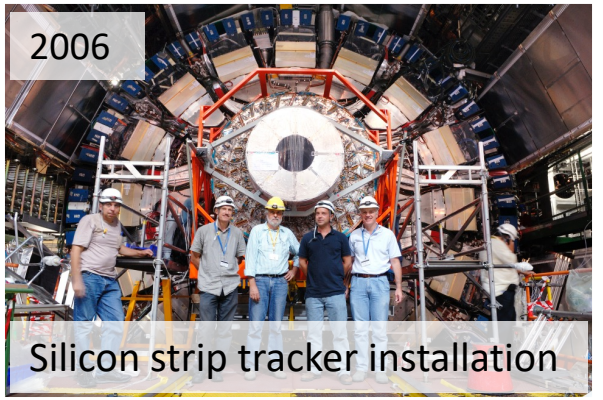




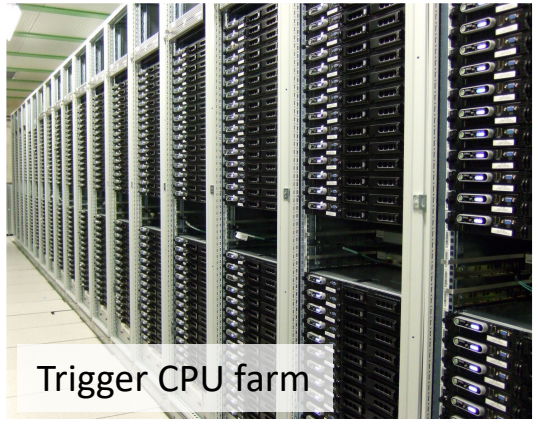








ATLAS EXPERIMENT



(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

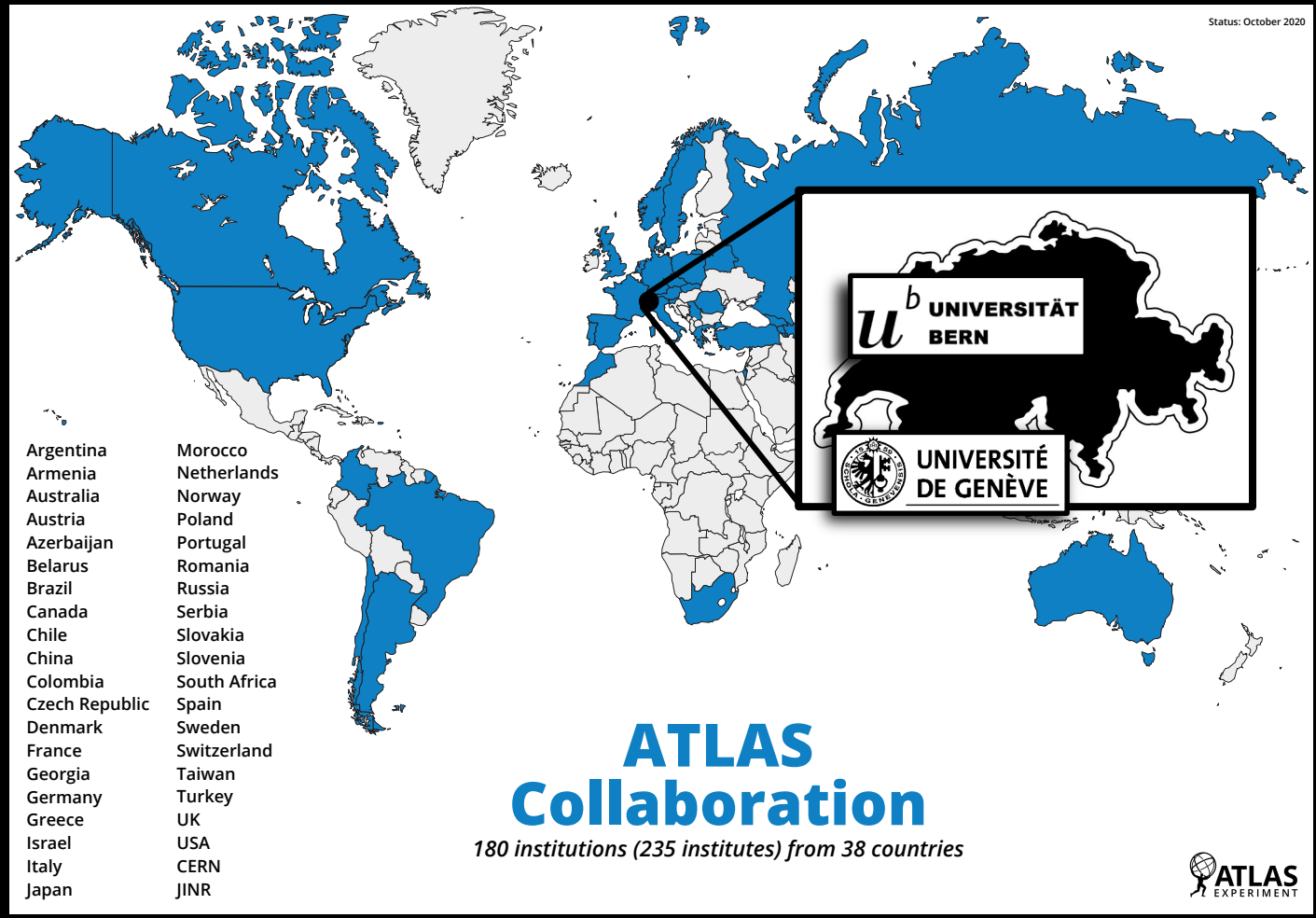
The ATLAS Collaboration

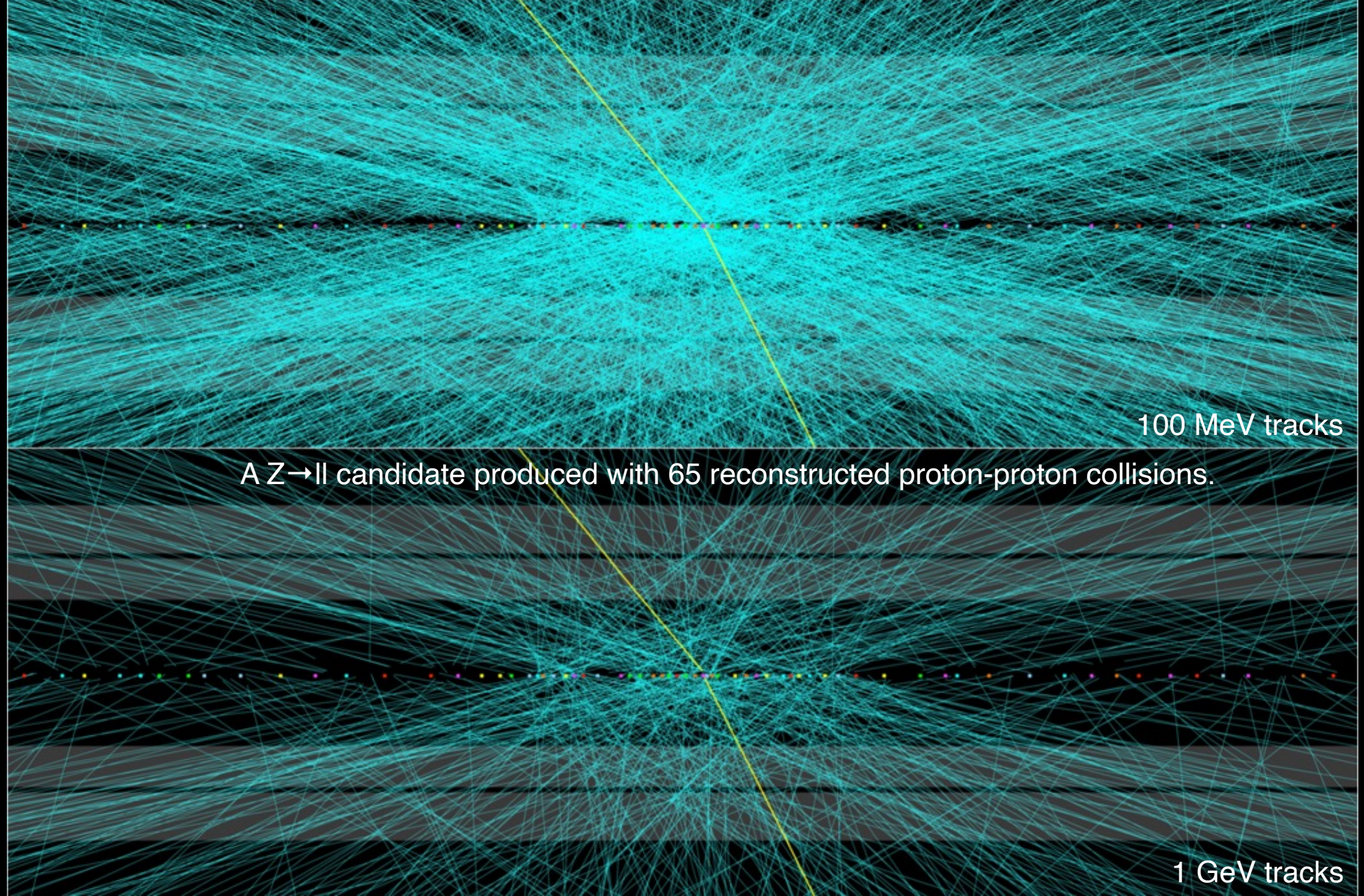
3000
Scientific authors

38
Countries

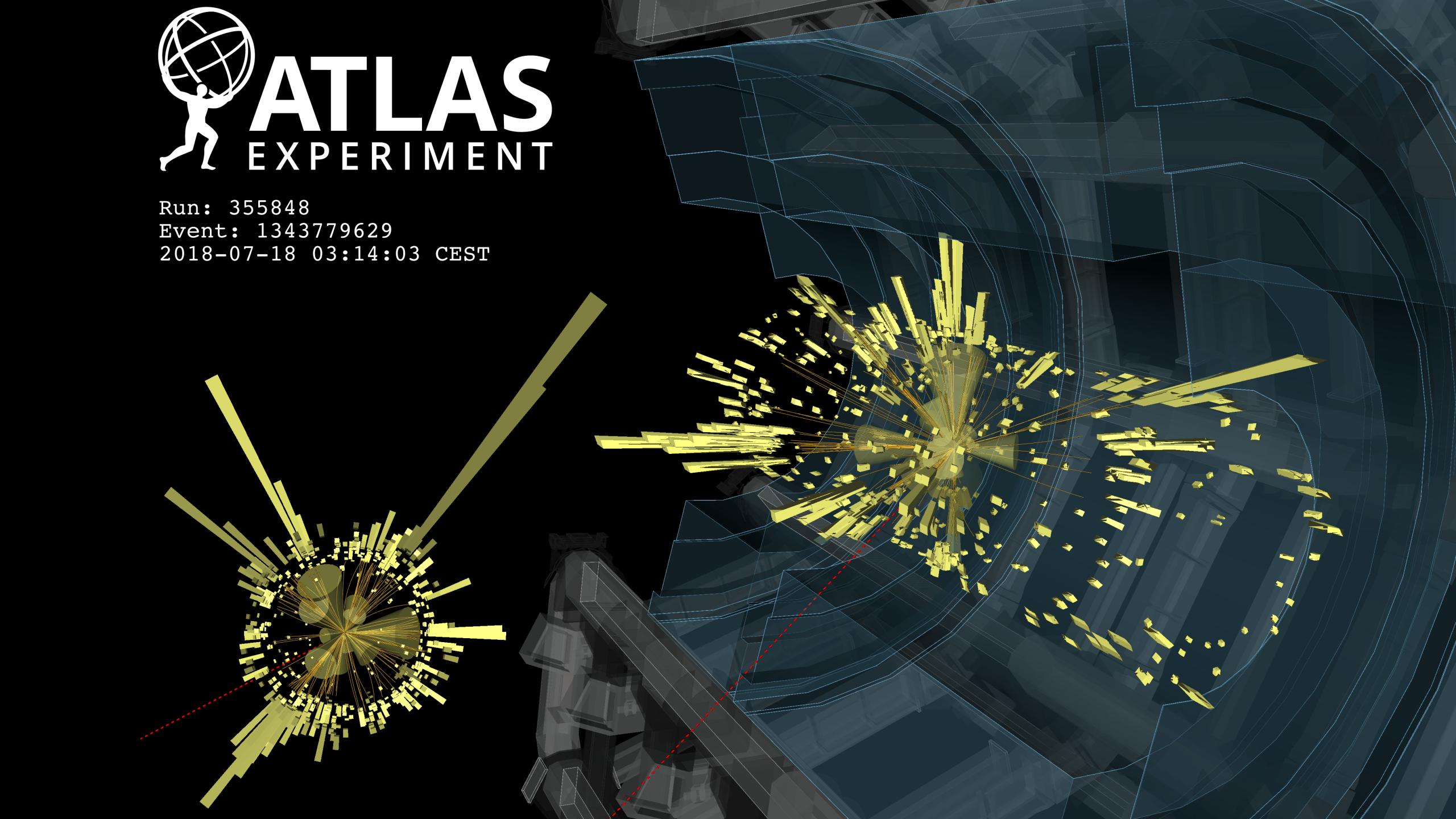
180
Institutions

1200
Doctoral students





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


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

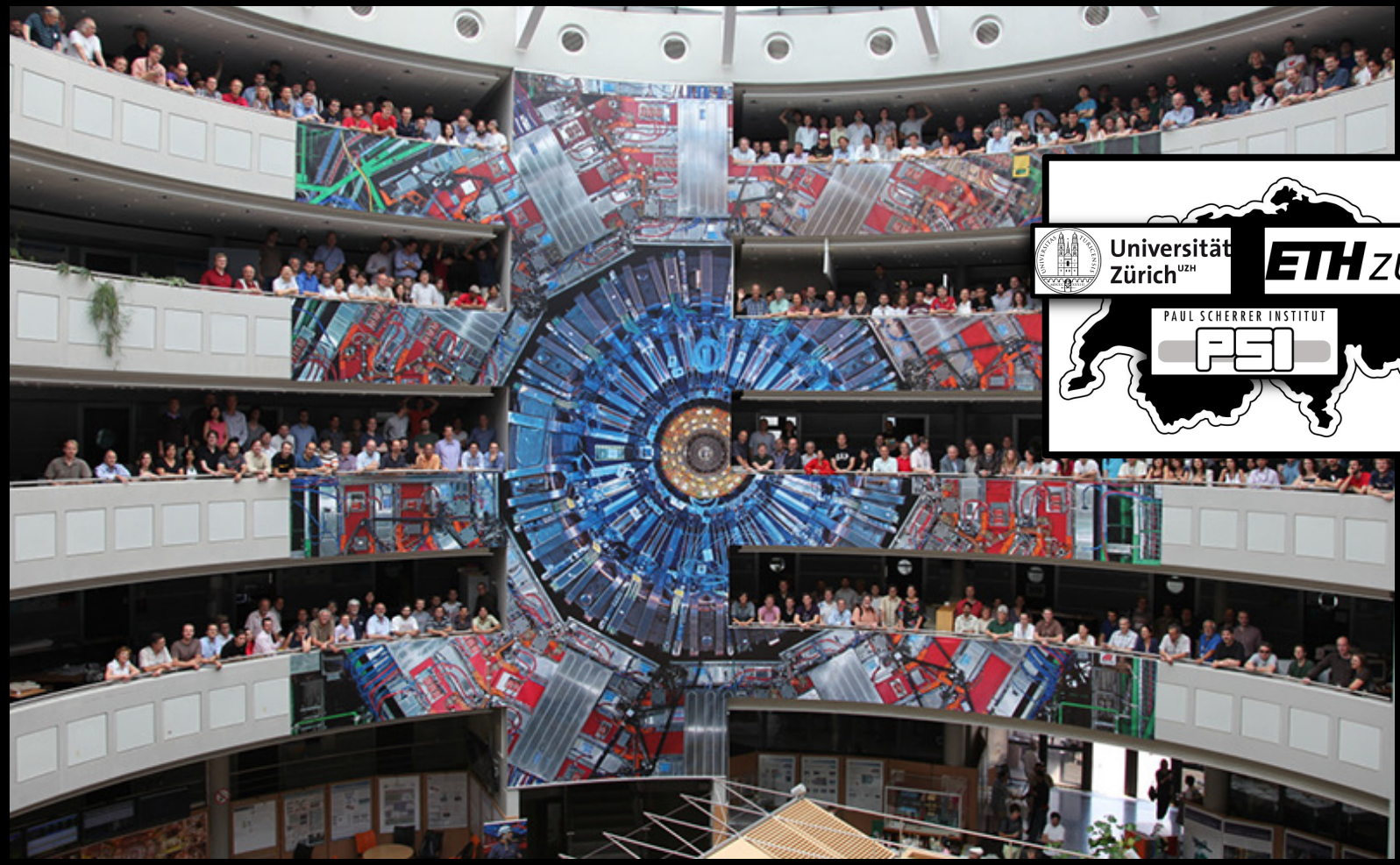
The CMS Collaboration

2100
Scientific authors

51
Countries

229
Institutions

1100
Doctoral students

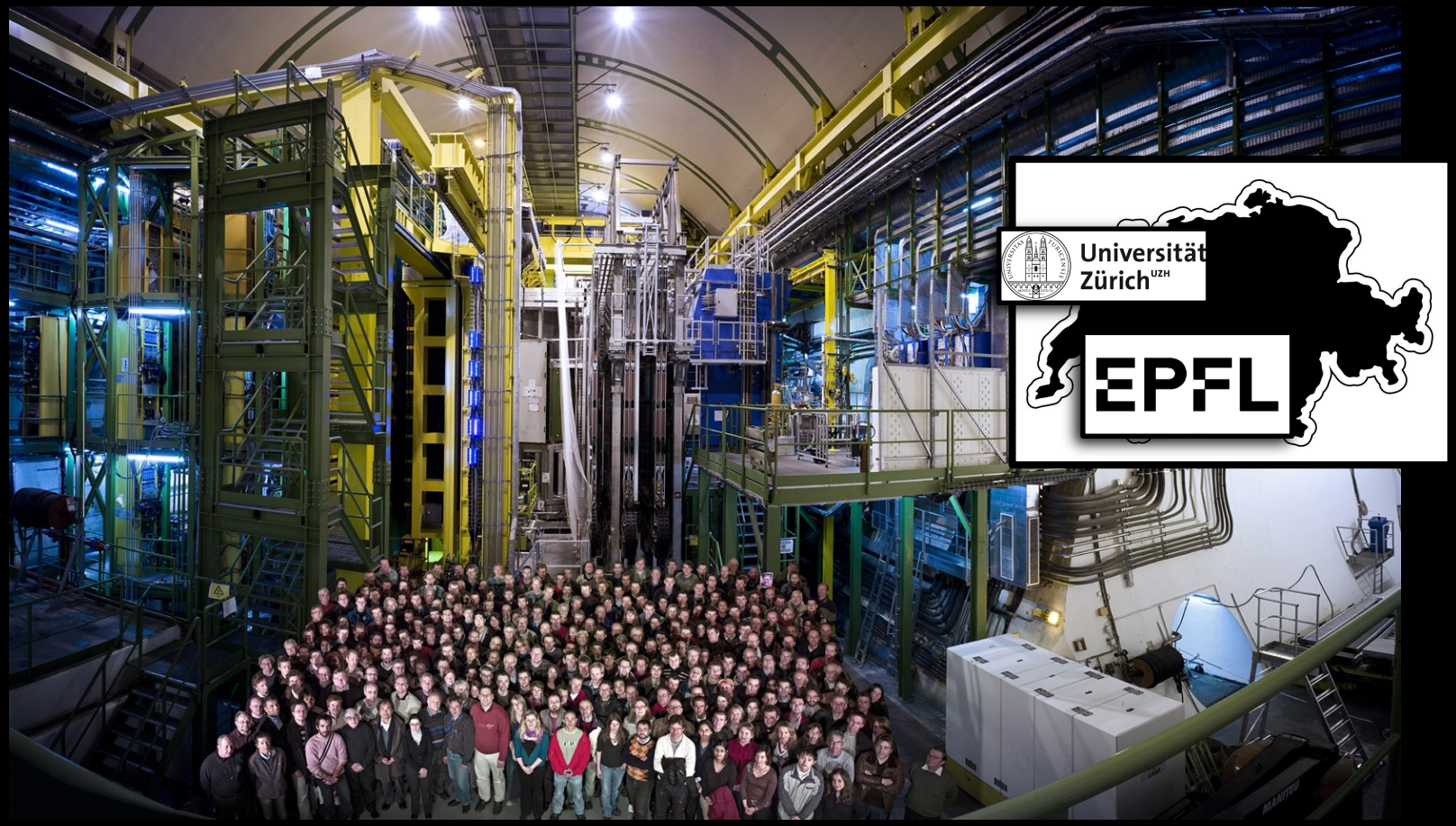


The LHCb Collaboration

1500
Members

19
Countries

87
Institutions

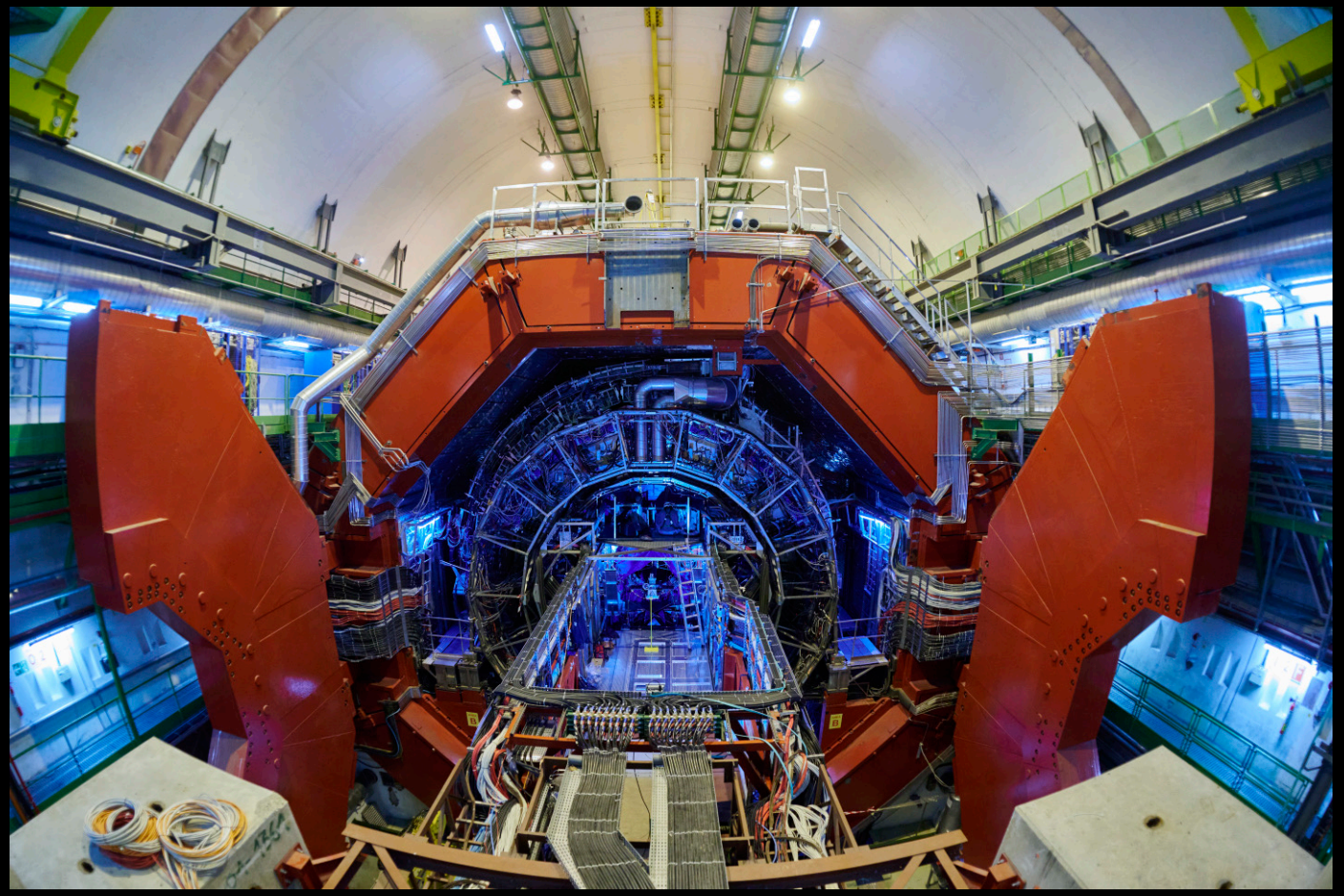


The ALICE Collaboration

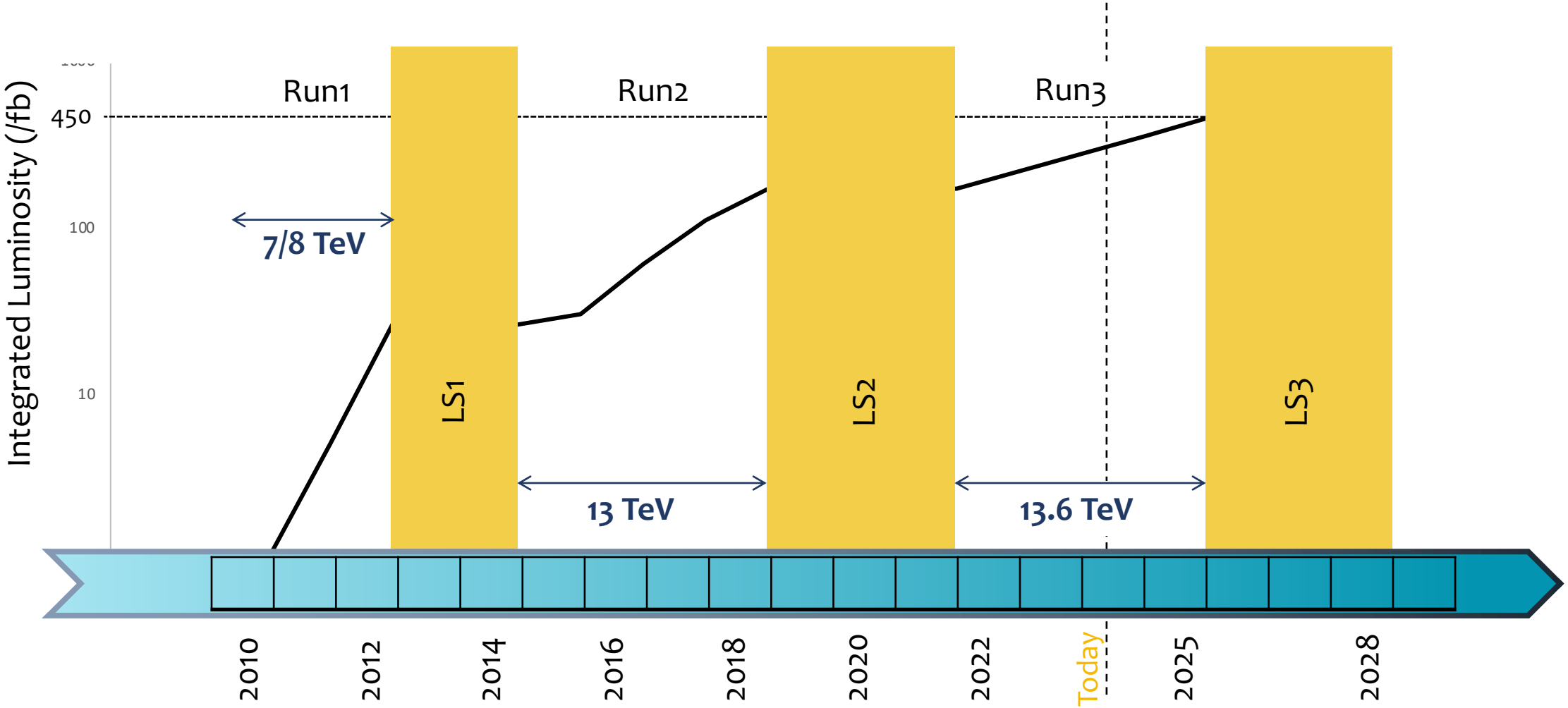
1990
Members

40
Countries

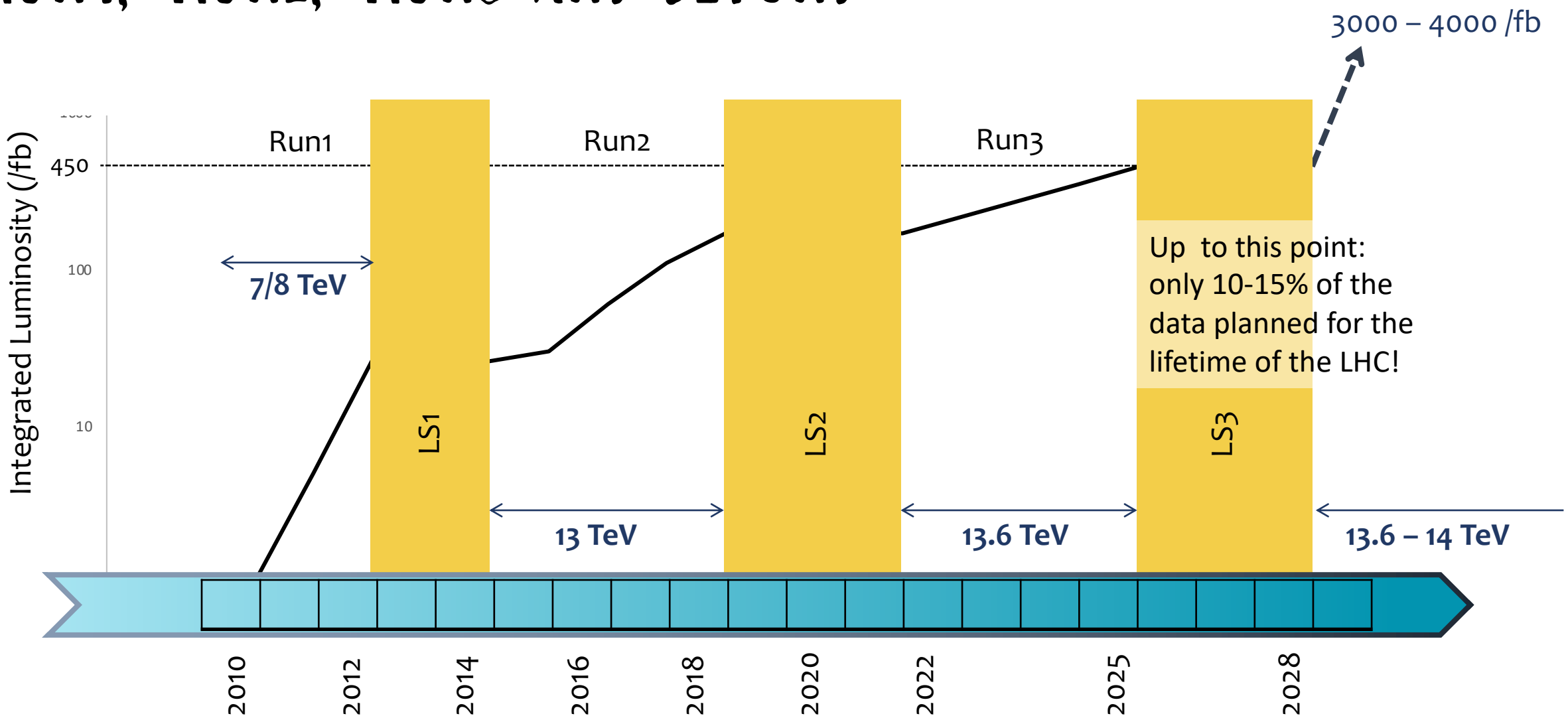
172
Institutions



Run1, Run2, Run3 ...

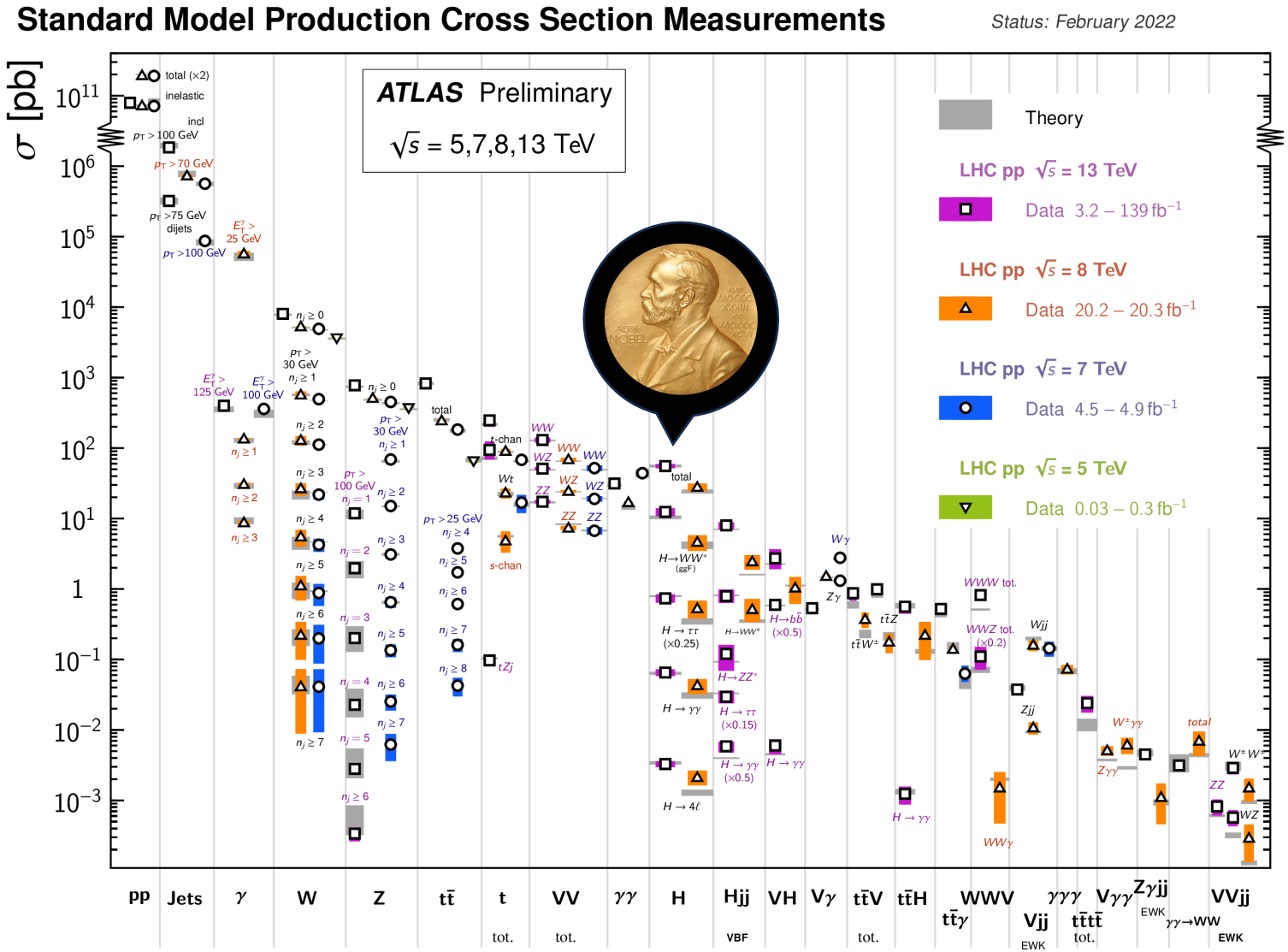


Run1, Run2, Run3 and beyond



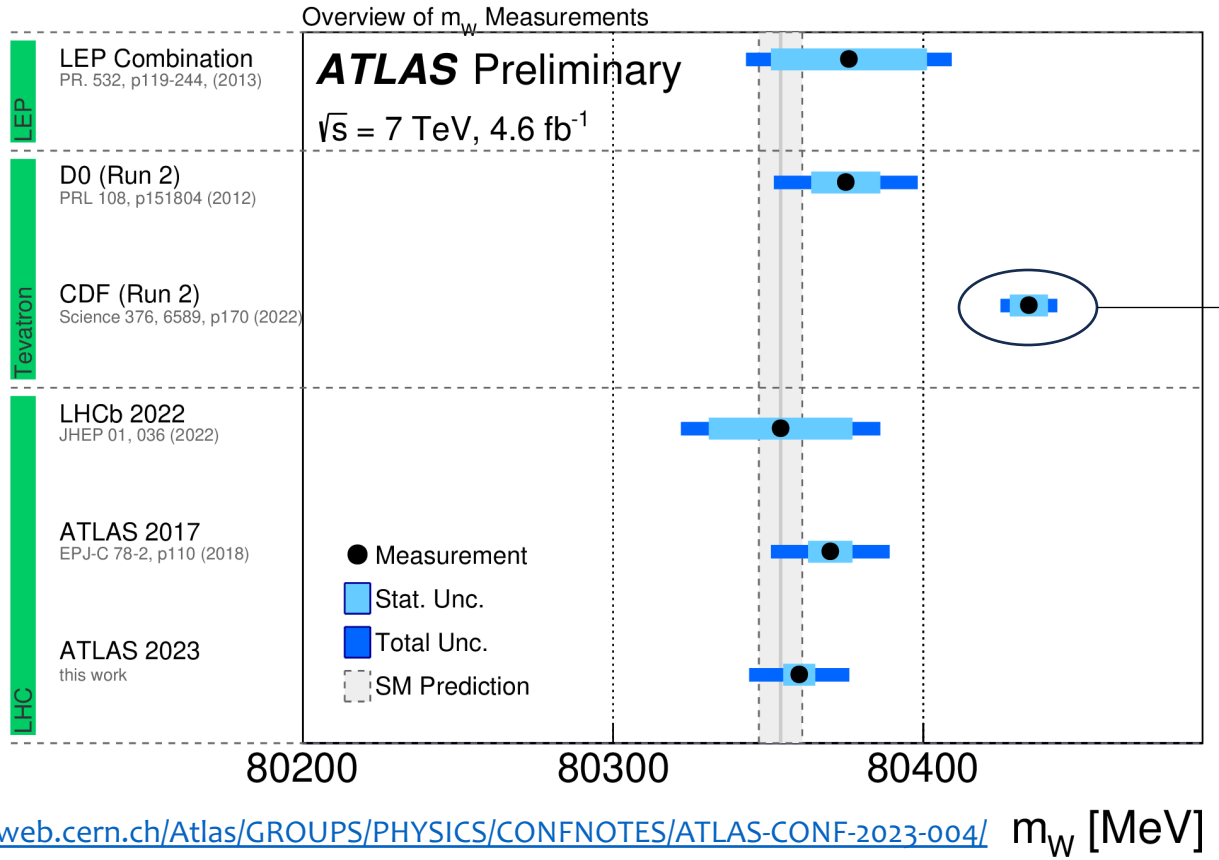
The Landscape of Particles

The Standard Model studied in detail



Masses

Extracted by fits to distributions and measurements that depend on the mass



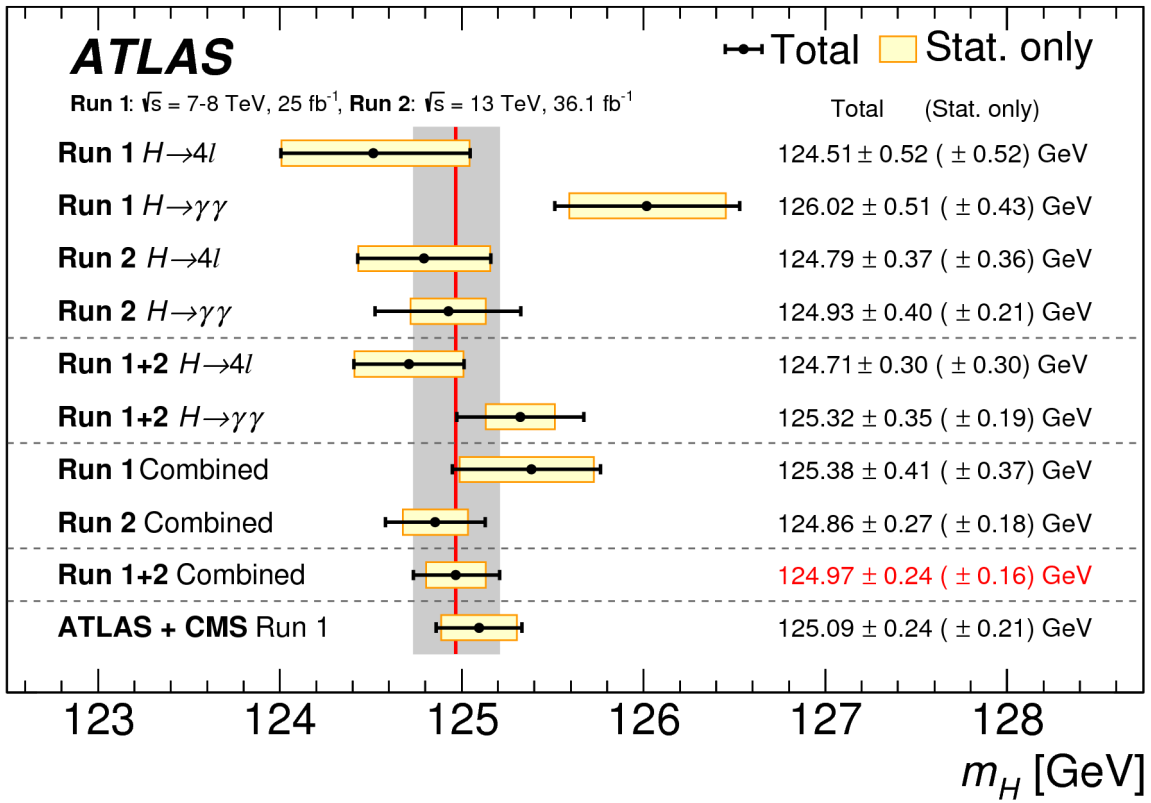
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-004/

"This measurement, M_W=80,433.5±9.4 MeV, is more precise than all previous measurements of M_W combined. A comparison with the SM expectation of M_W=80,357±6 MeV […] yields a difference with a significance of 7.0σ and suggests the possibility of improvements to the SM calculation or of extensions to the SM."

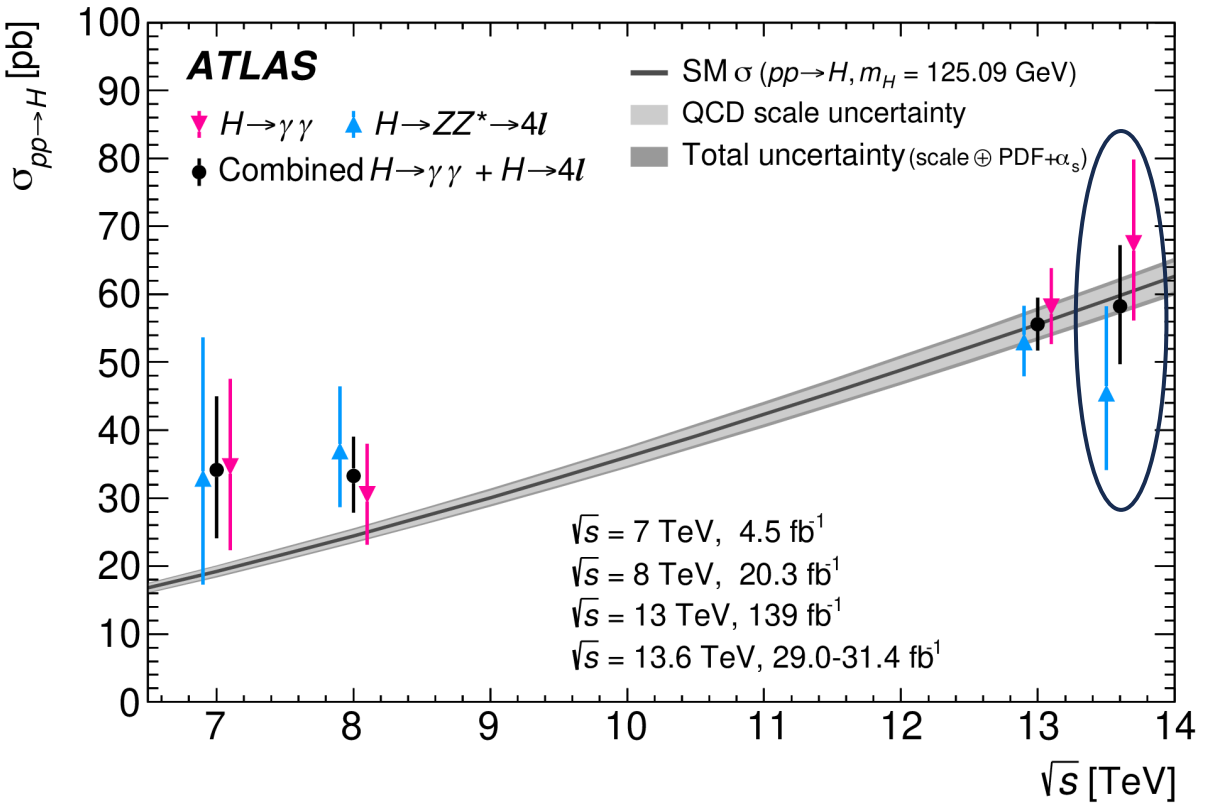
https://www.science.org/doi/10.1126/science.abk1781

The Higgs Boson

Intense efforts to asses its properties with high precision



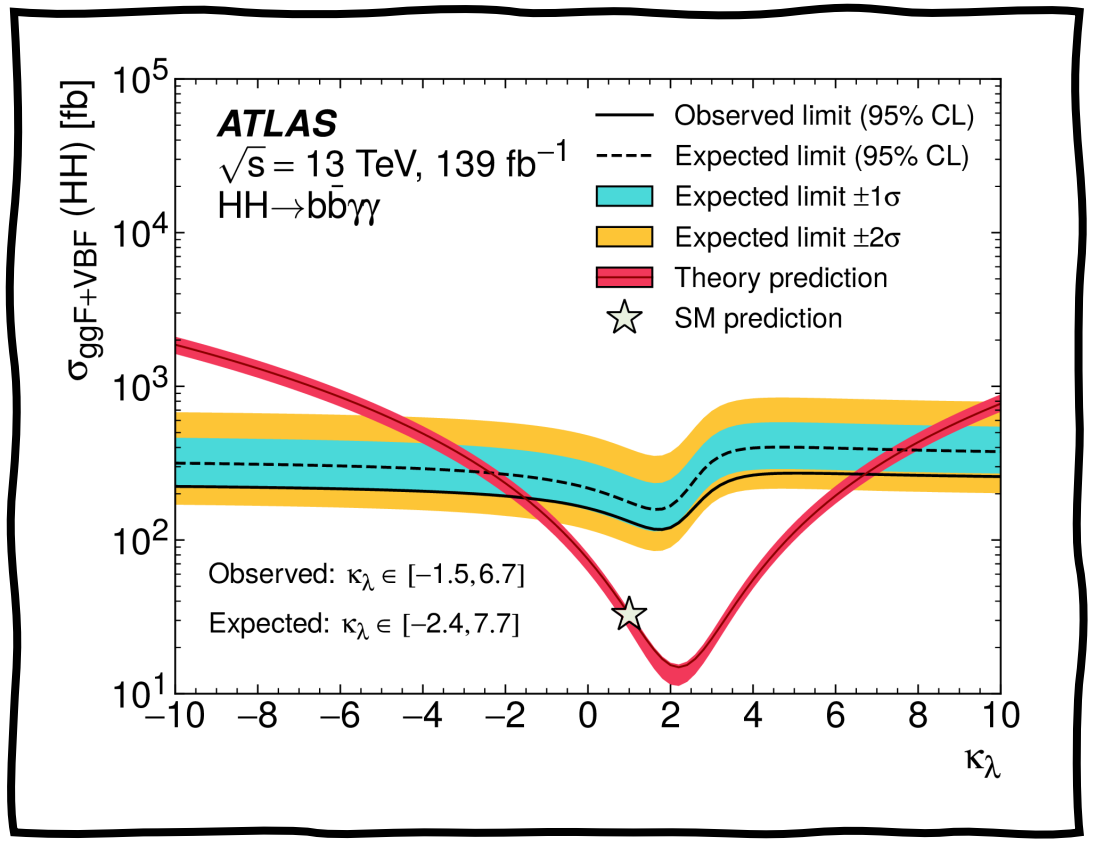
Mass

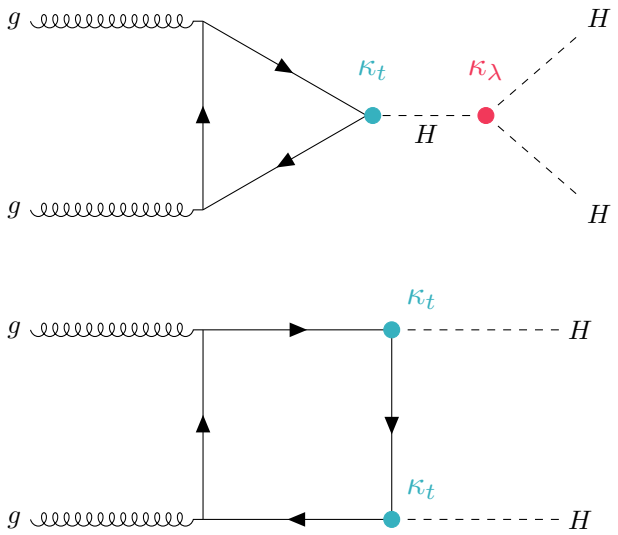


Production cross-section

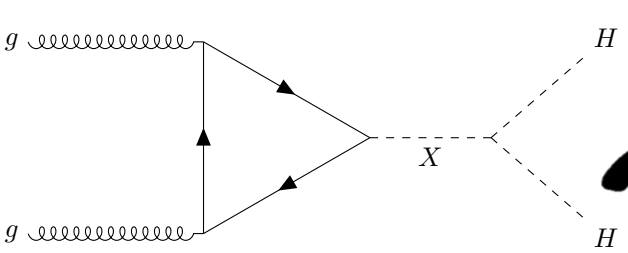
Higgs searches: Processes not yet observed

- 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





Sensitivity to new physics!

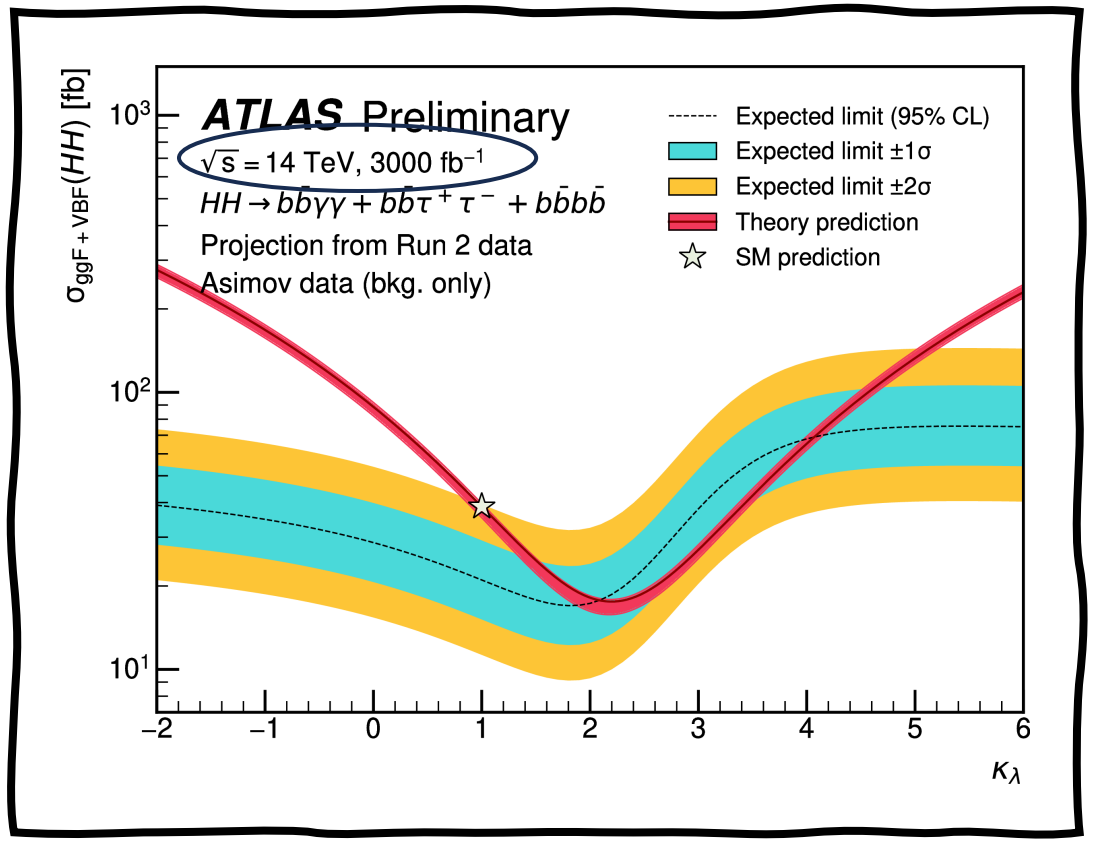


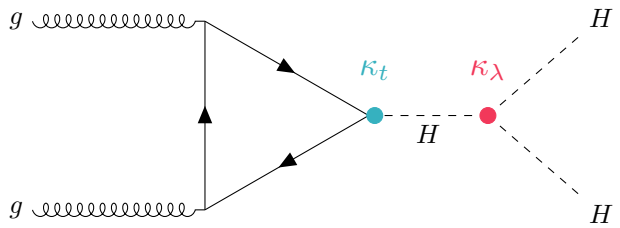
Recent HH->bbγγ results

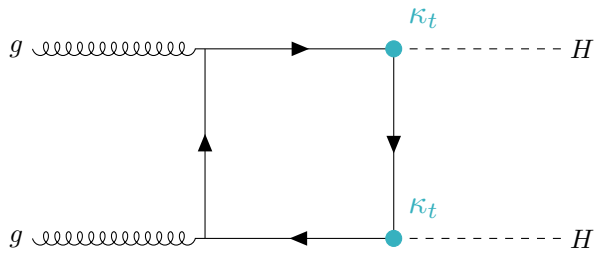
Higgs searches: Processes not yet observed

Need HL-LHC to see HH and start studying it!

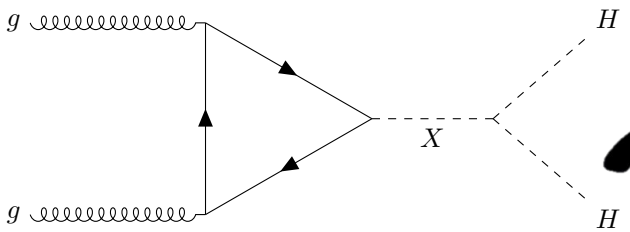
- There are still SM processes that have not been observed
  - Eg. HH production
  - We don't know if it occurs in rates as the SM predicts



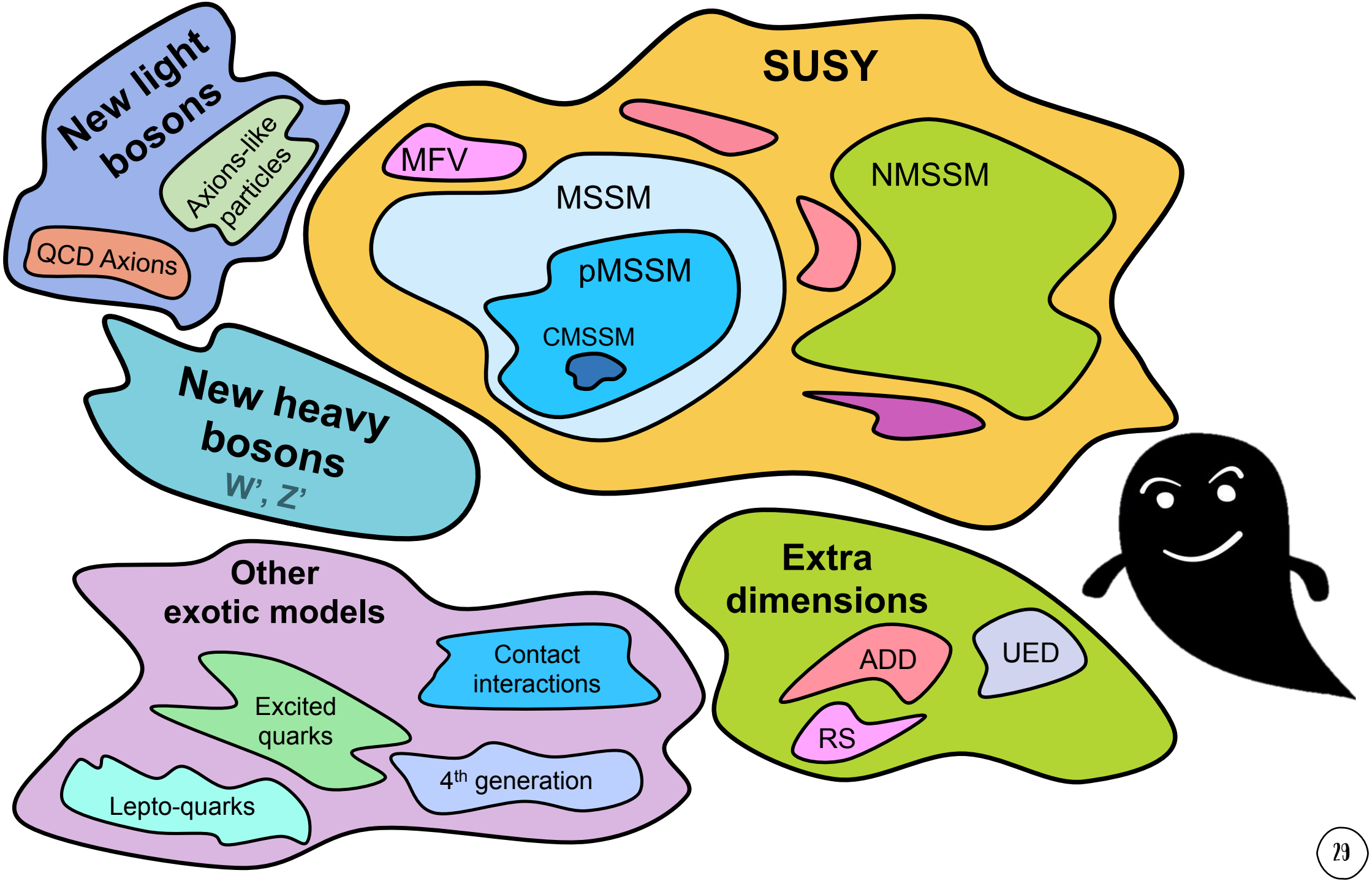




Sensitivity to new physics!

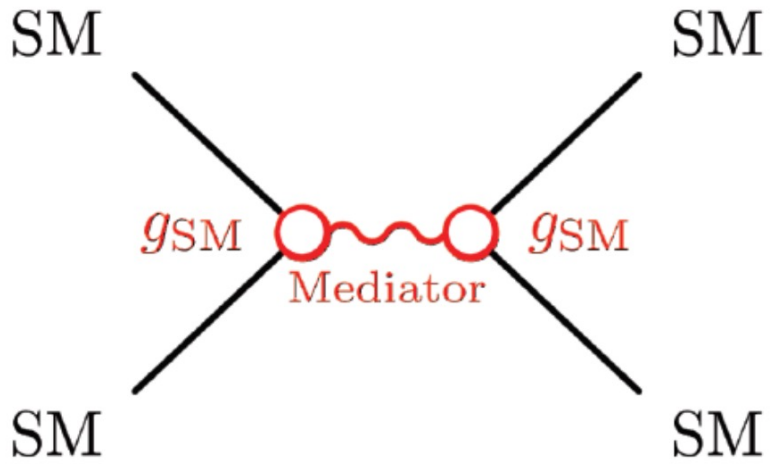


Projection to HL-LHC data set

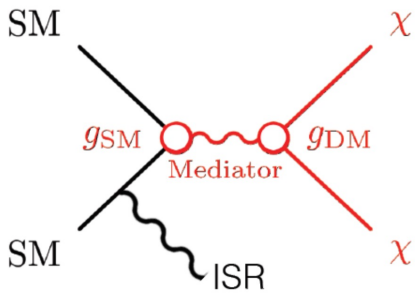

New light bosons
Axions-like particles
QCD Axions
SUSY
MFV
MSSM
pMSSM
CMSSM
NMSSM
New heavy bosons
W', Z'
Other exotic models
Contact interactions
Excited quarks
4th generation
Lepto-quarks
Extra dimensions
ADD
UED
RS

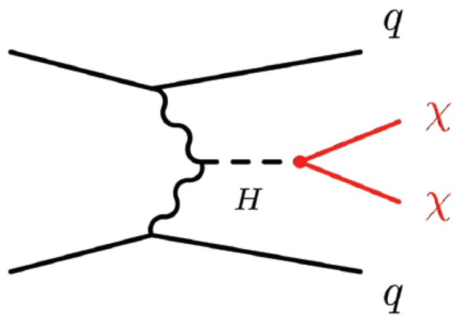
Dark Matter Searches

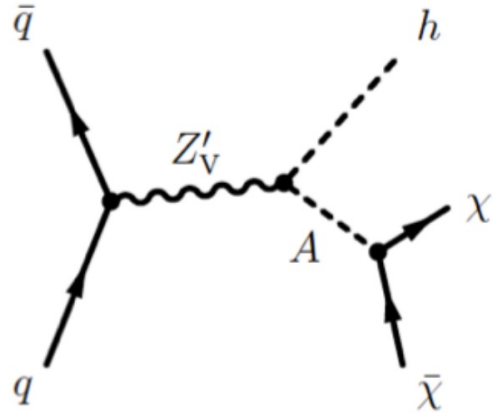
Mediator searches

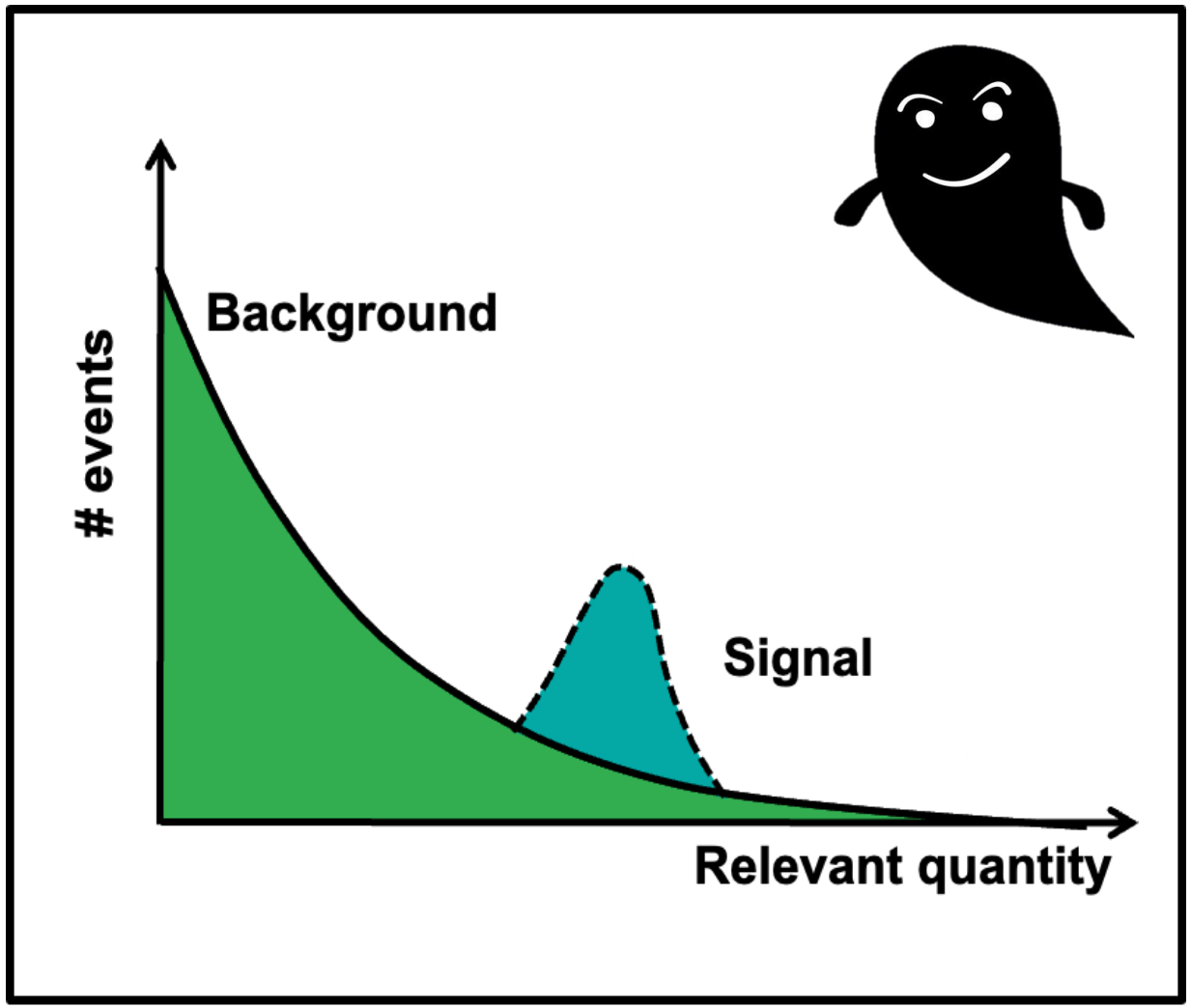


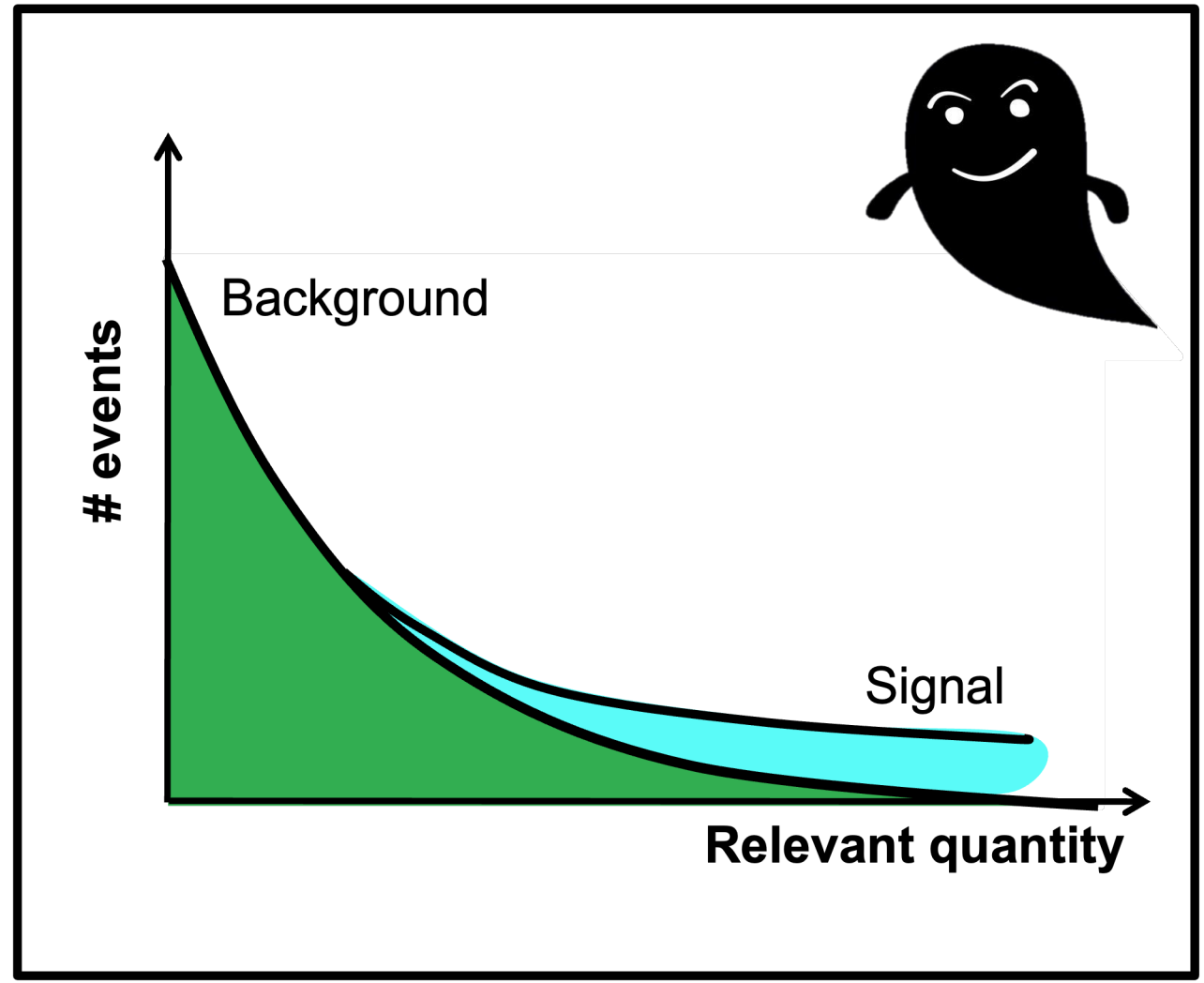
Direct searches



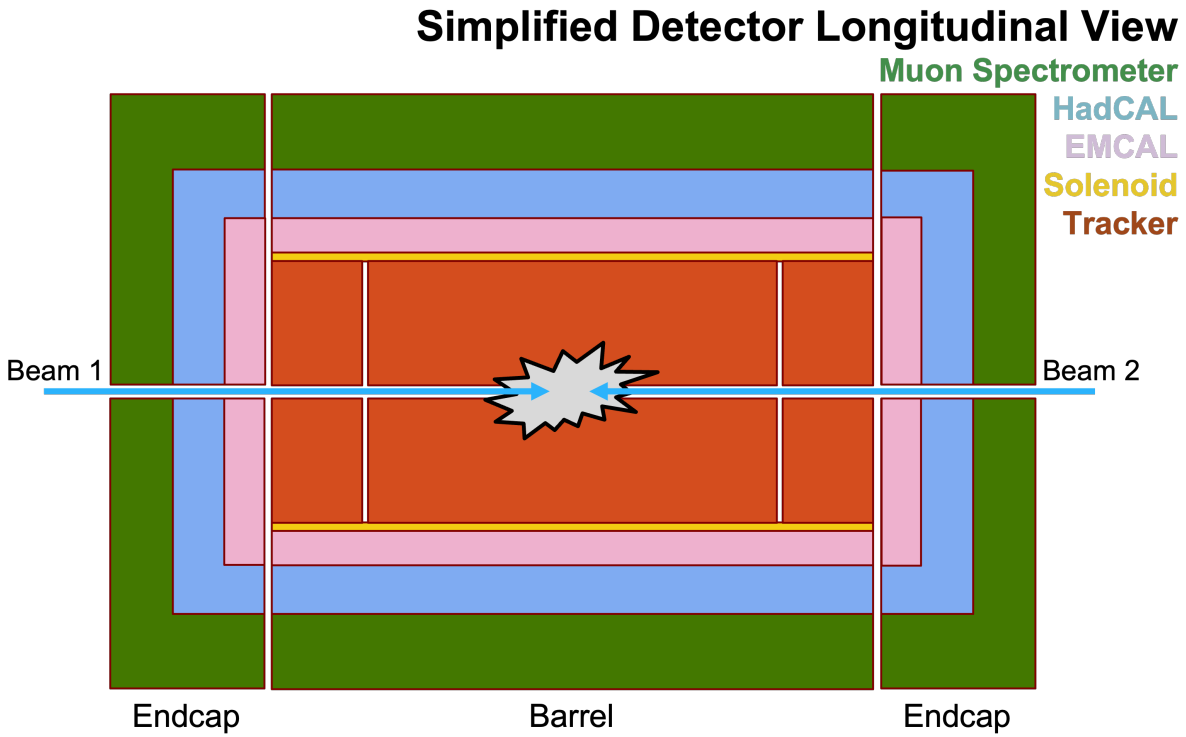


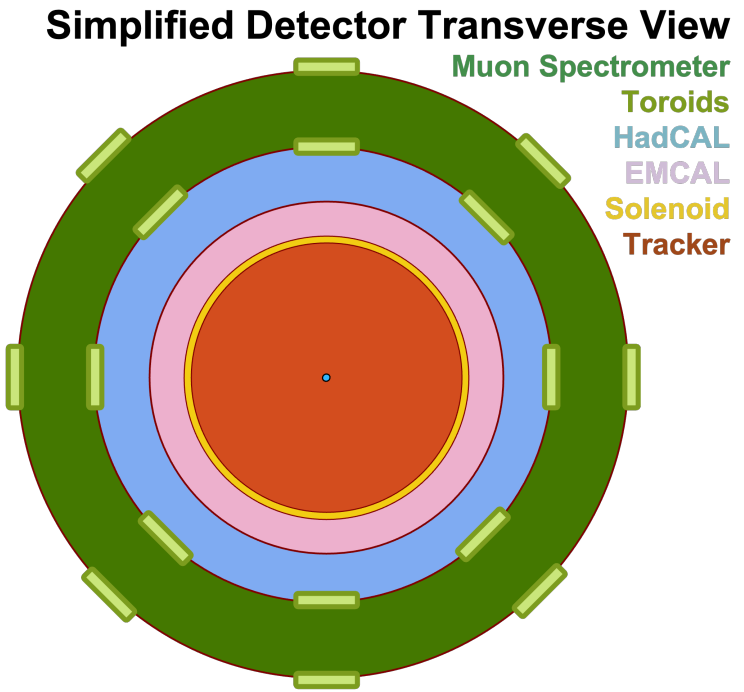



events
Background
Signal
Relevant quantity


events
Background
Signal
Relevant quantity

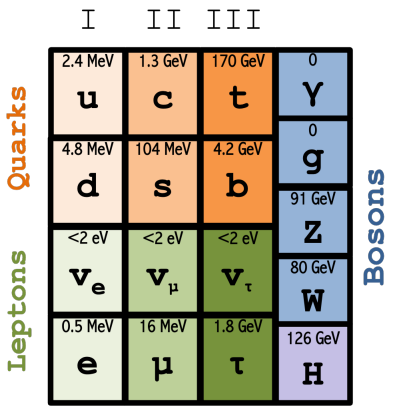
General purpose detectors at the LHC

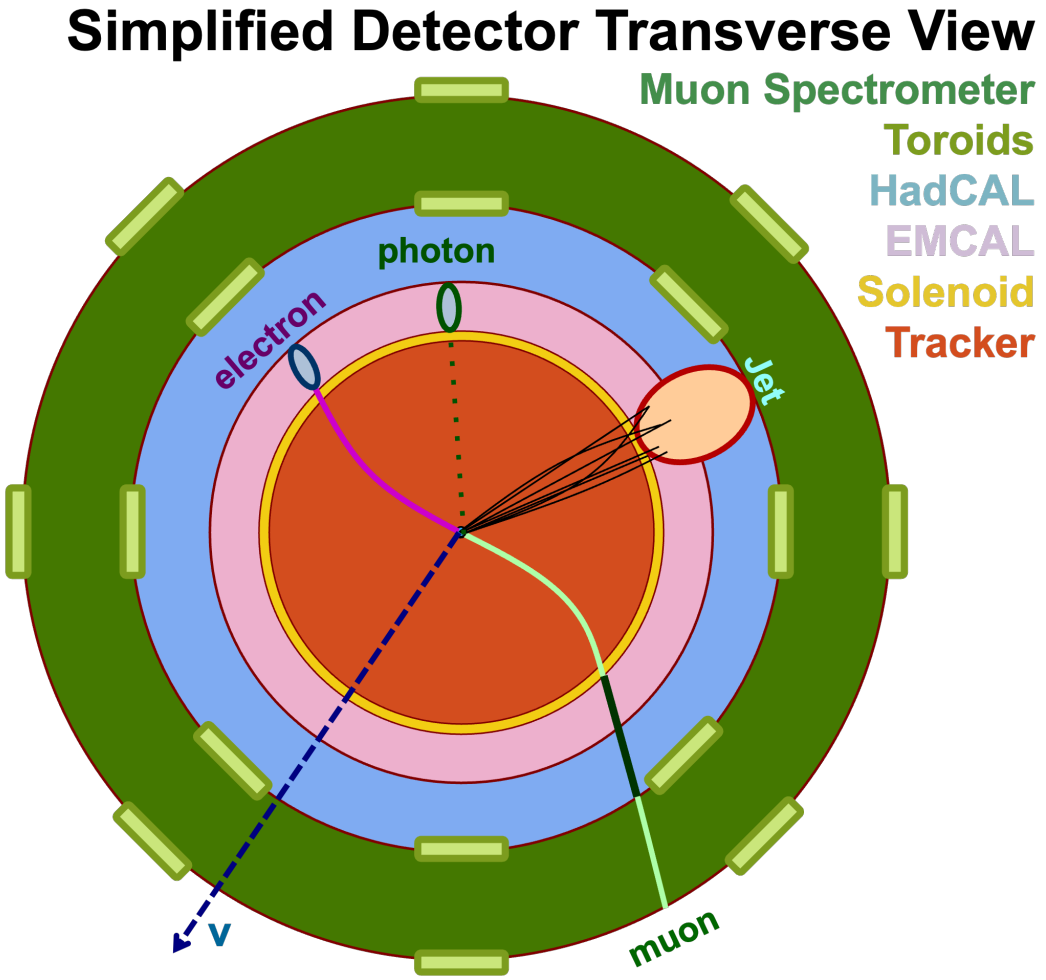




What do we reconstruct?

- Tracks and clusters
- Combining those:
  - "objects", i.e. "particles"

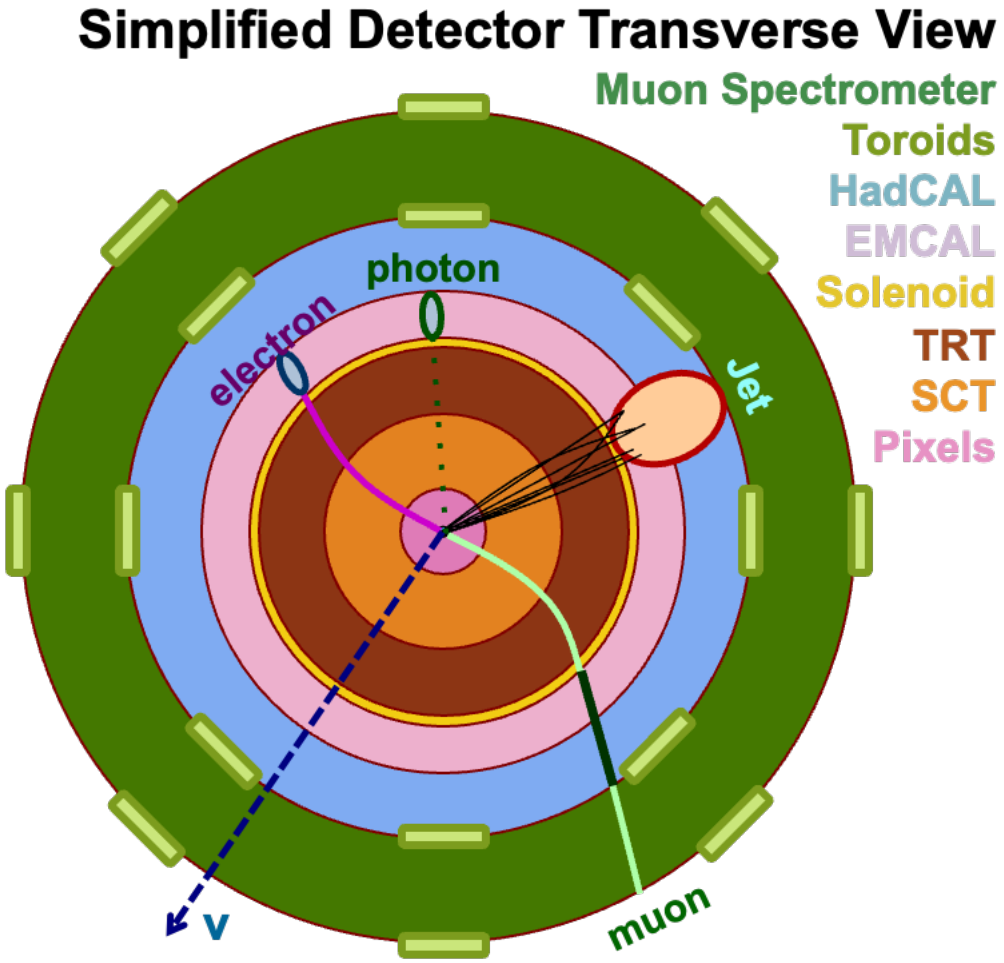




Missing Transverse Momentum – ME_T

	I	II	III	
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
Leptons	<2 eV ν_e	<2 eV ν_μ	<2 eV ν_τ	91 GeV Z
	0.5 MeV e	16 MeV μ	1.8 GeV τ	80 GeV W
				126 GeV H

Bosons



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

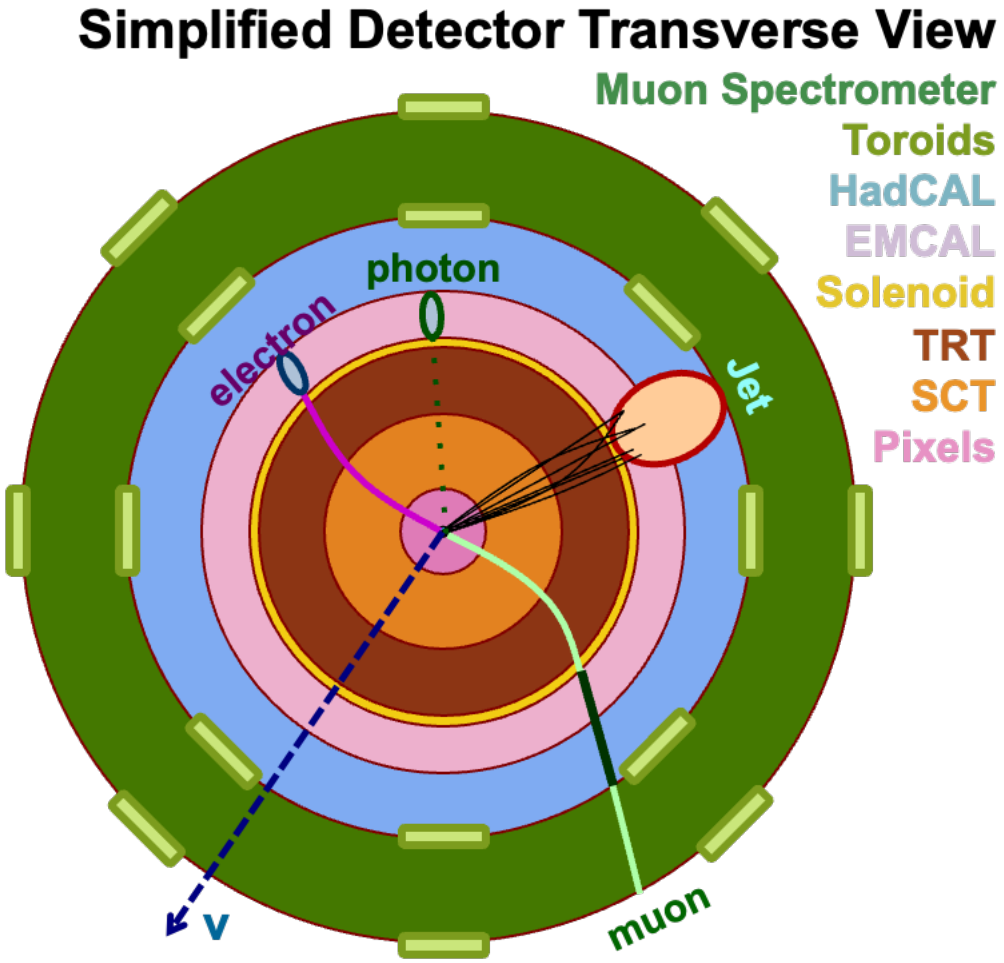
In the transverse plane:

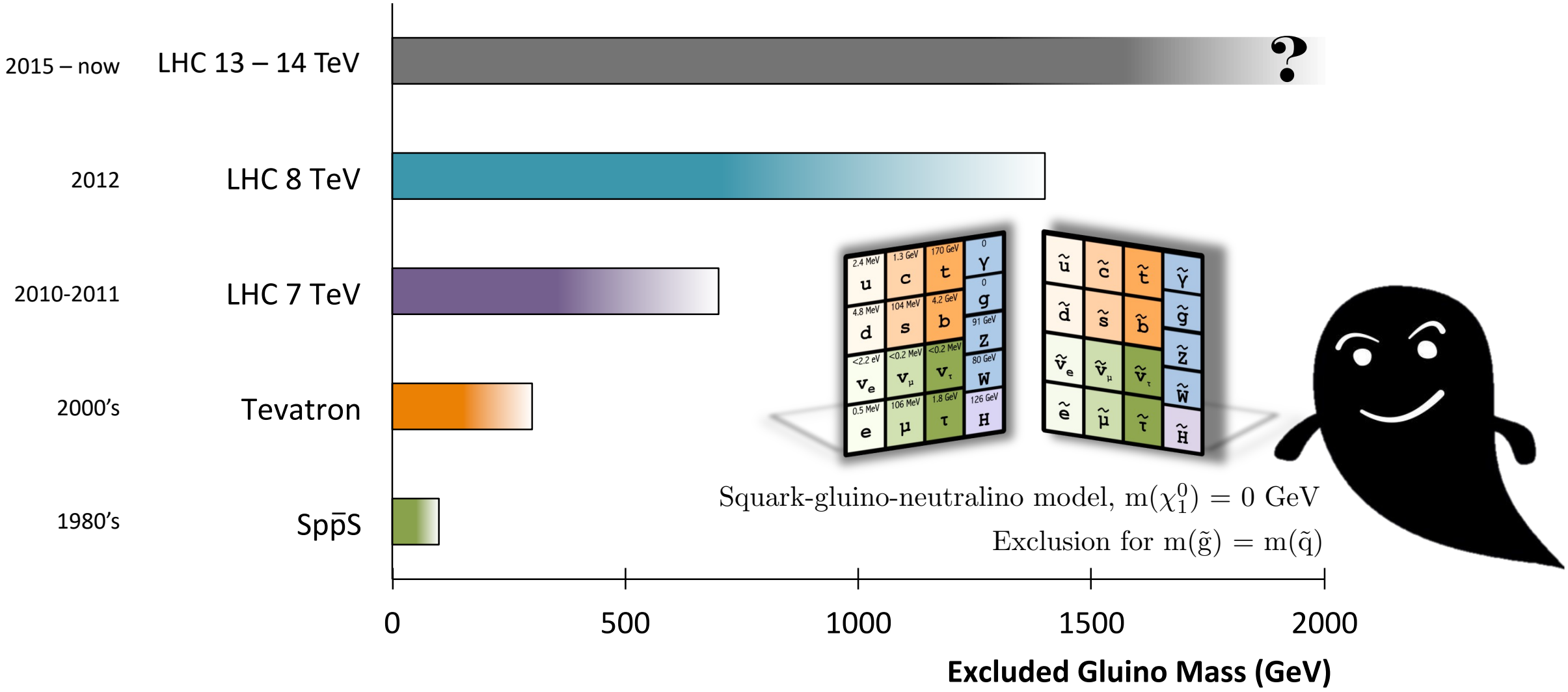
$$\Sigma_i \vec{p}_{T,i} = 0$$

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

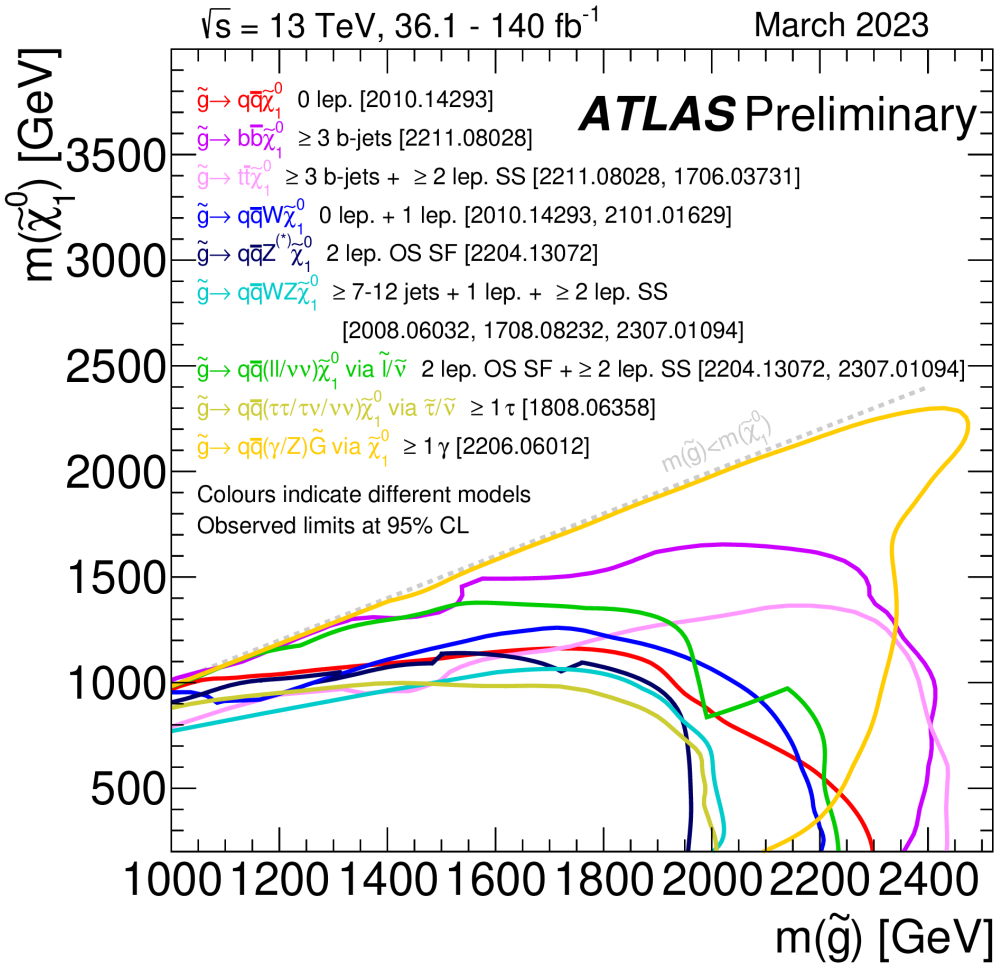
$$E_{\mathrm{T}}^{\mathrm{miss}} = -\Sigma_i \vec{p}_{T,i}$$

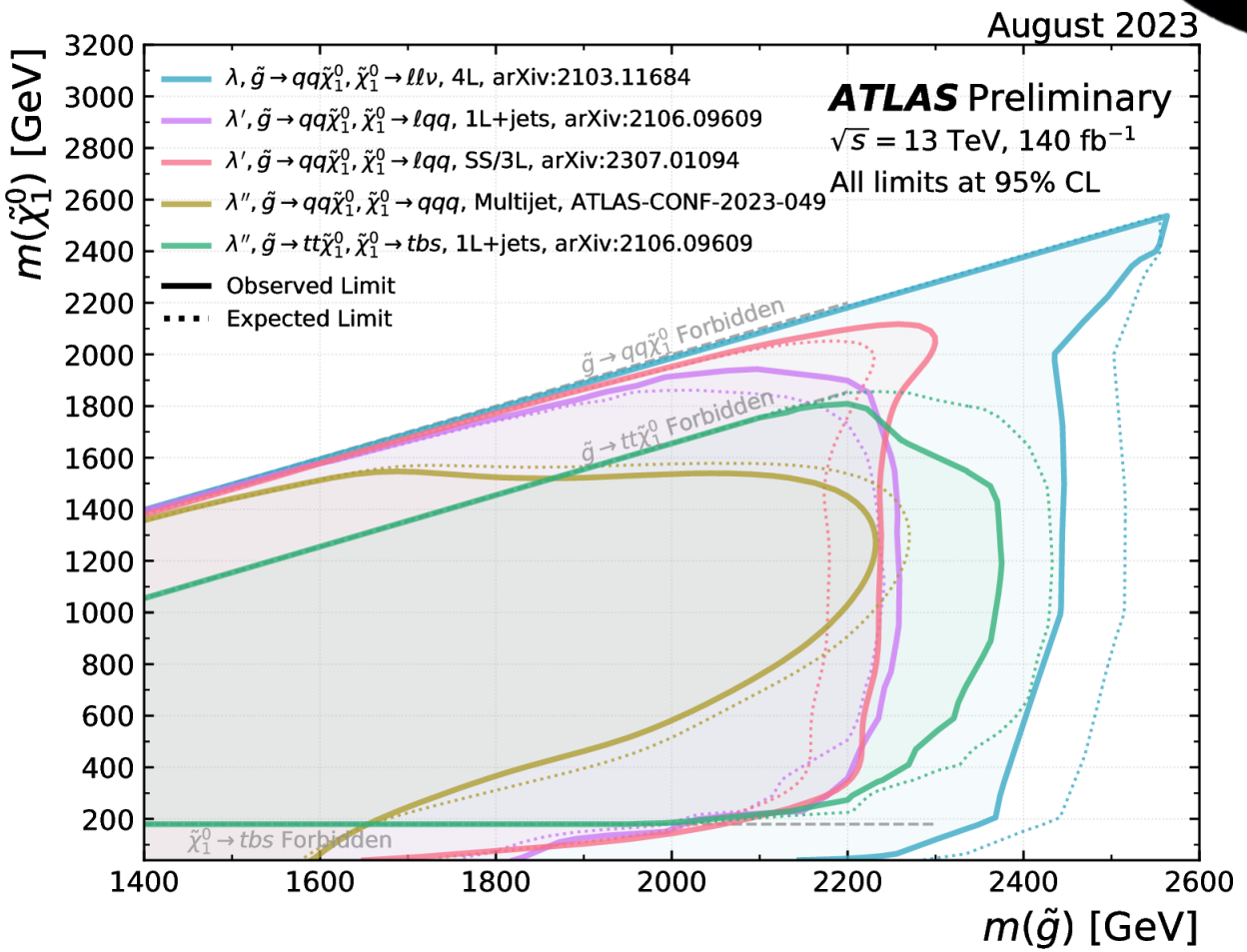
OR DARK MATTER CANDIDATES!




2015 – now
LHC 13 – 14 TeV
?
2012
LHC 8 TeV
2010-2011
LHC 7 TeV
2000's
Tevatron
1980's
SpS
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





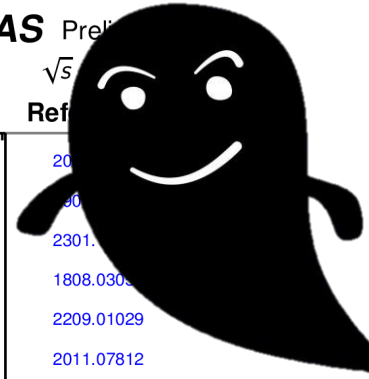
MANY OTHER SEARCHES...

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: March 2023

ATLAS Preli

$\int \mathcal{L}\, dt$ = (32.8 – 139) fb^{-1} $\sqrt{s}$



	Model	Signature	$\int \mathcal{L}\, dt$ [fb^{-1}]	Lifetime limit		Ref.
SUSY	RPV $\tilde{t} \to \mu q$	displaced vtx + muon	136	$\tilde{t}$ lifetime	0.003-6.0 m	$m(\tilde{t})$= 1.4 TeV	20
	RPV $\tilde{\chi}_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	32.8	$\tilde{\chi}_1^0$ lifetime	0.003-1.0 m	$m(\tilde{q})$= 1.6 TeV, $m(\tilde{\chi}_1^0)$= 1.3 TeV	9
	RPV $\tilde{\chi}_1^0 \to qqq$	displaced vtx + jets	139	$\tilde{\chi}_1^0$ lifetime	0.00135-9.0 m	$m(\tilde{\chi}_1^0)$= 1.0 TeV	2301.
	GGM $\tilde{\chi}_1^0 \to Z\tilde{G}$	displaced dimuon	32.9	$\tilde{\chi}_1^0$ lifetime	0.029-18.0 m	$m(\tilde{g})$= 1.1 TeV, $m(\tilde{\chi}_1^0)$= 1.0 TeV	1808.030
	GMSB	non-pointing or delayed γ	139	$\tilde{\chi}_1^0$ lifetime	0.24-2.4 m	$m(\tilde{\chi}_1^0, \tilde{G})$= 60, 20 GeV, $\mathcal{B}_{\mathcal{H}}$= 2%	2209.01029
	GMSB $\tilde{\ell} \to \ell\tilde{G}$	displaced lepton	139	$\tilde{\ell}$ lifetime	6-750 mm	$m(\tilde{\ell})$= 600 GeV	2011.07812
	GMSB $\tilde{\tau} \to \tau\tilde{G}$	displaced lepton	139	$\tilde{\tau}$ lifetime	9-270 mm	$m(\tilde{\ell})$= 200 GeV	2011.07812
	AMSB $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0, \tilde{\chi}_1^+\tilde{\chi}_1^-$	disappearing track	136	$\tilde{\chi}_1^{\pm}$ lifetime	0.06-3.06 m	$m(\tilde{\chi}_1^{\pm})$= 650 GeV	2201.02472
	AMSB $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^0, \tilde{\chi}_1^+\tilde{\chi}_1^-$	large pixel dE/dx	139	$\tilde{\chi}_1^{\pm}$ lifetime	0.3-30.0 m	$m(\tilde{\chi}_1^{\pm})$= 600 GeV	2205.06013
	Stealth SUSY	2 MS vertices	36.1	$\tilde{S}$ lifetime	0.1-519 m	$\mathcal{B}(\tilde{g} \to \tilde{S}g)$= 0.1, $m(\tilde{g})$= 500 GeV	1811.07370
	Split SUSY	large pixel dE/dx	139	$\tilde{g}$ lifetime	> 0.45 m	$m(\tilde{g})$= 1.8 TeV, $m(\tilde{\chi}_1^0)$= 100 GeV	2205.06013
	Split SUSY	displaced vtx + $E_{\mathrm{T}}^{\mathrm{miss}}$	32.8	$\tilde{g}$ lifetime	0.03-13.2 m	$m(\tilde{g})$= 1.8 TeV, $m(\tilde{\chi}_1^0)$= 100 GeV	1710.04901
	Split SUSY	0 ℓ, 2 – 6 jets + $E_{\mathrm{T}}^{\mathrm{miss}}$	36.1	$\tilde{g}$ lifetime	0.0-2.1 m	$m(\tilde{g})$= 1.8 TeV, $m(\tilde{\chi}_1^0)$= 100 GeV	ATLAS-CONF-2018-003
Higgs BR = 10%	$H \to ss$	2 MS vertices	139	s lifetime	0.31-72.4 m	$m(s)$= 35 GeV	2203.00587
	$H \to ss$	2 low-EMF trackless jets	139	s lifetime	0.19-6.94 m	$m(s)$= 35 GeV	2203.01009
	VH with $H \to ss \to bbbb$	2ℓ + 2 displ. vertices	139	s lifetime	4-85 mm	$m(s)$= 35 GeV	2107.06092
	FRVZ $H \to 2\gamma_d + X$	2 μ–jets	139	γ_d lifetime	0.654-939 mm	$m(\gamma_d)$= 400 MeV	2206.12181
	FRVZ $H \to 4\gamma_d + X$	2 μ–jets	139	γ_d lifetime	2.7-534 mm	$m(\gamma_d)$= 400 MeV	2206.12181
	$H \to Z_d Z_d$	displaced dimuon	32.9	Z_d lifetime	0.009-24.0 m	$m(Z_d)$= 40 GeV	1808.03057
	$H \to ZZ_d$	2 e, μ + low-EMF trackless jet	36.1	Z_d lifetime	0.21-5.2 m	$m(Z_d)$= 10 GeV	1811.02542
Scalar	Φ(200 GeV) $\to ss$	low-EMF trk-less jets, MS vtx	36.1	s lifetime	0.41-51.5 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1902.03094
	Φ(600 GeV) $\to ss$	low-EMF trk-less jets, MS vtx	36.1	s lifetime	0.04-21.5 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 50 GeV	1902.03094
	Φ(1 TeV) $\to ss$	low-EMF trk-less jets, MS vtx	36.1	s lifetime	0.06-52.4 m	$\sigma \times \mathcal{B}$= 1 pb, $m(s)$= 150 GeV	1902.03094
HNL	$W \to N\ell, N \to \ell\ell\nu$	displaced vtx ($\mu\mu$,μe, ee) + μ	139	N lifetime	0.74-42 mm	$m(N)$= 6 GeV, Dirac	2204.11988
	$W \to N\ell, N \to \ell\ell\nu$	displaced vtx ($\mu\mu$,μe, ee) + μ	139	N lifetime	3.1-33 mm	$m(N)$= 6 GeV, Majorana	2204.11988
	$W \to N\ell, N \to \ell\ell\nu$	displaced vtx ($\mu\mu$,μe, ee) + e	139	N lifetime	0.49-81 mm	$m(N)$= 6 GeV, Dirac	2204.11988
	$W \to N\ell, N \to \ell\ell\nu$	displaced vtx ($\mu\mu$,μe, ee) + e	139	N lifetime	0.39-51 mm	$m(N)$= 6 GeV, Majorana	2204.11988

0.001 0.01 0.1 1 10 100 $c\tau$ [m]

$\sqrt{s}$ = 13 TeV partial data

$\sqrt{s}$ = 13 TeV full data

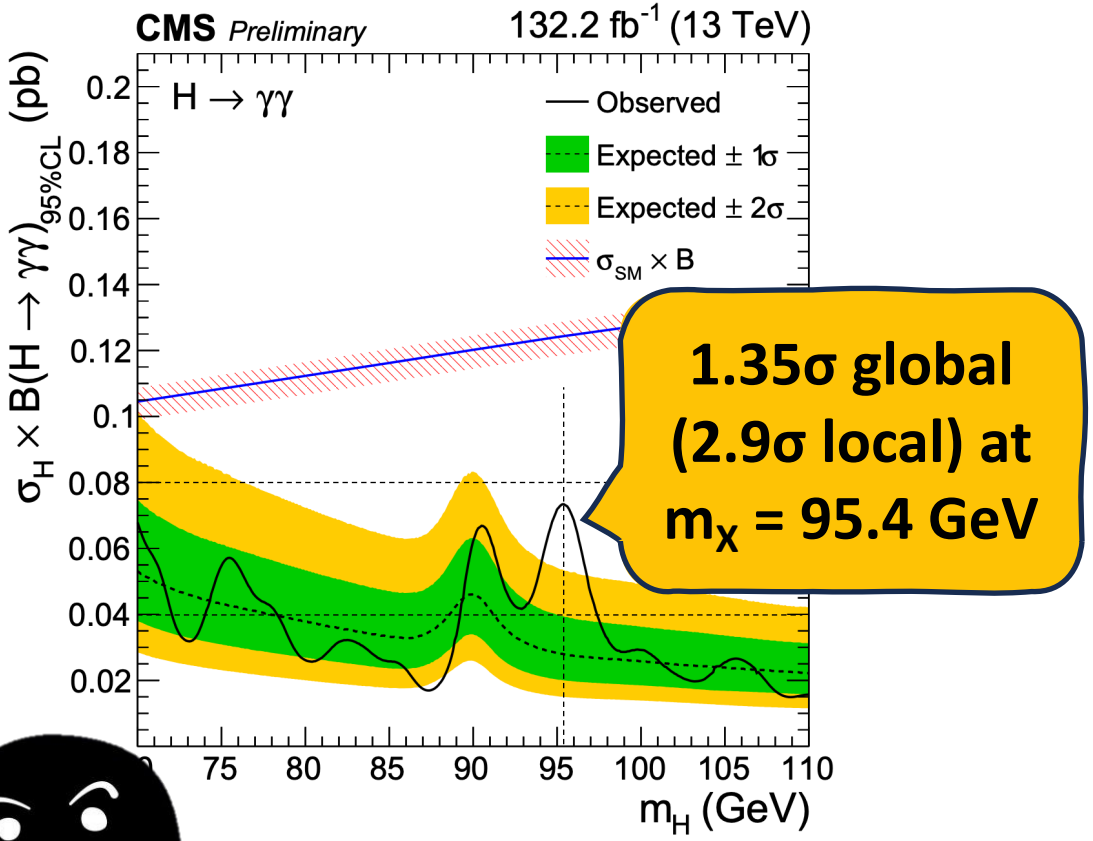
0.001 0.01 0.1 1 10 100 τ [ns]

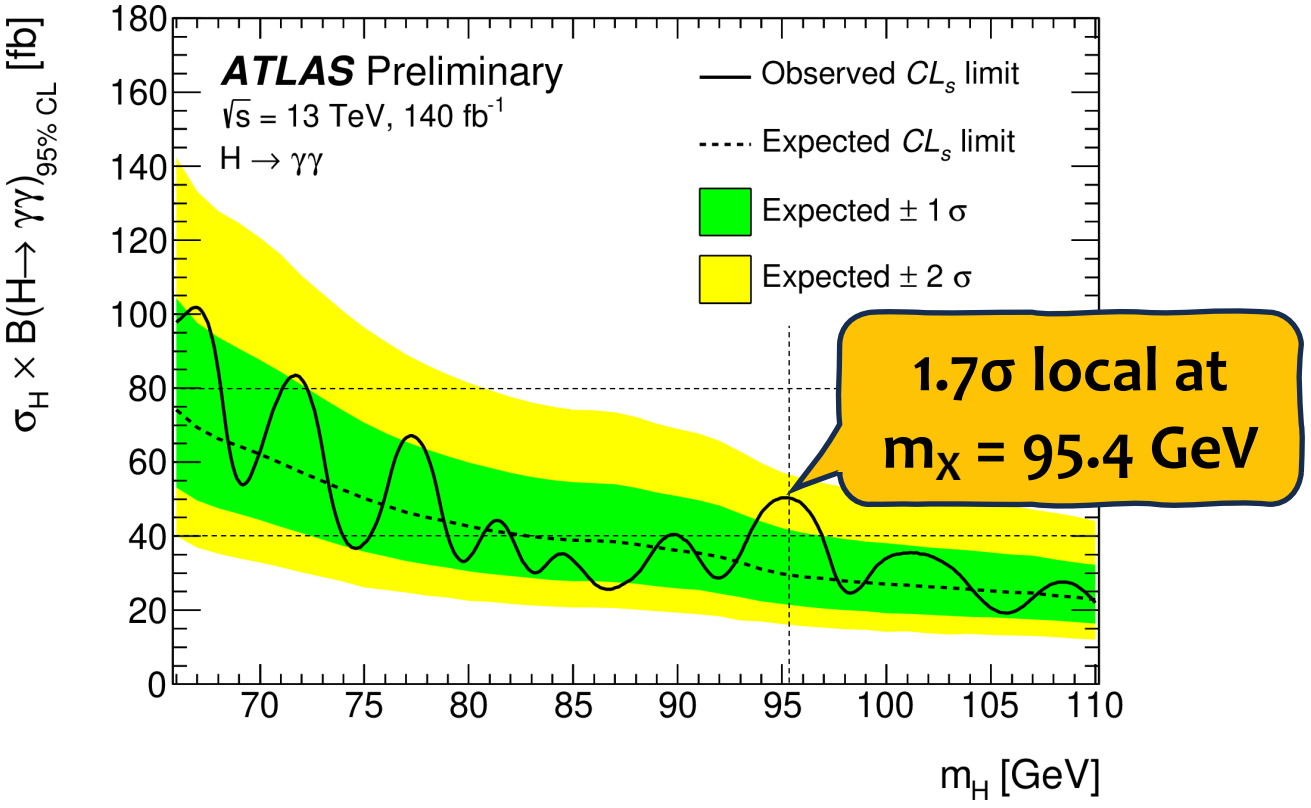
*Only a selection of the available lifetime limits is shown.

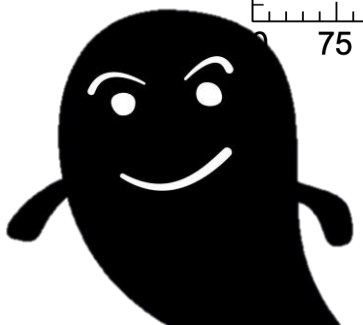
Tantalising results

Few ***tiny*** excesses in data
some even consistent beween experiments

For example, in Higgs-like di-photon signatures

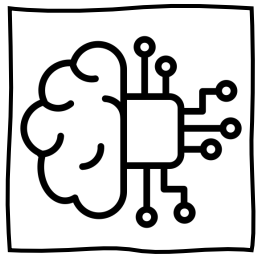


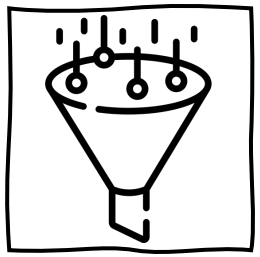


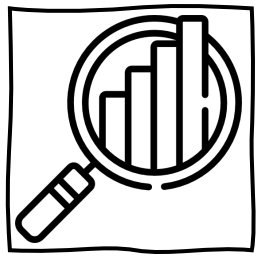


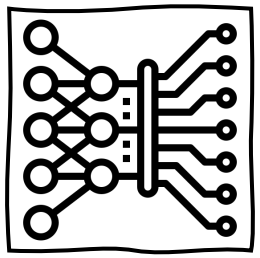
Only more data will tell if only stat fluctuation, or something exciting!

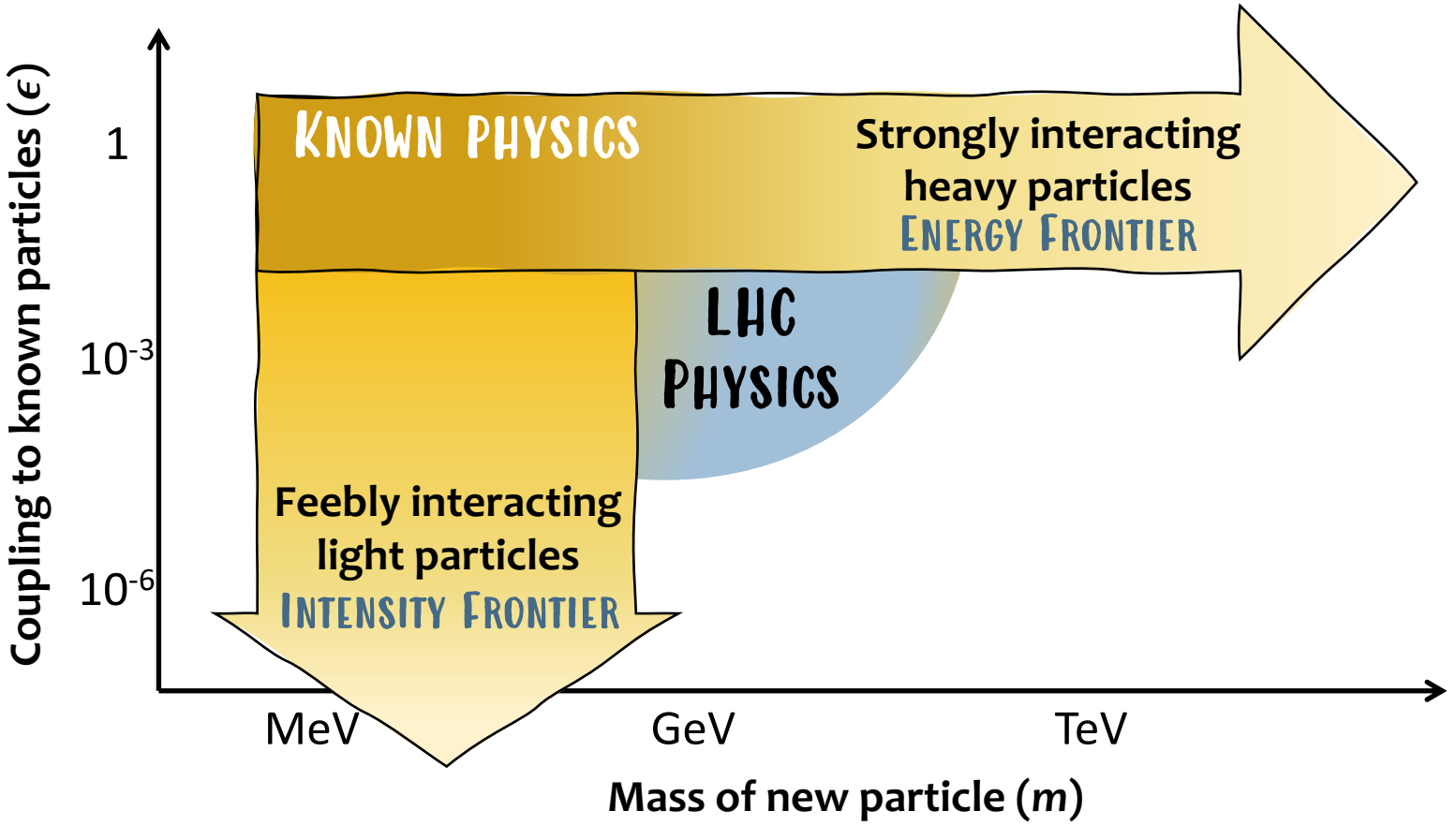
(remember: early Run2 750 GeV di-photon saga)



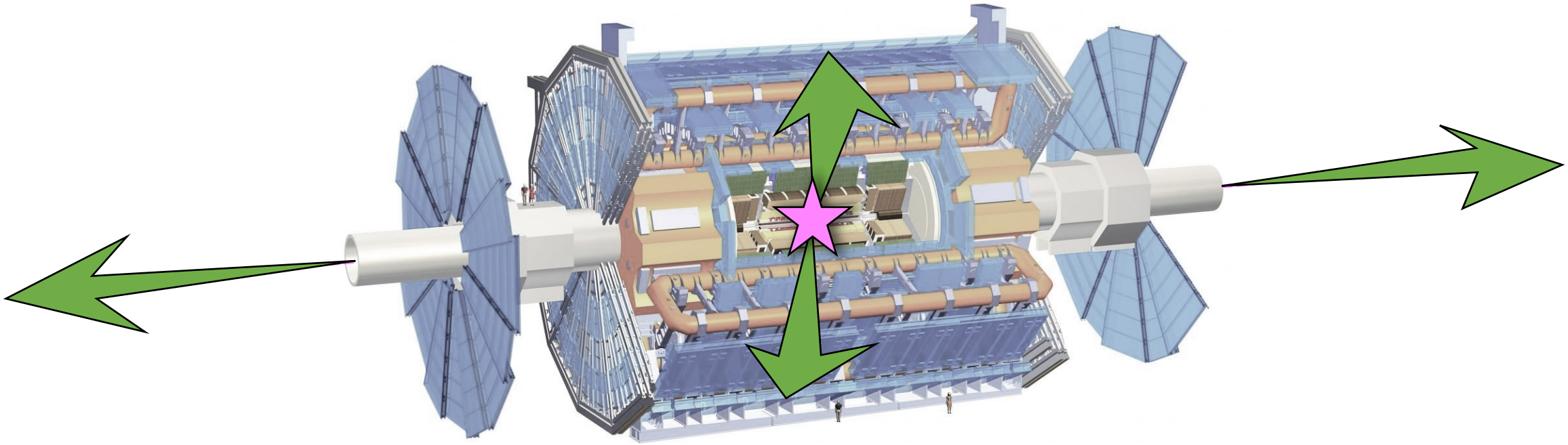




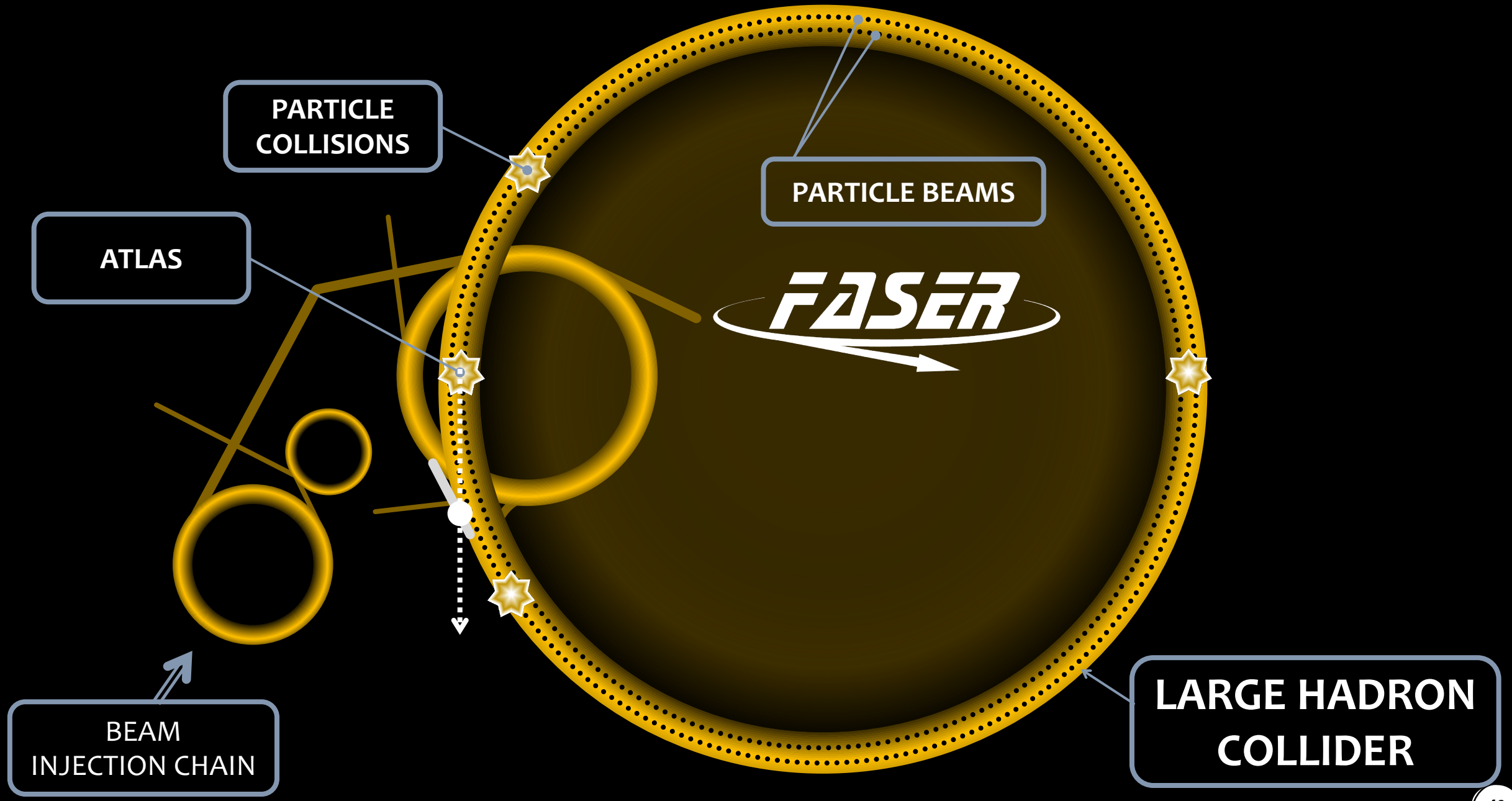




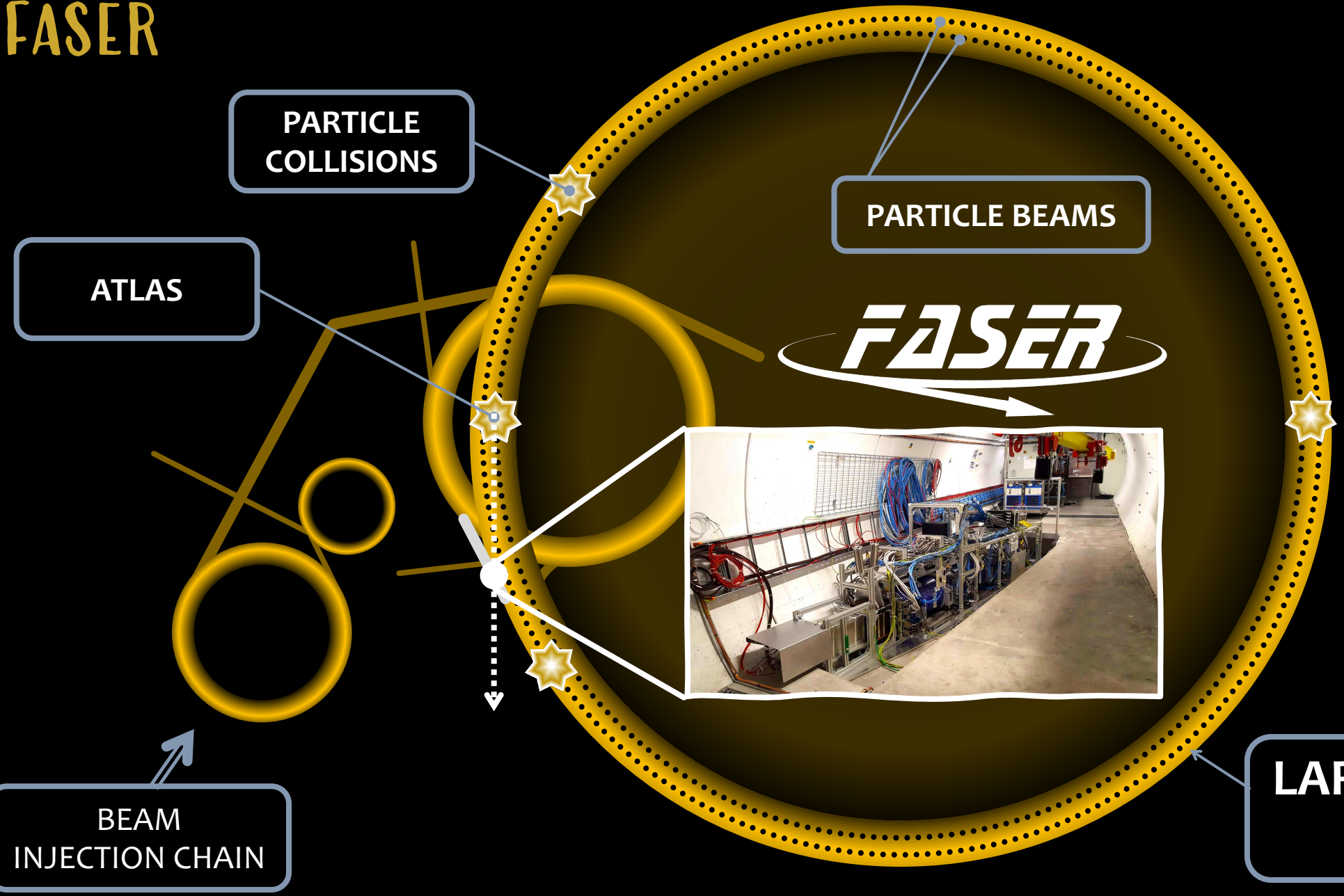
- Improve instrumentation / diversify experimental methods
- Get more data
- Look at higher energies



Very Forward experiments at the LHC


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

FASER


PARTICLE COLLISIONS
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FASER
BEAM INJECTION CHAIN
LARGE HADRON COLLIDER

FASER

PARTICLE COLLISIONS

ATLAS

PARTICLE BEAMS

FASER

ETH zürich

UNIVERSITÄT BERN

UNIVERSITÉ DE GENÈVE

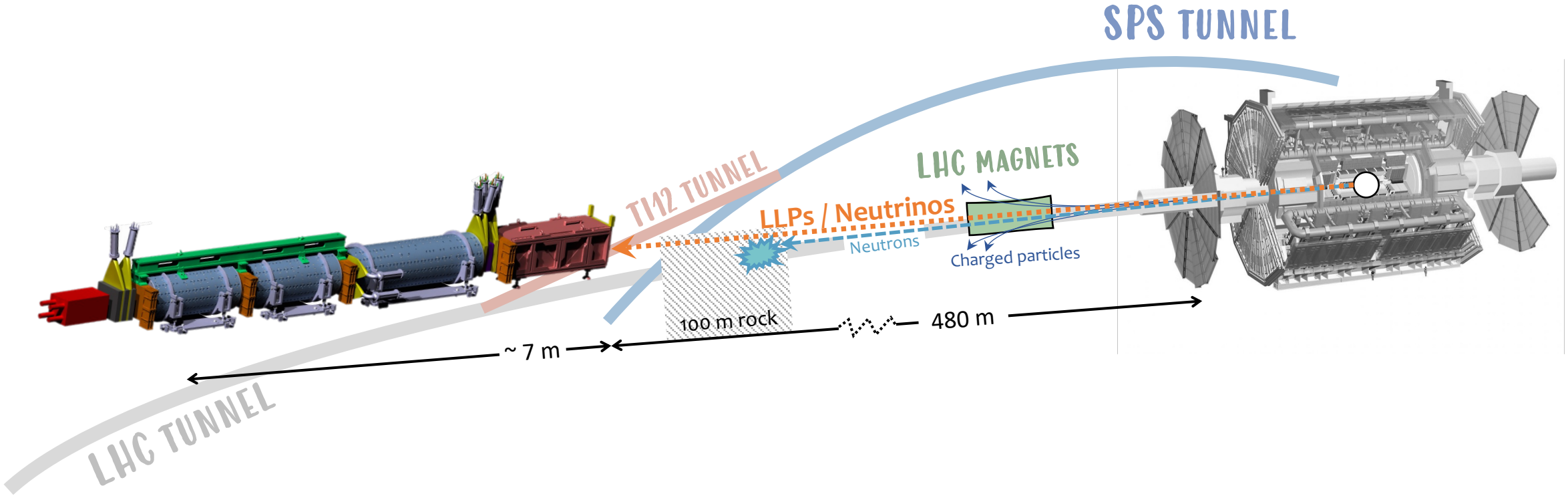
BEAM INJECTION CHAIN

LARGE HADRON COLLIDER


CMU 2t
ATTENTION
TENSION
DANGER
FASER
FASER

FORWARD SEARCH EXPERIMENT AT THE LHC

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



FORWARD SEARCH EXPERIMENT AT THE LHC

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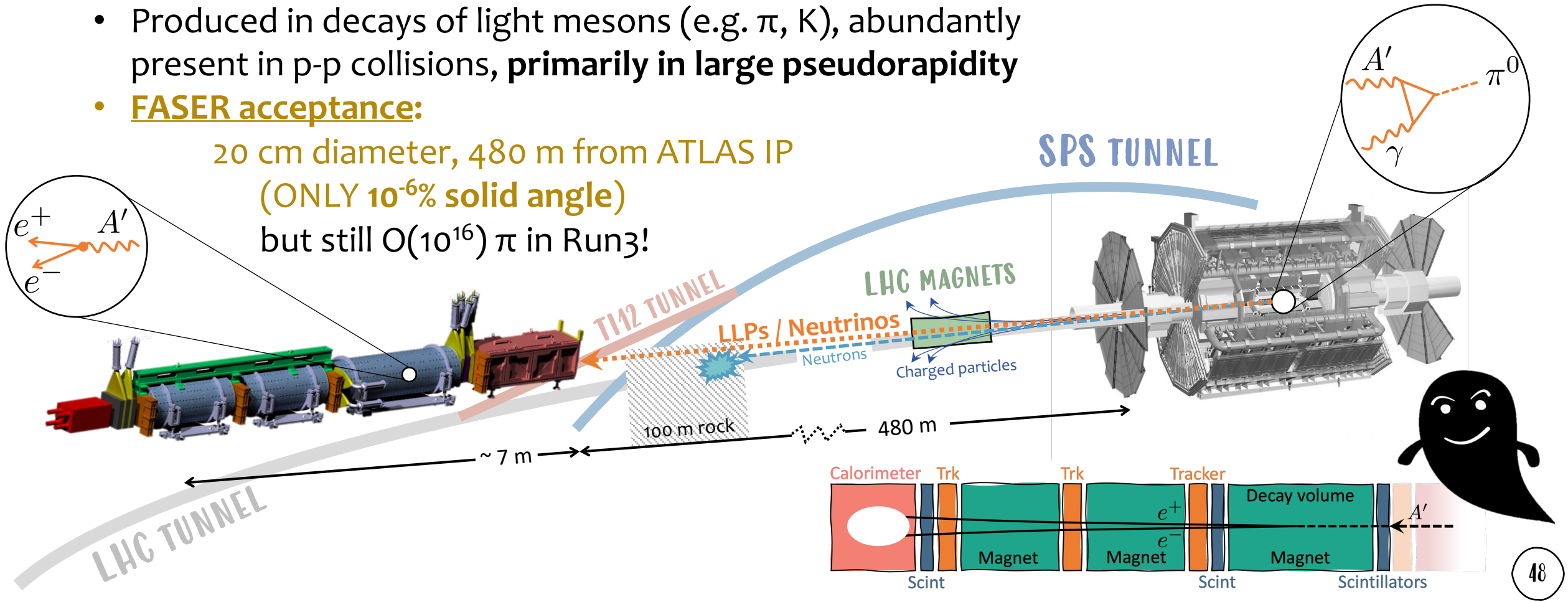
- Produced in decays of light mesons (e.g. π, K), abundantly present in p-p collisions, **primarily in large pseudorapidity**
- **FASER acceptance:**
  - 20 cm diameter, 480 m from ATLAS IP
  - (ONLY **10^{-6}% solid angle**)
  - but still O(10^{16}) π in Run3!



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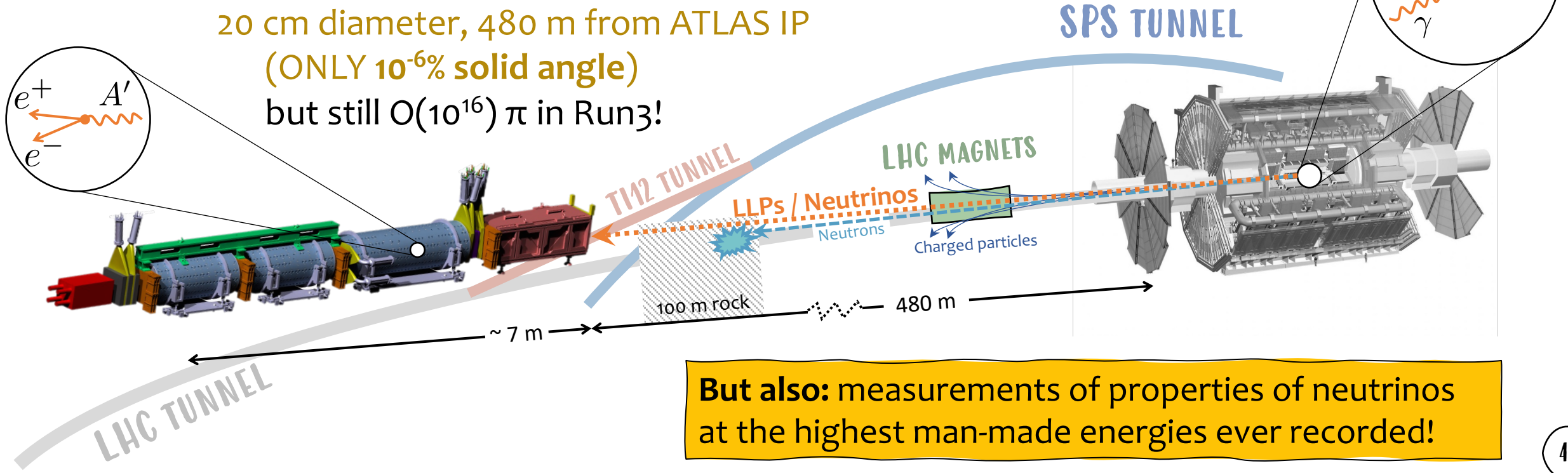


But also: measurements of properties of neutrinos at the highest man-made energies ever recorded!

Feebly Interacting Particles (FIPs)

- Due to interacting feebly, they are linked to a "hidden sector"
- Couplings between SM and hidden sector result from "portal" operators
- Large number of specific models; can be simplified to the following:

SM Higgs *h* — $(\mu S + \lambda S^2) H^\dagger H$ — Dark Higgs *S*

New scalar: **Dark Higgs**; couplings to SM μ, λ

SM EM *A* — $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} F_Y^{\mu\nu}$ — Dark EM A_D

New vector: **Dark photon**; coupling to SM $\propto \epsilon Q$

SM 2γ or $2f$ — 2γ: $\frac{\alpha}{f_\alpha} F_{\mu\nu} \tilde{F}^{\mu\nu}$; $2f$: $\frac{\partial_\mu \alpha}{f_\alpha} \bar{\psi} \gamma^\mu \gamma^5 \psi$ — α — ALP α

New pseudo-scalar: **ALP**; coupling to SM suppressed

(Axion Like Particle)

SM LH ν — $y_N h L \psi_D$ — HNL *N*

New fermion: **HNL**; coupling to LH SM and h $\propto y_N$

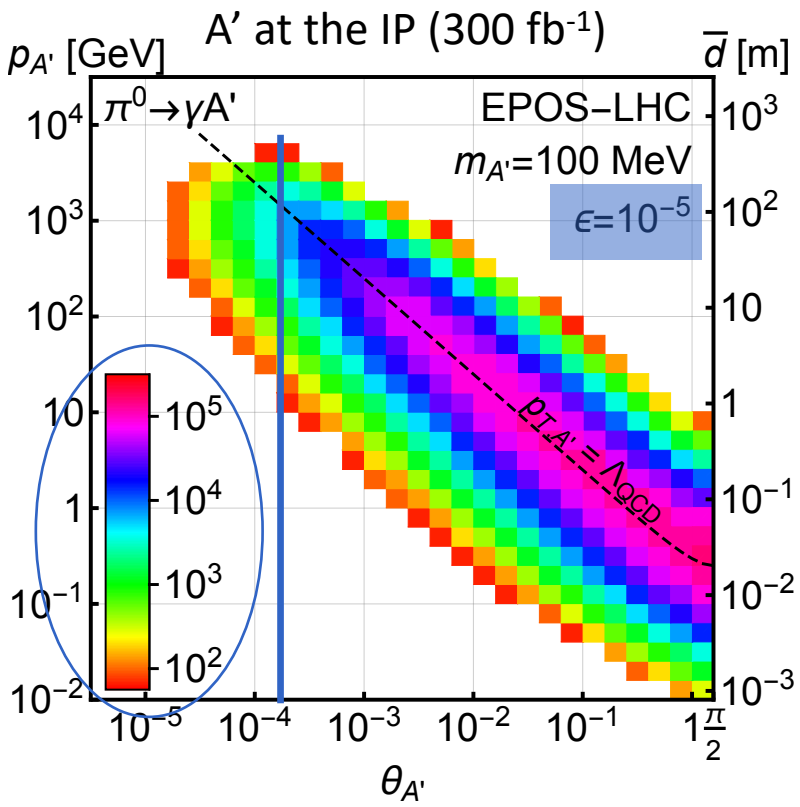
(Heavy Neutral Lepton)

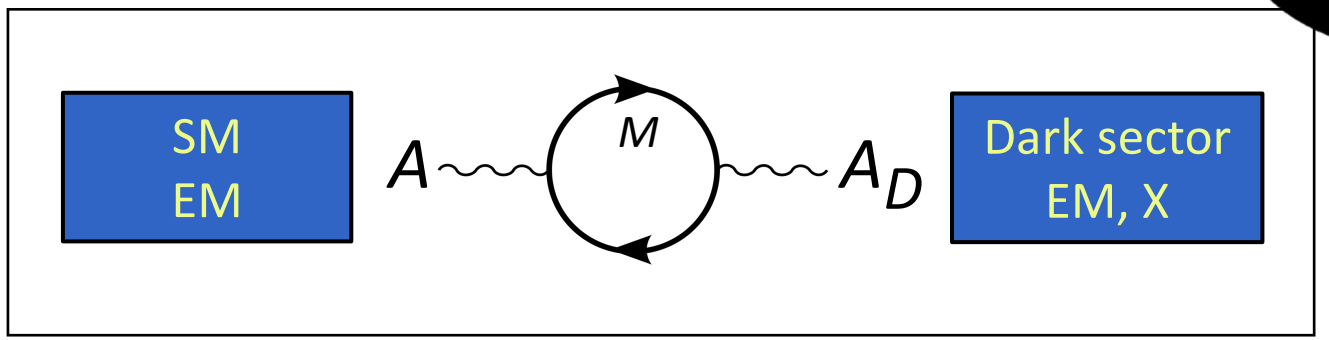
- The masses of the new particles can span several orders of magnitude

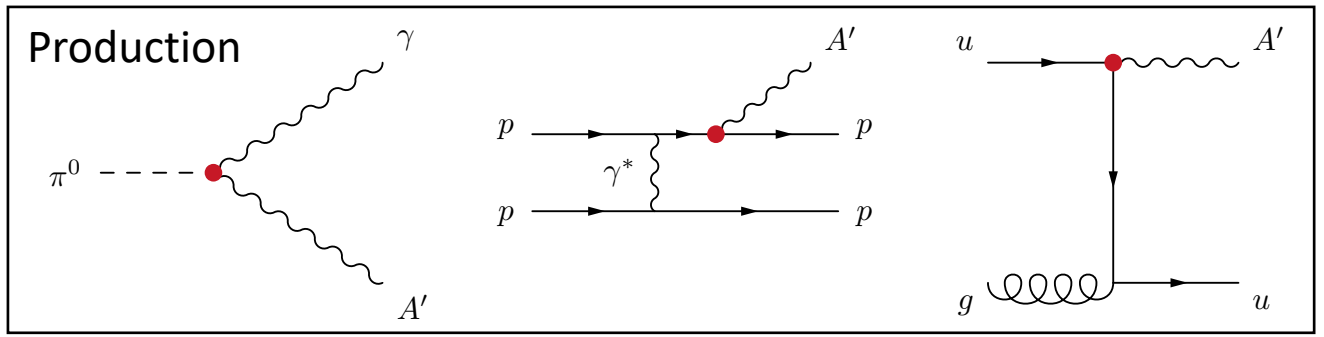
50

An example physics case: Dark Photon A'

- New **massive** gauge boson in a dark sector with dark matter candidate X
- Spin 1, couples weakly to SM fermions (εQ_f coupling, small ε) through mixing with the photon
  - Will be searched for via its **decay to an electron-positron pair**
- For $m_{A'}$=100 MeV, $\varepsilon \sim 10^{-5}$ and E~TeV, can travel long distance before decay







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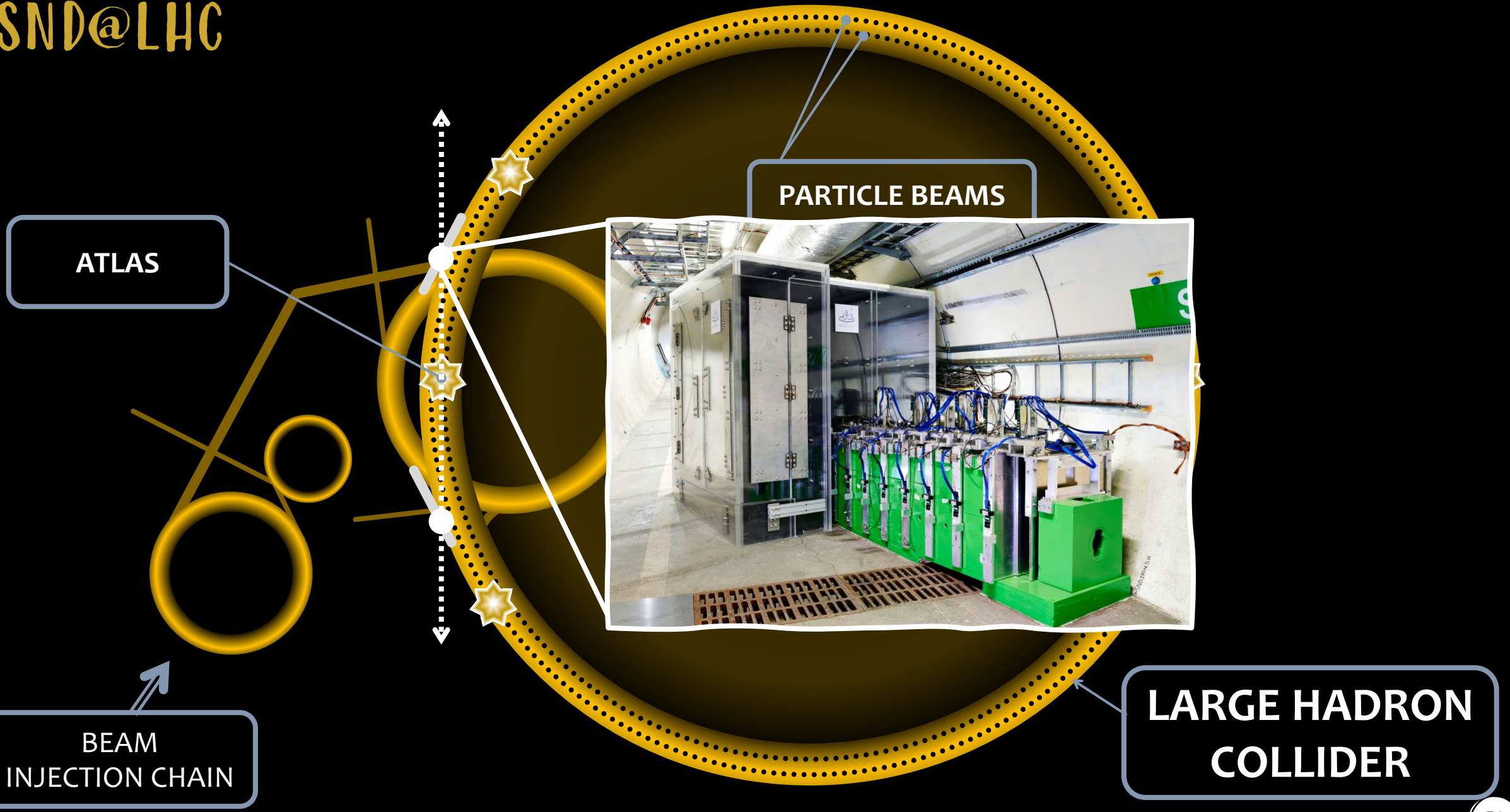
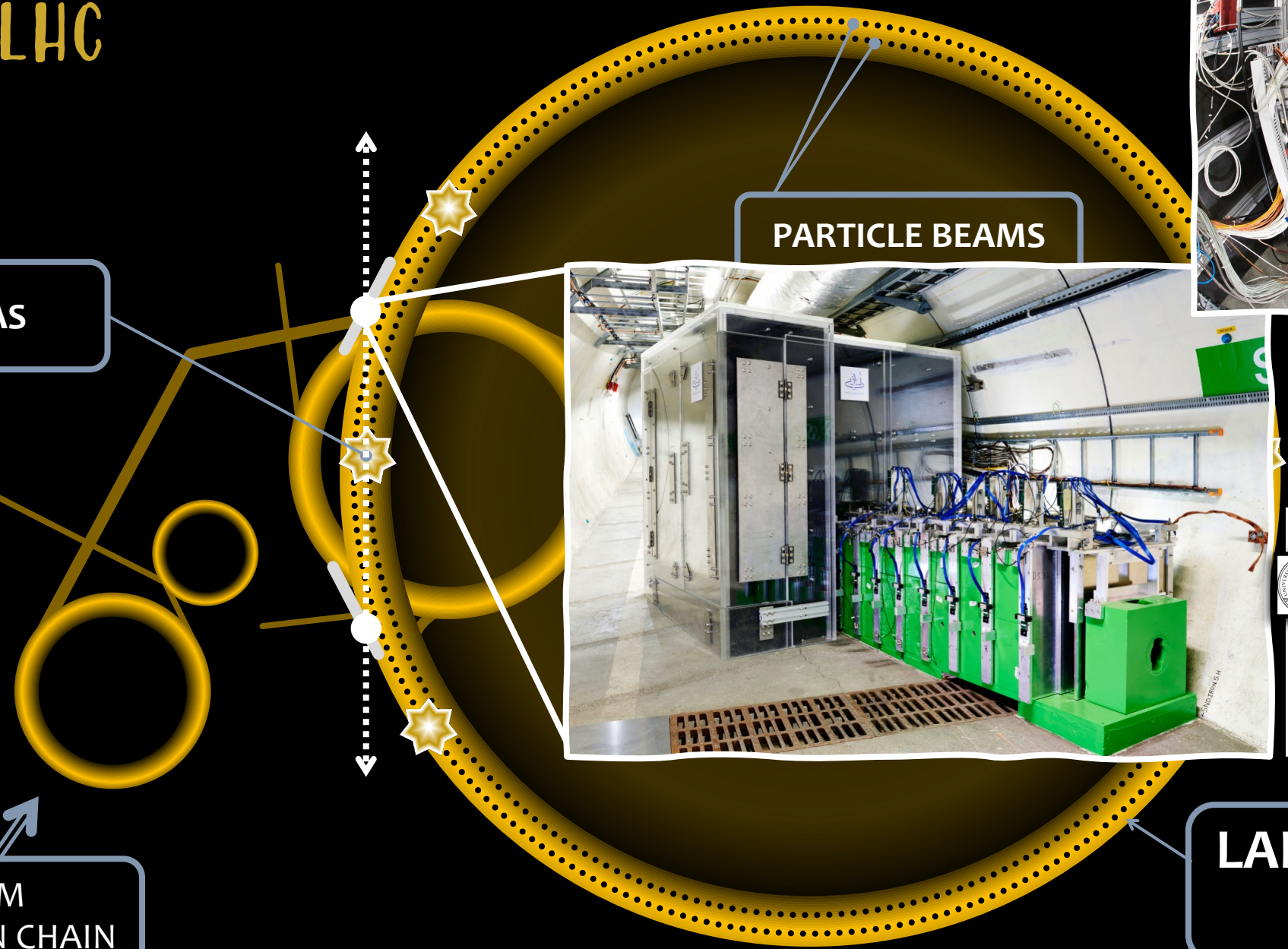
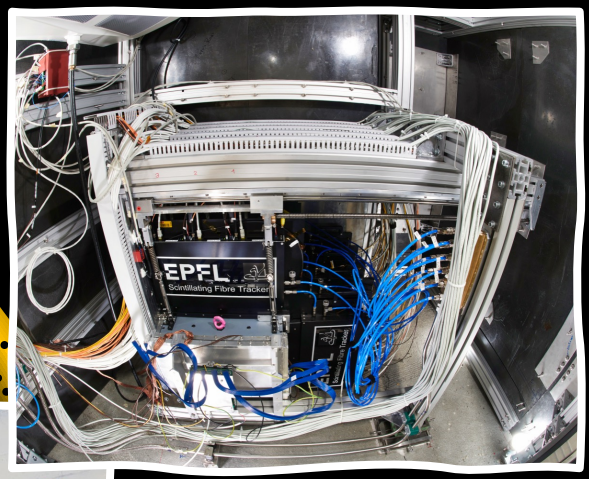
SND@LHC


ATLAS
PARTICLE BEAMS
BEAM
INJECTION CHAIN
LARGE HADRON
COLLIDER

SND@LHC





Universität Zürich[UZH]

EPFL

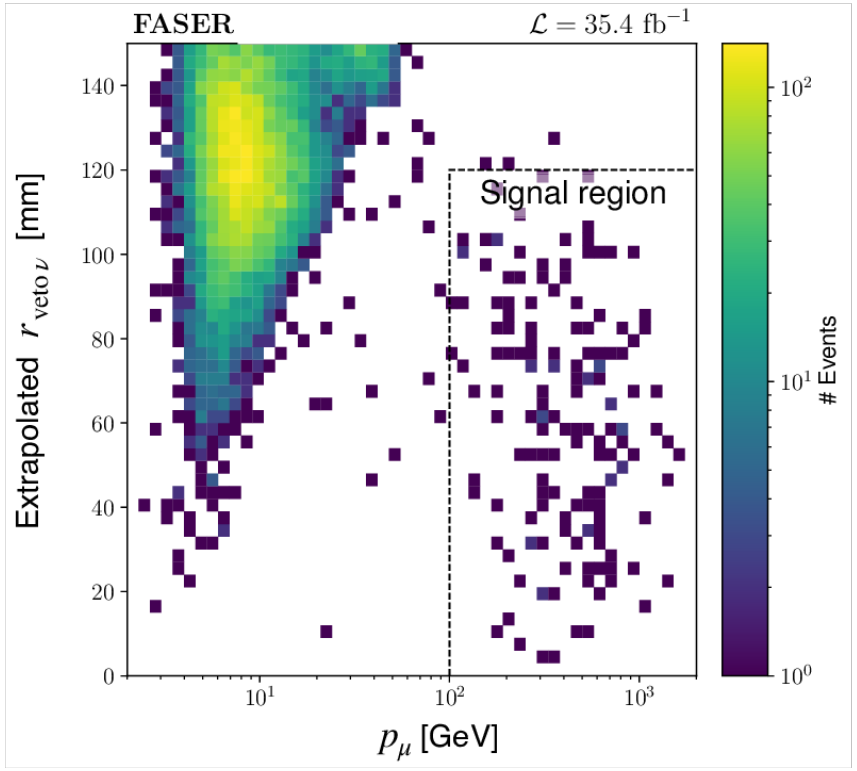
Highlights from recent results

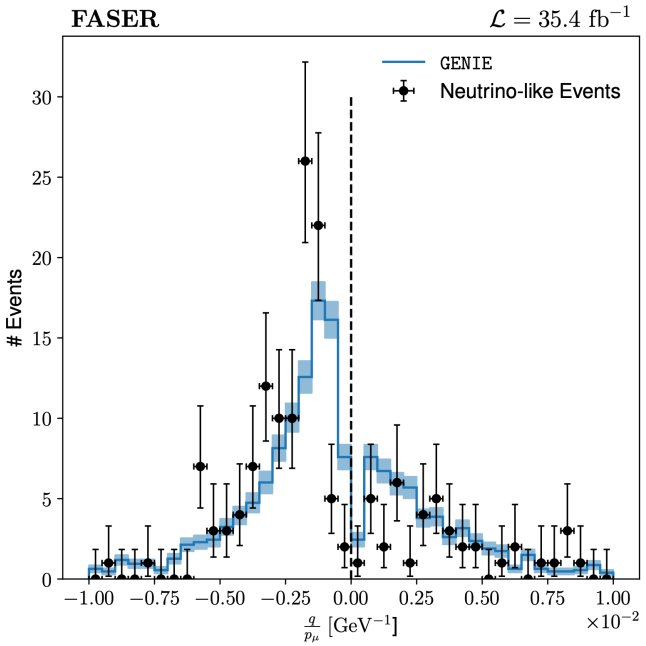
First Direct Detection of Collider Neutrinos

FASER

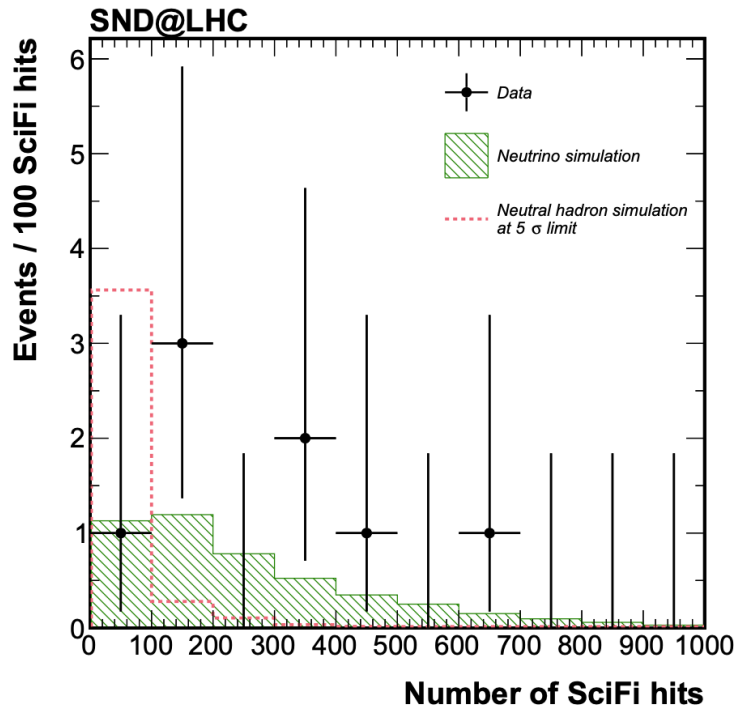
153 events ⟹ ≫ 5σ significance
Background ~ 0.2 events

8 events ⟹ > 5σ significance
Background < 0.1 events



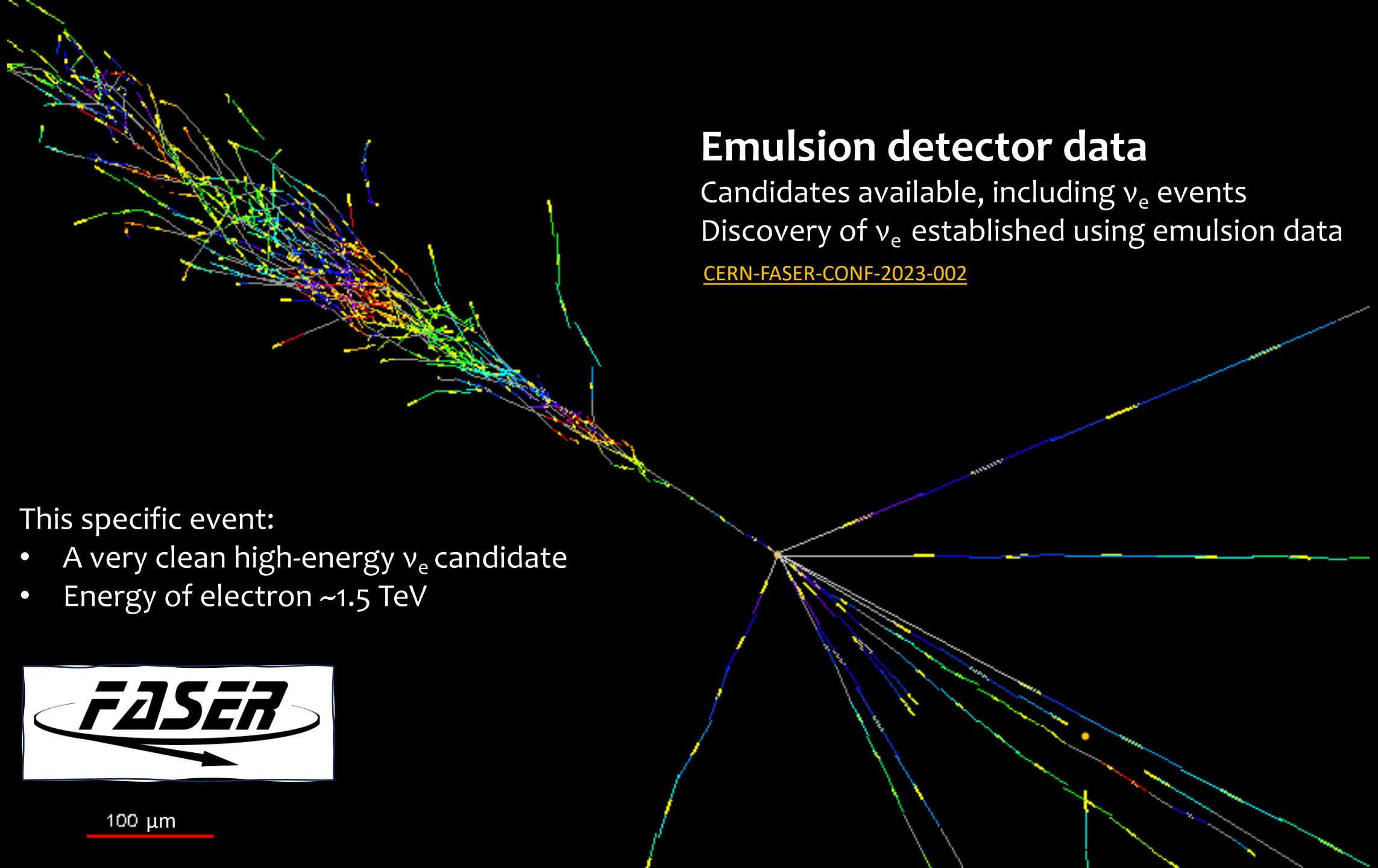


First evaluation of properties



arXiv: 2303.14185, PRL

arXiv: 2305.09383, PRL



Emulsion detector data

Candidates available, including ν_e events

Discovery of ν_e established using emulsion data

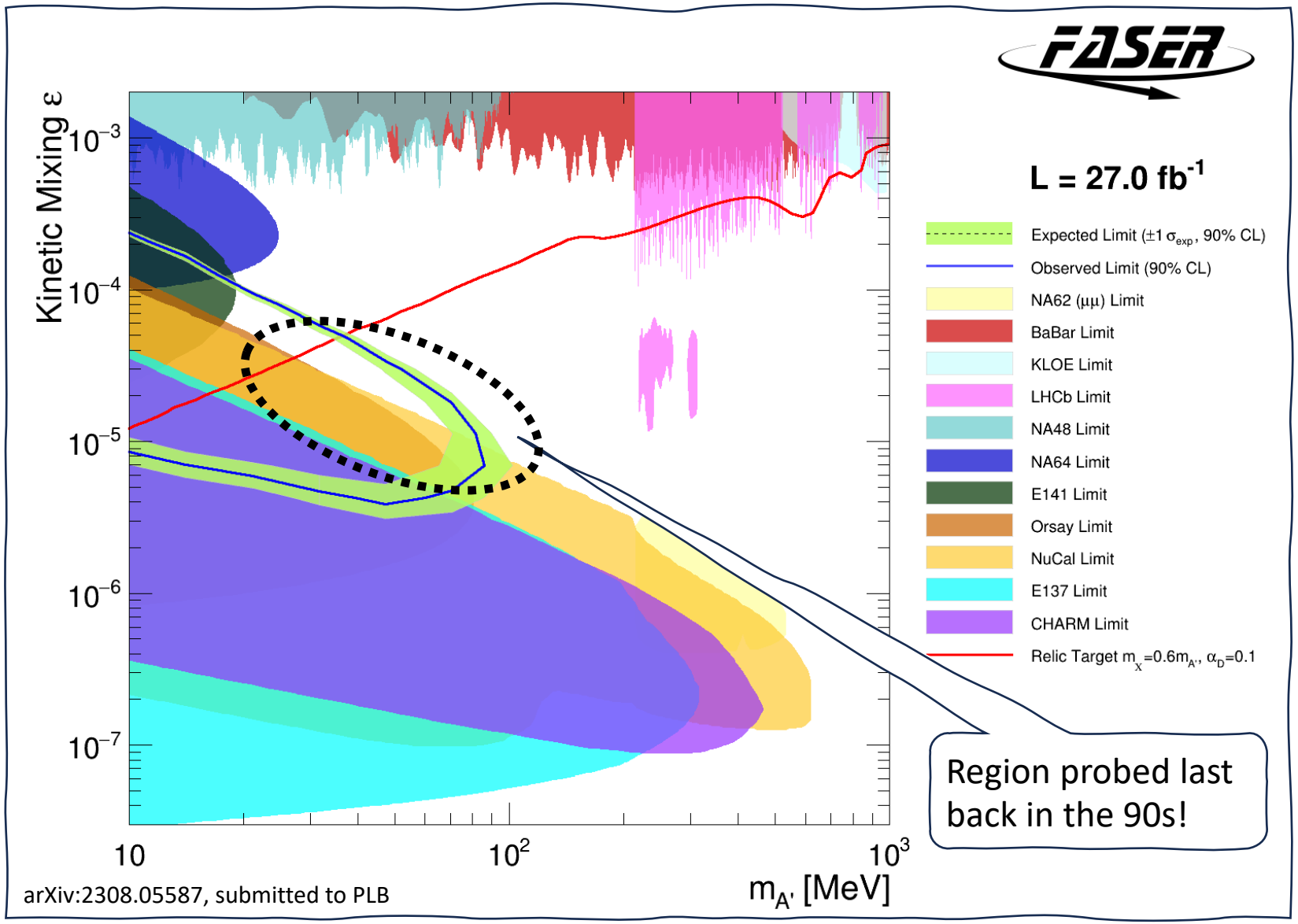
CERN-FASER-CONF-2023-002

This specific event:

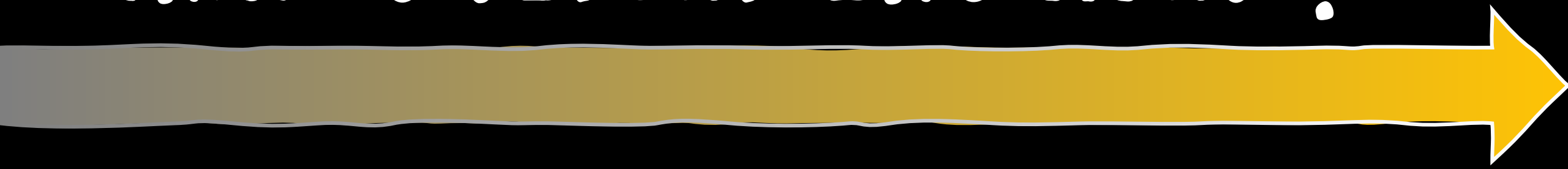
- A very clean high-energy ν_e candidate
- Energy of electron ~1.5 TeV

100 μm

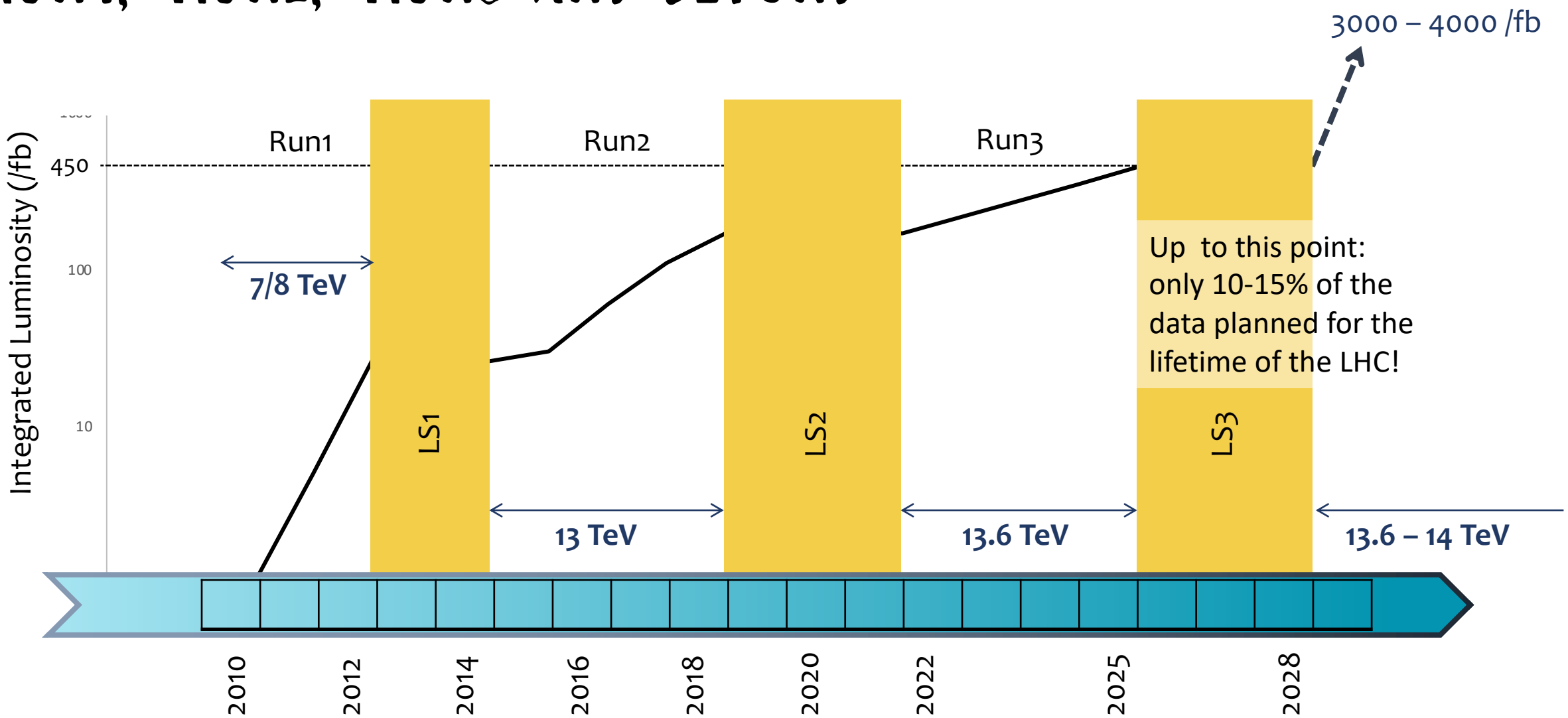
Searches for DARK Photons



What's beyond LHC Run3 ?



Run1, Run2, Run3 and beyond



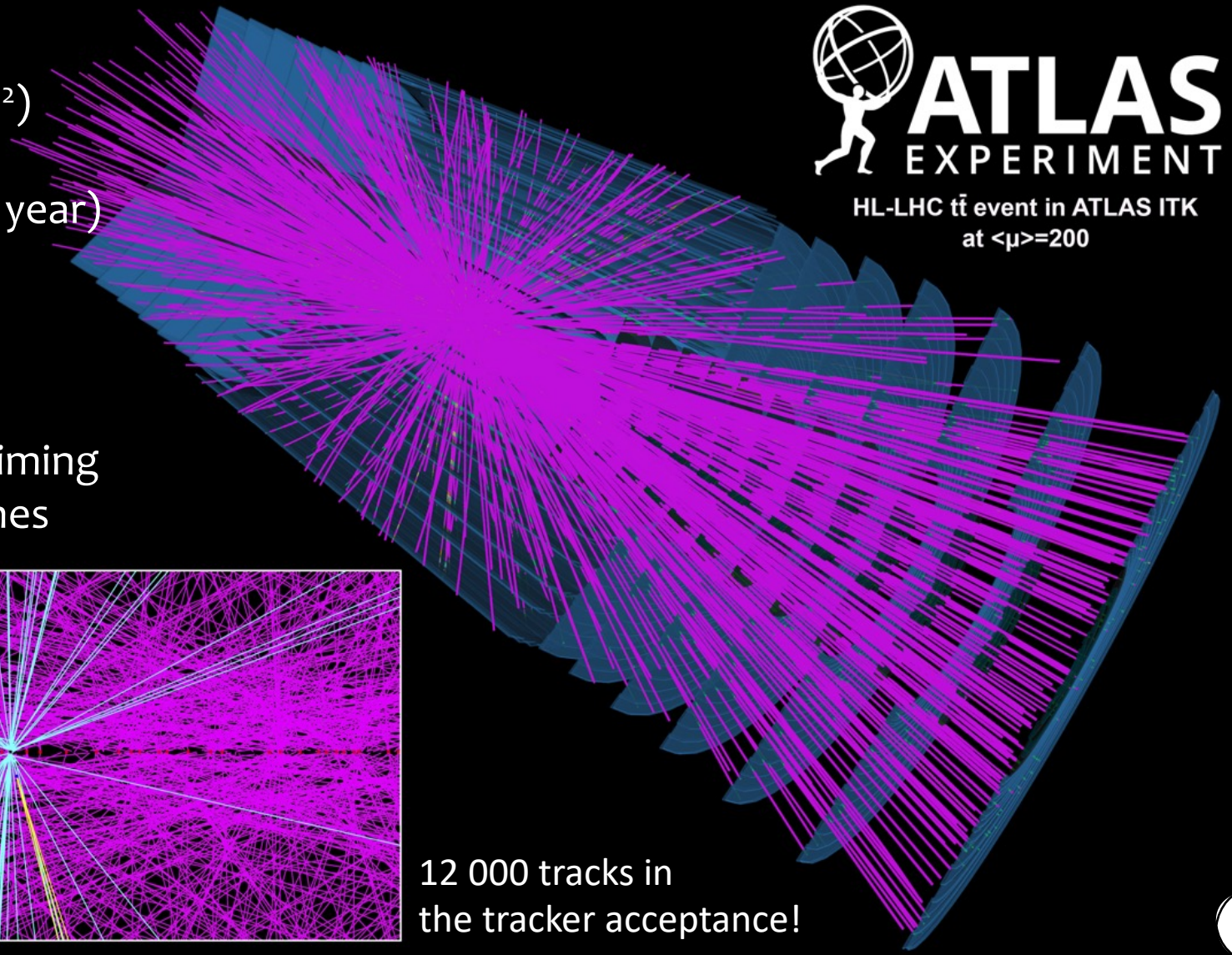
Required HL-LHC detector upgrades

Unprecedented challenges :

- amounts of radiation (~ 2×10^{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



12 000 tracks in
the tracker acceptance!

New (Forward) projects in the horizon

Aligned with the recommendations of recent community studies

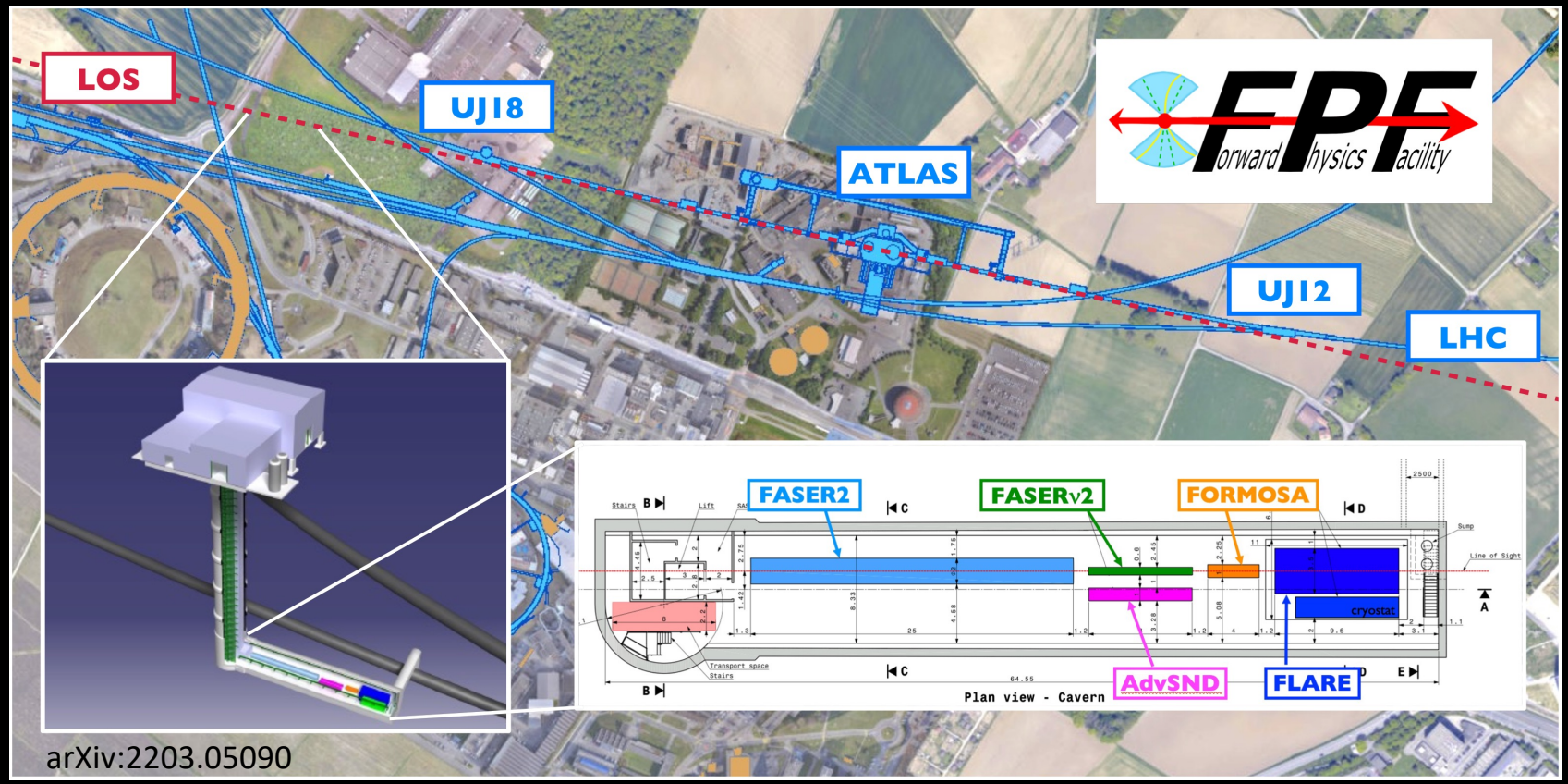
*The **full physics potential** of the LHC and the HL- LHC [...] should be exploited.*
1st recommendation of the 2020 European Strategy Update

*A **diverse programme that is complementary to the energy frontier** is an essential part of the European particle physics Strategy. **Experiments in such diverse areas** that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world*
Recommendation of the 2020 European Strategy Update

*Our highest immediate priority accelerator and project is the HL-LHC, [...] **including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.***
Snowmass 2021 Energy Frontier Report

A TEASER FOR THE PROPOSED FORWARD PHYSICS FACILITY

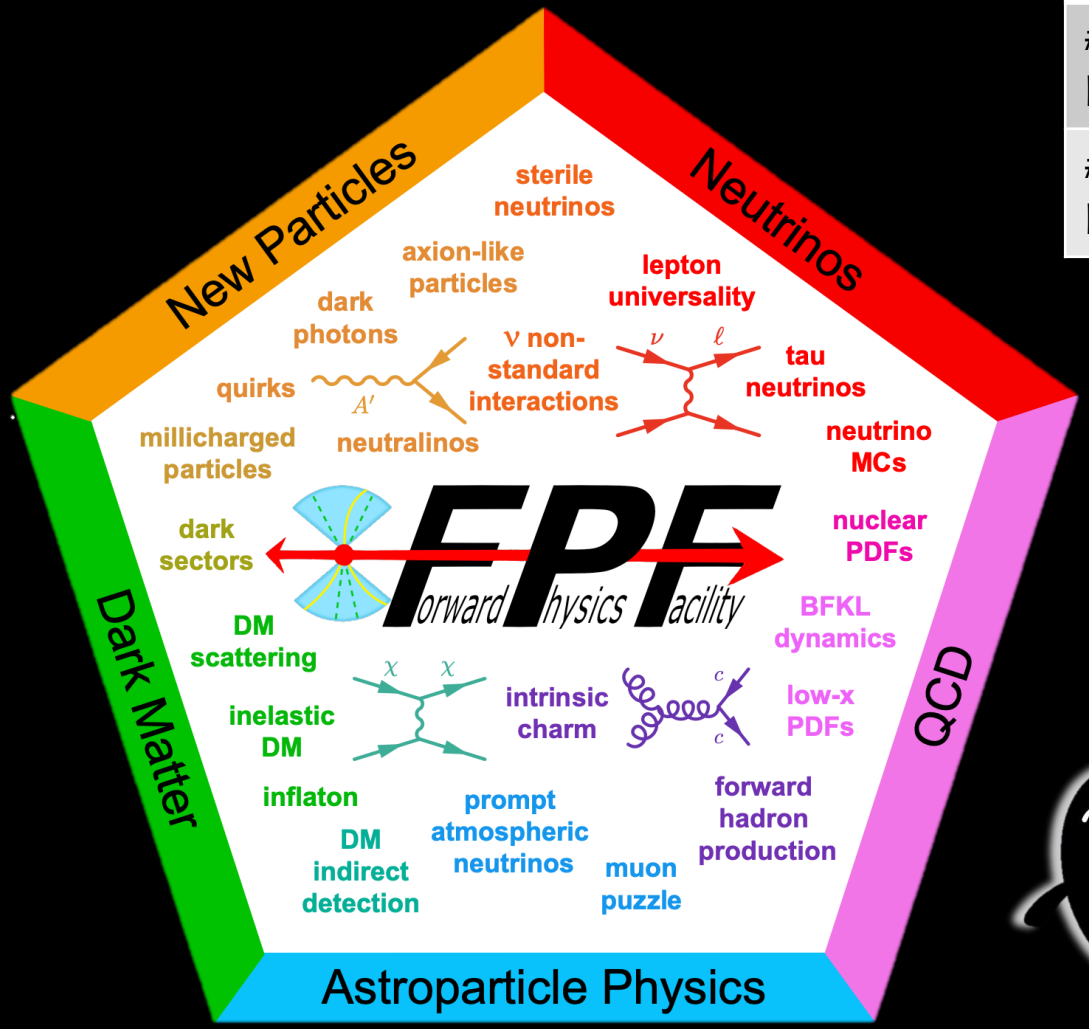
The rich physics program in the far-forward region strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2028-2040s



LoI expected by around the beginning of 2024

More: Submitted to P5 just in April 2023
LoI for SNOWMASS-2021
arXiv:2203.05090
FPF – Kickoff workshop
FPF – 5th workshop
FPF – 6th workshop just last week!

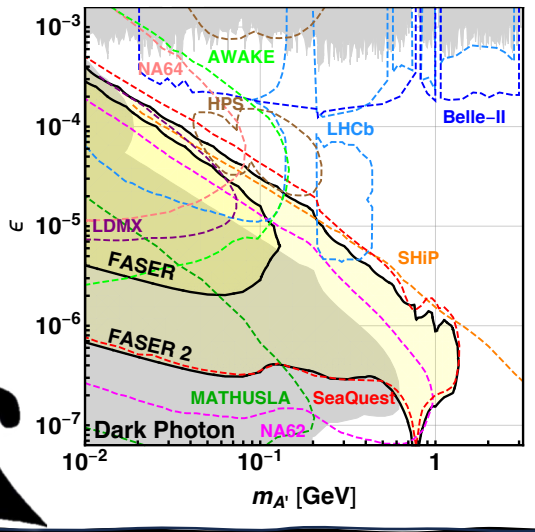
The Physics Programme of FPF

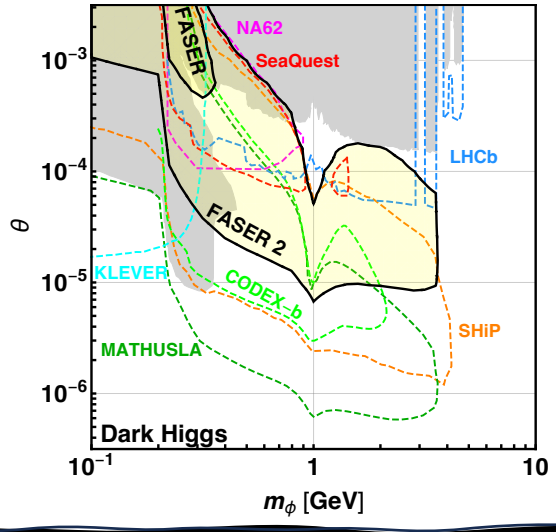


	Available lumi	Mass of ν detector	ν_e	ν_μ	ν_τ
# interacting in **FASERν**	150 / fb	1 tn Tungsten	~1000	~20000	~10
# interacting in **FASERν2**	3000 / fb	**10 tn** Tungsten	$\sim 10^5$	$\sim 10^6$	**$\sim 10^4$**

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

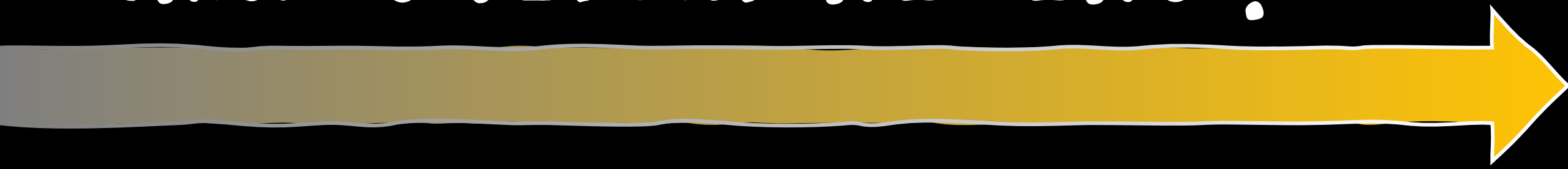
Increased BSM physics case **beyond** just increased luminosity

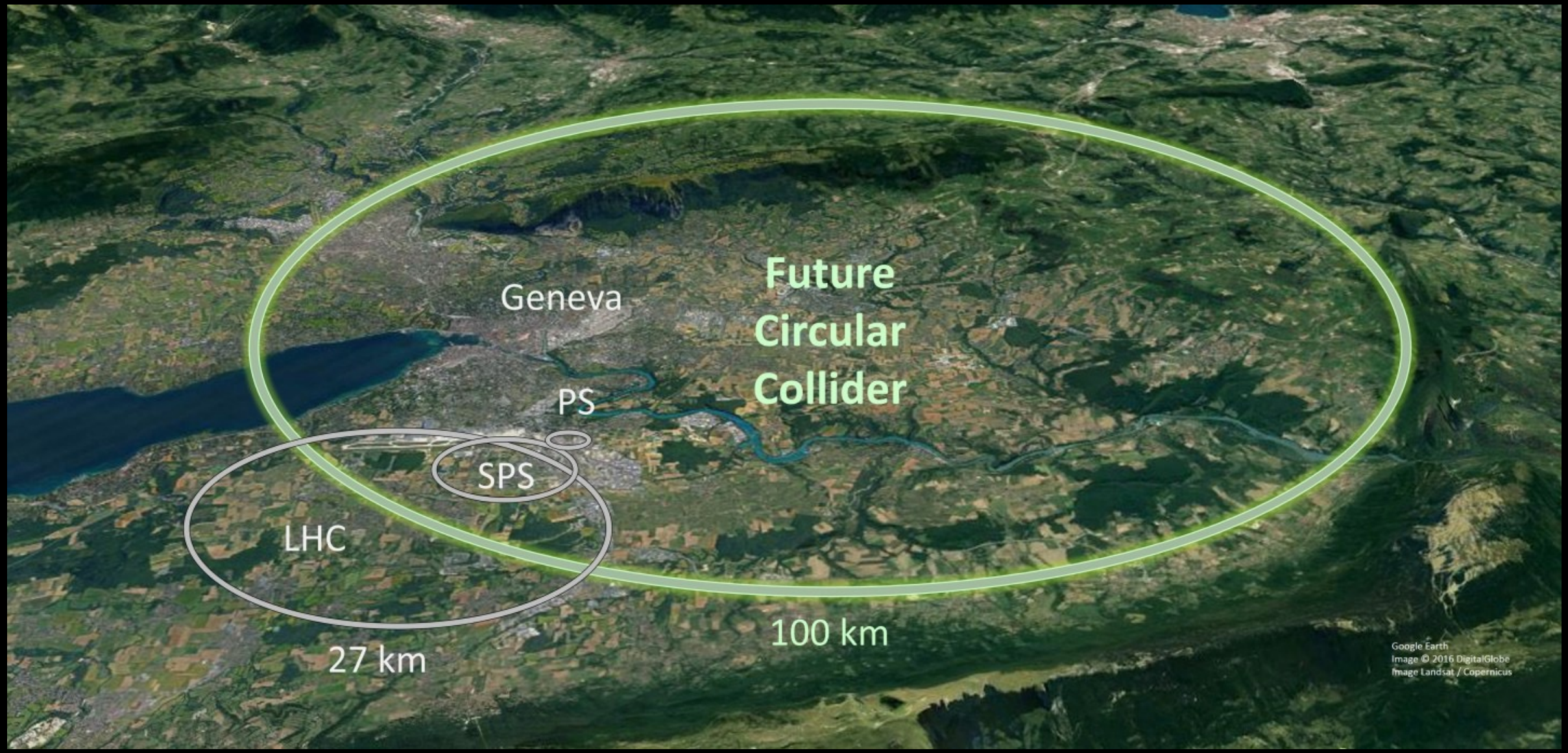




From https://pbc.web.cern.ch/sites/default/files/2023-04/FPFSummary_final.pdf

What's beyond HL-LHC ?




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

The FCC project

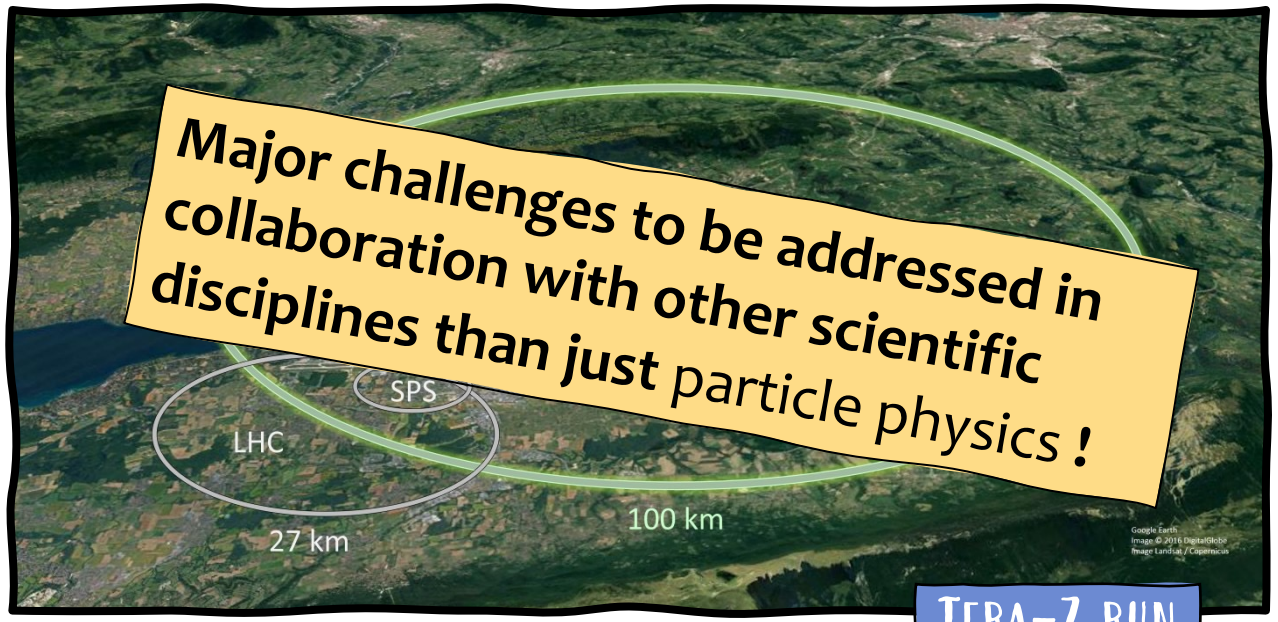
2020 European Strategy Update

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)

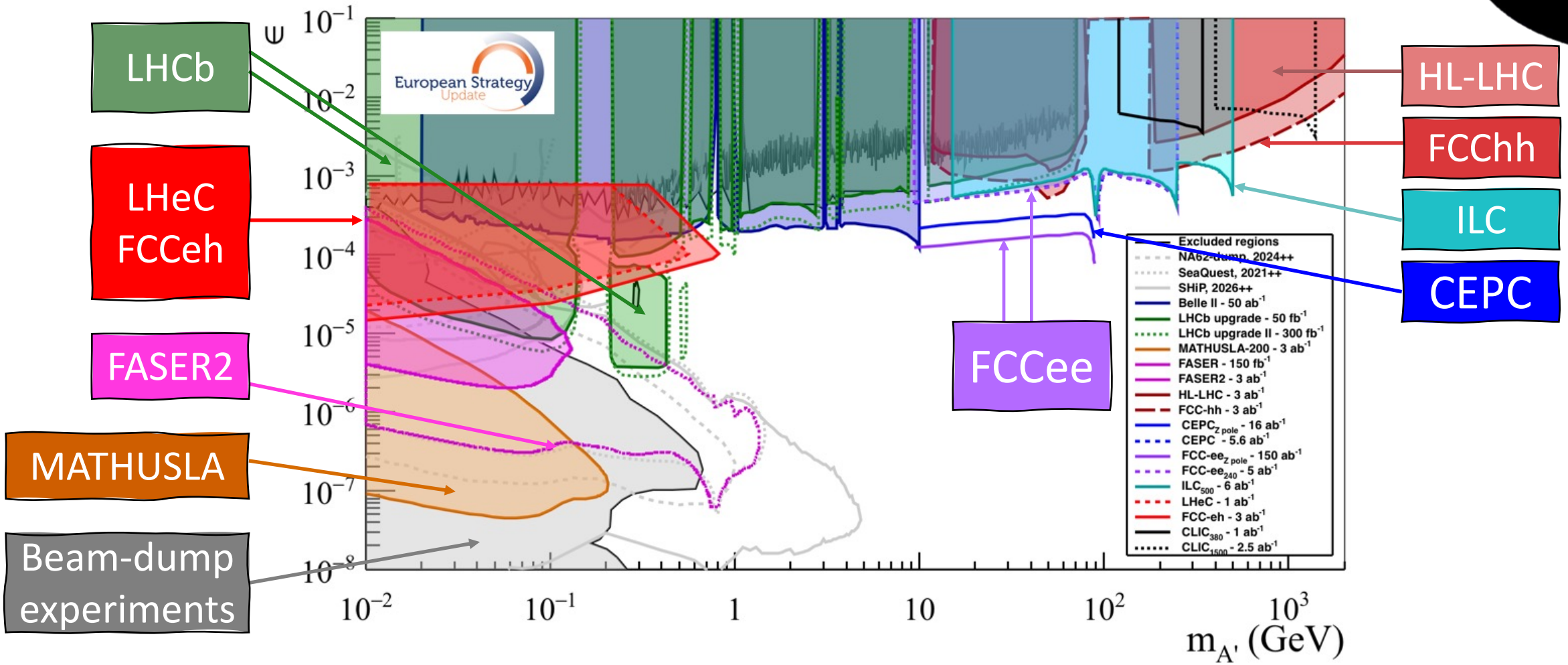


Stage	Collisions	CME	L (ab^{-1})	N events
FCC-ee	e^+e^-	90 GeV (Z-pole)	150	**$5x10^{12}$** Z
		160 GeV (WW)	10	10^8 WW
		240 GeV (HZ)	5	10^6 HZ
		365 GeV (tt)	1.5	10^6 tt
FCC-hh	pp	100 TeV	30	$2x10^{10}$ H $3x10^7$ HH
FCC-eh	ep	3.5 TeV		

Runs with heavy ions not included

Recent review – input to Snowmass – arXiv:2203.06520

Vector portal – Reach for dark photons



Complementarity of collider and other accelerator experiments

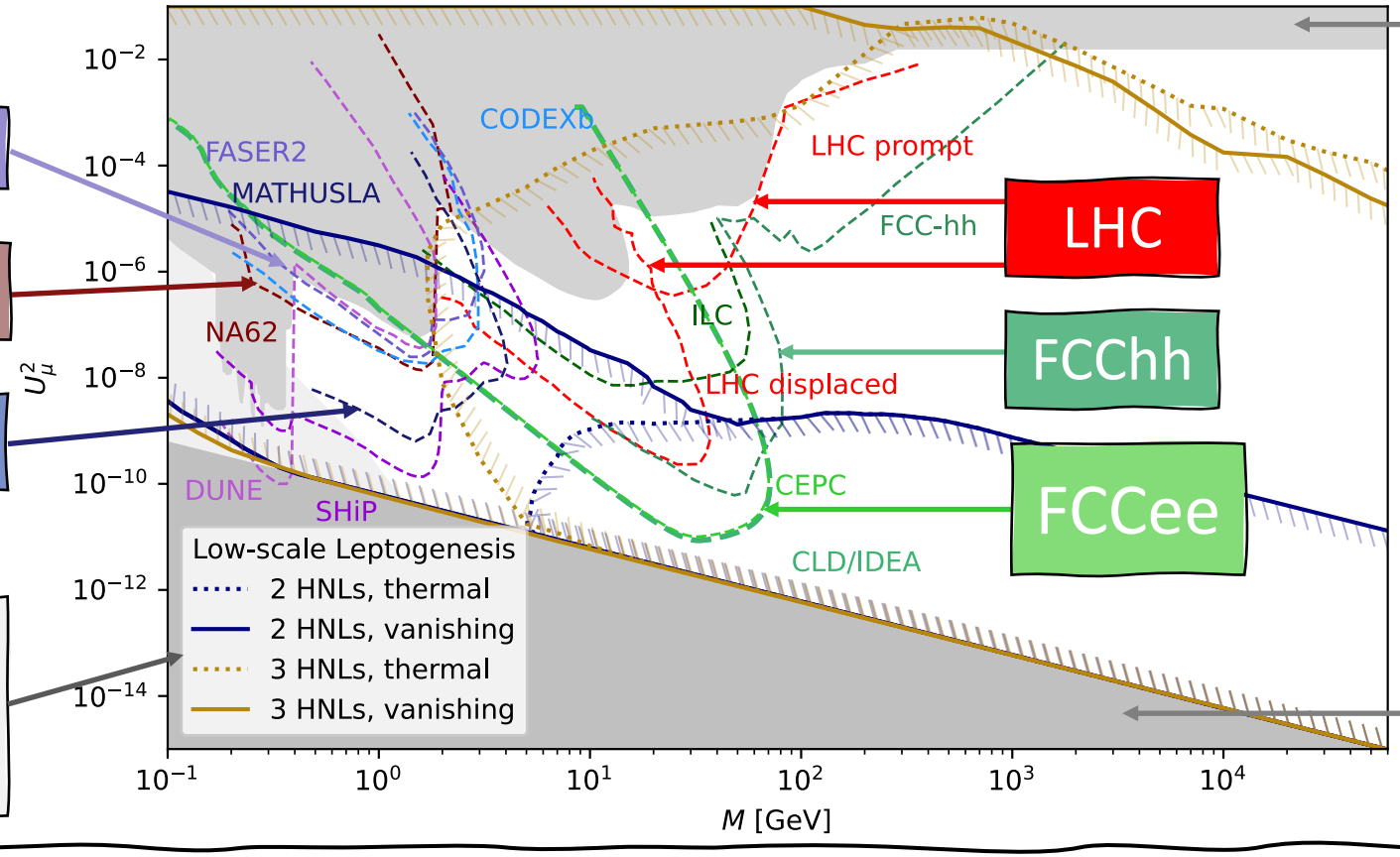
Physics briefing book – Input to EU strategy – arXiv:1910.11775

Reach for HNLs in future experiments

FASER2

NA62

MATHUSLA



LHC

FCChh

FCCee

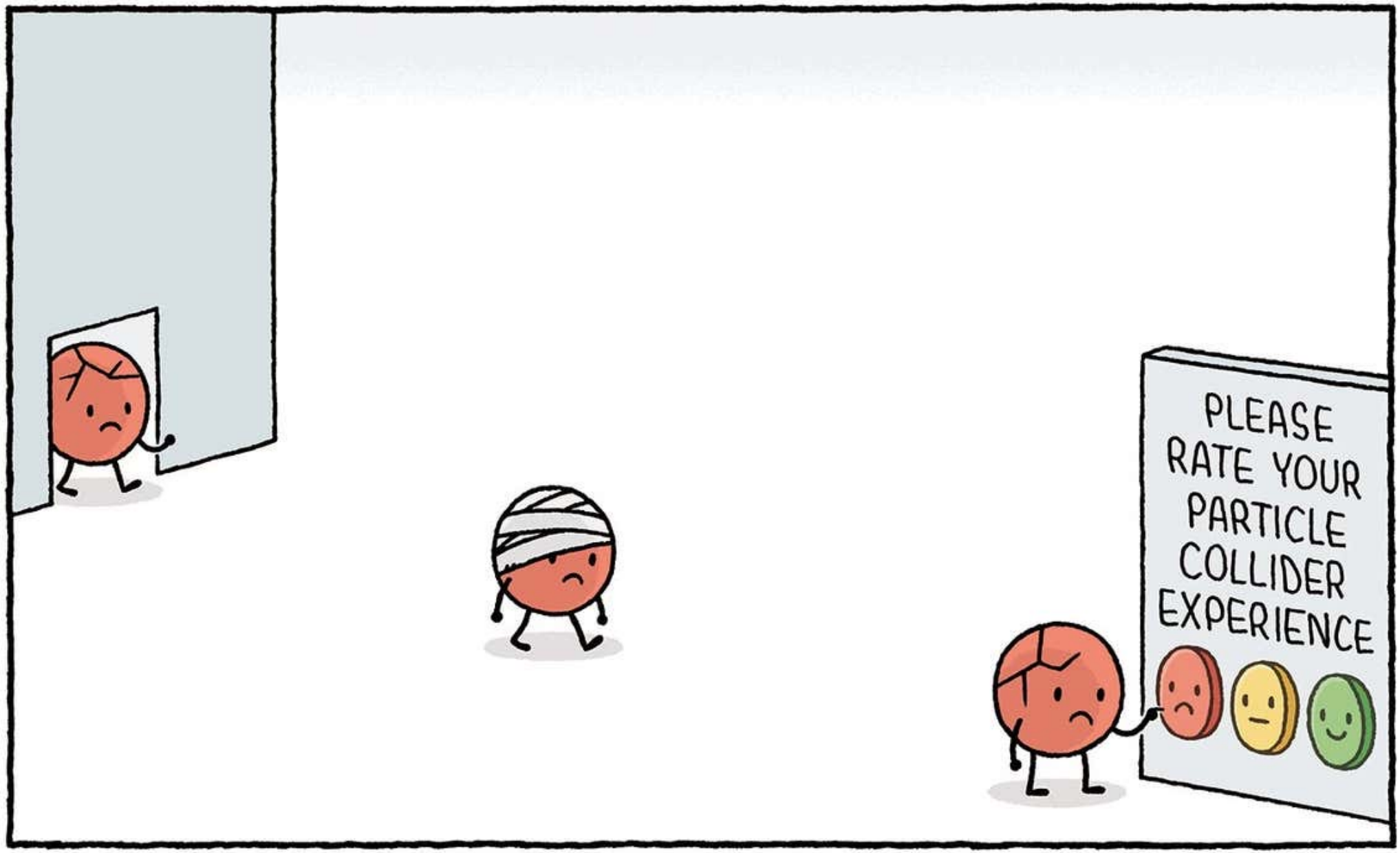
Constrains from past experiments

Lower bound from the requirement to explain light neutrino oscillation data

Different initial conditions in early universe

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

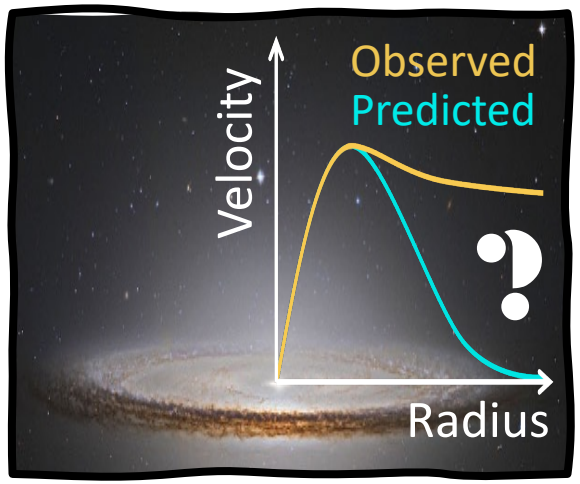
LLPs at FCC – 2203.05502



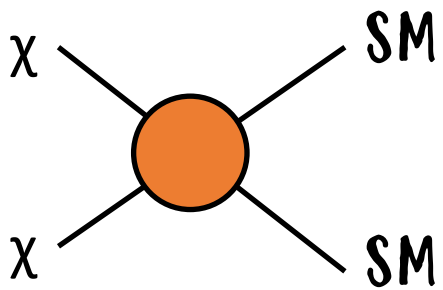
TOM GAULD for NEW SCIENTIST

Extras

The landscape of new particles @ colliders



- Simple mechanism for DM evolution: "freeze out"



Surviving DM density: $\Omega_X \propto \frac{m_X^2}{\epsilon_X^4}$