Looking FORWARD to NEW PHYSICS with the LHC

Joint Annual Meeting of SPS & ÖPG
4-8 September 2023, Basel

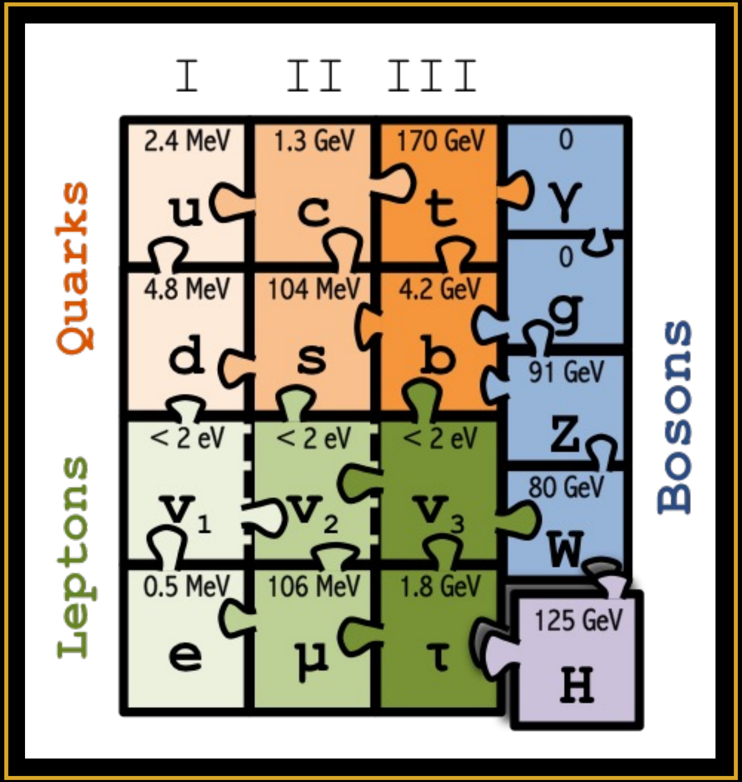
Anna Sfyrla

UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE

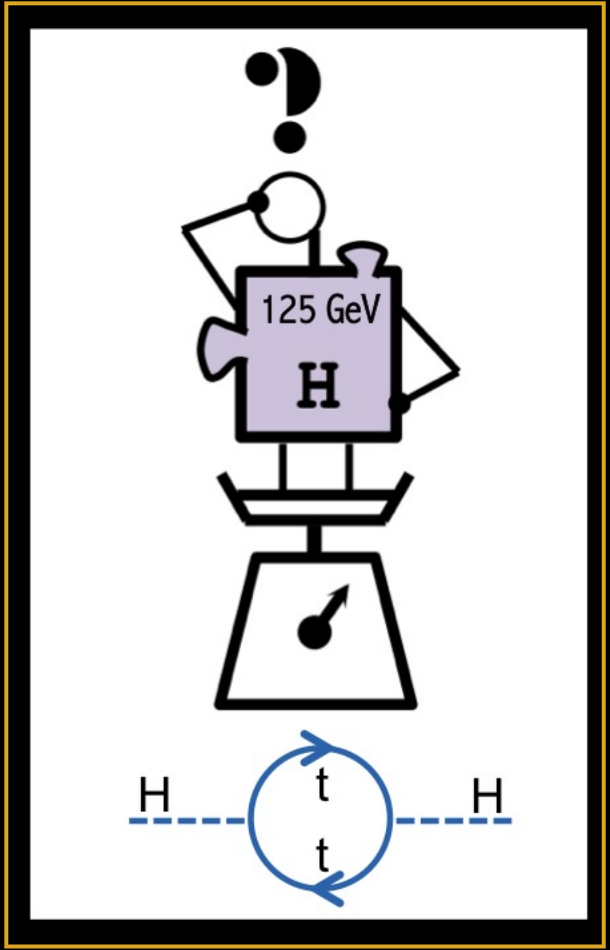
swiss physical society

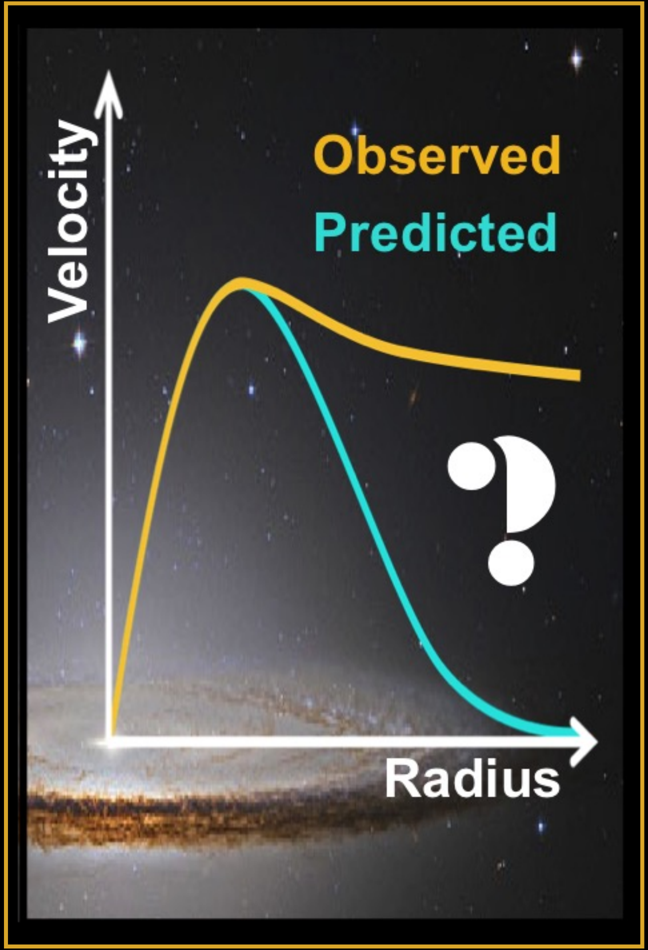
Austrian Physical Society

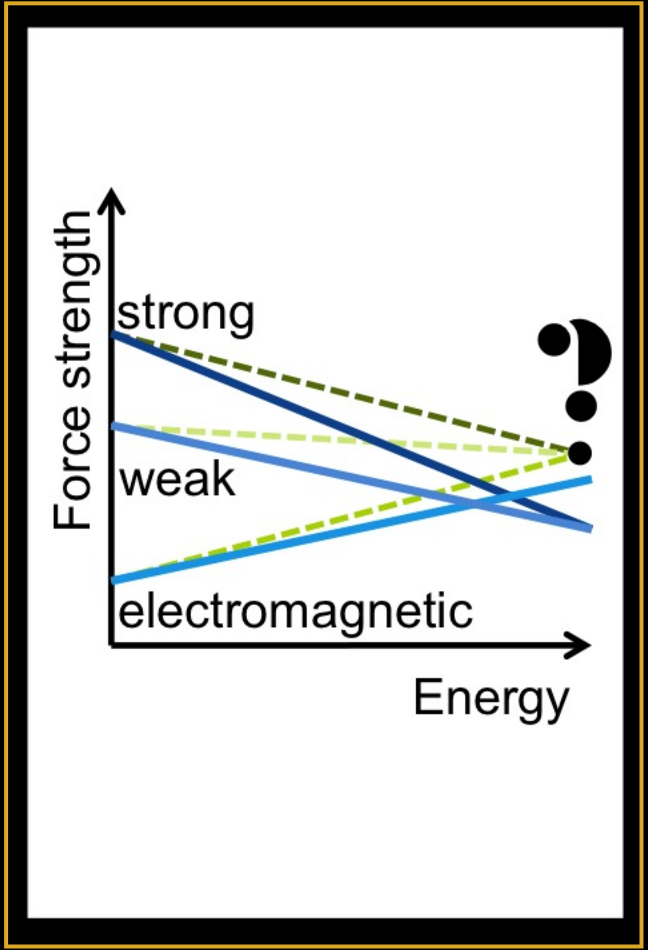
The Standard Model



...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:

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

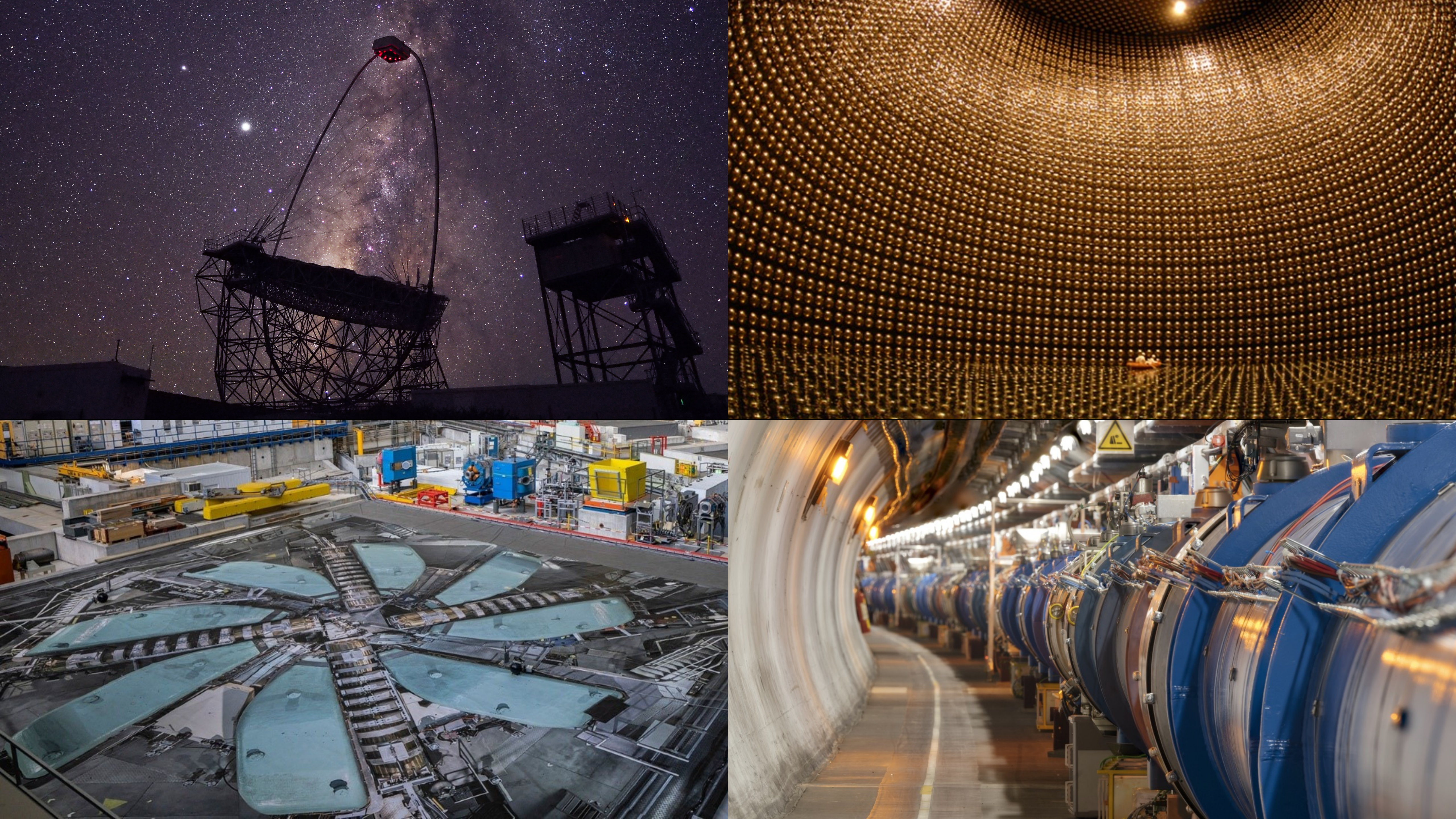
while measurements require that the vacuum angle θ is tiny!

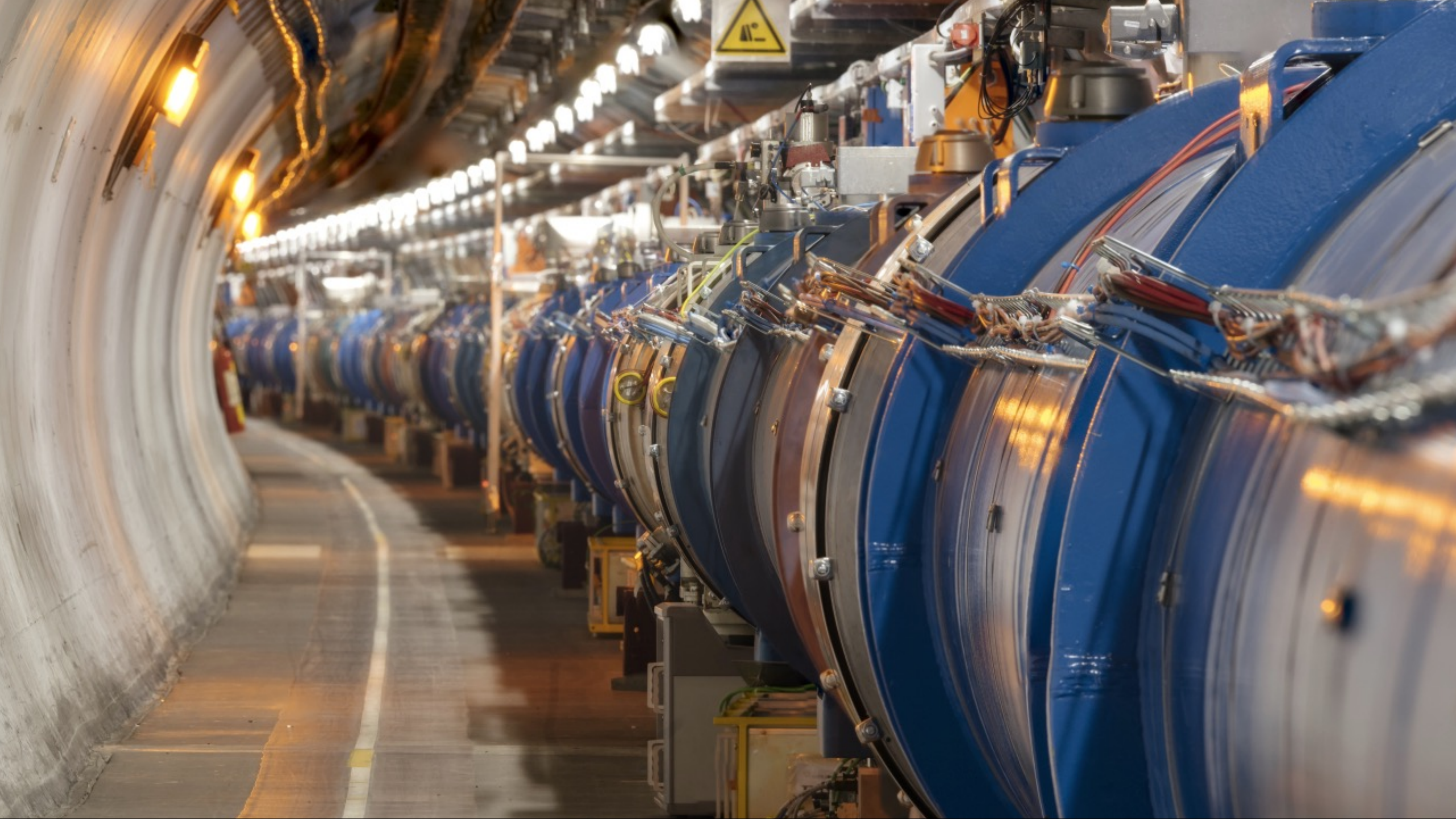
The non-zero angle θ implies non-zero neutron electric dipole moment (EDM)
The angle is stringently constrained by neutron EDM measurements

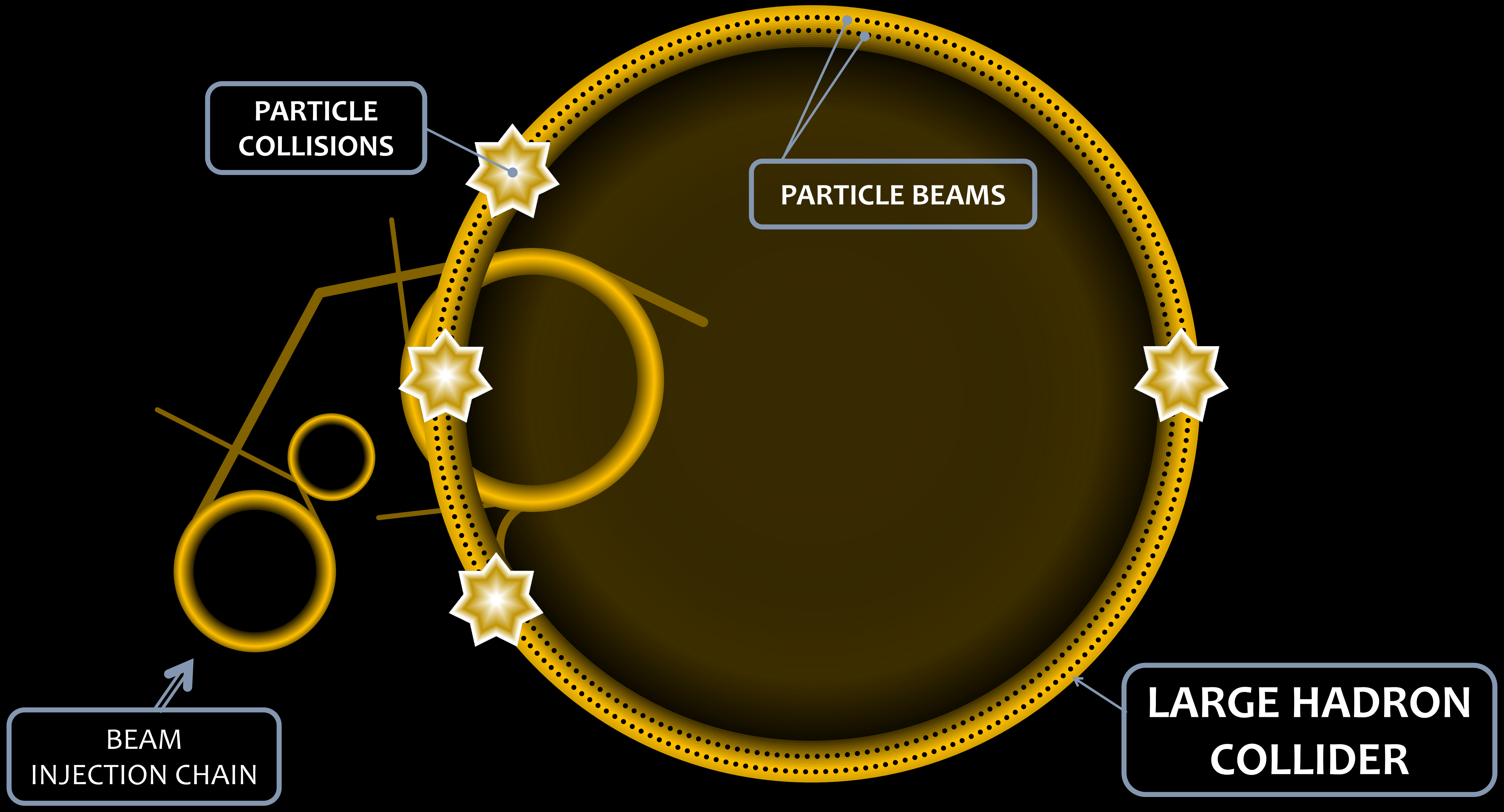
Most sensitive measurement on the neutron EDM to date achieved by the **PSI** experiment **nEDM**:

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

In other words,
The "strong CP problem": Why no measurable neutron EDM?





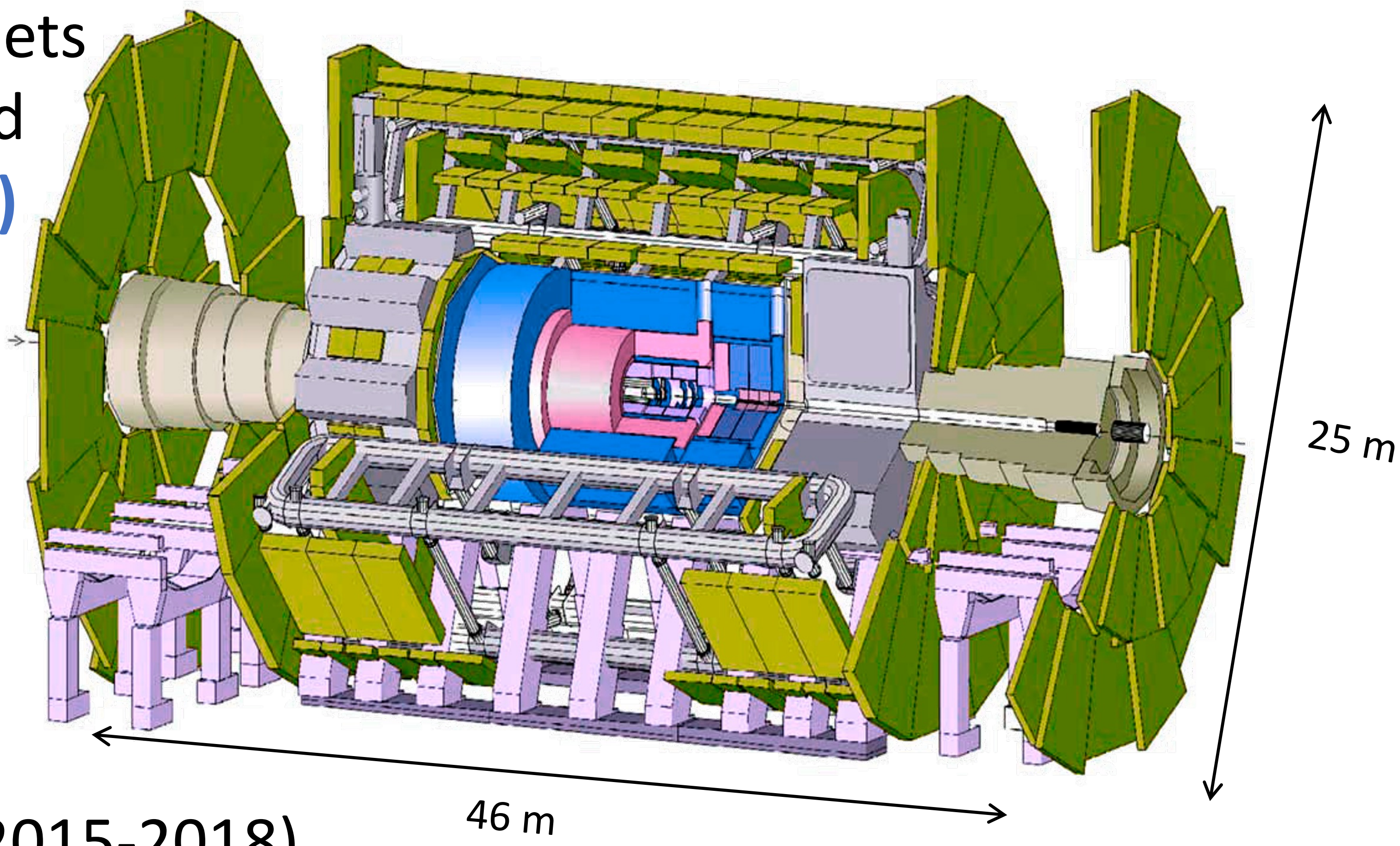

PARTICLE COLLISIONS
PARTICLE BEAMS
BEAM INJECTION CHAIN
LARGE HADRON COLLIDER

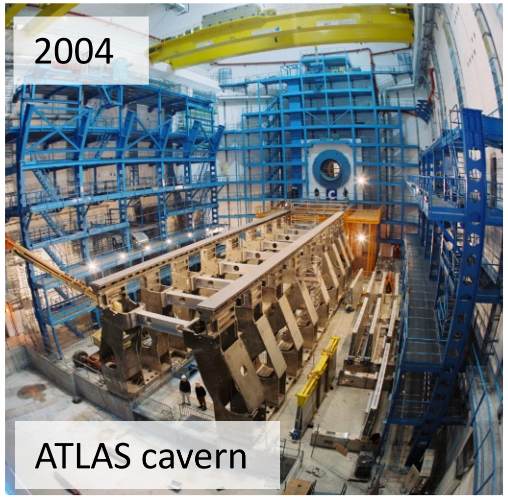
Example: The ATLAS detector in numbers

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

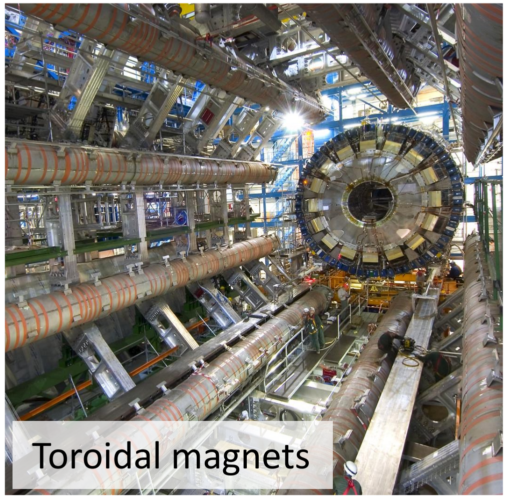
- ✓ 1 Giga collisions/second
- ✓ 1000 events/second stored
- ✓ 500 PB data on disk & tape
- ✓ 0.5 M CPU cores used 24/7

- ✓ 20 billion events collected (2015-2018)



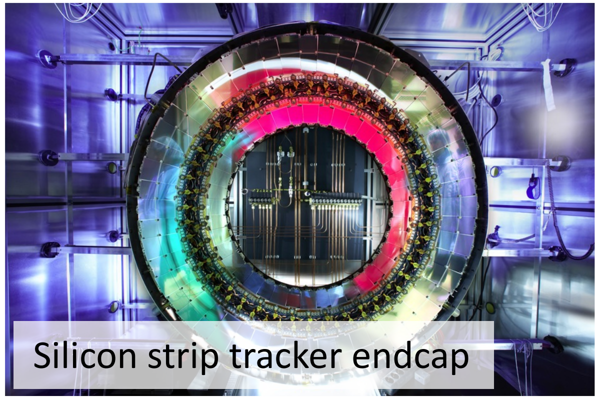


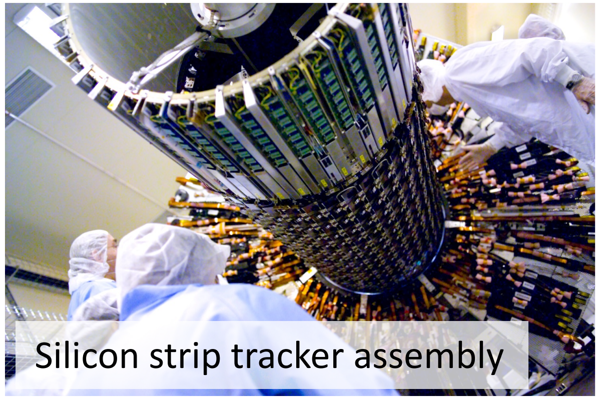
ATLAS cavern

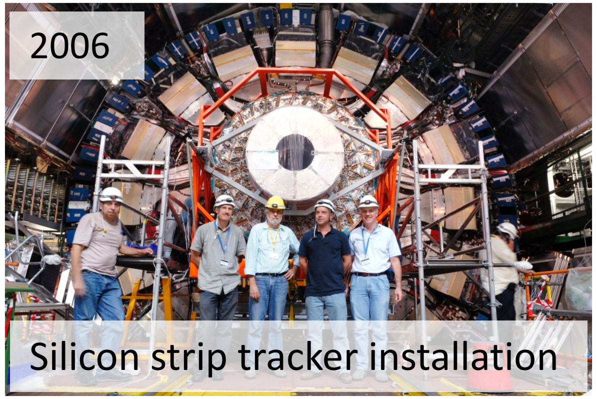

Toroidal magnets


Calorimeter


Pixel tracker


Silicon strip tracker endcap

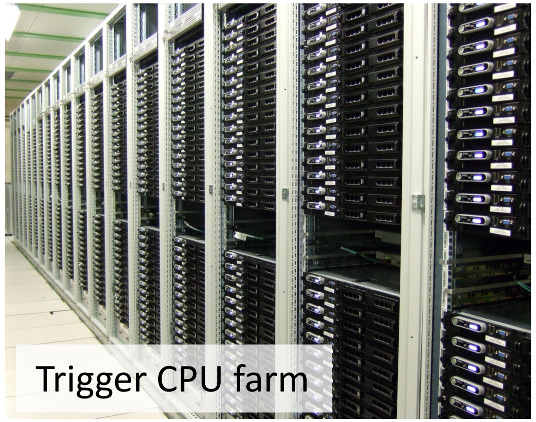

Silicon strip tracker assembly



Silicon strip tracker installation

ATLAS EXPERIMENT

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

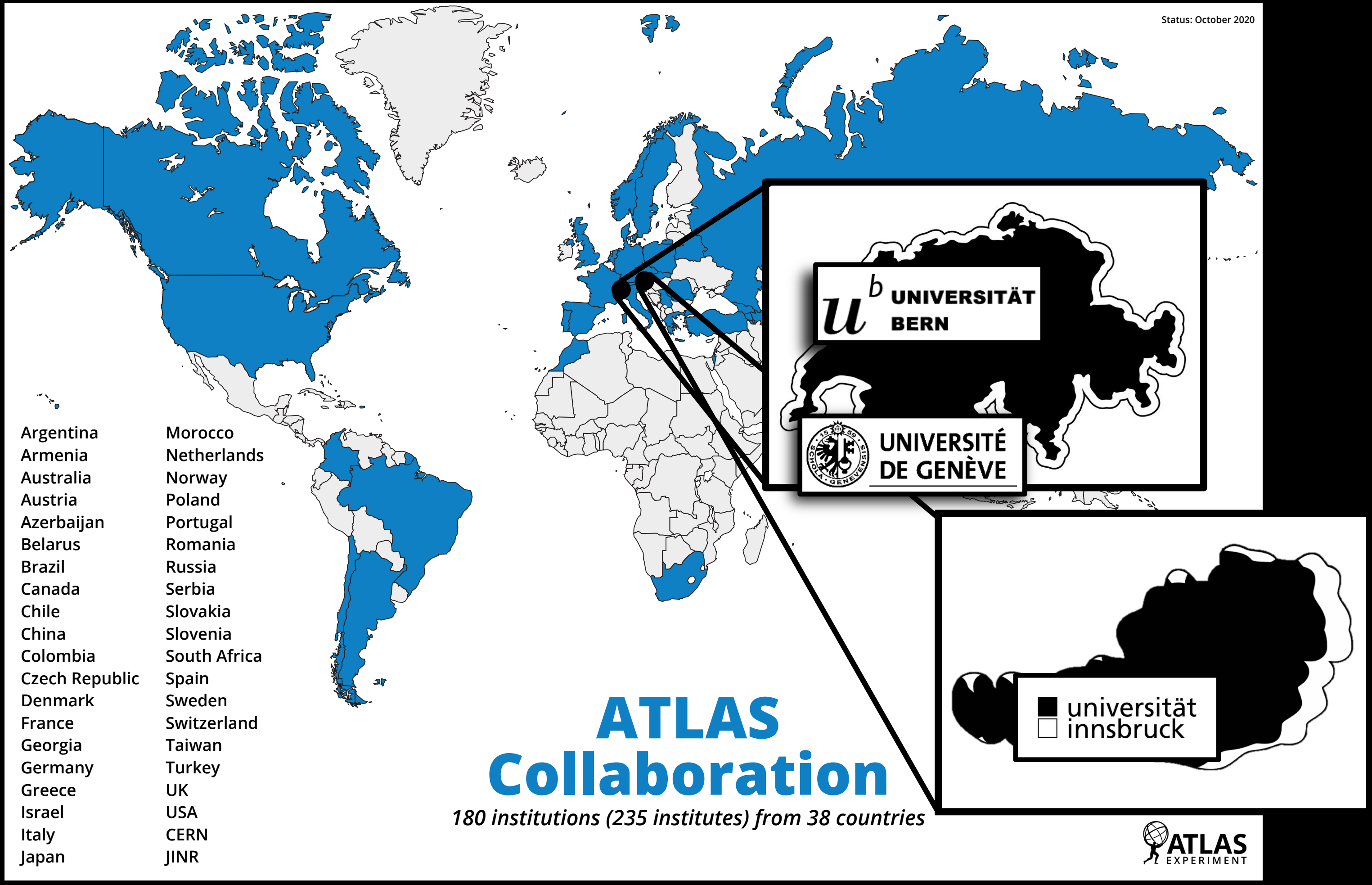
The ATLAS Collaboration

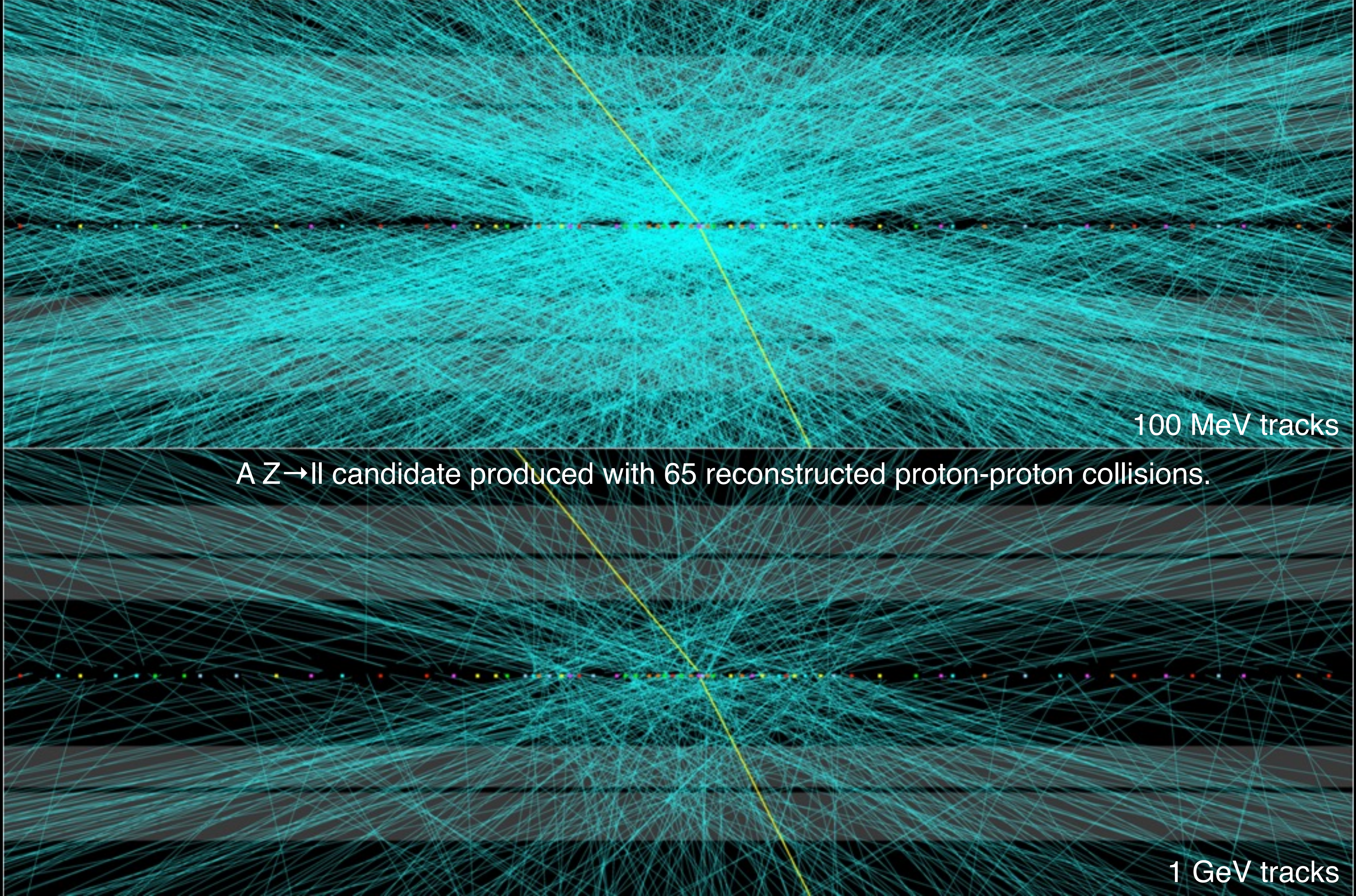
3000
Scientific authors

38
Countries

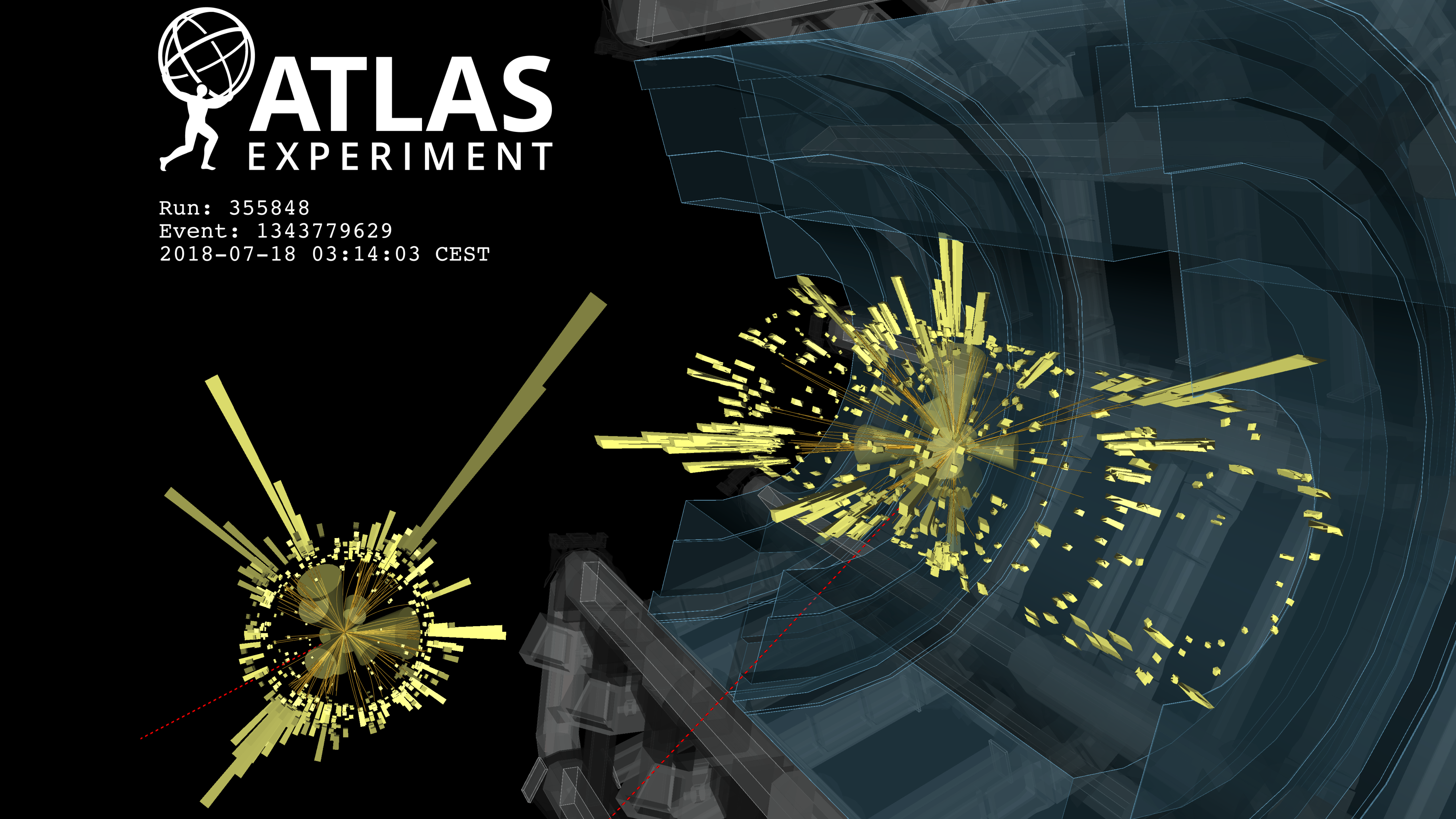
180
Institutions

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

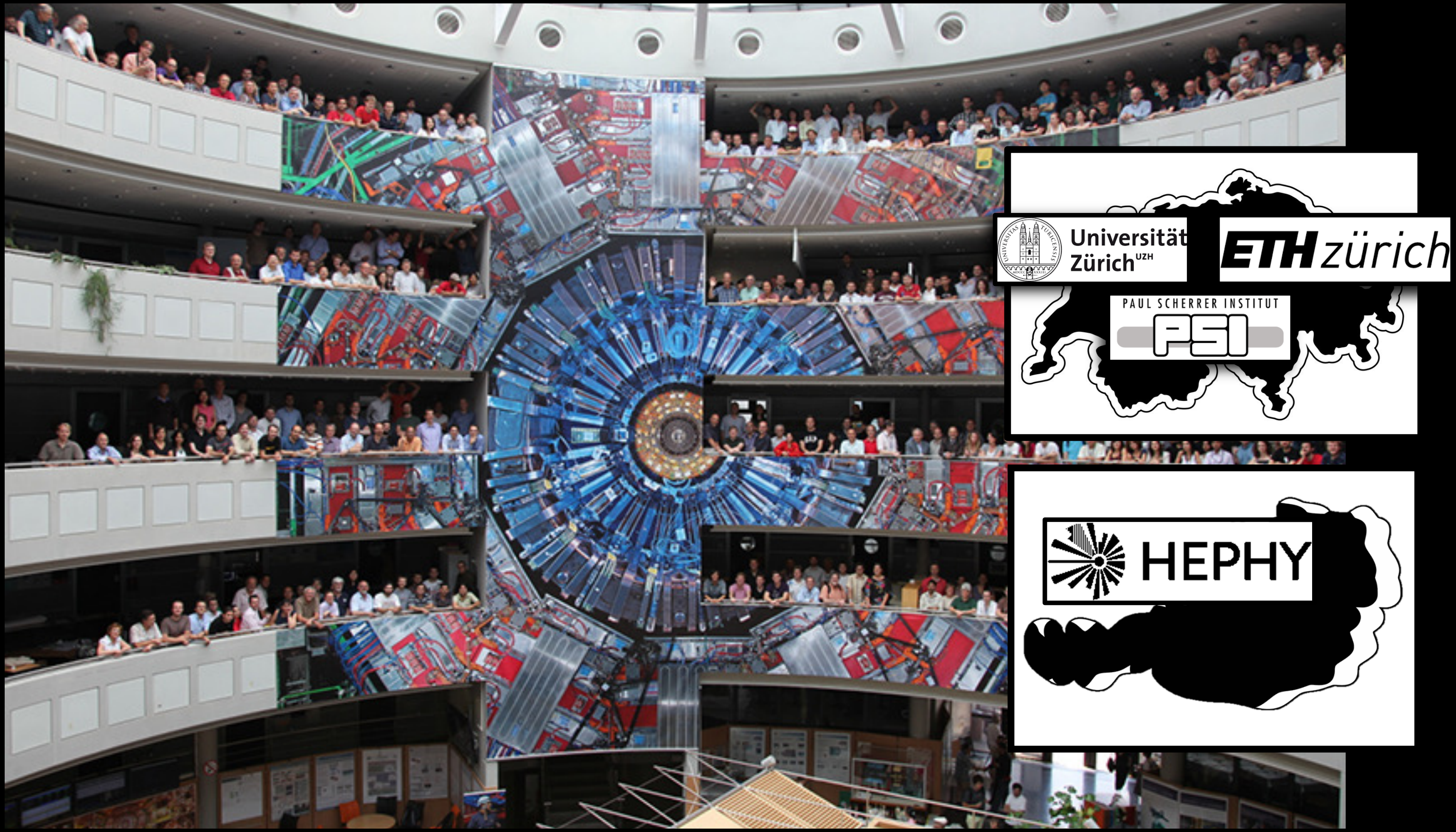
The CMS Collaboration

2100
Scientific authors

51
Countries

229
Institutions

1100
Doctoral students

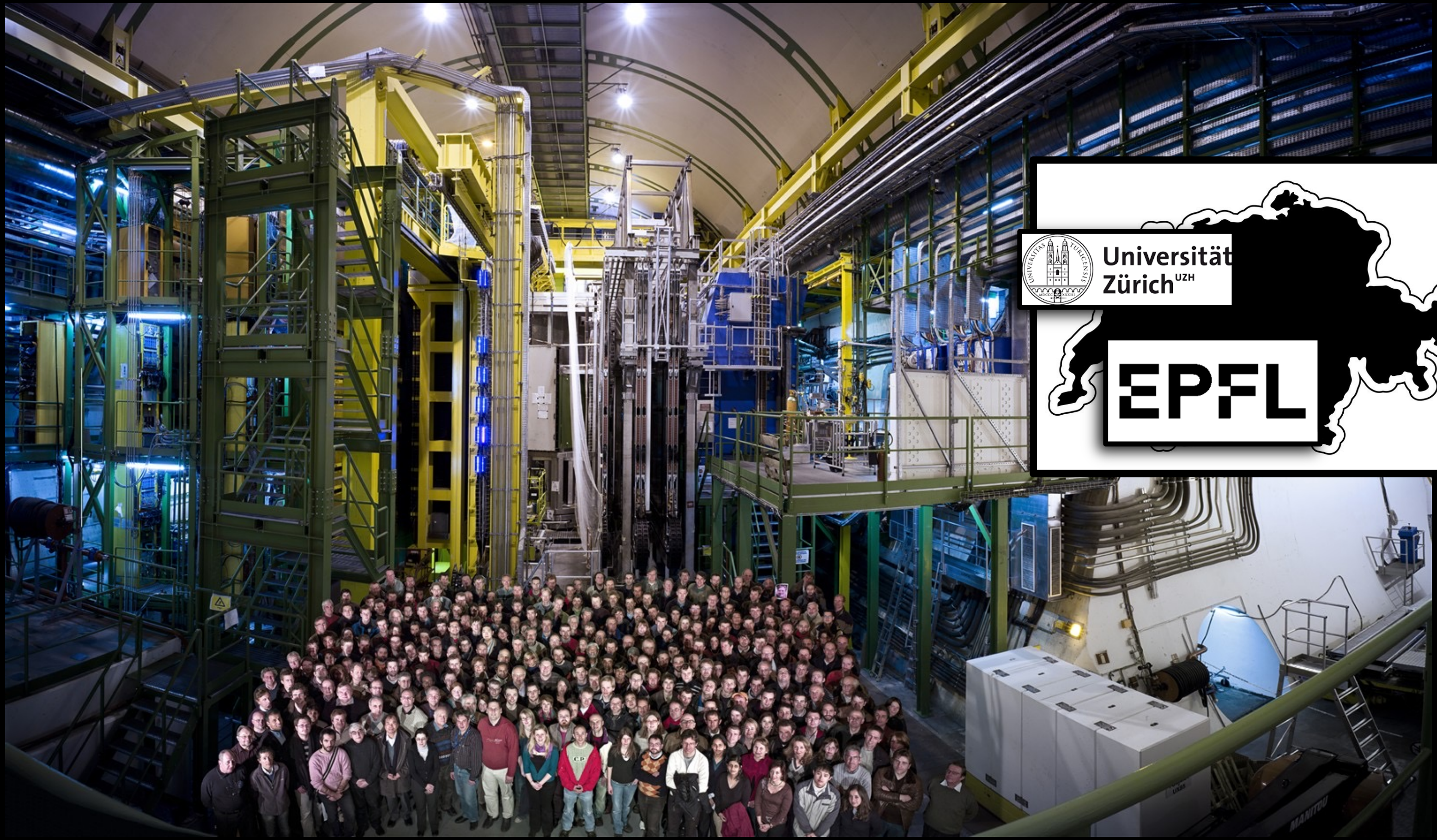


The LHCb Collaboration

1500
Members

19
Countries

87
Institutions



Universität Zürich UZH

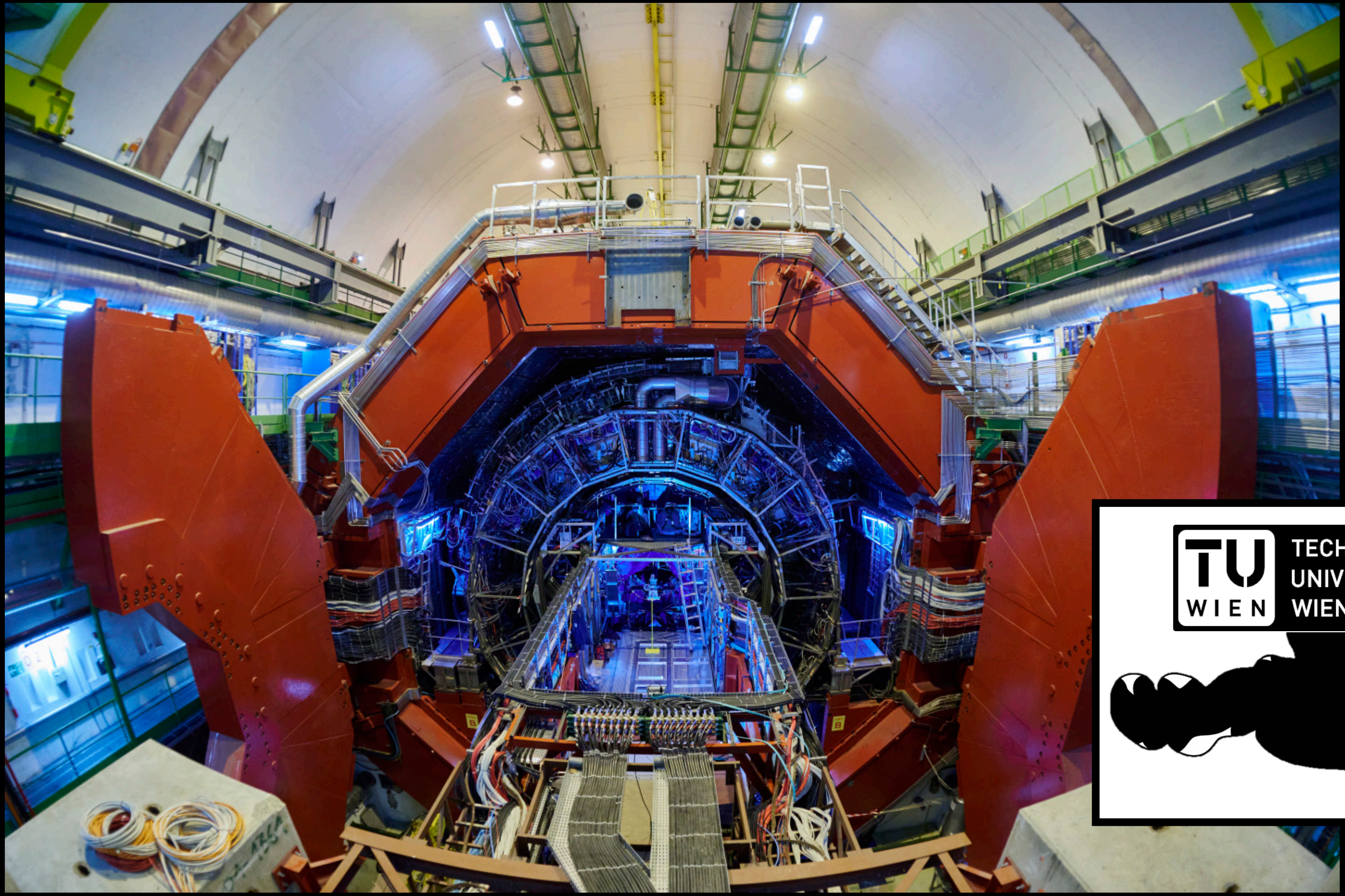
EPFL

The ALICE Collaboration

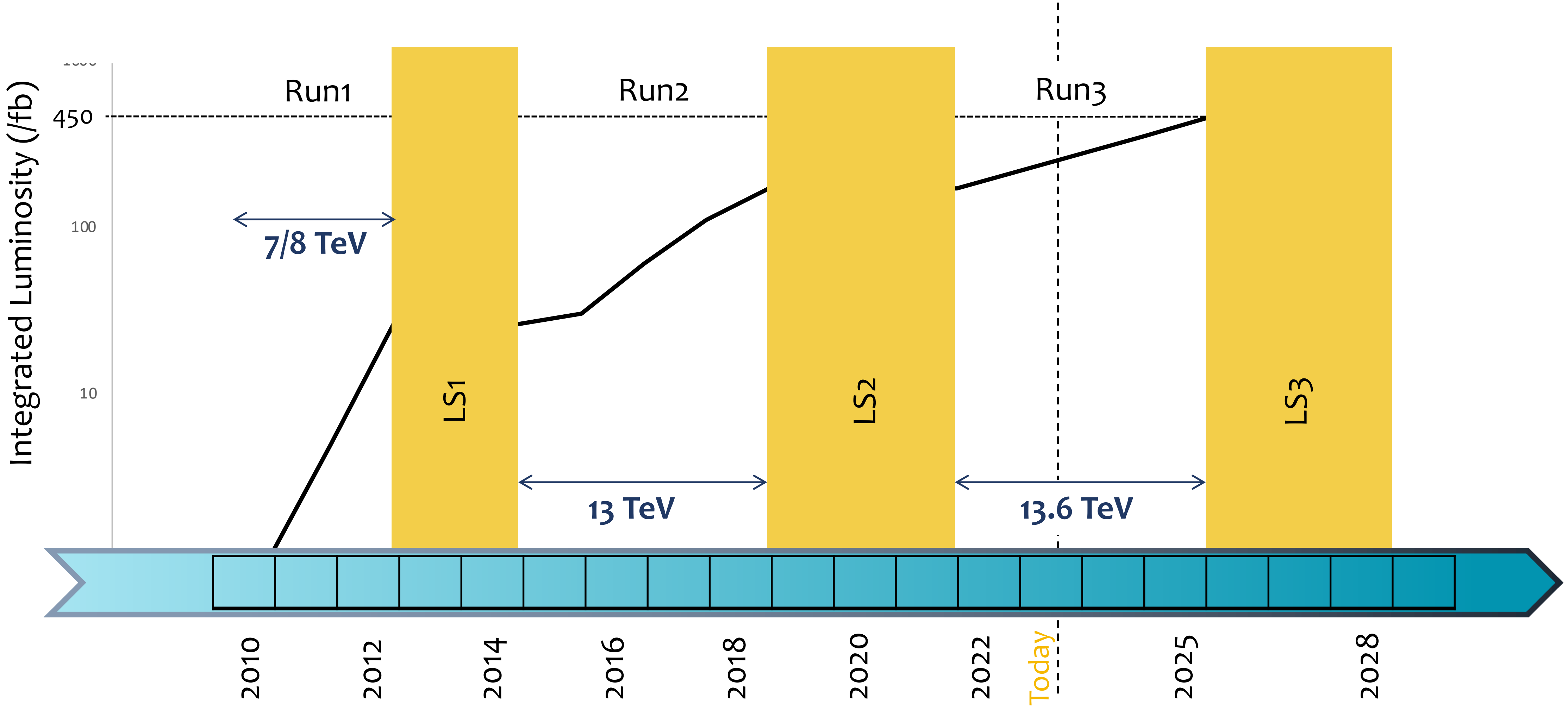
1990
Members

40
Countries

172
Institutions

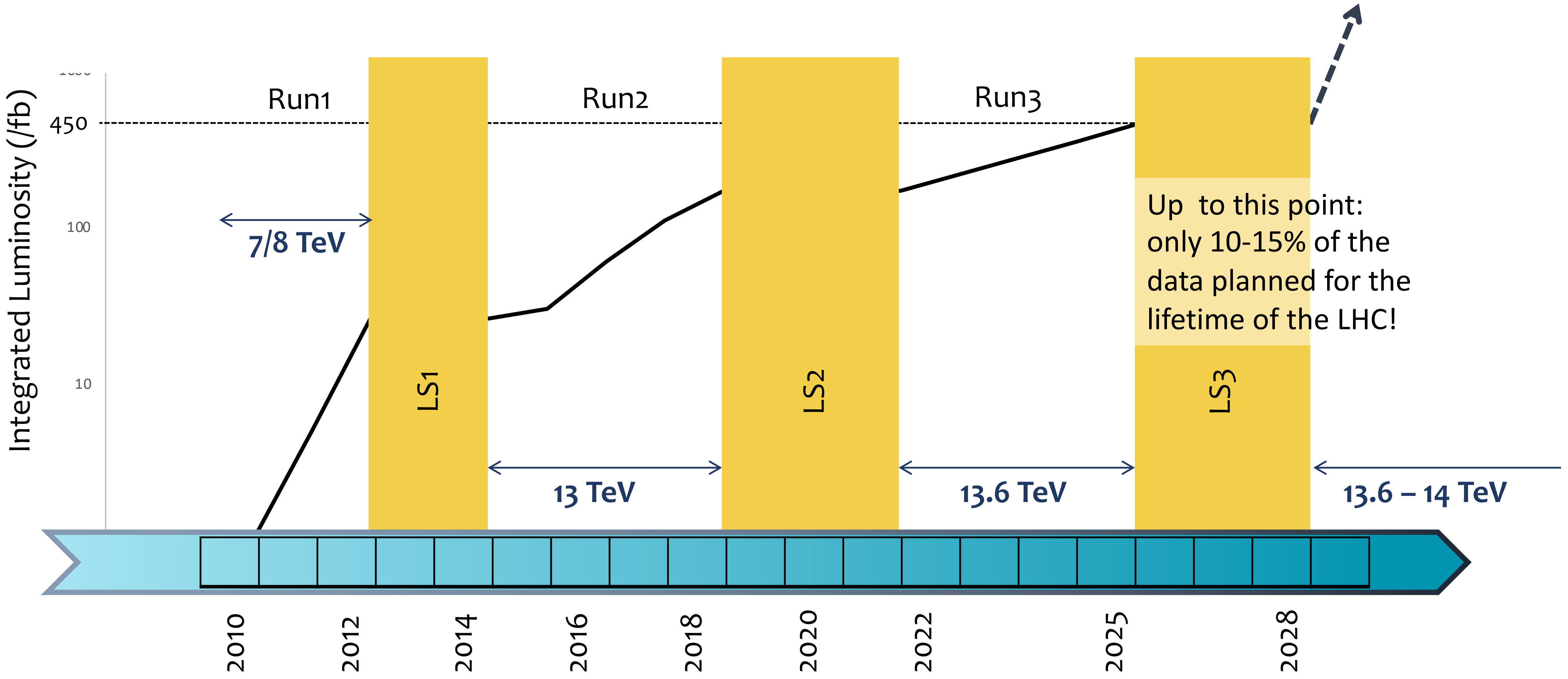


Run1, Run2, Run3 ...



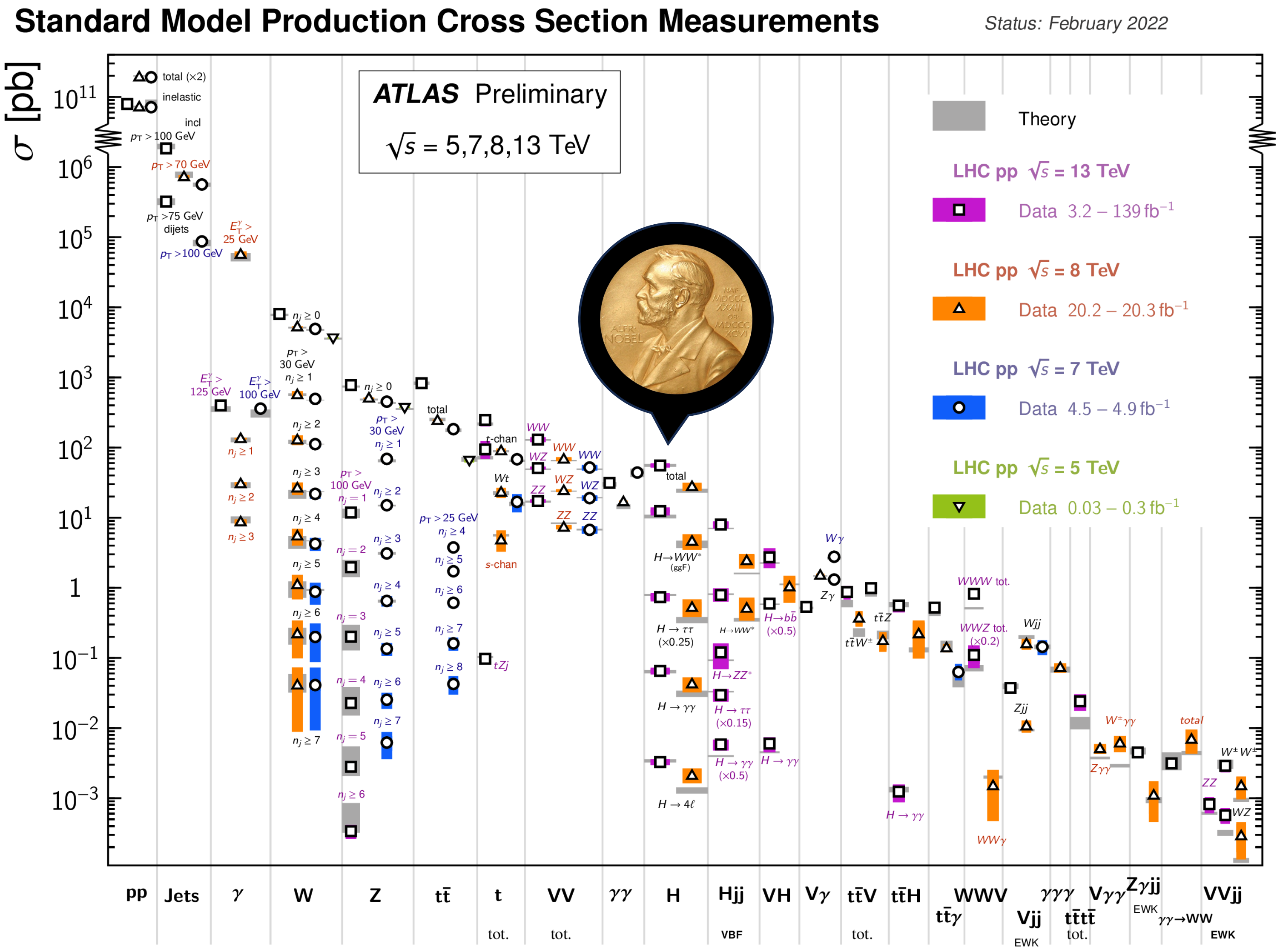
Run1, Run2, Run3 and beyond

3000 – 4000 /fb



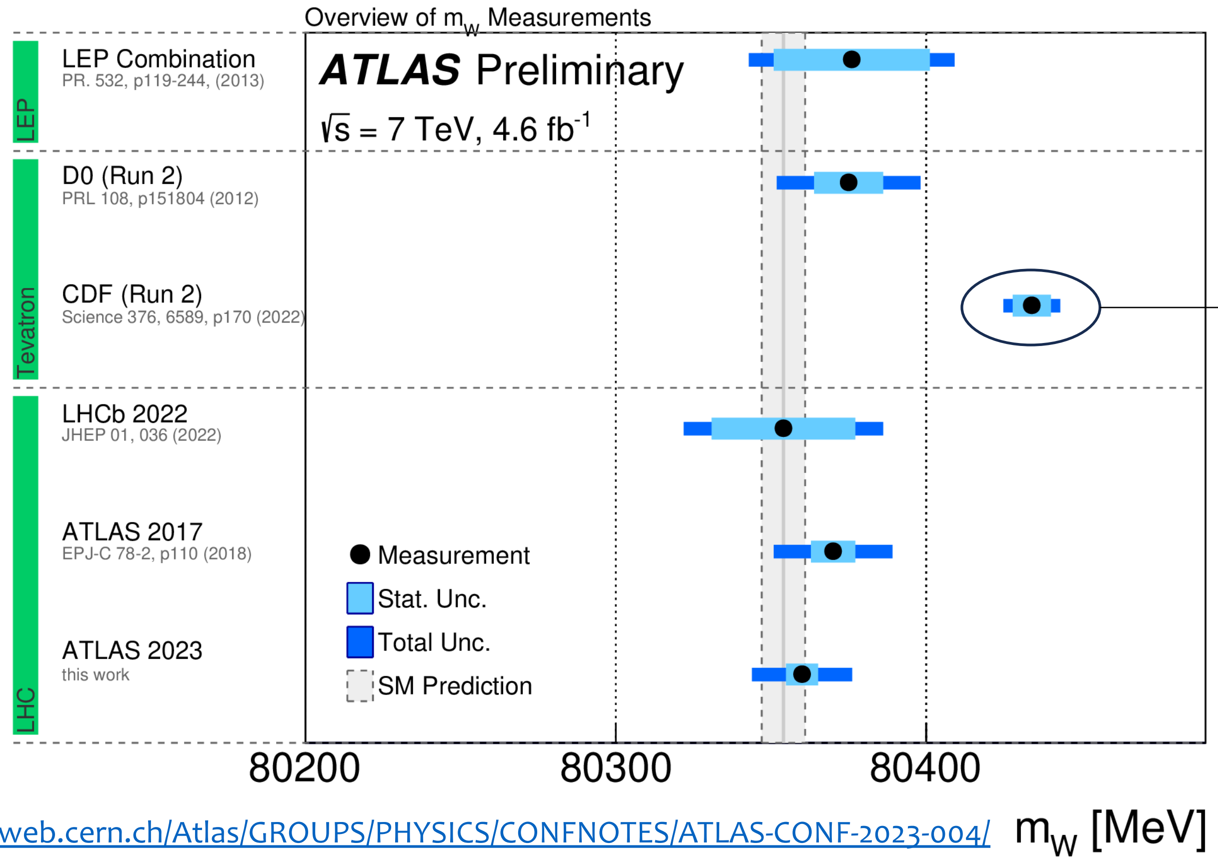
The Landscape of Particles

The Standard Model studied in detail



Masses

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



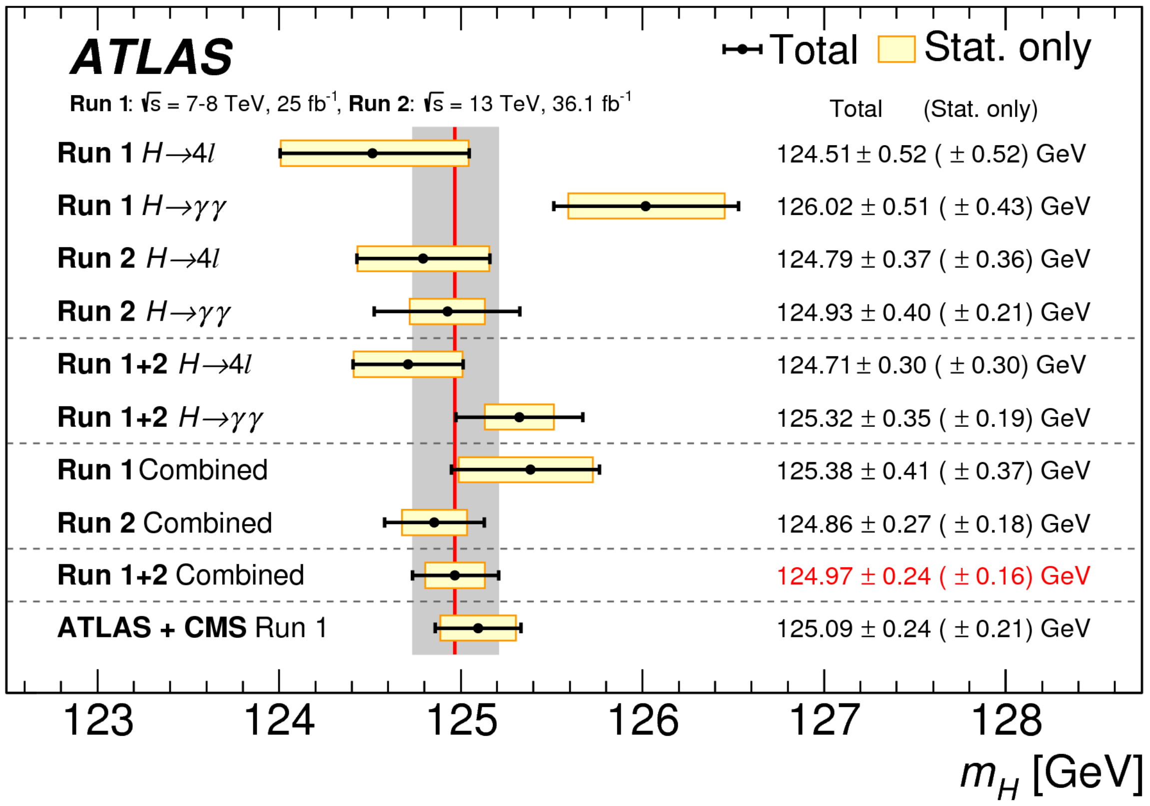
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-004/

"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."

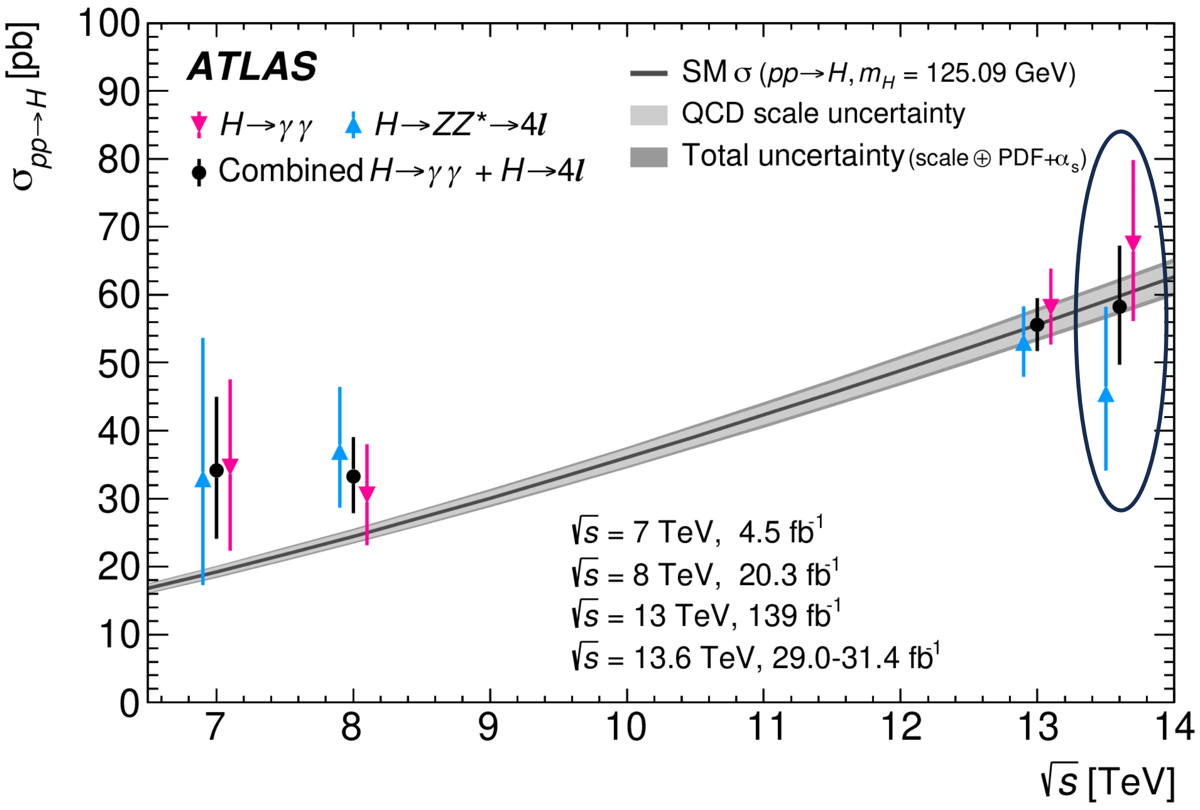
https://www.science.org/doi/10.1126/science.abk1781

The Higgs Boson

Intense efforts to asses its properties with high precision



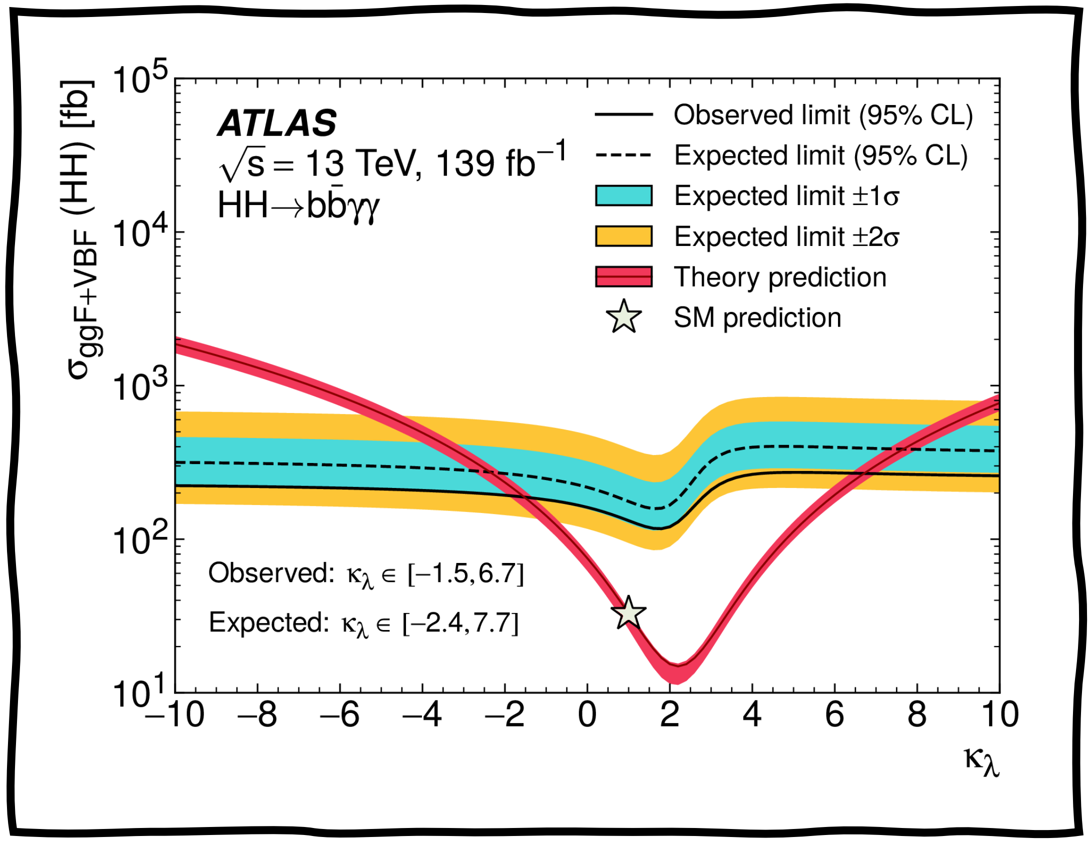
Mass

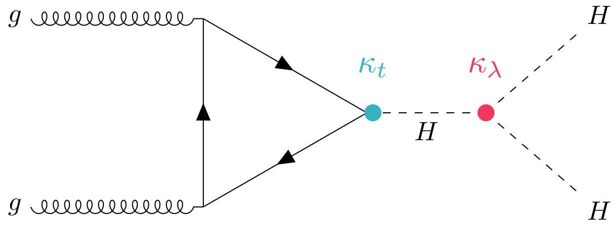


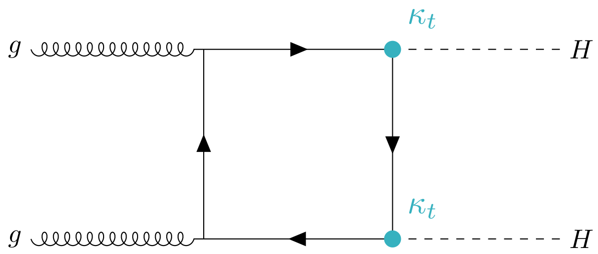
Production cross-section

Higgs searches: Processes not yet observed

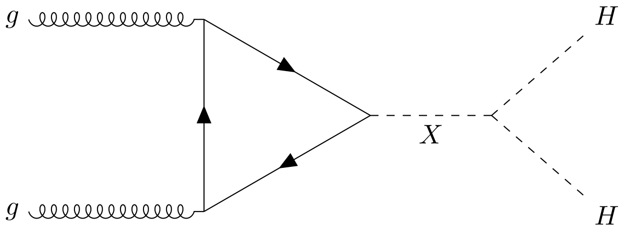
- There are still SM processes that have not been observed
  - Eg. HH production
  - We don't know if it occurs in rates as the SM predicts







Sensitivity to new physics!

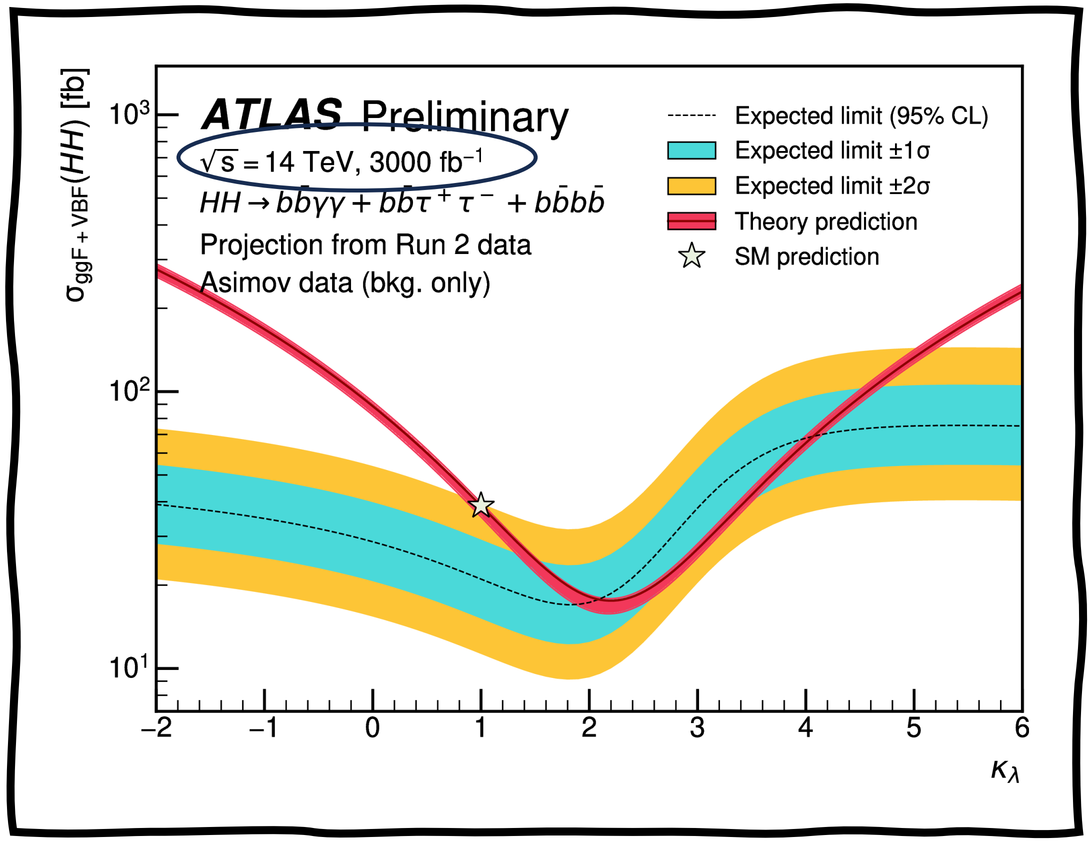


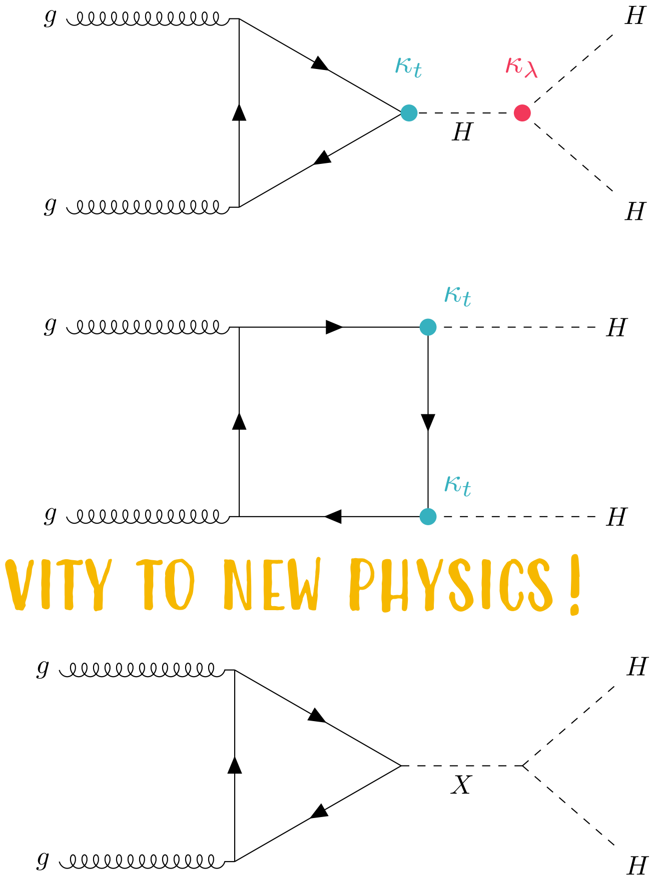
Recent HH->bbγγ results

Higgs searches: Processes not yet observed

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

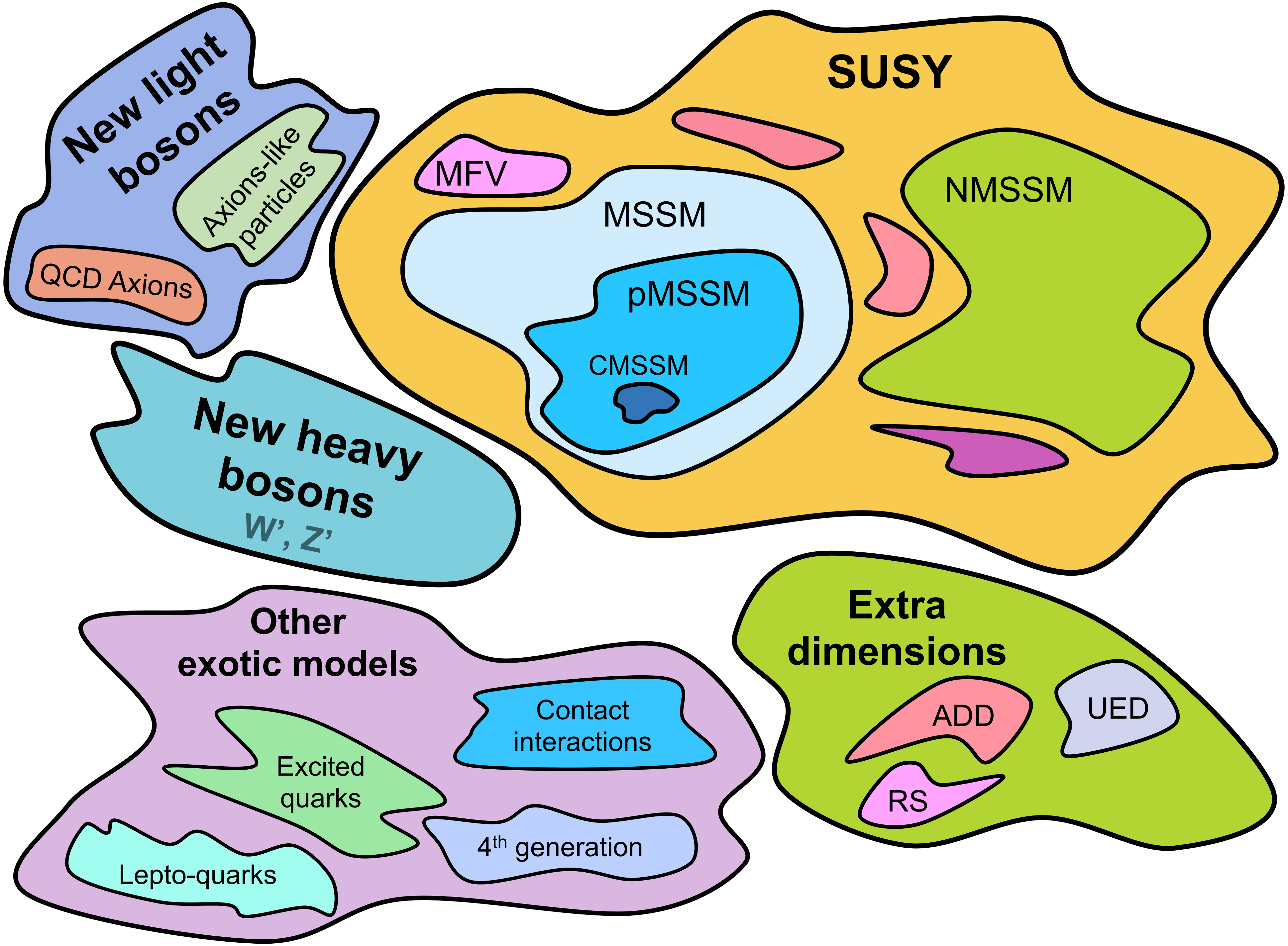
- There are still SM processes that have not been observed
  - Eg. HH production
  - We don't know if it occurs in rates as the SM predicts



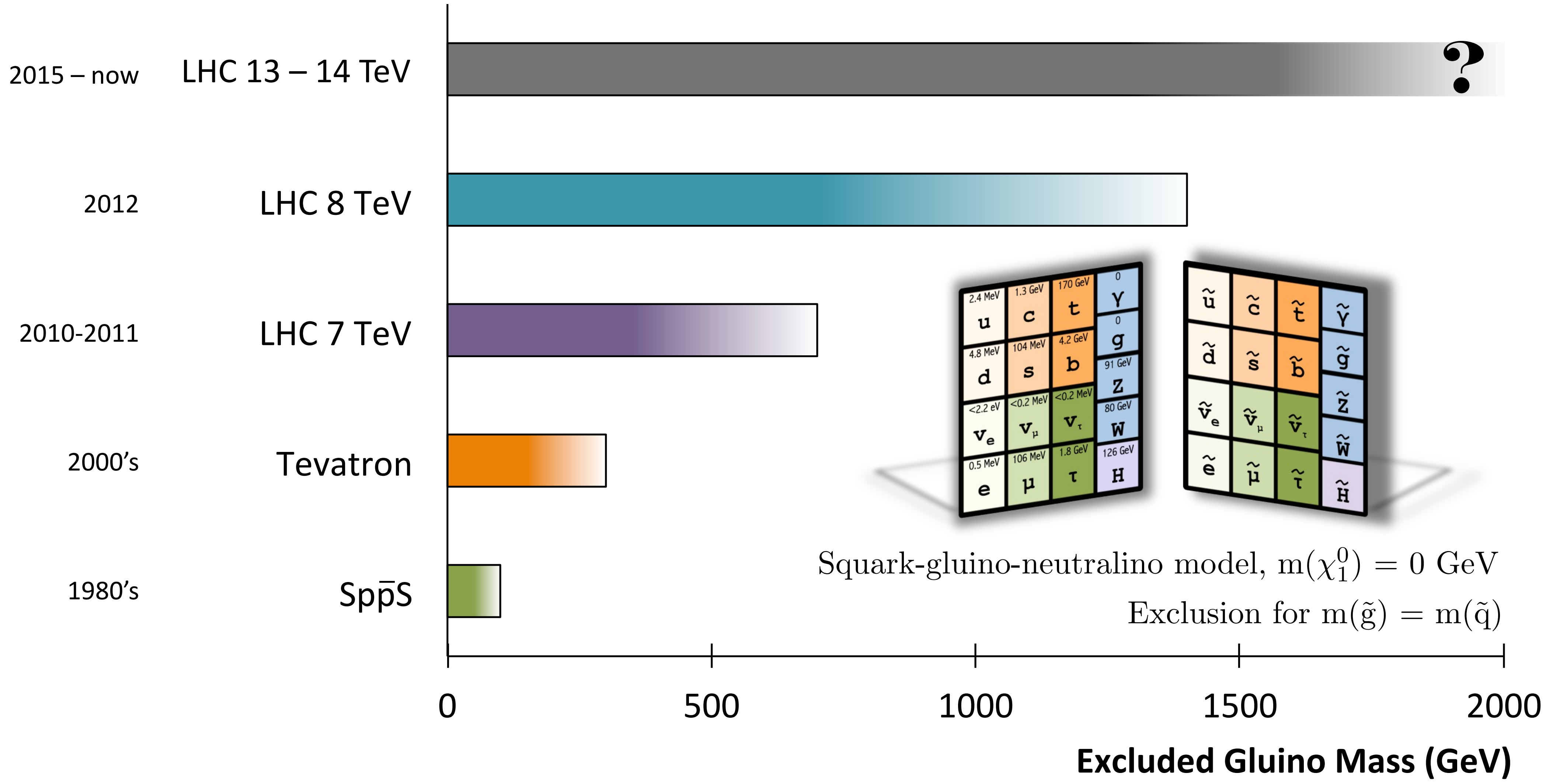


Sensitivity to new physics!

Projection to HL-LHC data set

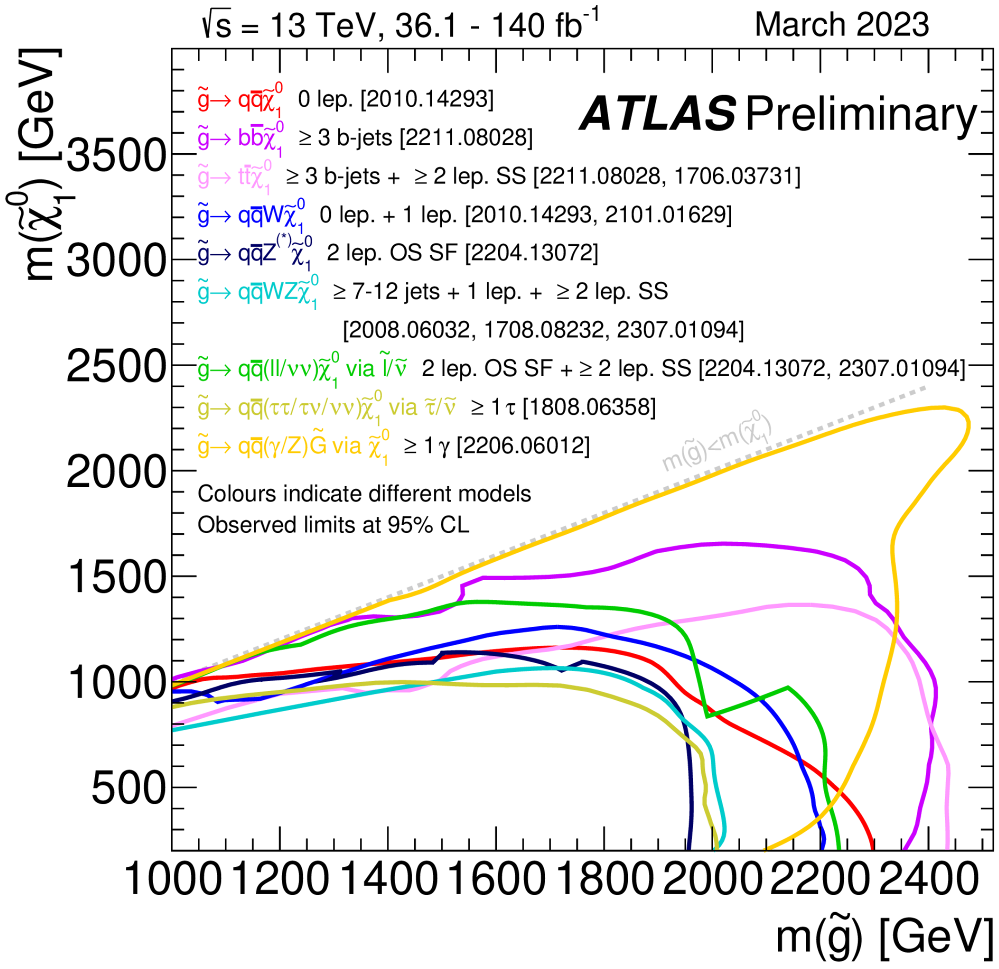


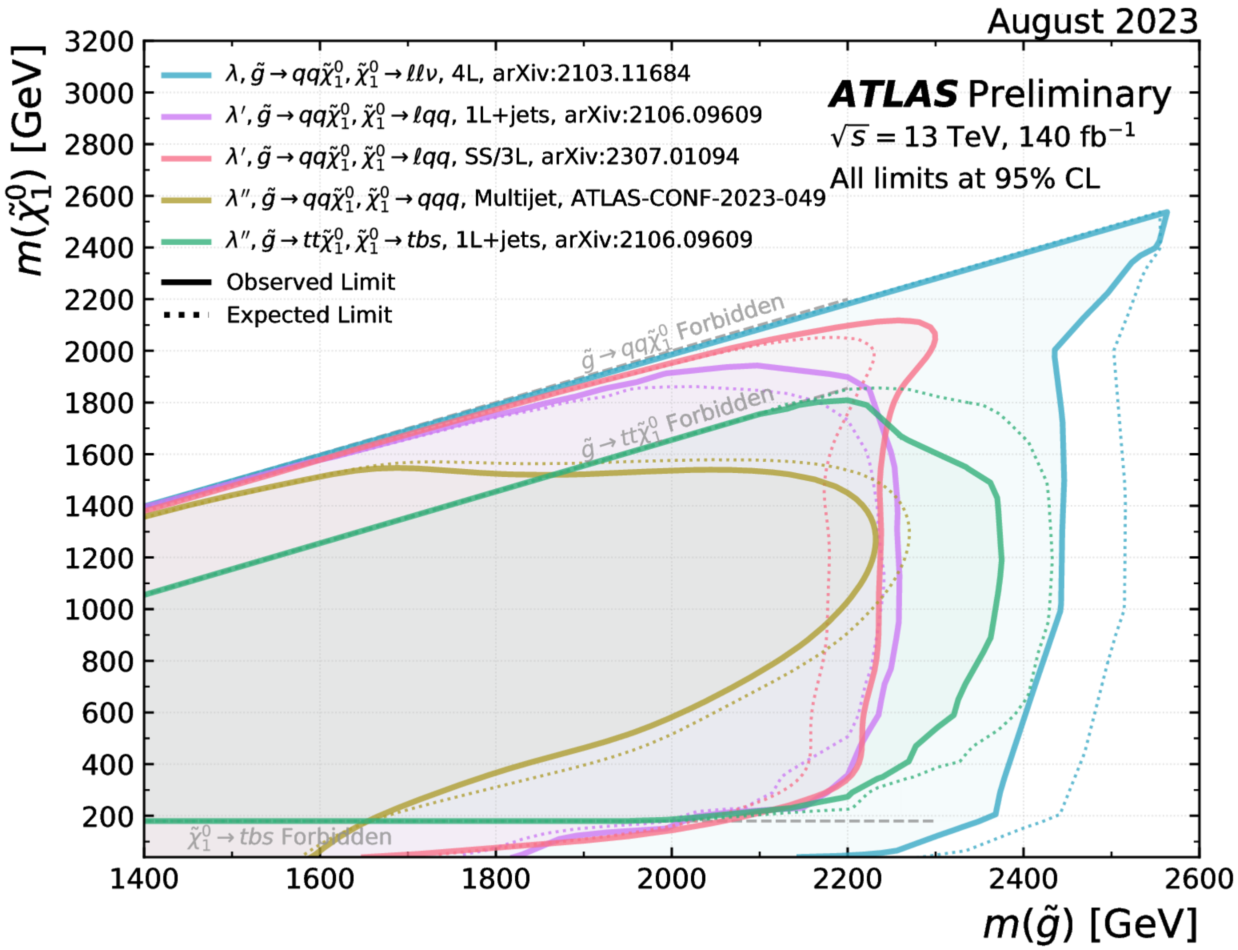
New light bosons
Axions-like particles
QCD Axions
SUSY
MFV
MSSM
pMSSM
CMSSM
NMSSM
New heavy bosons
W', Z'
Other exotic models
Contact interactions
Excited quarks
4th generation
Lepto-quarks
Extra dimensions
ADD
UED
RS



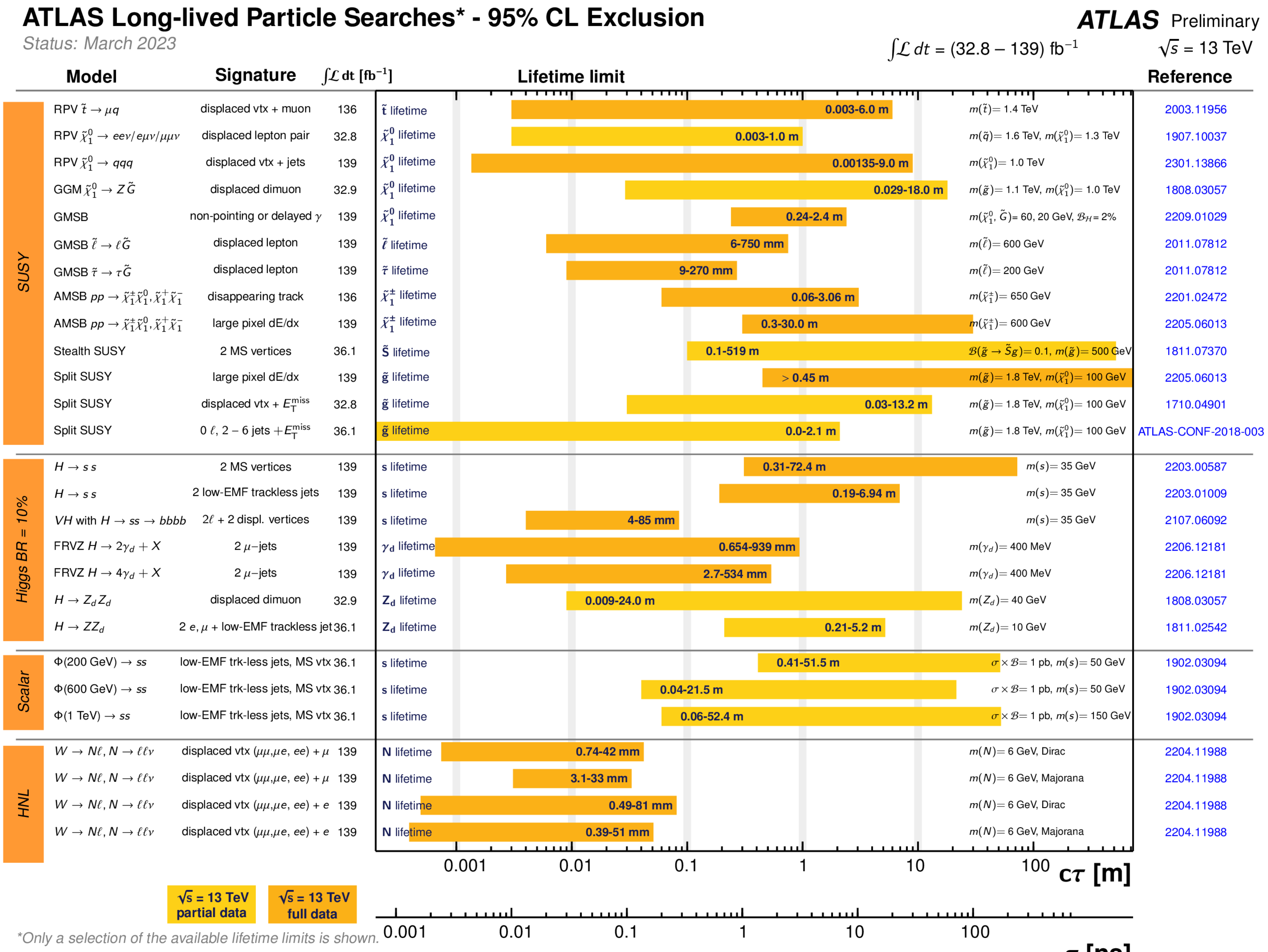
2015 – now
LHC 13 – 14 TeV
?
2012
LHC 8 TeV
2010-2011
LHC 7 TeV
2000's
Tevatron
1980's
Sp$\bar{p}$S
Squark-gluino-neutralino model, $m(\chi_1^0) = 0$ GeV
Exclusion for $m(\tilde{g}) = m(\tilde{q})$
0
500
1000
1500
2000
Excluded Gluino Mass (GeV)

SUSY searches: a plethora of results





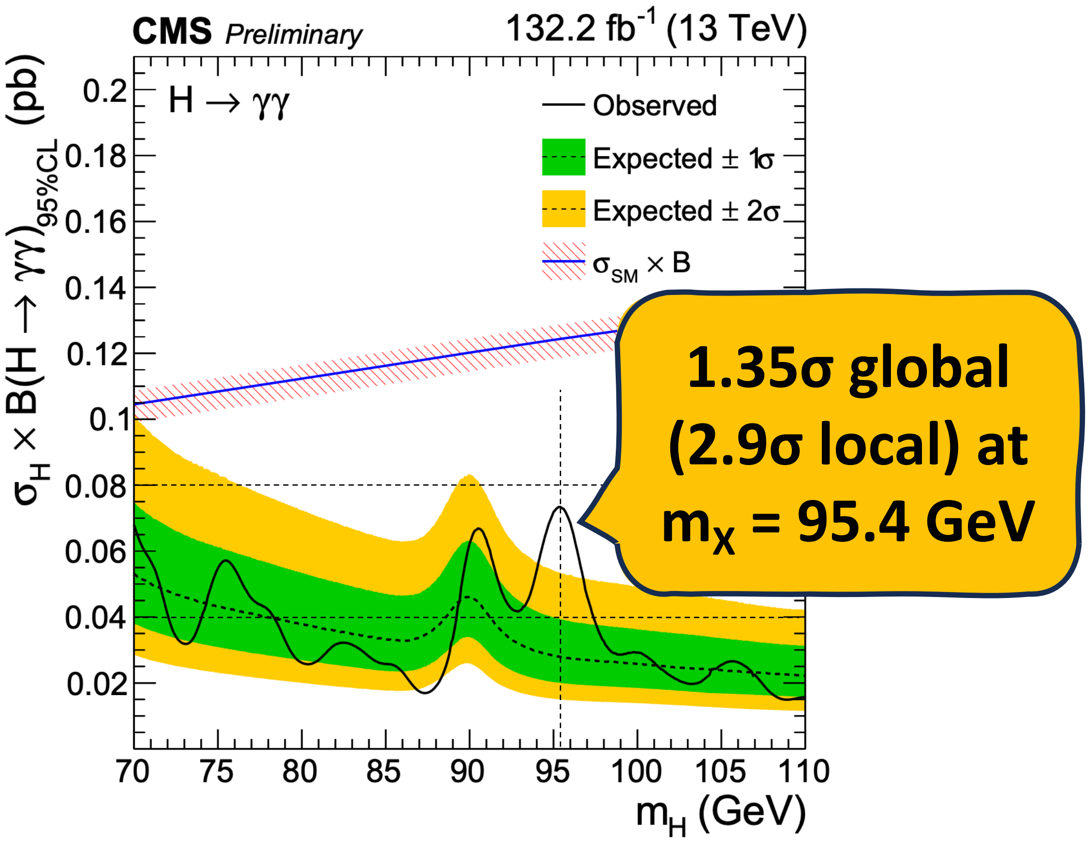
Many other searches...

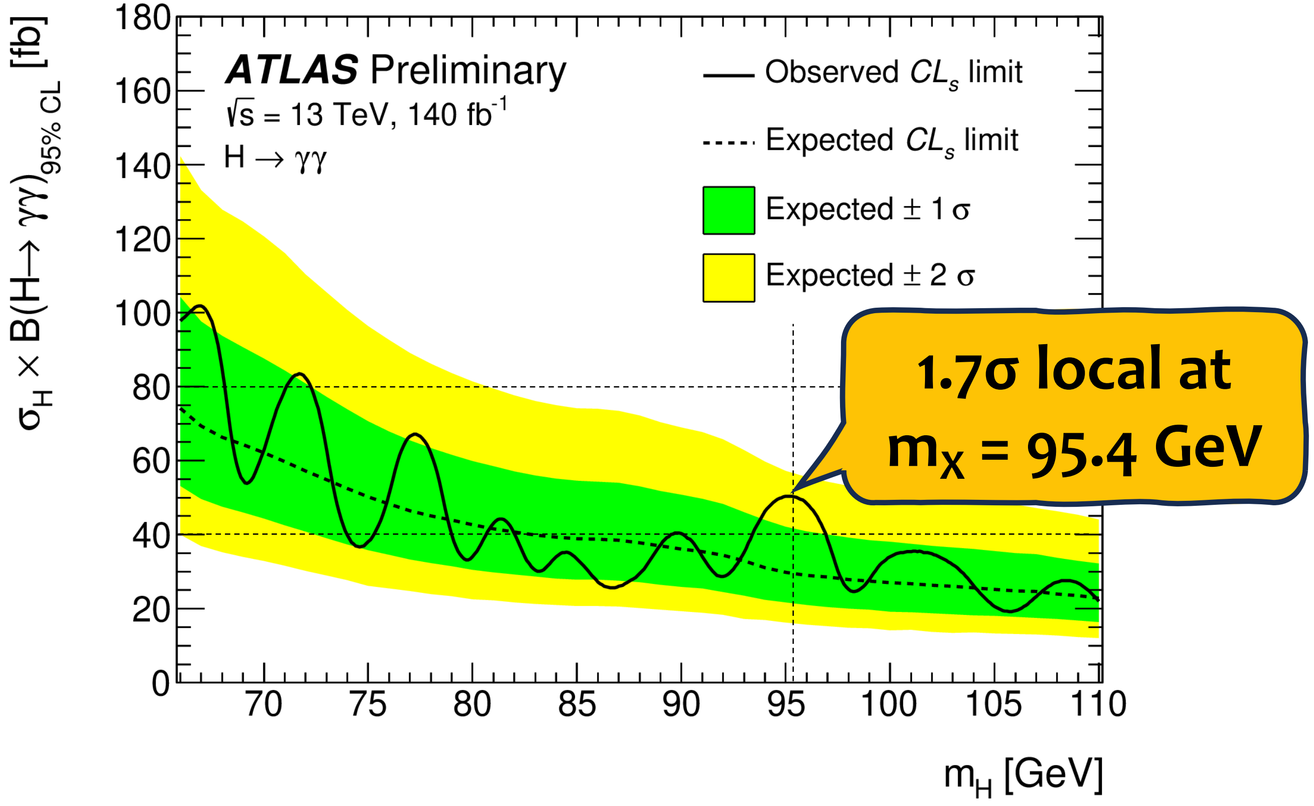


Tantalising Results

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

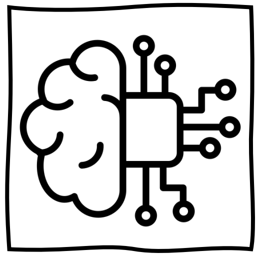
For example, in Higgs-like di-photon signatures

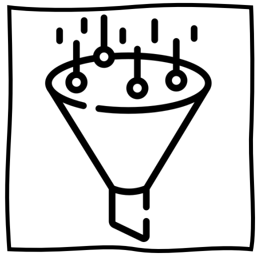


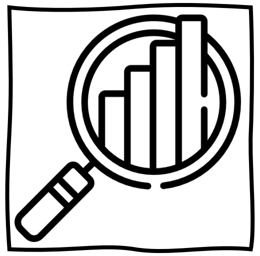


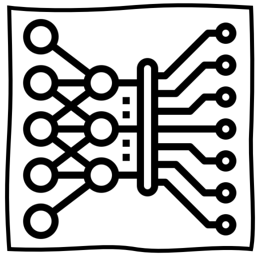
Only more data will tell if only stat fluctuation, or something exciting!

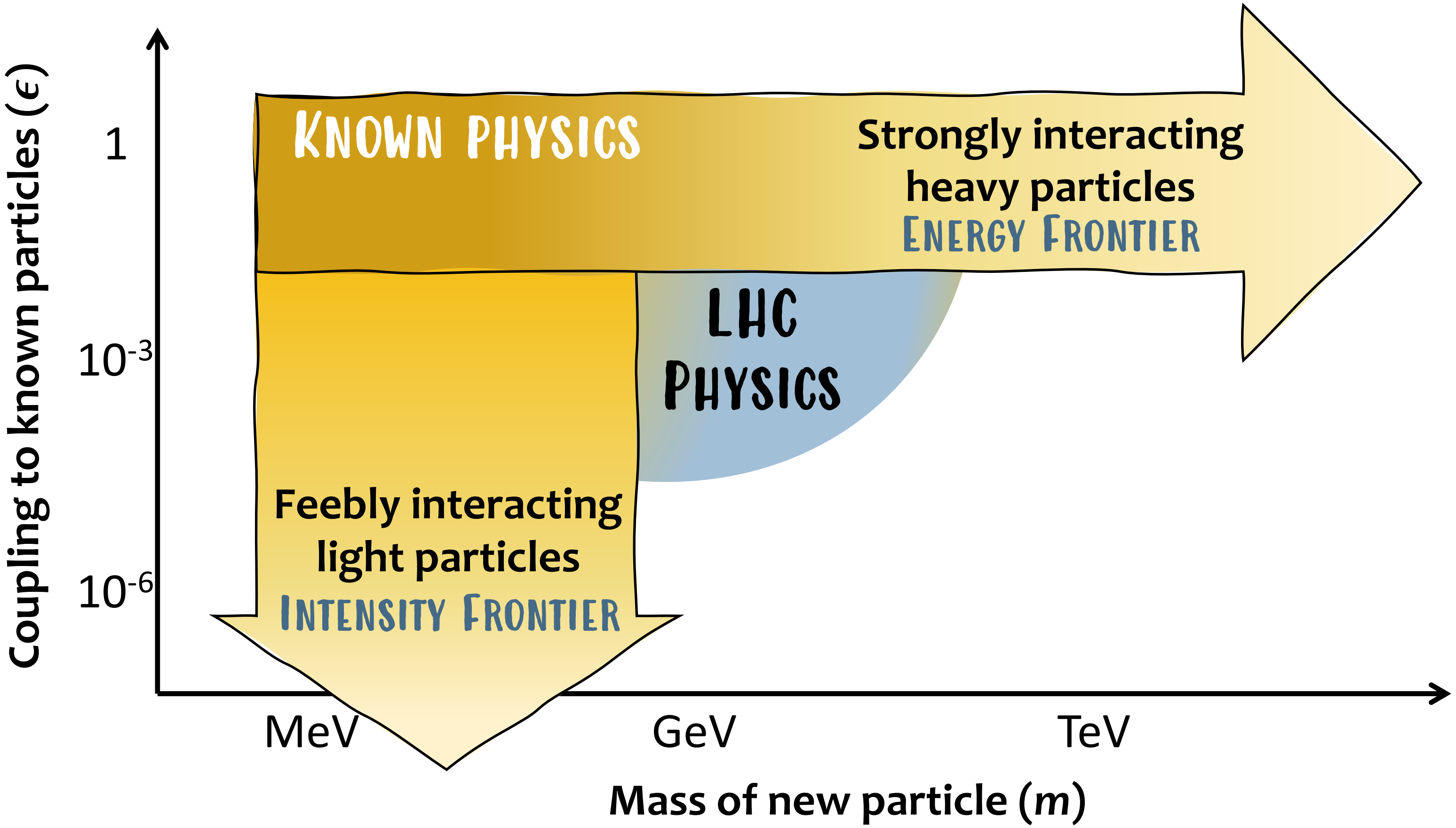
(remember: early Run2 750 GeV di-photon saga)



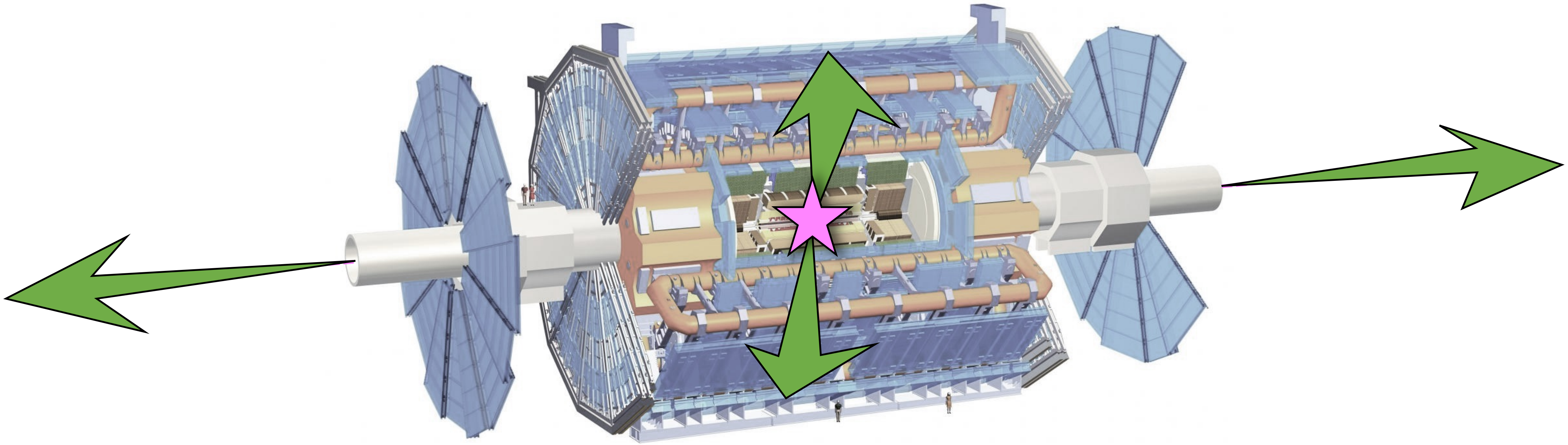




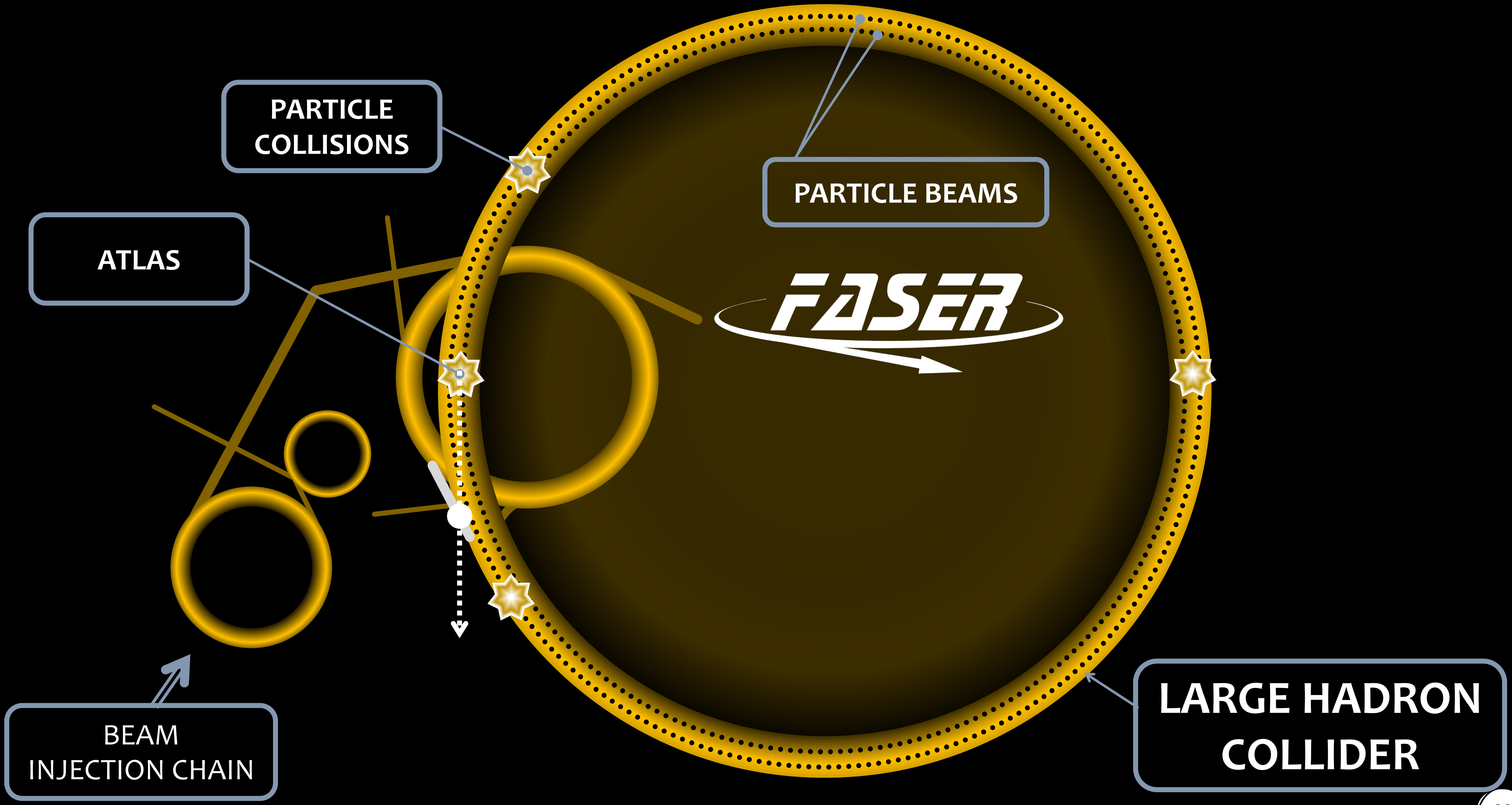




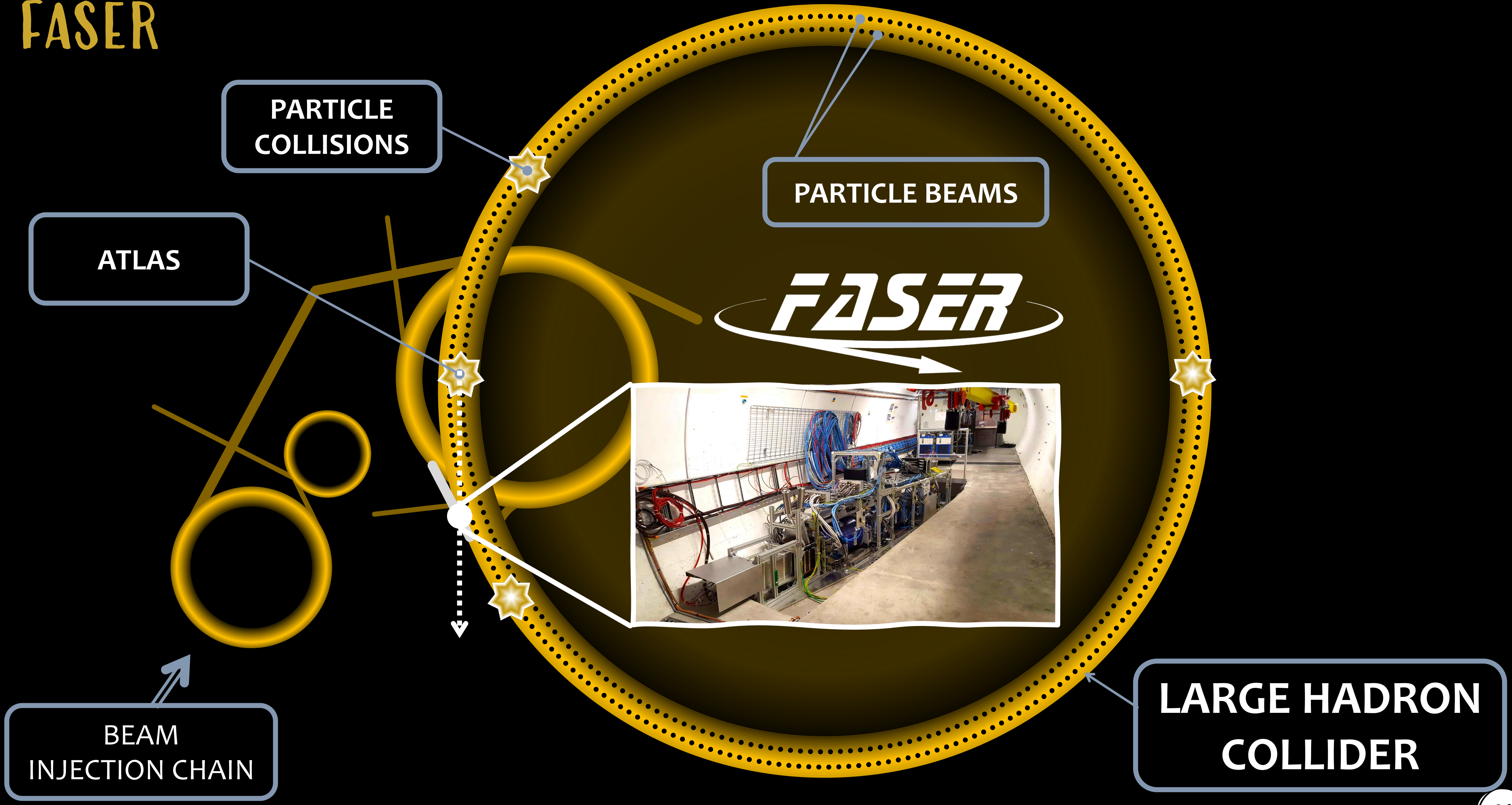
- Improve instrumentation / diversify experimental methods
- Get more data
- Look at higher energies



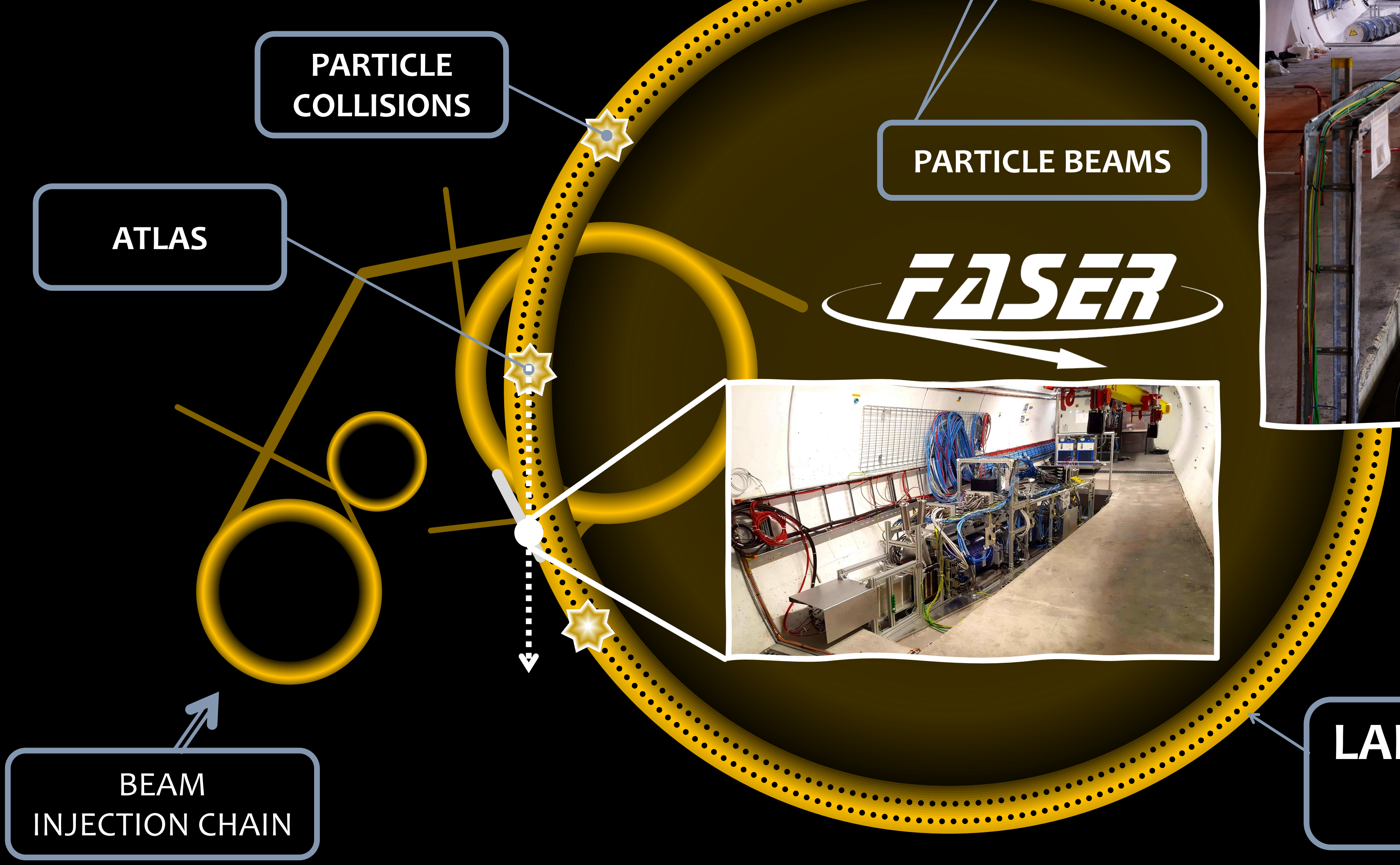
Very Forward experiments at the LHC


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

FASER


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

FASER



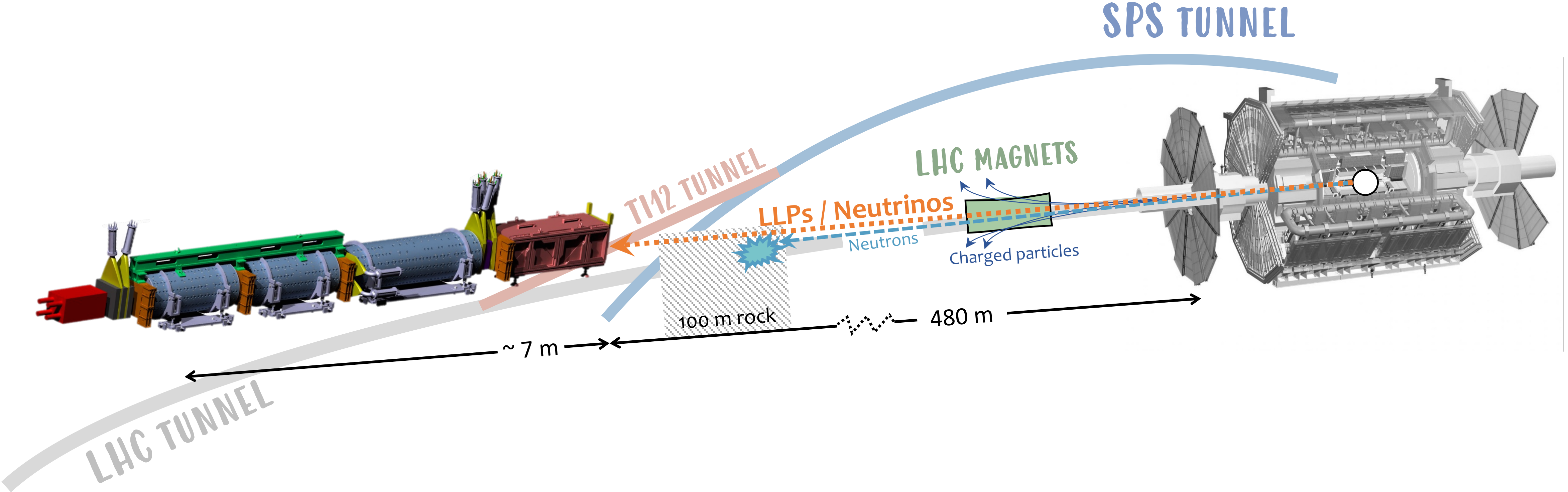
ETH zürich
UNIVERSITÄT BERN
UNIVERSITÉ DE GENÈVE

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

FASER

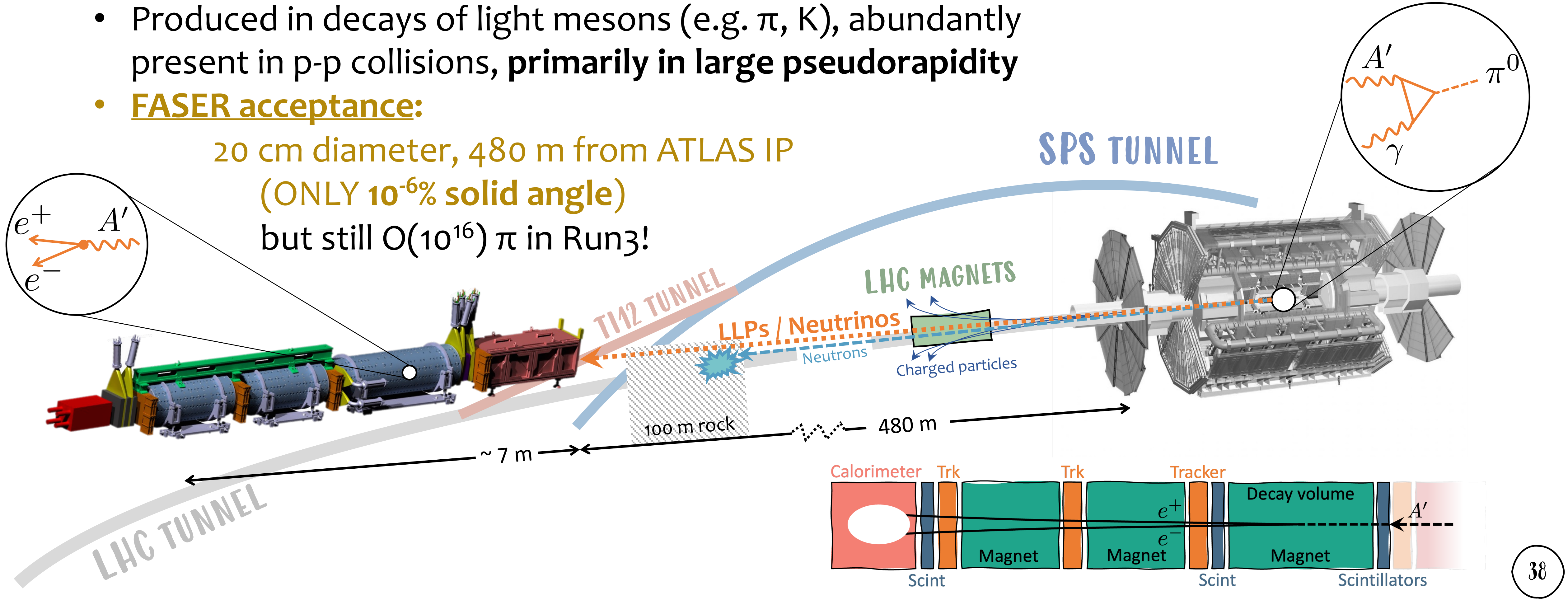
Primary goal: Searches for new weakly interacting light particles, coupling to SM via mixing with SM “portal” operator

- Produced in decays of light mesons (e.g. π, K), abundantly present in p-p collisions, **primarily in large pseudorapidity**
- <u>**FASER acceptance**</u>:

  20 cm diameter, 480 m from ATLAS IP

  (ONLY **10^{-6}% solid angle**)

  but still O(10^{16}) π in Run3!



Forward Search Experiment at the LHC

FASER

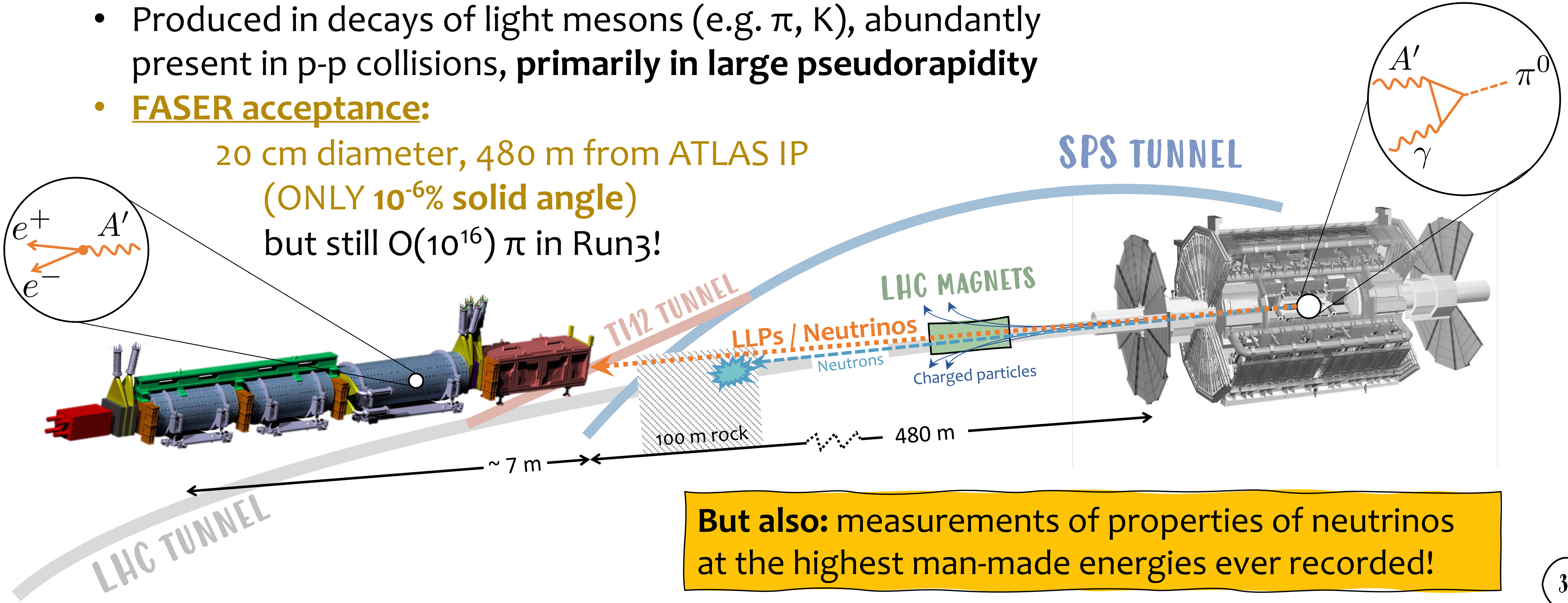
Primary goal: Searches for new weakly interacting light particles, coupling to SM via mixing with SM "portal" operator

- 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

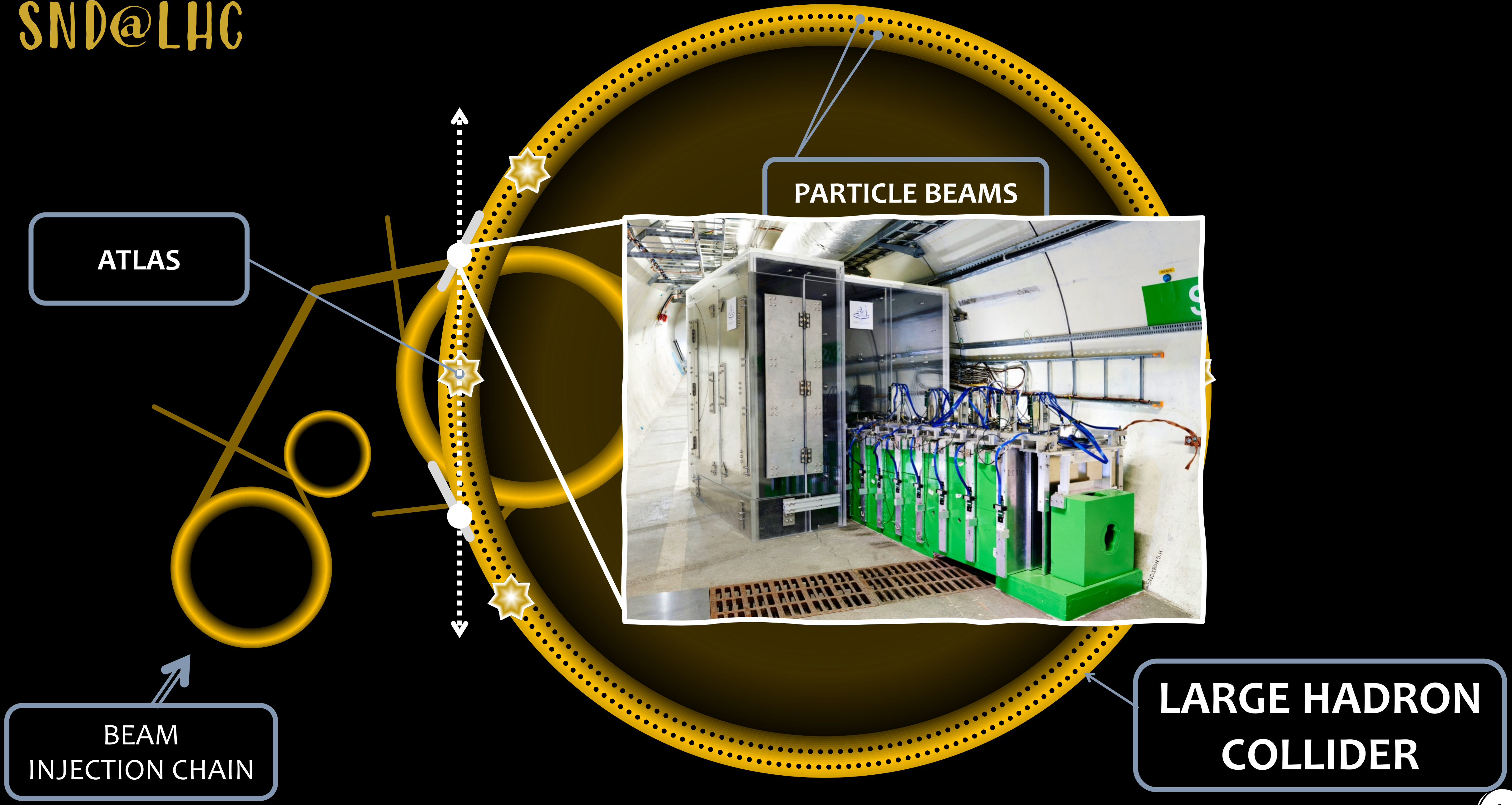
  (ONLY **10^{-6}% solid angle**)

  but still $O(10^{16})$ π in Run3!



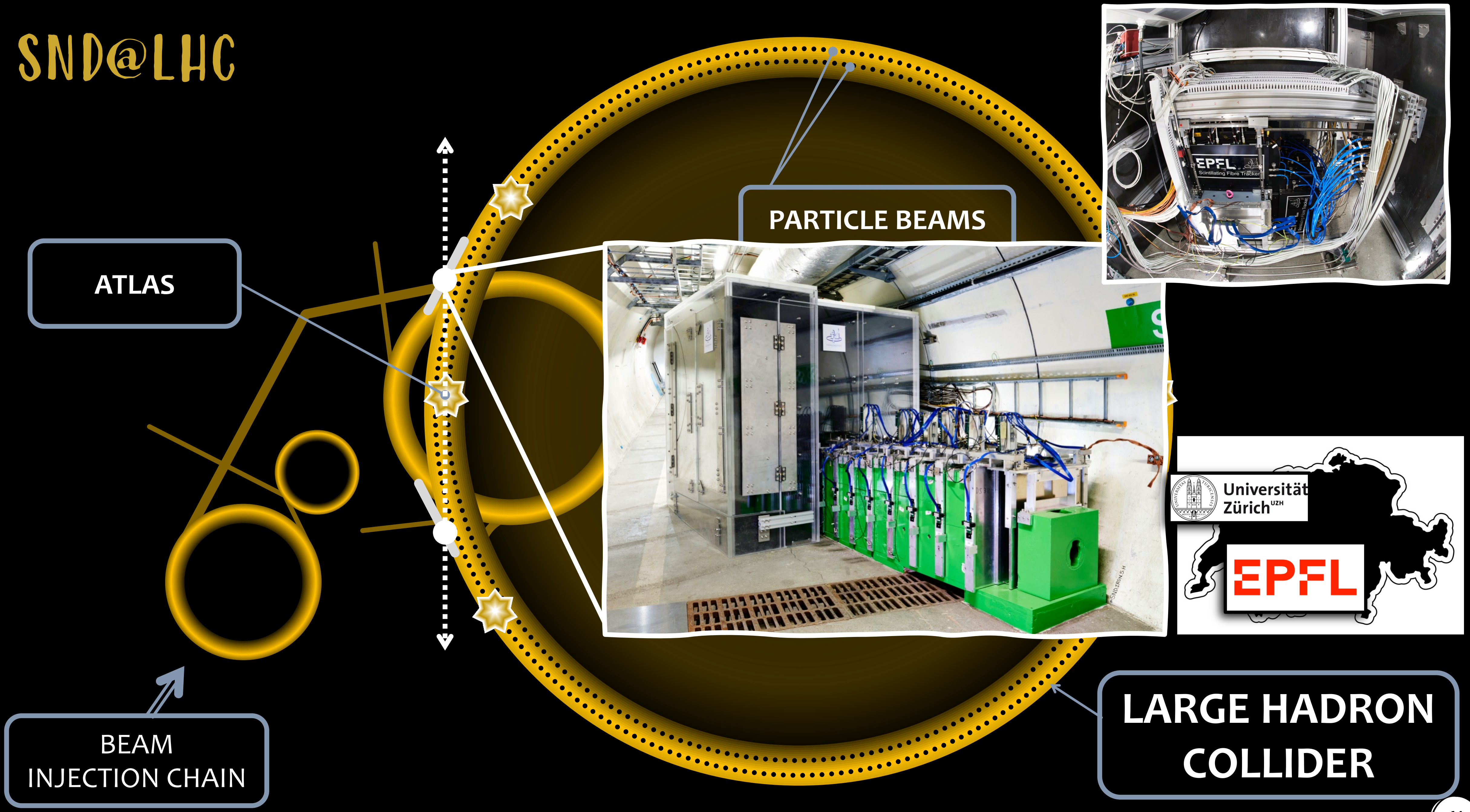
But also: measurements of properties of neutrinos at the highest man-made energies ever recorded!

SND@LHC



PARTICLE BEAMS
ATLAS
BEAM
INJECTION CHAIN
LARGE HADRON
COLLIDER

SND@LHC

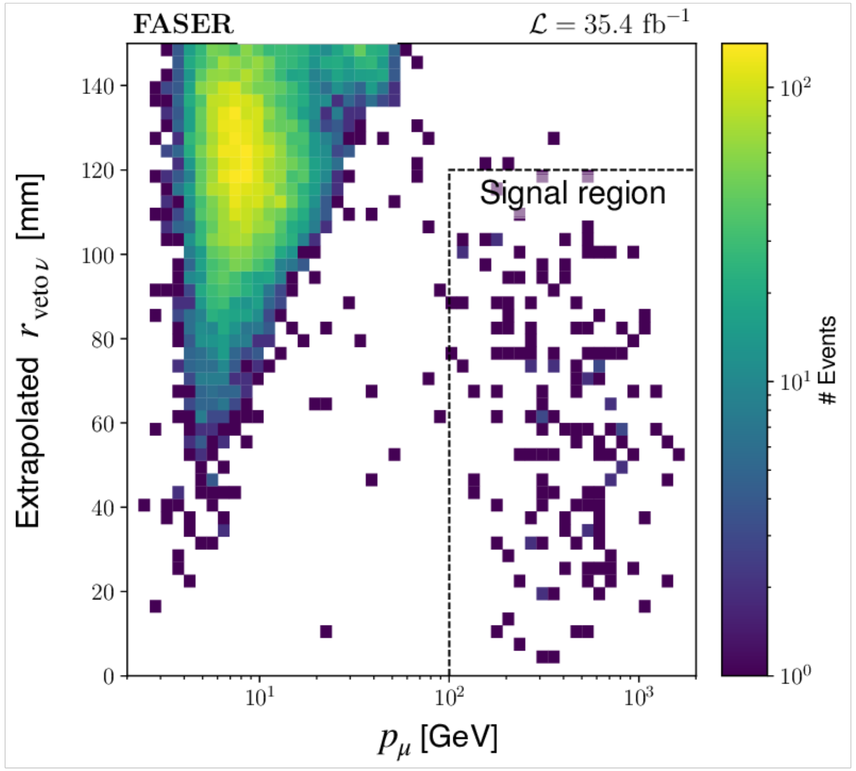

PARTICLE BEAMS
ATLAS
BEAM
INJECTION CHAIN
LARGE HADRON
COLLIDER
EPFL
Scintillating Fibre Tracker
Universität
Zürich UZH
EPFL

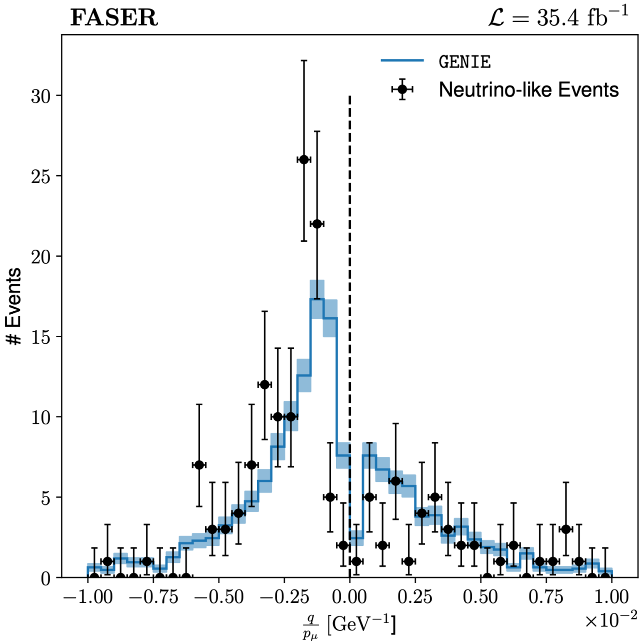
Highlights from recent results

First Direct Detection of Colliider Neutrinos

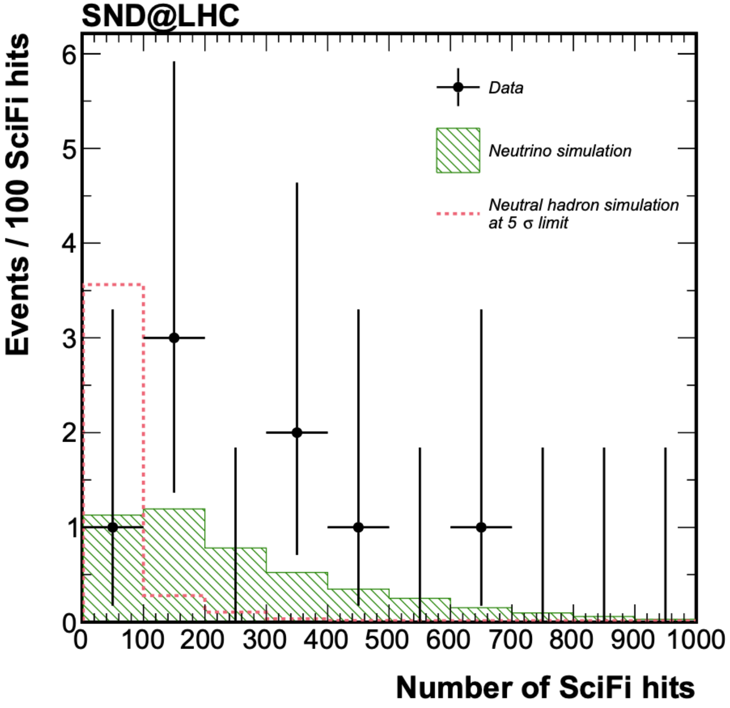
153 events ⟹ ≫ 5σ significance
Background ~ 0.2 events

8 events ⟹ > 5σ significance
Background < 0.1 events





First evaluation of properties



arXiv: 2303.14185, PRL

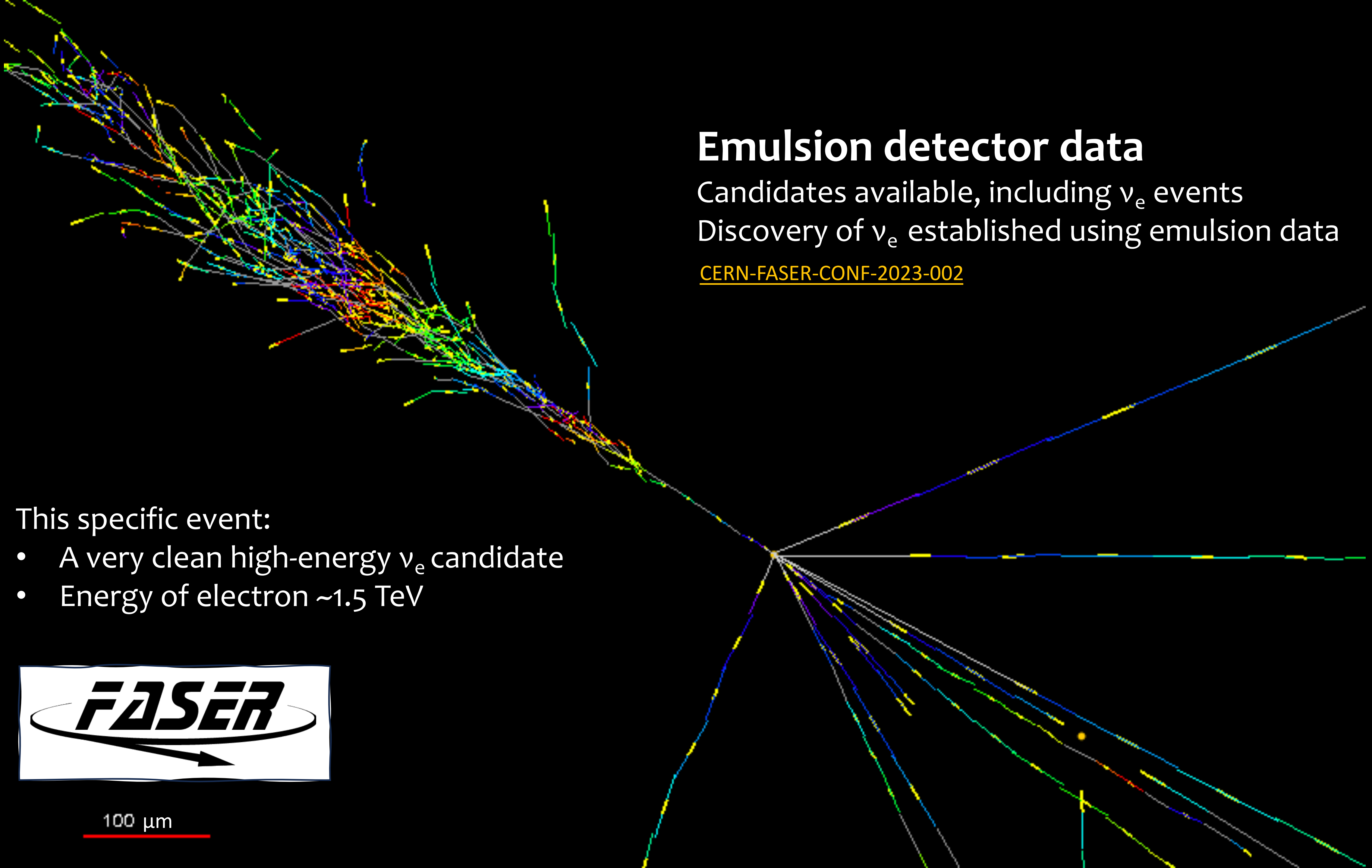
arXiv: 2305.09383, PRL

Emulsion detector data

Candidates available, including ν_e events

Discovery of ν_e established using emulsion data

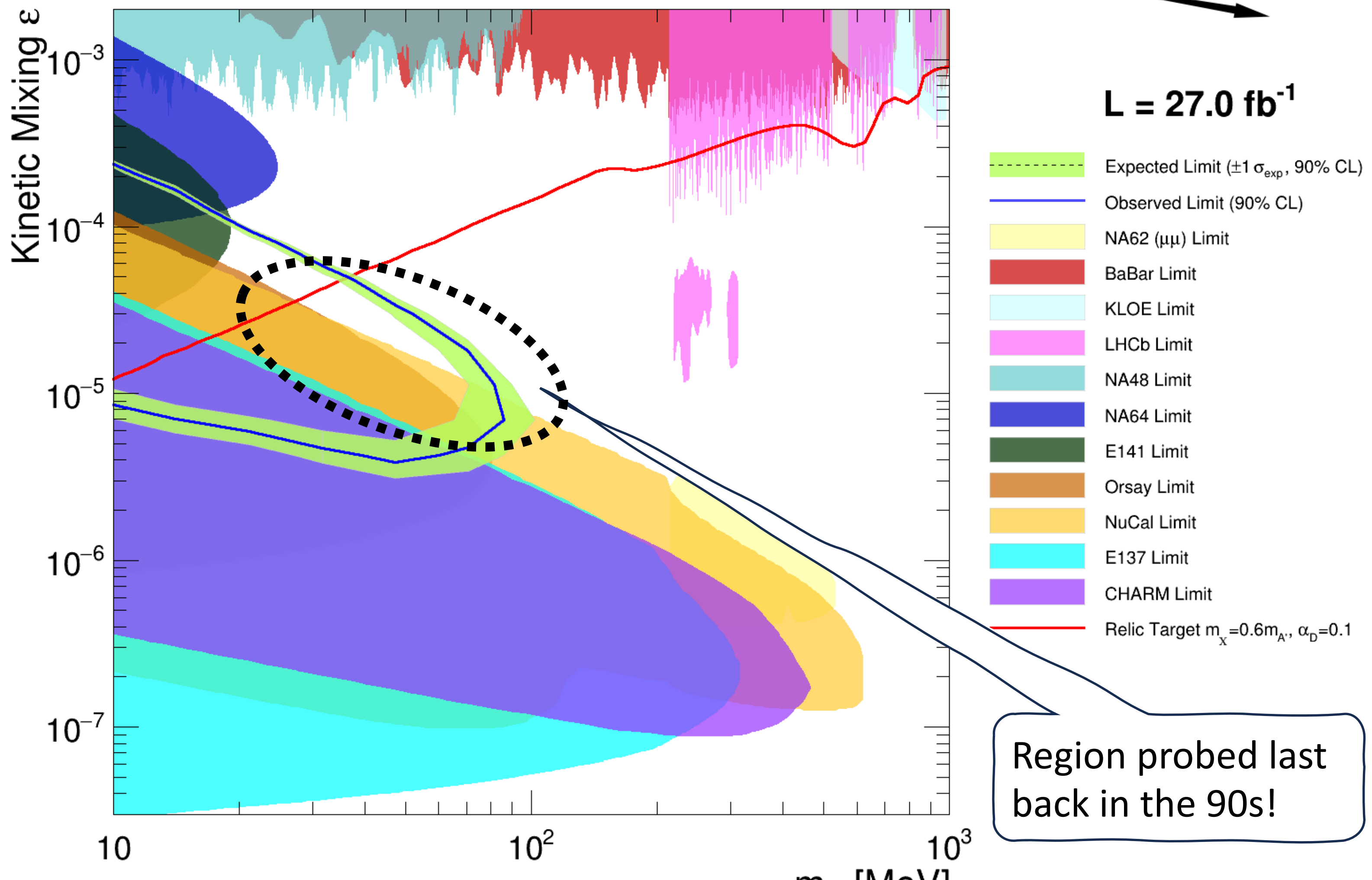
CERN-FASER-CONF-2023-002



This specific event:

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

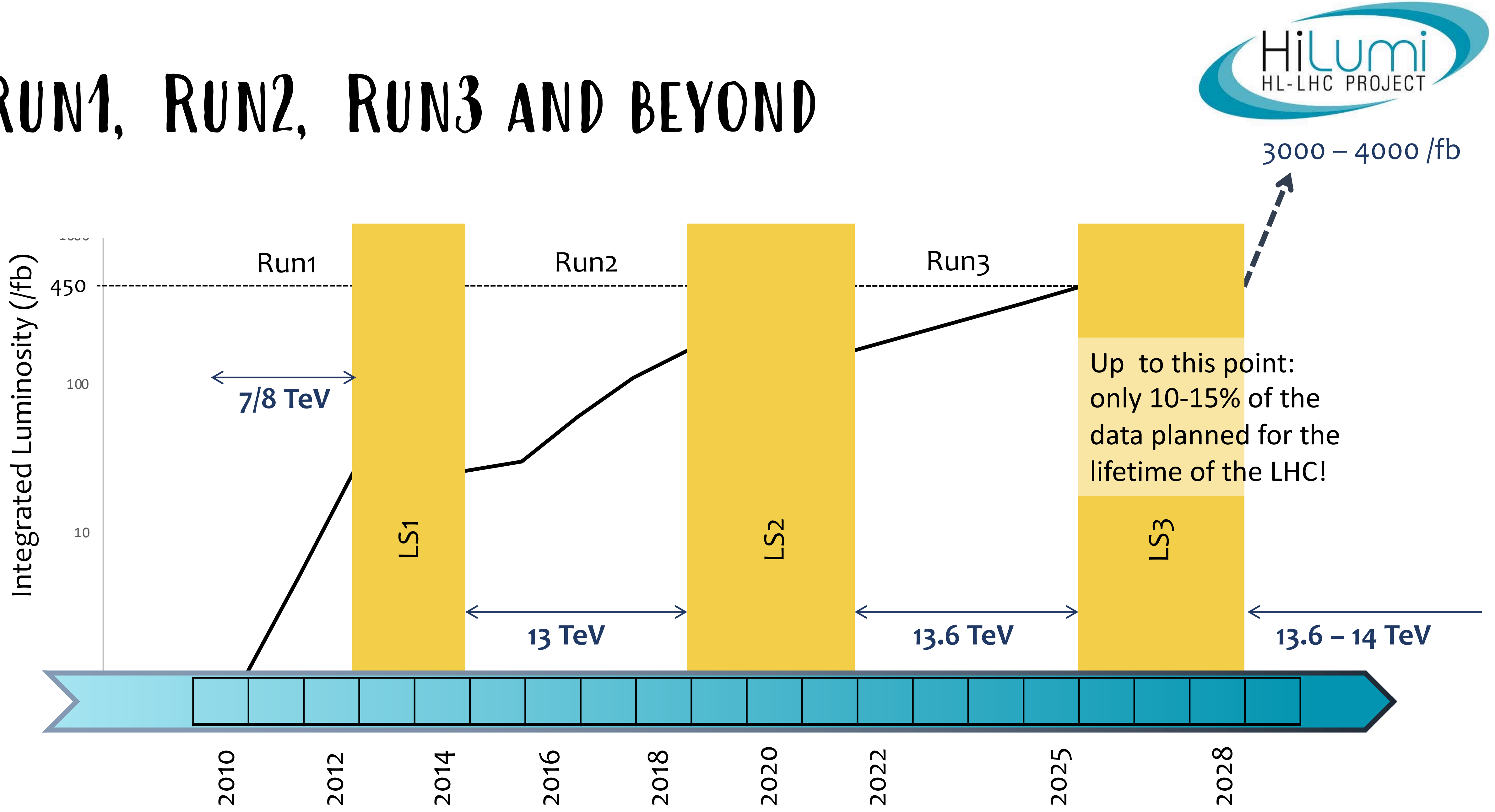
Searches for Dark Photons



arXiv:2308.05587, submitted to PLB

What's beyond LHC Run3 ?

Run1, Run2, Run3 and beyond



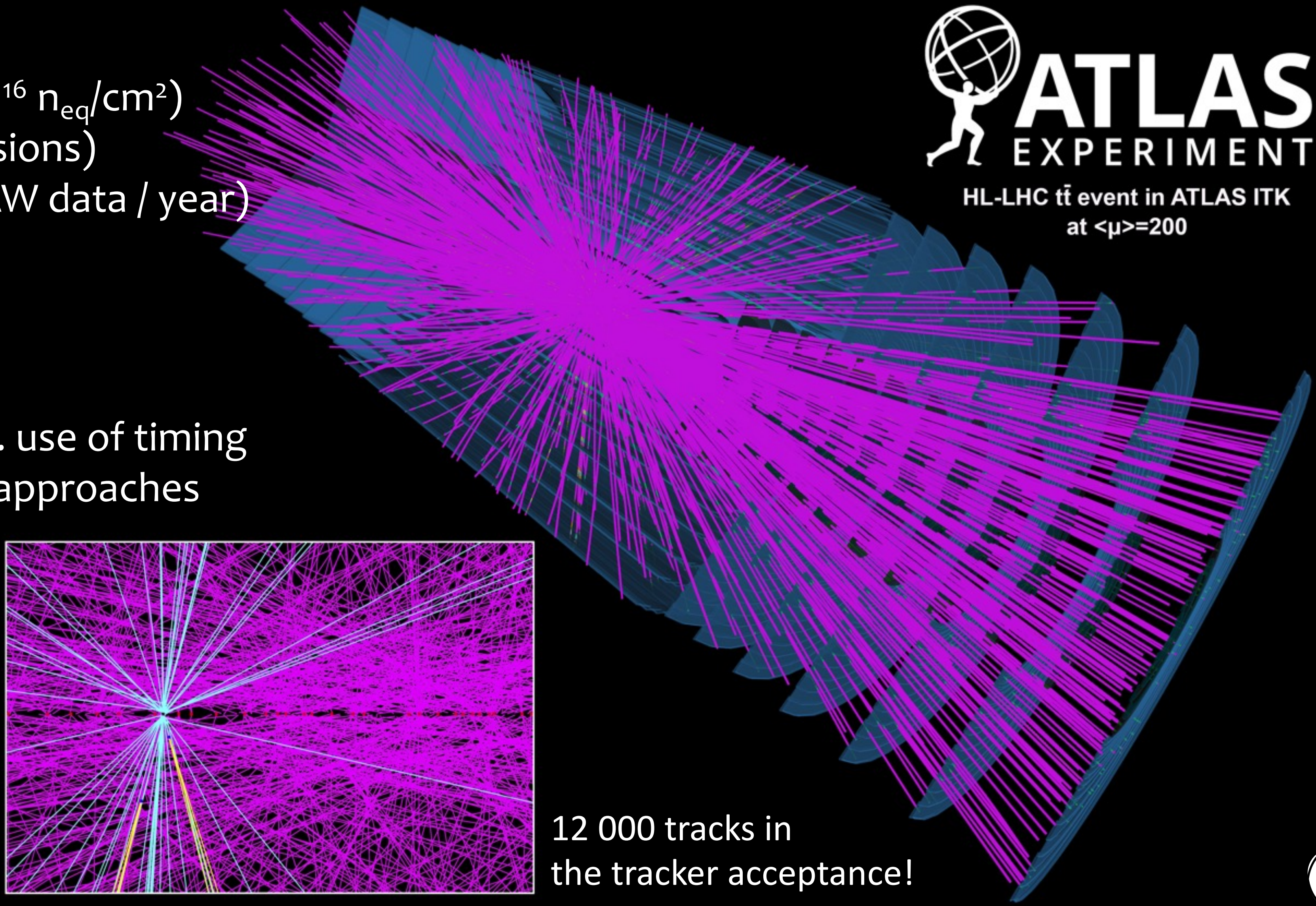
Required HL-LHC detector upgrades

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



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

12 000 tracks in
the tracker acceptance!

New (Forward) projects in the horizon

Aligned with the recommendations of recent community studies

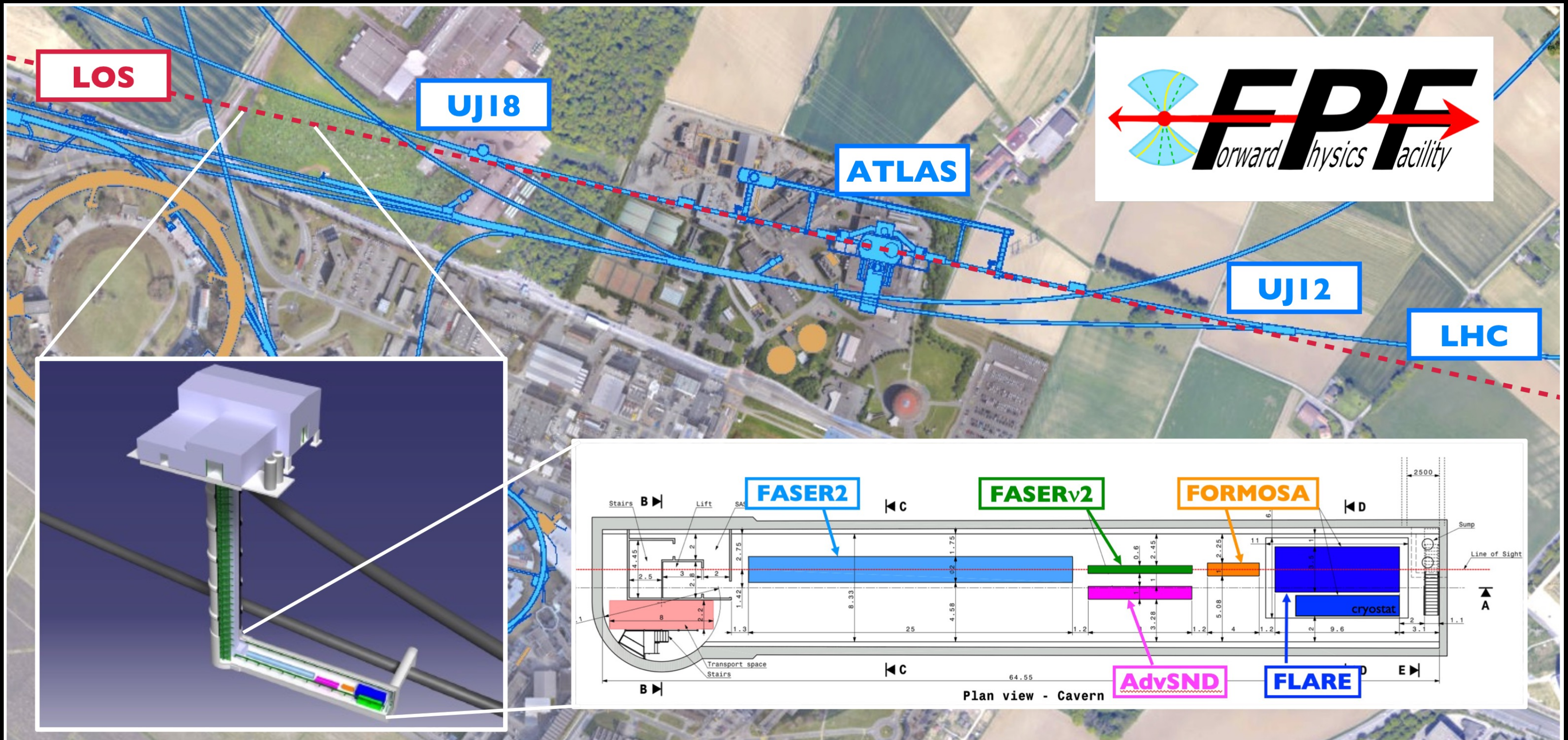
*The **full physics potential** of the LHC and the HL- LHC [...] should be exploited.*
1st recommendation of the 2020 European Strategy Update

*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

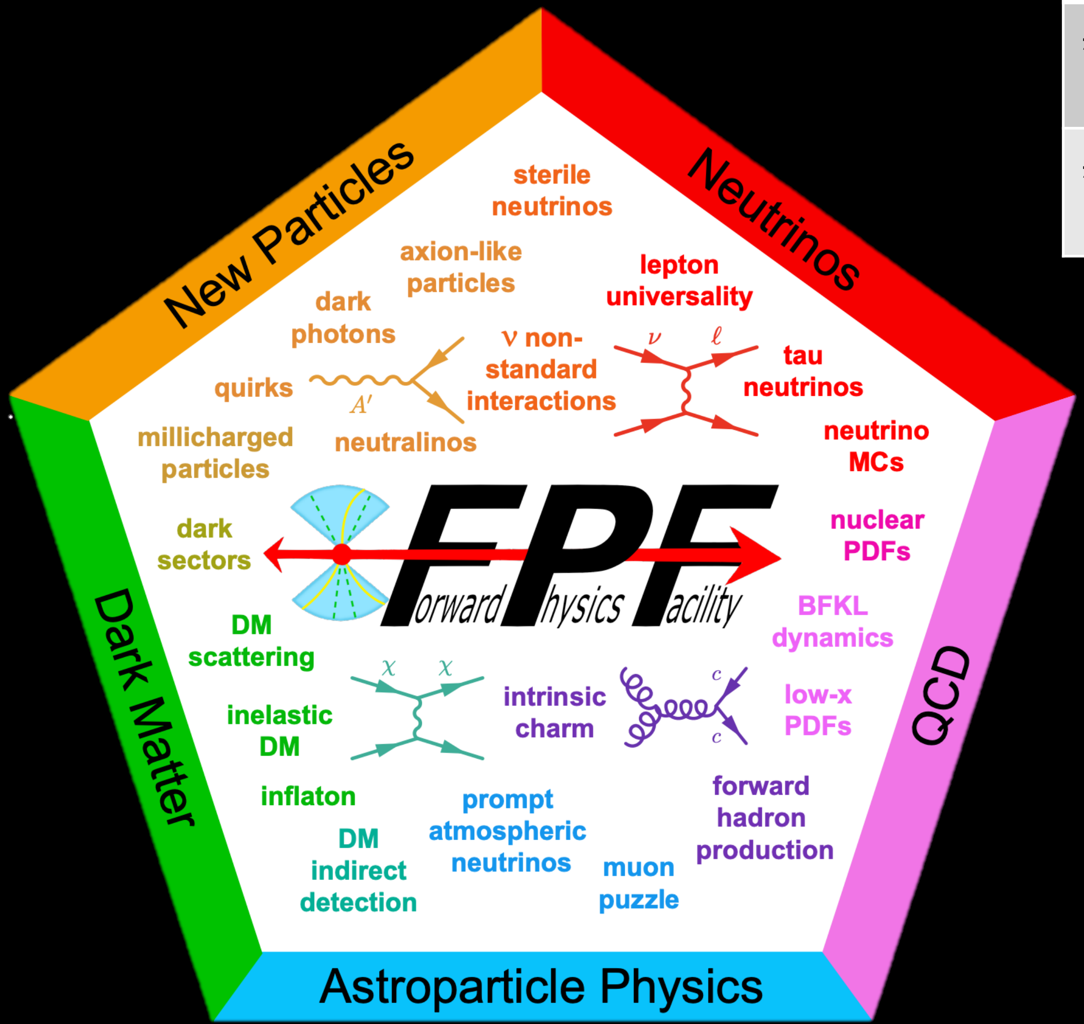


arXiv:2203.05090

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!

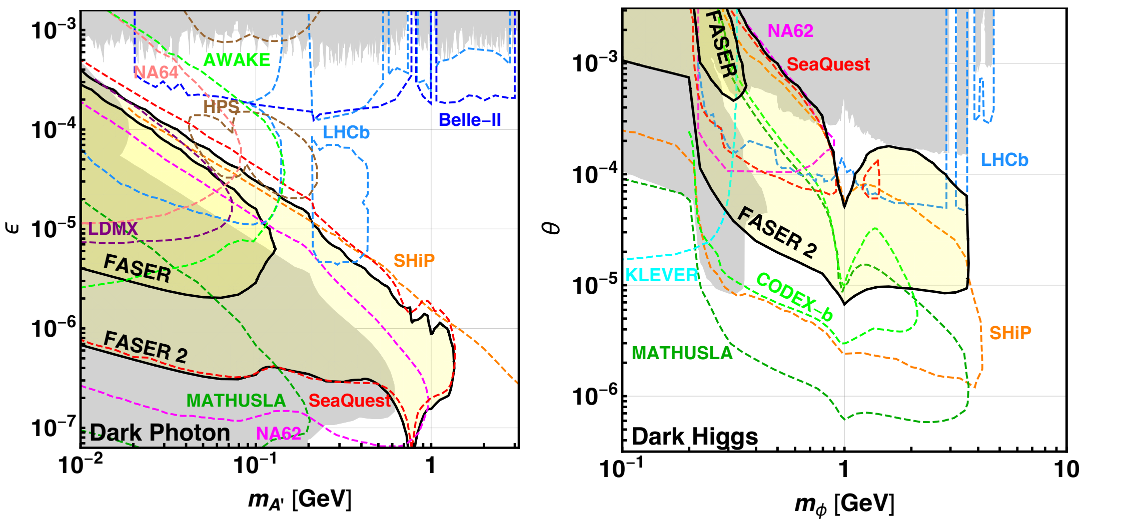
The physics programme of FPF



	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	~10^5	~10^6	**~10^4**

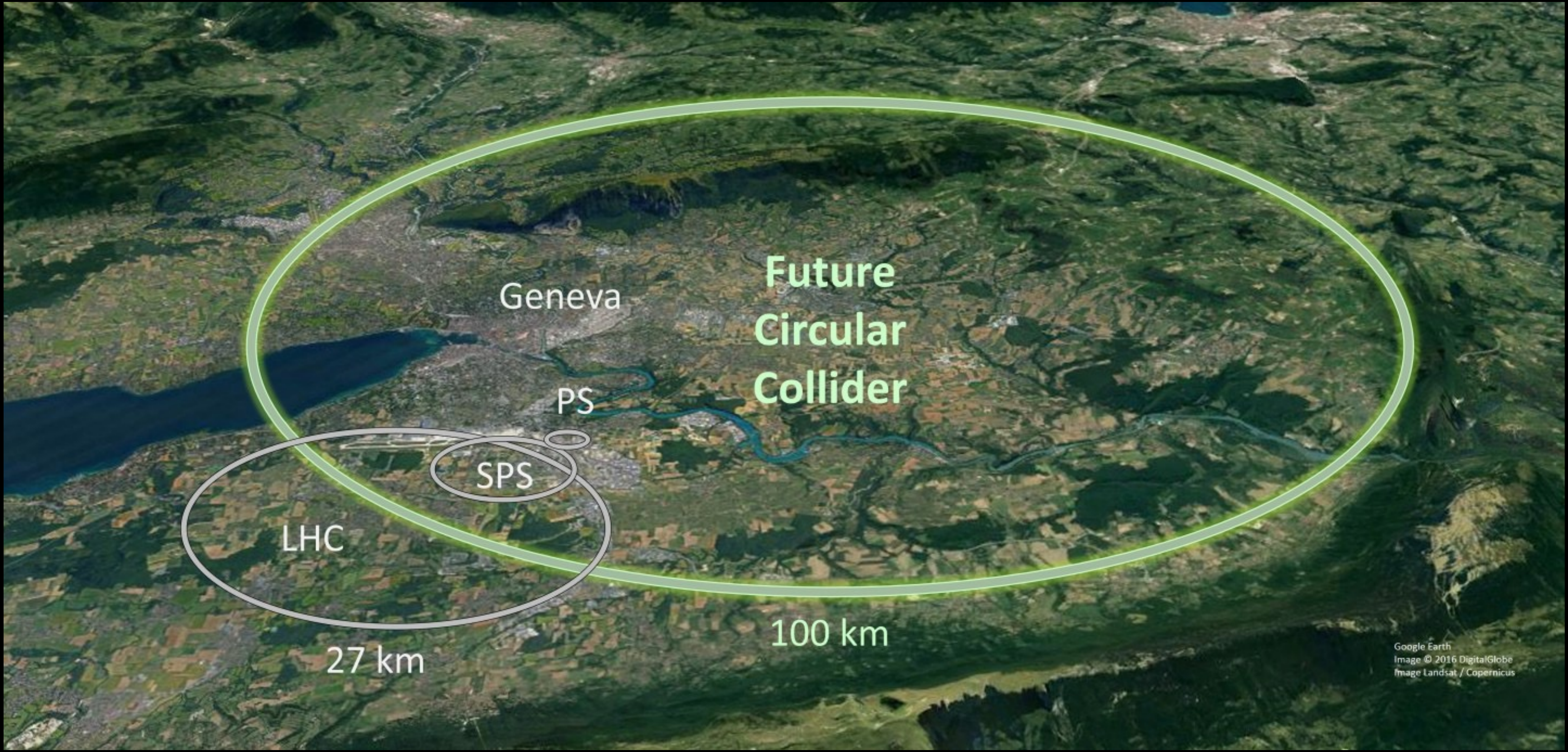
Unprecedented numbers of detectable neutrinos, at energy ranges where there is **currently no available data**!

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

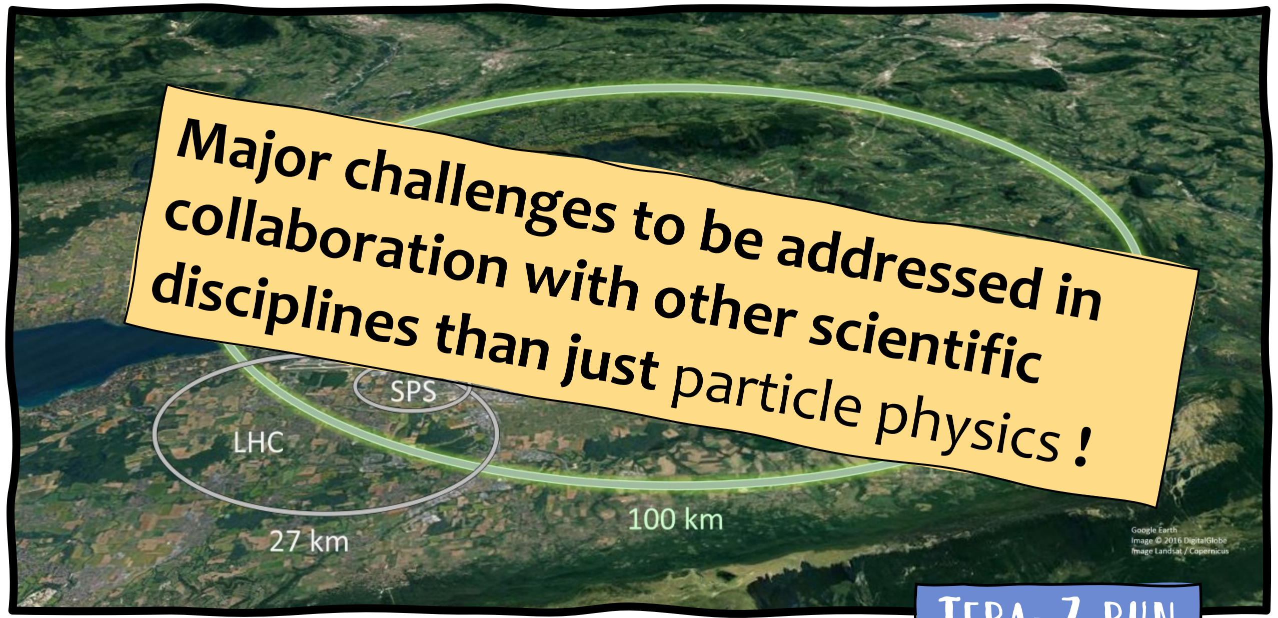
2020 European Strategy Update

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

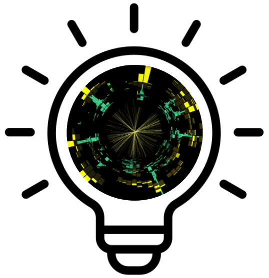
Recent review – input to Snowmass – arXiv:2203.06520

In Brief

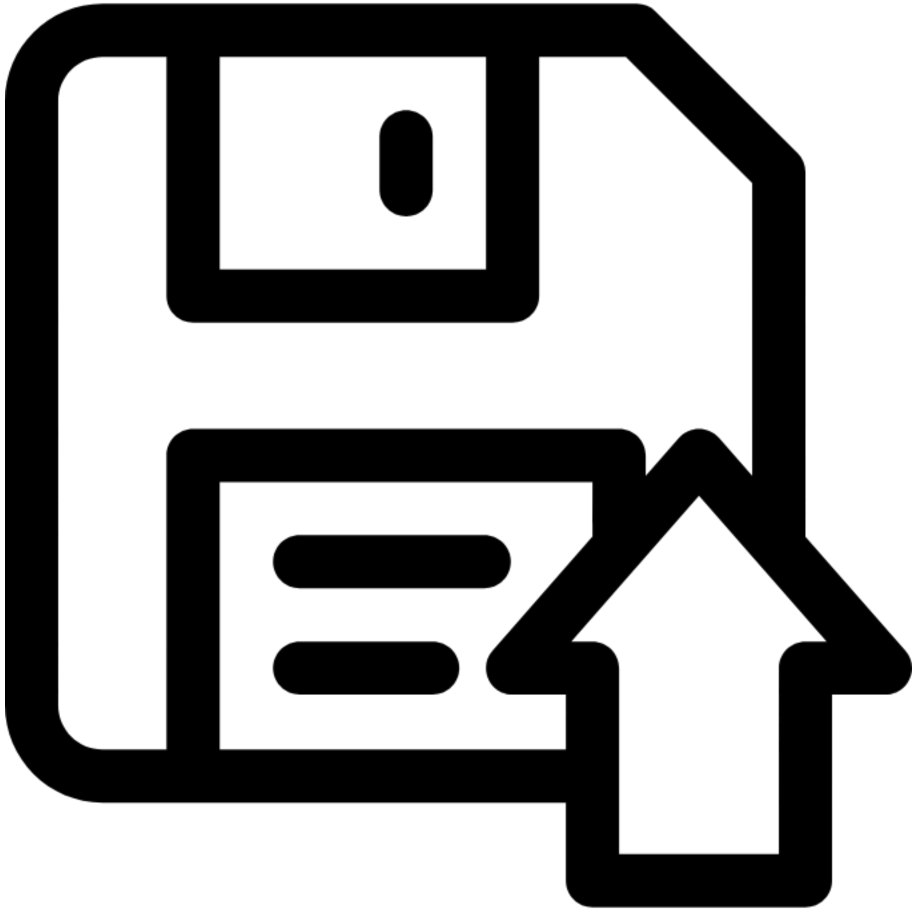
- The Standard Model, while highly accurate, leaves many fundamental questions unanswered

- The CERN Large Hadron Collider (LHC) is a powerful tool for exploring these open questions

- Particle physicists are utilizing innovative approaches to maximize the potential of the LHC



- As a community of physicists, we are both looking **forward** to the breakthroughs at the LHC and **forward**-looking in our quest to discover new physics



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	h ----- $(\mu S + \lambda S^2)H^\dagger H$ ----- S	Dark Higgs S

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

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

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

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

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

(Axion Like Particle)

SM LH ν	ν —— $y_N h L \psi_D$ —— N	HNL N

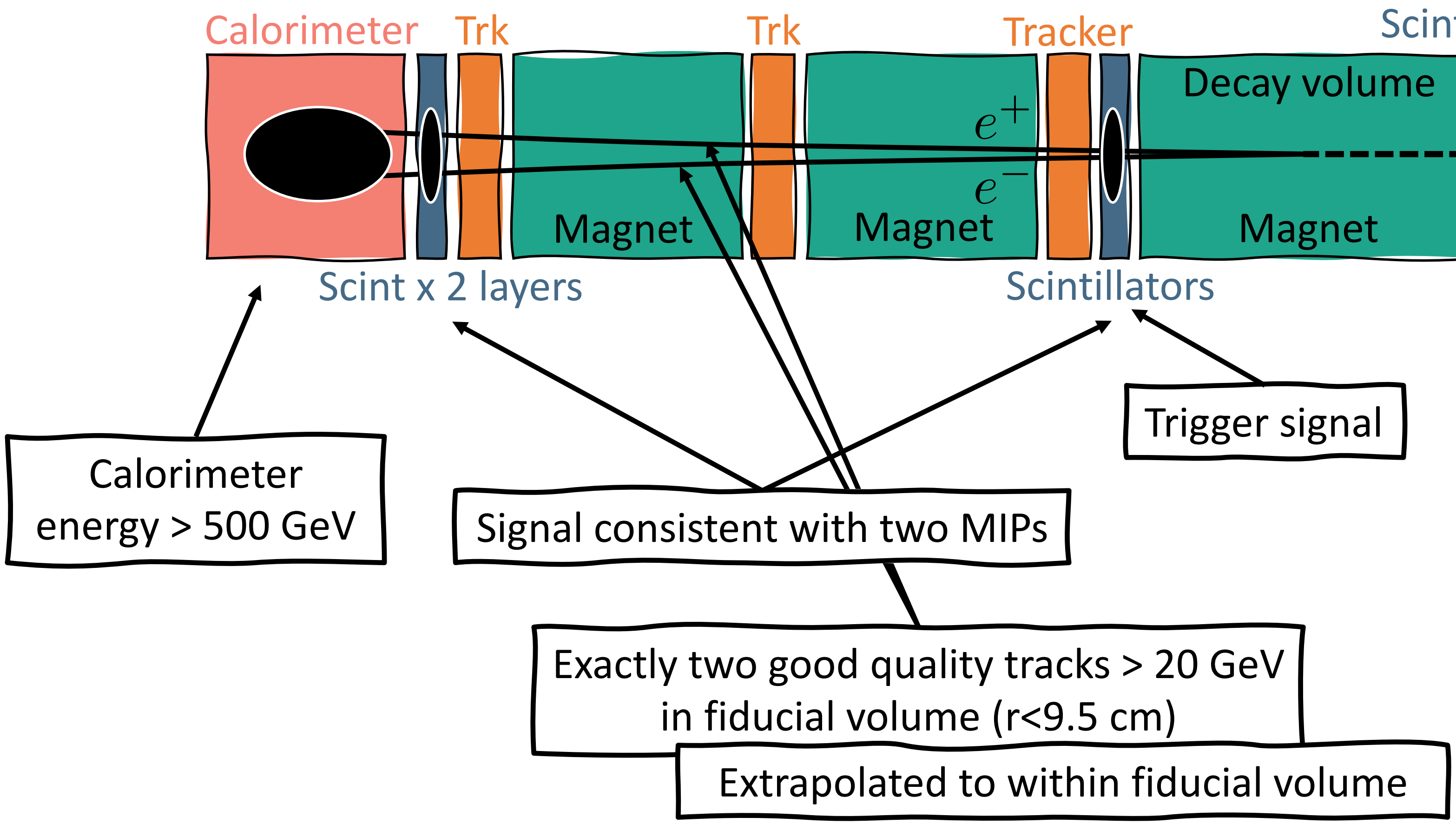
New fermion: **HNL**; coupling to LH SM and h $\propto y_N$

(Heavy Neutral Lepton)

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

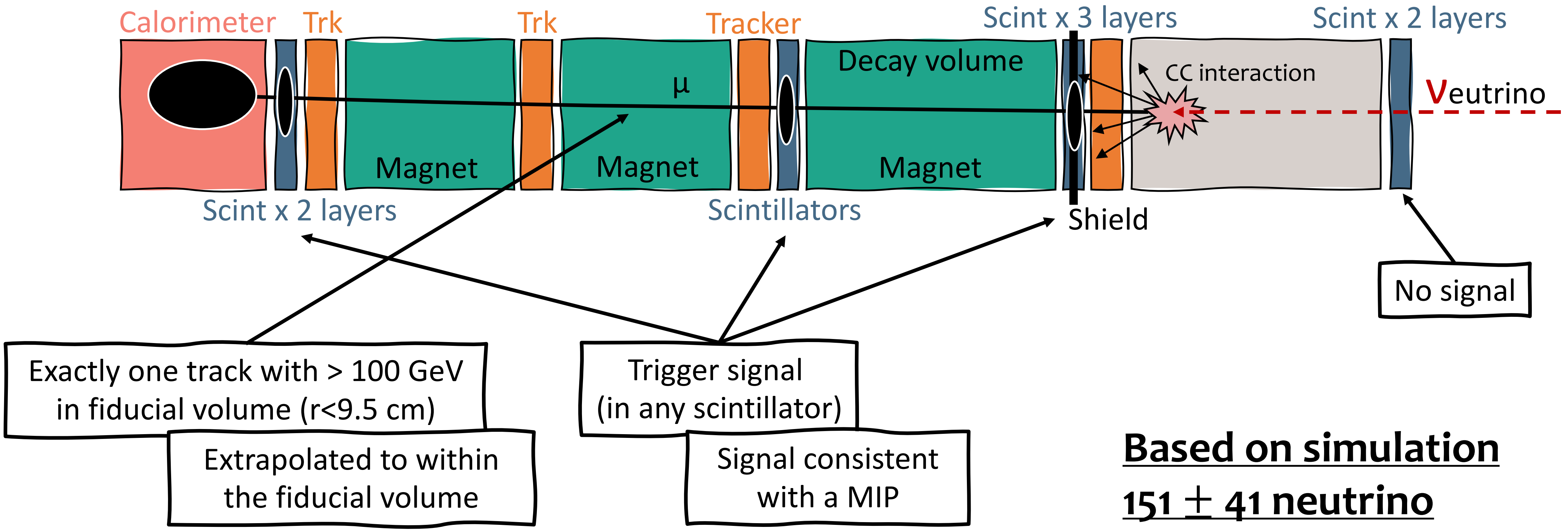
Signal Selection

Dark photon (A')

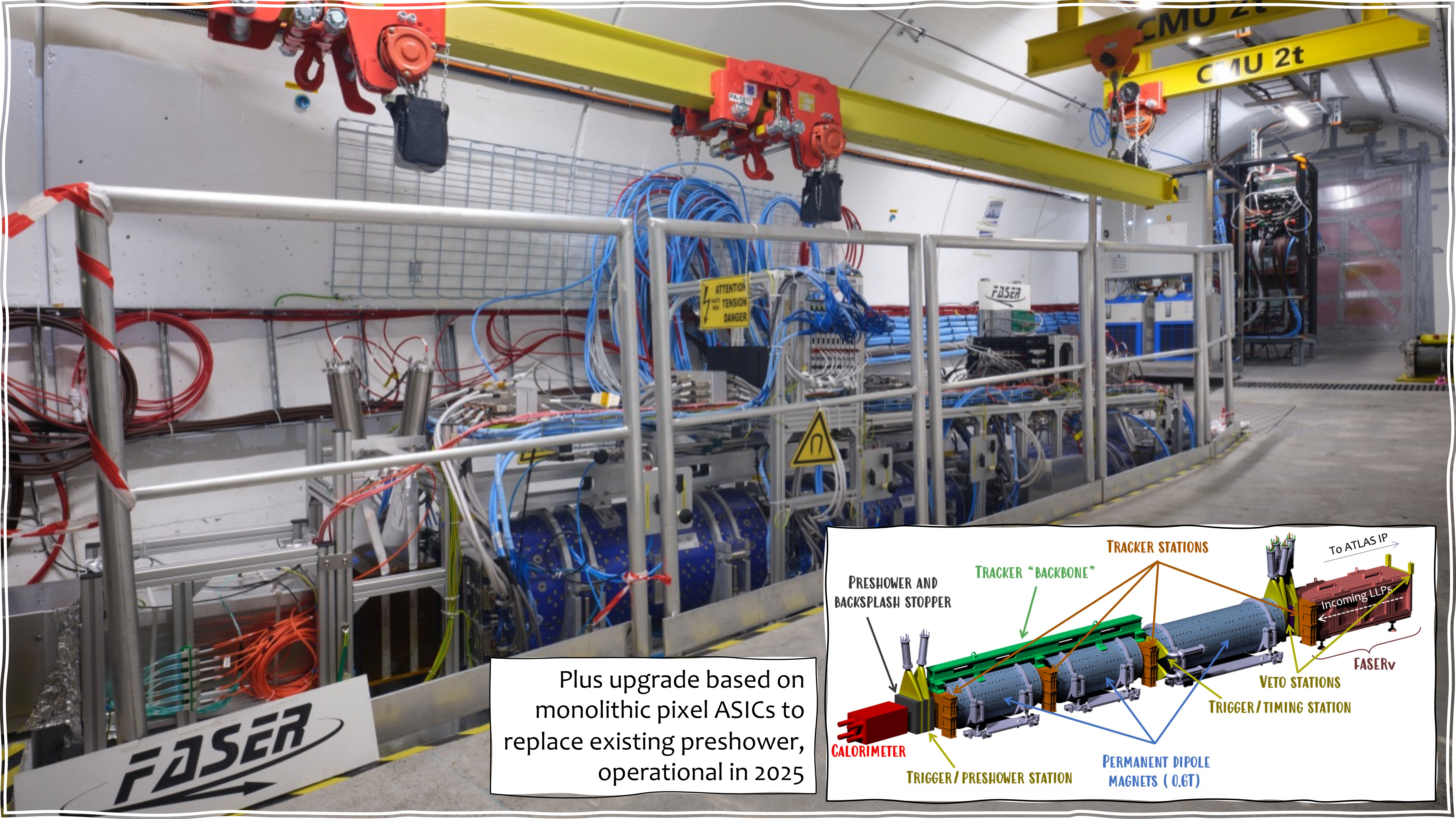


Simple selection, provides 40-45% efficiency in "relevant" phase-space

Signal Selection



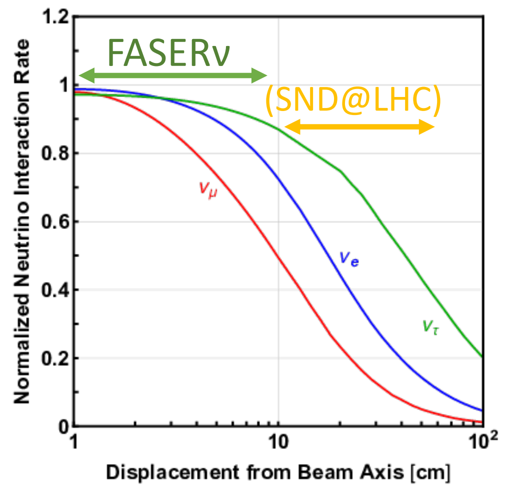
Based on simulation
151 ± 41 neutrino
events are expected

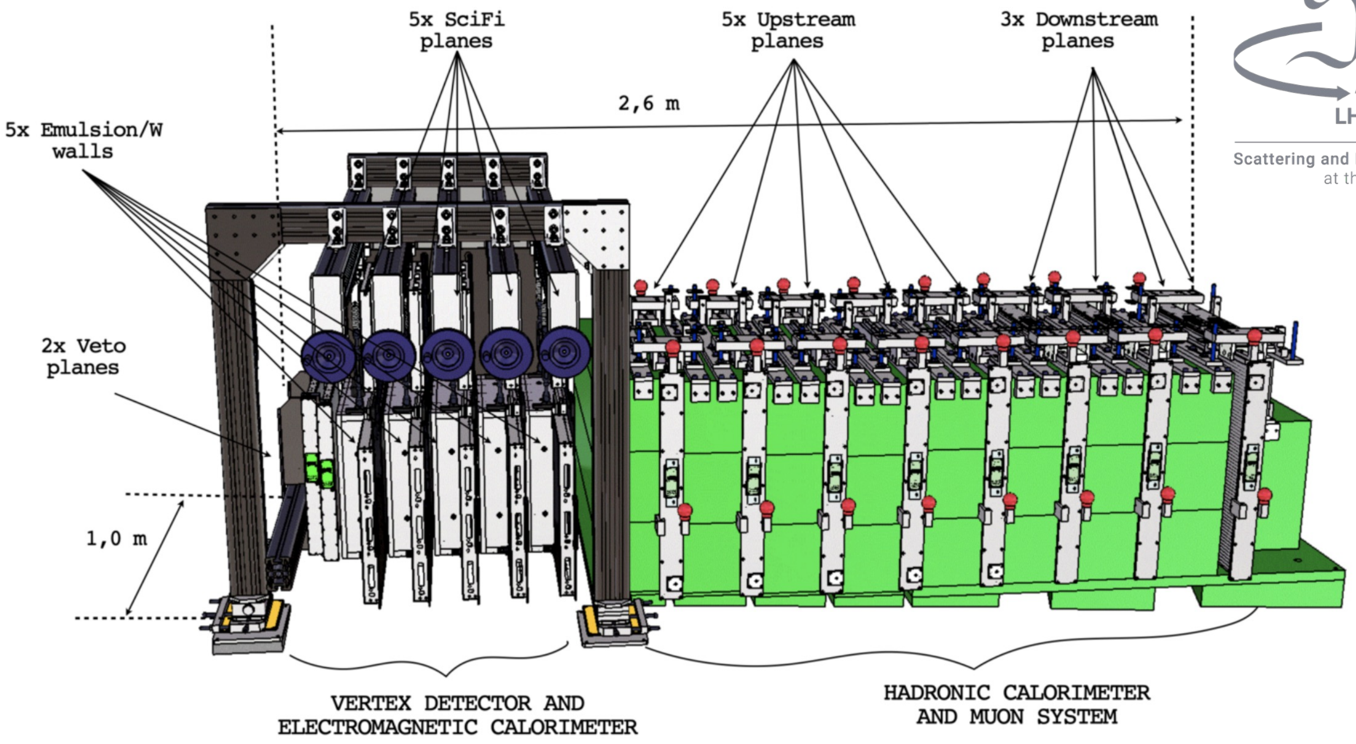


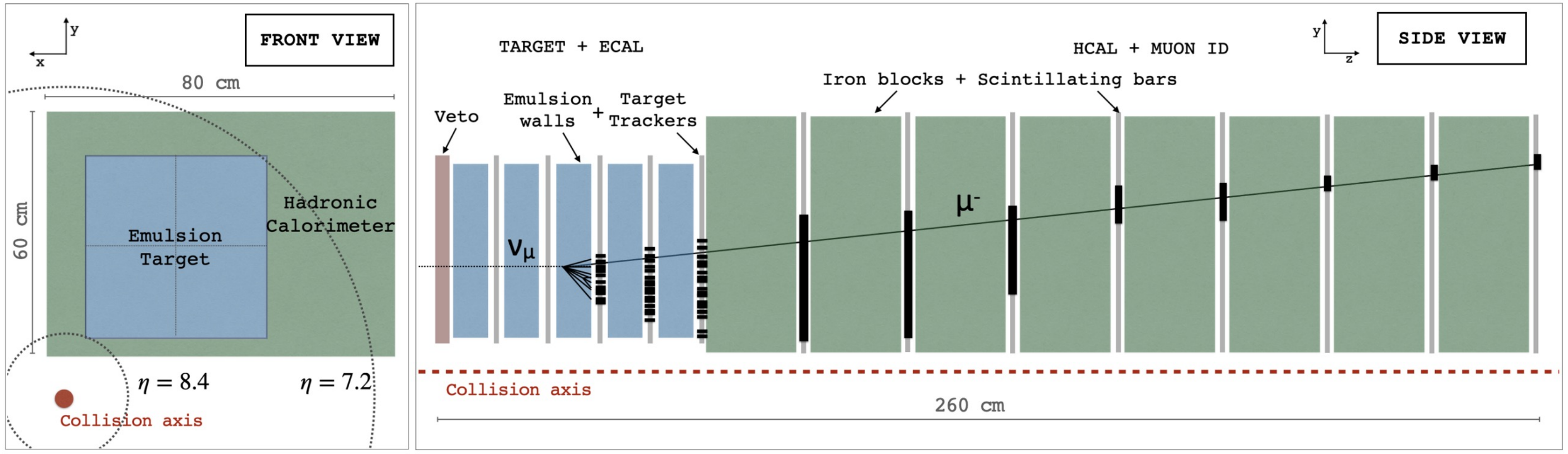
Plus upgrade based on monolithic pixel ASICs to replace existing preshower, operational in 2025

Scattering and Neutrino Detector at the LHC

Primary goal: Measurement of neutrinos from the LHC



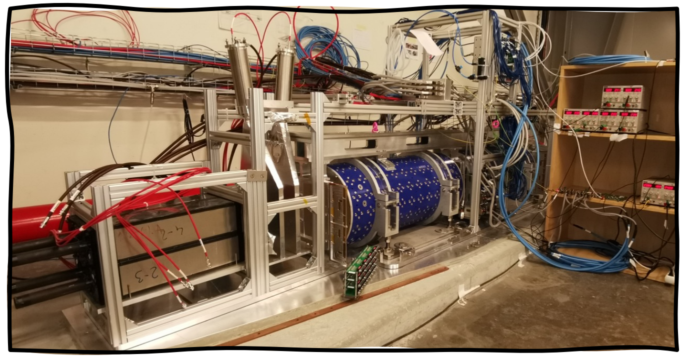




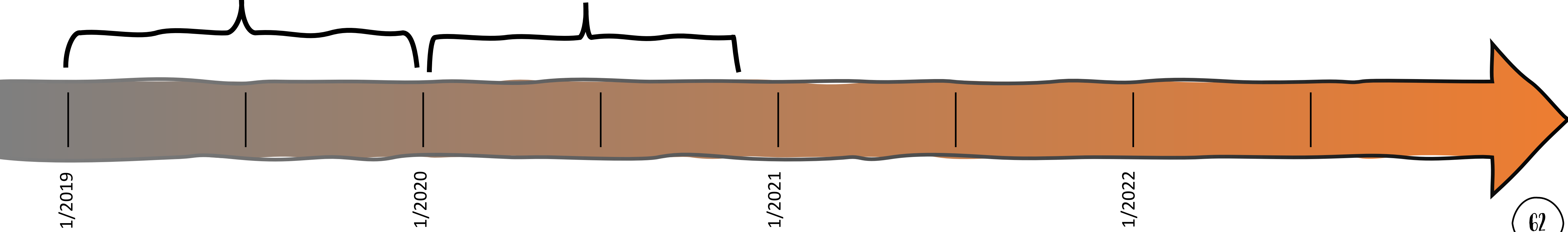
Commissioning

Timeline

Dedicated labs at CERN and UniGe for individual component testing



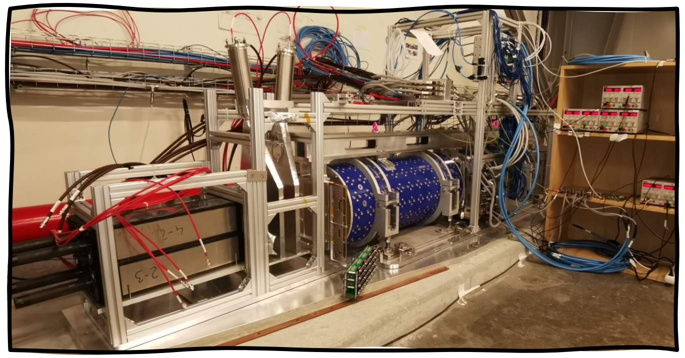
Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning



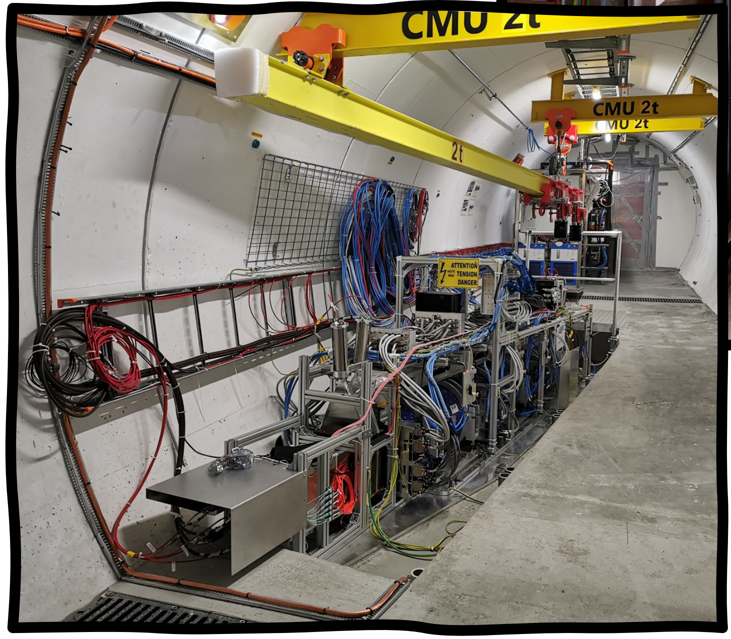
Commissioning

Timeline

Dedicated labs at CERN and UniGe for individual component testing



Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning



1/2019

1/2020

1/2021

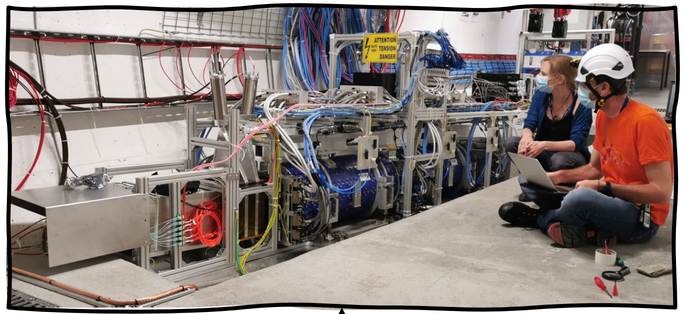
FASER Installation

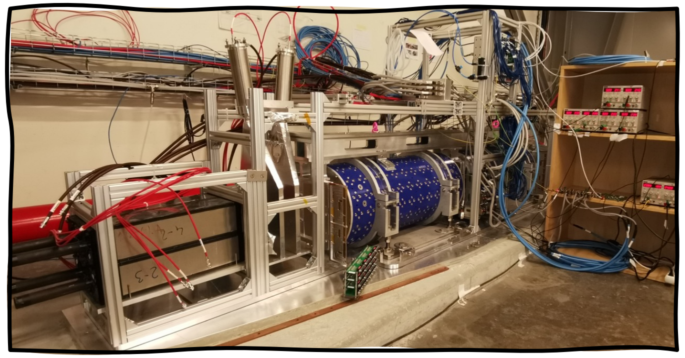
FASERν Installation

1/2022

Commissioning

Timeline

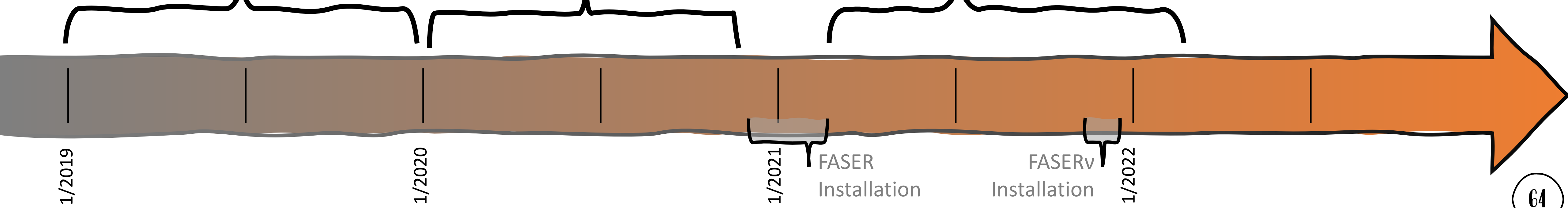




Dedicated labs at CERN and UniGe for individual component testing

Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

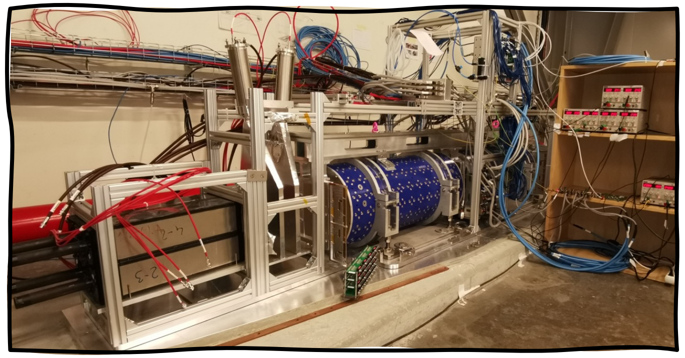
Extensive in-situ commissioning



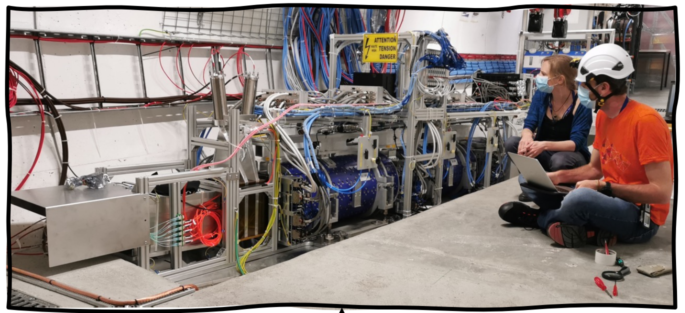
Commissioning

Timeline

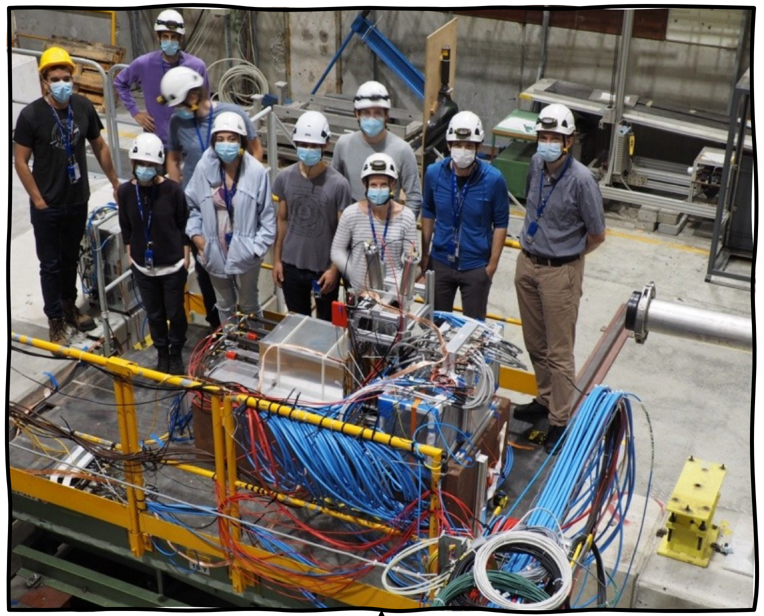
Dedicated labs at CERN and UniGe for individual component testing



Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning



Extensive in-situ commissioning



Testbeam

1/2019

1/2020

1/2021

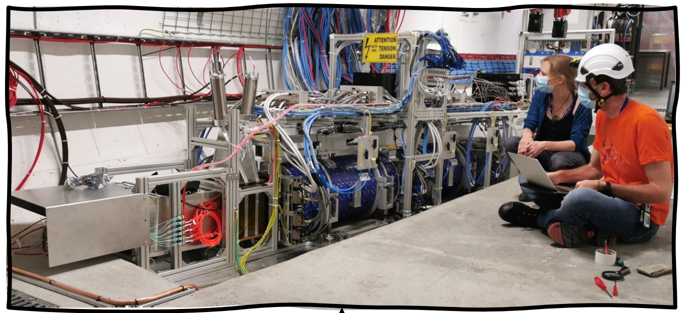
FASER Installation

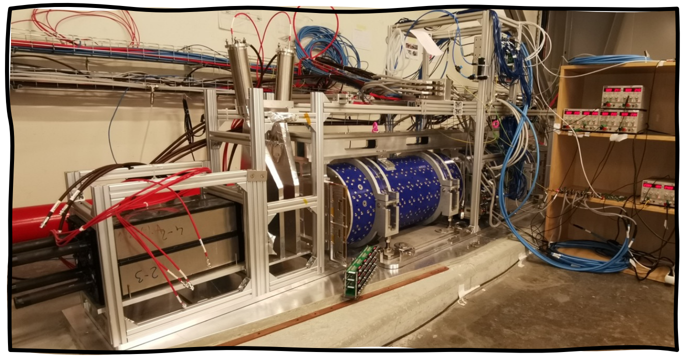
FASERν Installation

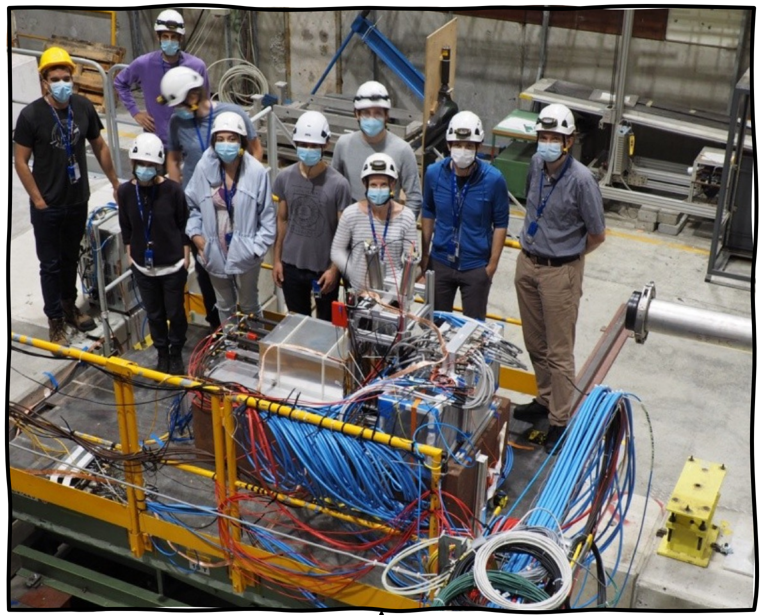
1/2022

Commissioning

Timeline







Dedicated labs at CERN and UniGe for individual component testing

Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

Extensive in-situ commissioning

Testbeam

Collisions!

1/2019

1/2020

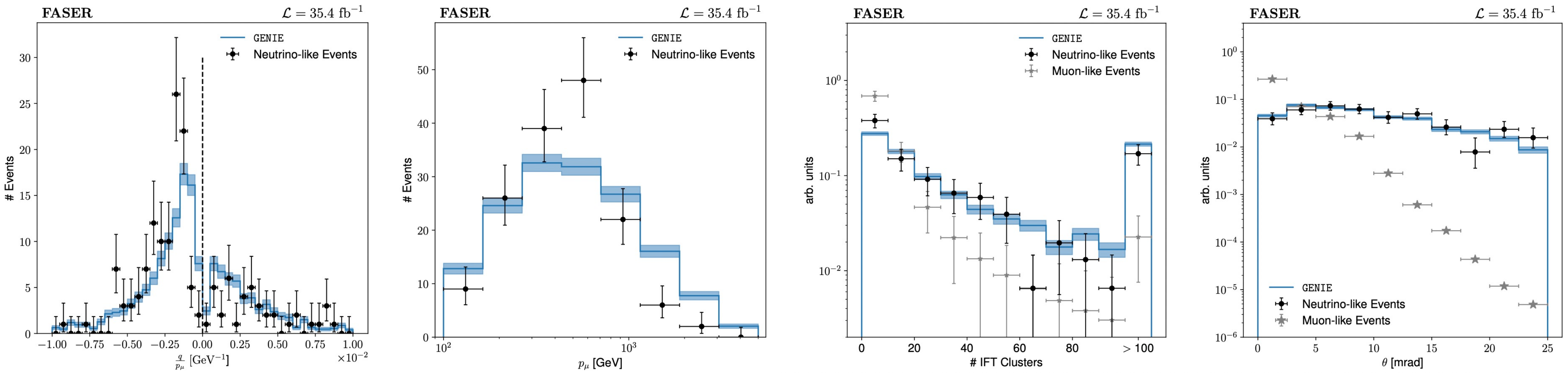
1/2021

FASER Installation

FASERν Installation

1/2022

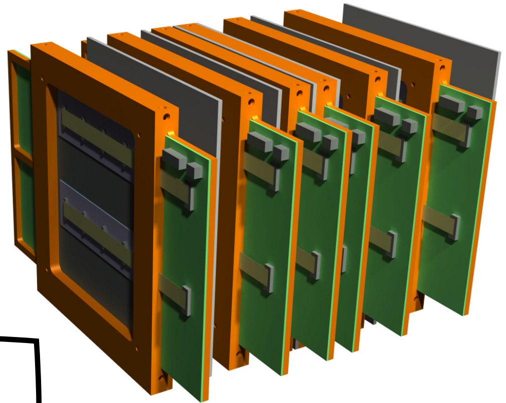
Properties of observed neutrino events



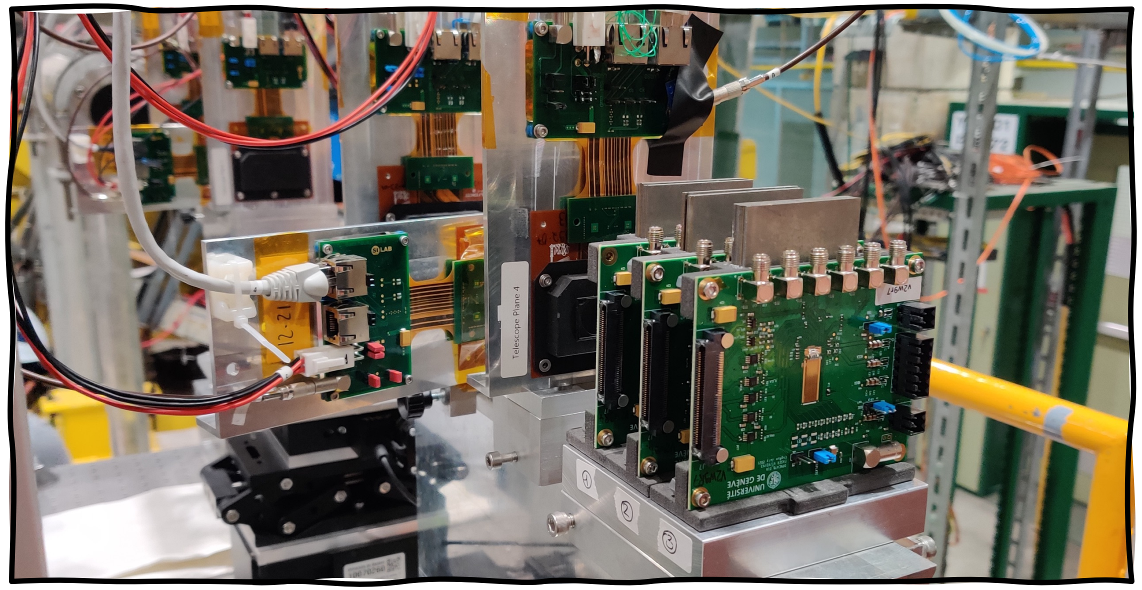
Detector Upgrade

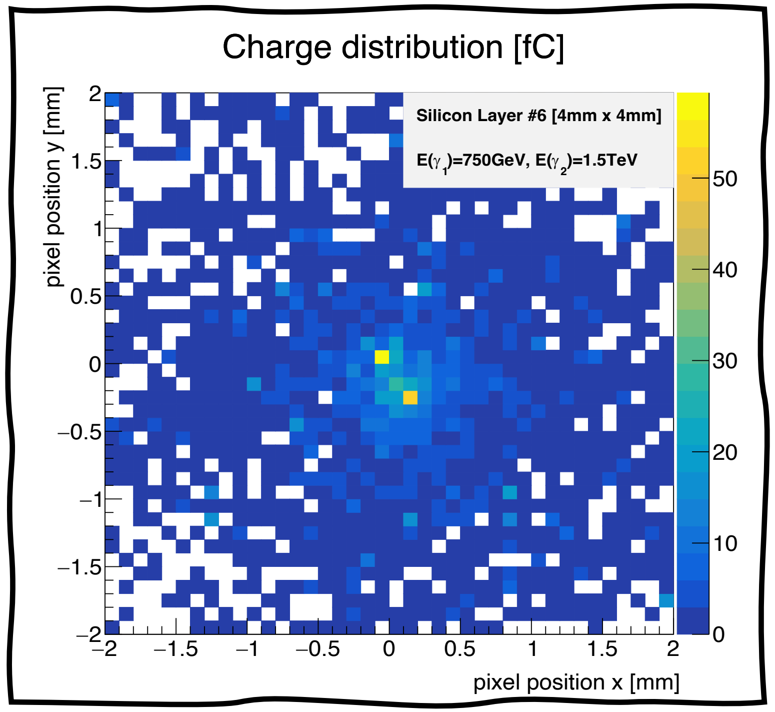
to enable 2-γ physics

- Existing pre-shower to be replaced with a high-resolution silicon pre-shower detector using monolithic pixel ASICs



Preproduction ASICs in testbeam, Sept 2022

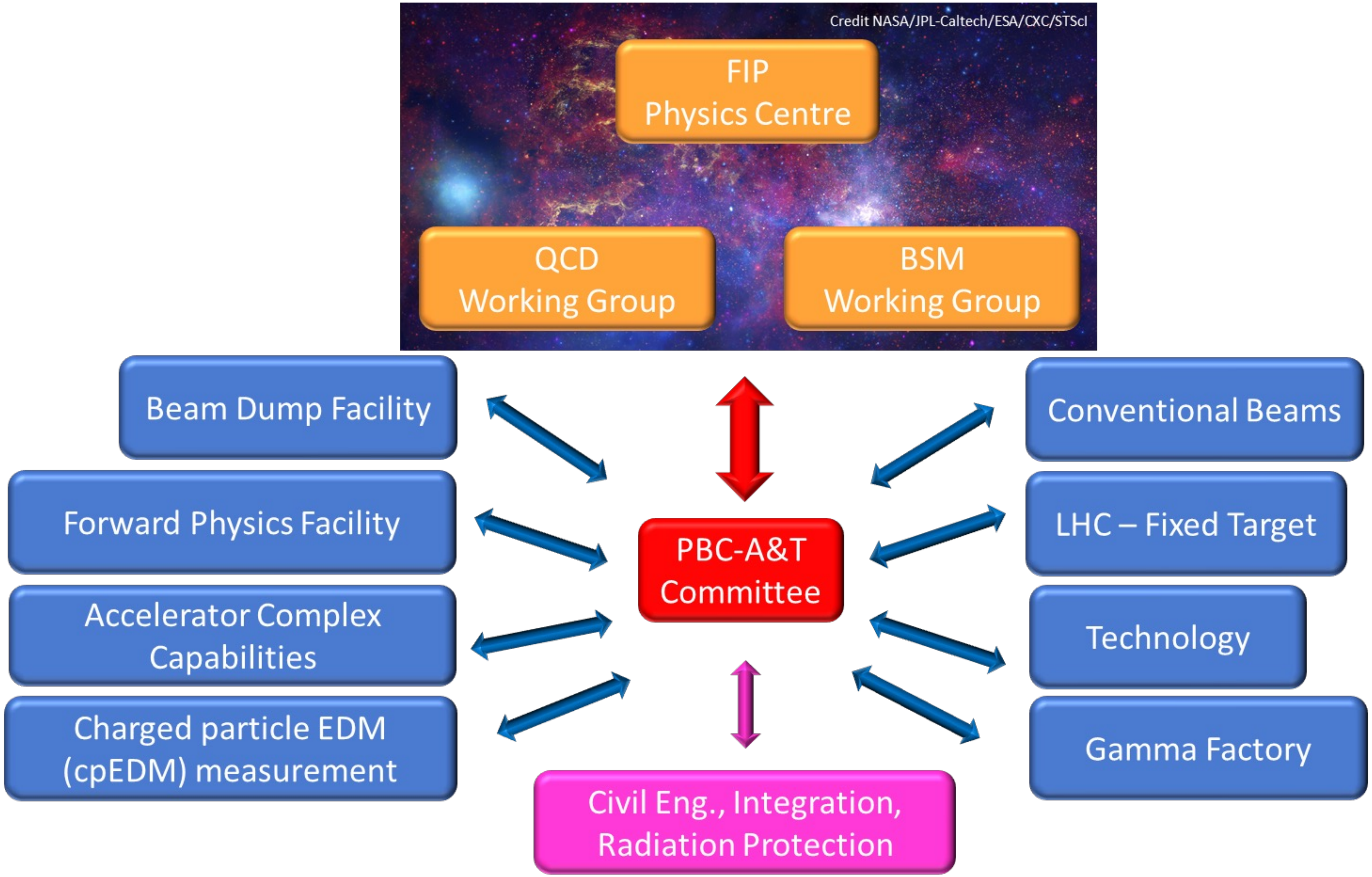




- Distance between two photons: 200 μm
- Distinguishable!

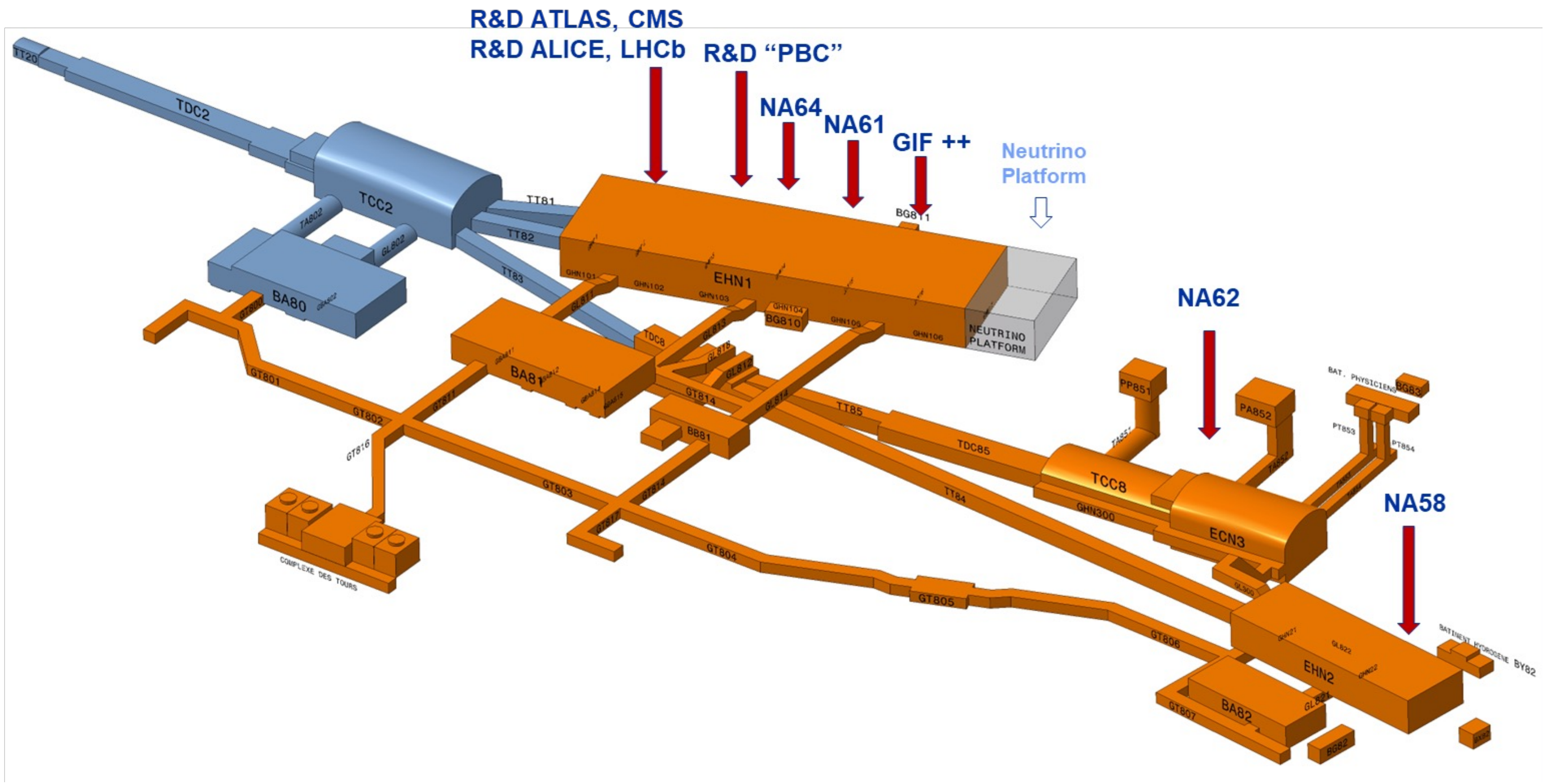
Detector to be used for 2025 data taking

https://cds.cern.ch/record/2803084

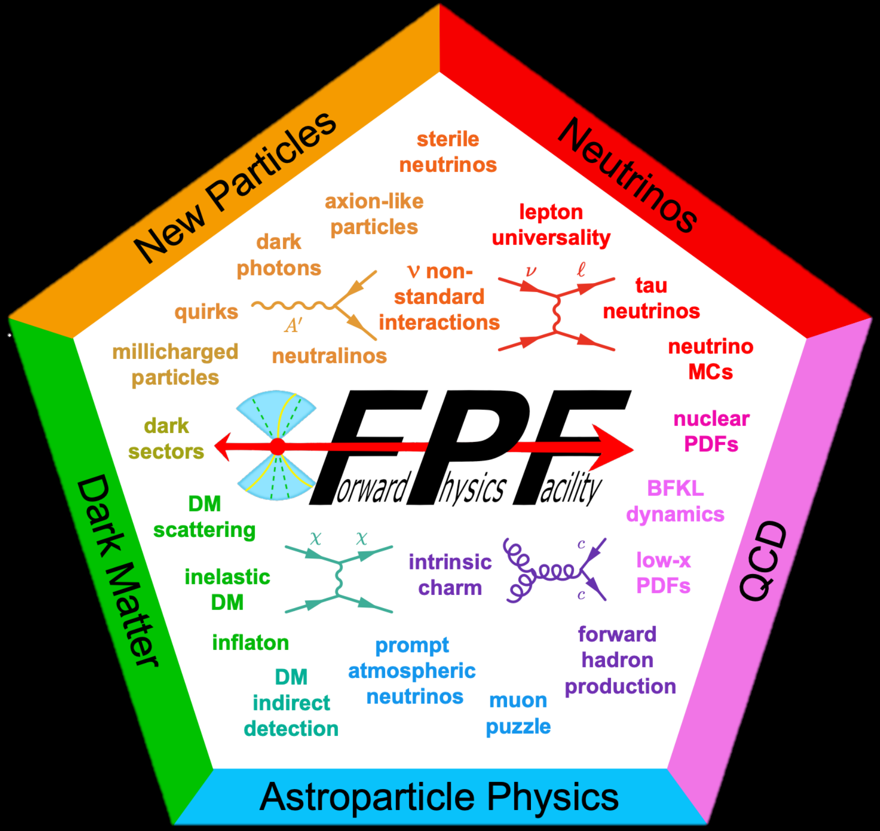

Credit NASA/JPL-Caltech/ESA/CXC/STScI
FIP
Physics Centre
QCD
Working Group
BSM
Working Group
Beam Dump Facility
Forward Physics Facility
Accelerator Complex
Capabilities
Charged particle EDM
(cpEDM) measurement
PBC-A&T
Committee
Conventional Beams
LHC – Fixed Target
Technology
Gamma Factory
Civil Eng., Integration,
Radiation Protection

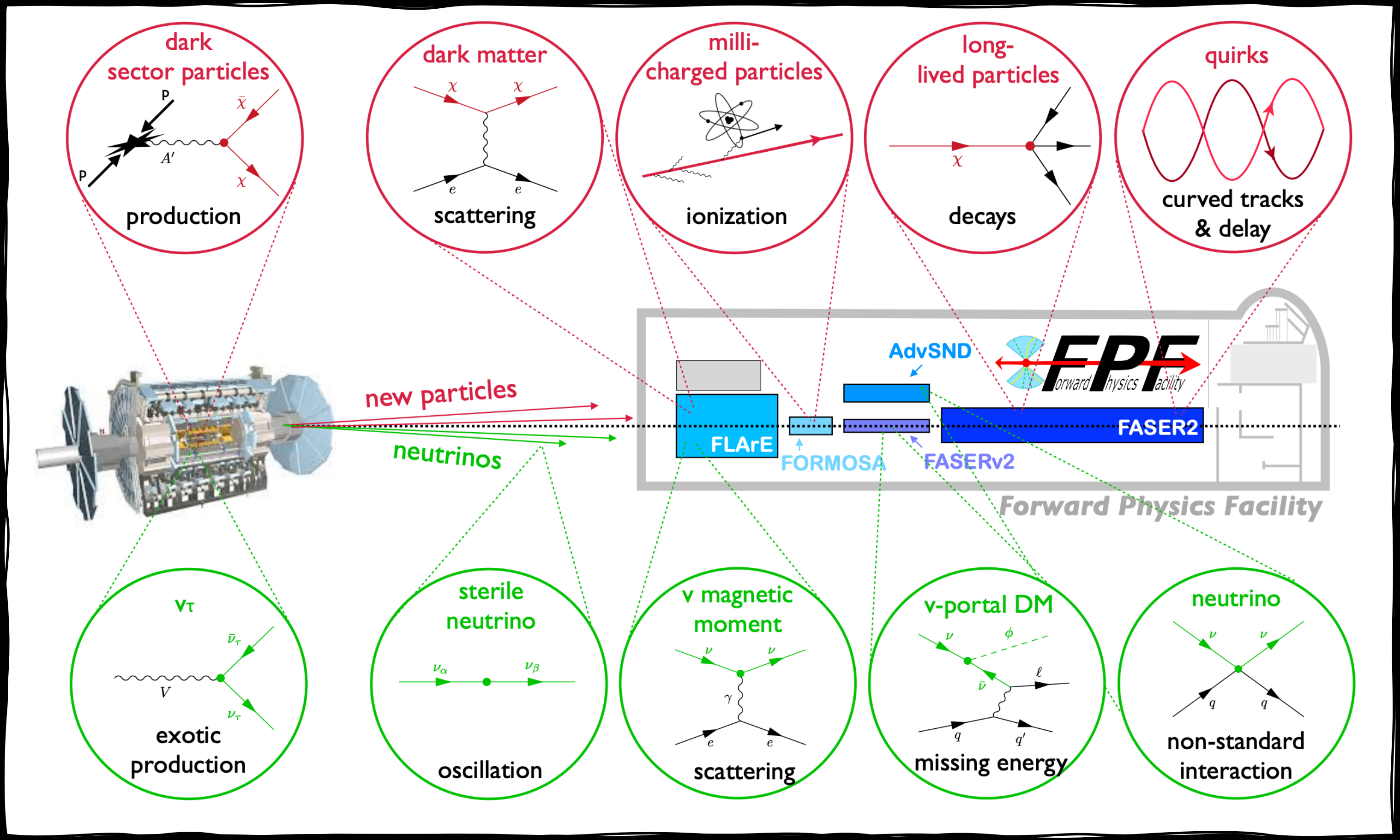
Phase 1: 2019 - 2028 => priority to TT20 & NA transfer tunnels

Phase 2: 2029 - 2034 => H2, H4, H6, H8, M2 and K12 beam lines



The physics programme of FPF



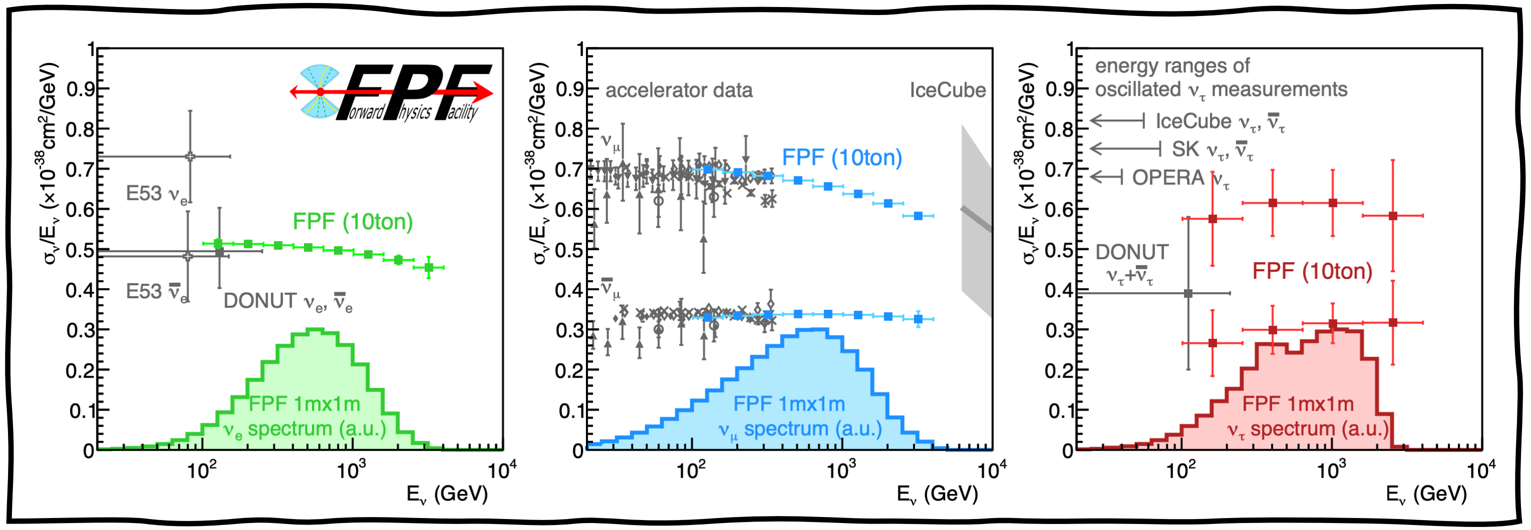


From https://pbc.web.cern.ch/sites/default/files/2023-04/FPFSummary_final.pdf

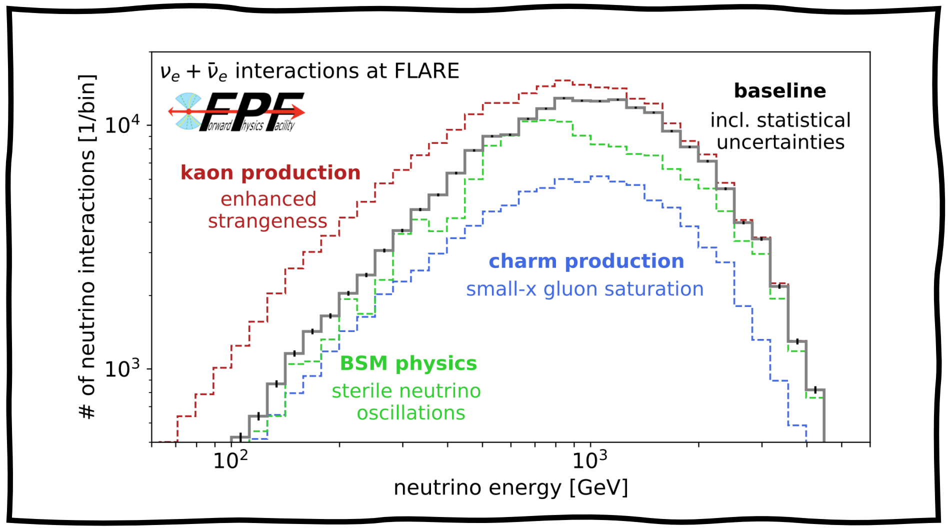
A RICH NEUTRINO PROGRAMME

	Available lumi	Mass of ν detector	ν_e	ν_μ	ν_τ
Main production source			kaon decay	pion decay	charm decay
# 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**!



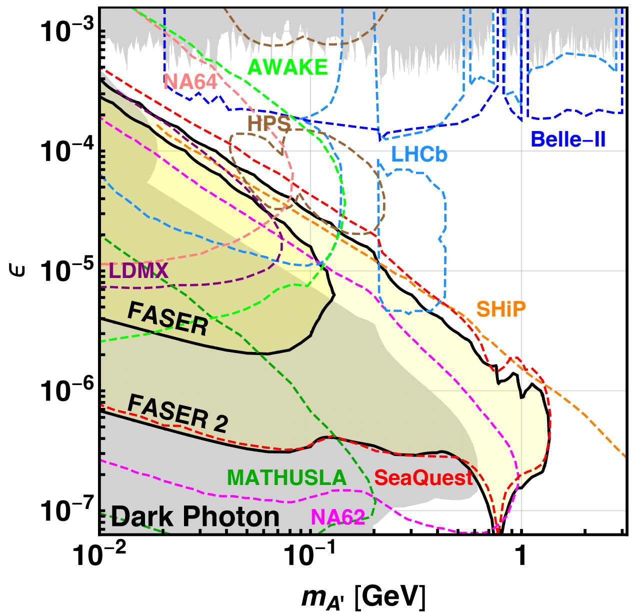
Expected precision of FPF measurements of the neutrino interaction cross section with nucleons

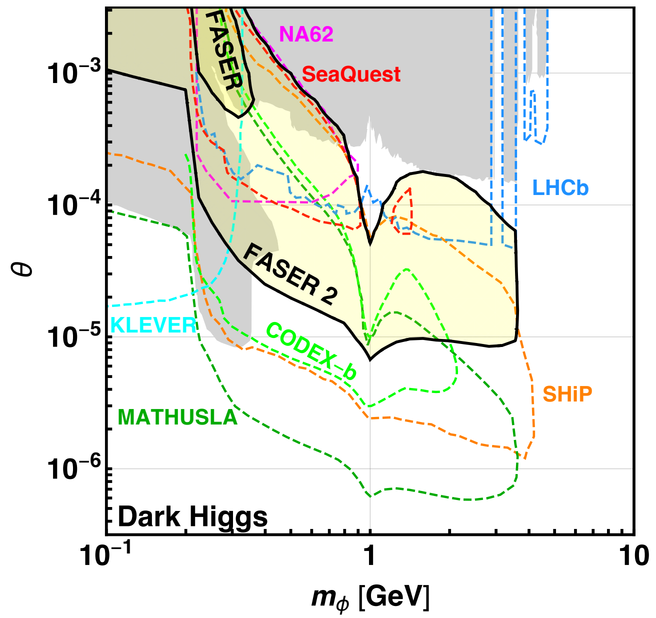


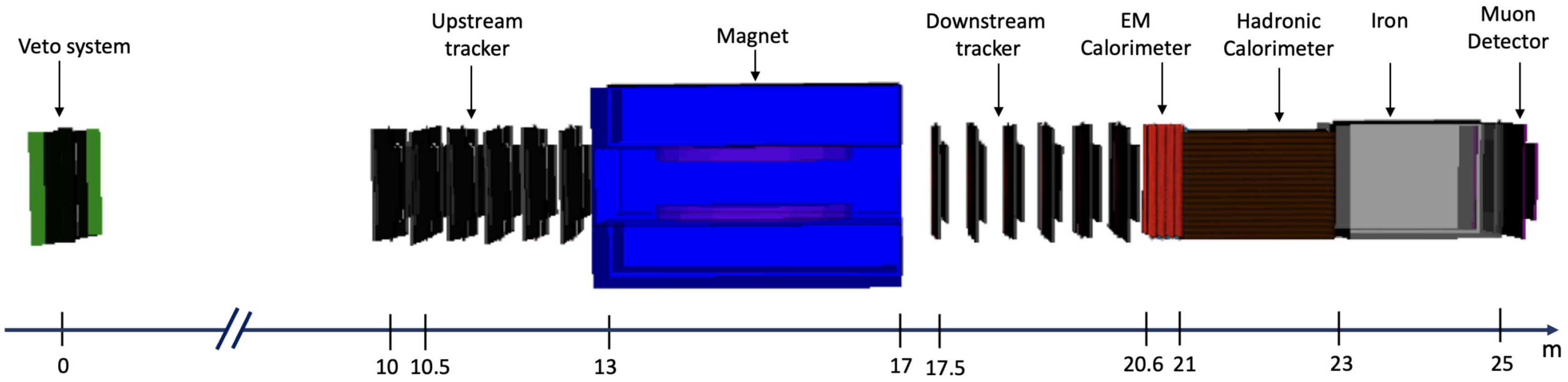
Coloured lines: three examples of physics that can change the expected flux, all probed at FPF

BSM & FASER2

Increased detector radius to 1 m allows sensitivity to particles produced in heavy meson (B, D) decays increasing physics case beyond just increased luminosity





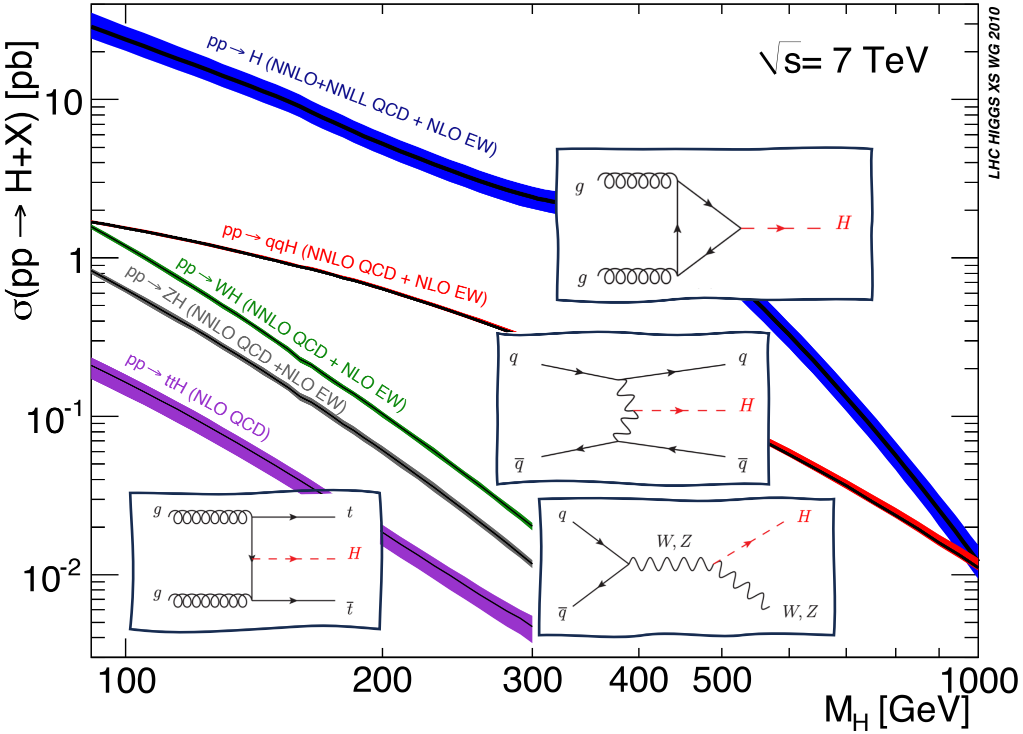


Possible FASER2 layout

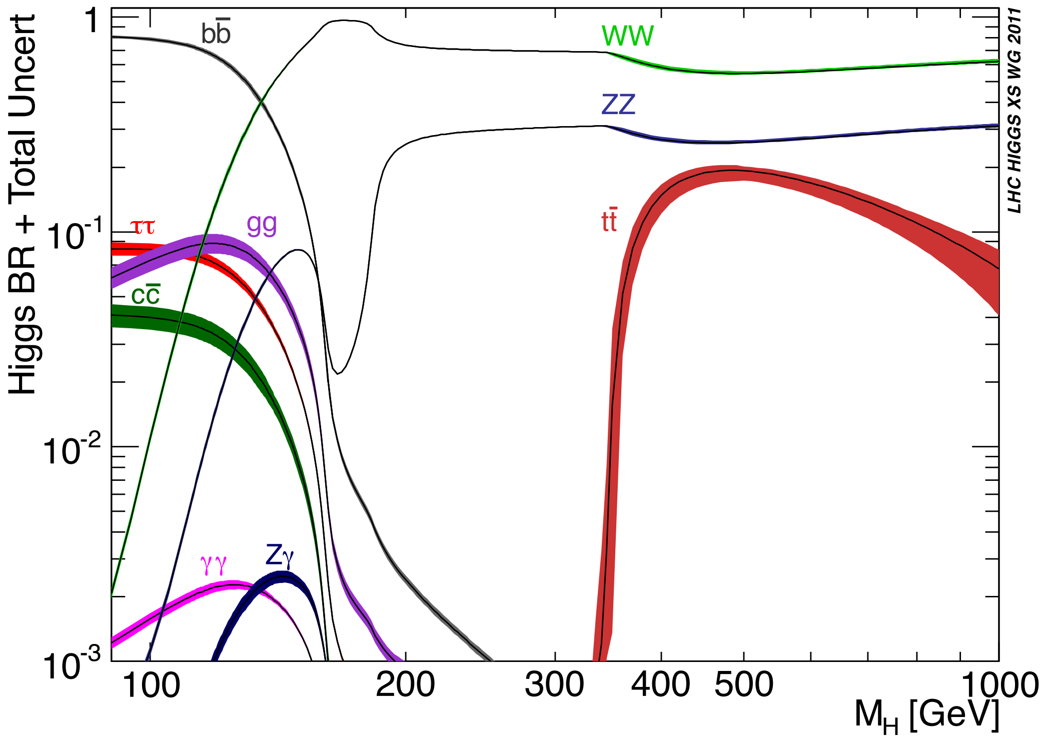
LHC General

Theory – before the Higgs discovery

Higgs production

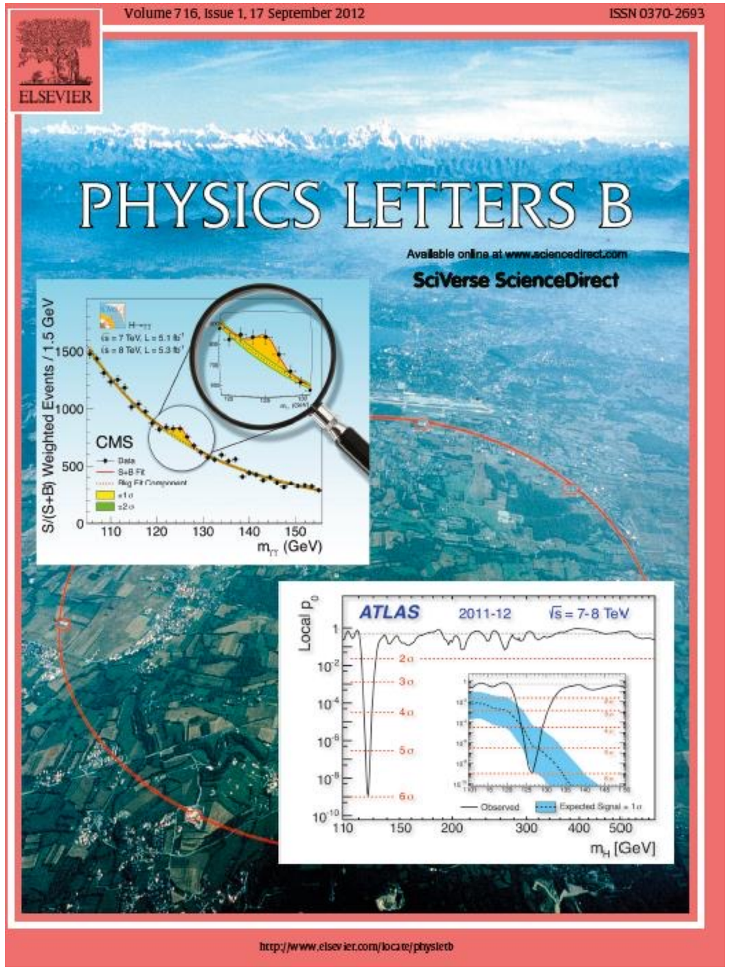


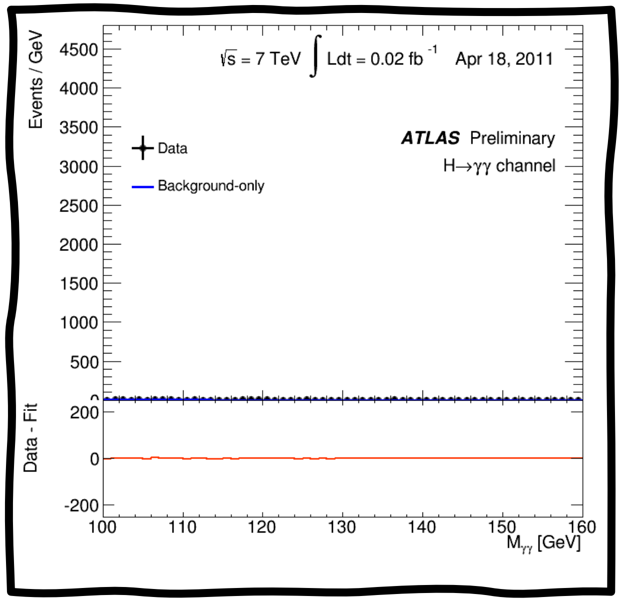
Higgs Decays

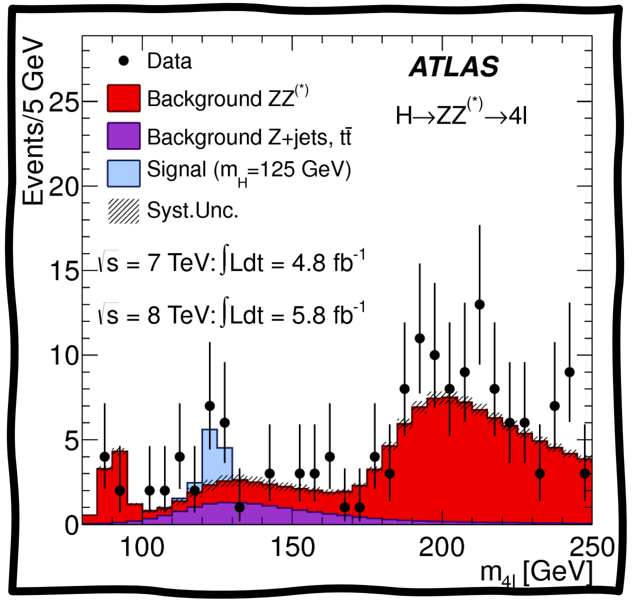


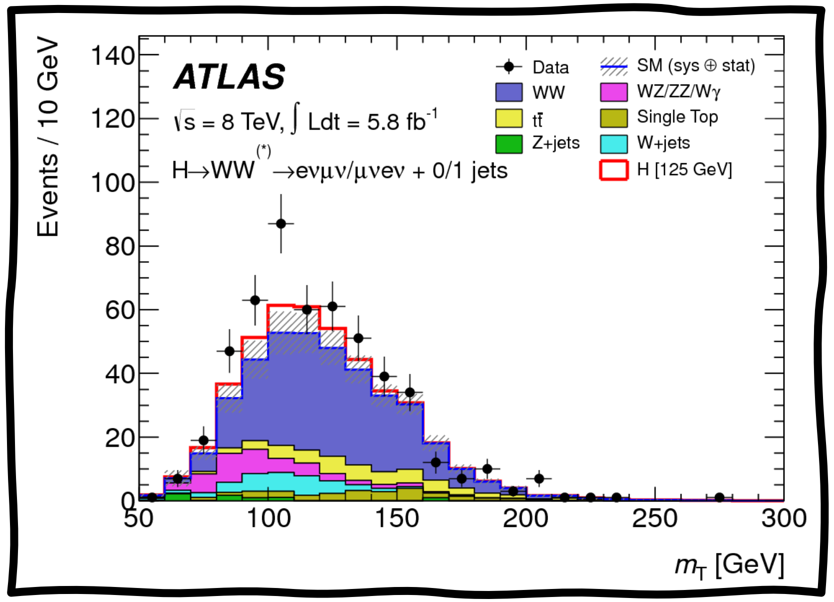
Where is the Higgs ??

The Higgs Discovery







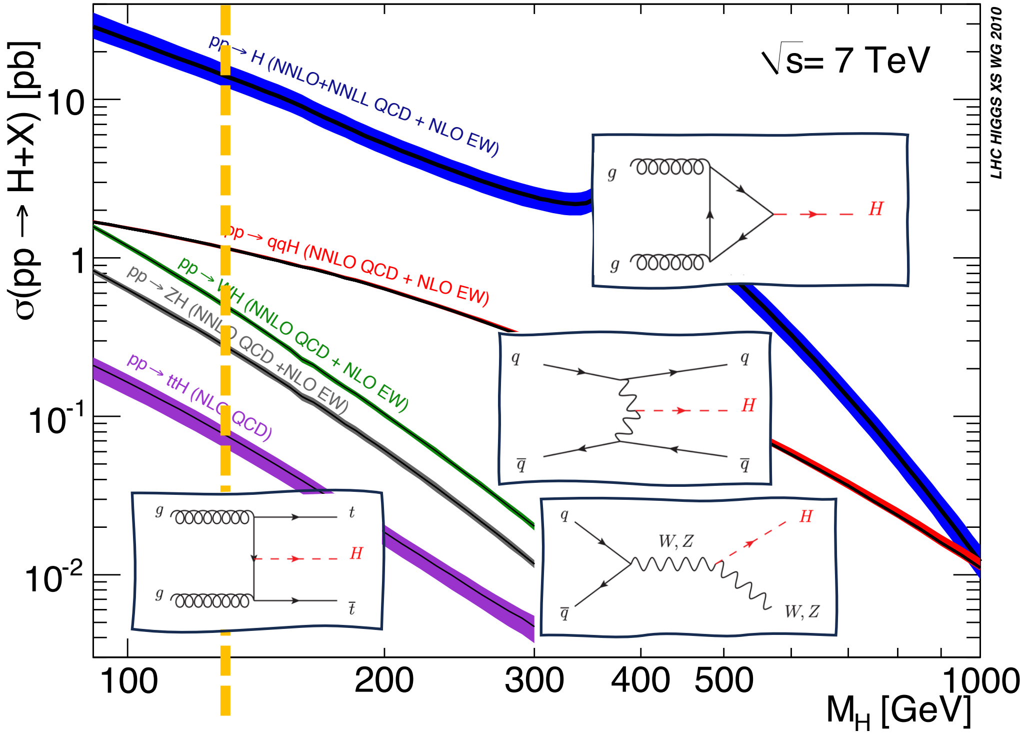


The three channels that contributed to the discovery

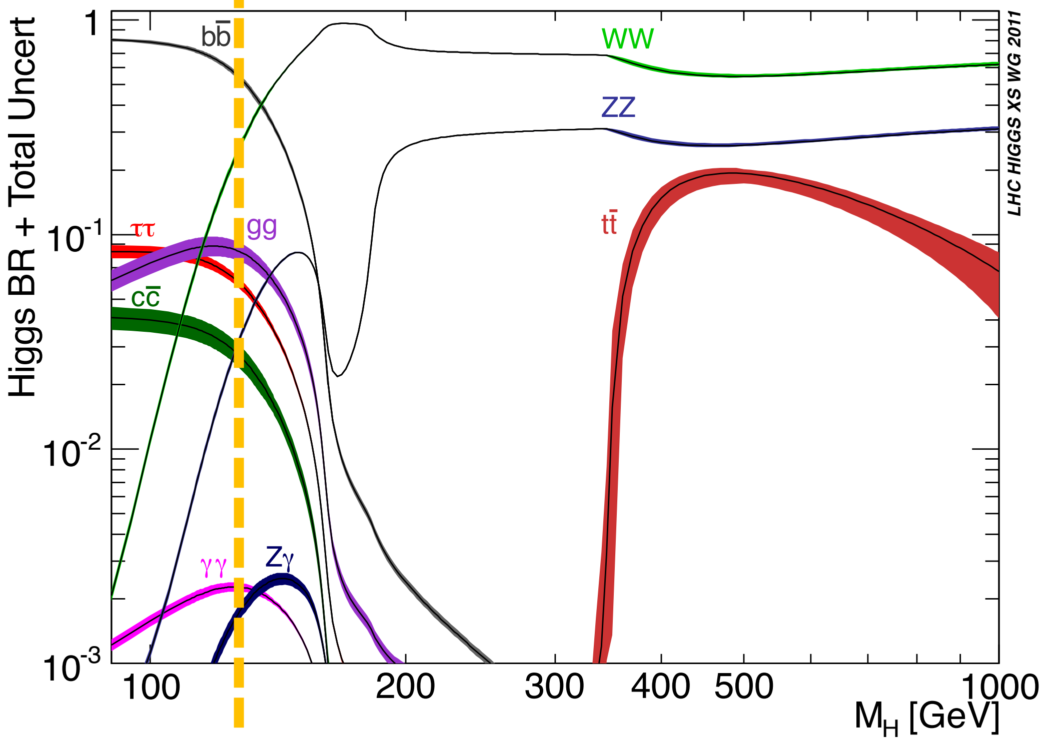
arXiv:1207.7214

Theory – after the discovery

Higgs production



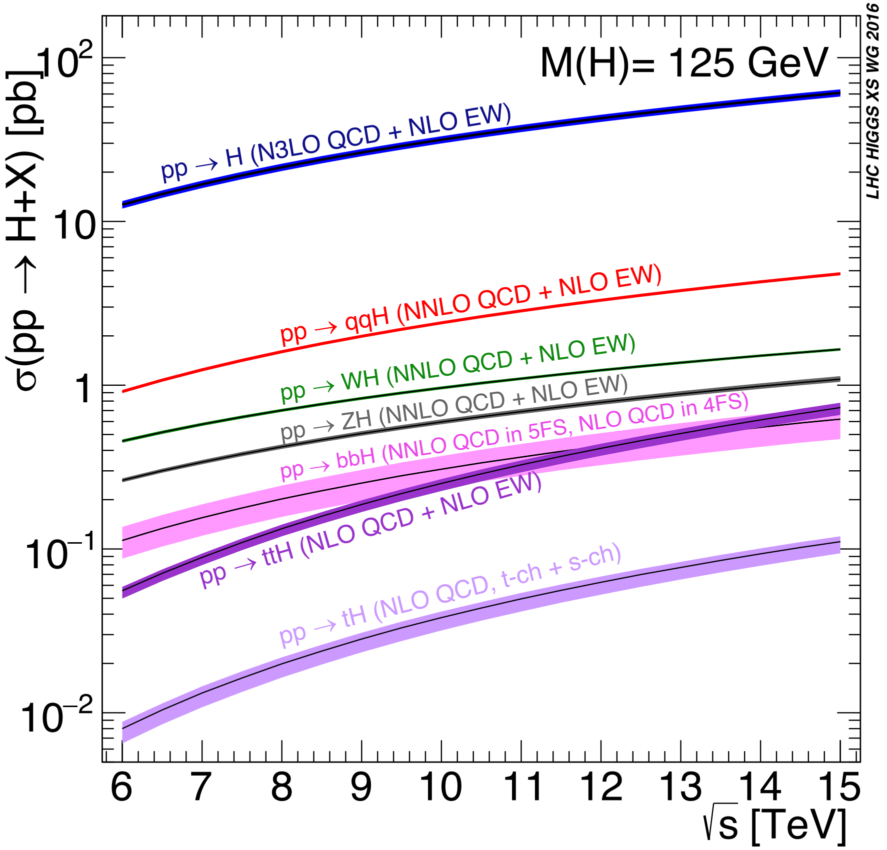
Higgs Decays



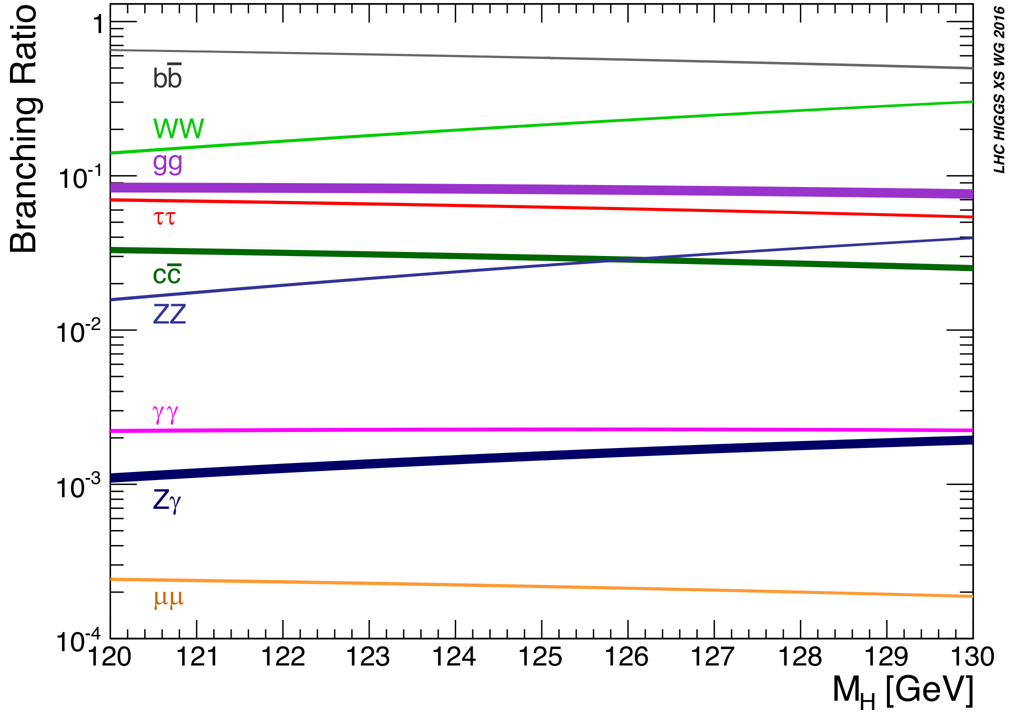
m(Higgs) = 125 GeV

What stats of Higgs available?

Assume Run2 : 150/fb

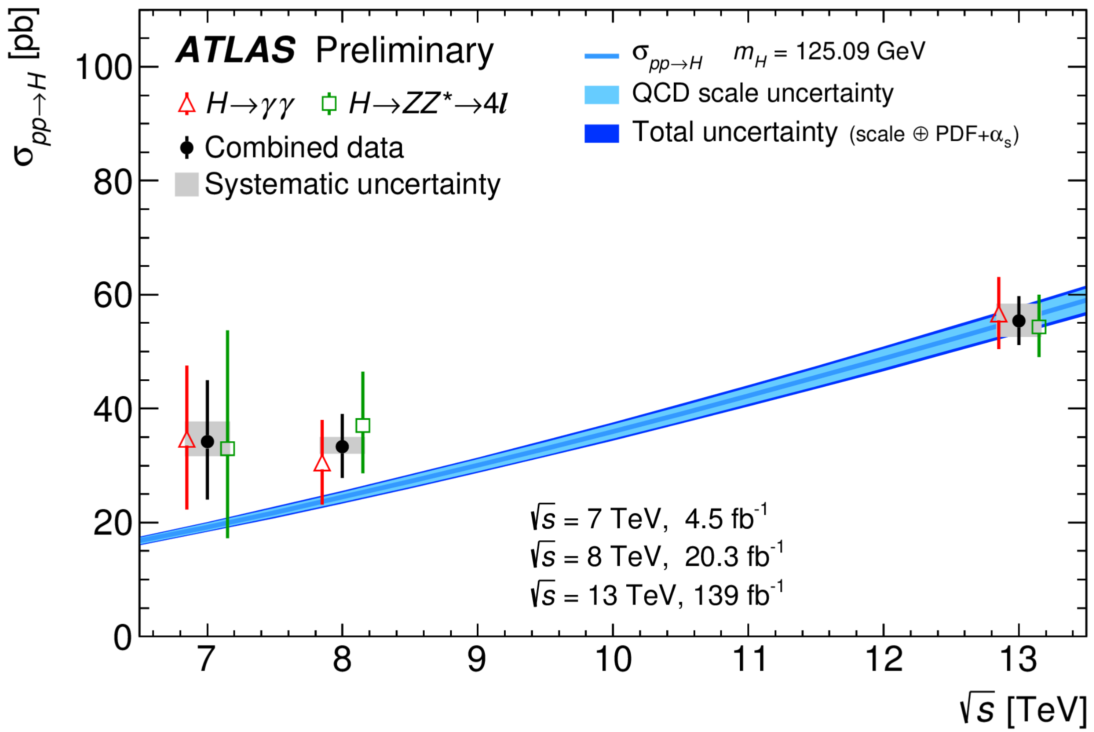


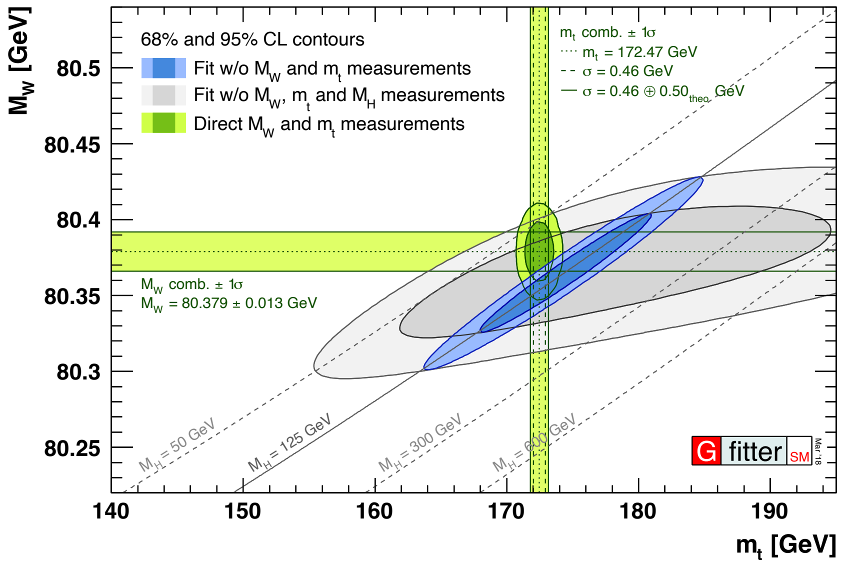
	Events
ggF	~8 M
VBF	~600 K
VH	~400 K
ttH	~100 K

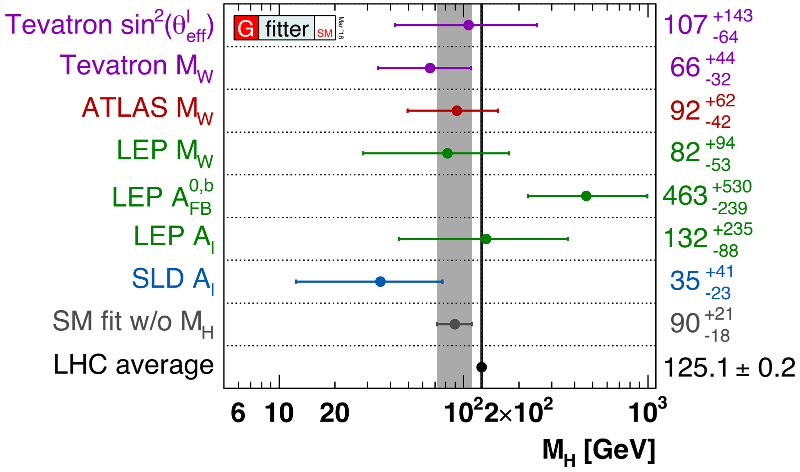


57 %
22 %
8 %
6 %
3 %
3 %
0.2 %
0.2 %
0.02 %

In particular, its latest discovered particle: The Higgs Boson



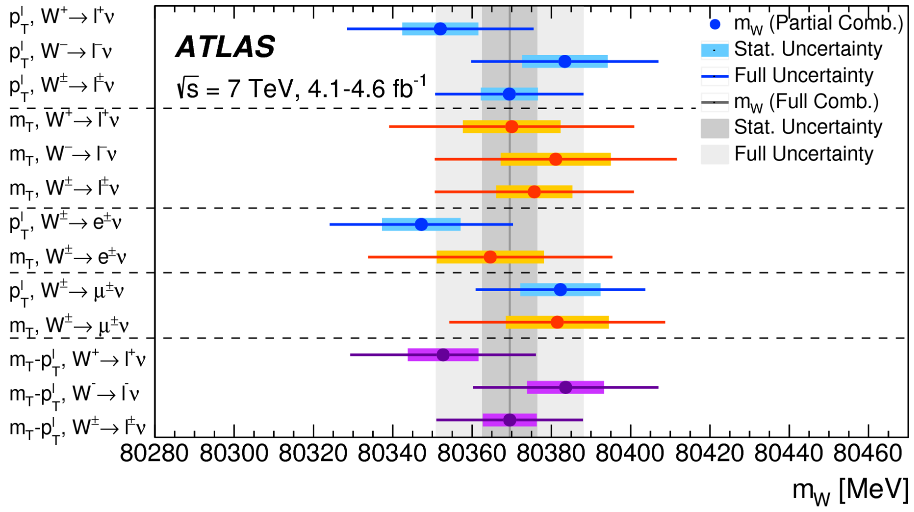


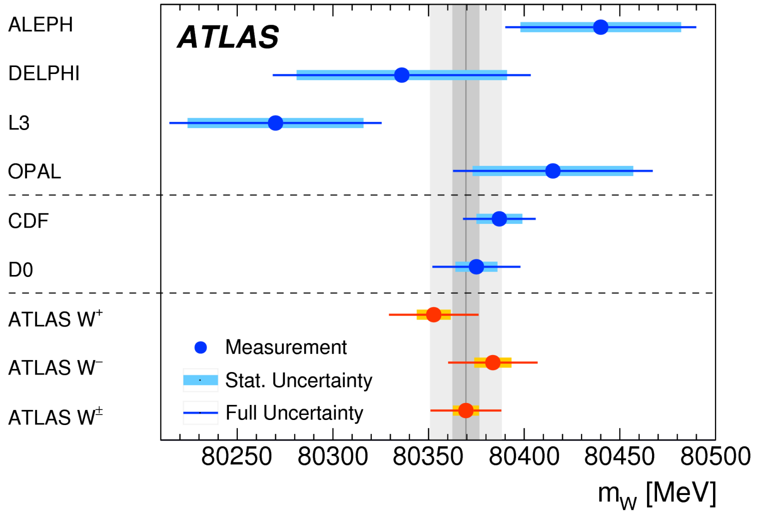


MASSES

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

W boson

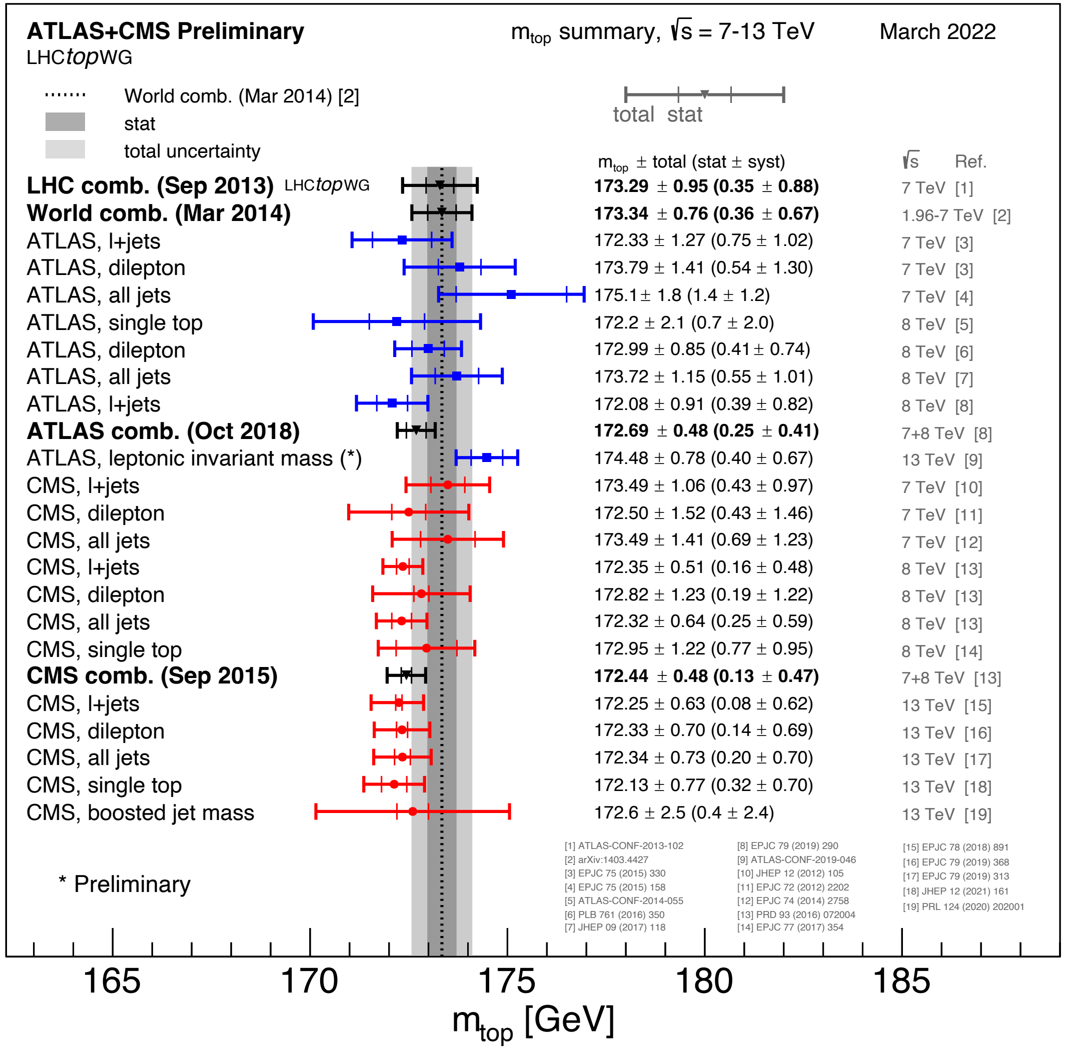




$m_W = 80370 \pm 19$ MeV

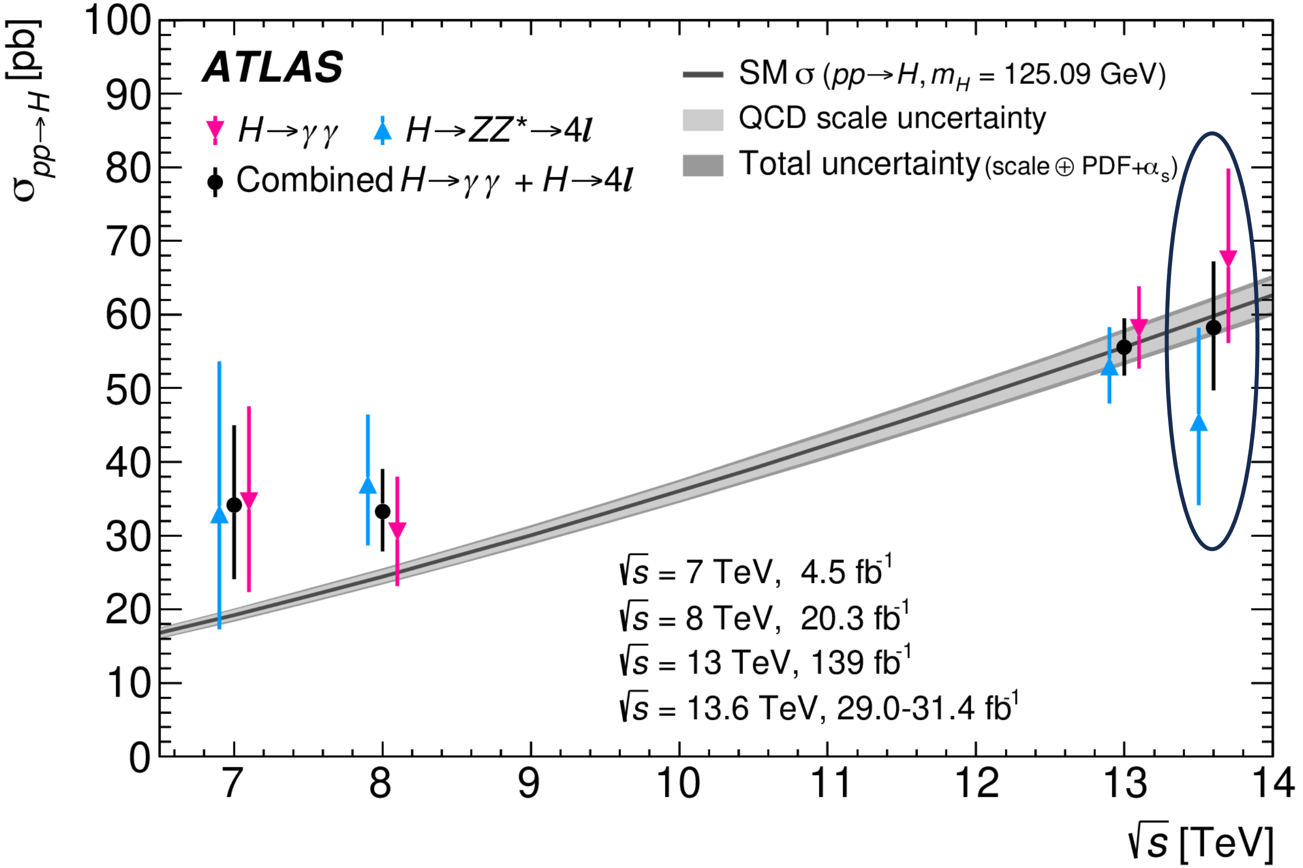
arXiv: 1701.07240

top quark

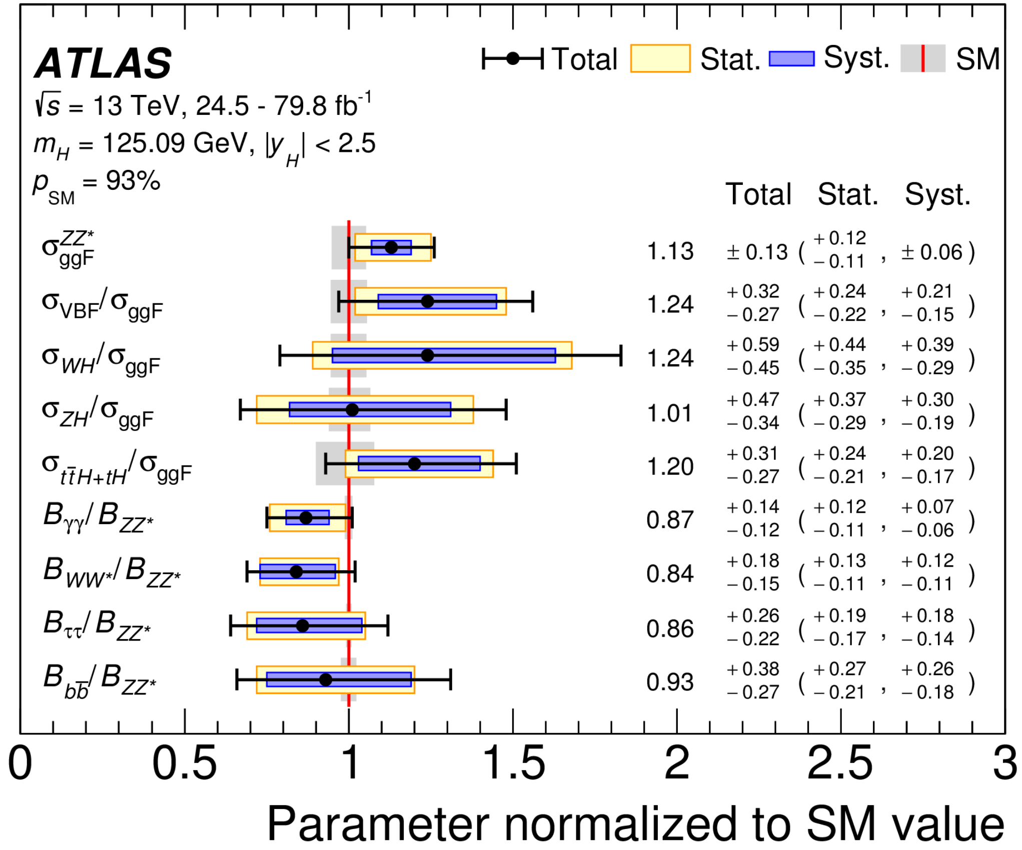


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

The Higgs Boson – other properties



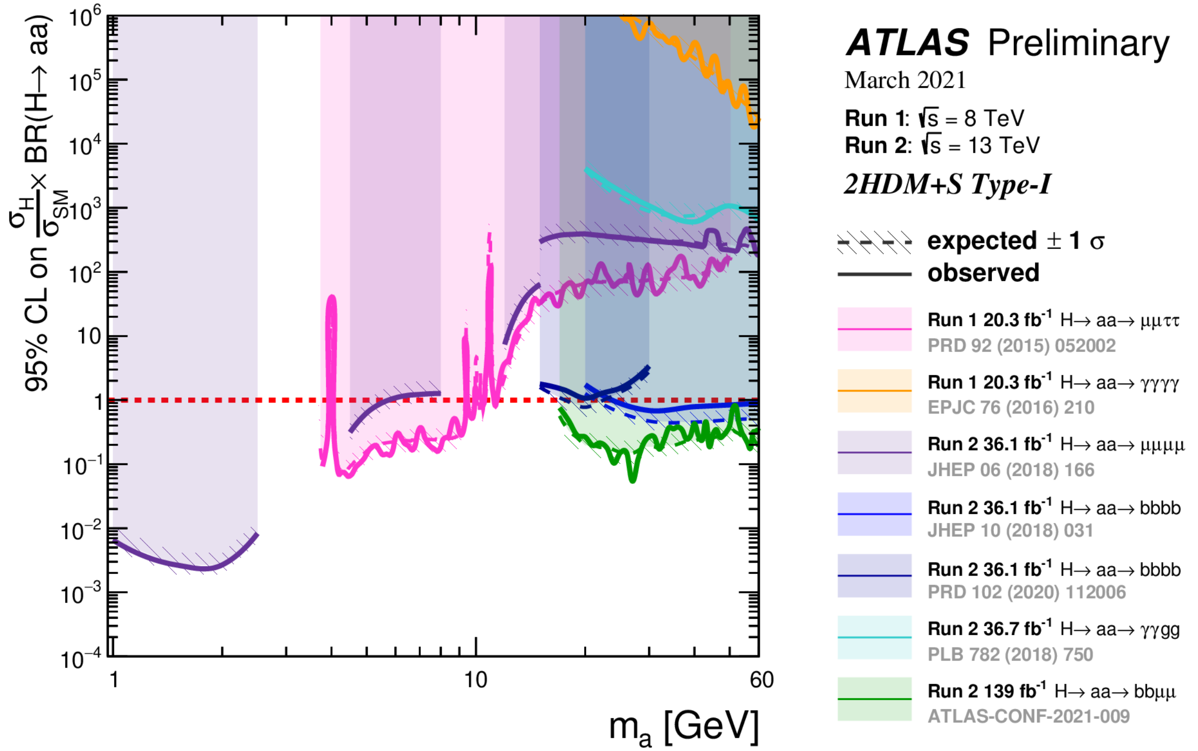
Production cross-section



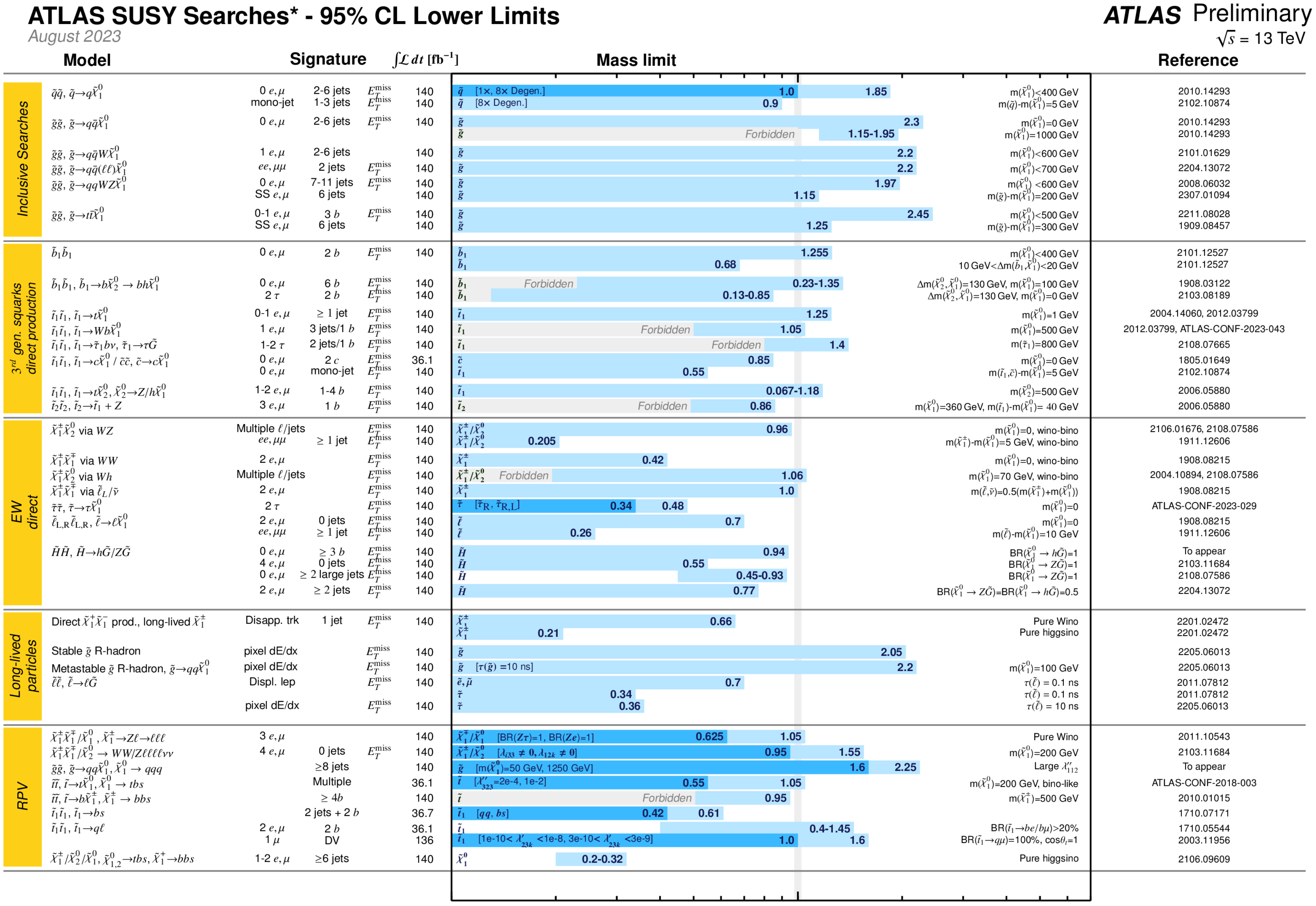
Cross section and partial decay width ratios

Higgs searches: New physics!

- The Higgs boson could be open up portals to new physics
  - E.g. it could preferably decay to new physics particles
  - Or its production could be enhanced by presence of new particles



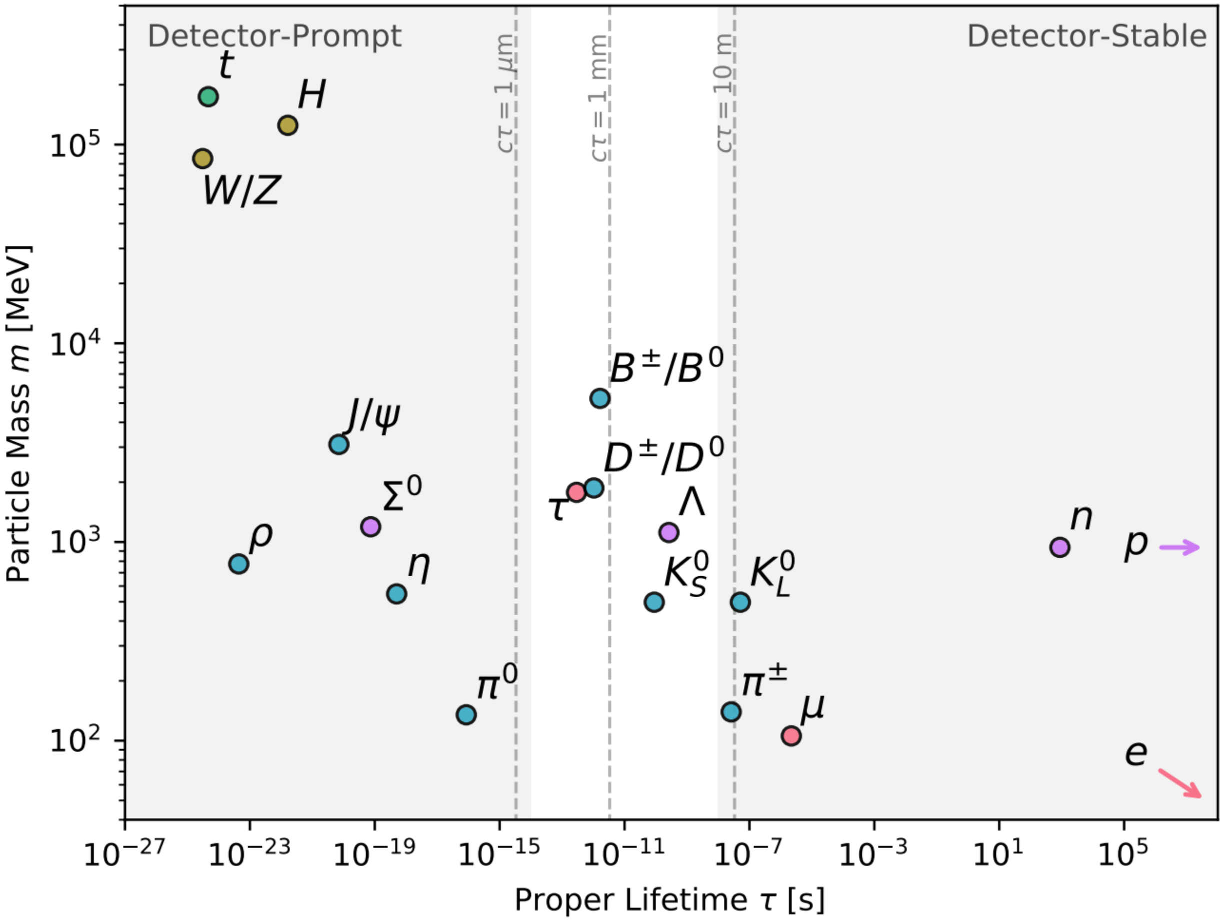
Recent results from searches of H->aa, with a being hypothetical spin-0 particles



*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.

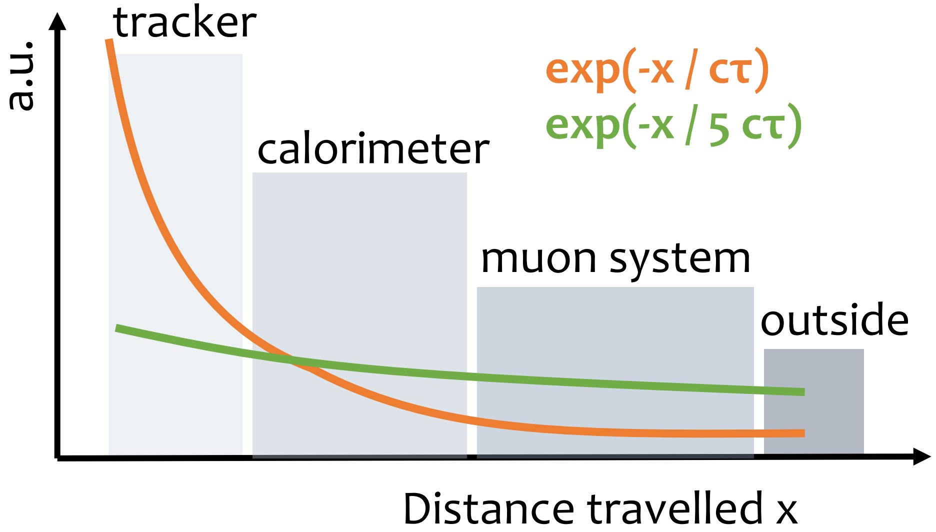
Non-conventional Signatures
e.g. Signatures of long-lived particles

The SM contains a large number of metastable particles

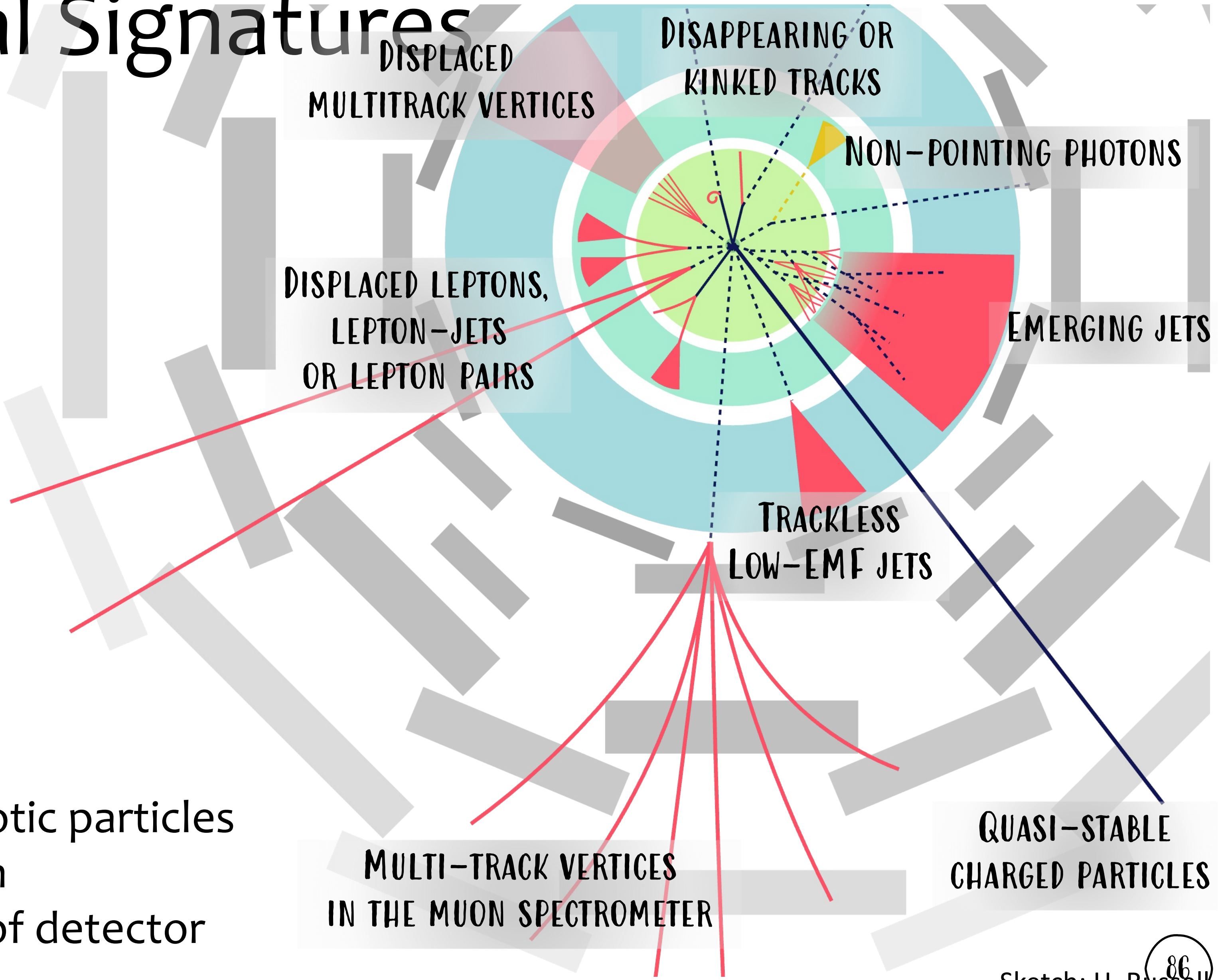


$$\frac{dN}{dt} = -\frac{N}{\tau}$$

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



Non-conventional Signatures



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

Sketch: H. Russell

The ALICE Collaboration