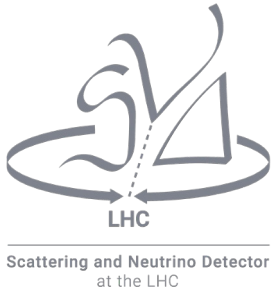
Taking physics FORWARD with



FORWARD and FIXED TARGET experiments at CERN

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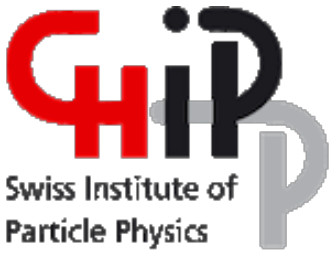
15 Juin 2023



Thanks very much for input to
Paolo Crivelli,
Radoslav Marchevski,
& Lesya Shchutska

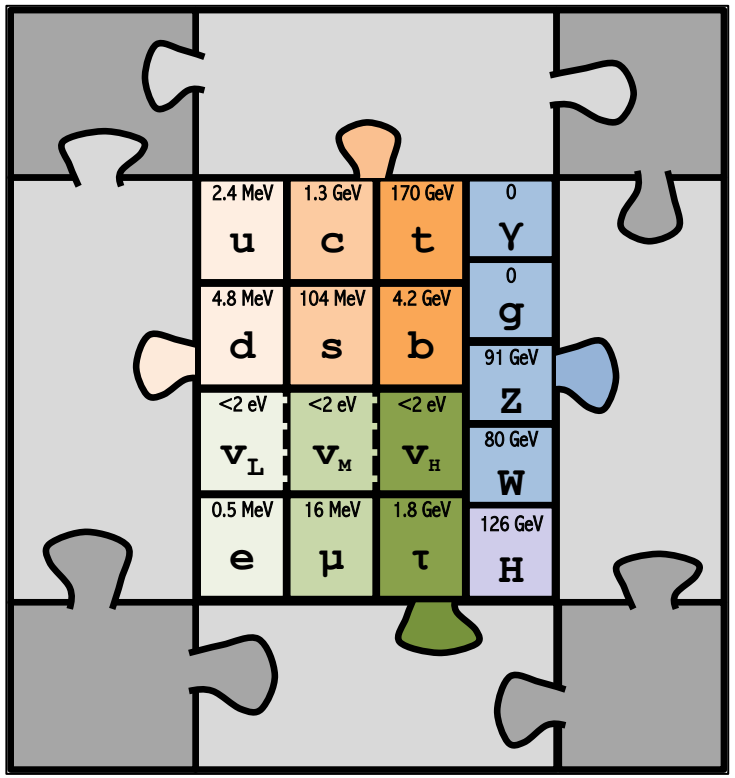
Anna Sfyrla

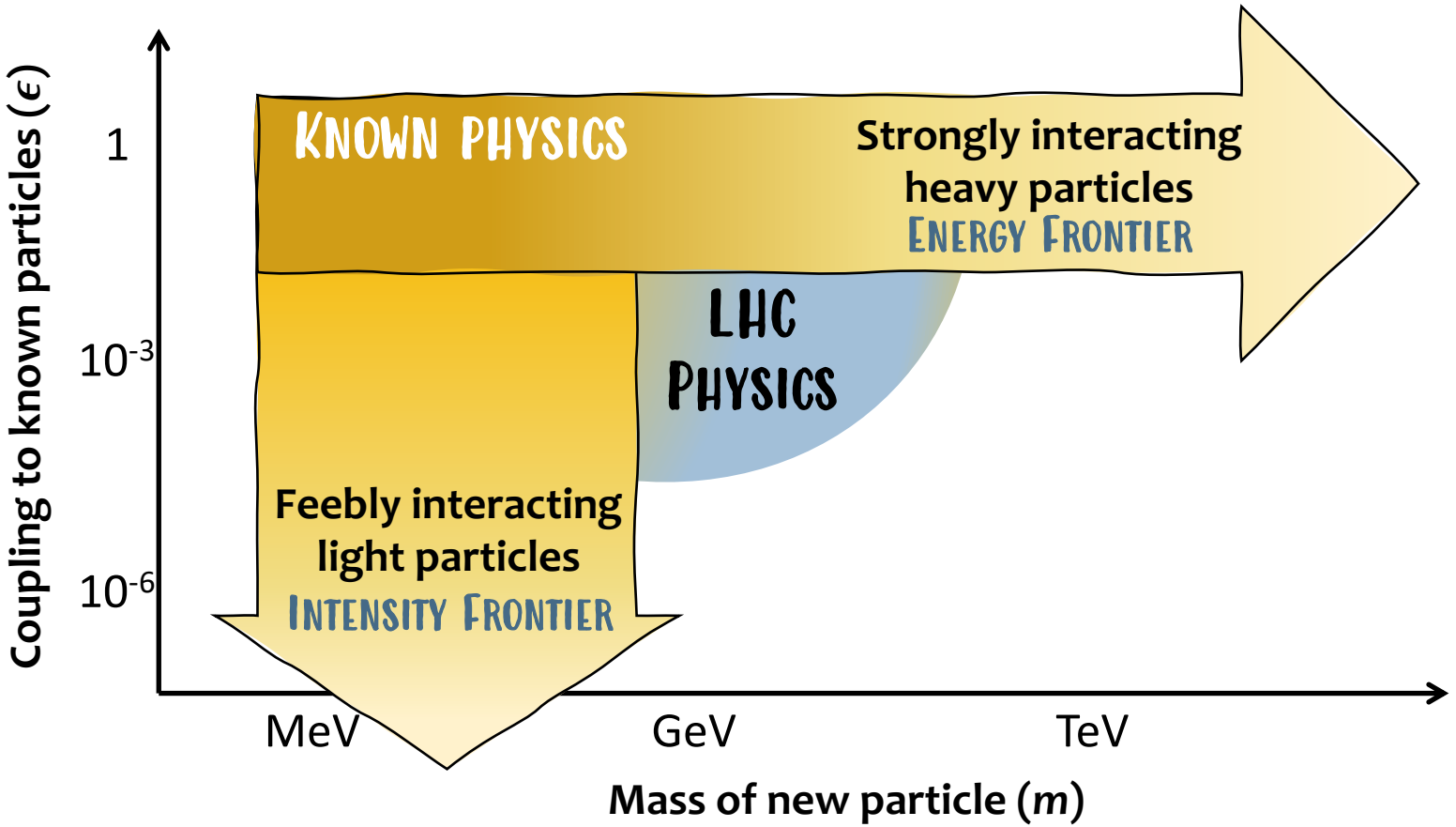
UNIVERSITÉ
DE GENÈVE

FACULTY OF SCIENCE

The landscape of new particles @ colliders

- Collider physics: a plethora of measurements and searches
- The Standard Model is complete and confirmed; Burning questions still remain!



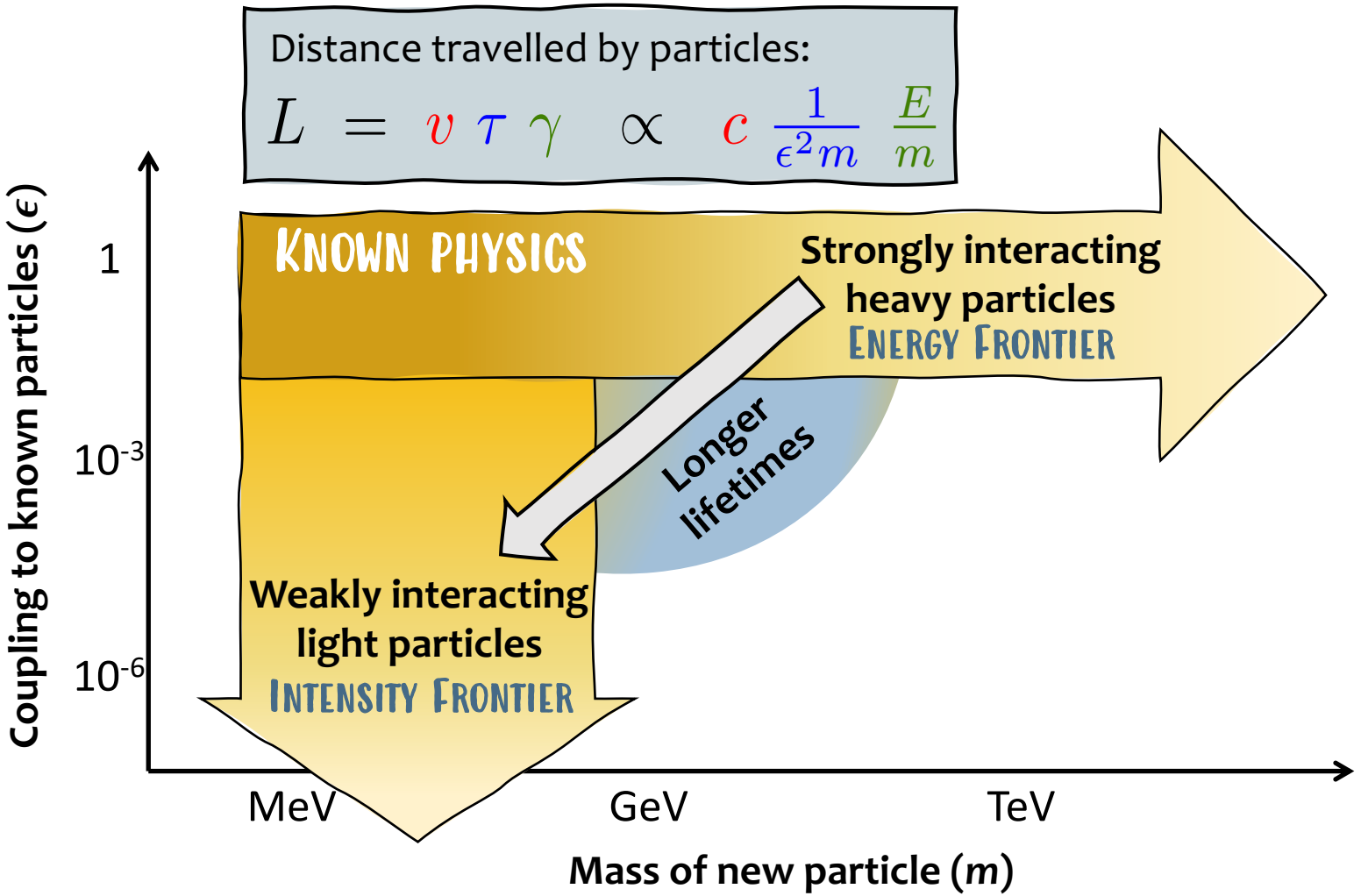


Opportunity #1 : Lifetime

Lifetime
a characteristic of weakly interacting light particles

Distinct signatures

Opportunity for exploration!



Opportunity #2 : Neutrinos !

Why not exploit the enormous number of neutrinos produced at the highest man-made energies ever recorded?

A bit of history

Experiments to study collider neutrinos have been proposed since the 80s, e.g.:

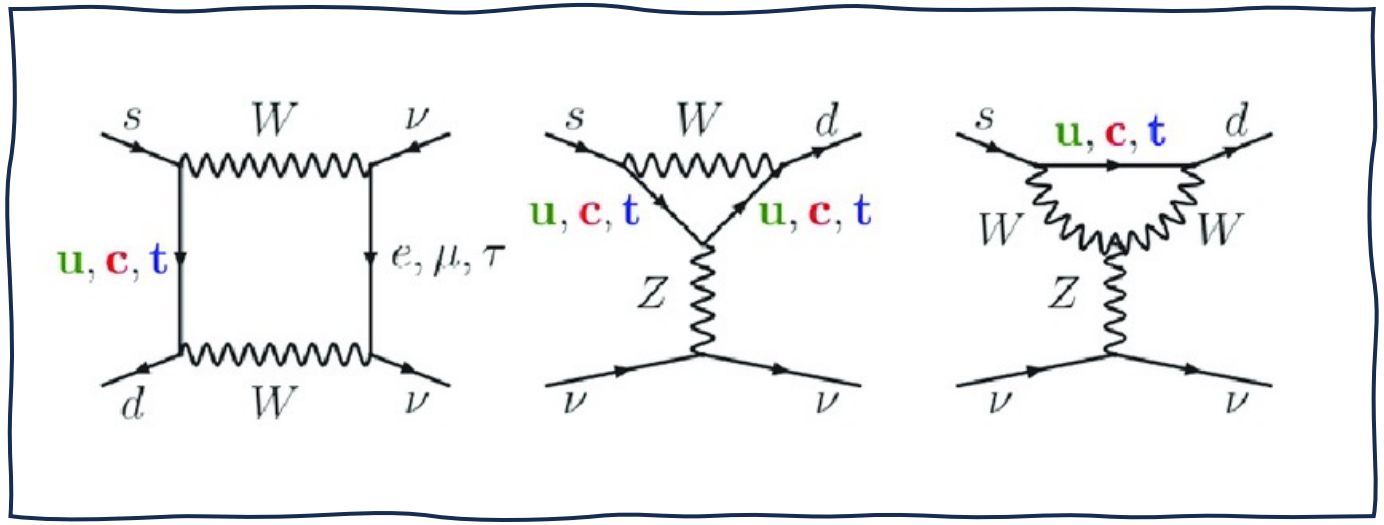
- A. De Rujula and R. Ruckl, "**Neutrino and muon physics in the collider mode of future accelerators**" ECFA-CERN Workshop on large hadron collider in the LEP tunnel, pp. 571–596, **1984.**
- Klaus Winter, **"Observing tau neutrinos at the LHC"**, LHC workshop, **1990.**

Opportunity #3 : Rare SM processes linked to BSM

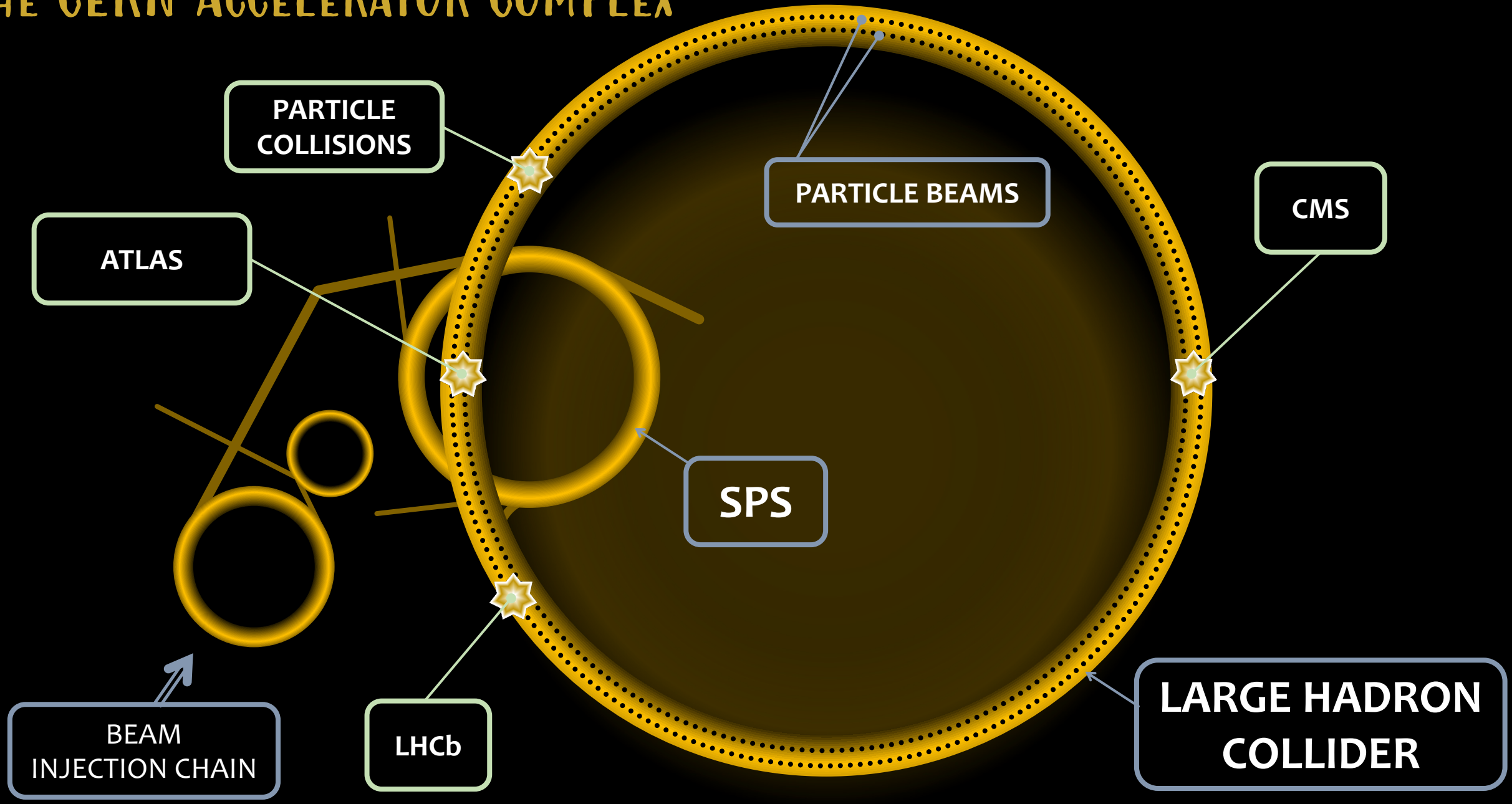
Particularly suppressed rare phenomena in the SM, not yet probed enough, could be linked to new physics. E.g. kaon decays.

s → d quark transition: loop + CKM suppressed, very rare in the SM

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = 7.73(61) \times 10^{-11} \text{ and } \mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = 2.59(29) \times 10^{-11}$$

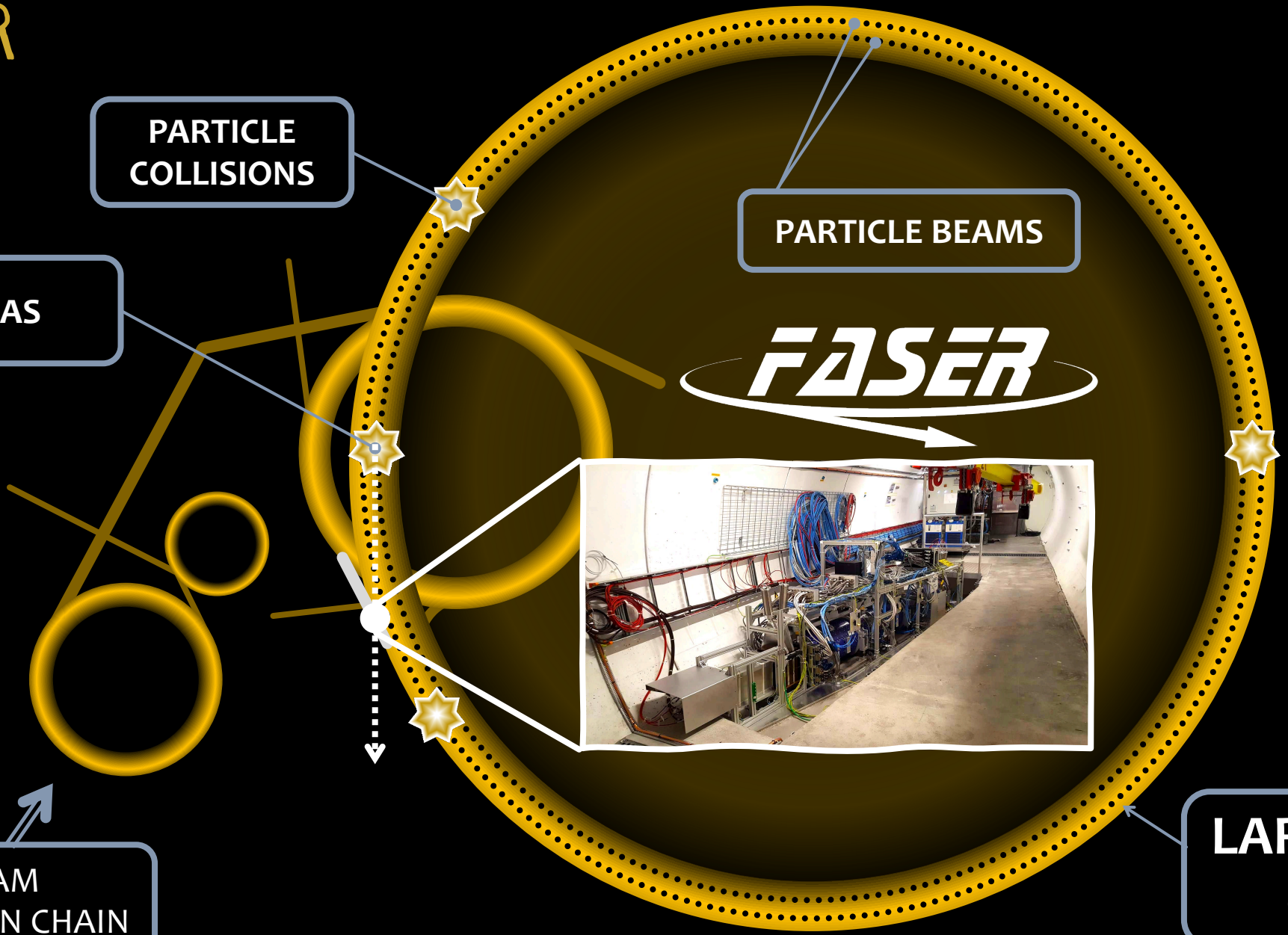


The CERN Accelerator Complex



Further explorations via much smaller and much cheaper experiments
Exploiting to the maximum the amazing CERN accelerator complex

FASER


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

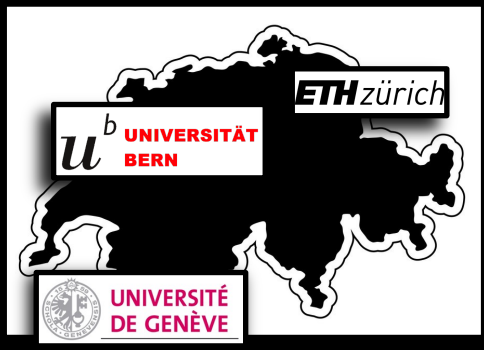
FASER

PARTICLE COLLISIONS

ATLAS

PARTICLE BEAMS

FASER

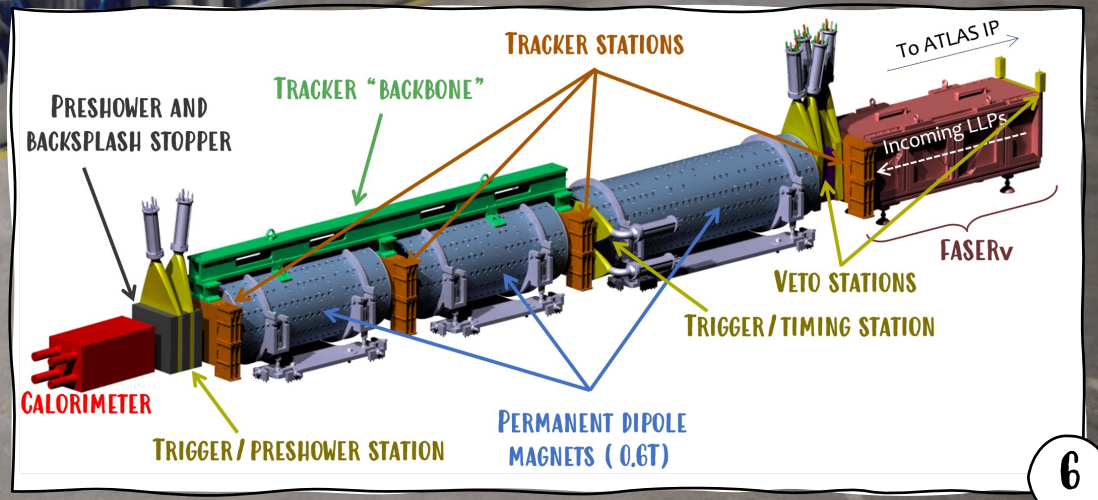


BEAM INJECTION CHAIN

LARGE HADRON COLLIDER

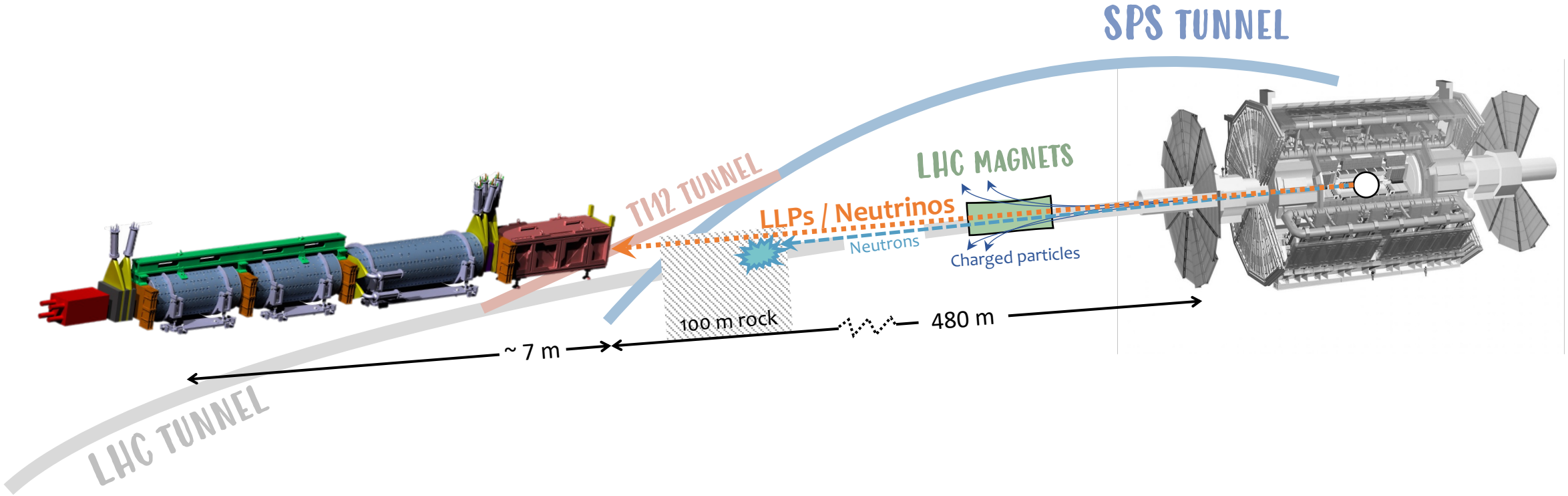

CMU 2t
ATTENTION
TENSION
DANGER
FASER
FASER

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



FORWARD SEARCH EXPERIMENT AT THE LHC

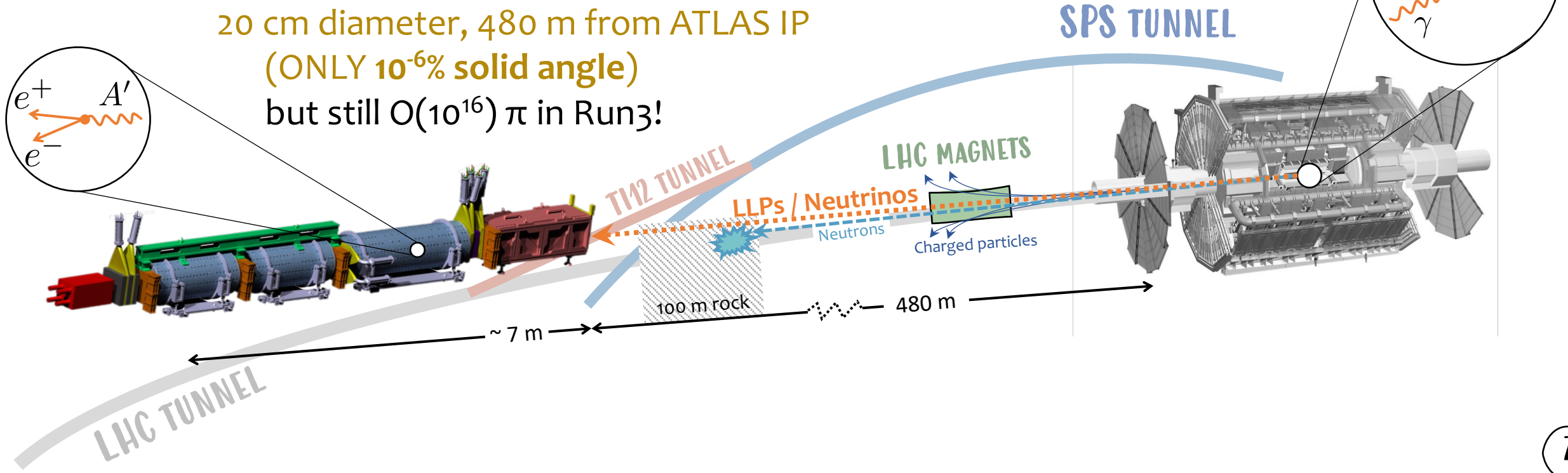
Primary goal: Searches for new weakly interacting light particles, coupling to SM via mixing with SM "portal" operator



FORWARD SEARCH EXPERIMENT AT THE LHC

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!



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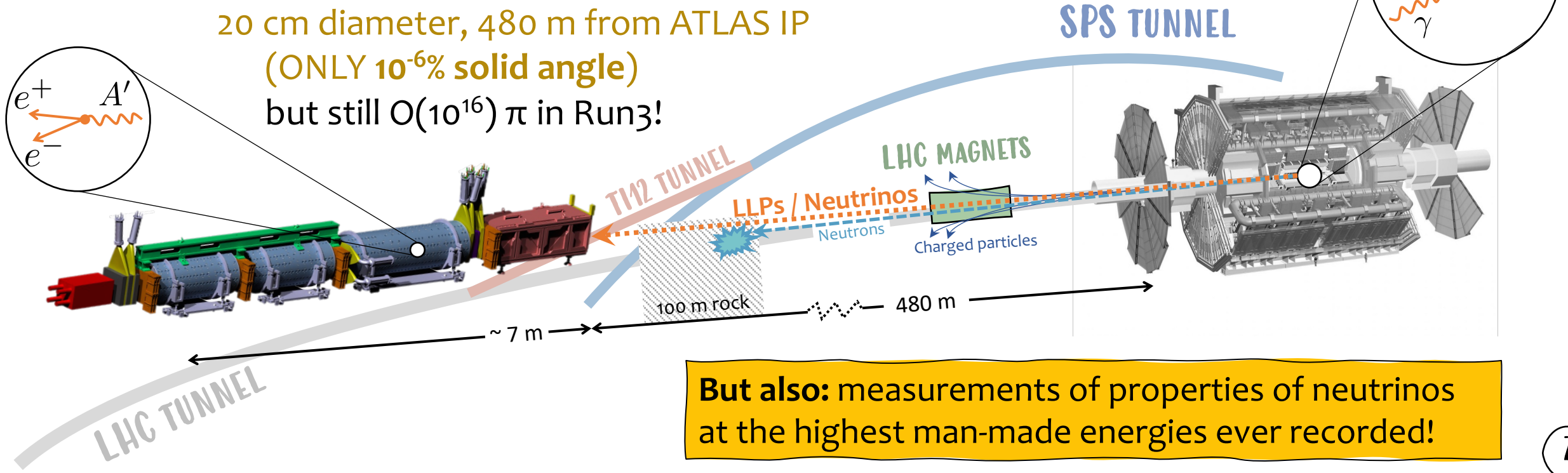
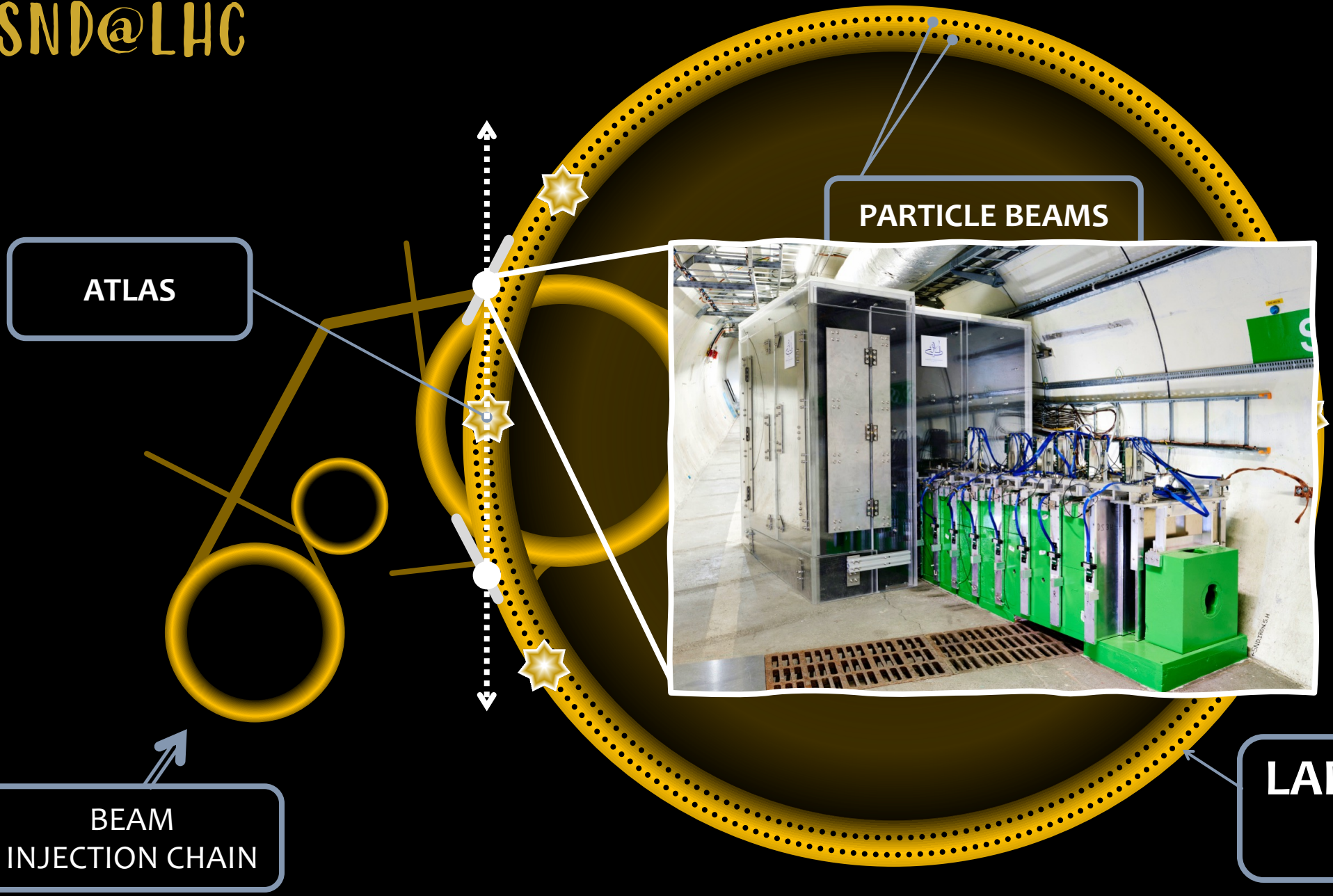
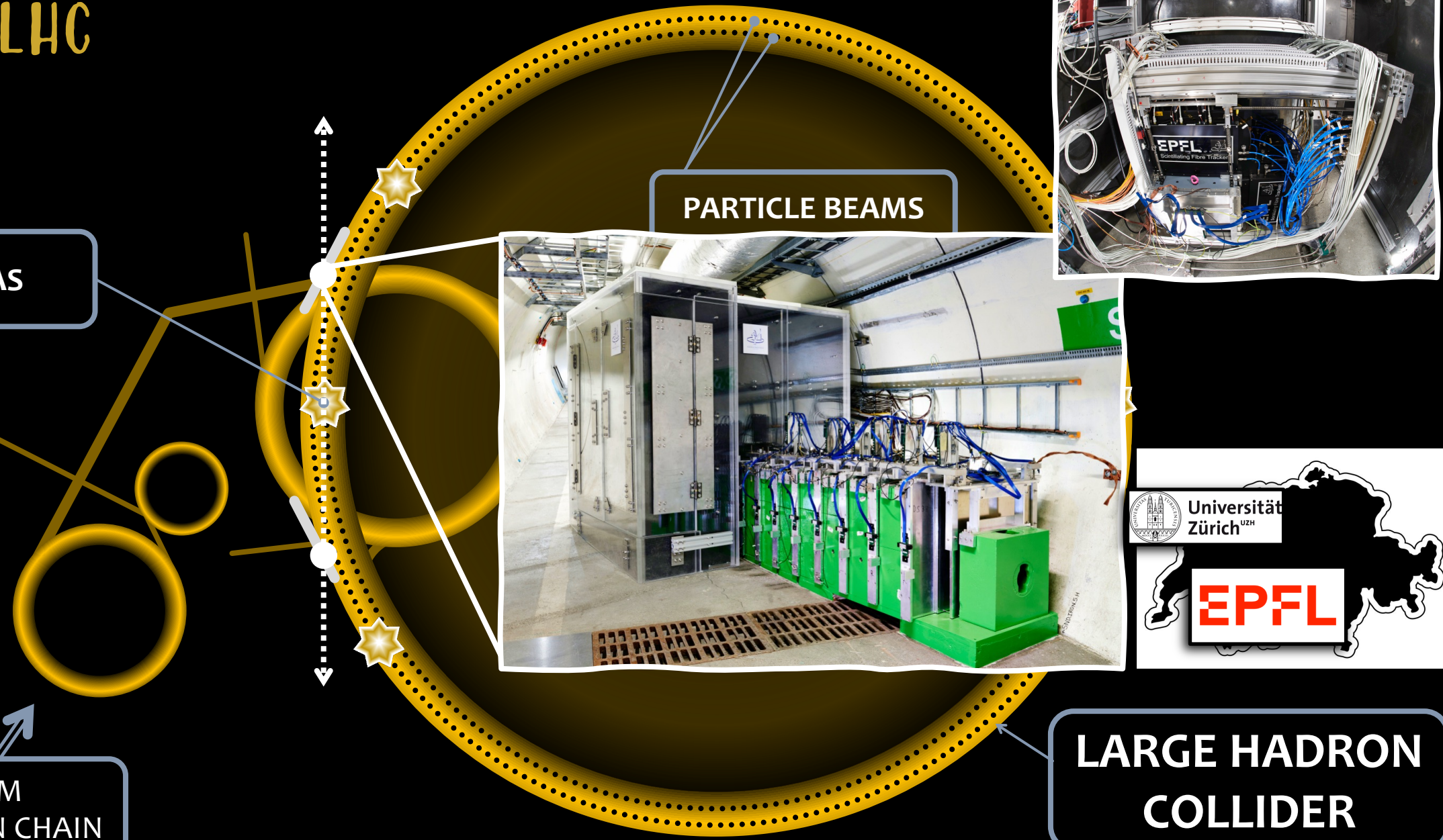


But also: measurements of properties of neutrinos at the highest man-made energies ever recorded!

SND@LHC

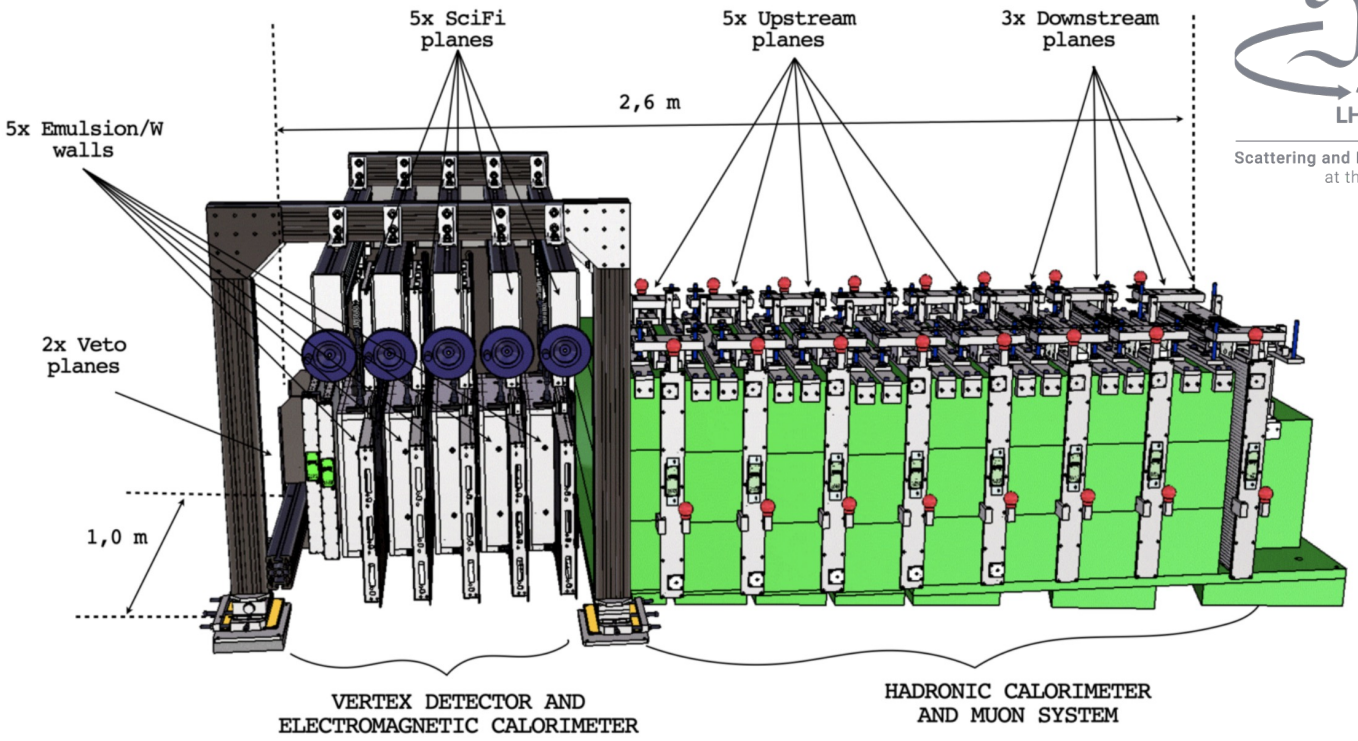

PARTICLE BEAMS
ATLAS
BEAM
INJECTION CHAIN
LARGE HADRON
COLLIDER

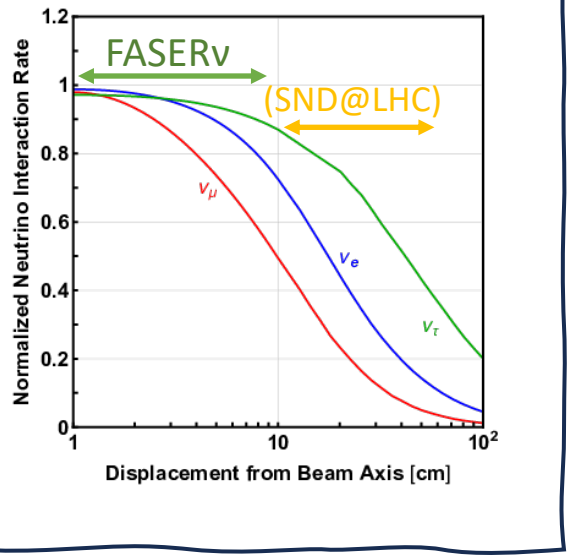
SND@LHC

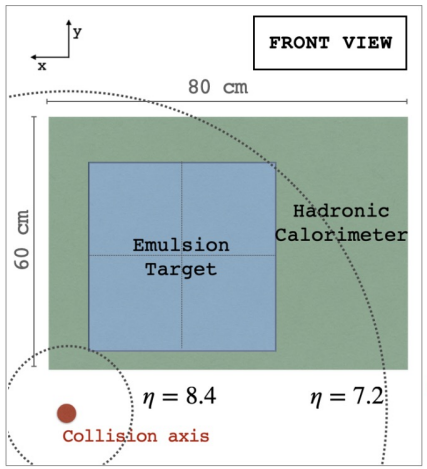

ATLAS
PARTICLE BEAMS
BEAM
INJECTION CHAIN
LARGE HADRON
COLLIDER
EPFL
Scintillating Fibre Tracker
Universität
Zürich[UZH]
EPFL

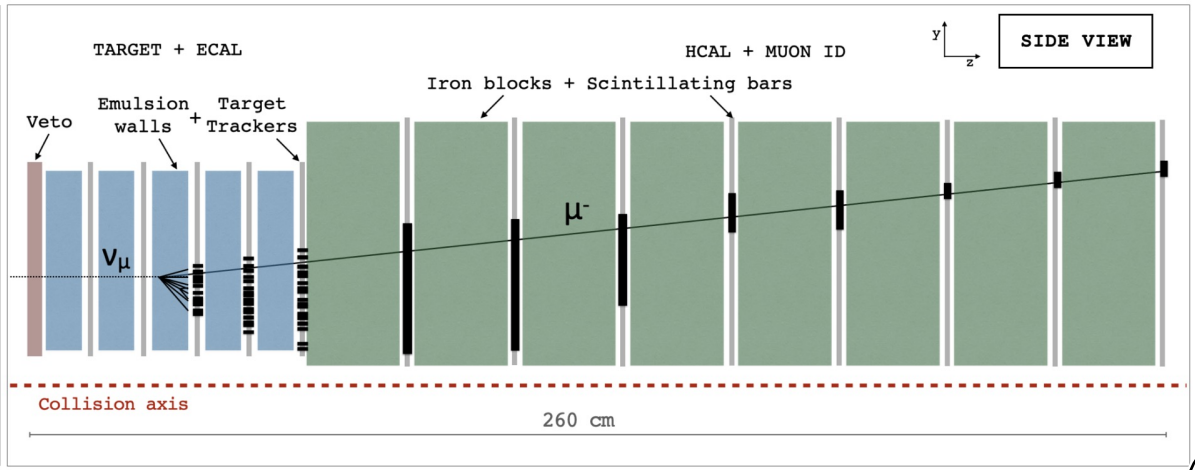
Scattering and Neutrino Detector at the LHC

Primary goal: Measurement of neutrinos from the LHC

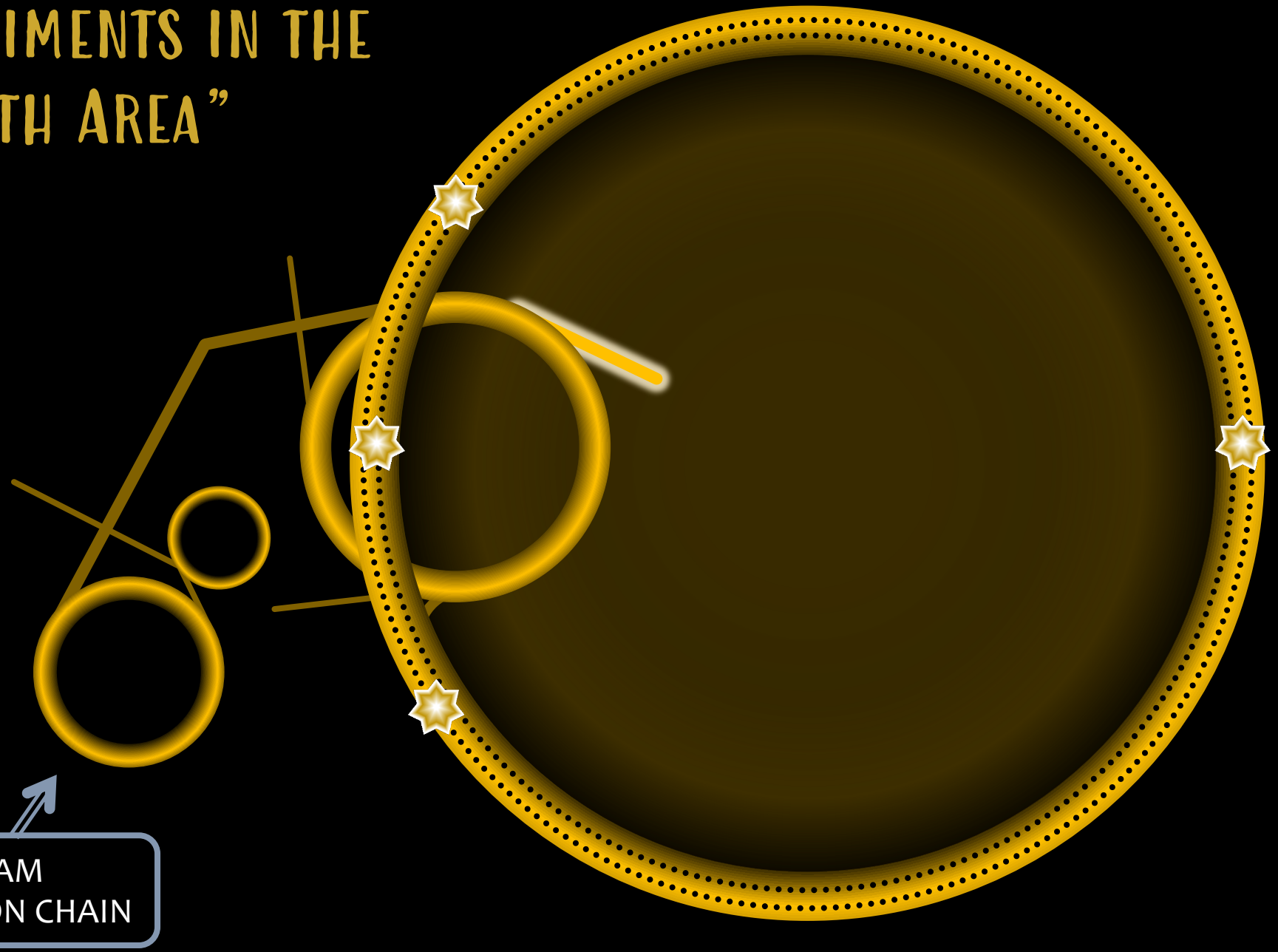




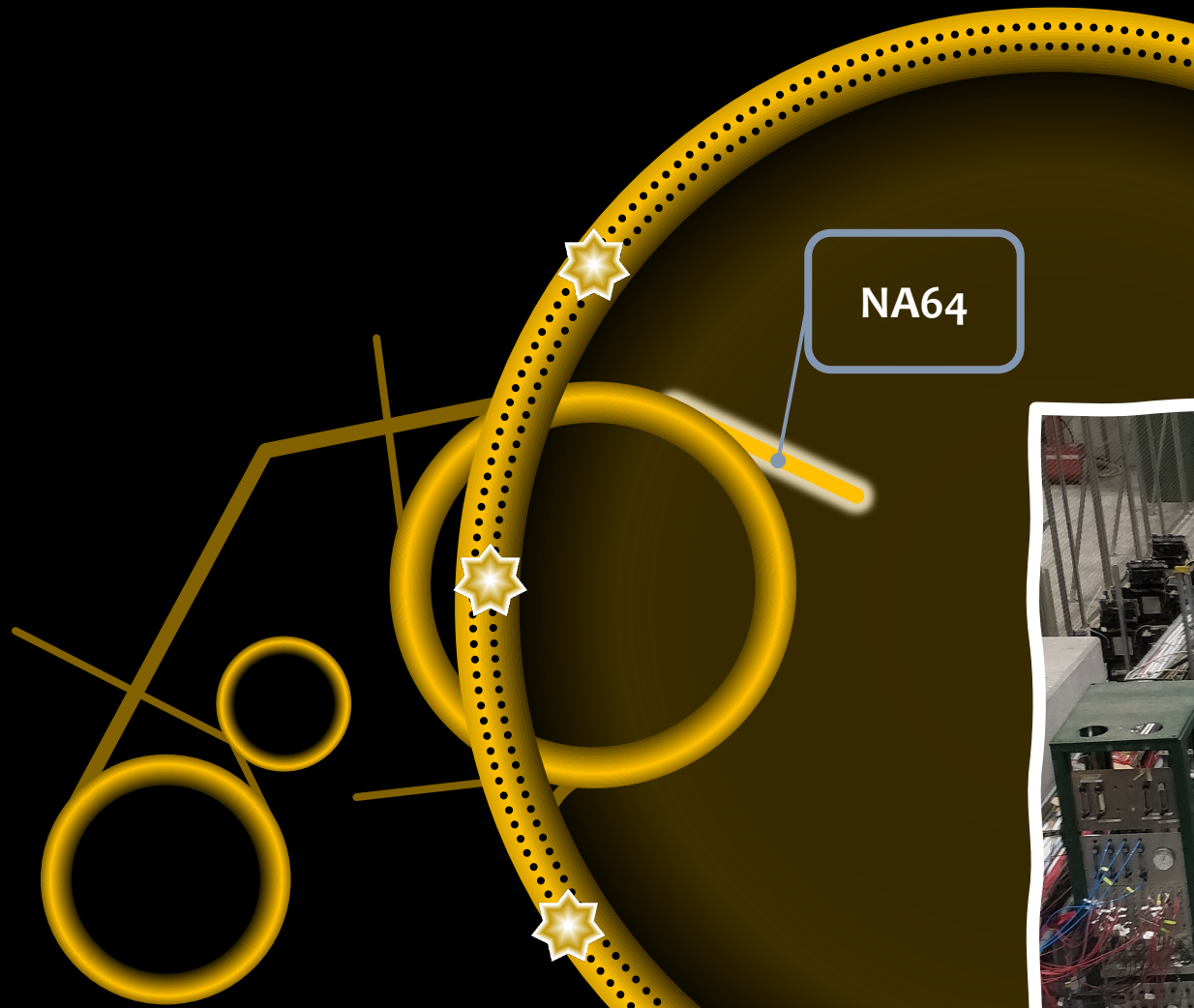




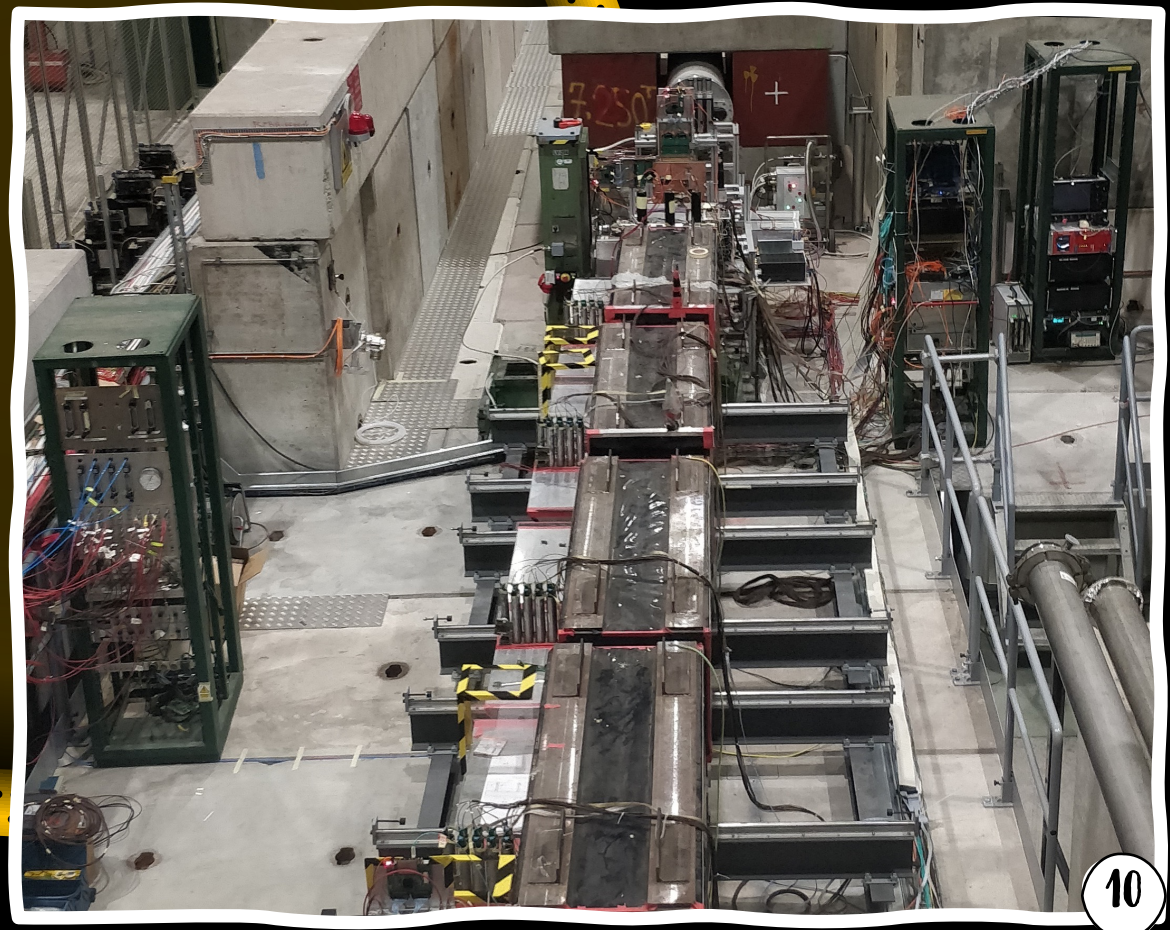
Experiments in the "North Area"



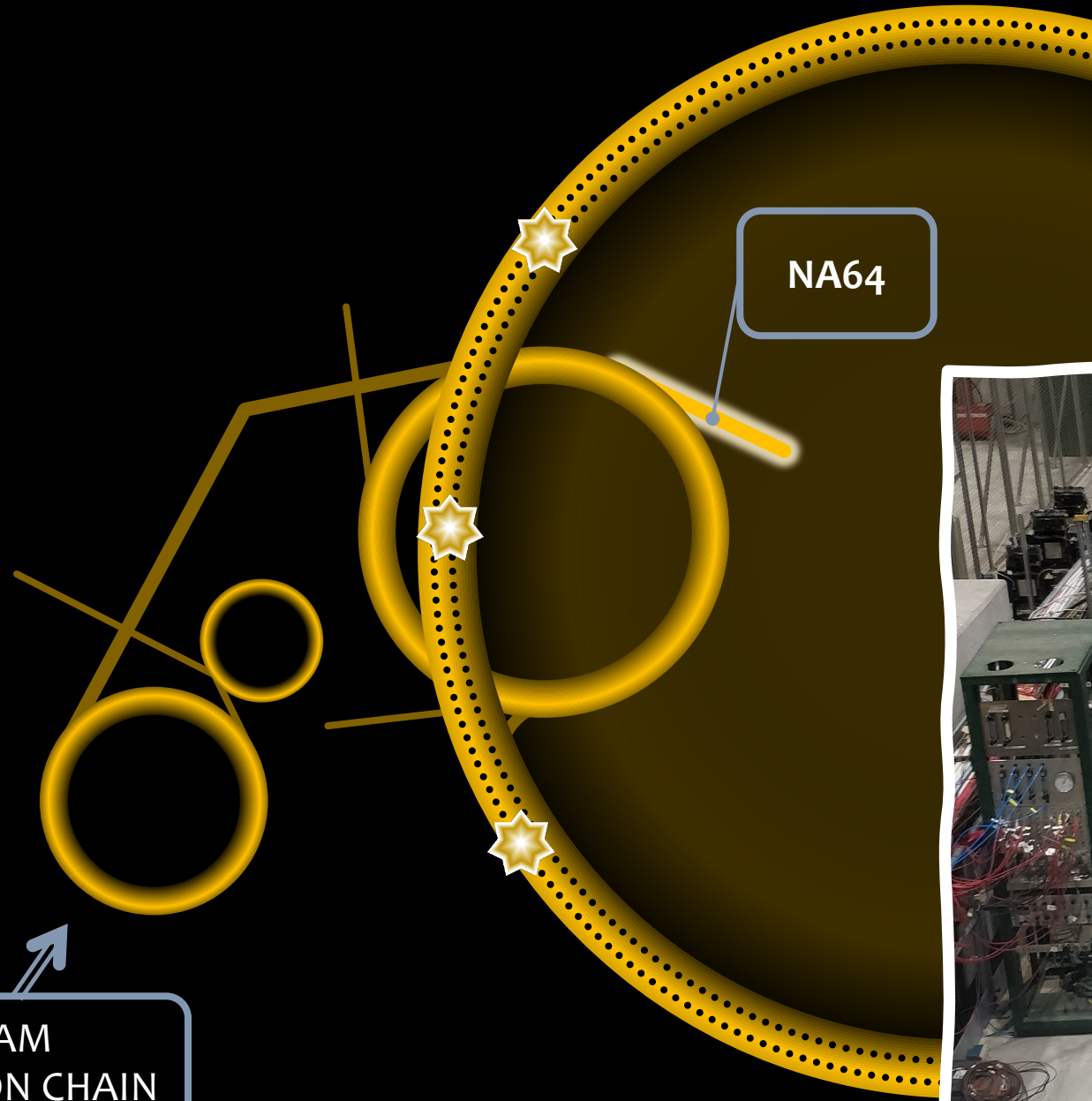
NA64



New area dedicated to NA64
prepared by CERN during LS2

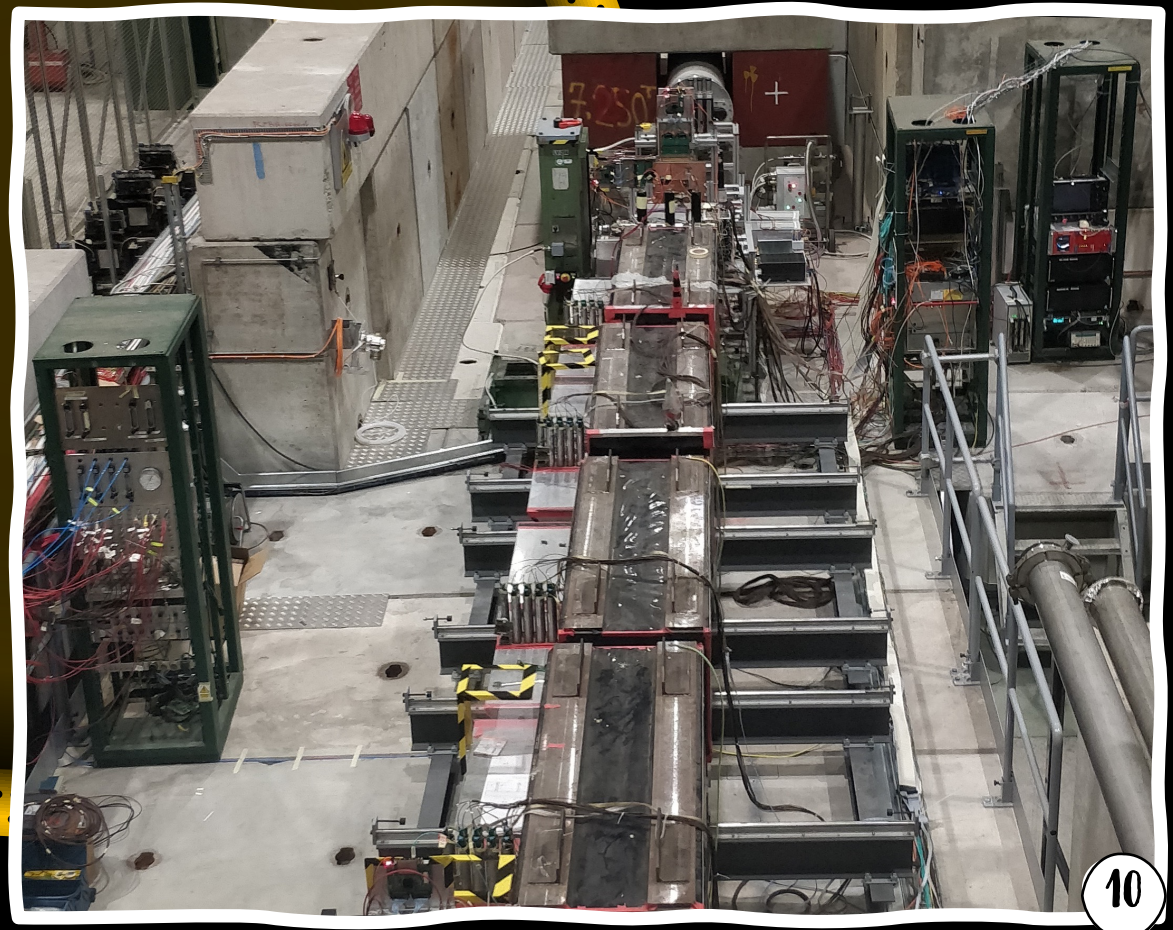


NA64



ETH zürich

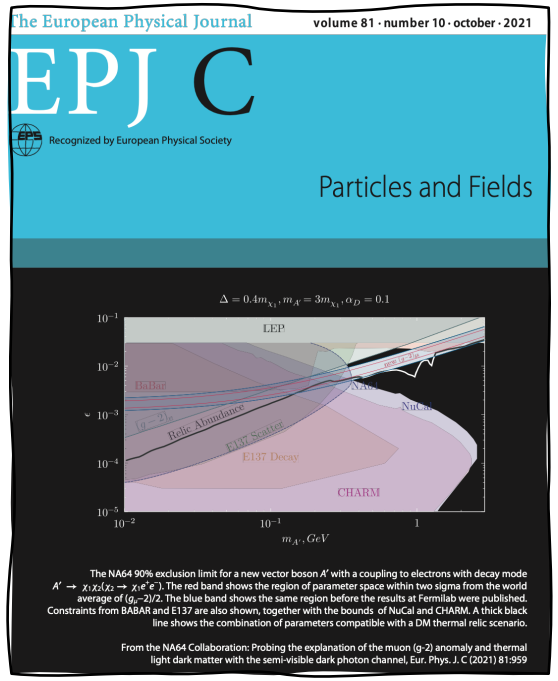
New area dedicated to NA64
prepared by CERN during LS2

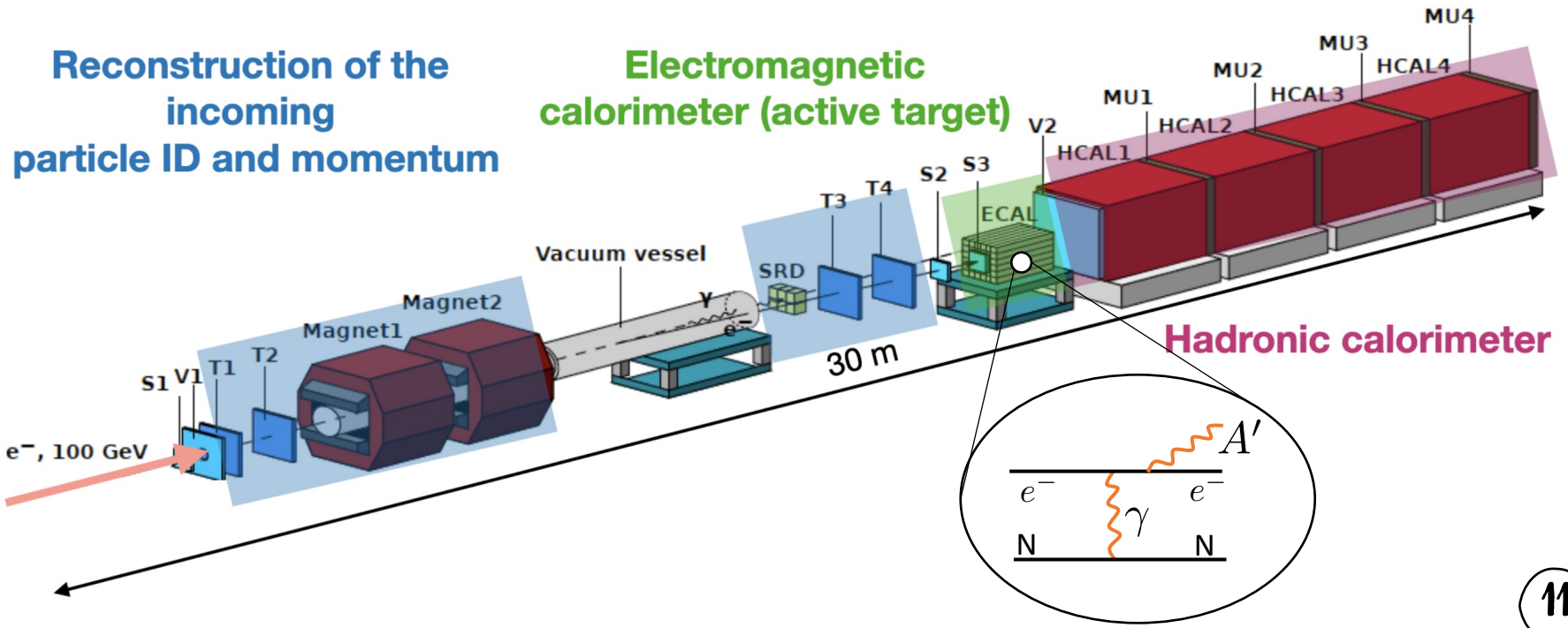


North Area Experiment #64

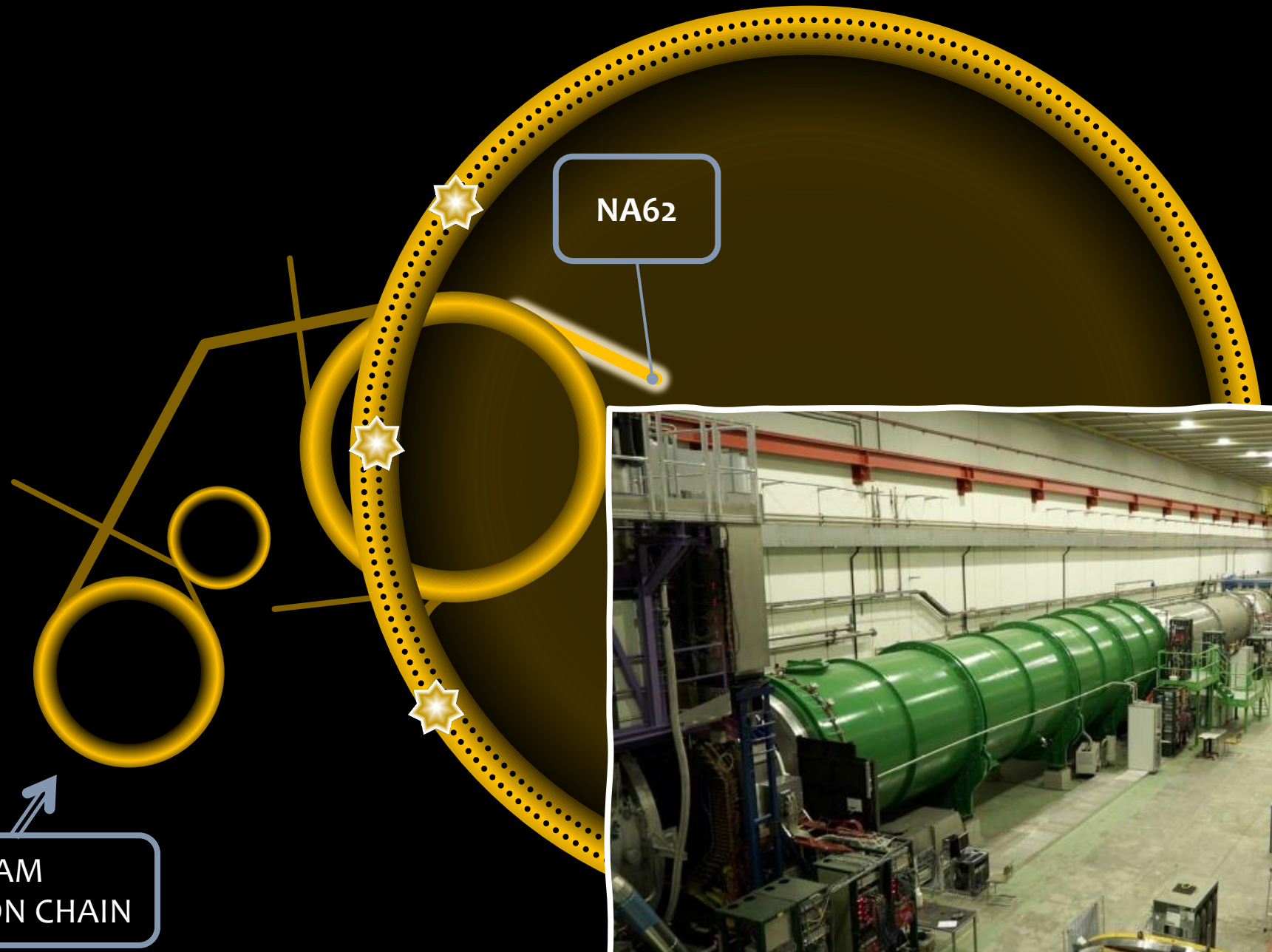
Primary goal: search for DARK SECTORS and light thermal dark matter (LTDM) with e/mu and hadron beams at the CERN SPS.

2016-2018: 2x10^{11} electrons-on-target leading sensitivity in MeV-GeV region for Dark photons, ALPs, generic X bosons, new Z', dark scalars, inelastic dark matter (*10 PRLs + >20 other publications*)
In 2022: 10^{12} electrons-on-target achieved! Pilot runs with muons, positrons and hadrons.

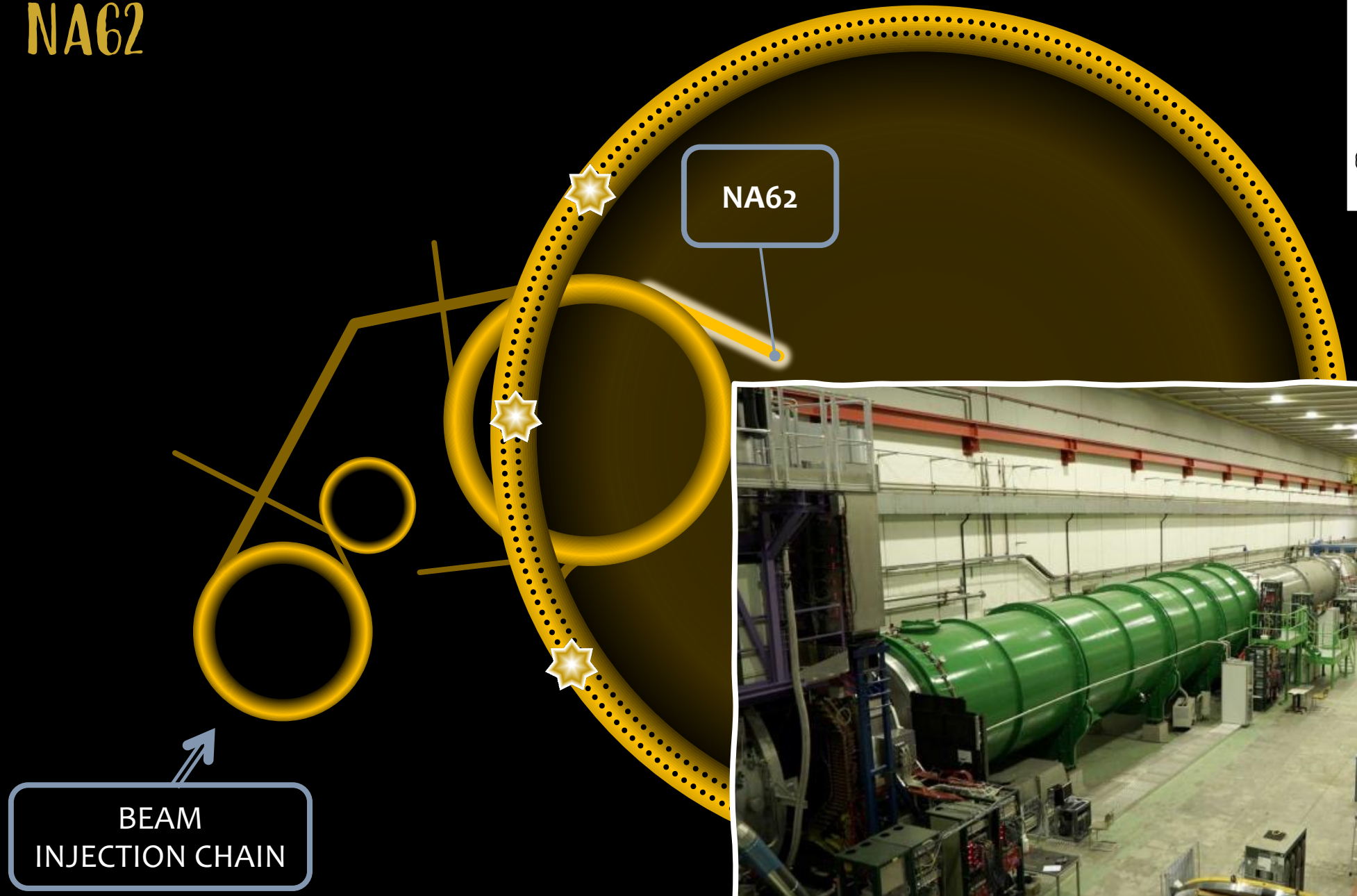


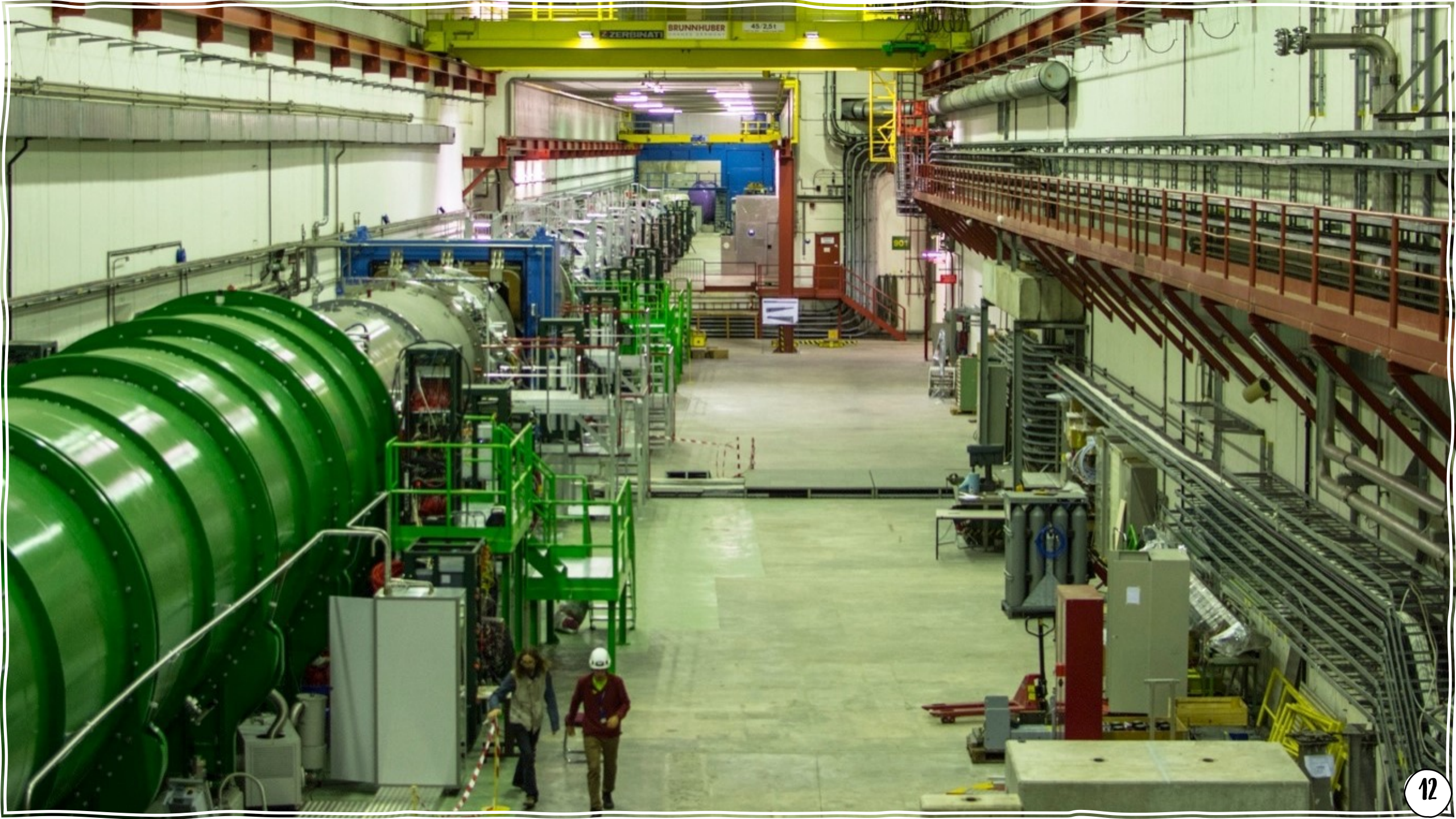


NA62



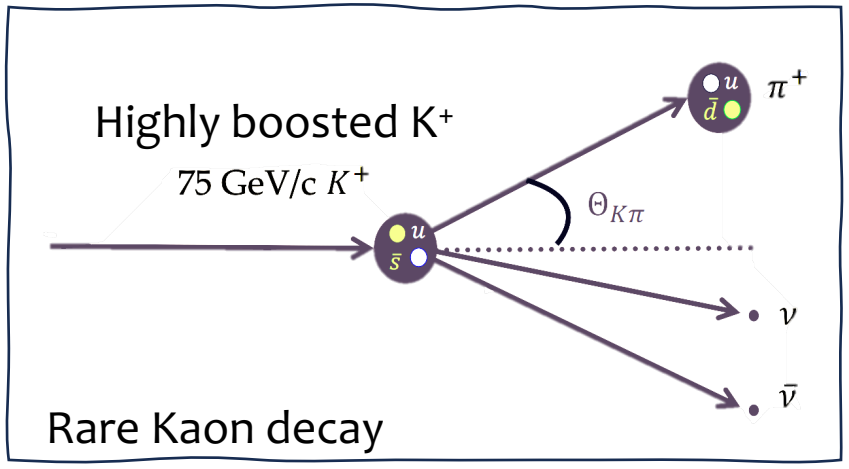
NA62

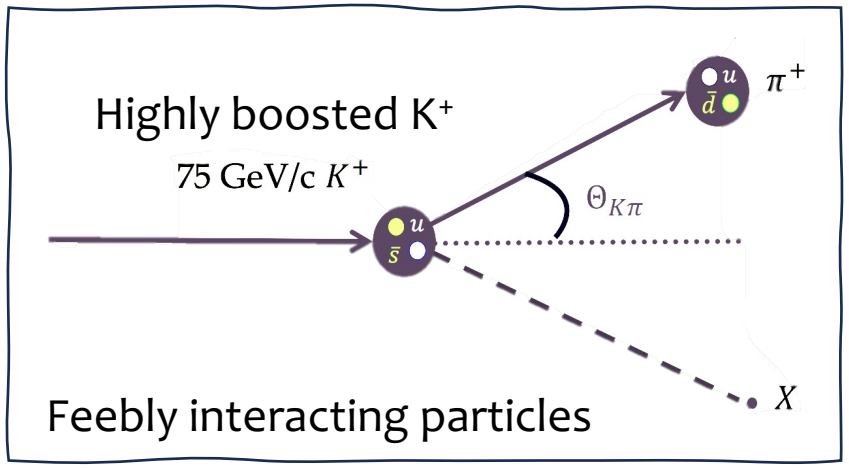



BRUNNHUBER
45/2,5t

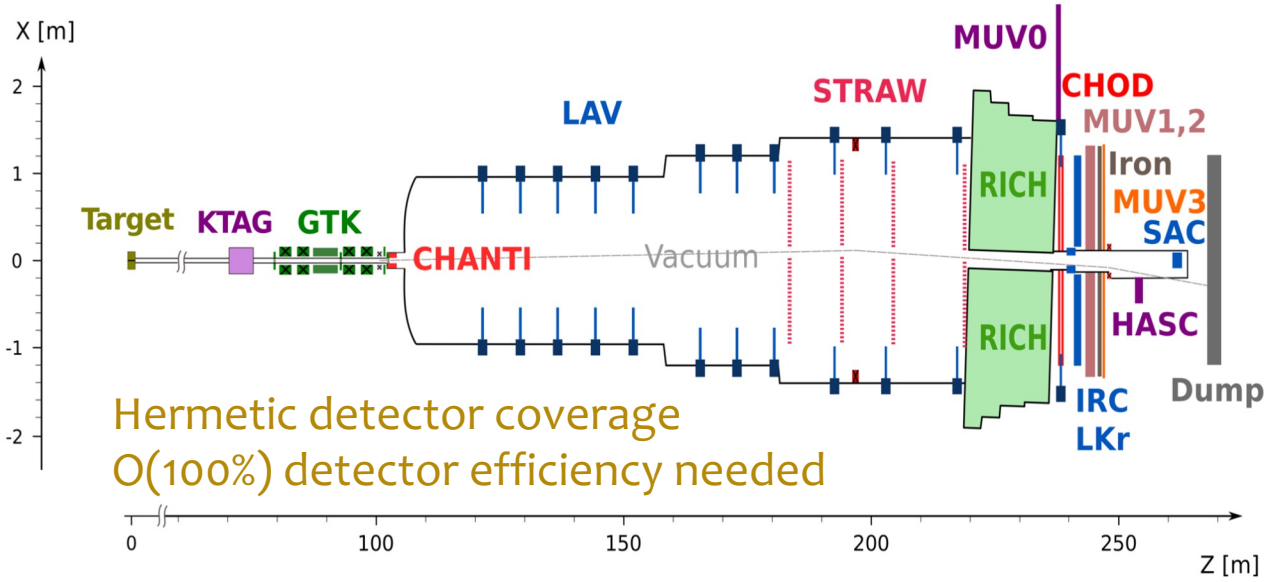
North Area Experiment #62

Key observable: $m^2 = P_K^2 - P_\pi^2$





- **Primary goal:** Rare Kaon decay measurement $K^+ \to \pi^+ \nu \bar{\nu}$
- Other rare charged kaon decays (e.g. $K^+ \to \pi^+ l^+ l^-$, $K^+ \to \pi^+ \gamma\gamma$)
- Precision measurements (radiative decays, LFU tests, $|V_{us}/V_{ud}|$, etc…)
- LFV/LNV searches
- Exotic searches (FIPs, Dark photon, HNL, etc…)

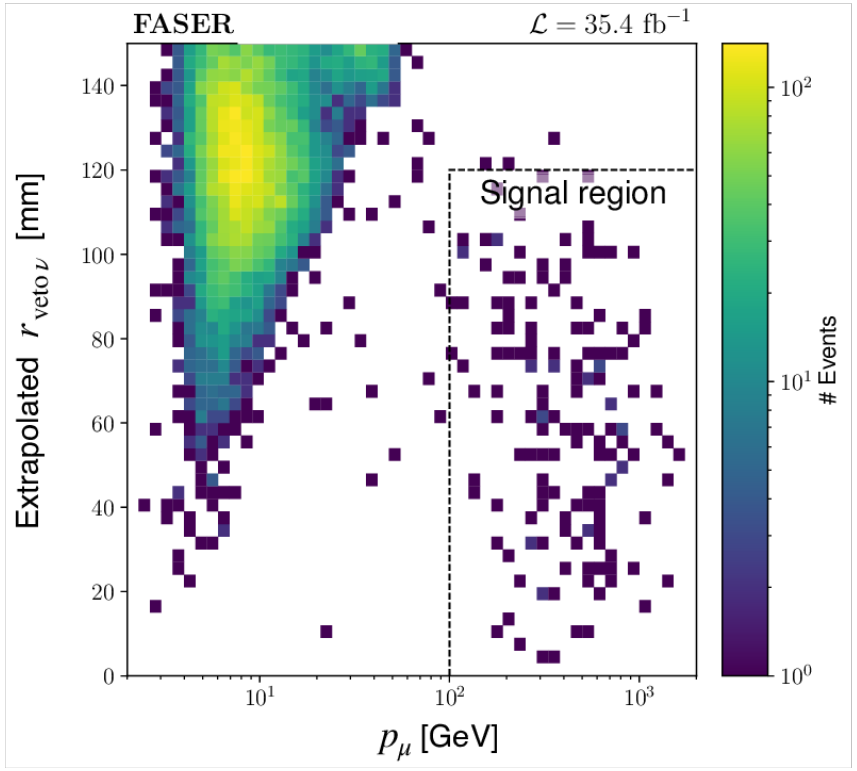


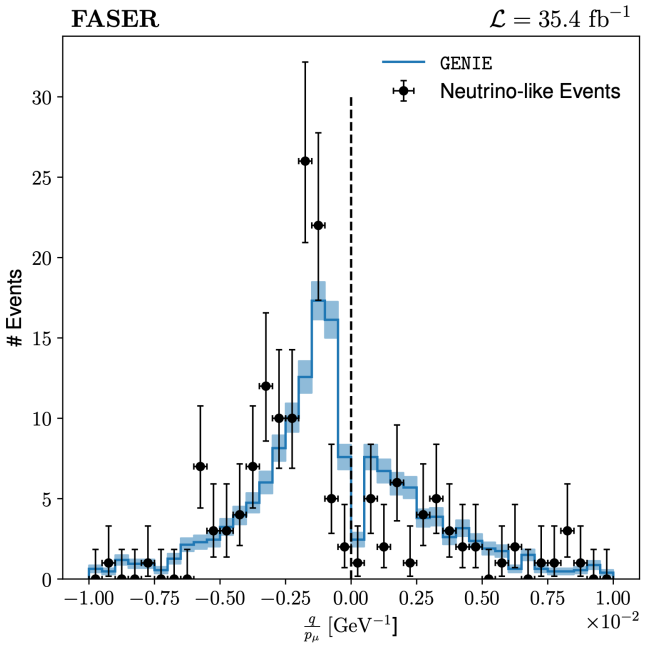
Highlights from recent results

First Direct Detection of Collider Neutrinos

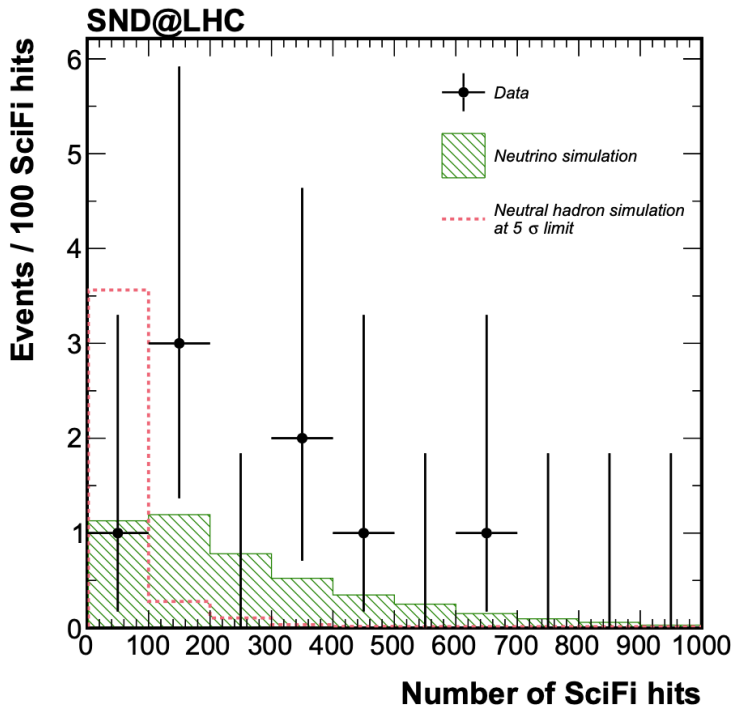
FASER: 153 events ⟹ ≫ 5σ significance
Background ~ 0.2 events

8 events ⟹ > 5σ significance
Background < 0.1 events



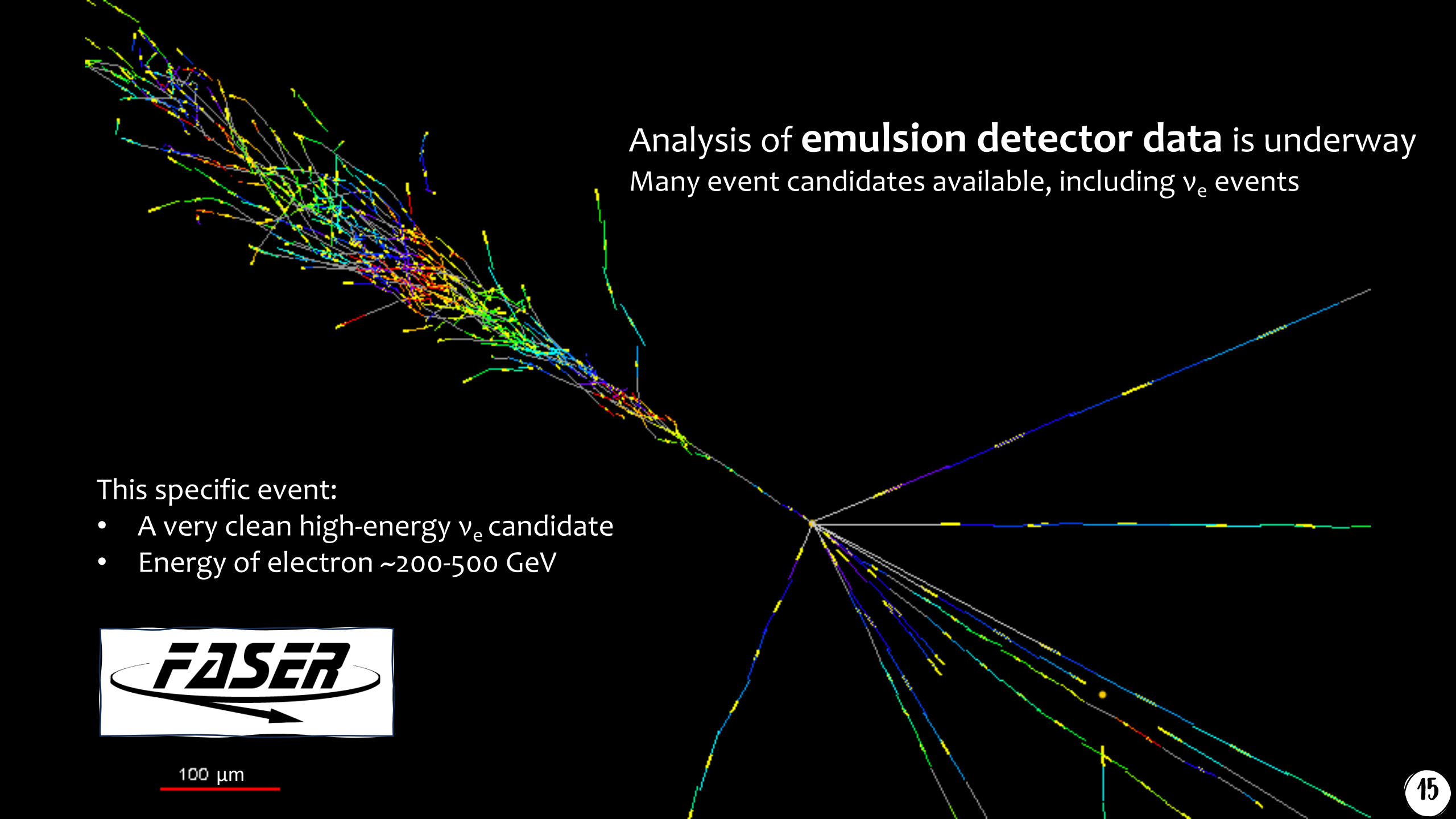


First evaluation of properties



arXiv: 2303.14185, accepted by PRL

arXiv: 2305.09383, submitted to PRL



Analysis of **emulsion detector data** is underway

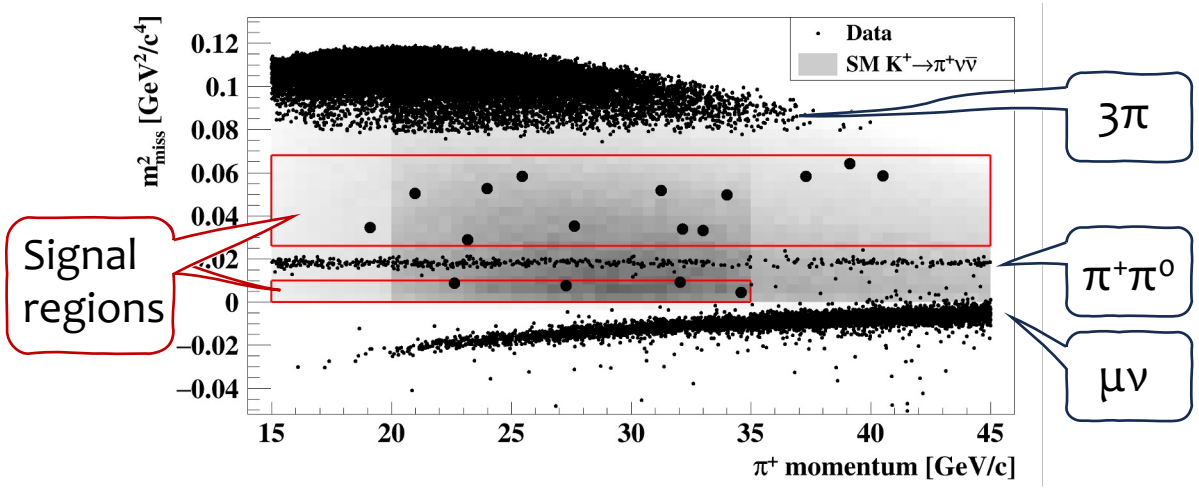
Many event candidates available, including ν_e events

This specific event:

- A very clean high-energy ν_e candidate
- Energy of electron ~200-500 GeV

Rare Kaon Decays

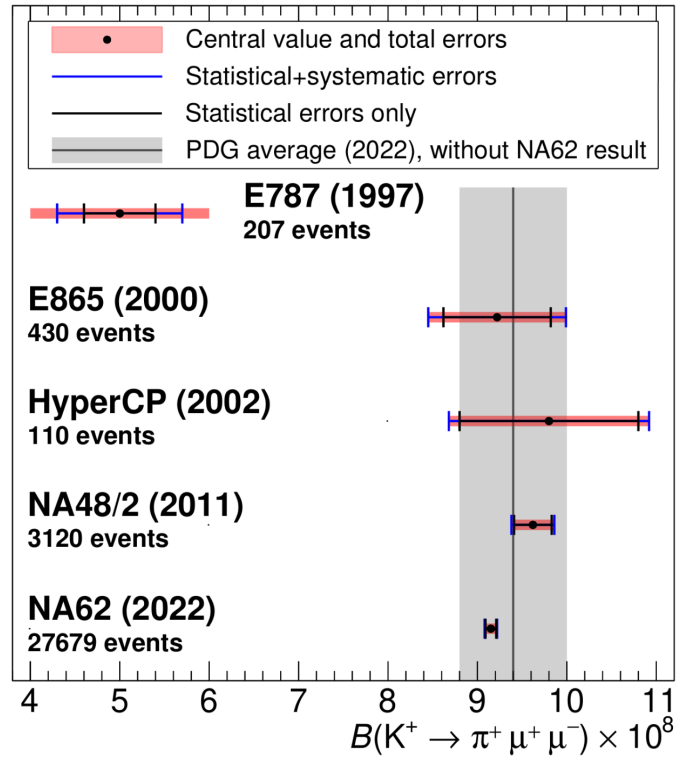
3.4 σ significance on $K^+ \to \pi^+ \nu\bar{\nu}$



- Combining the complete Run 1 data set (2016-18)
  - $N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
  - $N^{exp}_{bg} = 7.03^{+1.05}_{-0.82}$
  - $BR\,(SM^{exp}) = (8.4 \pm 0.5_{syst}) \times 10^{-11}$
- 20 events observed in signal region in NA62 Run 1 data
- $\boldsymbol{BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}}$

JHEP 06 (2021) 093

Very precise $BR(K^+ \to \pi^+ \mu^+ \mu^-)$

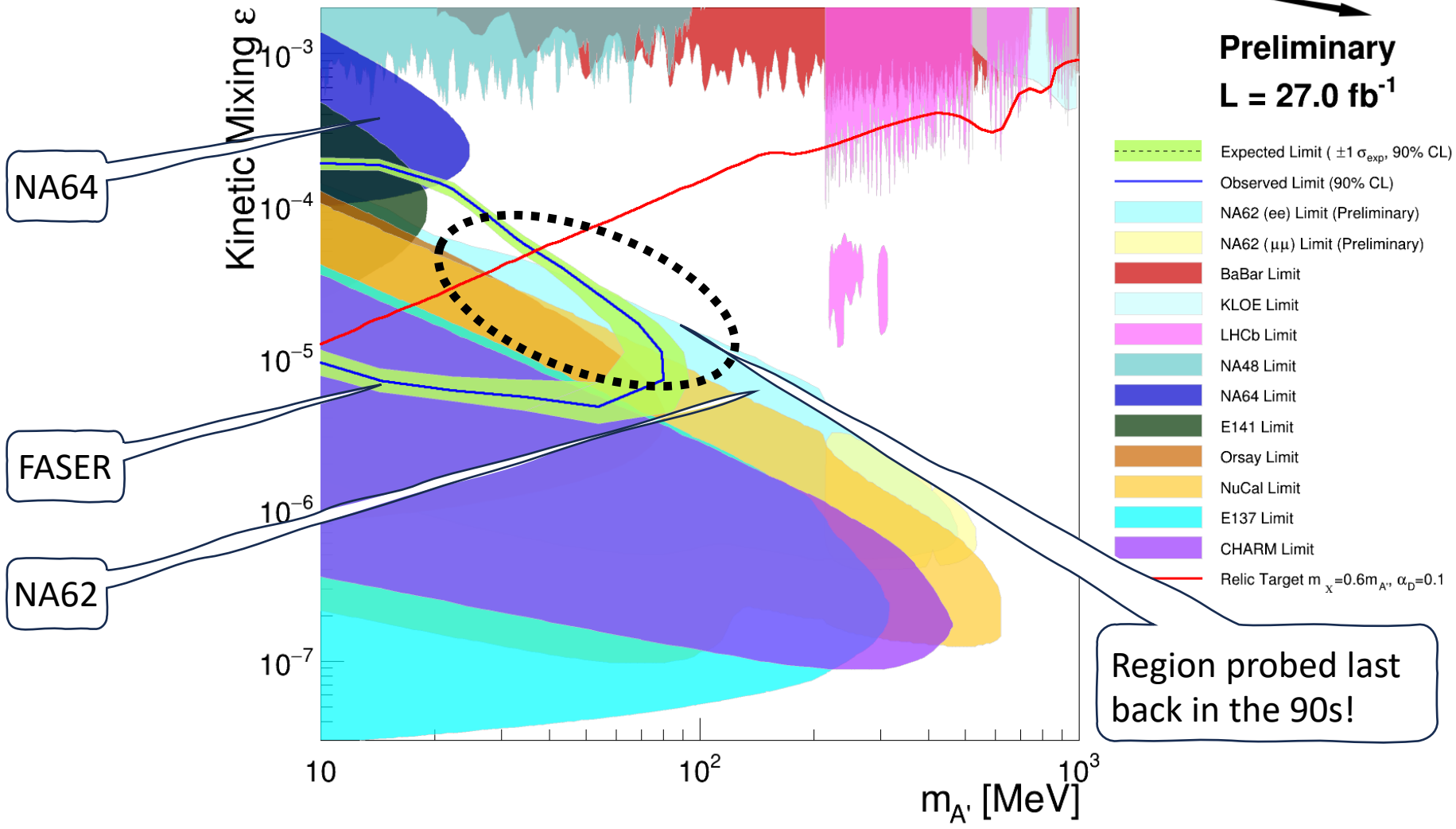


After signal selection:

- $N_{obs} = 27\,679$ events
- $N^{exp}_{bg} = 8$ events
- $\boldsymbol{BR(K^+ \to \pi^+ \mu^+ \mu^-) = (9.15 \pm 0.06_{stat}) \times 10^{-8}}$

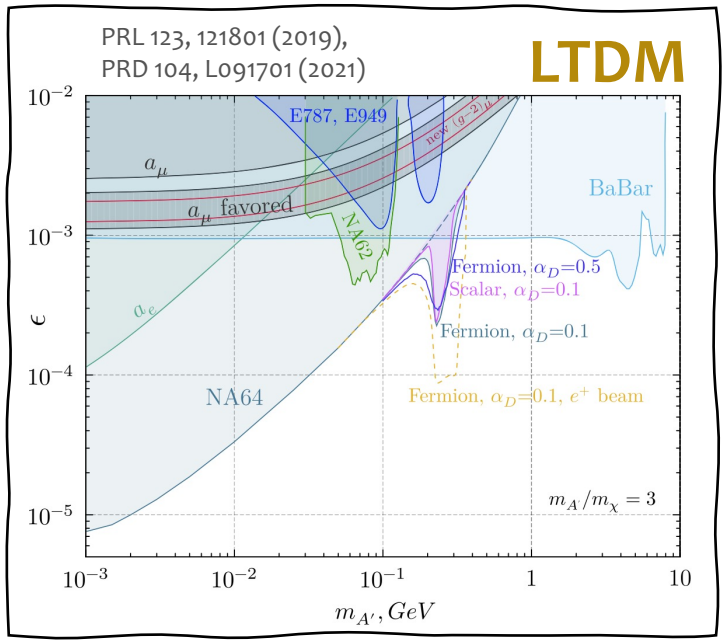
JHEP 11 (2022) 011

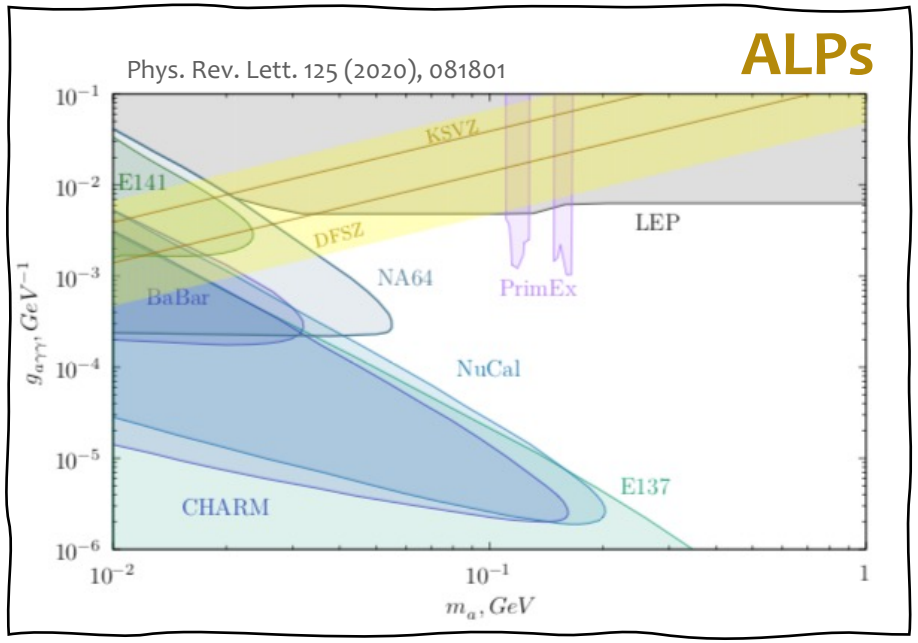
Searches for DARK Photons

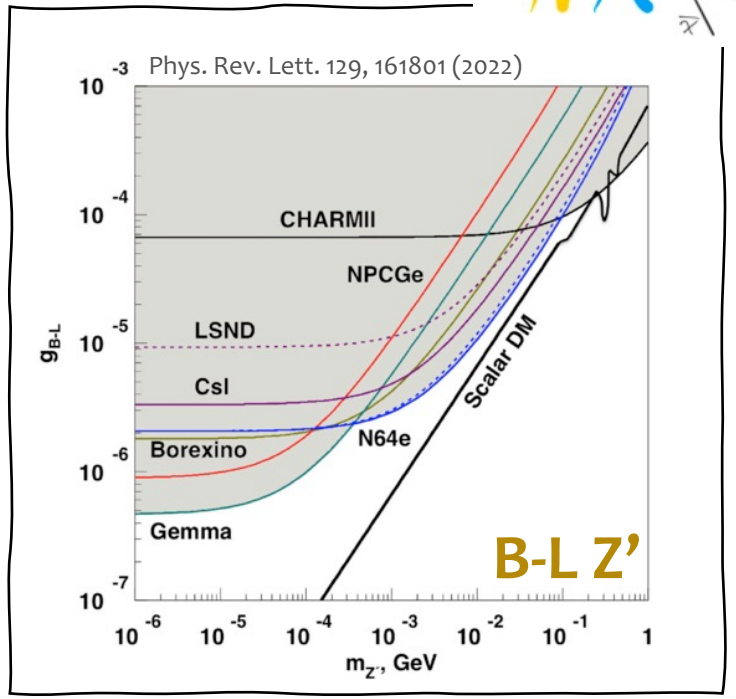


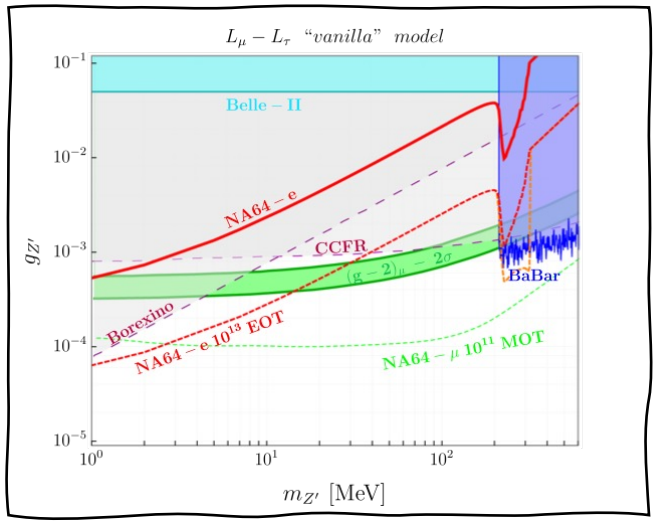
Many thanks to John Anders (CERN) for producing this summary plot!

Other Searches for other FIPs





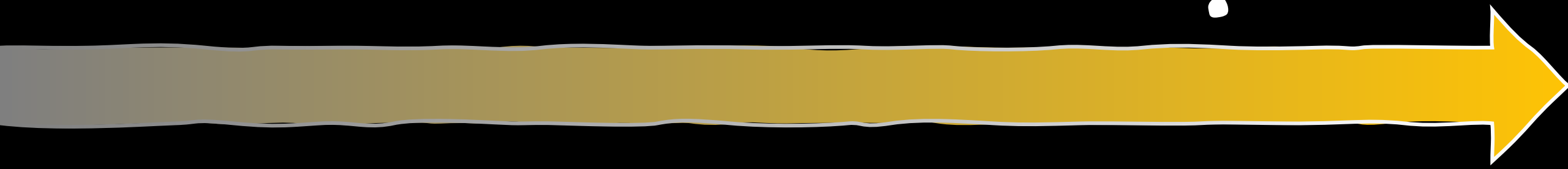




Plus more coming up including completely novel channels, e.g. in the muon mode of NA64

The rest of the experiments also have results in the makings

What's beyond Run 3 ?



New 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

North Area High Intensity Beams – ECN3

A number of proposals requiring higher intensities (factor 6 to 12 in p/spill – factor 6 to >20 in p.o.t./year) in the ECN3 underground cavern post-LS3:

- HIKE (High intensity Kaon Experiment)
  - Ultra Rare Kaon decay studies
  - search for FIP visible decays on axis
- SHADOWS (Search for Hidden And Dark Objects With the SPS)
  - search for FIP visible decays off-axis. Running in parallel to HIKE when operated in Beam-Dump mode
- SHiP (Search for Hidden Particle)
  - comprehensive investigation of the Hidden Sector in the O(GeV) domain
- A programme going beyond HL-LHC (~15 years of operation)

Strong support from SPSC for the High Intensity Upgrade of ECN3

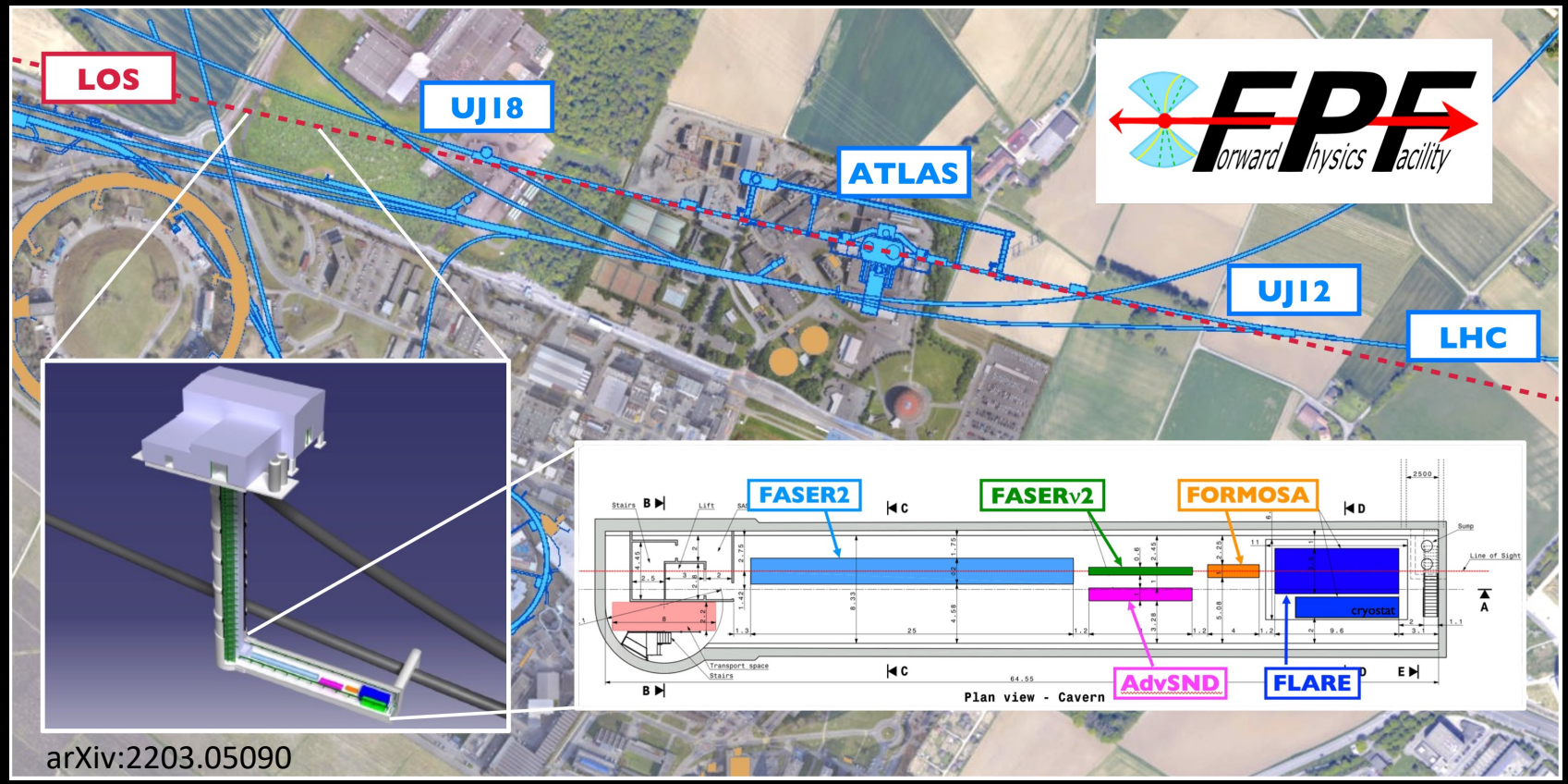
Final recommendation / decision on which experiment to host (SPSC & RB November/December 2023)

Possible start of the TDR phase in 2024

From G. Arduini's talk at FPF6 workshop: https://indico.cern.ch/event/1275380/contributions/5379589/

A TEASER FOR THE PROPOSED FORWARD PHYSICS FACILITY

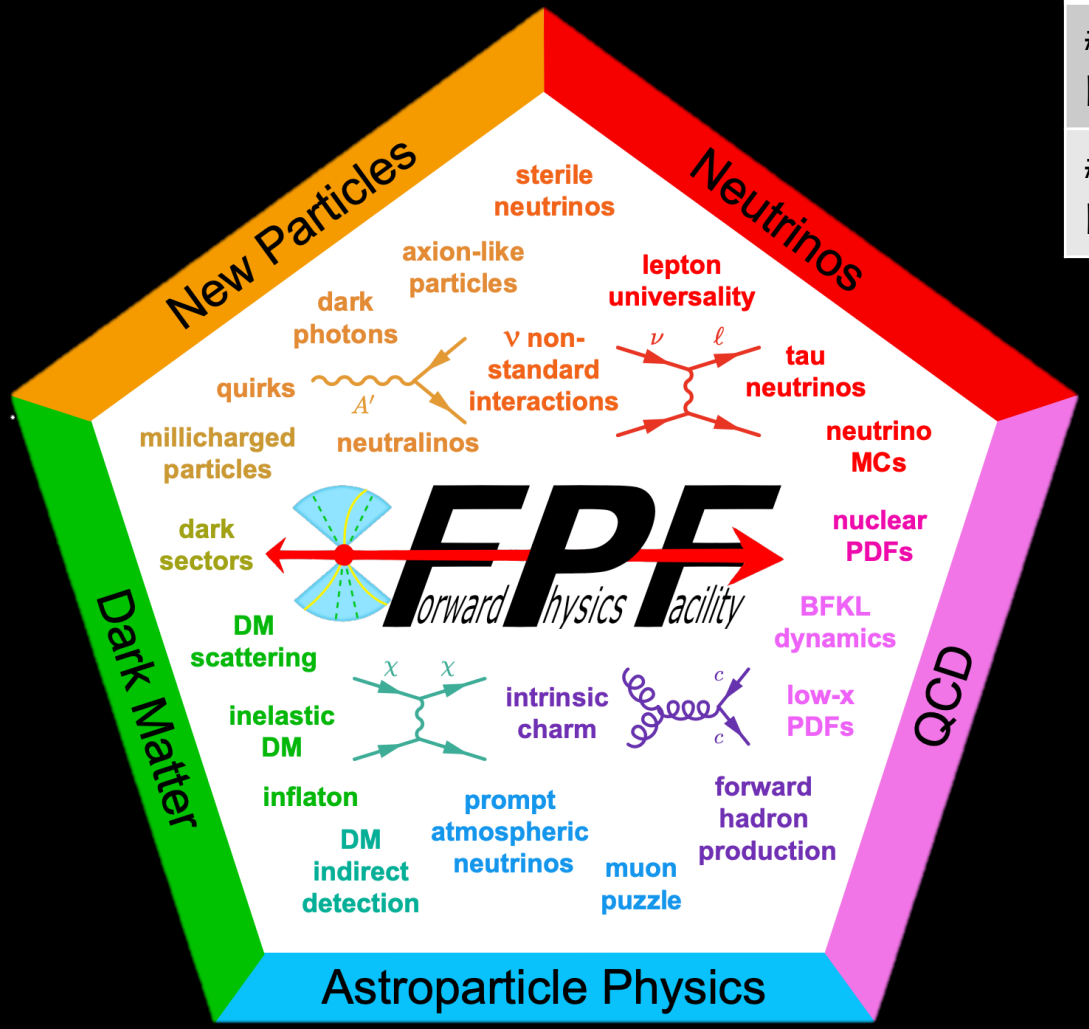
The rich physics program in the far-forward region strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2028-2040s



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!

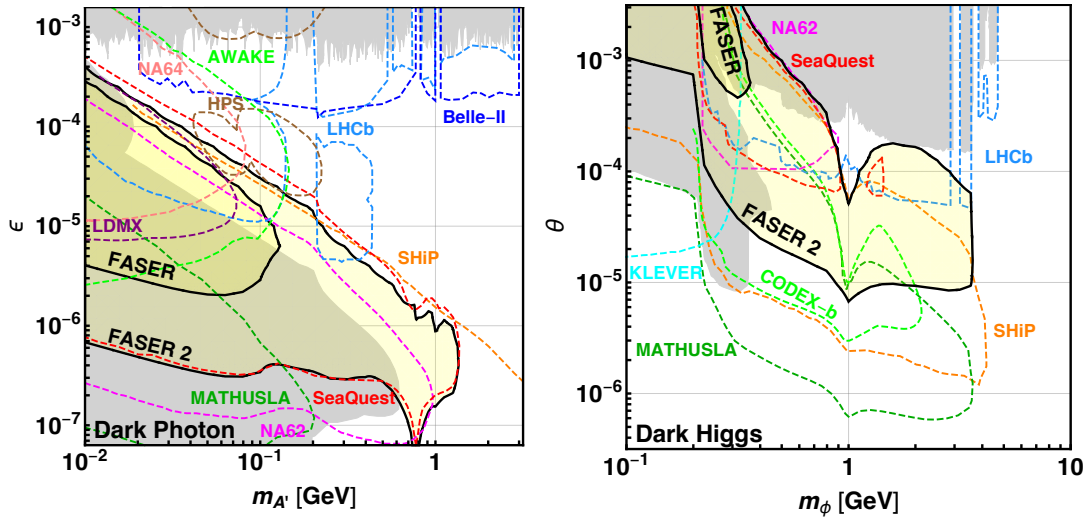
The Physics Programme of FPF



	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



Running experiments

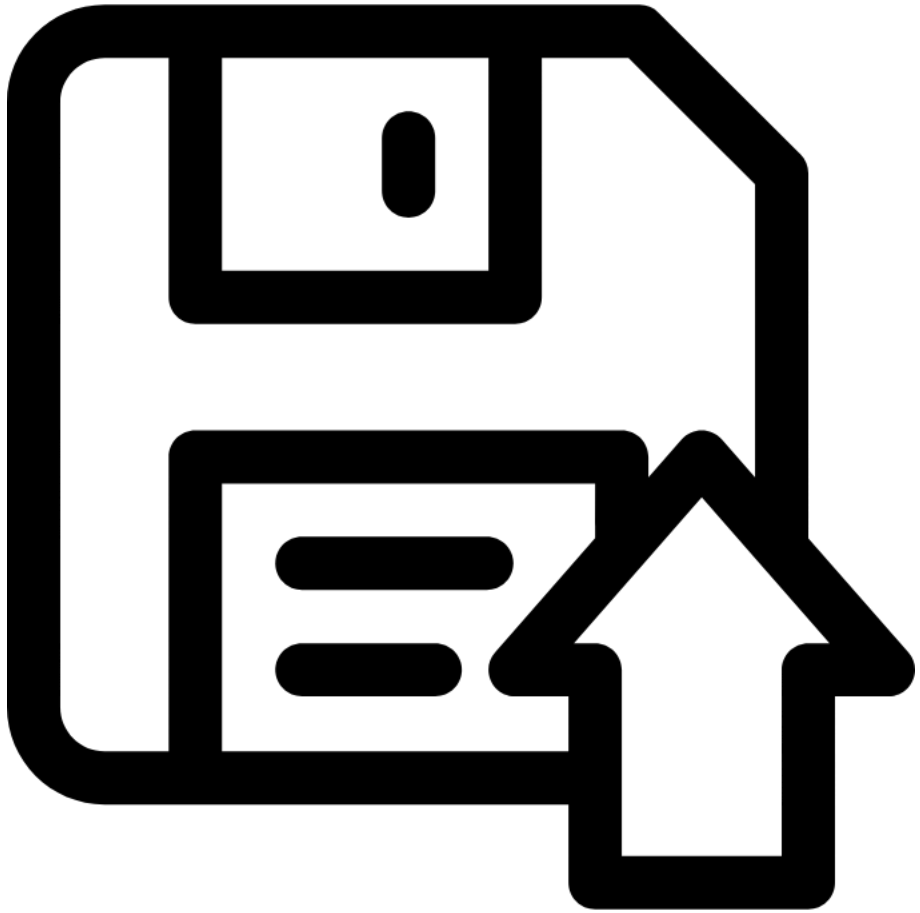
Machine	Experiment	Beam	Lumi / Yields	Running up to…
LHC	ATLAS / CMS	pp – up to 14TeV	Up to 3 / ab	2042
	LHCb		Up to 300 / fb	
	FASER / SND		Up to 300 / fb	2025
SPS	NA62	K+ – 75 GeV p – 400 GeV	10^{13} Kaon decays 10^{18} POT	2025
	NA64	e^+/e^- – 100 GeV μ^+/μ^- – 160 GeV	10^{13} e^+/e^- 10^{13} μ^+/μ^-	2032

Proposed experiments

Machine	Experiment	Beam	Lumi / Yields	Running during…	Where?
SPS	HIKE	K+ – 75 GeV K_L – 40 GeV	10^{14} Kaon decays 10^{14} Kaon decays	Run 4 – Run 5 Run 6	NA62 hall - the two running in parallel
	SHADOWS	p – 400 GeV	$5x10^{19}$ POT	Run 4 – Run 5	
	SHiP	p – 400 GeV	$2x10^{20}$ POT	Run 4 – Run 5	NA62 hall
LHC	FASER(ν) 2	pp – 14 teV	3 / ab	Run 4 – Run 6	New forward physics facility (FPF)
	FORMOSA				
	advSND@LHC				
	FLARE				

Outlook

- Four novel “intensity frontier” experiments where CH researchers are heavily involved
- Experiments that add diversity and enormous potential added to the energy frontier program of CERN!
- Lots of exciting results already produced, while the explorations of the potential of many new research directions has just begun!
- New exciting proposals in the horizon
- Lots of exciting physics ahead!



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

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

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

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

(Axion Like Particle)

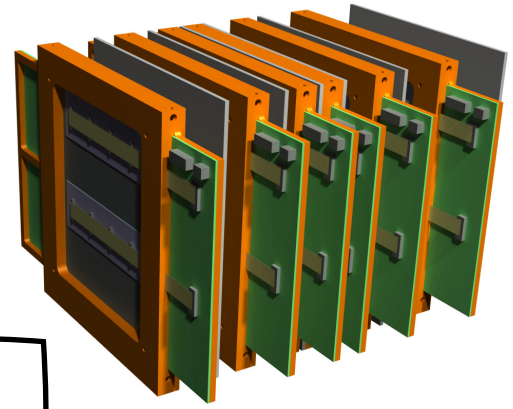
SM LH ν — ν — $y_N h L \psi_D$ — N HNL *N*

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

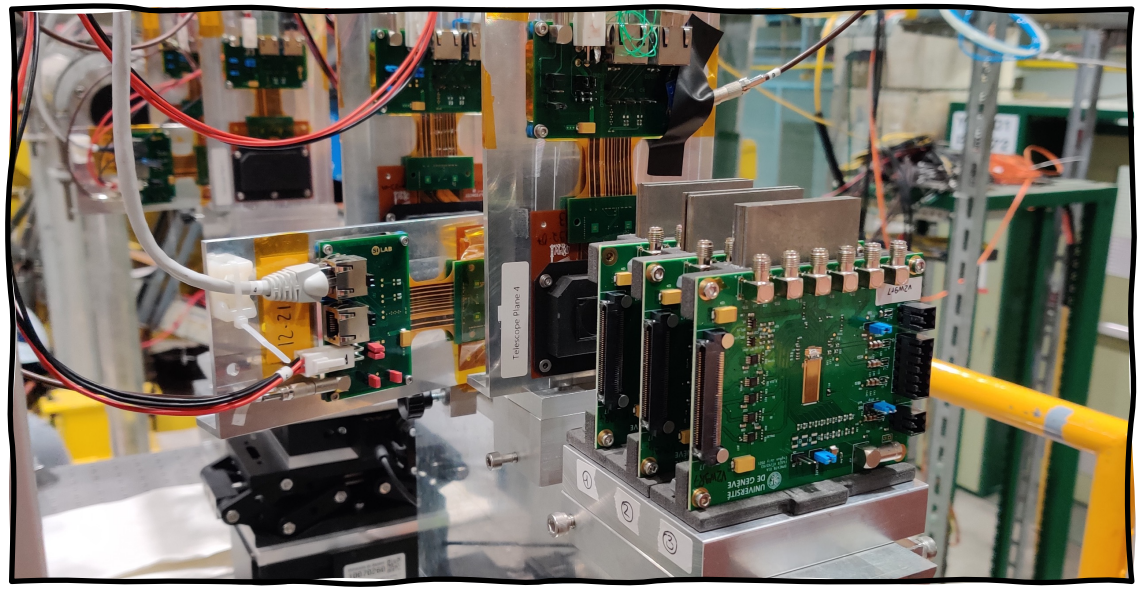
Detector Upgrade

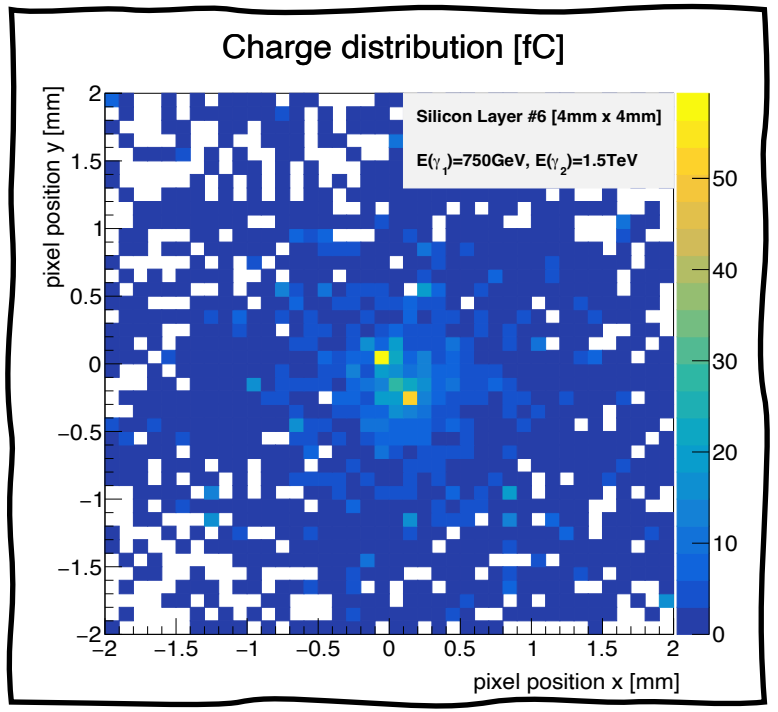


to enable 2-γ physics

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

Preproduction ASICs in testbeam, Sept 2022

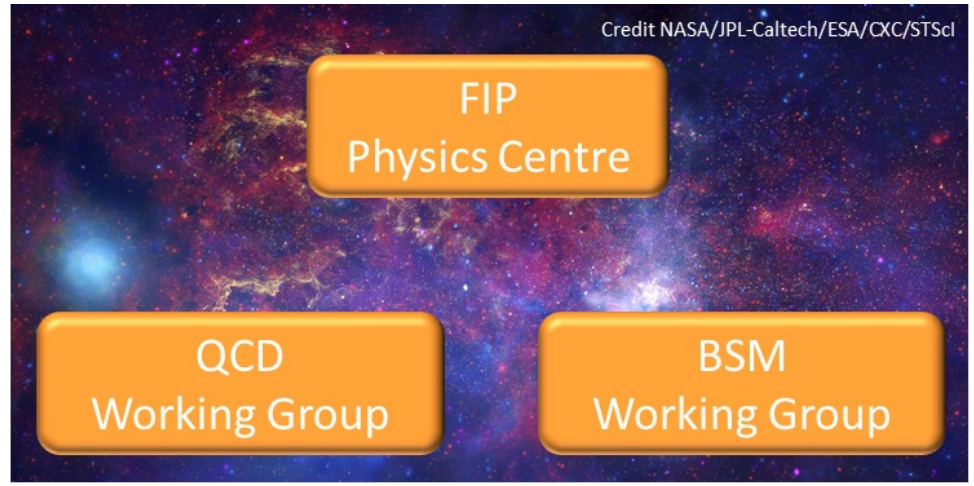




- Distance between two photons: 200 µm
- Distinguishable!

Detector to be used for 2025 data taking

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



Beam Dump Facility

Forward Physics Facility

Accelerator Complex Capabilities

Charged particle EDM (cpEDM) measurement

PBC-A&T Committee

Civil Eng., Integration, Radiation Protection

Conventional Beams

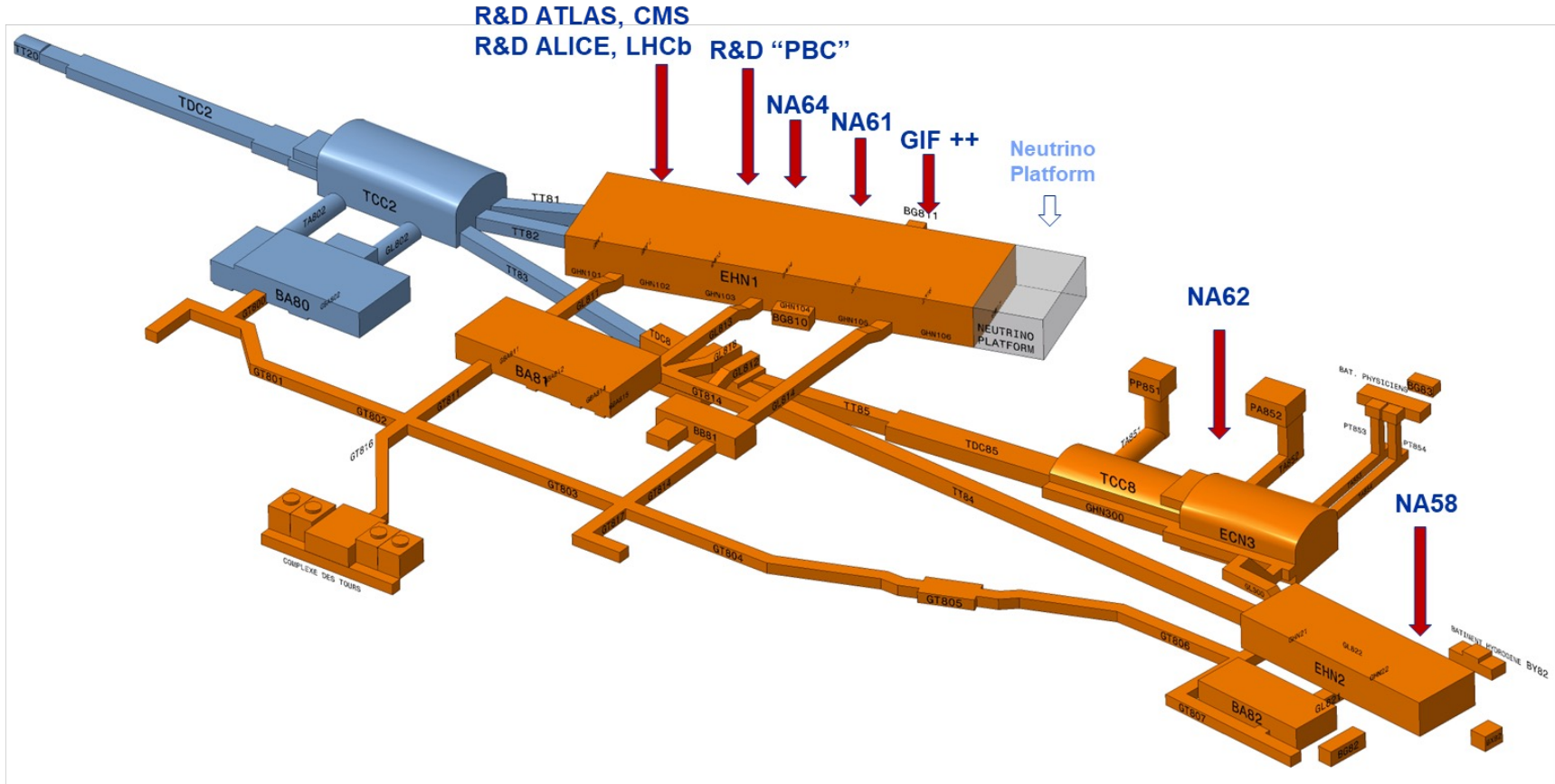
LHC – Fixed Target

Technology

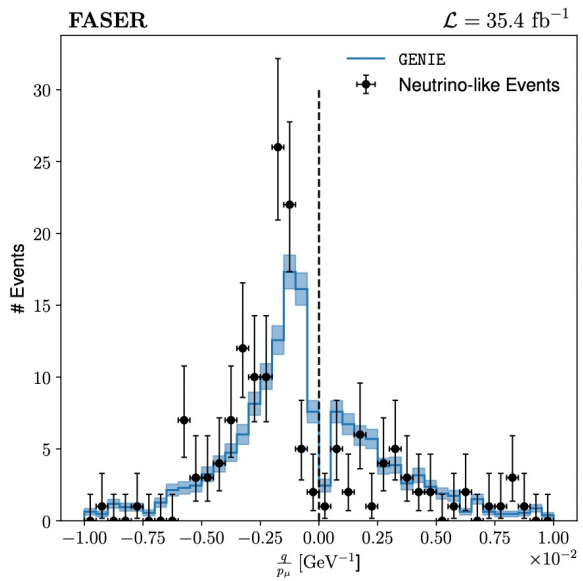
Gamma Factory

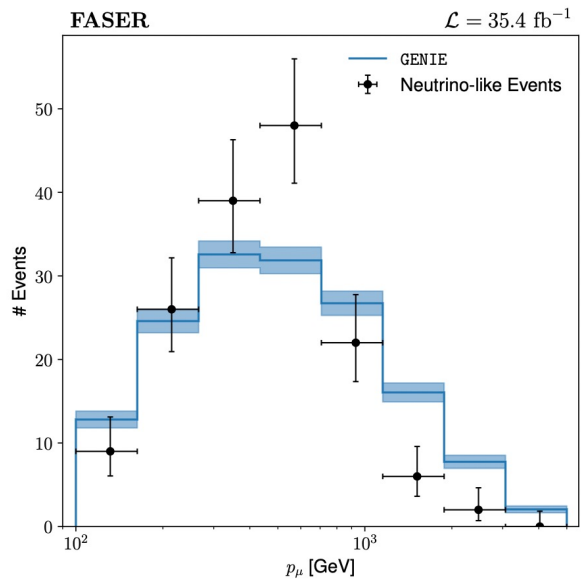
Phase 1: 2019 - 2028 => priority to TT20 & NA transfer tunnels

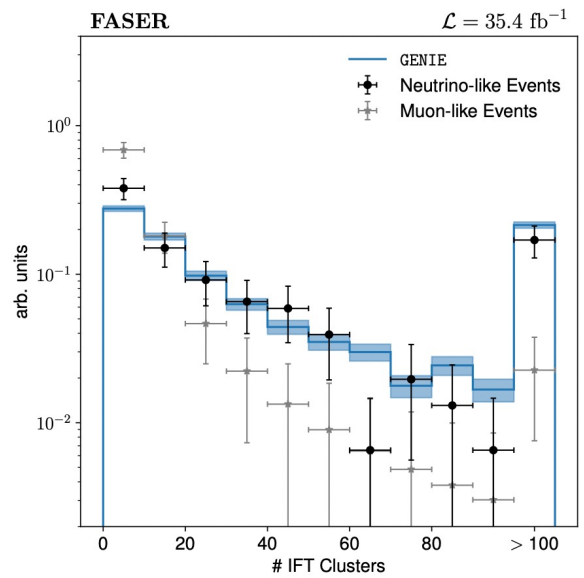
Phase 2: 2029 - 2034 => H2, H4, H6, H8, M2 and K12 beam lines

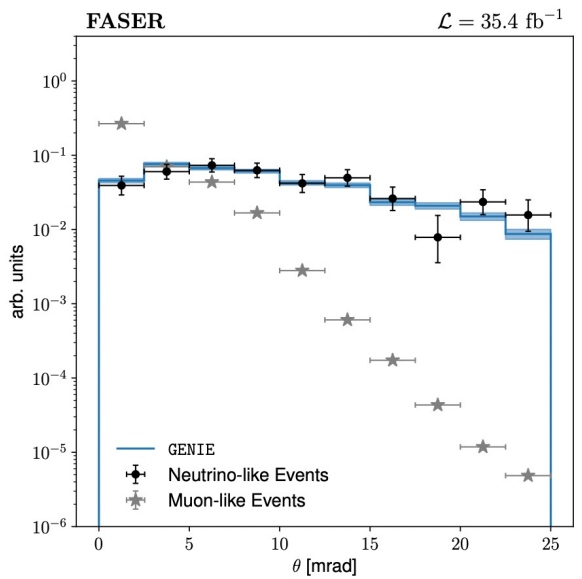


Properties of observed neutrino events

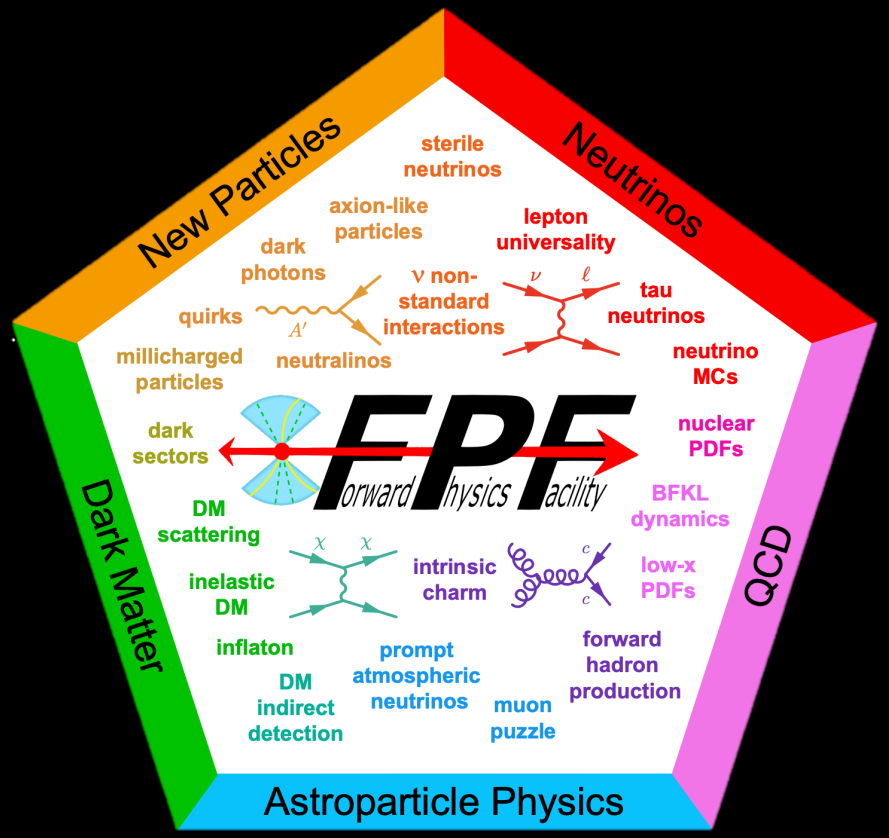


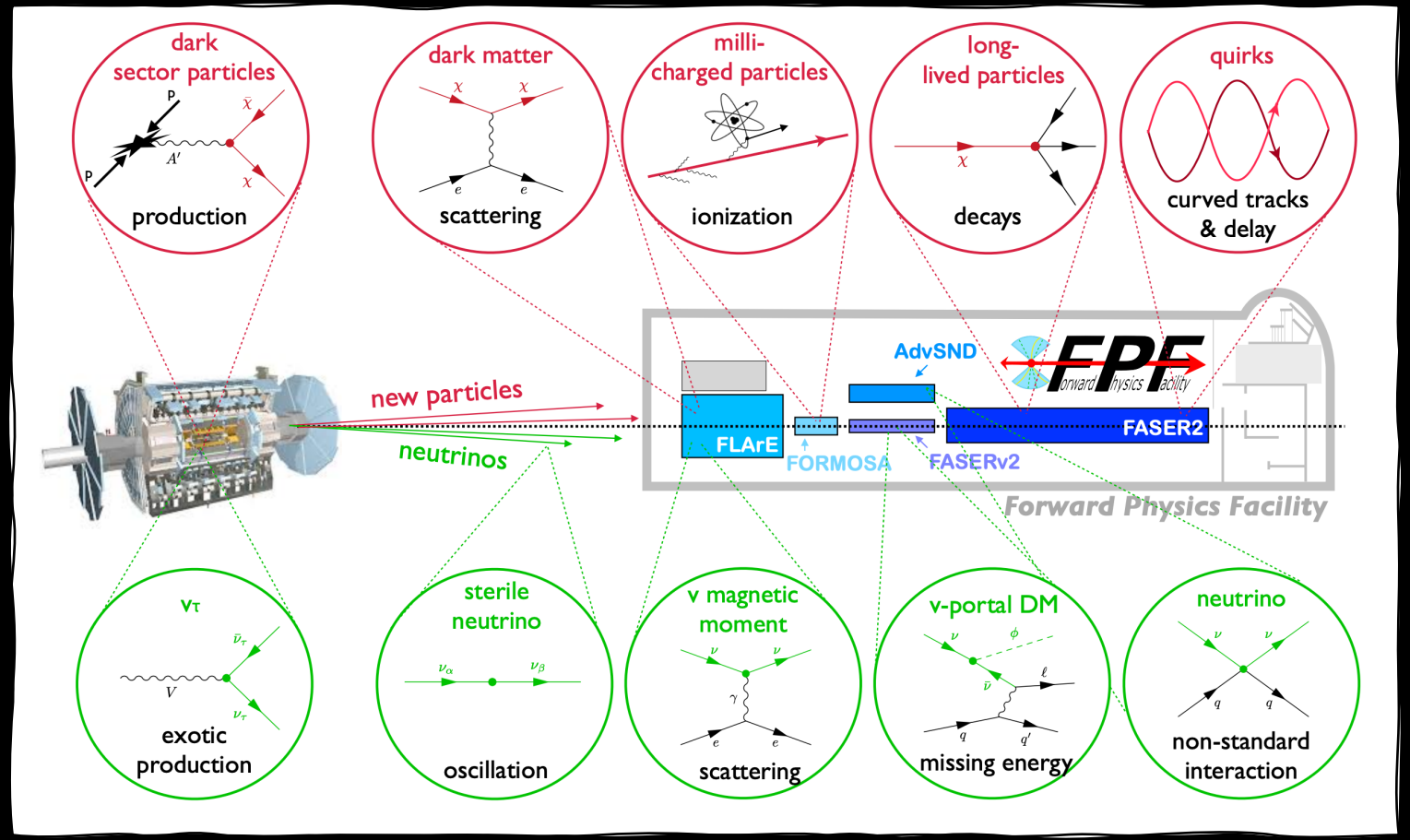






The Physics Programme of FPF

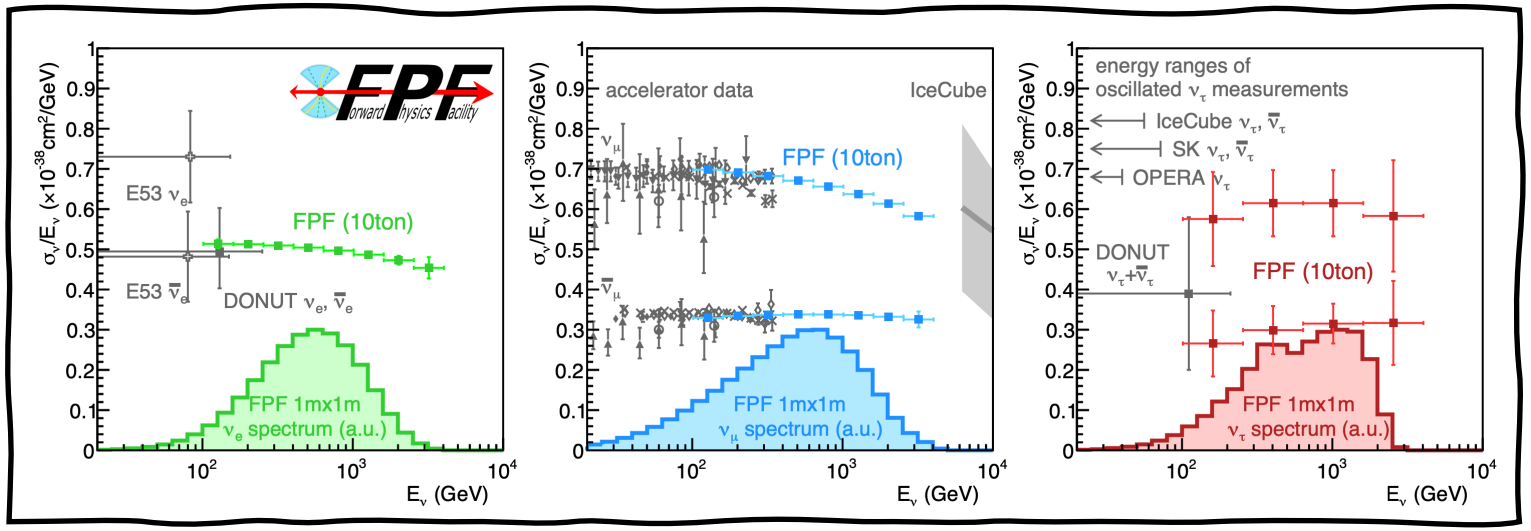




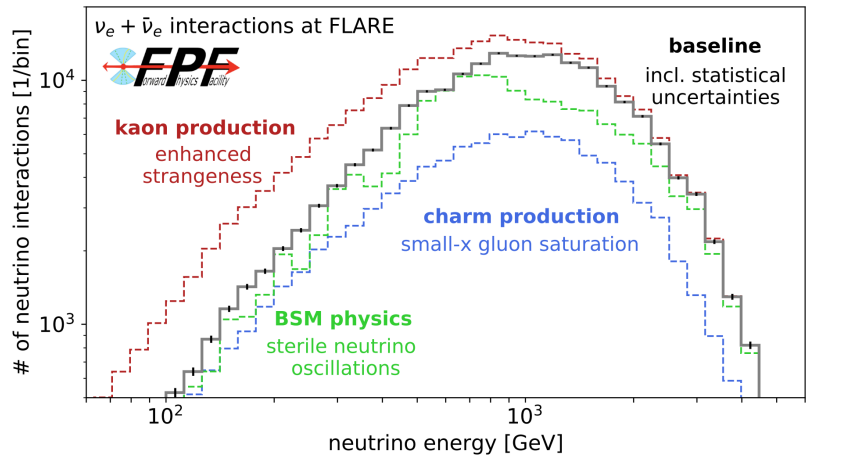
A RICH NEUTRINO PROGRAMME

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

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



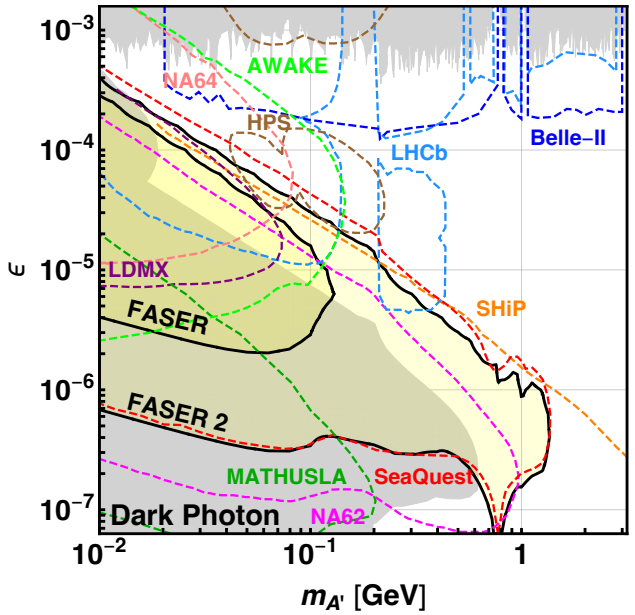
Expected precision of FPF measurements of the neutrino interaction cross section with nucleons

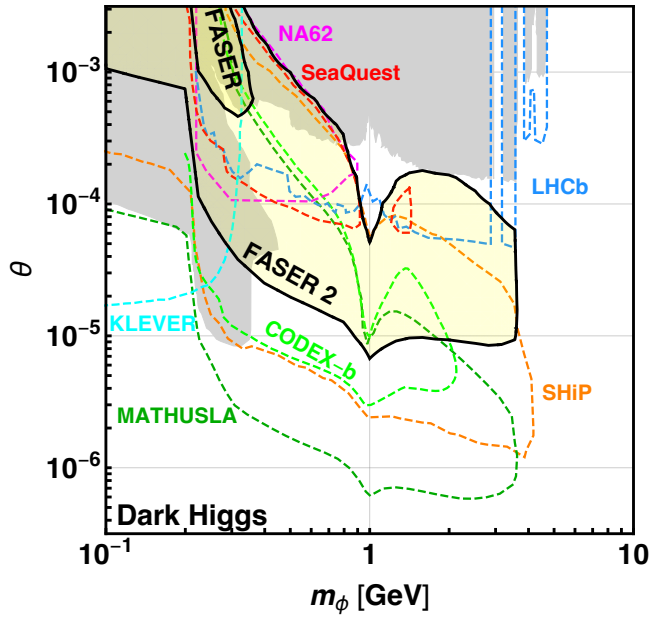


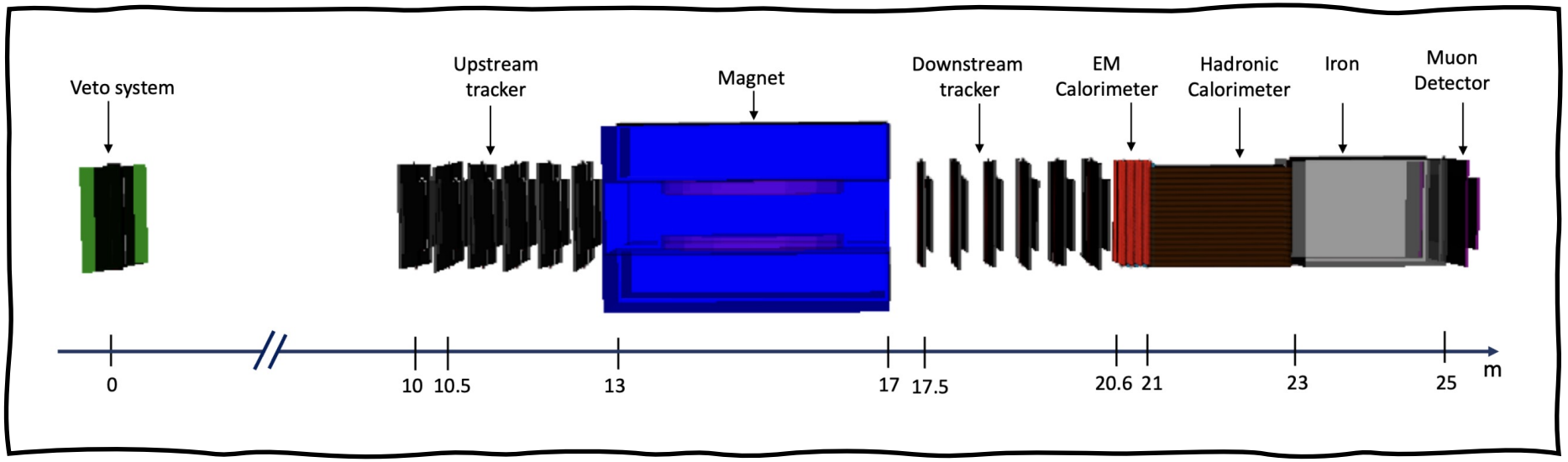
Coloured lines: three examples of physics that can change the expected flux, all probed at FPF

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