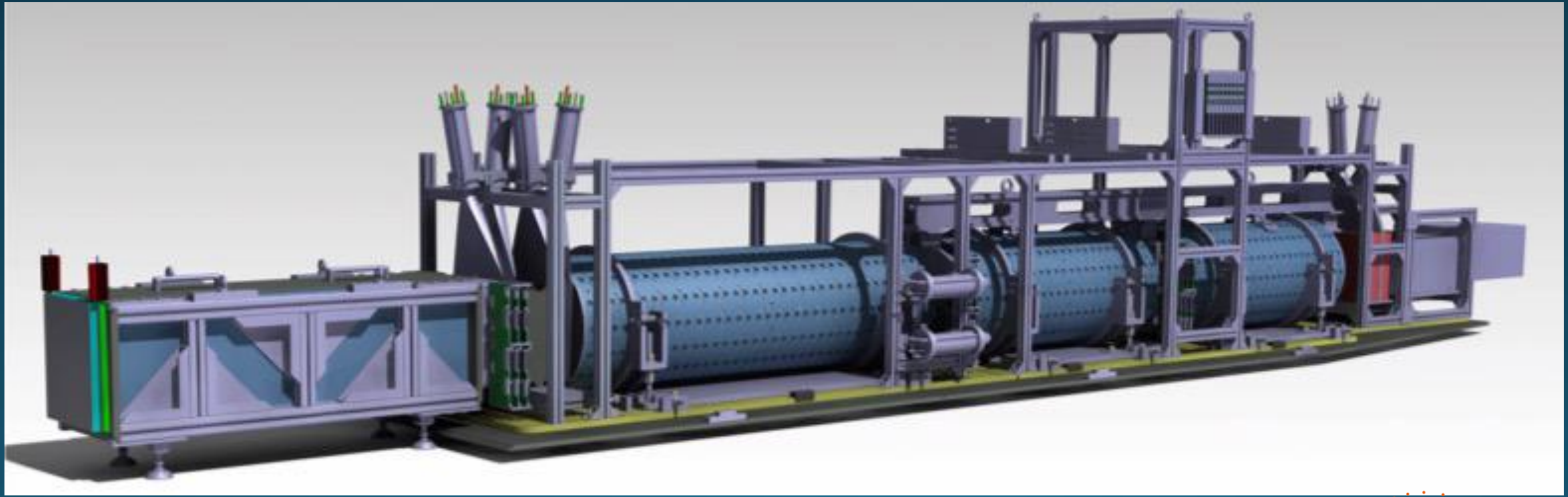
Akitaka Ariga

University of Bern / Chiba University

The FASER experiment:

Studying neutrinos and searching for new particles at the far forward region of the LHC

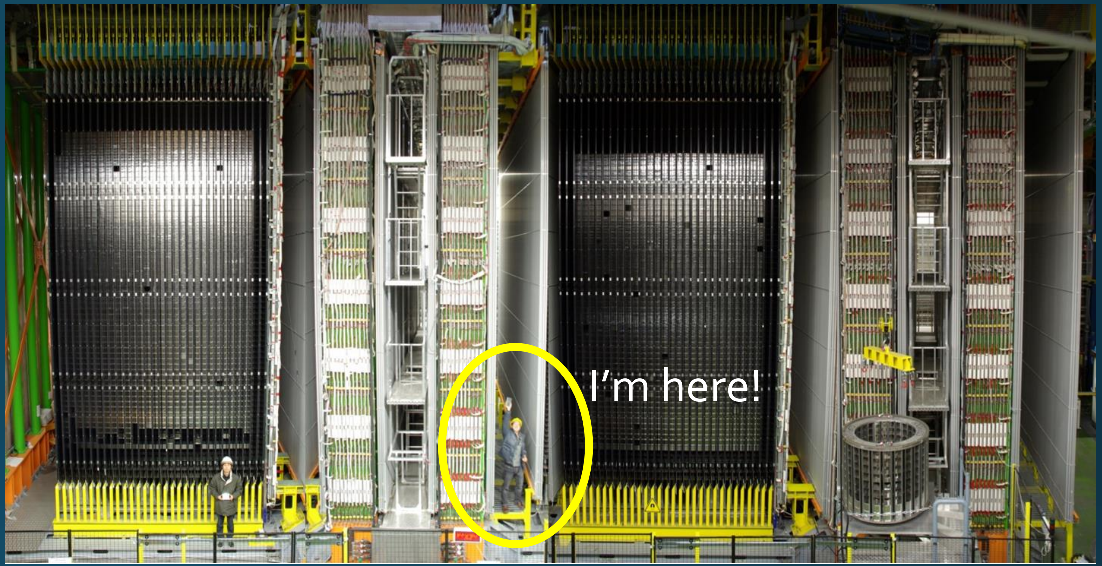


Supported by: HEISING-SIMONS FOUNDATION, SIMONS FOUNDATION, 科研費 KAKENHI, erc

Who am I

- OPERA, $\nu_\mu \rightarrow \nu_\tau$
- T2K, muon flux
- (HK)
- AEgIS/QuPlas, antimatter exps
- Eiger-mu, Glacier muon tomography
- NA65/DsTau, tau neutrino production
- FASERnu, LHC neutrinos

- Expertise with emulsion detectors

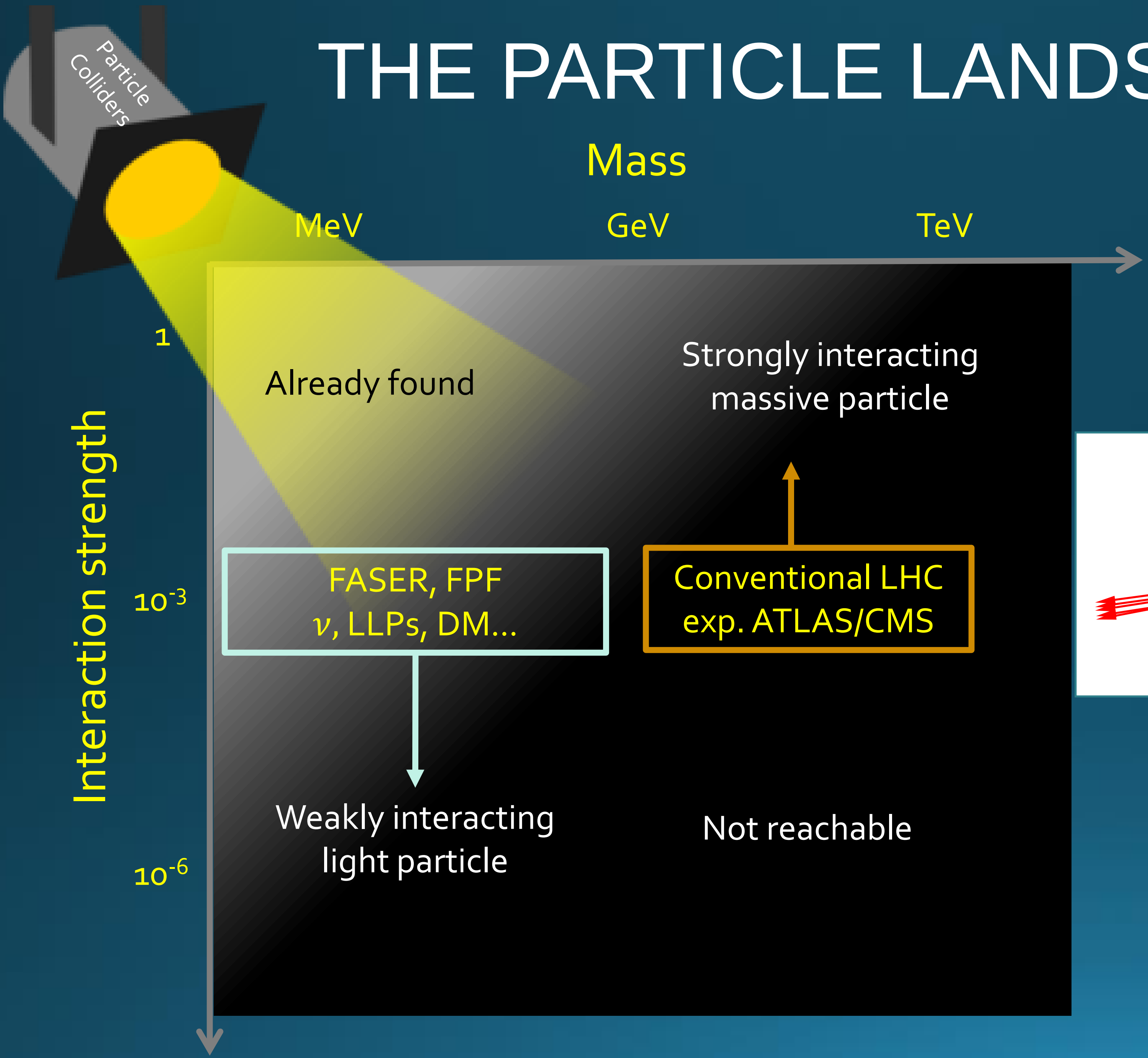


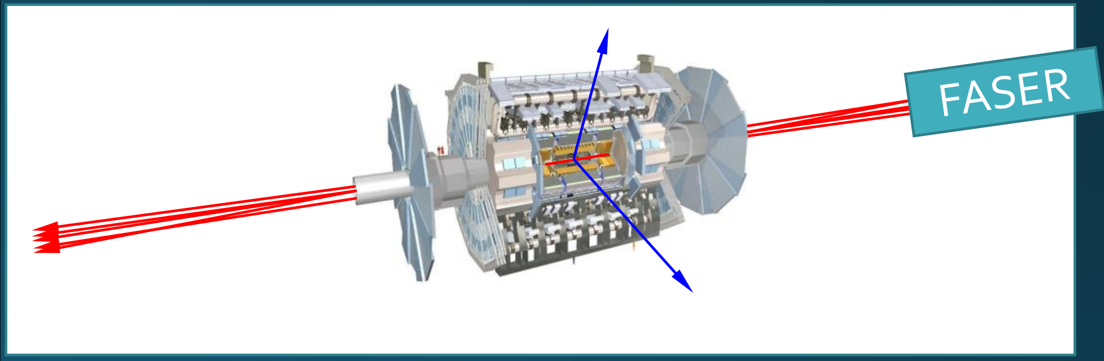
FASER experiment

Two pillars

- FASER: Search for new Long-Lived particles (LLPs) at the LHC
- FASERν: Study of TeV energy neutrinos at the LHC

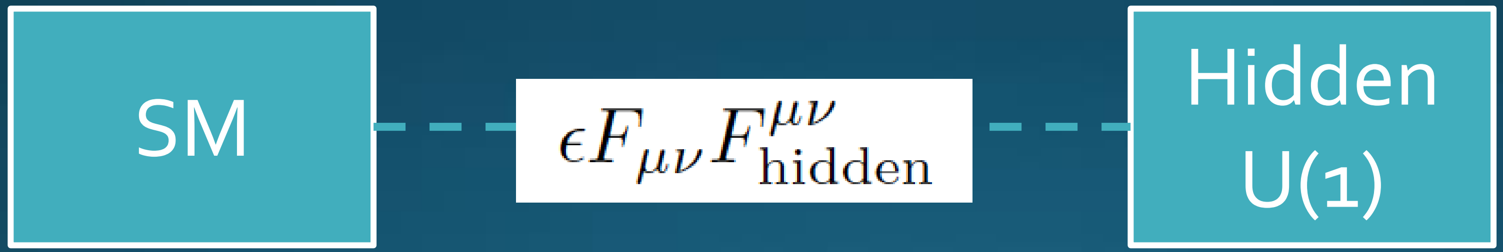
THE PARTICLE LANDSCAPE





DARK PHOTONS

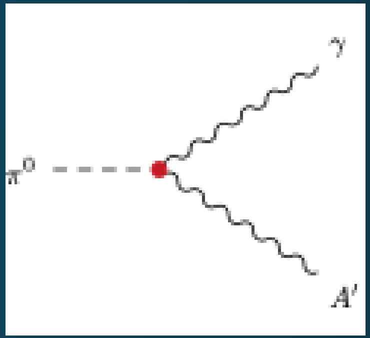
- Dark matter is our most solid evidence for new particles. In recent years, the idea of dark matter has been generalized to dark sectors
- Dark sectors motivate light, weakly coupled particles (WIMPless miracle, SIMP miracle, small-scale structure, ..)
- A prominent example: vector portal, leading to dark photons



- The resulting theory contains a new gauge boson A' with mass $m_{A'}$ and εQ_f couplings to SM fermions f

DARK PHOTON PROPERTIES

- Produced (very rarely) in meson decays, e.g.,



$$B(\pi^0 \to A'\gamma) \; = \; 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$

ϵ: kinematical mixing parameter

and also through other processes

- Travels long distances through matter without interacting, decays to e^+e^- , $\mu^+\mu^-$ for $m_{A'} > 2\ m_\mu$, other charged pairs

$$A' \to \bar{f} f$$

$$\bar{d} = c \frac{1}{\Gamma_{A'}} \gamma_{A'} \beta_{A'} \approx (80\ \mathrm{m})\ B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right]$$

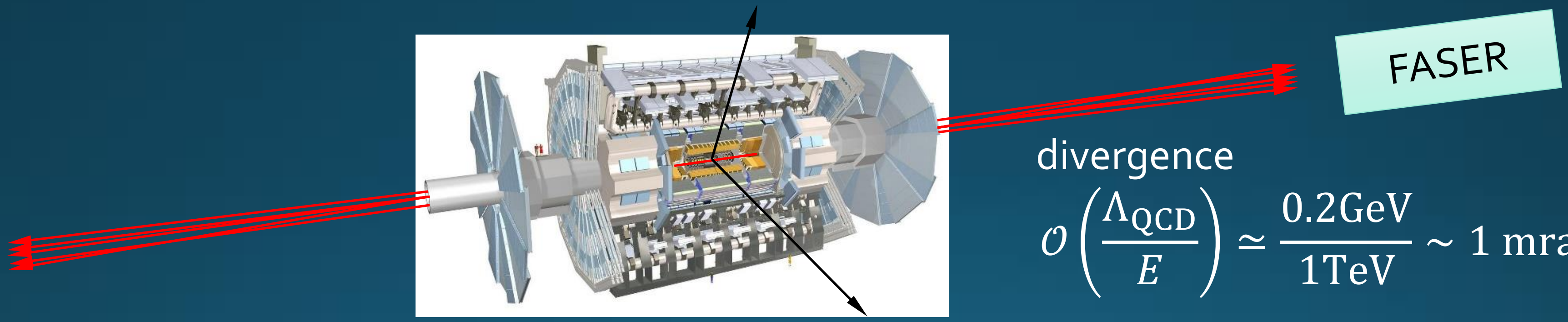
$$E_{A'} \gg m_{A'} \gg m_e$$

Branching to $e^{\pm}$

- TeV energies at the LHC → huge boost, decay lengths of ~100 m are possible for viable and interesting parameters

FASER: ForwArd Search ExpeRiment at the LHC

- ATLAS and CMS searches focus on high p_T → appropriate for heavy, strongly interacting particles
  - No evidence of new particles is detected so far.
- If new particles are light and weakly interacting to the SM particles (e.g. dark photon), they could be long-lived and collimated in the very forward region → FASER arXiv:1708.09389 , 1811.12522



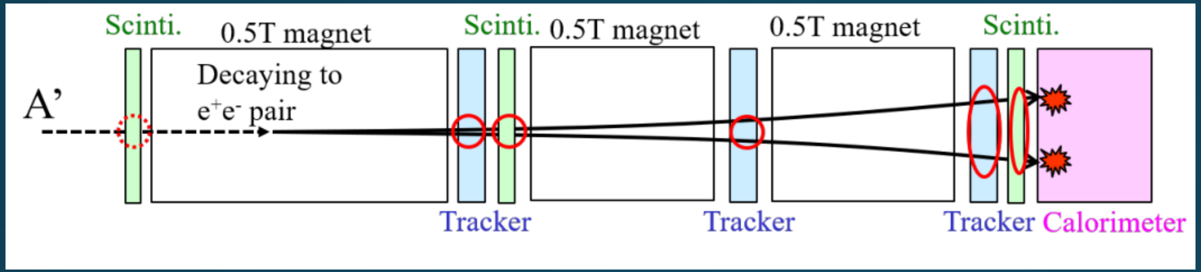
divergence

$$\mathcal{O}\left(\frac{\Lambda_{QCD}}{E}\right) \simeq \frac{0.2\mathrm{GeV}}{1\mathrm{TeV}} \sim 1\ \mathrm{mrad}$$

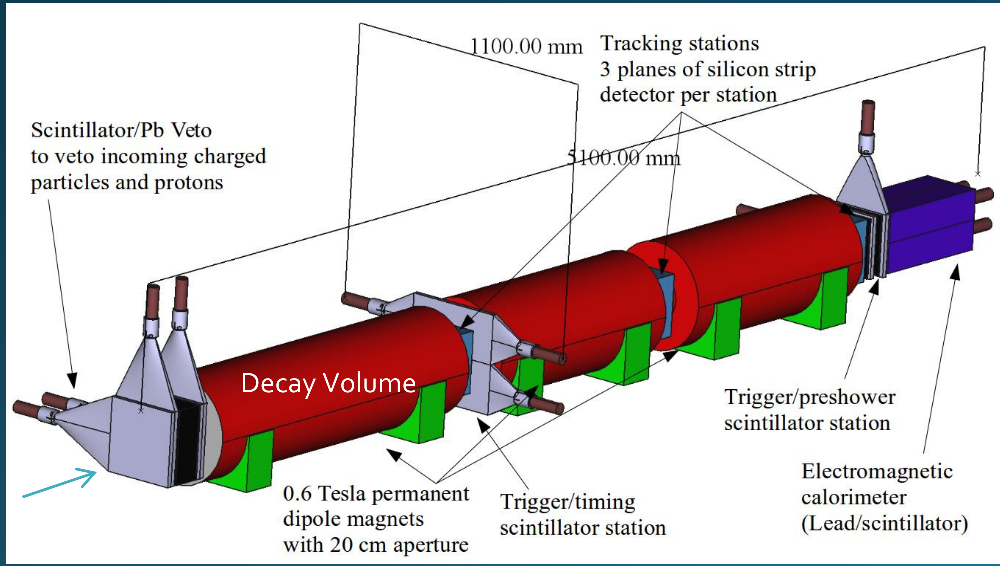
- The LOI (July 2018) and technical proposal (October 2018) were submitted. Approved by CERN in March 2019.
- Preparing for physics run in 2021 (Run3 of the LHC operation)

FASER detector & sensitivity

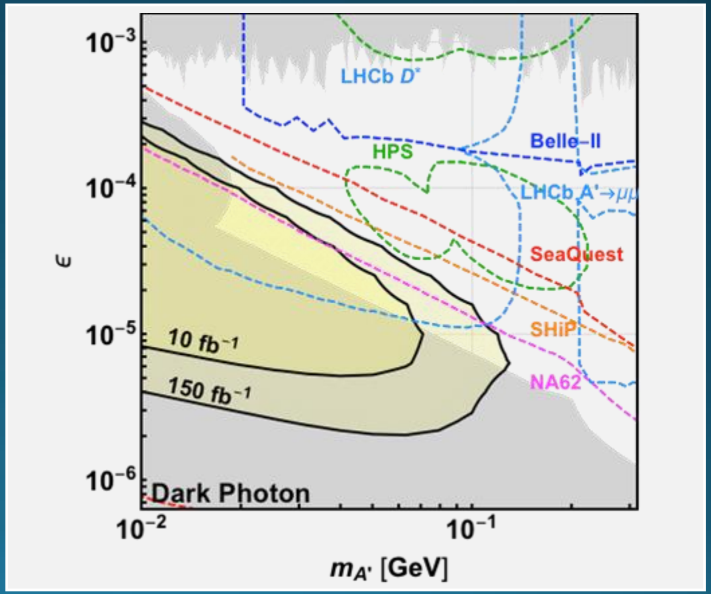
- Dark photon: Photon in dark sector, and it has mass
- Signal: Dark photon decay into e^+e^- pair



Detector schematic (original one without FASERnu)



Sensitivity for dark photon search in Run 3



THE FASER COLLABORATION

- 64 collaborators, 20 institutions, 8 countries

Henso Abreu (Technion), Yoav Afik (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Florian Bernlochner (Bonn), Jamie Boyd (CERN), Lydia Brenner (CERN), Dave Casper (UC Irvine), Franck Cadoux (Geneva), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Candan Dozen (Tsinghua), Yannick Favre (Geneva), Deion Fellers (Oregon), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Iftah Galon (Rutgers), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Sune Jakobsen (CERN), Enrique Kajomovitz (Technion), Felix Kling (SLAC), Umut Kose (CERN), Susanne Kuehn (CERN), Helena Lefebvre (Royal Holloway), Lorne Levinson (Weizmann), Ke Li (Washington), Jinfeng Liu (Tsinghua), Chiara Magliocca (Geneva), Josh McFayden (CERN), Sam Meehan (CERN), Dimitar Mladenov (CERN), Mitsuhiro Nakamura (Nagoya), Toshiyuki Nakano (Nagoya), Marzio Nessi (CERN), Friedemann Neuhaus (Mainz), Hidetoshi Otono (Kyushu), Carlo Pandini (Geneva), Hao Pang (Tsinghua), Brian Petersen (CERN), Francesco Pietropaolo (CERN), Markus Prim (Bonn), Michaela Queitsch-Maitland (CERN), Filippo Resnati (CERN), Jakob Salfeld-Nebgen (CERN), Osamu Sato (Nagoya), Paola Scampoli (Bern), Kristof Schmieden (Mainz), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Savannah Shively (UC Irvine), Jordan Smolinsky (Florida), Yosuke Takubo (KEK), Ondrej Theiner (Geneva), Eric Torrence (Oregon), Sebastian Trojanowski (Sheffield), Serhan Tufanli (CERN), Benedikt Vormwald (CERN), Dengfeng Zhang (Tsinghua), Gang Zhang (Tsinghua)

CERN · The University Of Sheffield · KYUSHU UNIVERSITY · UC IRVINE · UNIVERSITÄT BERN · Technion Israel Institute of Technology · NAGOYA UNIVERSITY · RUTGERS THE STATE UNIVERSITY OF NEW JERSEY · UNIVERSITÉ DE GENÈVE · מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE · KEK · UNIVERSITY of WASHINGTON · JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U · INFN · 清華大學 Tsinghua University · UNIVERSITY OF OREGON · ROYAL HOLLOWAY UNIVERSITY OF LONDON · SLAC NATIONAL ACCELERATOR LABORATORY

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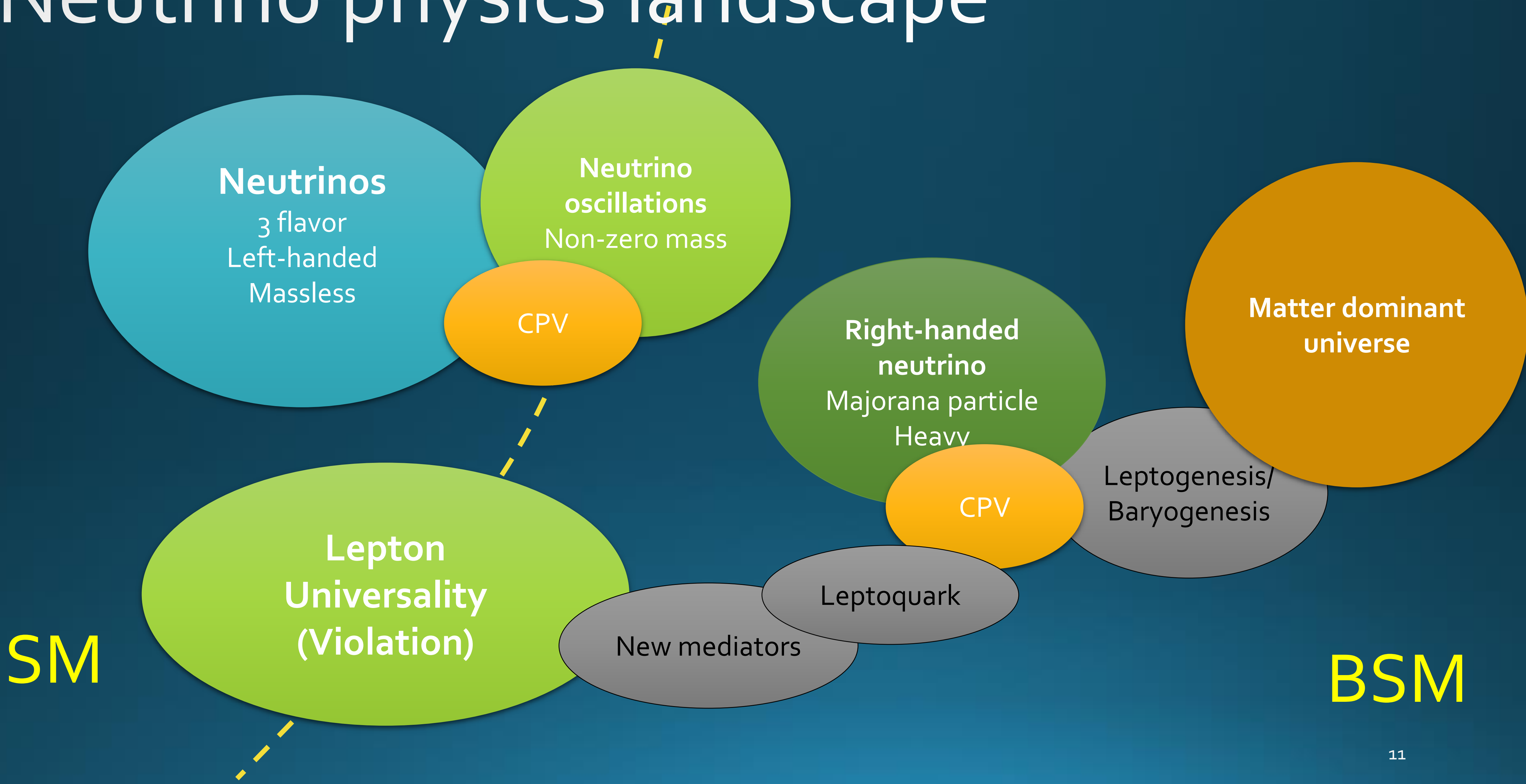
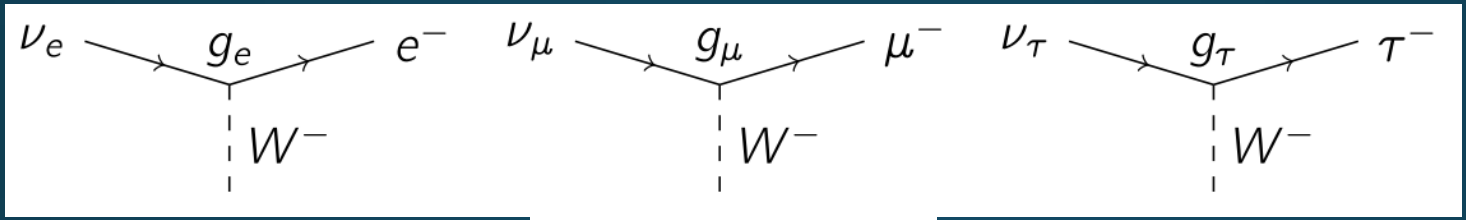
Part of the Collaboration at the first CM in Apr 2019

Neutrino physics landscape



Lepton Flavor Universality, "Sacred principle" of the SM

- Three lepton families equally couple to weak boson



$$g_e = g_\mu = g_\tau$$

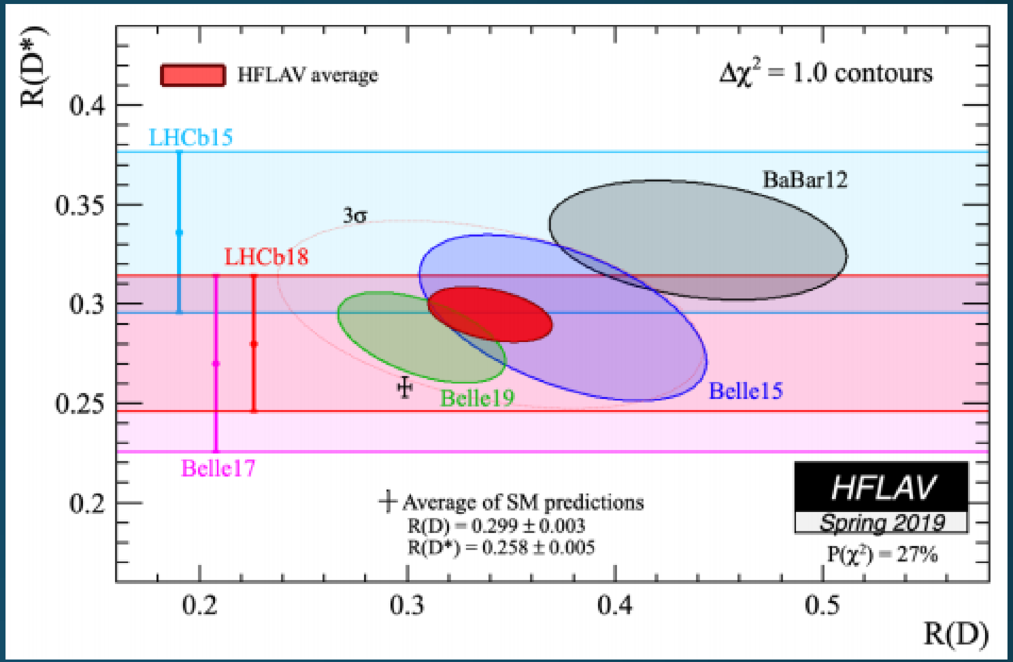
- Intensively verified with very high accuracy, for example

$$\left(\frac{g_\tau}{g_\mu}\right)^4 = 0.178 \left(\frac{m_\mu}{m_\tau}\right)^5 \left(\frac{\tau_\mu}{\tau_\tau}\right) \Rightarrow \frac{g_\tau}{g_\mu} = 0.999 \pm 0.003$$

- It was consistent with all experimental results,,, until recently

"Flavor anomaly"

$$R(D) = \frac{\mathcal{B}(B \to \tau \nu_\tau D)}{\mathcal{B}(B \to \mu \nu_\mu D)}$$

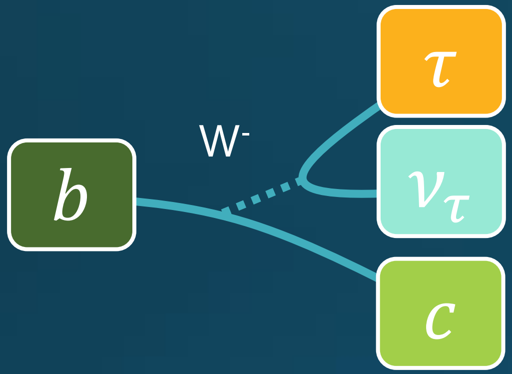


Possible contribution from new physics in heavy flavors!?

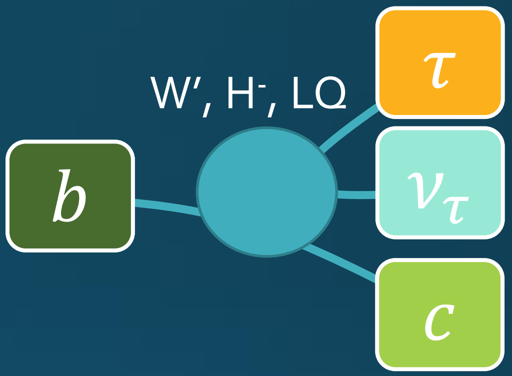
New physics effect?

B decays

SM

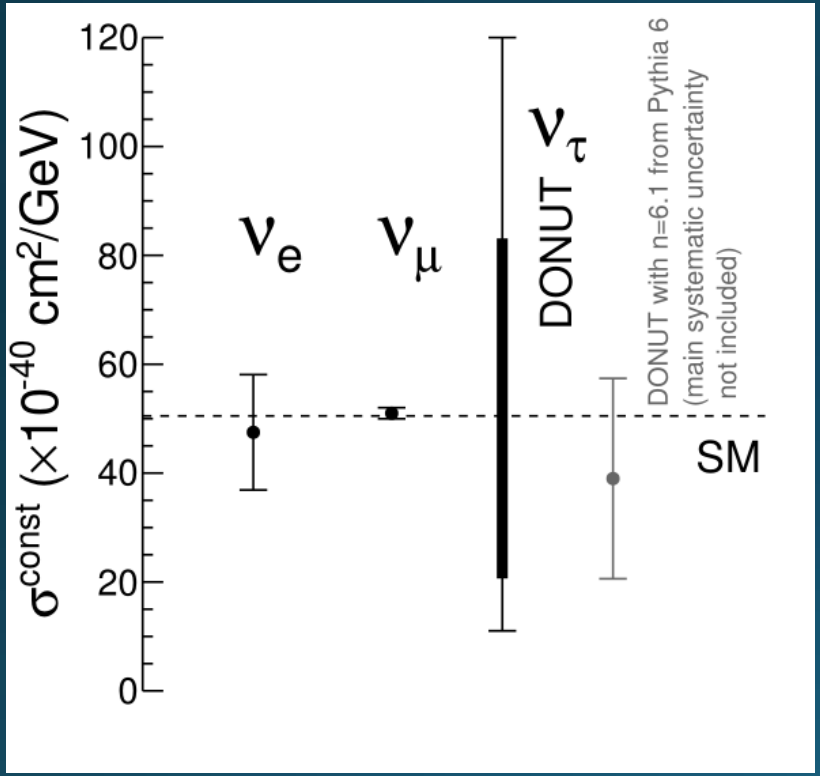


NP

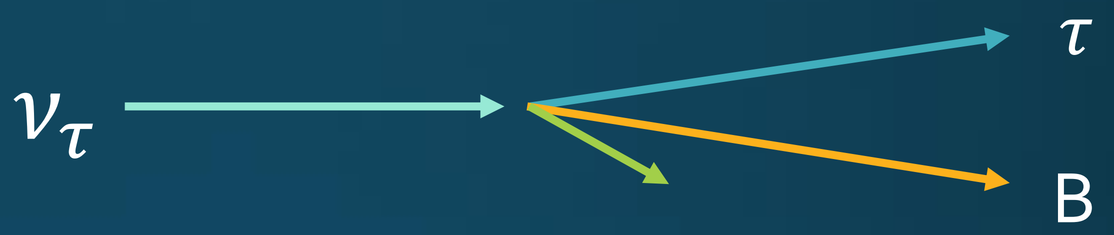


Neutrino CC beauty production

Status of Lepton Universality testing in neutrino scattering



Poor constraint for ν_τ



High energy neutrinos ($E_\nu > 100$ GeV) is required to access heavy flavor channels

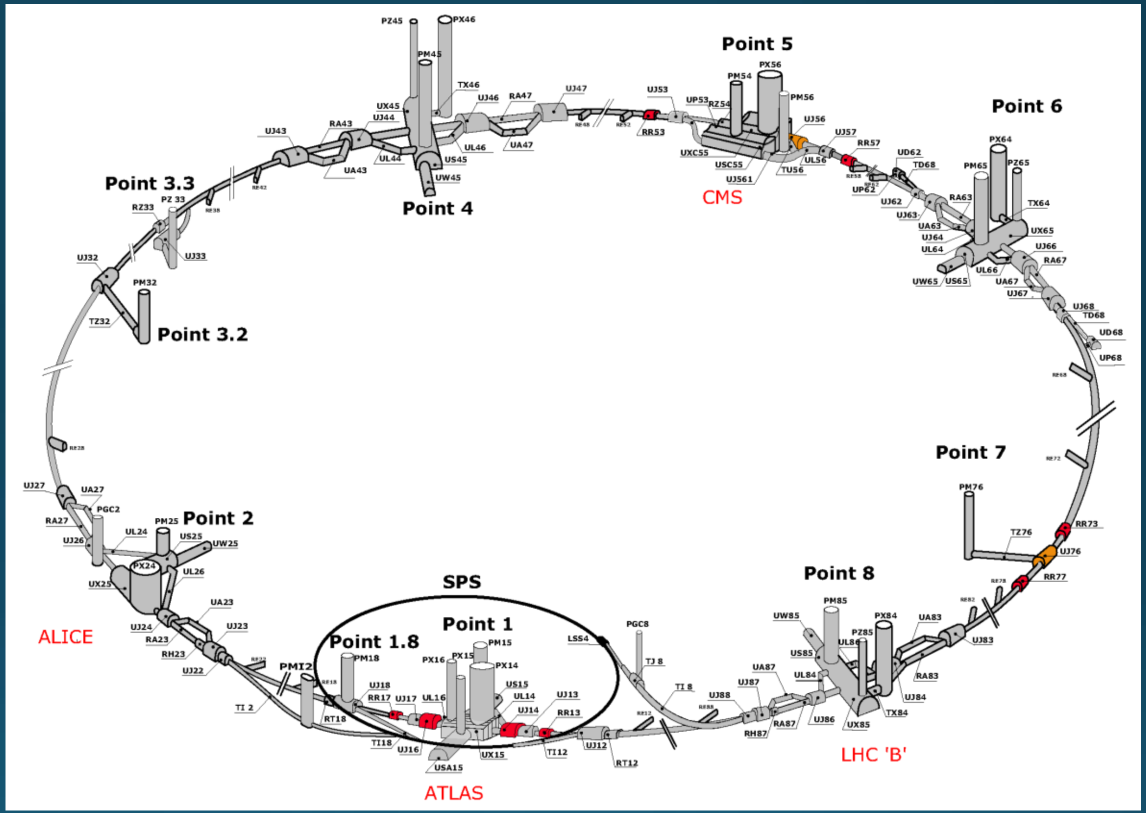
→ Need high statistics and high energy beam experiment!

LHC as neutrino source?

Large Hadron Collider

27 km circumference

7 TeV + 7 TeV



Let's open new domain of research! **Neutrino**

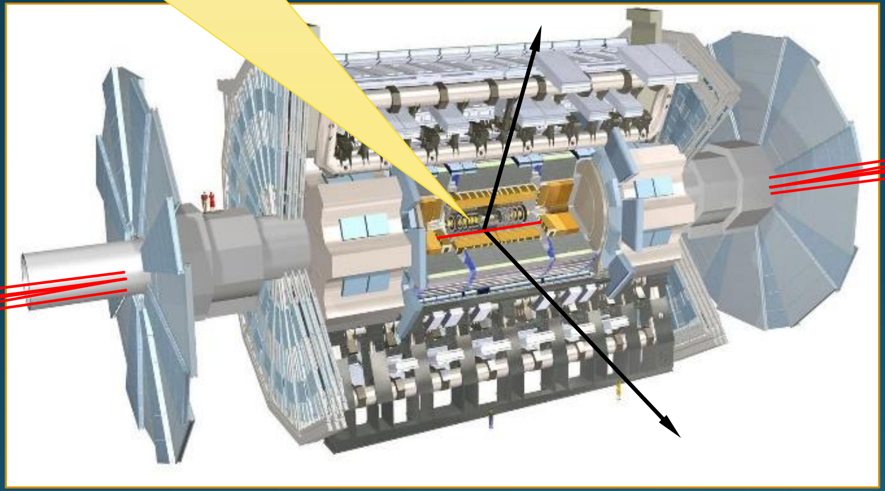
Wait! There is no neutrino beamline!!

LHC as a neutrino source

No experiment has sought neutrinos at the LHC so far!

14 TeV p-p collision

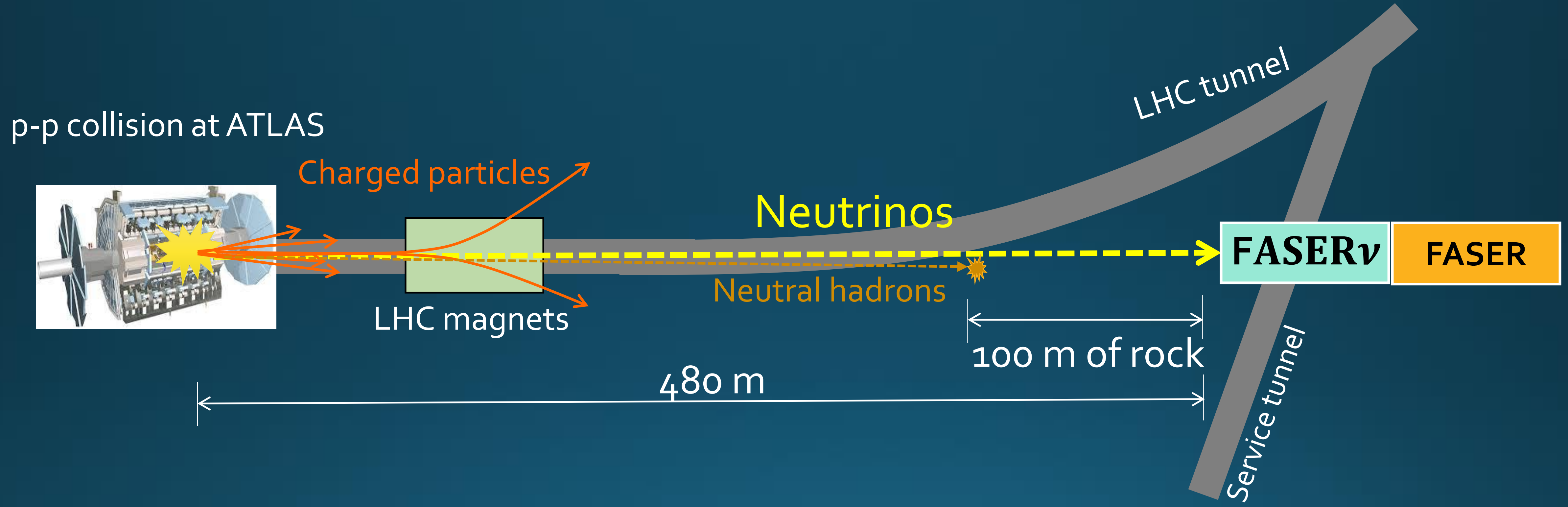
Intense neutrino beam (+ long lived particles, LLPs) here!



FASER

FASER (new particle searches) was approved by CERN in Mar 2019
FASERν (neutrino program) was approved by CERN in Dec 2019

Novel "neutrino beamline"

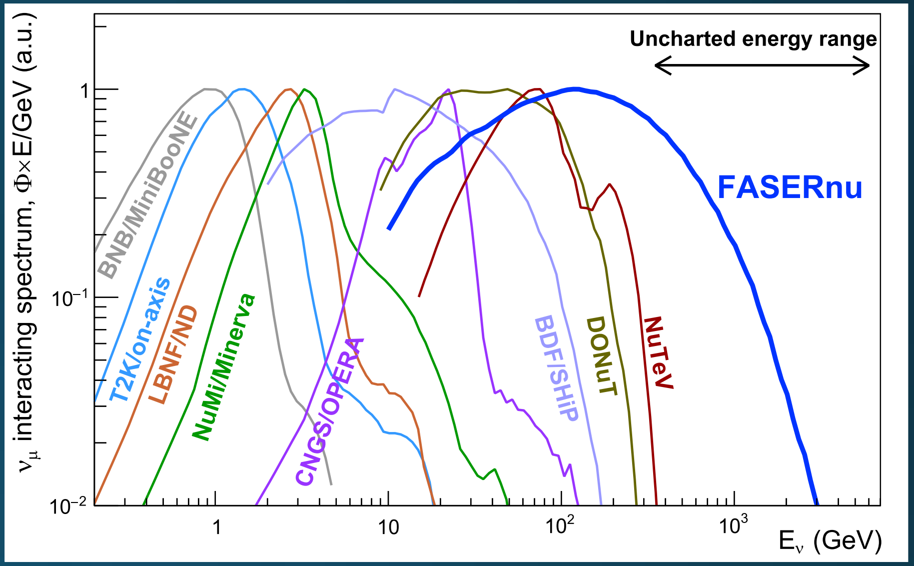


Negligible cost for infrastructure

High energy frontier

Neutrino energy

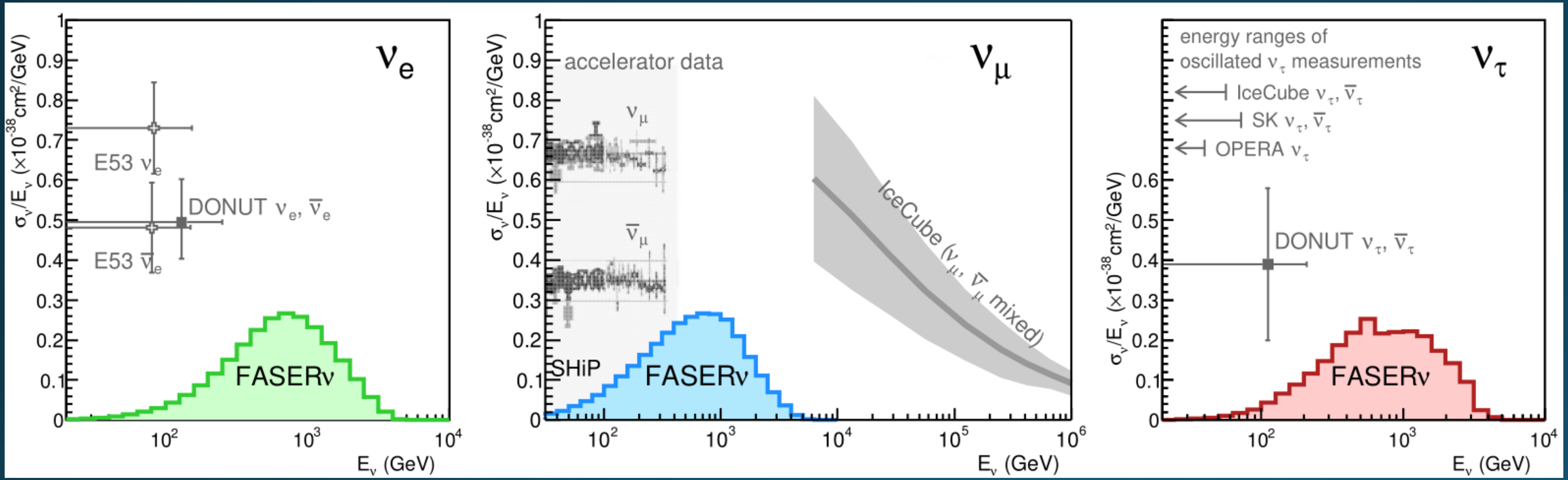
Past	350 GeV	Tevatron (US)
Current	10 GeV	T2K (Japan)
	20 GeV	DUNE (US)
Future	150 GeV	SHiP (CERN)

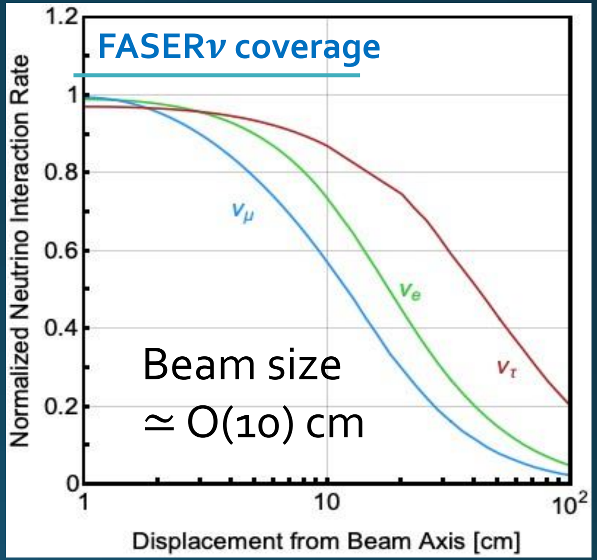


FASERν — Up to 6 TeV $(\nu_e, \nu_\mu, \nu_\tau)$

Unexplored energy range

Neutrino spectrum at FASERν





Unexplored energy regime for all three flavors

Collimated beam

Neutrinos at the LHC: New domain of neutrino research!

- Neutrinos by collider method
- High energy frontier ~ TeV
- Study of production, propagation and interactions of high energy neutrinos

Production

14 TeV p-p collision ≡ 100 PeV int in fixed target ($\sqrt{s}$ ~ 10 TeV)

Prompt neutrino production → Input for neutrino telescopes

QCD (charm/gluon PDF, intrinsic charm)

Propagation

Unique energy and baseline, $L/E \sim 10^{-3}$ m/MeV

Neutrino oscillation at $\Delta m^2 \sim 1000\ \mathrm{eV}^2$

Interaction

3-flavor neutrino cross sections in unexplored energy range

Neutrino induced heavy quark productions

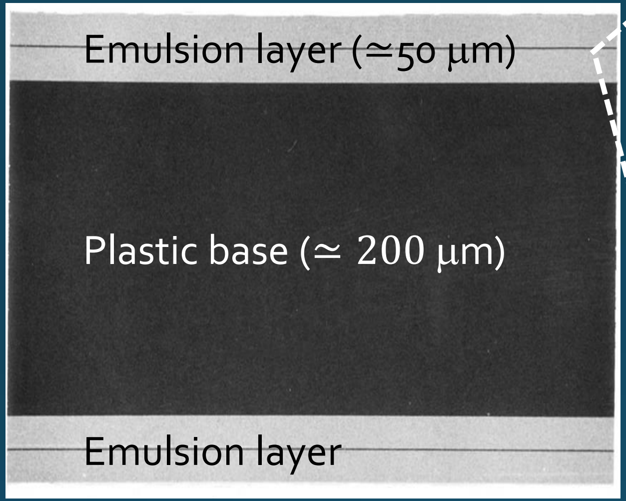
New physics effects

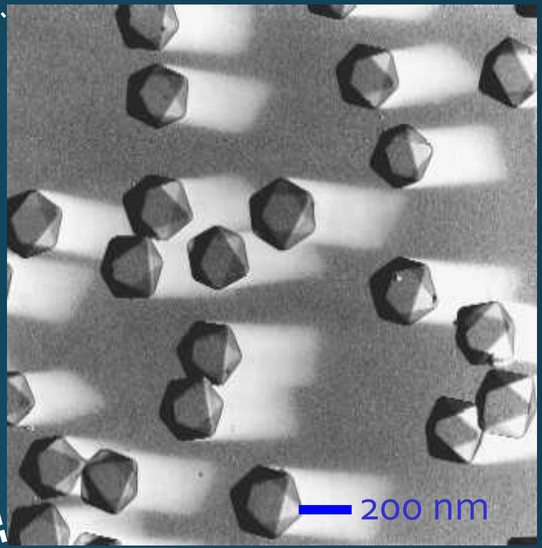
Emulsion detectors:
3D tracking device with 50 nm precision

AgBr crystal = detector
10^{14} channels/film or 10^{14} channels/cm^3

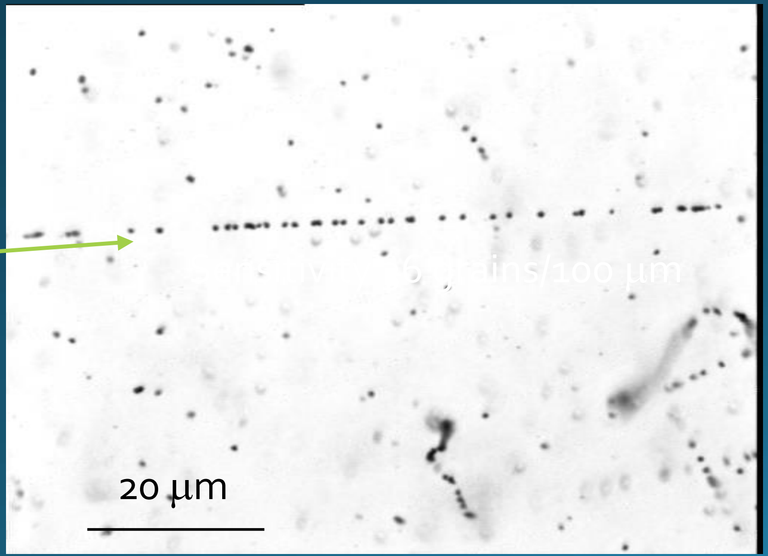
Emulsion film

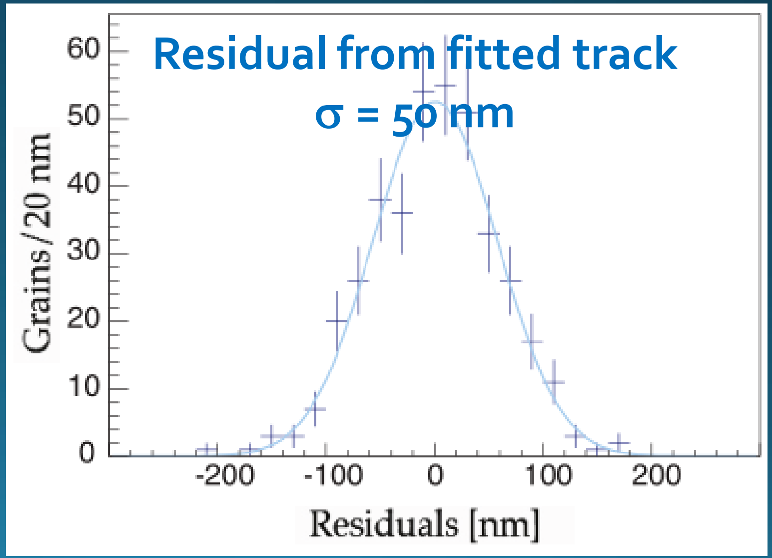
Cross-sectional view





10 GeV/c π
beam



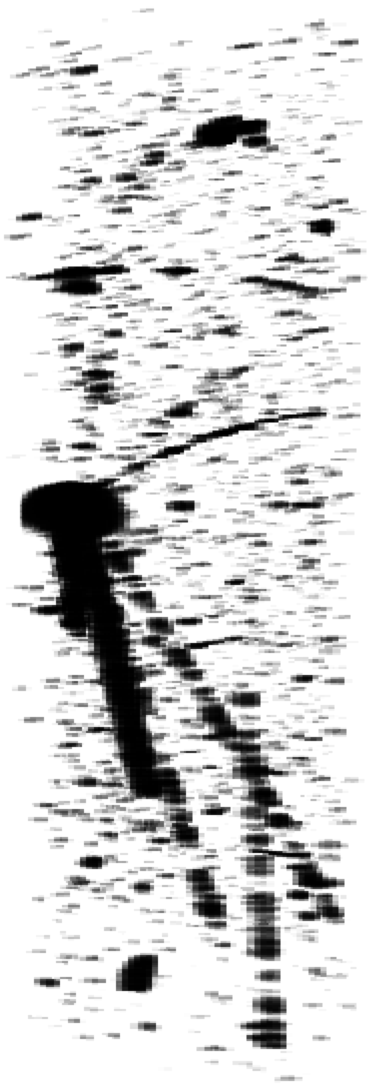


Antiproton annihilation in emulsion

Antiproton annihilation taken in AEgIS 2012

200 microns

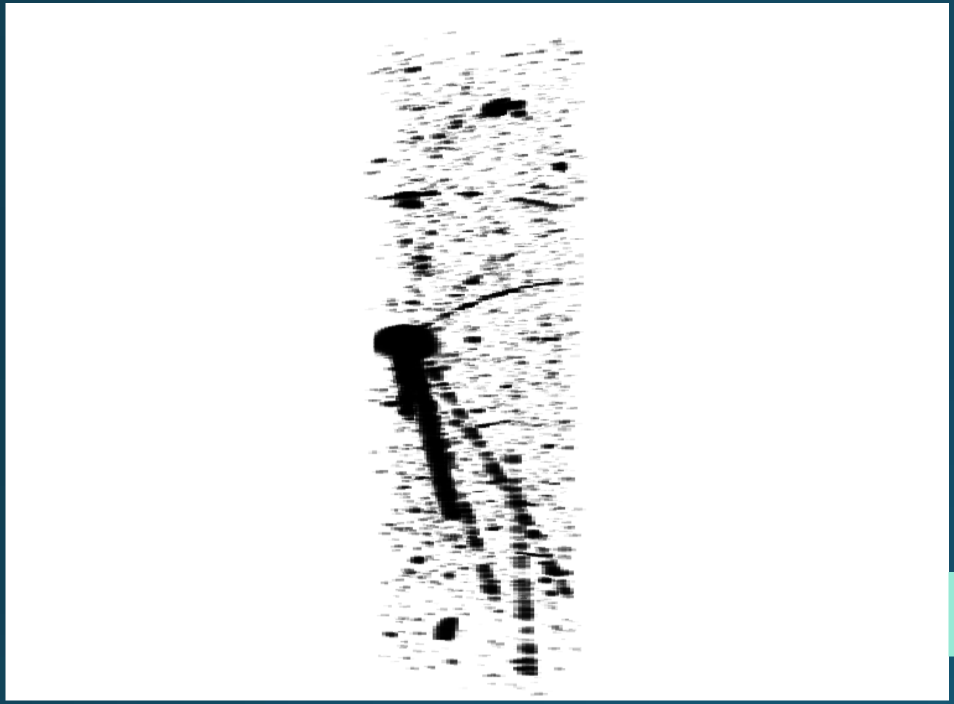
3D view of emulsion detector



150 μm x 120 μm x 50 μm

- 3D high resolution hits
- Work as tracker
- dE/dx proportional to darkness (Number of grains)

Emulsion = a detector with high detection channel density



150 μm x 120 μm x 50 μm

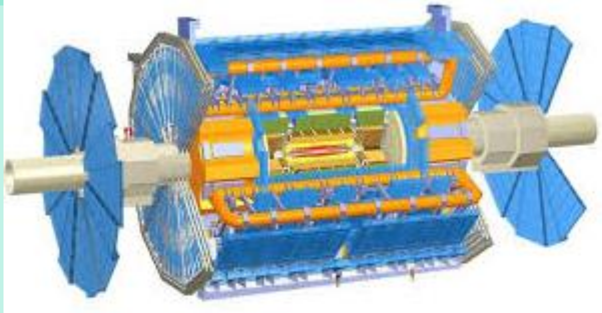
1.2x10^8 channels (crystal) in this volume.

1 film = 10^{14} channels

ATLAS-IBL pixel sensor FE-14

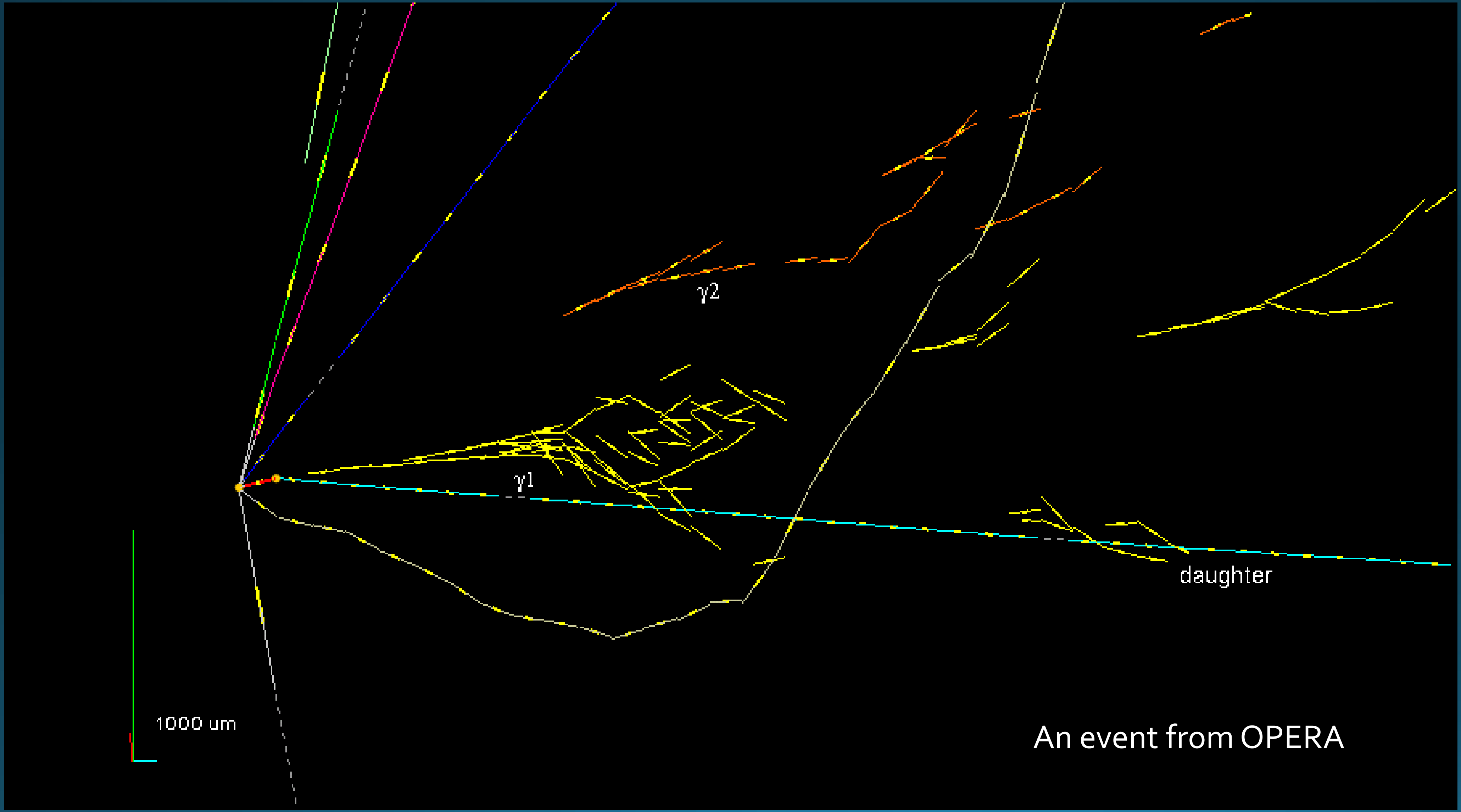
1 pixel = 250 μm x 50 μm x 200 μm

Sum of all channels in ATLAS = ~**10^8**

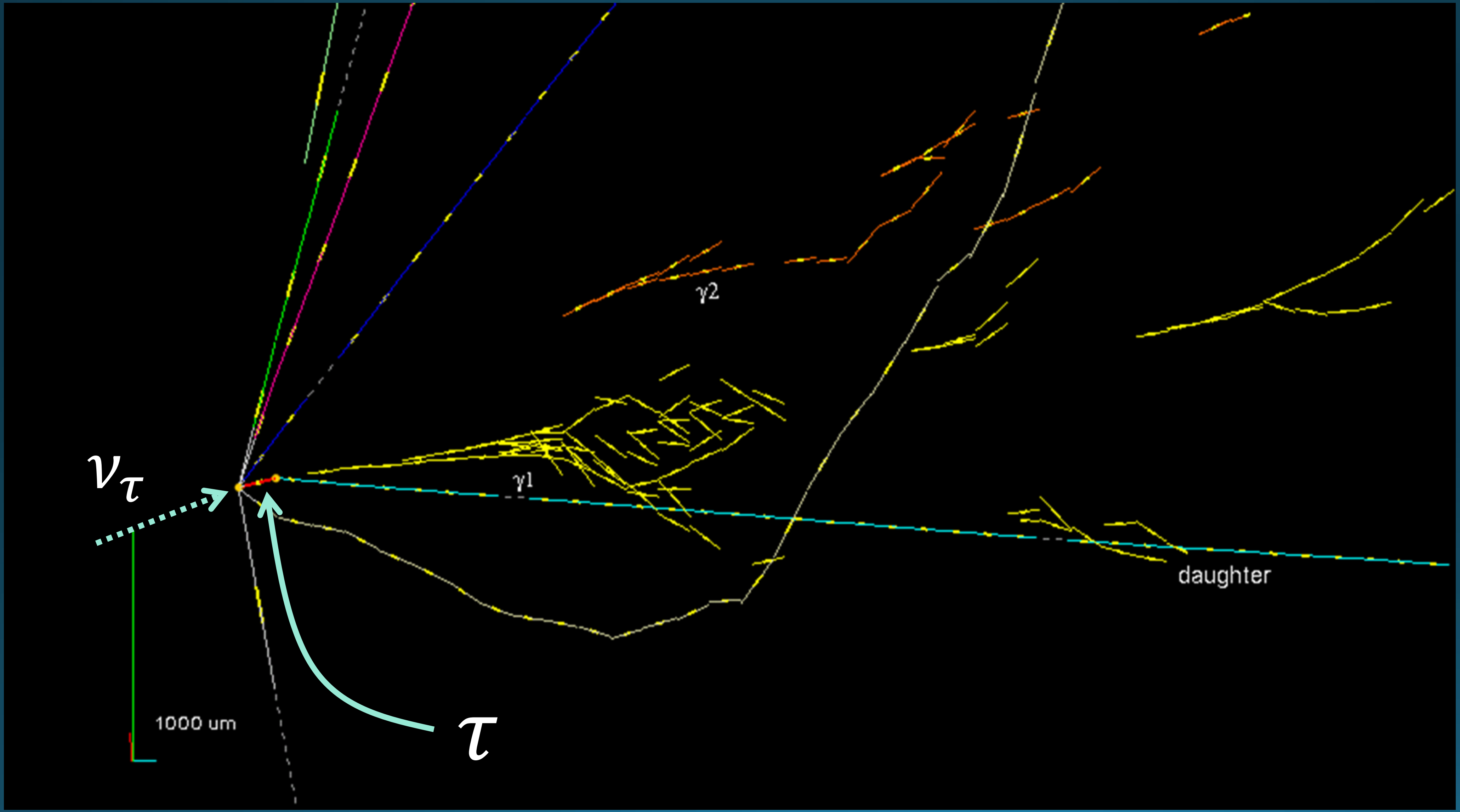


High density of detection channels, O(10^{14}) channels/cc, makes emulsion attractive for many purposes.

Emulsion-based neutrino detector

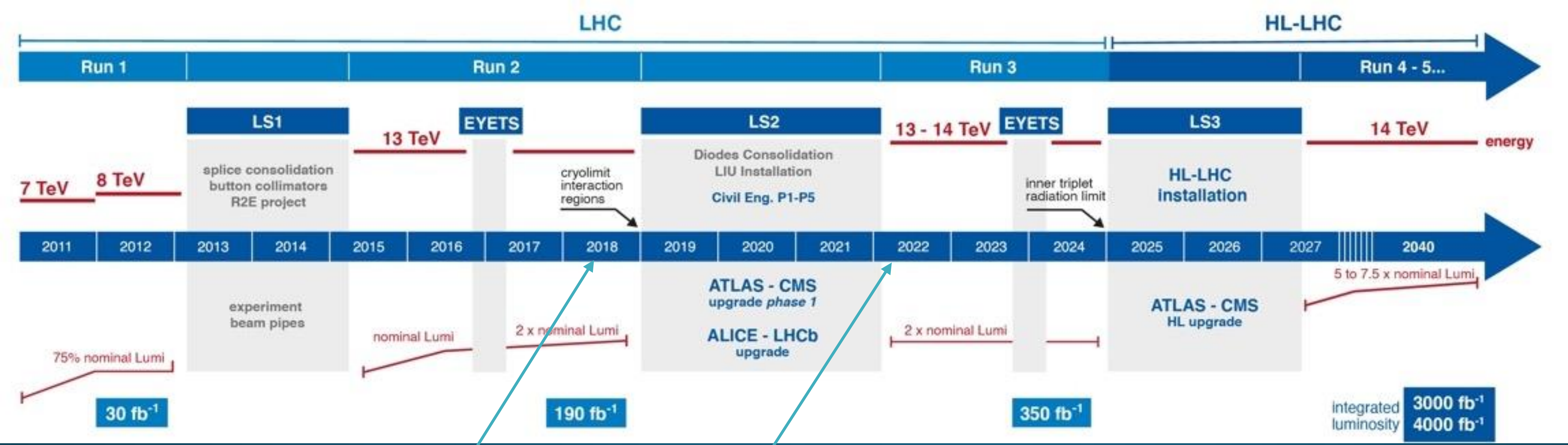


Emulsion-based neutrino detector



FASER Schedule

We are in LS2. Pilot run was performed in 2018.
Physics run will start in 2022.



BG measurement, pilot run in 2018

Physics run will start in 2022 (~150 fb^{-1})

FASERν history

2018, in Run 2 of LHC operation

- April, first discussion with FASER project
- June, install emulsion detectors for BG measurement
- July, Found that emulsions can work!
- Sep-Oct, install a pilot neutrino detector and data taking

- Nov, FASER TP

2019

- Jan, First neutral interactions
- Aug, FASERnu LOI
- Oct, FASERnu Technical proposal
- Dec, FASERnu Approval

- Mar, FASER approval
- Aug, FASER LOI
- Nov, FASER TP

10.1140/epjc/s10052-020-7631-5

CERN-EP-2019-160, KYUSHU-RCAPP-2019-003, SLAC-PUB-17460, UCI-TR-2019-19

arXiv:1908.02310v1 [hep-ex] 6 Aug 2019

Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC

FASER Collaboration

Henso Abreu,[1] Claire Antel,[2] Akitaka Ariga,[3,*] Tomoko Ariga,[3,4,*] Jamie Boyd,[5] Franck Cadoux,[2] David W. Casper,[6] Xin Chen,[7] Andrea Coccaro,[8] Candan Dozen,[7] Peter B. Denton,[9,†] Yannick Favre,[2] Jonathan L. Feng,[6] Didier Ferrere,[2] Iftah Galon,[10] Stephen Gibson,[11] Sergio Gonzalez-Sevilla,[2] Shih-Chieh Hsu,[12] Zhen Hu,[7] Giuseppe Iacobucci,[2] Sune Jakobsen,[5] Roland Jansky,[2] Enrique Kajomovitz,[1] Felix Kling,[6,13,*] Susanne Kuehn,[5] Lorne Levinson,[14] Congqiao Li,[12] Josh McFayden,[5] Sam Meehan,[5] Friedemann Neuhaus,[15] Hidetoshi Otono,[4] Brian Petersen,[5] Helena Pikhartova,[11] Michaela Queitsch-Maitland,[5] Osamu Sato,[16] Kristof Schmieden,[5] Matthias Schott,[15] Anna Sfyrla,[2] Savannah Shively,[6] Jordan Smolinsky,[6] Aaron M. Soffa,[6] Yosuke Takubo,[17] Eric Torrence,[18] Sebastian Trojanowski,[19] Callum Wilkinson,[20,†] Dengfeng Zhang,[7] and Gang Zhang[7]

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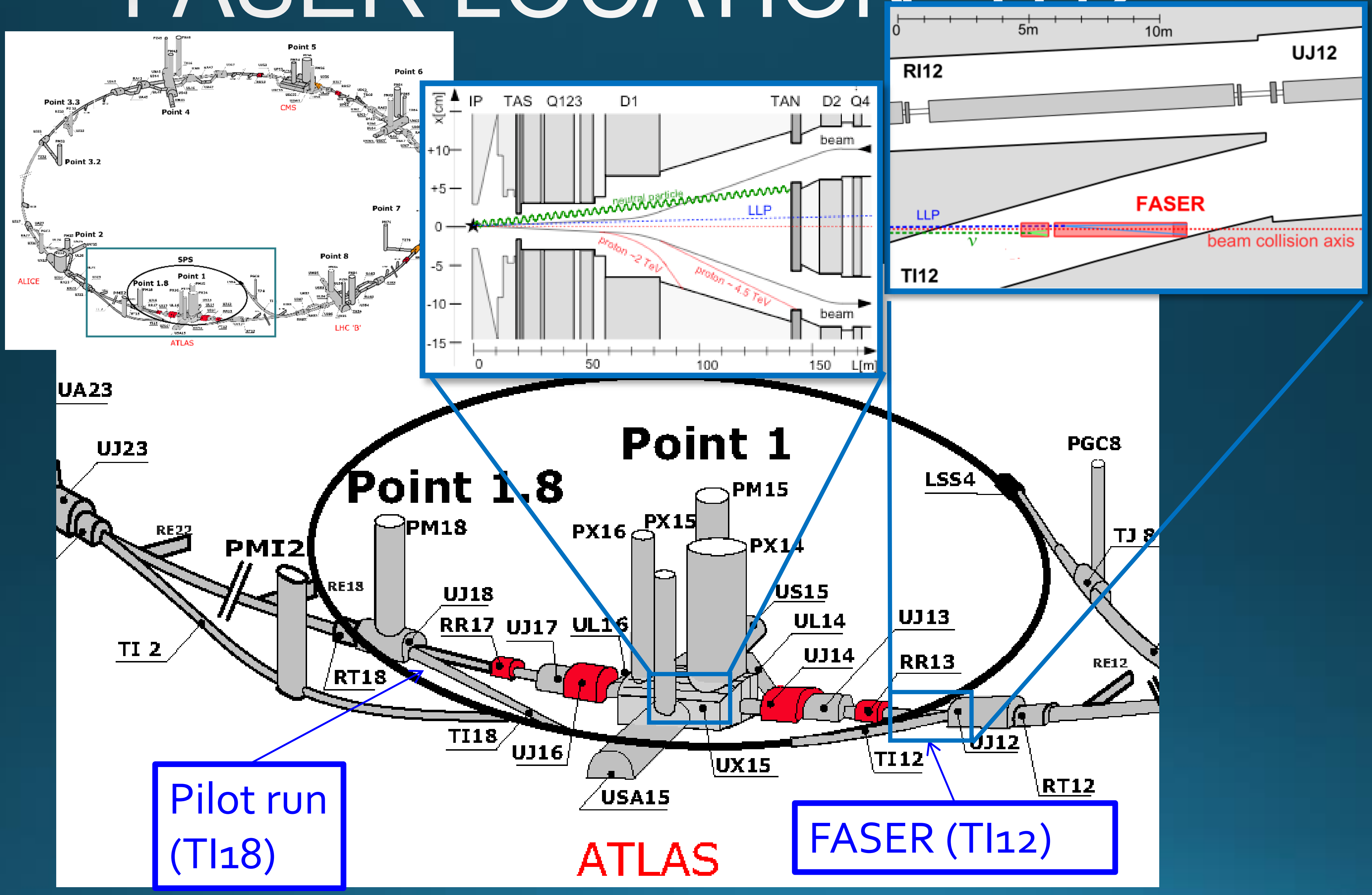
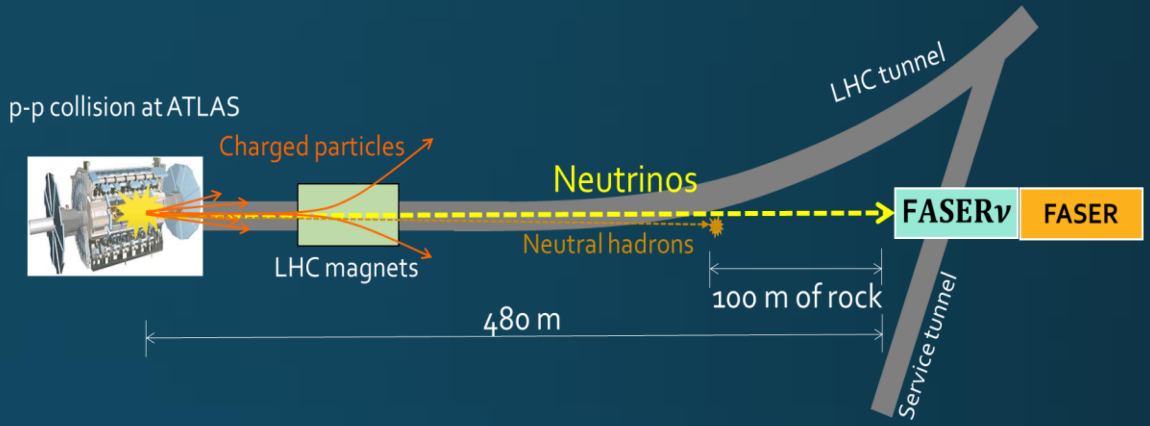
[3] *Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[4] *Kyushu University, Nishi-ku, 819-0395 Fukuoka, Japan*

FASER LOCATION: TI12

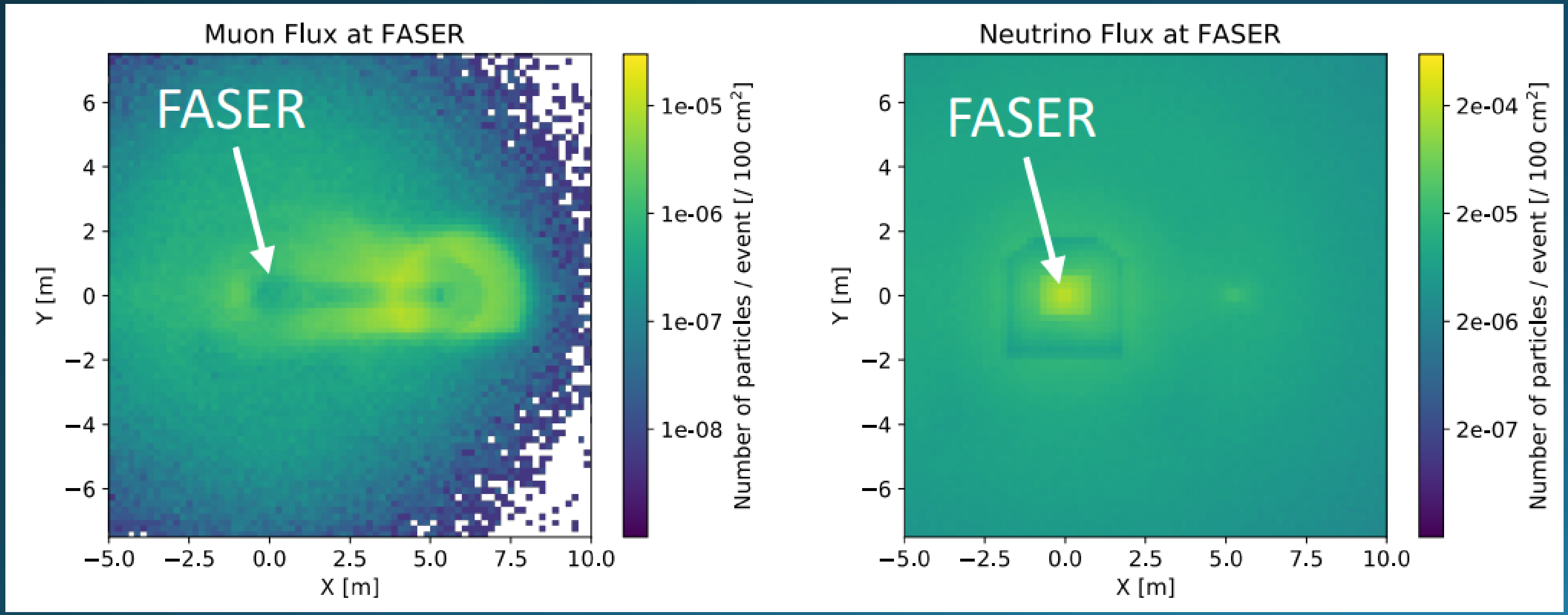


Particle fluence at the site

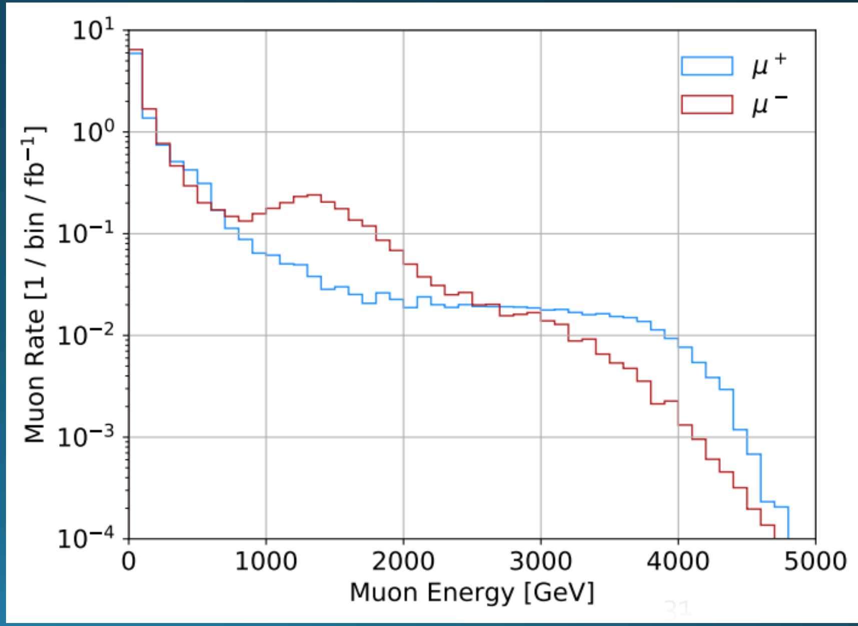
- Crucial for both neutrinos and LLP searches
- Simulation through the LHC infrastructures by FLUKA and BDSim
- Minimum muons, maximum neutrinos

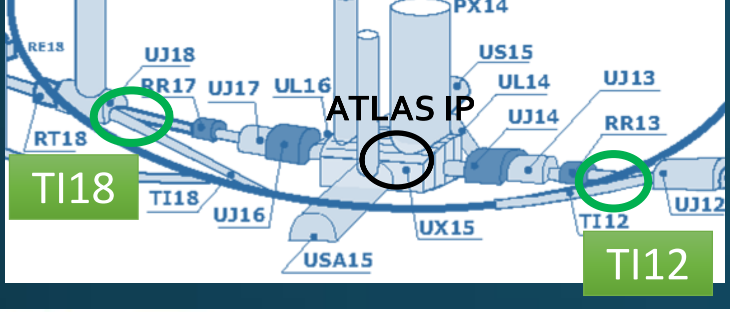


BDSim result for TI12, Lefebvre ICHEP2020



Muon energy (at 409m from IP, pilot run)
Simulated by CERN-STI group with FLUKA

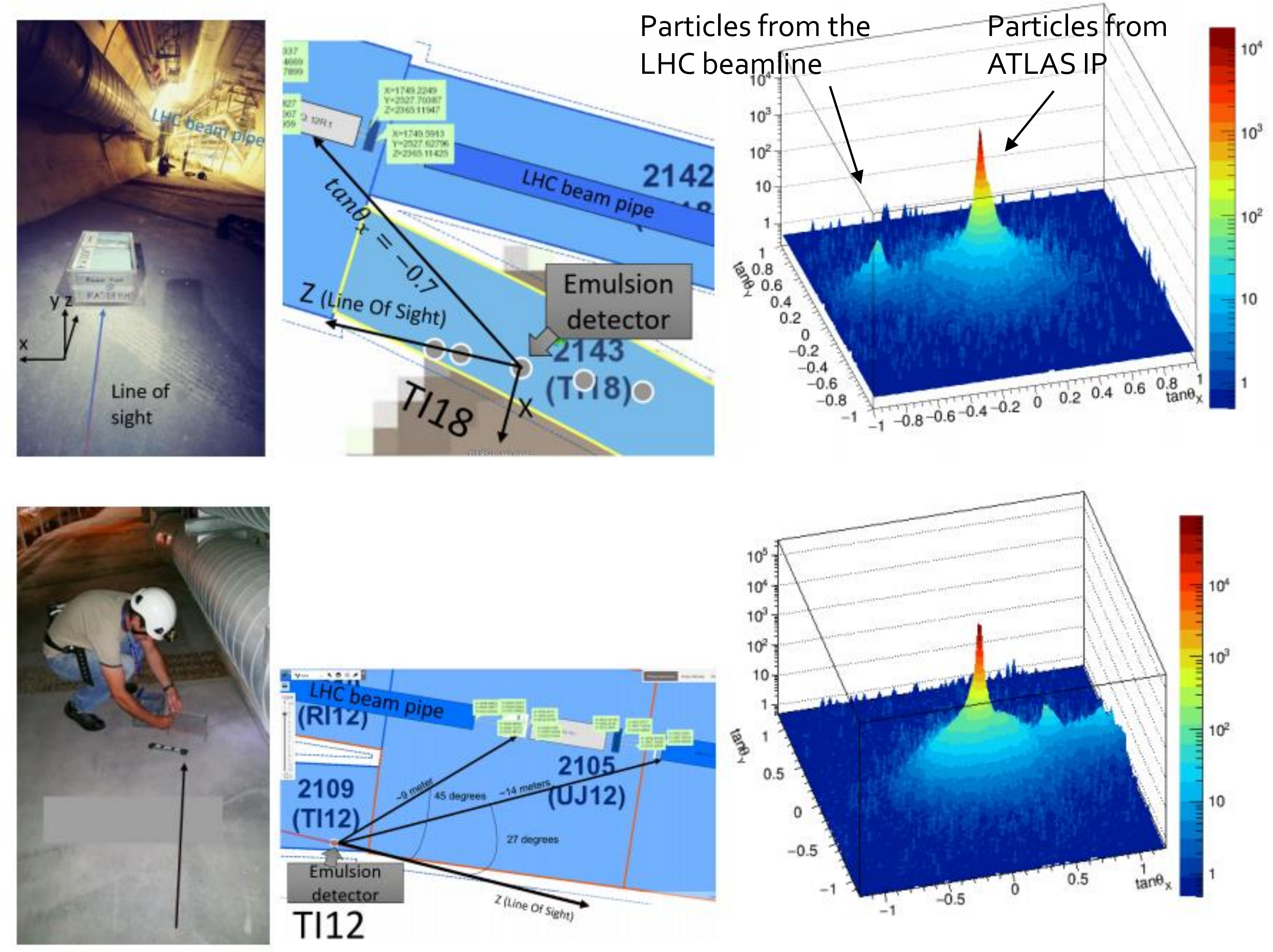




In situ measurements in 2018: Charged particle background

TI18

TI12

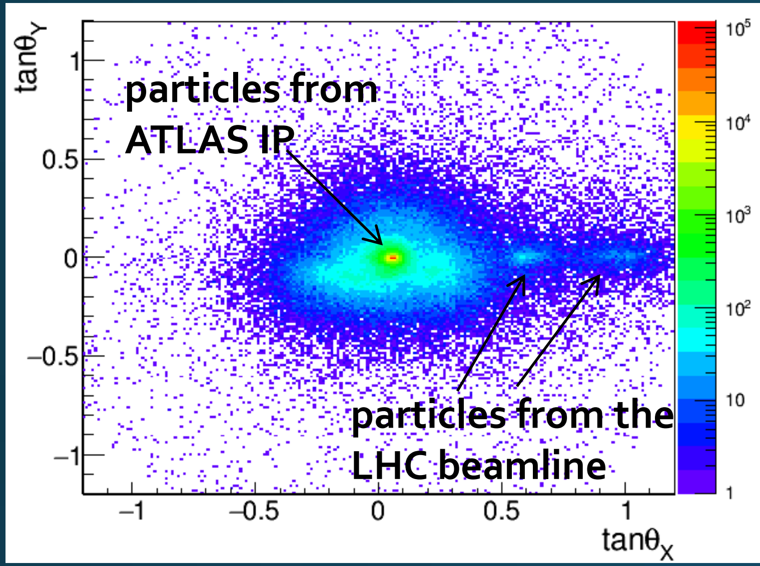


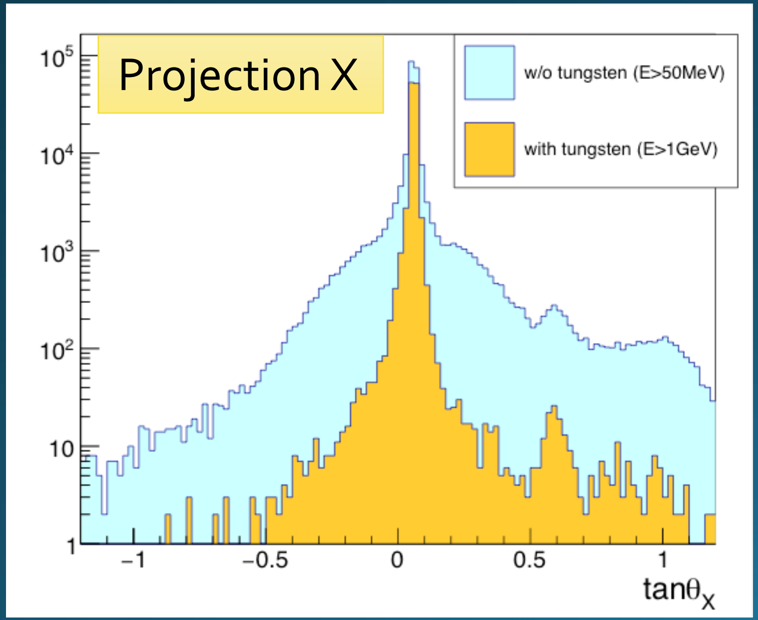
- Emulsion detectors were installed to investigate TI18 and TI12.
- **Low background was confirmed.**
- Few hadron tracks
- Consistent with the FLUKA prediction.

	Normalized flux (tracks/fb^{-1}/cm^2)
TI18	$(2.6 \pm 0.7) \times 10^4$
TI12	$(3.0 \pm 0.3) \times 10^4$

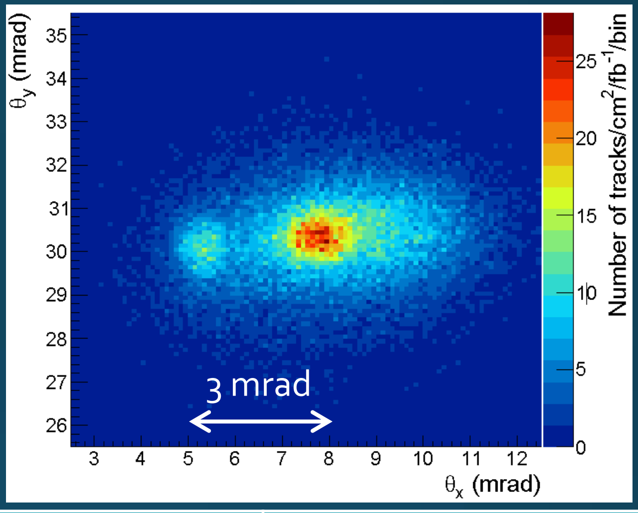
Emulsion detector can work at the actual environment!
(up to ~10^6/cm^2 ≃ 30 fb^{-1} of data)

Angular distributions of beam backgrounds





Close up to the main peak

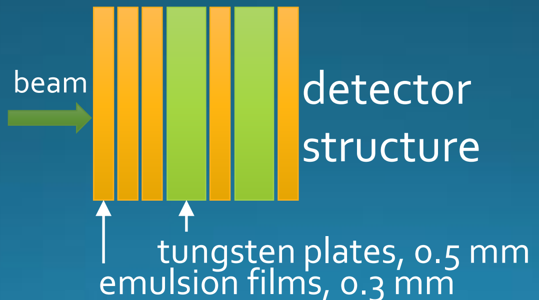


2 peak structure

$\sigma = 0.6\ mrad$

After 100 m of rock, it scatters only 0.6 mrad.
→ ~700 GeV

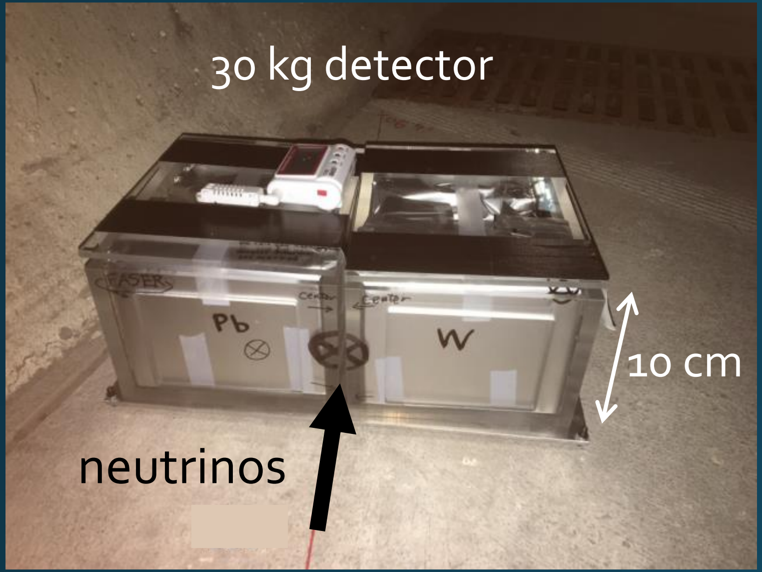
	Flux all [fb/cm²]	Flux in main peak [fb/cm²]
TI18 data	$2.6 \pm 0.7 \times 10^4$	$1.2 \pm 0.4 \times 10^4$
TI18 pilot		$1.7 \pm 0.1 \times 10^4$
TI12 data	$3.0 \pm 0.3 \times 10^4$	$1.9 \pm 0.2 \times 10^4$
FLUKA MC		2.5×10^4



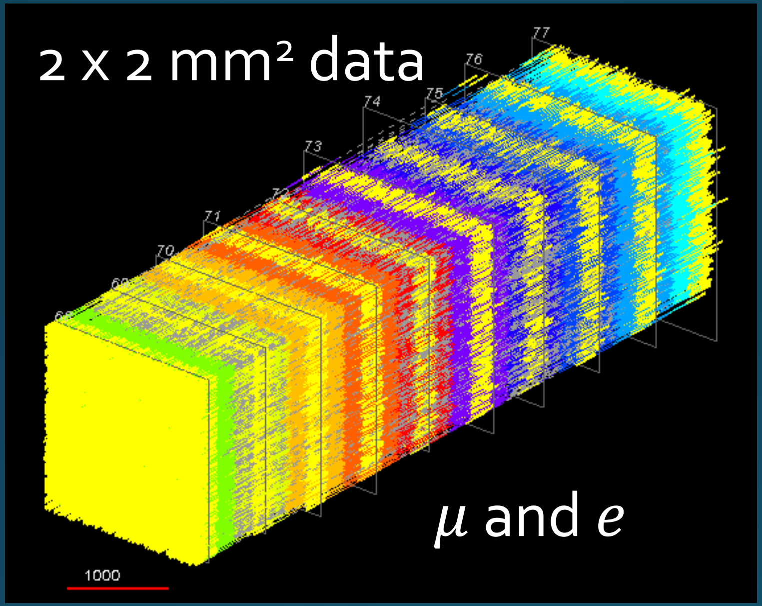
Data and the FLUKA (uncertainty 50%) prediction agrees within their uncertainties.

Pilot run in 2018

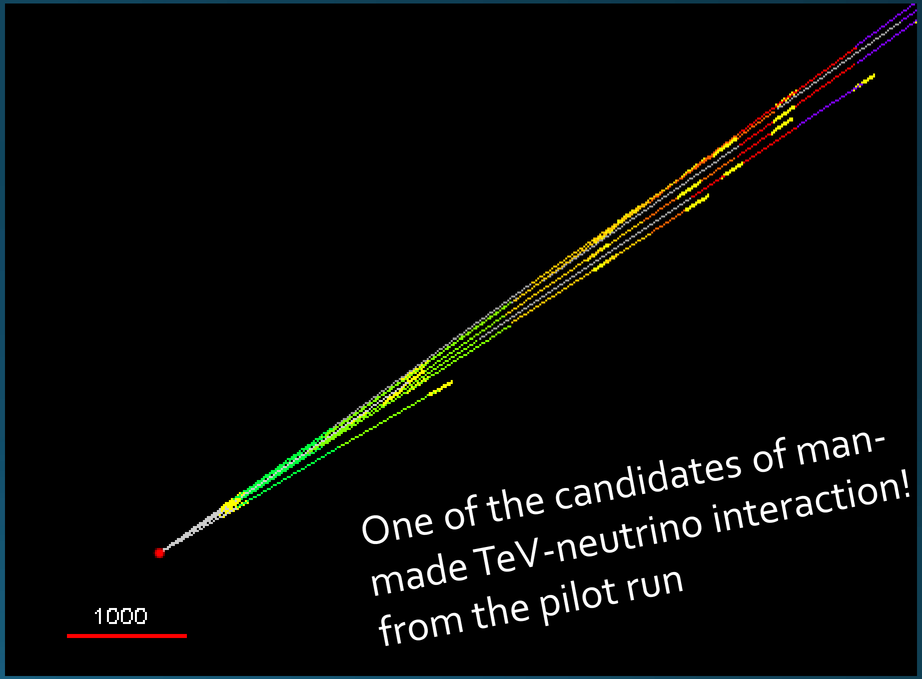
Aiming to demonstrate the feasibility of detection of collider neutrinos



6 weeks, 12.2 fb^{-1}

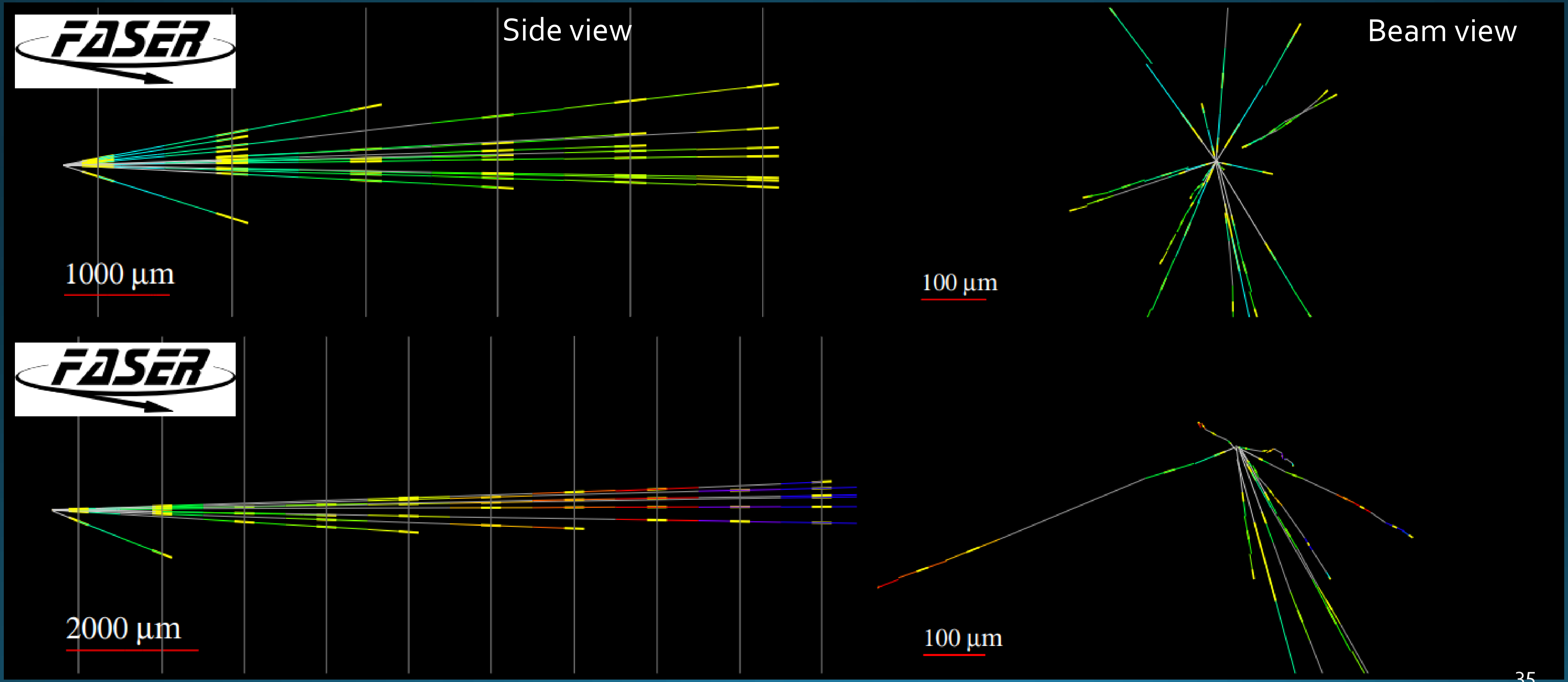


$\simeq 3 \times 10^5$ tracks/cm²



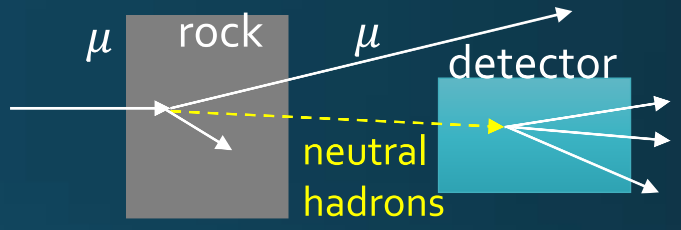
- A 30 kg emulsion based (lead, tungsten target) detector was installed on axis, 12.2 fb^{-1} of data was collected in Sep-Oct 2018 (6 weeks) arXiv:2105.06197

Neutrino interaction candidates



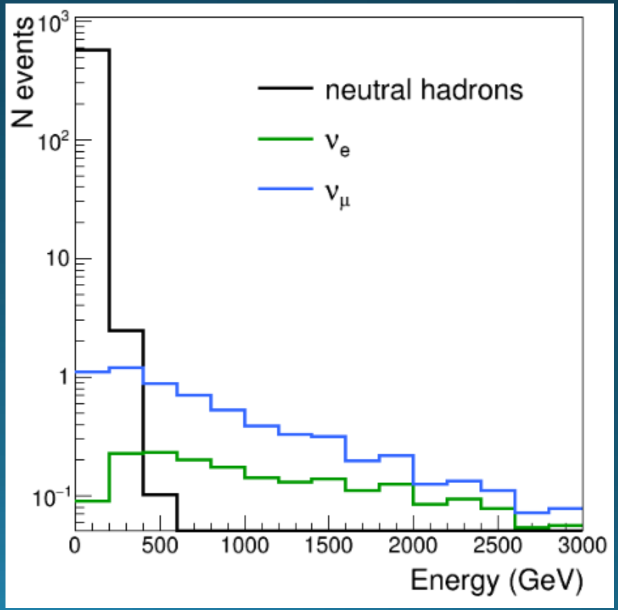
Background for neutrino analysis

- Muons rarely produce neutral hadrons in upstream rock or in detector, which can mimic neutrino interaction vertices
  - Probability of O(10^{-5})
- The produced neutral hadrons are low energy → Discriminate by vertex topology
- (For physics run, Lepton ID will kill most of background)



	Negative Muons	Positive Muons
K_L	3.3×10^{-5}	9.4×10^{-6}
K_S	8.0×10^{-6}	2.3×10^{-6}
n	2.6×10^{-5}	7.7×10^{-6}
$\bar{n}$	1.1×10^{-5}	3.2×10^{-6}
Λ	3.5×10^{-6}	1.8×10^{-6}
$\bar{\Lambda}$	2.8×10^{-6}	8.7×10^{-7}

Production rate per muon (E_{had}>10 GeV)



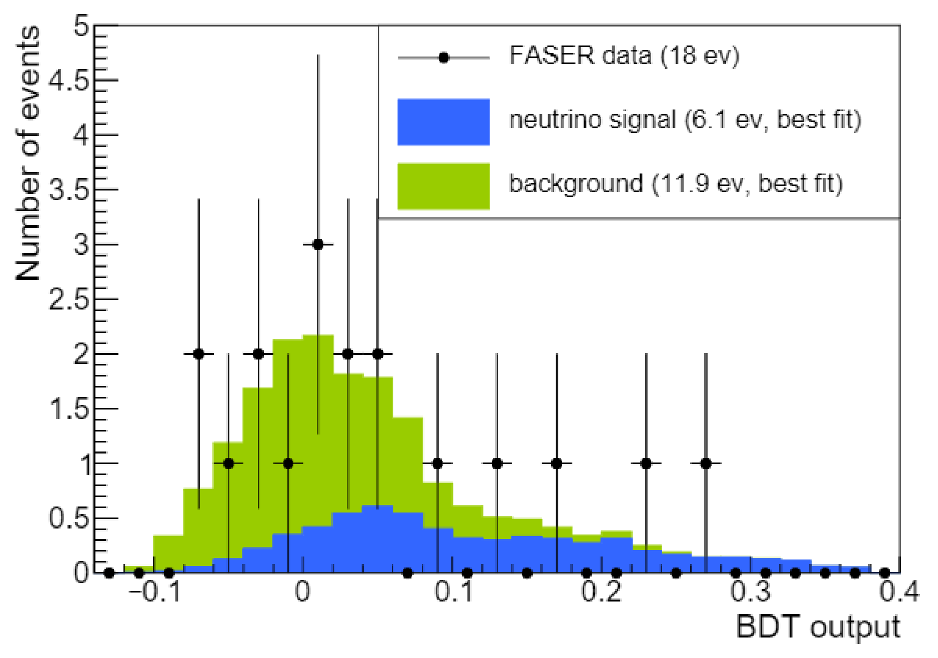
arXiv:2105.06197

Pilot run event statistics

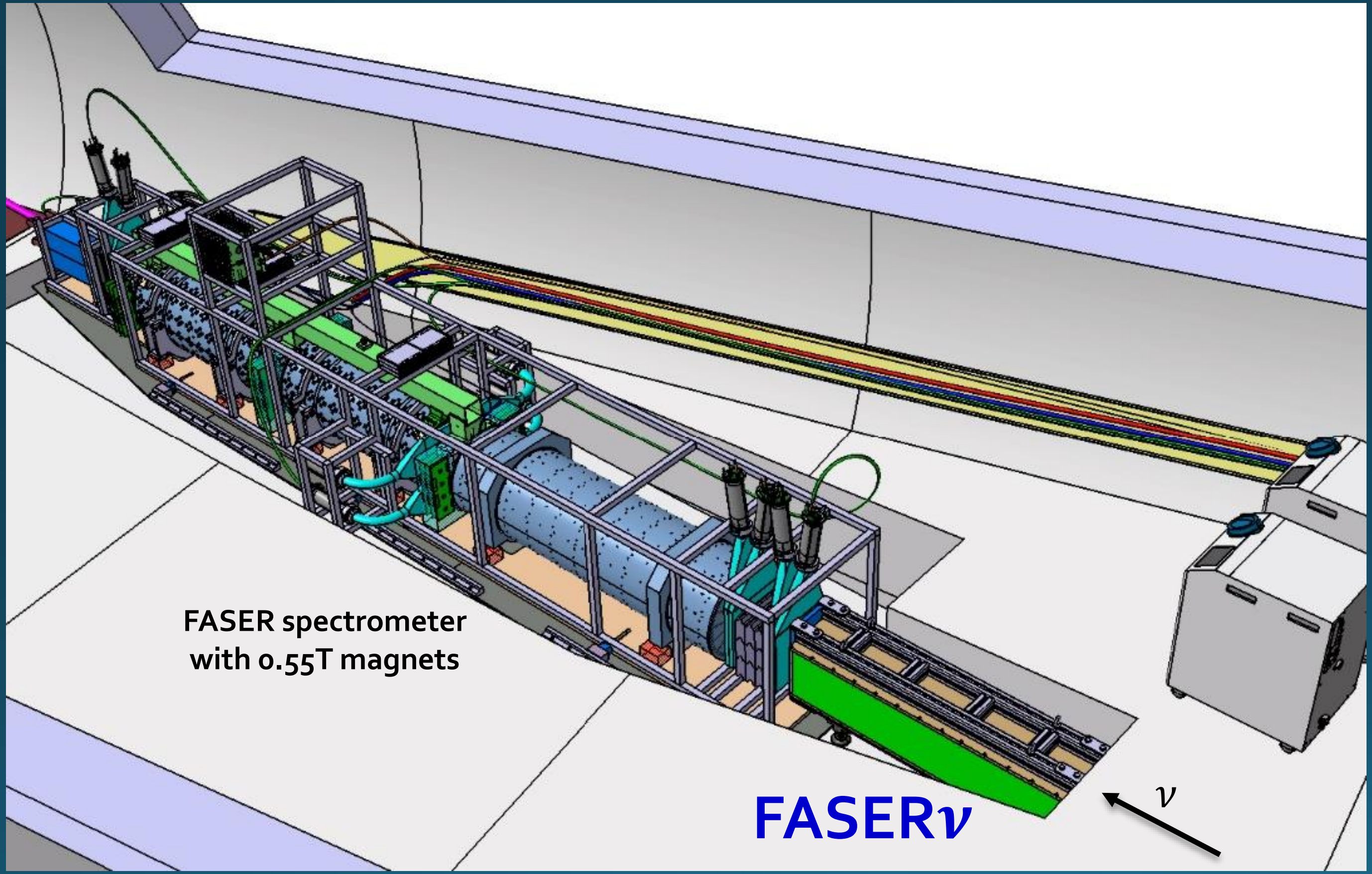
- Analyzed target mass of 11 kg
- Pilot neutrino detector doesn't have lepton ID
  - → Separation from neutral hadron BG (produced by muons) is challenging → tighter cuts
- Expected signal = $3.3^{+1.7}_{-0.95}$ events, BG = 11.0 events
- 18 neutral vertices were selected
  - by applying # of charged particle ≥ 5, etc.
- In BDT analysis, an excess of neutrino signal is observed. Statistical significance = 2.7 sigma from null hypothesis
- This result demonstrates the detection of neutrinos from the LHC

Vertex detection efficiency

Signal		Background		
			FTFP_BERT	QGSP_BERT
ν_e	0.490	K_L	0.017	0.015
$\bar{\nu_e}$	0.343	K_S	0.037	0.031
ν_μ	0.377	n	0.011	0.012
$\bar{\nu_\mu}$	0.266	$\bar{n}$	0.013	0.013
ν_τ	0.454	Λ	0.020	0.021
$\bar{\nu_\tau}$	0.368	$\bar{\Lambda}$	0.018	0.018



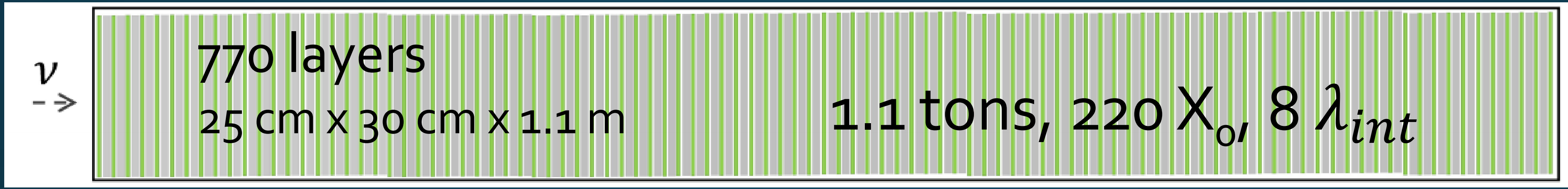
Detector in the LHC Run3 (2021-2024)

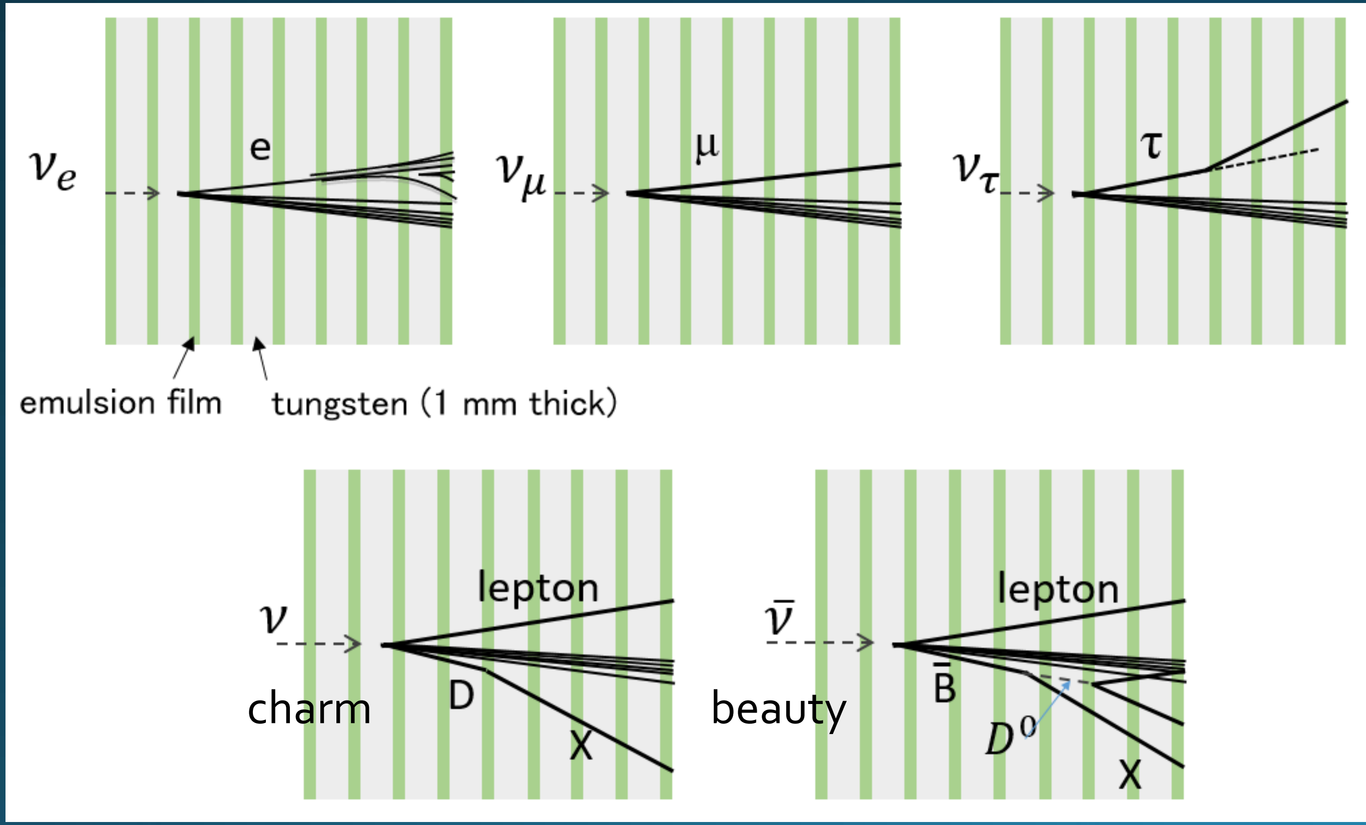


1.2 tons

Conceptual detector design

Emulsion films + tungsten plates

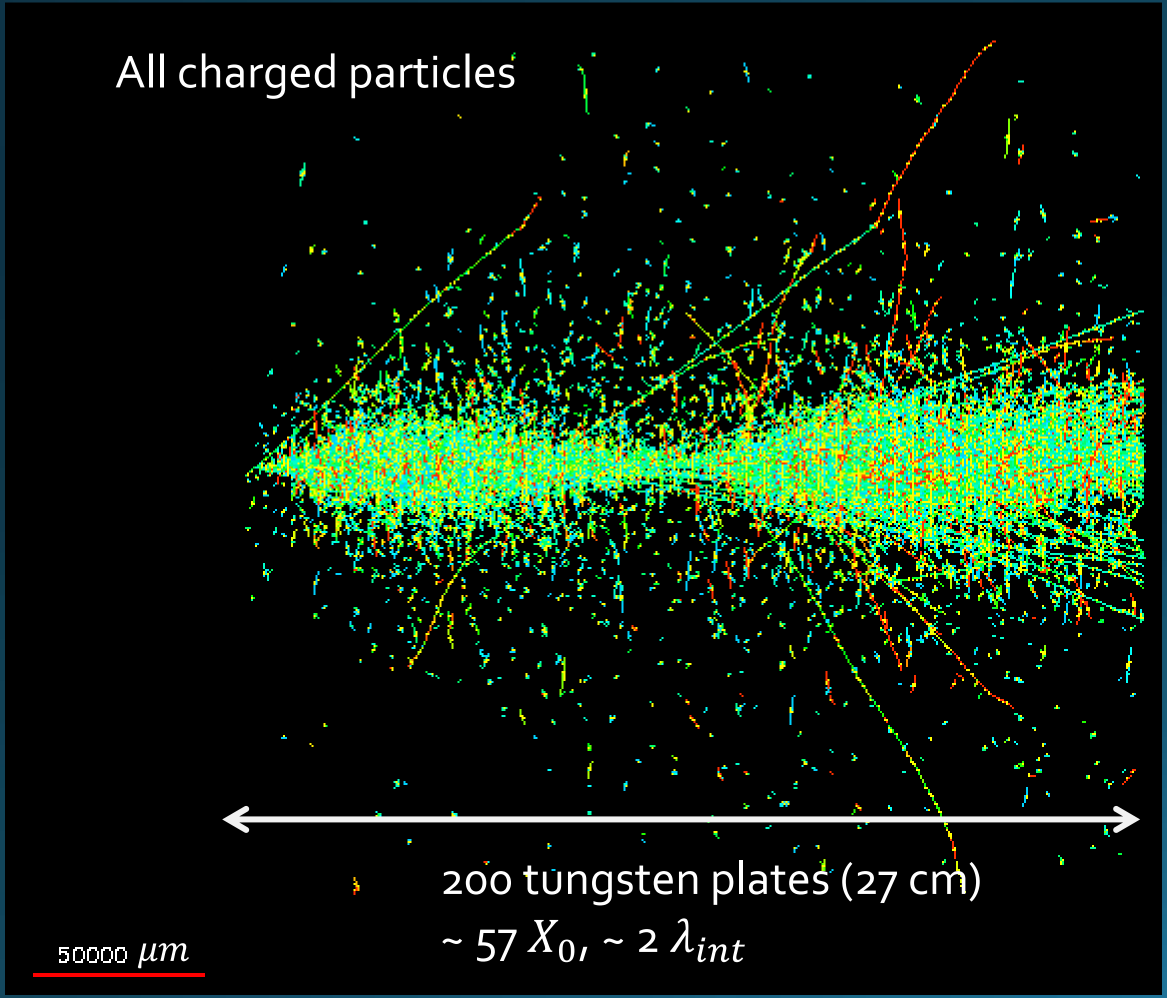


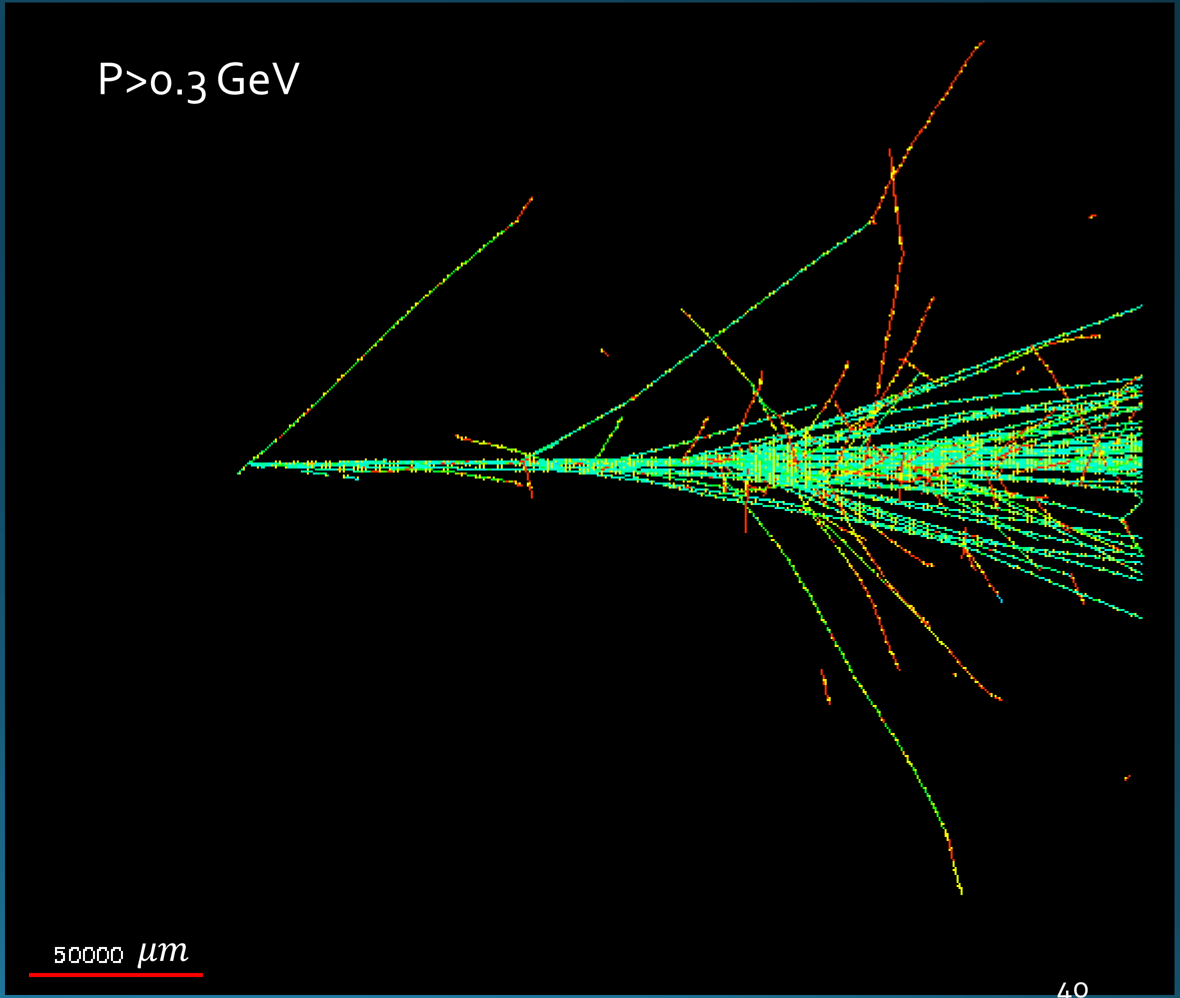


Exchange emulsions 9 times

2 0 2 2	3 ex	~80 fb^{-1}
2 0 2 3	3 ex	~80 fb^{-1}
2 0 2 4	3 ex	~80 fb^{-1}

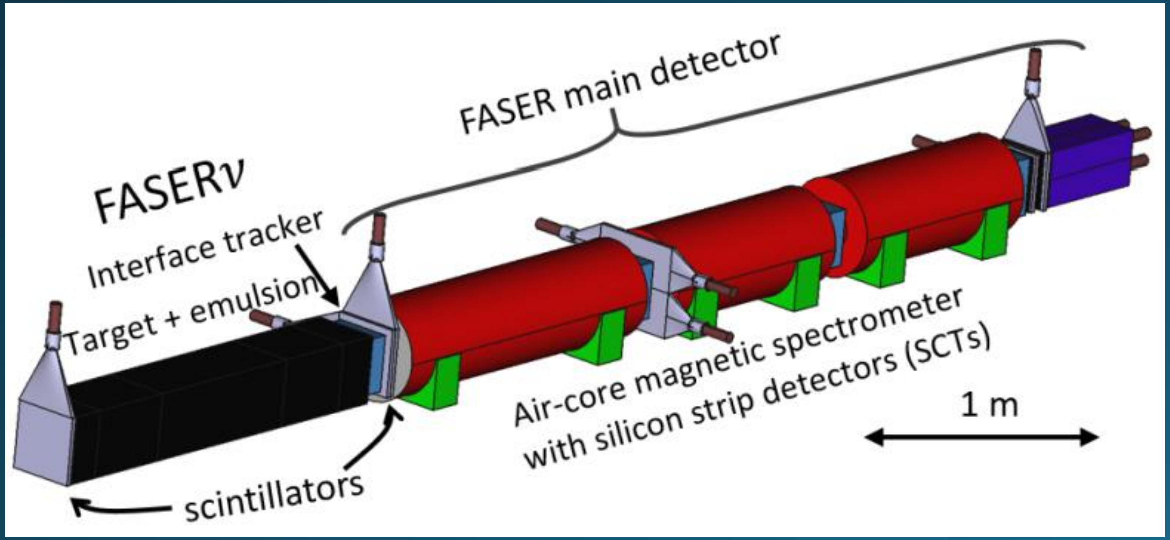
Simulated 1 TeV ν_μ CC interaction

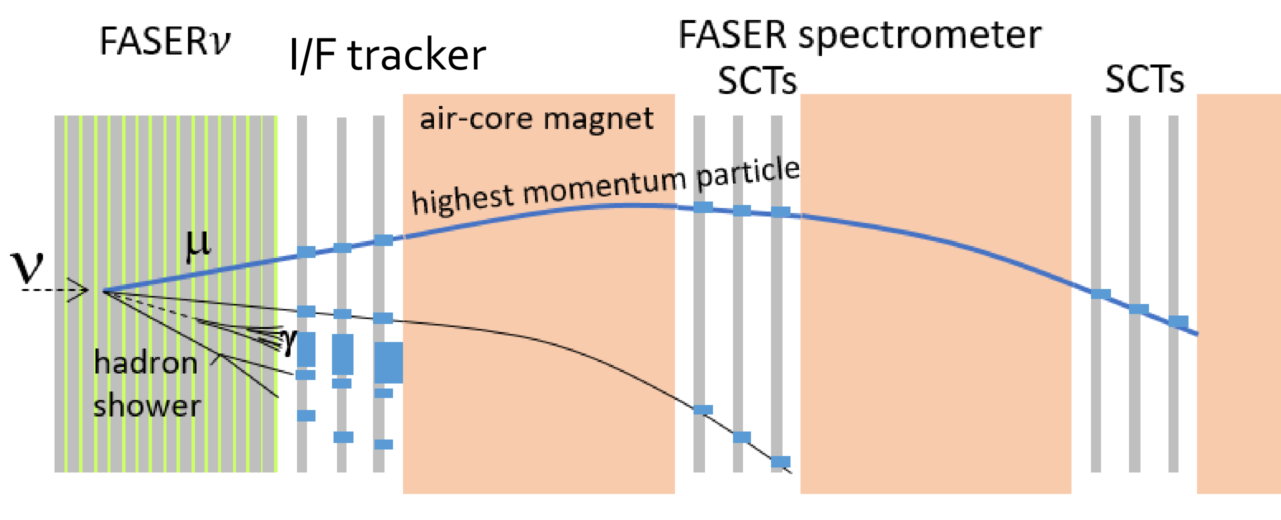




FASERν + FASER, hybrid configuration

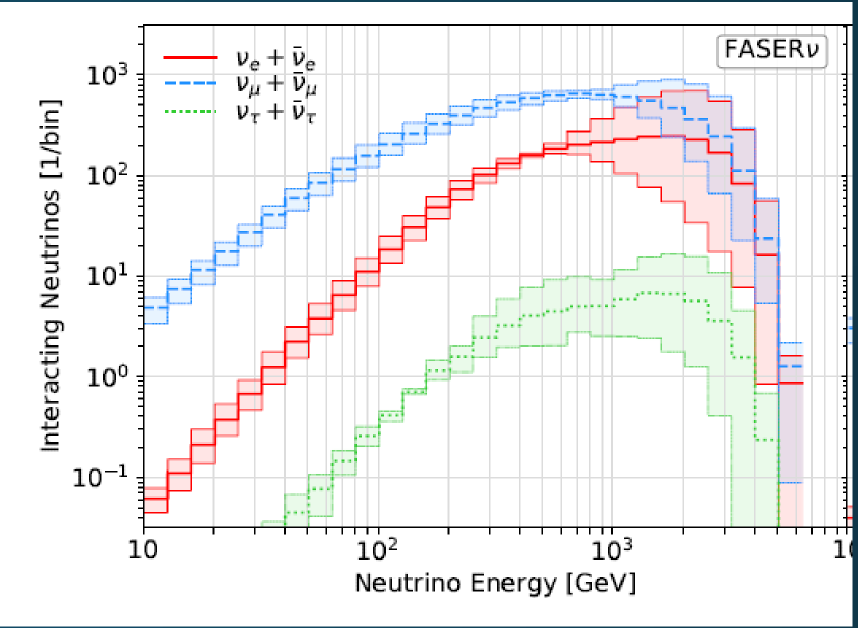
- Muon charge identification
- Distinguish ν_μ and $\bar{\nu}_\mu$ → Wider physics cases
- Improve neutrino energy reconstruction





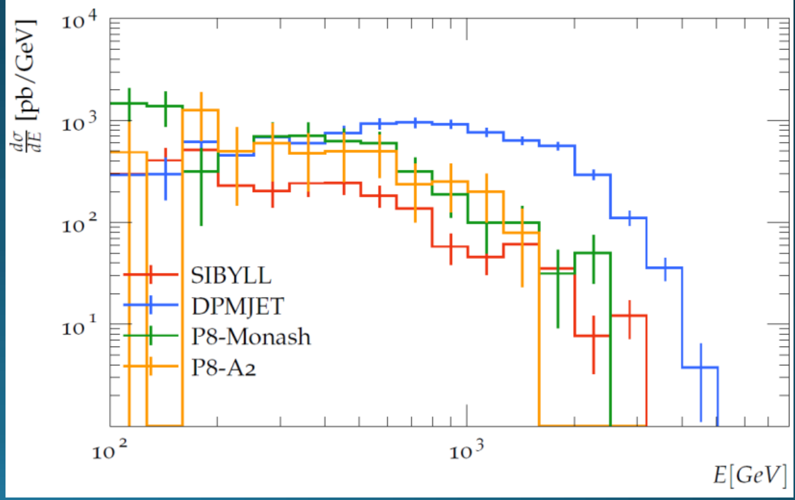
Neutrino event rate (2021-2024)

- **Small detector, but a lot of interactions ($\sim 10^4$ CC) are expected during Run3**
- Neutrino fluxes are being cross-checked among different simulations
  - Differences due to hadron generators and beamline infrastructure reproduction were identified. Currently, differences at hadron generators level is dominant



Expected number of CC interactions in FASERν in Run3 (14 TeV LHC, 150 fb⁻¹)

	SIBYLL	Pythia 8	DPMJET (used in FLUKA)
ν_e , $\bar{\nu}_e$	800, 452	826, 477	3390, 1024
ν_μ , $\bar{\nu}_\mu$	6571, 1653	7120, 2178	8437 , 2737
ν_τ , $\bar{\nu}_\tau$	16, 6	22, 11	111 , 43



Large variation between different hadron production models (at p-p collision)

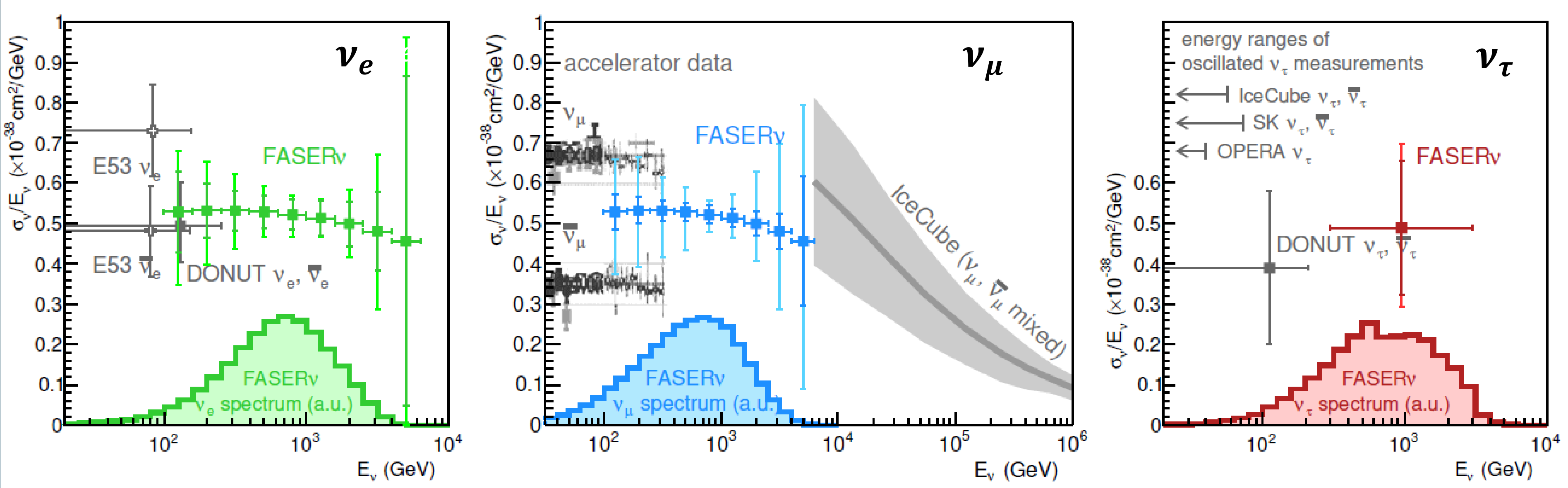
- Work in progress for quantifying and reducing these uncertainties
  - Creating a dedicated forward physics tune with Pythia8, using forward data (LHCf, FASER's muon measurements, etc.)

Physics studies in the LHC Run 3 (1): Cross sections

FASER Collaboration,
Eur. Phys. J. C 80 (2020) 61,
arXiv:1908.02310

- Neutrino cross section measurement at unexplored energy range
  - ν_e, ν_τ at the highest energy
  - Fill the gap between accelerator and cosmic data for ν_μ

Projected precision of FASERν measurement at 14-TeV LHC (150 fb[-1])

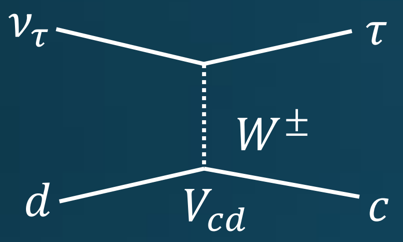


inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate corresponding to the range of predictions obtained from different MC generators.

Physics studies in the LHC Run 3 (2):

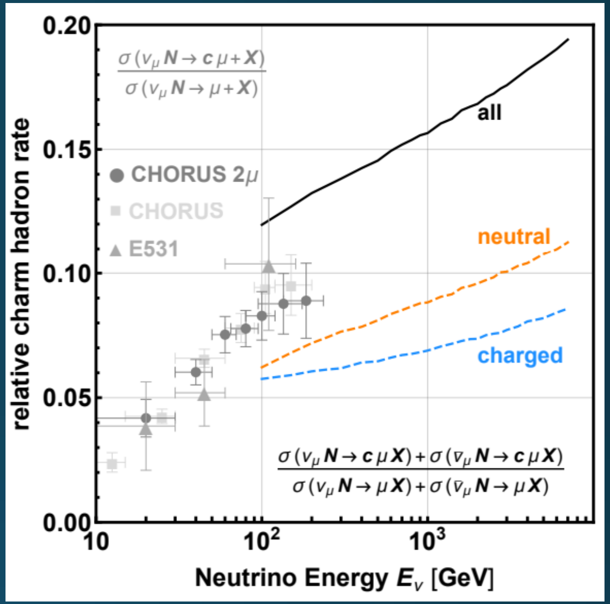
Heavy-flavor-associated channels

- Measure charm production channels
  - Large rate ~ 10% ν CC events, $\mathcal{O}(1000)$ events
  - First measurement of ν_e induced charm prod.

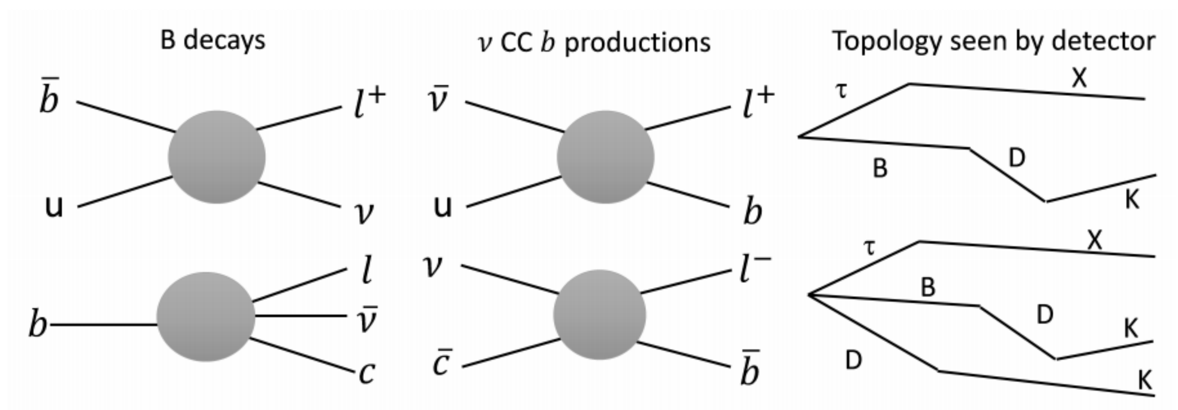


$$\frac{\sigma(\nu_\ell N \to \ell\, X_c + X)}{\sigma(\nu_\ell N \to \ell + X)}$$

$\ell = e, \mu$



- Search for Beauty production channels
  - Expected SM events (ν_μ CC b production) are $\mathcal{O}(0.1)$ events in Run 3, due to CKM suppression, $V_{ub}^2 \simeq 10^{-5}$



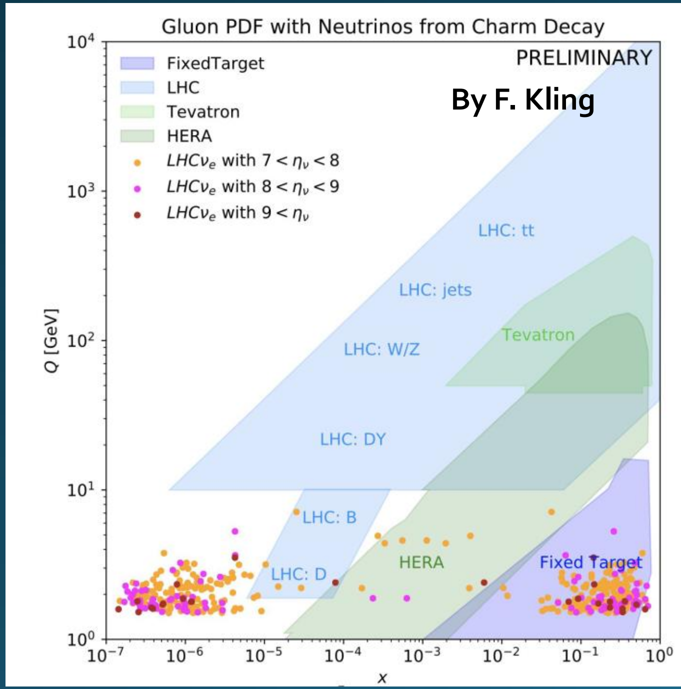
$\bar{\nu}N \to \ell \bar{B} X$

$\nu N \to \ell B D X$

Physics studies in the LHC Run 3 (3): QCD

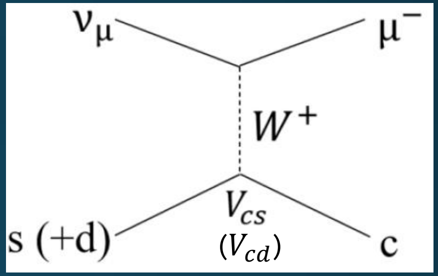
PDF in proton (neutrino production)

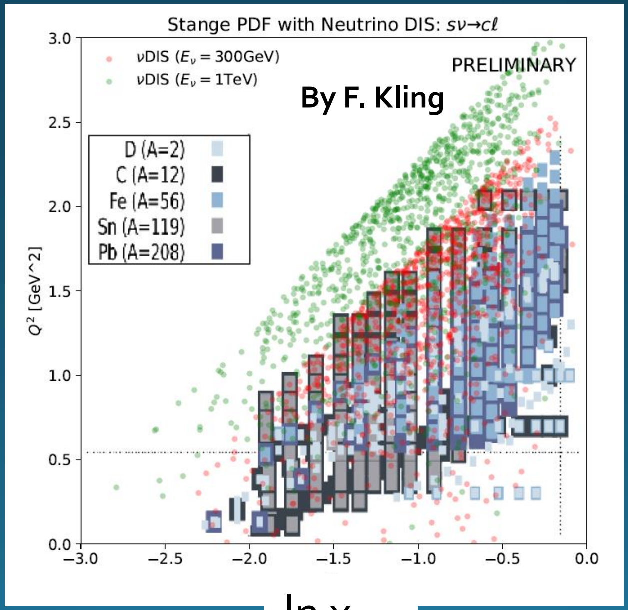
- Forward particle production is poorly constrained by other LHC experiments. FASERν's **neutrinos flux measurements** will provide novel complimentary constraints that can be used to validate/improve MC generators.
- Neutrinos from charm decay could allow to **test transition to small-x factorization, constrain low-x gluon PDF and probe intrinsic charm**.



PDF in target (neutrino interaction)

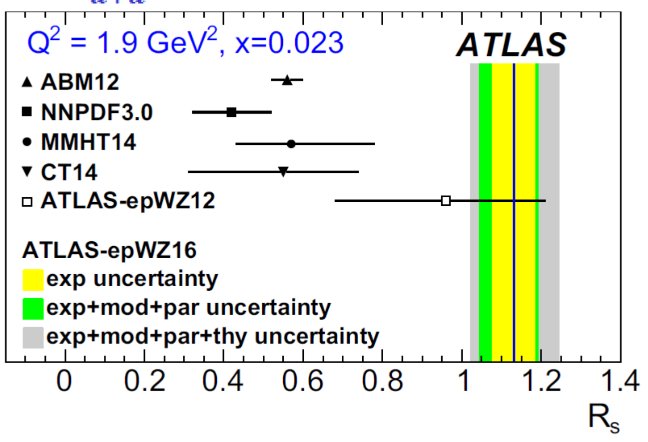
- It is also interesting to probe (nuclear) PDFs via DIS neutrino scattering. In particular, **charm associated neutrino events ($\nu\ s \rightarrow l\ c$) are sensitive to the poorly constrained strange quark PDF**.





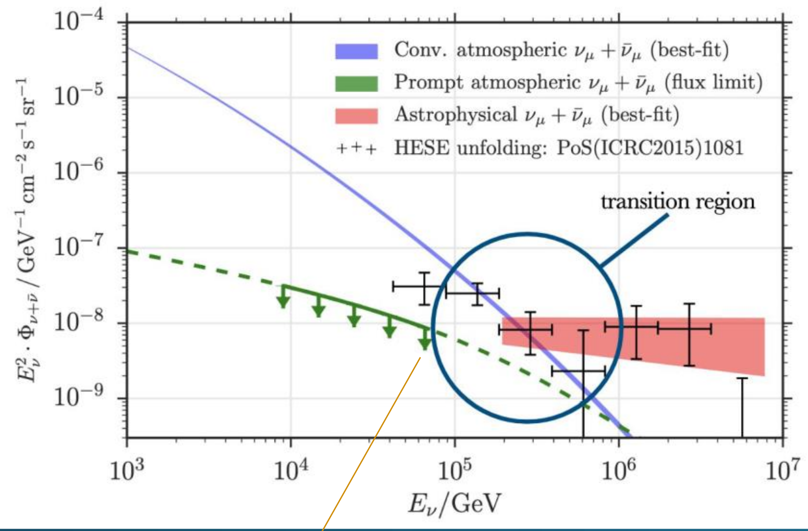
ln x

$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$ [Eur. Phys. J. C77 (2017) 367]



Physics studies in the LHC Run 3 (4):
Cosmic rays and neutrino

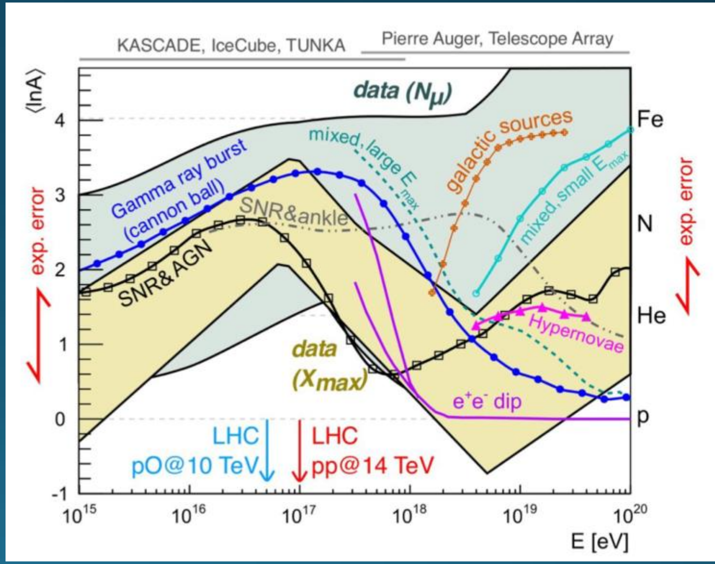
- In order for IceCube **to make precise measurements of the cosmic neutrino flux**, accelerator measurements of high energy and large rapidity charm production are needed.
- As 7+7 TeV p-p collision corresponds to 100 PeV proton interaction in fixed target mode, a direct **measurement of the prompt neutrino production at FASERν** would provide important basic data for current and future high-energy neutrino telescopes.



prompt atmospheric neutrinos

IceCube Collaboration, Astrophys. J. 833 (2016)

- Muon problem in CR physics: cosmic ray experiments have reported an excess in the number of muons over expectations computed using extrapolations of hadronic interaction models tuned to LHC data at the few σ level. New input from LHC is crucial to reproduce CR data consistently.

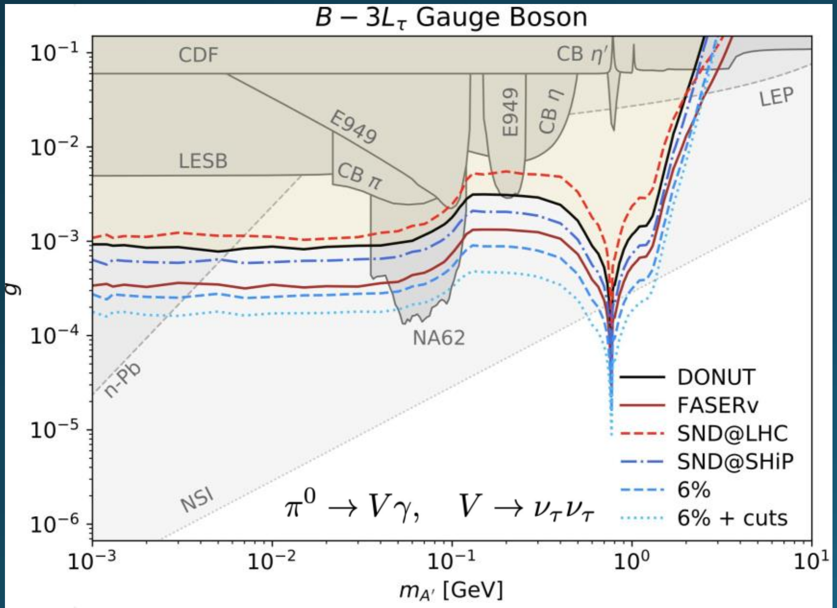


K.H. Kampert, M. Unger, Astropart. Phys. 35, 660 (2012),
H.P. Dembinski et al., EPJ Web Conf. 210, 02004 (2019)

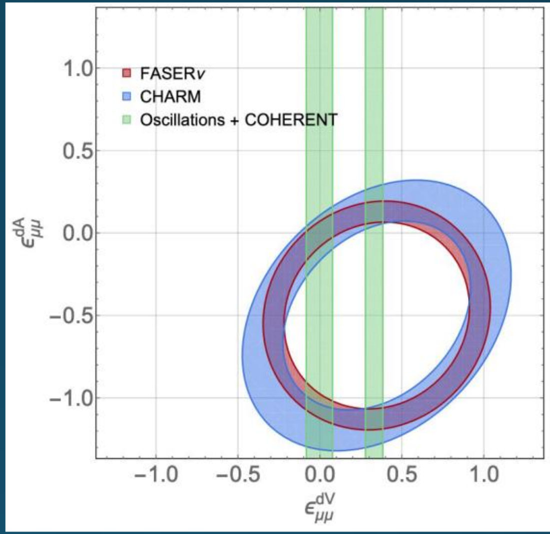
Physics studies in the LHC Run 3 (5):
BSM Physics

- The tau neutrino flux is small in SM. A **new light weakly coupled gauge bosons** decaying into tau neutrinos could significantly enhance the tau neutrino flux.

F. Kling, Phys. Rev. D 102, 015007 (2020), arXiv:2005.03594



- NC measurements at FASERν could constrain **neutrino non-standard interactions** (NSI).



A. Ismail, R.M. Abraham, F. Kling, arXiv: 2012.10500

- **Sterile neutrinos** with mass ~40 eV can cause oscillations at FASERν and the spectrum deformation may be seen.

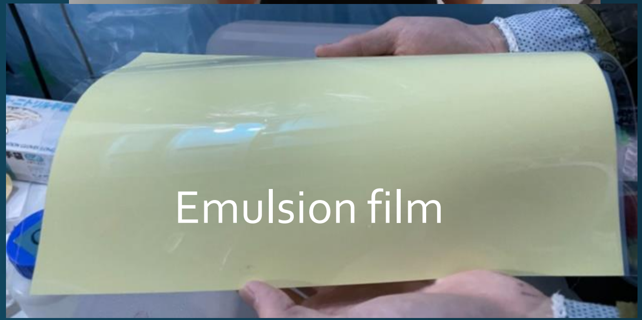
FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310

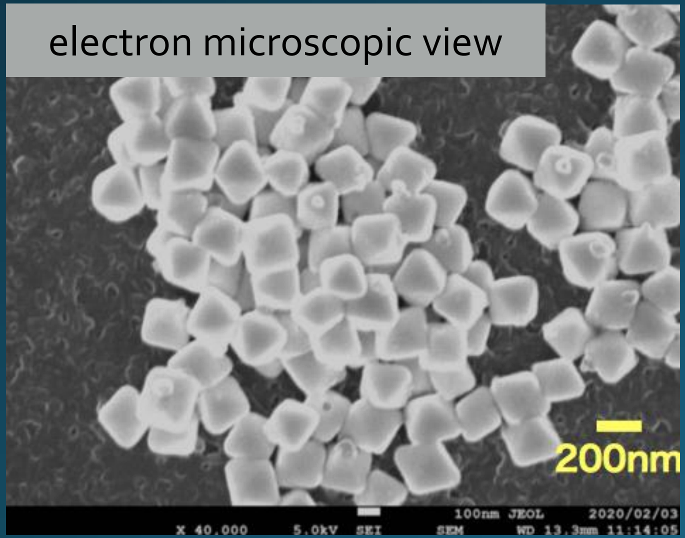
- If DM is light, the LHC can produce an energetic and collimated DM beam towards FASERν. FASERν could also search for **DM scattering**.

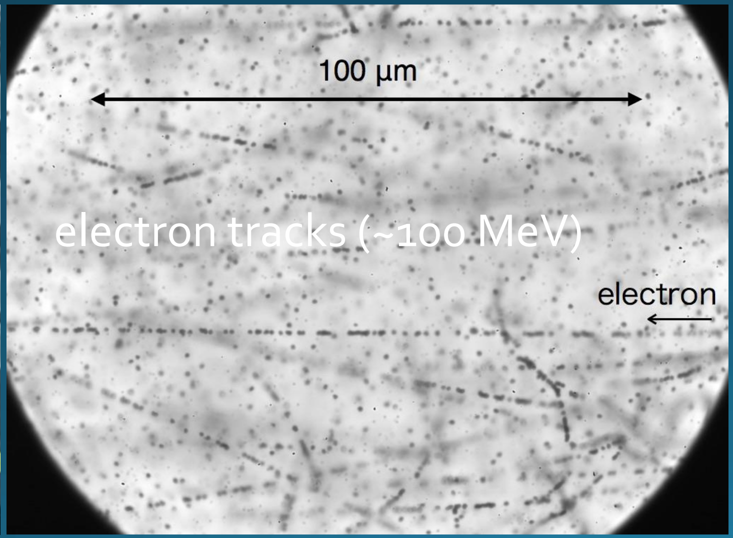
B. Batell, J. Feng, S. Trojanowski, 2020, in preparation

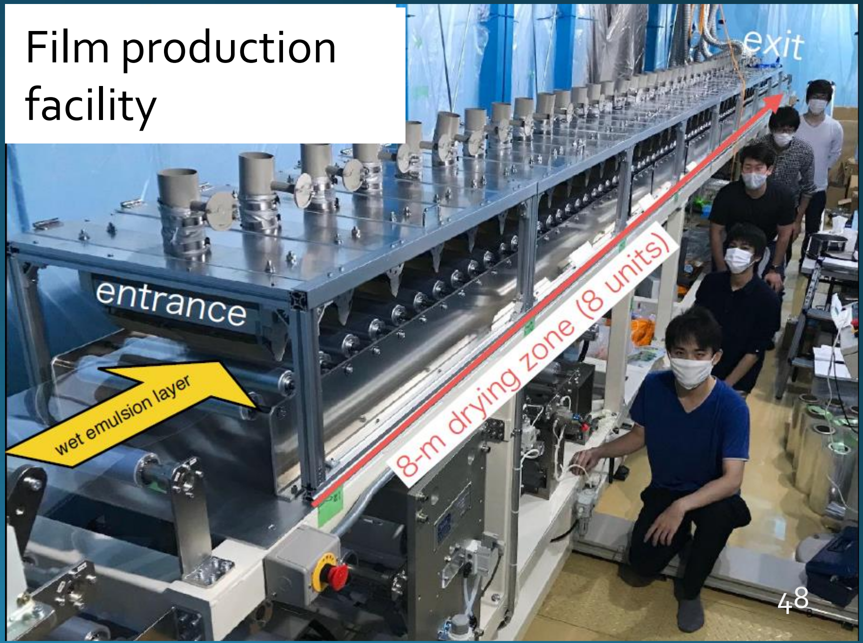
Emulsion detector preparation

- Emulsion gel and film production facilities in Nagoya have been set up in 2020. We are testing mass production
- Chemical compatibility of tungsten plates with emulsion film were tested

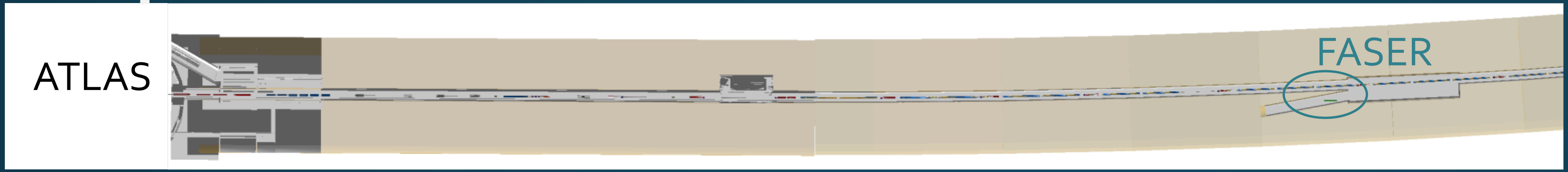


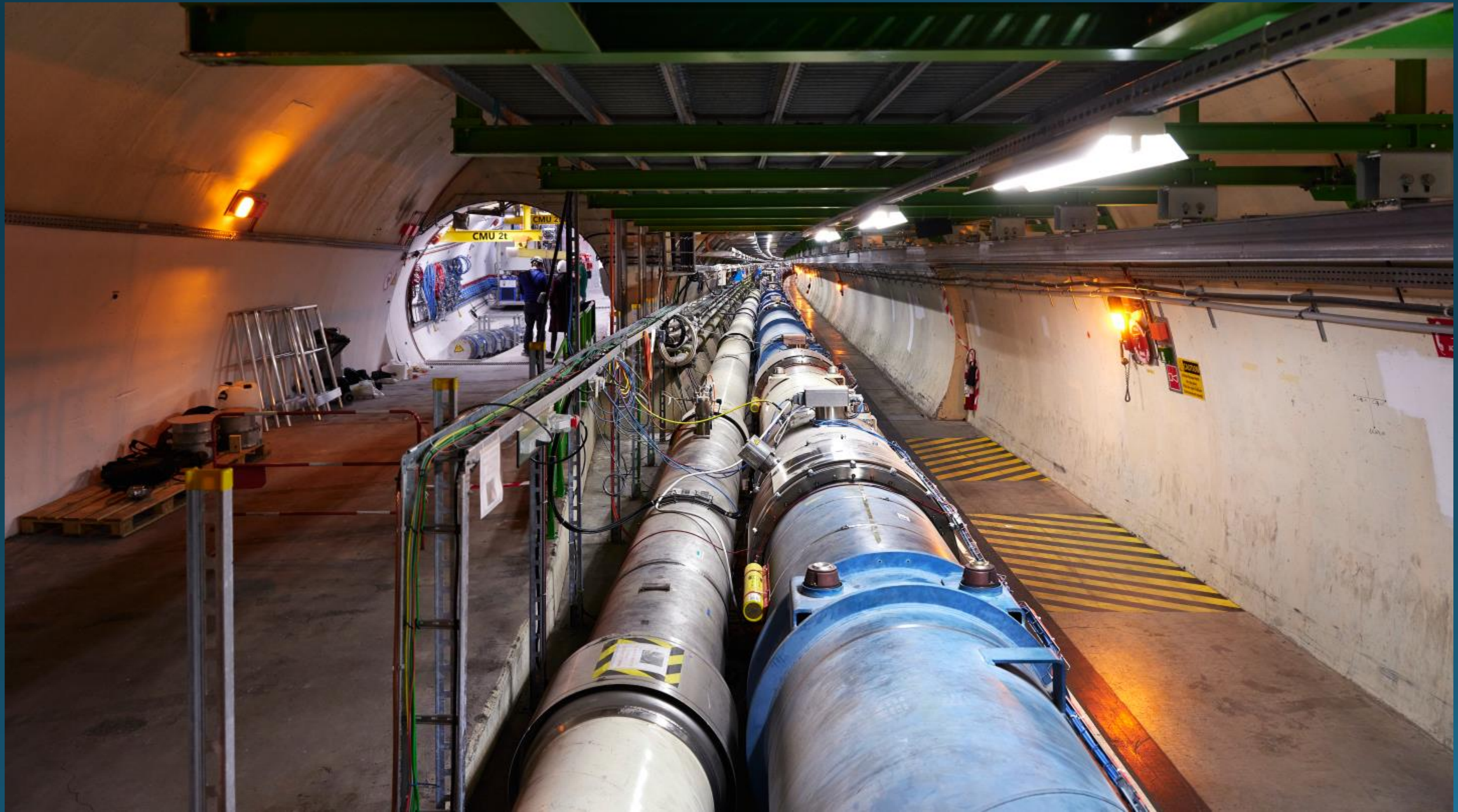




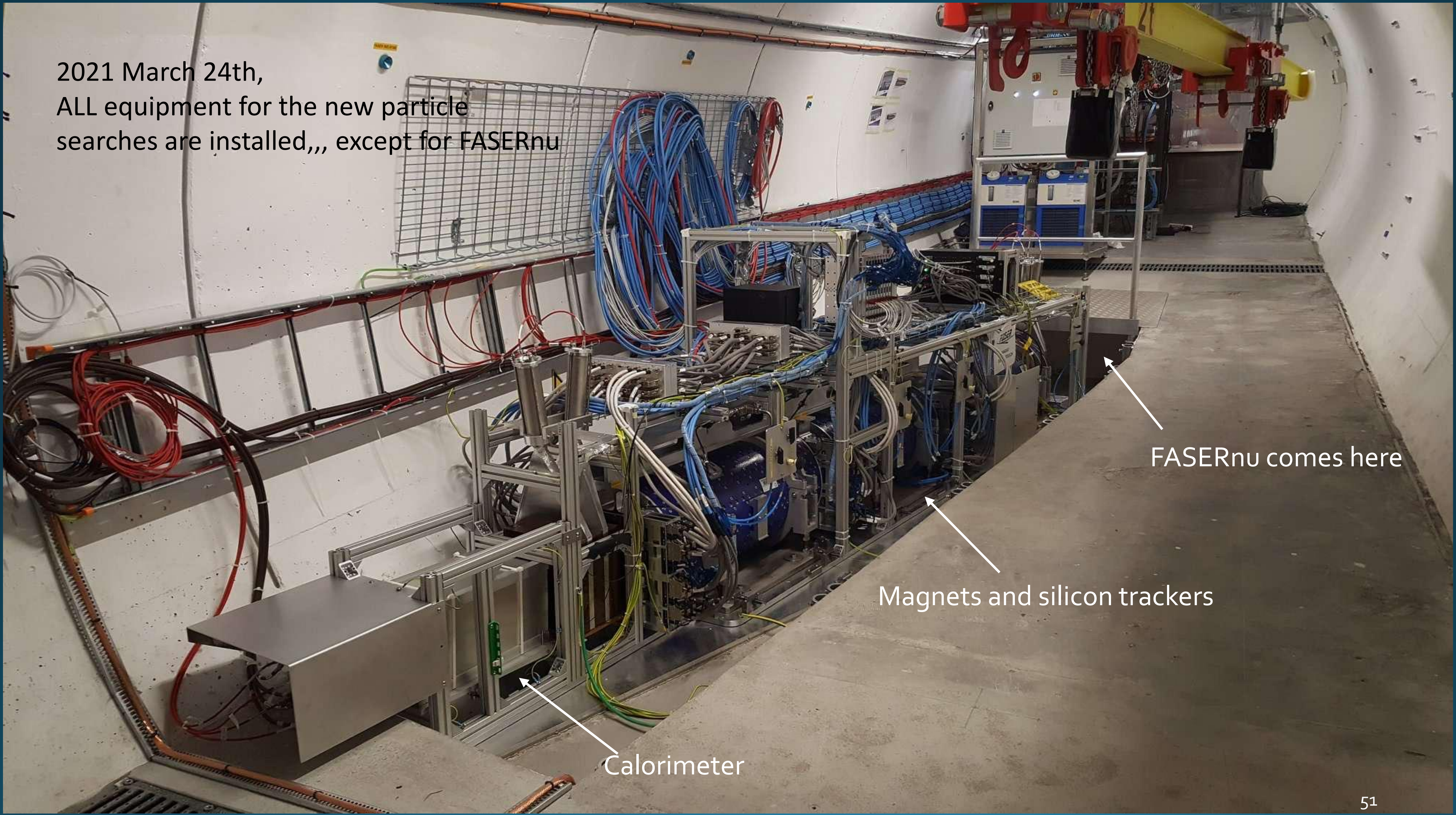


Experimental site





Evolution of TI12 tunnel for FASER installation


2021 March 24th,
ALL equipment for the new particle searches are installed,,, except for FASERnu
FASERnu comes here
Magnets and silicon trackers
Calorimeter

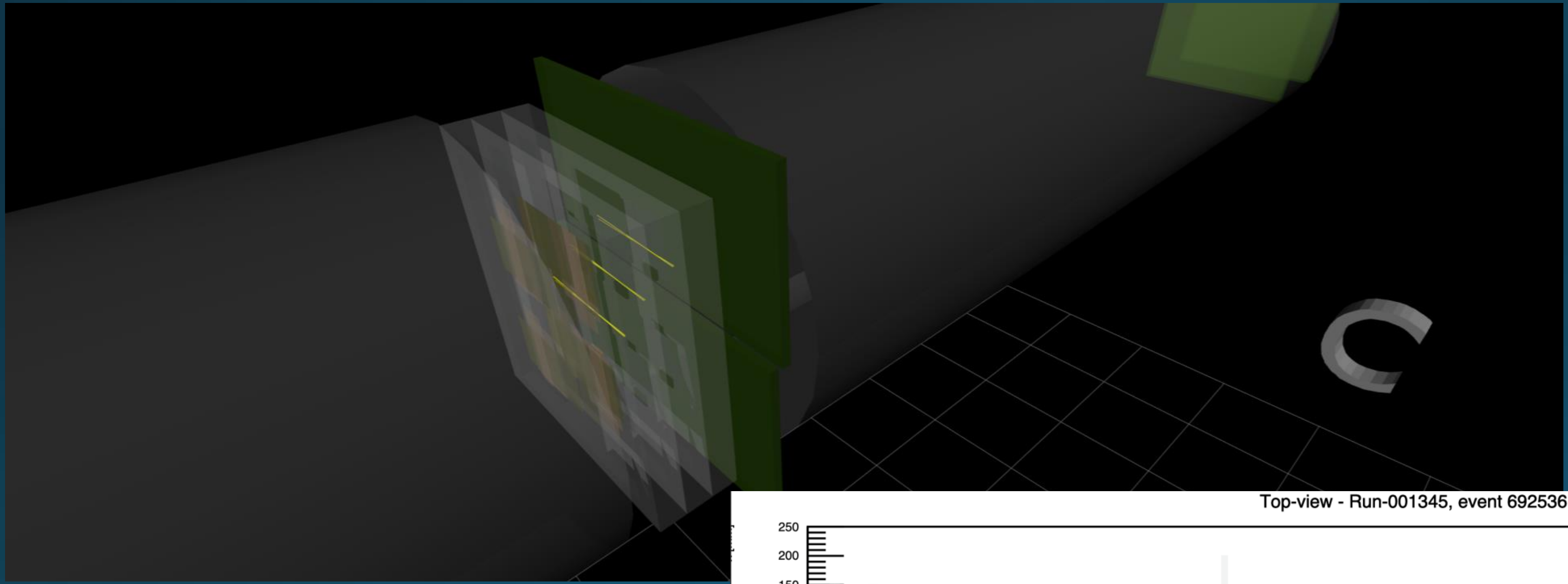
FASERν installation test in April 2021

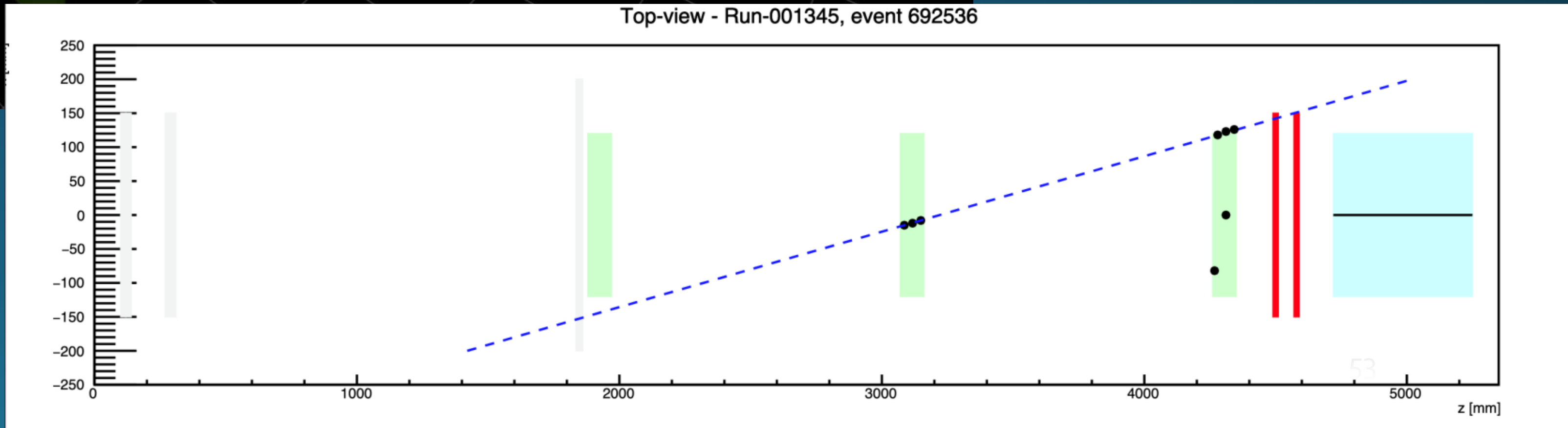
Transportation over the LHC beam pipe

Commissioning of FASER trackers

Cosmic-ray tracks at the experimental site (TI12 tunnel).

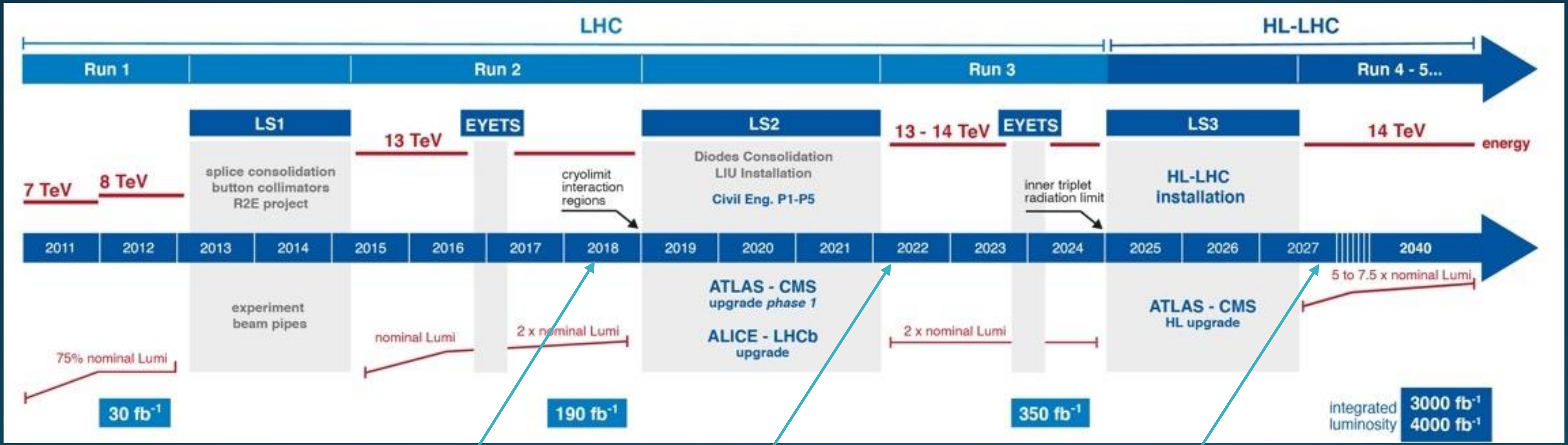
Rate of such tracks is 1 every 2 minutes.





LHC Schedule

- LHC Run-3 will start in 2022, aiming to double the integrated luminosity
- HL-LHC, starting in 2027, will deliver 10 times more integrated luminosity



BG measurement, pilot run in 2018

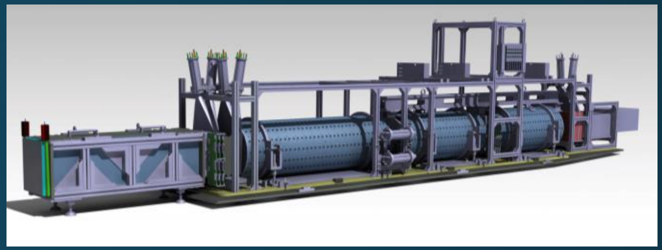
Physics run will start in 2022 (~150 fb^{-1})

Forward experiment in HL-LHC

Motivation to Forward Physics Facility (FPF)

- LHC is currently the high energy frontier, and in next 15 years.
- The high luminosity run (HL-LHC) will start in 2027. What is the best way to exploit it?
  - Conventional LHC exps (ATLAS, CMS) studies "Physics with high Pt, small cross sections (fb, pb, nb)
  - However, the total cross section is 100 mb, mostly at far forward direction (small Pt). Why not to use this abundant events?
- Far forward physics = unexplored physics domain, but explorable with a relatively small investment thanks to the existence of the LHC, as pioneered by FASER
- Proposal: "Let's build a Forward Physics Facility and host variety of experiments"
  - SM: tau neutrino, QCD, cosmic ray
  - BSM: LLPs, FIPs, dark sector particles, milli-charged particles

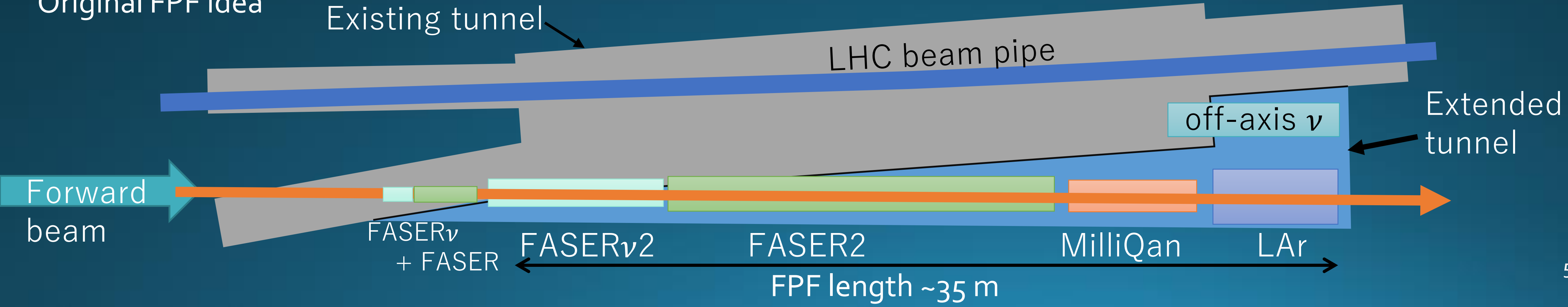
Idea of FPF



FASER

- Multiple single-purpose detectors
  - LLPs: FASER2, (FASER $\times O(1000)$)
  - Neutrino, FIP: FASERν2 (on-axis), SND2 (off-axis), LAr, (FASERν $\times O(1000)$)
    Milli-charged particle : MilliQan
- An experimental hall to host these experiments → Forward Physics Facility (FPF)
- Neutrino experiment with x200 statistics (x10 detector x20 beam)
  - Focus on tau neutrinos

Original FPF idea



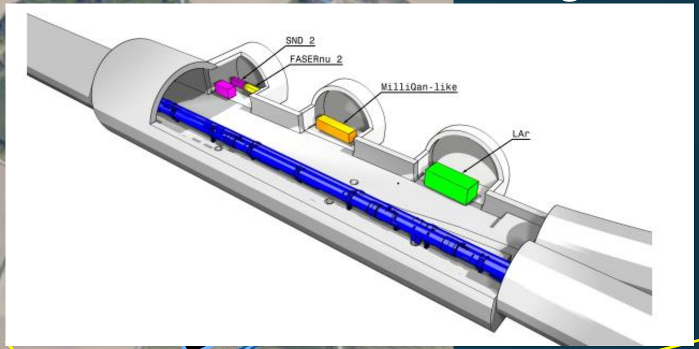
Forward Physics Facility at the HL-LHC

HL-LHC provides x20 proton collisions

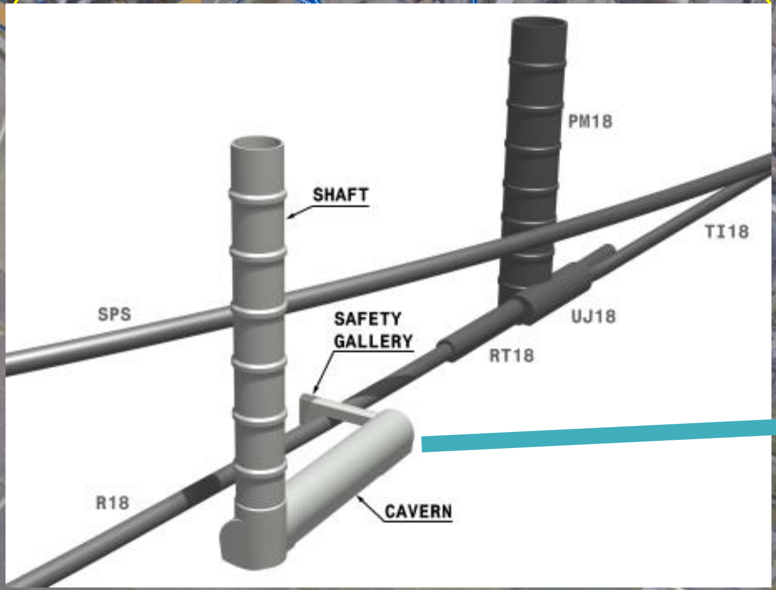
Extending sensitivities for new particle searches and neutrino physics by two orders of magnitude

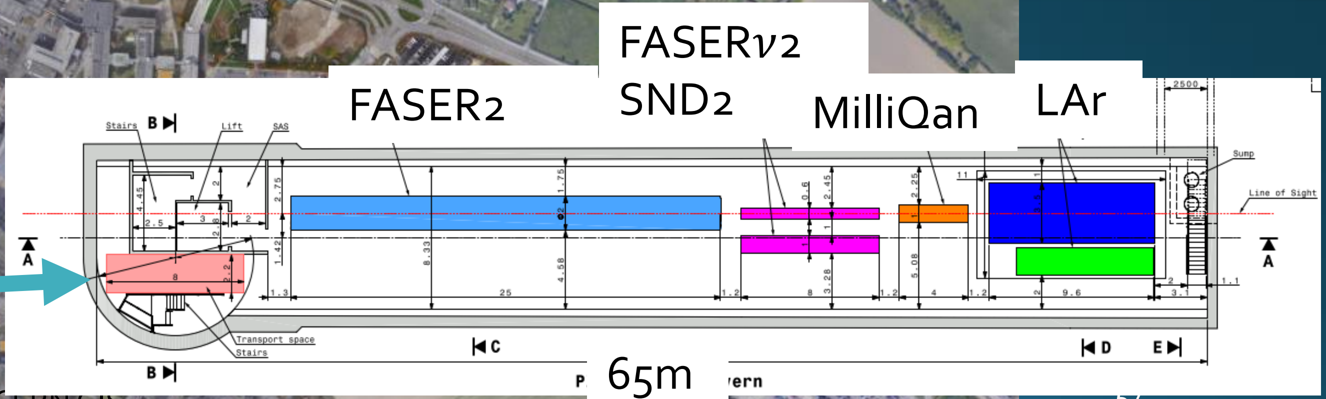
Wide discussion in periodical workshops indico.cern.ch/event/1022352

Option 1:
Extend existing tunnel



Option 2:
New shaft
and hall





CERN GIS

Current status of FPF

- FPF fits European and US's strategy
  - Update of the European Strategy(2020), diversity of particle physics, maximum use of the LHC
  - CERN's Physics Beyond Colliders, https://indico.cern.ch/category/7885/
  - US's Snowmass community study and P5 prioritization.
    - FPF https://doi.org/10.5281/zenodo.4059893 (over 200 signatures within 1 week)
    - LoIs FASER2: https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF9_EF6-NF3_NF6-RF6_RF0-CF7_CF0-AF5_AF0_FASER2-038.pdf
    - FASERnu2: https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF10_NF6-EF6_EF9-IF0_FASERnu2-006.pdf
    - Neutrino detector: https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF10_NF0-EF0_EF0_Ariga-072.pdf

- FPF kick-off workshop (9-10 November 2020)
  - 40 talks, lively discussions over wide topics
  - https://indico.cern.ch/event/955956
- Second workshop in 2 weeks https://indico.cern.ch/event/1022352/

- HL-LHC is going to start 2027. Now is the time to discuss physics and feasibility of FPF.

Summary

- The FASER experiment is a new experiment at the LHC with 2 pillars
  - FASER: Search for new particles
  - FASERν: Neutrinos
- FASERν is the first neutrino experiment with a collider
  - Beam at new kinematical regime, including 3 flavors
  - Detector with flavor sensitivity
  - Data taking in 2022-2024
  - Detection of neutrinos from the LHC was demonstrated with the pilot detector in 2018
- Future projects (FPF) at the HL-LHC are under discussion

Publications on FASER/FASERnu

- Publications of the FASER Collaboration
  - FASER Letter of Intent at CERN document server and in arXiv
  - FASER Technical Proposal at CERN document server and in arXiv
  - FASER's Physics Reach for Long-Lived Particles in Physical Review D and in arXiv
  - Input to the European Strategy for Particle Physics Update in arXiv
  - Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC in European Physical Journal C and in arXiv
  - Technical Proposal of FASERν neutrino detector at CERN document server and in arXiv
  - First neutrino interaction candidates at the LHC in arXiv

New since last week!

- Conference talks on FASERnu
  - Neutrinos at CERN, NEUTRINO 2020, 24 June 2020, Tomoko Ariga
  - FASERnu, ICHEP 2020, 28 July - 6 August, Akitaka Ariga

FASERν2: Neutrino physics

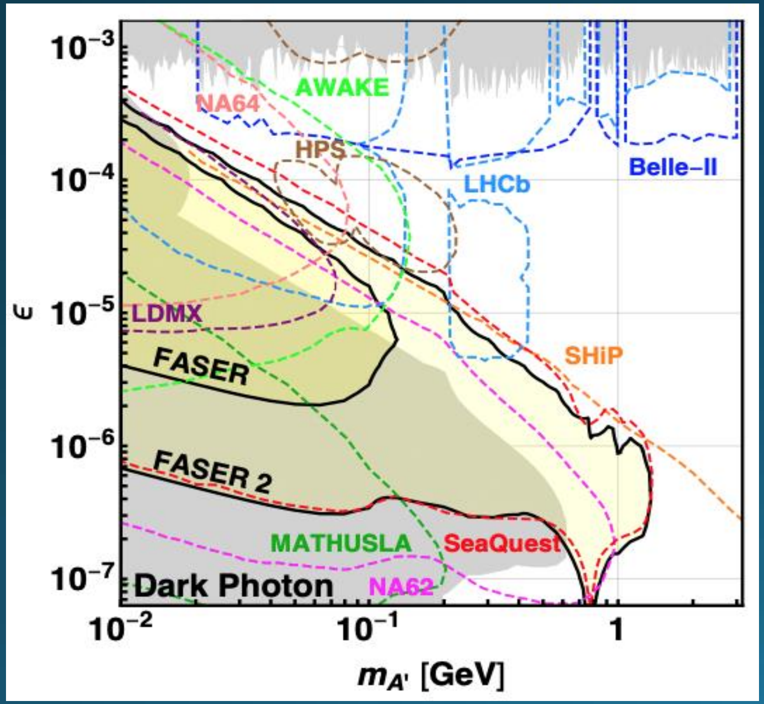
- FASERν @ LHC-Run 3 (1.2 ton)
  - Unexplored TeV energy ~1000 ν_e, ~10,000 ν_μ, ~10 ν_τ CC events
  - Also SND@LHC (off-axis)
- FASERν2 @HL-LHC (~10 ton)
  - FASERν2: Beam x 20, ~10 tons mass → 200 times FASERν
  - $\sim 10^5$ ν_e, 10^6 ν_μ, 10^3 ν_τ CC events
- Tau neutrino physics, precise measurement of cross sections, rare process

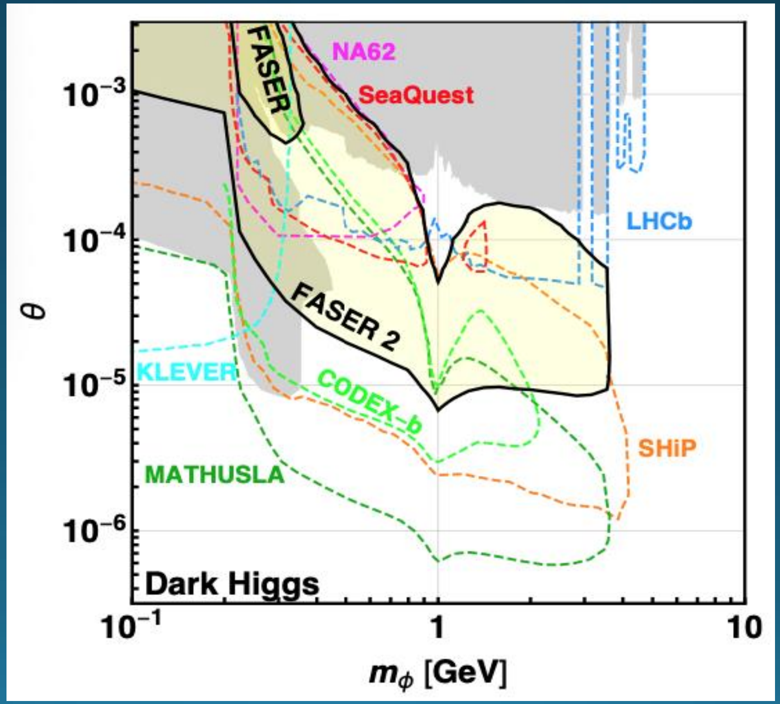
FASER2: New particle searches (Long Lived Particles)

- FASER2, New larger detector at Forward Physics Facility
  - FASER (R=10cm, L=1.5m, Run 3) → FASER 2 (R=1m, L=5m, HL-LHC)
  - Largely explore unexplored parameter space

x 300 decay volume
x 20 beam

Dark photon

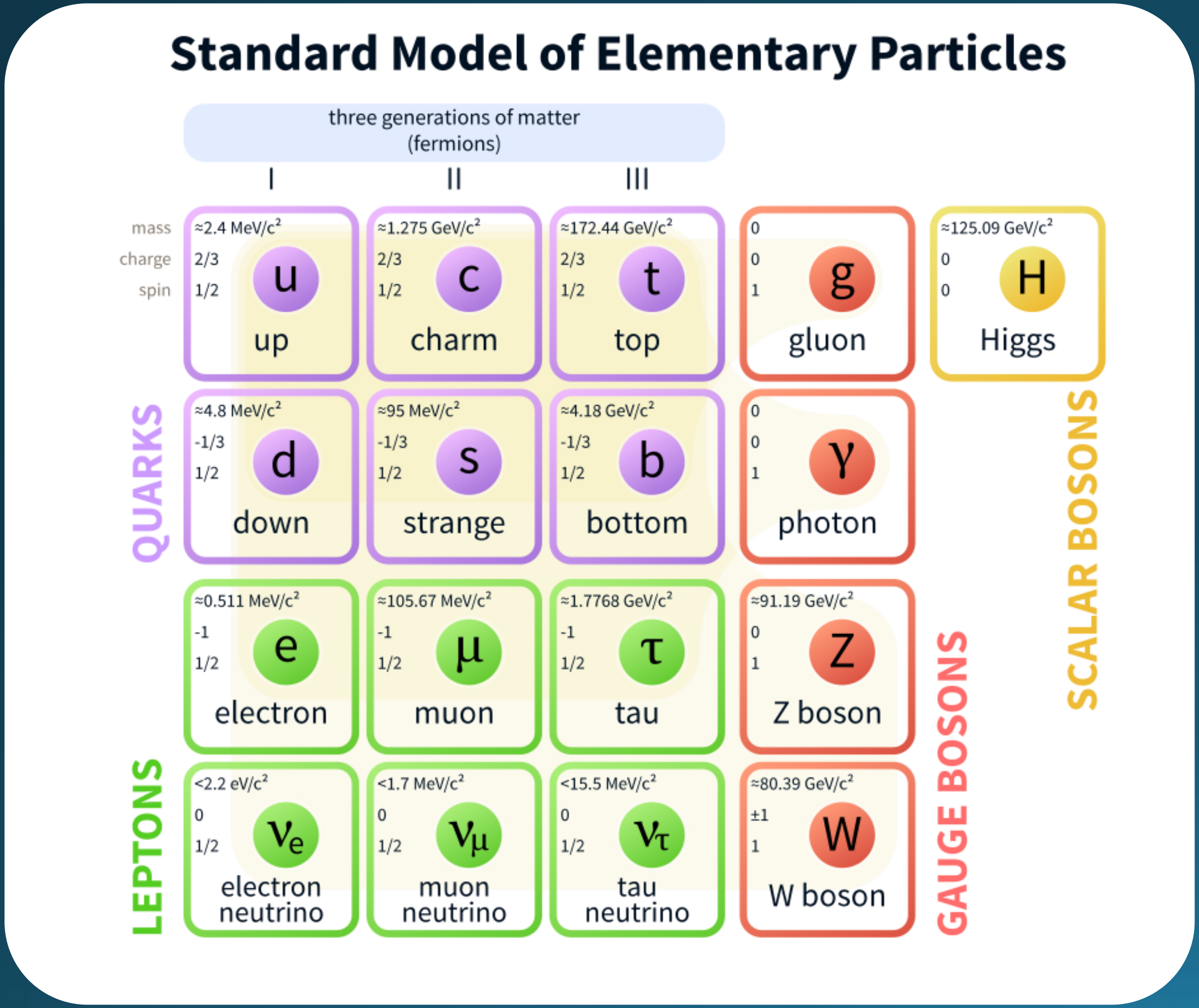




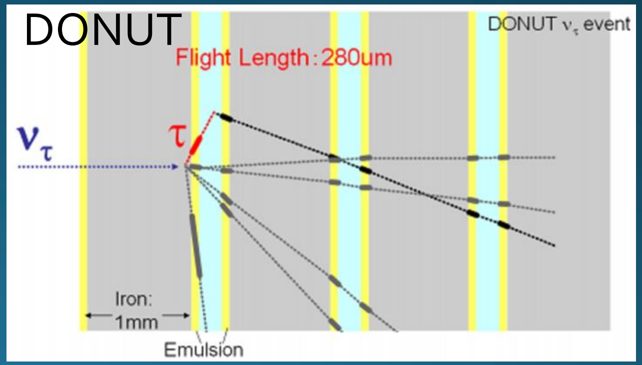
Dark Higgs

FASER Collaboration, 1811.12522 (2018)

Standard model and neutrinos



- In SM, neutrinos are
  - Neutral
  - Interact only with weak bosons
  - Left-handed → massless
  - 3 flavors



Lepton non-universality?

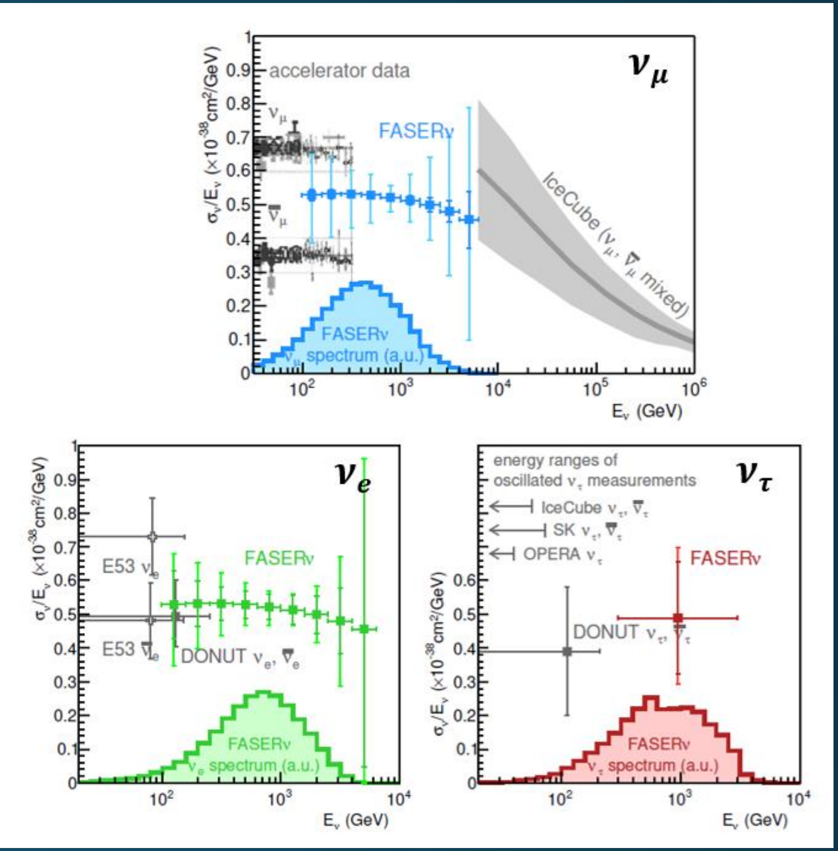
	channel	Lepton universality
W decay	$W \to \tau\nu_\tau$	△(2.8 σ)
B decays	full leptonic $B \to \tau\nu_\tau$	△
	R_D: semi leptonic $B \to D^{(*)}\tau\nu_\tau$	× (3σ)
	R_K: neutral semileptonic $B \to K\ell^+\ell^-$	× (3σ)
B_s decay	$B_s \to D_s\tau\nu_\tau$	△
	$B_c \to J/\psi\tau\nu_\tau$ / $B_c \to J/\psi\mu\nu_\mu$	△ (2σ)
Charm decay	full leptonic $D_s \to \tau\nu_\tau$ / $D_s \to \mu\nu_\mu$	O (1σ excess)
Lepton leptonic decay	$\tau \to \mu\nu\nu/\mu \to e\nu\nu$	⊙
Kaon decay	$K \to e\nu/K \to \mu\nu$	⊙
Pion decay	$\pi \to \mu\nu/\pi \to e\nu$	⊙
tau CC interaction	never measured	-
ν_τ CC interaction	$\nu_\tau N \to \tau X$	△ (too few statistics)

Physics potential:

High-energy neutrino interactions

- Primary goal: Cross section measurements of three flavors at the unexplored TeV energies
- NC measurements
  - Could constrain neutrino non-standard interactions (NSI).
- Neutrino CC interaction with charm production ($\nu s \rightarrow lc$)
  - Study the strange quark content.
  - Probe inconsistency between the predictions and the LHC data [Eur. Phys. J. C77 (2017) 367].
  - LU test
- Search for neutrino CC interaction with beauty production

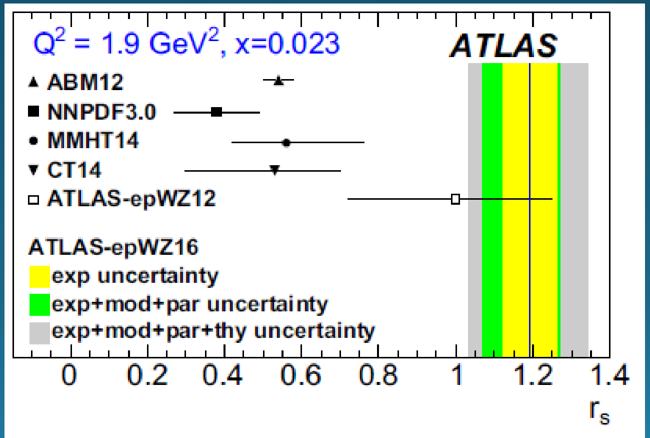
FASER Collaboration, Eur. Phys. J. C 80 (2020) 61, arXiv:1908.02310

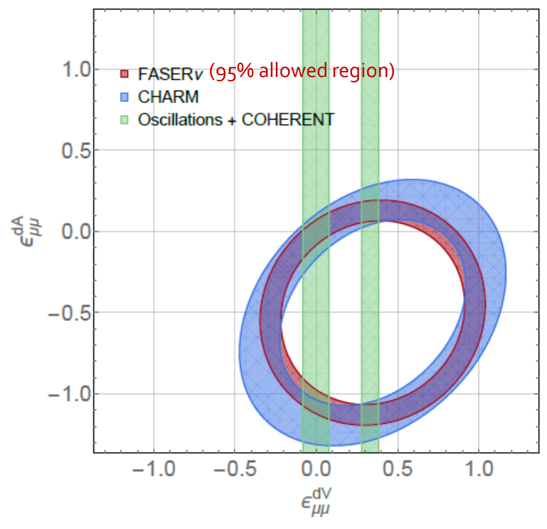


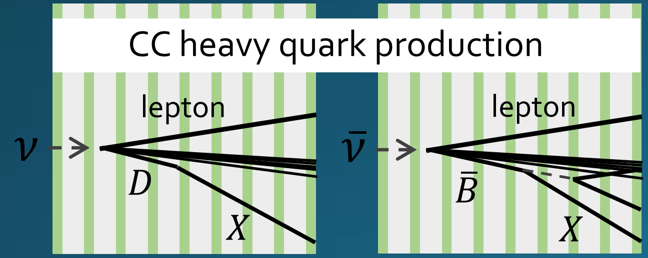
A. Ismail, R.M. Abraham, F. Kling, Phys. Rev. D 103, 056014 (2021), arXiv:2012.10500

$$r_s = \frac{s + \bar{s}}{2\bar{d}}$$

Eur. Phys. J. C77 (2017) 367

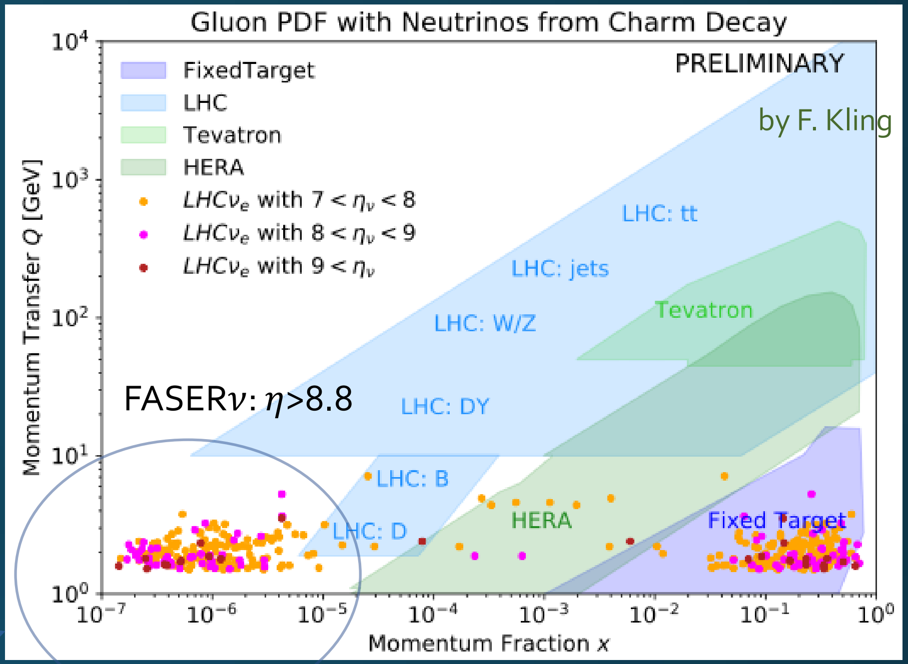






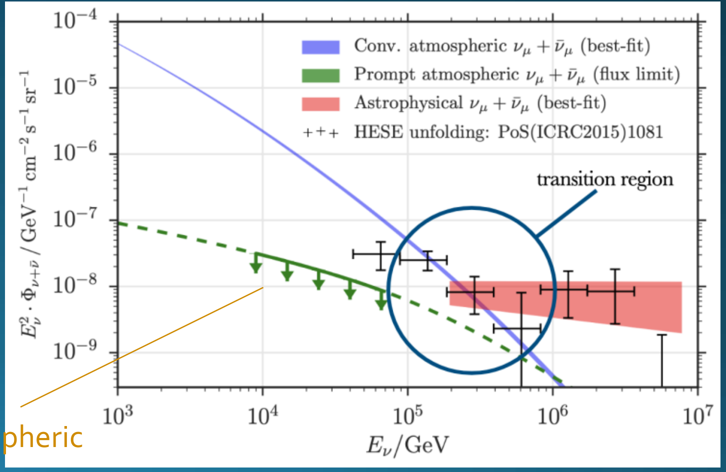
Physics potential:
Forward particle production

- Neutrinos are from the decay of hadrons, mainly pions, kaons, and charm particles. But, forward particle production is poorly constrained by other LHC experiments.
- FASERν provides novel input to validate/improve generators
  - First data on forward kaon, hyperon, charm



- Neutrinos from charm decay could allow to test transition to small-x factorization, probe intrinsic charm.
- Relevant for neutrino telescopes (such as IceCube).
  - To make measurements of astrophysical neutrinos, a precise knowledge of prompt neutrinos is important
  - 7+7 TeV p-p collision corresponds to 100 PeV proton interaction in fixed target mode → a direct measurement of PeV atmospheric (prompt) neutrino production. FASERν would provide important basic data for current and future high-energy neutrino telescopes.

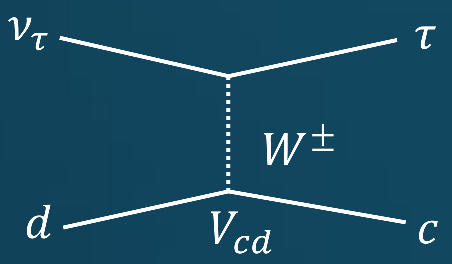
IceCube Collaboration, Astrophys. J. 833 (2016)



prompt atmospheric neutrinos

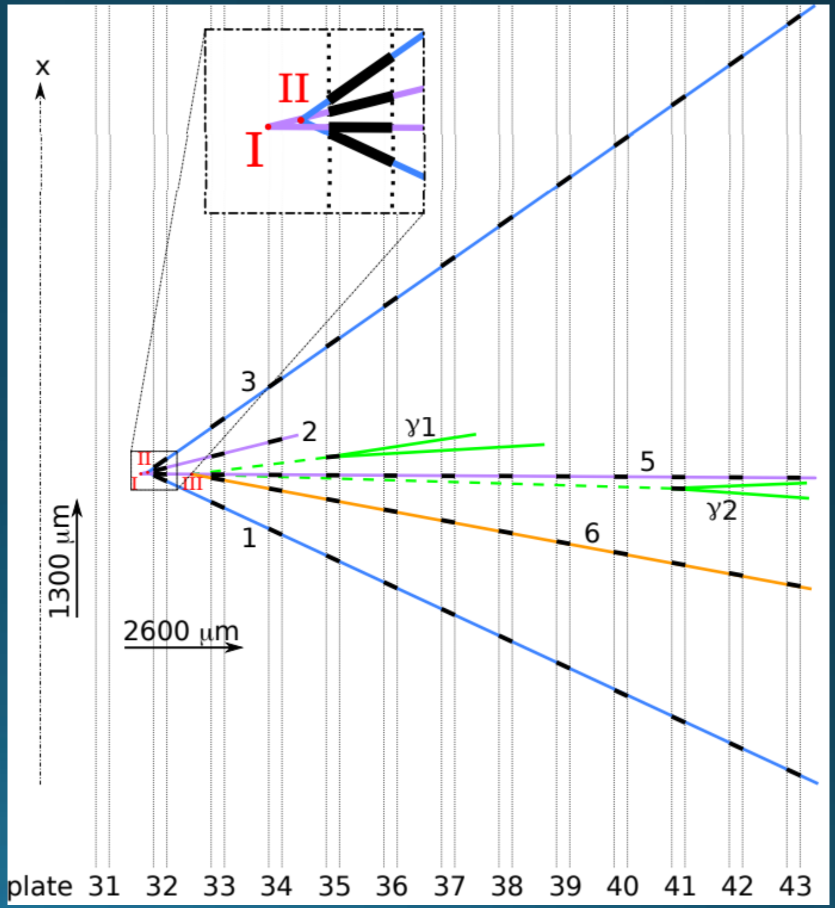
OPERA's ν_τ induced charm production event

SM process, charm production via mixing

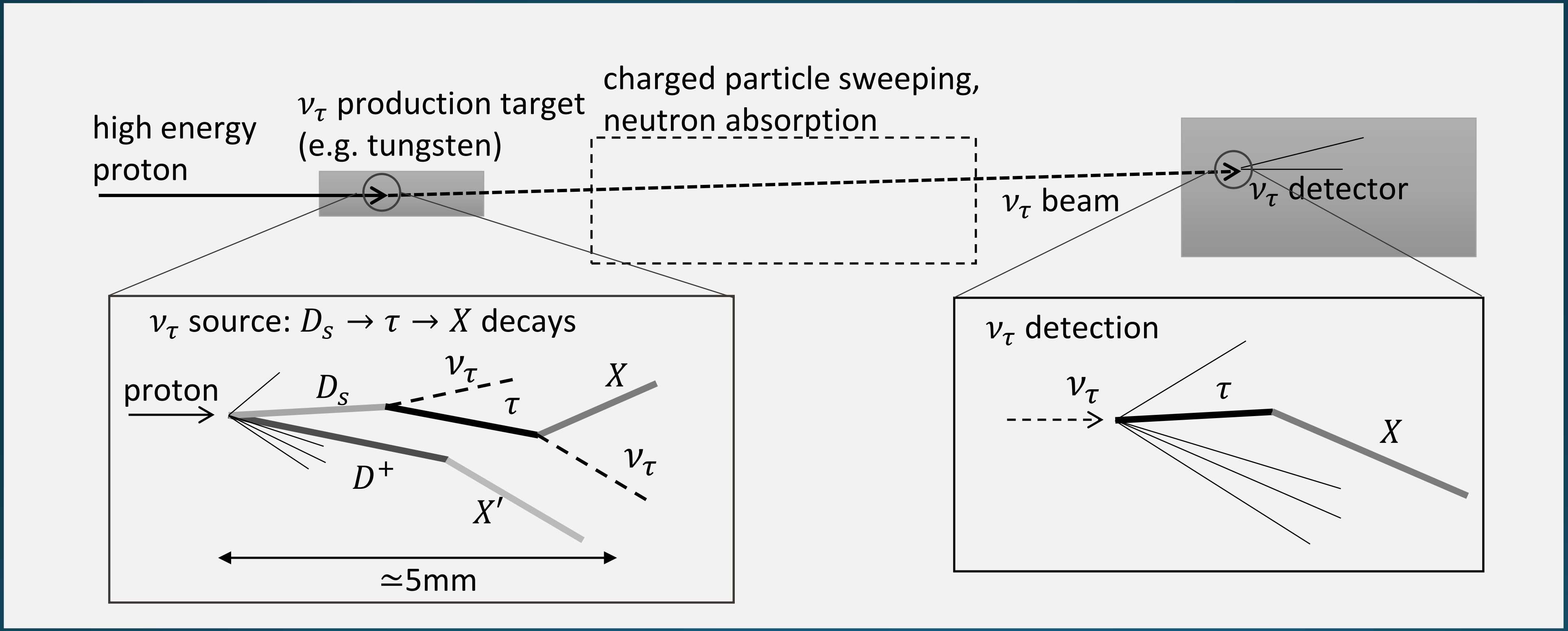


Well measured for ν_μ

- 1 event was observed with surprise
- Expectation:
  - Signal 0.04
  - Background <0.05
- Could also be a hint of new physics!?



Accelerator-based ν_τ cross section measurement



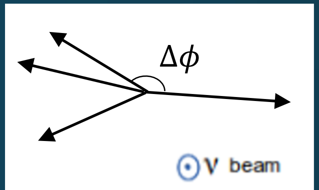
ν_τ production study: DsTau (NA65)

- No experimental data on the Ds differential cross section
- Large systematic uncertainty (~50%) in the ν_τ flux prediction

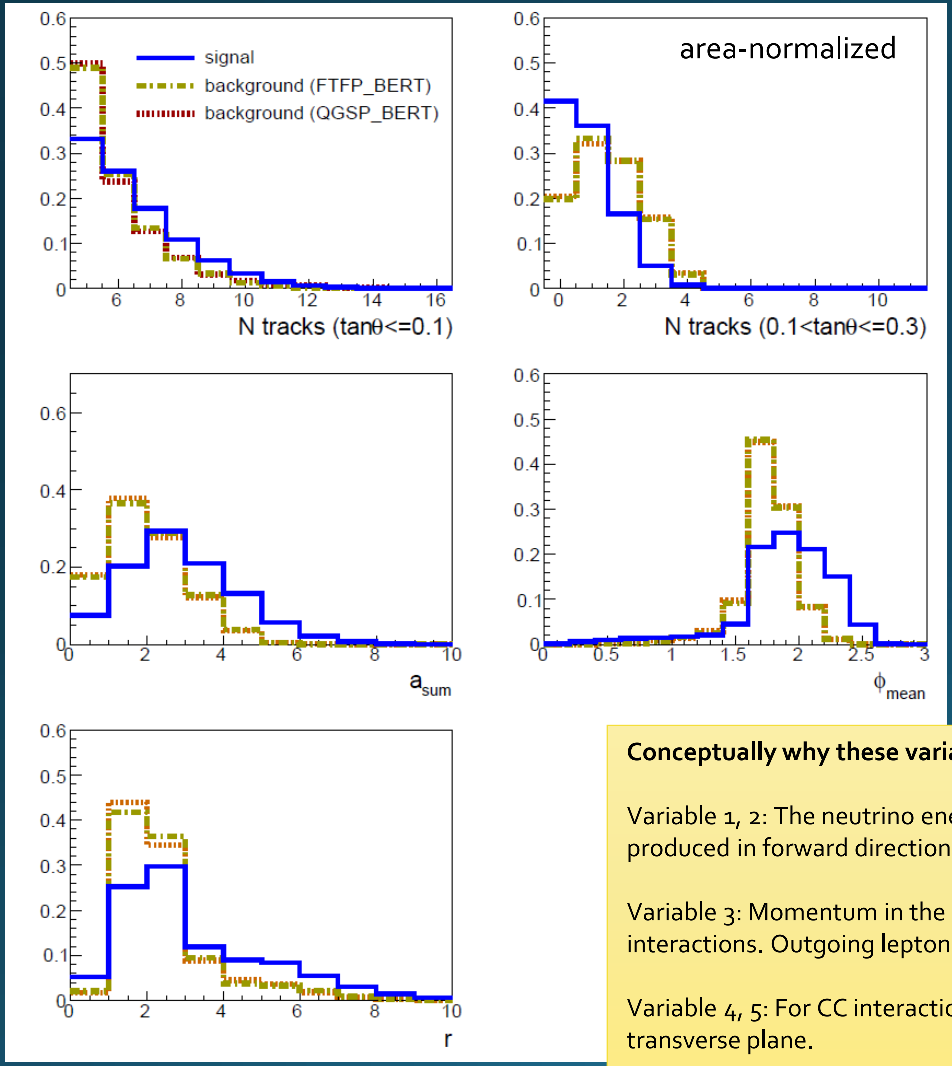
ν_τ detection: e.g. DONuT, SHiP, FASERν

- Statistical uncertainty 33% in DONUT
- Will be reduced to the 2% level in future experiments

Variables for MVA



Expected distributions of the variables



5 variables used in the analysis

1. the number of tracks with tanθ<=0.1 with respect to the beam direction
2. the number of tracks with 0.1<tanθ<=0.3 with respect to the beam direction
3. the absolute value of vector sum of transverse angles calculated considering all the tracks as unit vectors in the plane transverse to the beam direction (a_{sum})
4. for each track in the event, calculate the mean value of opening angles between the track and the others in the plane transverse to the beam direction, and then take the maximum value in the event (ϕ_{mean})
5. for each track in the event, calculate the ratio of the number of tracks with opening angle <=90 degrees and >90 degrees in the plane transverse to the beam direction, and then take the maximum value in the event (r).

Multiplicity and Pseud rapidity distribution

Momentum balance

Back-to-back kinematics at vertex

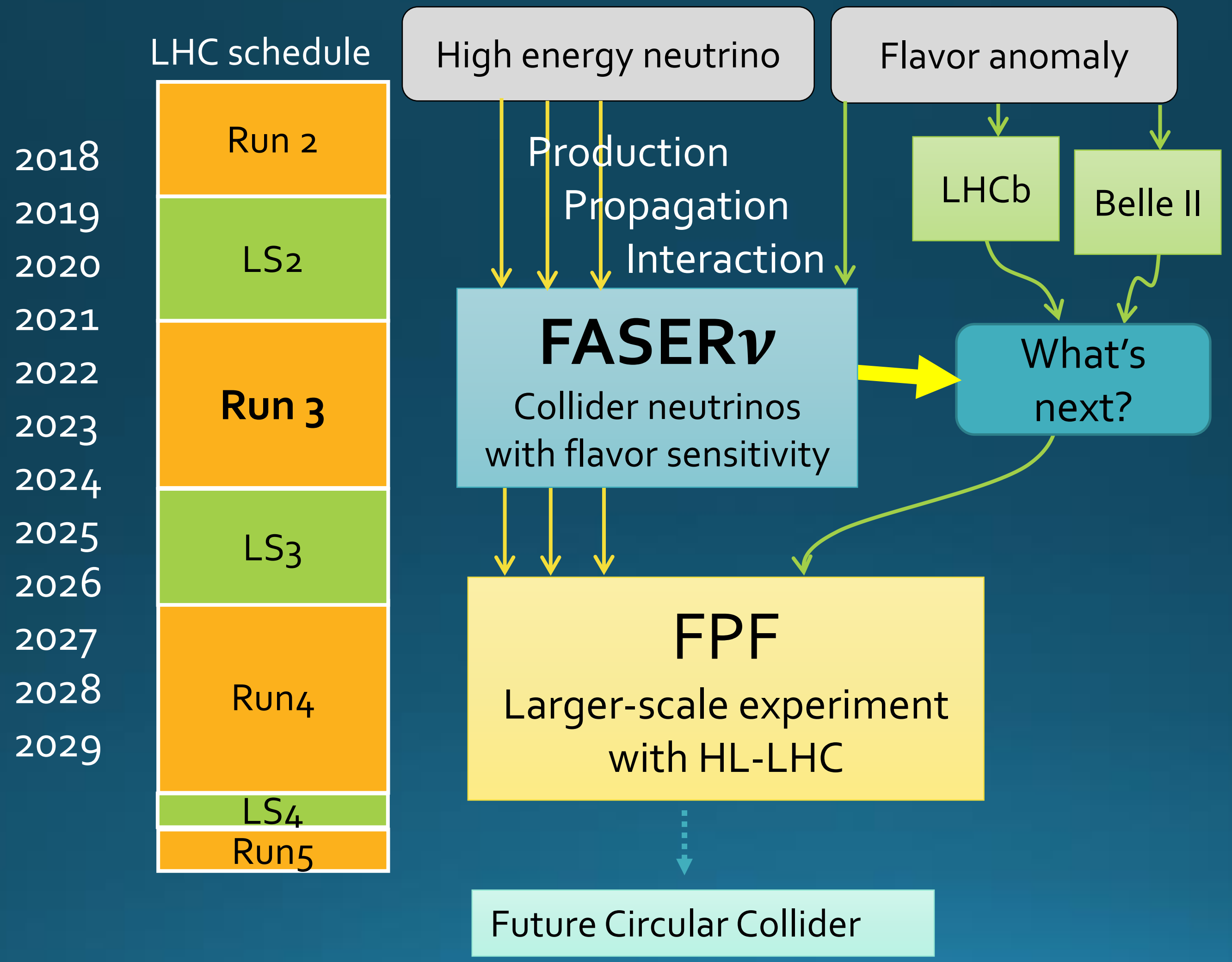
Conceptually why these variables are good:

Variable 1, 2: The neutrino energy is higher than the neutral hadron energy. Higher energy, more particles are produced in forward direction, i.e. tan(theta)<0.1 (var 1), and higher ratio of var1/var2.

Variable 3: Momentum in the transverse plane is more balanced in hadron interactions than neutrino CC and NC interactions. Outgoing leptons in neutrino interactions take a major energy, which distorts this variable.

Variable 4, 5: For CC interactions, we expect the outgoing lepton and hadron system are back to back in the transverse plane.

Roadmap towards a future experiment



1811.12522

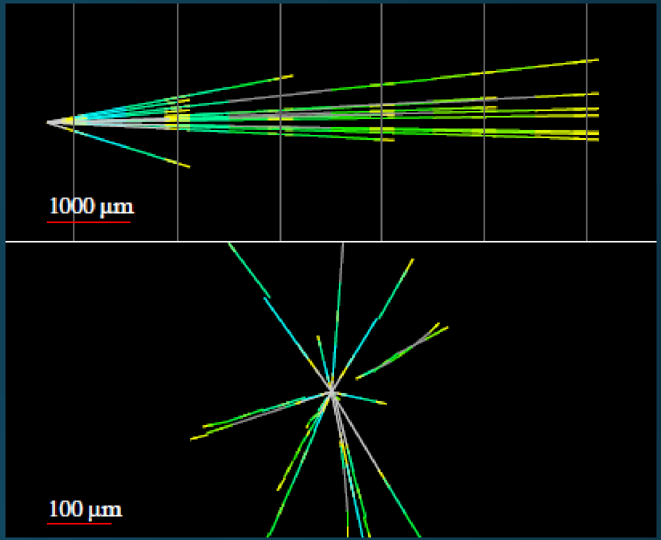
FASER 2 – PHYSICS REACH

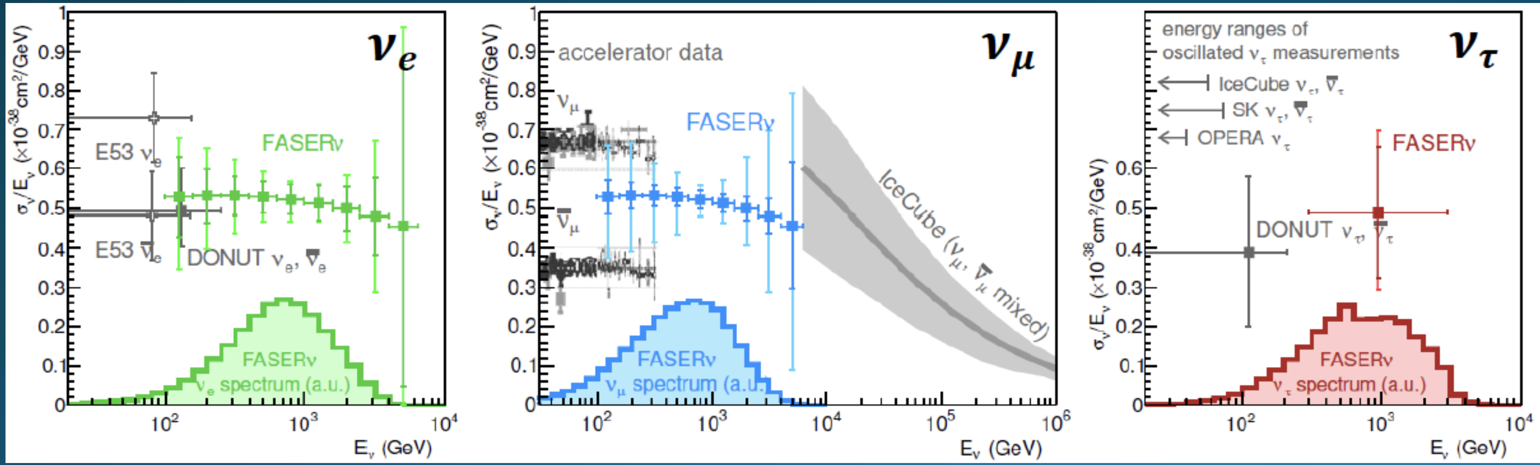
- FASER 2 increases the set of models that can be targeted
- Sensitivity for all models with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ, f, g); etc…

Benchmark Model	FASER 1	FASER 2	References
BC1: Dark Photon	√	√	Feng, Galon, Kling, Trojanowski, 1708.09389
BC1′: $U(1)_{B-L}$ Gauge Boson	√	√	Bauer, Foldenauer, Jaeckel, 1803.05466; 1811.12522
BC2: Invisible Dark Photon	–	–	–
BC3: Milli-Charged Particle	–	–	–
BC4: Dark Higgs Boson	–	√	Feng, Galon, Kling, Trojanowski, 1710.09387 Batell, Freitas, Ismail, McKeen, 1712.10022
BC5: Dark Higgs with hSS	–	√	Feng, Galon, Kling, Trojanowski, 1710.09387
BC6: HNL with e	–	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC7: HNL with μ	–	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC8: HNL with τ	√	√	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC9: ALP with photon	√	√	Feng, Galon, Kling, Trojanowski, 1806.02348
BC10: ALP with fermion	√	√	1811.12522
BC11: ALP with gluon	√	√	1811.12522

FASERν2: Neutrino physics

- FASERν @ LHC-Run 3 (1.2 ton)
  - Unexplored TeV energy ~1000 ν_e, ~10,000 ν_μ, ~10 ν_τ CC events
  - Also SND@LHC (off-axis)
- FASERν2 @HL-LHC (~10 ton)
  - FASERν2: Beam x 20, ~10 tons mass →200 times FASERν~10^5 ν_e, 10^6 ν_μ, 10^3 ν_τ CC events
- Tau neutrino physics, precise measurement of cross sections, rare process

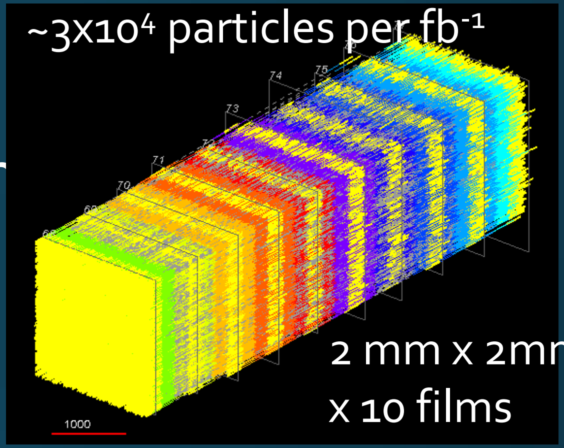


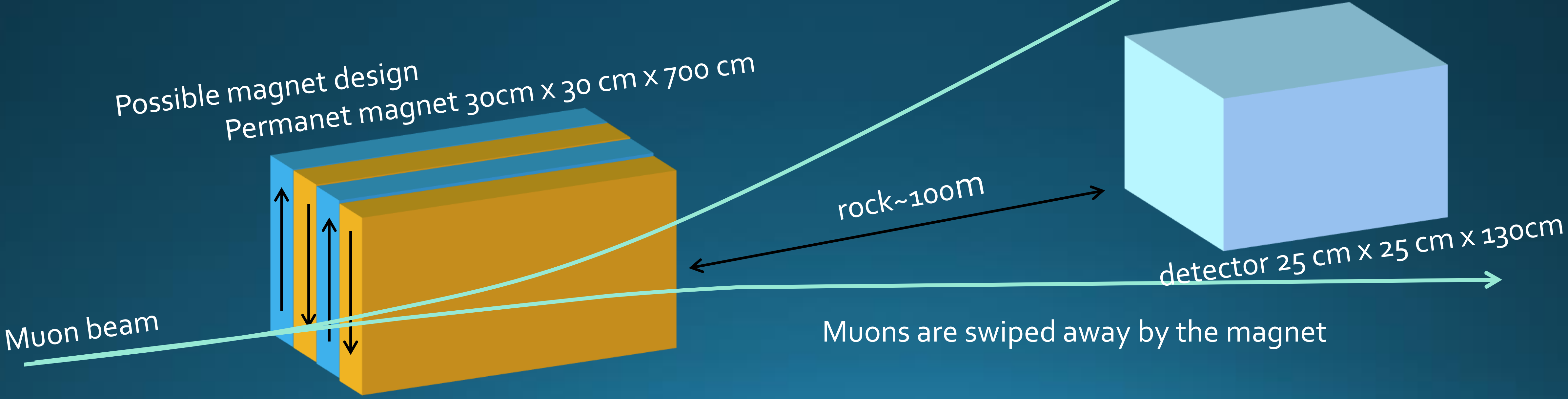


Muon background

- High energy muon background is crucial for neutrino and millicharge experiments
- Reduction of muons is important
  - One way is to put a magnet upstream of FPF

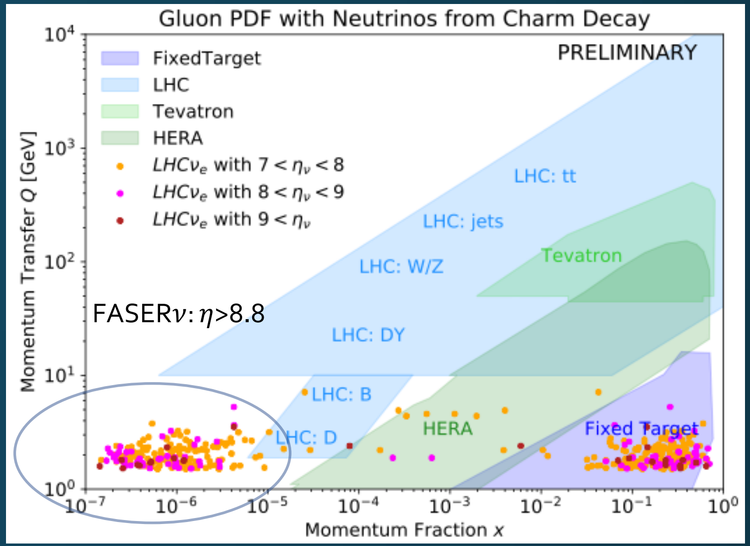
FASER data in 2018



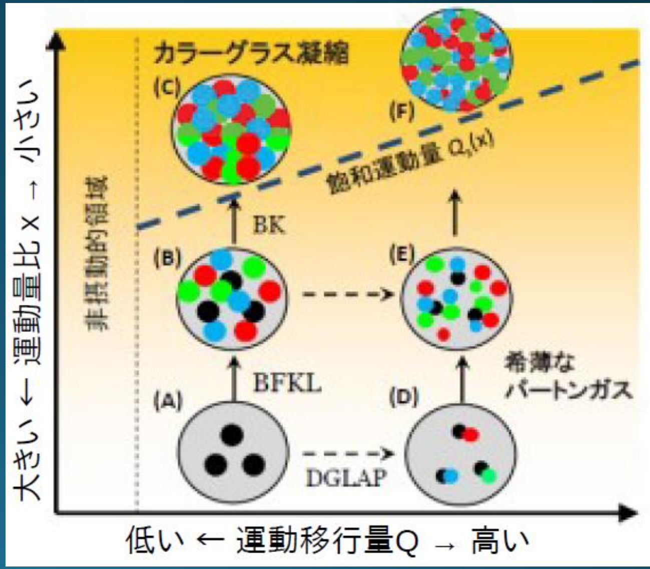


FASERν2:QCD physics

- 超前方ハドロン生成
  - 現状、データの欠如・大きな不定性。
    - モデルにより大きく違う(EPOS-LHC, QGSJET, DPMJET, SIBYLL, PYTHIA)
    - 陽子陽子衝突時、Small-x とLarge-xのパートンが寄与。カラーグラス凝縮、Intrinsic charm→ニュートリノスペクトルにゆがみ
  - 宇宙線物理学へのインプット。E.g.) IceCubeでの高エネルギー宇宙ニュートリノ解析へのプロンプトニュートリノ背景事象に制限
- FASERν2 にてQCDの詳細解析
  - ニュートリノ生成
    - 陽子内パートン $(K, D \to \nu_e, \pi \to \nu_\mu, D \to \nu_\tau)$
  - ニュートリノ反応
    - ν CC チャーム粒子生成による標的中のストレンジネスパートンの研究　$\nu_\ell s \to \ell c$



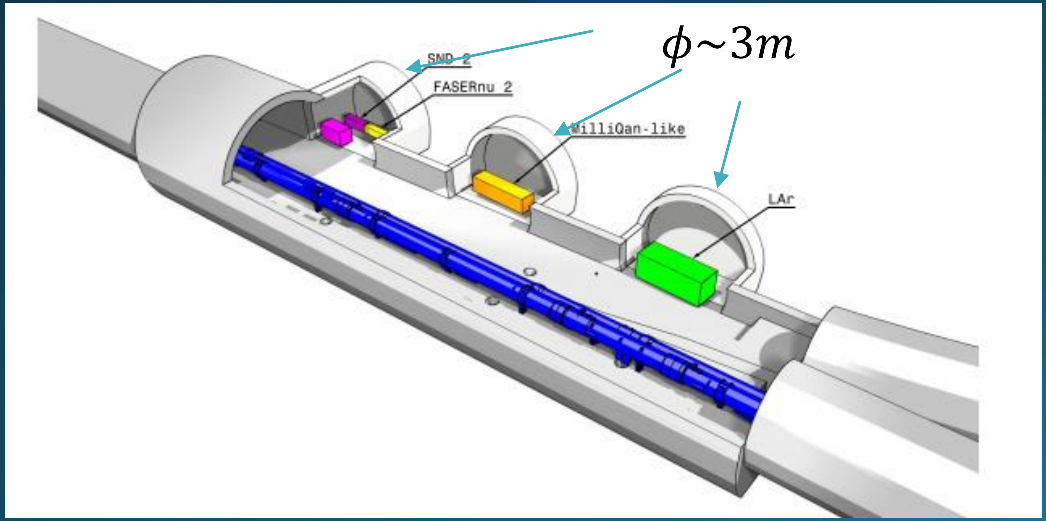
ν flux at FASERνに寄与するパートン

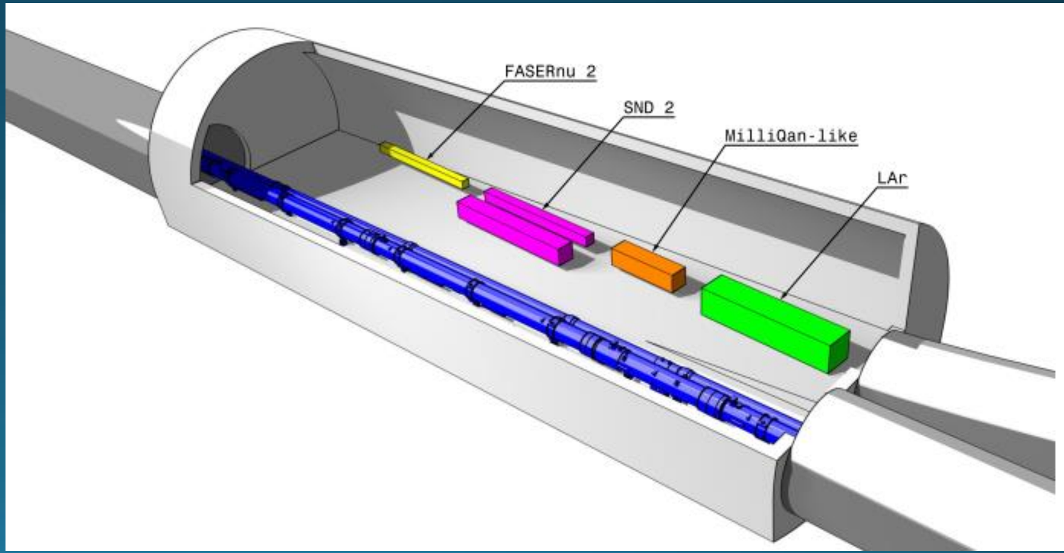


複数のFPFオプション
～既存のトンネルの拡張

- Option 1
- 既存のLHCトンネルに横穴
- 安価だが使えるスペースが限定的

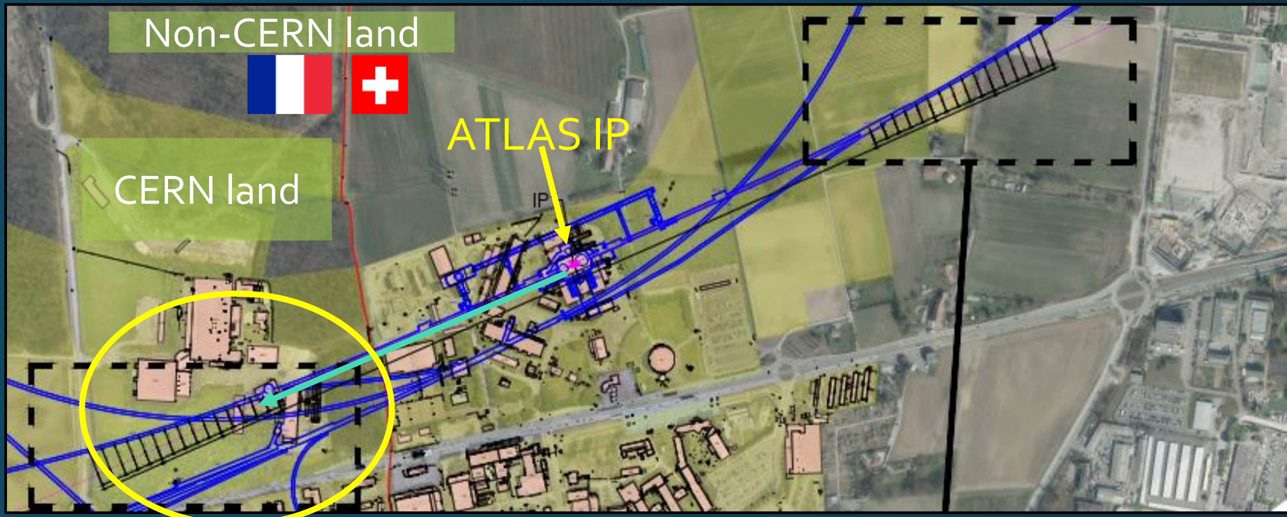
- Option 2
- 既存のトンネルを拡張
- 大規模な工事が必要
- 高価

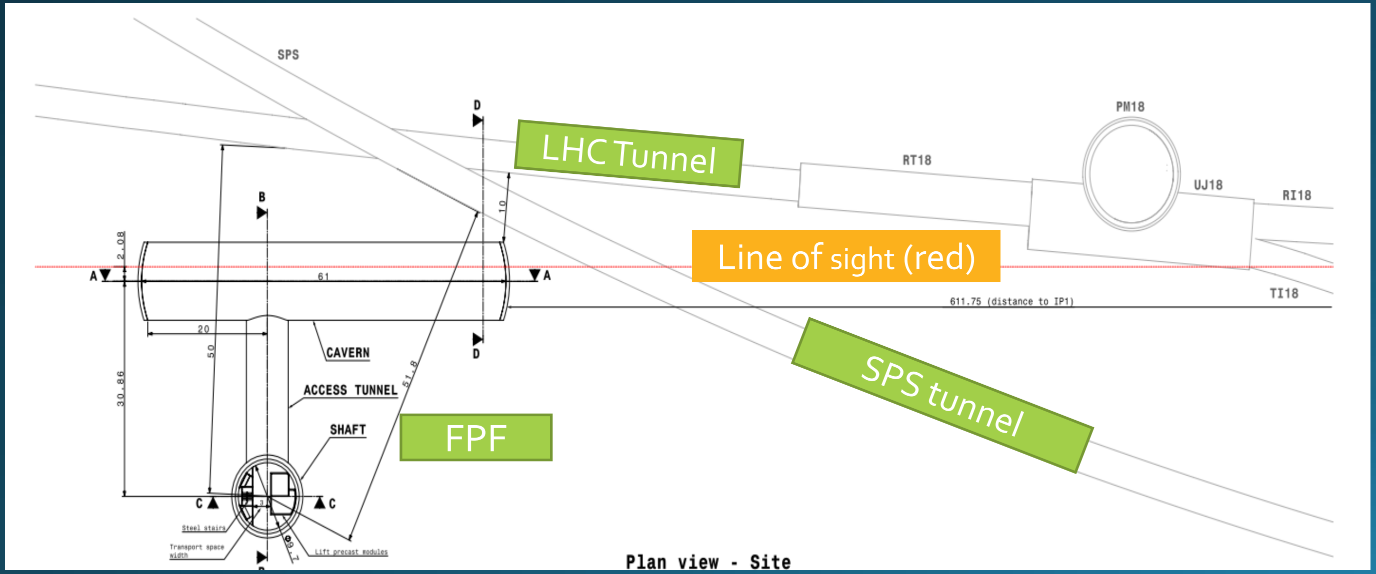


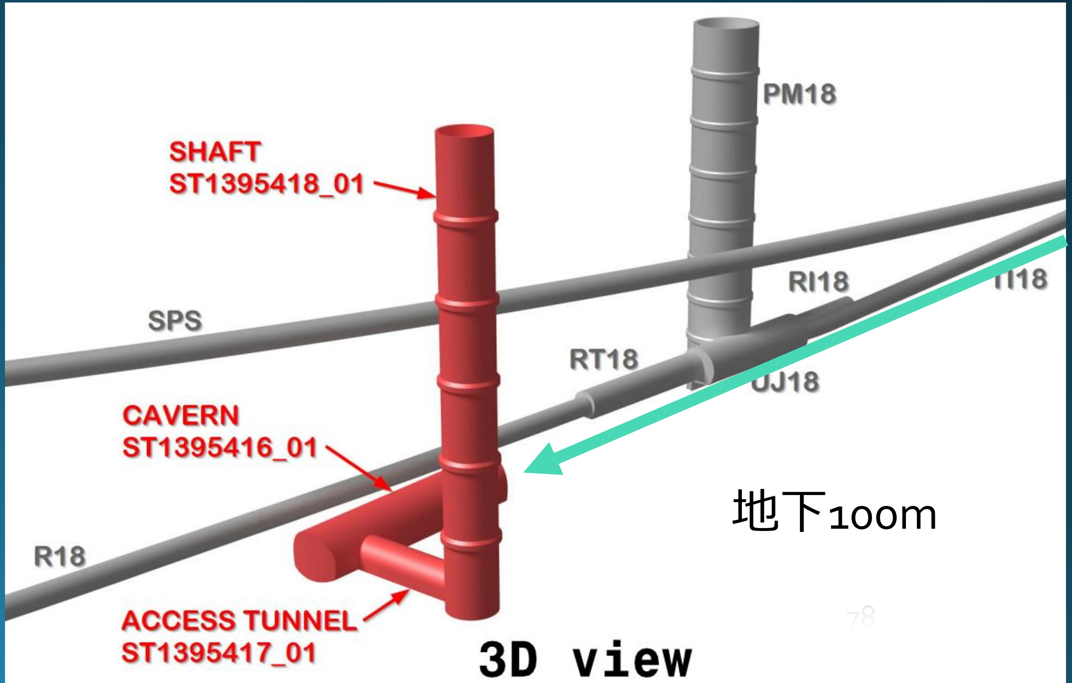


複数のFPFオプション～新しい縦穴

- ATLASから600-800m地点に縦穴を掘り、実験ホールを作る。
- 高価だがスペースの大きさ、建設スケジュールの立てやすさ等にメリット。LHCのスケジュールに非干渉。



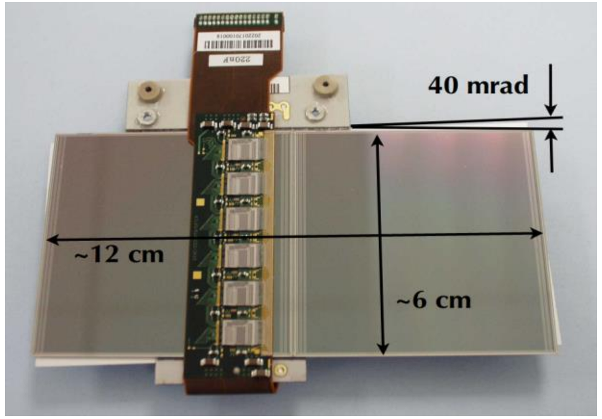




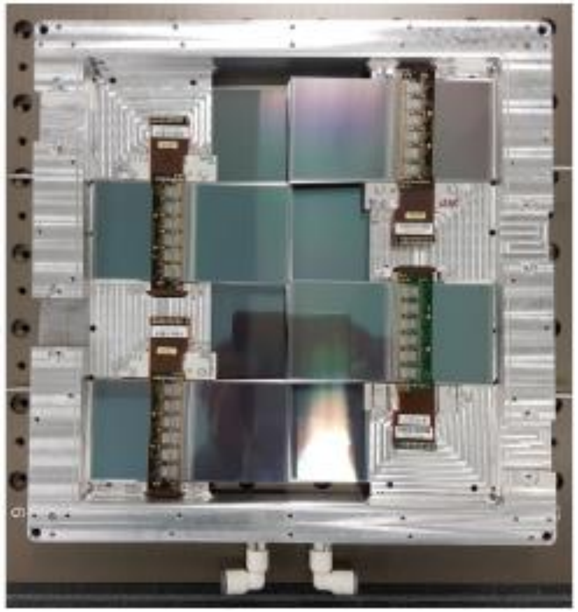
地下100m

FASER TRACKER

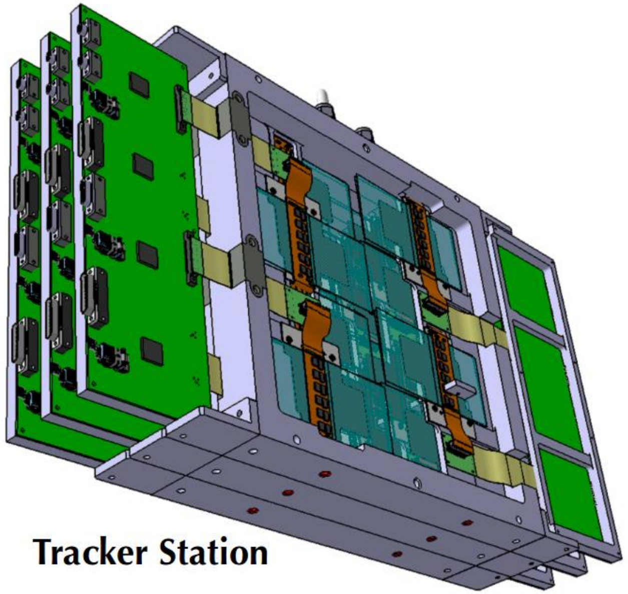
- FASER Tracker needs to be able to efficiently separate very closely spaced tracks
- The FASER Tracker is made up of 3 tracking stations
- Each containing 3 layers of double-sided silicon micro-strip sensors
  - Spare ATLAS SCT modules are used
    - 80μm strip pitch, 40mrad stereo angle (17μm / 580μm resolution)
      - precision measurement in bending (vertical) plane
    - ***Many thanks to the ATLAS SCT collaboration!***
- 8 SCT modules give a 24cm x 24cm tracking layer
- 9 layers (3/station, 3 stations) => 72 SCT modules needed for the full tracker
  - 10^5 channels in total



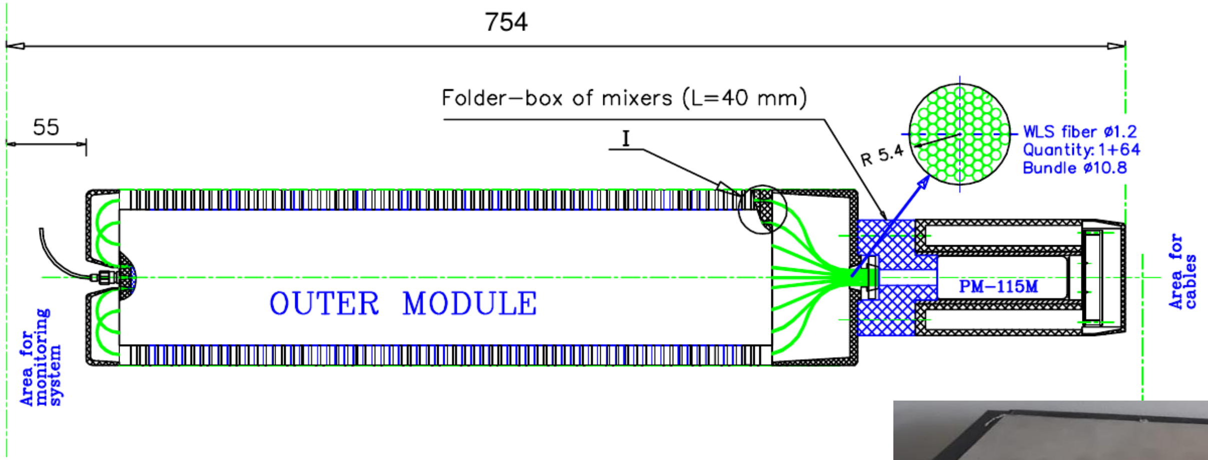
SCT module



Tracking layer

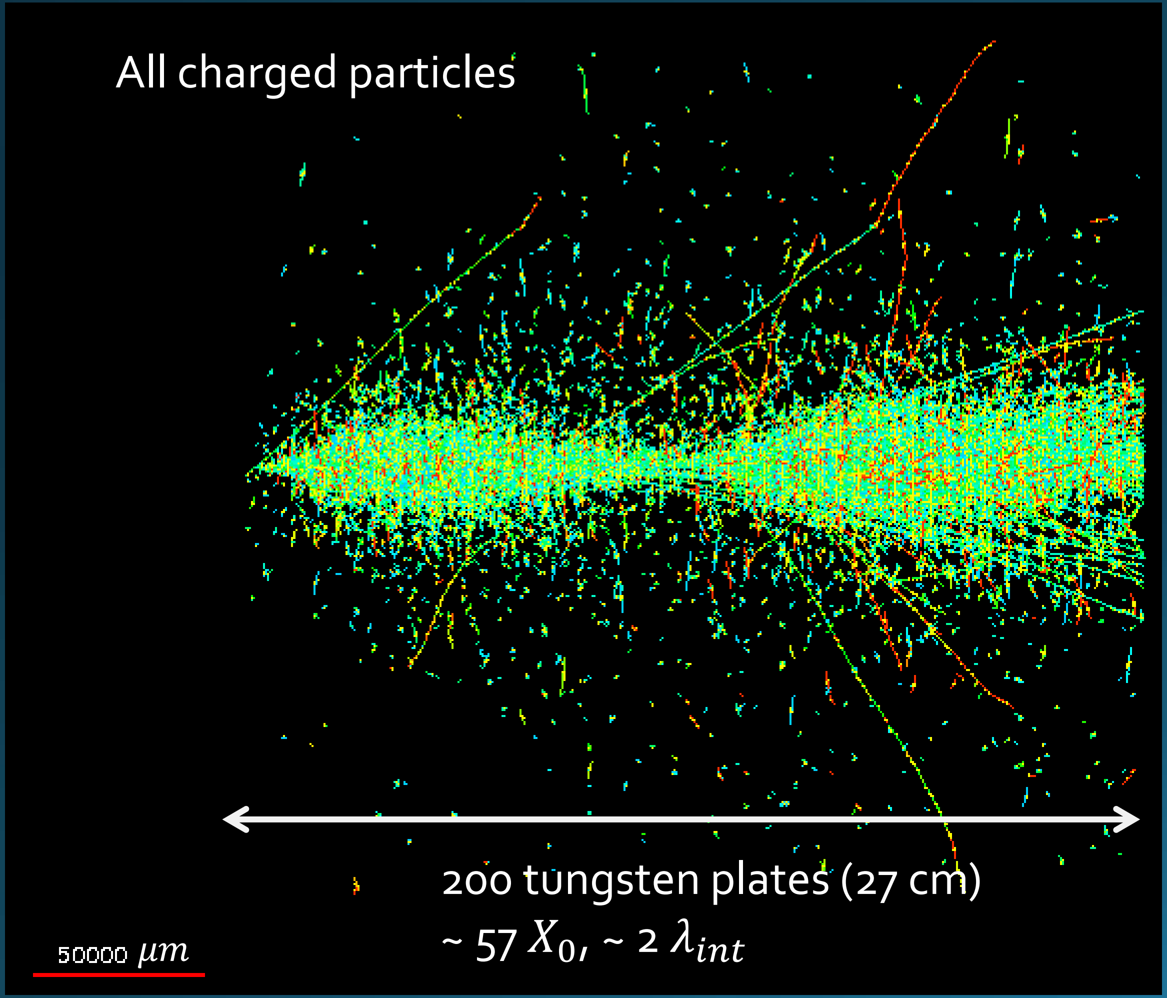


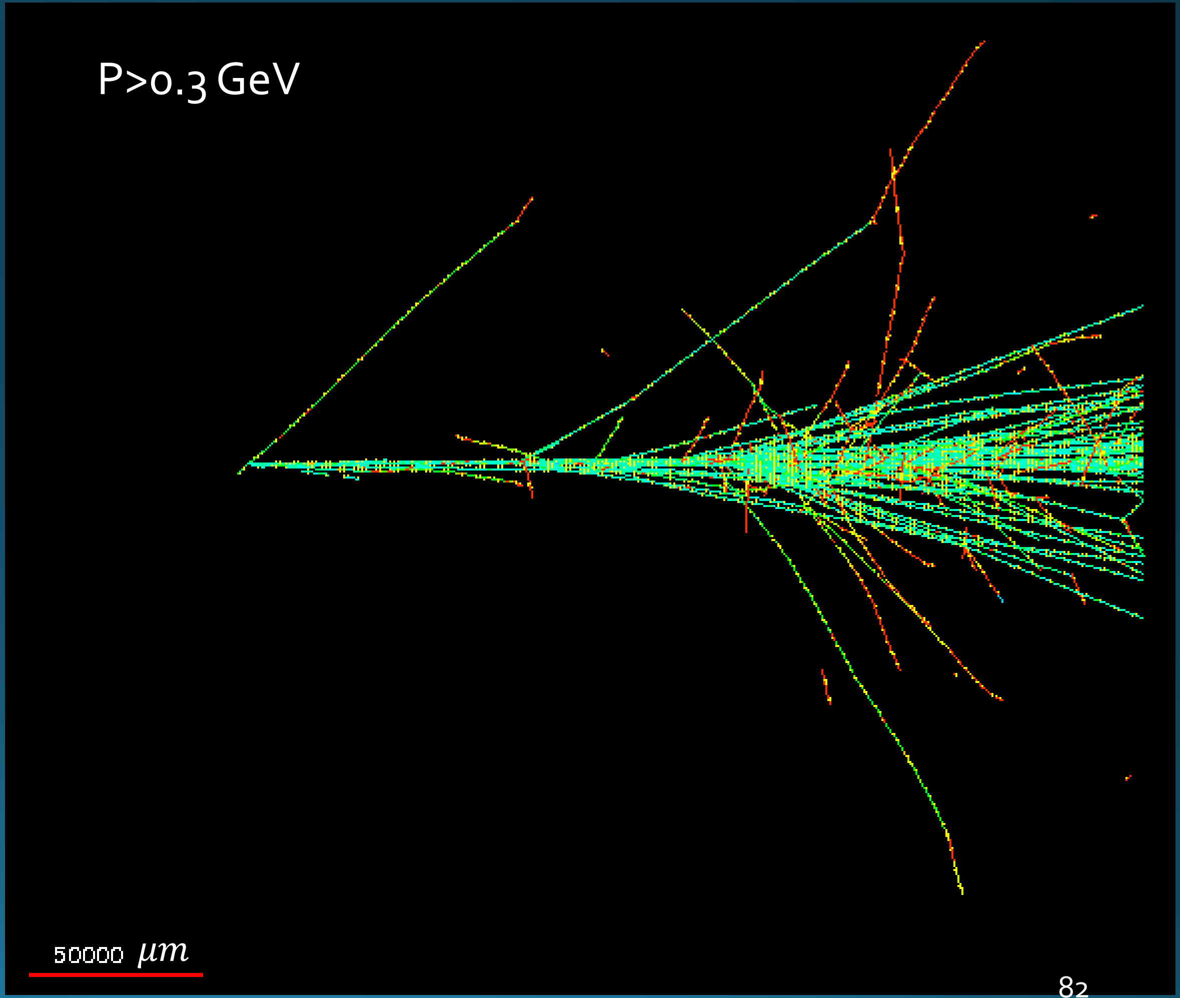
CALORIMETER



- FASER EM calorimeter for:
  - Measuring the EM energy in the event
  - Electron/photon identification
  - Triggering
- Uses 4 spare LHCb outer ECAL modules
  - ***Many thanks to LHCb*** for allowing us to use these!
  - 66 layers of lead/scintillator, light out by wavelength shifting fibers
    - 25 radiation lengths long
  - Readout by PMT (no longitudinal shower information)
    - Only 4 channels in full calorimeter
  - Dimensions: 12cm x 12cm – 75cm long (including PMT)
  - Provides ~1% energy resolution for 1 TeV electrons
    - Resolution will degrade at higher energy due to not containing full shower in calorimeter; Energy scale will depend on the calibration

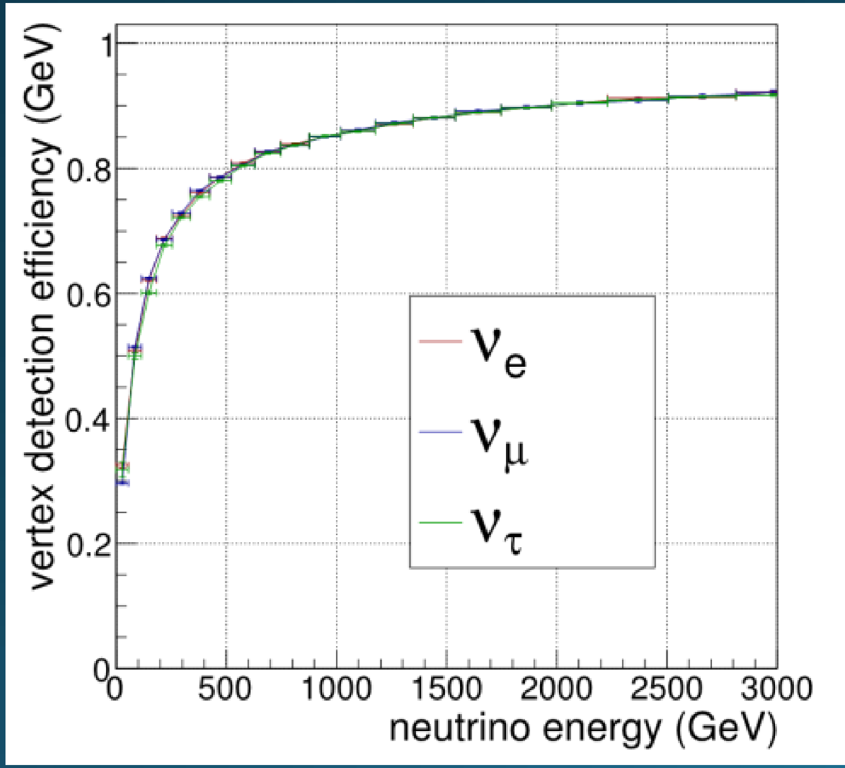
Simulated 1 TeV ν_μ CC interaction



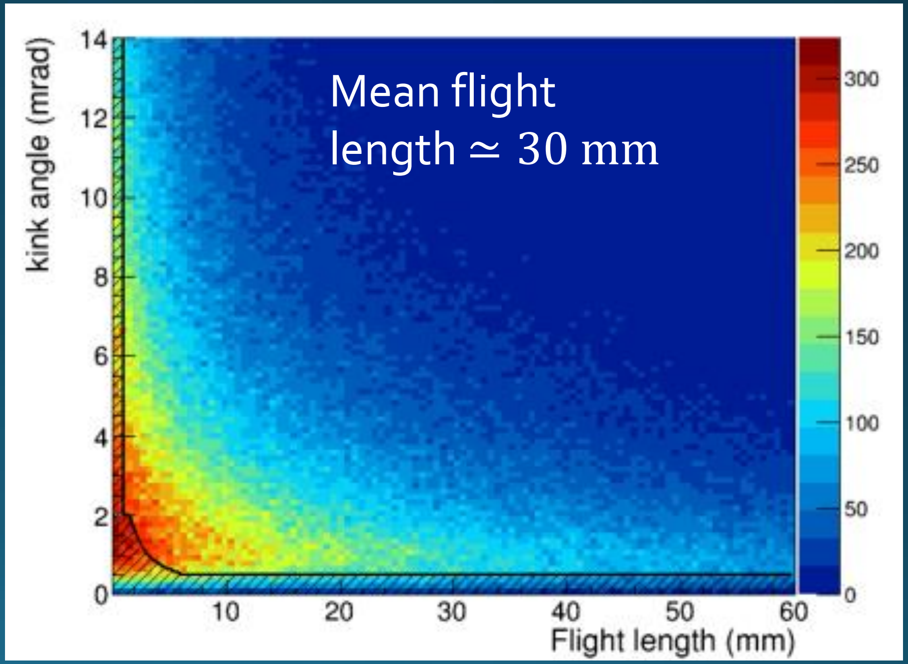


Detection efficiency

Vertex detection efficiency
(charged multiplicity>=5)



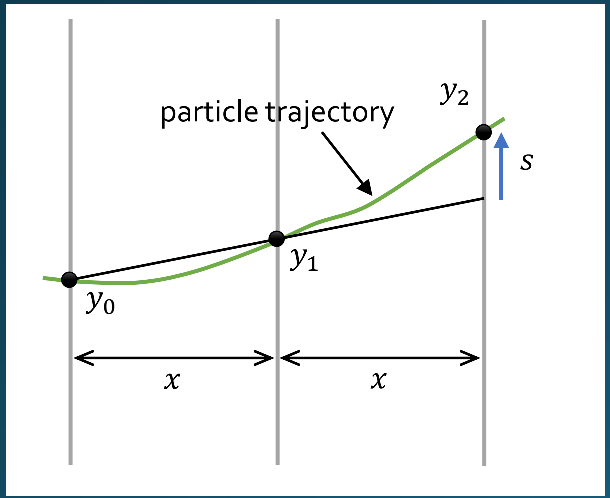
Tau decay detection efficiency
=75% ($\tau \rightarrow 1$ prong)



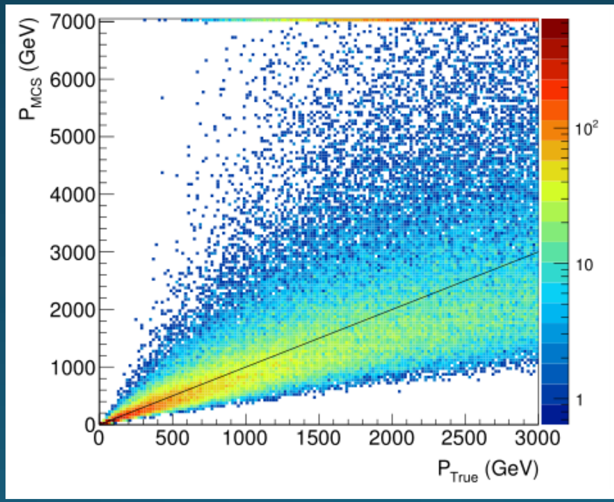
Particle momentum measurement

by multiple Coulomb scattering (MCS)

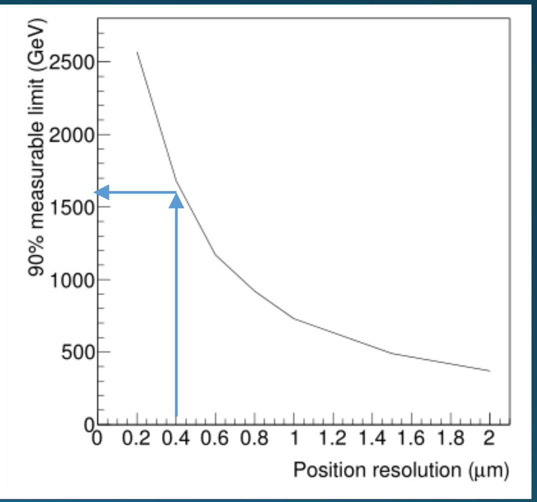
- Sub-micron precision alignment using muon tracks
  - Our experience = 0.4 μm (in the DsTau experiment)
- This allow to measure particle momenta by MCS, even above 1 TeV.



$$(s^{\mathrm{RMS}})^2 = \left(\sqrt{\frac{2}{3}}\frac{13.6(\mathrm{MeV})}{\beta P}x\sqrt{\frac{x}{X_0}}\right)^2 + \left(\sqrt{6}\,\sigma_{\mathrm{pos}}\right)^2$$



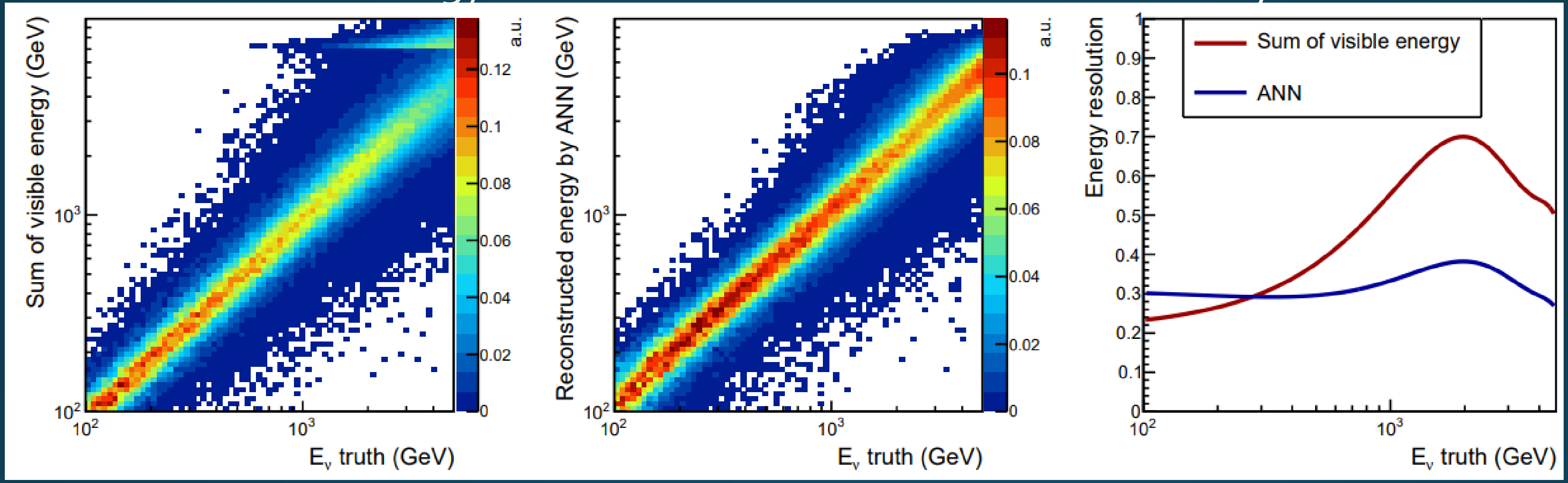
Performance with position resolution of 0.4 μm, in 100 tungsten plates (MC)



Measurable energy vs position resolution

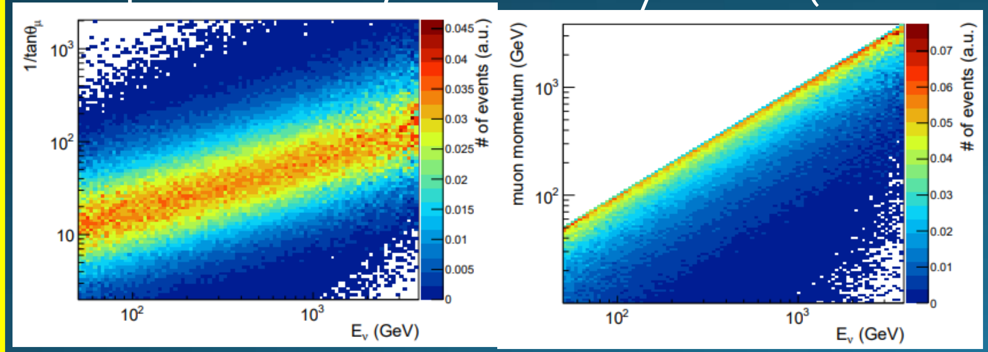
Energy reconstruction (ν_μ CC)

Sum of visible energy ANN method $\Delta E/E$



(smeared)

inputs for ANN, simulated by GENIE (MC truth)



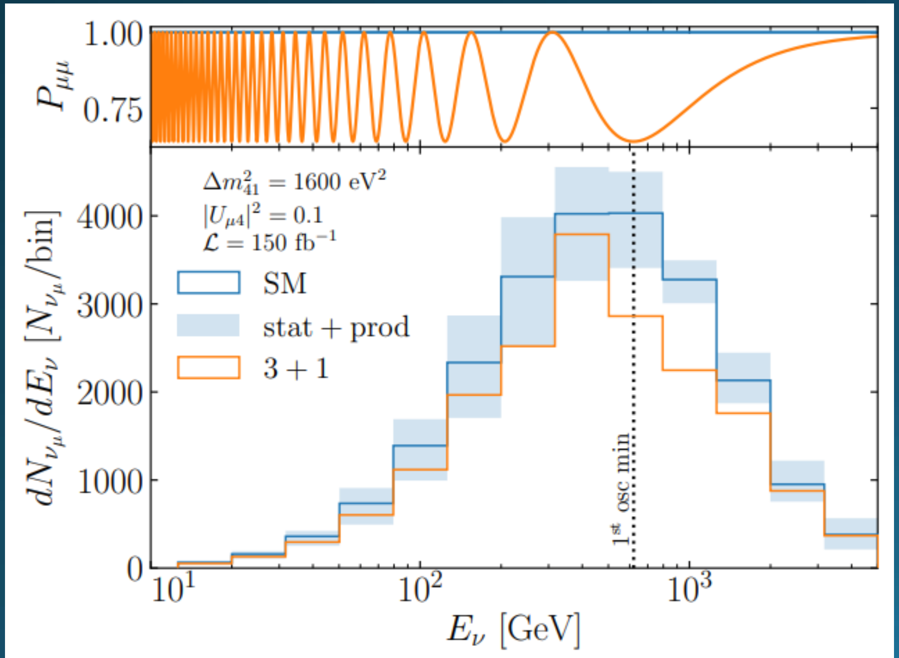
Angular info Momentum

…

- Sum of visible energy (model independent) already gives a reasonable resolution
- ANN can solve problem at high energy and gives about 30% resolution at relevant energy range.

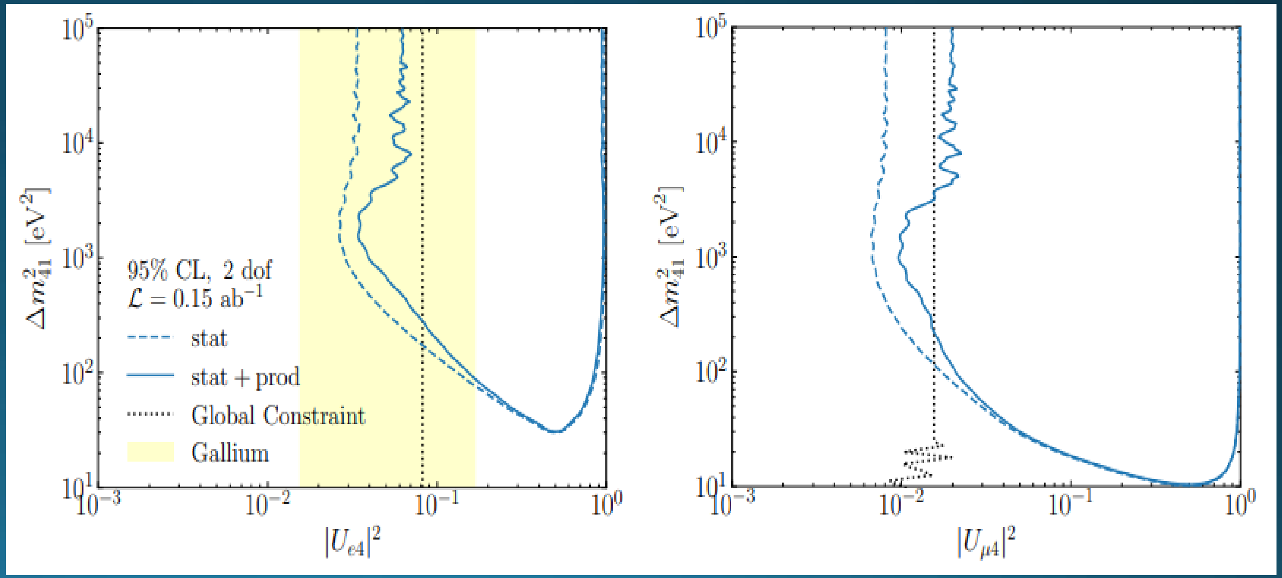
Sterile neutrino oscillation

- Due to unique energy and baseline ($L/E \sim 10^{-3}$ m/MeV), FASERν is sensitive to large $\Delta m^2 \sim 10^3$ eV².
- Neutrino spectrum deformation
- Competitive in disappearance channels.



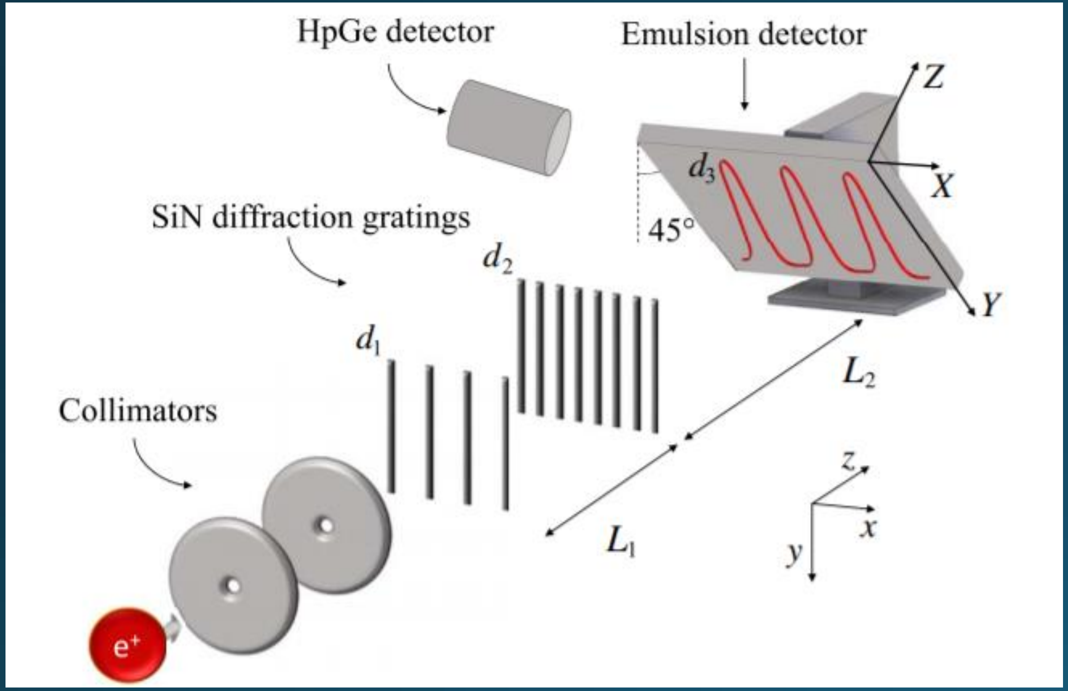
ν_e disappearance

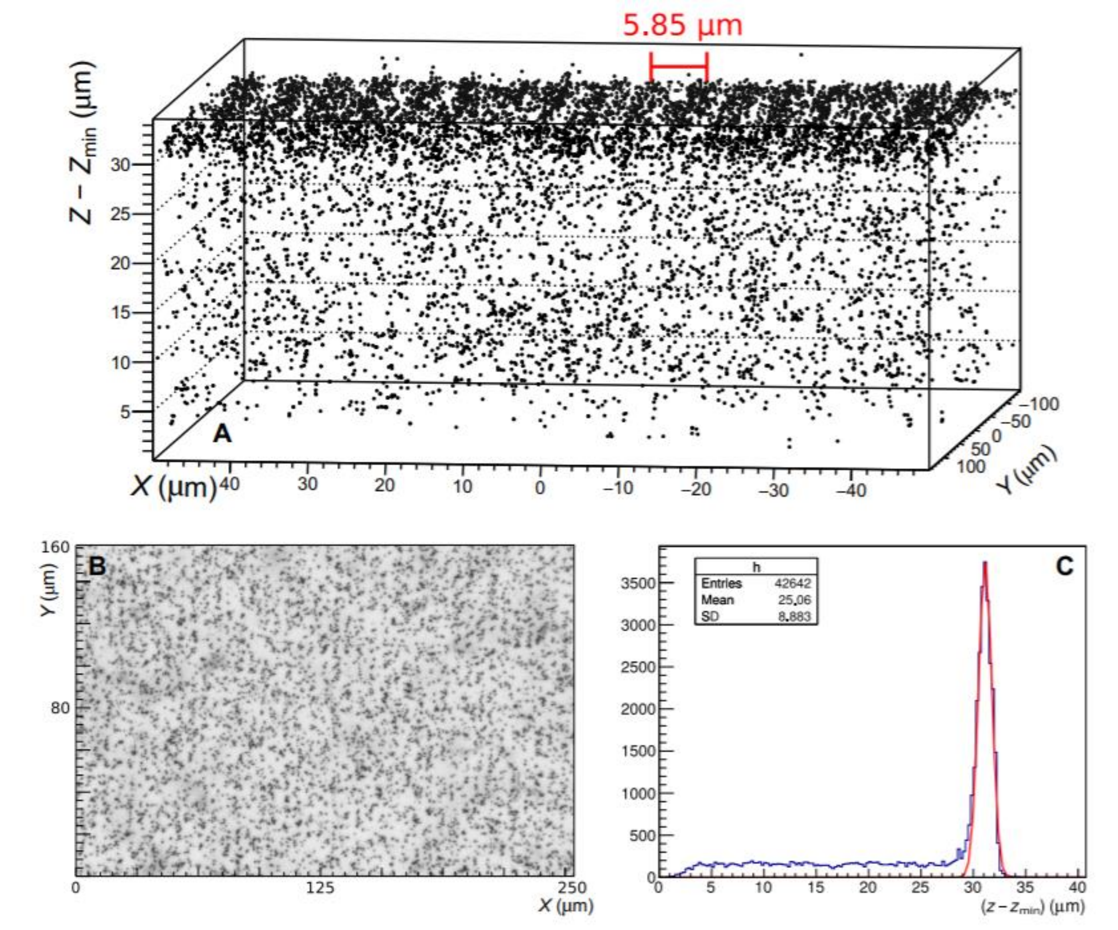
ν_μ disappearance



QUPLAS: First demonstration of antimatter wave interferometry

physicsworld TOP 10 BREAKTHROUGH 2019





- 8-14 keV positron

Glacier bedrock radiography

- Muon radiography applied to Swiss alps
- Discovery of steep bedrock shape, need a new understanding of glacial erosion process.

- [Nature Scientific Reports]
- [s41598-019-43527-6]