Study of high-energy neutrinos in the FASER experiment at the LHC

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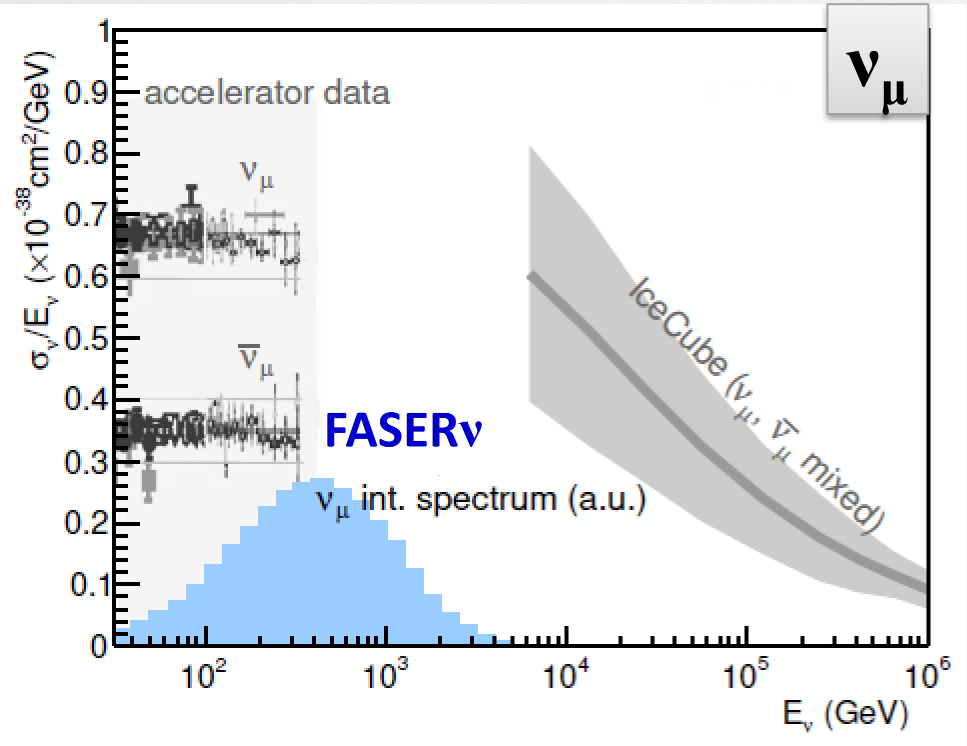
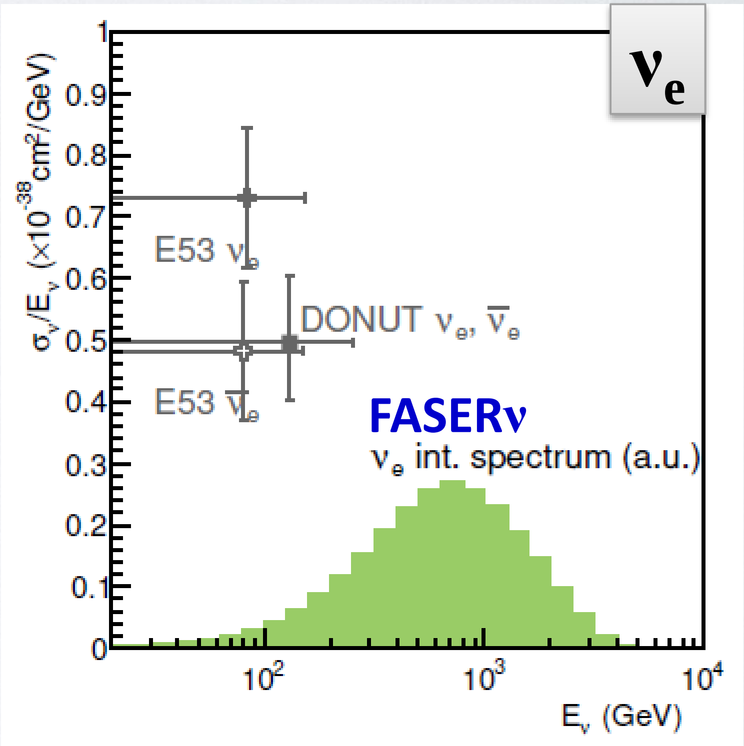
on behalf of the FASER Collaboration

Physics motivation of the FASERν program

- Study of high-energy neutrinos at TeV scale
  - First detection of collider neutrinos in far forward location, where high-energy neutrino flux is concentrated
  - Cross-section measurements of all flavors in **unexplored energy region**
  - Search for new physics effects in high-energy neutrino interactions





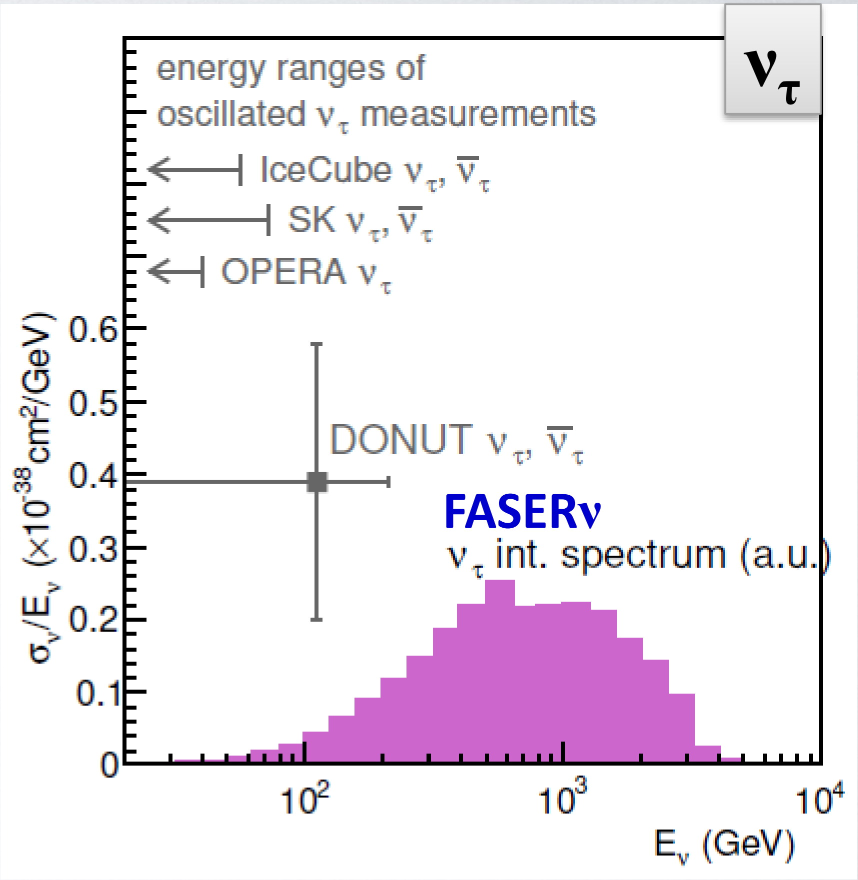
Tau neutrino

- Tau neutrino is one of the least studied particles
  - Only a few measurements

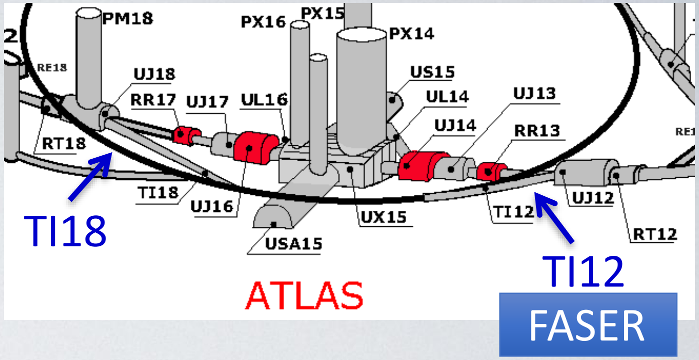
    Direct ν_τ beam: DONuT

    Oscillated ν_τ: OPERA, Super-K, IceCube

- FASERν aims to measure **ν_τ cross section at the highest energy ever**



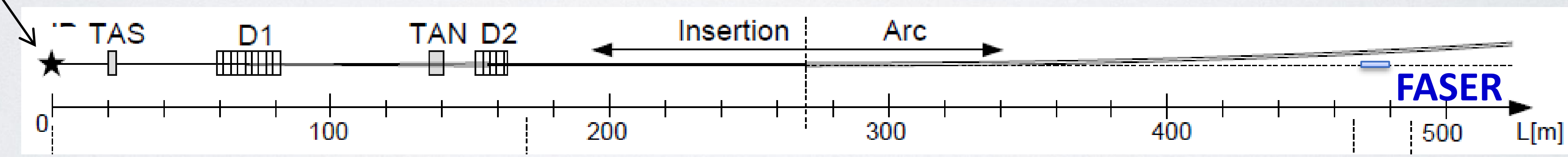
The FASER experiment



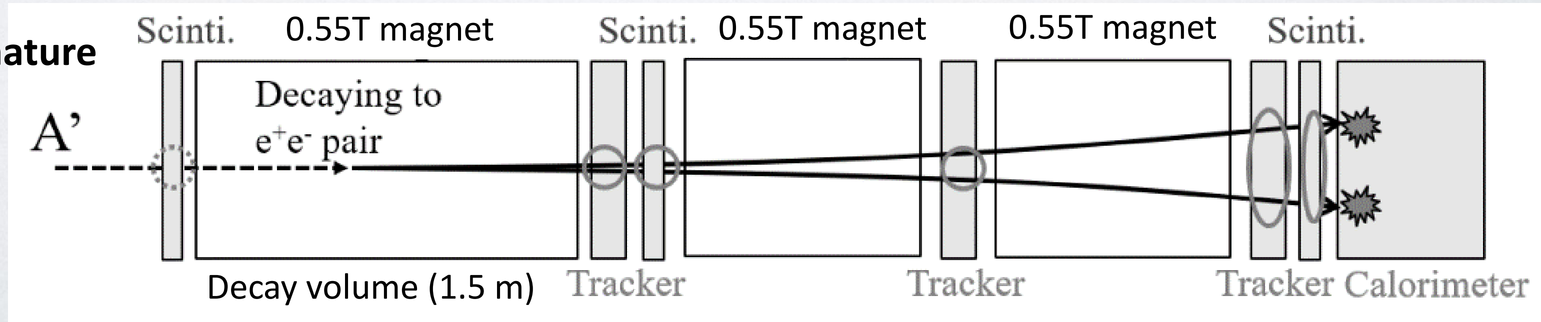
- Current searches for new physics at the LHC focus on high p_T (appropriate for heavy, strongly interacting particles)
- **FASER** is a new experiment at the LHC aiming to **search for light, weakly-interacting particles**
  - A particle detector will be located 480 m downstream of the ATLAS interaction point (**low p_T along the beamline**)

ATLAS interaction point

pp → LLP + X, LLP travels ~480 m, LLP → e^+e^-, $\mu^+\mu^-$, …



Signal signature



The FASER experiment

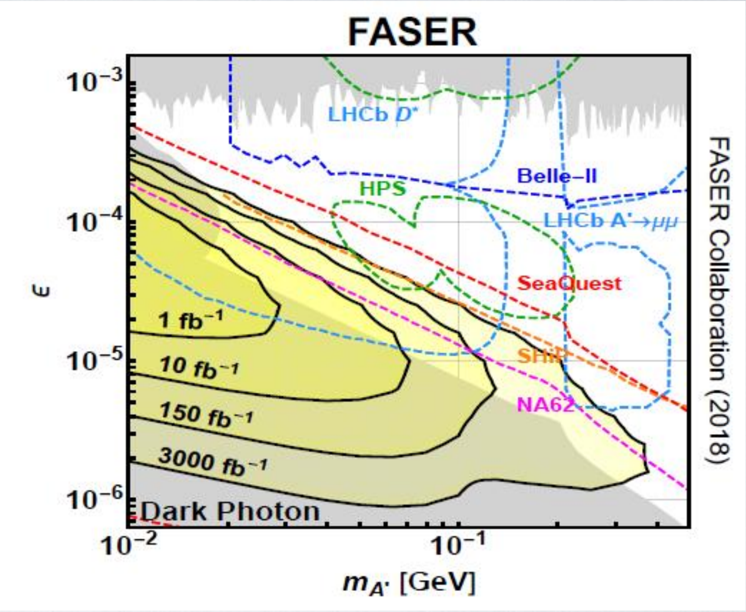
- **FASER** LOI, TP reviewed by LHCC
- **Approved by CERN** in Mar. 2019
- **Funded** by the Heising-Simons Foundation and the Simons Foundation with support from CERN

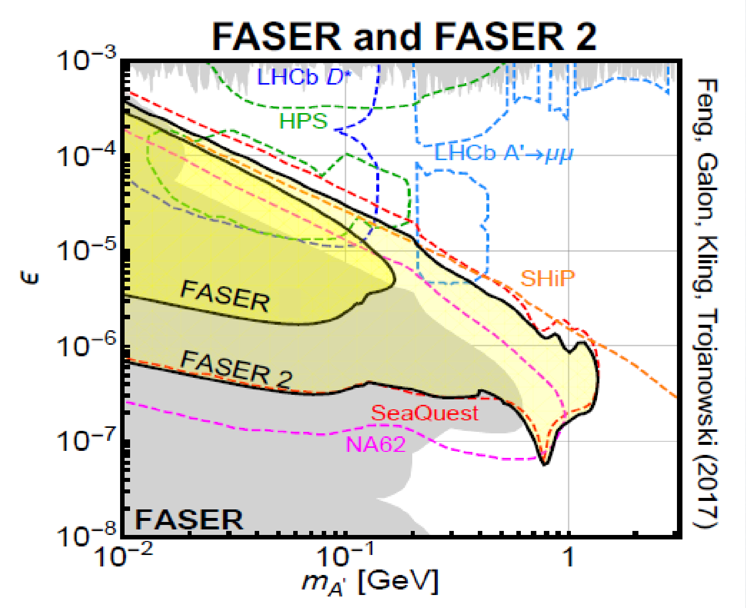
- **FASER** installation planned in 2020
  - Data-taking in Run3 (2021-2023) (150 fb^{-1})
  - Decay volume: R = 10 cm and L = 1.5 m
- **FASER2** (possible future upgrade)
  - Data-taking at the HL-LHC (3 ab^{-1})
  - Decay volume: R = 1 m and L = 5 m

In addition to searches for new particles, **we also aim to study high-energy neutrinos of all flavors**

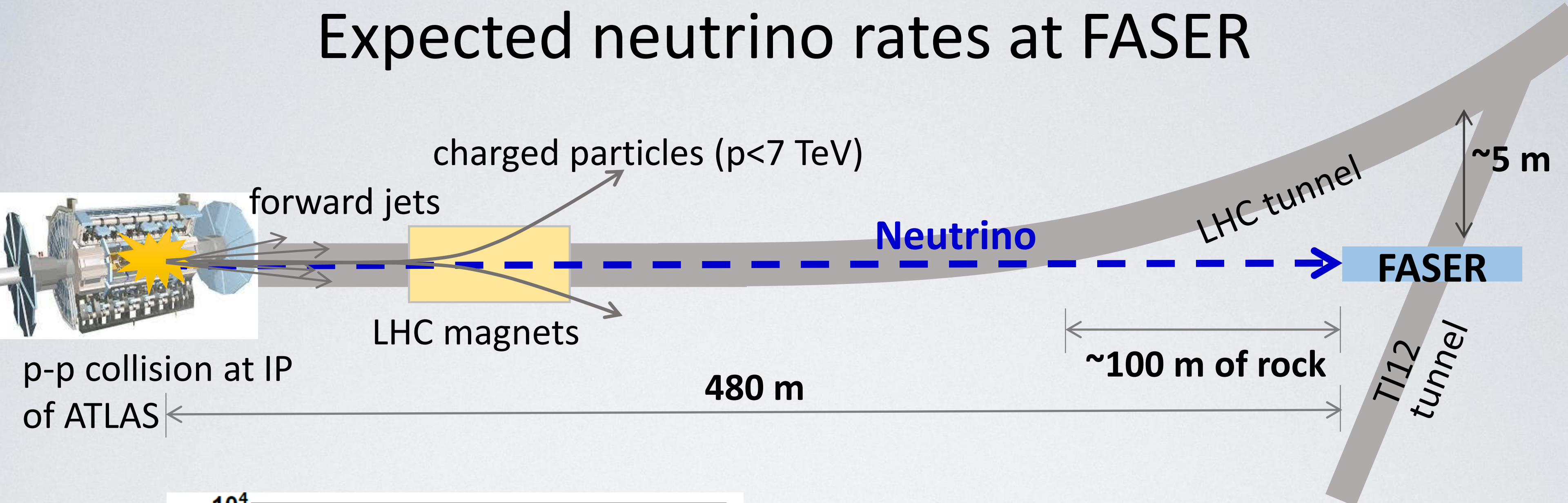
No one has ever detected neutrinos at the LHC

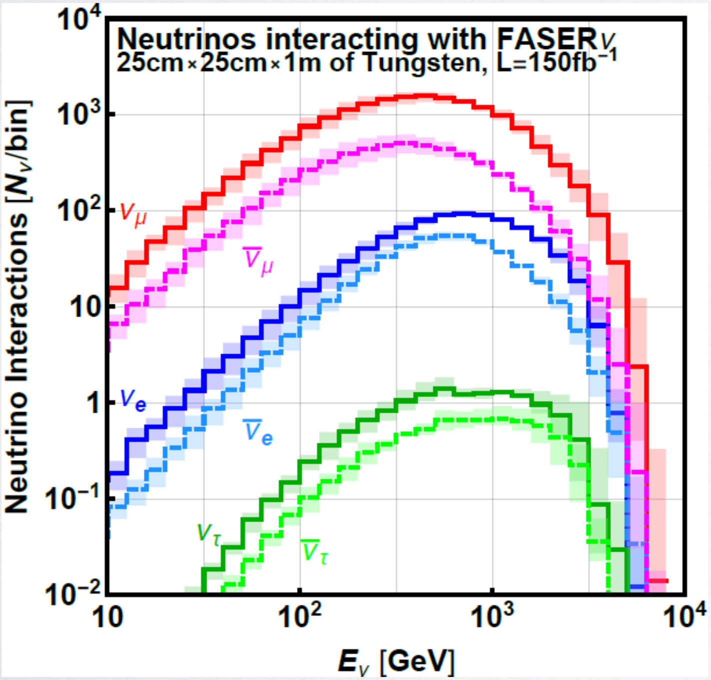
Dark photon sensitivity reach





Expected neutrino rates at FASER

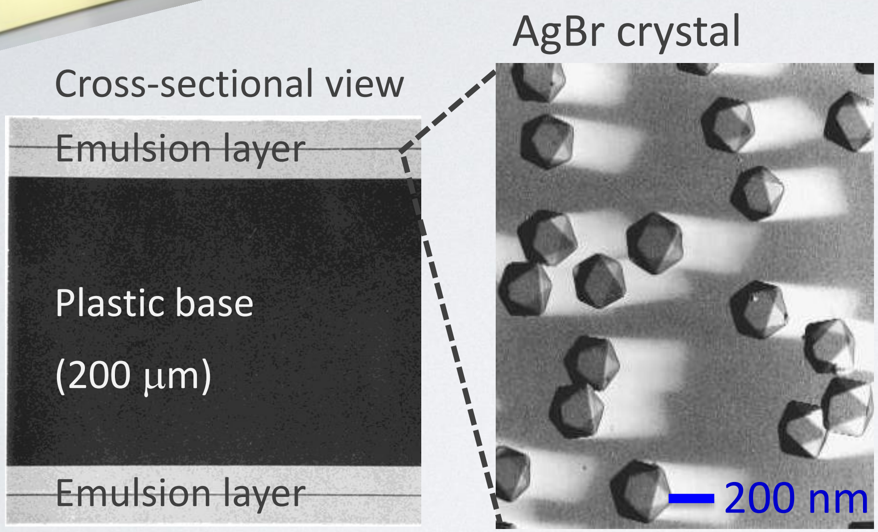


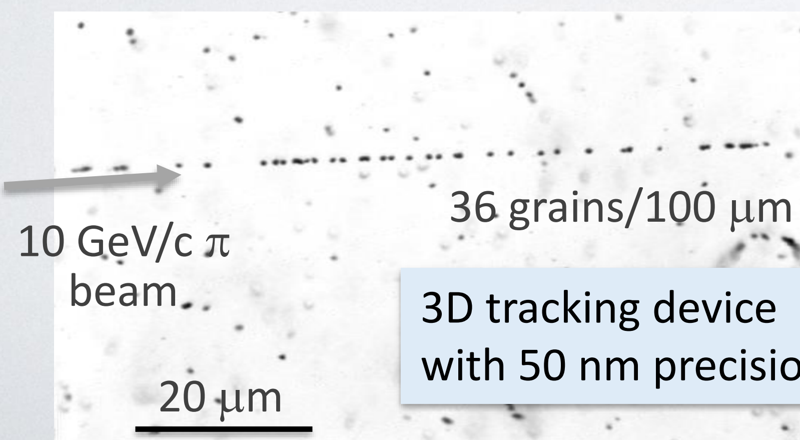


Expected yields in Run 3 (2021-2023)

	# of CC interactions	Mean energy (GeV)
$\nu_e + \bar{\nu}_e$	1296	827
$\nu_\mu + \bar{\nu}_\mu$	20439	631
$\nu_\tau + \bar{\nu}_\tau$	21	965

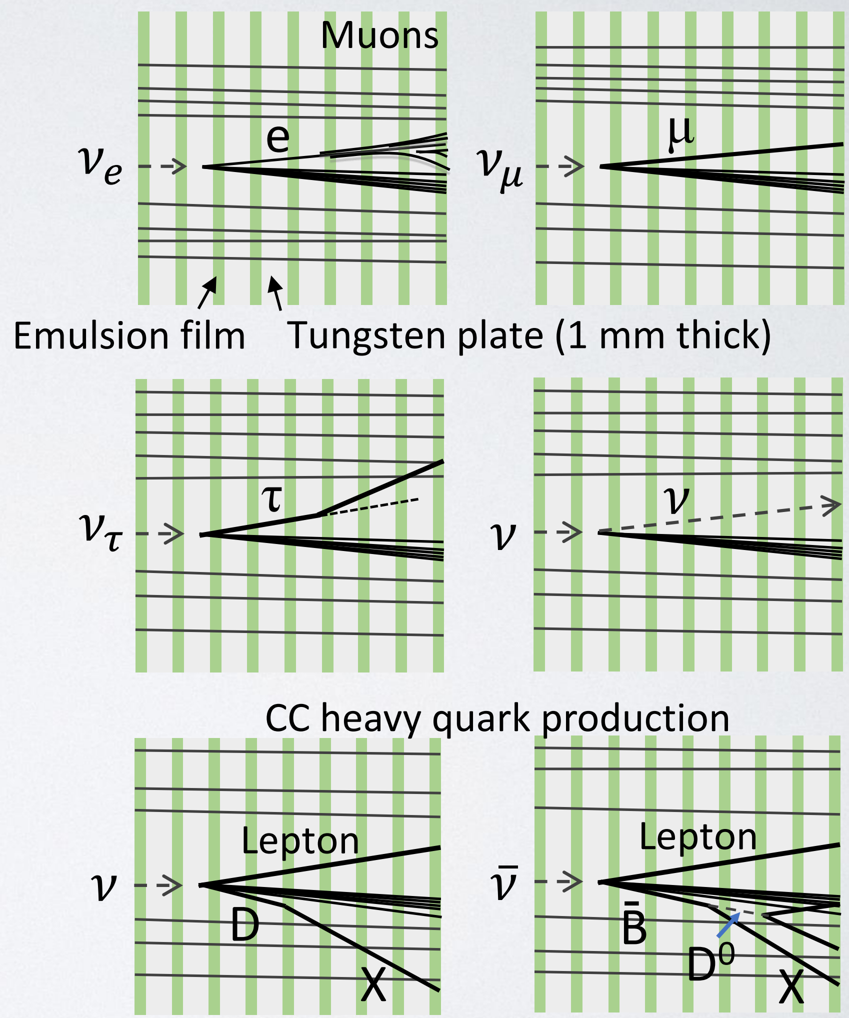
Neutrino detector with emulsions





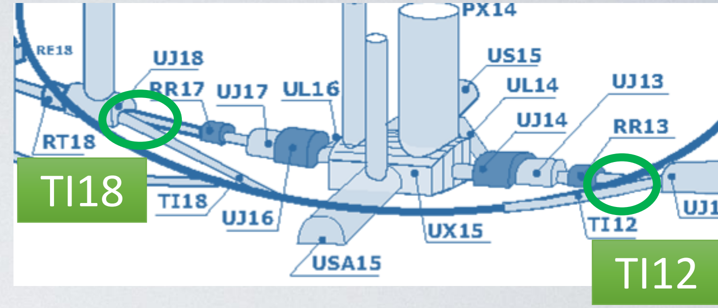
3D tracking device
with 50 nm precision

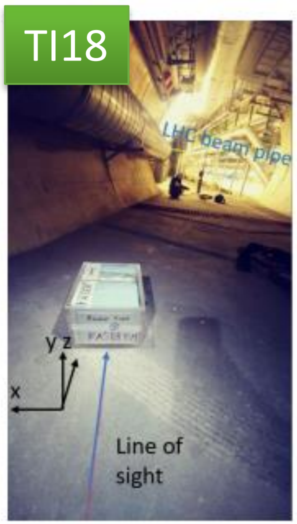
Signal topologies

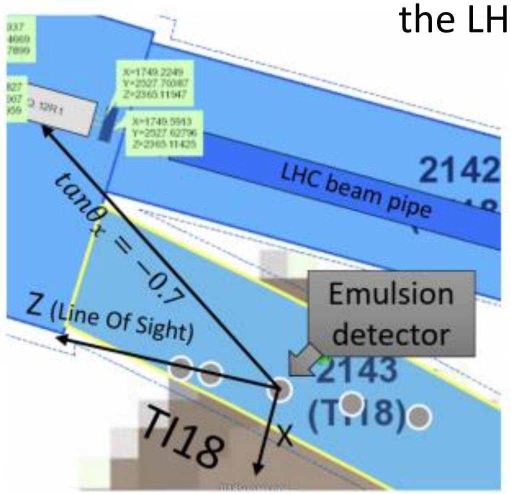


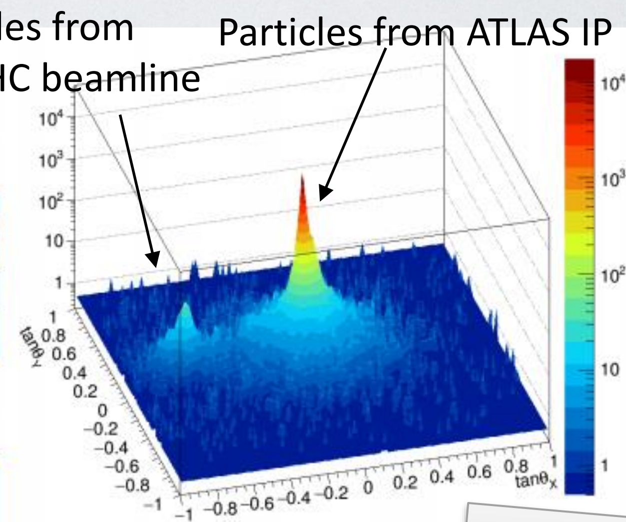
In situ measurements in 2018:

detector environment

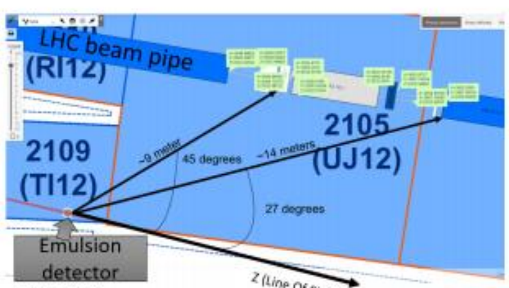




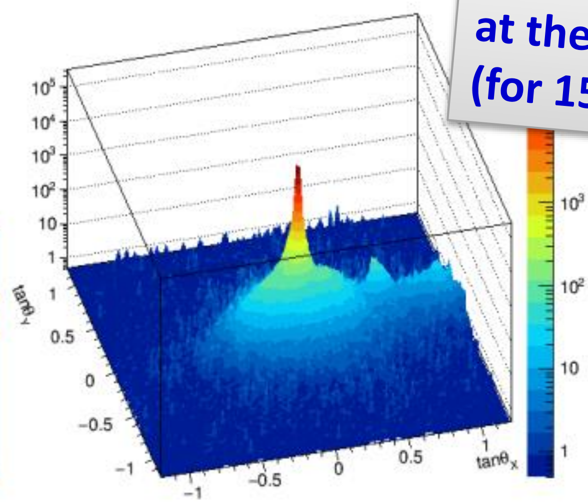




	Normalized flux (fb/cm²)
TI18	$(2.6 \pm 0.7) \times 10^4$
TI12	$(3.0 \pm 0.3) \times 10^4$



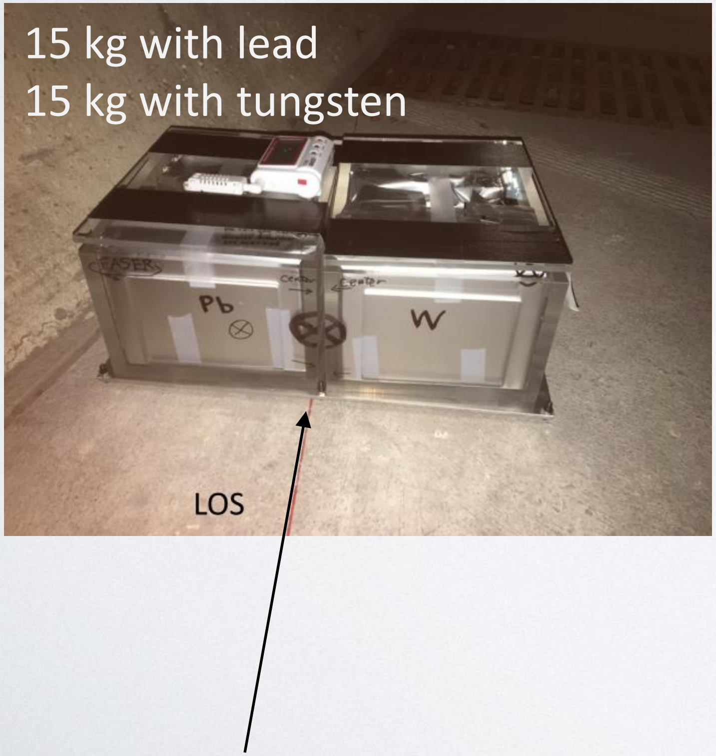
TI12



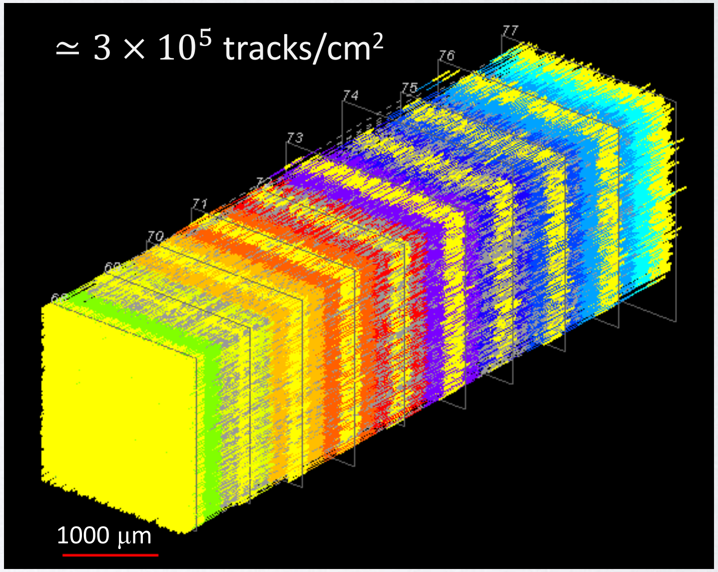
Emulsion detector can work at the actual environment (for 15 fb^{-1} of data)

Test run in 2018: data for possible neutrino detection

- **Aims**: possible neutrino detection and gamma background measurement
- A 30-kg emulsion detector was installed in TI18 and exposed to ~12.5 fb^{-1}



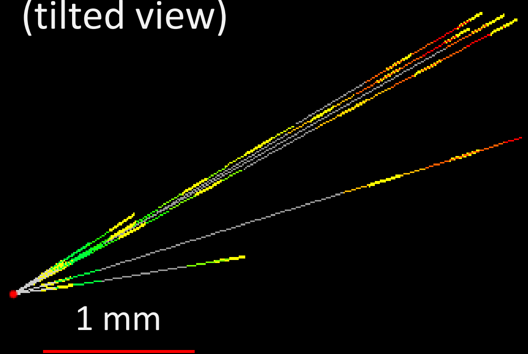
Reconstructed data (2 x 2 mm^2)

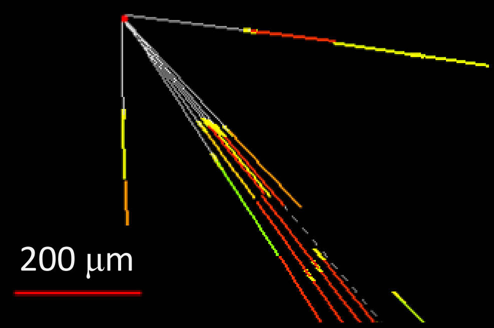


Test run in 2018: data for possible neutrino detection

Vertex candidates

(tilted view)

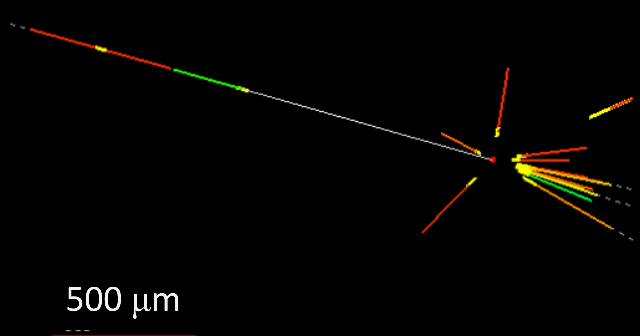




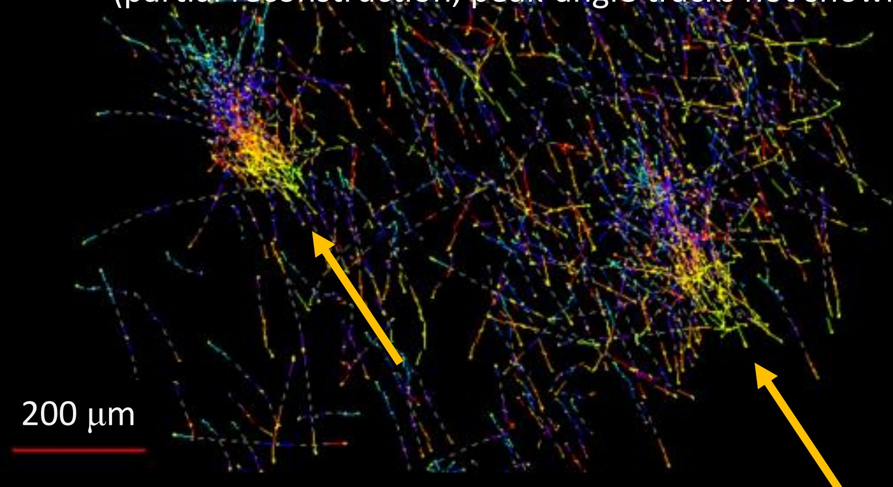
No muon ID in the 2018 run
→ More background

Neutrino / neutral hadron separation is under study

Vertex but with parent:
pion interaction

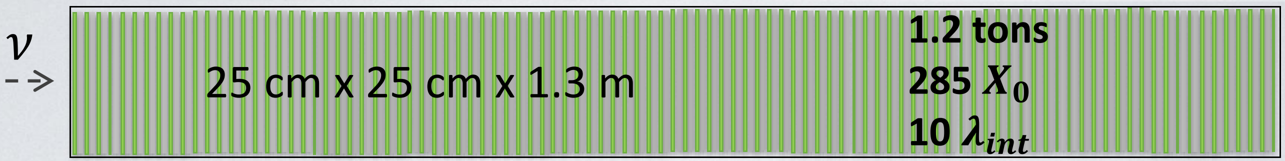


Electromagnetic showers
(partial reconstruction, peak-angle tracks not shown)

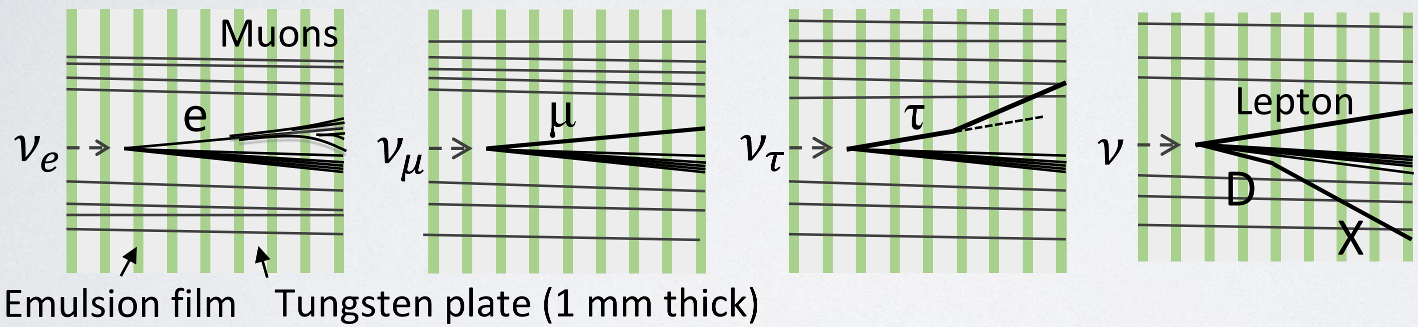


Possible detector design for LHC-Run3 (2021-2023)

Total 1000 emulsion films interleaved with 1-mm-thick tungsten plates



Muon ID: muons are identified by their track length in the detector

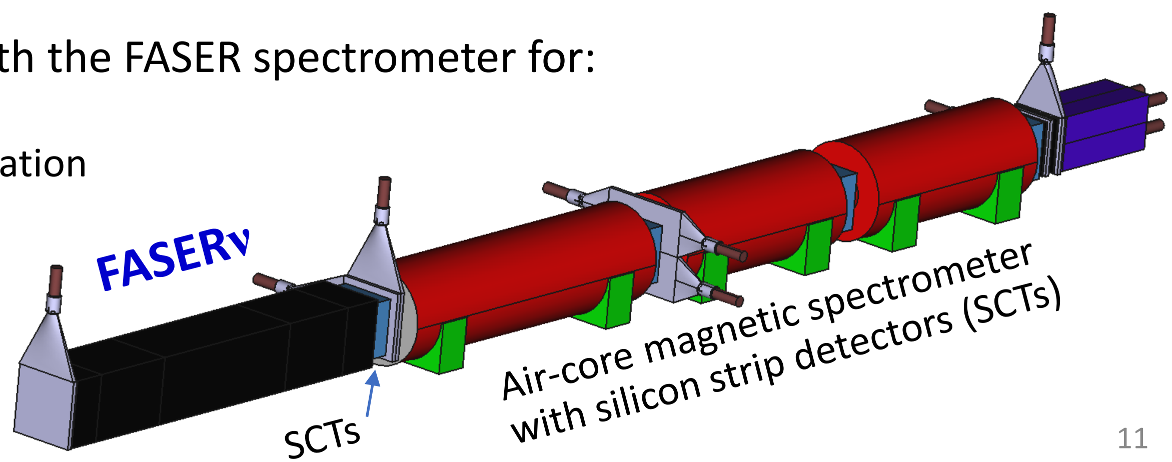


Expected yields in Run3

	# of CC int.
$\nu_e + \bar{\nu}_e$	1296
$\nu_\mu + \bar{\nu}_\mu$	20439
$\nu_\tau + \bar{\nu}_\tau$	21

Possibly upgraded to couple with the FASER spectrometer for:

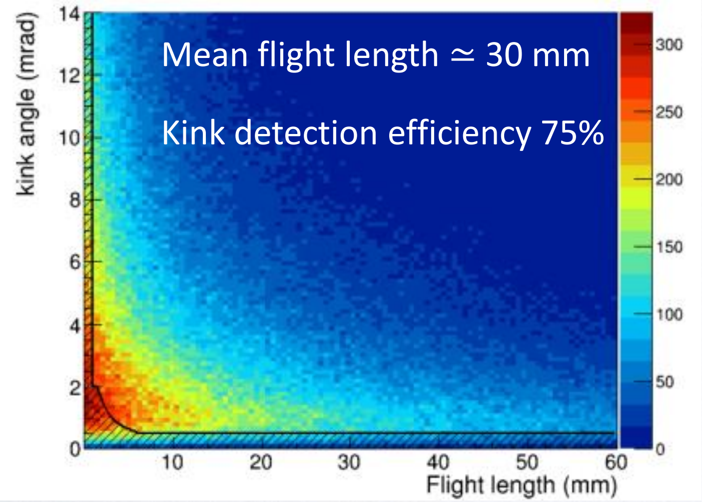
- charge measurement
- improvement of the energy estimation
- background suppression



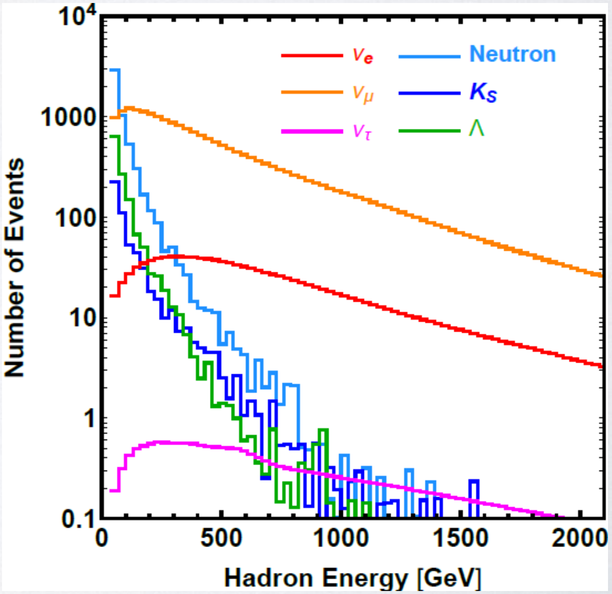
Signal features and backgrounds

	ν_e CC	ν_μ CC	ν_τ CC	NC
How to identify	High energy electron	Muon ID	Detection of τ decays	
Background	π^0 from ν interactions		▪ ν_μ CC charm production ▪ Hadron interactions	Neutral hadron interactions
How to suppress the background	Thin target		▪ Muon ID ▪ Topological variables	Topological / kinematical variables

Detection of τ decays: flight length / kink angle



Energy spectrum of neutral hadrons produced in rocks in front of FASERν



Neutrino energy reconstruction

- Neutrino energy will be reconstructed by combining topological and kinematical variables

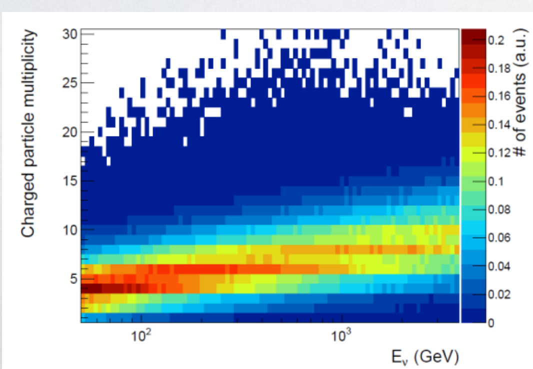
An ANN algorithm was built with

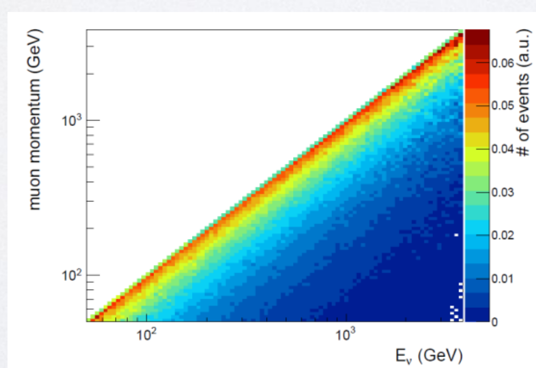
topological variables

- # of charged tracks $\rightarrow E_h$
- # of γ showers $\rightarrow E_h$
- inverse of lepton angle $\rightarrow E_\ell$
- sum of inverse of hadron track angles $\rightarrow E_h$
- inverse of median of all track angles $\rightarrow E_h, E_\ell$

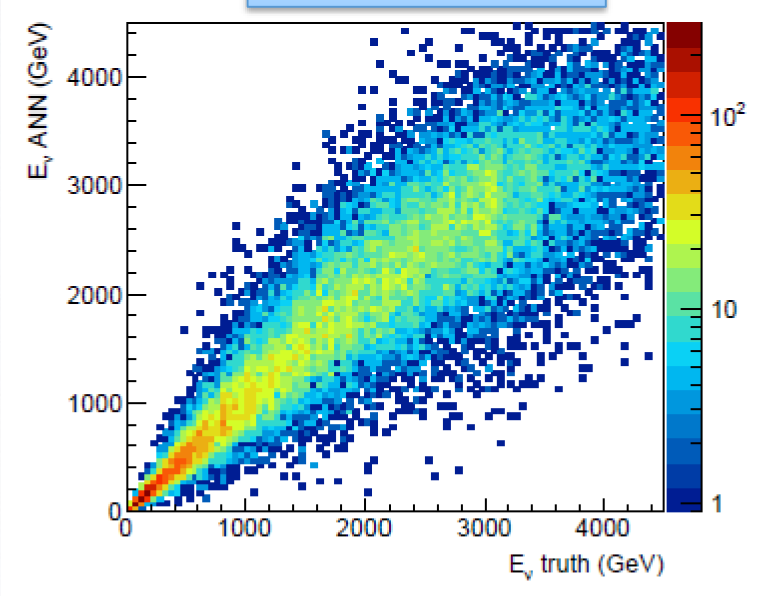
kinematical info (smeared)

- lepton momentum $\rightarrow E_\ell$
- sum of charged hadron momenta $\rightarrow E_h$
- sum of energy of γ showers $\rightarrow E_h$





$E_\nu - E_{ANN}$

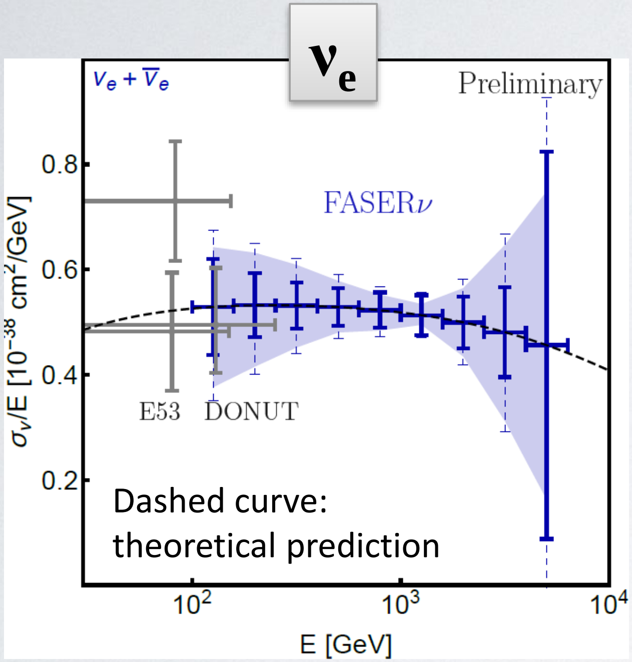


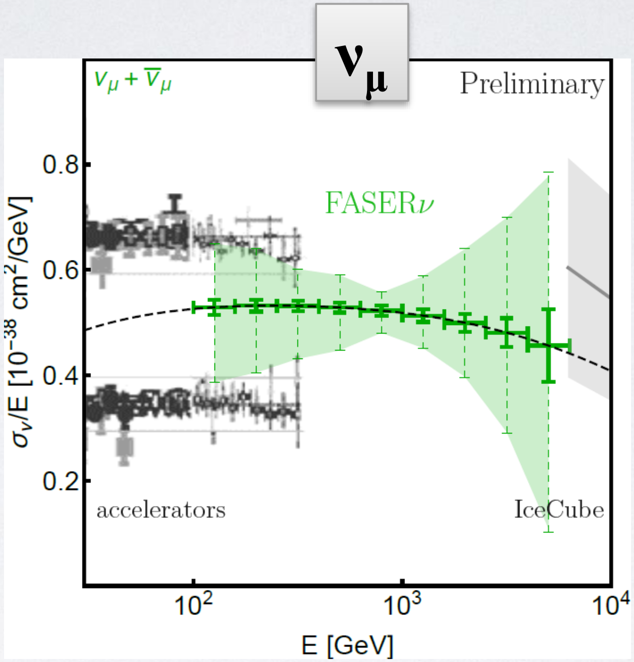
$$\frac{\Delta E}{E} = 25\% \text{ (RMS) (preliminary)}$$

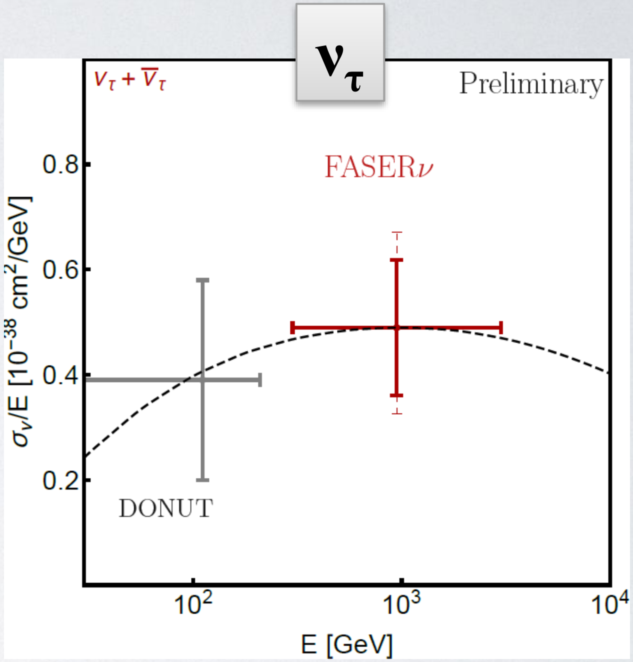
Detailed detector simulation under way

Prospects for cross section measurements at 14-TeV LHC

in Run3 (150 fb^{-1}) using a 1.2-ton tungsten/emulsion detector







Solid error bars: statistical uncertainties.
Dashed error bars: also include uncertainties from neutrino production rate corresponding to the range of predictions obtained from different Monte Carlo generators.

Summary

- At the LHC-FASER, neutrino cross sections will be measured in the currently **unexplored energy range between 350 GeV and 6 TeV**. In particular, **tau-neutrino cross section will be measured at the highest energy ever**.
- As a feasibility study, **a test run was performed in 2018** at the proposed detector location with a 30-kg lead/tungsten emulsion-based neutrino detector. Data of 12.5 fb^{-1} was collected and the event analysis is in progress.
- **For LHC-Run3 (2021-2023), we are planning to deploy a 1.2-ton tungsten/emulsion detector**, possibly coupled with the FASER magnetic spectrometer, which would yield about 20000 muon neutrinos, 1300 electron neutrinos, and a few tens of tau neutrinos interacting in the detector.
  - So far, a JSPS grant and a research grant by the Mitsubishi foundation have been approved to support partially the FASER neutrino program. We are seeking for additional funding.
  - **A paper on the prospects for neutrino studies will be submitted soon.**

The FASER Collaboration

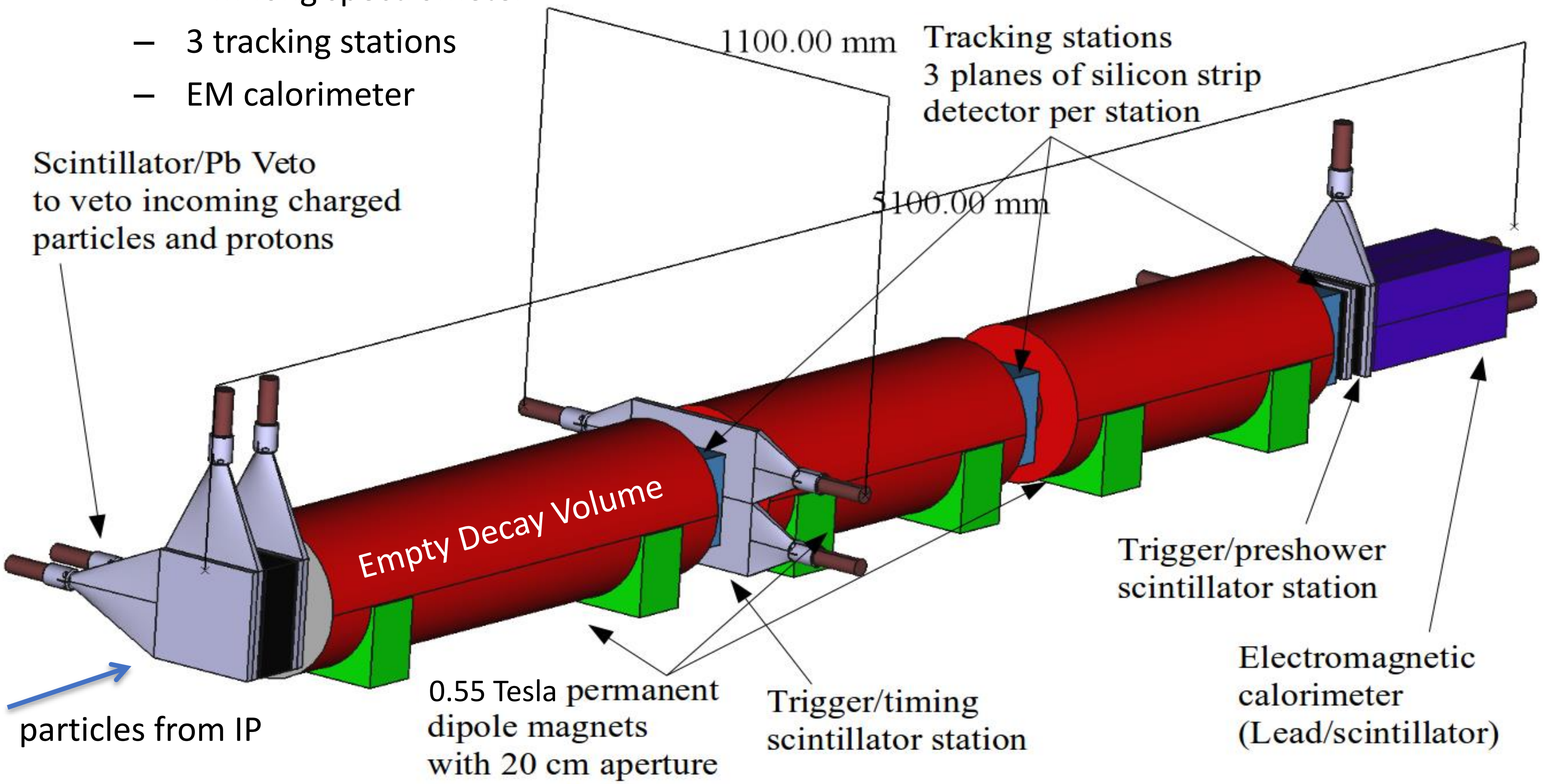
Henso Abreu (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Jamie Boyd (CERN), Dave Casper (UC Irvine), Franck Cadoux (Geneva), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Candan Dozen (Tsinghua), Yannick Favre (Geneva), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Iftah Galon (Rutgers), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Sune Jakobsen (CERN), Roland Jansky (Geneva), Enrique Kajomovitz (Technion), Felix Kling (UC Irvine), Susanne Kuehn (CERN), Lorne Levinson (Weizmann), Congqiao Li (Washington), Josh McFayden (CERN), Sam Meehan (CERN), Friedemann Neuhaus (Mainz), Hidetoshi Otono (Kyushu), Brian Petersen (CERN), Helena Pikhartova (Royal Holloway), Michaela Queitsch-Maitland (CERN), Osamu Sato (Nagoya), Kristof Schmieden (CERN), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Savannah Shively (UC Irvine), Jordan Smolinsky (UC Irvine), Aaron Soffa (UC Irvine), Yosuke Takubo (KEK), Eric Torrence (Oregon), Sebastian Trojanowski (Sheffield), Dengfeng Zhang (Tsinghua), Gang Zhang (Tsinghua)

Part of the Collaboration

Backup

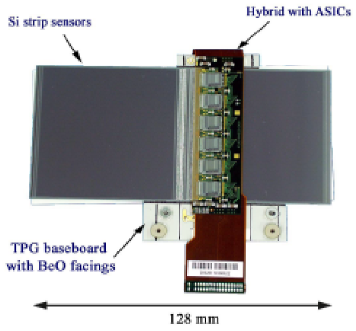
THE FASER DETECTOR

- The entire detector is 5.5 m long. It consists of
  - Scintillator veto
  - 1.5 m-long decay volume
  - 2 m-long spectrometer
  - 3 tracking stations
  - EM calorimeter

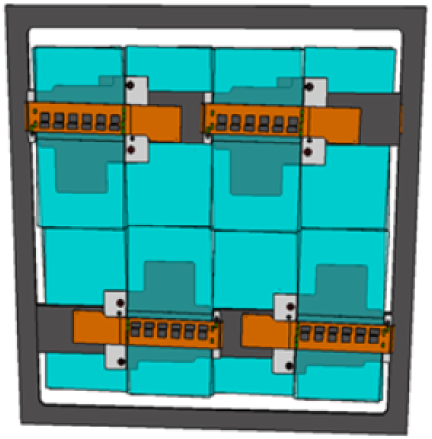


FASER TRACKER

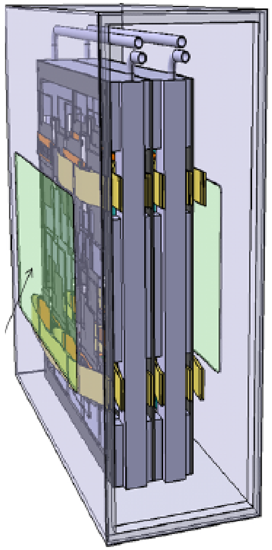
- The FASER Tracker will be made up of 3 tracking stations
- Each containing 3 layers of double sided silicon micro-strip detectors
  - Spare ATLAS SCT modules will be used
    - 80μm strip pitch, 40mrad stereo angle
    - Many thanks to the ATLAS SCT collaboration!
- 8 SCT modules give a 24cm x 24cm tracking layer
- 9 layers (3/station, 3 stations) => 72 SCT modules needed for the full tracker
  - 10^5 channels in total



SCT module



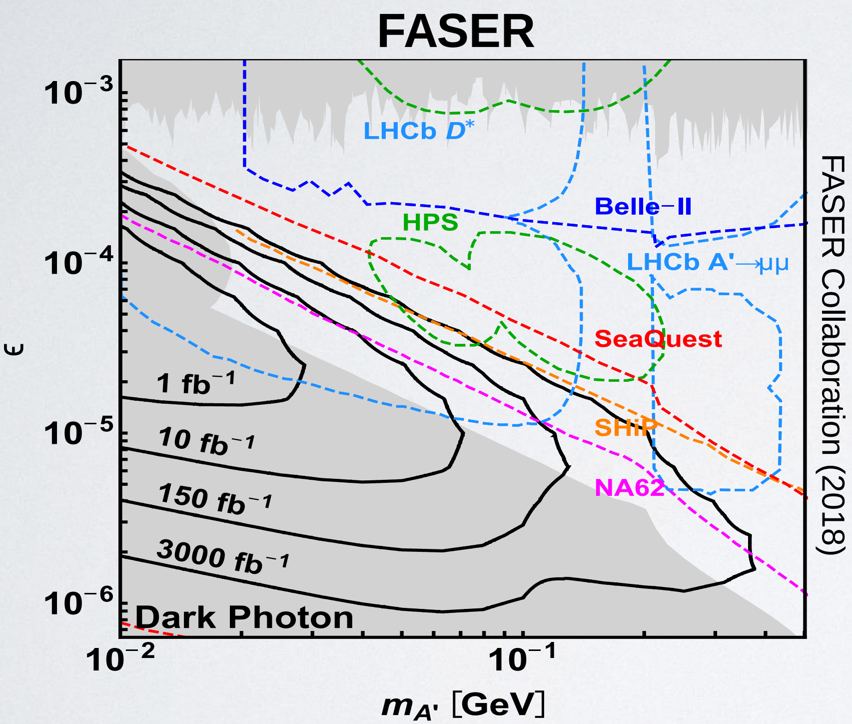
Tracking layer

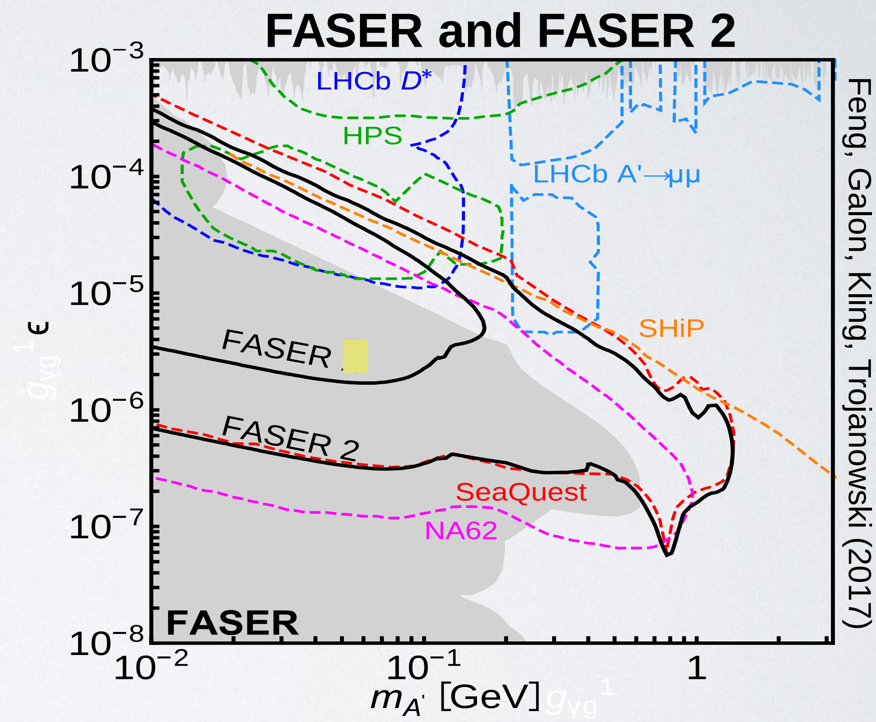


Tracking station

DARK PHOTON SENSITIVITY REACH

- Combine $\pi,\eta \rightarrow A'\gamma$, $qq \rightarrow qqA'$, etc., plot N_S=3 (10 makes little difference)
- FASER: R=10cm, L=1.5m, Run 3;   FASER 2: R=1m, L=5m, HL-LHC



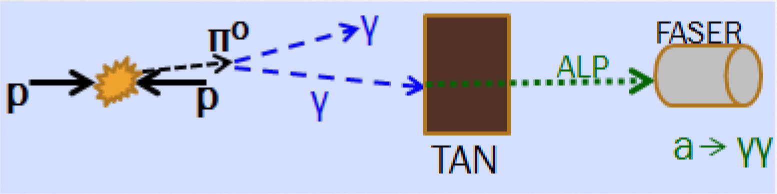


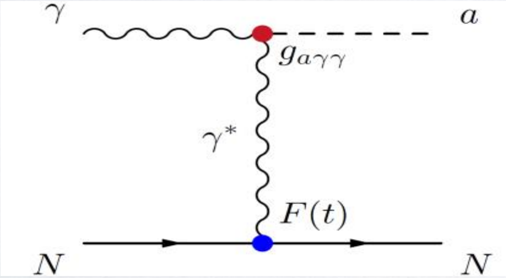
- FASER probes new parameter space with just 1 fb^{-1} starting in 2021
- Without upgrade, HL-LHC extends (L*Volume) by factor of 3000; with possible upgrade to FASER 2, HL-LHC extends (L*Volume) by $\sim 10^6$

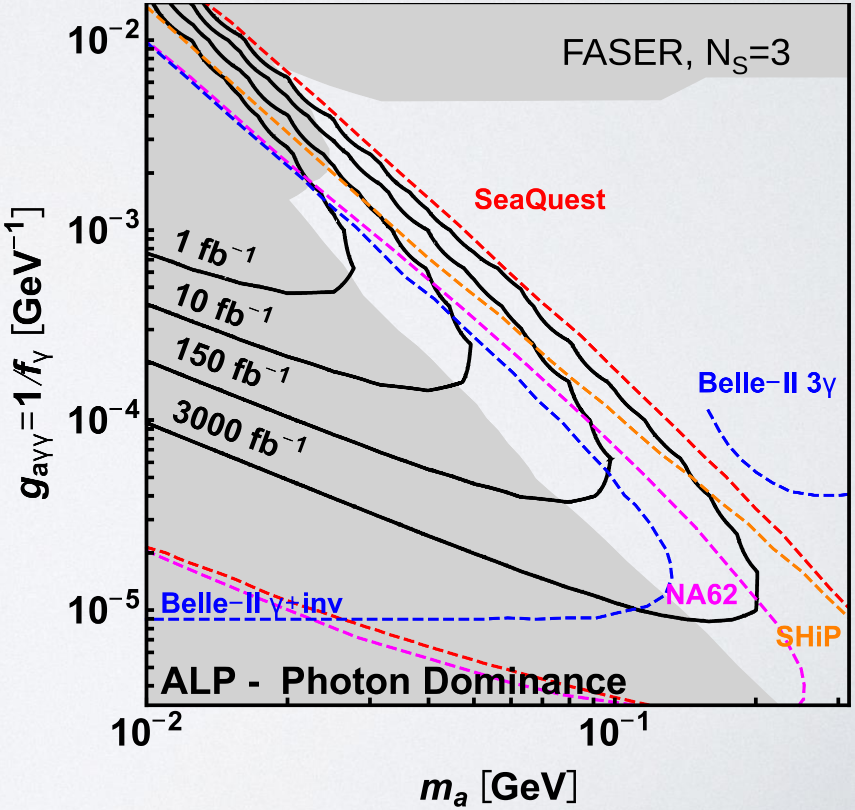
MORE FASER PHYSICS: ALPS WITH PHOTONS

- FASER can also discover ALPs and other LLPs produced not at the IP, but further downstream
- For example: ~TeV photon from IP collides with TA(X)N ~140 m downstream (between beams), creates Axion-Like Particle, which decays through a → γγ, detected in FASER calorimeters

- "Photon beam dump" or "light shining through walls"

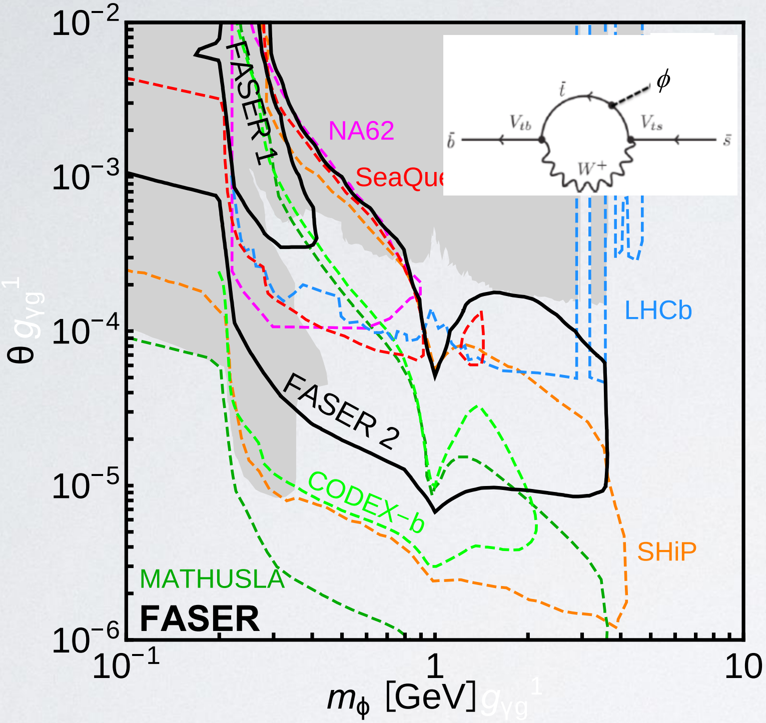






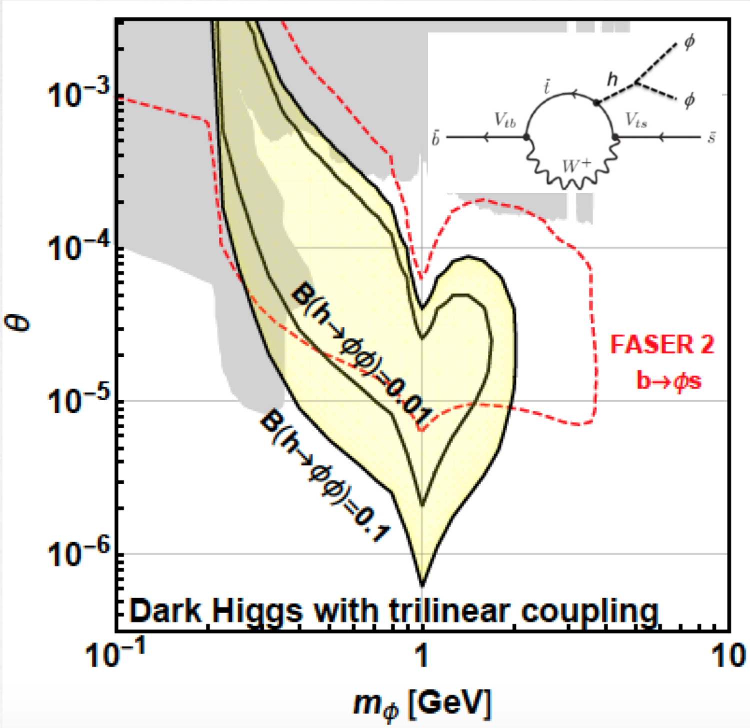
MORE FASER PHYSICS: DARK HIGGS BOSONS

- **SINGLE PRODUCTION**



- Dark Higgs produced in B decays. $N_B/N_\pi \sim 10^{-2}$ at FASER
  (cf. $N_B/N_\pi \sim 10^{-7}$ at beam dumps)
- Reach is complementary to other experiments

- **DOUBLE PRODUCTION**



Feng, Galon, Kling, Trojanowski (2017)

- Probes $h\phi\phi$ trilinear coupling
- Complementary to probes of exotic Higgs decays $h \rightarrow \phi\phi$
- FASER probes SM Higgs properties, exotic decays

1811.12522

PBC BENCHMARK SUMMARY

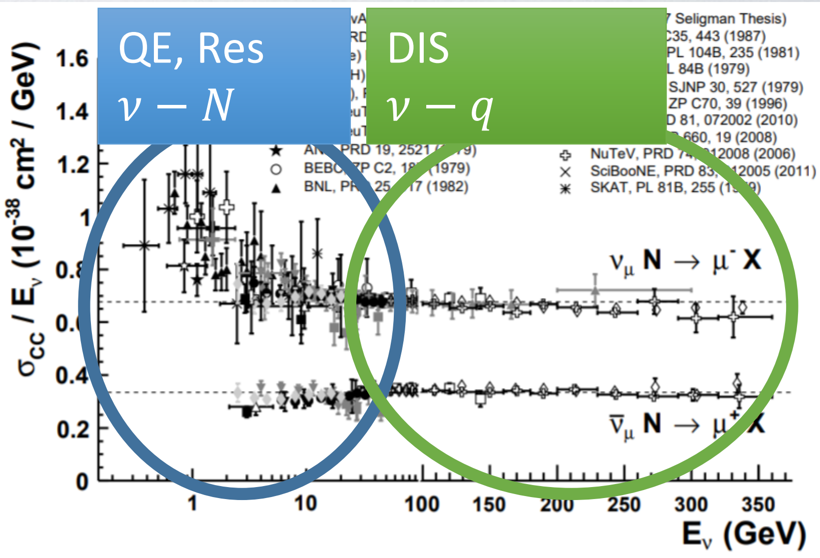
- FASER has a full physics program: can discover all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ, f, g); and examples that are not PBC benchmarks.

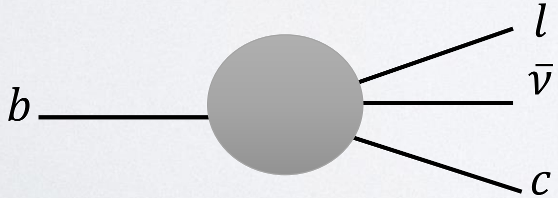
Benchmark Model	FASER 1	FASER 2	References
BC1: Dark Photon	√	√	Feng, Galon, Kling, Trojanowski, 1708.09389
BC1': $U(1)_{B\text{-}L}$ Gauge Boson	√	√	Bauer, Foldenauer, Jaeckel, 1803.05466; 1811.12522
BC2: Invisible Dark Photon	–	–	–
BC3: Milli-Charged Particle	–	–	–
BC4: Dark Higgs Boson	–	√	Feng, Galon, 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

Study of neutrino CC interaction with heavy quark production

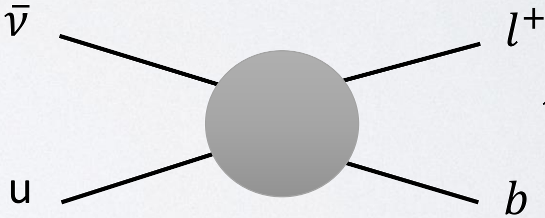
- Neutrino-quark scattering are basic tools to study interactions between leptons and quarks
  - Those in high energy (DIS regime) tell fundamental interactions between neutrinos and quarks
- Flavor physics with high energy neutrinos, ν_e, ν_μ, ν_τ and charm, beauty
- BSM search, e.g. flavor anomaly involving heavy leptons and quarks

Muon neutrino cross-sections (PDG)

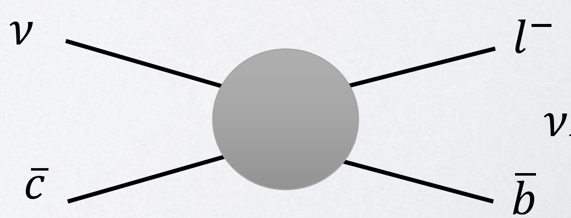




Anomalous b semi-leptonic decay



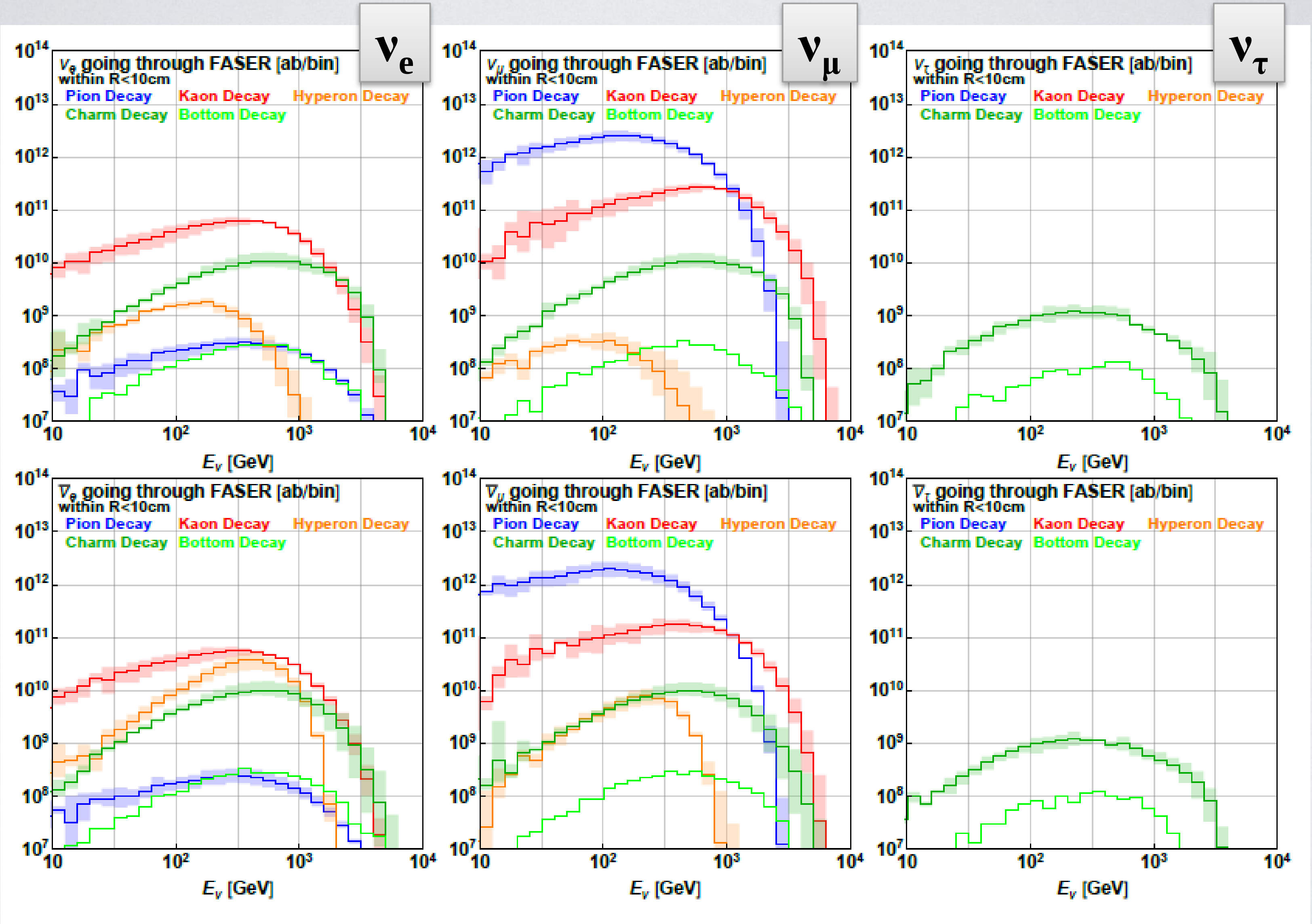
$\bar{\nu}N \to \ell\bar{B}X$



$\nu N \to \ell BDX$

ν CC b production

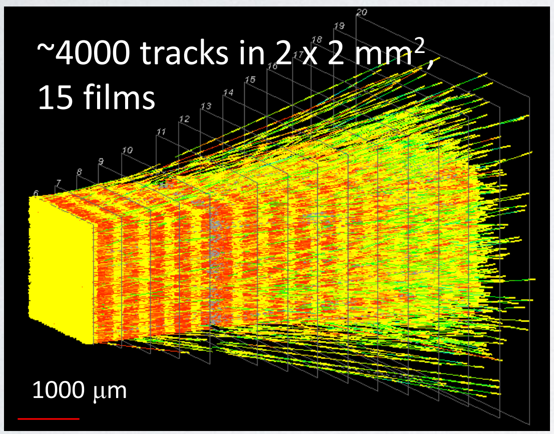
Neutrino fluxes at 14-TeV LHC



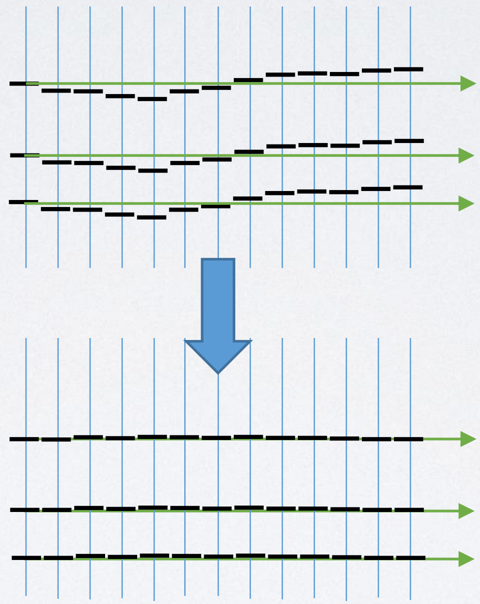
Shaded area: uncertainties from neutrino production rate corresponding to the range of predictions obtained from different Monte Carlo generators.

Angular resolution

Reconstructed tracks

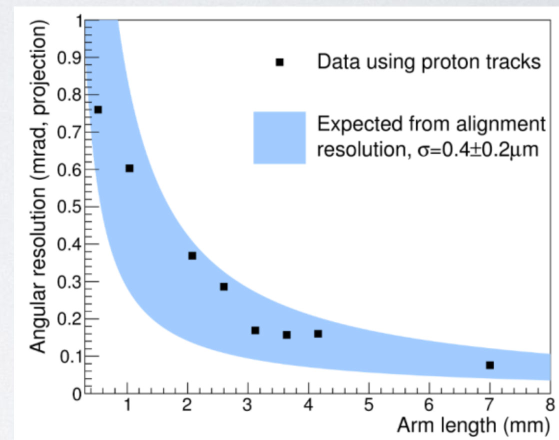


Align films with proton tracks (100 tracks/mm^2)



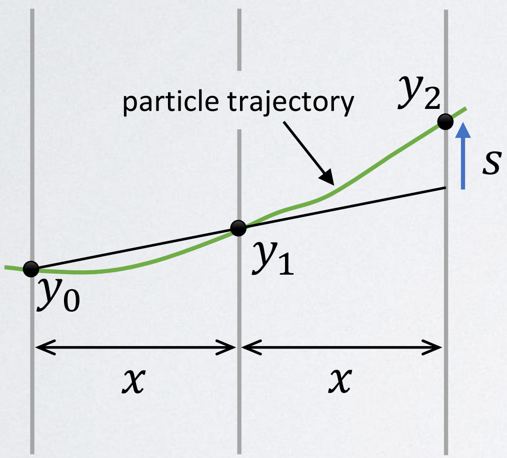
Residual of track segments to fitted line (RMS) $\simeq$**0.4 μm**

Angular resolution vs Track length

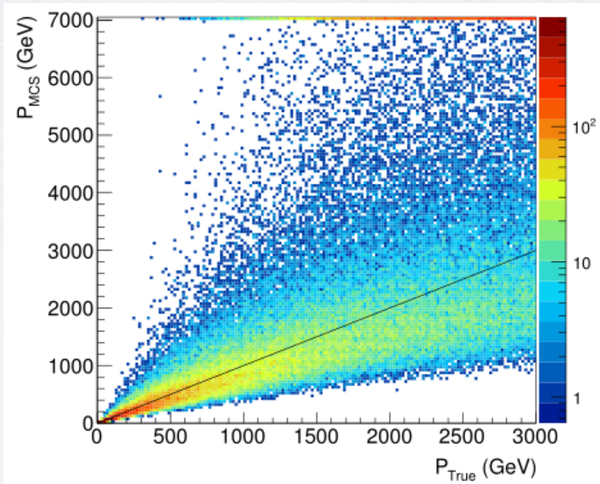


Particle momentum measurement by multiple Coulomb scattering (MCS)

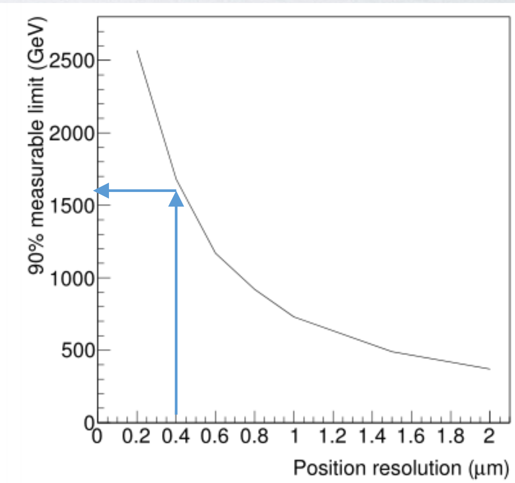
- Sub-micron precision alignment using muon tracks
  - Our experience = 0.4 μm (in the DsTau experiment)
- This allow to measure particle momenta by MCS, even above 1 TeV



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

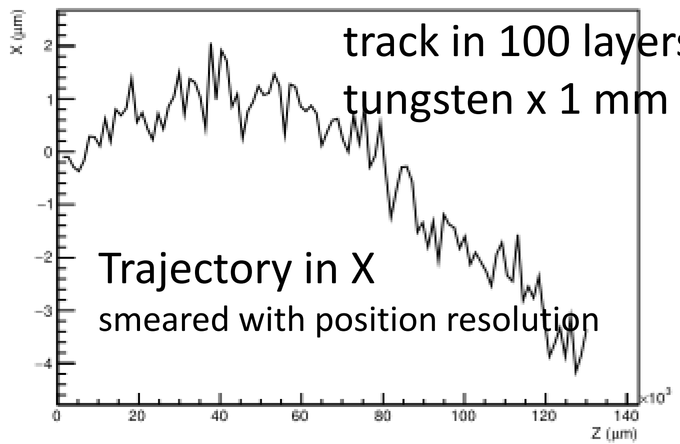


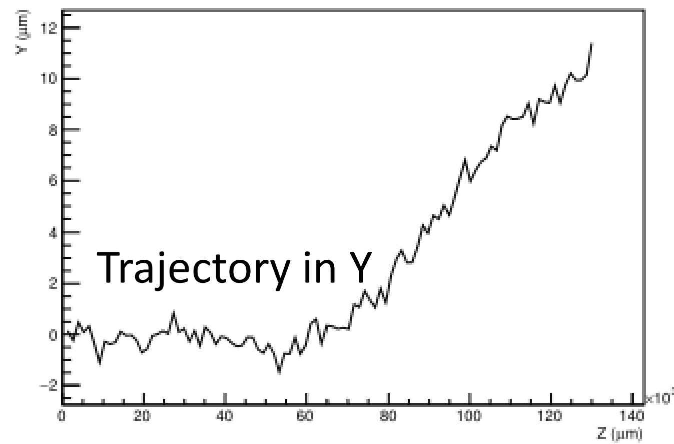
Performance with position resolution of 0.4 μm, in 100 tungsten plates (MC)

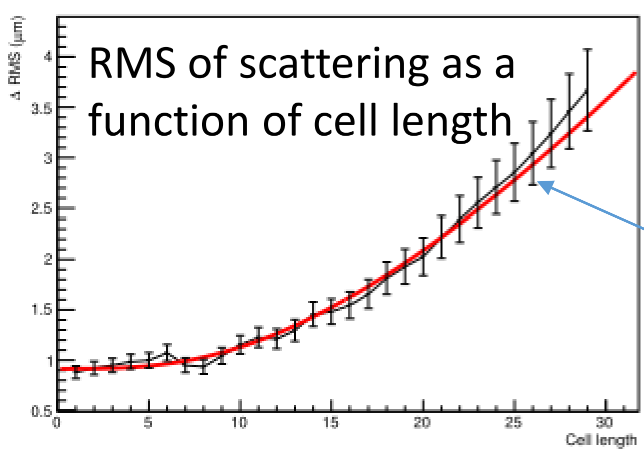


Measurable energy vs position resolution

Example of MCS and fit







Ptrue = 325.5

Preco = 367.1

Fitting result

$$F(P,\delta) = \sqrt{\left(\frac{0.0136}{P}\sqrt{\frac{2}{3}}x\sqrt{\frac{x}{X_0}}\right)^2 + \delta^2}$$

position resolution = 0.4 μm

High-energy EM shower in emulsion/lead chambers

Astrophys. J. 760 (2012) 146.

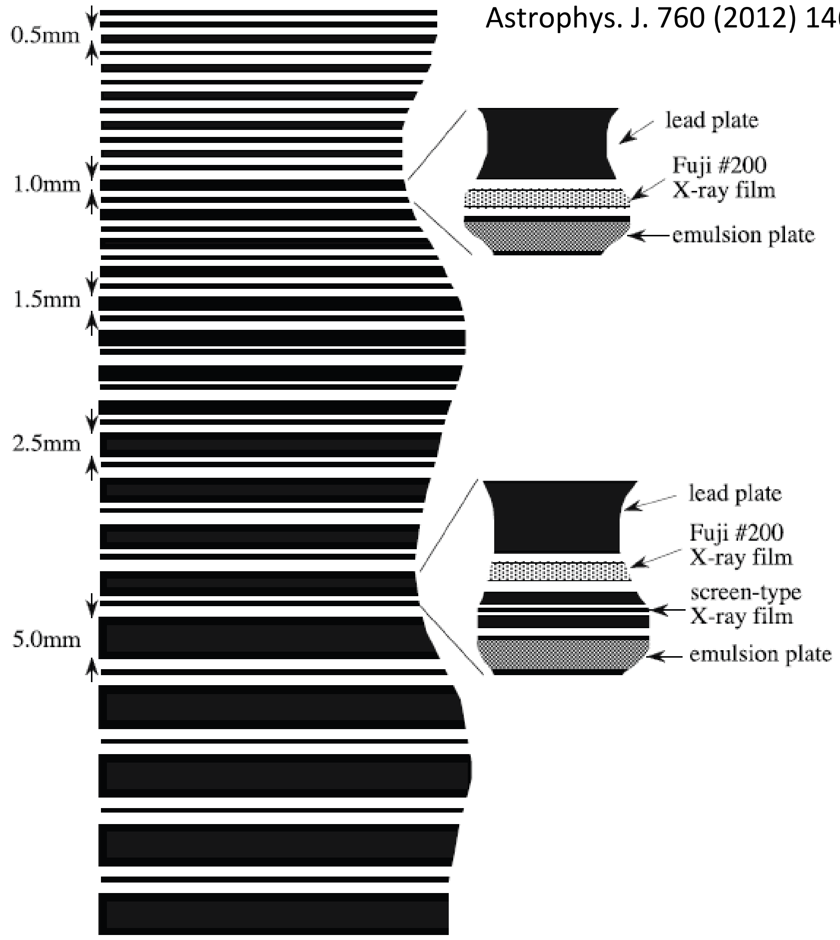


Figure 1. Typical configuration of the emulsion chamber in cross-sectional drawing from a side view.

Longitudinal development of the averaged number of shower tracks within a circle of radius 100 μm

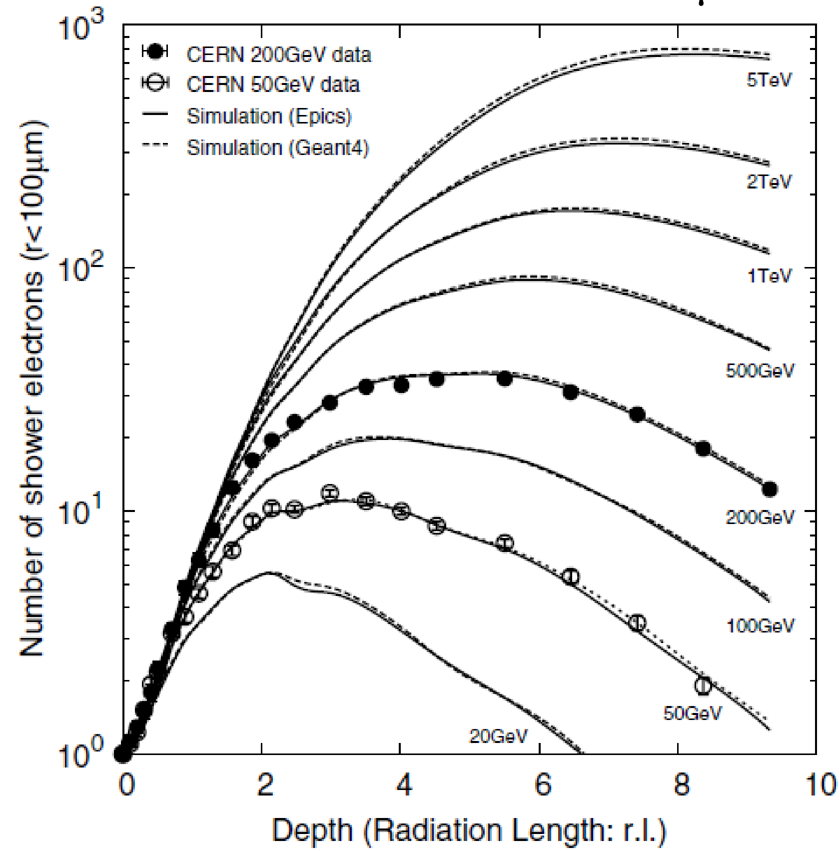


Figure 6. Longitudinal developments of the averaged number of shower tracks within a radius of 100 μm from the simulations compared to the experimental data.

Energy resolutions 10.6% at 200 GeV