Looking forward to LHC Neutrinos with FASER

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Fermilab

SLAC NATIONAL ACCELERATOR LABORATORY

HEISING-SIMONS FOUNDATION

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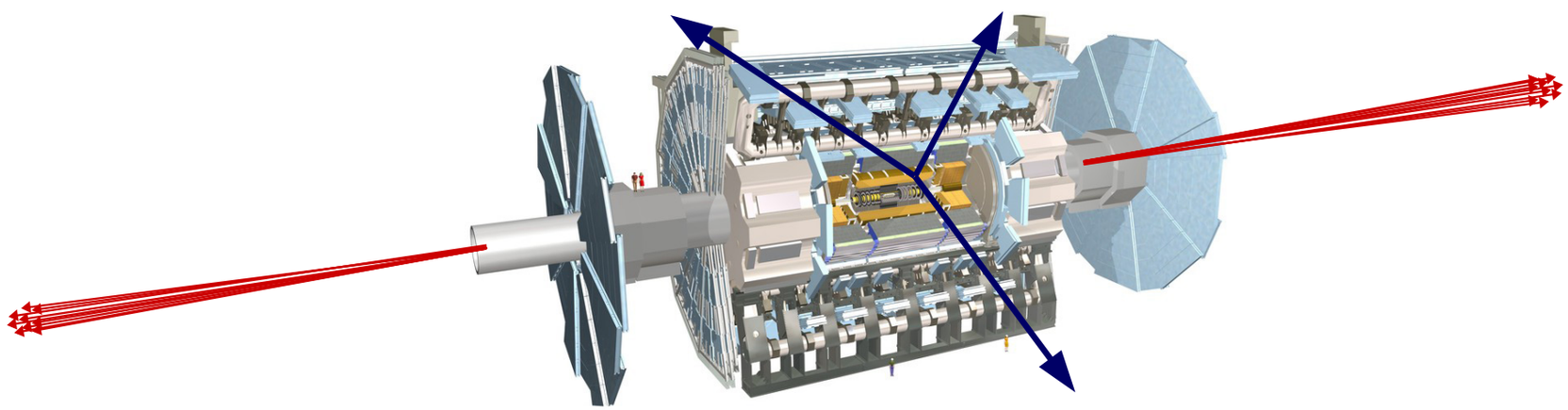
Motivation and Idea

- LHC searches/experiments focus on **central region**, which is motivated by heavy, strongly interacting particles
  * small rates: σ ~ fb - pb or $N_H \sim 10^7$ at $\mathcal{L} = 300\ \mathrm{fb}^{-1}$
  * high pT, produced ~ isotropical



- For light and weakly interacting particles, this may be completely misguided
  * light: we can produce them in π, K, D, B decays
  * weakly-interacting: need extremely large SM event rate to see them

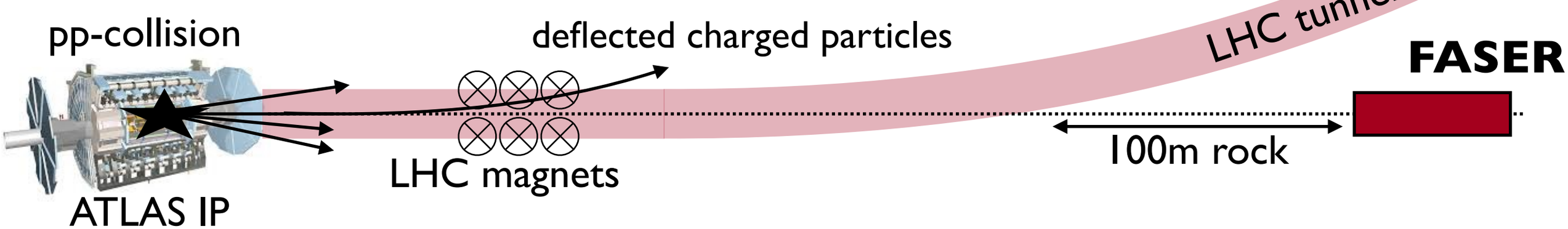
- We should go where the pions are: **forward region** along the beam line
  * enormous event rates: σ_{inel} ~ 100mb or $N_\pi \sim 10^{17}$ at $\mathcal{L} = 300\ \mathrm{fb}^{-1}$
  * highly energetic beam remnants: E ~ TeV
  * low pT ~ Λ_{QCD} → particles are collimated θ ~ Λ_{QCD}/E ~ mrad

Motivation and Idea

- We can't place a reasonably-sized detector on the beam line near the IP
  * blocks the proton beams, subject to large radiation

- However, weakly-interacting particles do not interact with matter
  → place detector few 100m away along the "collision axis" after beam curves
  * LHC infrastructure acts and rock act as shielding

- At this location, particles are still highly collimated
  * 100m x mrad ~ 10cm spread in transverse plane



- This motivates small, fast and cheap inexpensive detector
  FASER: Forw**A**rd **S**earch **E**xpe**R**iment at the LHC

- Applications for light long-lived particles searches and neutrinos

Outline

The FASER Experiment

Location / Detector / Environment / Timeline

Long-Lived Particle Searches

Dark Photons

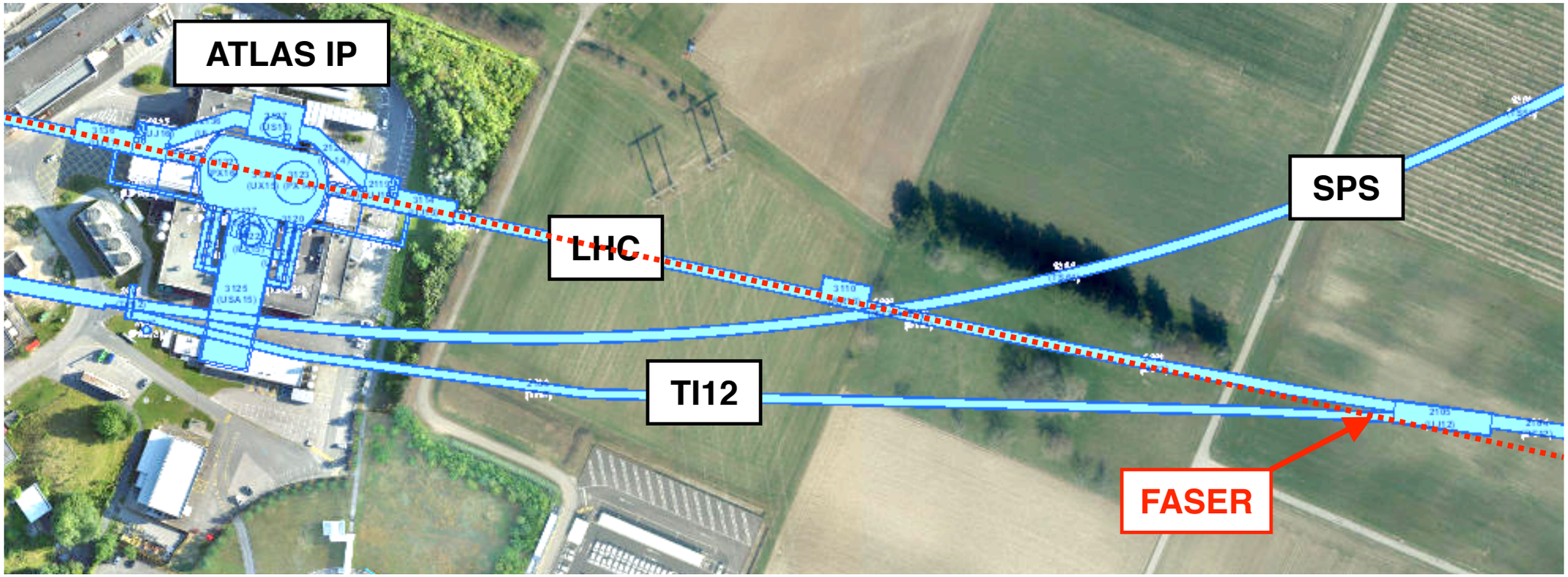
Neutrino Physics

FASERν / Neutrino Measurements

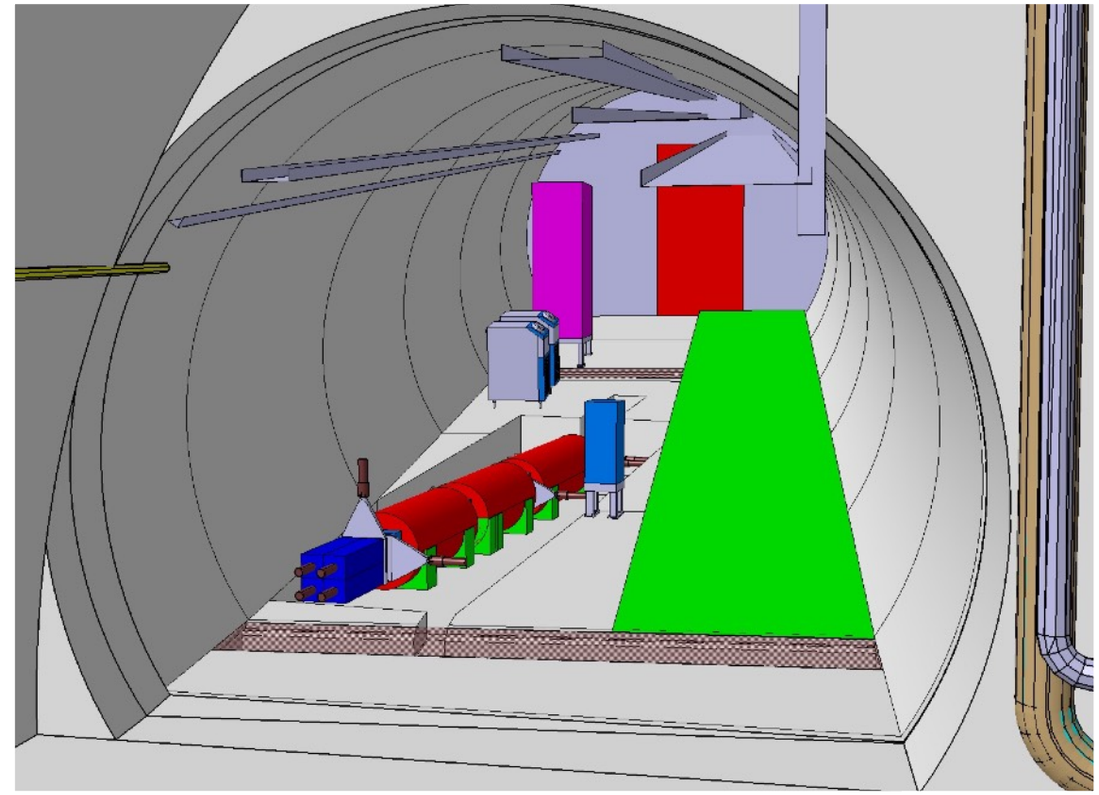
Summary and Conclusion

The FASER experiment

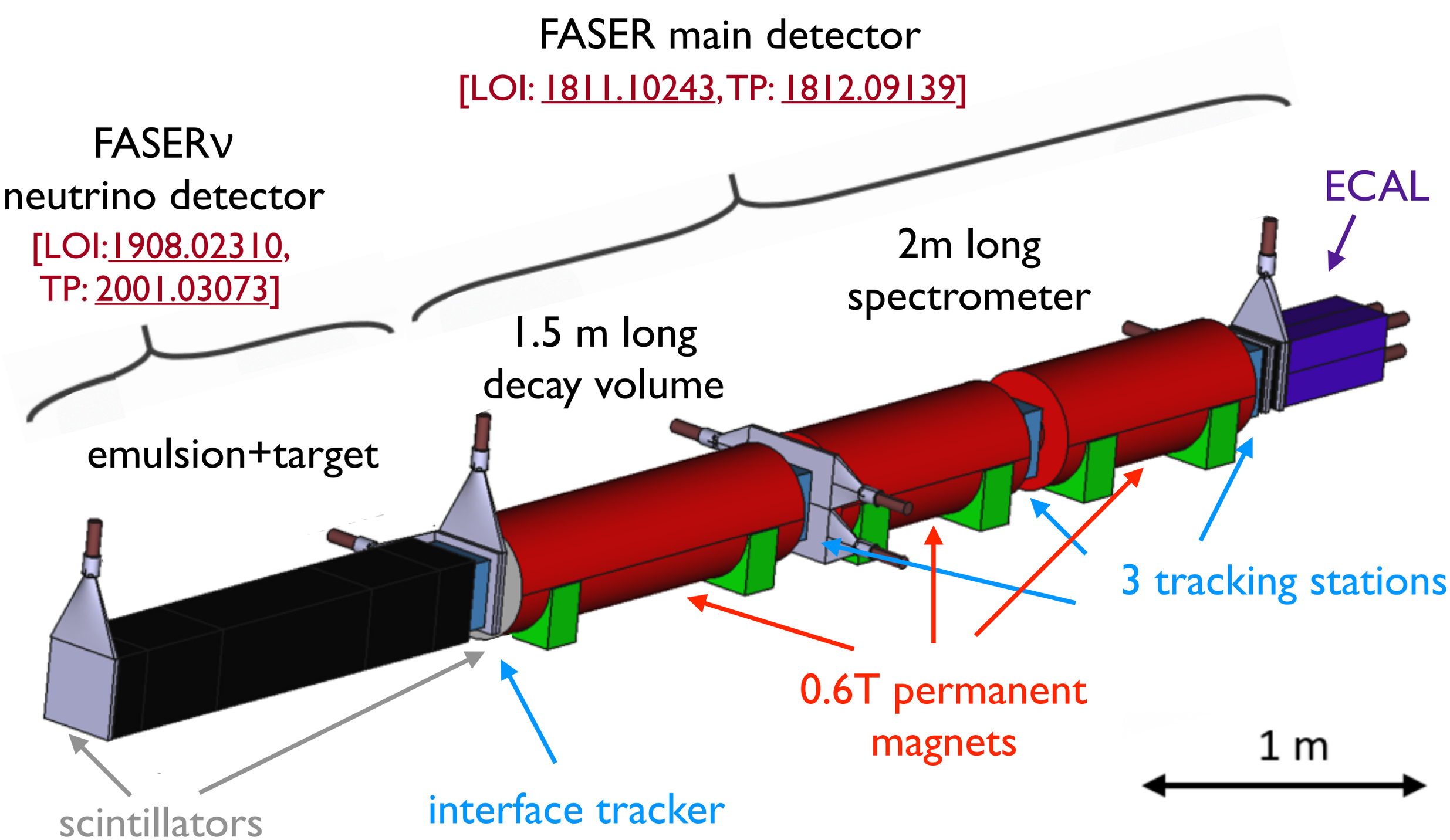
Location



FASER Location



FASER Detector



FASER Environment

General Considerations

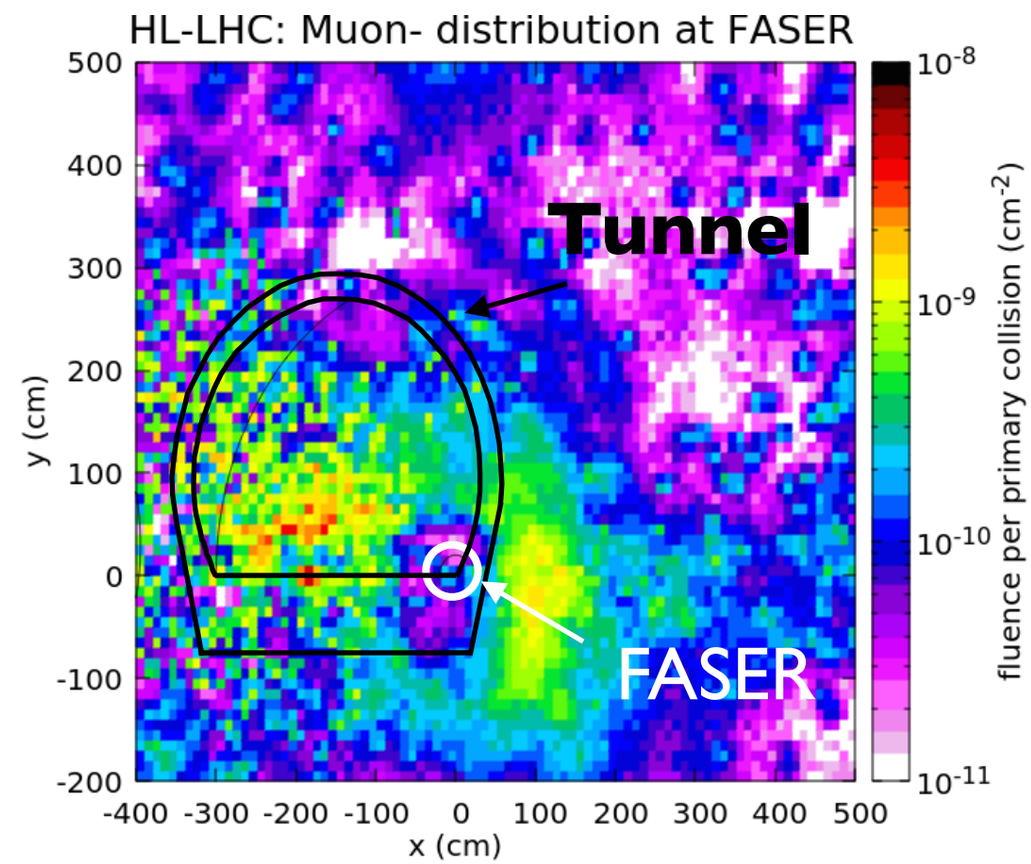
- FASER's location is very quiet
- shielded by 100m of rock / magnets
- only muons/neutrino can transport TeV energies through ~100m rock

FLUKA simulation

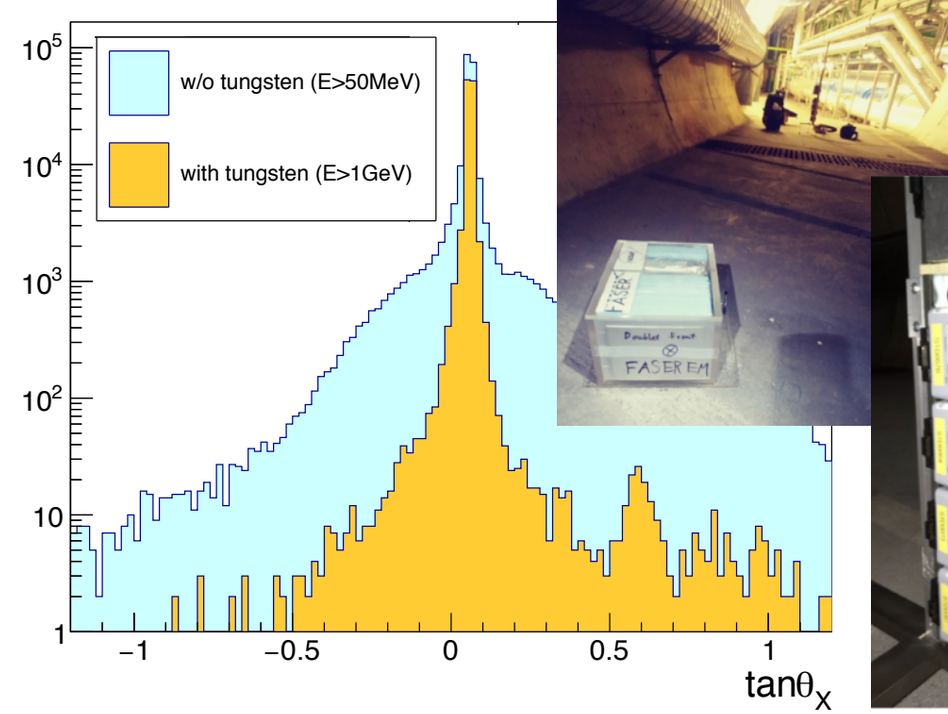
- performed by CERN STI group
- estimated muon flux: $2 \cdot 10^4$ fb/cm^2
  * use scintillator to veto muons
  * FASER is in 'shadow' of LHC magnets
- other HE particles produced in muon radiative processes
- no HE particles from beam-gas collisions and showers in dispersion suppressor

2018 in situ measurements

- emulsion detector: charged particle flux agrees with FLUKA simulation
- BatMon: low radiation levels close to FASER



abate-Gilarte, Cerutti, Tsinganis (2018)



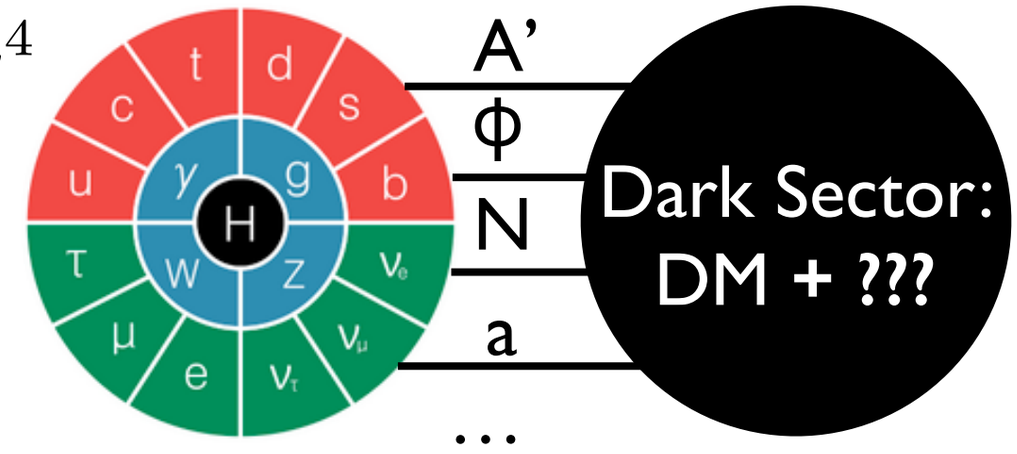
Long Lived Particles Searches at FASER

Idea: 1708.09389
LOI: 1811.10243
TP: 1812.09139
Physics: 1811.12522

Long Lived Particles at FASER

Motivation

- Dark matter solid evidence for new particles
  - * thermal freeze out: $\Omega_{DM} \sim 1/\langle \sigma v \rangle \sim m^2/g^4$
  - * WIMP miracle: $m \sim m_{weak}, \; g \sim g_{weak}$
  - * light DM (m~GeV) requires new mediators
    - → $m < m_{weak}, \; g < g_{weak}$
    - → light weakly coupled particles
- Anomalies: muon g-2, Be-8, KOTO, …



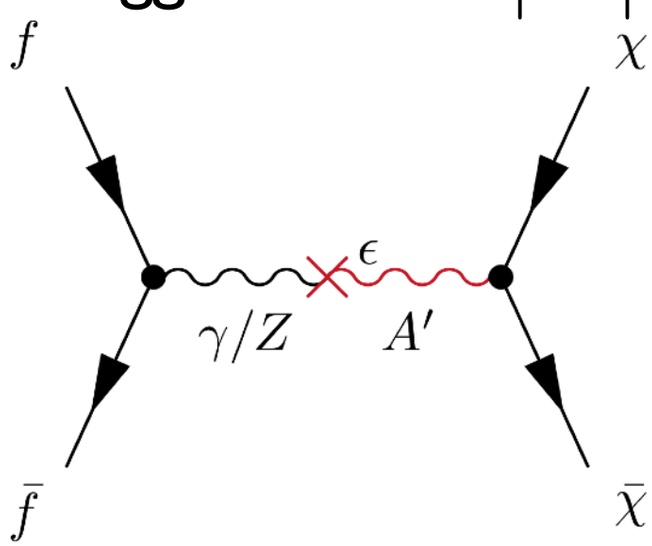
Prominent examples

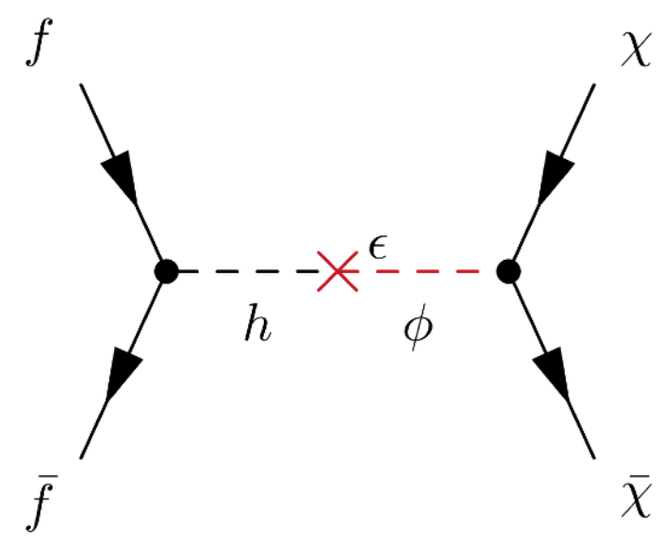
Dark Photon Portal: $\epsilon F^{\mu\nu} F'_{\mu\nu}$

Dark Higgs Portal: $\epsilon |H|^2 \phi^2$

Neutrino Portal: $y L H N$

Axion Portal: $g a F^{\mu\nu} \tilde{F}_{\mu\nu}$





Long Lived Particles at FASER

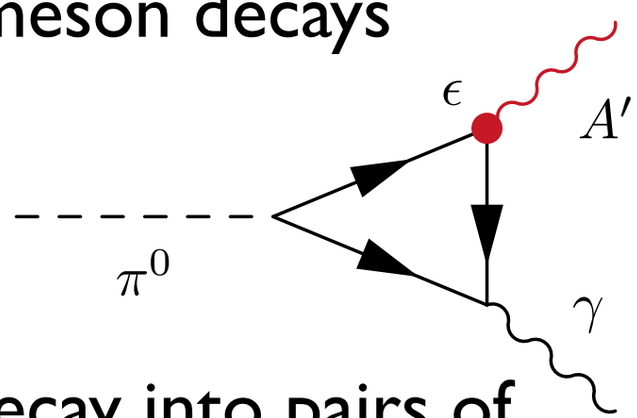
Dark Photons

- similar to the SM photon but
  * massive, with mass $m_{A'}$
  * couplings to SM particles suppressed by ε

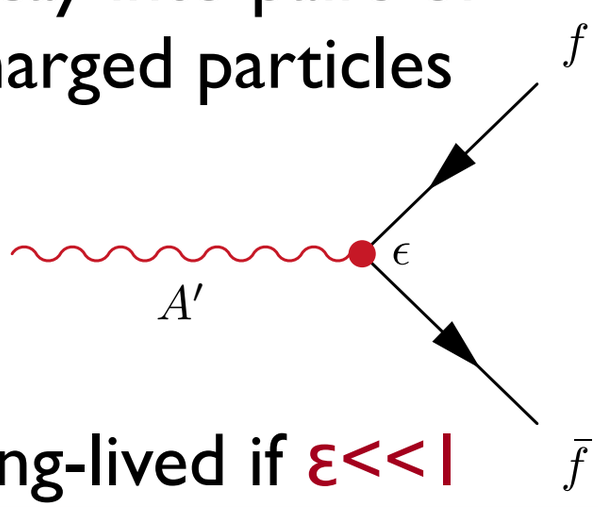
$$\mathcal{L} = \frac{1}{2} m_{A'}{}^2 A'_\mu A'^\mu + \sum \bar{f}(i\,\partial\!\!\!/ - \epsilon e q_f A\!\!\!/')f$$

Dark Photons at FASER

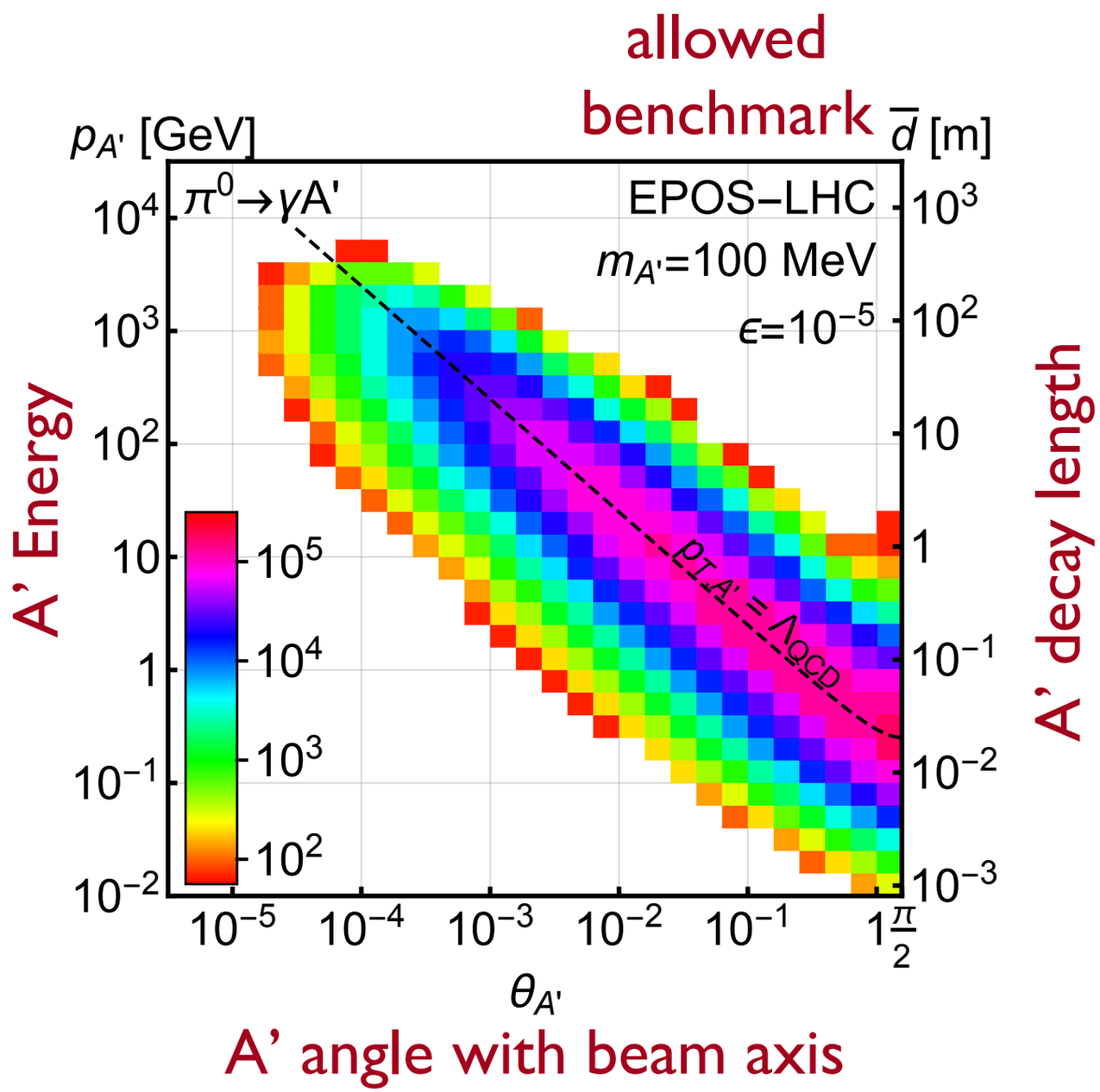
- produced for example in meson decays



- decay into pairs of charged particles



- long-lived if $\varepsilon << 1$



Long Lived Particles at FASER

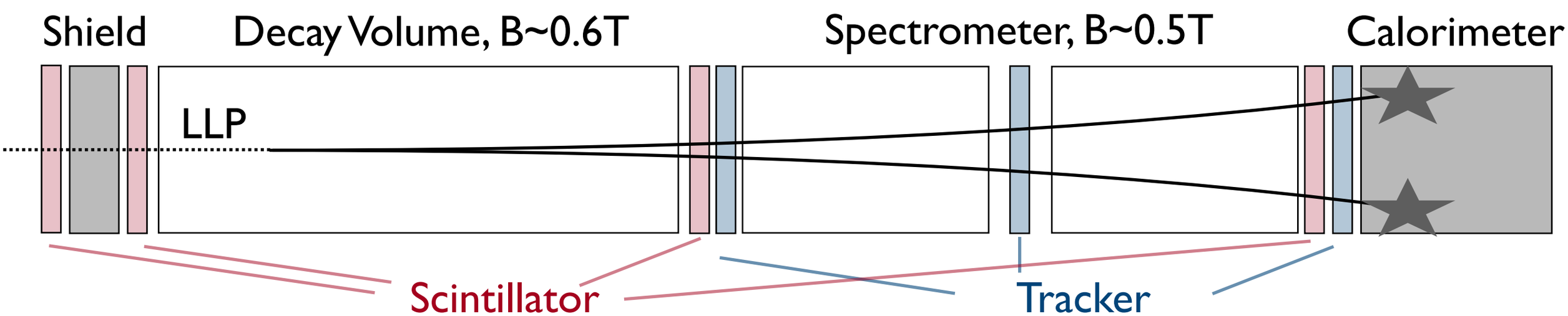
pp→LLP + X, LLP travels ~ 480m, LLP→charged tracks + X

Signal is striking

- two opposite-sign, high energy (E > 500 GeV) charged particles
- originate from a common vertex in a small, empty decay volume
- point back to the IP through 90 m of rock

Background considerations

- comic rays and neutrino interactions (different kinematics) not a problem
- HE muon-associated radiative events are leading BG if muon is not vetoed
- incoming muons can be identified using scintillators
  → reduce BG to negligible levels

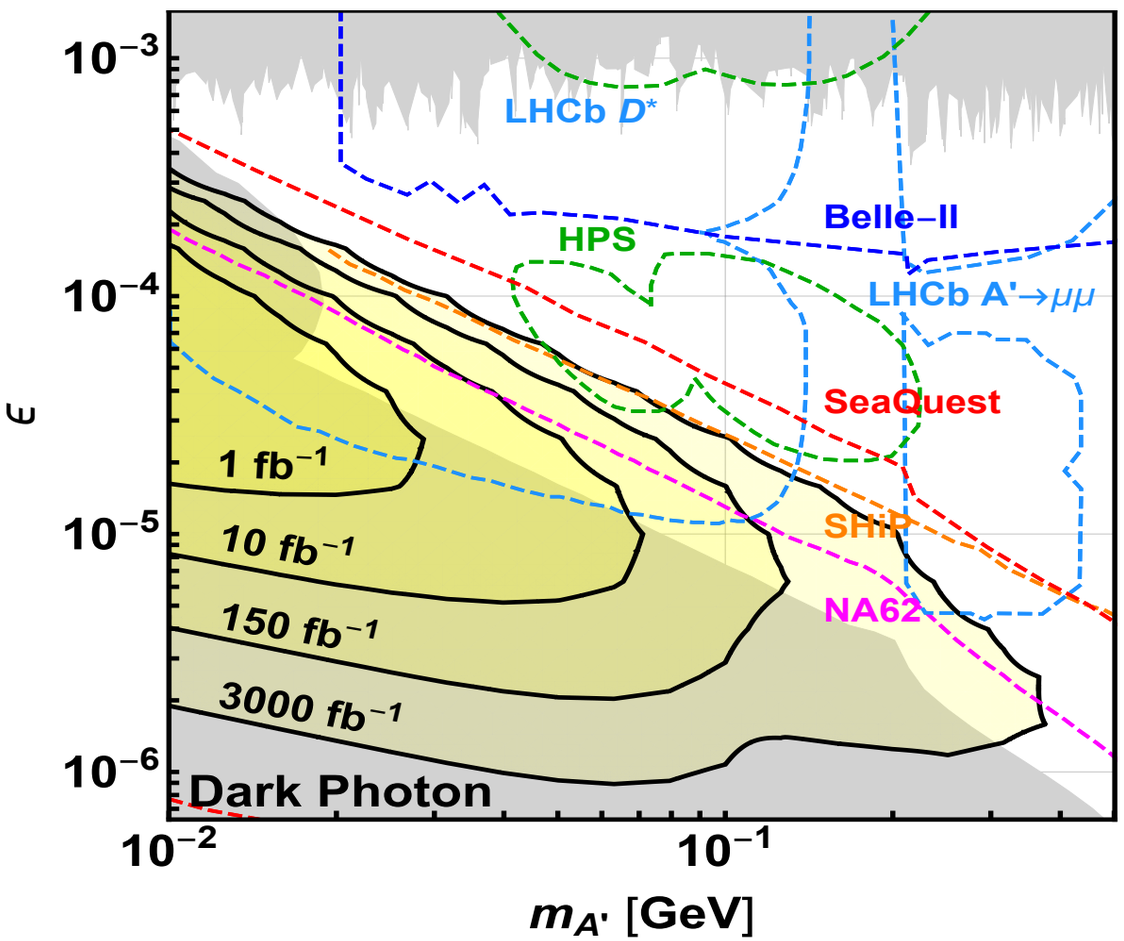


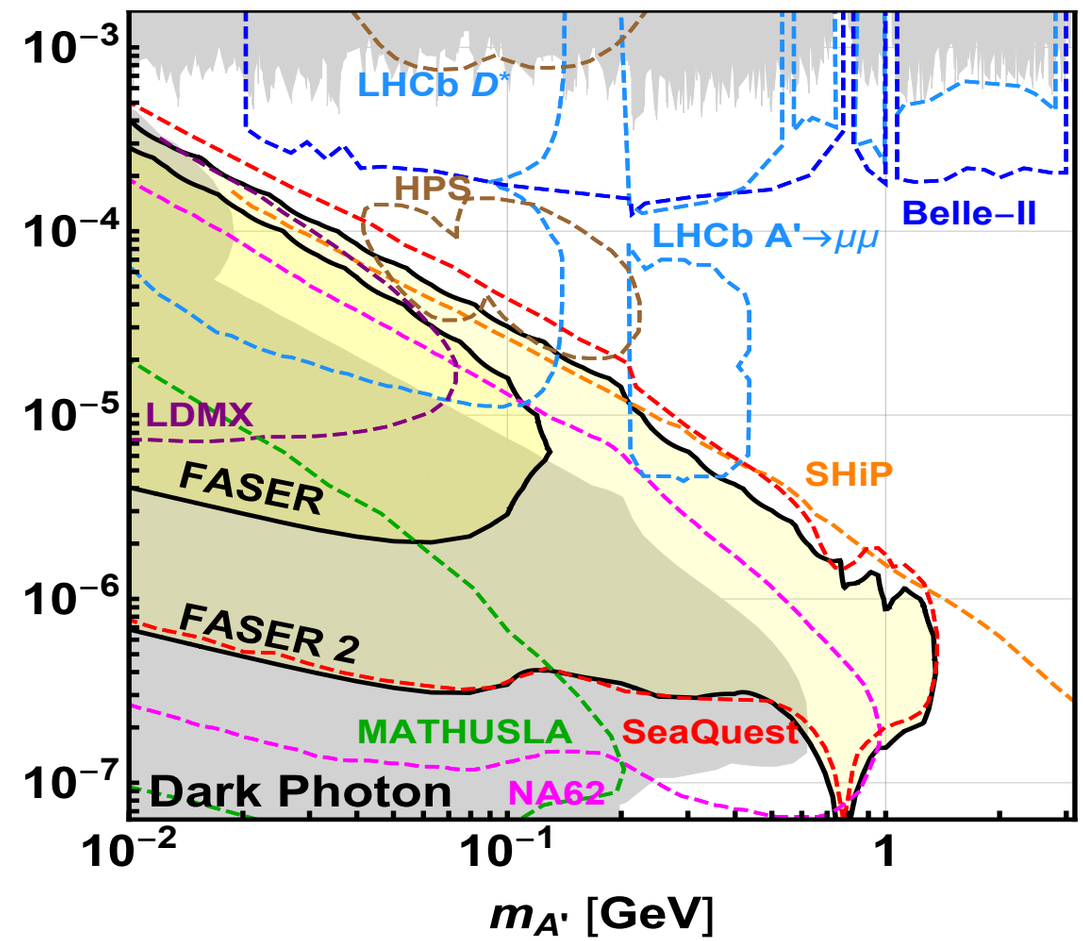
Long Lived Particles at FASER

Dark Photon Reach

- consider all production channels
- include A' → ee, μμ, $\pi^+\pi^-$
- require N=3 events

- two detector benchmarks
  * FASER: R=10cm, L=1.5m, Run3
  * FASER 2: R=1m, L=5m, HL-LHC



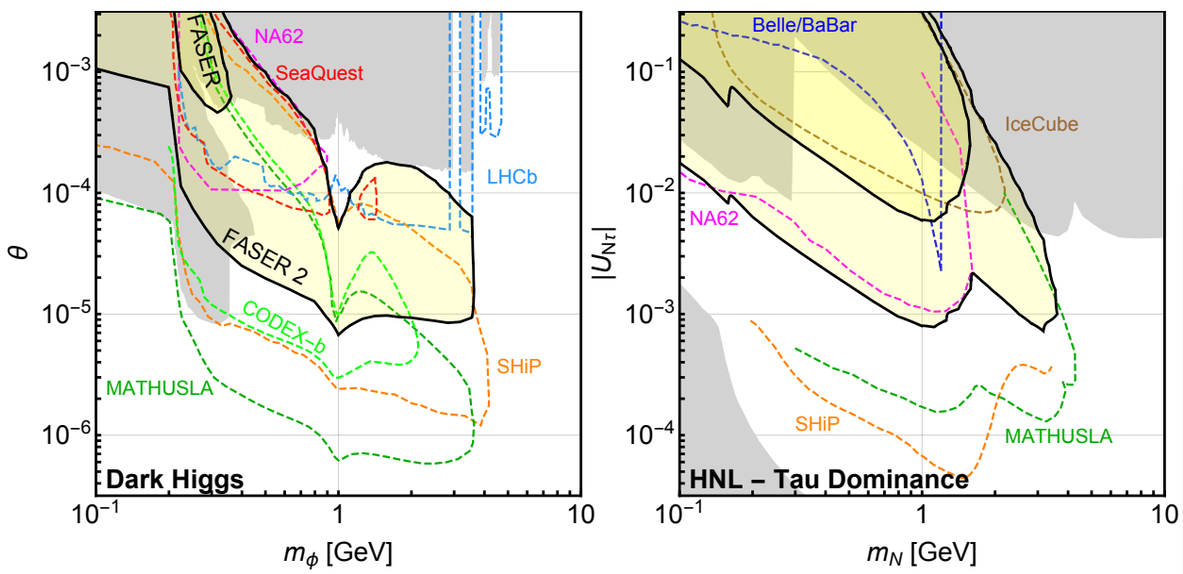


- reach limited by decay length (high ε) and production rate (low ε)
- new parameter space probed with just 1 fb^{-1} in 2021
- FASER 2 significantly improves reach at higher masses

Long Lived Particles at FASER

Physics Sensitivity Studies

- FASER is sensitive to many more LLP models
- FASER Physics Case: 1811.12522



Benchmark Model	Label	Section	PBC	Refs	FASER	FASER 2
Dark Photons	V1	IV A	BC1	[7]	√	√
$B-L$ Gauge Bosons	V2	IV B	—	[30]	√	√
$L_i - L_j$ Gauge Bosons	V3	IV C	—	[30]	—	—
Dark Higgs Bosons	S1	V A	BC4	[26, 27]	—	√
Dark Higgs Bosons with hSS	S2	V B	BC5	[26]	—	√
HNLs with e	F1	VI	BC6	[28, 29]	—	√
HNLs with μ	F2	VI	BC7	[28, 29]	—	√
HNLs with τ	F3	VI	BC8	[28, 29]	√	√
ALPs with Photon	A1	VII A	BC9	[32]	√	√
ALPs with Fermion	A2	VII B	BC10	—	—	√
ALPs with Gluon	A3	VII C	BC11	—	√	√
Dark Pseudoscalars	P1	VIII	—	[36]	—	√

- Many other studies related to FASER on FASER website: https://faser.web.cern.ch/

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20. R. Maciula, A. Szczurek, Intrinsic charm in the nucleon and charm production at large rapidities in collinear, hybrid and kT-factorization approaches
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Neutrino Measurements at FASER

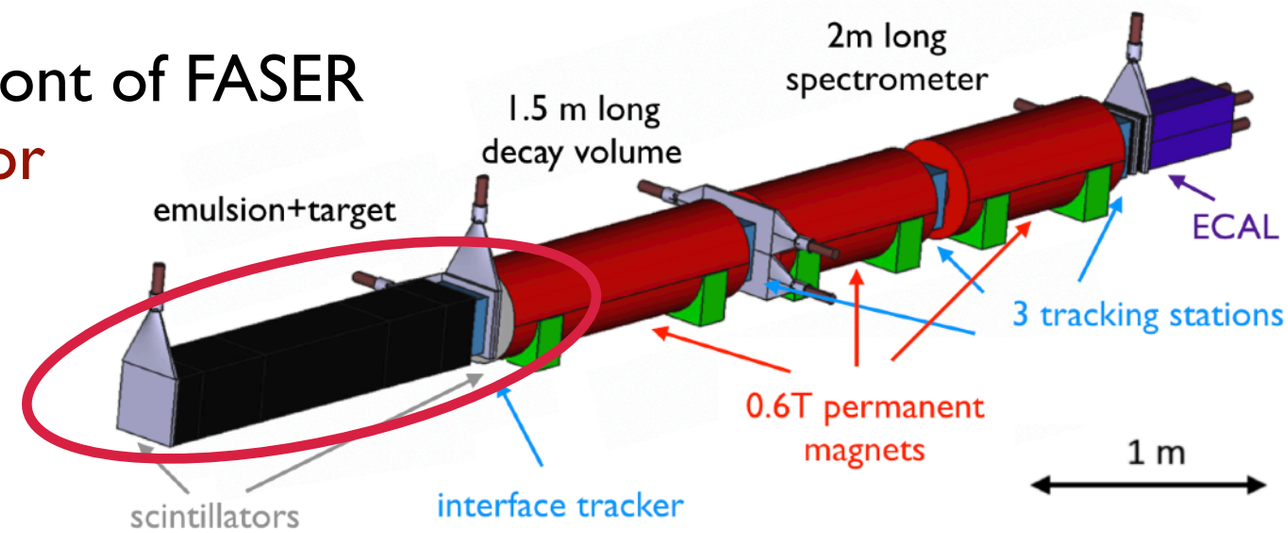
Idea/LOI: 1908.02310
TP: 2001.03073

FASERν Motivation

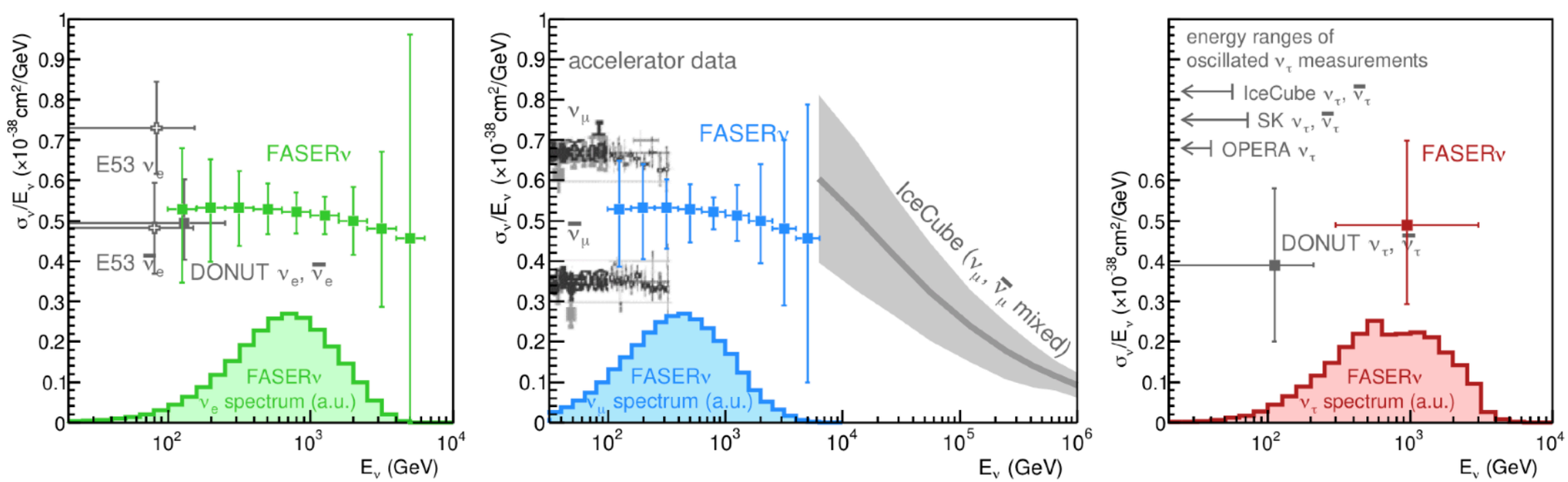
- neutrinos detected from many sources, but not from colliders

- many neutrinos at LHC produced in π, K, D meson decay
  → ATLAS provides intense highly collimated neutrino beam towards FASER
    * ~10^{12} neutrino in LHC Run 3 * highly collimated * E~TeV

- dedicated FASERν neutrino detector in front of FASER
  * 25cm x 25cm x 1.3m emulsion detector
  * tungsten target with 1.2 ton mass
  * ~ 20000 ν_μ, ~ 2000 ν_e, ~ 20 ν_τ during LHC Run 3



- neutrino physics at TeV energies
  * probe unconstrained neutrino cross sections at TeV for all 3 flavors

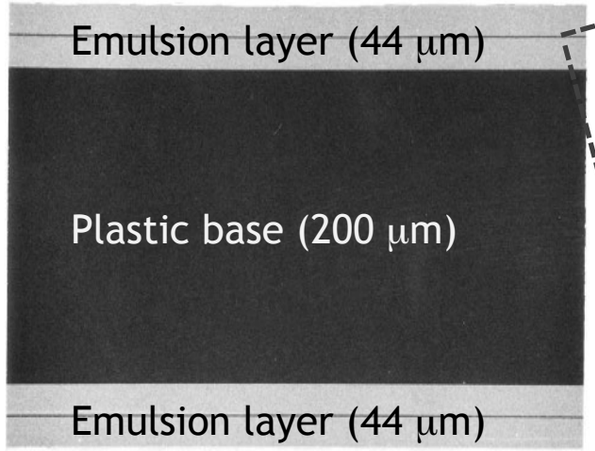


FASERν Detector

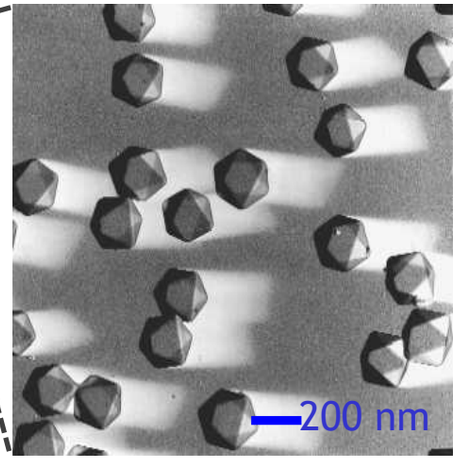
- emulsion detectors technology
  * used by many other neutrino experiments: CHORUS, DONUT, OPERA

Emulsion film

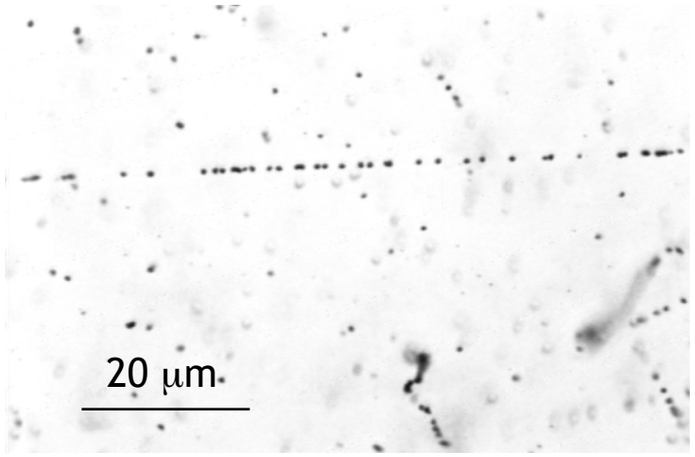
Cross-sectional view



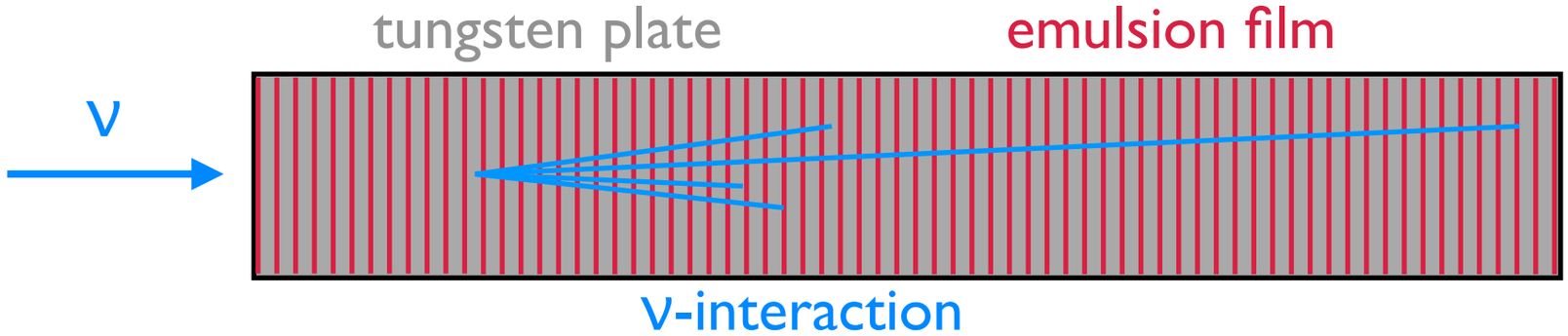
AgBr crystal

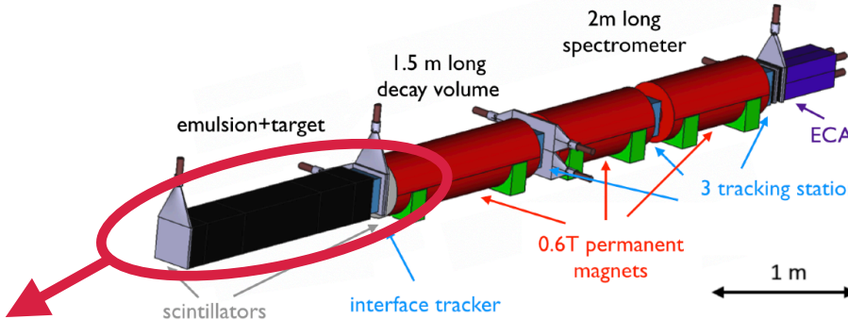


Track in emulsion film

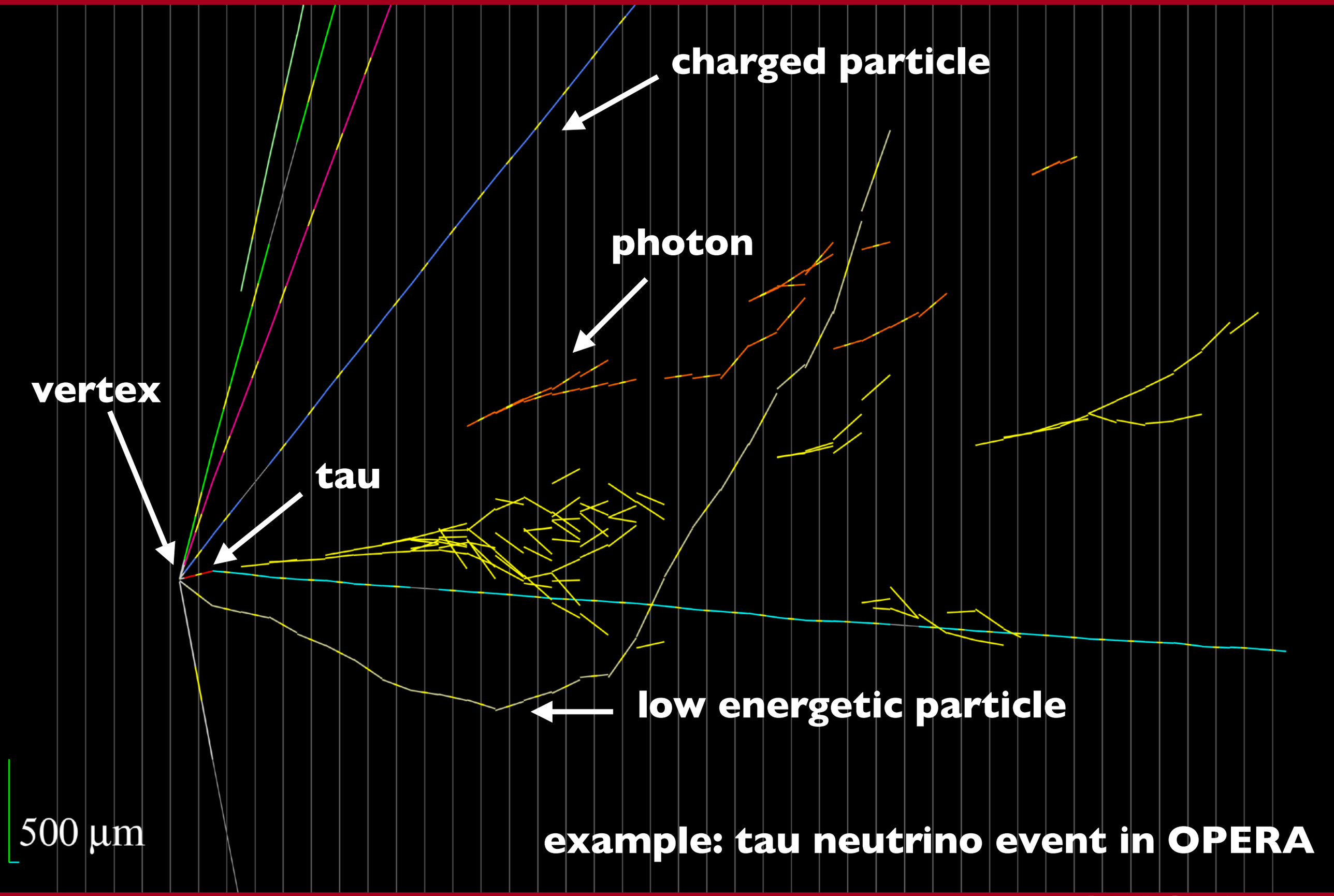


- FASERν: 1000 emulsion films interleaved with 1mm tungsten plates
  * 3D tracking devices with 50 nm spatial precision
  * sensitive to neutrino interactions
  * allows particle identification





FASERν Detector

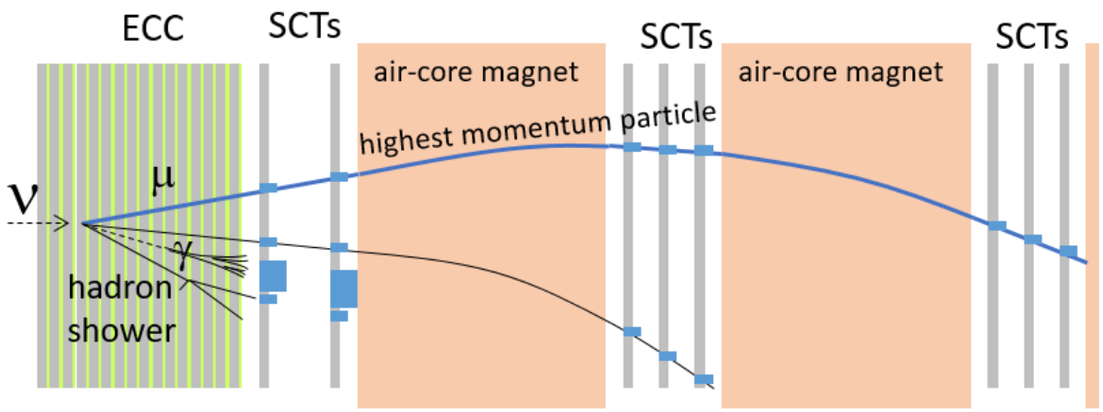


example: tau neutrino event in OPERA

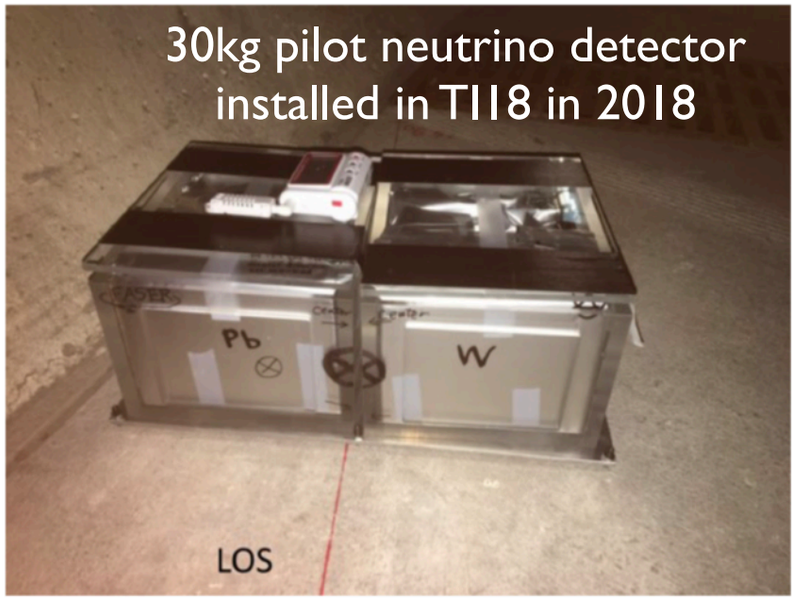
FASERν Detector

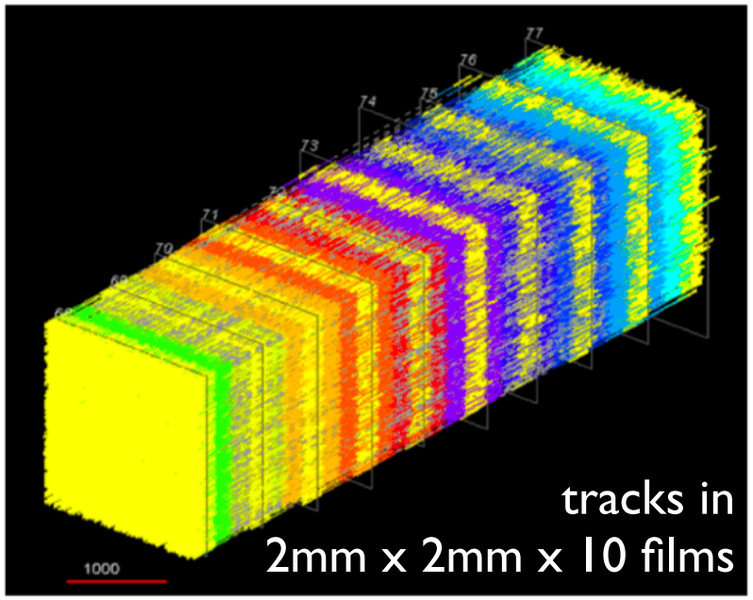
- detector performance has been studied
  * flavor identification
  * vertex finding efficiency: ~80%
  * energy resolution: ~30%

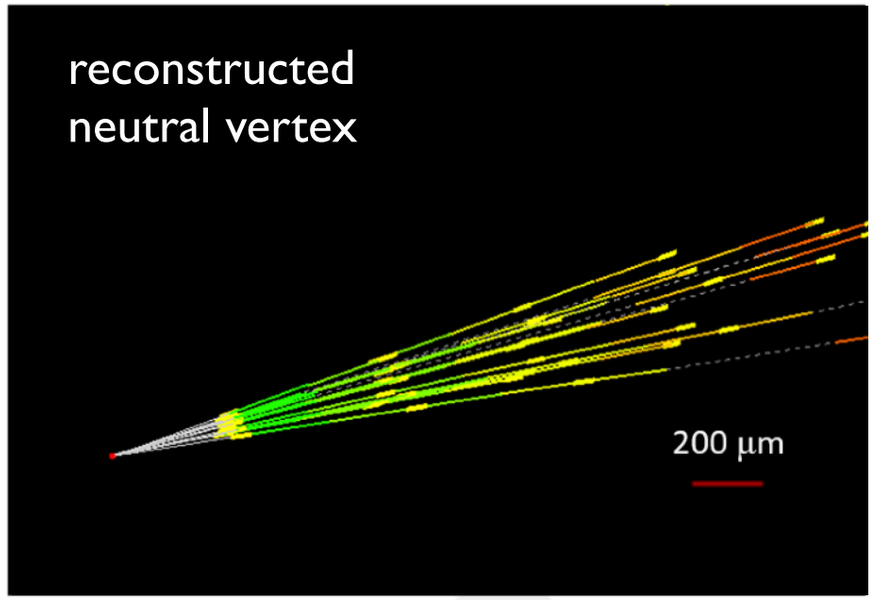
- global reconstruction with the FASER detector
  * distinguish neutrino / anti-neutrino
  * improve neutrino energy reconstruction
  * background rejection



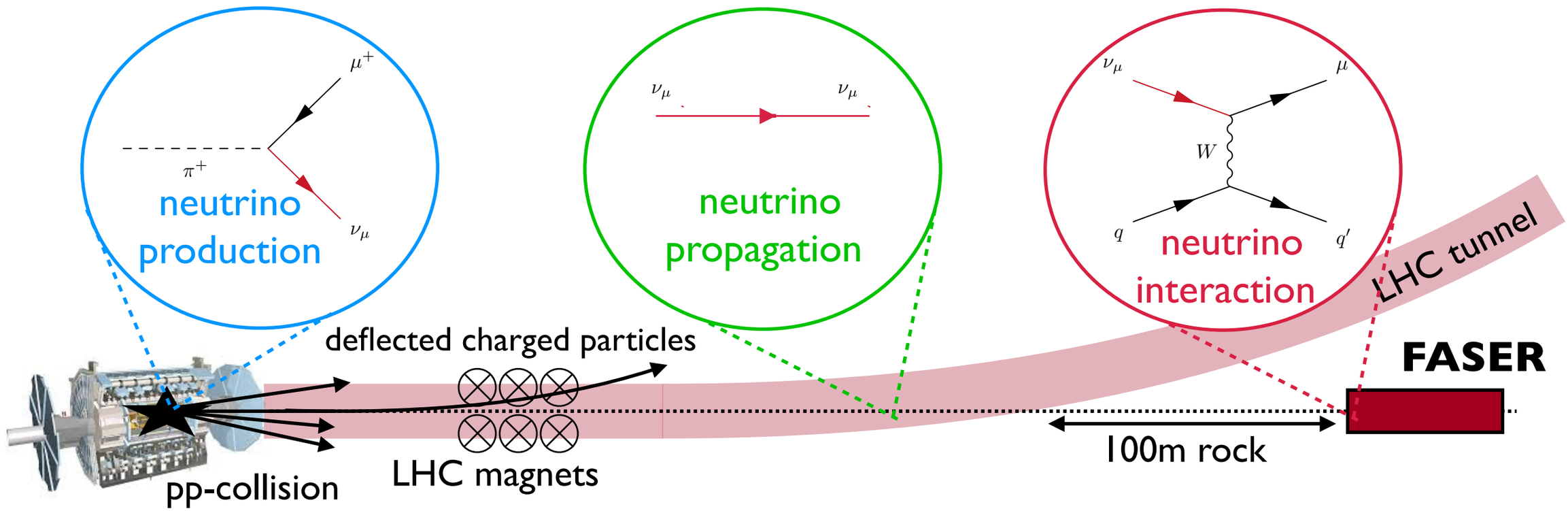
- pilot detector data is currently analyzed
  * 30 kg detector was installed in TI18, 12.5 fb^{-1} of data collected 2018
  * goal: first neutrino detection at the LHC







FASERν Physics Potential

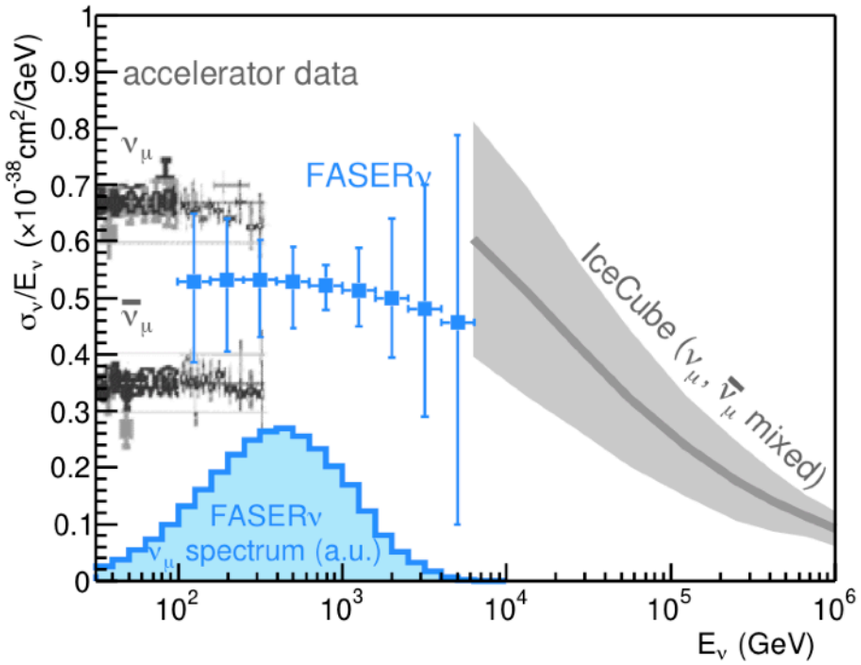


In the following, I will present some ideas.

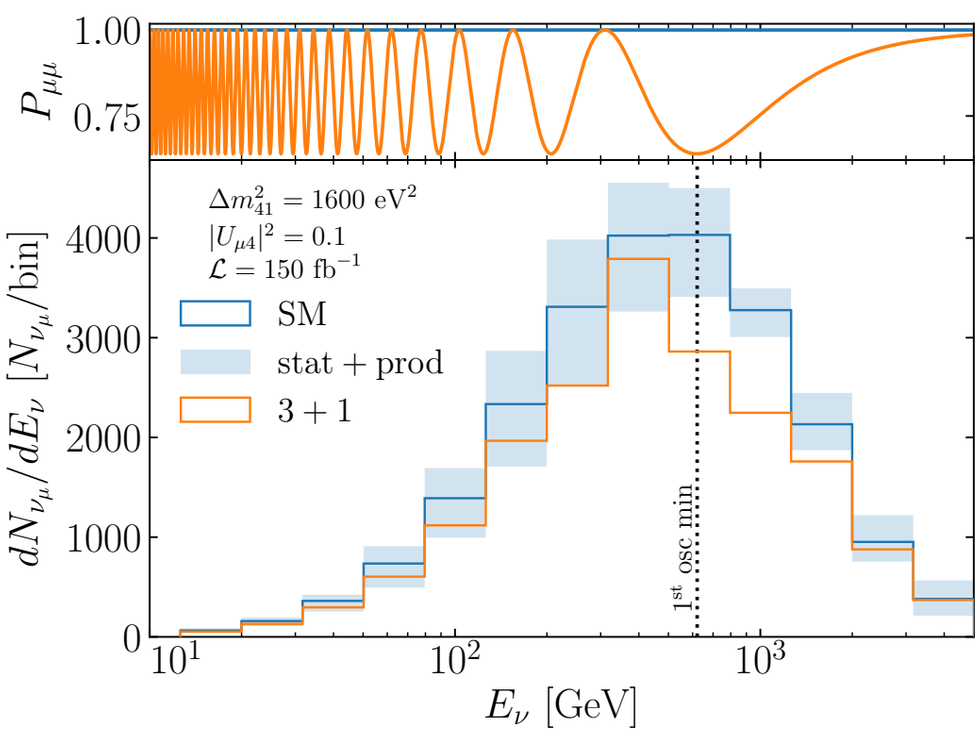
Most of them were not investigated in detail yet.

FASERν Physics Potential: Neutrino Physics

FASERν will measure neutrino cross section at unexplored TeV energies for all three flavors. Both CC and NC are possible.



FASERν will detect ~10 tau neutrino interactions, which is similar to DONuT and OPERA. Thousands of tau neutrino events possible at HL-LHC, allowing for precision studies of tau neutrino properties.

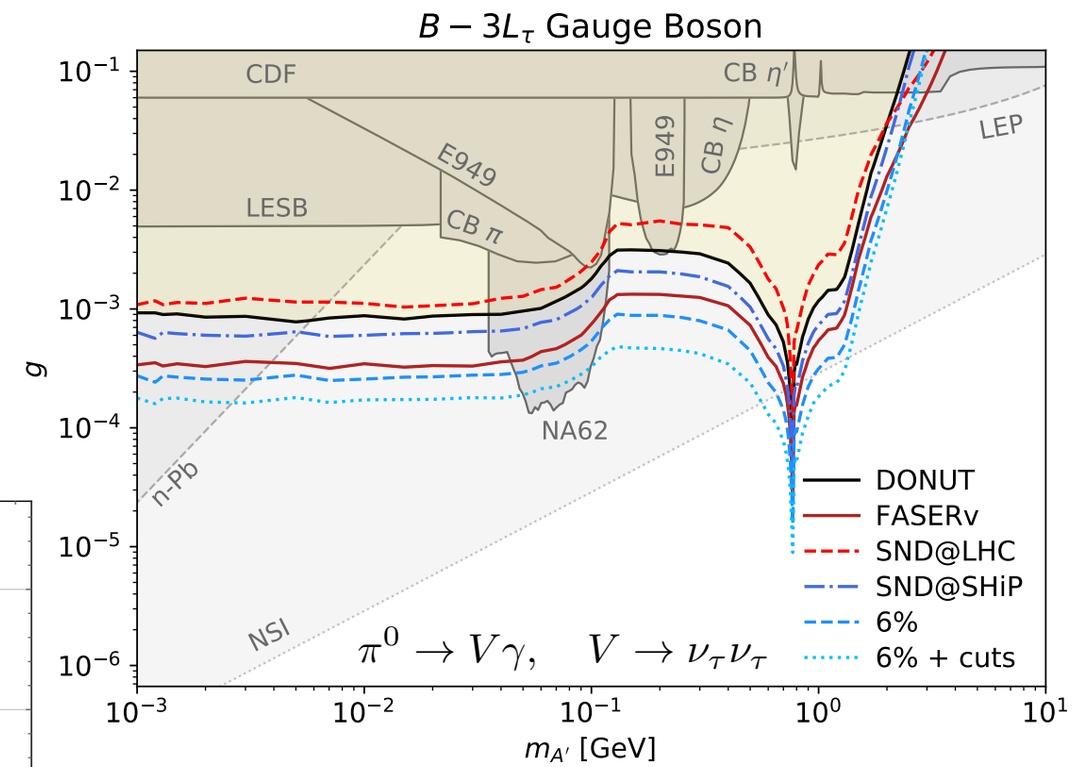


FASERν will record neutrino interaction event shapes with high precision. This could be useful for validation/tuning of neutrino event generators.

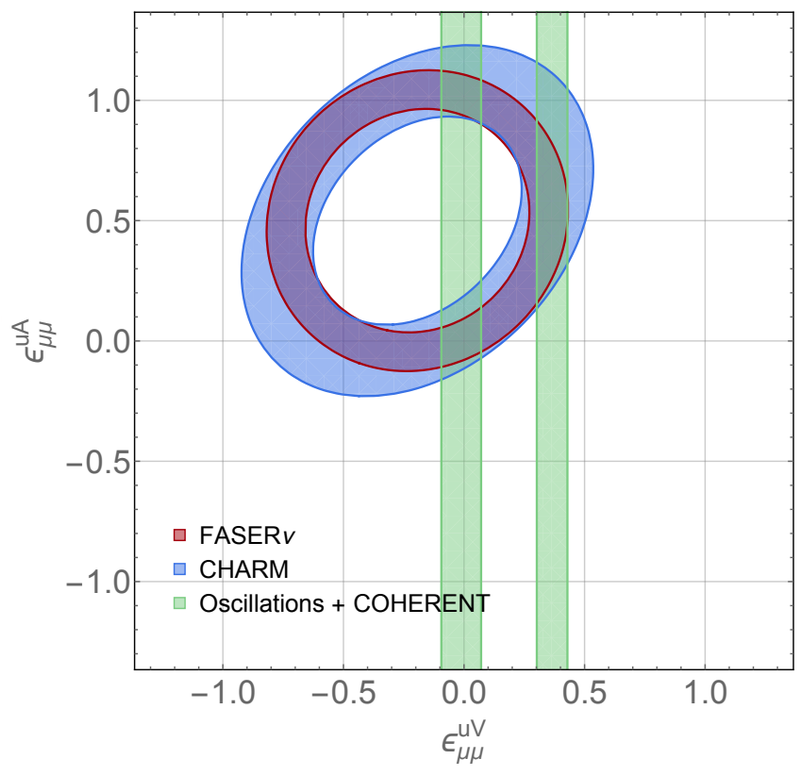
SM neutrino oscillations are expected to be negligible at FASERν. However, sterile neutrinos with mass ~40eV can cause oscillations. FASERν could act as a short-baseline neutrino experiment.

FASERν Physics Potential: BSM Physics

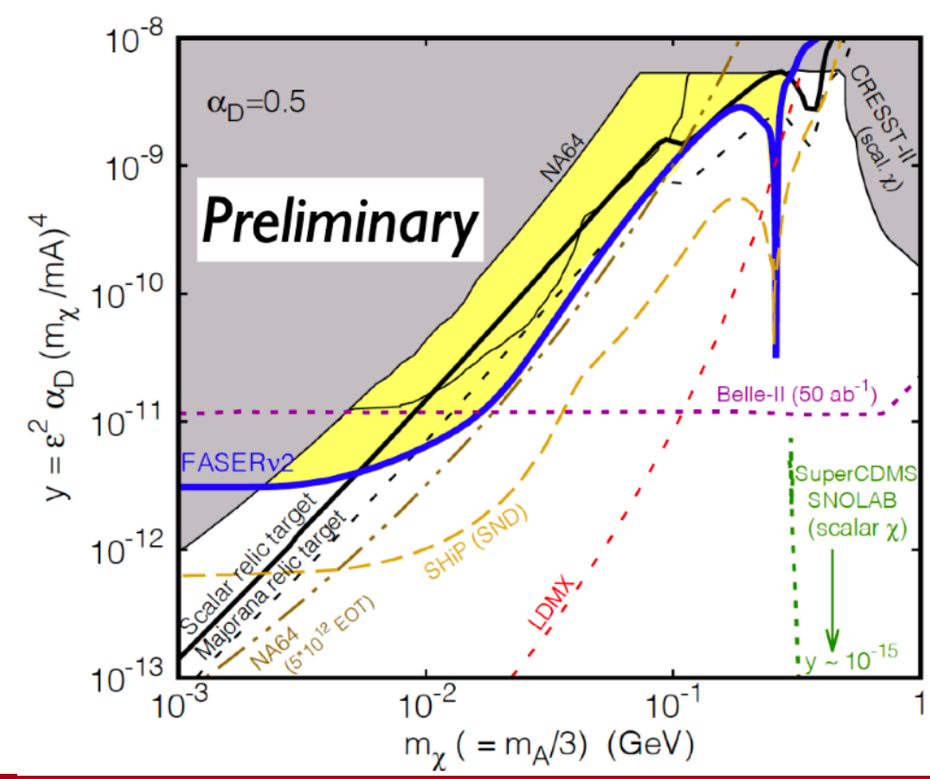
The tau neutrino flux small in SM . A new light weakly coupled gauge bosons decaying into tau neutrinos could significantly enhance the tau neutrino flux. Kling 2005.03594



NC measurements at FASERν could constrain neutrino non-standard interactions (NSI). Abraham, Ismail, Kling 2020 (to appear)



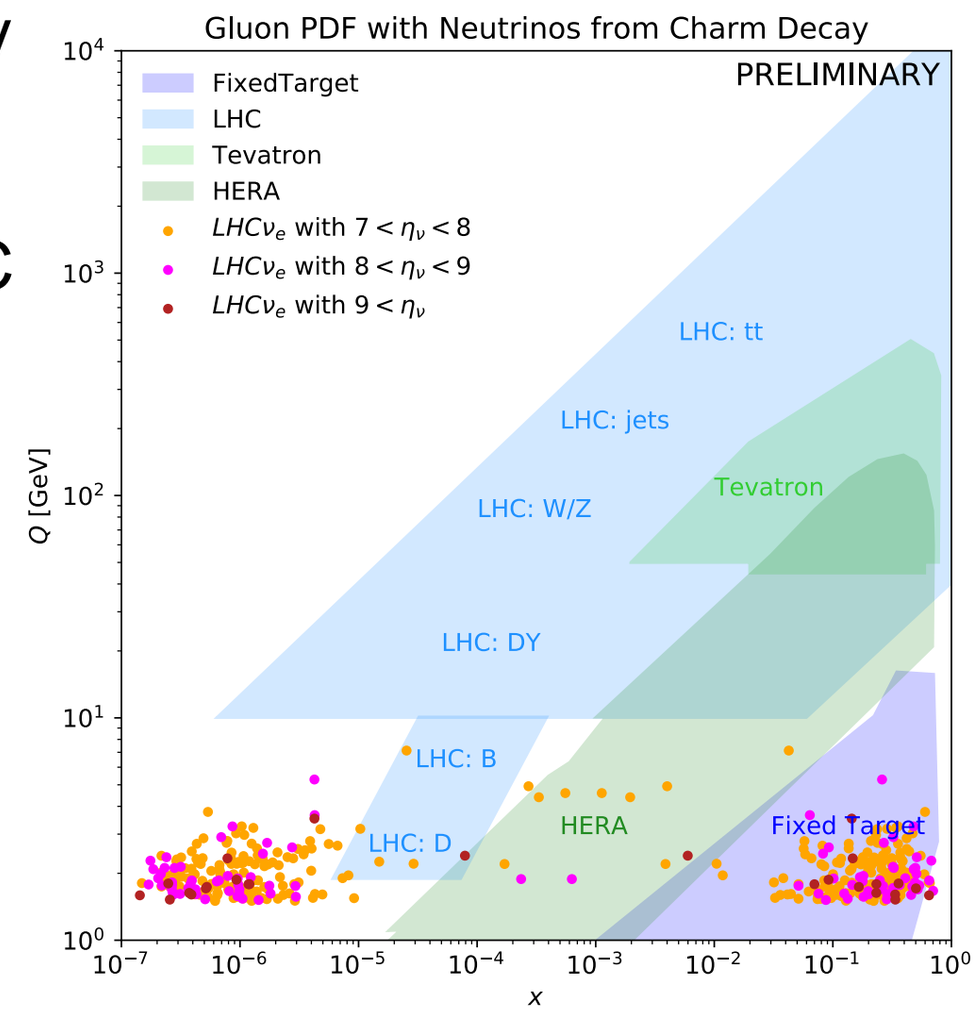
If DM is light, the LHC can produce an energetic and collimated DM beam towards FASERν. FASERν could therefore also search for DM scattering.
Batell, Feng, Trojanowski 2020 (to appear)

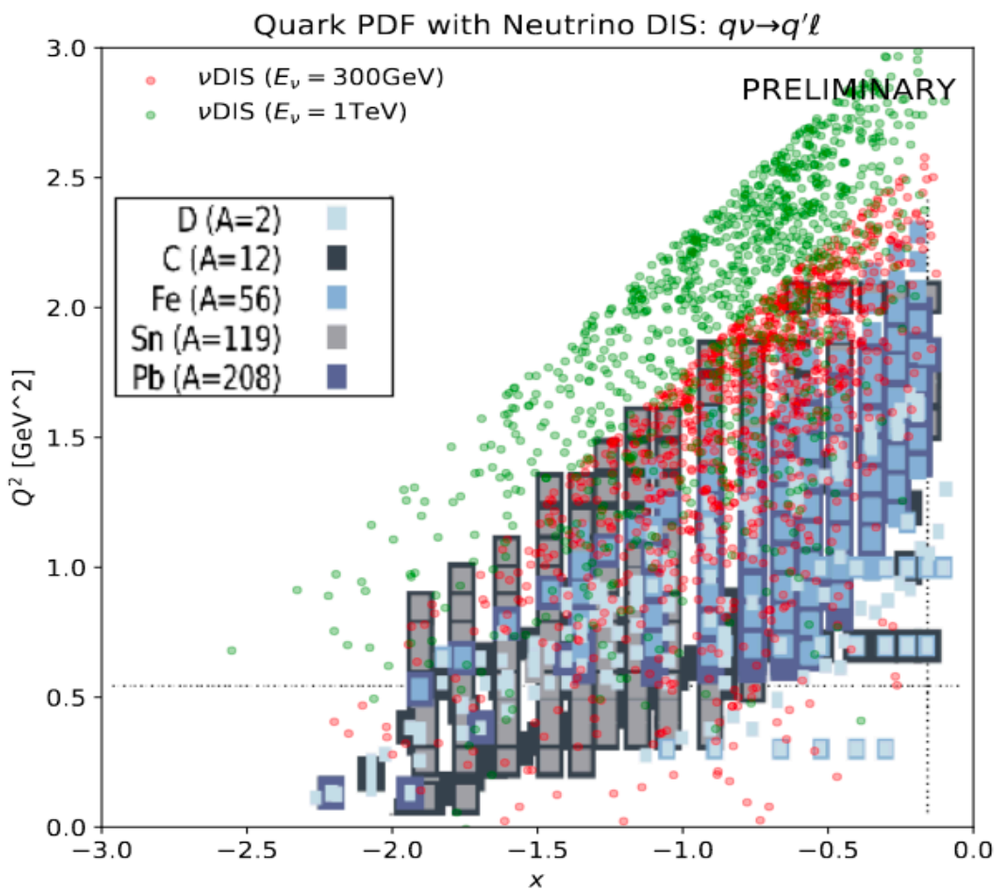


FASERν Physics Potential: QCD

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.

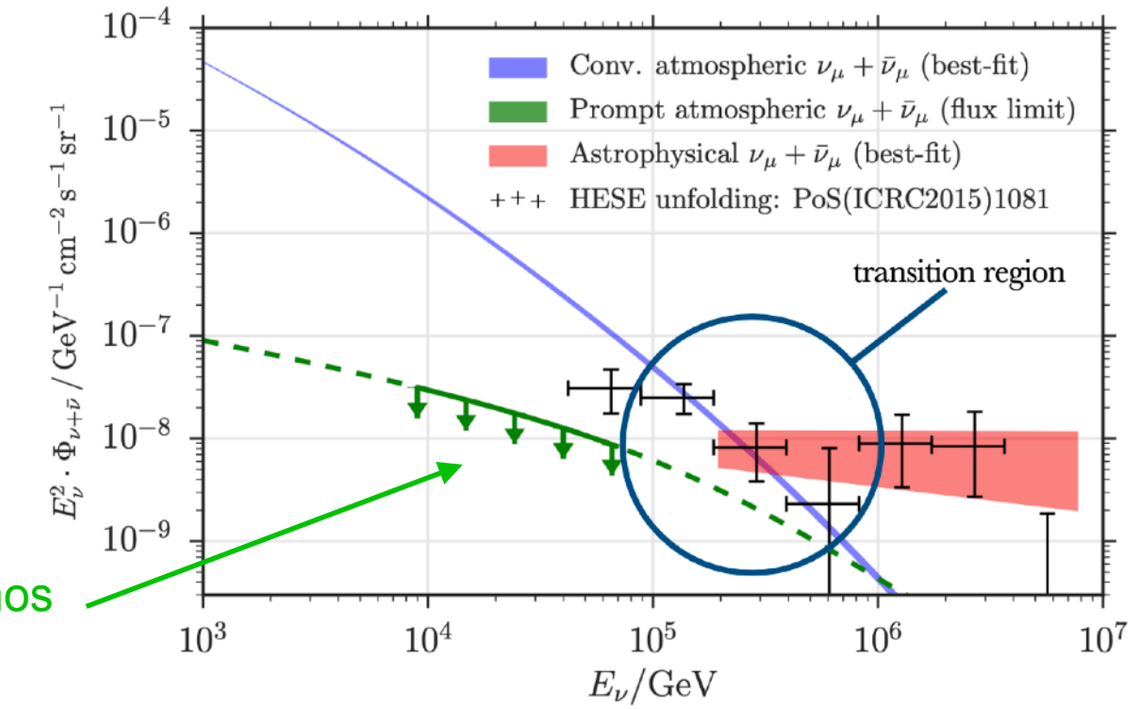


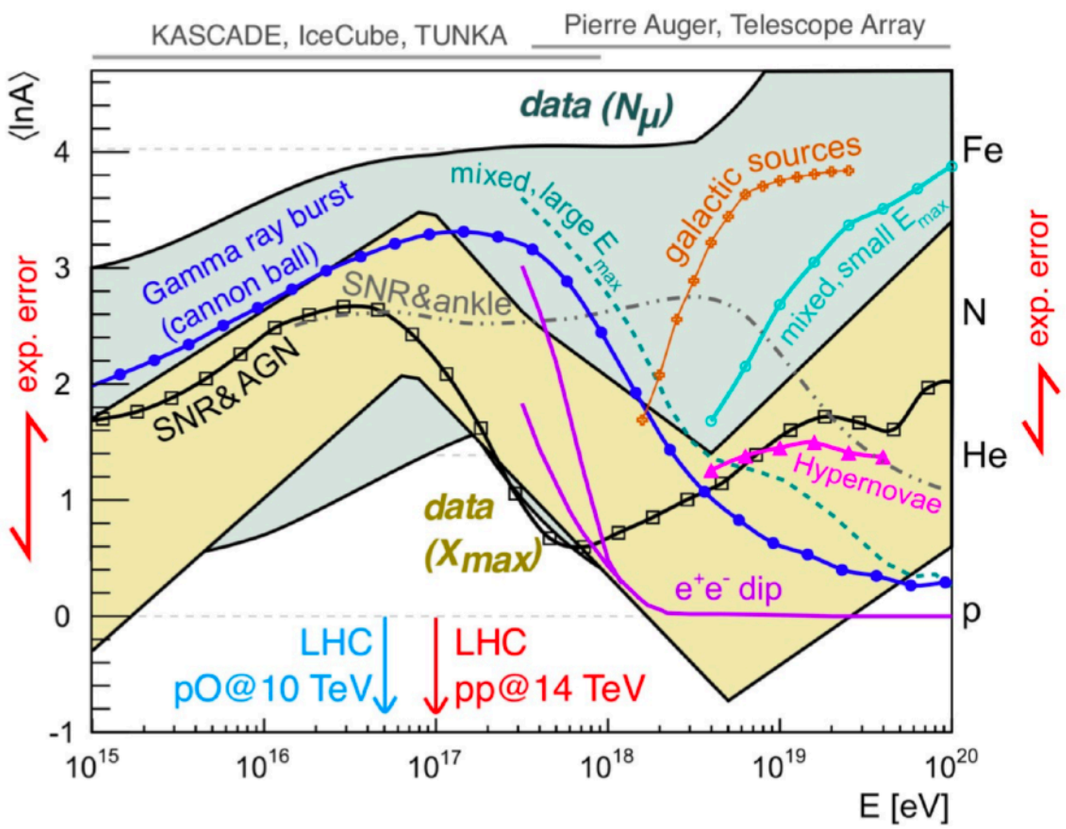


It might also be possible to probe (nuclear) PDFs via DIS neutrino scattering. In particular, charm associated neutrino events (ν s → l c) are sensitive to the poorly constrained strange quark PDF.

FASERν Physics Potential: Comics

In order for IceCube to make precise measurements of the cosmic neutrino flux, we need accelerator measurements of high energy and large rapidity charm production.





Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

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. FASERν's muon and muon neutrino flux can help.

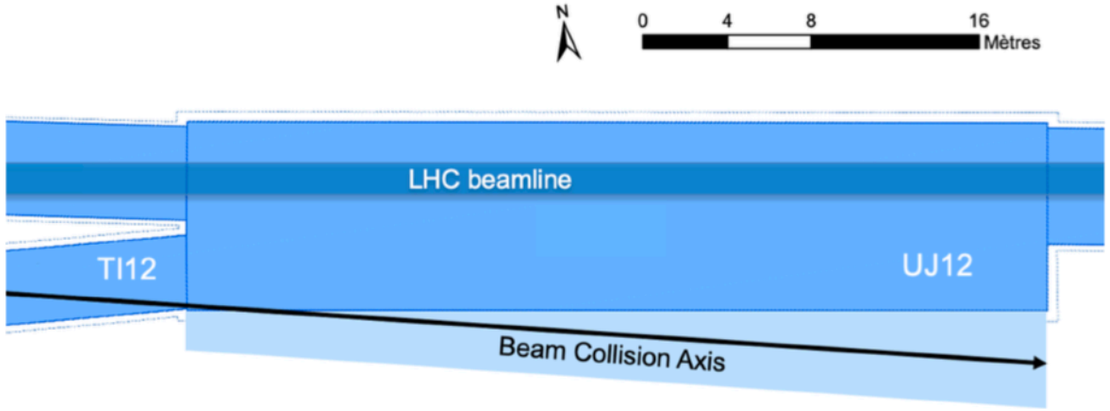
Summary and Outlook

Planning for the future

FASER and FASERν are approved, funded and under construction. They will take data during Run3 of the LHC (2021-2024), but also pave the way for a high energy forward search and neutrino program, opening up many new opportunities for neutrino physics, new physics searches and QCD, significantly extending the LHC's physics program.

As part of the Snowmass 2021 community study, we aim to investigate the full physics potential of FASER and FASERν during the HL-LHC era.

1. We propose an upgraded FASER2 detector with enhanced sensitivity for LLP searches. See the FASER2 Snowmass LOI
2. We propose an enlarged neutrino detector with roughly ten times the mass of FASERnu operating at the HL LHC. Such a detector would collect roughly ~$10^5 \nu_e$, ~10^6 ν_μ and ~10^3 ν_τ at TeV energies. See the FASERnu2 Snowmass LOI
3. We proposal to enlarge an existing cavern and create a Forward Physics Facility to house a variety of experiments. See the Forward Physics Facility Snowmass LOI and first FPF workshop.



We would like to invite the HEP community (so you) to help us explore the physics potential of this program.

Summary and Outlook

FASER
- newest experiment at the LHC
- quick, small and inexpensive
- funded and approved

Envisioned Timeline
- build/install FASER in LS2 (2019-20)
- take data during Run 3 (2021-23, 150 fb^{-1})
- upgrade to FASER 2 in LS3 for HL-LHC

Physics:
- search for light long-lived particles at the LHC
- neutrino measurements at TeV energies
- and many more unexplored opportunities …

  → help us explore them

For more information, see our website: https://faser.web.cern.ch/

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

Many thanks to the Heising-Simons Foundation, the Simons Foundation, and to CERN for invaluable support

We look forward to feedback and suggestions

Backup

FASER Timeline

09/2017 - Original FASER idea paper arXiv:1708.09389

spring 2018 - FASER collaboration forms

07/2018 - Letter of Intent arXiv:1811.10243

11/2018 - Technical Proposal arXiv:1812.09139

11/2018 - LLP Physics Potential arXiv:1811.12522

12/2018 - Funding

03/2019 - Approval by CERN

08/2019 - Proposal of FASERν arXiv:1908.02310

11/2019 - FASERν TP arXiv:2001.03073

65 collaborators
18 institutions
8 countries

Detector Construction and Integration - **2019-2020**

Collecting Data - **2021-2023**

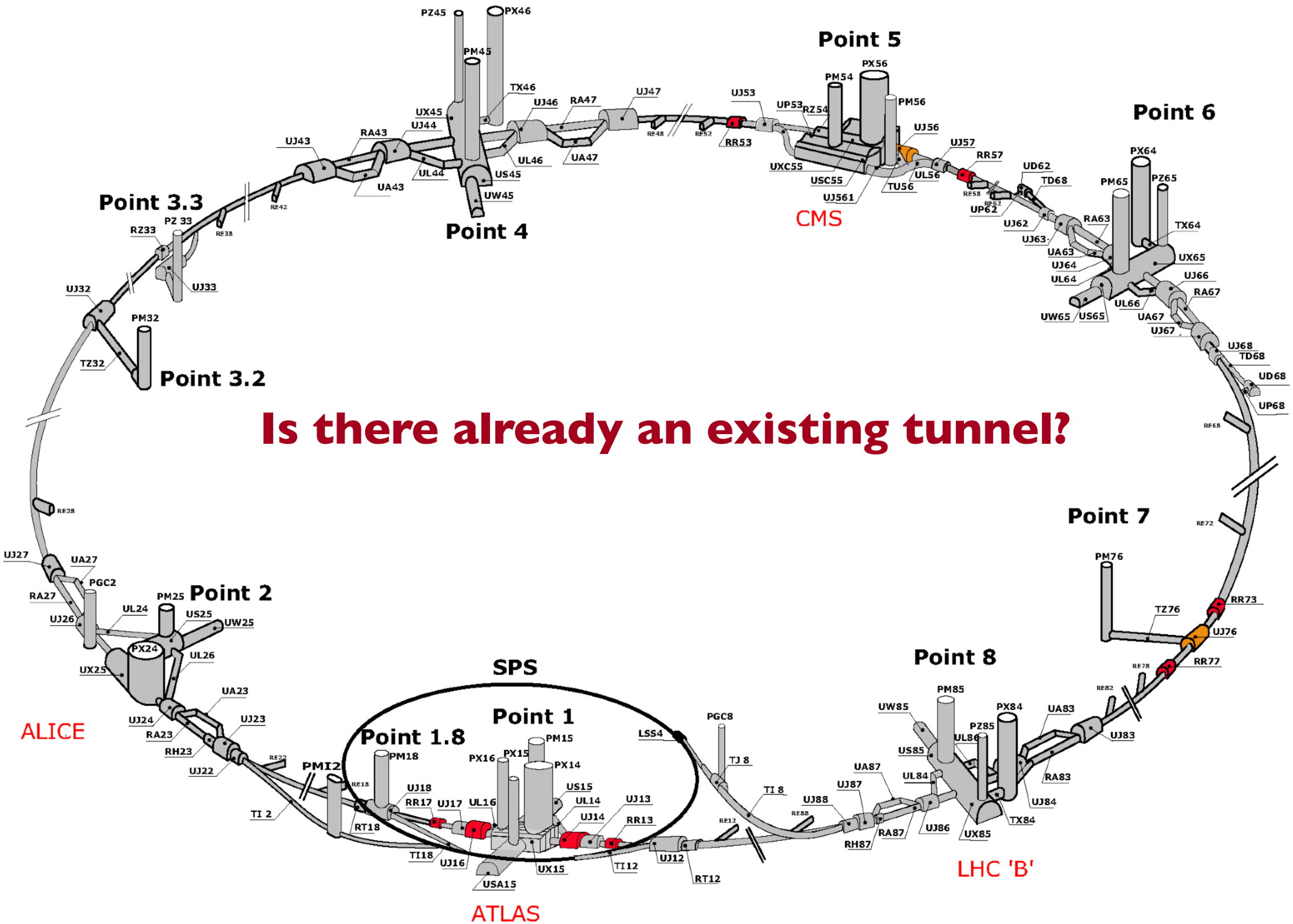
FASER 2 Upgrade - **HL-LHC era**

Acknowledgements

The FASER Collaboration gratefully acknowledges the contributions of many people.

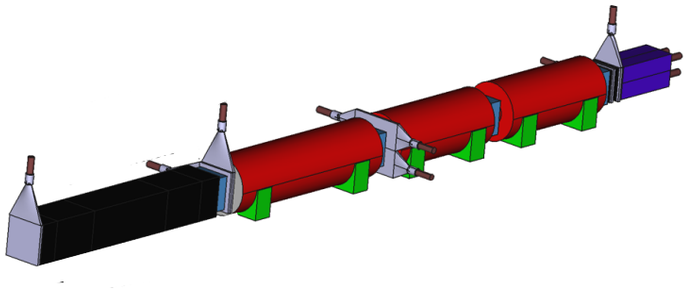
We are grateful to the ATLAS SCT project and the LHCb Calorimeter project for letting us use spare modules as part of the FASER experiment. In addition, FASER gratefully acknowledges invaluable assistance from many people, including the CERN Physics Beyond Colliders study group; the LHC Tunnel Region Experiment (TREX) working group; Rhodri Jones, James Storey, Swann Levasseur, Christos Zamantzas, Tom Levens, Enrico Bravin (beam instrumentation); Dominique Missiaen, Pierre Valentin, Tobias Dobers (survey); Jonathan Gall, John Osborne (civil engineering); Caterina Bertone, Serge Pelletier, Frederic Delsaux (transport); Francesco Cerutti, Marta Sabaté-Gilarte, Andrea Tsinganis (FLUKA simulation and background characterization);Pierre Thonet, Attilio Milanese, Davide Tommasini, Luca Bottura (magnets); Burkhard Schmitt, Christian Joram, Raphael Dumps, Sune Jacobsen (scintillators); Dave Robinson, Steve McMahon (ATLAS SCT); Yuri Guz (LHCb calorimeters); Salvatore Danzeca (Radiation Monitoring);Stephane Fartoukh, Jorg Wenninger (LHC optics), Michaela Schaumann (LHC vibrations); Marzia Bernardini, Anne-Laure Perrot, Katy Foraz, Thomas Otto, Markus Brugger (LHC access and schedule); Simon Marsh, Marco Andreini, Olga Beltramello (safety); Stephen Wotton, Floris Keizer (SCT QA system and SCT readout); Liam Dougherty (integration);Yannic Body, Olivier Crespo-Lopez (cooling/ventilation); Yann Maurer (power); Marc Collignon, Mohssen Souayah (networking); Gianluca Canale, Jeremy Blanc, Maria Papamichali (readout signals); Bernd Panzer-Steindel (computing infrastructure); and Mike Lamont, Fido Dittus, Andreas Hoecker, Andy Lankford, Ludovico Pontecorvo, Michel Raymond, Christoph Rembser, Stefan Schlenker (useful discussions).

FASER Location

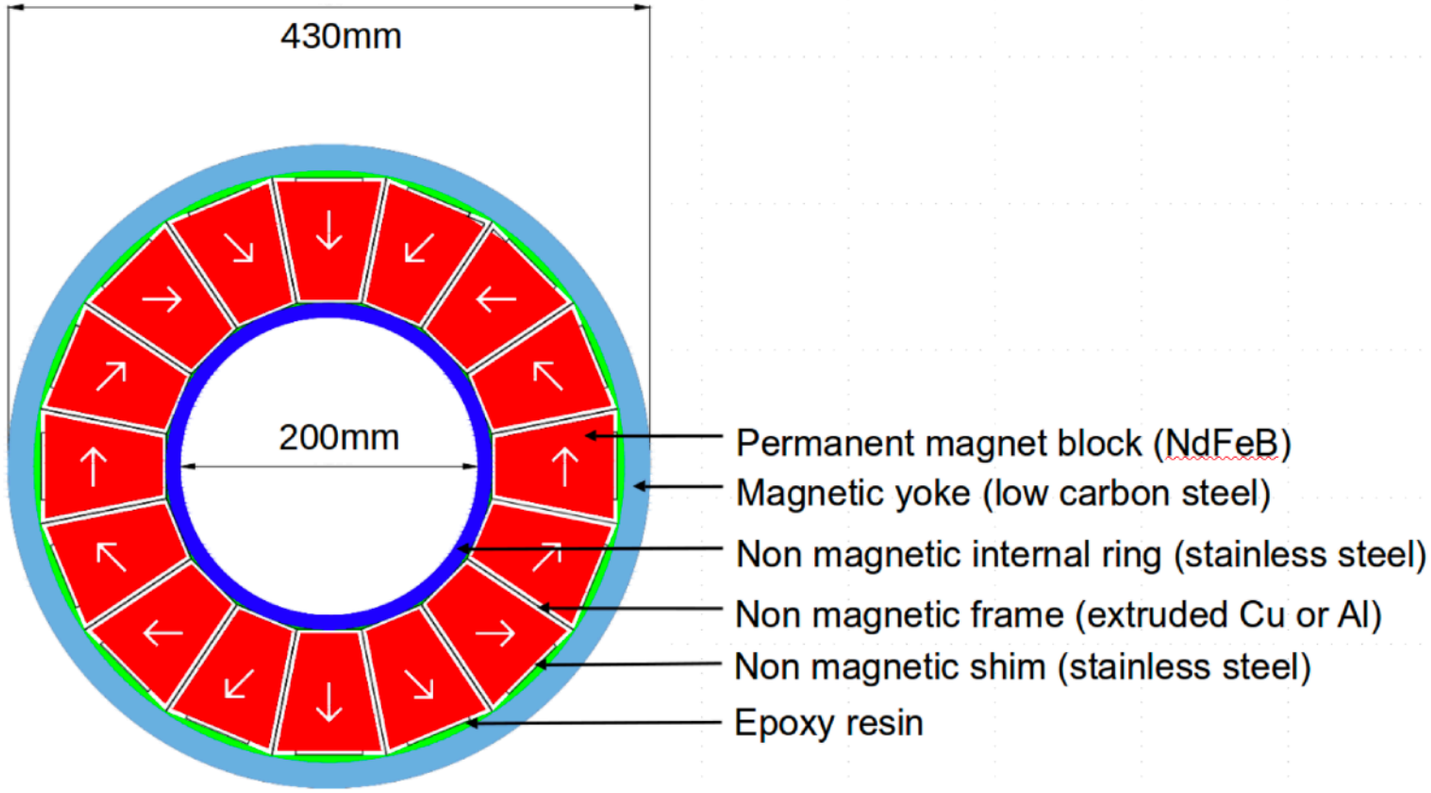


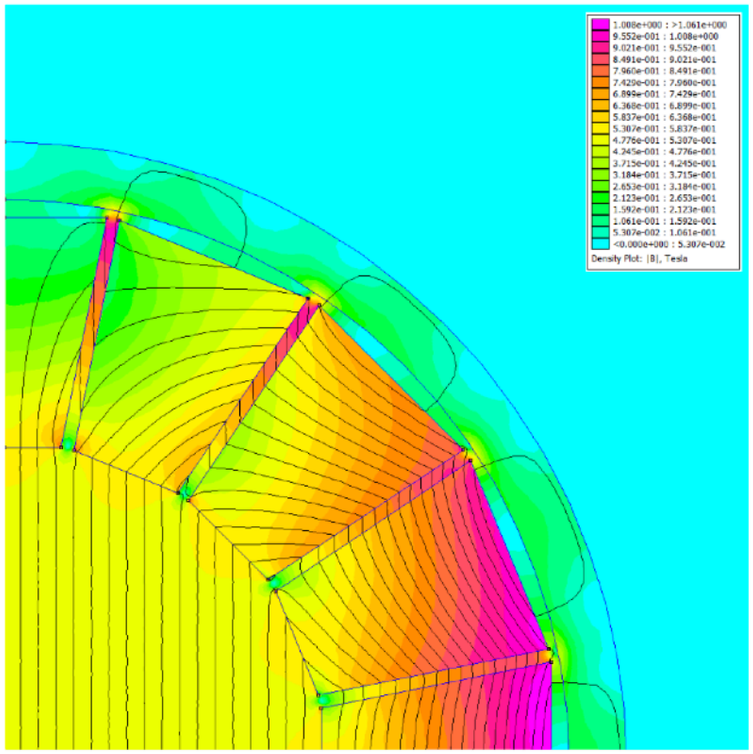
Is there already an existing tunnel?

FASER Magnet



- 0.6T permanent dipole magnets
- Halbach array design
  - LOS to passes through the magnet center
  - minimum digging to the floor in TI12
  - minimized needed services (power, cooling etc..)
- to be constructed by the CERN magnet group

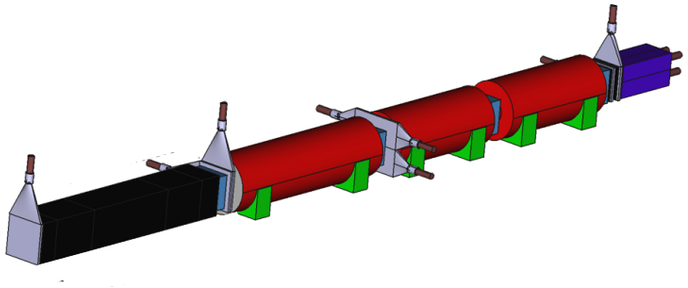


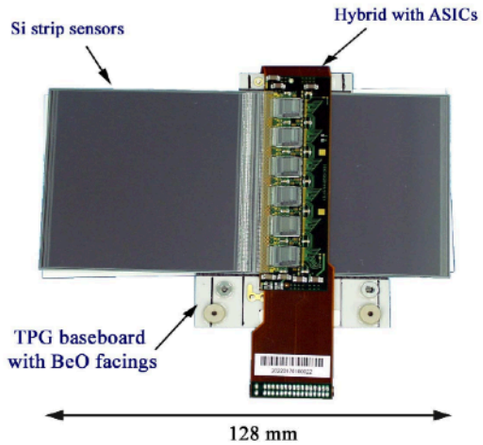


FASER Detector

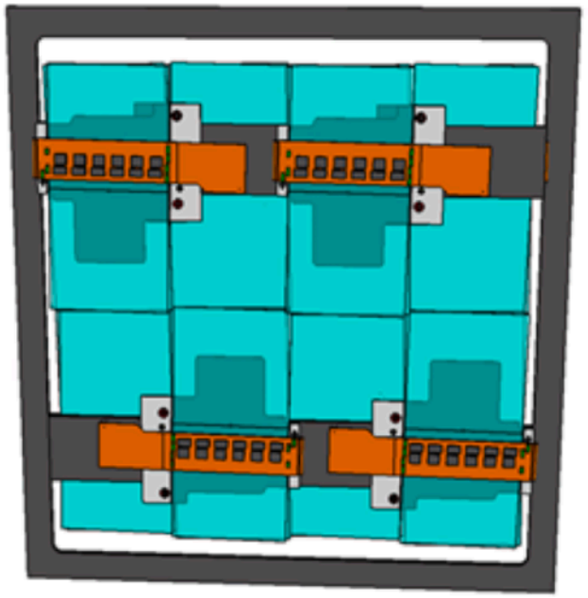
FASER Tracker

- 3 tracking stations, each with 3 tracking layers
- double sided silicon micro-strip detectors
- ATLAS SCT spare modules will be used
  - 80µm strip pitch, 40mrad stereo angle
  - many thanks to the ATLAS SCT collaboration!
  - 72 SCT modules for the full tracker

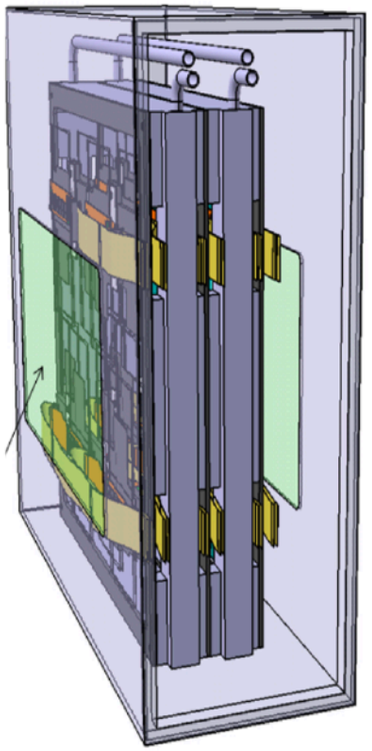




SCT module



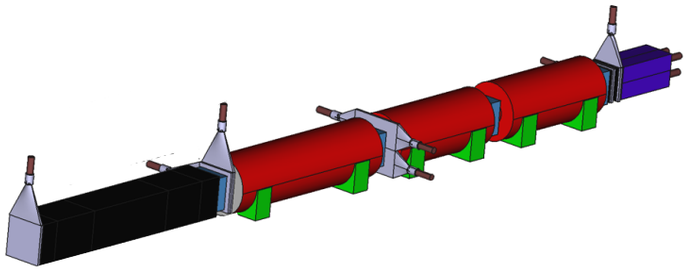
Tracking layer



Tracking station

FASER Detector

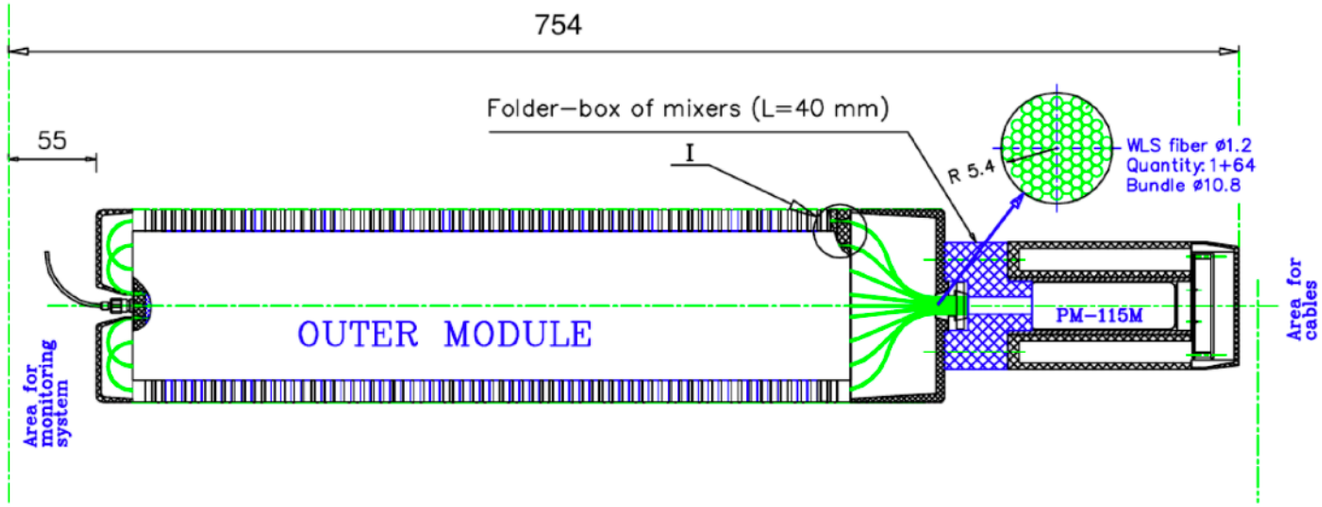
FASER ECAL

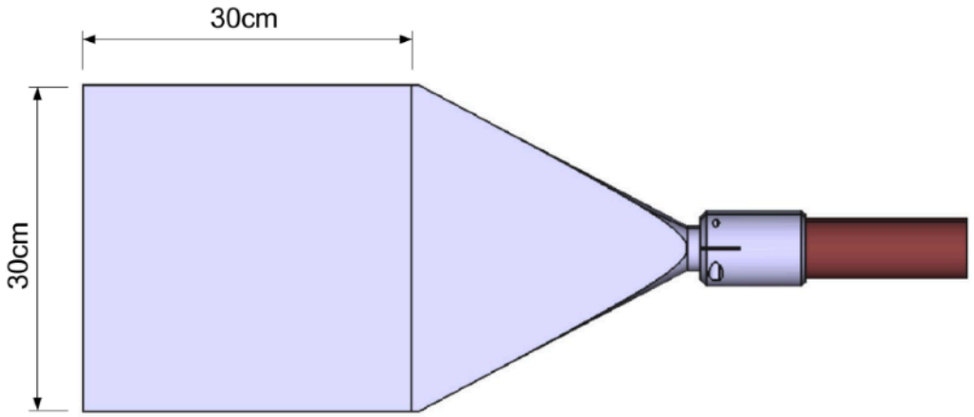


- EM energy measuring / triggering / electron/photon identification
- FASER will use spare LHCb outer ECAL modules
  - ~1% energy resolution for 1 TeV electrons
  - Many thanks for LHCb for allowing us to use these!

FASER Scintillators

- vetoing charged particles entering the decay volume / triggering
- to be produced at CERN scintillator lab

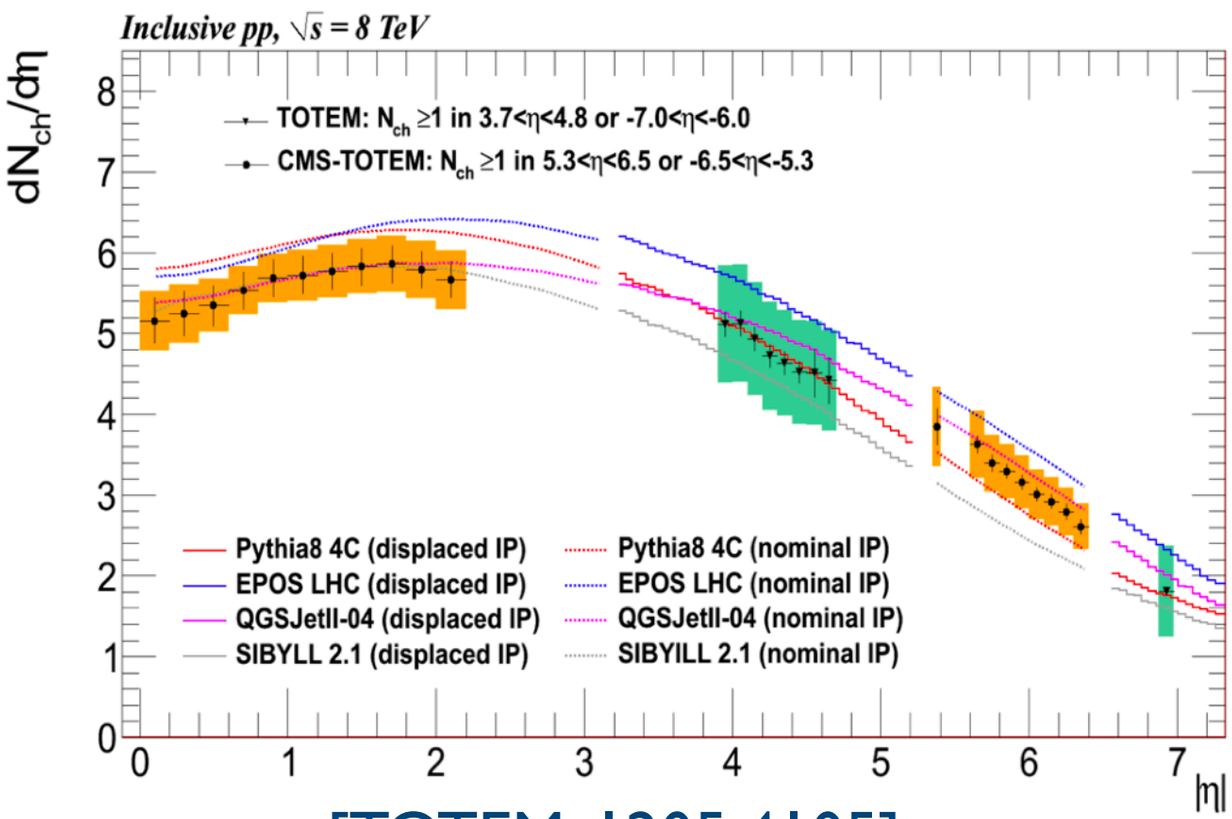




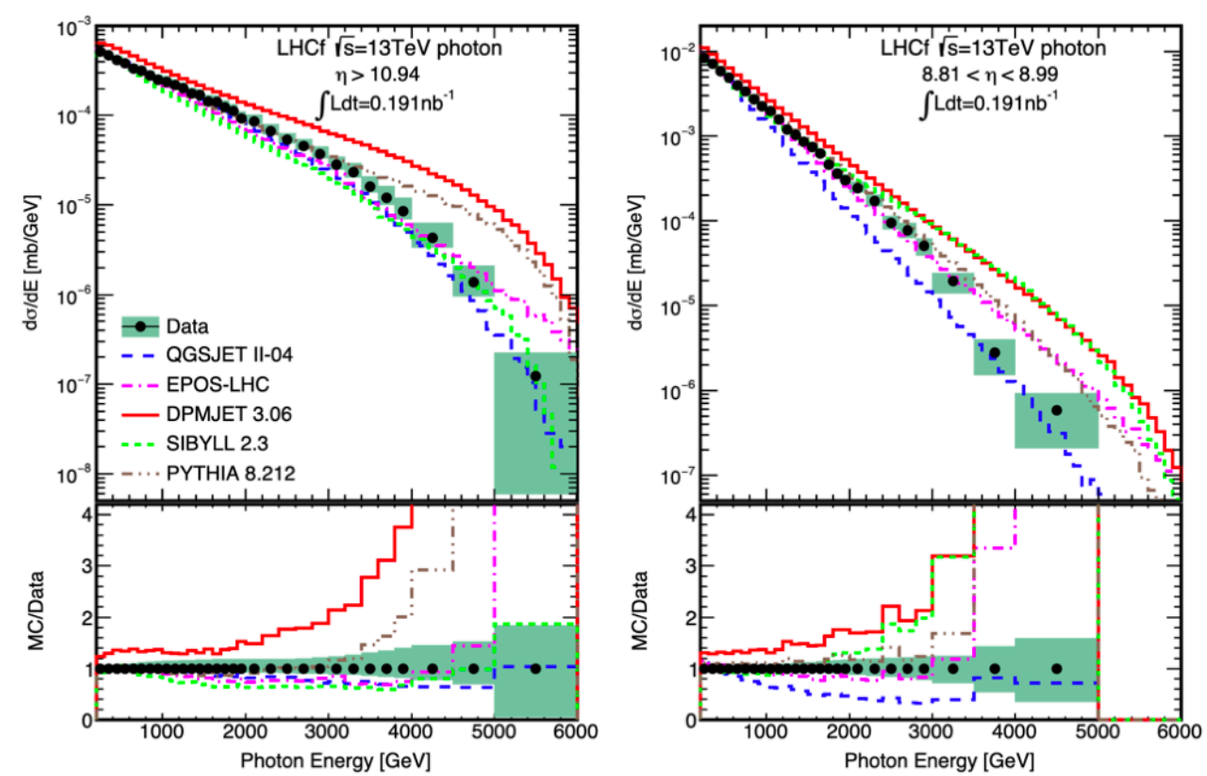
FASERν Physics

- cross section measurements limited by neutrino flux uncertainty
  * we need to quantify and reduce these uncertainties
- forward particle production not described by pQCD, but soft physics
  * use hadronic interaction models
- simulators based on sophisticated modeling of microscopic physics
  * phenomenological parameters need to be tuned
  * include tuning uncertainties (similar to PDFs)

→ develop dedicated forward physics tune using forward data



[TOTEM: 1205.4105]

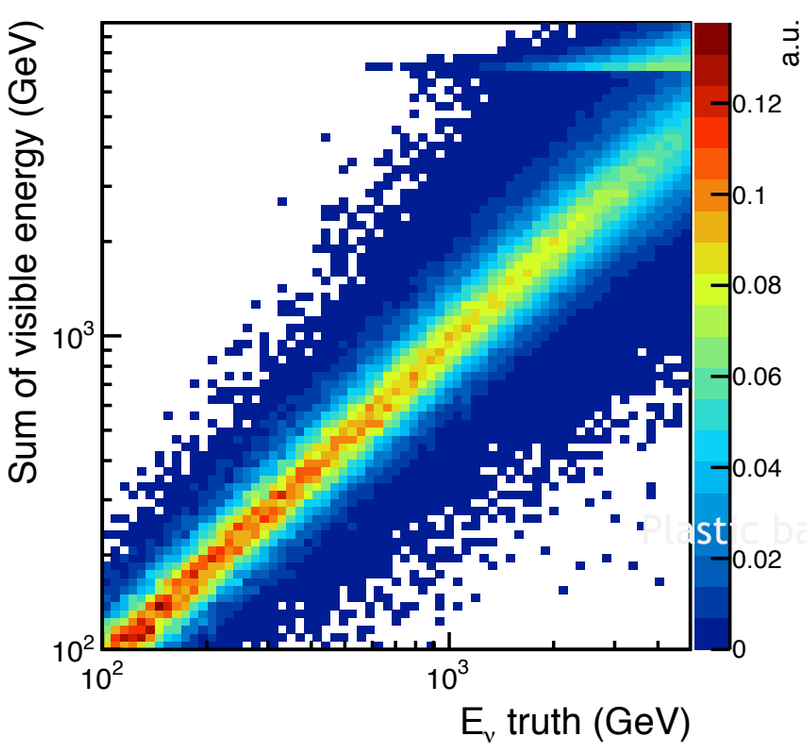


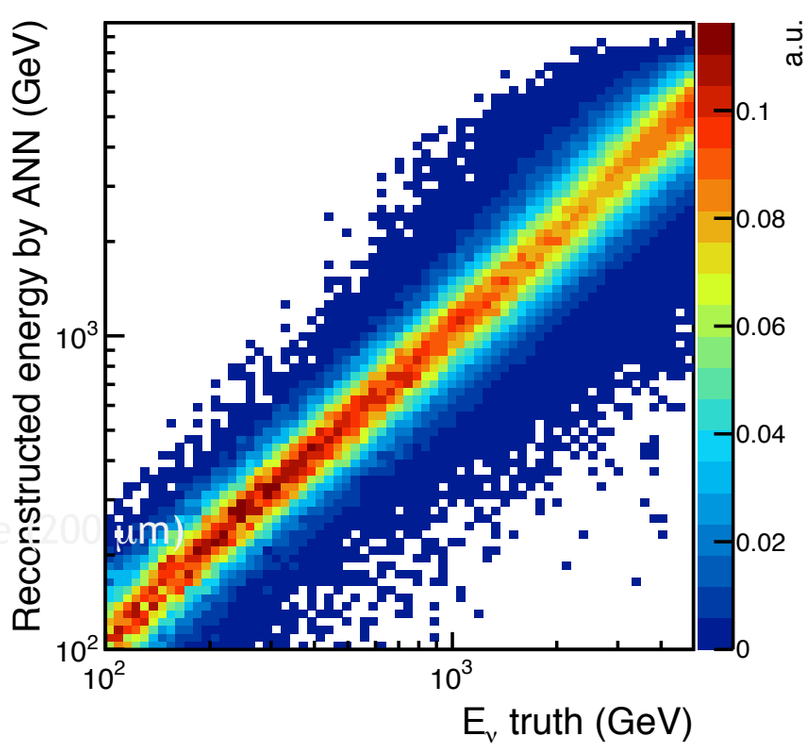
[LHCf: 1703.07678]

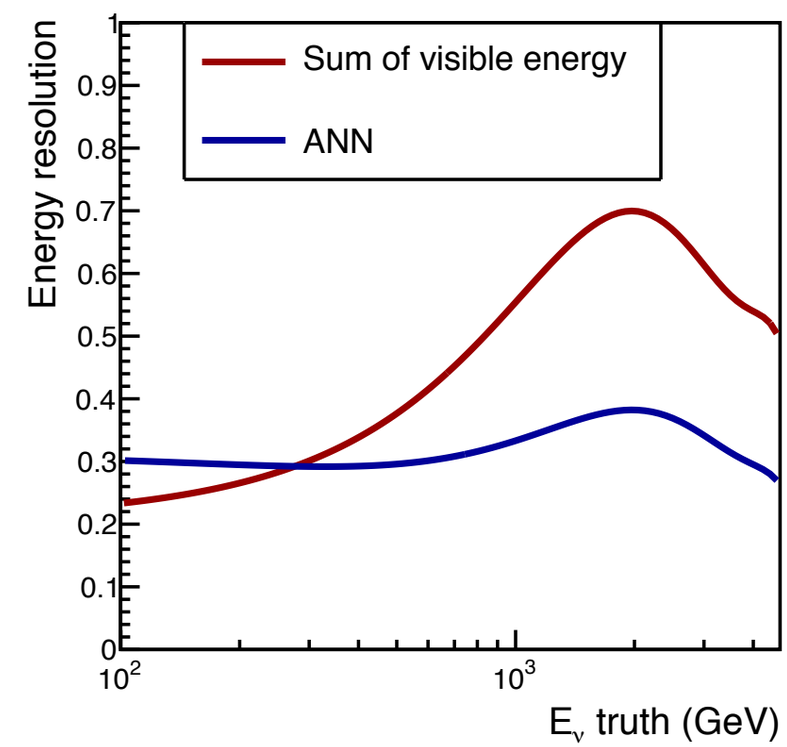
FASERν Detector

- neutrino energy reconstruction
  * use topological + kinematic observables
  * train NN to estimate neutrino energy
  * 30% energy resolution seems achievable

Topological Variables		related to
n_{tr}	charged tracks multiplicity	E_{had}
n_γ	photon multiplicity	E_{had}
$\lvert 1/\theta_\ell \rvert$	lepton angle	E_ℓ
$\sum \lvert 1/\theta_{\mathrm{had}} \rvert$	sum of inverse hadron track angles	E_{had}
$1/\theta_{\mathrm{median}}$	inverse of median of all track angles	E_{had}, E_ℓ
Kinematical Variables		
p_ℓ^{MCS}	lepton momentum from MCS	E_ℓ
$\sum p_{\mathrm{had}}^{\mathrm{MCS}}$	charged hadron momenta from MCS	E_{had}
$\sum E_\gamma$	energy in photon showers	E_{had}

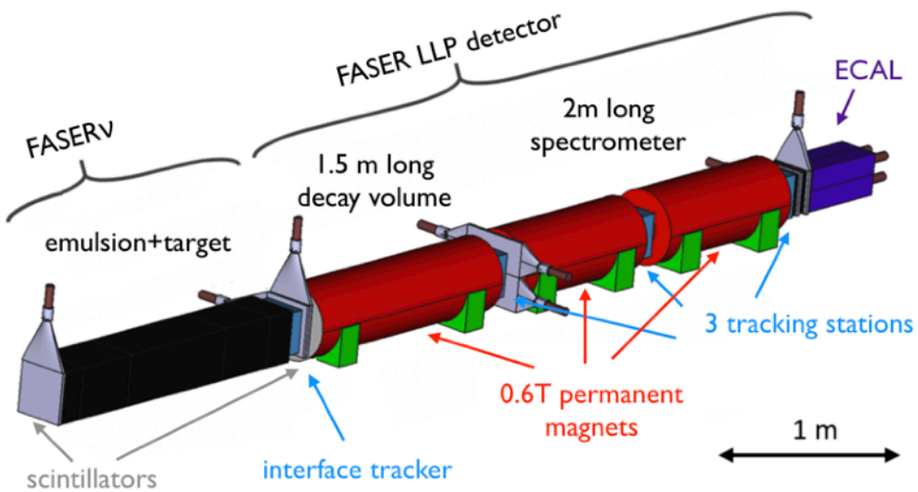


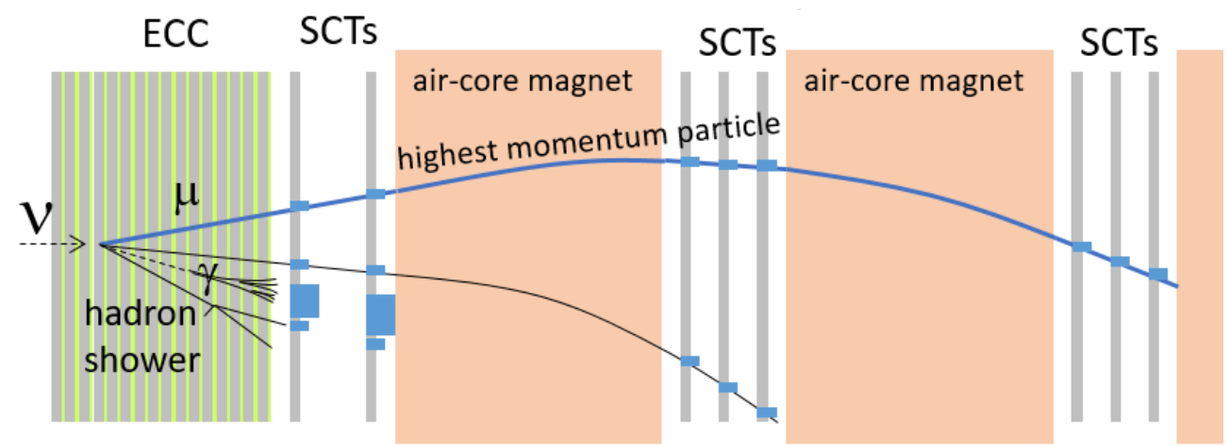




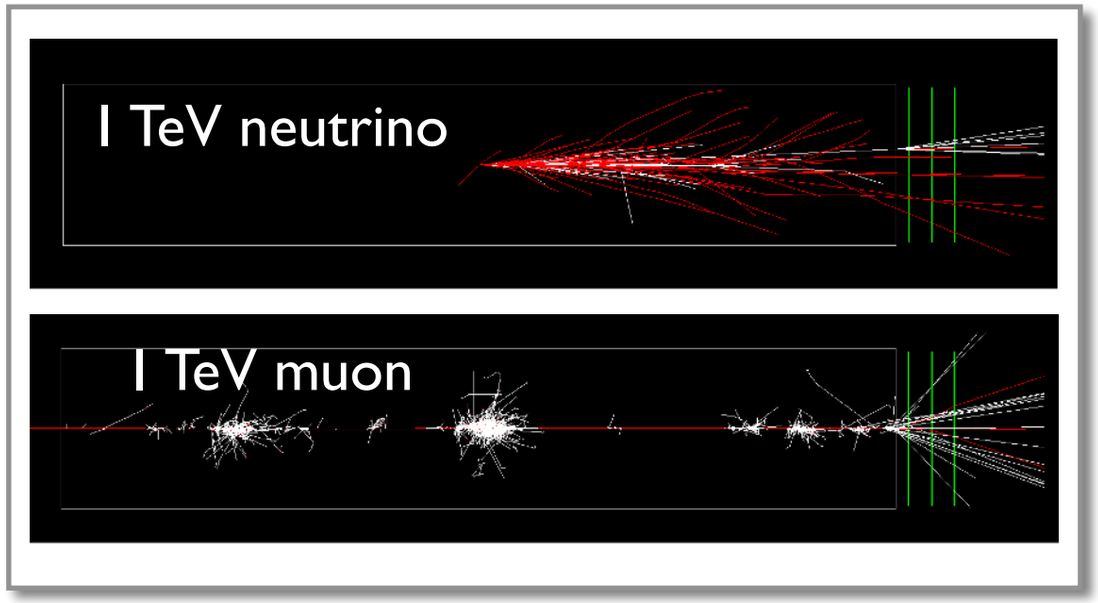
FASERν Detector

- possibility for future: global reconstruction with the FASER detector
  * interface FASERν to the FASER spectrometer
  * requires additional tracking layer to allow matching





- muon charge identification
  → distinguish neutrino / anti-neutrino
- momentum of charged tracks
  → improve neutrino energy reconstruction
- timestamp events and identify additional activity (muon)
  → background rejection

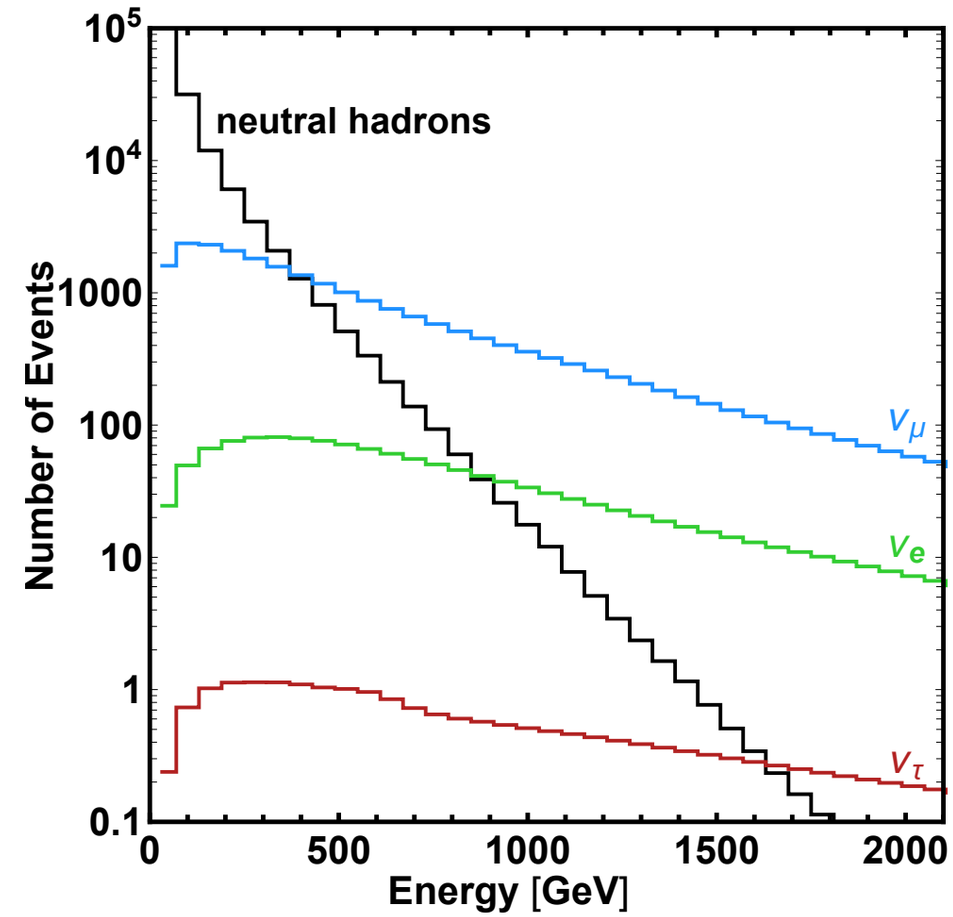


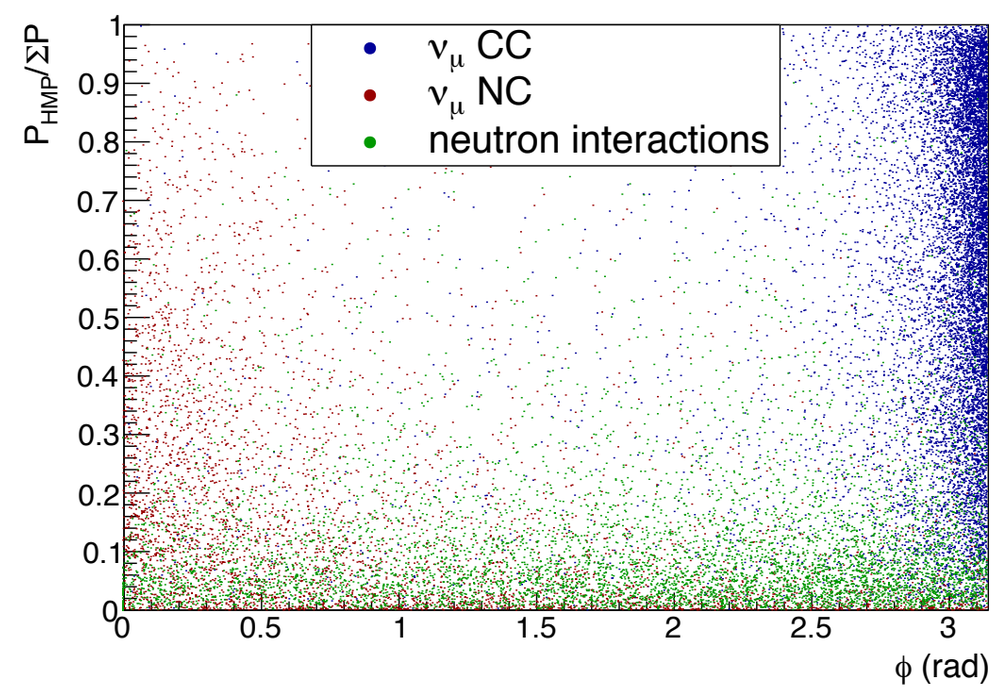
FASERν Backgrounds

- neutrino interaction signal is striking
  * neutral vertex identified with >5 tracks
  * points back to IP
  * high energy event
  * charged lepton identified

- neutral hadrons could mimic neutrino signal
  * simulated with FLUKA
  * rejection based on energy, lepton ID and kinematics

- lepton identification
  * ν_μ: highest momentum particle without interactions
  * ν_e: single-electron initiated EM shower
  * ν_τ: kink from displaced τ-decay vertex



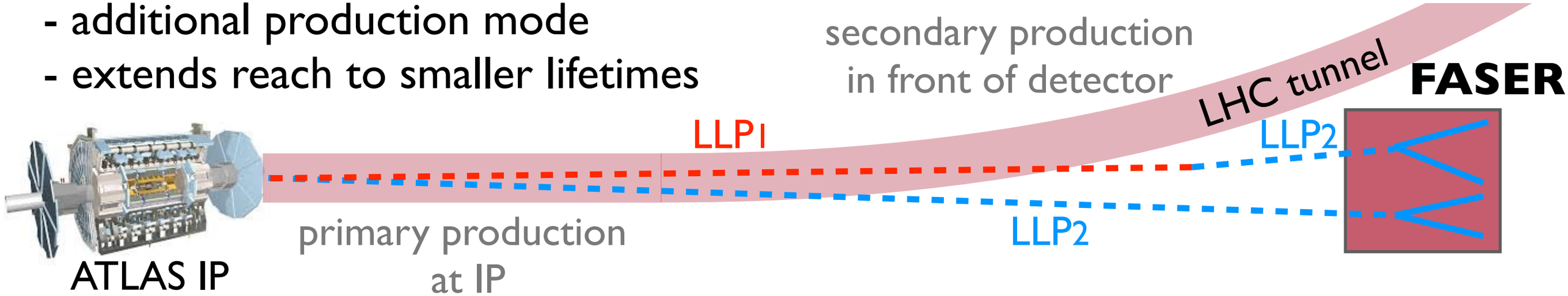


Long Lived Particles at FASER

Secondary LLP Production

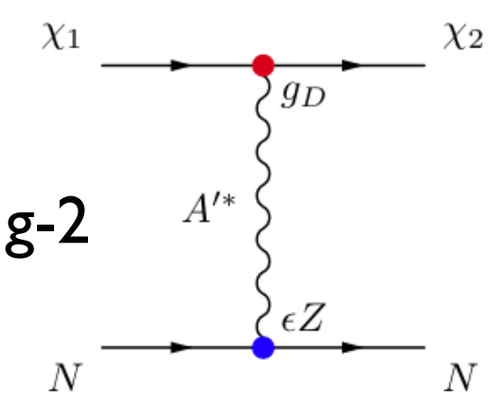
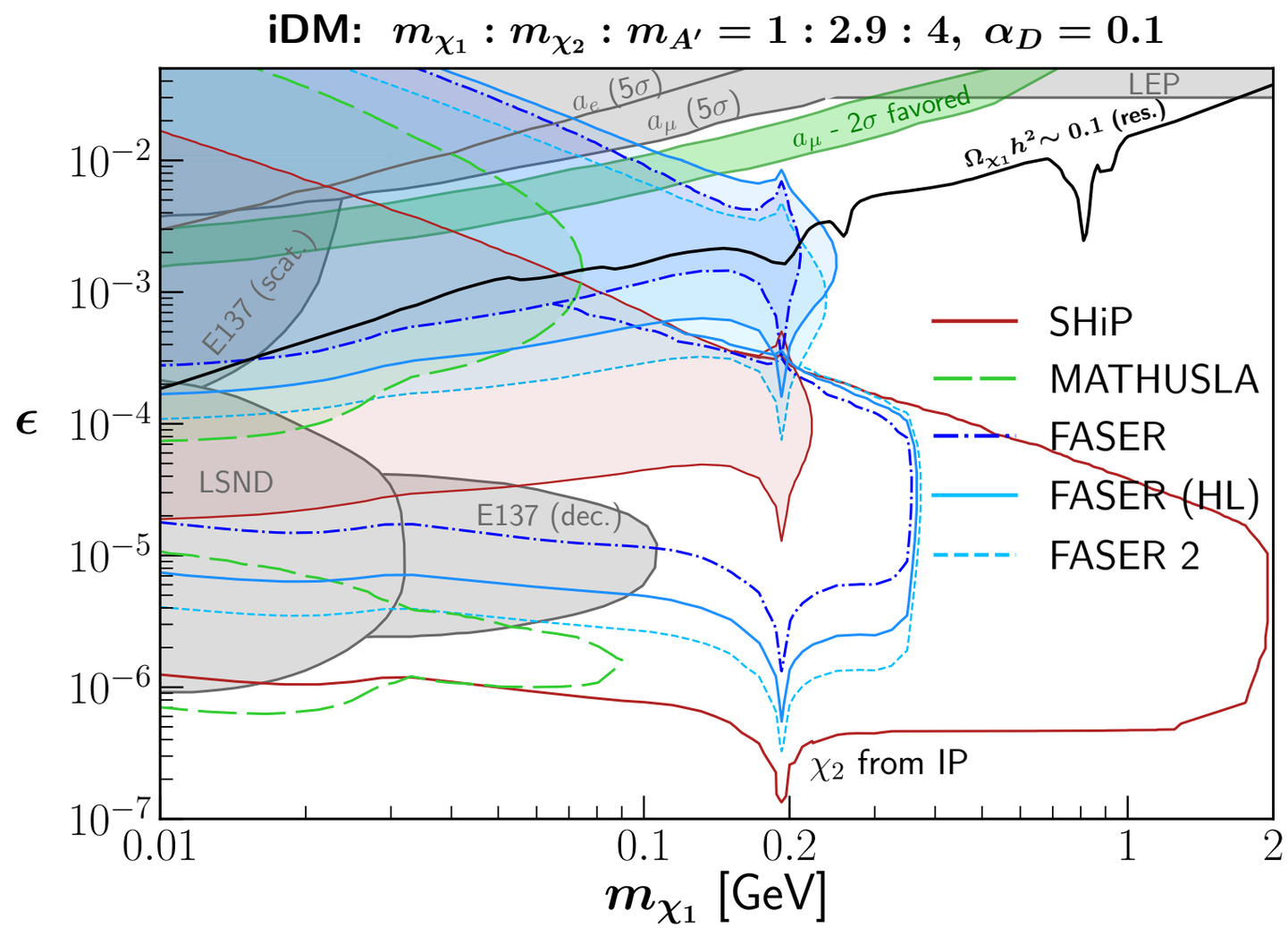
[K. Jodłowski, FK, L. Roszkowski, S. Trojanowski: 1810.01879]

- additional production mode
- extends reach to smaller lifetimes



Example: inelastic DM

- A' couples diagonally to X_1 + X_2
- X_1=LLP1, X_2=LLP2
- primary production $\pi^0 \to \gamma X_1 X_2$
- secondary production: $X_1 N \to X_2 N$
- decay: $X_2 \to X_1 ee$



- enhanced reach
- relevant for DM & g-2