FASER

Looking forward to new Physics with FASER

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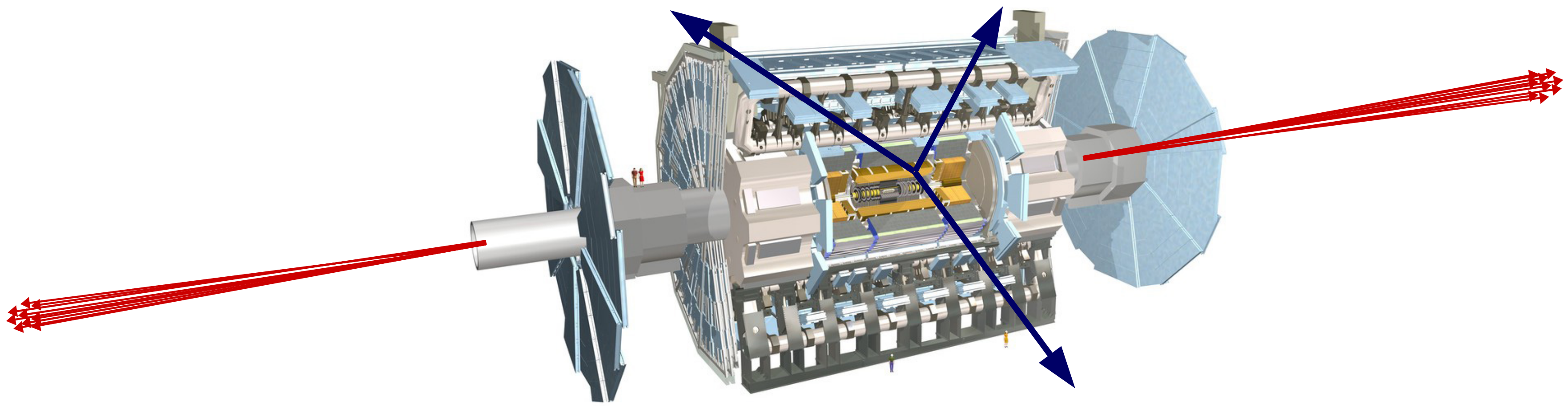
Oklahoma State HEP seminar

SLAC NATIONAL ACCELERATOR LABORATORY
HEISING-SIMONS FOUNDATION
SIMONS FOUNDATION

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

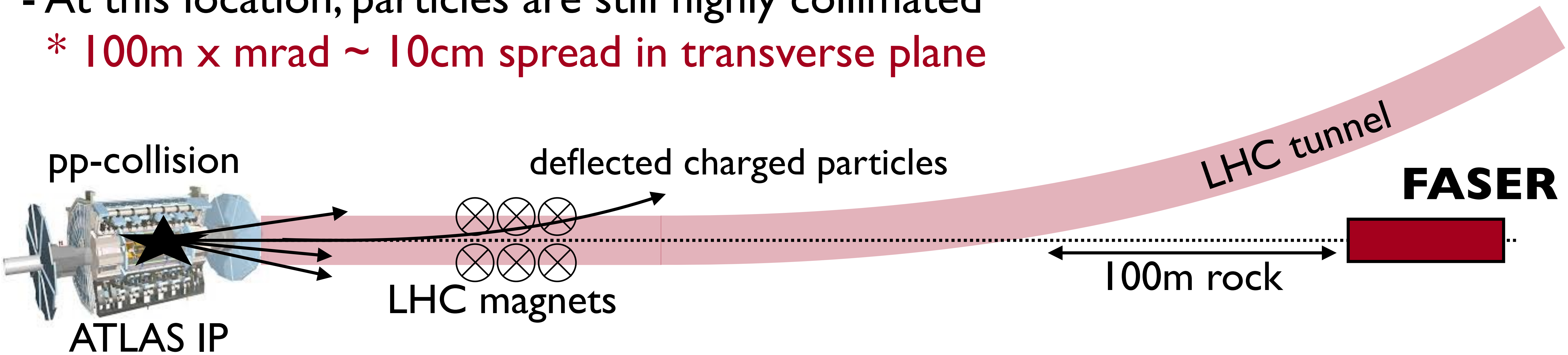
- We should go where the pions are: **forward region** along the beam line
  * enormous event rates: σ_{inel} ~ 100mb or $N_\pi \sim 10^{17}$ at $\mathcal{L} = 300\ \mathrm{fb}^{-1}$
  * highly energetic beam remnants: E ~ TeV
  * low pT ~ Λ_{QCD} → particles are collimated θ ~ Λ_{QCD}/E ~ mrad

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



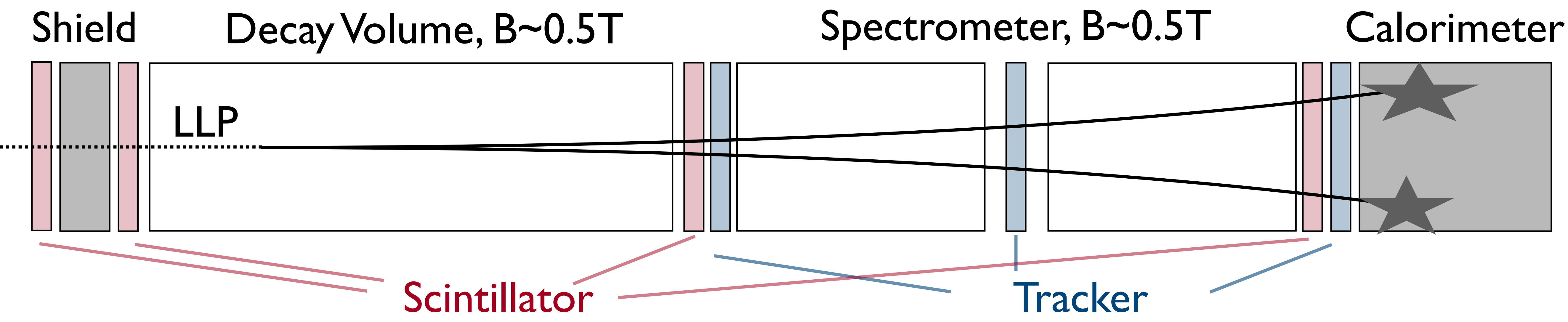
- This motivates small, fast and cheap inexpensive detector
  FASER: Forw**A**rd **S**earch **E**xpe**R**iment at the LHC

- Applications for light long-lived particles searches and neutrinos

Motivation and Idea

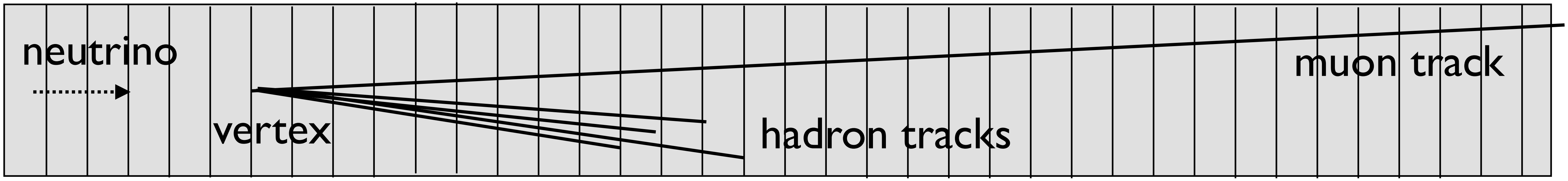
Long-Lived Particles Searches

search for appearance of high-energy particles from LLP decay in empty decay volume



Neutrino Measurements

search for neutrino interaction vertex in dense material using emulsion detector



emulsion detector + tungsten target

The FASER Experiment
Location / Detector / Environment / Timeline

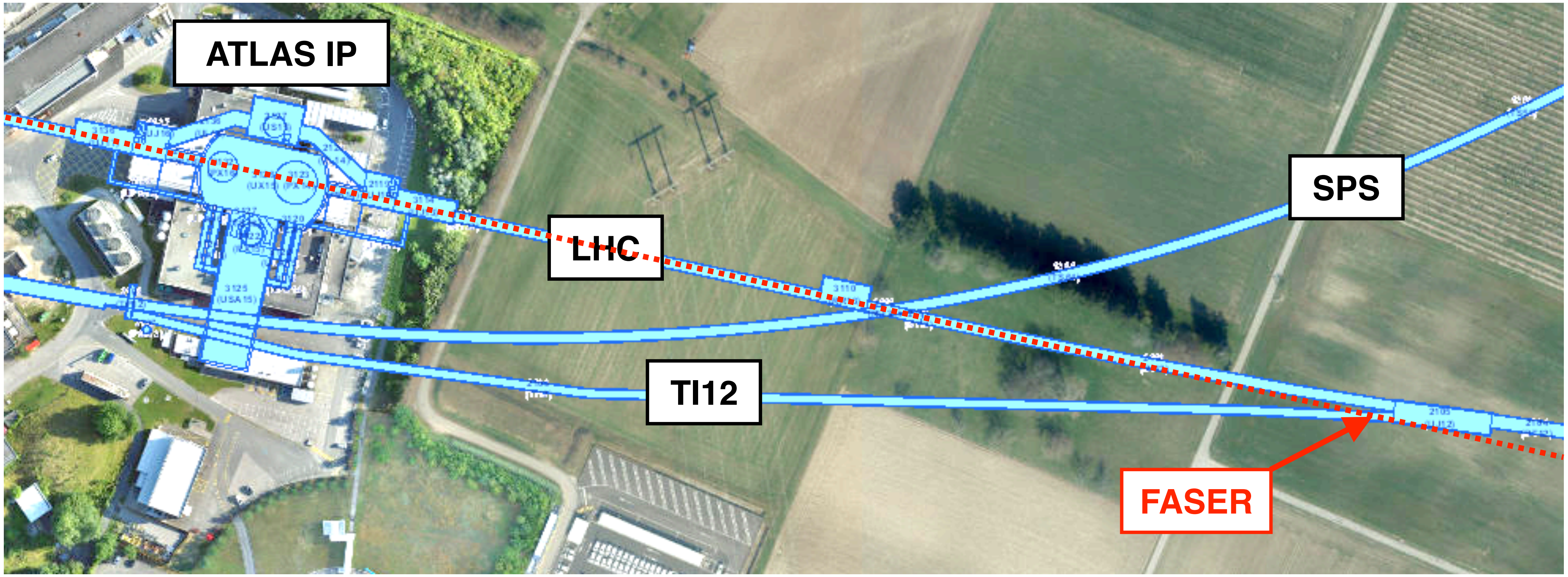
Long-Lived Particle Searches
Dark Photons

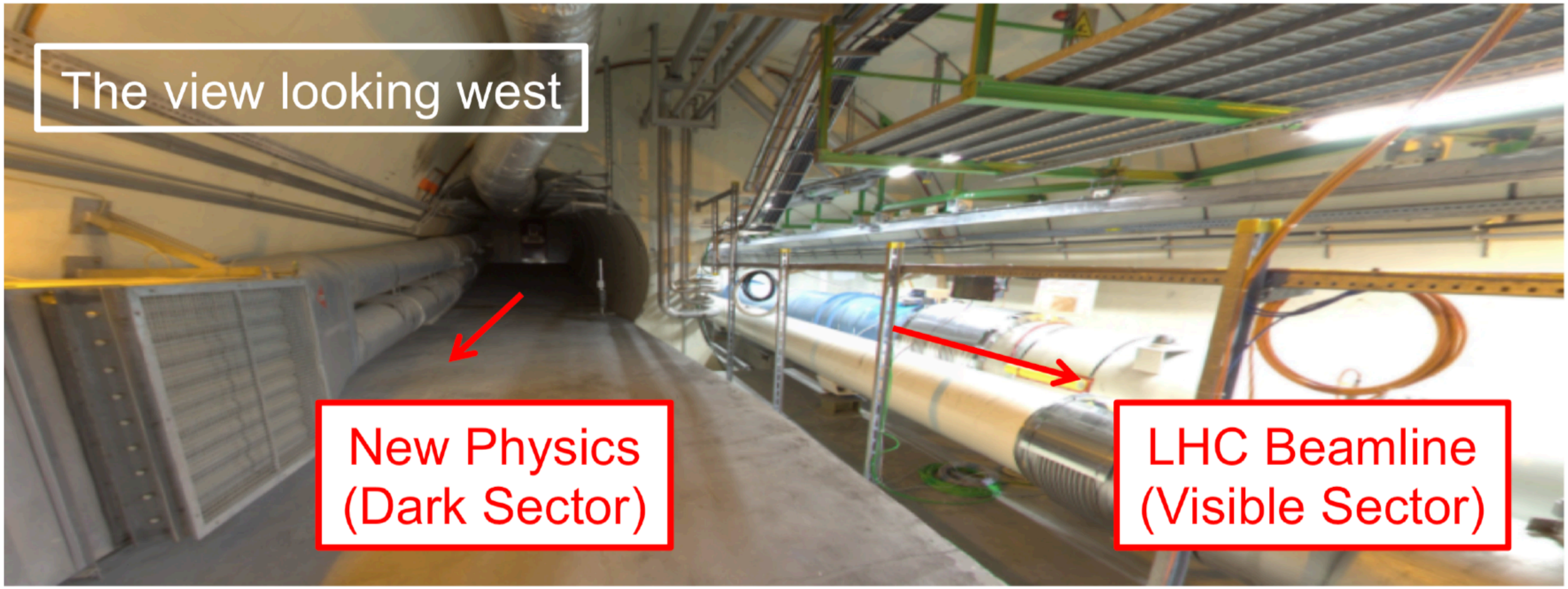
Neutrino Physics
FASERν / Neutrino Measurements

Summary and Conclusion

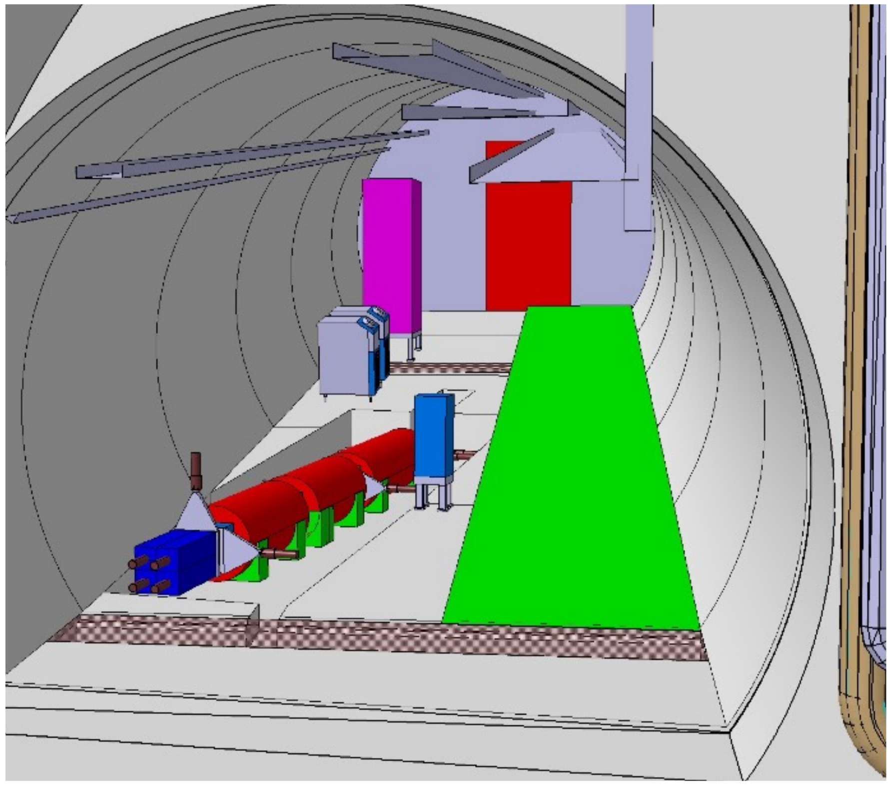
The FASER experiment

Location


ATLAS IP
LHC
SPS
TI12
FASER

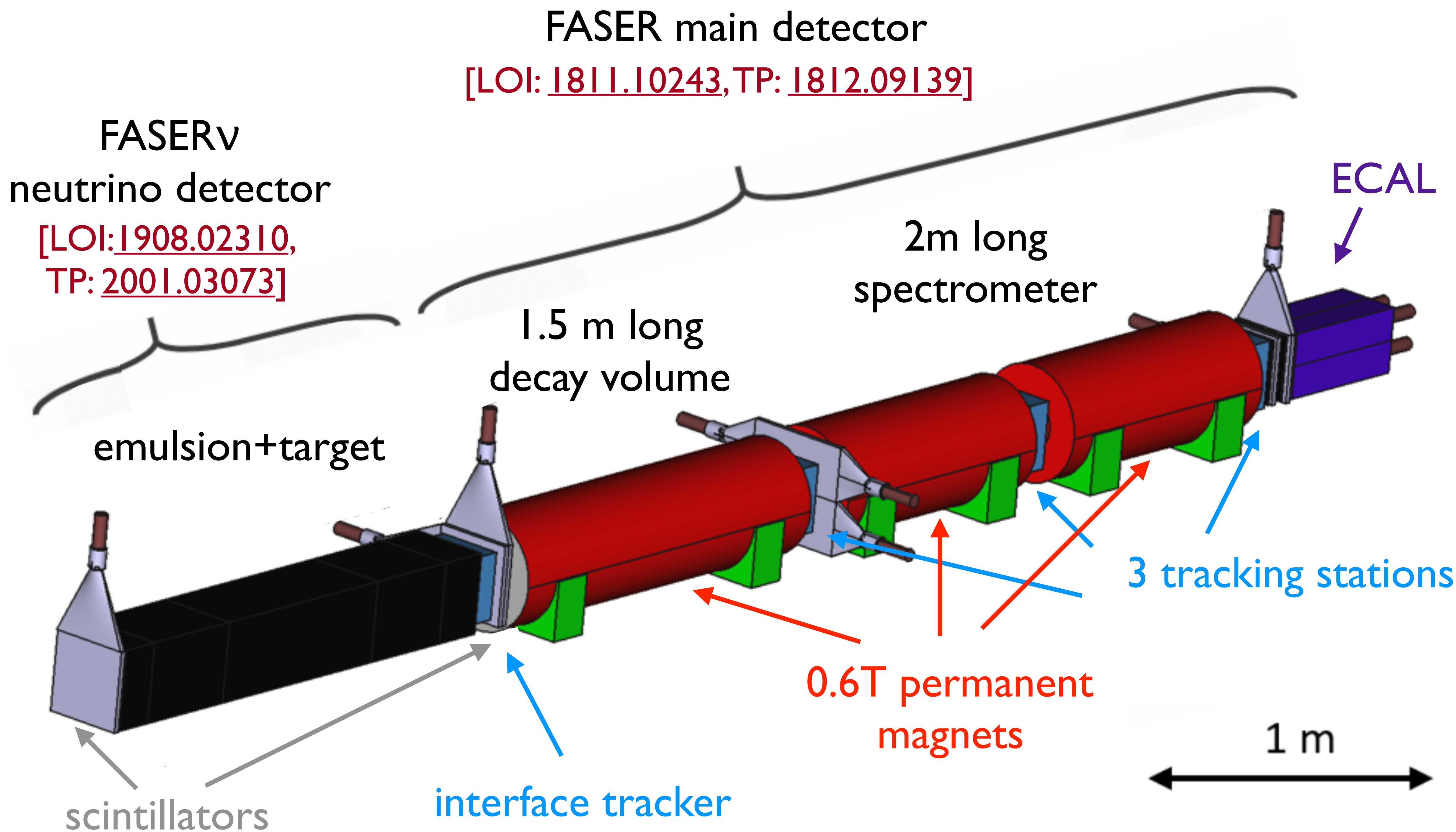

The view looking west
New Physics
(Dark Sector)
LHC Beamline
(Visible Sector)

FASER Location



FASER location is being prepared

FASER Detector



FASER Environment

General Considerations

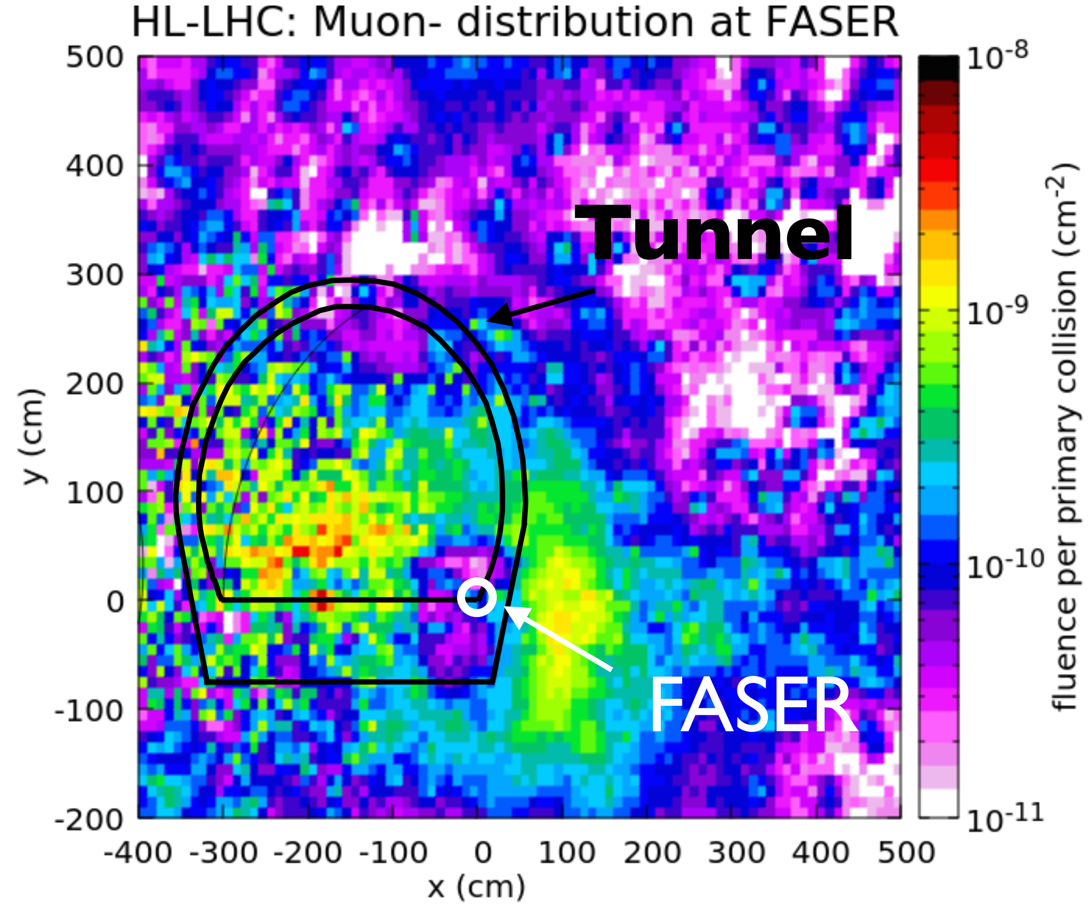
- LLP/neutrino signals have TeV energies, come from ATLAS IP
- shielding: natural (rock) and LHC infrastructure (magnets, absorbers)
- only muons/neutrino can transport TeV energies through ~100m rock

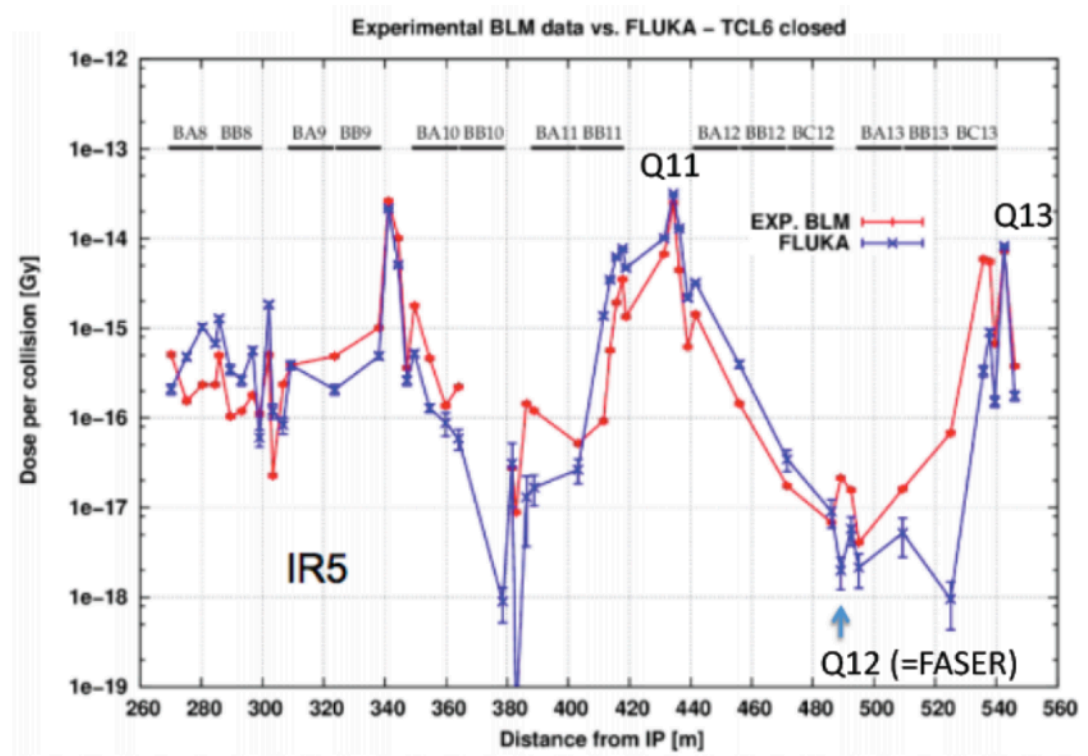
→ FASER's location is very quiet

FLUKA simulation (by CERN STI group)

- FASER in remarkable quite spot
- estimated muon flux from IP: $2{\cdot}10^4$ fb/cm^2
- HE particles from beam-gas collisions and proton losses near FASER are negligible
- other HE particles produced in muon radiative processes

→ use scintillator to veto muons for LLP searches

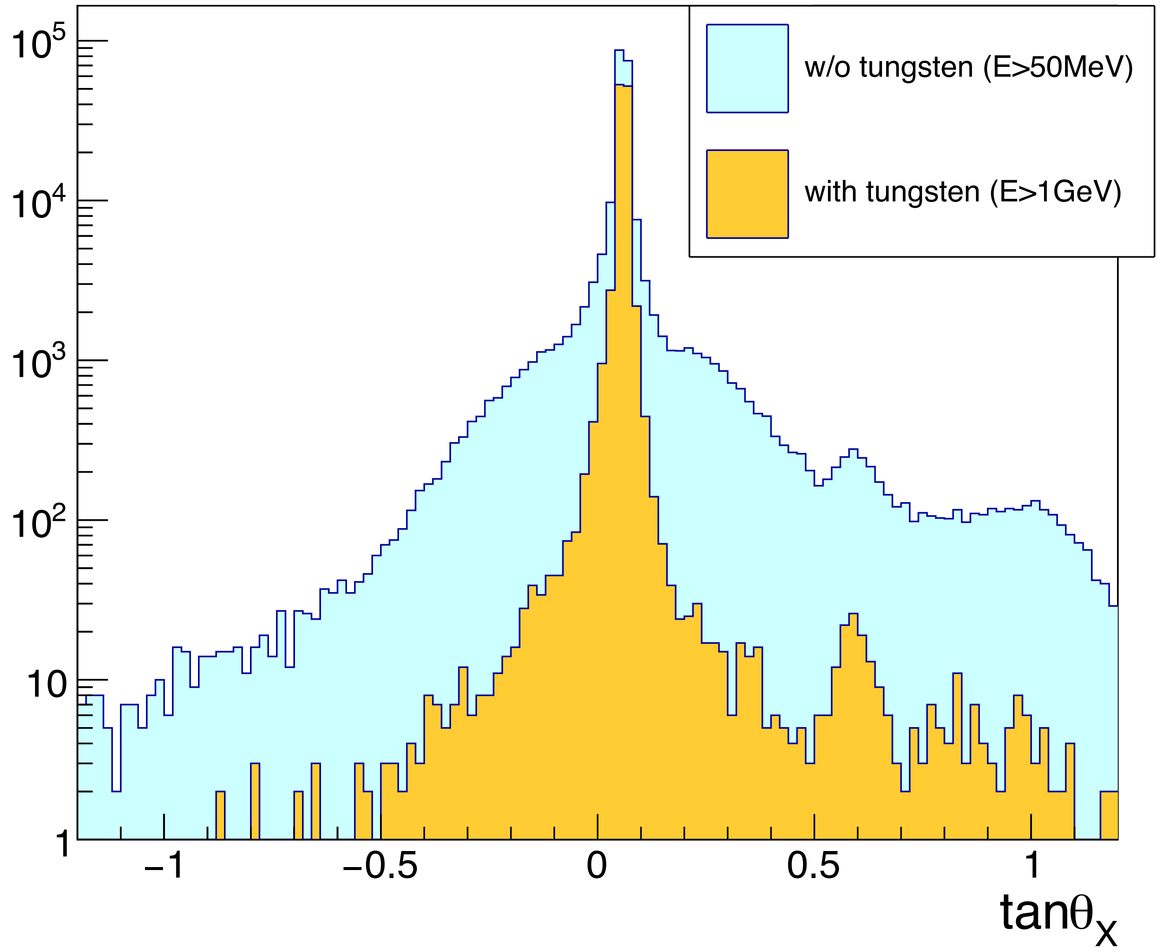




Sabate-Gilarte, Cerutti, Tsinganis (2018)

In-Situ Measurements

- BatMon radiation monitor:
  * low-energy radiation levels are promisingly low
- emulsion detector installed in 2018 in both TI18 and TI12
  * consistent with FLUKA simulations
  * more data analysis on-going



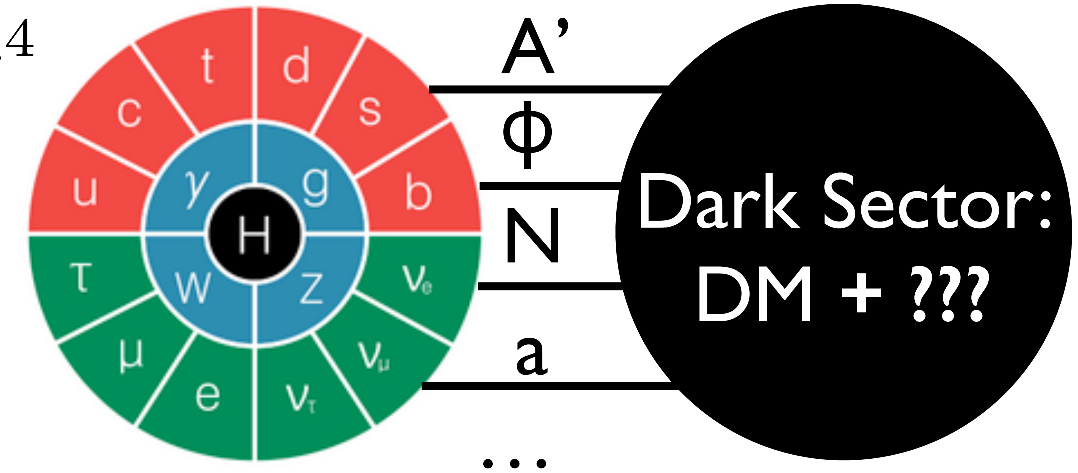
Long Lived Particles Searches at FASER

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, …



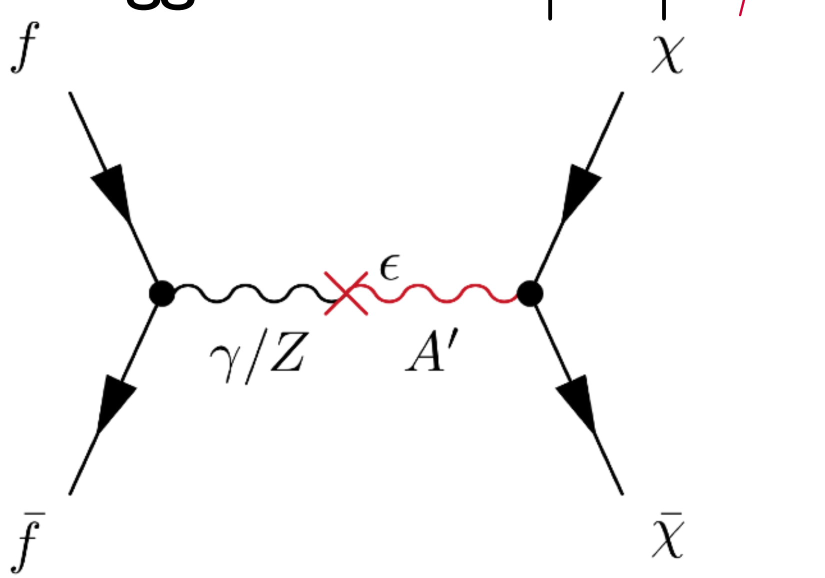
Prominent examples

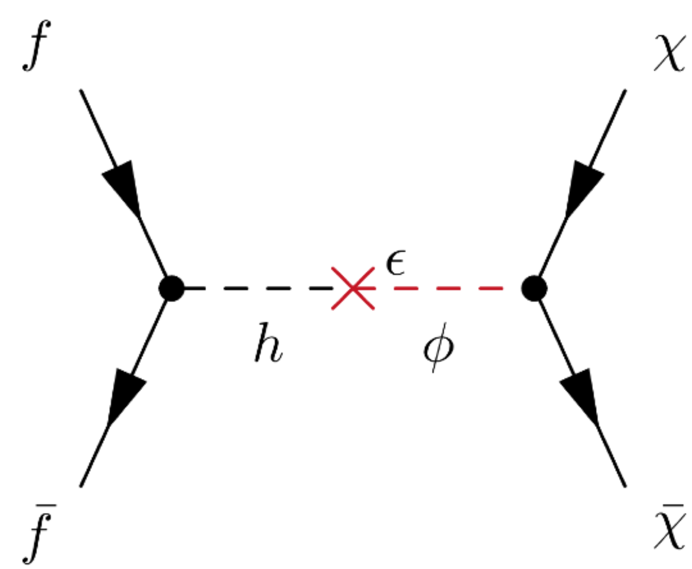
Dark Photon Portal: $\epsilon F^{\mu\nu} F'_{\mu\nu}$

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

Neutrino Portal: $yLHN$

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

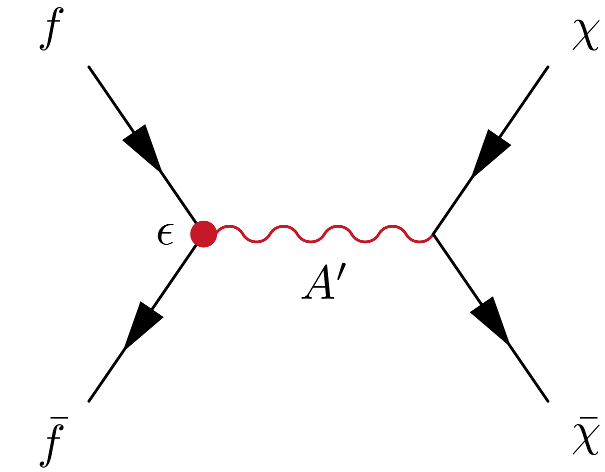




Long Lived Particles at FASER

Motivation

- dark matter solid evidence for new particles
- light DM (m~GeV) requires new mediators
  → light weakly coupled particles



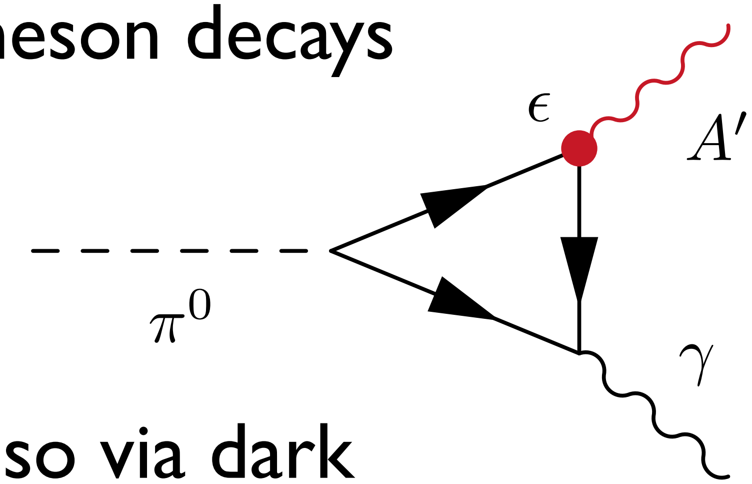
Dark Photons

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

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

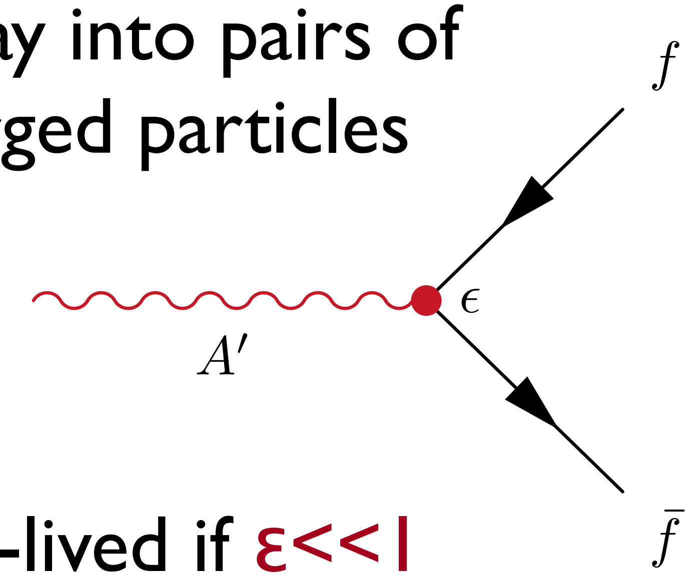
Dark Photons at FASER

- produced for example in meson decays



- also via dark Bremsstrahlung at large $m_{A'}$

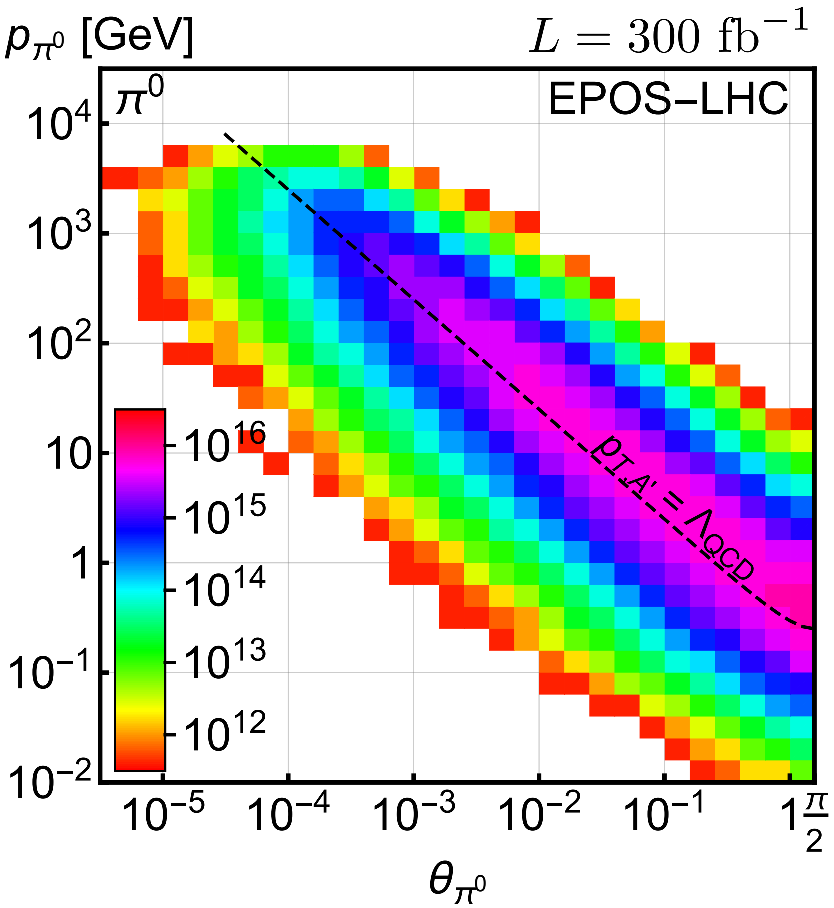
- decay into pairs of charged particles



- long-lived if ε<<1

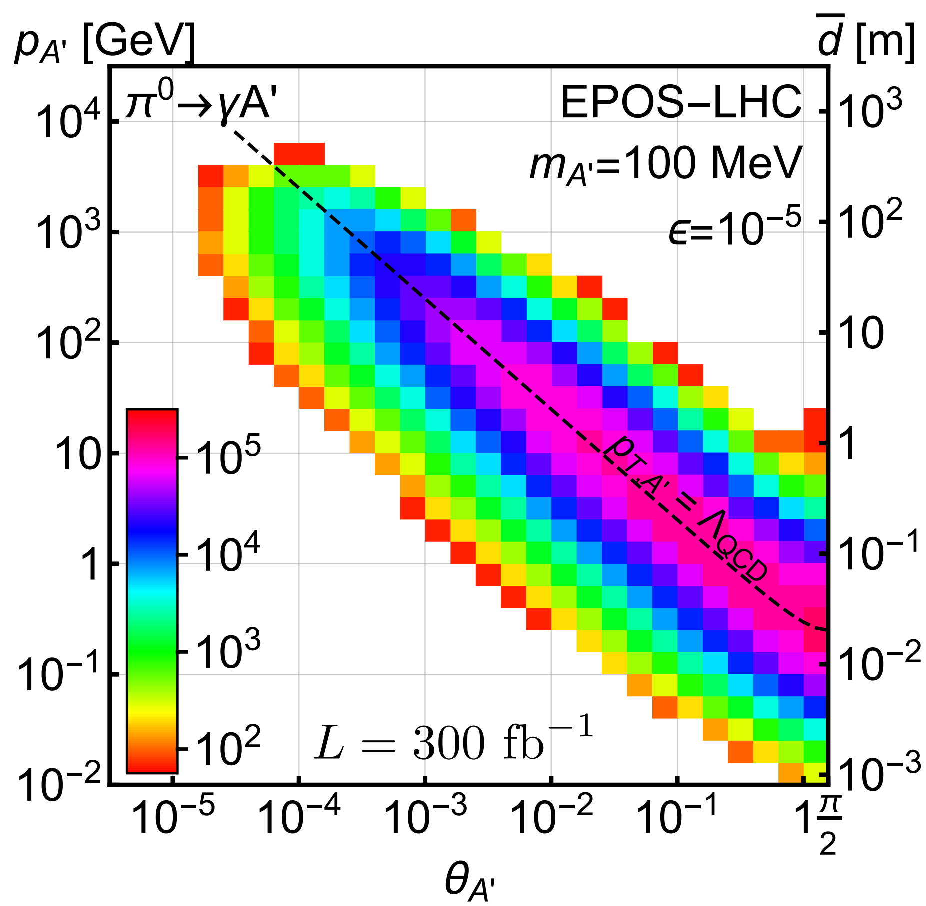
Long Lived Particles at FASER

Pions at IP



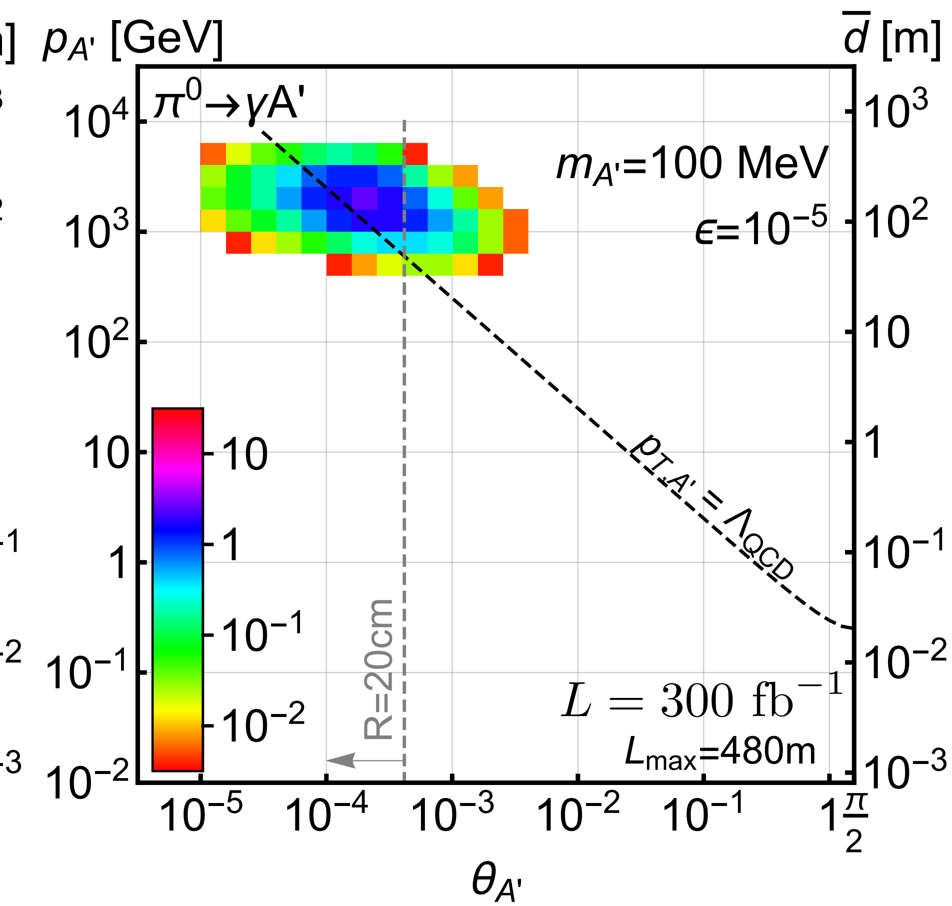
- dedicated hadronic interaction models, grounded on LHC data
- production peaks at pT~ Λ_{QCD}
- enormous event rates N ~ 10^{15} per bin

A' at IP



- production peaks at pT~ Λ_{QCD}
- rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- still rates N~10^5 per bin: LHC could be dark a photon factory

A' decay at FASER



- only highly boosted ~TeV A' arrive at FASER
- rates suppressed by decay requirements
- still rates N~100 signal events within 20cm of beam collision axis

Long Lived Particles at FASER

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

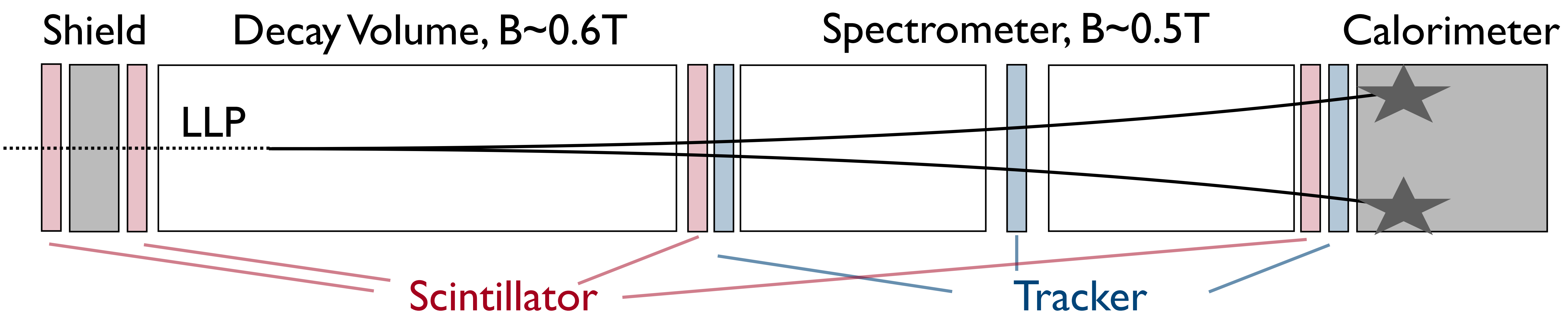
Signal is striking

- 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

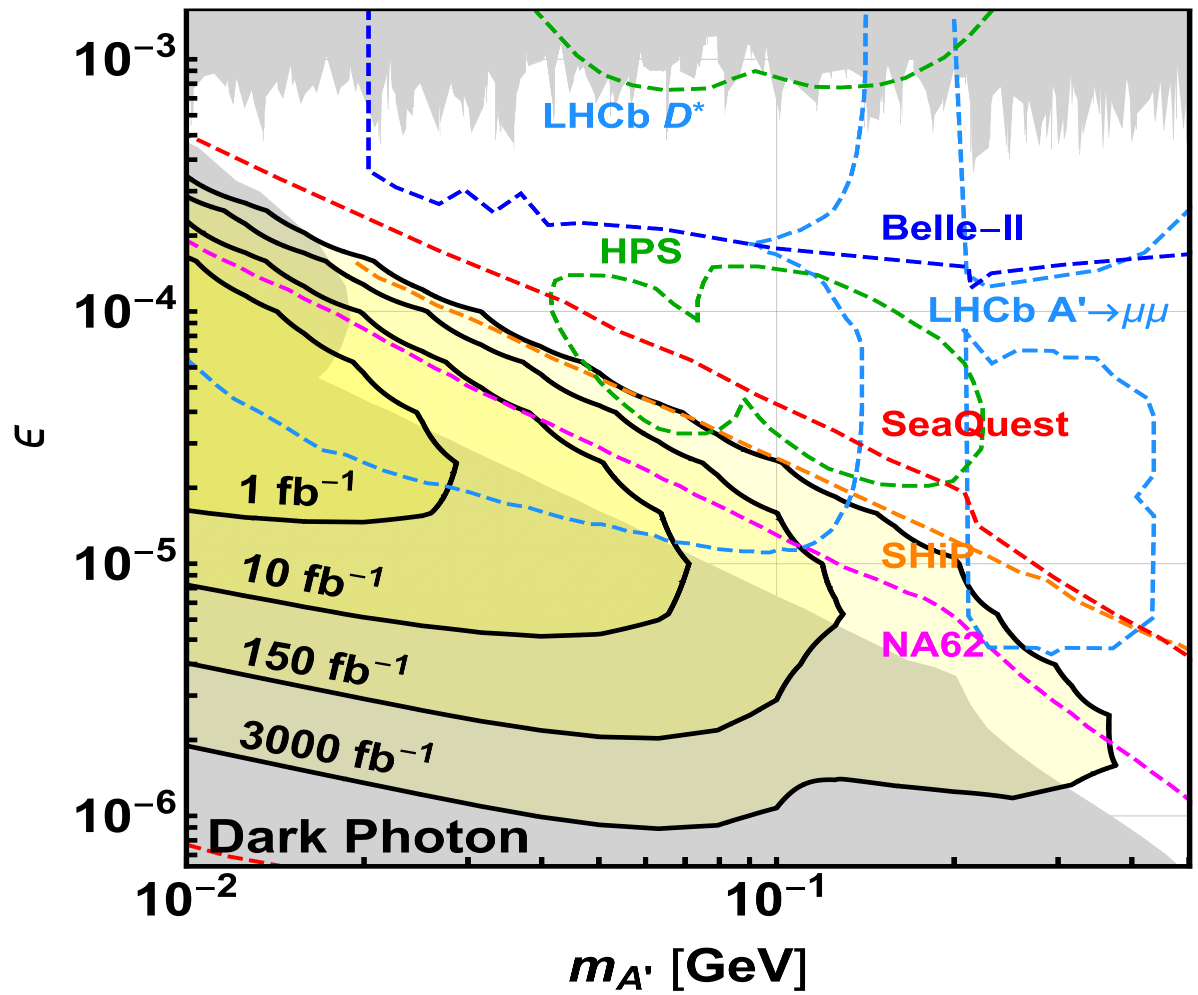
  → reduce BG to negligible levels

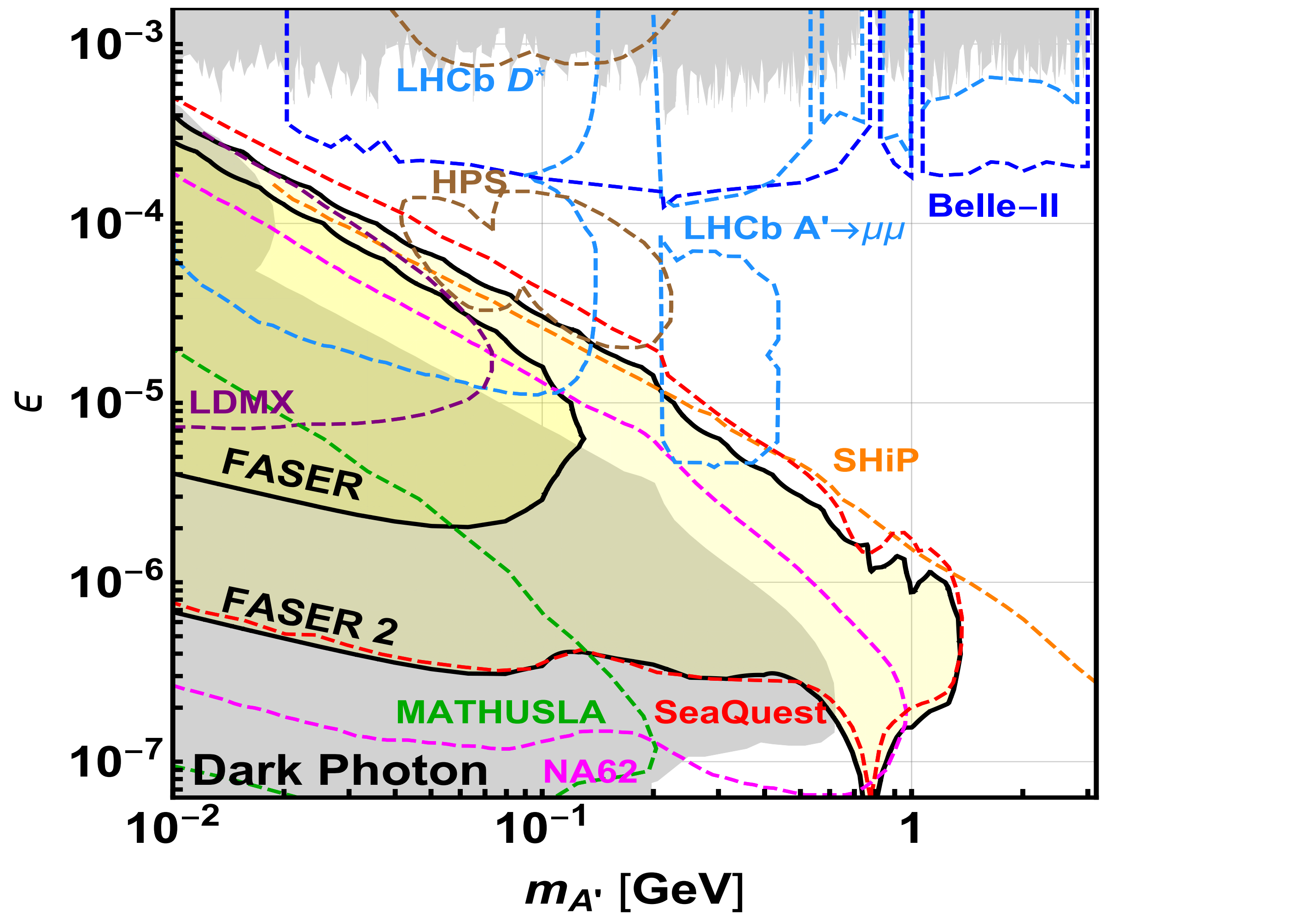


Dark Photon Reach

- consider all production channels
- include A' → ee, μμ, π⁺π⁻
- require N=3 events

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



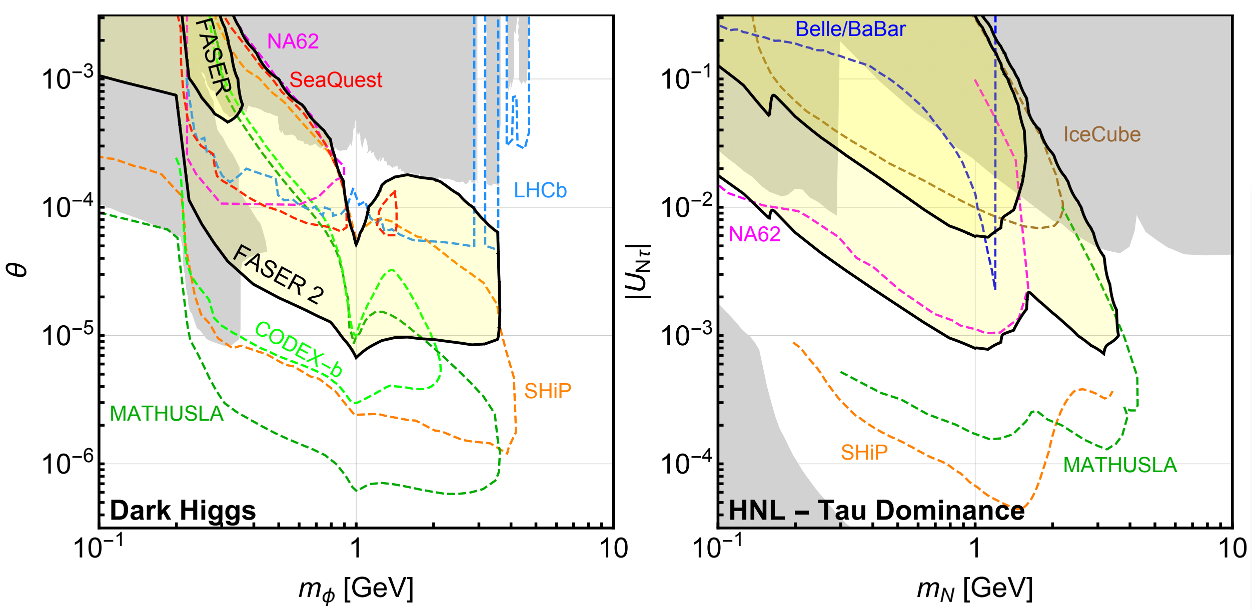


- reach limited by decay length (high ε) and production rate (low ε)
- new parameter space probed with just 1 fb^{-1} in 2021
- FASER 2 significantly improves reach at higher masses

Long Lived Particles at FASER

Physics Sensitivity Studies

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



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

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]	—	√

1. Jonathan L. Feng, Iftah Galon, Felix Kling, Sebastian Trojanowski, FASER: ForwArd Search ExpeRiment at the LHC, Phys. Rev. D 97, 035001 (2018)
2. Jonathan L. Feng, Iftah Galon, Felix Kling, Sebastian Trojanowski, Dark Higgs Bosons at FASER, Phys. Rev. D 97, 055034 (2018)
3. Brian Batell, Ayres Freitas, Ahmed Ismail, David McKeen, Flavor-Specific Scalar Mediators, Phys. Rev. D 98, 055026 (2018)
4. Felix Kling, Sebastian Trojanowski, Heavy Neutral Leptons at FASER, Phys. Rev. D 97, 095016 (2018)
5. Juan Carlos Helo, Martin Hirsch, Zeren Simon Wang, Heavy Neutral Fermions at the High-Luminosity LHC, JHEP 1807 (2018) 056
6. Martin Bauer, Patrick Foldenauer, Joerg Jaeckel, Hunting All the Hidden Photons, JHEP 1807 (2018) 094
7. Jonathan L. Feng, Iftah Galon, Felix Kling, Sebastian Trojanowski, ALPs at FASER: The LHC as a Photon Beam Dump, Phys. Rev. D 98, 055021 (2018)
8. Asher Berlin, Felix Kling, Inelastic Dark Matter at the LHC Lifetime Frontier: ATLAS, CMS, LHCb, CODEX-b, FASER, and MATHUSLA, Phys. Rev. D 99, 015021 (2019)
9. Daniel Dercks, Jordy de Vries, Herbi K. Dreiner, Zeren Simon Wang, R-parity Violation and Light Neutralinos at CODEX-b, FASER, and MATHUSLA, Phys. Rev. D 99, 055039 (2019)
10. Patrick deNiverville, Hye-Sung Lee, Implications of the dark axion portal for SHiP and FASER and the advantages of monophoton signals, Phys. Rev. D 100, 055017
11. Frank F. Deppisch, Suchita Kulkarni, Wei Liu, Heavy neutrino production via Z' at the lifetime frontier, Phys. Rev. D 100, 035005
12. I. Boiarska, K. Bondarenko, A. Boyarsky, M. Ovchynnikov, O. Ruchayskiy, A. Sokolenko, Light scalar production from Higgs bosons and FASER 2, JHEP 05 (2020) 049
13. N. Okada, D. Raut, Hunting Inflaton at FASER
14. K. Jodlowski, F. Kling, L. Roszkowski, S. Trojanowski, Extending the reach of FASER, MATHUSLA and SHiP towards smaller lifetimes using secondary production, Phys. Rev. D 101, 095020
15. M. Bahraminasr, P. Bakhti, M. Rajaee, Sensitivities to secret neutrino interaction at FASERν
16. P. Bakhti, Y. Farzan, S. Pascoli, Unravelling the richness of dark sector by FASERν
17. F. Kling, S. Trojanowski, Looking forward to test the KOTO anomaly with FASER
18. B. Dutta, S. Ghosh, J. Kumar, Opportunities for probing U(1)T3R with light mediators
19. C. Csaki, R. Tito D'Agnolo, M. Geller, A. Ismail, Crunching Dilaton, Hidden Naturalness
20. R. Maciula, A. Szczurek, Intrinsic charm in the nucleon and charm production at large rapidities in collinear, hybrid and kT-factorization approaches
21. K. J. Kelly, M. Sen, W. Tangarife, Y. Zhang, Origin of Sterile Neutrino Dark Matter via Vector Secret Neutrino Interactions
22. N. Okada, S. Okada, Q. Shafi, Light Z' and Dark Matter from U(1)X Gauge Symmetry
23. L. Darmé, S. A. R. Ellis, T. You, Light Dark Sectors through the Fermion Portal
24. R. N. Mohapatra, N. Okada, Dark Matter Constraints on Low Mass and Weakly Coupled B-L Gauge Boson
25. W. Bai, M. Diwan, M. V. Garzelli, Y. S. Jeong, M. H. Reno, Far-forward neutrinos at the Large Hadron Collider
26. F. Kling, Probing Light Gauge Bosons in Tau Neutrino Experiments
27. Y. Jho, J. Kim, P. Ko, S. C. Park, Search for sterile neutrino with light gauge interactions: recasting collider, beam-dump, and neutrino telescope searches
28. T. Araki, K. Asai, H. Otono, T. Shimomura, Y. Takubo, Dark Photon from Light Scalar Boson Decays at FASER

Neutrino Measurements at FASER

Idea/LOI: 1908.02310

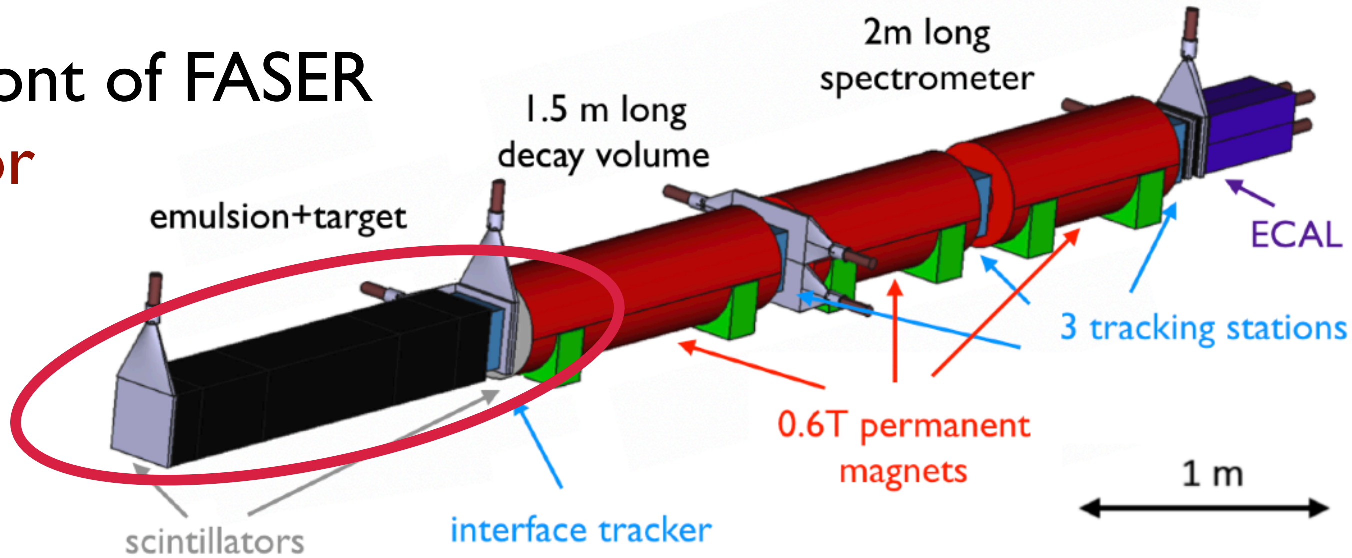
TP: 2001.03073

FASERν Motivation

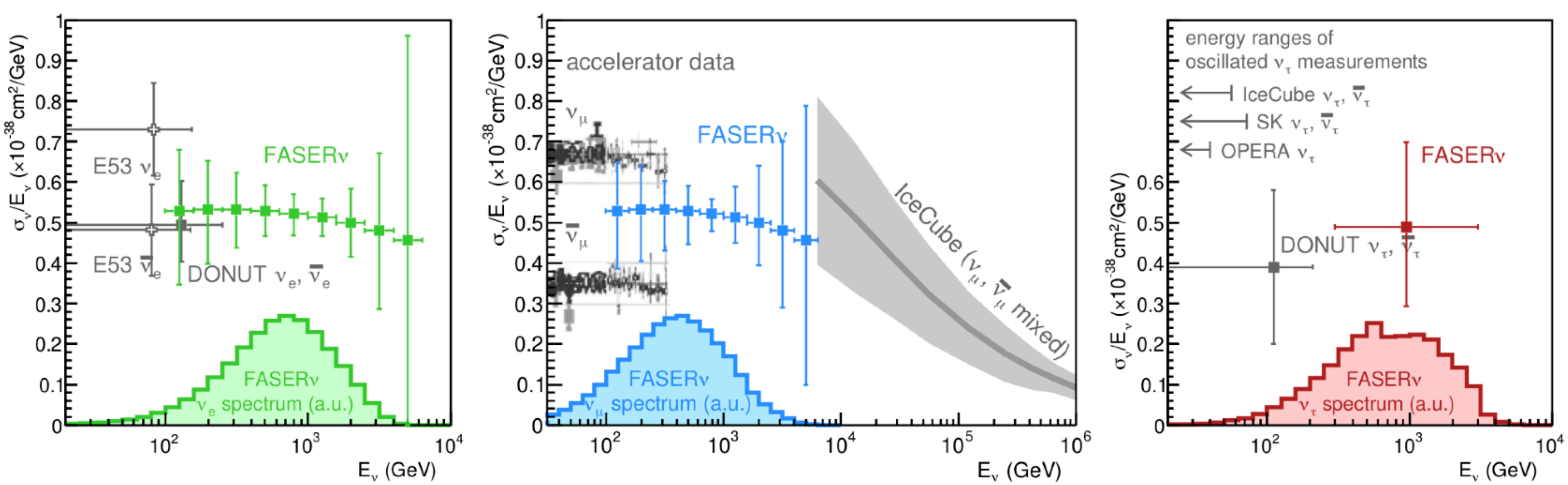
- neutrinos detected from many sources, but not from colliders

- 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

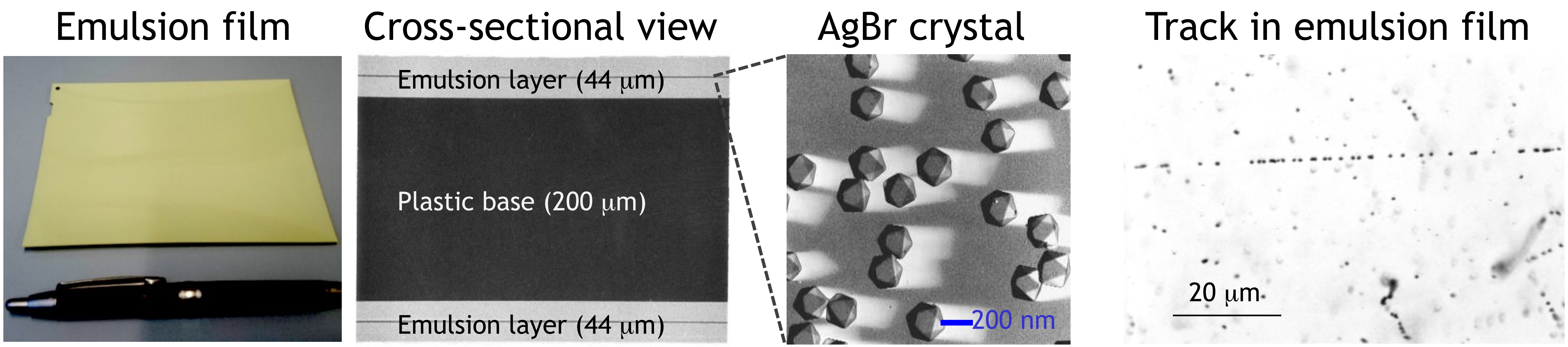


- neutrino physics at TeV energies
  * probe unconstrained neutrino cross sections at TeV for all 3 flavors

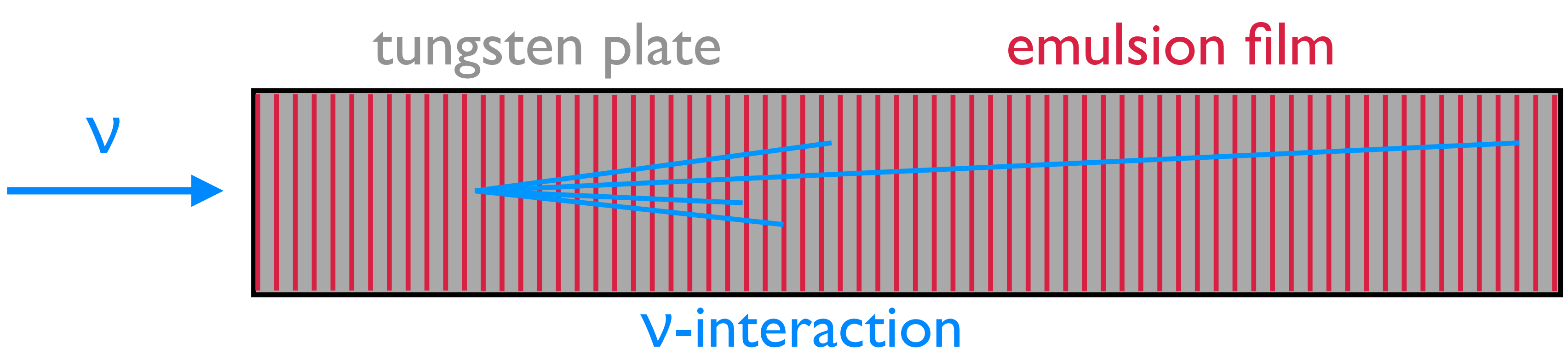


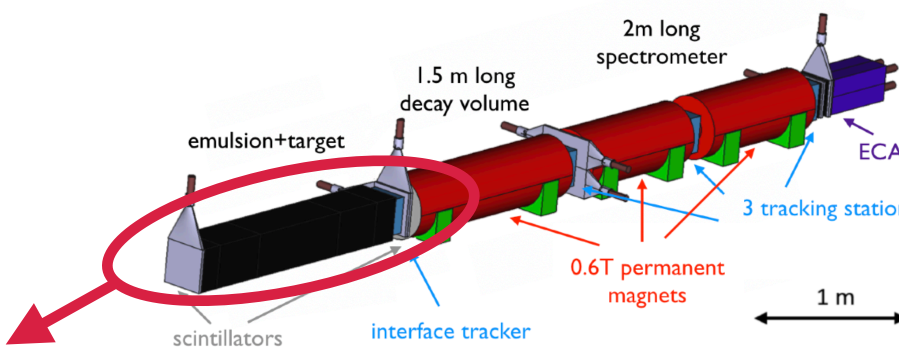
FASERν Detector

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

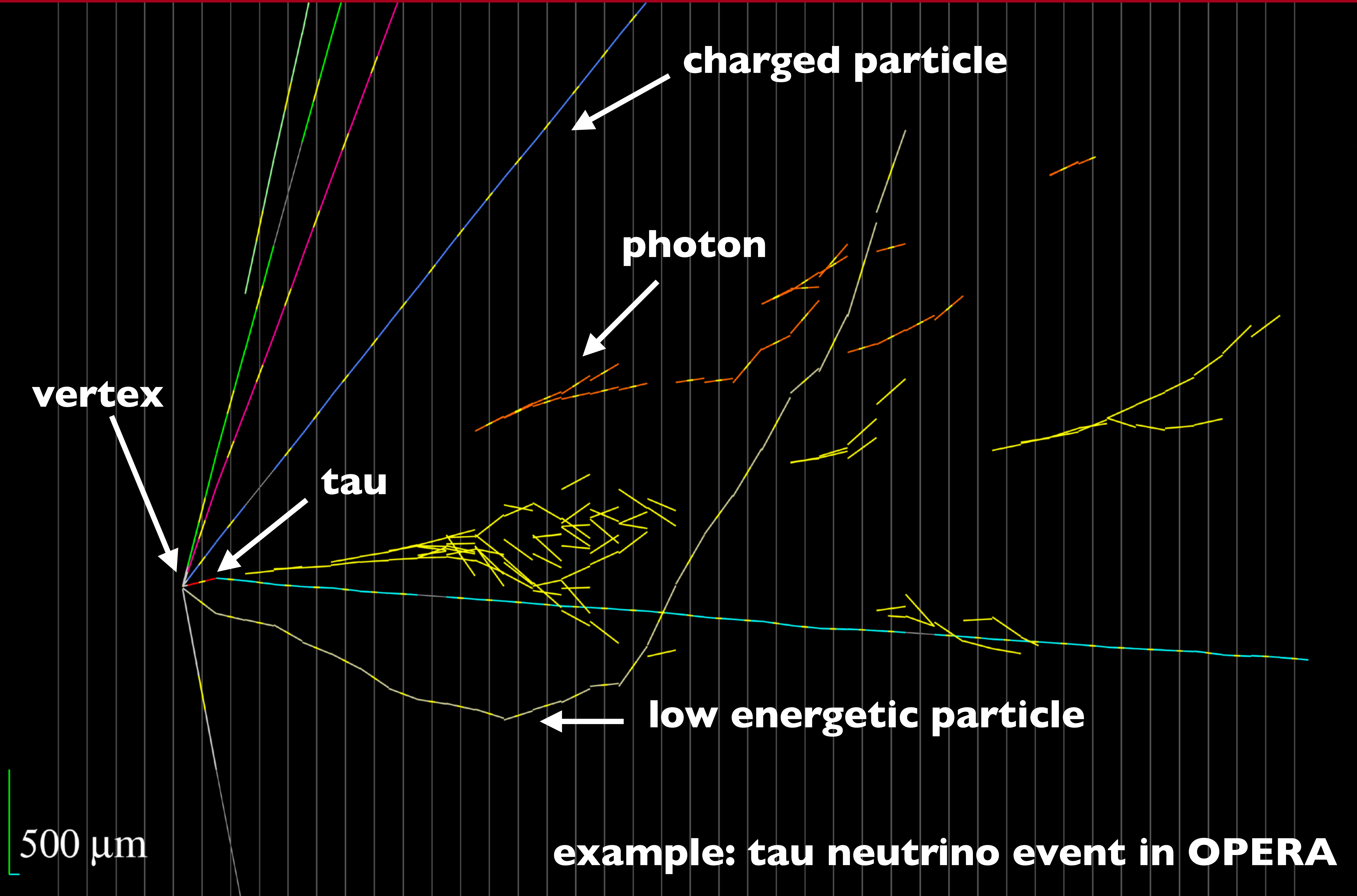


- FASERν: 1000 emulsion films interleaved with 1mm tungsten plates
  * 3D tracking devices with 50 nm spatial precision
  * sensitive to neutrino interactions
  * allows particle identification



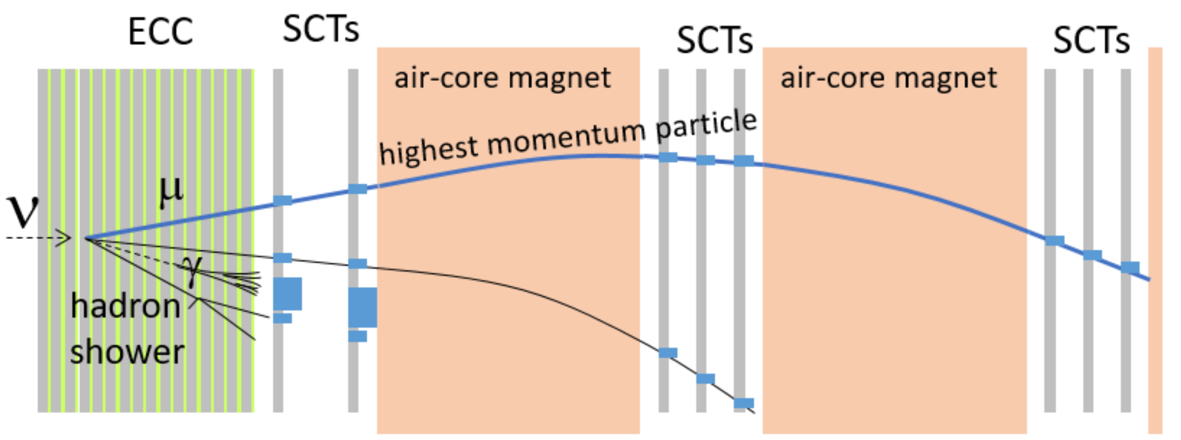


FASERν Detector



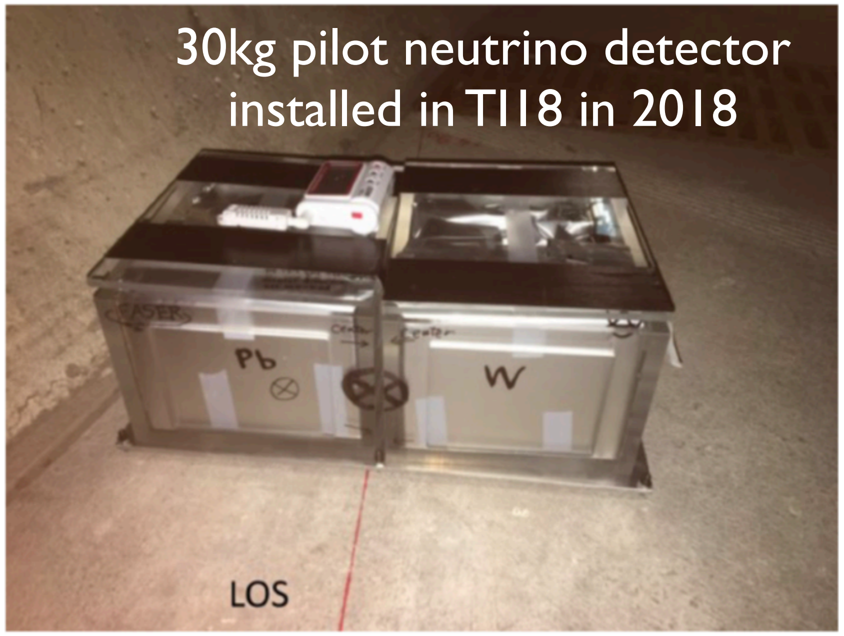
FASERν Detector

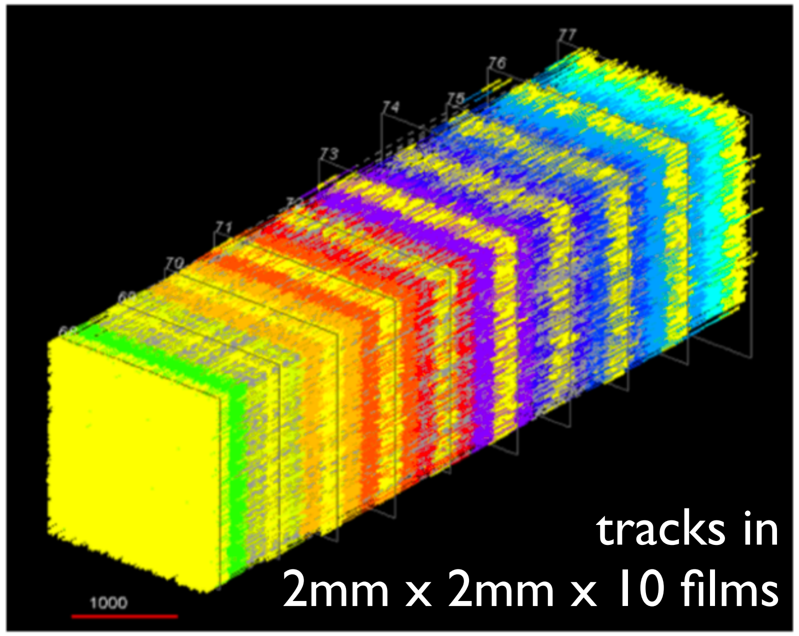
- detector performance has been studied
  * flavor identification
  * vertex finding efficiency: ~80%
  * energy resolution: ~30%

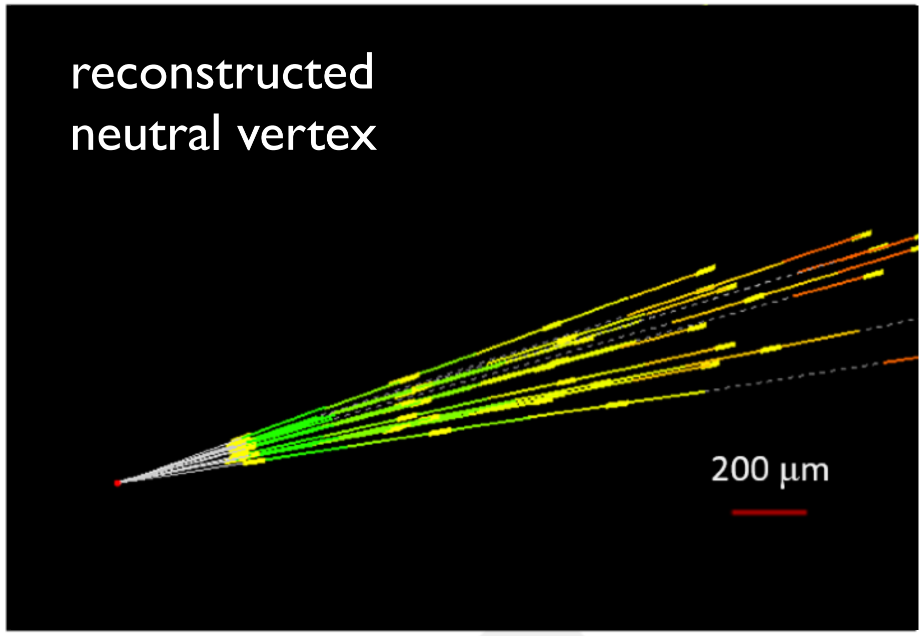


- global reconstruction with the FASER detector
  * distinguish neutrino / anti-neutrino
  * improve neutrino energy reconstruction
  * background rejection

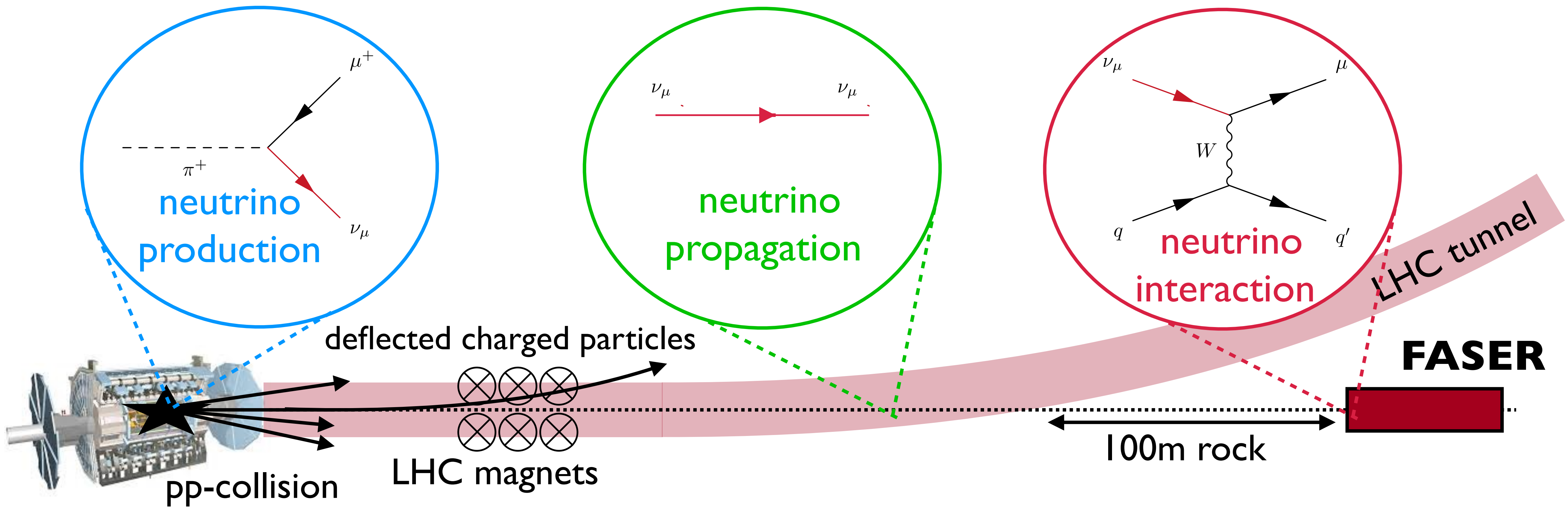
- pilot detector data is currently analyzed
  * 30 kg detector was installed in TI18, 12.5 fb^{-1} of data collected 2018
  * goal: first neutrino detection at the LHC







FASERν Physics Potential

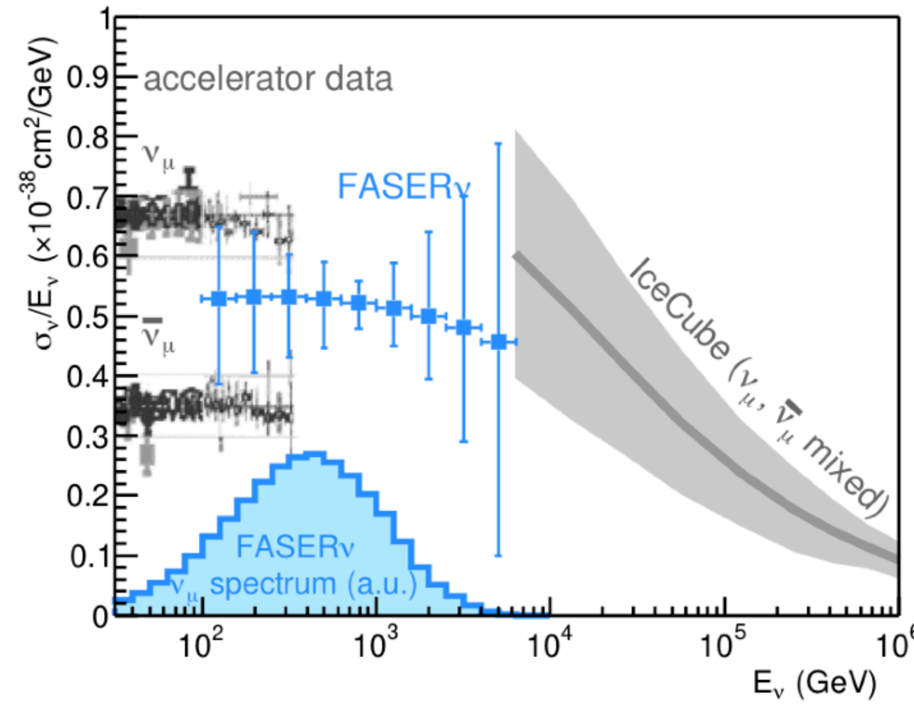


In the following, I will present some ideas.

Most of them were not investigated in detail yet.

FASERν Physics Potential: Neutrino Physics

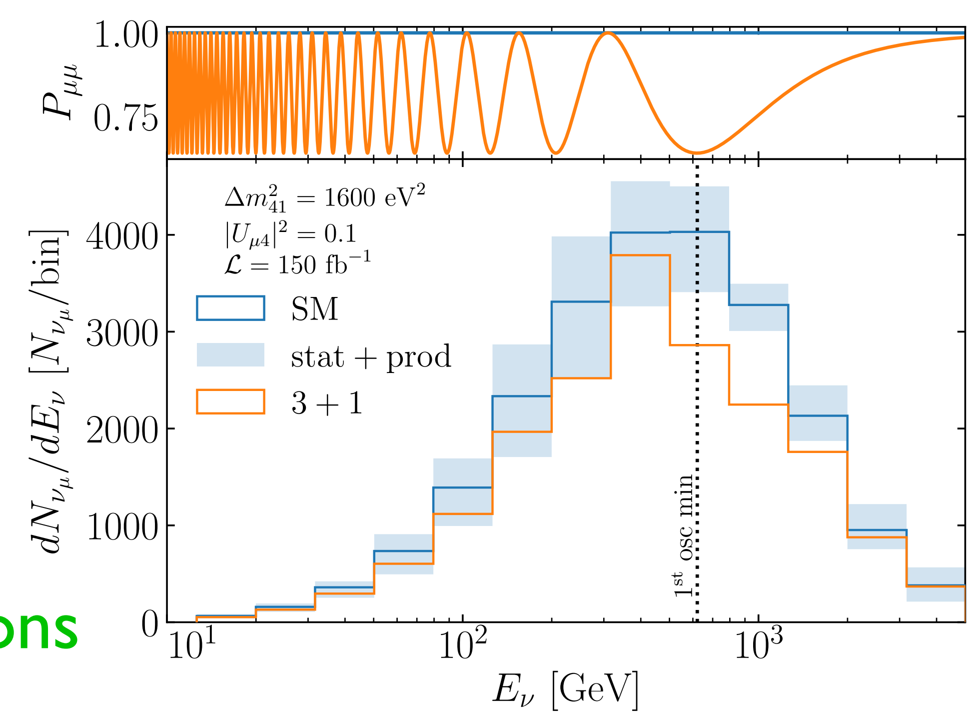
- **Neutrino cross section at TeV energies**
  * unexplored energy range for all three flavors
  * charged and neutral current interactions
    → sensitivity to non-standard interactions ?



- **Tau neutrino physics**
  * so far only ~20 tau neutrino interactions identified
  * thousands of tau neutrino events possible at HL-LHC
  * precision studies of tau neutrino properties
    → tau neutrino cross section
    → tau neutrino magnetic moment ?
    → test lepton flavor universality via ν_τ c → τ b ?

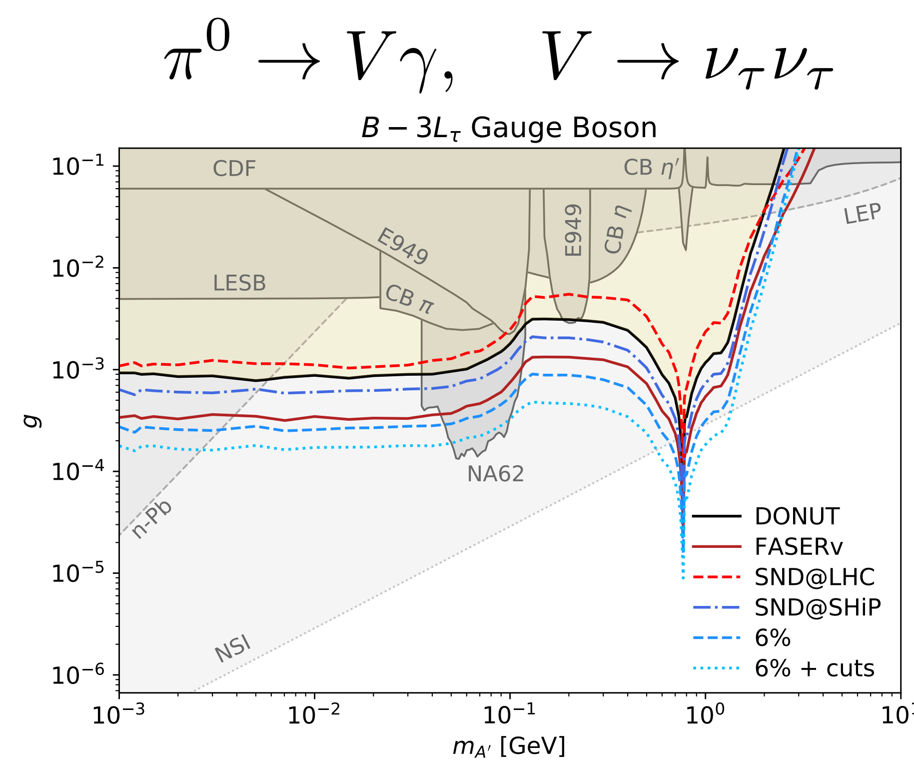
- **Neutrino interaction event shapes**
  * FASERν will record topology/kinematics of interaction
    → validation/tuning of neutrino event generators ?

- **Neutrino oscillations**
  * no neutrino oscillations expected in SM
  * sterile neutrinos with mass ~40eV can cause oscillations
  * use FASERν as short-baseline neutrino experiment



FASERν Physics Potential: BSM Physics

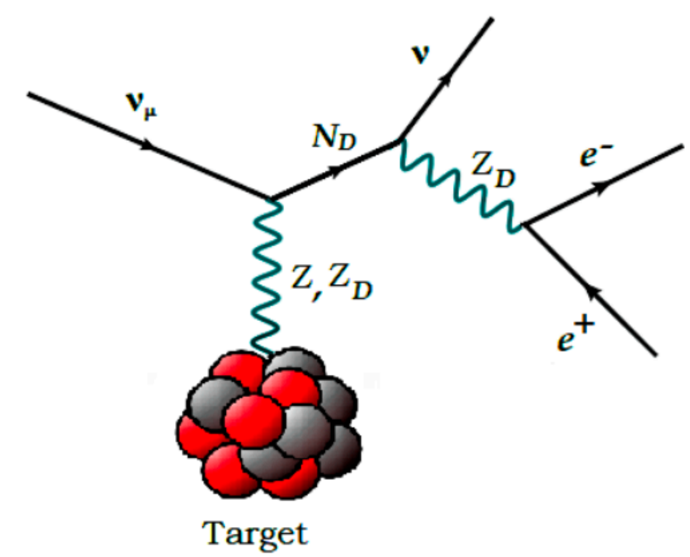
- **BSM tau-neutrino production**
  * tau neutrino flux small in SM
  * new light weakly coupled gauge bosons could decay into tau neutrinos: arXiv:2005.03594



- **DM scattering**
  * if DM is light, LHC can produce an energetic and collimated DM beam towards FASER
    → can we probe DM via scattering in FASERν ?
  * example: π→Vγ with V → XX

- **FASERν as muon beam dump**
  * about 10^9 muons will pass FASERν during LHC Run3
    → can we use FASERν as muon beam dump experiment ?

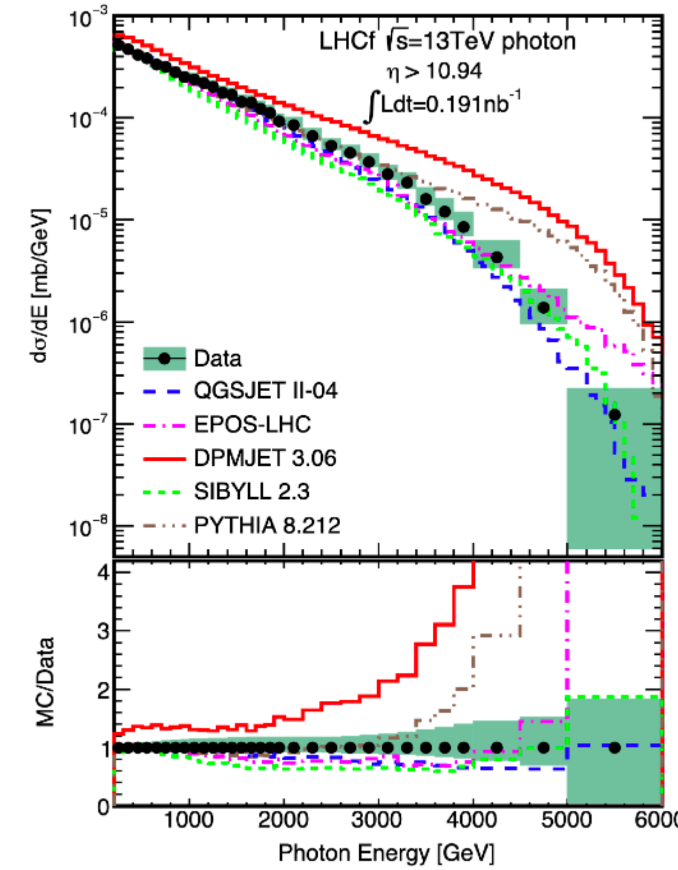
- **Probe of neutrino-philic new physics**
  * many models of new physics predict new particles that can interact with neutrinos
    → can we use FASERν to probe such models



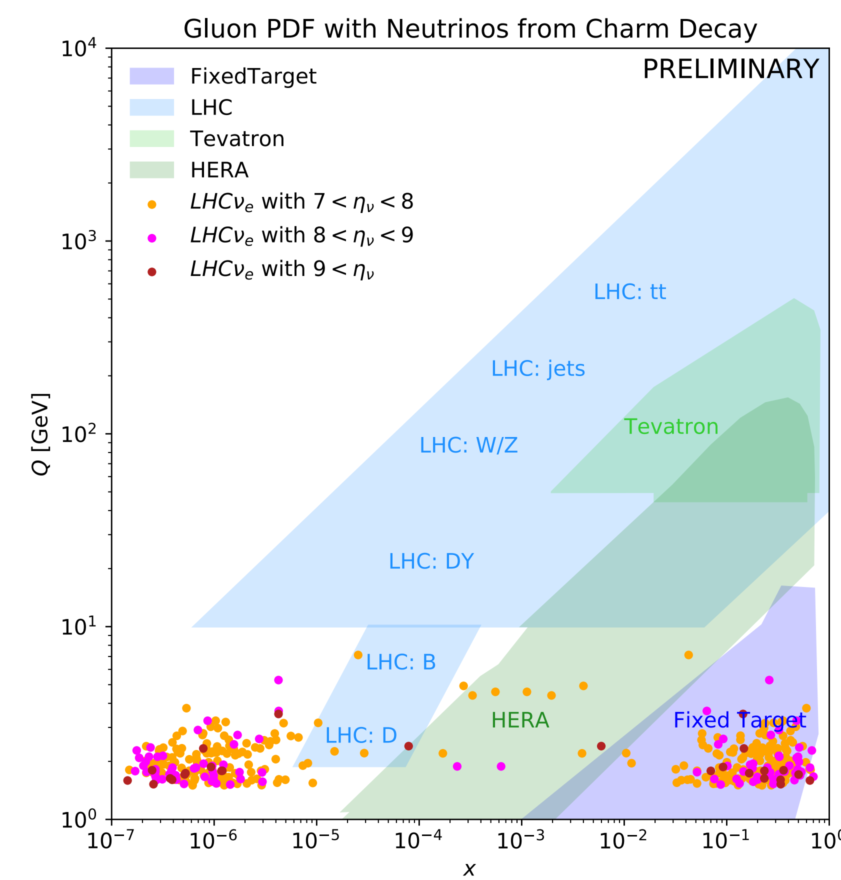
from arXiv:1807.09877

FASERν Physics Potential: QCD

- **Constraining forward particle production**
  - * forward particle production is poorly constrained
  - * FASERν neutrinos flux measurements will provide complimentary constraints
  - * light hadrons described by non-perturbative physics
    - → validate/improve these hadronic interaction models ?
  - * heavy hadrons can be described by perturbative QCD
    - → constrain low-x gluon PDF ?
    - → probe intrinsic charm ?



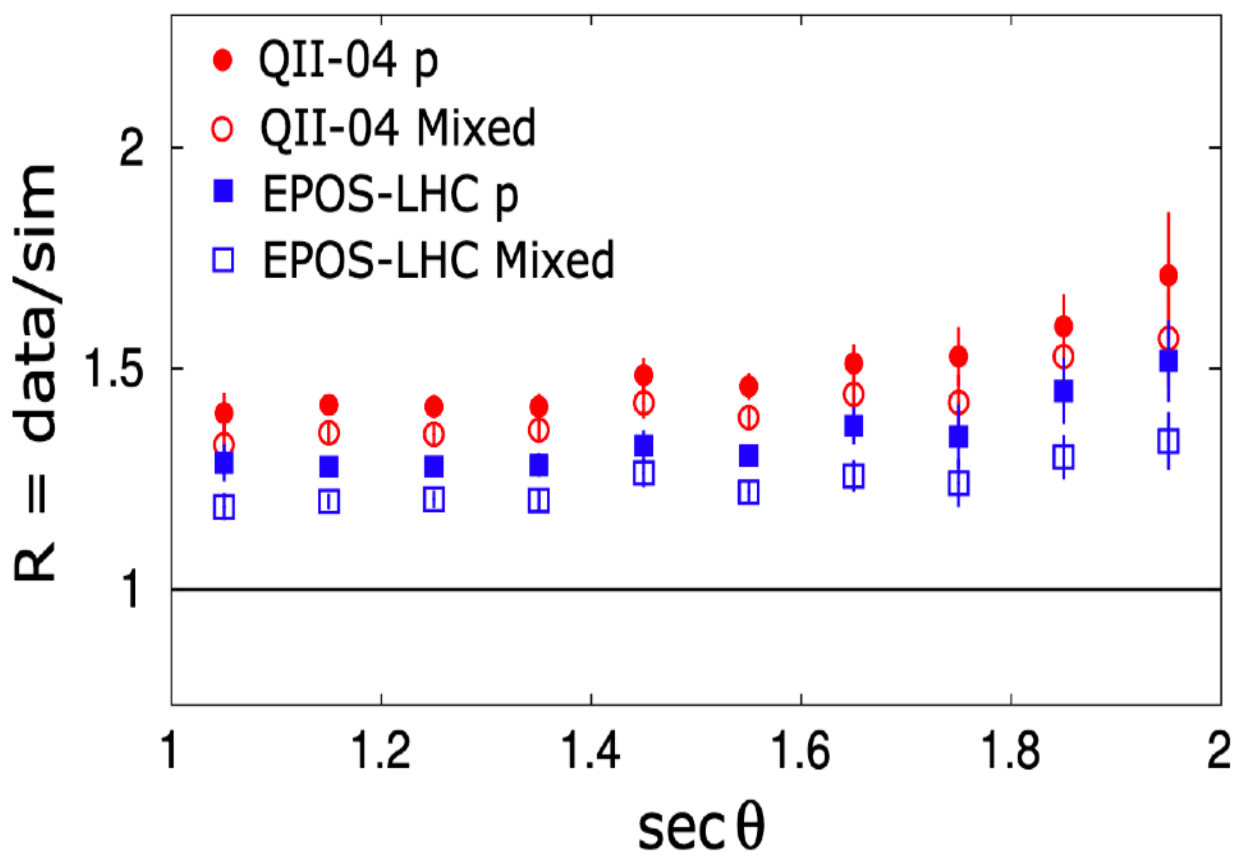
- **PDFs via Neutrino scattering**
  - * DIS neutrino scattering is sensitive to PDFs
    - → nuclear PDFs at a variety of targets ?
    - → ν s → l c as probe of the strange PDF ?

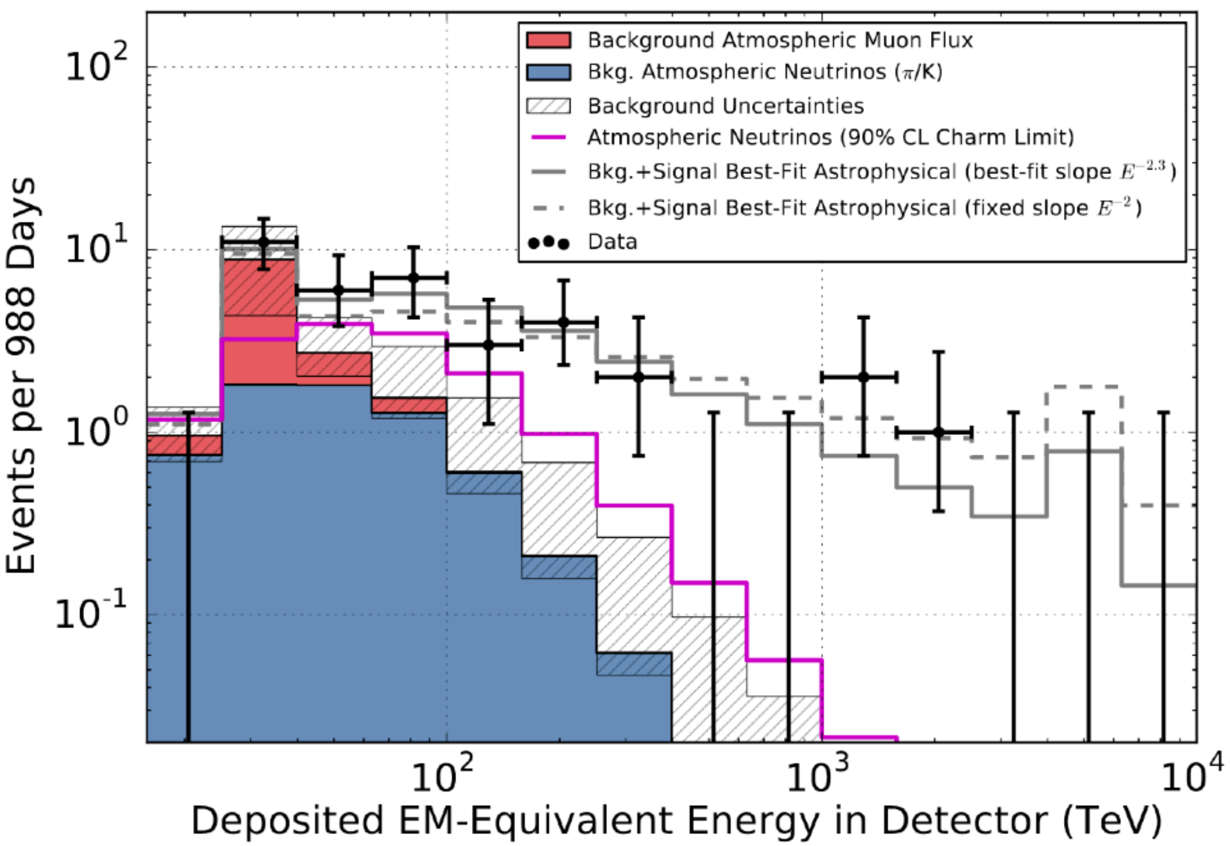


FASERν Physics Potential: Comics

- **Muon problem in CR physics**
  Cosmic Ray experiments have reported an excess in the number of muons over expectations competed using extrapolations of hadronic interaction models tuned to LHC data at the few σ level. See 1610.08509

- **Prompt Atmospheric Neutrinos**
  Prompt Atmospheric Neutrinos from charm decay are the dominant background for IceCube's comic neutrinos, and we currently have no data and no theory for this process. See 1405.5303



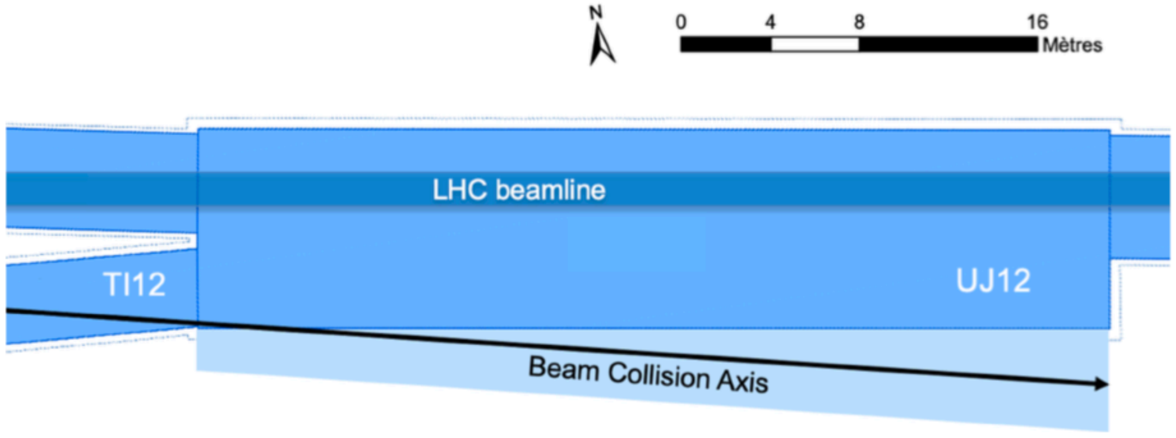


Summary and Outlook

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 are planning 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 $\sim 10^5 \nu_e$, $\sim 10^6 \nu_\mu$ and $\sim 10^3 \nu_\tau$ 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



- 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

SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

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

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

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**

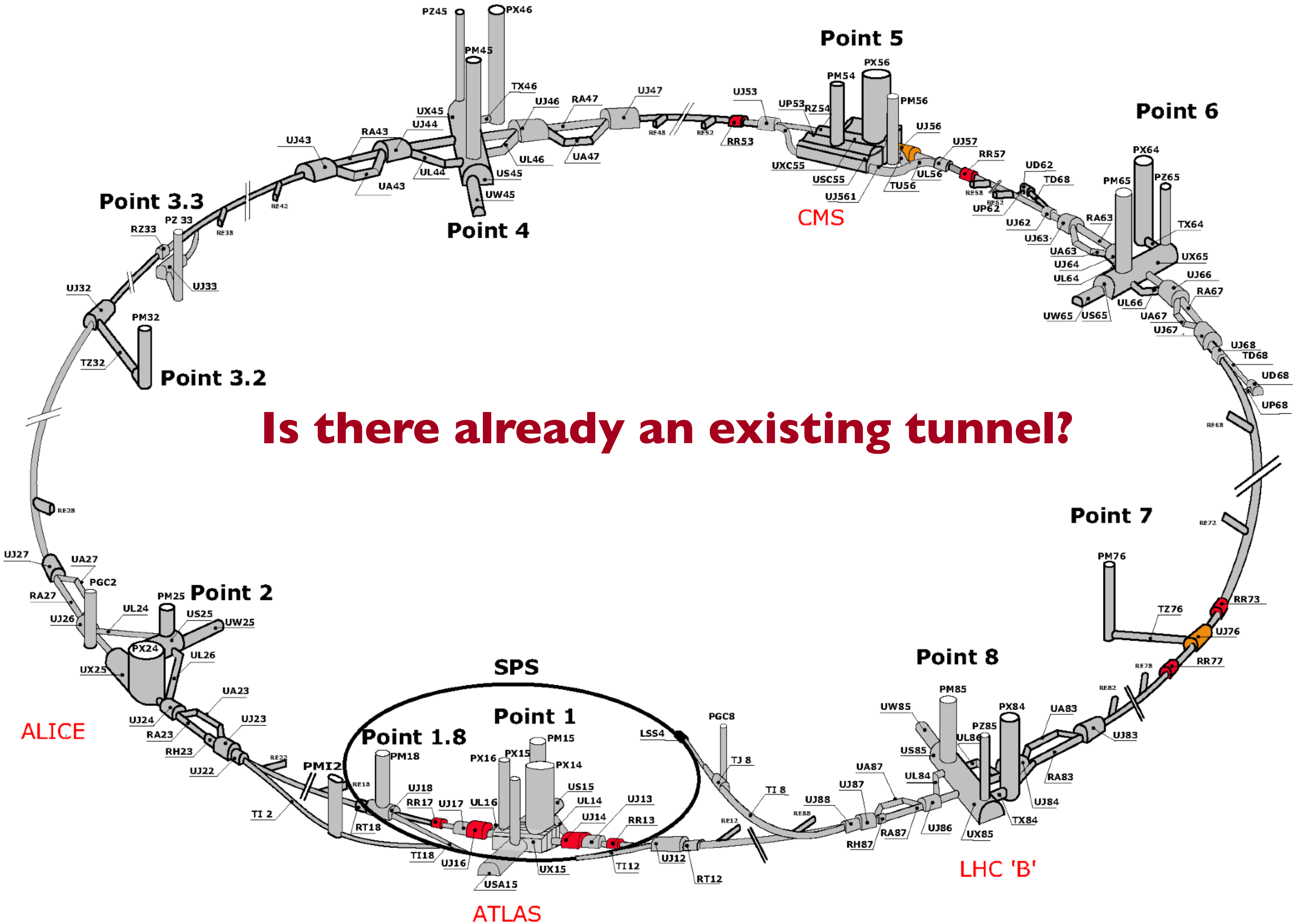
FASER 2 Upgrade - **HL-LHC era**

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).

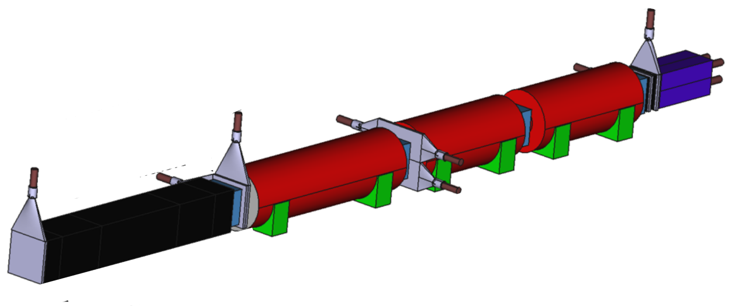
FASER Location



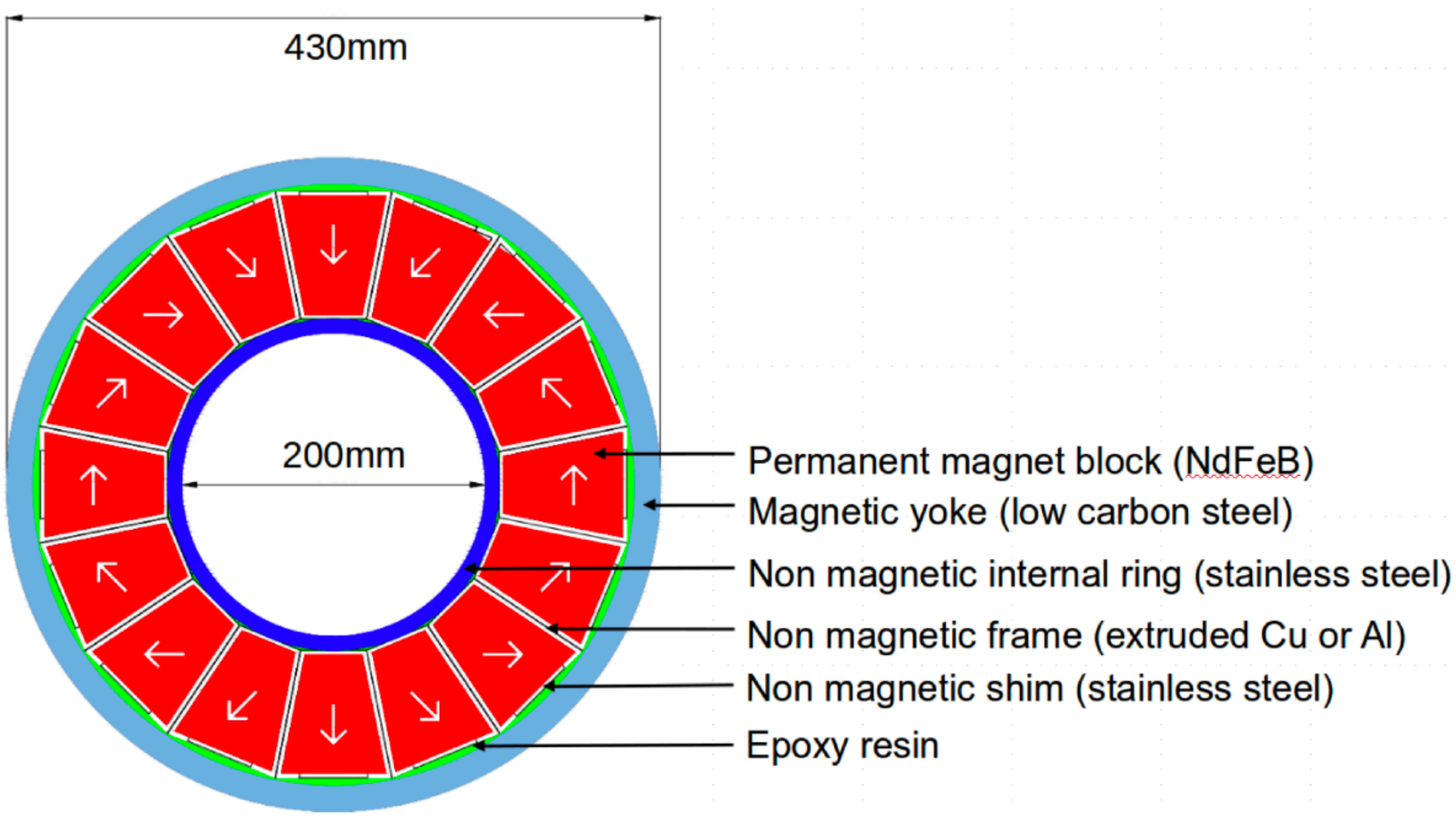
Is there already an existing tunnel?

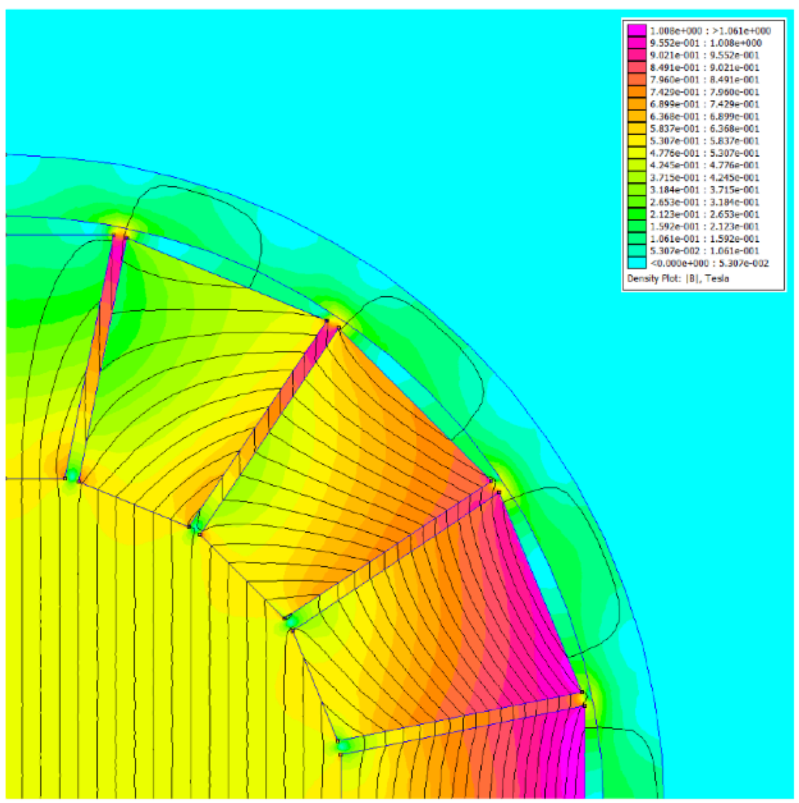
FASER Detector

FASER Magnet

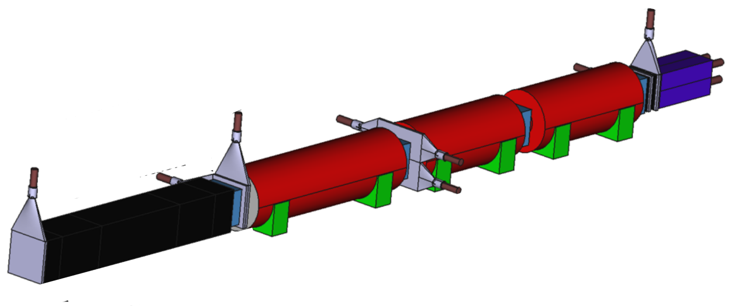


- 0.6T permanent dipole magnets
- Halbach array design
  - LOS to passes through the magnet center
  - minimum digging to the floor in TI12
  - minimized needed services (power, cooling etc..)
- to be constructed by the CERN magnet group

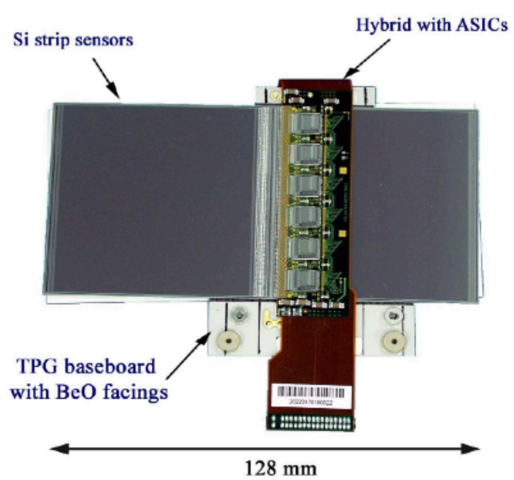




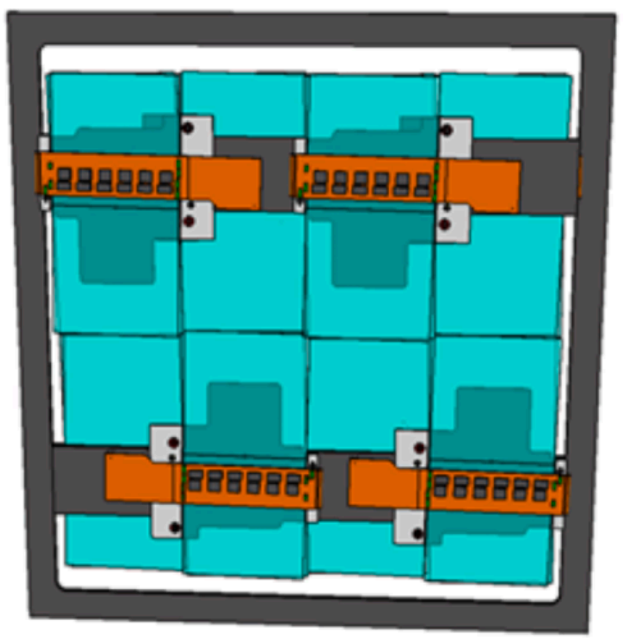
FASER Tracker



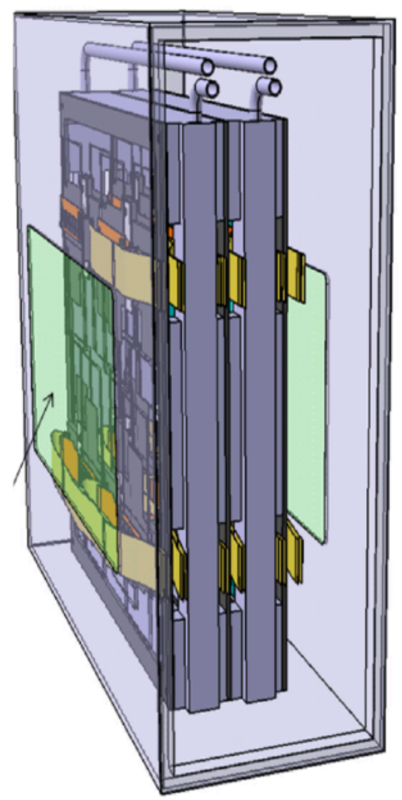
- 3 tracking stations, each with 3 tracking layers
- double sided silicon micro-strip detectors
- ATLAS SCT spare modules will be used
  - 80µm strip pitch, 40mrad stereo angle
  - many thanks to the ATLAS SCT collaboration!
  - 72 SCT modules for the full tracker



SCT module

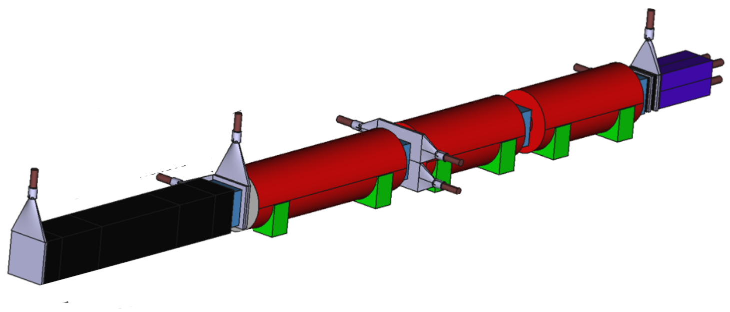


Tracking layer



Tracking station

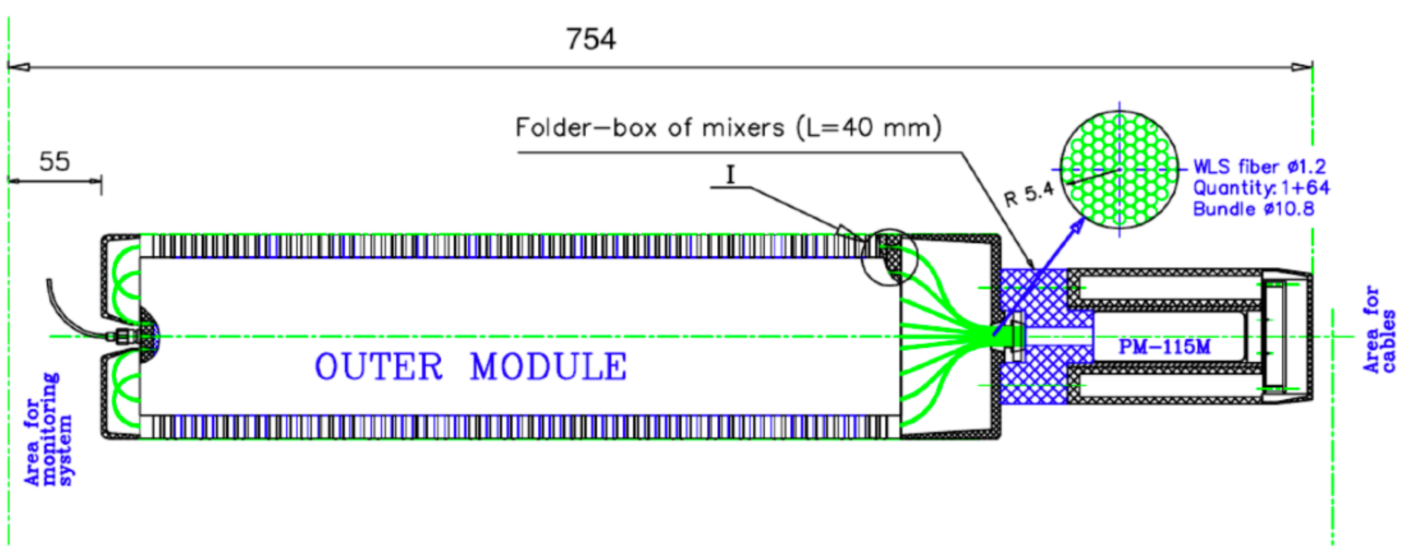
FASER ECAL

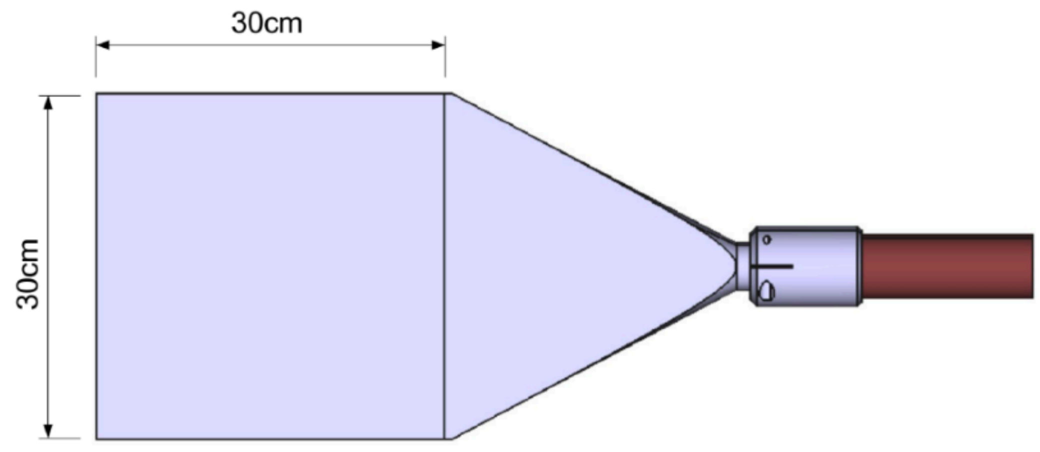


- EM energy measuring / triggering / electron/photon identification
- FASER will use spare LHCb outer ECAL modules
  - ~1% energy resolution for 1 TeV electrons
  - Many thanks for LHCb for allowing us to use these!

FASER Scintillators

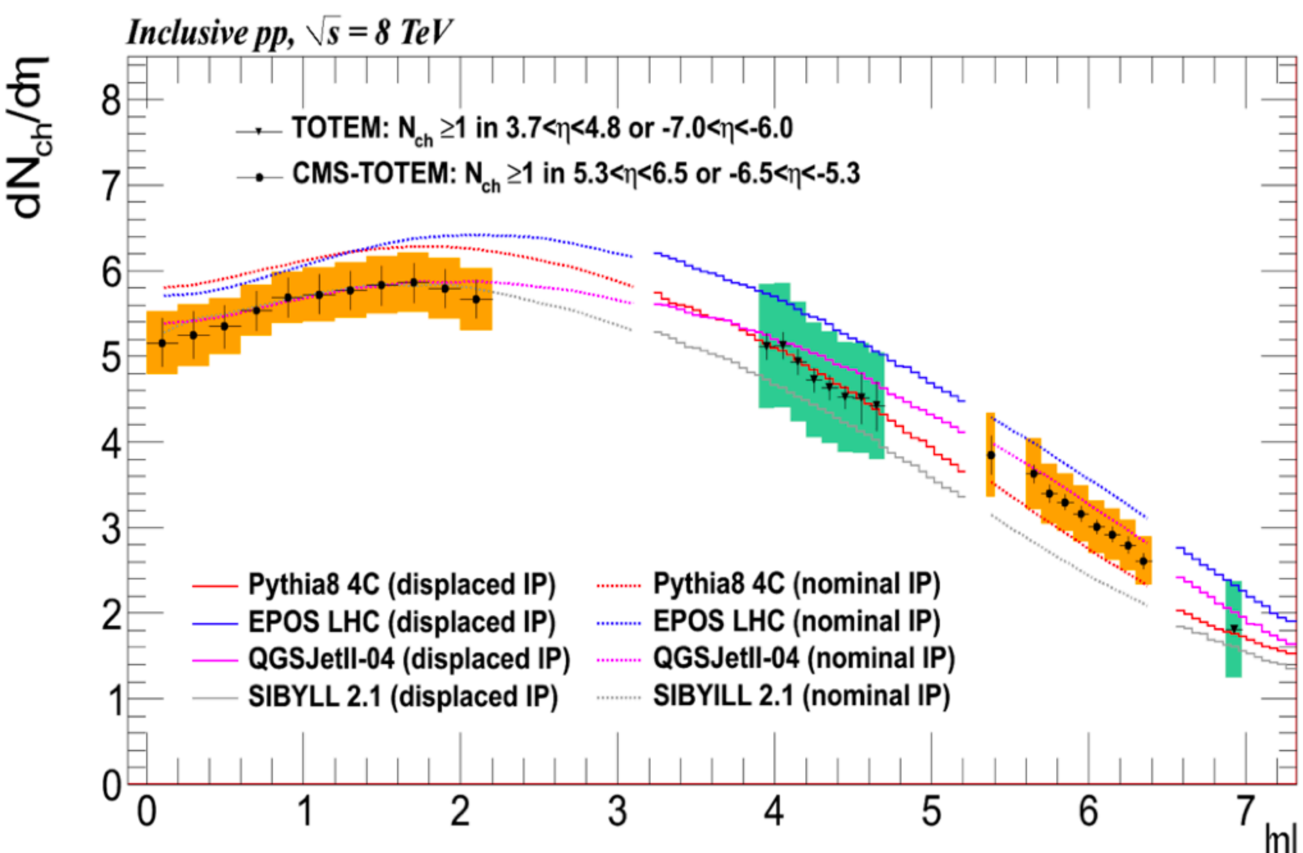
- vetoing charged particles entering the decay volume / triggering
- to be produced at CERN scintillator lab



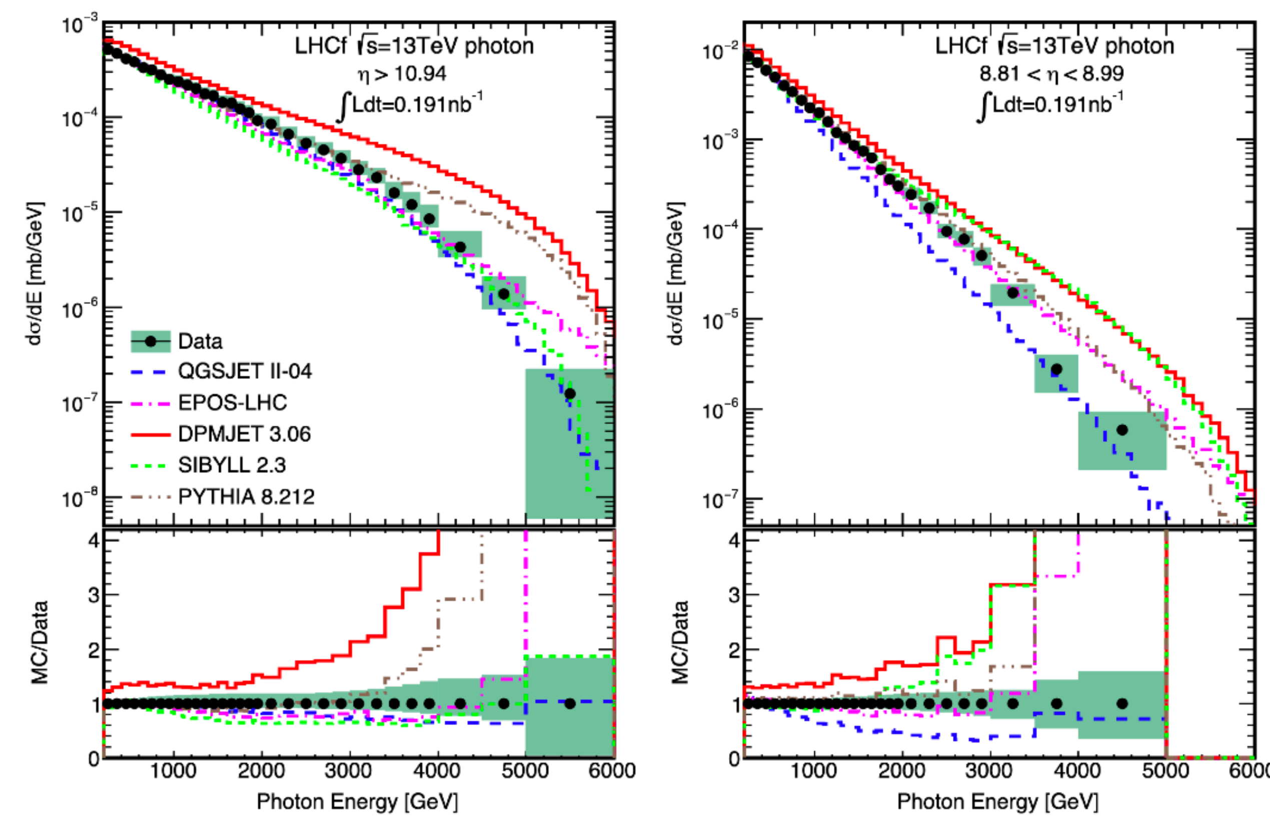


FASERν Physics

- 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]

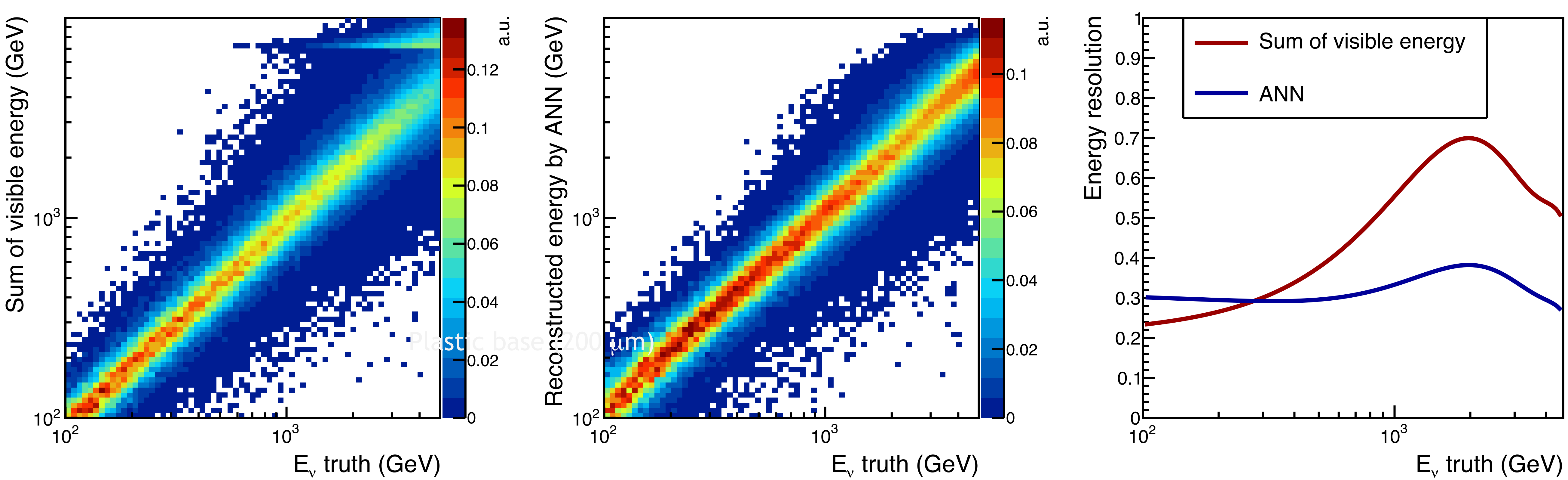


[LHCf: 1703.07678]

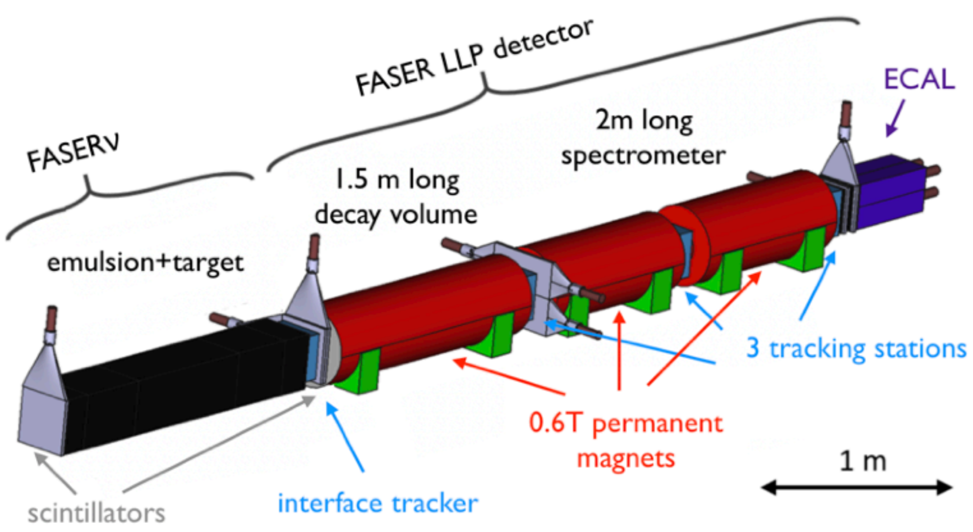
FASERν Detector

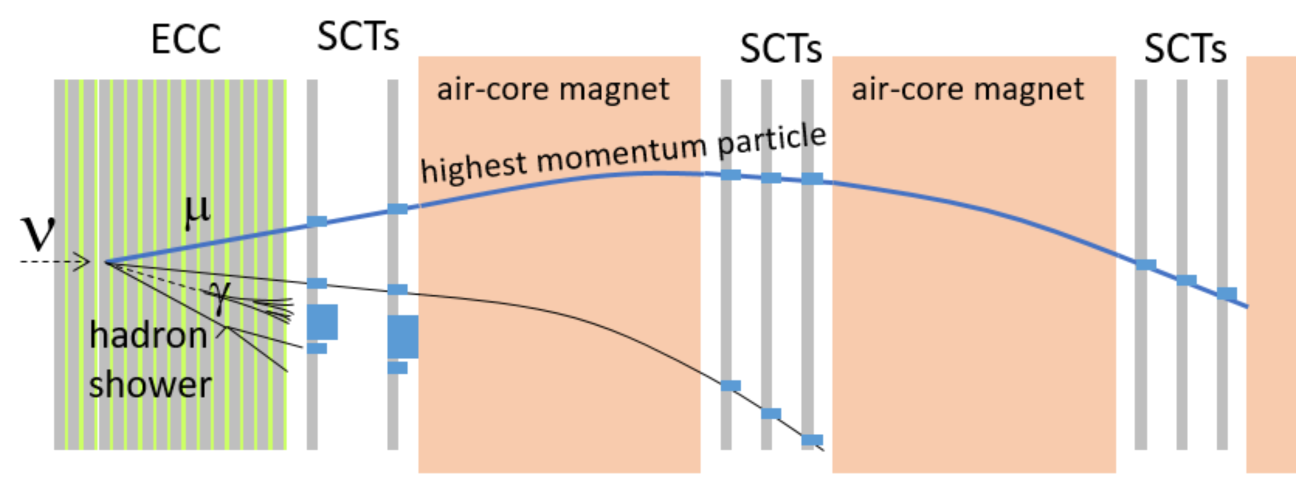
- neutrino energy reconstruction
  * use topological + kinematic observables
  * train NN to estimate neutrino energy
  * 30% energy resolution seems achievable

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

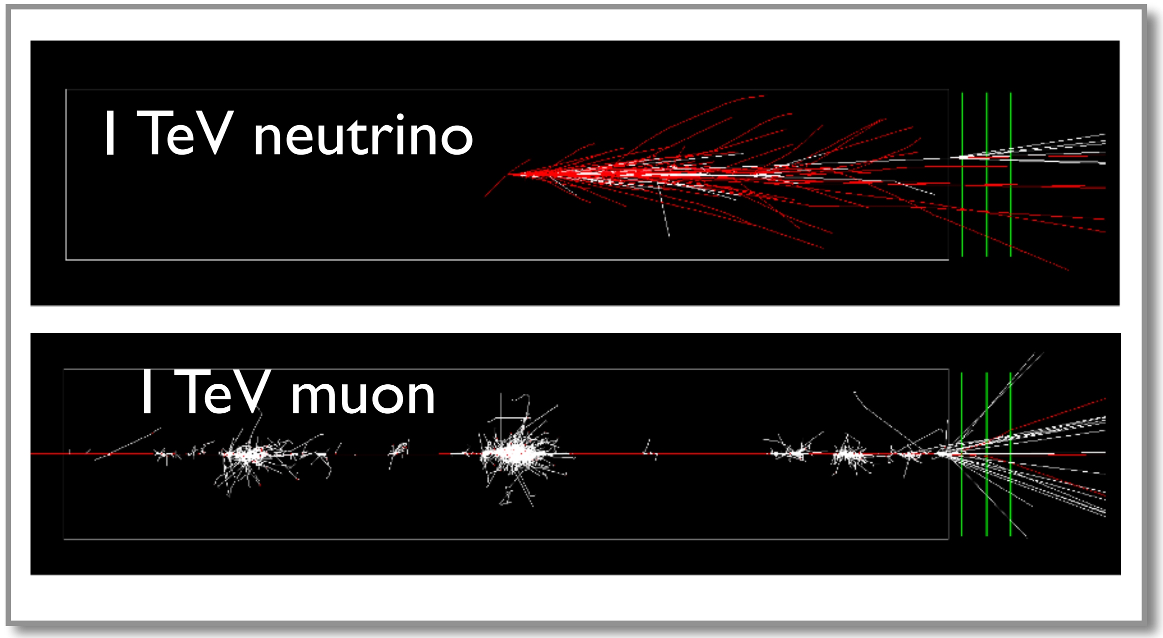


- possibility for future: global reconstruction with the FASER detector
  * interface FASERν to the FASER spectrometer
  * requires additional tracking layer to allow matching





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

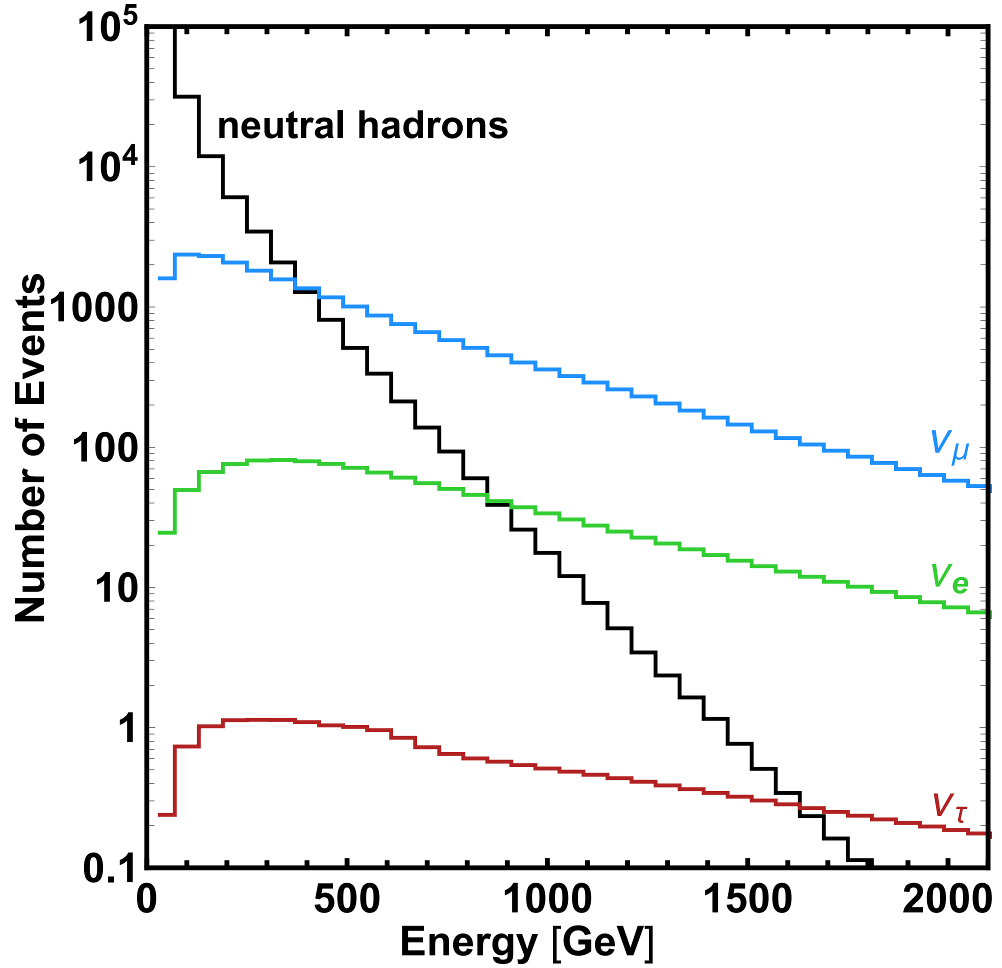


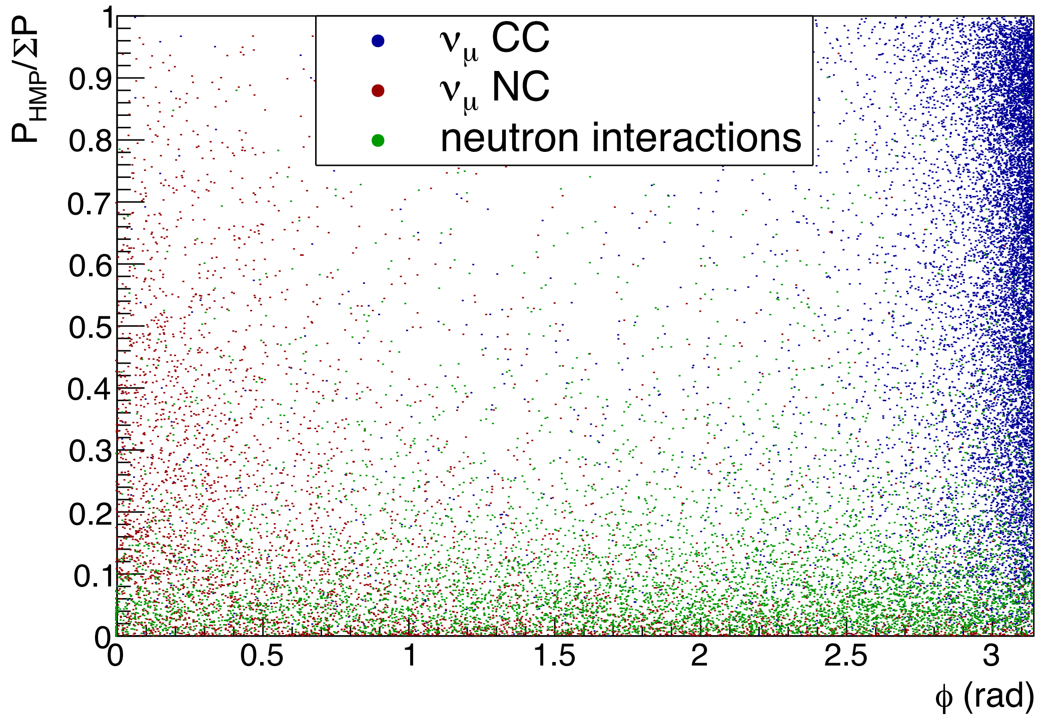
FASERν Backgrounds

- 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

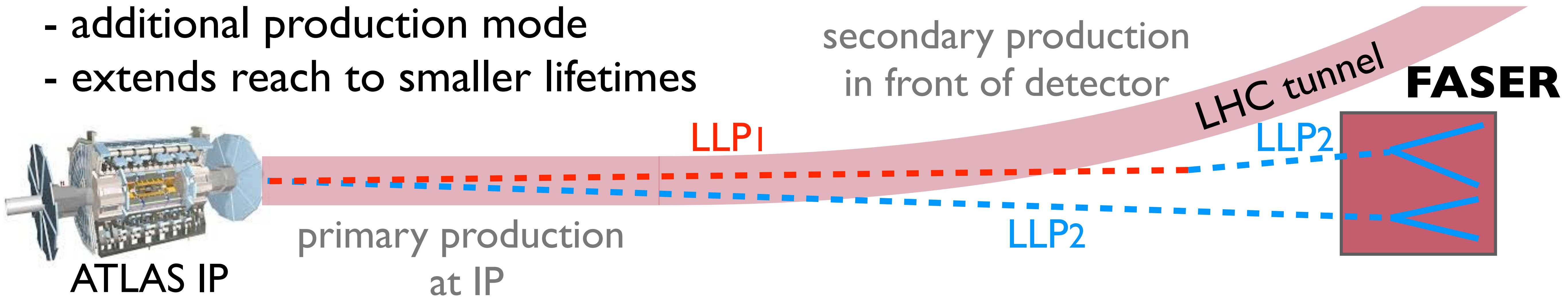




Secondary LLP Production

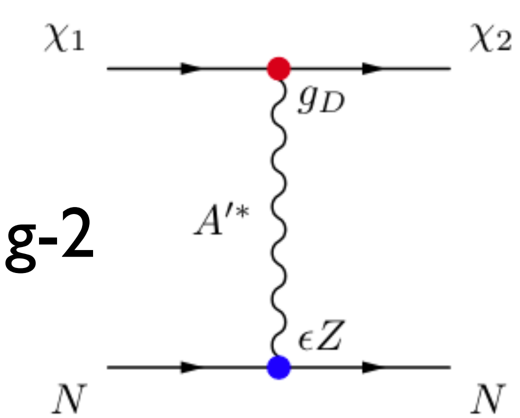
[K. Jodłowski, FK, L. Roszkowski, S. Trojanowski: 1810.01879]

- additional production mode
- extends reach to smaller lifetimes



Example: inelastic DM

- A' couples diagonally to X1 + X2
- X1=LLP1, X2=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