FASER:
ForwArd Search ExpeRiment at the LHC

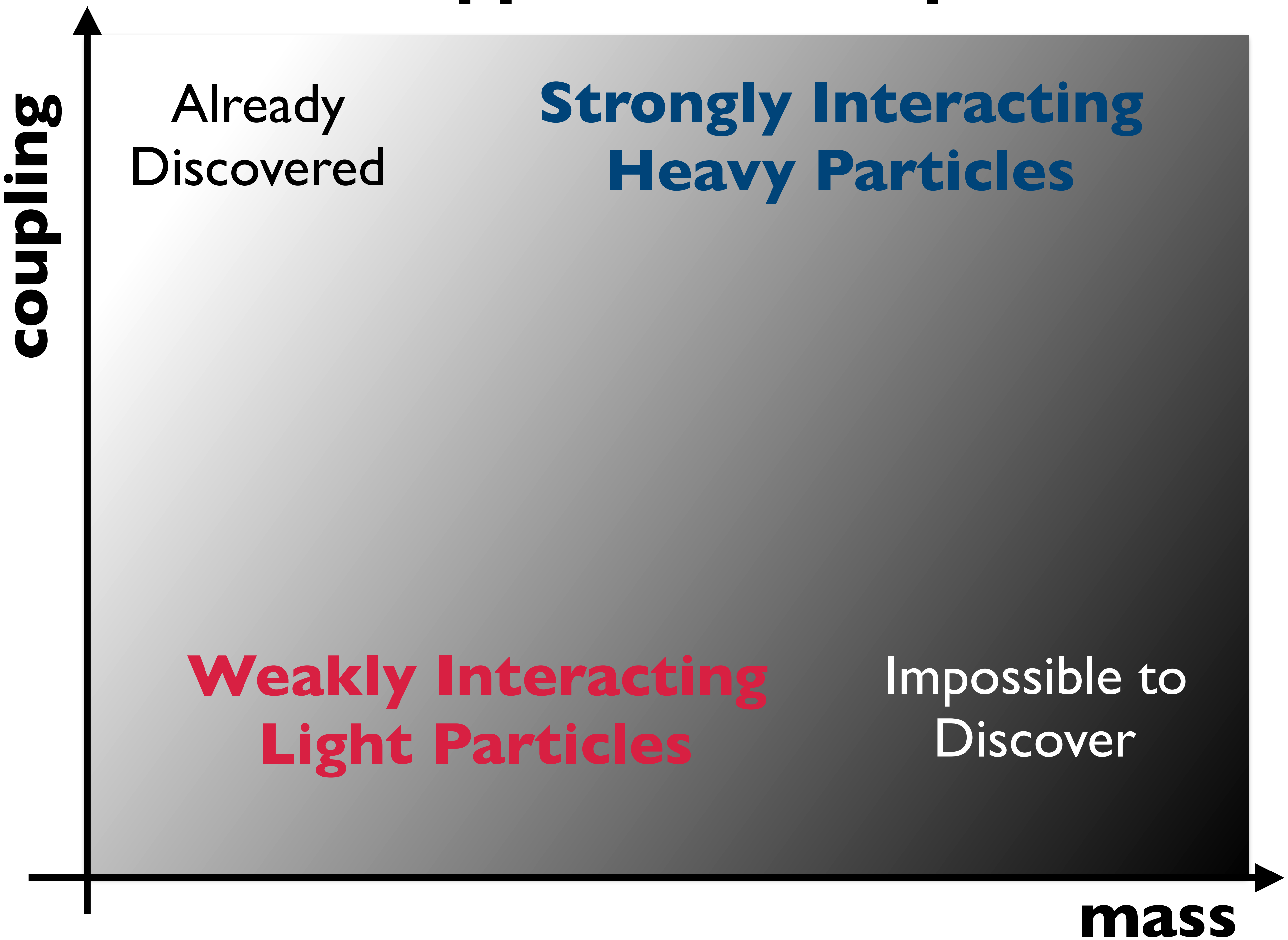
Felix Kling

UCIrvine

BNL

Introduction

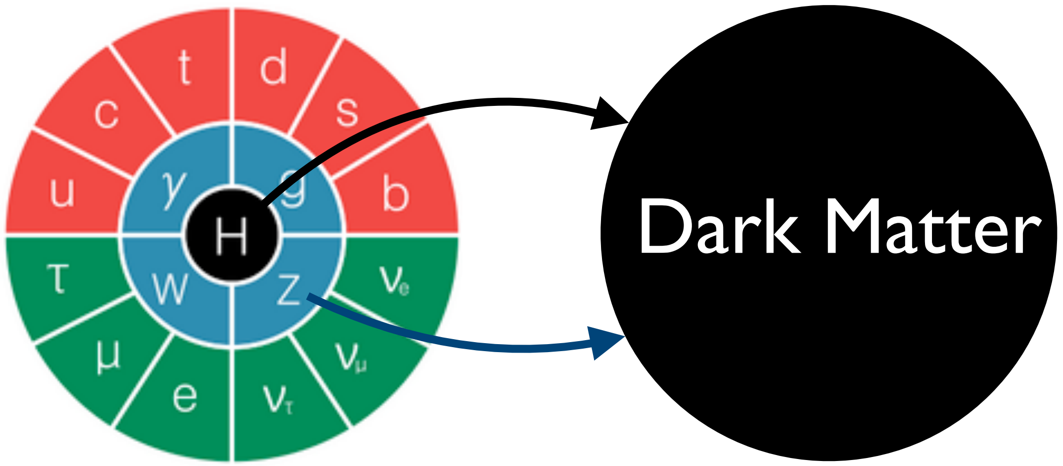
Lamppost Landscape



Strongly Interacting Heavy Particles

WIMP Miracle

- 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: $m \sim m_{weak}, \;\; g \sim g_{weak}$

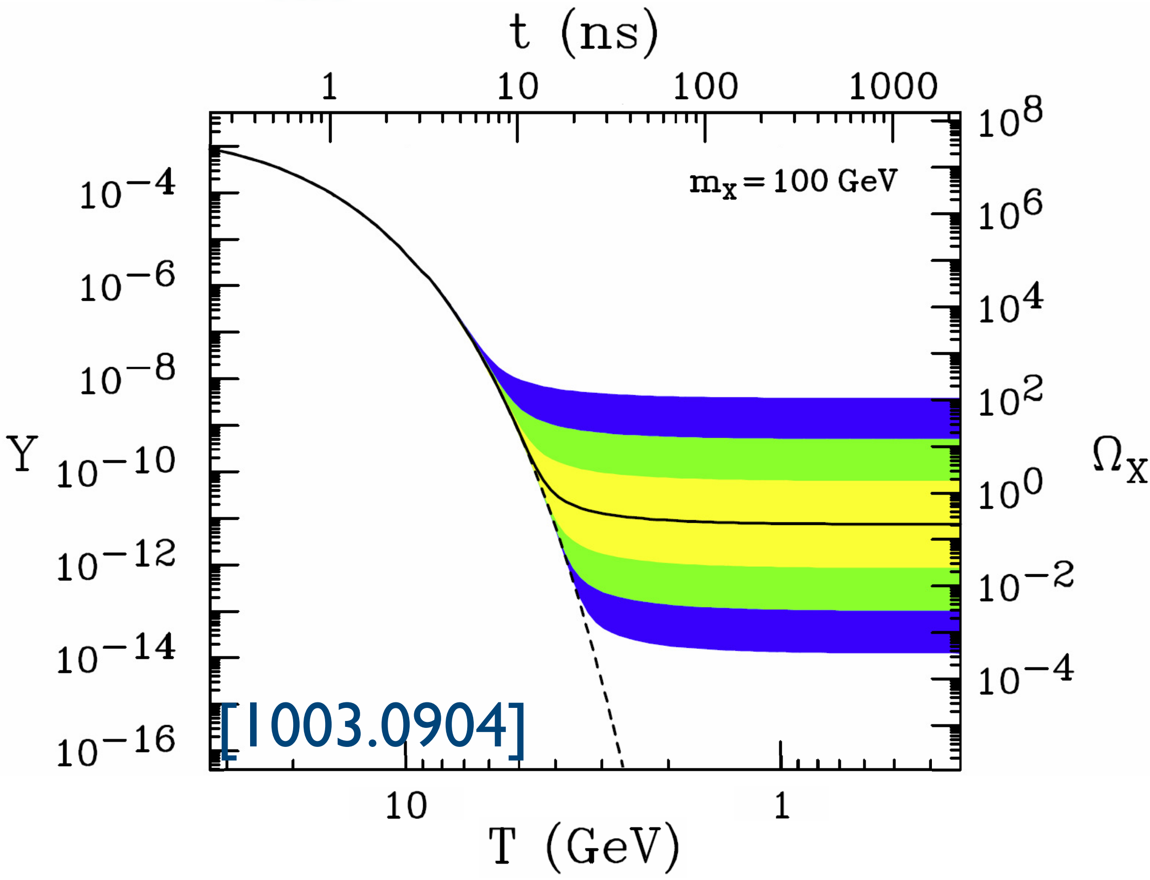


Electroweak Hierarchy Problem

- Why is Higgs mass small? $m_h \ll M_{Pl}$
- Higgs mass seems fine tuned

$$m_h^2 = m_{h0}^2 + \Delta m^2, \quad \Delta m^2 \sim \Lambda^2$$

- avoided if $\Lambda \lesssim 1$ TeV



Anomalies

- muon g-2
- anomalies in B-physics

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$$

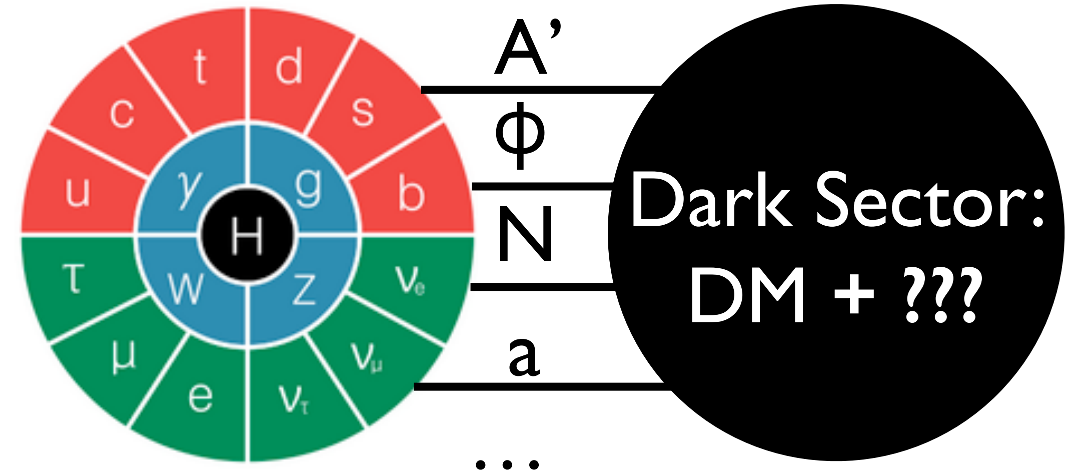
$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$

Introduction

Weakly Interacting Light Particles

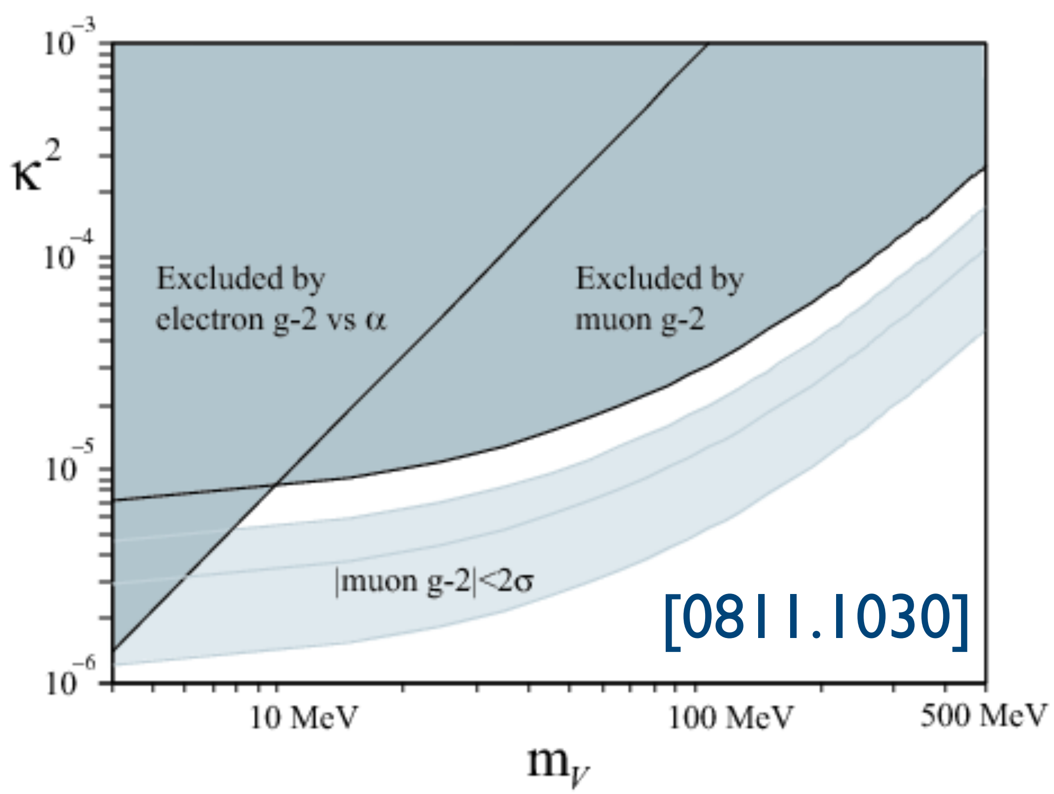
WIMPless Miracle

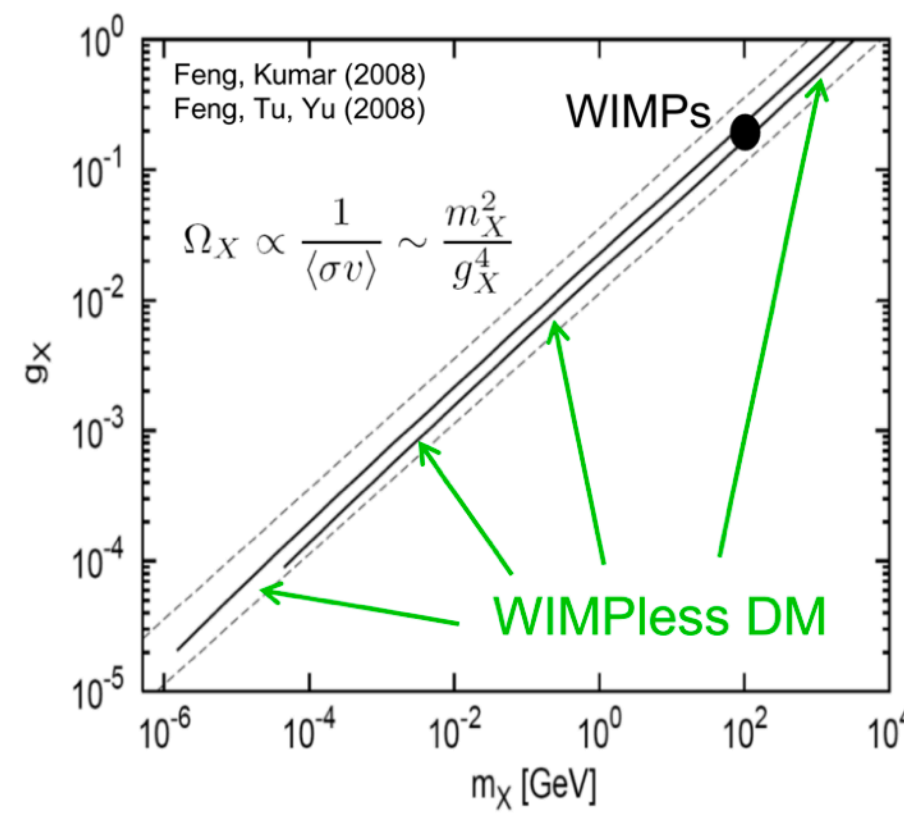
- thermal freeze out: $\Omega_{DM} \sim 1/\langle\sigma v\rangle \sim m^2/g^4$
- "broader" WIMP: $m < m_{weak},\ g < g_{weak}$
- new mediators
  → dark sector



Anomalies

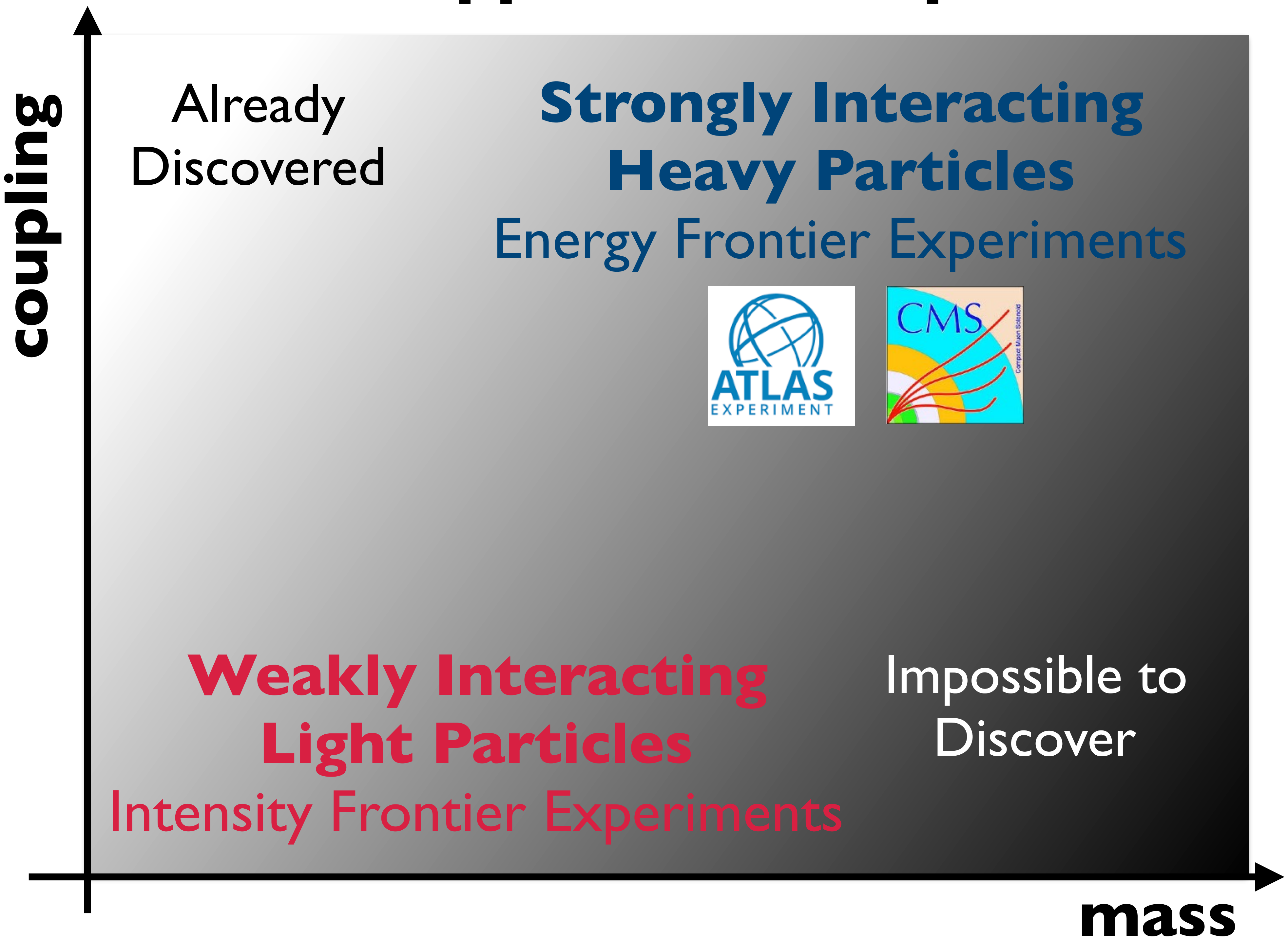
- muon g-2
- Be-8 anomaly





Introduction

Lamppost Landscape



Can we probe the Intensity Frontier at the LHC ?

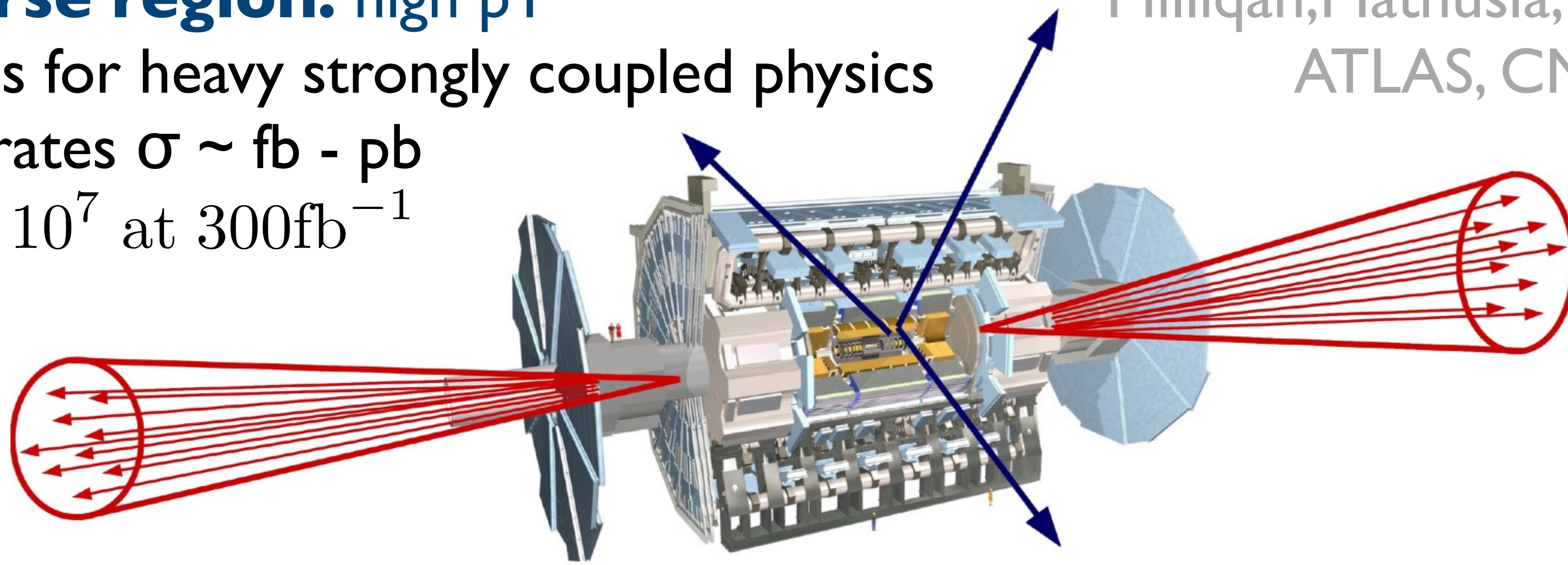
Introduction

transverse region: high pT

- searches for heavy strongly coupled physics
- typical rates σ ~ fb - pb

$N_H = 10^7$ at 300fb^{-1}

Milliqan, Mathusla, Codex-b
ATLAS, CMS



forward region

- mostly used for SM measurement

LHCf, TOTEM, ALFA, CASTOR

- **enormous** event rates: $\sigma_{inel} \sim 75$ mb : $N_\pi = 10^{17}$ at 300fb^{-1}

→ extremely weakly-coupled **long-lived** particles may be produced sufficiently

- most particles have small pT $\sim \Lambda_{QCD}$

→ energetic particles highly **collimated** $\theta \sim \Lambda_{QCD}/E \sim \text{mrad}$ for $E \sim \text{TeV}$

- we propose small ($\sim 1\ \text{m}^3$) inexpensive detector a few 100 m downstream

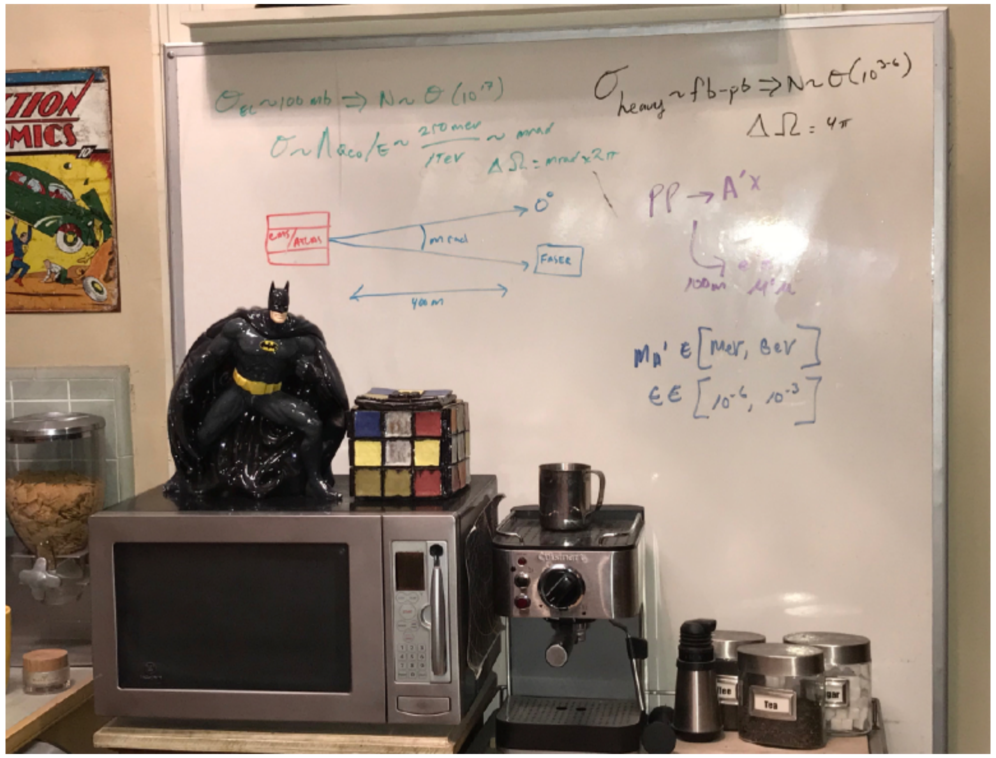
→ **FASER: F**orw**A**rd **S**earch **E**xpe**R**iment at the LHC

FASER in Popular Culture

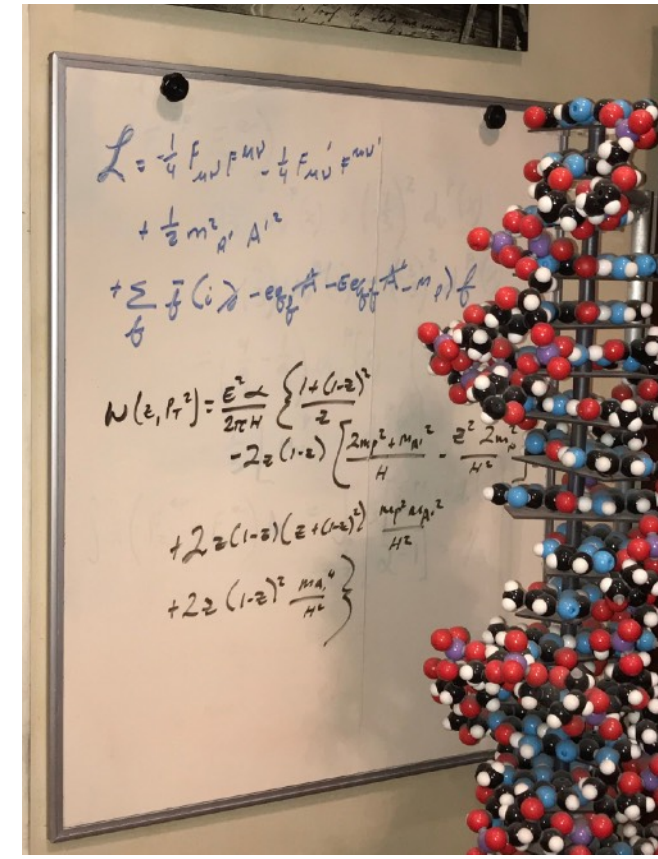
FASER

"The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds."

FASER in Popular Culture



the BIG BANG THEORY



Outline

FASER's Location and LHC Infrastructure

FASER's sensitivity for Long Lived Particles
Dark Photon and Dark Higgs / Kinematics / Expected Sensitivity

Detector Design

Backgrounds

Timeline/Status/Outlook

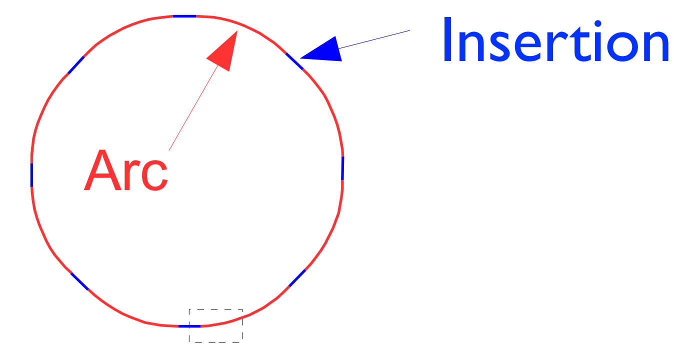
Summary and Conclusion

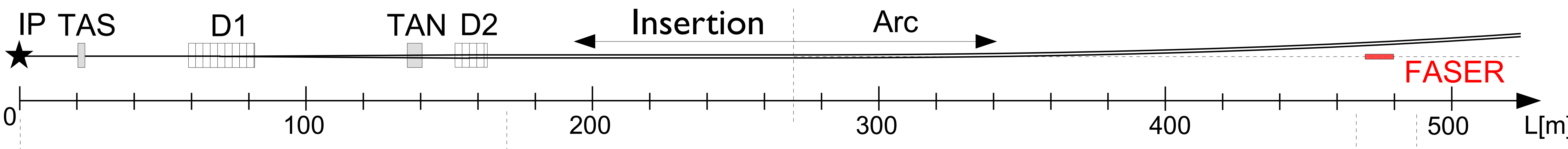
FASER's Location and LHC Infrastructure

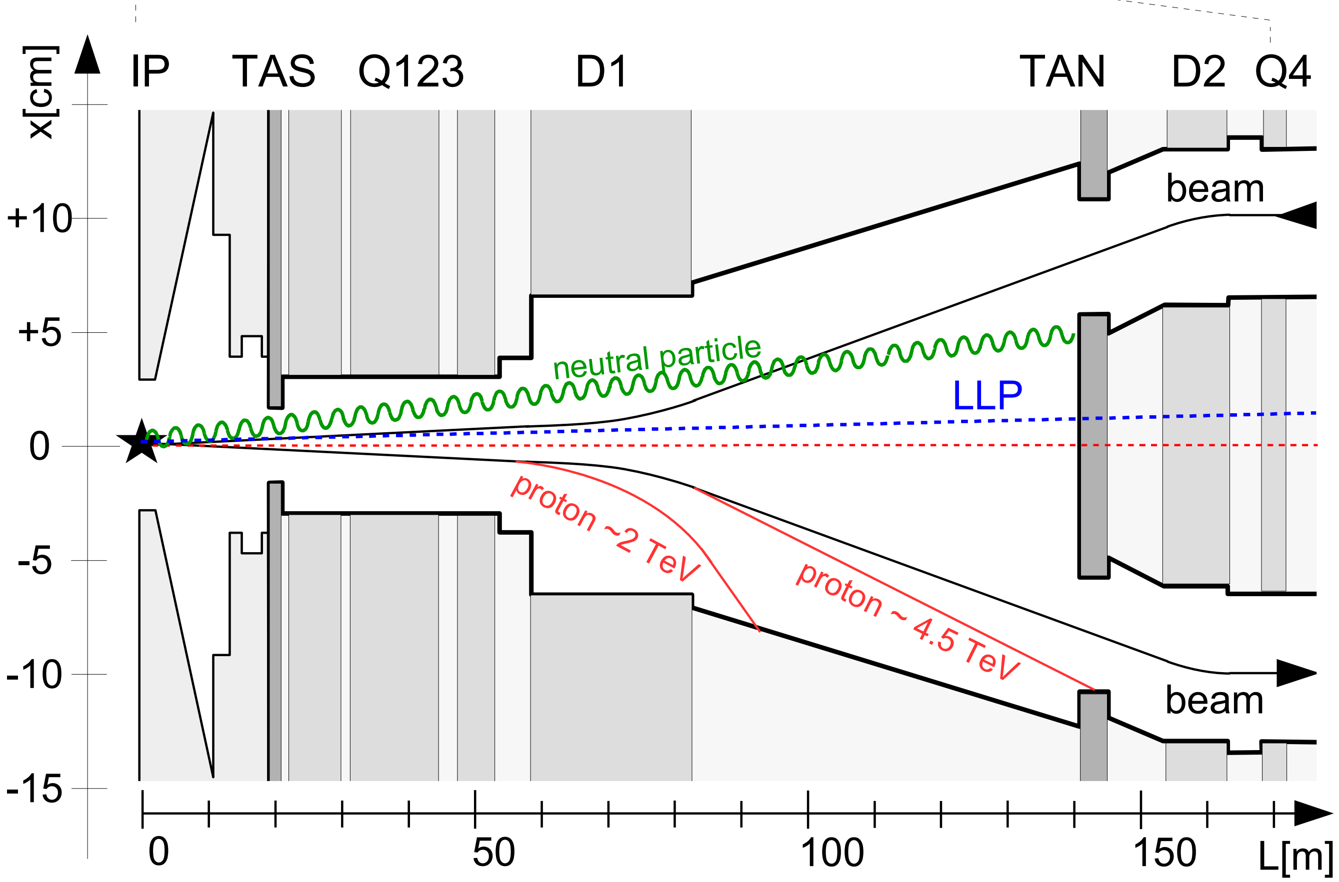
FASER's Location

Forward Infrastructure

- 8 straight 545 m long insertion regions and curved arcs
- infrastructure common to IP1 and IP5
- LLP produced at IP, collimated around beam axis







IP: LLP produced at ATLAS/CMS interaction point

D&Q: magnets deflect charged particles

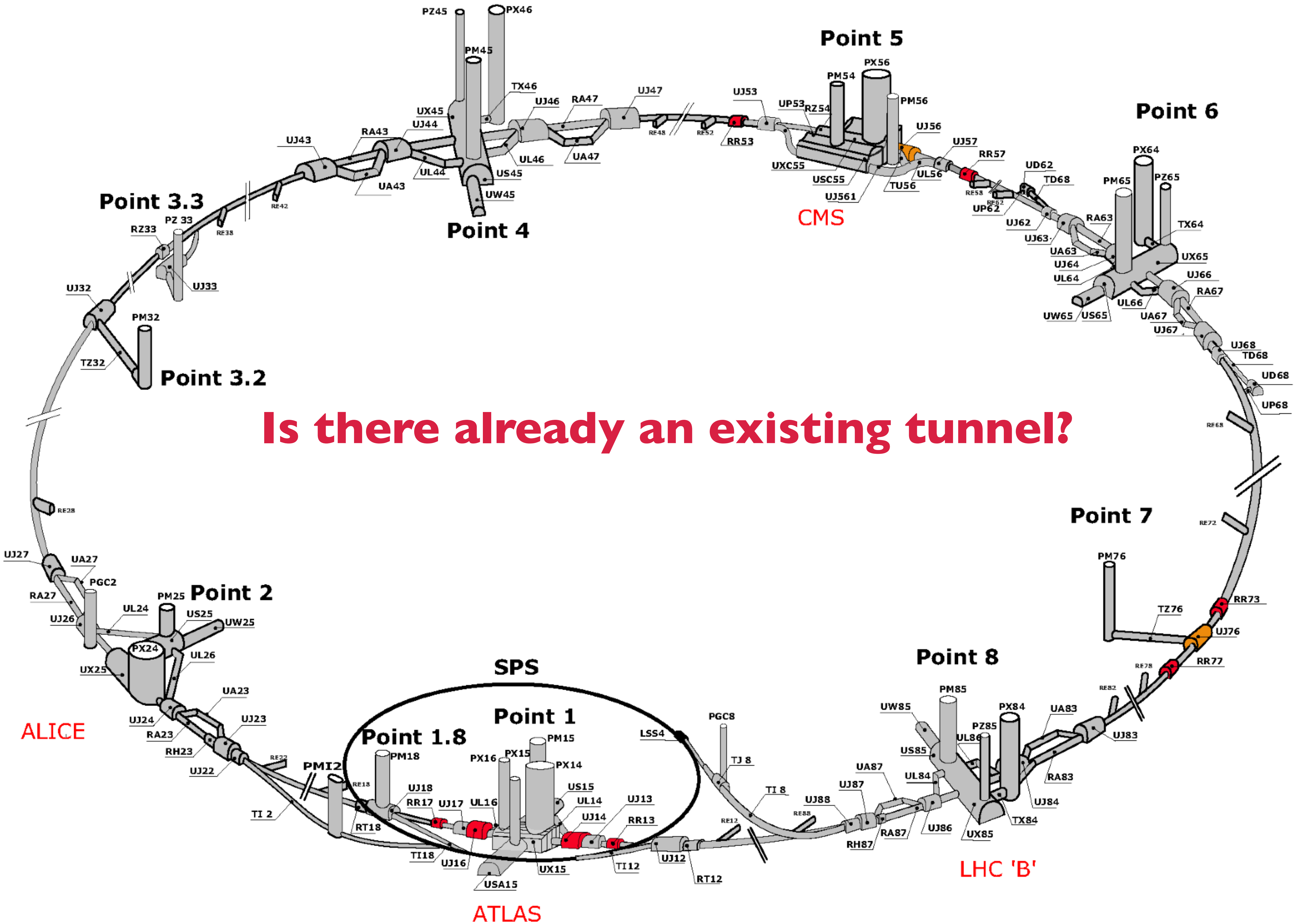
TAN: forward n,γ absorbed by Target Neutral Absorbers

Arc: beam starts to curve at L=272m

→ LHC Infrastructure acts as natural filter in forward direction

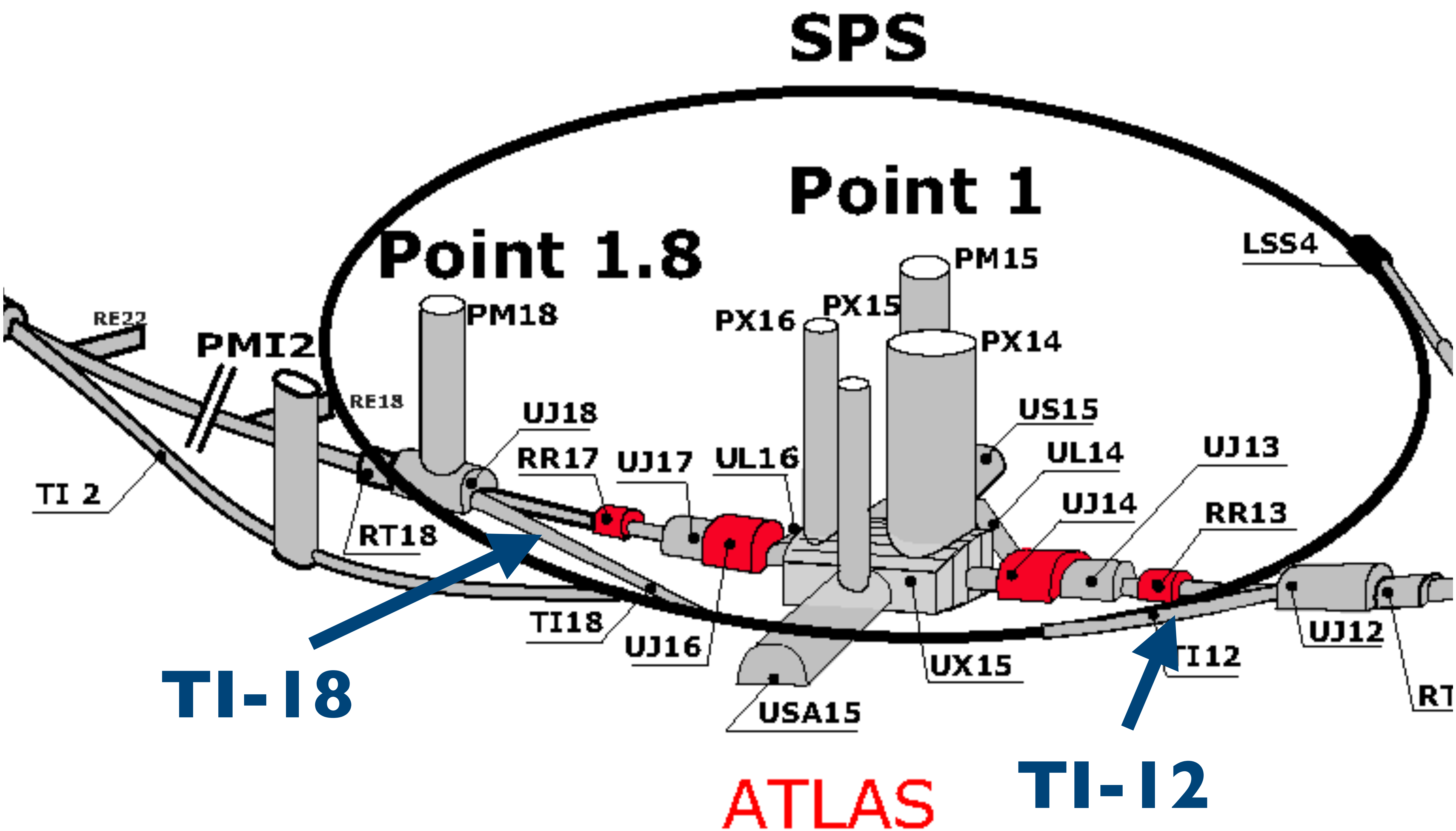
place FASER along beam axis after LHC curves

FASER's Location

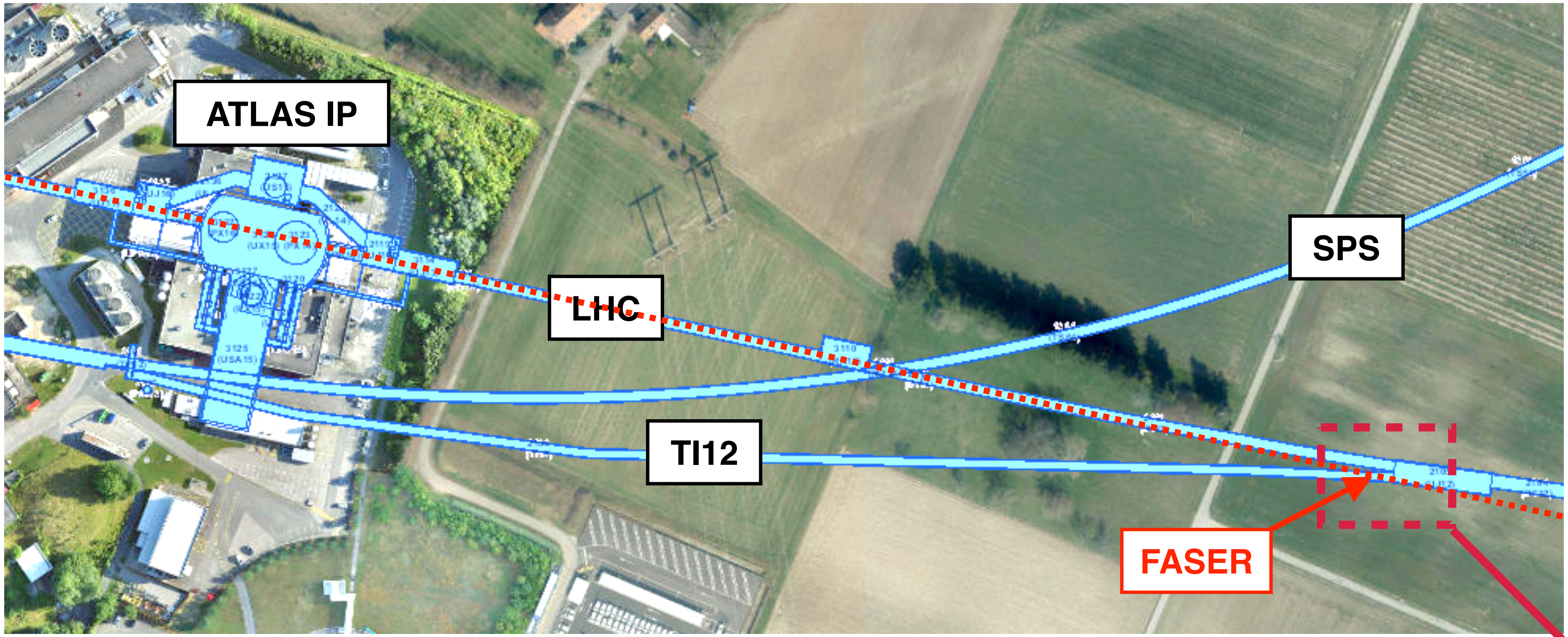


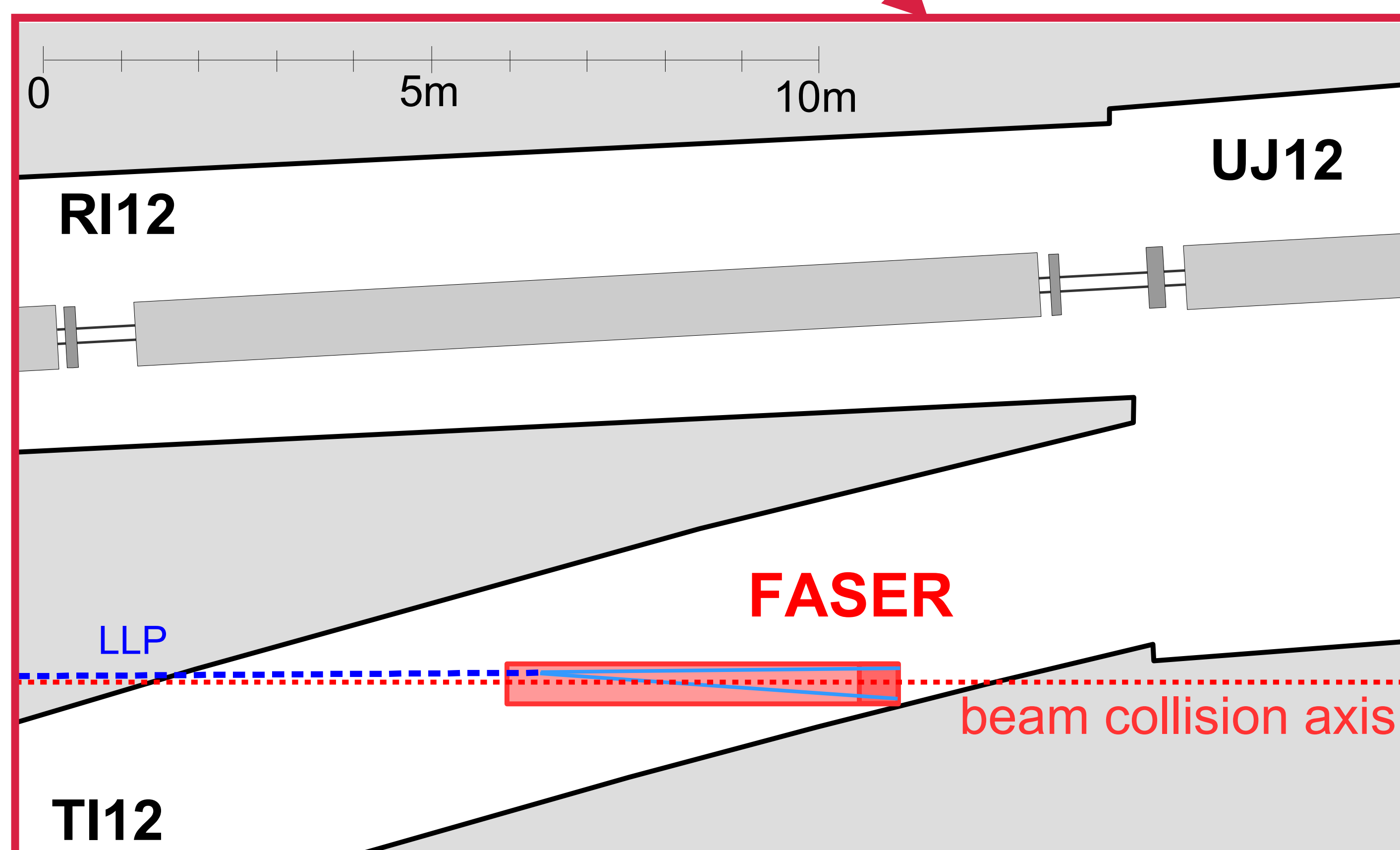
Is there already an existing tunnel?

FASER's Location



FASER's Location





FASER's Location

provided by Mike Lamont

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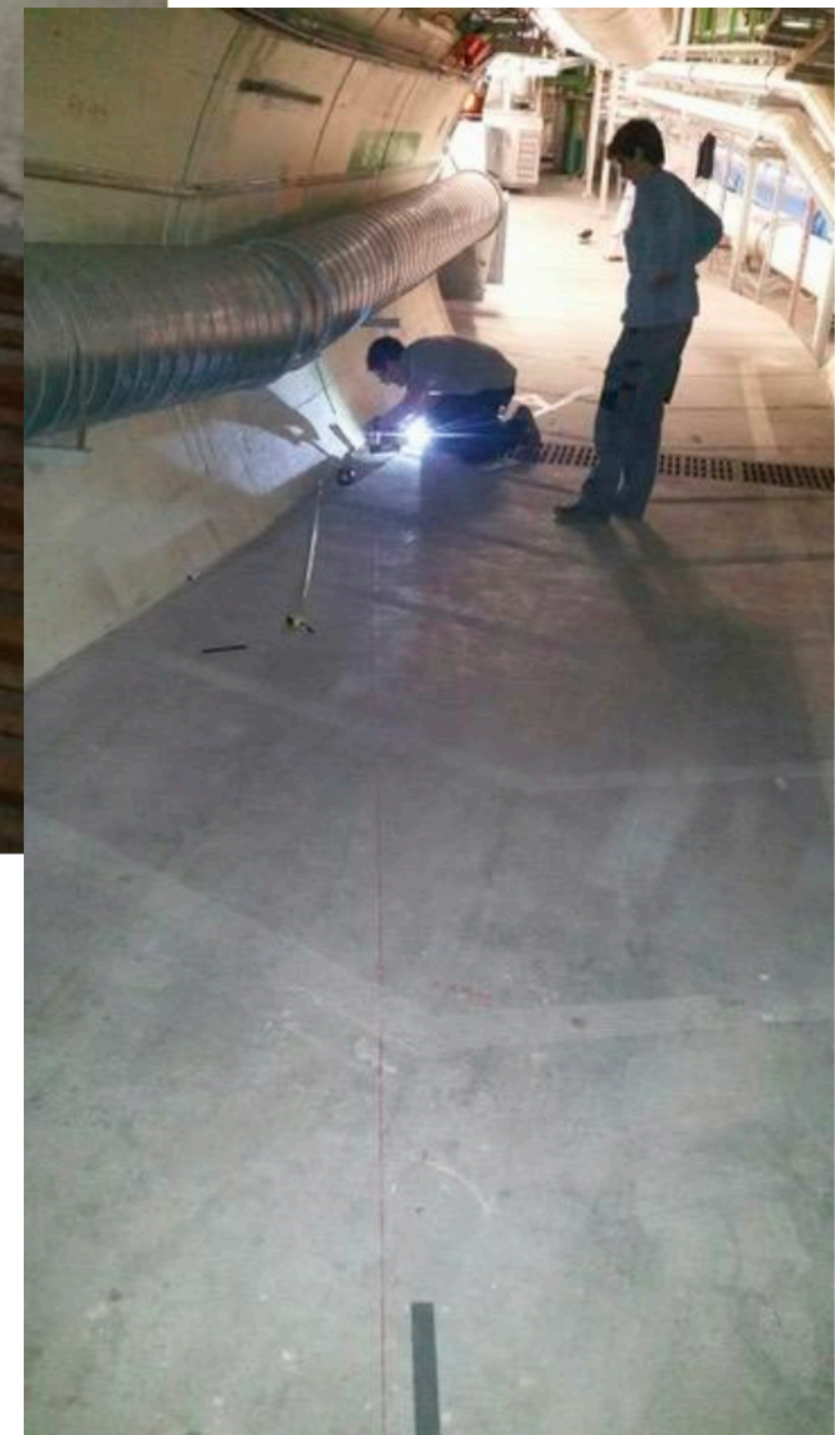
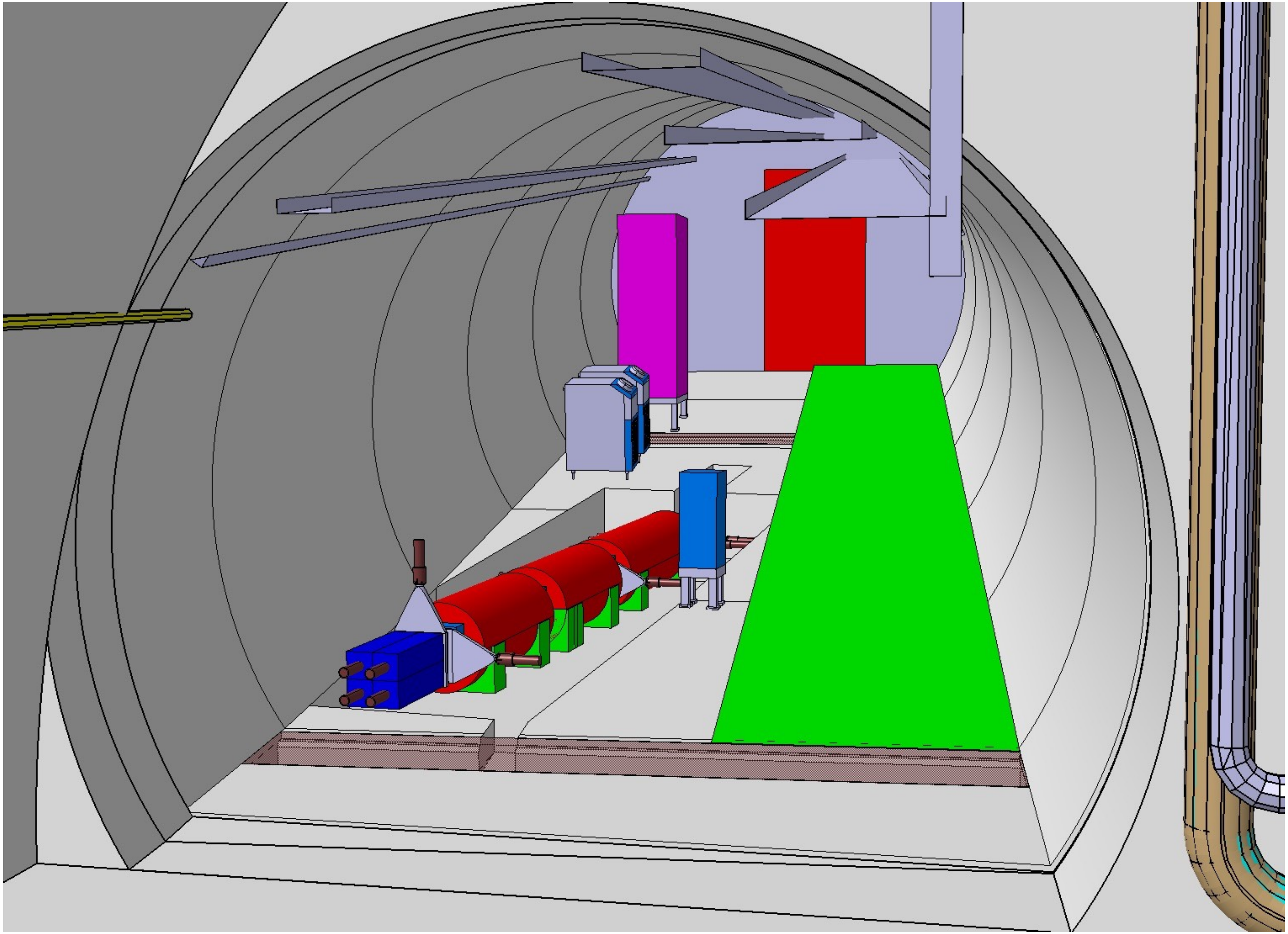
FASER's Location



Detailed measurements from the CERN survey team have mapped out the beam collision axis in both the TI18 and TI12 tunnels.

FASER's Location



FASER in TI12 (Technical Proposal)

FASER's sensitivity for Long Lived Particles

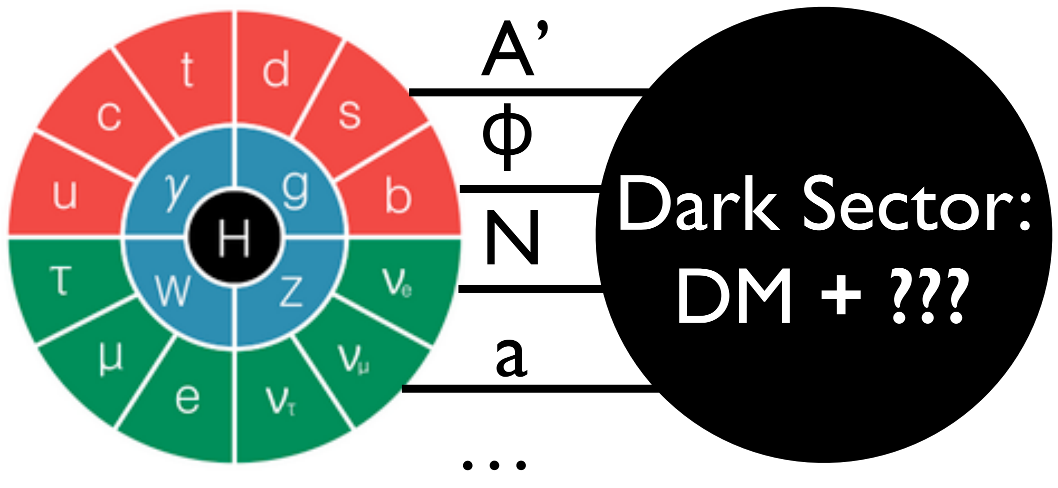
Long Lived Particles at FASER

Motivation

- Dark matter solid evidence for new particles
- In recent years, the idea of dark matter has been generalized to dark sectors
- light DM requires new mediators

$$m < m_{weak}, \quad g < g_{weak}$$

→ light weakly coupled particles



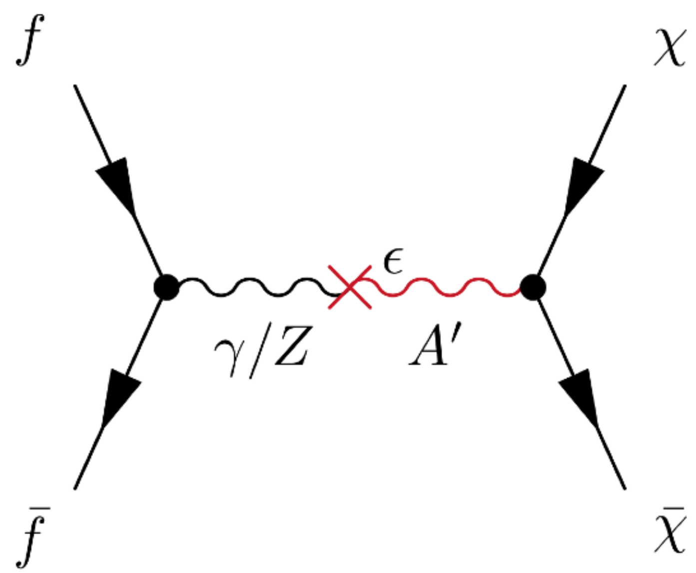
Prominent examples

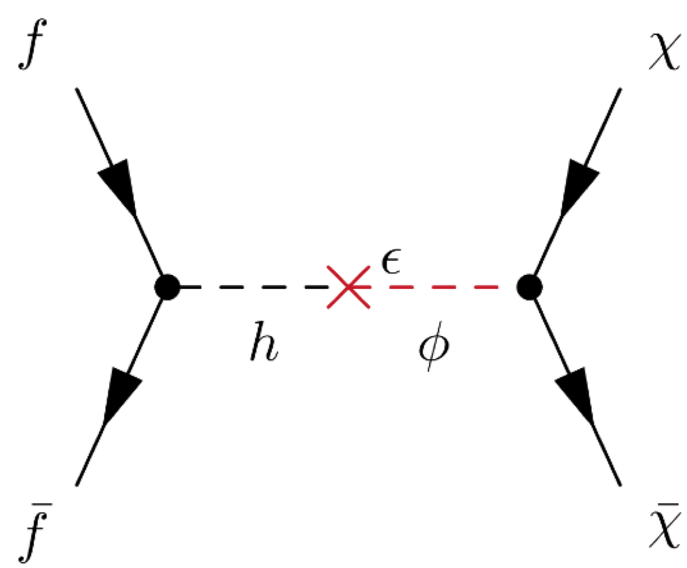
Dark Photon Portal: $\epsilon F^{\mu\nu} F'_{\mu\nu}$

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

Neutrino Portal: $yLHN$

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

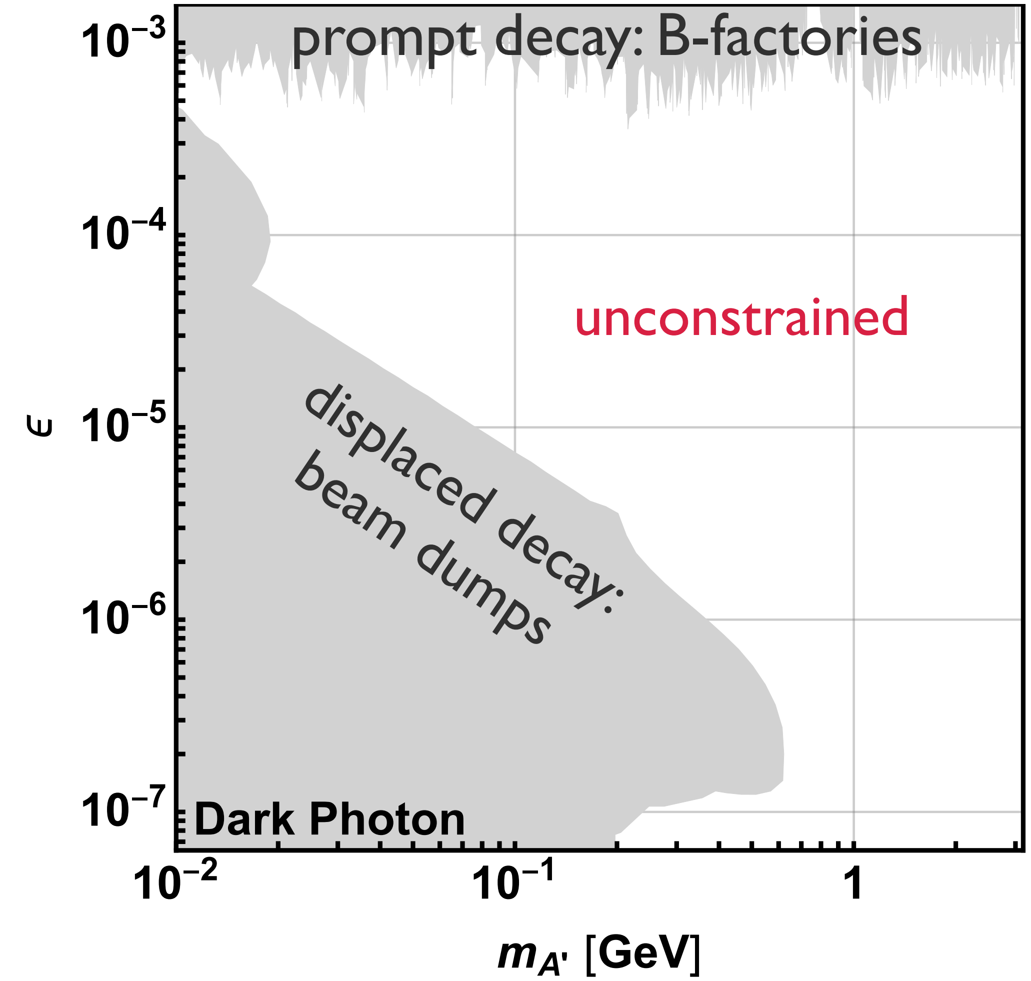




Long Lived Particles at FASER

Long Lived Particles

- if $m_{A'} < 2m_{DM}$
  - ➞ Mediator decays to SM
  - ➞ Long Lived Particle



Dark Photons

- (broken) dark U(1) gauge group mixing with the SM photon

$$\mathcal{L} \subset \epsilon F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}{}^2 A'_\mu A'^\mu$$

- after field re-definition:

$$\mathcal{L} \subset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}{}^2 A'_\mu A'^\mu + \sum \bar{f}(i \not{\partial} - \epsilon e q_f \not{A}') f$$

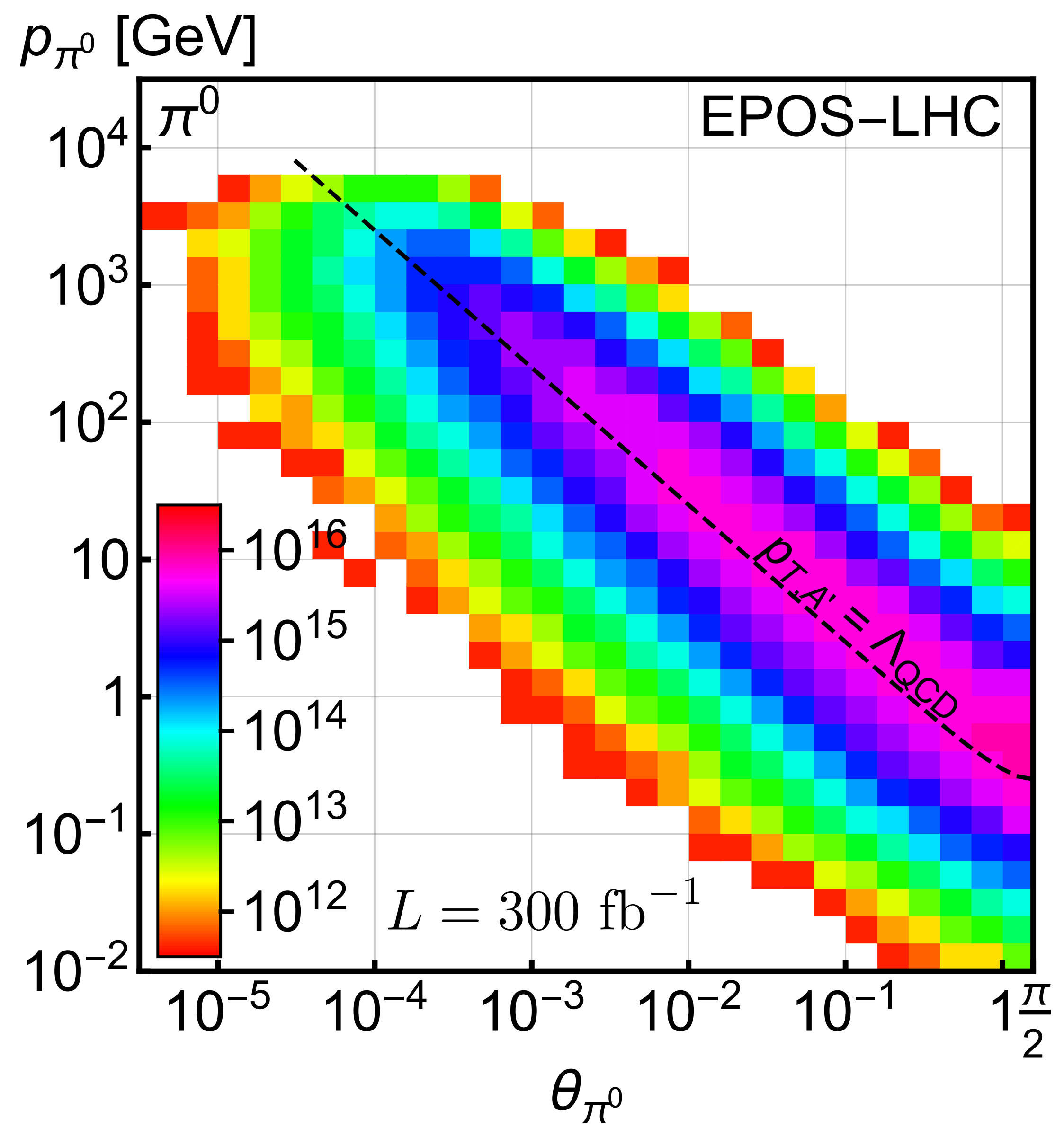
- FASER aims to probe $m_{A'} \sim 10 - 500 \text{ MeV}$ and $\epsilon \sim 10^{-6} - 10^{-4}$

Production Modes

- meson decays: mainly $\pi^0 \to \gamma A'$, $\eta \to \gamma A'$
- proton Bremsstrahlung: $pp \to pA'X$
- (direct production): $q\bar{q} \to gA'$, $qg \to qA'$

Meson Production

- use forward tools/models
  → EPOS-LHC, SIBYLL 2.3, QGSJETII-04
- boosted mesons highly collimated
  $p \cdot \theta = p_T \sim \Lambda_{QCD}$
- large rates at $L = 300\ \mathrm{fb}^{-1}$
  → $\sigma_{inel} \sim 75$ mb
  → $N_\pi = 10^{18}$ at $3000\ \mathrm{fb}^{-1}$



Spectrum of Pion

Long Lived Particles at FASER

Meson Decay to Dark Photons

- branching fractions:

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

- even small $\epsilon \sim 10^{-5}$ large sizable rate

$$N_{A'} \sim \epsilon^2 N_\pi \sim 10^8 \quad \text{at } 3000 \text{ fb}^{-1}$$

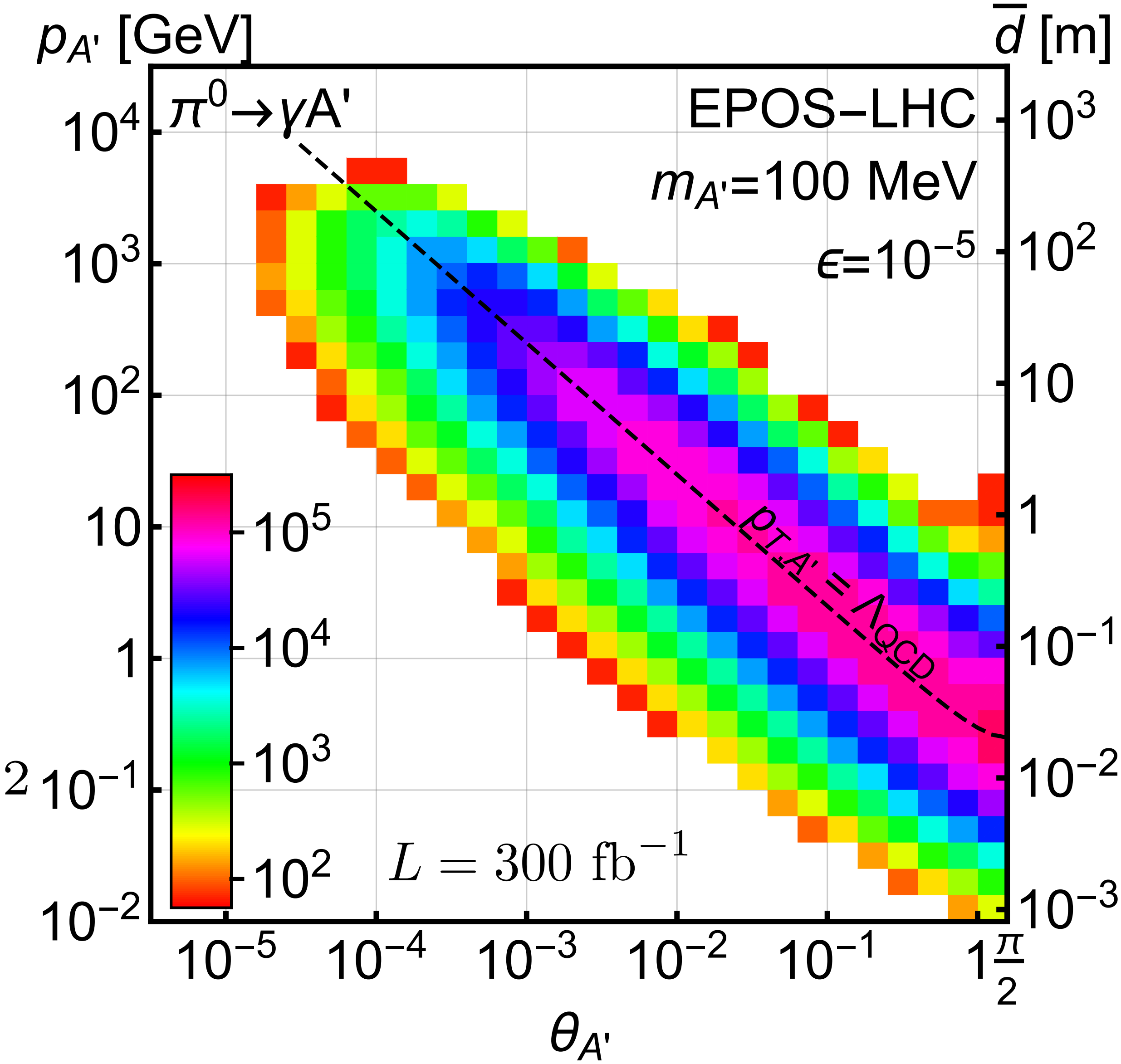
- LHC is a dark photon factory!

Dark Photon Decay

- A' is long lived: decay length

$$\bar{d} \approx 80\text{m} \ B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\text{TeV}}\right] \left[\frac{100 \text{ MeV}}{m_{A'}}\right]^2$$

- dark photons in FASER will have TeV-scale energies
- A' very forward $\theta_{A'} < 1 \text{ mrad}$
  → small detector radius



Spectrum of Dark Photons produced in Pion Decay

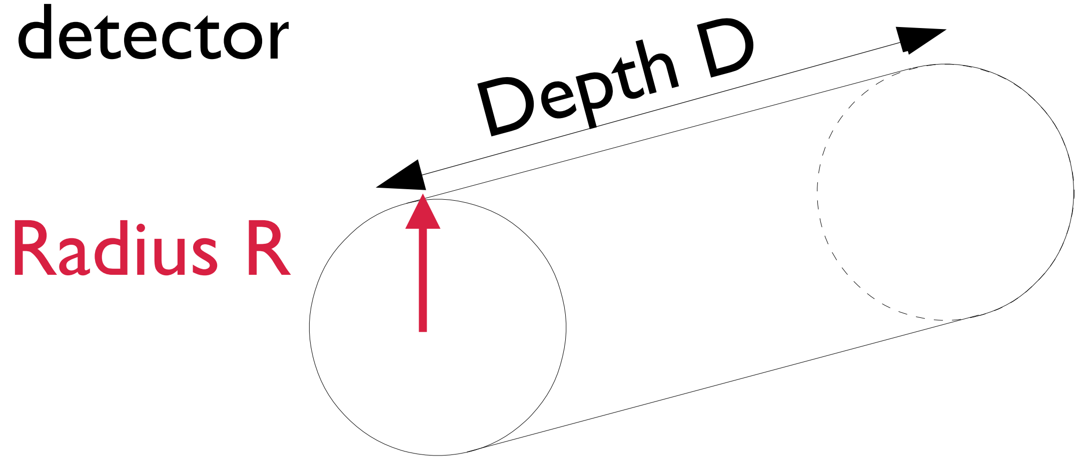
Long Lived Particles at FASER

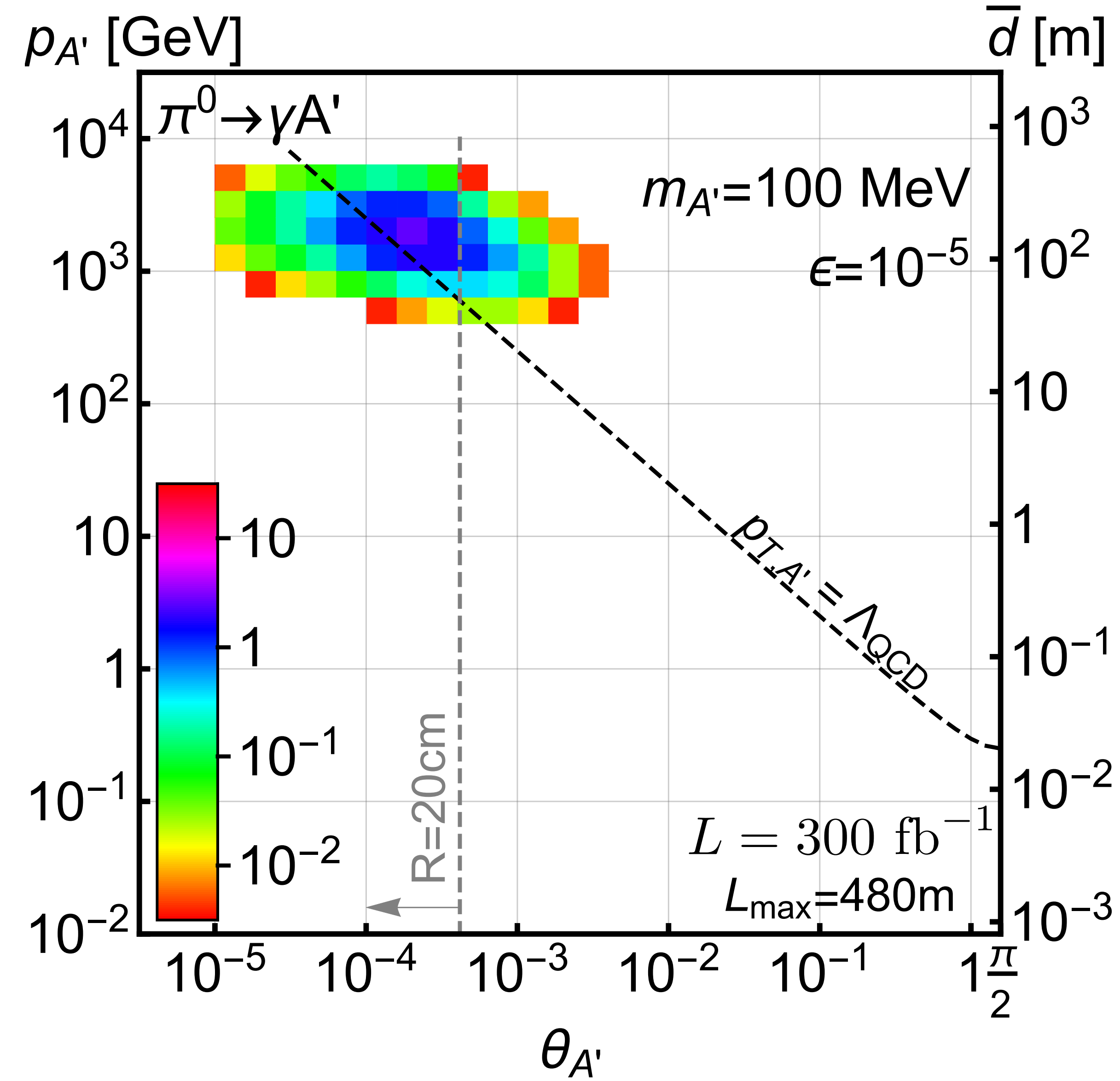
Dark Photon Decay in FASER

- only A' with E~TeV will reach detector
- A' very forward $\theta_{A'} < 1\ \mathrm{mrad}$
  → small detector radius

FASER dimensions:

- distance to IP: $L = 480\ \mathrm{m}$
- detector



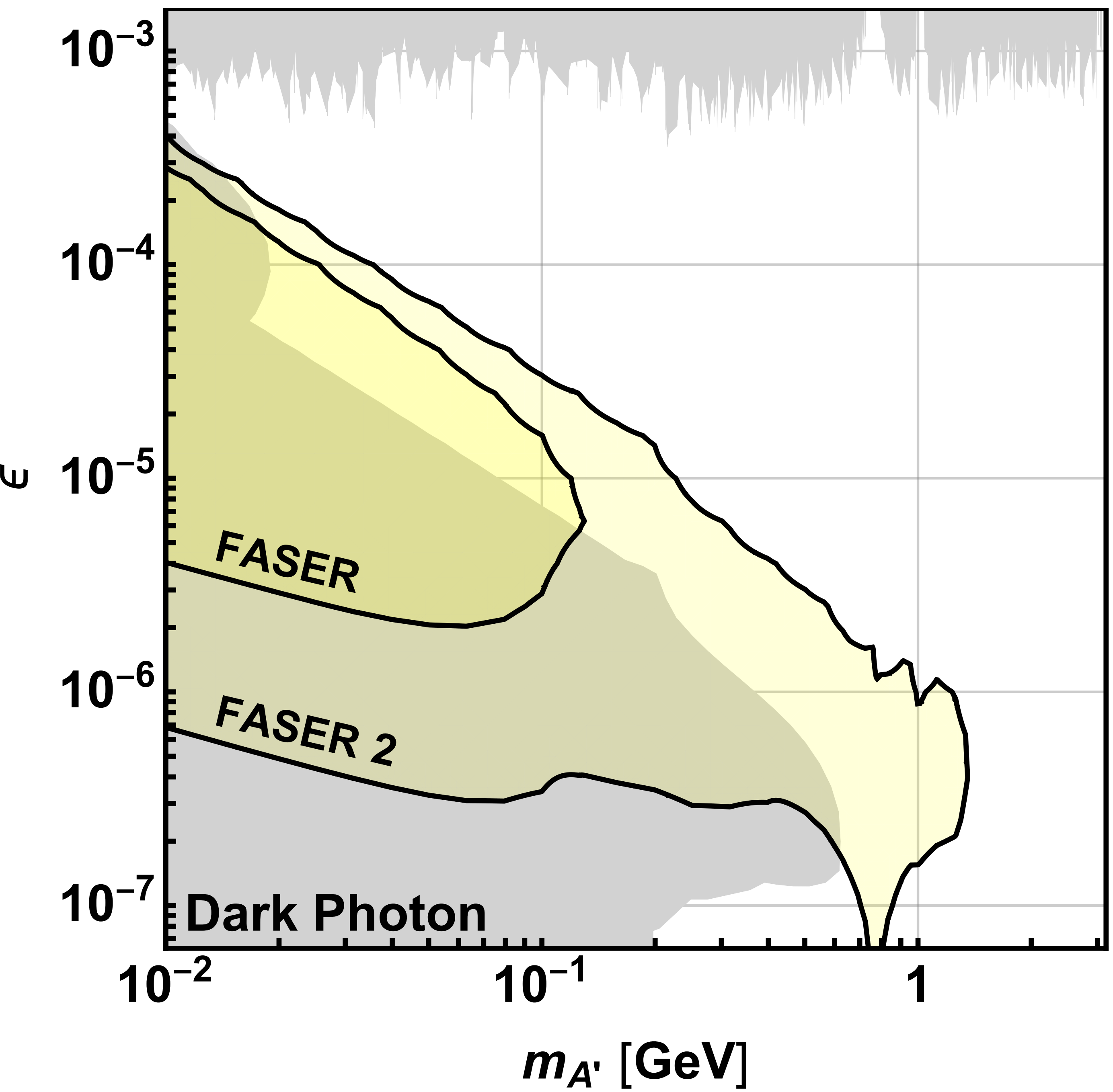


Dark Photons Spectrum wighted by probability to decay in FASER

$$\textbf{FASER:}\quad D = 1.5\ \mathrm{m},\ R = 10\ \mathrm{cm},\ \mathcal{L} = 150\ \mathrm{fb}^{-1}$$

$$\textbf{FASER 2:}\quad D = 5\ \mathrm{m},\quad R = 1\ \mathrm{m},\quad \mathcal{L} = 3\ \mathrm{ab}^{-1}$$

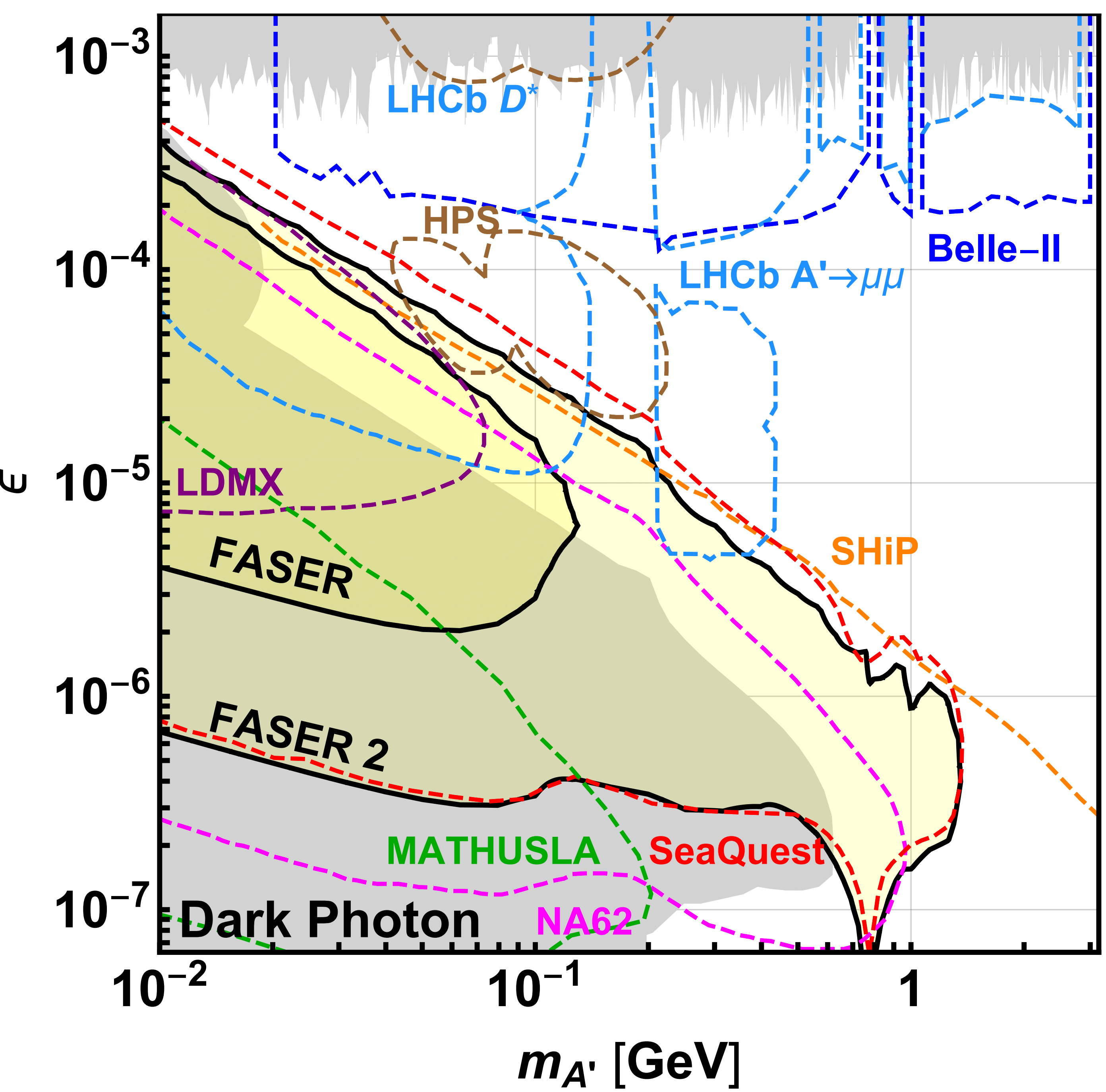
Long Lived Particles at FASER



FASER Reach

- signal acceptance almost 100%
- includes $A' \to ee, \mu\mu, \pi^{\pm}\pi^{\mp}$ modes
- almost background free

- low ε: limited production rate
- high ε: A' decay before detector
- high mass: direct production?



FASER Reach

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- includes $A' \to ee, \mu\mu, \pi^{\pm}\pi^{\mp}$ modes
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- low ε: limited production rate
- high ε: A' decay before detector
- high mass: direct production?

- reach similar to SeaQuest, SHiP

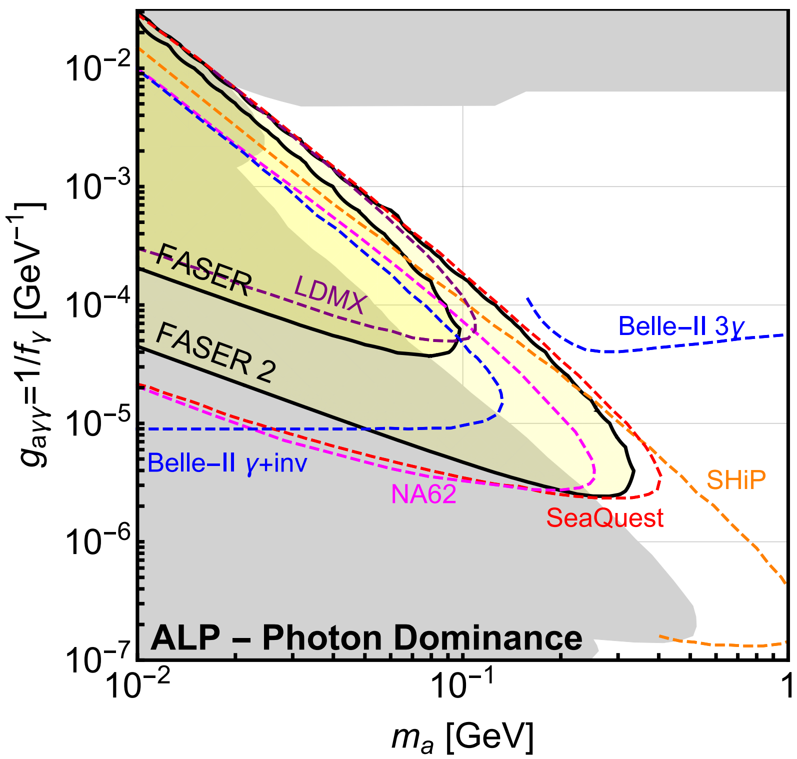
$$(m_{A'}\epsilon)^2|_{\max} \propto L/E_{A'}^{\text{Beam}}$$

Long Lived Particles at FASER

ALP

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

Primakoff Process:
$\gamma N \to a N$

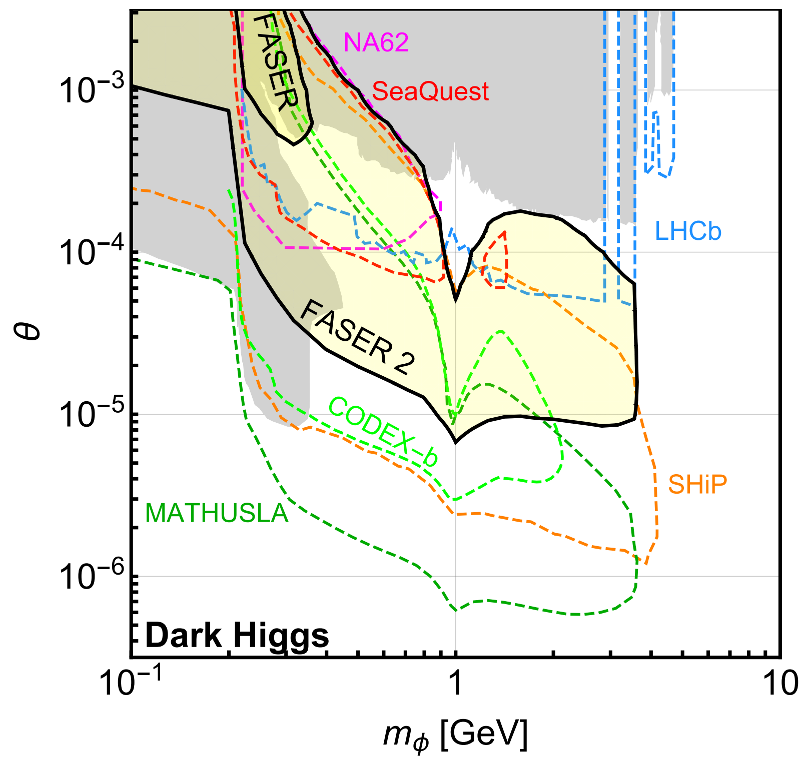


[1806.02348]

Dark Higgs

$$\epsilon |H|^2 \phi^2$$

$b \to s\phi$

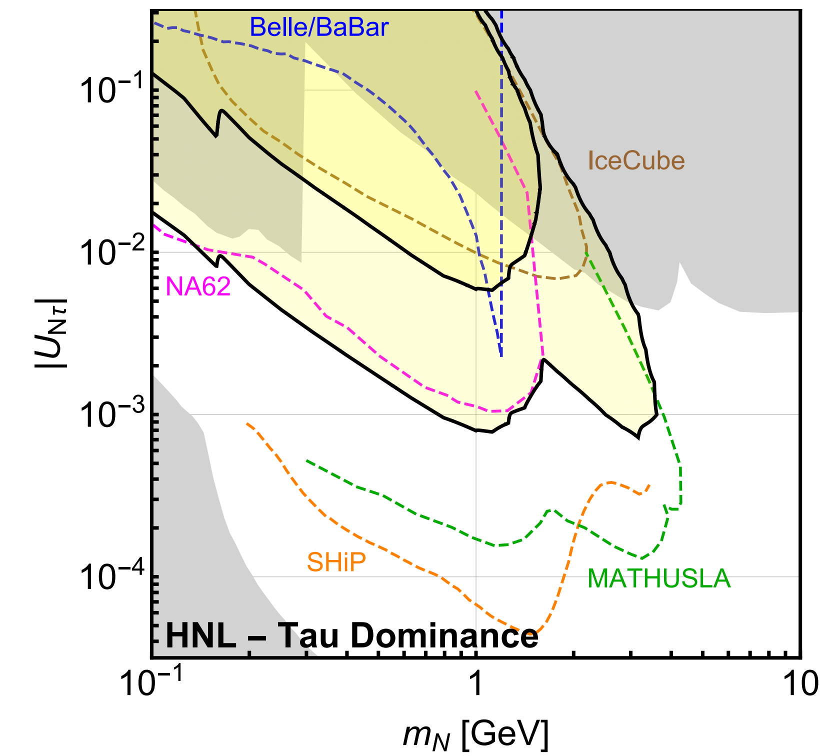


[1710.09387]

HNL

$$y L H N$$

$B^+ \to \ell N,\ B \to D \ell N$
$D_s \to \ell N,\ D \to K \ell N$



[1801.08947]

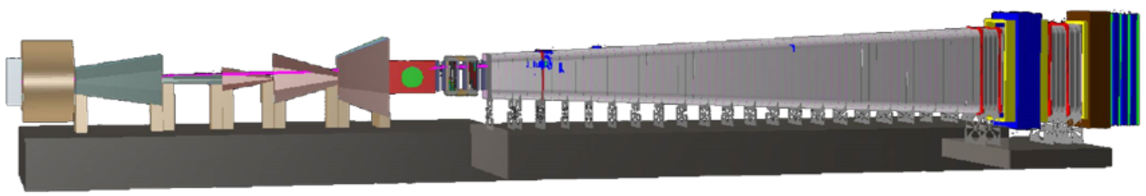
+ inelastic DM [A.Berlin, FK: 1810.01879]

+ more models in LLP summary document (to appear soon)

Long Lived Particles at FASER

Other proposed Experiments for Long Lived Particles

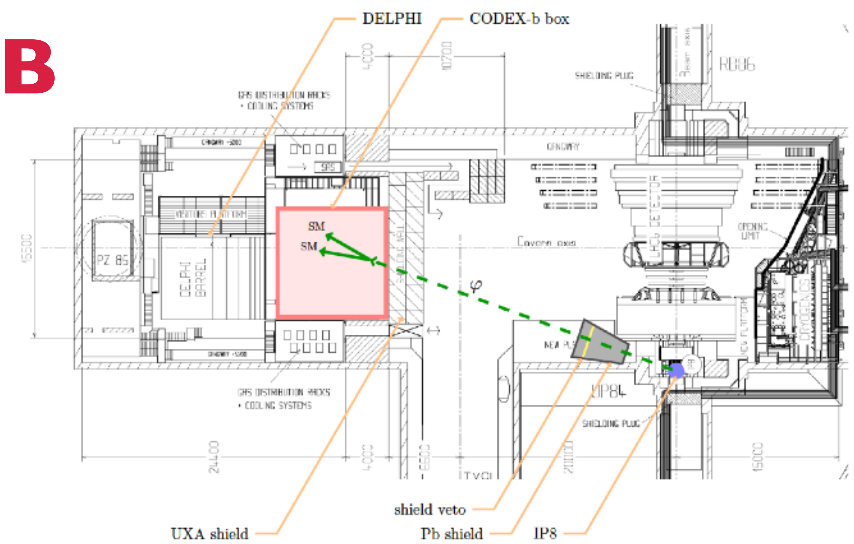
SHiP



~1000 m³, ~\$500M

Alekhin et al. (2015)

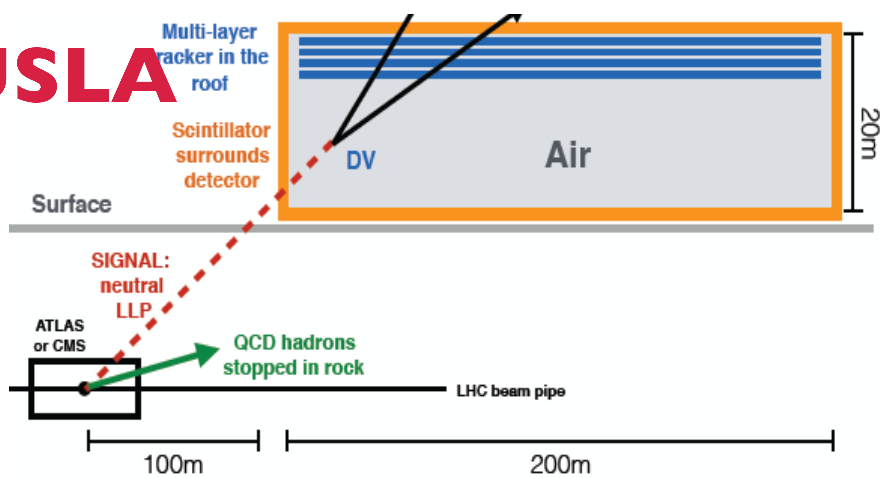
Codex-B



~1000 m³

Gligorov, Knapen, Papucci, Robinson (2016)

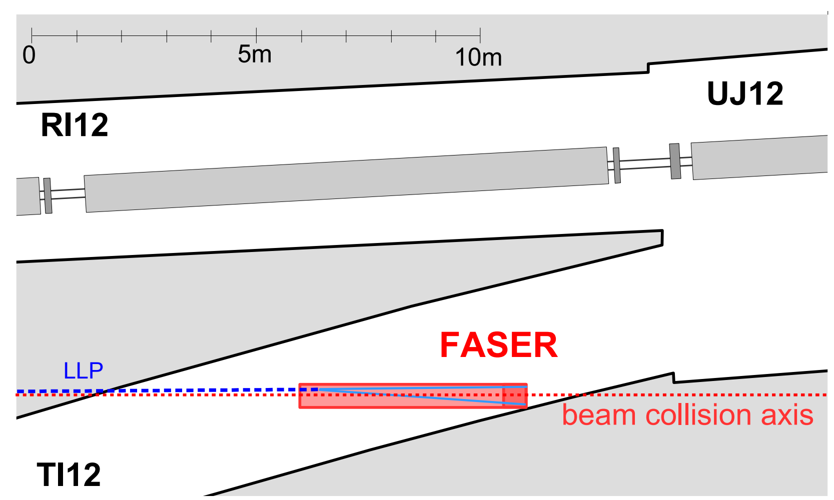
MATHUSLA



~2 10⁵ m³ ~ 1 IKEA, ~\$100M

Chou, Curtin, Lubatti (2016)

FASER



~1 m³ ~ μIKEA, ~\$2M

Feng, Galon, Kling, Trojanowski (2017)

Detector Design

Detector Design

$$pp \to \mathrm{LLP} + X, \quad \mathrm{LLP\ travels} \sim 480\ \mathrm{m}, \quad \mathrm{LLP} \to \mathrm{charged\ tracks} + X$$

Features of the Signal:

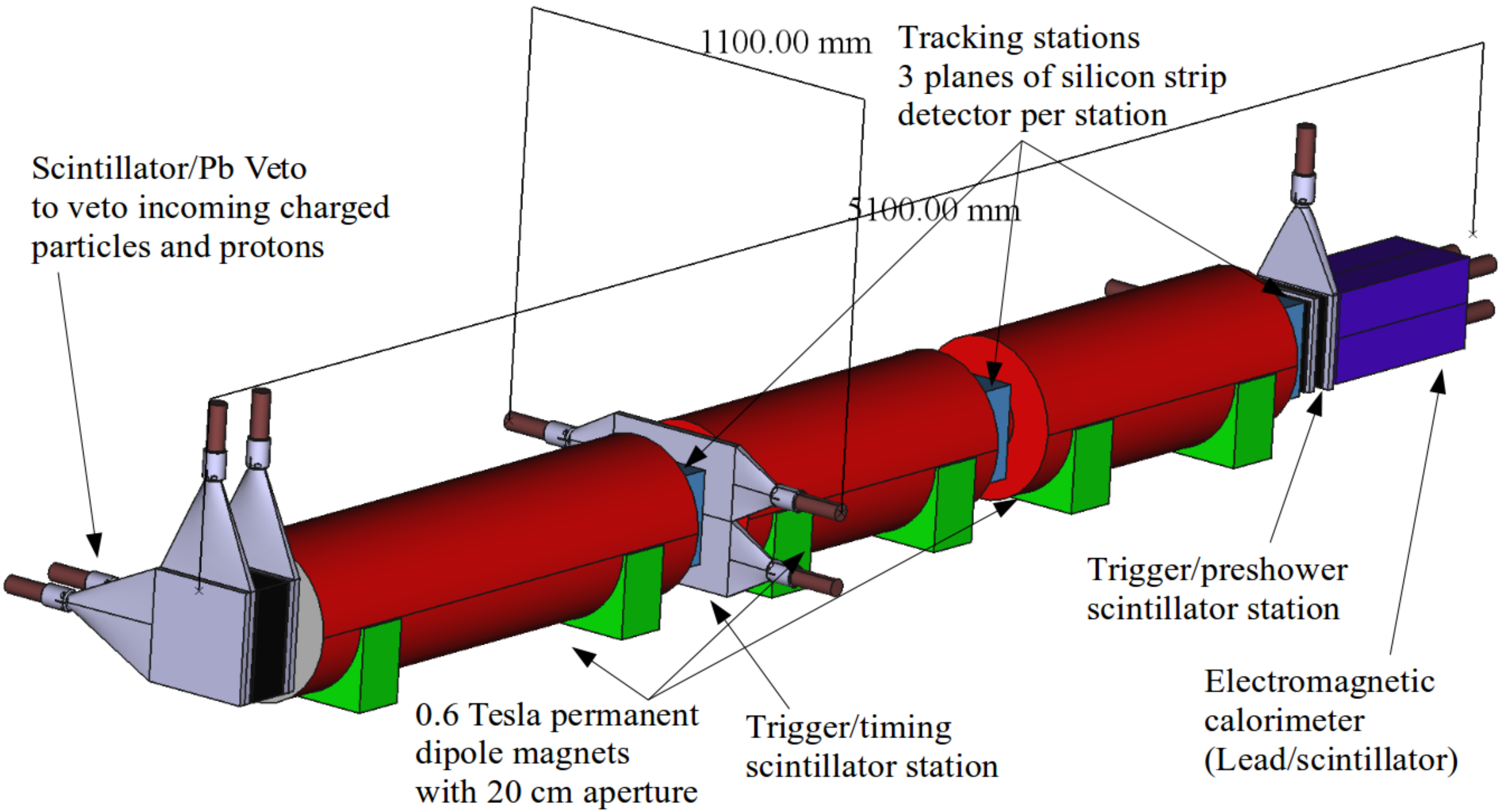
- two oppositely charged energetic tracks: E>500 GeV
- vertex inside detector volume
- combined momentum points towards IP

Proposed Detector Design:

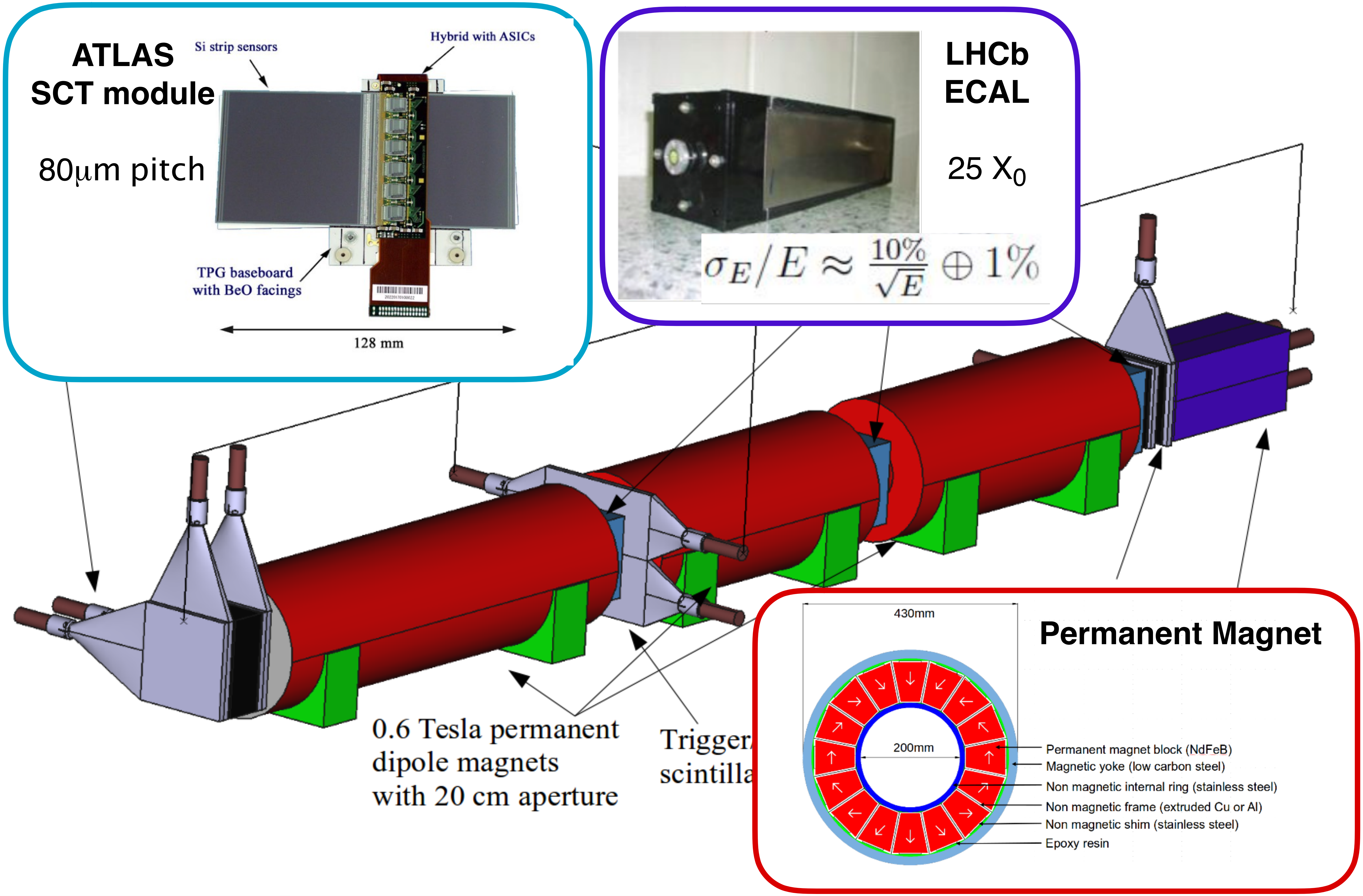
- FASER needs tracking, charge identification, rough energy estimate

$\longrightarrow$ tracking based technology, with magnet and calorimeter

Detector Design

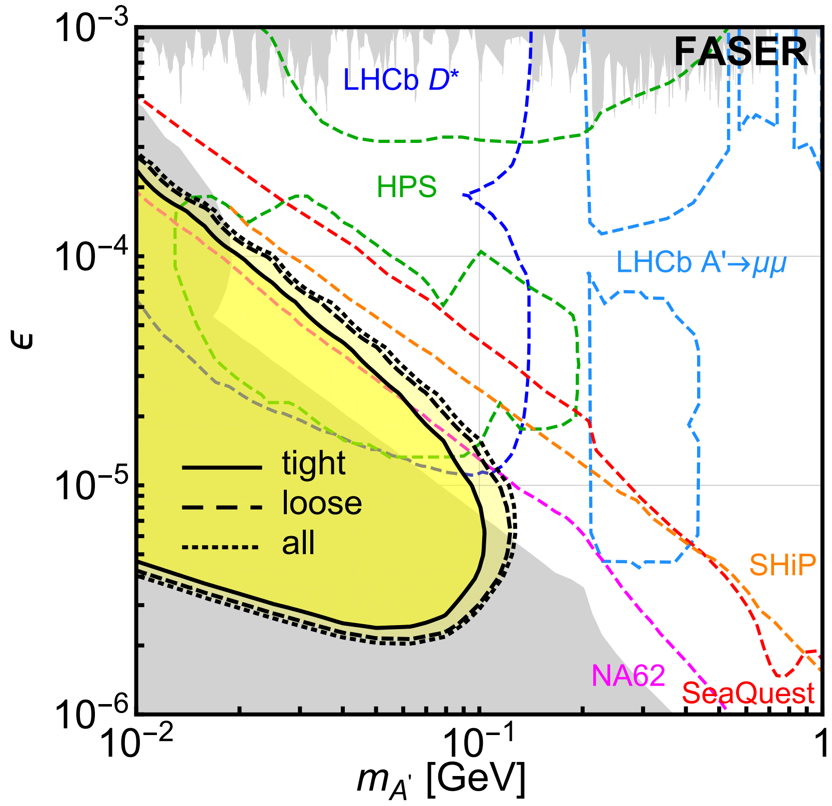


Detector Design

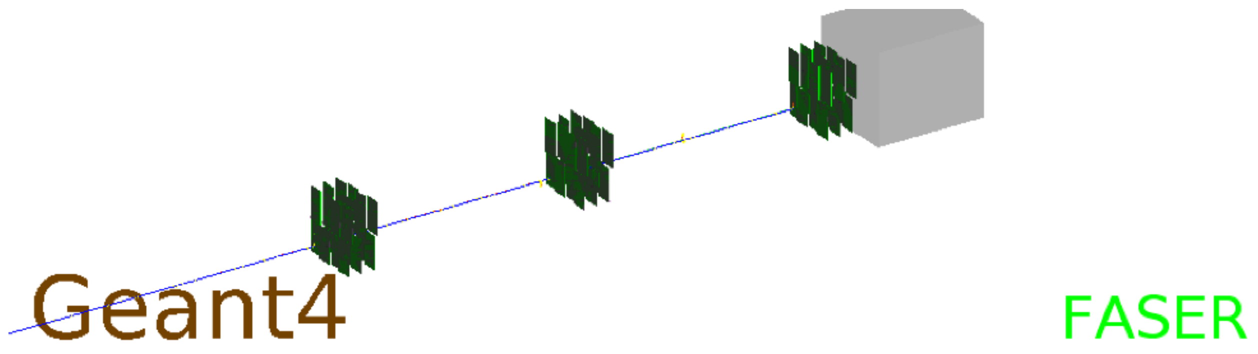


Detector Design

Letter of Intent
First estimate of signal efficiency
(require track separation >300μm)
→ reach essentially unaffected



Technical Proposal
Geant4 Simulations
Track Reconstructions
Development of Offline Software



Backgrounds

Backgrounds

Signal is striking

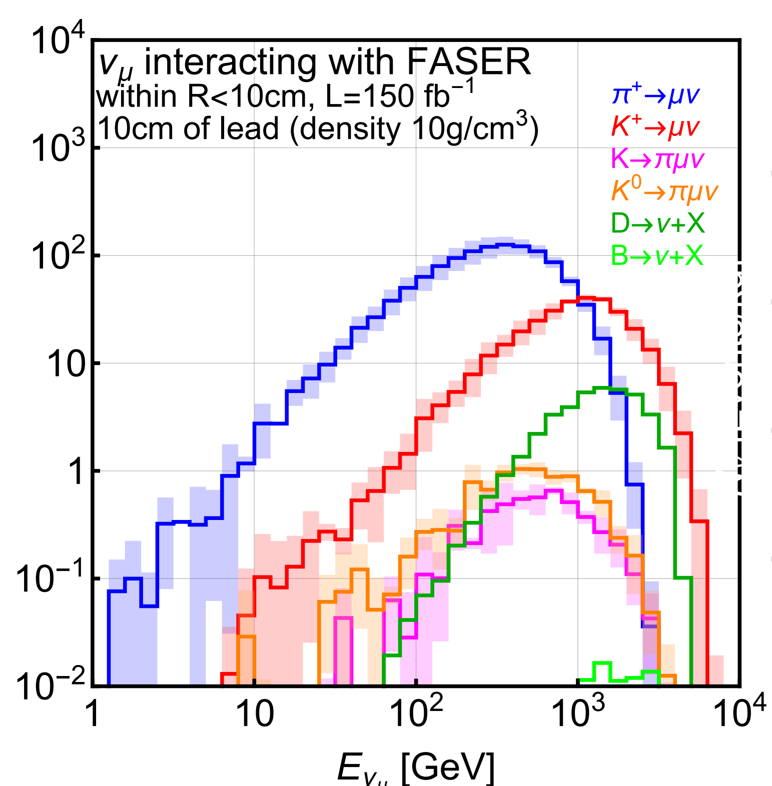
- two opposite-sign, high energy (E > 500 GeV) charged particles
- originate from a common vertex in a small, empty decay volume
- point back to the IP through 90 m of rock

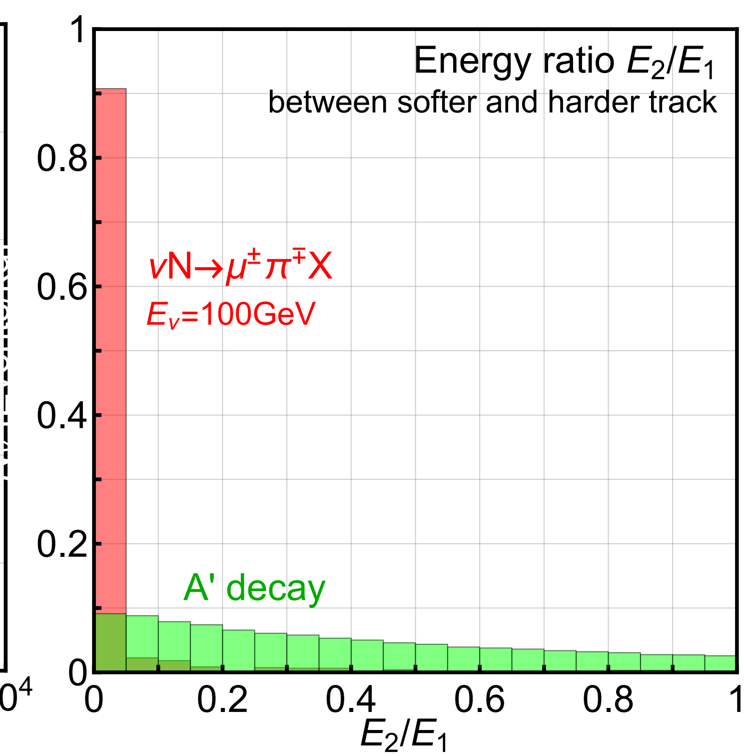
Background considerations

- shielding: natural (rock) and LHC infrastructure (concrete, magnets, absorbers)
- only muons/neutrino can transport TeV energies through ~100m rock

Neutrino Induced Events

- interaction with lead shield
  ⟶ low rate: 1000 interactions
- different kinematics

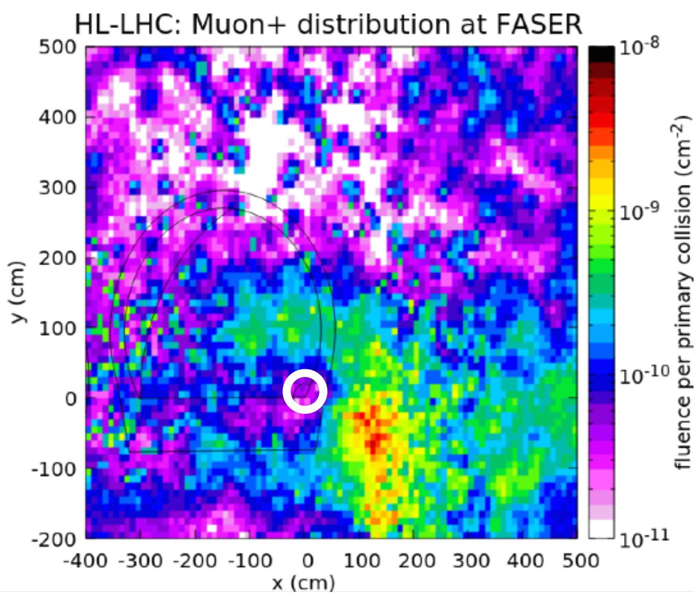


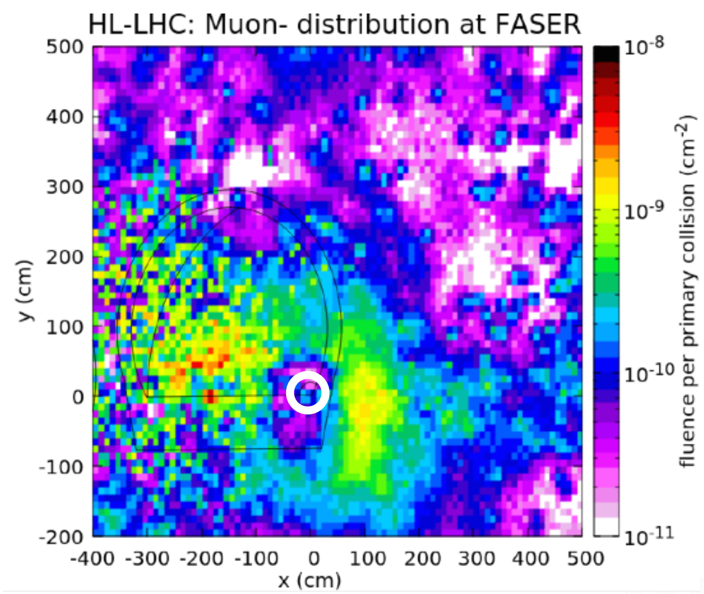


Backgrounds

FLUKA Study

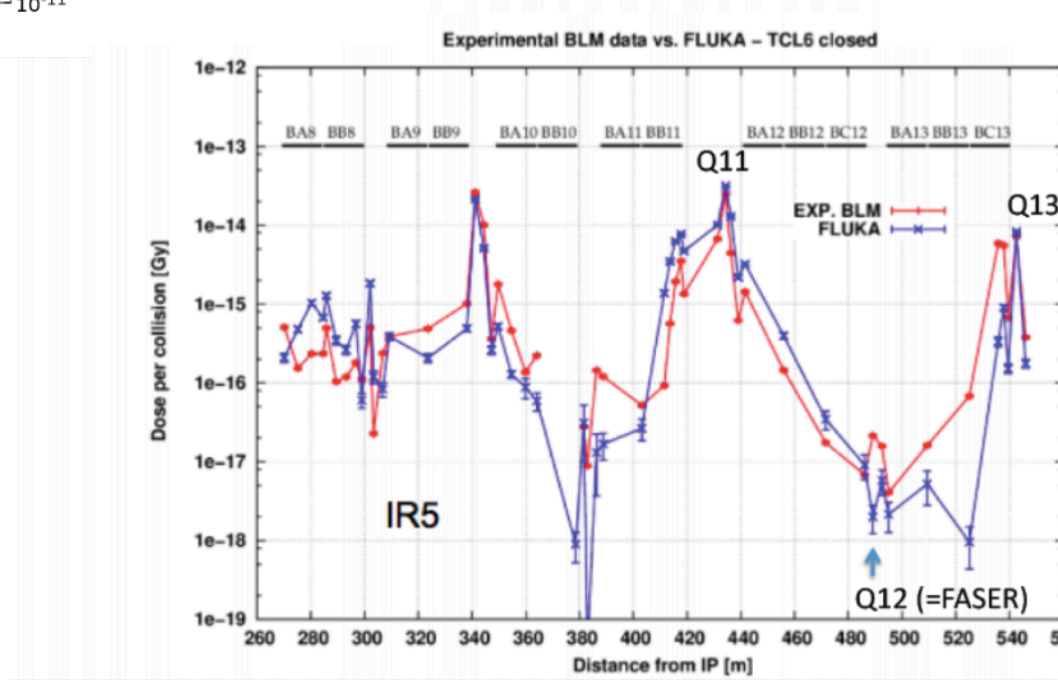
- CERN STI group performed FLUKA simulation
- most backgrounds associated with muon from collision debris
  → estimated flux: 0.2 Hz/cm^2 for E>100GeV
  → can be vetoed with scintillators





Process	Number
μ	540M
$\mu+\gamma_{\text{brem}}$	41K
$[\mu+(\gamma_{\text{brem}}\to e^+e^-)]$	[7.4K]
$\mu+$ EM shower	22K
$\mu+$ hadronic shower	21K

- no HE particles from beam-gas collisions and showers in dispersion suppressor
- low radiation levels close to FASER



F. Cerutti's talk at Chamonix 2018

Backgrounds

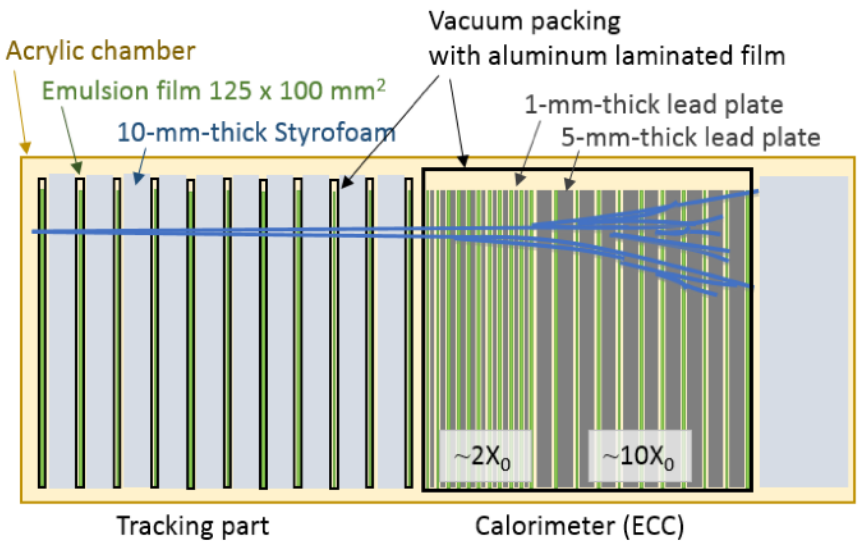
In-Situ Measurements

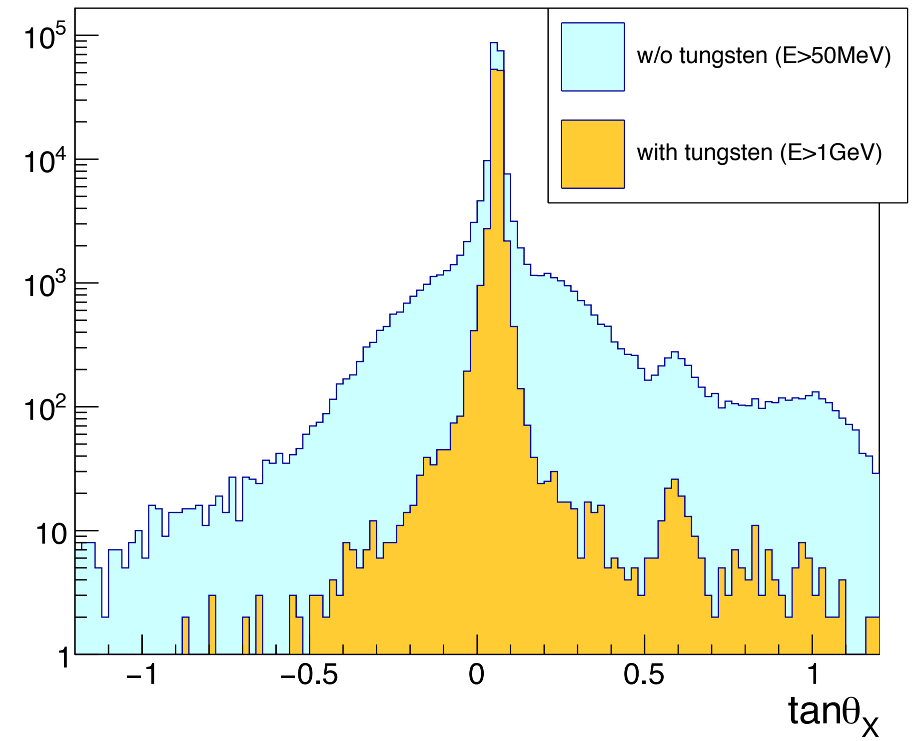
- using emulsion detectors
- first measurements already performed in TI18 and TI12
- consistent with FLUKA simulations

FLUKA: $2{\cdot}10^4$ fb/cm^2 Emulsion Detector: $(1.2\text{-}1.9){\cdot}10^4$ fb/cm^2

- data analysis on-going

- additional measurements with TimePix3 Beam Loss Monitor / BatMon (Battery-operated radiation monitor)





Timeline/Status/Outlook

Timeline and Status

May 2017: First idea on blackboard

Sep. 2017: Original FASER paper appears

Spring 2018: Collaboration with experimentalists
- identification of tunnel
- first detector concepts
- FLUKA study

Summer 2018: Background measurements

July 2018: FASER Logo

July 2018: Letter of Intend

Oct. 2018: SCT modules / calorimeter

Nov. 2018: Technical Proposal

2019-2020: Detector Construction and Civil Engineering

2021-2023: Collecting Data in Run 3

HL-LHC era: FASER 2 Upgrade

FASER: ForwArd Search ExpeRiment at the LHC

Jonathan L. Feng,[1,*] Iftah Galon,[1,†] Felix Kling,[1,‡] and Sebastian Trojanowski[1,2,§]

LETTER OF INTENT

FASER

FORWARD SEARCH EXPERIMENT AT THE LHC

Akitaki Ariga,[1] Tomoko Ariga,[1,2] Jamie Boyd,[3,*] David W. Casper,[4] Jonathan L. Feng,[4,†] Iftah Galon,[5] Shih-Chieh Hsu,[6] Felix Kling,[4] Hidetoshi Otono,[2] Brian Petersen,[3] Osamu Sato,[7] Aaron M. Soffa,[4] Jeffrey R. Swaney,[4] and Sebastian Trojanowski[8]

TECHNICAL PROPOSAL

FASER

FORWARD SEARCH EXPERIMENT AT THE LHC

Akitaki Ariga,[1] Tomoko Ariga,[1,2] Jamie Boyd,[3,*] Franck Cadoux,[4] David W. Casper,[5] Francesco Cerutti,[3] Salvatore Danzeca,[3] Liam Dougherty,[3] Yannick Favre,[4] Jonathan L. Feng,[5,†] Didier Ferrere,[4] Jonathan Gall,[3] Iftah Galon,[6] Sergio Gonzalez-Sevilla,[4] Shih-Chieh Hsu,[7] Giuseppe Iacobucci,[4] Enrique Kajomovitz,[8] Felix Kling,[5] Susanne Kuehn,[3] Mike Lamont,[3] Lorne Levinson,[9] Hidetoshi Otono,[2] John Osborne,[3] Brian Petersen,[3] Osamu Sato,[10] Marta Sabaté-Gilarte,[3,11] Matthias Schott,[12] Anna Sfyrla,[4] Jordan Smolinsky,[5] Aaron M. Soffa,[5] Yosuke Takubo,[13] Pierre Thonet,[3] Eric Torrence,[14] Sebastian Trojanowski,[15] and Gang Zhang[16]

Timeline and Status

The FASER collaboration

Akitaki Ariga,[1] Tomoko Ariga,[1,2] Jamie Boyd,[3] Franck Cadoux,[4] David W. Casper,[5]
Yannick Favre,[4] Jonathan L. Feng,[5] Didier Ferrere,[4] Iftah Galon,[6] Sergio Gonzalez-Sevilla,[4]
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Sato,[10] Matthias Schott,[11] Anna Sfyrla,[4] Jordan Smolinsky,[5] Aaron M. Soffa,[5]
Yosuke Takubo,[12] Eric Torrence,[13] Sebastian Trojanowski,[14,15] and Gang Zhang[16]

九州大学
KYUSHU UNIVERSITY

名古屋大学
NAGOYA UNIVERSITY

Weizmann Institute of Science

UNIVERSITY OF OREGON

Timeline and Status

The FASER Collaboration gratefully acknowledges the contributions of many people.

ACKNOWLEDGMENTS

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).

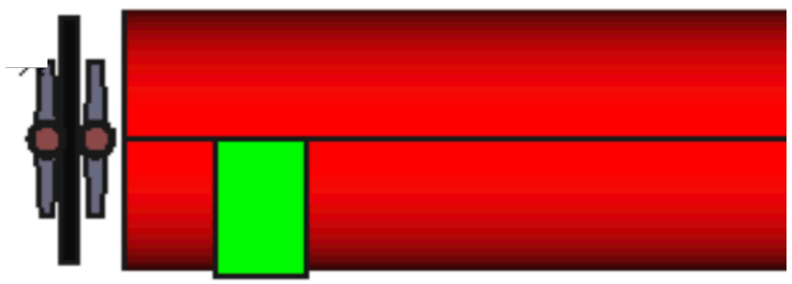
Outlook and Future Directions

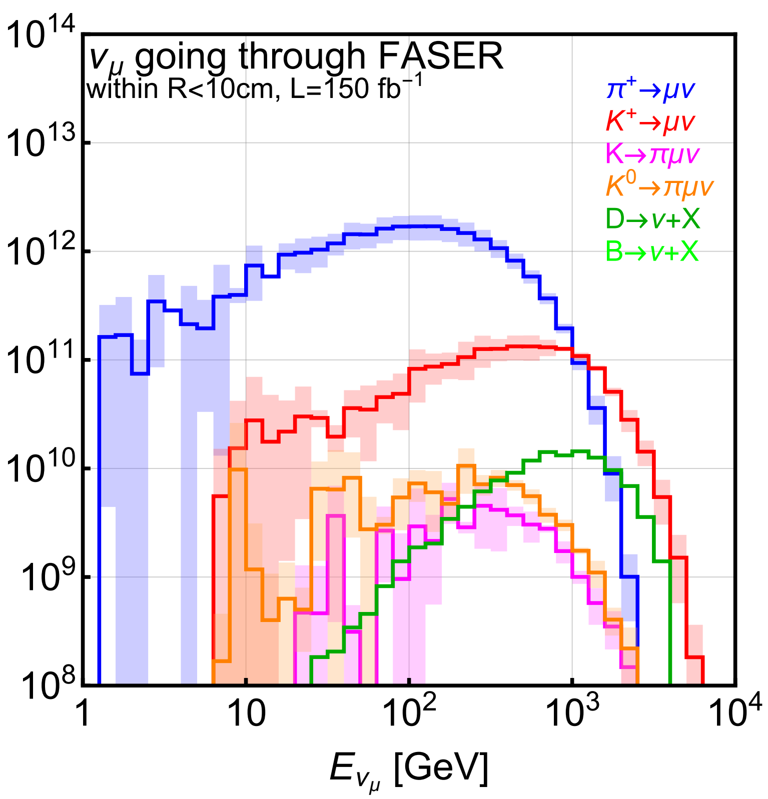
FASER and Neutrino Physics

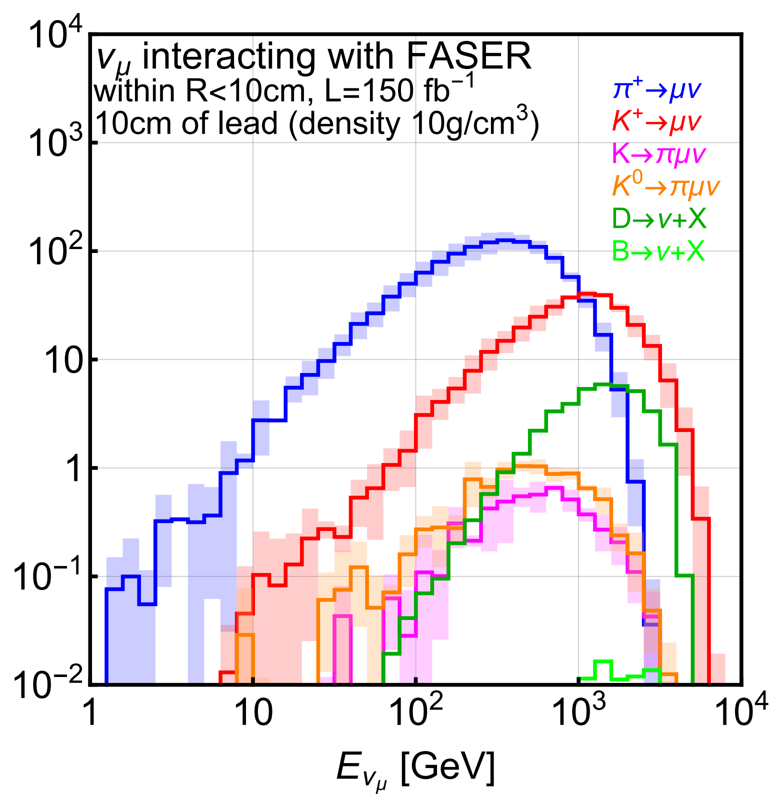
- large flux of high energy neutrinos going though in FASER
- some of them will interact with lead shield
- estimation of flux ongoing
  ~1000 CC muon neutrinos expected
  → detection of first neutrino at the LHC ?
  → neutrino XS measurements ?
- detector requirements? emulsion detectors?

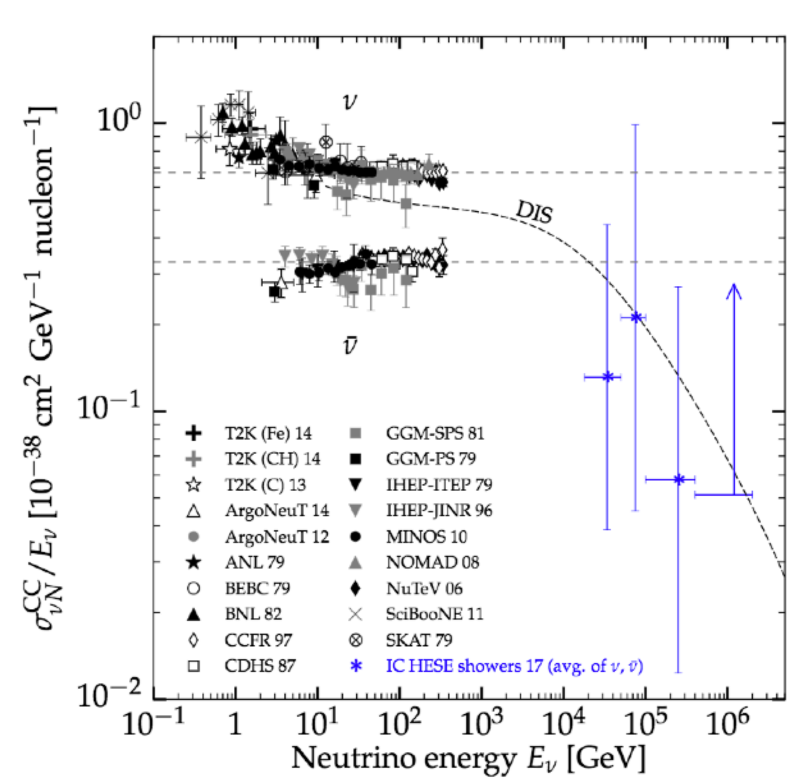
lots of neutrinos in here

lead shield







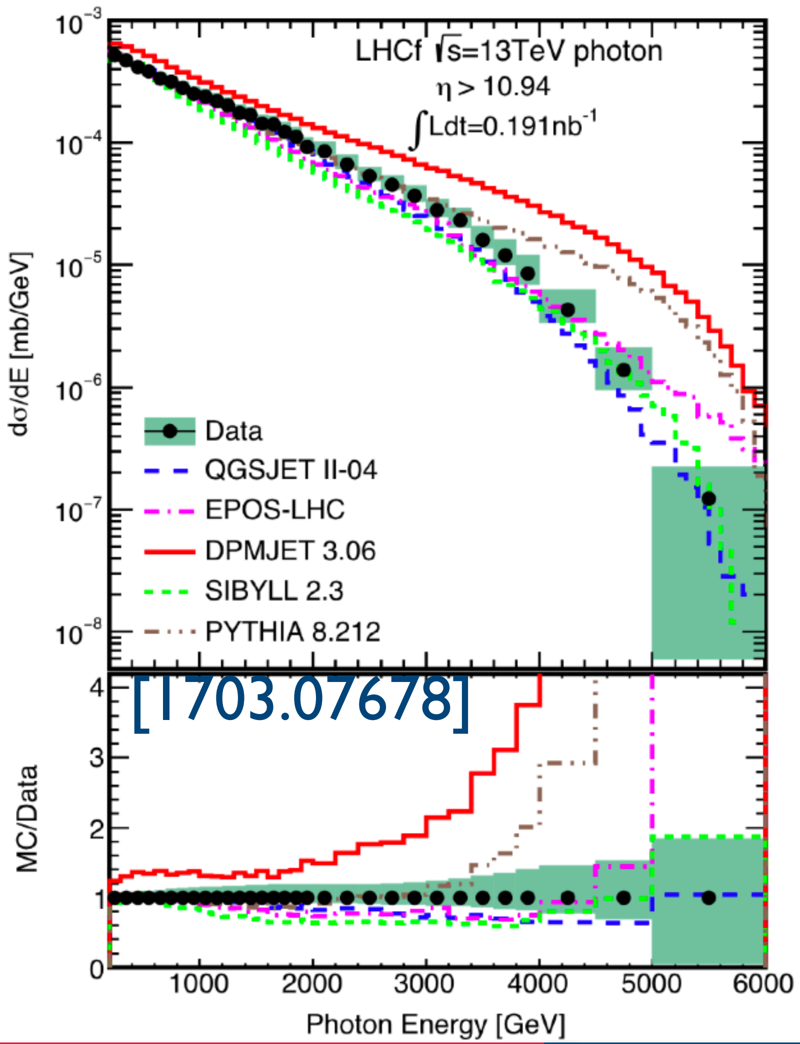


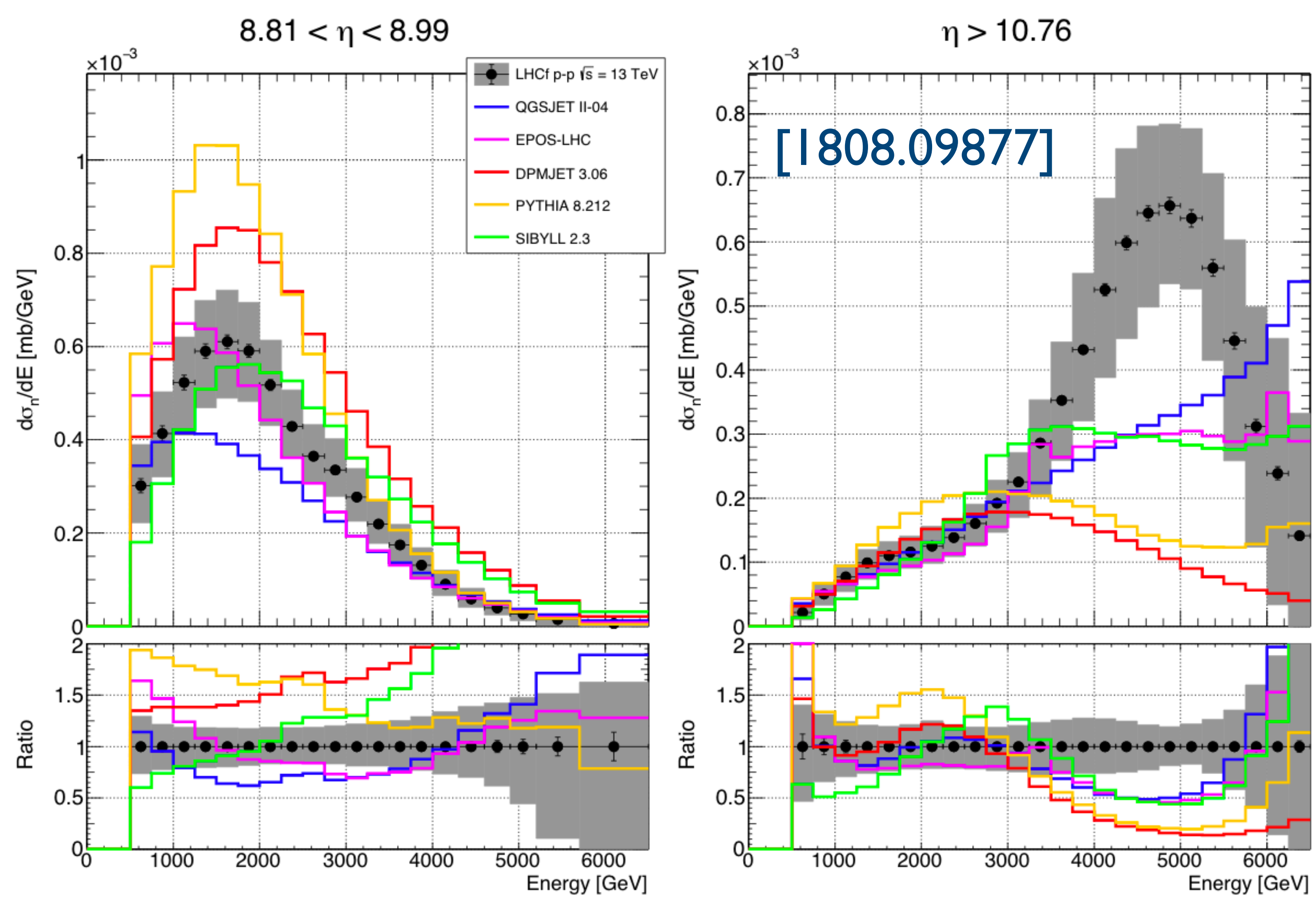
Outlook and Future Directions

Analysis of In-Situ measurements

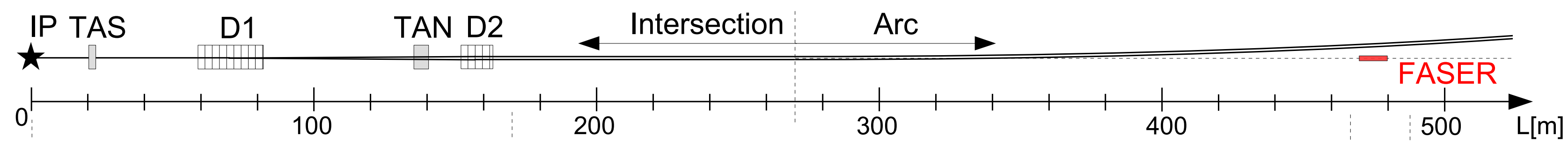
- data collected in both TI18 (3 fb^{-1}) and TI12 (7 fb^{-1})
- total rate agrees with FLUKA simulation
- Can we see neutrino interactions in emulsion detector? (~10 expected)
- forward Monte Carlo has sizable uncertainties

  ⟶ Can emulsion detector data / FASER constrain forward Monte Carlo?



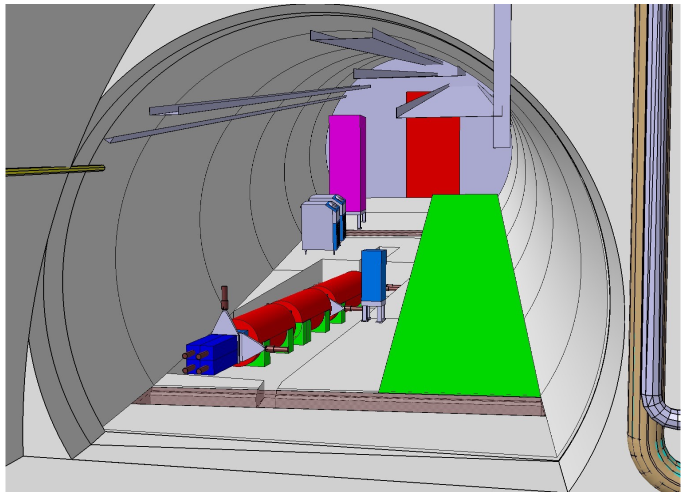


Summary and Outlook



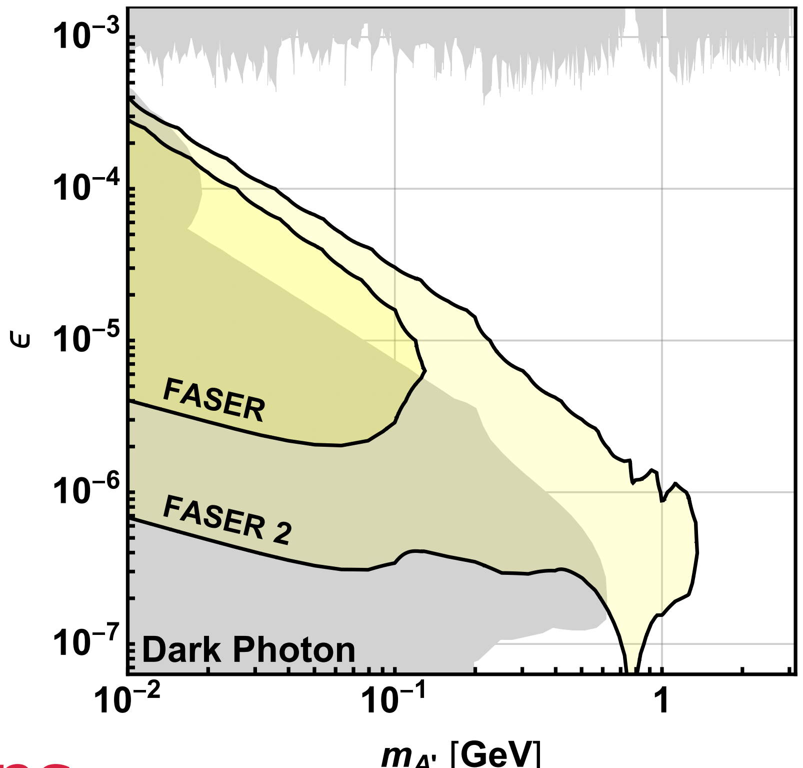
Forward Physics

- large event rates in forward direction
- energetic particles very forward $\theta < 1\ \mathrm{mrad}$
- search for light weakly coupled particles



FASER

- location identified in unused tunnel
- signature: 2 energetic tracks with $E \sim \mathrm{TeV}$
- equipped with tracking system + magnetic field
- significant discovery potential for many LLPs



Status and Outlook

- Letter of Intent and Technical Proposal submitted
- 2019-2020: Construction
- 2021-2023: data taking
- explore more physics opportunities

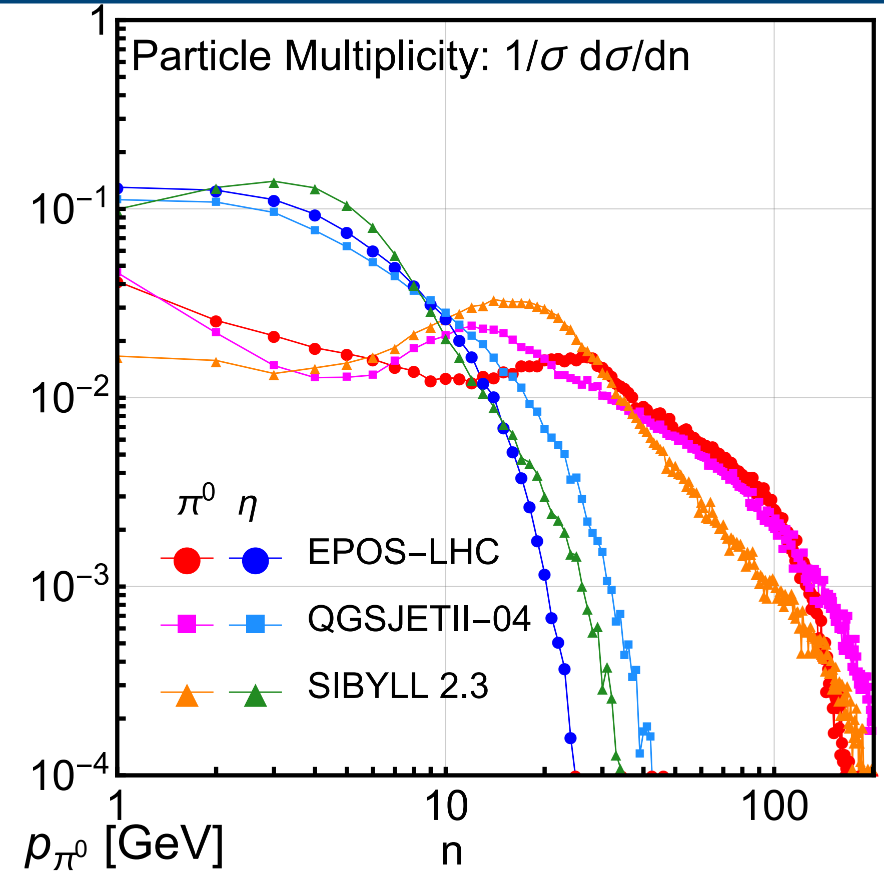
We look forward to feedback and suggestions

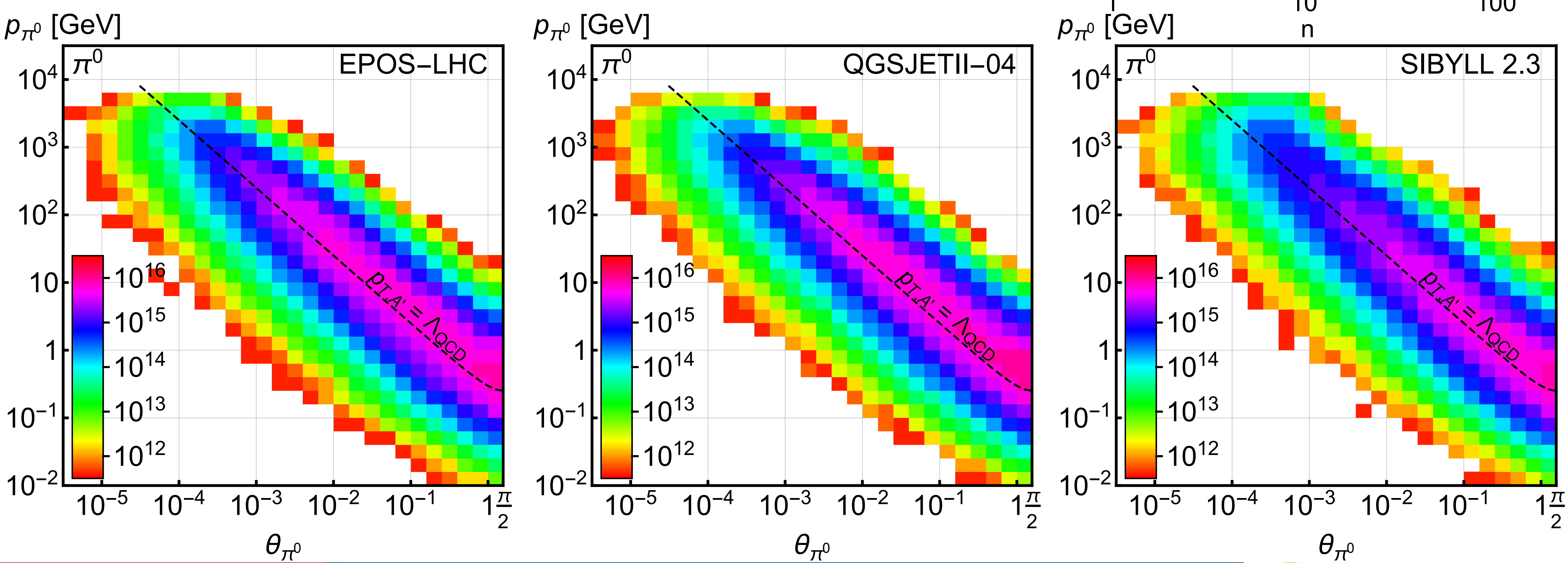
Backup

Backup - MC Generators

Comparison of Forward Physics Models

- traditionally relied on data from ultra-high-energy cosmic-ray experiments
- new models are tuned to match LHC data (LHCf, ALFA)
- predictions are consistent





Backup - Dark Higgs

Dark Higgs Phenomenology

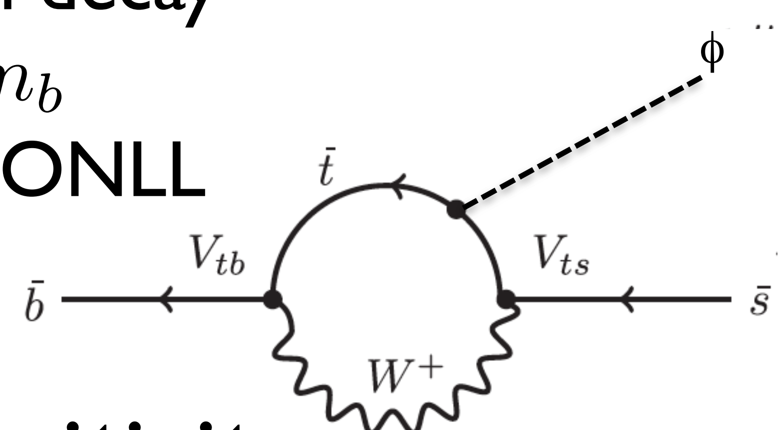
- phenomenological parameterization after EWSB: dark Higgs ϕ

$$\mathcal{L} \subset -m_\phi^2 \phi^2 - \sin\theta \, \frac{m_f}{v} \, \phi \bar{f} f - \lambda v h \phi\phi$$

- Higgs-like couplings to fermions suppressed by θ
- mainly decays to heaviest possible state

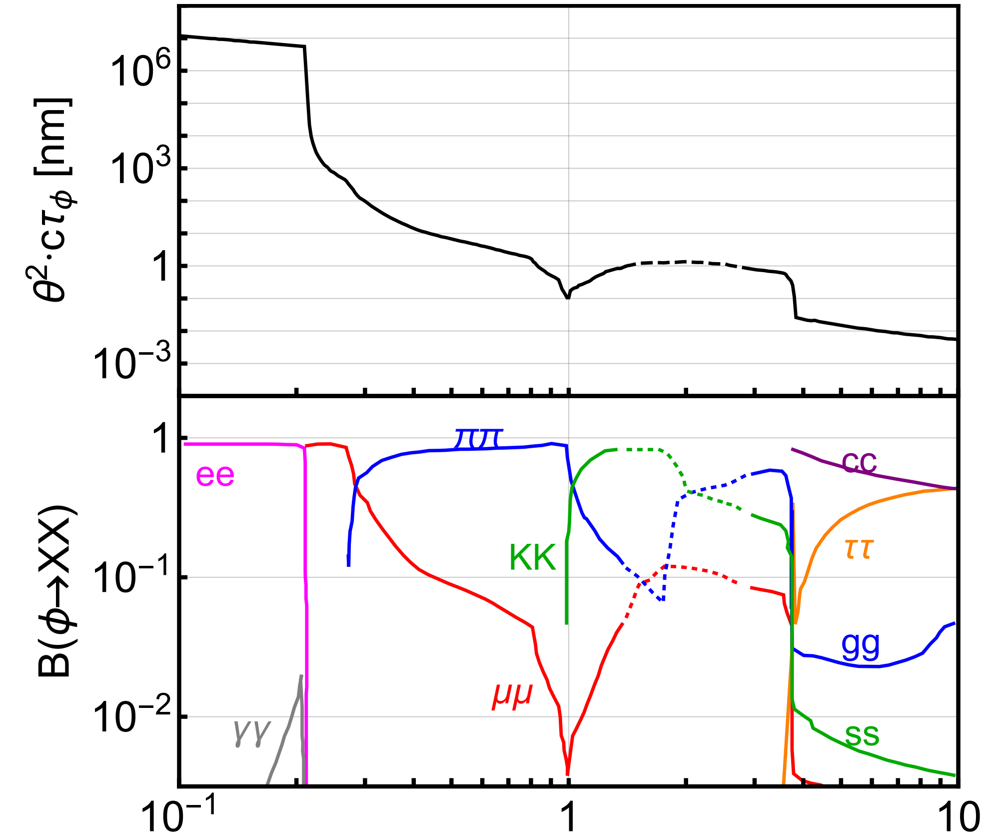
Dark Higgs Production for FASER

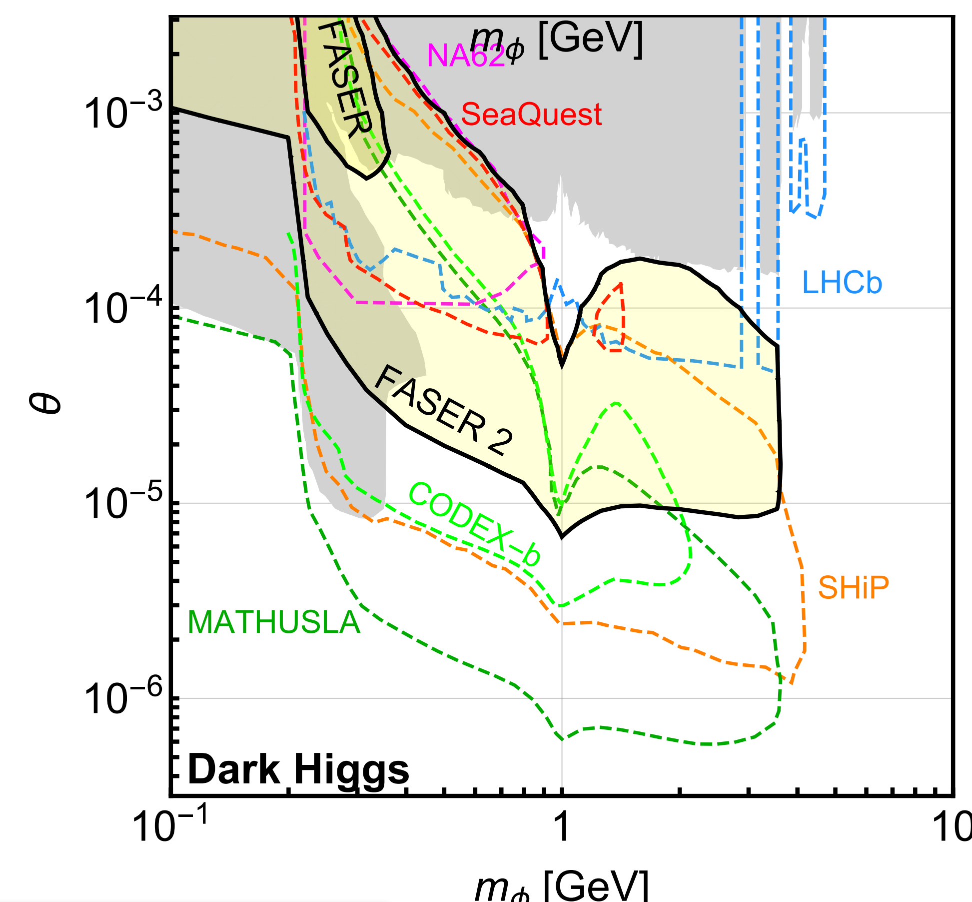
- mainly via B-meson decay
  - ⟶ typical $p_T \sim m_b$
  - ⟶ simulated via FONLL



Dark Photon Sensitivity

- larger radius R=1m increases sensitivity
- hadronic final states become important
- complementary to other current and proposed experiments





Other Models - Dark Higgs

Dark Higgs Phenomenology

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$$\mathcal{L} \subset -m_\phi^2 \phi^2 - \sin\theta \, \frac{m_f}{v} \, \phi \bar{f} f - \lambda v h \phi \phi$$

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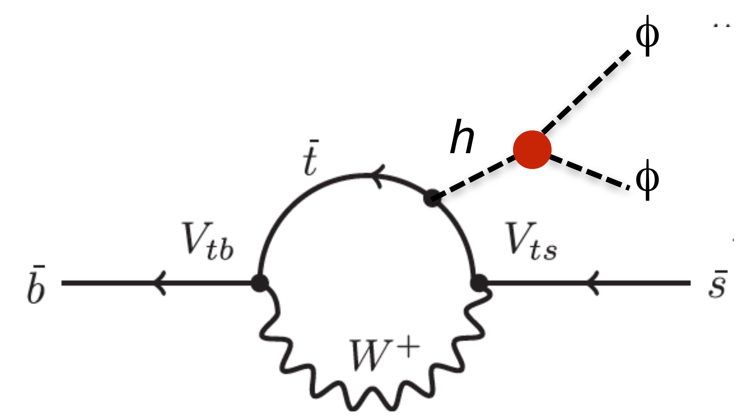
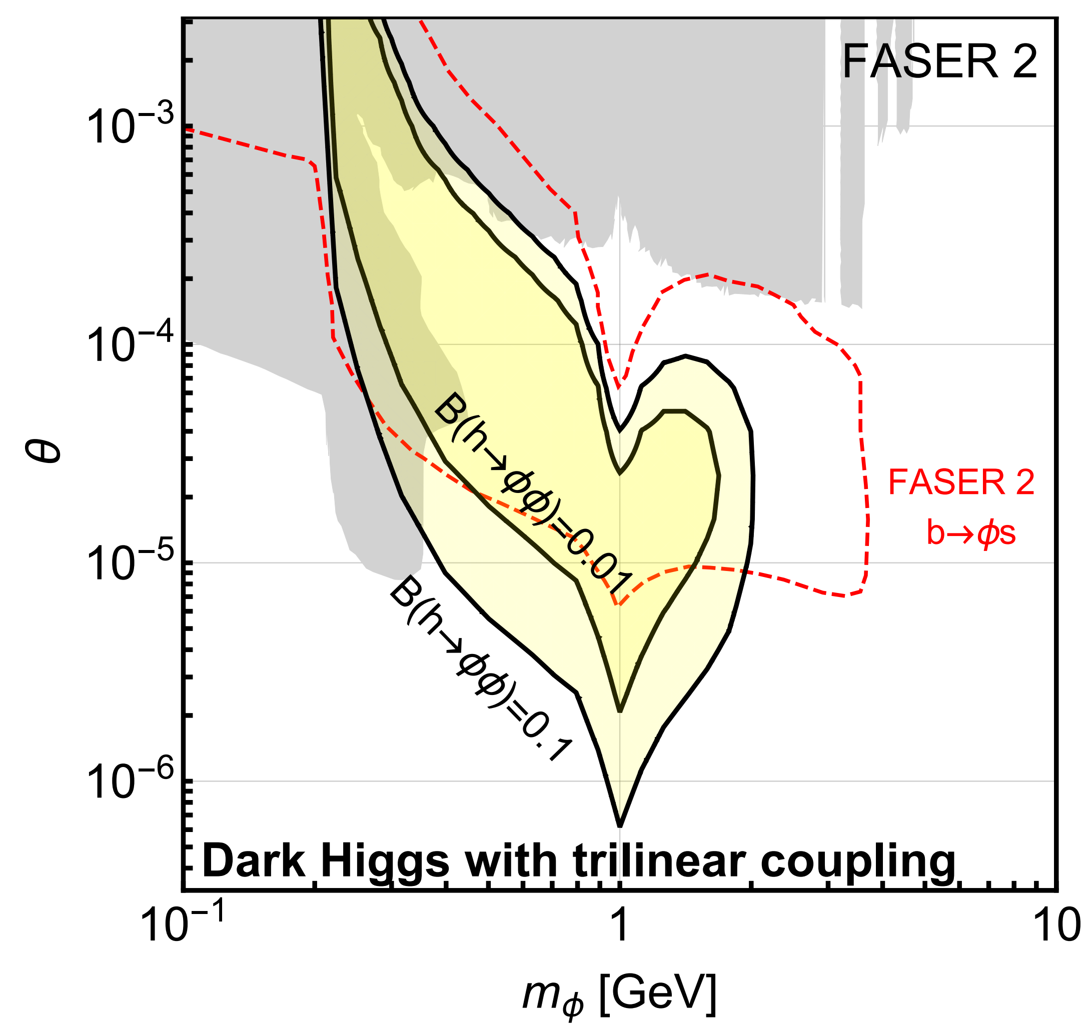


Probing the trilinear coupling

- FASER can also probe the trilinear coupling
- This competes with h→ϕϕ (invisible)
- up to 100s of events from "double dark Higgs" production



Other Models - HNLs

HNL Theory

- phenomenological parameterization after EWSB: HNLs N_I

$$\mathcal{L} \subset \bar{N}_I(i\partial\!\!\!/ - m_N)N_I - (g/\sqrt{2})W_\mu \bar{\ell}_{L,\alpha}\gamma^\mu U_{\alpha I} N_I$$

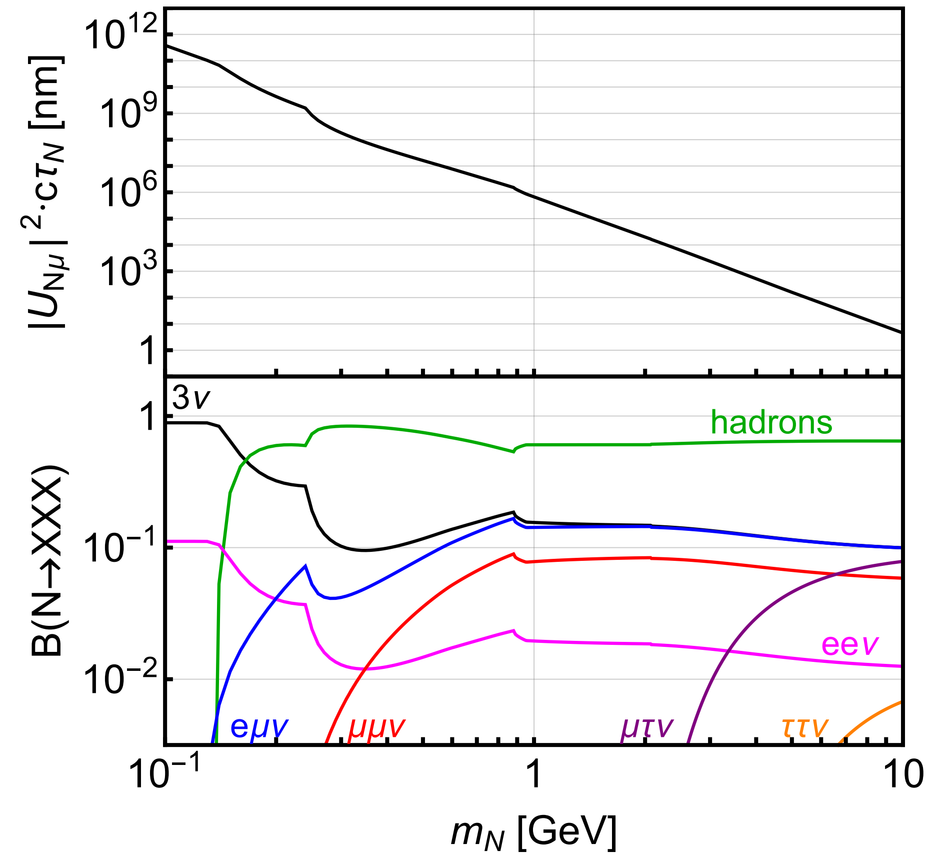
- for simplicity only $U_{\mu I} \neq 0$

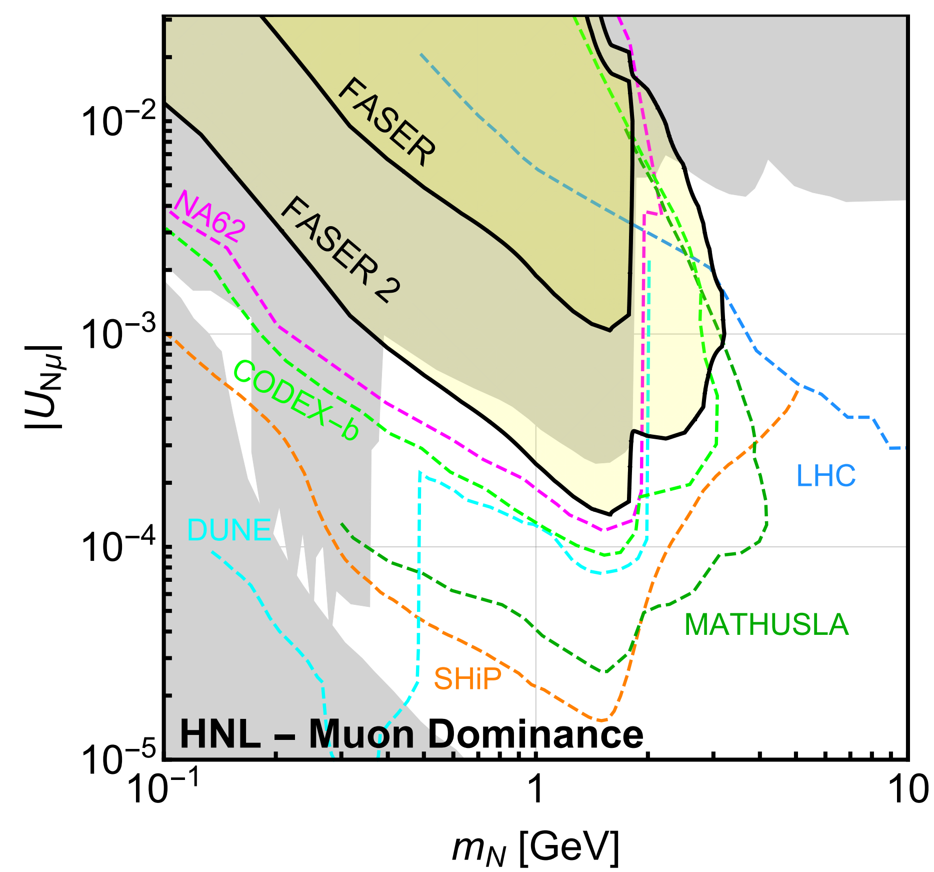
HNL Production for FASER

- mainly via B-meson and D-meson decay
  → simulated via FONLL

HNL Reach

- typically large lifetime: $c\tau\gamma \sim 10^3 - 10^7$ m
  → large boost and small volume of FASER is limitation
- larger radius R=1m increases sensitivity
- mainly extends reach for $m_N > m_D$

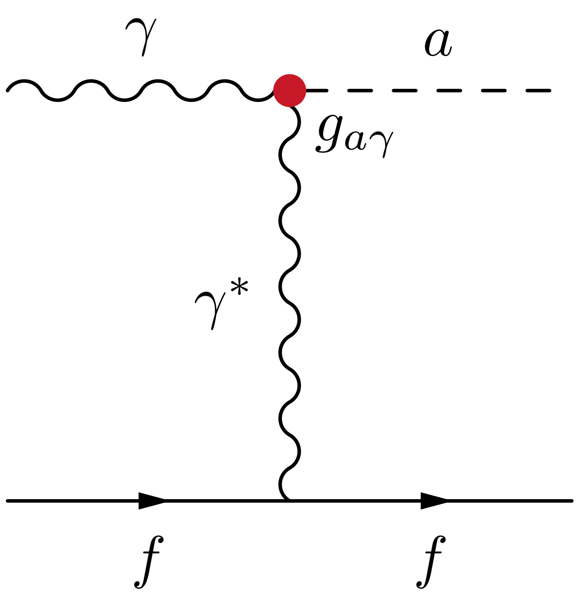




Other Models - ALPs

ALP Phenomenology

$$\mathcal{L} \subset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

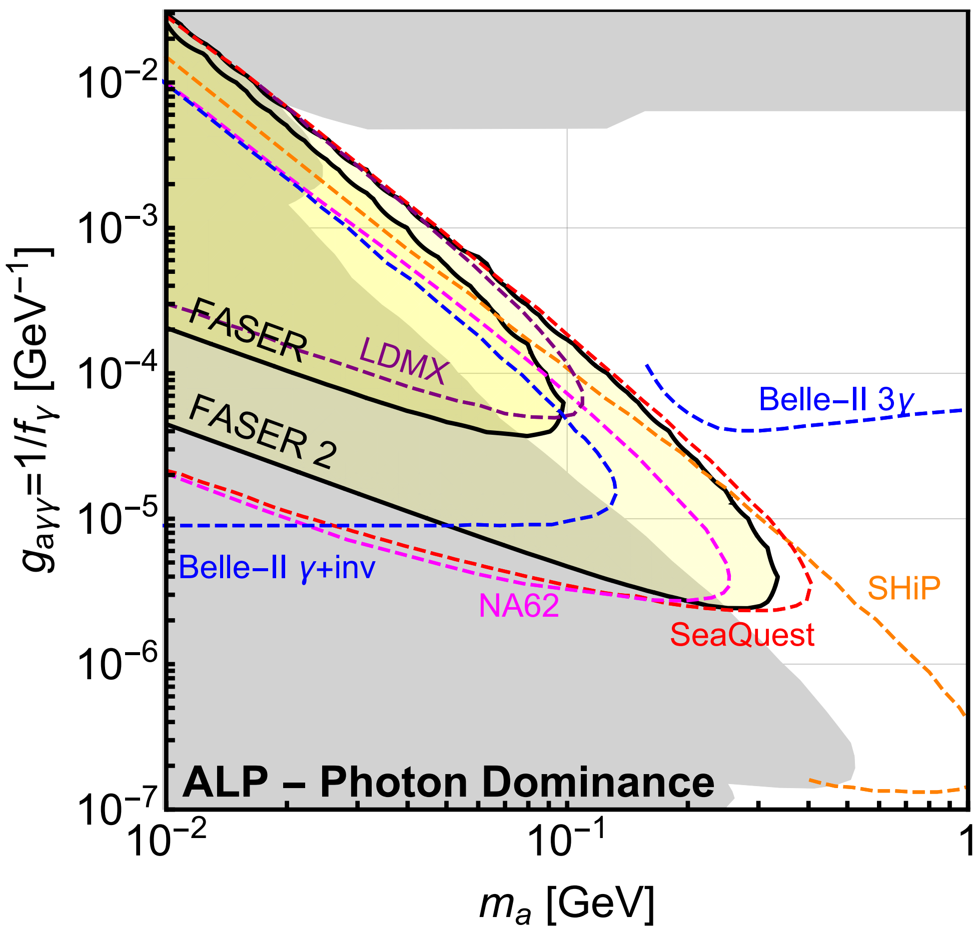


ALP Production for FASER

- collimated photon beam from pion decay
- ALP production via Primakoff process
  → photons colliding with TAN
- small momentum transfer: $p_a^\mu \approx p_\gamma^\mu$
  → ALP and photon are almost collinear

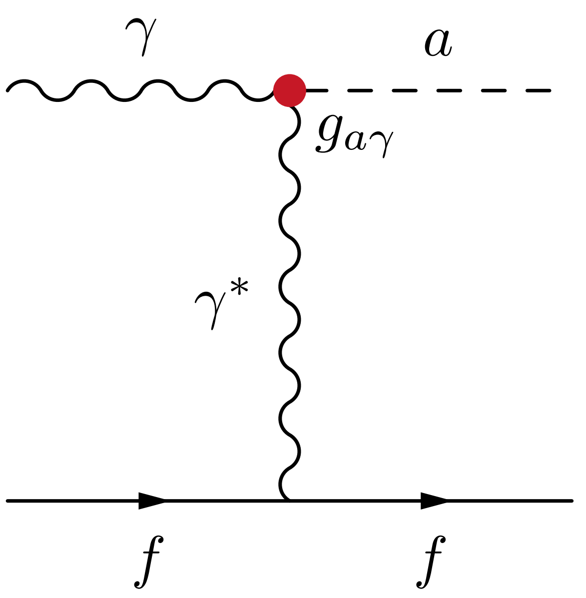
ALP Reach

- large signal rates possible
- FASER needs additional ECAL
- depending on backgrounds, good di-photon identification required



ALP Theory

$$\mathcal{L} \subset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$



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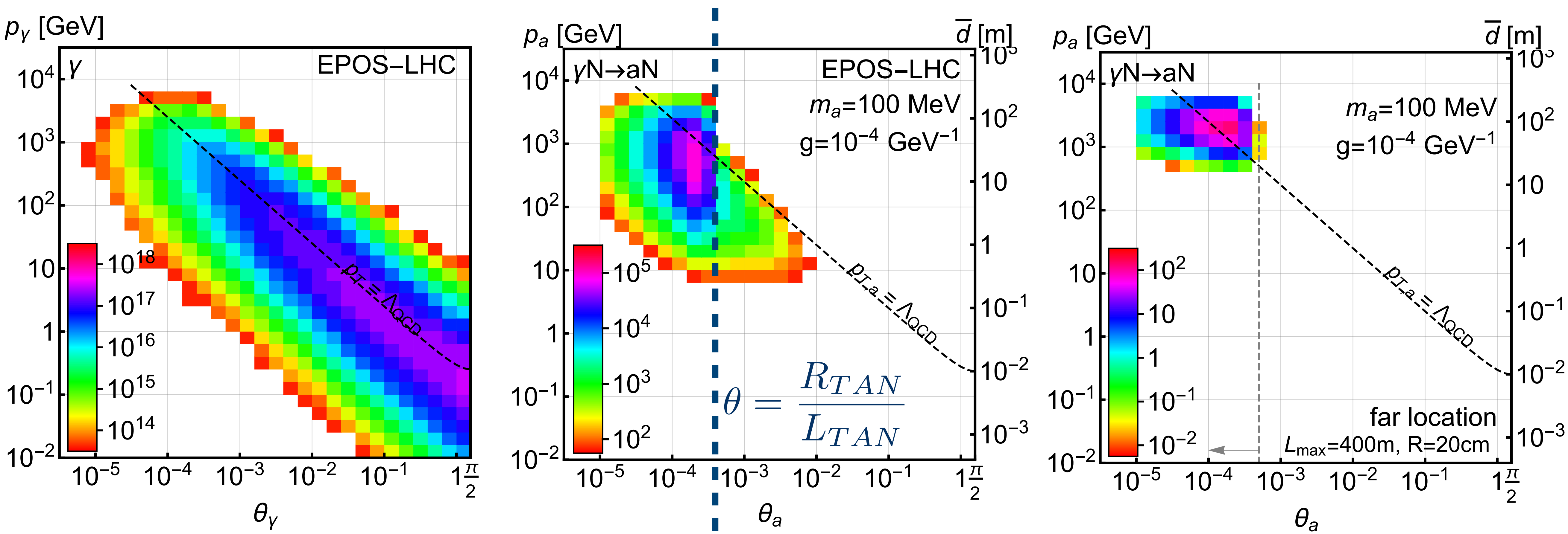
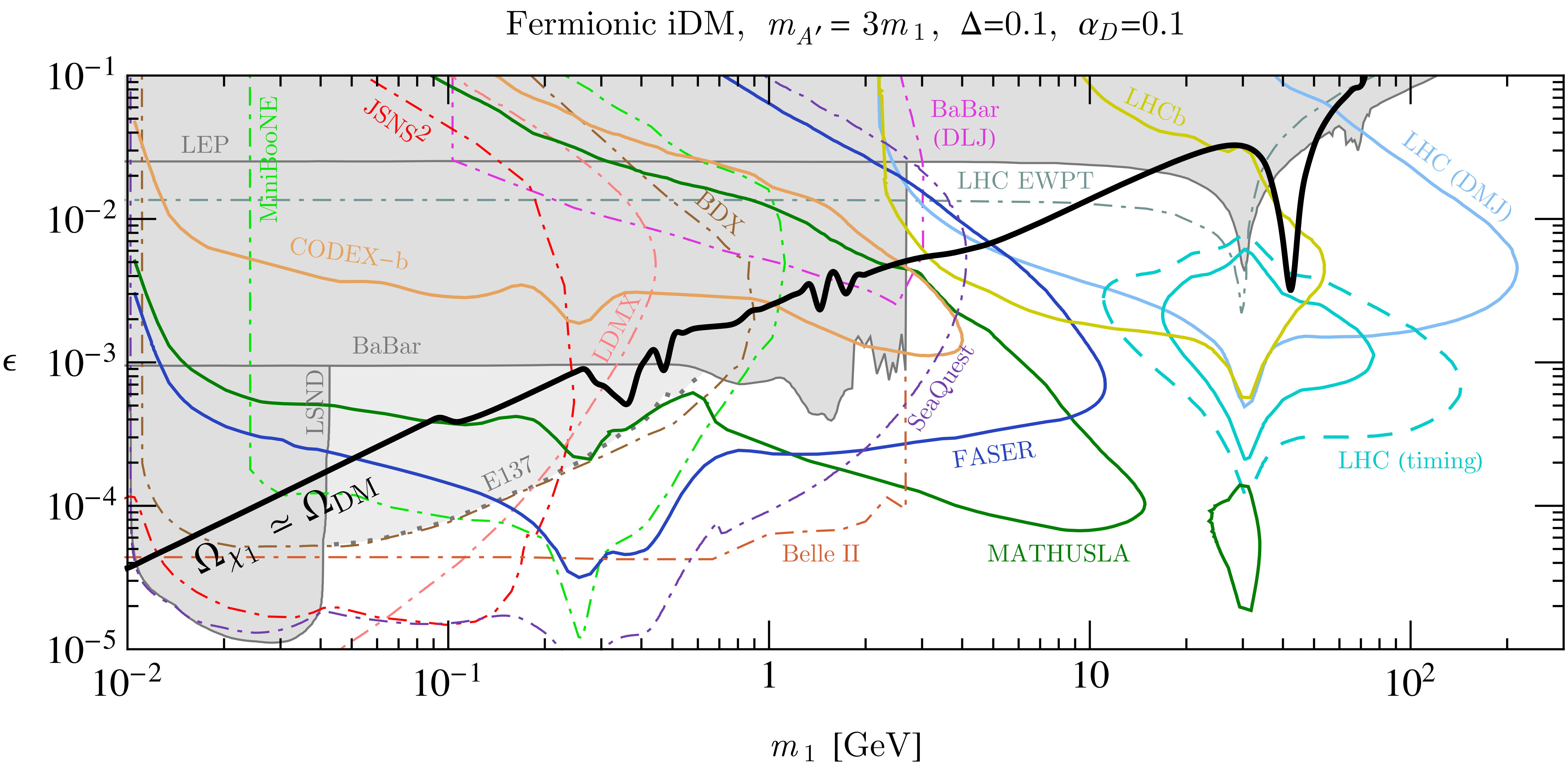


Backup: Inelastic Dark Matter



$$\mathscr{L} \supset ie_D \, A'_\mu \, \bar{\chi}_1 \gamma^\mu \chi_2$$