FASER: ForwArd Search ExpeRiment at the LHC

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(FASER group see https://twiki.cern.ch/twiki/bin/viewauth/FASER/WebHome)

Email to the group: faser-all@cern.ch

arXiv:1708.09389;1710.09387;1801.08947;1806.02348 (PRD,with J.L.Feng,I.Galon,F.Kling)

OUTLINE

- Motivation and idea of the FASER experiment
- Location of the experiment
- Detector layout
- Models of new physics in FASER (connection to DM searches)
  -- dark photons,
  -- dark Higgs bosons
  -- axion-like particles,
- Background: simulations & in-situ measurements
- Conclusions

MOTIVATION

Traditionally, new physics has been searched for in the **high-p_T** region
Focus on heavy and strongly-coupled particles, e.g., Higgs, SUSY, extra dim,...

σ ~ fb – pb, e.g., $N_H \sim 10^7$ at 300 fb^{-1} ⇨ **energy frontier**

here also missing energy searches for heavy WIMP DM

Dark sectors with light mediators – rapidly emerging field !

SIDM (solving some problems of ΛCDM?), secluded annihilation, SIMP or ELDER DM, hidden valleys,…
(for reviews see 1311.0029, 1608.08632, 1707.04591)
also Monday plenary talk: S. Matsumto

More opportunities of considering light new physics particles:
viable models for $(g\text{-}2)_\mu$ & muonic hydrogen, other anomalies (Beryllium?), ...

However, light and weakly-coupled new particles typically escape detection in high-p_T region,
they can be produced e.g. in rare meson decays, and typically go in the far **forward region**

σ_{inel} ~ 75 mb, e.g., $N_\pi \sim 10^{17}$ at 3 ab^{-1} ⇨ **intensity frontier**

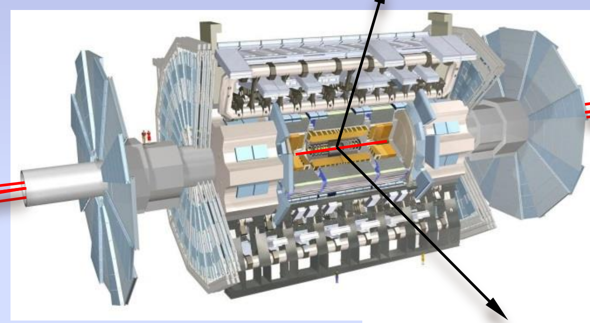
$p_T \sim \Lambda_{QCD}$, **$\theta \sim \Lambda_{QCD}/E$ ~ mrad,** new light particles are highly collimated along the beam-axis

FASER - IDEA

FASER – newly proposed, small (**~1 m³**) and inexpensive (**~1.5M$**) detector to be placed few hundred meters downstream away from the ATLAS/CMS IP

to harness large, currently „wasted" forward LHC cross section

σ_{inel} **~ 75 mb,** e.g., $N_\pi \sim 10^{17}$ at 3 ab^{-1}



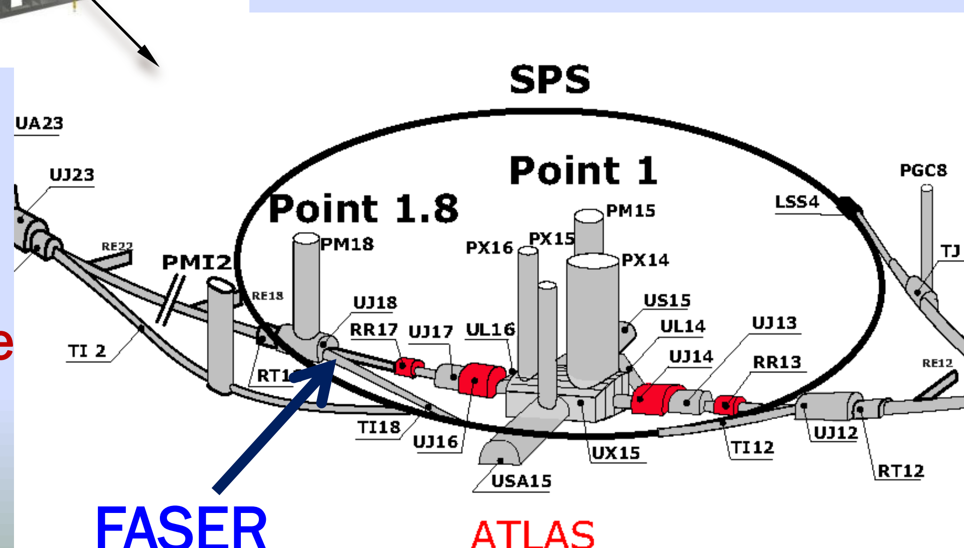
new physics ---- FASER

π, K, D, B, ...

SM

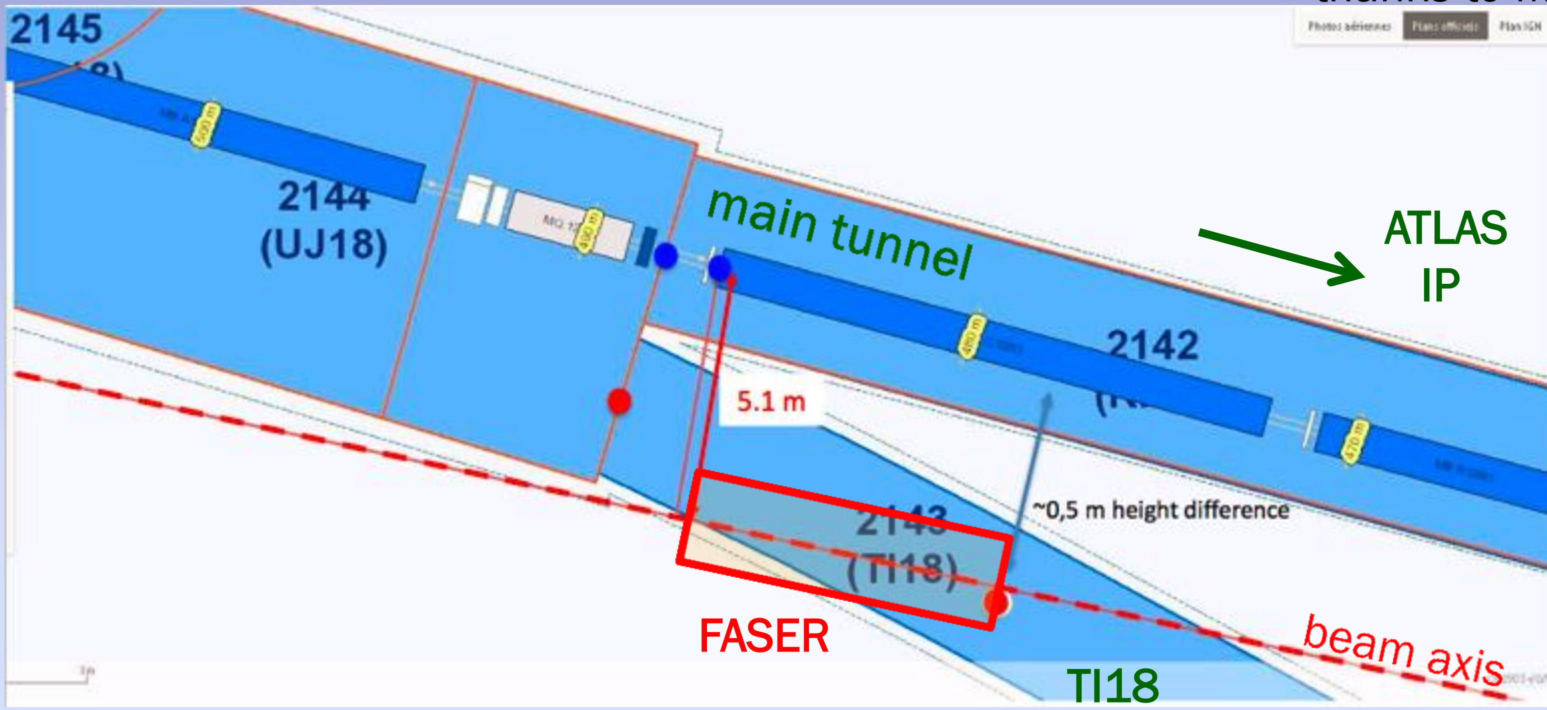
LHCf, TOTEM, ALFA, CASTOR

In the context of DM FASER will search for various possible light mediators



FASER LOCATION – TUNNEL TI18

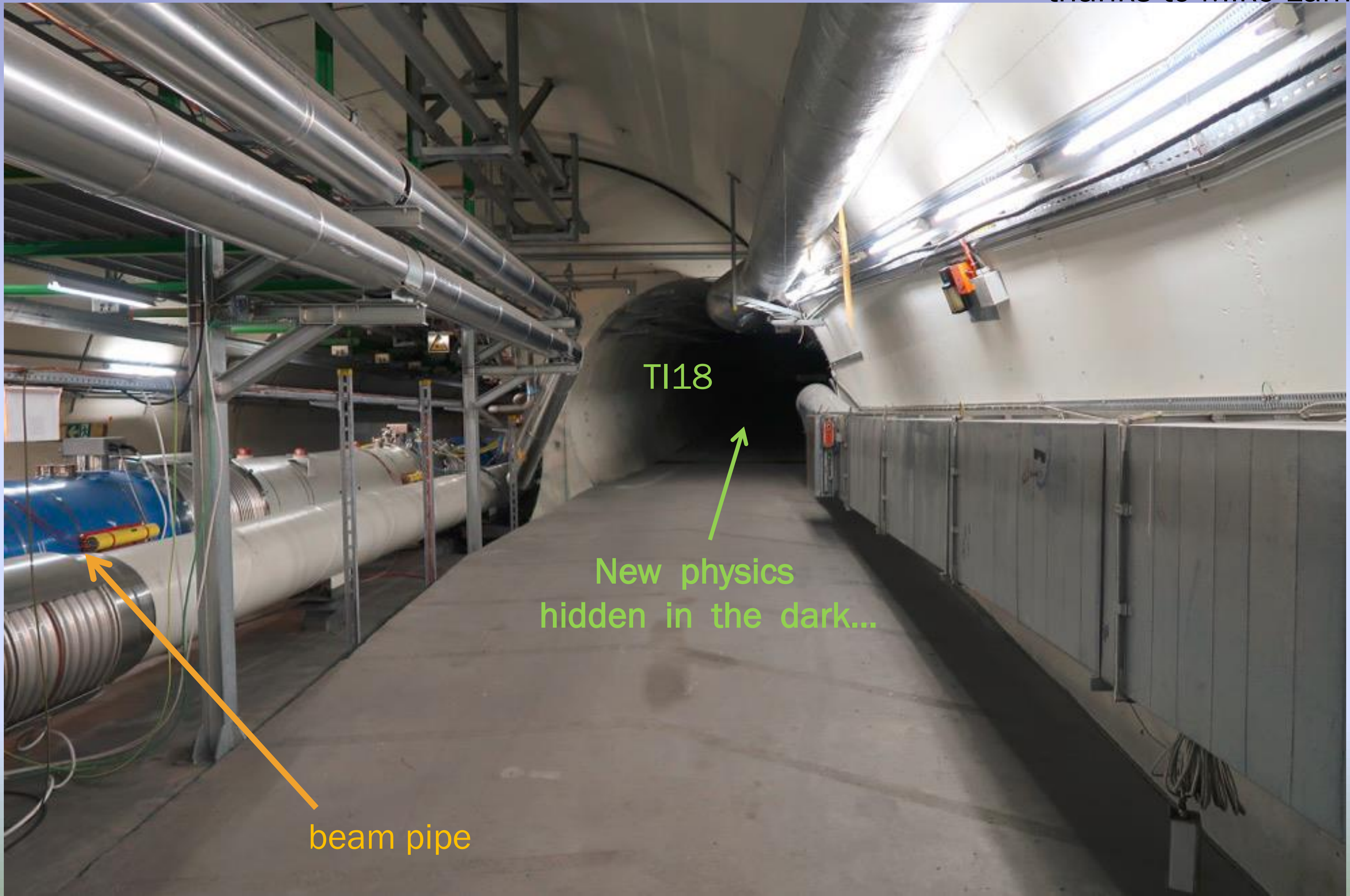
thanks to Mike Lamont



- promising location in a side tunnel TI18 (former service tunnel connecting SPS to LEP)
- about **L ~ 480m** away from the IP along the beam axis
- space for a **few-meter-long** detector
- precise position of the beam axis in the tunnel up to **mm precision** (CERN Engineering Dep)
- corrections due to beam crossing angle (for 300μrad the displacement is 7 ~ cm)

FASER LOCATION PHOTO (1)

thanks to Mike Lamont

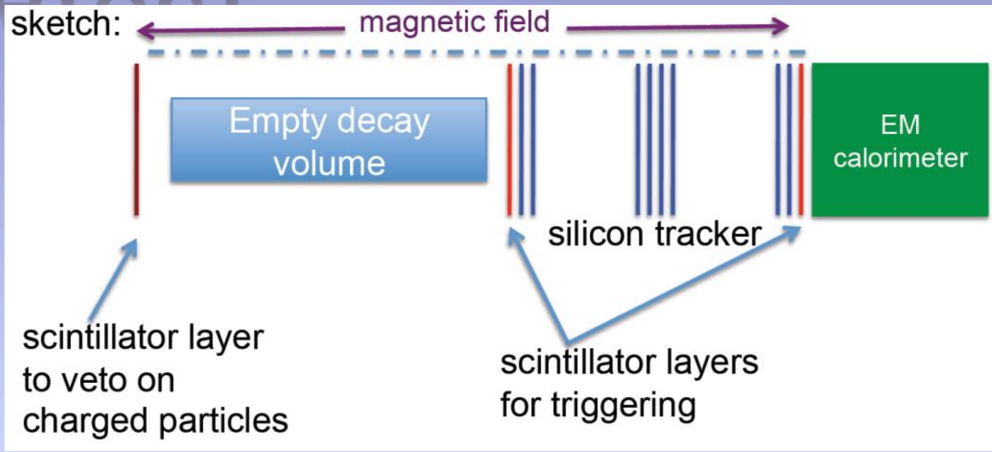


FASER LOCATION PHOTO (2)

thanks to Mike Lamont

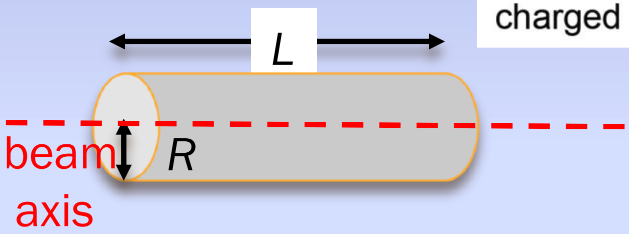
…can be brought to light

BASIC DETECTOR LAYOUT

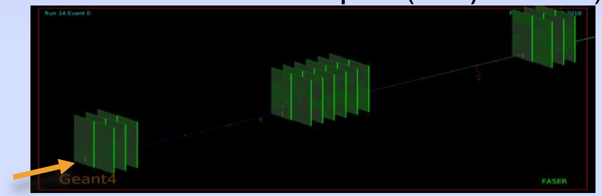


- GEANT4 studies for optimization of:
  - lenght of decay volume,
  - number and placement of tracking layers,
  - strength and region of B field.

- cylindrical detector



Dave Casper (UCI/ATLAS)



0.5 T magnetic field over **1m** length for track separation

- 2 stages of the project:

FASER 1: L = 1.5 m, R = 10 cm, V = 0.05 m^3, 150 fb^{-1} (Run 3)

FASER 2: L = 5 m, R = 1 m, V = 16 m^3, 3 ab^{-1} (HL-LHC)

Signal is a pair of oppositely charged high-energy particles e.g. 1 TeV A' -> e^+e^-

Practically zero BG search –

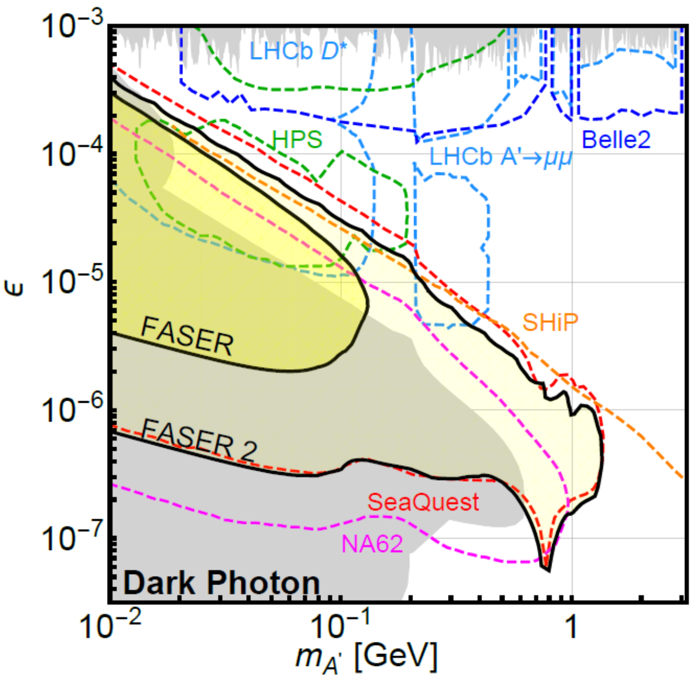
In the following we assume 100% detection efficiency for a better comparison with other exps

DARK PHOTON

- (broken) dark $U(1)$ gauge group,
- kinetic mixing with the SM photon: $\epsilon\, F^{\mu\nu}\, F'_{\mu\nu}$,
- after field redefinition:

$$\mathcal{L} \supset -\frac{1}{4}\, F^{\mu\nu} F_{\mu\nu} - \frac{1}{4}\, F'^{\mu\nu} F'_{\mu\nu} + \frac{1}{2}\, m^2_{A'}\, A'_\mu A'^\mu + \sum \bar{f}(i\partial\!\!\!/ - \epsilon\, e q_f\, A')f$$

- production: π^0 and η decays, bremsstrahlung, direct production in $q\bar{q}$ scatterings (pp⟶pA′X)
- decays: dominantly into e^+e^- and $\mu^+\mu^-$ up to ~ 500 MeV, then various hadronic decay modes



- typical decay length

$$\bar{d} = c\,\frac{1}{\Gamma_{A'}}\,\gamma_{A'}\beta_{A'} \approx (80\ \mathrm{m})\ B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2$$

for $\varepsilon \sim 10^{-7}$-10^{-3} and $m_{A'} \sim$10MeV-1GeV in the range of FASER

A' as a DM-SM mediator

e.g. for $m_{A'} \sim m_\chi$ we obtain $\langle\sigma v\rangle \sim \varepsilon^2 \alpha\alpha_D / (m_{A'})^2$

requiring $\langle\sigma v\rangle \sim \alpha^2_{weak} / m^2_{weak}$ and putting $\alpha\alpha_D \sim \alpha^2_{weak}$

one obtains $\varepsilon \sim m_{A'} / m_{weak} \sim 10^{-3}$-$10^{-5}$ for $m_{A'} \sim$1-100 MeV

DARK HIGGS BOSONS AT FASER

1710.09387

– Dark Higgs boson: additional hidden real scalar field ϕ,

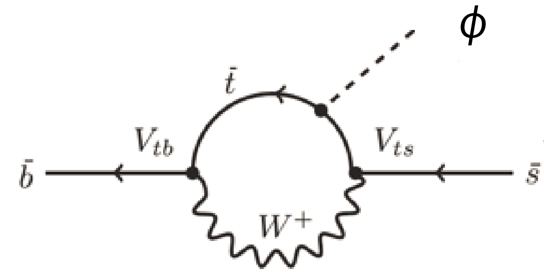
– often adopted phenomenological parametrization:

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

– Higgs-like couplings suppressed by θ^2,

– production: B and K decays, $h \to \phi\phi$,

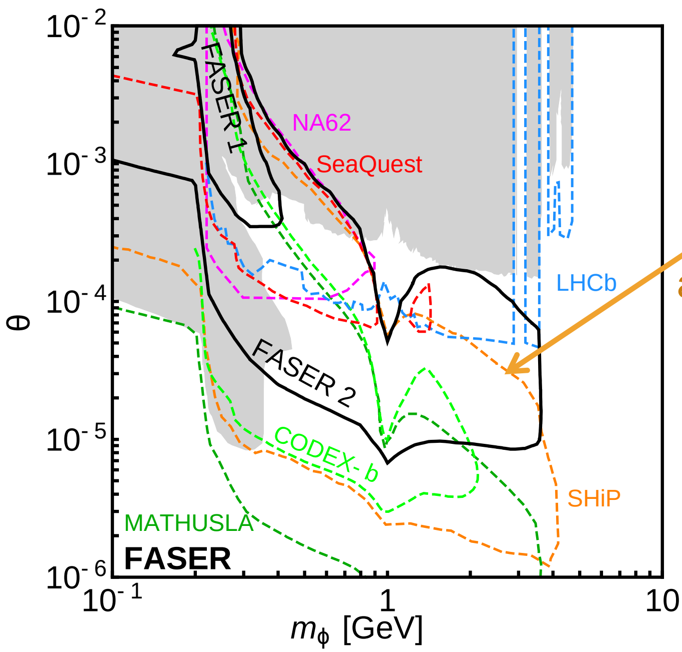
– decays: into the heaviest kinematically allowed states: $\mu^+\mu^-$, $\pi\pi$, KK, ...



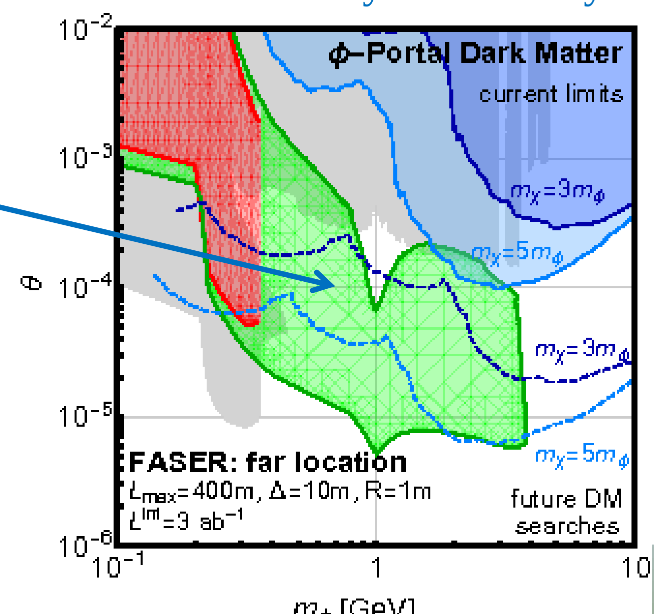
- at FASER energies: **N_B/N_π ~10^{-2}** (10^{-7} for typical beam+dumps)
- Typical p_T ~m_B ⇨ improved reach for FASER 2 (R=1m)

Dark Higgs-DM portal $\mathcal{L} \supset -\frac{1}{2}\kappa\,\phi\,\bar{X}X$

$\langle\sigma v\rangle \sim \kappa^4 \;\rightarrow \kappa$ fixed by relic density



complementarity between FASER and other proposed experiments (large boost, probing lower τ)



ALPS AT FASER – LHC AS A PHOTON BEAM DUMP

1806.02348

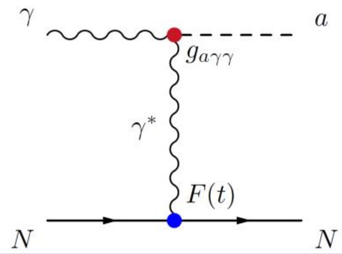
– similarly to the QCD axion, they can appear as pseudo-Nambu-Goldstone bosons in theories with broken global symmetries

– suppressed dim-5 couplings to gauge bosons $(1/\Lambda) a V^{\mu\nu} \tilde{V}_{\mu\nu}$,

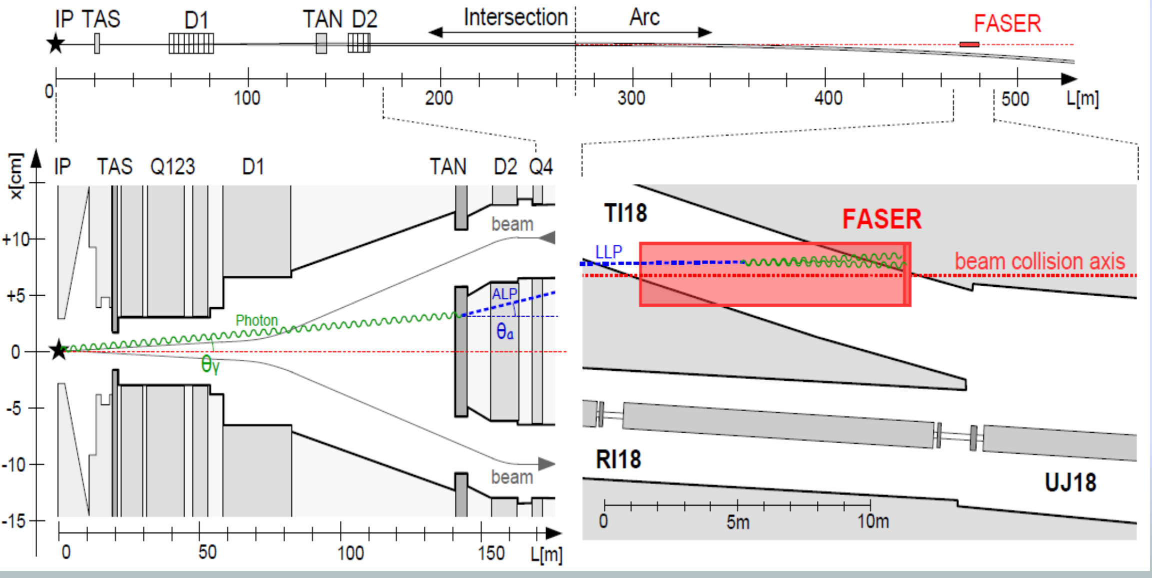
– dim-5 couplings to fermions also allowed $(\partial_\mu a/\Lambda) \bar{f} \gamma_\mu \gamma_5 f$,

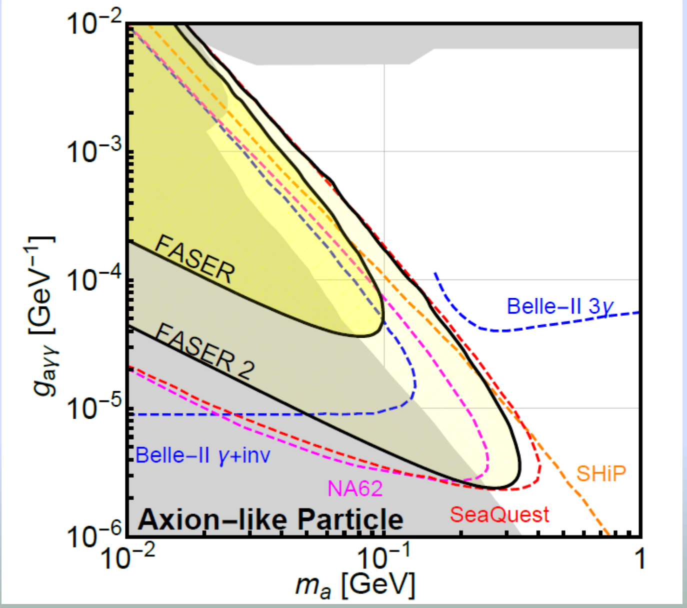
– interesting pheno scenario – dominant $a\gamma\gamma$ coupling

B. Döbrich *et al*, JHEP 1602 (2016) 018



„aγγ" coupling – dominant production mode for FASER is the **Primakoff process (γN→aN)**





BACKGROUNDS – SIMULATIONS (FLUKA)

Spectacular signal:

-- two opposite-sign, high energy (E > 500 GeV) charged tracks,
-- that originate from a common vertex inside the decay volume,
-- and point back to the IP (+no associated signal in a veto layer in front of FASER),
-- and are consistent with bunch crossing timing.

- Neutrino-induced events: low rate + highly asymmetric momentum distribution

- Very small activity close to FASER from diffractive proton losses

- The radiation level in TI18 is low ($<10^{-2}$ Gy/year), encouraging for detector electronics.

- Proton showers in a nearby Disperssion Suppresor lead to negligible BG after ~90m of rocks in front of FASER

- Muons coming from the IP – front veto layers

Other particles: detailed simulations, highly reduced rate (shielding + LHC magnets)

	Cut T > 100 GeV		Cut T > 500 GeV		Cut T > 1 TeV	
Part. type	fluence rate (cm^{-2} s^{-1})	fluence per bunch crossing per cm^2	fluence rate (cm^{-2} s^{-1})	fluence per bunch crossing per cm^2	fluence rate (cm^{-2} s^{-1})	fluence per bunch crossing per cm^2
$\mu+$	0.18	$6.1 \cdot 10^{-9}$	0.02	$5.8 \cdot 10^{-10}$	0.002	$6.8 \cdot 10^{-11}$
$\mu-$	0.40	$1.3 \cdot 10^{-8}$	0.22	$7.4 \cdot 10^{-9}$	0.14	$4.6 \cdot 10^{-9}$
n_0	$\sim 10^{-7}$	$\sim 10^{-14}$	0	0	0	0
γ	$\sim 10^{-4}$	$\sim 10^{-12}$	$\sim 10^{-6}$	$\sim 10^{-13}$	$\sim 10^{-6}$	$\sim 10^{-13}$
π	$\sim 10^{-5}$	$\sim 10^{-12}$	$\sim 10^{-7}$	$\sim 10^{-14}$	0	0

- HL-LHC conditions:
  - Luminosity: $5 \cdot 10^{34}$ (cm^{-2} s^{-1})
  - Cross section p-p collision: 85 mb
  - Pile-up: 140 (events/bunch crossing)

5-10% uncertainty

study by the members of the CERN FLUKA team:
Marta Sabate-Gilarte, Francesco Cerutti,
Andrea Tsinganis

BACKGROUNDS – IN SITU MEASUREMENTS

Done & more ongoing

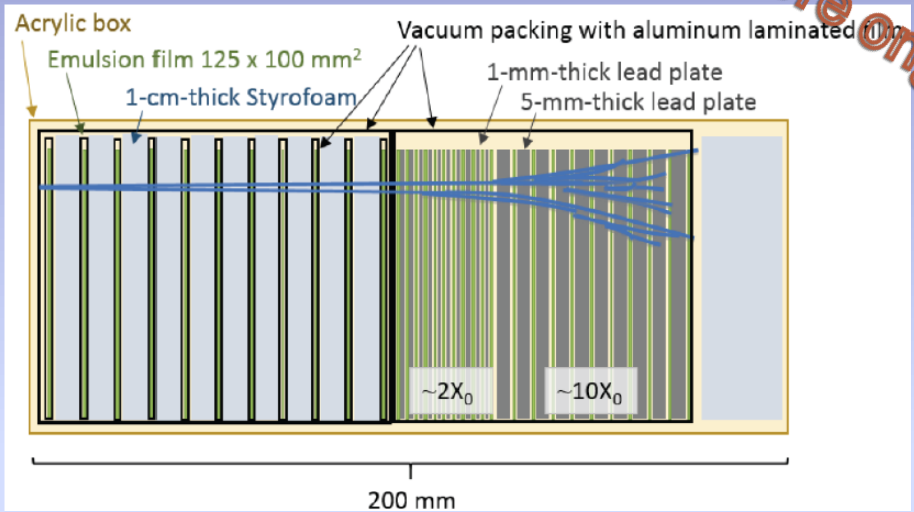
- First measurements already performed

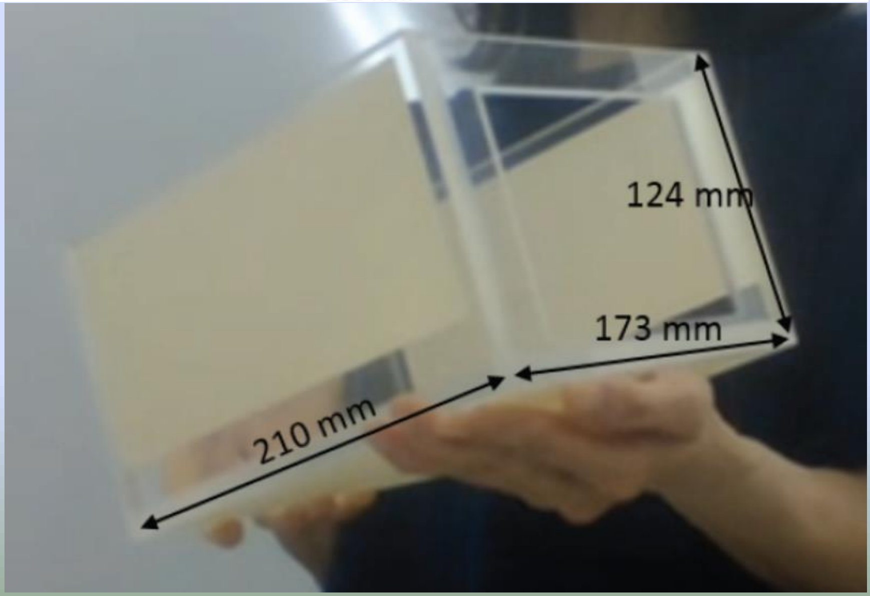
- Emulsion detectors

A. Ariga, T. Ariga (Kyushu, BERN), O. Seto (Nagoya)

- BatMon (battery-operated radiation monitor)

First results promising
(consistent with FLUKA)
Currently:
ongoing thorough data analysis





GROWING COLLABORATION

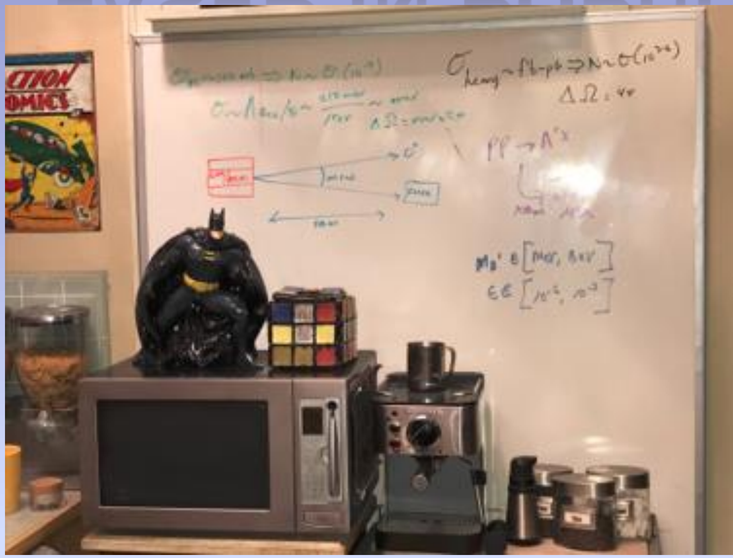
August/September 2017 - first paper ~1 year ago (1708.09389),
since then 3 more papers from the FASER group + increasing interest outside the group
Batell, Freitas, Ismail, McKeen, 1712.10022; Bauer, Foldenauer, Jaeckel, 1803.05466; Helo, Hirsch, Wang, 1803.02212

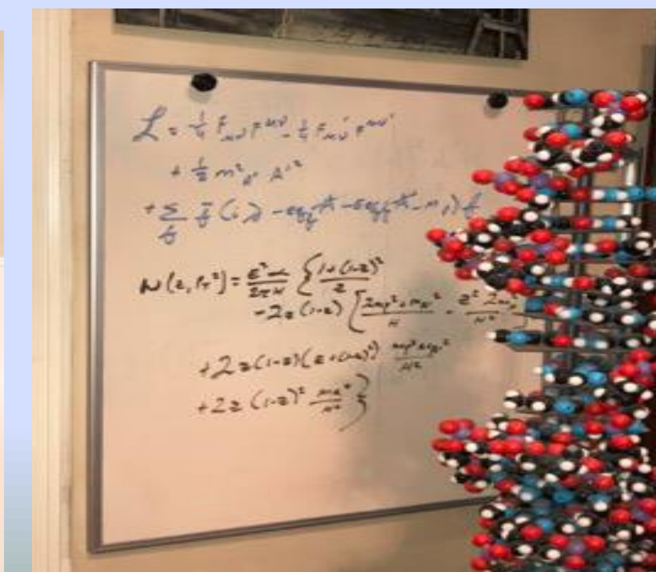
November 2017 – join the Physics Beyond Colliders (PBC) working group at CERN,
May 2018 – first results of detailed BG simulations,
June 2018 – first BG in-situ measurements,
Currently > 10 active members (mostly experimentalists) from ~8 institutions in 4 countries,

- Akitaka Ariga (Bern, experimentalist)
- Tomoko Ariga (Kyushu/Bern, experimentalist)
- Jamie Boyd (CERN, experimentalist) (contact with PBC accelerator CERN working group)
- Dave Casper (UCI, experimentalist)
- Jonathan Feng (UCI, theorist) (contact with PBC BSM CERN working group)
- Iftah Galon (Rutgers, theorist)
- Shih-Chieh Hsu (Washington, experimentalist)
- Felix Kling (UCI, theorist)
- Hidetoshi Otono (Kyushu, experimentalist)
- Brian Petersen (CERN, experimentalist)
- Osamu Sato (Nagoya, experimentalist)
- Aaron Soffa (UCI, experimentalist)
- Jeffrey Swaney (UC Irvine, experimentalist)
- Sebastian Trojanowski (National Center for Nuclear Research, theorist)

+ additional input from CERN Engineering Dep (e.g., BG simulations)

FASER IN POPULAR CULTURE





related article

LA Times

CONCLUSIONS

- **FASER** is a newly proposed, small and inexpensive experiment to be placed at the LHC to search for Light Long-lived Particles (LLPs) to complement the existing experimental programs at the LHC, as well as other proposed experiments,
- proposed location is ~480m away from the ATLAS IP in a side tunnel,
- significant progress in BG undestanding (simulations, in-situ measurements)…
- …and in studies on detector design (Geant 4),
- **FASER would not affect any of the existing LHC programs and do not have to compete with them for the beam time etc.**
- Rich physics prospects:

- popular LLP models (dark photon, dark Higgs boson, GeV-scale HNLs, ALPs…),
- Many connections to DM and cosmology
- Invisible decays of the SM Higgs,
- LHC as a photon beam-dump (aγγ coupling),
- **… (place for an input from you !!!)**

- Currently pursuing funding options and seeking CERN approval. If successful, a possible timeline and plan is

Install FASER 1 in LS2 (2019-20) for Run 3 (150 fb^{-1})

- R = 10 cm, L = 1.5 m, requires lowering floor by 50cm in existing tunnel
- Target dark photons, B-L gauge bosons, ALPs, etc.

Install FASER 2 in LS3 (2023-25) for HL-LHC (3 ab^{-1})

- R = 1 m, L = 5 m, requires some extension of the existing tunnel
- Full physics program: dark photons, B-L, ALPs, dark Higgs, HNLs, etc.

BACKUP

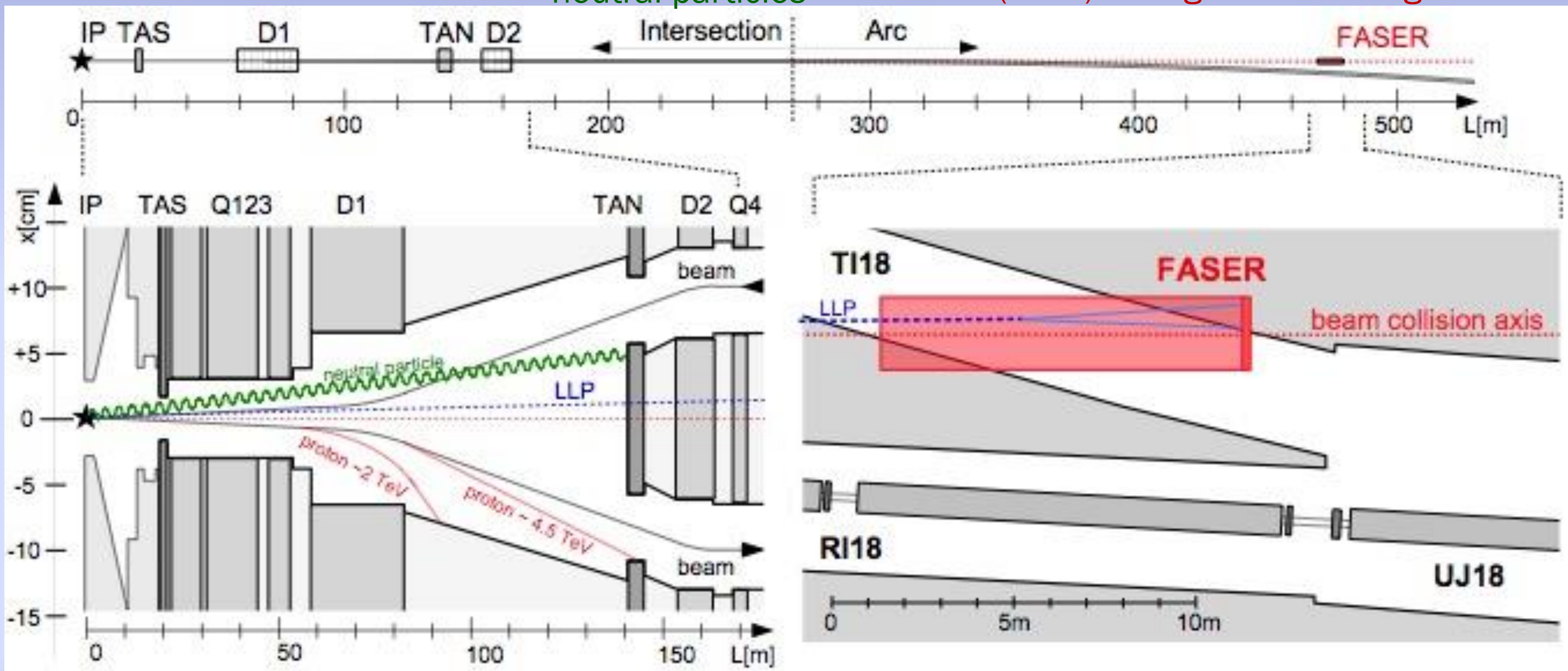
LHC INFRASTRUCTURE AROUND

LLP – Light Long-lived Particle

LLPs produced at the IP

TAN absorber for neutral particles

Some LLPs decay in FASER
two (~TeV) charged tracks e.g. e^+e^-



LHC magnets effectively deflect charged particles (reduced μ BG)

Other LHC infrastructure + ~90m of rocks (shielding from the IP)

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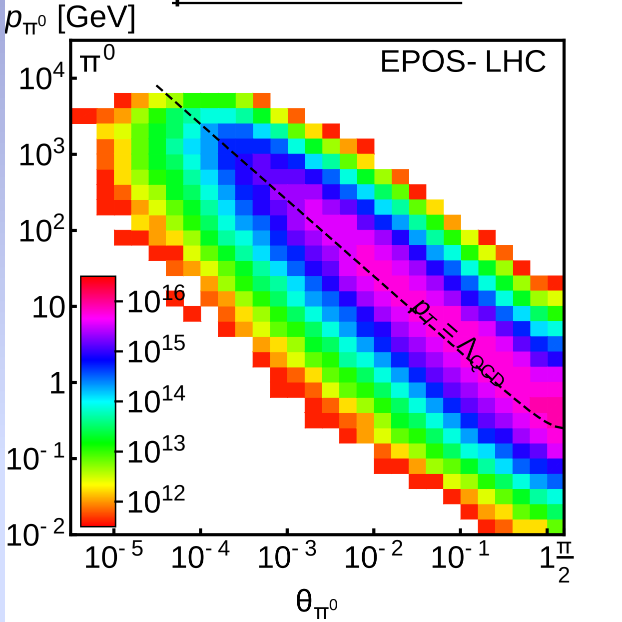
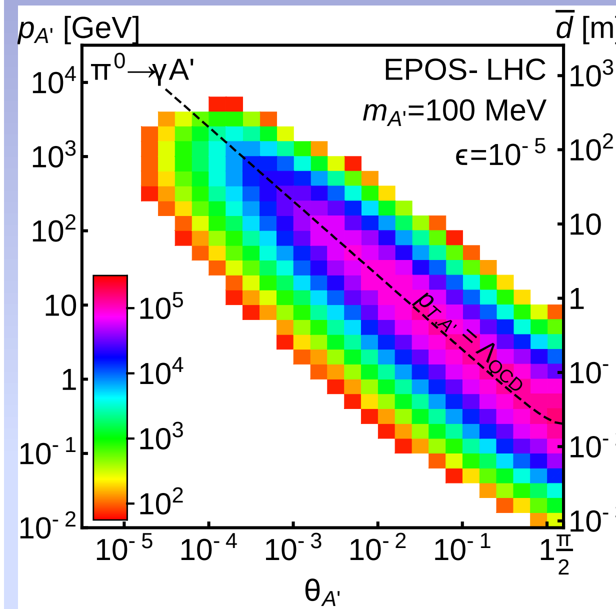
DARK PHOTONS AT FASER – KINEMATICS

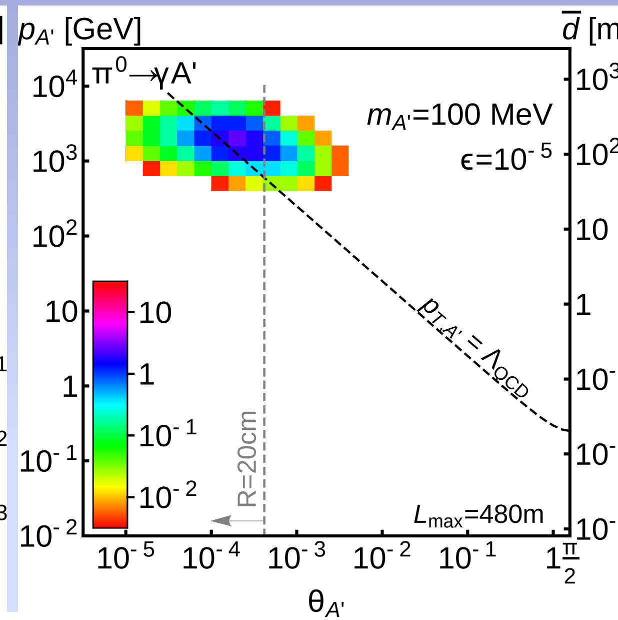
pions at the IP



A's at the IP



A's decaying in FASER



- Monte Carlo fitted to experimental data (LHCf, ALFA)
- typically $p_T \sim \Lambda_{QCD}$
- for E~TeV ⇨ p_T/E ~0.1 mrad
- even ~10^{15} pions per (θ,p) bin

- $\pi^0 \to A'\gamma$
- high-energy π^0 ⇨ collimated A's
- $\varepsilon^2 \sim 10^{-10}$ suppression but still up to 10^5 A's per bin

- only highly boosted A's survive until FASER **$E_{A'}$ ~TeV**
- further suppression from decay in volume probability
- still up to **$N_{A'}$ ~100 events** in FASER, mostly within **r<20cm**

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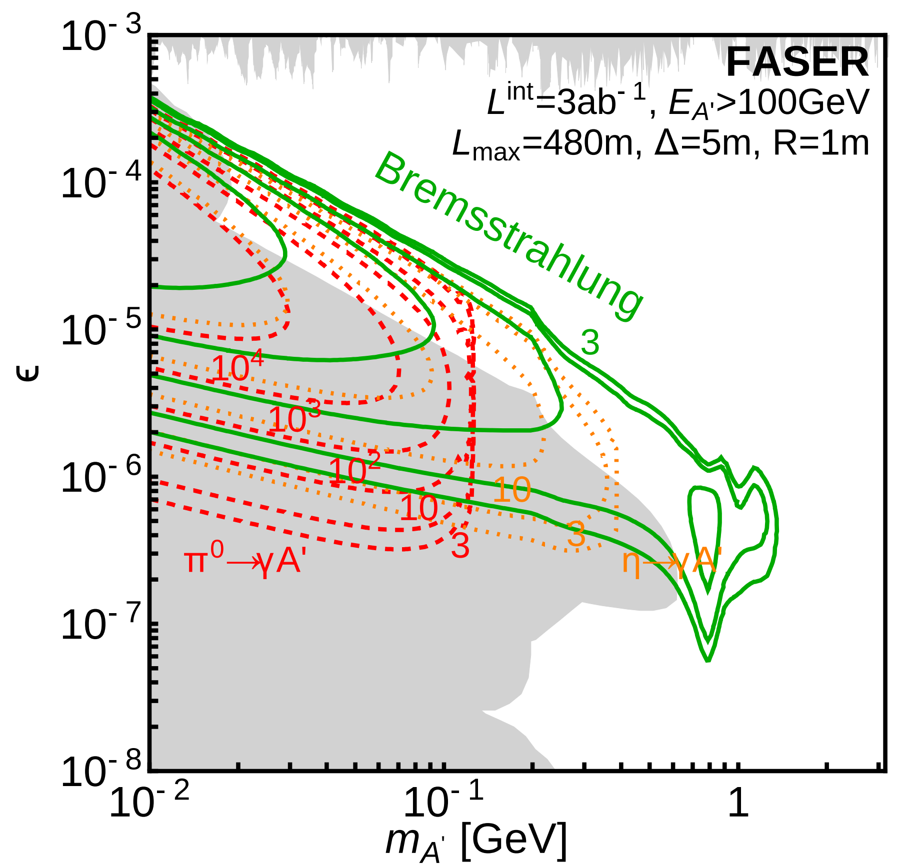
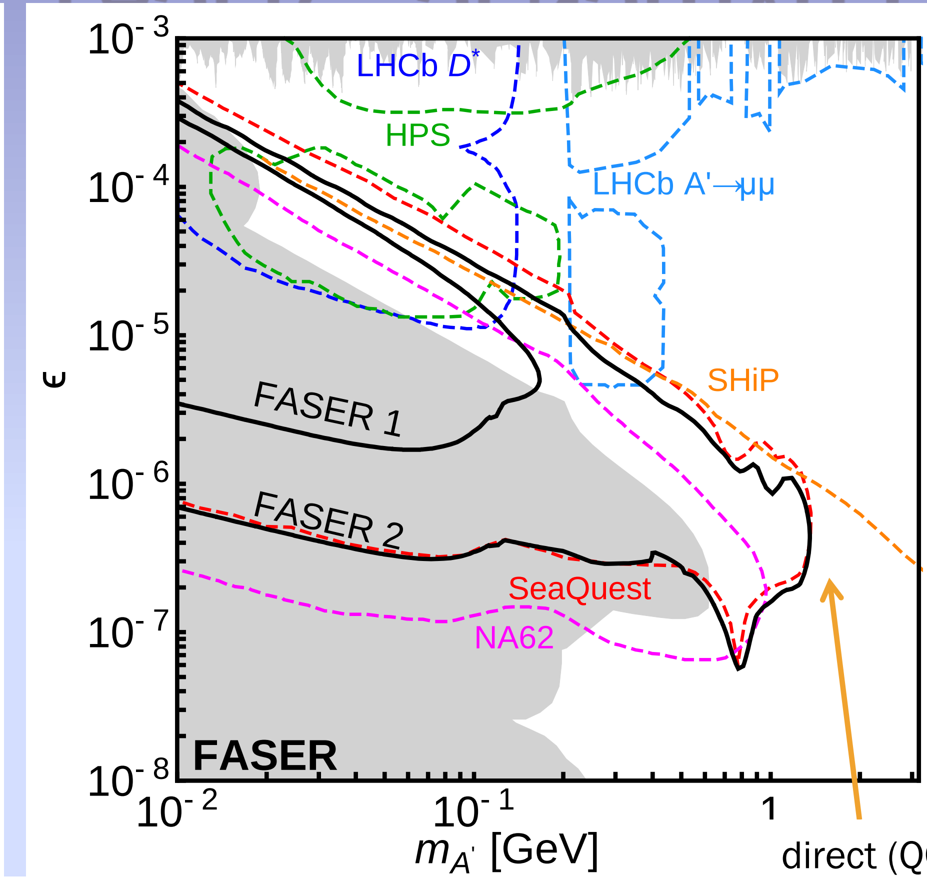
DARK PHOTONS AT FASER – SENSITIVITY





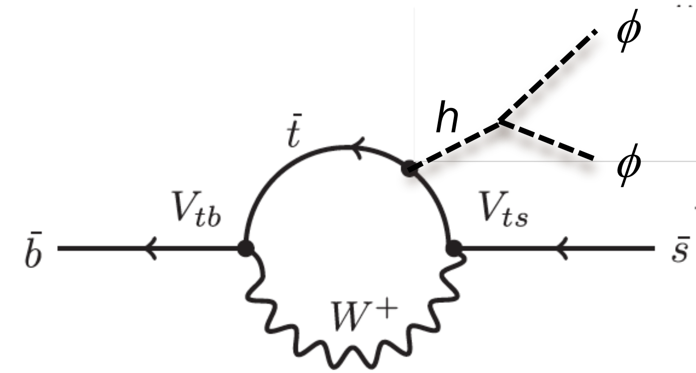
direct (QCD) production currently not included

- both FASER 1 and FASER 2 can have world-leading sensitivity at the time of operation,
- in FASER 2 the reach extends to $m_{A'}$ > 1GeV for $\varepsilon \sim 10^{-7}$-10^{-6},
- for $\varepsilon \sim 10^{-4}$-10^{-6} contours with $N_{A'}$=const are very densely spaced (exponential suppression for decay length << L~480m)
- **the reach is then similar for FASER and much larger experiments,**
- also reach there is very mildly sensitive to the exact number of BG events, detector efficiency etc.

1710.09387

PROBING INVISIBLE DECAYS OF THE SM HIGGS

$$\mathcal{L} \supset -\lambda v h \phi\phi$$

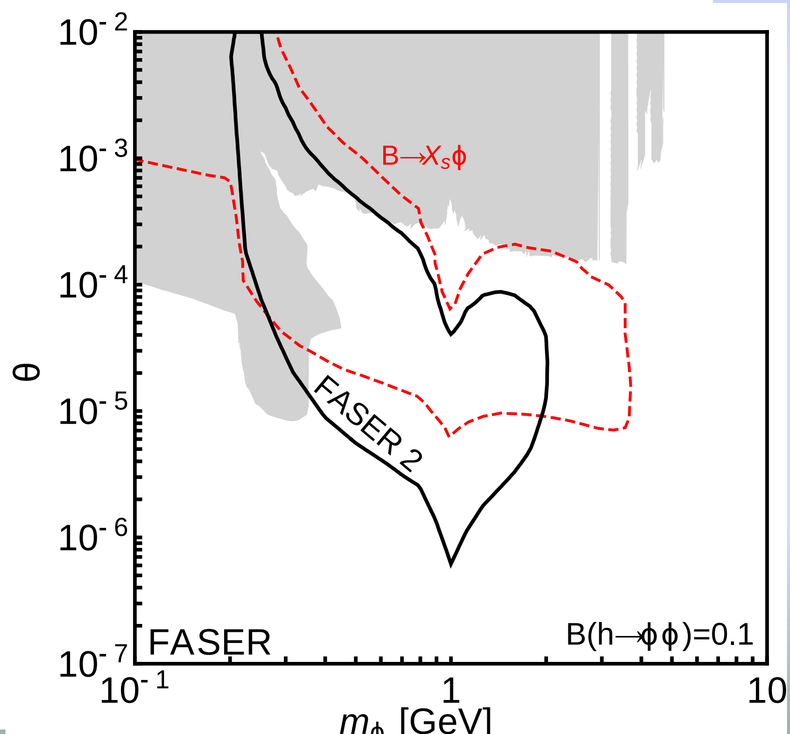


- trilinear coupling
  ⇨ invisible Higgs decays $h \to \phi\phi$

- far-forward region: efficient production via off-shell Higgs, $B \to X_s h^*(\to \phi\phi)$

- can extend the reach in θ up to 10^{-6} for $B(h \to \phi\phi)$~0.1

- up to ~100s of events



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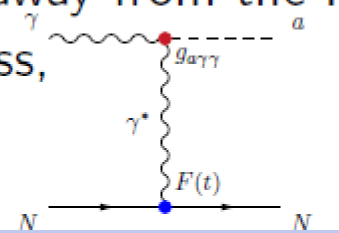
ALP DIPHOTON COUPLING – FASER REACH

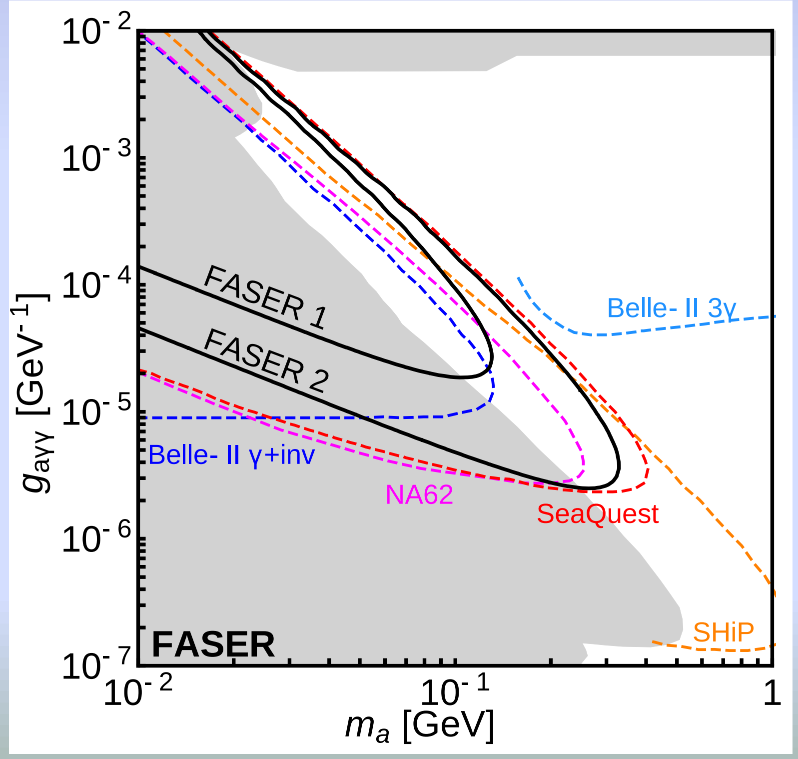
– high-energy γs produced at the IP,
– γs hit the neutral absorber TA(X)N $\sim$ 130 m away from the IP,
– ALP production mainly in the Primakoff process,
– also exotic π^0 and η decays,
– ALPs decay into 2 photons in FASER



- signal = 2 high-energy photons (γγ),
- need of calorimeter;

existing technology e.g. LHCf calorimeter:
-- 23cm long,
-- 5% energy resolution for E>100GeV
(used also for a few TeV energies)
-- 2 photons reconstructed with 90% efficiency
if they are **1mm** away from each other

- E_a~ few hundred GeV,
for m_a~100MeV ⇨ $\gamma_{Lor} = E_a/m_a$~few x10^3
typical opening angle $\theta_{\gamma\gamma}\sim 2/\gamma_{Lor} < 1$ mrad
after >1m both photons are separated ~1mm
(more details see 1806.02348)
- possible conversions in the tracker layers (γe^+e^-)

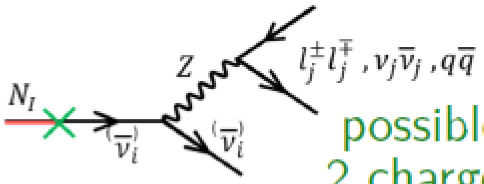


HEAVY NEUTRAL LEPTONS

- seesaw mechanism, e.g., for type-I seesaw

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\,\bar{\tilde{N}}_I \partial\!\!\!/ \tilde{N}_I - F_{\alpha I} \bar{L}_\alpha \tilde{N}_I \tilde{\Phi} - \frac{1}{2} \bar{\tilde{N}}^c_I M_I \tilde{N}_I + {\rm h.c.}$$

- popular model: νMSM with the lightest N_1 being a DM candidate possibly consistent with 3.5 keV excess and two heavier HNLs, $N_{2,3}$, detectable in LLP searches,
- typically considered in searches for LLPs, possibly a primary motivation to build SHiP
- they mix with the SM (active) neutrinos,
- phenomenologically they behave like *heavy* or *sterile* neutrinos with masses m_{N_I} and mixing angles U_{eI}, $U_{\mu I}$, $U_{\tau I}$
- HNLs can decay into lighter SM particles ⇒ signatu



possible 2 charged tracks

HEAVY NEUTRAL LEPTONS AT FASER

1801.08947

Typical simplified approach:

- we focus on only one HNL leaving a signature in FASER
- we vary as free parameters

$$m_N, \quad U_{eN}, \quad U_{\mu N}, \quad U_{\tau N}, \quad \text{where only one } U_{\ell N} \neq 0 \text{ at a time.}$$

B **and** D **meson decays** – we consider about ~ 20 production channels, dominant ones dictated by the CKM suppression, kinematics and fragmentation fractions

$$D^{0,\pm} \to N\, e^{\pm}\, K^{\mp,0,(*)},\ D_s^{\pm} \to N\, e^{\pm}, \ldots$$
$$B^{0,\pm} \to N\, e^{\pm}\, D^{\mp,0,(*)},\ B^{\pm} \to N\, e^{\pm},$$
$$B_c^{\pm} \to N\, e^{\pm}, \ldots$$

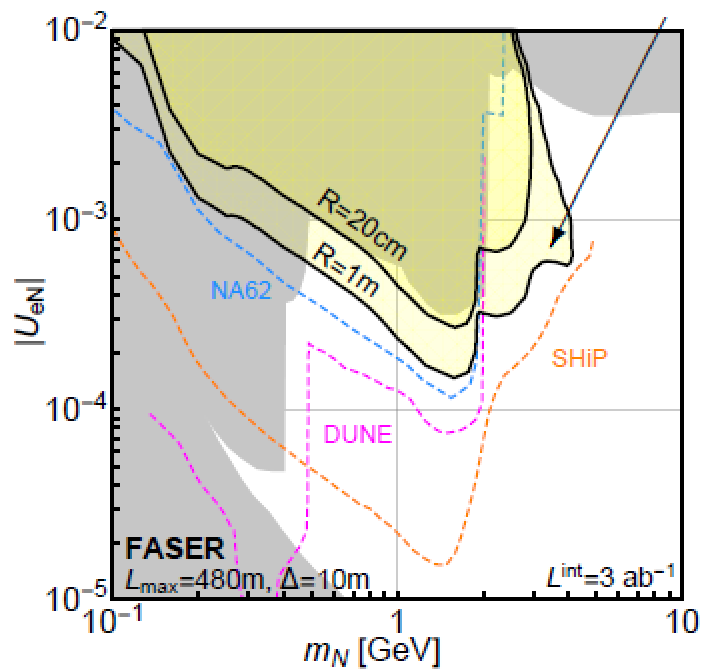
Decay modes:

BR$(N \to 3\nu) \sim 10\% - 20\%$ invisible

BR$(N \to \nu\, l_1^+\, l_2^-) \sim 20\%$ (BR$(N \to \nu\, e^+\, e^-) \sim$ few percent)

BR$(N \to \text{hadrons}) \sim 60\% - 70\%$, various final states

FASER 2



FASER 2

⇒ up to $\sim 10^3$ events for $m_N \gtrsim m_D$

⇒ for $m_N \lesssim m_D$ possible $\sim 10^1$-10^2 events

INELASTIC DARK MATTER AT FASER

For more details see : A. Berlin, F. Kling, 1806.xxxxx
(also MATHUSLA, Codex-b, LHC)

Pseudo-Dirac pair χ_1 and χ_2 nearly degenerate in mass

$$-\mathscr{L} \supset m_D\, \eta\, \xi + \frac{1}{2}\,\delta_\eta\, \eta^2 + \frac{1}{2}\,\delta_\xi\, \xi^2 + \text{h.c.}\ ,$$

$$\chi_1 \simeq \frac{i}{\sqrt{2}}\,(\eta - \xi)$$
$$\chi_2 \simeq \frac{1}{\sqrt{2}}\,(\eta + \xi)\ ,$$

small mass splitting

$$\Delta \equiv \frac{m_2 - m_1}{m_1} \simeq \frac{\delta_\eta + \delta_\xi}{m_D} \ll 1$$

A'-portal, dominant off-diagonal coupling to A'

$$\mathscr{L} \supset i e_D\, A'_\mu\, \bar{\chi}_1 \gamma^\mu \chi_2 + \mathcal{O}(\delta_{\eta,\xi}/m_D)$$

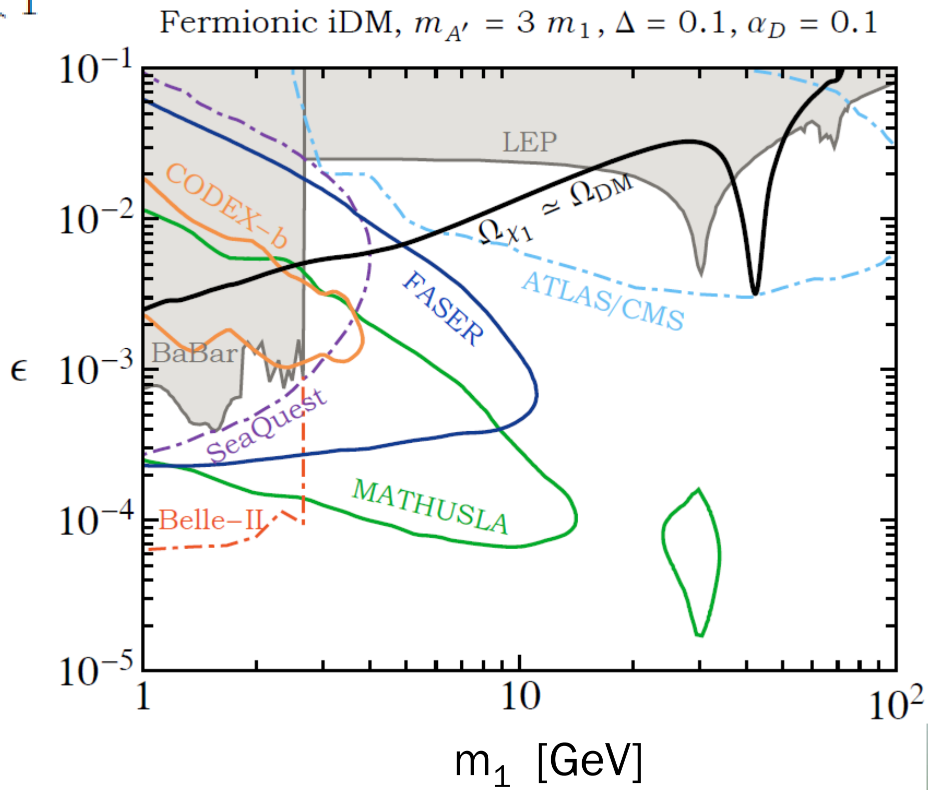
Production $pp \to A' \to \chi_1\chi_2$ goes through A'/Z:
-- meson decays,
-- dark Bremstrahlung,
-- Drell-Yan

χ_2 decays are delayed by adjusting Δ:

$$\Gamma(\chi_2 \to \chi_1\, \ell^+\ell^-) \simeq \frac{4\,\epsilon^2\,\alpha_{\rm em}\,\alpha_D\,\Delta^5 m_1^5}{15\pi\, m_{A'}^4}\ ,$$

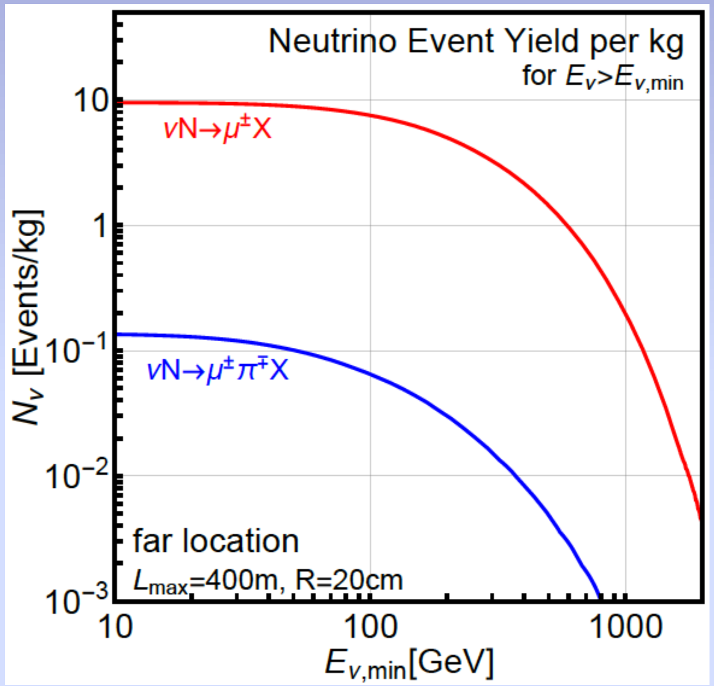
⇨ up to 100s of events in FASER
⇨ reach can go up to $m_{A'}=3m_1$ > 30GeV !

FASER 2 PRELIMINARY



MORE ABOUT BACKGROUND (1)

The rate of neutrino induced events

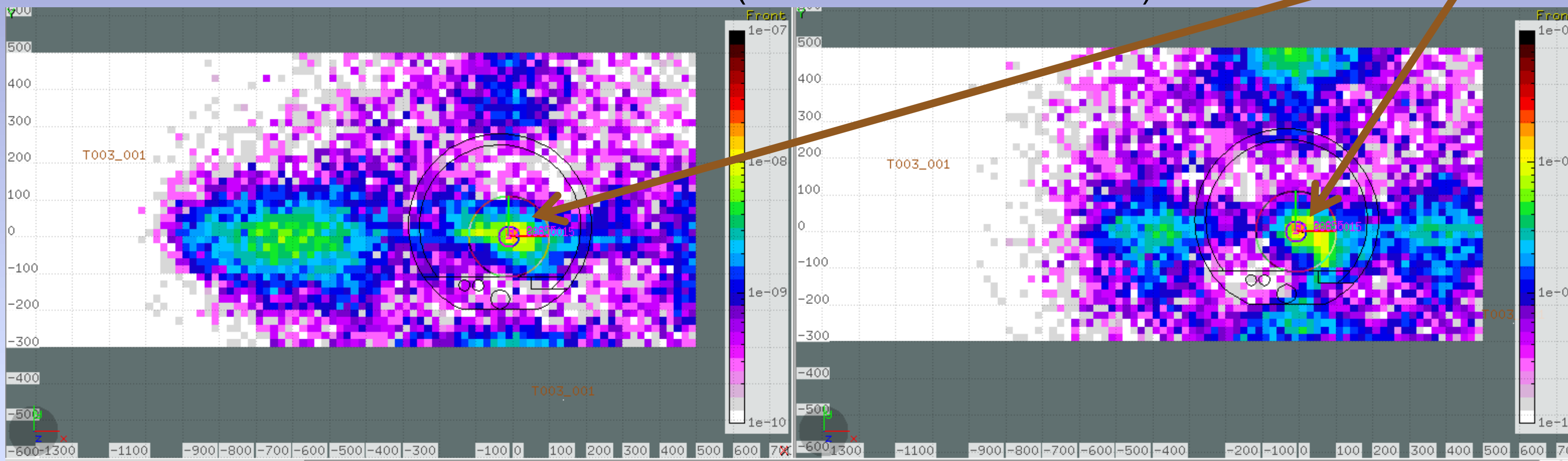


MORE ABOUT BACKGROUND (2)

Helpful role of the LHC magnets

At the entrance of the DS (~90m before FASER)

beam axis



μ^{-} FASER (in TI18) μ^{+}