FASER

ForwArd Search ExpeRiment at the LHC

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New Physics with Displaced Vertices
NCTS, Hsinchu, 21 June 2018

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

arXiv:1708.09389, 1710.09387, 1801.08947, 1806.02348 (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

  -- dark photons,

  -- dark Higgs bosons + invisible decays of the SM Higgs,

  -- heavy neutral leptons at GeV scale,

  -- axion-like particles,

  -- inelastic dark matter.
- Background: simulations & in-situ measurements
- Conclusions

MOTIVATION AND IDEA

● Traditionally, new physics particles have 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**

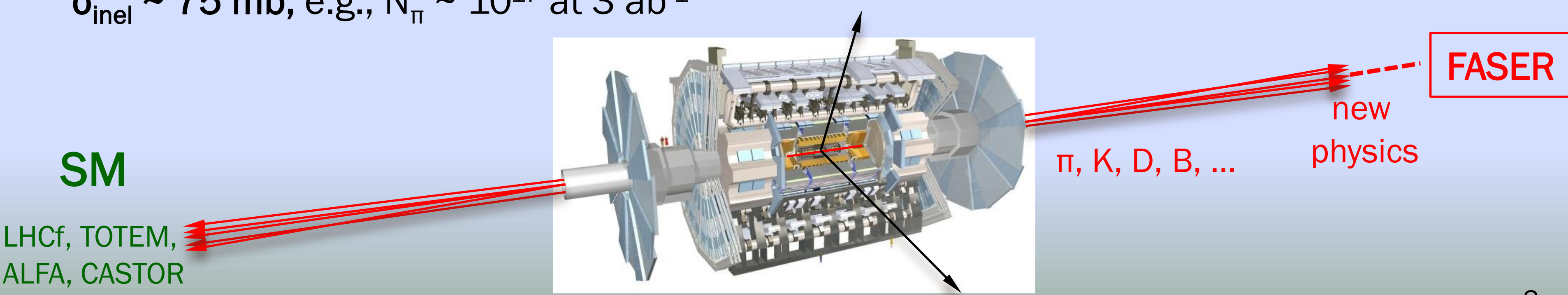
● However, light and weakly-coupled new particles typically escape such detection, they can be produced e.g. in rare meson decays, and typically go in the far **forward region**

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

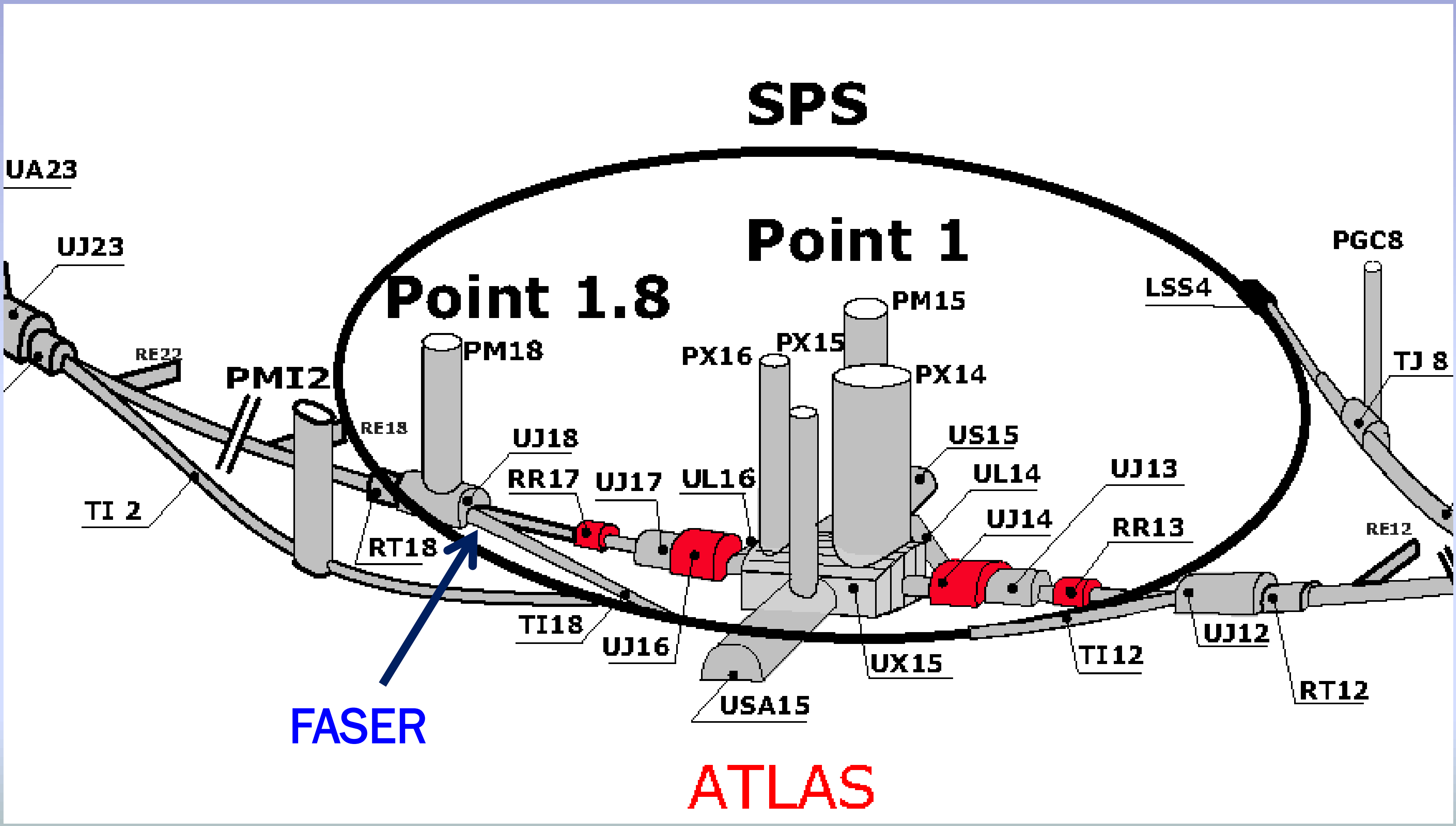
● FASER – newly proposed, small (**~1 m^3**) and inexpensive (**~1M$**) detector
to be placed few hundred meters downstream away from the ATLAS/CMS IP

to harness large, currently „wasted” forward LHC cross section ⇨ **intensity frontier**

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

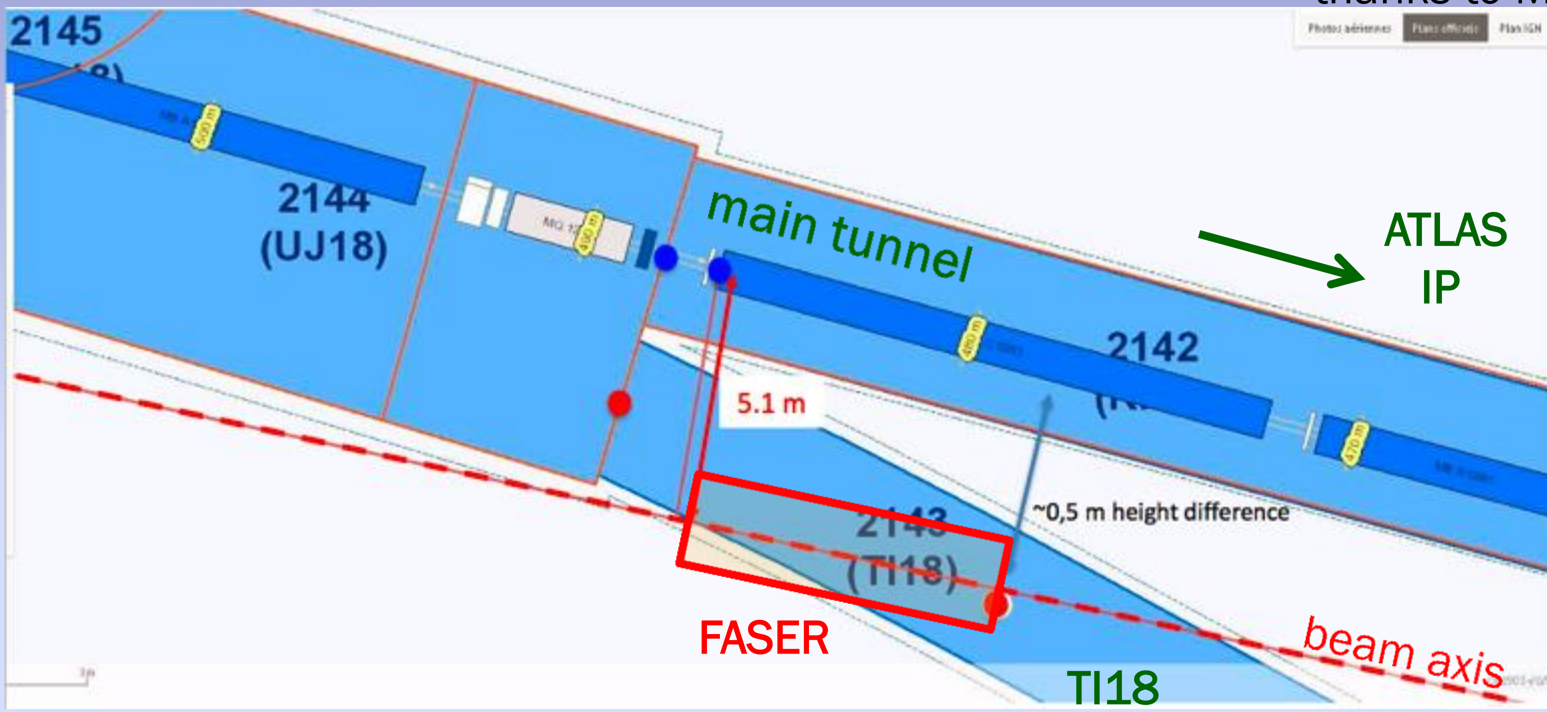


FASER LOCATION



FASER LOCATION – TUNNEL TI18

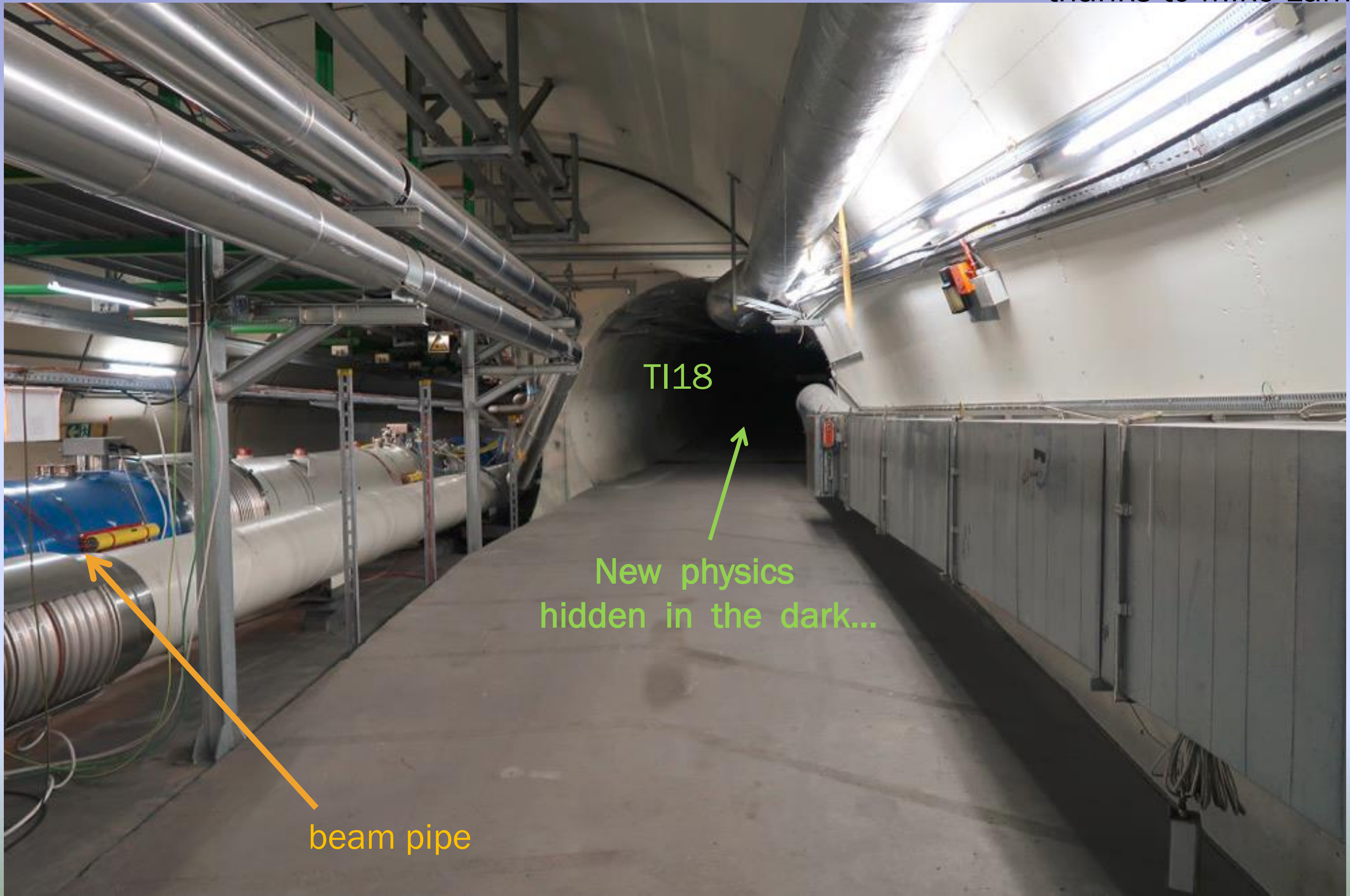
thanks to Mike Lamont



- 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

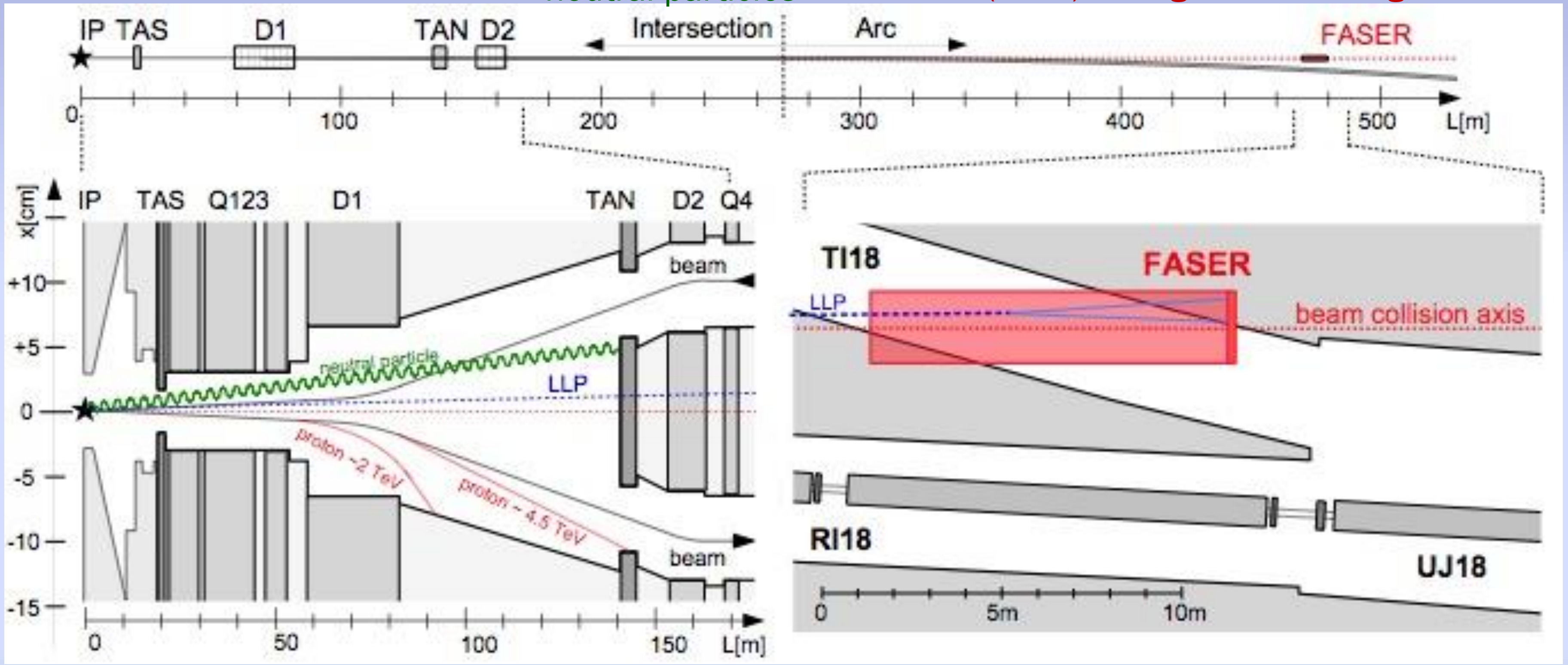
LHC INFRASTRUCTURE AROUND

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^-

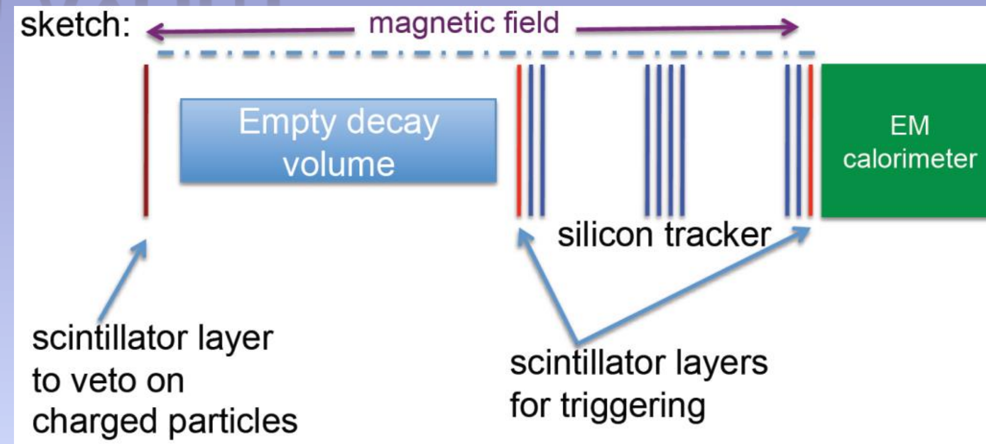


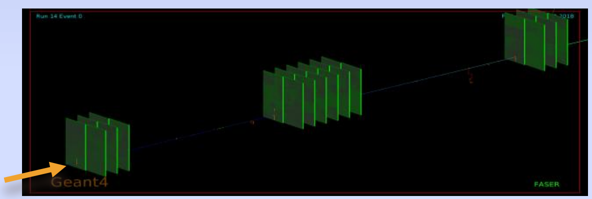
LHC magnets effectively deflect charged particles (reduced μ BG)

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

BASIC DETECTOR LAYOUT

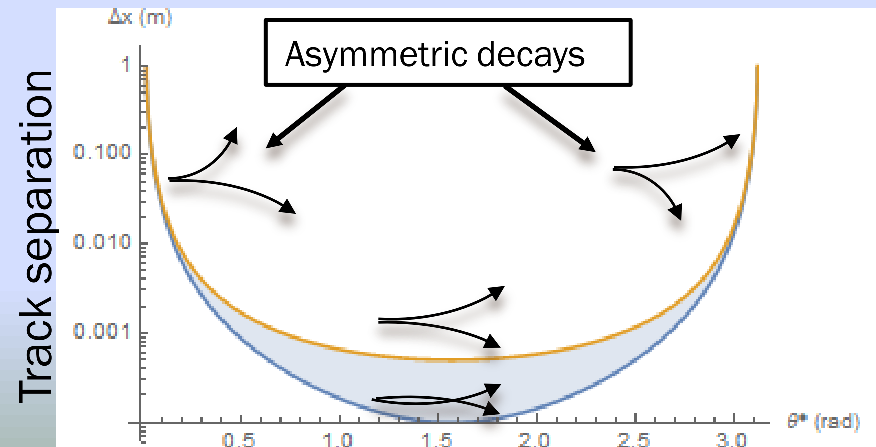
- ongoing GEANT4 studies
for optimization of:
- lenght of decay volume,
- number and placement of tracking layers,
- strength and region of B field.





Dave Casper (UCI/ATLAS)

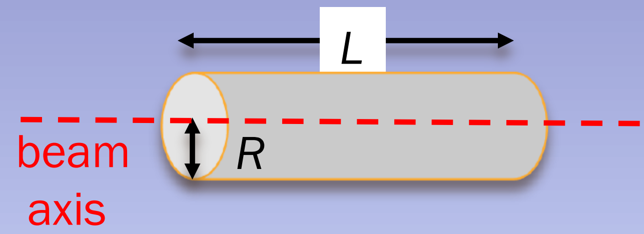
E.g., 1 TeV A' → e^+e^- :
- **0.5 T** magnetic field over **1m** length,
- sufficient to separate **~50%** of the charged tracks by **> 1 mm**,
- much larger separation possible for asymmetric decays.



Decay angle in A' frame

In the following we assume 100% detection efficiency

FASER – BENCHMARK SETUP(S)



- **convenient for pheno modelling** – cylindrical detector

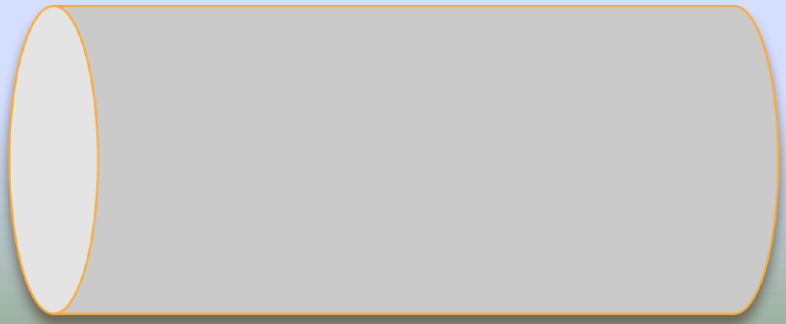
- 2 stages of the project:

FASER 1: L = 3 m, R = 10 cm, V = 0.1 m^3, 150 fb^{-1} (Run 3)

cost ~ \$1M

Ongoing efforts: state-of-the-art BG simulation (done by CERN Engineering Dep),
scheduled in-situ BG measurements (CERN approved), (**THIS WEEK !!!**)
ongoing GEANT4 studies – detector design

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

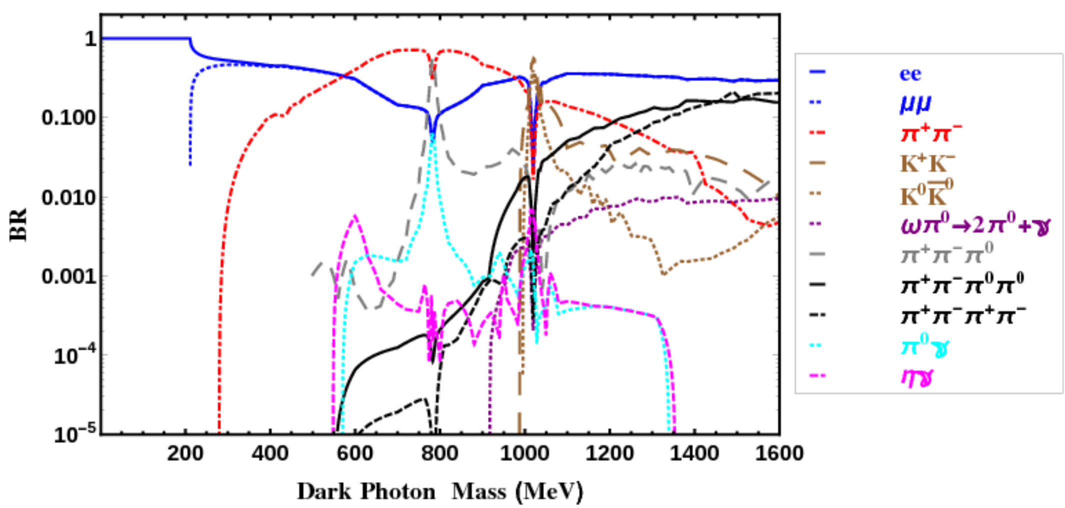


DARK PHOTON

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

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

- production: π^0 and η decays, bremsstrahlung (pp→pA′X)
  direct production in $q\bar{q}$ scatterings
- 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 $m_{A'} \sim 10$MeV-1GeV in the range of FASER

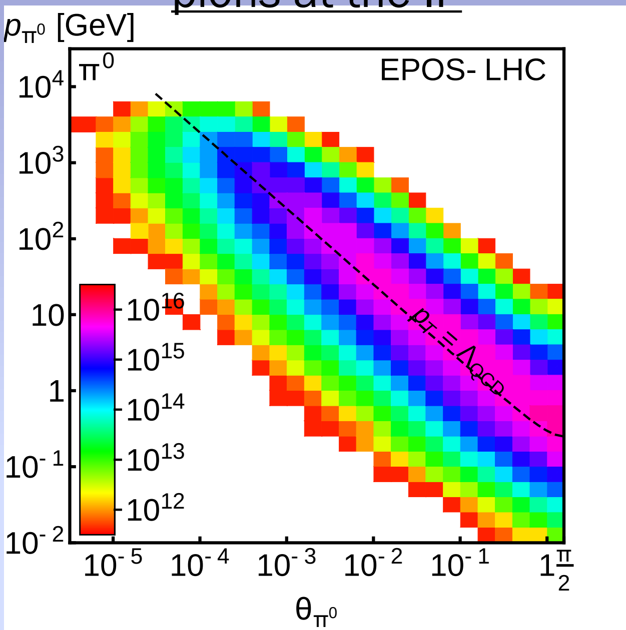
- **production rates suppressed by ε^2**
  e.g. in π^0 decays
  $BR(\pi^0 \to A'\gamma) = 2\,\varepsilon^2\,(1 - m_{A'}^2/m_\pi^2)^3$

J. Alexander *et al.*, Dark Sectors 2016 Workshop: Community Report

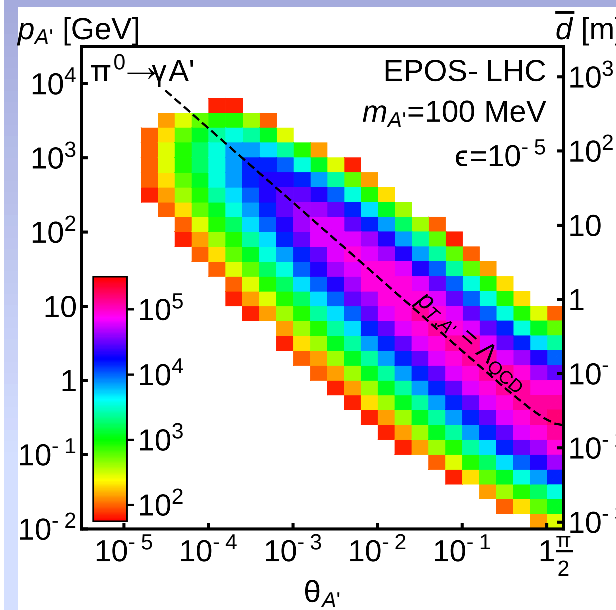
1708.09389

DARK PHOTONS AT FASER – KINEMATICS

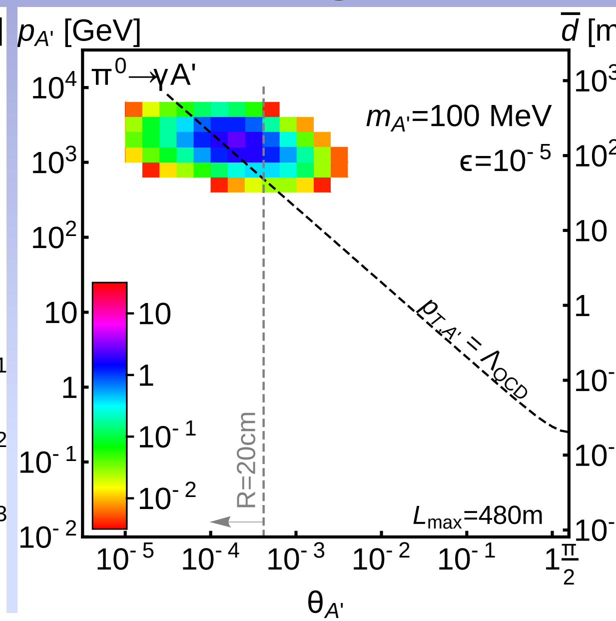
pions at the IP



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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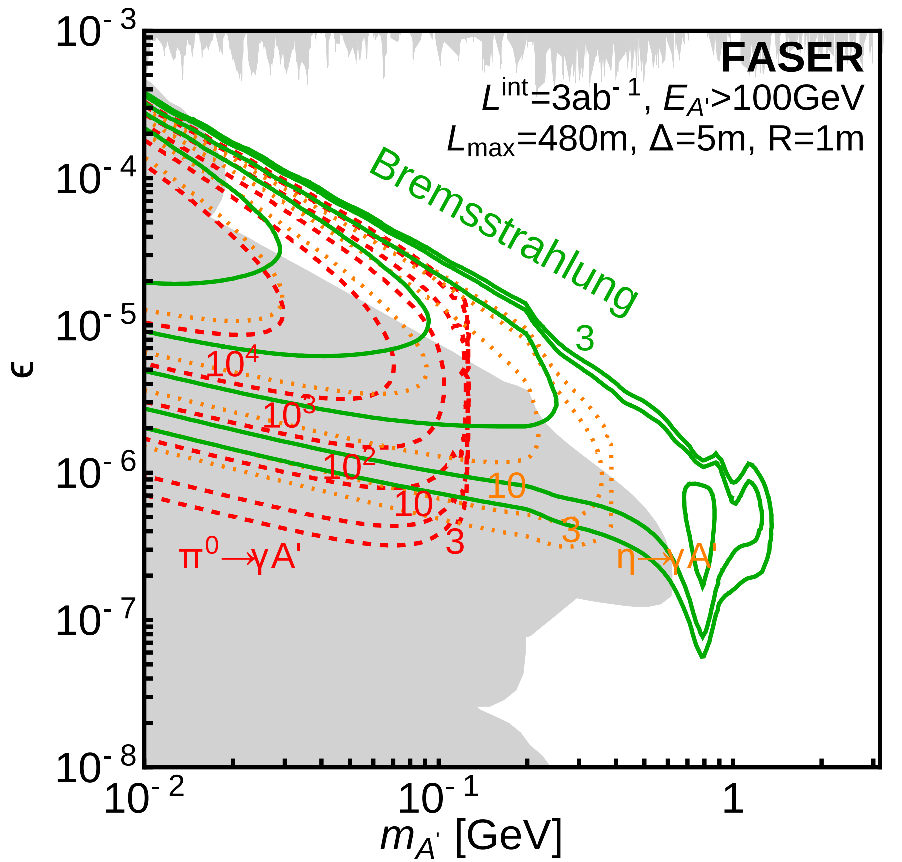
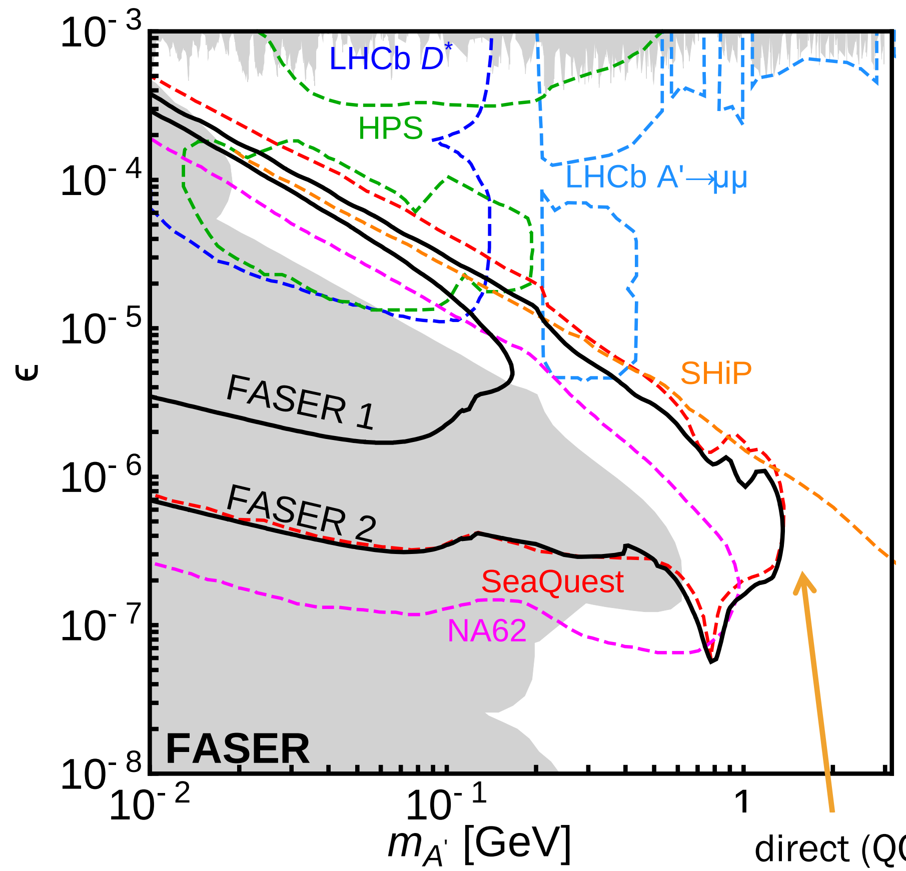
DARK PHOTONS AT FASER – SENSITIVITY





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.

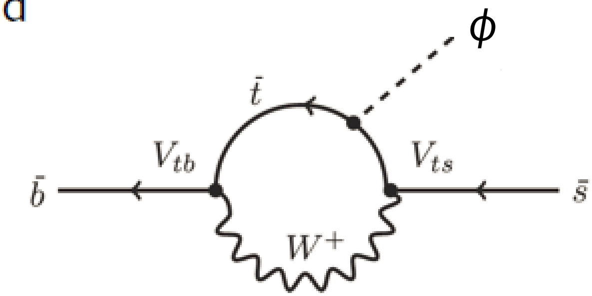
DARK HIGGS BOSONS AT FASER

1710.09387

– Dark Higgs boson: additional hidden real scalar field

– 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,

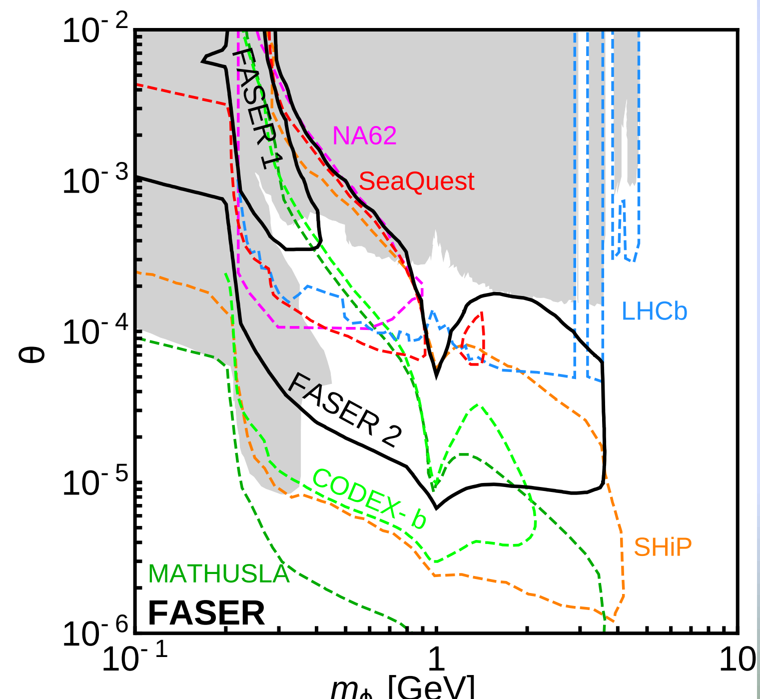
– production: B and K decays, $h \to \phi\phi$,

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

- Important production channel: $B \to X_s \phi$
at FASER energies: **N_B/N_π ~10^{-2}**
for beam-dumps typically $N_B/N_\pi < 10^{-7}$

- FASER's reach is complementary
to other proposed experiments
(large boost allows to probe lower lifetime)

- Typical p_T ~m_B
➡ improved reach for FASER 2 (R=1m)



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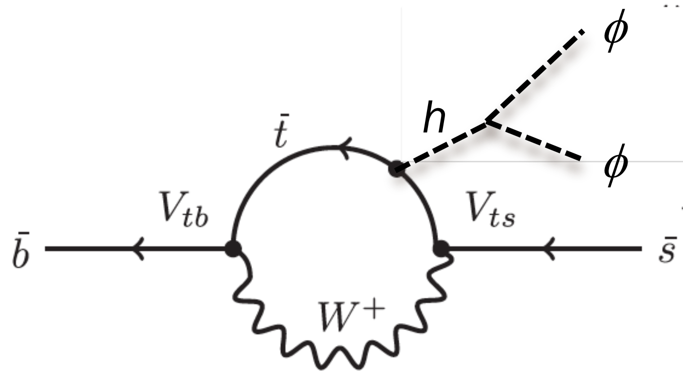
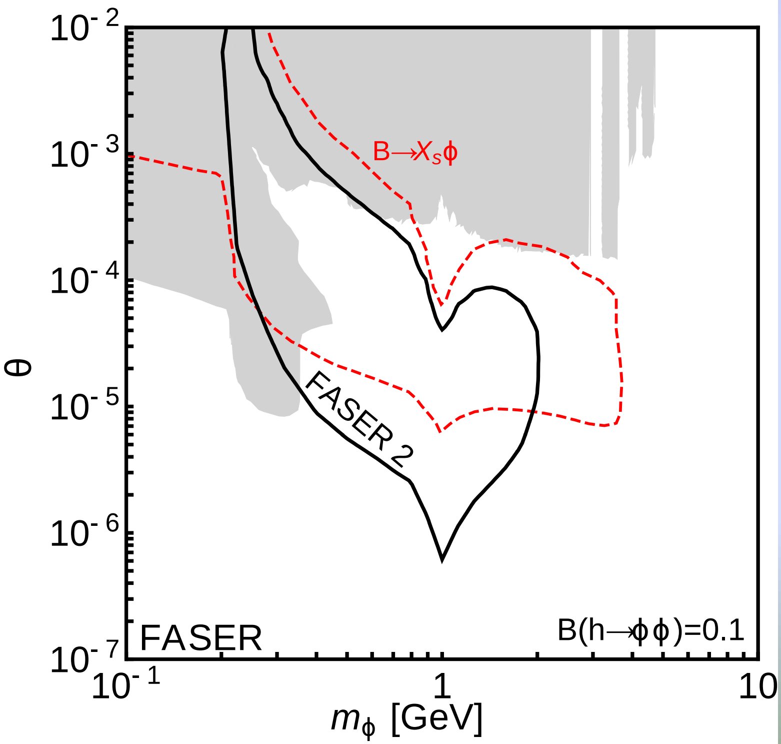
PROBING INVISIBLE DECAYS OF THE SM HIGGS

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



- 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 $B(h \to \phi\phi) \sim 0.1$
- up to ~100s of events

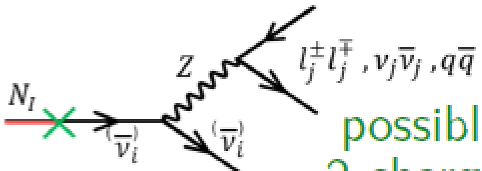


HEAVY NEUTRAL LEPTONS

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

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

- 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 $\Rightarrow$ 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

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

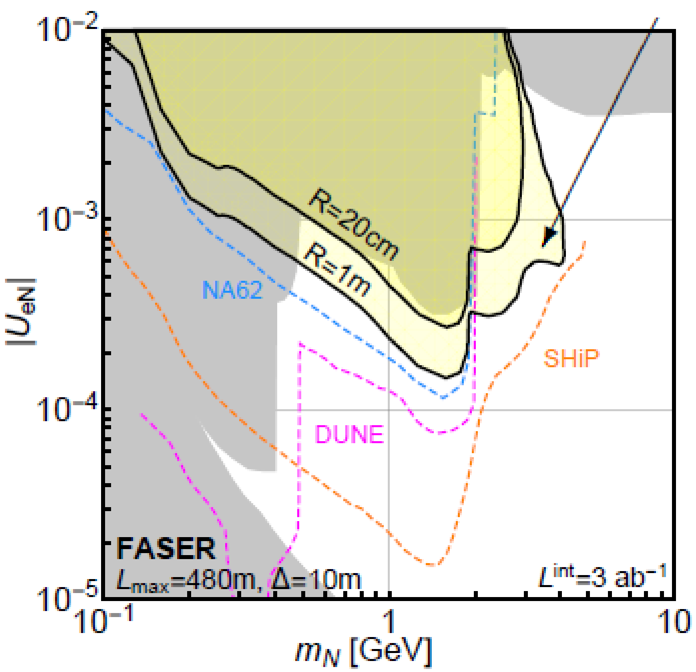
Decay modes:

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

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

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

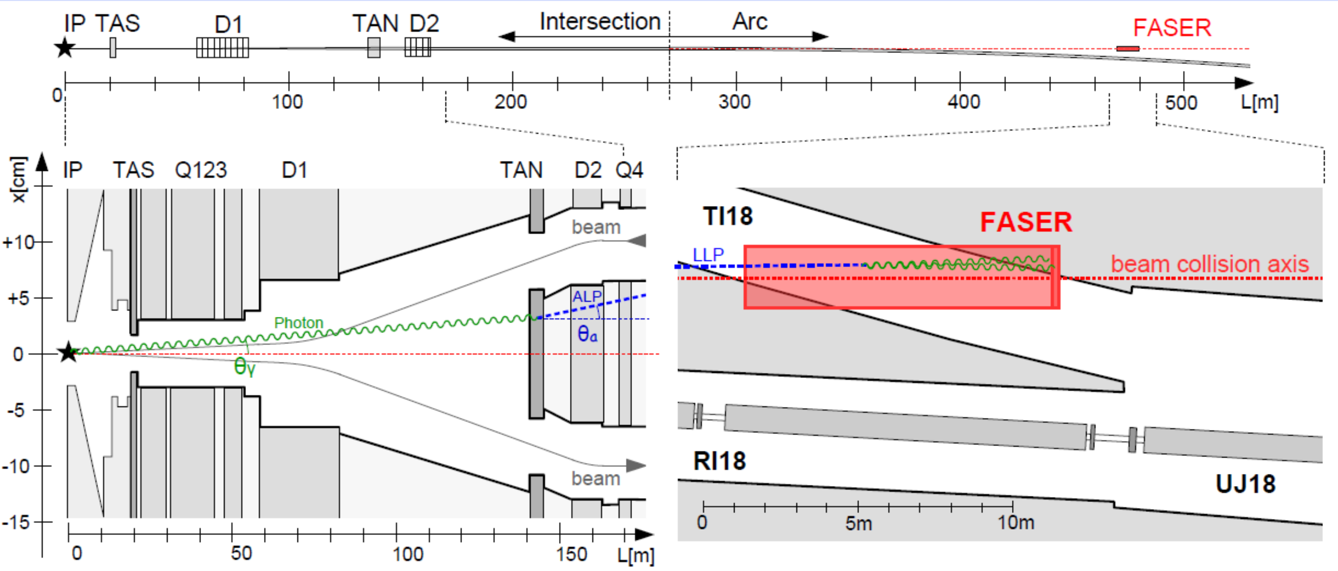
ALPS AT FASER – LHC AS A PHOTON BEAM DUMP

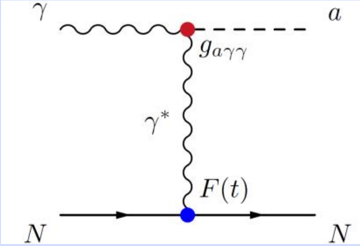
1806.02348

- 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 $(1/\Lambda)aV^{\mu\nu}\tilde{V}_{\mu\nu}$,
- 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

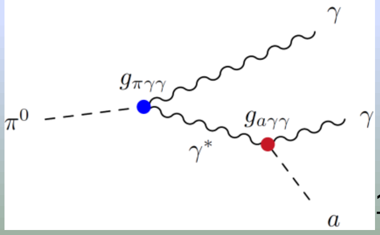
B. Döbrich *et al*, JHEP 1602 (2016) 018

Dominant „aγγ" coupling – production modes: **a) Primakoff process (γN→aN)**





b) Rare decays of π^0 and η



1806.02348

ALP DIPHOTON COUPLING – FASER REACH

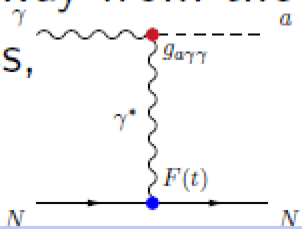
– high-energy γs produced at the IP,

– 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,

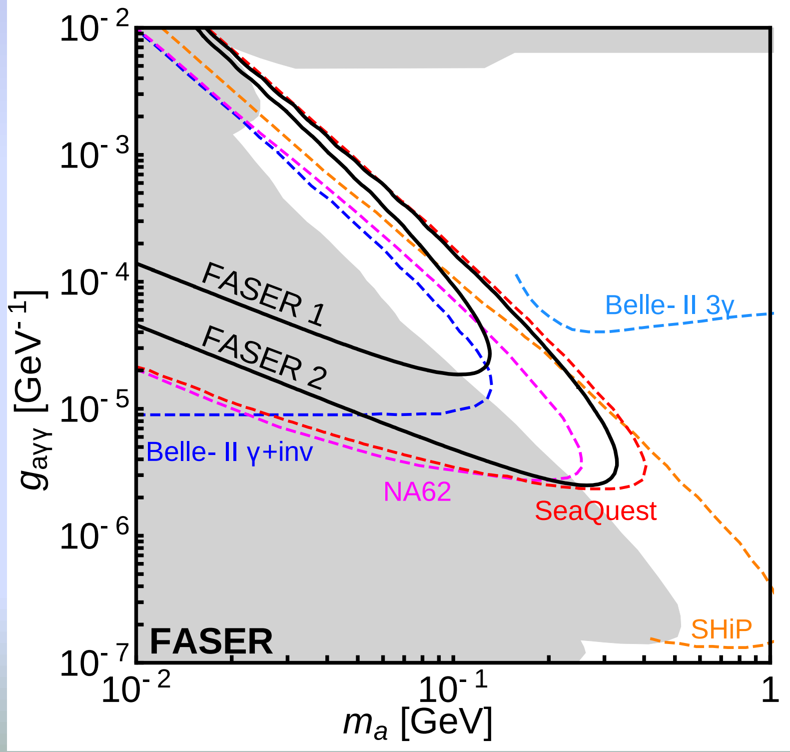
for m_a~100MeV ⇨ $\gamma_{Lor} = E_a/m_a$~few x10^3

typical opening angle $\theta_{\gamma\gamma}$~$2/\gamma_{Lor}$ < 1 mrad

after >1m both photons are separated ~1mm

(more details see 1806.02348)

- possible conversions in the tracker layers (γe^+e^-)



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'

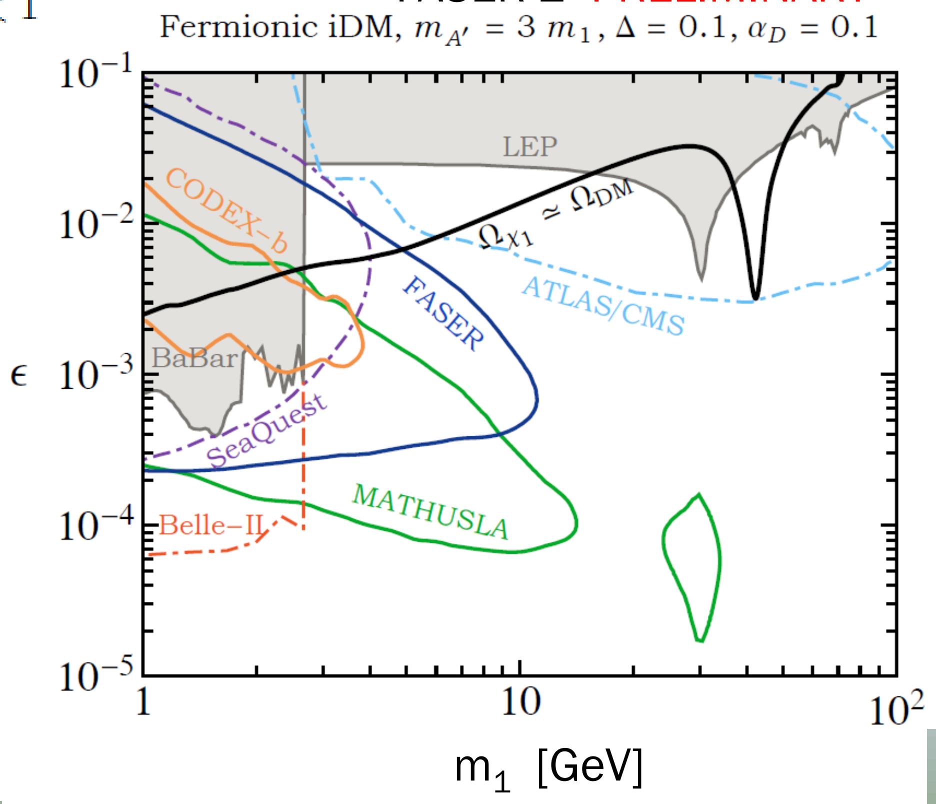
$$\mathscr{L} \supset i e_D\, A'_\mu\, \bar{\chi}_1 \gamma^\mu \chi_2 + \mathcal{O}(\delta_{\eta,\xi}/m_D)$$

Production pp→A'→$\chi_1\chi_2$ 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 $m_{A'}=3m_1 > 30$GeV !

FASER 2 PRELIMINARY



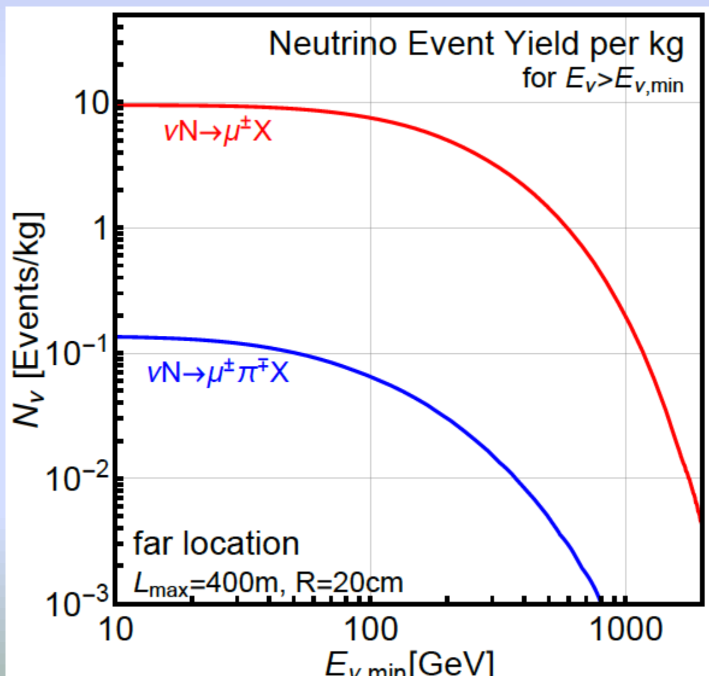
BACKGROUNDS – SIMULATIONS (1)

Done & more ongoing

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



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
μ+	0.18	$6.1 \cdot 10^{-9}$	0.02	$5.8 \cdot 10^{-10}$	0.002	$6.8 \cdot 10^{-11}$
μ-	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

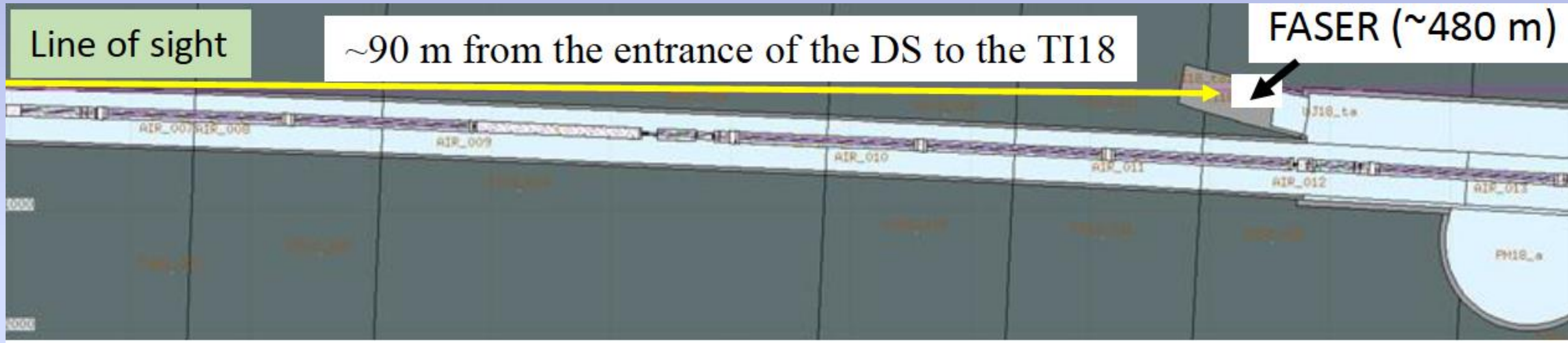
study by the members of the CERN FLUKA team:
Marta Sabate-Gilarte, Francesco Cerutti,
Andrea Tsinganis

Done & more ongoing

BACKGROUNDS – SIMULATIONS (2)

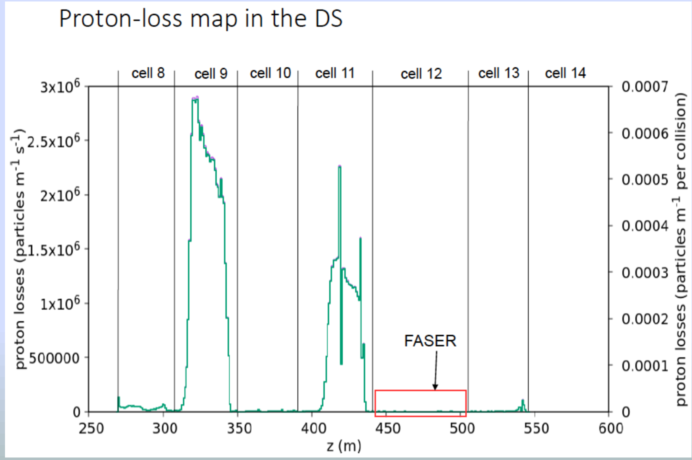
LHC Dispersion Suppressor (DS) – located around the connection between straight („intersection") regions of the LHC and the curved („arc") regions,

- Recent FLUKA study finds that proton showers in a nearby DS lead to negligible BG after ~90m of rocks before particles could reach FASER



- The activity close to FASER from diffractive proton losses is very small. It would be orders of magnitude higher 50m along LHC in either direction.

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

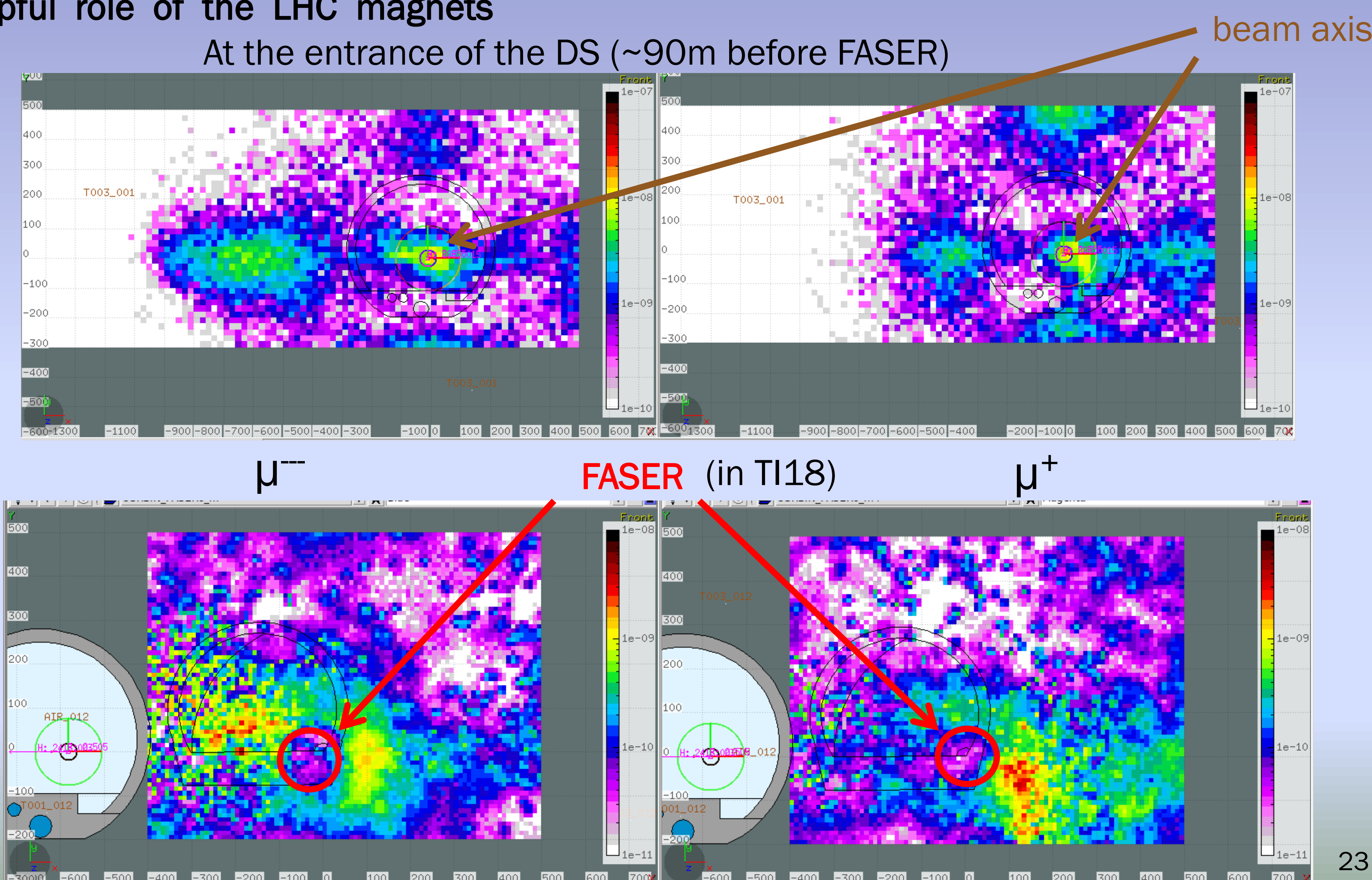


- FLUKA study: beam-gas backgrounds (from "beam 2") are also negligible

BACKGROUNDS – SIMULATIONS (3)

Helpful role of the LHC magnets

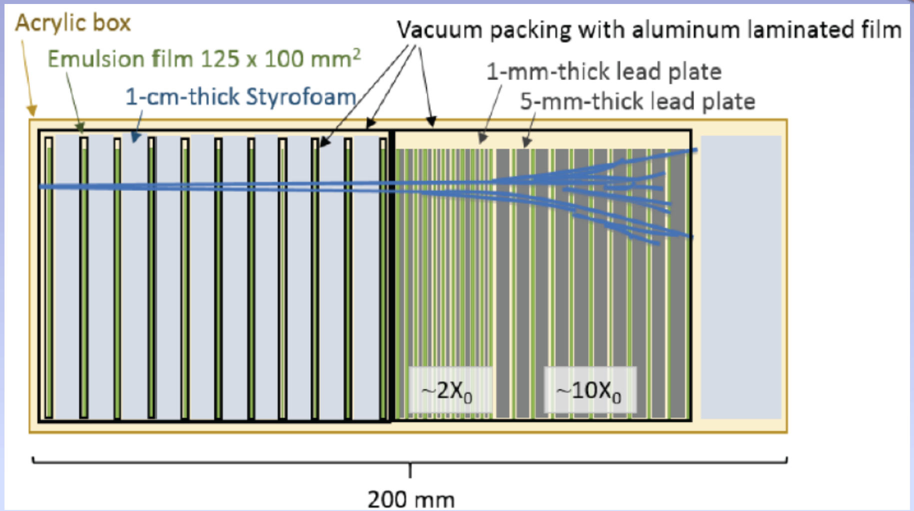
At the entrance of the DS (~90m before FASER)



BACKGROUNDS – IN SITU MEASUREMENTS

Begin THIS WEEK

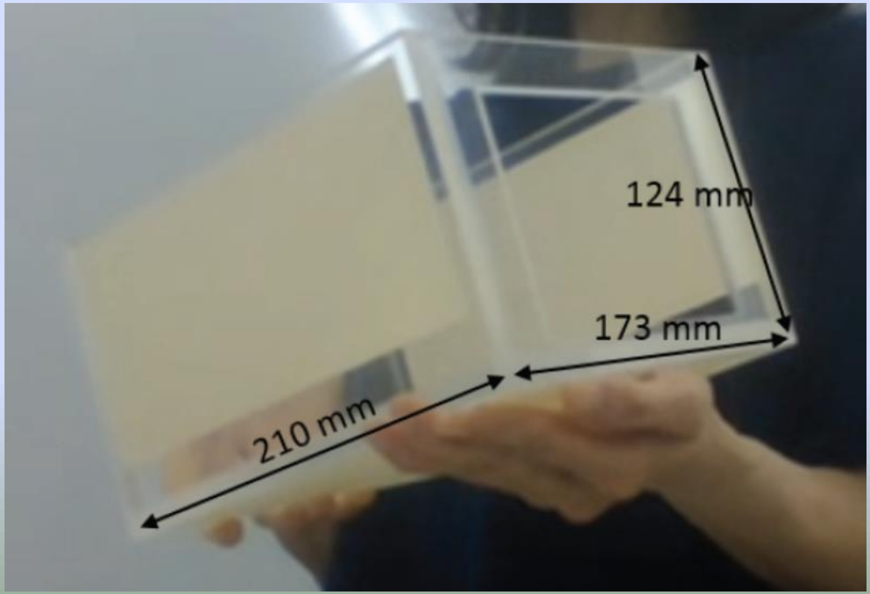
- First measurements right after Technical Shutdown 1 (TS1); installation **this week**



- CERN survey team will map out and mark the “on-axis” line in TI18 to ~mm accuracy.

- An emulsion detector has been prepared and will be placed at the FASER location in TS1, removed in TS2 (or before).

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



- A BatMon (battery-operated radiation monitor) will also be installed.

GROWING COLLABORATION

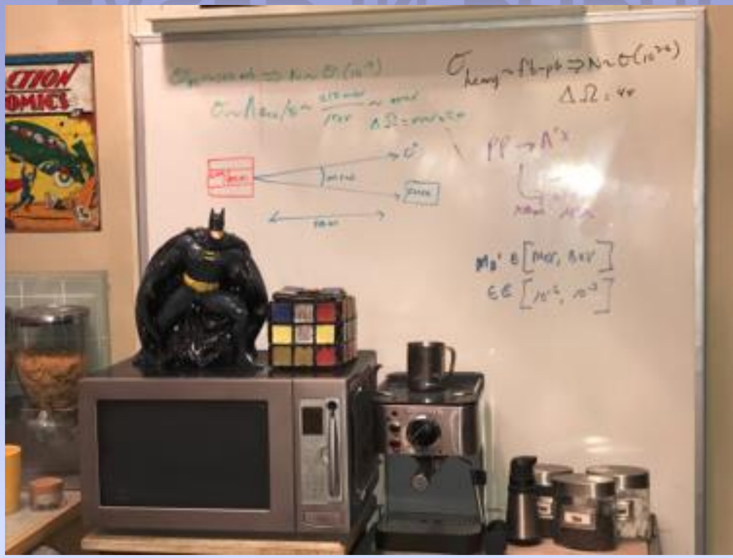
August/September 2017 - first paper ~10 months ago (1708.09389),
since then 3 more papers from the FASER group + increasing interest outside the group
Batell, Freitas, Ismail, McKeen, 1712.10022; Bauer, Foldenauer, Jaeckel, 1803.05466; Helo, Hirsch, Wang, 1803.02212

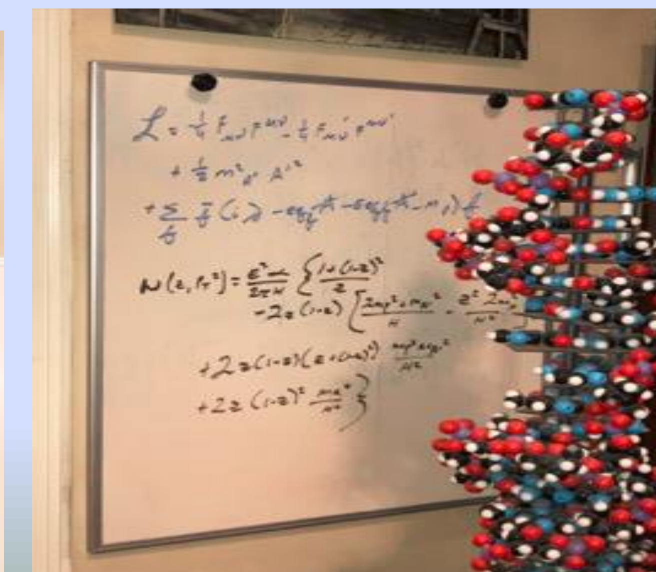
January 2018 – join the Physics Beyond Colliders (PBC) working group at CERN,
May 2018 – first results of detailed BG simulations,
June 2018 – BG in-situ measurements begin,
Currently > 10 active members (mostly experimentalists) from ~8 institutions in 4 countries,

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

+ 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, start of in-situ measurements)
- ongoing 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...),
- Invisible decays of the SM Higgs,
- LHC as a photon beam-dump ($a\gamma\gamma$ coupling),
- Inelastic DM,
- **... (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 = 3 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 existing tunnel
- Full physics program: dark photons, B-L, ALPs, dark Higgs, HNLs, etc.

FURTHER FUTURE

„FASER 3” - even more compact and cheaper, but still very powerful !

Proof of concept:

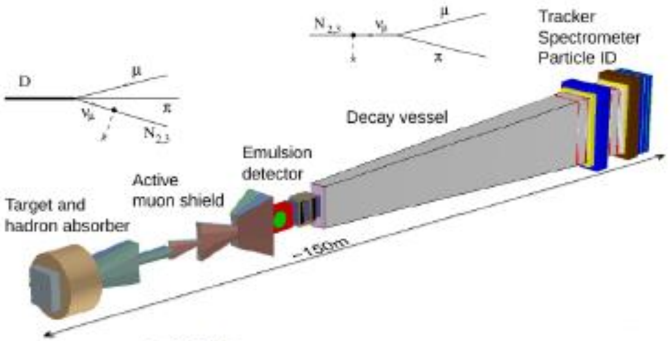
Working prototype for ~ $100

first tests
fixed target experiments

Now hiring !

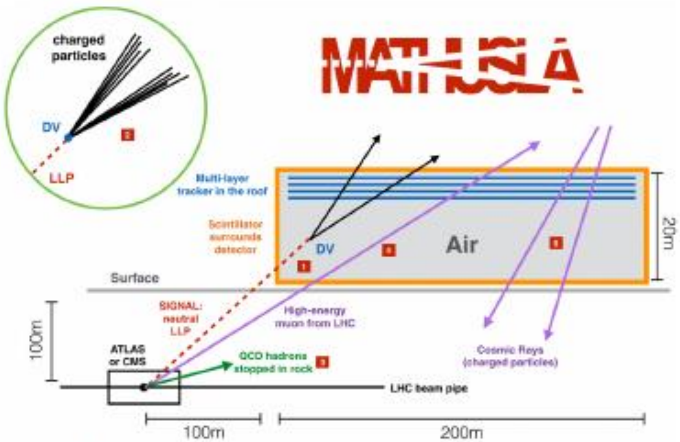
Detailed plans for FASER 3:
final detector will start operating right after the Warp drive is introduced !!!

FASER & OTHER PROPOSED EXPERIMENTS



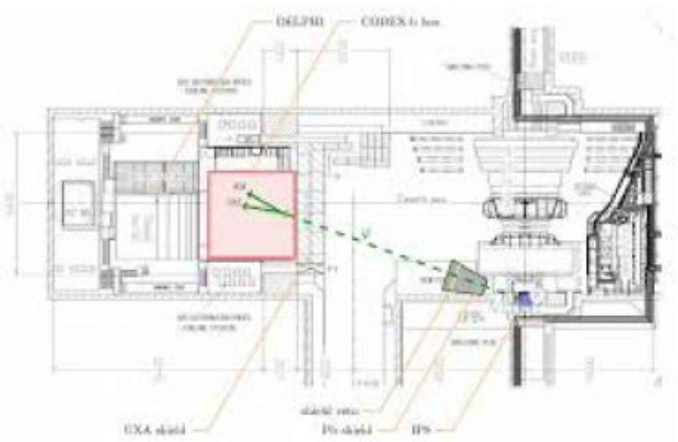
SHiP, Alekhin et al. (2015)

$\sim 1000\ \mathrm{m}^3$, a few hundred million \$



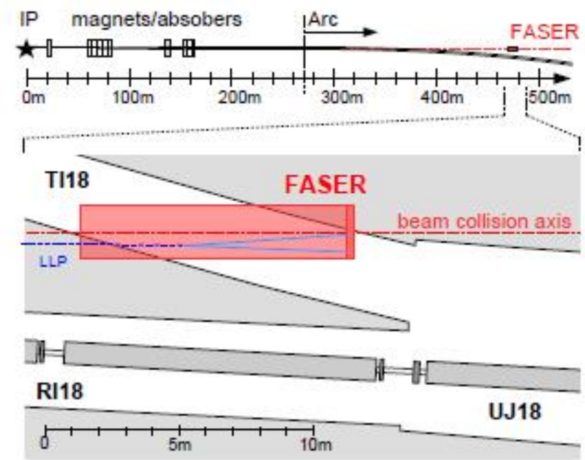
MATHUSLA, Chou, Curtin, Lubatti (2016)

$\sim 10^6\ \mathrm{m}^3$, $\sim 50\mathrm{M}\$$



CODEX-b, Gligorov, Knapen, Papucci, Robinson (2016)

$\sim 1000\ \mathrm{m}^3$



FASER, Feng, Galon, Kling, Trojanowski (2016)

$\sim 1-10\ \mathrm{m}^3$ ~\$1M