Physics Potential of FASER

Sebastian Trojanowski (University of Sheffield)

MPIK Heidelberg
July 15, 2019

arXiv: 1708.09389; 1710.09387; 1801.08947; 1806.02348 (PRD,with J.L.Feng, I.Galon, F.Kling)
FASER Collaboration: arXiv:1811:10243 Letter of Intent (CERN-LHCC-2018-030)
arXiv:1811.12522 Physics case (PRD)
arXiv:1812.09139 Technical Proposal (CERN-LHCC-2018-036)
arXiv:1901.04468 Input to the European Particle Physics Strategy

FASER APPROVAL

related article

symmetry
dimensions of particle physics

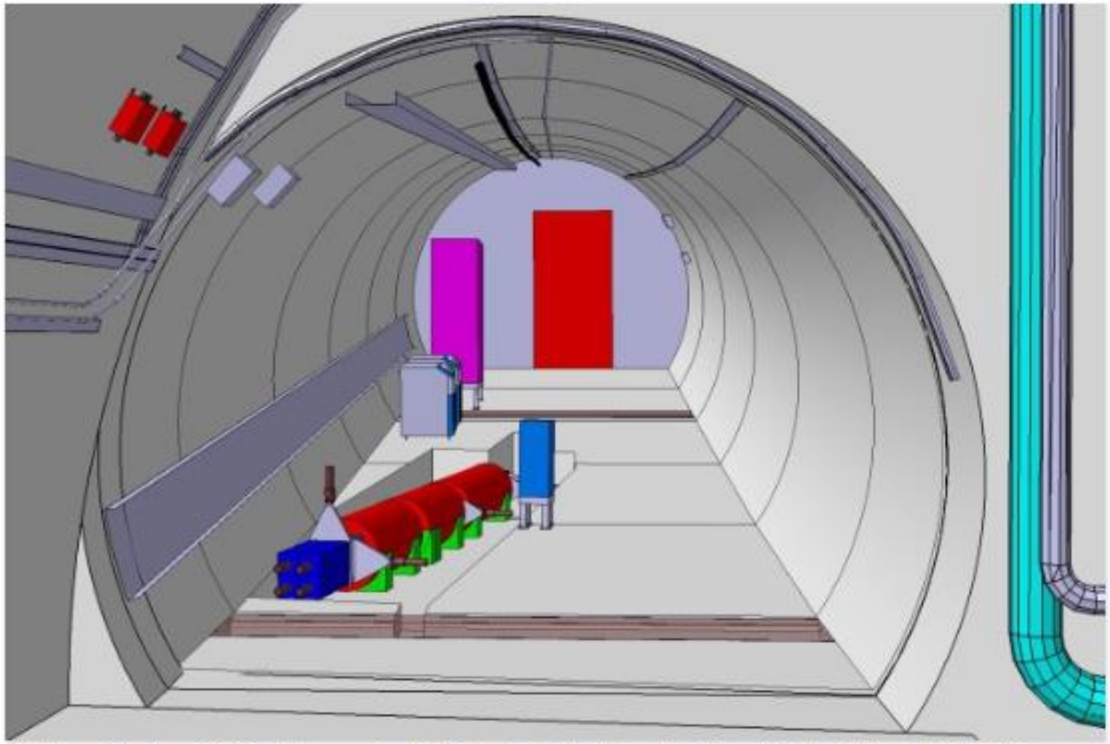
physics today

Voir en français

FASER: CERN approves new experiment to look for long-lived, exotic particles

The experiment, which will complement existing searches for dark matter at the LHC, will be operational in 2021

5 MARCH, 2019 | By Cristina Agrigoroae



A 3D picture of the planned FASER detector as seen in the TI12 tunnel. The detector is precisely aligned with the collision axis in ATLAS, 480 m away from the collision point (Image: FASER/CERN) (Image: CERN)

Geneva. Today, the CERN Research Board approved a new experiment designed to look for light and weakly

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

FASER COLLABORATION

Spokespersons: J. Boyd, J. L. Feng

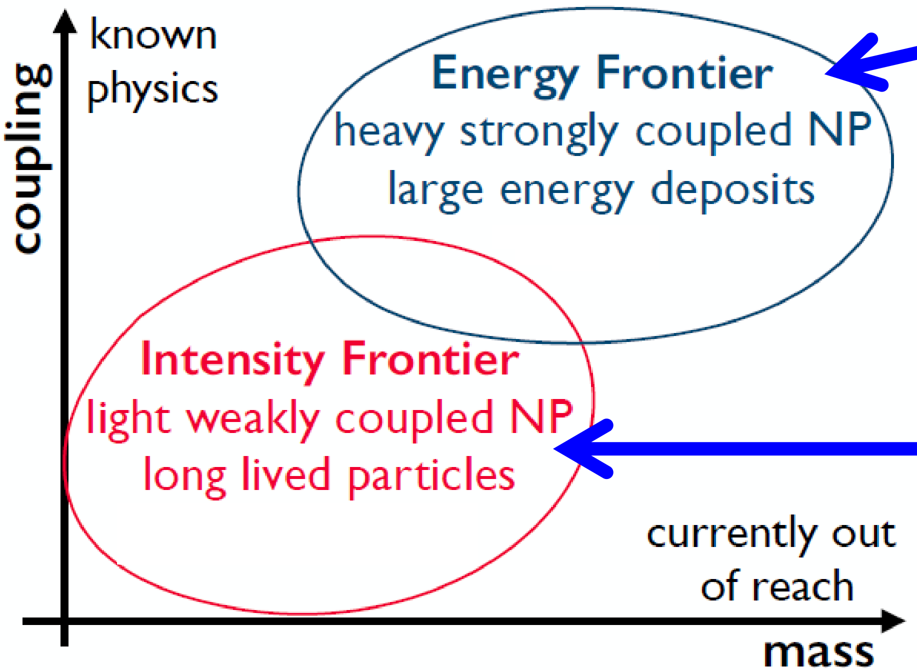
- The FASER Collaboration: ~40 collaborators, 17 institutions, 8 countries

  Henso Abreu (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Jamie Boyd (CERN), Dave Casper (UC Irvine), Franck Cadoux (Geneva), Xin Chen (Tsinghua), Andrea Coccaro (Genova), Candan Dozen (Tsinghua China), Yannick Favre (Geneva), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Iftah Galon (Rutgers), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Sune Jakobsen (CERN), Roland Jansky (Geneva), Enrique Kajomovitz (Technion), Felix Kling (UC Irvine), Susanne Kuehn (CERN), Lorne Levinson (Weizmann), Congqiao Li (Washington), Sam Meehan (CERN), Josh McFayden (CERN), Friedemann Neuhaus (Mainz), Hidetoshi Otono (Kyushu), Lorenzo Paolozzi (Geneva), Brian Petersen (CERN), Helena Pikhartova (Royal Holloway), Osamu Sato (Nagoya), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Savannah Shively (UC Irvine), Jordan Smolinsky (UC Irvine), Aaron Soffa (UC Irvine), Yosuke Takubo (KEK), Eric Torrence (Oregon), Sebastian Trojanowski (Sheffield), Gang Zhang (Tsinghua China)

OUTLINE

- Light Long-lived Particles (LLP)
- FASER: ForwArd Search ExpeRiment at the LHC (idea and basic detector design)
- FASER physics
  - remarks about BSM programme (modeling production in the forward region)
  - selected BSM models
  - possible neutrino measurements
- SM backgrounds
- Concluding remarks

MOTIVATION



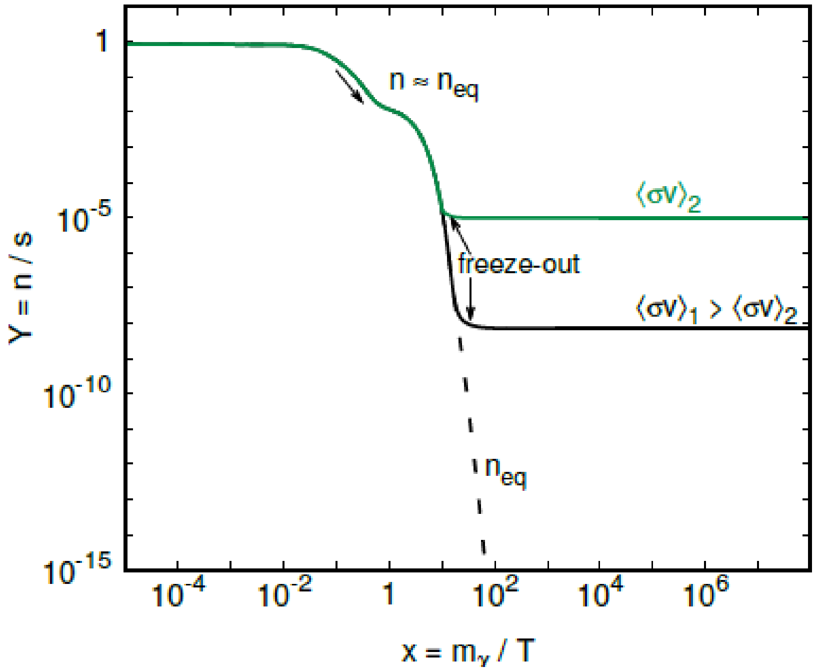
heavy and strongly-coupled new physics
e.g. SUSY, extra dimensions, ...
here also missing energy searches for heavy WIMP DM, magnetic monopoles,...

Light and very weakly coupled new physics:
-- requires large „luminosities" (statistics)
-- new particles decay back to SM, but with highly displaced vertices
-- SM BG needs to be highly suppressed

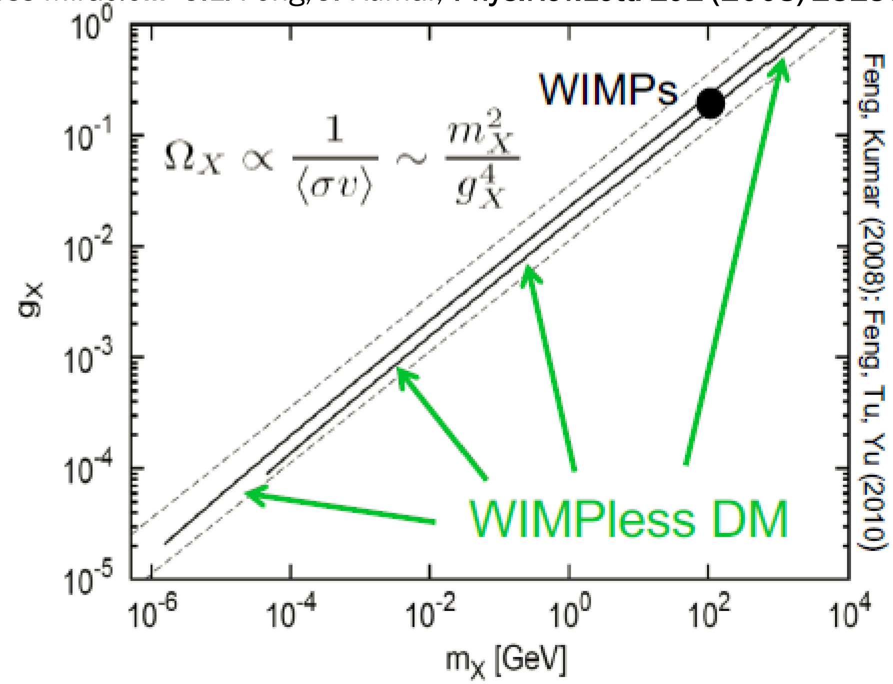
Exciting physics:
-- cosmology
(dark matter, inflation, bariogenesis,...)
-- neutrino masses
(GeV-scale heavy neutral leptons)
-- $(g\text{-}2)_\mu$
-- ...

GENERALIZED DM FREEZE-OUT

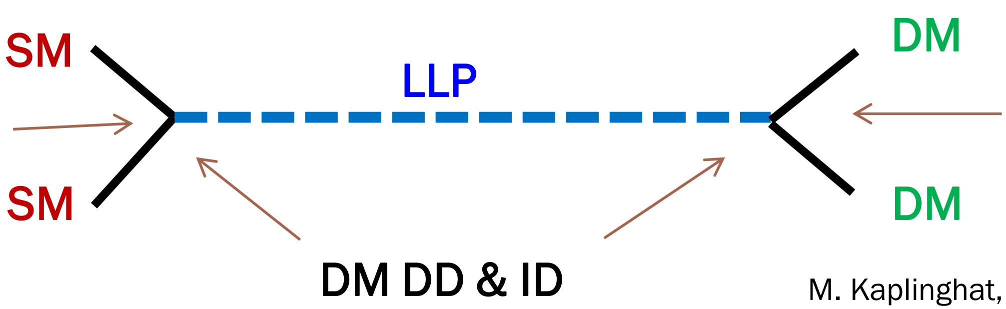
L. Roszkowski, E.M. Sessolo, ST, 1707.06277



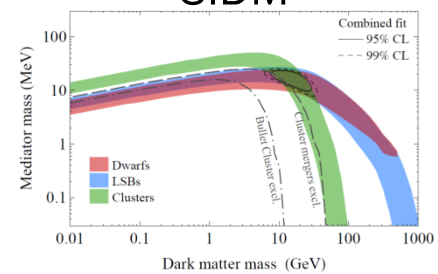
„The WIMPless Miracle…" J.L. Feng, J. Kumar, **Phys.Rev.Lett. 101 (2008) 231301**



LHC



SIDM



M. Kaplinghat, S. Tullin, H.-B. Yu, 1508.03339

e.g. M. J. Dolan, F. Kahlhoefer, C. McCabe, 1711.09906
J.L. Feng, J. Smolinsky, F. Tanedo, 1509.07525, 1602.01465

HIDDEN SECTOR PORTALS

- new „hidden" particles are SM singlets
- interactions between the SM and „hidden" sector arise due to mixing through some SM portal

$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

B. Patt, F. Wilczek, 0605188
B. Batell, M. Pospelov, A. Ritz, 0906.5614

Renormalizable portals

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

PBC report, 1901.09966

SOME MORE COMPLETE MODELS

– **SUSY**

RPV with light bino-like neutralino and lepton number violating terms

J.C. Helo, M. Hirsh, Z.S. Wang, JHEP 1807 (2018) 056

RPC with some superWIMP LSP (e.g. superpartner of ALP, displaced decays ~B -> ~a γ)

K.-Y. Choi, T. Inami, K. Kadota, I. Park, O. Seto, 1902.10475

– **Right-handed neutrinos** e.g.**νMSM** (ν masses and oscillations, DM, baryon asymmetry)

T. Asaka, S. Blanchet and M. Shaposhnikov, *Phys. Lett.* **B631** (2005) 151–156
T. Asaka and M. Shaposhnikov, *Phys. Lett.* **B620** (2005) 17–26

– **gauge some global symmetry of the SM** e.g. $\mathbf{U(1)_{L_e-L_\mu}}$, $\mathbf{U(1)_{B-L}}$, ⇨ new dark vector

M. Bauer, P. Foldenauer, J. Jaeckel, **JHEP 1807 (2018) 094**

Kinetic mixing induced at a loop-level involving SM fermions

– **dark photon mass from dark Higgs mechanism** $\phi A'_\mu A'^\mu$;

(both light vector and light scalar can be present)

$\phi \to A' A'$; or dark Higgs can be radiated off dark photon leg – additional prod modes

– **mirror sector / Twin Higgs scenarios**

(hidden photons and neutrinos can naturally be light and weakly coupled to the SM

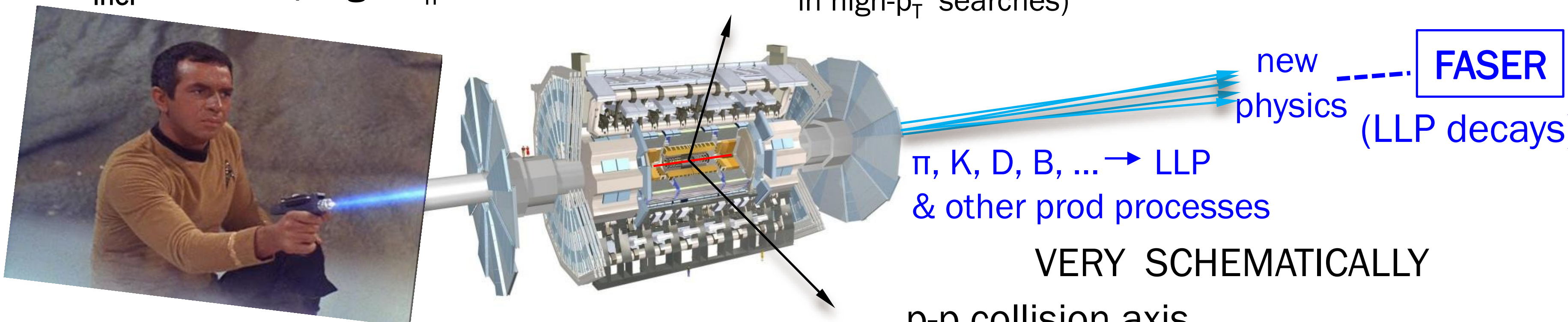
FASER - IDEA

FASER – small (**~0.05 m³**) and inexpensive (**~1M$**) experiment
detector to be placed few hundred meters downstream away from the ATLAS IP

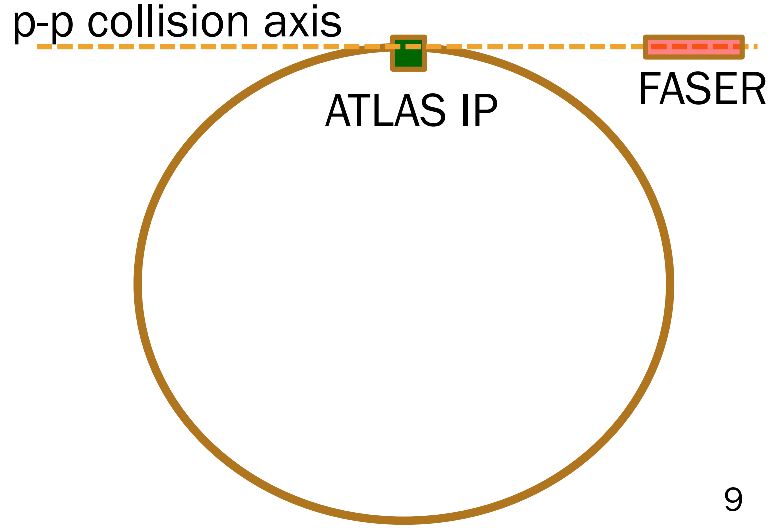
to harness large, currently „wasted” forward LHC cross section

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

(for comparison **σ ~ fb – pb,** e.g., $N_H \sim 10^7$ at 300 fb^{-1} in high-p_T searches)



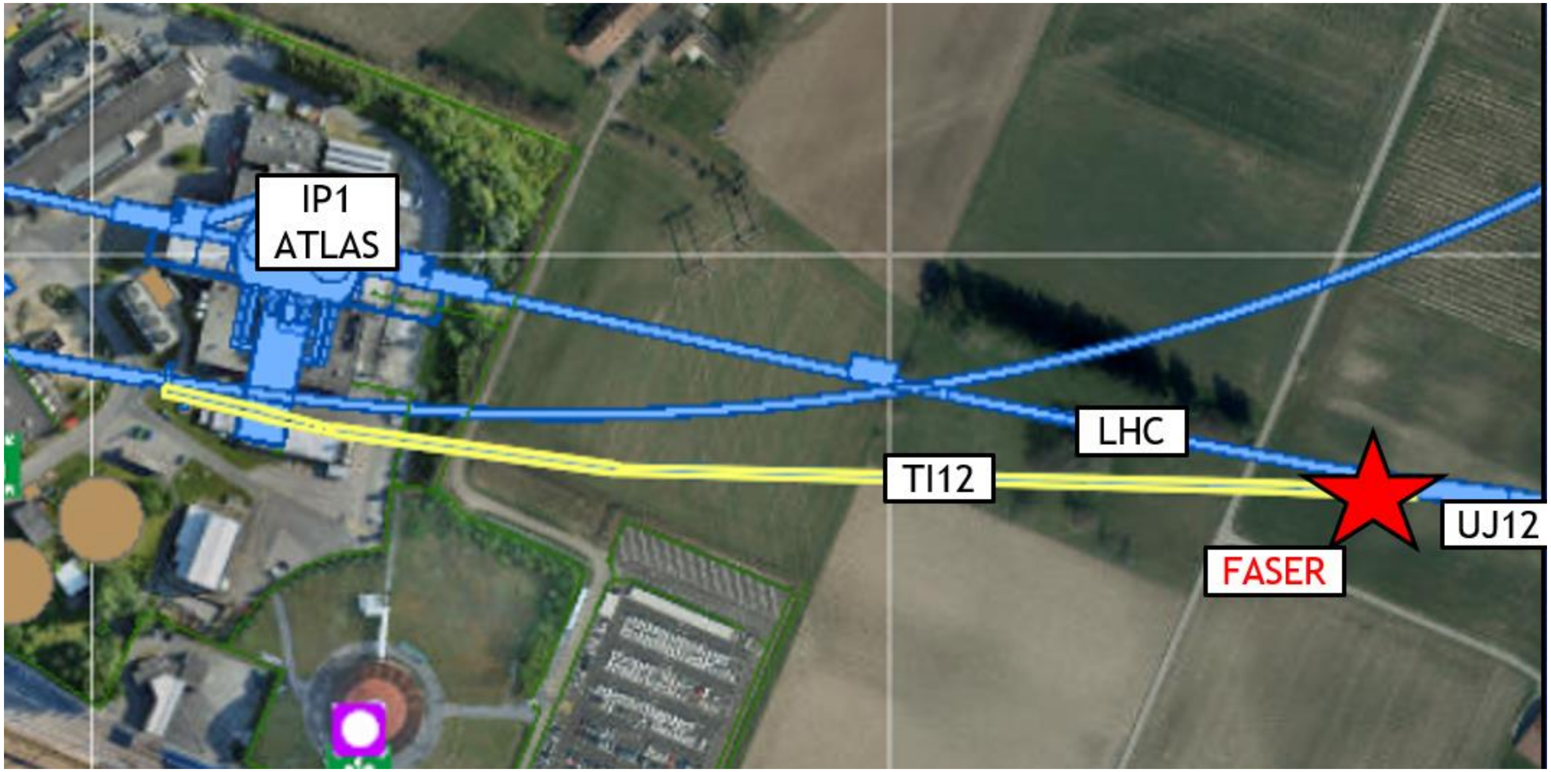
VERY SCHEMATICALLY



FASER will complement ATLAS/CMS by searching for highly-displaced decays of new Light Long-Lived Particles

(part of Physics Beyond Colliders Study Group at CERN)

FASER LOCATION – TUNNEL TI12



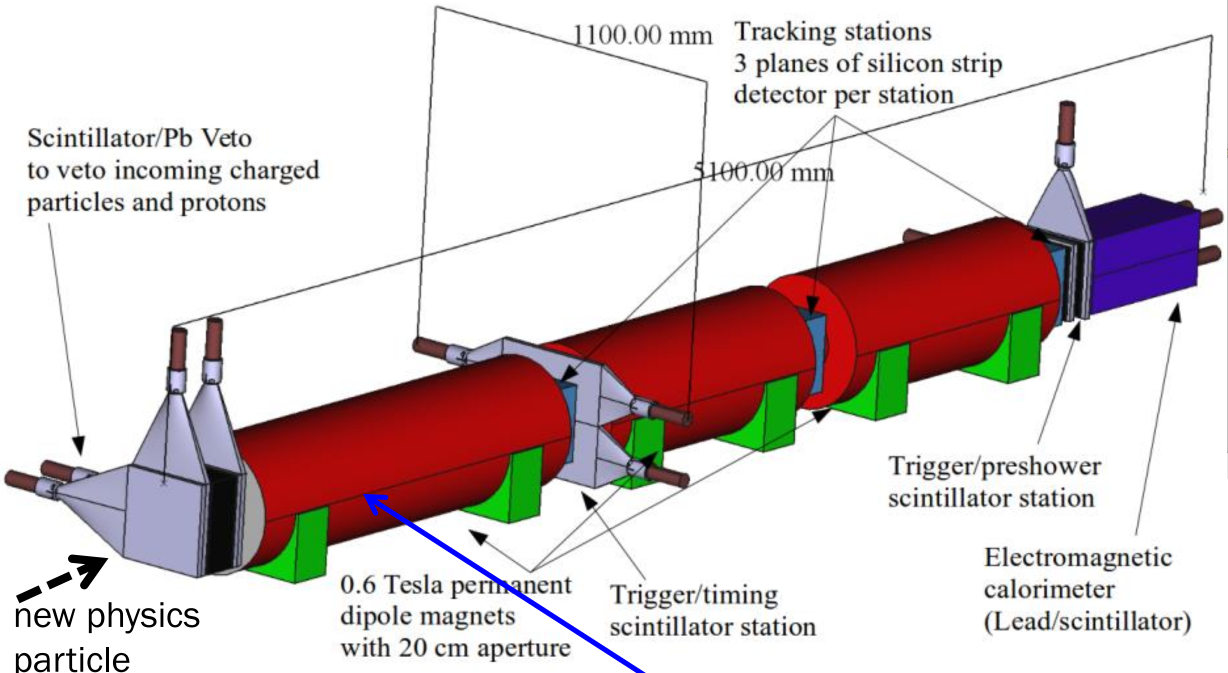
- location in a side tunnel TI12 (former service tunnel connecting SPS to LEP)
- **L ~ 485m** away from the IP along the beam axis
- space for a **5-meter-long** detector
- precise position of the beam axis in the tunnel up to **mm precision** (CERN Engineering Dep)
- corrections due to beam crossing angle (for ~300μrad the displacement is ~7-8 cm)

TUNNEL TI12

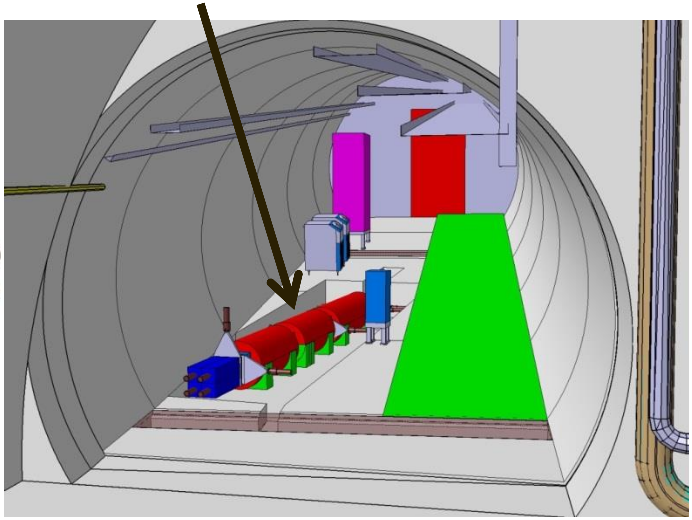
new physics
(hidden in the dark)

main LHC tunnel

BASIC DETECTOR LAYOUT



small civil engineering
(max 50cm digging)

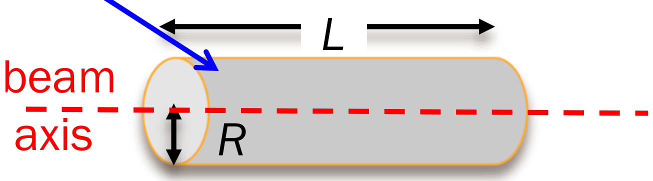


Thank you !!!

Recycling existing spare modules:

- ATLAS SCT modules (Tracker)
- LHCb ECAL modules (Calorimeter)

- cylindrical decay volume



- 2 stages of the project:

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

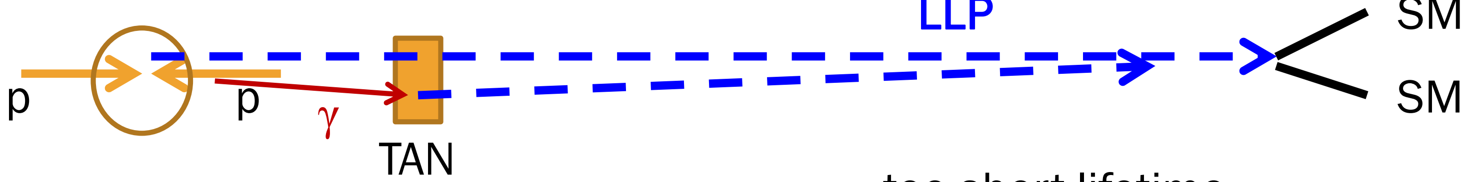
FASER 2: L = 5 m, R = 1 m, V = 16 m^3, 3 ab^{-1} (HL-LHC)
possible upgrade with bigger detector for HL-LHC; not yet considered for approval

FASER PHYSICS

SIMPLIFIED MODELS

Production | **Decay**

Coupling: the larger the better | too large not good (too early decays)

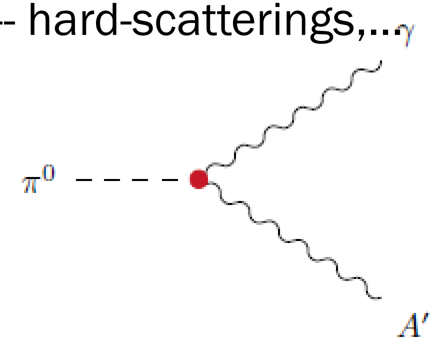


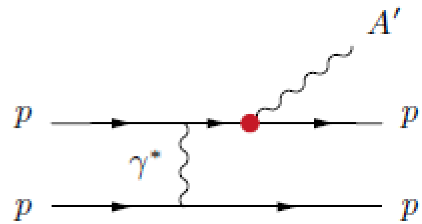
too short lifetime

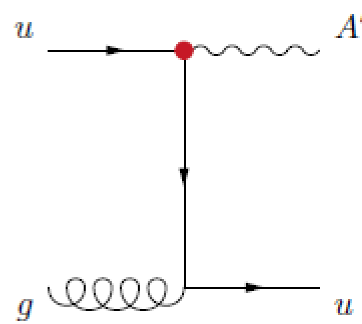
=> Exponential suppression of # events

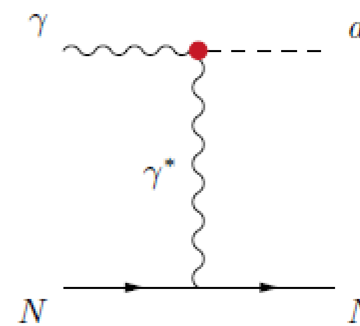
$$N_{\rm sig} \propto \begin{cases} \mathcal{L}^{\rm int}\,\epsilon^2\, e^{-L_{\rm min}/\bar{d}} & \text{for} \quad \bar{d} \ll L_{\rm min} \\ \mathcal{L}^{\rm int}\,\epsilon^2\, \frac{L_{\rm max}-L_{\rm min}}{\bar{d}} & \text{for} \quad \bar{d} \gg L_{\rm min}\,. \end{cases}$$

Various production mechanisms:
-- meson decays
-- bremsstrahlung
-- hard-scatterings,...









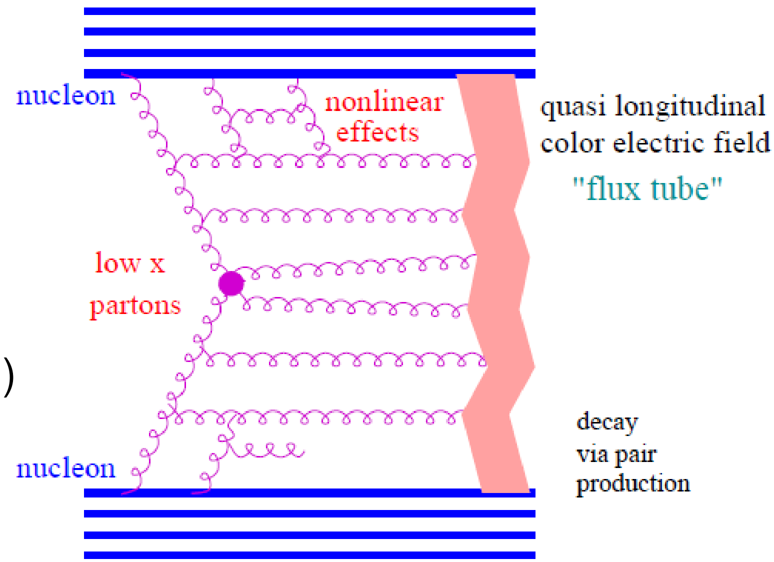
Production and decay can be more independent e.g. - 2 couplings (leptophobic models)
- compressed spectrum

FORWARD SPECTRUM OF LIGHT MESONS

Example MC – **EPOS LHC**

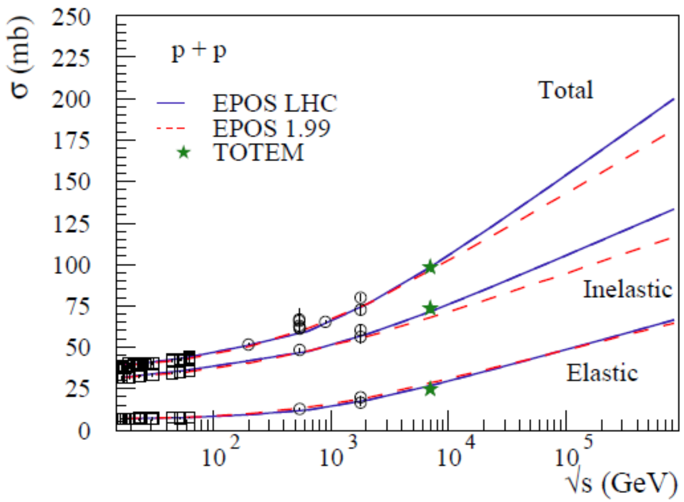
e.g. 1306.0121 T.Pierog etal

- based on Parton-Based Gribov Regge Theory
- extensively tuned to the LHC data (both forward and for smaller η)

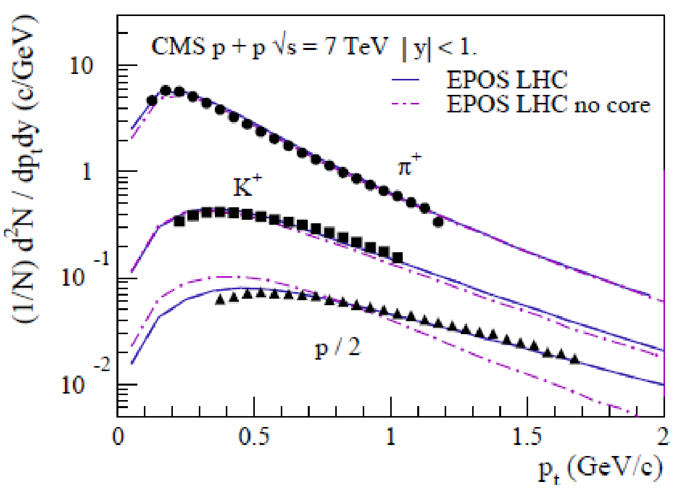


Other MC tools: QGSJET, DPMJET, SIBYLL

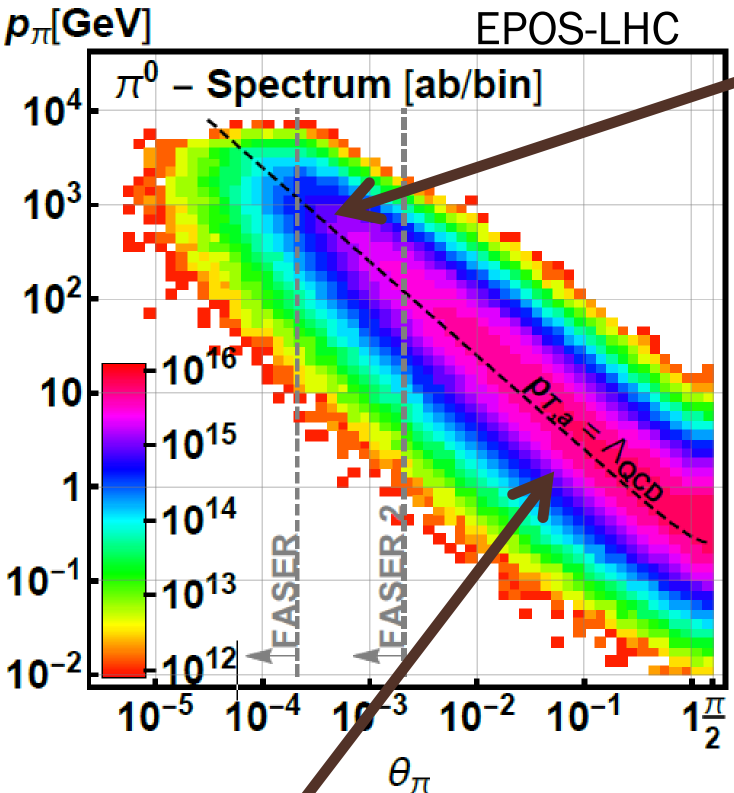
EPOS-LHC vs TOTEM data for cross section



EPOS-LHC vs CMS low p_T data

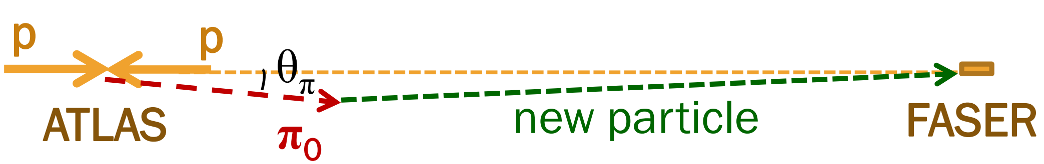


LLP FROM PION PRODUCTION AT THE IP



Hard pions highly collimated along the beam axis since their $p_T \sim \Lambda_{QCD}$ e.g. for $E_{\pi 0} \geq 10$ GeV
~ 1.7% of π_0s go towards FASER
~ 24% of π_0s go towards FASER 2

This can be compared to the angular size of both detectors with respect to the total solid angle of the forward hemisphere (2π) :
~ (2×10^{-6})% for FASER
~ (2×10^{-4})% for FASER 2

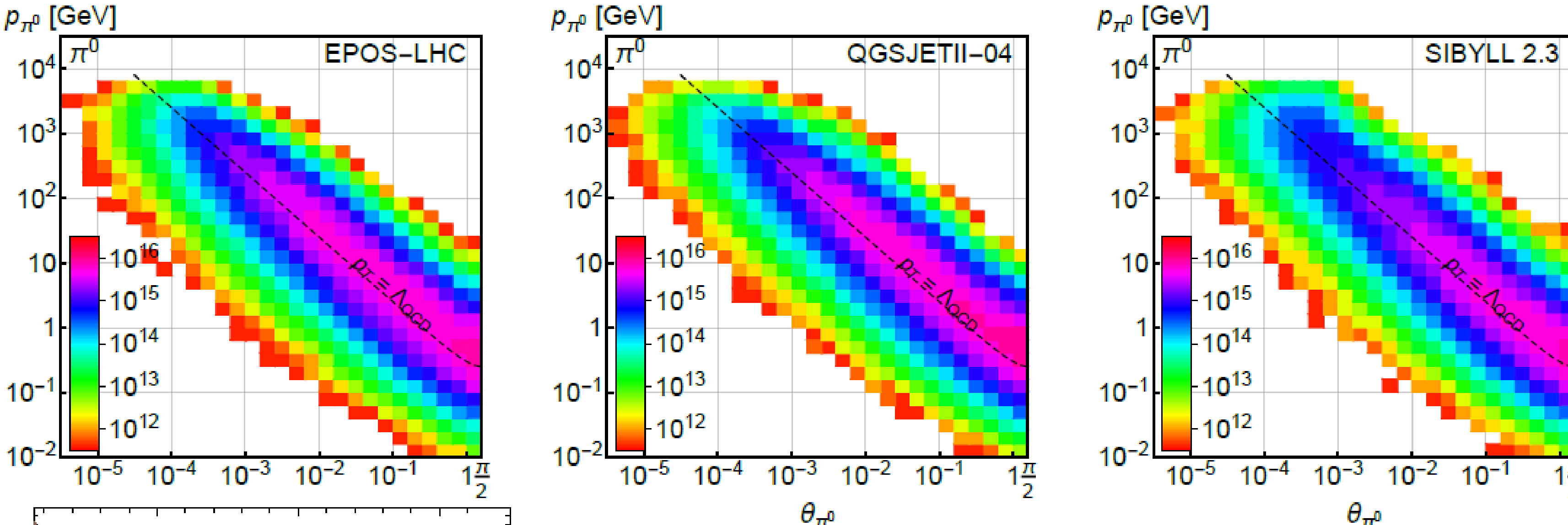


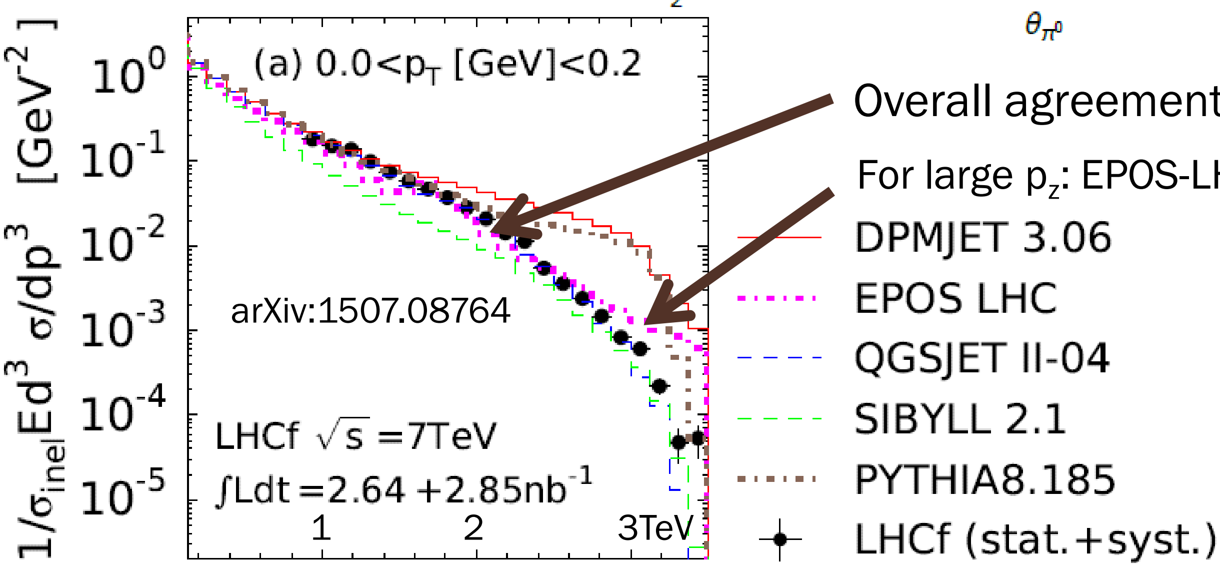
Soft pions going towards high-p_T detectors:
- produced LLPs would be too soft for triggers
- large SM backgrounds

CRMC package

COMPARISON – VARIOUS MC TOOLS

CRUCIAL CONTRIBUTION FROM LHC FORWARD PHYSICS AND DIFFRACTION WG





Overall agreement between MC and data

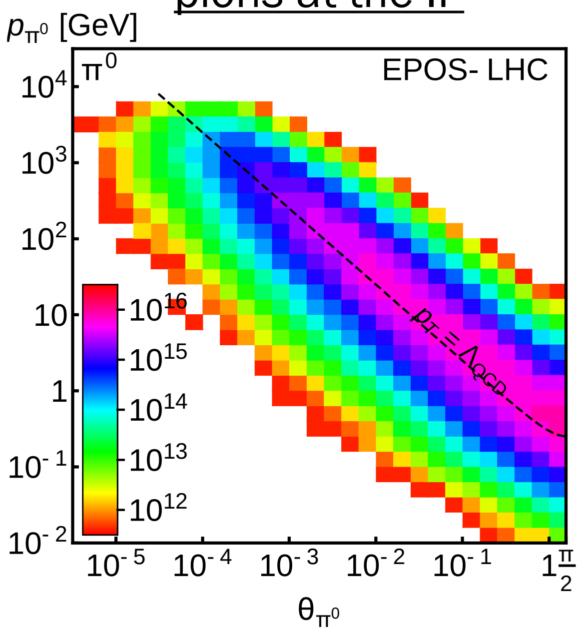
For large p_z: EPOS-LHC gives some overestimate

QGSJET II, SIBYLL lower estimates

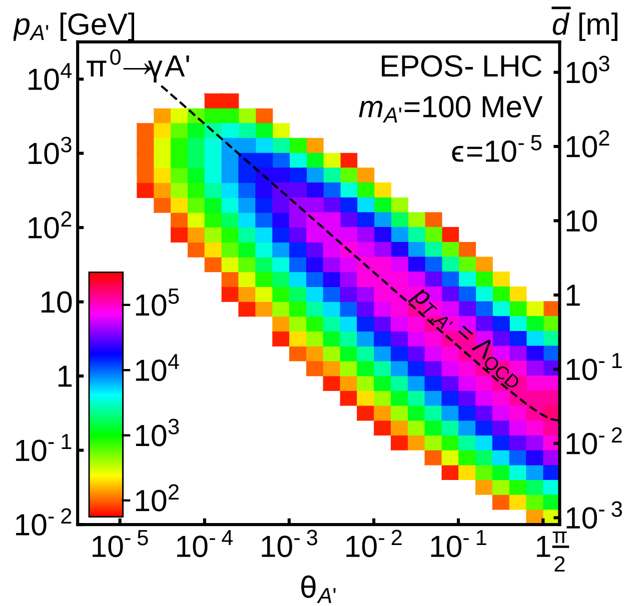
THESE DISCREPANCIES HAVE TYPICALLY VERY LITTLE IMPACT ON FASER SENSITIVITY

DARK PHOTONS AT FASER – KINEMATICS

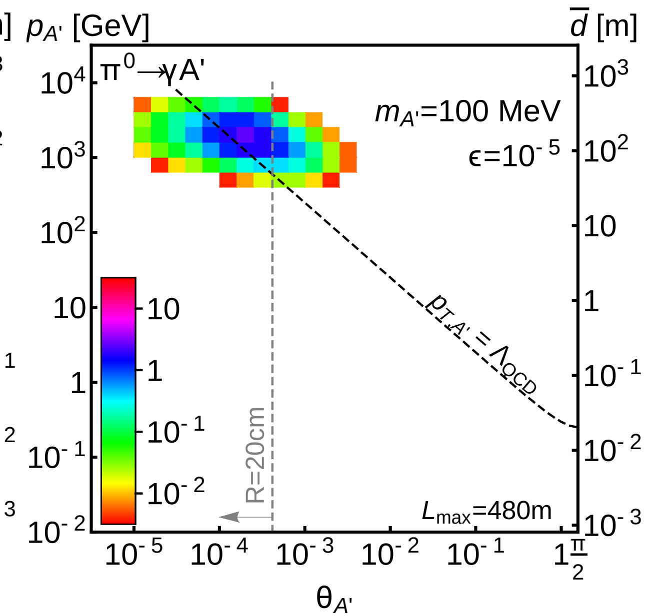
pions at the IP



A's at the IP



A's decaying in FASER



- physics reach insensitive to describing forward particle production with different MCs (EPOS, QGSJET, SIBYLL)
- 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 FASER radius

FORWARD SPECTRUM OF HEAVY MESONS

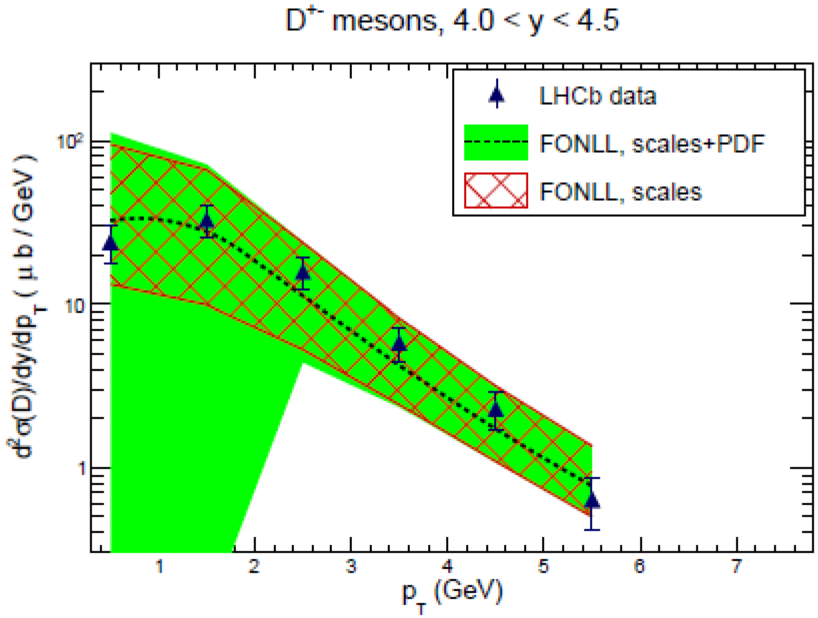
- charmed and beauty meson spectra (e.g. Pythia or semi-analytical approach employed by the FONLL tool)
- analytical fragmentation functions: BCFY (charmed), Kartvelishvili et al. (beauty)
- good agreement with the LHCb data

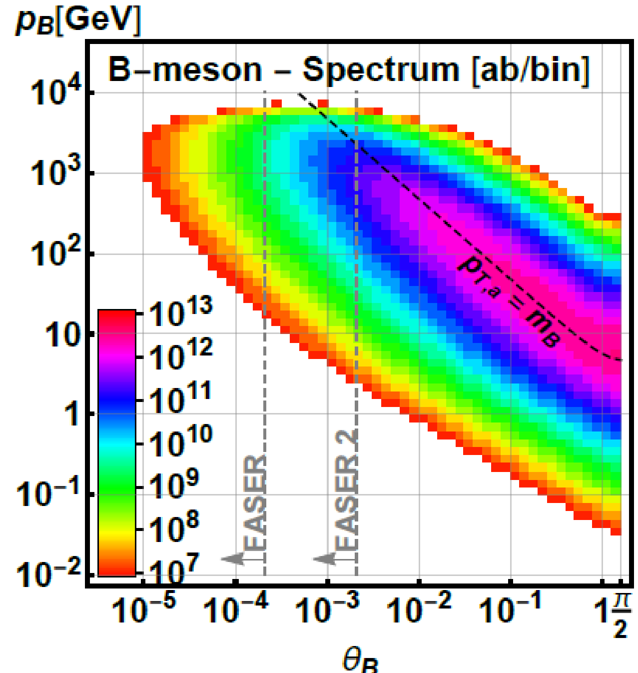
LLPs produced from B mesons in FASER 2

$p_T \sim m_B$ ⇒ larger angular spread ⇒ target for FASER 2

at FASER energies: $\mathbf{N_B/N_\pi \sim 10^{-2}}$ (10^{-7} for typical beam dumps)

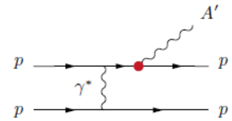
FONLL vs LHCb data for charged D





OTHER PRODUCTION MECHANISMS

BREMSSTRAHLUNG



• simple approach: Fermi-Weizsacker-Williams approx

2 -> 3 process effectively divided into:
splitting p -> p' + A' & hard pp scattering

• form factors should take into account e.g. possible misixng of A' with vector mesons
P. De Niverville, C.-Y. Chen, M. Pospelov, A. Ritz, hep-ph/1609.01770

• Going beyond simple FWW Y.-S. Liu, G.A. Miller 1705.01633

HARD SCATTERING

• Large uncertainties on PDFs for small Q^2 and small x

• Typical $p_T \sim \Lambda_{QCD}$ per parton might play some role (not commonly treated in MC)

• For larger mass of dark photon more reliable results possible, but

• ... heavier A' is produced more isotropically and often decays too early to reach FASER

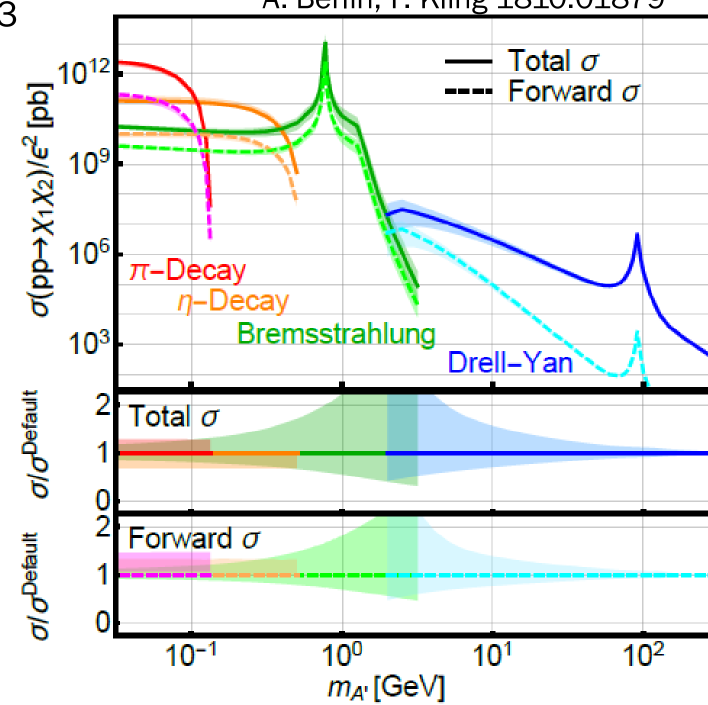
MORE (subdominant for A') e.g.:

- secondary mesons in TAN,
- dark Compton etc.

(also EM shower development in TAN
see also S. S. Chakrabarty, I. Jaegle (in preparation)

- ...

A. Berlin, F. Kling 1810.01879

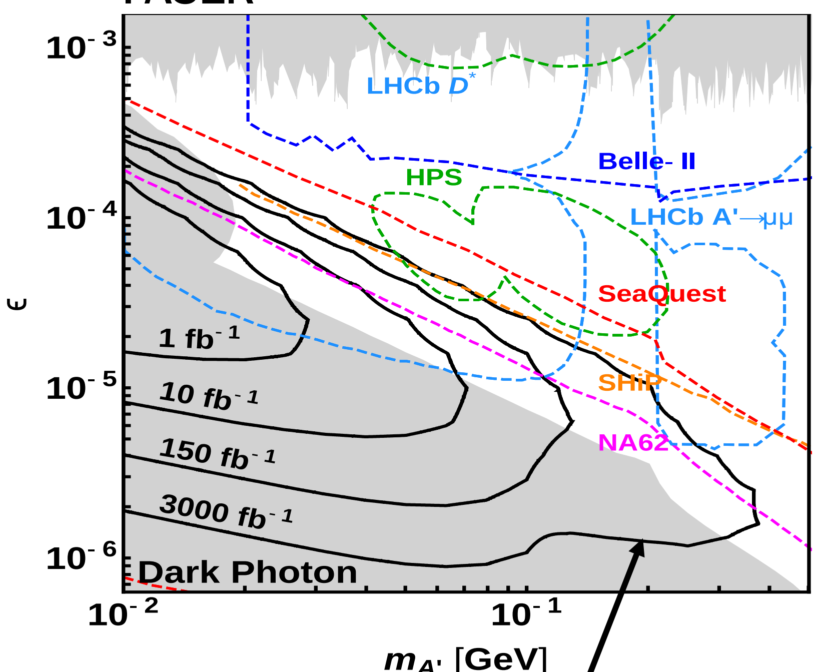


DARK PHOTON REACH

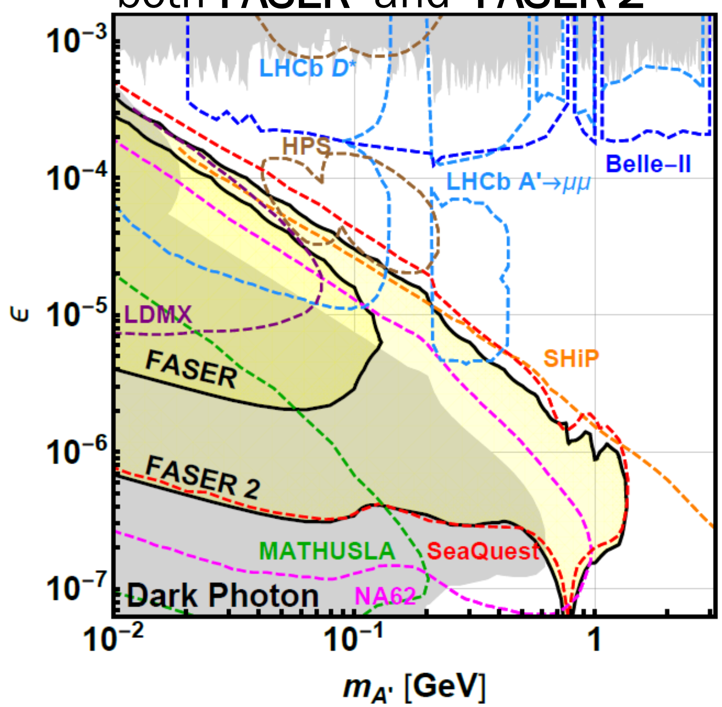
- kinetic mixing with the SM photon: $\epsilon F^{\mu\nu} F'_{\mu\nu}$,
- after field redefinition:

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

FASER



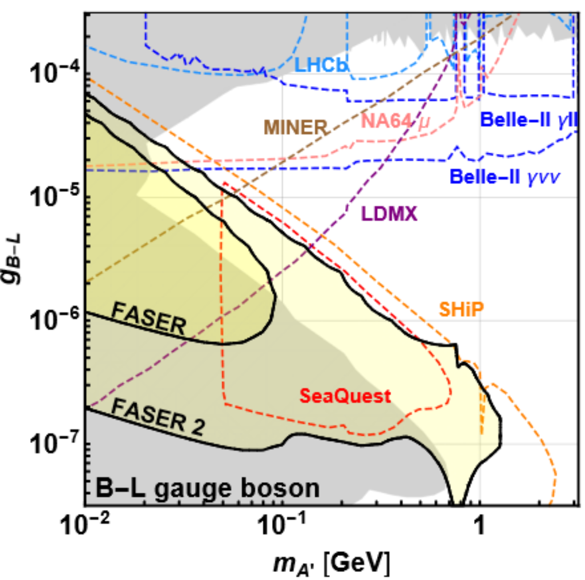
both **FASER** and **FASER 2**



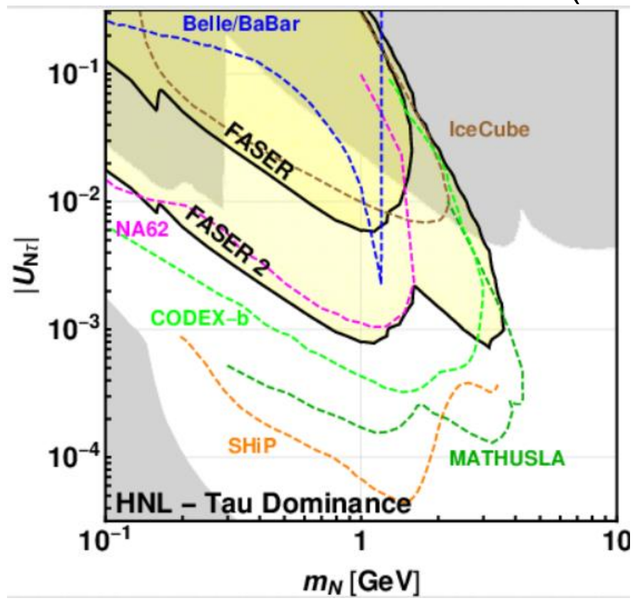
FASER reach
if left for the entire HL-LHC era

SELECTED OTHER REACH PLOTS

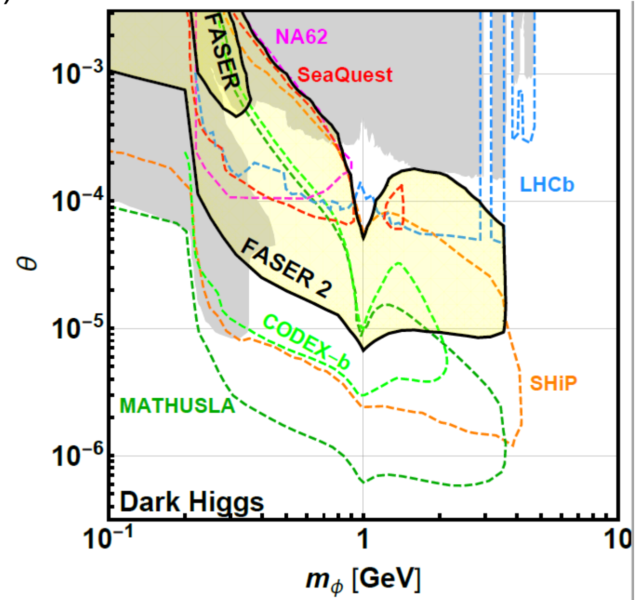
B-L GAUGE BOSON



HEAVY NEUTRAL LEPTON (TAU)



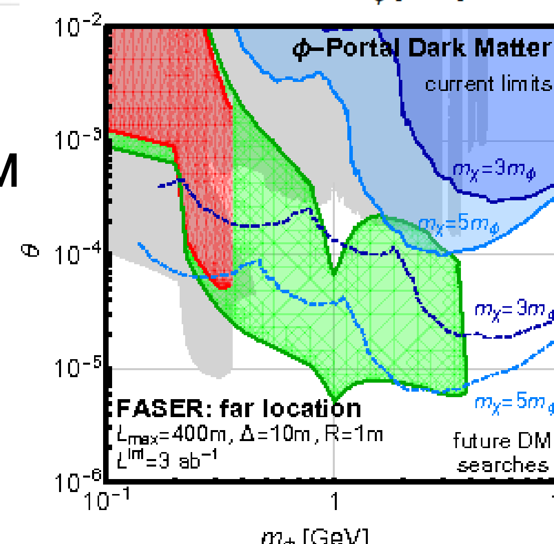
DARK HIGGS BOSON



Example: complementarity between FASER and DM searches for **Dark Higgs-DM portal**

$$\mathcal{L} \supset -m_\phi^2\,\phi^2 - \sin\theta\,\frac{m_f}{v}\,\phi\bar{f}f - \frac{1}{2}\kappa\,\phi\bar{X}X$$

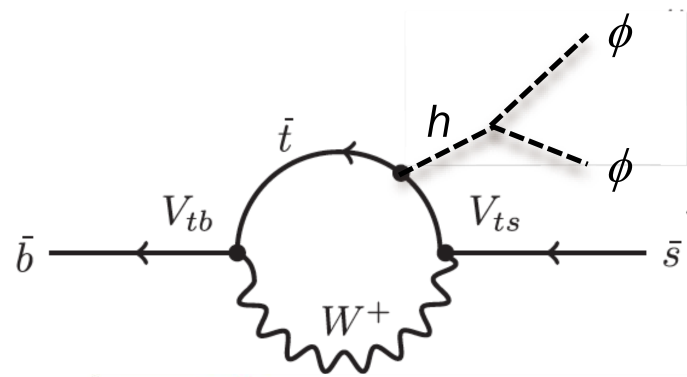
$\langle\sigma v\rangle \sim \kappa^4 \rightarrow \kappa$ fixed by relic density



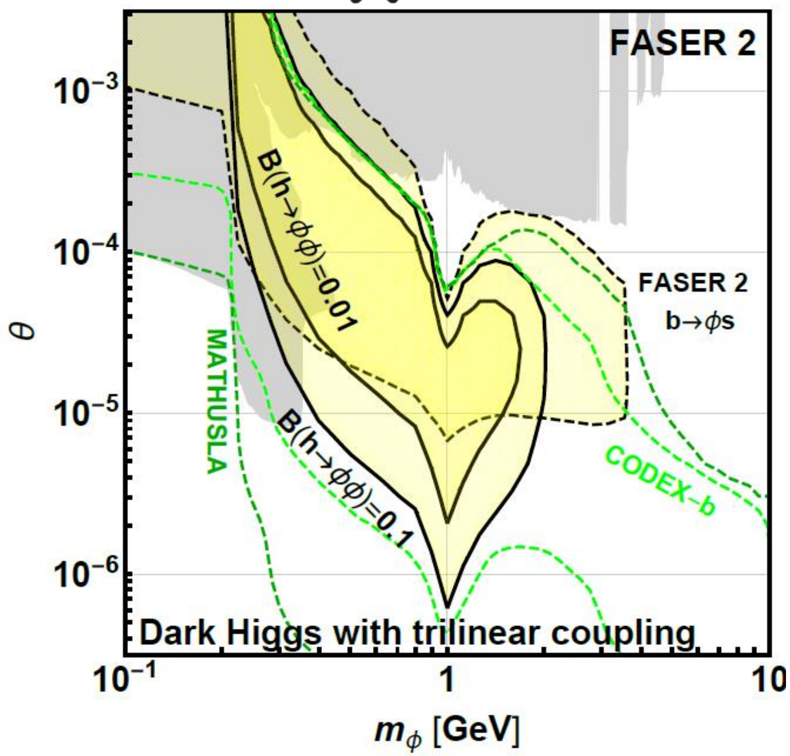
1710.09387, PRD 97 (2018) no.5, 055034

PROBING INVISIBLE DECAYS OF THE SM HIGGS

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

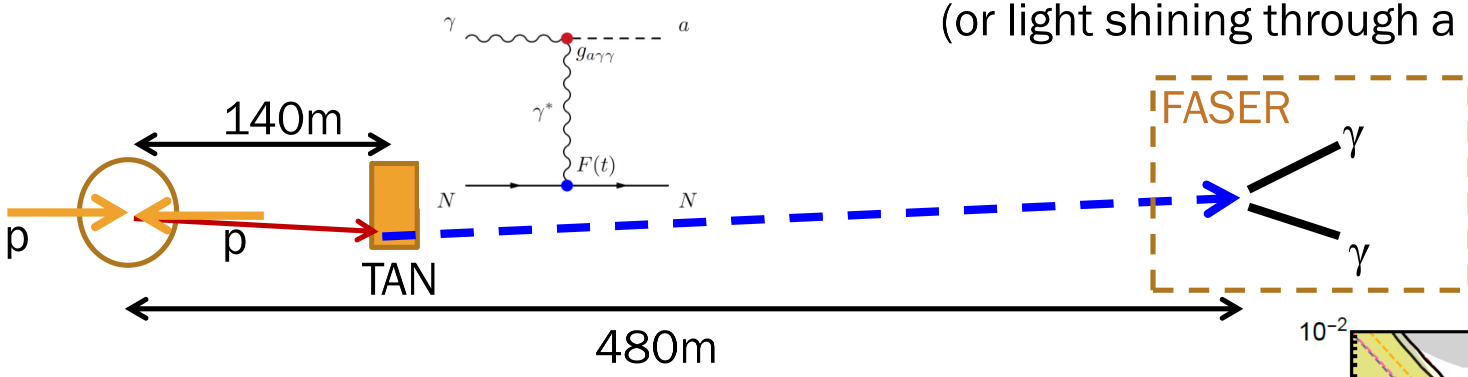


- trilinear coupling
  ➡ invisible Higgs decays h → $\phi\phi$
- far-forward region: efficient production via off-shell Higgs, B → X_sh*(→ $\phi\phi$)
- can extend the reach in θ up to 10^{-6} for B(h → $\phi\phi$)~0.1
- up to ~100s of events



PRODUCTION IN THE TAN (ALP-DIPHOTON)

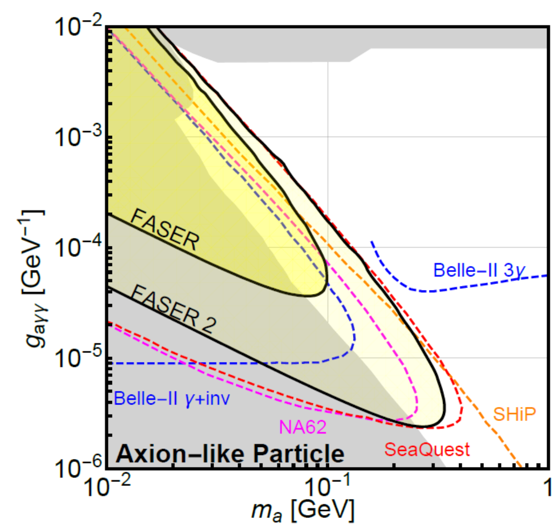
LHC as a high-energy photon beam –dump
(or light shining through a wall exp)



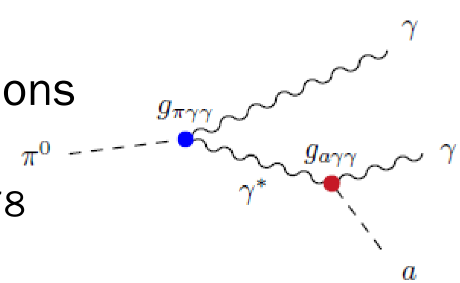
Primakoff process, diff. Cross section

$$\frac{d\sigma_{\rm Prim}}{d\theta_{a\gamma}} = 2\pi\alpha Z^2 F^2(t)\frac{8\Gamma_a}{m_a^3}\frac{p_a^4\sin^3\theta_{a\gamma}}{t^2} = \frac{1}{4}g_{a\gamma\gamma}^2\alpha Z^2 F^2(t)\frac{p_a^4\sin^3\theta_{a\gamma}}{t^2}$$

$$F(t) = \begin{cases} \frac{a^2 t}{1+a^2 t} & t < 7.39\ m_e^2 \\ \frac{1}{1+t/d} & t > 7.39\ m_e^2 \end{cases}$$



Additional prod mechanism: 3-body decays of pions



See also: L. Harland-Lang, J. Jaeckel, M. Spannowsky, hep-ph/1902.04878
D. Aloni, C. Fanelli, Y. Soreq, M. Williams, hep-ph/1093.03586,
B. Dobrich, J. Jaeckel, T. Spadaro, hep-ph/1904.02091

1811.12522, (physics case)

MORE MODELS OF NEW PHYSICS

(table refers to the benchmark scenarios of the Physics Beyond Colliders CERN study group)

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	—	√	√

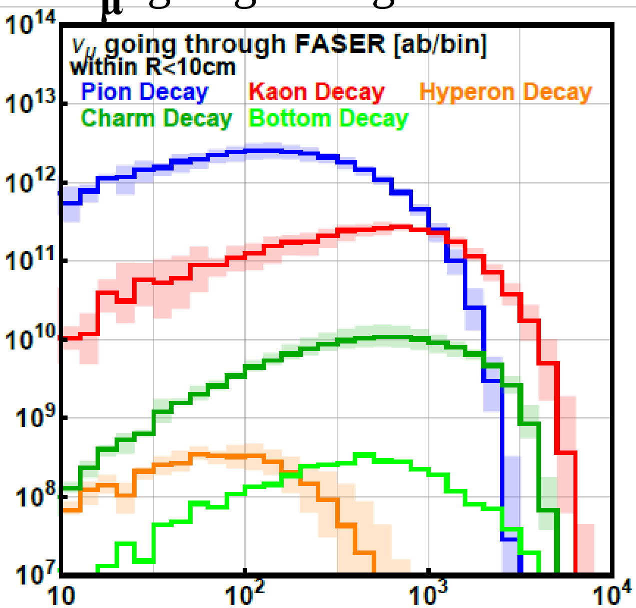
Other models & FASER sensitivity studies e.g.:
- RPV SUSY (D. Drecks, J. de Vries, H.K. Dreiner, Z.S. Wang, 1810.03617)
- Inelastic dark matter (A. Berlin, F. Kling, 1810.01879)

See also
Batell, Freitas, Ismail, McKeen, 1712.10022, Bauer, Foldenauer, Jaeckel, 1803.05466; 1811.12522, Helo, Hirsch, Wang, 1803.02212, deNiverville, Lee 1904.13061, …

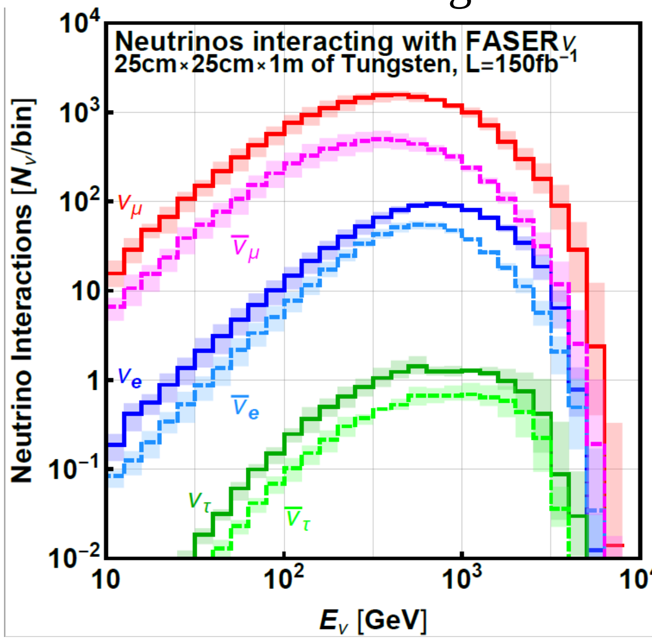
150/fb, 1.2tonne tungsten/emulsion detector

SM NEUTRINOS IN FASER

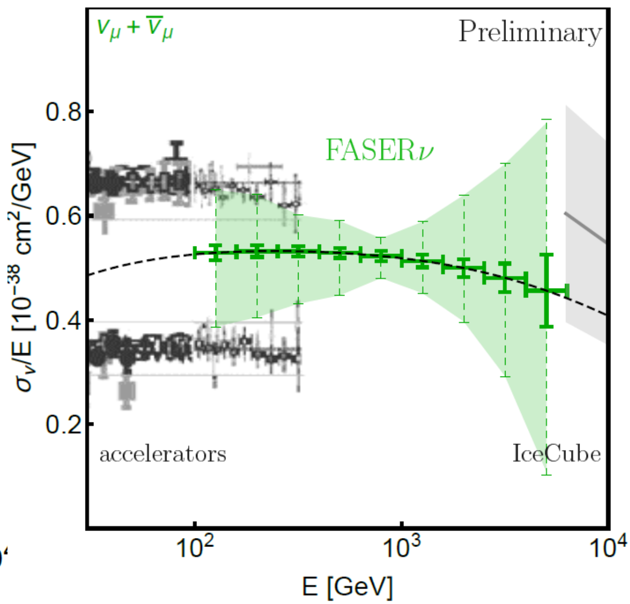
ν_μ going through



interacting



expected measurement precision



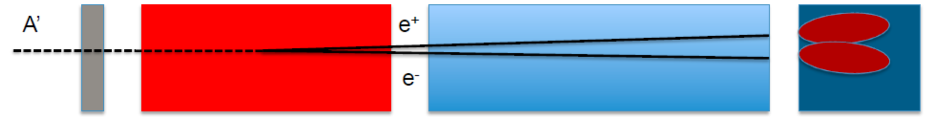
- LHC: lots of forward-going neutrinos
- Currently investigated possibility: install dedicated emulsion detector in front of FASER (**FASERν**)

Potentially thousands of events in FASER**ν**

- Measurement of the neutrino scattering cross section for E_ν ~TeV (currently unexplored regime)
- Possible detection of ~20 high-energy tau neutrino events
- ...and even more BSM opportunities

SM BACKGROUNDS

BACKGROUNDS – SIMULATIONS (FLUKA)



Spectacular signal:

-- two opposite-sign, high energy (few hundred 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
- The radiation level in TI18 is low ($<10^{-2}$ Gy/year), encouraging for detector electronics
- Showers in the nearby Disperssion Suppresor are suppressed due to the dispersion function of the machine at the FASER location.
- Beam-gas is suppressed due to the excellent vacuum of the LHC
- Particles produced at the IP are suppressed due to the 100m of rock in front of FASER (and the LHC magnets)
- Muons coming from the IP – front veto layers

Expected trigger rate ~650 Hz

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

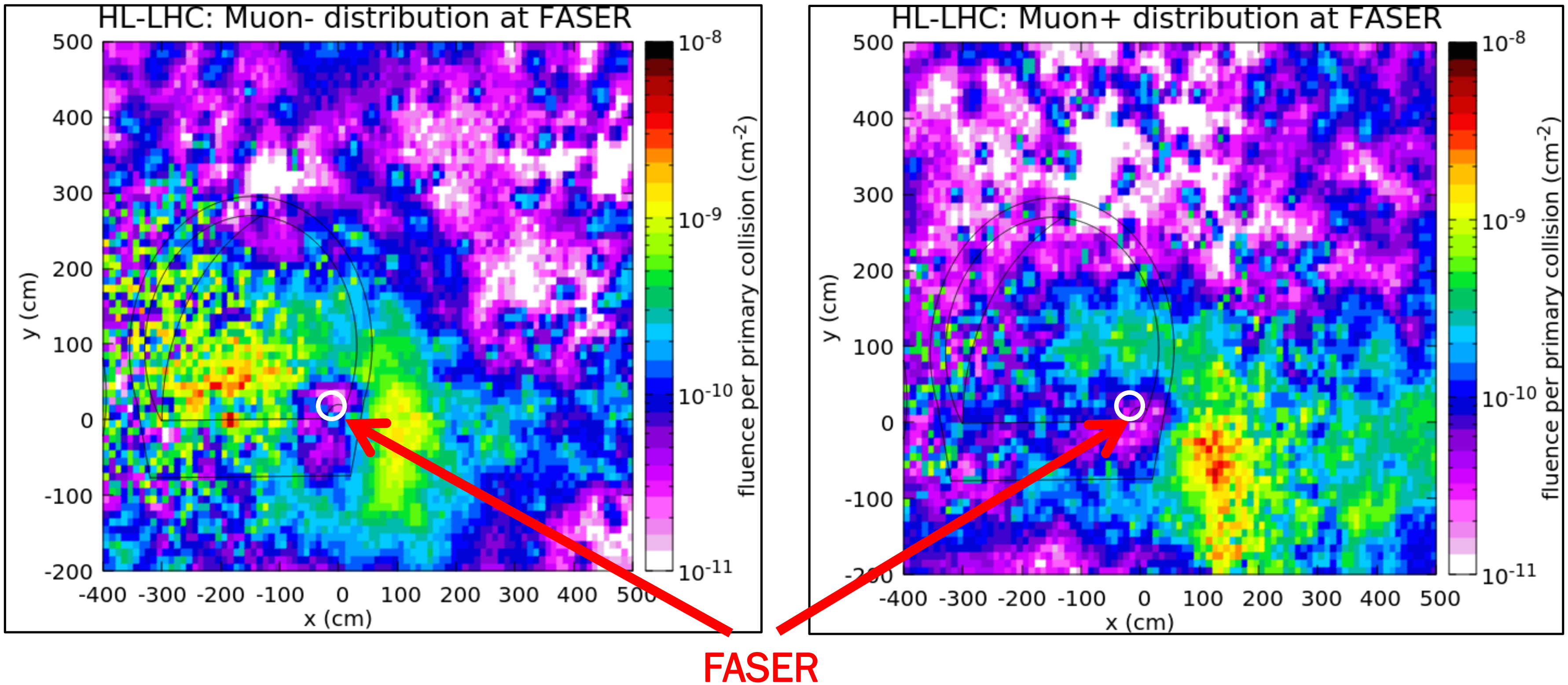
study by the members of the CERN FLUKA team:

	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	$6.1\cdot10^{-9}$	0.02	$5.8\cdot10^{-10}$	0.002	$6.8\cdot10^{-11}$
$\mu-$	0.40	$1.3\cdot10^{-8}$	0.22	$7.4\cdot10^{-9}$	0.14	$4.6\cdot10^{-9}$
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

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

BACKGROUNDS – SIMULATIONS (2)

Cross section of the tunnel containing FASER

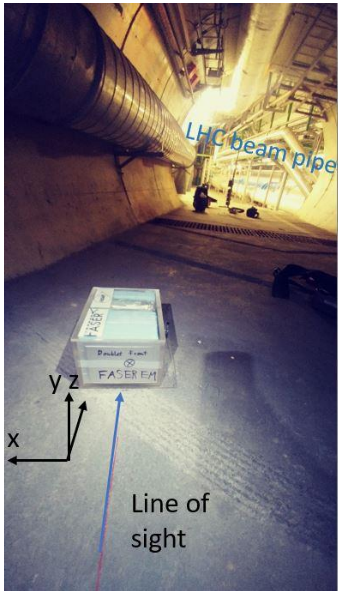


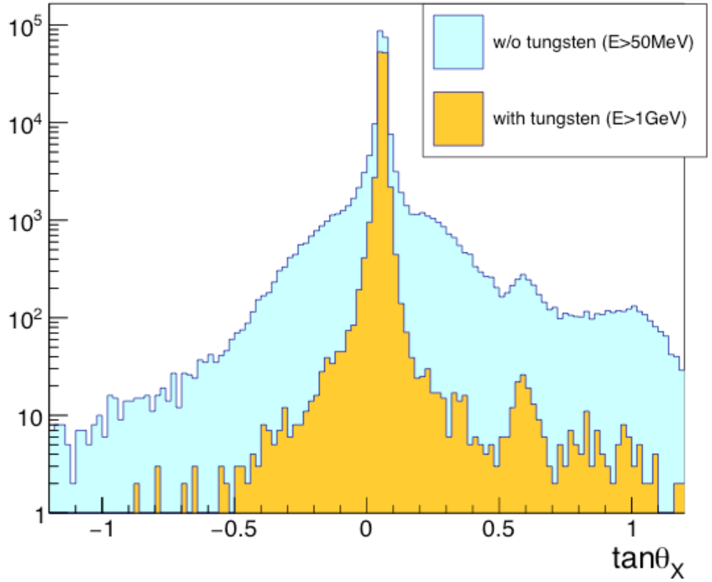
At FASER location:

muon flux reduced along the beam collision axis (helpful role of the LHC magnets)

BACKGROUNDS – IN-SITU MEASUREMENTS

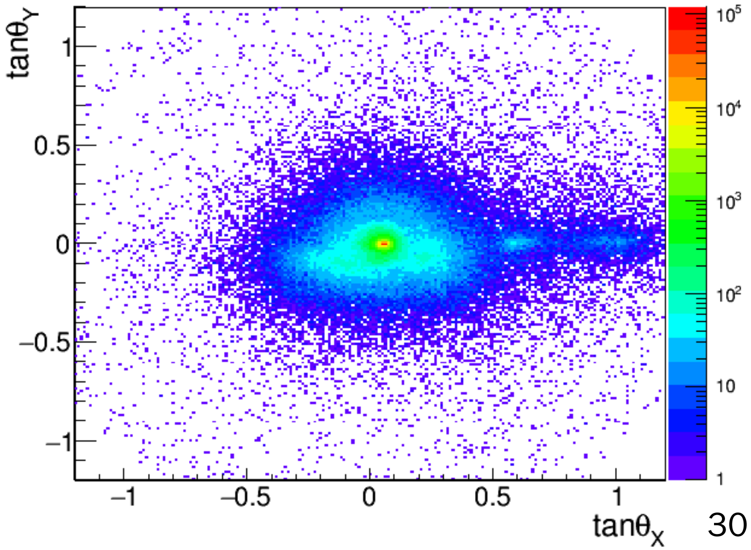
- Emulsion detectors – focusing on a small region around the beam axis (FASER location)
- TimePix Beam Lumi Monitors (signal correlated with lumi in IP1)
- BatMons (battery-operated radiation monitors)





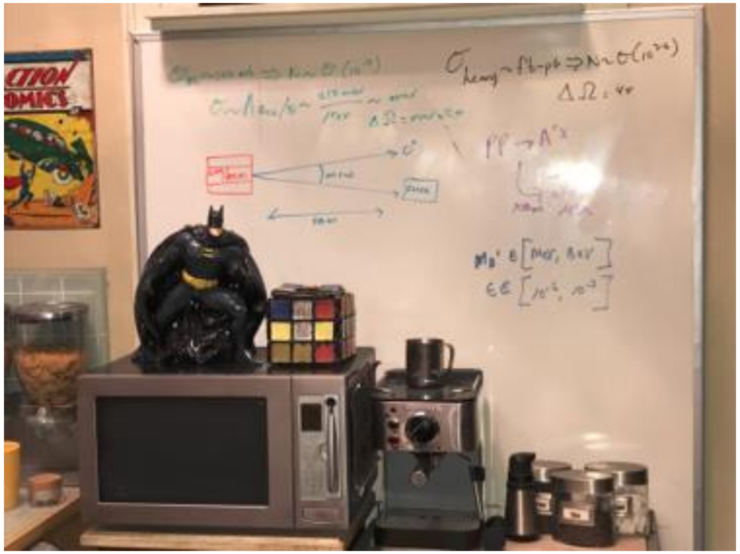
Results are consistent with FLUKA simulations

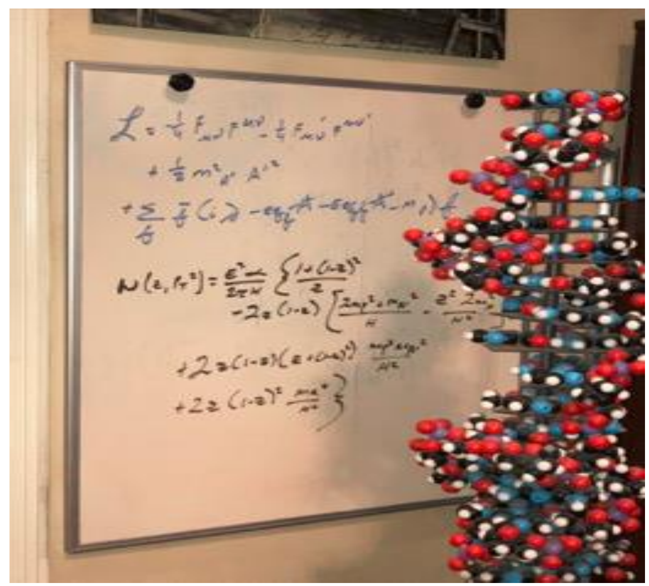
	beam [fb^{-1}]	normalized flux, all [fb cm^{-2}]	normalized flux, main peak [fb cm^{-2}]
TI18	2.86	$(2.6 \pm 0.7) \times 10^4$	$(1.2 \pm 0.4) \times 10^4$
TI12	7.07	$(3.0 \pm 0.3) \times 10^4$	$(1.9 \pm 0.2) \times 10^4$
FLUKA, E>10 GeV	2×10^4		



PRACTICALLY ZERO BG SEARCH

FASER IN POPULAR CULTURE

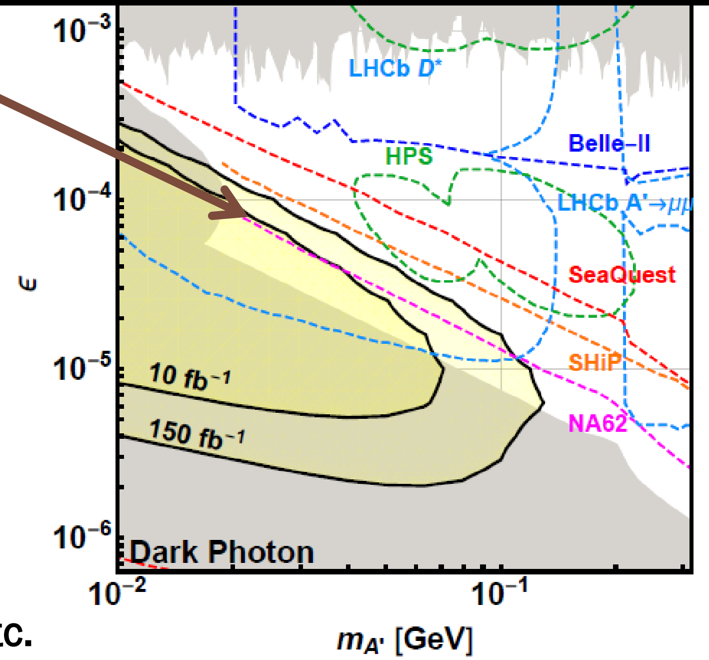




related article

LA Times

New physics reach even after first 10fb^{-1} (end of 2021?)



CONCLUSIONS

- Light Long-lived Particles (LLPs) – exciting new physics !!!
- **FASER** is a new, small and inexpensive experiment to be placed at the LHC to search for light long-lived particles to complement the existing experimental programs at the LHC, as well as other proposed experiments,
- **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,
- Measurments of SM neutrinos

Many thanks for the support from the Heising-Simons, and Simons Foundations, as well as from CERN!

- Timeline:

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

– R = 10 cm, L = 1.5 m, Target dark photons, B-L gauge bosons, ALPs, HNLs(τ)...

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

– R = 1 m, L = 5 m, Full physics program: dark vectors, ALPs, dark Higgs, HNLs...

BACKUP

ACKNOWLEDGEMENTS

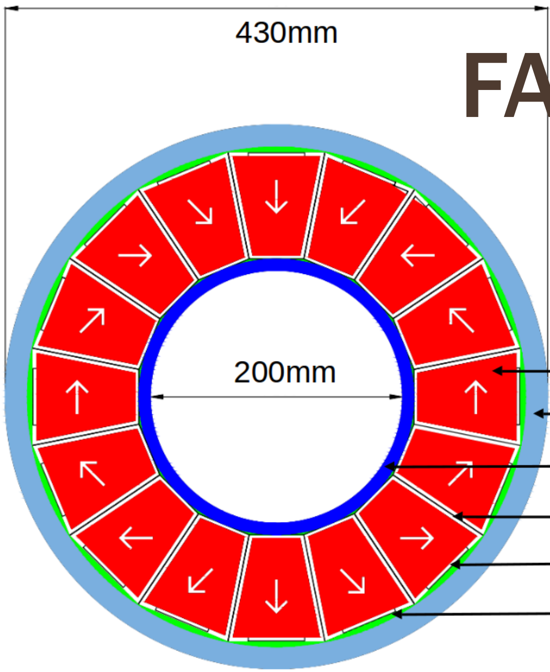
The FASER Collaboration has also received essential support from many others

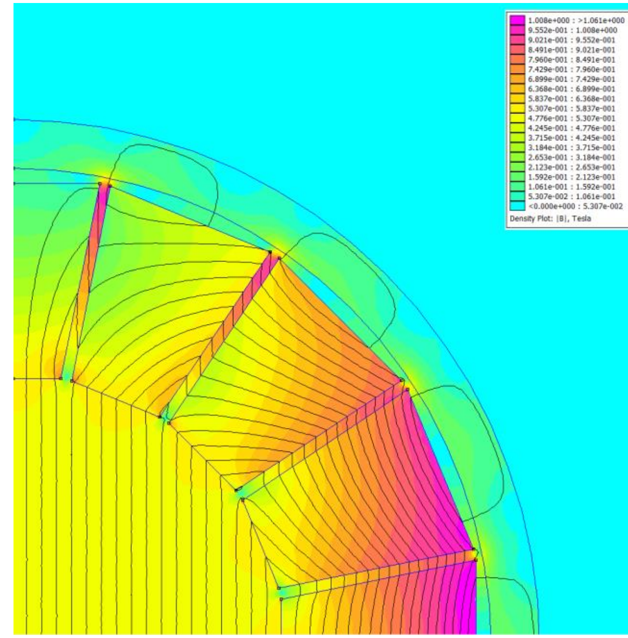
We are grateful to the ATLAS SCT project and the LHCb Calorimeter project for letting us use spare modules as part of the FASER experiment. In addition, FASER acknowledges the invaluable assistance from the CERN Physics Beyond Colliders study group; the LHC Tunnel Region Experiment (TREX) working group; the LHC Machine Committee; the LS2 Committee and the LHCC. FASER gratefully acknowledges the contributions from:

- Jonathan Gall, John Osborne (civil engineering);
- Liam Dougherty, Francisco Galan (integration);
- Pierre Thonet (magnets);
- Francesco Cerutti, Marta Sabate Gilarte (FLUKA simulation and background characterization);
- Salvatore Danzeca, Serge Chalaye (radiation measurements);
- James Storey, Swann Levasseur (beam instrumentation);
- Pierre Valentin, Tobias Dobers (survey);
- Caterina Bertone, Serge Pelletier, Frederic Delsaux (transport);
- Gael Girardot, Olivier Crespo-Lopez, Yann Maurer, Maria Papamichali (LS2 works);
- Marzia Bernardini, Anne-Laure Perrot, Katy Foraz, Markus Brugger (LHC access and schedule);
- Marco Andreini, Olga Beltramello, Thomas Otto (safety);
- Dave Robinson (ATLAS SCT), Yuri Guz (LHCb calorimeters);
- Stephen Wotton, Floris Keizer (SCT QA system and SCT readout);
- Burkhard Schmitt, Raphael Dumps, Sune Jacobsen, Giovanna Lehmann (CERN-DT contributions);
- Mike Lamont, Andreas Hoecker, Ludovico Pontecorvo, Christoph Rembser (useful discussions).

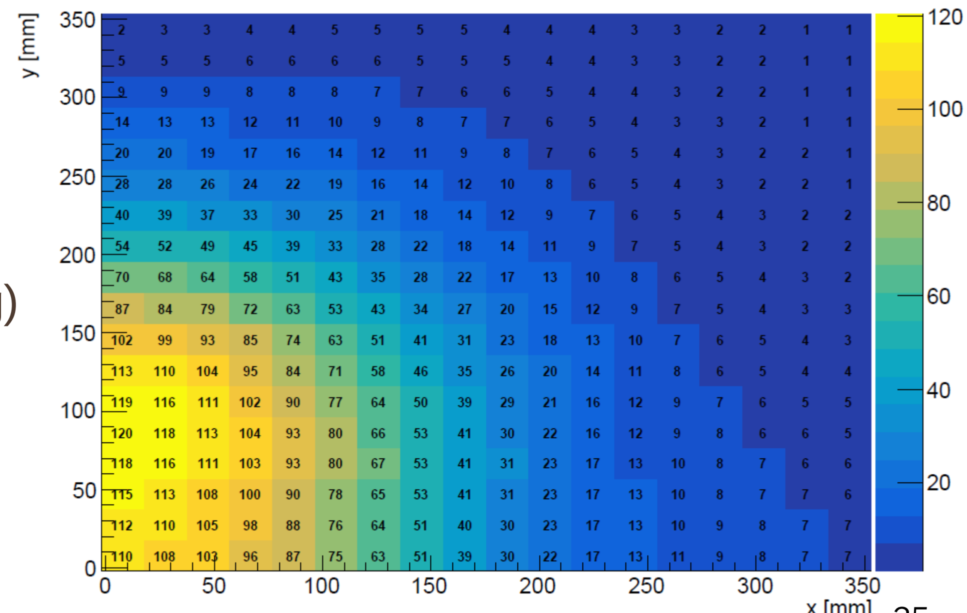
Thanks also to the CERN management for their support!

FASER MAGNET





|B| [mT] at z=1100 mm

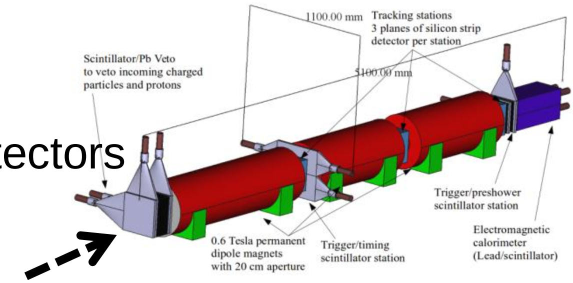


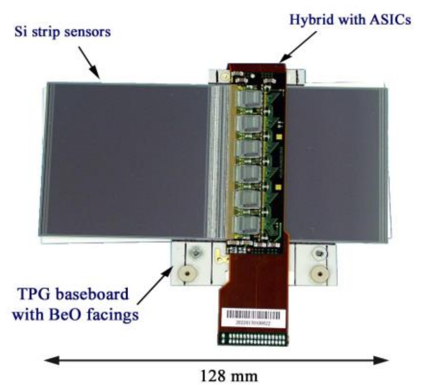
- 0.55T permanent dipole magnets based on the Halbach array design
  - LOS to pass through the magnet center
  - minimum digging to the floor in TI12
  - minimized needed services (power,cooling)

- manufacture: CERN magnet group
- stray field around scintillator PMTs ~5mT
  → shielding (mu-metal)

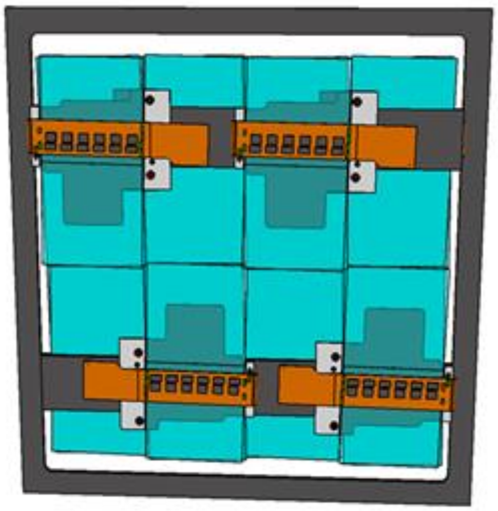
FASER TRACKING STATIONS

- The FASER Tracker will be made up of 3 tracking stations
- Each containing 3 layers of double sided silicon micro-strip detectors
- Spare ATLAS SCT modules will be used
  - 80µm strip pitch, 40mrad stereo angle
  - Many thanks to the ATLAS SCT collaboration!
- 72 SCT modules needed for the full tracker
- Due to the low radiation in TI12 the silicon can be operated at room temperature, but the detector needs to be cooled to remove heat from the on-detector ASICs
- Tracker readout using FPGA based board from University of Geneva (already used in Baby MIND neutrino experiment)

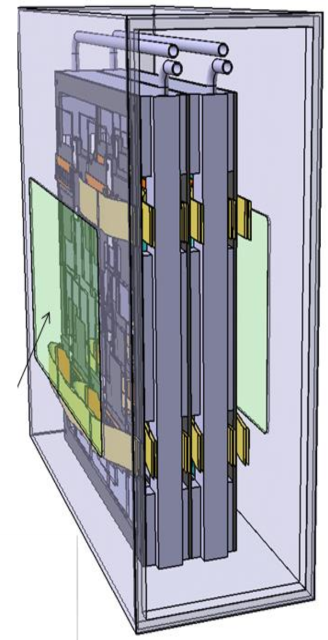




SCT module



Tracking layer

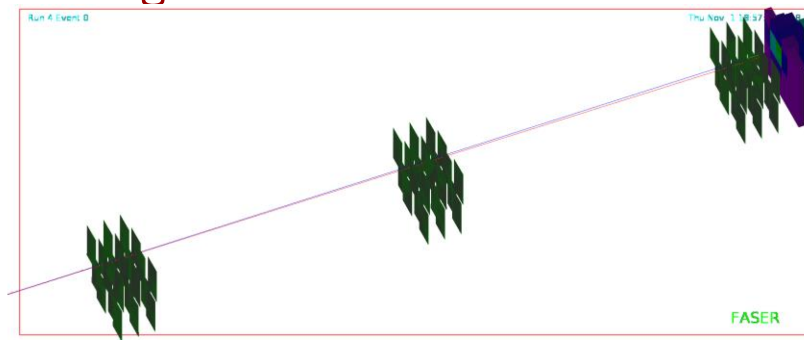


Tracking station

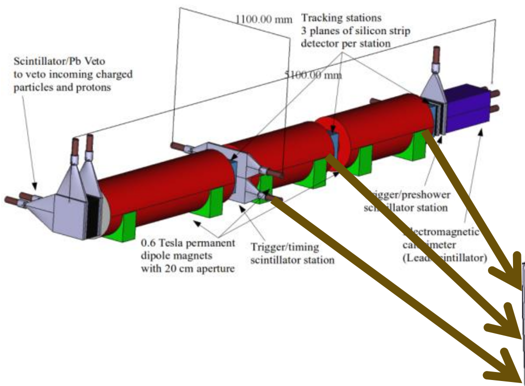
EXPECTED PERFORMANCE (TRACKS)

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

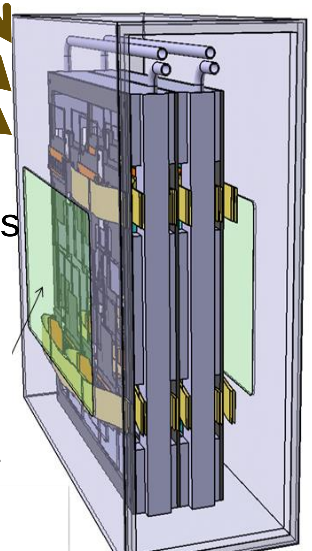
In the following we assume 100% detection efficiency for a better comparison with other experiments



Ongoing work on full detector simulations

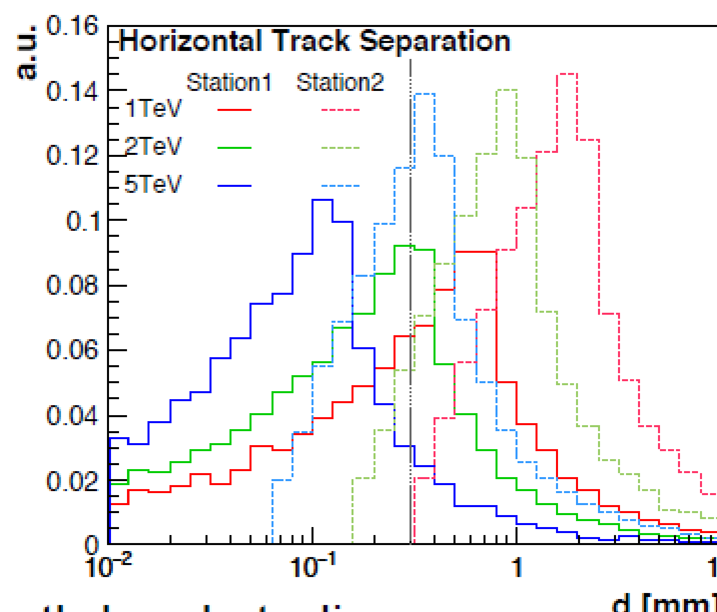


tracking stations



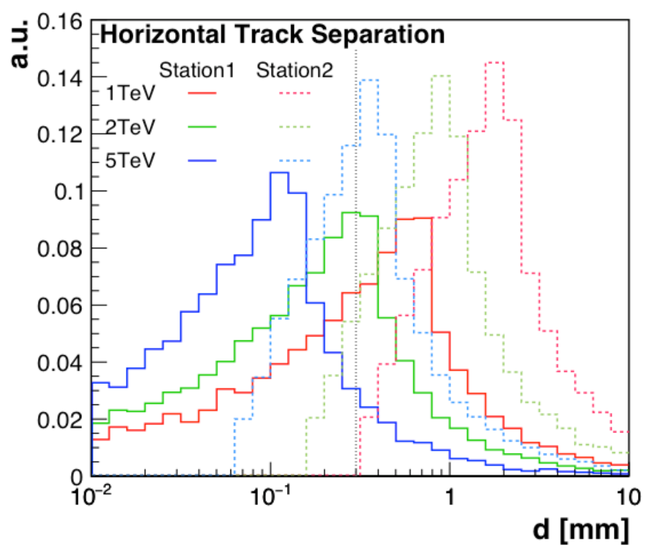
- The FASER Tracker will be made up of 3 tracking stations
- Each containing 3 layers of double sided silicon micro-strip detectors
- Spare ATLAS SCT modules will be used
- 72 SCT modules needed for the full tracker

CHARGED TRACK SEPARATION EFFICIENCY

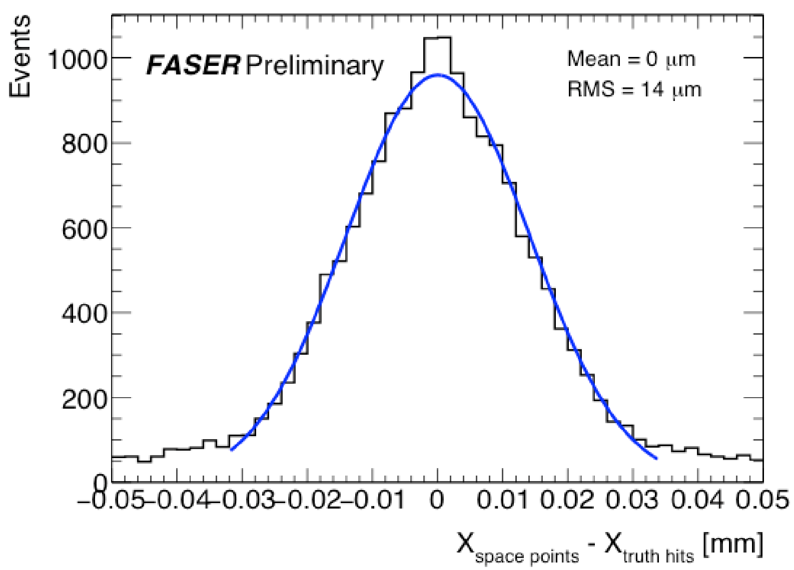


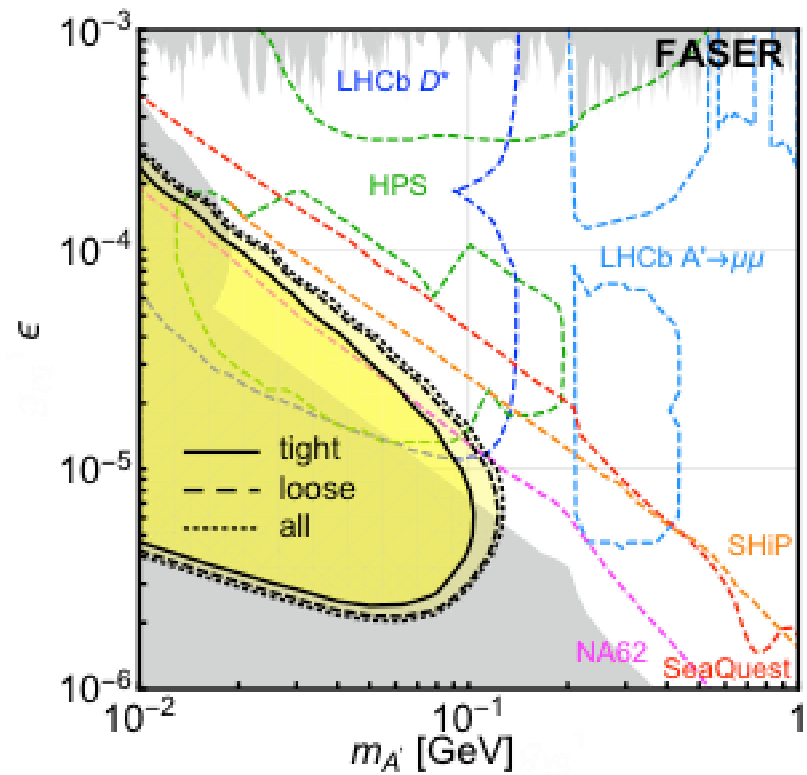
truth level studies

MORE ABOUT TRACK SEPARATION

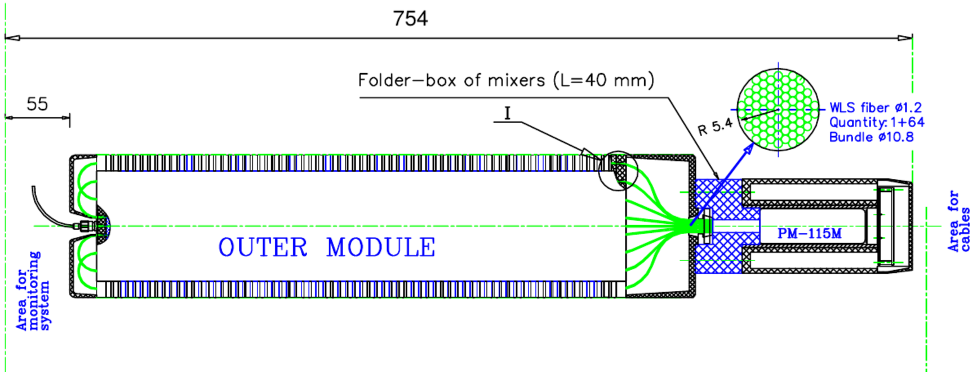


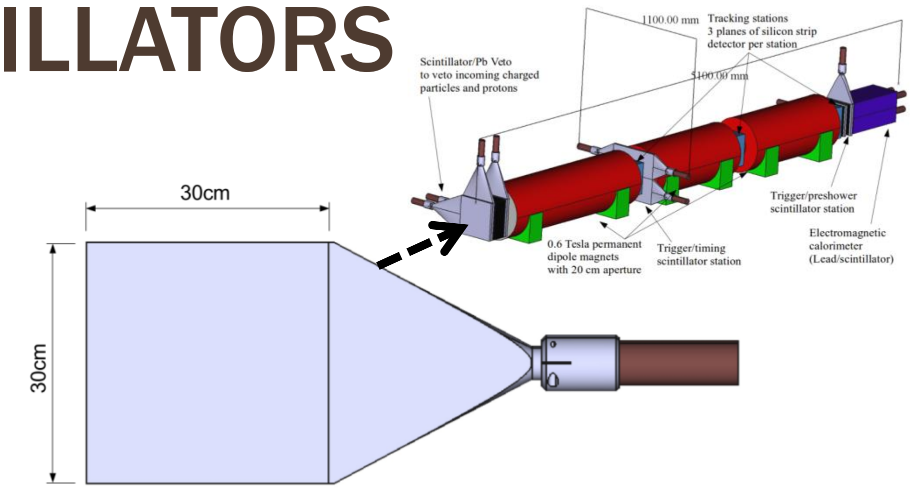
GEANT 4





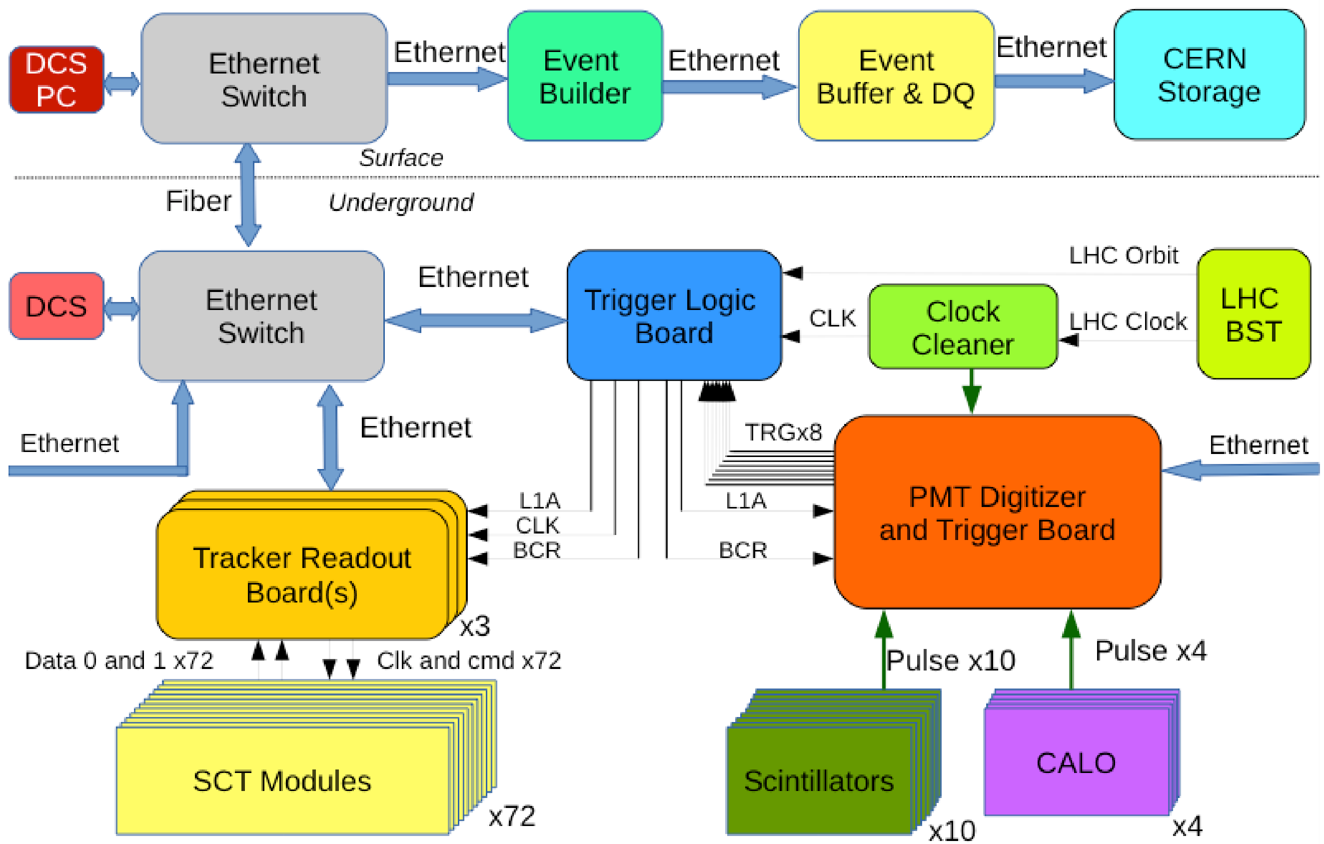
CALORIMETER & SCINTILLATORS





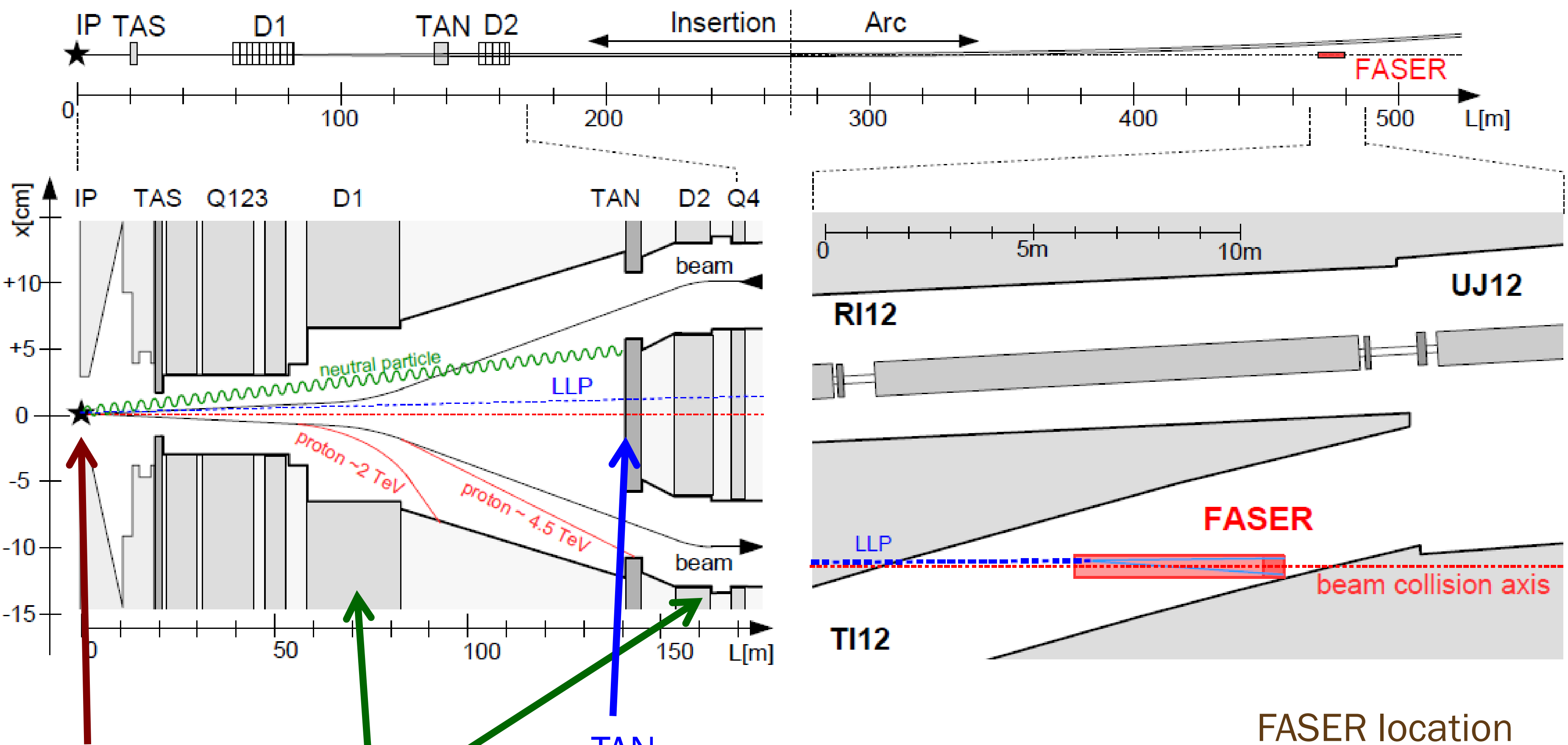
- FASER will have an ECAL:
  measuring the EM energy in the event (up to 1% accuracy in energy ~1 TeV)
- Will use 4 spare LHCb outer ECAL modules
  - Many thanks to LHCb Collaboration for allowing us to use these!
  - 66 layers of lead/scintillator (2mm lead, 4mm plastic scintillator)
    - 25 radiation lengths long
    - no longitudinal shower information
    - Resolution will degrade at higher energy due to not containing full shower in calorimeter
- Scintillators used for vetoing charged particles entering the decay volume, for triggering and as a preshower
  - To be produced at CERN scintillator lab
  - Vetoing: achievable extremely efficient charged particle veto (eff>99.99%)
  - Trigger: also timing the signal with respect to timing of the pp interactions
  - Preshower: thin radiator in front, photon showering (disentangling from ν interactions in ECAL)

FASER TDAQ



- Trigger rate expected to be ~600 Hz, dominated by muons from IP.
- Trigger will be an OR of triggers from scintillators and from the ECAL.
- Largely independent of ATLAS; only need to know bunch crossing time and ATLAS luminosity for off-line analysis.

FASER AND SURROUNDING LHC INFRASTRUCTURE



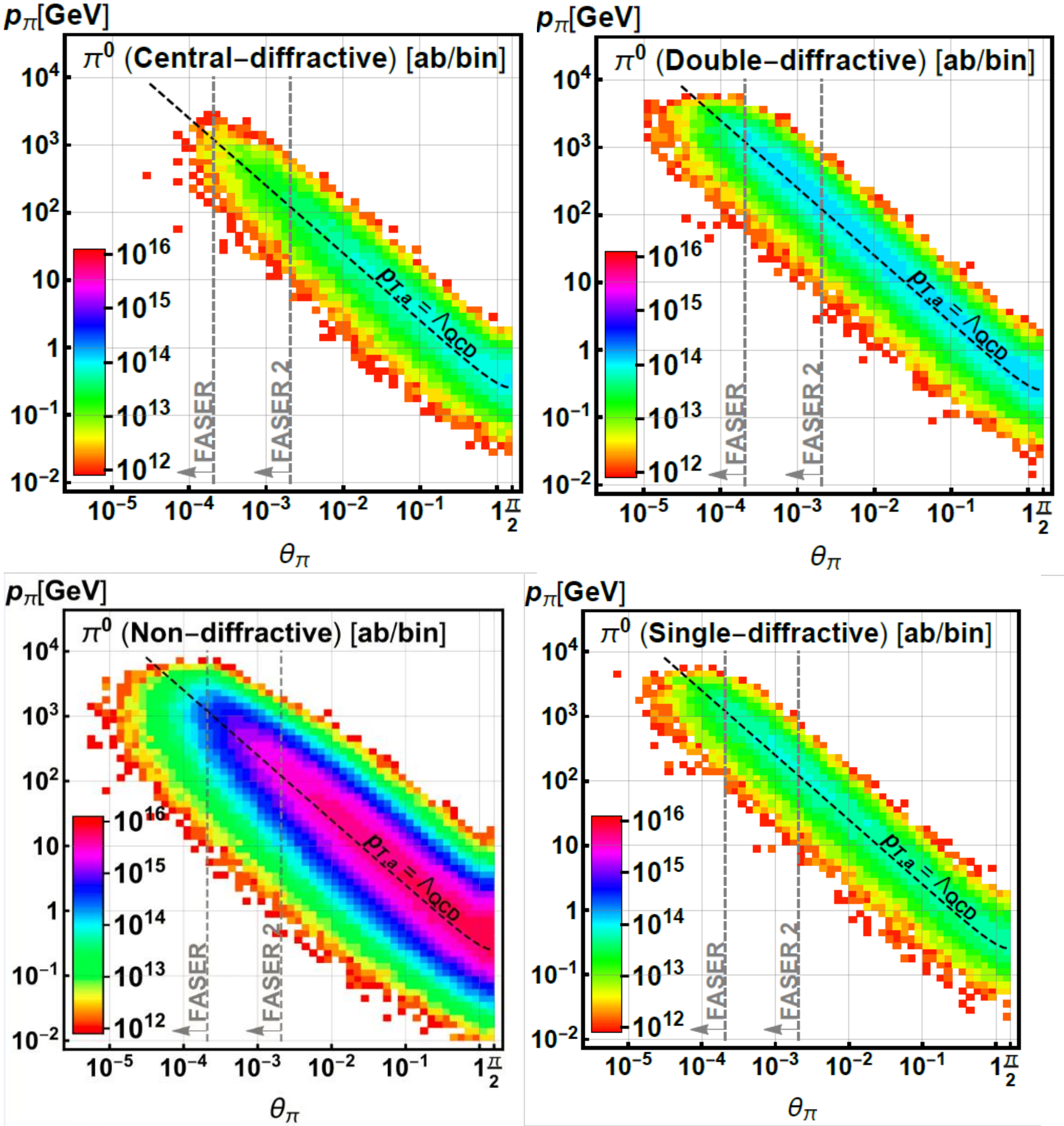
ATLAS Interaction Point (IP)

Strong LHC dipole magnets

TAN
Neutral Particle Absorber
~140m away from the IP

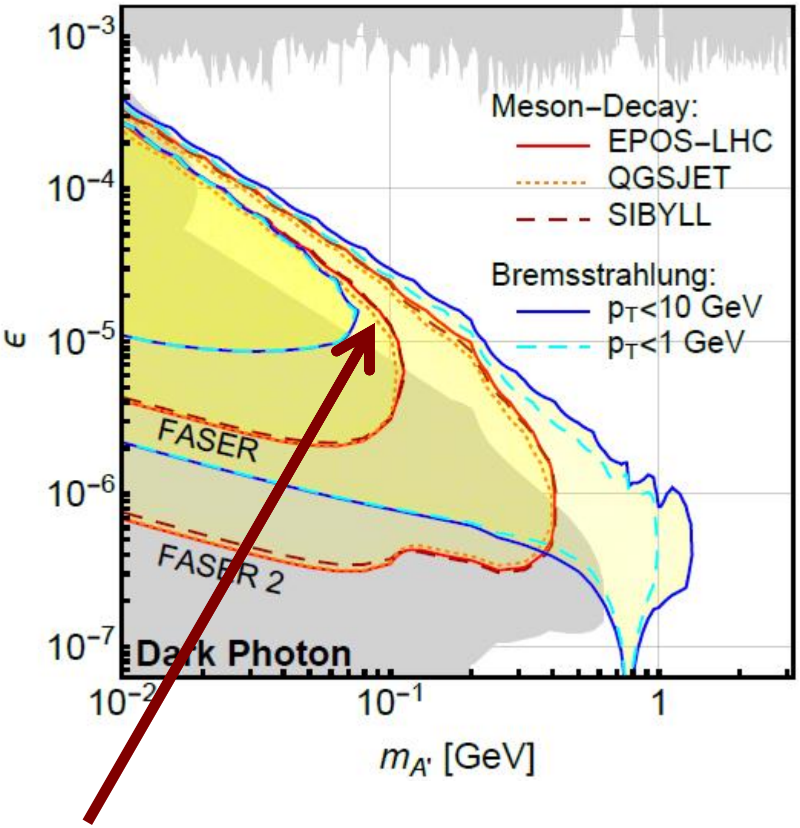
FASER location
tunnel TI12
~480m away from the IP

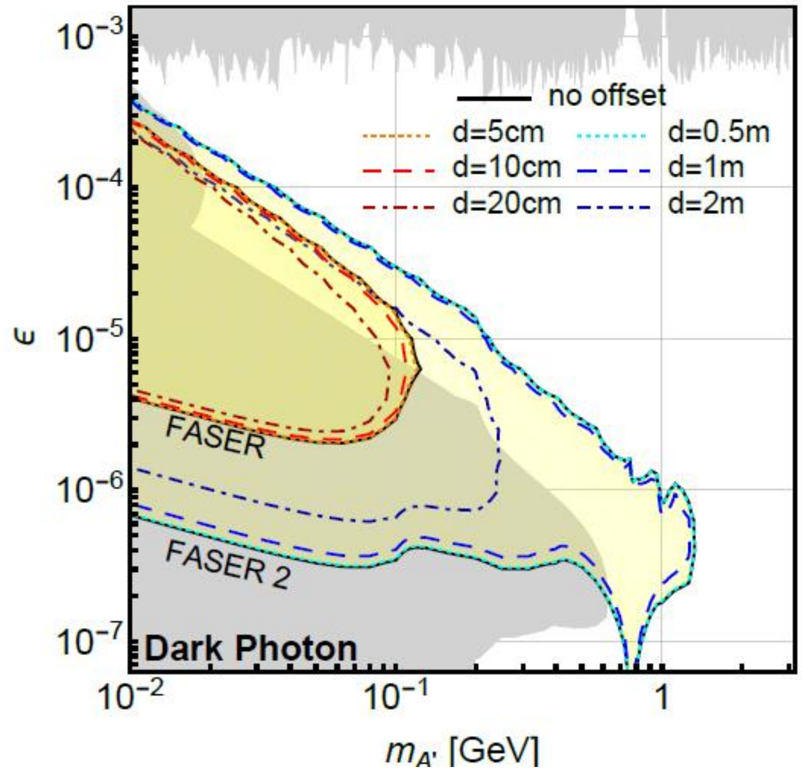
INELASTIC P-P COLLISIONS



EPOS-LHC

DARK PHOTON REACH – VARIOUS MC TOOLS & OFFSET





Almost impreceptible differences in reach for various MC tools

FASER reach unaffected by a small offset as long as the beam collision axis goes through the detector

$\bar{d} \sim \varepsilon^{-2}$

$$N_{\rm sig} \propto \mathcal{L}^{\rm int}\, \epsilon^2\, e^{-L_{\rm min}/\bar{d}} \quad \text{for} \quad \bar{d} \ll L_{\rm min}$$

no of events grows exponentially with a small shift in ε

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

$\Rightarrow$ 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