Looking forward to new physics and neutrinos at the LHC

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AstroCeNT

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OUTLINE

- Motivation & Fundamentals

- FASER: **F**orw**A**rd **S**earch **E**xpe**R**iment at the LHC (idea and basic detector design)

- Far-forward BSM physics at the LHC
  - new physics production in the far-forward region of the LHC
  - selected BSM models
  - BSM particle production away from the ATLAS IP,

- High-Energy neutrino physics at the LHC

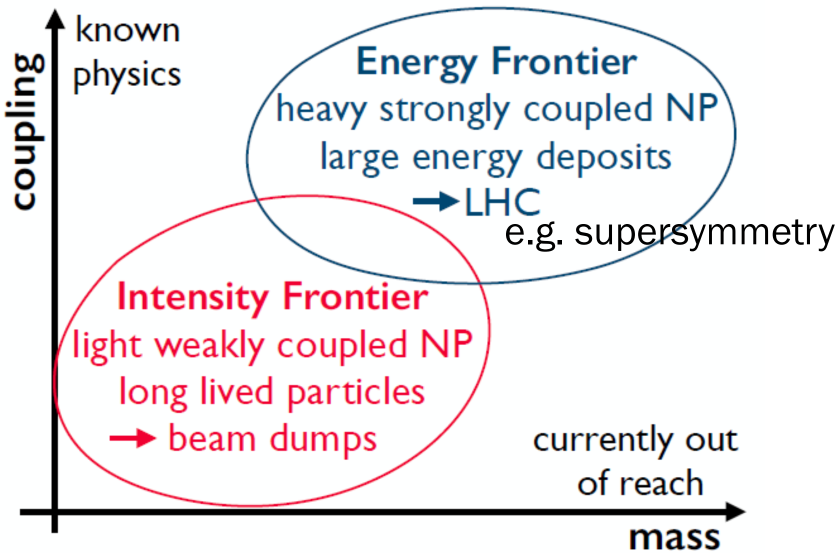
- Remarks about the SM backgrounds

- Additional opportunites
  - DM direct detection at the LHC
  - Forward Physics Facility

- Concluding remarks

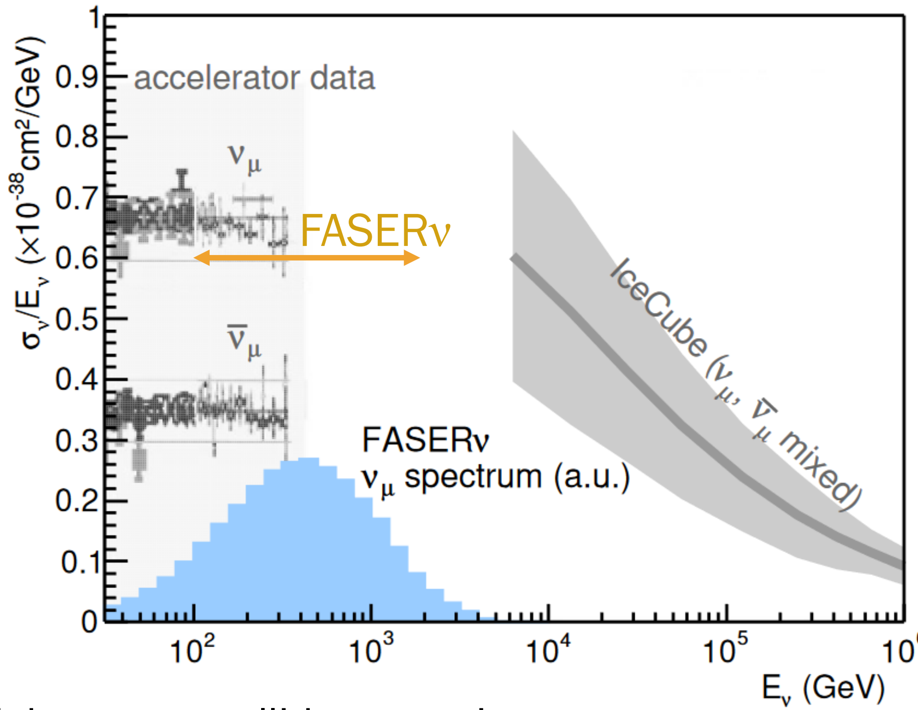
MOTIVATION

LIGHT NEW PHYSICS



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

LIGHT „KNOWN" PHYSICS



High-energy collider neutrinos:
-- first neutrino measurements at the LHC !
-- ~TeV neutrinos remain unexplored
-- any new tau neutrinos ν_τ highly welcome
-- other possibilities:
charm-associated ν interactions
-- some room for new physics

FUNDAMENTAL EFFORTS

BSM: Light and Long-lived Particles
Physics Beyond Colliders at the LHC
(lots of theory studies,
growing experimental effort)

Forward SM & cosmic-ray physics
LHC WG on Forward Physics and diffraction
(experiments, MC tools, theory)

High-energy neutrino physics
- Emulsion Cloud Chamber (ECC) already tested in OPERA
- Neutrino MC generators (GENIE, NuWro…), will be improved with new data

More opportunities:
- Muon physics
- Direct DM detection
- Milli-charged particles
- …

Far-forward physics program at the LHC

Run 3: FASER experiment
HL-LHC opportunities:
FASER 2,
Forward Physics Facility
(to host more exps.)
J. L. Feng, F. Kling etal, Snowmass 2021 LoI

FASER EXPERIMENT

J.L. Feng, I. Galon, F. Kling, ST, 1708.09389
FASER Collaboration: 1811:10243, 1812.09139
1908.02310, 2001.03073

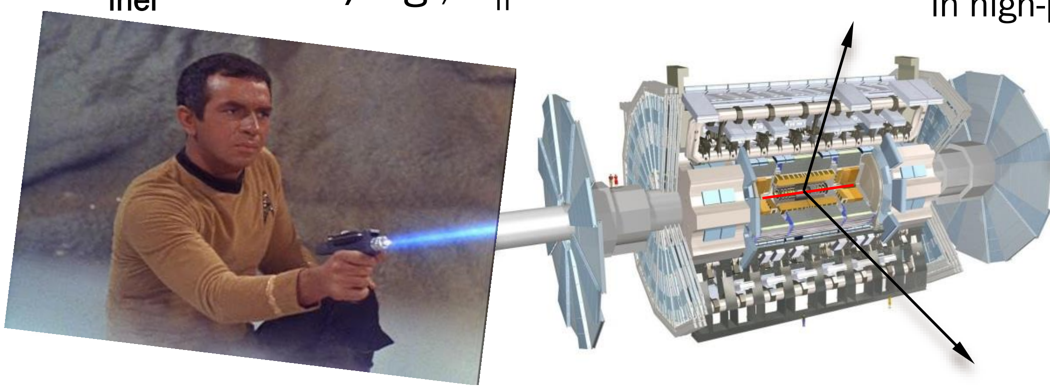
FASER - IDEA

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)

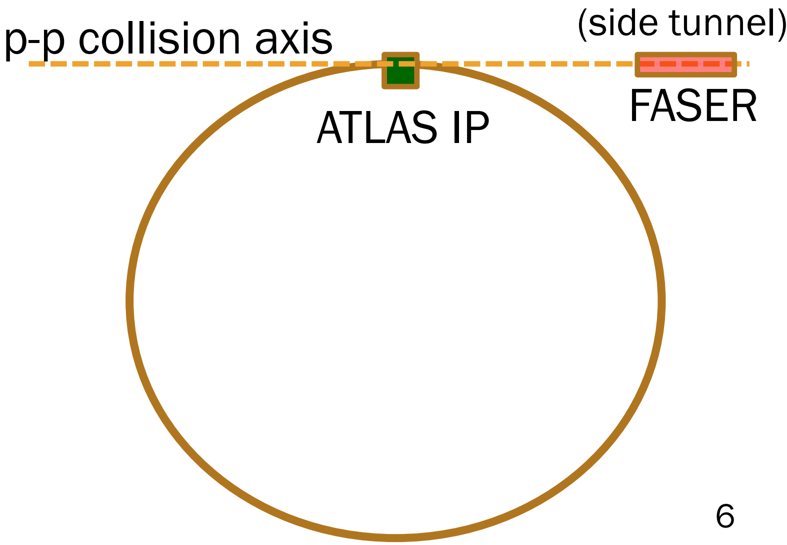


new physics & neutrinos

FASER

π, K, D, B, ... → LLP
& other prod processes

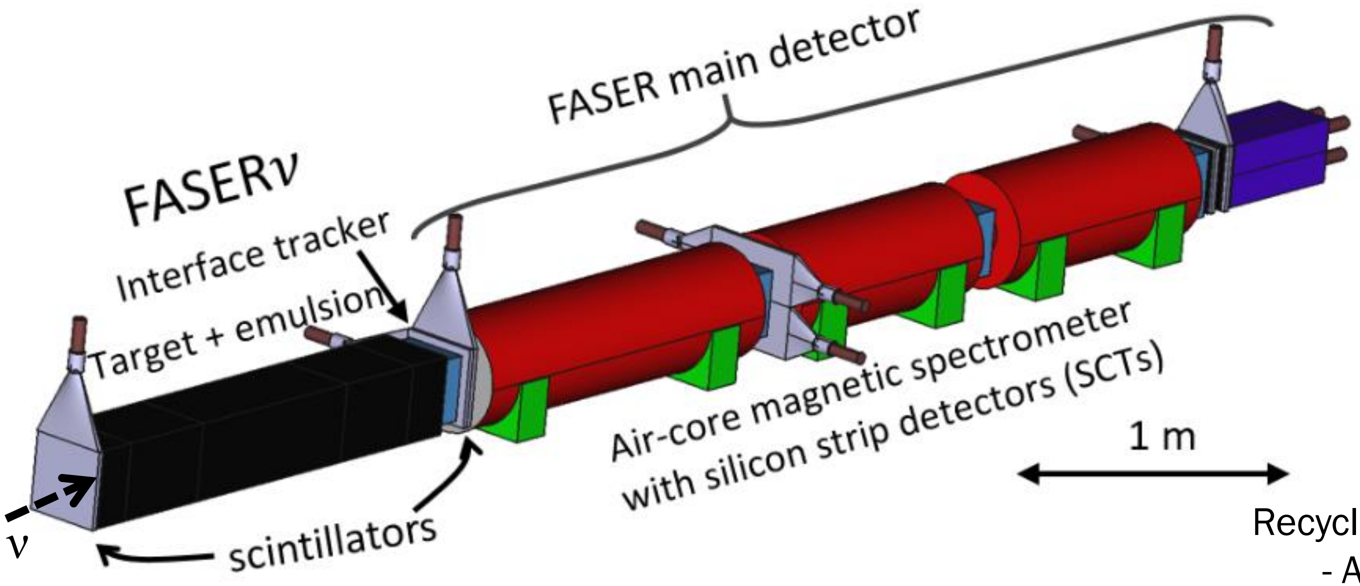
VERY SCHEMATICALLY



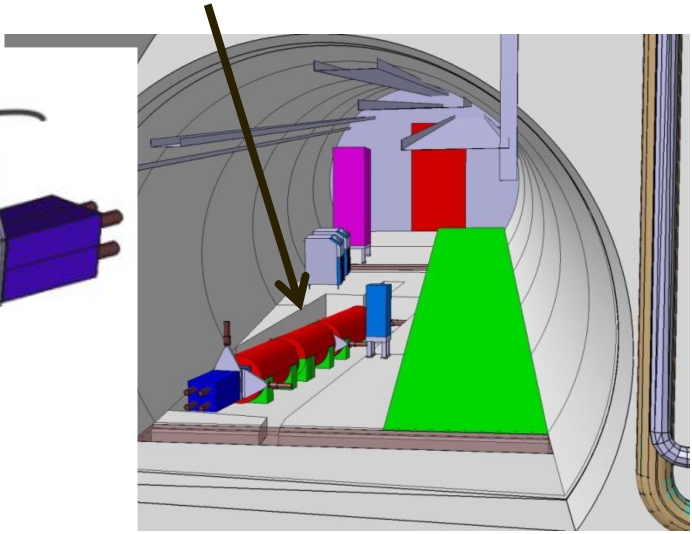
FASER will complement ATLAS/CMS
by searching for highly-displaced decays of
new Light Long-Lived Particles
&
FASERν will initiate
neutrino physics program at the LHC

FASER LoI & TP: 1811:10243, 1812.09139
FASERν LoI & TP: 1908.02310, 2001.03073

BASIC DETECTOR LAYOUT



small civil engineering



Recycling existing spare modules:
- ATLAS SCT modules (Tracker)
- LHCb ECAL modules (Calorimeter)

FASERν – neutrino subdetector:
Emulsion film interleaved with tungsten layers (ECC); total volume 25 cm×25 cm×1.35 m

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

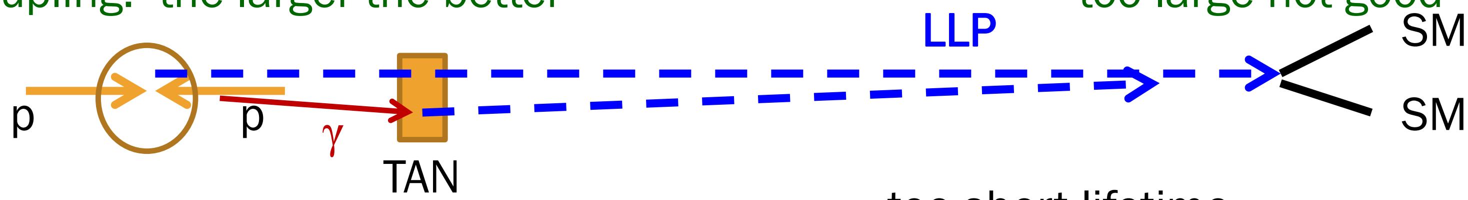
(possible upgrade) FASER 2: L = 5 m, R = 1 m, V = 16 m^3, 3 ab^{-1} (HL-LHC)

FAR-FORWARD BSM PROGRAM

SEARCH FOR HIGHLY DISPLACED DECAYS

Production (ATLAS IP, ...) **Decay**

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



too short lifetime

=> Exponential suppression of # events

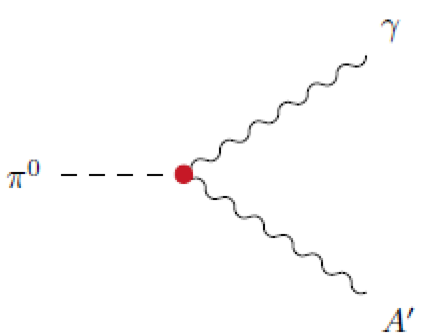
$$N_{\rm sig} \propto \begin{cases} \mathcal{L}^{\rm int}\,\epsilon^2\, e^{-L_{\rm min}/\bar{d}} & \text{for } \bar{d} \ll L_{\rm min} \\ \mathcal{L}^{\rm int}\,\epsilon^2\, \frac{L_{\rm max}-L_{\rm min}}{\bar{d}} & \text{for } \bar{d} \gg L_{\rm min}\,. \end{cases}$$

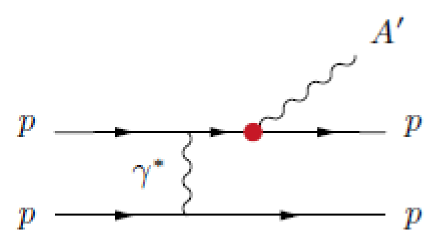
Various production mechanisms:

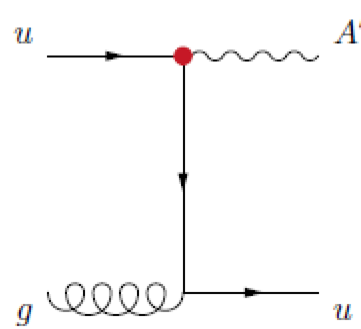
-- meson decays (light & heavy)

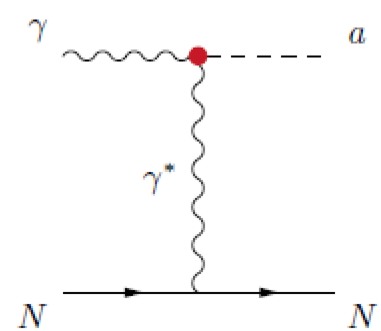
-- bremsstrahlung

-- hard-scatterings,...



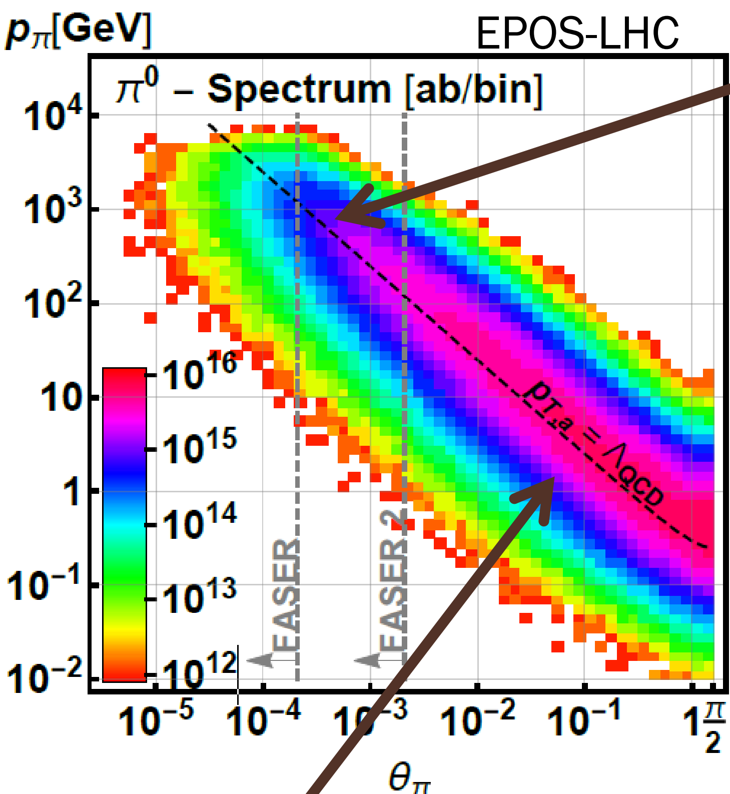






NEW PHYSICS FROM RARE PION DECAYS AT THE ATLAS IP

J.L. Feng, I. Galon, F. Kling, ST, 1708.09389



Hard pions highly collimated along the beam axis since their $p_T \sim \Lambda_{QCD}$ e.g. for $E_{\pi 0} \geq 10$ GeV

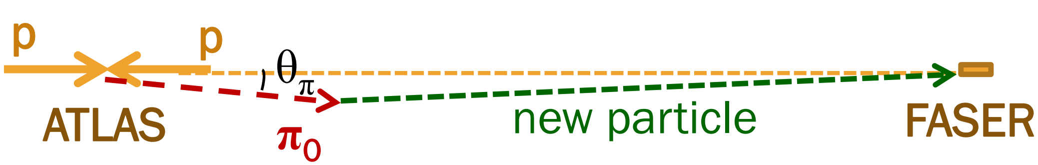
~ 1.7% of π_0s go towards FASER

~ 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

HIDDEN SECTOR PORTALS

- new „hidden" particles are SM singlets (but gauged $U(1)_{B\text{-}L}$ etc. are also considered)
- interactions between the SM and „hidden" sector arise due to mixing through some SM portal

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

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	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}^{\mu\nu}_i$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

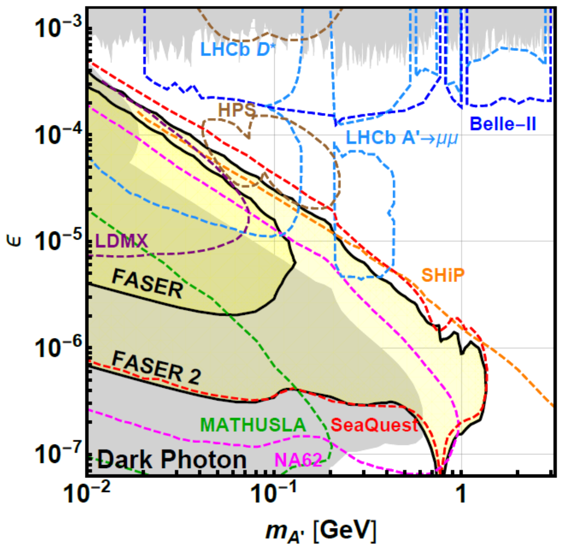
PBC report, 1901.09966

⇨ plethora of more complete models, neutral naturalness, mirror sector, ...

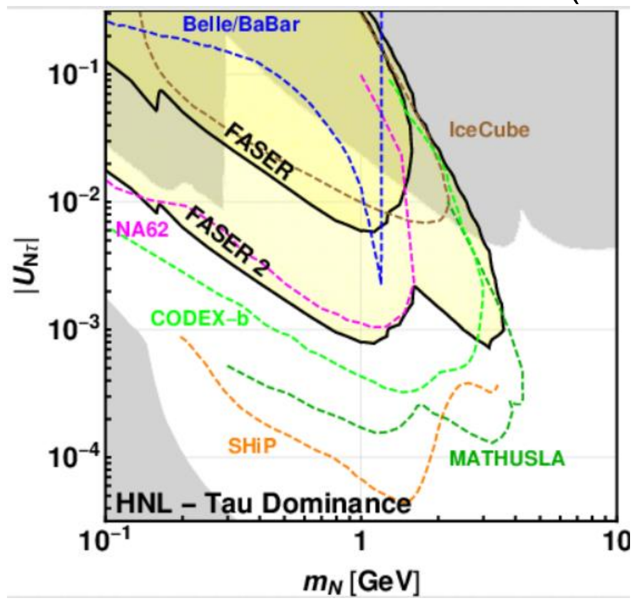
FASER Collaboration, 1811.12522

SELECTED SENSITIVITY REACH PLOTS

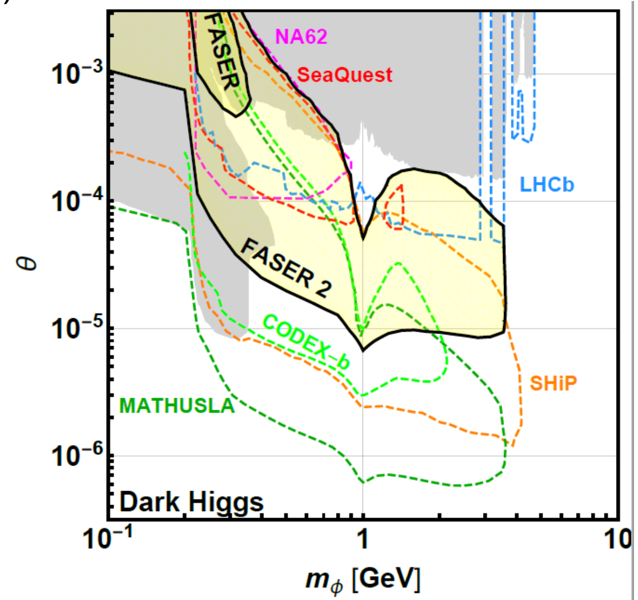
DARK PHOTON



HEAVY NEUTRAL LEPTON (TAU)



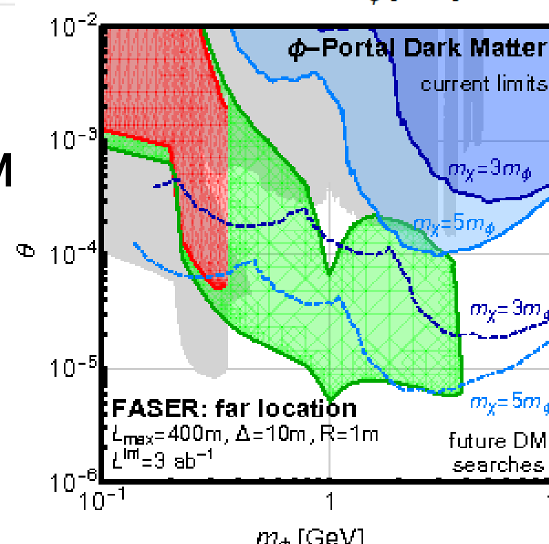
DARK HIGGS BOSON



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

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

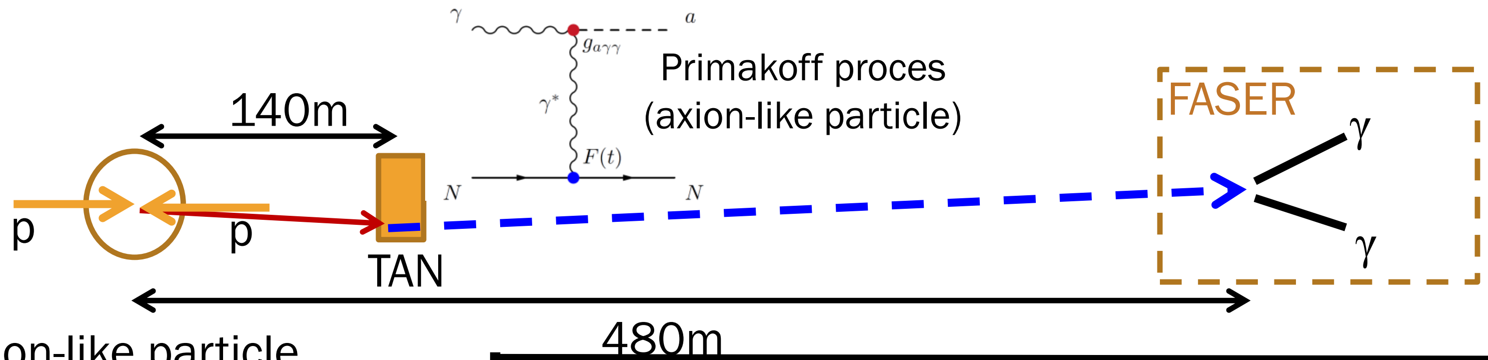
$\langle\sigma v\rangle \sim \kappa^4 \;\rightarrow\; \kappa$ fixed by relic density



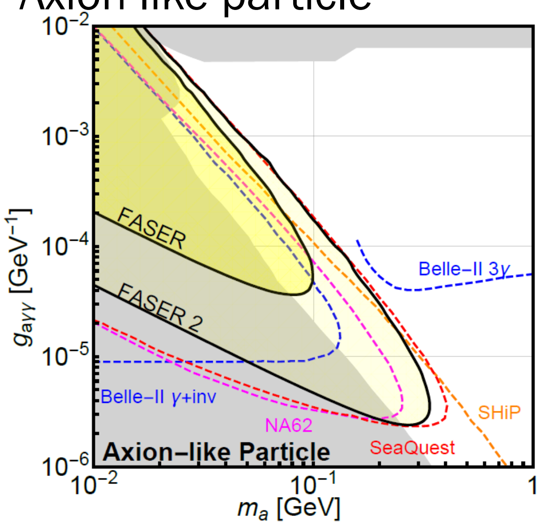
NOT ONLY ATLAS IP

J. L. Feng, I. Galon, F. Kling, ST, 1806.02348

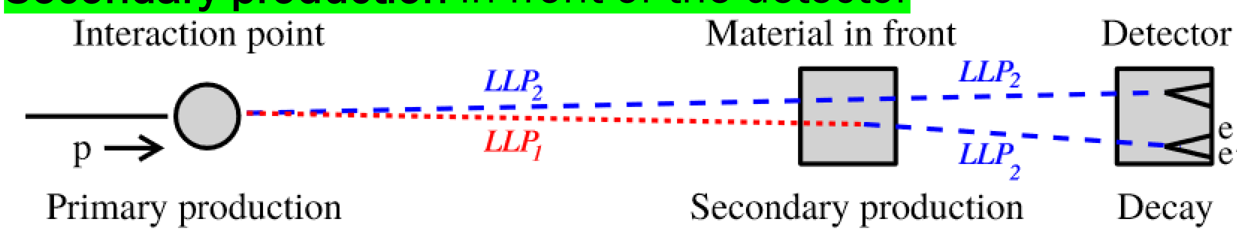
LHC as a **high-energy photon beam–dump** (or **light shining through a wall exp**)



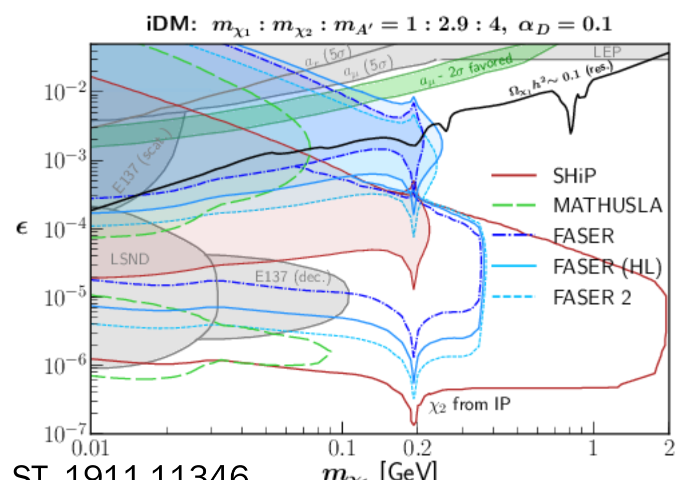
Axion-like particle



Secondary production in front of the detector



Inelastic DM
secondary prod.➡(g-2)$_\mu$

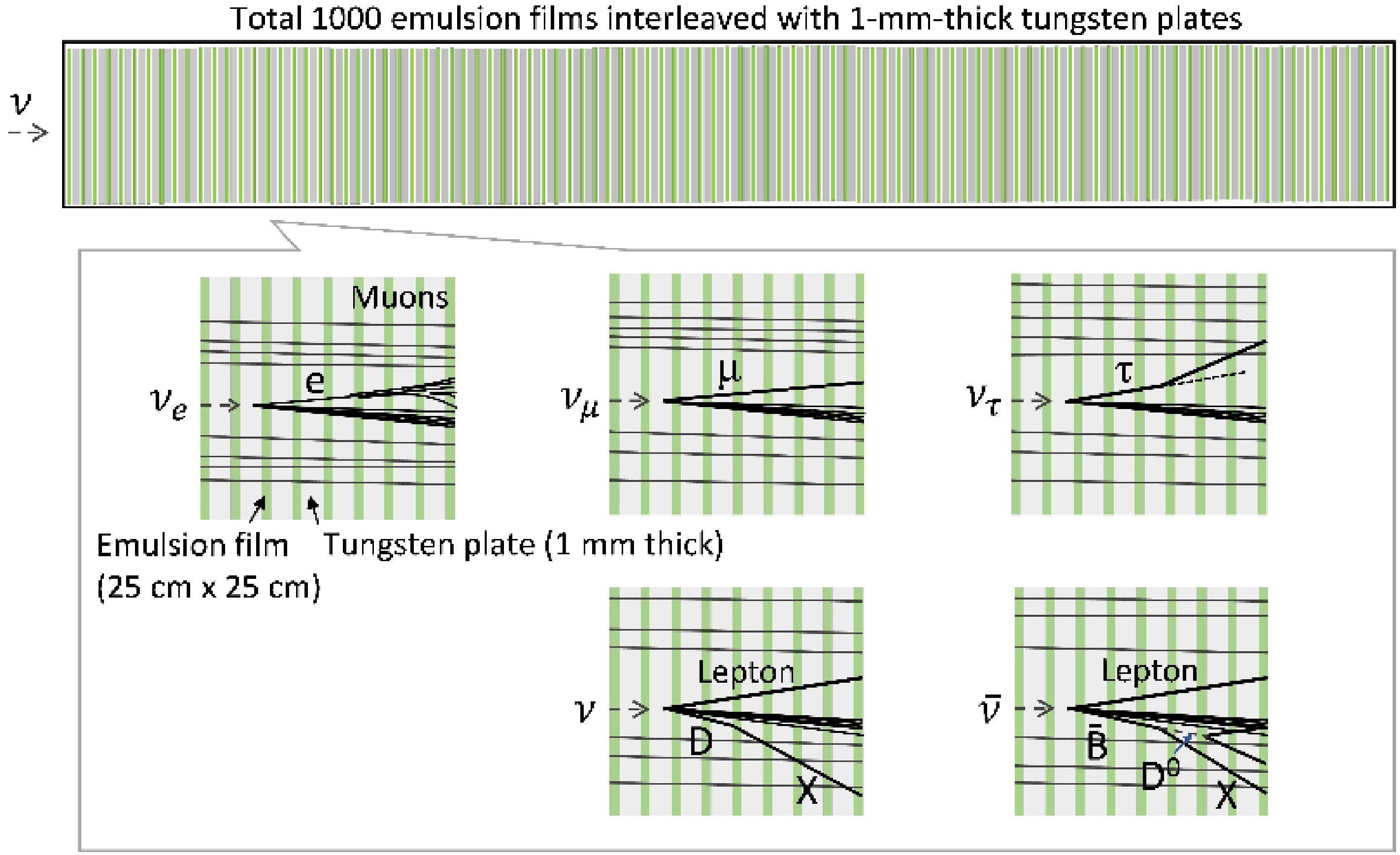


K. Jodłowski, F. Kling, L. Roszkowski, ST, 1911.11346

FAR-FORWARD NEUTRINO PROGRAM

FASER Collaboration, 1908.02310, 2001.03073

FASERν – NEUTRINO SUBDETECTOR (RUN 3)



- Excellent spatial resolution (even 50nm),
- Can deal with high track density (up to 10^6 tracks/cm^2),
- Flux of through-going muons used to precisely align emulsion films, but also a potential source of muon-induced BG (neutral hadrons)

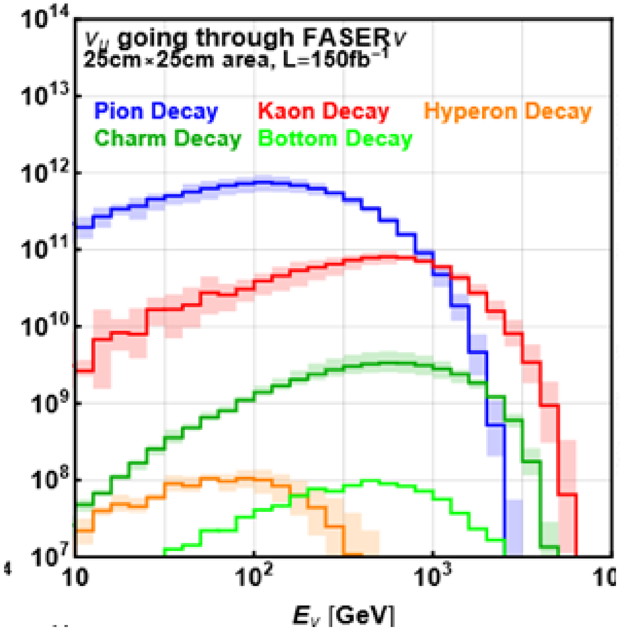
FASER Collaboration, 1908.02310

FAR-FORWARD NEUTRINOS

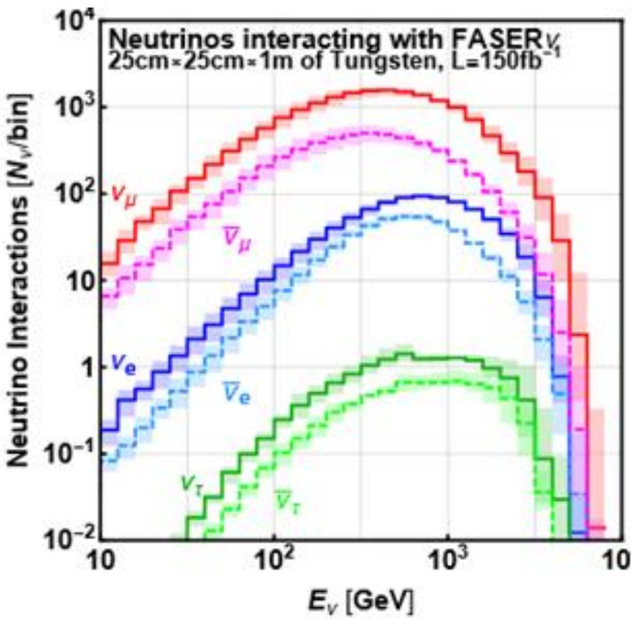
- LHC: lots of forward-going neutrinos from meson decays
- Measurement of the neutrino scattering cross section for E_ν ~TeV (currently unexplored regime)
- Possible detection of 10-20 high-energy tau neutrino events

MUON NEUTRINOS (RUN 3)

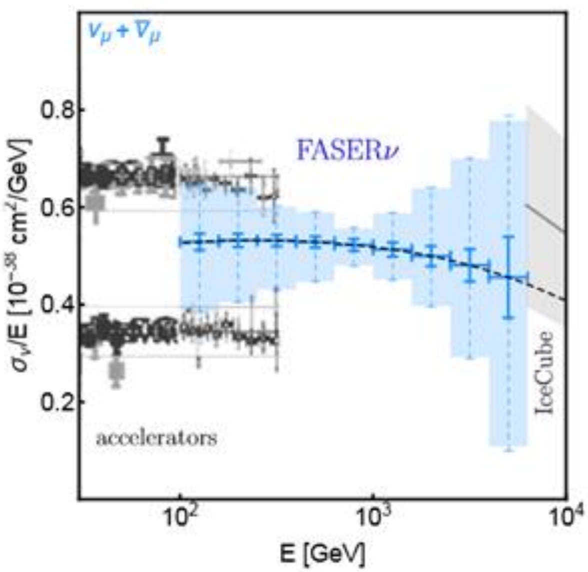
Going-through



Interacting



Scattering cross section



PLANS for HL-LHC extension with ~10^5 total expected neutrino events

NEUTRINOS – ADDITIONAL OPPORTUNITIES

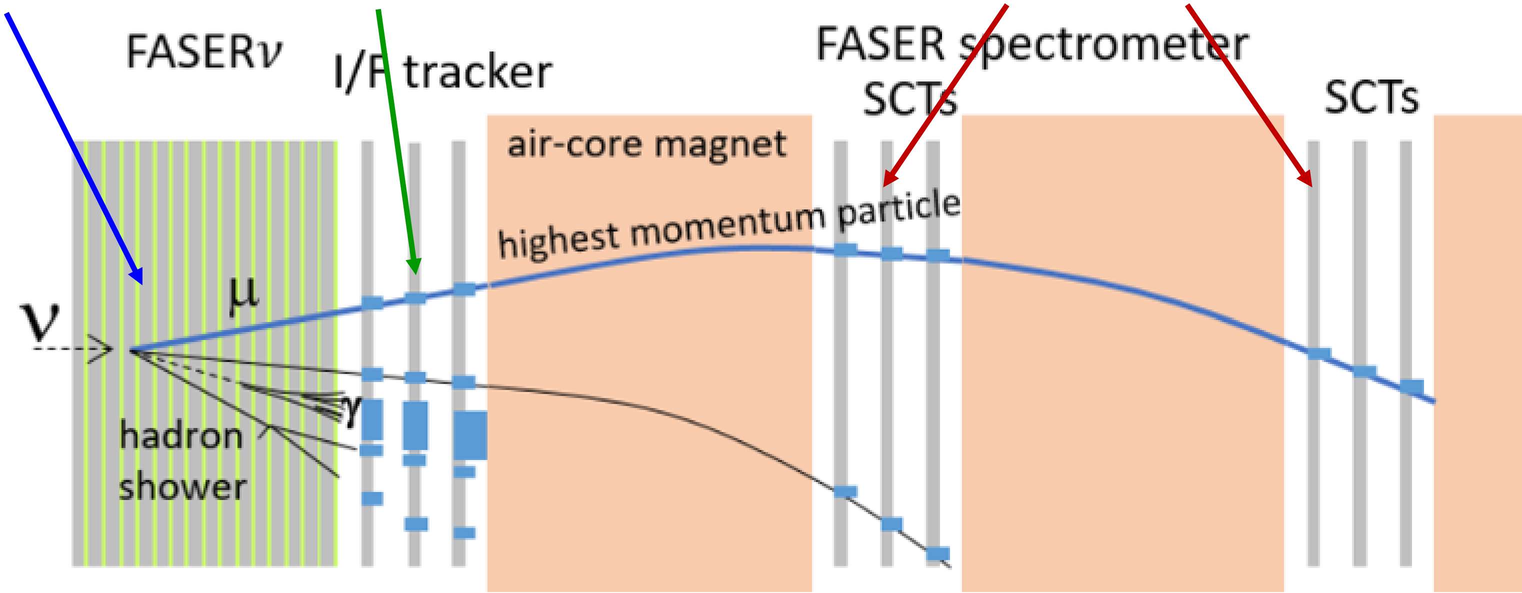
- Detailed event characteristics of ~TeV neutrino energy scatterings ⇨ improved MC tools
- Interface detector – charge measurement, disentangling ν_μ and $\overline{\nu}_\mu$ for separate measurements
- Measuring neutrino flux and spectrum: further tuning of forward MC tools
- more BSM opportunities (F. Kling, 2005.03594, K. Jodłowski, ST, in preparation)

INTERFACE DETECTOR

Matching events between:

FASER Collaboration, 2001.03073

emulsion layers, interface detector, main spectrometer



SM BACKGROUNDS

FASER Collaboration: 1811:10243, 1812.09139, 1908.02310

BACKGROUNDS – SIMULATIONS (FLUKA)

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

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

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

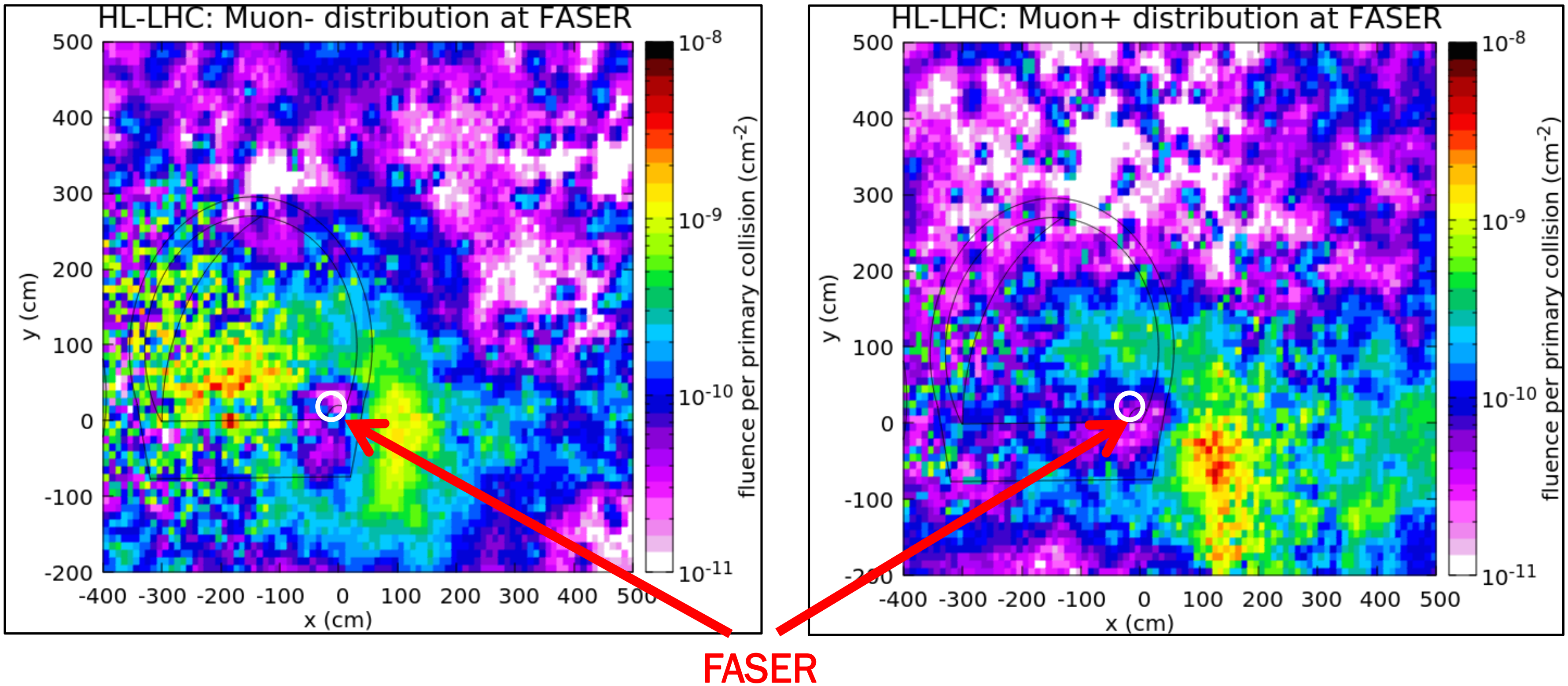
- Showers in the nearby Disperssion Suppresor are suppressed due to the dispersion function of the machine at the FASER location.

- 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)

BACKGROUNDS – REDUCED MUON FLUX

Cross section of the tunnel containing FASER

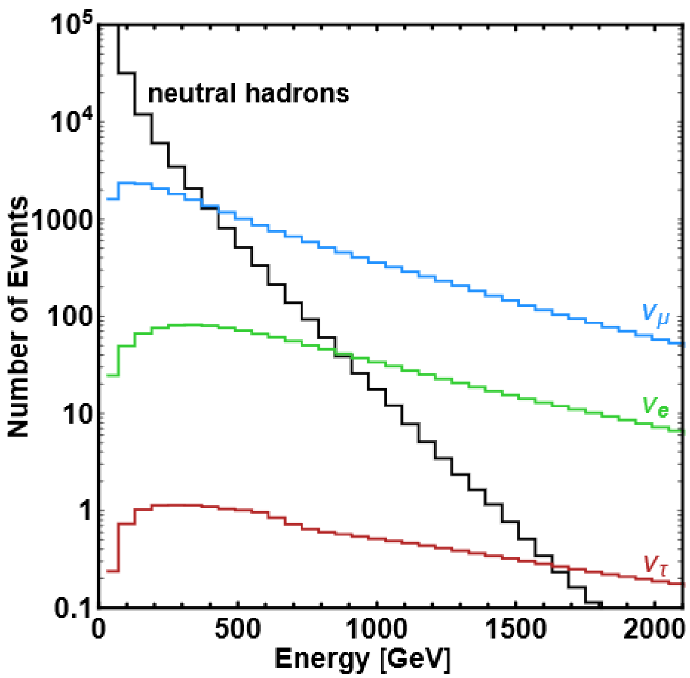


At FASER location:

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

BACKGROUNDS FOR NEUTRINO PROGRAM

Muon-induced BG



Particle	Expected number of particles passing through FASERν			
	$E > 10$ GeV	$E > 100$ GeV	$E > 300$ GeV	$E > 1$ TeV
Neutrons n	27.8k / 138k	1.5k / 11.5k	150 / 1.1k	2.2 / 42
Anti-neutrons $\bar{n}$	15.5k / 98k	900 / 9k	110 / 1.5k	2.8 / 46

+ similar number of kaons, and less other neutral hadrons

$\nu_\mu + \bar{\nu}_\mu$ (signal int.)	23.1k	20.4k	13.3k	3.4k

BG from neutral hadrons: different spectrum
+ no outgoing lepton

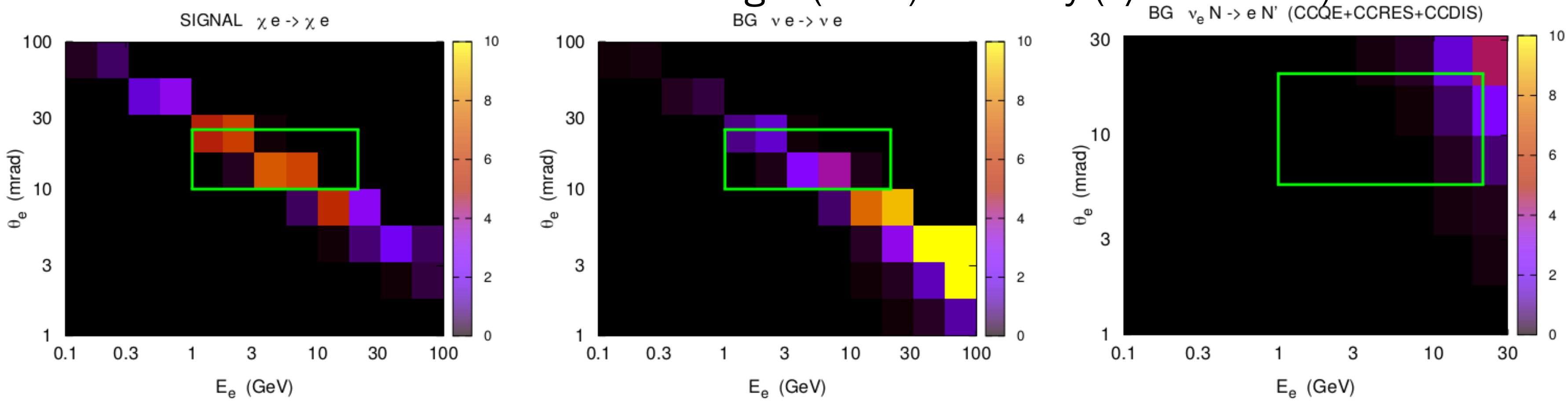
Muon neutrinos mimicing other neutrino flavors
-- mostly controllable (based on outgoing muon identification)
-- multivariate analysis to be employed for better identification

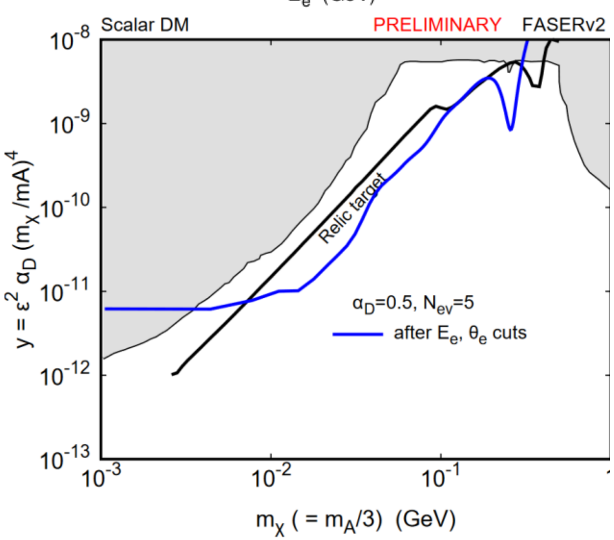
FURTHER OPPORTUNITIES

B. Batell, J. L. Feng, ST, in preparation

DM DIRECT DETECTION AT THE LHC

- Light dark matter particles can also be abundantly produced in the far-forward region
- They can scatter in the emulsion detector
- Neutrino-induced BG much reduced for light (BSM) vs heavy (Z/W bosons) mediator mass





only ~5 expected BG events after cuts on the electron recoil energy and angle

- Muon-induced BG can be problematic
  – need of active muon veto and/or strong sweeping magnet

- thermal-relic target can be probed in HL-LHC in some popular models
  \+ assuming 50cm x 50cm x 200cm detector

J. L. Feng, F. Kling, etal, Snowmass 2021 LoI

FORWARD PHYSICS FACILITY (HL-LHC)

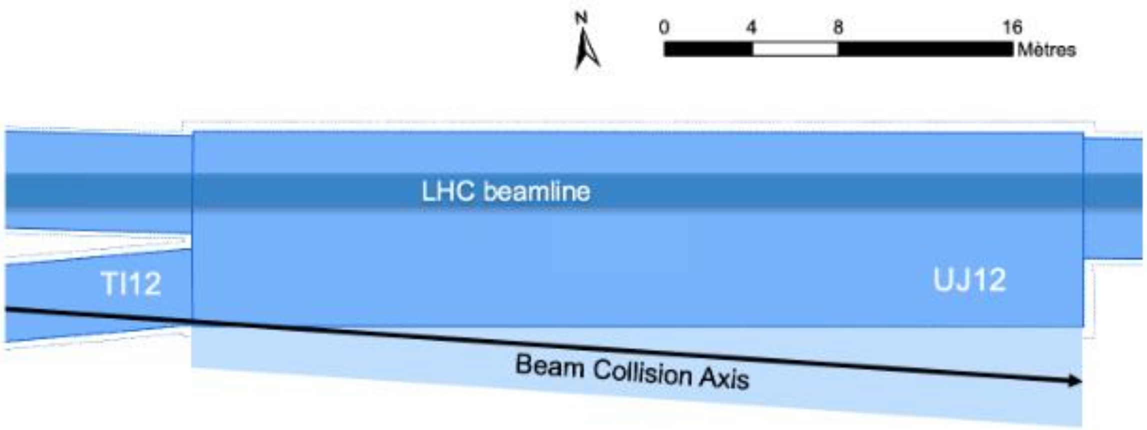
- facility to host a number of experiments in the far-forward region of the LHC
- proposed as an extension of the FASER physics program during HL-LHC
- possible experiments currently considered include:

- FASER 2 and FASERν2 (FASER Collaboration, Snowmass 2021 LoI)
- DM direct detection experiment (either FASERν2 or other technology e.g. LAr, …)

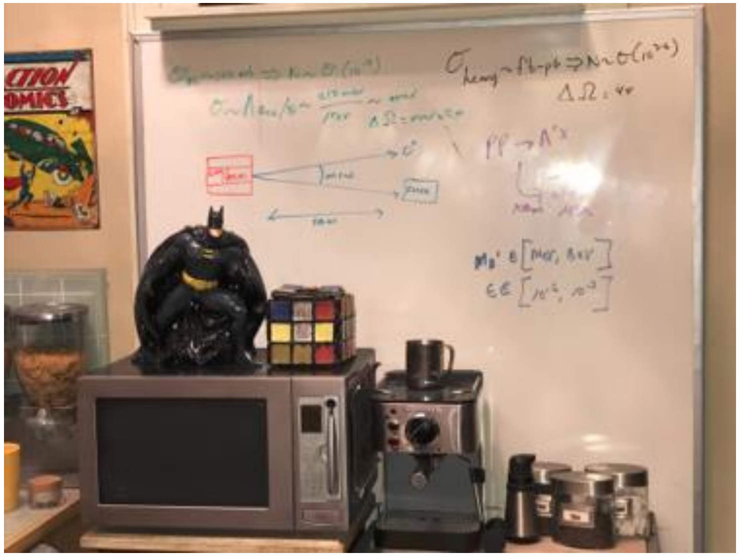
B. Batell, J.L. Feng, ST, in preparation

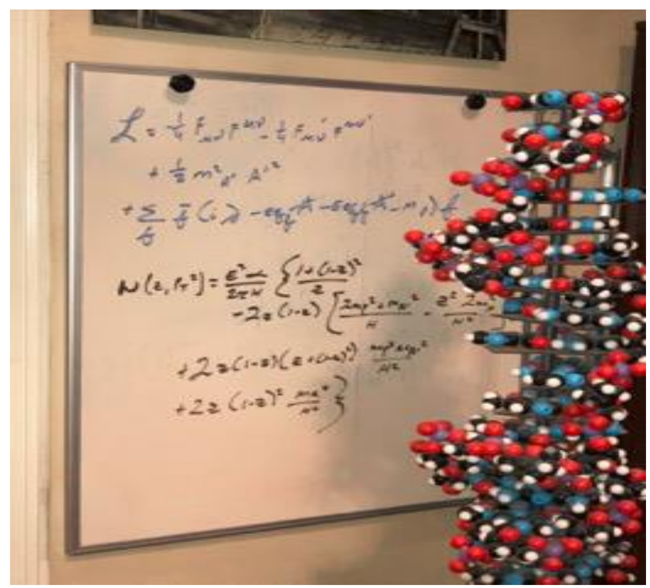
- MilliQan-type detector to search for milli-chrged particles

S. Foroughi, F. Kling, and Y.-D. Tsai, in preparation



FASER IN POPULAR CULTURE

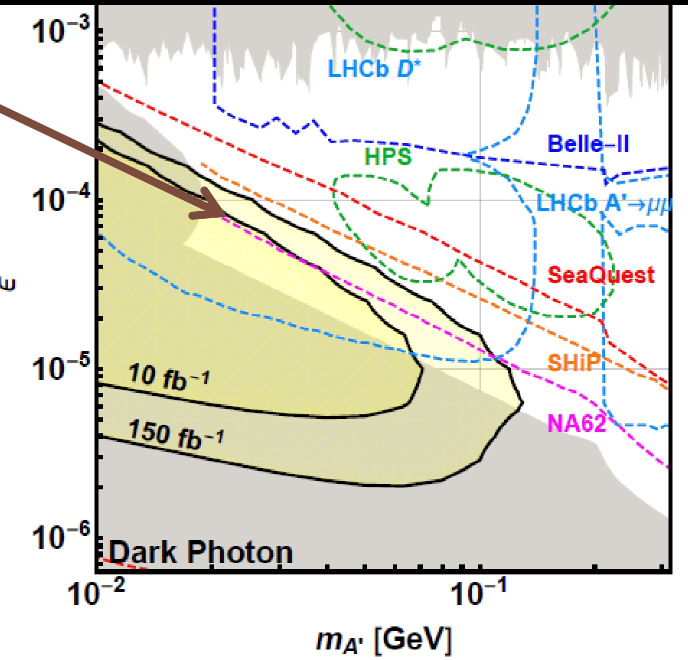




related article

LA Times

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



CONCLUSIONS

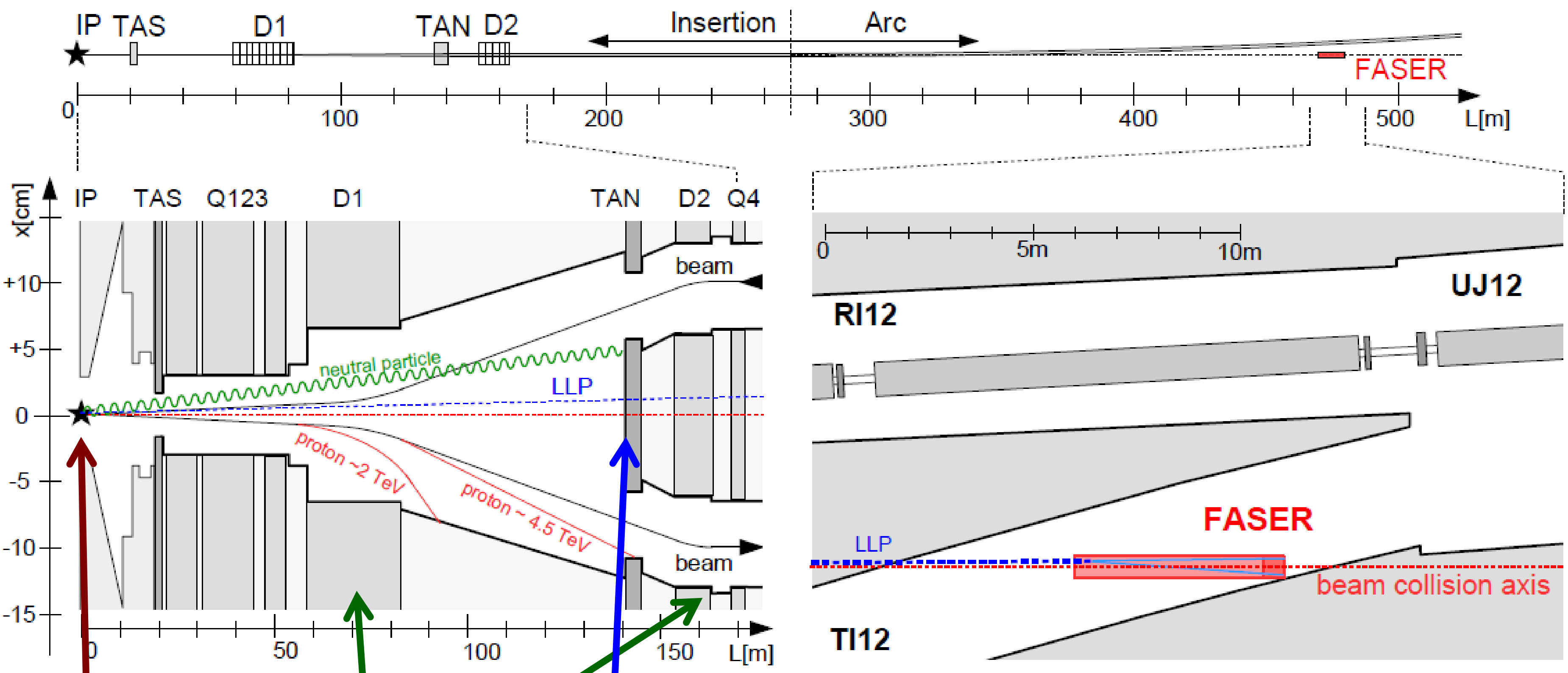
- Far-forward LHC physics – exciting new physics program !!!
- **FASER** experiment will initiate it during Run 3
- **It could be continued towards HL-LHC: Forward Physics Facility**
- Rich physics prospects:

- popular BSM models (dark photon, dark Higgs boson, GeV-scale heavy neutral leptons, ALPs…),
- Many connections to DM and cosmology
- Invisible decays of the SM Higgs, (J. L. Feng, I. Galon, F. Kling, ST, 1710.09387)
- High-energy neutrino scattering cross section measurments
- Prospects for independent studies of experimental anomalies (e.g. KOTO, F. Kling, ST, 2006.10630)

THANK YOU !

BACKUP

FASER AND SURROUNDING LHC INFRASTRUCTURE



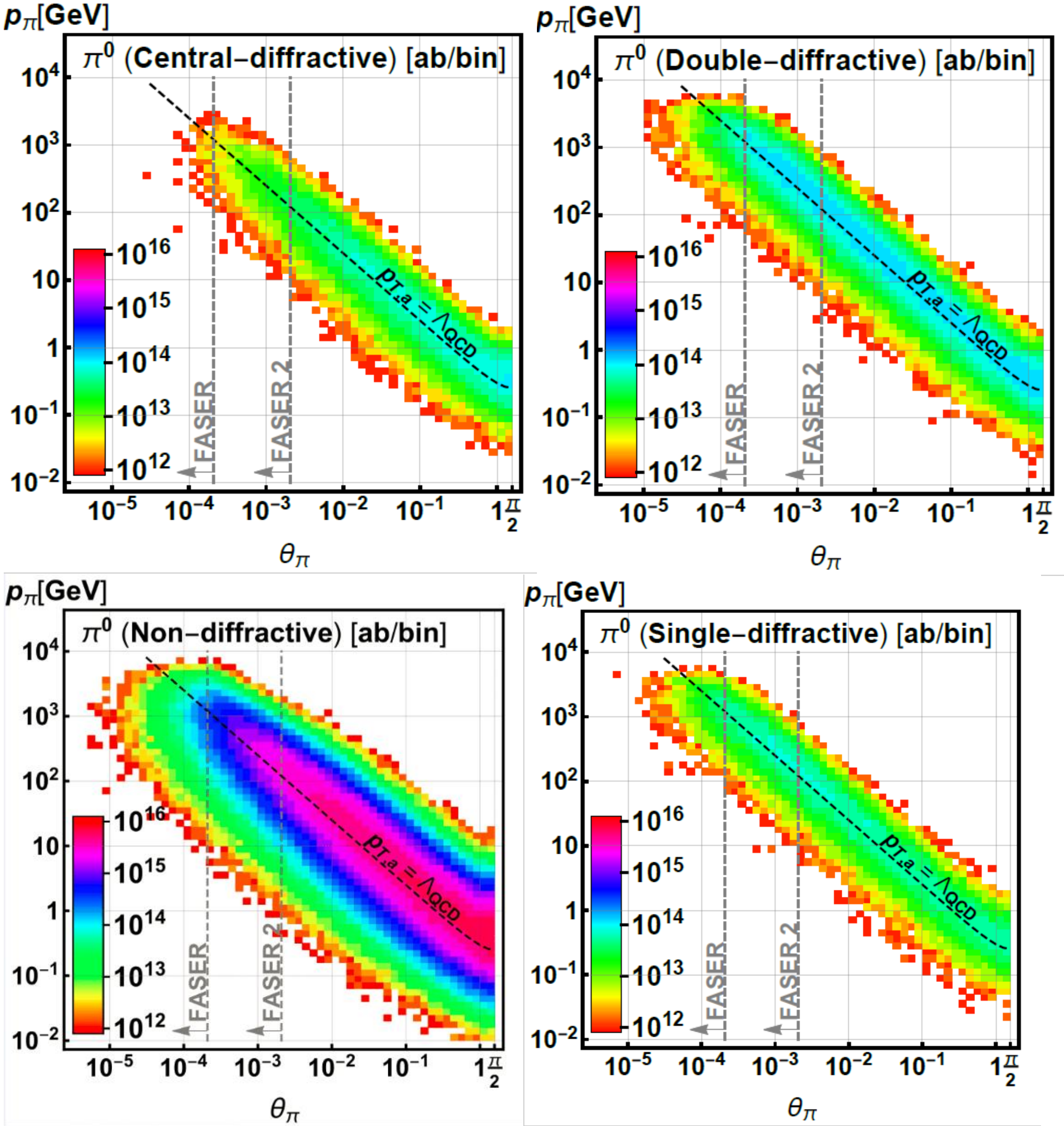
ATLAS Interaction Point (IP)

Strong LHC dipole magnets

TAN
Neutral Particle Absorber
~140m away from the IP

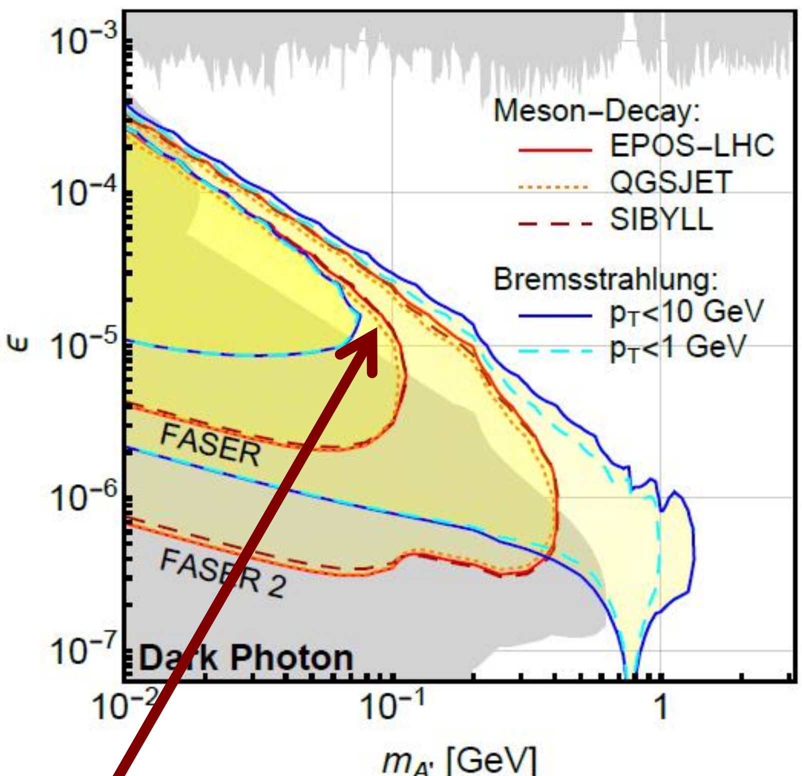
FASER location
tunnel TI12
~480m away from the IP

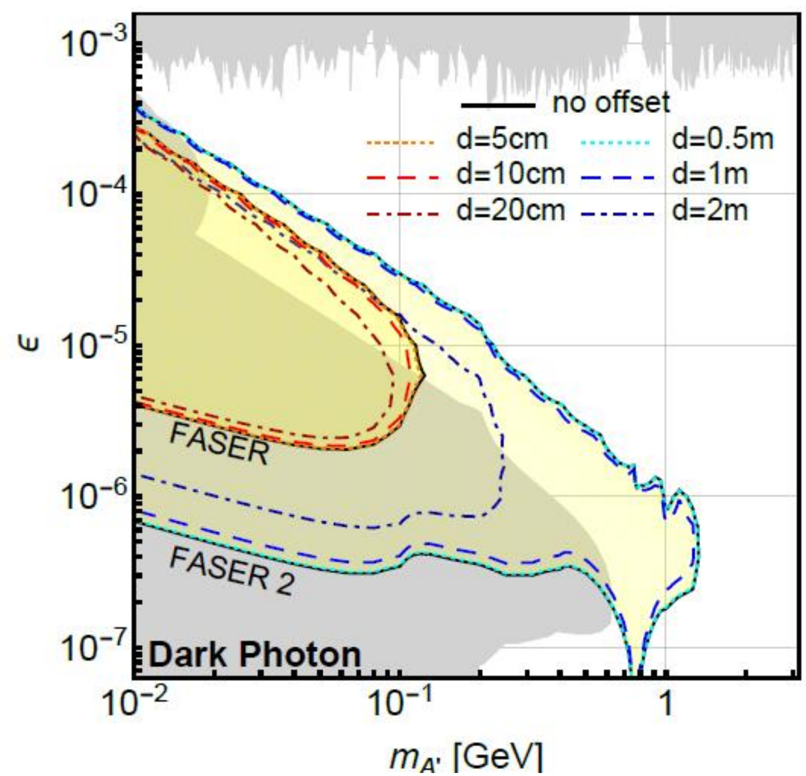
INELASTIC P-P COLLISIONS



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

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

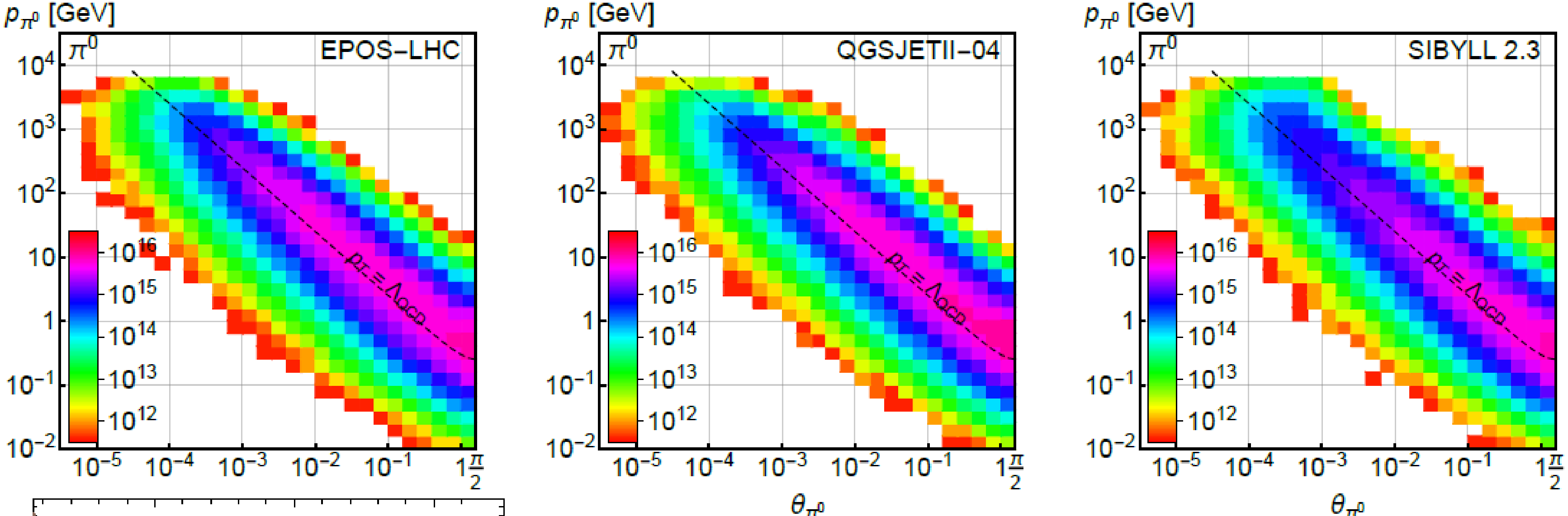
$$N_{\rm sig} \propto \mathcal{L}^{\rm int}\,\epsilon^2\,e^{-L_{\rm min}/\bar{d}} \quad \text{for} \quad \bar{d} \ll L_{\rm min}$$

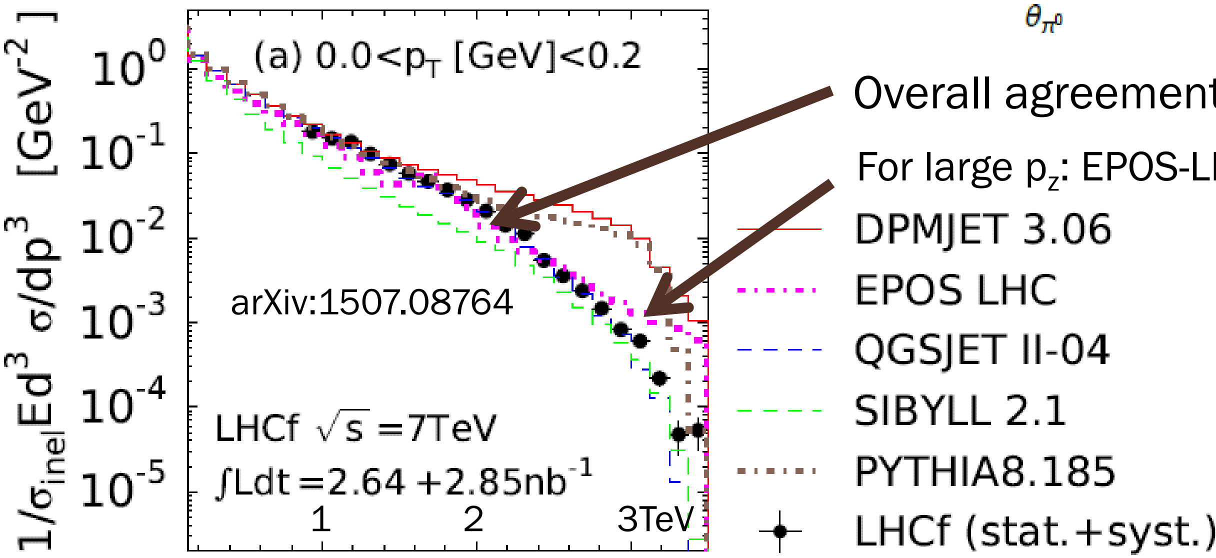
no of events grows exponentially with a small shift in ε

CRMC package

COMPARISON – VARIOUS MC TOOLS

CRUCIAL CONTRIBUTION FROM LHC FORWARD PHYSICS AND DIFFRACTION WG





Overall agreement between MC and data

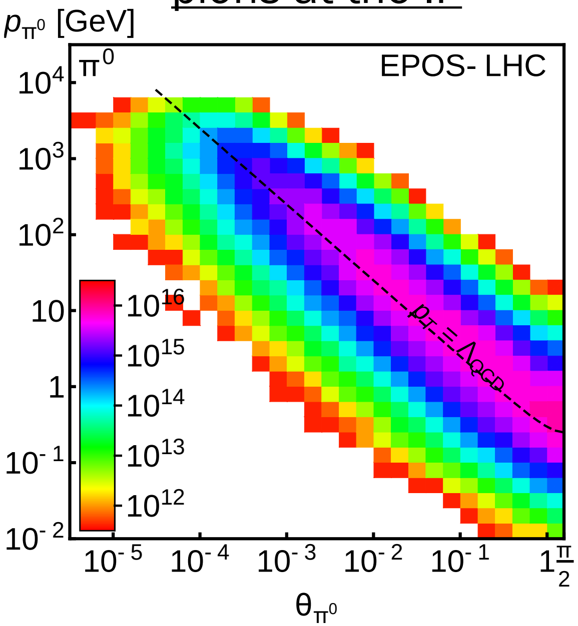
For large p_z: EPOS-LHC gives some overestimate

QGSJET II, SIBYLL lower estimates

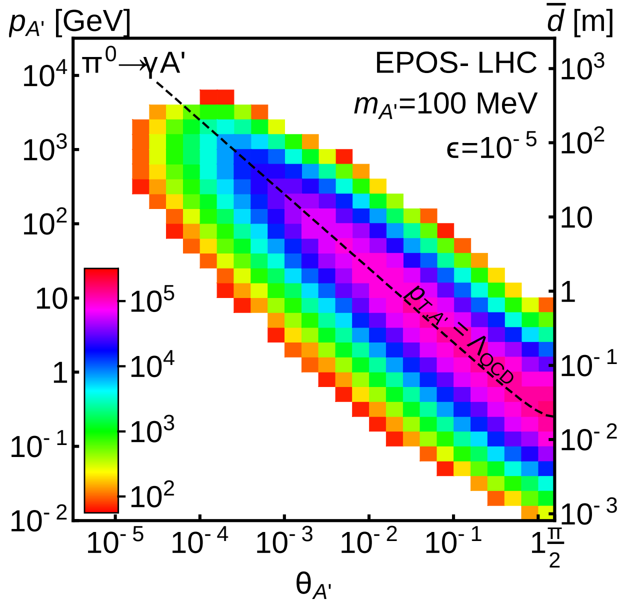
THESE DISCREPANCIES HAVE TYPICALLY VERY LITTLE IMPACT ON FASER SENSITIVITY

DARK PHOTONS AT FASER – KINEMATICS

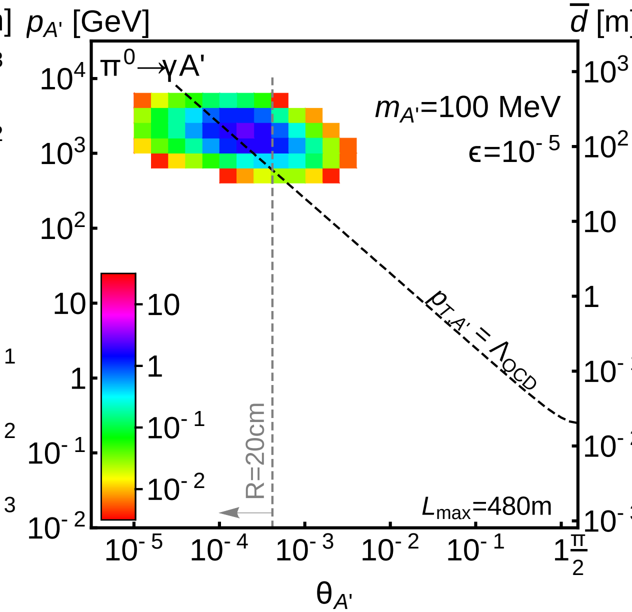
<u>pions at the IP</u>



<u>A's at the IP</u>



<u>A's decaying in FASER</u>



- 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

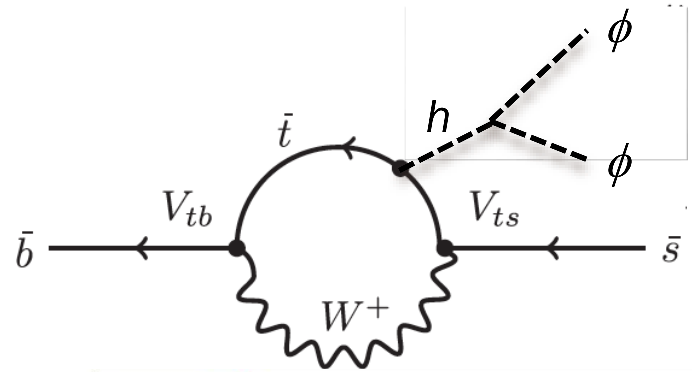
- $\pi^0 \to A'\gamma$
- high-energy π^0 ⇨ collimated A's
- $\varepsilon^2 \sim 10^{-10}$ suppression but still up to 10^5 A's per bin

- 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

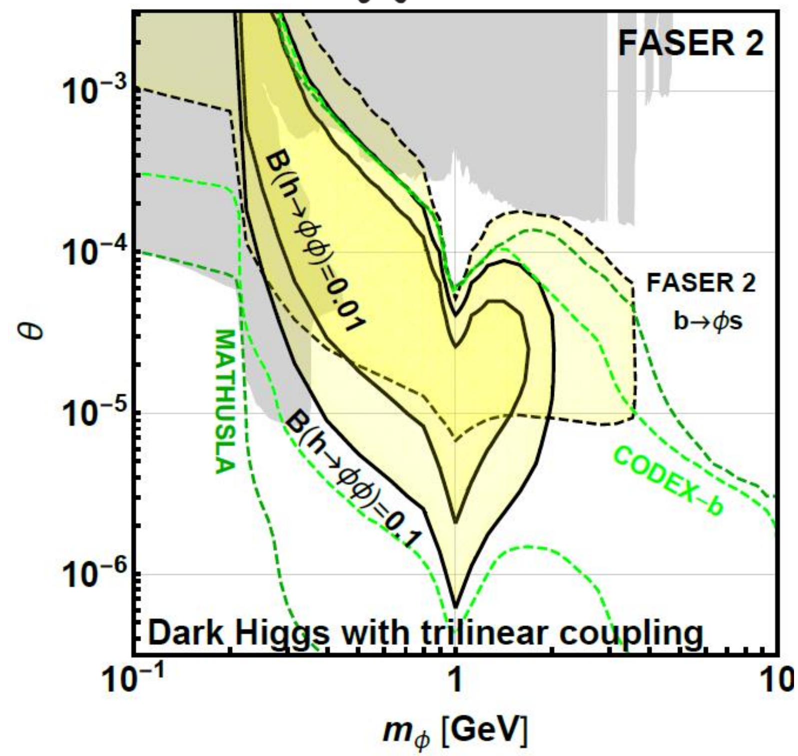
1710.09387, PRD 97 (2018) no.5, 055034

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



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, ...

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. $\mathbf{U(1)_{Le\text{-}L\mu}}$, $\mathbf{U(1)_{B\text{-}L}}$, ⇨ 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