FASER:
ForwArd Search ExpeRiment at the LHC

Iftah Galon

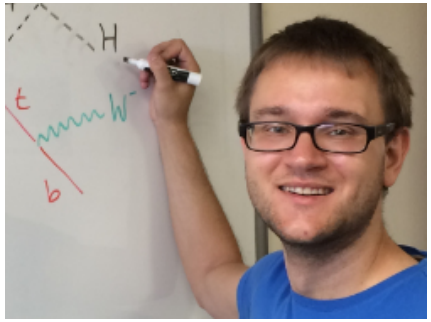
Rutgers, NHETC

April 4, 2018

Feng, IG, Kling, Trojanowski arXiv:1708.09389 Dark Photons @FASER
Feng, IG, Kling, Trojanowski arXiv:1710.09387 Dark Higgses @FASER
Kling, Trojanowski arXiv:1801.08947 Hevay Neutral Leptons @FASER
Feng, IG, Kling, Trojanowski arXiv:1804.XXXXX ALPs @FASER

My Collborators

Jonathan L. Feng
(UC Irvine)



Felix Kling
(UC Irvine)

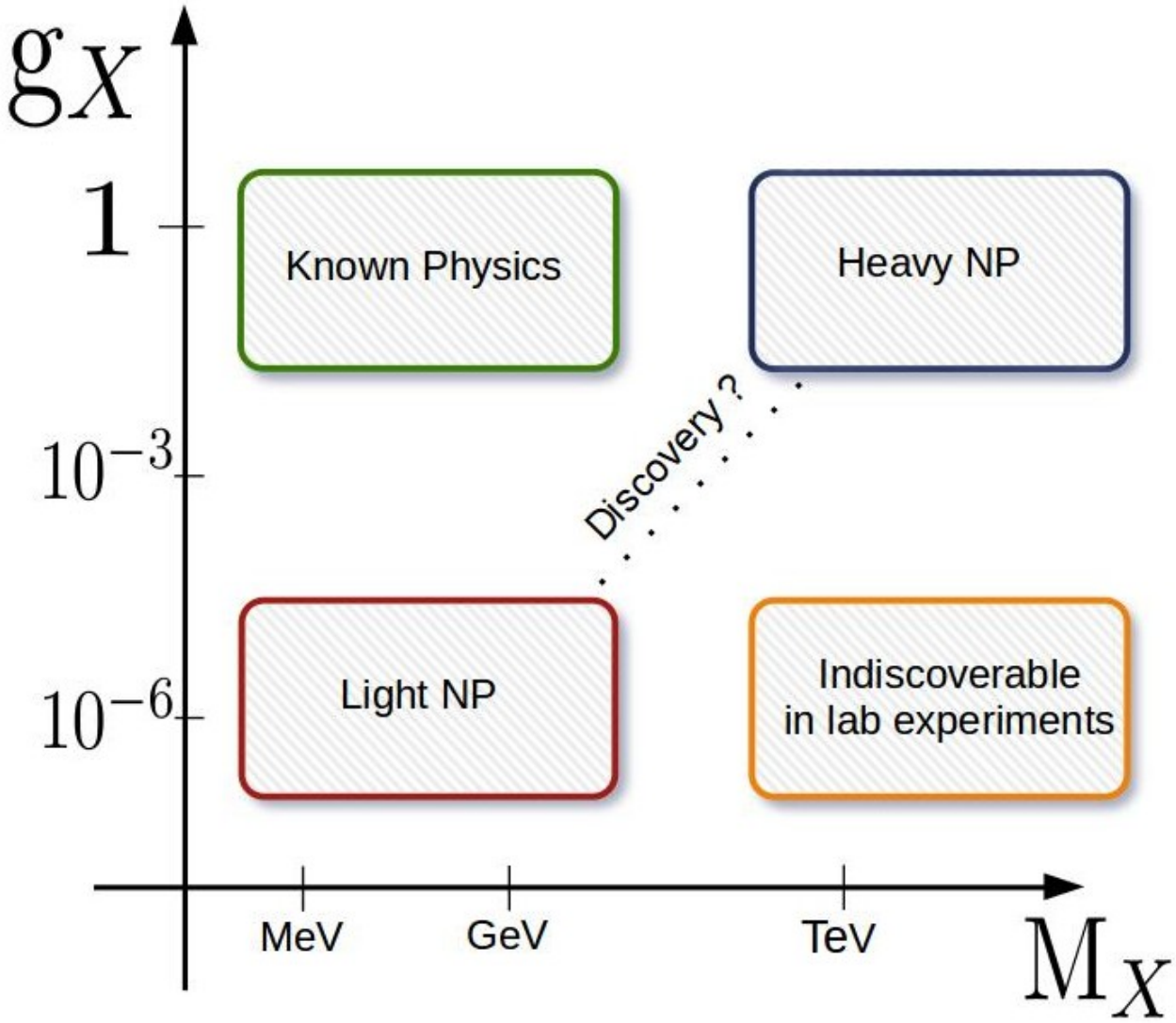
Sebastian Trojanowski
(UC Irvine)

and
Dave Casper (UC Irvine),
Shih-Chieh Hsu (U. Washington),
Jamie Boyd (CERN),
Mike Lamont (CERN),
Francesco Cerutti (CERN radiation study group)

...

Recently: Joined the Physics Beyond Collider (PBC) study @CERN

FASER - Motivation



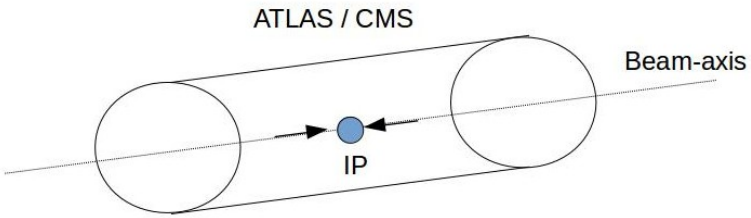
Heavy New Physics

- WIMP Dark Matter
  $\Omega_X \propto \frac{1}{<\sigma v>} = \frac{M_X^2}{g_X^4}$
- Anomalies: $(g-2)_\mu$
- Hierarchy Probelm

Energy Fronitier

High p_T signaures

$\Downarrow$



$$\sigma(@LHC) \sim \mathrm{pb} - \mathrm{fb}$$

$$\Downarrow$$

$$N_{\mathrm{events}}^{\mathcal{L}^{\mathrm{int}}=300\ \mathrm{fb}^{-1}} \sim 10^3 - 10^6$$

Light New Physics

- WIMPless Dark Matter
  $\Omega_X \propto \frac{1}{<\sigma v>} = \frac{M_X^2}{g_X^4}$
- Anomalies: $(g-2)_\mu$, $^8\mathrm{Be}$
- Pelthora of models: A', a, h_D, $N, \ldots$
- Long-Lived Particles

Intensity Fronitier

Extraordinary event rates
Dedicated experiments:

- beam-dumps
- fixed-target
- low-E colliders
- conversion experiments
- ....

The FASER Pitch / Summary Slide (1/2)

Look for Long-Lived Particles @LHC

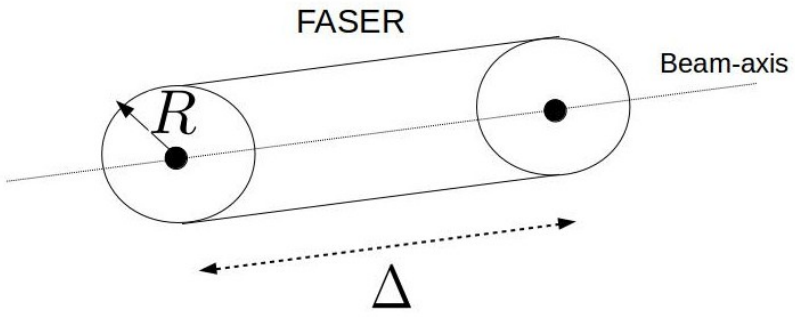
- Huge Event Rate
  $\sigma_{pp}^{\rm inel} \sim 75\ {\rm mb}$ @$\sqrt{s} = 13\ {\rm TeV}$
  $N_{\rm pp}^{\mathcal{L}^{\rm int}=300\ {\rm fb}^{-1}} \sim 10^{16}$

- Forward
  $\theta \sim \Lambda_{QCD}/E \sim 1\ {\rm mrad}$
  for $E \sim 100\ {\rm GeV} - 1\ {\rm TeV}$

- Accelarator Infrastructure
  Magnets + Absorbers

New Detector

- $L = 480\ {\rm m}$ downstream from ATLAS/CMS IP
- $\begin{cases} R = 20\ {\rm cm} \\ \Delta = 10\ {\rm m} \end{cases}$



The FASER Pitch / Summary Slide (2/2)

FASER can explore the Lifetime Frontier

- small $\Rightarrow$ relatively cheap
- concurrent with LHC - no beam cost
- Huge event rate $N_{\rm pp}^{\mathcal{L}^{\rm int}=300\ {\rm fb}^{-1}} \sim 10^{16}$
- large boosts $\Rightarrow$ long propagation
- LHC filters backgrounds

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



Photos by J. L. Feng

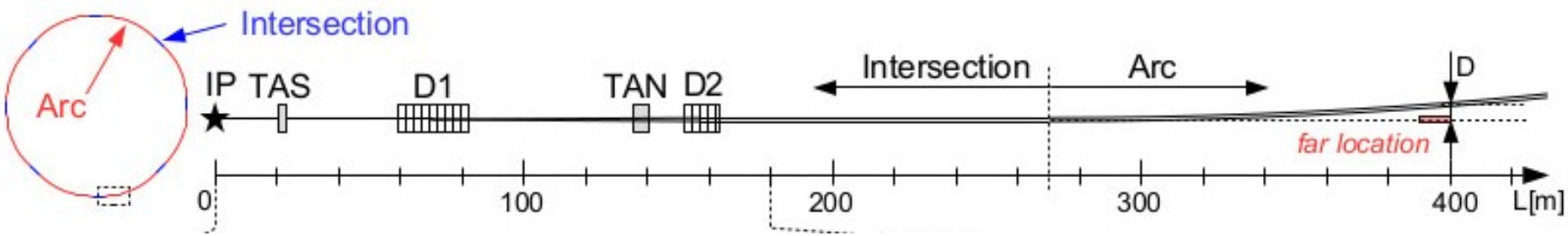
@Seattle StarTrek Museum exhibit

Outline

- LHC infrastructure and the FASER location
- Learn by example - The dark photon physics case
  - Model characteristics
  - Production in the forward region of *pp*-collisions
  - Detector considerations
  - Backgrounds
  - Sensitivity Reach
- Complementary experimental ideas
- Outlook
- Conclusions

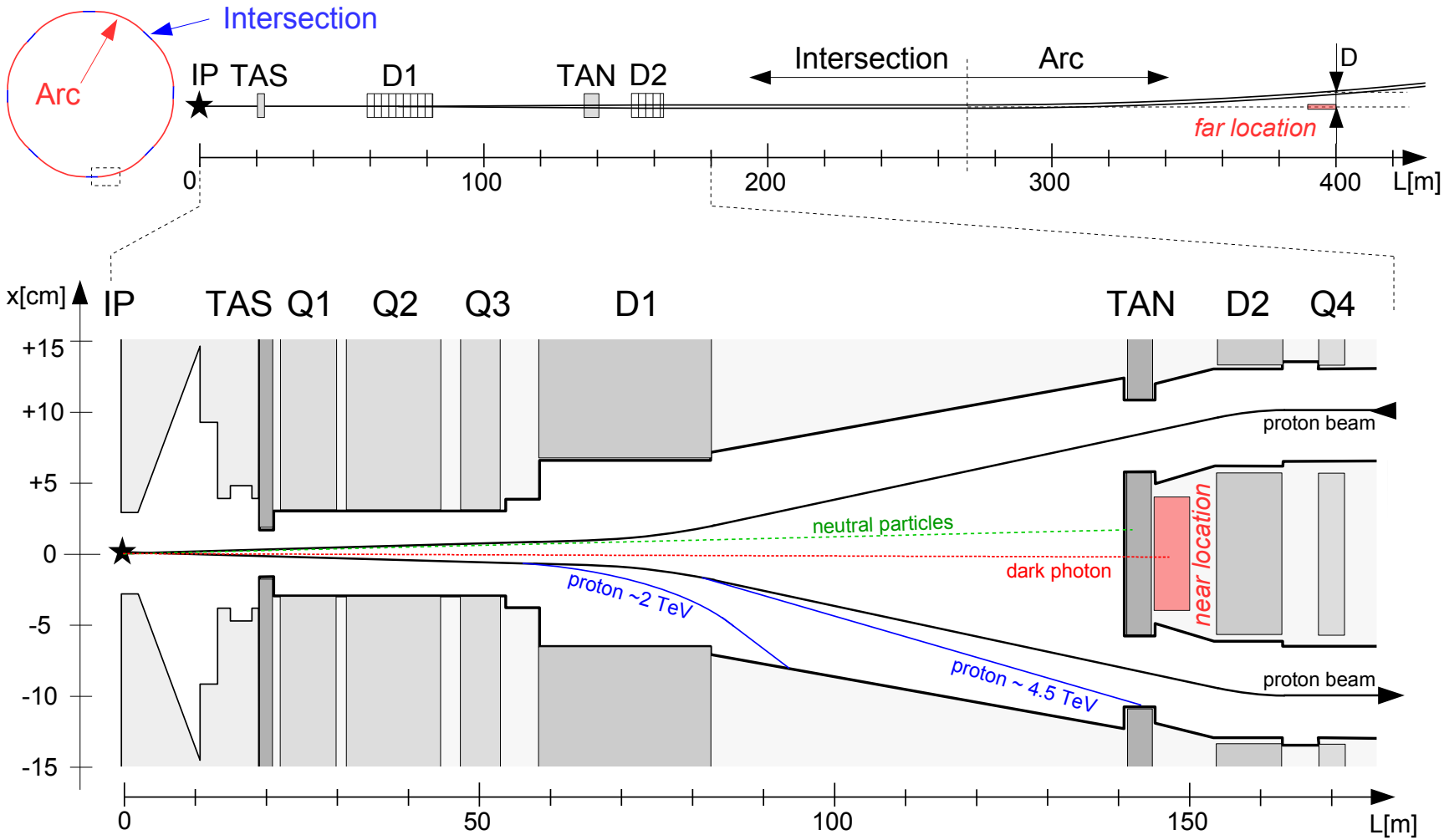
LHC Infrastructure

The LHC beam-lines run in tunnels which consists of 8 straight, 545 m long Intersections and curved Arcs connecting them.



The forward region is common to IP1 and IP5 and includes the LHC forward physics experiments: LHCf, TOTEM, CASTOR, ALPHA

LHC Infrastructure



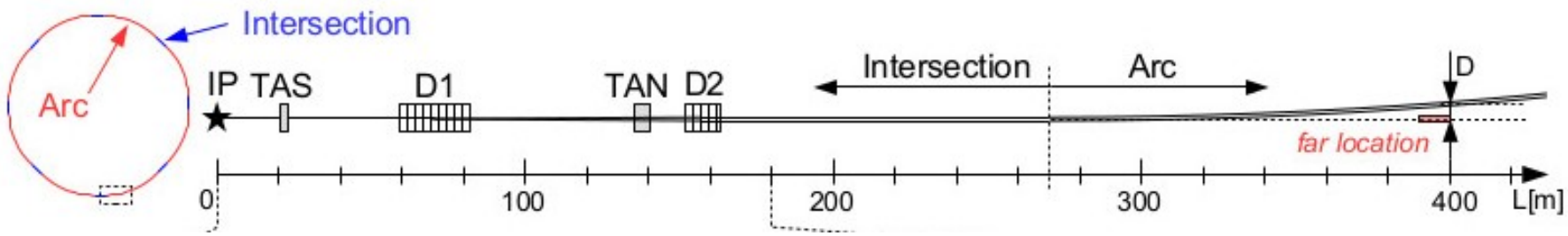
TAS: 1.8 m of copper, $r_{hole} = 17$ mm $\theta \sim 0.85\mu$rad

TAN: γ, n: 5 m steel, marble, copper

D&Q magnets: $\begin{cases} \text{focus beams} \\ \text{deflect charged} \end{cases}$

LHC Infrastructure

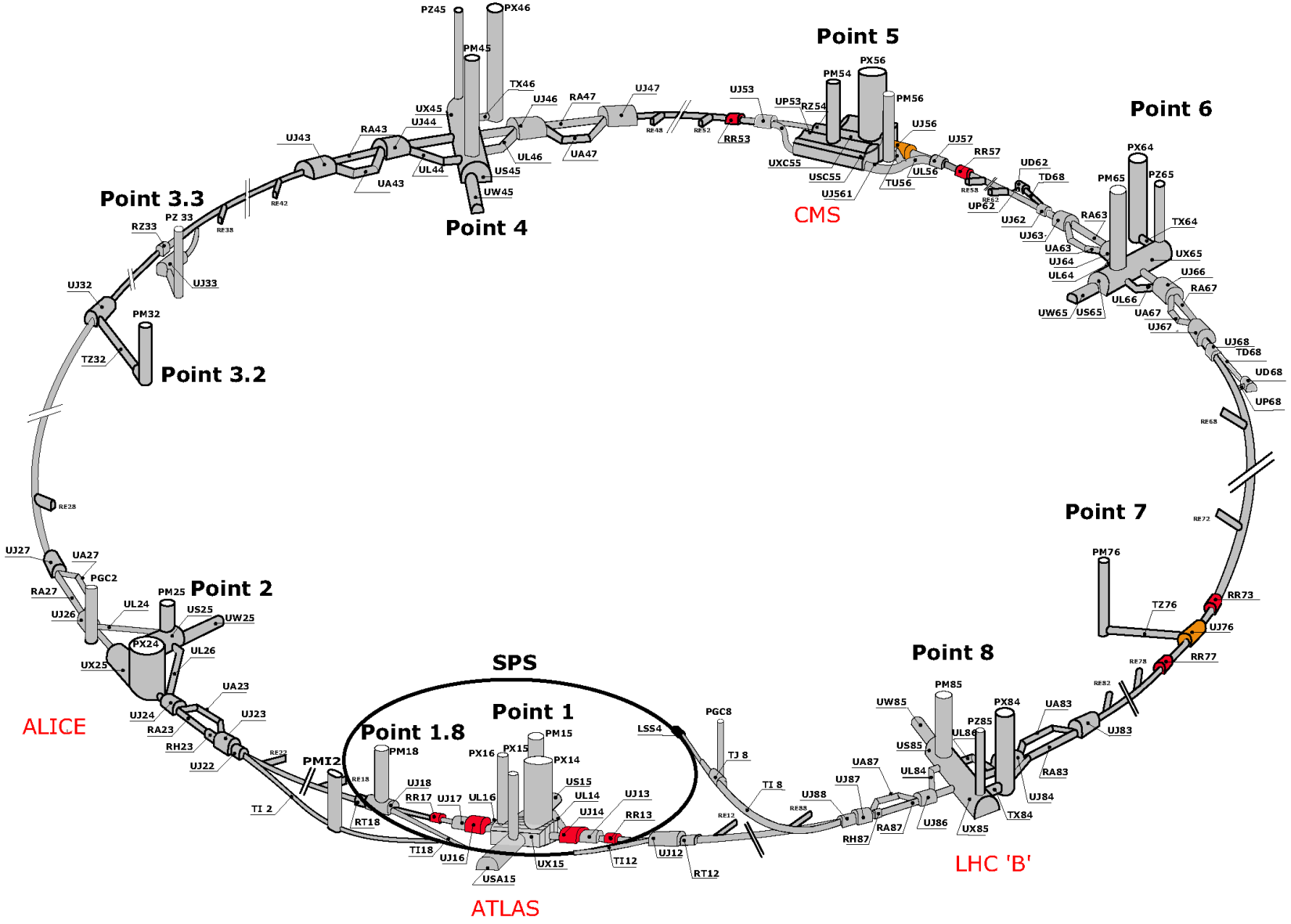
LHC infrastructure $\Longrightarrow$ filter of non-proton beam particles



FASER position: $L = 485\ \mathrm{m}$ - after LHC curves

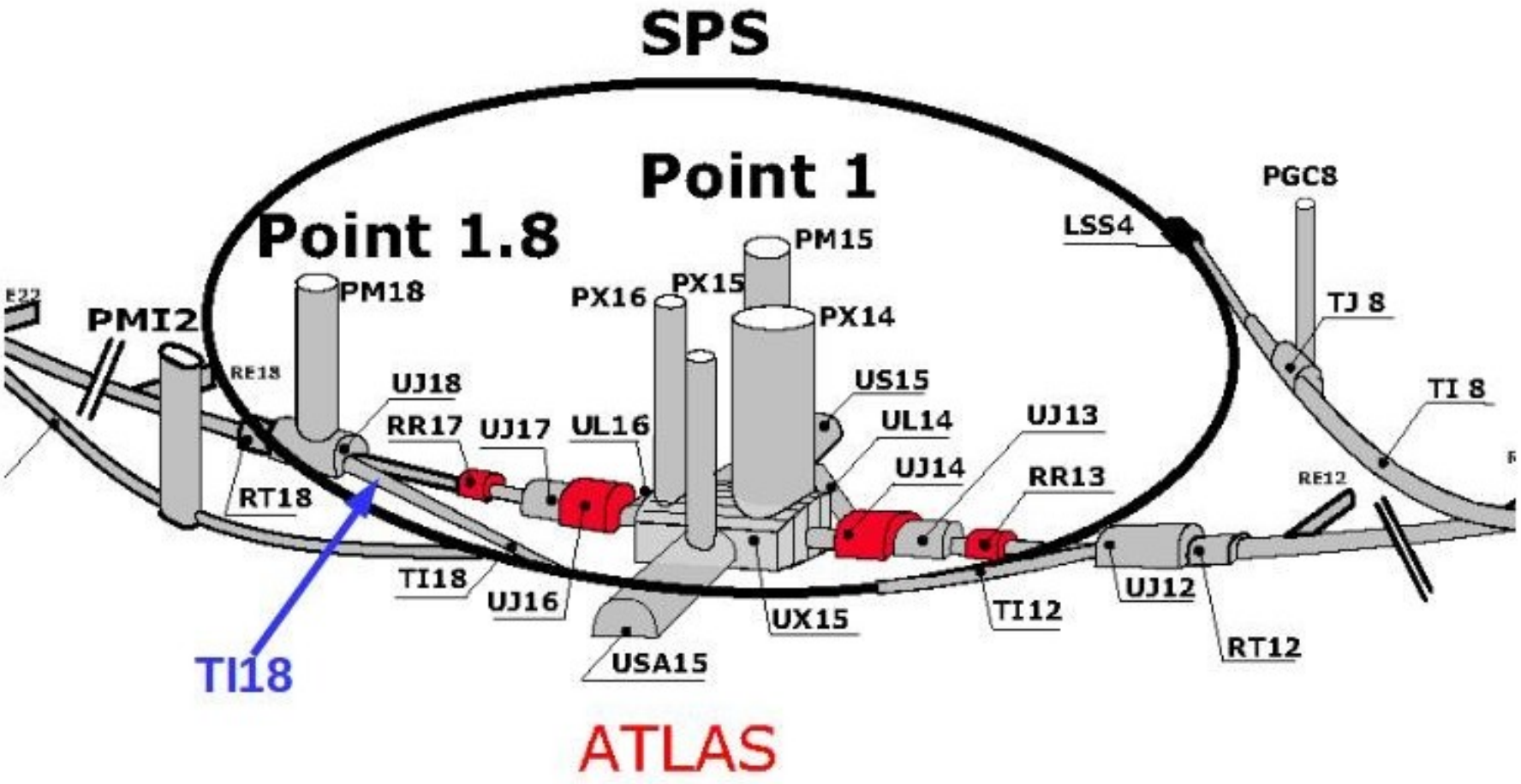
- The Arc starts at $L = 272\ \mathrm{m}$, and the beam axis leaves the tunnel at $L =\sim 350\ \mathrm{m}$ $\Longrightarrow$ Rock shielding
- Beam crossing angle at ATLAS/CMS IP 285 $\mu\mathrm{rad}$ vertical/ horizontal plane. At HL-LHC, 590 $\mu\mathrm{rad}$, orientation not fixed yet, and may change throughout run. $\Longrightarrow$ At the $L = 485\ \mathrm{m}$ this shifts the FASER vertical/horizontal location by 14.3 cm.

LHC Infrastructure - Layout



LHC Infrastructure - The TI18 Tunnel

Old LEP remnant. Now: tunnel has a detour.



LHC Infrastructure - The TI18 Tunnel

Beam line passes through TI18

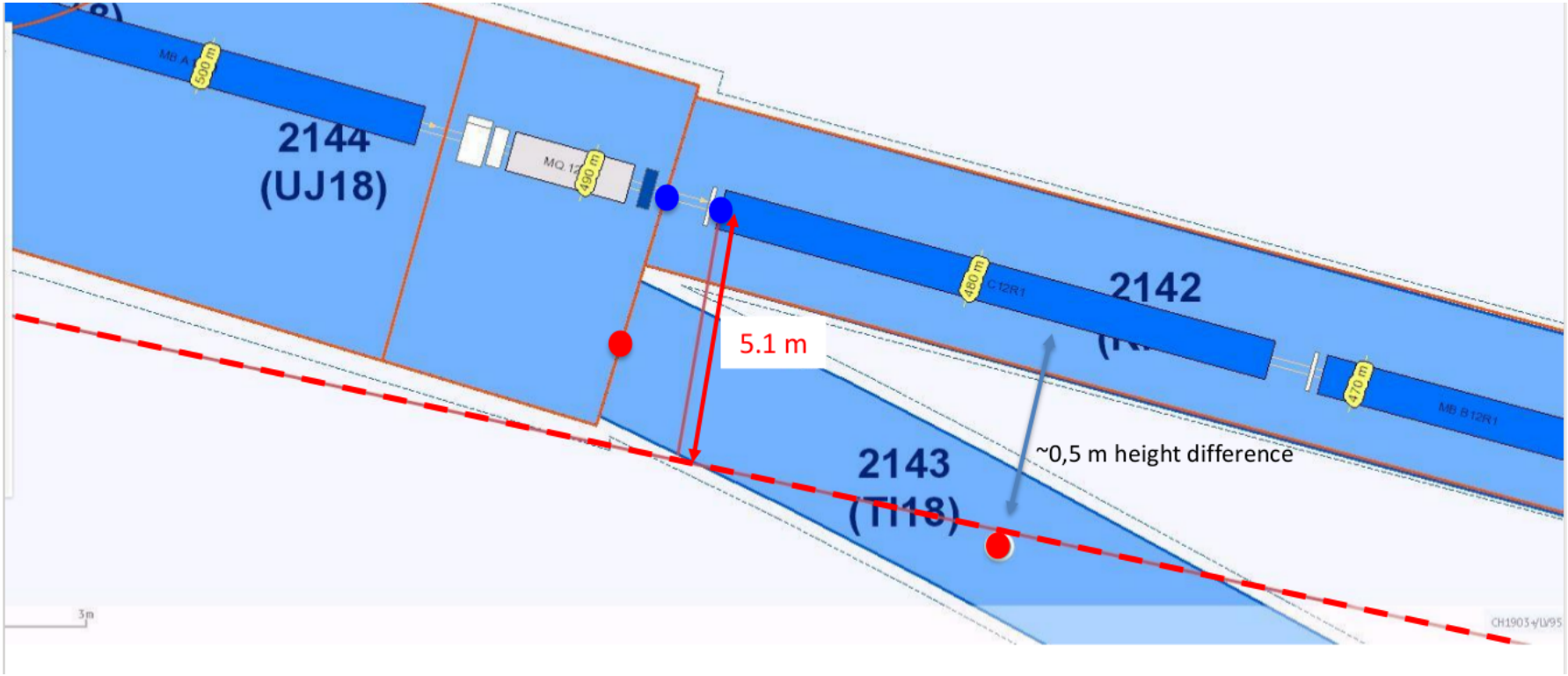


Image by Mike Lamont

LHC Infrastructure - The TI18 Tunnel

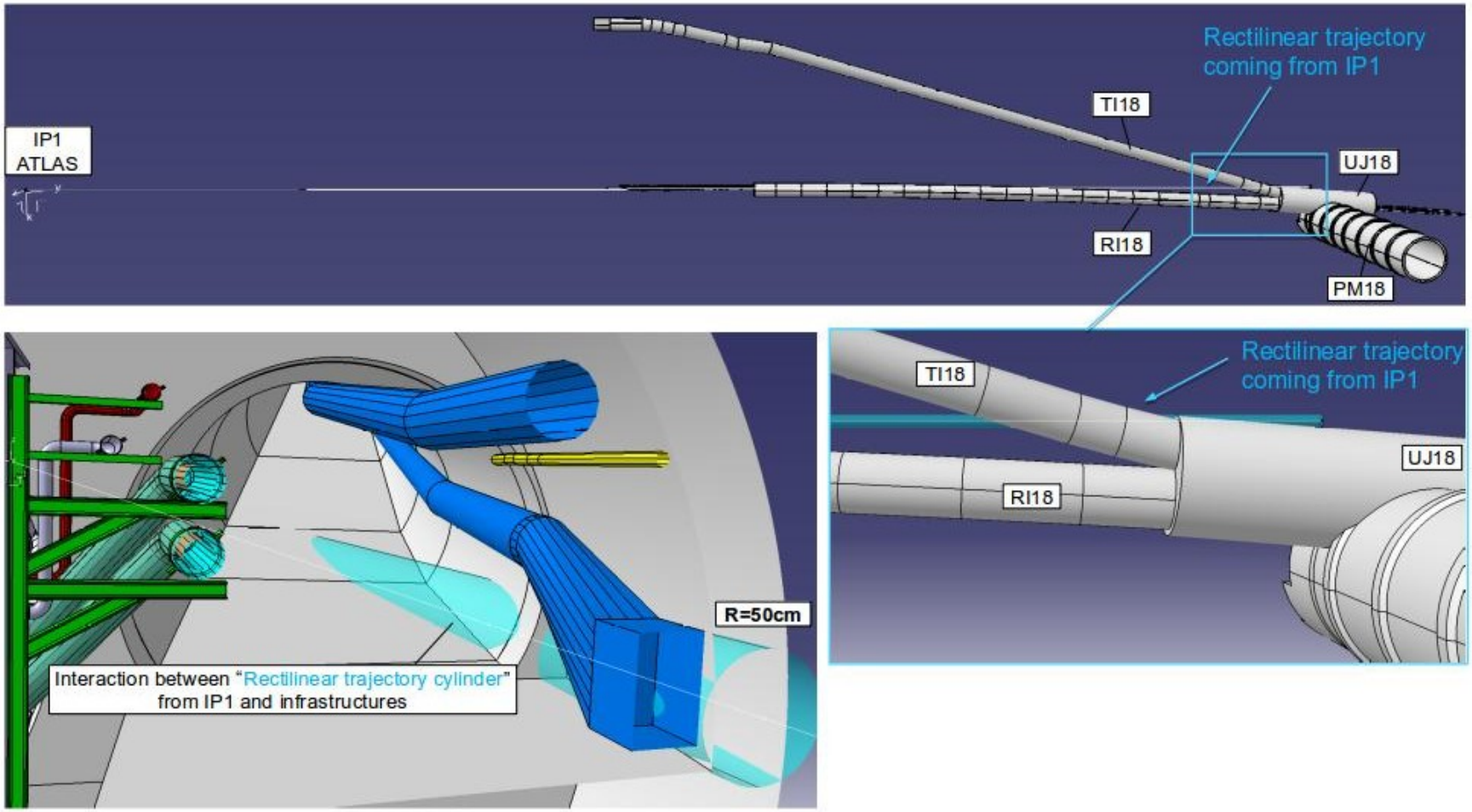
The UJ18 hallway

LHC Infrastructure - The TI18 Tunnel

The TI18 tunnel. Note the incline $\sim 0.5\ \mathrm{m}$

LHC Infrastructure - The TI18 Tunnel

The TI18 tunnel in FLUKA geometry + line-of-sight intersection



Images by F. Cerutti

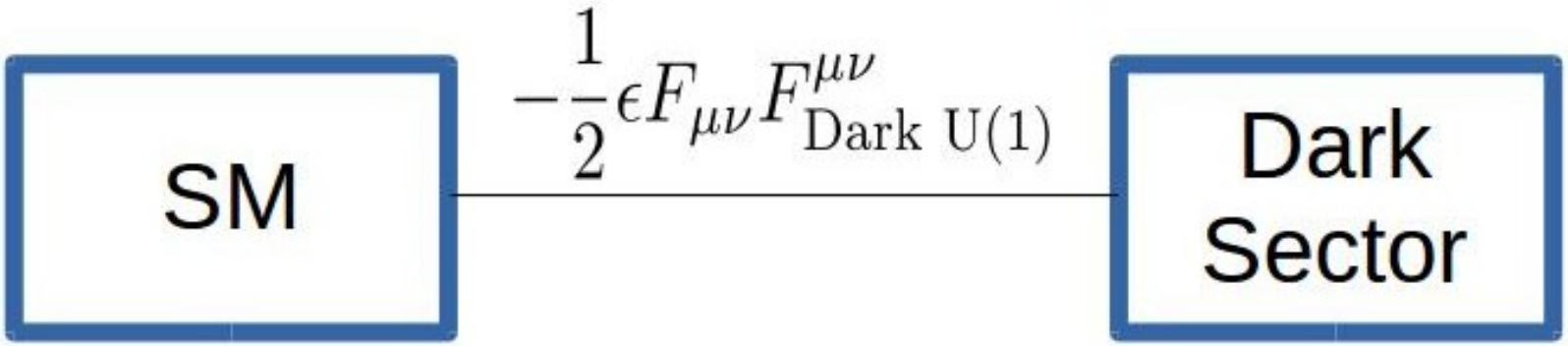
Learn by example: The Dark Photon Physics Case

Other models studied:
Dark Higgses, Feng, IG, Kling, Trojanowski arXiv:1710.09387
HNLs, Kling, Trojanowski arXiv:1801.08947

Current work:
ALPs, Feng, IG, Kling, Trojanowski
iDM, Kling & Berlin

Dark Photon - Model Characteristics

- General motivation - Dark Matter $\Longrightarrow$ Dark Sector
- The Vector portal



- After field redefinition, and bringing to canonical form

$$\mathcal{L}_{\text{int}} \supset -\epsilon e A'_\mu J^\mu_{\text{EM}}$$

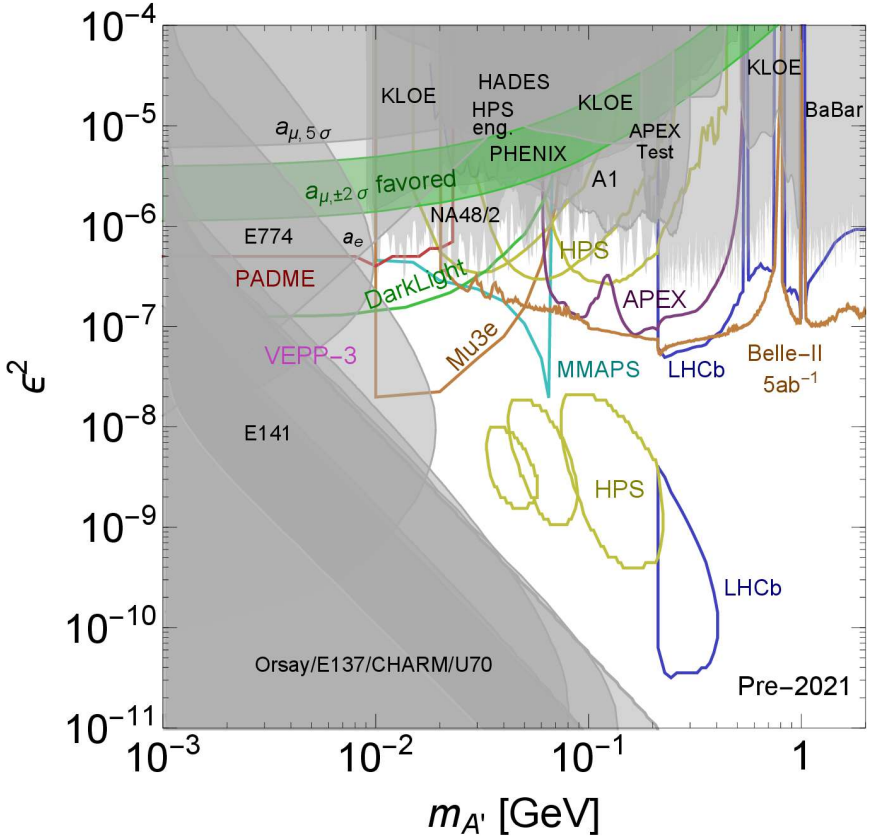
i.e., the A' inherits the photon couplings to fermions: $-\epsilon e Q_f \bar{\psi} \not{A}' \psi$

assuming $m_{A'} \ll m_Z$ the mixing is primarily with the photon. For heavier masses, there could be a dark Z'

Dark Photon - Model Characteristics

- Dark Photon production $\sigma \propto \epsilon^2$
- Dark Photon decay width
  $$\Gamma_{A'} = \frac{\epsilon^2 e^2 m_{A'}}{12\pi B_e(m_{A'})}\left[1-\left(\frac{2m_e}{m_{A'}}\right)^2\right]^{1/2}\left[1+\frac{2m_e^2}{m_{A'}^2}\right]$$
- Dark Photon mean propagation distance
  $$\bar{d} \approx (80\ \mathrm{m})\ B_e\left[\frac{10^{-5}}{\epsilon}\right]^2\left[\frac{E_{A'}}{\mathrm{TeV}}\right]\left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2$$
- competing effects: production & propagation
- swath of uncovered parameter-space
  $$\begin{cases} m_{A'} > 10\ \mathrm{MeV} \\ 10^{-6} < \epsilon < 10^{-3} \end{cases}$$

Current status for visibly decaying A'



US Cosmic Visions 2017

Production in the forward region of pp-collisions

- Hadron decays: $h \to A'X$, primarily light neutral mesons
  Decay driven by the chiral anomaly

$$\begin{cases} B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma) \\ B(\eta \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_\eta^2}\right)^3 B(\eta \to \gamma\gamma) \end{cases}$$

  other modes are Phase-Space suppressed or have small branching fraction to γs

- A'-bremsstrahlung in coherent-proton scattering, $pp \to ppA'$

  evaluated in the FWW approximation

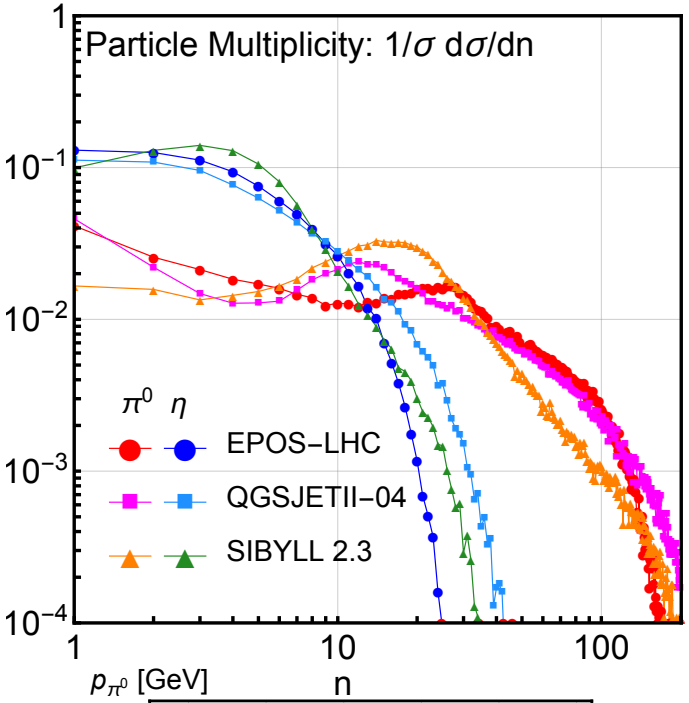
- QCD-like hard-processes

  large uncertainties of PDFs at low-Q^2, and small x

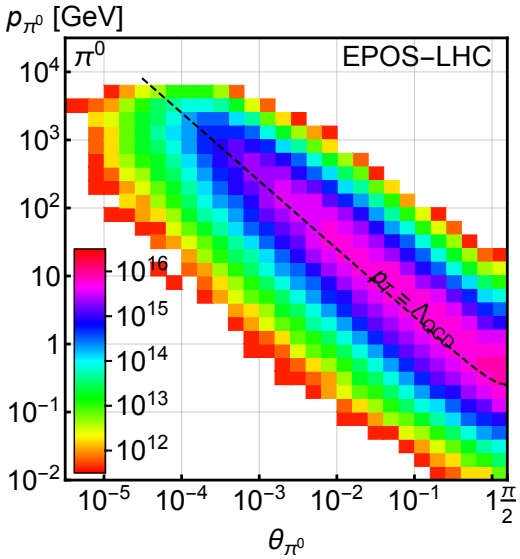
Production in the forward region of *pp*-collisions

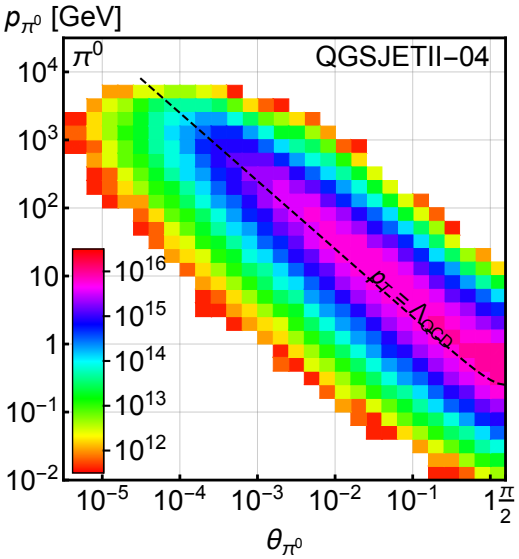
The forward hadronic spectrum

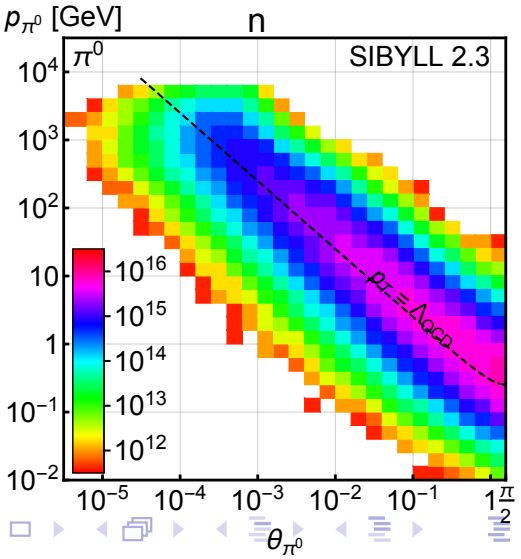
- Traditionally - from UHECR
- Recently: LHCf, TOTEM, ALFA, CASTOR MC's tuned to new data ⇒ now consistent



At $\mathcal{L}^{\rm int} = 300\ {\rm fb}^{-1}$, $N_\pi \sim 10^{17}$!!!

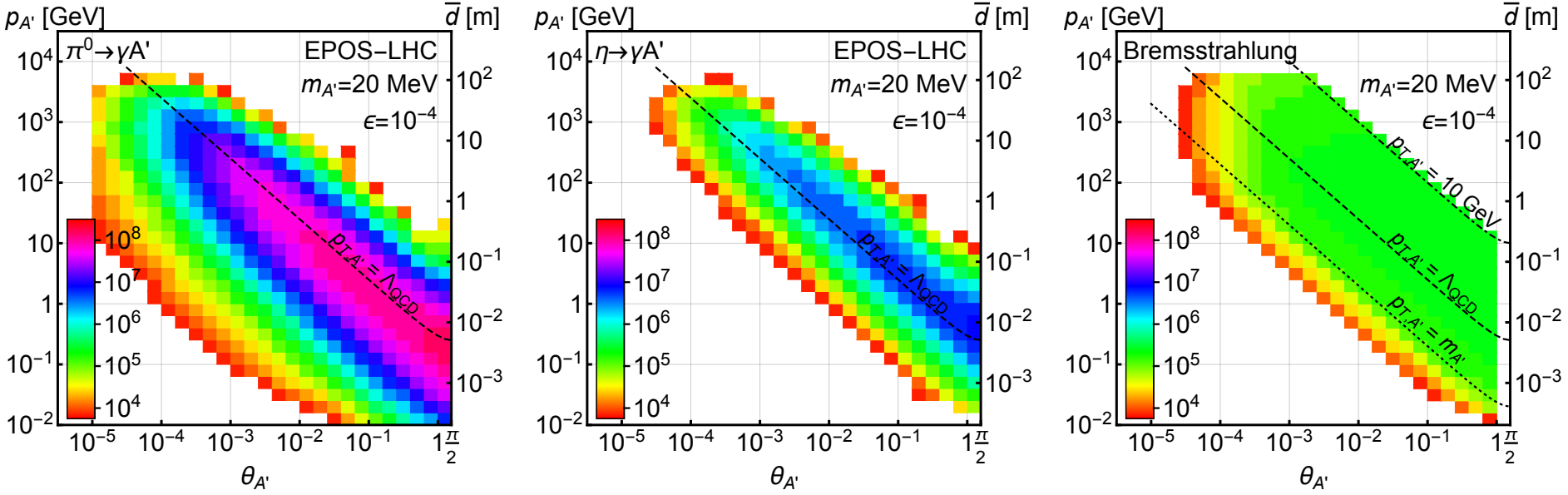






Production in the forward region of *pp*-collisions

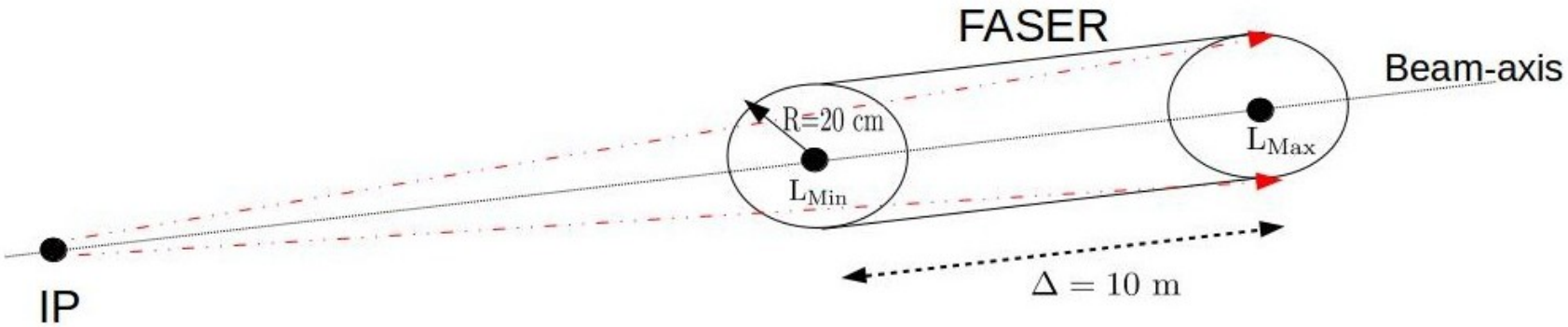
Representative point: $\epsilon = 10^{-4}$, $m_{A'} = 20$ MeV



Note:

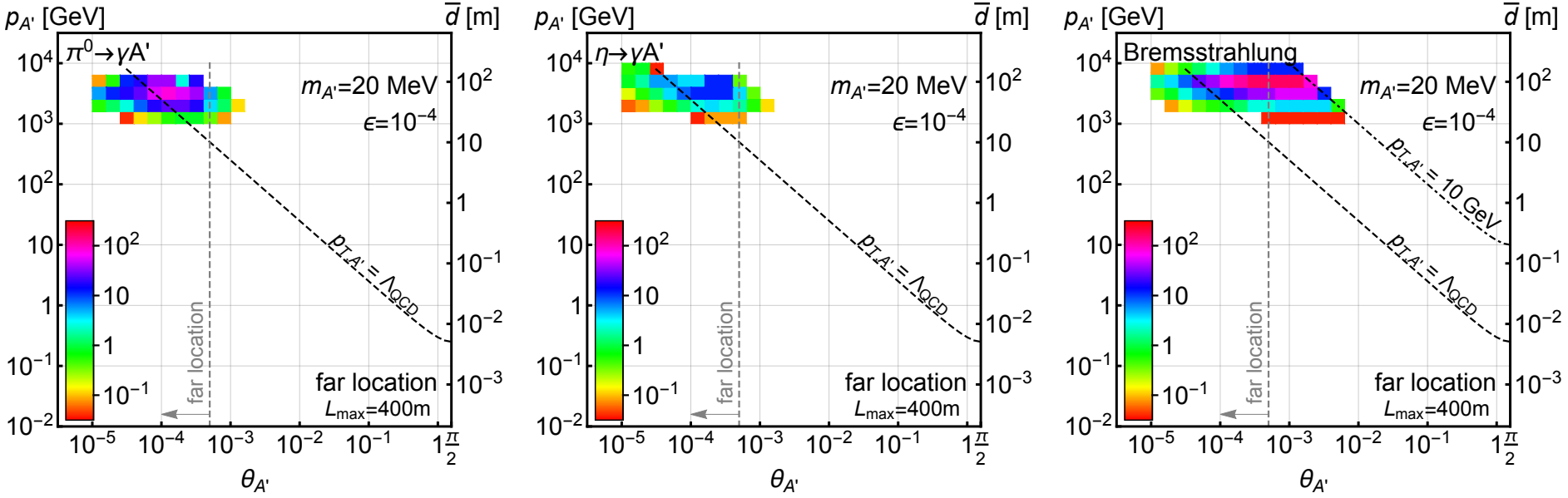
- "inherited" spectra, $p_{A'}^{\rm lab}| \approx \frac{1}{2} p_{\pi^0,\eta}[1 + \cos\theta_{A'} + (m_{A'}^2/m_{\pi^0,\eta}^2)(1 - \cos\theta_{A'})]$
- spectra centered around $p_T \sim \Lambda_{QCD}$
- bremsstrahlung spectrum $\sim 1/p_{TA'}^2$, $Q^2 > \Lambda_{QCD}^2$

Detector considerations



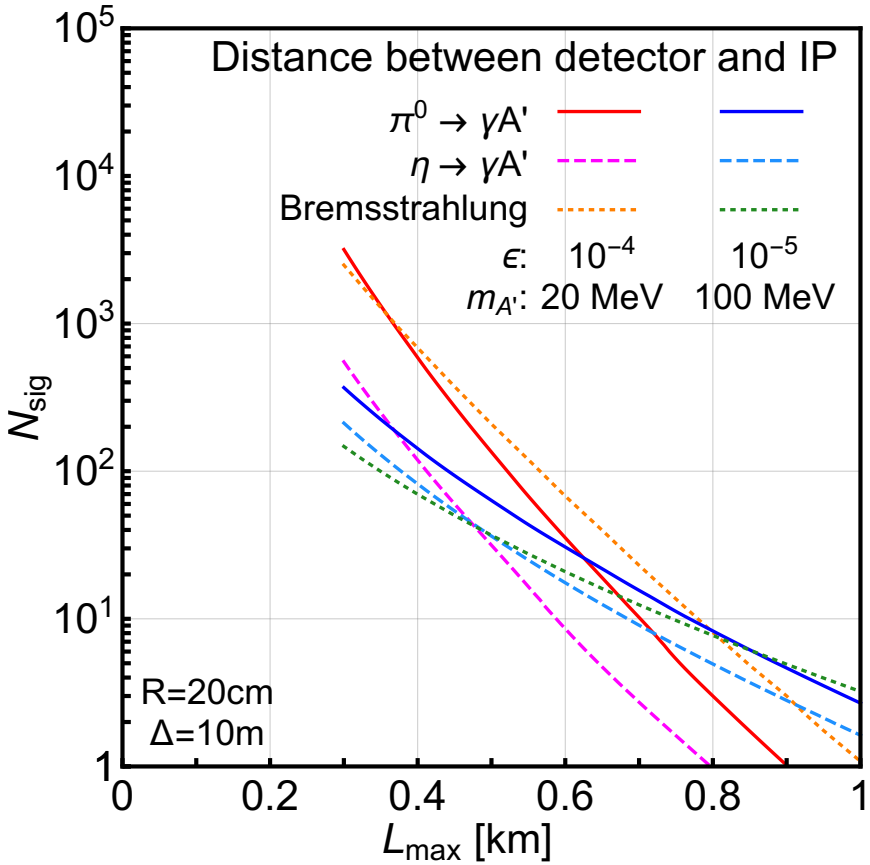
Decay-in-volume probability

$$\mathcal{P}^{det}_{A'}(p_{A'}, \theta_{A'}) = \left(e^{-L_{\rm min}/\bar{d}} - e^{-L_{\rm max}/\bar{d}}\right)\,\Theta(R - \tan\theta_{A'} L_{\rm max})$$

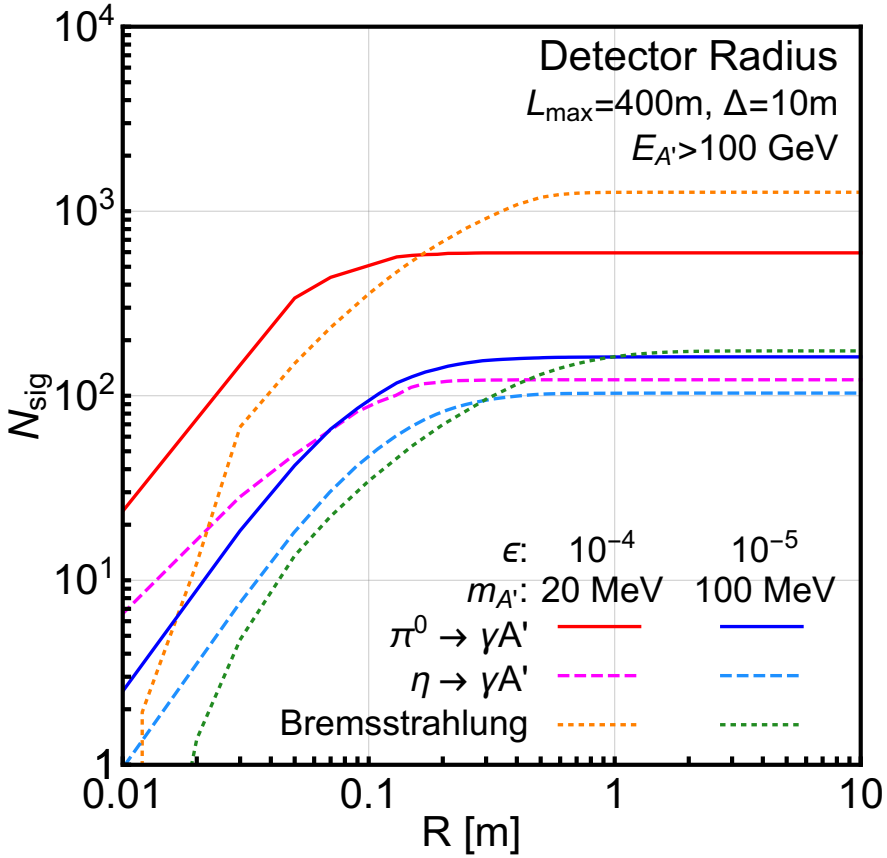


Many surviving A''s, mostly with high-energy

Detector considerations



- larger ϵ ⇒higher rate closer to IP
- larger ϵ ⇒drops faster away from IP



- $p_T \sim \Lambda_{QCD} \Rightarrow \pi^0,\ \eta$ contribution saturates quickly
- Bremsstrahlung saturates slower

Detector considerations

Signal Characteristics:

- two simultaneous opposite charge tracks with $E > 500\ \mathrm{GeV}$
- tracks meet at a vertex inside decay volume
- combined momentum points back to IP
- small opening angle: $\theta_{tracks} \sim m_{A'}/E_{A'}$
  for $m_{A'} = 100\ \mathrm{MeV}$, $E_{A'} = \mathrm{TeV} \Rightarrow \theta_{\mathrm{tracks}} = 100\mu\mathrm{rad}$

Requirements

- High granularity detector: pixel, strips ...
- magnetic field $h_B \approx \frac{ec\ell^2}{E} B = 3\ \mathrm{mm} \left[\frac{1\ \mathrm{TeV}}{\mathrm{E}}\right] \left[\frac{\ell}{10\ \mathrm{m}}\right]^2 \left[\frac{\mathrm{B}}{0.1\ \mathrm{T}}\right]$
- magnetic field: rough energy estimate (TeV vs. GeV)
- can be probably achieved with $0.1\mathrm{T}$

Backgrounds

LHC & FASER location natural filter

- Magnets deflect charged particles away from FASER
- LHC Absorbers & rock surrounding FASER provide shielding
- cosmic rays have typically wrong directionality, wrong energy (rock shielding), or cannot give two-simultaneous tracks

Most particles are either deflected or absorbed

What's left ?

- Neutrino induced backgrounds
- Beam induced backgrounds

Backgrounds - Summary

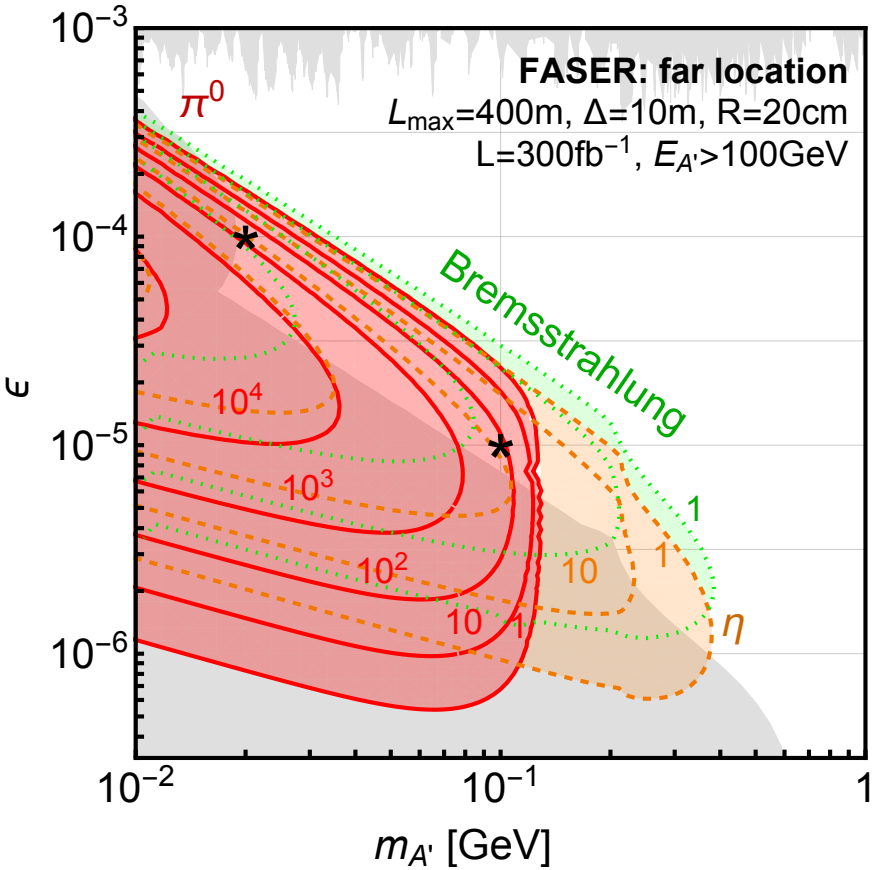
No significant background identified - "Zero-background" ?

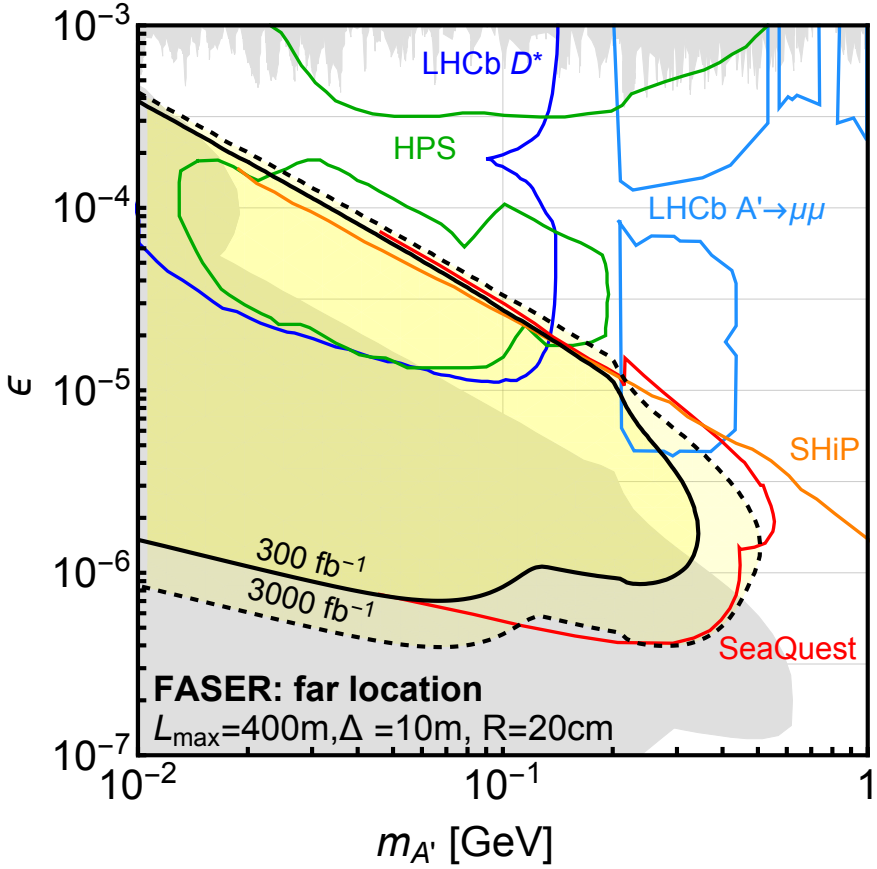
For a reliable estimate:

- Experimental data ⇒ put prototype
- detailed simulation tools: FLUKA, MARS with full LHC geometry in place.

Use results to (re-)optimize detector

Yield & sensitivity reach



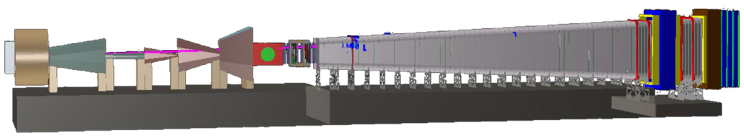


- $\sim$ 100% 2-track decays: $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$
- large ϵ (or $m_{A'}$) $\Rightarrow$ prompt
- smaller ϵ (or $m_{A'}$) $\Rightarrow$ long-lived
- competes with production $\sigma \propto \epsilon^2$

- assumes: 0-Bkg, 100%-eff
- Similar reach for small, known, and well-understood Bgk's
- upper reach similar to Seaquest, and SHIP, $(m_{A'}\epsilon)^2 \propto L_{\max}/p$

Complementary experimental ideas

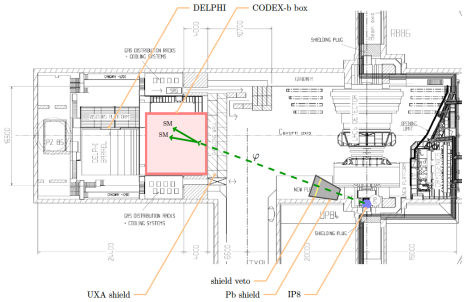
SHIP



$\sim 1000\ \mathrm{m}^3$, $\sim 100M$ CHF

Alekhin et al. (2015)

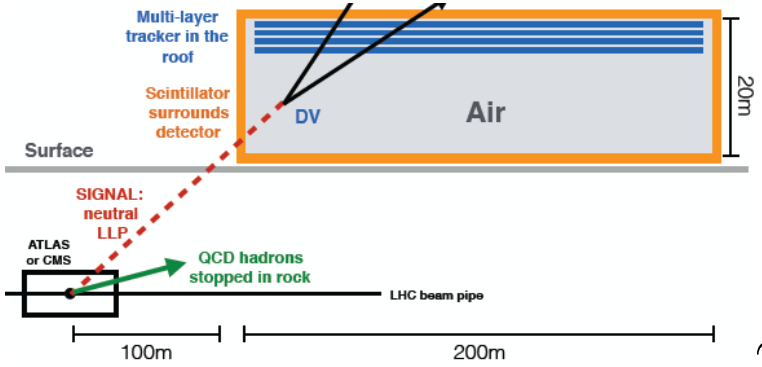
CODEX-b



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

Gligorov, Knapen, Papucci, Robinson (2016)

MATHUSLA



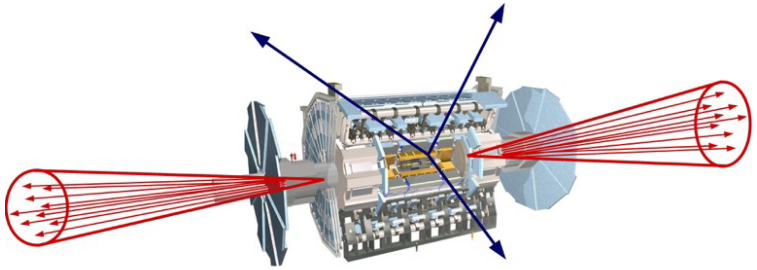
$\sim$

$2 \times 10^5\ \mathrm{m}^3 \sim$1 IKEA, \$50M

Chou, Curtin & Lubatti (2016)

Curtin & Peskin (2017)

FASER



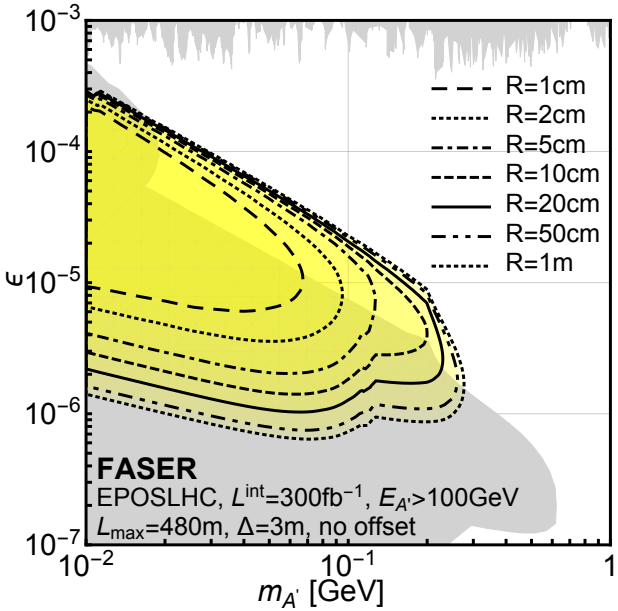
$\sim 1\ \mathrm{m}^3 \sim 5\mu$IKEAs

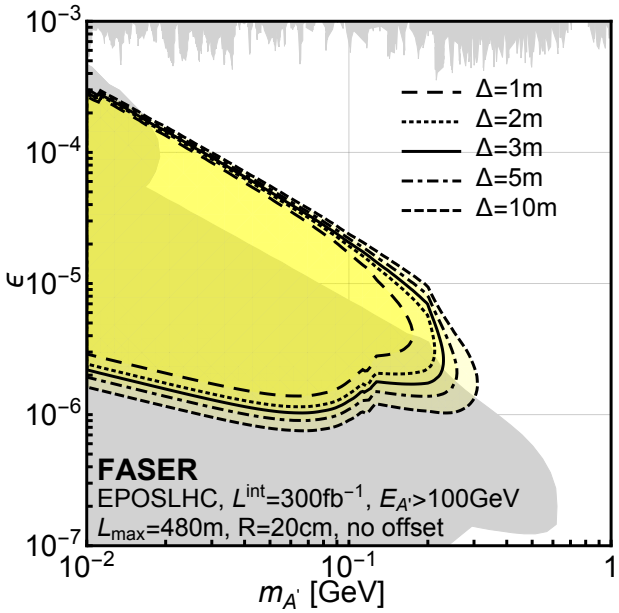
Feng, Galon, Kling & Trojanowski (2017)

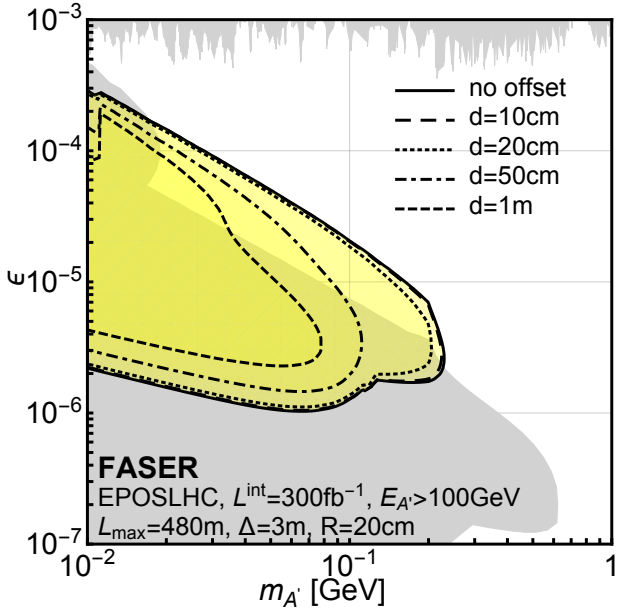
Outlook

- The FASER collaboration is broadening
- Real life considerations for detector-optimization
  - Location constraints: line of sight exact intercept with tunnel
  - Detector geometry : fiducial volume, radius
  - Technology: pixel, strips, caloremeter ...
  - magnetic field vs. resolution
  - preliminary Geant4 simulation underway (D. Casper, S. Hsu)
  - cost $$$
- Joined the CERN PBC study
- Background study underway by CERN radiation study group

Sensitivity reach Vs. Optimization







- optimal radius differs between models $A' \to R \sim 20$ cm, $\phi \to R \sim 1$ m
- location determines maximal radius
- radius affects cost as r^2

- location in TI18 determines fiducial volume
- $\Delta = 10$ m $\to 3$ m similar reach
- future: possible civil engineering effort during LS3

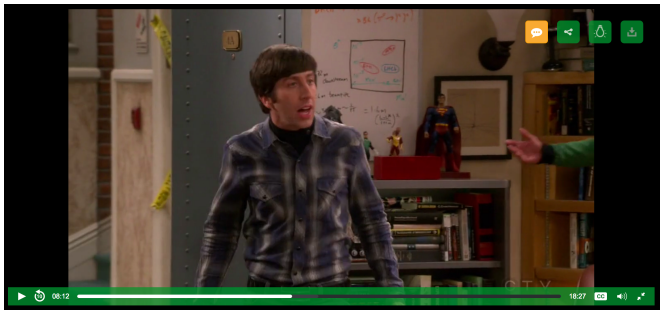
offset from line-of-sight:

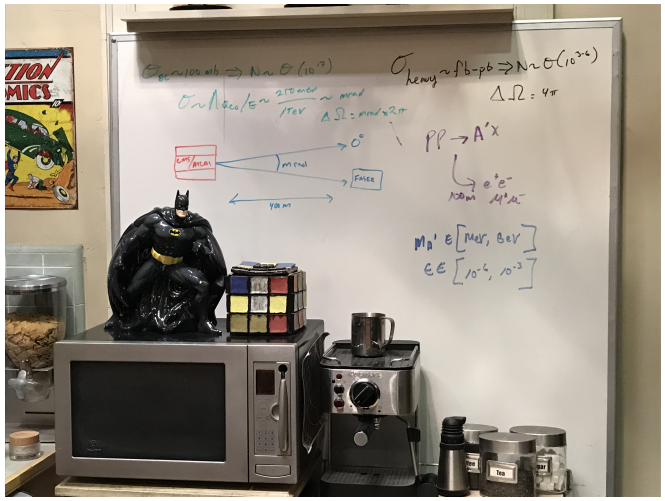
- beam crossing-angle changes
- l.o.s intersection in tunnel limitations (goes through floor)
- at $d \sim 20$ cm is still ok

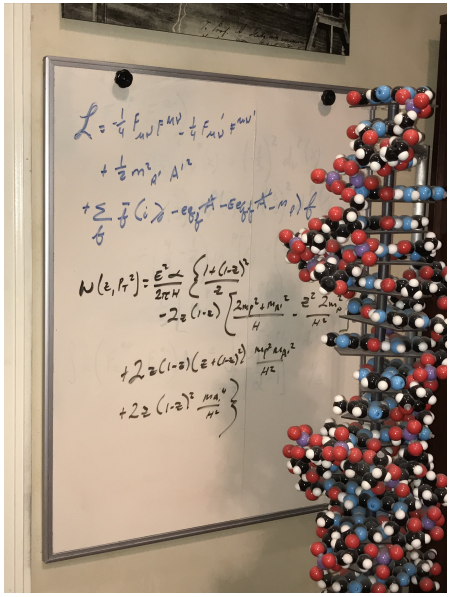
Conclusions

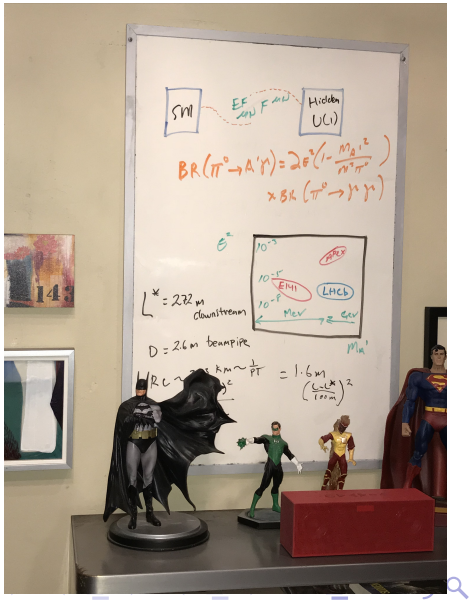
- The null results of NP searches at the high-p_T region of pp-collisions at the LHC are disappointing, and call for new ideas to hunt for NP.
- FASER will be a small, relatively cheap, extremely forward detector, running concurrently with the LHC. It will be sensitive to a large swath of parameter-space in a variety of NP models, and benefit from:
  - the high pp-collision event rate
  - the filtering of background by the LHC
  - the high c.o.m energy which results in large boosts and distinct signatures
- The plan is to get a prototype during LS2 (2019-2020), and full detector in LS3 for the HL-LHC phase

Thank You - BBT, a SoCal advantage





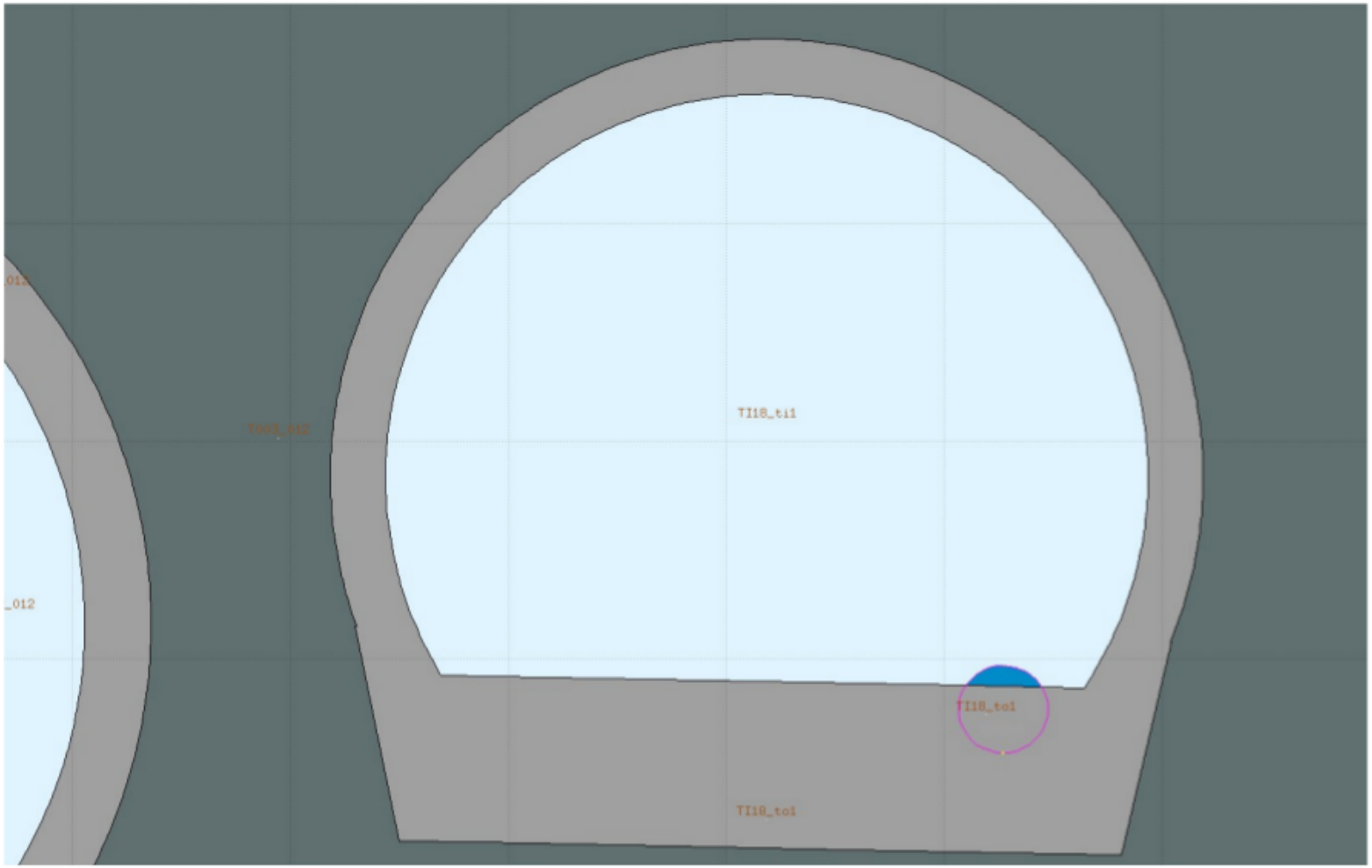




Backup Slides

FLUKA Modeling

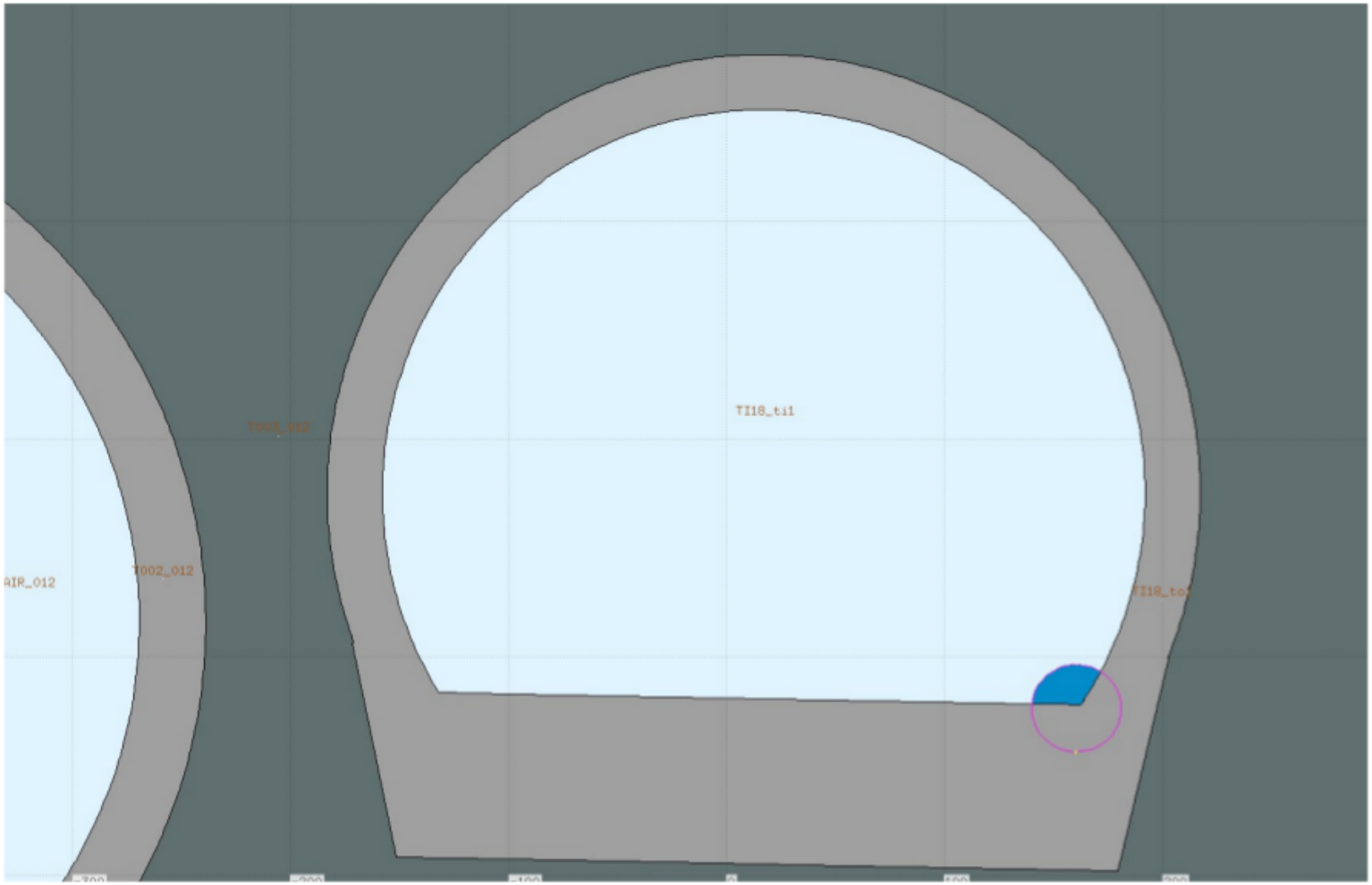
Centered at 483.45 m from IP1



by Francesco Cerutti

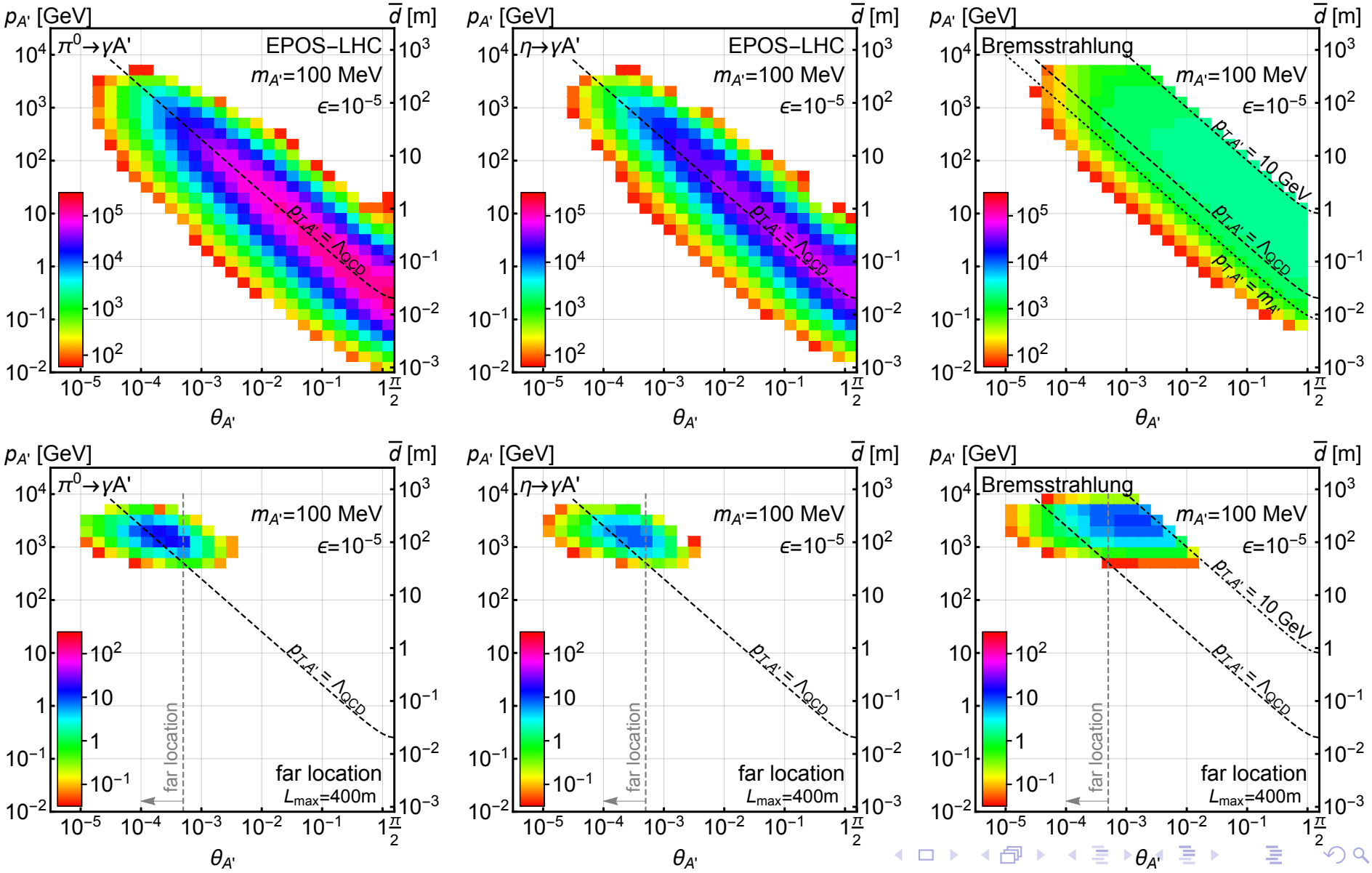
FLUKA Modeling

Centered at 484.85 m from IP1



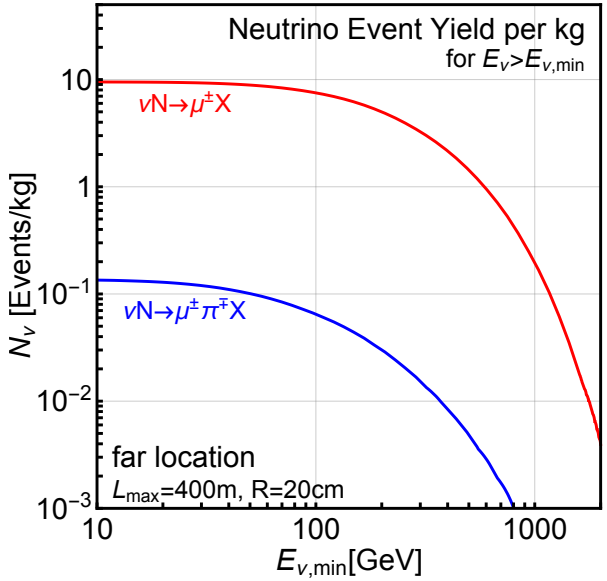
by Francesco Cerutti

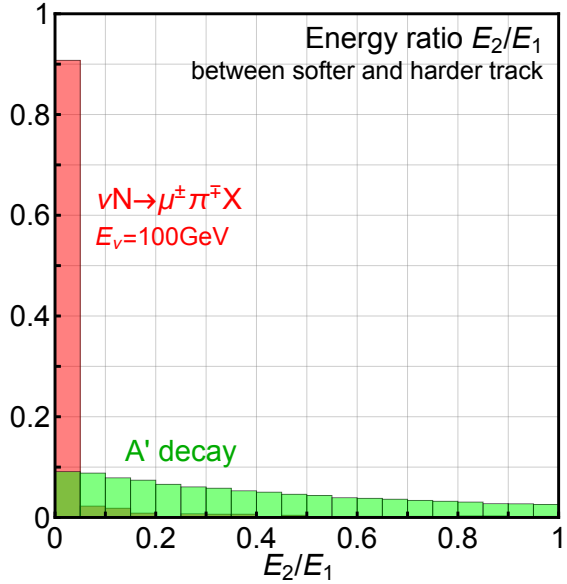
Alternative point: $\epsilon = 10^{-5}$, $m_{A'} = 100$ MeV



Neutrino Induced Backgrounds

- Neutrino source: mainly from ν_μ in $\pi^\pm$ decays-in-flight before D1 magnet
- similar contribution from heavier mesons (arXiv:1110.1971)
- νs propagate towards FASER and interact with the material inside or before the detector
- $\nu N \to \mu X \sim 8/\text{kg}$ detector for $E > 100$ GeV
- <u>2-track events:</u> $\nu N \to \mu\pi X \sim 10^{-1}/\text{kg}$
- low nuclear recoil: π-soft, $\to E_\pi/E_\mu < 0.05$
- Similarly: $\nu \to K_{L,S}$ contribute negligibly





Background estimates - back of the envelope

Neutrino background:

$$N_\pi \Big|_{\begin{cases} E_\pi > 1 \text{ TeV} \\ \theta_\pi < 0.5 \text{ mrad} \end{cases}} \sim 10^{15}$$

Probability to decay before the D1 magnet

$$P_\pi = 1 - \exp\left(-\frac{L_{\text{D1}}\, m_{\pi^\pm}}{p_{\pi^\pm}\tau_{\pi^\pm}}\right) \approx 10^{-3}\left[\frac{\text{TeV}}{p_{\pi^\pm}}\right]$$

with $L_{D1} \approx 59$ m, $\text{p}_\pi = 1$ TeV, $\tau_\pi = 2.6 \times 10^{-8}$s

$$P_\nu \simeq \Delta\ \sigma(E_\nu)\,\rho_{\text{det}}\, N_A \simeq 6 \times 10^{-12}\left[\frac{\sigma(E_\nu)}{10^{-35}\ \text{cm}^2}\right]\left[\frac{0.1\ \text{m}^2}{A_{\text{det}}}\right]\left[\frac{M_{\text{det}}}{1\ \text{kg}}\right],$$

Then

$$N_\pi P_\pi P_\nu \sim 10/\text{kg}$$

for $\mathcal{L}^{int} = 300$ fb^{-1} and $E_\nu \sim 200$ GeV

Beam Induced Backgrounds

- Particles from IP direction must pass magnets & $\sim$ 50 m of rock
  $\Rightarrow$ only muons could be relevant
- ATLAS beam-gas induced background study (2011)
  $\Rightarrow \Phi \sim 10^{-3}\mathrm{Hz/cm}^2$ for $E_\mu > 100\ \mathrm{GeV}$
  typically deflected
- Upper bound on coincident muons: $\sim$ 0.1(0.01) per LHC-year given a detector resolution of 100(10) ps.

muons arrival corresponds to bunch crossings: 25 ns bunch spacing and 1 ns bunch crossing time

Background estimates - back of the envelope

$$P_{\delta t} = \Phi A_{\text{det}} \frac{t_{\text{spacing}}}{t_{\text{bunch}}} \delta t \sim 3 \times 10^{-9}$$

Assume Poisson distribution

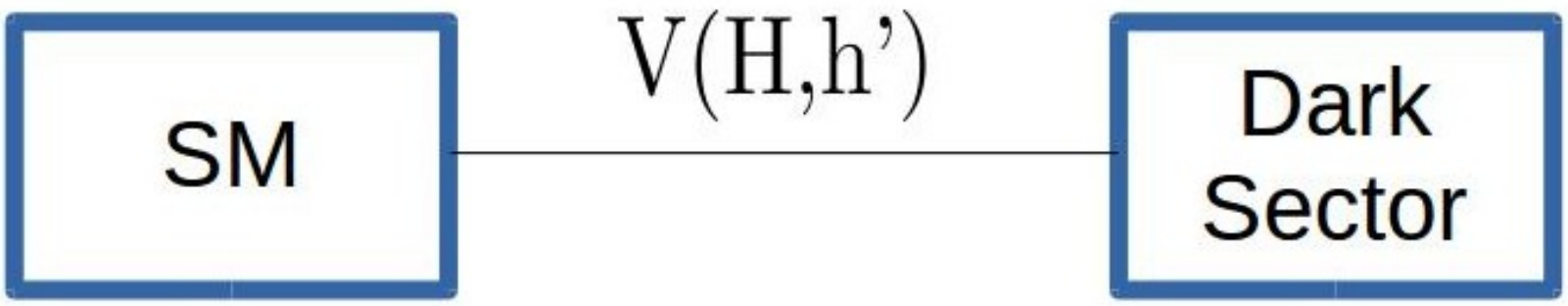
$$N_{\mu^+\mu^-} = P_{\delta t}^2 \, T / \left(\delta t \, \frac{t_{\text{spacing}}}{t_{\text{bunch}}} \right) \sim 0.1$$

with $T \sim 10^7$ for an LHC year and $\frac{t_{\text{spacing}}}{t_{\text{bunch}}} = 25$, $\delta t = 10 \text{ ps}$, and $A_{\text{det}} = \pi (0.2 \text{ cm})^2 \approx 1300 \text{ cm}^2$

Other models

Dark Higgses

- The Higgs portal



- After EWSB, can be reparameterized as

$$\mathcal{L} \supset -\frac{1}{2} m_\phi^2 \phi^2 - \sin\theta \frac{m_\psi}{v} \phi \bar{\psi} \psi - \lambda v h \phi \phi + \ldots$$

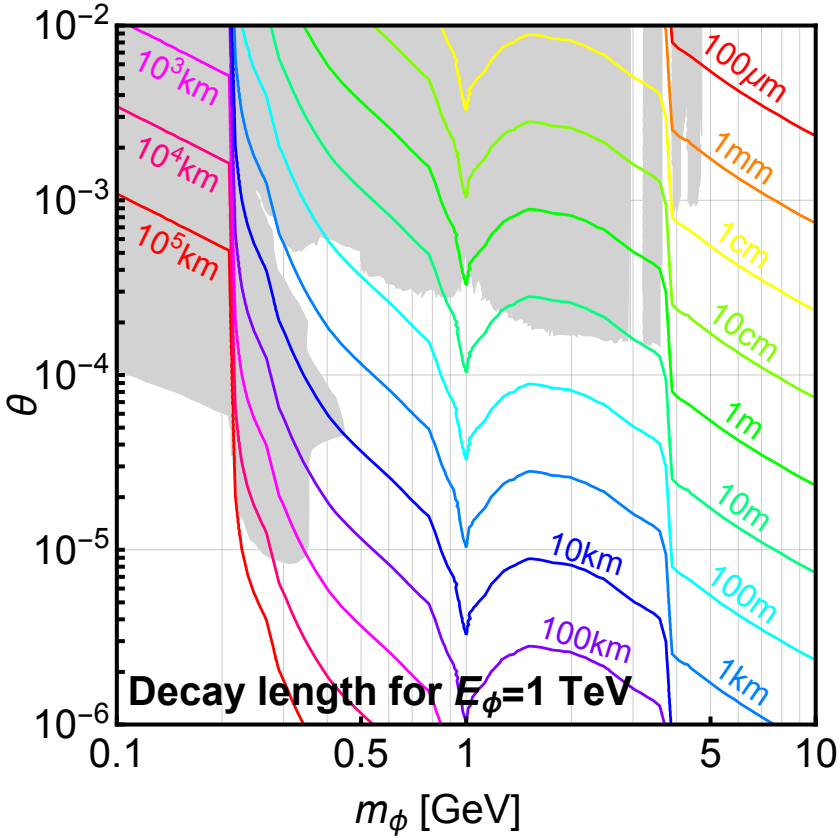
Couples to mass. $\sin\theta \sim \theta \ll 1$

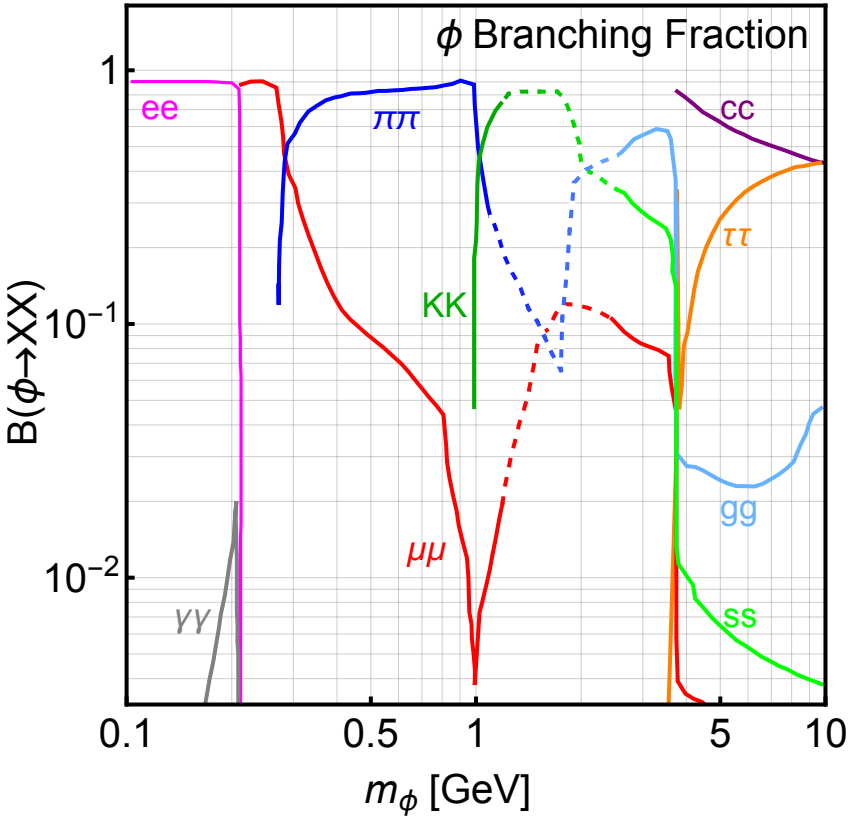
Dark Higgses

@LHC: Production: $N_B \ll N_K \sim N_\pi$

Decay: $B(B \to \phi) \gg B(K \to \phi) \gg B(\eta, \pi \to \phi)$

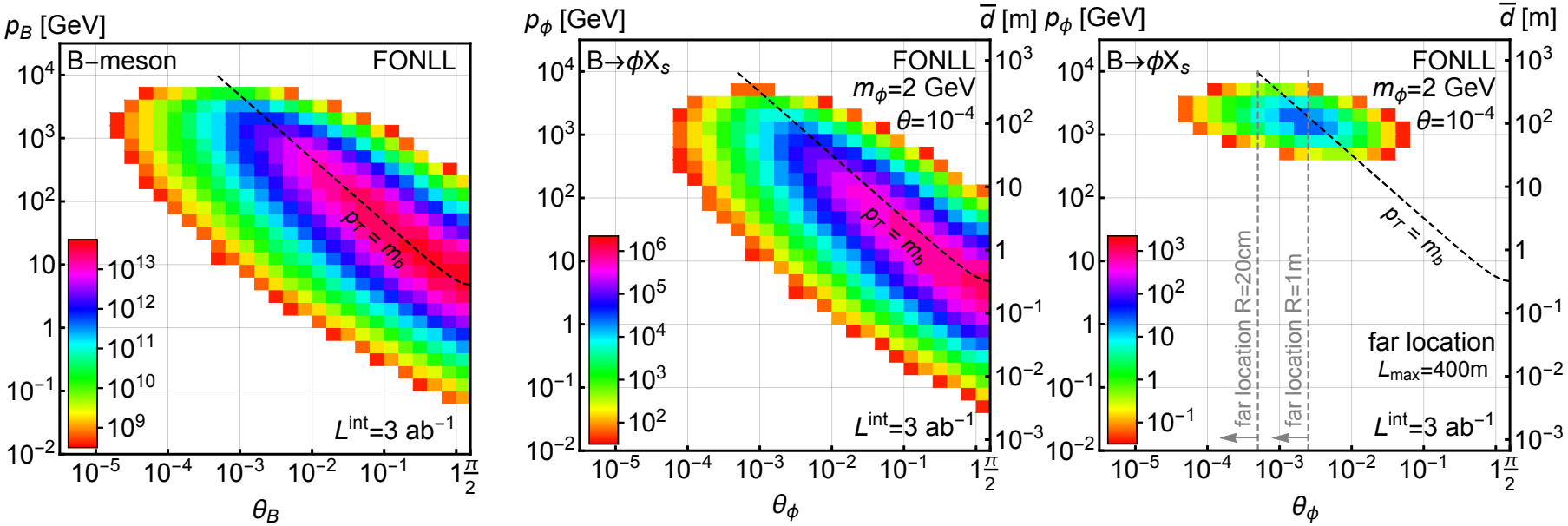
$\Longrightarrow$ B & K are the dominant decay modes





Dark Higgses - via B-mesons

- $B(B \to X_s \phi) \simeq 5.7 \left(1 - \frac{m_\phi^2}{m_b^2}\right)^2 \theta^2$
- simulate B spectrum with FONLL

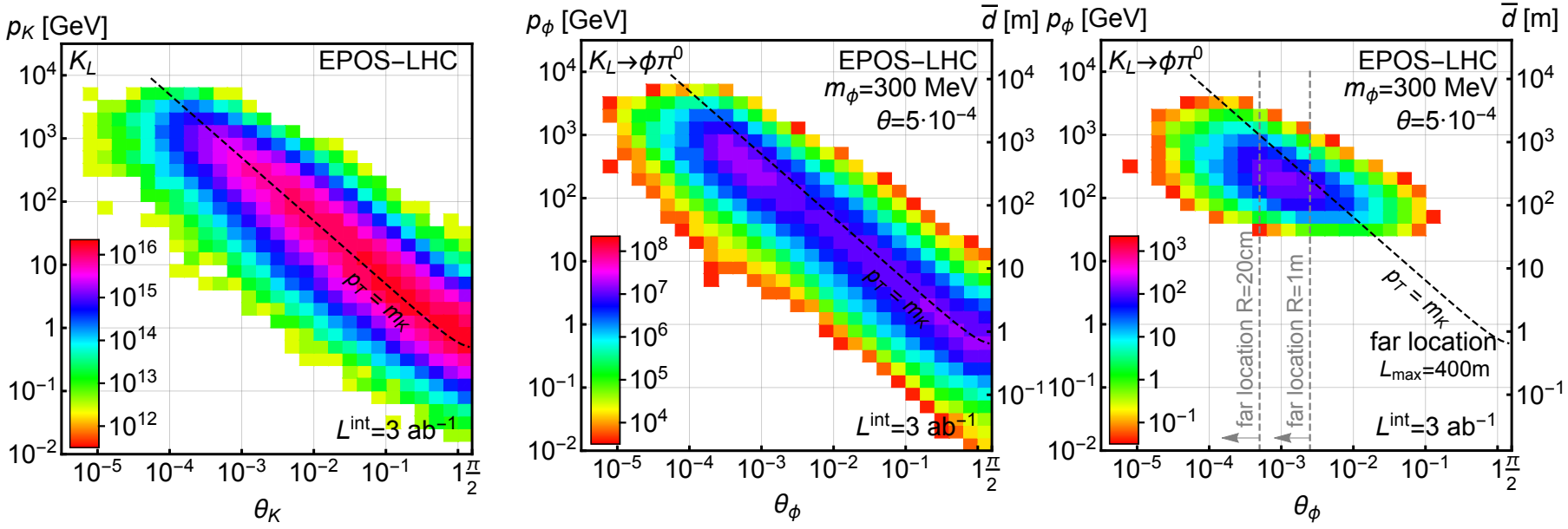


- B-mesons: $p_T \sim m_b$
- ϕ's not as collimated as A''s

Dark Higgses - via K-mesons

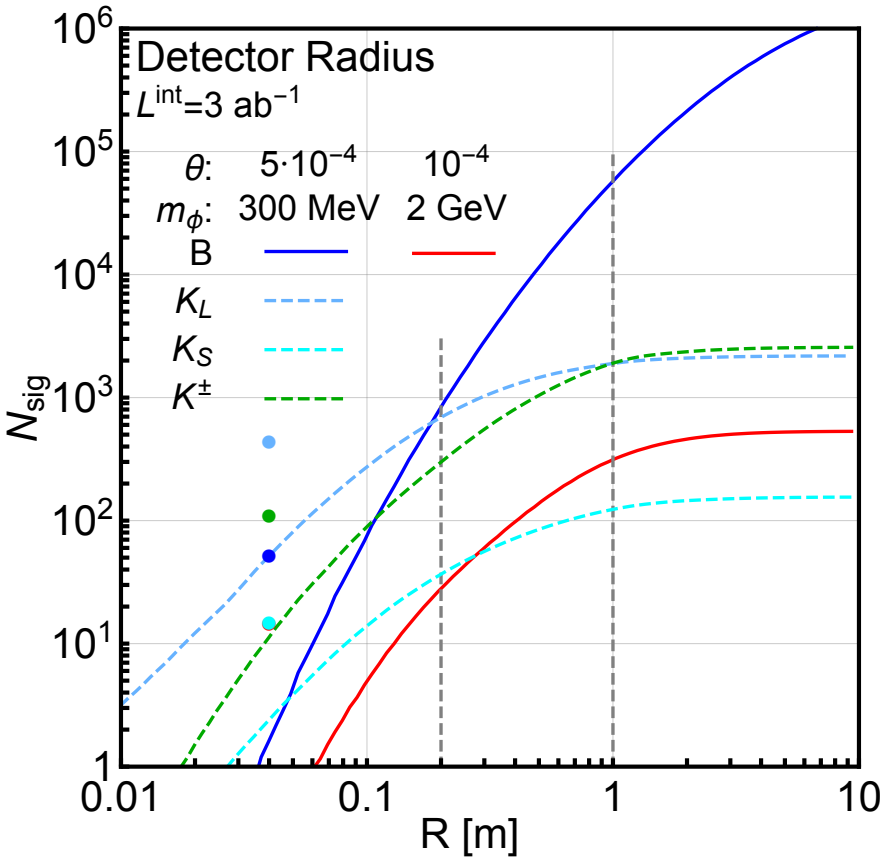
$$B\left(\begin{cases} K^{\pm} \to \pi^{\pm}\phi \\ K_L \to \pi^0\phi \\ K_S \to \pi^0\phi \end{cases}\right) = \left(\begin{cases} 2.0 \times 10^{-3} \\ 7.0 \times 10^{-3} \\ 2.2 \times 10^{-6} \end{cases}\right) \frac{2p_\phi^0}{m_K}\,\theta^2$$

p_ϕ^0 - dark higgs momentum in the Kaon rest frame

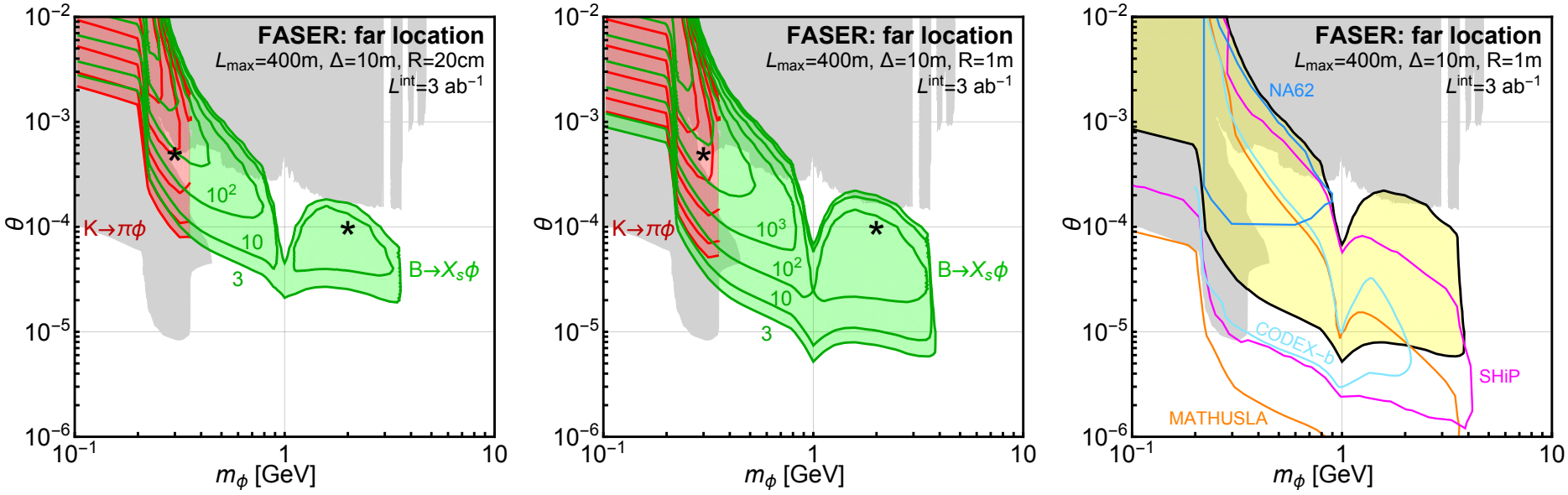


Dark Higgses - detector considerations

- K's, B's heavier than π's, η's
- Yield slowly saturates with R
- $\Uparrow p_T \rightarrow \Uparrow R$ more efficient



Dark Higgses - Yield & sensitivity reach



- For dark higgs ⇒ better coverage with a bigger detector $R = 1\ \mathrm{m}$
- Parameter space ⇒ complementarity of proposed experiments
  Sensitivity: $2m_\mu < m_\phi < 2m_\tau$ (not too prompt/long-lived)
- SHIP is better at longer lifetimes, where it does not require large boosts:
  $E_\phi^{max-SHIP} = 400\ \mathrm{GeV}$, $E_\phi^{mean-SHIP} = 25\ \mathrm{GeV}$
- Example: $\theta = 10^{-4} \Rightarrow E \sim \mathrm{TeV}$ for $\bar{d} = L_{\mathrm{max}}^{\mathrm{SHIP}} = 120\ \mathrm{m} \Rightarrow \exp(-\mathrm{TeV}/\mathrm{E}_\phi)$ suppression
- lower θ's need lower E_ϕ's
  @FASER - overshoot/not in angular cone, @SHIP - sensitive with lower E_ϕ's

Axion Like Particles (ALP) - Preliminary

Non renomalizable portal Focus on

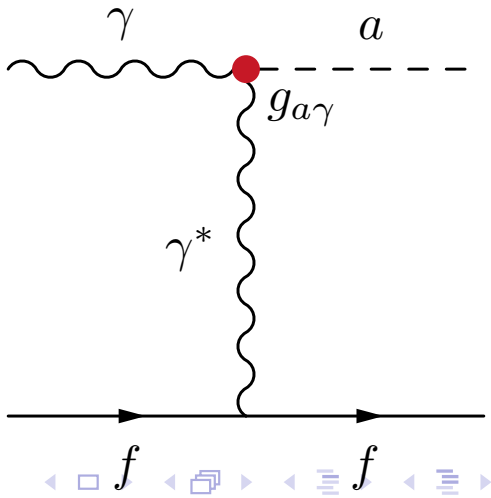
$$\mathcal{L} \supset -\frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu} + \ldots$$

- @beam-dumps: "ALPtraum": $p\ Nuc \to p\ Nuc\ a$
- @LHC: does not work $\to$ forced to fixed-target kinematics

<u>Instead:</u>

LHC+FASER = photon beam-dump

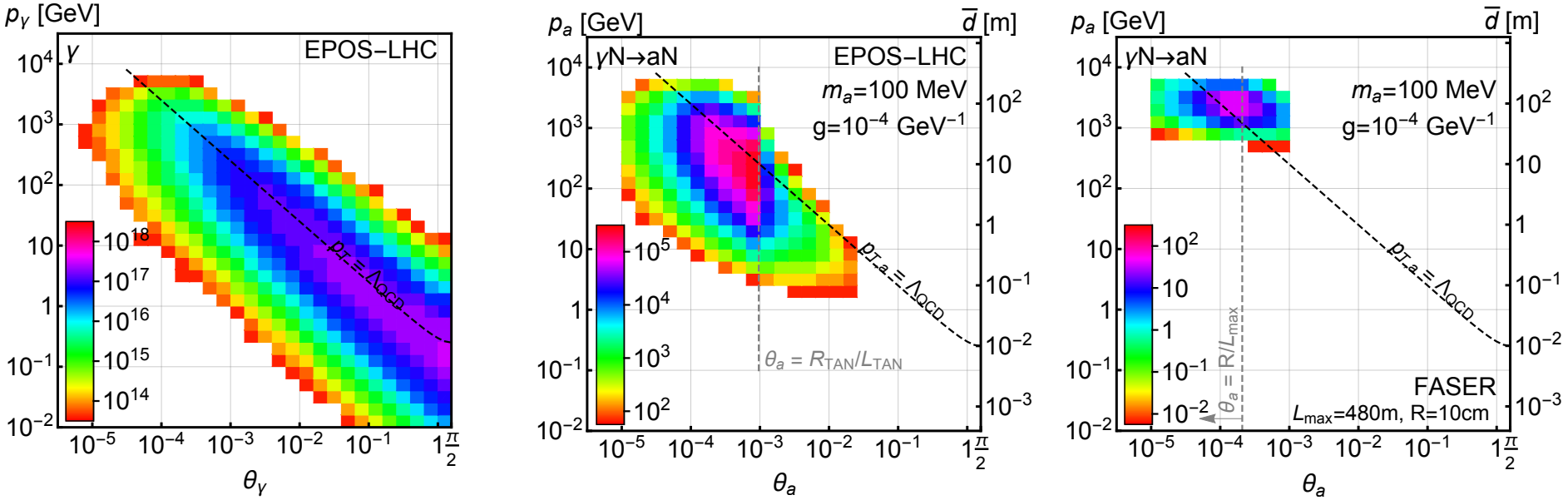
- Huge forward γ flux
- TAN / TAXN = dump
- Primakoff production



Axion Like Particles (ALP) - Preliminary

$$\frac{d\sigma_{\text{Primakoff}}}{d\theta_{a\gamma}} \equiv \frac{d\sigma_{\gamma\ \text{Nuc}\to\text{a Nuc}}}{d\theta_{a\gamma}} = \frac{1}{4} g_{a\gamma}^2 \alpha Z^2 F^2(t) \frac{p_a^4 \sin^3\theta_{a\gamma}}{t^2}$$

$F(t)$ - structure function of the nucleus



- suppressed nuclear-recoils (t is small)
- $p_a \approx p_\gamma$
- @high-E: γ-a collinearity, $\theta_a \sim \theta_\gamma$

Axion Like Particles (ALP) - Preliminary

- Large event yield:
  competitive with NA62, SHIP.
- semi-open questions:
  - photon identification - ECAL
  - two photon-separation
  - backgrounds ?