Illuminating the Dark Sector of the Universe*

Augusto Ceccucci/CERN/EP-SME

EP-DT Group Meeting, June 12, 2019

*This talk is adapted from the presentation I gave in Granada at the EPPSU Open Symposium with less formulas and the addition of one commercial

Open Commercial {

Precision Timing is hot!!

3. Knowledge, training, career

European Strategy Update

According to the ECFA survey:

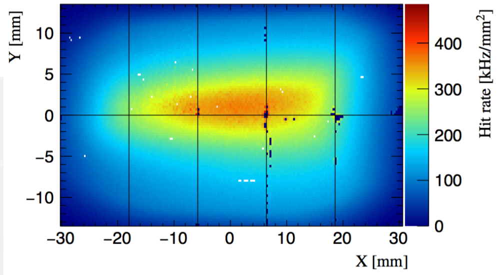
Most promising areas of R&D

Most promising future R&Ds	% respondents to ECFA survey
Precision timing	56
Precise position resolution	17
Rad Hard	8
Precise energy measurements	7
CMOS HV-MAPS monolithic	6
High granularity imaging calorimetry	6
Artificial intelligence / Machine Learning	4
Fast (tracker) triggers (online)	4
4D tracking	4
High rate capability	4
Low power consumption systems/electronics	4
Fast detectors/electronics	3
High energy resolution	3
PID TOF	3
Low mass detectors & services	3
Silicon photomultipliers	3

ECFA European Committee for Future Accelerators

Precision Timing: NA62 Gigatracker

- Si pixel
- ~0.5% X_0
- ~ 18 cm^2
- 100 MHz/ cm^2
- σ_t ~ 100 ps
- $\sigma_{x,y}$ ~ 100 μm
- Microchannel cooling



Absolutely crucial for NA62:
today and **tomorrow**

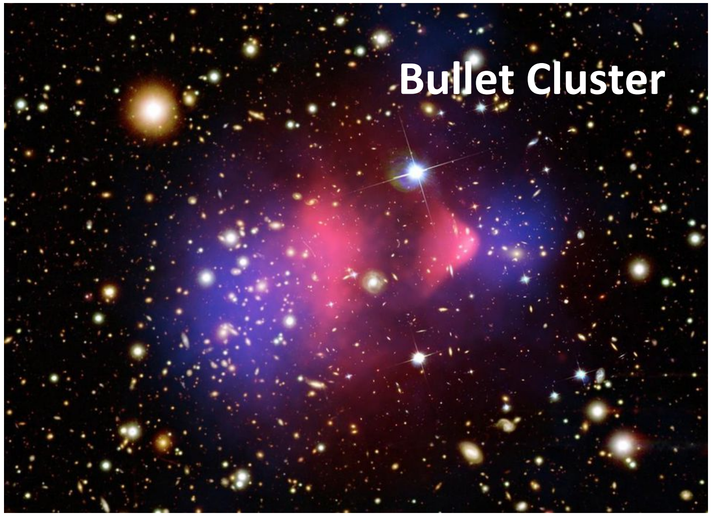
Huge Thanks to EP-DT and EP-ESE

Please keep supporting NA62

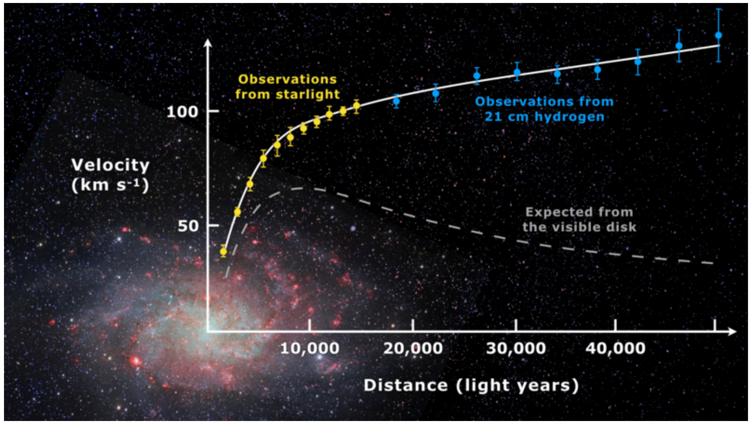
} Close Commercial

Evidence for Dark Sector:

Dark Matter

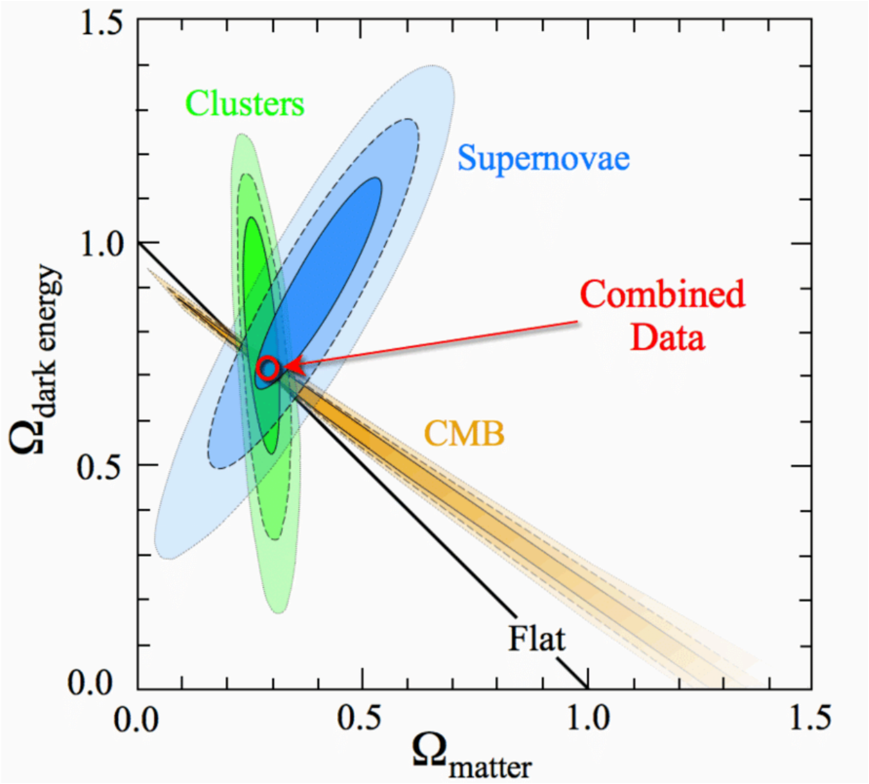


Pink: X-rays from interstellar gas
Blue: Mass from gravitational lensing



Rotation curve of spiral galaxies

Dark Energy



Astrophysical observations tell us that we are dominated by Dark Sectors

Dark Sector & Particle Physics

To shed light on the Dark Sectors is a compelling goal for particle physics

- **Planck 2013:**
  - Ordinary matter 4.9%
  - Dark Matter 26.8%
  - Dark Energy 68.3%

- **Can we interact with the Dark Sector using particle physics?**
  - Direct and Indirect searches of Dark Matter, Colliders
  - Portals to and from the Dark Sector?
  - Mixing of ordinary photons to "Dark Photons"?
  - Mixing of ordinary neutrinos to HNL?
  - Feebly interacting (long-lived) neutral scalars?
  - Exploration of hidden valleys?
  - "Invisible decays" of ordinary particles?

In addition to very strong non-accelerator and collider programmes, there is also an opportunity "Beyond Colliders" (this talk)

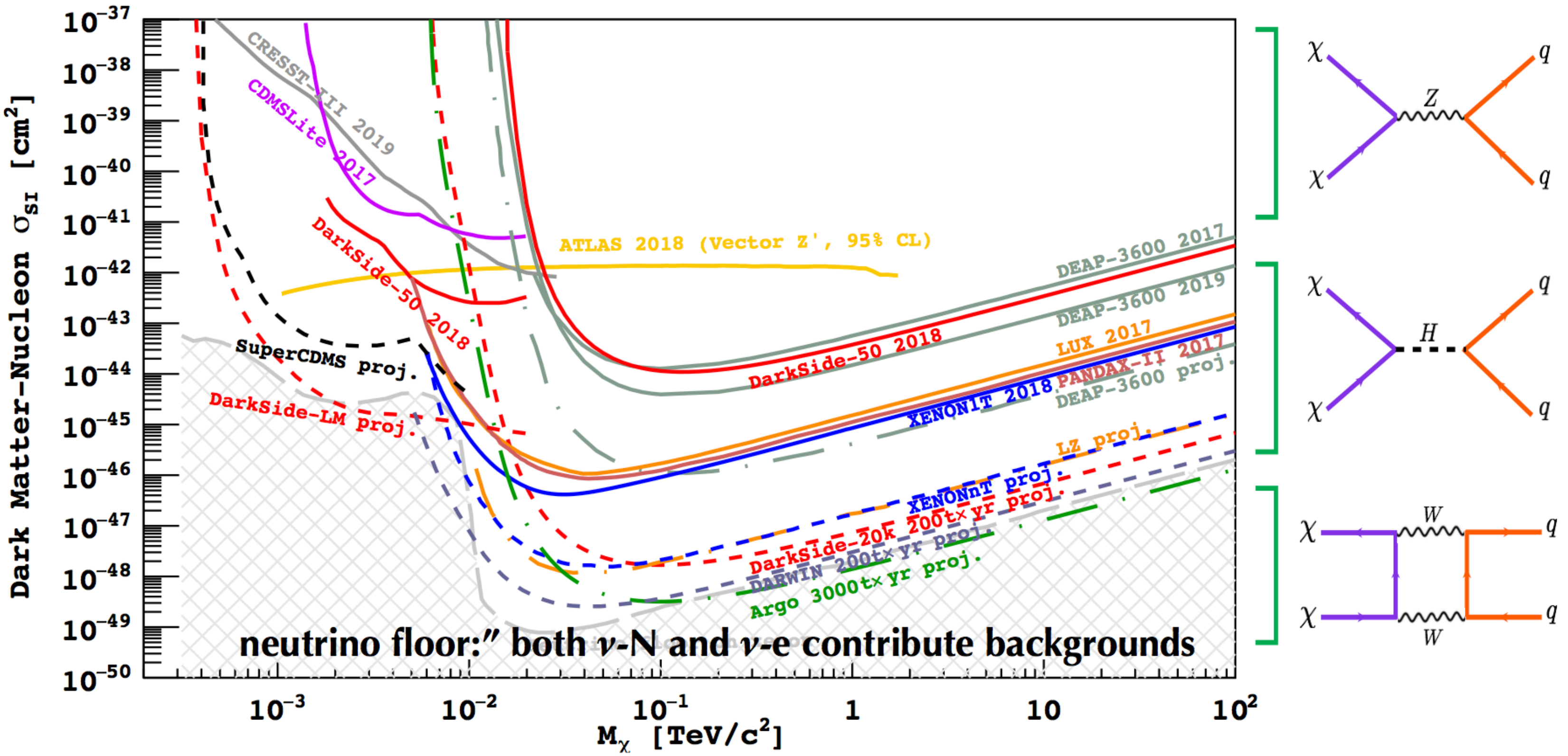
Weak
Interacting
Massive
Particle

The WIMP Miracle

European Strategy Update

WIMP Direct Detection Searches

Primary Weak Interactions



Marching down to the Neutrino Floor

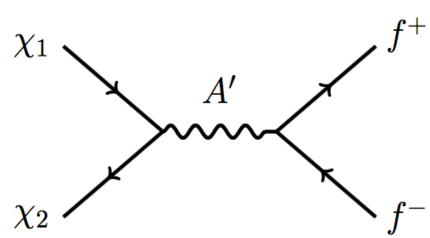
J. Monroe's talk

WIMP SUSY "miracle" pushed to ~ TeV masses→ Strong motivation for new colliders

Dark Matter and Mediators

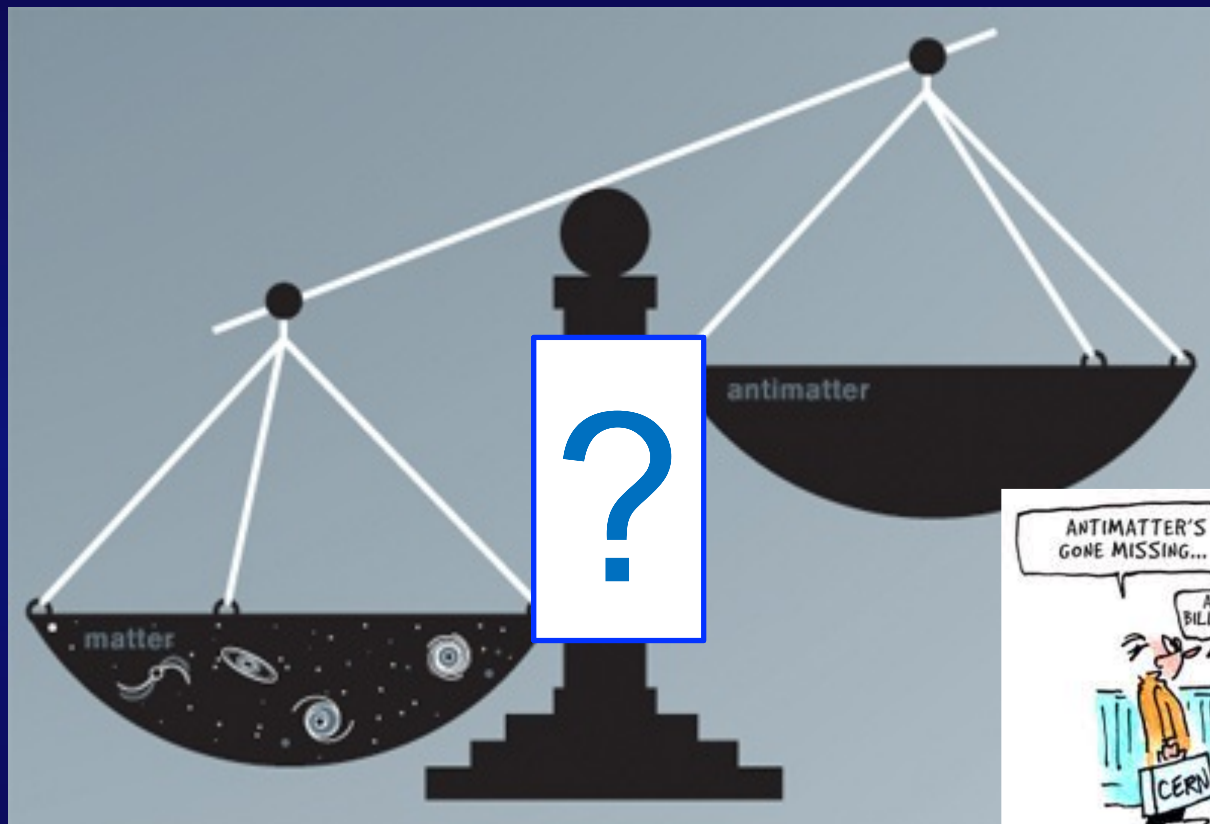
- Dark Matter mediated by Weak Interactions ~ excluded?
  - **σ(Z mediated)~10^{-39} -10^{-38} cm^2 (excluded 1-110 GeV)**
  - **H mediator~10^{-4}-10^{-5} *σ(Z mediated) (heavily constrained)**
  - **EW loop~10^{-9} *σ(Z mediated) starting to be probed**
- Avoid Lee-Weinberg bound **(M_{WIMP}>2 GeV)** postulating new light bosons mediators: Dark Vector, Dark Scalar,… , to increase the annihilation cross section

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	$y_N L H N$



Define benchmark point to harmonize comparisons between projects

Another Compelling Puzzle: Baryon Asymmetry of the Universe (BAU)



$n_{quark}-n_{antiquark}/n_{quark}$ (Proto Universe) $\sim n_{baryon}/n_{photon}$ (Today)$\sim$**5×10^{-10}**

Why CP-Violation is so cool


Scanned at the American Institute of Physics

Andrei Sakharov (1967) conditions for BAU:

To allow the development of an asymmetry between matter and anti-matter

1. Violation of Baryonic Number

2. Thermodynamic Non-equilibrium

3. Violation of C & CP

CP-Violation found (so far!) in the quarks (CKM) is not enough to explain BAU … will neutrinos help??

Terra Incognita

Middle Age

- Griffin, beast
  - A beast with the body of a lion and the wings and head of an eagle
- Hydrus, serpent
  - The enemy of the crocodile, which it kills from the inside
- Mandrake, plant
  - A plant with human-shaped roots, that shieks when it is pulled from the earth
- Manticore, beast
  - A composite beast with a man's face, a lion's body and the stinger of a scorpion

http://bestiary.ca/beasts.htm

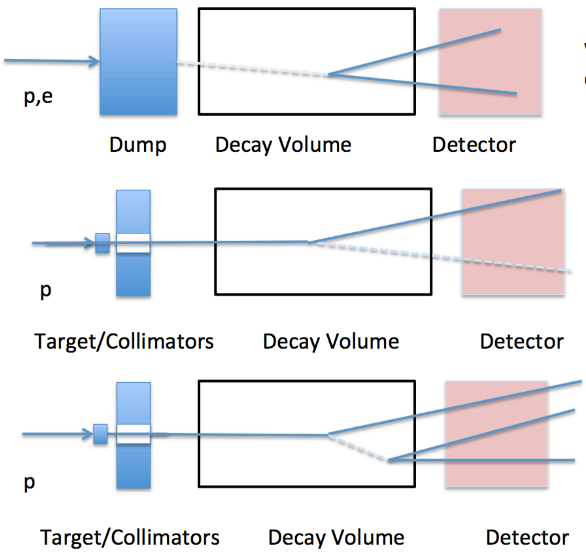
Modern Times

- Heavy Neutral Lepton
  - A RH cousin of the neutrino that may explain dark matter, neutrino mixing and baryogenesis
- Dark Photon
  - Invisible (or visible) heavy photon that may explain the g-2 anomaly and dark matter
- Dark Scalar
  - A minimally coupled scalar field postulated to account for the dark matter
- Axion like particle
  - Something like an extension of the "QCD axion" that couples to EM and strong interactions

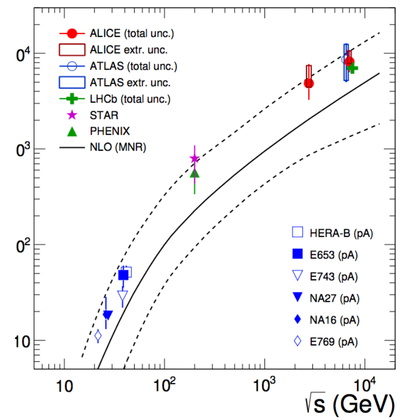
I will refer to the comparisons presented in the BSM group of the "Physics Beyond Collider" (PBC) study (**arXiv:1901.09966**) and in the PBC summary (**arXiv:1902.00260**)

Brief Experimental Review

Decay Experiments



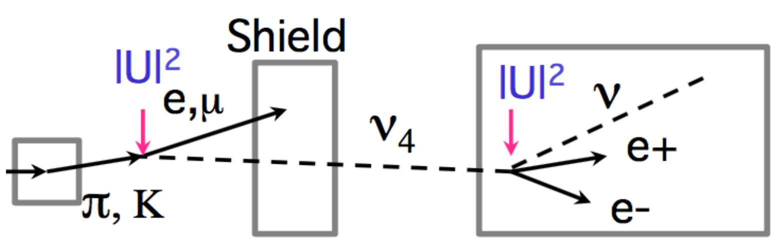
To search for exotic decays originating from **charm and beauty,** one sends protons directly to a **dump** in order to remove the light mesons before they decays into muons and neutrinos **(backgrounds)**



ALICE: arXiv:1605.07569

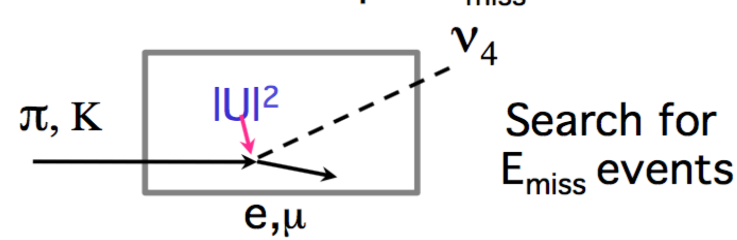
Charm cross section at fixed target (SPS energy, 400 GeV) is already high enough to compare favorably with colliders: **luminosity outweighs cross section**

Visible vs. Invisible



Sensitivity $\sim |U|^4$

active beam dump + E_{miss}



Sensitivity $\sim |U|^2$

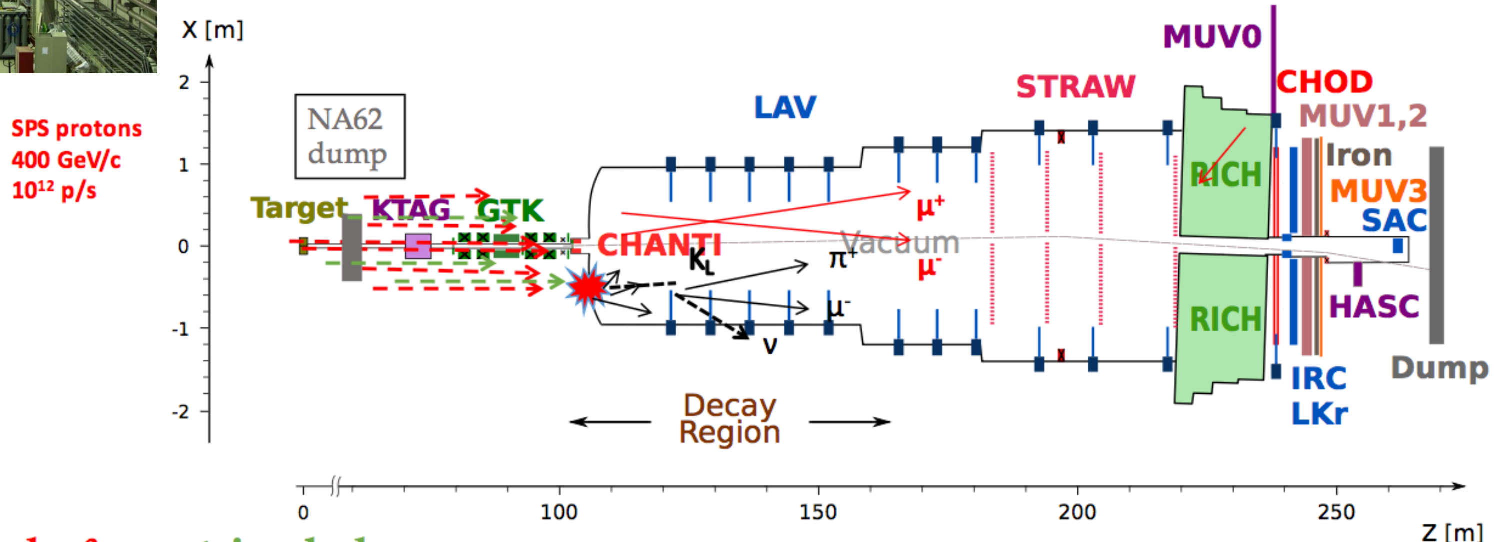
In general experiments looking for visible decays or recoils are sensitive to **$|U|^4$** while those looking for missing energy or momentum are sensitive to **$|U|^2$**

NA62

Unique feature: switch between Beam and Dump within "minutes"

G. Lanfranchi, EPS 2017

Main Backgrounds in dump mode



Muon halo & neutrino halo

- In *beam mode* about ~ 5 MHz of μ^+ and 150 kHz μ^- are present due to early decays in flight of K and π in the beam;
- **In *dump mode*, the muon halo is reduced by (at least) 2 orders of magnitudes**
- **Muons produce inelastic interactions and combinatorial background**

Neutrinos can produce inelastic interactions in the material surrounding the FV.

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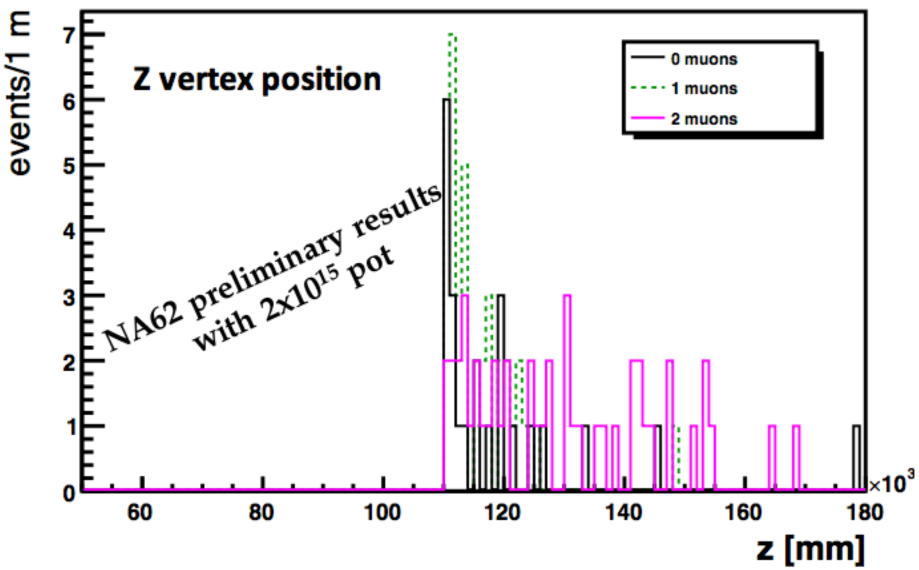
NA62

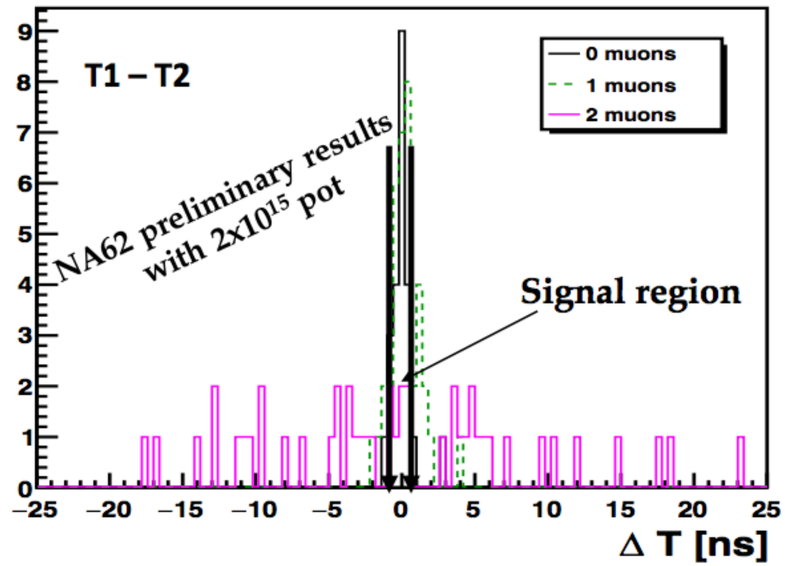
G. Lanfranchi, EPS 2017

NA62-DUMP: data driven background estimate

Distribution of the z-coordinate of the vertex



Distribution of the 2-track time difference



Sample divided in 2-, 1- and 0-muon categories:

- 2-μ sample has vertices spread along the FV and tracks mostly out-of-time:
  ⟶ combinatorial background
- 0- or 1-μ samples are concentrated at the beginning of the FV, and tracks are mostly in-time:
  ⟶ background from inelastic interactions in the last λ_I of the final collimator

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See prospects/details in PBC conventional beams summary **ESPP input#20**

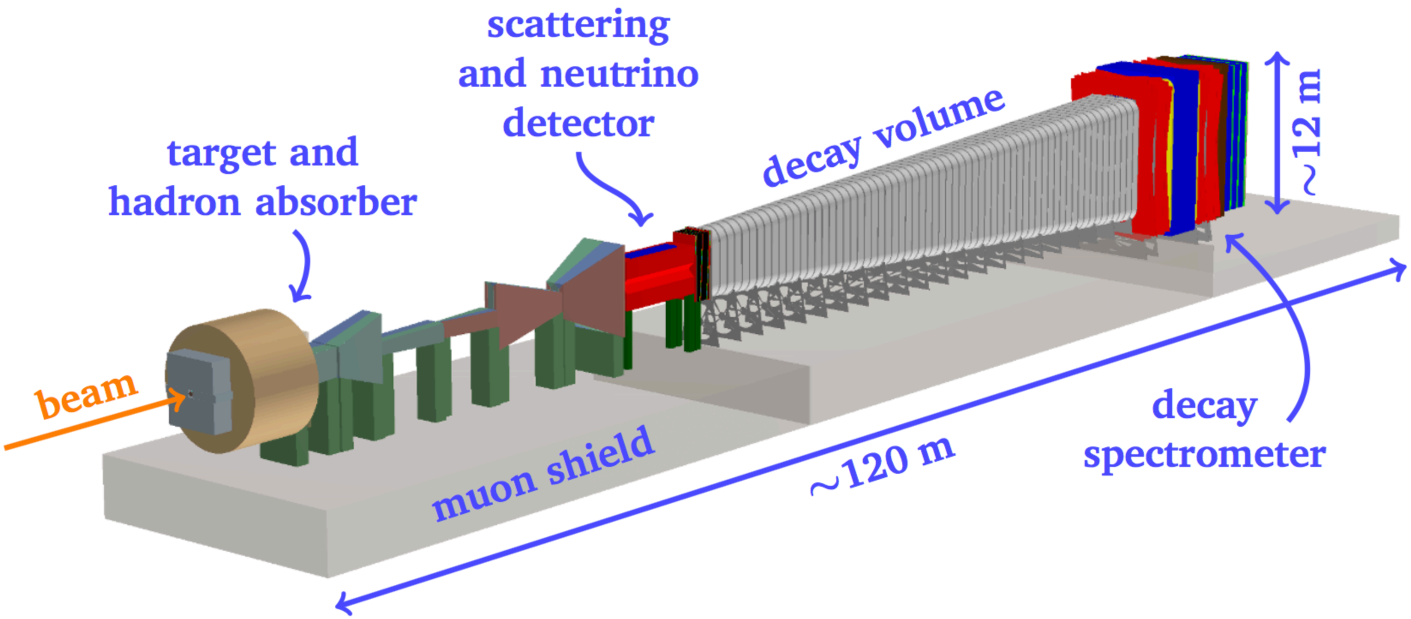
ESPP input#12

BDF/SHiP

Elena Graverini, PBC Jan 2019
→ EPPSU, DM&DS session

SHiP

[ins-det:1504.04956]

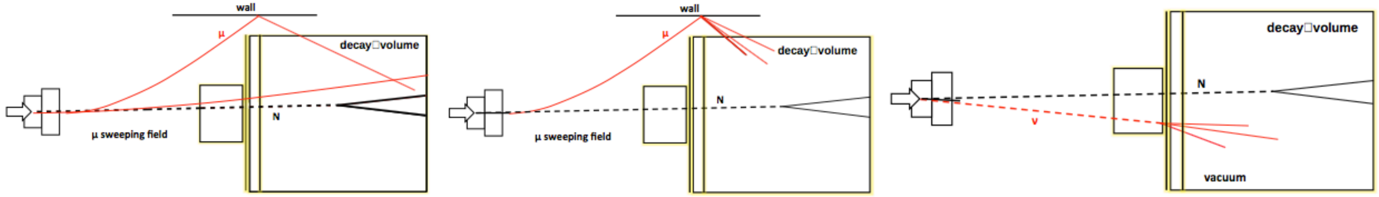


- 2×10^{20} *pot* in 5 years: $> 10^{18} D$, $> 10^{16} \tau$
- zero background beam dump expt. with spectrometry and PID
- large geometrical acceptance: long volume close to dump
- complementary detectors for scattering/decay signatures

SHiP

Hidden sector: backgrounds

Elena Graverini, PBC Jan, 2019

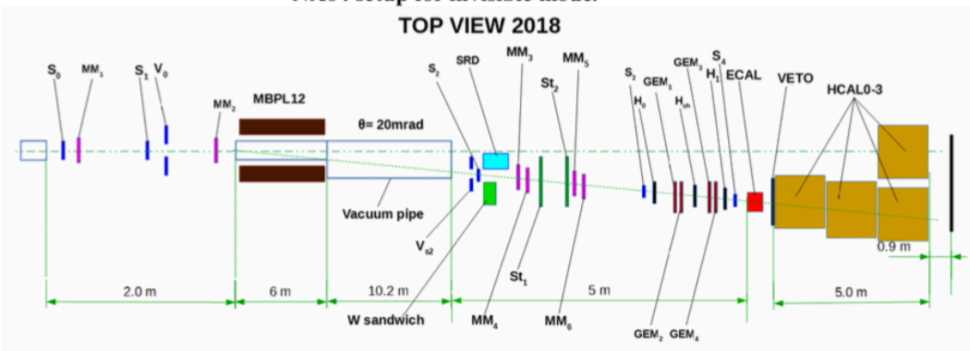


- **Muon combinatorial:**
  - $10^{16} \xrightarrow{\text{selection}} 10^{9} \xrightarrow{\Delta t < 340\text{ps}} 10^{-2}$ candidates in 5 years @ $90\% CL$
  - ML used to generate large sample of dangerous μ
- **Muon inelastic:**
  - 5 years of SHiP operation simulated
  - ~~correlation~~ between VETO and selection: $< 6 \times 10^{-4}$ @ $90\% CL$
- **ν interactions:**
  - 10 years of SHiP simulated, increasing to 100
  - ν-air: $< 10^{-2}$ in 5 years with pressure ~ 1 mbar
  - ν-material: $5 \times 10^{5} \begin{cases} \xrightarrow{\text{cuts (fully reco)}} 0 \\ \xrightarrow{\text{cuts (part. reco)}} 2 \xrightarrow{\text{opening angle}} 0 \end{cases}$ @ $90\% CL$

NA64

ESPP input#9

NA64 setup for invisible mode.



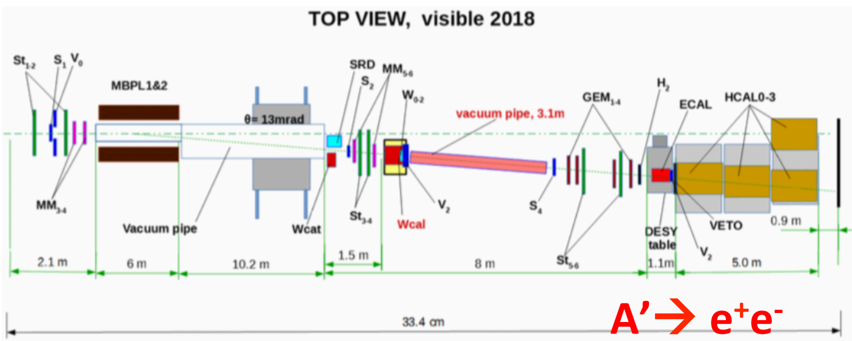
100 GeV e^- SPS secondary beam

e^- tagging: tracking + SRD

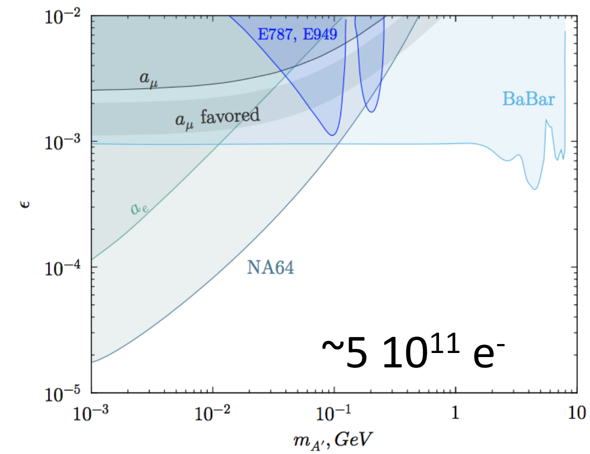
Missing energy in calorimeters

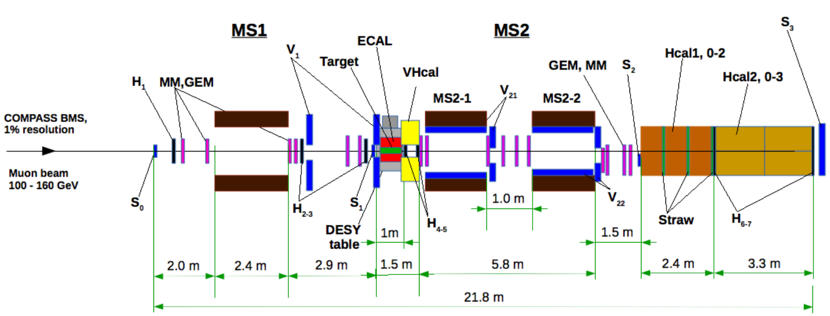
A'→ Invisible

arXiv:1710.00971



A'→ e^+e^-





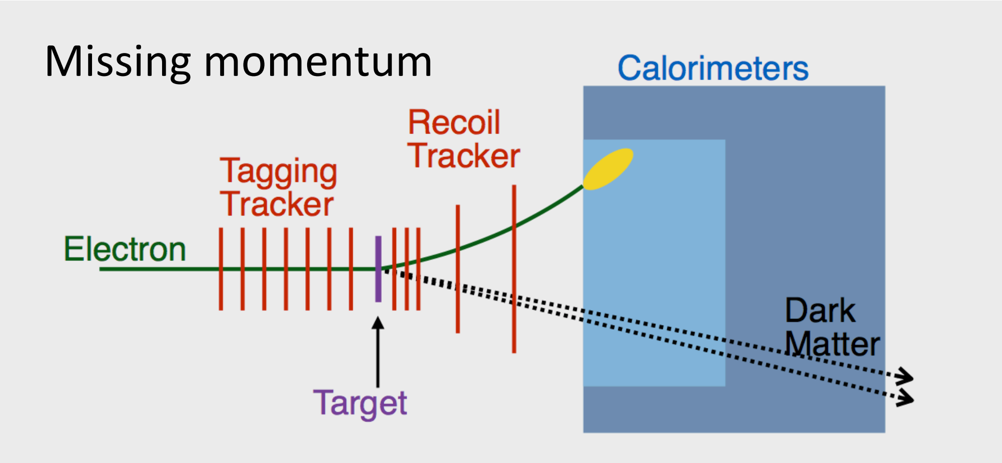
M2 Muon Beam (Proposal)

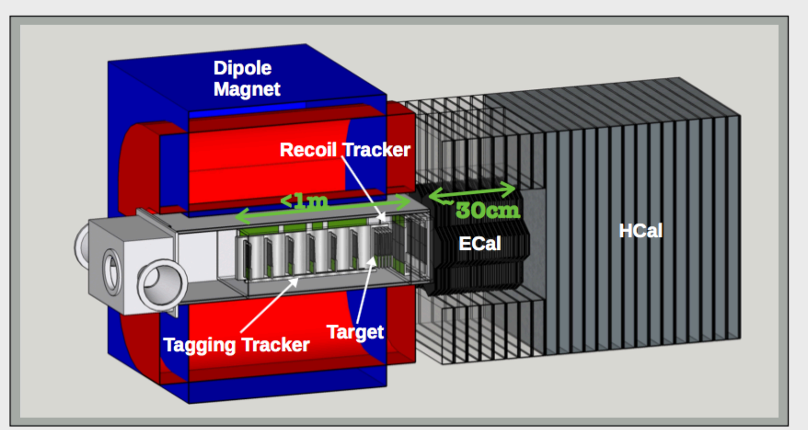
$\mu + Z \rightarrow \mu + Z + Z_\mu$ (invisible)

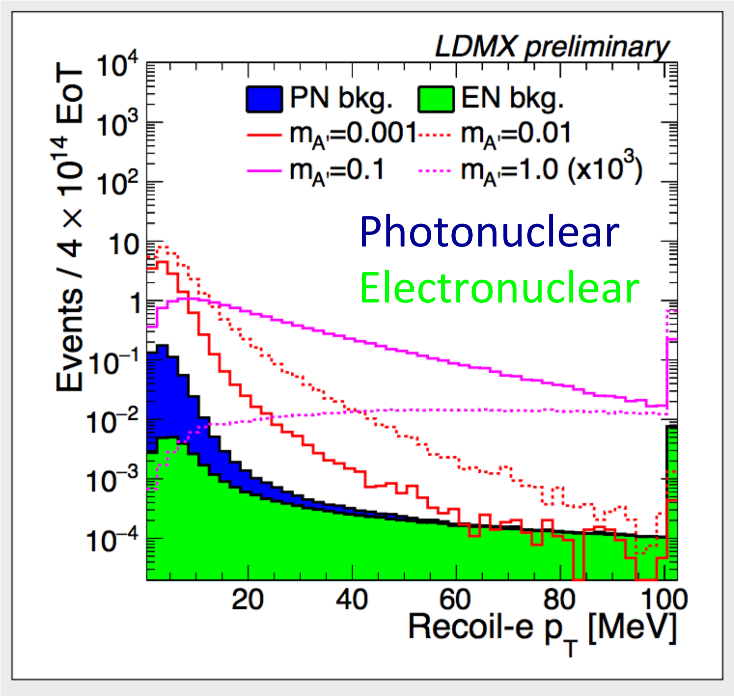
Also option with π,K,p beams to look for $\pi^0,\eta,\eta' K_S/K_L \rightarrow$ invisible, BR~(10^{-6}-10^{-8})

eSPS/LDMX

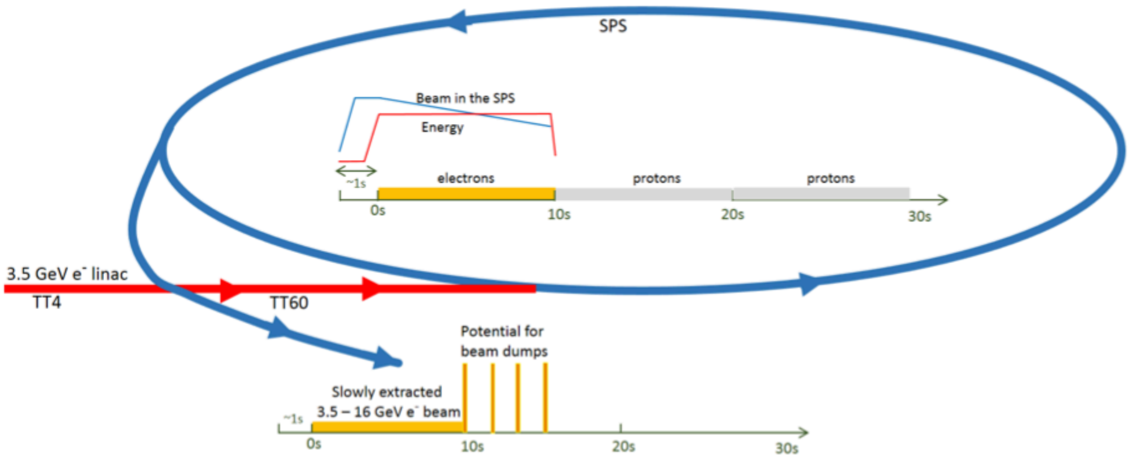
ESPP input#36







arxiv:1805.12379

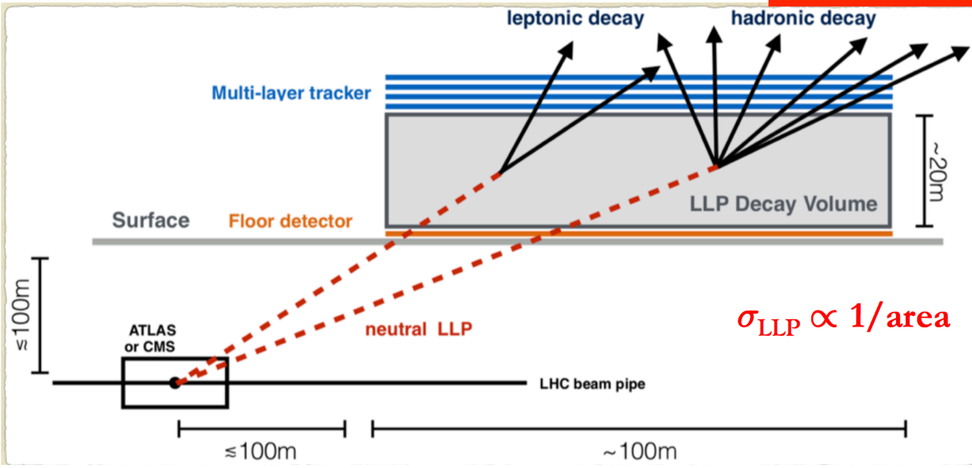


3.5 e⁻ GeV LINAC based on CLIC technology up to 16 GeV from SPS

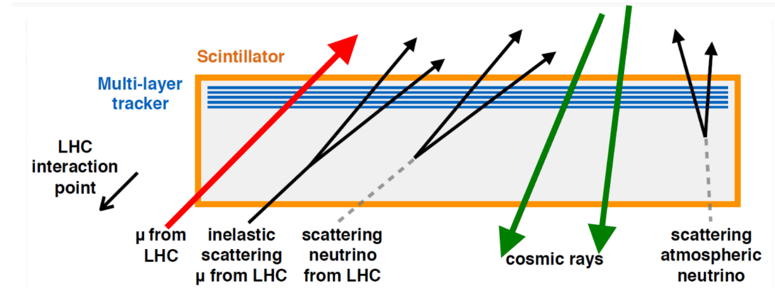
Long Lived Particles @ LHC

MATHUSLA arXiv:1606.06298

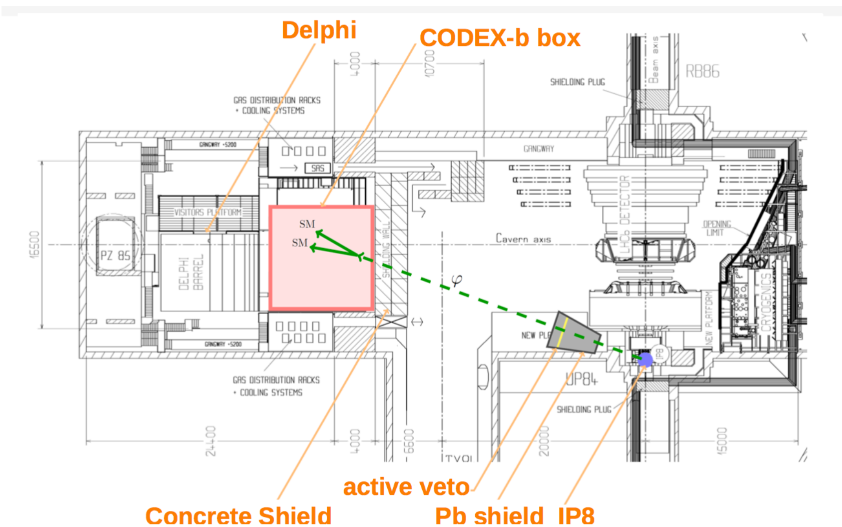
ESPP input#75



Higgs exotic decays arXiv:1312.4992

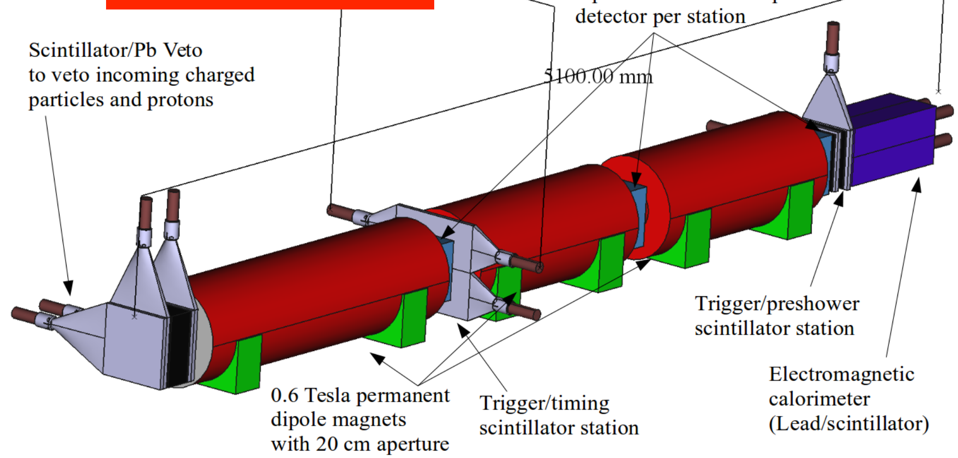


CODEX-b arXiv:1708.09395



FASER arXiv:1811.12522

ESPP input#94

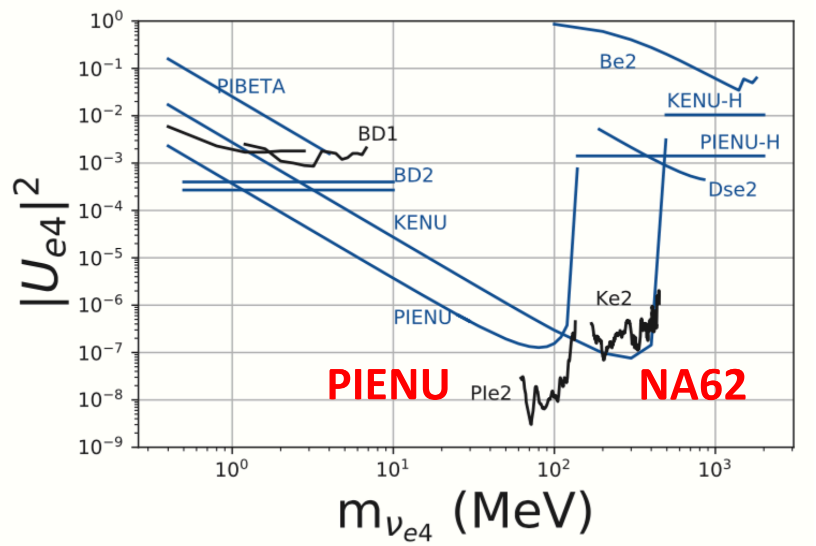


Heavy Neutral Leptons (HNL)

- We know precisely the number of stable and light (M_ν<45 GeV) neutrino families from the Z width at LEP: **N_ν = 2.92 +/- 0.05**

HNL can mix with standard neutrinos via some matrix element:

$$\nu_\alpha = \sum_I U_{\alpha I} N_I$$



- HNL could give mass to the normal neutrinos via the **see-saw mechanism** (but typically are expected to have GUT mass scales)
- The **νMSM** model (Asaka et et. Al., arXiv:hep-ph/0503065) posits heavy neutrinos with masses below the EW scale to solve **dark matter, baryon asymmetry of the universe and be consistent with neutrino oscillations**

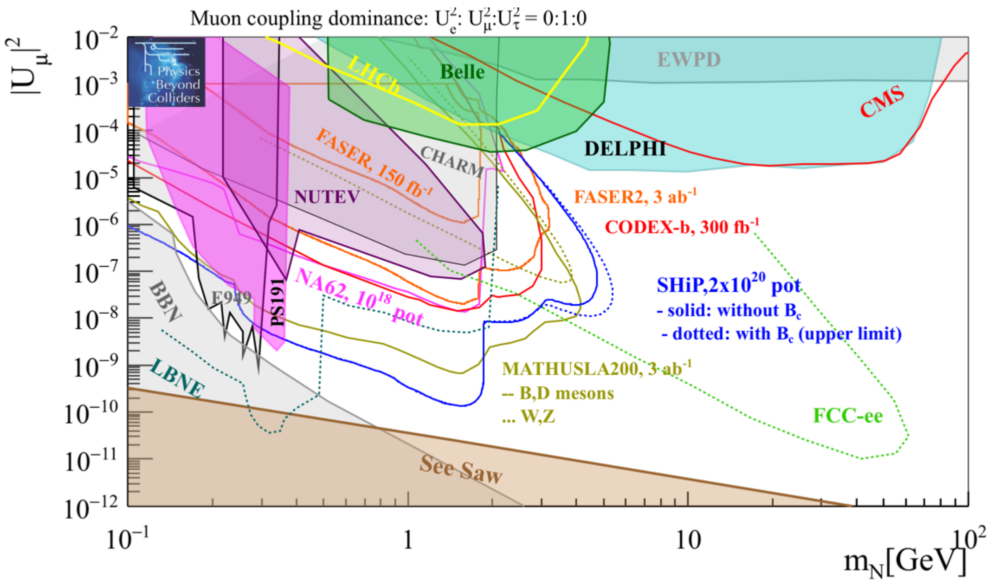
Heavy Neutral Leptons

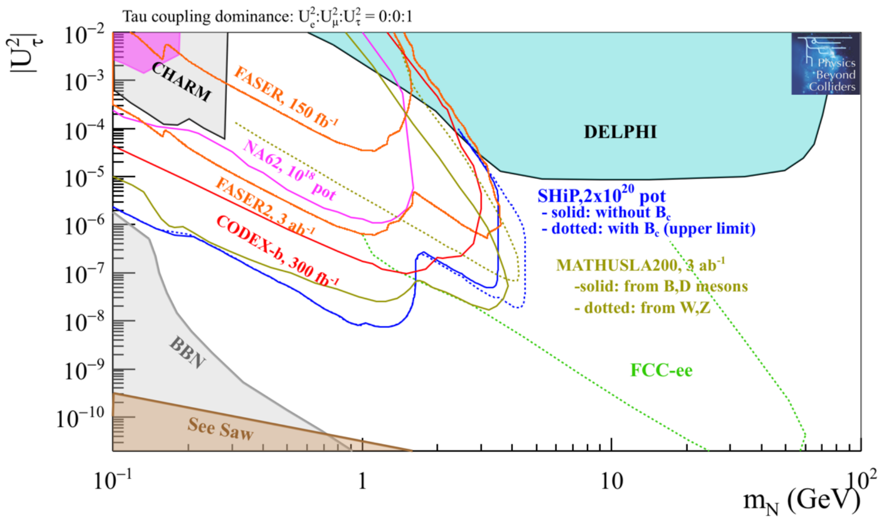
Physics Beyond Collider (PBC) Summary: arXiv:1902.00260
PBC BSM WG Report: arXiv:1901:09966

ESPP input#42

PBC BC7 Benchmark: HNL coupling to μ

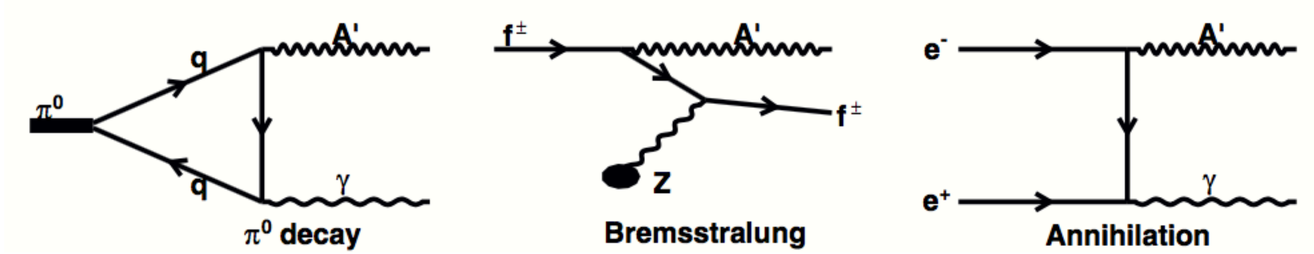
PBC BC8 Benchmark: HNL coupling to τ



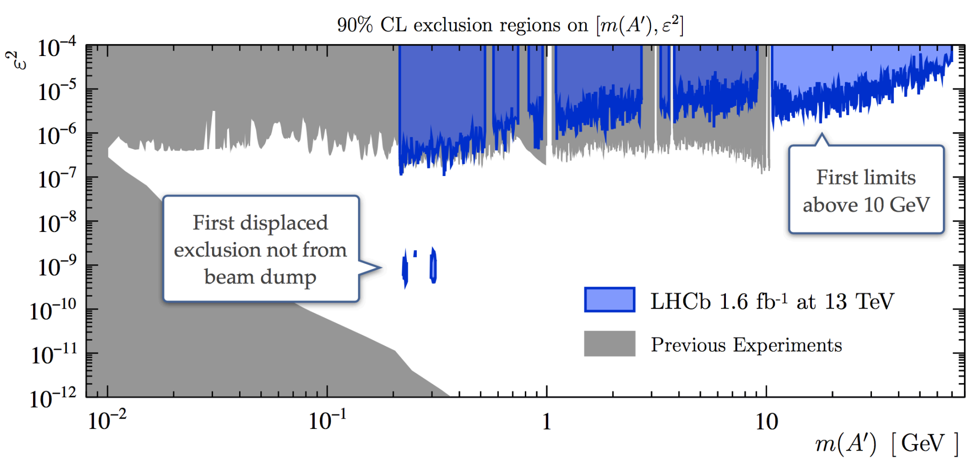


Experiments considered in the PBC study

Dark Photons



- **Visible:** decay to SM particles
  - **Bump hunts** in invariant mass spectra using the visible decays, e.g. A' → e^+e^-, $\mu^+\mu^-$ and A' → $\pi^+\pi^-$,

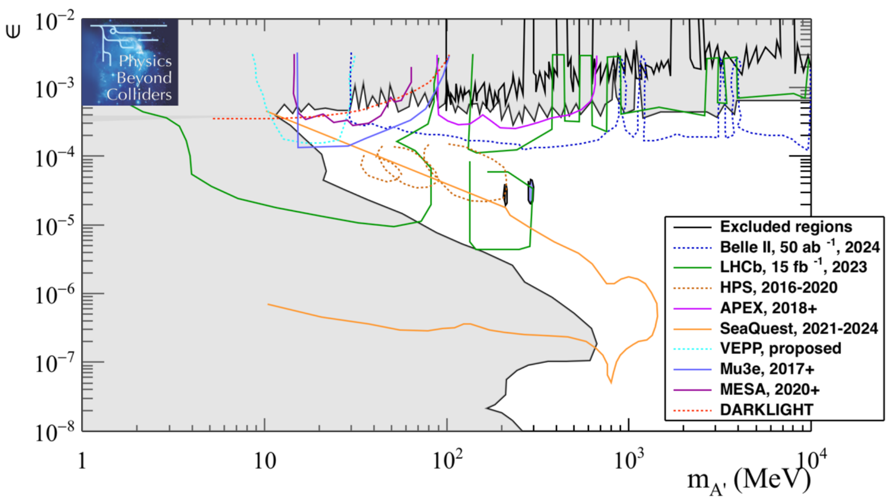


- **Invisible:** decays to dark particles (m_χ <1/2$M_{A'}$)

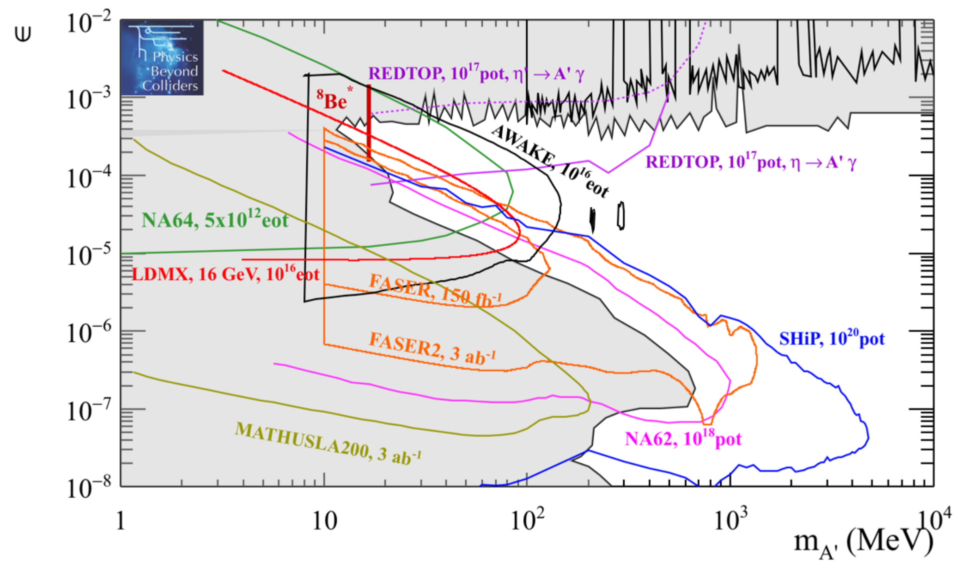
Visible Dark Photon

Physics Beyond Collider (PBC) Summary: arXiv:1902.00260
PBC BSM WG Report: arXiv:1901.09966

PBC BC 1 Benchmark: A’ decays back to SM particles

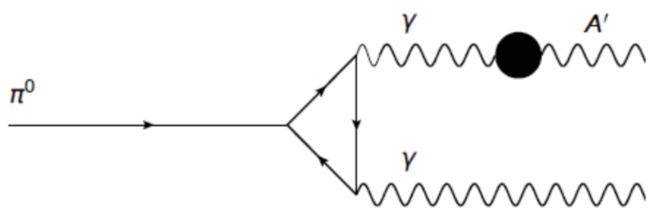


Projections for other experiments



Experiments considered in the PBC study

Invisible Dark Photon: $\pi^0 \rightarrow \gamma + A'$

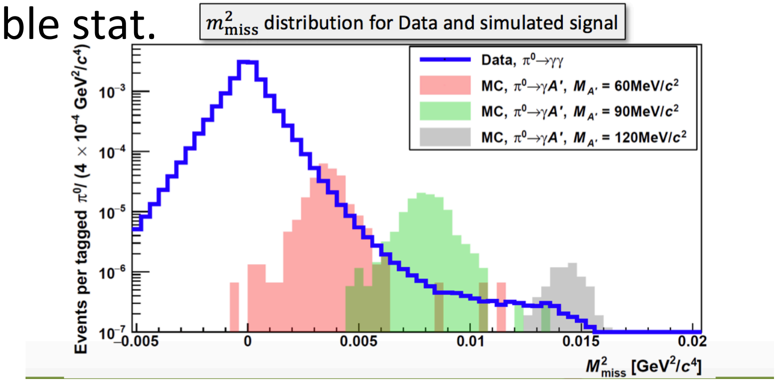


~4 10^8 tagged π^0
from $K^+ \rightarrow \pi^+\pi^0$
~1% available stat.

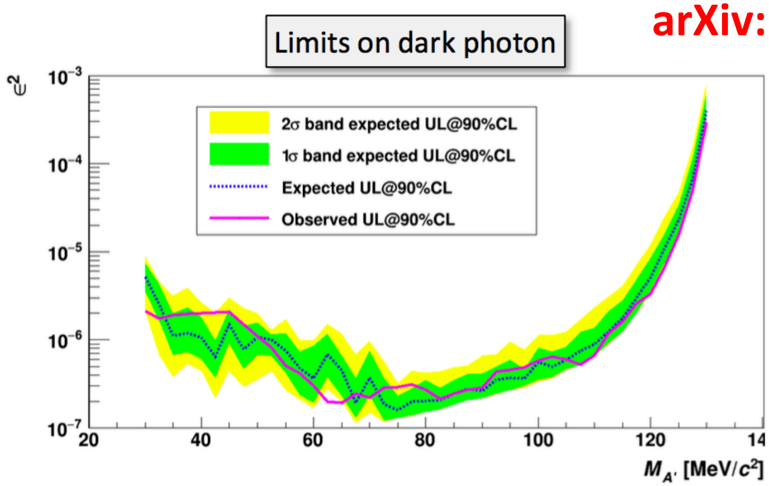
$$m^2_{\text{miss}} = (P_K - P_\pi - P_\gamma)^2$$

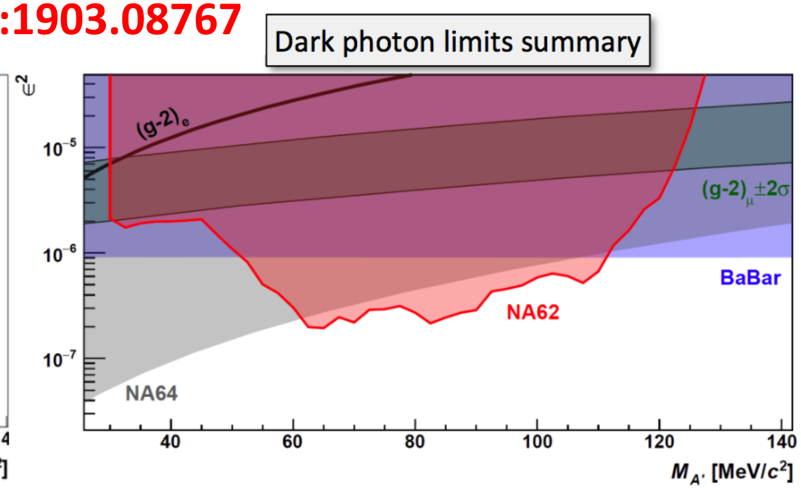
$$\frac{\mathcal{B}(\pi^0 \to \gamma A')}{\mathcal{B}(\pi^0 \to \gamma\gamma)} = 2\varepsilon^2 \left(1 - \frac{m^2_{A'}}{m^2_{\pi^0}}\right)^3$$

NA62



arXiv:1903.08767





Complementary to searches with electrons

For η,η' decays see REDTOP

ESPP input#28

Summary: Dark Sector (MeV-GeV)

There seems to be a genuine window of opportunity left open by the current data

- **Short term:**
  - By products from current flavour experiments offer cost-effective and timely explorations to of the dark sector
  - existing experiments such as **NA62, NA64, FASER** at CERN, among others, are valuable training grounds towards ultimate beam dump explorations
- **Medium term:**
  - Future facilities like **BDF/SHiP** and **eSPS/LDMX** will allow for significant progress to dark sectors. The BDF could have an impact also on flavour (for instance **tauFV@BDF**)
  - Several experiments are proposed for full exploitation of LHC/HL-LCH (e.g. **MATHUSLA, CODEX-b, FASER2**)
- **Longer term:** Ordinary and Dark Flavour: **FCC-ee** can do a lot of both **(5 10^{12} Z)**

We owe a big thank to the PBC study:

- "Physics Beyond Collider" (PBC) summary: **arXiv:1902.00260**
- PBC BSM WG: **arXiv:1901.09966**

ESPP input#42