Synchrotron radiation tagging of 100 GeV electrons in NA64 experiment at CERN SPS

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On behalf of the NA64 collaboration

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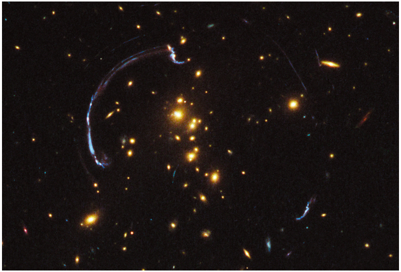
Dark Matter

- Several cosmological observations suggest the existence of Dark Matter, e.g. galaxy rotation curves[1], gravitational lensing and spectrum of CMB radiation
- In addition to the most popular model (WIMP, SUSY etc.) various DM model motivate "light" new physics that could be observed in low energy experiment.
- One possibility is a dark sector of SM singlets coupled to ordinary matter by gravity and possibly other very weak forces. An extra (broken) U(1)' symmetry would implies a new massive boson A' (**Dark Photon**)



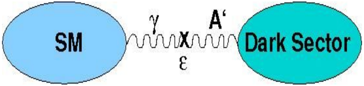
Gravitational lensing, from Hubble mission

Dark Matter

- One possibility is a dark sector of SM singlets coupled to ordinary matter by gravity and possibly other very weak forces. An extra (broken) U(1)' symmetry would implies a new massive boson A' (**Dark Photon**)

Dark Photon

- $\Delta L = \epsilon F^{\mu\nu} A'_{\mu\nu}$ kinetic mixing γ-A', ϵ coupling strength
- natural coupling $\epsilon \sim 10^{-3} - 10^{-4}$, $M_{A'} \sim \epsilon^{1/2} M_Z$
- Decay Modes:
  1. **Visible:** $A' \rightarrow e^- e^+, \mu^- \mu^+$
  2. **Invisible:** $A' \rightarrow \chi\overline{\chi}$



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  2. **Invisible:** $A' \rightarrow \chi\overline{\chi}$ NA64 focus $\Longrightarrow$ **Searching for missing momentum**

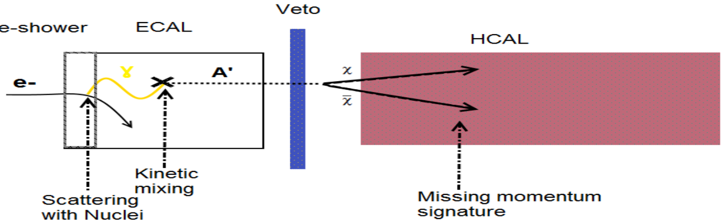
Motivations

1. if $M_{A'} \geq 2M_{DM}$ and $\alpha_{DM} \gg \epsilon^2 \alpha$ invisible decay is the most relevant .
2. can explain (g-2)$_\mu$ hint[2]
3. can explain various cosmological observation[3]

H.S. Lee., Phys. Rev. D 90, 091702 (2014)

N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, and N. Weiner, Phys. Rev. D 79, 015014 (2009)

Dark Photon signal

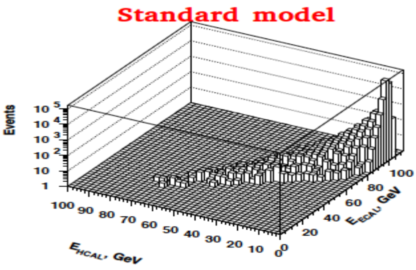


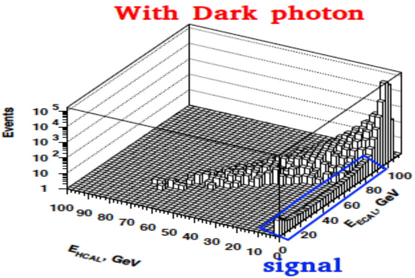
Dark photon signal

Dark photon is produced through kinetic mixing of a Bremstrahlung-γ in the ECAL. The Dark photon would escape then the setup undetected through the invisible decay A'$\rightarrow \chi\overline{\chi}$

Dark Photon signal:

- Missing energy in the ECAL ($E_{ECAL} \leq E_{thresh}$)
- no activity in VETO and HCAL
- reconstructed momentum compatible with a 100 GeV particle
- emitted synchrotron radiation compatible with an electron





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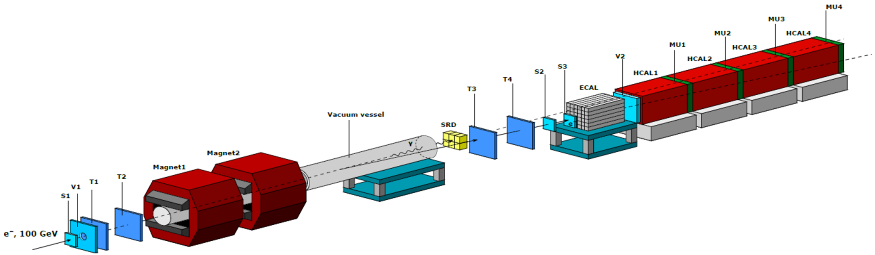
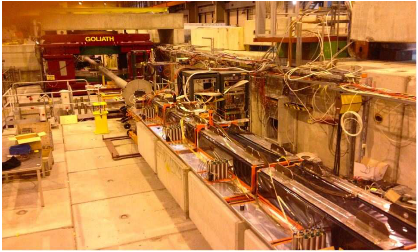
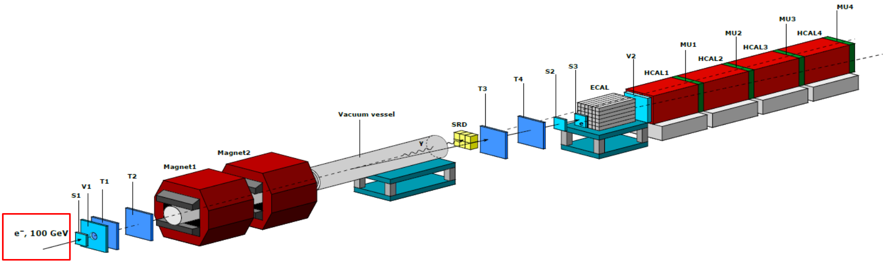




NA64 setup

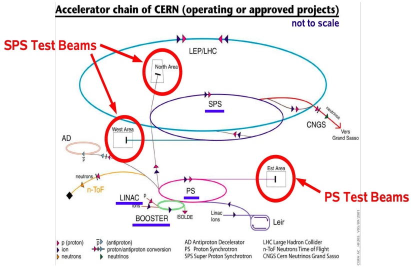
Key features of the experiment:

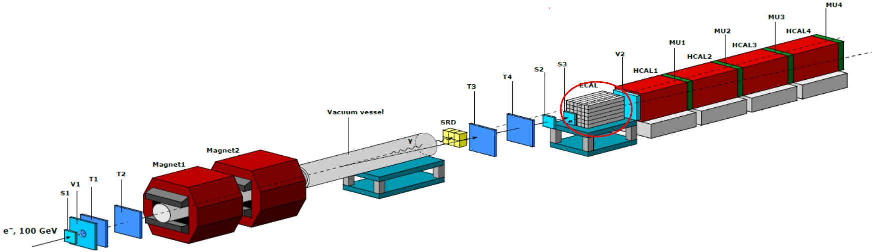


NA64 setup

Key features of the experiment:

- **High energy particle to trigger the reaction:** 100 GeV e^- from CERN SPS
- **Main impurities of H4 beam:** π^-, low energy e^- ($\sim$1%) μ^- and K^- ($\lesssim$0.1%)

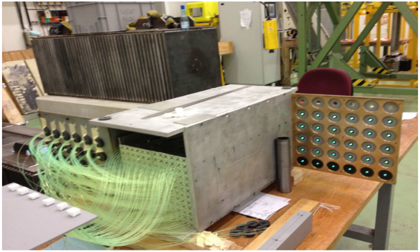


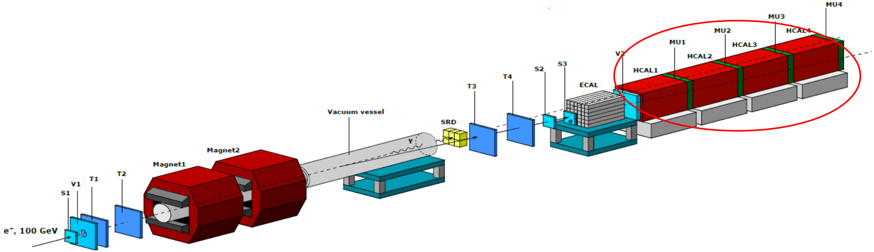


NA64 setup

Key features of the experiment:

- **High hermeticity:** ECAL PbSc sandwich, $38\times38\times445$ mm^3 ($\sim$40 X_0) with WLS fiber inserted in spiral and $9\%(E[GeV])^{-1/2}$ energy resolution

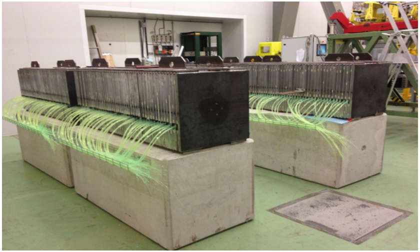


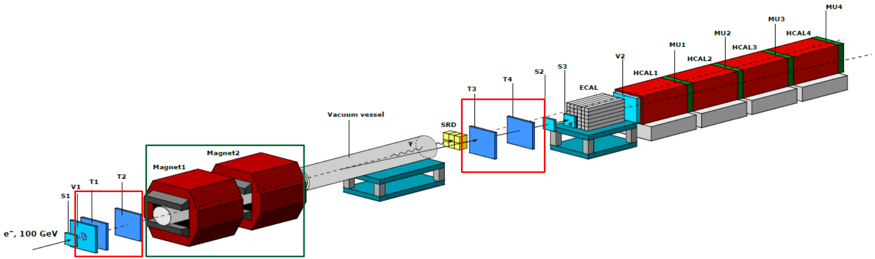


NA64 setup

Key features of the experiment:

- **High hermeticity:** 4 HCAL FeSc sandwich modules, $60\times60\times150$ cm^3 ($\sim$7 λ for each module) with WLS fiber and 60%(E[GeV])$^{-1/2}$ energy resolution

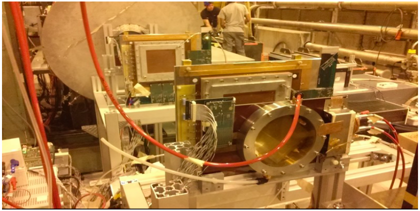


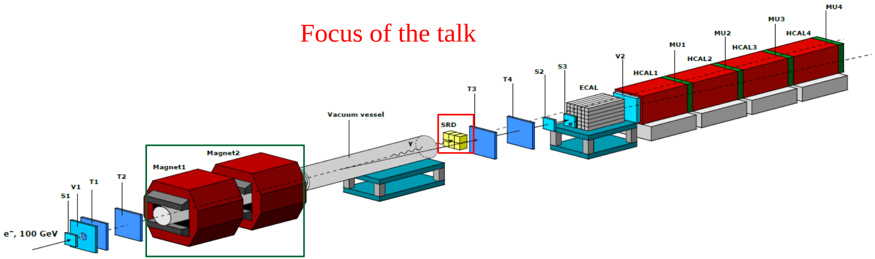


NA64 setup

Key features of the experiment:

- **Measure momentum:** Tracking system made of 4 MicroMegas modules and 2 GEM detectors together with 2 MPBL magnet [7 T· m] to measure momentum of incoming particles.





NA64 setup

Key features of the experiment:

- **Suppress hadronic background:** Synchrotron radiation tagging system (BGO scintillator) to reject μ^-,π^- and K^- decay in flight after interaction with ECAL **Focus of the talk**

Synchrotron radiation is the radiation emitted by a charged particle accellerated radially to its momentum's direction.
The radiated power emitted per meter can be expressed as:

$$P = \frac{e^2 c}{6\pi_0 (mc^2)^4} \frac{E^4}{R^2} \tag{1}$$

- Power emitted scales on the fourth power of the energy. $\Rightarrow$ works better for high e^- momentum
- Power emitted scales to the inverse fourth power of mass $\Rightarrow$ very high separation between heavy charged particle and e^-! (basically no radiation below 1 TeV for particles heavier than e^-)
- Scales as the inverse square power of the radius of the particle track $\Rightarrow$ Total emitted power is proportional to the integrated field seen by the particle.
- emission angle $\theta_{synch} \sim 1/\gamma$ in the laboratory system, basically collinear to particle's momentum at high energies.

Synchrotron radiation

In **NA64** heavy charged particle (mainly π^- and μ^-) can leave a fake signal with invisible decay or neutral punchtrough.
$\Rightarrow$ They can be rejected by measuring emitted synchrotron radiation during their passage in the MPBL magnets.

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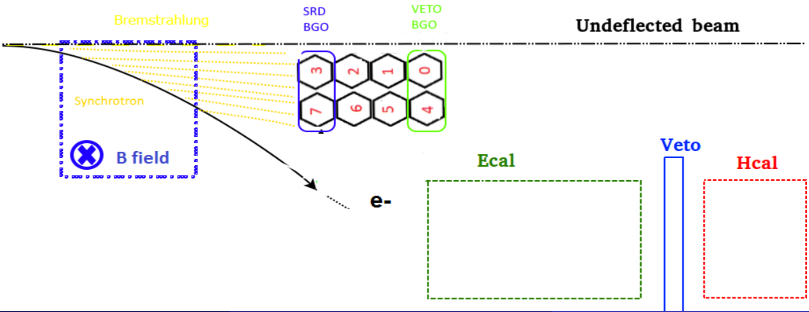
- Synchrotron photon are detected with two row of 4 BGO crystal placed in the ~32 cm space between the deflected and undeflected beam
- First two crystal of each row are used to detect synchrotron radiation (SRD BGO). Last two crystal in each row are used to reject hard bremstrahlung events and backscattering from ECAL (VETO BGO).



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⇒ They can be rejected by measuring emitted synchrotron radiation during their passage in the MPBL magnets.

BGO detector

- 2 rows of 4 BGO hexagonal crystal, 55mm external diameter and 200mm length
- Wrapped in Teflon tape to improve light collection efficiency
- glued to EMI 9603 PMT
- Very high probability of photoelectric absorption due to high Z
- 8500 γ/MeV light yield
- energy resolution of $\sim$17% (FWHM) at 1.27 MeV
- Decay time of $\sim$300ns

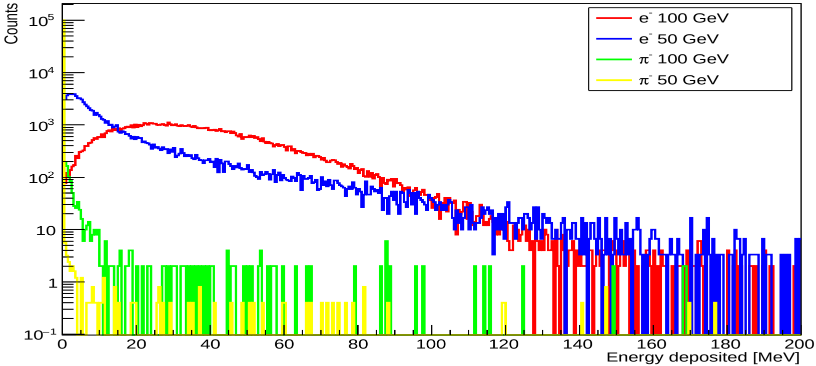
In **NA64** heavy charged particle (mainly π^- and μ^-) can leave a fake signal with invisible decay or neutral punchtrough.
$\Rightarrow$ They can be rejected by measuring emitted synchrotron radiation during their passage in the MPBL magnets.

- Method was previously tried for smaller energies[4]($\sim$50 GeV), with smaller efficiency(77%) and suppression factor (10^{-2})
- Good alternative to Cherenkov at high energies for e$^-$ tagging[5]:
    - Energy radiated is higher
    - emission angle $\theta_{cher} \propto 1/\beta$ and at high energy $|\beta_{\pi^-} - \beta_{e^-}|$ is very small
- Requires relatively simple detector (scintillator)

[d] W.Busza, M.Chen and D.Luckey,Application of synchrotron radiation for the identification of electrons in high energy beam,Nuclear instrument and method in physics,105(1972)

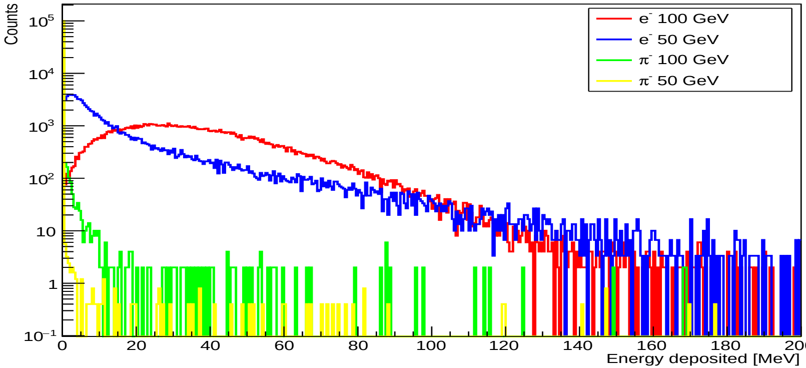
[e] E. Nappi,RICH detector,CERN EP/99-149,1999

- The suppression factor for particle heavier than e$^-$ should be in the order of $(m_e/m_{\pi^-})^4 \leq 10^{-8}$ only considering synchrotron radiation. However MC simulations show larger fraction of high energy deposit.



K.A. Olive et al. (PDG),Passage of particles through matter,Chin. Phys.,C38,2014

- Most of the energy lost by heavy particle with energy in the MIP range is due low energy electron ionization (typically few keV), rare high-energy electron ionization interactions (**knock-on** electrons) however can leave enough energy to mimic a synchrotron signal and limit the suppression to $\sim 10^{-3}$ using simple cut on total energy deposited in the SRD detector.



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Distribution of electrons with kinetic energy T much larger than ionization energy I ($T \gg I$) can be described as[6]:

$$\frac{dN}{dTdx} = \frac{1}{2} K z^2 \frac{Z}{A} \frac{1}{\beta^2} \frac{F(T)}{T^2} \tag{2}$$

- Number N of electron emitted with energy T roughly dependent on the inverse of T
- $T \leq W_{max}$, where W_{max} is the maximum energy transfer for a particle to an electron which scales roughly as the square of the particle energy for heavy particle ($W_{max} \propto \gamma^2$)

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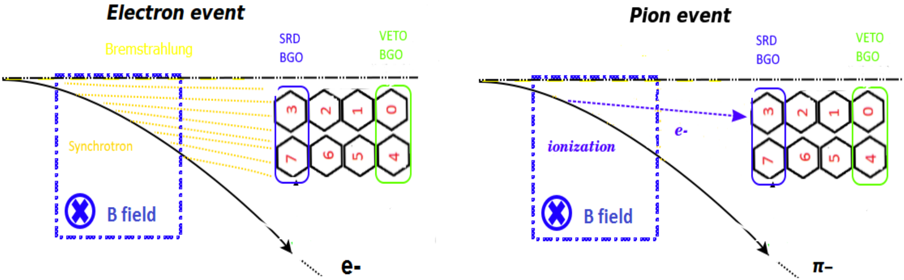
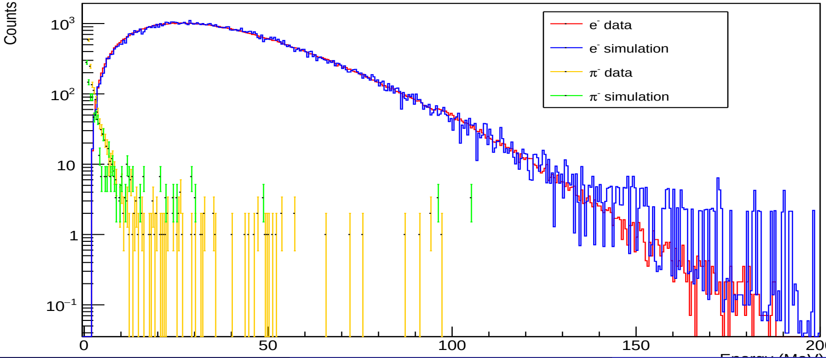
- Idea: Typically no more than one such interaction is produced per event. It should be possible to exploit detector **transverse segmentation** to distinguish synchrotron radiation (homogeneously distributed in the whole detector) from knock-on electrons (spacially localized since most of the energy is trasported by a single electron).

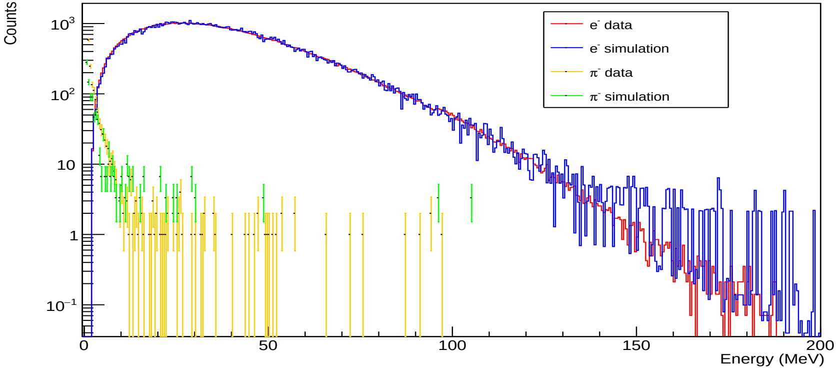


Outline

- This Method was tested during the beam time in July 2016 with the BGO detector, the ability of rejecting π^- and μ^- efficiently was confirmed both for the nominal 100 GeV e^- of the experiment using ECAL and HCAL to distinguish incoming particles and directly using a 100 GeV pi^- beam ($\sim 9.8\times10^4$ events collected).
- A detailed MC simulation of the full **NA64** setup was prepared and the results was compared to the acquired data.

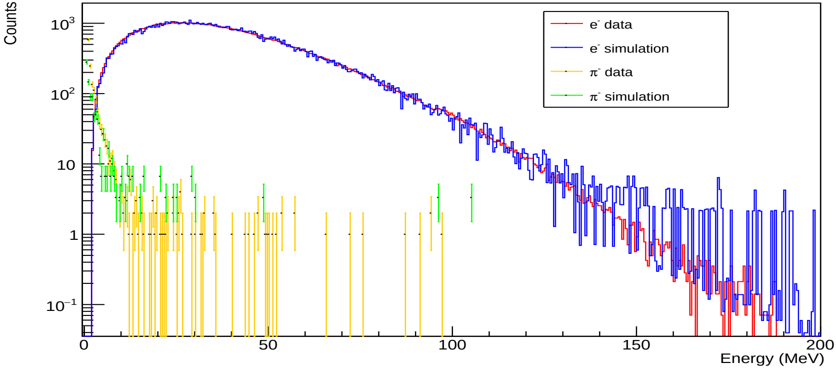


- Results: generally very good agreement between the spectra for typical synchrotron energies.
- Some disagreement in the high energy spectrum of electron were recovered by eliminating high energy contamination using the VETO BGO and by adding the expected pileup ($\sim$1%) for the intensity of the beam ($\sim 3.5\times10^{5}$ particles/spill)

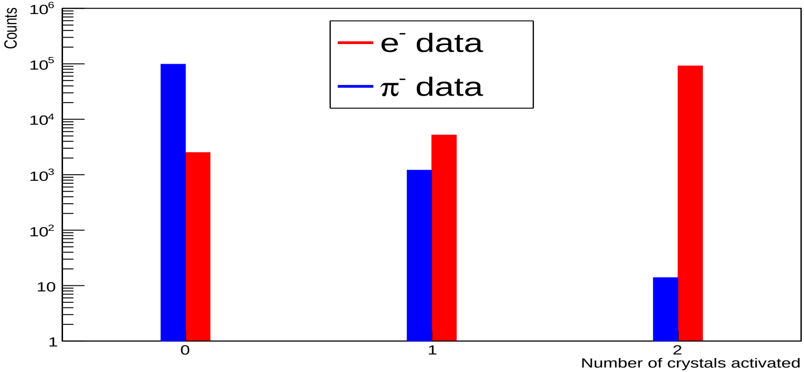


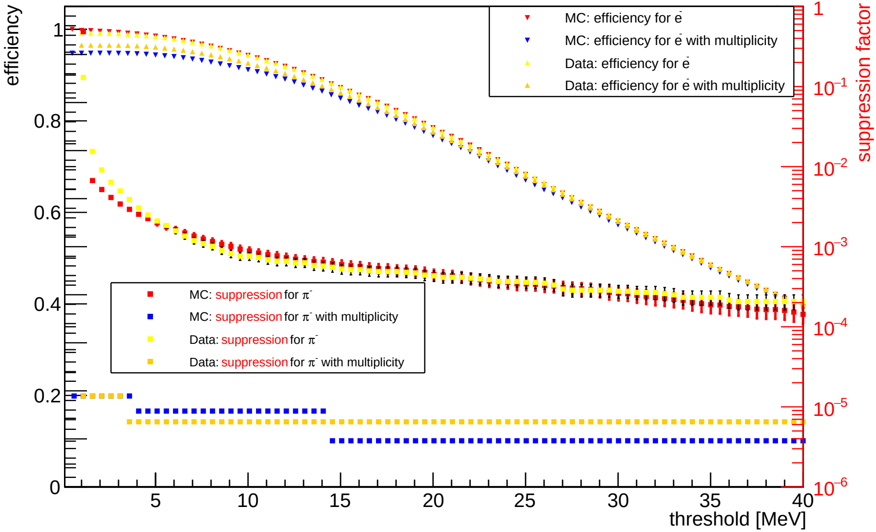
Results during test beam

- Results: generally very good agreement between the spectra for typical synchrotron energies.
- some disagreement in synchrotron range between data and simulation for π^-. Probably due beam impurites.



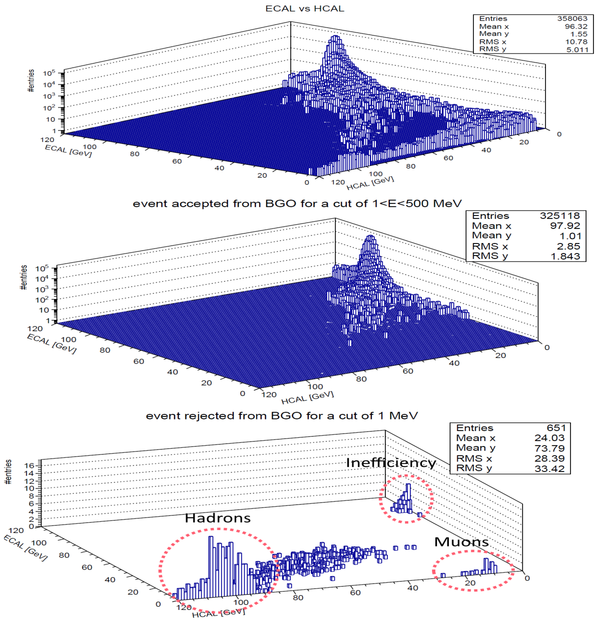
- Number of crystal activated (more than 1 MeV of energy deposition) was checked in the data to be correlated with particle type as expected.
- few events in the π^- run with 2 activated crystals were eliminated by requiring the total energy deposited in the BGO detector to be larger than 5 MeV. Such events are probably caused by knock-on electrons that further ionize during their travel to the detector.





efficiency
1
0.8
0.6
0.4
0.2
0
5
10
15
20
25
30
35
40
threshold [MeV]
suppression factor
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
MC: efficiency for e⁻
MC: efficiency for e⁻ with multiplicity
Data: efficiency for e⁻
Data: efficiency for e⁻ with multiplicity
MC: suppression for π⁻
MC: suppression for π⁻ with multiplicity
Data: suppression for π⁻
Data: suppression for π⁻ with multiplicity

ECAL vs HCAL plot



Outline

- **Synchrotron radiation** can be used to efficiently tag electrons in a beam by placing a **scintillator** in the region between undeflected and deflected beam.
- **transverse segmentation** of the detector can be exploited to detect spacial distribution of the synchrotron radiation and improve further the tagging, bringing the suppression factor down to $\sim 10^{-5}$ and allowing so to suppress μ^- and hadrons down to $\leq 10^{-12}$ per e^- in the **NA64** setup.
- efficiency above 95%

Conclusion

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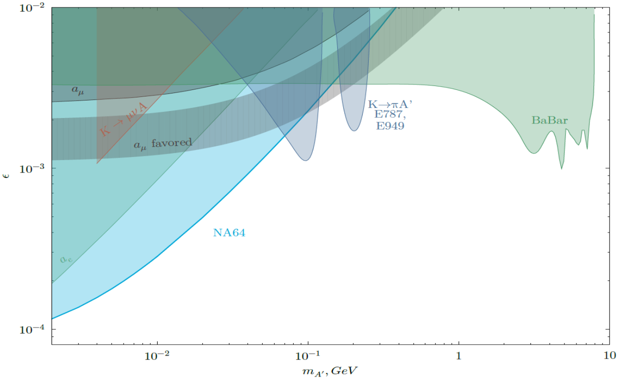
- efficiency above 95%

Upgrade:

- some faster scintillator can help reduce pileup at high intensity (PbSc sandiwich with decay time 20ns$\leq$ and larger segmentation has been tested), green extended R9420-100 hamamatsu PMT to improve energy resolution and timing.
- larger segmentation might be helpful but smaller crystal means lower threshold $\Rightarrow$ Energy resolution might become an issue

Result of July test beam:

- collected $\sim 2.75 \times 10^9$ events on target.
- 90% exclusion plot already covers a good portion of unexplored parameter space![7]
- collected $> 10^{10}$ events on target during October 2016 test run $\rightarrow$ analysis in progress...

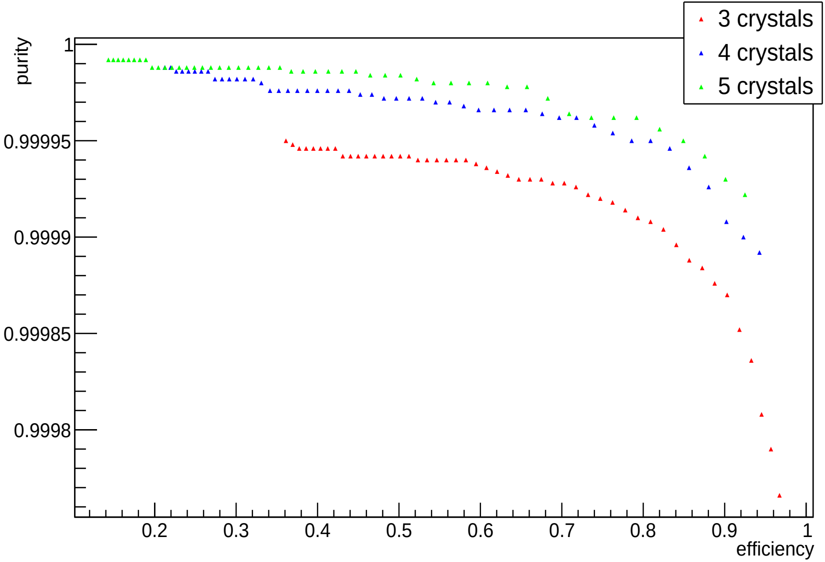


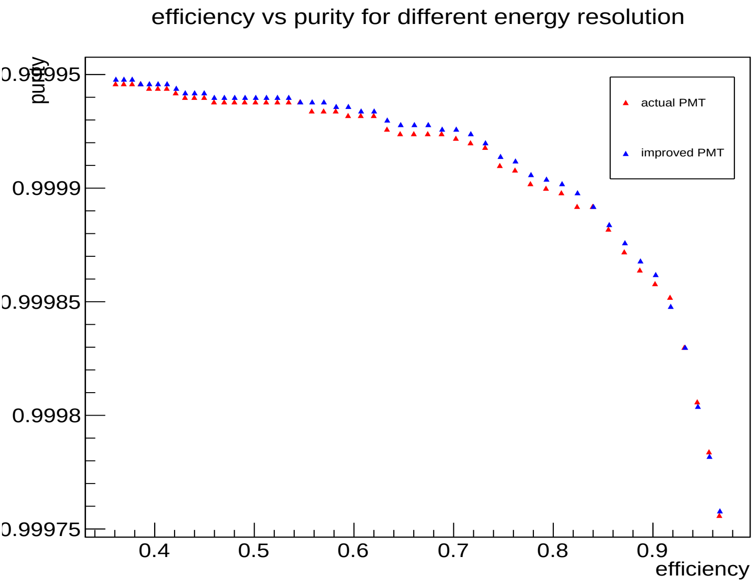
Search for Invisible Decays of Sub-GeV Dark Photons in Missing-Energy Events at the CERN SPS,Phys. Rev. Lett. 118,011802(2017)

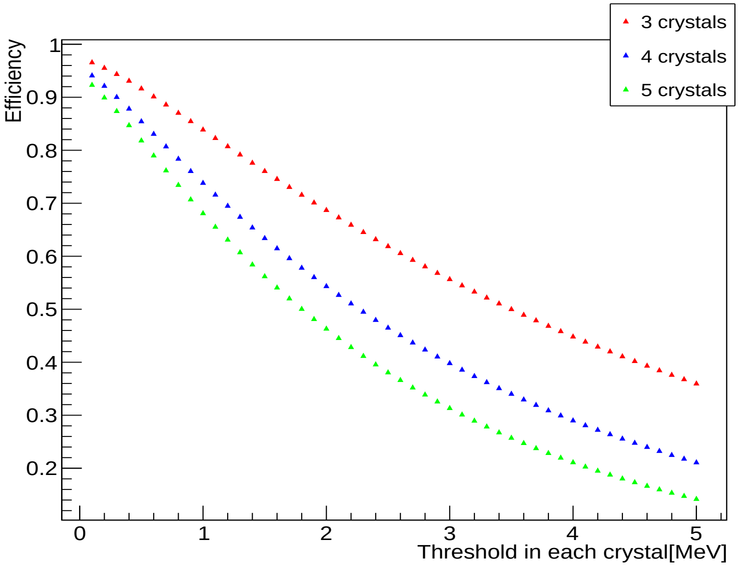
Thank You!

Questions?

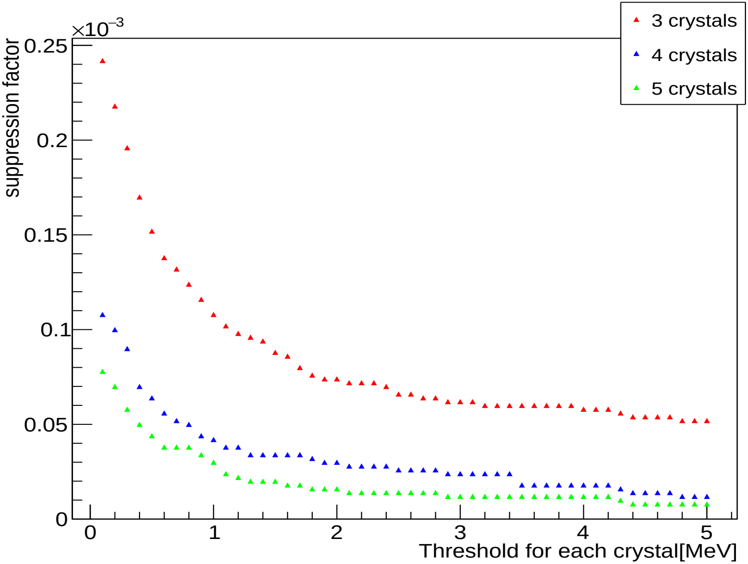
Influence of larger segmentation




efficiency vs purity for different energy resolution
purity
0.99995
0.9999
0.99985
0.9998
0.99975
0.4
0.5
0.6
0.7
0.8
0.9
efficiency
actual PMT
improved PMT



3 crystals
4 crystals
5 crystals
Efficiency
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
1
2
3
4
5
Threshold in each crystal[MeV]


3 crystals
4 crystals
5 crystals
$\times 10^{-3}$
suppression factor
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
Threshold for each crystal[MeV]