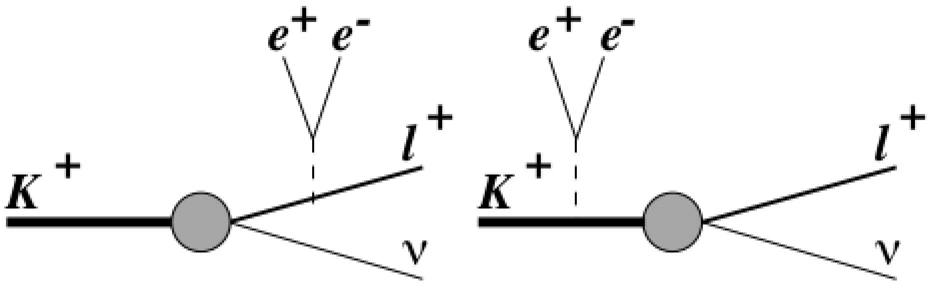
Study of the $K^+ \rightarrow e^+ \nu_e e^+ e^-$ Decay with the NA62 Experiment

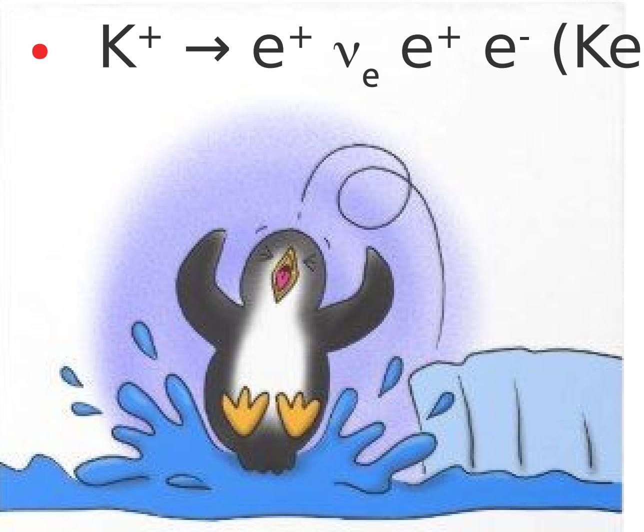
Wigner Seminar
24. 10. 2022.

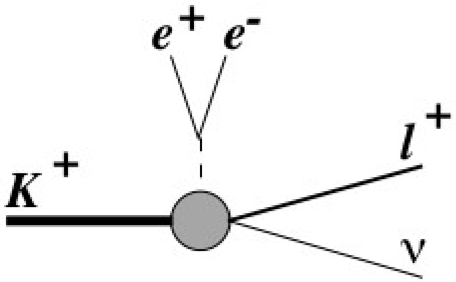
Anna Fehérkuti
CERN Summer Student 2022 (27. 6. - 23. 9.)
Supervisors: Francesco Brizioli, Monica Pepe
EP-UFT, Small Medium Expt

Motivation: K-physics

- $K^+ \to l^+ \nu\, l^+ l^-$ described by Chiral Perturbation Theory (ChPT) → test & inputs
- Decay amplitude includes:
  - Inner Bremsstrahlung (IB) well predicted by $K^+ \to l^+ \nu$
  - Structure-Dependent components (SD): form factors (F_A, F_V, R)
    - General K^+-decay sensitive to F_A, F_V
    - R contributes only to decays with $e^+ e^-$ from γ^*
- $K^+ \to e^+ \nu_e\, e^+ e^-$ (Ke2ee): SD > IB (← e^--helicity suppression)







About Branching Ratios

Collecting either *K*$^+$ *(6 %)*, *π*$^+$ *(70 %)*, *p*$^+$ *(24 %)*
Secondary beam of 75 GeV (750 MHz)

SPS
400 GeV

+ target (Be)

- Absolute measurement (of N$^{\text{channel of interest}}$/N$^{\text{all}}$) impossible (interesting vs *everything?*)
- Normalization channel Br_2 from PDG: Br_1/Br_2
  - Likely process → small external uncertainty (propagated, but negligible vs syst/stat)
  - Similar process → small systematic error (many uncertainty factors fall out)
- Which one is better in this case?

Uncertainties

$$\frac{Br^{signal}}{Br^{norm}} = \frac{N^{signal}}{N^{norm}} \cdot \frac{\varepsilon^{norm}}{\varepsilon^{signal}} = \frac{N^{signal}}{N^{norm}} \cdot \frac{Acc^{norm}}{Acc^{signal}} \cdot \frac{Trig^{norm}}{Trig^{signal}}$$

- *Br*: branching ratio
- *N*: actual measured counts
- ε: selection efficiency
- *Acc*: acceptance, efficiency of the offline selection
  - From Monte Carlo (MC)
- *Trig*: efficiency of the online trigger selection
  - Different masks for signal and noralization

- Same cuts: *Acc* of signal vs normalization cancel
- Perfect MC: *N* & *Acc* balance each other

Studied Processes

$K^+ \rightarrow e^+ \; \nu \; e^+ \; e^-$

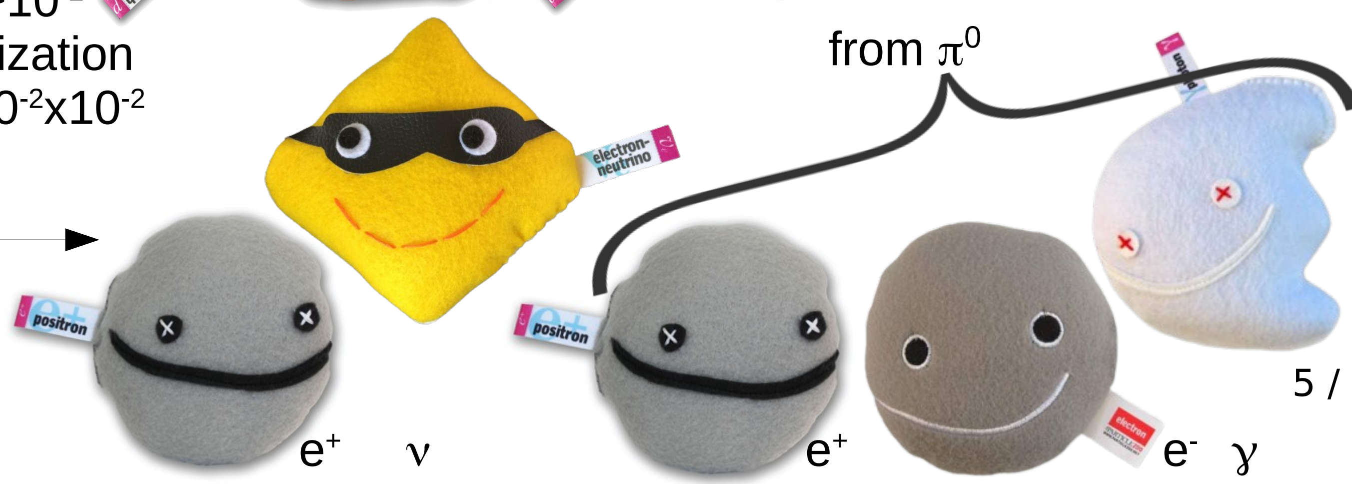
signal
Br~10^{-8}

$K^+ \rightarrow \pi^+ \; \pi^+ \; \pi^-$

Br~10^{-2}

normalization
Br~10^{-2}x10^{-2}

from π^0



$K^+ \rightarrow e^+ \; \nu \; e^+ \; e^- \; \gamma$

Previous studies

Table 7: Theoretical values for the branching ratios for the decay $K^+ \to e^+\nu_e e^+ e^-$ for various cuts.

	tree level	form factors as given by CHPT
full phase space	$\approx 4 \cdot 10^{-9}$	$1.8 \cdot 10^{-7}$
$z,\ z_1 \geq 10^{-3}$	$3.0 \cdot 10^{-10}$	$1.22 \cdot 10^{-7}$
$z,\ z_1 \geq (50\ MeV/M_K)^2$	$5.2 \cdot 10^{-11}$	$8.88 \cdot 10^{-8}$
$z,\ z_1 \geq (140\ MeV/M_K)^2$	$2.1 \cdot 10^{-12}$	$3.39 \cdot 10^{-8}$

- Theory [1]:
  - z: $m_{e-,e+}$
- Experimental results (BNL, 2002) [2]: $N_{signal} = 410$ (including 10% background contamination)

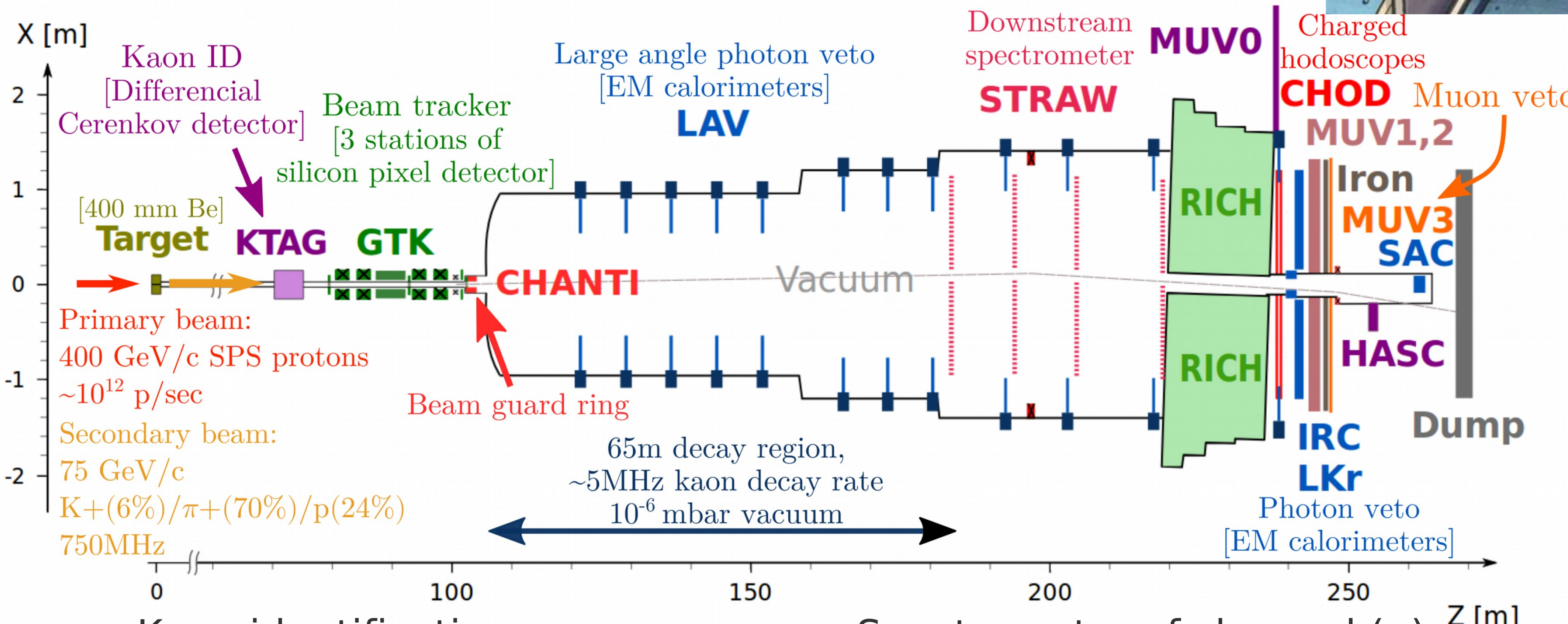
$Br(m_{e-,e+} > 140\ MeV) = [291 \pm 16(\text{stat}) \pm 17(\text{syst}) \pm 0.7(\text{ext from model})] \cdot 10^{-10}$

→ NA62: data collected 2016-2021

→ Full 2017-18 sample

+ v3.1.3 MC: kenuee, k3pi, k2pi.pi0d

The NA62 Experiment



- Kaon identification
- Tracking the beam
- Collimator vs *upstream* → Fiducial Volume (FV): decay
- Photon vetoes (vs π^0)
- Spectrometry of charged (p)
- Cherenkov radius of charged (β)
- Electromagnetic & hadronic calorimeters
- Muon vetoes

Event Selection I.

- General conditions:
  - 1 single 3 track event
  - Precise enough vertex ($\chi^2 < 25$) of charge +1, in FV ($z \in [105, 180]$ m) within 6 ns wrt trigger (vtx: CHOD vs trig: RICH)
  - Opposit-charged particles in time wrt trigger:

    $|t^1_{NewCHOD} - t^2_{NewCHOD}| < 2$ ns, $|t^i_{NewCHOD} - t_{CHOD}| < 2$ ns
  - Tracks in detector acceptance (STRAW, RICH, CHOD, NewCHOD, LKr)
  - Reasonable track separation (15 mm in each STRAW chamber, 200 mm in LKr plane)
  - Extra activity vetos: γs, μs (reject event if activity within 2 ns wrt vertex)
  - Good association between KTAG-GTK & RICH-CHOD:

    $|t_{GTK} - t_{KTAG}| < 1.4$ ns, $|t_{vertex} - t_{RICH}| < 2$ ns
  - Vertex-building from the three downstream tracks and the GTK track, where the GTK candidate gives the minimal χ^2_{vertex}
  - Momentum of each track separately $\in [8, 50]$ GeV
  - 3-track momentum < 78 GeV
  - HLT (L1): KTAG was ok, no exotics in STRAW

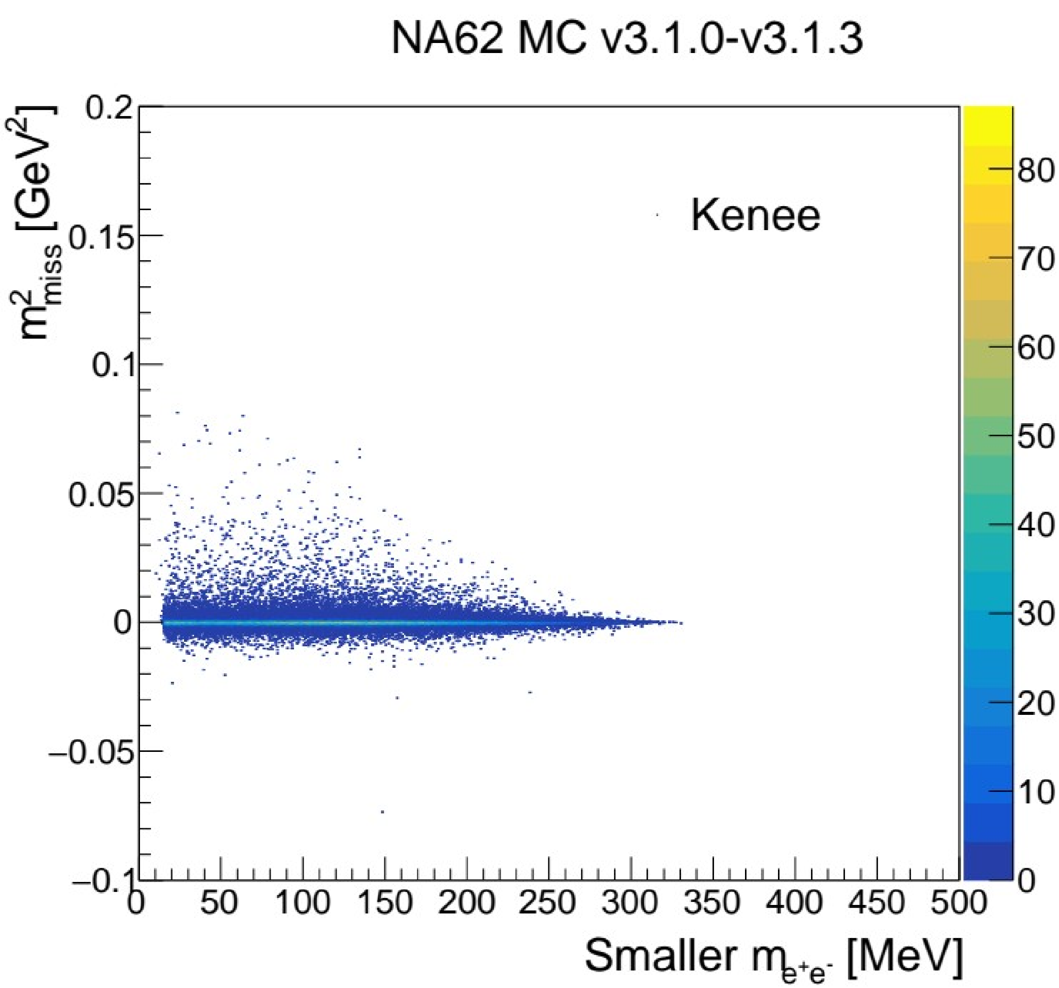
* see on Slide 11

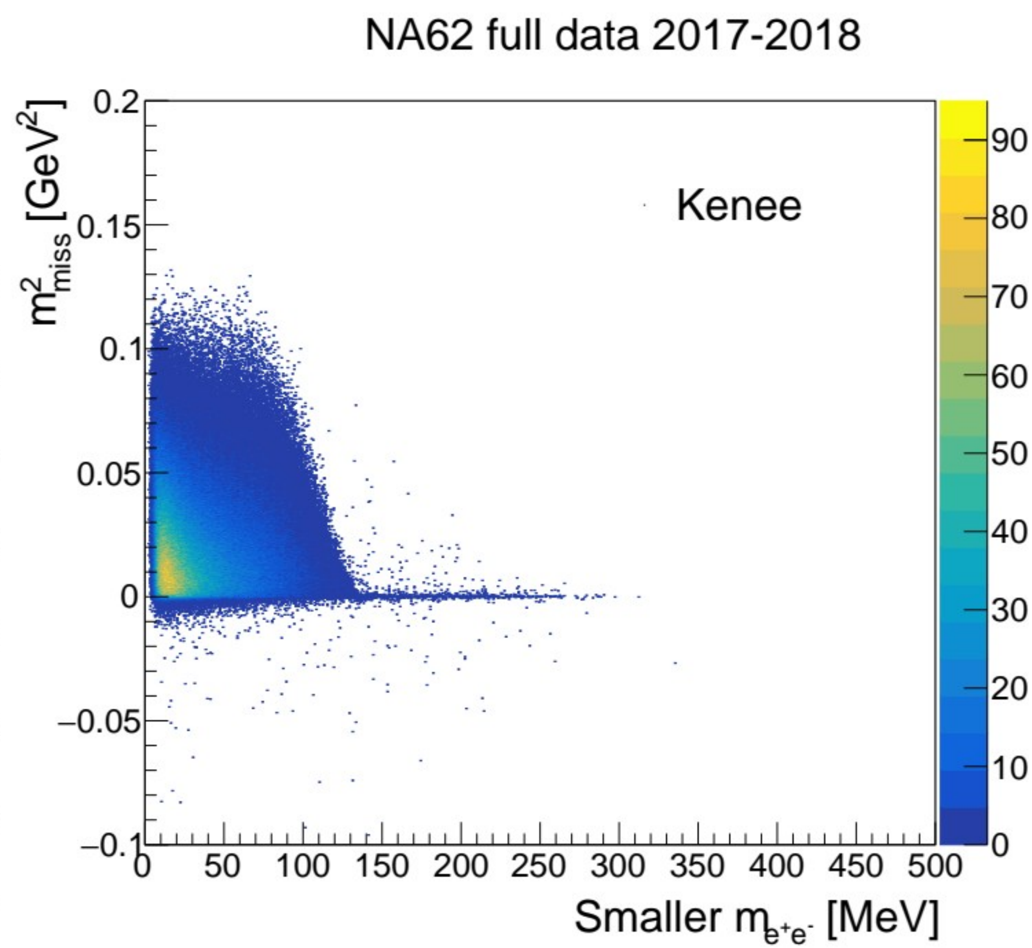
Event Selection II.

- Signal selection:
  - Particle identification (PID):
    - e^- probability from calorimetric BDT > 0.5 for the positive tracks (Boosted Decision Tree, BDT: neural algorithm)
    - e^- RICH likelihood > 0.5 for the positive (!) tracks
    - No EoP (from LKr) condition needed (EoP > 0.9 [3])!
  - Kinematics:
    - Neutrino momentum (lower boundary): $p_\nu > 200$ MeV
    - p^T in GTK (lower boundary): $p^T_{GTK} > 8$ MeV
    - Electron-positron invariant mass (lower boundary): $m_{e-,e+} > 140$ MeV
      - Theory: vs divergence in the decay rate due to the small-energy γ
      - Experimetally: vs $K^+ \rightarrow e^+ \nu \; \pi^0$, $\pi^0 \rightarrow e^- e^+ \nu$ (Dalitz mode)
    - Missing mass (upper boundary): $m_{miss}^2 < 0.03\ GeV^2$
  - Trigger mask4 (“di-electron”), downscaling of 8: extra condition (over mask5*) on LKr total energy (minimum 20 MeV)

$m_{miss}{}^2$ vs $m_{e-,e+}$

- Well-peaked distribution → suitable for selection
- $\nu \rightarrow 0 = m_{miss}{}^2$





2 way for $m_{e-,e+}$ (2 positrons):
Choose the smaller
→ minimum cut on $m_{e-,e+}$: cut on both

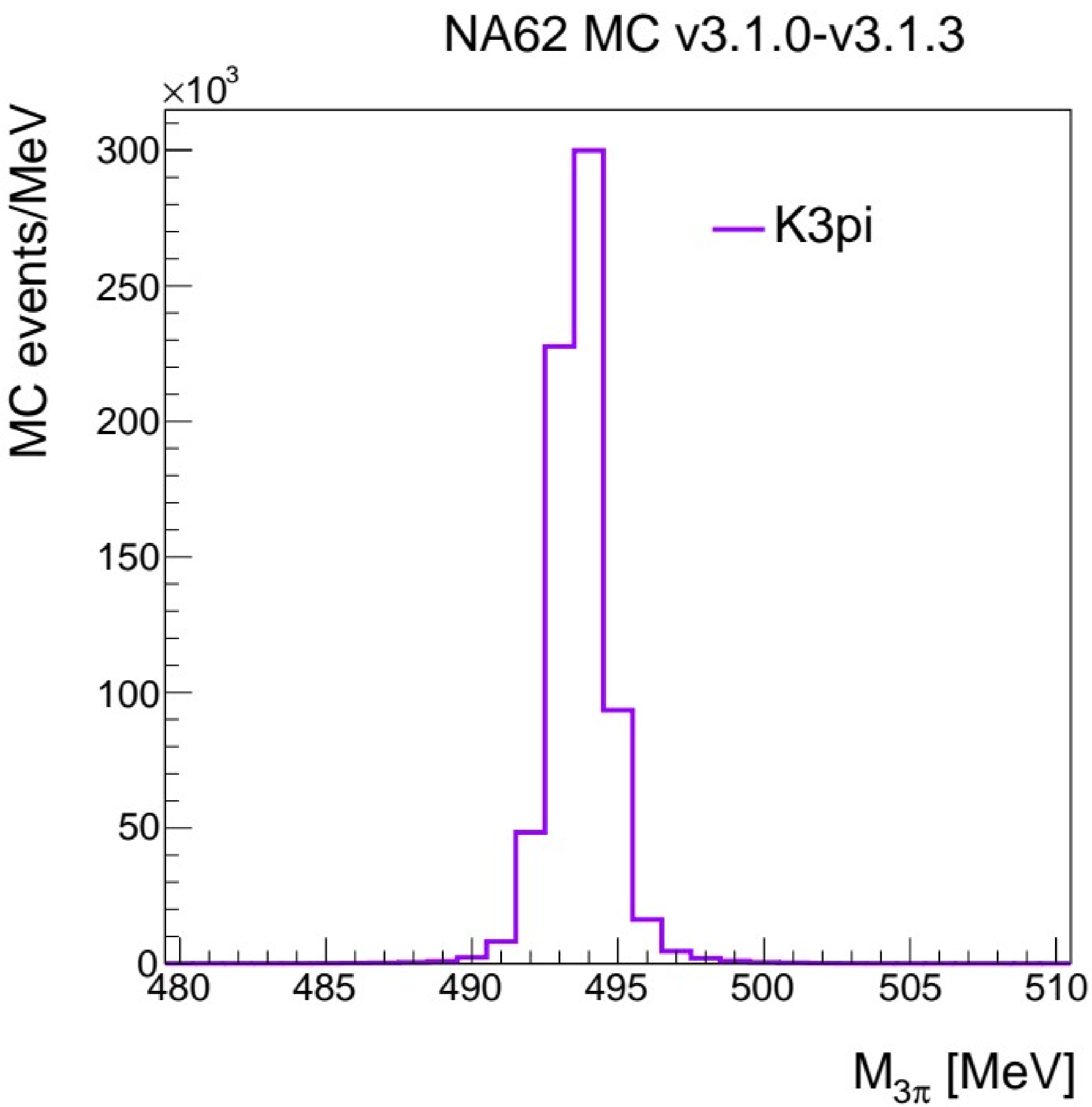
Event Selection III.

- Normalization selection:
  - Kinematics:
    - Kaon invariant mass: $|m_{3\pi} - m_{K+}| < 4$ MeV

      (check if GTK was ok first)
  - No PID needed! (clean enough sample)
  - Separating data (events already identified as signal shall not be analyzed again):

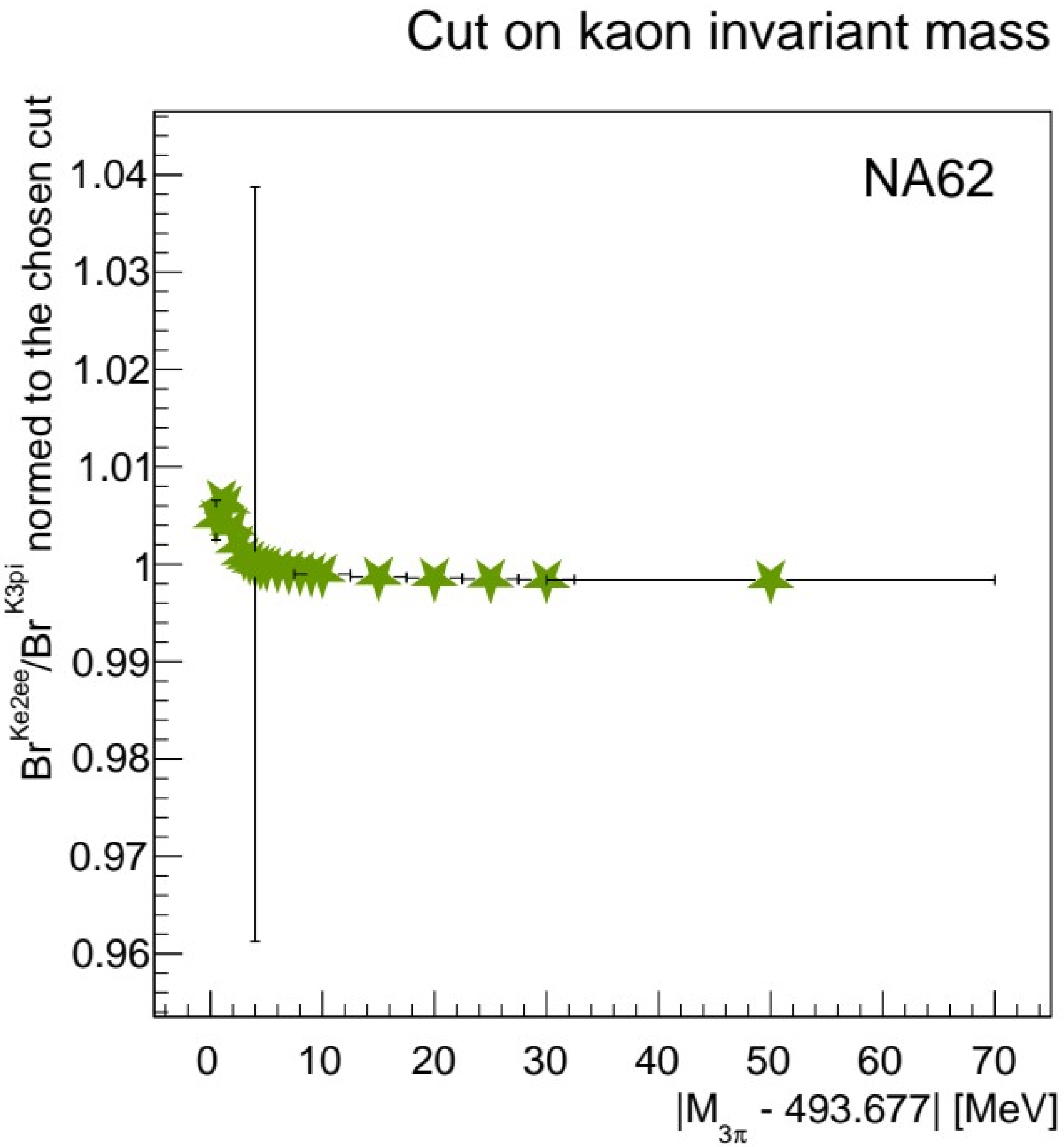
    EoP < 0.9
  - Trigger mask5 (“multi-track”), downscaling of 100:
    - RICH was ok
    - Good newCHOD candidates

Kaon invariant mass (K3pi MC)



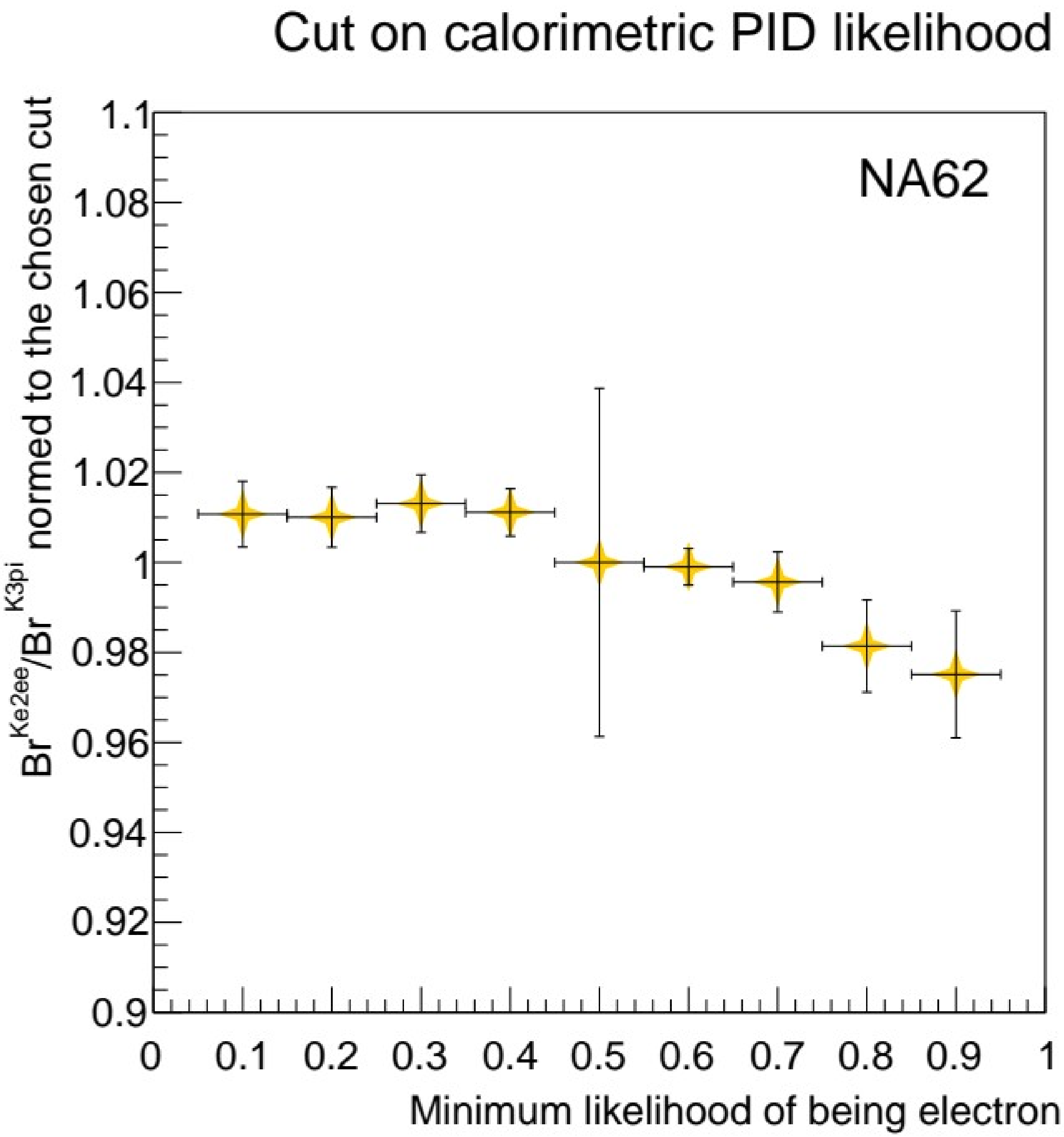
- Well-peaked distribution → suitable for selection
- Official value [4]: 493.677± 0.013 MeV

Stability studies: kaon invariant mass

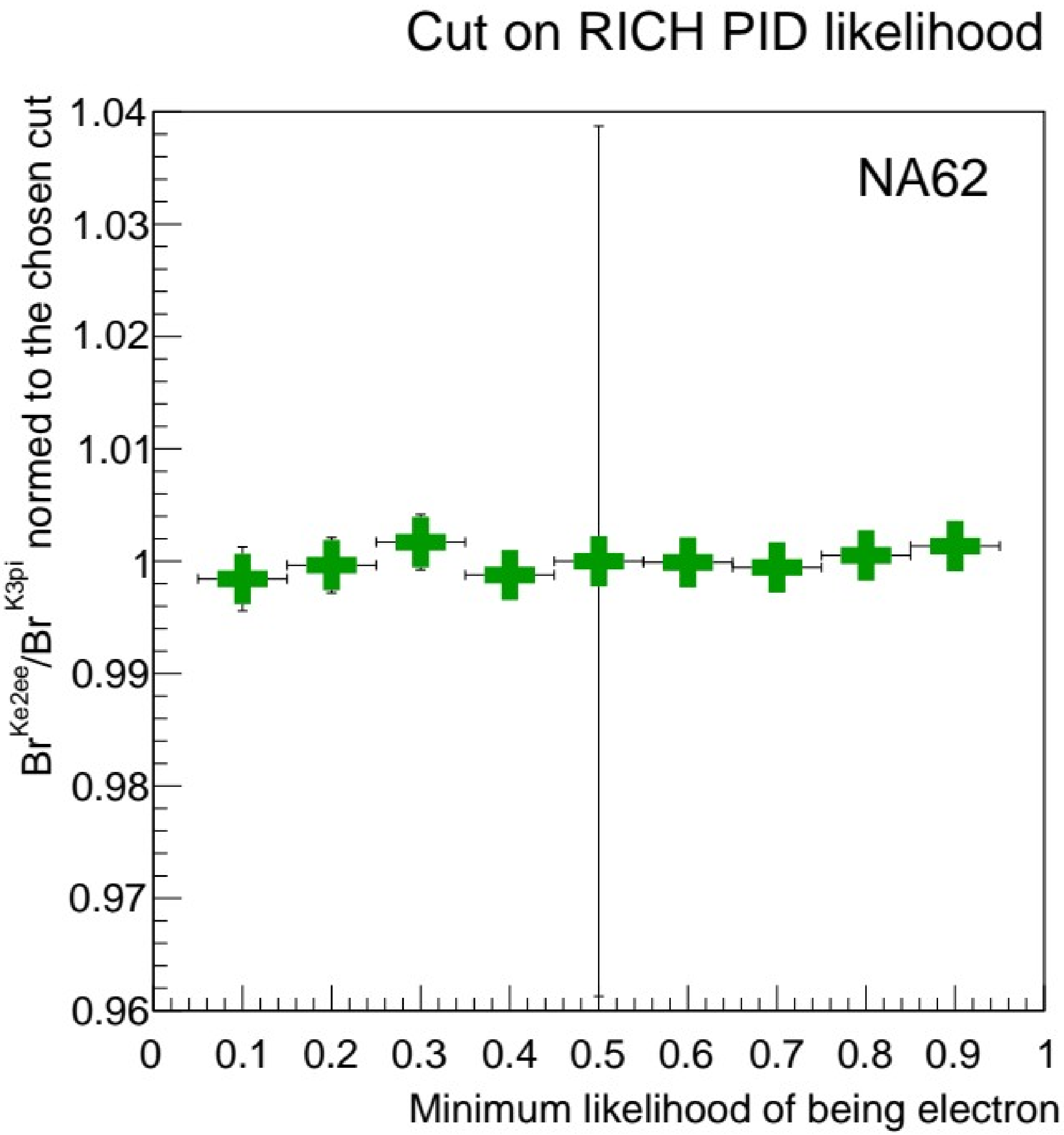


- Normed to the chosen cut
- Uncertainty of the central value: all stat + syst
- Uncertainty of the other values: relative to the central
- (On the following plots as well...)

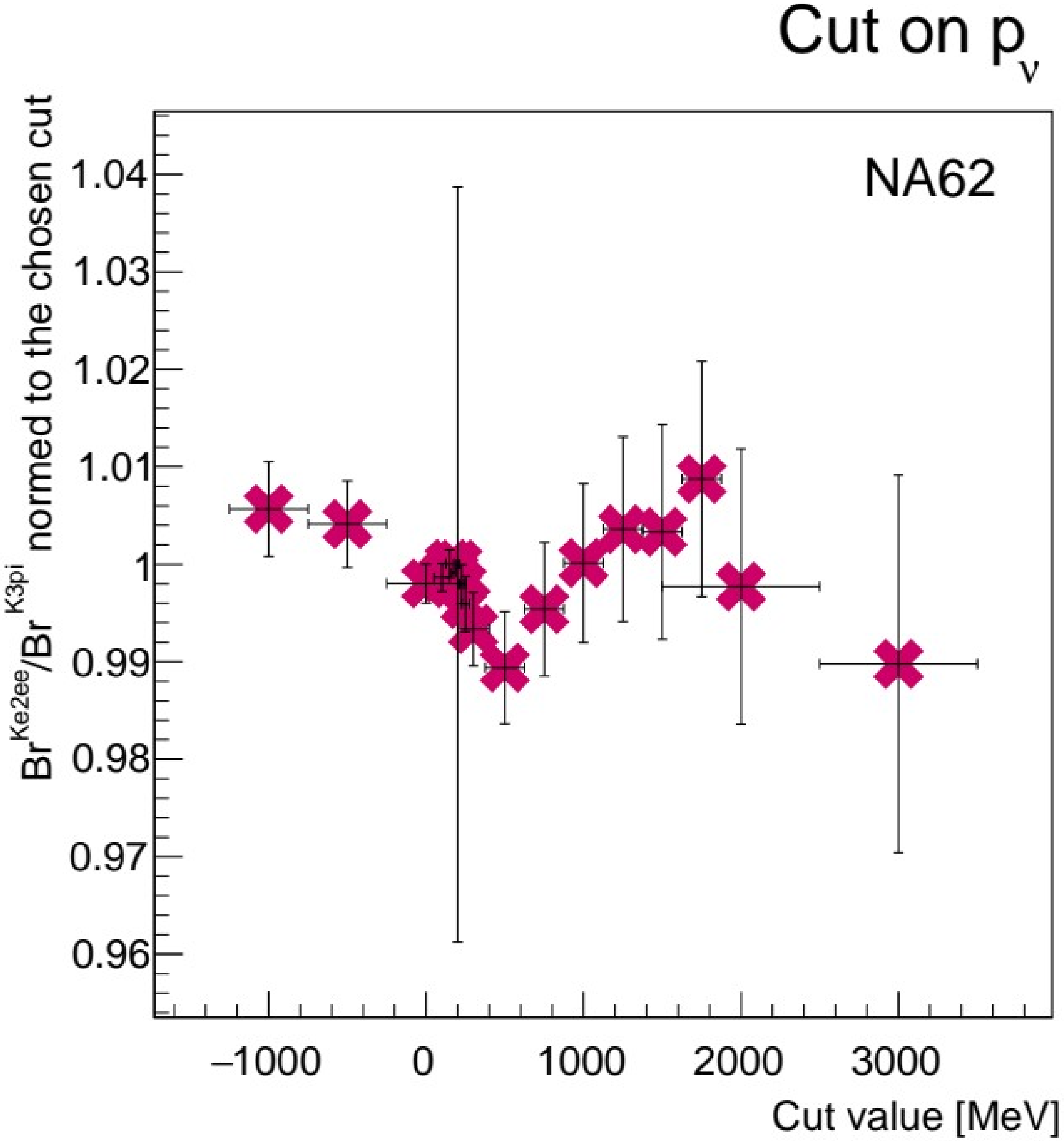
Stability studies: BDT PID



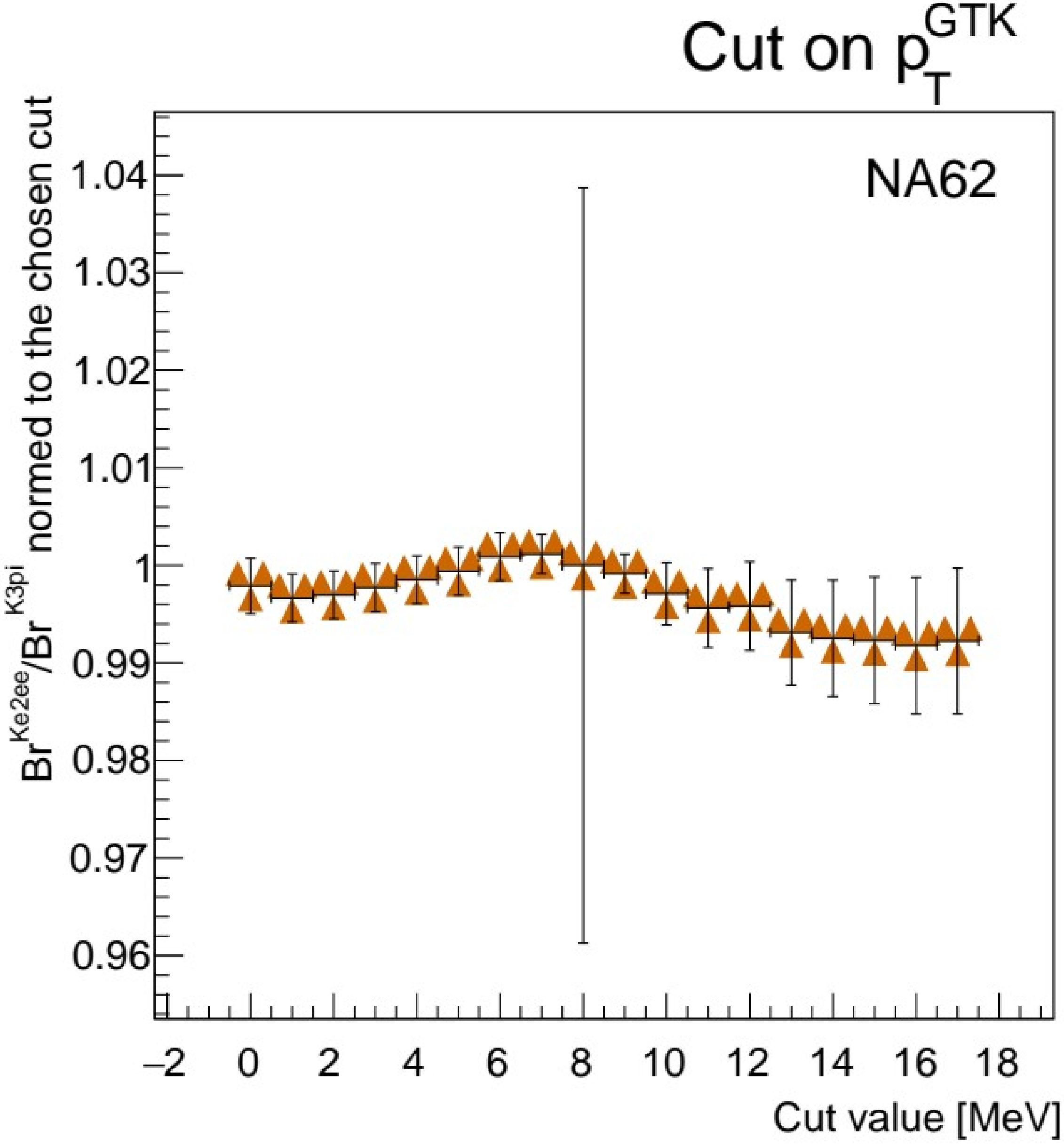
Stability studies: RICH PID



Stability studies: p_ν

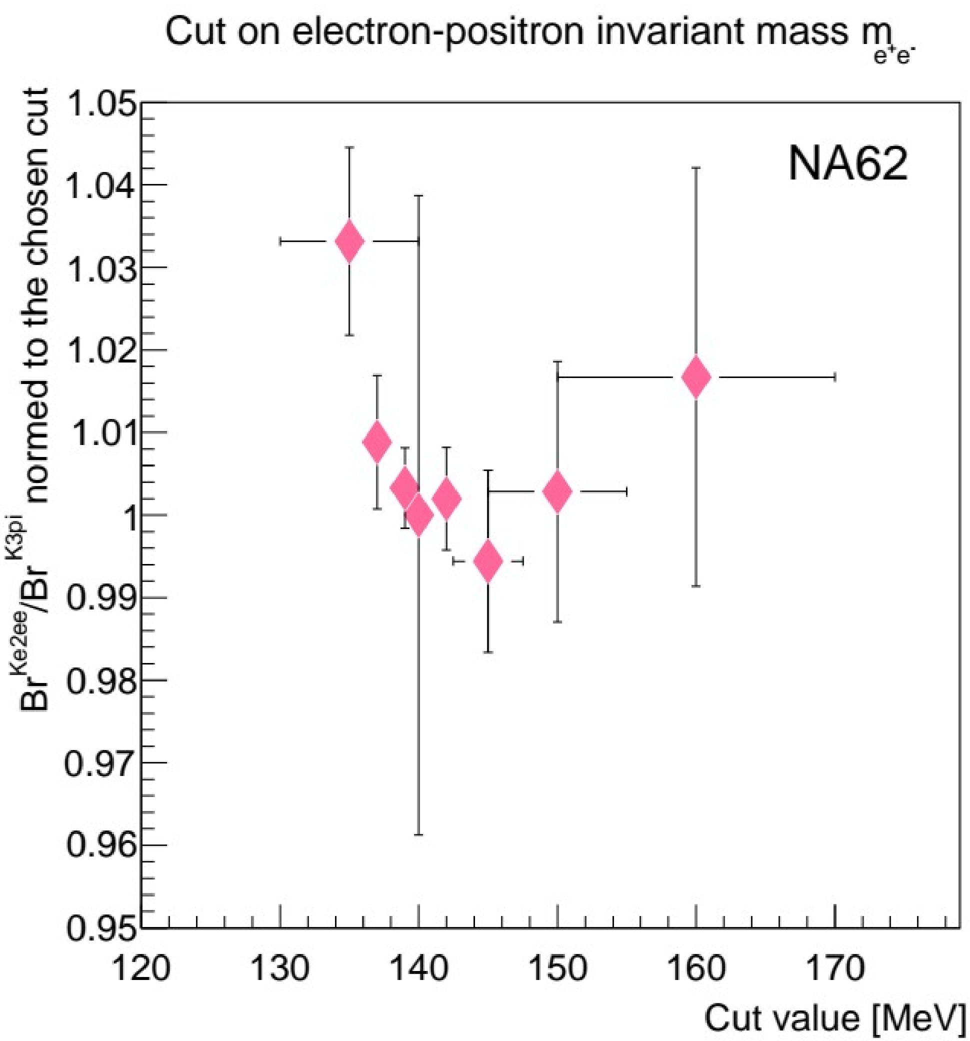


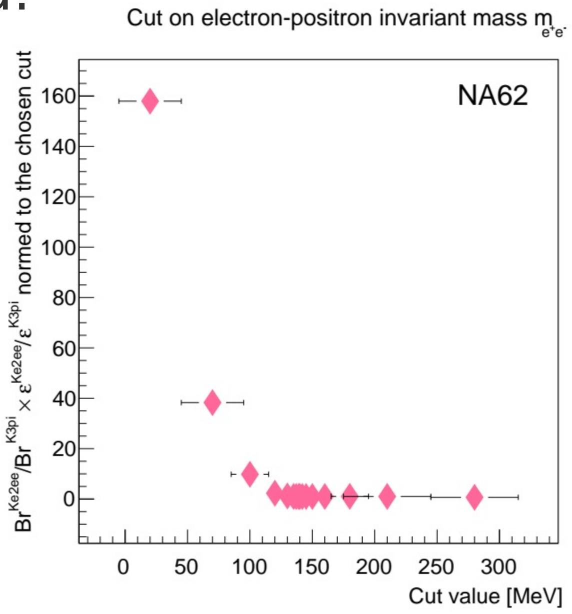
Stability studies: p_T^{GTK}

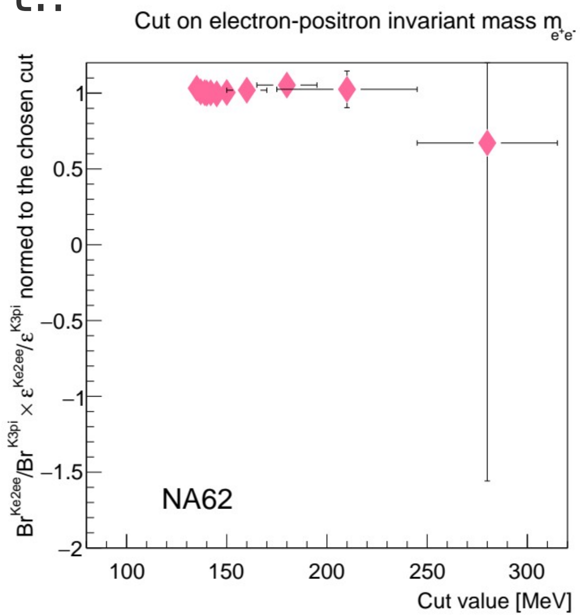


Stability studies: $m_{e-,e+}$

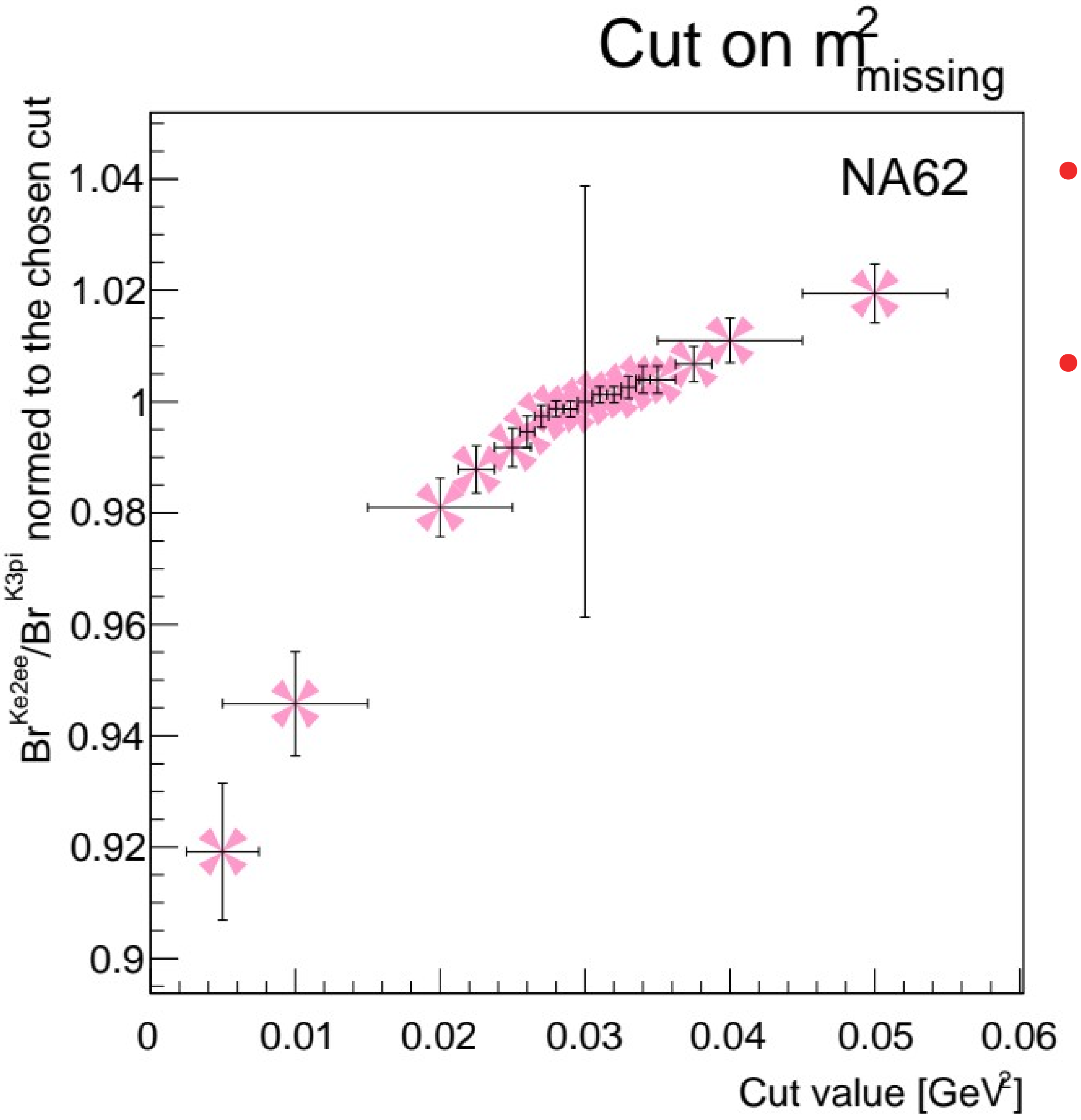
- Differently zoomed:
  - Too loose requirement → misidentified signals
  - Too strict → hardly remaining events: big uncert.:







Stability studies: m_{miss}^2



- Cut has to be where it is stable enough
- Not in the range of uncertainty: also almost different order of magnitude

Trigger efficiency

- Wrt selection
- From data: control (CTRL) data needed
  - Signal: mask4/CTRL = 708/11 (too low stat)
  - Normalization: mask5/CTRL = 91.7%
- From MC, emulating L0 triggers as well:
  - Signal (RICH, NewCHOD, LKr): 92.6%
  - Normalization (RICH, NewCHOD): 91.3%

  → ratio: (98.5±0.8)%

  /extra condition in mask4 and not in mask5 (LKr20): very small inefficiency/

Summary I. - The Task

- Event selection for collecting signal & normalization events
  - Choosing a very likely normalization channel → small statistic uncertainty
  - Using as many as possible common cuts → decrease systematic uncertainty
- Examining acceptance & trigger efficiency
- Get the branching ratio from the branching fraction
  - Propagate uncertainty from $Br_{normalization}$

Summary II. - Results in Numbers

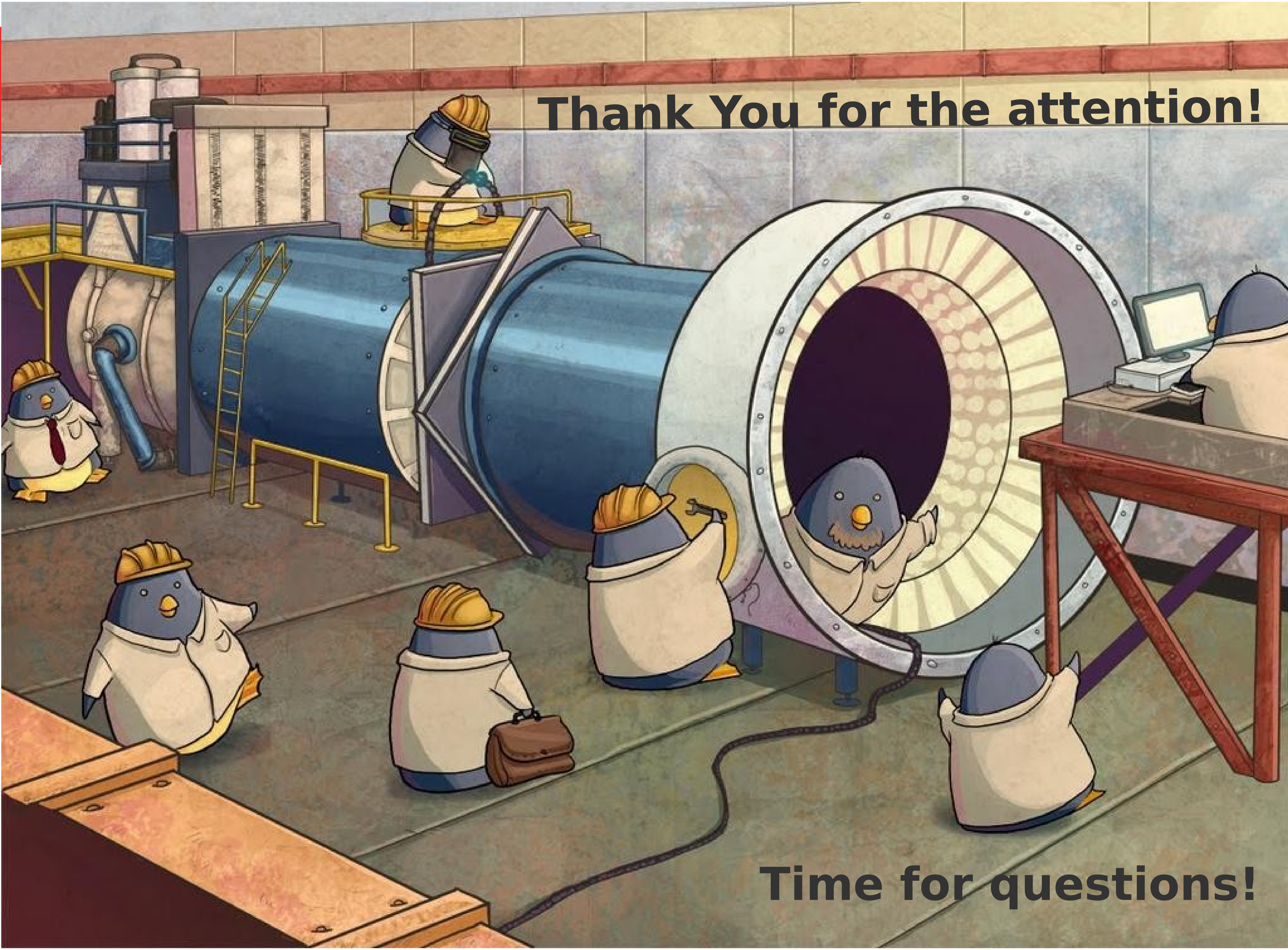
- Values from the literature:
  - $Br_{normalization}^{PDG}$: (5.583 ± 0.024)% [4]
  - $Br_{signal}^{theory}(m_{e-,e+} > 140\ MeV)$: $3.39 \cdot 10^{-8}$ [1]
  - $Br_{signal}^{measurement}(m_{e-,e+} > 140\ MeV)$: $(2.91 \pm 0.34) \cdot 10^{-10}$ [2]
- My analysis:
  - $Br_{signal}(m_{e-,e+} > 140\ MeV)$: $\mathbf{(3.13 \pm 0.12) \cdot 10^{-8}}$

	Signal	Normalization	Ratio
N	708±26.61	230419472±15180	$(3.073 \pm 0.116) \cdot 10^{-6}$
Acc	0.02837±0.00015	0.06300±0.00008	2.221±0.012
ε	0.9265±0.0069	0.9126±0.0017	0.9851±0.0076

Outlook

- Examining background contamination in signal case (cca. 20 events [3] vs 708)
- Analysis on bigger data

Thank You for the attention!



Time for questions!

Backup slides

Parts of the NA62 Experiment

KTAG

- Kaon-tagging vs proton
- PMTs
- Front-end readout
- Flashed with N_2

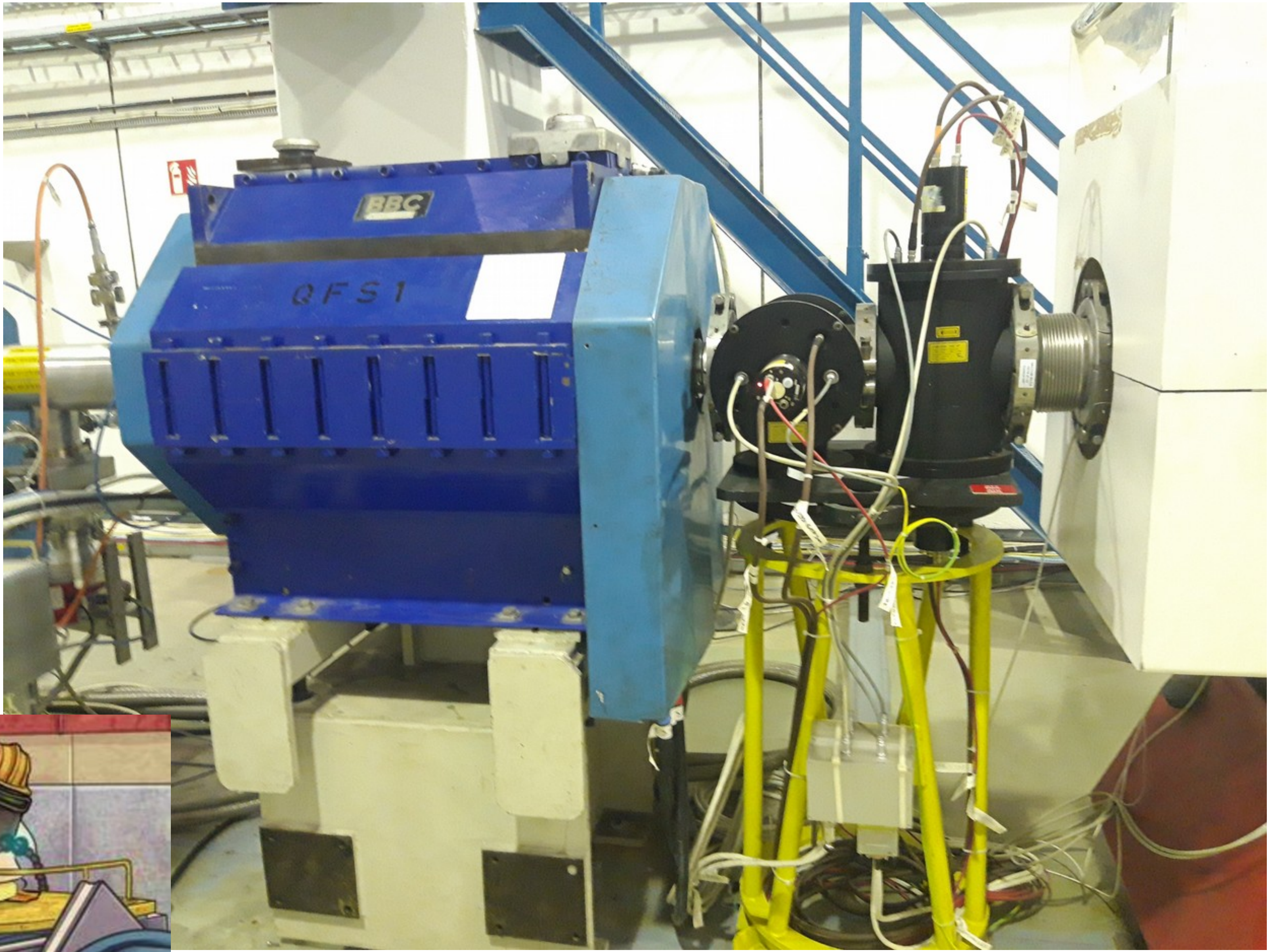
CEDAR

- Differential Cherenkov with KTAG
- Chromatic correctors +Mirrors
- 1.6 m
- N_2

Safe Volume

- For emergency cases: leakage on beam pipe
- N_2 into CEDAR vs mechanical wave

Magnets



GTK

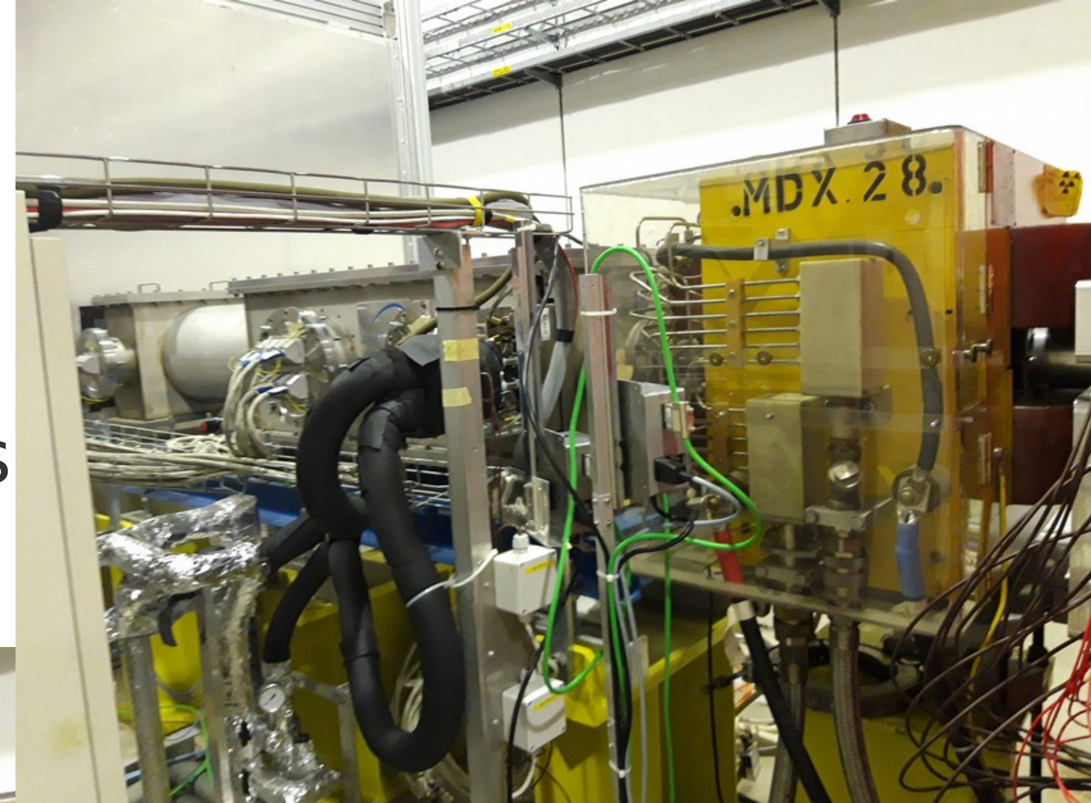
- GigaTracker: beam
- Between dipoles
  - 4 stations
- Si pixel

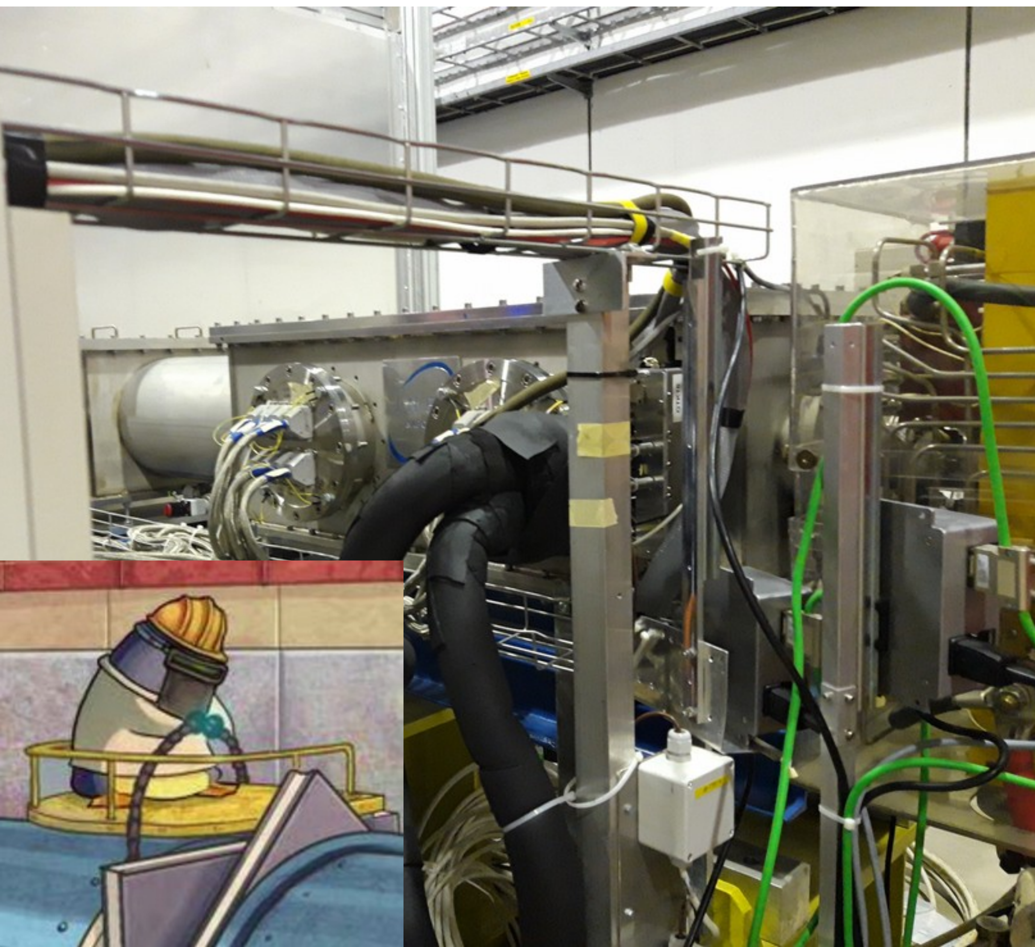
Collimator

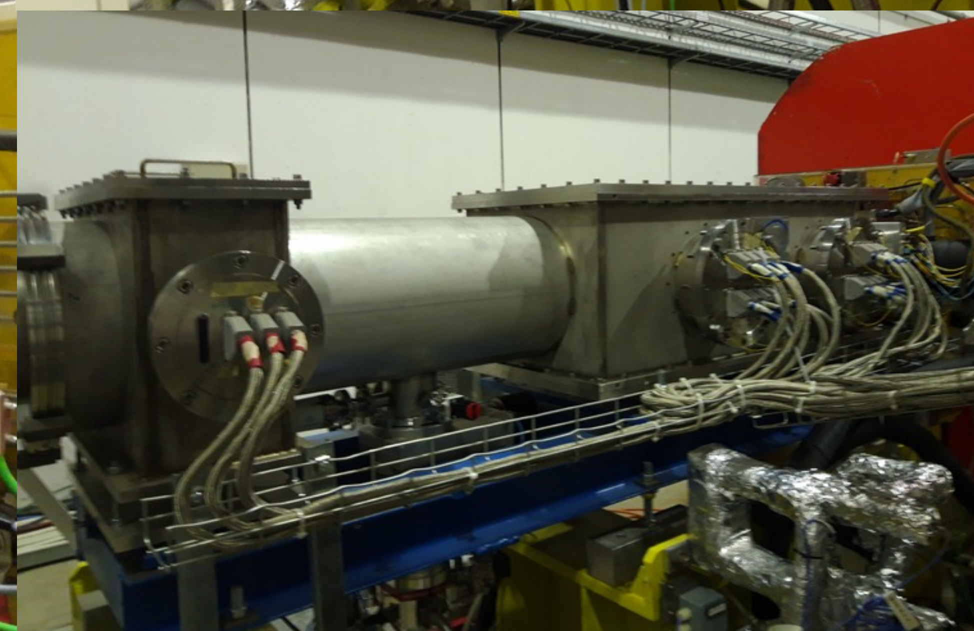
- Rainbow :)
- Vs upstream

CHANTI

- Charged ANTIcounter
- Hodoscope: scintillators
- Veto vs upstream



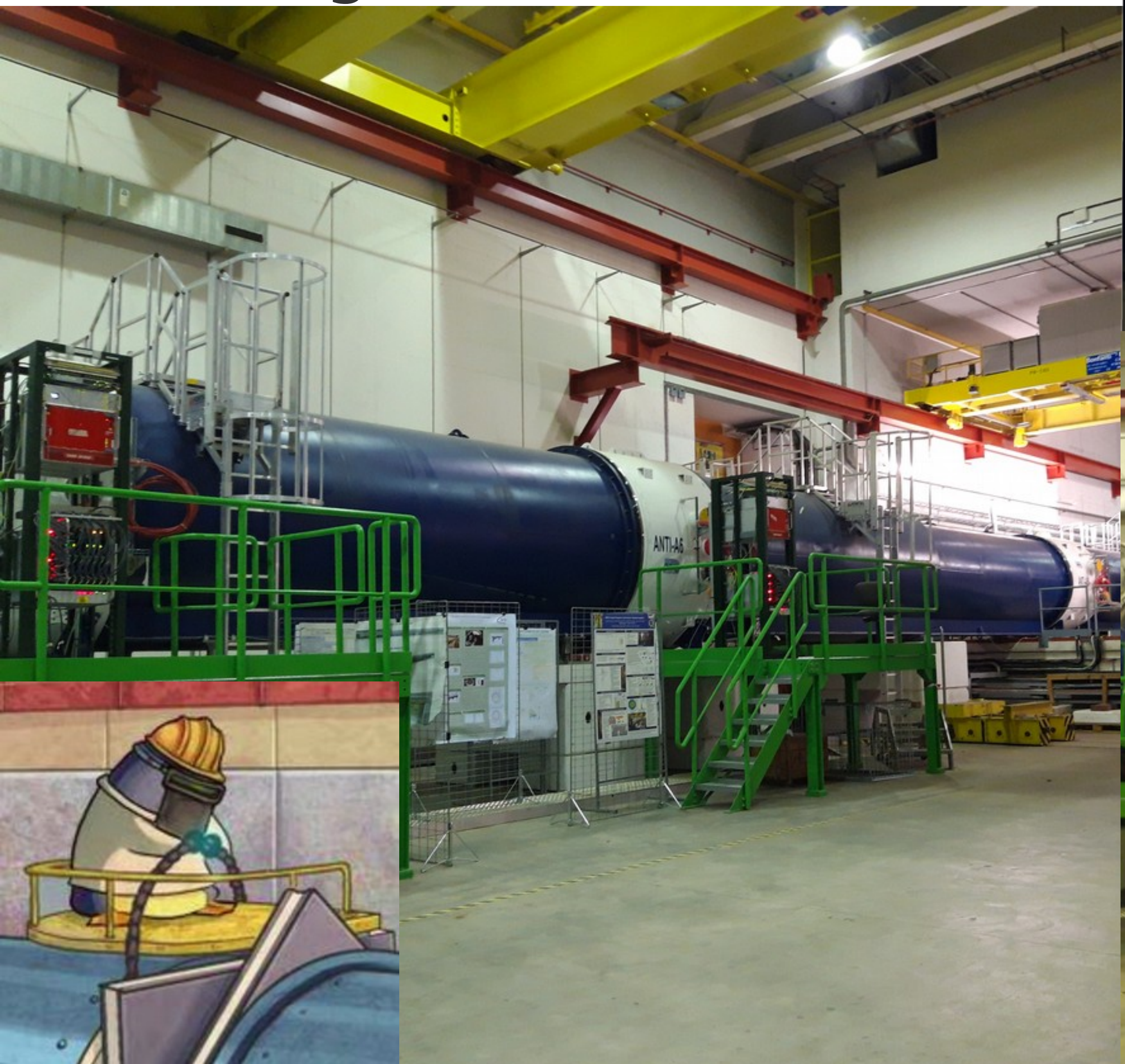




Beginning of the Fiducial Volume

LAVs

- Vetoes against photons
- Leadglass scintillators



STRAW

- Spectrometer
  - p of particle

- 4 stations
- 35 m

Strong magnet for STRAW

- 0.9 Tm: horizontal momentum kick of 270 MeV/c
  - 75 GeV/c beam deflected too, by -3.6 mrad

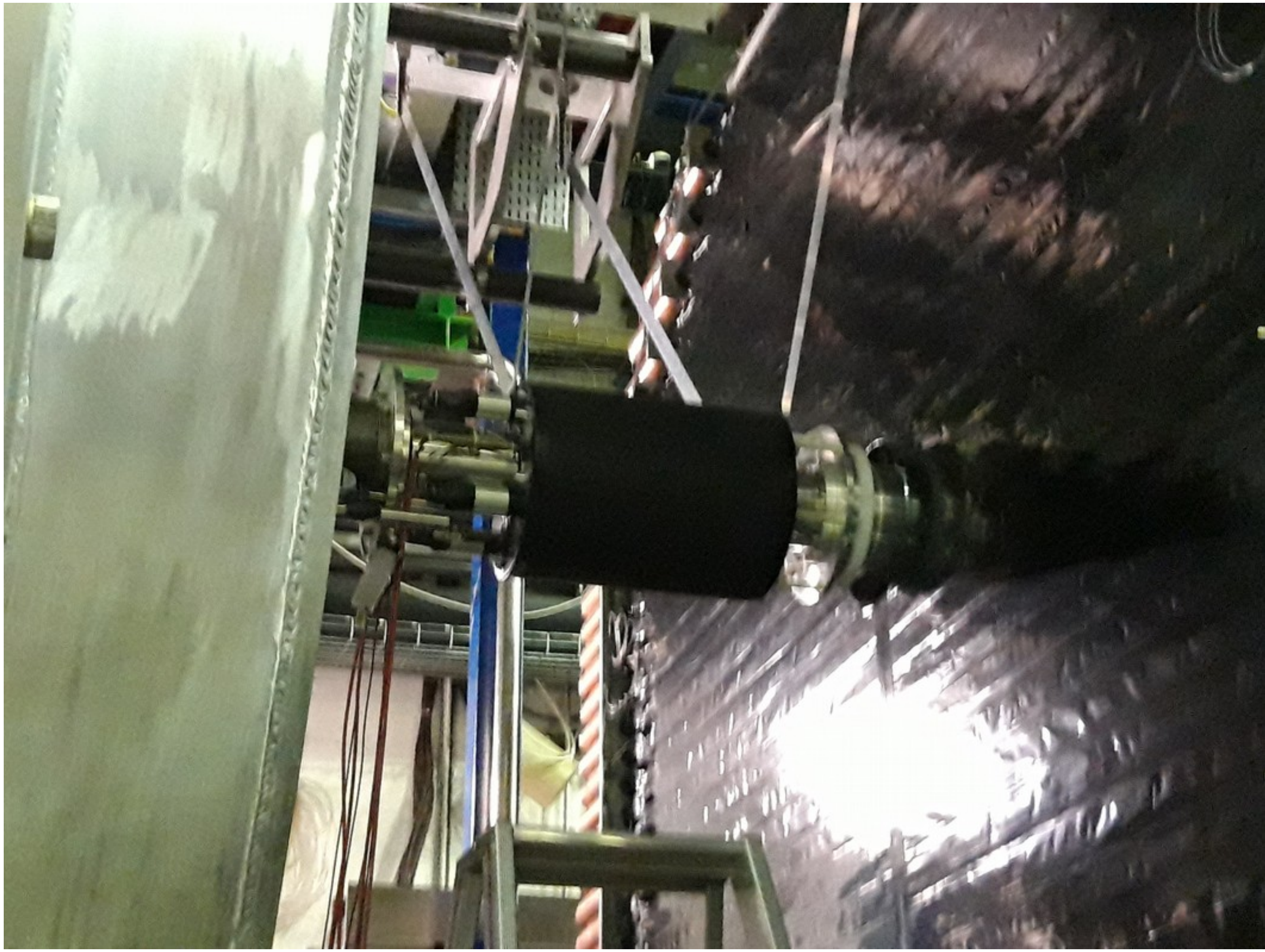
RICH

- Ring Imaging Cherenkov: Ne
- β of the charged particles

- Mirror mosaic
- PM disk

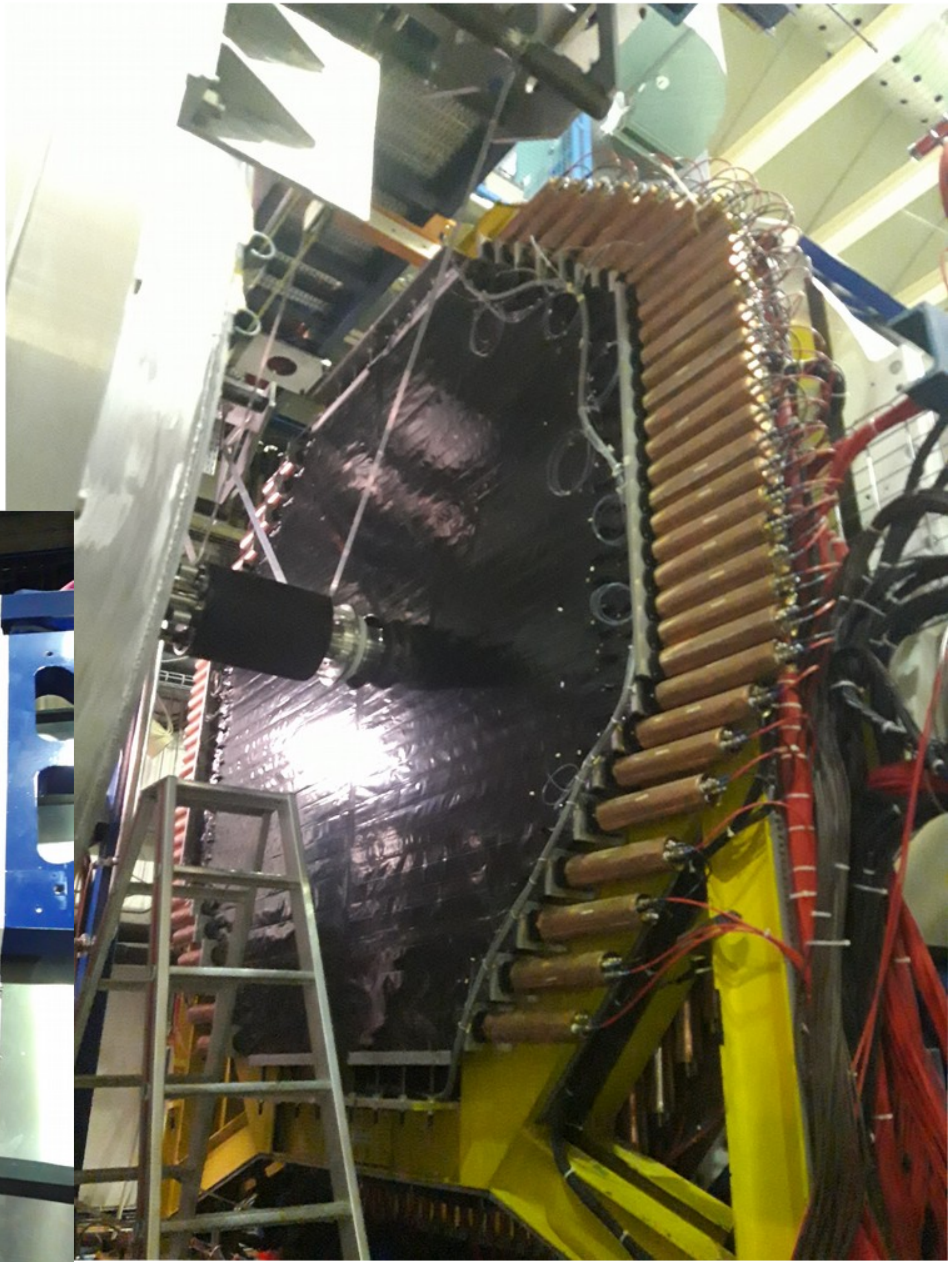
IRC

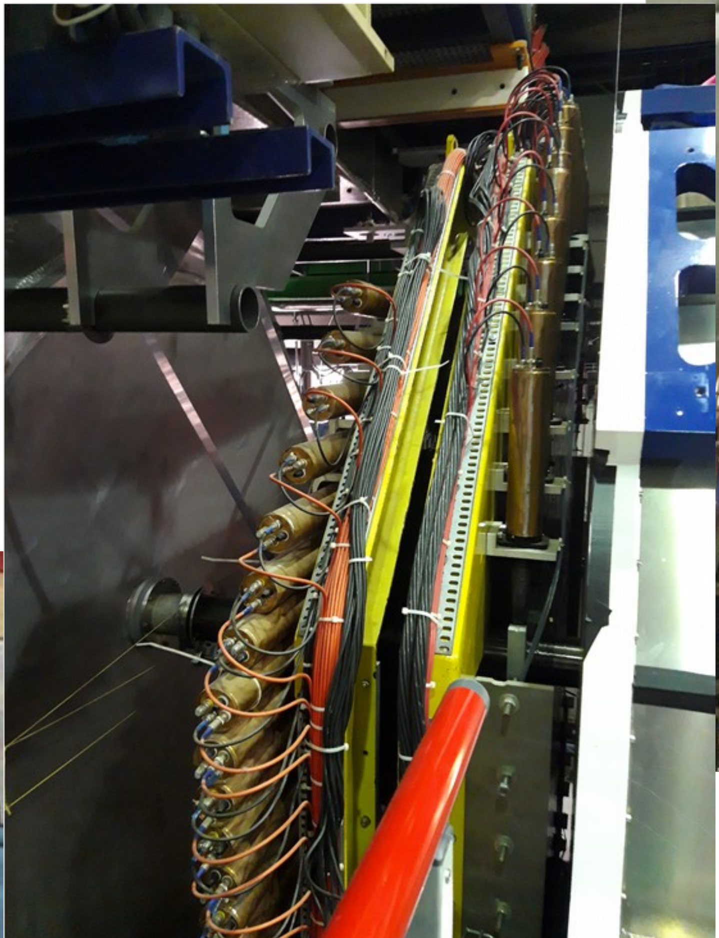
- Intermediate Ring Calorimeter
- Photon-veto
- Pb / scintillator Shashlyk



(New)CHOD

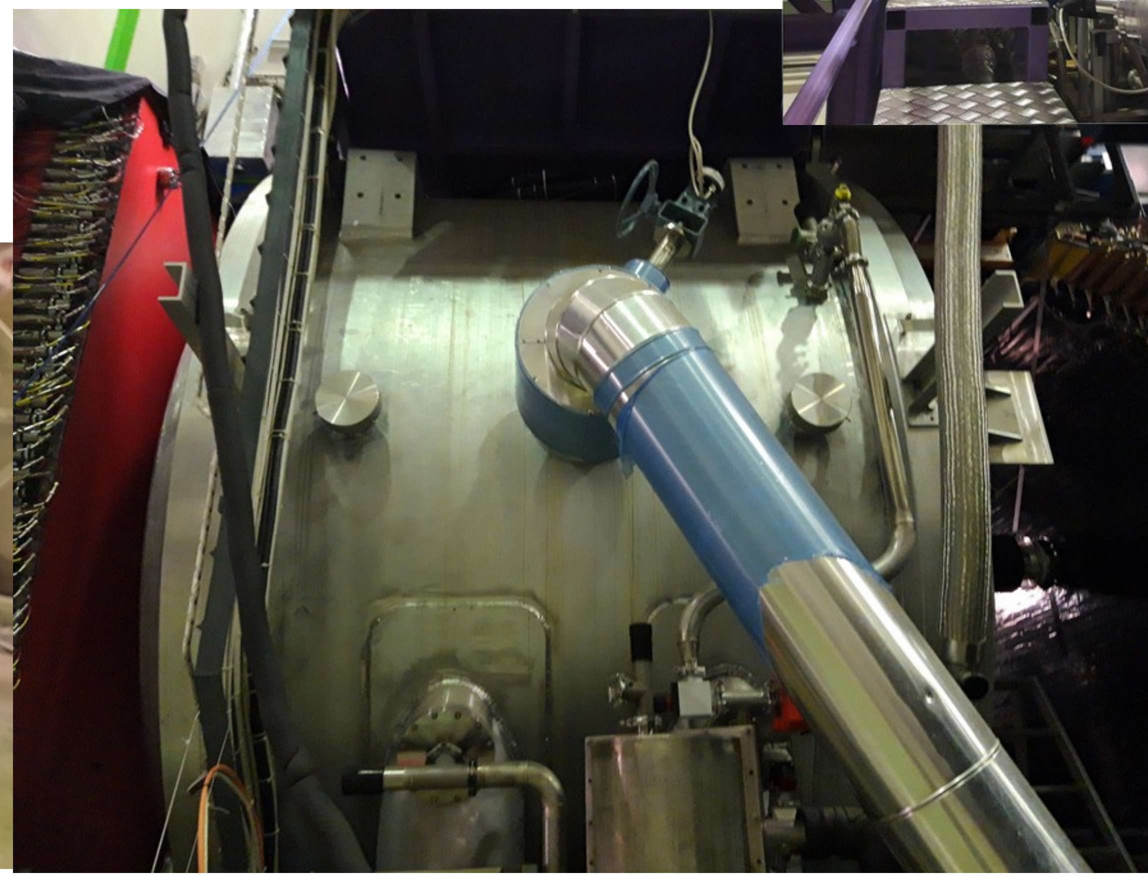
- Hodoscope: scintis
- Time → minimum bias trigger





LKr

- EM calorimeter from NA48
- Accordeon Cu ribbons
- 9 m^3 liquid Kr

MUV1,2

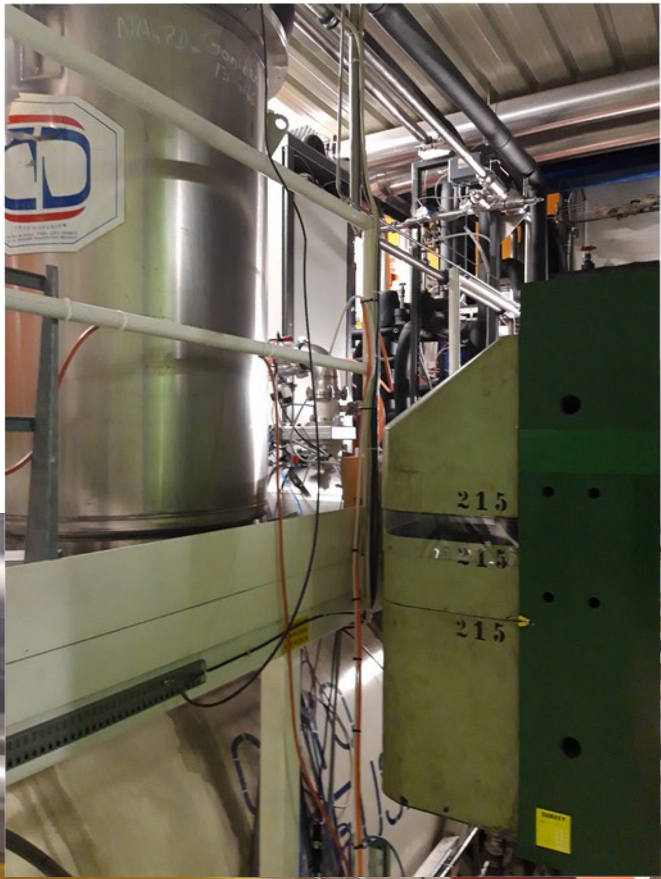
- Sampling hadronic calorimeters
- Fe / scintillators

MUV3

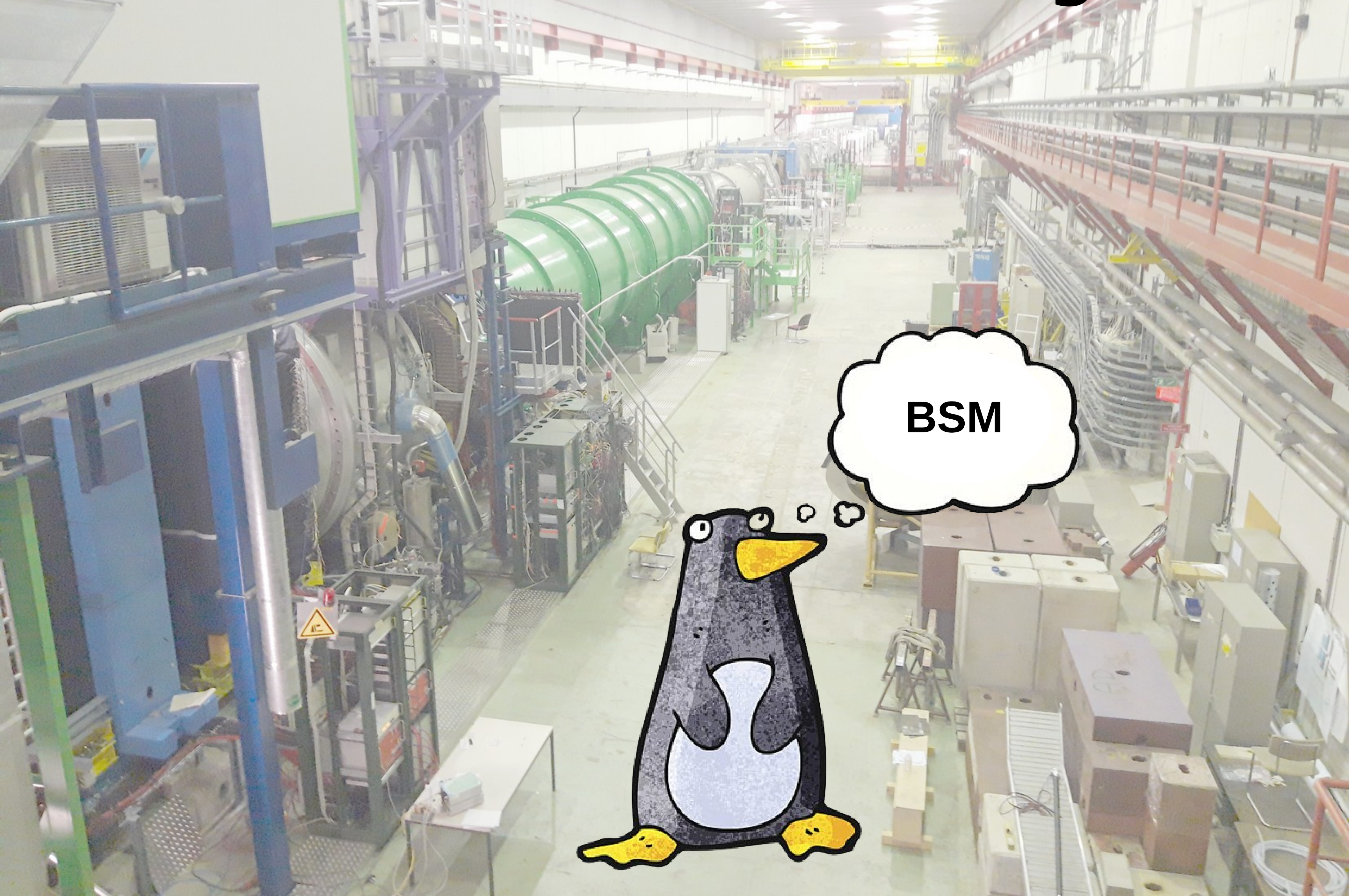
- Extra iron before it
- Only muons
- Plastic scintillators

HASC, SAC

- HASC:
  - Vs multitrack ($\pi^+ > 50$ GeV)
  - Sampling calorimeter
- SAC ~ last LAV:
  - Small angle calorimeter
  - Photon veto
  - Shashlyk



About the theoretical background



Motivation of NA62: BSM Probes

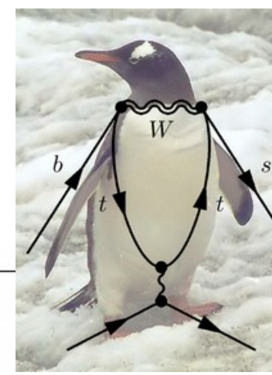
- CKM (Wolfenstein) → unitarity triangle
  - Area related to the amount of CPV
- (Semi)leptonic kaon decays: $|V_{cb}|$, $|V_{us}|$, γ
  - $K^+ \rightarrow \pi^+ \nu \nu$
- Inconsistency between channels of measurement:
  - Hint to BSM

$$\lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}$$

$$A = \frac{|V_{cb}|}{\lambda^2\sqrt{|V_{ud}|^2 + |V_{us}|^2}}$$

$$\rho = \frac{Re(V_{ub})}{A\lambda^3}$$

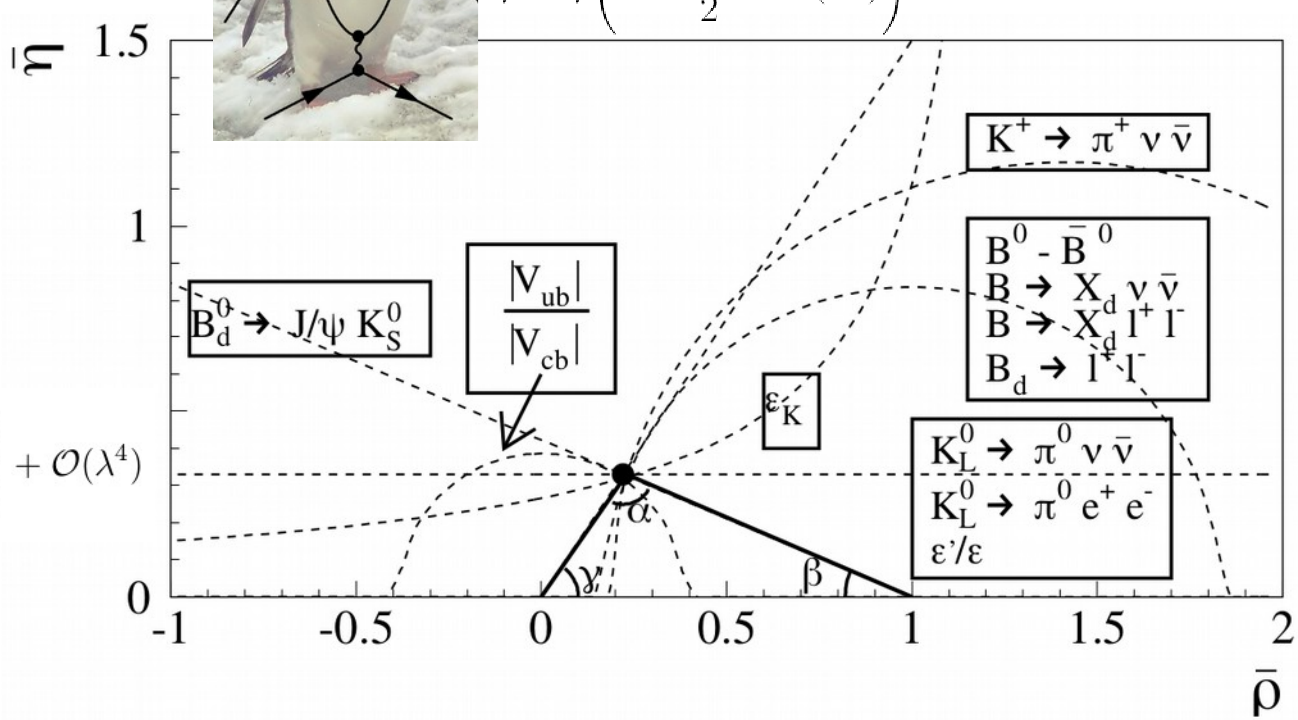
$$\eta = \frac{Im(V_{ub})}{A\lambda^3}$$



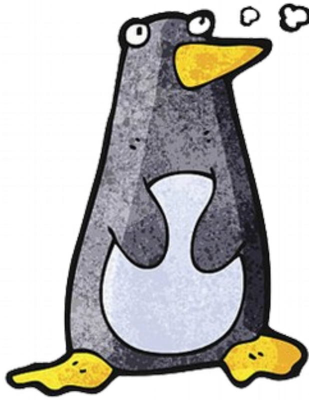
$$\bar{\rho} = \rho\left(1 - \frac{\lambda^2}{2} + \mathcal{O}(\lambda^4)\right)$$

$$\bar{\eta} = \eta\left(1 - \frac{\lambda^2}{2} + \mathcal{O}(\lambda^4)\right)$$

$$V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



Unitarity triangle



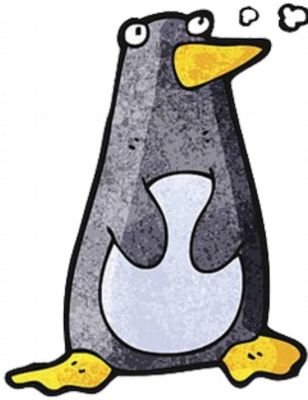
- Restriction on matrix elements by unitarity:

$$\mathbb{1} \equiv \mathbf{V}_{\mathbf{CKM}} \cdot \mathbf{V}^{\dagger}_{\mathbf{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} V^*_{ud} & V^*_{cd} & V^*_{td} \\ V^*_{us} & V^*_{cs} & V^*_{ts} \\ V^*_{ub} & V^*_{cb} & V^*_{tb} \end{pmatrix} =$$

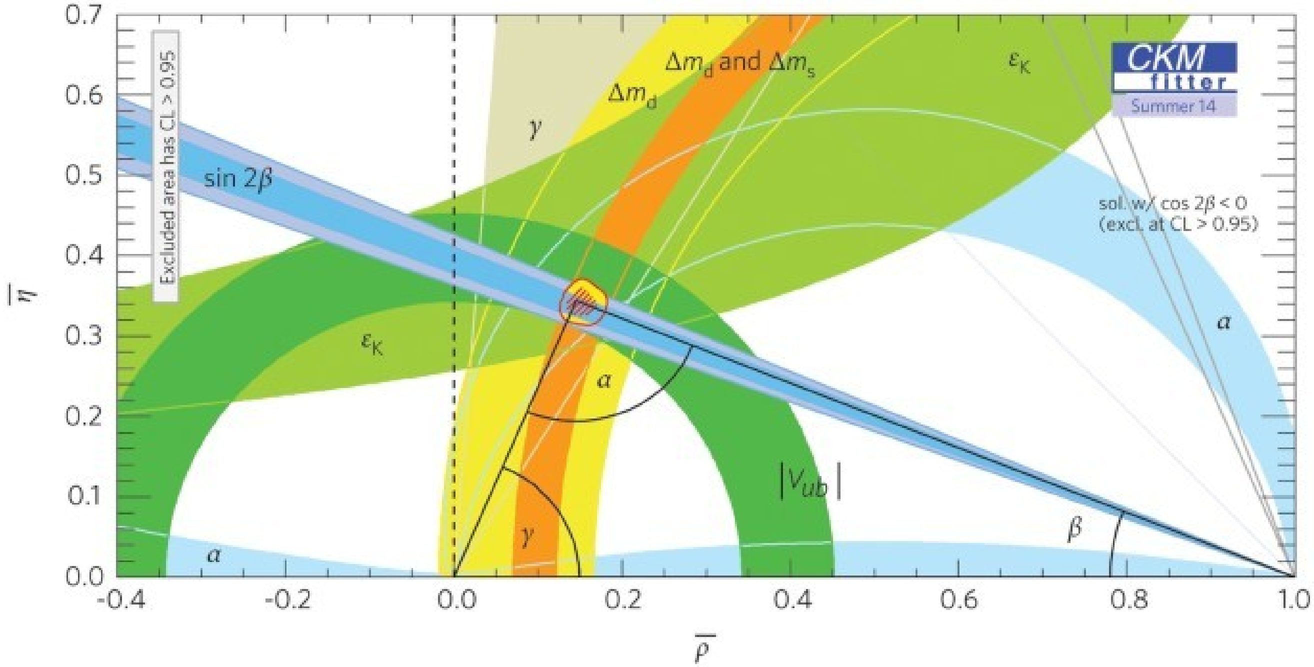
$$\begin{pmatrix} V_{ud}V^*_{ud} + V_{us}V^*_{us} + V_{ub}V^*_{ub} & V_{ud}V^*_{cd} + V_{us}V^*_{cs} + V_{ub}V^*_{cb} & V_{ud}V^*_{td} + V_{us}V^*_{ts} + V_{ub}V^*_{tb} \\ V_{cd}V^*_{ud} + V_{cs}V^*_{us} + V_{cb}V^*_{ub} & V_{cd}V^*_{cd} + V_{cs}V^*_{cs} + V_{cb}V^*_{cb} & V_{cd}V^*_{td} + V_{cs}V^*_{ts} + V_{cb}V^*_{tb} \\ V_{td}V^*_{ud} + V_{ts}V^*_{us} + V_{tb}V^*_{ub} & V_{td}V^*_{cd} + V_{ts}V^*_{cs} + V_{tb}V^*_{cb} & V_{td}V^*_{td} + V_{ts}V^*_{ts} + V_{tb}V^*_{tb} \end{pmatrix} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- 3 angle per triangle
  - 6 triangles vs same: 1 CPV complex phase
- Area of the triangle → CP violation
- Inconstistency in predictions in $(\bar{\varrho}, \bar{\eta})$ plane → BSM

Unitarity triangle



- Tree-level: semi-leptonic K-, B-decays
  - $|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$ & R_b within SM
- Other measurement channels → apex A on the plane
  - Loop-induced decays & transitions
  - CP violating B decays



References

- [1] J. Bijnens, G. Ecker, and J. Gasser. “Radiative semileptonic kaon decays”. In: Nucl.Phys. B 396 (1993), pp. 81–118. doi: 10.1016/0550-3213(93)90259-R. arXiv:hep-ph/9209261 (cit. on p.2).
- [2] A. A. Poblaguev et al. “Experimental study of the radiative decays K+ —> mu+ nu e+ e- and K+ —> e+ nu e+ e-”. In: Phys. Rev. Lett. 89 (2002), p.061803. doi:10.1103/PhysRevLett.89.061803. arXiv: hep-ex/0204006 (cit. on p. 3).
- [3] G. Romolini, Study of the K + → e + ν e + e − decay with the NA62 experiment at CERN.
- [4] M. Tanabashi et al. (Particle Data Group), Charged Kaon Mass, Phys. Rev. D, 2018, 98, 030001.
- https://www.particlezoo.net/
- https://www.facebook.com/NA62Experiment
- https://phys.org/news/2020-07-cern-evidence-ultra-rare-physics.html
- https://cernbox.cern.ch/index.php/s/Q6l8onTbmJtSOlD
- https://www.mdpi.com/2218-1997/4/11/119/htm
- https://www.istockphoto.com/de/fotos/penguin-thinking
- https://www.pinterest.ch/pin/cute-penguin-jumping-cartoon-notepad-baby-gifts-child-new-born-gift-idea-diy-cyo-special-unique-design--733664595519053629/
- https://en.wikipedia.org/wiki/Penguin_diagram
- https://www.nature.com/articles/nphys3464
- https://www.physik.uzh.ch/dam/jcr:8cb19cb1-d67a-4a44-9a73-c26871988dd8/chap05.pdf
- https://arxiv.org/abs/hep-ph/0304132v2