# Standard Model tests with rare hadrons and leptons decays

Michał Silarski
Jagiellonian University

1. Stadard model test with rare decays of neutral and charged kaons
2. Invisible decays of mesons
3. Positronium as a probe for New Physcics

**Discrete Symmetries in Particle, Nuclear and Atomic Physics and implications for our Universe,**
8-12 October 2018, ECT* - Villa Tambosi, Trento

# * The neutral kaons system

- Time evolution of the $K^0 \leftrightarrow \overline{K^0}$ system in the rest frame:

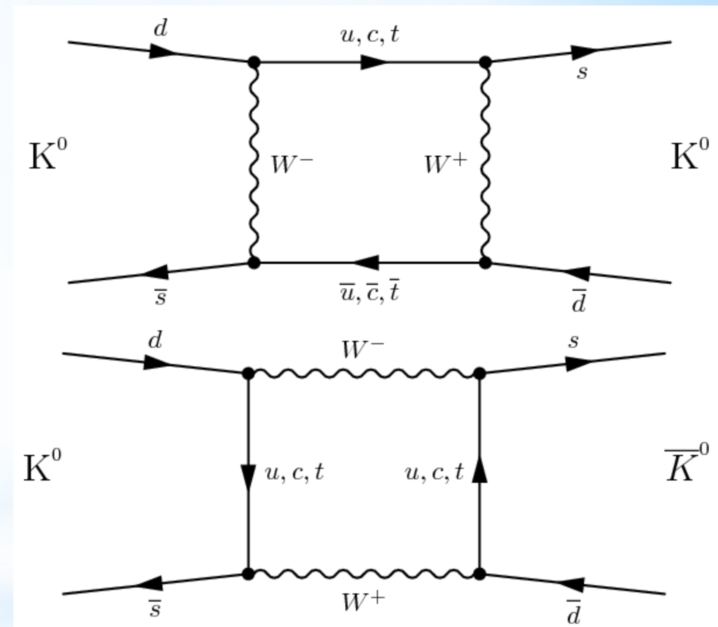
$$\boldsymbol{M} = \begin{pmatrix} M_{11} & M_{12} \\ M^*_{12} & M_{22} \end{pmatrix}$$

$$i\frac{\partial}{\partial t}\begin{pmatrix} |K^0> \\ |\overline{K^0}> \end{pmatrix} = \mathbf{H}\begin{pmatrix} |K^0> \\ |\overline{K^0}> \end{pmatrix} = \left[\boldsymbol{M} - \frac{i}{2}\boldsymbol{\Gamma}\right]\begin{pmatrix} |K^0> \\ |\overline{K^0}> \end{pmatrix}$$

$$\boldsymbol{\Gamma} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma_{22} \end{pmatrix}$$

- In the basis of the CP operator:

$$|K_1> = \frac{1}{\sqrt{2}}(|K^0> + |\overline{K^0}>) \qquad \text{(CP = 1)}$$
$$|K_2> = \frac{1}{\sqrt{2}}(|K^0> - |\overline{K^0}>) \qquad \text{(CP = -1)}$$




- The eigenstates of **H**:

$|K_S>$ ($\tau = 0.9 \cdot 10^{-10}$ s; $c\tau = 2.68$ cm)
$|K_L>$ ($\tau = 5.1 \cdot 10^{-8}$ s; $c\tau = 15.5$ m)

- The main hadronic decay modes:

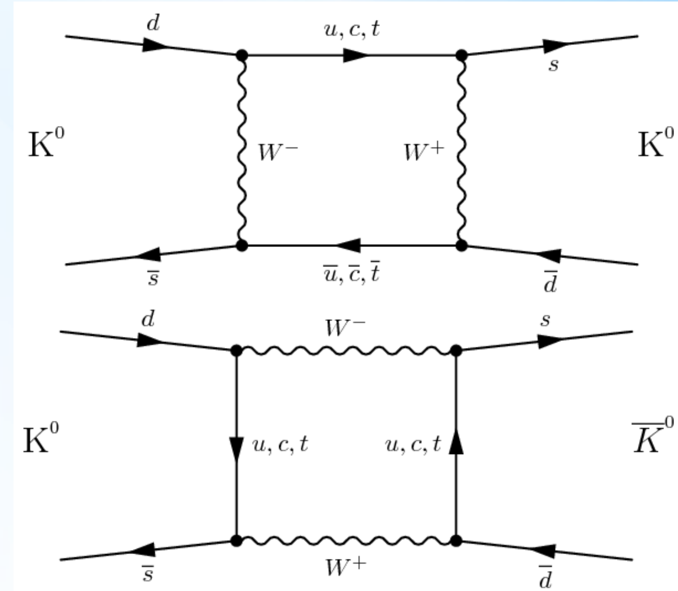
$|K_S> \to \pi^+\pi^-$
$|K_S> \to 2\pi^0$ (CP = 1)

$|K_L> \to \pi^0\pi^+\pi^-$ (CP = -1 for I=0, 2, ...)
$|K_L> \to 3\pi^0$ (CP = -1)

# The neutral kaons system

- But $K_S$ and $K_L$ are not CP eigenstates:

BR($K_L \to \pi^+\pi^-$) = $1.97 \cdot 10^{-3}$
BR($K_L$ $\pi^0\pi^0$) = $8.64 \cdot 10^{-4}$
[M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)]

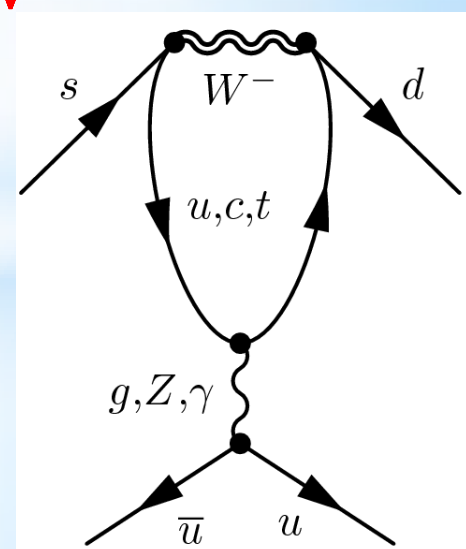



- CP violation in mixing (ΔS=2):

$$|K_S> = \frac{1}{\sqrt{1+|\varepsilon_S|^2}}(\,|K_1> + \,\varepsilon_S|K_2>\,)$$

$$|K_L> = \frac{1}{\sqrt{1+|\varepsilon_L|^2}}(|K_2> \; + \varepsilon_L|K_1>)$$

$\varepsilon_S \neq \varepsilon_L \Rightarrow$ **CPTV**




- CP violation directly in the decay (ΔS=1):

$$|K_1> \to 2\pi, \quad |K_2> \to 3\pi$$

# * Standard Model tests with the $K_S \to 3\pi^0$ decay

- **$K_S \to \pi^0\pi^0\pi^0$: unambiguous sign of CP violation**
- $K_S \to \pi^+\pi^-\pi^0$: CPV for for L=0,2, but contains also conserving amplitude

$$\eta_{000} = \frac{\langle \pi^0\pi^0\pi^0 | H | K_S \rangle}{\langle \pi^0\pi^0\pi^0 | H | K_L \rangle} = \varepsilon + \varepsilon'_{000} \qquad \eta_{+-0} = \frac{\langle \pi^+\pi^-\pi^0 | H | K_S \rangle}{\langle \pi^+\pi^-\pi^0 | H | K_L \rangle} = \varepsilon + \varepsilon'_{+-0}$$

- In the lowest order of the xPT: $\varepsilon'_{000} = \varepsilon'_{+-0} = -2\varepsilon'$

$$Im(\eta_{+-0}) = -0.002 \pm 0.009; \qquad Im(\eta_{000}) = (-0.1 \pm 1.6) \cdot 10^{-2}$$

- KLOE set the best upper limit on $|\eta_{000}|$:

$$BR(K_S \to 3\pi^0) < 2.6 \cdot 10^{-8} \Rightarrow |\eta_{000}| = \sqrt{\frac{\tau_L\, BR(K_S \to 3\pi^0)}{\tau_S\, BR(K_L \to 3\pi^0)}} \leq 0.0088 \text{ @ } 90\%\ C.L.$$

D. Babusci et al., Phys. Lett. B 723 (2013) 54

- **The Standard Model prediction on BR ($K_S \to 3\pi^0$) is at the level of $10^{-9}$**
- Current experimental accuracy on BR($K_S \to \pi^+\pi^-\pi^0$) amounts to ~30% (CPLEAR, NA48 and E621)
- First direct search for $K_S \to \pi^+\pi^-\pi^0$ is ongoing with the old KLOE data set (with expected accuracy lower than 20 %)
- **With KLOE-2 data we expect to improve sensitivity for both branching ratios**

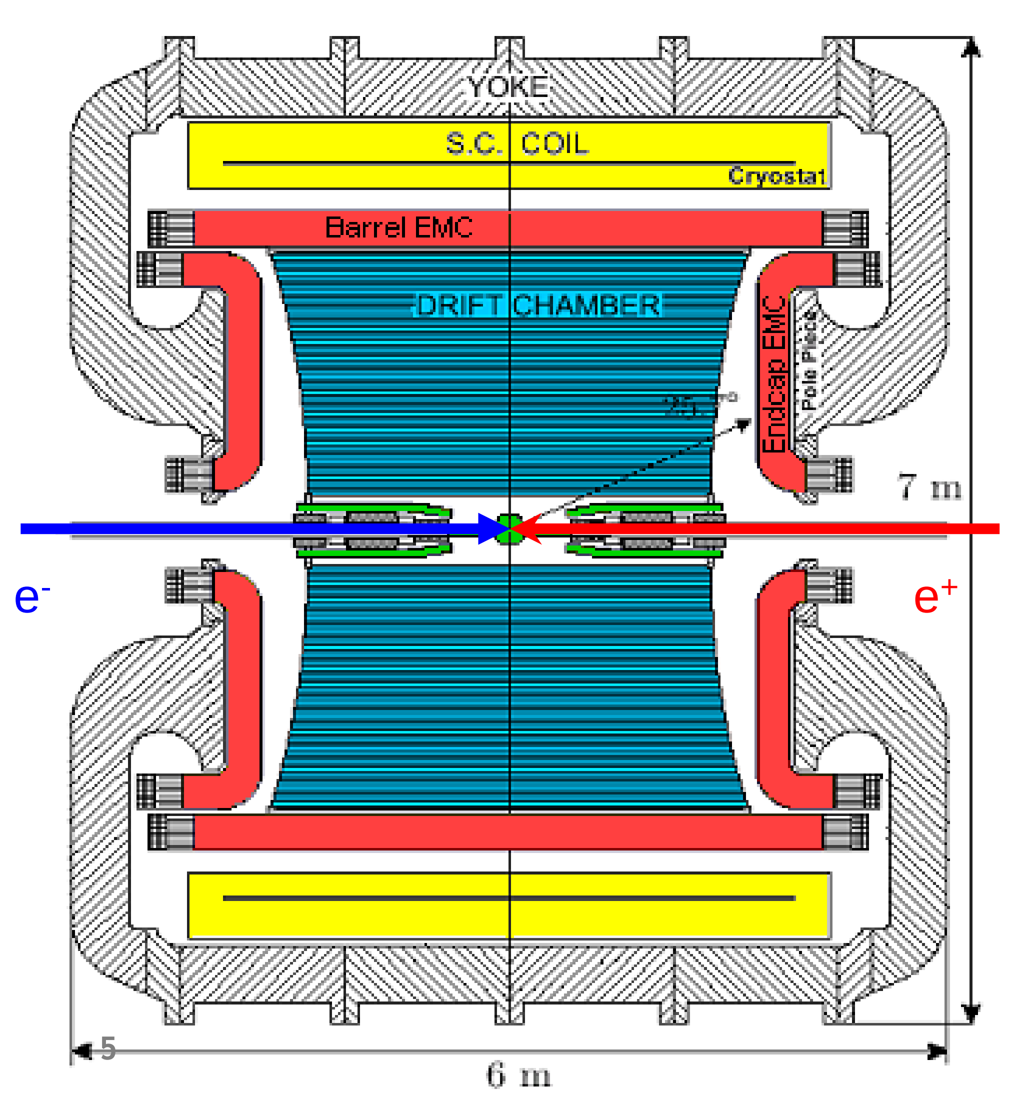
# * KLOE (K LOng Experiment)

**Large cylindrical drift chamber**

- Uniform tracking and vertexing in all volume
- Helium based gas mixture (90% He – 10% $IsoC_4H_{10}$)
- Stereo wire geometry

$\sigma_p/p = 0.4$ %
$\sigma_{xy} = 150$ µm; $\sigma_z = 2$ mm
$\sigma_{vtx} \sim 3$ mm
$\sigma(M_{\pi\pi}) \sim 1$ MeV

**Superconducting coil**
B = 0.52 T



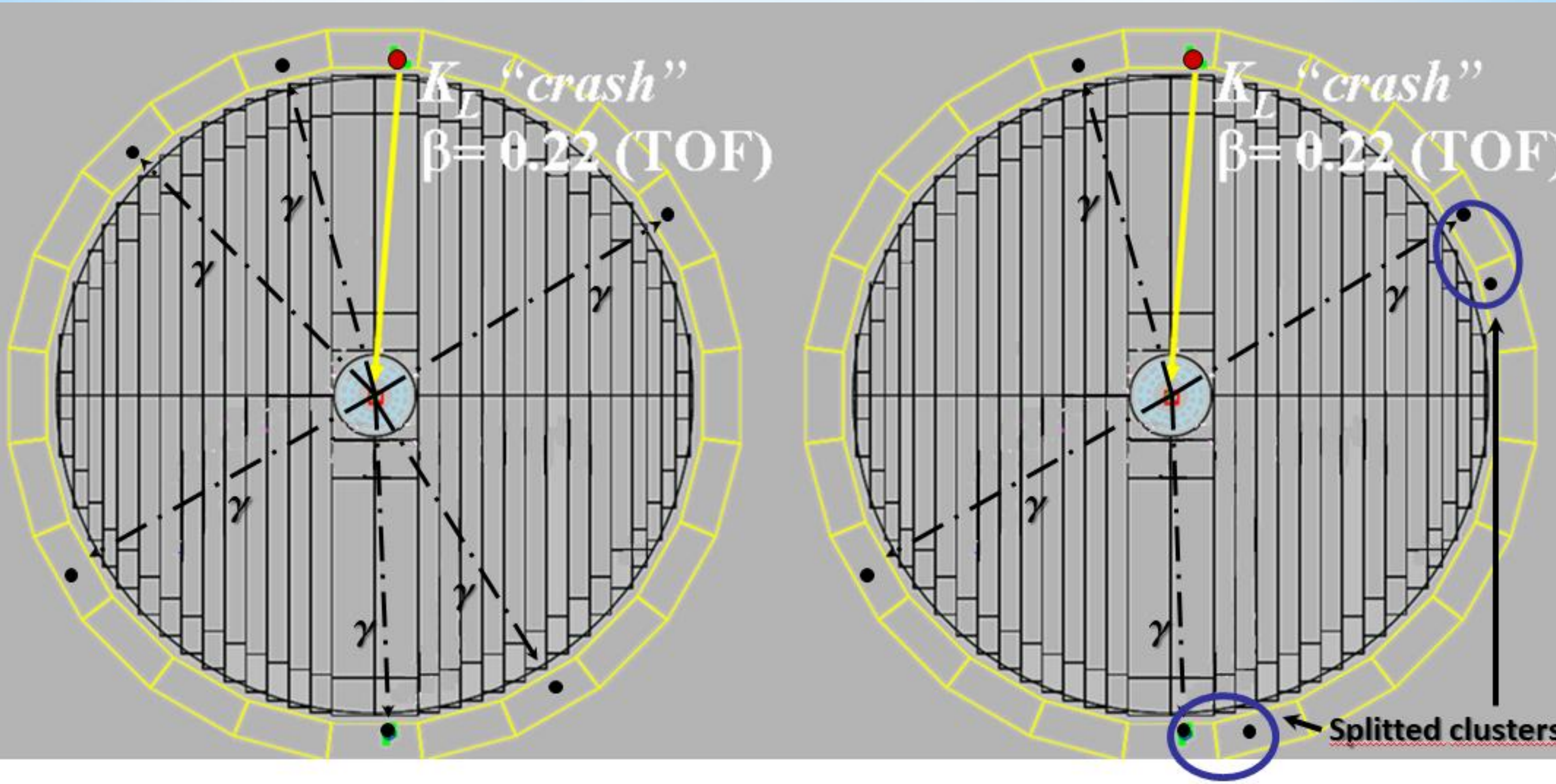

**Lead/scintillating-fiber calorimeter**

- Hermetical coverage
- High efficiency for low energy photons

$\sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})}$
$\sigma_t = 54/\sqrt{E(\text{GeV})} \oplus 100$ ps

# * Standard Model tests with the $K_S \to 3\pi^0$ decay at KLOE

**SIGNAL** **BACKGROUND**



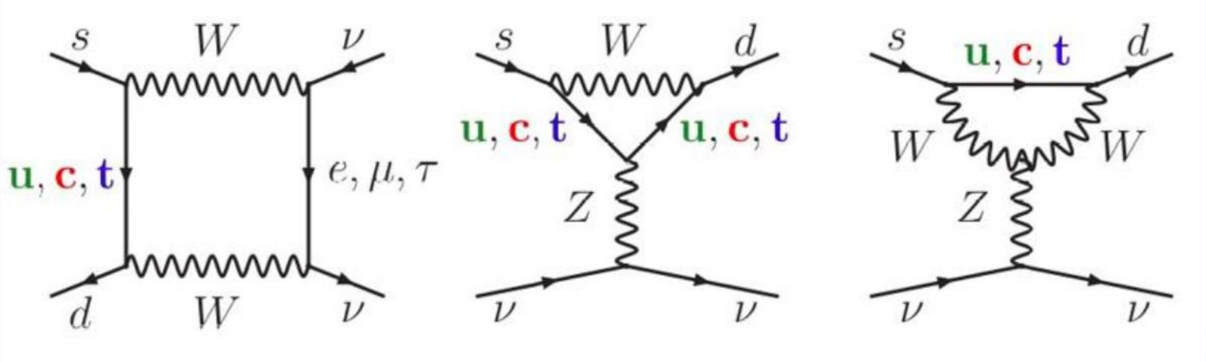

$K_S \to 3\pi^0 \to 6\gamma$

$K_S \to 2\pi^0$ + accidental/splitted clusters

$K_L \to 3\pi$, $K_S \to \pi^+ \pi^-$ ( „fake $K_L$-crash" )

# * Search for the $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

❖ CP violating decays with short distance contribution dominated by Z penguin and W box diagrams




❖ Clean theoreticaly ⇒ sensitive to BSM physics

❖ Standard Model predictions:

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6)\cdot 10^{-11}$$
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0)\cdot 10^{-11}$$

Experimental status:

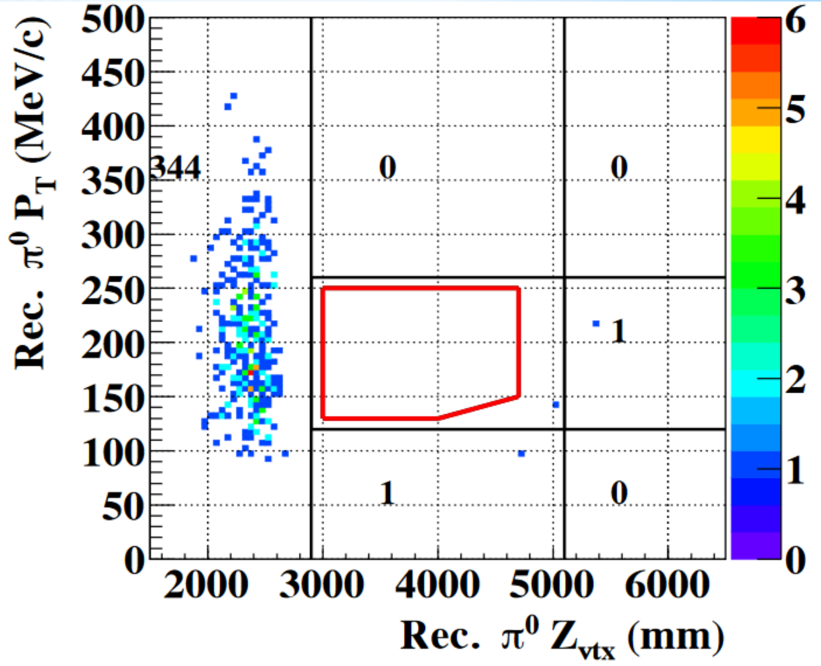
$BR(K_L \to \pi^0 \nu\bar{\nu}) < 3.0 \cdot 10^{-10}$ (KOTO, preliminary)

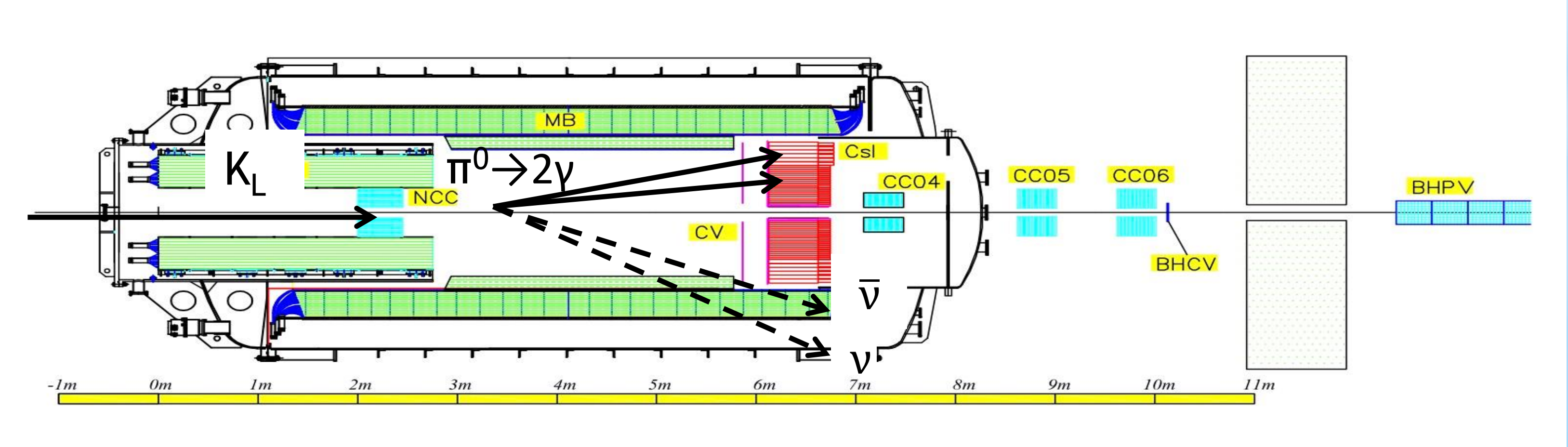
$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.7 \pm 1.1)\cdot 10^{-10}$ (E787/E949 @ BNL)

# Search for the $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

- $K_L \to \pi^0 \nu\bar{\nu}$ search with KOTO @ JPARC
  - $2\gamma$ + nothing
  - $\pi^0$ transverse momentum + decay vertex

  - Background:
  - $K_L \to 2\pi/3\pi$ (particles missing in the forward direction)
  - Halo neutrons ($\pi^0$ production & direct interaction in the forward calorimeter)



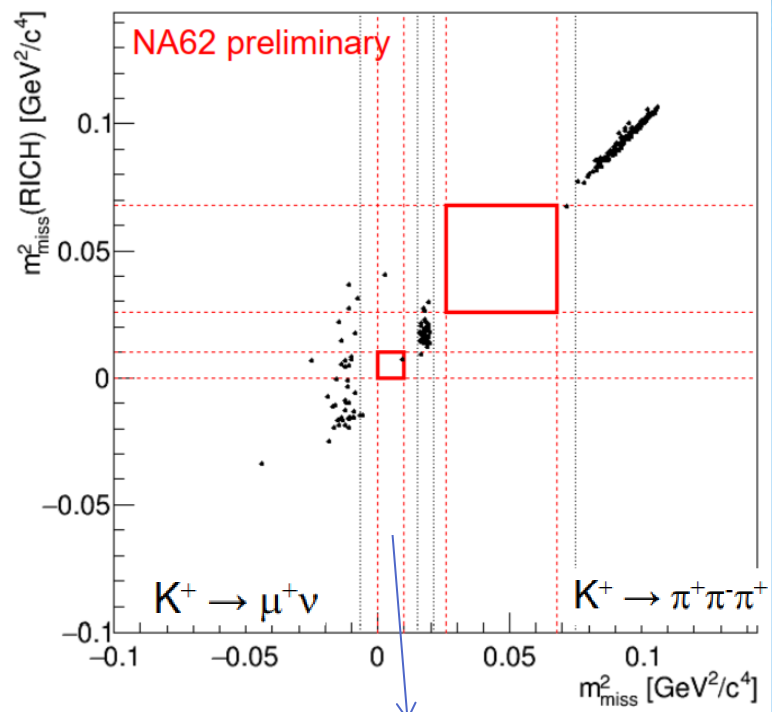
# * Search for the $K^+ \to \pi^+ \nu \bar{\nu}$

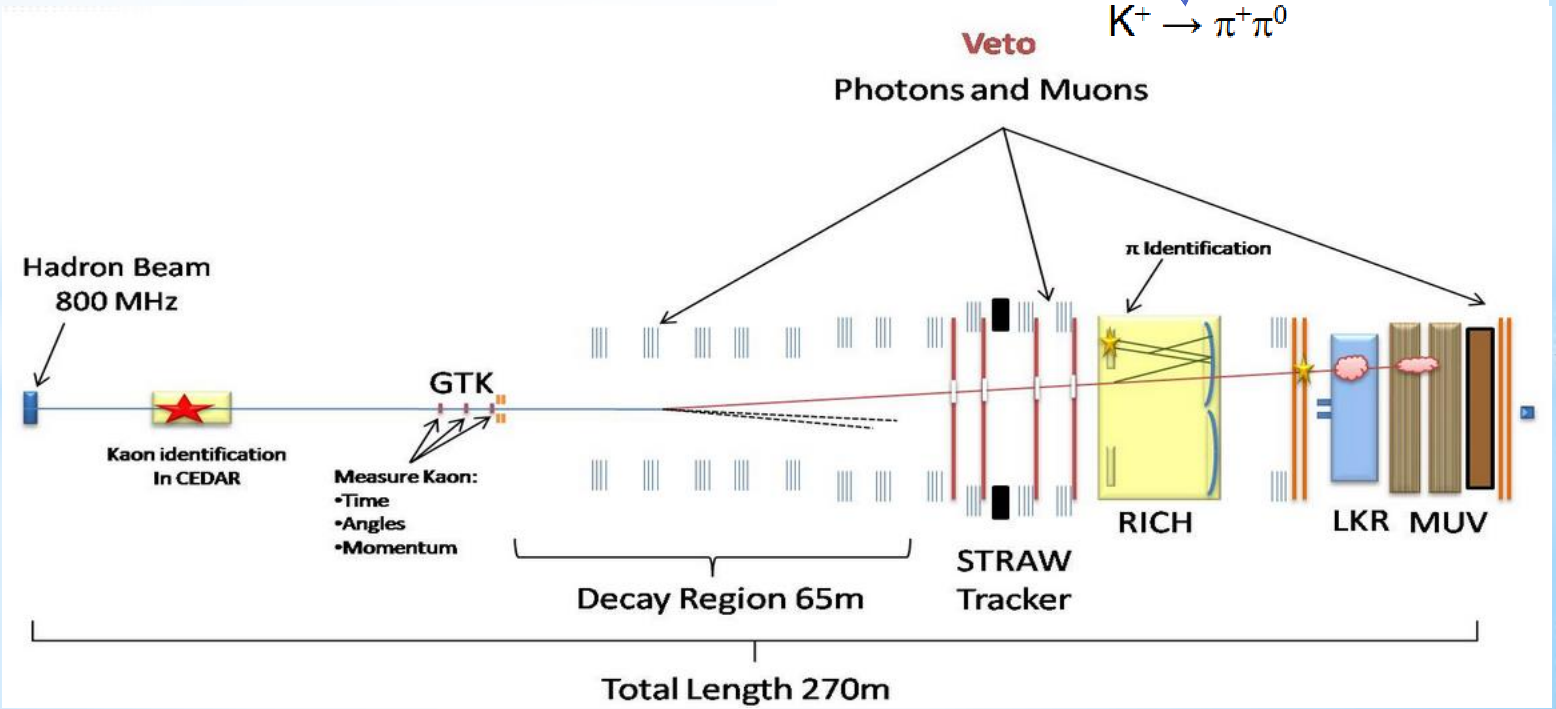
❖ $K_L \to \pi^+ \nu \bar{\nu}$ search: NA62

- ✓ ~$10^{12}$ $K^+$ decays aquired
- ✓ No signal so far ( with ~5% of the statistics)
- ✓ Identificaton based on the missing mass

$$m^2_{miss} = \left(p^{GTK}_{K^+} - p^{STRAW}_{\pi^+}\right)^2$$

$$m^2_{miss}(RICH) = \left(p^{GTK}_{K^+} - p^{RICH}_{\pi^+}\right)^2$$



# Search for the invisible decays of neutral hadrons

❖ According to the Standard Model: $\Gamma(M^0 \longrightarrow \nu\bar{\nu}) \sim \left(\frac{m_\nu}{m_{M^0}}\right)^2 < 10^{16}$

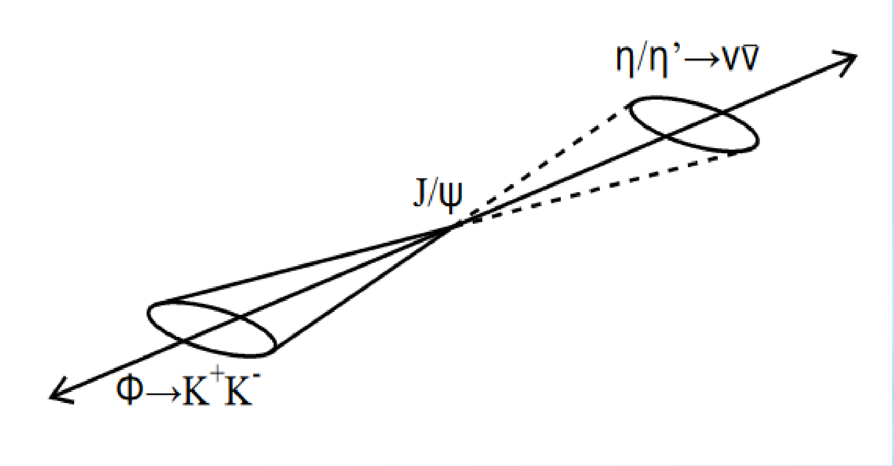
| Channel | SM expectation | Experimental limit | Experiment |
|---|---|---|---|
| BR($K_s \rightarrow$ *invisible*) | $< 10^{-17}$ | None | KLOE/KLOE-2 (?) |
| BR($K_L \rightarrow$ *invisible*) | $< 10^{-17}$ | None | KLOE/KLOE-2 (?) |
| BR($\eta \rightarrow$ *invisible*) | $< 4 \cdot 10^{-12}$ | $< 1 \cdot 10^{-4}$ | BES |
| BR($\phi \rightarrow$ *invisible*) | $< 10^{-8}$ | $< 3.4 \cdot 10^{-4}$ | BESIII |
| BR($\omega \rightarrow$ *invisible*) | $< 10^{-8}$ | $< 8.1 \cdot 10^{-5}$ | BESIII |
| BR($\pi^0 \rightarrow$ *invisible*) | $< 5 \cdot 10^{-10}$ | $< 2.7 \cdot 10^{-7}$ | E949 |
| BR($\eta' \rightarrow$ *invisible*) | $< 4 \cdot 10^{-12}$ | $< 5.2 \cdot 10^{-4}$ | BES |

❖ Observation of any of these decays at the level higher tha the SM predicion would be a sign of BSM physics

# Search for the invisible decays of neutral hadrons

- Measurement principle (based on the BES results):
  - $J/\Psi$ decay: tagging one meson with the decay of the other
  - BR normalization to the visible decay ($\varphi \to K^+K^-$, $\eta/\eta' \to \gamma\gamma$)

  - Main ackgrounds for the $\varphi$ and $\omega$ decays search: $J/\psi \to V\,\eta$ with the V meson decaying into purely neutral final states

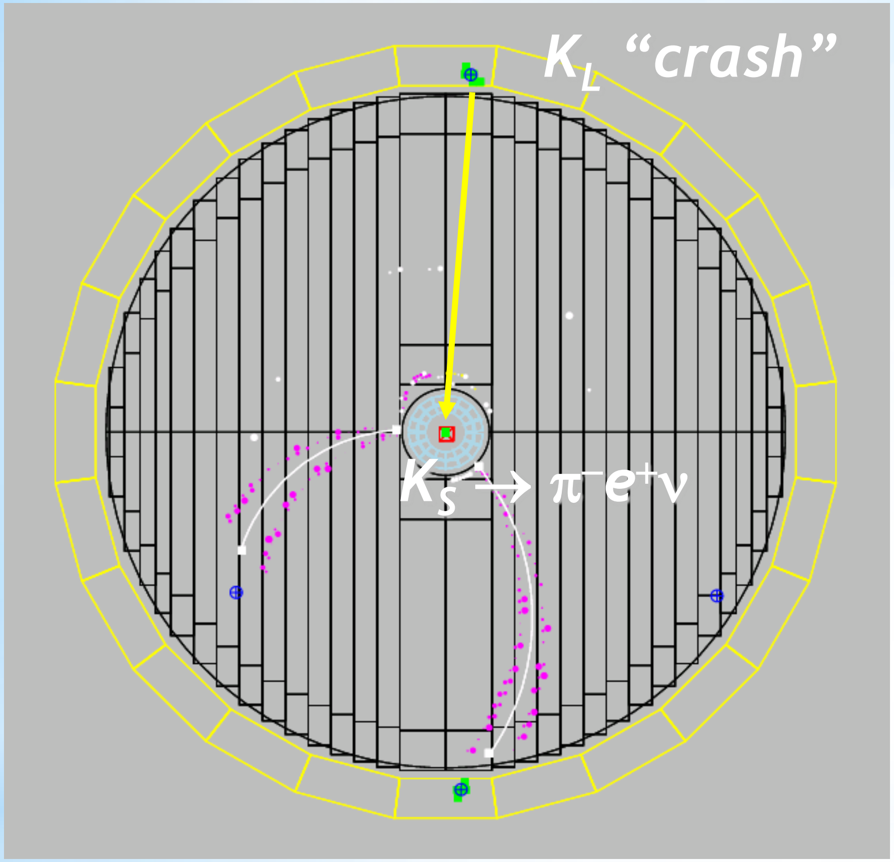



- Decays into invisible states were studied also for $J/\psi$ and $\Upsilon(1S)$ (BES II & BABAR)

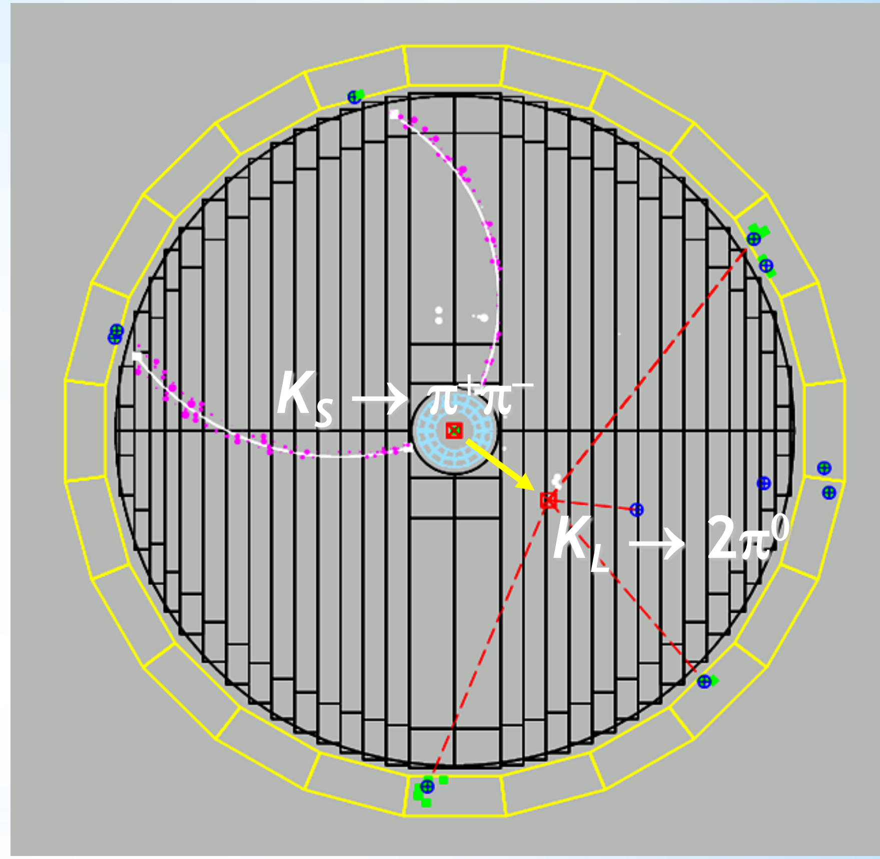
- Still no limits measured for neutral kaons

- Would it be fissilbe to do the measurement at KLOE-2 ?

# * $K_S$ and $K_L$ tagging @ KLOE-2




**$K_S$ tagged by $K_L$ interaction in EmC**
Efficiency ~ 30%
$K_S$ angular resolution: ~ 1°(0.3° in φ)
$K_S$ momentum resolution: ~ 2 MeV




**$K_L$ tagged by $K_S \to \pi^+\pi^-$ vertex at IP**
Efficiency ~ 70%
$K_L$ angular resolution: ~ 1°
$K_L$ momentum resolution: ~ 2 MeV

# * Positronium as a probe for physics beyond Standard Model

- The lightest purely leptonic object

- Eigenstate of the **CP** operator: $e^+e^-$ state (**C** eigenstate) bound by a central potential (**P** eigenstate)

| Ps state | τ [ns] | L | S | J | $J_z$ | P | C | CP |
|---|---|---|---|---|---|---|---|---|
| $^1S_0$ (para-Ps) | 0.125 | 0 | 0 | 0 | 0 | - | + | - |
| $^3S_1$(ortho-Ps) | 142 | 0 | 1 | 1 | -1,0,1 | - | - | + |

$$\mathrm{P}|Ps> = (-1)^L|Ps>$$
$$\mathrm{C}|Ps> = (-1)^{L+S}|Ps>$$

- Effects due the weak interaction can lead to the violation at the order of $10^{-14}$.
  [M. Sozzi, Discrete Symmetries and CP Violation, Oxford University Press (2008)]

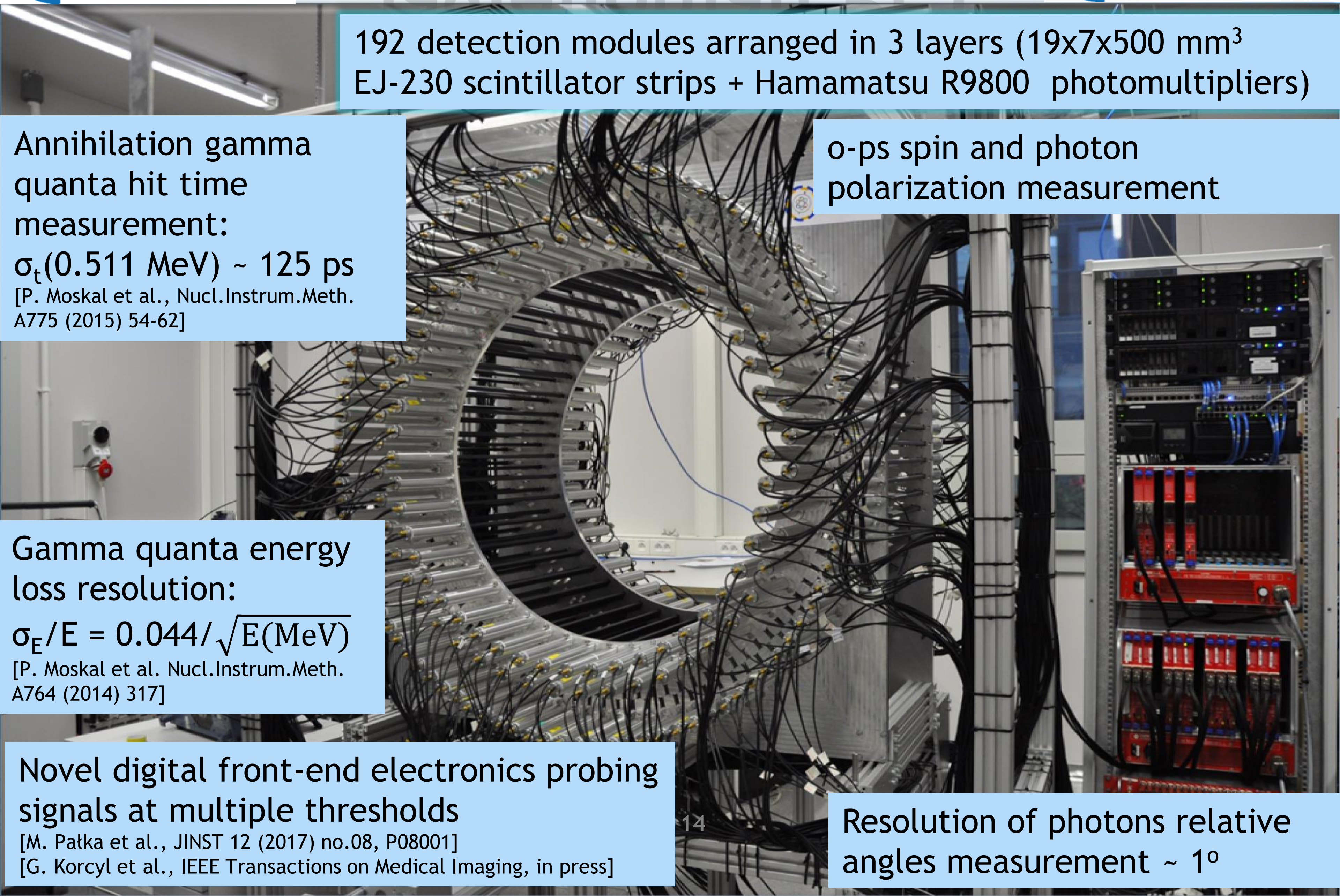
- No charged particles in the final state (radiative corrections very small $2\cdot10^{-10}$)
  [B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988); W. Bernreuther et al., Z. Phys. C 41, 143 (1988)]

❖ **C tests**: search for decays to forbidden decays:
[A. Pokraka, A. Czarnecki, Phys. Rev. D 96, 093002 (2017)]

$$\mathrm{BR(oPs \to 4\gamma/oPs \to 3\gamma) < 2.6 \cdot 10^{-6} \text{ at } 90\%\ C.L.}$$
$$\mathrm{BR(pPs \to 3\gamma/pPs \to 2\gamma) < 2.8 \cdot 10^{-6} \text{ at } 68\%\ C.L.}$$
$$\mathrm{BR(pPs \to 5\gamma/pPs \to 2\gamma) < 2.7 \cdot 10^{-7} \text{ at } 90\%\ C.L.}$$

[J. Yang et al., Phys. Rev. A54, 1952 (1996), A.P. Mills, S. Berko, Phys. Rev. Lett. 18, 420 (1967), P.A. Vetter, S.J. Freedman, Phys. Rev. A66, 052505 (2002)]

# Jagiellonian PET



192 detection modules arranged in 3 layers ($19\times7\times500$ mm$^3$ EJ-230 scintillator strips + Hamamatsu R9800 photomultipliers)

Annihilation gamma quanta hit time measurement:
$\sigma_t(0.511\ \mathrm{MeV}) \sim 125$ ps
[P. Moskal et al., Nucl.Instrum.Meth. A775 (2015) 54-62]

o-ps spin and photon polarization measurement

Gamma quanta energy loss resolution:
$\sigma_E/E = 0.044/\sqrt{E(\mathrm{MeV})}$
[P. Moskal et al. Nucl.Instrum.Meth. A764 (2014) 317]

Novel digital front-end electronics probing signals at multiple thresholds
[M. Pałka et al., JINST 12 (2017) no.08, P08001]
[G. Korcyl et al., IEEE Transactions on Medical Imaging, in press]



Resolution of photons relative angles measurement ~ 1°

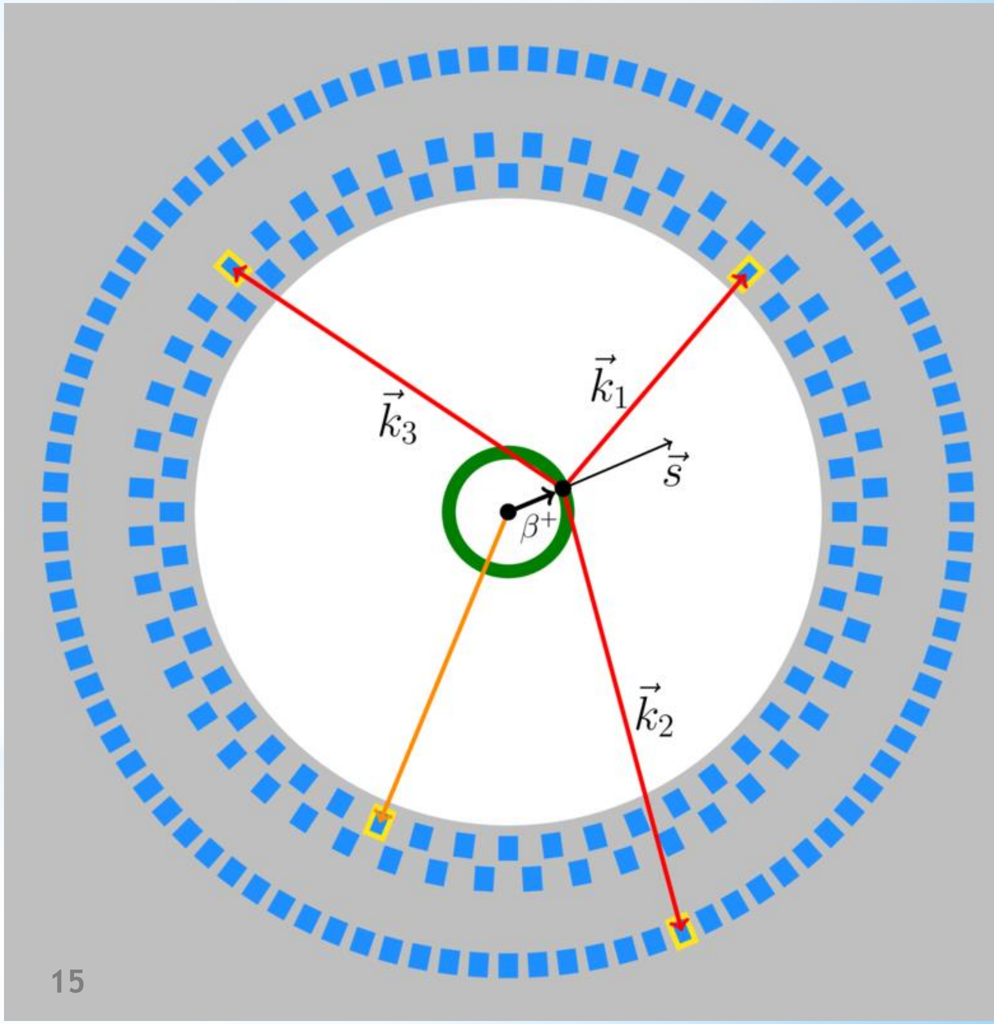
# * Discrete symmetries tests with the J-PET detector

- **Positrons source:**
  $^{22}Na$ $\beta^+$ decay (parity violation)

$$^{22}\boldsymbol{Na} \rightarrow {}^{22}\boldsymbol{Ne}^{*} + \boldsymbol{e}^{+} + \boldsymbol{\nu_e}$$
$$\downarrow$$
$$^{22}\boldsymbol{Ne}^{*} \rightarrow {}^{22}\boldsymbol{Ne} + \boldsymbol{\gamma}(1.247\ \text{MeV}, \tau \approx 3.7\ \text{ps})$$

- **Target around the source**
  - $e^+$ thermalization + o-Ps formation

- **Signal signature:**
  - 3/4γ quanta with common vertex reconstructed in the target
  - Deexcitation photon identyfication based on the TOT measurement
  - Early/late decay with respect to the registration of the de-excitation photon




[P. Moskal et. al., Acta Phys.Polon. B47 (2016) 509 ]

# * Summary and outlook

- ❖ Rare decays consitute an important part of the Standard Model test and search for the New Physics
- ❖ The new exciting test in the kaon sector are about to finish in few years
- ❖ There is still a lot to be done for the invisible decays of neutral mesons, in particular neutral kaons
- ❖ Positronium constitutes a powerfull probe for physics beyond Standard Model search
- ❖ New measurements of the positronium decays are under way (e.g. J-PET, AEGIS)

THANK YOU FOR ATTENTION