Lepton flavor universality violation in NA62

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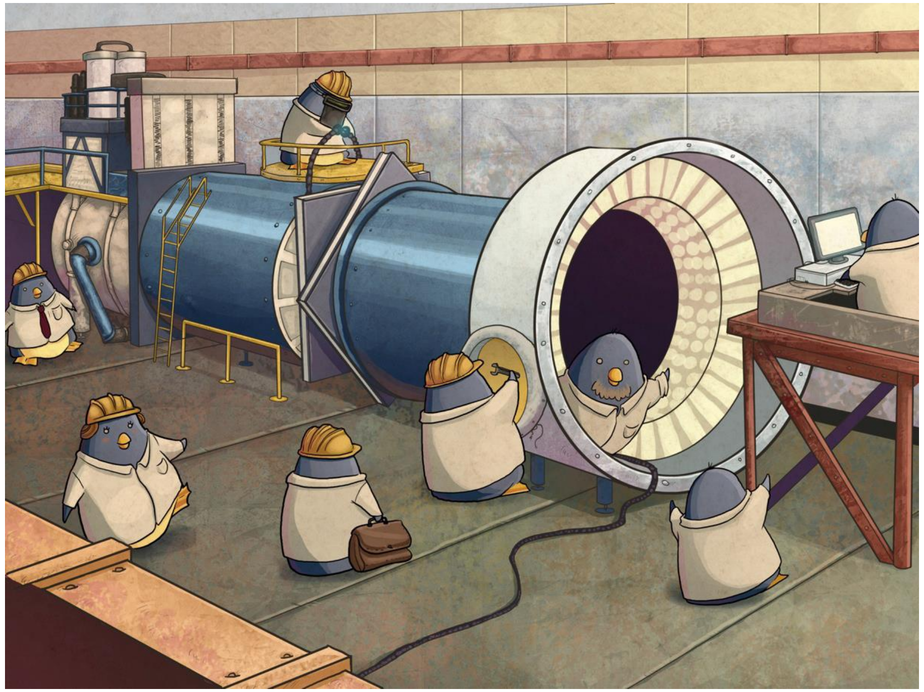

Fellini
Fellowship for Innovation at INFN

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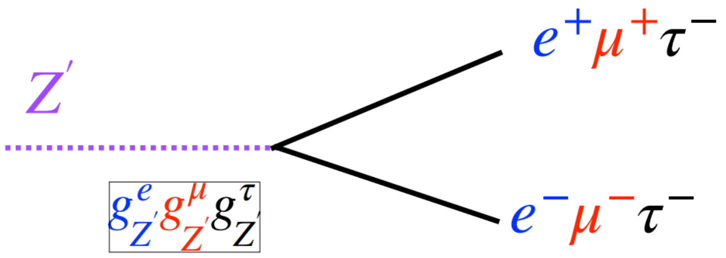
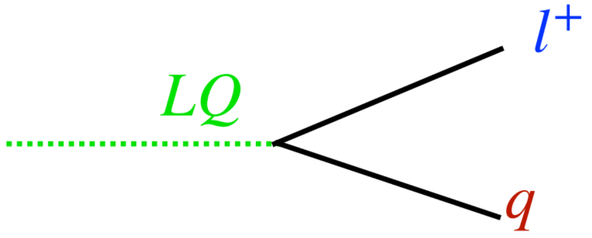
Lepton Flavour Universality

The Higgs particle has provided the ultimate experimental verification of the Standard Model. However, theoretical arguments and experimental observations point towards the existence of physics beyond the SM. An hint was a possible observation of a lepton flavour universality violation.

- In Standard Model the electroweak couplings between the gauge bosons and the leptons are flavour independent
- The only flavour non-universal terms are the lepton masses
- The processes differences (between the leptons) are given by the phase space and the helicity suppression
- New Physics models predict new particles breaking the Lepton Flavour Universality

Any LFU violation observation is a direct sign of New Physics

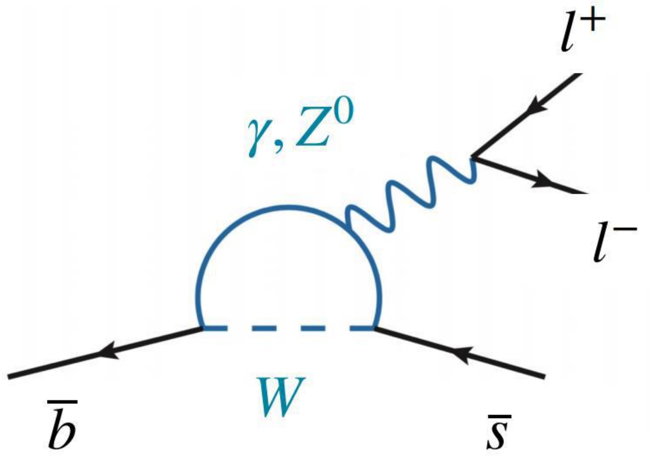




LHCb observation

Recently an hint of NP come from a possible lepton flavour universality violation observed by the LHCb experiment in the decays $B^+ \rightarrow K^+ l^+ l^-$ and $B^0 \rightarrow K^{*0} l^+ l^-$ decays with a significance O(3) standard deviations.

These decays involving $b \rightarrow s l^+ l^-$ transitions, mediated by flavor-changing neutral currents, are suppressed in the SM, as they proceed only through amplitudes that involve electroweak loop diagrams.



These processes are sensitive to virtual contributions from new particles (for example z' boson or leptoquark), which could have masses that are inaccessible to direct searches for resonances, even at Large Hadron Collider experiments.

LHCb results

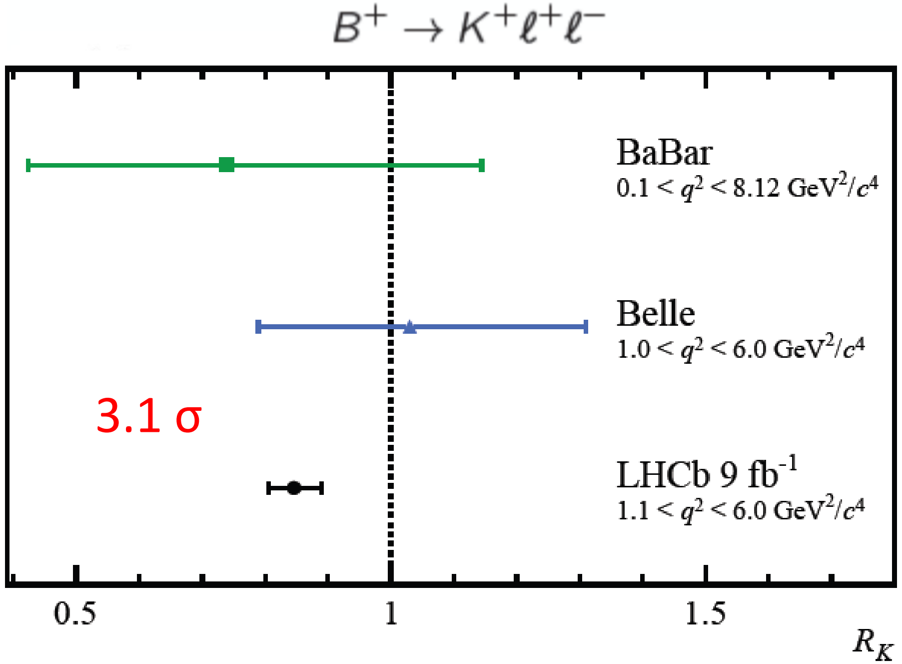
$$R_K = \frac{B(B^+ \to K^+\mu^+\mu^-)}{B(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Big/ \frac{B(B^+ \to K^+e^+e^-)}{B(B^+ \to K^+J/\psi(e^+e^-))}$$

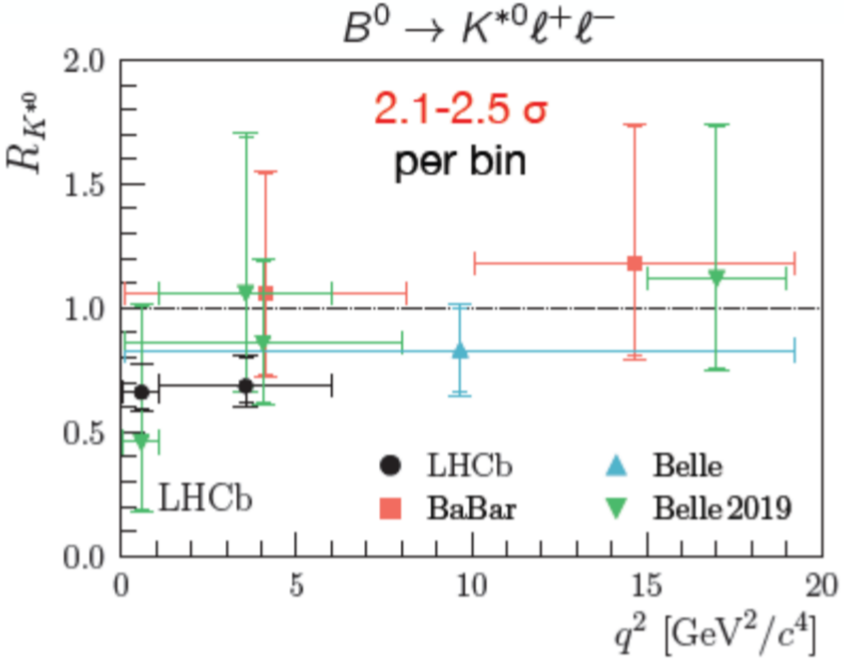
The SM predicts:

- R_K to be unity with O(1%) precision
- $R_{K^{*0}}$ to be in the range:
  - [0.906, 0.925] for $0.045 < q^2 < 1.1$ GeV^2/c^4
  - [0.996, 1] for $1.1 < q^2 < 6.0$ GeV^2/c^4

$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}(stat) \pm 0.03(syst) & \text{for} \quad 0.045 < q^2 < 1.1\ \mathrm{GeV}^2/c^4 \\ 0.69^{+0.11}_{-0.07}(stat) \pm 0.05(syst) & \text{for} \quad 1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4 \end{cases}$$





[LHCb, PRL 113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]
[Belle, arXiv:1904.02440]

Probe LFU with Kaon

The same NP mediators explaining the observed flavour anomalies in B mesons can induce effects of lepton flavour universality violation in rare kaon decays as of $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+e^+e^-$.

The week form factor of these K decays can be parametrized at Next–to–Leading–Order (NLO) in Chiral Perturbation Theory (ChPT) as

$$V_+(z) = a_+ + b_+ z + V_+^{\pi\pi}(z)$$

Where a_+ and b_+ are phenomenological constants, $V_+^{\pi\pi}(z)$ is a pion loop term and z is the transferred momentum.

If Lepton Flavour Universality (LFU) is not violated, the parameters a_+ and b_+ must be identical for both the decays $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+e^+e^-$.

$BR(K^+ \to \pi^+\mu^+\mu^-) = (9.4 \pm 0.6) \times 10^{-8}$

$BR(K^+ \to \pi^+e^+e^-) = (3.00 \pm 0.09) \times 10^{-7}$

State of Art

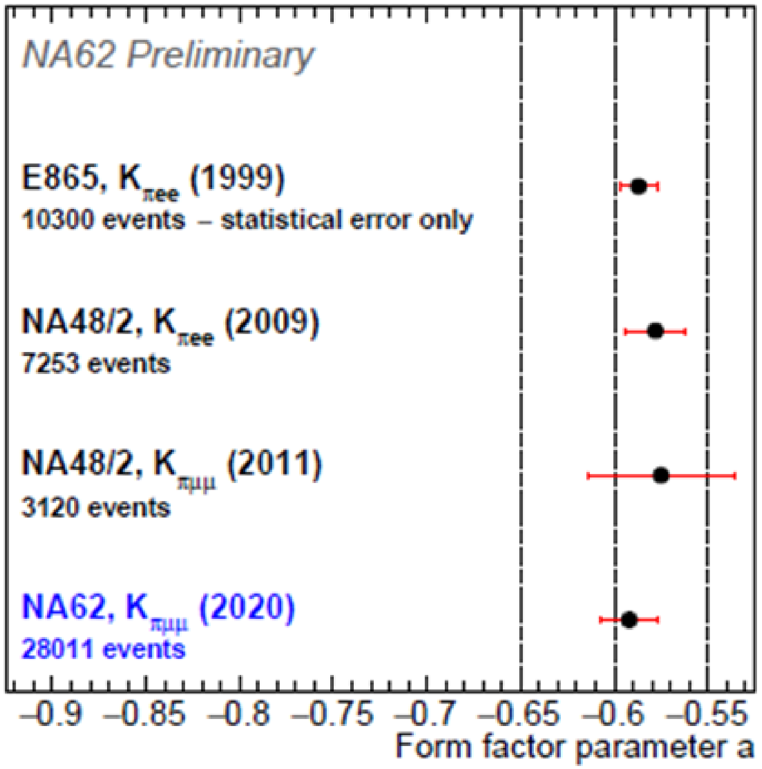
$$a^{\mu\mu}_{NA48/2} = -0.575 \pm 0.039, \quad a^{ee}_{NA48/2} = -0.578 \pm 0.016, \quad a^{ee}_{E865} = -0.587 \pm 0.010,$$

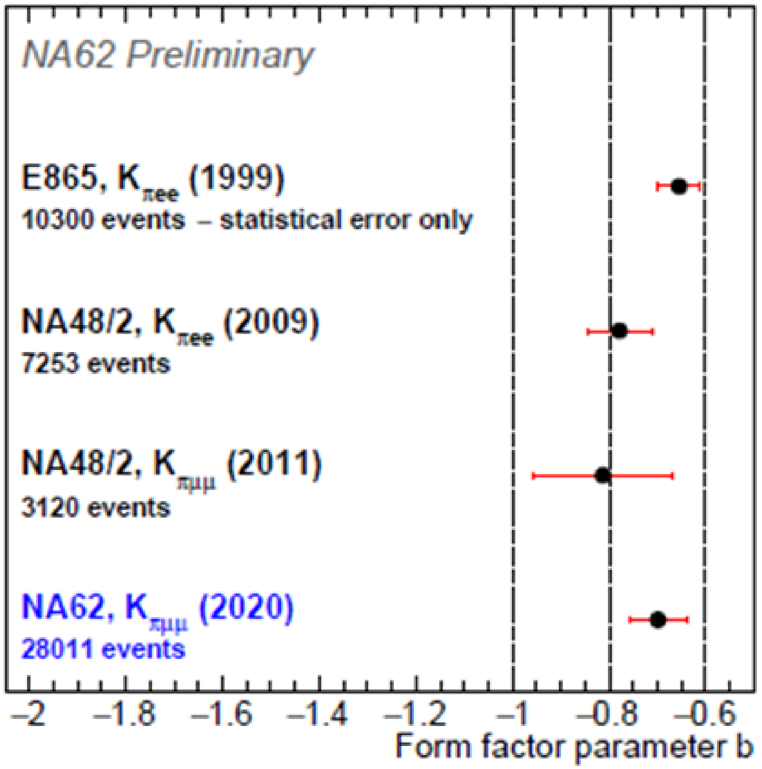
$$b^{\mu\mu}_{NA48/2} = -0.813 \pm 0.145, \quad b^{ee}_{NA48/2} = -0.779 \pm 0.066, \quad b^{ee}_{E865} = -0.655 \pm 0.044,$$

NA62

$$a = -0.592 \pm 0.013_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.001_{\text{ext}} = -0.592 \pm 0.015$$

$$b = -0.699 \pm 0.046_{\text{stat}} \pm 0.035_{\text{syst}} \pm 0.003_{\text{ext}} = -0.699 \pm 0.058$$





Current Limitations in NA62

$$a = -0.592 \pm 0.013_{\text{stat}} \pm 0.007_{\text{syst}} \pm 0.001_{\text{ext}} = -0.592 \pm 0.015$$
$$b = -0.699 \pm 0.046_{\text{stat}} \pm 0.035_{\text{syst}} \pm 0.003_{\text{ext}} = -0.699 \pm 0.058$$

Current limitations in NA62:

- Statistic error: during the 2016-2018 run there was a trigger downscaling conditions that limited the collected statistic (~28000 event of di-muons and ~8000 events of di-electrons);
- Systematics error:
  - The main source of systematic error is due to the tracks' reconstruction algorithm (optimized for one track events, mis-reconstruction due to accidental hits);
  - A secondary source of error is due to the trigger inefficiency: STRAW tracker high level trigger and charged hodoscope hardware trigger.

Probe LFU with Kaon

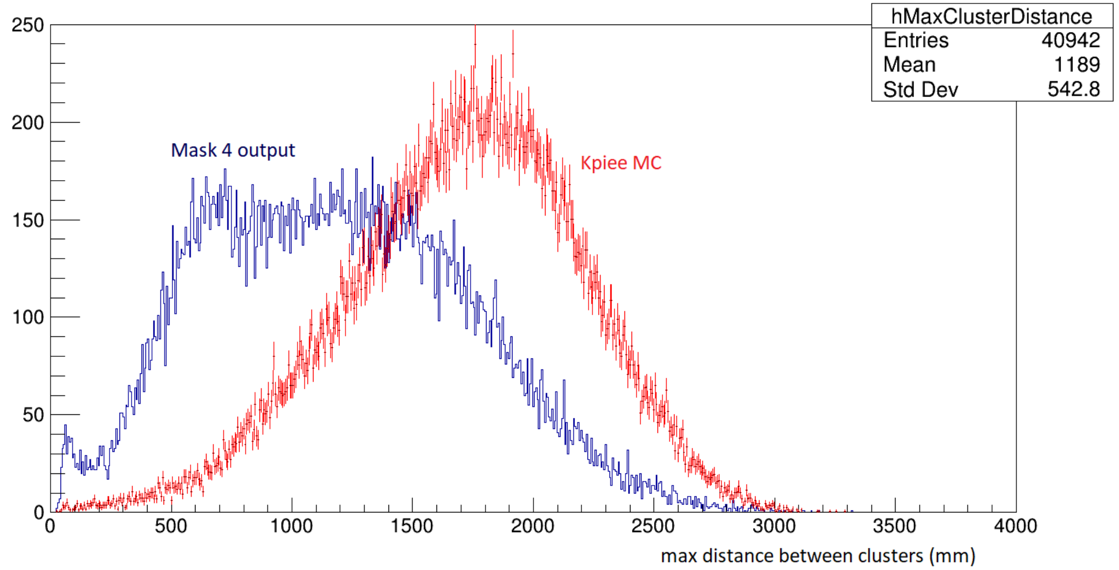
My FELLINI project aims to improve the actual measurement of the form factor parameters a and b, by collecting O(200k) candidates of $K^+ \to \pi^+ \mu^+ \mu^-$ and $K^+ \to \pi^+ e^+ e^-$ decays with the experiment NA62.

- I have done:
  - Improvement of the hardware trigger to remove the downscaling conditions;
  - Improvement the STRAW high level trigger algorithm.
- I'm doing:
  - To improve the offline tracks reconstruction;
  - to start the analysis of the data that will be collected in the 2021-23 data taking.
- Next step:
  - to study the possibility of implementing the Recurrent Neural Networks or the Graph Neural Networks to improve the HLT algorithm and the offline reconstruction;

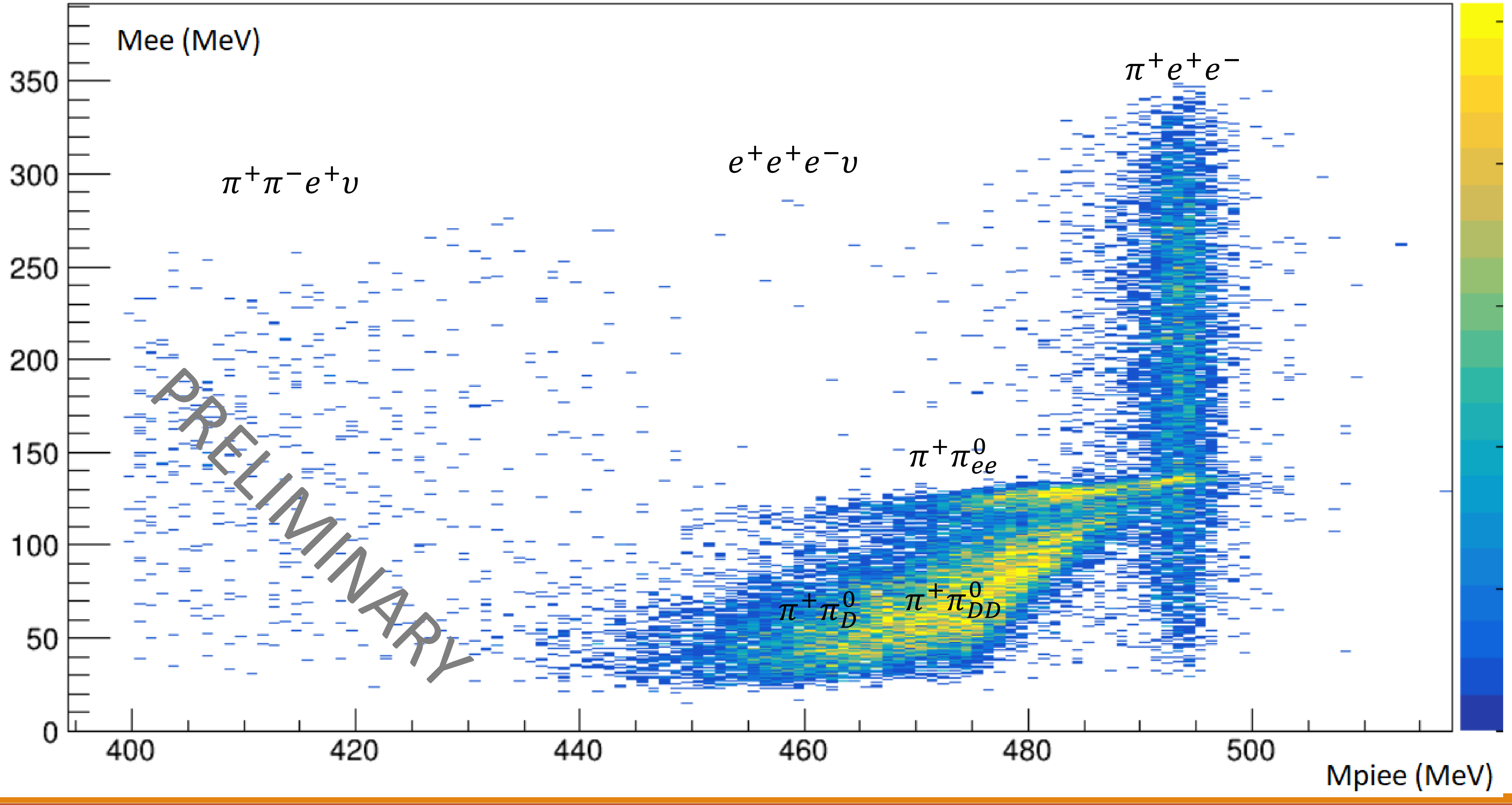
Trigger Hardware

Mask Condition	RUN 9238 (∼ 55%)	RUN 8597 (∼ 64%)	RUN 8647 (∼ 67%)	RUN 8784 (∼ 70%)
RICH8-QX-E20	1.38	1.35	1.35	1.35
RICH-QX-H3-E20	1.32	1.33	1.32	1.32
RICH8-QX-H3-E20	1.76	1.74	1.73	1.73
RICH8-QX-H3-E20-!MUV	2.37	2.42	2.39	2.46
RICH8-QX-H3-C2E20-!MUV	-	2.52	2.50	2.57
RICH8-QX-H3-C2D5-E20-!MUV	3.29	-	3.16	3.25
RICH8-QX-H3-C2D12-E20-!MUV	6.23	-	6.10	6.24

- Additional reduction factors to the trigger rate of the 2018 di-electron mask;
- Alternative condition stored in the data packet or emulated;
- Detectors used: RICH, Charged Hodoscope, Electromagnetic Calorimeter, Muon Veto.
- Hadronic Calorimeter condition to be emulated;
- GPU RICH condition to be emulated.

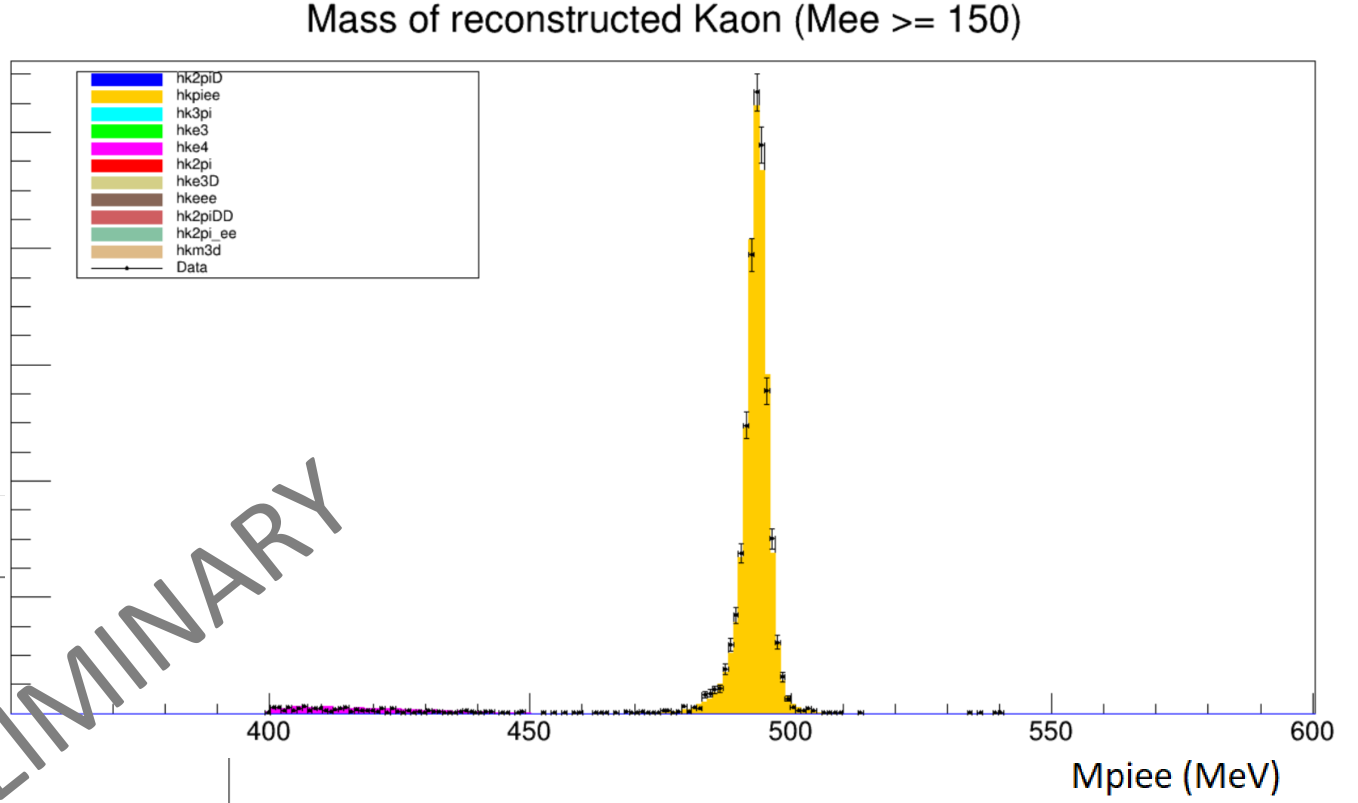


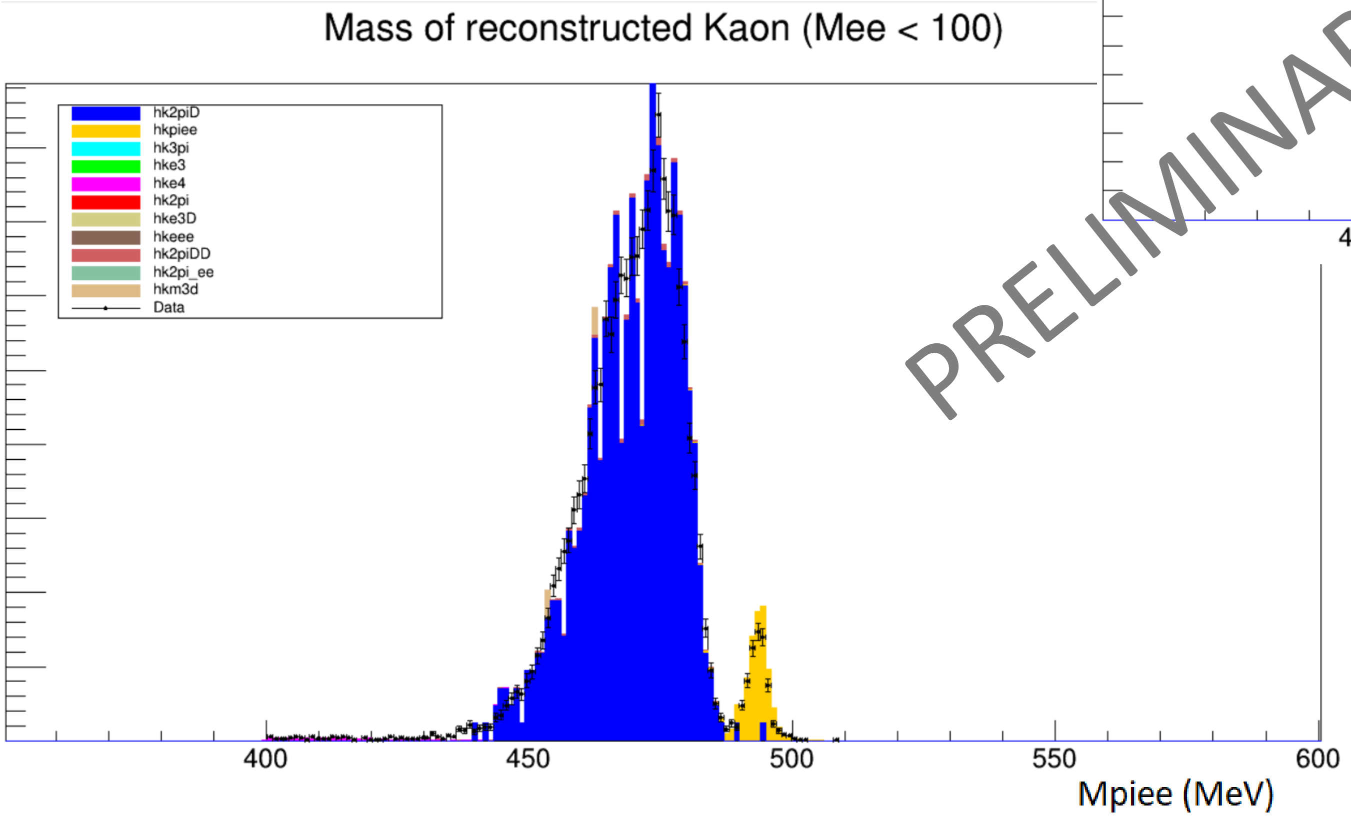
Analysis



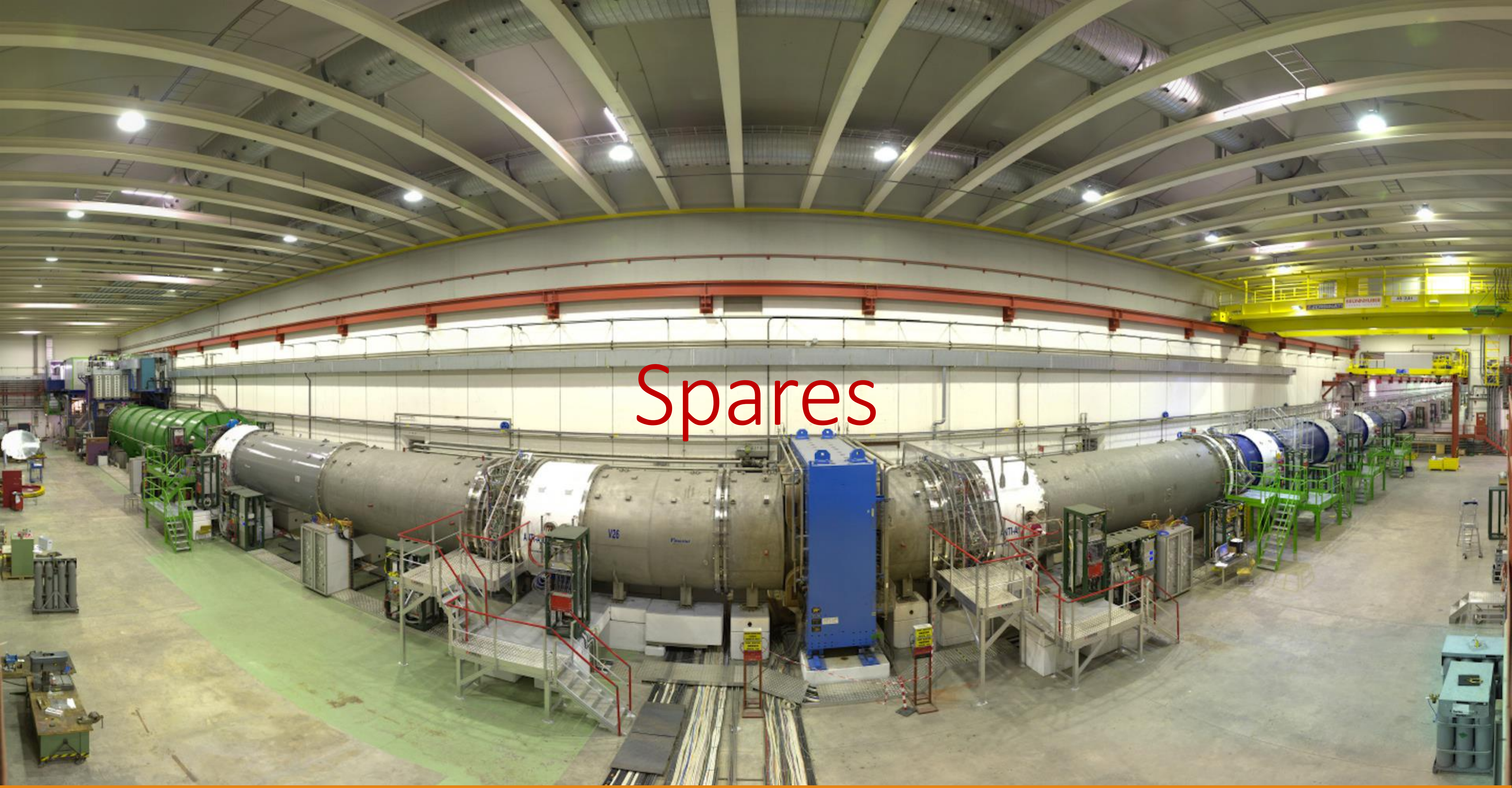
Mee (MeV)
350
300
250
200
150
100
50
0
400
420
440
460
480
500
Mpiee (MeV)
$\pi^+ e^+ e^-$
$e^+ e^+ e^- \upsilon$
$\pi^+ \pi^- e^+ \upsilon$
$\pi^+ \pi^0_{ee}$
$\pi^+ \pi^0_D$
$\pi^+ \pi^0_{DD}$
PRELIMINARY

MC and Data





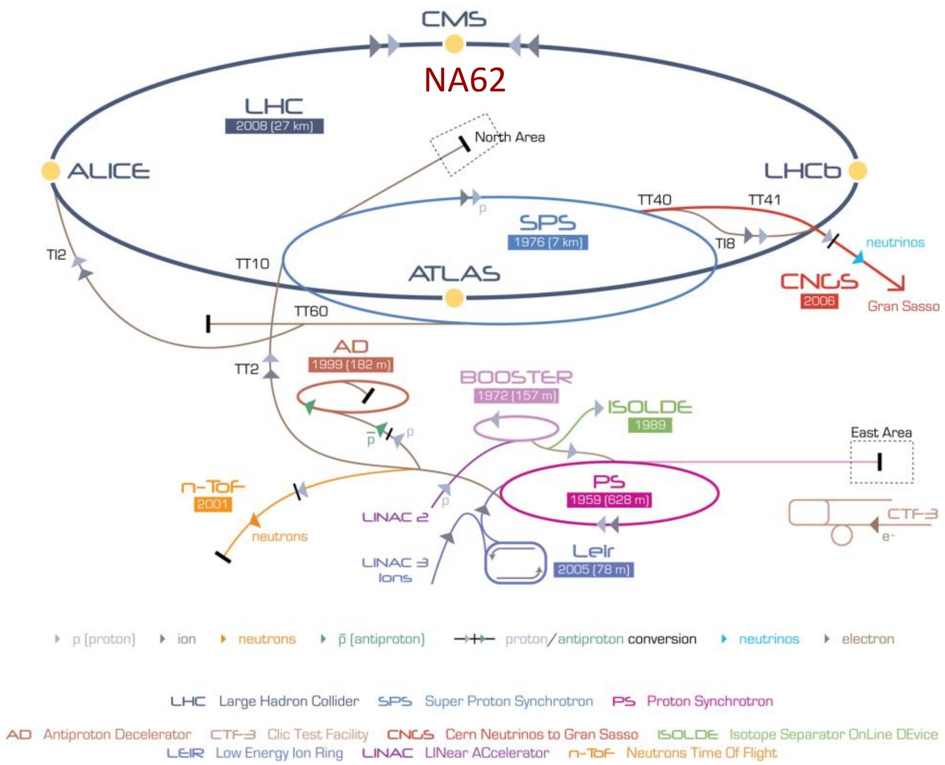
PRELIMINARY



Spares

The NA62 Experiment

- NA62: High precision fixed-target Kaon experiment at CERN SPS
- Main goal: measurement of BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$)
- Broader physics program: LFV / LNV in K^+ decays, hidden sector particles searches.



NA62 Timeline

- 2008: NA62 Approval
- 2014: NA62 Pilot Run (partial layout)
- 2015: Commissioning run
- Full detector installation completed in September 2016
- 2016 : First $\pi\nu\nu$ dataset in 2016
- Continuous data-taking until the end of 2018
- data-taking will be resumed in 2021 with improvements

~ 200 participants from: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Torino, TRIUMF, Vancouver UBC

NA62 Layout

SPS Beam:
- 400 GeV/c protons
- $1{,}9 \cdot 10^{12}$ protons/spill
- 3.5s spill

Secondary positive Beam:
- 75 GeV/c momentum
- 1 % bite 100 mrad divergence (RMS)
- 60x30 mm2 transverse size
- K^+ (6%)/π^+ (70%)/p(24%)
- 33×10^{11} ppp on T10 (750 MHz at GTK3)