The $K^+ \to \pi^+\nu\bar{\nu}$ decay and New Physics searches at NA62

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on behalf of the NA62 Collaboration

Excited QCD – February 2020
The NA62 experiment
The NA62 experiment

- Fixed target experiment, located in the North Area of the CERN SPS.
- Main goal: \( \text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) \) with decay in flight technique.
- \( \text{BR}_{\text{th}}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11} \) [Buras et al., JHEP11(2015)033]
- \( \text{BR}_{\text{exp}}(K^+ \to \pi^+ \nu \bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-11} \) [E949, Phys. Rev D 79, 092004 (2009)]
- \( \sim 200 \) participants from \( \sim 30 \) institutes: 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, Sofia, Torino, TRIUMF, Vancouver UBC.
The NA62 experiment

Main goal

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]

Exotic searches

Heavy neutral leptons, dark photons, dark scalars, axion-like particles, ...

Forbidden decays

\[ K^+ \rightarrow \pi^- e^+ e^+ , \quad K^+ \rightarrow \pi^- \mu^+ \mu^+ , \quad \ldots \]

Rare decays

\[ K^+ \rightarrow \pi^+ \mu^+ \mu^- , \quad K^+ \rightarrow \pi^+ \gamma \gamma , \quad \ldots \]
Status and timeline:

- **2016**
  - Commissioning + 1st physics run.
  - First $K^+ \rightarrow \pi^+\nu\bar{\nu}$ result published.

- **2017**
  - Physics run, better collection efficiency for physics data.
  - $3 \times 10^{12}$ $K^+$ decays recorded (> 10x more than 2016).
  - Preliminary results on $K^+ \rightarrow \pi^+\nu\bar{\nu}$  This talk

- **2018**
  - Physics run, better shielding of upstream background.
  - $5 \times 10^{12}$ $K^+$ decays recorded (> 20x more than in 2016).

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$
**K^+ → π^+ν̅ν:** theoretical framework

- K^+ → π^+ν̅ν and K_L → π^0ν̅ν provide an important test for the SM.
- FCNC processes dominated by Z-penguins and box amplitudes, main uncertainties from CKM matrix elements.
- Theoretically clean.

\[
BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left(8.39 \pm 0.30\right) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}
\]

\[
BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) = \left(3.36 \pm 0.05\right) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^2 \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^2 \cdot \left[\frac{\sin \gamma}{\sin 73.2^\circ}\right]^2
\]

- Measuring both K^+ → π^+ν̅ν and K_L → π^0ν̅ν provides the CKM unitarity triangle independently from measurements in B mesons sector.

[Buras et al., JHEP 1551 (2015) 033]
**K⁺→π⁺νν: theoretical framework**

- Correlations between $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ in most of the NP models.

![Graph showing correlations between BR($K_L \rightarrow \pi^0 \nu \bar{\nu}$) and BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)]

- Custodial Randall-Sundrum  
- MSSM Analysis  
- Simplified Z, Z' models  
- Littlest Higgs with T-parity  
- LFU violation models  
- Primary beam: 400 GeV/c protons from SPS.
- Secondary beam: 75 GeV/c positively charged particles, 70% $\pi^+$, 23% p, 6% K$^+$. 
**K⁺→π⁺ν̅ν: decay in flight technique at NA62**

The squared missing mass is the main variable used to kinematically separate signal from background:

\[ m_{\text{miss}}^2 = (P_K - P_\pi)^2 \]

15 GeV/c < \( P_\pi < 35 \) GeV/c

- Two signal region on each side of the \( K⁺→\pi⁺\pi⁰ \) peak.
- Cut based analysis (mostly), blind analysis procedure.

**Main background sources**

- \( K⁺→\pi⁺π⁰(\gamma) \)
- \( K⁺→e⁺π⁰ν_\gamma \)
- \( K⁺→μ⁺π⁰ν_\mu \)

**Decay mode** | **BR** | **Main rejection tools**
---|---|---
\( K⁺→μ⁺ν(\gamma) \) | 63% | \( μ\text{-ID + kinematics} \)
\( K⁺→π⁺π⁰(\gamma) \) | 21% | \( γ\text{-veto + kinematics} \)
\( K⁺→π⁺π⁺π⁻ \) | 6% | \( \text{multi + kinematics} \)
\( K⁺→π⁺π⁰π⁰ \) | 2% | \( γ\text{-veto + kinematics} \)
\( K⁺→π⁰e⁺ν_\gamma \) | 5% | \( e\text{-ID + γ-veto} \)
\( K⁺→π⁰μ⁺ν_μ \) | 3% | \( μ\text{-ID + γ-veto} \)

- Requirements:
  - \( O(100 \) ps\) timing between sub-detectors
  - \( O(10⁴) \) background suppression with kinematics
  - \( O(10⁷) \) background muon suppression \( (K⁺→μ⁺ν_\mu) \)
  - \( O(10⁷) \) photon suppression \( (K⁺→π⁺π⁰) \)
\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]: signal and control regions

- Two signal regions kept blinded

- In order to evaluate the background from K decays, the tails of the distribution are extrapolated into the signal regions.

- The control regions are kept blinded too, to validate the procedure.

- Selection:
  - single track in final state
  - \( \pi^+ \) identification
  - photon rejection
  - Multiplicity rejection
  - \( 110 \text{ m} < z_{\text{vertex}} < 165 \text{ m} \)
  - \( 15 \text{ GeV/c} < p_{\pi^+} < 35 \text{ GeV/c} \), in order to have at least \( E_{\text{miss}} = 40 \text{ GeV} \) and have an optimal \( \pi/\mu \) separation in the RICH.

- Performances:
  - \( \varepsilon(\mu^+) \sim 10^{-8} \) (64% \( \pi^+ \) efficiency)
  - \( \varepsilon(\pi^0) \sim 1.4 \cdot 10^{-8} \)
  - \( \sigma(m^2_{\text{miss}}) \sim 10^{-3} \text{ GeV}^2/c^4 \)
  - \( \sigma_t \sim O(100 \text{ ps}) \)
\[ N_{\pi\nu\nu}^{\text{expected}}(\text{SM}) = \frac{BR_{\pi\nu\nu}(\text{SM})}{SES} \]

\[ SES = \frac{1}{N_K \cdot \sum_j \left( A_{\pi\nu\nu}^j \cdot \epsilon_{\text{trig}}^j \cdot \epsilon_{\text{RV}}^j \right)} \]

- \( A_{\pi\nu\nu} \): signal acceptance
- \( \epsilon_{\text{trig}} \): trigger efficiency
- \( \epsilon_{\text{RV}} \): random veto efficiency
- \( j \): bin of momentum and beam intensity

\[ N_K = \frac{N_{\pi\pi} \cdot R}{A_{\pi\pi} \cdot BR_{\pi\pi}} = (1.3 \pm 0.1) \times 10^{12} \]

- \( N_{\pi\pi} \): number of \( K^+ \rightarrow \pi^+\pi^0 \) observed
- \( A_{\pi\pi} \): normalization decay acceptance
- \( BR_{\pi\pi} \): normalization decay branching ratio
- \( R \): reduction factor applied to CTRL trigger

\[ SES = (0.389 \pm 0.021) \times 10^{-10} \]

\[ N_{\pi\nu\nu}^{\text{expected}}(\text{SM}) = 2.16 \pm 0.12_{\text{stat}}^{\pm 0.26_{\text{extr}}} \]
Expected background from $K^+ \rightarrow \pi^+ \pi^0$

Control data used to study tails of $m_{miss}^2$ distributions

$$N_{\pi\pi}^{\text{exp}}(\text{region}) = N(\pi^+ \pi^0) \cdot f_{\text{kin}}(\text{region})$$

- $N_{\pi\pi}^{\text{exp}}(\text{region})$: expected $K^+ \rightarrow \pi^+ \pi^0$ events in the signal region after the $\pi\nu\nu$ selection

- $N(\pi^+ \pi^0)$: events in the $K^+ \rightarrow \pi^+ \pi^0$ region after the $\pi\nu\nu$ selection

- $f_{\text{kin}}(\text{region})$: fraction of $K^+ \rightarrow \pi^+ \pi^0$ in signal region measured on control data
**Upstream background**

**Upstream events**: particles originated before the fiducial decay volume (early decays and interactions).

**Normal K^+ decay**: back-extrapolation of the charged track in final state is far from the beam direction. Tracks back-extrapolated near the beam direction are rejected.
Background if in-time pile-up beam particle (in KTAG and GTK). The upstream generated track enters the fiducial decay region and undergoes multiple scattering in the 1st chamber of the STRAW.
### $K^+ \to \pi^+ \nu \bar{\nu}$: expected background (2017)

#### 2017 data preliminary

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \to \pi^+ \nu \bar{\nu}$ (SM)</td>
<td>$2.16 \pm 0.12_{\text{stat}} \pm 0.26_{\text{ext}}$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+ \pi^0(\gamma)$ IB</td>
<td>$0.29 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \to \mu^+ \nu_\mu(\gamma)$ IB</td>
<td>$0.15 \pm 0.02_{\text{stat}} \pm 0.04_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+ \pi^- e^+ \nu_e$</td>
<td>$0.12 \pm 0.05_{\text{stat}} \pm 0.03_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+ \pi^- \pi^+$</td>
<td>$0.02 \pm 0.02_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+ \gamma \gamma$</td>
<td>$0.005 \pm 0.005_{\text{syst}}$</td>
</tr>
<tr>
<td>$K^+ \to l^+ \pi^0 \nu_l$</td>
<td>negligible</td>
</tr>
<tr>
<td>Upstream background</td>
<td>$0.9 \pm 0.2_{\text{stat}} \pm 0.2_{\text{syst}}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$1.5 \pm 0.2_{\text{stat}} \pm 0.2_{\text{syst}}$</td>
</tr>
</tbody>
</table>
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: 2017 preliminary results

**Signal events expected in signal region (SM)**

$2.16 \pm 0.12_{\text{stat}} \pm 0.26_{\text{ext}}$

**Background events expected in signal region**

$1.50 \pm 0.30$

2 events observed in region 2!
**K^+→π^+νν̅: 2016 + 2017 preliminary results**

### 2016 + 2017 uncorrelated

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Events observed</td>
<td>3</td>
</tr>
<tr>
<td>Single Event Sensitivity</td>
<td>(0.346 ± 0.017) × 10^{-10}</td>
</tr>
<tr>
<td>Expected background</td>
<td>1.65 ± 0.31</td>
</tr>
</tbody>
</table>

**Upper limits:**
\[
\text{BR}(K^+→π^+νν̅) < 1.85\times10^{-10} \quad \text{@ 90\% CL}
\]
\[
\text{BR}(K^+→π^+νν̅) < 2.44\times10^{-10} \quad \text{@ 95\% CL}
\]

**Two-sided 68\% sideband:**
\[
\text{BR}(K^+→π^+νν̅) = 0.47^{+0.72}_{-0.47}\times10^{-10}
\]

**New Grossman-Nir limit:**
\[
\text{BR}(K_L→π^0νν̅) < 8.14\times10^{-10} \quad \text{@ 90\% CL}
\]

**SM prediction on the Branching Ratio:**
\[
\text{BR}(K^+→π^+νν̅) = (0.84±0.10)\times10^{-10}
\]
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$: experimental status

![Graph showing BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) vs. Year of Publication]

- **E787+E949**:
  - Experimental two-sided limit
  - Theoretical prediction
  - Upper Limit

- **NA62 '16 + '17**:
  - 95% CL
  - 90% CL

NA62 Preliminary
Exotic searches and Forbidden decays
\( \pi^0 \rightarrow \text{invisible} \)

- A-priori evaluation of \( \pi^0 \) suppression in \( K^+ \rightarrow \pi^+ \pi^0 \) kinematic region

- Same selection of \( K^+ \rightarrow \pi^+ \bar{\nu} \bar{\nu} \)

- Normalization channel: \( \pi^0 \rightarrow \gamma \gamma \)

- Number of expected background events: \( 10^{+22}_{-8} \)

- Number of observed events: 12

- Preliminary result: \( \text{BR}(\pi^0 \rightarrow \text{invisible}) < 4.4 \times 10^{-9} \) @90% C.L.

- Factor 60 improvement with respect to the state of the art.
LNV and LFV: NA62 search

- In the SM, if neutrinos are massless, lepton flavour numbers and total lepton number are conserved
- E.g. $K^+ \rightarrow \pi^- e^+ e^+$, $K^+ \rightarrow \pi^- \mu^+ \mu^+$
- NA62 results with a subset of 2017 data improve world upper limits on the BR of $K^+ \rightarrow \pi^- e^+ e^+$ and $K^+ \rightarrow \pi^- \mu^+ \mu^+$ by a factor 2-3:
  \[
  \text{BR}(K^+ \rightarrow \pi^- e^+ e^+) < 2.2 \times 10^{-10} \quad 90\% \ C.L.
  \]
  \[
  \text{BR}(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11} \quad 90\% \ C.L.
  \]
- Full data sample (2016-2018): 3x more statistics
• The **νMSM** predicts three heavy sterile neutrinos, with $N_1 \sim O(10 \text{ keV}/c^2)$ and $N_{2,3} \sim O(1 \text{ GeV}/c^2)$.

• Production of $N_{2,3}$ in meson decays, such as $K^+\rightarrow e^+N$ and $K^+\rightarrow \mu^+N$.

• Mass scan in the range 141-462 (220-383) MeV/$c^2$ in the $e^+$ ($\mu^+$) case.

• Preliminary 2016+2017 result: new upper limit on mixing parameter $|U_{14}|^2$ [Goudzovski KAON 2019]

• More than 2 orders of magnitude improvements with respect to previous results.

• Improvement by almost a factor 2 with the full data set.
Dark Photons

- SM extension – new vector field $A'$ mixing with the SM $\gamma$
  

- $K^+ \to \pi^+ \pi^0$, $\pi^0 \to A' \gamma$, $A' \to$ invisible

- $\text{BR}(\pi^0 \to A' \gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \times \text{BR}(\pi^0 \to \gamma \gamma)$

- Missing mass squared is computed, a peak is expected around $m_{A'}^2$.

- Main background comes from $\pi^0 \to \gamma \gamma$ with a lost photon.
Dark Photons

- Evaluation of background from data, inverting the veto condition on the charged hodoscopes; background normalized to data in the region already covered by other experiments.

- Analysed a subsample of 2016 data, ~1% of 2016-2018 data.

- No signal observed, new upper limits at 90% CL in the \((\varepsilon^2, m_{A'})\) plane.

- \(\text{BR} (\pi^0 \rightarrow \gamma \nu \bar{\nu}) < 1.9 \times 10^{-7} \) @ 90% C.L. [JHE05 (2019) 182]
  - Improvement on the state of the art by more than 3 orders of magnitude
Beam dump

- Beam dumped in the TAXes (2 copper collimators, 25 m after the target, $2 \times 10.7 \lambda_i$).
- Dumping the beam before the detector allows for the production of exotic particles or $B$ and $D$ mesons decaying promptly into exotic mediators and SM particles.
- In this way, the exotic searches extend up to masses of $\sim 1.7$ GeV.
- $3 \times 10^{16}$ protons on target already taken in 2017-2018
- 3-4 months of run in dump mode foreseen after the LS $\rightarrow O(10^{18})$ protons on target (POT).
- In the next slides, expected limits in 5 years are shown.
• NA62 can explore ALPs masses in the MeV to GeV range.  
  \[ \pi^0 \text{ are a major background to } K^+ \rightarrow \pi^+\nu\bar{\nu}, \text{ therefore an hermetic photon veto is essential to the measurement: search } \text{ALP} \rightarrow \gamma\gamma. \]

• Dark photon visible decay at NA62: DP produced in the dump, $A' \rightarrow l^+l^-$. 

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**Axion-like particles**

- $g_{a\gamma}[\text{GeV}^{-1}]$ vs. $m_a [\text{GeV}/c^2]$ 
  - Various experiments: E141, BaBar, NuCal, SeaQuest, Phase I, NA62, 10^{18} POT, SHiP, 10^{20} POT, SN1987

**DP visible decay**

- Various searches: NA64, PRL 120 (2015), 239602, AWAKE, 10^4 pot, REDTOP, 10^6 pot, Nd → X gamma, LDMX, 16 GeV, 10^3 pot, FASER, 150.0 pb^{-1}, FASER2, 3 ab^{-1}, MATHUSLA200, 3 ab^{-1}, NA62, 10^3 pot, SHiP, 10^3 pot
- Dark scalar: $S \rightarrow \mu^+\mu^-$

- **HNL**: $\frac{D}{D_s} \rightarrow \ell^+ N$, $N \rightarrow \pi e$, $N \rightarrow \pi \mu$

- Exclusion plots at 90% CL, zero background hypothesis.
Conclusions

\( K^+ \rightarrow \pi^+ \nu \bar{\nu} \)

- 2 signal candidates observed in 2017.
- SES = \((0.389 \pm 0.021) \times 10^{-10}\)
- Expected background events: \(1.5 \pm 0.3\)
- Preliminary results (2016+2017): \( \text{BR} \left( K^+ \rightarrow \pi^+ \nu \bar{\nu} \right) < 1.85 \times 10^{-10} \) @ 90% CL
  \( \text{BR} \left( K^+ \rightarrow \pi^+ \nu \bar{\nu} \right) < 2.44 \times 10^{-10} \) @ 95% CL
- Constraints on largest enhancements allowed by NP models.

Exotic searches

- \( \text{BR}(\pi^0 \rightarrow \text{invisible}) \) upper limit
- HNL upper limits (\( K^+ \rightarrow e+N, K^+ \rightarrow \mu+N \))
- LNV/LFV upper limits (\( K^+ \rightarrow \pi^0 e^+e^+, K^+ \rightarrow \pi^0 \mu^+\mu^+ \))
- Limits on DP mass and \( \text{BR}(\pi^0 \rightarrow \gamma \nu \bar{\nu}) \)
- \( \text{BR}(\pi^0 \rightarrow \gamma \nu \bar{\nu}) \) upper limit
Future prospects

- **$K^+ \to \pi^+ \nu \bar{\nu}$**
  - Analysis of 2018 data on-going.
  - Factor 2 wrt 2017 data set.
  - On-going studies to optimize the signal selection, reduce the random veto and increase the signal efficiency.
  - Shape analysis and statistical treatment.

- **Data taking after the LS2 ($\geq 2021$)**
  - Plans to strongly suppress the upstream background (modification to the beam line, add fourth GTK station).
  - Higher beam intensity.

- **Exotic searches**
  - Improvements expected with the analysis of the full data sample.
  - Special beam-dump runs already taken to study the background for future beam dump data taking.
  - Dedicated beam-dump runs expected after the LS2 ($O(10^{18})$ protons on target).
DZIĘKUJĘ!
(Thank you!)
BACKUP
\( K^+ \rightarrow \pi^+ \nu \bar{\nu} \): results (2016)

1 event observed in region 2

\[
\text{BR}_{\text{NA62}}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \cdot 10^{-10} \quad @ 95\% \text{ CL}
\]

### $K^+ \to \pi^+ \nu \bar{\nu}$: 2017 preliminary results

<table>
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<tr>
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<tr>
<td>Single Event Sensitivity</td>
<td>$(0.389 \pm 0.021) \times 10^{-10}$</td>
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<td>Expected background</td>
<td>$1.50 \pm 0.30$</td>
</tr>
</tbody>
</table>

Upper limits:

\[
\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) < 1.76 \cdot 10^{-10} \quad @ 90\% \text{ CL} \\
\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) < 2.11 \cdot 10^{-10} \quad @ 95\% \text{ CL}
\]

Two-sided 68\% sideband:

\[
\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = 0.20^{+0.69}_{-0.20} \times 10^{-10}
\]

SM prediction on the Branching Ratio:

\[
\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}
\]
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: New Grossman-Nir limit

![Graph showing Br($K_L \rightarrow \pi^0 \nu \bar{\nu}$) vs Br($K^+ \rightarrow \pi^+ \nu \bar{\nu}$).]


[G. Ruggiero, KAON 2019]
Beam dump: Axion-Like Particles

- ALPs are candidates for cold dark matter.
- **NA62** can explore ALPs masses in the MeV to GeV range. [JHEP 1602 (2016) 018]
  - $\pi^0$ are a major background to $K^+ \to \pi^+\nu\bar{\nu}$, therefore an hermetic photon veto is essential to the measurement: search $ALP \to \gamma\gamma$.

- Beam dump: **Primakoff** production of ALPs via beam protons interactions with the TAXes:
  - In dump mode, only $\mu e \nu$ reach the fiducial decay volume.
  - ALPs are produced with a low transverse momentum: a small detector far away from the production point has a good acceptance for the process.
Beam dump: Dark Photon

Dark photon visible decay in NA62.

- \( pN \rightarrow X\pi^0, \pi^0 \rightarrow A'\gamma, \ A' \rightarrow l^+l^- \)
- \( pN \rightarrow XA', \ A' \rightarrow l^+l^- \)

- Assuming \(10^{18}\) POT with 400 GeV.
- \(A'\) produced from interaction with target (bremsstrahlung and meson decays).
- Exclusion plot at 90% CL, in the zero background hypothesis.
- Better sensitivity expected taking into account \(A'\) QCD production and production in the dump (at the moment, only production in the target is considered).
- \(3 \times 10^{17}\) POT taken during 2016/2017 di-\(\mu\) trigger, \(5 \times 10^{16}\) with ee trigger.