New constraints on LLPs by T2K near detector

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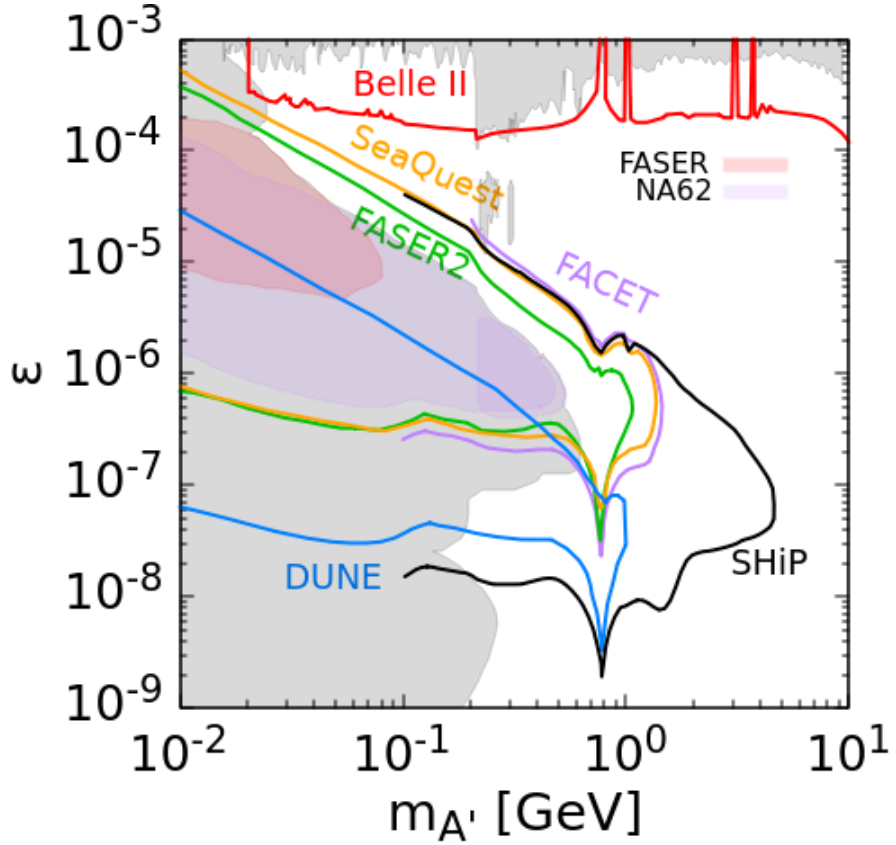
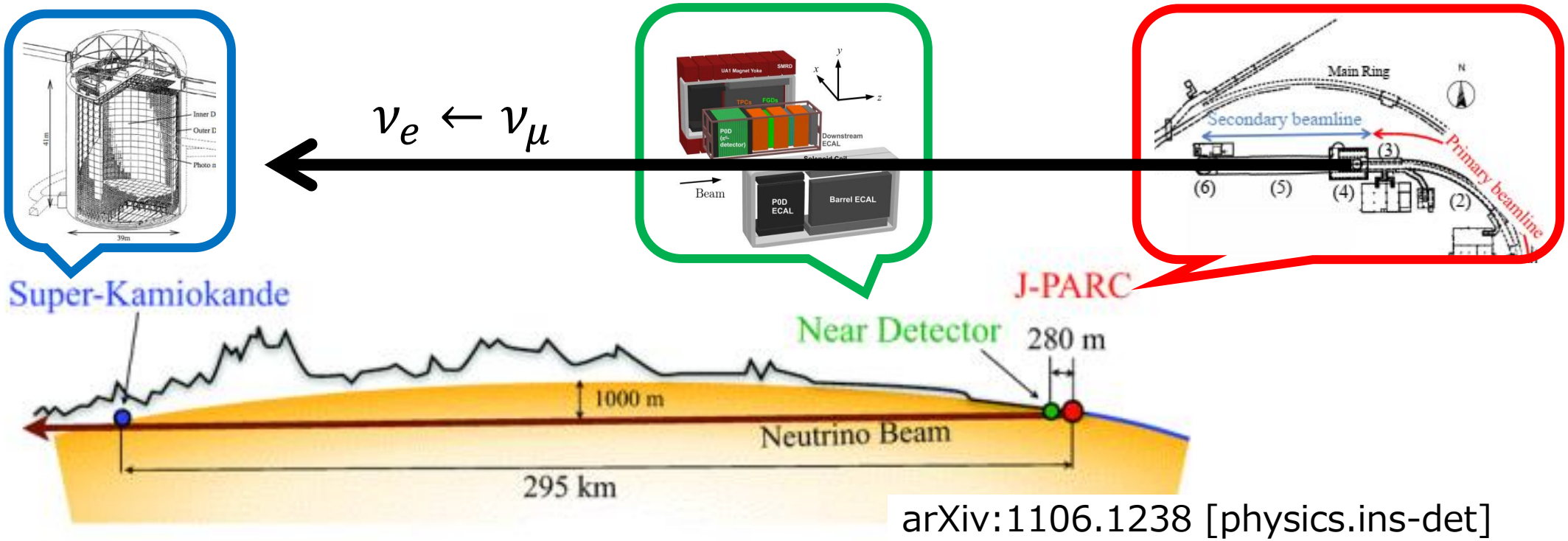
Introduction: LLPs

- A growing interest in Long-Lived Particles (LLPs) !!
- NA62 and FASER recently released new data.
- Many future experiments.
- Many theoretical motivations:
  - dark matter,
  - muon g-2,
  - Neutrino mass,
  - Hubble tension.
- In this talk, **LLP search at T2K**.



T2K (Tokai-to-Kamioka)

- T2K is a long-baseline neutrino oscillation experiment in Japan.
- A 30 GeV proton beam collides with the graphite target, producing charged pions; then, the charged pions decay into muon-neutrinos.
- The produced neutrinos first go through the near detector ND280.



arXiv:1106.1238 [physics.ins-det]

Motivation and Goal

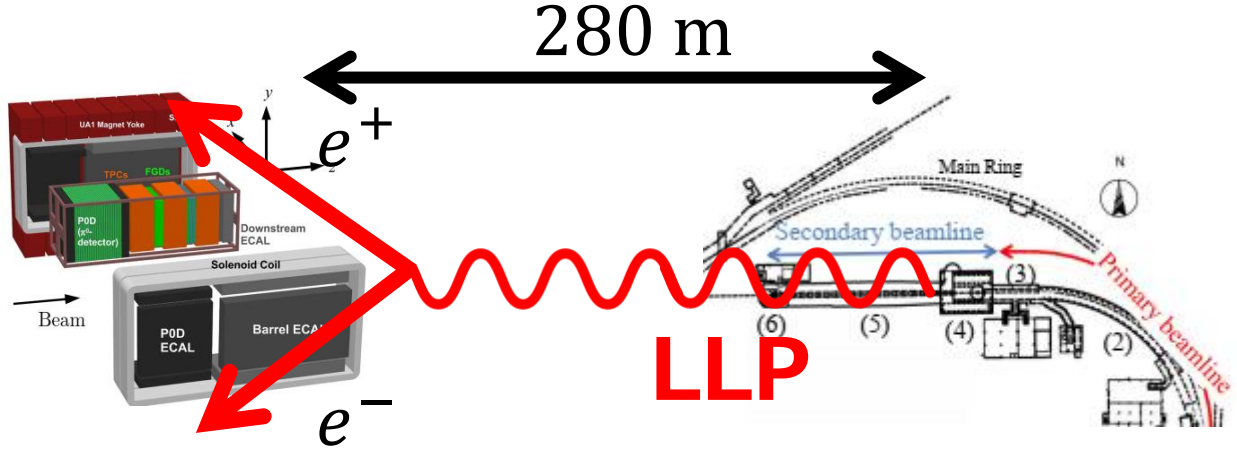
- The experimental setup of T2K is applicable to an LLP search.
- LLPs can be produced from meson decays and proton bremss.
- The location of ND280 is ideal for long-lived particles.

$$d = \frac{\hbar c}{\Gamma}\beta\gamma \simeq \mathbf{100} \times \left(\frac{0.1\ \mathrm{GeV}}{m_X}\right)^2 \times \left(\frac{10^{-7}}{g_X}\right)^2 \times \left(\frac{p_X}{1\ \mathrm{GeV}}\right) \quad ※\ g_X X \bar{e} e$$

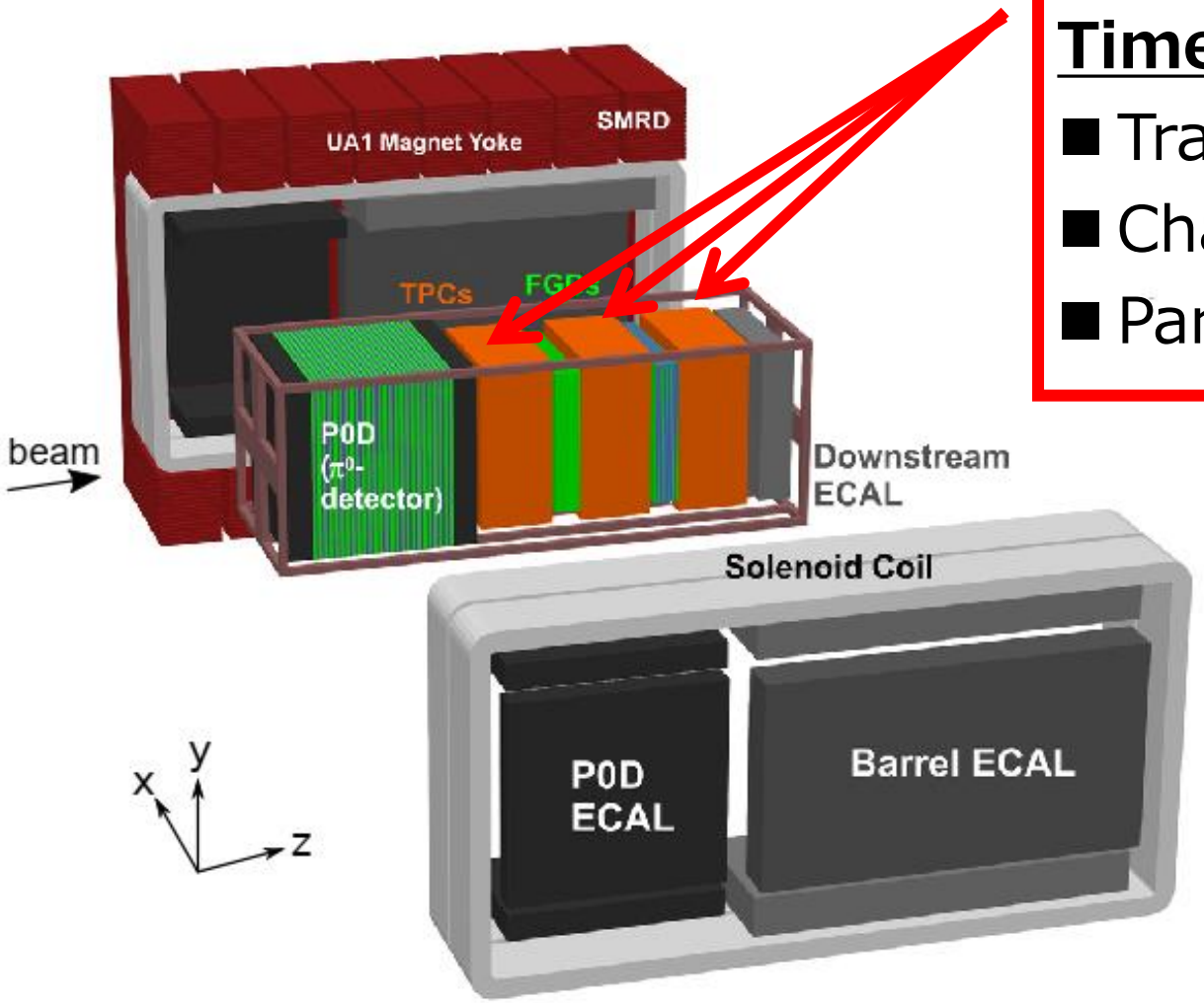
- T2K has accumulated

$$N_{pot} = 3.8 \times 10^{21}\ .$$

- New constraints on LLPs should be derived.
- The previous work on HNLs:
  [T. Asaka et al, JHEP03(2013), 125]
  [T2K, PRD100(2019), 052006]



ND280



Time Projection Chambers (TPCs)

- Tracking detectors.
- Charged particle momentum.
- Particle ID.

Dark Photon (DP)

- We consider the minima dark photon model in this talk:

$$\mathcal{L}_{DP} = -\varepsilon e\, A'_\mu\, J^\mu_{em} + \frac{1}{2} m_{A'}\, A'_\mu\, A'^\mu \,. \qquad \text{※} -\frac{\varepsilon}{2\cos\theta_w} F'_{\mu\nu}\, F^{\mu\nu}$$

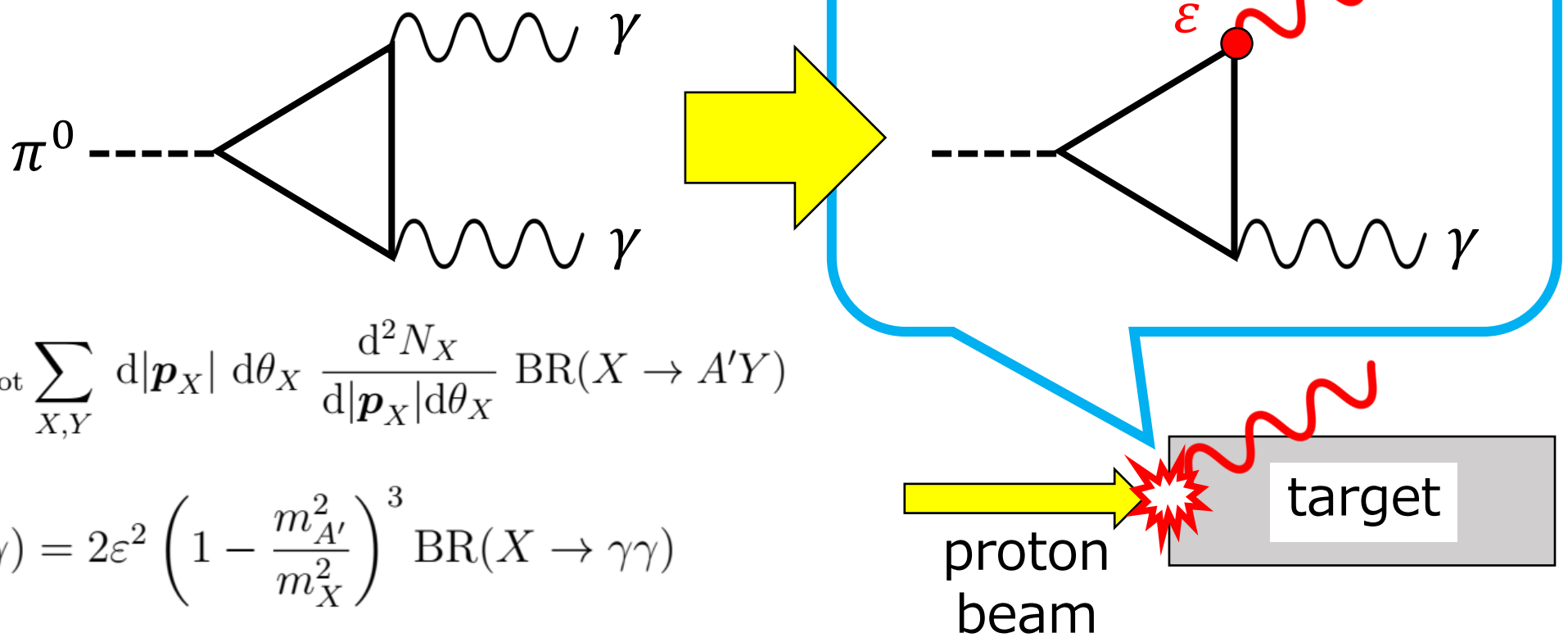
- DPs interact with the SM fermions through the EM current

$$j^\mu_{em} = \bar{u}\gamma^\mu \left(2/3\right) u + \bar{d}\gamma^\mu \left(-1/3\right) d + \bar{e}\gamma^\mu (-1) e \,.$$

- We do not consider the origin of the dark photon mass.
- **Only two parameters: $m_{A'}$ and ε .**

Production: Meson decays

- Dark photons can be produced from neutral meson decays by replacing an SM photon with a dark photon.
- $\pi^0,\ \eta,\ \eta'$ are dominant in T2K.



$$\mathrm{d}N_{\mathrm{DP}}^{\mathrm{meson}} = N_{\mathrm{pot}} \sum_{X,Y} \mathrm{d}|\boldsymbol{p}_X|\ \mathrm{d}\theta_X\ \frac{\mathrm{d}^2 N_X}{\mathrm{d}|\boldsymbol{p}_X|\mathrm{d}\theta_X}\ \mathrm{BR}(X \to A'Y)$$

$$\mathrm{BR}(X \to A'\gamma) = 2\varepsilon^2 \left(1 - \frac{m_{A'}^2}{m_X^2}\right)^3 \mathrm{BR}(X \to \gamma\gamma)$$

Production: Bremsstrahlung

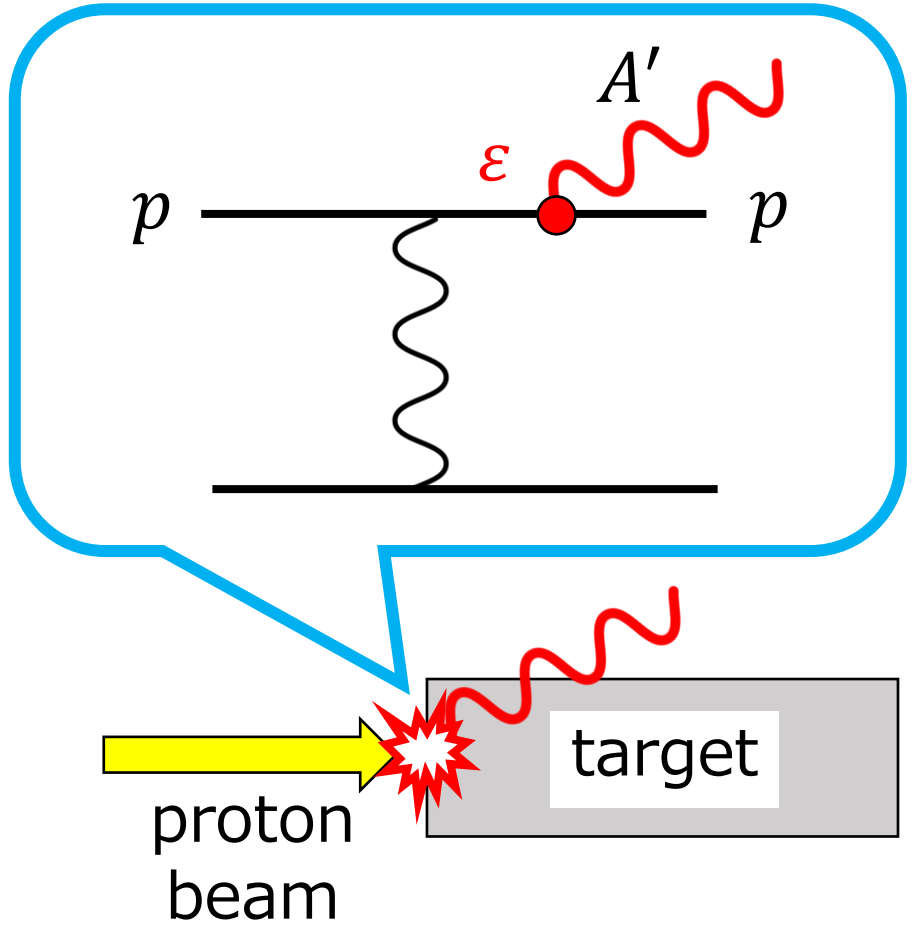
- DPs can also be produced from proton bremsstrahlung.

$$\mathrm{d}N_{\mathrm{DP}}^{\mathrm{brems}} = N_{\mathrm{pot}} |F(m_{A'}^2)|^2 \, \mathrm{d}z \, \mathrm{d}p_{A',t}^2 \, \frac{\sigma_{pp}(s')}{\sigma_{pp}(s)}$$

$$\times \; w(z, p_{A',t}^2) \, \Theta(\Lambda_{\mathrm{QCD}}^2 - q_{\mathrm{min}}^2)$$

[J. Blumlein and J. Brunner, PLB**731** (2014) 320–326]

[J. L. Feng, I. Galon, F. Kling, and S. Trojanowski, PRD**97** (2018) 035001]



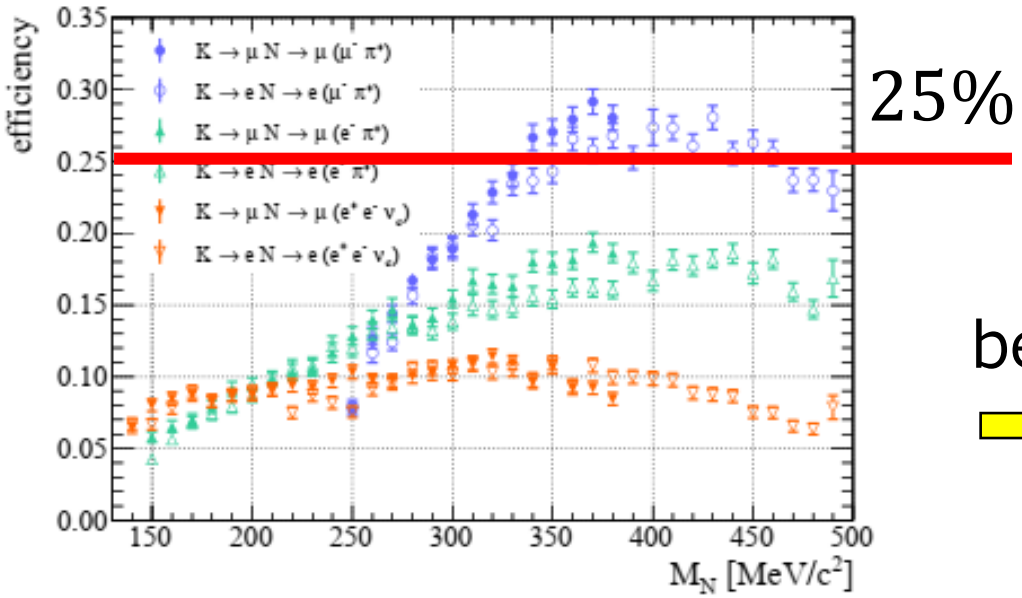
- We take into account resonances with vector mesons: ρ, ω.

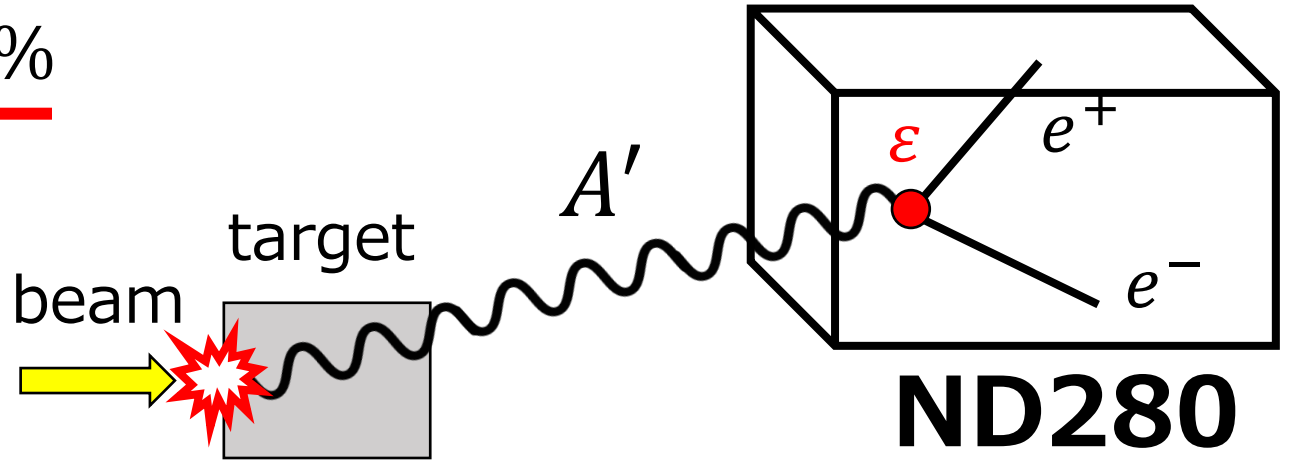
$$F(p_{A'}^2) = \sum_V \frac{f_V m_V^2}{m_V^2 - p_{A'}^2 - i m_V \Gamma_V} \quad \text{at } p_{A'} = m_{A'}.$$

Detection: Signal events

- Two tracks of opposite charge inside the TPCs of ND280.
- We regard $A' \to e^+e^-,\ \mu^+\mu^-,\ \pi^+\pi^-$ as signal events.
- A signal selection efficiency is assumed to be 25%; for details, please refer to the analysis for HNLs by the T2K collaboration.

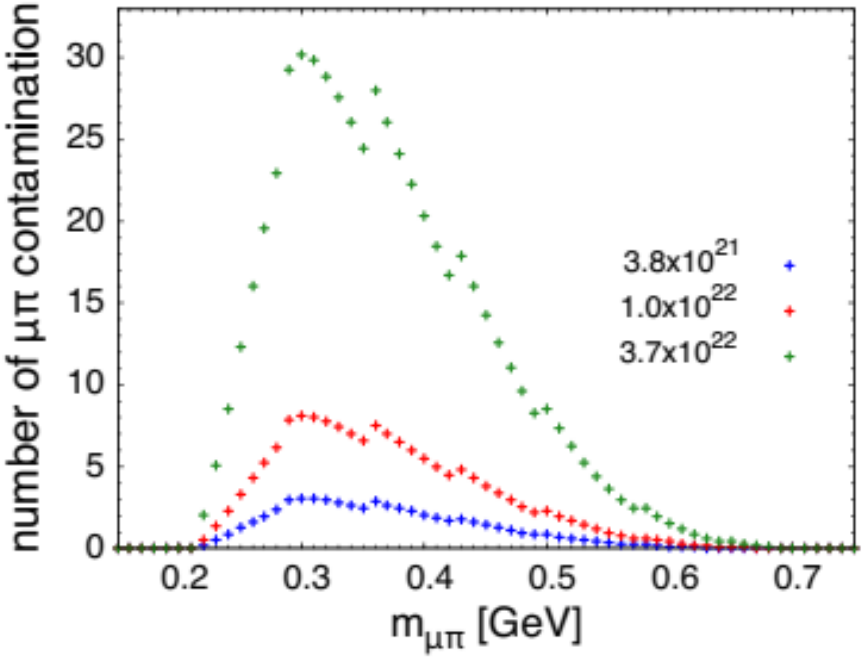
[T2K, PRD100(2019), 052006]

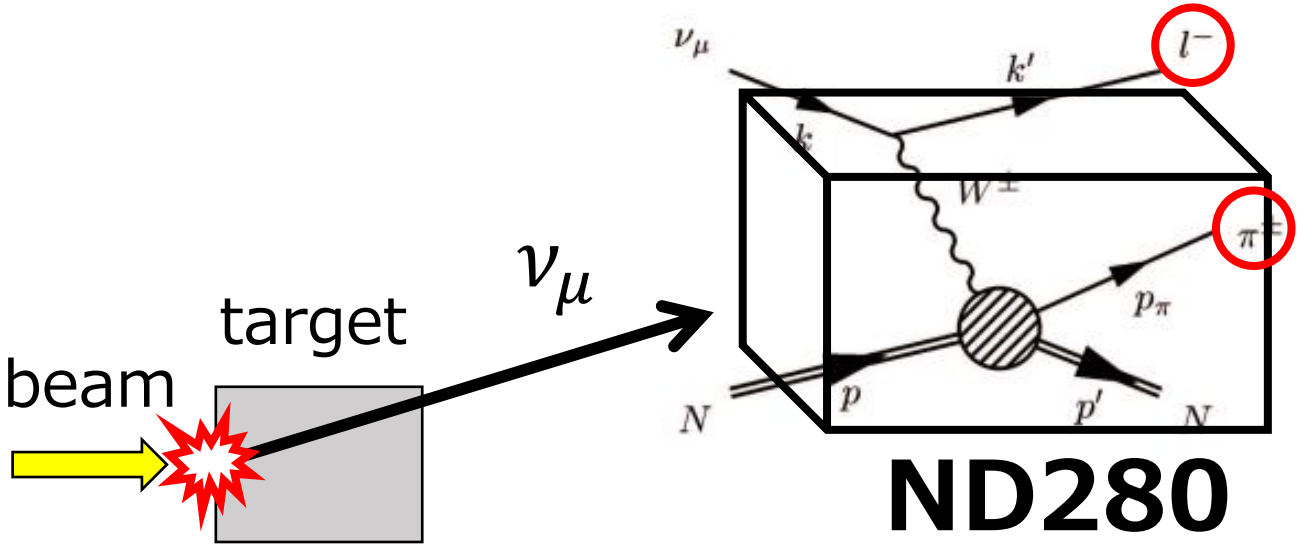




Detection: Backgrounds

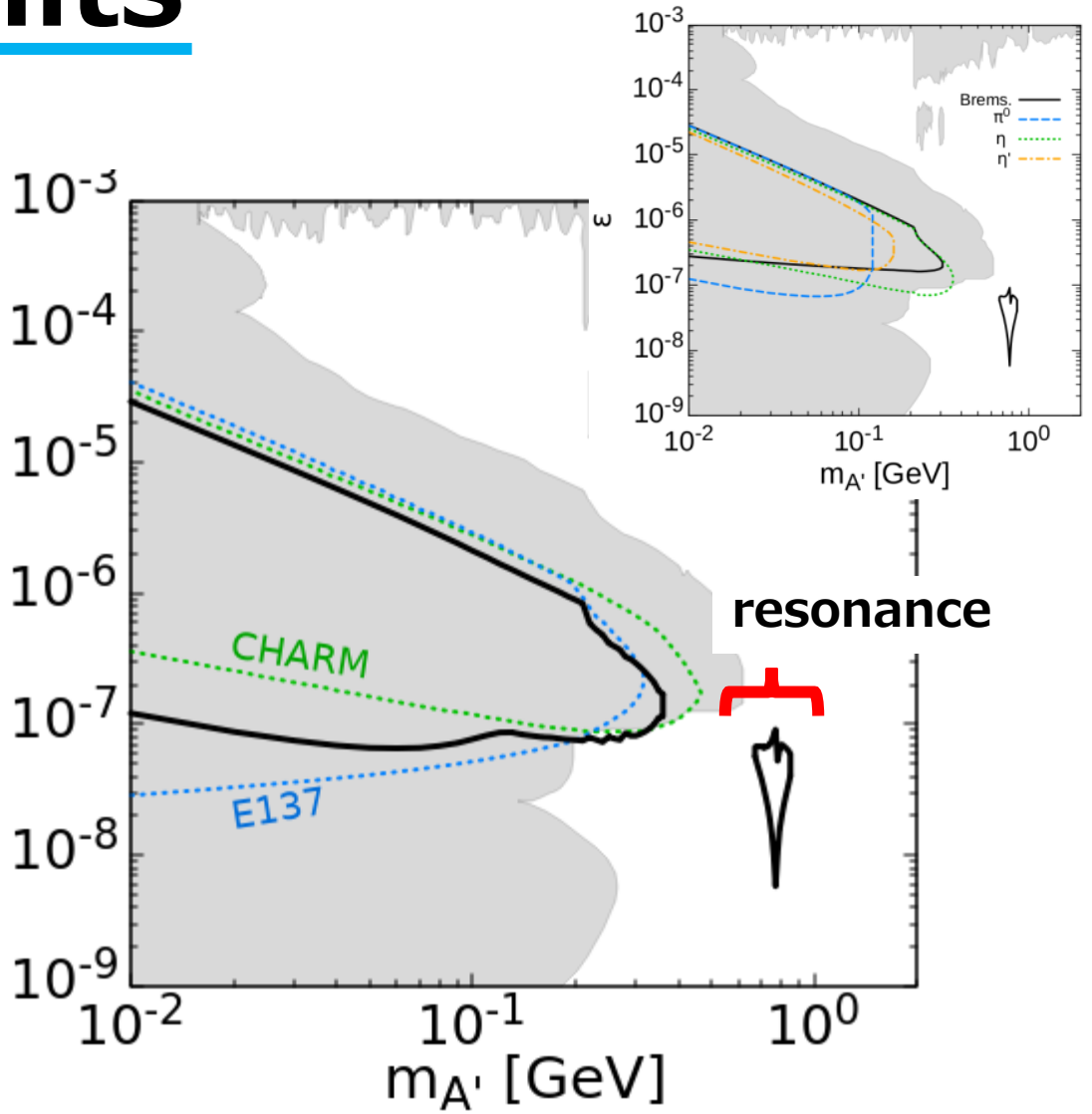
- Processes having $\mu^{\pm}$ and $\pi^{\mp}$ in the final state mimic our signals, e.g., the neutrino-induced coherent pion production.
- The BG simulation by T2K is scaled by N_{pot}, and the invariant mass distribution is generated by running GENIE v3.0.6.





Results: Current limits

- The 95% C.L. exclusion regions for $N_{pot} = 3.8 \times 10^{21}$.
- Unfortunately, most of our excluded regions are buried in the previous constraints...
- Fortunately, near the resonance, we have obtained a small new excluded region.
- We need more POT !!



Results: Future sensitivity

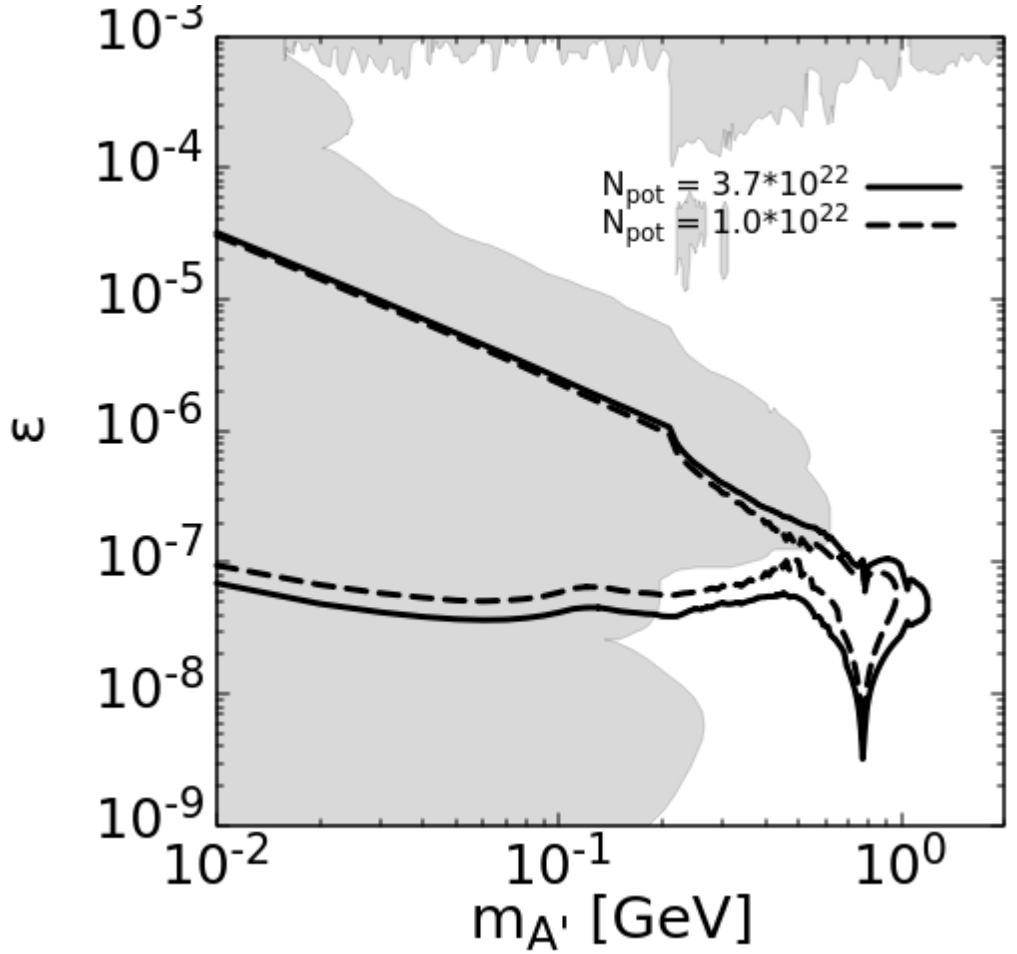
- T2K is an ongoing experiment.
- ND280 was ungraded in 2023; T2K plans to accumulate

  ➡ $N_{pot} = 1.0 \times 10^{22}$

  by 2027.
- After 2027, T2K with Hyper-K will start and accumulate

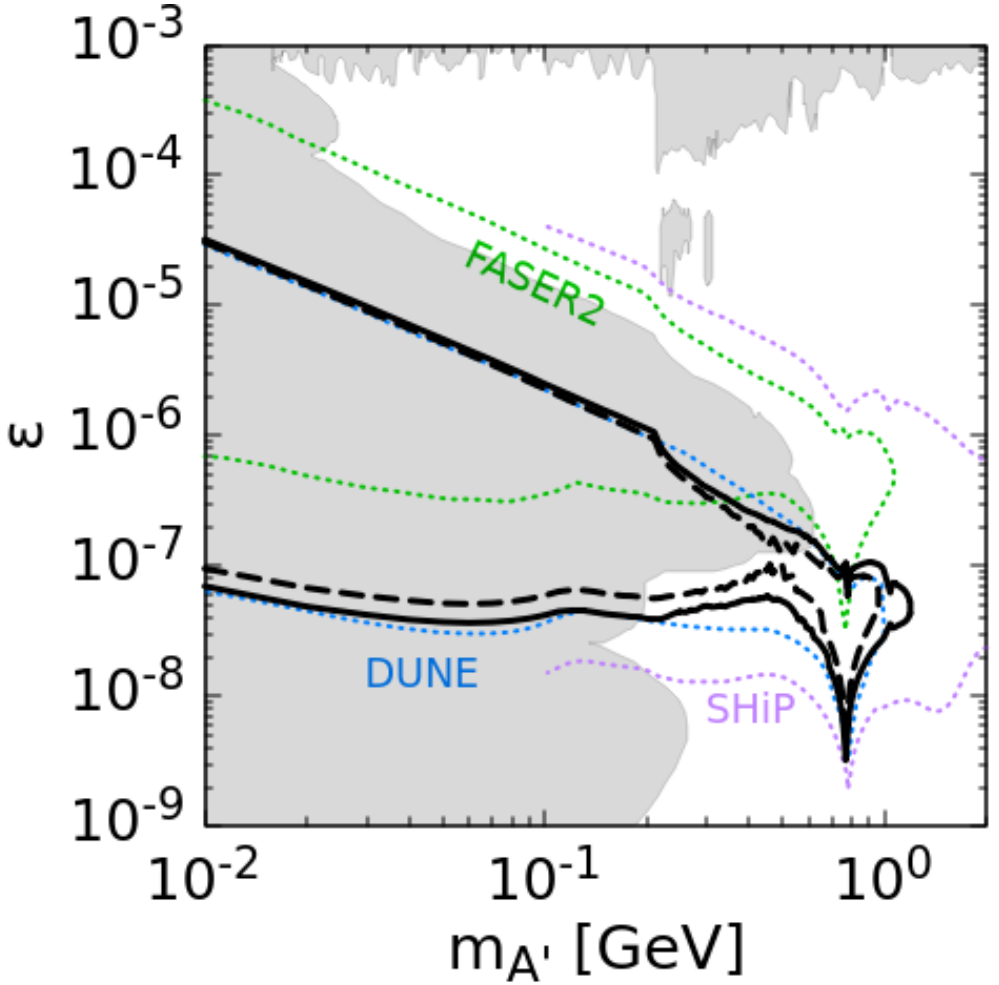
  ➡ $N_{pot} = 3.7 \times 10^{22}$

  in ten years.



Results: Future sensitivity

- T2K has a sensitivity to smaller mixing regions in comparison with other experiments.
- T2K compensates collider and beam-dump experiments, and it is expected to provide us with distinct constraints in near future.



Summary

- The location of the T2K near detector ND280 is idea for an LLP search.
- We have derived the 95% C.L. excluded regions; a small exclude region has been found.
- In the near future, T2K will accumulate more POT; the excluded regions will become broader.

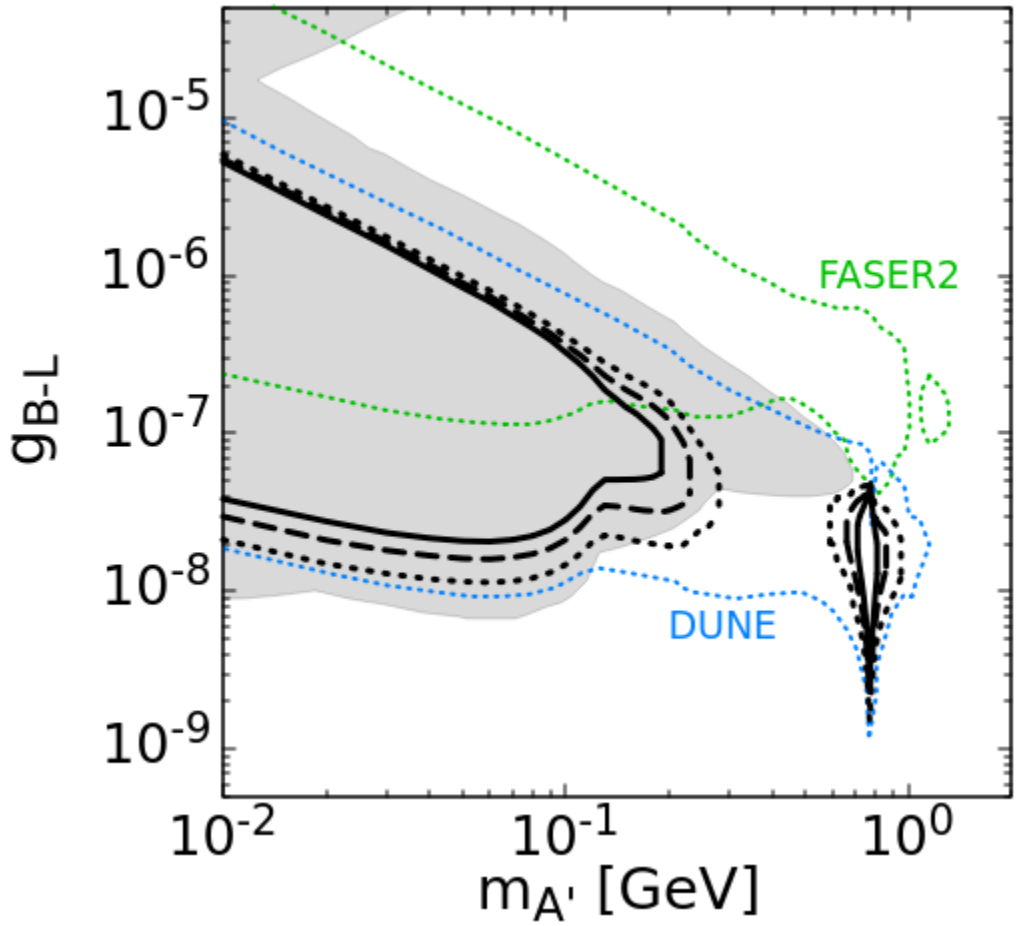
backup

Results: $U(1)_{B-L}$

- The 95% C.L. exclusion region (solid) and expected sensitivity regions (dashed, dotted) for the $U(1)_{B-L}$ model:

$$\mathcal{L}_{B-L} = -g_{B-L} \sum_f Q_f \; \bar{f}\gamma^\mu f \; A'_\mu + \frac{1}{2} m^2_{A'} A'_\mu A'^\mu$$

- The excluded regions disappear between 0.3GeV - 0.6GeV since no resonance with ρ mesons.



※ Mixing with the rho meson is proportional to $(q_u - q_d)^2$

Num. of events

$$N_{\rm sig} = \int \left(\, {\rm d}N^{\rm meson}_{\rm DP} + {\rm d}N^{\rm brems}_{\rm DP} \, \right) \times \mathcal{P}^{\rm det}(|\boldsymbol{p}_{A'}|, \theta_{A'}) \times {\rm BR}(A' \to f\bar{f})$$

$$\times 0.25 \times 0.82$$

$${\rm d}N^{\rm meson}_{\rm DP} = N_{\rm pot} \sum_{X,Y} {\rm d}|\boldsymbol{p}_X| \, {\rm d}\theta_X \, \frac{{\rm d}^2 N_X}{{\rm d}|\boldsymbol{p}_X| {\rm d}\theta_X} \, {\rm BR}(X \to A'Y)$$

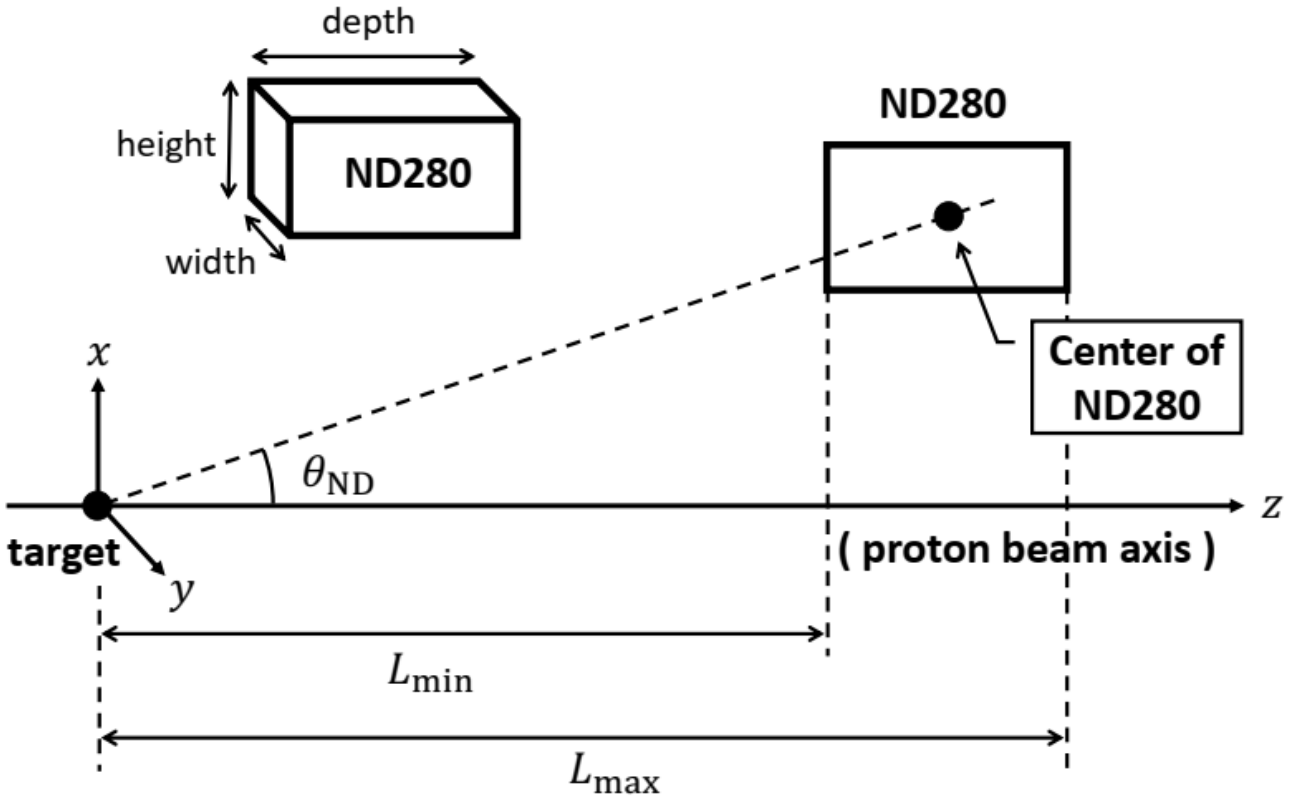
$${\rm d}N^{\rm brems}_{\rm DP} = N_{\rm pot} |F(m^2_{A'})|^2 \, {\rm d}z \, {\rm d}p^2_{A',t} \, \frac{\sigma_{pp}(s')}{\sigma_{pp}(s)} \, w(z, p^2_{A',t}) \, \Theta(\Lambda^2_{\rm QCD} - q^2_{\rm min})$$

$$\mathcal{P}^{\rm det}(|\boldsymbol{p}_{A'}|, \theta_{A'}) = \left(e^{-L_{\rm min}/d_z} - e^{-L_{\rm max}/d_z} \right) \times \frac{1}{\pi} \arcsin \left(\frac{1.2\,{\rm m}}{283\,{\rm m} \times \tan\theta_{A'}} \right)$$

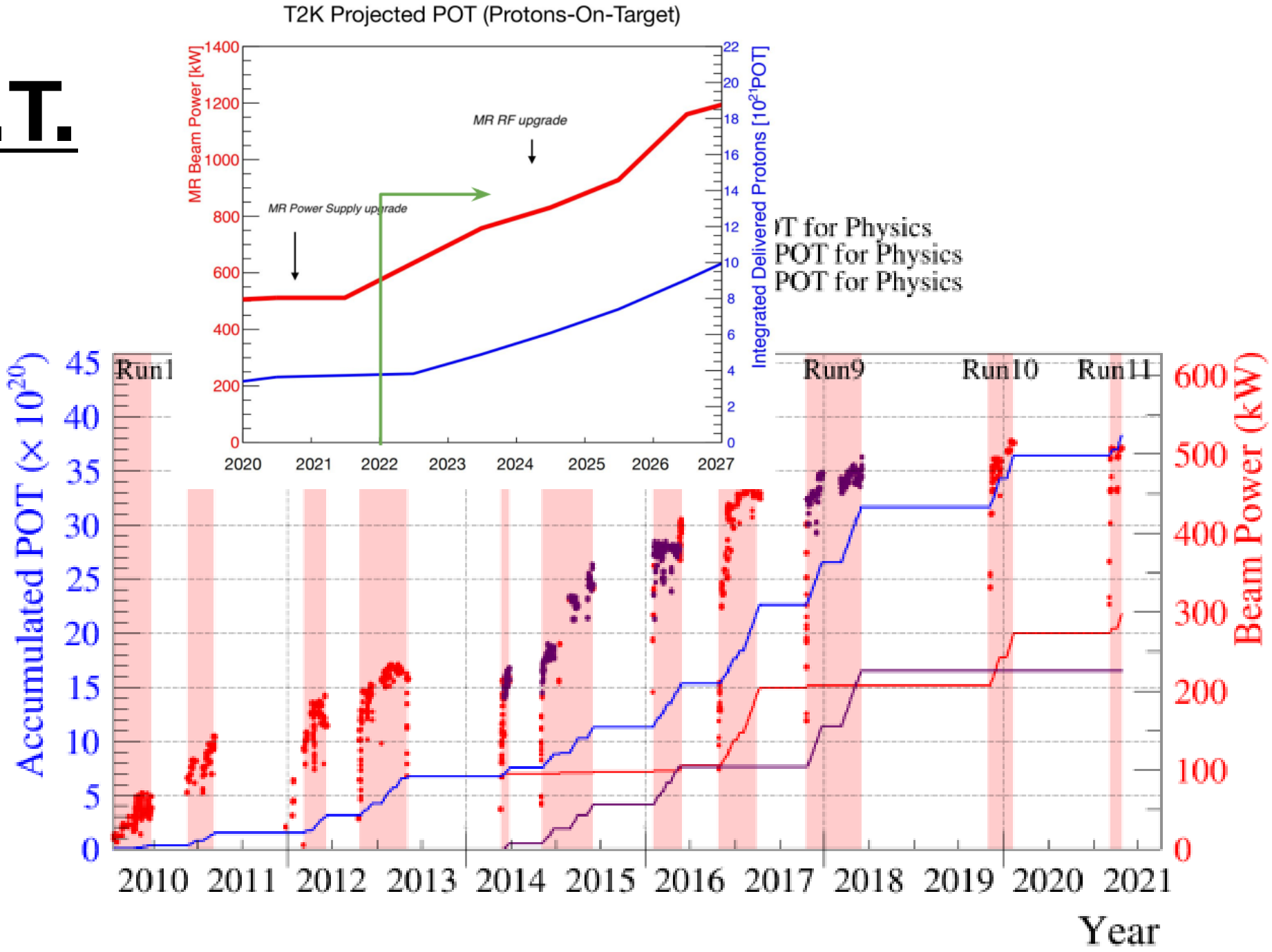
$$\times \Theta(\theta_{\rm upr} - \theta_{A'}) \times \Theta(\theta_{A'} - \theta_{\rm lwr}) \ ,$$

Dimensions

width (m)	height (m)	depth (m)	L_{min} (m)	L_{max} (m)	θ_{ND} (deg)
2.4	2.4	5.8	280.1	285.9	2.0



P.O.T.


T2K Projected POT (Protons-On-Target)
MR Beam Power [kW]
Integrated Delivered Protons [10^21POT]
MR RF upgrade
MR Power Supply upgrade
2020
2021
2022
2023
2024
2025
2026
2027
T for Physics
POT for Physics
POT for Physics
Run1
Run9
Run10
Run11
Accumulated POT (× 10^20)
Beam Power (kW)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
Year

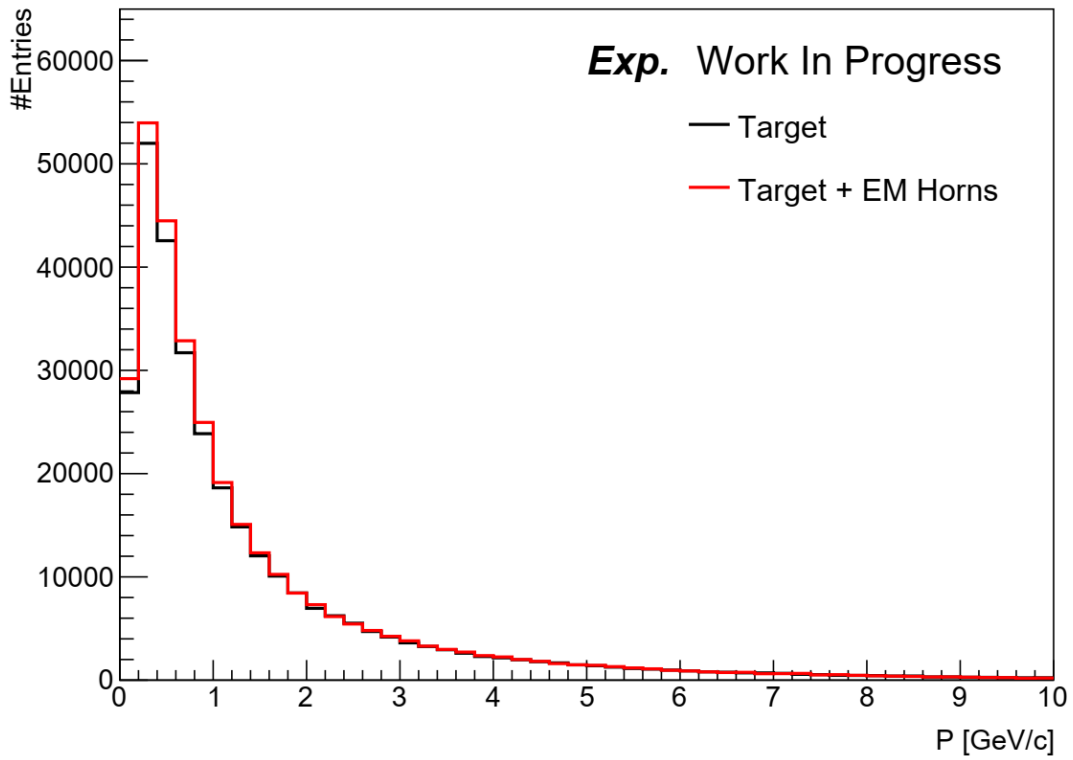
Backgrounds

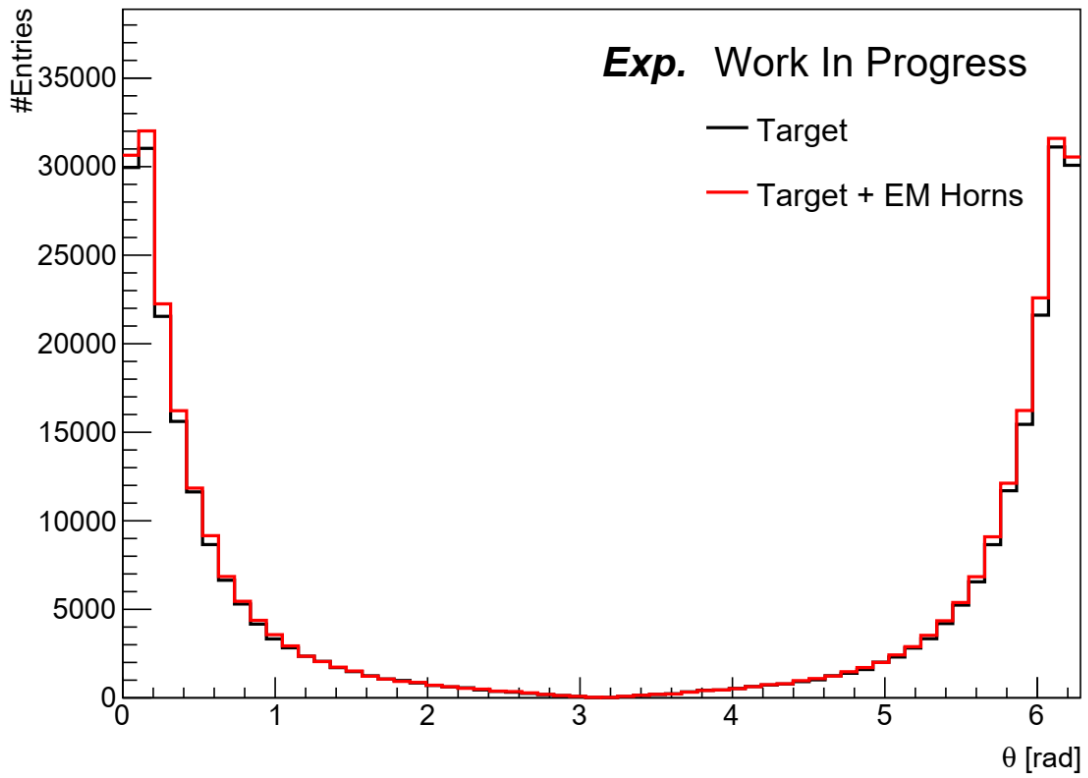
Mode	Ch.	Expected background	Uncertainties				
			stat.	flux	det.	model	total
neutrino	$\mu^{\pm}\pi^{\mp}$	1.543	0.366	0.154	0.165	0.285	0.516
	$e^{-}\pi^{+}$	0.376	0.213	0.038	0.104	0.097	0.259
	$e^{+}\pi^{-}$	0.328	0.186	0.033	0.117	0.115	0.250
	$\mu^{+}\mu^{-}$	0.216	0.107	0.022	0.045	0.062	0.133
	$e^{+}e^{-}$	0.563	0.192	0.056	0.092	0.074	0.233
anti-neutrino	$\mu^{\pm}\pi^{\mp}$	0.384	0.161	0.038	0.058	0.100	0.202
	$e^{-}\pi^{+}$	0.018	0.018	0.002	0.005	0.005	0.020
	$e^{+}\pi^{-}$	0.219	0.155	0.022	0.140	0.122	0.243
	$\mu^{+}\mu^{-}$	0.038	0.038	0.004	0.007	0.011	0.040
	$e^{+}e^{-}$	0.015	0.015	0.002	0.001	0.004	0.016

[T2K, PRD100(2019), 052006]

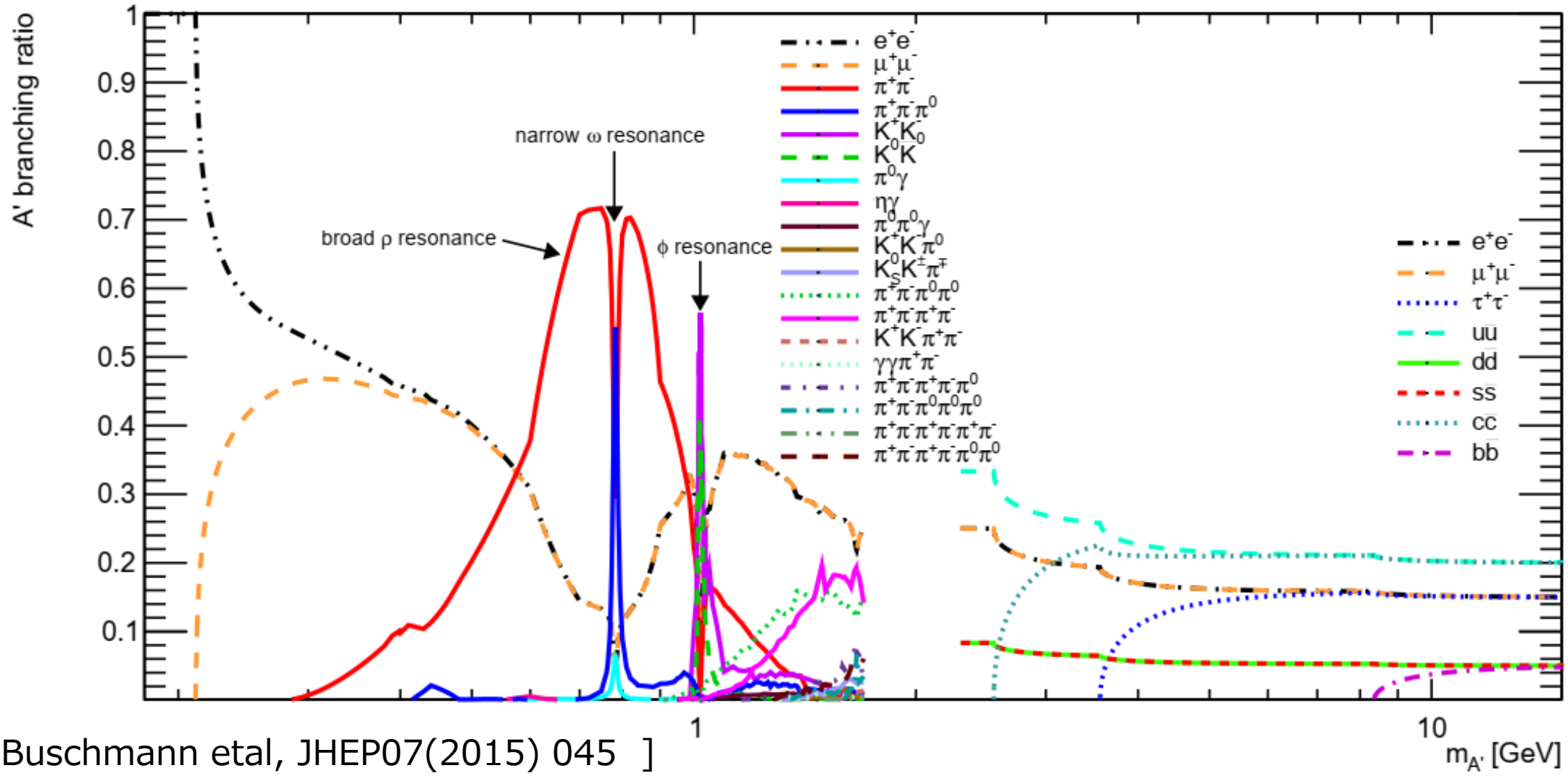
Meson distributions

- GEANT4 package and QGSP BERT package are used.
- Secondary productions at EM-Horns contribute a few %.





Branching ratios of DP



[M. Buschmann etal, JHEP07(2015) 045]