Study of the $\bar{K}NN$ state in photoproduction with LEPS2 Detectors

Ryo Kobayakawa for the LEPS2 Collaboration
RCNP, Osaka University

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Outline

- **Physics motivation**
  - Physics interest with $\bar{K}NN$ state
  - Experimental Review on $\bar{K}NN$ search
  - A New Experiment with LEPS2 Solenoid Detectors
- **LEPS2 Experiment**
  - SPring-8 and LEPS2 Beam line
  - LEPS2 Solenoid detectors
  - Analysis Reports

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The simplest kaonic nucleus $\bar{K}NN(I = 1/2)$

$\bar{K}N$ interaction

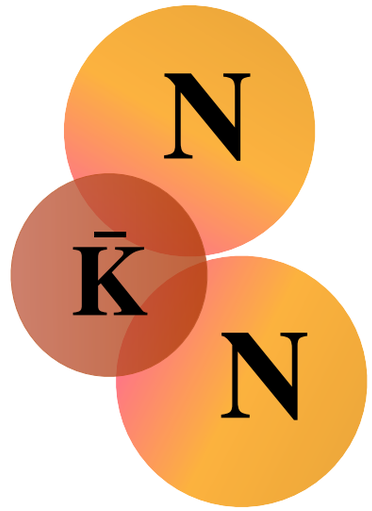
Known to be strongly attractive ($\bar{K}N(I = 0)$ channel)
from K-p atomic X-ray shift and low energy K- p scattering data

The simplest kaonic nucleus $\bar{K}NN(I = 1/2)$

$$|\bar{K}[NN]_{I=0}\rangle_{I=1/2} = -\frac{1}{2}|[\bar{K}N]_{I=0}N\rangle_{I=1/2} + \frac{\sqrt{3}}{2}|[\bar{K}N]_{I=1}N\rangle_{I=1/2}$$

$$|\bar{K}[NN]_{I=1}\rangle_{I=1/2} = \frac{\sqrt{3}}{2}|[\bar{K}N]_{I=0}N\rangle_{I=1/2} + \frac{1}{2}|[\bar{K}N]_{I=1}N\rangle_{I=1/2}$$

$$|\bar{K}[NN]_{I=1}\rangle_{I=3/2} = -|[\bar{K}N]_{I=1}N\rangle_{I=3/2}$$



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Experimental results of $\bar{K}NN$ search

Signal Present

FINUDA@DAΦNE
PRL 94 (2005) 212303

DISTO@SATURNE
PRL104(2010) 132502

E27@J-PARC
PTEP(2015) 021D01

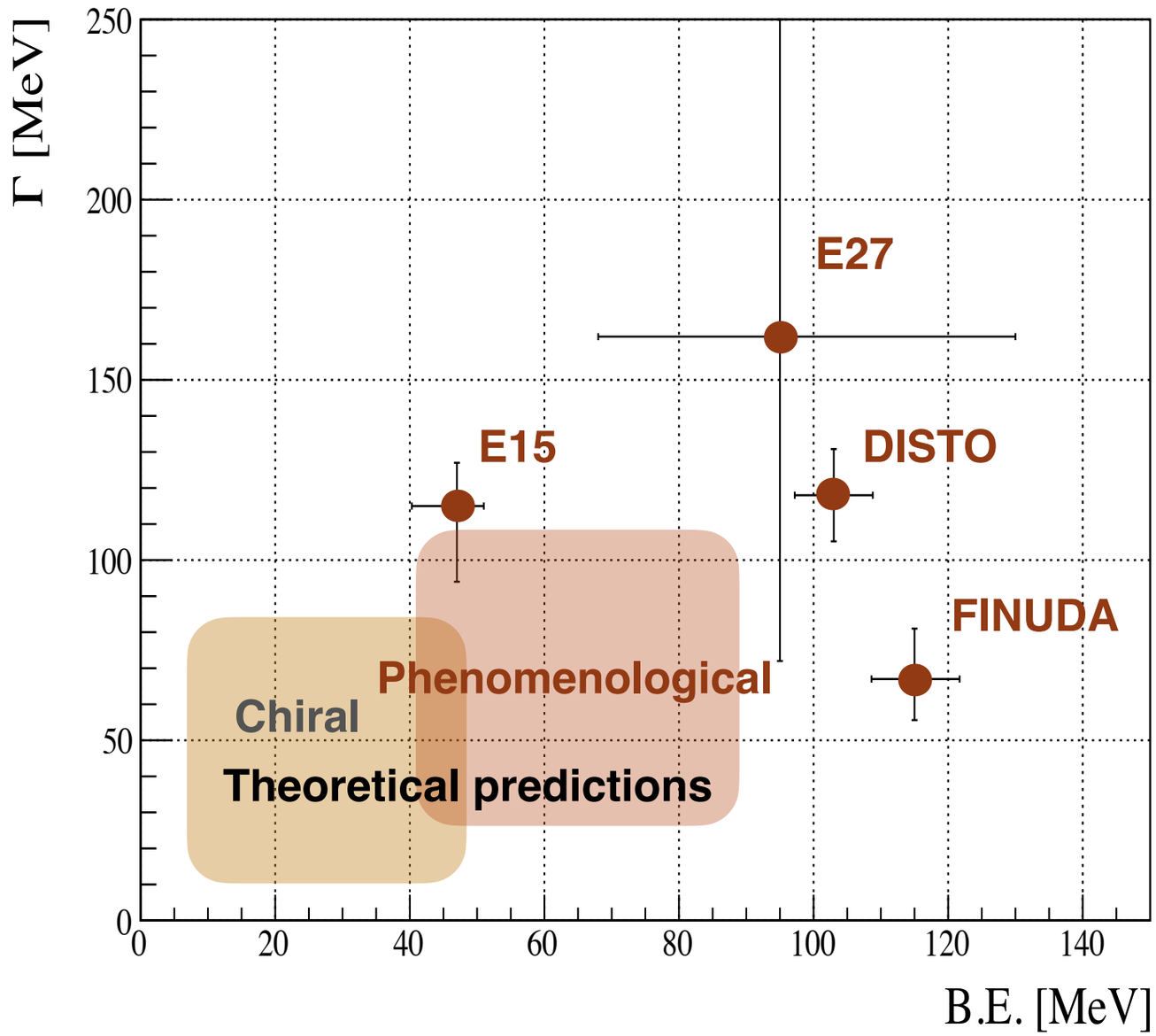
E15@J-PARC
PLB789 (2019) 620

Signal Absent

AMADEUS@DAΦNE
arXiv:1809.07212

LEPS@SPring-8
PLB 728 (2014) 616

HADES@GSI
PLB742(2015) 242



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Study for $\bar{K}NN$ with various beams

J-PARC E15	J-PARC E27	LEPS
$^3\mathrm{He}(K^-, \Lambda p)n$	$d(\pi^+, K^+)Yp$	$d(\gamma, K^+\pi^-)X$
$P_K = 1.0$ **GeV**/c	$P_\pi = 1.69$ **GeV**/c	$P_\gamma = 1.5 - 2.4$ **GeV**/c

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Study for $\bar{K}NN$ with various beams

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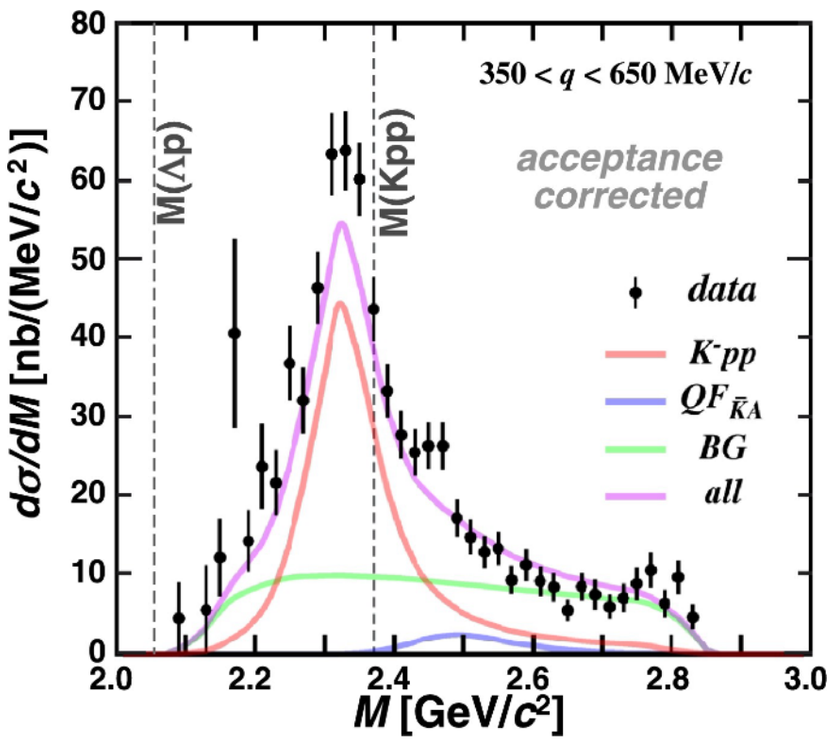
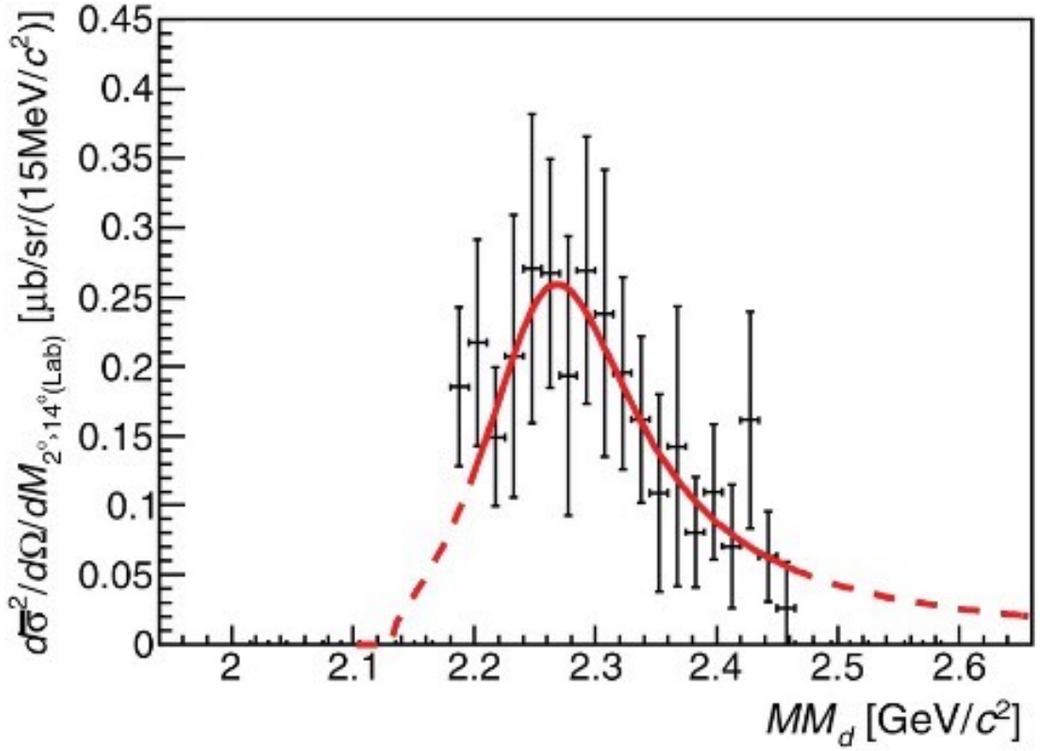
PLB789 (2019) 620	PTEP(2015) 021D01

key point

detected or tagged Y, p

in the side region





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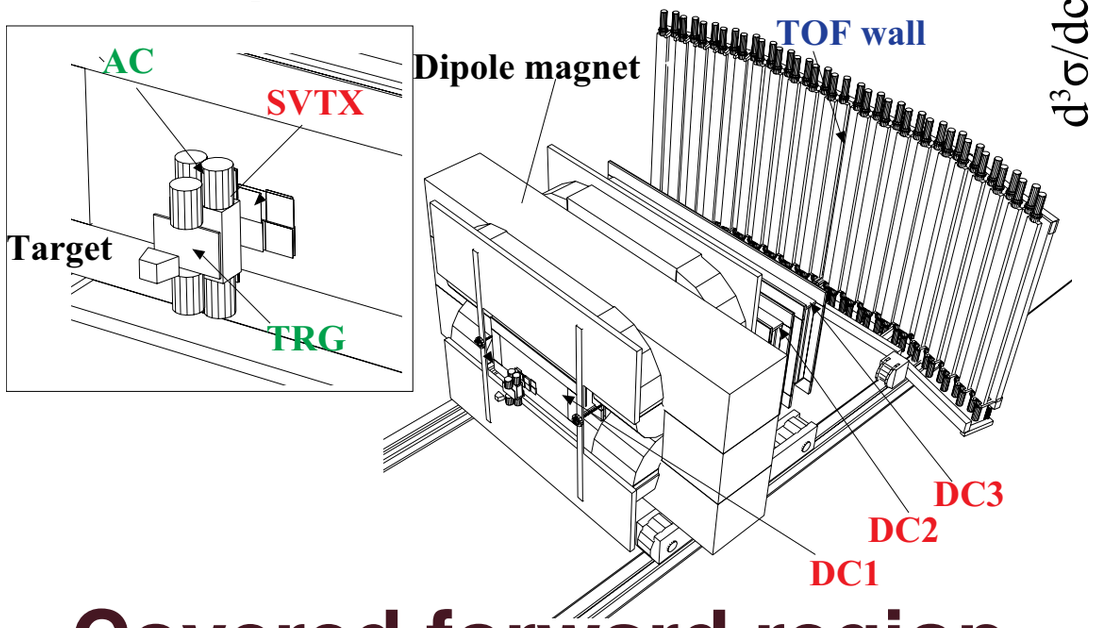
Study for $\bar{K}NN$ with photon beam

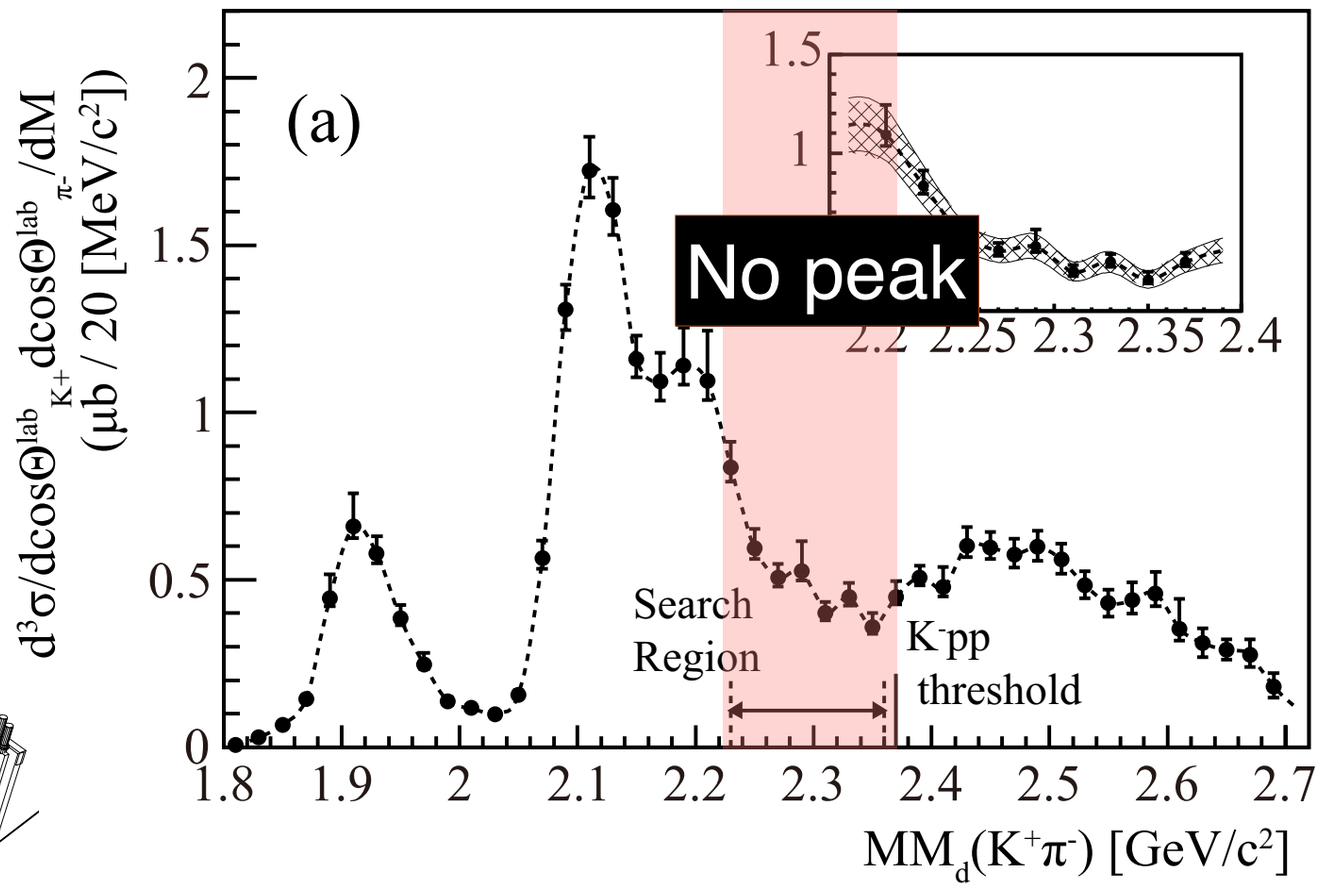
LEPS

$\mathbf{d}(\gamma, \mathbf{K}^+\pi^-)\mathbf{X}$
$P_\gamma = 1.5 - 2.4$ **GeV**/c

LEPS dipole detectors



Covered forward region



PLB 728 (2014) 616

An upper limit is ~ 1 μb

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Study for $\bar{K}NN$ with photon beam

LEPS

$\mathbf{d}(\gamma, \mathbf{K}^+\pi^-)\mathbf{X}$

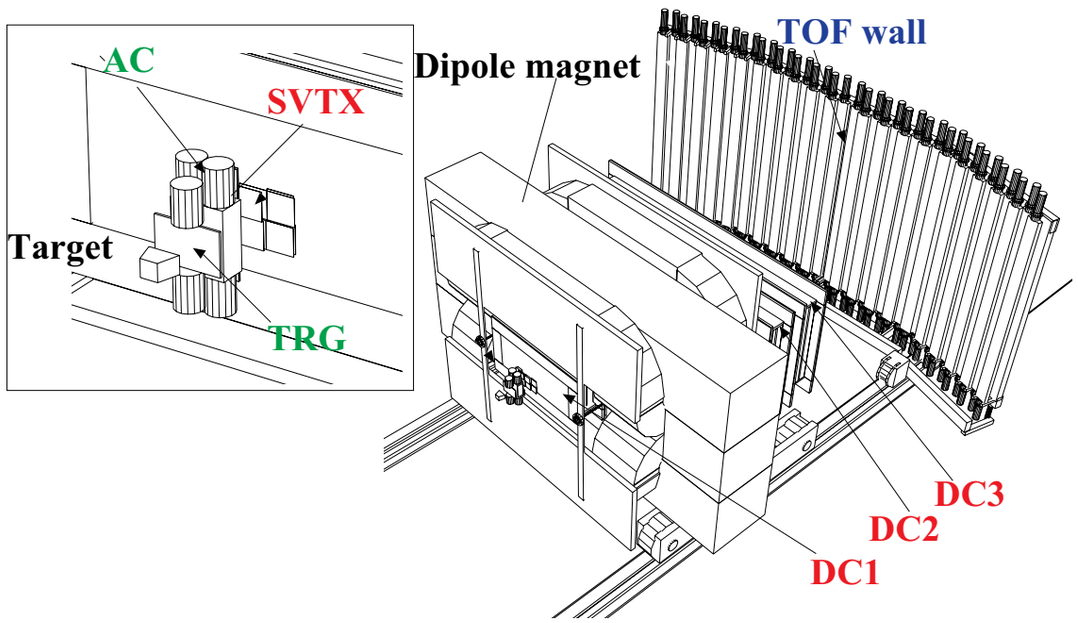
$P_\gamma = 1.5 - 2.4$ **GeV**/c

LEPS2

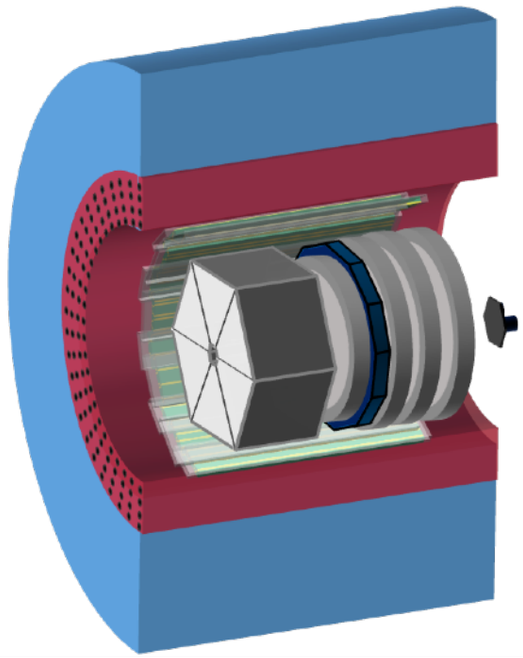
$\mathbf{d}(\gamma, \mathbf{\Lambda p})\mathbf{K^0}$

$P_\gamma = 1.3 - 2.4$ **GeV**/c

Inclusive measurement



Exclusive measurement



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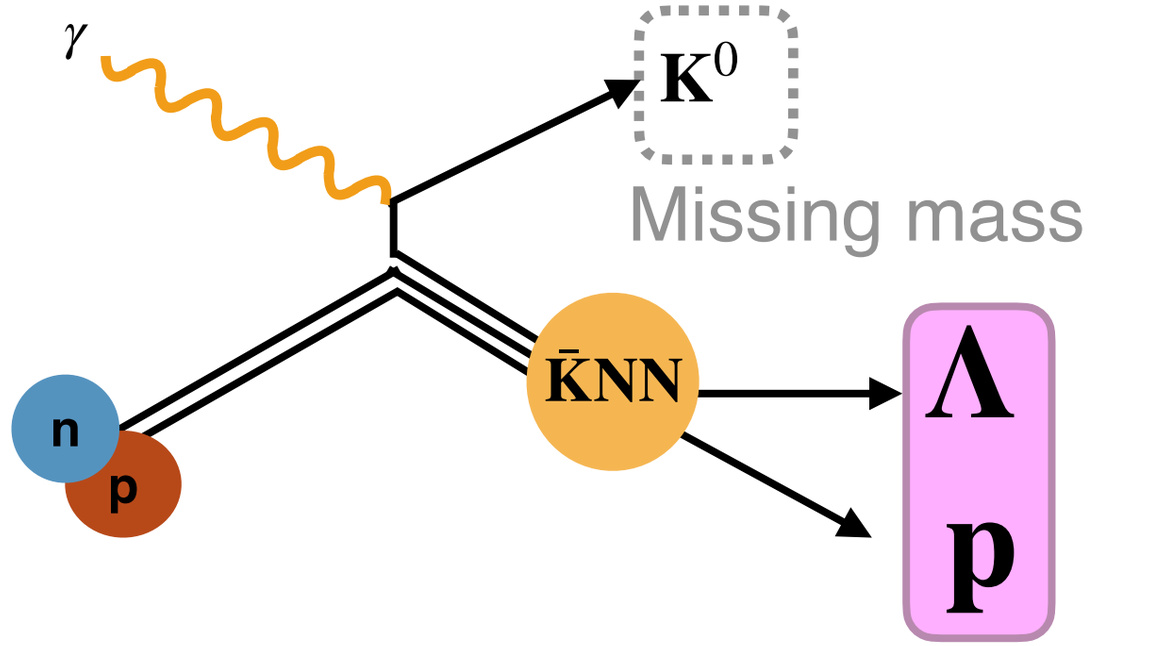
Decay modes of $\bar{K}NN$ state

◆ **non-mesonic decay mode**

$\gamma d \rightarrow K^0(\bar{K}NN)_{B.S.} \rightarrow K^0\Lambda p$

Λp, $\Sigma^0 p$, $\Sigma^+ n$

First step of LEPS2



Detected by TPC

◆ **mesonic decay mode**

$\Lambda\pi N$, $\Sigma\pi N$

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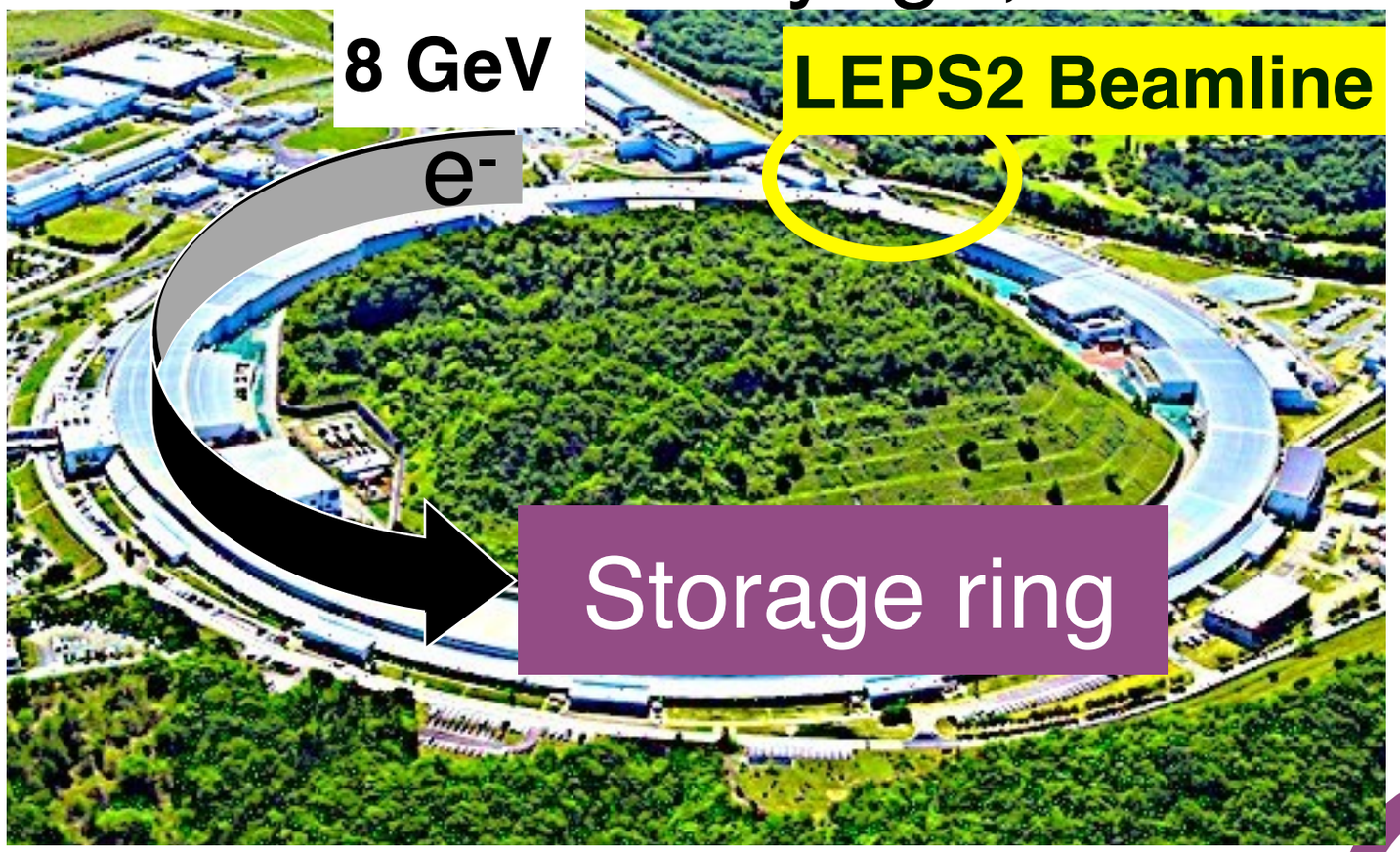
What's LEPS2 Experiment ?

SPring-8

@Hyogo, JAPAN



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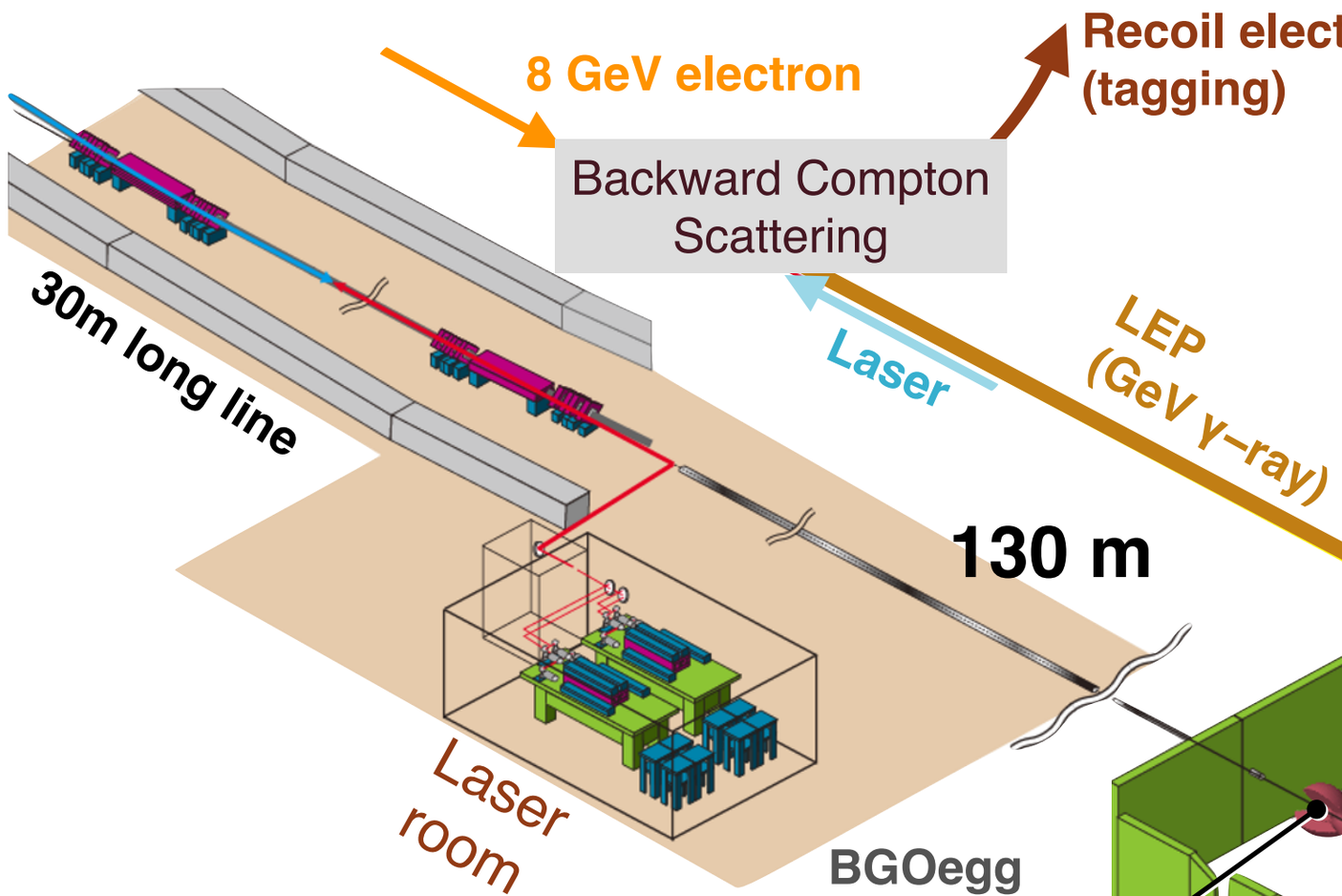
LEPS2 Beam Line

2nd Laser Electron Photon beam line at SPring-8

Photon beam produced via the laser-induced Compton scattering



- **Energy** $1.3 - 2.4$ **GeV**
- **ΔE** 12 **MeV**
- **Intensity** 2.3×10^6 **cps**

NIMA 1033(2022) 166677

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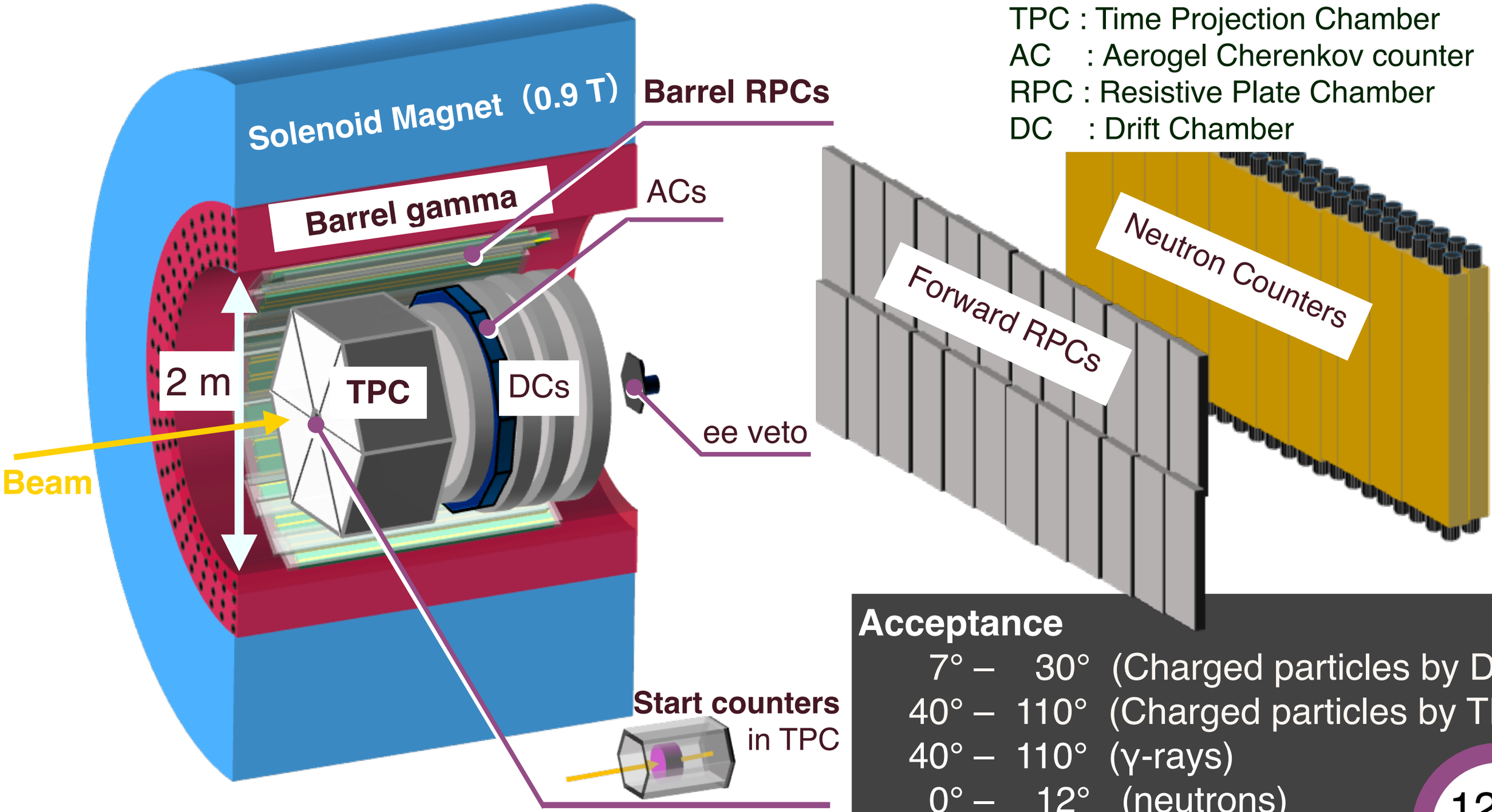
LEPS2 Solenoid Detectors

TPC : Time Projection Chamber
AC : Aerogel Cherenkov counter
RPC : Resistive Plate Chamber
DC : Drift Chamber



Acceptance

7° –	30°	(Charged particles by DC)
40° –	110°	(Charged particles by TPC)
40° –	110°	(γ-rays)
0° –	12°	(neutrons)

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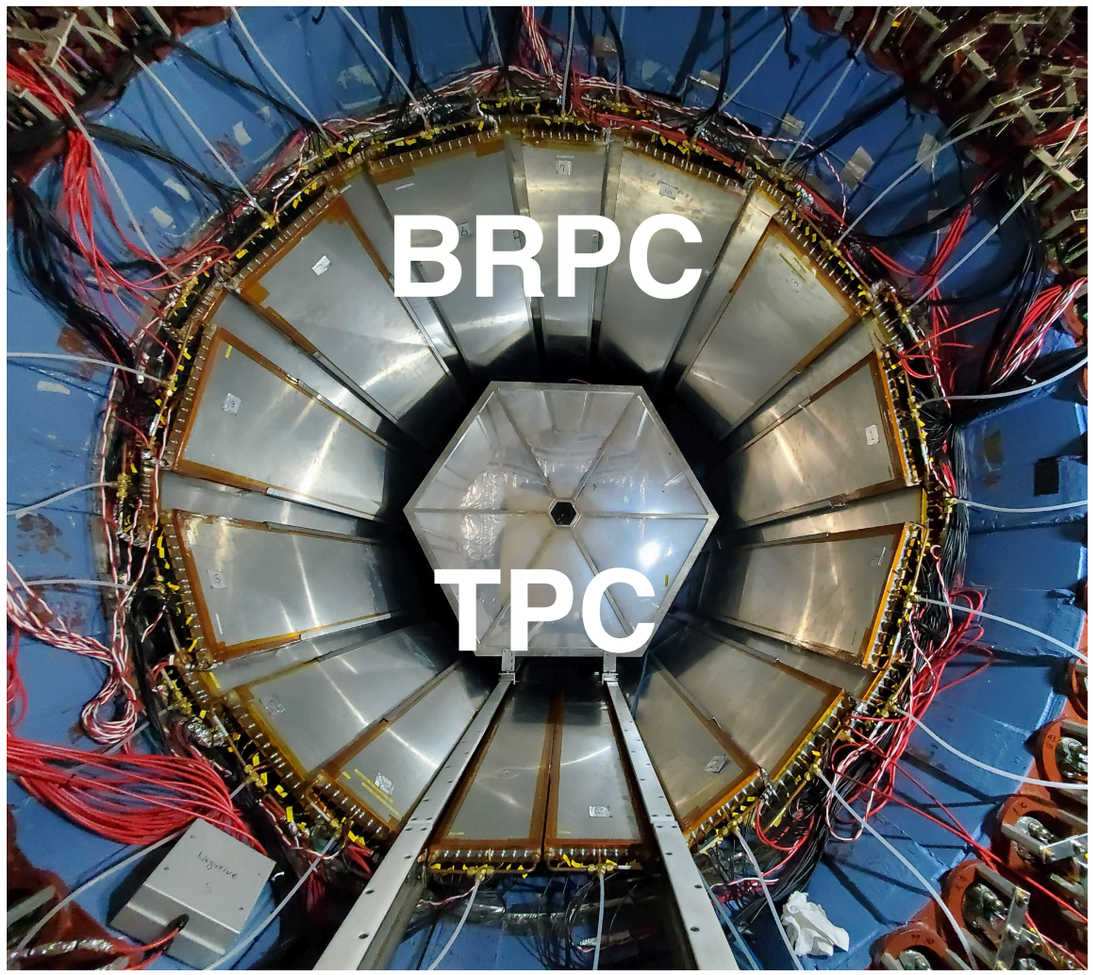
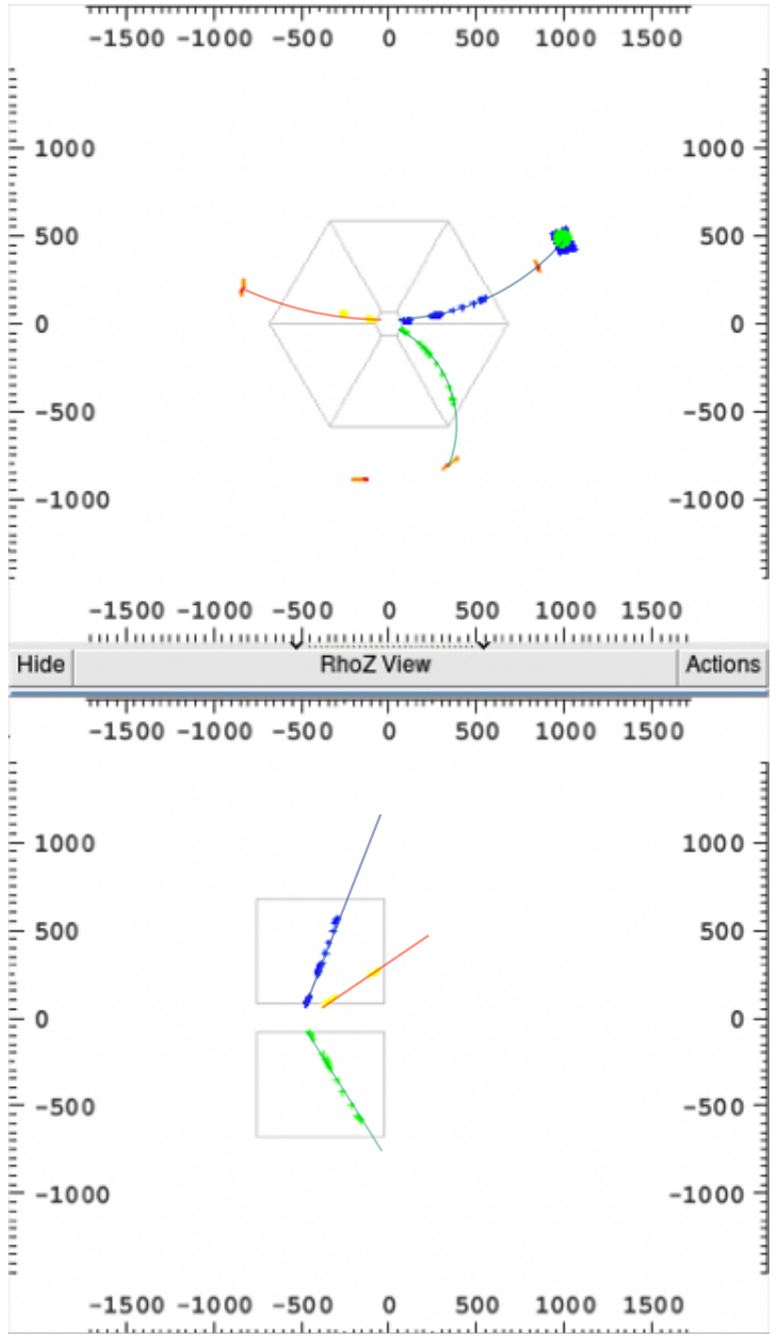
LEPS2 Detectors in the side region

Data taking in 2022 - 2023

LH_2 Data ~ 1.9 x 10^{12} photons

LD_2 Data ~ 5.7 x 10^{12} photons





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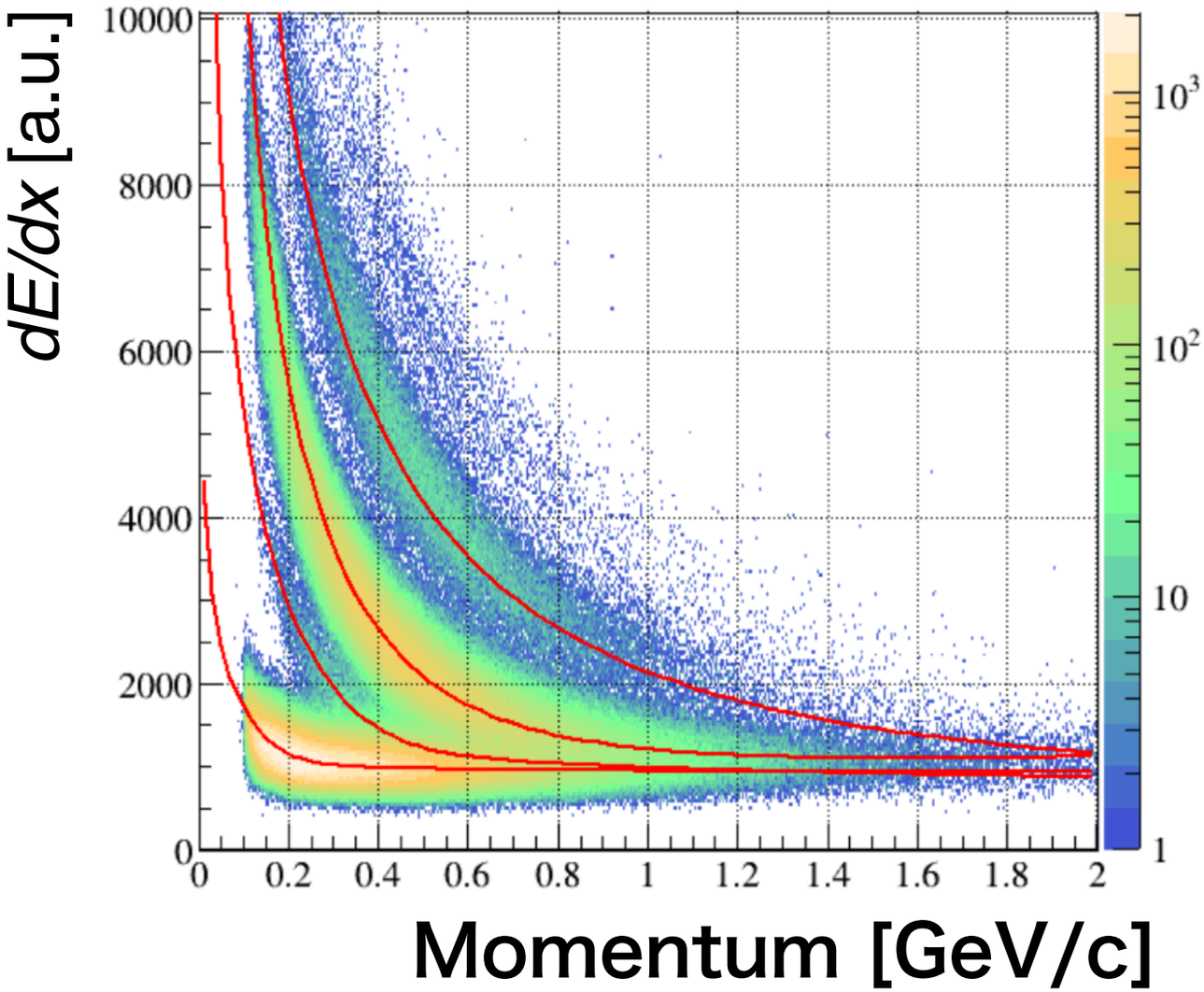
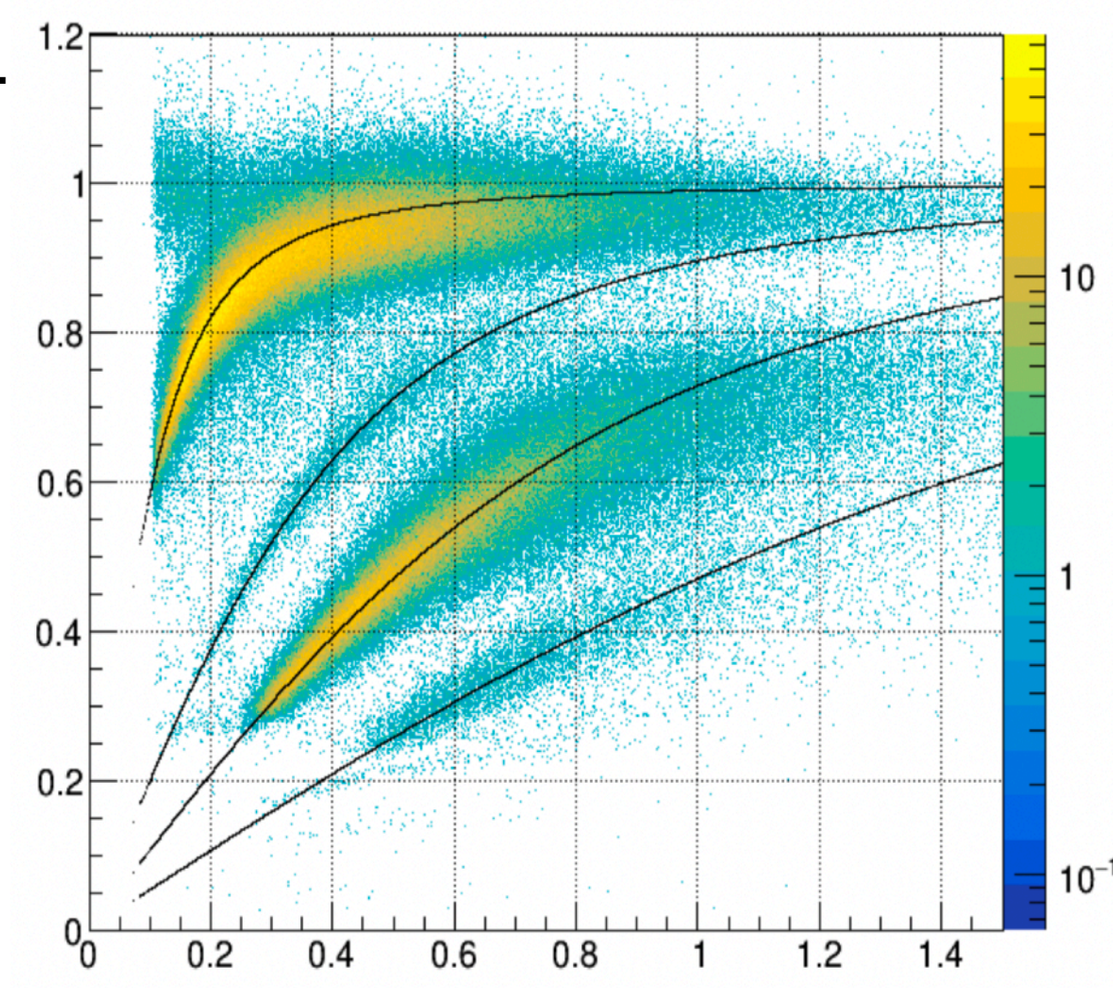
Particle Identification using TPC&BRPC

TPC dE/dx



Time Of Flight



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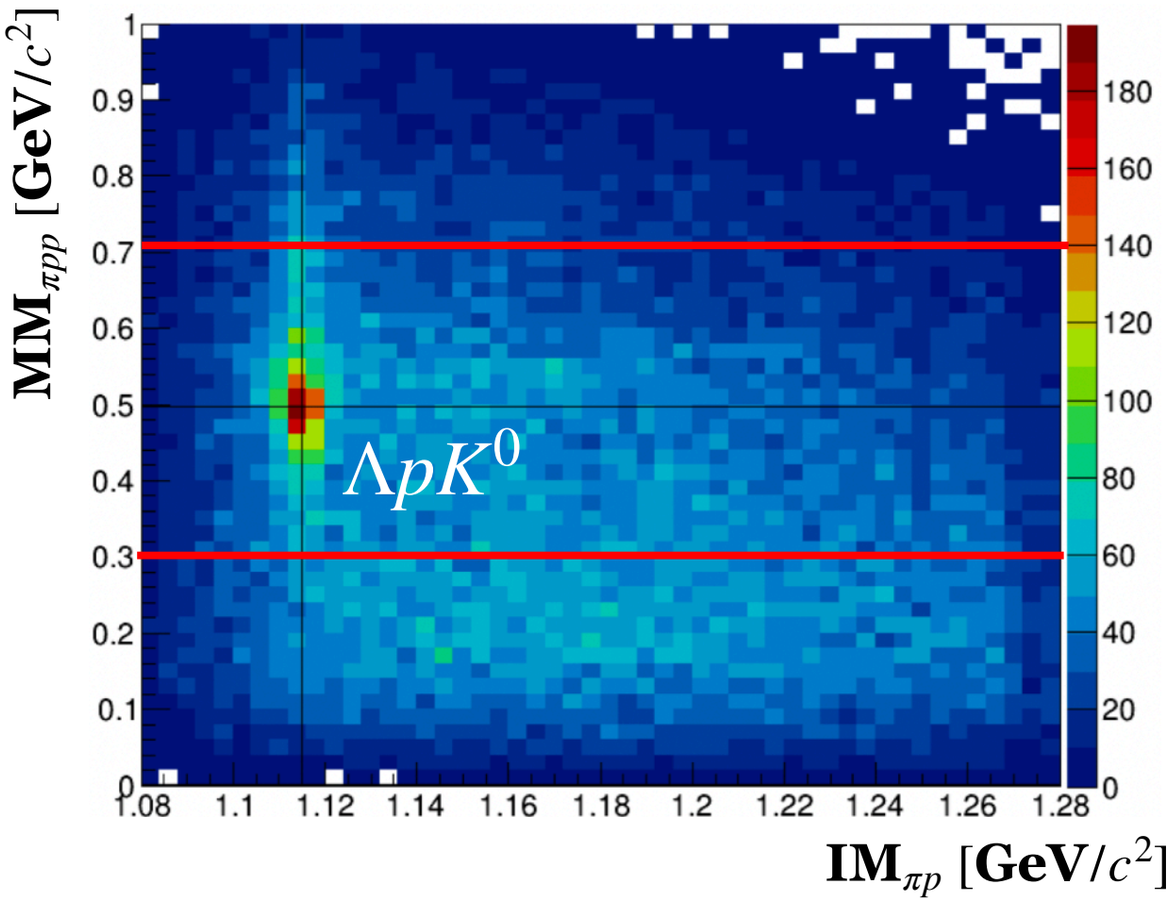
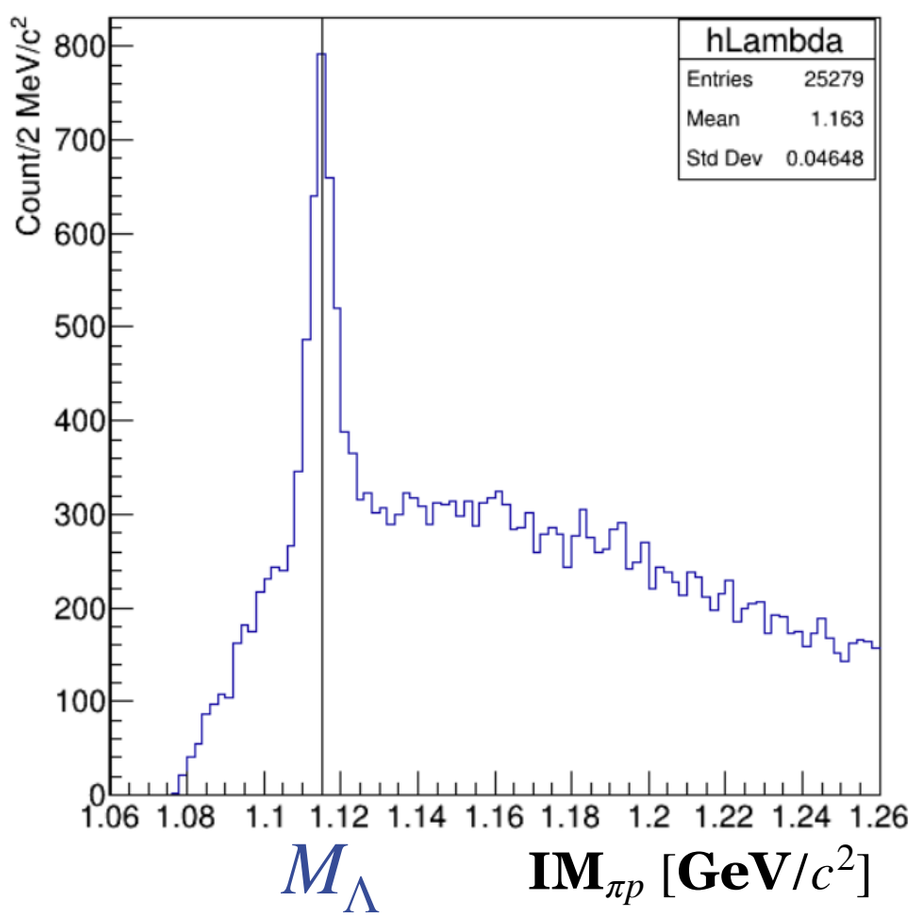
LD_2 Data Analysis

$$\gamma \mathbf{d} \rightarrow \underbrace{\pi^- \mathbf{p}}_{\Lambda} \mathbf{p} \underbrace{\mathbf{X}}_{K^0}$$

Select the events that has three tracks

$(2\mathbf{p}, \pi^-)$ in sideway region($\theta_{Lab} > 40^\circ$)





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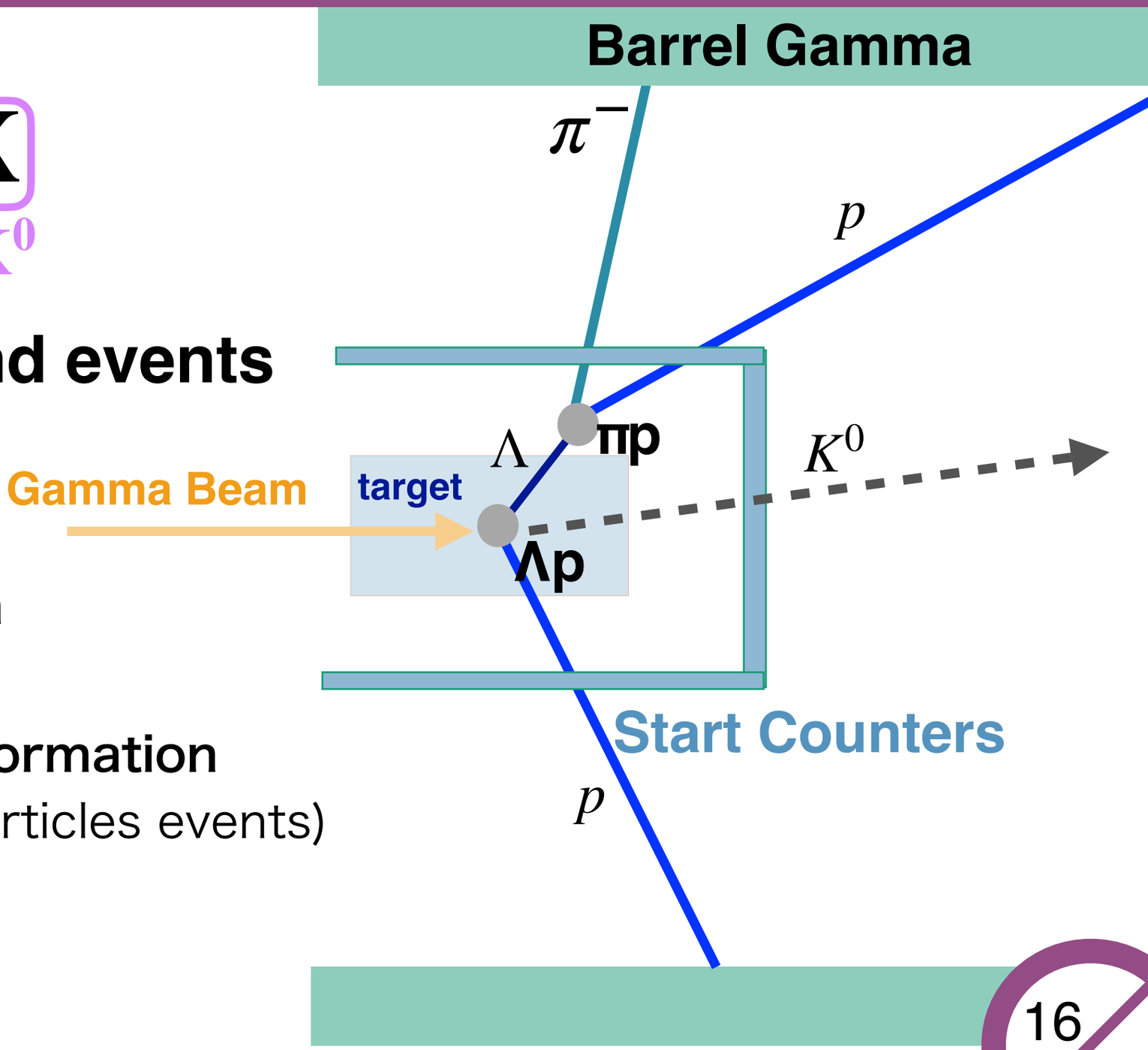
Selection of the $\Lambda p K^0$ Events

$$\gamma \mathrm{d} \rightarrow \underbrace{\pi^- \mathrm{p}}_{\Lambda} \mathrm{p} \underbrace{\mathrm{X}}_{\mathrm{K}^0}$$

To eliminate background events

- Vertex information($\pi^- p$, Λp)
  (Λ flight length > 18 [mm])
- **Barrel Gamma information**
  (remove γ tracks events)
- **Forward Start Counter information**
  (remove forward charged particles events)



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Selection of the $\Lambda p K^0$ Events

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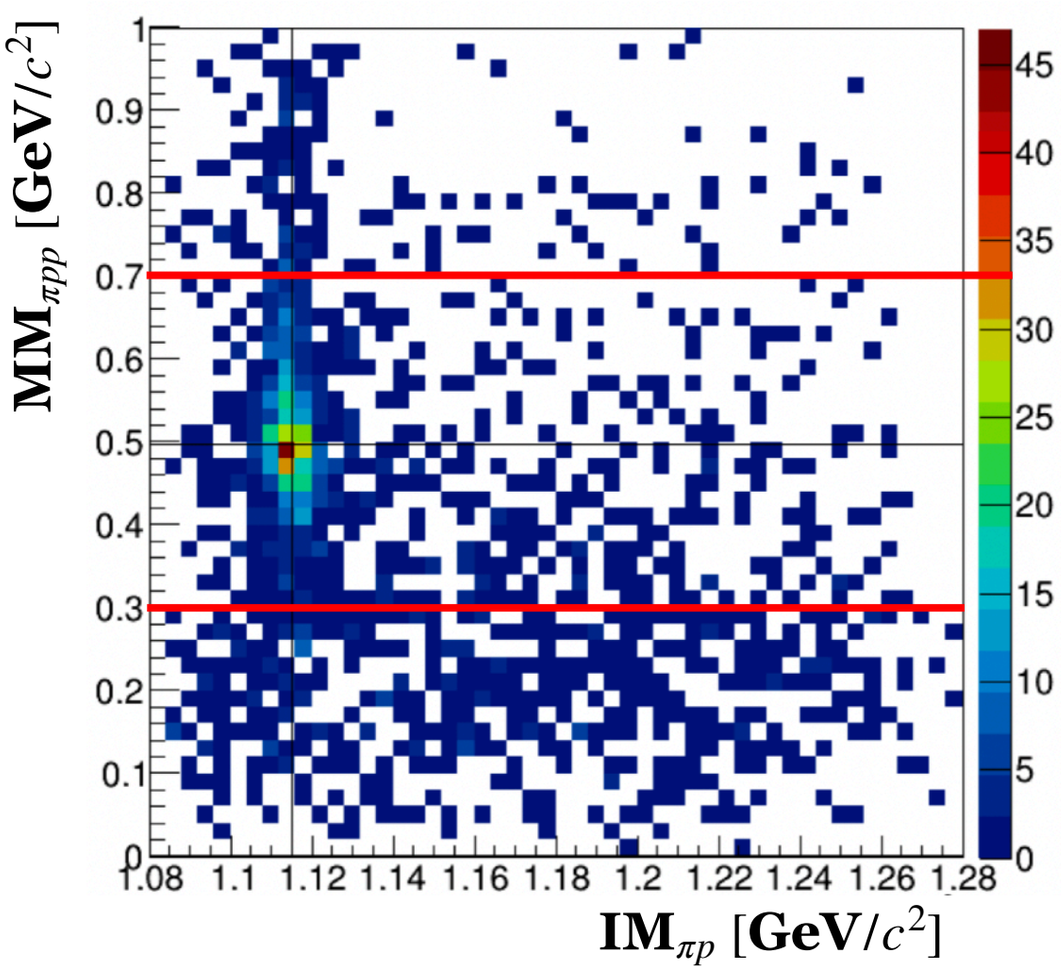

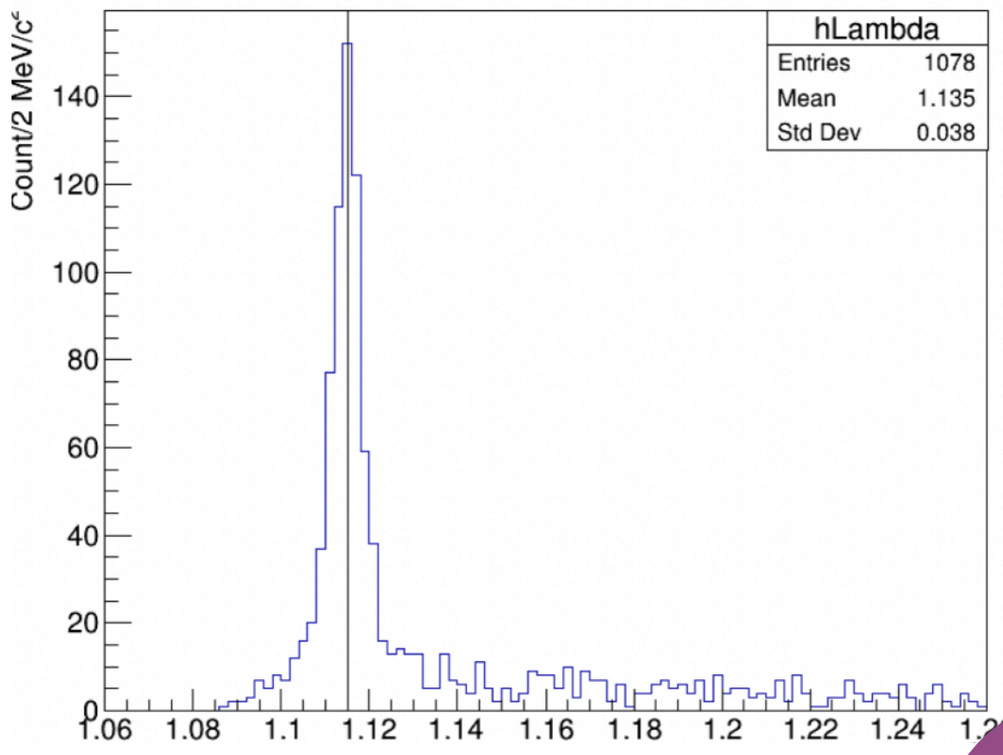

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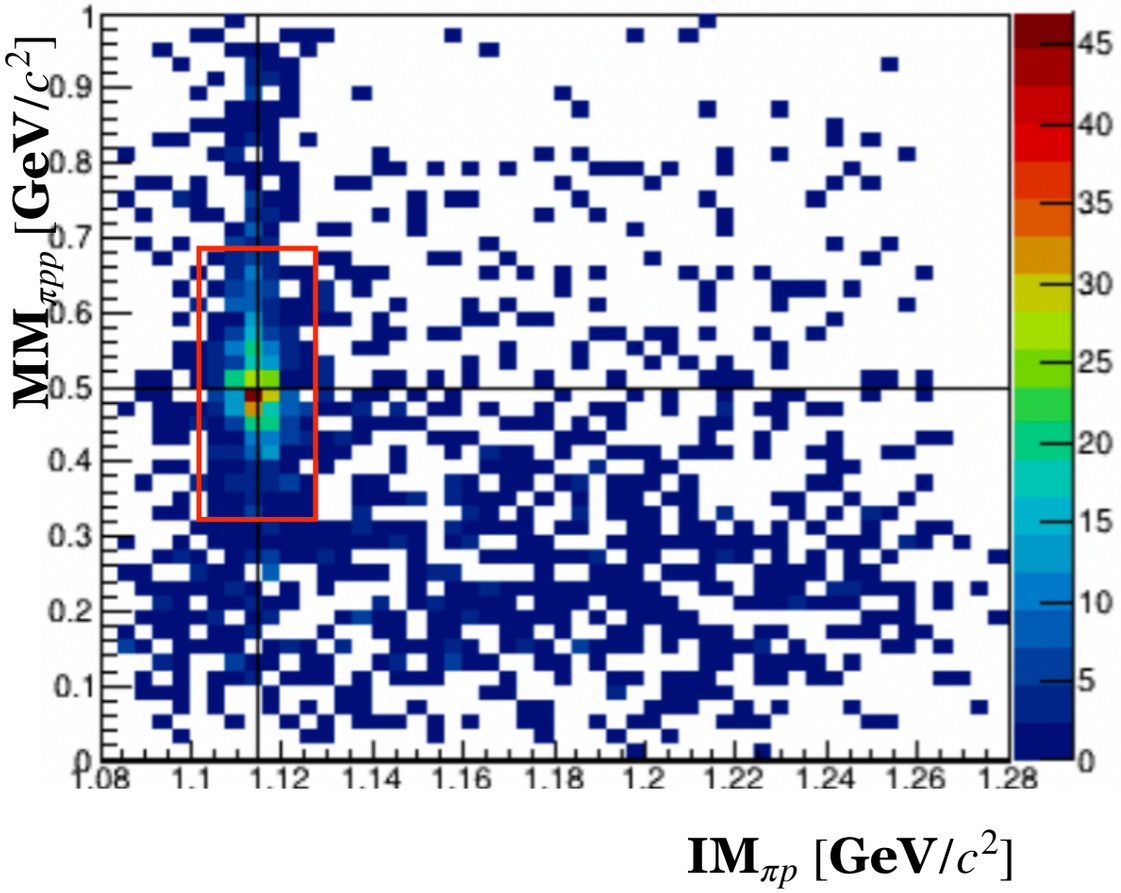
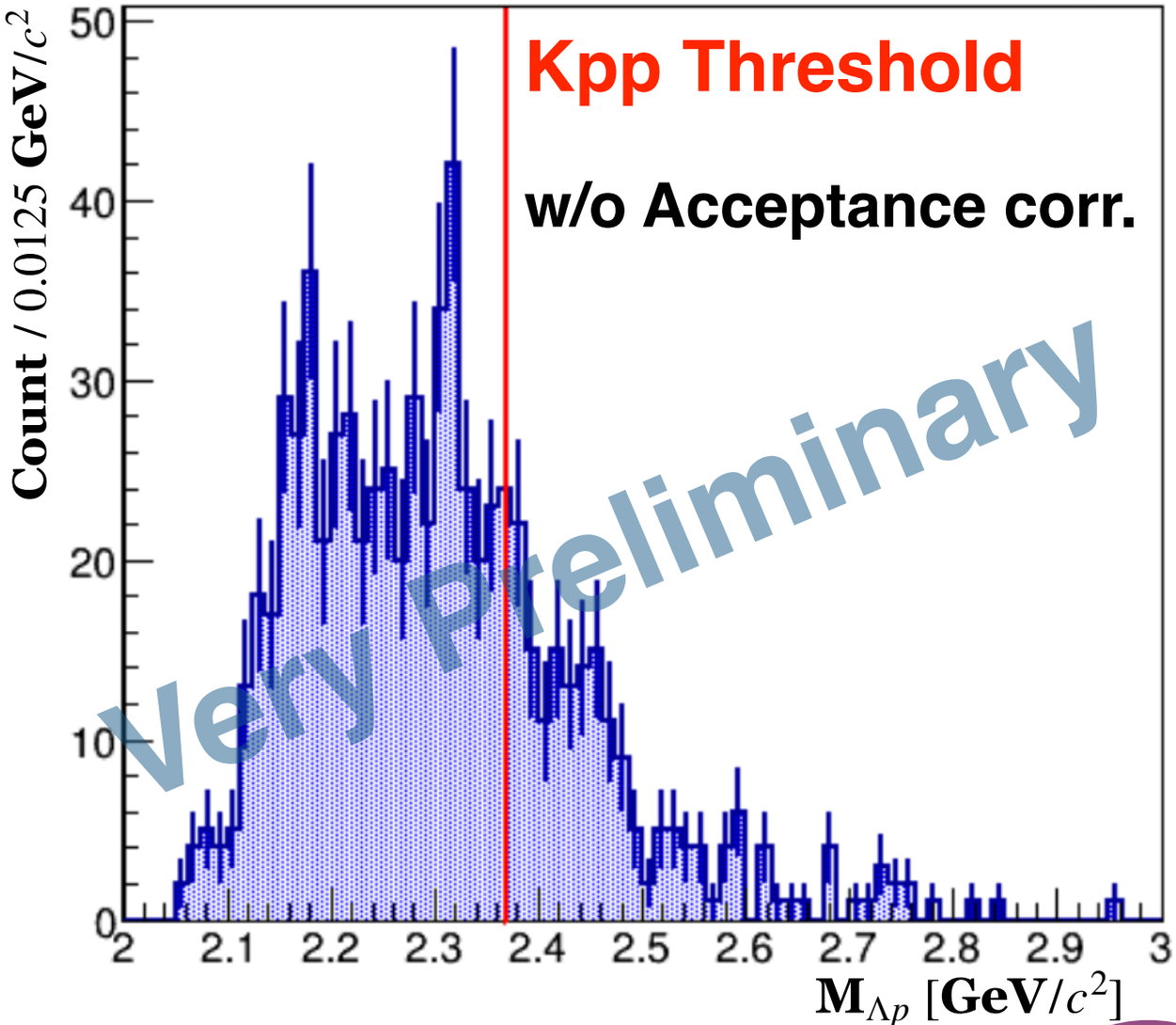
The Invariant Mass of Λp in $\gamma d \to \Lambda p K^0$

$$\gamma \mathrm{d} \to \overbrace{\pi^- \mathrm{p}}^{\Lambda} \mathrm{p} \overbrace{\mathrm{X}}^{\mathrm{K}^0}$$



The Invariant Mass of Λp



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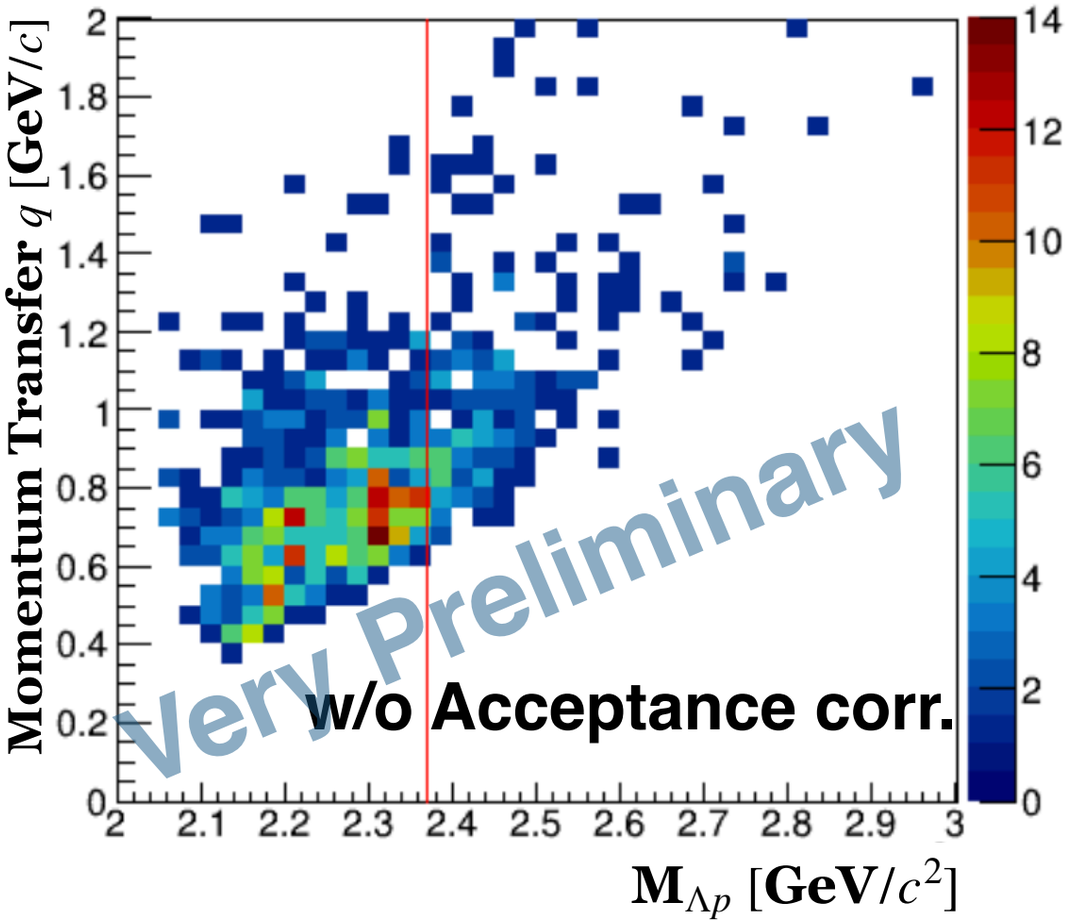
Momentum Transfer Distribution

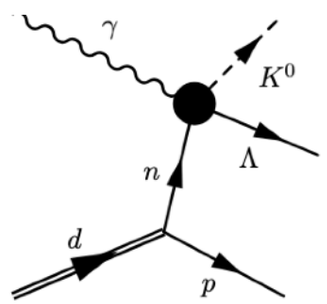
$\mathbf{d}(\gamma, \mathbf{\Lambda p})\mathbf{K^0}$
$P_\gamma = 1.3 - 2.4\ \mathbf{GeV}/c$

Detected Λ and proton

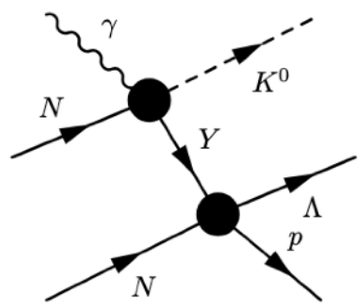
in sideway region.



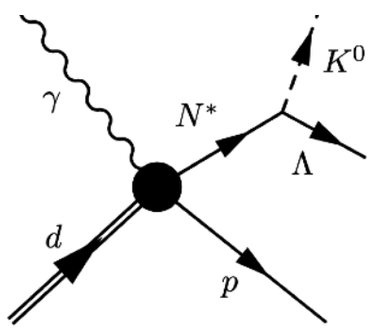
spectator proton



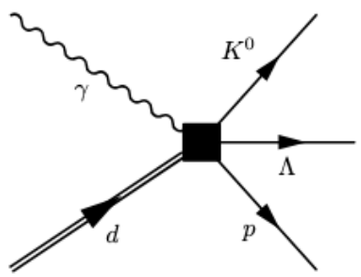
Two step



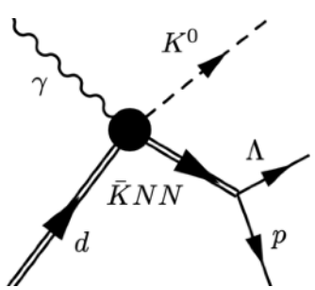
N*



Non Resonance



Signal



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Summary

- We search for the $\bar{K}NN$ state in photoproduction.
- Large-acceptance LEPS2 solenoid spectrometer is best suited for the $\bar{K}NN$ search with the detection of all decay particles, such as Λp.
- We collected the physics data with LH_2 and LD_2 target.
- We can select the $\gamma d \to \Lambda p K^0$ events
- **A concentration of events is observed below the mass threshold of K^-pp**
- **We plan to open the final results after verifying the photon beam and momentum measurement, studying background reactions, and optimizing the background reduction criteria.**

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Back Up

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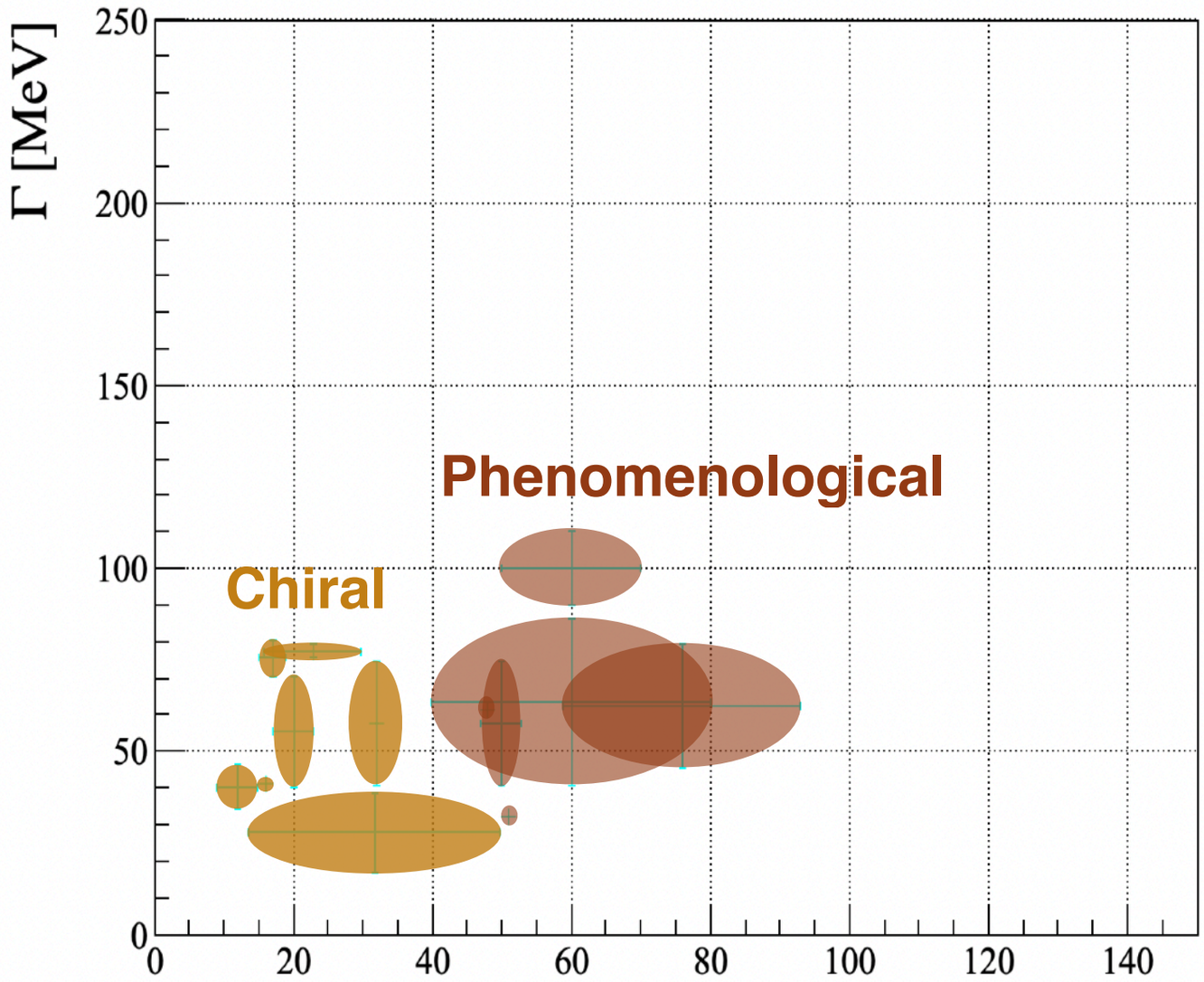
Theoretical prediction of $\bar{K}NN$ state

Work	B [MeV]	Γ [MeV]	Method	Type of potential
Barnea et al. [106]	16	41	Variational	chiral
Dote et al. [107]	17-23	40-70	Variational	chiral
Dote et al. [108]	14-50	16-38	ccCSM	chiral
Ikeda et al. [109]	9-16	34-46	Faddeev	chiral
Bayar et al. [110]	15-30	75-80	Faddeev	chiral
Sekihara et al. [111]	15-20	70-80	Faddeev	chiral
Yamazaki et al. [112]	48	61	Variational	phenomenological
Shevchenko et al. [113]	50-70	90-110	Faddeev	phenomenological
Ikeda et al. [114]	60-95	45-80	Faddeev	phenomenological
Wycech et al. [115]	40-80	40-85	Variational	phenomenological
Dote et al. [116]	51	32	ccCSM	phenomenological
Revai et al. [117]	32/ 47-54	50-65	Faddeev	chiral/phenomenological

Laura Tolos and Laura Fabbietti,
arXiv:2002.09223v1 (2020)



Theoretical prediction of B.E. and Γ depend on the $\bar{K}N$ interaction and theoretical framework.

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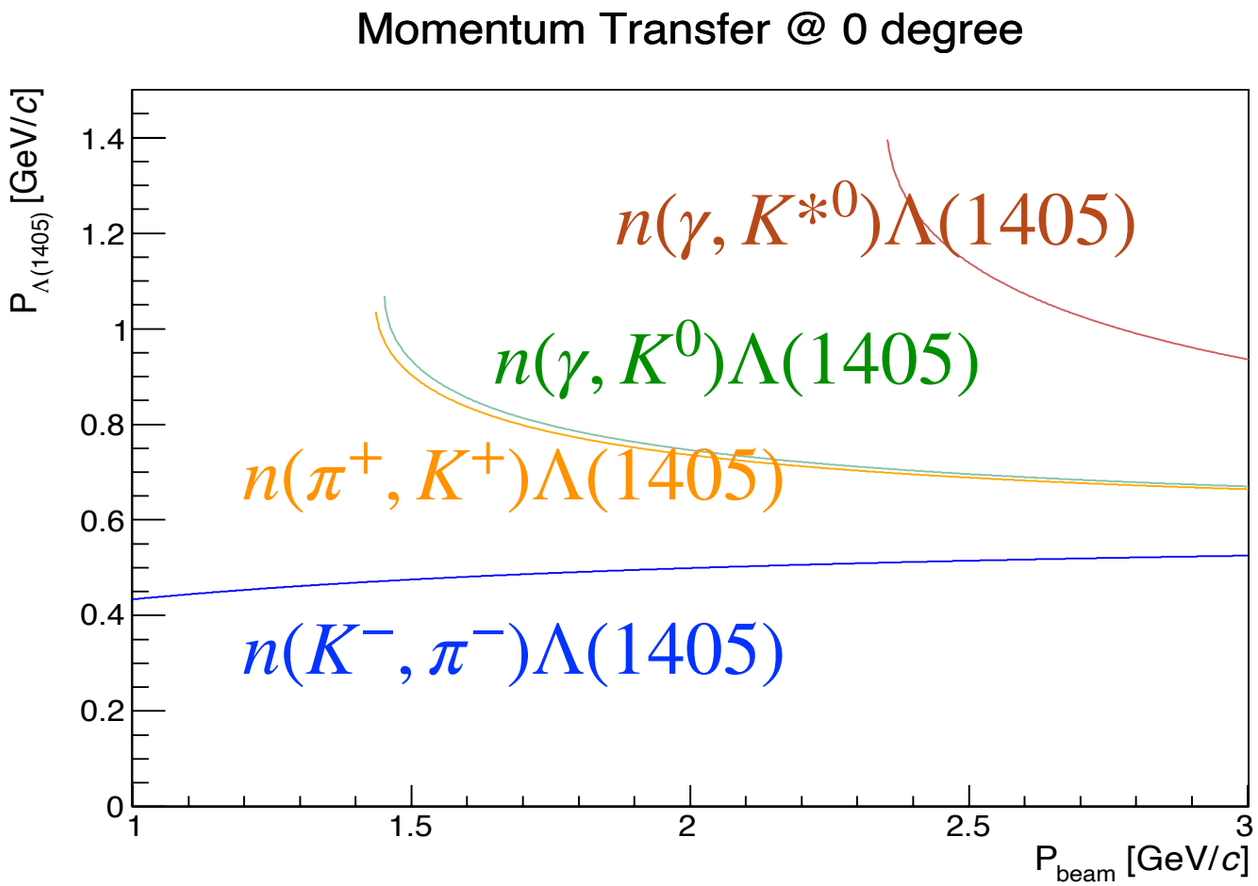
Study of $\bar{K}NN$ with various beams

$\bar{K}NN$ state is produced from the Λ(1405) doorway process



The momentum transfer of $n(\gamma, K^0)\Lambda(1405)$ is similar to that of $n(\pi^+, K^+)\Lambda(1405)$

LEPS2

$\mathbf{d}(\gamma, \Lambda\mathbf{p})\mathbf{K^0}$

$P_\gamma = 1.3 - 2.4$ **GeV/c**

Detected Λ and proton

J-PARC E27

$\mathbf{d}(\pi^+, \mathbf{K^+})\mathbf{Yp}$

$P_\pi = 1.69$ **GeV/c**

Tagged 2 protons

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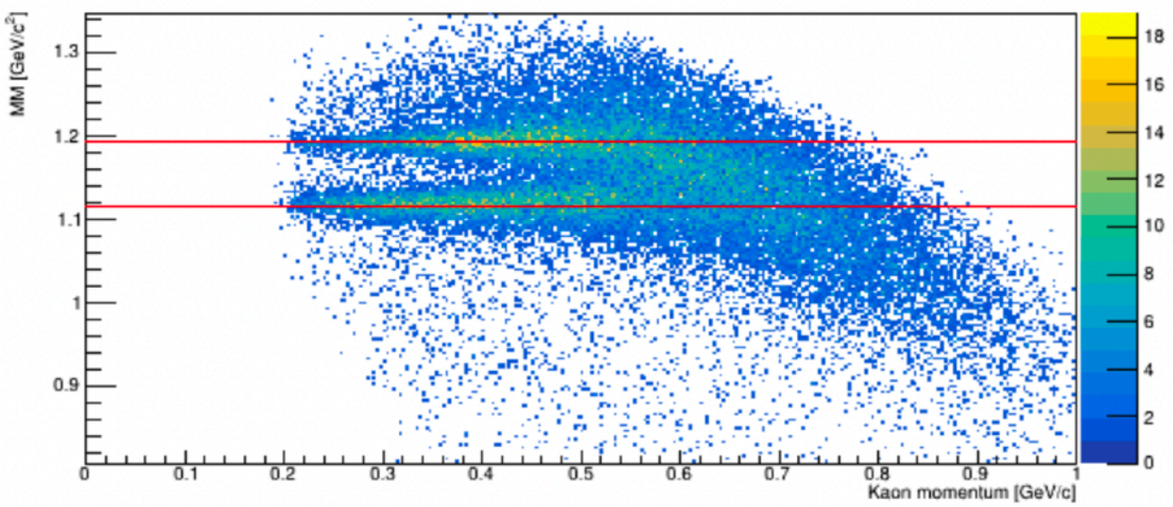
LH_2 Data Analysis

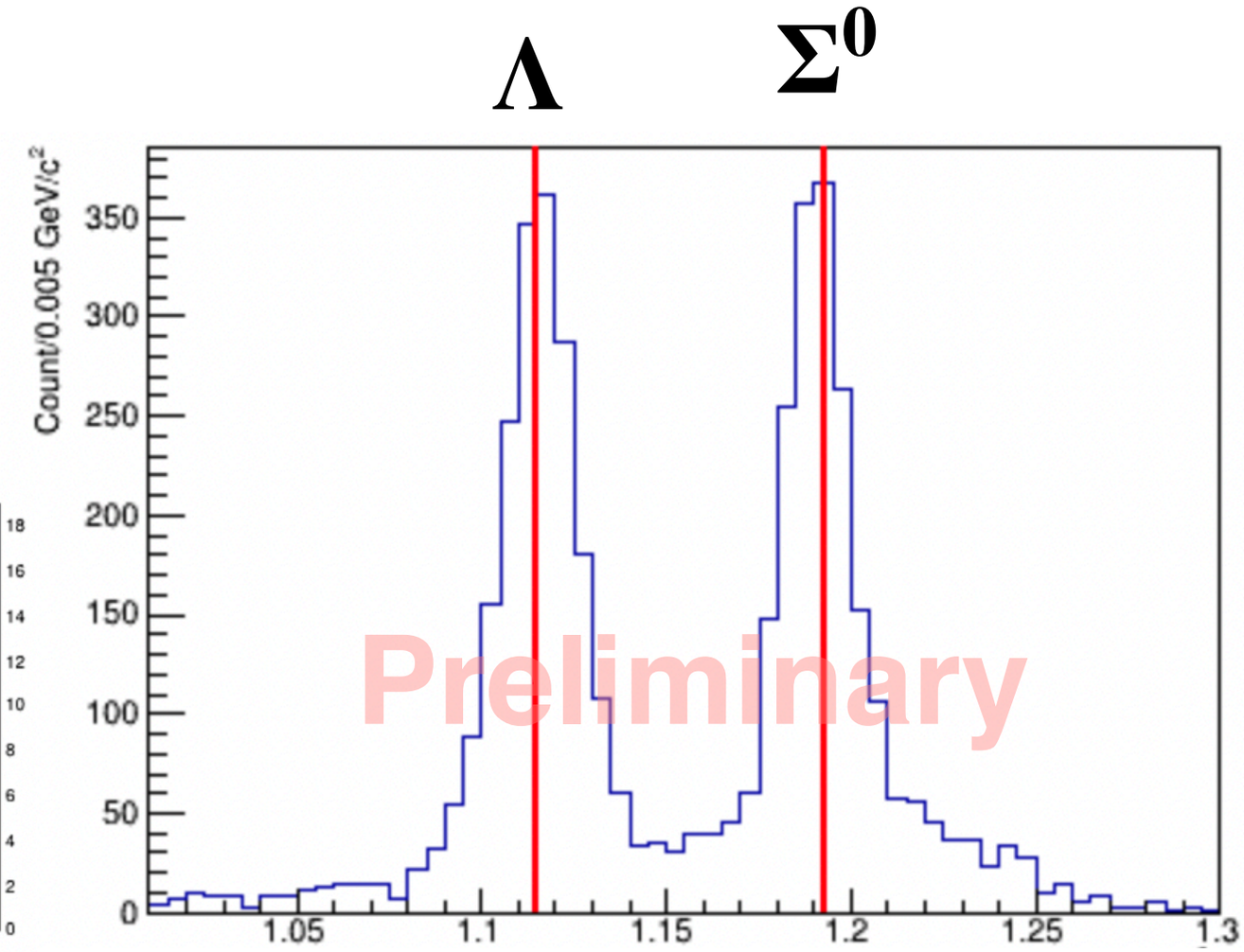
Detected by TPC & BRPC

$$\gamma p \rightarrow \boxed{K^+} X$$

Eg < 1.5 GeV/c



Mom < 0.4 GeV/ c



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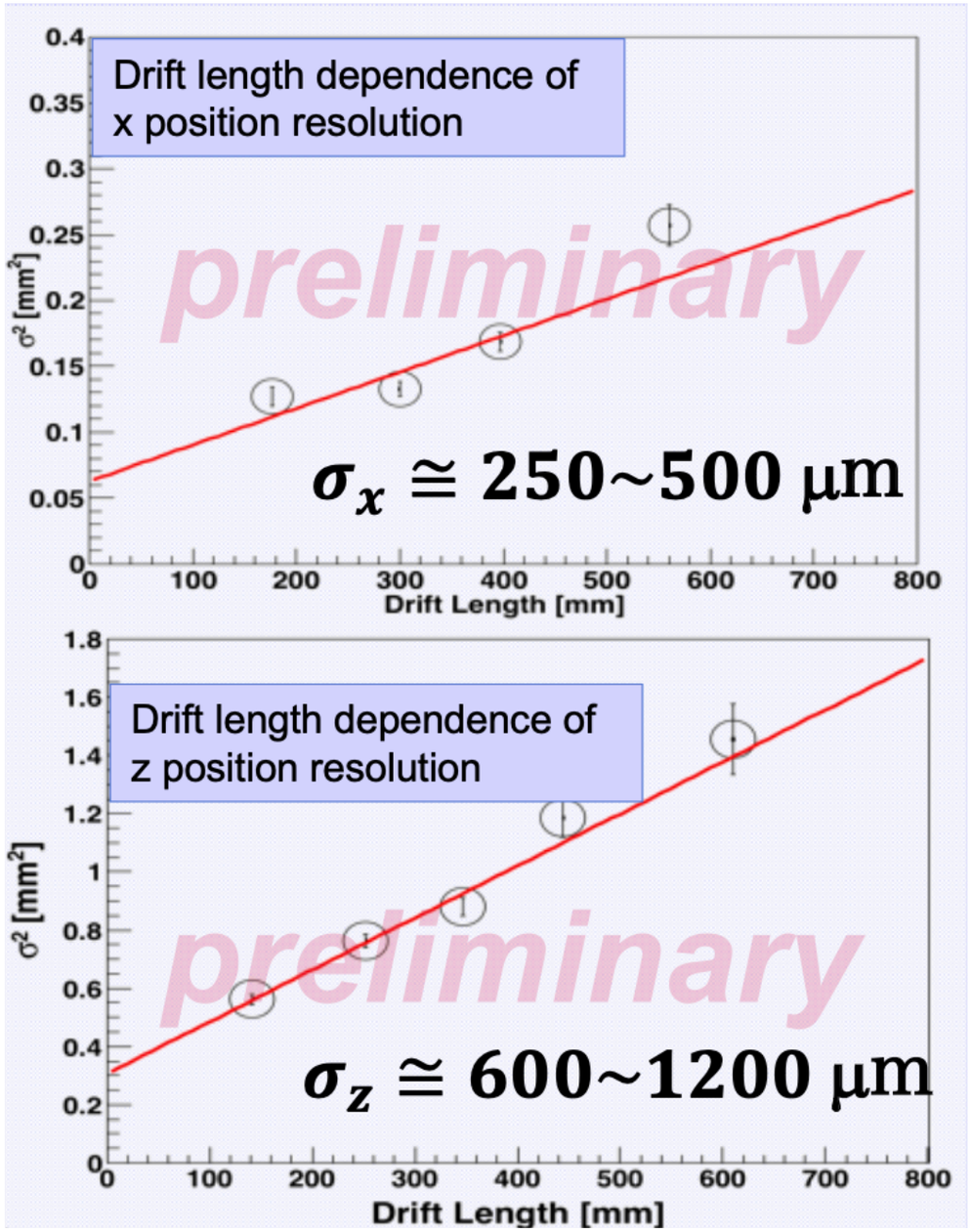
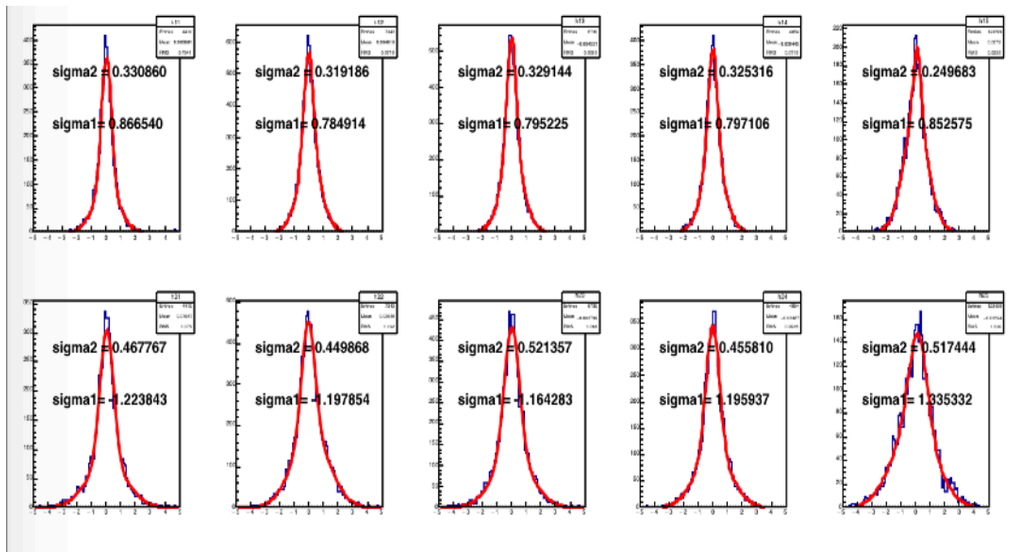
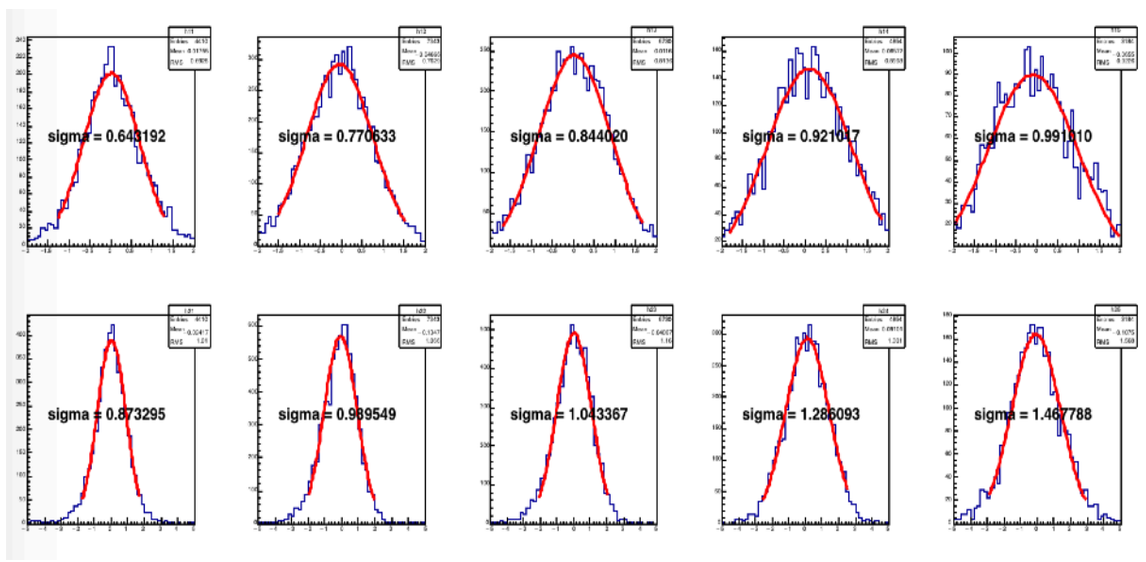
The Performance of LEPS2TPC







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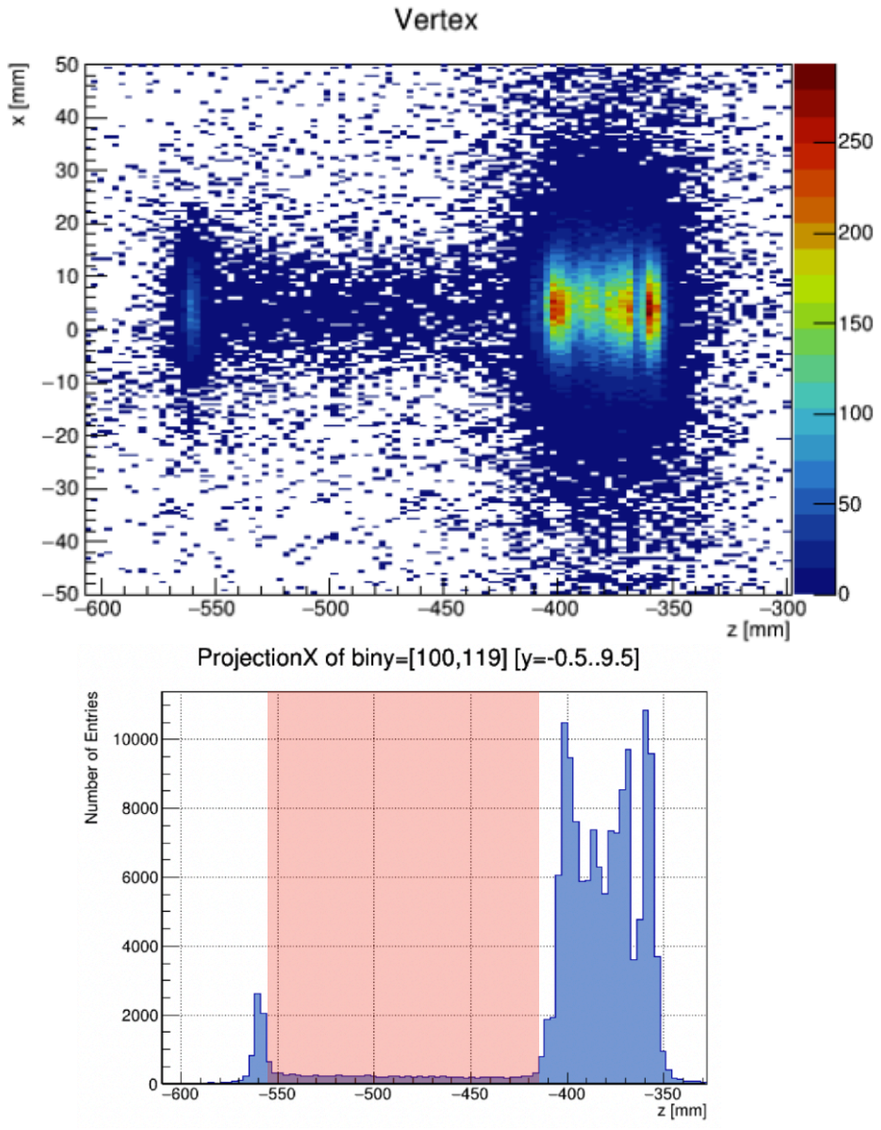
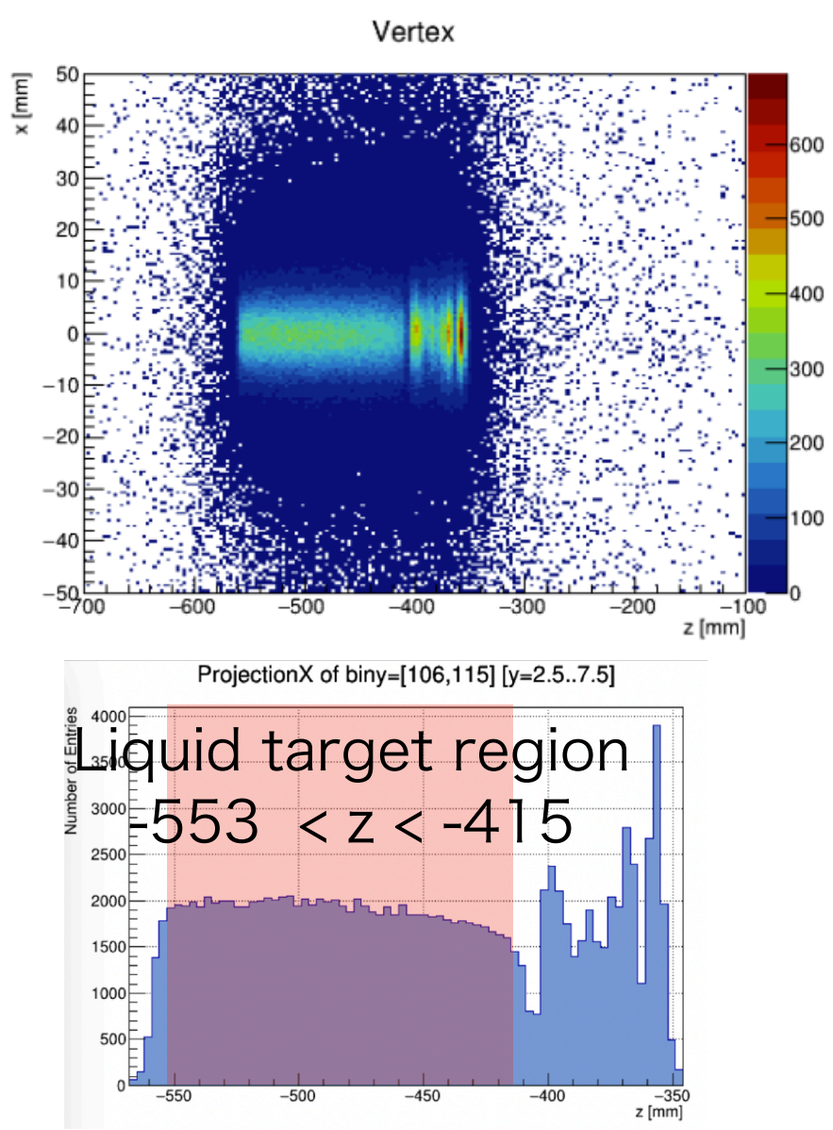
Two tracks vertex

Empty target



LH2 target



Liquid target region
-553 < z < -415

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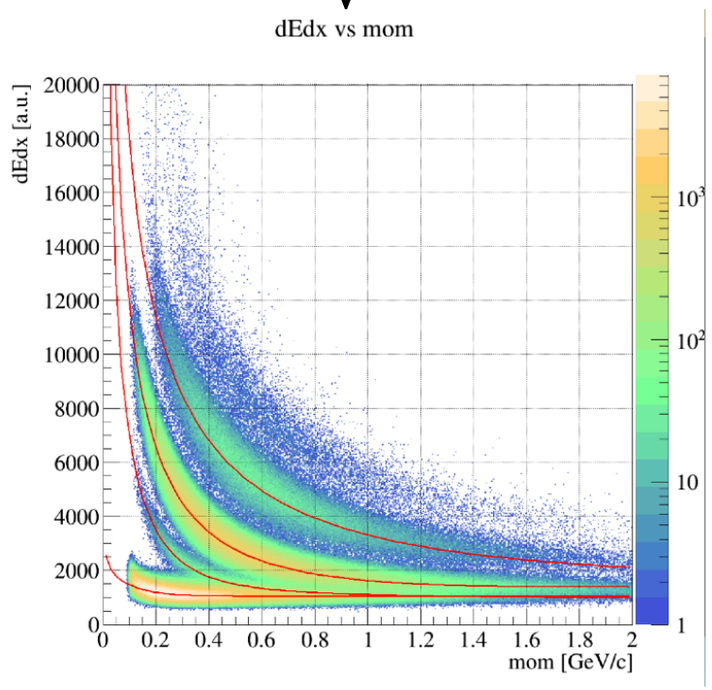
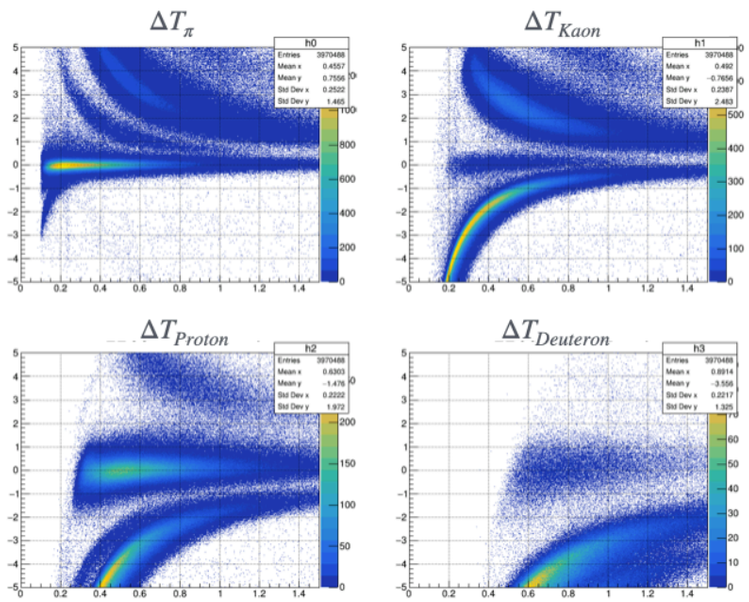
Particle Identification

$$L_{TPC}(dEdx\,|\,H_i) = \frac{1}{\sqrt{2\pi\sigma}} \exp^{-\frac{(dEdx-\mu)^2}{2\sigma^2}}$$

$$L_{ToF}(ToF\,|\,H_i) = \frac{1}{\sqrt{2\pi\sigma}} \exp^{-\frac{(\delta_{tof})^2}{2\sigma^2}}$$





$$P(S\,|\,H_i) = \prod_{detectors} L_{detector}(S\,|\,H_i)$$

$$P(H_i) = \frac{P(S\,|\,Hi)}{\sum_{k=\pi,k,p,d} P(S\,|\,H_k)}$$

$$N\sigma_{tof} = \Delta T/\sigma_{tof}$$

$$N\sigma_{tpc} = \Delta dEdx/\sigma_{dEdx}$$

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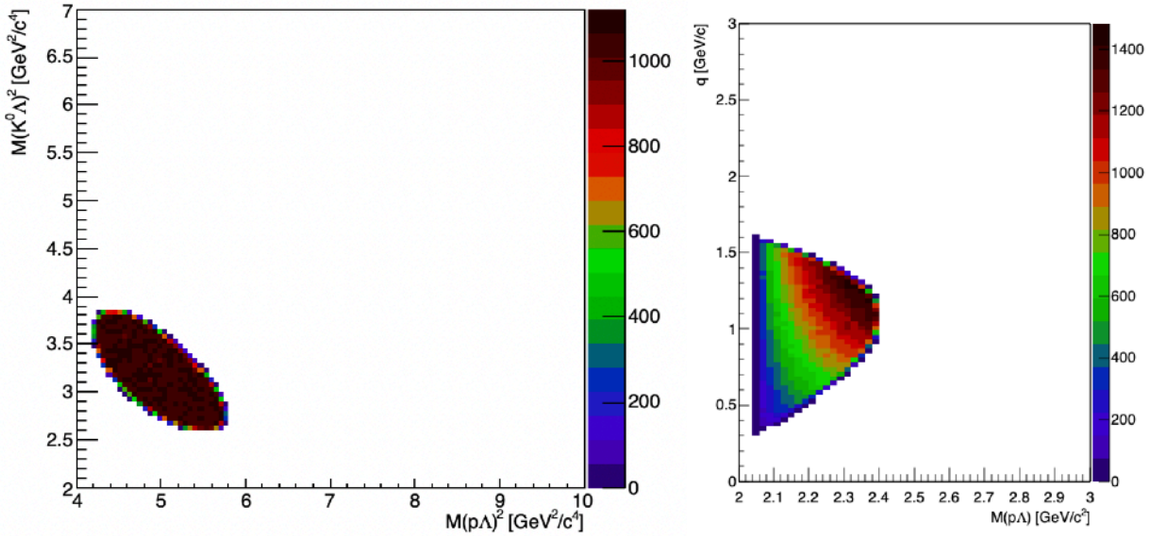
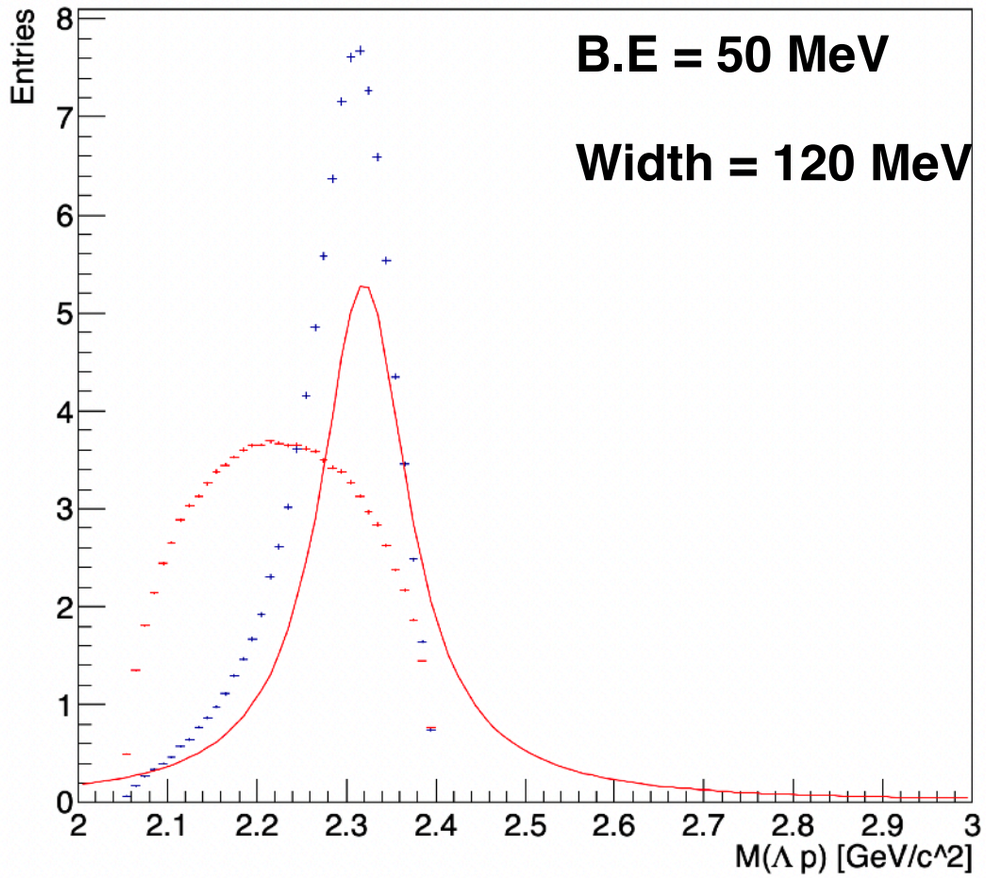
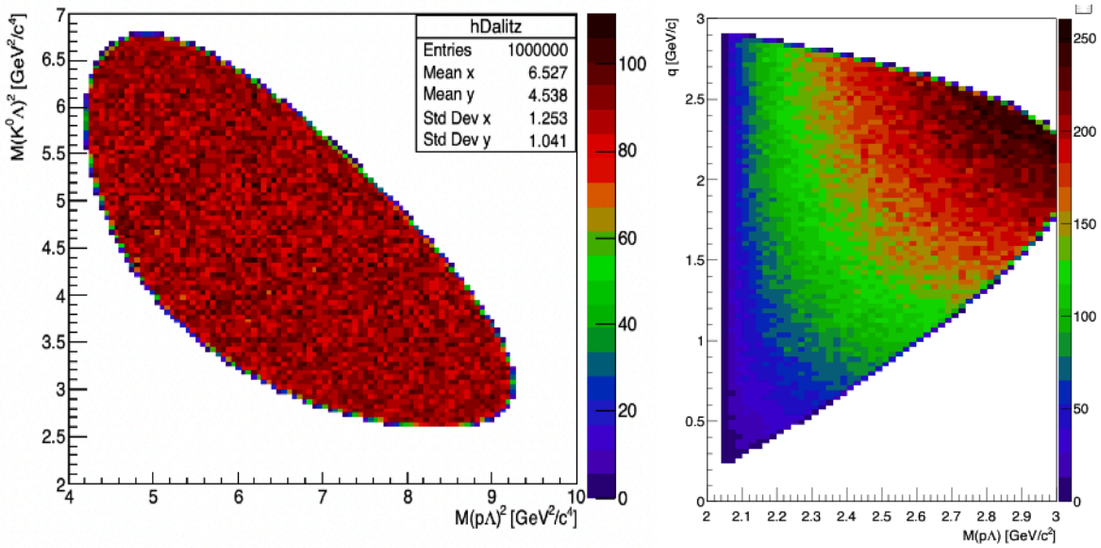
Toy MC

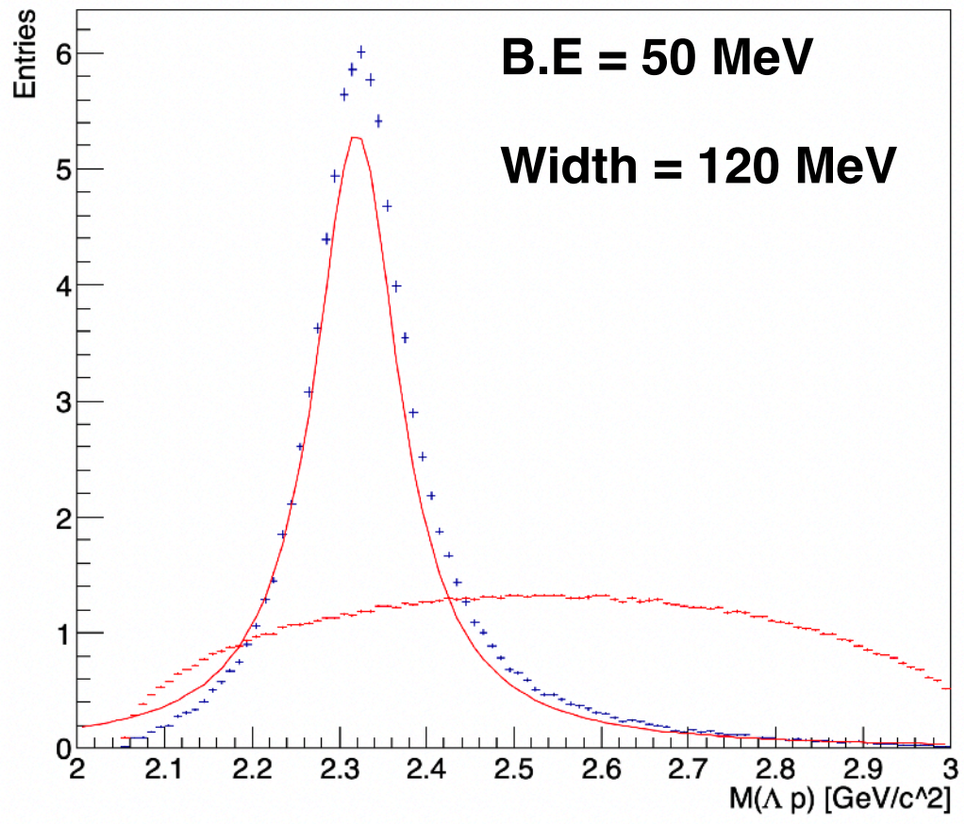
Eg = 1.3





Eg = 2.4





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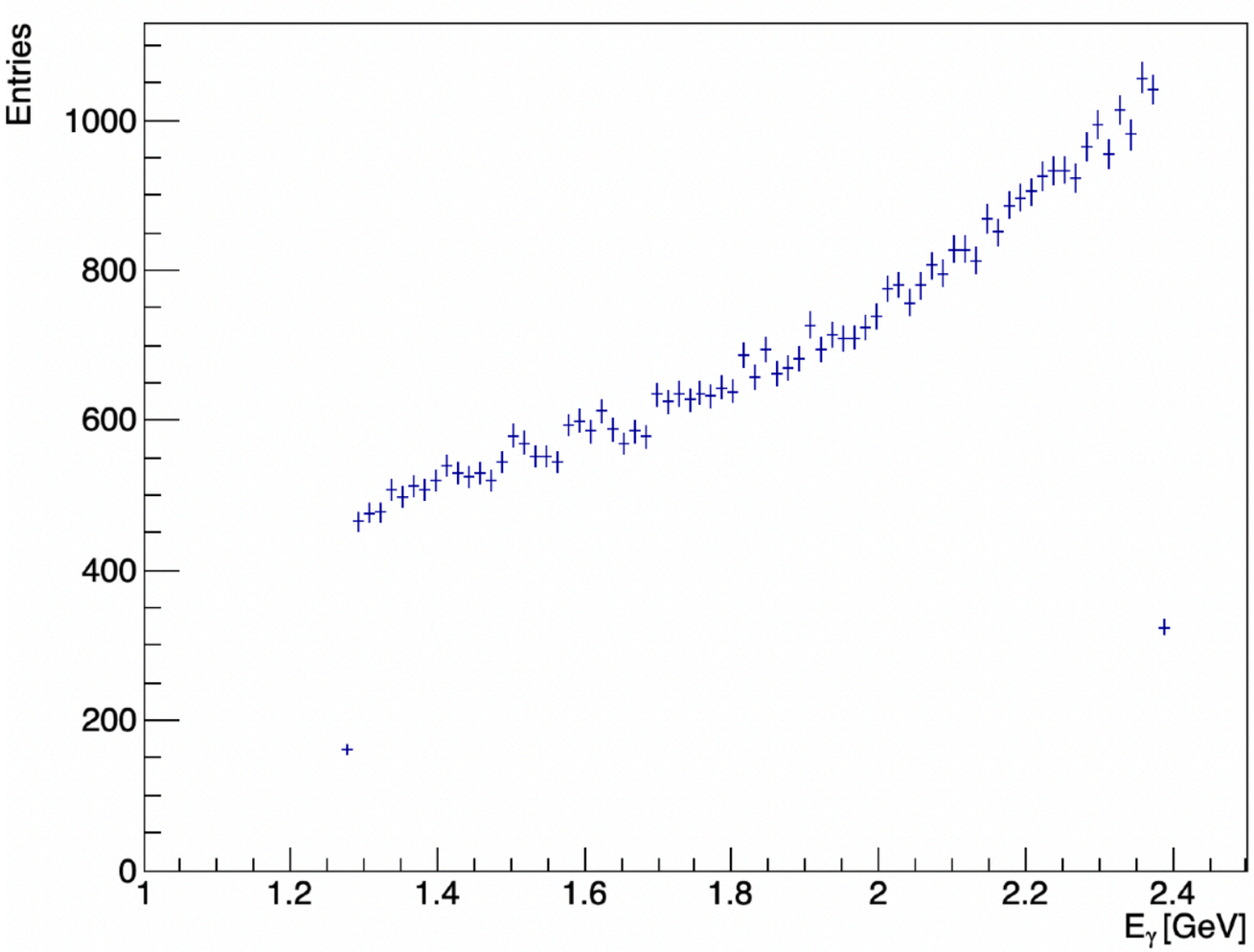
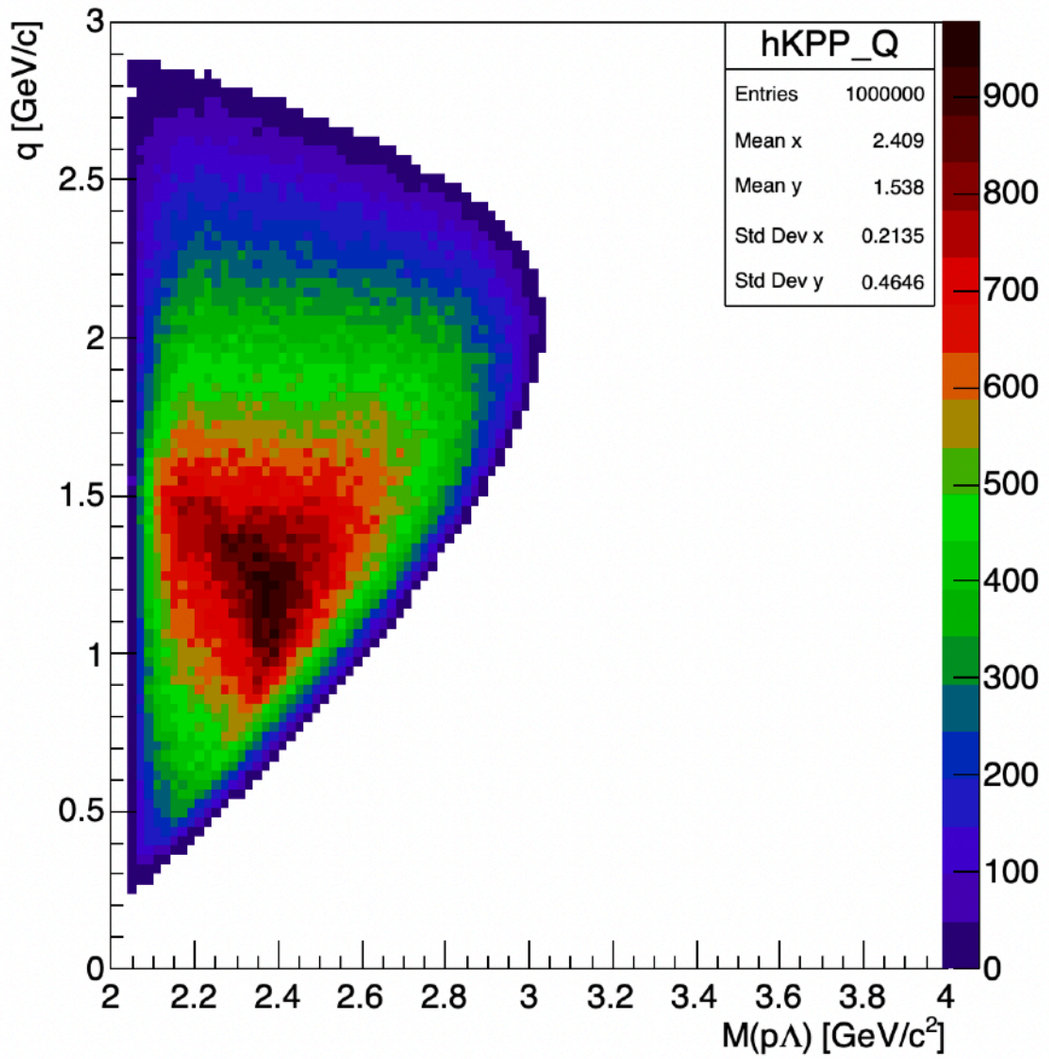
Toy MC

using continuous photon beam





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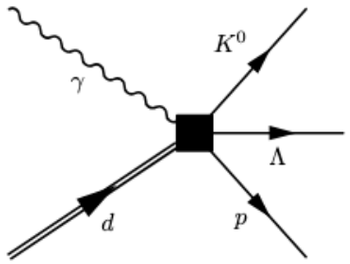
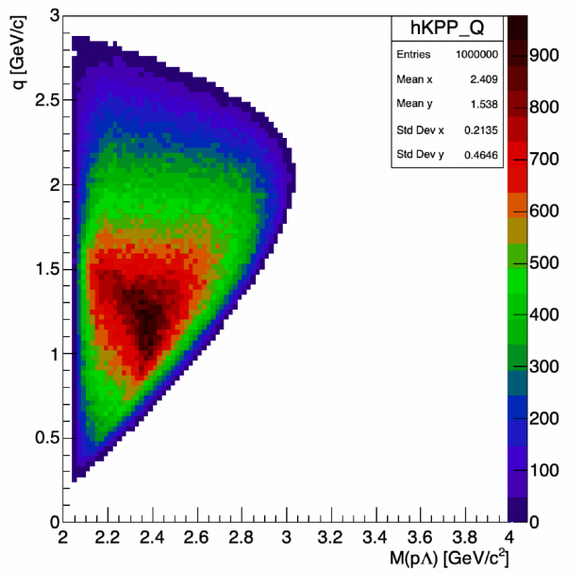
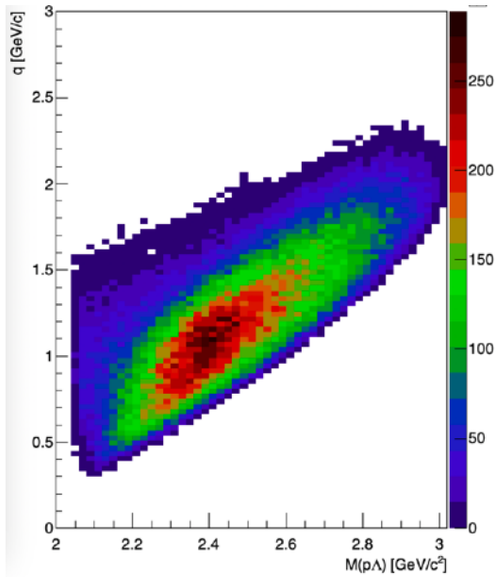
Toy MC



all Eg



Detected in side region

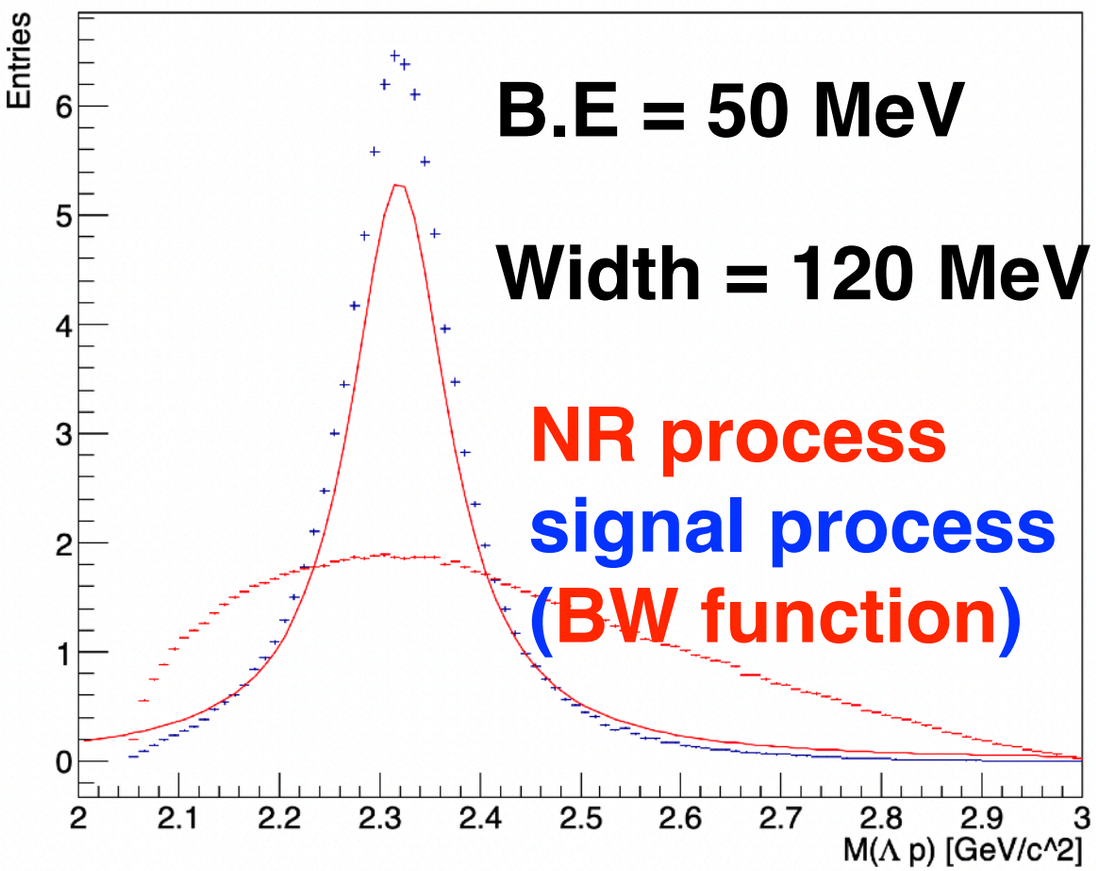


proton 40°~ 110°

Lambda 40°~ 110°

Mom_p > 0.2 GeV/c

Mom_Λ > 0.2 GeV/c



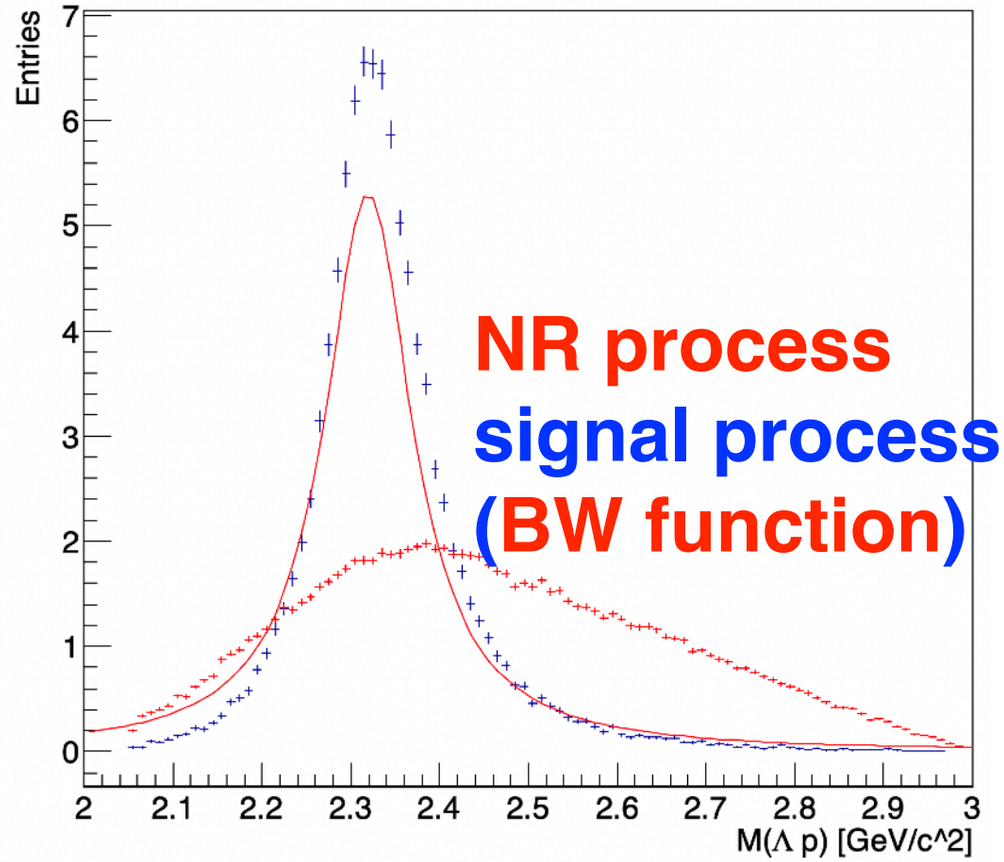
B.E = 50 MeV

Width = 120 MeV

NR process

signal process

(BW function)



NR process

signal process

(BW function)

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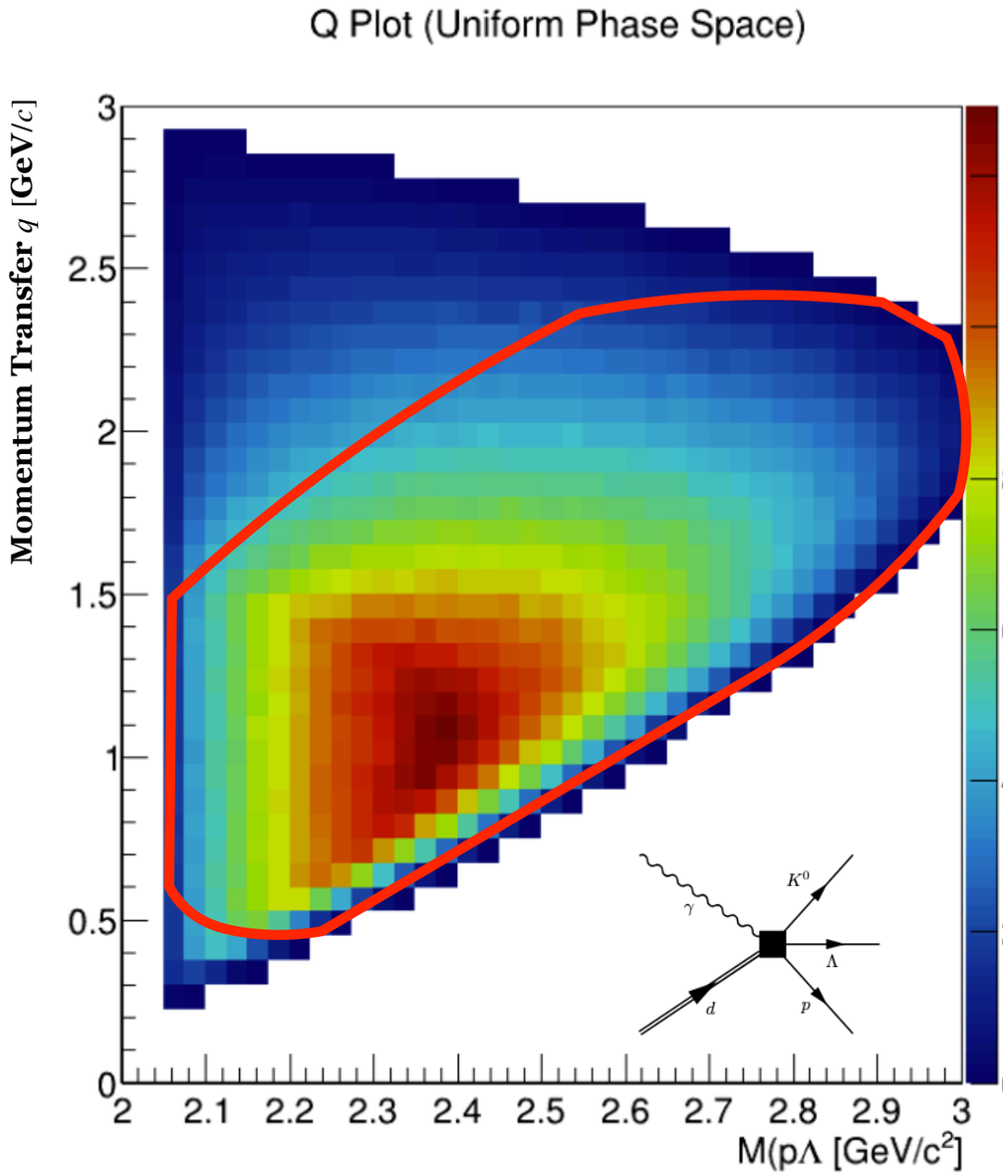
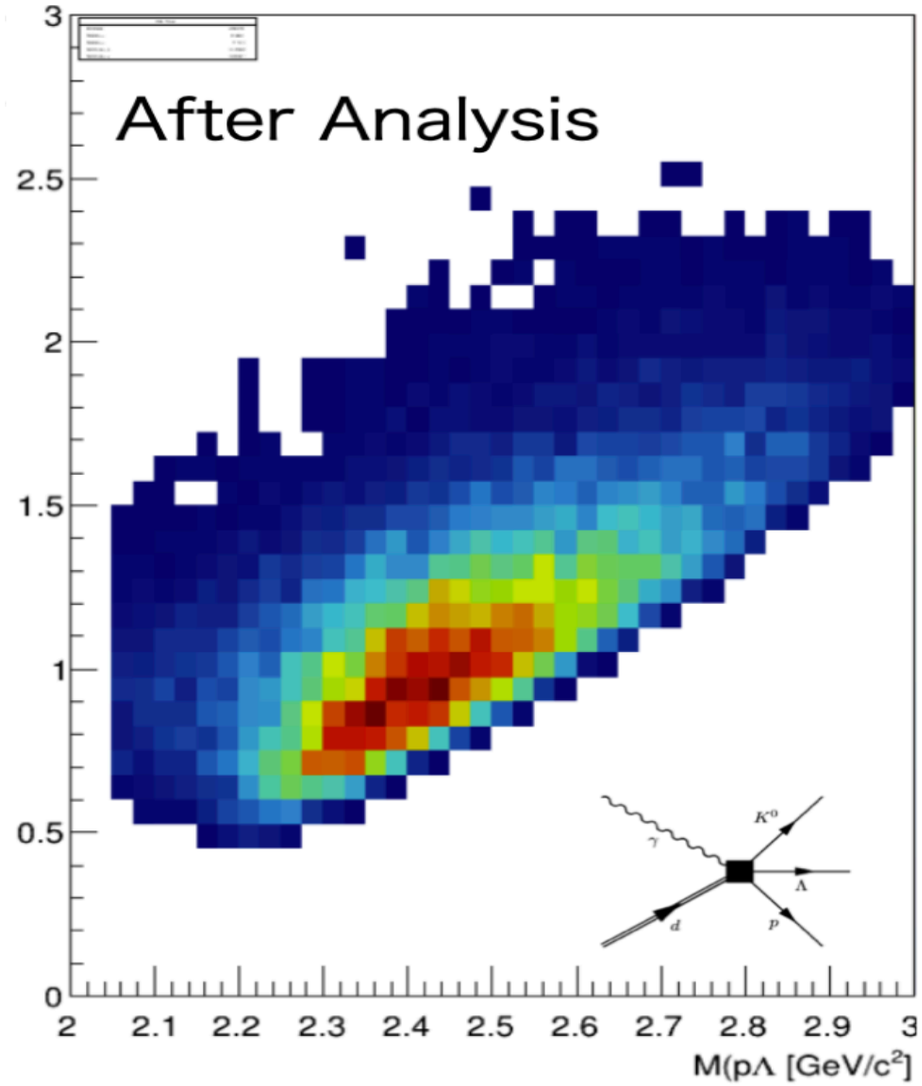
Geant4





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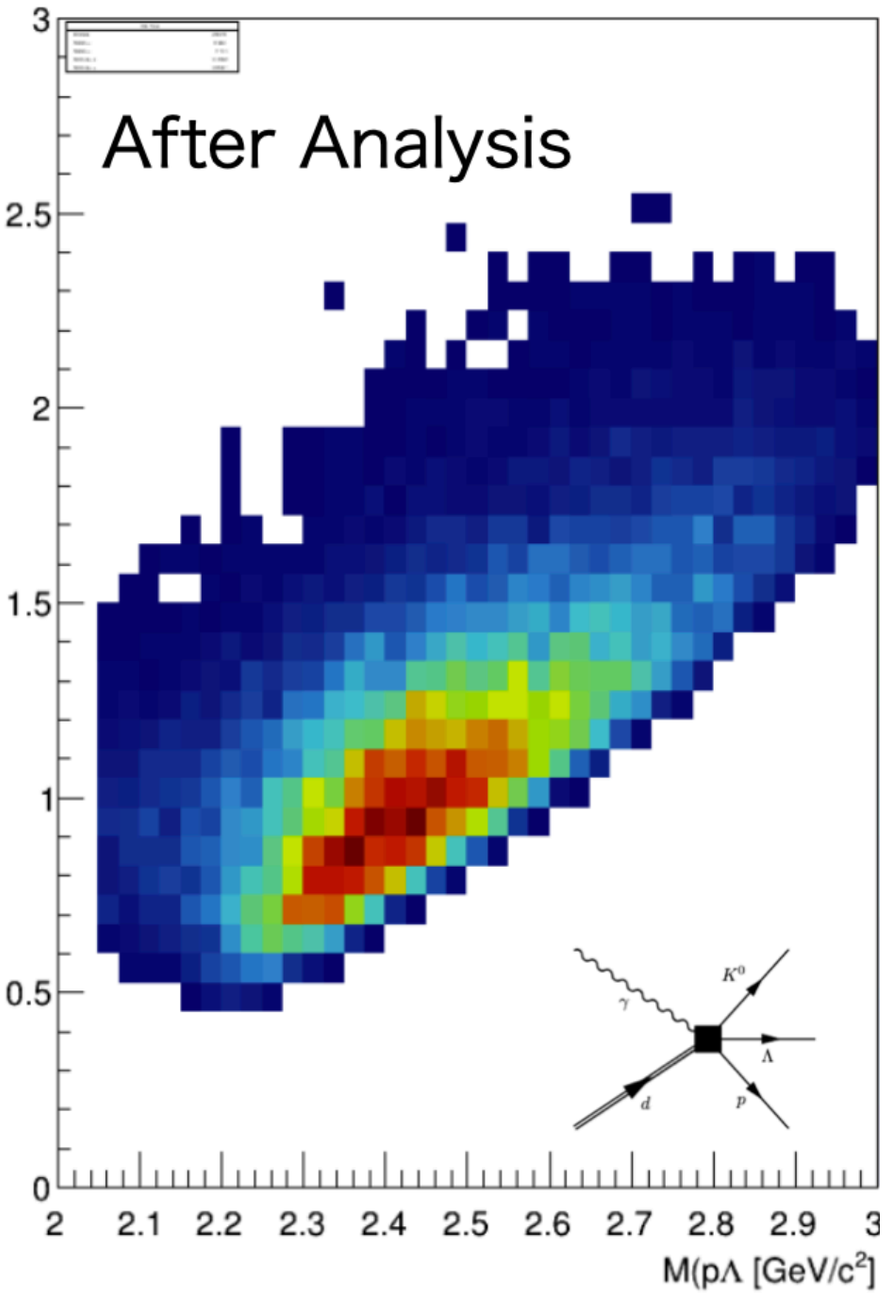
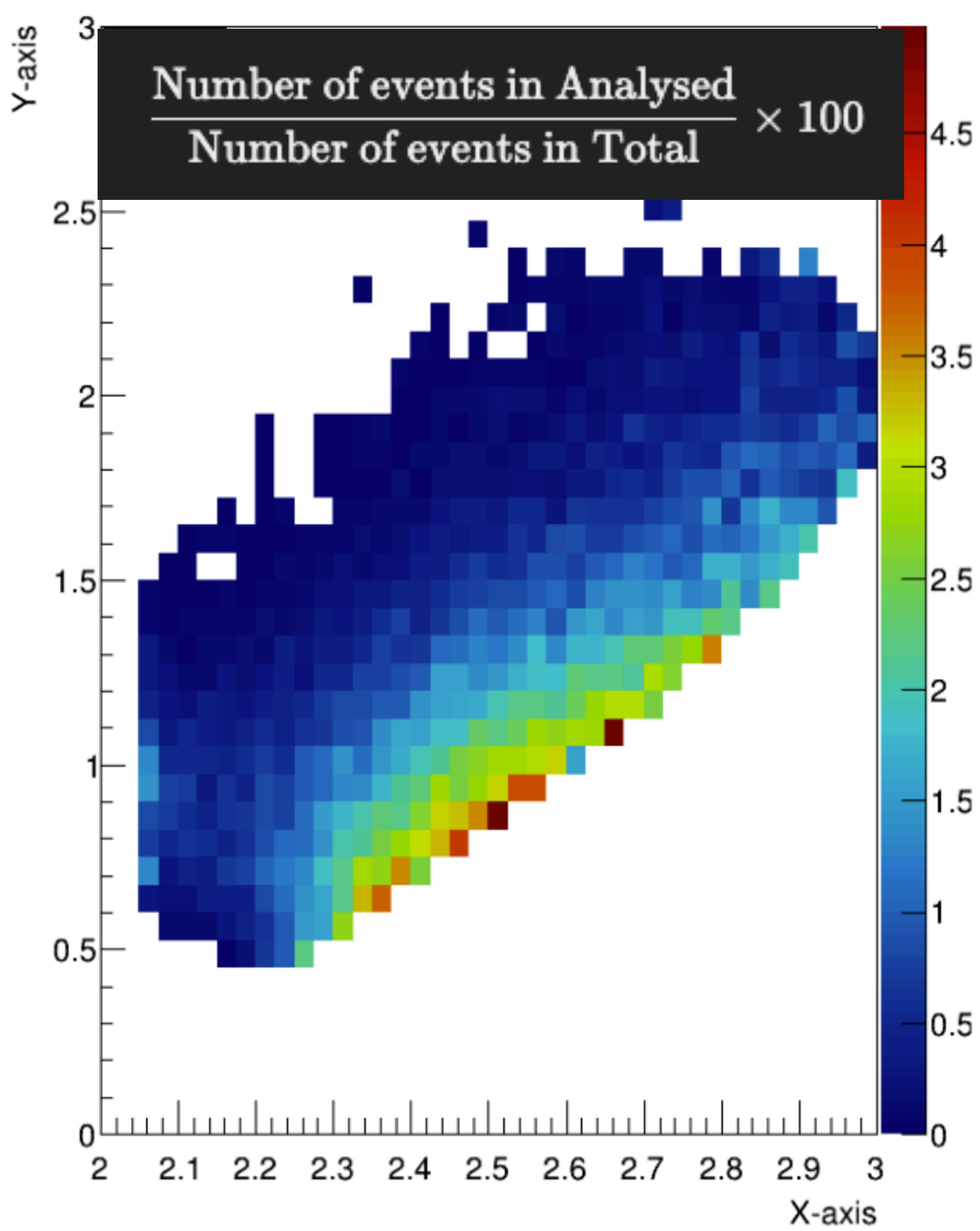
Geant4



survival ratio



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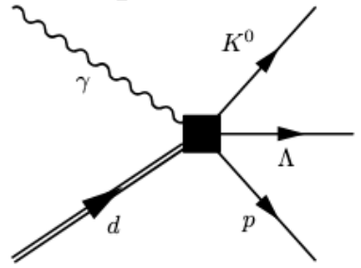
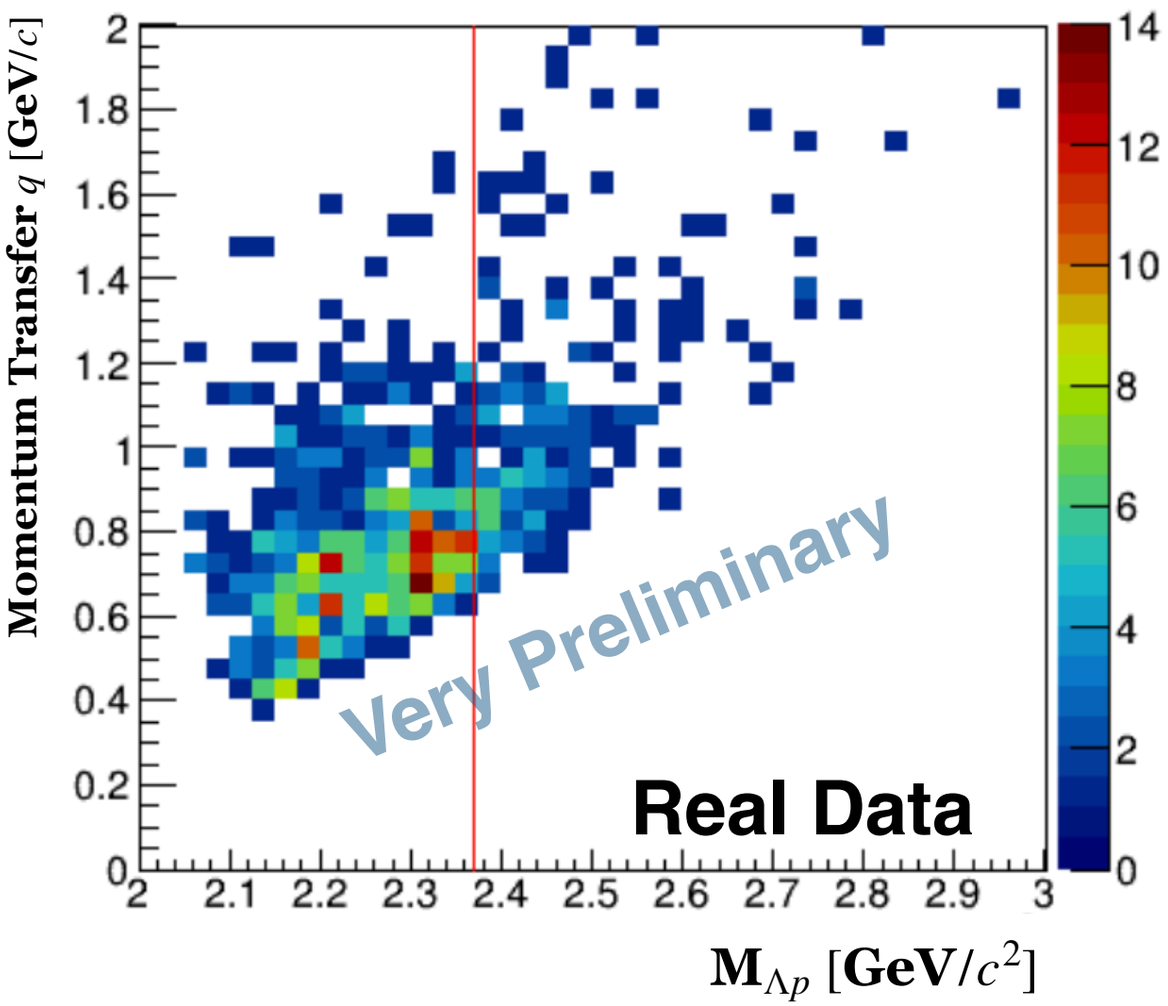
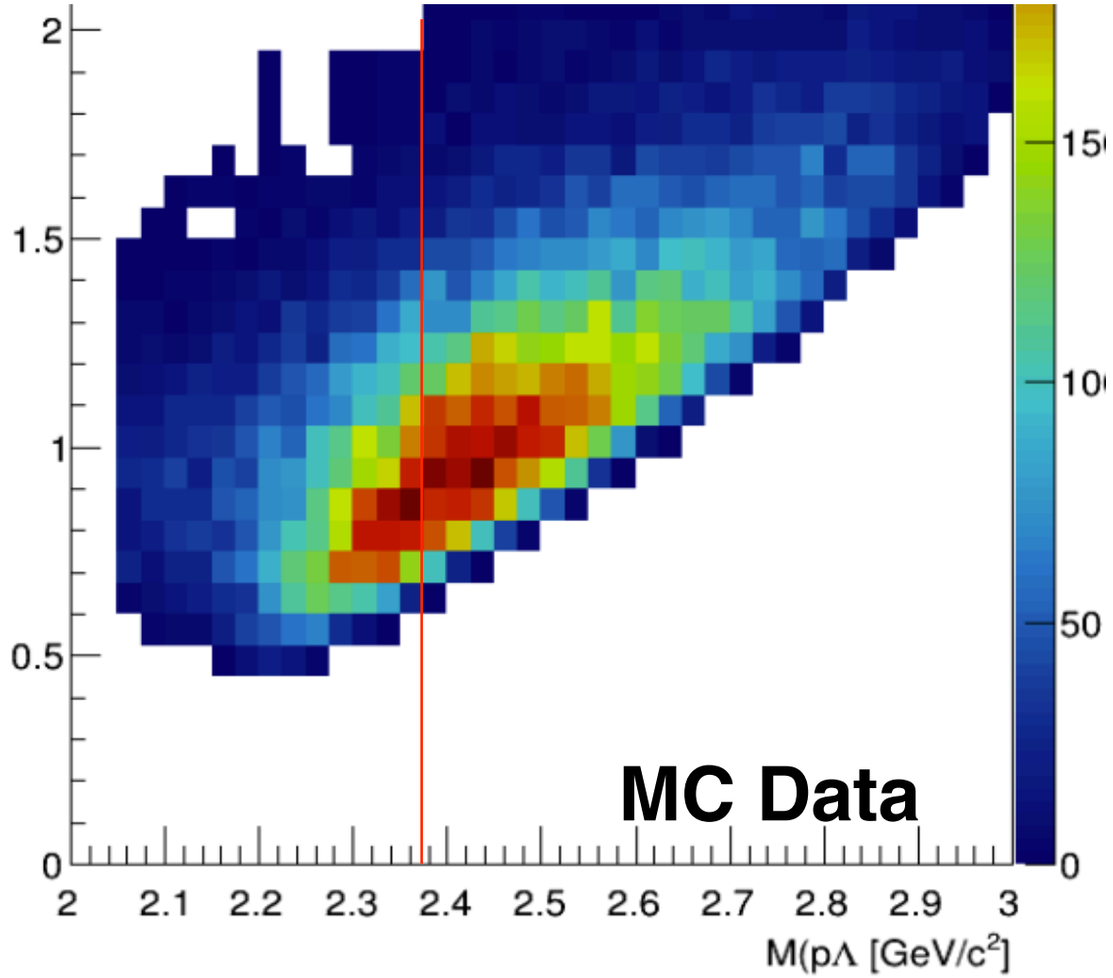
Geant4

NR process







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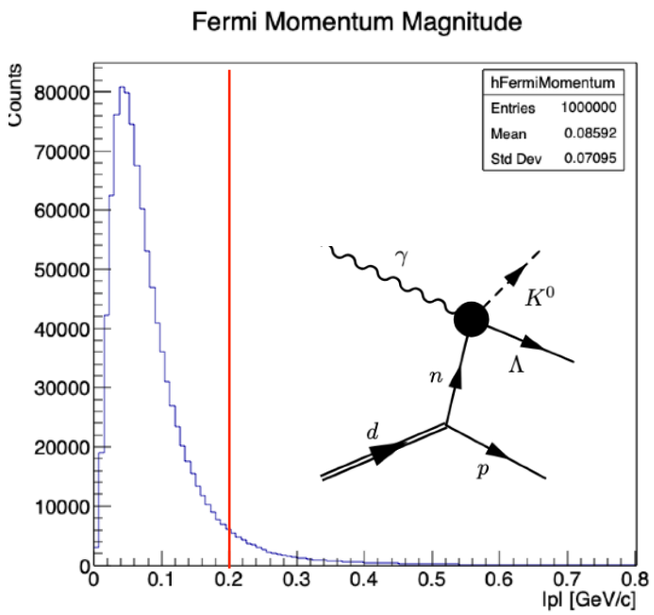
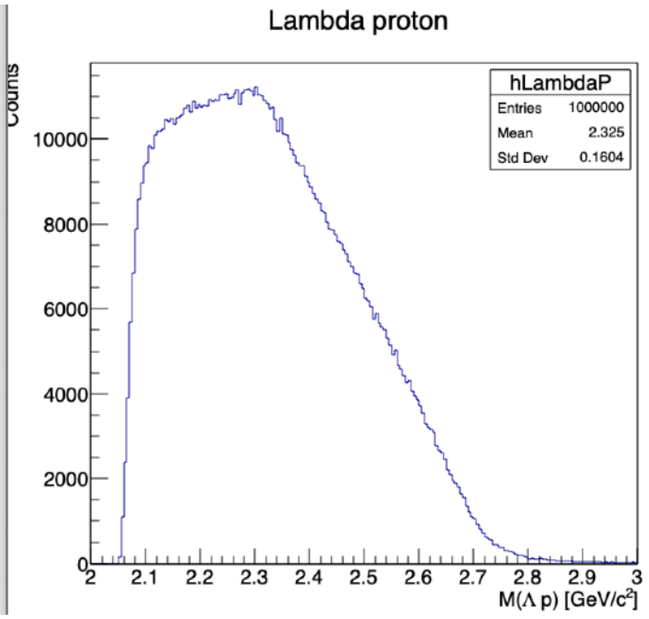
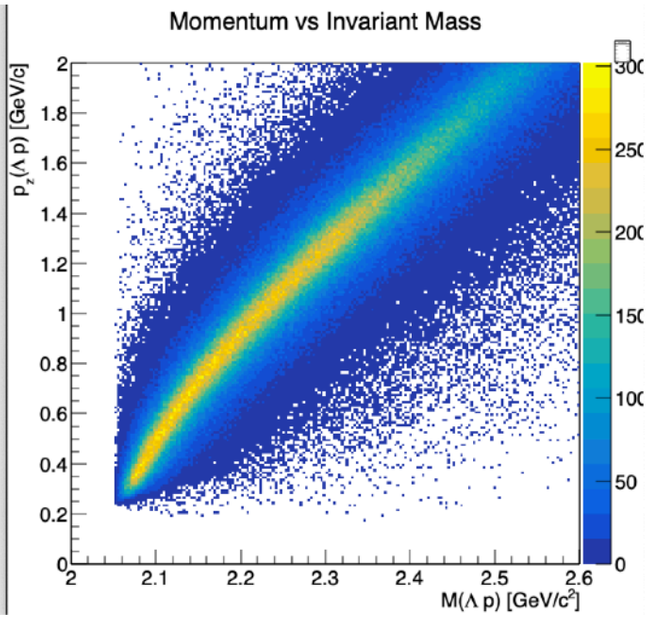
Toy MC

proton is spectator





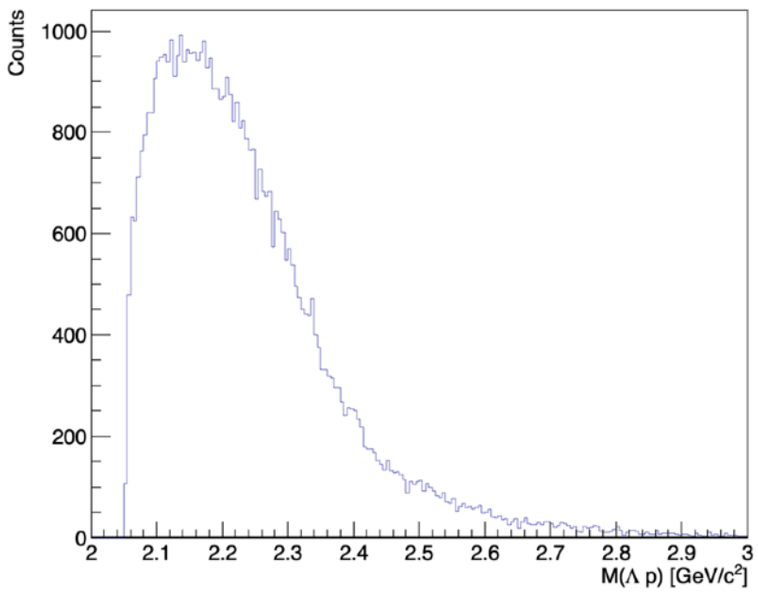


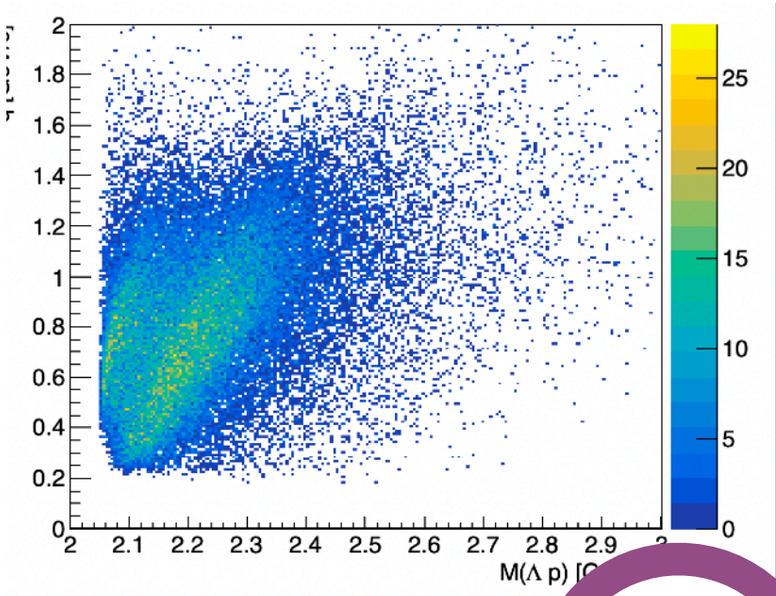
Detected in side region

proton 40°~ 110°

Lambda 40°~ 110°

Mom_p > 0.2 GeV/c





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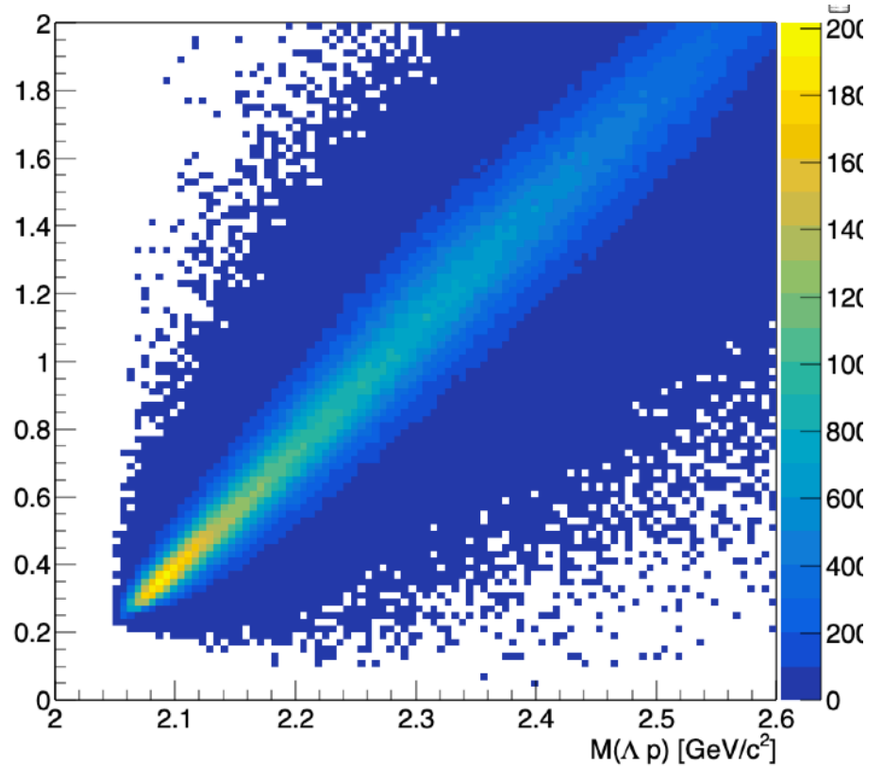
Toy MC

2 Step process

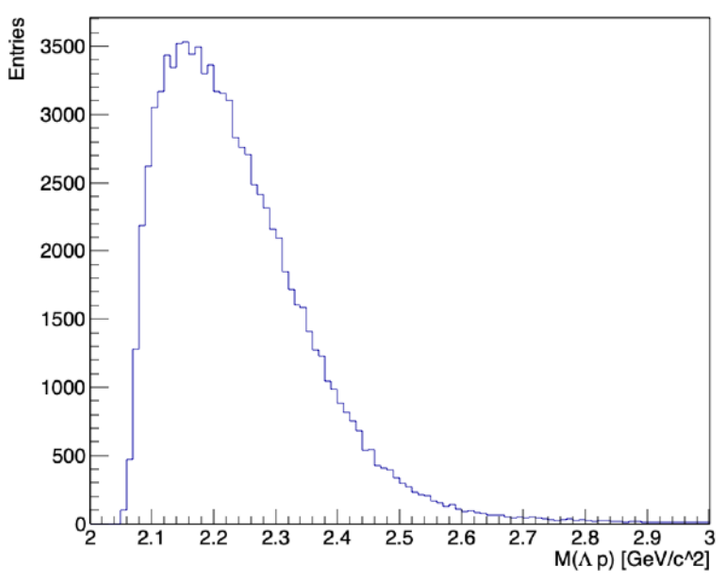


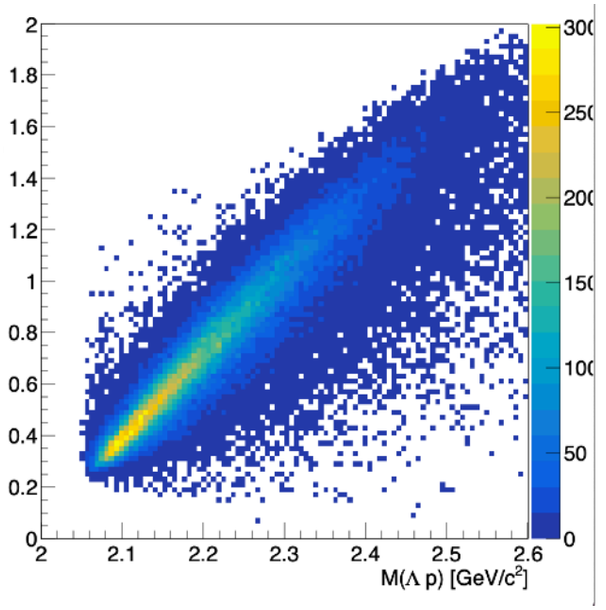
Detected in side region

proton 40°~ 110°

Lambda 40°~ 110°

Mom_p > 0.2 GeV/c





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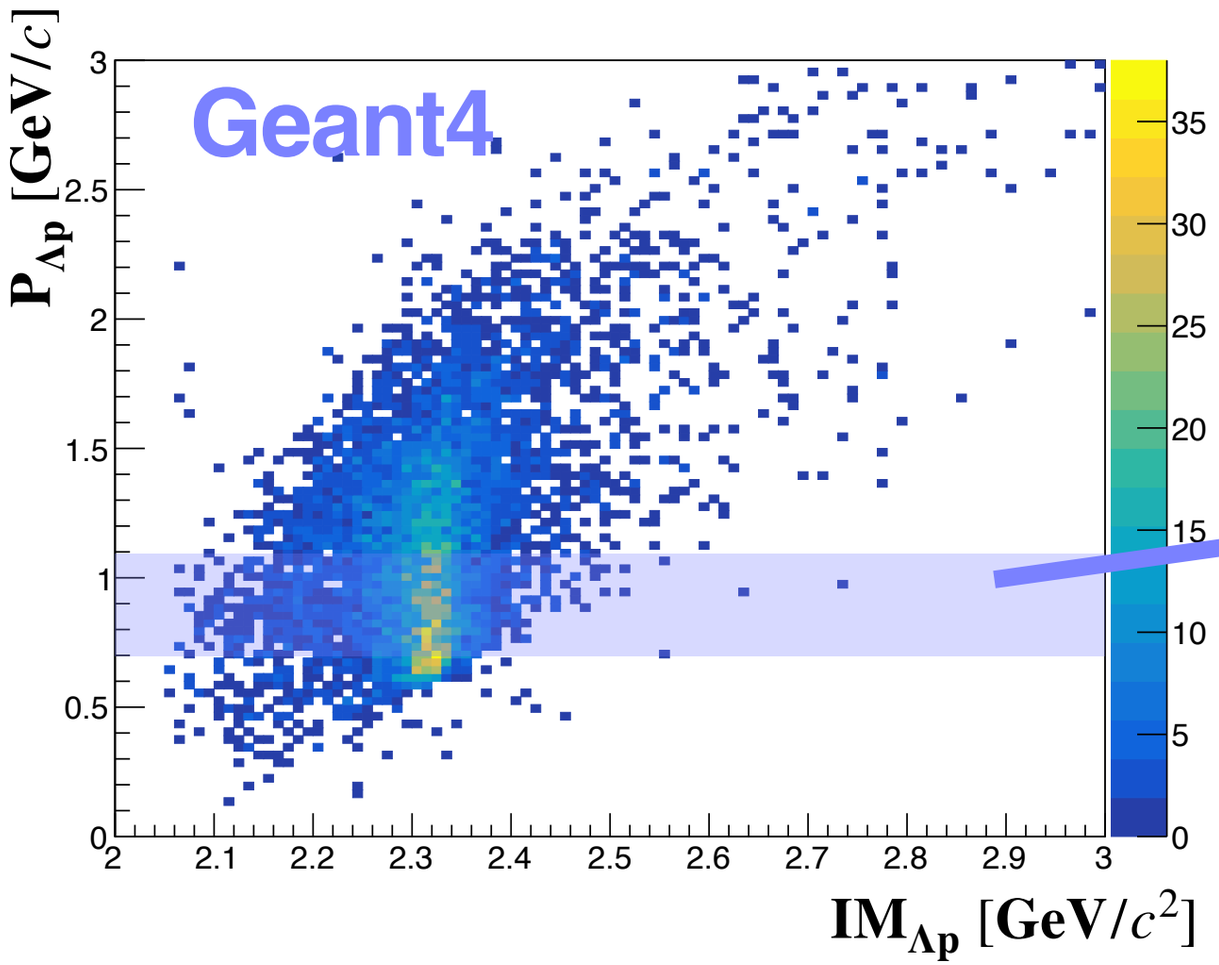
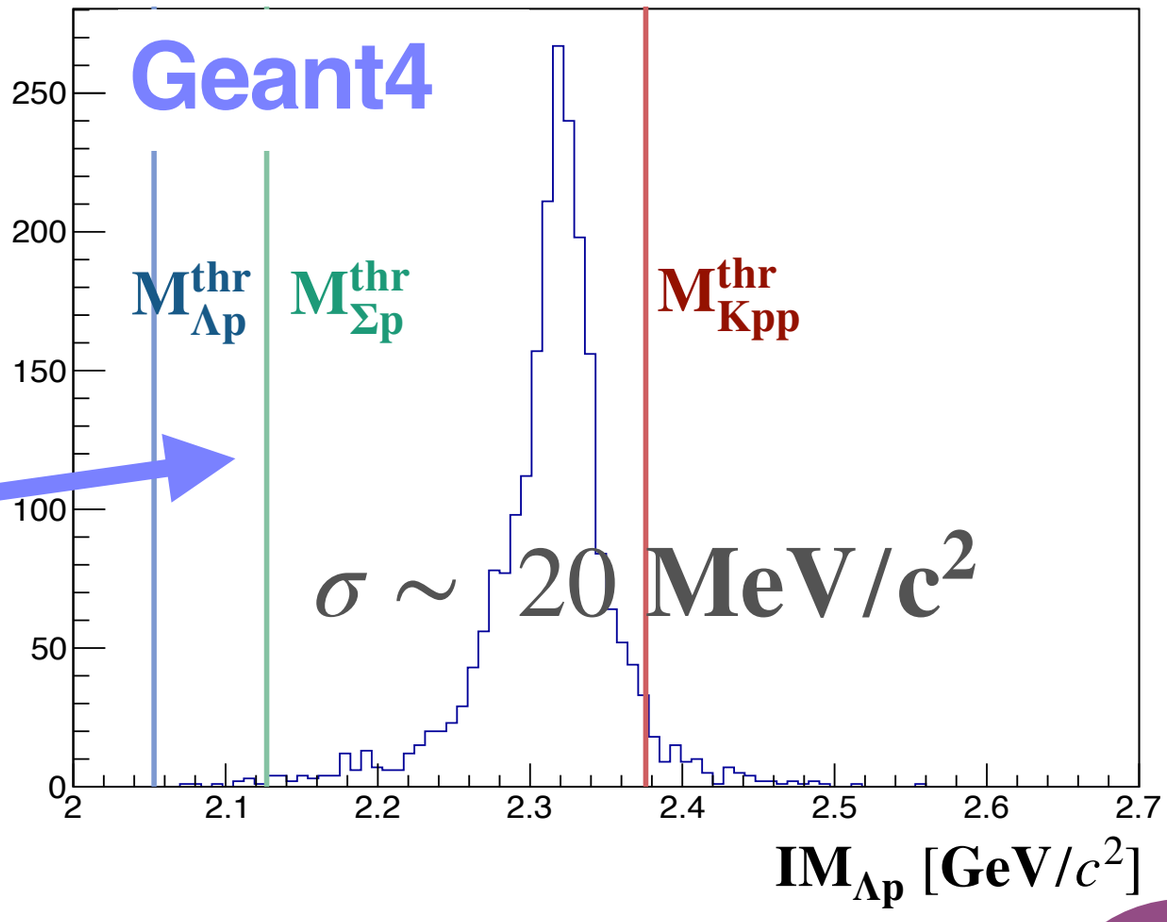
Mass resolution

$$\gamma d \rightarrow K^0(\bar{K}NN)_{BS} \rightarrow K^0 \Lambda p$$

Mass : **2 . 324 GeV/c^2**
(B.E = **50** MeV)
Width : **0** GeV/c²





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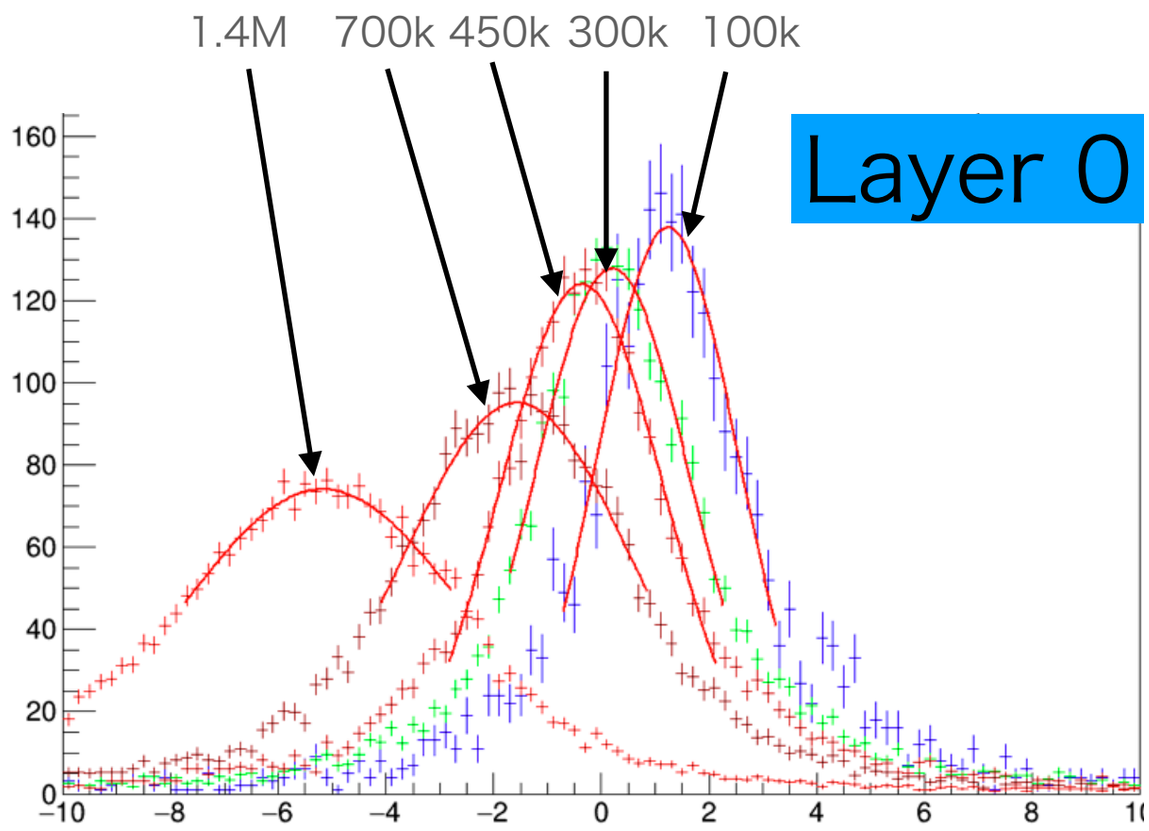
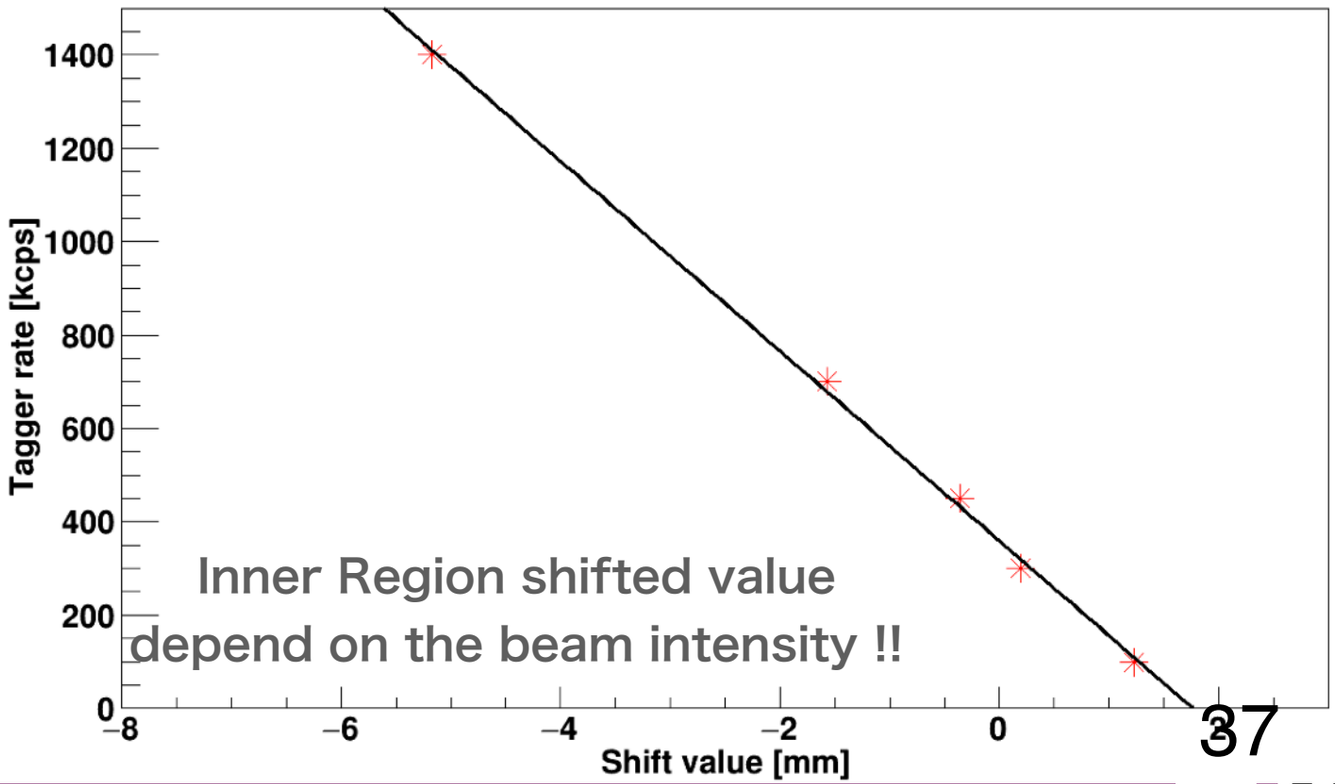
Tagger Rate



residual @ Layer0 [mm]

2022A (LH2 Target)



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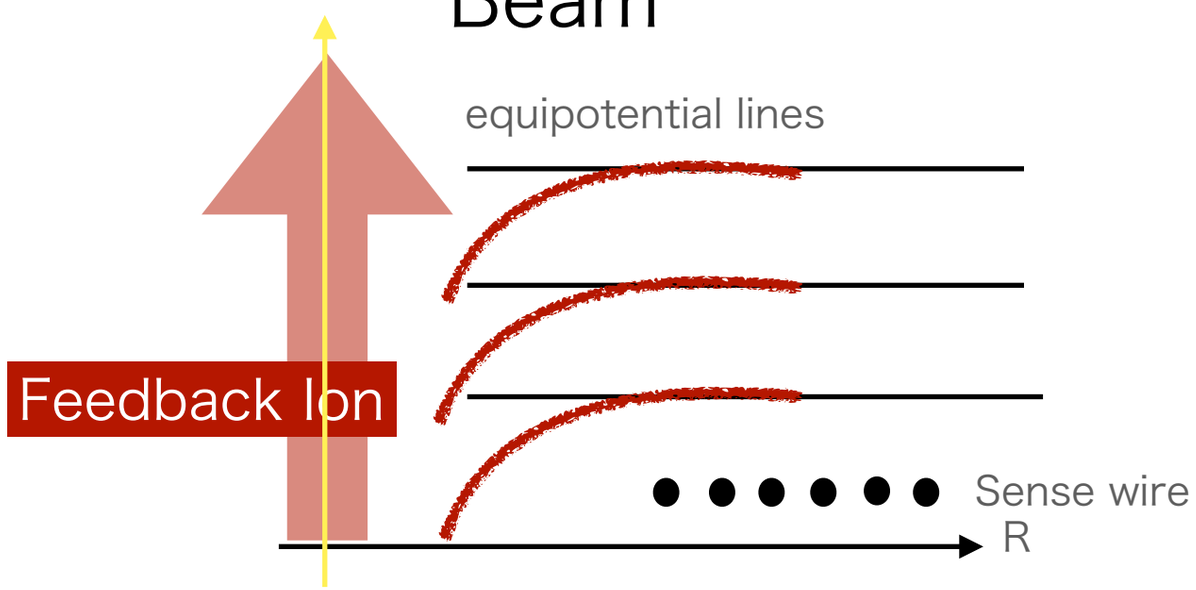
$E_z = 16$ [V/mm]

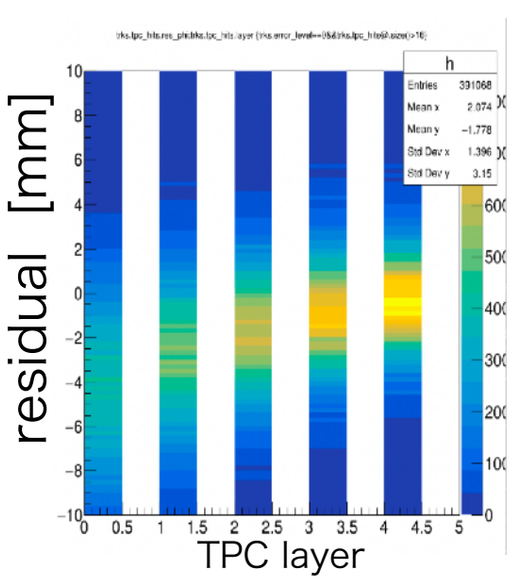
$\mathbb{E} = (0,0,E_z)$

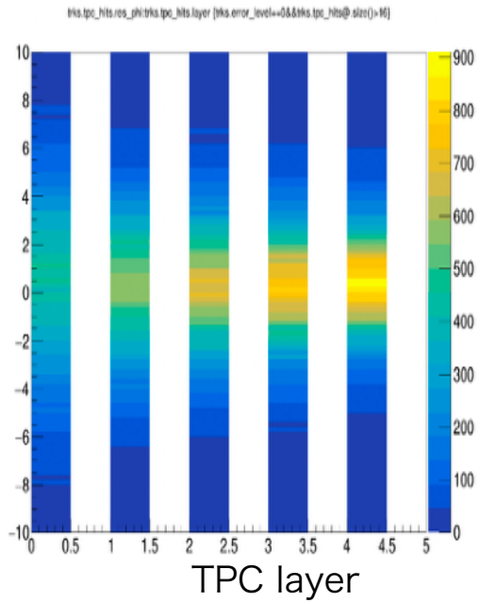


if(R < 140 [mm])

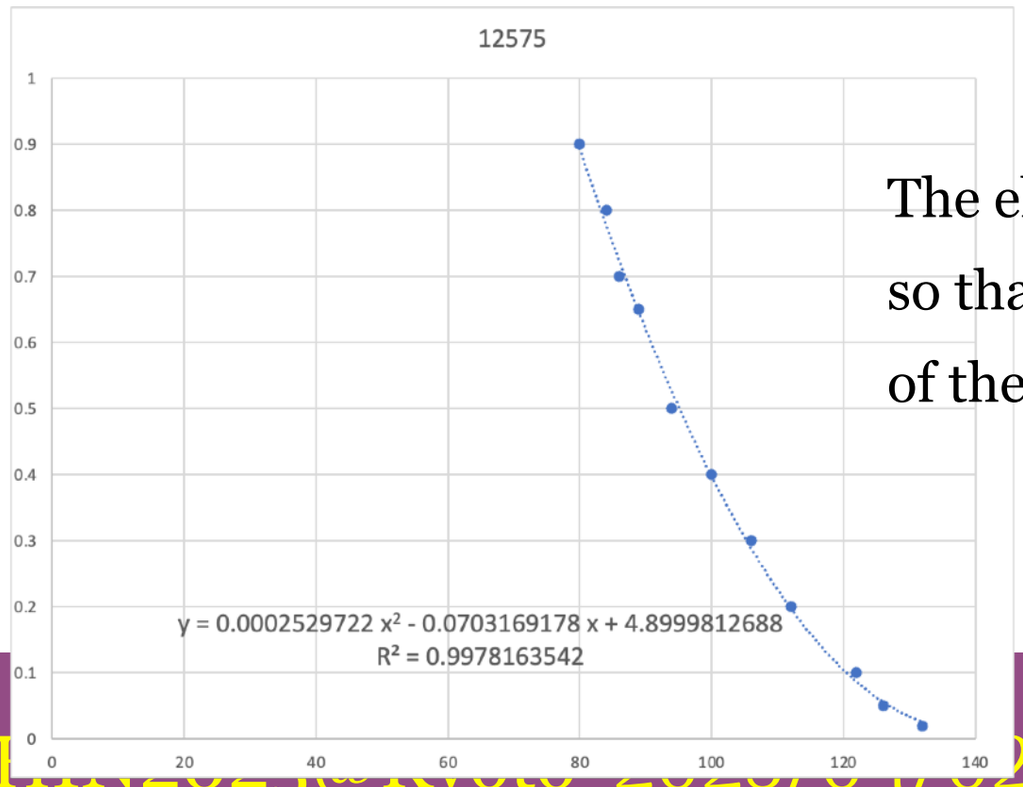
$\mathbb{E} = (E_r(r)\sin\phi,\ E_r(r)\cos\phi,\ E_z)$

$E_r(r) = -0.0002441r^2 + 0.06841r - 4.816$





-E_r [V/mm]



The electric field is manually adjusted
so that the center of the residuals
of the predicted position, obtained from the outer hits, is zero.

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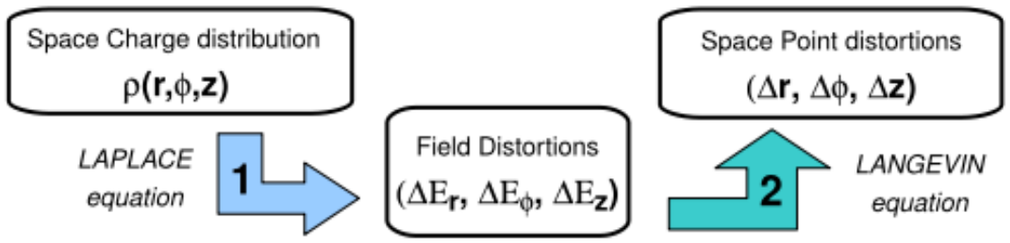
analysis by various reactions

$$\gamma p \rightarrow \pi^+\pi^-\pi^+(n)$$



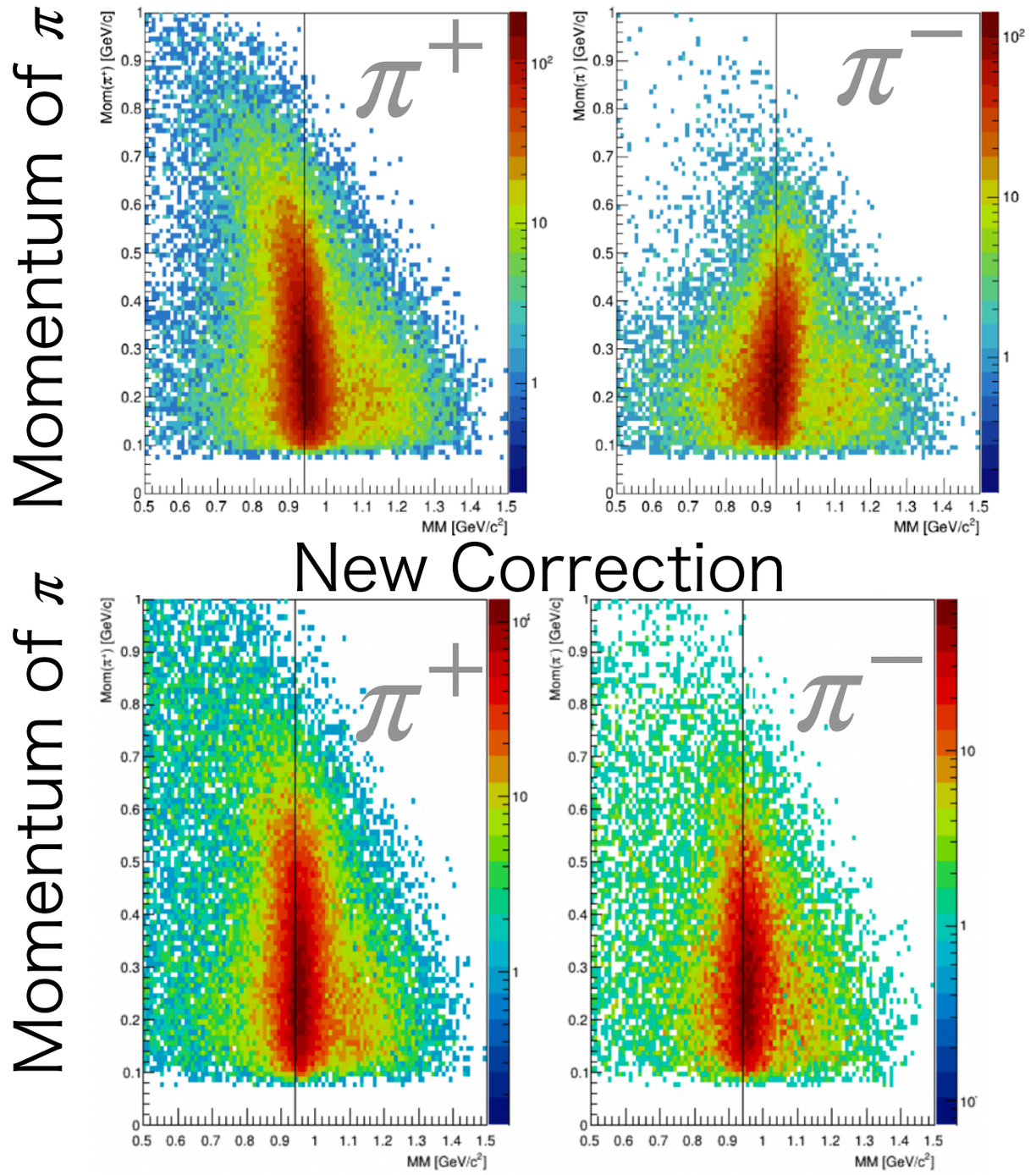
$$\Delta\phi = -\frac{\rho}{\epsilon}$$

$$\frac{\rho}{\epsilon} = C_1/r^2$$

$$E_r = C_1 \times \frac{1}{r} - A \times C_1 \times \frac{1}{r^2}$$

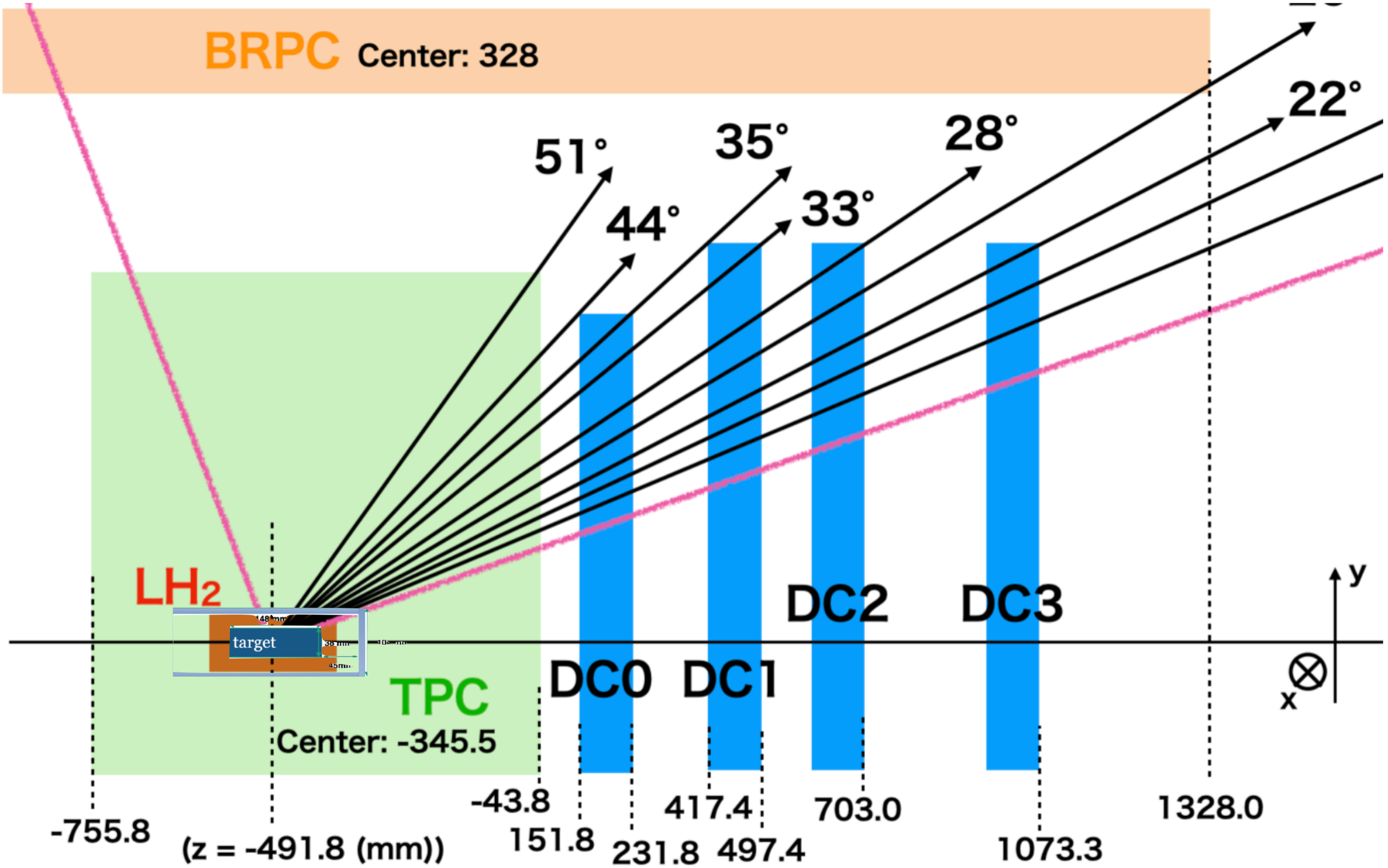
Old Correction

New Correction



$C_1 \propto$ Interaction Rate(SSC(n>2)/Clock)

A : Determined by the boundary conditions of the TPC



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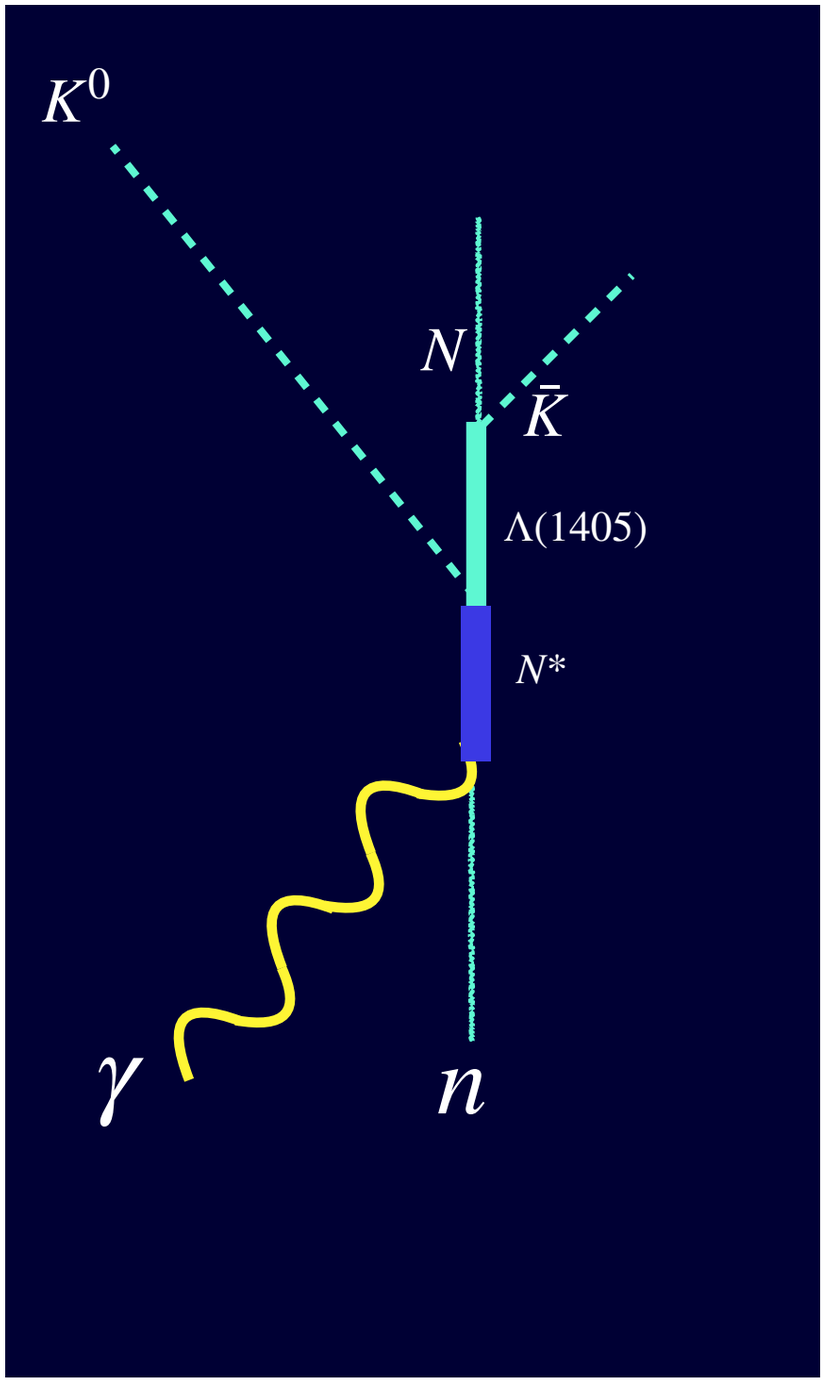
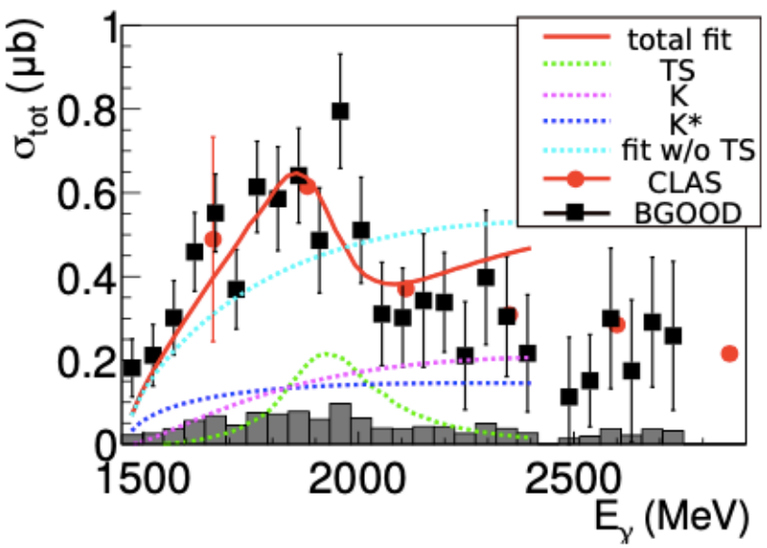


Photoproduction of $K^+\Lambda(1405) \to K^+\pi^0\Sigma^0$ extending to forward angles and low momentum transfer

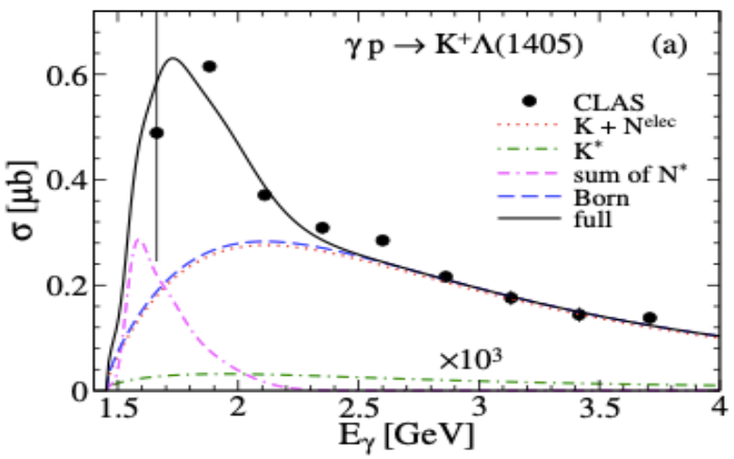
G. Scheluchin,[1,*] S. Alef,[1] P. Bauer,[1] R. Beck,[2] A. Braghieri,[3] P. Cole,[4] R. D. Salvo,[5] D. Elsner,[1] A. Fantini,[5,6] O. Freyermuth,[1] F. Ghio,[7,8] A. Gridnev,[9] D. Hammann,[1,†] J. Hannappel,[1] T. Jude,[1] K. Kohl,[1] N. Kozlenko,[9] A. Lapik,[10] P. L. Sandri,[11] V. Lisin,[10] G. Mandaglio,[12,13] R. Messi,[6,7,†] D. Moricciani,[6] A. Mushkarenkov,[10] V. Nedorezov,[10] D. Novinsky,[9] P. Pedroni,[3] A. Polonski,[10] B.-E. Reitz,[1,†] M. Romaniuk,[6,14] H. Schmieden,[1] V. Sumachev,[9,‡] and V. Tarakanov[9]
(BGOOD Collaboration)



$\gamma n \to \Lambda(1405) K^0$

N* contribution
~ 0.5 ub

K* contribution
~ 0.4 ub



N* contribution
~ 0.03 ub

K* contribution
~ 0 ub

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Role of a triangle singularity in the $\gamma p \to K^+\Lambda(1405)$ reaction

PHYSICAL REVIEW C **95**, 015205 (2017)

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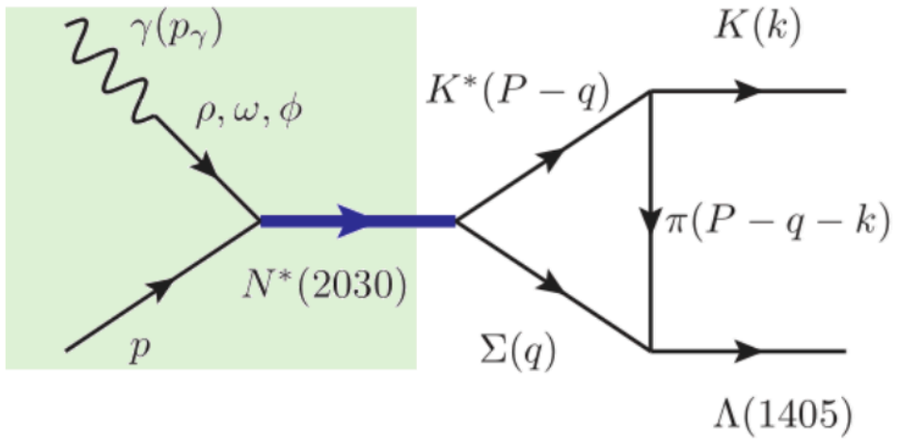
and Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC Institutos de Investigación de Paterna, Apartado 22085, 46071 Valencia, Spain

N^* process



$$-i\tilde{t} = i\frac{e}{g}\mathcal{C}_{\gamma V}\epsilon_l(\gamma)$$

$$[\gamma \to V\ (V = \rho^0, \omega, \phi)]$$

$$\mathcal{C}_{\gamma V} \equiv \begin{cases} \frac{1}{\sqrt{2}} & \rho^0 \\ \frac{1}{3\sqrt{2}} & \omega \\ -\frac{1}{3} & \phi \end{cases}$$

$$g_{N^*N\rho} = -0.3 - 0.5i, \quad g_{N^*N\omega} = -1.1 - 0.4i,$$

$$g_{N^*N\phi} = 1.5 + 0.6i, \quad g_{N^*K^*\Sigma} = 3.9 + 0.2i.$$

(*NV*: isospin basis)

Eur. Phys. J. A **44**, 445–454 (2010)

Dynamically generated resonances from the vector octet-baryon octet interaction

E. Oset[1] and A. Ramos[2,a]

$$|\rho N\rangle^{I_z=+1/2}_{I=1/2} = -\sqrt{\frac{2}{3}}|\rho^+ n\rangle - \sqrt{\frac{1}{3}}|\rho^0 p\rangle$$

$$|\rho N\rangle^{I_z=-1/2}_{I=1/2} = +\sqrt{\frac{1}{3}}|\rho^0 n\rangle - \sqrt{\frac{2}{3}}|\rho^- p\rangle$$

$$[|\rho^+\rangle = -|I=1, I_z=+1\rangle]$$

$$g_{\gamma N,N^*} = \sum_{V=\rho^0,\omega,\phi} \mathcal{C}_{\gamma V} g_{N^*NV}$$

$$= \frac{1}{\sqrt{2}}\left(\frac{\mp 1}{\sqrt{3}} g_{N^*N\rho}\right) + \frac{1}{3\sqrt{2}} g_{N^*N\omega} - \frac{1}{3} g_{N^*N\phi}$$

(−: proton, +: neutron)

$$\frac{|g_{\gamma n,n^*}|^2}{|g_{\gamma p,p^*}|^2} \sim 2.5$$

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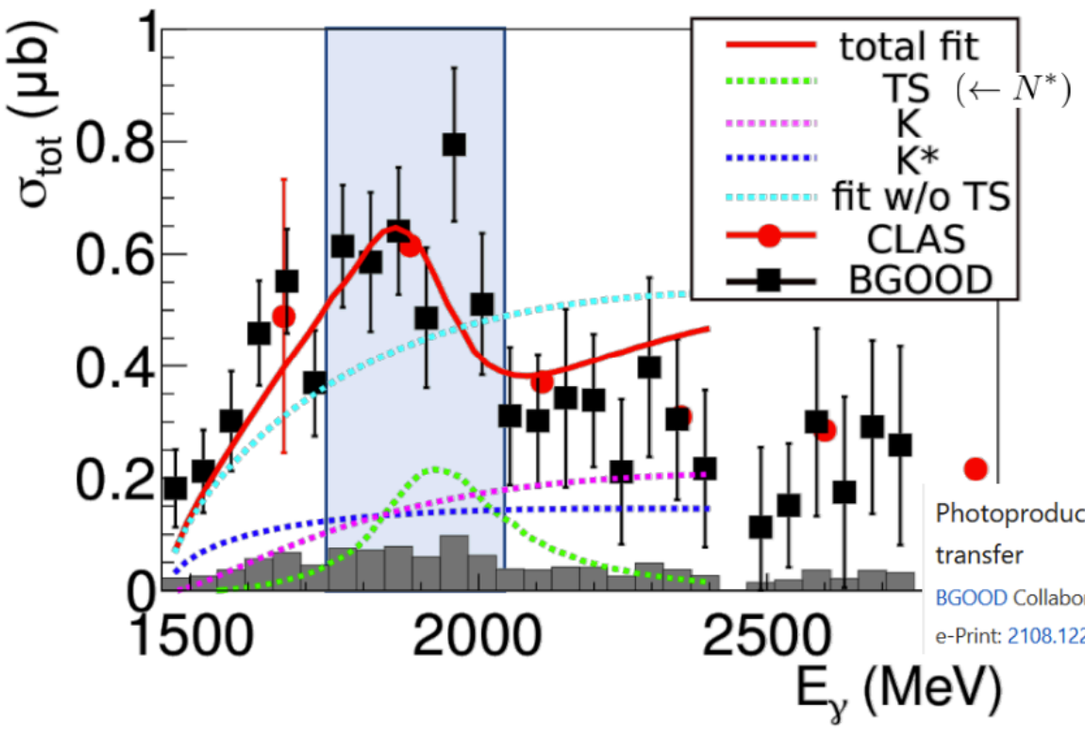

Photoproduction of $K^+\Lambda(1405) \to K^+\pi^0\Sigma^0$ extending to forward angles and low momentum transfer

BGOOD Collaboration • G. Scheluchin (Bonn U.) et al. (Aug 27, 2021)

e-Print: 2108.12235 [nucl-ex]

- Estimation (incoherent sum)

$$(2.5 \times 0.2)_{N^*} + (2.5 \times 0.15)_{K^*} + (0 \times 0.15)_{K} + (? \times 0.05)_{K\bar{K}N}$$

$$\sim 0.9\ \mu\text{b} \ + \ ?_{K\bar{K}N}$$

$$[E_\gamma \sim 1.9\ \text{GeV}]$$

$$\sigma_{\gamma n \to K^0\Lambda(1405)} \sim 0.9\ \mu\text{b?}$$

$$(\sigma_{\gamma n \to n^* \to K^0\Lambda(1405)} \sim 0.5\ \mu\text{b})$$

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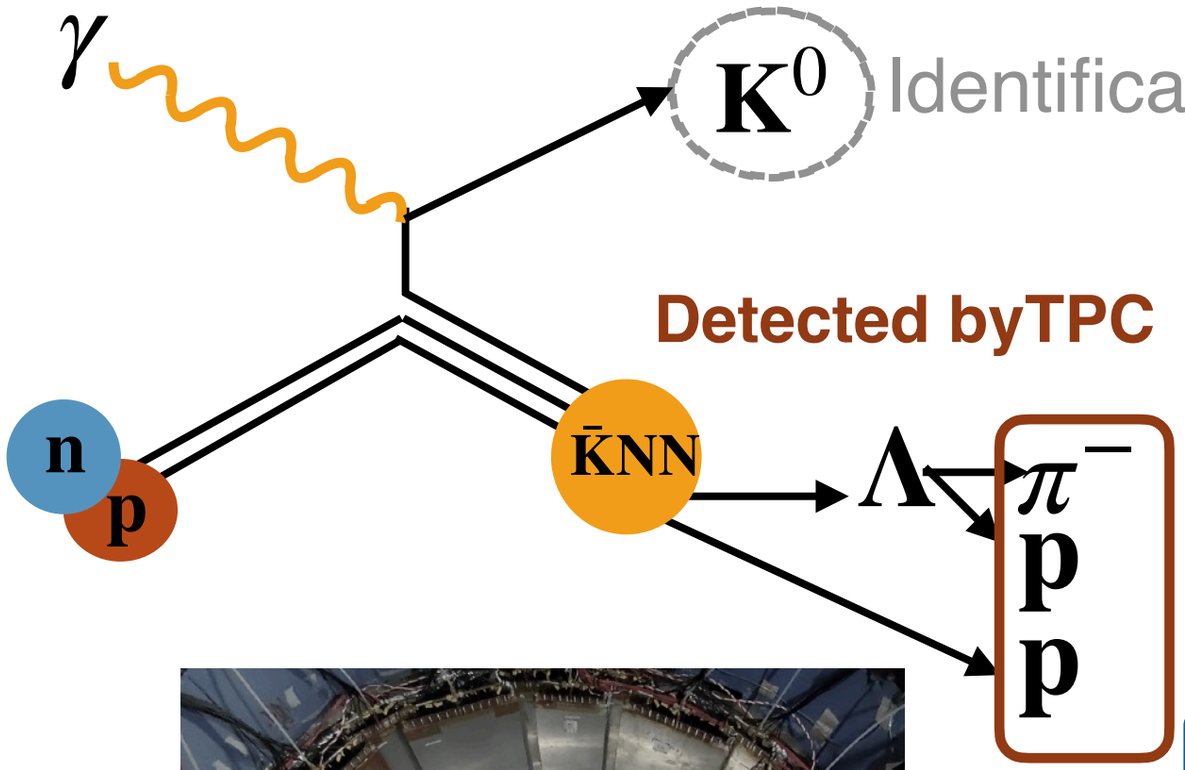
Estimation of the $\bar{K}NN$ yield



Identification by missing mass

Detected byTPC

$$Y(\bar{K}NN \rightarrow \Lambda p \text{ mode})$$

$$= \#\text{photons}\ (5.7 \times 10^{12}(2022-2023))$$

$$\times \#\text{deuterons}(\ 6.7 \times 10^{23})\quad \text{14 cm } LD_2 \text{ target}$$

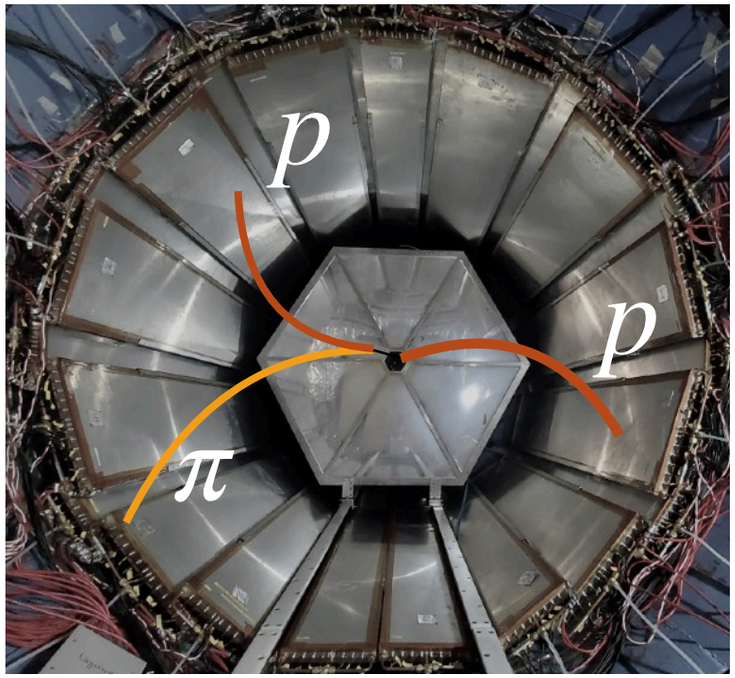
$$\times \sigma_{\bar{K}NN \rightarrow \Lambda p}\ :\ (7.5-75\ \text{nb})$$

$$\sigma_{\gamma n \rightarrow K^0\Lambda(1405)}\ :\ (0.1-1\ \mu\text{b})$$ Ref.E27

$$\times \text{the Probability of } \Lambda^* p \rightarrow (\bar{K}NN) \rightarrow \Lambda p(\ 7.5\%)$$

$$\times \text{Geometric acceptance}\ (\approx 5\%)$$

$$\approx 3000\ \text{events}(\text{if}\ \sigma_{Kpp \rightarrow \Lambda p} = 15\text{nb})$$



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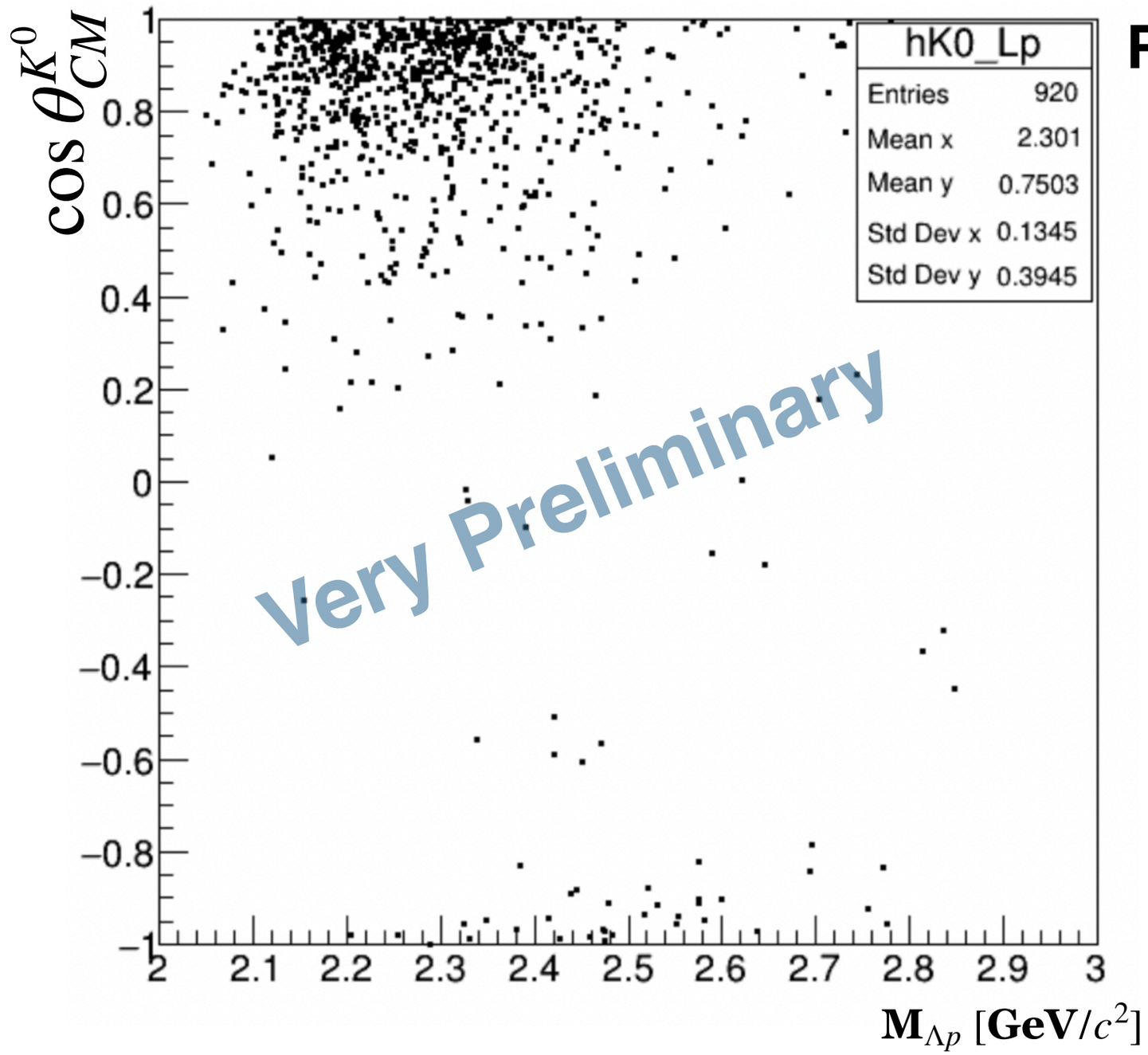
K^0 polar angle



Real Data

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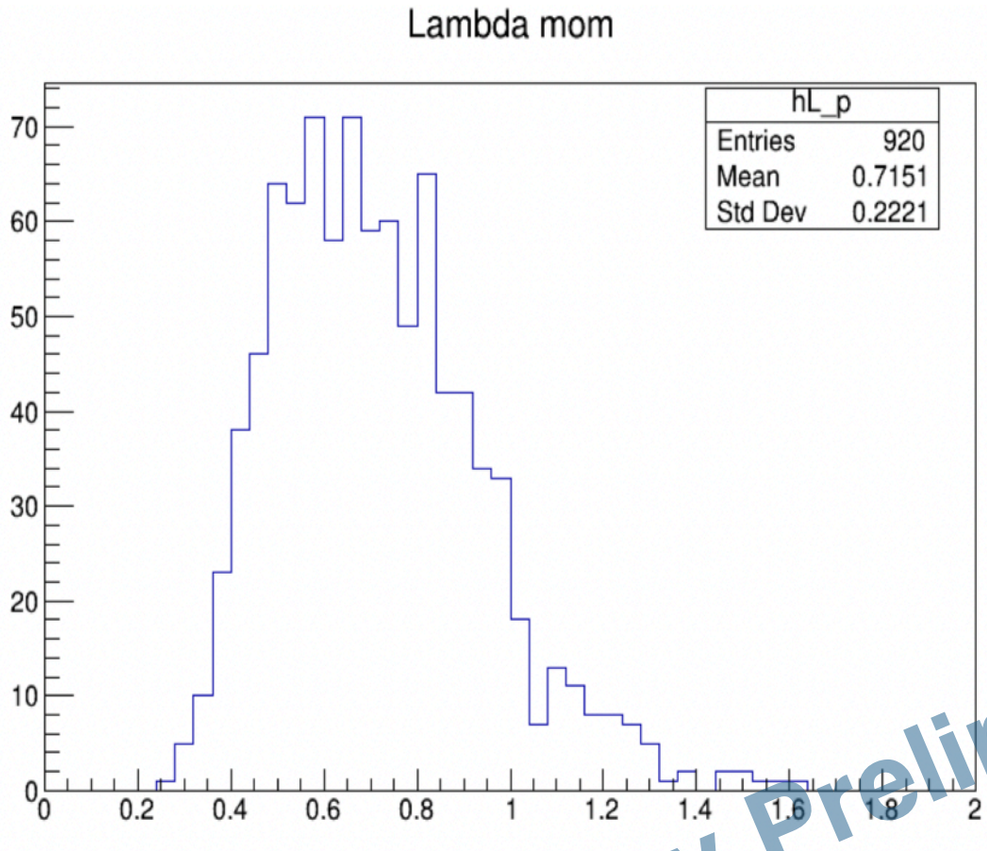

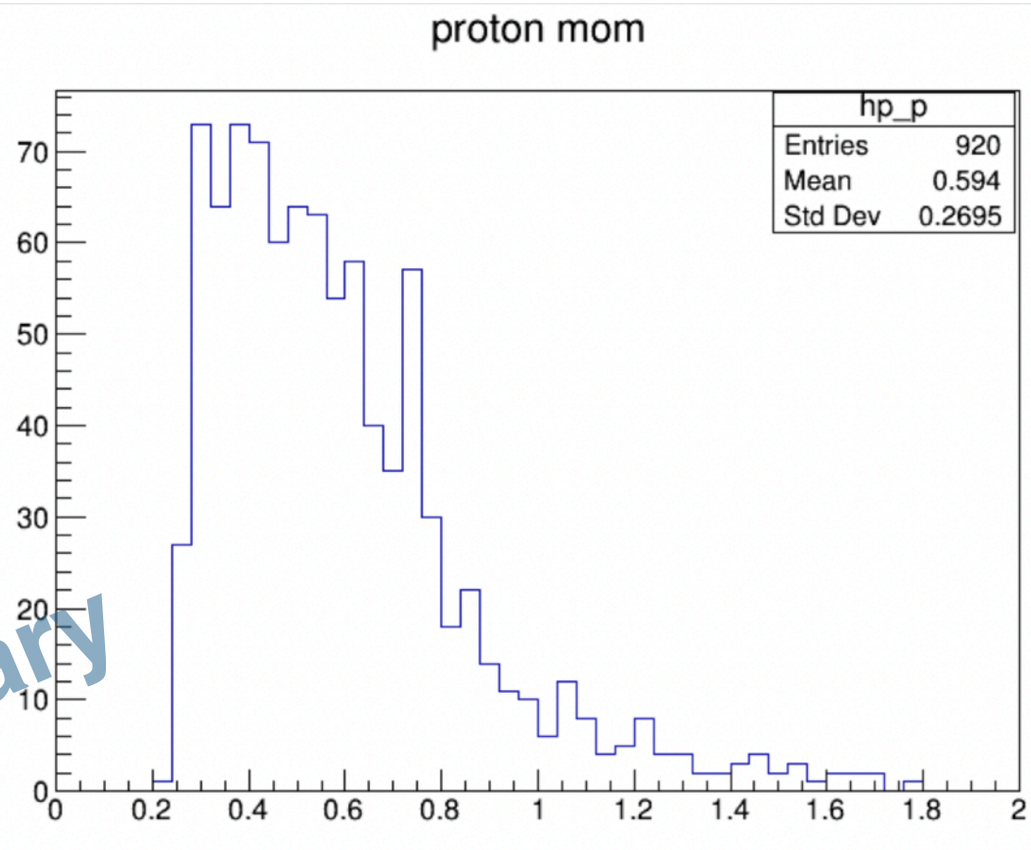

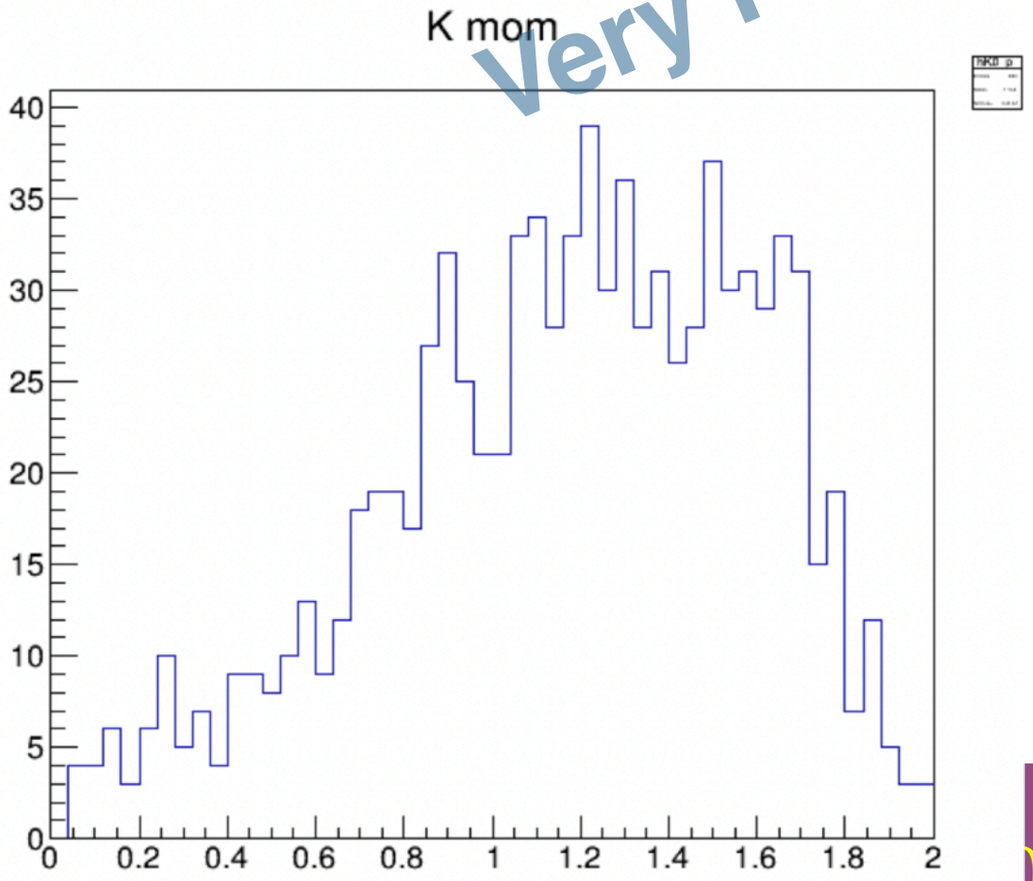

Real Data

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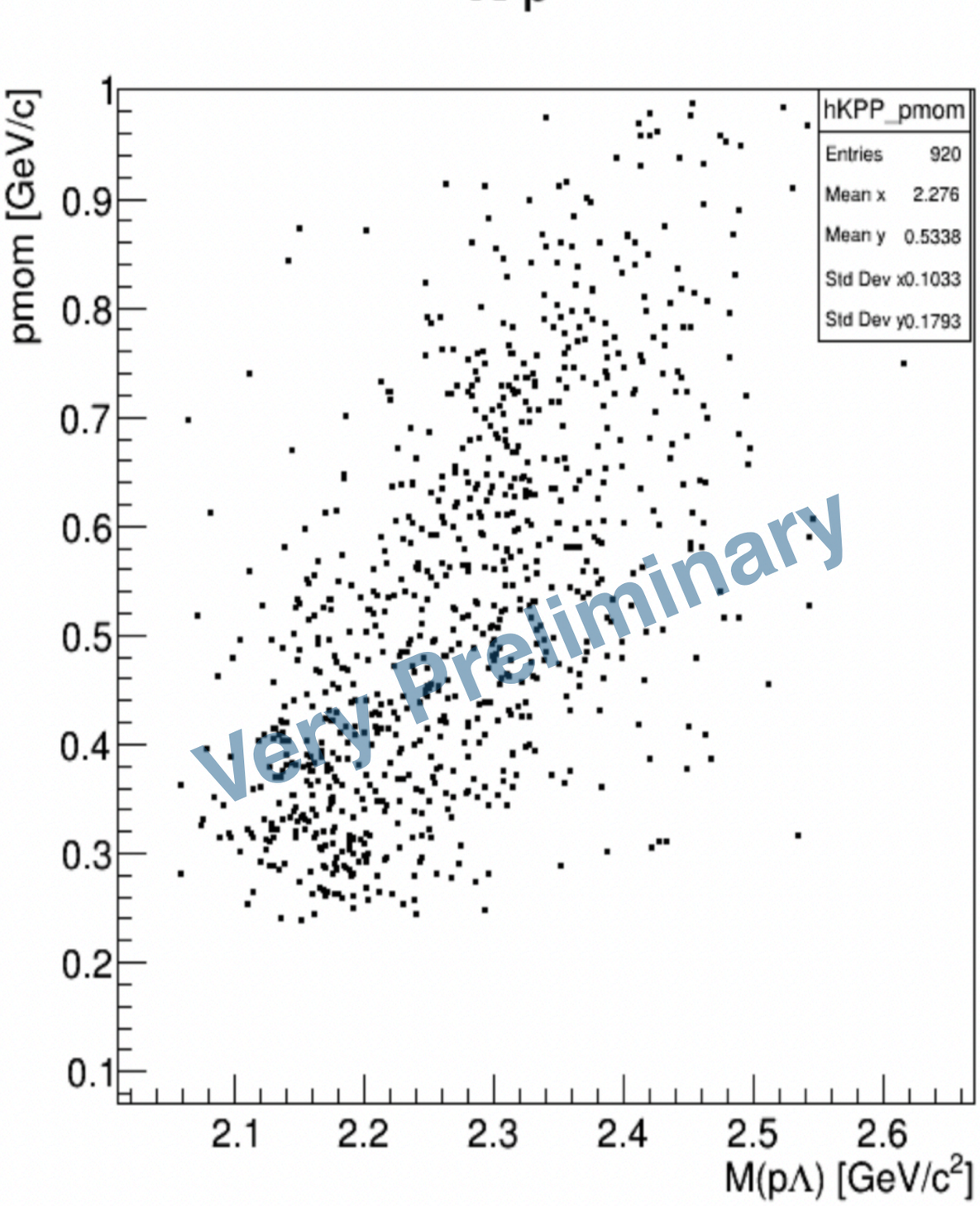
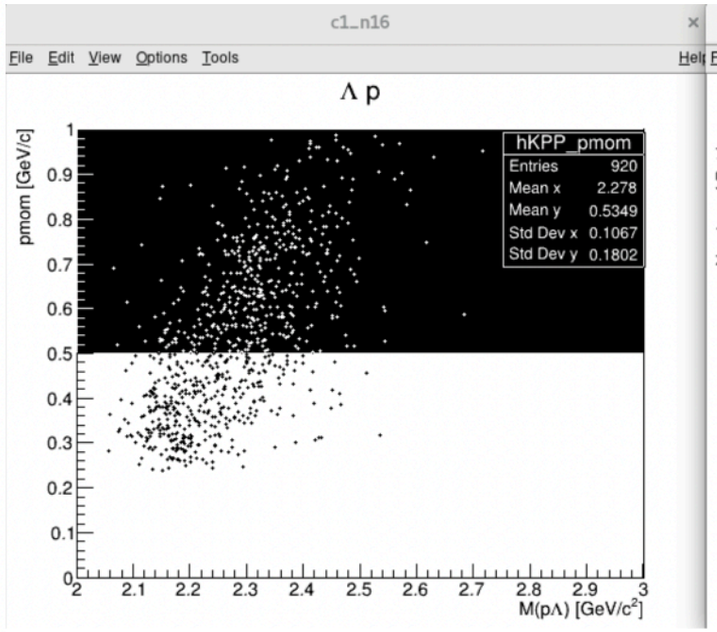
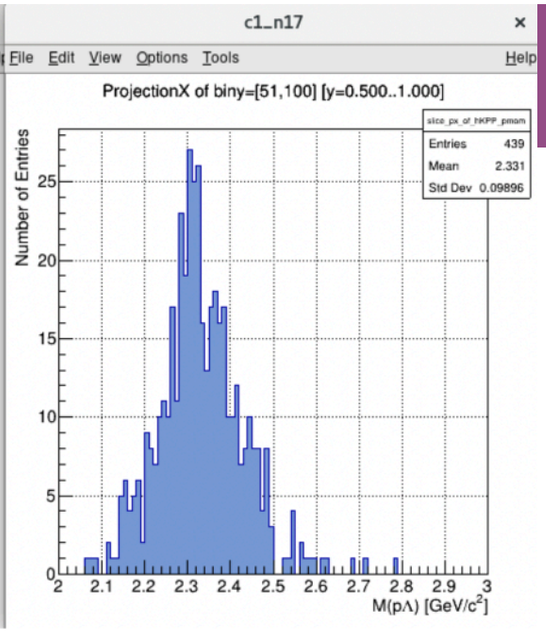
Real Data

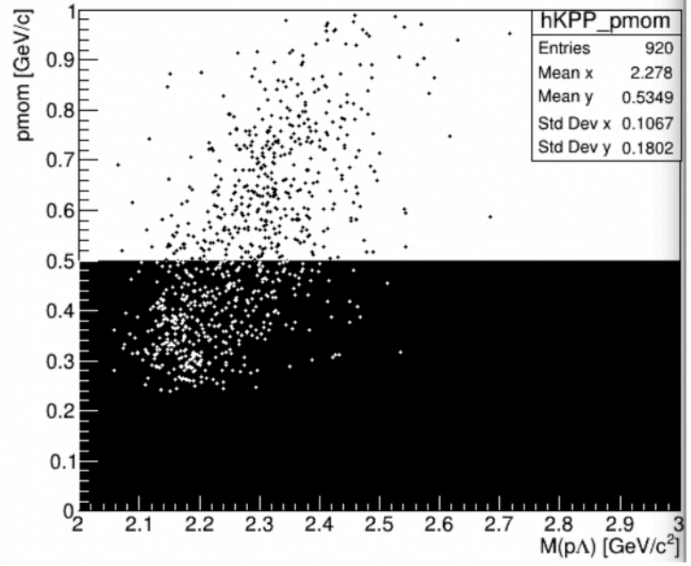


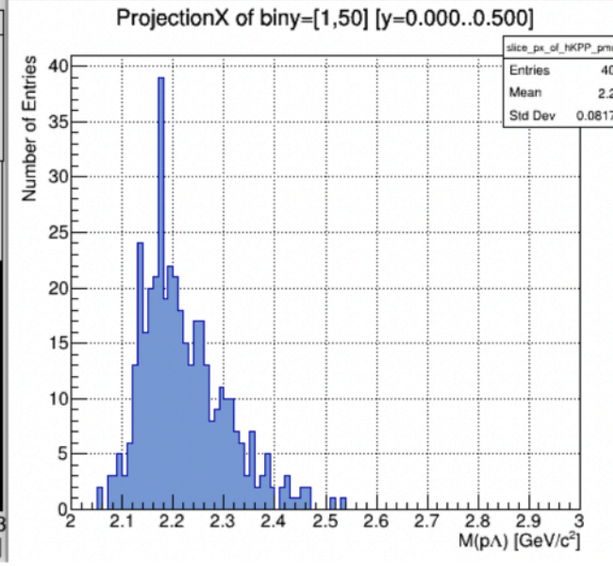
proton > 0.5 GeV/c





proton < 0.5 GeV/c





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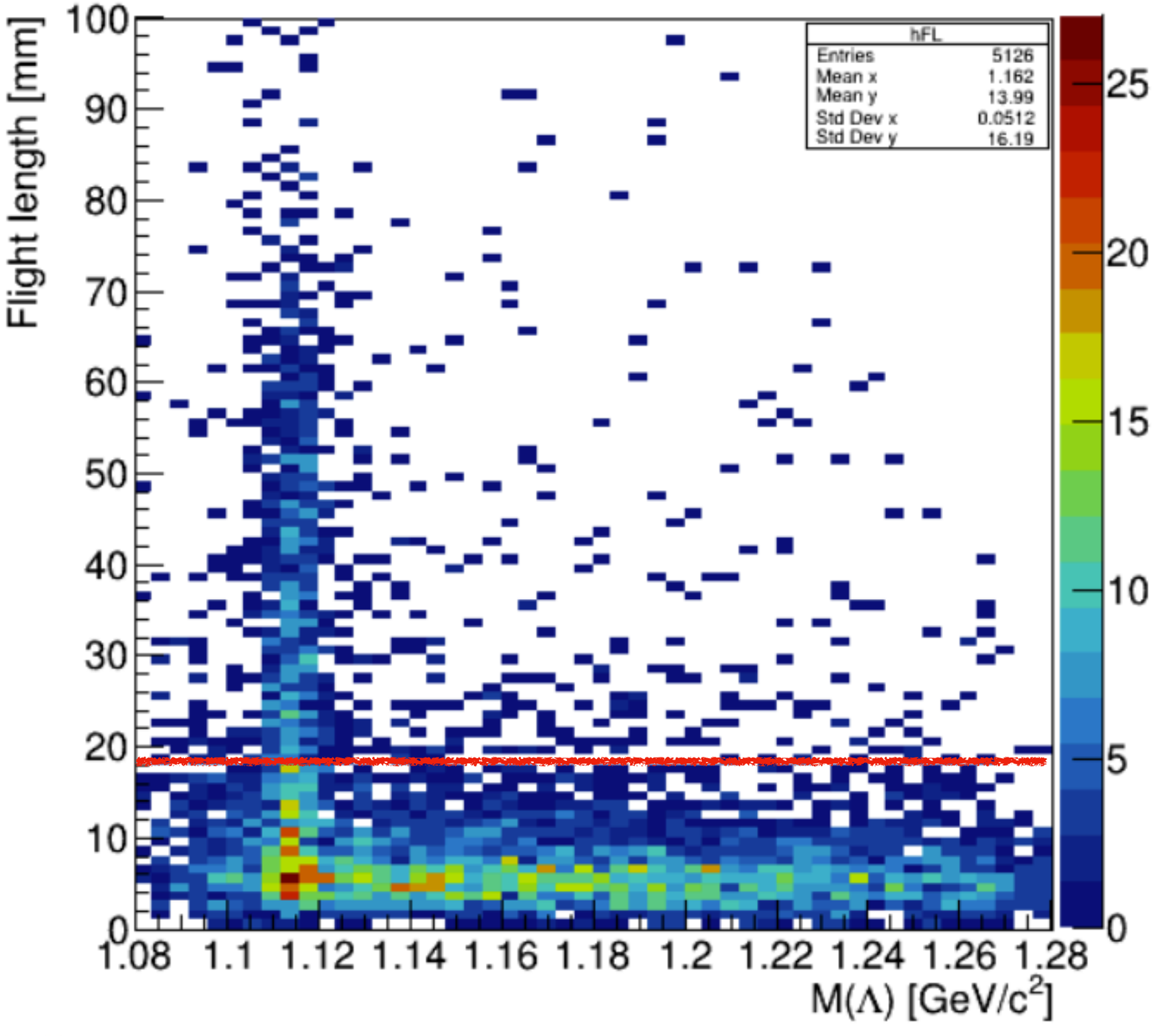
Lambda Flight length cut



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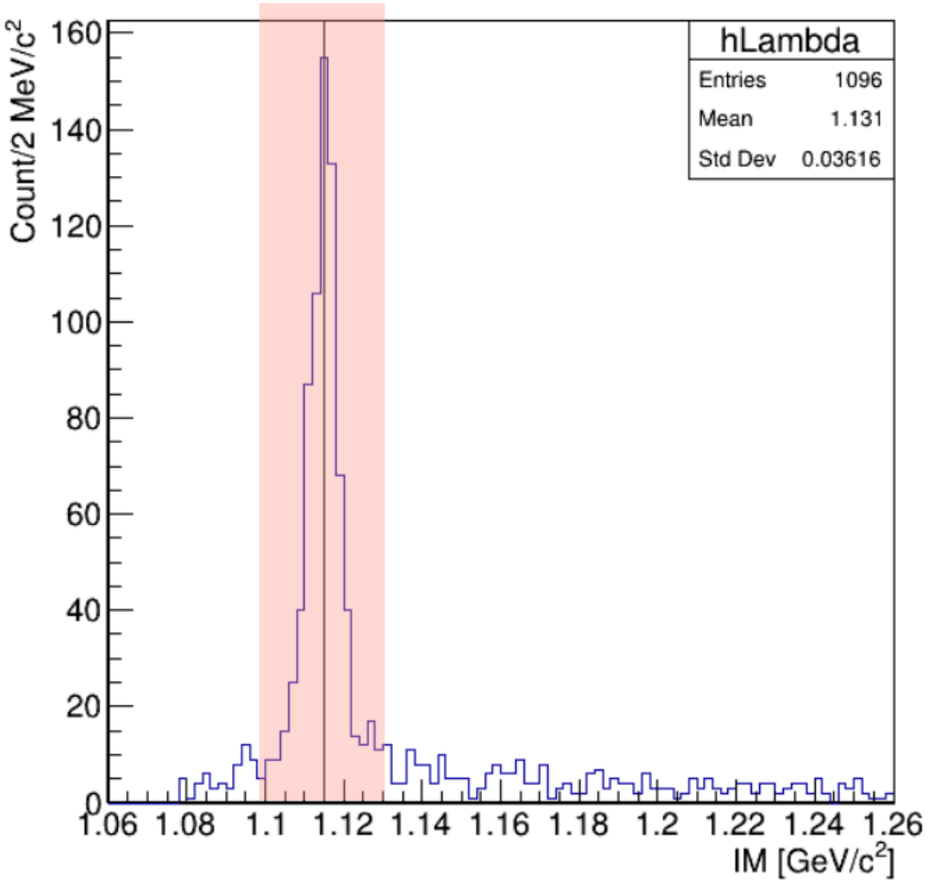
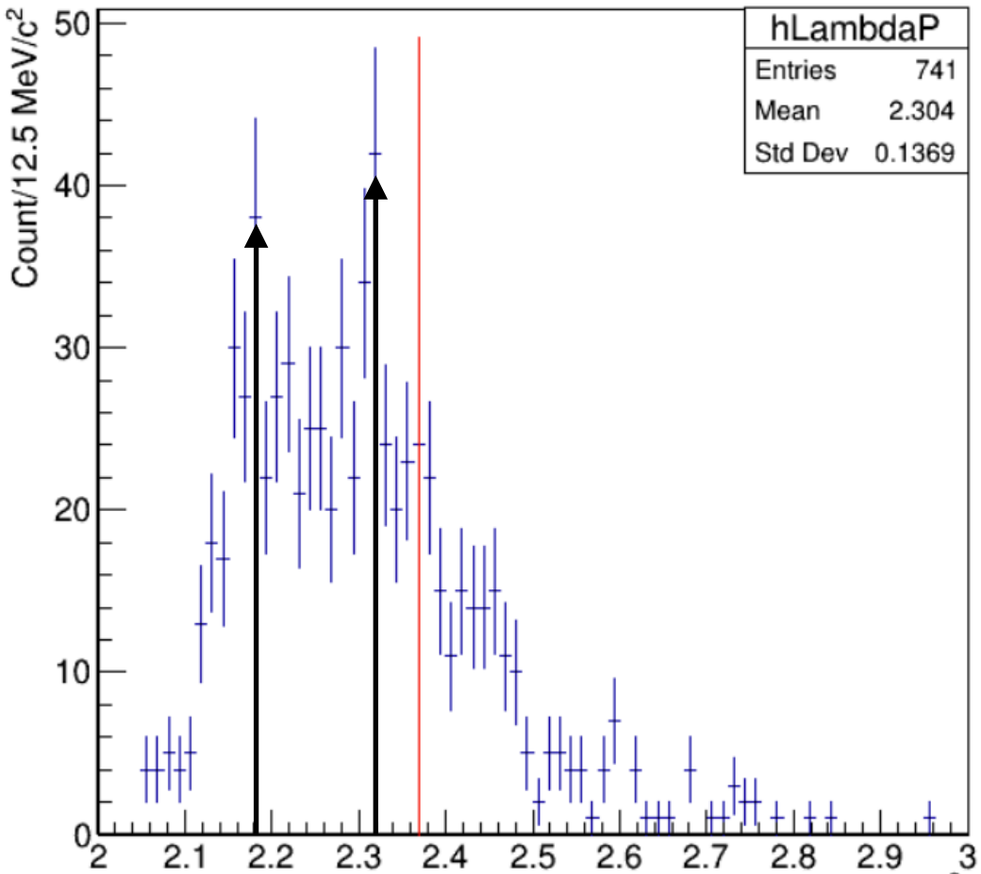
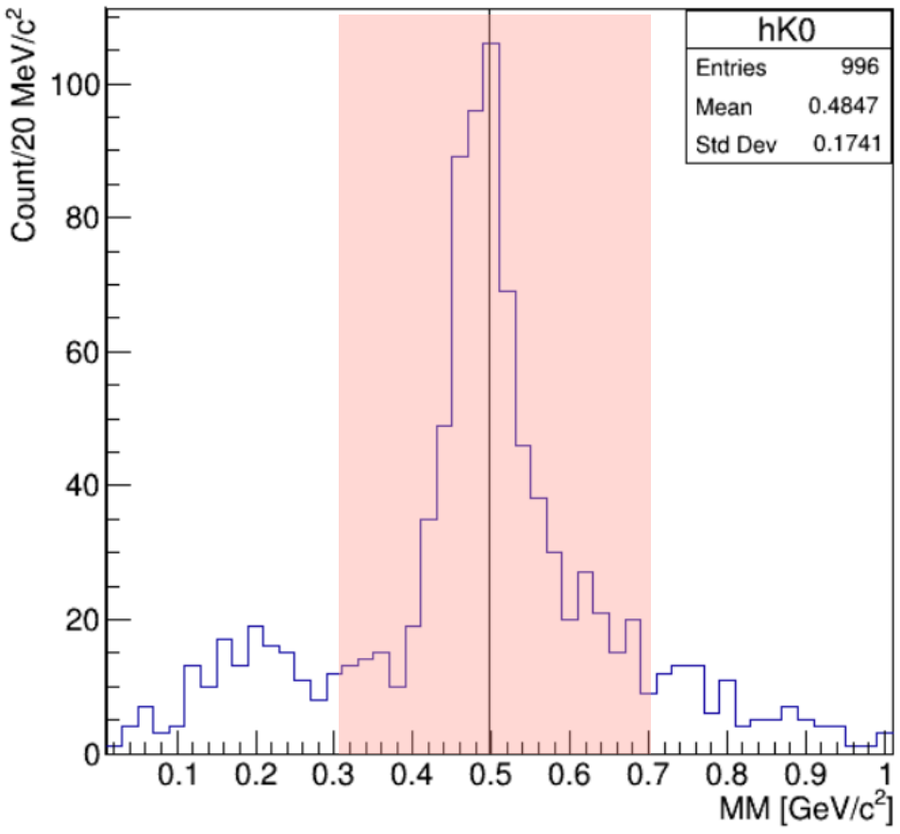
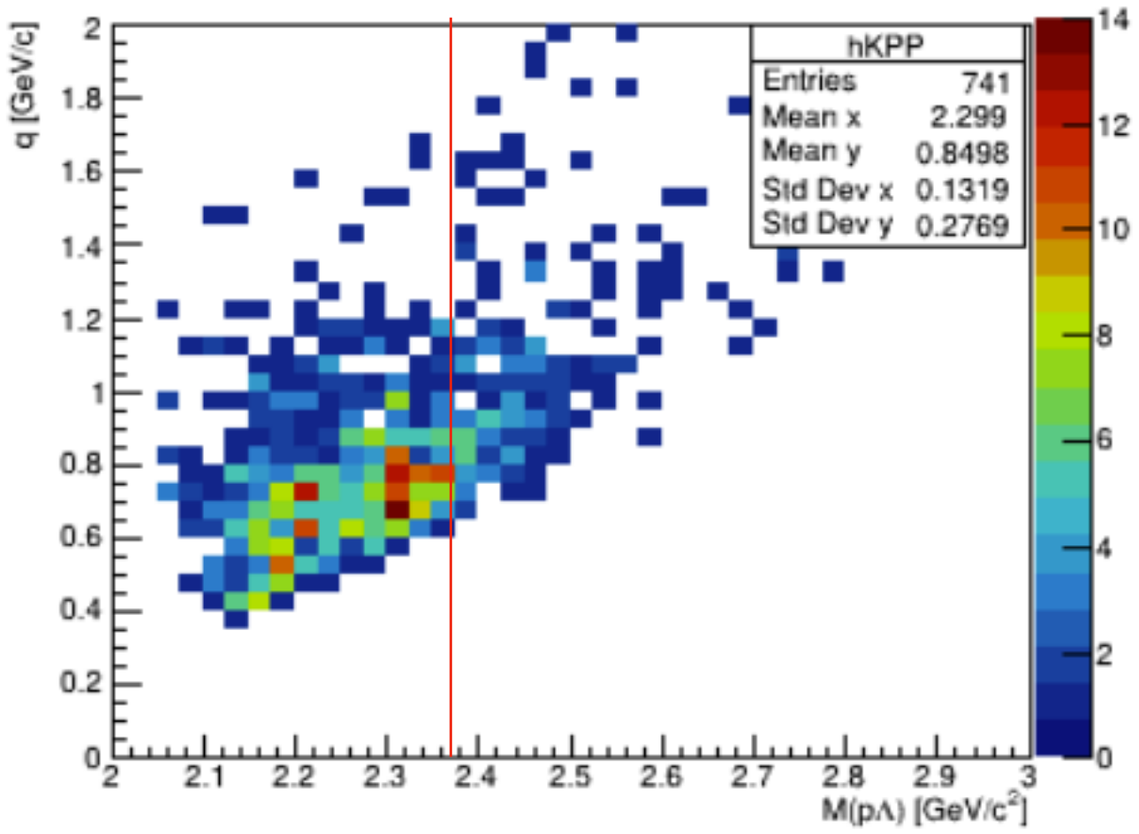
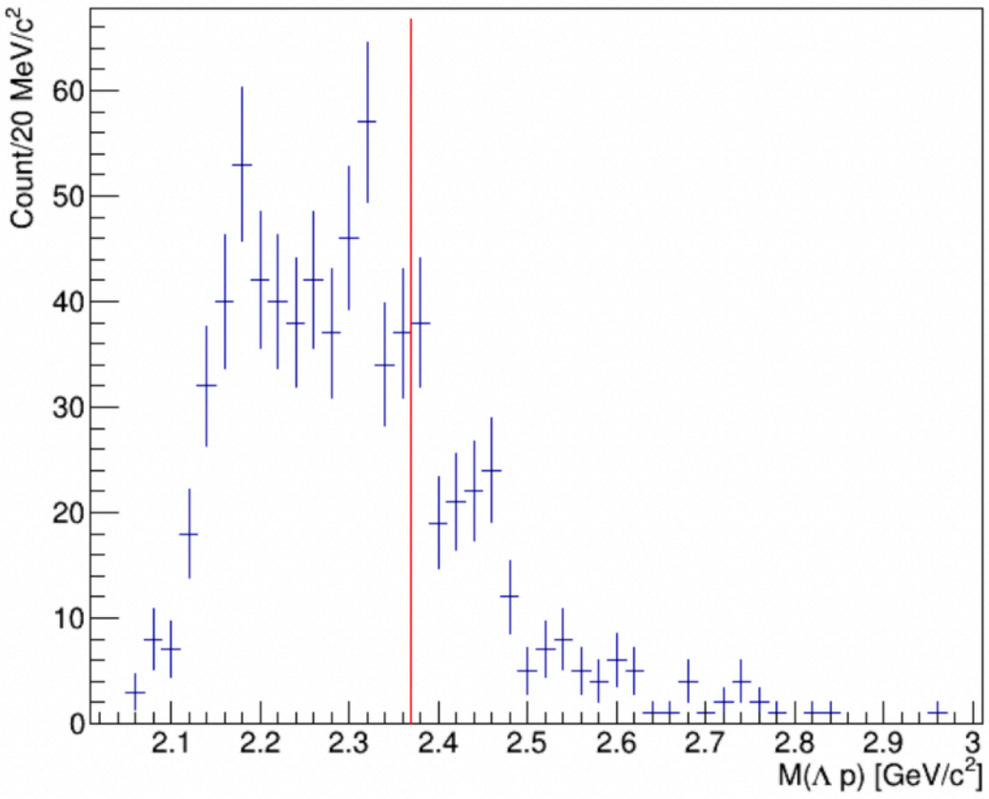

hLambda
Entries 1096
Mean 1.131
Std Dev 0.03616
Count/2 MeV/c²
IM [GeV/c²]

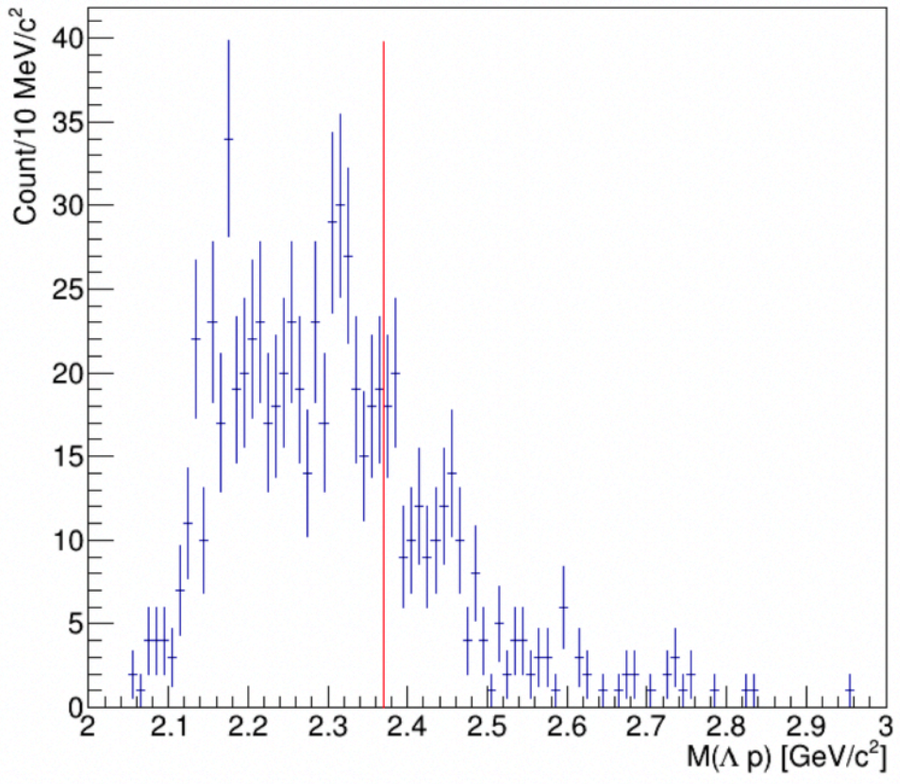

hLambdaP
Entries 741
Mean 2.304
Std Dev 0.1369
Count/12.5 MeV/c²
M(Λ p) [GeV/c²]

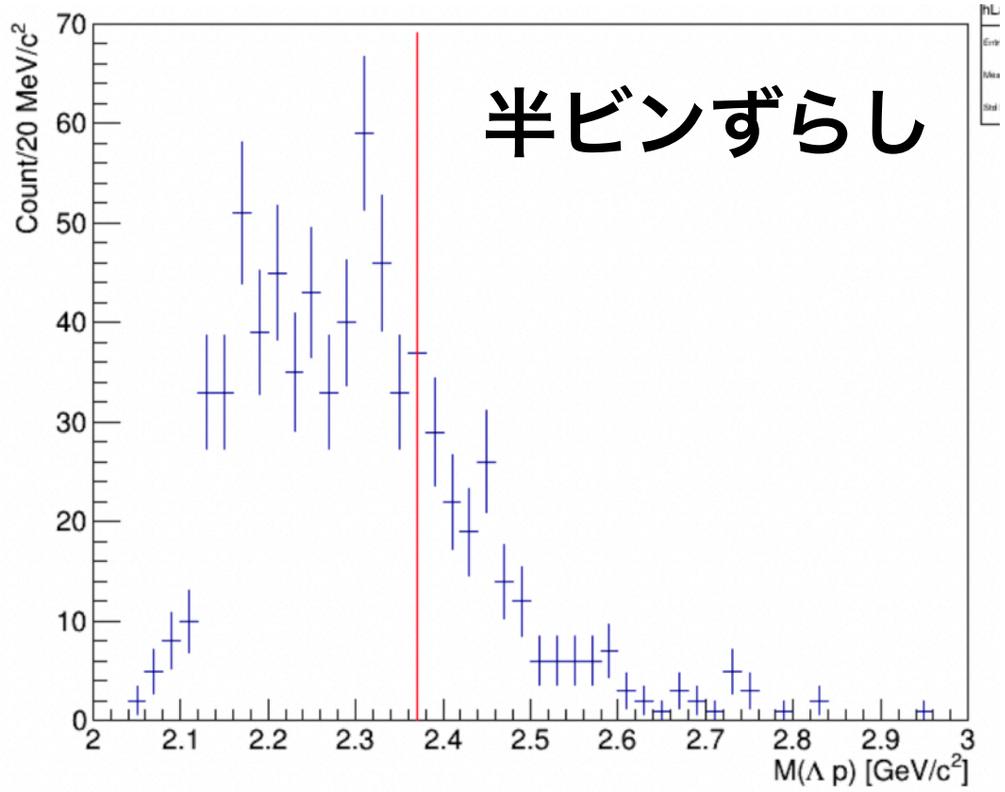

hK0
Entries 996
Mean 0.4847
Std Dev 0.1741
Count/20 MeV/c²
MM [GeV/c²]

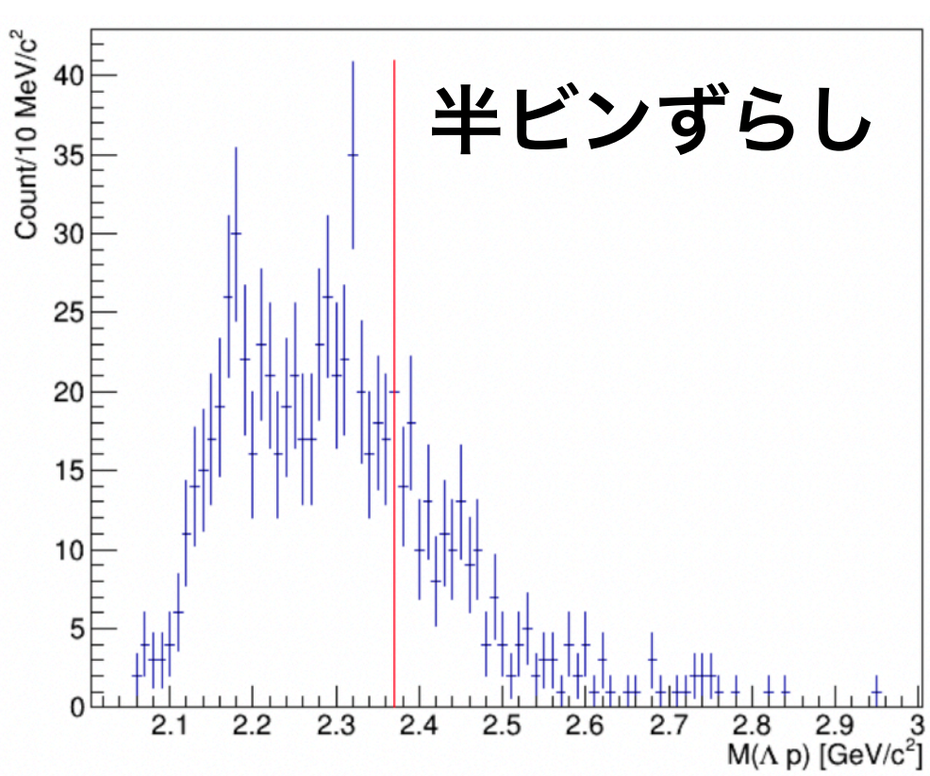

hKPP
Entries 741
Mean x 2.299
Mean y 0.8498
Std Dev x 0.1319
Std Dev y 0.2769
q [GeV/c]
M(pΛ) [GeV/c²]

/02-04









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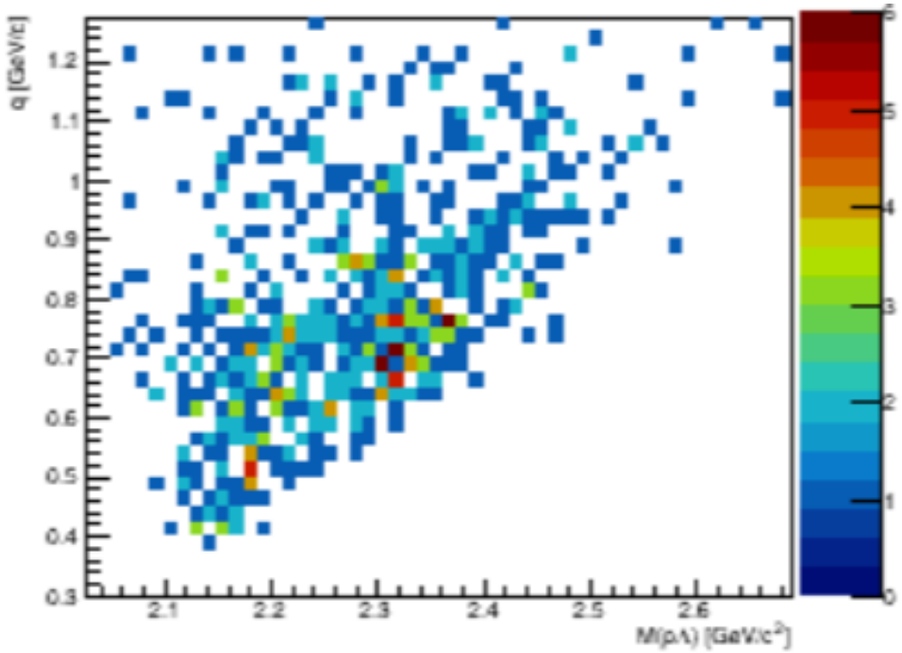

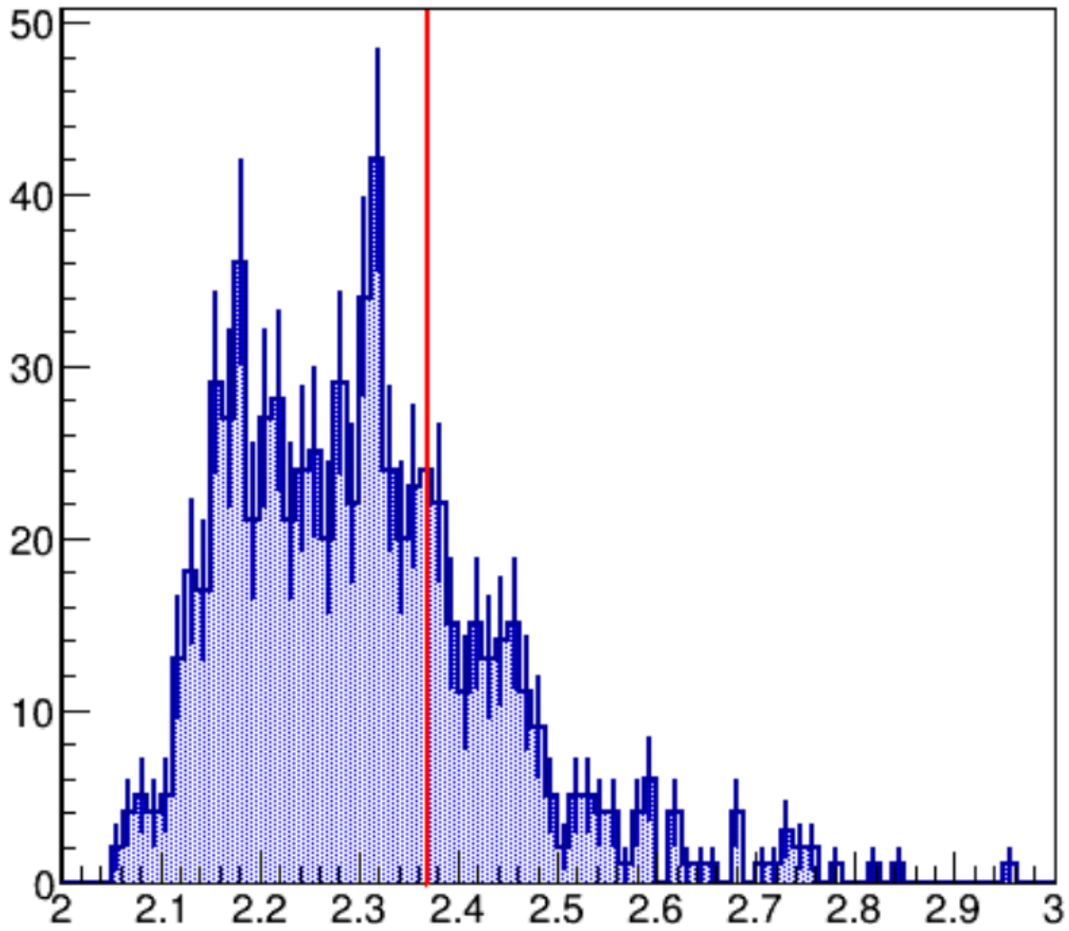

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