Simulation of $K_L + p \to \theta^+ \to K^+ + n$ and Background Reactions in GlueX detector

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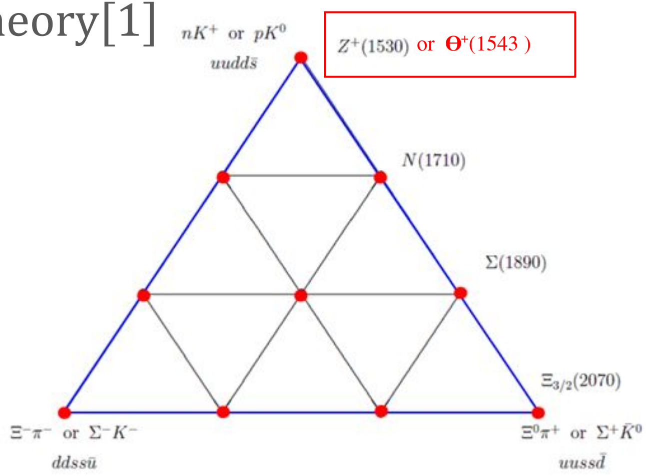
1. Motivation and expectations.
2. Measuring Method, θ^+ signal in K_L beam profile .
3. KLF Beam, Fluxes, and Backgrounds.
4. MC generators and PID samples.
5. Trigger effect on θ^+ signal.
6. Background vs θ^+. Standard MC generator.
7. Background vs θ^+. Cocktail MC generator.
8. Preshower Trigger and Reduced Magnetic Field
9. Conclusion

1. Motivation for Θ^+ Searches

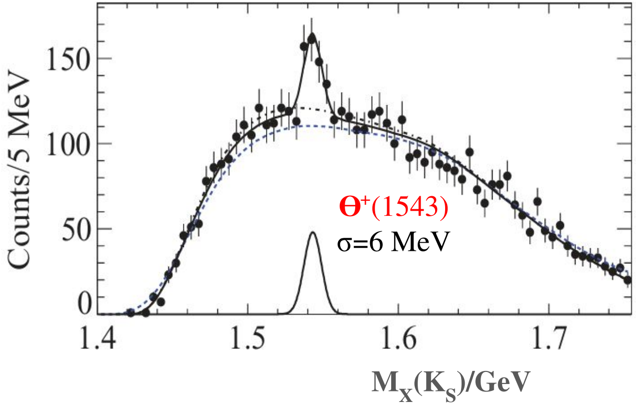
Theory[1]



Anti-decuplet of baryons [1].

Experiment [2]

$\gamma+p\to p\phi\to pK_L K_s$ $\gamma+p\to K_S\Theta^+\to pK_L K_S$

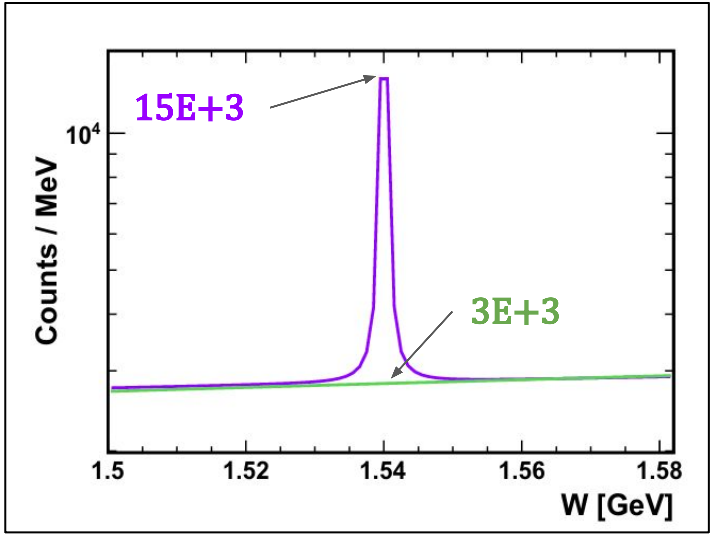


- Effect of Θ^+ must be seen in $K_L p \to K^+ n$ in GlueX detector at KLF (?).
- Using Hall D MC we show that GlueX detector is ideal tool for Θ^+ search (!).

[1] D. Diakonov, V. Petrov, and M. V. Polyakov, "Exotic anti-decuplet of baryons: Prediction from chiral solitons.", Z. Phys. A 359, 305 (1997)

[2] M. Amaryan, "20 Years of Light Pentaquark Searches", arXiv:2503.21545v2 [hep-ph] 29 Mar 2025. https://arxiv.org/html/2503.21545v2.

Predictions and Expectations



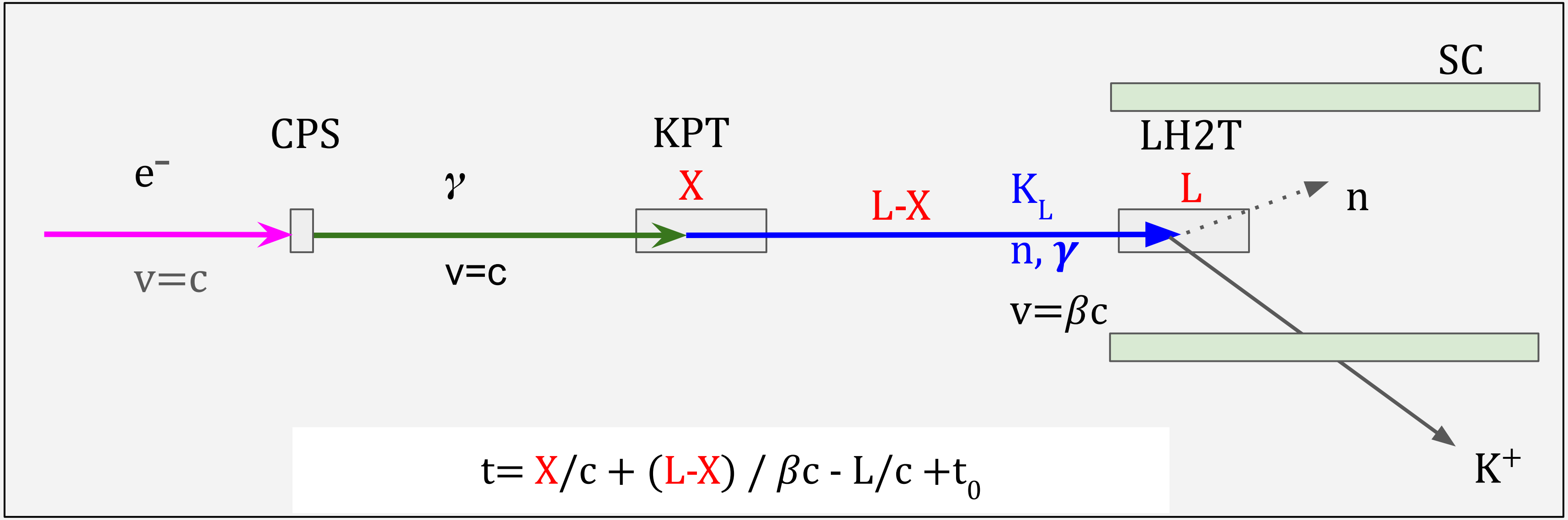
1. We expect ~20,000 of $K_L p \to \Theta^+ \to K^+ n$ during 100 days beam.
2. The **background** $K_L p \to K^+ n$ was simulated using model [18].
3. Number of events under purple curve for $\mathbf{\Theta^+}$ (1 MeV wide) is ~**10000** at ~50% Reconstruction Efficiency [16].
4. Reconstruction Efficiency to be determined below.
5. Expected background under $\mathbf{\Theta^+}$ = 3,000/15000=**~20 %**

[16] Moskov J. Amaryan, Shu Hirama, Daisuke Jido, and Igor I. Strakovsky "Search for Θ^+ in $K_L p \to K^+ n$ reaction in KLF at JLab," Mod. Phys. Lett. A 39 (2024).

[18] Y. Iizawa, D. Jido, and S. Huebsch, "K^+N elastic scatterings for estimation of in-medium quark condensate with strange quarks," [arXiv:2308.09397 [hep-ph]].

2. Measuring Method

$K_L p \rightarrow \boldsymbol{\theta}^{+} \rightarrow K^{+} n$



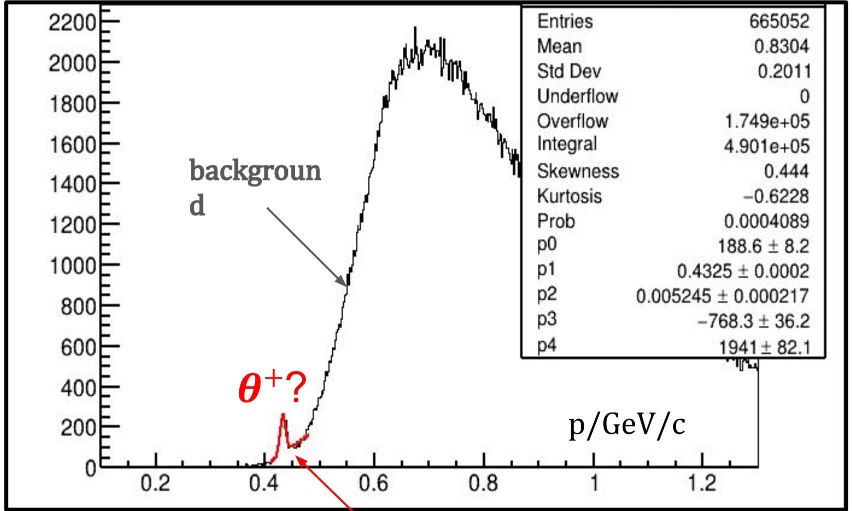
$t = X/c + (L\text{-}X) / \beta c - L/c + t_0$

- **K_L-momentum** (and W) - via **time** interval t between **RF/16** and **K^+-signal in SC extrapolated to Vertex** using K^+-momentum from GlueX tracker.

Measuring Method for $K_L p \rightarrow \theta^+ \rightarrow K^+ n$.

Time Of Flight and K_L momentum resolution.

Toy MC. $K_L p \rightarrow \theta^+ \rightarrow K^+ n$ and background



Time t between K^+ signal in SC and RF/16:

$t = X/c + (L\text{-}X)/\beta c - L/c + t_0$;

$\beta = (1+c(t-t_0)(L\text{-}X)^{-1})^{-1}$,

where X - coordinate in KPT; L-in LH2 target.

Both X and L fluctuates ; plus smearing in SC, and across LH2 target . Therefore resulting

σ_p(0.44 GeV/c)=**5** MeV/c ;

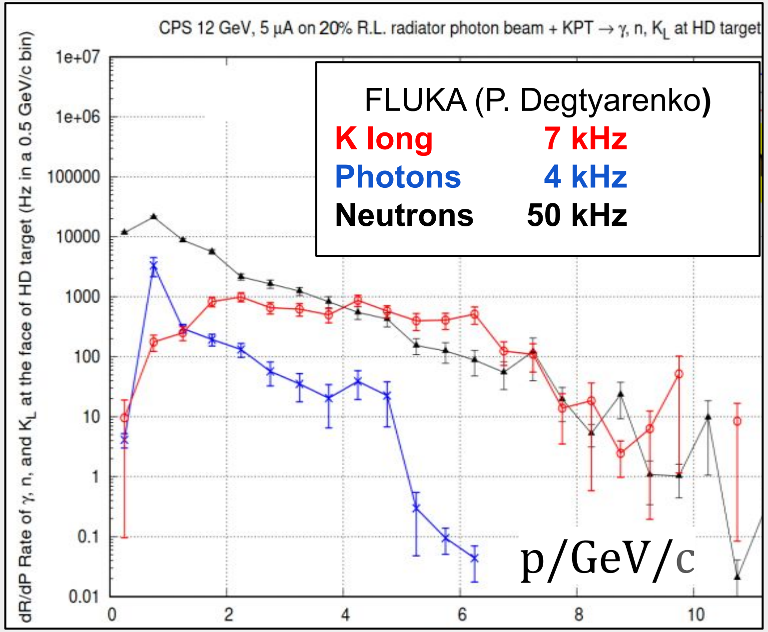
σ_W(1.54 GeV) =**2** MeV.

- To observe θ^+ we explore the **K_L momentum profile** for K^+n final state with a hope **to see a narrow (** σ_p=5 MeV/c) **peak at p =0.44 GeV/c** (W=1.54 GeV/c) on top of **background (??).**

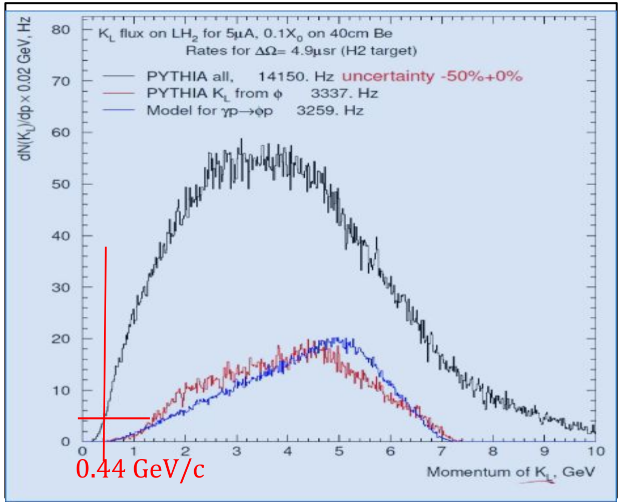
3. Fluxes and Backgrounds

K_L-beam is wide and contains neutron and photon components. Backgrounds:

1. From various K_L+p → … reactions.
2. From **n-** and $\boldsymbol{\gamma}$-beams on the LH2 target.
3. From the "bleed through" of 16 beam bunches.



Expected number of $K_L+p\to\theta^+\to K^+ + n$ after 100 days run at 5 μA



$N(\theta^+) = I\, t\, \sigma(\_\theta^+)\, \rho$; $\{ I\,[s^{-1}] \times t[s] \times \sigma(\theta^+)[cm^2] \times \rho[^1H/cm^2]\}$.

1. I=0.1 Hz <= θ^+ width =1 MeV/c; dI/dp=0.1 Hz/MeV/c.
2. $\sigma(\theta^+)$ =~12 mb, Ref. [a].
3. ρ=1.7E+24 [$^1H/cm^2$].

Expected amount of pentas to be produced during 100 day run:

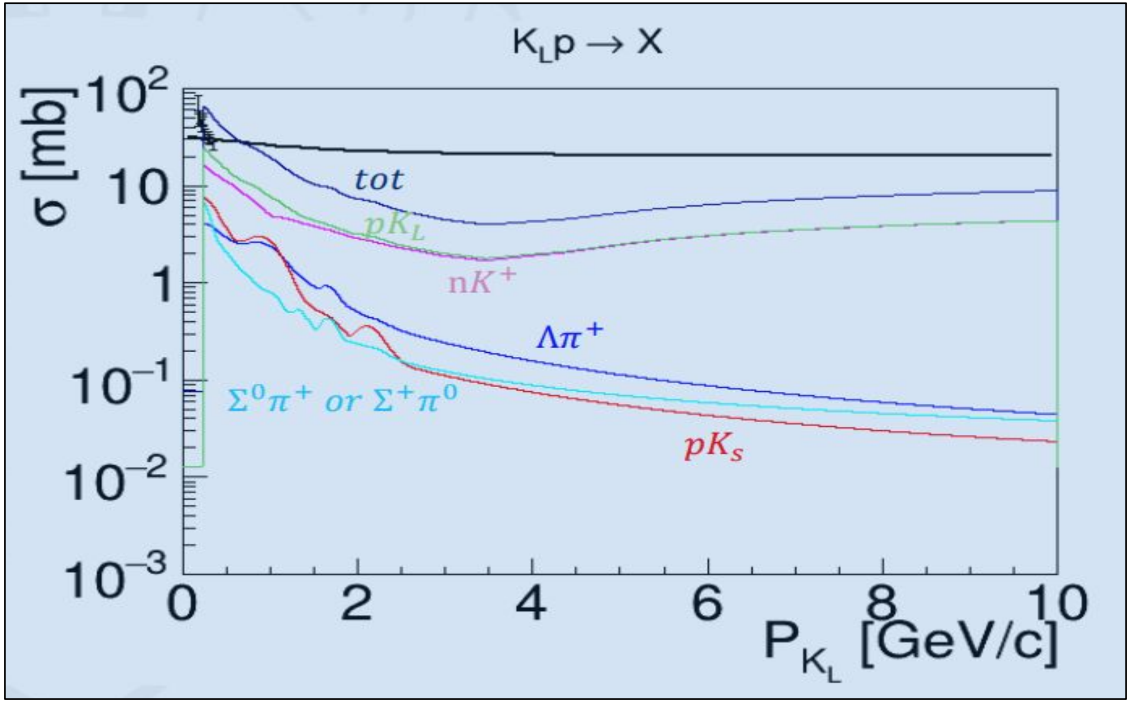
$N(\theta^+)$= 1.0 E-1[s^{-1}]×8.5 E+6[s]×12.0 E-27×1.7 E+24= **18,000**.

- Electron beam 12 GeV, 5 μA. Kaon Production Target X_0=0.1, Be , 40 cm along beam.
- The K_L flux at p = 0.44 GeV/c = dN(K_L)/dt/MeV/c =~4 Hz/20 MeV/c =0.2 Hz/MeV/c.
- For θ^+ production we admit Flux(K_L) at 0.44 GeV/c **= 0.1 Hz/MeV/c** ; (PYTHIA).

[a] M.J. Amaryan *et.al.*, "Search for Theta+ in K_L p -> K^+ n reaction in KLF at JLab", Mod. Phys. Lett. A 39, 2450063 (2024).

Cross sections of background reactions

(from M. Bashkanov)



- What is $\boldsymbol{\theta}^+$-Reconstruction Efficiency GlueX detector under these backgrounds?

4. MC Generators and PID examples

Standard Generator

For $K_L p \rightarrow \boldsymbol{\theta}^{+} \rightarrow K^{+}n$ mixed with one of Background Reactions:

1. $K_L + p \rightarrow K^{+} + n$
2. $K_L + p \rightarrow K^{+} + n$ leak
3. $n + p \rightarrow \boldsymbol{\pi}^{+} + 2n$
4. $n + p \rightarrow \boldsymbol{\pi}^{+} + 2n$ leak
5. $K_L + p \rightarrow \pi^{+} + \Lambda(1115)$
6. $K_L + p \rightarrow \pi^{+} + \boldsymbol{\Sigma}(1192)$
7. $K_L + p \rightarrow p + \pi^{+} + K^{-}$

- Standard MC generates events following phase space ditribution. No cross sections.
- Arbitrary BG statistics allows prompt study of individual contribution.

Cocktail MC Generator

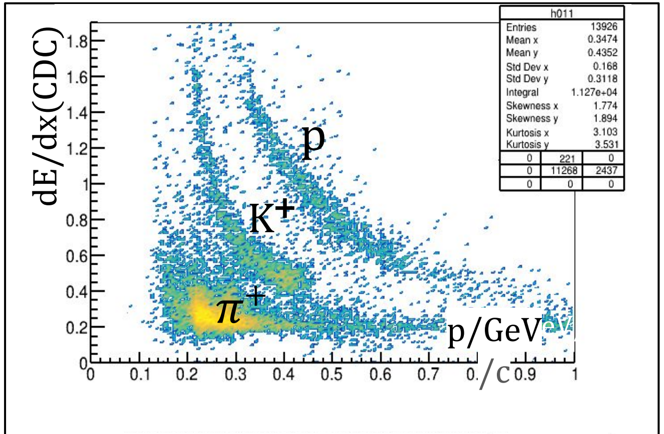
For $K_L p \rightarrow \boldsymbol{\theta}^{+} \rightarrow K^{+} n$ mixed with all background reactions.

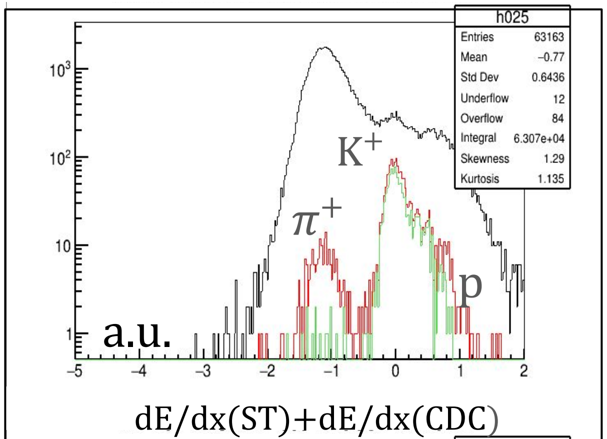
M. Bashkanov, https://wiki.jlab.org/klproject/images/2/29/KLF_Jun25_Coctail.pdf

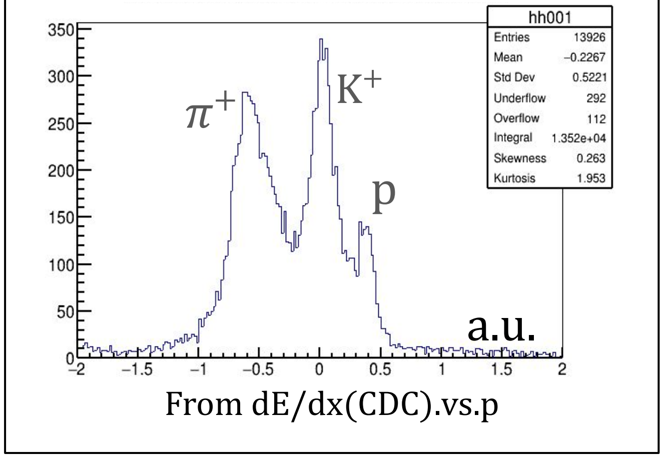
MC code	**Reaction**	Fract.tion
kl1	$K_L p \rightarrow nK^+$	0.433
kl2	$K_L p \rightarrow pK_s$	0.024
kl3	$K_L p \rightarrow \Xi^0 K^+$	0.001
kl4	$K_L p \rightarrow \Lambda\pi^+$	0.043
kl5	$K_L p \rightarrow \Sigma^+\pi^0$	0.021
kl6	$K_L p \rightarrow \Sigma^0\pi^+$	0.021
kl9	$K_L p \rightarrow pK_L$	0.457

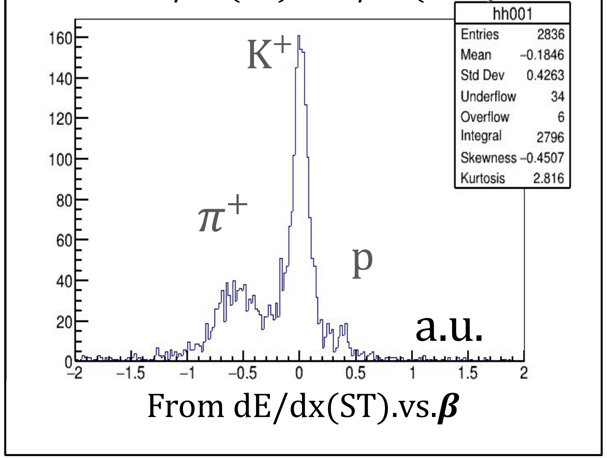
- Cocktail MC utilizes differential and total cross sections of listed+ reactions.
- Controls the statistics via “beam time”. In progress.

PID samples. K^+ Identification via dE/dx.vs.p in CDC & SC

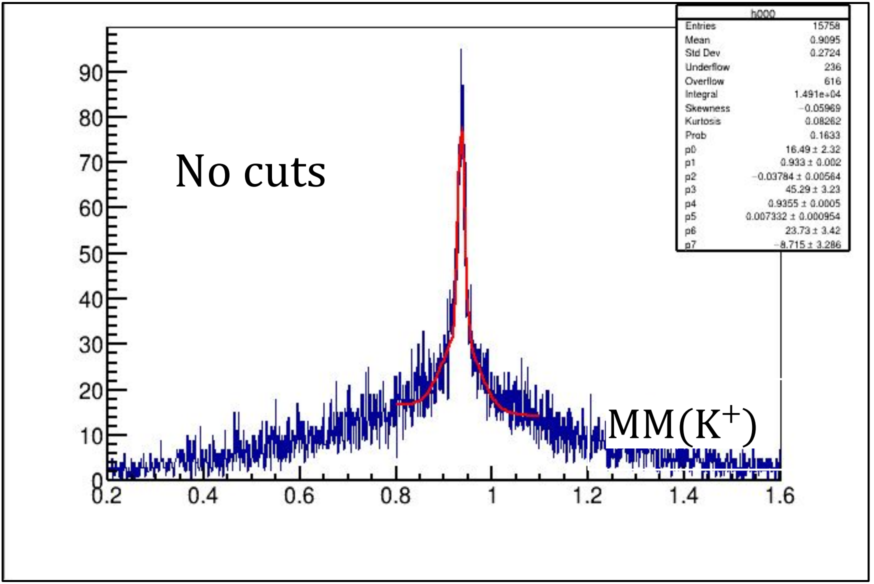


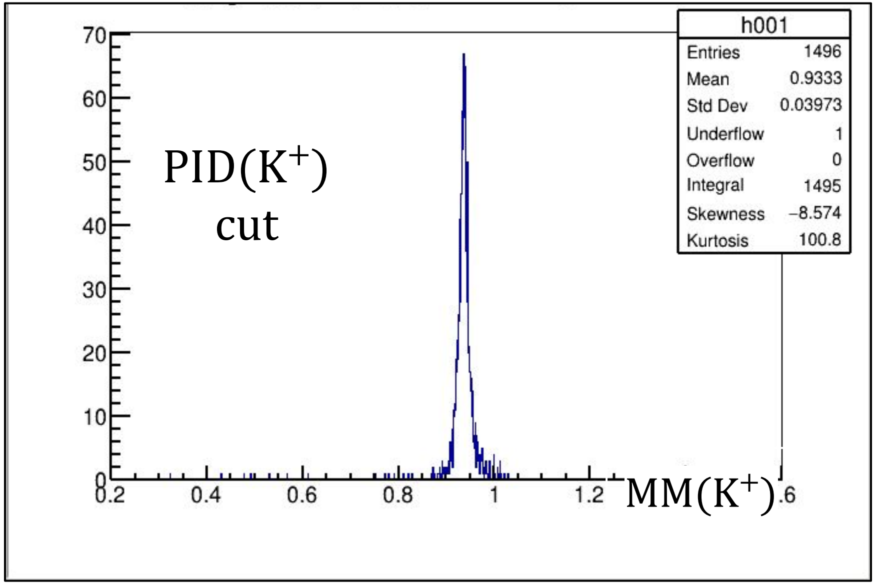






PID sample. Neutron Identification in $K_L p \to \boldsymbol{\theta}^+ \to K^+ n$ mixed with $K_L p \to K^+ n$

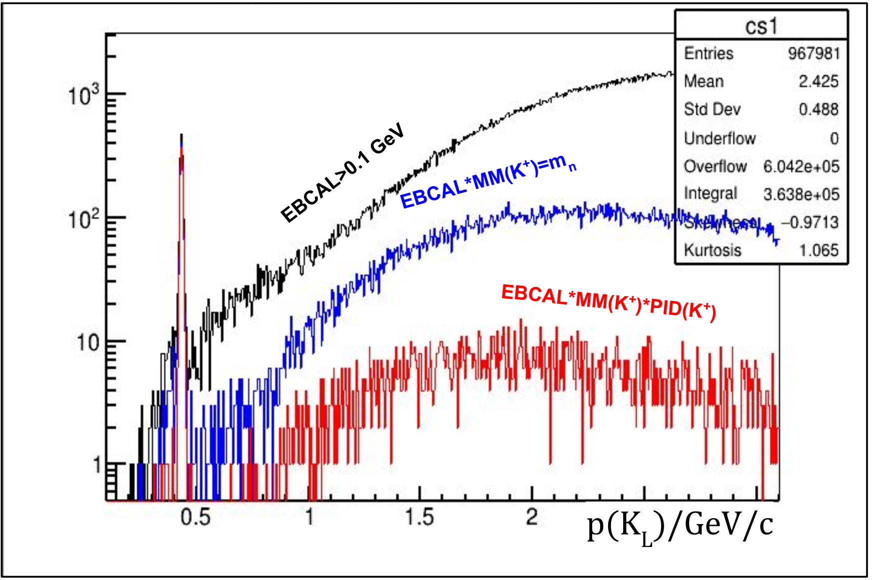




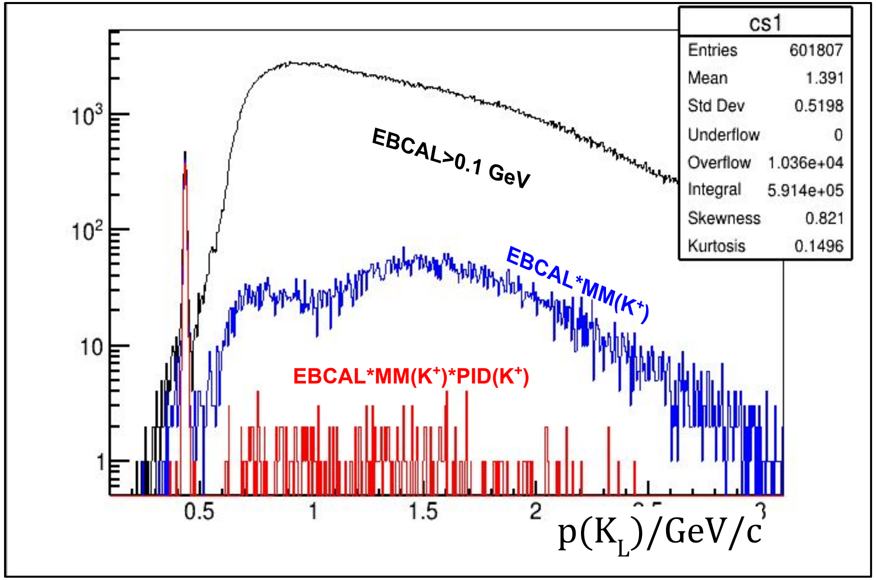
- "Neutron" peak in MM(K^+) spectrum: $\boldsymbol{\sigma}$=~10 MeV, mean=0.933.
- Neutron selection cut: abs[MM(K^+)-mean] < 0.025 GeV.

Example. Effect of the PID(K^+) cuts.
$K_L p \to \boldsymbol{\theta}^+ \to K^+ n$ mixed with $K_L p \to K^+ n$ or $np \to \boldsymbol{\pi}^+ 2n$

$K_L p \to K^+ n$



$np \to \boldsymbol{\pi}^+ 2n$

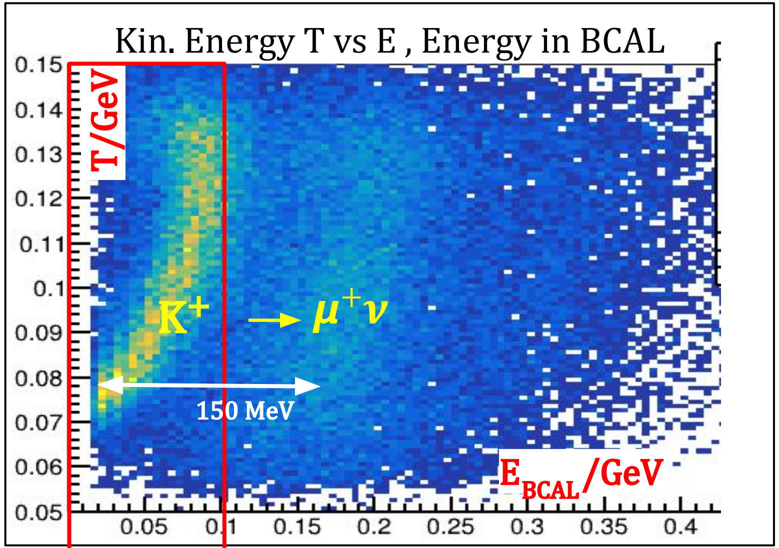


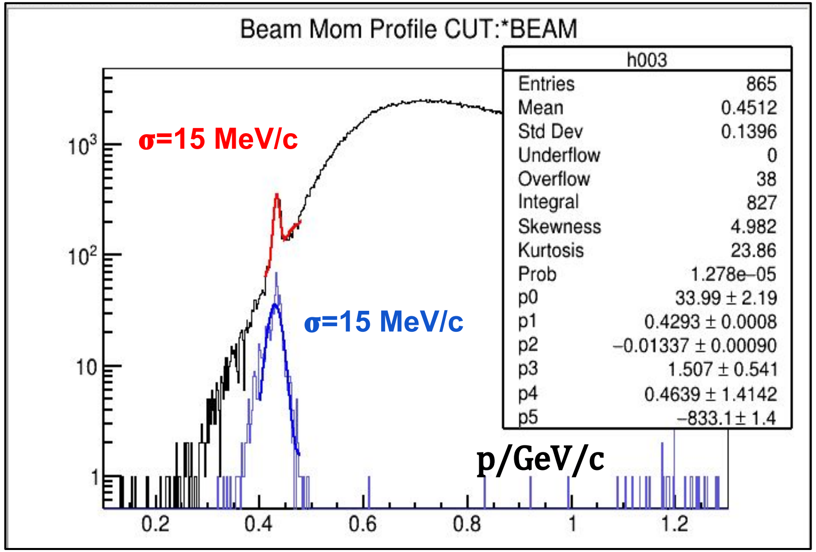
1. EBCAL cut : Energy in BCAL >0.1 GeV (trigger).
2. MM(K^+) cut : $m_n \pm$ 25 MeV (neutron, slide 13).
3. PID(K^+) cut : dE/dx(CDC).vs.p & From dE/dx(ST).vs.$\boldsymbol{\beta}$ (PID, slide 12).

5. Critical parameter: TRIGGER !

- Effect of BCAL trigger: Energy Deposition >0.1 GeV.
- Yield of pentas and TOF resolution.

Unexpected problem. $K_L p \rightarrow \theta^+ \rightarrow K^+ n$. Trigger: Signal in BCAL **>0.1 GeV**



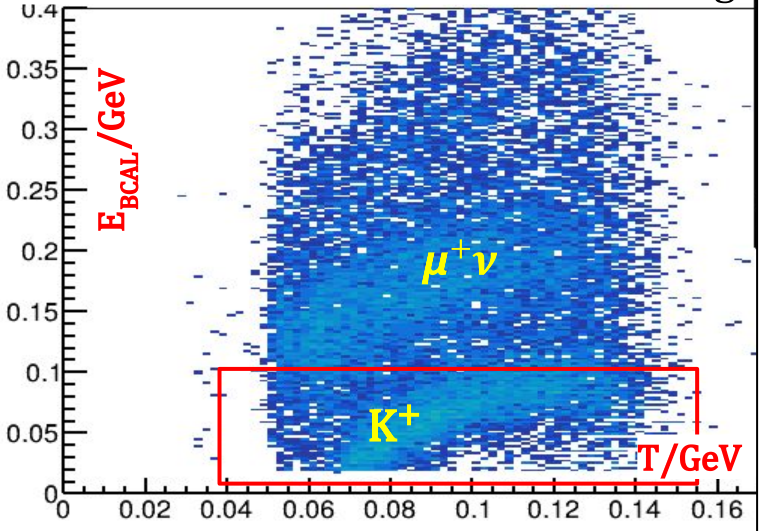


< No> trigge r

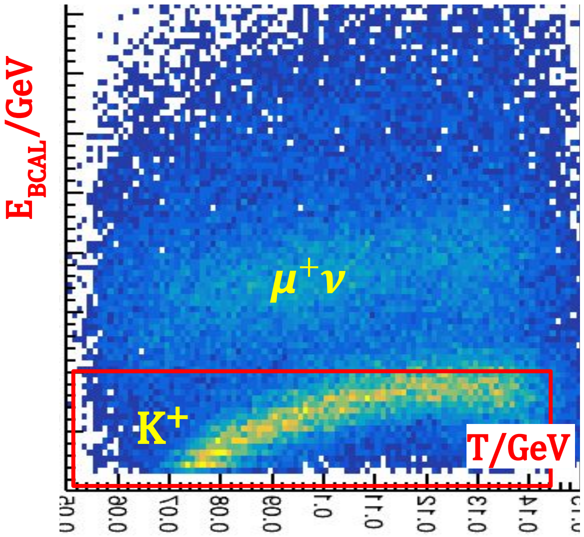
- K^+ from θ^+ decay **get stuck in BCAL** , then **decay** $K^+ \rightarrow \mu^+ \nu$ with **τ=12 ns** .
- **Muon deposits 150 MeV** to that of K^+ and triggers BCAL.
- **But** K_L timing is **spoiled by** μ^+ delay when **BCAL timing** is used.
- Respectively the **yield is ~5%** and K_L-beam **σ=15 MeV/c** is poor.

Solution for $K_Lp \rightarrow \theta^+ \rightarrow K^+n$. Signals in BCAL >0.1 GeV

NEW:Time window **64 ns & SC** timing



OLD:Time window **2 ns & BCAL** timing.



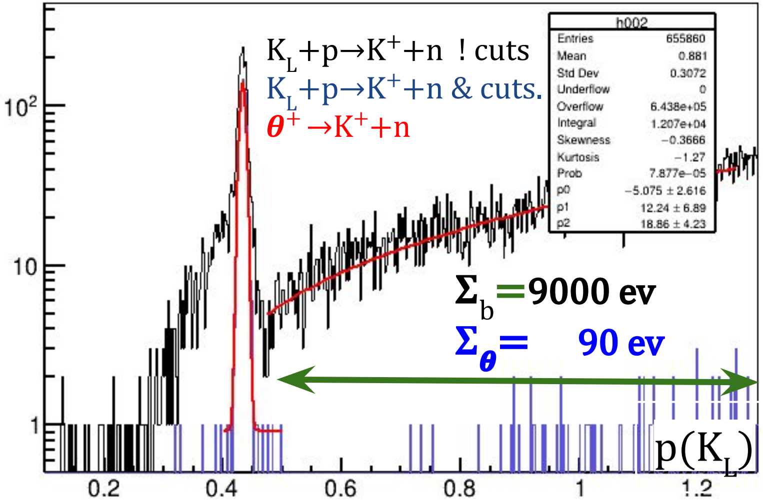
- Obviously **significantly higher yield** of triggering muons and θ^+ respectively.
- **Timing** resolution is also **recovered** (next slide).

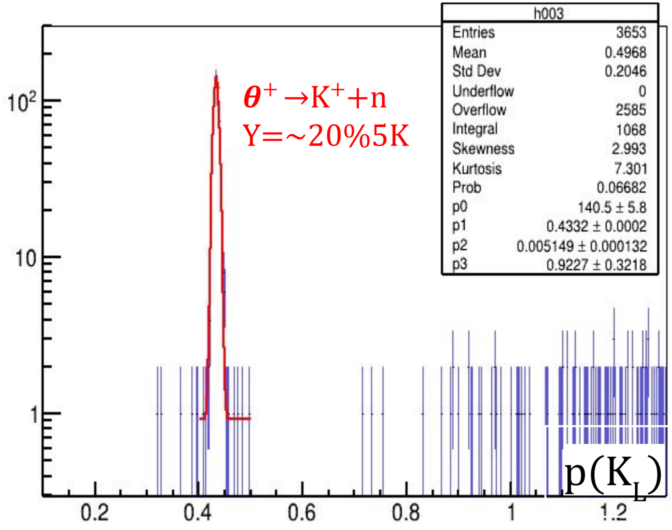
6. Background estimates

with standard MC generator

(1) Recovered $K_L p \rightarrow \theta^+ \rightarrow K^+ n$ (5K) mixed with $K_L p \rightarrow K^+ n$ (2M)

Yield of θ^+ vs Beam Momentum. Time window 64 ns. SC timing.





- After PID cuts θ^+ peak σ_p = 5 MeV/c; Amplitude = 140 ev/ch; Yield of θ^+ = 20%.
- Background under θ^+, n_b=3.5 ev/ch, translates to $n_b(\Sigma_\theta / \Sigma_b)$ in blue profile, if shapes are similar.
- **Next slide estimates** background under θ^+ in blue profile with PID cuts.

Background estimation procedure

$N_b(t) = J t \varrho\, \sigma_b$; $N_\theta(t) = I t \varrho\, \sigma_\theta$; t- collection time, ϱ -nuclei density. Yield_per_1_$\theta = N_b(t)/N_\theta(t) = (J/I)\,(\sigma_b/\sigma_\theta)$;

1. Pentaquark production $\sigma_\theta =$ 12 mb ;
2. Background total $\sigma_b =$ 20 mb ;
3. Flux of K_L on LH2: **J=** **7.E+3** s^{-1} ; $N_b^{sim} =$ 2000000; $\Sigma_b = 9000.$
4. Flux of K_L at 0.44 GeV/c: **I=** **1.E-1** s^{-1} ; $N_\theta^{sim} =$ 5000.; $\Sigma_\theta =$ 90.
5. Read **Background** under the θ^+ peak **with no cuts** $n_b =$ **3.5 [ev/ch]** .
6. **RESCALED** background under the θ^+ peak **after all PID cuts** yields:

$$n^R_b = n_b(\Sigma_\theta/\Sigma_b)\,(J/I)\,(\sigma_b/\sigma_\theta)(N_\theta^{sim}/N_b^{sim}) = 10\ [ev/ch]\ ;$$

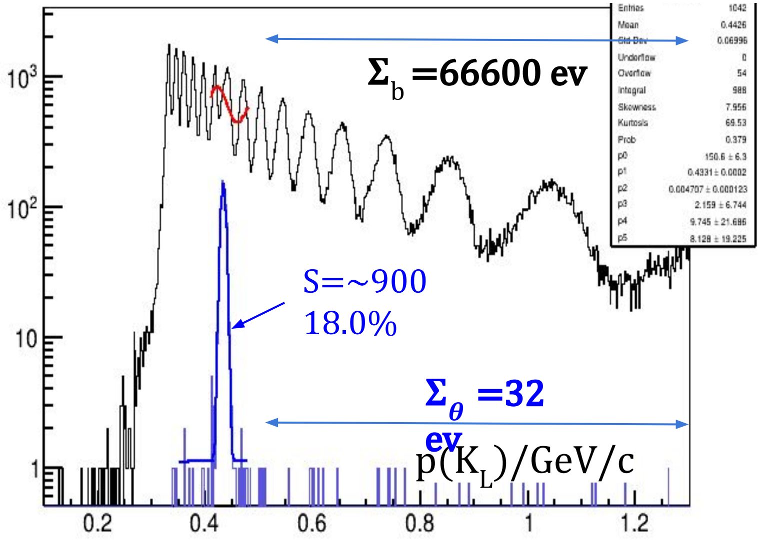
For beam Leak, since only 1 bunch create background ander a narrow peak

$$n^R_b = n_b(\Sigma_\theta/\Sigma_b)(1\%)\,(J/I)\,(\sigma_b/\sigma_\theta)(N_\theta^{sim}/N_b^{sim});$$

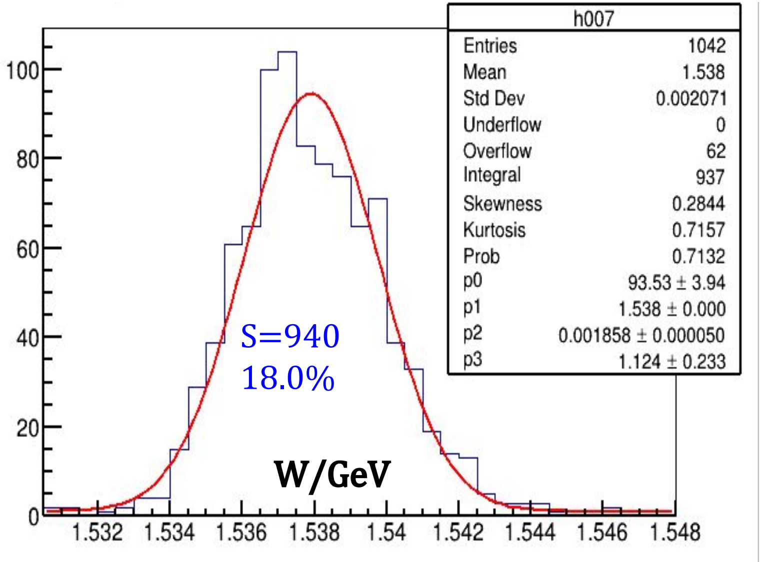
- To be compared to **140 [ev/ch]** in θ^+maximum and tabulated below.

(1) K^+ signal in BCAL>0.1 GeV; 5K of Θ^+ mixed with 2M non-resonant K^+n Time window 64 ns. SC timing. Beam leak

#1: ChargedHypo__Energy_BCAL >**0.1**

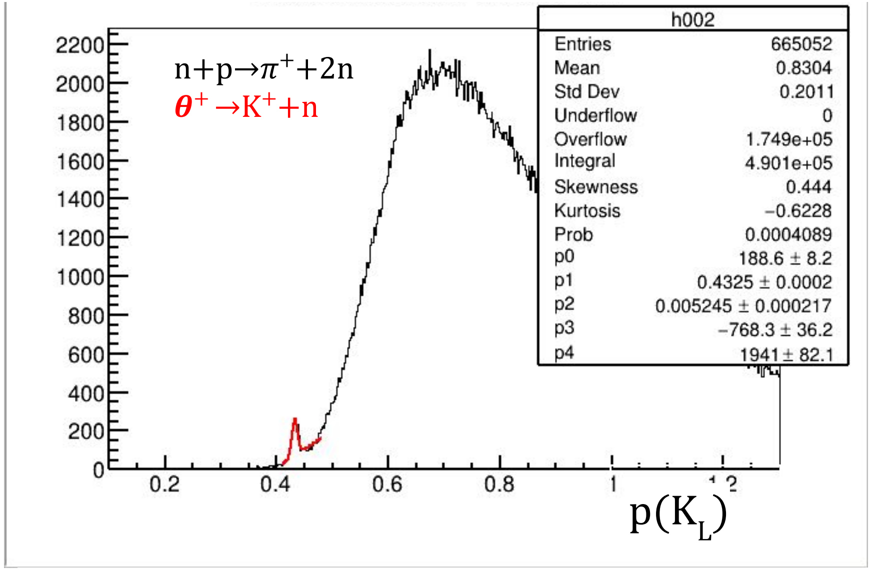


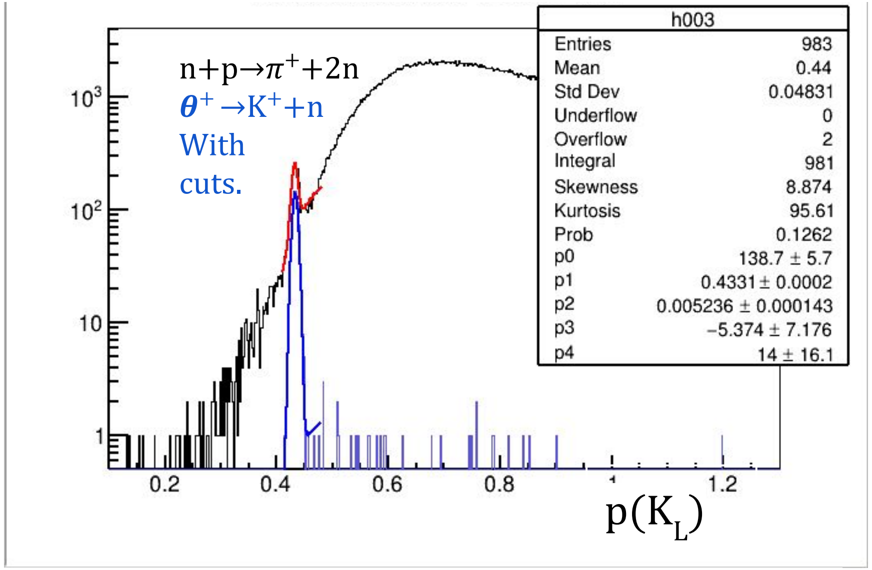
#2: ChargedHypo__Energy_BCAL >**0.1**



- The yield of $\boldsymbol{\Theta^+}$**=18.0%** ; max 150 ev; Σ_θ =32 ev.; Σ_b =66600 ev.
- RESCALED background under Θ^+ in blue profile with all cuts $\mathbf{n^R_b(0.44)=}$ **1.5 [ev/ch]**

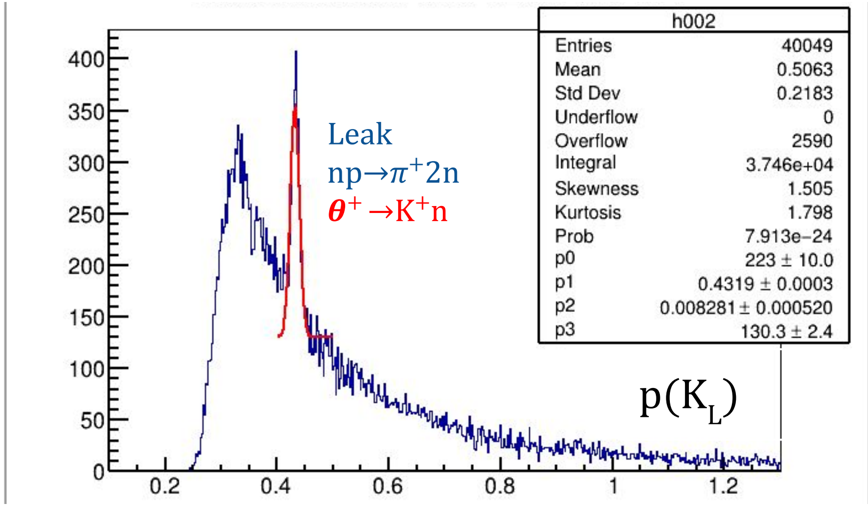
(2) Example. $K_L p \to \boldsymbol{\theta}^+ \to K^+ n$ mixed with 2M of $np \to \pi^+ nn$

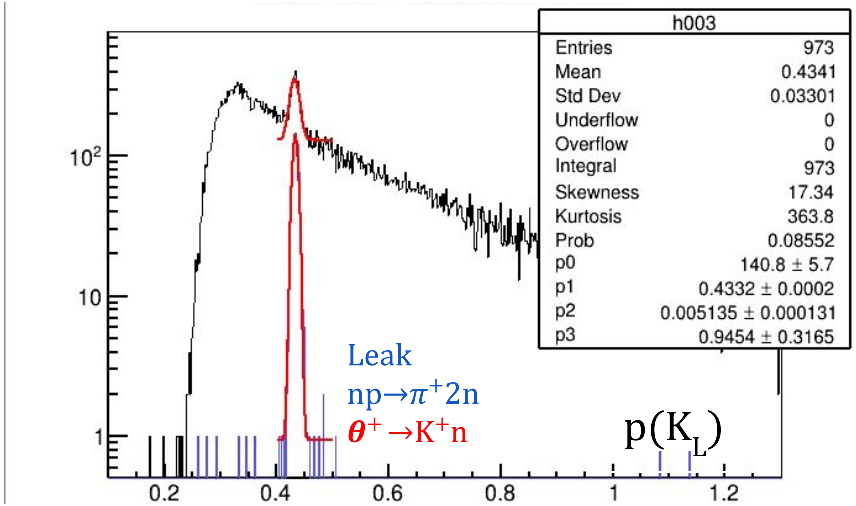




- Right: Ratio of Histogram's Integrals $\boldsymbol{\Sigma_\theta} / \boldsymbol{\Sigma}_b$ (0.5:1.3)= 30 ev /480000 ev.
- RESCALED background under the $\boldsymbol{\theta}^+$-peak: n^R_b= **7.2 ev/ch.**

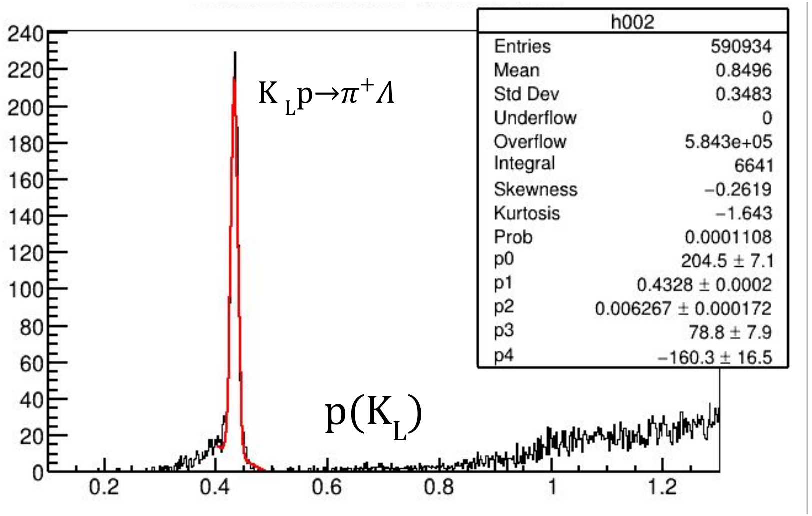
(2) Example. $K_L p \to \theta^+ \to K^+ n$ mixed with 0.2M of $np \to \pi^+ nn$
Beam Leak !

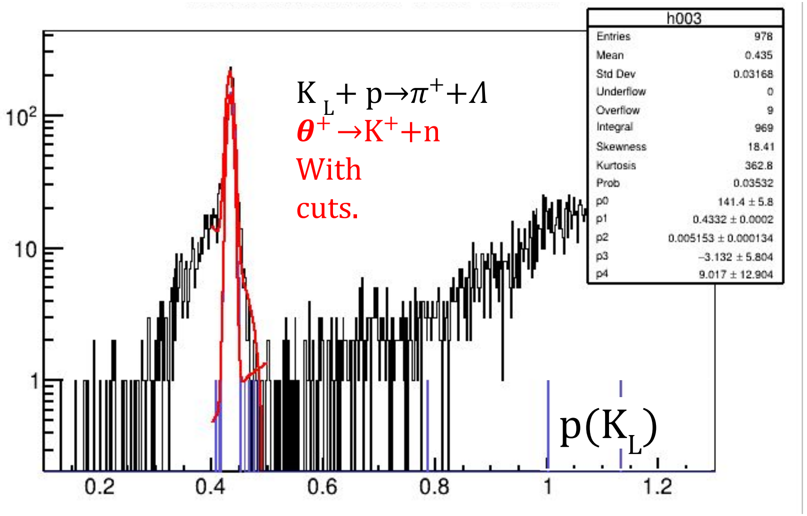




- Right: Ratio of Histogram's Integrals Σ_θ / Σ_b (0.5:1.3)= 11 ev /3.5E+4 ev.
- RESCALED background under the θ^+-peak: n^R_b= **4 ev/ch.**

(3) Example. $K_L p \rightarrow \boldsymbol{\theta}^+ \rightarrow K^+ n$ mixed with $K_L p \rightarrow \pi^+ \Lambda$





- Right: Ratio of Histogram's Integrals $\boldsymbol{\Sigma}_{\boldsymbol{\theta}} / \boldsymbol{\Sigma}_b$ (0.5:1.3)= 5 ev /3,840 ev.
- RESCALED background under the $\boldsymbol{\theta}^+$-peak: n^R_b= **0.02 ev/ch.**

Summary table for Standard Generator

Reaction	Comment	Bleed through current	#evets gener.	Cross section	Beam intensity	Background Scaling Factor	Events per Chanel at p=0.44 GeV/c	Effective bgrd statistics
$K_L + p \rightarrow \boldsymbol{\theta}^+ \rightarrow K^+ + n$	main		5,000	12 mb	7 kHz	n/a	140	
$\mathbf{K_L + p \rightarrow K^+ + n}$			2.0 M	20 mb	7 kHz	250	**10 ± 10%**	90 ev
$K_L + p \rightarrow K^+ + n$	Leak	1% I_{hall}	1.4 M	30 mb	7 kHz	4.3	1.6 ± 16%	37 ev
$\mathbf{n + p \rightarrow \boldsymbol{\pi}^+ + 2n}$			2M	3 mb	20 kHz	2,000	**7.2 ± 18%**	30 ev
$\mathbf{n + p \rightarrow \boldsymbol{\pi}^+ + 2n}$	Leak	1% I_{hall}	200,000	3 mb	20 kHz	10	**4± 50%**	4 ev
$K_L + p \rightarrow \pi^+ + \Lambda_{1115}$			2.0 M	1.2 mb	7 kHz	18	0.02 ± 50%	5 ev
$K_L + p \rightarrow \pi^+ + \boldsymbol{\Sigma}_{1192}$			2.0 M	1.2 mb	7 kHz	18	0.01± 50%	4 ev
$K_L + p \rightarrow p + \pi^+ + K^-$			2.0 M	1.2 mb	7 kHz	18	0.1± 50%	2 ev
All backgrounds							S=23 **(16%)**	

7. Advanced Cocktail generator

(M. Bashkanov)

Cocktail Generator for background reactions with positive particles in final state

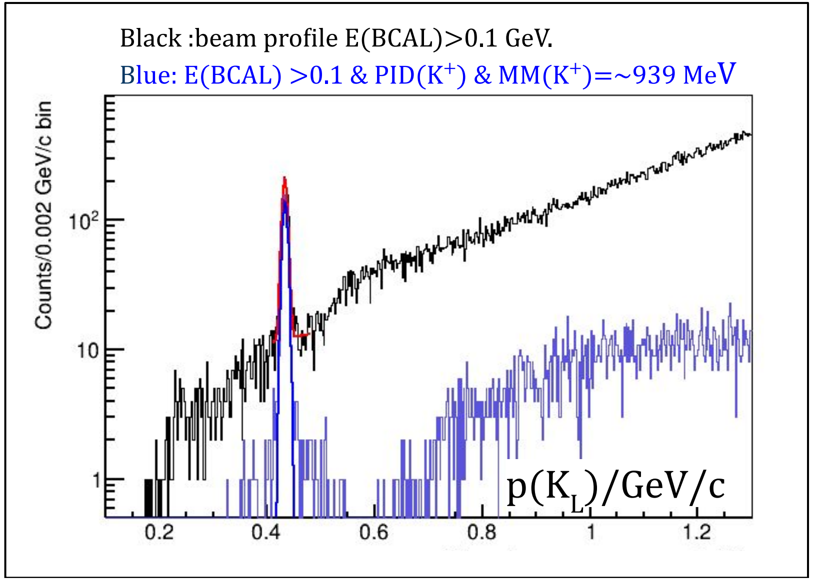
M. Bashkanov, https://wiki.jlab.org/klproject/images/2/29/KLF_Jun25_Coctail.pdf

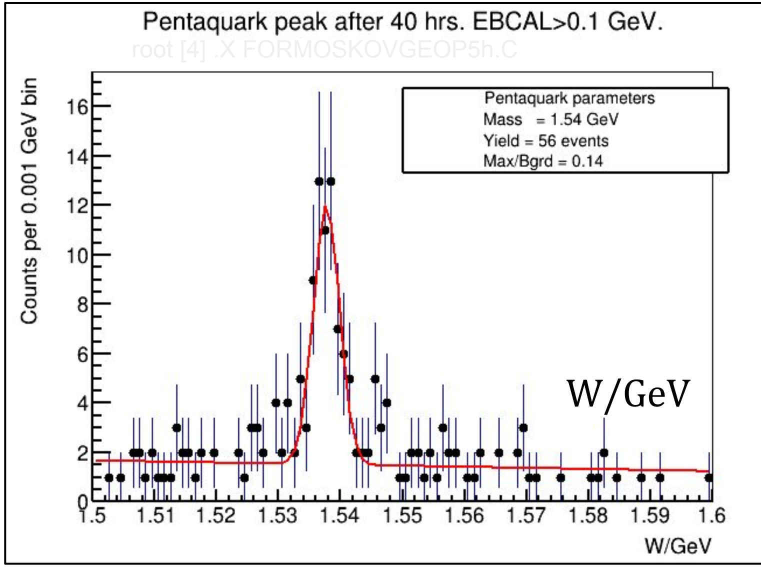
MC code	**Reaction**	Fract.
kl1	$K_L p \rightarrow nK^+$	0.433
kl2	$K_L p \rightarrow pK_s$	0.024
kl3	$K_L p \rightarrow \Xi^0 K^+$	0.001
kl4	$K_L p \rightarrow \Lambda\pi^+$	0.043
kl5	$K_L p \rightarrow \Sigma^+\pi^0$	0.021
kl6	$K_L p \rightarrow \Sigma^0\pi^+$	0.021
kl9	$K_L p \rightarrow pK_L$	0.457
	All	1.000

- Cocktail MC utilizes differential and total cross sections of listed+ reactions.
- Drives the statistics via “beam time”. In progress.

(4) $K_L p \to \theta^+ \to K^+ n$ mixed with Seven background $K_L p$ reactions after 40 hrs beam

root tree_kpmissn__B0_F0_5Kpent+14Mcock.root KPNTRYVBT.C

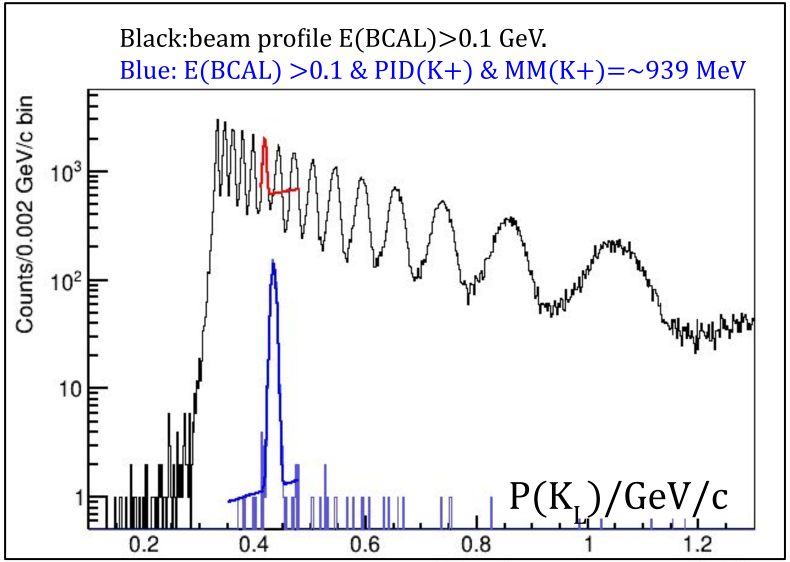


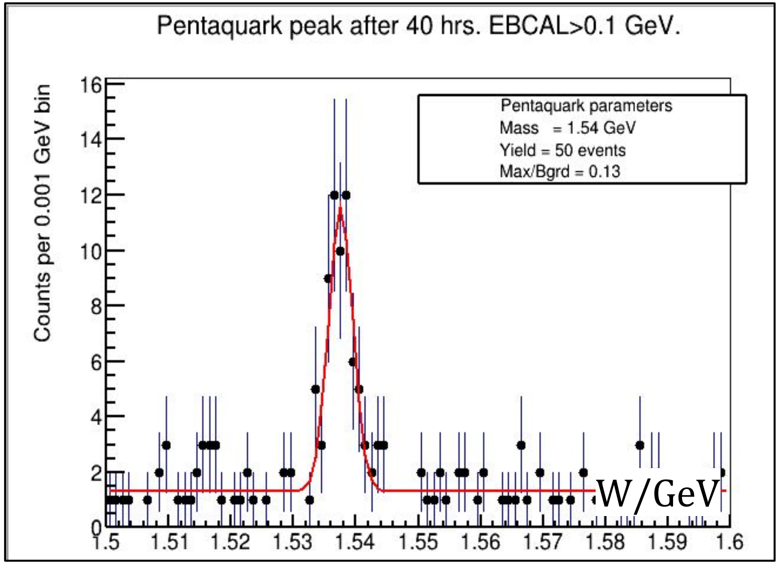


- Number of "generated" $N(K_L p \to \theta^+ \to K^+ n)$ = 333 (20,000 θ^+ per 2400 hrs).
- Number of "detected" decays $N(\theta^+ \to K^+ n)$ = 56 (Yield =**17 %** of generated).
- The background under the peak maximum = **14 %**.
- Resolution .... σ_p = 5 MeV/c (σ_W=2 MeV).

(4) $K_L p \to \theta^+ \to K^+ n$ mixed with "1% beam leak" of Seven $K_L p$ reactions after 40 hrs beam

root tree_kpmissn__B0_F0_coctail_0d01_5K5q+14MKL1_bleed_16.root KPNTRYVBT.C



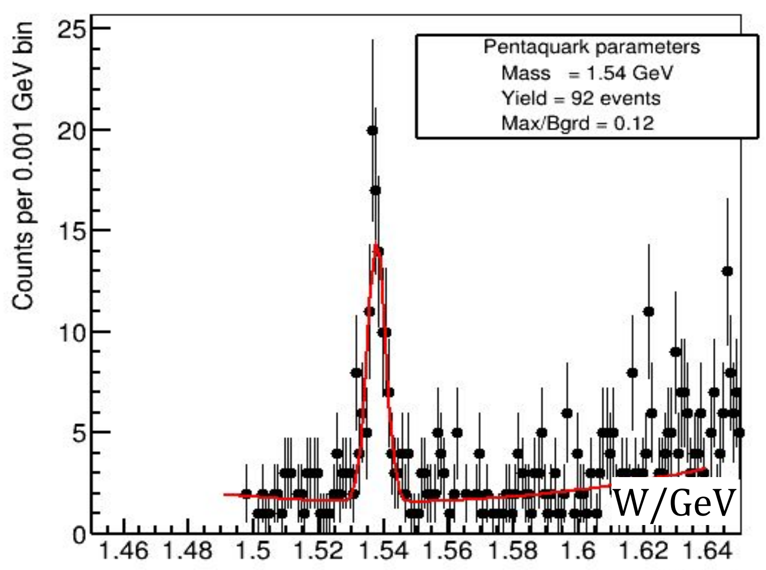


- After 40 hrs the total number of generated $N(K_L p \to \theta^+ \to K^+ n) = 333$.
- Number of "detected" $N(\theta^+ \to K^+ n) = 50$ (~15 % of generated θ^+).
- The "beam leak" background under the peak maximum is of 13 %.
- The resulting total background under θ^+ peak maximum = ~13% + ~14% = ~27 %.

8. Effect of Preshower Trigger and Reduced Magnetic Field

Effect of Preshower Trigger $E_{BCALPresh}$>0.01 GeV. Seven background reactions. Beam time 40 hrs

EBCALPresh>0.01 , # $K_L p \rightarrow \theta^+ \rightarrow K^+ n$= **92 vs 56**

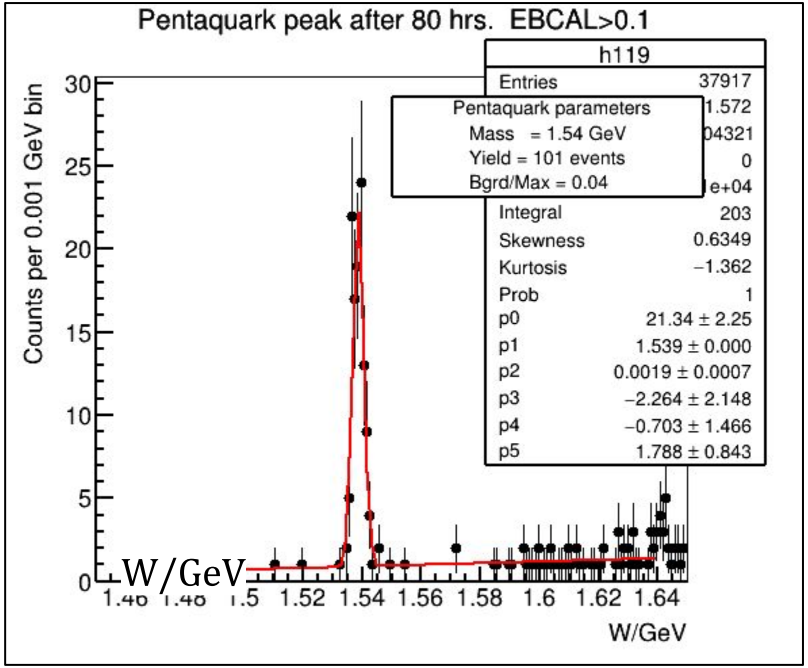


- **Preshower** Trigger $E_{BCALPresh}$>0.01 **about doubles the yield** of pentas.
- Whether Preshower Trigger $E_{BCALPresh}$>0.01 is practical ?

Sixteen $K_L p \to$... reactions in new Cocktail-2 Generator 2025

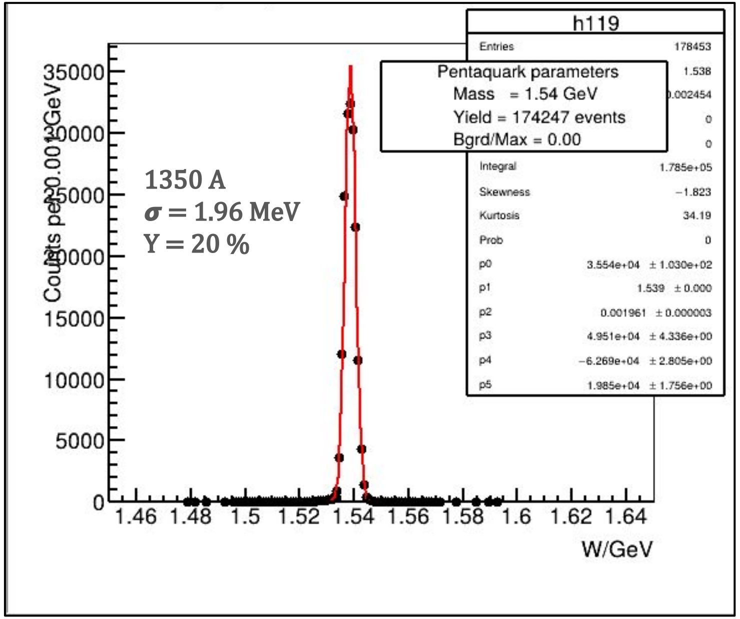
(by M. Bashkanov)

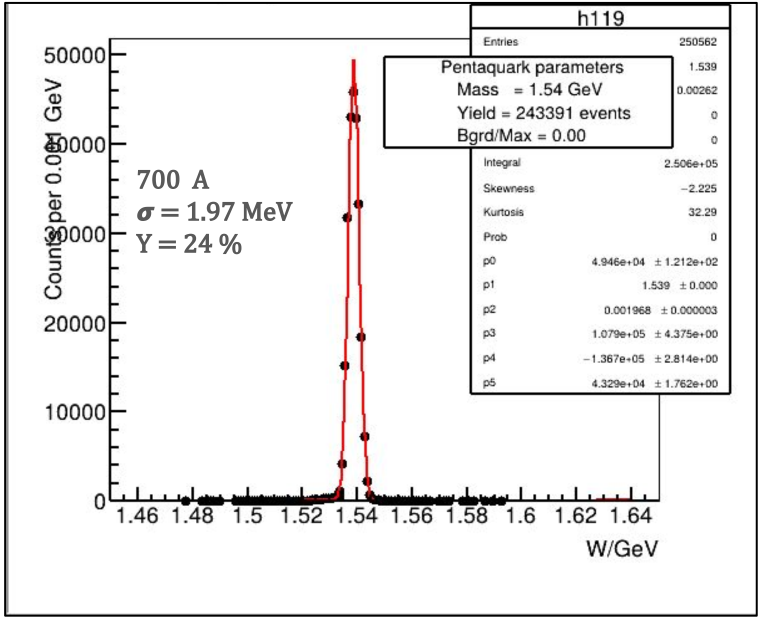
1.	kl1	Klong p --> K+ n
2.	kl2	Klong p --> Ks p
3.	kl3	Klong p --> K+ Xi
4.	kl4	Klong p --> pi+ Lambda
5.	kl5	Klong p --> pi0 Sigma+
6.	kl6	Klong p --> pi+ Sigma
7.	kl7	Klong p --> K+ pi- p
8.	kl8	Klong p --> K- pi+ p
9.	kl9	Klong p --> Kl p
10.	kl10	Klong p -->K-Delta++ --> K- pi+ p
11.	kl11	Klong p -->K0-bar Delta+ --> K0-bar pi0 p
12.	kl12	Klong p -->K0-bar Delta+ --> K0-bar pi+ n
13.	kl13	Klong p -->K0 Delta+ --> K0 pi0 p
14.	kl14	Klong p -->K0 Delta+ --> K0 pi+ n
15.	kl15	Klong p -->K+ Delta0 --> K+ pi0 n
16.	kl16	Klong p -->K+ Delta0 --> K+ pi- p



- Analysis in progress; no critical changes in backgrounds.

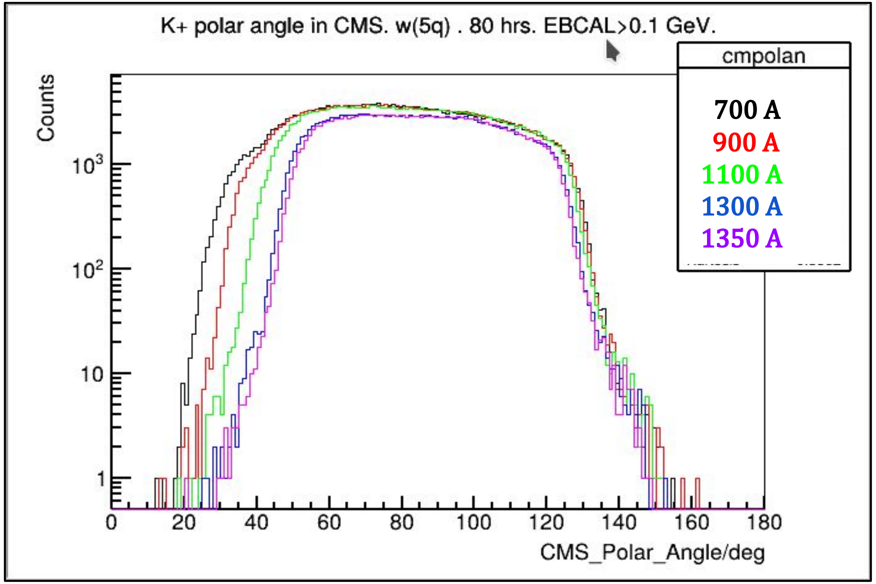
$K_L p \to \theta^+ \to K^+ n$ only. W resolution vs Solenoid Magnetic Field

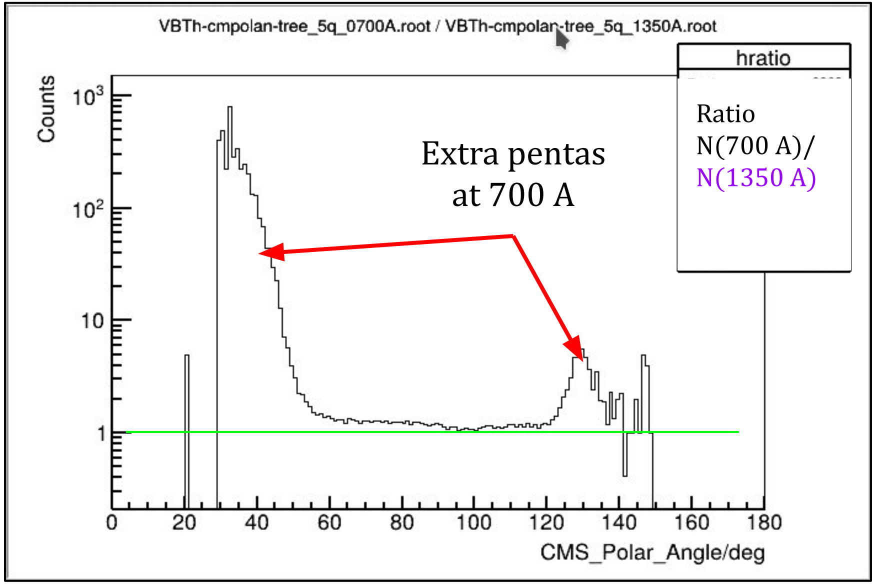




- K^+ momentum resolution drops to **5.5 MeV** (700 A) from **3.4 MeV (** 1350 A).
- W-resolution (2 MeV) **does not vary** with Solenoid Current due to TOF method.

$K_L p \rightarrow \theta^+ \rightarrow K^+ n$ only. CMS Polar Angle Distribution of K^+ from θ^+ decay vs Solenoid Magnetic Field





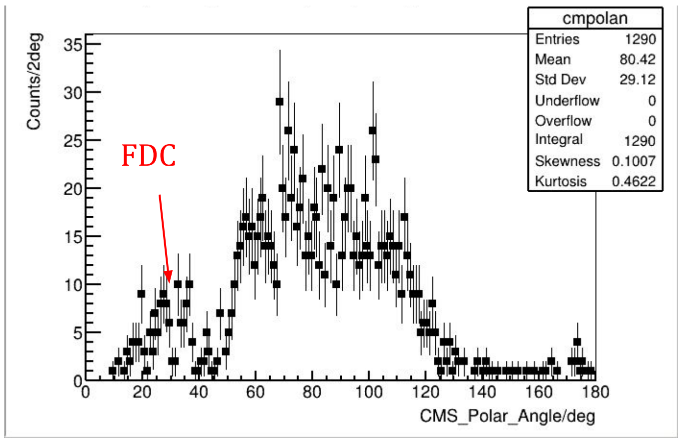
- At low B(700 A) **we gain ~30%** to θ^+ yield which concentrates within (20°,60°) CMS.

Conclusion

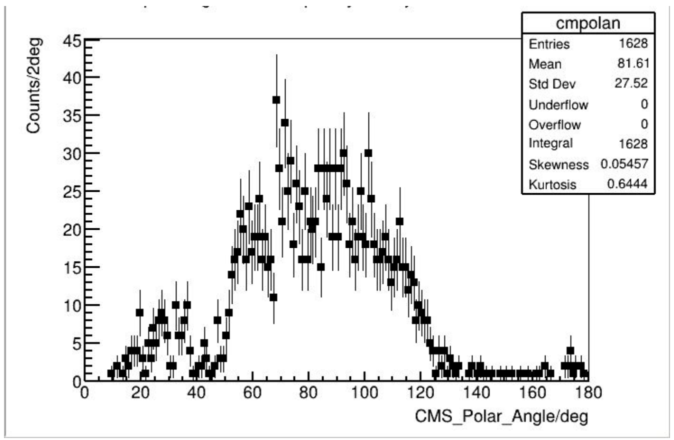
1. These simulations show that about 20% of produced θ^+ may be reconstructed as a narrow peak in the beam profile at 0.44 GeV/c with sigma of 5 MeV/c.
2. The expected statistics of θ^+under peak is 3000 - 4000 events after 100 beam days.
3. The θ^+ peak sigma in W profile will be of 2 MeV.
4. Overal Background under θ^+ peak maximum expected to be of 20 %.
5. Preshower Trigger adds 30% of penta's statistics.
6. Twice lower magnetic field adds 30% of penta's statistics, which concentrates at CMS decay angles < 50^o.
7. GlueX detector is ideal for θ^+ observation.

Backup slides

θ^+ decay and angular acceptance of Gluex Detector



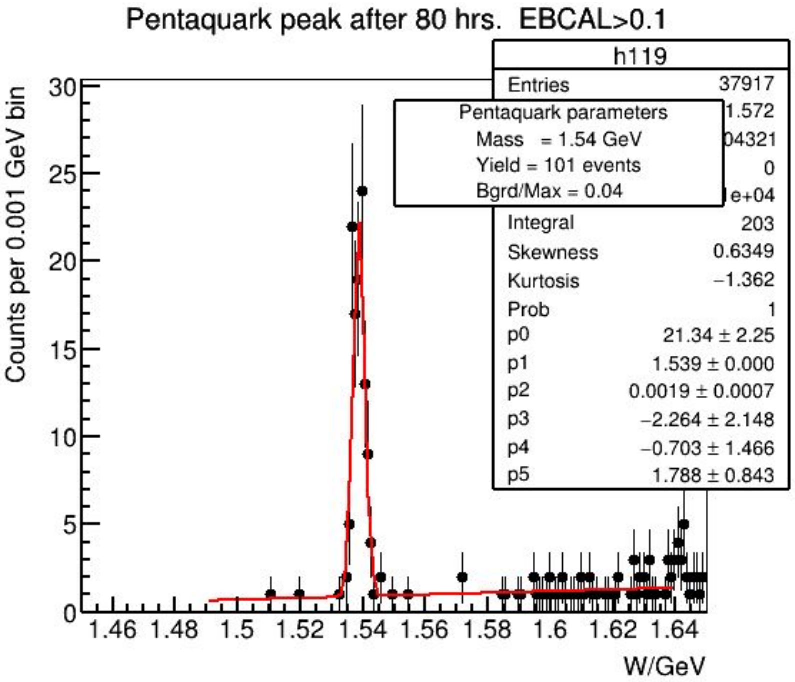
Polar Angle of K+ from 5q decay in CMS.
REQUIREMENT "dE/dx in FDC >0 || EBCAL>0.1 G"
About 1,300 events out of 5,000 pentaquarks.

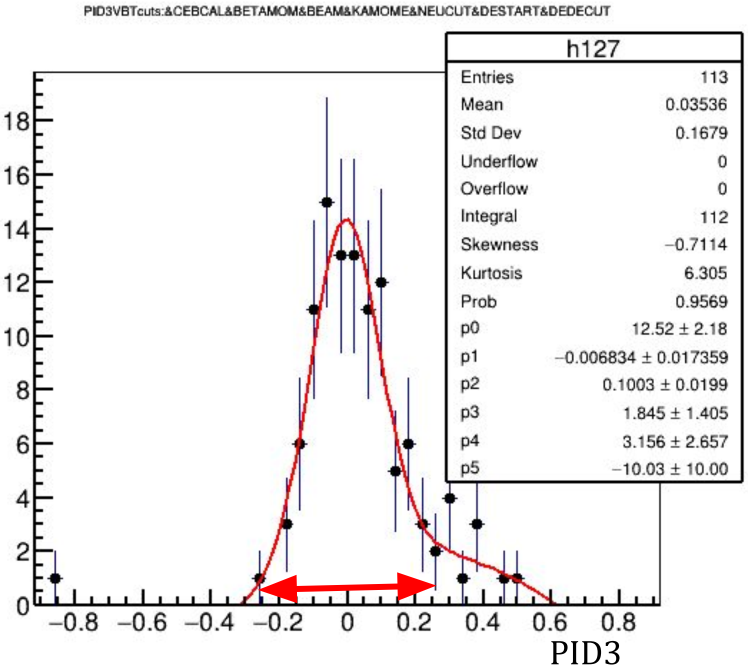


Same as in l, but REQURES "EBCAL>0.05 GeV"
About 1,600 events

- Trigger dE/dxFDC>0. GeV recovers the domain (10,45) deg in CMS.
- Trigger EBCAL> 0.05 does not affect angular acceptance but adds 20% to the yield.

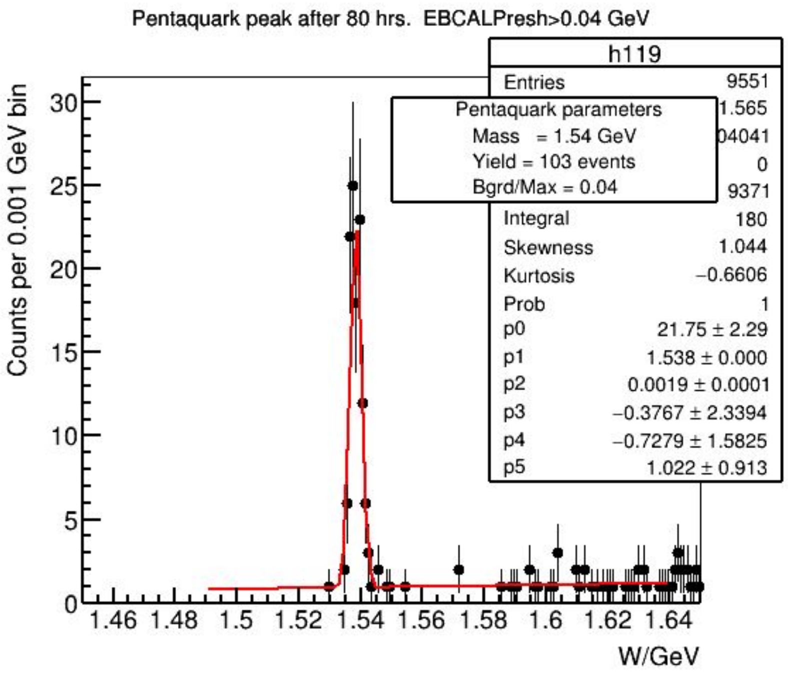
BCAL Trigger. Pentaquarks vs background from sixteen reactions

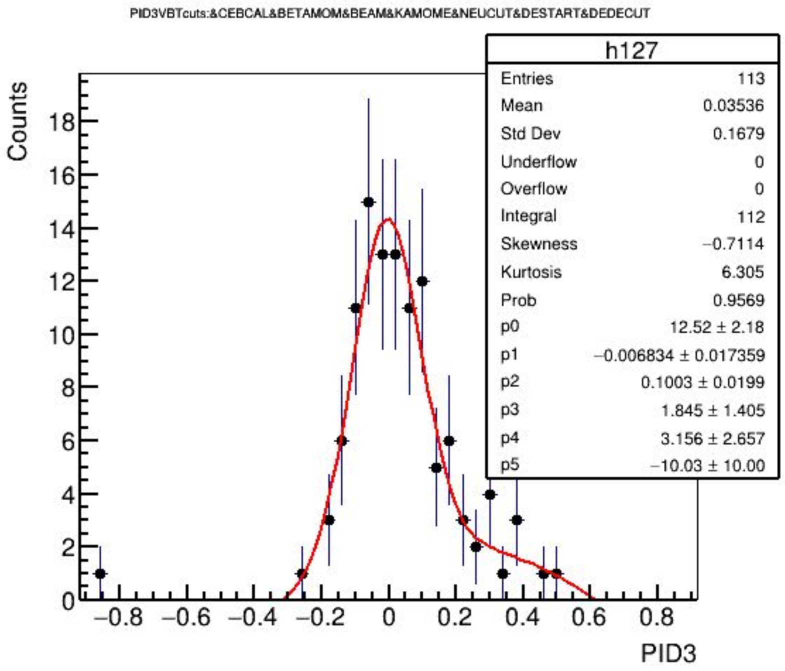




- Gaussian area yields 101 pentas after 80 hrs of beam time.
- Bgrd/Max =4%.

Preshower Trigger. Pentaquarks vs background from sixteen reactions

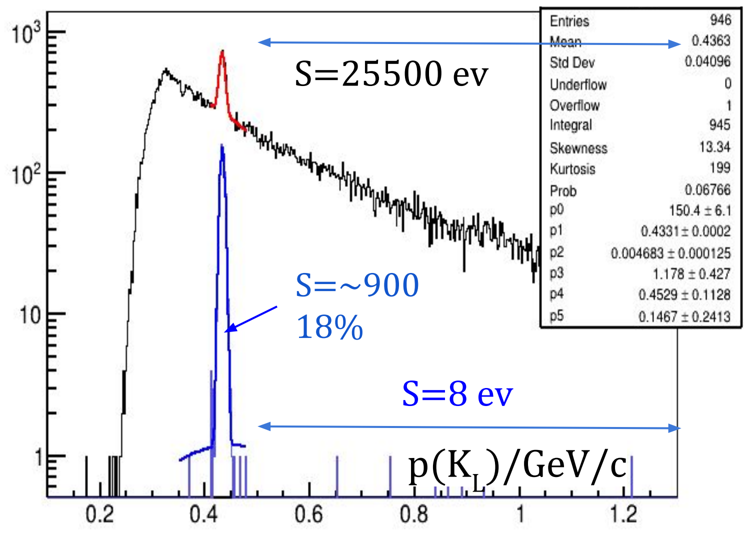




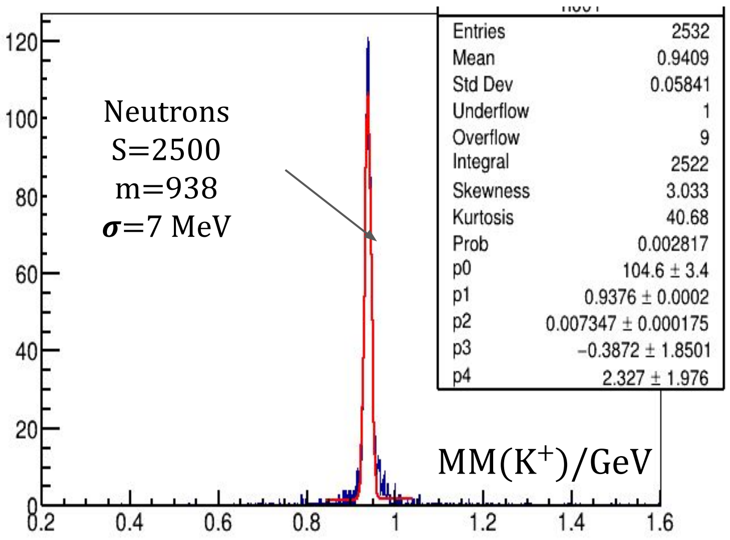
- Gaussian area yields 103 pentas after 80 hrs of beam time. Similar to BCAL Trigger.

K^+ signals in BCAL>0.1 GeV; 5K of Θ^+ mixed with leak of 0.2 M $np\to\pi^+nn$. Time window 64 ns. SC timing

#1: ChargedHypo__Energy_BCAL >**0.1**



#2: ChargedHypo__Energy_BCAL >=**0**



- The yield of Θ^+ =18.0%; max 150 ev; In_bg(0.47:1.3)= 8 ev.; In_bg(0.47:1.3)=25,500 ev.
- **Rescaled** **n_b(0.44)=** ~300 ev/ch*(**8 ev** **/25500 ev**)=~0.1 [ev/ch]; n_b to be used below.