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# $K_L$-Beam Facility at Jefferson Lab


Hovanes Egiyan

Jefferson Lab

(for KLF Collaboration)


Jefferson Lab
Thomas Jefferson National Accelerator Facility

K LONG FACILITY

# Overview

- Introduction
- Physics Motivation
- Hall D at Jefferson Lab
- KLF facility
  - Compact Photon Source (CPS)
  - Kaon Production Target (KPT)
  - Kaon Flux Monitor (KFM)
- Status of the project
- Conclusions and Outlook

# KLF Experiment

- Use CEBAF electron beam to create a tertiary $K_L$ beam *<u>to study strange hadron spectroscopy</u>*.
- Use existing GlueX experimental setup in Hall D that has been used to study meson spectroscopy in photoproduction.
  - Very good detector system for studying exclusive final states.
- Create intense $K_L$ flux (~$10^4$ kaons/s) on cryo-target.
- Experimental proposal approved by JLAB Program Advisory Committee in 2020.
  - 100 days on $LH_2$ target
  - 100 days on $LD_2$ target.
- Estimated cost to JLAB of ~$2.3M .
- Formal KLF collaboration is currently being formed to construct the equipment and to conduct the experiments.
  - New collaborators are welcome.

Proposal for JLab PAC48

## Strange Hadron Spectroscopy with Secondary $K_L$ Beam in Hall D


Experimental Support:

Shankar Adhikari[43], Moskov Amaryan (Contact Person, Spokesperson)[43], Arshak Asaturyan[1], Alexander Austregesilo[49], Marouen Baalouch[8], Mikhail Bashkanov (Spokesperson)[63], Vitaly Baturin[43], Vladimir Berdnikov[11,35], Olga Cortes Becerra[19], Timothy Black[60], Werner Boeglin[13], William Briscoe[19], William Brooks[54], Volker Burkert[49], Eugene Chudakov[49], Geraint Clash[63], Philip Cole[32], Volker Crede[14], Donal Day[61], Pavel Degtyarenko[49], Alexandre Deur[49], Sean Dobbs (Spokesperson)[14], Gail Dodge[43], Anatoly Dolgolenko[26], Simon Eidelman[6,41], Hovanes Egiyan (JLab Contact Person)[49], Denis Epifanov[6,41], Paul Eugenio[14], Stuart Fegan[63], Alessandra Filippi[25], Sergey Furletov[49], Liping Gan[60], Franco Garibaldi[24], Ashot Gasparian[39], Gagik Gavalian[49], Derek Glazier[18], Colin Gleason[22], Vladimir Goryachev[26], Lei Guo[14], David Hamilton[11], Avetik Hayrapetyan[17], Garth Huber[53], Andrew Hurley[56], Charles Hyde[43], Isabella Illari[19], David Ireland[18], Igal Jaegle[49], Kyungseon Joo[57], Vanik Kakoyan[1], Grzegorz Kalicy[11], Mahmoud Kamel[13], Christopher Keith[49], Chan Wook Kim[19], Eberhard Klempt[5], Geoffrey Krafft[49], Sebastian Kuhn[43], Sergey Kuleshov[2], Alexander Laptev[33], Ilya Larin[26,59], David Lawrence[49], Daniel Lersch[14], Wenliang Li[56], Kevin Luckas[28], Valery Lyubovitskij[50,51,52,54], David Mack[49], Michael McCaughan[49], Mark Manley[30], Hrachya Marukyan[1], Vladimir Matveev[26], Mihai Mocanu[63], Viktor Mokeev[49], Curtis Meyer[9], Bryan McKinnon[18], Frank Nerling[15,16], Matthew Nicol[63], Gabriel Niculescu[27], Alexander Ostrovidov[14], Zisis Papandreou[53], KiJun Park[49], Eugene Pasyuk[49], Peter Pauli[18], Lubomir Pentchev[49], William Phelps[10], John Price[7], Jörg Reinhold[13], James Ritman (Spokesperson)[28,68], Dimitri Romanov[26], Carlos Salgado[40], Todd Satogata[49], Susan Schadmand[28], Amy Schertz[56], Axel Schmidt[19], Daniel Sober[11], Alexander Somov[49], Sergei Somov[35], Justin Stevens (Spokesperson)[56], Igor Strakovsky (Spokesperson)[19], Victor Tarasov[26], Simon Taylor[49], Annika Thiel[5], Guido Maria Urciuoli[24], Holly Szumila-Vance[19], Daniel Watts[63], Lawrence Weinstein[43], Timothy Whitlatch[49], Nilanga Wickramaarachchi[43], Bogdan Wojtsekhowski[49], Nicholas Zachariou[63], Jonathan Zarling[53], Jixie Zhang[61]

Theoretical Support:

Alexey Anisovich[5,44], Alexei Bazavov[38], Rene Bellwied[21], Veronique Bernard[42], Gilberto Colangelo[3], Aleš Cieplý[46], Michael Döring[19], Ali Eskanderian[19], Jose Goity[20,49], Helmut Haberzettl[19], Mirza Hadžimehmedović[55], Robert Jaffe[36], Boris Kopeliovich[54], Heinrich Leutwyler[3], Maxim Mai[19], Terry Mart[65], Maxim Matveev[44], Ulf-G. Meißner[5,29], Colin Morningstar[9], Bachir Moussallam[42], Kanzo Nakayama[58], Wolfgang Ochs[37], Youngseok Oh[31], Rifat Omerovic[55], Hedim Osmanović[55], Eulogio Oset[62], Antimo Palano[64], Jose Peláez[34], Alessandro Pilloni[66,67], Maxim Polyakov[48], David Richards[49], Arkaitz Rodas[49,56], Dan-Olof Riska[12], Jacobo Ruiz de Elvira[3], Hui-Young Ryu[45], Elena Santopinto[23], Andrey Sarantsev[5,44], Jugoslav Stahov[55], Alfred Švarc[47], Adam Szczepaniak[22,49], Ronald Workman[19], Bing-Song Zou[4]

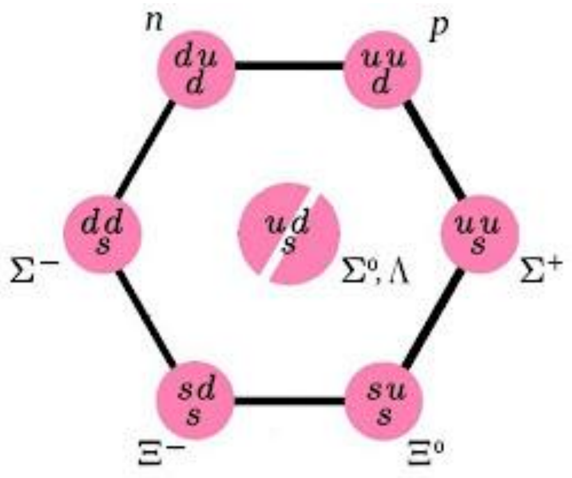
# Collaboration Map

# Strange Baryons

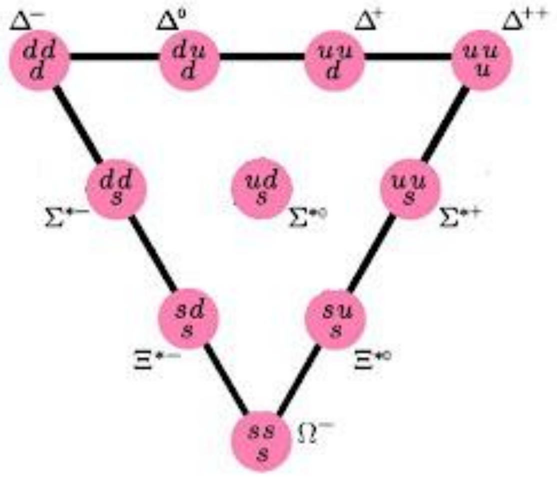
- CQM and LQCD expect more hyperon states than experimentally observed.
  - Mismatch in the number of states is significantly worse for hyperons than for N* sector.
- Study of the properties of the states with strange quarks gives insight into the underlying dynamics and into the relevant degrees of freedom.
- Important input to high-density/temperature hadron physics

| | PDG 2004 | PDG 2020 | LQCD |
|---|---|---|---|
| N* | 15 | 21 | 62 |
| Δ | 10 | 12 | 38 |
| Λ | 14 | 14 | 71 |
| Σ | 10 | 9 | 66 |
| Ξ | 6 | 6 | 73 |
| Ω | 2 | 2 | 36 |

[PDG 3* & 4* states]



S=1/2



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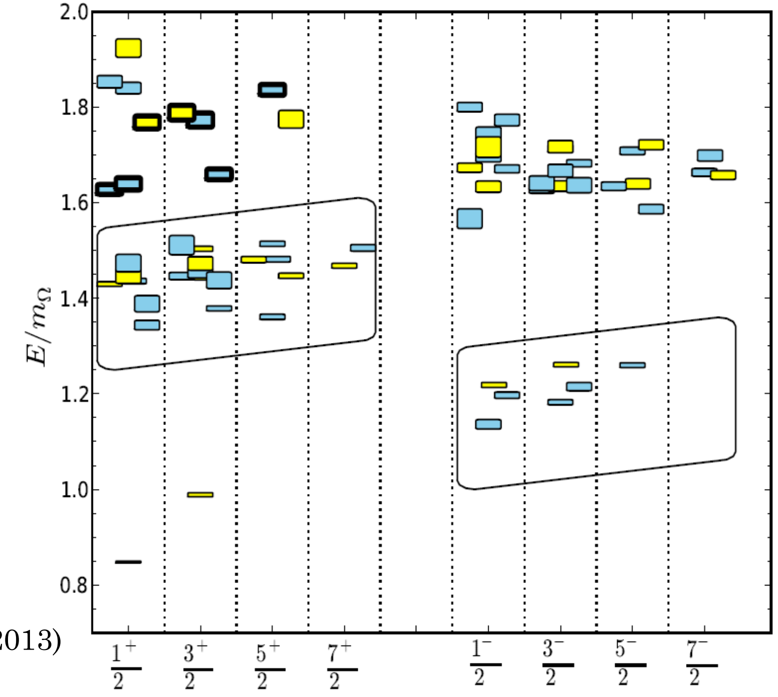
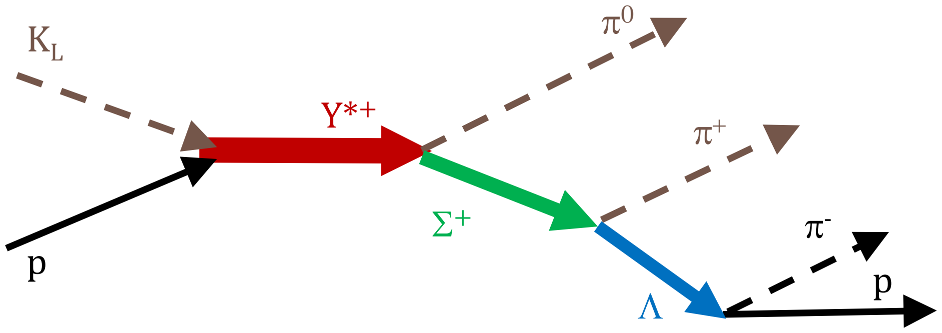



Ξ-s in LQCD
Phys. Rev. D 87, 054506 (2013)

# $\pi\Sigma$ and $\pi\Lambda$ Channels

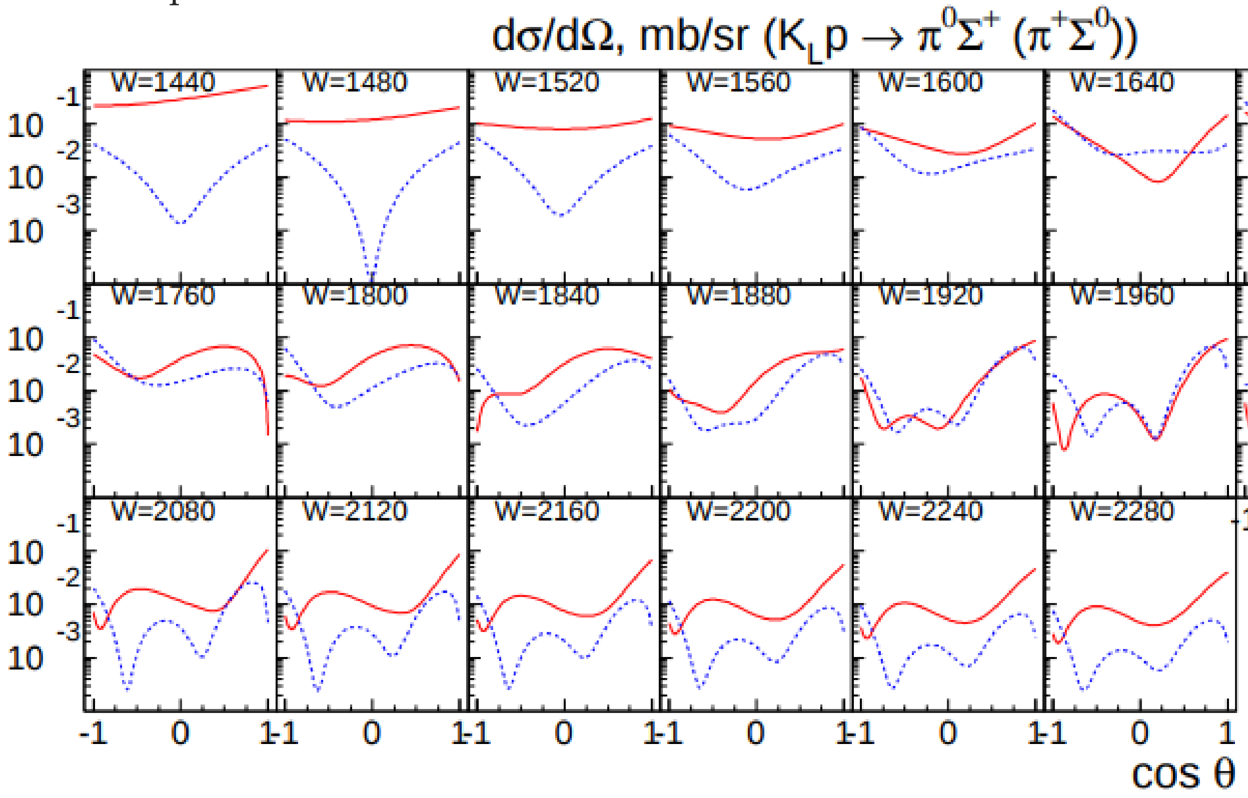



- Using $\pi\Sigma$ and $\pi\Lambda$ channels, we can access excited $\Sigma^*$ and $\Lambda^*$ state.
- Reactions using ($K_L$& p) in the initial state has different isospin contributions in the amplitudes from when using ($K_L$ & n) or ($K^-$ & p) in the initial state.
- Perform global PWA analysis to settle the spectrum of excited state hyperons.
  - We can measure cross sections and induced polarizations

$$|A(K^-p)|^2 = \frac{1}{2}(|A_1|^2 + |A_0|^2 + 2Re(A_1A_0^*))$$

$$|A(K^0n)|^2 = \frac{1}{2}(|A_1|^2 + |A_0|^2 - 2Re(A_1A_0^*))$$

$$|A(K^0p)|^2 = |A_1|^2$$

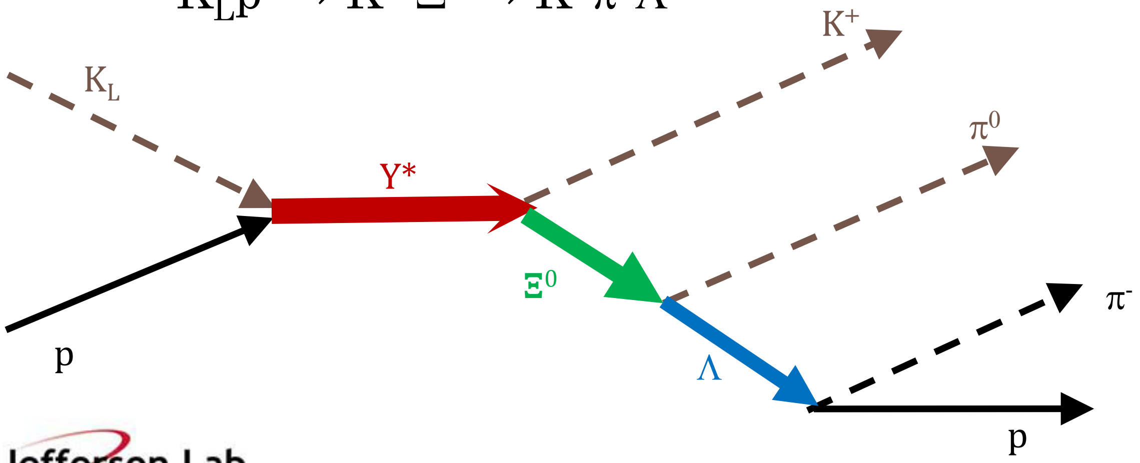


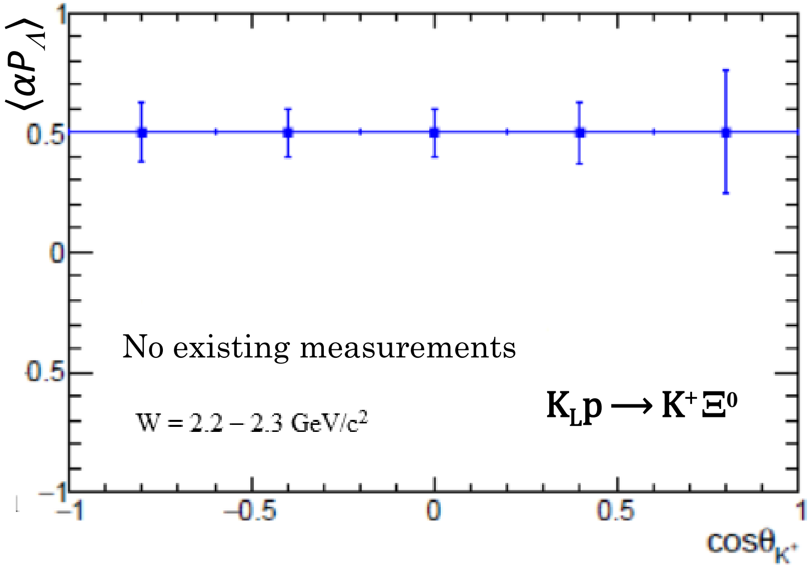

arXiv:2008.08215v3

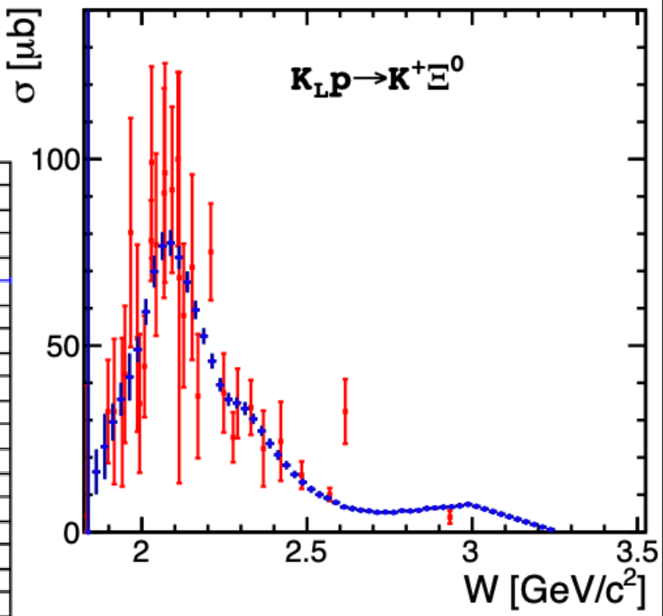
# K Ξ Channel

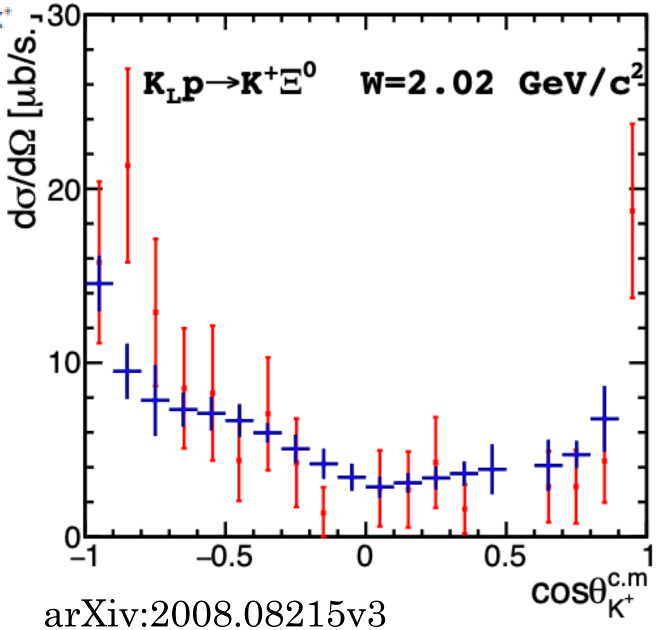
- Can access hyperon states that do not directly couple to $\pi\Lambda$ or $\pi\Sigma$ channels.
- Measure differential cross section and induced polarization using measured angular distribution of decay products.
  - Constrains underlying dynamics.
- To identify resonance contributions, we must perform a coupled-channeled PWA to extract spin-parity and pole positions of excited hyperons.
- Similarly impressive expectations are for the neutron target.

$$K_L p \longrightarrow K^+ \Xi^0 \longrightarrow K^+ \pi^0 \Lambda$$



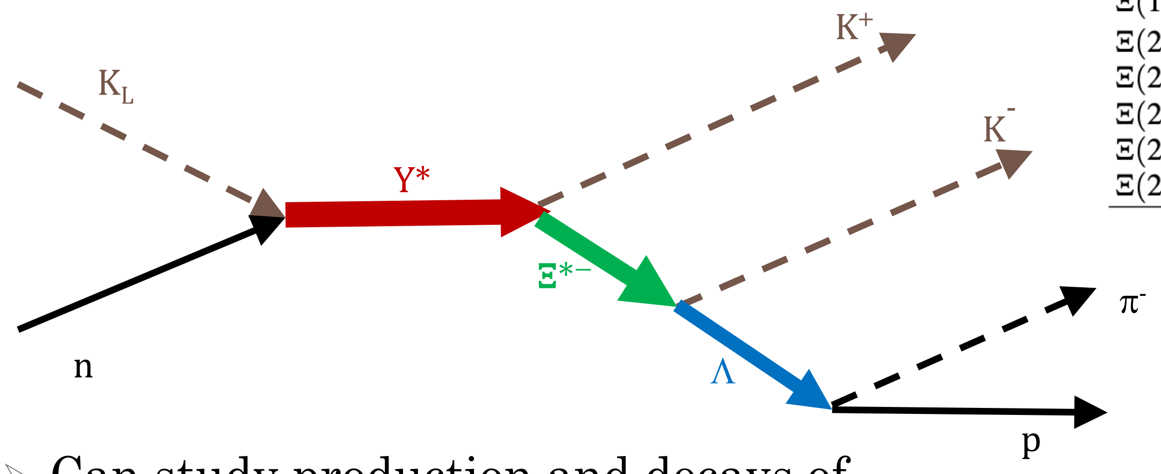




arXiv:2008.08215v3

# Excited Cascades $\Xi^*$

$K_L n \longrightarrow Y^* \longrightarrow K^+ \Xi^{*-} \longrightarrow K^+ K^- \Lambda$

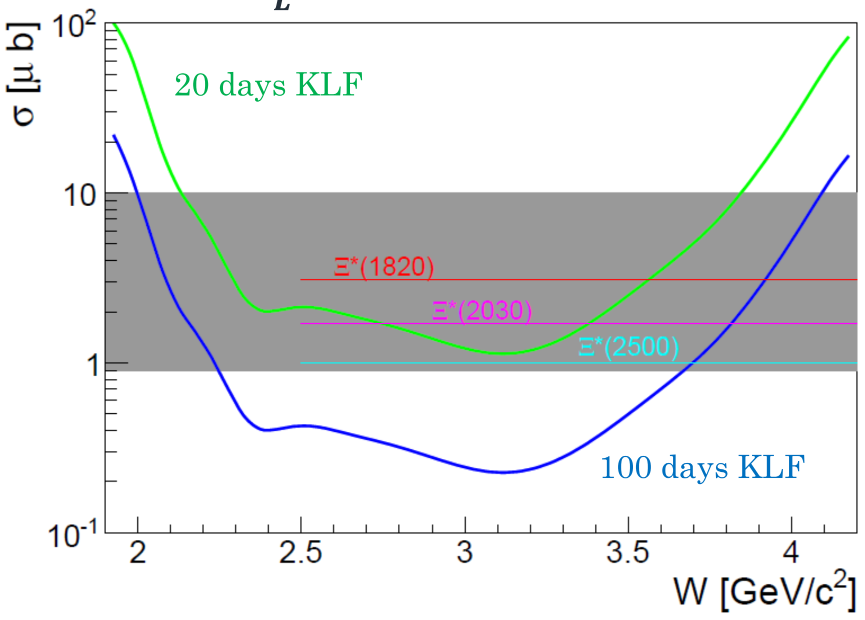


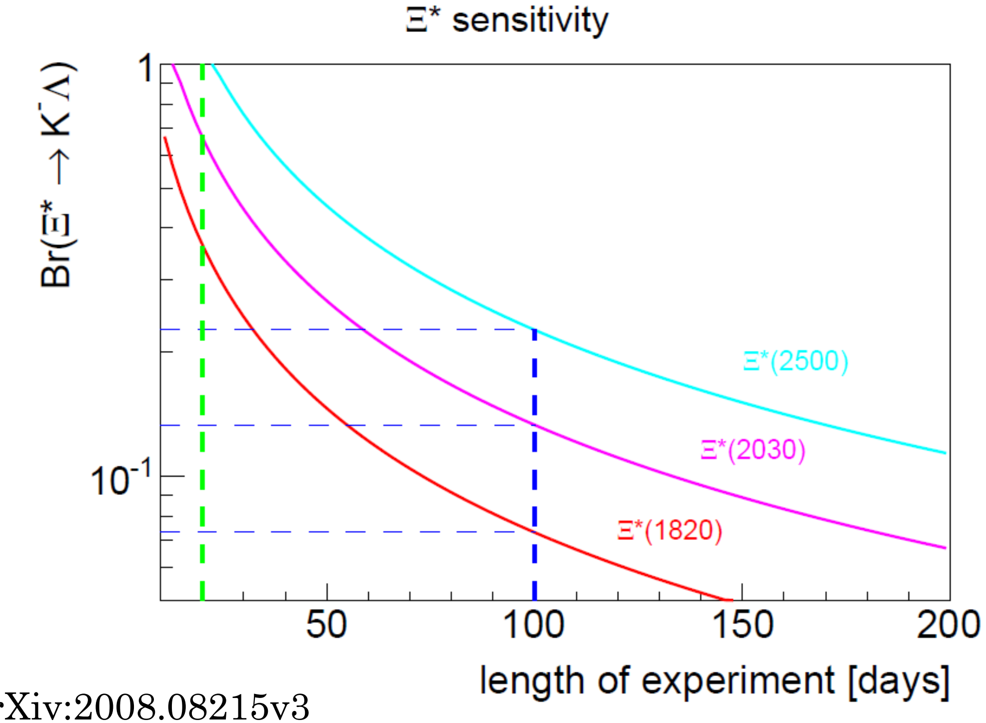

- Can study production and decays of excited cascades.
  - Most of our knowledge of cascade spectrum comes from beam experiments in the 60s–80s.
  - Quantum numbers for some of the excited cascades are not determined.
- We can measure branching ratios for $K^- \Lambda$ decays of $\Xi^*$ down to ~4% .

| State | $J^P$ | Overall Status |
|---|---|---|
| $\Xi(1318)$ | $1/2^{+a}$ | **** |
| $\Xi(1530)$ | $3/2^+$ | **** |
| $\Xi(1620)$ | | * |
| $\Xi(1690)$ | | *** |
| $\Xi(1820)$ | $3/2^-$ | *** |
| $\Xi(1950)$ | | *** |
| $\Xi(2030)$ | $5/2^?$ | *** |
| $\Xi(2120)$ | | * |
| $\Xi(2250)$ | | ** |
| $\Xi(2370)$ | | ** |
| $\Xi(2500)$ | | * |

$\Xi^* \rightarrow \Lambda K$
$\Xi^* \rightarrow \Xi \pi$
$\Xi^* \rightarrow \Xi \eta$
$\Xi^* \rightarrow \Xi \omega$
$\Xi^* \rightarrow \Sigma K$

$K_L n \rightarrow K^+ \Xi^{*-} \rightarrow K^+ K^- \Lambda$




arXiv:2008.08215v3

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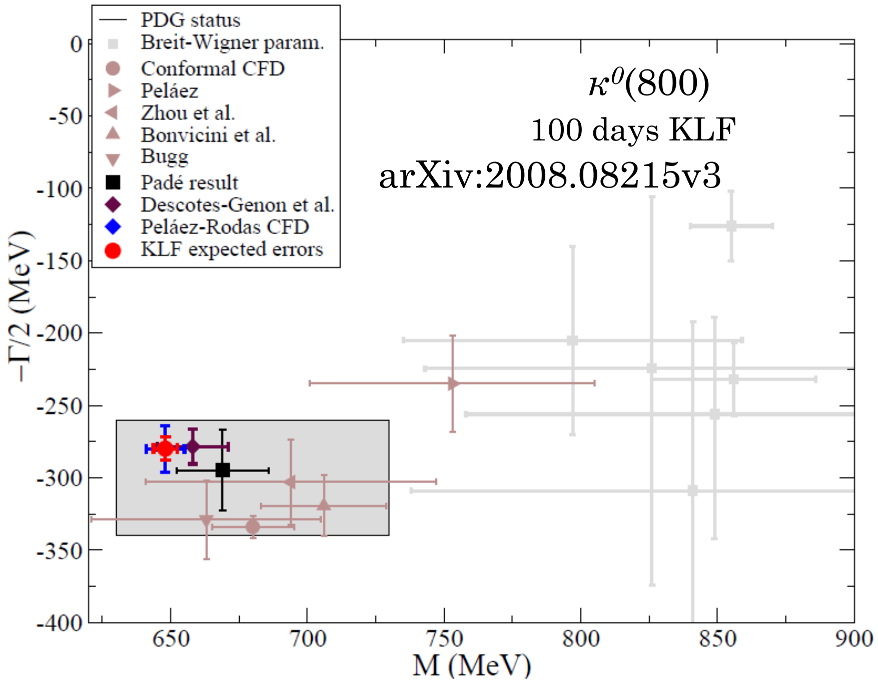
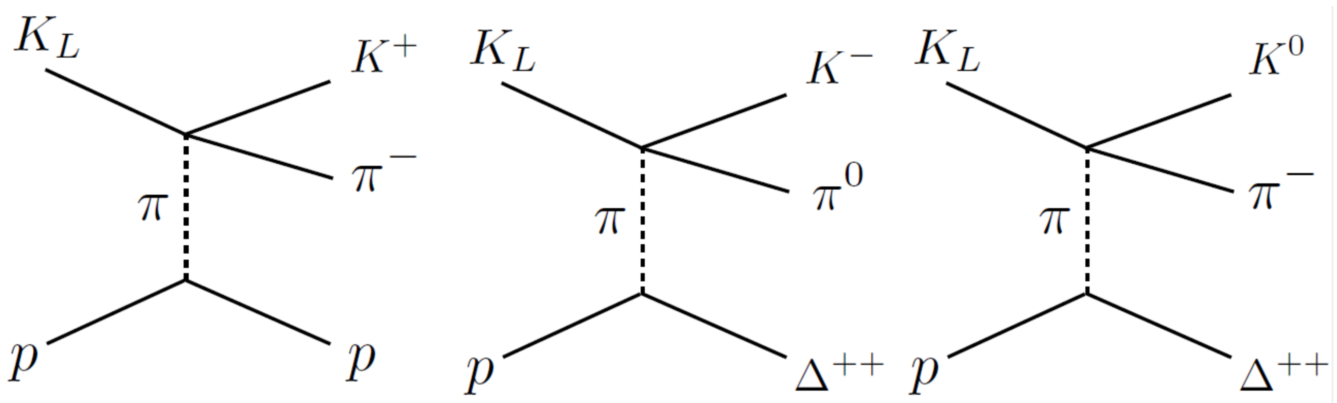
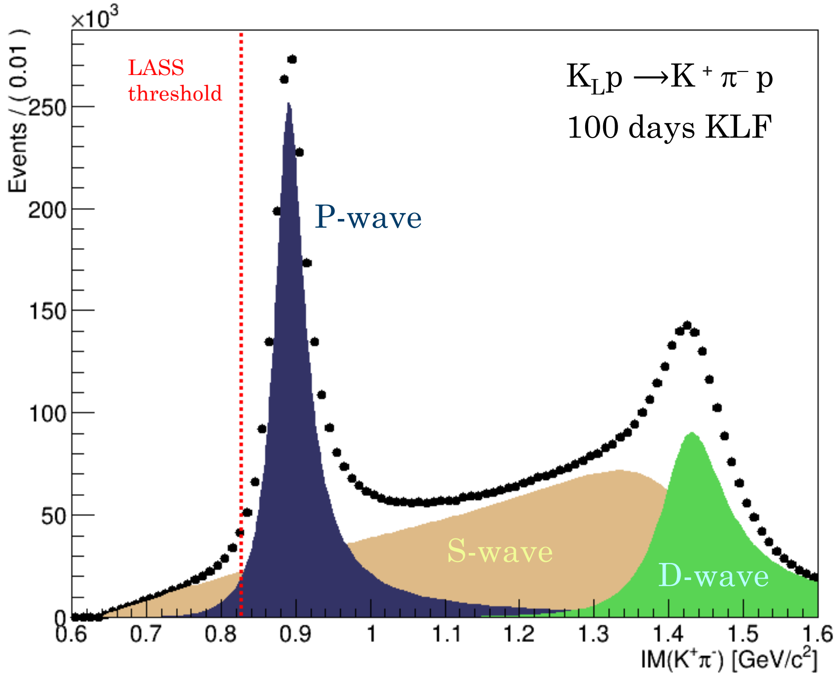
# Kπ Spectroscopy

$$K_L p \to K_L \pi^0 p,$$
$$K_L p \to K^{\pm} \pi^{\mp} p,$$
$$K_L p \to K_{(L,S)} \pi^+ n,$$
$$K_L p \to K^+ \pi^0 n,$$
$$K_L p \to K^- \pi^0 \Delta^{++},$$
$$K_L p \to K_{(L,S)} \pi^- \Delta^{++}$$

- The simplest hadronic reaction that involves s-quark
  - crucial for understanding non-pQCD.
- Locate pole positions in I=1/2 & I=3/2 channels
  - Existence of the scalar $\kappa^0(700)$ (I=1/2, S-wave $0^{++}$) is still unclear.
    - Need data at invariant masses closer to ~650 MeV to reconcile ChPT models, data, and LQCD.
  - Separating isospin contributions will require $K_L$ detection.

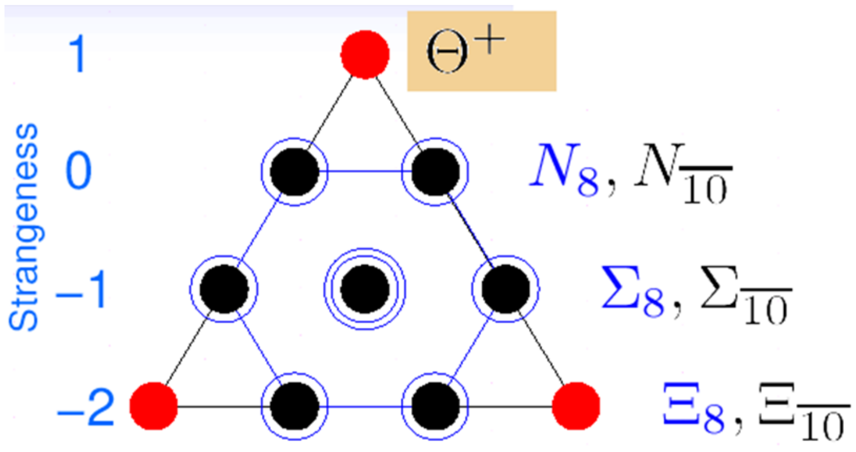


# Other topics

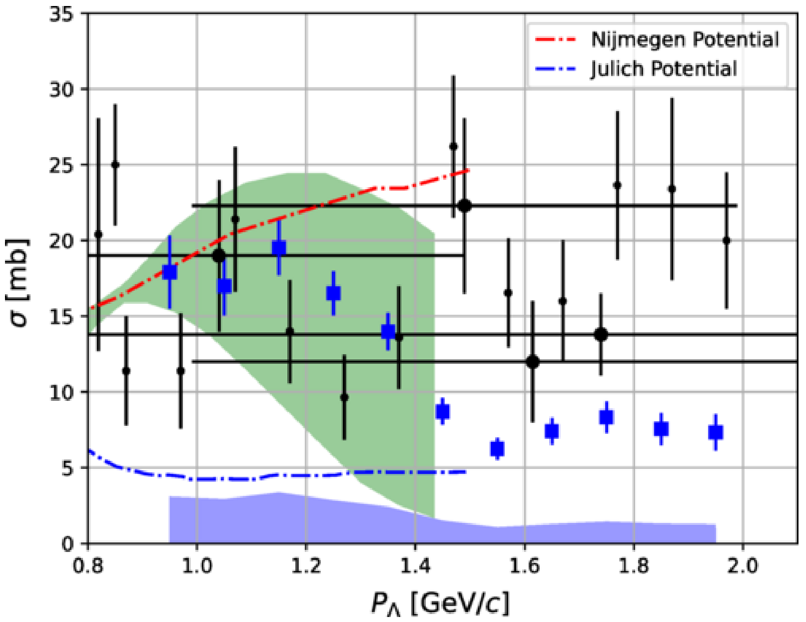
S=1/2




Pentaquark Antidecuplet

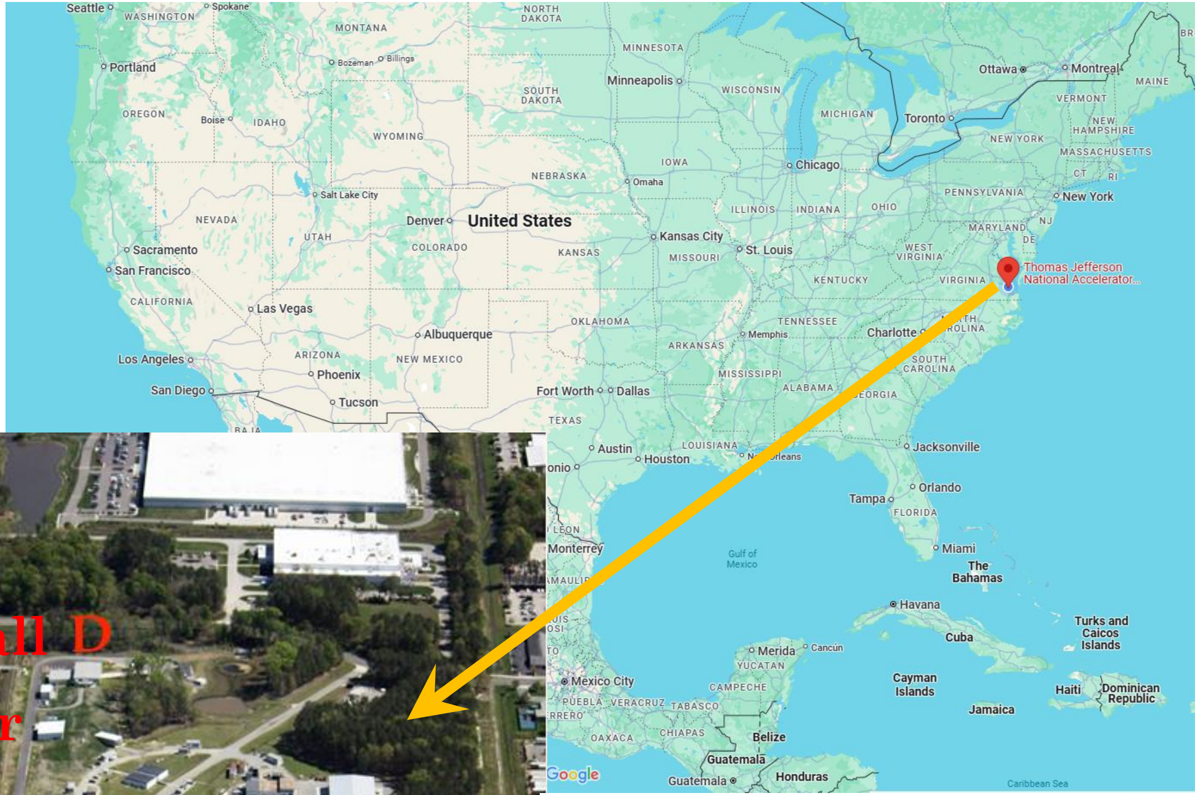
- Study of $\Omega^*$ ($S$=-3) states.
- Neutron induced reactions.
- $K_L p \to K^+ n$ reaction to study non-resonant background to hyperon production
  - Resonant structure would mean an exotic state.
- Hyperon-nucleon scattering.
  - Important for neutron star equation of state
- "Parasitic" experimental setups to study hypernuclei.

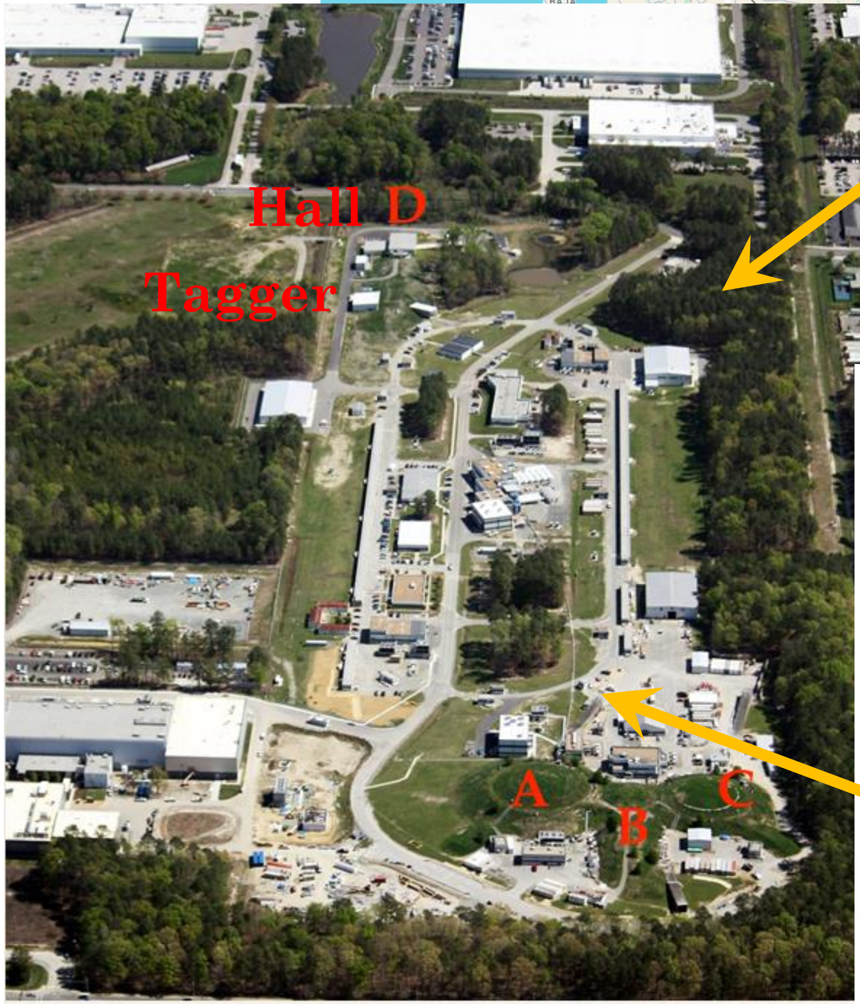
Phys. Rev. Lett. **127**, 272303

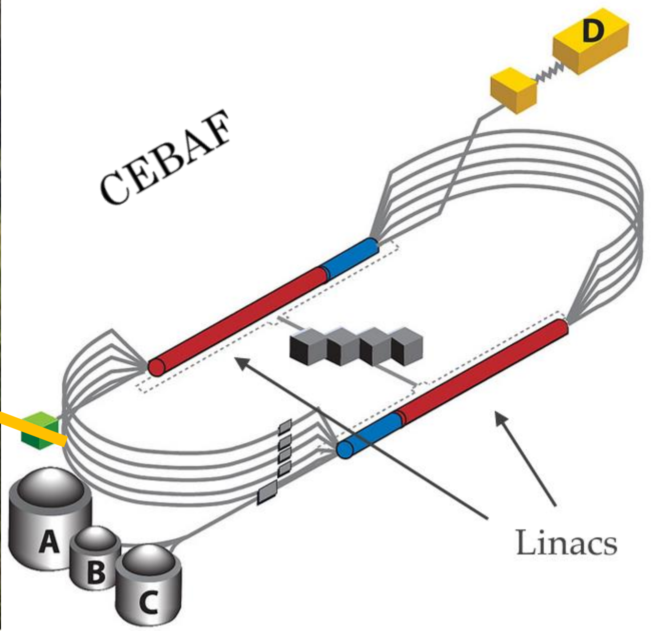


# CEBAF @ JLAB

- Up to 12 GeV polarized continuous electron beam
  - ~1.5 GHz beam time structure
- Four experimental Halls: A, B, C, D
  - Each halls receives an electron beam bunch every ~4ns
- Experimental program concentrates predominantly on hadronic physics.
  - Hall D :
    - Meson spectroscopy
    - $J/\Psi$ near-threshold photoproduction
    - Rare meson decays
    - Pion polarizabilities
    - Color transparency and short-range correlations in nuclei.

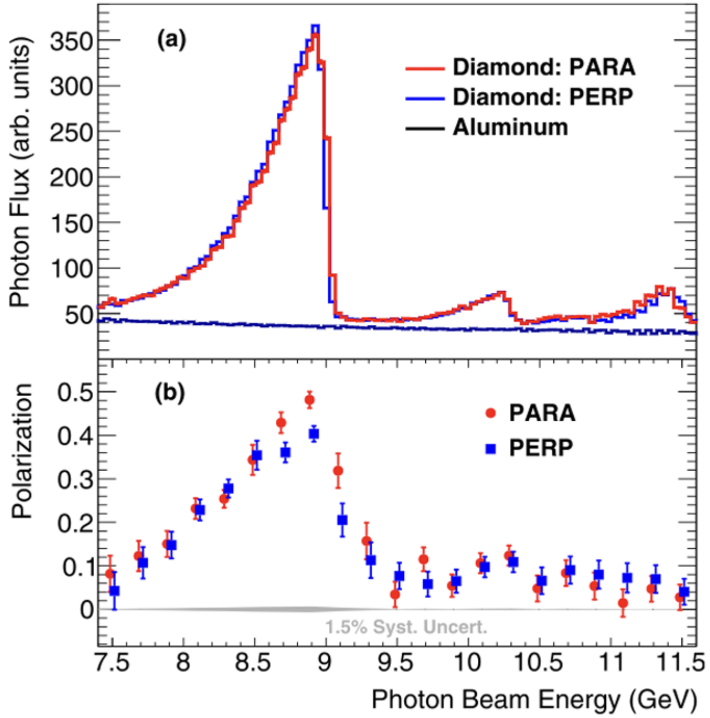


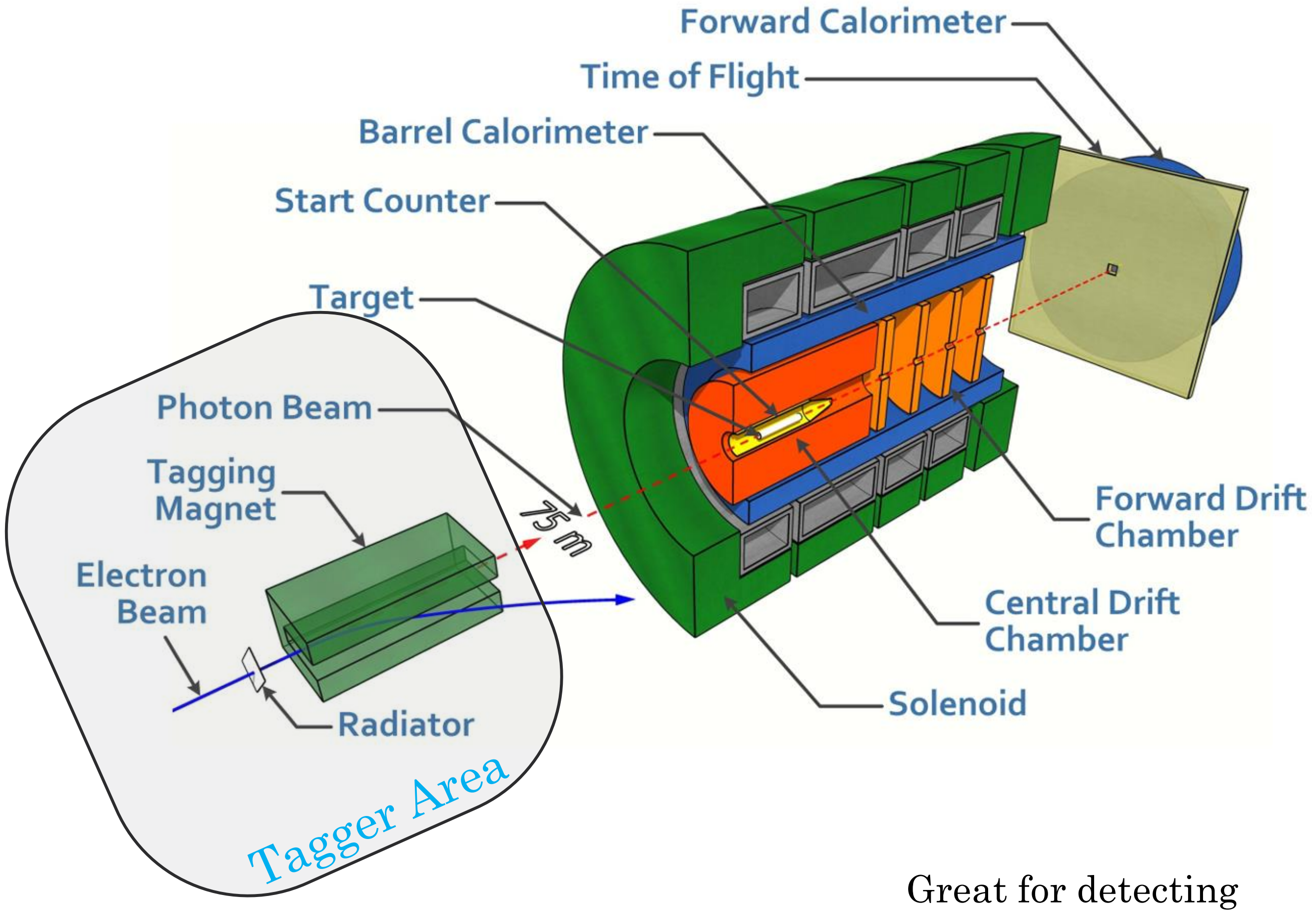



# GlueX in Hall D

- 12 GeV electrons with 4ns beam bunch separation
- Linearly polarized photon beam produced via coherent bremsstrahlung of electrons on a thin ($5x10^{-4}$ X0) diamond radiator.
- Photons are tagged by detecting the electrons in a scintillating detectors (photon tagger).




Great for detecting charged particles and photons in the final states.

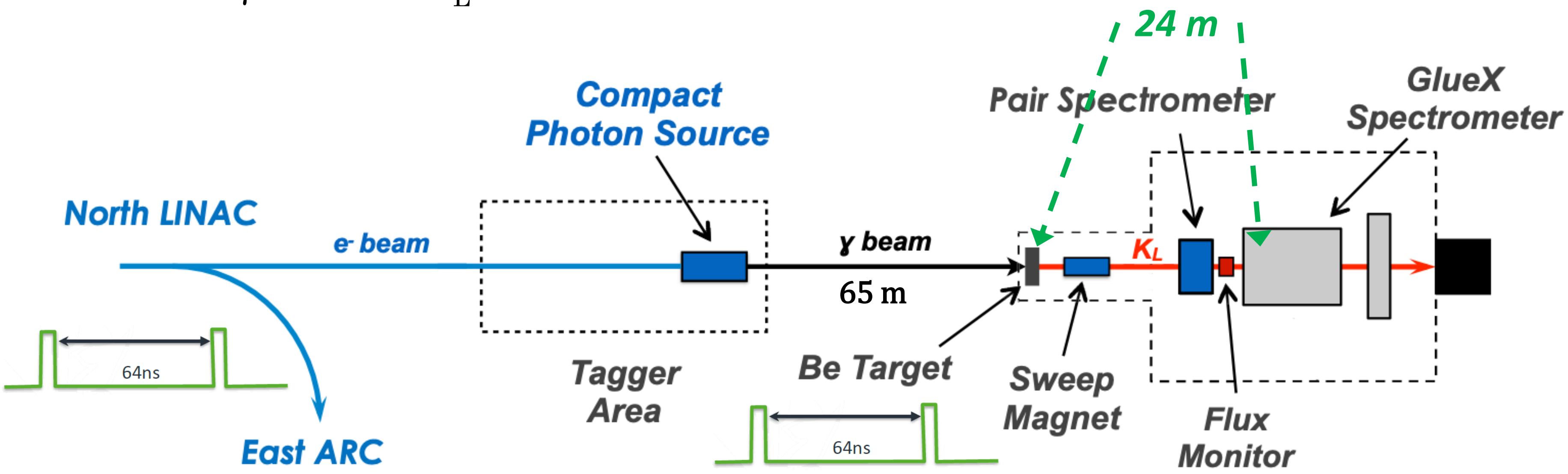
- Acceptance: $\theta_{lab} \approx 1^\circ$ - $120^\circ$
- Charged particles: $\sigma_p/p \approx 1\%-3\%$
  - PID using TOF $\oplus$ dE/dx $\oplus$ DIRC
- Photons: $\sigma_E/E = 6\% / E \oplus 2\%$

# KLF in Hall D

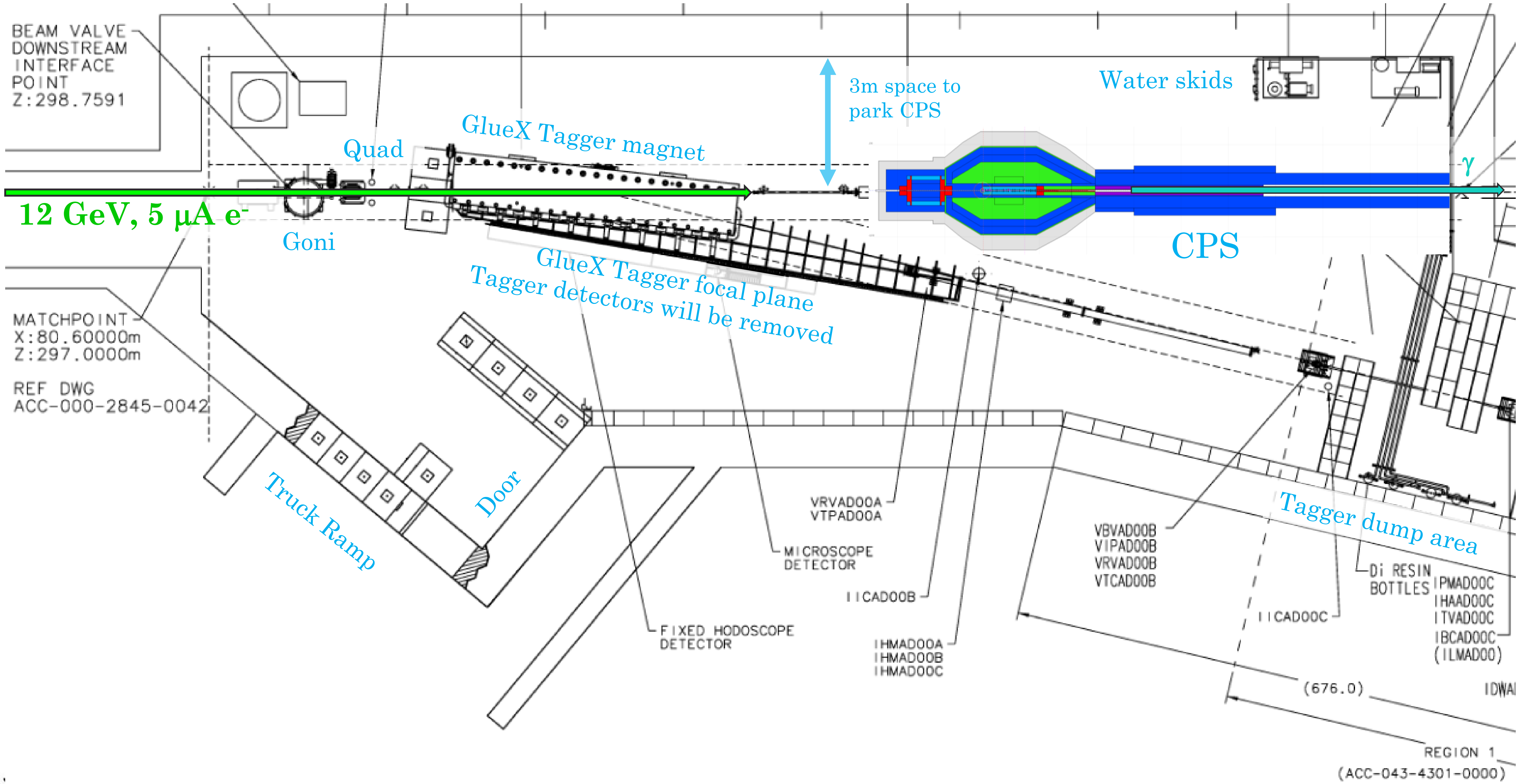
- Use the electron beam delivered to Hall D to produced a high intensity untagged photon beam on ~2% X0 amorphous radiator in the tagger building of Hall D.
- Use a Beryllium target in Hall D collimator cave to produce tertiary beam and absorbed the rest of the beam.
- Use $K_L$ in-flight decays to measure kaon flux in the beamline.
- Tertiary $K_L$ -beam impacts a liquid hydrogen target to produce the final states of interest.
  - LH2 target will need some modifications.
- To determine the momentum of the beam that caused the event in GlueX, KLF will use 64-ns beam structure to allow the low energy kaons to travel the 24m distance between the kaon production point and the hydrogen target.
- Estimated conversion time from γ-beam to $K_L$-beam is ~18 months.

Tertiary beam:

$e^- \longrightarrow \gamma \longrightarrow K_L$

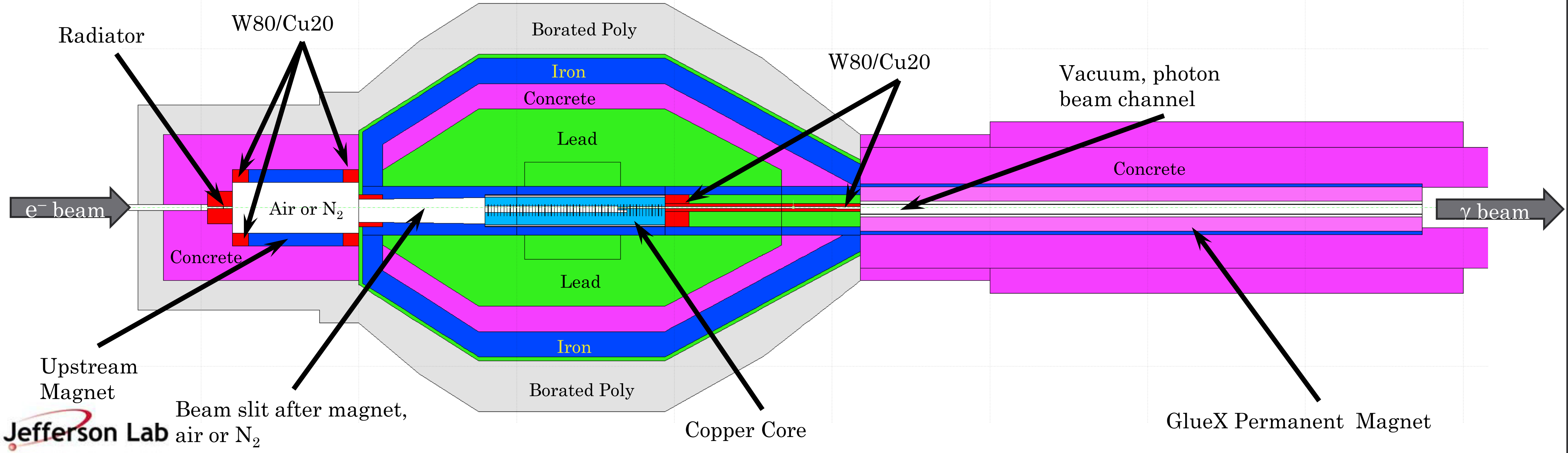


# CPS in Tagger Hall



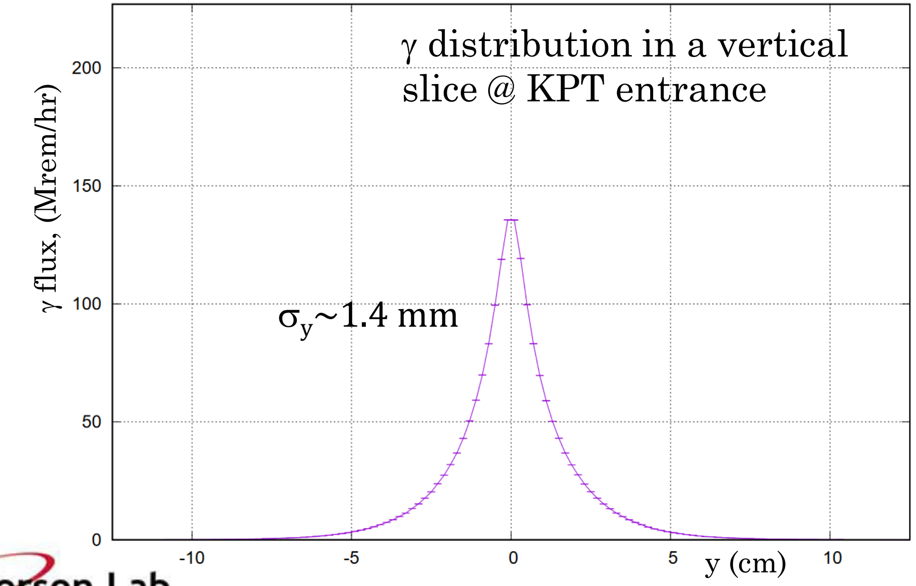
# Compact Photon Source

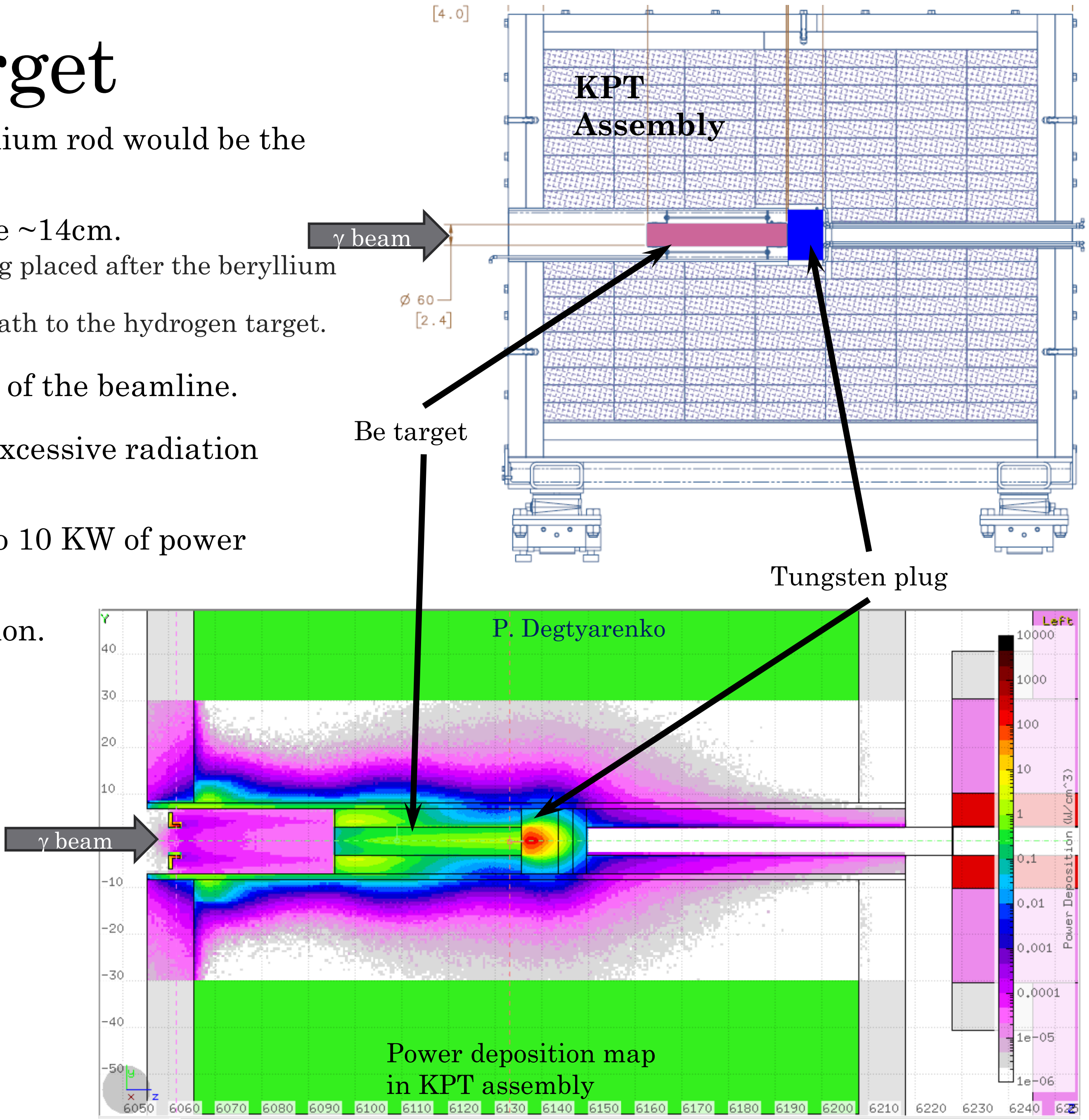
- CPS creates intense photon beam for KLF and absorbs the primary electron beam in a cooled copper core.
- Radiator in the upstream section of CPS followed by a horizontally bending magnet.
- Permanent magnet at the exit of CPS to clean up charged particles.
- CPS can be pushed aside for photon beamline restoration.
- CPS shielding is designed to provide radiation environment in the tagger hall with dose rates comparable to nominal GlueX photoproduction experiments.
  - Detail simulations have been done using FLUKA software package to estimate dose rates and power deposition.
- Total estimated weight of CPS is approximately 75 metric tons.
- Estimated cost of the current design is ~$1.2M for CPS.



# Kaon Production Target

- Based on our studies, a 40cm long and 6cm wide Beryllium rod would be the optimal choice for producing $K_L$ beam.
- A tungsten plug to stop other particles is expected to be ~14cm.
  - Photons and charged particles are absorbed in a tungsten plug placed after the beryllium target.
  - Significant amount of $K_L$ survive the tungsten plug and the path to the hydrogen target.
- Two magnets after KPT to sweep charged particles out of the beamline.
- Be-target and W-plug are heavily shielded to prevent excessive radiation levels.
- KPT assembly is designed to absorb and dissipate up to 10 KW of power delivered by the photon beam.
- KPT can be pushed aside for photon beamline restoration.



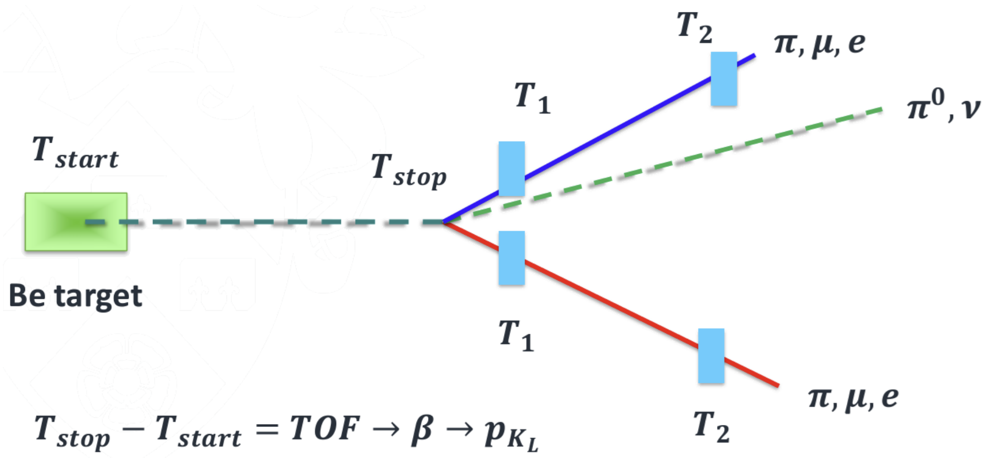
# Kaon Flux Monitor

$K_l \to \pi^{\pm} e^{\mp} \nu_{\mu}$

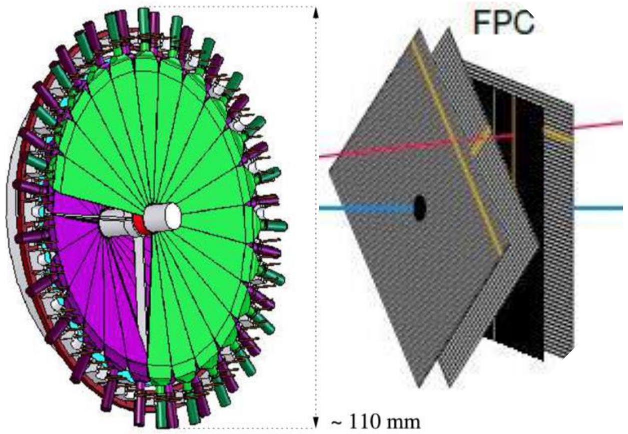
$K_l \to \pi^{\pm} \mu^{\mp} \nu_{\mu}$

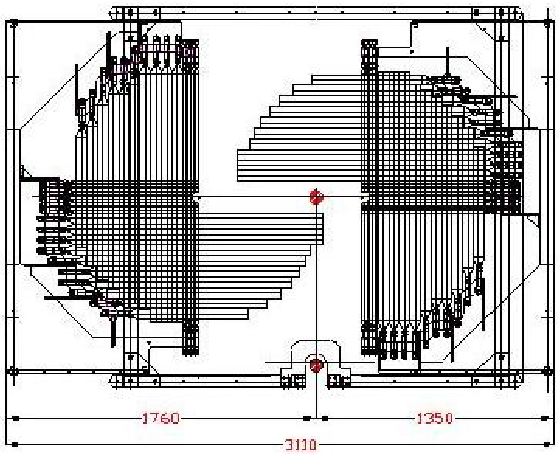
$K_l \to \pi^{+} \pi^{-} \pi^{0}$

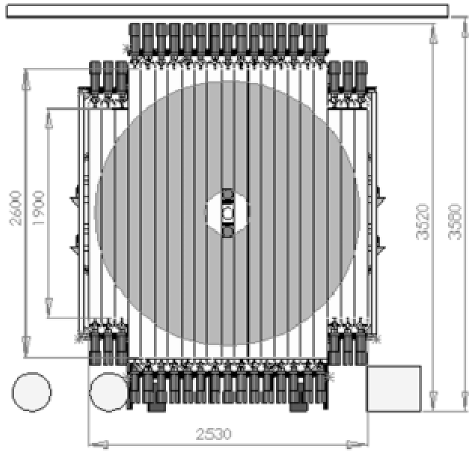
- We can use $K_L$ in-flight decays to measure the KL flux versus momentum and versus transverse position w.r.t beam axis.
  - $K_L$ momentum determined using TOF between KPT and the decay vertex.
- Install Kaon Flux Monitor (KLF) in the location of GlueX Pair Spectrometer.
- We plan to use three separate packages of scintillator detectors, and a tracking system based on straw tubes.
  - All are excess equipment from WASA available free to KLF.




$K_L$ Beam




$K_L$ Beam

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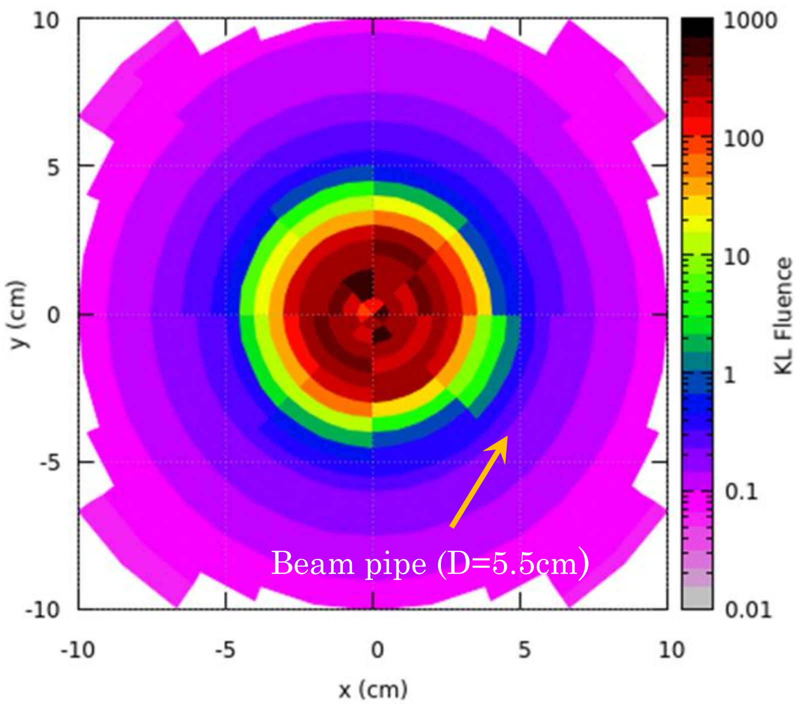
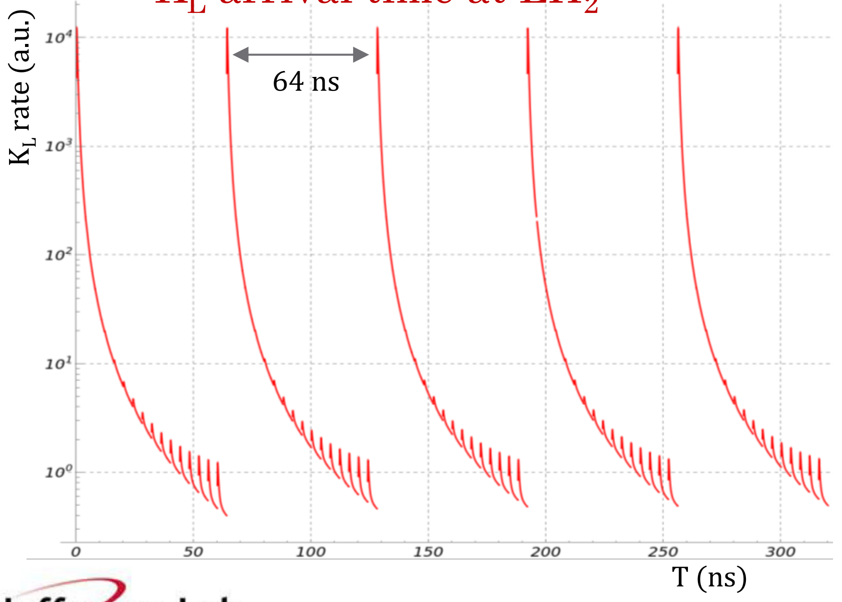
# $K_L$ Beam

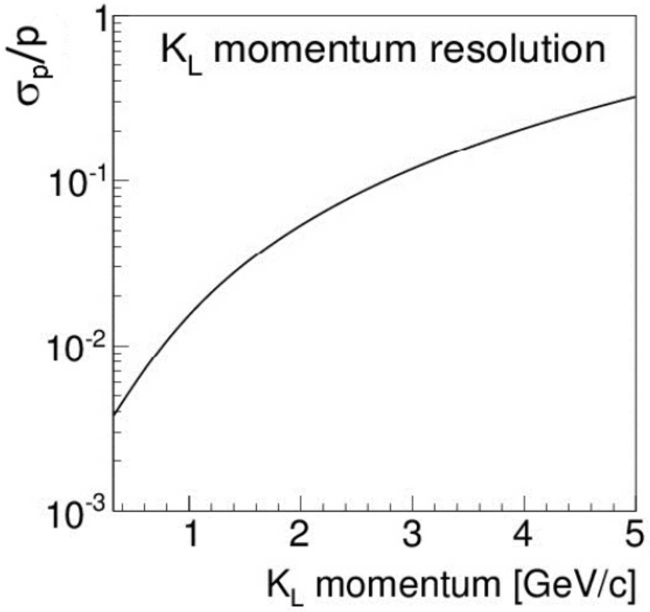
- Kaon beam is mostly constrained to the beam pipe due to the collimation.
- Kaons are created every 64ns – KLF electron beam bunching.
  - Small ~2% bleed-through bunches is expected.
- $K_L$ momentum determined using TOF between KPT and $LH_2$.
  - Above W>2.1 GeV/c², $K_L$ momentum determined using e detected final state.
- We expect neutron background in the beam which should be rejected in the event reconstruction.

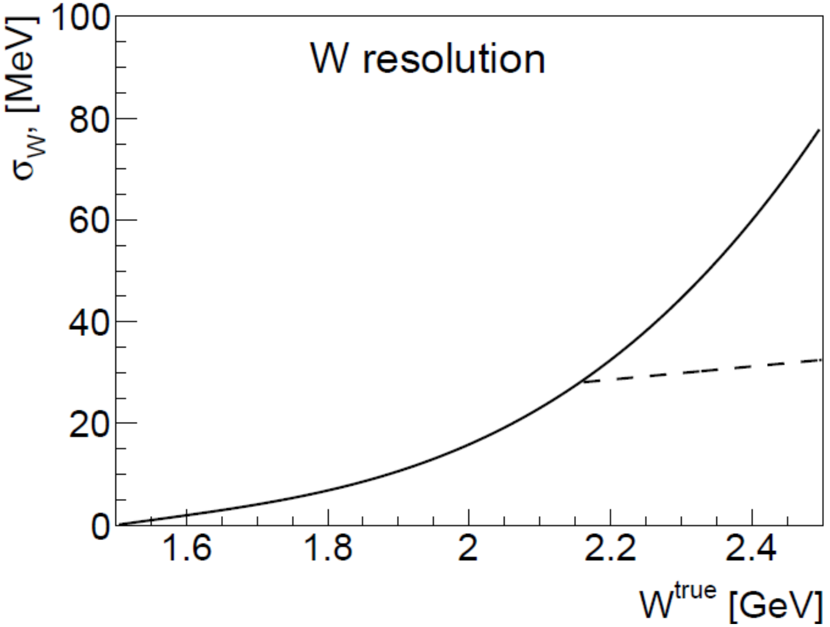
$K_L$ fluence at the $LH_2$ target, P. Degtyarenko




$K_L$ arrival time at $LH_2$

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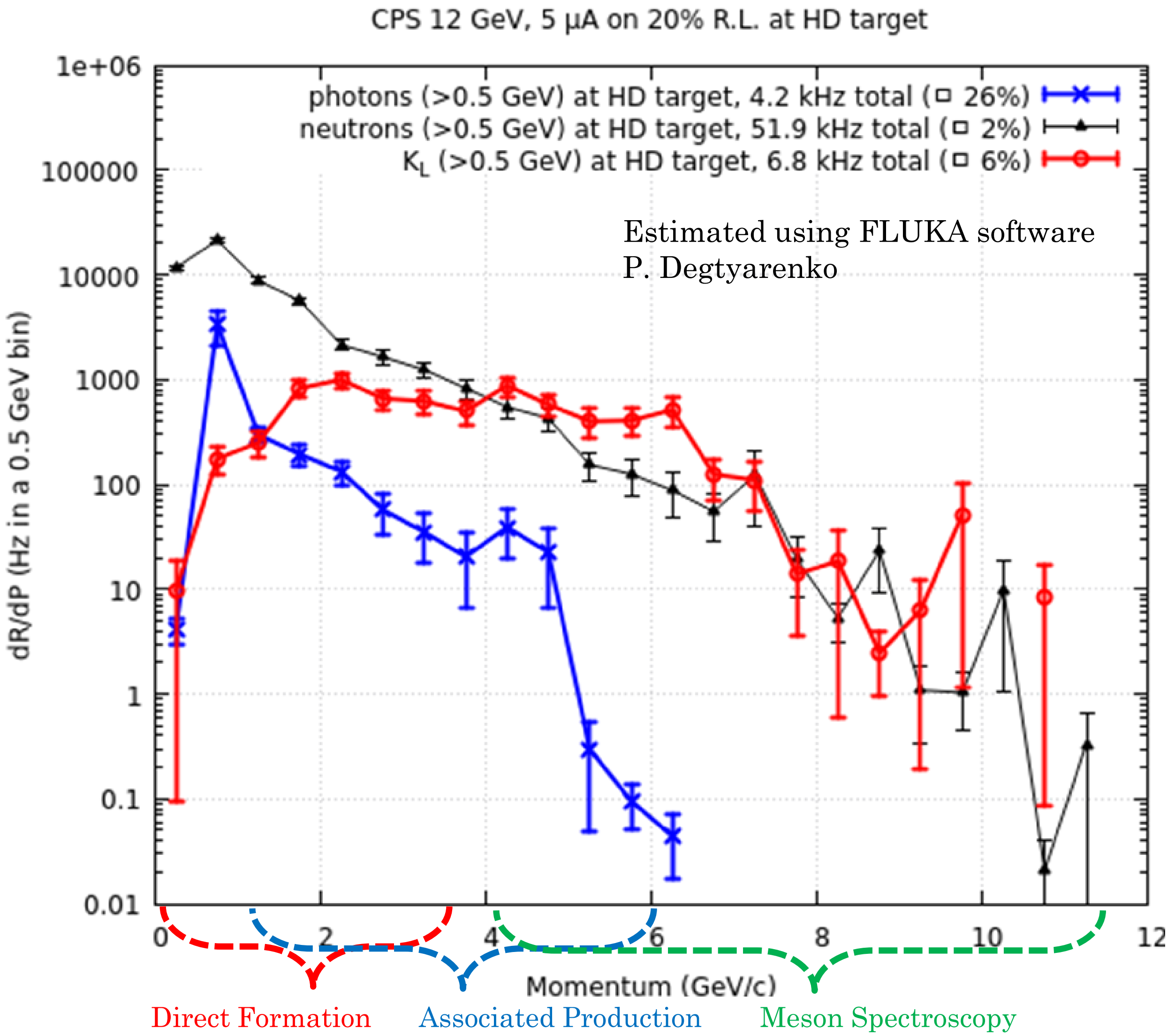
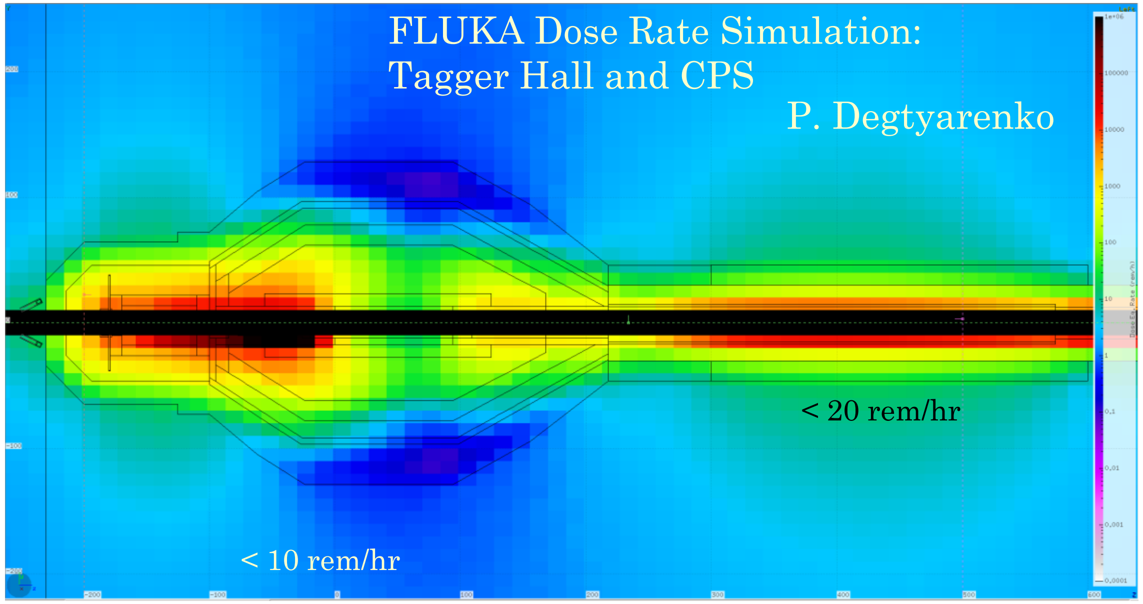
# Beam Particle Spectra

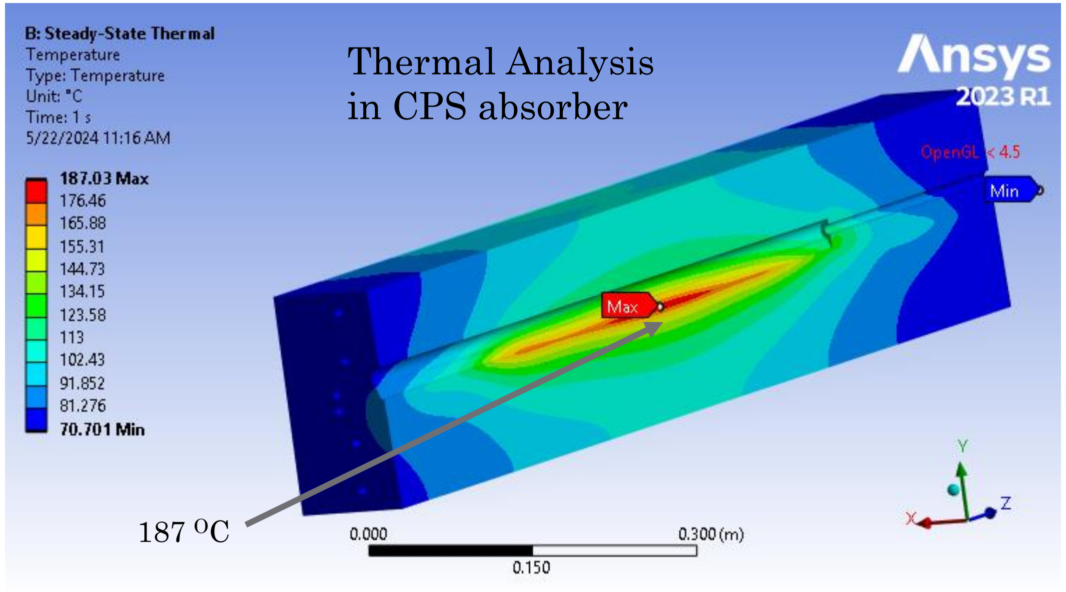
- KLF beam at $LH_2$ target is expected to contain a mix of different kind of particles.
- At low momenta, most of the particles in the beam pipe will be neutrons.
- At high momenta, above 5 GeV/c, we expect mostly $K_L$-s in the beam line.
  - We expect approximately ~10 KHz $K_L$ per second on the $LH_2$ target.
- There is also significant number of muons that originate in the KPT assembly, but they are not constrained to the beam pipe.



# Challenges

- Maintaining radiation environment safe for people and equipment.
  - We perform detailed simulations with FLUKA package to estimate the radiation levels at various beam conditions and adjust our design accordingly.
- Prevent excessive temperatures in CPS that could result in deformation of the photon beam exit channel.
  - Closely monitor beam positions, temperatures in CPS to shut down beam if needed.
- Maintain detector counting rates comparable to those during GlueX-II running.
  - We perform detailed GEANT4 simulations with KLF and GlueX conditions to adjust KLF design parameters.
  - We are considering building a new Start Counter around the target to match the 6cm KLF target diameter.
- Separating out-of-time beam buckets from Hall D laser and bleed-through from other Halls.
  - Simulate various final states with out-of-time beam bunches and physics background channels to evaluate the impact.
  - Initial indication that these should not be a significant problem for $K^+n$ final state.



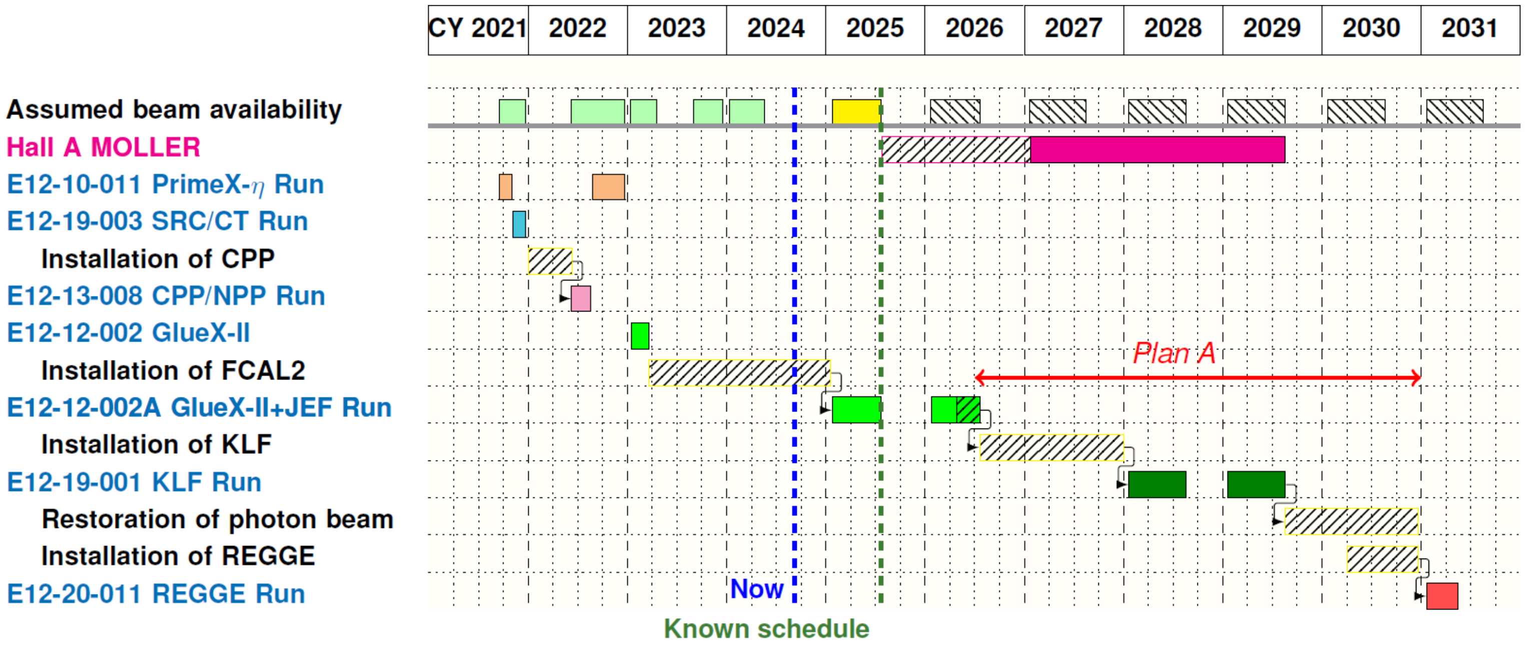

Jefferson Lab

# Status and Timeline

- Conceptual designs of CPS and KPT nearing completion.
  - Some procurements have already started.
- Kaon Flux Monitors detectors physically exist.
  - Need to be shipped from Germany to Jefferson Lab for testing and installations.
- $LH_2$ target requires relatively small modifications
  - Will be constructed by Jefferson Lab target group.
- We are aiming for beginning of KLF installations in the summer of 2026.
  - The experiment would start in the winter of 2028 in this scenario.

- Assumes 25 weeks of CEBAF running in FY25 and 30 weeks afterwards.
- Approved GlueX-III run is not shown

- There are many uncertainties related to the schedule.
  - Funding levels for JLAB
  - Compatibility with MOLLER experiment in Hall A.
  - Available manpower to design and install the new equipment.



# Conclusions and Outlook

- K-Long Facility will be the first hadronic beam experiment at Jefferson Lab.
  - Approved for running for 200 days.
- Data from KLF is expected to make major impact in strangeness physics:
  - identify excited hyperons with masses up to 2.5 GeV/$c^2$ in formation and production reactions,
  - have a significant impact on our knowledge on $K\pi$ scattering amplitudes,
  - improve determination of K*'s parameters, including those for $\kappa^0(700)$.
- Significant progress has been made in the design of KLF equipment.
  - Some technical challenges are being addressed.
- KLF may start running as early as winter of 2028
  - Subject to funding availability and potential scheduling incompatibilities with other experiments.
- New collaborators are welcome !!!
  - This is a good time to join KLF.