The Physics Opportunities with K^0_L Beam at

Jefferson Lab
Thomas Jefferson National Accelerator Facility

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Old Dominion University

ODU Nuclear Group Seminar, June 23, 2016

A Letter of Intent to Jefferson Lab PAC-43.

Physics Opportunities with a Secondary K_L^0 Beam at JLab.

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(Dated: May 15, 2015)

Outline

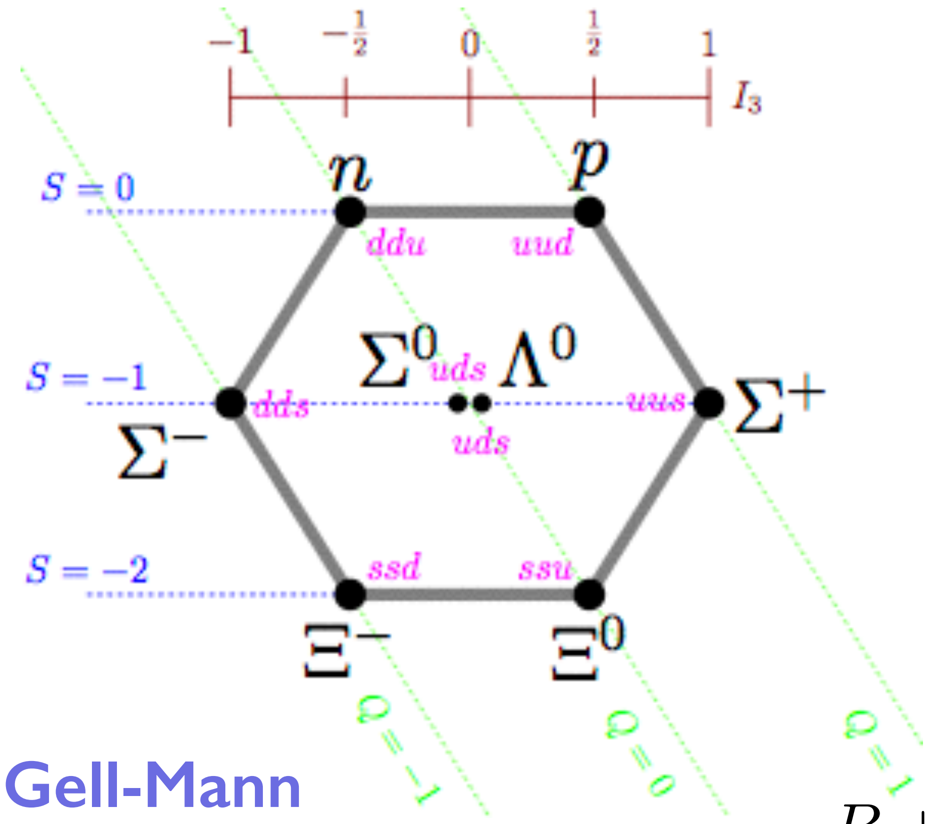
- Introduction
- Baryon Multiplets
- Reactions with K^0_L beam on proton target
- Experimental Arrangement
- K^0_L Beam at GlueX
- Expected rates
- Summary

The nonexistent is whatever we
have not sufficiently desired.
Franz Kafka
(In some cases it may be true M.A.)

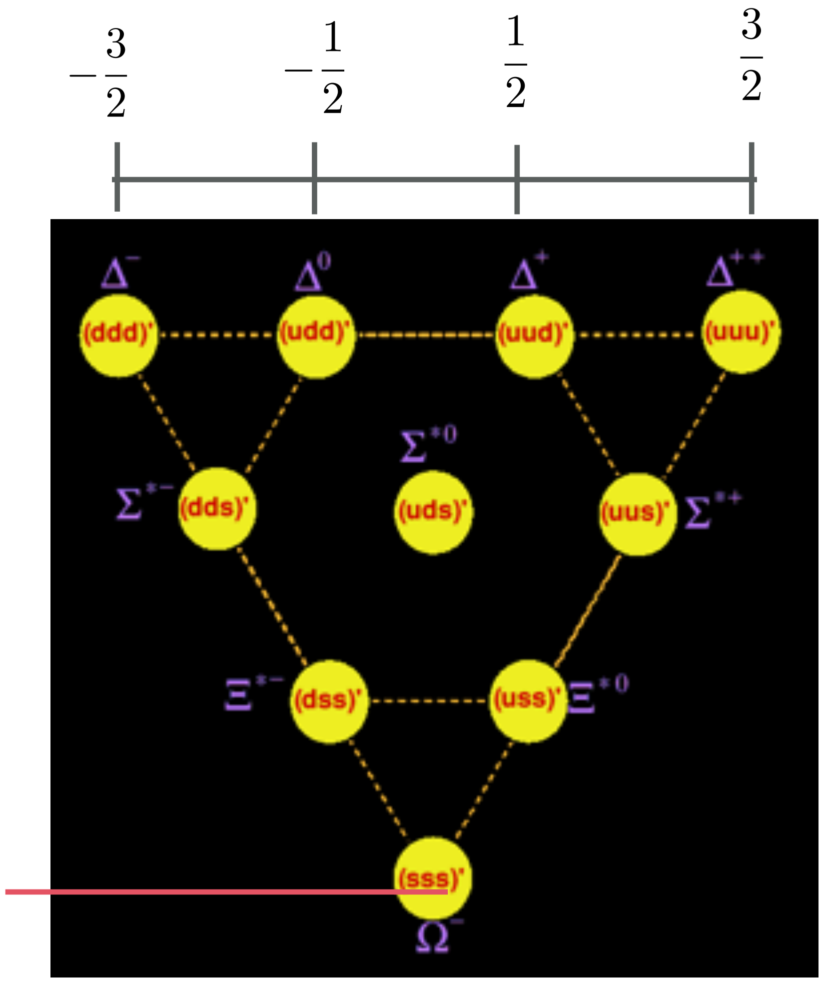
Constituent Quark Model

SU(3)

Octet



Decuplet



S=-3

Gell-Mann
Nishidjima

$$Q = I_3 + \frac{B+S}{2}$$

But there are many more states predicted, where are they?

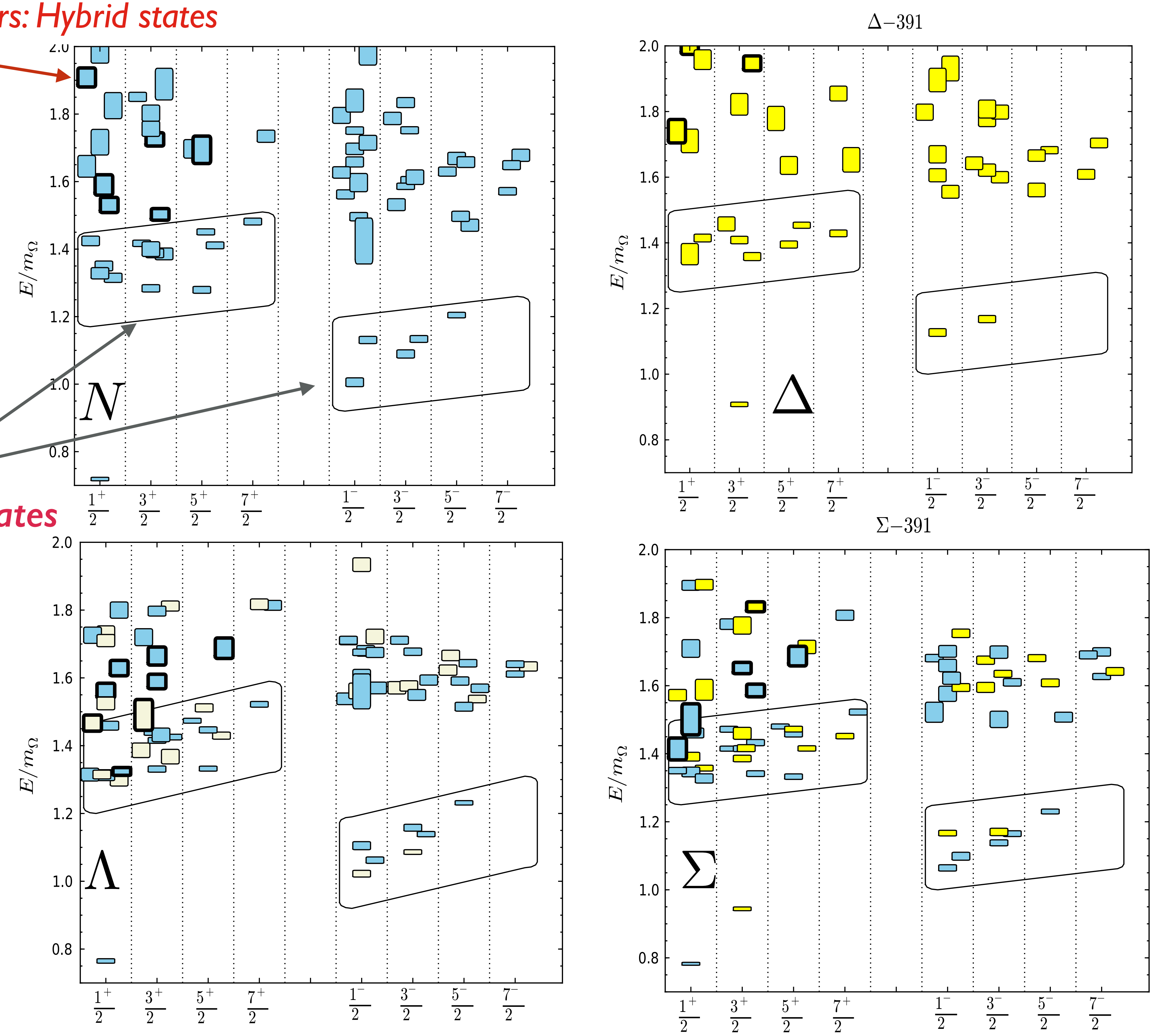
Where are hybrids, glueballs, multiquark states ?

Well, some of them may already have been observed?

Lattice QCD calculations

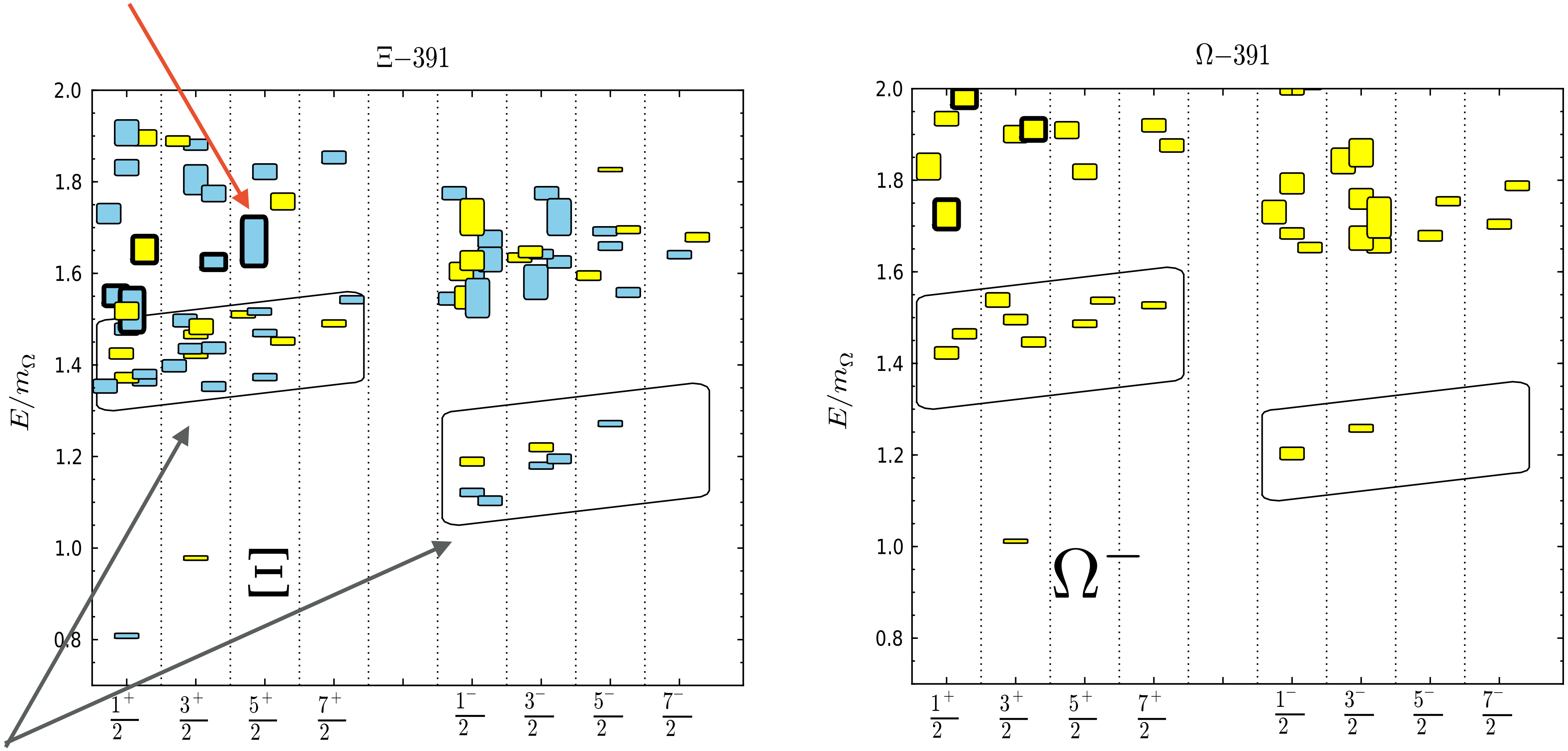
Thick borders: Hybrid states

Low Lying states



Lattice QCD calculations

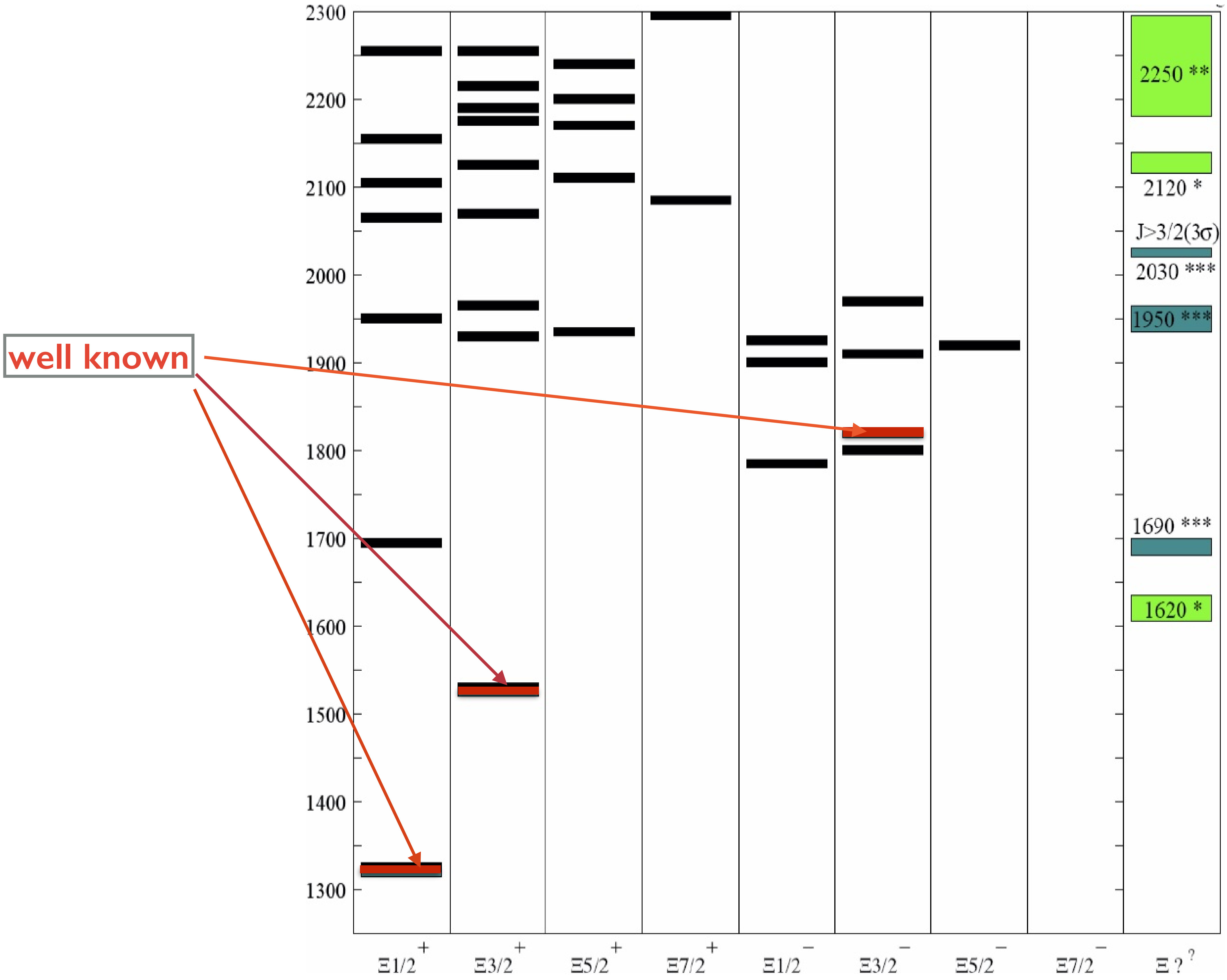
Thick borders: Hybrid states



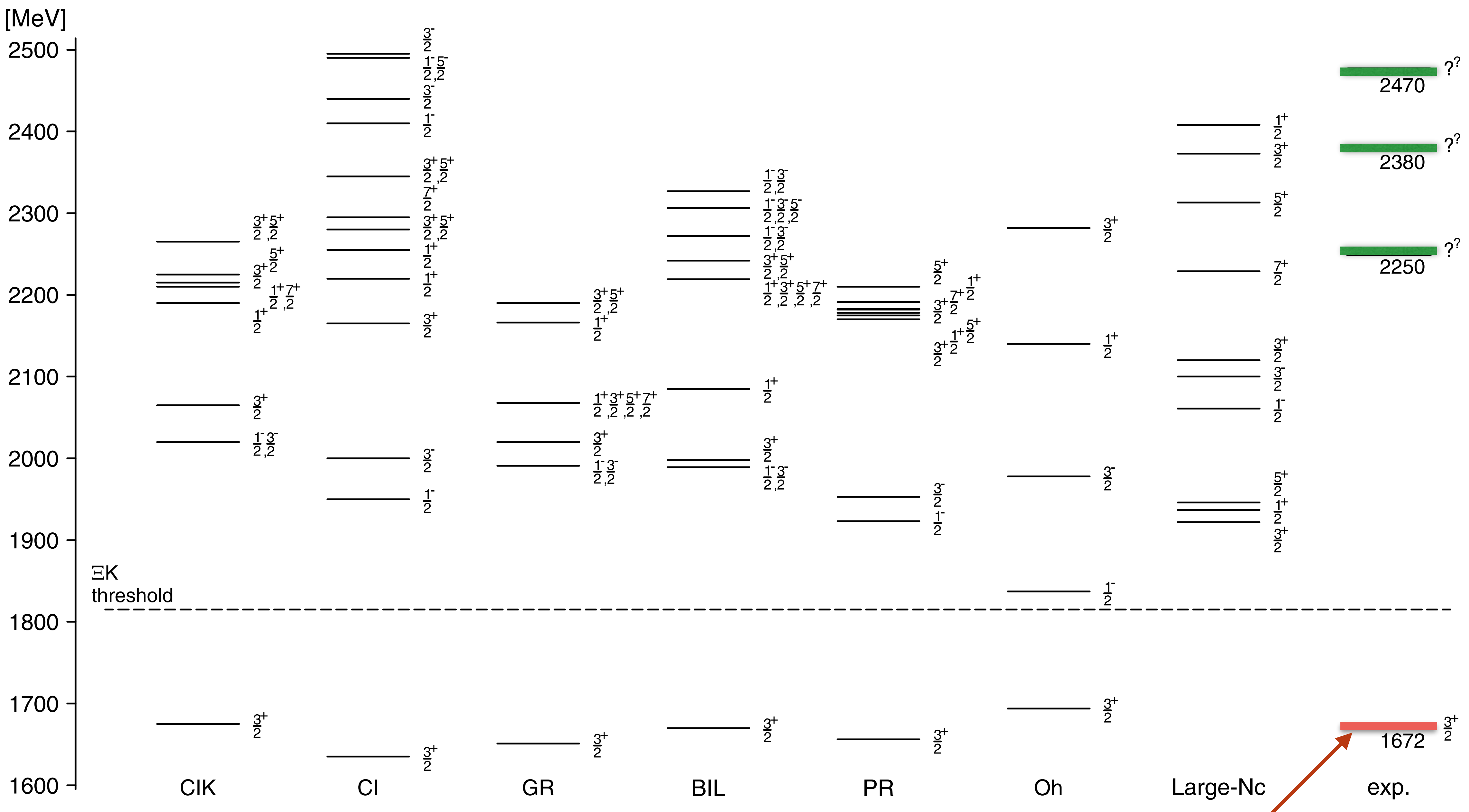
Low Lying states

Edwards, Mathur, Richards and Wallace
Phys. Rev. D 87, 054506 (2013)

Status of Ξ^*


well known
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
2250 **
2120 *
J>3/2(3σ)
2030 ***
1950 ***
1690 ***
1620 *
Ξ1/2 +
Ξ3/2 +
Ξ5/2 +
Ξ7/2 +
Ξ1/2 −
Ξ3/2 −
Ξ5/2 −
Ξ7/2 −
Ξ ? ?

Status of Ω^{-*}



only one well known state?

- **Three light quarks** can be arranged in **6** baryonic families, **N***, **Δ***, **Λ***, **Σ***, **Ξ***, & **Ω***.
- **Number of members** in a family that can exist **is not arbitrary**.
- If **SU(3)$_F$** symmetry of **QCD** is controlling, then:

Octet: **N***, **Λ***, **Σ***, **Ξ***
Decuplet: **Δ***, **Σ***, **Ξ***, & **Ω***

  - Number of experimentally identified resonances of each baryon family in PDG summary tables is **17 N***, **24 Δ***, **14 Λ***, **12 Σ***, **7 Ξ***, & **2 Ω***.
  - **Constituent Quark** models, for instance, predict existence of no less than **64 N***, **22 Δ*** states with **mass < 3** GeV.

- Seriousness of "**missing-states**" problem is obvious from these numbers.

- To complete **SU(3)$_F$** multiplets, one needs no less than **17 Λ***, **41 Σ***, **41 Ξ***, & **24 Ω***.

Recourse to the Neutral Kaon System

Strangeness eigenstates with $J^{PC} = 0^{-+}$

$$|K^0\rangle = |d\bar{s}|, \qquad |\bar{K}^0\rangle = |\bar{d}s|$$

S=+1 **S=-1**

Party *eigenstates with intrinsic* $P = -1$

$$P|K^0\rangle = -|K^0\rangle, \qquad P|\bar{K}^0\rangle = -|\bar{K}^0\rangle$$

Effect of ***C-Party*** *can be taken to be*

$$C|K^0\rangle = |\bar{K}^0\rangle, \qquad C|\bar{K}^0\rangle = |K^0\rangle$$

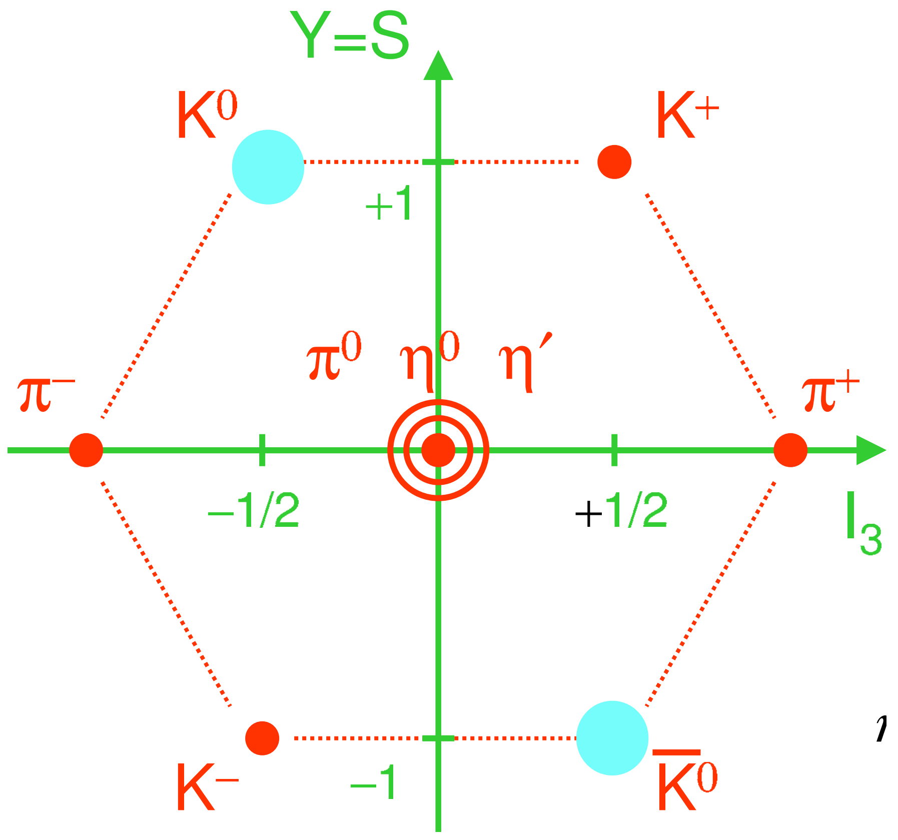
However not ***CP*** *eigenstates*

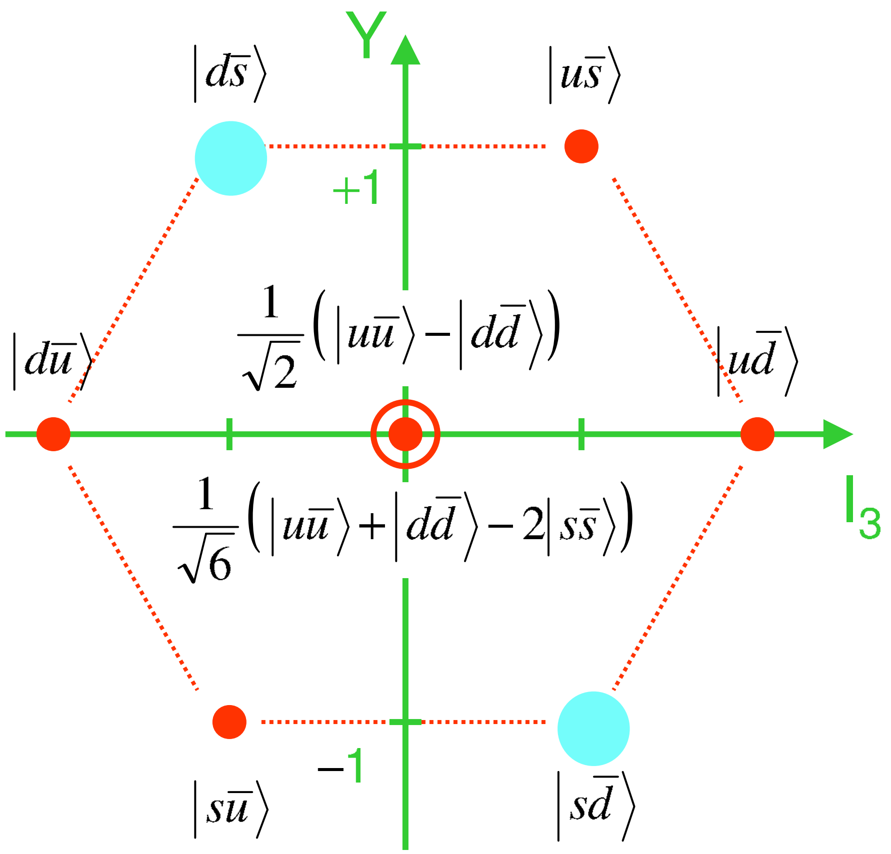
$$CP|K^0\rangle = -|\bar{K}^0\rangle, \qquad CP|\bar{K}^0\rangle = -|K^0\rangle$$

CP eigenstates can be formed

$$|\mathrm{K}_1\rangle \equiv \frac{1}{\sqrt{2}}\left(|\mathrm{K}^0\rangle - |\overline{\mathrm{K}}^0\rangle\right) \; ; \qquad CP\,|\mathrm{K}_1\rangle = +\,|\mathrm{K}_1\rangle$$

$$|\mathrm{K}_2\rangle \equiv \frac{1}{\sqrt{2}}\left(|\mathrm{K}^0\rangle + |\overline{\mathrm{K}}^0\rangle\right) \; ; \qquad CP\,|\mathrm{K}_2\rangle = -\,|\mathrm{K}_2\rangle$$





$$K^0 \quad and \quad \bar{K}^0$$

are unstabile particles decaying via WI

$$K_S(K - short) \quad and \quad K_L(K - long)$$

propagate as free particles and have distinct lifetimes

$$\tau_S = 0.9 \times 10^{-10} s \quad and \quad \tau_L = 0.5 \times 10^{-7} s \ (c\tau = 15\ m)$$

$$|K_S\rangle \equiv \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_1\rangle + \epsilon|K_2\rangle) \approx |K_1\rangle$$

$$|K_L\rangle \equiv \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_2\rangle + \epsilon|K_1\rangle) \approx |K_2\rangle$$

$|\epsilon| \approx 2.3 \times 10^{-3}$ **defines the level of CP violation**

CP conserving decays

$$\begin{aligned} \mathrm{K_S} &\to \pi^+\pi^- && \mathrm{BR} = 68.6\% \\ &\to \pi^0\pi^0 && \mathrm{BR} = 31.4\% \end{aligned}$$

$$\begin{aligned} \mathrm{K_L} &\to \pi^+\pi^-\pi^0 && \mathrm{BR} = 12.6\% \\ &\to \pi^0\pi^0\pi^0 && \mathrm{BR} = 21.1\% \\ &\to \pi^-\mathrm{e}^+\nu_\mathrm{e} && \mathrm{BR} = 19.4\% \\ &\to \pi^+\mathrm{e}^-\overline{\nu}_\mathrm{e} && \mathrm{BR} = 19.4\% \\ &\to \pi^-\mu^+\nu_\mu && \mathrm{BR} = 13.6\% \\ &\to \pi^+\mu^-\overline{\nu}_\mu && \mathrm{BR} = 13.6\% \end{aligned}$$

CP violating decays observed in 1964

$$\begin{aligned} \mathrm{K_L} &\to \pi^+\pi^- && \mathrm{BR} = 2.1 \times 10^{-3} \\ &\to \pi^0\pi^0 && \mathrm{BR} = 9.4 \times 10^{-4} \end{aligned}$$

What if we have a K^0_L beam ?

List of reactions:

Elastic and charge-exchange

$$K^0_L p \to K^0_S p$$
$$K^0_L p \to K^+ n$$

Two-body with S=-1

$$K^0_L p \to \pi^+ \Lambda$$
$$K^0_L p \to \pi^+ \Sigma^0$$

Two-body with S=-2

$$K^0_L p \to K^+ \Xi^0$$
$$K^0_L p \to K^+ \Xi^{0*}$$

Three-body with S=-2

$$K^0_L p \to \pi^+ K^+ \Xi^-$$
$$K^0_L p \to \pi^+ K^+ \Xi^{-*}$$

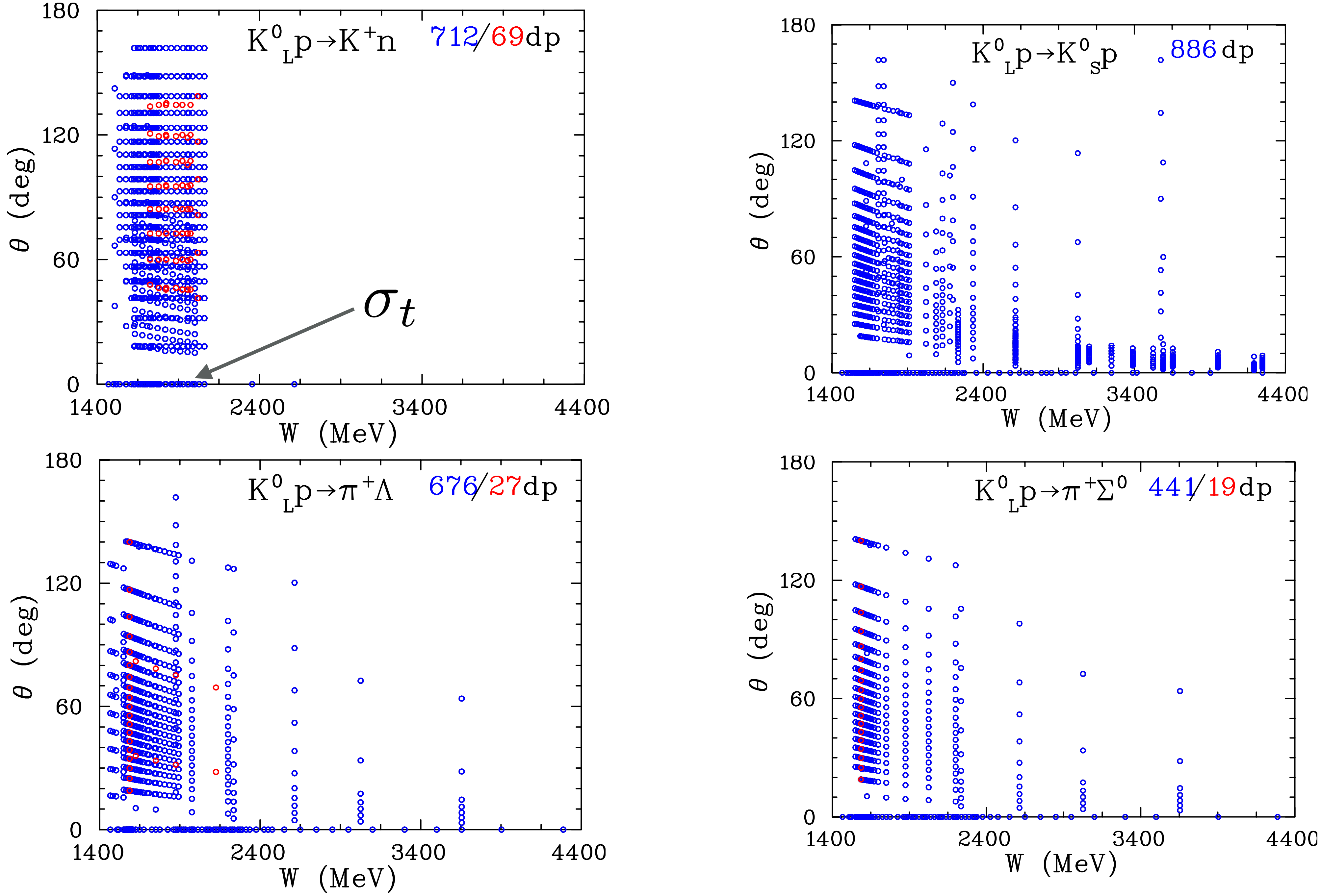
Three-body with S=-3

$$K^0_L p \to K^+ K^+ \Omega^-$$
$$K^0_L p \to K^+ K^+ \Omega^{-*}$$

Very Limited World Data with K_L beam

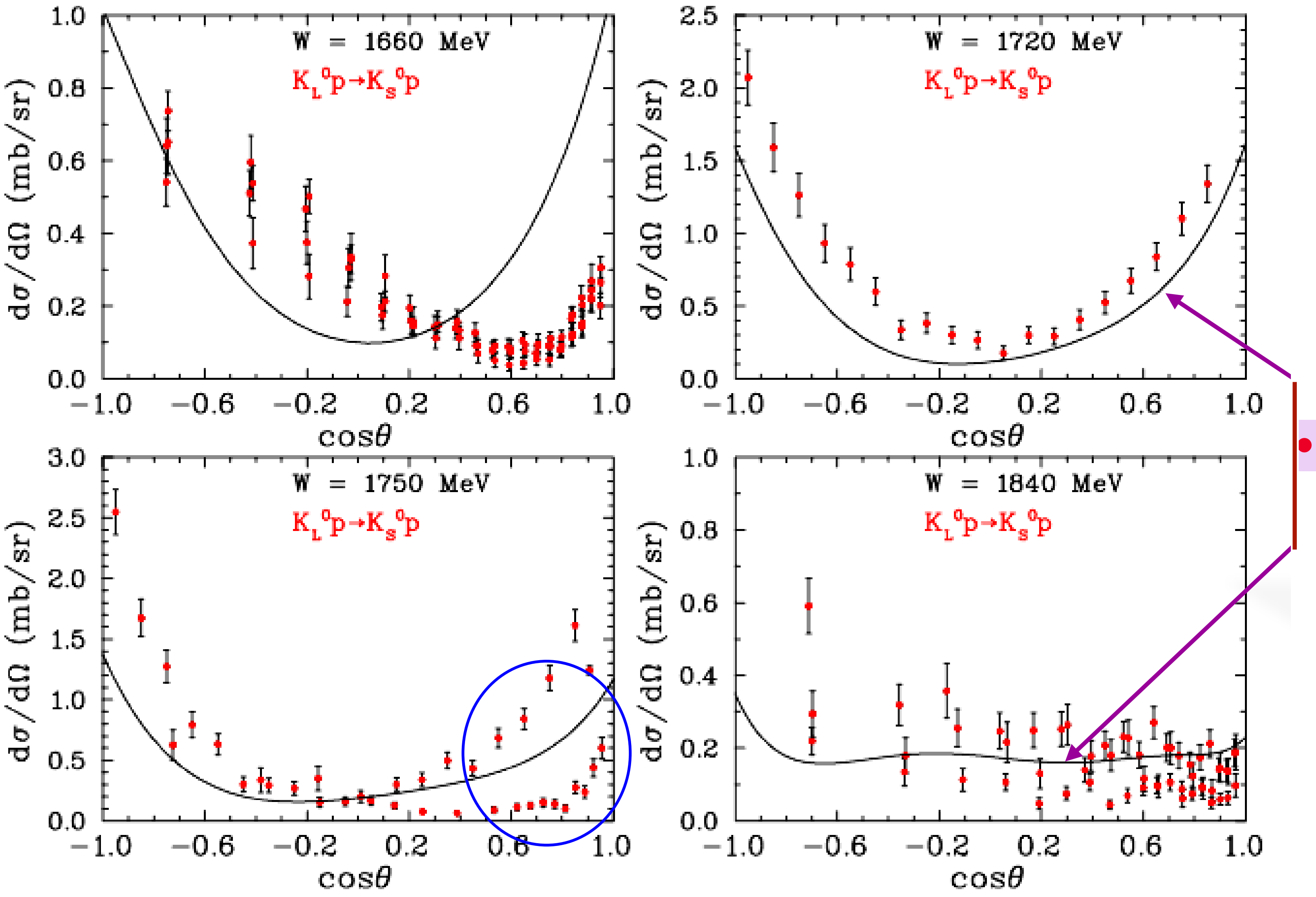
(mainly low stat. bubble chamber data **compilation by I. Strakovsky)**

blue points: $d\sigma/d\Omega$ *red points: Polarization*



we are not aware of any data on Neutron target

Data for $K_L p \rightarrow K_S p$



- **PWA** (**KSU**&**GW**) predictions

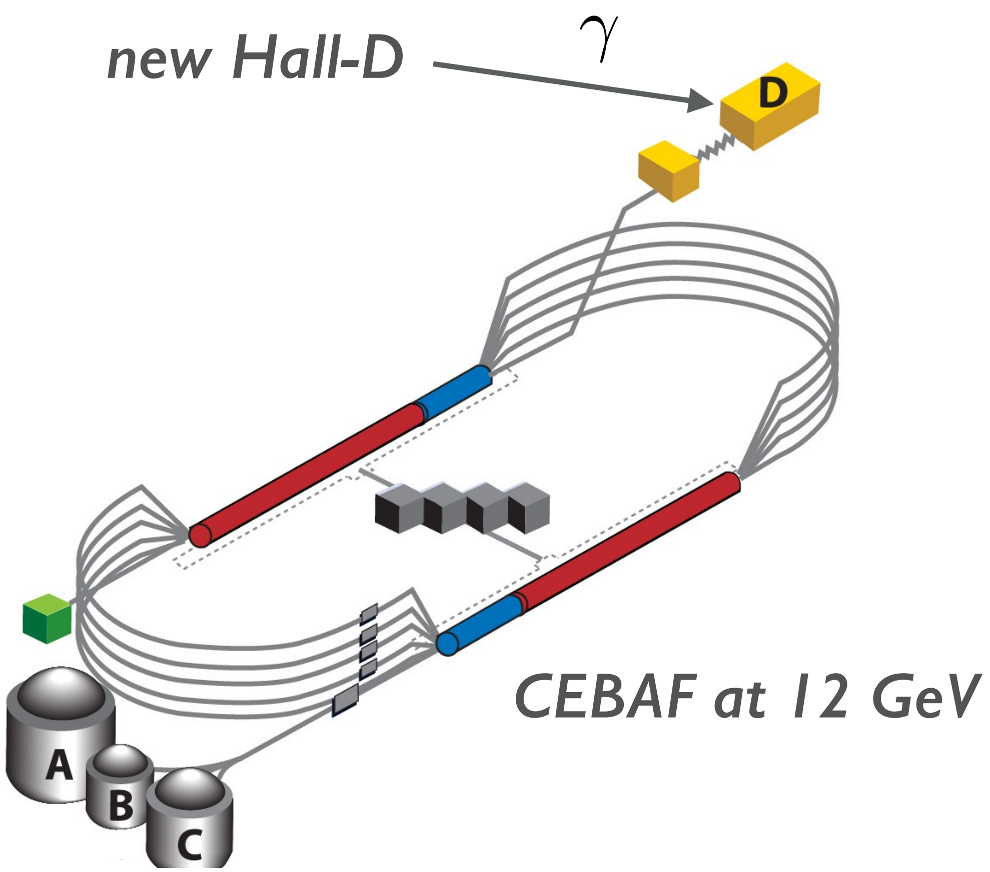
Courtesy of Mark Manley, KL2016

- **Many details in KL2016 Workshop Proceedings**
  - **arXiv: 1604.02141**

How to make a kaon beam?

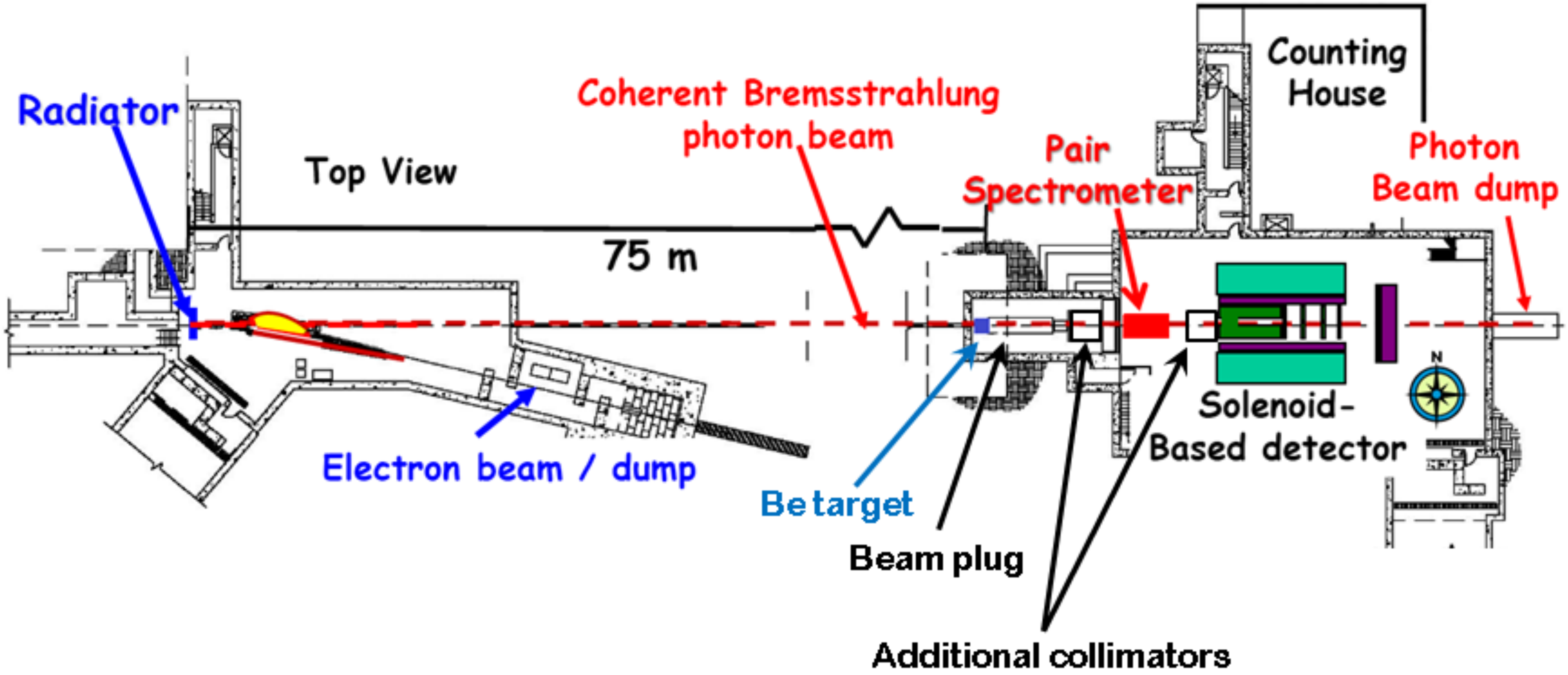
Thomas Jefferson National Accelerator Facility

Aerial View

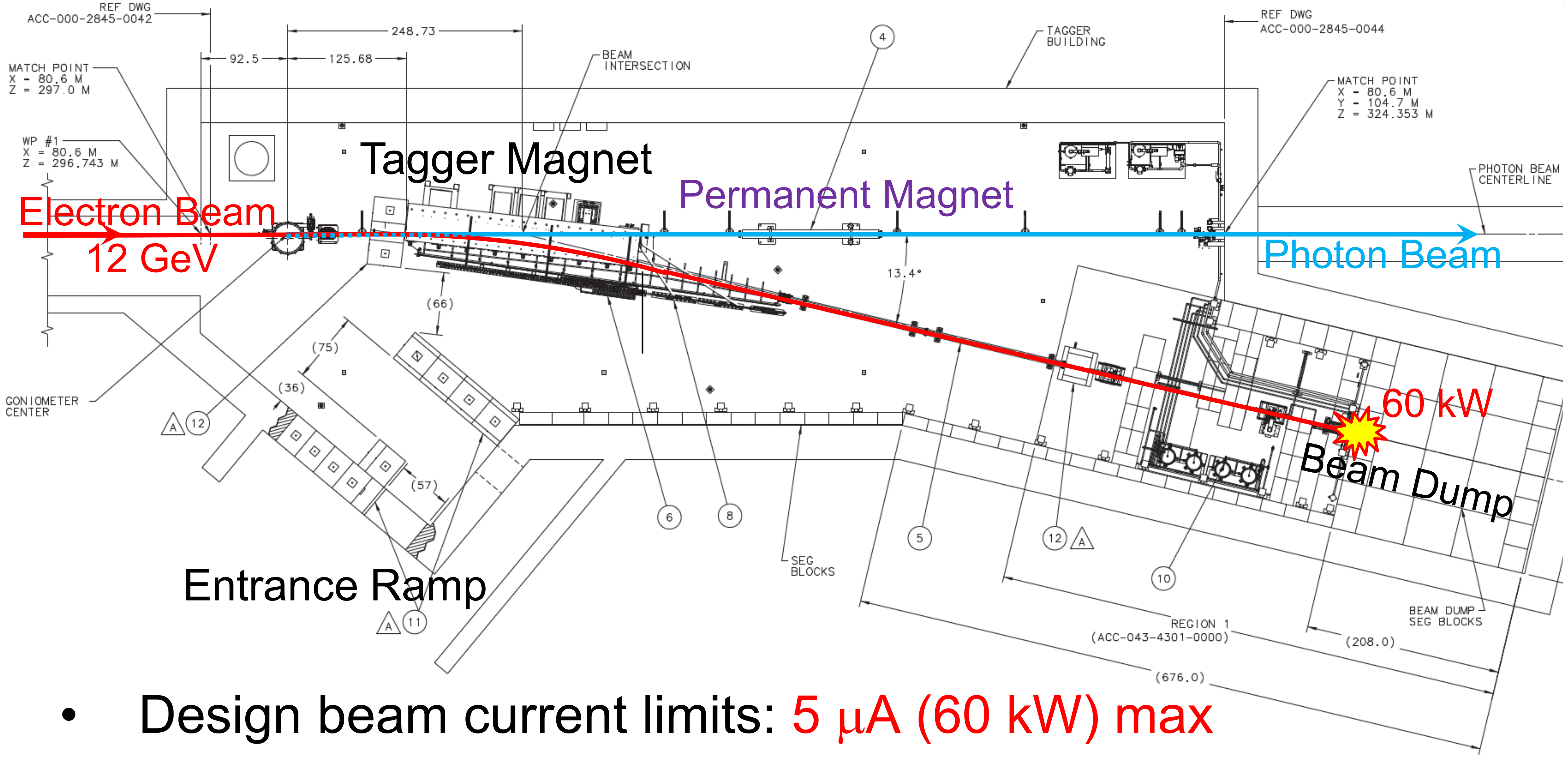


Hall D Beamline

Current setup



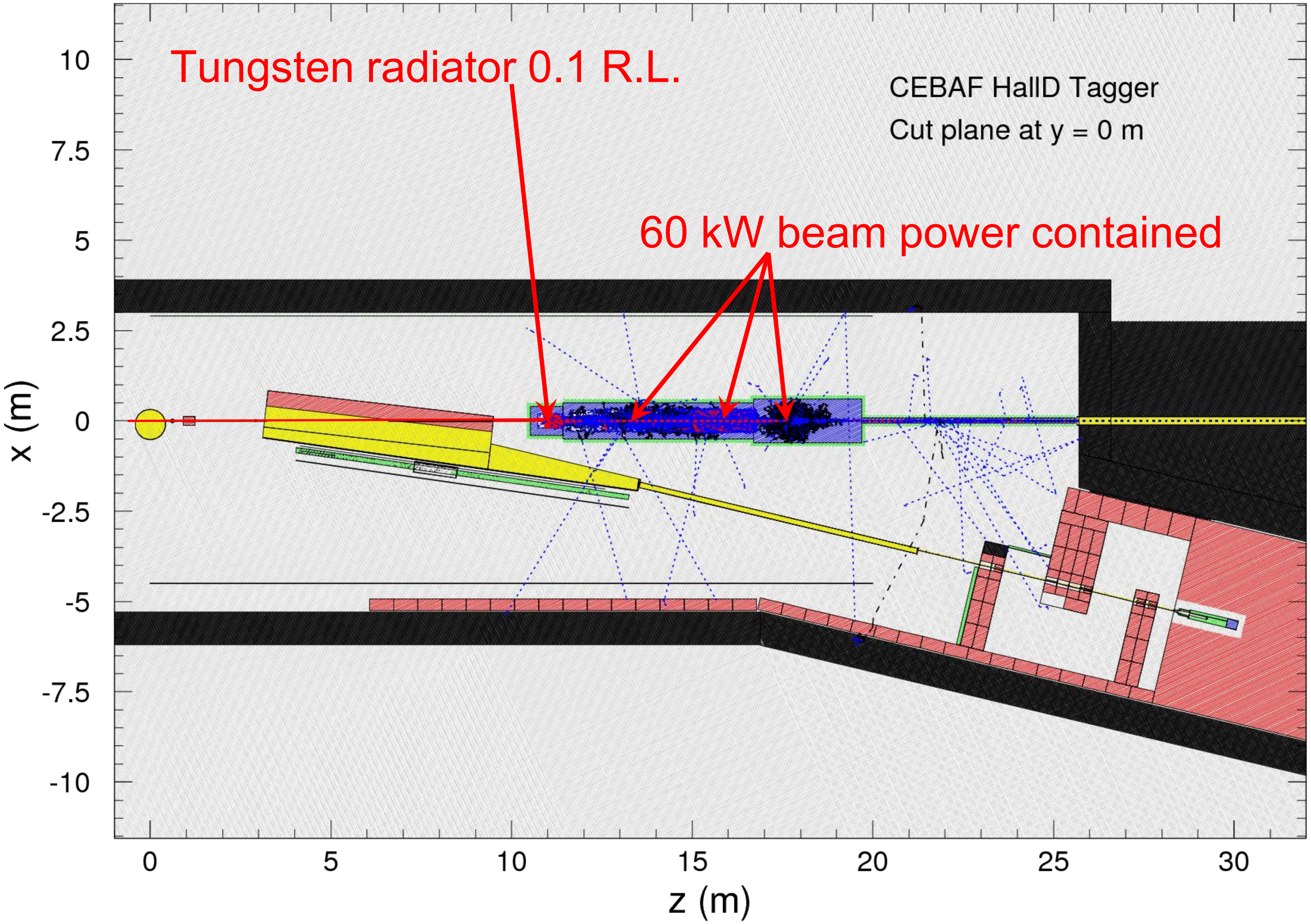
Hall D Tagger Area



- Design beam current limits: 5 μA (60 kW) max
- Design radiator thickness: ~0.0005 Radiation Lengths max
- Challenge: Increase radiator thickness to 0.05-0.10 R.L.?!

GEANT3 Model, 2000 electrons at 12 GeV

Compact γ Source



Compact Photon Source Concept

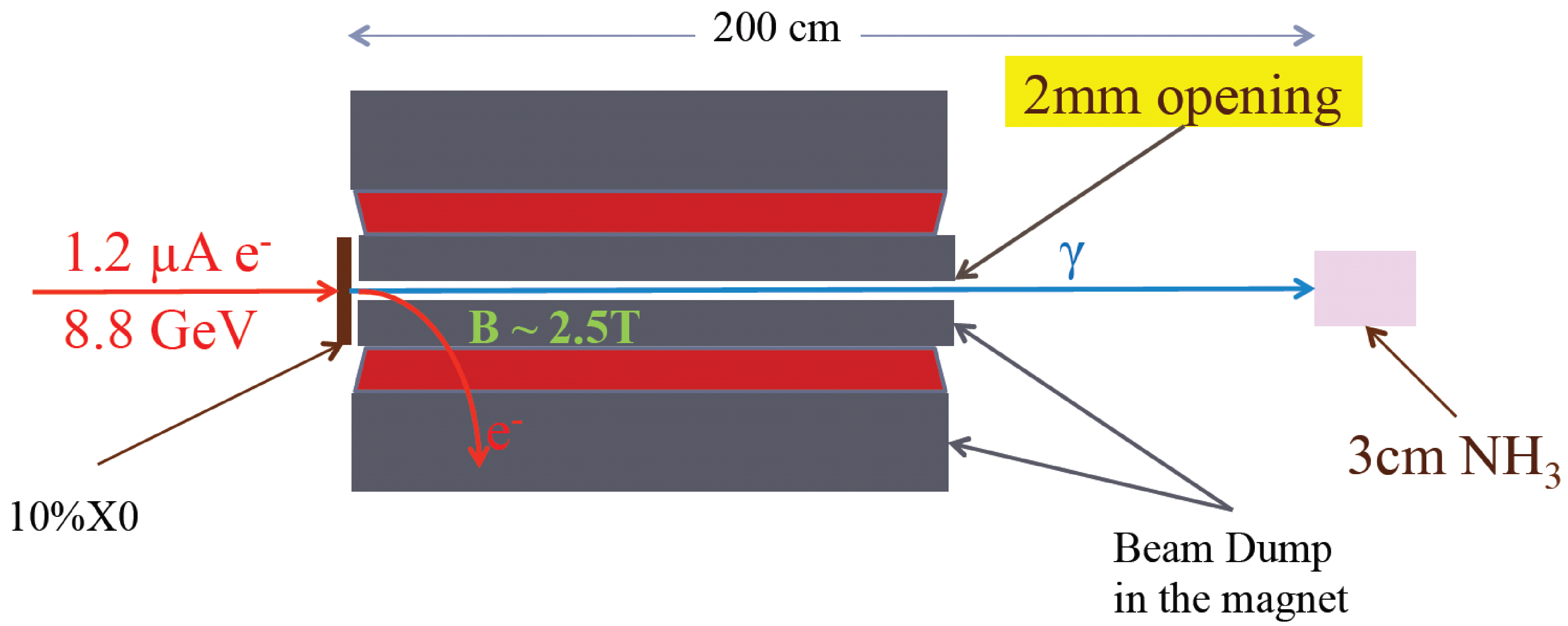
- Strong magnet after radiator deflects exiting electrons
- Long-bore collimator lets photon beam through
- Electron beam dump placed next to the collimator
- Water-cooled Copper core for better heat dissipation
- Hermetic shielding all around and close to the source
- High Z and high density material for bulk shielding
- Borated Poly outer layer for slowing, thermalizing, and absorbing fast neutrons still exiting the bulk shielding
- No need in tagging photons, so the design could be compact, as opposed to the Tagger Magnet concept

CPS: PR12-15-003 Proposal at JLab

Application example: CPS concept for new experiment in Hall A

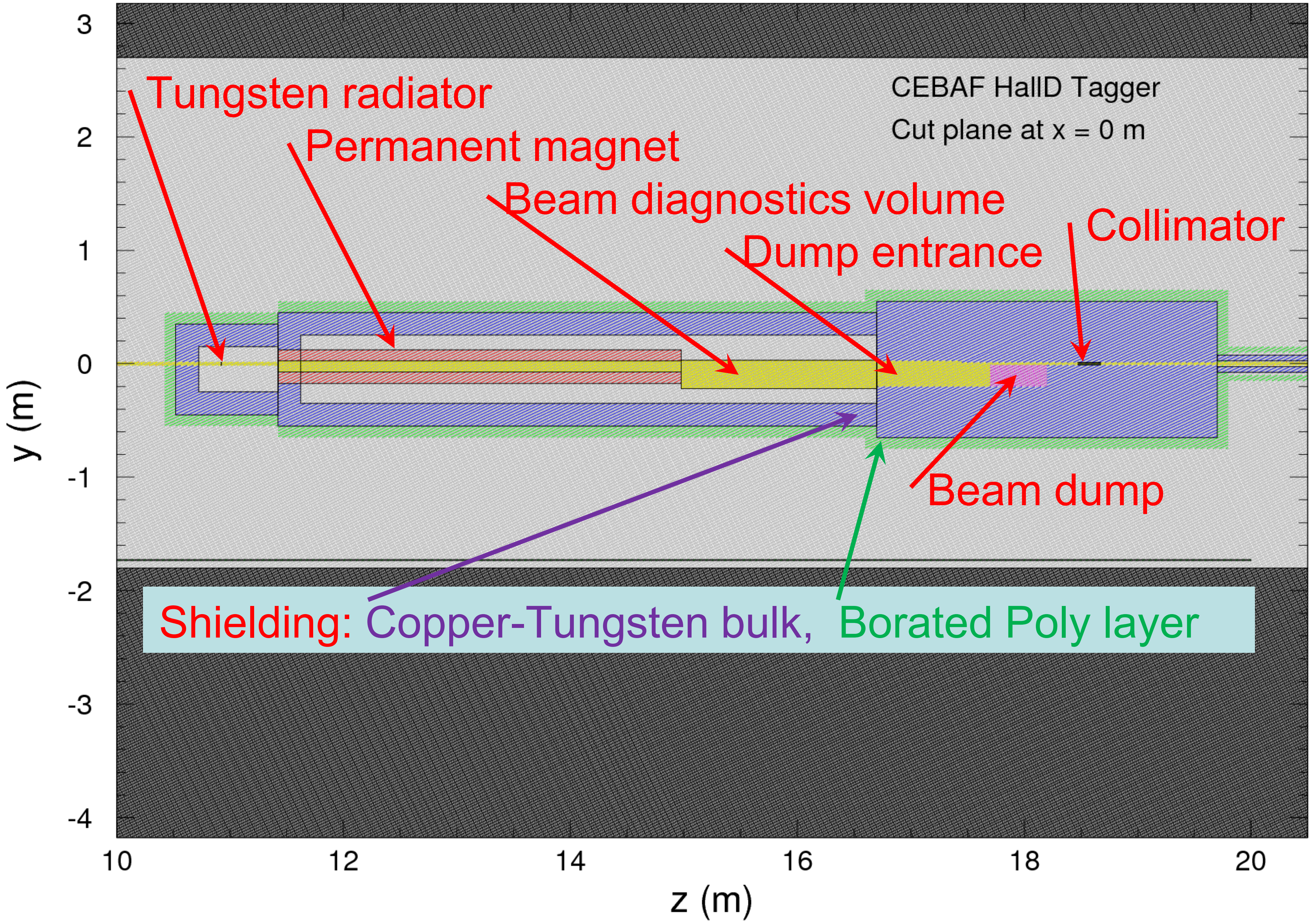
Distance to target ~200 cm

photon beam diameter on the target ~ 0.9 mm



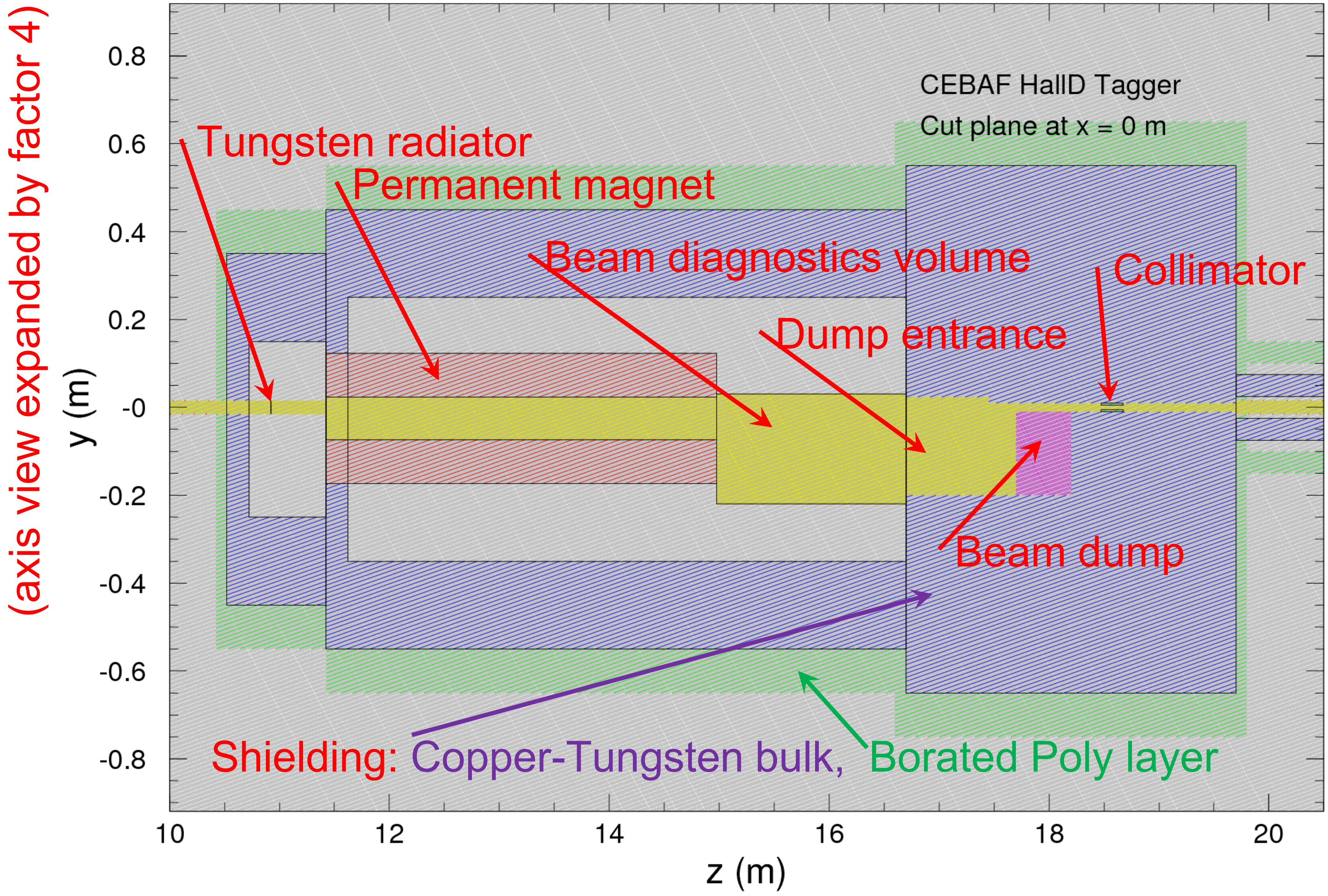
MC simulation and direct calculations show acceptable background rates on SBS and NPS.

CPS at the Hall D Tagger Area



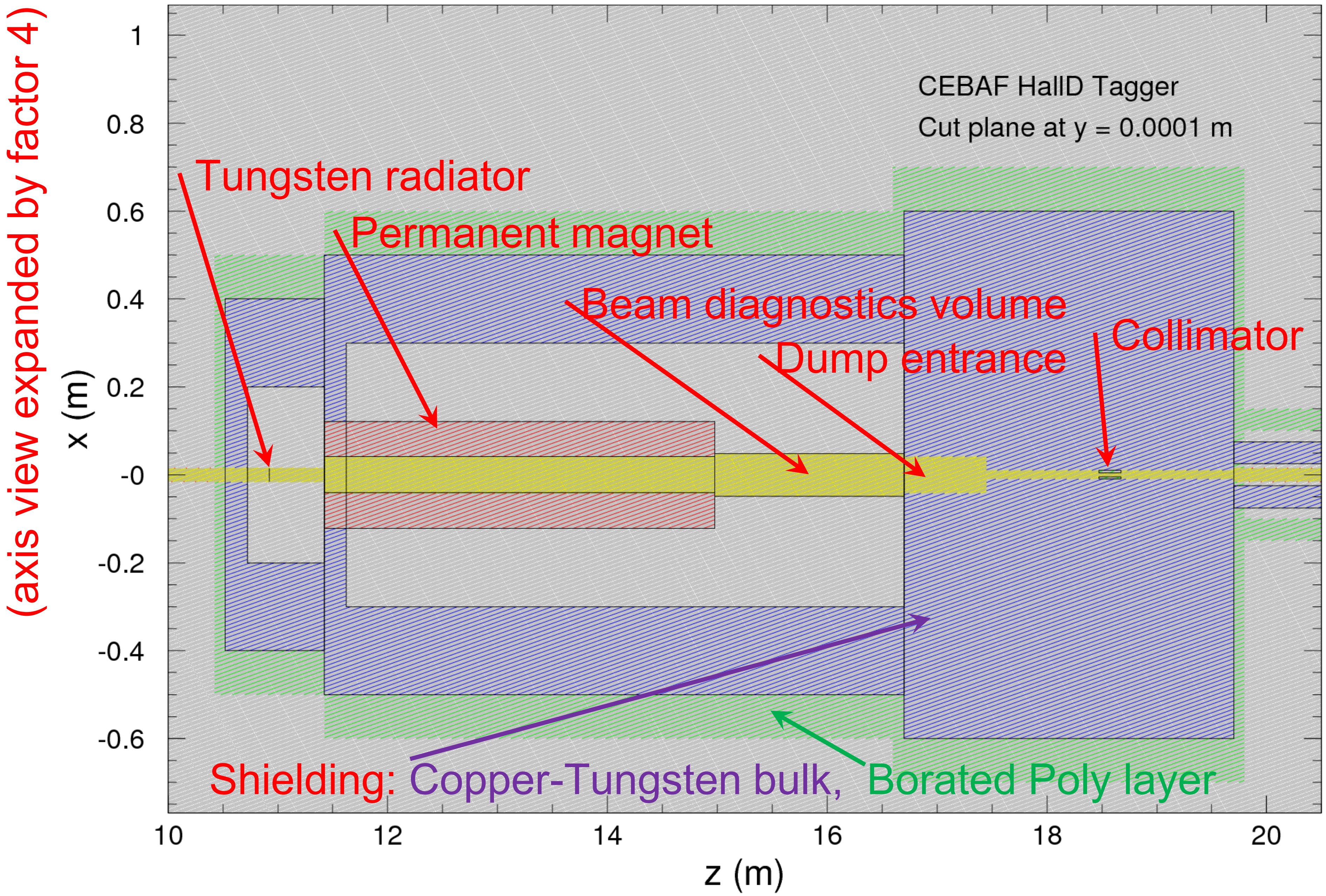
Shielding: Copper-Tungsten bulk, Borated Poly layer

CPS, vertical plane cut

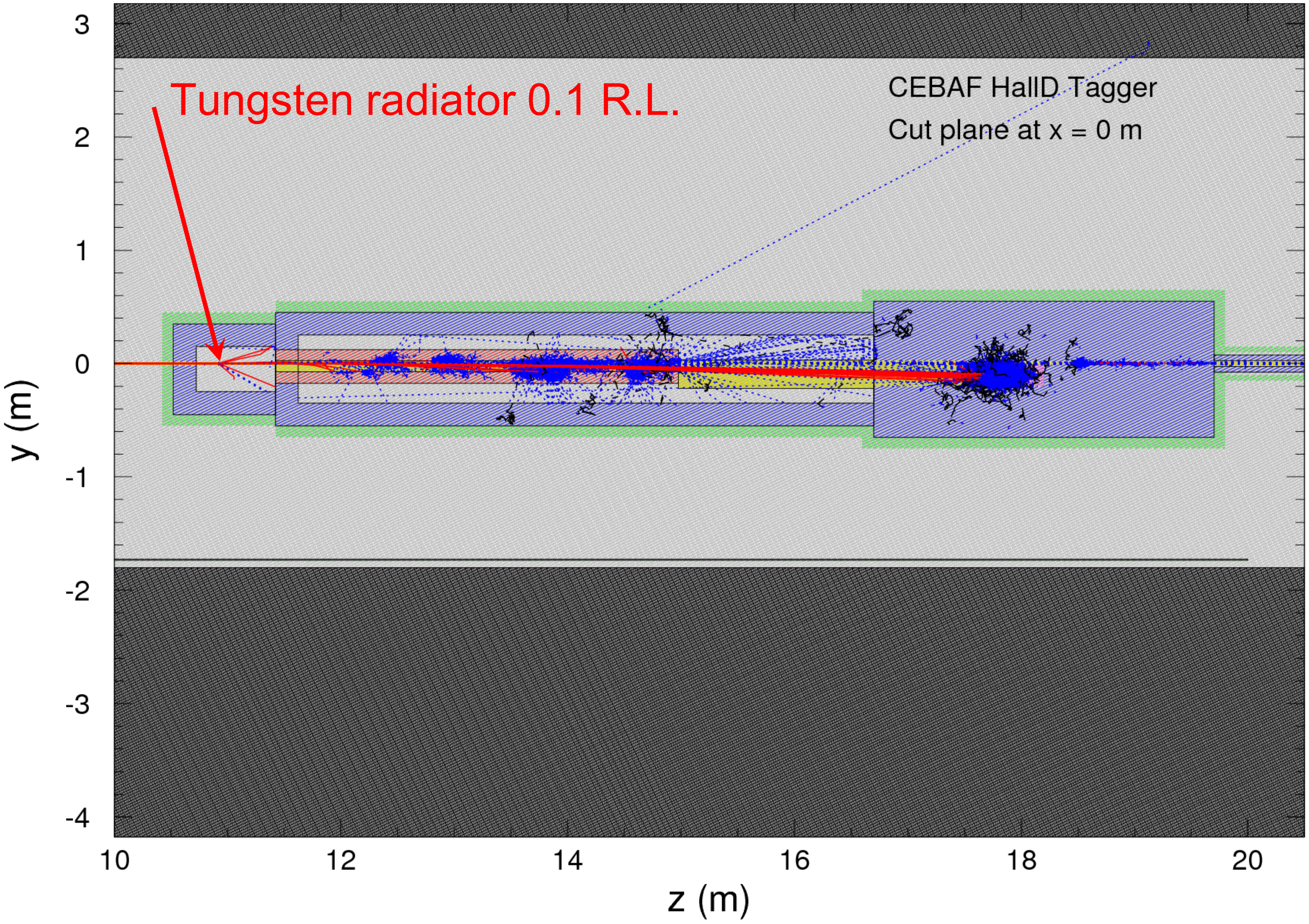


Shielding: Copper-Tungsten bulk, Borated Poly layer

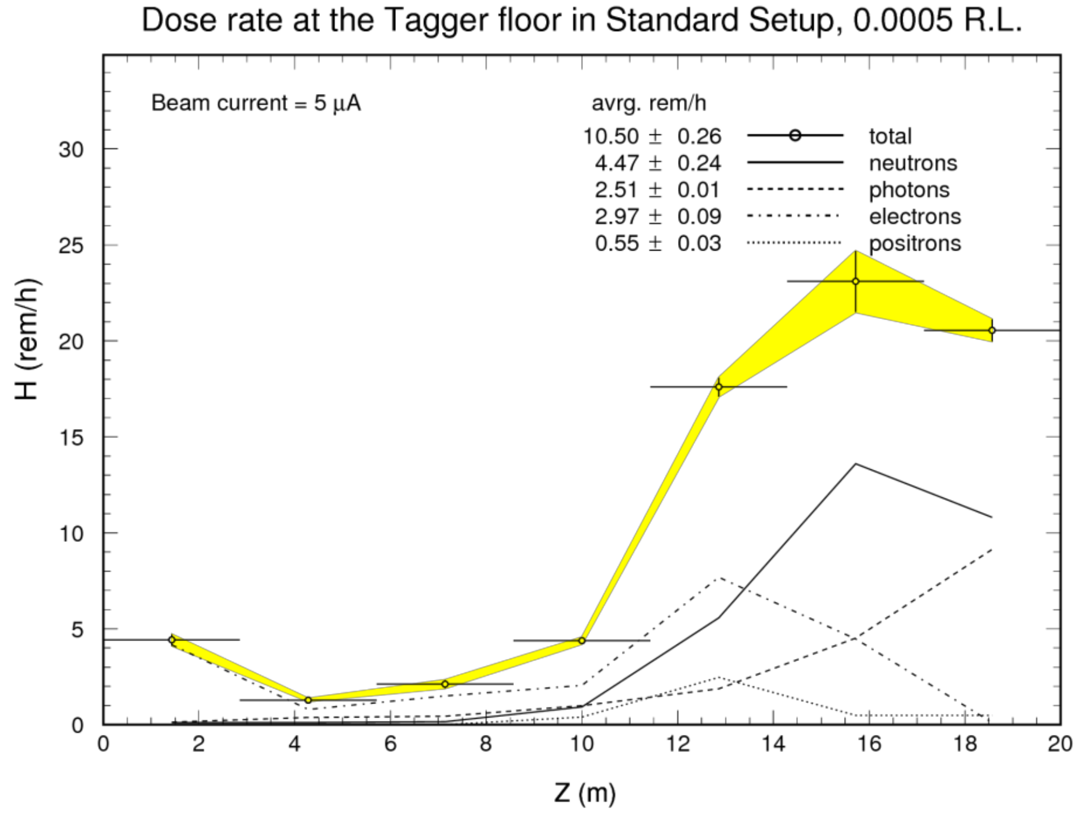
CPS, horizontal plane (1)

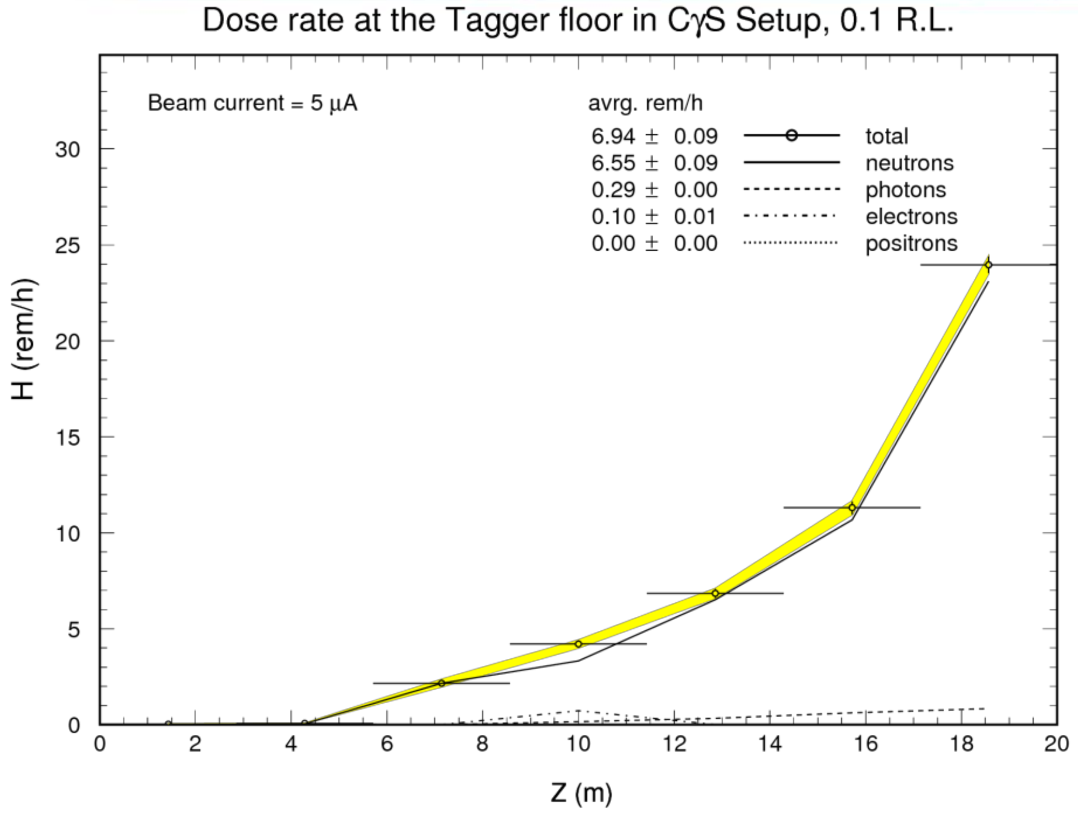


CPS, 50 electrons at 12 GeV



Dose Rate Evaluation and Comparison


Dose rate at the Tagger floor in Standard Setup, 0.0005 R.L.


Dose rate at the Tagger floor in CγS Setup, 0.1 R.L.

- The dose rates in the Tagger vault for the CPS setup with 10% R.L. radiator are close to Standard XD ops
- The radiation spectral composition is different; most of the contribution in the CPS setup is from higher energy neutrons

Dose Rate Evaluation and Comparison

- The plots show comparison of dose rate estimates in the Tagger Area in two conditions: (1) nominal Hall D operation with the standard amorphous radiator at 0.0005 R.L., - with (2) radiator at 0.1 R.L., used as part of the Compact Photon Source setup.
- The comparison indicates that at equal beam currents, gamma radiation dose rates are much smaller for the CPS run (~order of magnitude), and neutron dose rates in the area are comparable.
- Design and shielding optimization may improve the comparison further in favor of the CPS solution

K^0_L beam (continued)

-Electron beam with $I_e = 5\mu A$

-Delivered with 60ns bunch spacing avoids overlap in the range of P=0.35-10.0 GeV/c

-Momentum measured with TOF

-K^0_L flux mesured with pair spectrometer

-*Side remark: Physics case with polarized targets is under study and feasible*

Implementation Advantages

- Most of all present Tagger Area equipment stays in place; CPS is assembled around the gamma line
- Re-use of the available permanent magnet (pending thermal engineering analysis, <~1.5 kW to dissipate)
- Re-use of the dump cooling system (max 60 kW)
- No extra prompt irradiation or extra beam line activation for existing structures in the area
- No problem switching between the two modes of Hall D operations: low intensity tagged photon beam, and high intensity photon beam from CPS
- Disassembly and decommissioning could be postponed until radioactive isotopes decay inside to manageable levels (self-shielded in place)

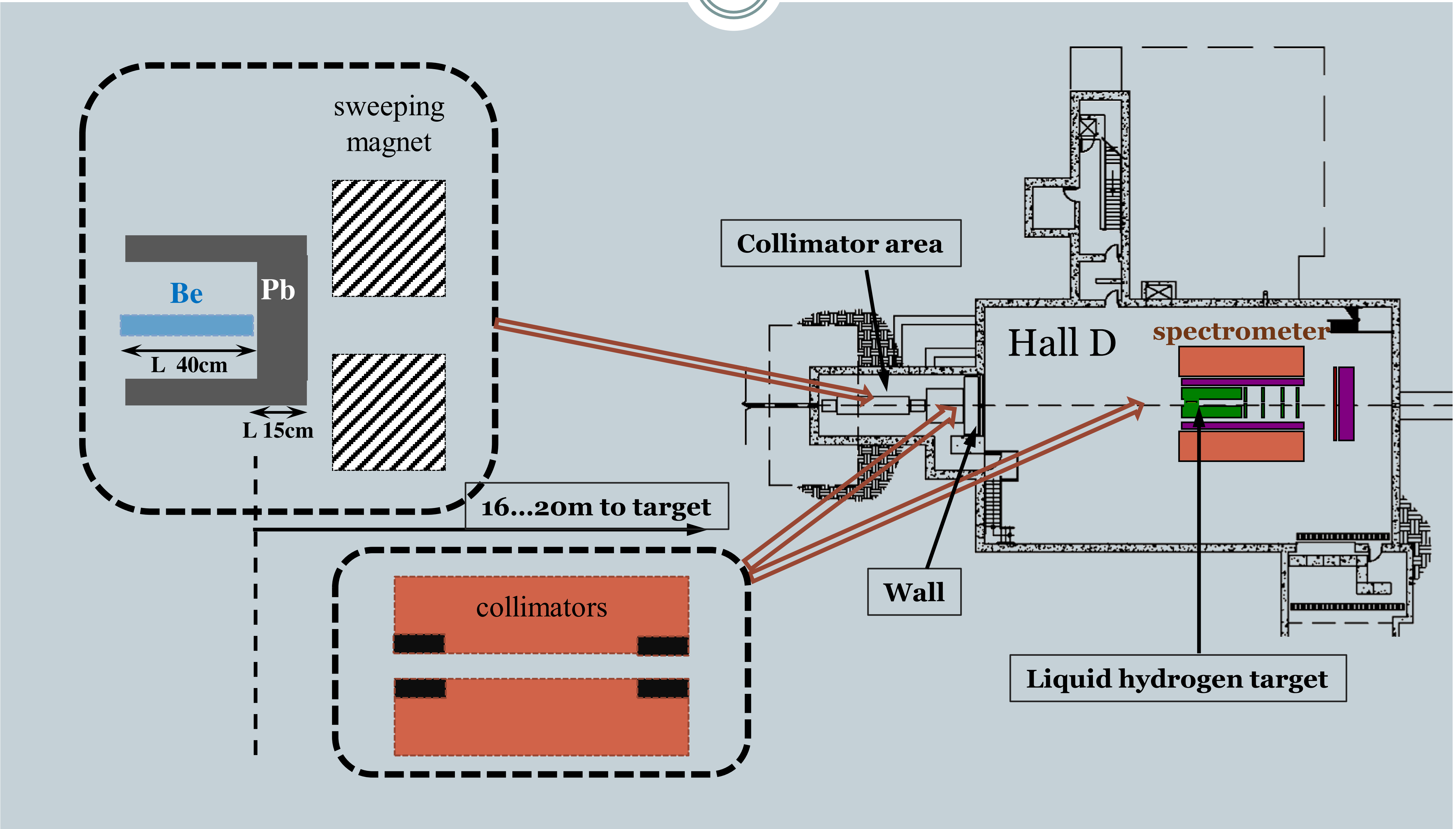
Detailed Design and Cost Estimate

- We do not see show-stoppers for implementation of the CPS concept in the experiment.
- 60 kW Copper-core dump will have characteristics close to the one installed already
- To make long and narrow photon beam collimation we propose to build the core using two symmetric flat plates, left and right, and make matching grooves in them for the beam entry cones, beam line, and the aperture collimator
- Cost would include detailed iterative modeling and simulation to optimize operation parameters, design, engineering and production, plus the choice and cost of bulk shielding material
- Crude cost expectation: within $0.5M

Conclusions

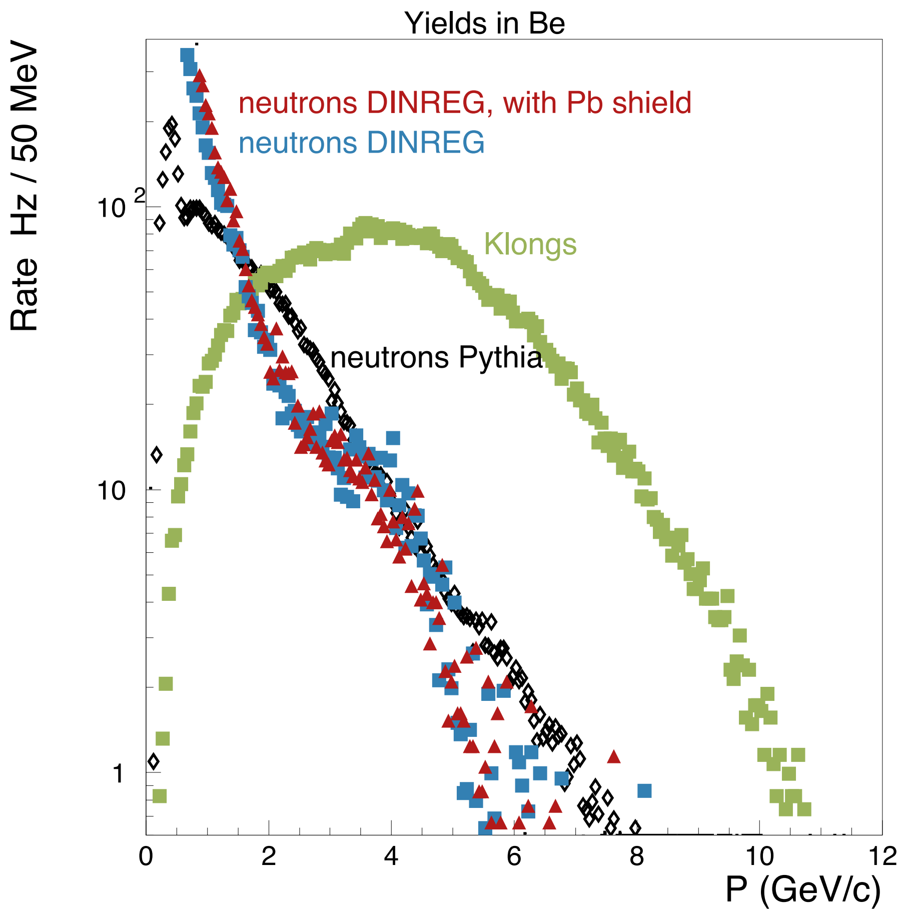
- Compared to the alternative, the proposed CPS solution presents several advantages, including much less disturbance of the available infrastructure at the Tagger Area, and better flexibility in achieving high-intensity photon beam delivery to the Hall D
- The proposed CPS solution will satisfy proposed K^0_L beam production parameters
- We do not envision big technical or organizational difficulties in the implementation of the conceptual design

K_L-beam line


sweeping magnet
Be
Pb
L 40cm
L 15cm
16…20m to target
collimators
Collimator area
Hall D
spectrometer
Wall
Liquid hydrogen target

Rate of neutrons and K^0_L on GlueX target

- **JLAB**



- **PRL22.996 (1969) Brody et al.**

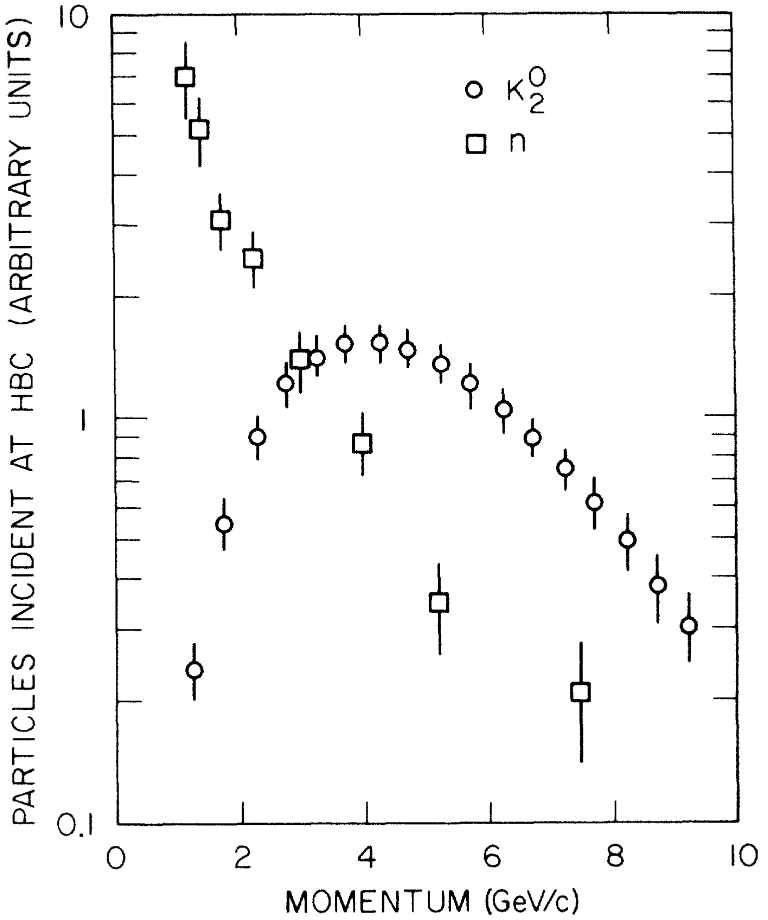


FIG. 2. Comparison of the neutron and K_2^0 fluxes at the hydrogen bubble chamber for 2° production with 16-GeV electrons.

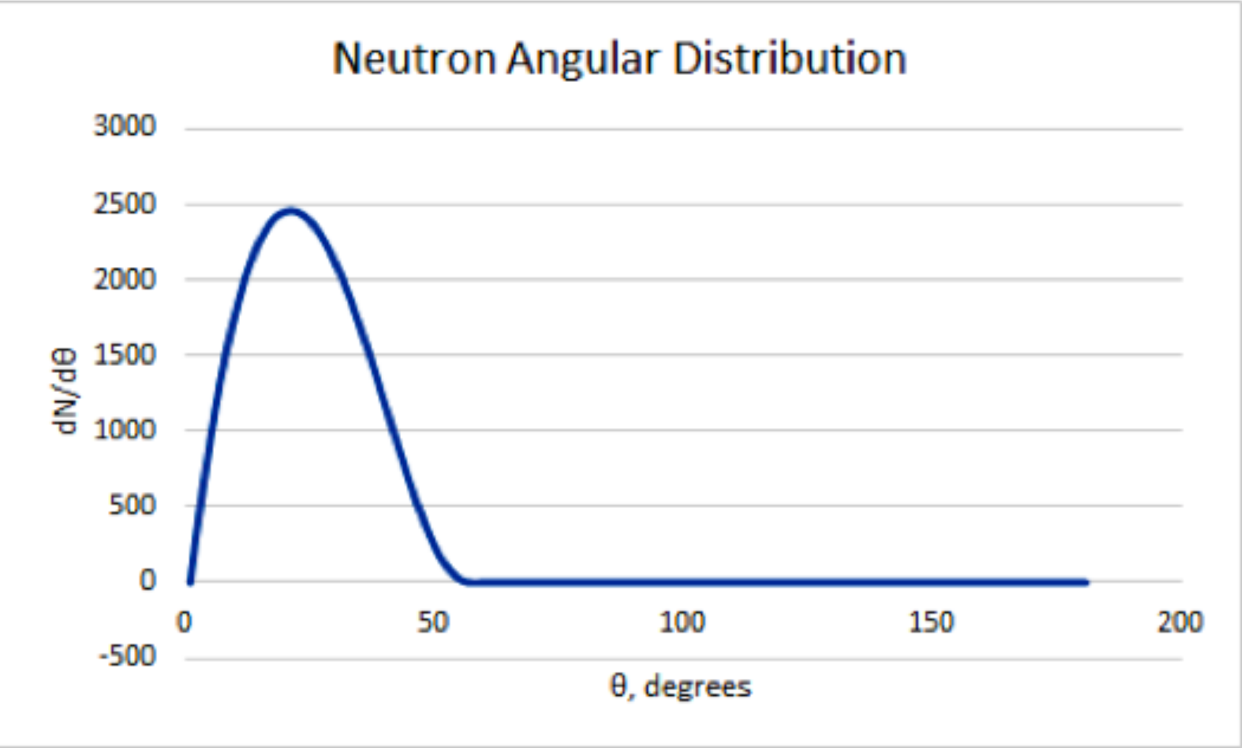
- **With a proton beam ratio $n/K_L = 10^3$-10^4**

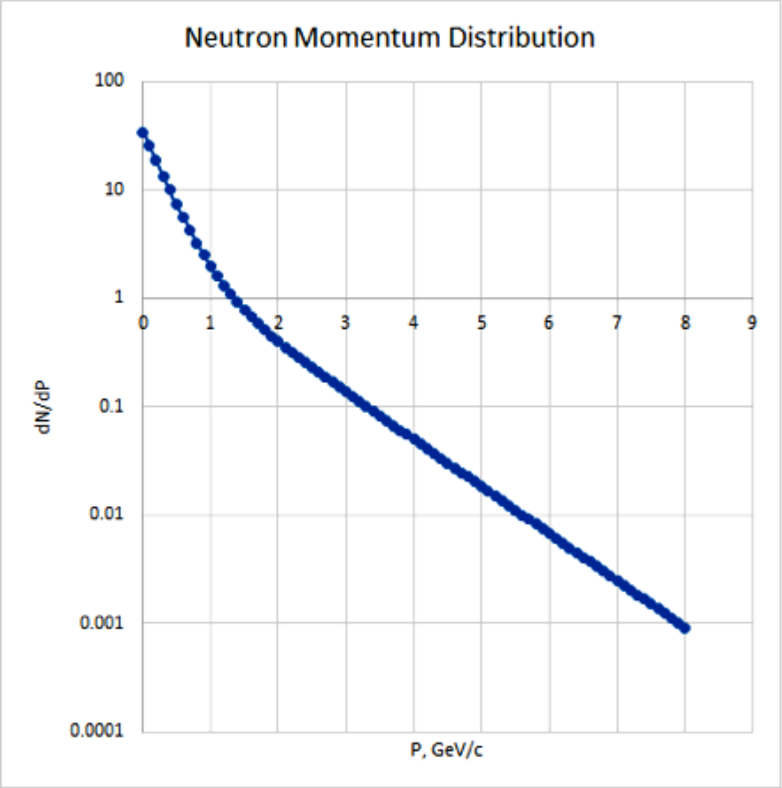
K^0_L beam

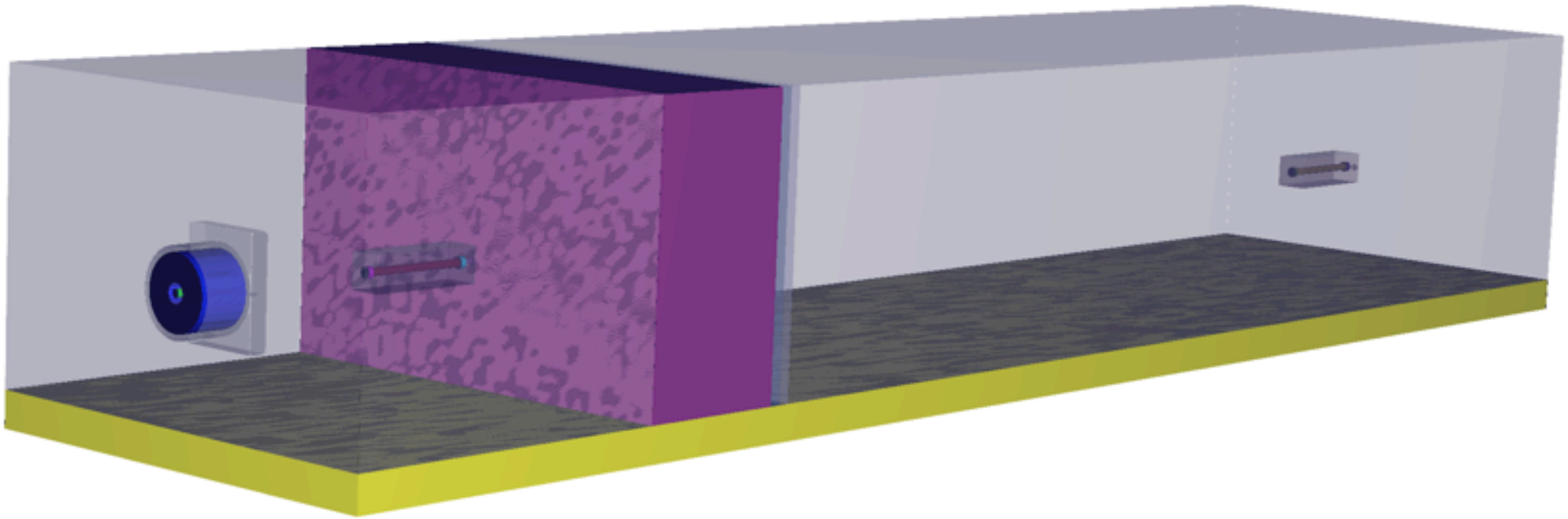
Electron beam	$E_e = 12GeV; I_e = 5\mu A$
Radiator (rad. length)	10%
Be target (R=3cm)	$L = 40cm$
LH2 target(L=30cm)	$R = 3cm$
Distance Be-LH2	16m
K_L Rate/sec	$\sim 10^4$

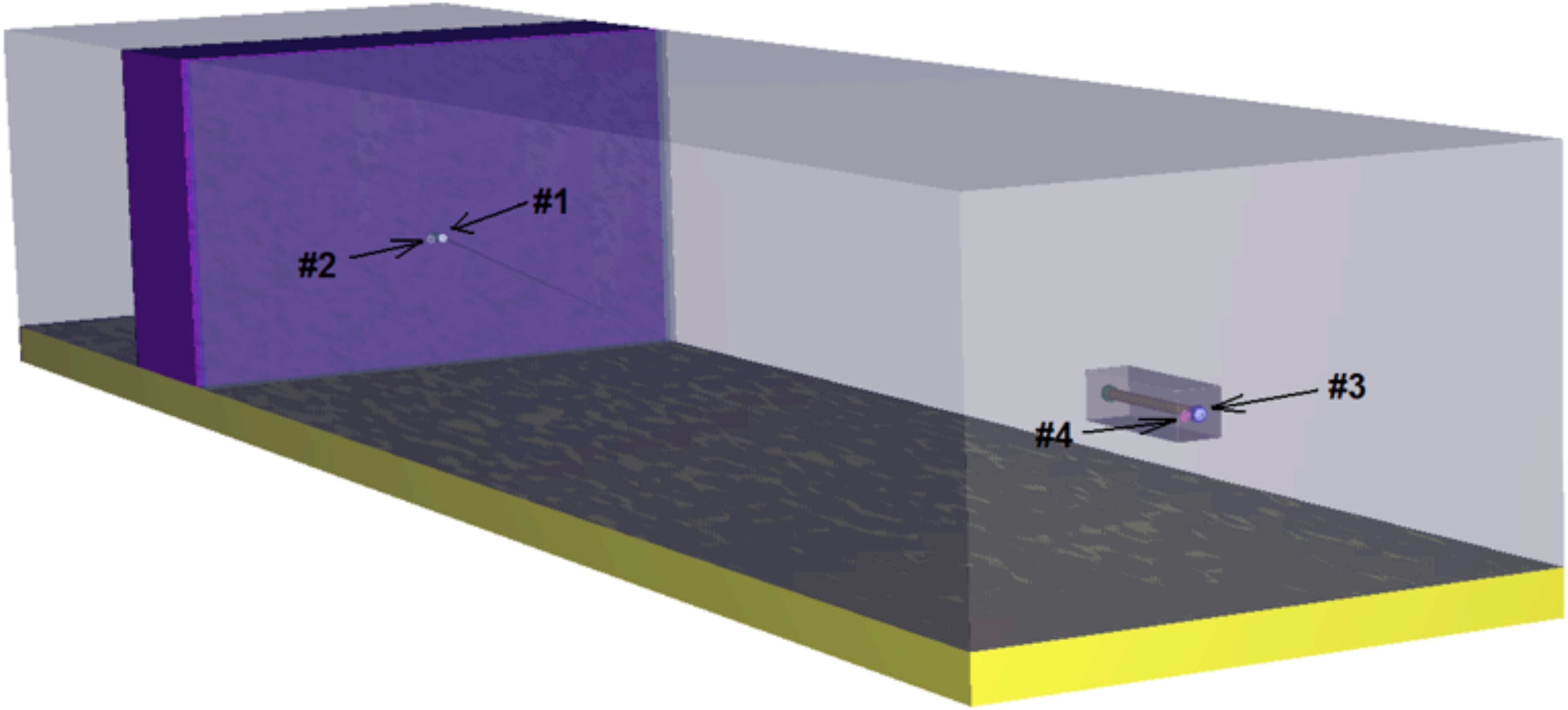
Neutron Background

Neutron calculations for the KLF Project using MCMP6








#1
#2
#3
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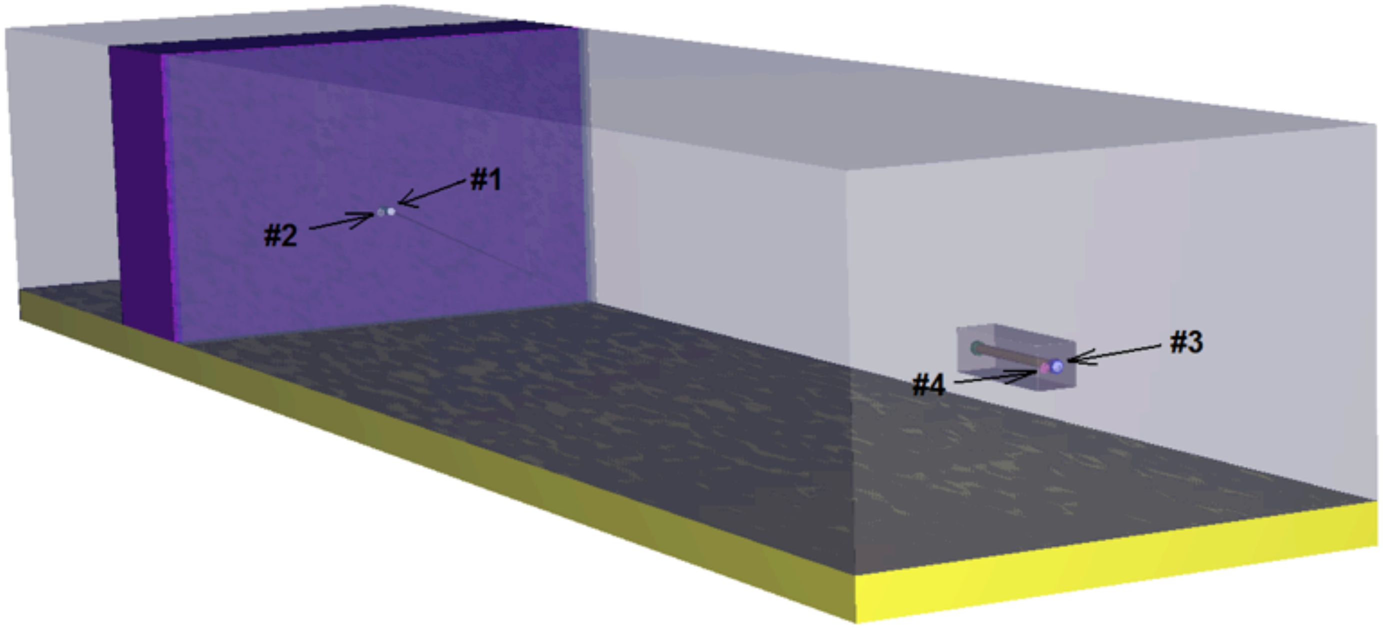
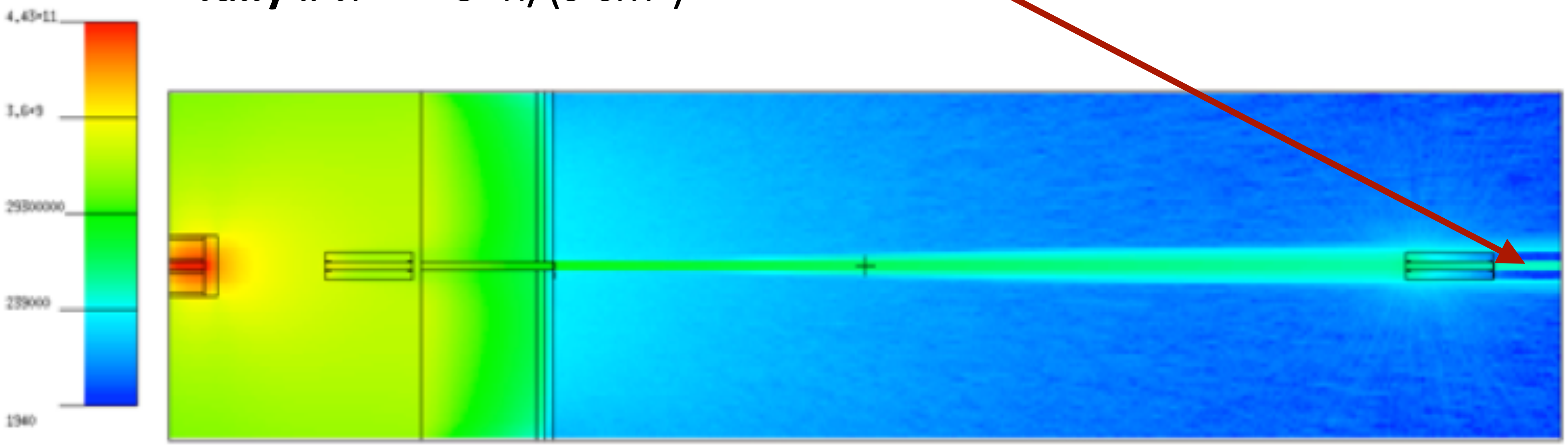


Results:

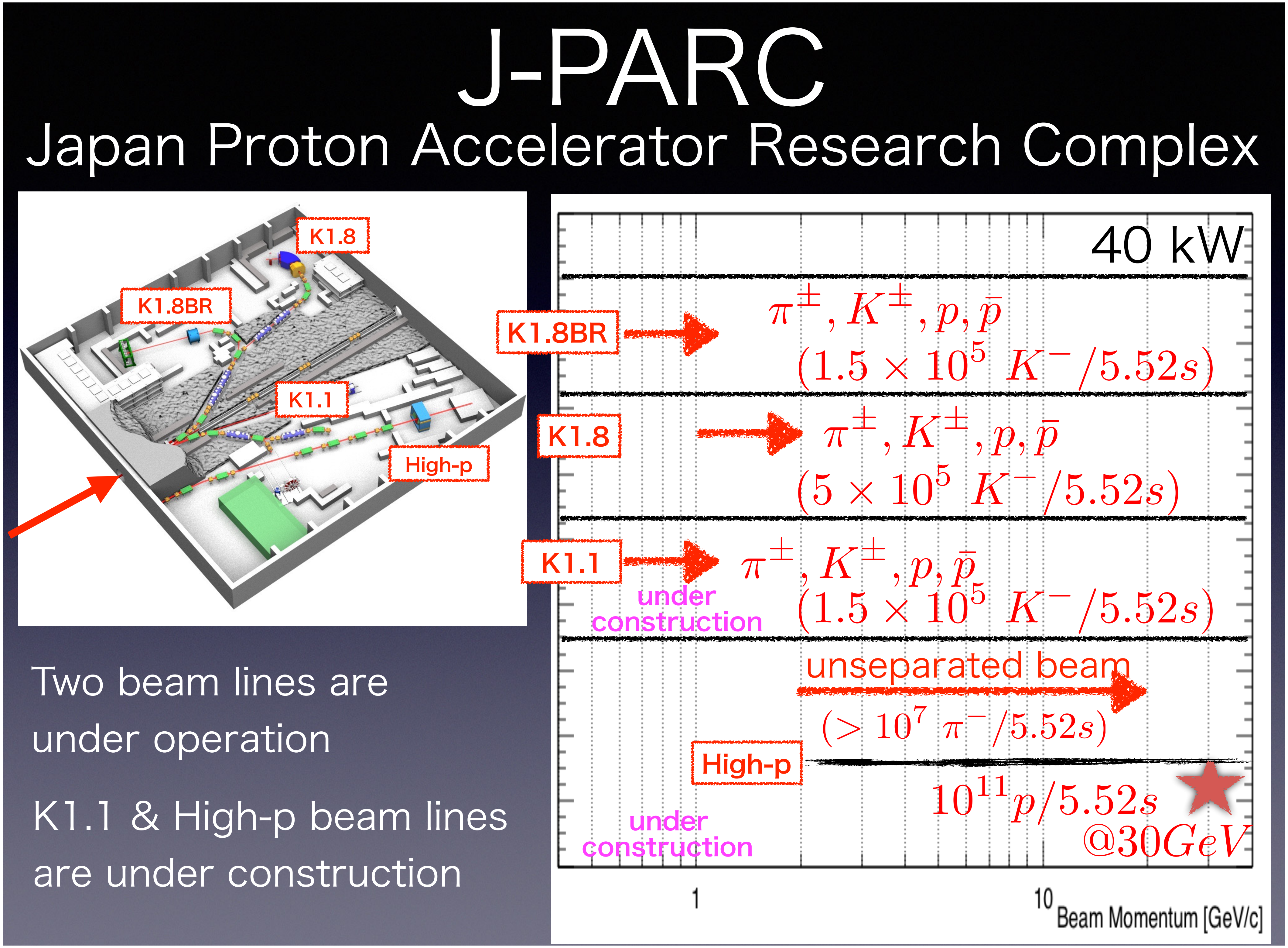
Tally #1: 3200 n/(s cm^2)
Tally #2: 40 n/(s cm^2)
Tally #3: 140 n/(s cm^2)
Tally #4: 3 n/(s cm^2)

Neutron Flux 10e+10/4*pi*/s



- **Conclusion: Neutron Flux in Hall D is tolerable**

- **Talk by Onishi at KL2016**



J-PARC

Japan Proton Accelerator Research Complex

Two beam lines are under operation

K1.1 & High-p beam lines are under construction

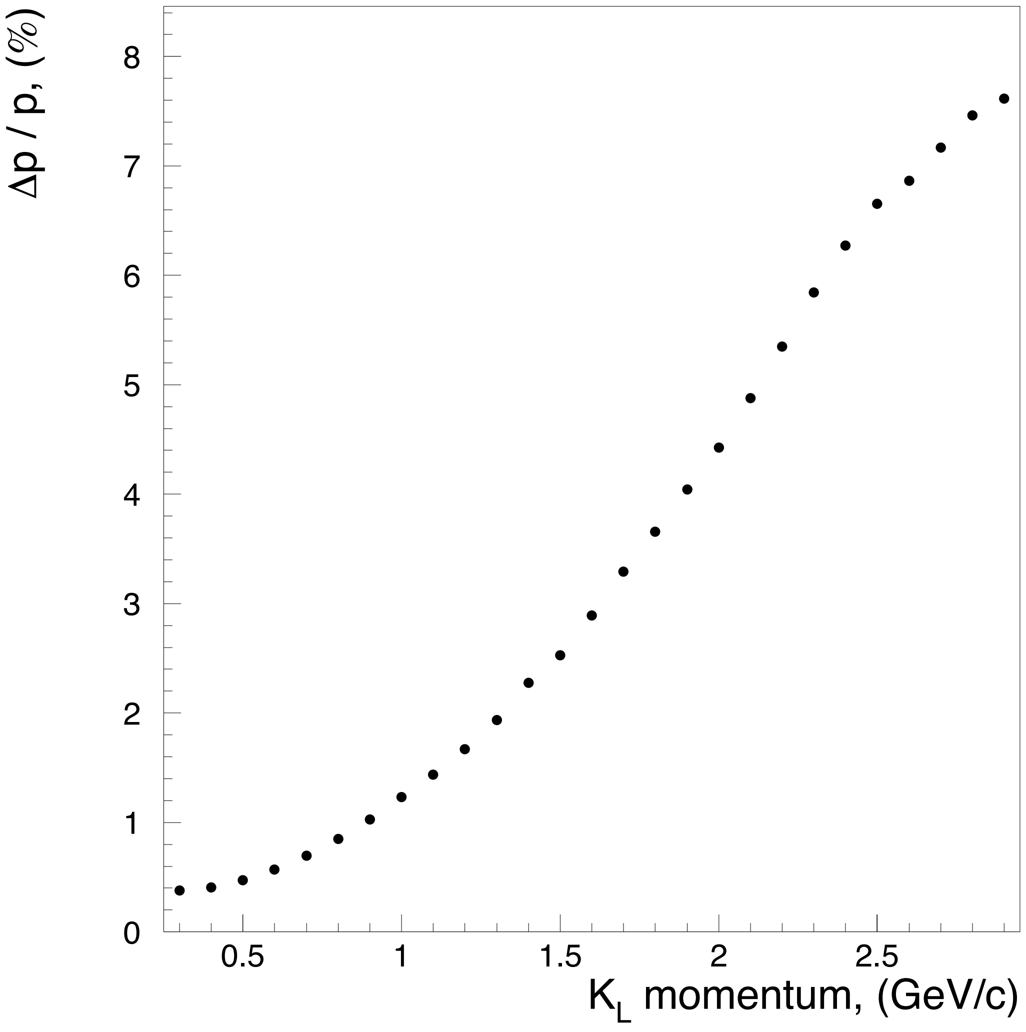
• ProjectX (Fermi Lab) arXiv:1306.5009

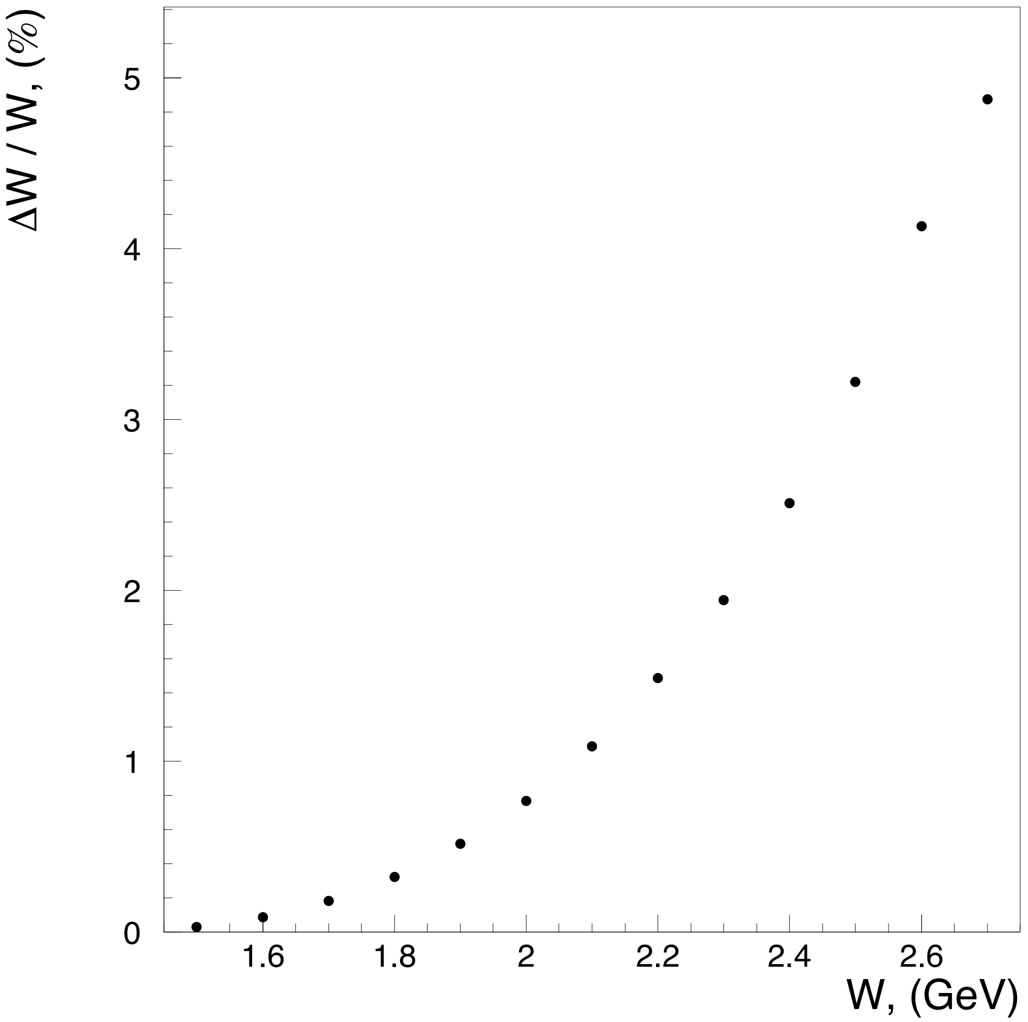
Table III-2: Comparison of the K_L production yield. The BNL AGS kaon and neutron yields are taken from RSVP reviews in 2004 and 2005. The *Project X* yields are for a thick target, fully simulated with LAQGSM/MARS15 into the KOPIO beam solid angle and momentum acceptance.

	Beam energy	Target (λ_I)	$p(K)$ (MeV$/c$)	K_L/s into 500 μsr	$K_L : n$ ($E_n > 10$ MeV)
BNL AGS	24 GeV	1.1 Pt	300-1200	60×10^6	$\sim 1:1000$
Project X	3 GeV	1.0 C	300-1200	450×10^6	$\sim 1:2700$

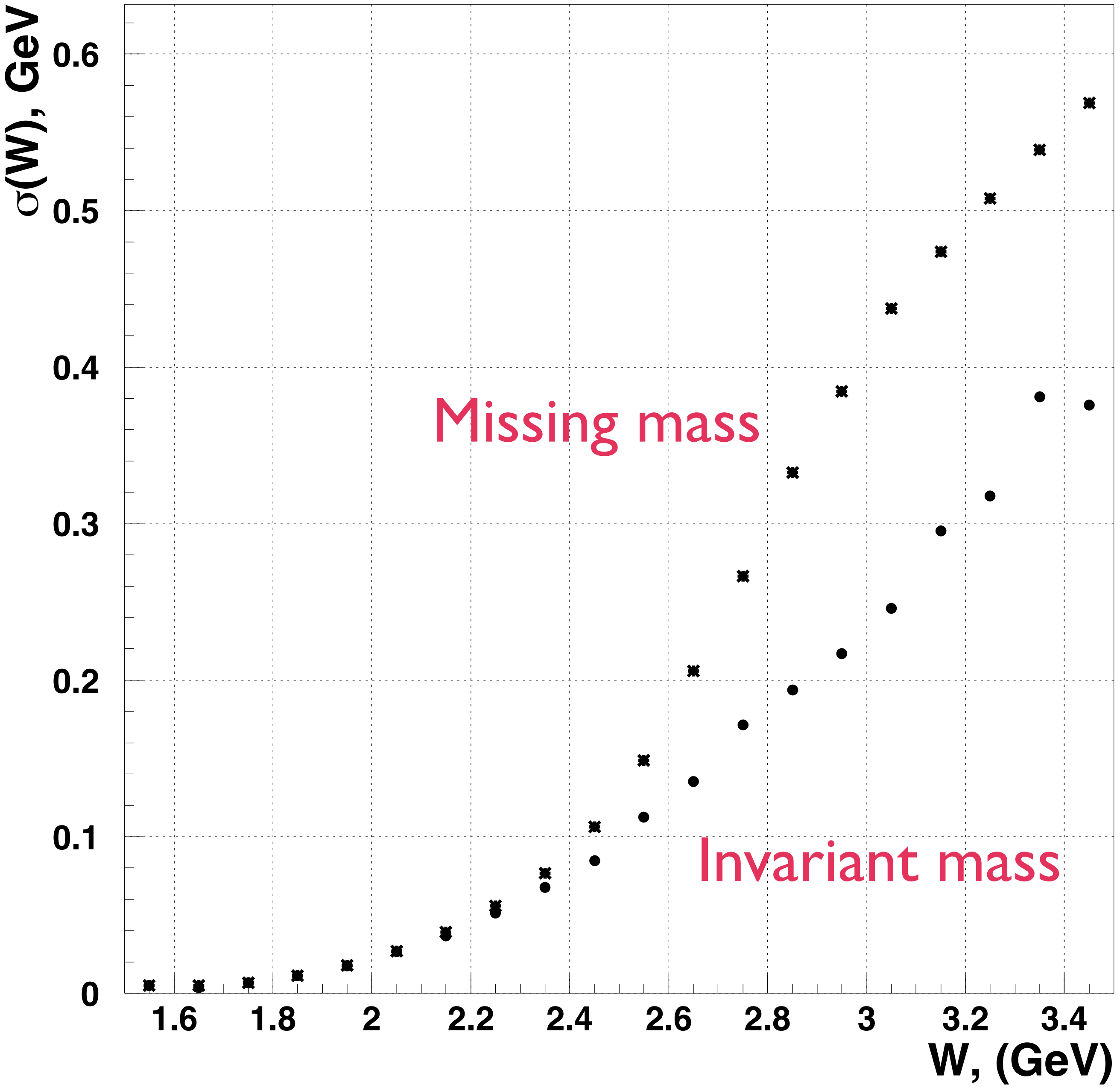
KL beam can be used to study rare decays
However it will be impossible to use for hyperon spectroscopy
because of momentum range and n/K Ratio

Momentum and W Resolution



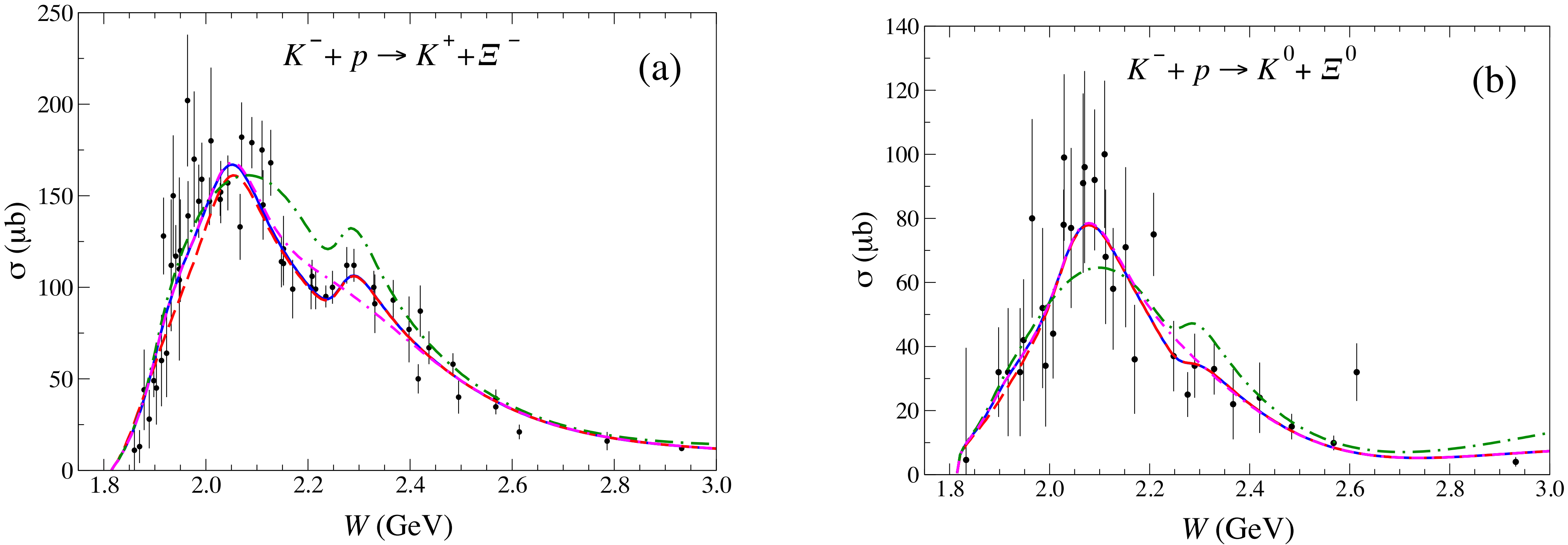


W-Resolution

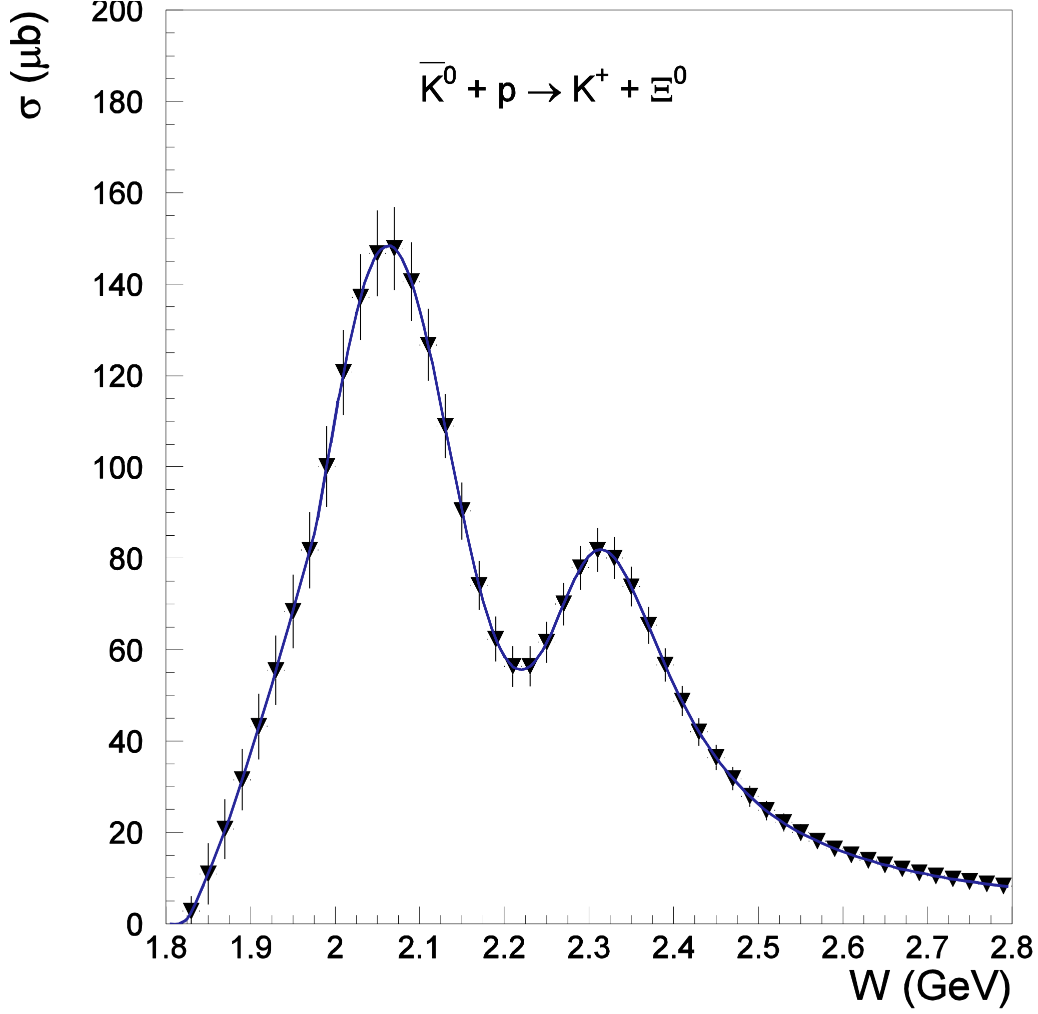


see more from
Simon Taylor's talk

World Data on Ξ

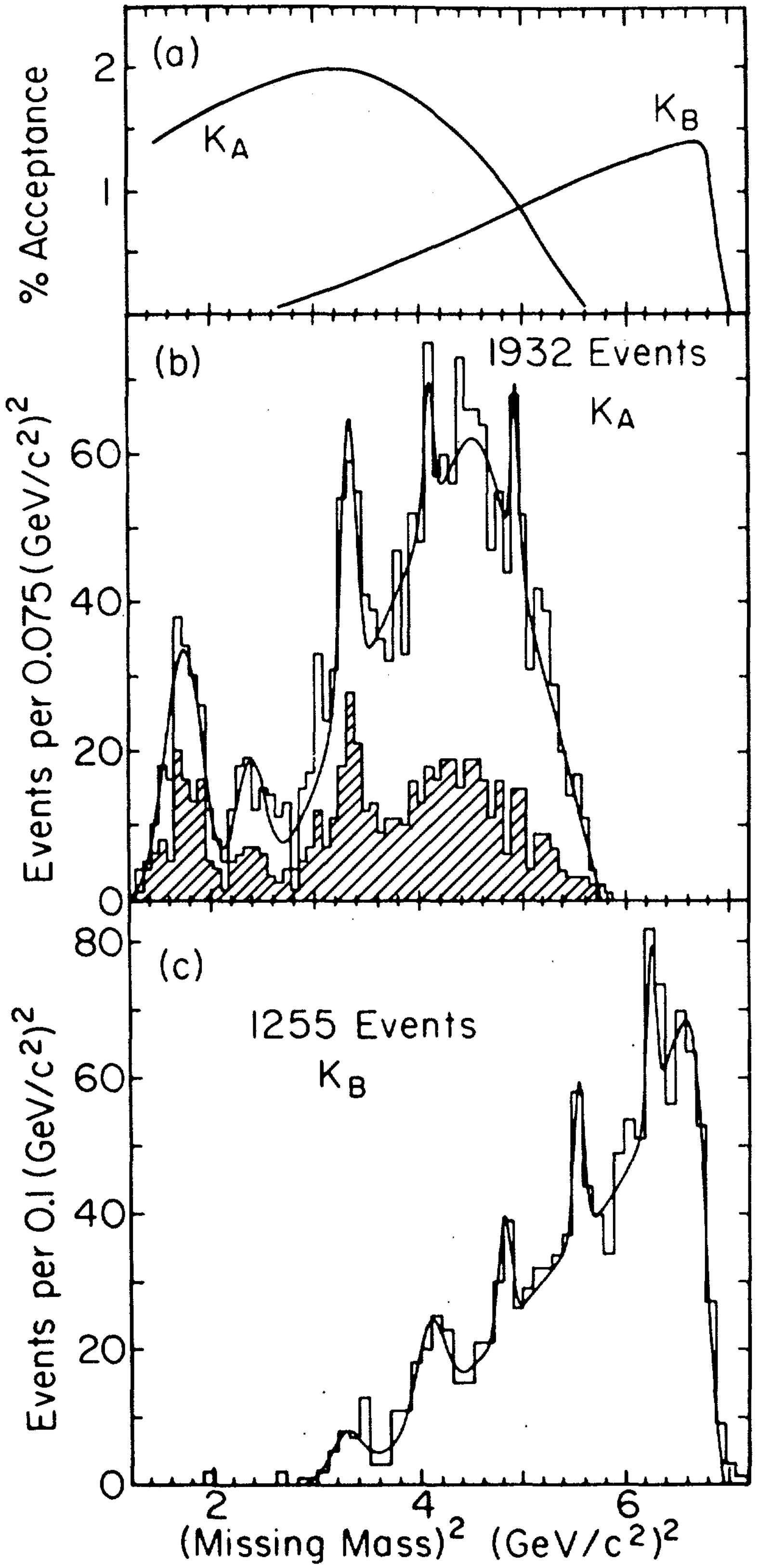


Simulated with GlueX
10^4 K_L/sec, one day of running



Jackson, Oh, Haberzettl, Nakayama
Phys. Rev. C 91, 065208 (2015)

Status of Ξ^*

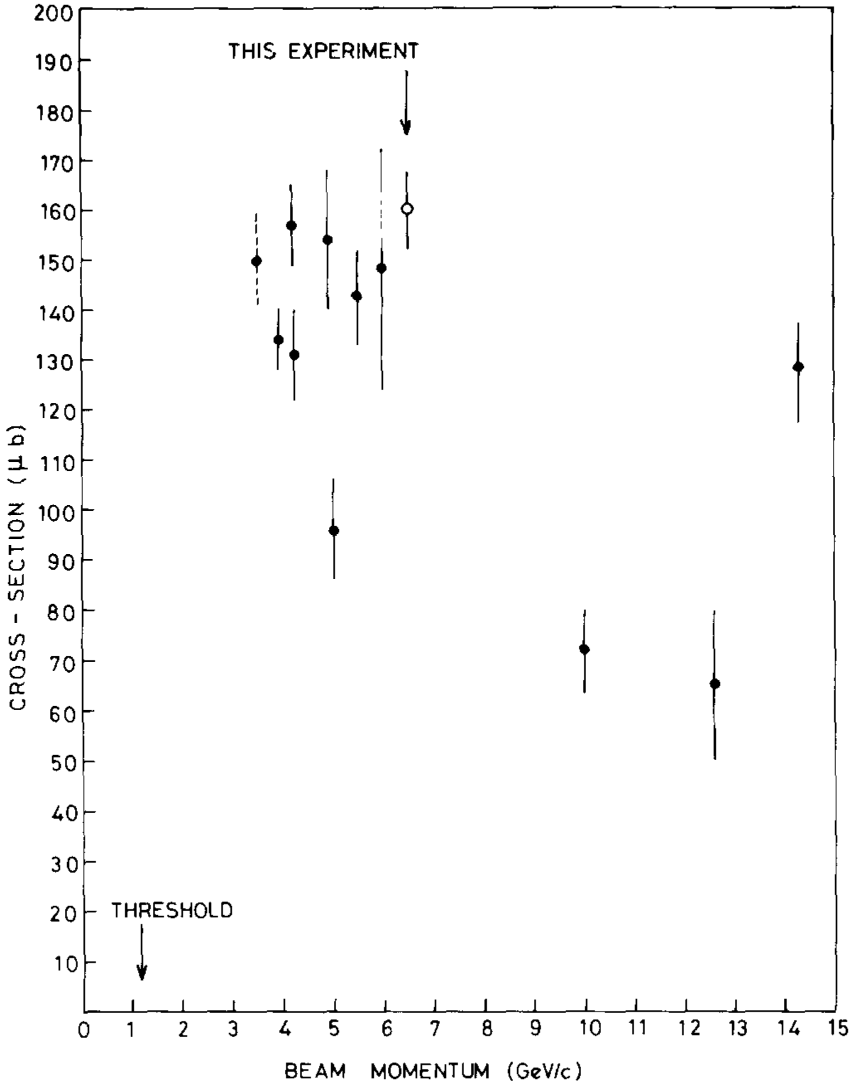


Very poorly measured at AGS (BNL) 32 years ago

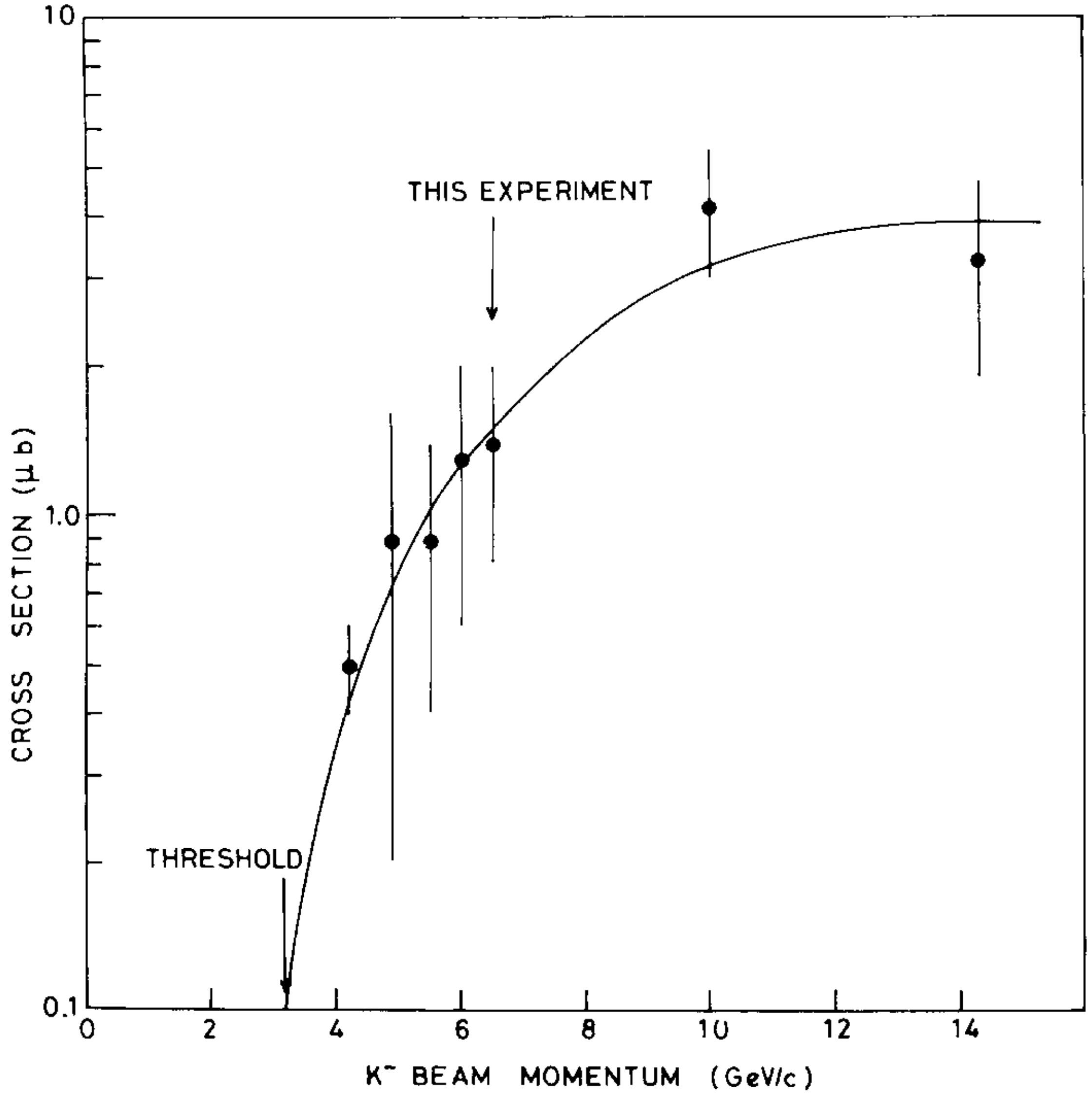
. **C.M. Jenkins et al., Phys. Rev. Lett. 51, 951 (1983)**

Cross Sections

$$K^- p \to \Xi^- X$$



$$K^- p \to \Omega^- X$$



J.K. Hassal et al., NPB 189 (1981)

Expected rates

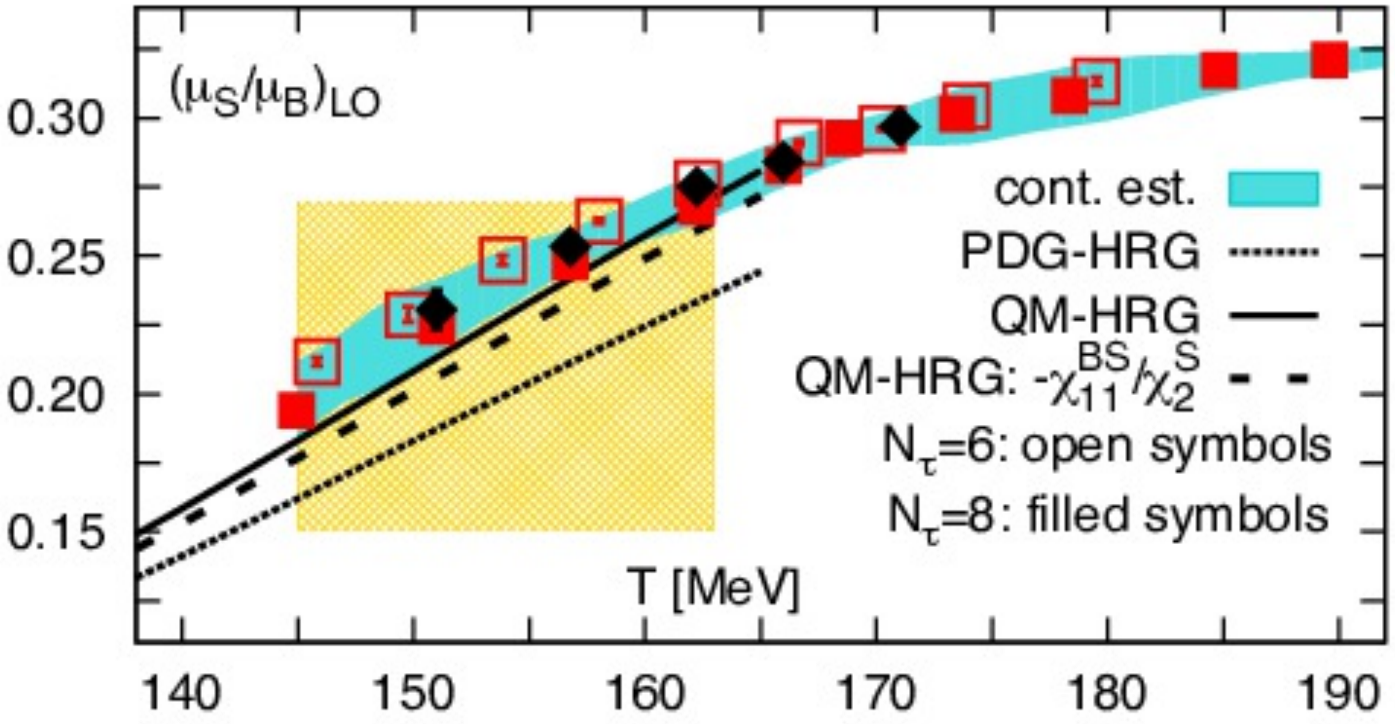
Production	J-PARC*	Jlab (this proposal)
flux/s	$3 \times 10^4 K^-$	$10^4 K_L^0$
$\Xi^* / month$	3×10^5	2×10^5
$\Omega^{-*} / month$	600	4000

* H.~Takahashi, NP A 914, 553 (2013)
M.~Naruki and K.~Shirotori, LOI-2014-JPARC

Missing states and freezout in heavy ion collisions

Close to T_c relaxation rates become small compared to the expansion rates and the system created in heavy ion collisions freezes out
The freeze-out is characterized by: (T^f, μ^f_B, μ^f_S) and hadron abundancies can be calculated from HRG

Lattice QCD Calculations

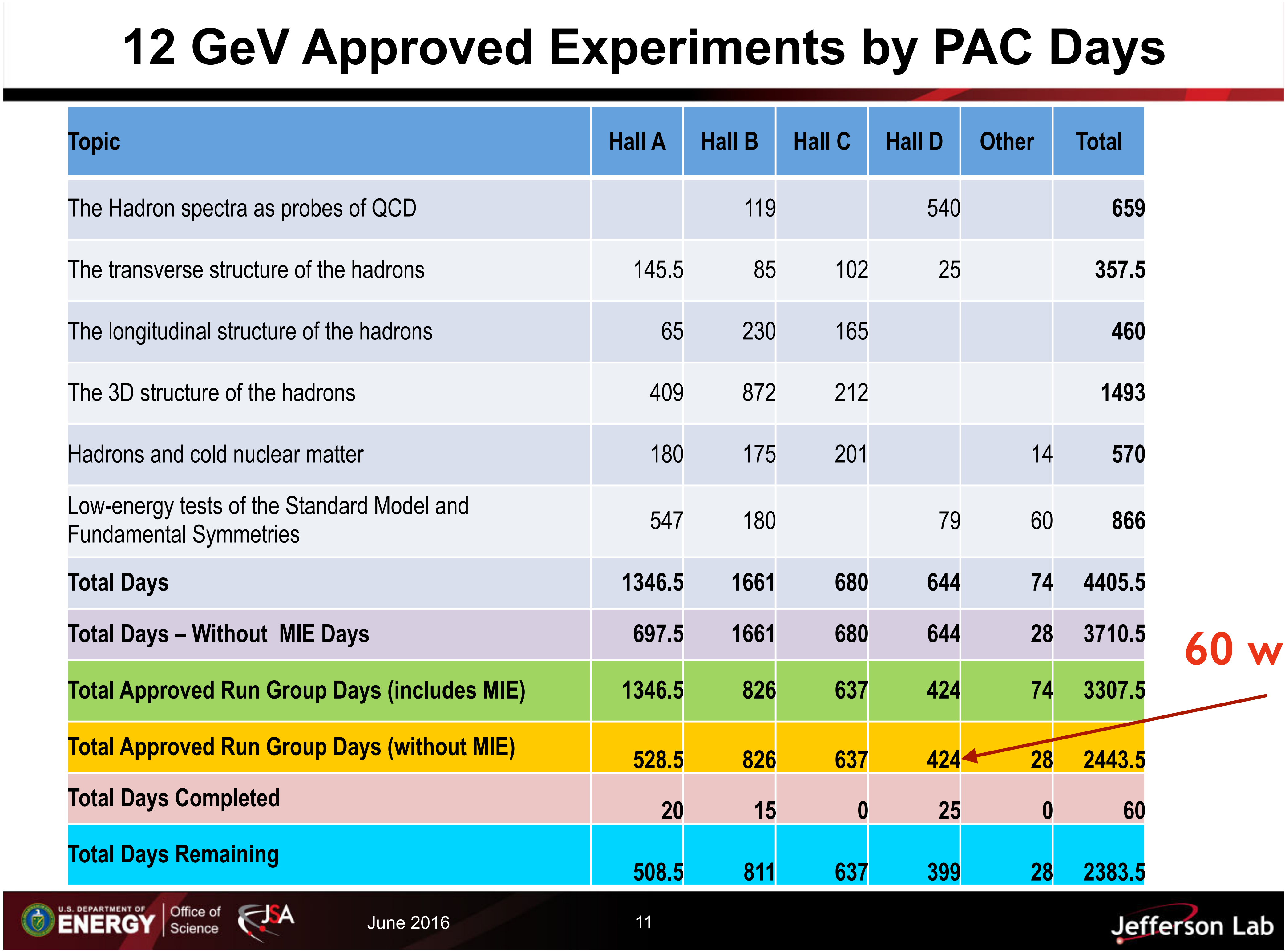


APS, April 2016, Peter Petreczky

$$dU = TdS - PdV + \sum_{i=1}^{n} \mu_i dN_i$$

$$\mu_i = \frac{\partial U_i}{\partial N_i}$$

Bazavov et al., PRL 113(2014) 072001



12 GeV Approved Experiments by PAC Days

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD		119		540		**659**
The transverse structure of the hadrons	145.5	85	102	25		**357.5**
The longitudinal structure of the hadrons	65	230	165			**460**
The 3D structure of the hadrons	409	872	212			**1493**
Hadrons and cold nuclear matter	180	175	201		14	**570**
Low-energy tests of the Standard Model and Fundamental Symmetries	547	180		79	60	**866**
Total Days	**1346.5**	**1661**	**680**	**644**	**74**	**4405.5**
Total Days – Without MIE Days	**697.5**	**1661**	**680**	**644**	**28**	**3710.5**
Total Approved Run Group Days (includes MIE)	**1346.5**	**826**	**637**	**424**	**74**	**3307.5**
Total Approved Run Group Days (without MIE)	**528.5**	**826**	**637**	**424**	**28**	**2443.5**
Total Days Completed	**20**	**15**	**0**	**25**	**0**	**60**
Total Days Remaining	**508.5**	**811**	**637**	**399**	**28**	**2383.5**

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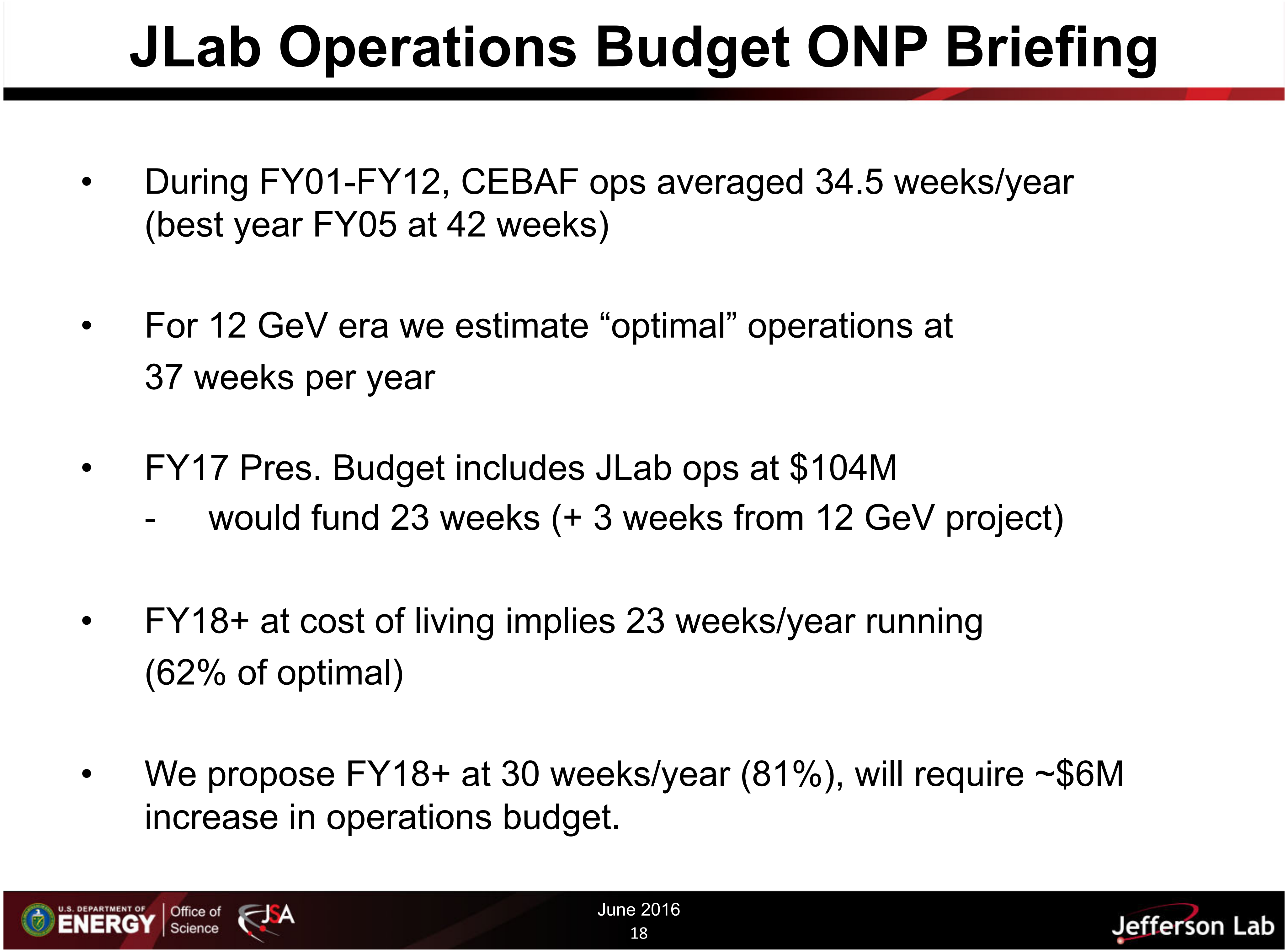
60 weeks

- **Bob McKeown's talk at 2016 UG meeting**



JLab Operations Budget ONP Briefing

- During FY01-FY12, CEBAF ops averaged 34.5 weeks/year (best year FY05 at 42 weeks)
- For 12 GeV era we estimate “optimal” operations at 37 weeks per year
- FY17 Pres. Budget includes JLab ops at $104M
  - would fund 23 weeks (+ 3 weeks from 12 GeV project)
- FY18+ at cost of living implies 23 weeks/year running (62% of optimal)
- We propose FY18+ at 30 weeks/year (81%), will require ~$6M increase in operations budget.

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- **Slide from Mont’s talk at 2016 UG meeting**
- **Hall D Physics Program will be completed in 2-3 years**

Summary

- KN scattering still remains very poorly studied

- lack of data on excited hyperon states requires significant experimental efforts to be completed

- Our preliminary studies show that few times $10^4 K^0_L$/s at Jlab is feasible with GlueX setup in Hall D

-Proposed setup will have highest intensity K^0_L beam ever used for hadron spectroscopy
two orders of magnitude higher than
in LASS (SLAC) experiment

-Data obtained at Jlab will be unique and partially complementary to charged kaon data

-The possibility to run with polarized H and D targets is possible (see talk by C. Keith at KL2016 Workshop)

Thank You!