Run Group E
Readiness Report

W. Brooks
on behalf of the rest of the spokespersons

W. Armstrong, W. K. Brooks, R. Dupre, A. El Alaoui, L. El Fassi, G. Gilfoyle, H. Hakobyan, K. Hicks, M. Holtrop, K. Joo, T. Mineeva, G. Niculescu, M. Niculescu, M. Wood

10 institutions

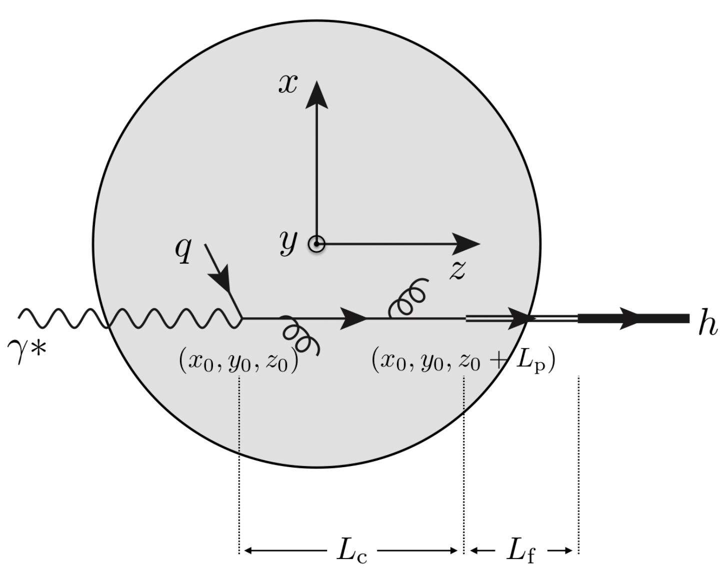
19 June 2019
CLAS Collaboration Meeting

Color Propagation Through Strongly Interacting Systems
Run Group E

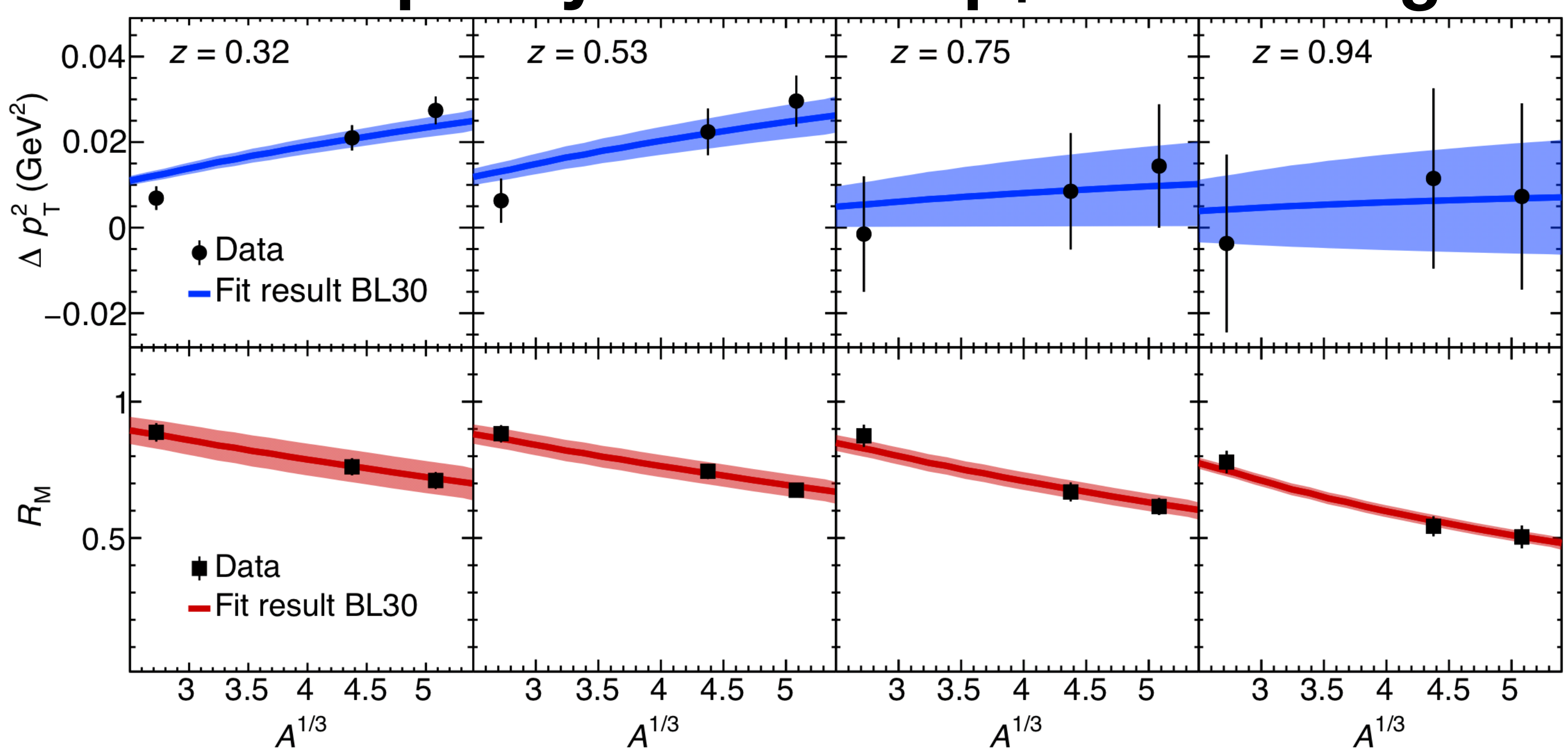
How long can an energetic quark remain "free"?

How large is quark energy loss in nuclei?

How do hadrons form from quarks?



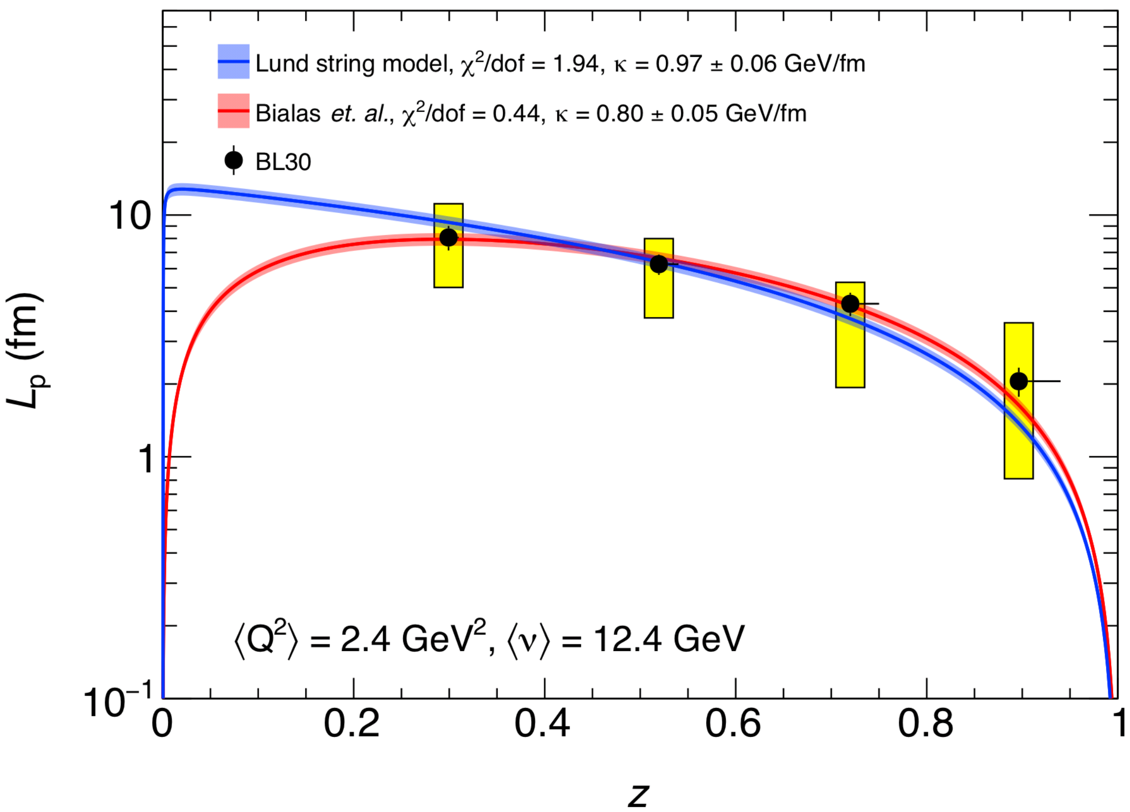
Simultaneous Fit to HERMES Data for Multiplicity Ratio and p_T broadening:



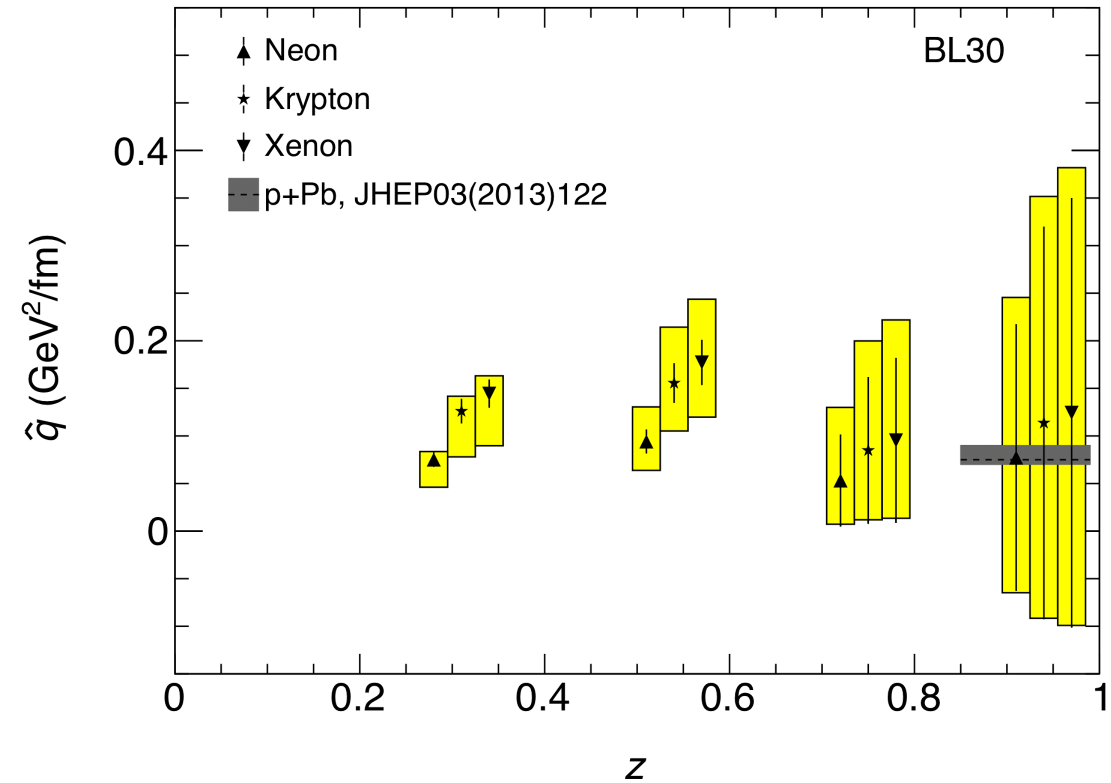
WB and Jorge López

Independent determination of Lund Model string tension

Color Lifetime

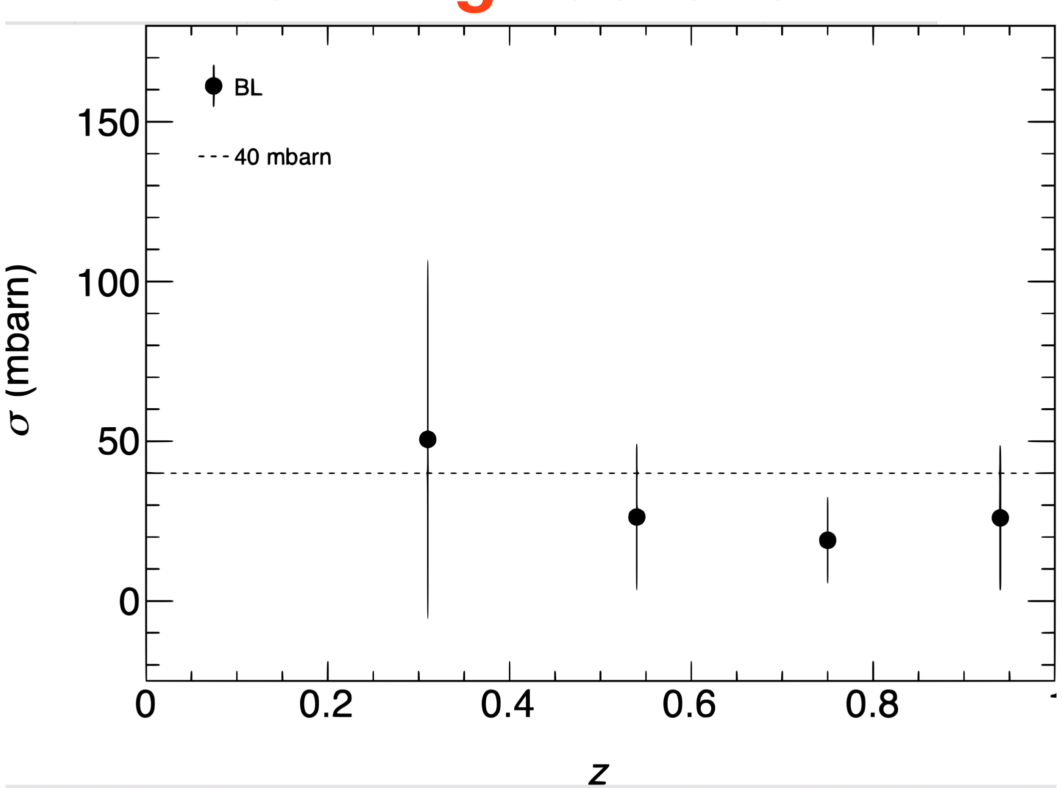


Determination of transport coefficient consistent with LHC

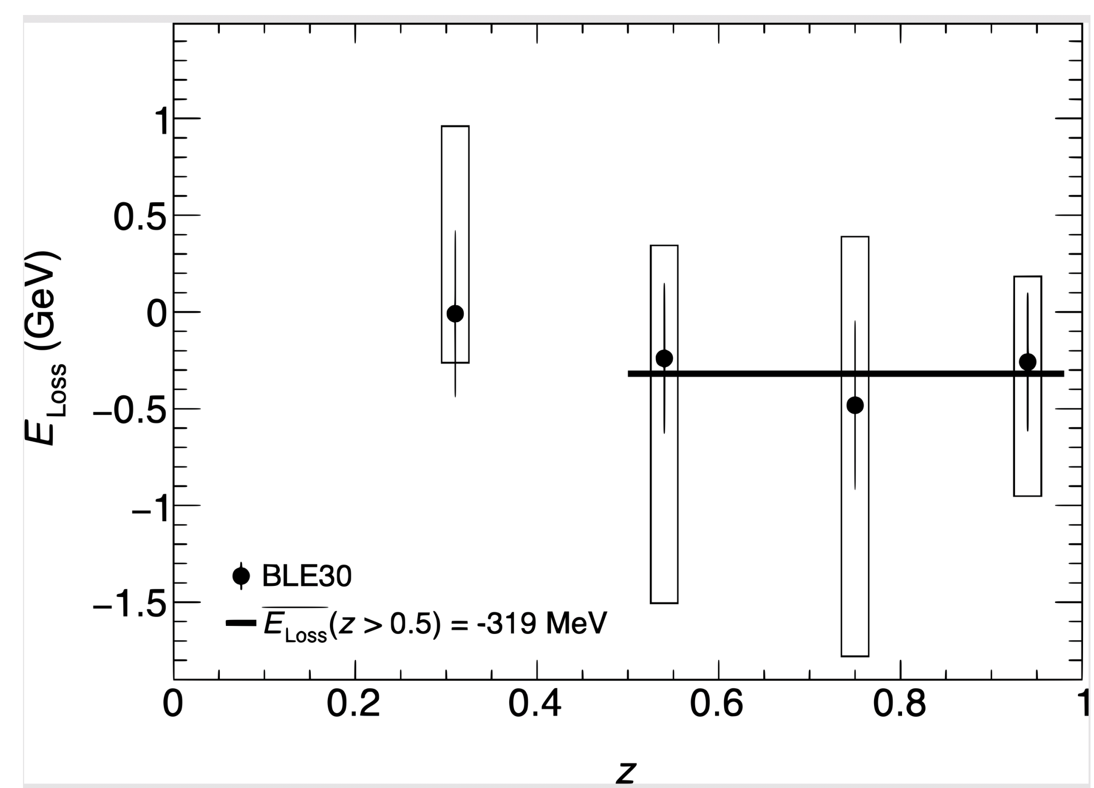


Suppressed cross-section for forming hadrons

Prehadron-nucleon cross-section



Quark total energy loss vs. z_h



We will do the same analyses for CLAS12 data.

But instead of being in one dimension, we can study multiple variable dependences of the color lifetime and of quark energy loss. This would be a world's first.

Instead of large error bars we will have small error bars.

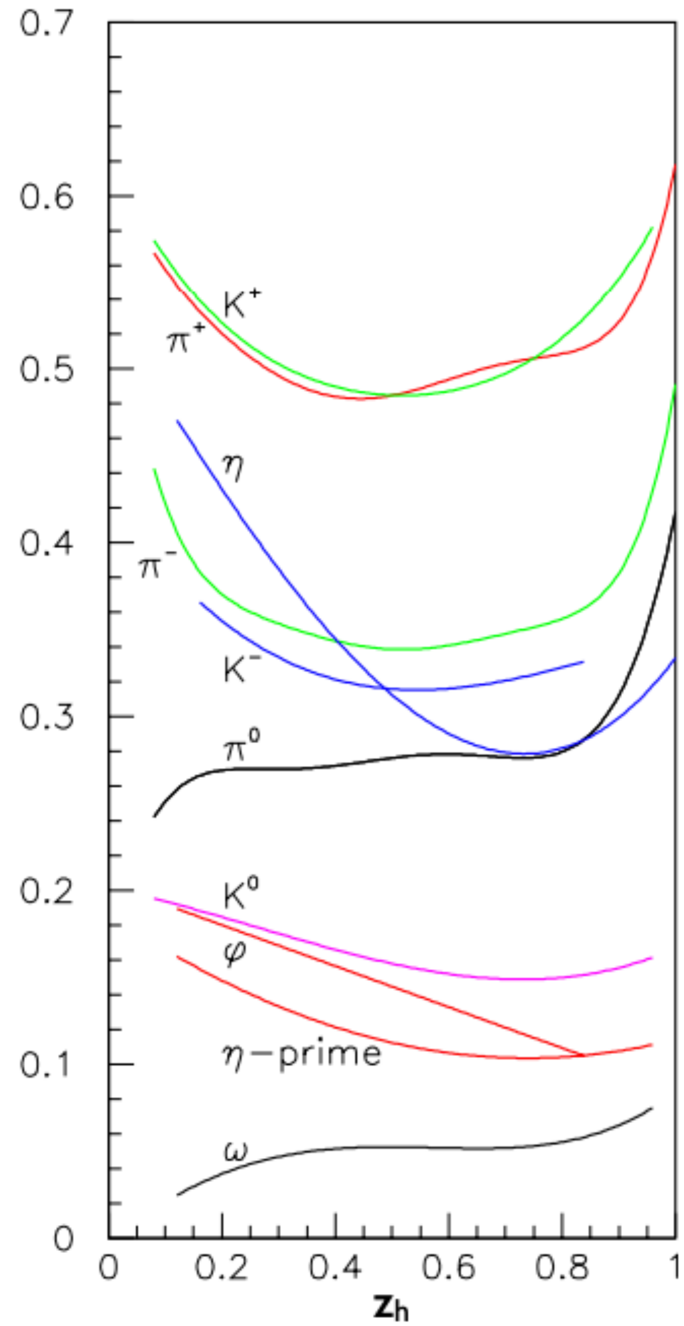
Quark Propagation and Hadron Formation

hadron	cτ	mass	flavor content	limiting error (60 PAC days)
π^0	25 nm	0.13	$u\bar{u}d\bar{d}$	5.7% (sys)
π^+, π	7.8 m	0.14	$u\bar{d}$, $d\bar{u}$	3.2% (sys)
η	170 pm	0.55	$u\bar{u}d\bar{d}s\bar{s}$	6.2% (sys)
ω	23 fm	0.78	$u\bar{u}d\bar{d}s\bar{s}$	6.7% (sys)
η'	0.98 pm	0.96	$u\bar{u}d\bar{d}s\bar{s}$	8.5% (sys)
ϕ	44 fm	1.0	$u\bar{u}d\bar{d}s\bar{s}$	5.0% (stat)*
f1	8 fm	1.3	$u\bar{u}d\bar{d}s\bar{s}$	-
K^0	27 mm	0.50	$d\bar{s}$	4.7% (sys)
K^+, K^-	3.7 m	0.49	$u\bar{s}$, $\bar{u}s$	4.4% (sys)
p	stable	0.94	ud	3.2% (sys)
$\bar{p}$	stable	0.94	$\overline{ud}$	5.9% (stat)**
Λ	79 mm	1.1	uds	4.1% (sys)
$\Lambda(1520)$	13 fm	1.5	uds	8.8% (sys)
Σ^+	24 mm	1.2	us	6.6% (sys)
Σ^-	44 mm	1.2	ds	7.9% (sys)
Σ^0	22 pm	1.2	uds	6.9% (sys)
Ξ^0	87 mm	1.3	us	16% (stat)*
Ξ^-	49 mm	1.3	ds	7.8% (stat)*

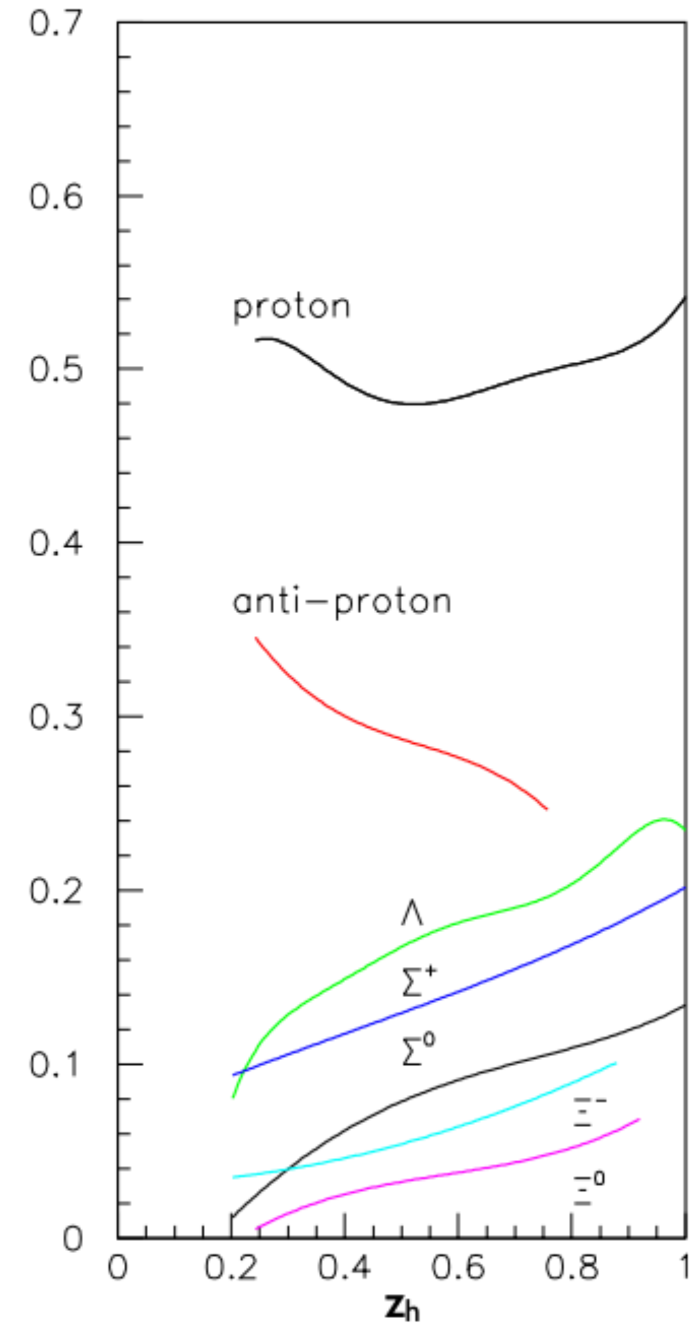
*in a bin in z from 0.7-0.8, integrated over all ν, p_T, ϕ_{pq}, and Q^2>5 GeV^2

**in a bin in z from 0.6-0.7, integrated over all ν, p_T, ϕ_{pq}, and Q^2>5 GeV^2

Dependency of observables (and thus derived quantities, such as production time, formation times, transport coefficient, in-medium cross section, etc.) on mass, flavor, and number of valence quarks



CLAS12 Acceptance for Mesons



CLAS12 Acceptance for Baryons

HERMES Data

One dimensional

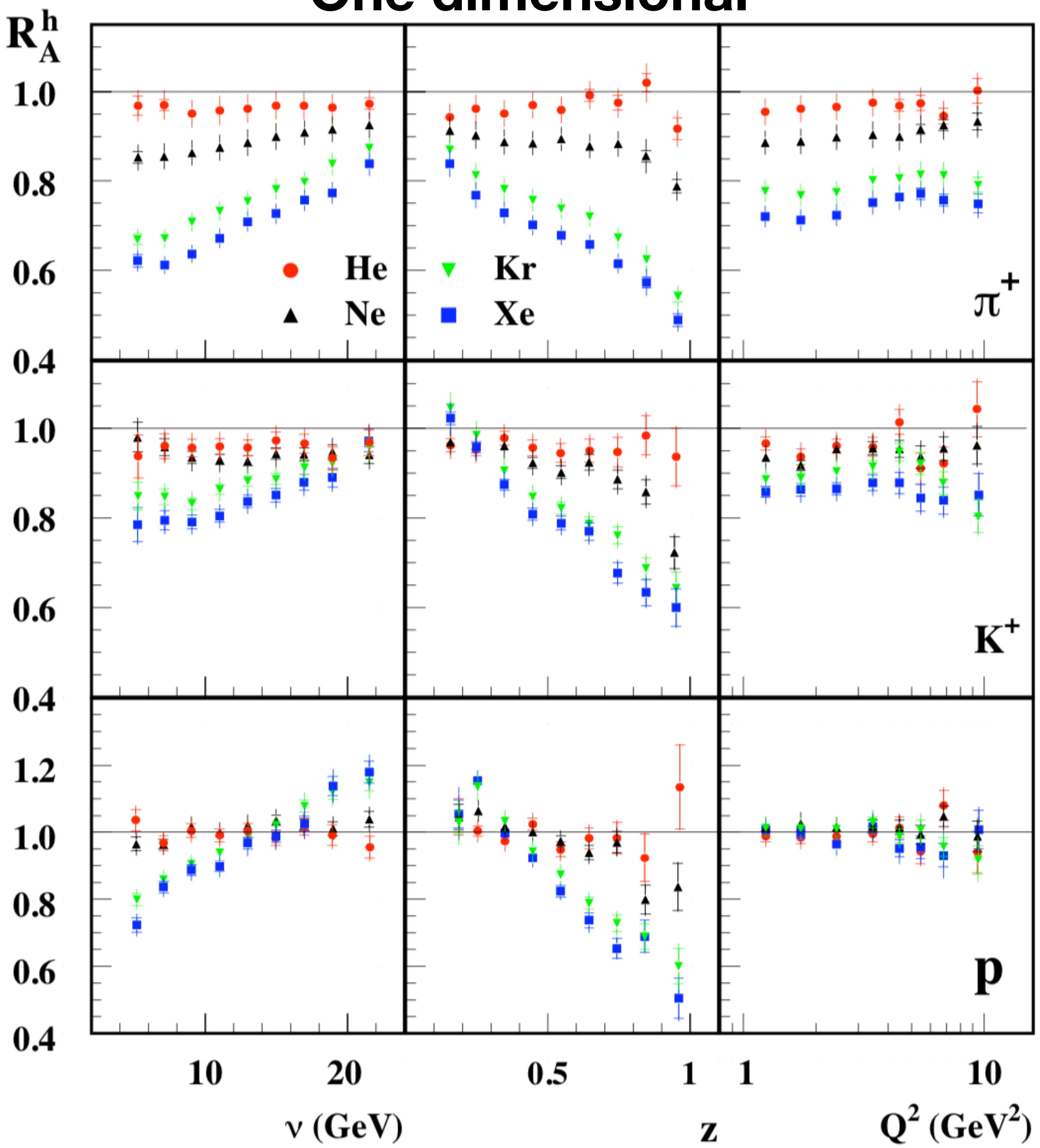


Fig. 2. Values of R^h_A for positively charged hadrons as a function of ν, z, and Q^2. The data as a function of ν are shown for $\nu > 4$ GeV and those as a function of z for $z > 0.1$. The inner error bars represent the statistical uncertainty, while the outer ones show the total uncertainty. https://arxiv.org/abs/0704.3270v1

Two dimensional

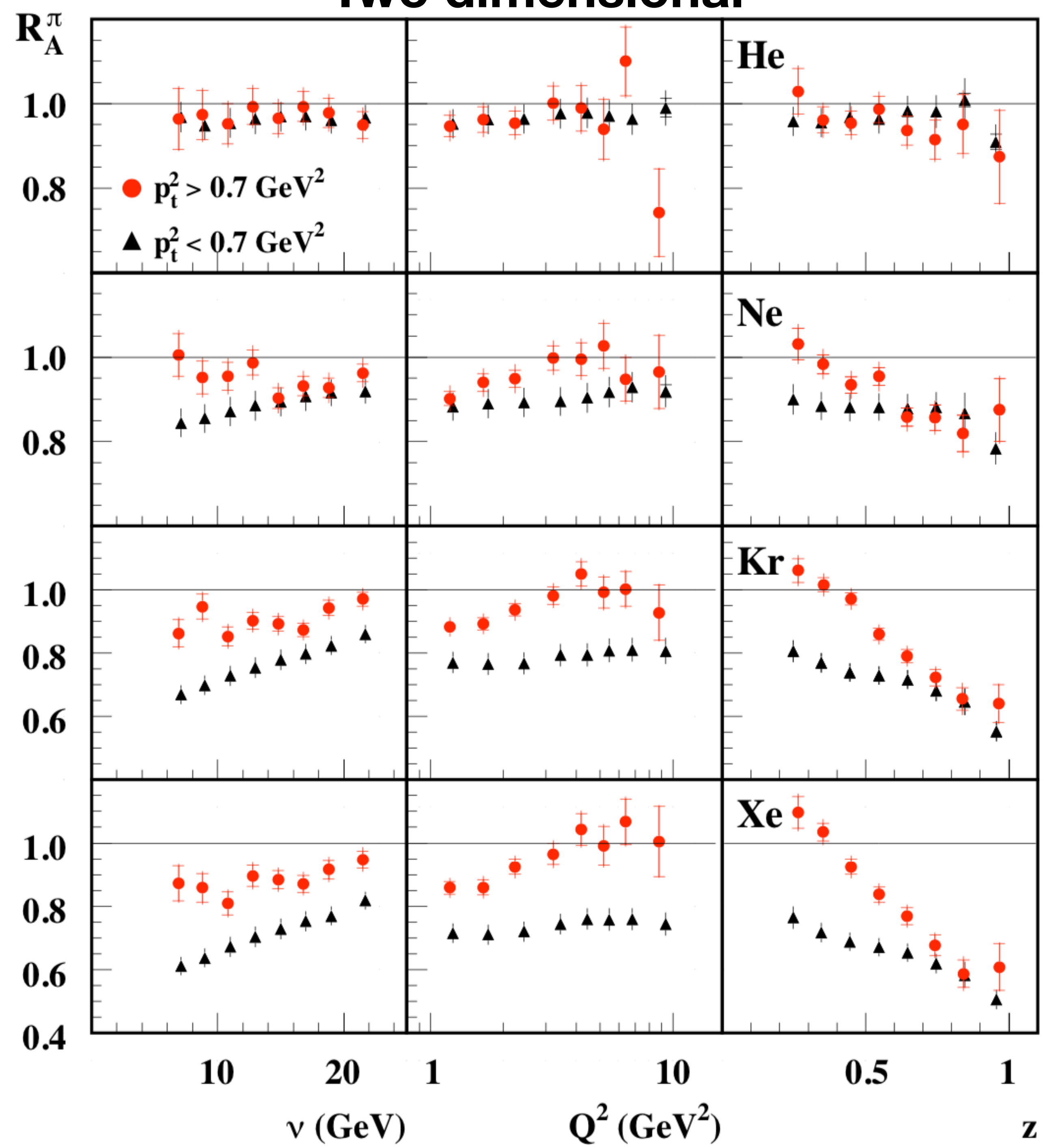


Fig. 8. Values of R^h_A for charged pions for two p_t^2 ranges. Error bars as in Fig. 2.

The Hermes data have small *systematic* uncertainties, up to 2-dimensional analyses.
CLAS data MUST have similarly small uncertainties, up to 4/5-dimensional at 11 GeV.

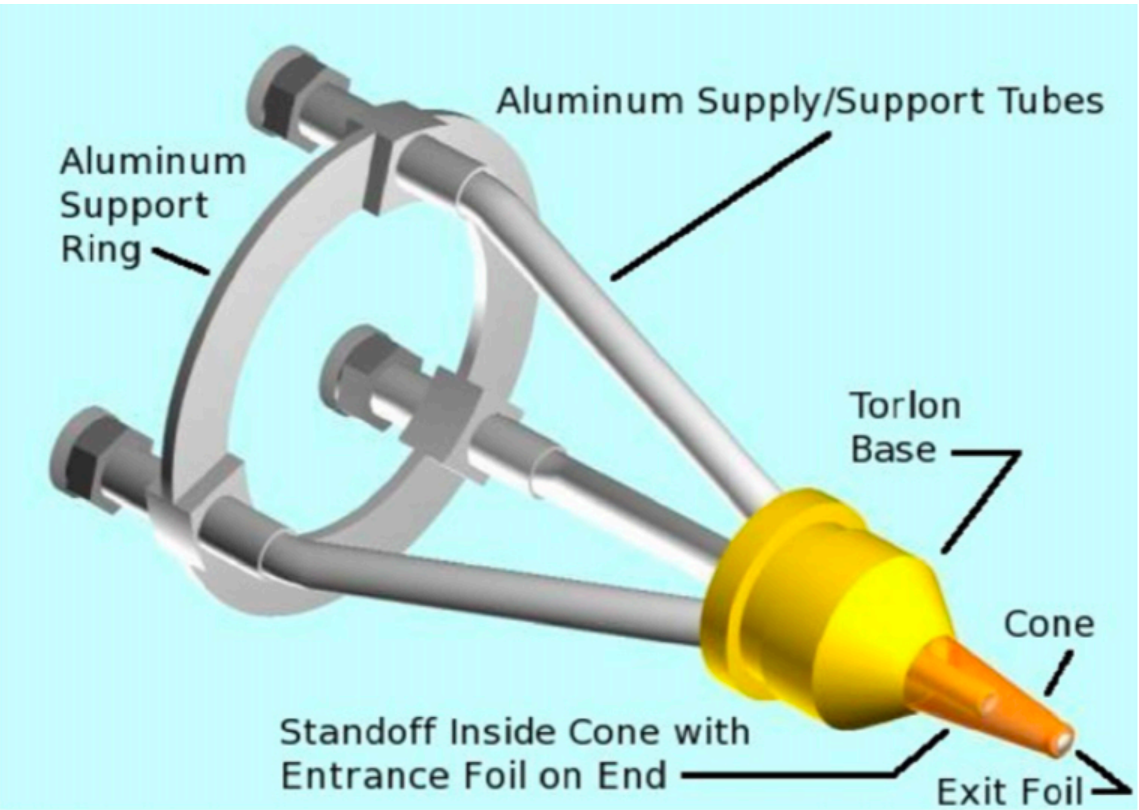
Use of the dual target

- The experiment makes a precise comparison of observables in a large nucleus A with a small nucleus D

- The foundational observable is the multiplicity ratio, which measures the suppression or enhancement of hadron production.

$$R_M^h(Q^2,\nu,z_h,p_T) \equiv \frac{\left.\dfrac{N_h(Q^2,\nu,z_h,p_T)}{N_e(Q^2,\nu)}\right|_{\mathrm{A}}}{\left.\dfrac{N_h(Q^2,\nu,z_h,p_T)}{N_e(Q^2,\nu)}\right|_{\mathrm{D}}}$$

- A key ingredient in making a *precise* measurement is the ***dual target approach***



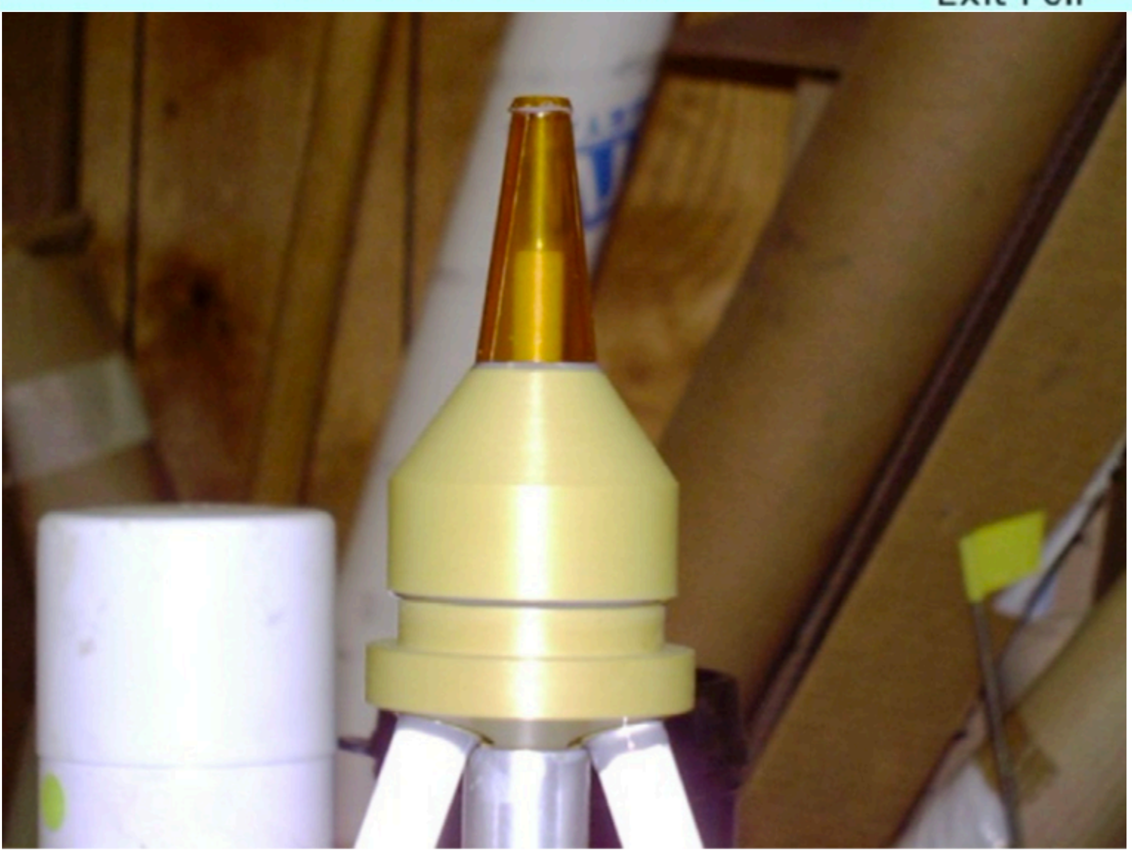
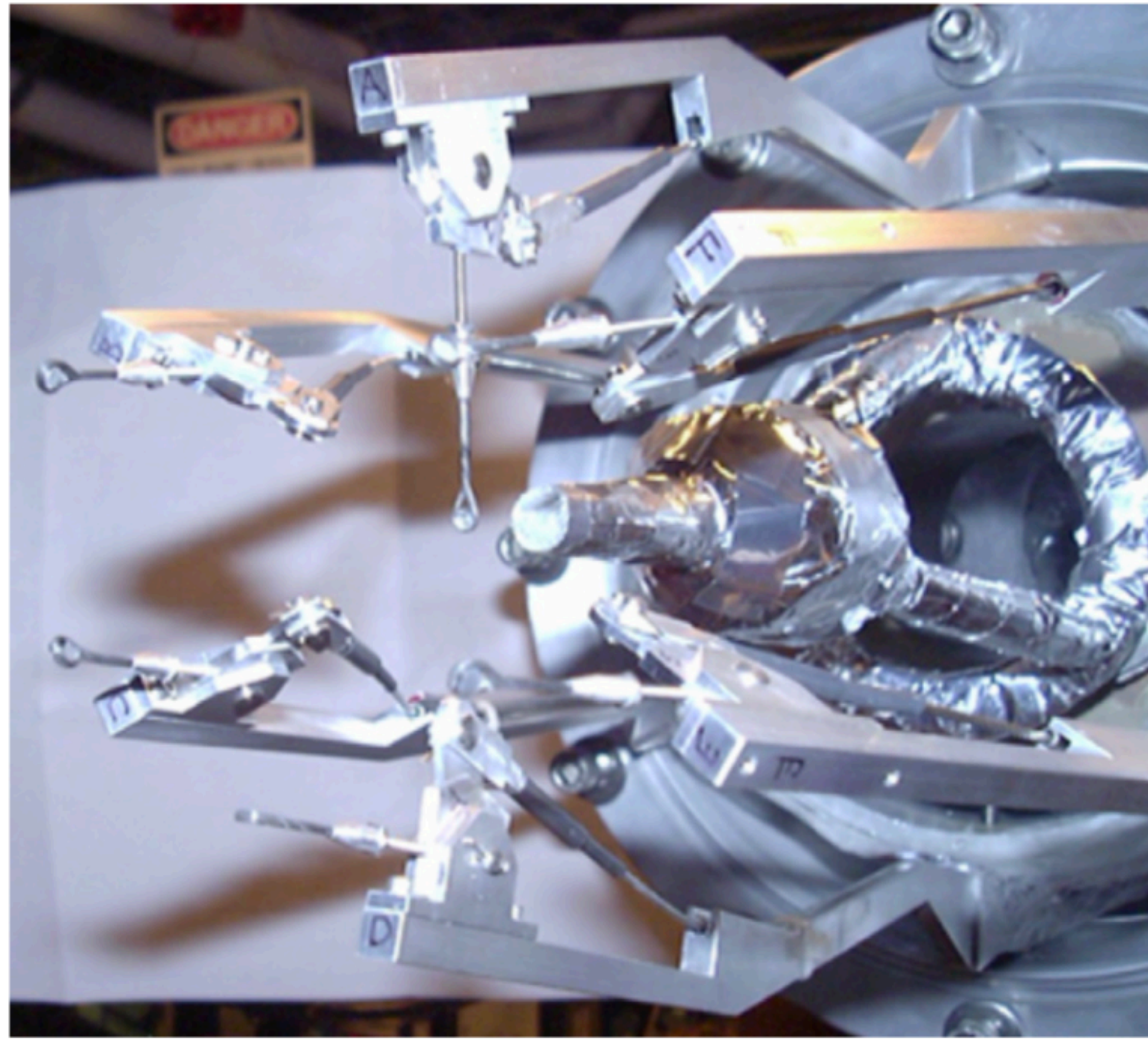


Fig. 2. A photograph of the cryotarget cell assembly, showing the cryotarget base standoff, and outer cone with lap joint fabrication.

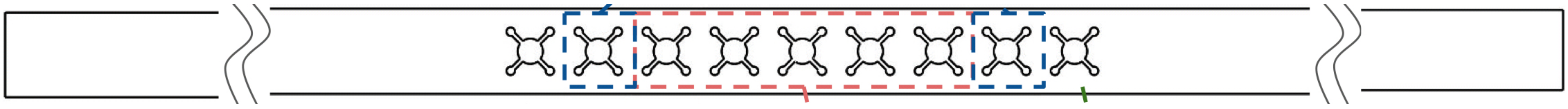


"A double-target system for precision measurements of nuclear medium effects," H. Hakobyan et al.

NIM A 592 (2008) 218– 223

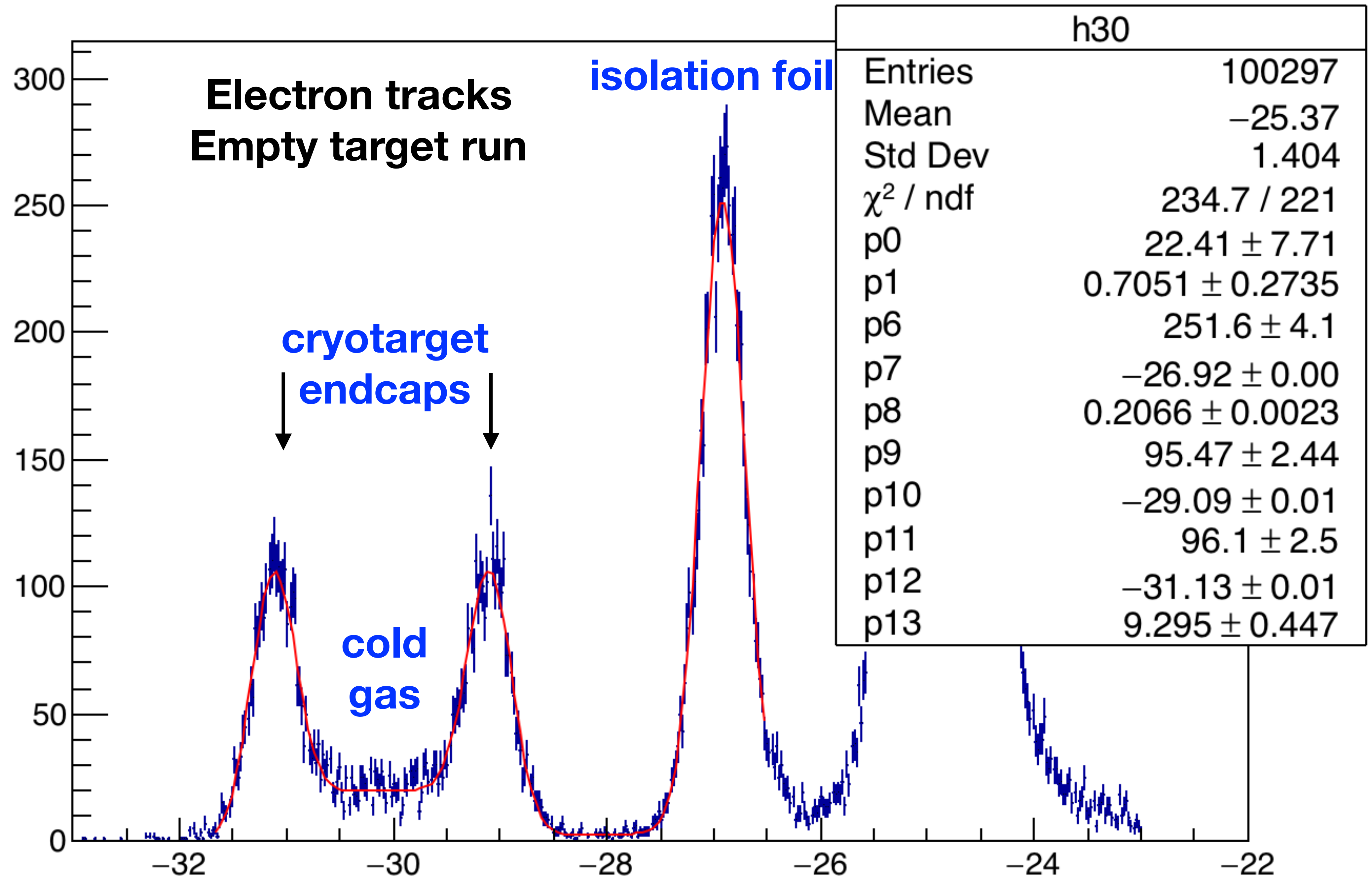
New Dual Target

The solid targets are glued into the holes on this band. The band slides in a channel in the black outer holder, positioned by a piezoelectric motor. The radiation dose to that motor has been calculated by Lorenzo Zana, and it is well below the levels to which similar motors have been tested and found to continue operating, in published studies.



Space for extra targets and crossed wire. ¡Hecho en Chile!

CLAS vertex performance during the EG2 run period



The fit uses Gaussian peaks, vy<1.4 cm, and equal widths for all three peaks. Background parameter is a straight line.

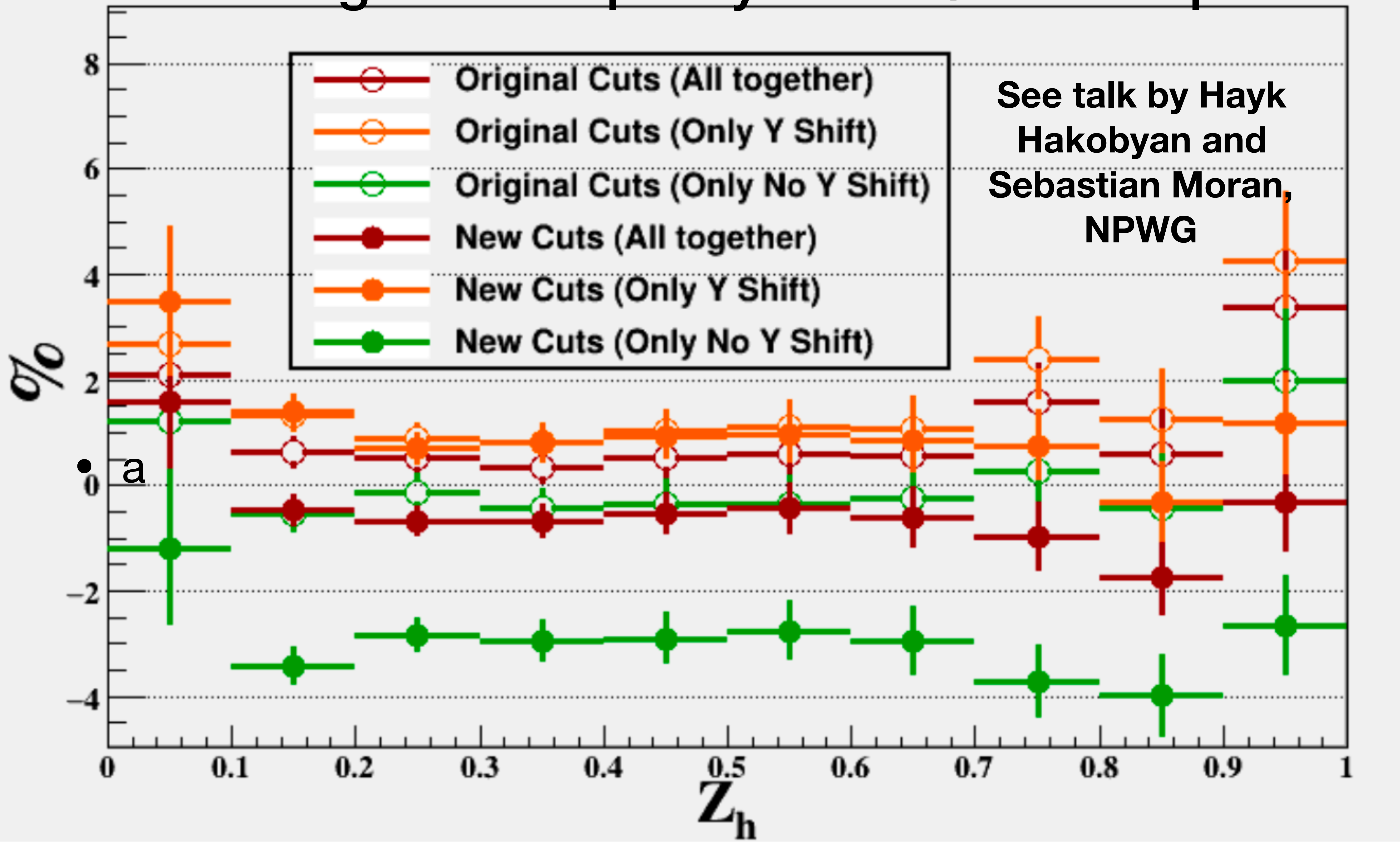
Chisquared/dof = 1.06

Vertex resolution 2.1 mm (parameter 8)

Can resolve targets separated by 1.2 cm - acceptance difference is negligible

C

Percent change in multiplicity ratio w/wo acceptance

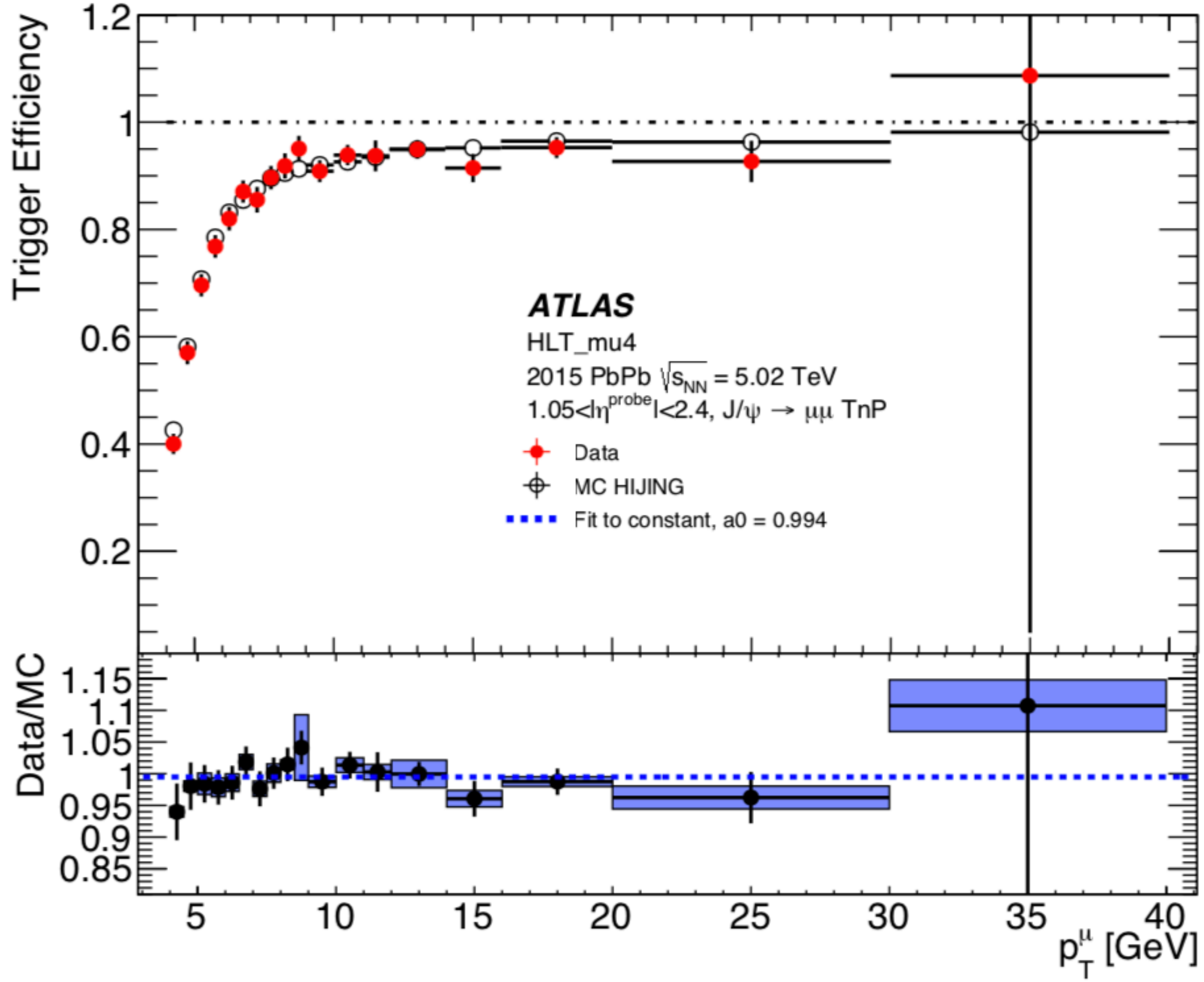


Red points are the relevant ones - acceptance correction changes the multiplicity ratio by 0±2% for the carbon target.

Benefits of the Dual Target Approach

Corrections that divide out in the multiplicity ratio		
Acceptance correction		Almost perfect cancellation
Trigger efficiency		Perfect cancellation
Tracking efficiency		Almost perfect cancellation
Time-dependent effects	Dead channels in detectors(acceptance), electron beam current variations, DAQ dead time, background changes after beam	Perfect cancellation

Example of Trigger Correction, ATLAS/LHC

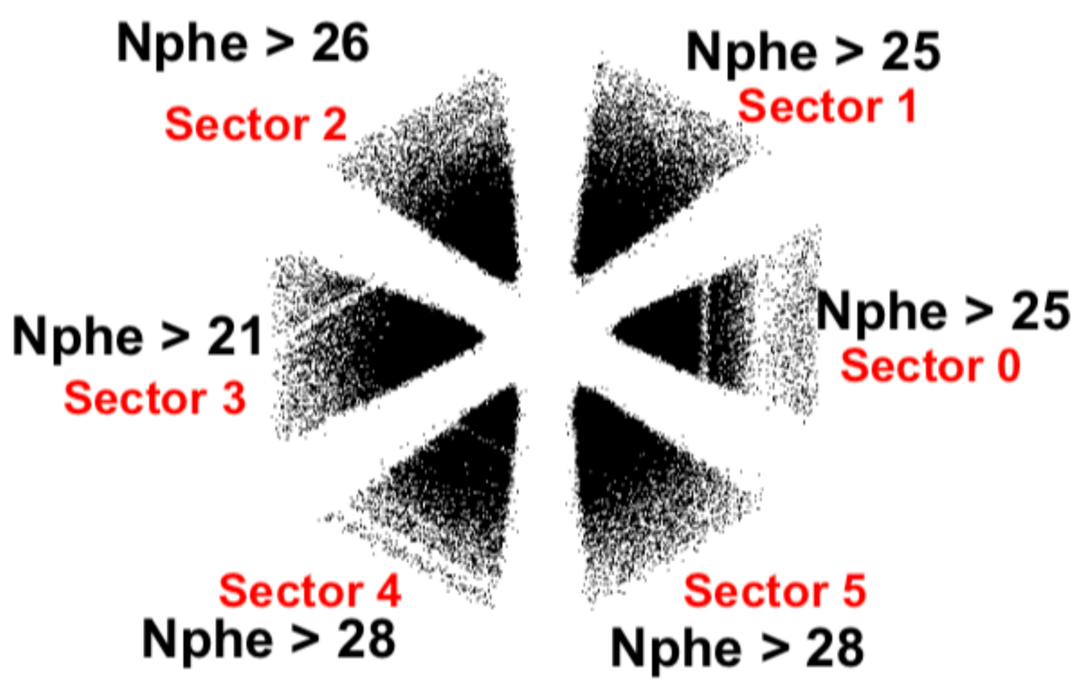


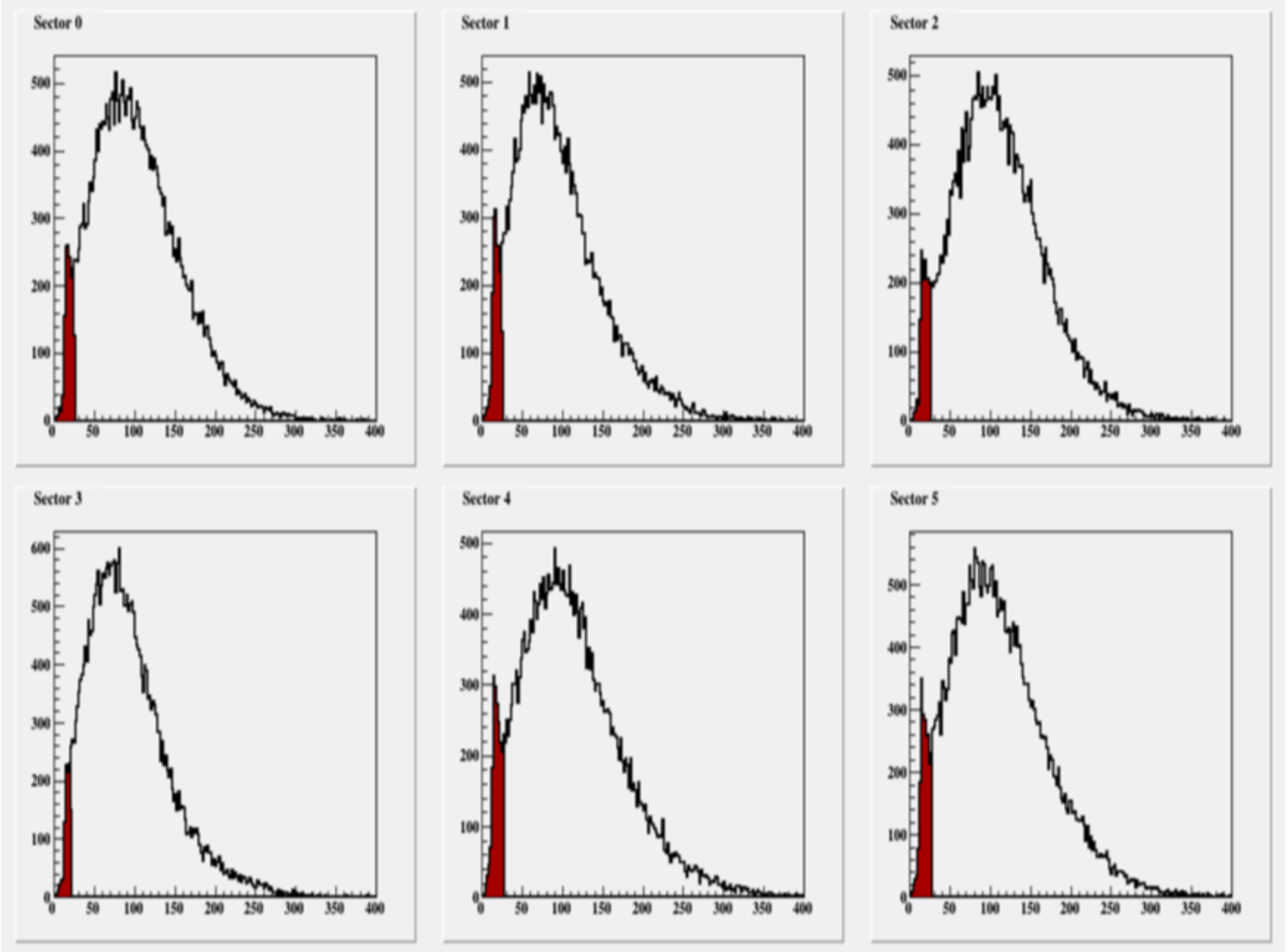
- Measured with data and also with simulation; consistent

  See thesis of Dr. Sebastián Tapia (USM, now at Illinois):

  https://repositorio.usm.cl/handle/11673/25835

Immunity to trigger inefficiency is an important benefit of the dual target





See NPWG talk by Hayk Hakobyan and Sebastian Morán

Obvious comment on tracking efficiency determination for nuclear targets

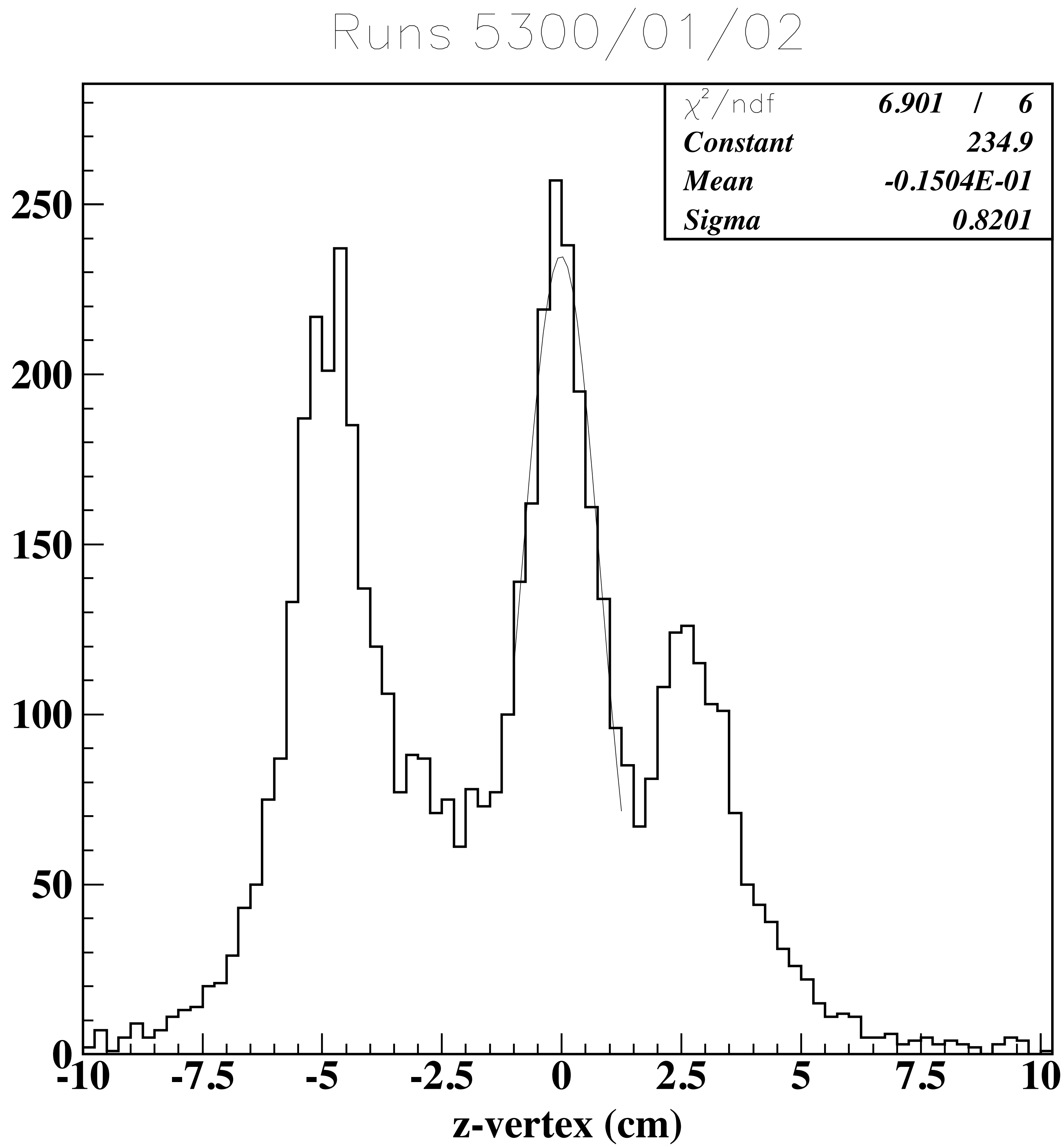
One “easy” way to measure tracking efficiency is e-p elastic scattering. One can validate the simulation in the kinematics covered by elastic scattering and extrapolate outside those kinematics. But, you can’t do this with nuclear targets beyond A=1.

For nuclear targets, it’s not clear that there are any easy ways. May need new ideas and developments if this has to be measured directly.

Why we don’t want to use the RG-D target

Additional corrections we would have to do for each of the **six** targets, each of which adds a new systematic uncertainty:		
Acceptance correction		Must take into account dead channels for six targets
Trigger efficiency		Must measure the trigger efficiency for six targets
Tracking efficiency		Must measure the tracking efficiency for six targets
Time-dependent effects	beam current variations, DAQ dead time, background changes after beam re-tuning	Must measure each of these variations for six targets

- The current z vertex resolution is 6-8 mm. At 6 GeV it was 2 mm as shown earlier. When I wrote the proposal in 2006, the simulations of CLAS12 were predicting a resolution <1 mm.
- Three sigma separation for the two targets is 48 mm.
- The detector is only capable of resolving two objects cleanly if they are separated by 5 cm. (At 6 GeV it was 1.2 cm)
- With this situation, it is simply not possible to use a dual target with two closely spaced targets.



Principles we used for target selection and thicknesses

- Need nuclear targets so that scattering products pass through the nuclear medium.

- Need the widest possible range of pathlengths, from small to large. Previous data (CLAS, HERMES) suggests carbon is a good minimum size to compare to deuterium. Five nuclei spanning the range permits good shape determination of measured observables.

- Need spherical nuclei for modeling (so no uranium). Radius goes as $A^{1/3}$, so the difference between gold and lead, for example, is less than 2%. It needs to be a solid at room temperature and not melt very easily. It is ideal if the mass numbers are similar or identical to those of previous measurements.

Principles we used for target selection and thicknesses

- The electromagnetic backgrounds scale with the number of radiation lengths X_0 of target thickness. Past experience and simulations suggest an upper limit of 2.5% of X_0.
- The baseline cryotarget is 5 cm (although we would prefer 1 or 2 cm; but we were told that is not possible in the near term). This sets the baseline for the target thickness in areal mass density as 0.85 g/cm^2.
- For the heavier targets, the thickness is given by Max(0.85,0.025*X_0). A table of the resulting values is in the following.
- The luminosity is 1E35 for D, C, Al, Cu. An additional reduction in the luminosity limit of 40% and 35% (for tin and lead, respectively) has been added based on experience in the EG2 run.
- We add an additional weight factor in the number of days of running on each target based on the expected hadron suppression. This will give us approximately equal statistics on the heavy targets as on deuterium at higher z_h.

Principles we used for target selection and thicknesses

ISSUE: 5 cm long cryotarget

- We prefer to have a shorter cryotarget because the maximum thickness in radiation lengths of Pb is 2.5%, but that equates to a mass density of 0.16 g/cm^2. A 5 cm LD2 target has a mass density of 0.85 g/cm^2. To get comparable rates you'd need five times as much beam current on the Pb as on the LD2.
- The table that follows assumes a 5 cm LD2 cryotarget, but if possible we'd like a shorter one in the future. We have been told it cannot happen in the near term.
- In principle, a shorter cryotarget means a greater proportion of the scattering comes from the aluminum endcaps, contaminating the deuterium data. In EG2 we developed a method that avoids placing hard cuts in the z vertex coordinate (documented in Taya's analysis note). Therefore a shorter cryotarget is feasible without losing statistics due to vertex cuts.

Planned targets

Target	Areal density (g/cm^2)	Physical length (mm)	Radiation length (cm)	Radiation length times 0.025 (mm)	Density (g/cc)	ASSUMED decrease in CLAS12 luminosity limit based on 5 GeV running
Deuterium	0.85	**50**	724	18	0.169	0
Carbon	0.85	**3.9**	18.8	4.7	2.2	0
Aluminum	0.59	**2.2**	8.9	2.2	2.7	0
Copper	0.32	**0.36**	1.43	0.36	8.96	0
Tin	0.22	**0.30**	1.21	0.30	7.31	40%
Lead	0.16	**0.14**	0.56	0.14	11.35	35%

Run Plan

Target	PAC days	Beam current (nA)	Luminosity (/cm^{2}s)	Backup target in case of melting
Commission	3	-	-	
Deuterium	4	32	1.00E+35	
Carbon	6	31	1.00E+35	
Aluminum	7	45	1.00E+35	
Copper	8	83	1.00E+35	
Tin	15	72	6.00E+34	Ag; 83*0.60 = 50 nA
Lead	17	108	6.50E+34	Au; 99*0.65 = 64 nA
Magnets	60% field inbending electrons 90% of the time 60% field outbending electrons 10% of the time			

Compatibility with mutual running of RGD

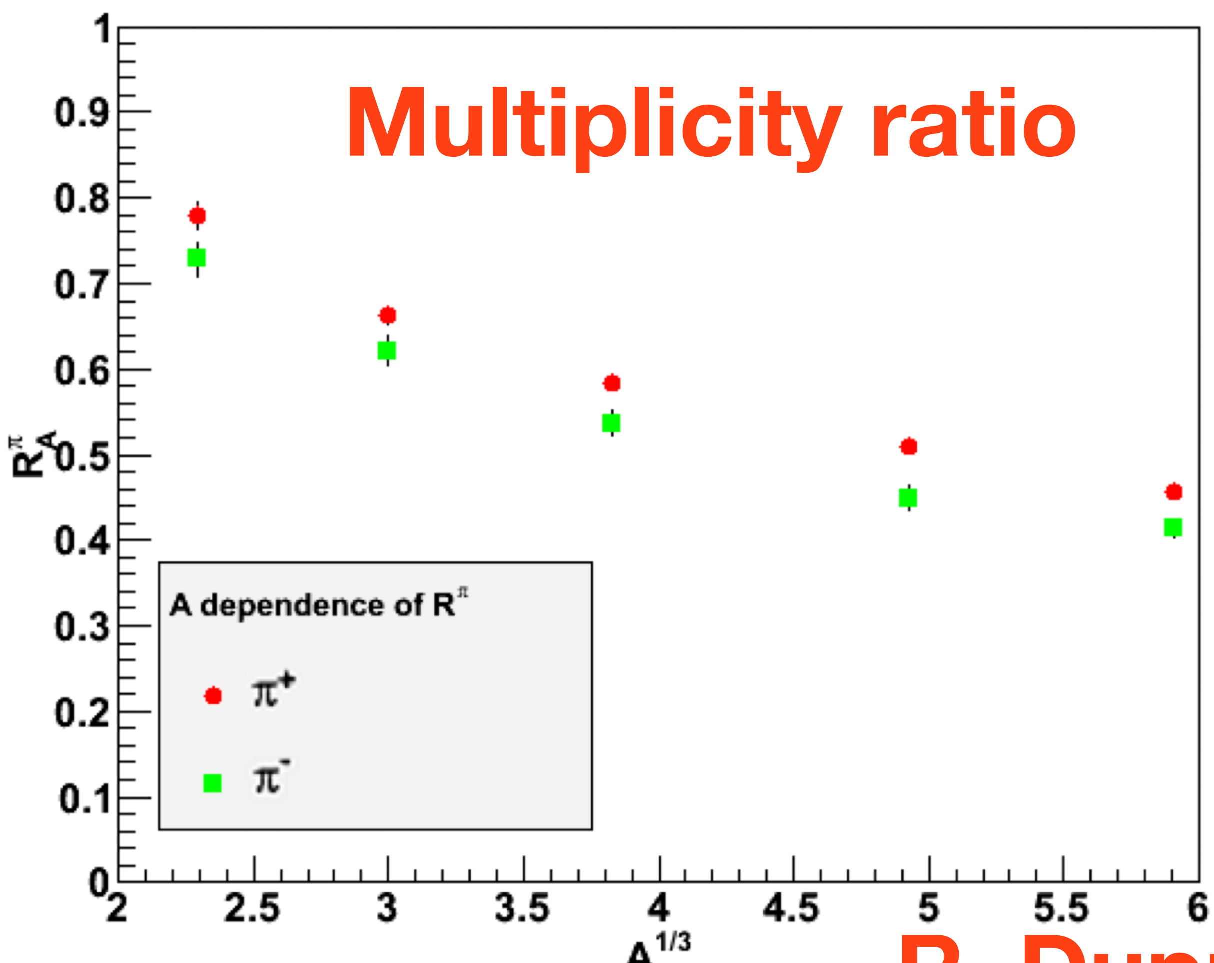
- We have discussed the situation within RGE and we do not want to run a large fraction of our 60 PAC days without the dual target.

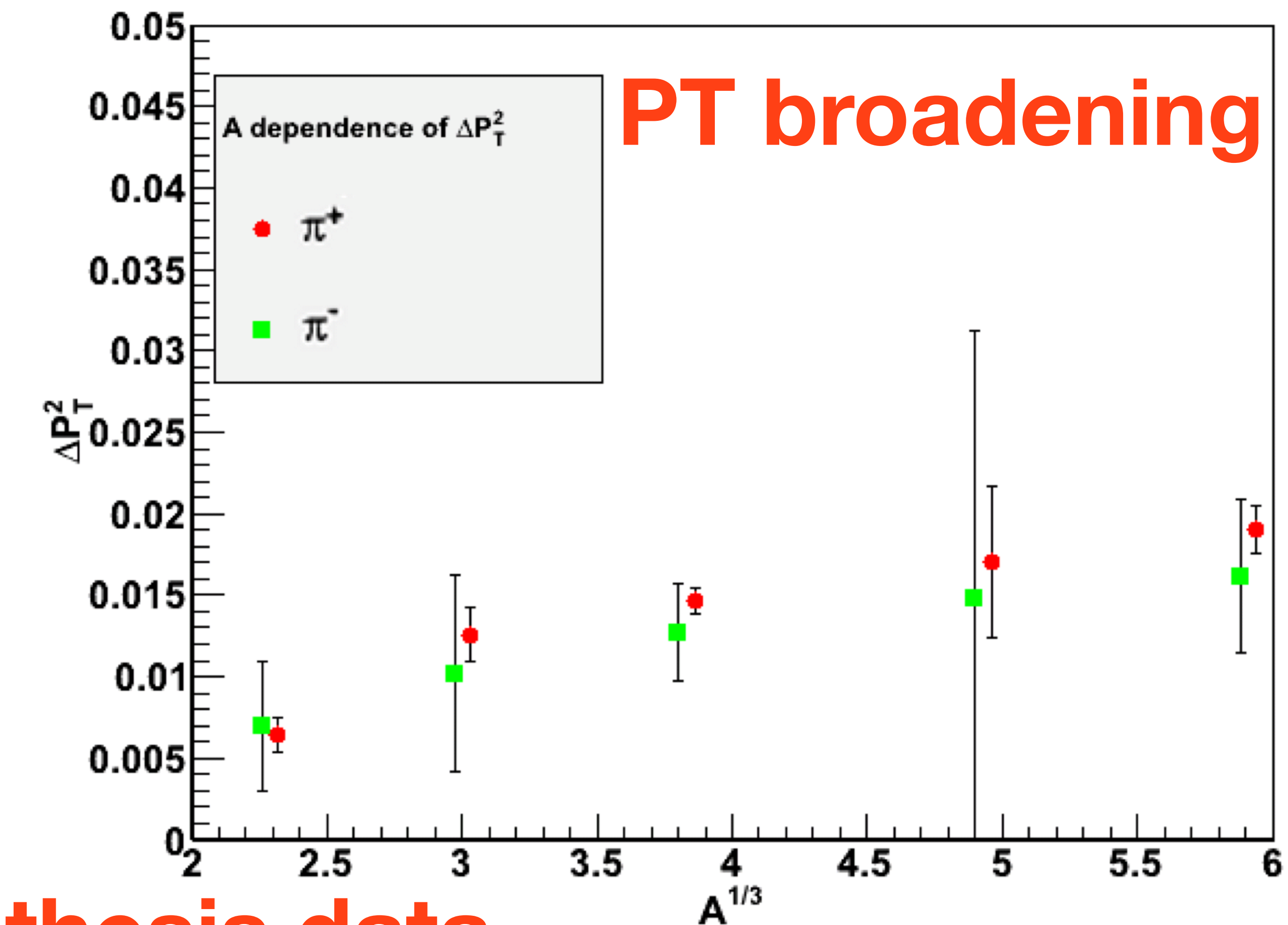
- However, a possible compromise is to run the aluminum target days (7 PAC days) with RGD. Having larger systematic uncertainties for 1 target of the six targets will not make a significantly negative impact. Aluminum has the smallest impact on fits of the A dependences and on the pathlengths through the nuclear medium.

- Running more than 1 target in the RG-D mode will clearly damage the quality of the overall measurement enough to compromise the scientific goals of RG-E.

Measuring the A dependence of two observables

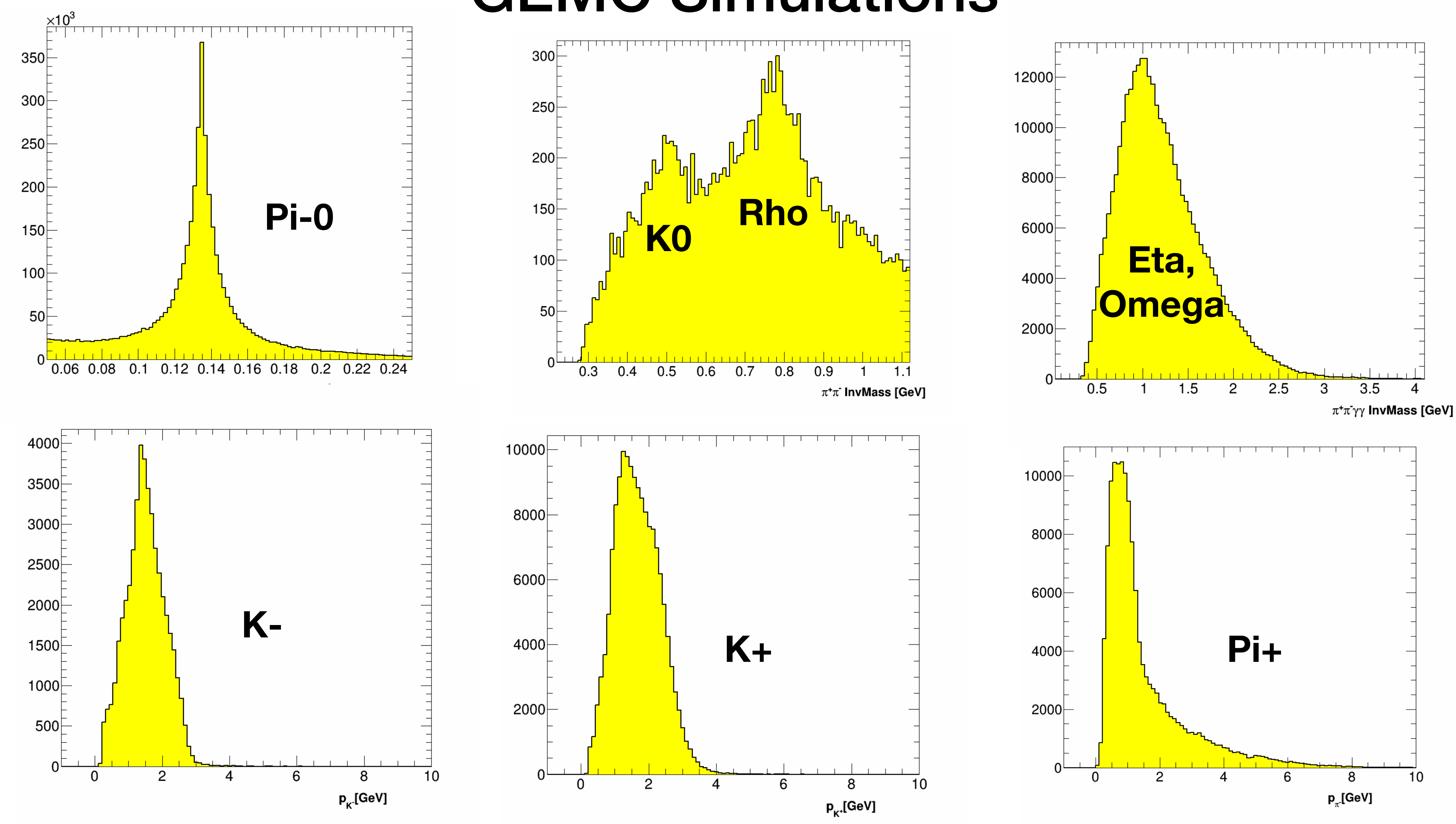
- The A dependence seen at 5 GeV was smooth, although nonlinear. Larger systematic uncertainties on the aluminum target will not have a strongly negative impact on the fits of these dependencies.
- At 12 GeV, the multiplicity ratios will all move toward 1.0 (but less so than for the HERMES data) and the p_T broadening will increase for all nuclei.





R. Dupré thesis data

GEMC Simulations



Ahmed El Alaoui has simulated electrons, protons, charged and neutral pions, charged kaons. Acceptances are consistent with expectations. Resolutions are worse than expected. http://atlasusr.fis.utfsm.cl/alaoui/clas12_sim/index.php

Conclusions

- CLAS12 is on a trajectory toward achieving the technical performance goals of the upgrade
- In carrying out this important experiment, it would be a pity and a waste not to achieve the full performance of which CLAS12 is capable.
- We agree to use the RGD target for the 7 PAC days of our aluminum run, as a compromise.

Backup slides

RG Schedule (strawman)

Run Group	Days	CY2016	CY2018	CY2019	CY2020	CY2021	CY2022	CY2023	Rest
All Run Groups	**1136[#)]**	**30**	**58**	**93**	**42 + 25?**	**110**	**110**	**110**	**583**
HPS	180*	15		35		31		30	70
PRad	15*	15							0
RG-A	139*		46	13				50	30*
RG-B (deuteron)	90*			22 23					45*
RG-F (BoNuS)	42*				42				0
RG-C (NH_3,ND_3)	185					40	50		95
RG-E (Hadr.)	60							30	30
RG-H (Transv Targ)	110*								110
RG-D (CT)	60						30		30
RG-G (LiD)	55								55
RG-K (N^*_G/Conf.)	100		11			39			50
RG-L (ALERT)	55						30		25
RG-M (e4v, src)	45				25 ?				20

Accelerator down

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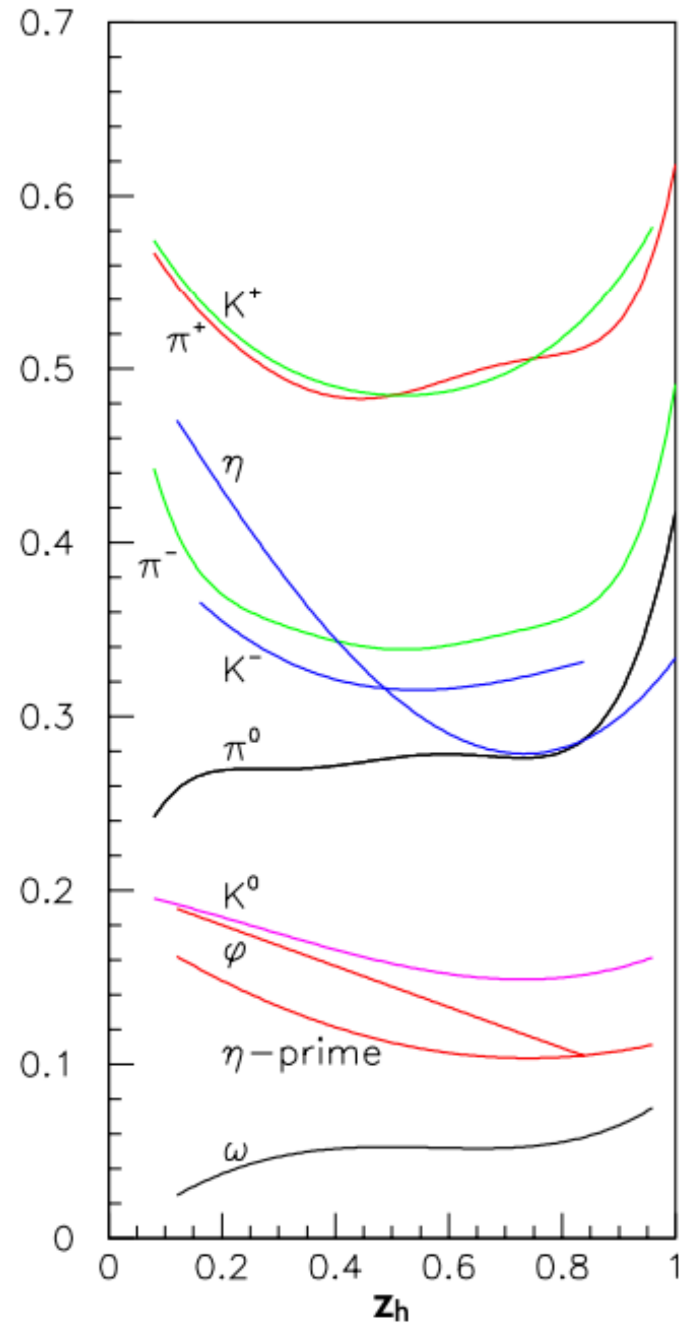
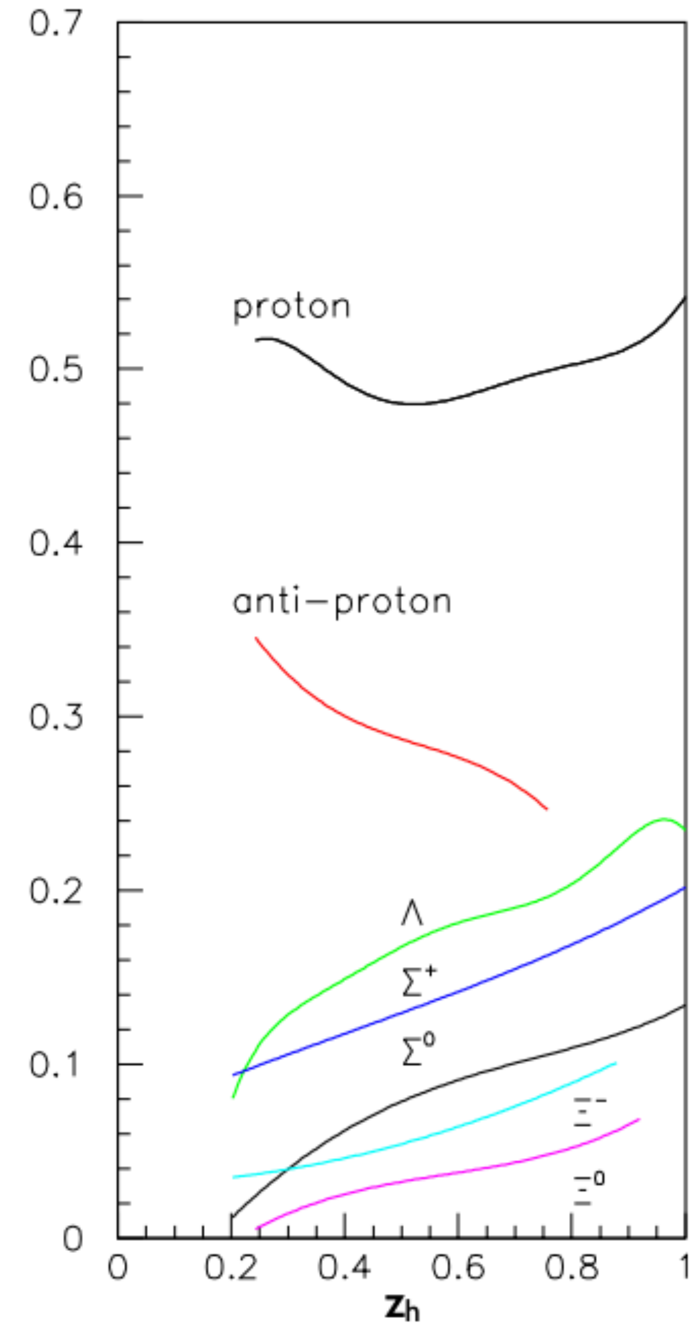


CLAS12 Acceptance for Mesons



CLAS12 Acceptance for Baryons

Quark Propagation and Hadron Formation

- This will be a *definitive* study: CLAS12 has the luminosity, acceptance, and particle ID to do the ultimate measurement in this energy range, where characteristic times ≈ nuclear dimensions

- A *complete* program of measurements that provides a path to understand hadronization on a microscopic, quantitative basis:
  - <u>*fundamental to QCD:*</u>
    - *hadronization mechanisms*
    - *flavor, mass, baryon number dependence*
  - <u>*strong connections*</u> to the rest of nuclear and high energy physics:
    - confinement and hadron structure
    - neutrino physics
    - Drell-Yan measurements in p-A collisions
    - heavy ion physics

- An *important* experiment with a wide range of *impacts*

Simulation (by Ahmed El Alaoui)

Three targets were simulated: lH2, EG2USM, EG2p{foil1,foil2,foil3}

Modified version of pythia 6.4.28 is used to generate physics event

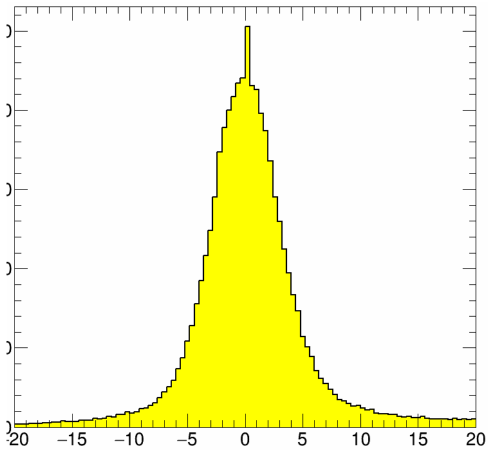
- Include Fermi motion.
- Correct some issues related to the use of relatively “low” beam energy
- Use of nuclear pdf.

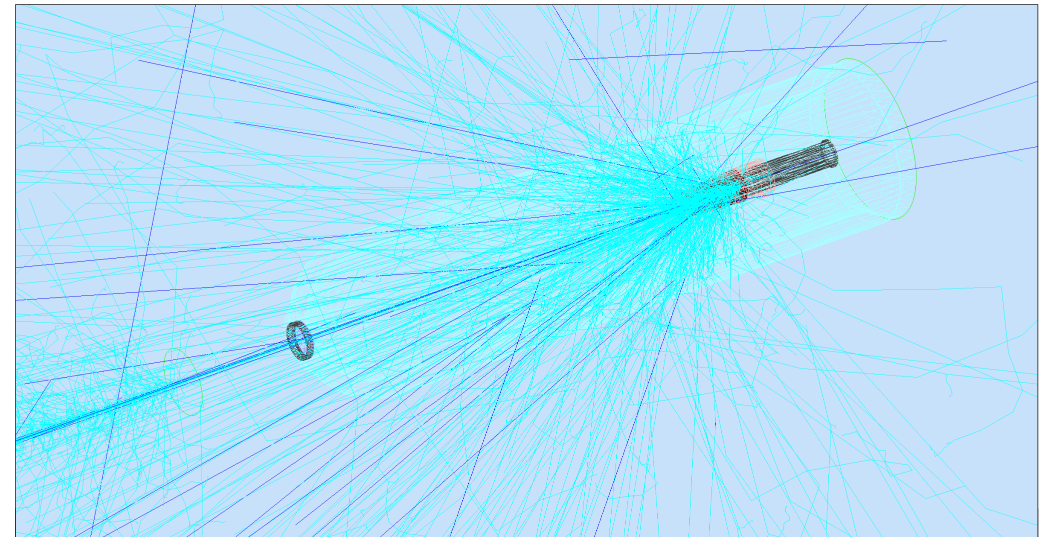
GEMC: version 2.7

Decoder, Reconstruction: CLARA/COATJAVA version 5.9.0

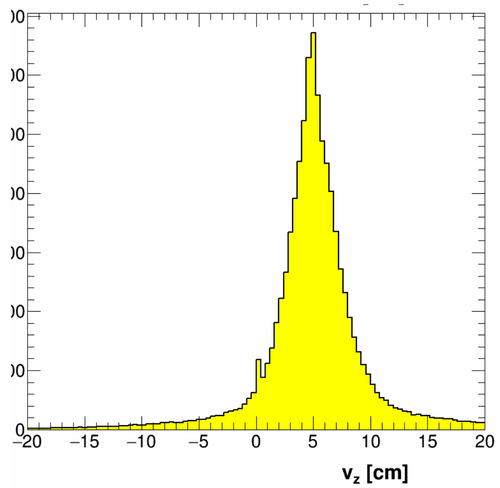
For cross check, three independent codes (C++, java, groovy) were used to analyse the data. All of them produced the same result.

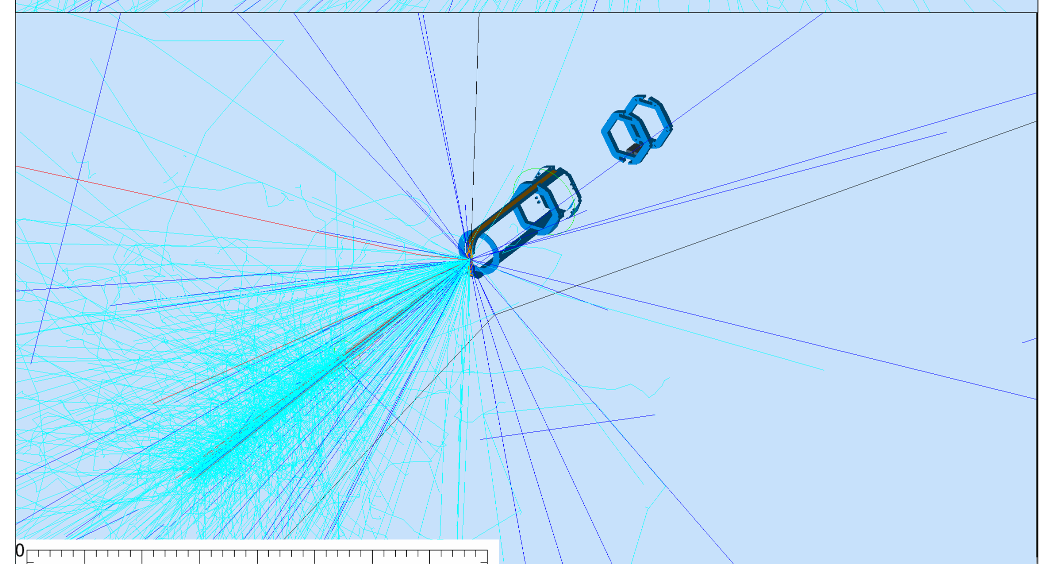
lH2

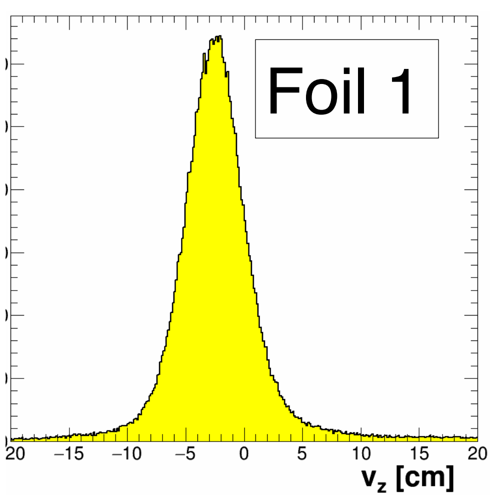


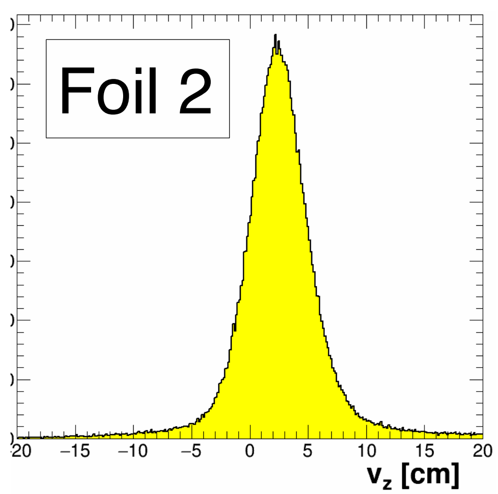


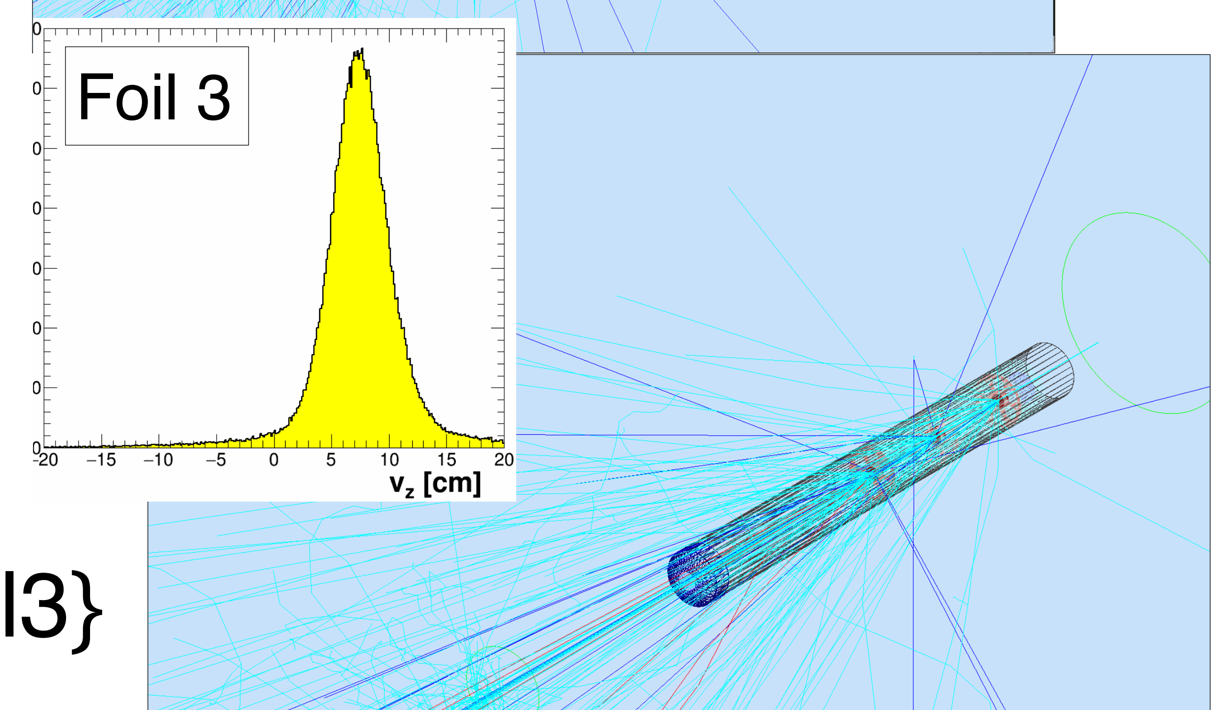
EG2USM



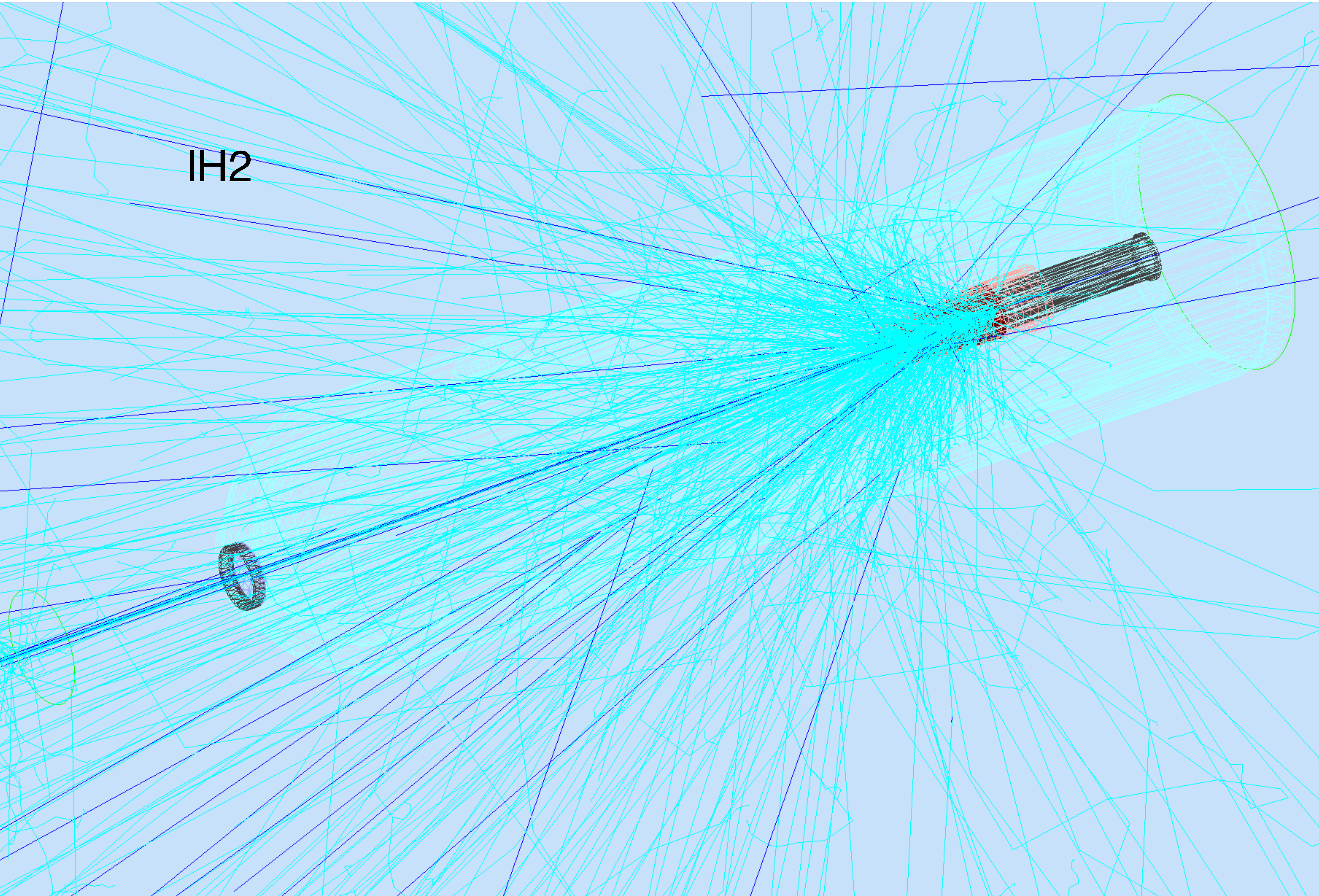


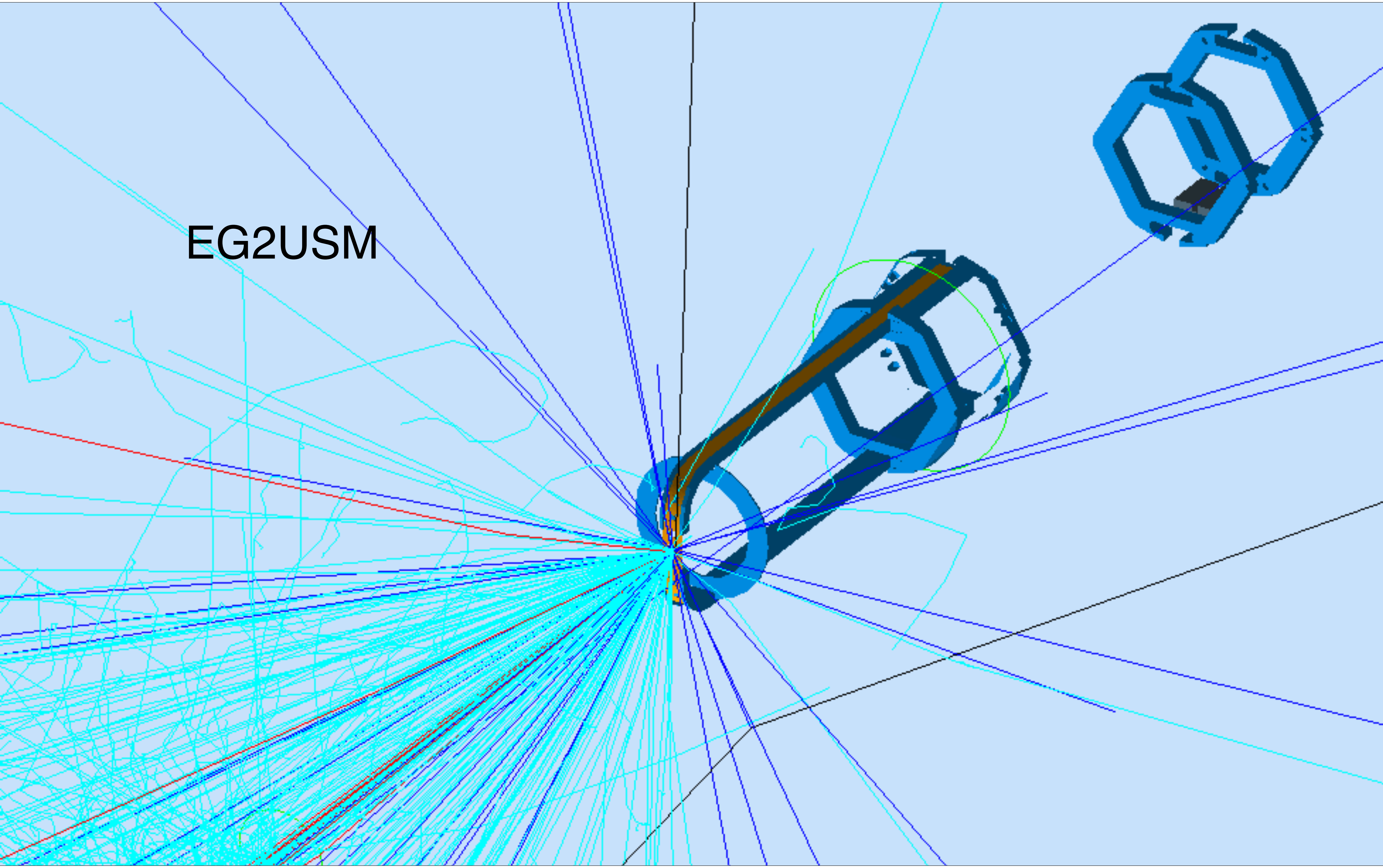


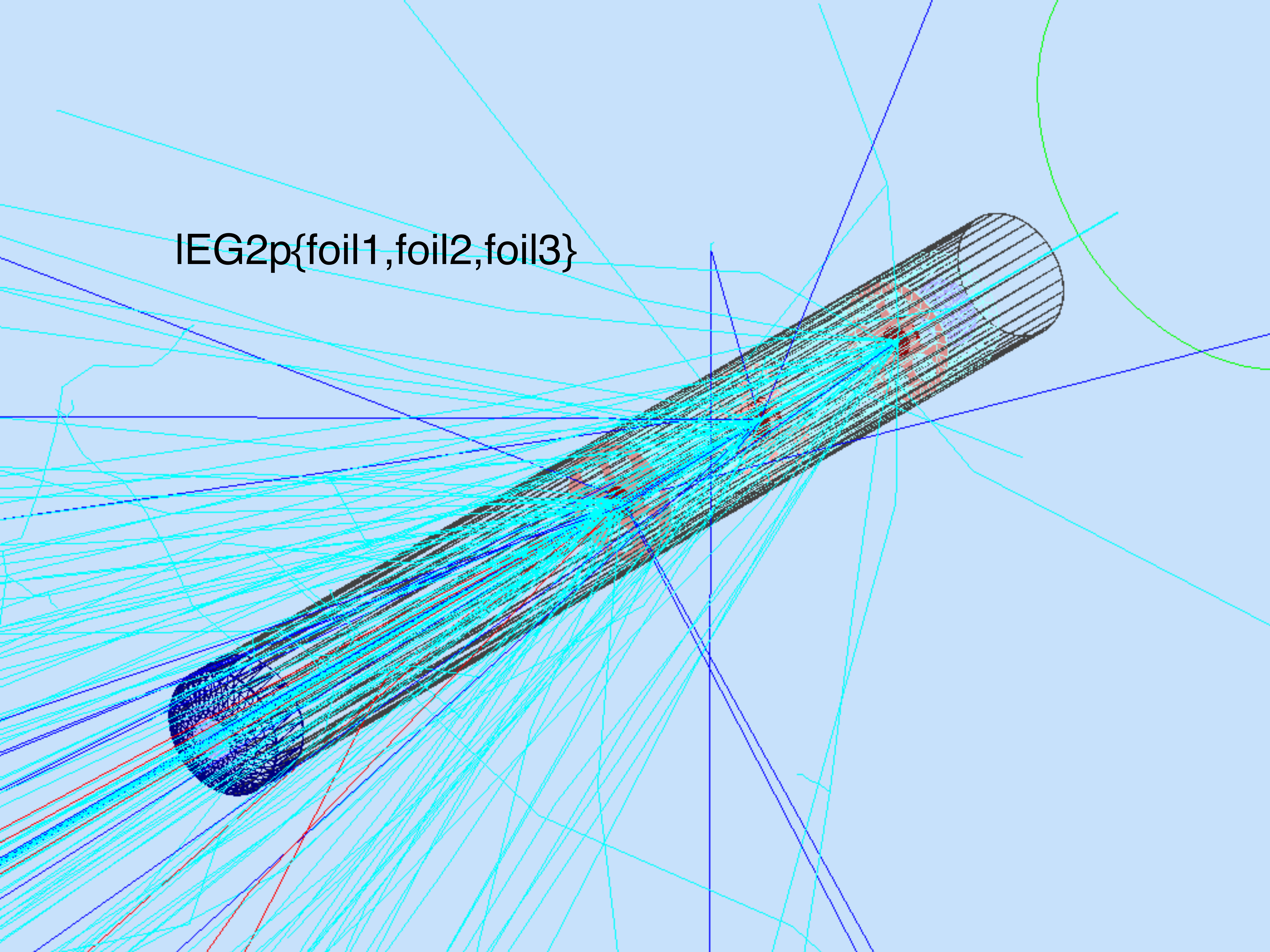




lEG2p{foil1,foil2,foil3}


lH2


EG2USM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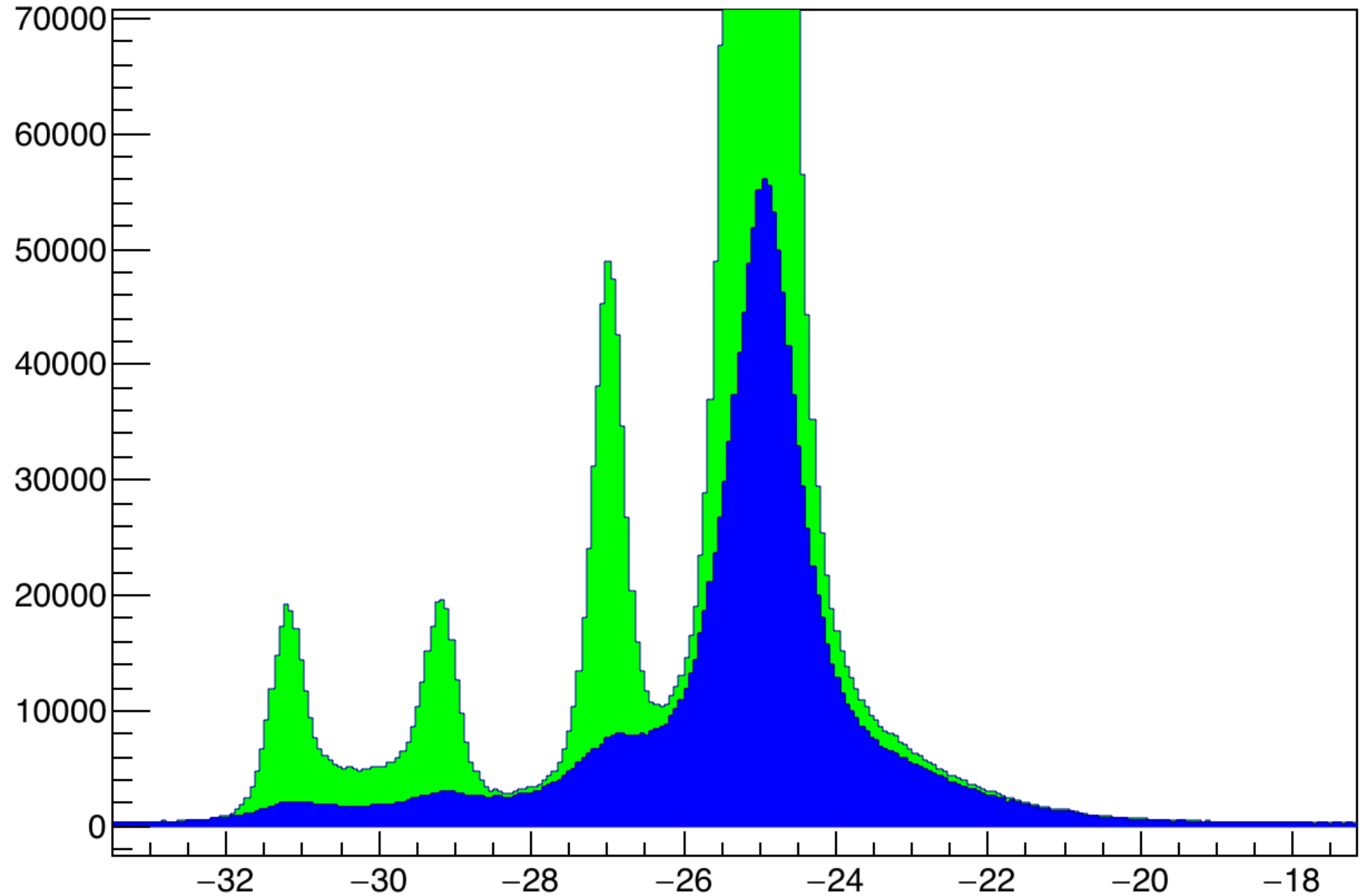
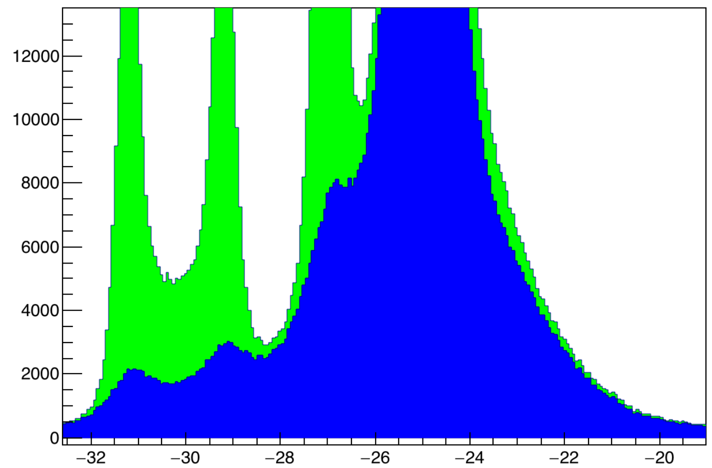
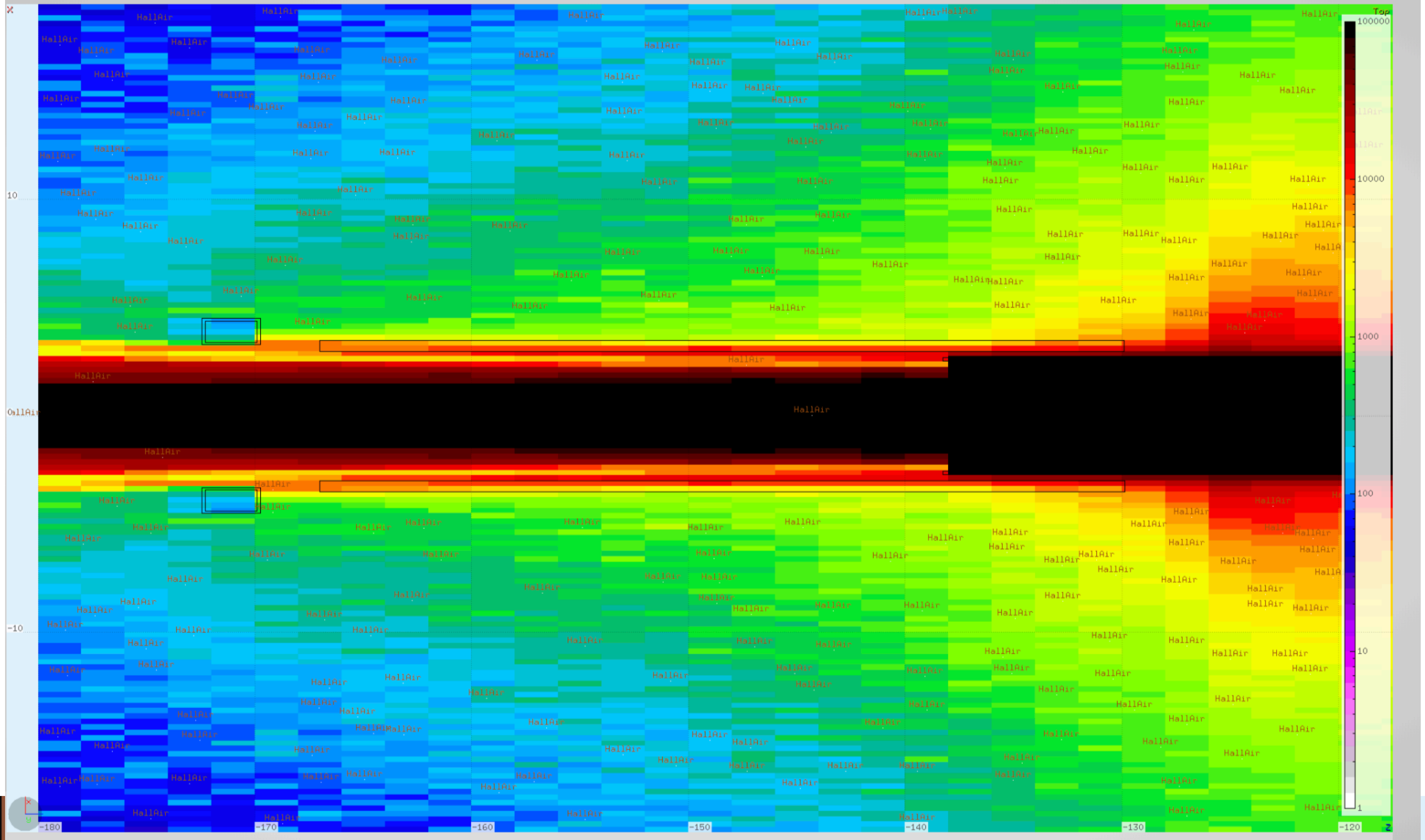


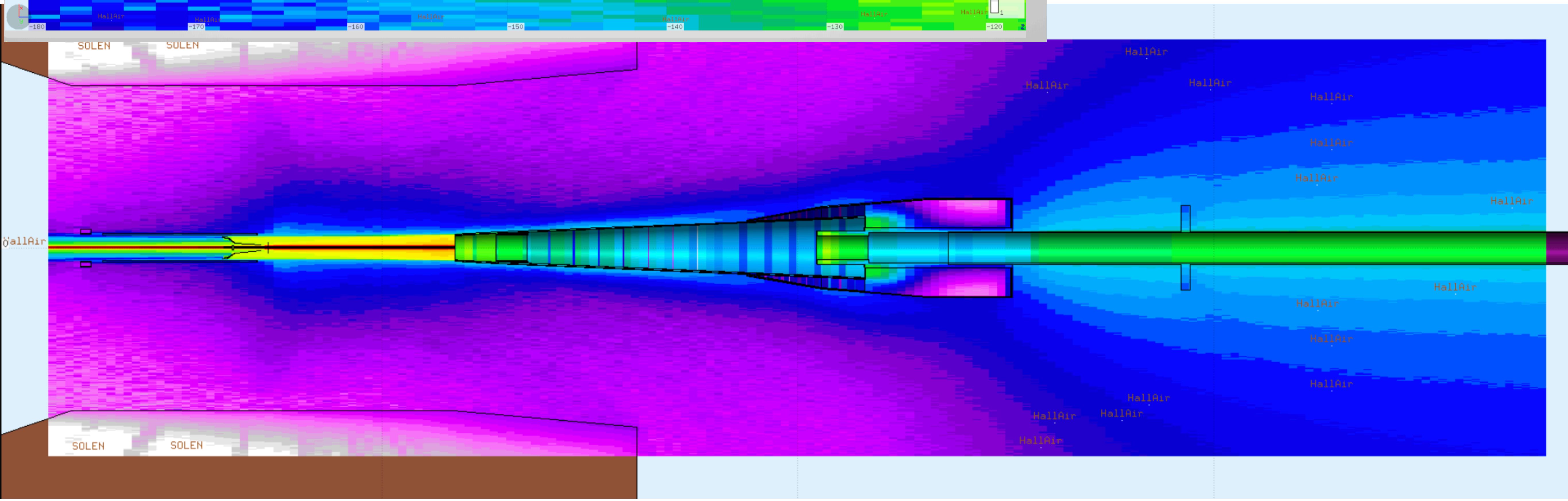
Events less than or greater than vyec = 1.4 cm.
The resolution shape for vyec can be seen by right side of the large peak.
Background is nearly zero at vzec = -28 cm for vyec < 1.4 cm.
Many of the events within the cryotarget region come from the reference foil.
Cuts on vzec in general will not remove all aluminum signals.



Events less than or greater than vyec = 0.1 cm.
The background under the endcaps is visible from the slope on which the two equal-height peaks are positioned

Accumulated Dose(rad) for full experiment (Motor)





Simulation by Lorenzo Zana of JLab RCG

Thermal study of USM targets

MUM, June/04/2019

Assuming the following parameters for each target:

Z	Material	Areal density (g/cm2)	Physical length from Prof. Will Brooks (mm)	Melting point (K)	Density (g/cm3)	Radiation Length (cm)	Conductivity (W/mK)	Emissi (-)
1	Deuterium	0.85	**50**	-	0.17	769.1	-	-
6	Carbon	0.85	**3.9**	4098	2.21	19.32	25	0.8
13	Aluminum	0.59	**2.2**	933.5	2.7	8.9	204	0.03
29	Copper	0.32	**0.36**	1358	8.96	1.44	385	0.02
50	Tin	0.22	**0.3**	505.1	7.31	1.21	65	0.0
82	Lead	0.16	**0.14**	600.6	11.35	0.56	35	0.05
			BACKUP					
47	Silver	0.32	**0.3 (?)**	1235.2	10.5	0.8543	427	0.0
79	Gold	0.27	**0.14 (?)**	1337.2	19.3	0.3344	315	0.0

Also for the heat source we have the following information:

- Beam diameter: 100 [microns]
- Power for each target: 60 [mW]

Considering a steady state heat equation with radiation boundary conditions we have Fourier's Law:

$$\boxed{-k\nabla T = Q} \qquad (1)$$

With $T(x,y,z)$ the temperature map, $Q(x,y,z)$ the heat flow and k the thermal conductivity. We using Finite Elements Method to solve the above equation (1) using a commercial Software.

$$\boxed{[K(T)]\{T\} = \{Q(T)\}} \qquad (2)$$

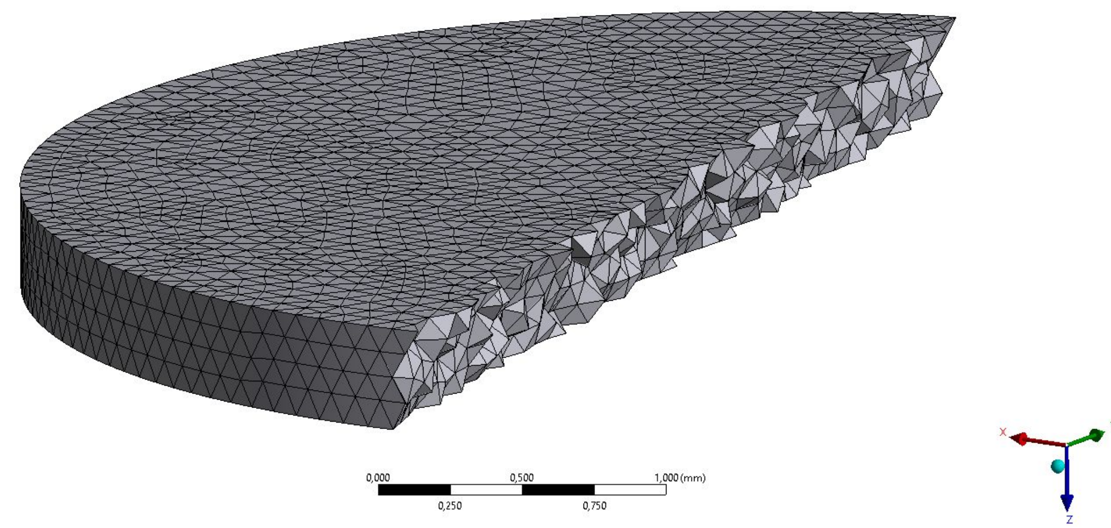


Fig 1: Copper target section plane discretization.

1. Temperature study without conductive ribbon

First we solved the problem for each target without a conductive ribbon to dissipate the heat. The boundary condition for all the faces is of radiation kind to a 0°C ambient temperature. We can see that the highest temperatures are where the beam is concentrated.

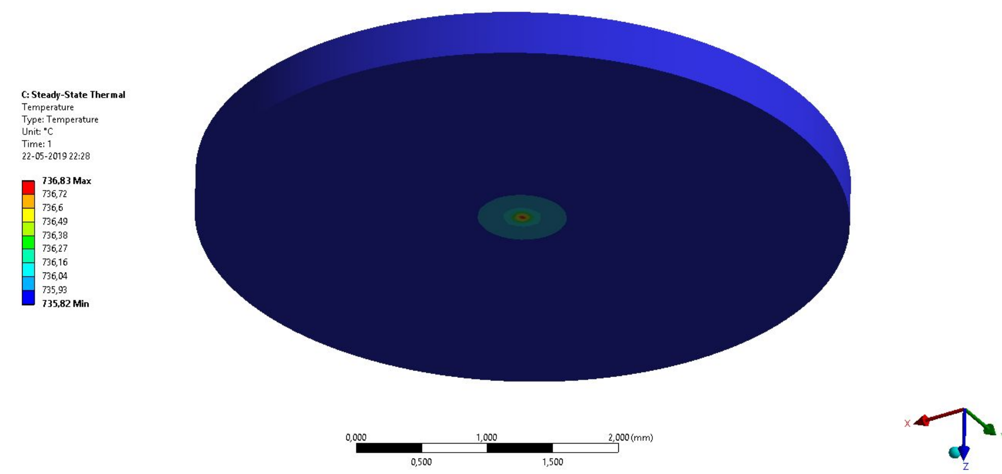


Fig 2: Copper target simulation.

We can study how the temperature of each target is related with the emissivity and the conductivity of the targets.

(a) (b)

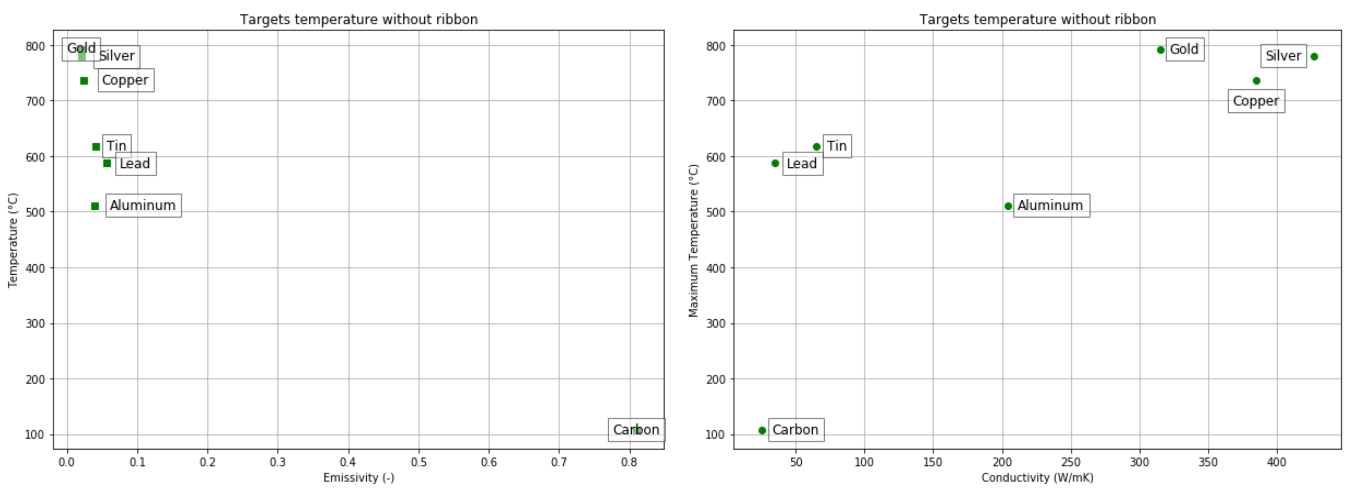


Fig 3: Targets temperature plots. (a) Target maximum temperature vs target emissivity. (b) Target maximum temperature vs target conductivity.

2. Temperature study with conductive ribbon

In this section we study the heat dissipation from the target glued to a conductive ribbon assuming the same boundary conditions than before but now including the thermal characteristics for the conductive ribbon:

- Conductivity: 385 [W/mK]
- Emissivity: 0.8 [-]

The heat it’s irradiated to a 0°C ambient temperature from the upper face of the conductive ribbon and the upper face of each target.

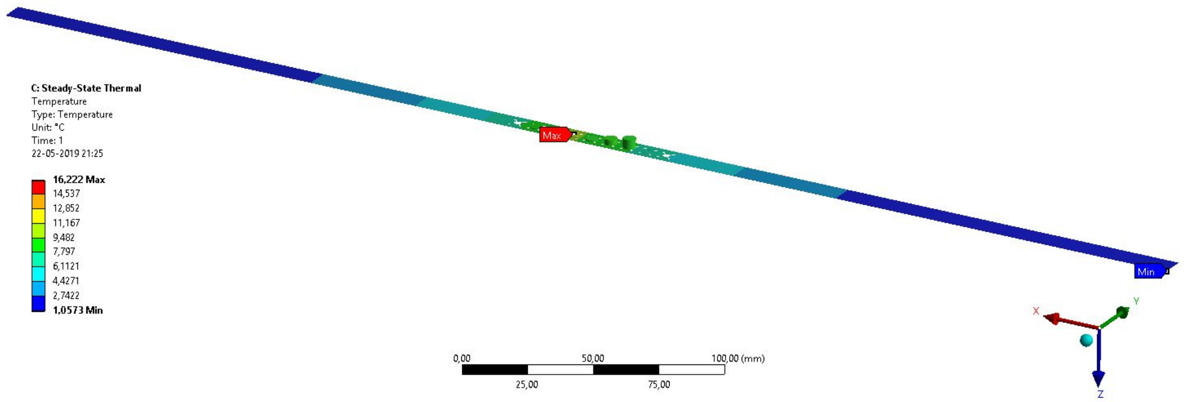


Fig 4: Ribbon with carbon, aluminum, copper, tin, lead, silver and gold targets. The beam is in the tin target.

We consider 4 different conductive ribbon thickness: 75, 100, 125 and 150 [microns].

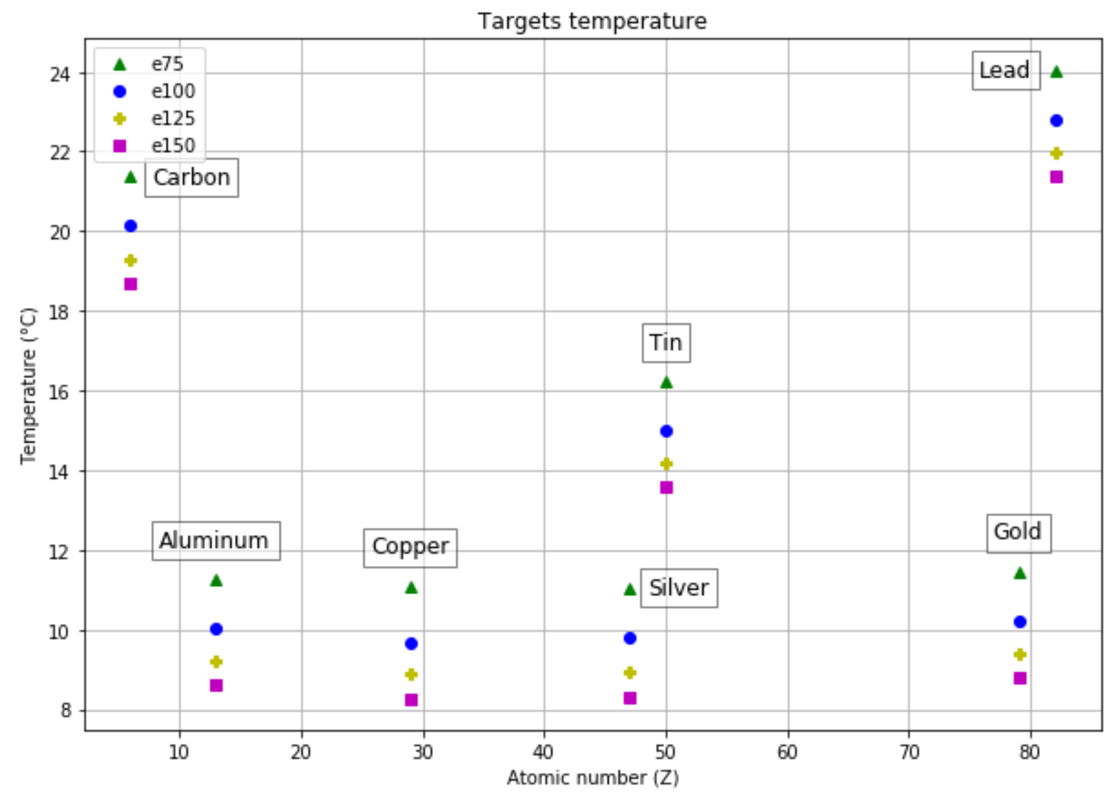


Fig 5: Targets maximum temperature plot for the 4 different conductive ribbon thickness.

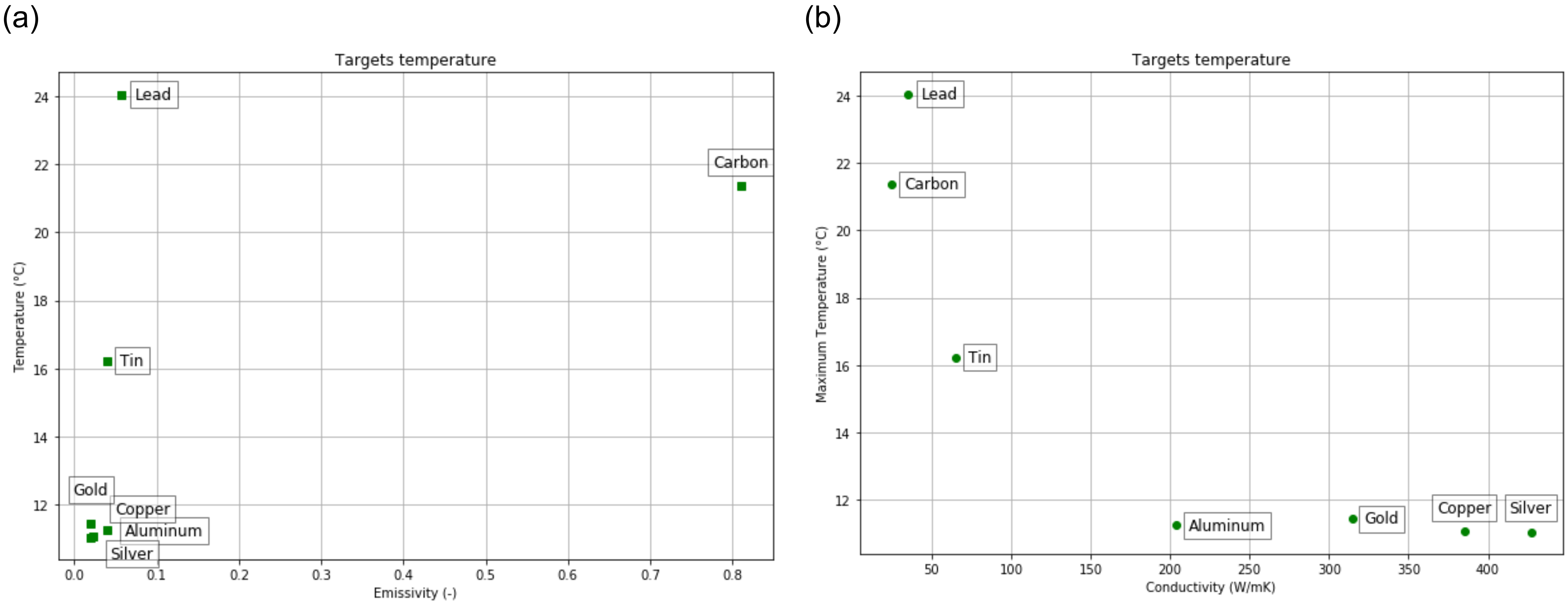


Fig 6: Targets temperature plots assuming a 75 microns ribbon. (a) Target maximum temperature vs target emissivity. (b) Target maximum temperature vs target conductivity.

Assuming that the results are accurate, we can achieve a temperature reduction of more than 95% for all the targets, except carbon, which has a temperature reduction approximately 80% in comparison with the simulations with the target only (without conductive ribbon). **This results must be compared with experimental tests.**