Photonuclear Reactions and the mystery of UHECRs

NEWS Colloquium talk 2026/05/28

Dr Jacob Bekker

with special thanks to the PANDORA Collaboration

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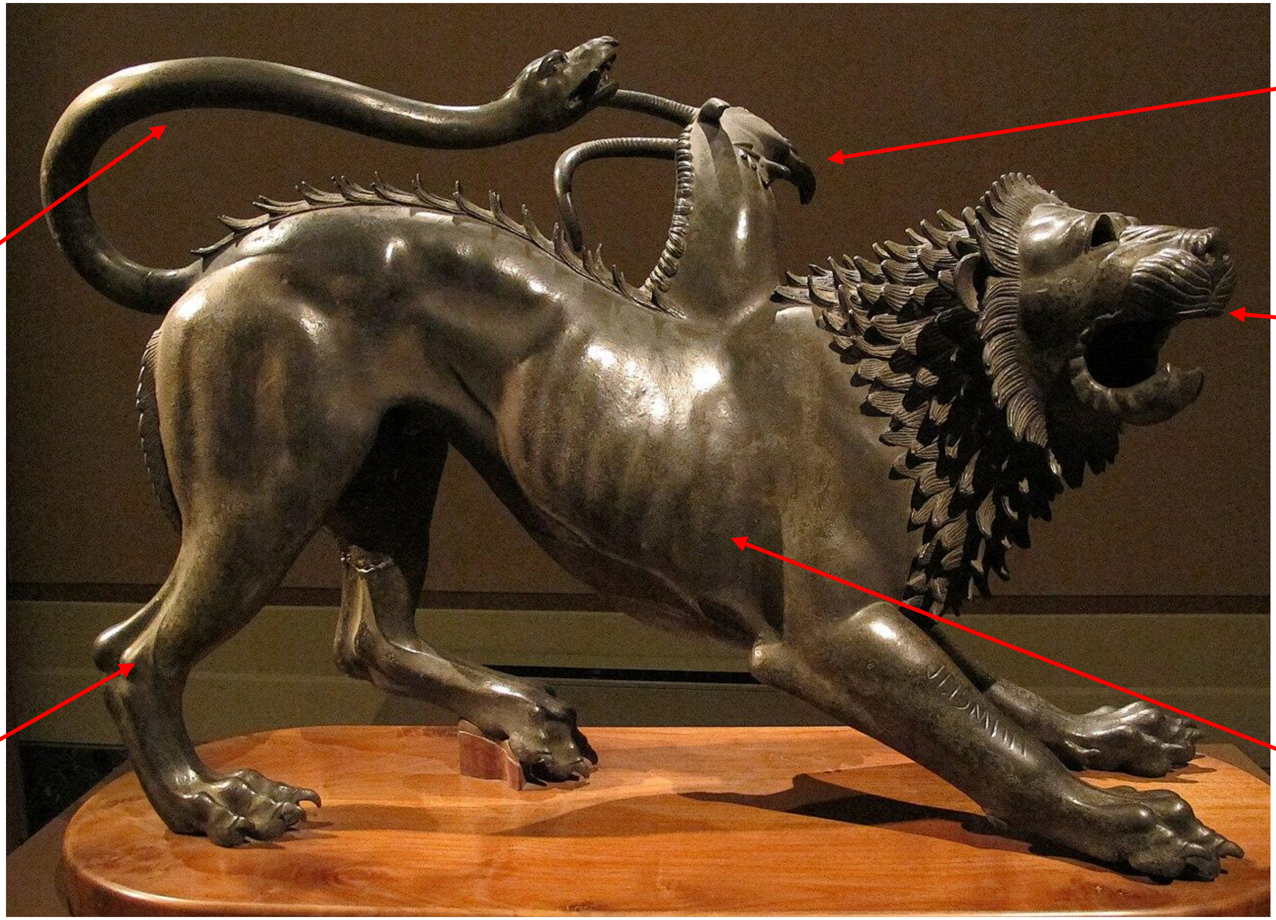
Who am I?

- (Quite recently Dr) Jacob Bekker
- Current Postdoc at the University of the Witwatersrand in South Africa
- Completed my PhD in experimental nuclear astrophysics using the PANDORA data taken at RCNP in October 2023.

The Problem of UHECR (Ultra-high energy cosmic rays) is many sided and almost mythical in proportion…

Particle Physics

Astronomy



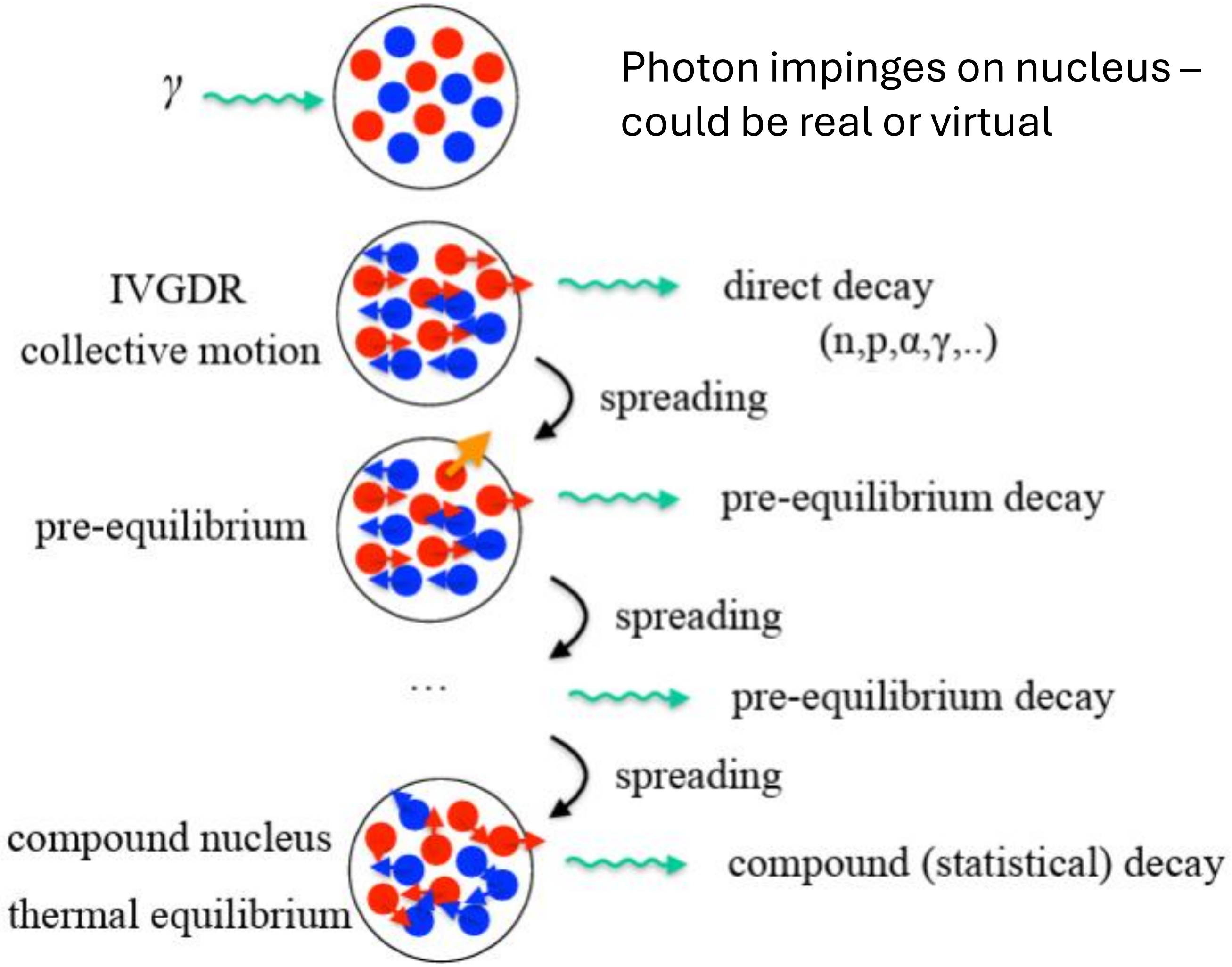
Theoretical Physics

Nuclear Physics

Astrophysics

*Hence, the talk **requires** a bit of preamble*

Photoabsorption in a nutshell

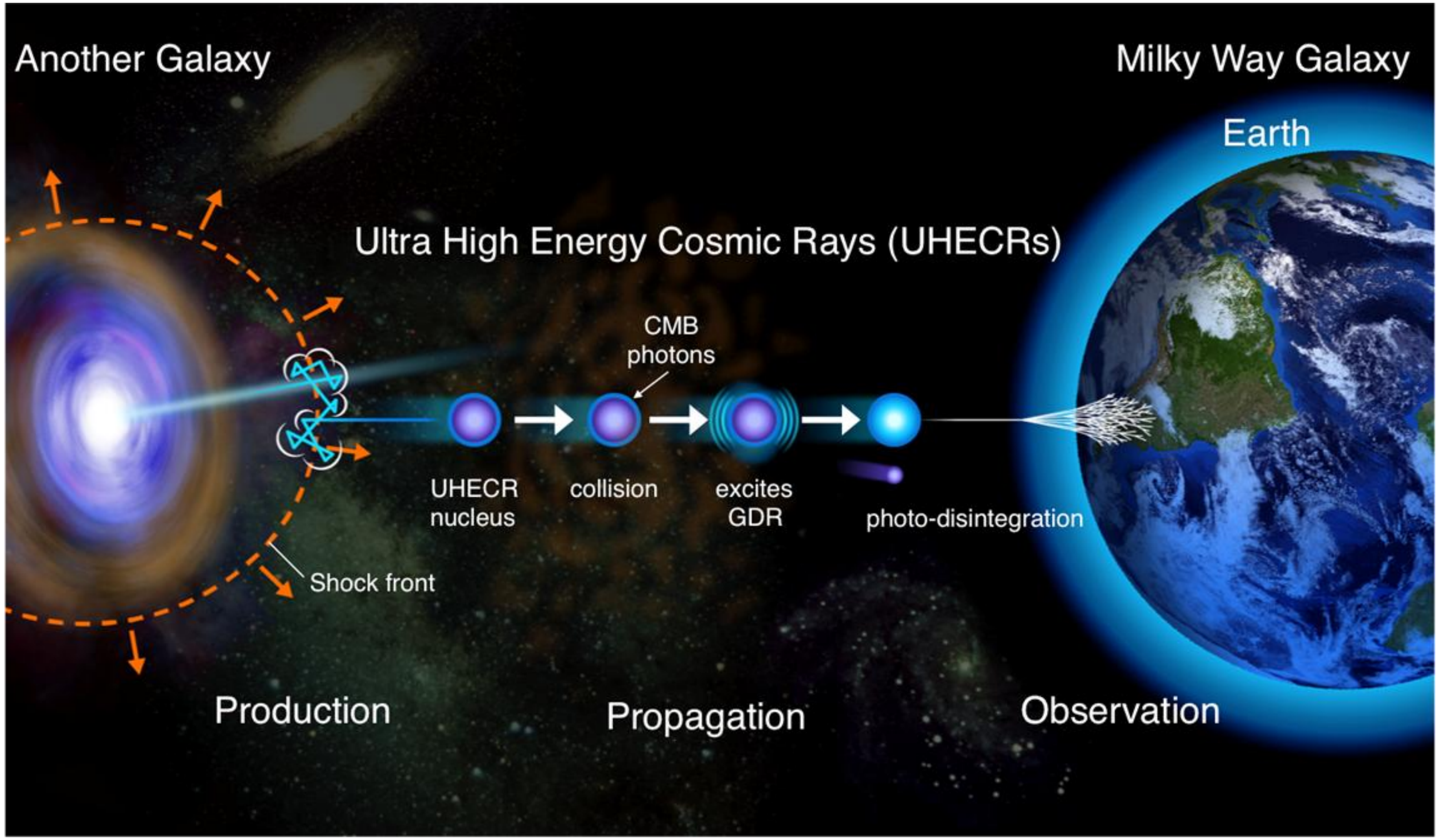


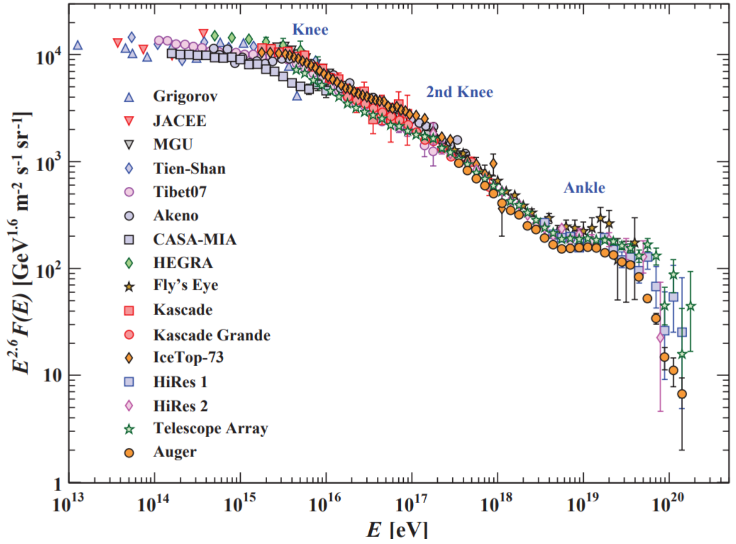
Photon impinges on nucleus – could be real or virtual

Typically occurs within the scale of 5-50 MeV

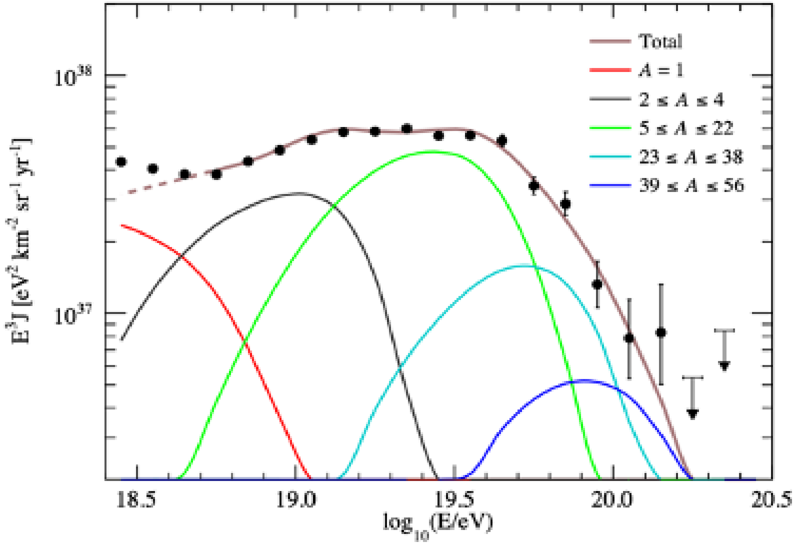
Looks simple but is it really?

Photoreactions of UHECRs





A.Aab et al. (The Pierre Auger Collaboration), Phys. Rev. Lett. 125, 121106 (2020)



We also care about other stuff such as the effect of clustering in light nuclei, dipole polarizability, fragmentation of the IVGDR etc!

Tanabashi et al. Review of particle physics. Phys. Rev. D, 98:030001, Aug 2018.

Enter the PANDORA Project

(**P**hoto-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics)

Multinational collaboration

L. Pellegri — A. Tamii — P-A. Söderström

Astrophysics

Theory

- Propagation Calculations
- Cosmic magnetic field
- Acceleration mechanisms

Experiment

- Measurements of UHECRs
- AUGER array
- TA (Telescope Array)
- Composition Analysis

(Amaterasu @ 244 EeV)

Nuclear/Particle physics

Theory

- Reaction theory
- Structure Theory
- Systematics
- Extensions to unstable Nuclei

Experiment

- Virtual Photon Method, RCNP, Japan and iThemba LABS, South Africa
- Real Photon measurements, ELI-NP, Hiγs

The target nuclides of the 2nd PANDORA beamtime at RCNP:

- ^{12}C, ^{16}O, and ^{27}Al -> Reference cases
- ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B -> Very light nuclei IVGDR
- (^{20}Ne), ^{24}Mg, ^{28}Si, ^{32}S, (^{36}Ar), ^{40}Ca -> α-cluster effect, deformation
- ^{26}Mg, ^{48}Ca, ^{56}Fe -> N>Z nuclei
- ^{13}C, ^{14}N, ^{51}V -> odd and odd-odd nuclei

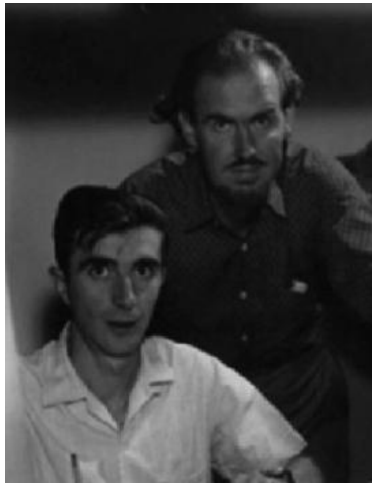
Happened in October 2025

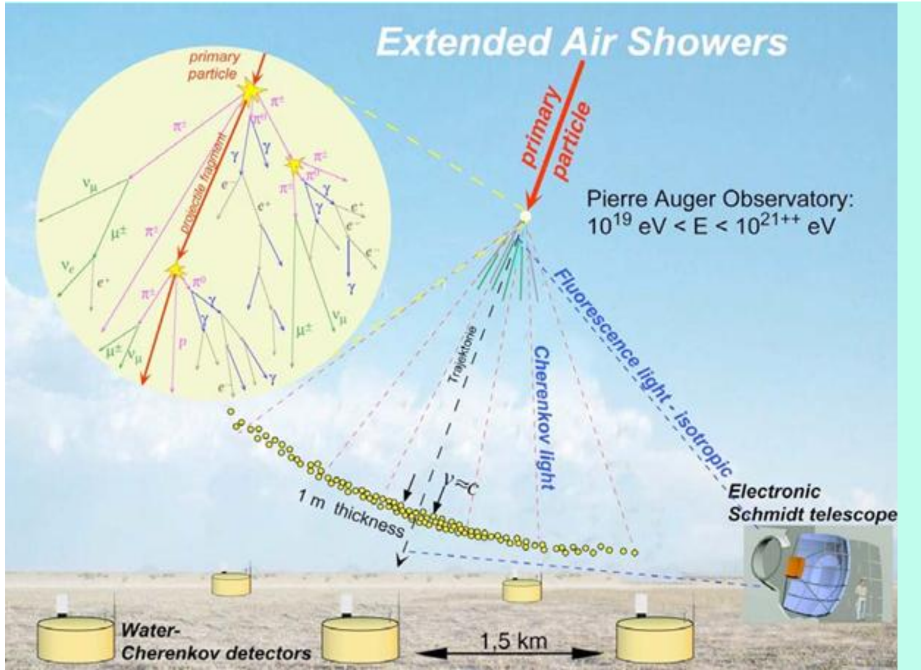
UHECR Propagation: Terrestrial Measurements

- First UHECR was measured at Volcano Ranch in the New Mexico by J. Linslay and L. Scarvi.
- This was due to a lot of work done by **Auger** on Extensive Air Showers caused by high energy particles hitting the atmosphere edge.
- Since then there were many experiments made to measure this phenomena, Auger, TA, Fly-Eye etc
- Focus on two detection methods to observe air showers :

➞ sample the particle content at ground level: Ground arrays

➞ observe the shower development throughout the atmosphere: Fluorescence telescopes





AUGER array: Water Cerenkov

*Three ingredient soup:

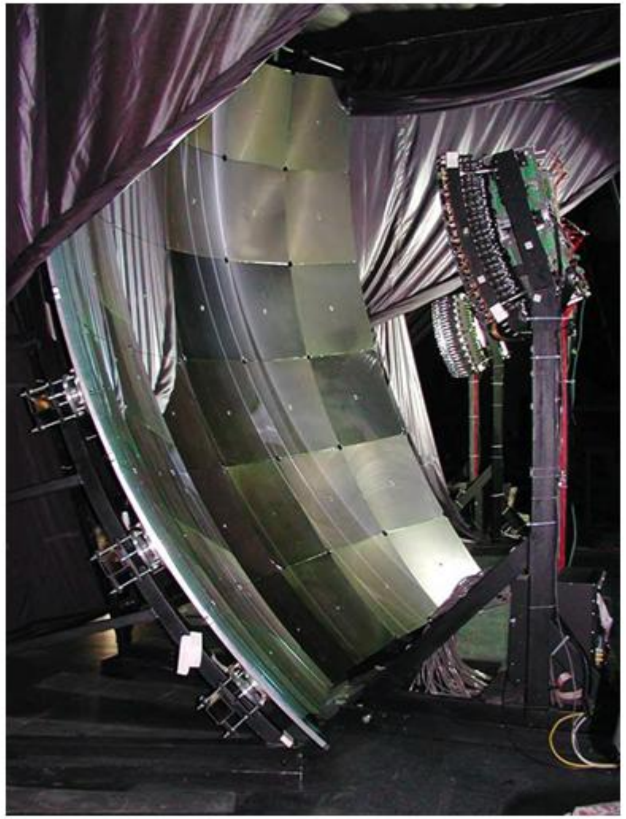
Water (must be pure)

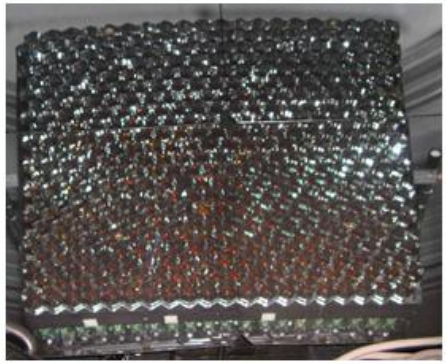
PMT (where the magic happens)

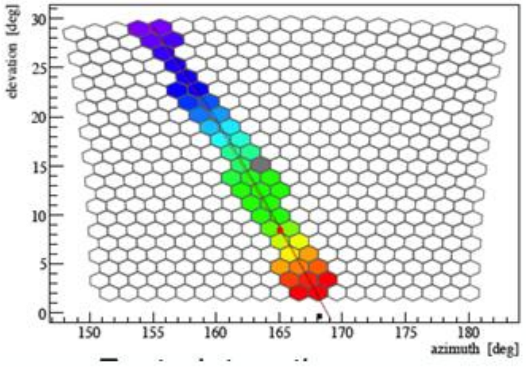
Lots of space: 3000 km^2 in Argentina

There is a lot more to making the measurement sensible like the coincidence circuits etc but the premise is quite simple.

AUGER array: florescence telescope



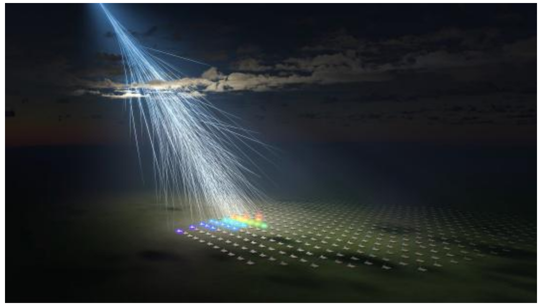




- **Fluorescence Detection of Air Showers**
- UV light from shower development is captured by photomultiplier tubes (PMTs)
- Timing information from different channels constrains the shower geometry
- Shower energy is estimated by integrating the longitudinal light profile
- The depth of shower maximum (X_{max}) provides statistical discrimination of primary particle composition
- Works on dark nights only – “*when the moon hits fly eye that is not amore*”

D. Allard and B. Brunet are the experts so I can easily deflect any questions you may have to them :D

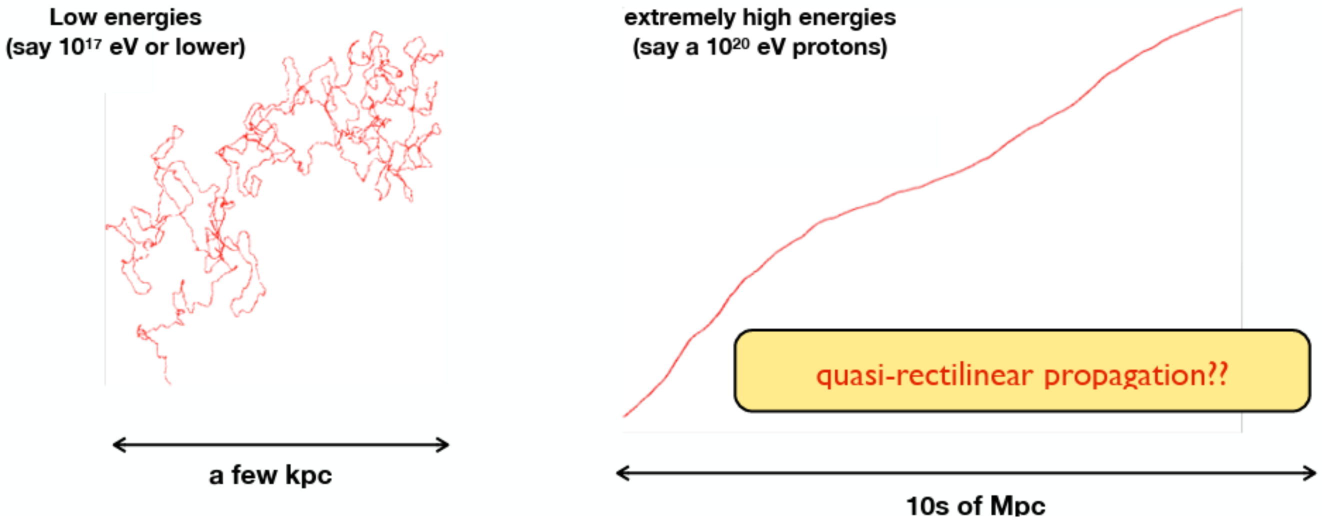
In a nutshell: UHECR measurements



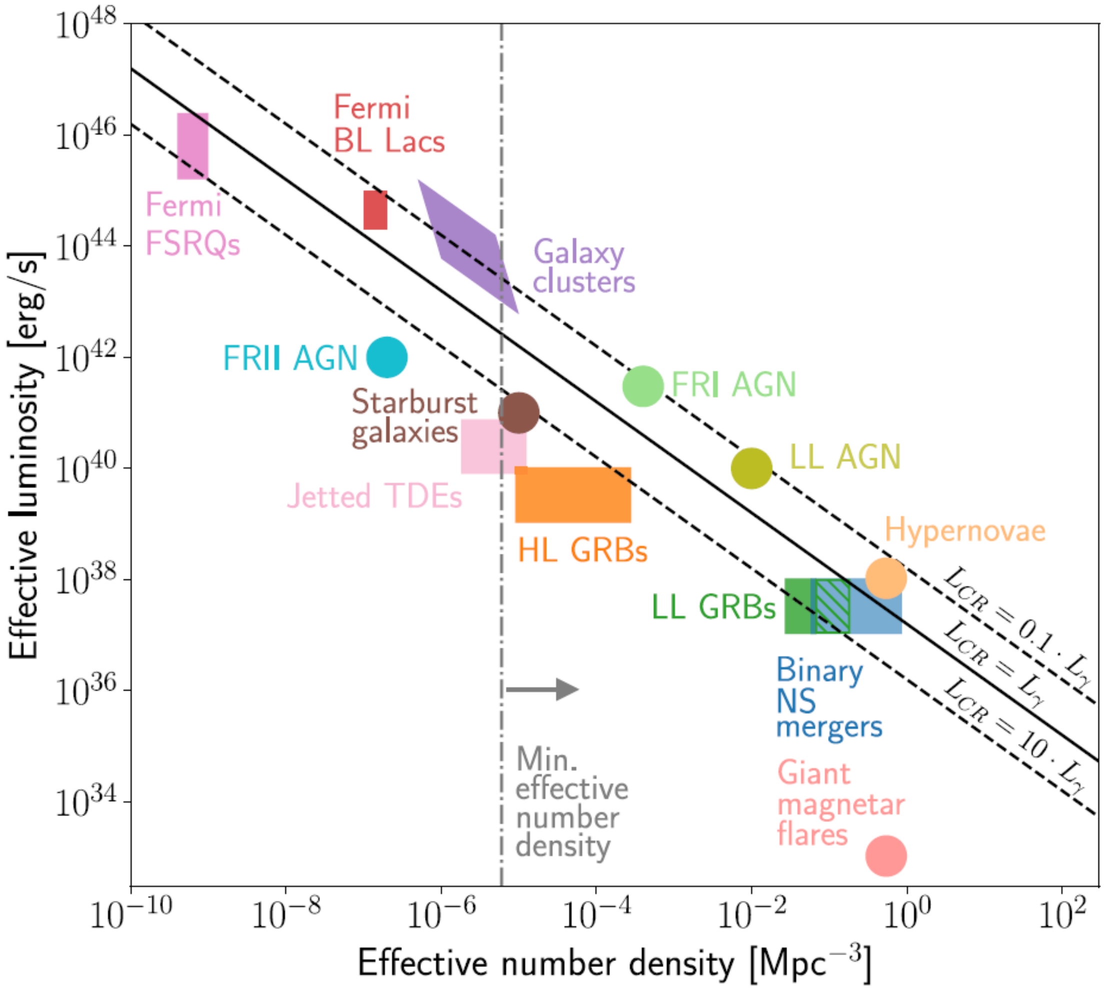
- Wait for a dark night in Argentina and wish upon a cosmic ray.
- Then measure the atmospheric depth where the maximum number of particles are present, X_{max}.
- Infer from the X_{max} the charge of the particle that caused it -> heavier elements are “shallower” than protons.
- Hope that the reconstructed energy is above $1x10^{19}$ eV, and Voilà, you have measured a UHECR…

But where does it come from?

Another conundrum: Universal magnetic field



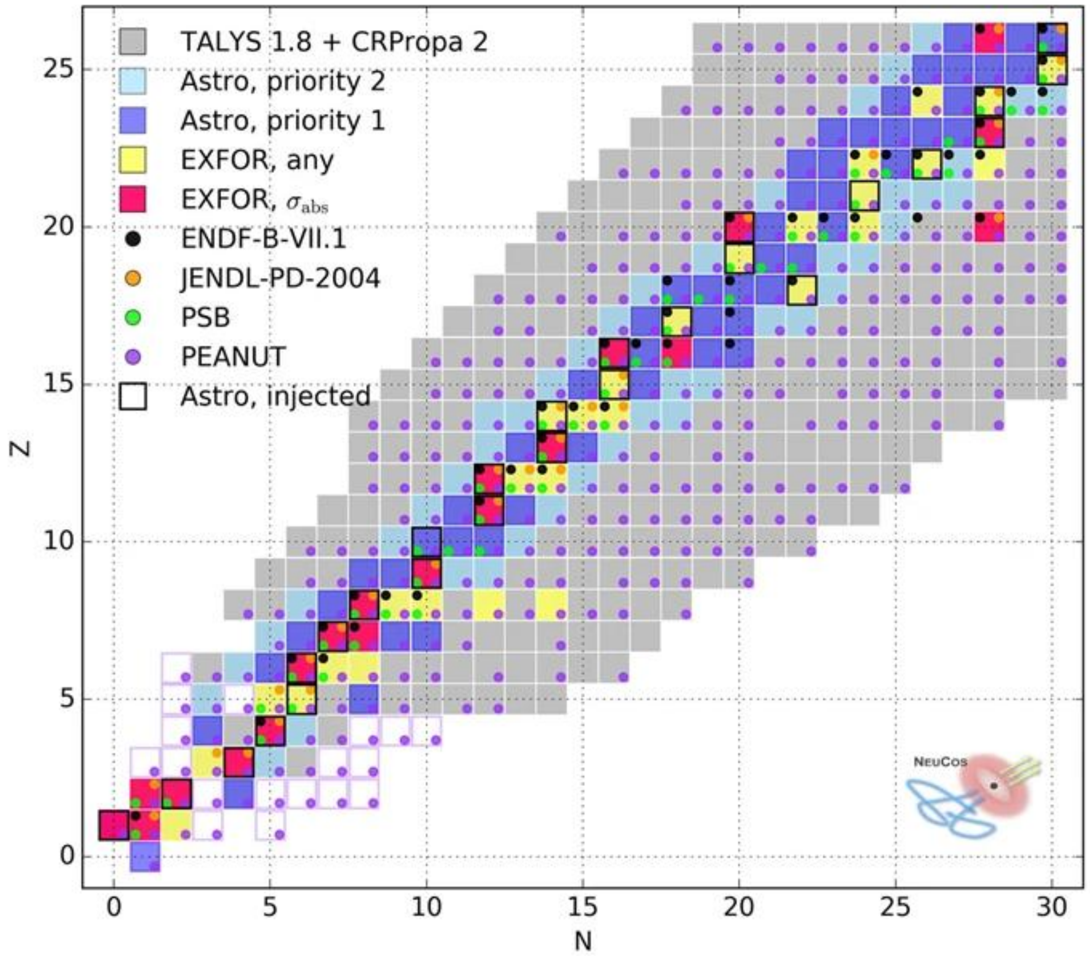
Possible sites?



Hard to find a "Goldilocks" type origination site. Has to have a high enough flux but not too high, be near enough but not too close, energetic enough to accelerate particles to UHECR levels but not too violent to destroy them in the process.

**Most importantly though…*

We need lots of Data!



- From ^{56}Fe down to a helium nucleus we need data.
- 1000+ datasets where photoabsorption and charged particle decay is required in some manner.
- Currently it is hard to find 10 such datasets that are consistent and complete.
- Measure what we can and theorize what we cannot.

The astrophysics and Hadron physics seems complicated, what about the Nuclear Physics?

- Also complicated, but we have a recipe and most of the tools to get a crack on.
- Large part of the initial work done by RCNP, KVI and iThemba LABS.
- It turns out the *best way to measure photoabsorption is by avoiding photons.
- Real photon/gamma beams are tricky to generate and are limited in some sense by the method used to generate the beam.

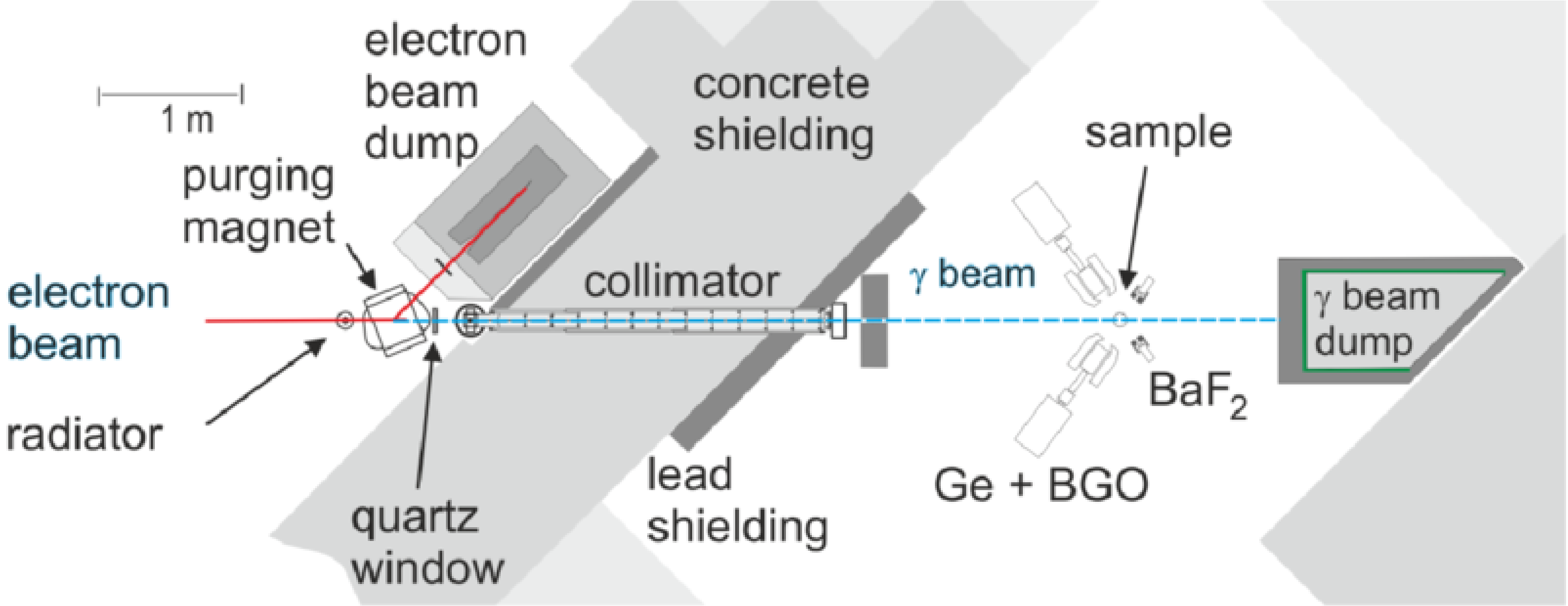
**best is entirely subjective, but there is some merit to the claim.*

Basic Principle of Real Photons

- Make a γ-beam of known energy. (trickier than it sounds)
- Impinge γ-beam on target material. (Need lots of target material)
- Measure the decay particles. (Easy in isolation, hard in coincidence)
- Measure the amount of flux that was absorbed ~ photoabsorption. (Pretty tricky above particle threshold)
- Many issues arise from the fact that there are usually distinct ways of measuring above and below particle thresholds.

Typical γ-beam measurements

- Bremsstrahlung beams usually use electron accelerator.



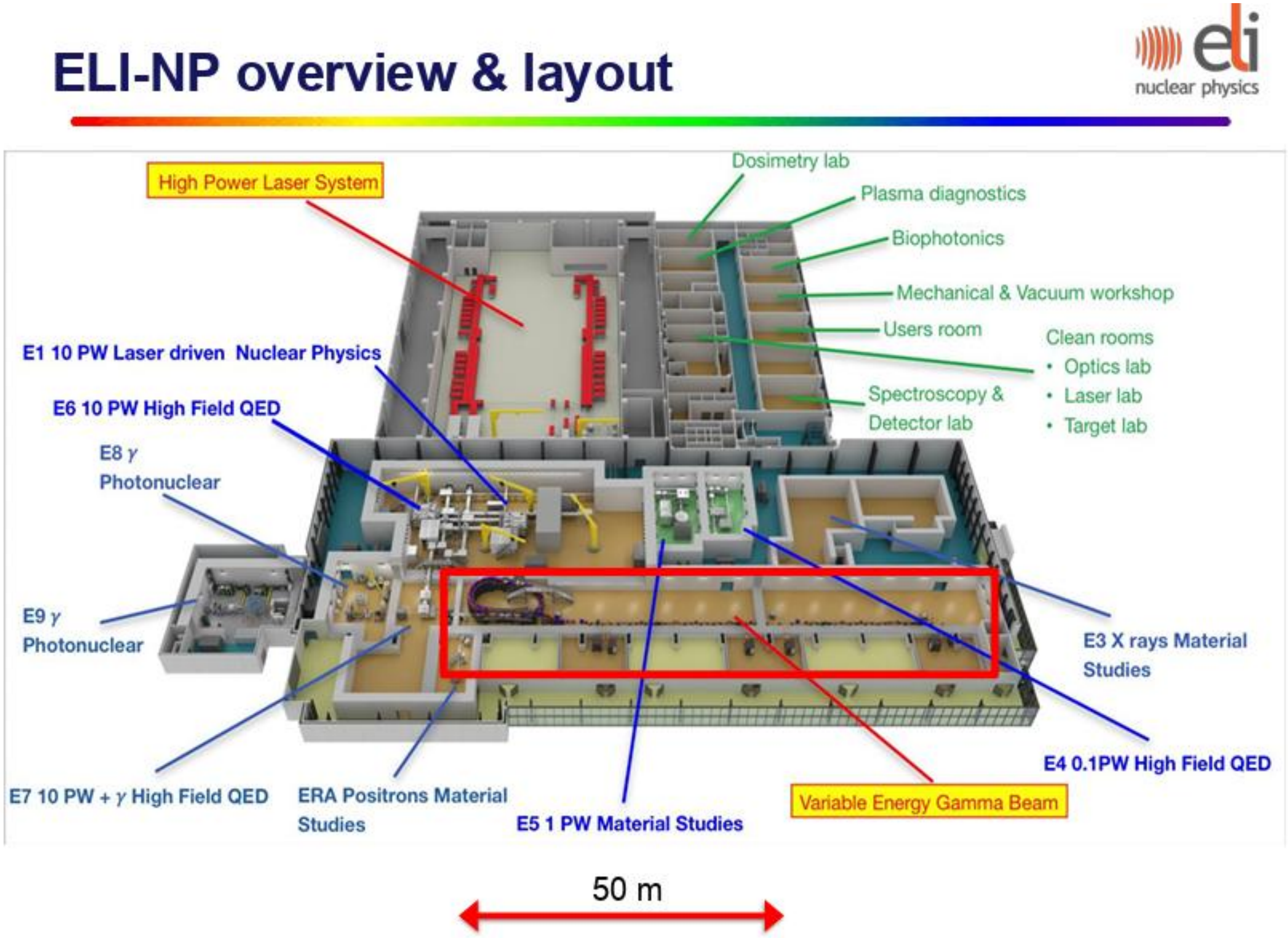
Typical γ-beam measurements

- Benchmark measurements on light nuclei were taken with a magnetic Compton spectrometer pair (Ahrens 1972).
- One of the few ways to directly measure total photoabsorption.
- Only works on “easy” and cheap targets.
- ^{12}C, ^{27}Al, ^{28}Si etc
- Relatively good standard but only for photoabsorption not charged particle decay

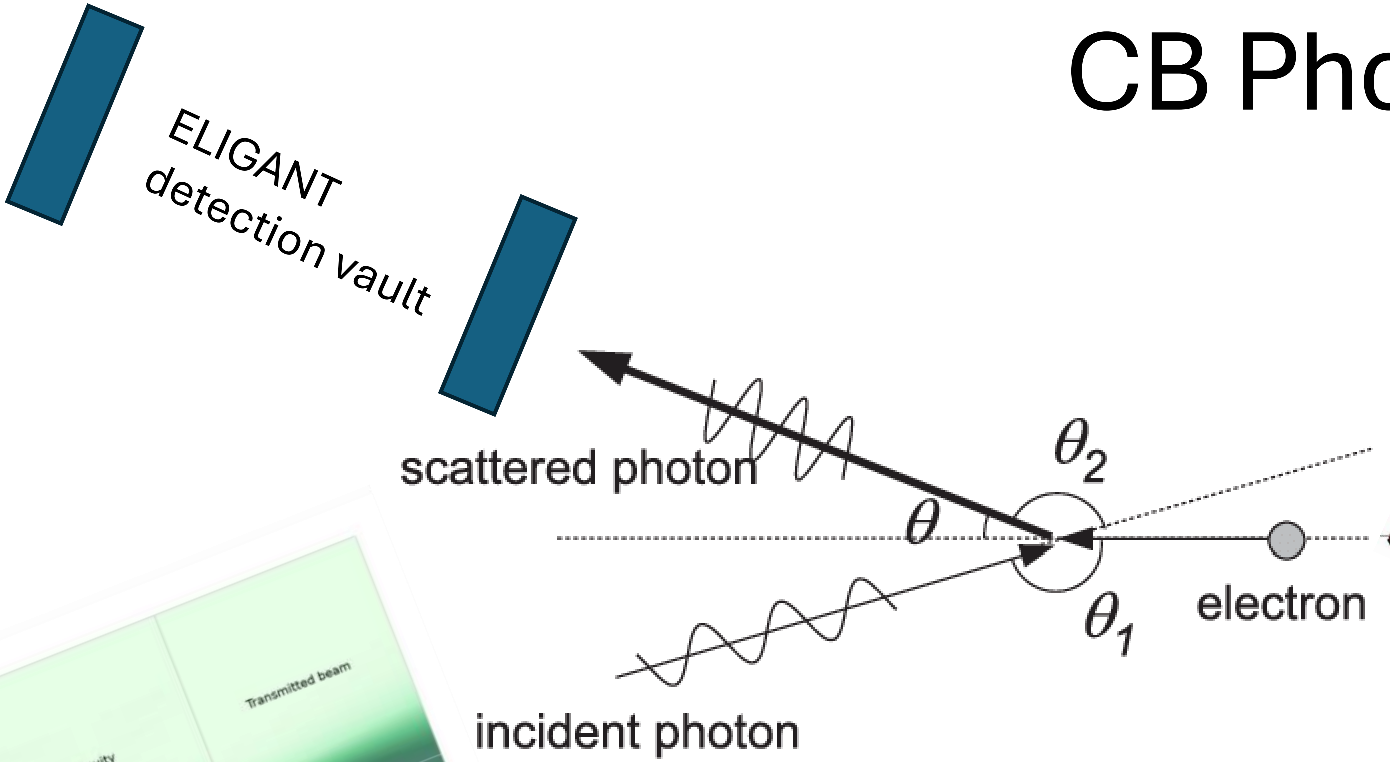
Ahrens, J., et al. Nuclear physics A 251.3 (1975): 479-492.

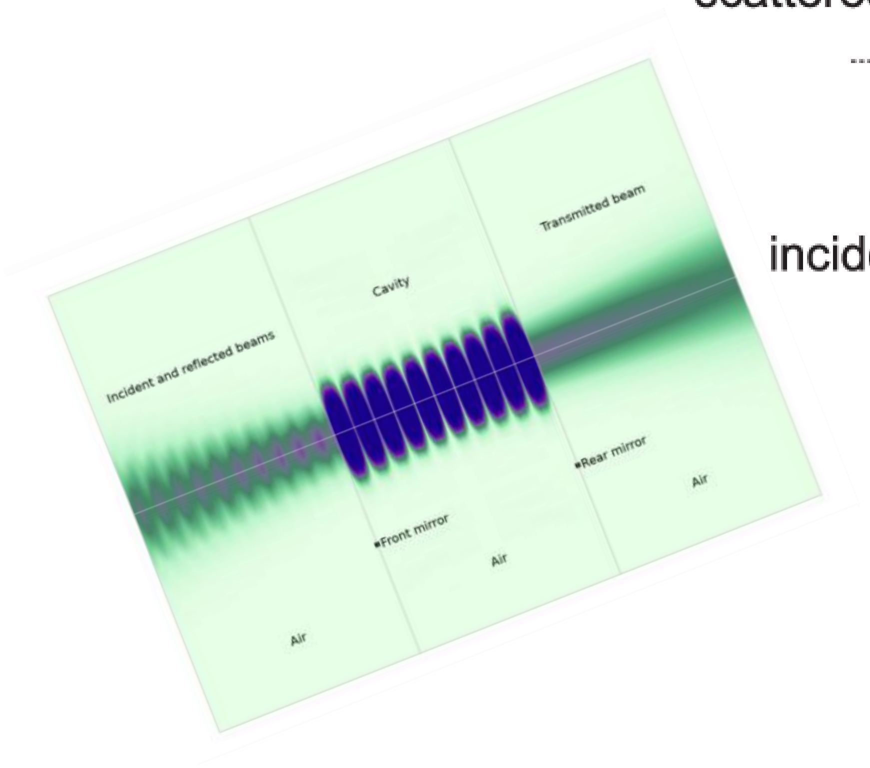
ELI-NP: The Future?

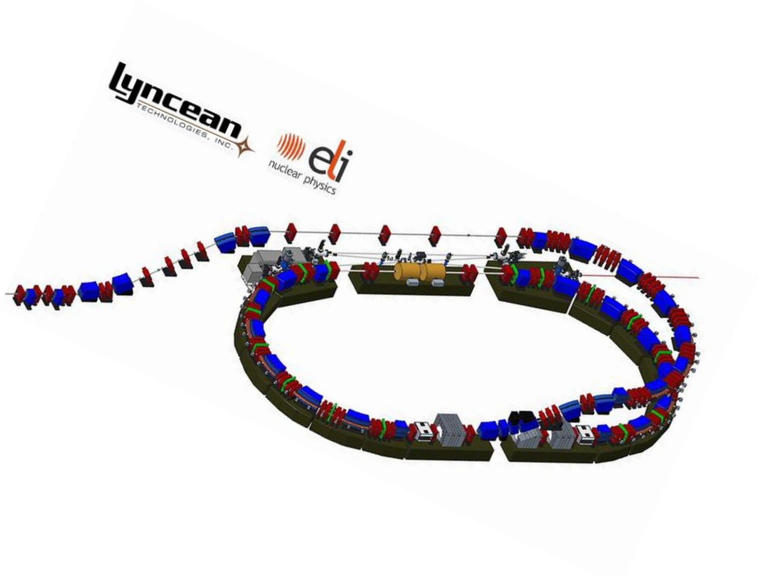
- New facility
- Star Trek appropriate laser driving the nuclear physics program
- Compton backscattering principle.



CB Photon beam







What about virtual photons?

Virtual photon method

Semiclassical

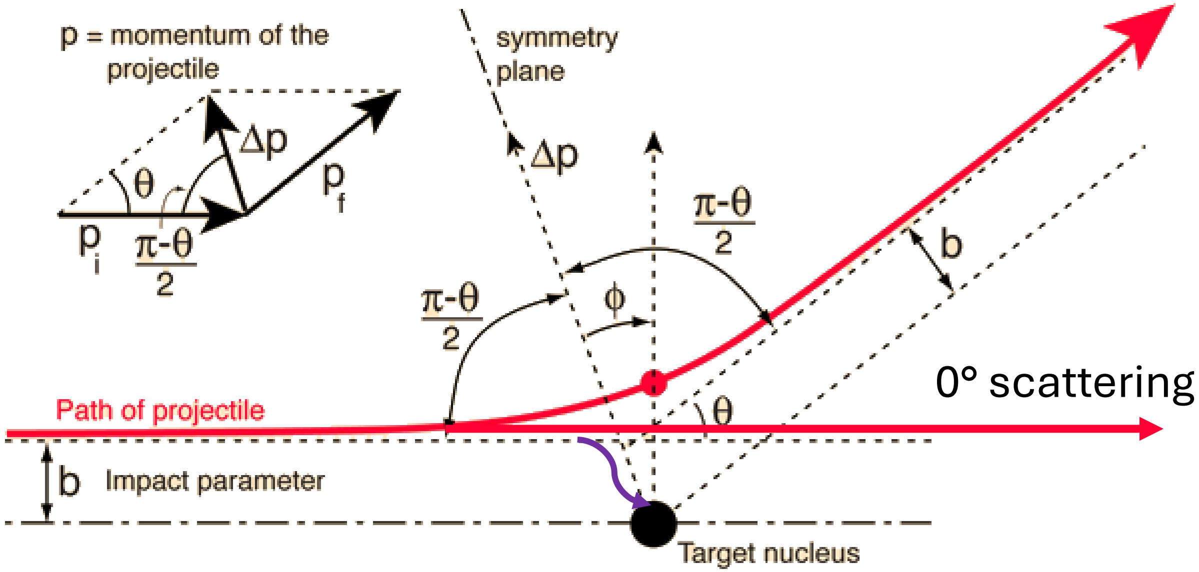
$$\left(\frac{dn_{E1}}{d\Omega} = \frac{Z_1^2\alpha}{4\pi^2}\epsilon^2\beta^{-2}x^2[K_1^2(x) + K_0^2(x)]\right)$$

vs

$$\frac{dN_{\lambda\pi}}{d\Omega} = Z_p^2\alpha\left(\frac{\omega k}{\gamma\nu}\right)^2 \frac{\lambda[2\lambda+1]!!}{(2\pi)^3(\lambda+1)}\sum_m |G_{\pi\lambda m}|^2|\Omega_m(q)|^2.$$

$$\Omega_m(q) = \int_0^\infty bJ_m(qb)\left(\frac{\omega b}{\gamma\nu}\right)\exp(i\chi(b))db.$$

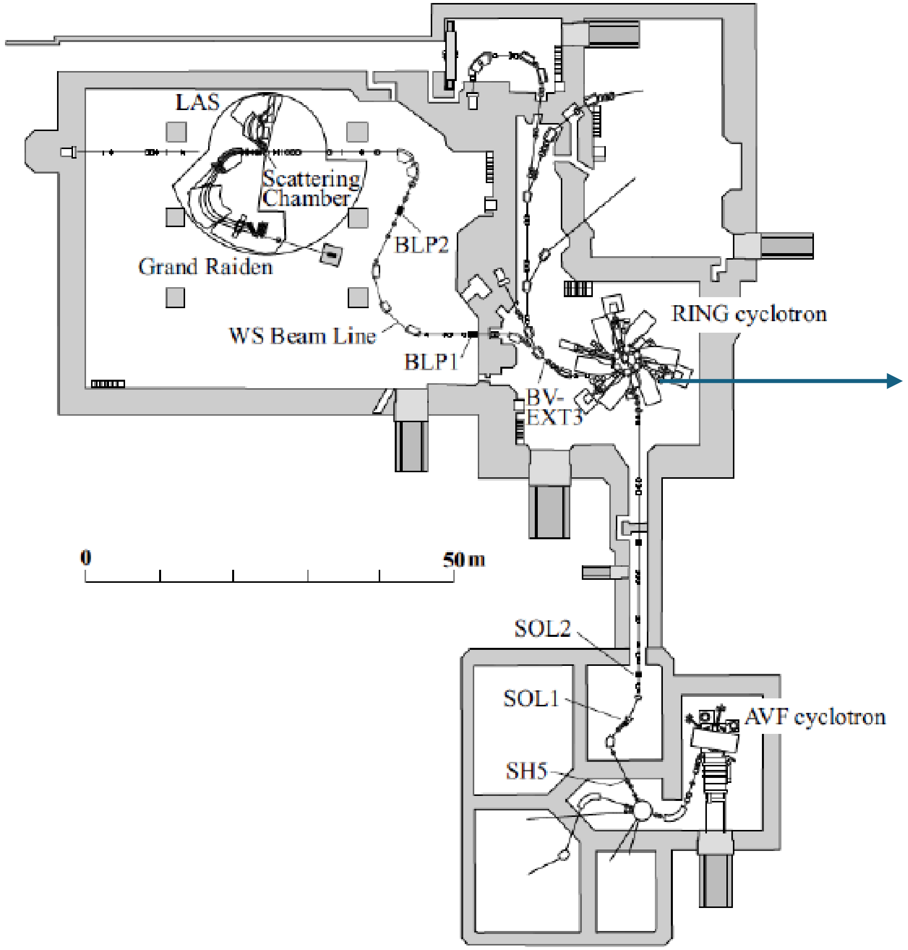
Eikonal approximation

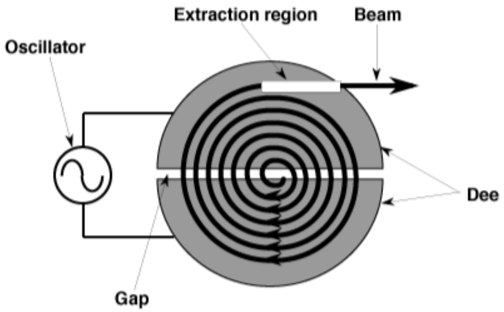


$$\frac{d^2\sigma}{d\Omega dE_\gamma} = \frac{1}{E_\gamma}\frac{dN_{E1}}{d\Omega}\sigma_\gamma^{\pi\lambda}(E_\gamma)$$

Theory and Applications of Coulomb Excitation. (C. A. Bertulani 2009) – VirtualPhotonCalculator code

Beam: Ring cyclotron-> very pretty but also powerful.



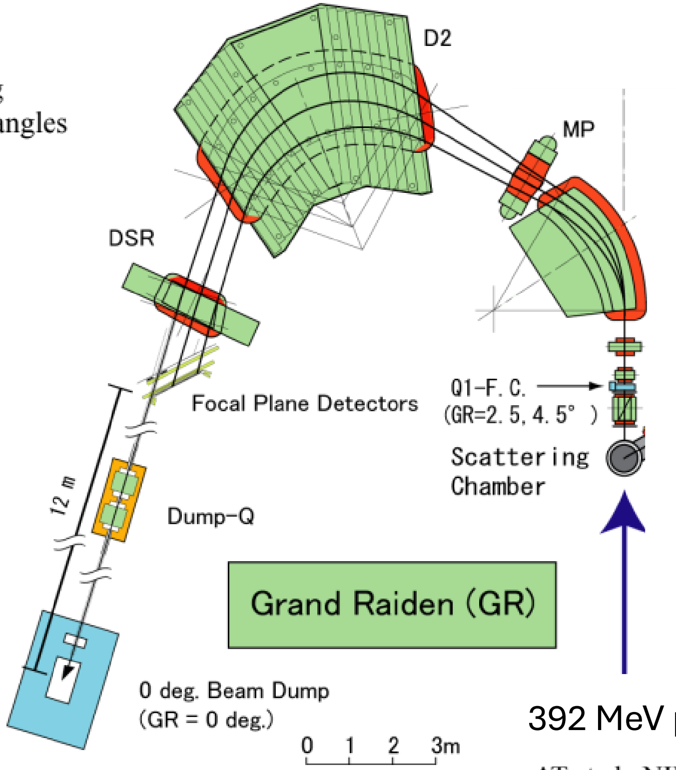


GRAND RAIDEN

$B\rho = P/q$

$P = Brq$

Proton scattering
at very forward angles

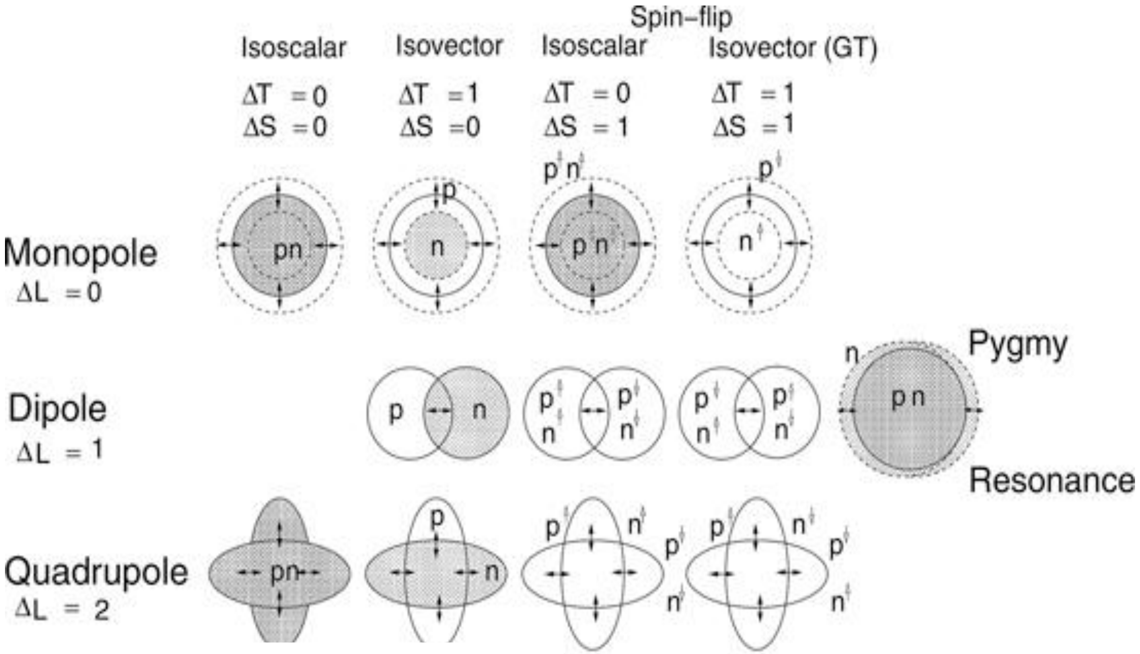


AT et al., NIMA605, 326 (2009)

Capable of 0° measurements

Why do we want to measure at 0°?

To try and separate a 0° scattering event from the main particle beam is really a case of measuring a candle in front of the sun.



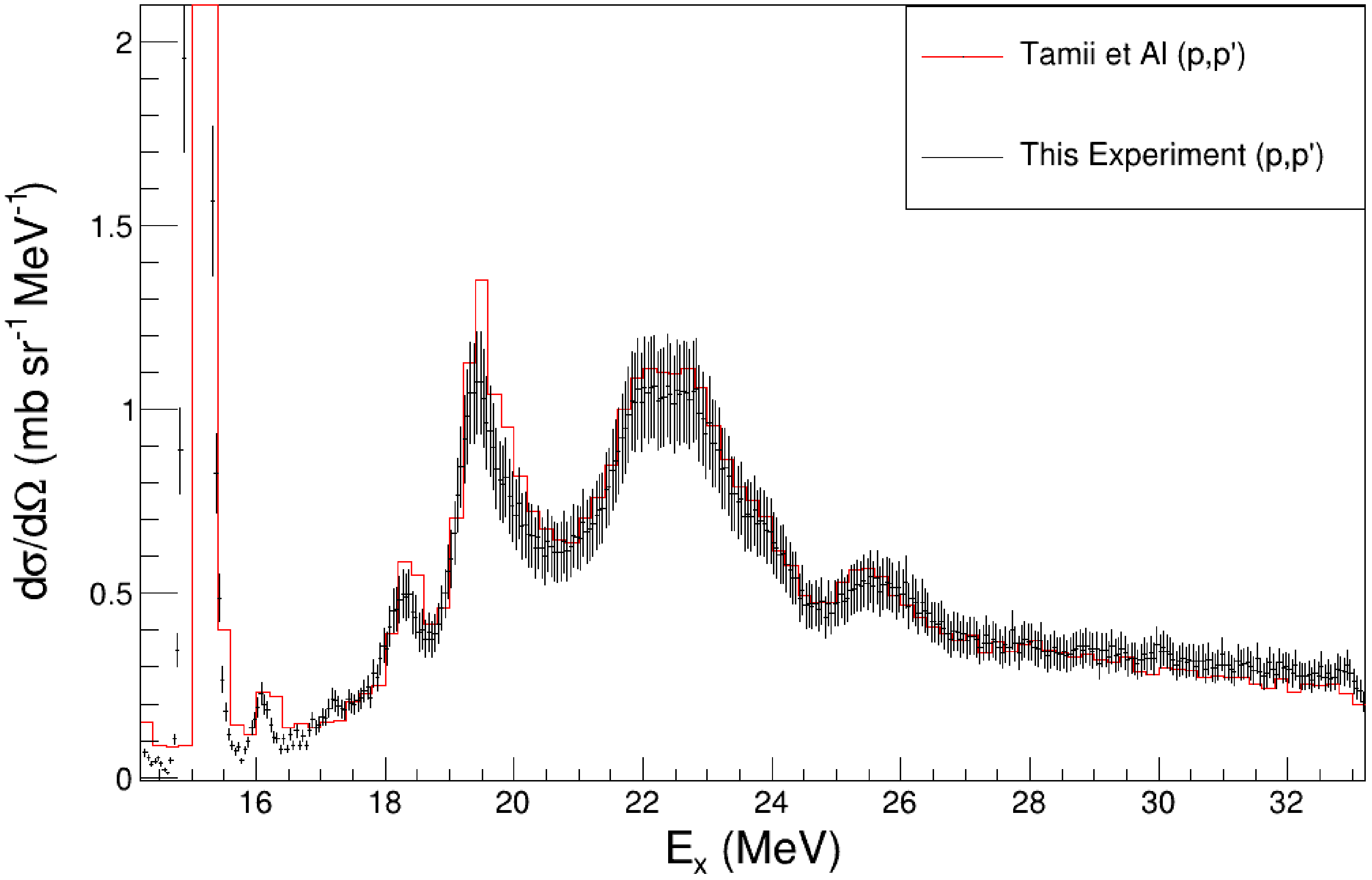
$$\theta_{lab}^{max} = \frac{Z_{eff}}{b\mu\gamma\beta^2},$$

→ Less than 2°

Usually protons are an unselective probe, but at 392 MeV and very forward angles the situation becomes quite clean.

Takashima Yajuro: Candle and sunrise

Comparison to previous similar conditions



Very close agreement with previous data set that is experimentally similar:

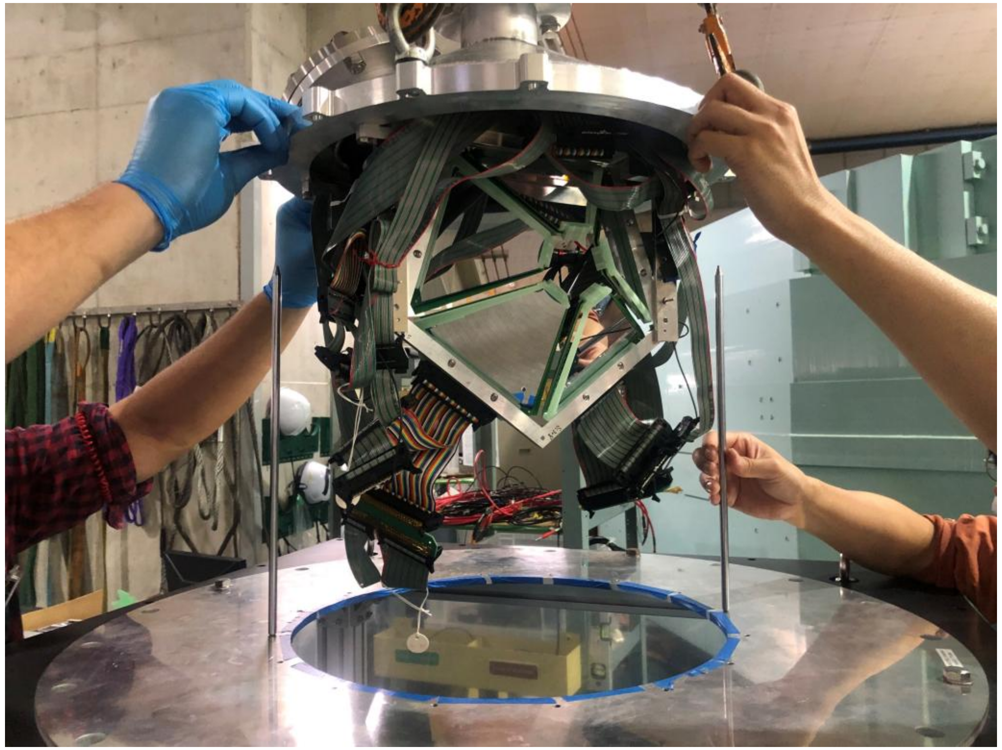
Both data sets at 0^{o} central angle

Same horizontal acceptance
1^{o} Difference in vertical acceptance

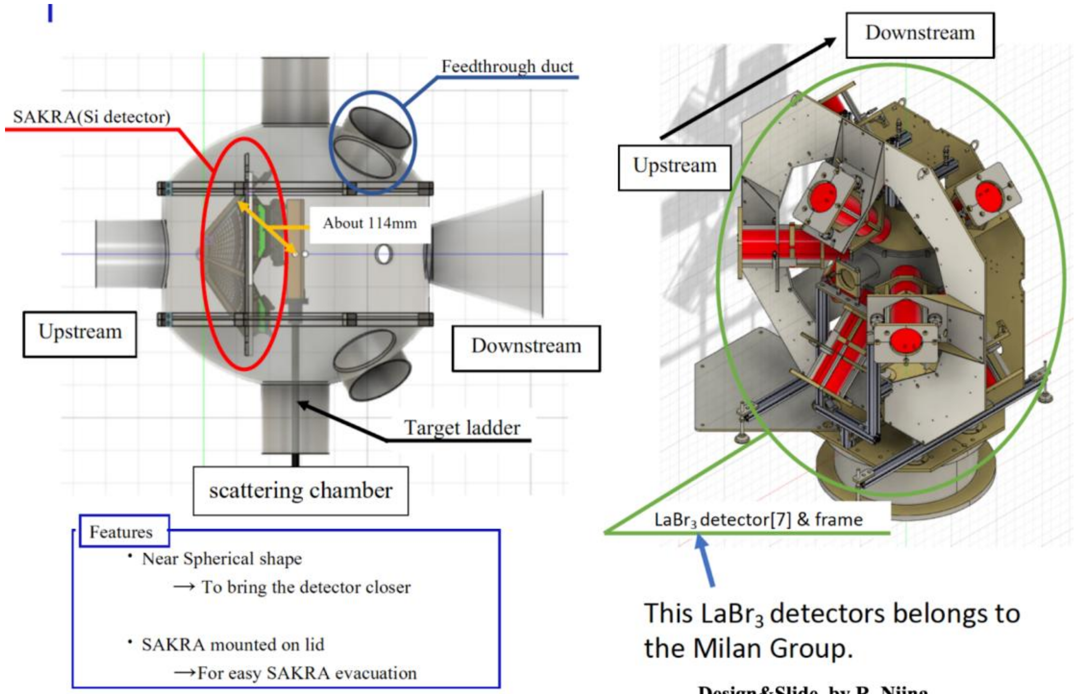
Energies both at 392 MeV

Targets are thin 1 mg/cm2 versus 30 mg
Dispersion matched vs not dispersion matched

RCNP-SAKRA



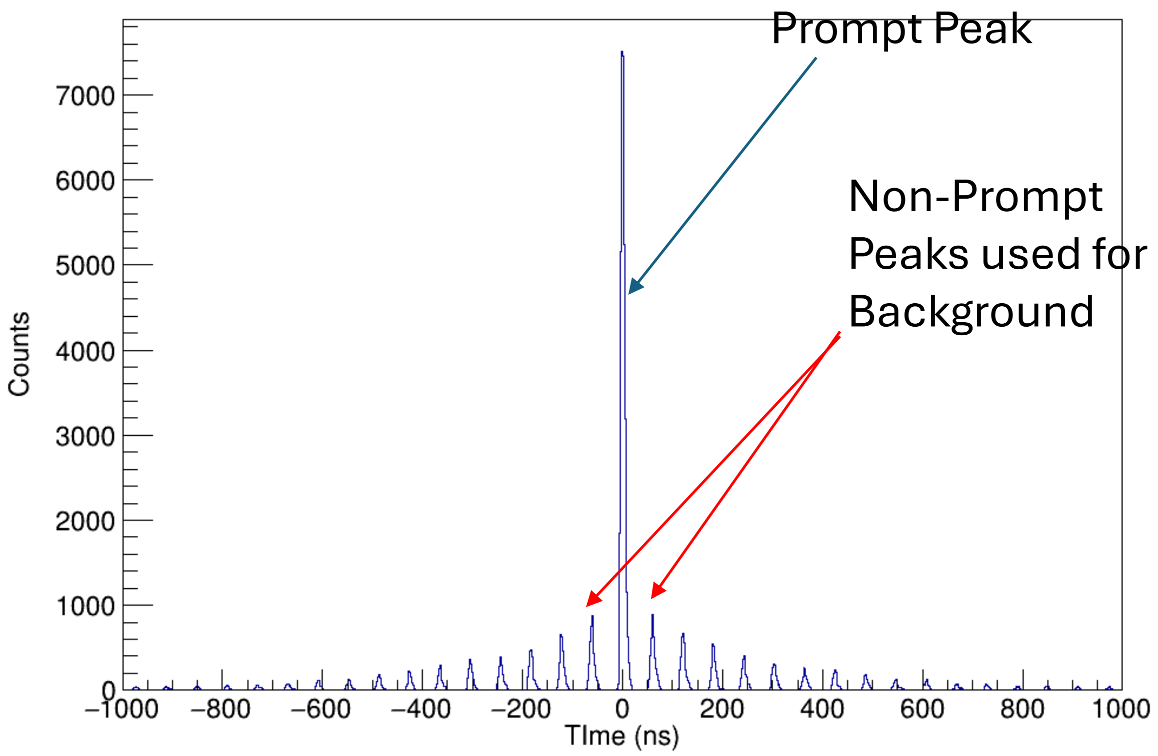
- Charged particle coincidence decay setup.
- 10 Double Sided Silicon Strip Detectors (DSSSDs) at backwards angles.
- Two layers of 500μm detectors, to measure protons up to 12 MeV.
- Covers ~23% solid angle with for the configuration with 5 MMMs



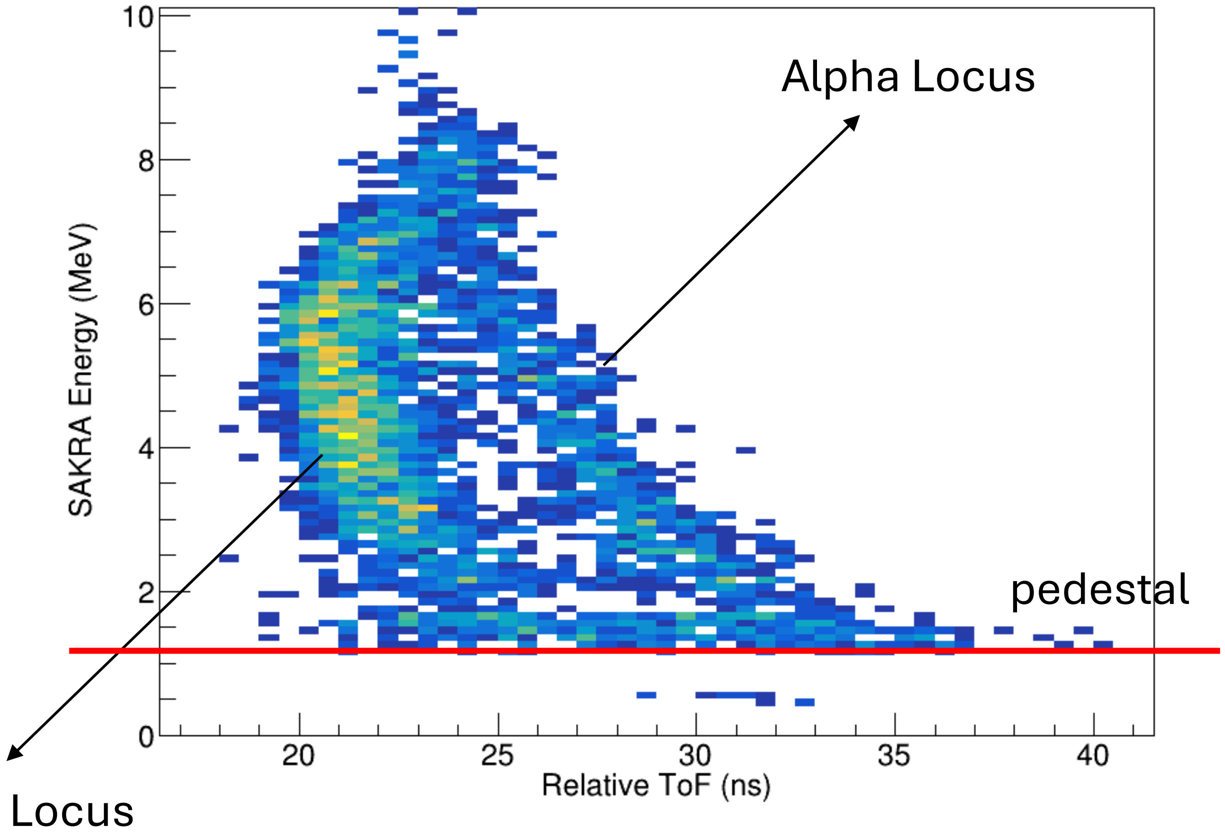
This $LaBr_3$ detectors belongs to the Milan Group.

Design&Slide by R. Niina

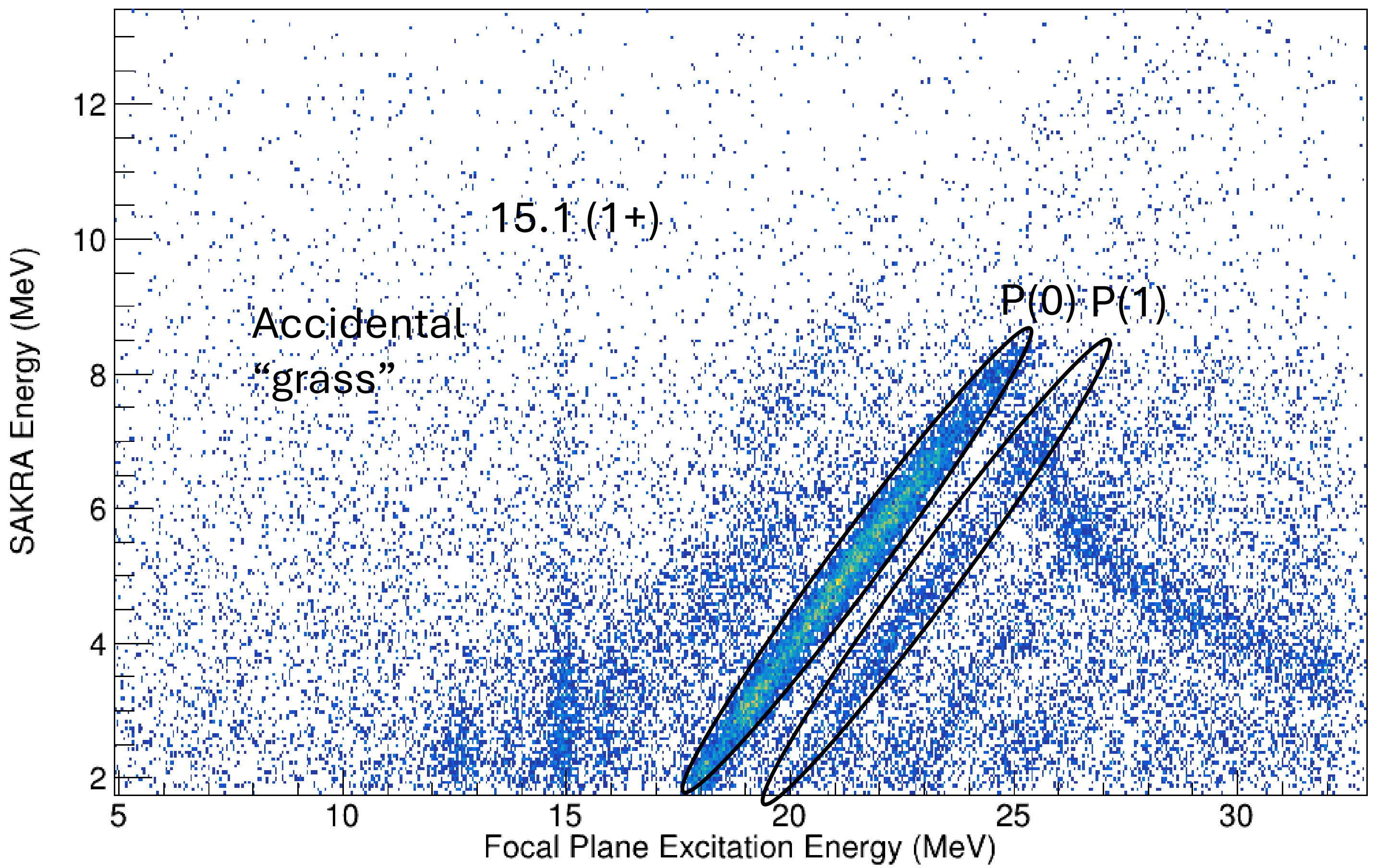
Timing and Time of Flight Selection



Lopsidedness of the Random times due to some time structure in the ion source

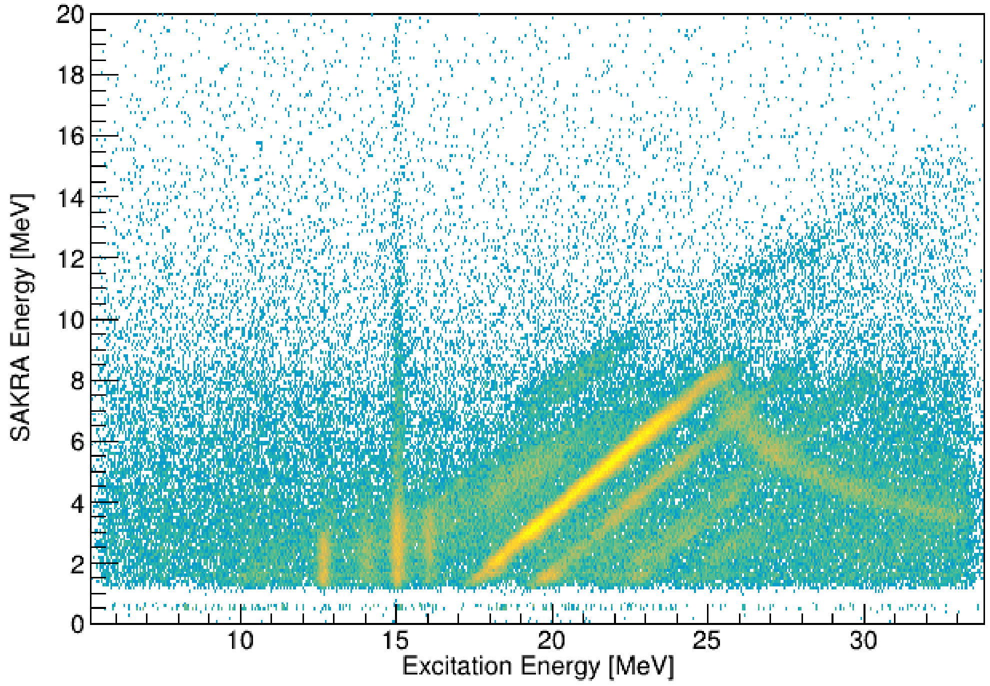


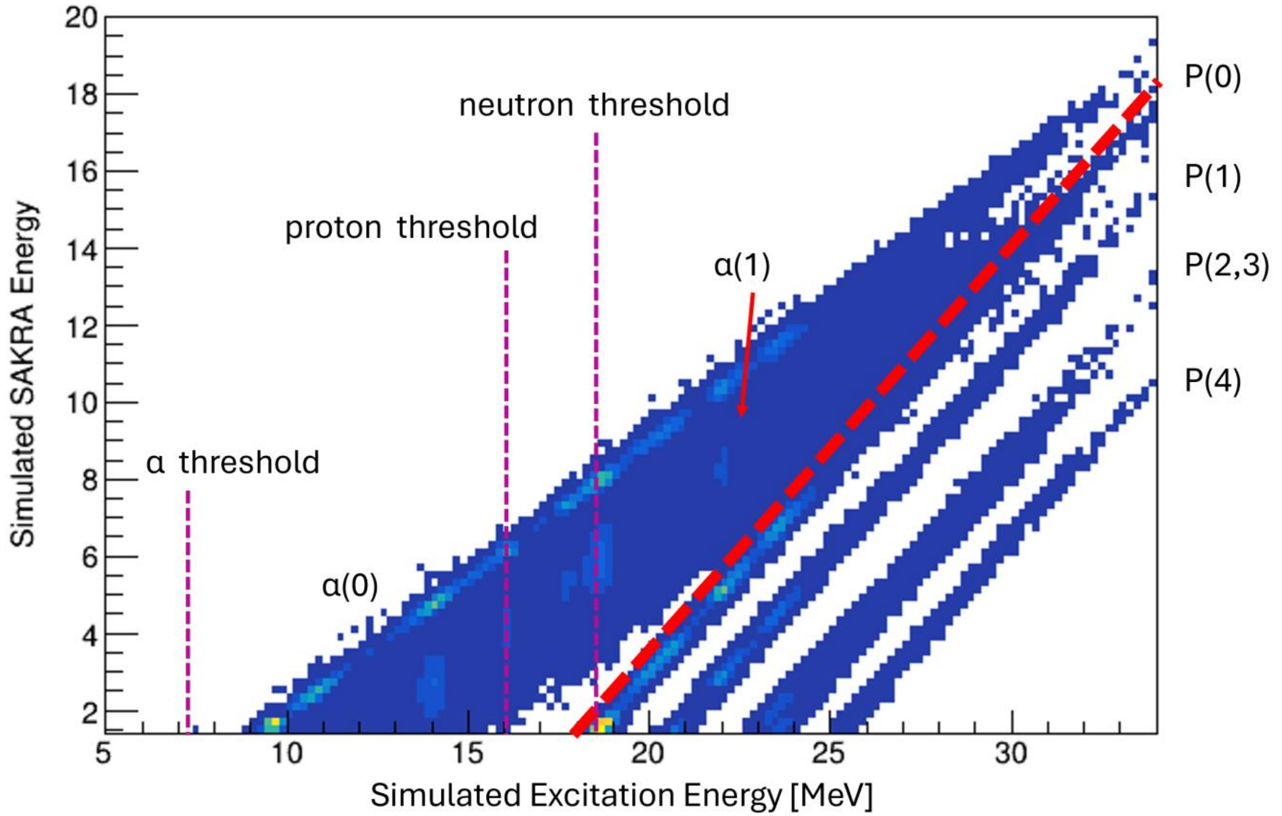
Proton Coincidence Loci for ^{12}C



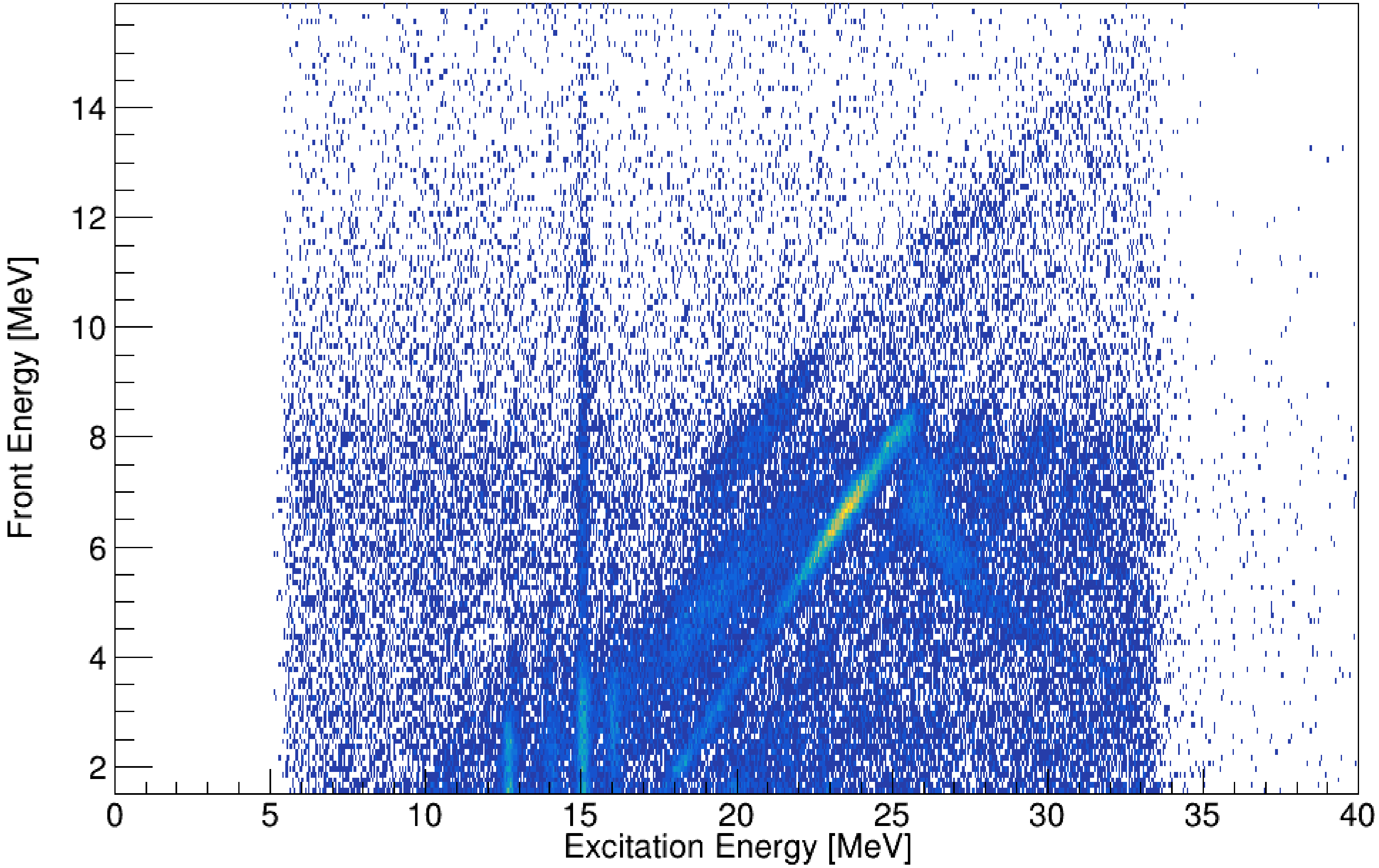
- The proton Locus starts at ~16 MeV and the different decay modes can be seen here.
- GDR Starts at ~17 MeV
- Proton Punch through of the first silicon occurs at roughly 8 MeV and of the second at 12 MeV.

No PID cuts Sakra vs Simulation



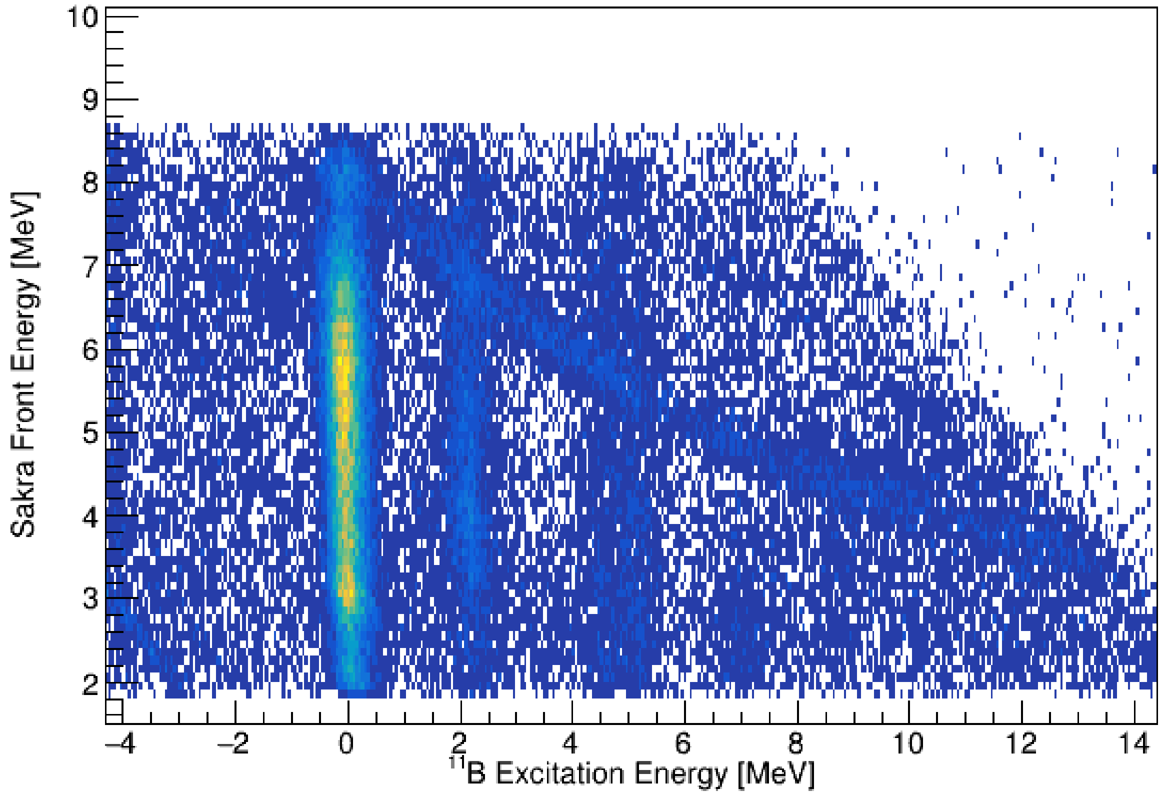


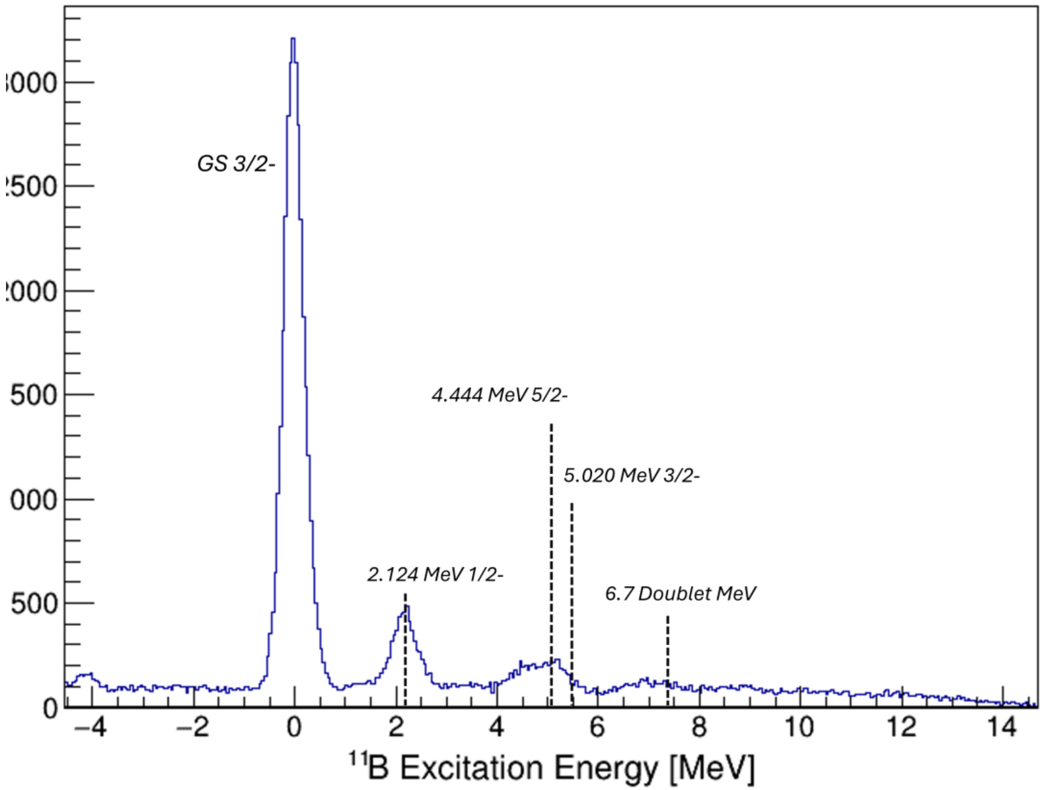
Alpha Coincidence Loci for ^{12}C



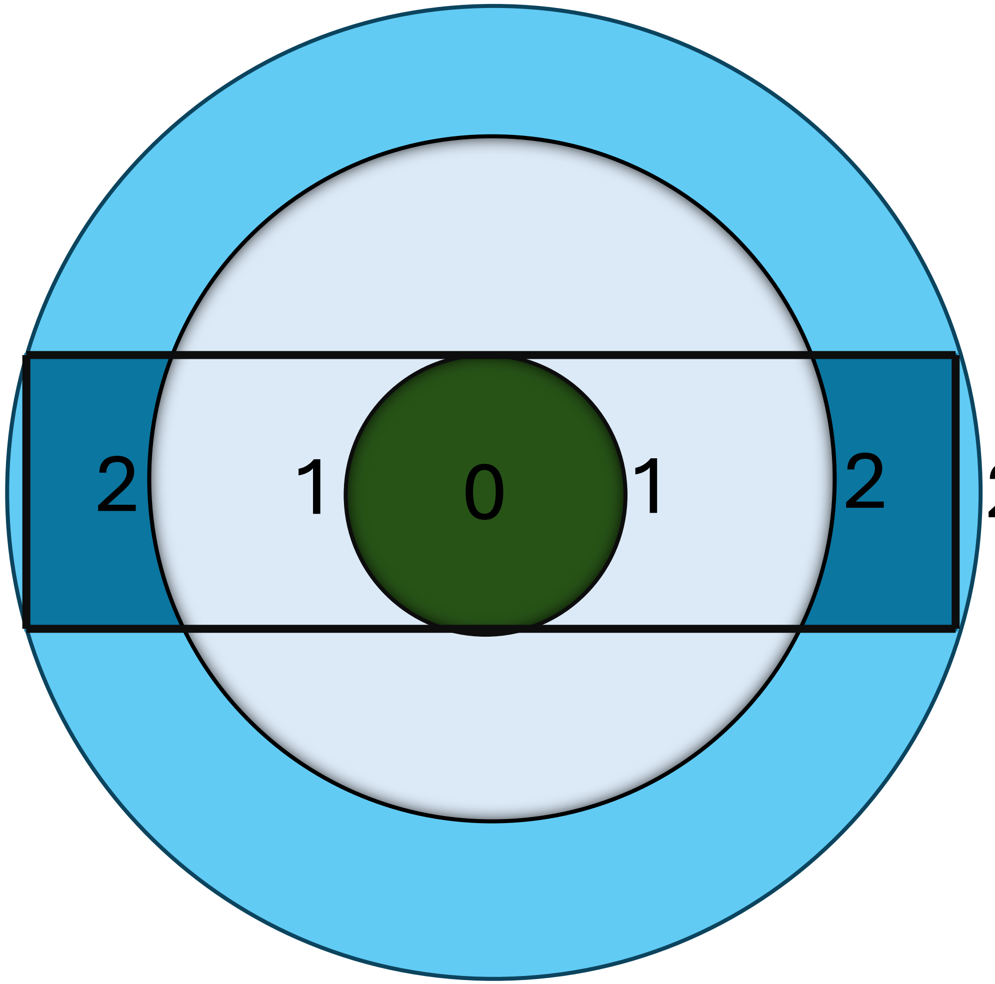
- The Alpha Decay threshold starts at the 7.36 MeV.
- GDR Starts at ~17 MeV
- Strange structure seen at 18-22 MeV (Not related to the GDR?)

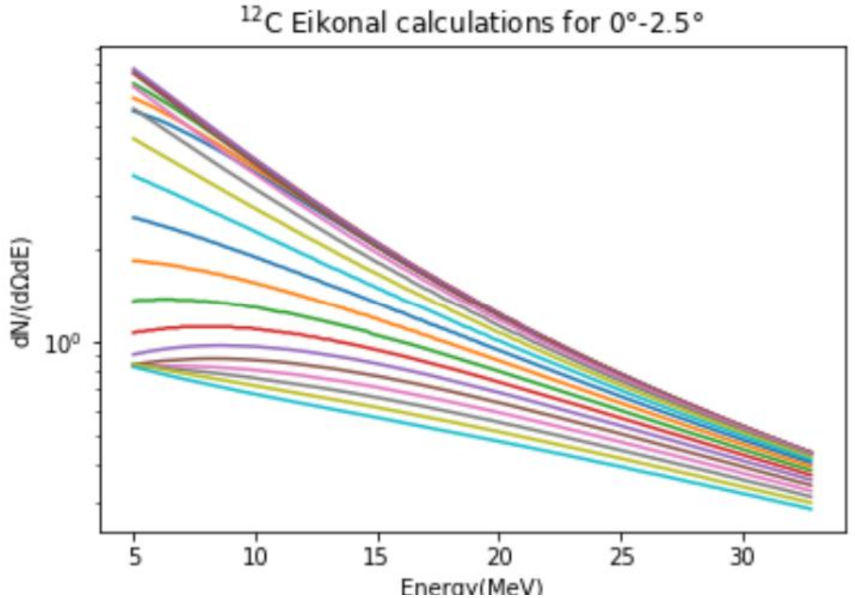
^{11}B Excited states by rotating the ^{12}C Ex vs SAKRA Energy plot

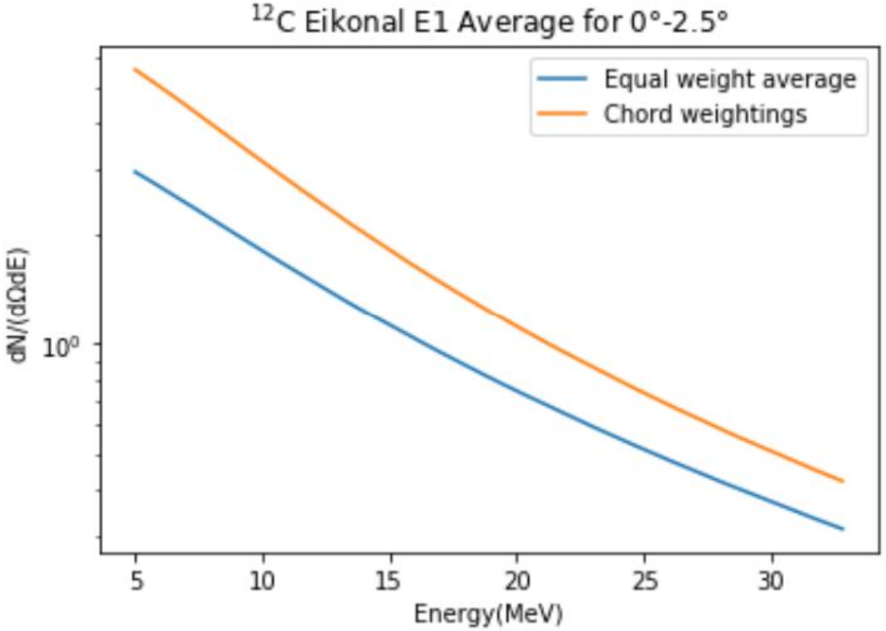




Virtual Photon numbers- Eikonal Estimate

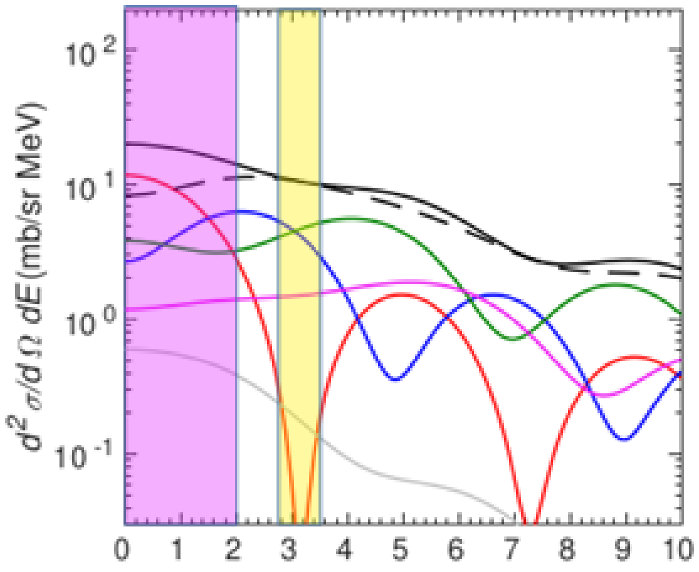




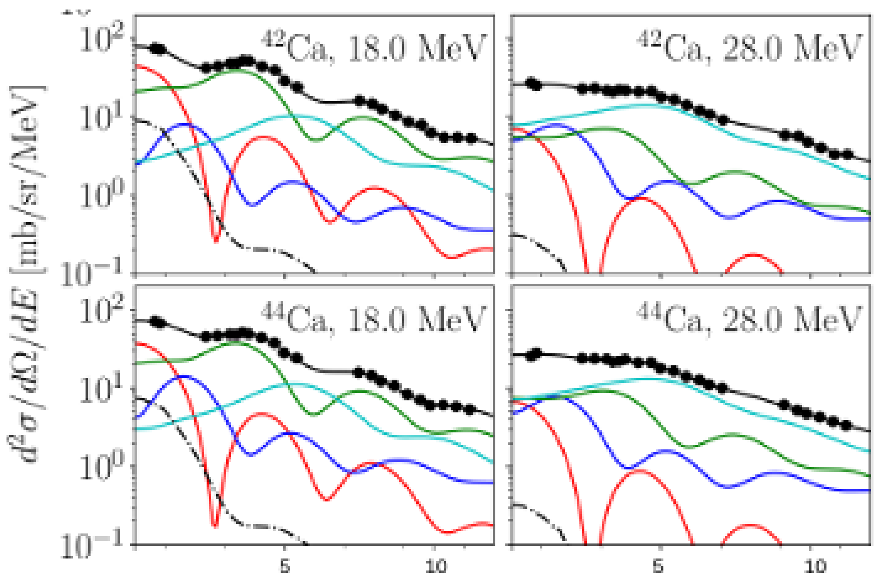


DoS Method

DoS (Difference of Spectra) *versus* MDA (Multipole Decomposition Analysis)



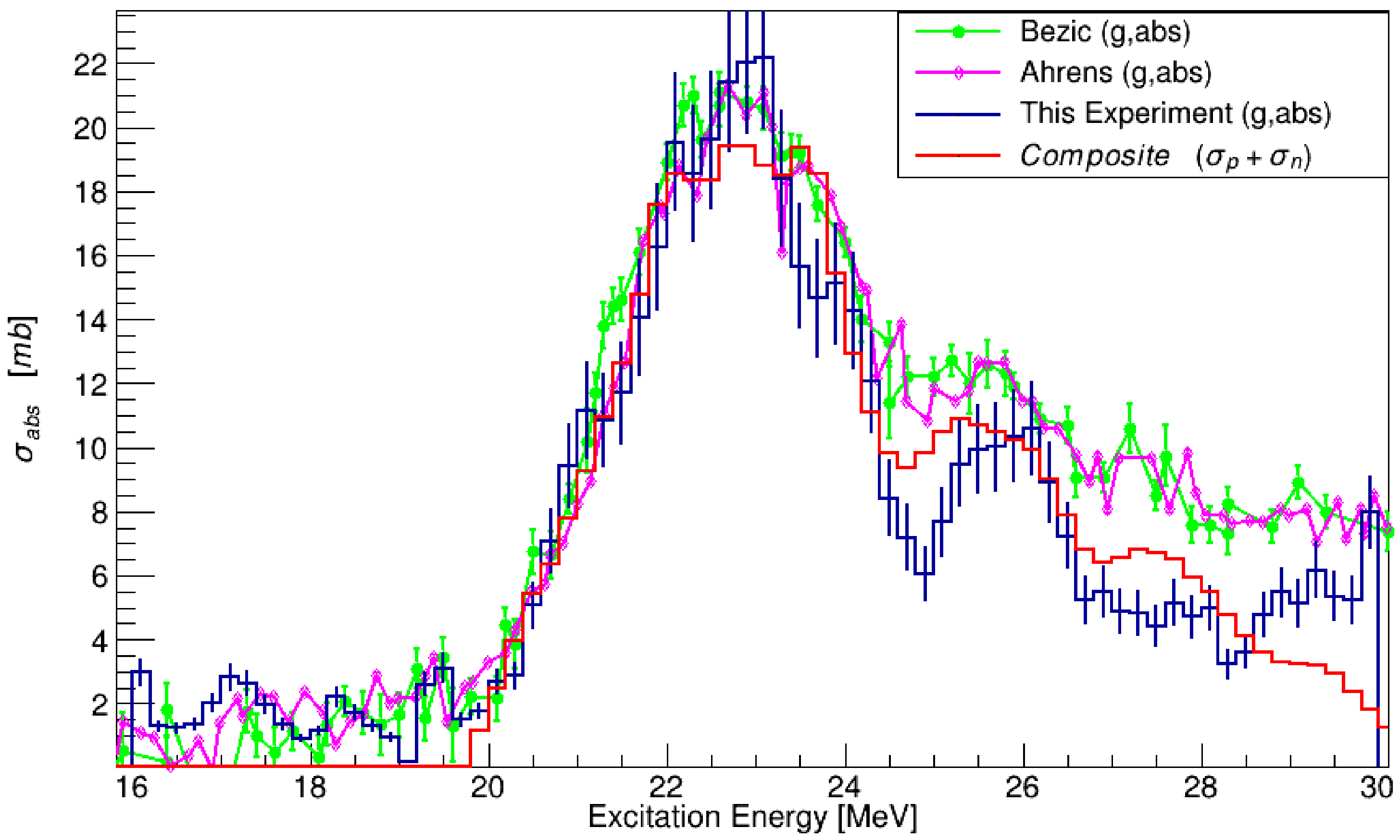
$$\frac{d^2\sigma^{exp}(\theta_{c.m.}, E_x)}{d\Omega\, dE_x} = \sum_{\lambda} A_\lambda(E_x) \frac{d^2\sigma_\lambda^{DWBA}(\theta_{c.m.}, E_x)}{d\Omega\, dE_x}.$$



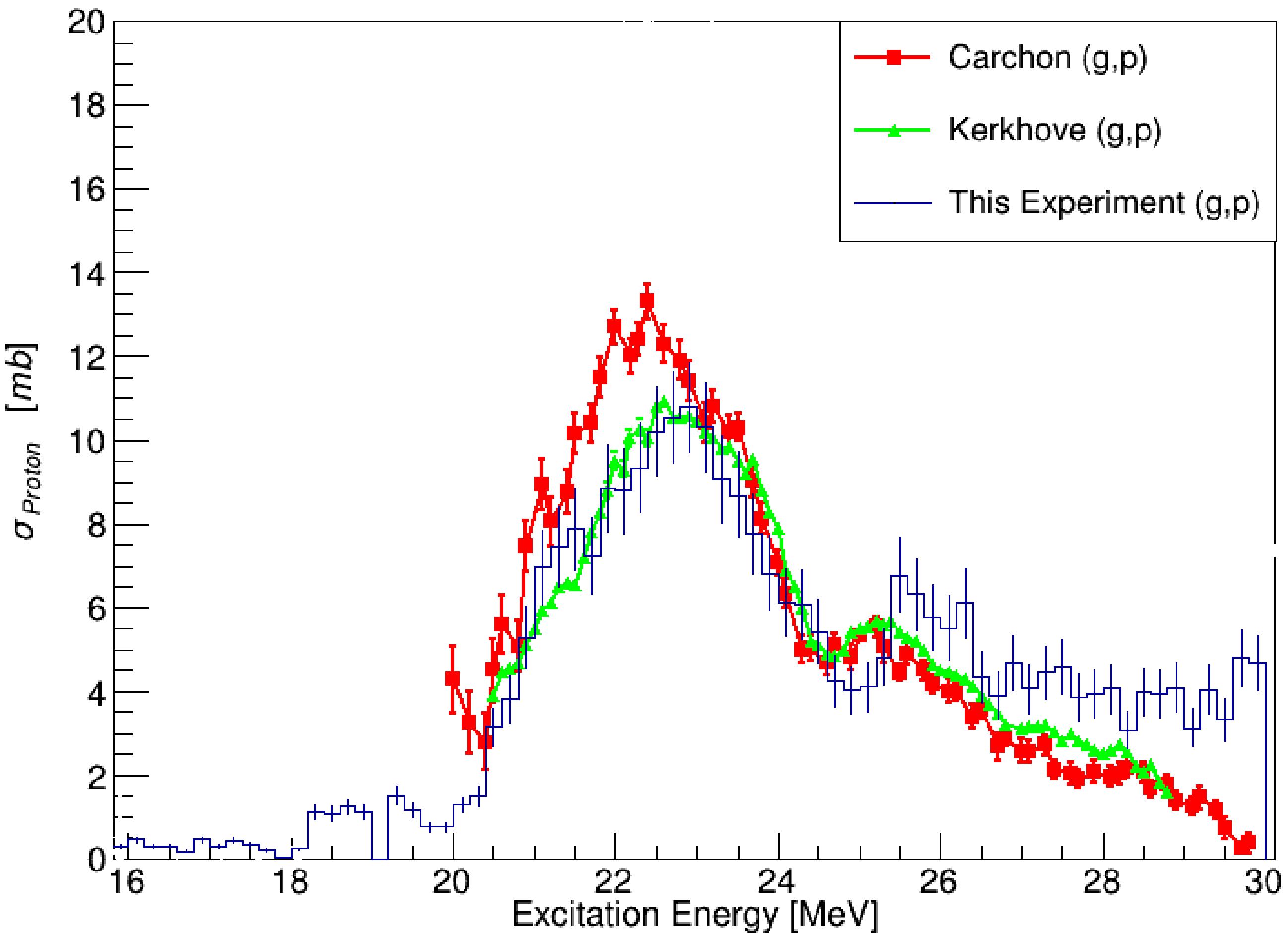
Our analysis depends on the DoS method

For this type of study with protons it is not yet well established!

^{12}C Total photoabsorption compared to EXFOR and composite cs

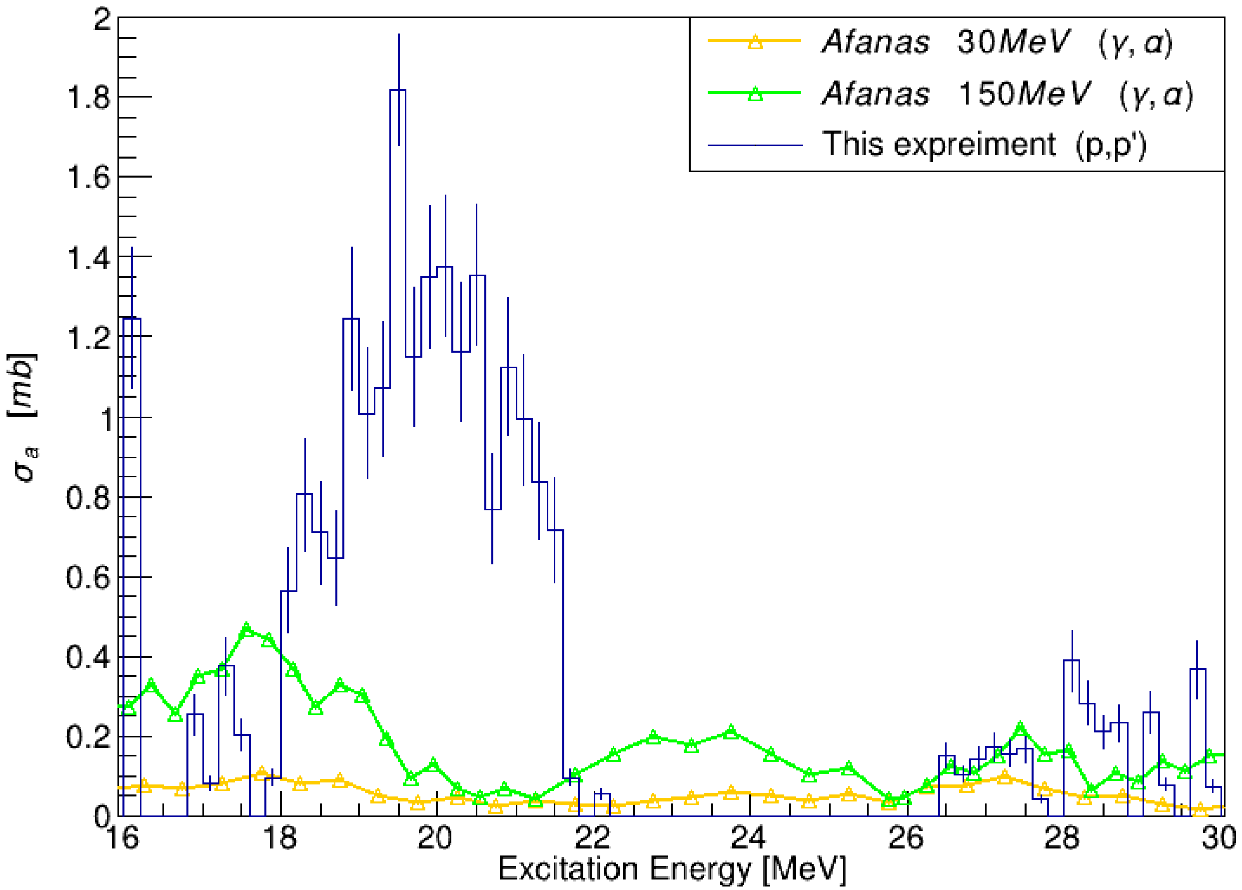


^{12}C proton branching compared to Exfor



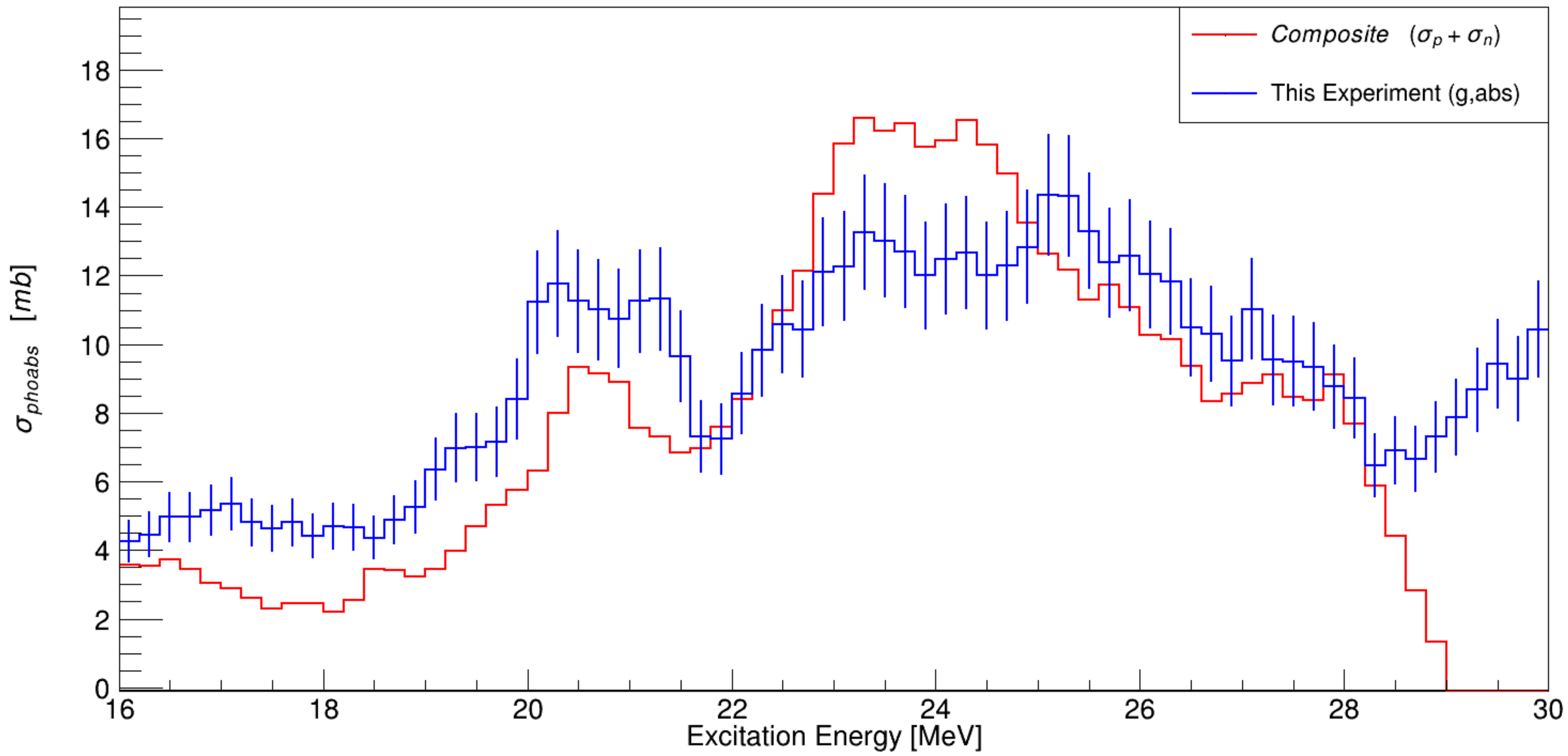
- Slightly higher peak in one Carchon measurement
- Decrease towards higher energies is spurious when comparing to (g,n) and (g,abs) data.

^{12}C alpha branching compared to EXFOR.

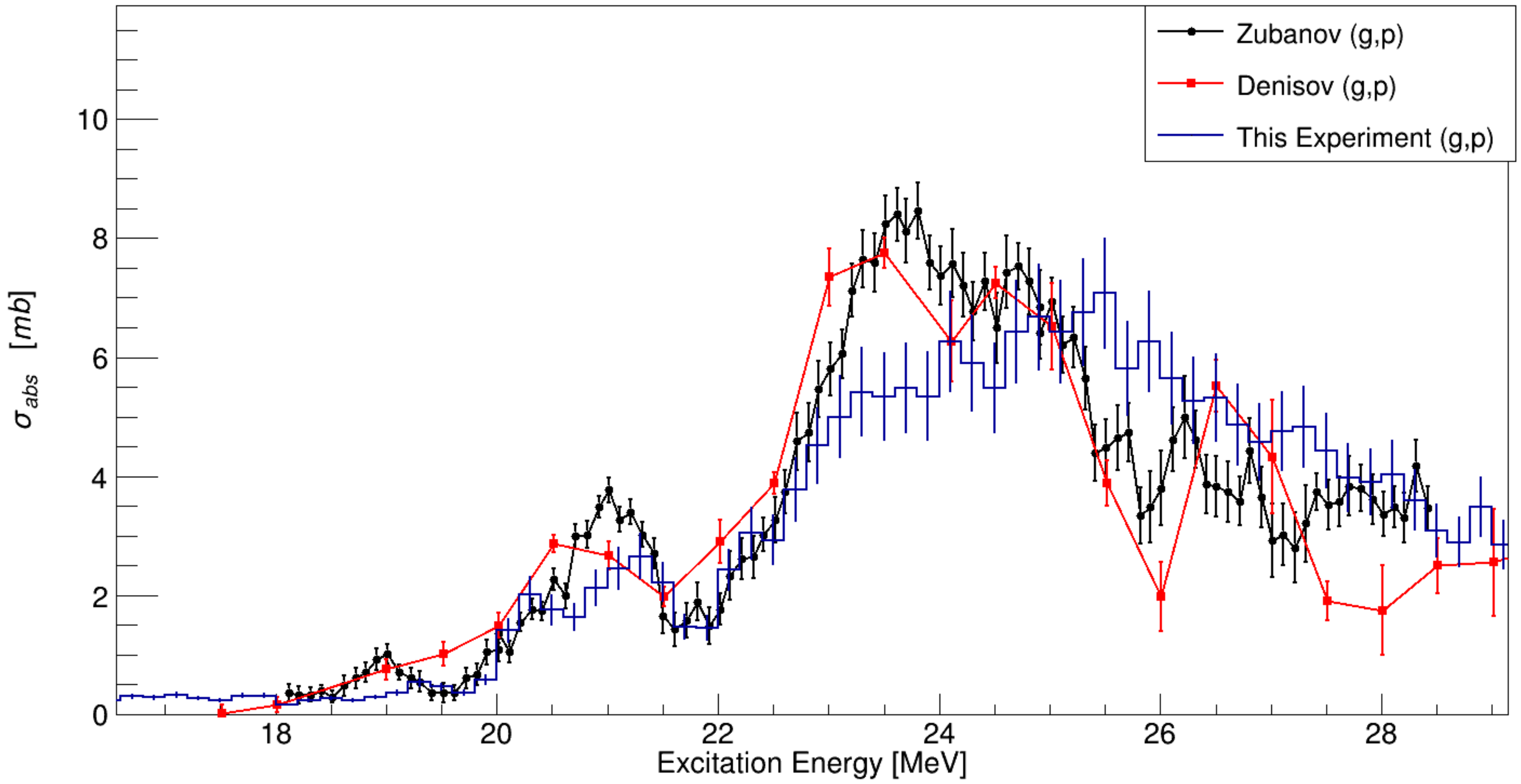


- Only 1 dataset available from a previous TPC experiment.
- Structure at ~20 MeV was not seen in this experiment.

^{13}C total photoabs compared to composite



^{13}C (g,p) compared to EXFOR

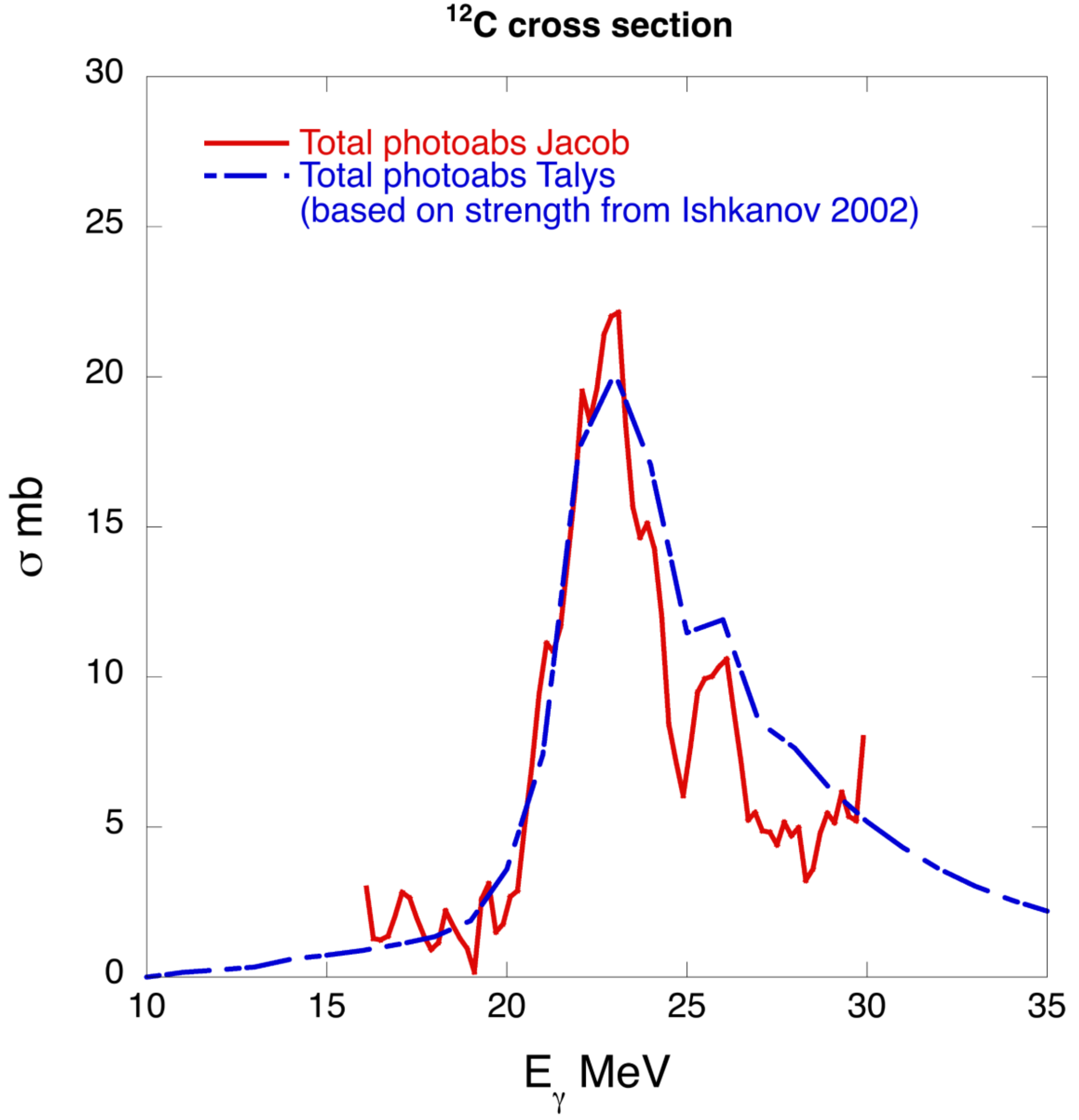


- (g,p) and (g,n) are our only references with the ^{13}C case.
- The (g,p) is in very decent agreement

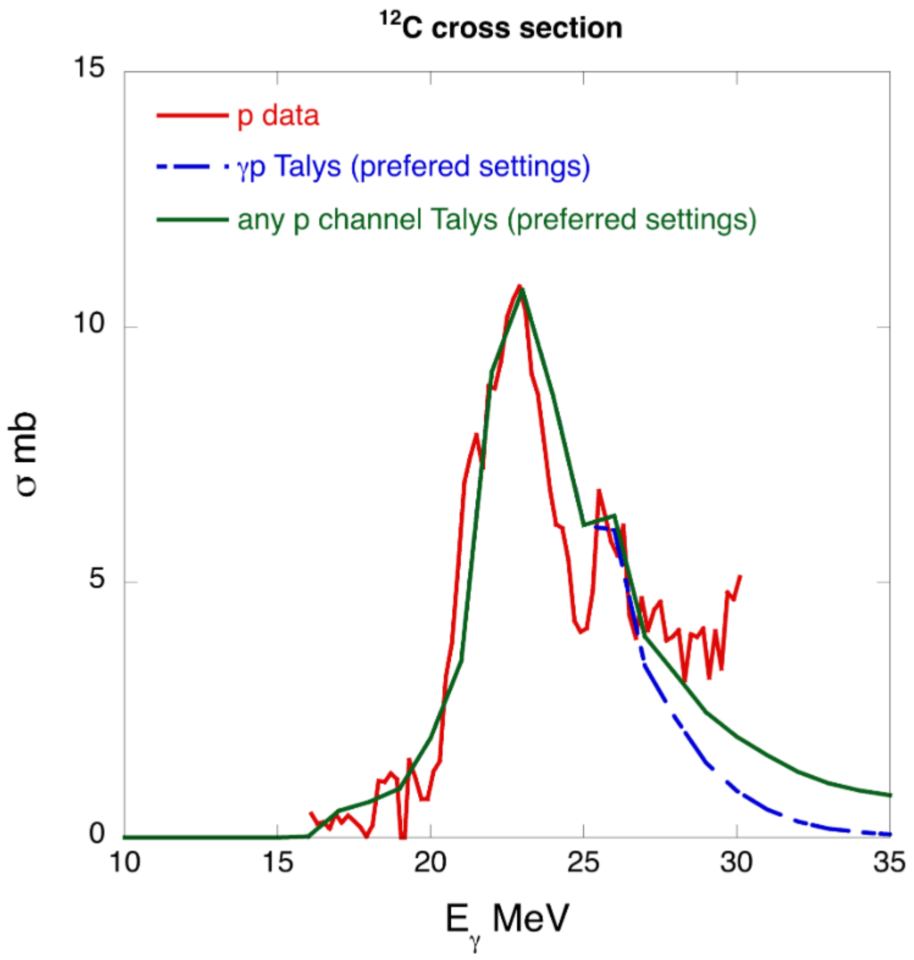
As a whole the cross sections are respectable.

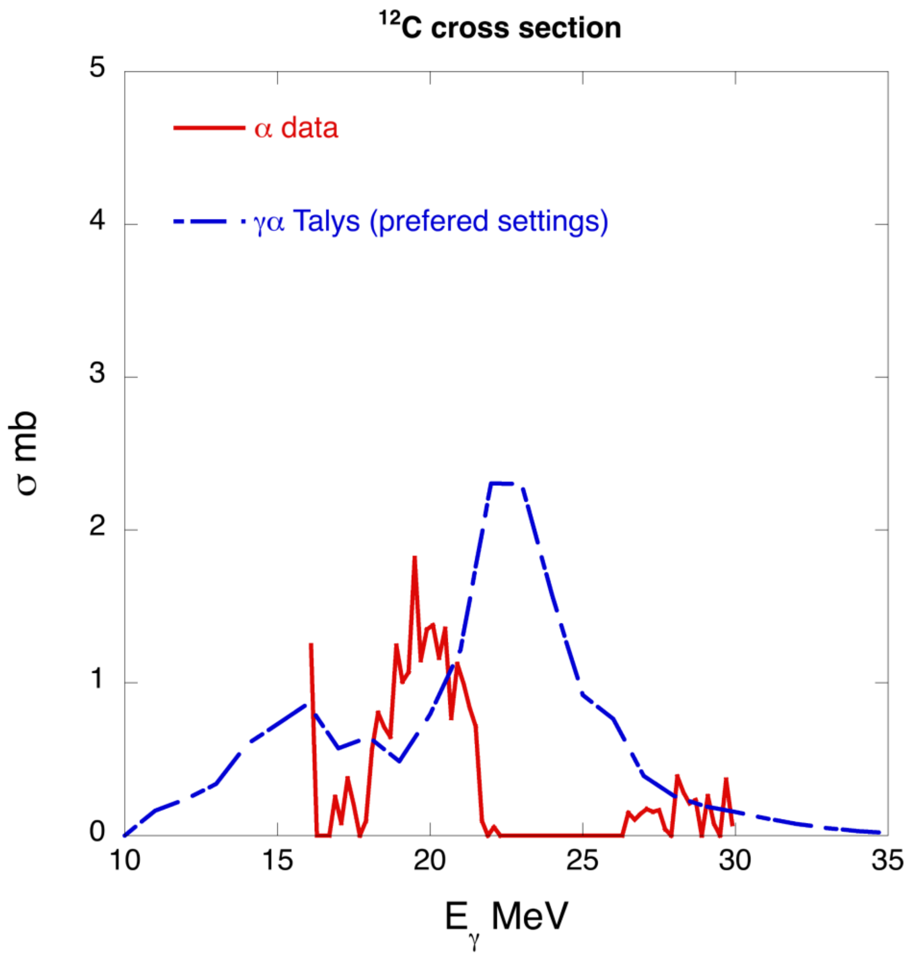
	σ_{tot}	σ_p	σ_α	Γ_p	Γ_α
^{12}C	104.6±12.5	59.1±7.6	4.3±0.9	0.56±0.07	0.04±0.01
^{13}C	127.5±16.2	42.7±6.0	24.4±3.41	0.33±0.04	0.19±0.02

^{12}C Total photoabs vs Talys



^{12}C proton and alpha channels





Adding the cross sections back to the UHECR soup.

Reaction occurrence

$$\lambda = m_n \sigma_n^{-1}$$

$$\zeta_{part} = \frac{A_{part}}{A_{tot}}$$

Reaction inelasticity

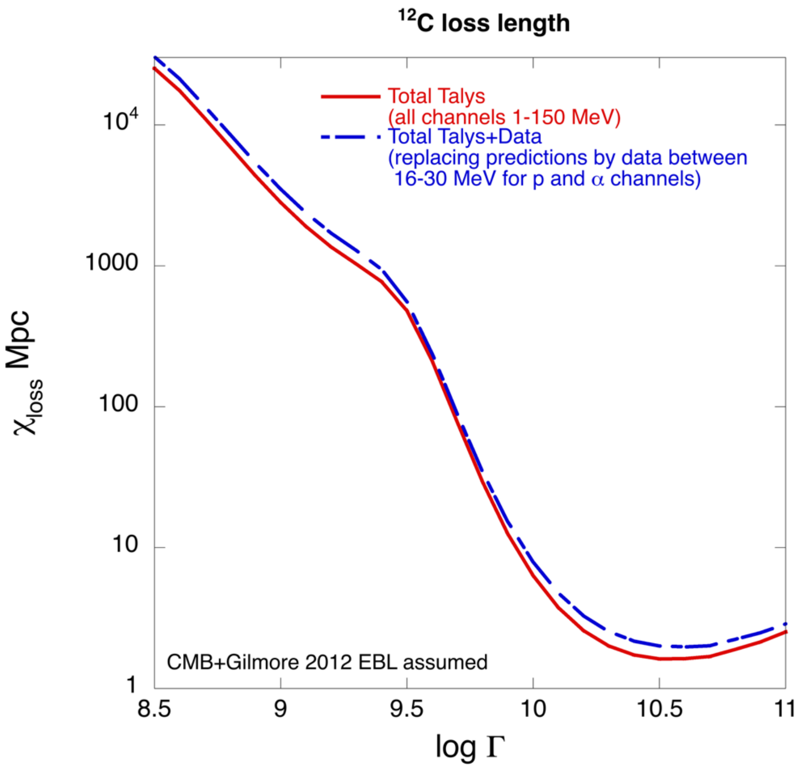
Effect of our XS on the current calculation

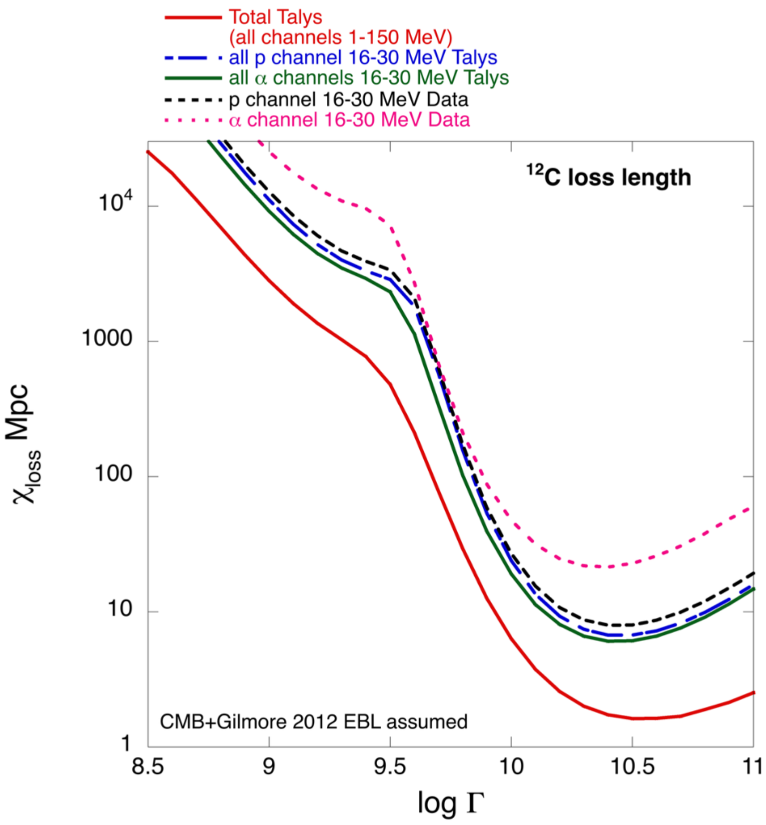
$$\chi_{loss}^{tot} = \left(\frac{1}{\chi_{tot}^{sim}} - \frac{1}{\chi_{tot}^{\alpha\ sim}} - \frac{1}{\chi_{tot}^{p\ sim}} + \frac{1}{\chi_{tot}^{\alpha\ exp}} + \frac{1}{\chi_{tot}^{p\ exp}}\right)^{-1}$$

We obtain larger XS or branching ratios, the loss length becomes larger and vice versa.

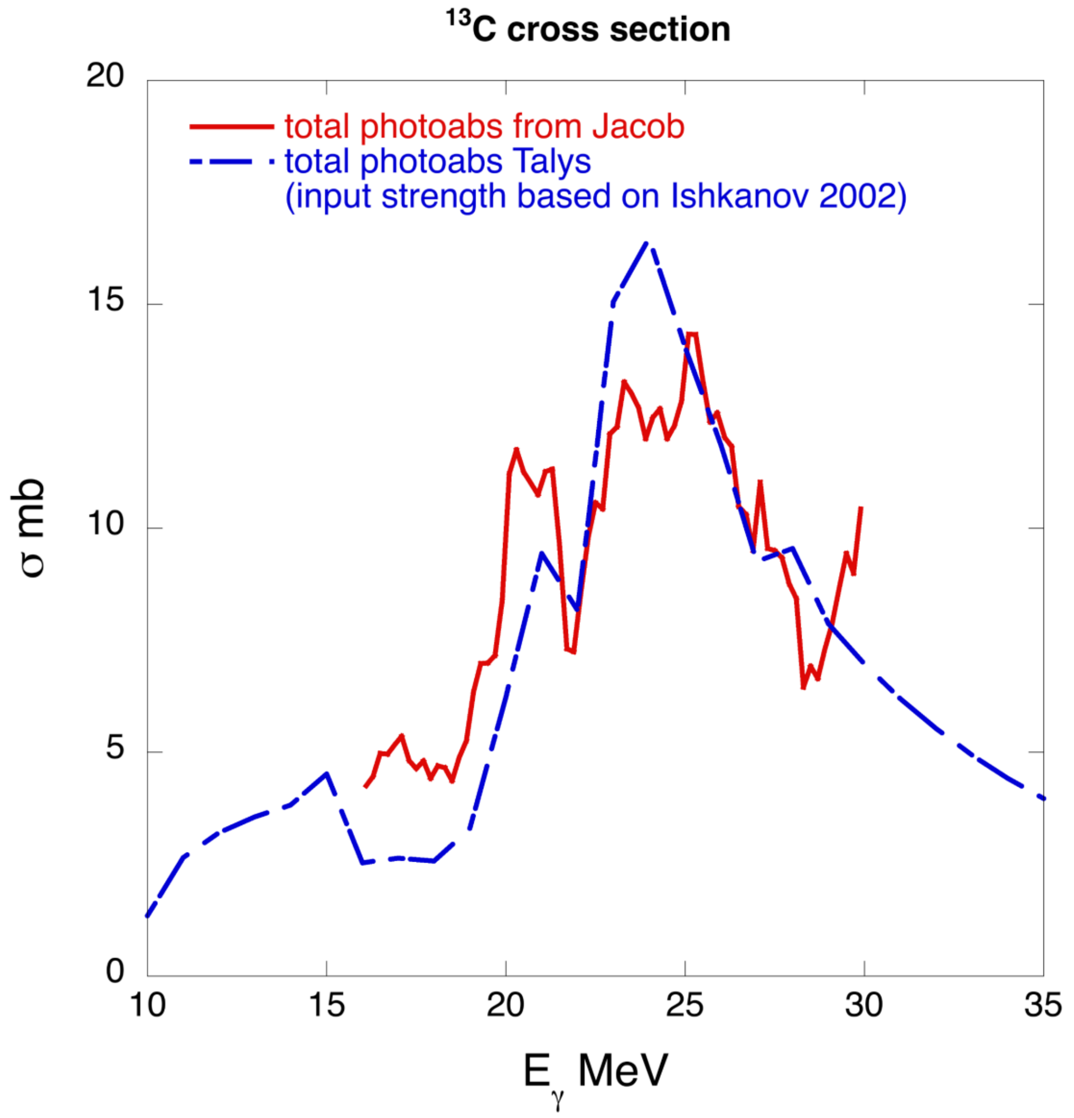
Particularly relevant for particle decay because is dubious to model with lighter nuclei.

^{12}C loss length comparisons, total vs partials

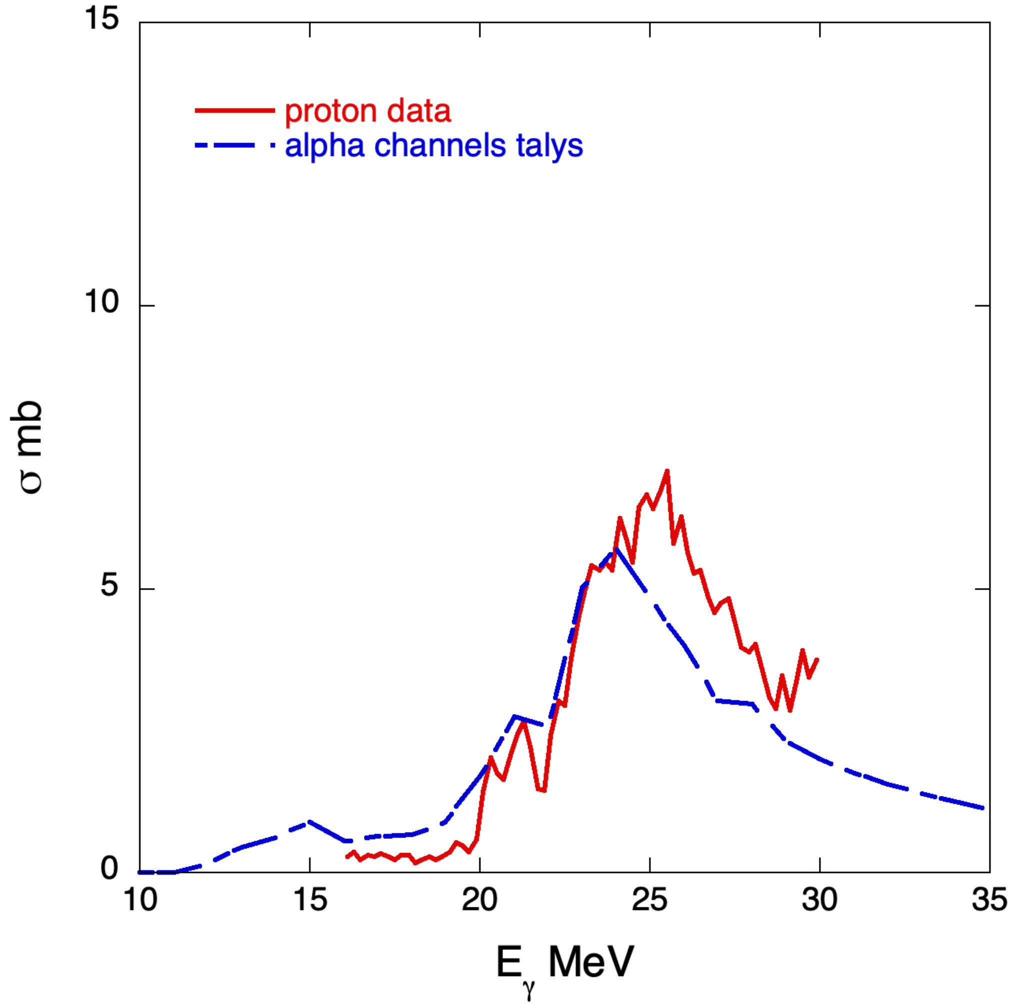


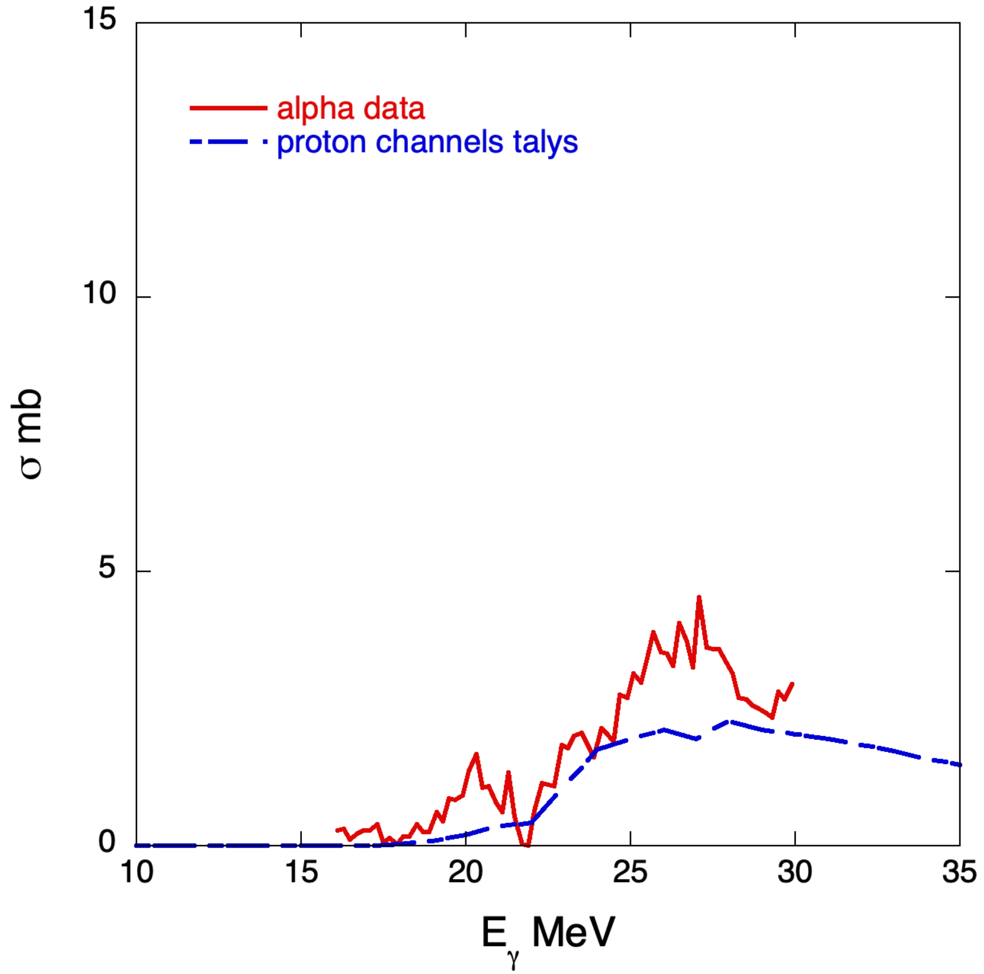


^{13}C Total vs Talys

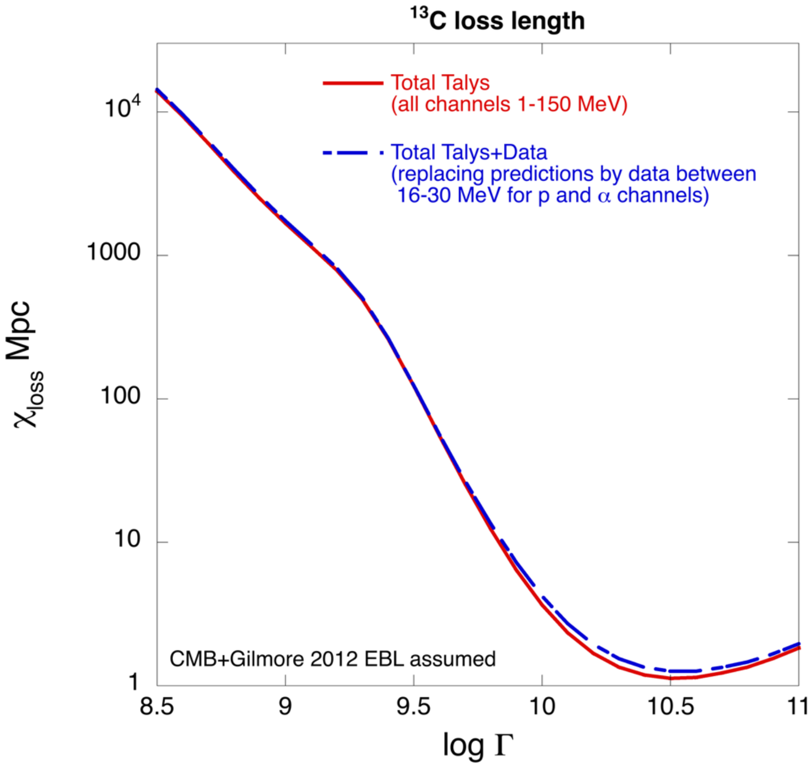


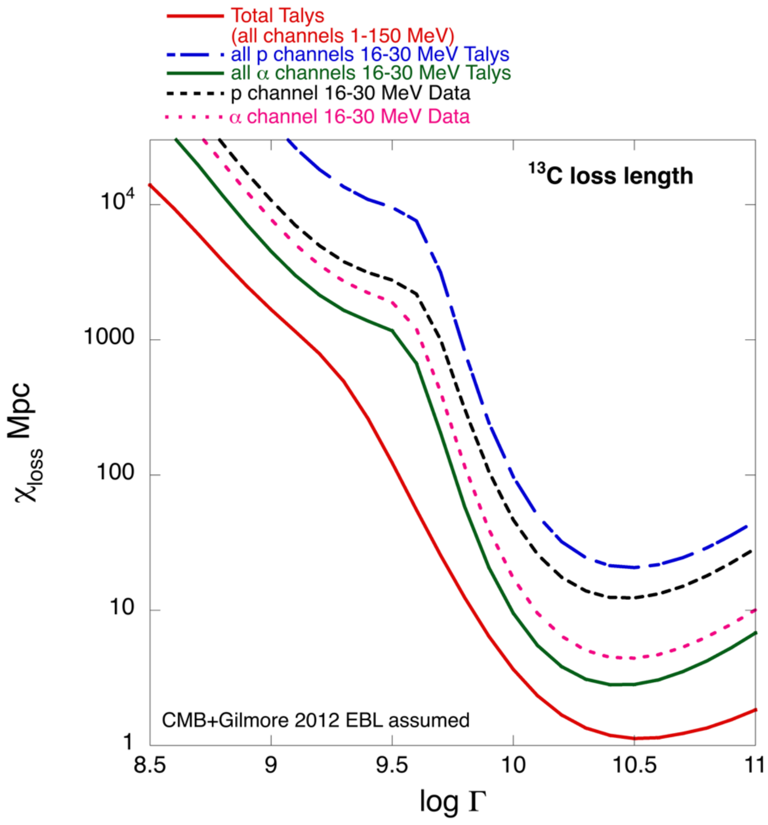
^{13}C Proton and alpha channels





^{13}C loss length comparisons, total vs partials

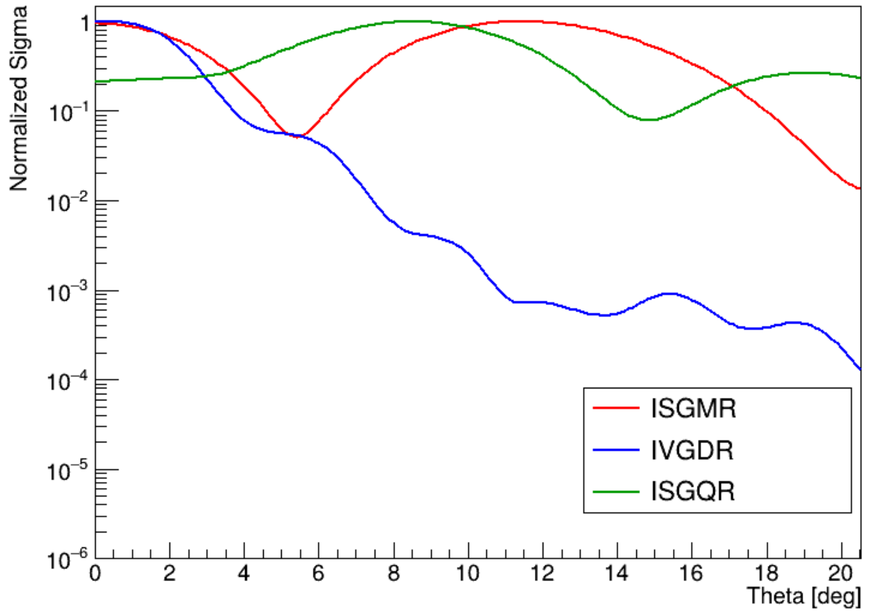


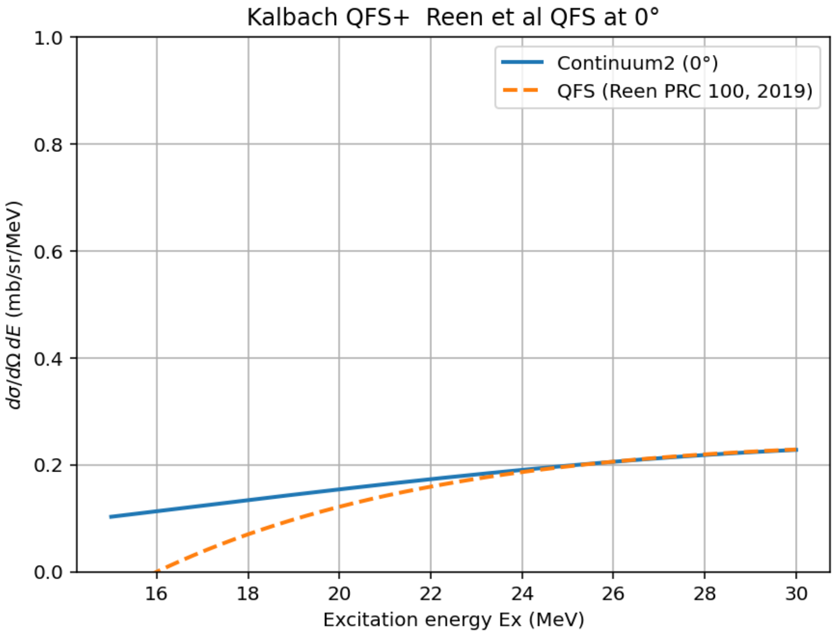


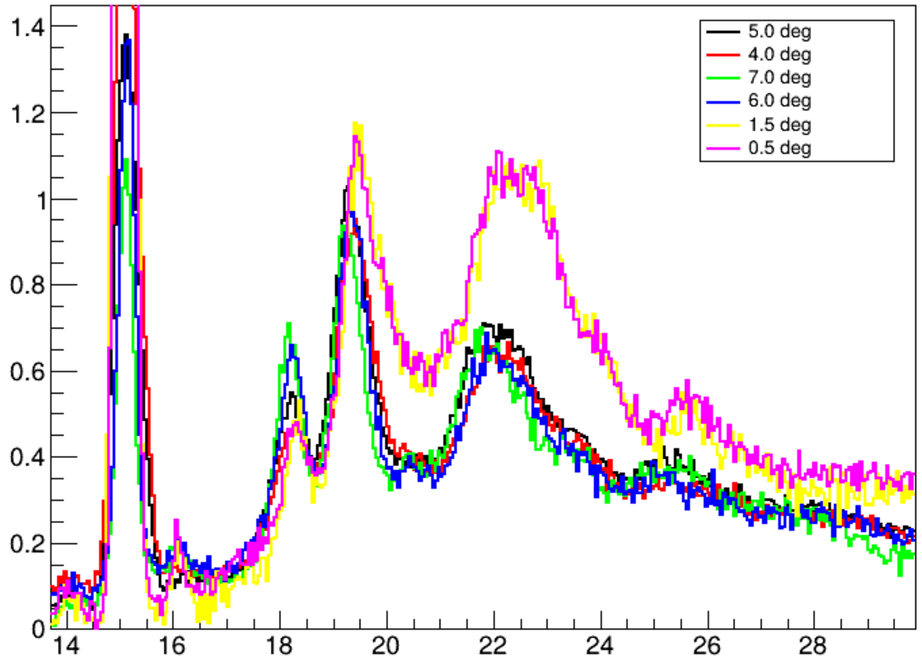
MDA vs DoS – validation and Comparison

- Idea is to compare the DoS vs MDA for this experiment.
- If there is a large discrepancy to understand where that comes from and to have the confidence to do be able to use both in situations where it is necessary.
- For MDA we require DWBA and Continuum background calculations –Fresco and Kalbach systematics.

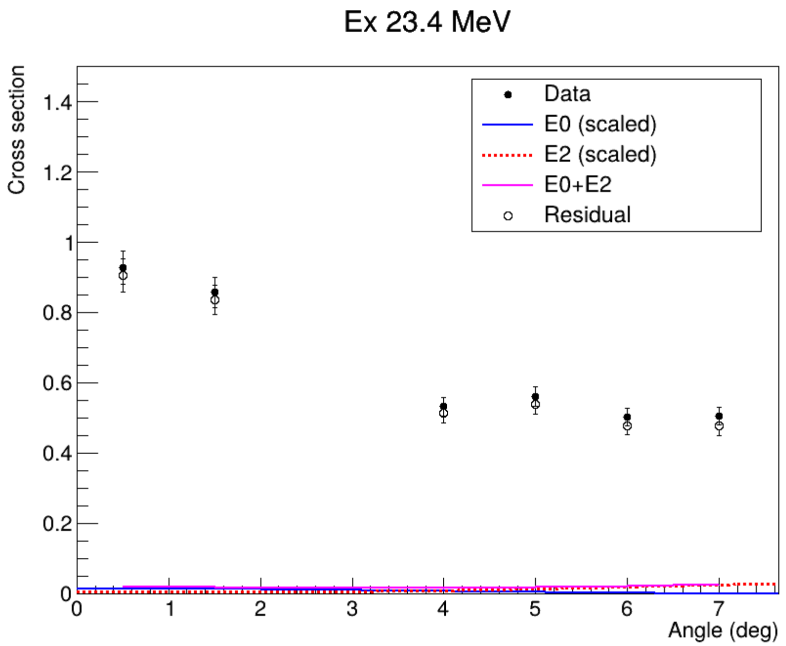
Three DWBA and a QFS scattering curve

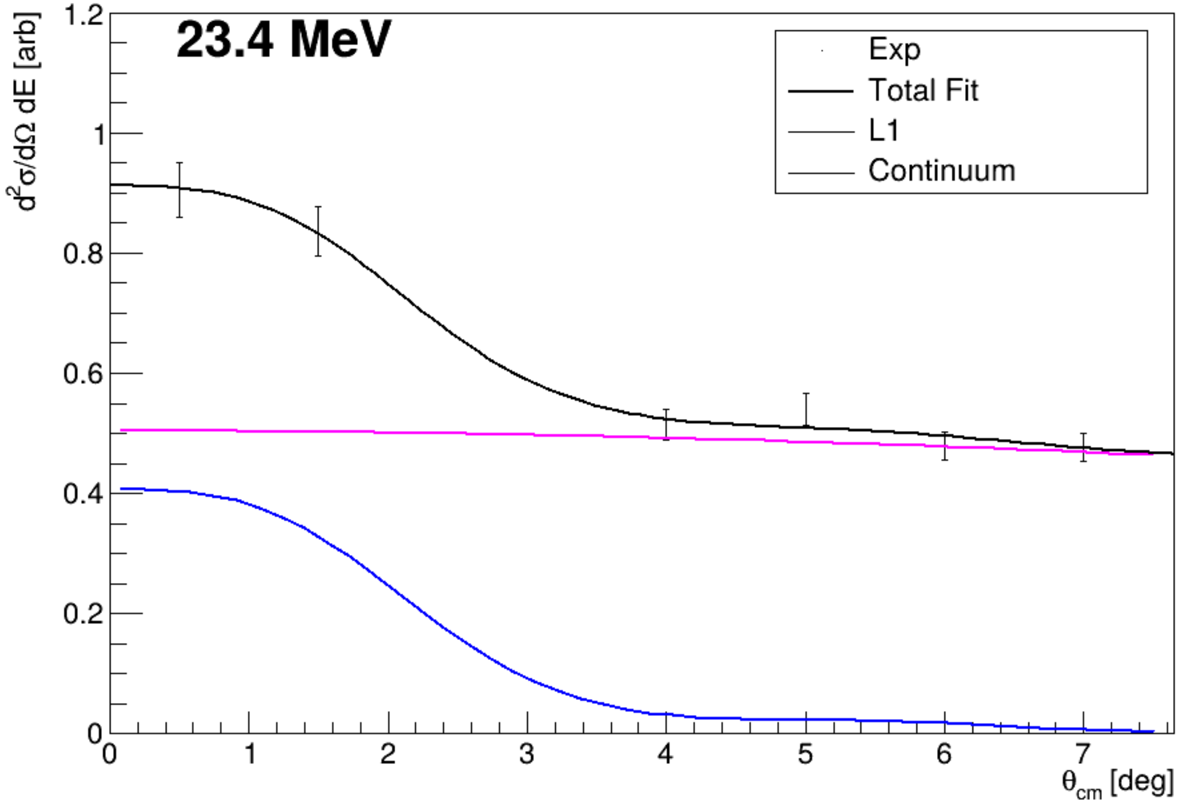


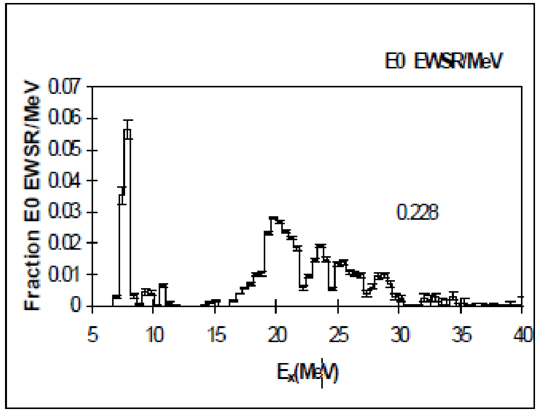


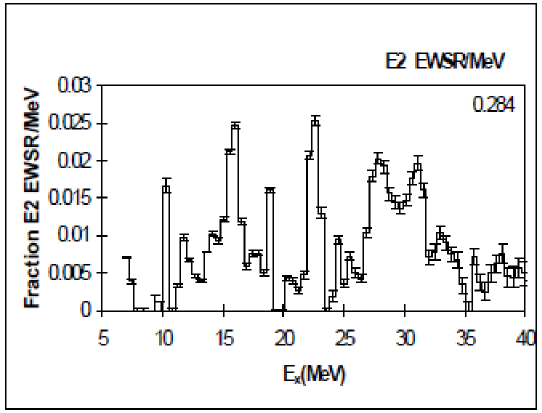


Sample extraction of the MDA





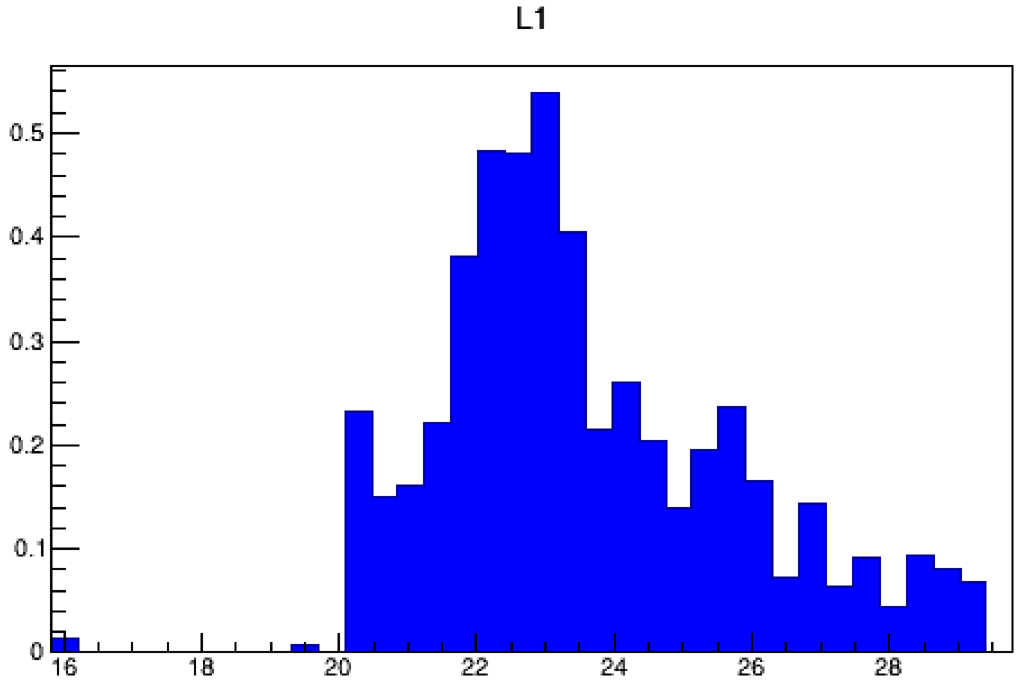


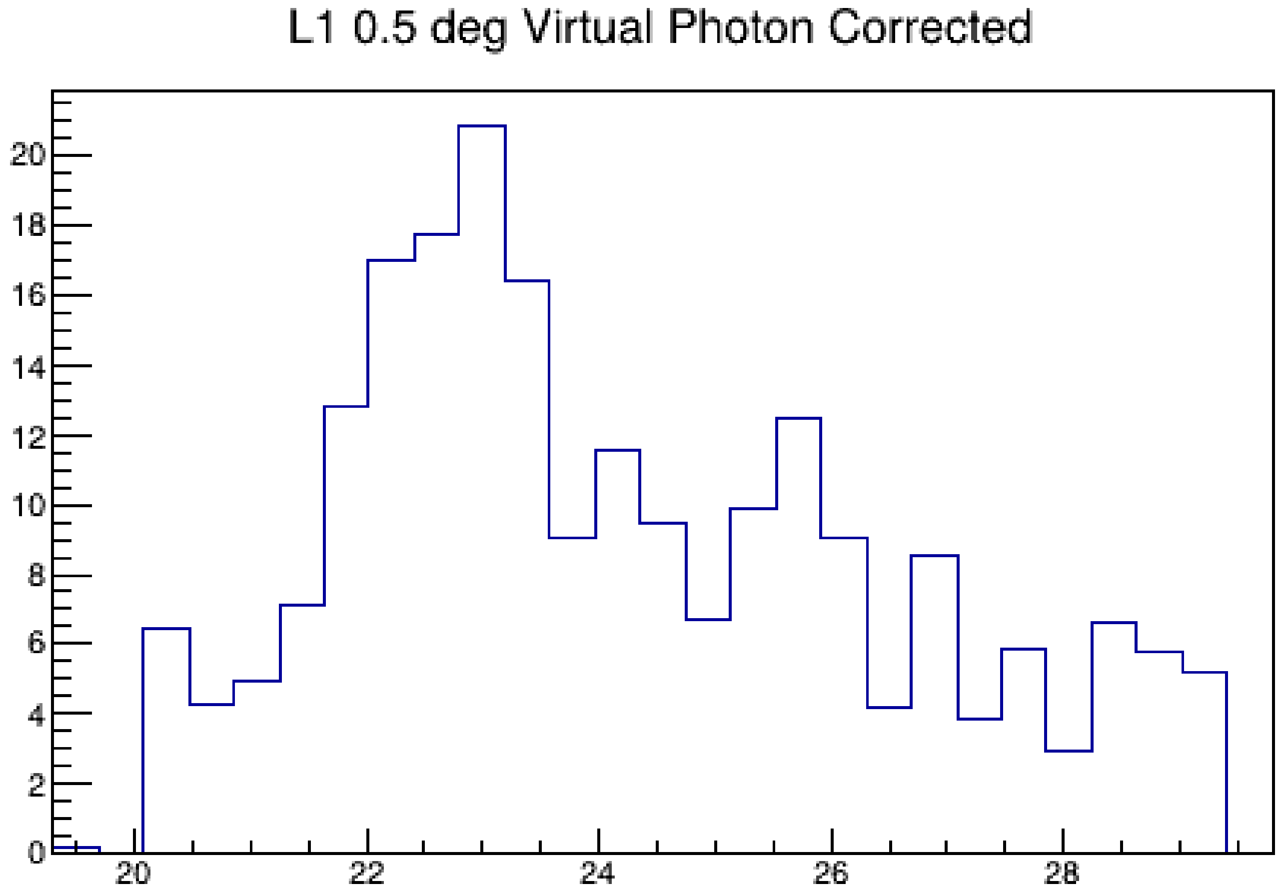


Isoscalar E0, E1, and E2 Strengths in ^{12}C

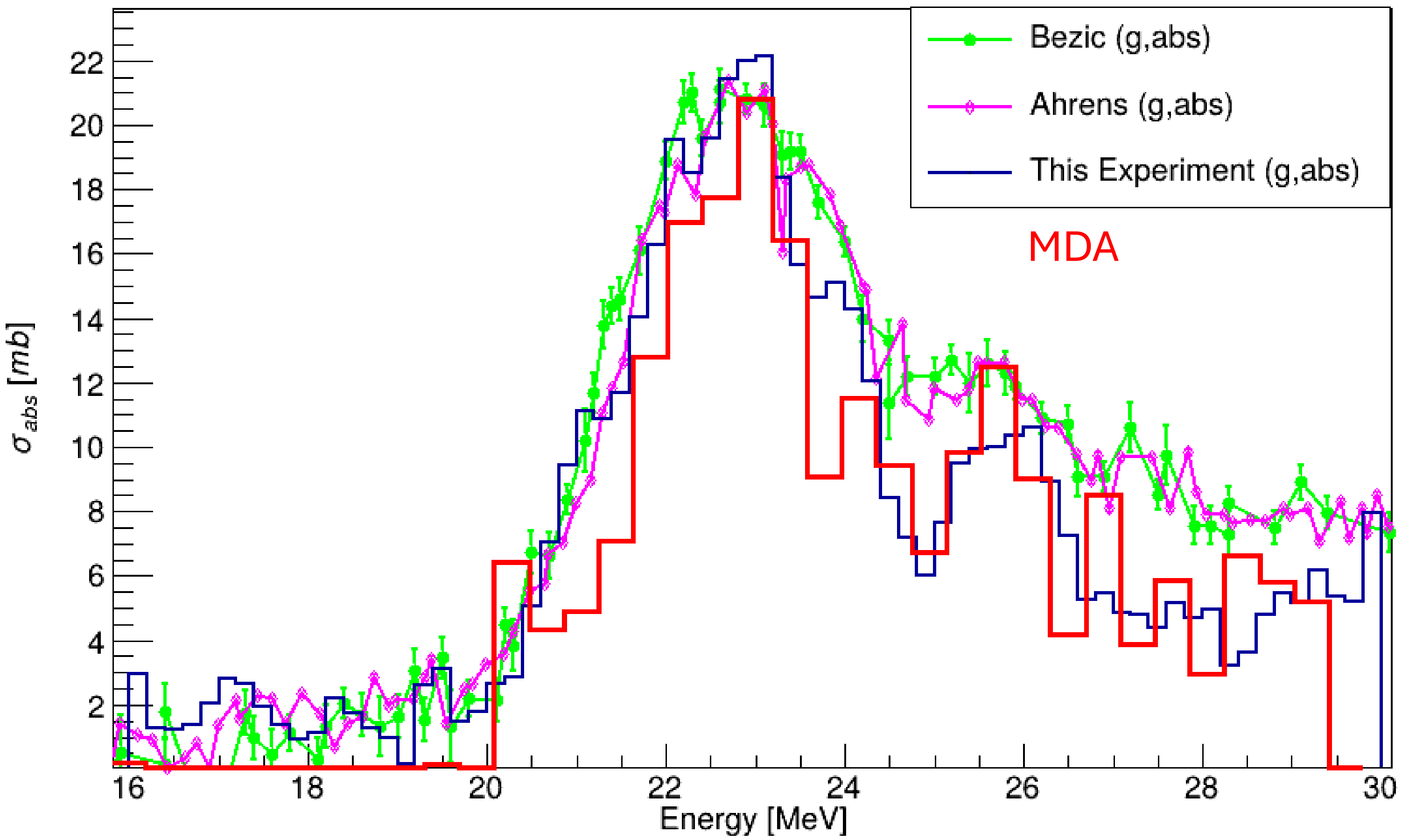
Bency John, Y. Tokimoto, Y. -W. Lui, H. L. Clark, and D. H. Youngblood

From the MDA the IVGDR appears!





And it compares well with real data, maybe a slight undershoot.



Questions?