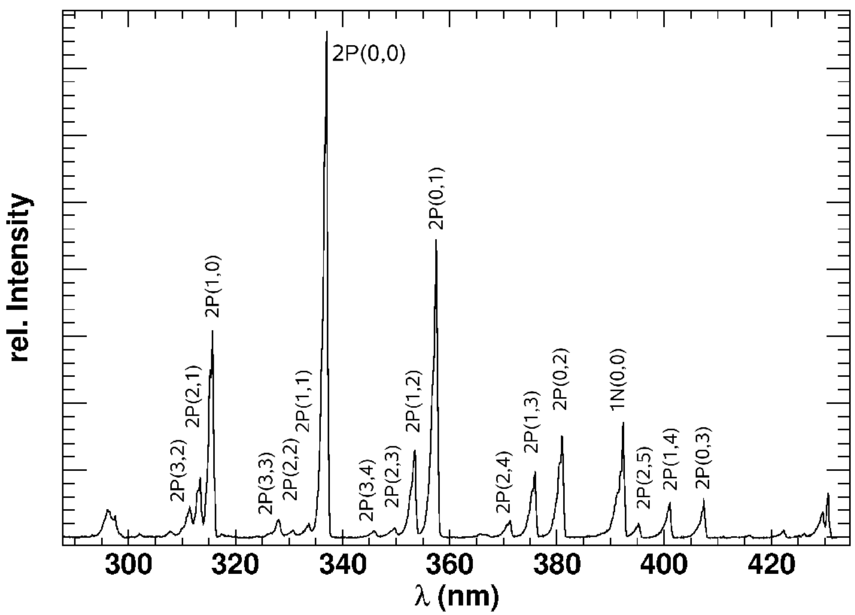
International Symposium on the Recent Progress of Ultra-High Energy Cosmic Ray Observation
December 10-12, 2010 Nagoya, Japan

Measurement of the Air Fluorescence Yield by

AIRFLY



Paolo Privitera

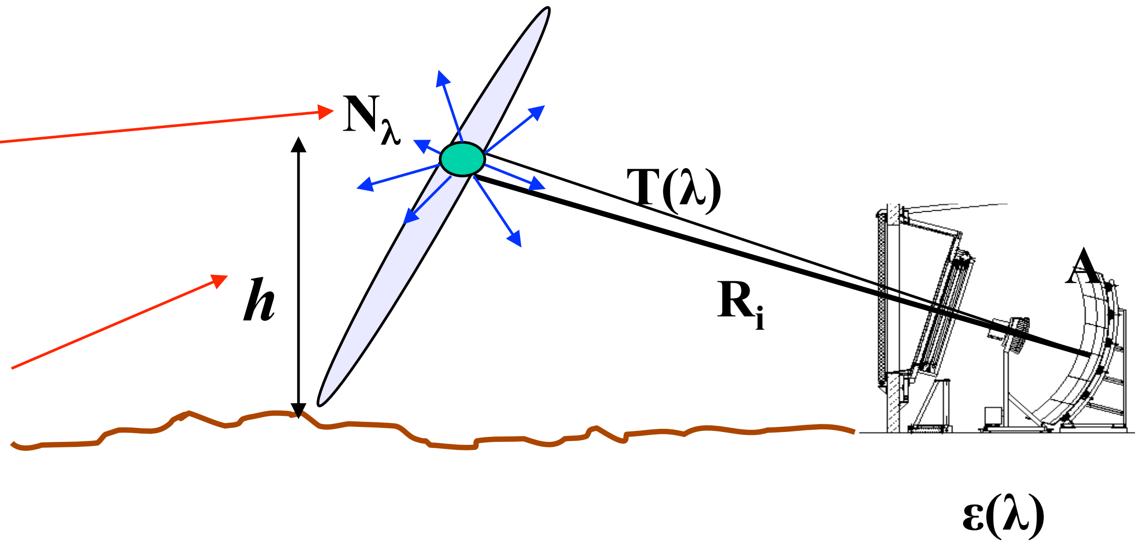
THE UNIVERSITY OF CHICAGO
PHYSICAL SCIENCES

The Enrico Fermi Institute
The Kavli Institute for Cosmological Physics

for the AIRFLY Collab.

UHECR Fluorescence Detection and Fluorescence Yield

- Fluorescence Spectrum
- p, T and humidity dependence
- Proportionality to energy deposit
- Absolute yield



$$N_\lambda^{\mathrm{shower}}(h) = E_{\mathrm{dep}}^{\mathrm{shower}}(h) Y_{\mathrm{air}}(\lambda, p, T)$$

ΔE/E = 22% in Auger - largest syst. is 14% from absolute yield

AIRFLY strategy

- Precise measurement of fluorescence band intensities dependence on p, T, and H (relative to 337 nm band)
- Measurement of the absolute yield of 337 nm band

$$Y_{\mathrm{air}}(\lambda, p, T) = Y_{\mathrm{air}}(337, p_0, T_0) I_\lambda(p_0, T_0) \frac{1 + \frac{p_0}{p'_{\mathrm{air}}(\lambda, T_0)}}{1 + \frac{p}{p'_{\mathrm{air}}(\lambda, T_0)\sqrt{\frac{T}{T_0}\frac{H_\lambda(T_0)}{H_\lambda(T)}}}}.$$

Absolute yield of 337 nm line (photons/MeV)

Band intensity relative to the 337 nm line

Quenching reference pressure

Temperature dependence

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AIRFLY

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+ **Fermilab** (C. Hojvat, F. Kuehn)

AIRFLY beams

Beam Test Facility INFN FRASCATI (50-750 MeV)

Chemistry Division Van de Graaff (0.5-3 MeV)

HEP Division
Advanced
Wakefield
Accelerator

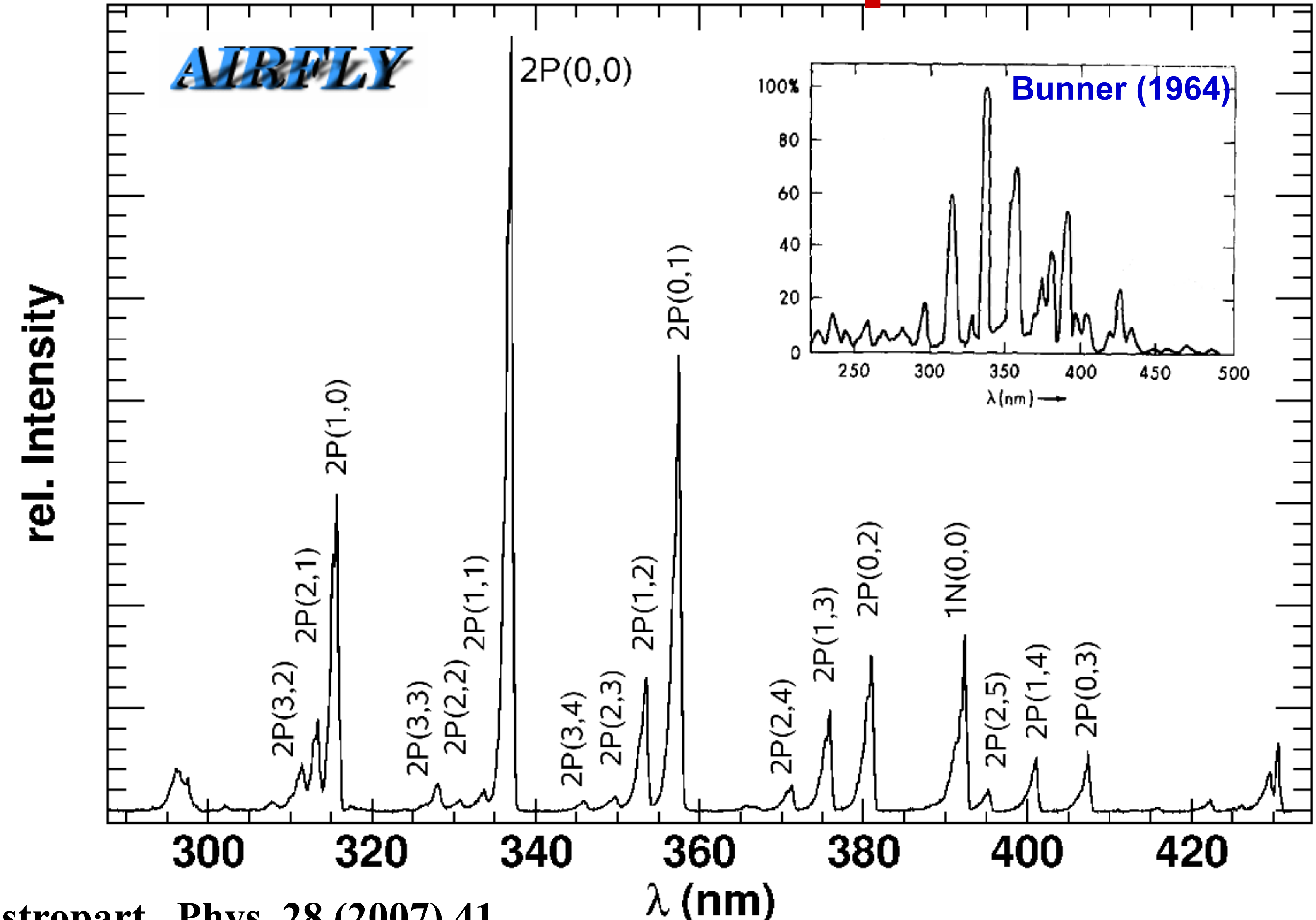
(3 MeV-15 MeV)

Advanced
Photon
Source

(6-30 KeV)

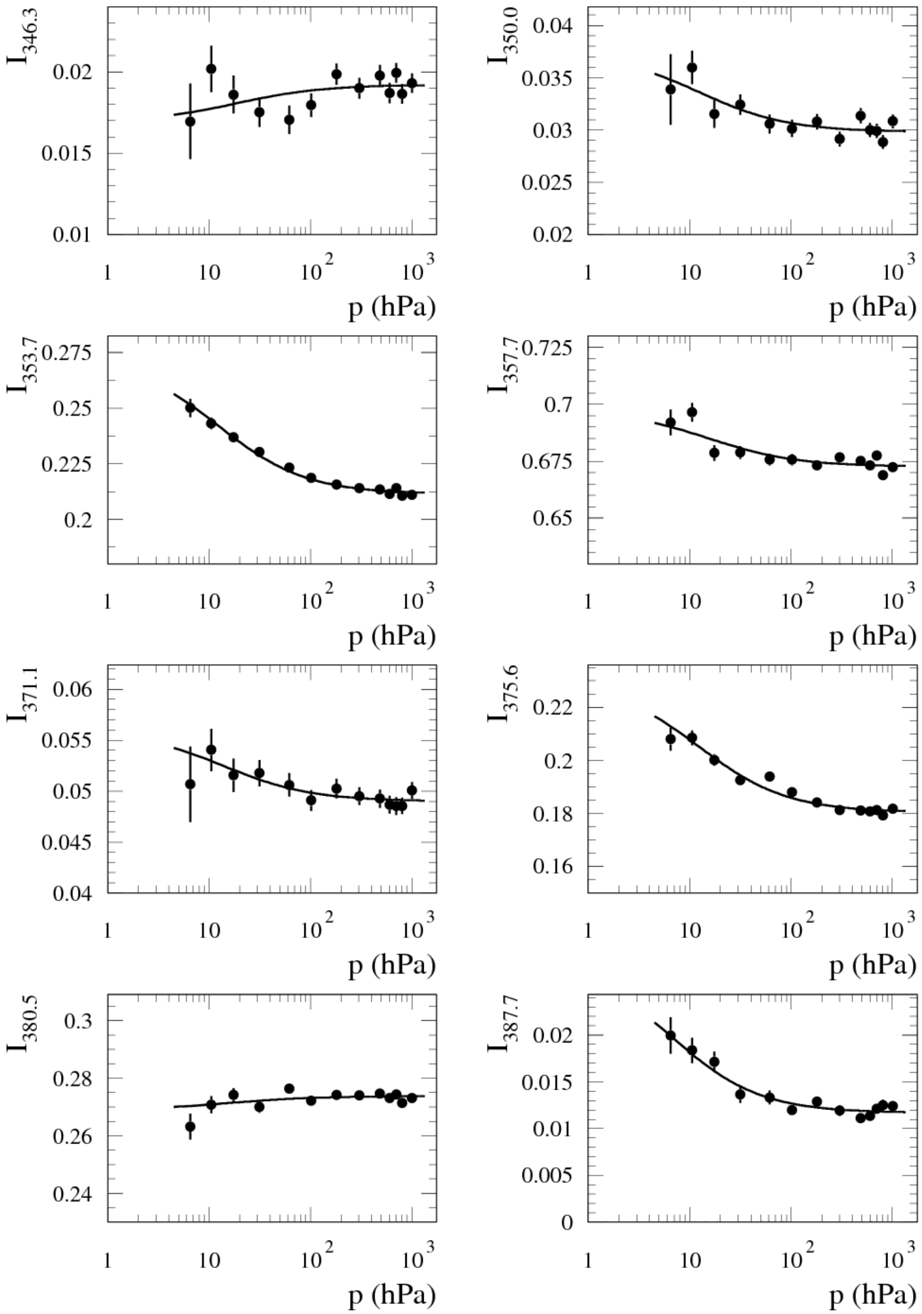
Meson Test Beam (Up to 120 GeV)

Air fluorescence spectrum



Astropart. Phys. 28 (2007) 41

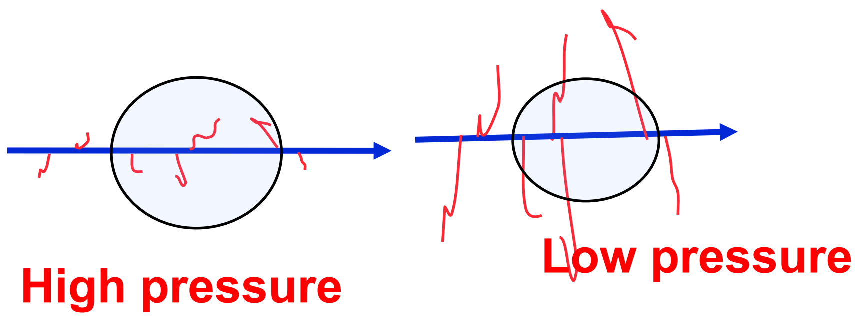
34 band intensities measured (relative to the 337 nm line)



Pressure dependence

- AIRFLY measurement solved previous discrepancies due to neglecting secondary electrons escaping the field of view

(**~all the fluorescence emission is produced by secondary electrons**)



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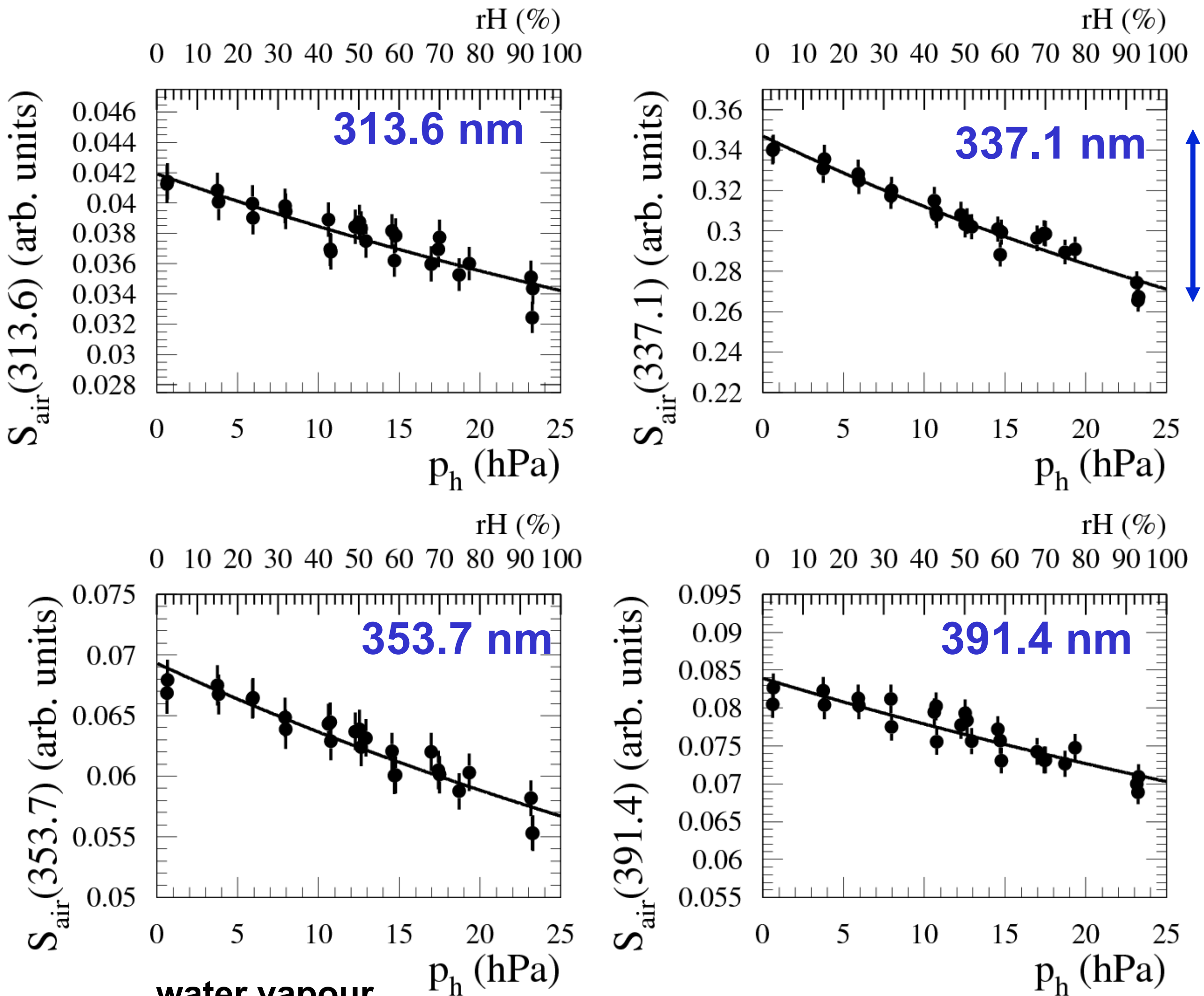


20 % !

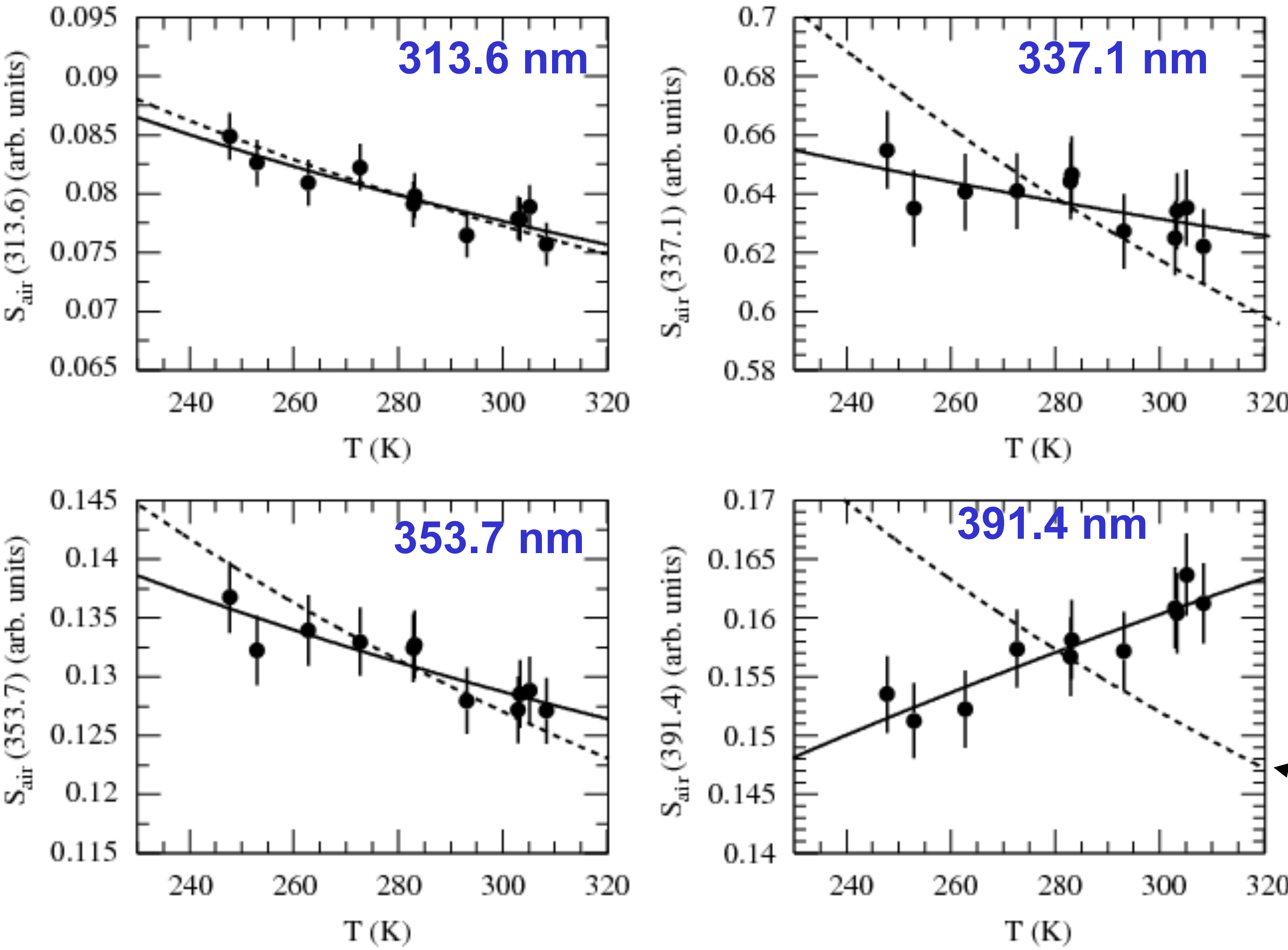
Humidity dependence

NIM A597 (2008) 50

water vapour partial pressure

$$\frac{1}{p'_{air}} \rightarrow \frac{1}{p'_{air}}\left(1-\frac{p_h}{p}\right)+\frac{1}{p'_{H_2O}}\frac{p_h}{p}$$

	λ (nm)	p'_{H_2O} (hPa)
2P(2,1)	313.6	1.21 ± 0.13
2P(0,0)	337.1	1.28 ± 0.08
2P(1,2)	353.7	1.27 ± 0.12
1N(0,0)	391.4	0.33 ± 0.03



RANGE [-40,30] ^{0}C

up to 10 % effect!

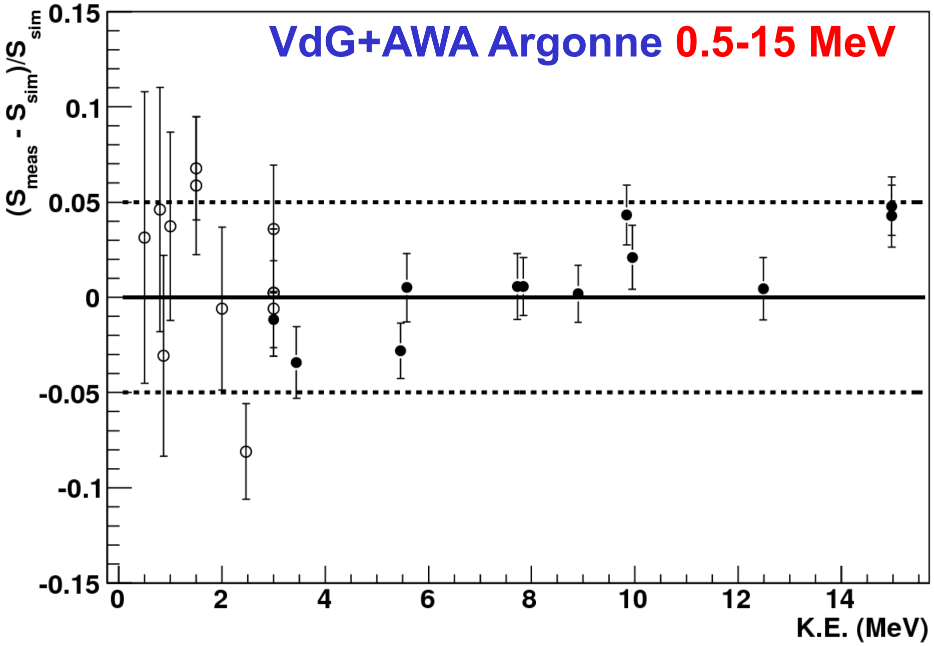
$\alpha = 0$
(assumed)

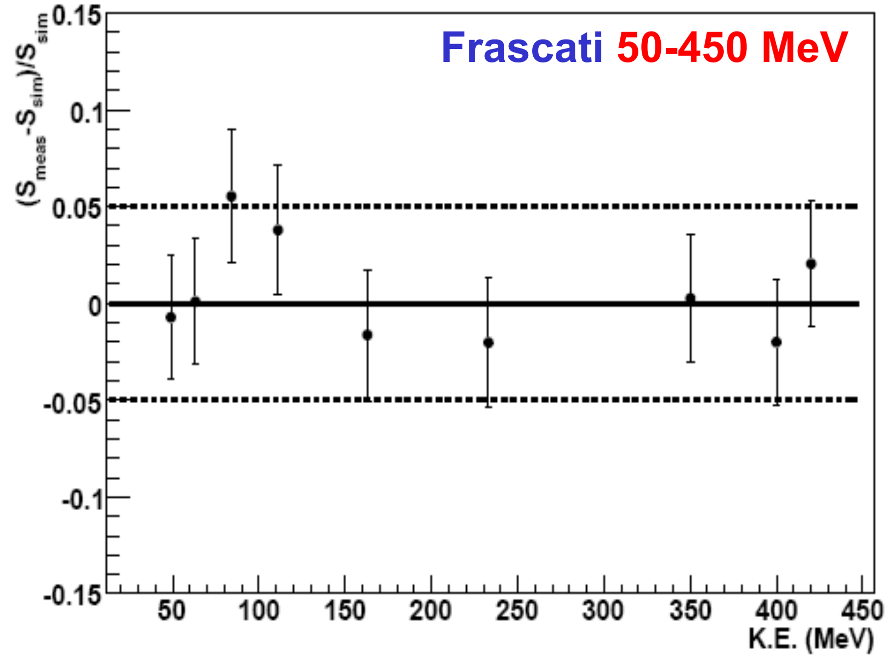
Temperature dependence

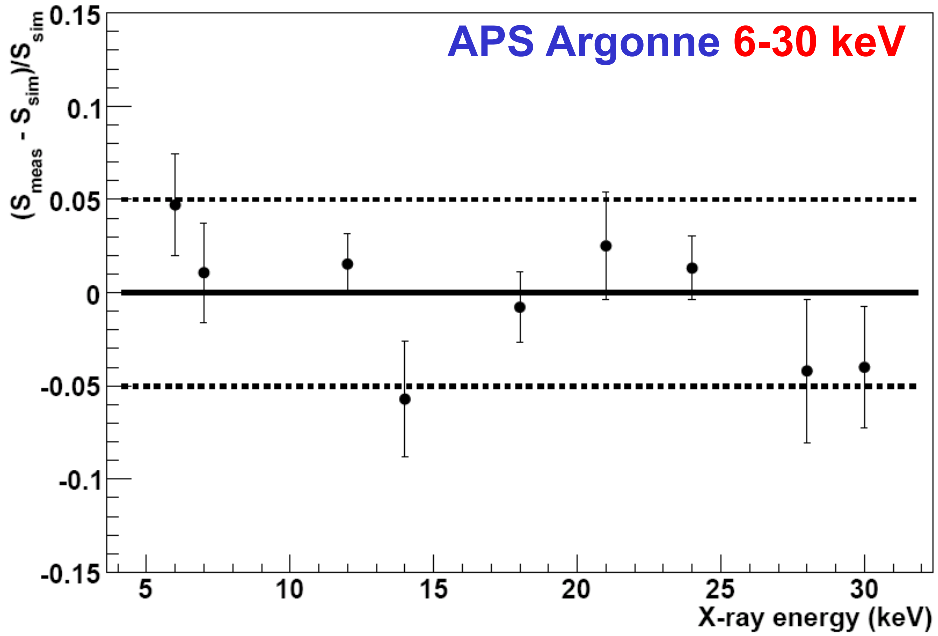
	λ (nm)	α_λ
2P(2,1)	313.6	-0.09 ± 0.10
2P(0,0)	337.1	-0.36 ± 0.08
2P(1,2)	353.7	-0.21 ± 0.09
1N(0,0)	391.4	-0.80 ± 0.09

$\alpha \neq 0$!

NIM A597 (2008) 50







Energy dependence

NIM A597 (2008) 46

Proportionality of fluorescence yield to E_{dep} at few %

Absolute yield of the 337 nm line

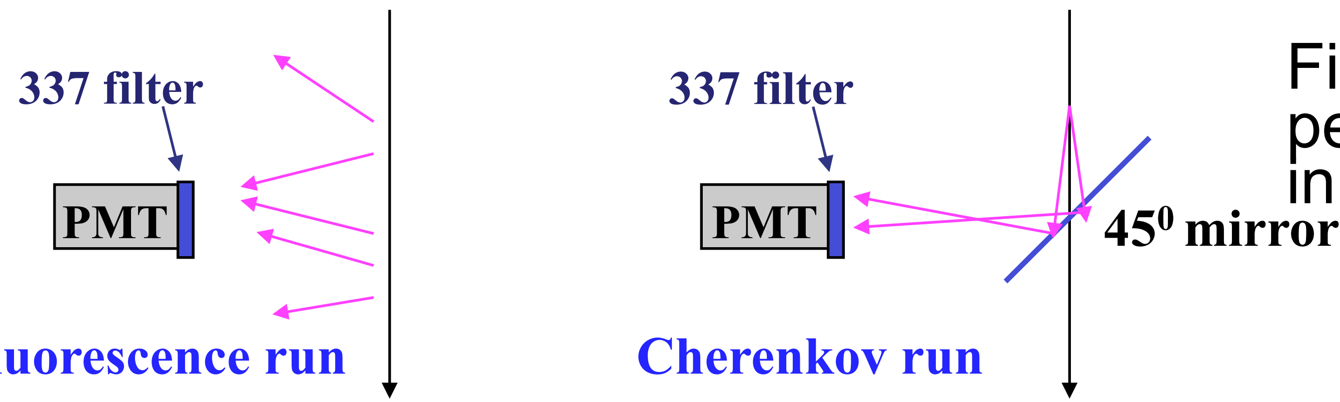
Main systematic comes from absolute QE of photon detector

AIRFLY: normalize to a well known process (Cherenkov emission) to cancel detector systematics

$$N_{337}(\text{fluor.}) = \text{FLY} \times \text{Geom}_{fluor} \times T_{filter} \times QE_{337}\ .$$

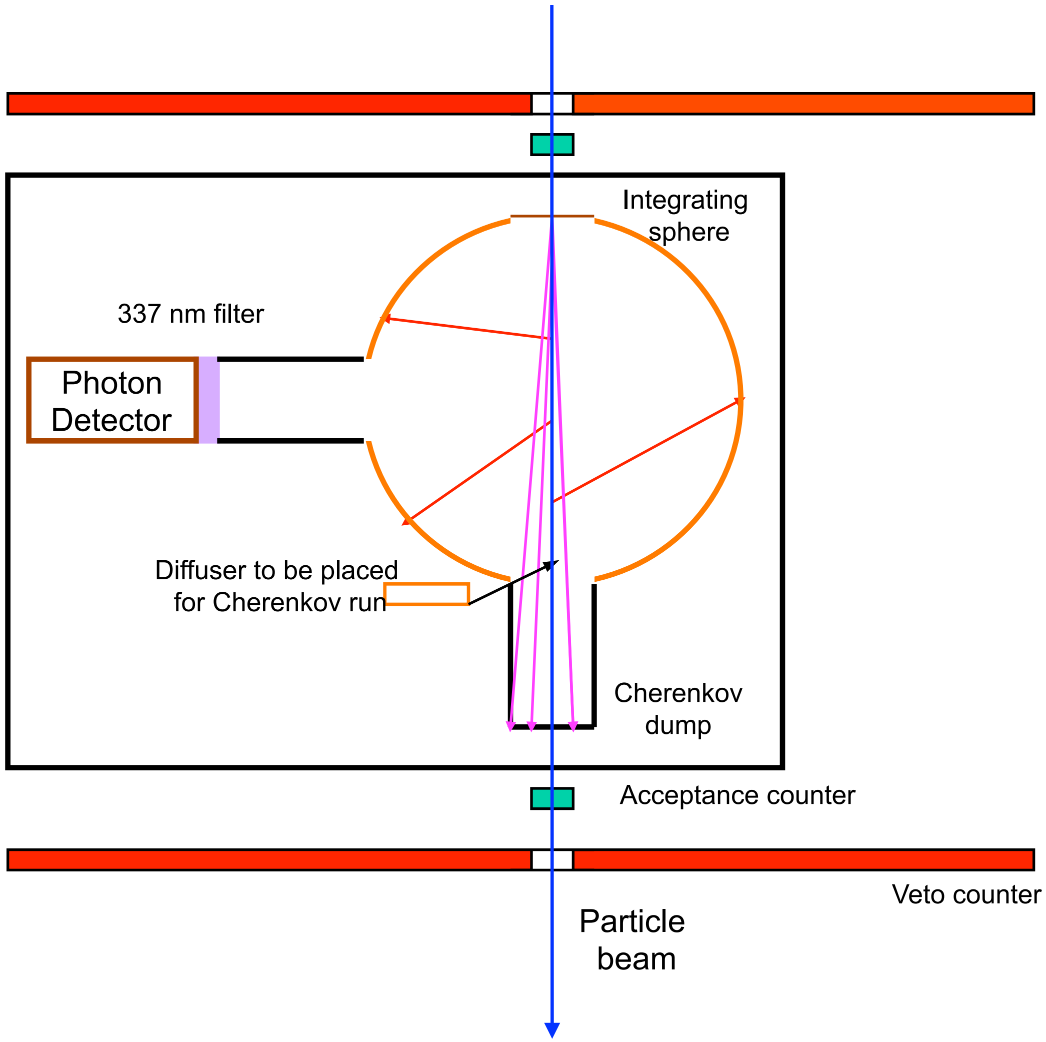
measured known MC ~cancel! measured

$$N_{337}(\text{Cher.}) = \text{CHY} \times \text{Geom}_{cher} \times T_{filter} \times QE_{337.} \times \varepsilon_{mirr}$$



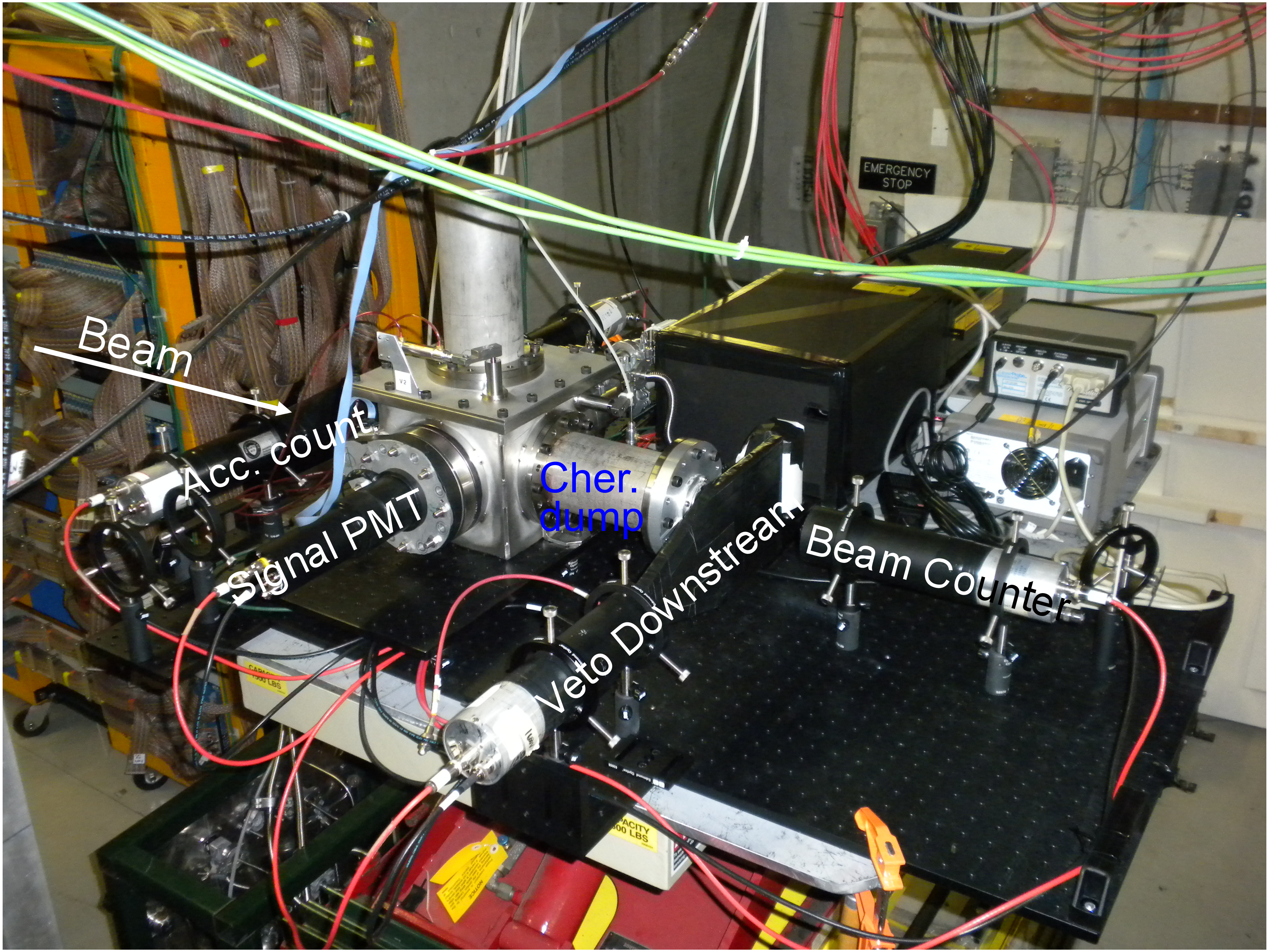
First test performed in Frascati

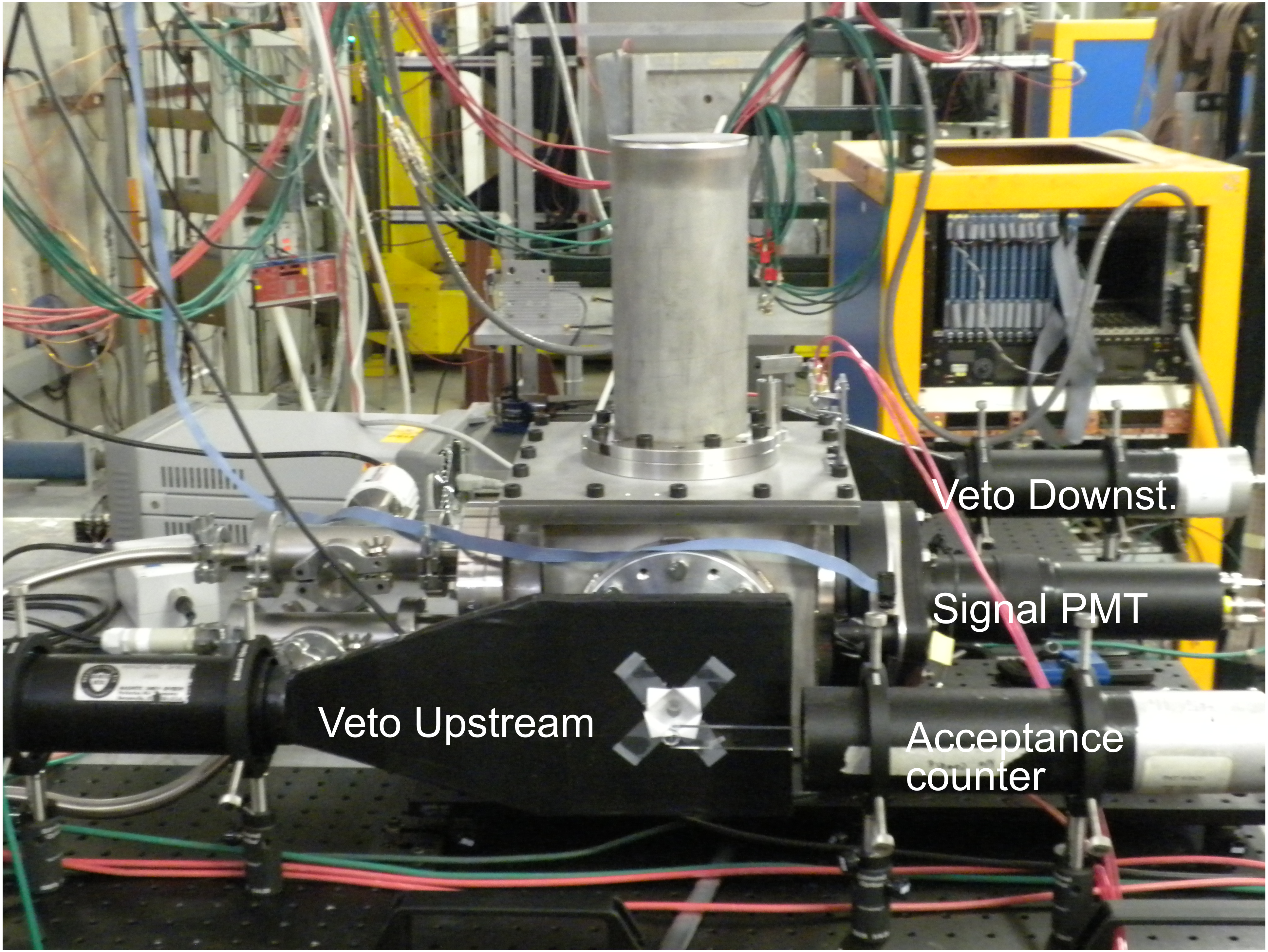
AIRFLY at the Fermilab Test Beam

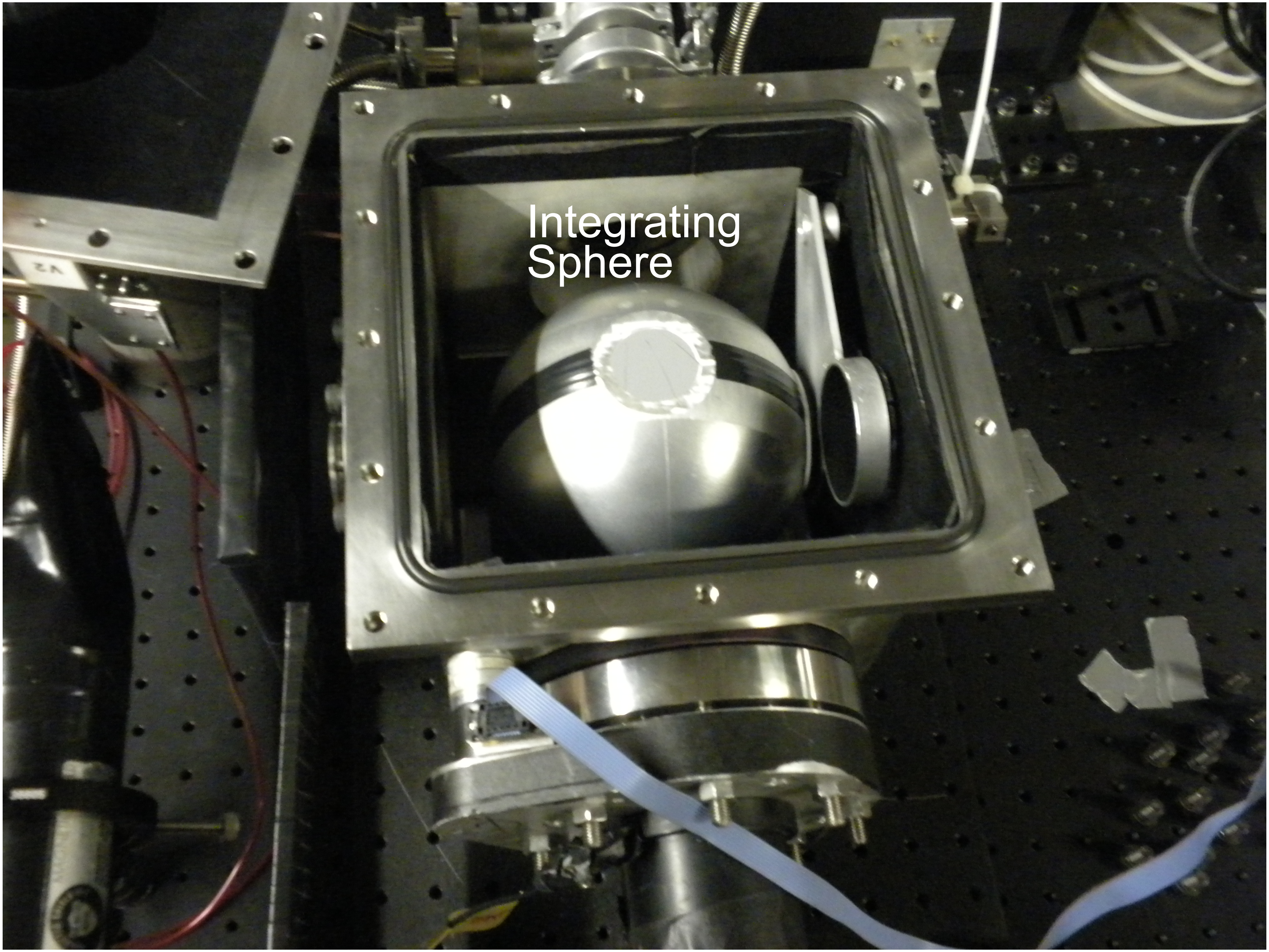


- High energy up to 120 GeV
- Well defined beam: single particle trigger and geometry
- Wide range of particles type and intensity (p, e, μ, π)

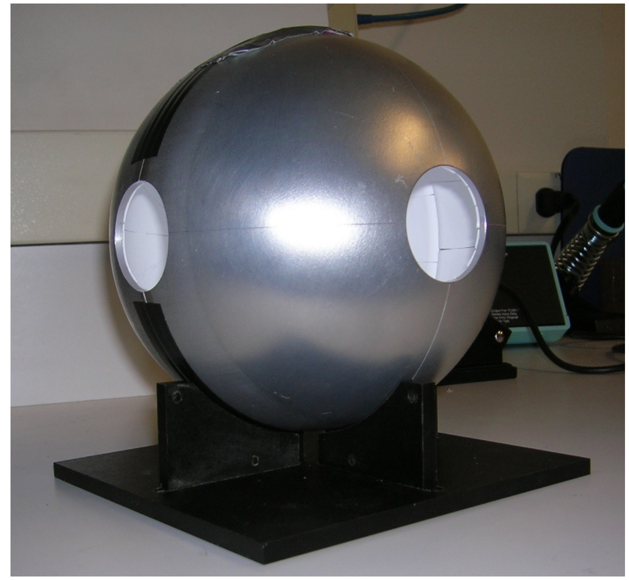
- Absolute calibration with <u>two independent methods</u>: Cherenkov and laser light


Beam
Acc. count.
Signal PMT
Cher.
dump
Veto Downstream
Beam Counter
EMERGENCY
STOP


Veto Downst.
Signal PMT
Veto Upstream
Acceptance counter


Integrating
Sphere

Why use an Integrating Sphere?



• Lambertian light output independent of input light distribution

Fluorescence isotropic –

Cherenkov highly beamed

• Depolarize light

•**Fluorescence unpolarized –**

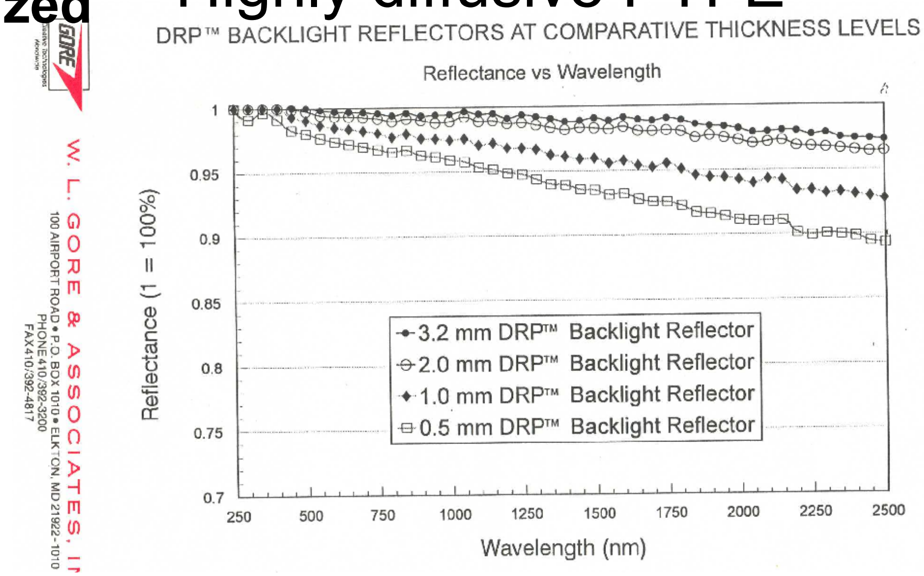
Cherenkov polarized

no syst. from angular or polarization dependent efficiency of PMT+337 nm filter

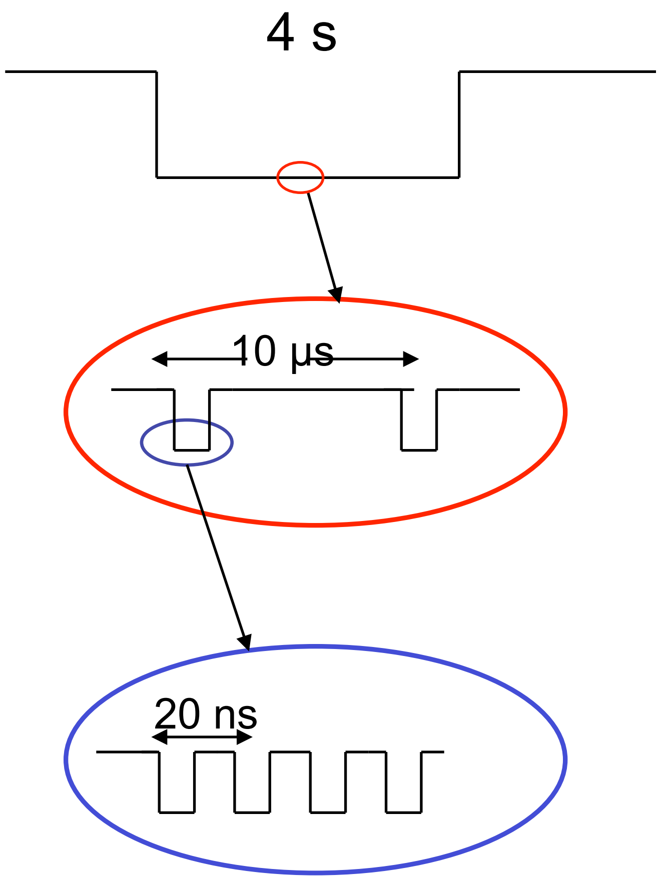
• Collect photons over ~4π

Improve signal/bkg ratio

Highly diffusive PTFE

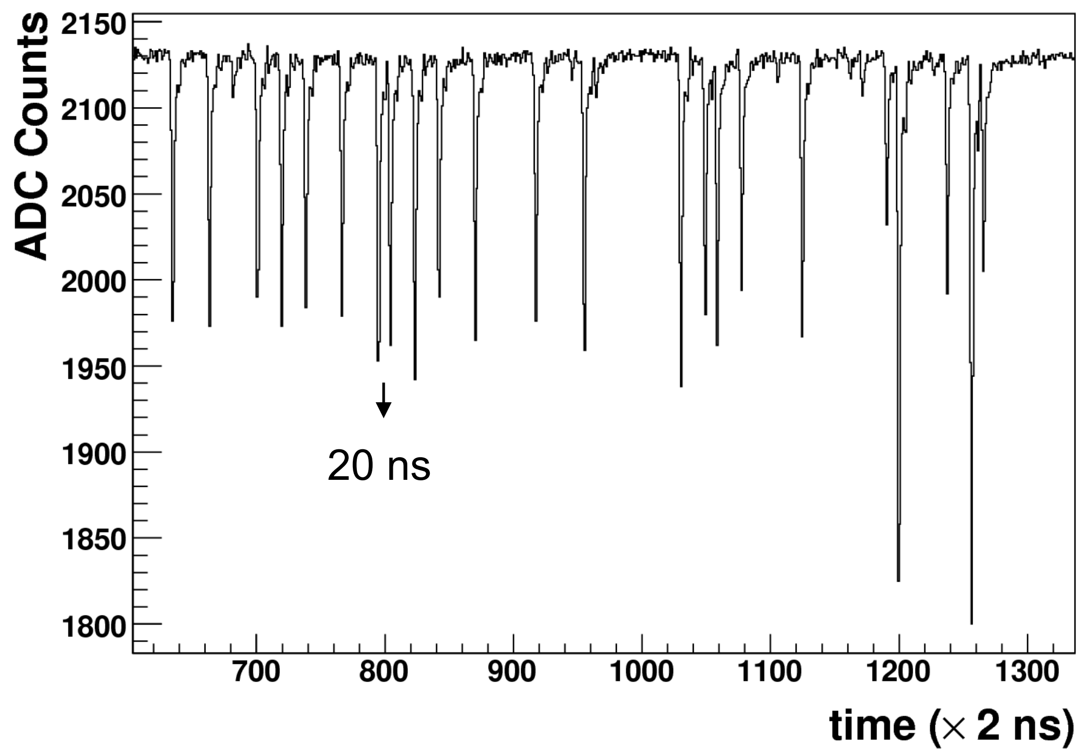


Single particle triggering



1 spill / min

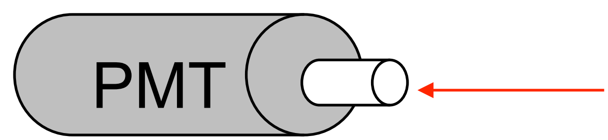
Several 10^5 particles/spill



Up to 70 bunches

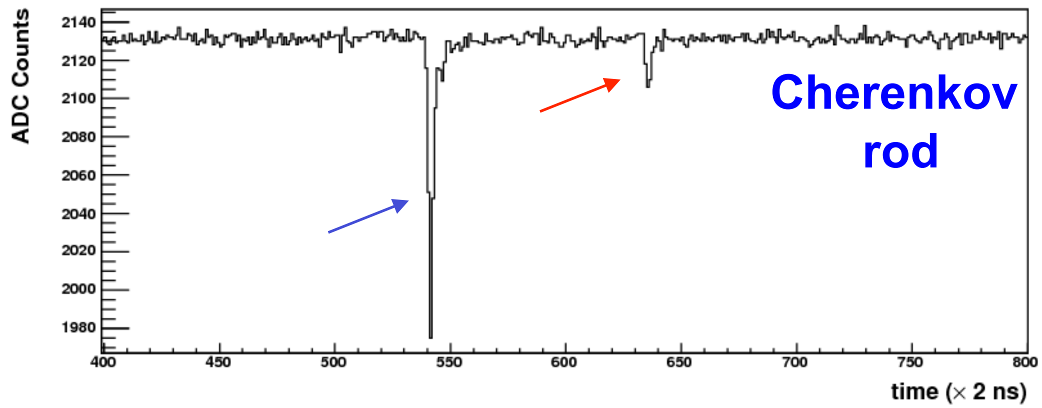
Need single particle resolution, fast detector

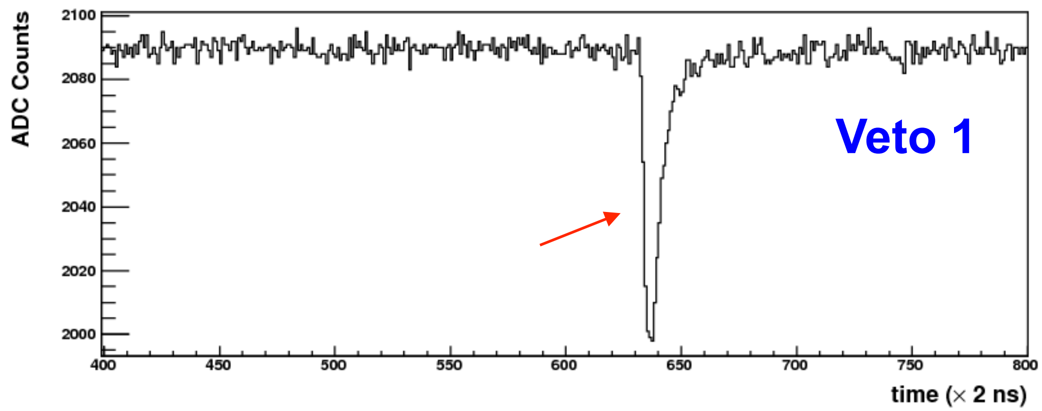
Cherenkov, FADC 500 MHz

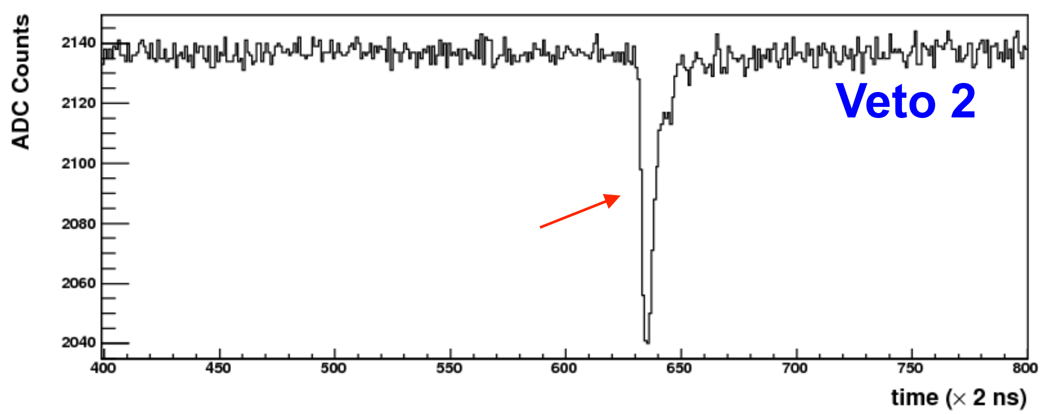


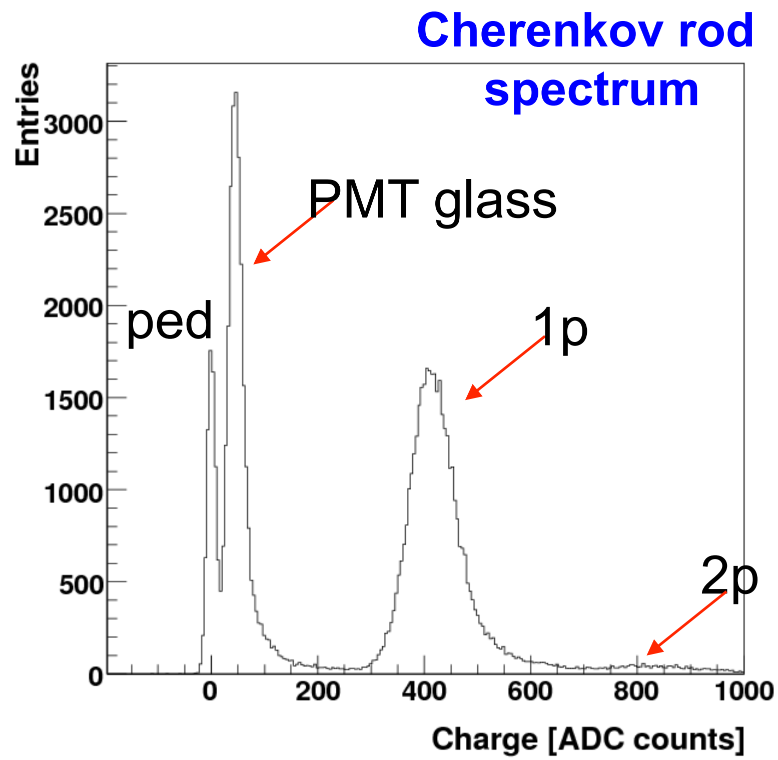
UV transparent acrylic rod

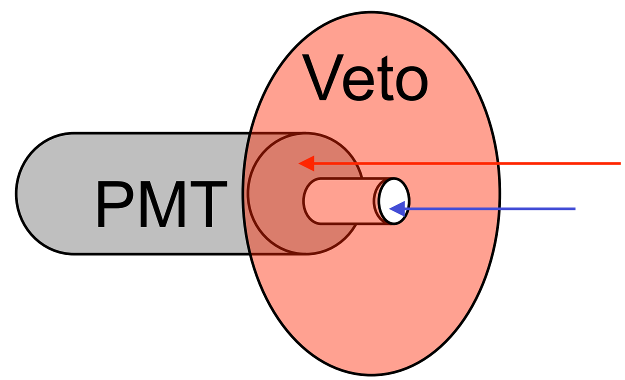
Single particle triggering







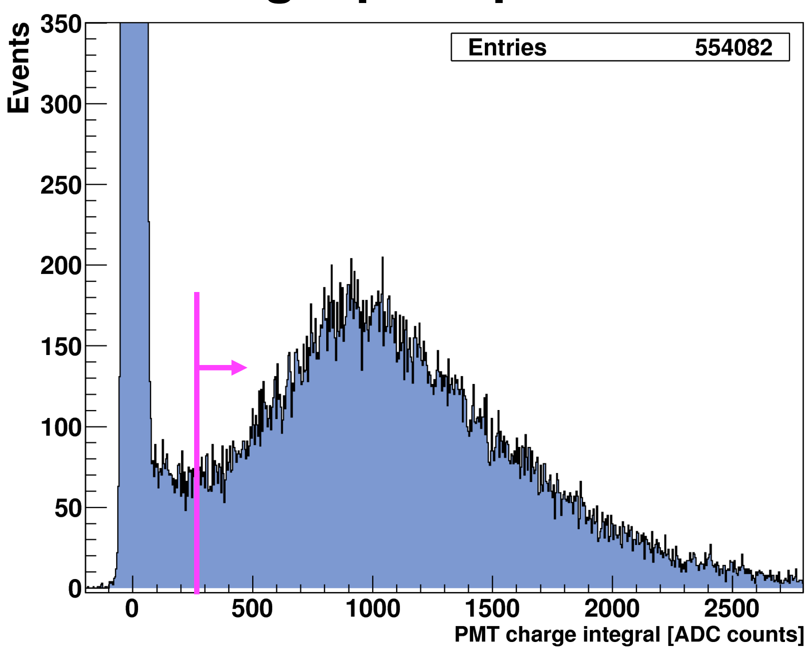


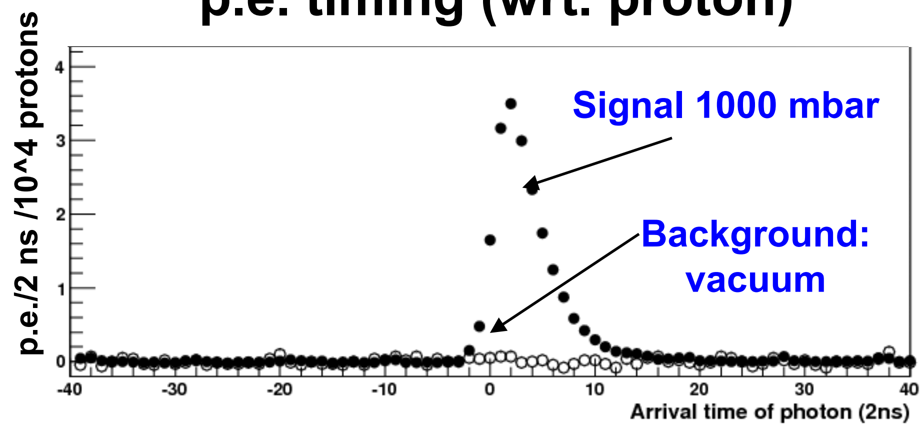


Very clean single particle selection

Fluorescence Measurement in N_2

120 GeV protons

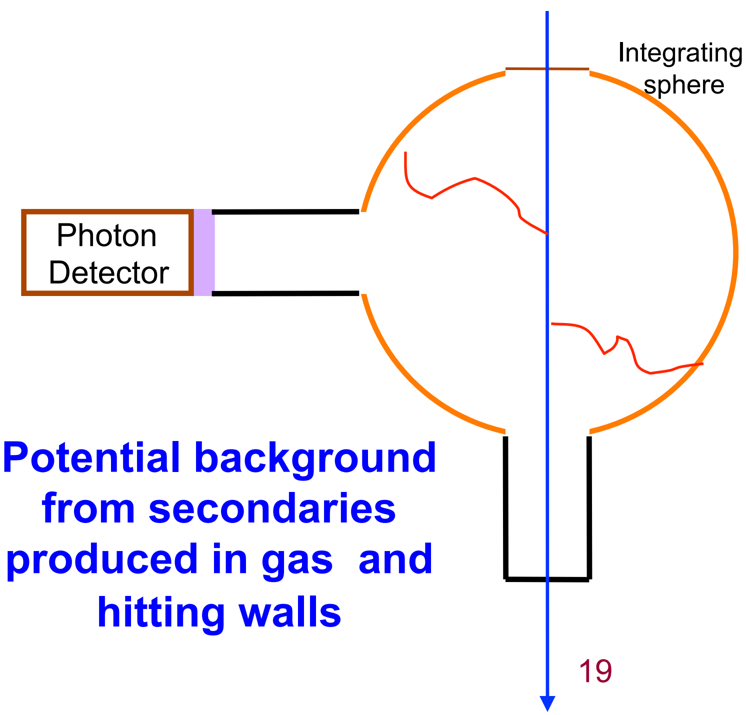




S_{FL} (N_2)= (20.05 ± 0.11) 10^{-4} p.e./proton

S_{FL}(vac) = (0.48 ± 0.09) 10^{-4} p.e./proton

Counting experiment: select (single, clean) protons and then count the photons they produced.



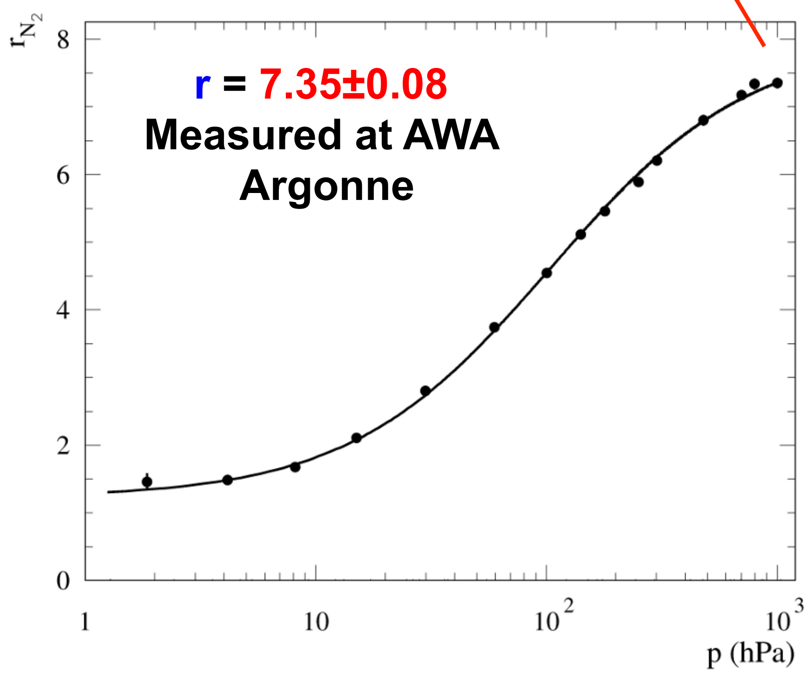
Potential background from secondaries produced in gas and hitting walls

Fluorescence Measurement in N_2 and air

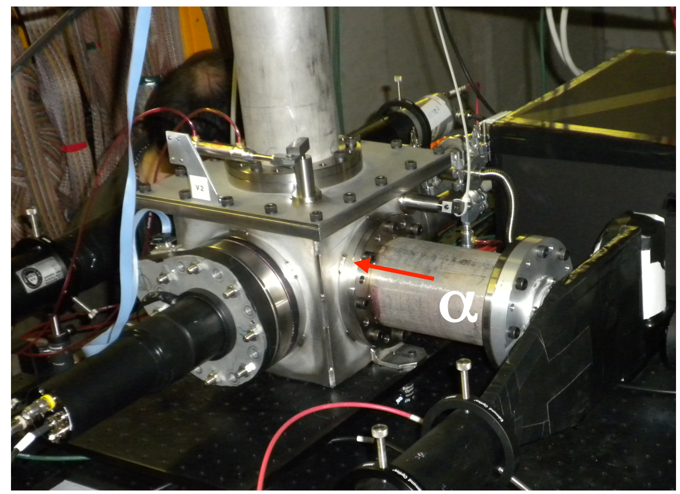
$S_{Fl}(N_2) - S_{Fl}(air) = (Fl_{N2} + Bkg) - (Fl_{air} + Bkg)$

Same background from secondaries produced in air and N_2

$= Fl_{N2} - Fl_{air} = \quad Fl_{N2}\,(1 - 1/r)$



r = 7.45±0.08 measured in the Fermilab apparatus with an alpha source



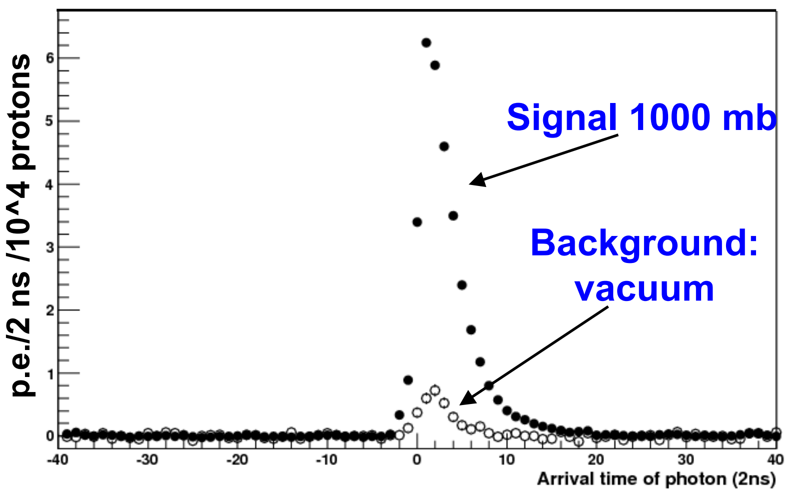
$Fl_{N2} = (19.44 \pm 0.15)\ 10^{-4}$ p.e./proton

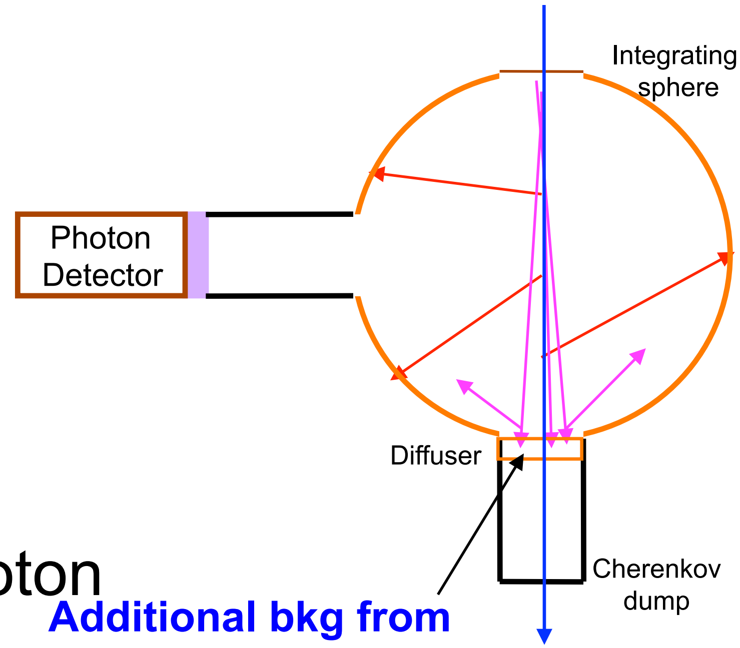
$Bkg = (0.61 \pm 0.08)\ 10^{-4}$ p.e./proton

1% statistical unc.

consistent with vacuum bkg only 3% of signal

Cherenkov Measurement in N_2 and air





$S_{Ch}(N_2) = (32.89 \pm 0.15)\ 10^{-4}$ p.e./proton

$= Ch_{N2} + Fl_{N2} + Bkg + Bkg_{Ch}$

Additional bkg from Cherenkov of beam in DRP (teflon)

$Bkg_{Ch} = (2.57 \pm 0.13)\ 10^{-4}$ p.e./beam particle

Bkg ~10% of Fl+Ch
Measured in vacuum, He

$Ch_{N2} = (10.27 \pm 0.23)\ 10^{-4}$ p.e./beam particle

2% statistical unc.

$Ch_{air} = (10.28 \pm 0.25)\ 10^{-4}$ p.e./beam particle

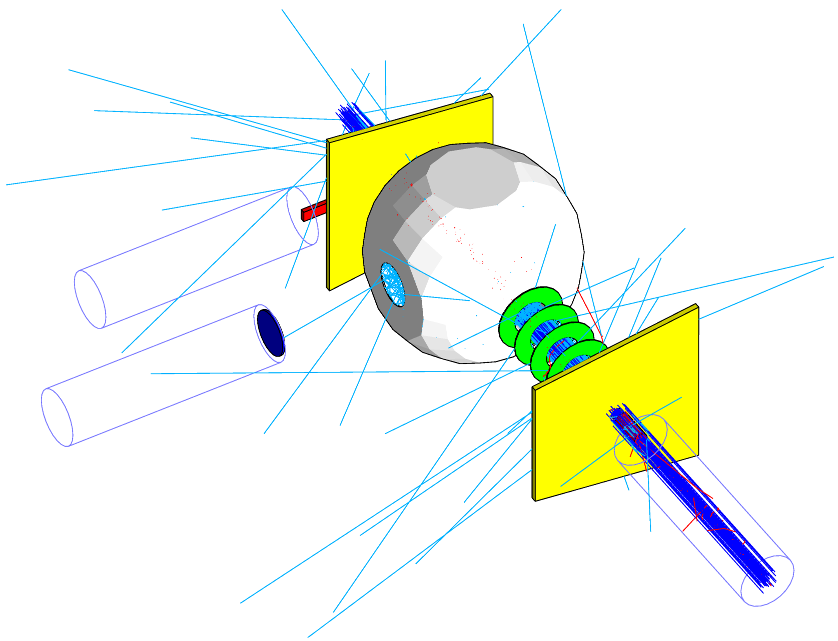
Air ~ N_2

Absolute Yield of 337 nm line

Fluorescence to Cherenkov ratio

Preliminary

$$R_{N2} = \frac{Fl_{N2}}{Ch_{N2}} = 1.893 \pm 0.045$$



Geant4 MC simulation of the experiment.
All individual components simulated according to measurement: wavelength and angular dependence of 337 nm filter transmittance, sphere transmission, PMT QE, relative intensities of fluorescence bands, etc.
Given an absolute fluorescence yield in the simulation, $(Y_{air})_{MC}$, we obtain the expected Fluorescence/Cherenkov ratio, $(R_{air})_{MC}$

$$Y_{air} = \frac{(R_{N2} / r)}{(R_{air})_{MC}} (Y_{air})_{MC} = 5.60 \pm 0.13_{stat} \text{ photons}_{337}\text{/MeV}$$

2.4 % statistical unc., systematic discussed later

Currently used in Auger: 5.05 photons/MeV (Nagano)

A few of many checks

• Measurement reproducibility:

2 test beam periods, each 2 weeks. Apparatus taken apart and mounted again. Very stable results. Gas purity stable.

• Is DRP scintillating?

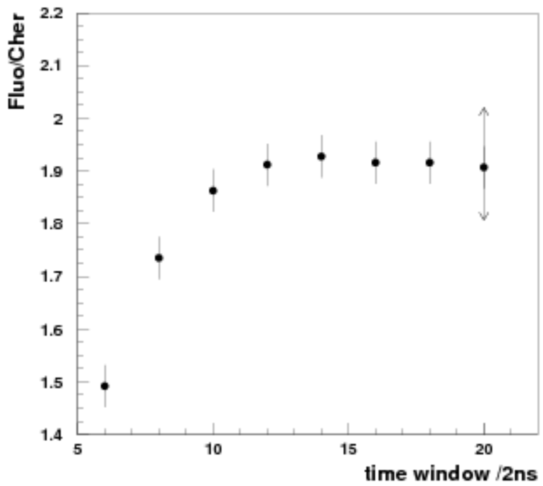
Checked with alphas hitting the sphere under vacuum. No scintillation observed.

• Bkg from secondaries produced in the DRP port in Cherenkov mode?

$S_{Ch}(N_2)$-S_{Ch}(air) = $S_{Fl}(N_2)$-S_{Fl}(air), thus no bkg from secondaries produced in the DRP port

• Fluorescence/Cherenkov stability

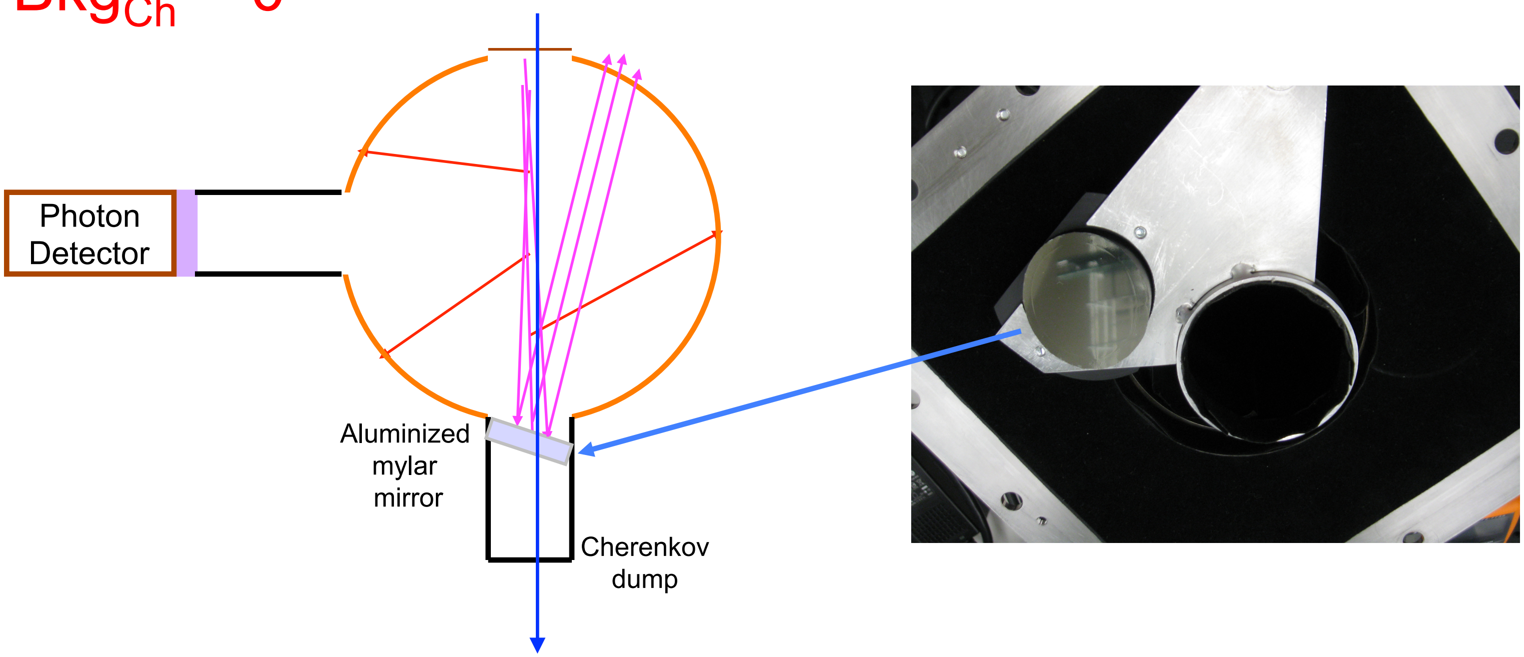
Eg. with respect to time integration of signal



Cross-Check of Fl/Ch

Use an aluminized mylar mirror to bounce Cherenkov light back into the sphere. Eliminate bkg from beam Cherenkov in the DRP

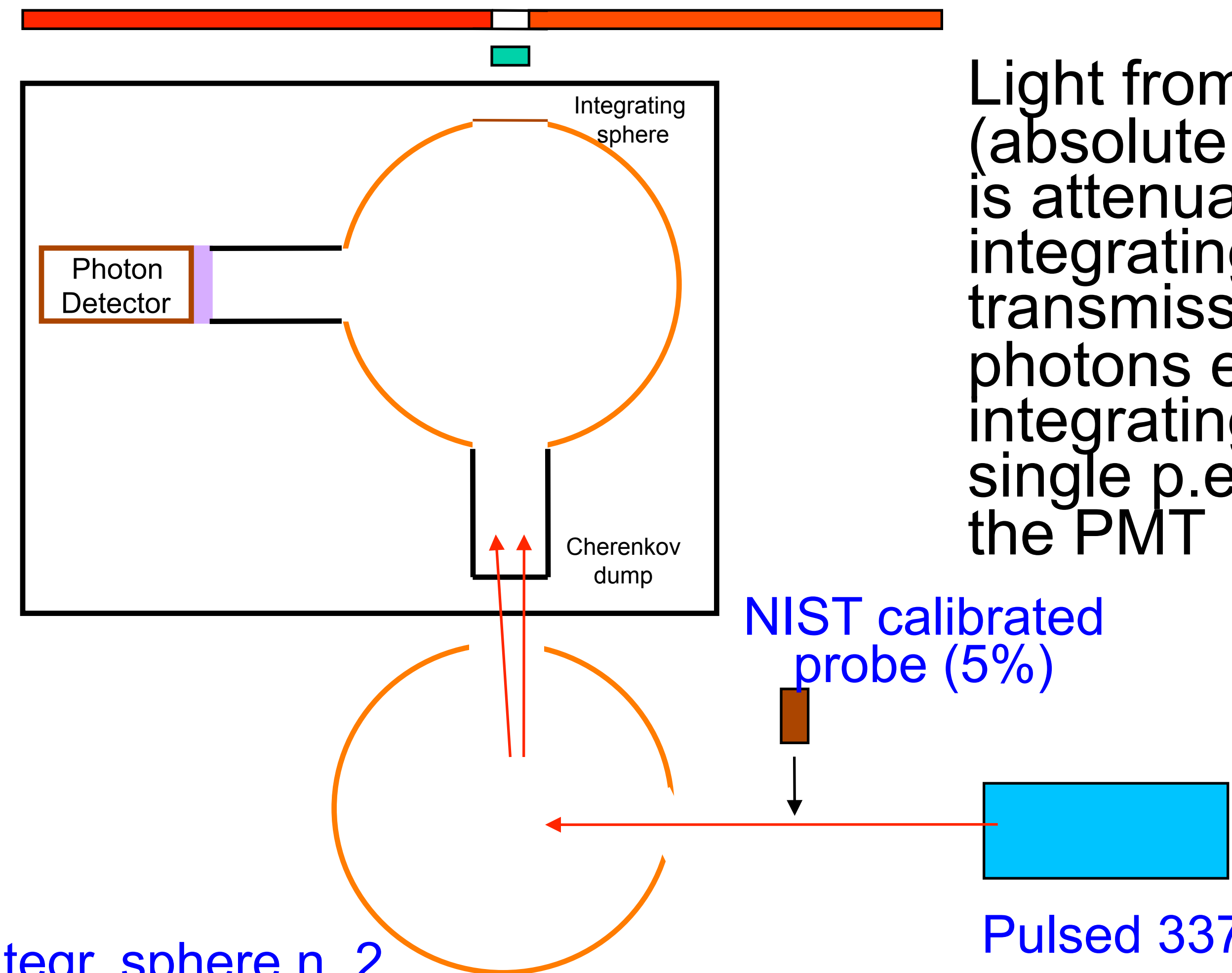
$Bkg_{Ch} = 0$



Independent Y_{air} measurement, <u>consistent within 2%</u> (4% stat. uncertainty)

Absolute calibration with 337 mn laser

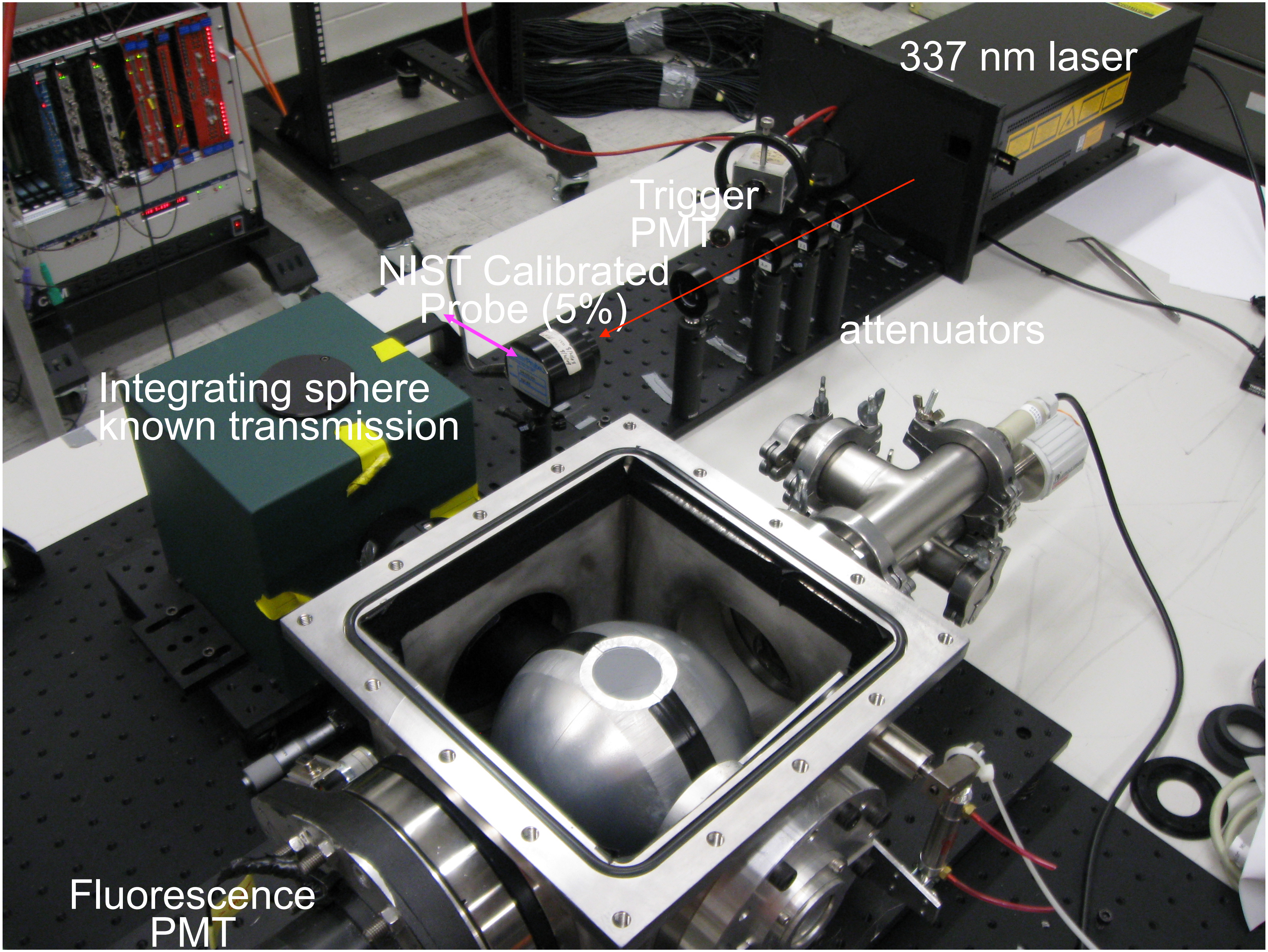
Light from a 337 nm laser (absolute calibration at 5%), is attenuated in a second integrating sphere of know transmission. A known n. of photons enter the AIRFLY integrating sphere, and single p.e. are measured in the PMT



Pulsed 337 nm laser

Integr. sphere n. 2
(efficiency measured independently)

Eff = (10.64 ± 0.11) 10^{-4} p.e./photon_{337}


337 nm laser
Trigger PMT
NIST Calibrated Probe (5%)
attenuators
Integrating sphere known transmission
Fluorescence PMT

Absolute Yield of 337 nm line

Laser Calibration

Preliminary

$$L_{N2} = \frac{Fl_{N2}}{Eff} = (1.757 \pm 0.023) \text{ photons}_{337}/\text{proton}$$

A Geant4 MC simulation of the laser calibration is performed and $(Eff)_{MC}$ is obtained

$$Y_{air} = \frac{(L_{N2} / r)}{(L_{air})_{MC}} \quad (Y_{air})_{MC} = 5.56 \pm 0.07_{stat} \text{ photons}_{337}/\text{MeV}$$

1.3 % statistical unc.

Consistent with the Fluorescence to Cherenkov ratio measurement

NOTE:
In situ laser calibration during test beam. Laser calibration reproduced in the lab at 1% level. Different probes consistent within 3%

Fluorescence data sample independent of the Fl/Ch measurement

337 nm laser line vs Cherenkov light integrated over a 10 nm FWHM interference filter. Different systematic

Systematic Uncertainties

Fluorescence to Cherenkov ratio

- Reflectivity of the sphere	~ 1%
- PMT quantum efficiency	~ 1.5%
- Monte Carlo statistics	~ 1%
- N_2/Air ratio	~ 1%
- Geometry	~ 1%
- Filter transmittance	~ 2%
- Background subtraction	~ 1%
- E_{dep} model in MC	(% level, large sphere Ongoing check with F.Arqueros)

Preliminary

- ………….

Total systematic uncertainty expected < 5%

Systematic Uncertainties

Laser Calibration

- Laser probe calibration	~ 5%
- Transmission sphere n. 2	~ 2%
- Monte Carlo statistics	~ 1%
- N_2/Air ratio	~ 1%
- Geometry	~ 1%
- Background subtraction	~ 1%
- E_{dep} model in MC	(% level, large sphere)
- ………..	

Preliminary

NOTE:
Largest systematic (5%) from calibrated probe (laser pulse). Currently working to reduce uncertainty to 2% by a DC NIST calibrated probe.

Fluorescence produced by secondary electrons: high energy beam particle not important. We confirmed by measuring fluorescence with 32 GeV pions and 8 GeV electrons.

Summary

- AIRFLY has performed a precise measurement of the absolute fluorescence yield of the 337 nm line. Two independent calibration methods have been used, Cherenkov and laser light, giving compatible results. The preliminary results are consistent within the larger uncertainties of other experiments. We expect a final measurement with a total uncertainty of ~ 5%.

- Together with AIRFLY measurements of the air fluorescence spectrum and its pressure, temperature and humidity dependence, the total uncertainty on the energy scale of UHECR will be reduced to ~ 5%.