Energy calibration of NPS

summary of elastic calibration
and the status of calibration using $\pi^0 \rightarrow \gamma\gamma$

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NPS Collaboration Meeting
2024.07.18

Elastic calibrations in 2023

- 2 iterations were performed at the beginning for the first set of production HVs
- No update of HVs for columns which were OFF due to radiation damage

	Date	Runs used (pass of beam)	Purpose	Calo. status
1	Sep. 25	1341, 1342, 1413-1421 (5)	New HV settings	full
2	Sep. 26	1437-1442 (5)	New HV settings	full
3	Oct. 2	1555-1560 (5)	Calibration with new HVs	full
		1507, 1510, 1511, 1556, 1557, 1559 (5)	Sparse ON vs. OFF	
		1549-1554 (5)	Temperature dependence	
4	Oct. 20	1971-1982 (5)	Calibration	col. 0 OFF
5	Nov. 12	2855-2867, 2869, 2871 (5)	New HV settings	col. 0-4 OFF
6	Nov. 13	2875, 2876, 2879, 2881-2885 (5)	Calibration with new HVs	col. 0-4 OFF
7	Nov. 15	2907, 2909-2919 (4)	Calibration with new HVs	col. 0-4 OFF

- No dependency
- Dependency was found
- **Experiment started**
- First radiation-damaged base found in mid-October
- **Pass change**
- Comparison between 4-pass and 5-pass

Elastic calibrations in 2024

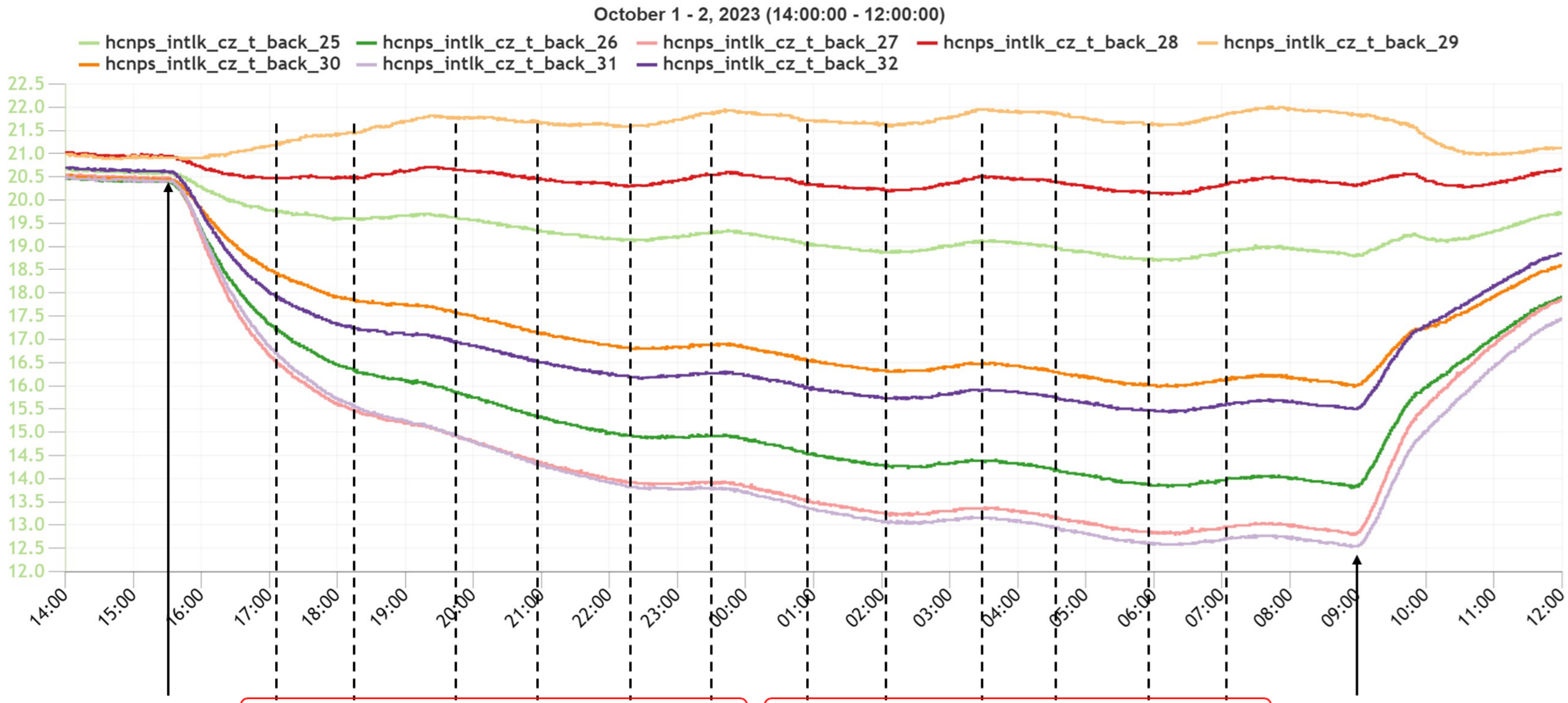
- ➢Replacement with bypassed bases in column 0-19 are done during the Christmas break
- ➢Calibrations are done with all columns
- ➢Refurbishment of the rest of columns without swapping PMTs

	Date	Runs used (pass of the beam)	Purpose
8	Jan. 26	3883-3889 (5)	New HV settings
9	Jan. 27	3893-3898 (5)	Calibration with new HVs
10	Feb. 18	4469, 4470 (5)	Only col. 10-29 are illuminated
11	Mar. 10	5183-5207 (5)	New HV settings
12	Mar. 11	5217, 5219-5225 (3)	Calibration with old HVs
13	Mar. 12	5226-5236 (3)	Calibration with new HVs
14	Apr. 22	6151-6156 (3)	New HV settings (using new gain curve from Julie)
15	Apr. 24	6171-6176 (4)	Calibration with old HVs
16	Apr. 24	6180-6183 (4)	Calibration with new HVs

- Refurbishment of col. 20-23 (Feb. 16)
- Refurbishment of col. 24-25 (Feb. 22)
- **Pass change**
- Comparison between 3 and 5-pass
- Refurbishment of col. 26-29 (Mar. 16)
- **Pass change**
- Comparison between 3 and 4-pass

Effects of temperature on elastic calibration

Thermal sensor at middle column (back 25-32)



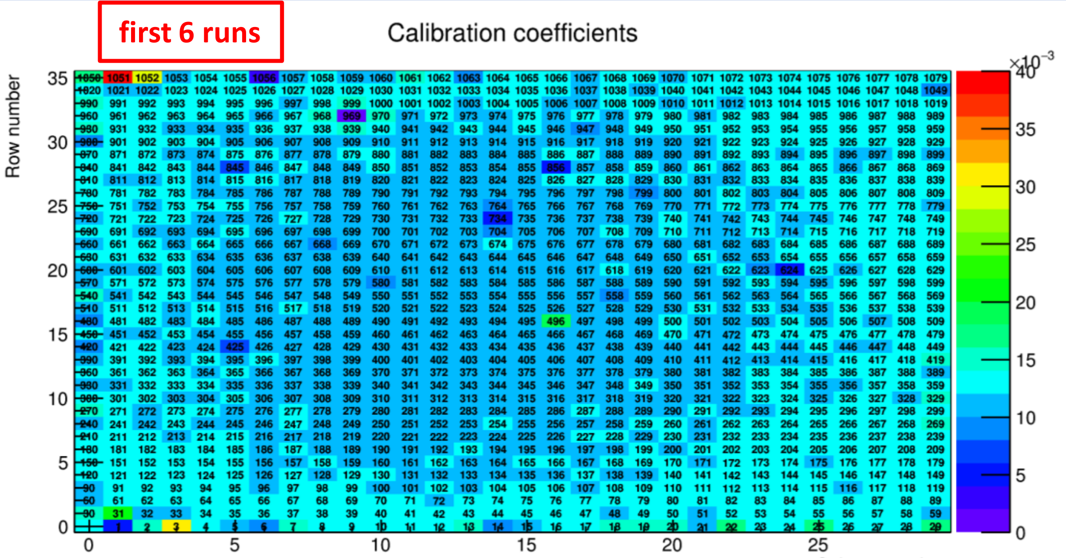
HV ON 1549 1550 1551 1552 1553 1554 1555 1556 1557 1558 1559 1560 HV OFF

NPS angle: 15.98 14.89 17.18 17.18 15.98 14.89

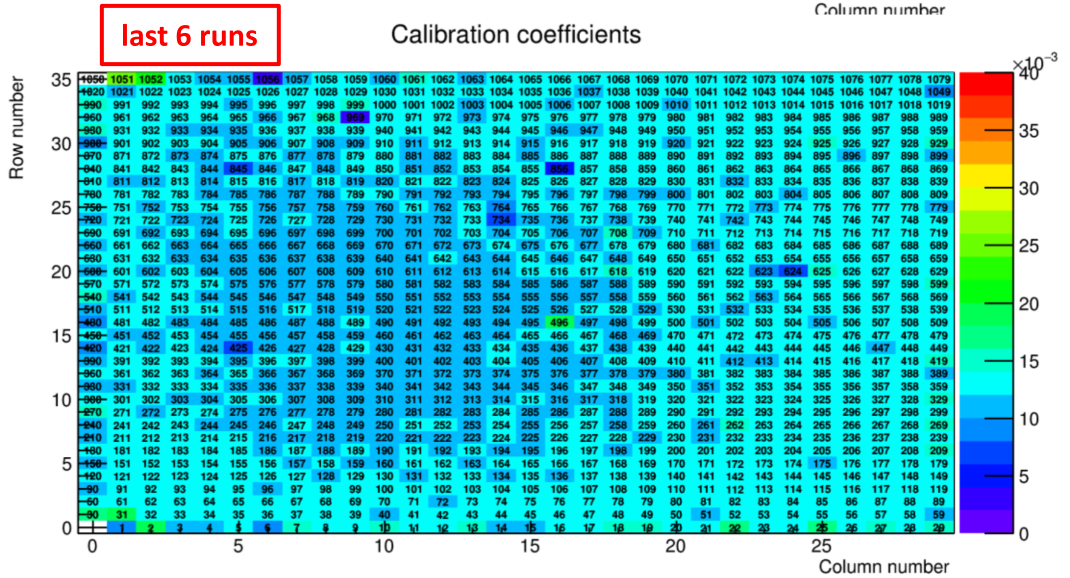
- Data from EPICS
- Reversed values due to the reversed wire connection (Fixed by Josh closed to the end of the experiment)

Results of calibration associated with temperature

first 6 runs



last 6 runs

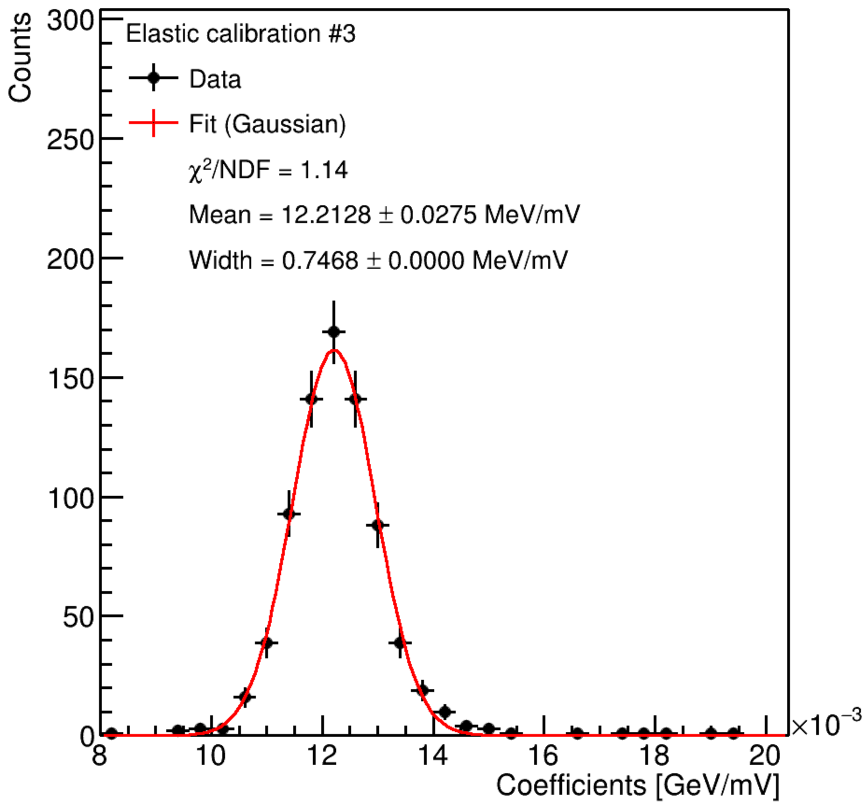


- Higher temperature in the calorimeter reduces the light yield of the crystals
- First 6 runs
  - Taken right after turning on the HVs
  - Non-uniform calibration coefficients due to the non-steady temperature in the calorimeter
- Last 6 runs
  - More uniform calibration coefficients after the temperature got more steady
- Conclusion
  - Data for calibration and production should be taken after the temperature is steady

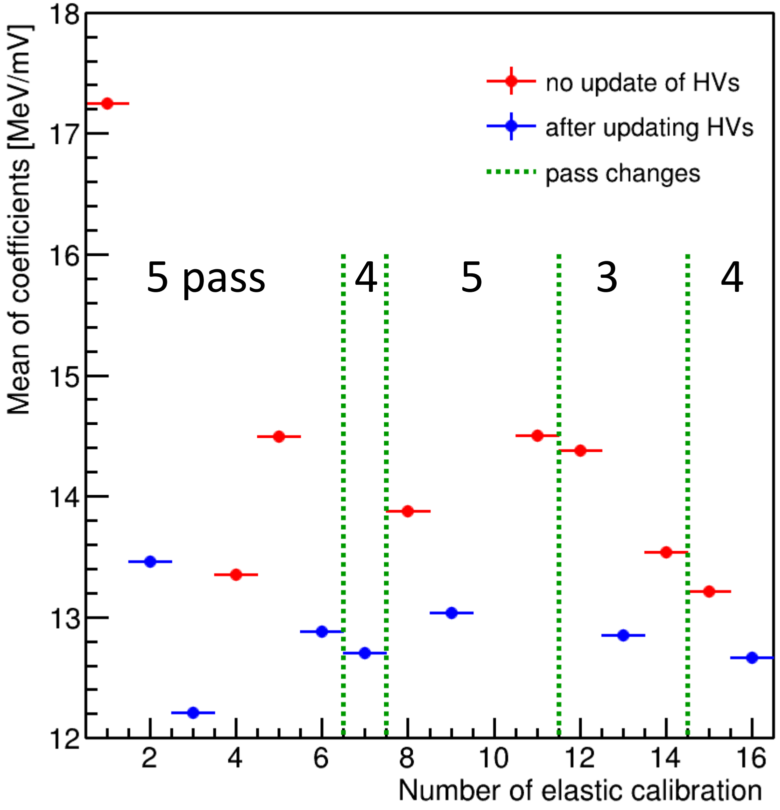
Calibration coefficients as a function of time

- Distributions of coefficients from blocks in column 6-28 and row 1-34
- Fit the distribution of coefficients to extract the mean value

Coefficients of elastic calibration #3

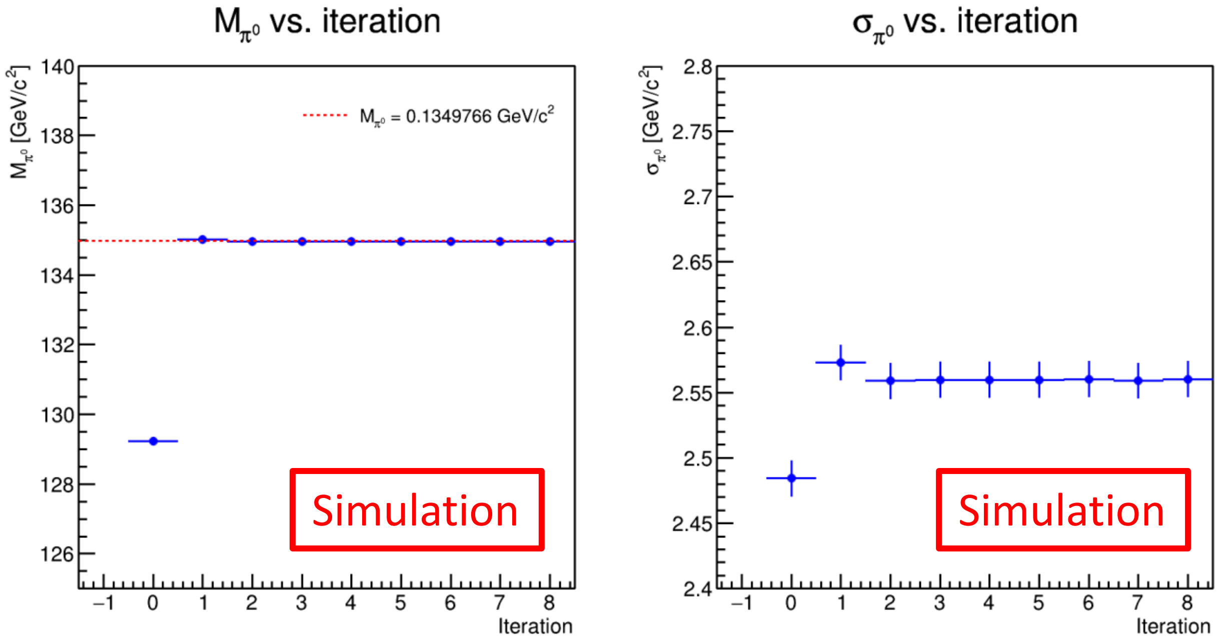


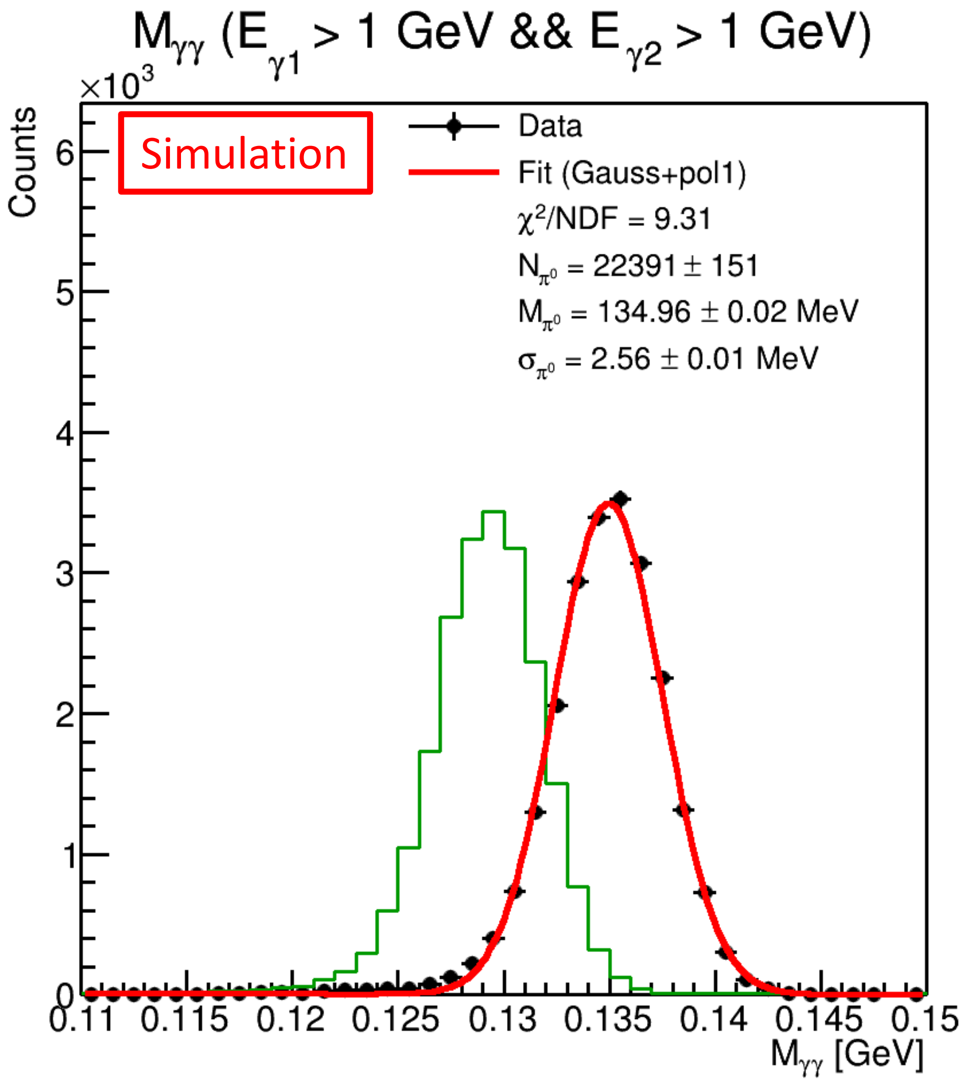
Coefficients vs. time



Performance of π^0 calibration with simulation

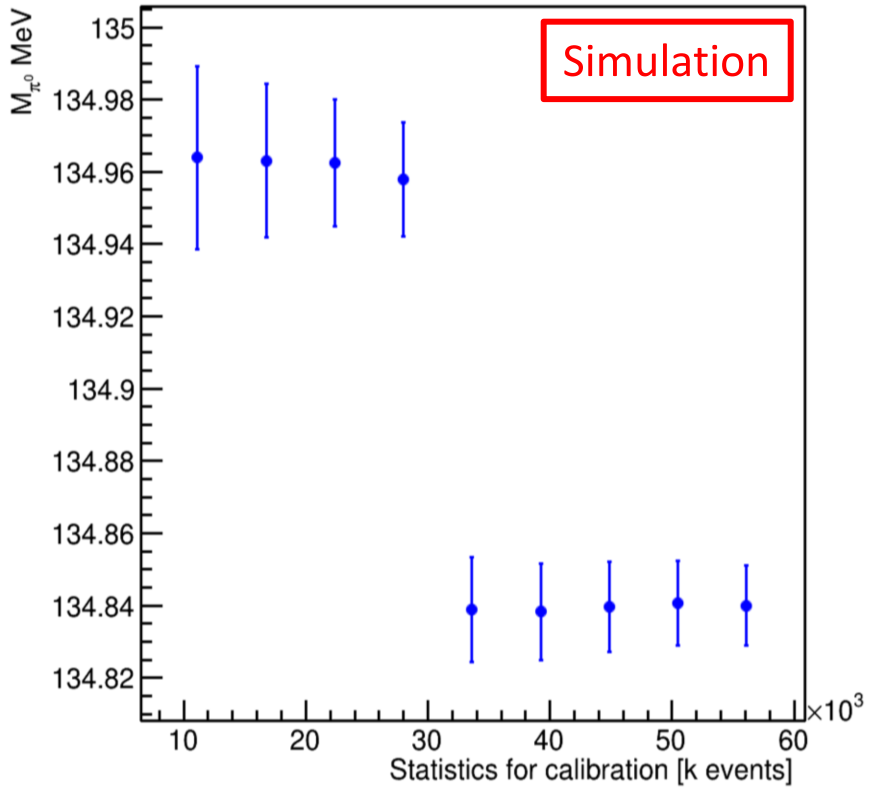
- MC data reconstructed using Geant4
  - ~300k events of $\pi^0 \longrightarrow \gamma\gamma$ were generated
  - HMS momentum = -6.667 GeV/c, angle = 12.493 degree
  - SHMS angle = 36.88 degree, NPS angle = 20.58 degree
  - NPS at 3 meter (the first kinematic we took)
- Very good performance of the calibration scripts



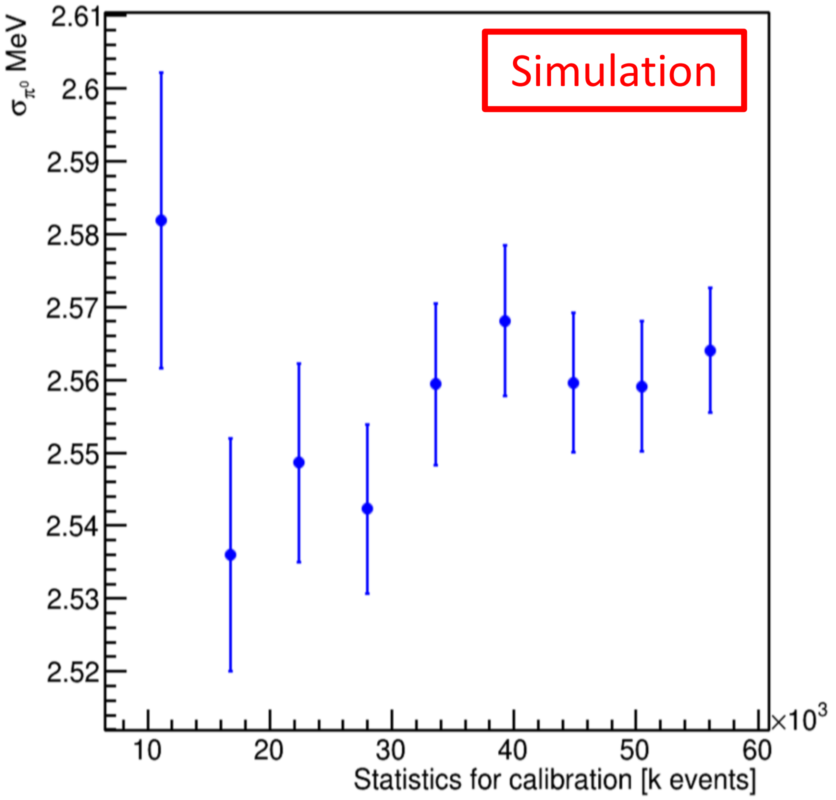


Required statistics for calibration

- 20k of π^0 events seems to be enough for calibration
  (0.5 hours of beam time with KinC_x36-5; 2-3 hours with x60-3 and x60-4 on LH2)

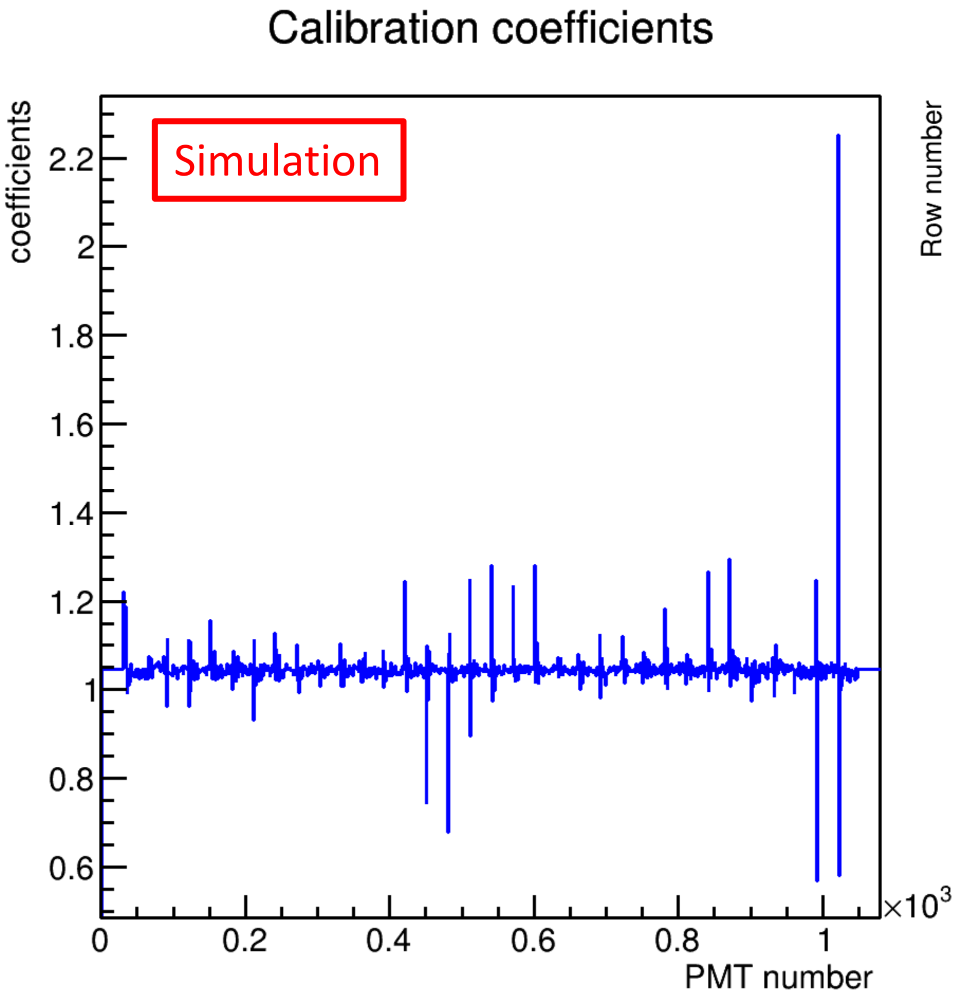


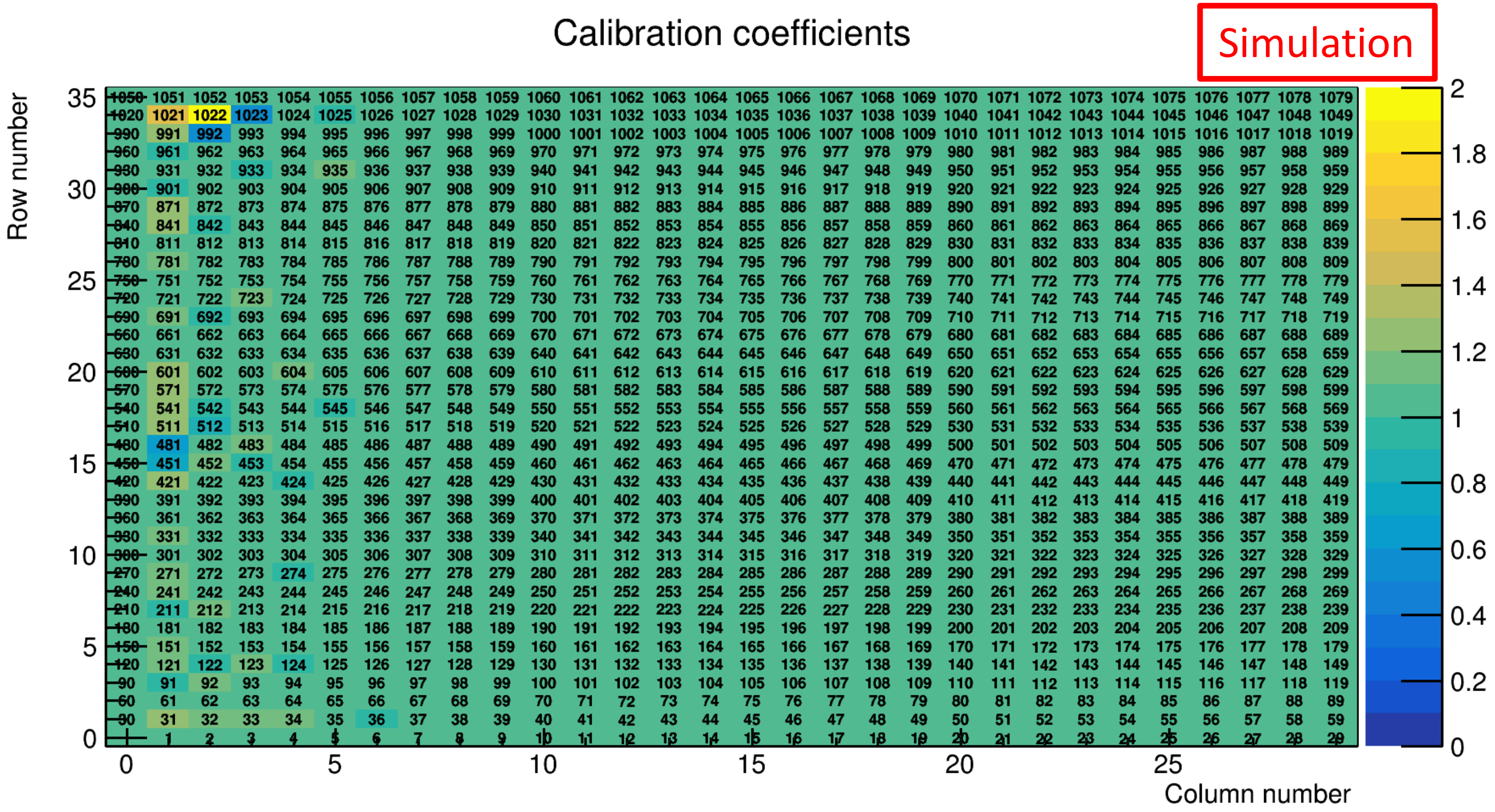
M_{π^0} vs. number of π^0 used for calibration



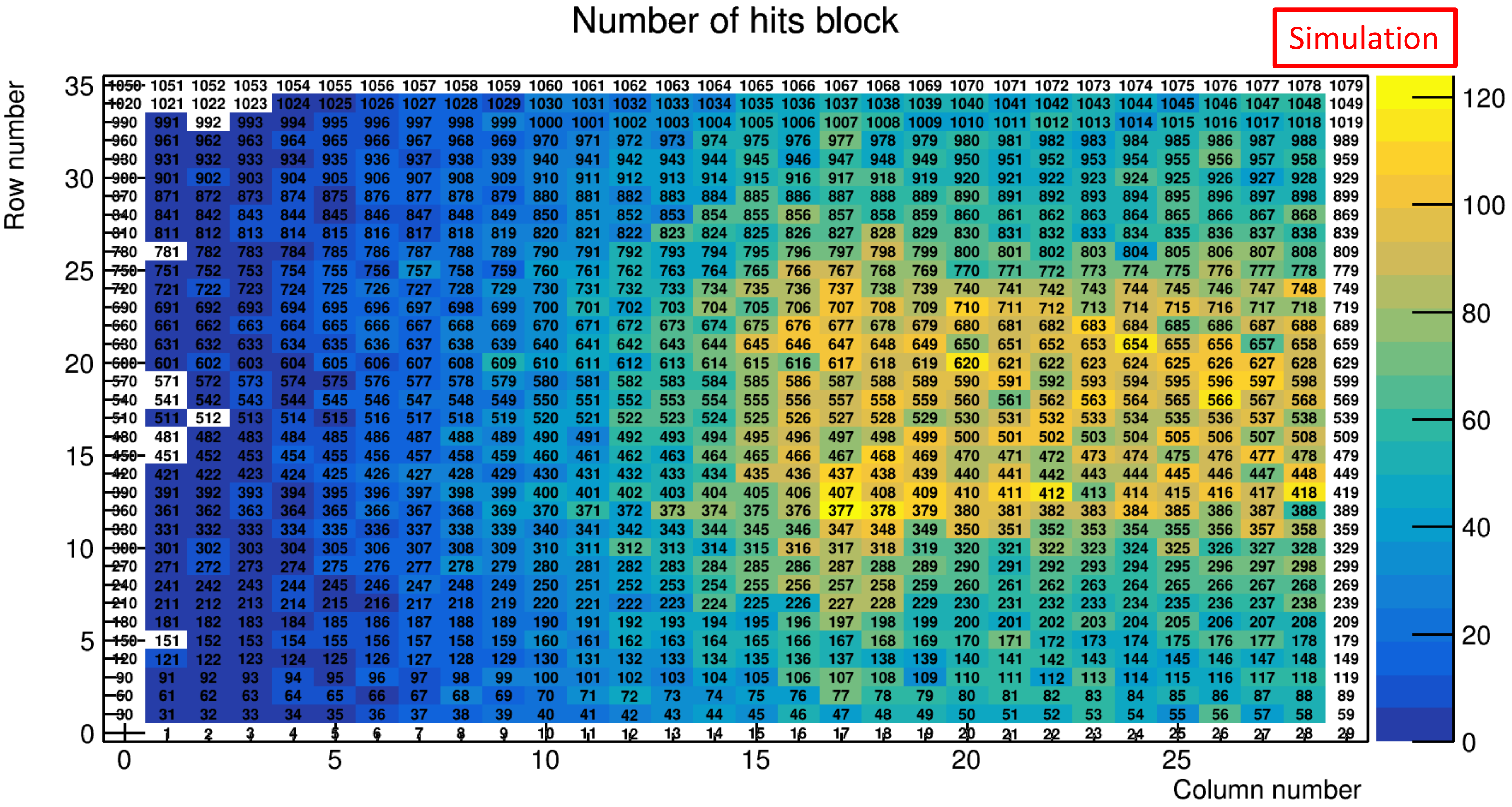
σ_{π^0} vs. number of π^0 used for calibration

Calibration performance with 20k π^0 events





Number of photons per block with $20\text{k}\ \pi^0$ events



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930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959
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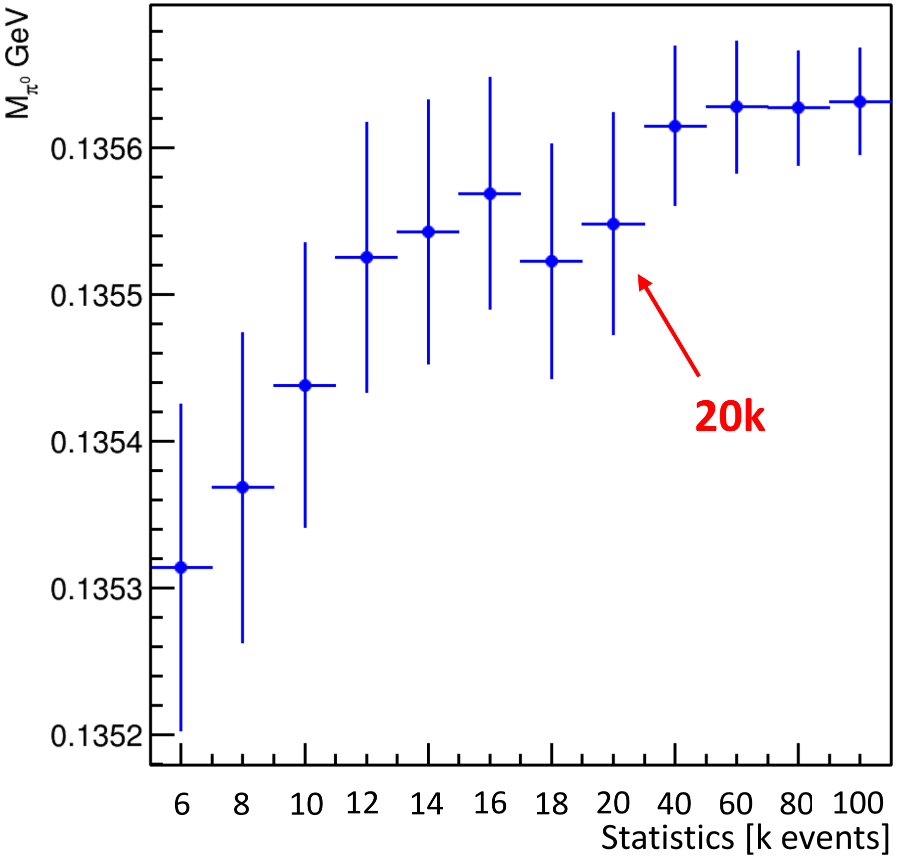
30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29

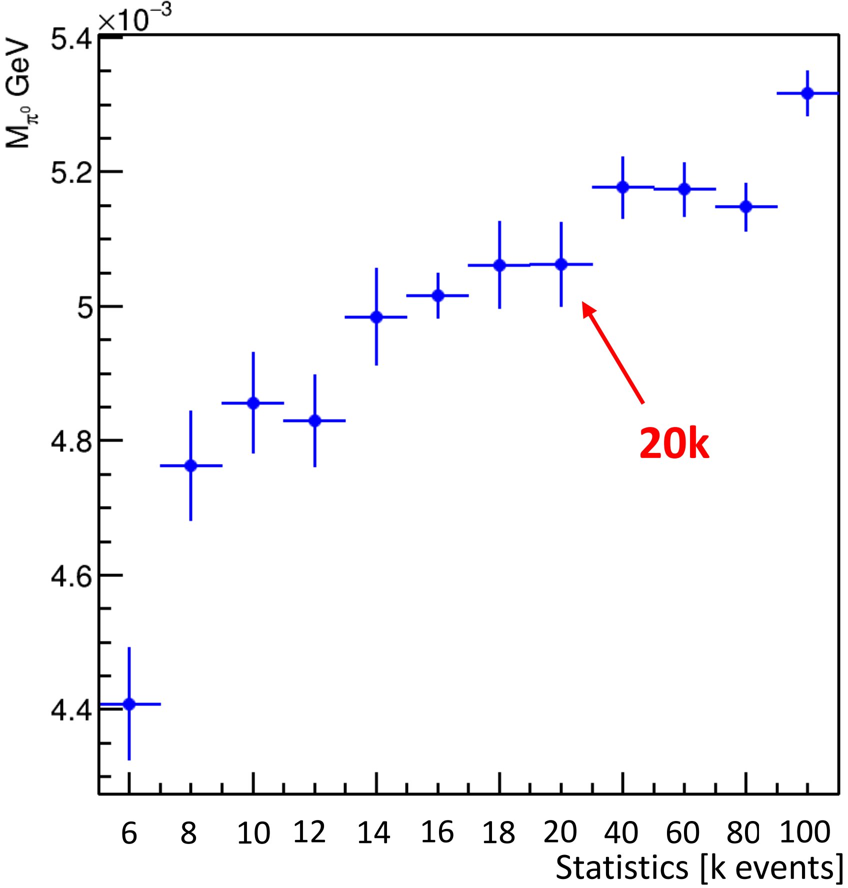
Required statistics for calibration with data

- Kinematics: KinC_x36-5
- Same conclusion as simulation: 20k of π^0 events may be enough

M_{π^0} vs. number of π^0 used for calibration

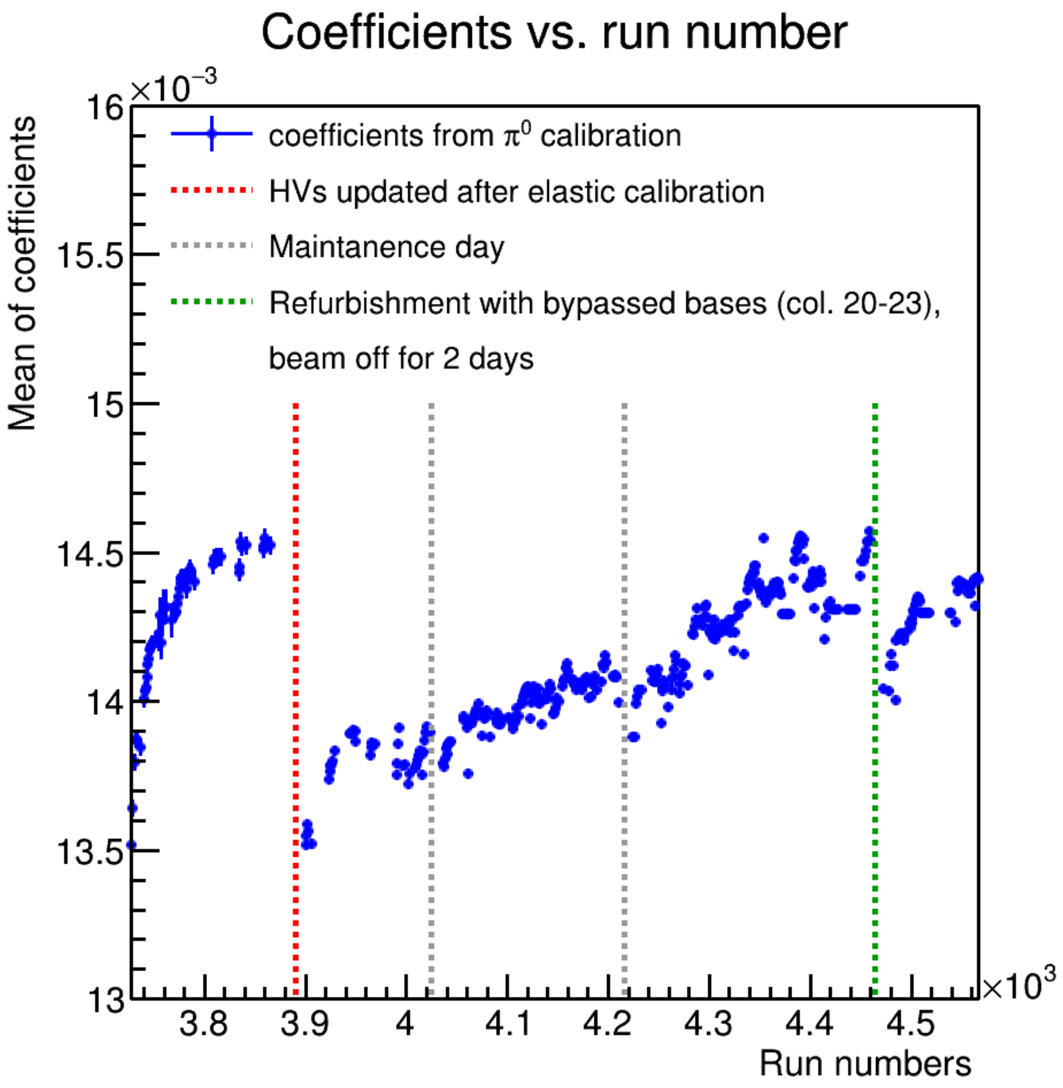


σ_{π^0} vs. number of π^0 used for calibration



Results of calibration as a function of run number

- First month of data in 2024
- 8 kinematics, run 3728-4550
- Calibrated using ~100k π^0 events
- Elastic calibration was done after taking 7 days of production data
- Decrease of coefficients after updating HVs and long time of beam OFF

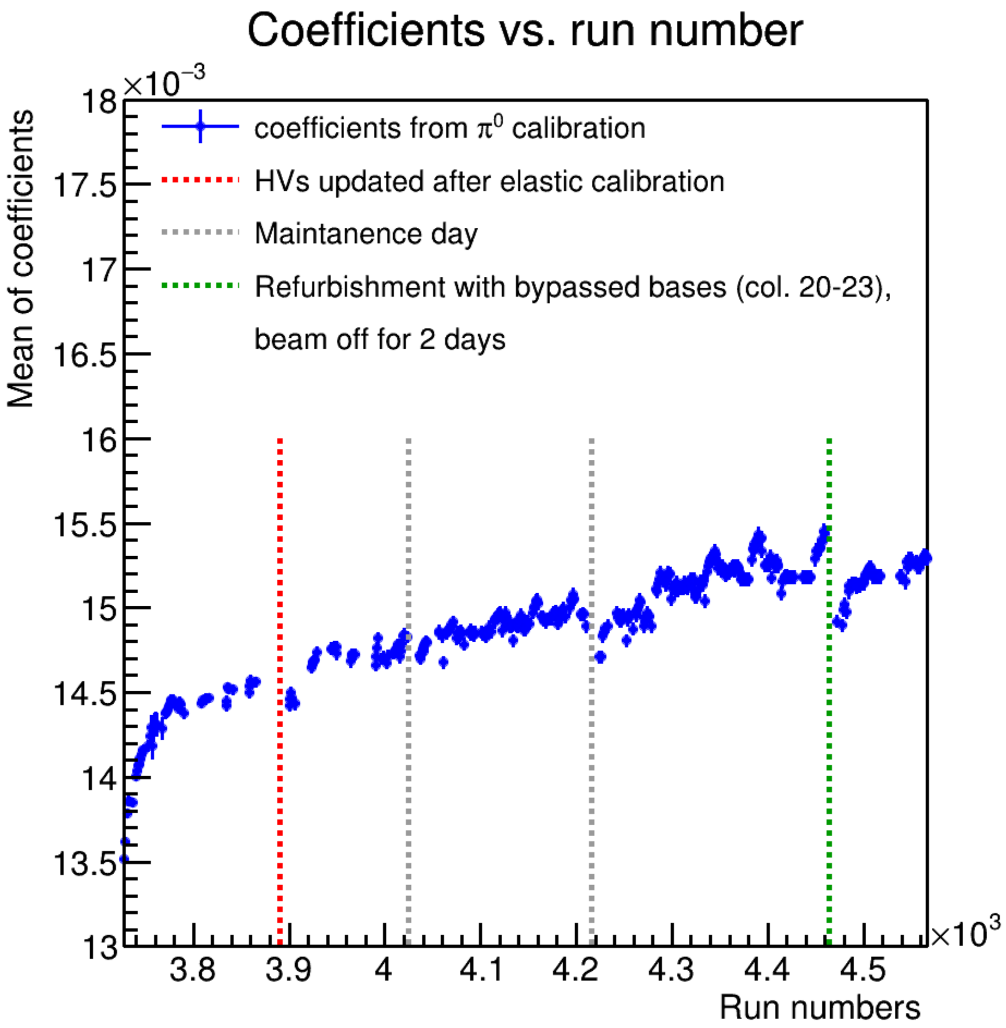


If we didn't update HVs

- Restore to the old coefficients with

$$C^k_{old} = C^k_{new} \times \left(\frac{\mathrm{HV}_{new}}{\mathrm{HV}_{\mathrm{old}}}\right)^b, b = 5.9$$

- Radiation damages of the crystal were saturated and increased steady after some point
- Cure of the crystals might be meaningless if the damages come back too fast

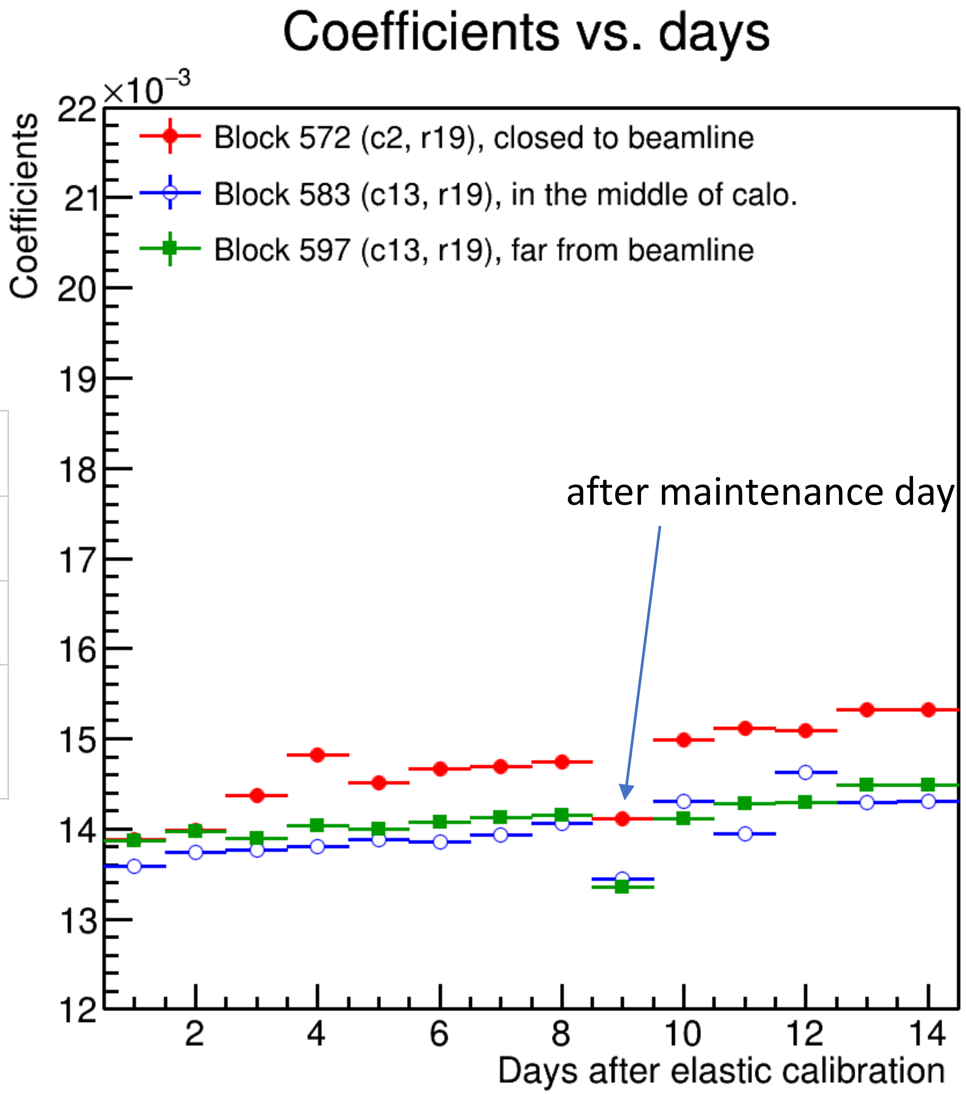


Comparison between different blocks

- Average of coefficients after elastic calibration at the edge and in the middle of calorimeter
- Coefficients of blocks closed to the beamline were increased more than the others as we expected

Block number	572	583	597
Coefficients (right after elastic calibration) [MeV/mV]	13.8860	13.5846	13.8736
Coefficients (two weeks after elastic calibration) [MeV/mV]	15.3157	14.2997	14.4826
Increased coefficients [MeV/mV]	1.4297 (10.3%)	0.7157 (5.27%)	0.6090 (4.39%)

⟵ ⟵ ⟵ **BEAM**



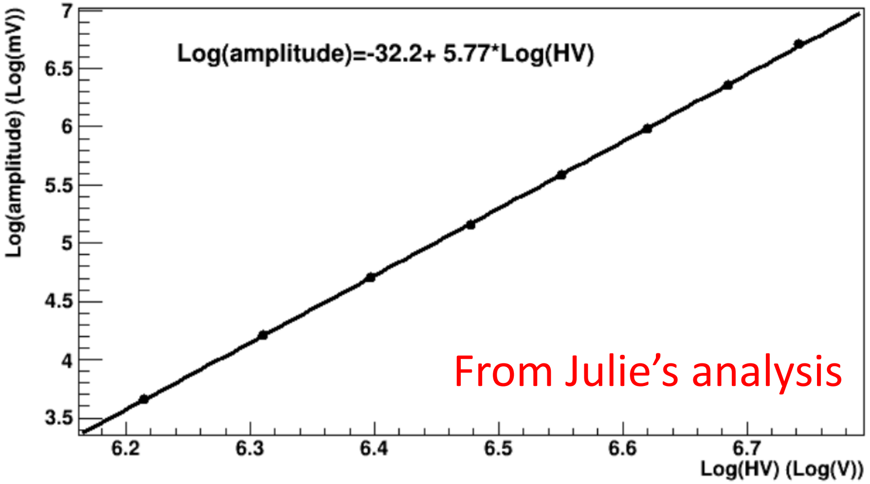
Conclusion

- 16 elastic calibrations was done
- HV settings were updated for 6 times to have uniform gain in each PMT for better trigger
- Coefficients depend on the temperature. Keep HVs ON for data taking and calibration.
- Study of performance of π^0 calibration was done using simulated data
- 20k of pure π^0 events seems to be enough for calibration
- The frequency of calibration depends on kinematics and beamtime
- π^0 calibration were done for the 1st month of data in 2024
- Fast damage of crystals after the Christmas break.
  Would be interested to compare with the beginning of the experiment.

Backups

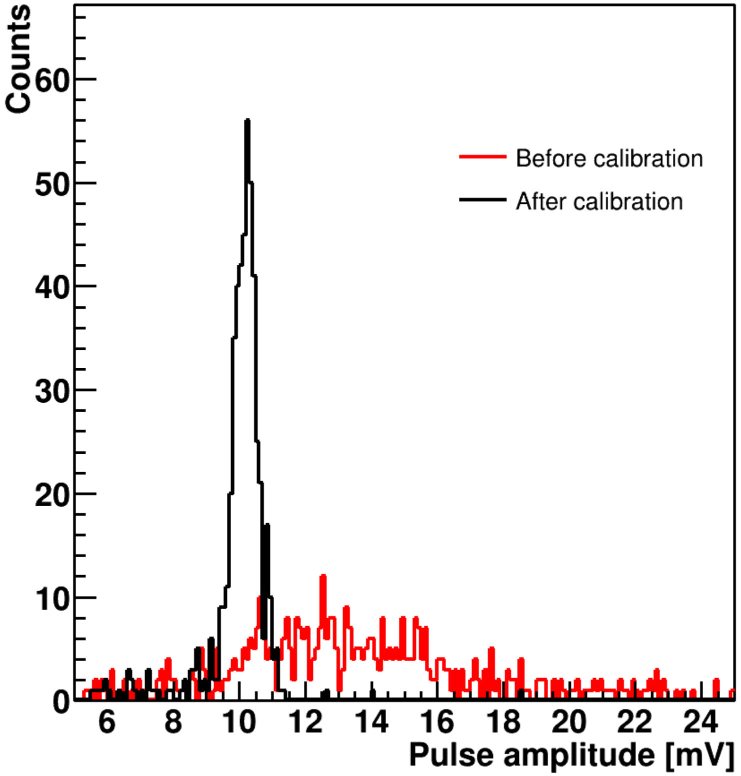
NPS calibration with cosmic rays

- Check the performance after installation, troubleshooting, etc.
- Pre-calibration before calibrating with elastic data
  - Gain matching for similar amplitudes in each block
  - $Amp. = \alpha \times HV^{\beta}$
  - $new\ HV. = old\ HV \times (\frac{new\ Amp.}{old\ Amp.})^{\frac{1}{\beta}}$
  - β = 5.77
  - New amplitudes are set to 10 mV



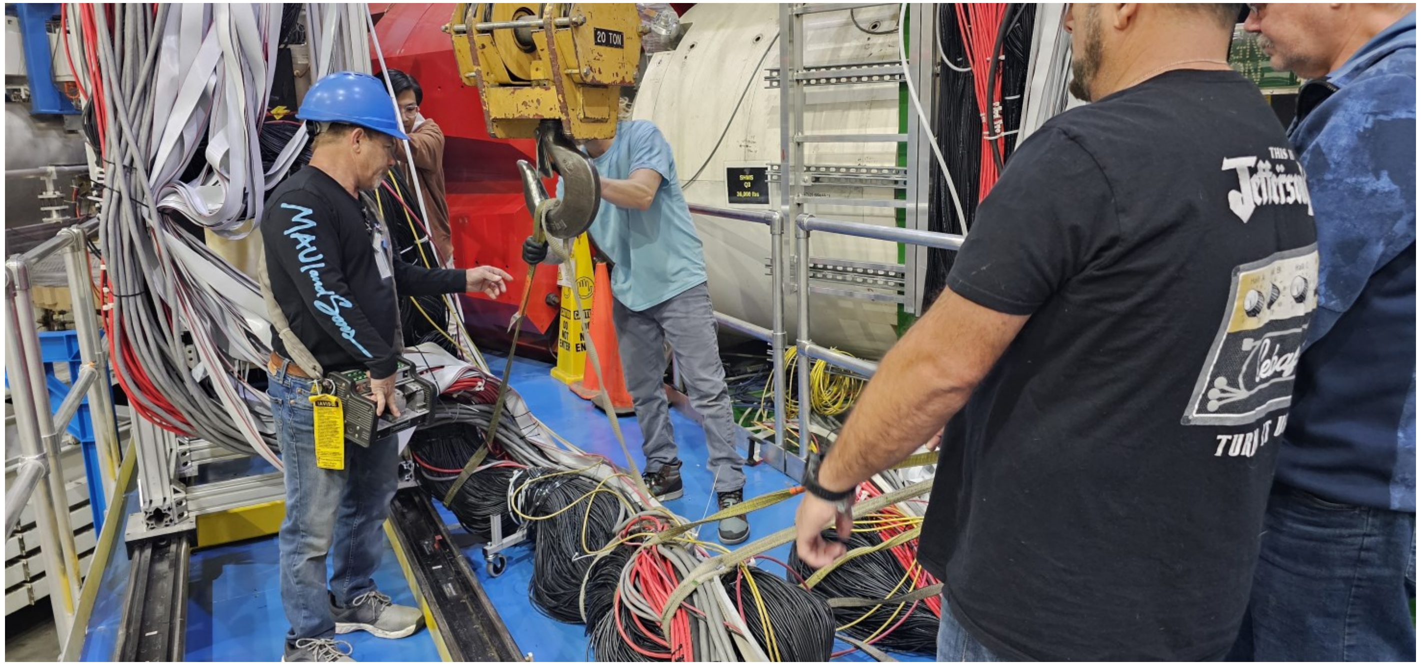
From Julie's analysis

Amplitudes before & after calibration



Elastic calibration

- Preparation of taking data of elastic events (e + p → e’ + p’)
  - Move the NPS to 9.5-meter position (coordinate with the Techs)
  - Change the polarity to detect scattered electron (e’) in the NPS and recoil proton (p’) in the HMS
  - Three different angles of the NPS are required to illuminate the whole calorimeter and have enough statistics at the edge



Calculation of calibration coefficients

- Precise prediction of scattered electron from the measured proton in the HMS
- Linear equations of 1080 crystals are used for the minimization:
  - According to energy conservation, the energy E_i of scattered electron in event i is:

    $$E_i = E_b + M_p - E_i^p$$

    where E_b is the beam energy, M_p is the mass of target proton, E_i^p is the energy of proton detected in the HMS
  - By comparing E_i with $\Sigma_j C_j A_j^i$
    - C_j is the calibration coefficient of block j in the caloremeter
    - A_j^i is the amplitude (deposited energy) if block j in event i

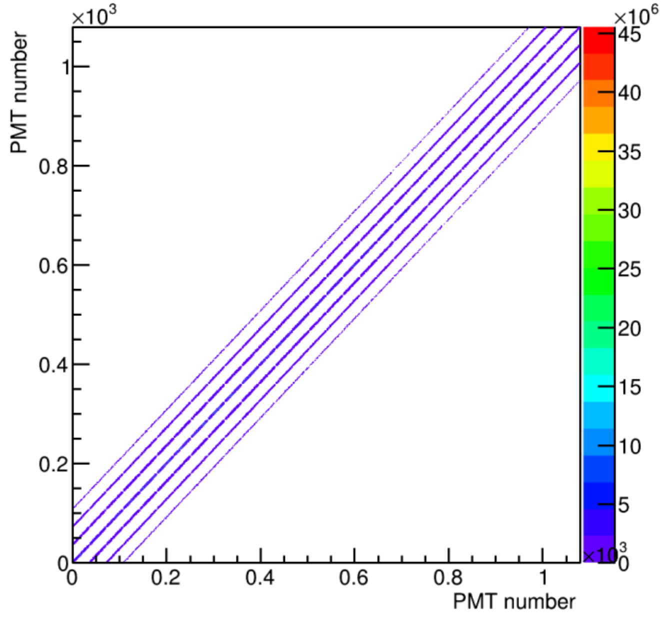
    we can build $\chi^2 = \Sigma_i (E_i - \Sigma_j C_j A_j^i)^2$
  - The calibration coefficient C_j can be calculated by minimizing the χ^2:

    $$\frac{\partial \chi^2}{\partial C_k} = -2C_k \Sigma_i (E_i - \Sigma_j C_j A_j^i) A_k^i = 0$$

    which can be witten as:

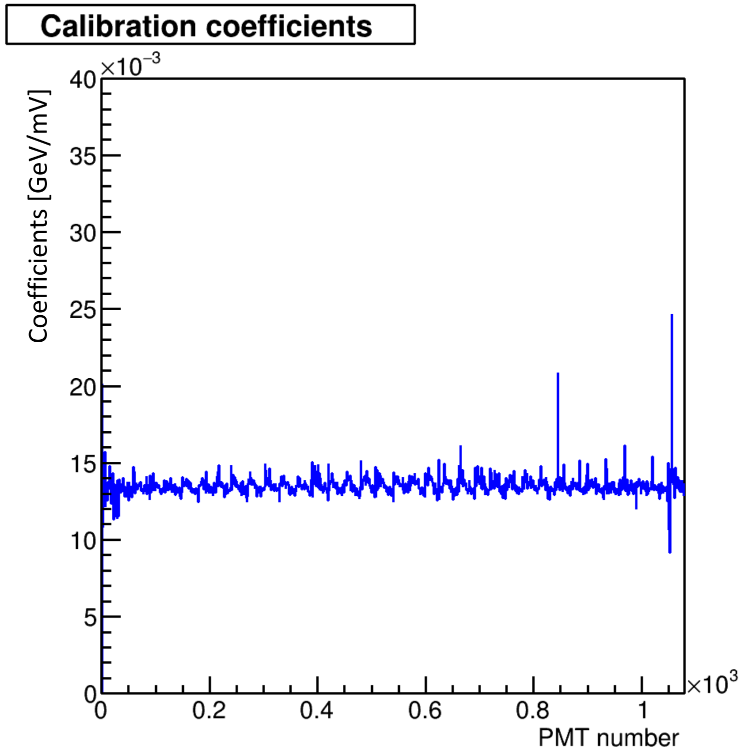
    $$\Sigma_i E_i A_k^i = \Sigma_j [\Sigma_i A_j^i A_k^i] C_j$$
  - Then, C_j can be calculated by inverse the matrix $[\Sigma_i A_j^i A_k^i]$ and multiply $\Sigma_i E_i A_k^i$

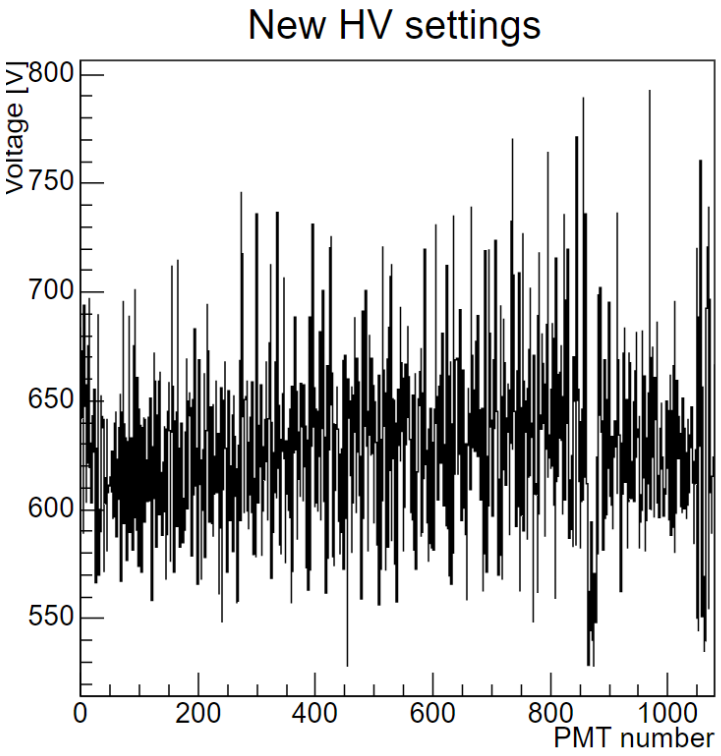
Matrix $[\sum_i A_j^i A_k^i]$



Elastic calibration

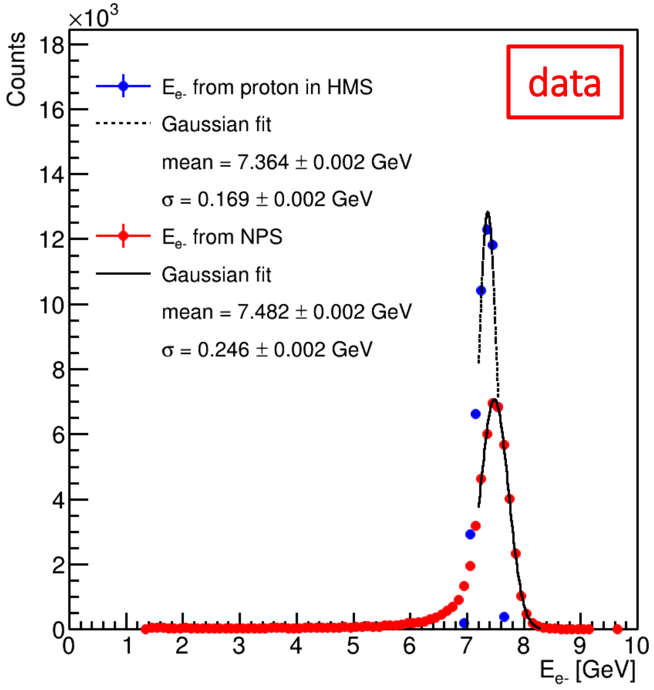
- Adjust the high voltage (HV) of PMTs to have 600 mV of amplitude for the photon from DVCS process
- Based on the gain curve and their calibration coefficients



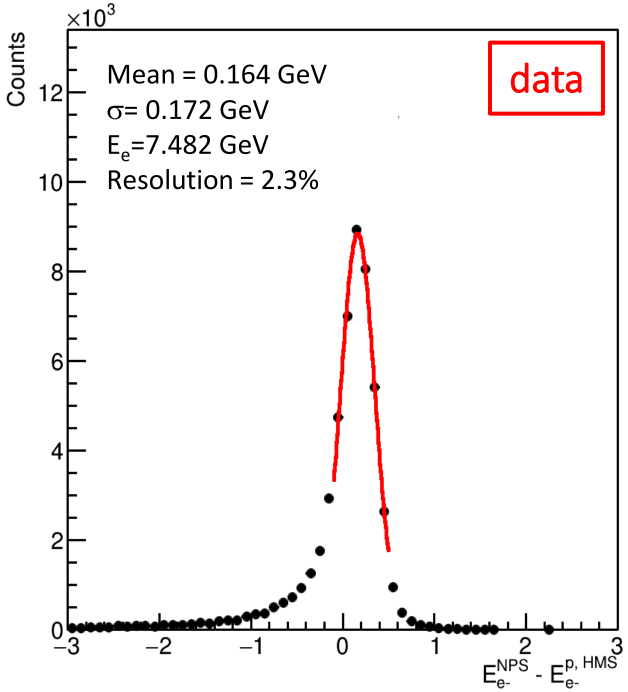


Results of elastic calibration

- ➢ Good agreement of the electron energy between the prediction from HMS and the measurement in NPS after calibration
- ➢ The measured energy resolution is still larger than the expectation (~2%/√E ⊕ 1% ~1.2%) from simulation (work ongoing)

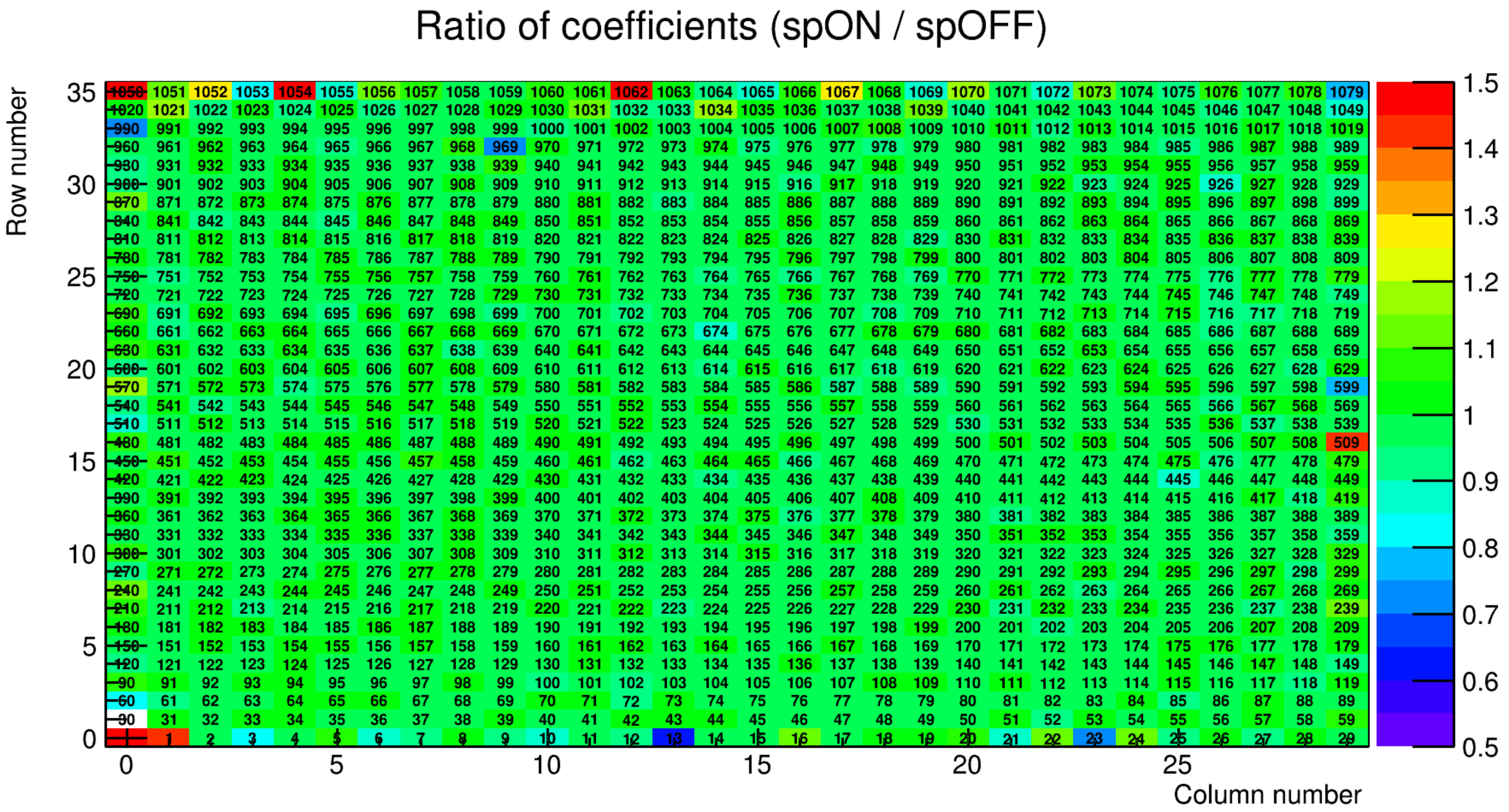


Electron energy



Energy resolution in the calorimeter

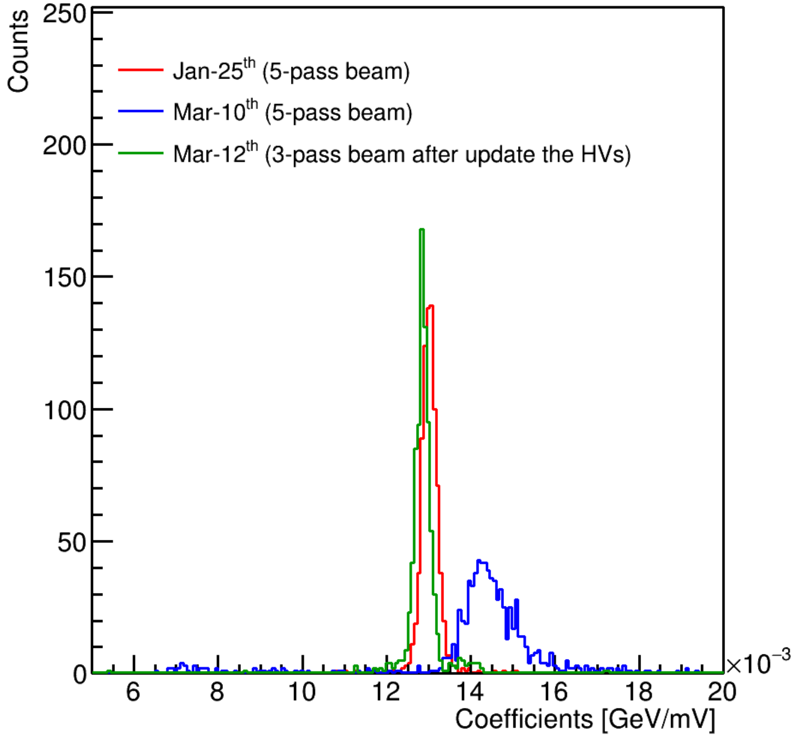
Coefficients, sparse ON vs. OFF



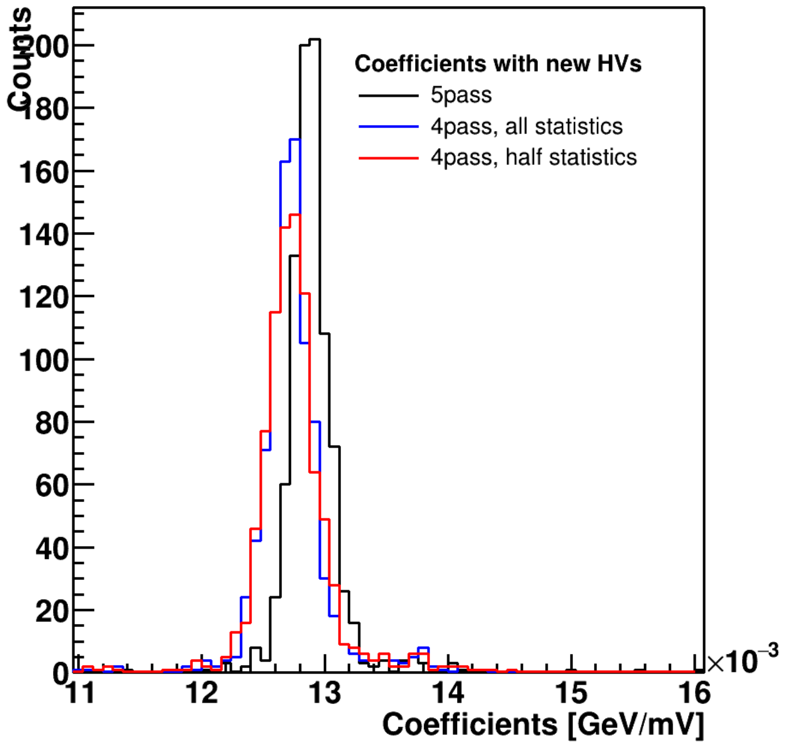
Comparison between different beam energy

- ➢Comparisons of coefficients with the same and updated HVs
- ➢Very small discrepancies were found between different energies

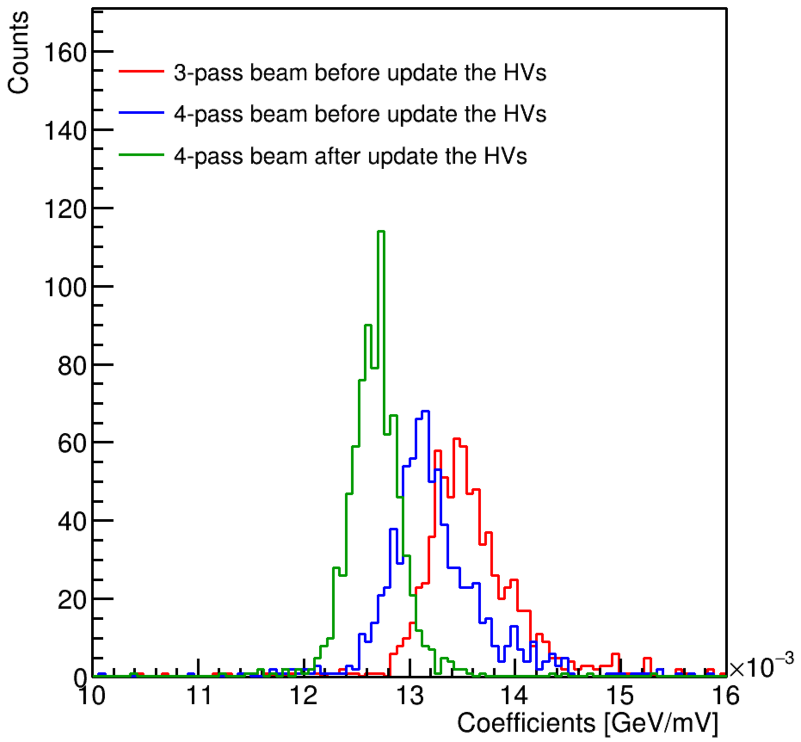
3 pass vs. 5pass



4 pass vs. 5pass



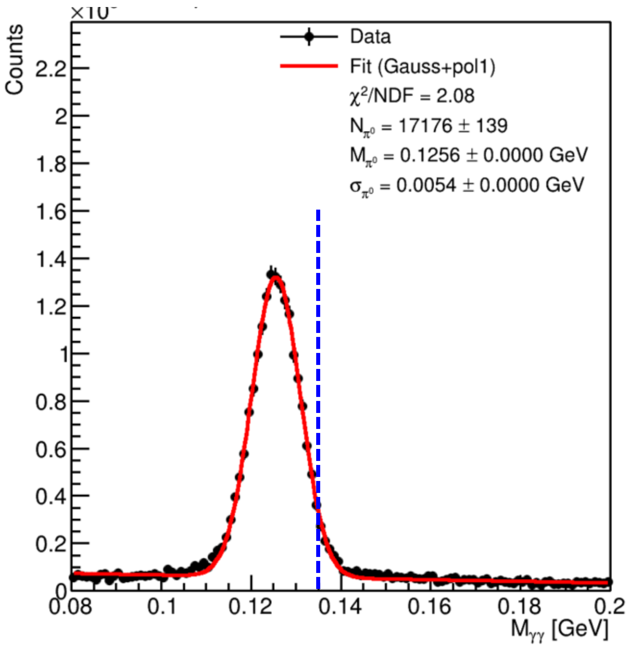
3 pass vs. 4pass



Energy calibration with π^0

- The energy in the NPS are shifted when taking production data
- Possible causes: fringe field effects from the magnet on PMTs, non-linear effects on the energy response of the calorimeter
- Calibration with $\pi^0 \rightarrow \gamma\gamma$ is another approach to extract the correct calibration coefficients in each crystal

π^0 invariant mass before π^0 calibration



Method of π^0 calibration

- The minimization method is based on the paper *"A bootstrap method for gain calibration and resolution determination of a lead-glass calorimeter"* *(Nuclear Instruments and Methods in Physics Research A 566 (2006) 366–374)*
- This method is used to constrain the mean of π^0 invariant mass and reduce its width based on:

$$F = \boxed{\sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)^2} + \boxed{2\lambda \sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)}$$

resolution term

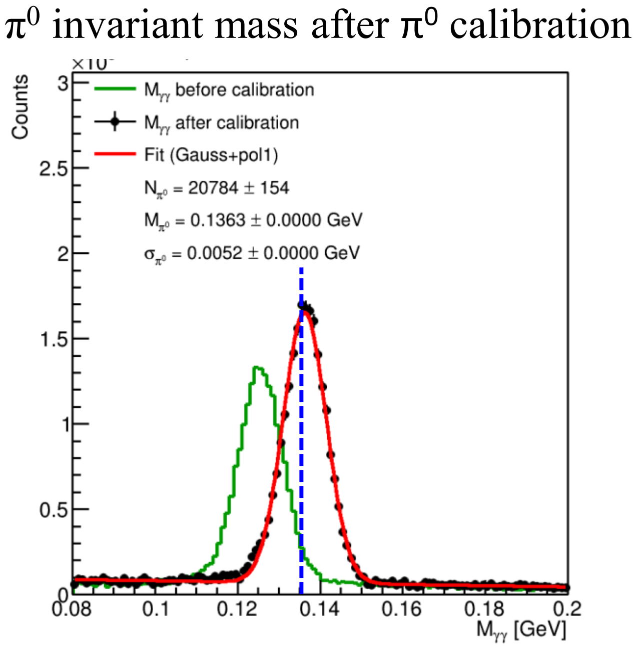
embody the constraint $\langle m_i^2 \rangle = m_0^2$

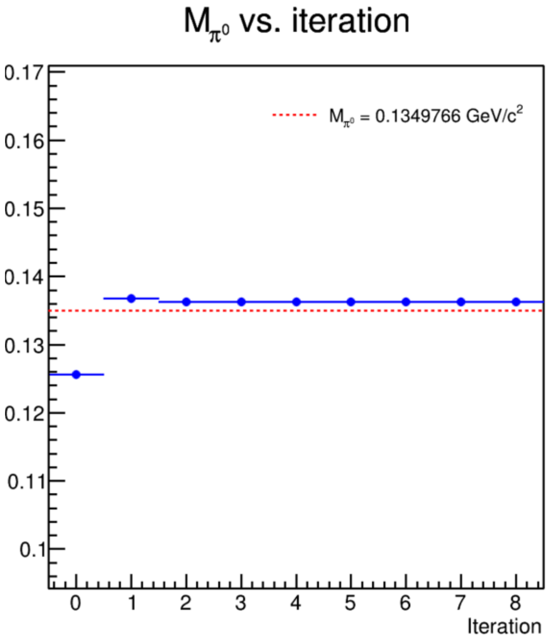
$m_0 = M_\pi = 0.1349766$ GeV
m_i: reconstructed $M_{\gamma\gamma}$
λ: Lagrange multiplier

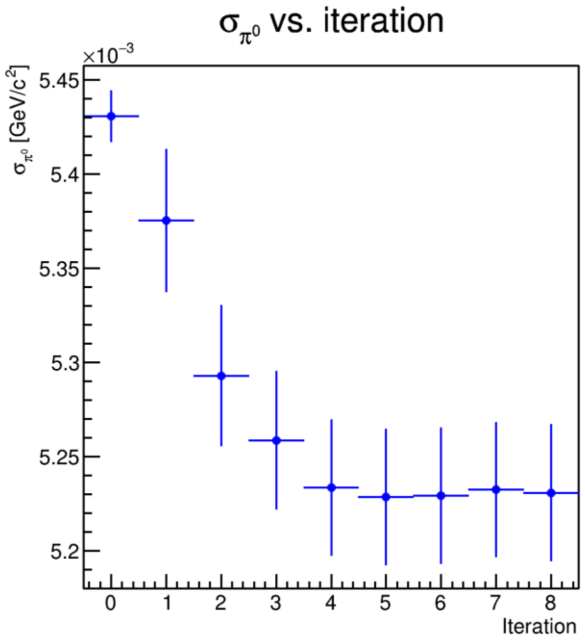
- Iterations are required till the mean and width of π^0 are converged

Results of π^0 calibration

- ➢Mean value of π^0 mass is stable after 3 iterations
- ➢At least 5 iterations are required to make its width stable
- ➢Both mean and width are improved after calibration


π^0 invariant mass after π^0 calibration


M_{π^0} vs. iteration


σ_{π^0} vs. iteration

Additional correction for π^0 calibration

- Used in previous DVCS experiment in Hall A for the fast darkening of crystals
- $C'_k = C_k \times \frac{m_\pi = 0.1349\ GeV}{< m_\pi^{reconstruct} >}$ for each block k