# The Status of 3-inch PMT Performance Study for JUNO

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On behalf of the JUNO collaboration

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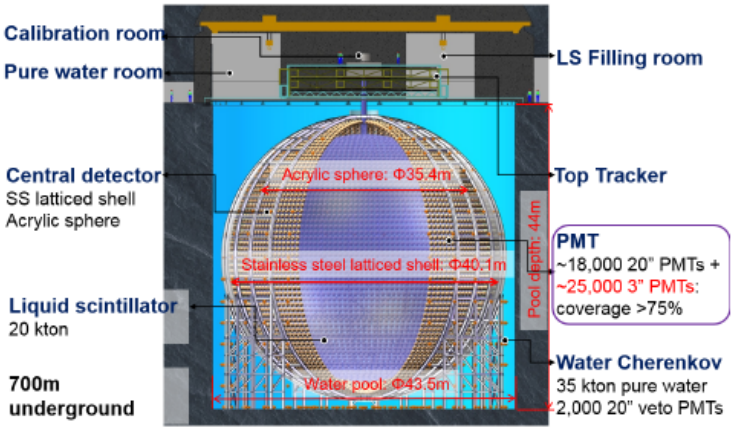
# Introduction of JUNO

**JUNO:**

**Jiangmen Underground Neutrino Observatory**

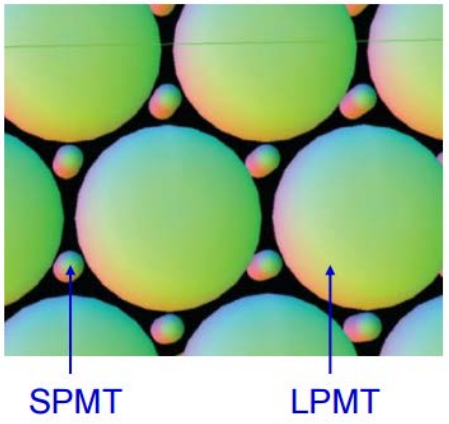
- **Multipurpose neutrino experiment**
- **Primary goal:**
  - **neutrino mass hierarchy**
  - **precise measurement of neutrino oscillation parameters…**
- **Energy resolution: $3\%/\sqrt{E}$**

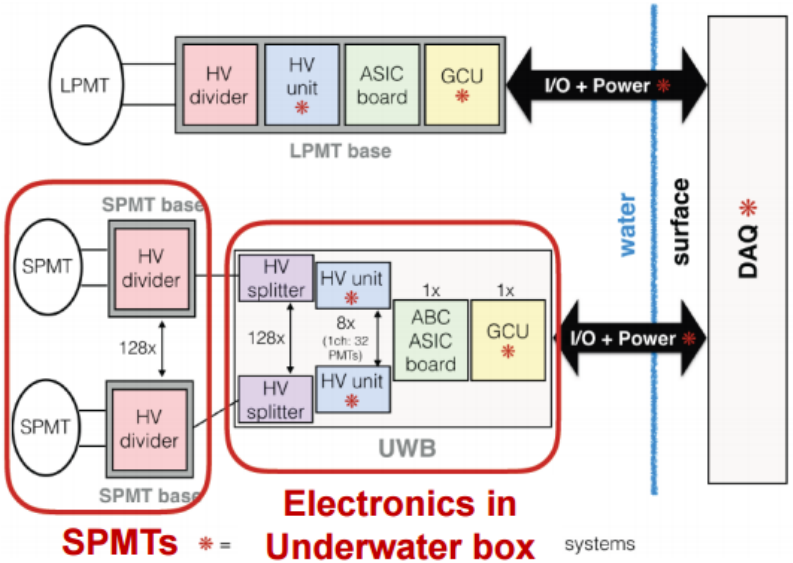



# SPMT System

## LPMT & SPMT
## Double calorimetry system of JUNO

- **2 independent read-put systems**
  - 18,000 20-inch Large PMTs (LPMTs)~1200 p.e./MeV
  - 25,000 3-inch Small PMTs (SPMTs)~50 p.e./MeV
- **SPMTs almost always work in SPE mode**
- **Improvement for the calibration to non-linear response of the single channel charge**





**XP72B22, supplied by HZC Photonics**
**Co-development with JUNO-SPMT collaboration**

# The R&D for 3-inch PMT Performance

## ➢ Requirement for 3-inch PMT Performance

| No. | Parameter | Specified Value (Average) | Specified Value (Range) |
|---|---|---|---|
| 1 | Bulb Diameter | 80mm | $80 \pm 2mm$ |
| 2 | QE x CE @420nm | 24% | >22% |
| 3 | HV @$3 \times 10^6$ Gain | | <1300V |
| 4 | P - V Ratio | 3 | >2 |
| 5 | Resolution of SPE ($\sigma$) | 35% | <45% |
| 6 | Dark Rate @1/4 PE | 1kHz | <1.8kHz |
| 7 | Dark Rate @3 PE | 3Hz | <30Hz |
| 8 | TTS (FWHM) | | <5ns |
| 9 | QE Uniformity | | <11% |

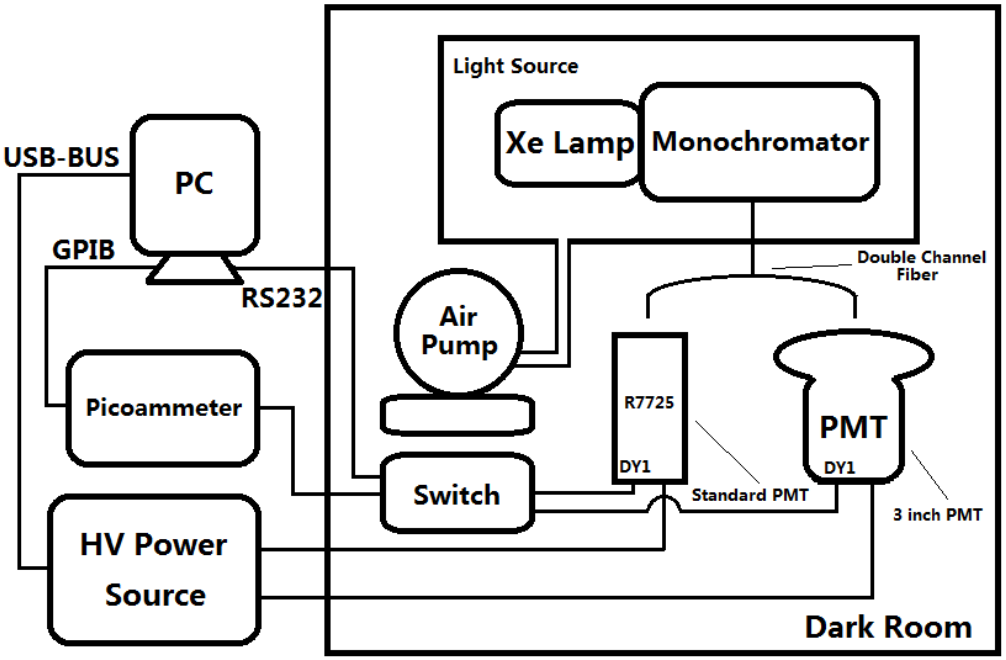
| No. | Parameter | Specified Value (Average) | Specified Value (Range) |
|---|---|---|---|
| 10 | Prepulse Ratio (in a 80ns window) | 4.5% | <5% |
| 11 | Afterpulse Ratio (in a 20μs window) | 10% | <15% |
| 12 | Effective Diameter of Cathode | 76mm | >74mm |
| 13 | Spectral Response Range | 300~600nm | 300~600nm |
| 14 | Glass Radiation Level | $^{238}U$<145ppb $^{232}Th$<272ppb $^{40}K$<162ppb | $^{238}U$<400ppb $^{232}Th$<400ppb $^{40}K$<200ppb |
| 15 | Water Pressure Resistant | 1.0MPa | >1.0MPa |

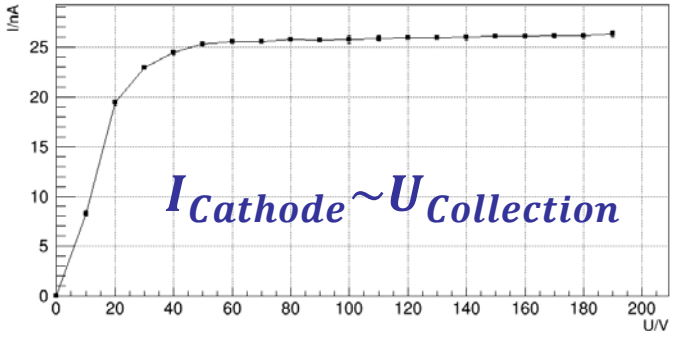
# The R&D for 3-inch PMT Performance

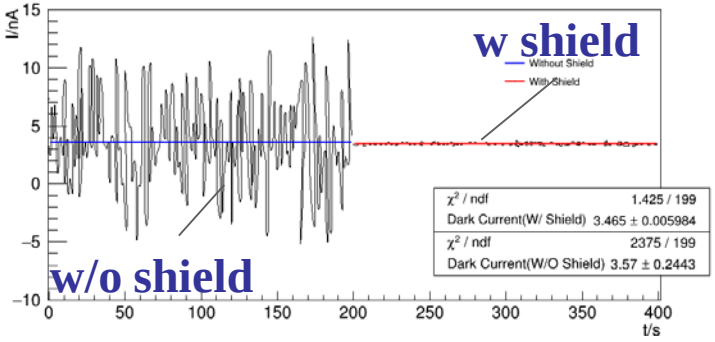
- **Measurement System @ IHEP**

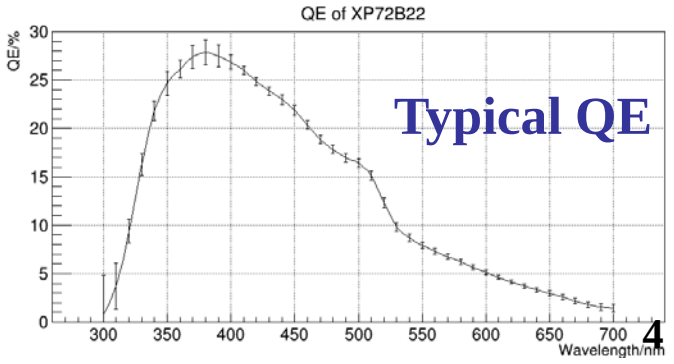
  The system for QE measurement

  - **Relative measurement, reference PMT: R7725 (Hamamatsu)**
  - **Range of wavelength: 200nm-1100nm**



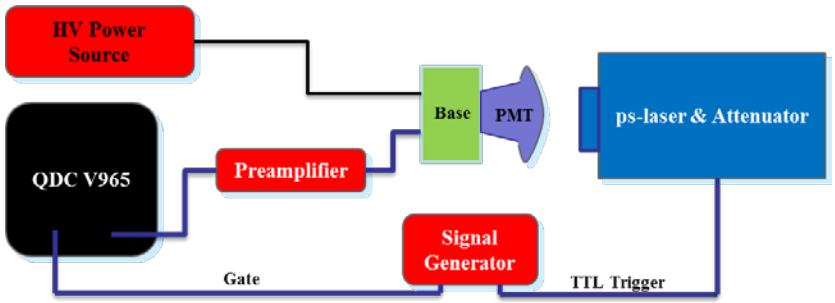



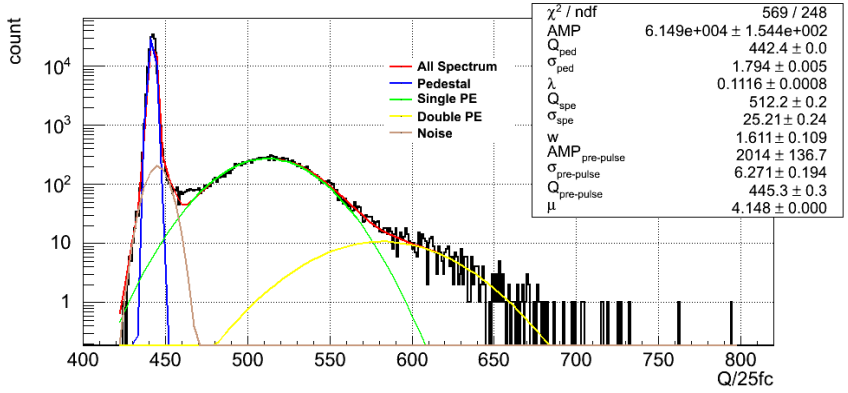



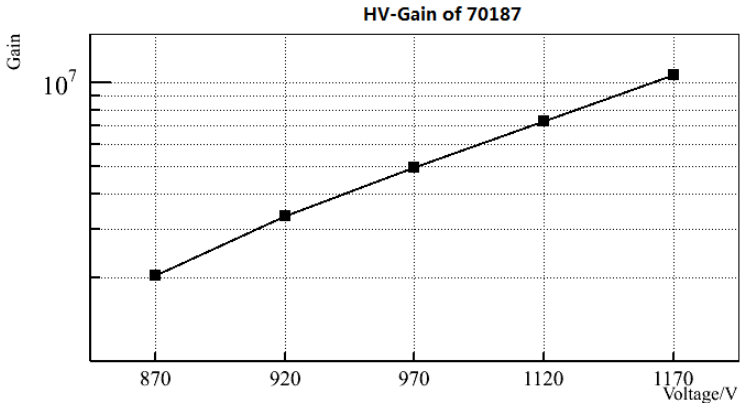
# The R&D for 3-inch PMT Performance

## The system for SPE measurement



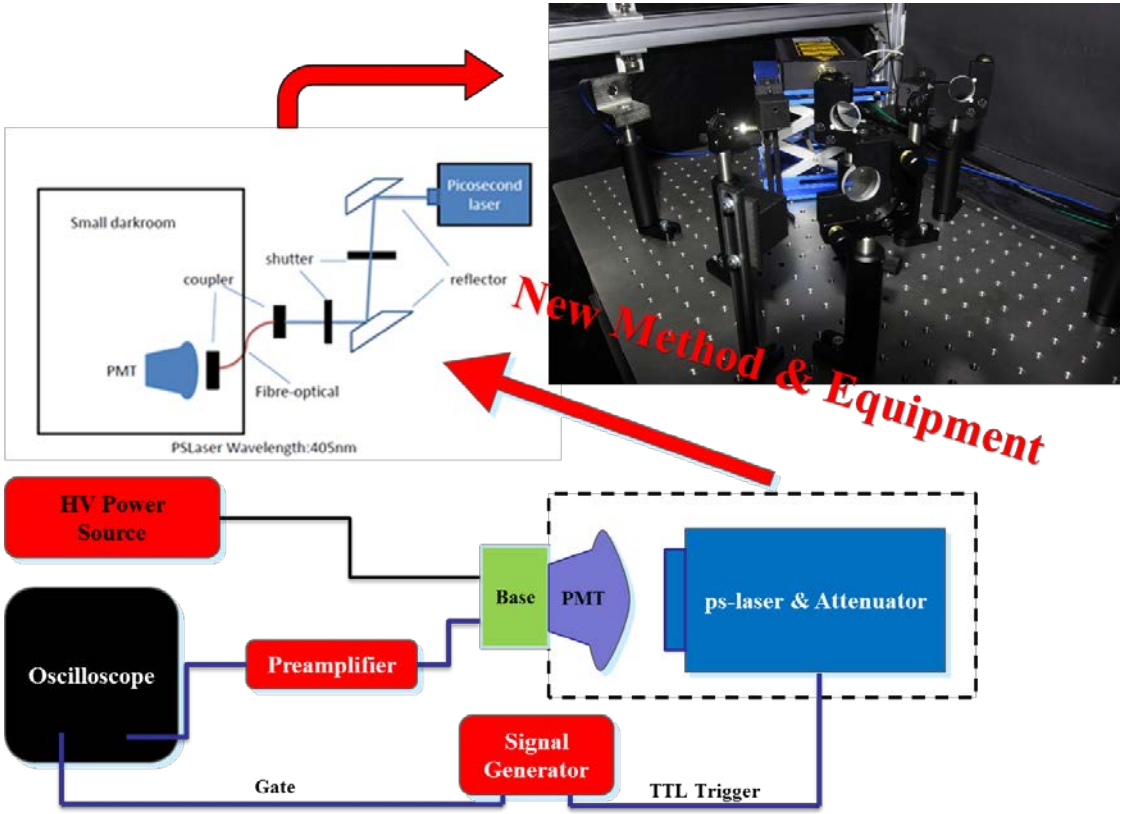

- **Light source: ps-laser (405nm)**
- **Synchronous trigger**
- **SPE Spectrum (Gain, P-V Ratio, Resolution)**



# The R&D for 3-inch PMT Performance

The system for time performance measurement
(TTS, pre-pulse/after-pulse)




**ps-SPE-laser:**

- **405nm**
- **Attenuator with reflecting structure**
- **Jitter < 40ps**

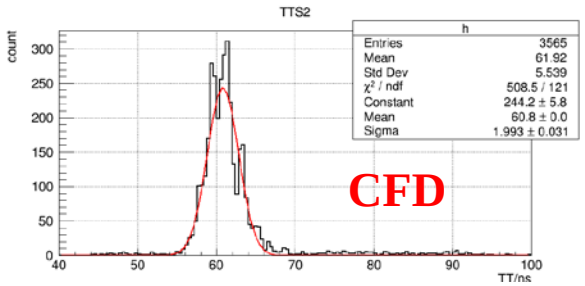
**Oscilloscope:**

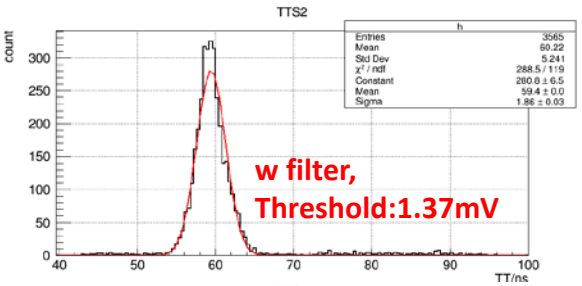
- **High sampling rate: 20Gas/s**
- **High waveform saving speed: >60 cps**
- **DAQ remotely**

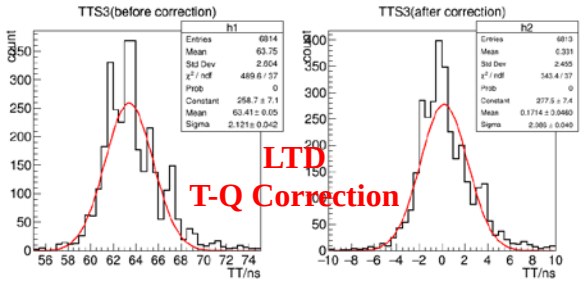
# The R&D for 3-inch PMT Performance

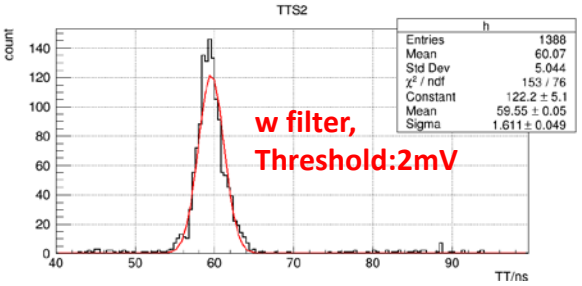
Comparison for TTS by different analysis method to waveform

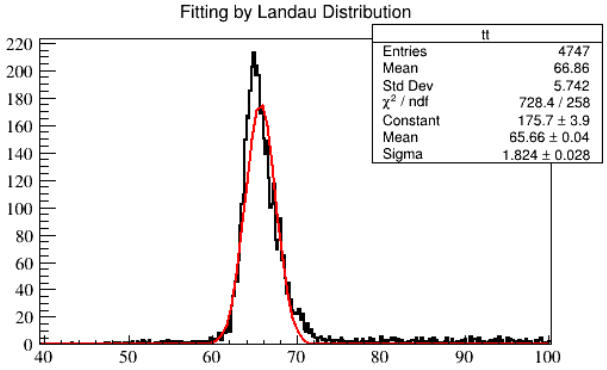
| Method | Threshold/mV | Entries | TTS(σ)/ns |
|---|---|---|---|
| CFD, w/o LPF | 2 | 3565 | 1.99±0.03 |
| LTD, w/o LPF | 2 | 3565 | 2.09±0.04 |
| W LPF | 1.37 | 3565 | 1.86±0.03 |
| W LPF | 2 | 1388 | 1.61±0.05 |
| Fitting by Landau Distribution | 2 | 3548 | 1.83±0.03 |



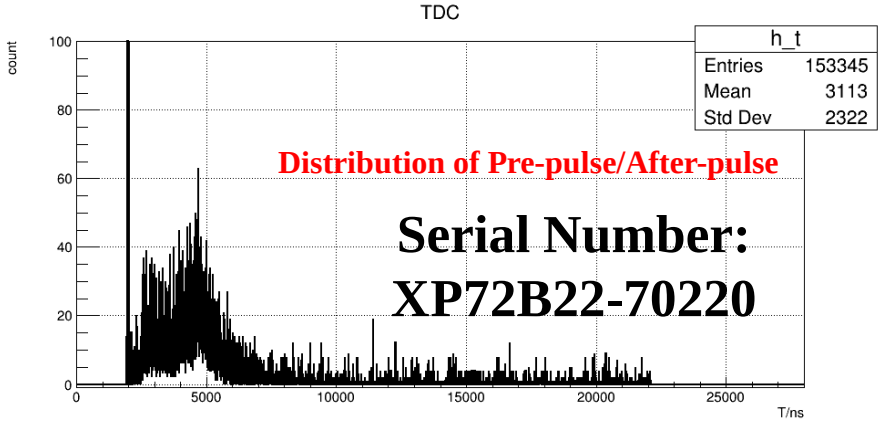



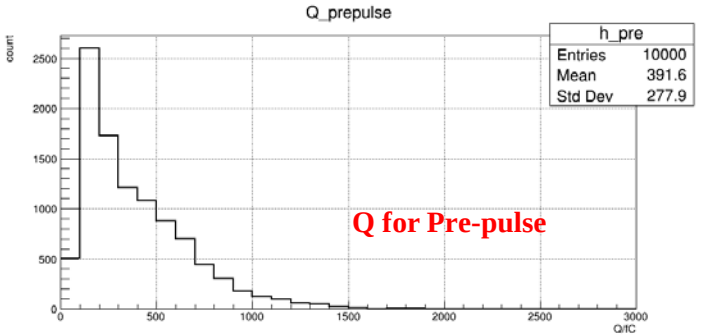



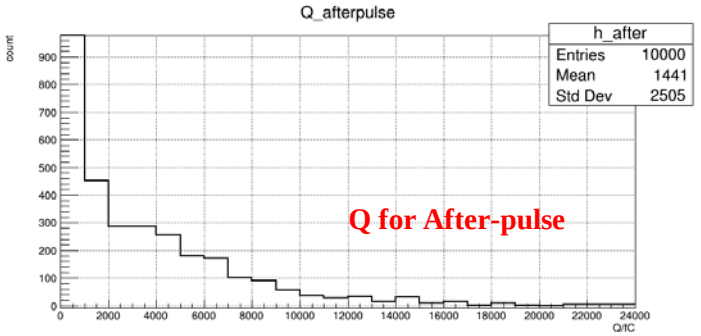



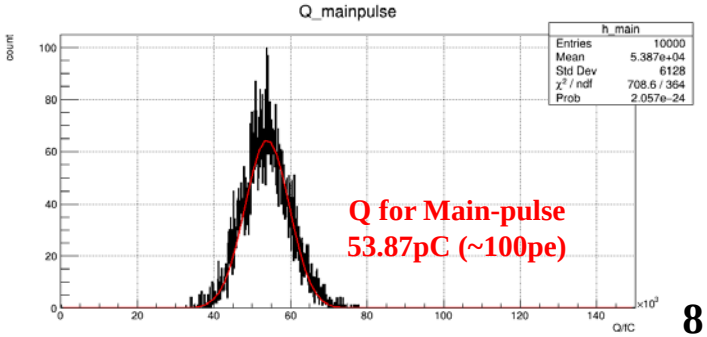
# The R&D for 3-inch PMT Performance

## Measurement for Pre-pulse & After-pulse




**Result:**

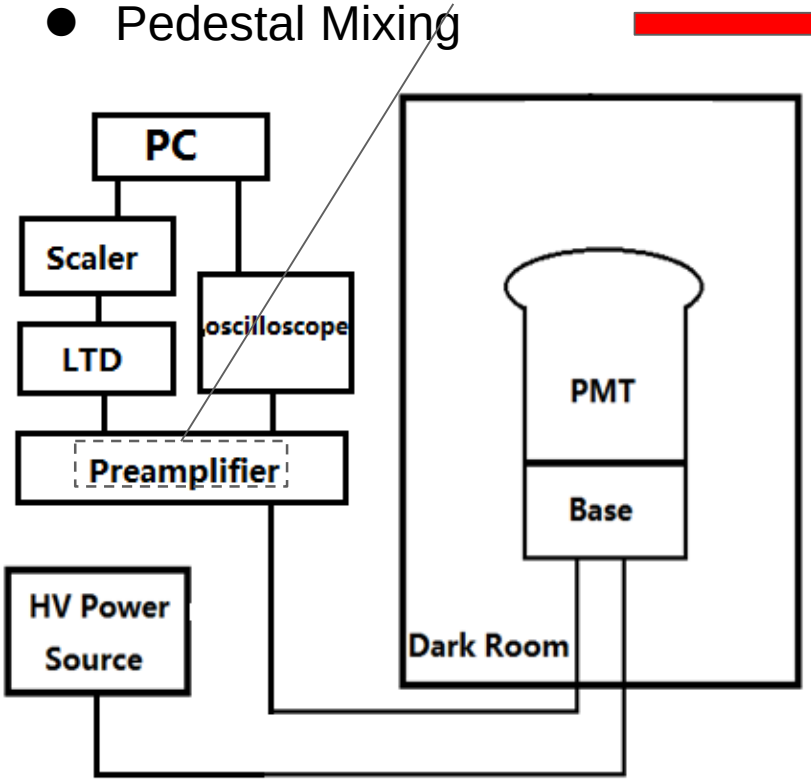
- **Pre-pulse Ratio(Q): 0.08%**
- **After-pulse Ratio(Q): 1.04%**

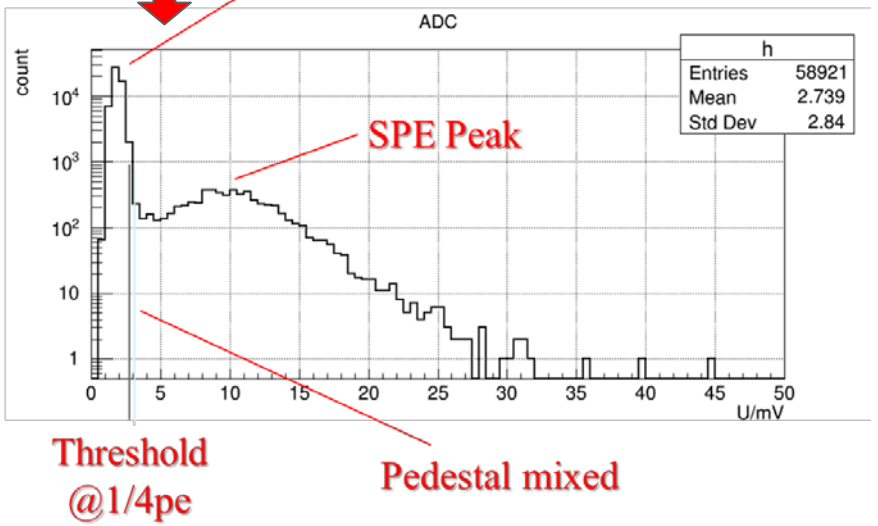
**Time Per Request:**
**18min/PMT**
**(1000 waveforms)**

# The R&D for 3-inch PMT Performance

The system for dark noise measurement

- Threshold setting
- Influence by the width of pedestal
- Influence by preamplifier
- Pedestal Mixing



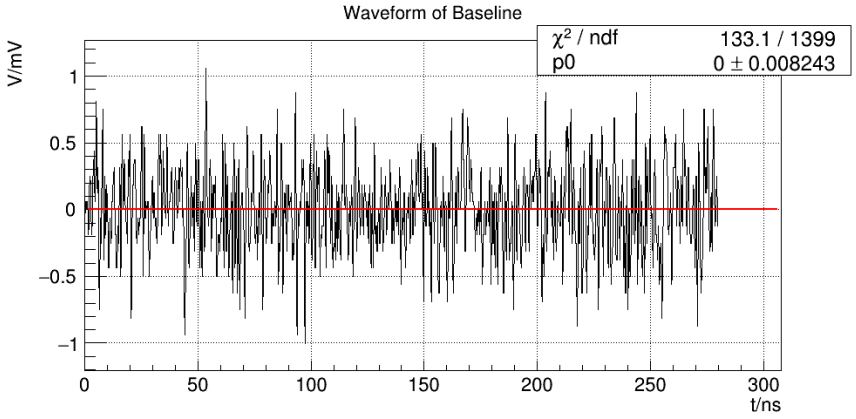



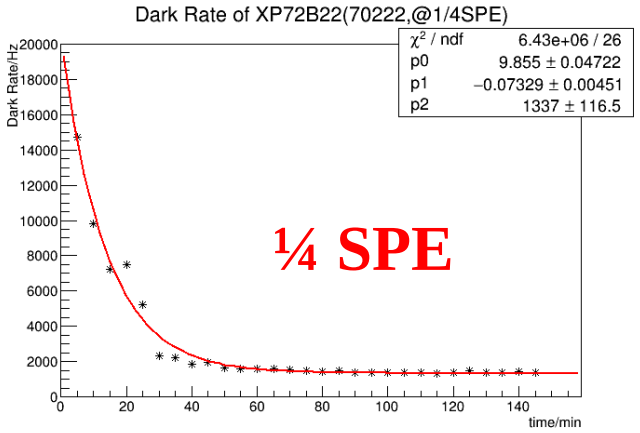

**w preamplifier: width of pedestal increasing**
**w/o preamplifier: threshold setting difficultly**

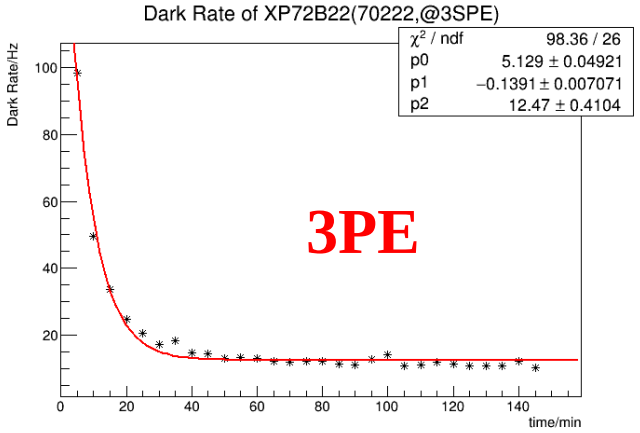
# The R&D for 3-inch PMT Performance

Baseline & Electronic Noise

Typical result of dark noise with time increasing



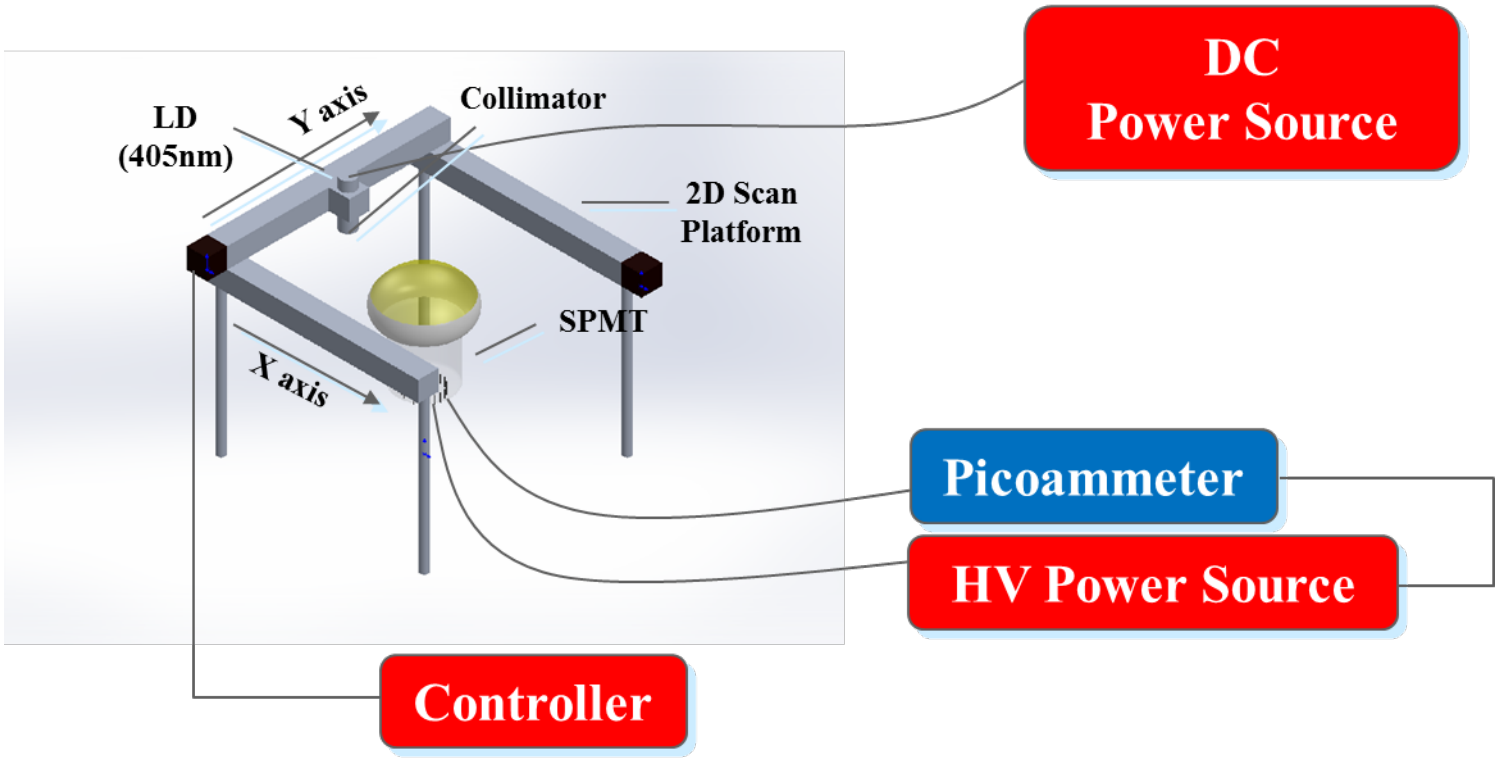




- **The level of electronic noise(σ): 0.06mV**
- **Dark noise becomes stable after coming into dark room 1~2 h.**

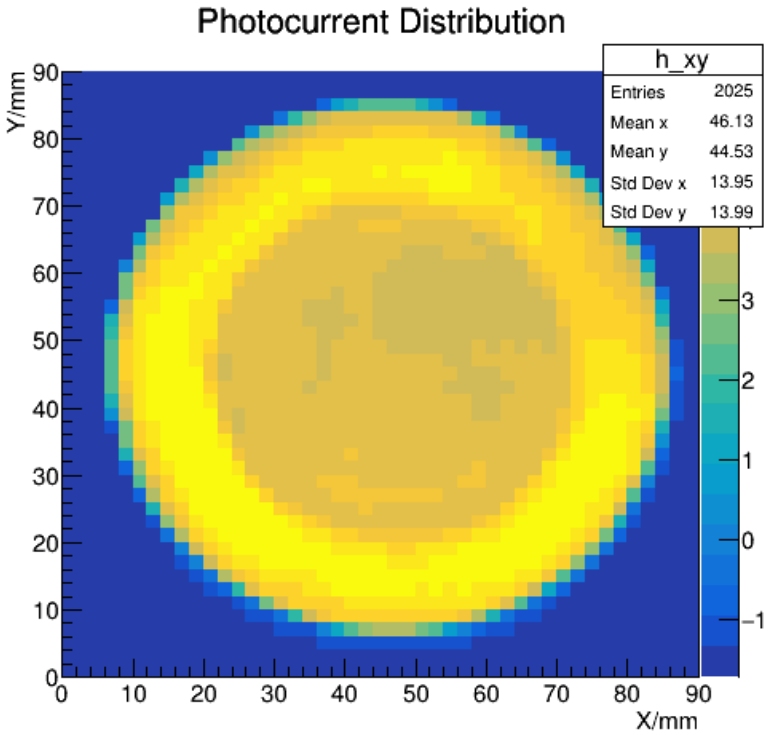
# The R&D for 3-inch PMT Performance

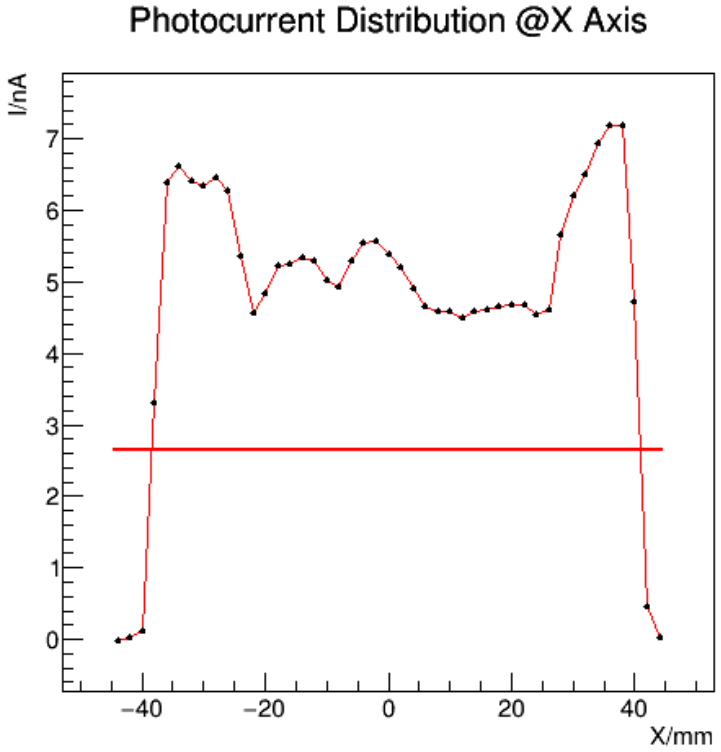
The system for uniformity of PMT cathode measurement



# The R&D for 3-inch PMT Performance

- **Diameter of collimator: 1.4mm**
- **Controlling by PC, automatic scan (2D)**
- **Measured the current from 1st dynode (cathode current)**
- **Definition: RMS/Mean**



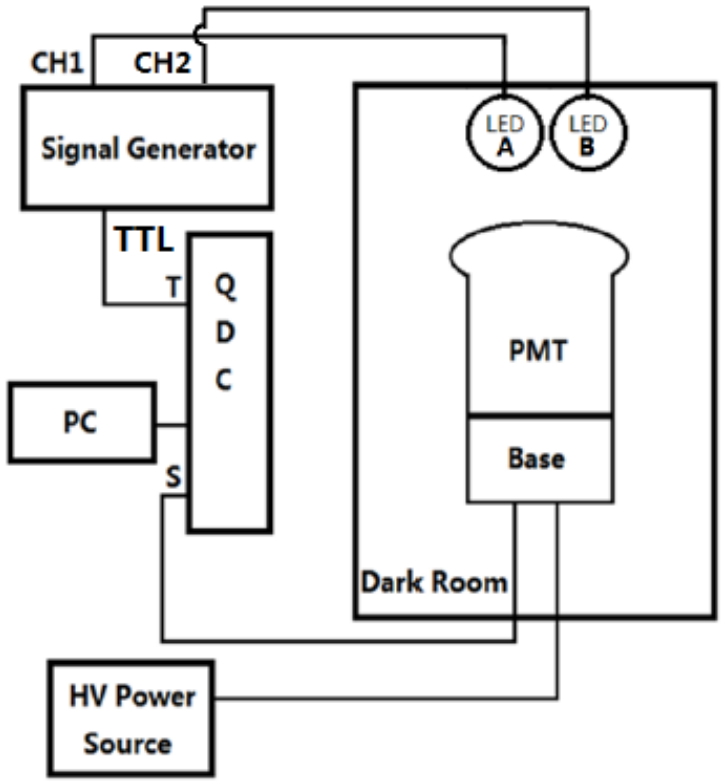



# The R&D for 3-inch PMT Performance

The system for nonlinearity measurement

| SN of PMT | Pedestal | LED A | LED B | LED A + LED B | Nonlinearity |
|---|---|---|---|---|---|
| 70187 | 39 | 557 | 203 | 724 | 0.44% |
| 70219 | 38 | 538 | 182 | 689 | 1.08% |
| 70220 | 38 | 493 | 164 | 617 | -0.35% |
| 70222 | 39 | 494 | 172 | 629 | 0.34% |
| 70226 | 39 | 529 | 179 | 675 | 0.94% |

- (Unit: CH, 612CH~100pe)



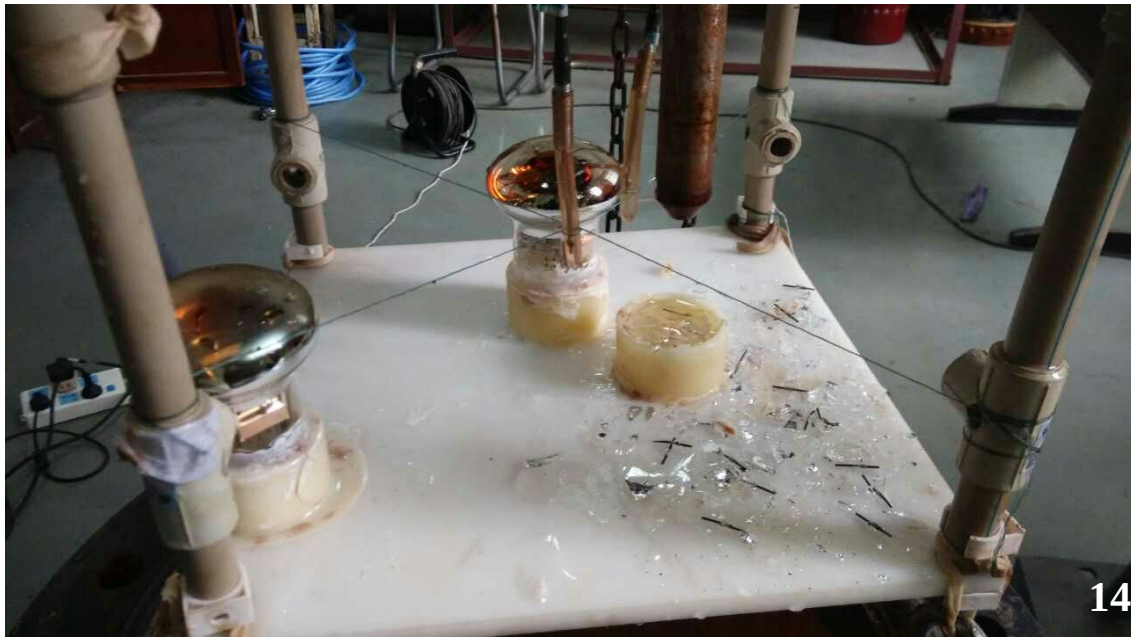
# The R&D for 3-inch PMT Performance

Implosion protection: Water Pressure Resistant

- 3 times of implosion threshold tests for HZC 3-inch glass shell

| 1.83MPa | 1.70MPa | 1.54MPa |
|---|---|---|

- 3 times of chain reaction tests under 0.5MPa water
  - No chain reaction for PMTs at 15mm and 150mm
- Protection for small PMT is not necessary



# The R&D for 3-inch PMT Performance

## SPMT Low Background Control

- Before Sept., 2017, Th232 and U238 always exceed our requirement.
- Visited glass factories with HZC manager in Sept. 2017.
- Get 4 kinds of materials, tested.

**Unit: Bq/kg**

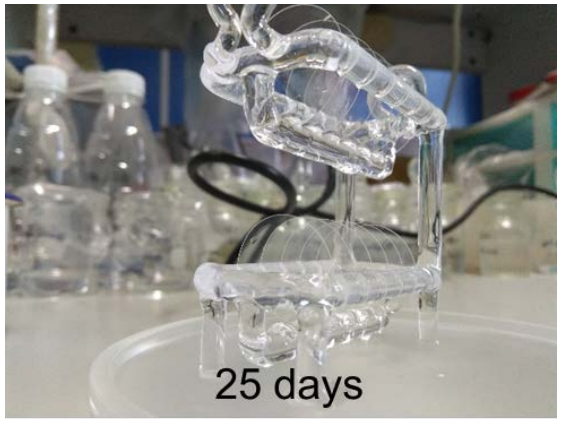
| Quartz sands | U238 (Pb214/Bi214) | U238 (Ra226) | Th232 (Ac228/Pb212/Tl208) | K40 |
|---|---|---|---|---|
| Pmt glass with Acid-washed sand | 1.75±0.07 | 1.91±0.33 | 1.05±0.05 | 13.26±0.86 |
| Acid-washed sand | 1.03±0.04 | 0.99±0.17 | 0.18±0.02 | 9.35±0.58 |
| High-pure sand | 0.29±0.03 | 0.28±0.21 | 0.06±0.02 | 66.47±3.59 |
| Sand with brand Anhui Fengyang | 2.95±0.09 | 3.15±0.36 | 4.07±0.12 | 8.37±0.53 |
| Requirement in contract | <4.94 | | <1.63 | <52.47 |

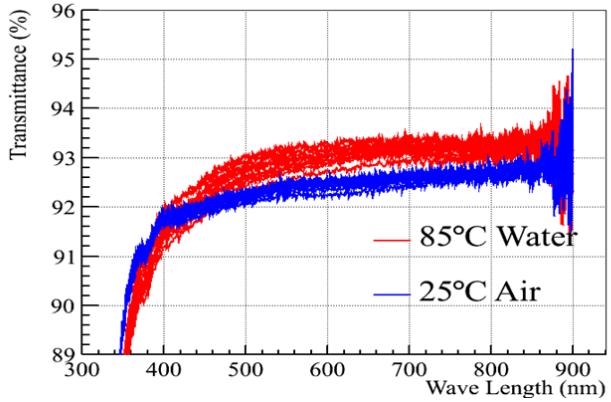
- **Acid-washed sand and its glass can meet our requirement.**
- **HZC MUST use glass with acid-washed sand material to produce spmt.**

# The R&D for 3-inch PMT Performance

## Water compatibility of SPMT glass

- Some papers point out that the Na+, K+ can be dissolved in pure water for long time immerse. This may cause glass surface dim and influence the light transmission, even influence the structural strength.
- Important for JUNO.
- Testing method:
  - Reference group of 12 glass slices. Just in the air.
  - Immersed water group of 12 glass slices. Immersed in pure water with temperature 85℃. Change fresh pure water every day, keep immerse one month.

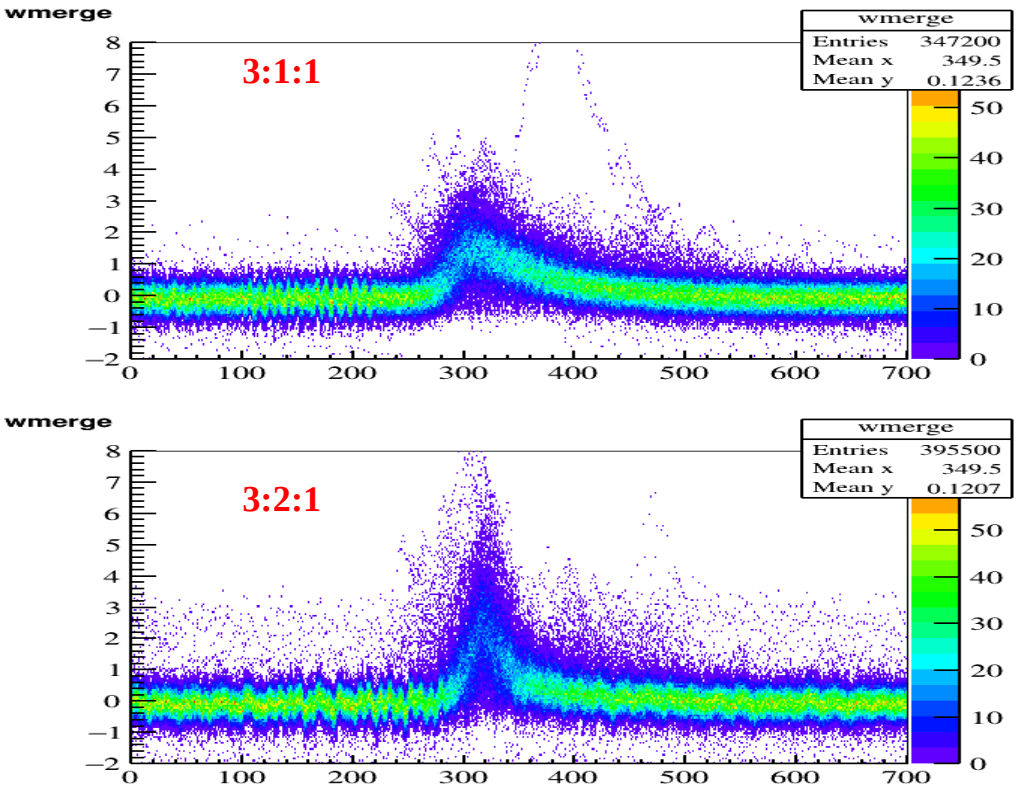



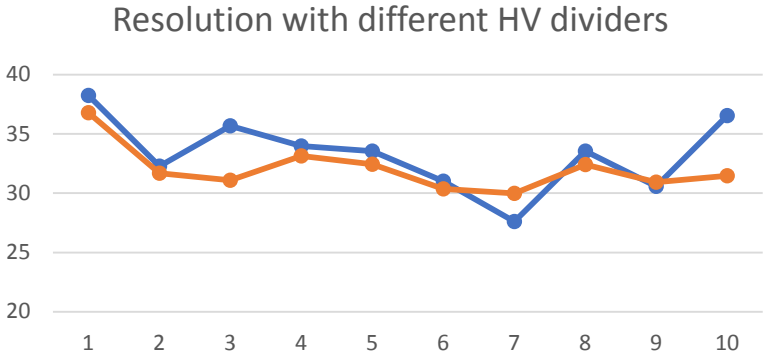

- **No obvious dim by eye, transmittance become better.**
- **Can be used as JUNO spmt glass.**

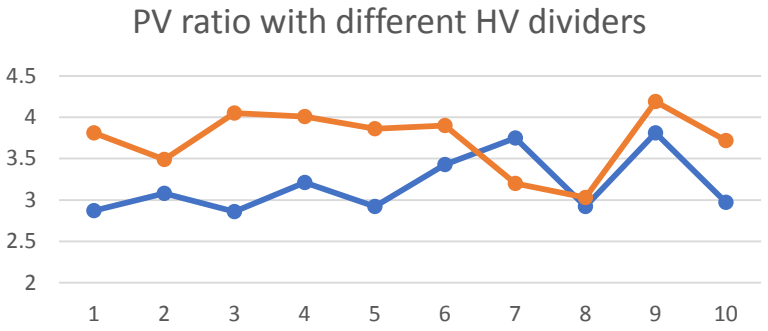
# The R&D for 3-inch PMT Performance

Comparison on waveforms come from bases with different HV divider @ $3 \times 10^6$ gain



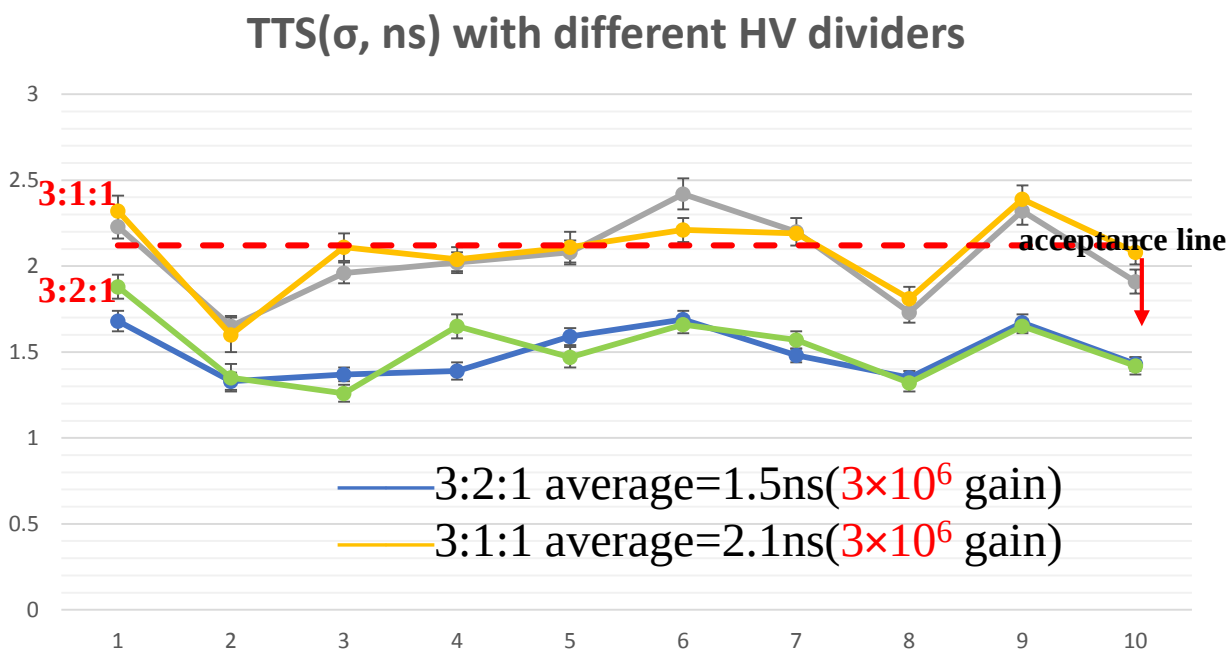

- **Waveforms come from 3:2:1 voltage divider is obviously higher and narrower than the waveforms come form 3:1:1 voltage divider.**



# The R&D for 3-inch PMT Performance

TTS(σ) with different HV dividers




- **TTS(σ) with 3:2:1 voltage divider is better than the results with 3:1:1 voltage divider. 1-1.5/2.1= 29% improvement.**
- **With the same HV divider, we didn't see significant changes when we changed the high voltages**

- **Resolution & P-V ratio didn`t become worse when HV divider changing to 3:2:1.**
- **TTS became much better when HV divider changing to 3:2:1.**

**3:2:1 will be used to be the HV divider ratio!!!**

# The R&D for 3-inch PMT Performance

## ➢ Some Result of Sample PMT Performance @IHEP

- 5 sample PMTs have been measured @IHEP
- Both 15 parameters can satisfy our requirement.

| No. | Parameter | Measured Value (Range) | Specified Value (Range) |
|---|---|---|---|
| 1 | Bulb Diameter | [78, 81]mm | $80 \pm 2mm$ |
| 2 | QE x CE @420nm | [23.5, 26.3]% | >22% |
| 3 | HV @$3 \times 10^6$ Gain | [905, 1202]V | <1300V |
| 4 | P - V Ratio | [2.28, 2.40] | >2 |
| 5 | Resolution of SPE ($\sigma$) | [31.8, 43.2]% | <45% |
| 6 | Dark Rate @1/4 PE | [0.68, 1.34] kHz | <1.8kHz |
| 7 | Dark Rate @3 PE | [4.7, 19.0]Hz | <30Hz |
| 8 | TTS (FWHM)* | [4.0, 4.4]ns | <5ns |
| 9 | QE Uniformity | [5.3, 7.9]% | <11% |

| No. | Parameter | Measured Value (Range) | Specified Value (Range) |
|---|---|---|---|
| 10 | Prepulse Ratio (in a 80ns window) | [0.6, 1.0]% | <5% |
| 11 | Afterpulse Ratio (in a 20μs window) | [2.1, 5.0]% | <15% |
| 12 | Effective Diameter of Cathode | [78, 80]mm | >74mm |
| 13 | Spectral Response Range | 300~[650, 700]nm | 300~600nm |
| 14 | Glass Radiation Level | $^{238}U$<145ppb $^{232}Th$<272ppb $^{40}K$<162ppb | $^{238}U$<400ppb $^{232}Th$<400ppb $^{40}K$<200ppb |
| 15 | Water Pressure Resistant | [1.54, 1.83] MPa | >1.0MPa |

***: The HV divider ratio is 3:1:1.**

# Mass Production & Test for 3-inch PMT

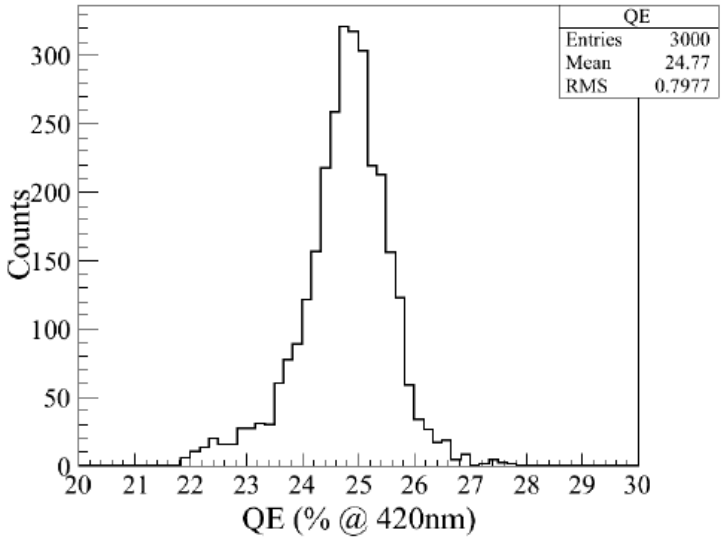
➢ **The Status of Production & Acceptance Test @HZC**

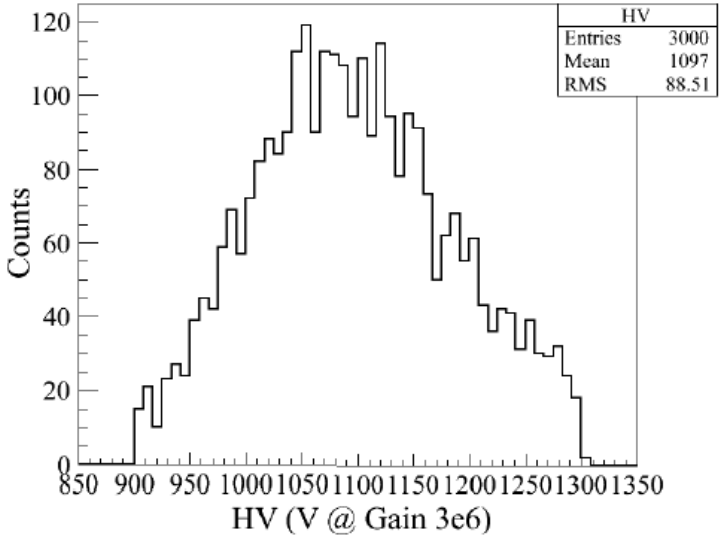
- **Production speed ~1000/month**
- **Almost 6000 PMTs was produced and passed HZC's test @ end of Jul.**
- **Acceptance test with <=10% samples has started in Feb. 2018 @ HZC**

# Mass Production & Test for 3-inch PMT

- **The Result of Acceptance Test @HZC**

Static testing (QE & HV)



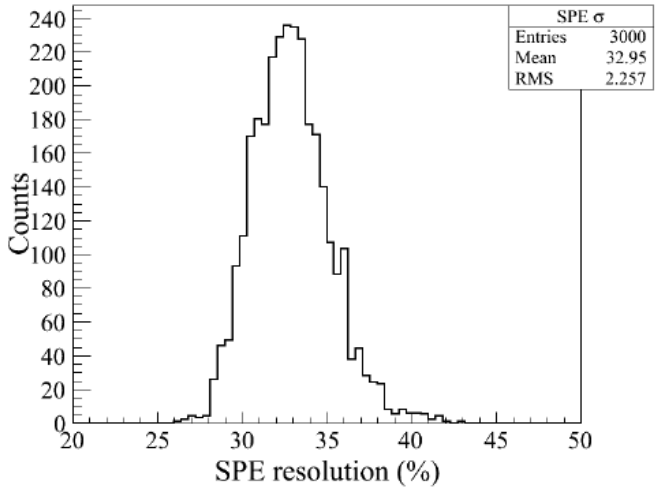



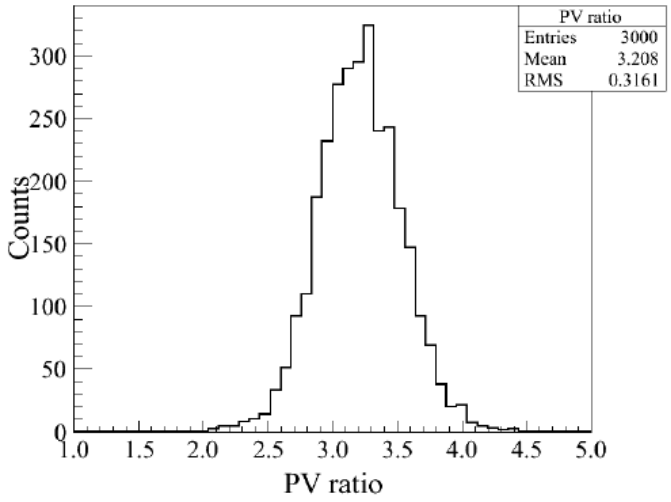

**1-20 batches, total 3000 pcs final.**

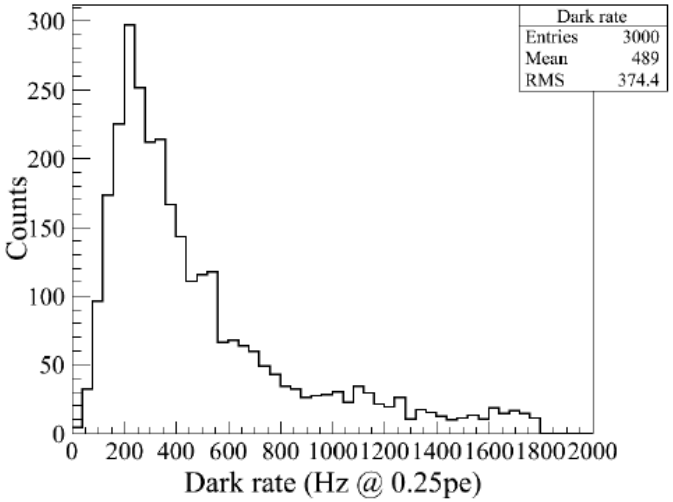
- **Requirement: QE>22%, HV<1300V**
- All satisfied our requirements.

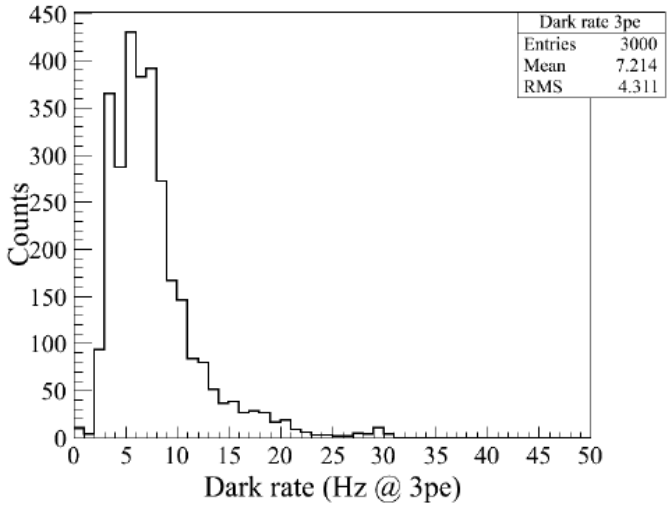
# Mass Production & Test for 3-inch PMT

Impulse testing (SPE & Dark Rate)




**1-20 batches, total 3000 pcs final.**

- **Requirement:**

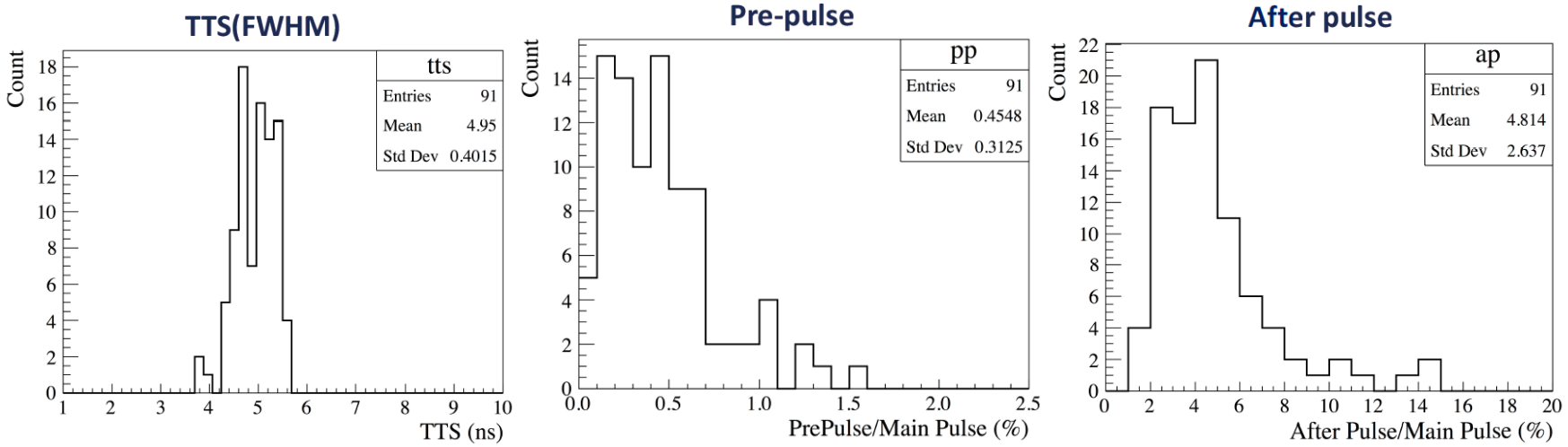
**SPE Resolution<45%,**
**P-V Ratio>2,**
**Dark Rate@1/4PE<1.8kHz,**
**Dark Rate@3PE<30Hz**

- All satisfied our requirements.

# Mass Production & Test for 3-inch PMT

Testing to time performance (TTS & Pre-pulse/After-pulse)

**Measurement System @HZC has developed by IHEP**

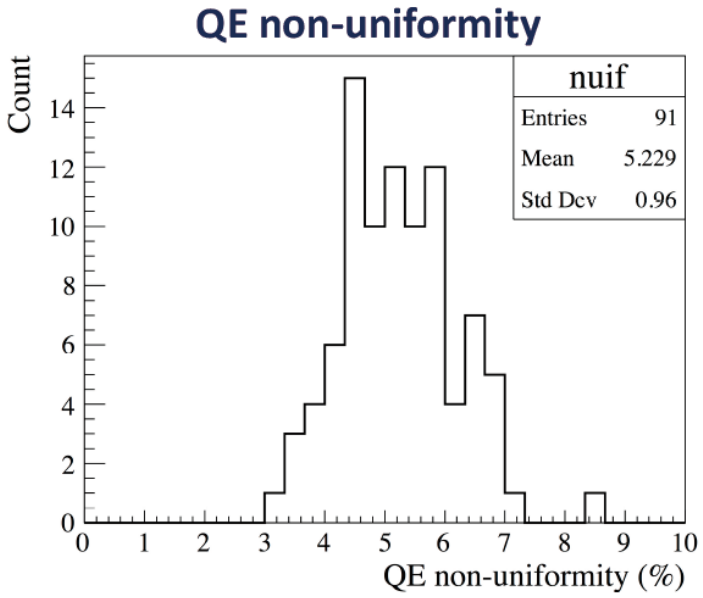


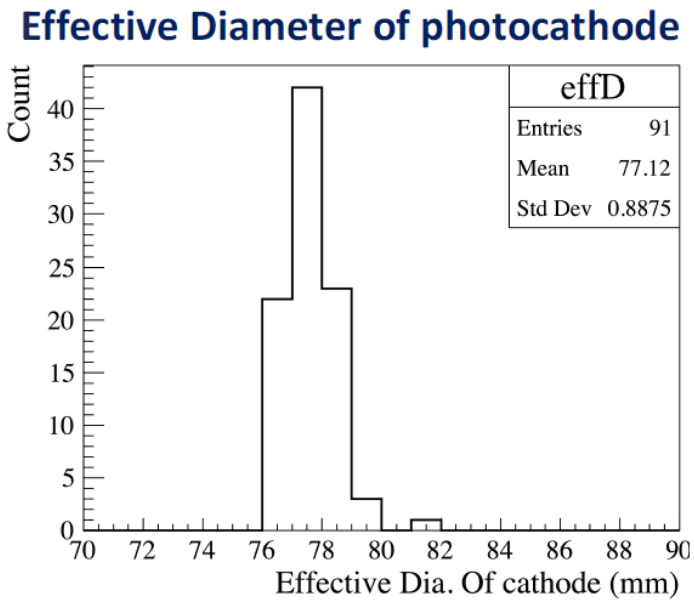

**1-20 batches, sample testing.**

- **Requirement: TTS<5ns, Pre-pulse<5%, After-pulse<15%**
- All satisfied our requirements.

# Mass Production & Test for 3-inch PMT

Cathode uniformity testing




**1-20 batches, sample testing.**

- **Requirement: QE Uniformity<11%,**
  **Effective Diameter of Cathode>74%**
- All satisfied our requirements.

# Mass Production & Test for 3-inch PMT

3-inch PMTs acceptance test summary

| Parameters | Sampling data req. | Mean |
|---|---|---|
| 1. Diameter Of Glass Bulb (mm) | 78<Dia. <82 | ✓ |
| 2. QEXCE@420nm (%) | >22 (Mean>24) | 25 |
| 3. HV@3X10$^6$gain | 900-1300 | 1097 |
| 4. SPE resolution (%) | <45 (Mean<35) | 33 |
| 5. P-V Ratio | >2 (Mean>3) | 3.2 |
| 6. Dark Rate@0.25PE (Hz) | <1.8k (Mean<1k) | 489 |
| 7. Dark Rate@3PE (Hz) | <30 | 7.2 |
| 8. SPE TTS (FWHM) (ns) | <5 | 4.9 |
| 9. Pre pulse ratio (10-90$ns$) | <5 (Mean<4. 5) | 0.4 |
| 10 .After pulse ratio (50$ns$ -20$\mu s$) | <15 (Mean<10) | 4.8 |
| 11. QE non-uniformity (%) | <11 | 5.2 |
| 12. Effective Dia. Of cathode (mm) | >74 (Mean>76) | 77.1 |
| 13. Spectral response range (%) | QE320>5 | 13.4 |
| | QE550>5 | 8.8 |

**The quality of the 3-inch PMTs is under control.**

# Summary

- @IHEP
  - The SPMT performance measurement system has been developed in IHEP.
  - 5 sample PMT has been measured and the measurement result can satisfy our requirement.

- @HZC
  - The performance of TTS has improved observably when HV dividers ratio changed to 3:2:1 from 3:1:1.
  - 3-inch PMTs production are on the progress, 1000 pcs/month.
  - Acceptance testing started in February, 2018.
  - The quality of the 3-inch PMTs is under control.

*Thanks!*