

# BEPCII上束流能量测量系统(BEMS)的原理与实现

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# 主要内容

- BEMS简介
- BEMS的工作原理
- BEMS的实现
- BEMS的测量结果
- 总结

# Beijing Electron Positron Collider (II)

Linac

Storage ring

2004: Start BEPCII upgrade  
2009 - : BESIII data taking

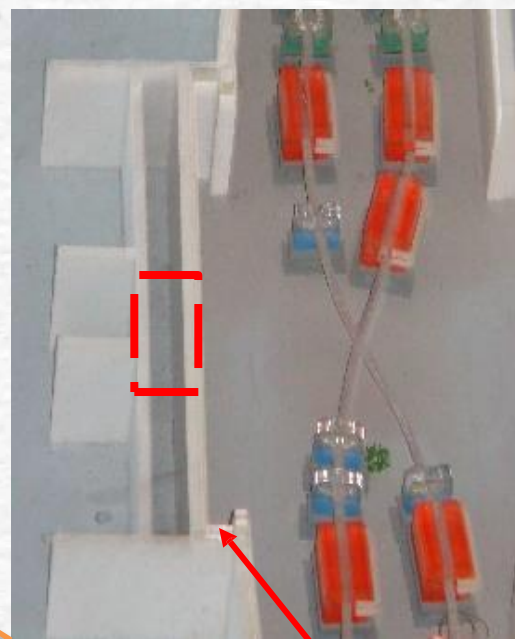
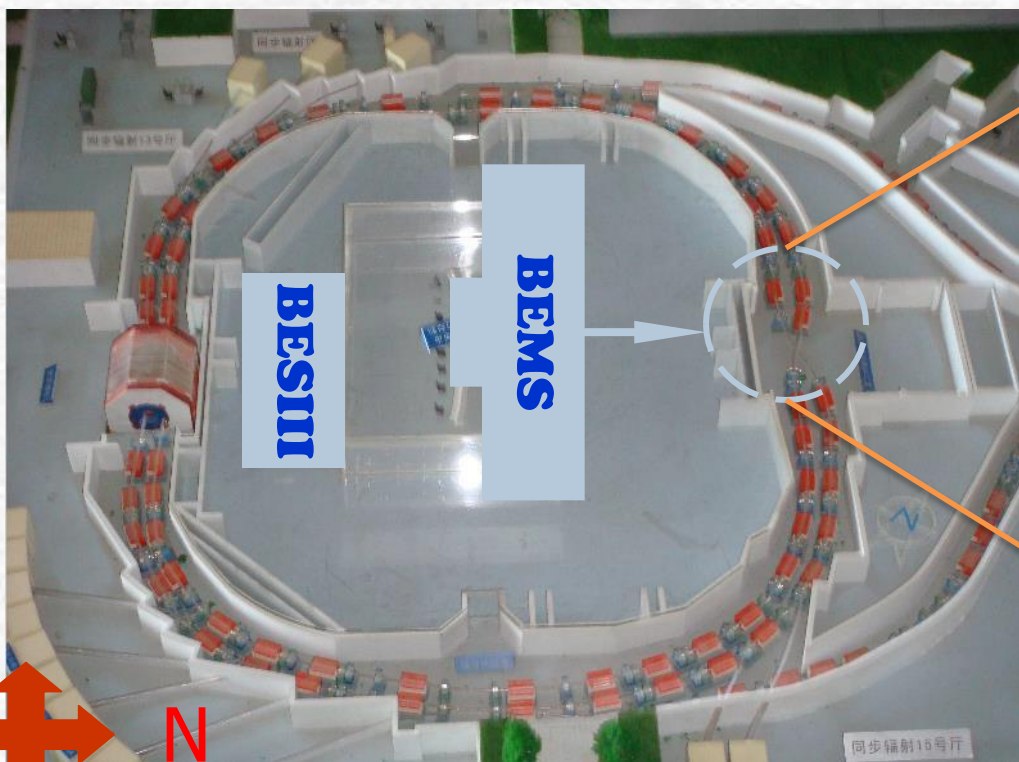
BESIII

# BEMS简介

- 精确测量束流能量对加速器和北京谱仪都有重要的意义
- 对于共振态质量测量，特别是陶轻子的质量测量，能量不确定度是改善其测量精度的瓶颈
- 目标：束流能量1-2GeV，相对精度  $5 \times 10^{-5}$



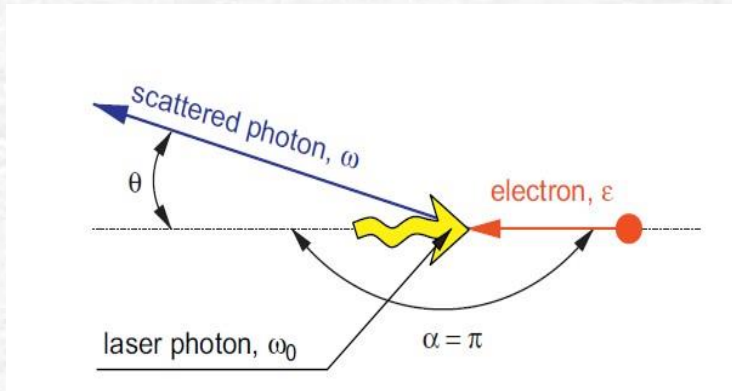
# BEMS位置



Corridor where optics system is located

BEMS 位于BEPCII储存环北交叉点

# BEMS工作原理：康普顿散射



散射光子的能量：

$$\omega = \omega_0 \frac{1 - \beta \cos \alpha}{1 - \beta \cos \theta + \frac{\omega_0}{\epsilon} (1 - \cos \Theta)}$$

康普顿背散射时：

$$\omega_{max} = \frac{\epsilon^2}{\epsilon + m_e^2 / 4\omega_0}$$

反解出束流能量：

$$\epsilon = \frac{\omega_{max}}{2} \left[ 1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{max}}} \right]$$

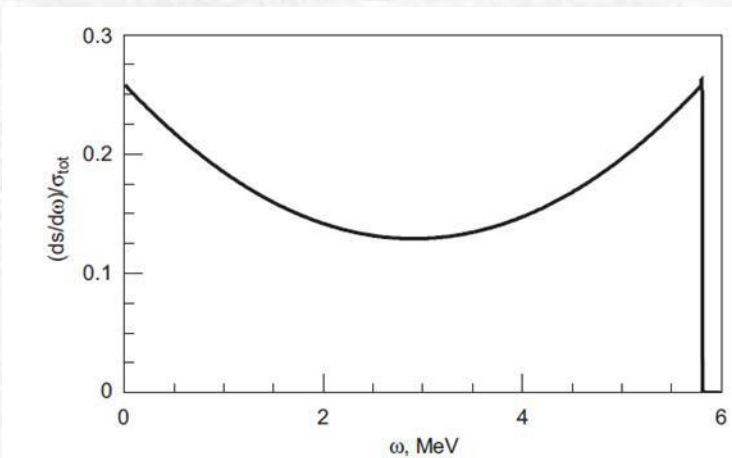
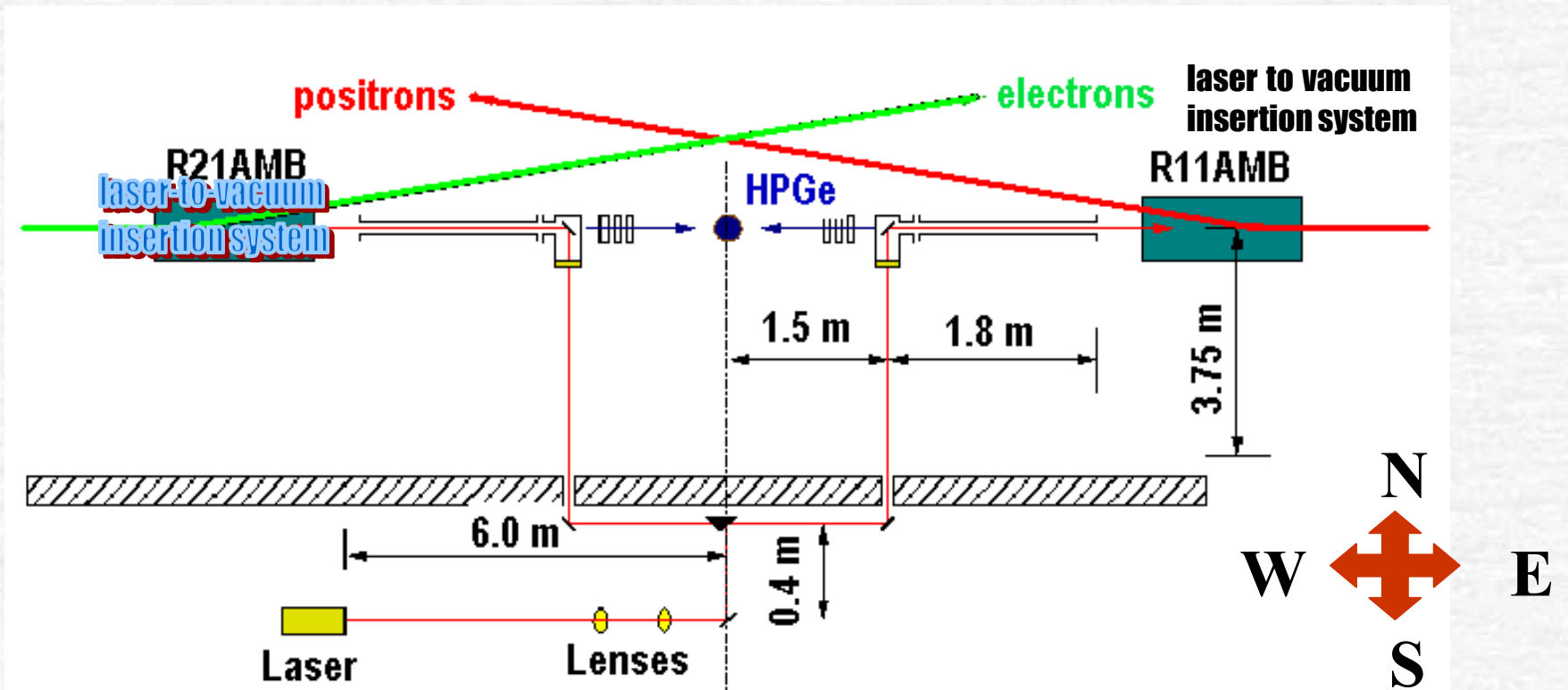


Fig. 3. Energy spectrum of scattered Compton photons. The initial electron and photon energies are  $\omega_0 = 0.12$  eV and  $\epsilon = 1770$  MeV, respectively, and  $\alpha = \pi$ .

# BEMS示意图



Laser and optics system

Laser to beam interaction system

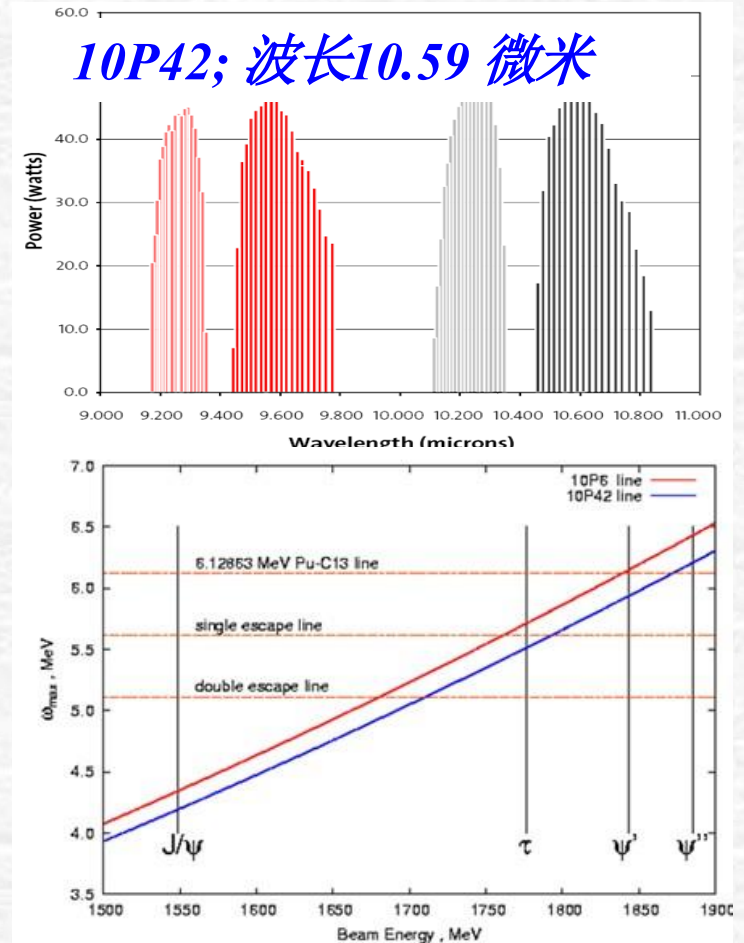
HPGe detection system

Data acquisition system

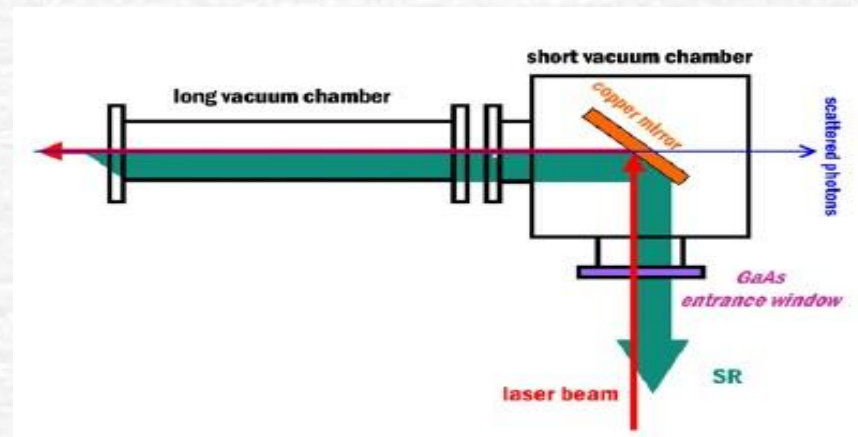
# BEMS的实现-激光器



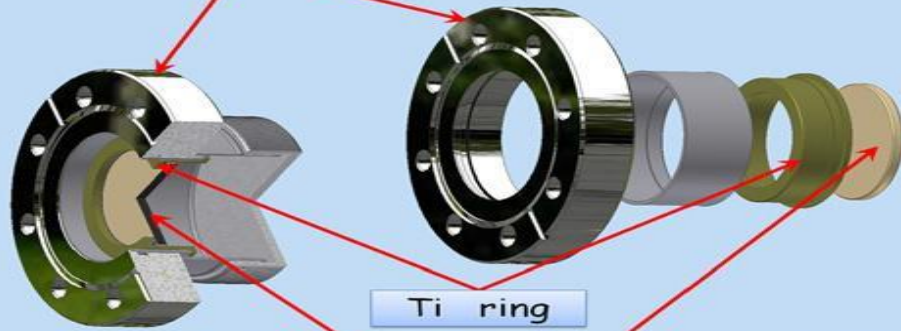
GEM-select50 型二氧化碳激光器  
功率: 45W, 能量: 0.12 eV



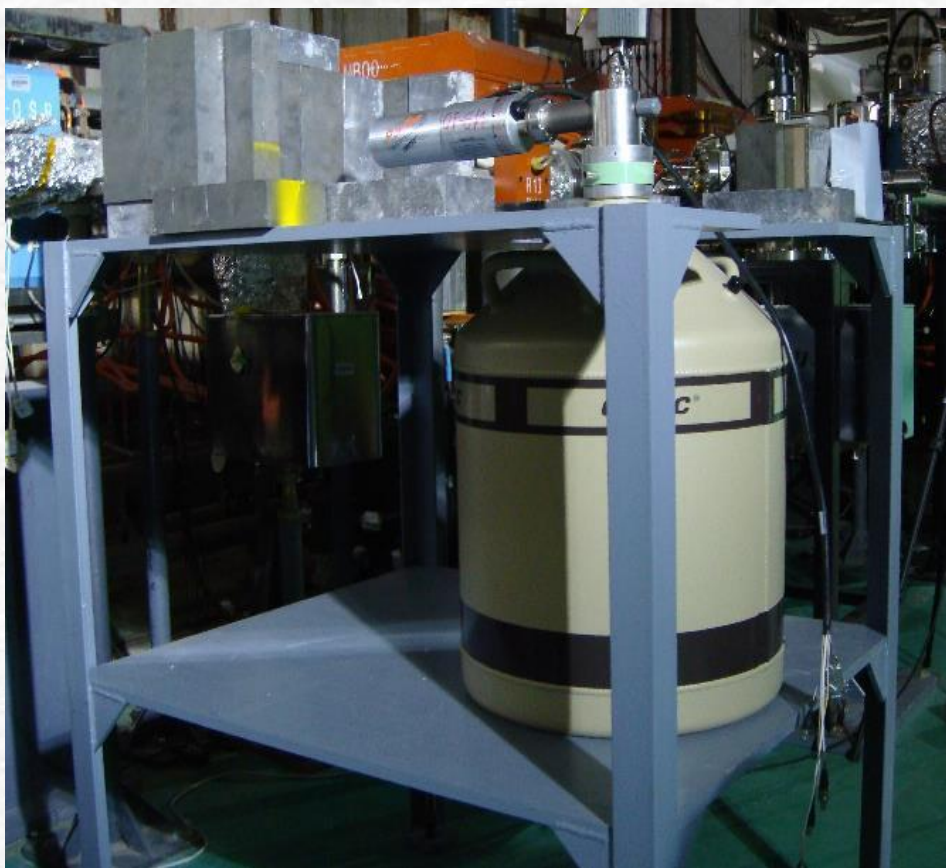
# BEMS的实现-真空部分



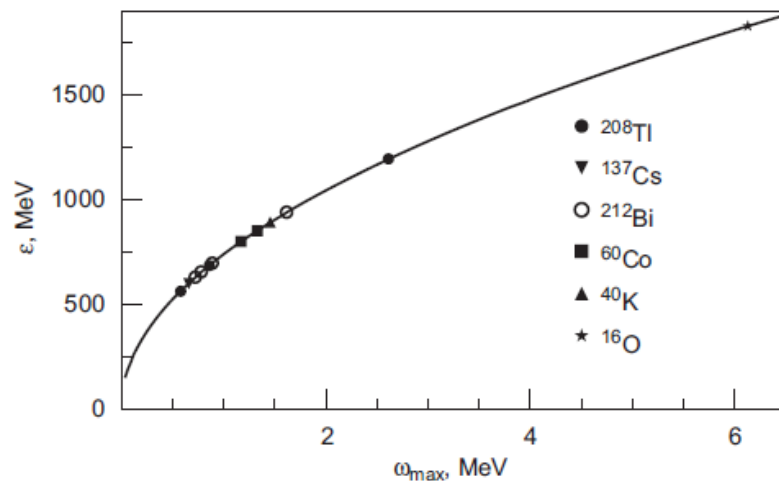
Conflat flange DN63



# BEMS的实现-高纯锗探测器



ORTEC P型,  
晶体尺寸: 直径 57.8, 长 52.7 毫米  
相对效率: 25%  
分辨率: 1.74 keV ( $^{60}\text{Co}$  1.33MeV)  
配备了Dspec-pro





**laser-to-vacuum insertion part**

**Backing,  
vacuum up to  
 $2.0 \times 10^{-10}$   
torr**



**chamber  
installation**



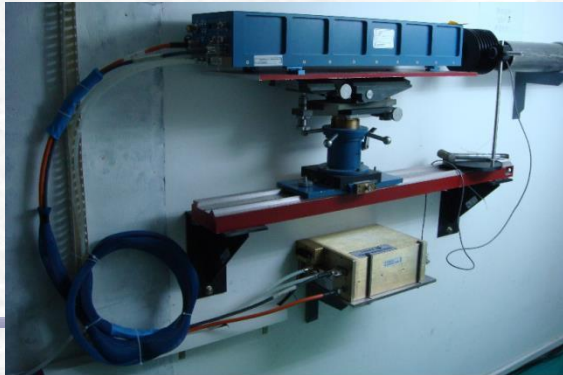
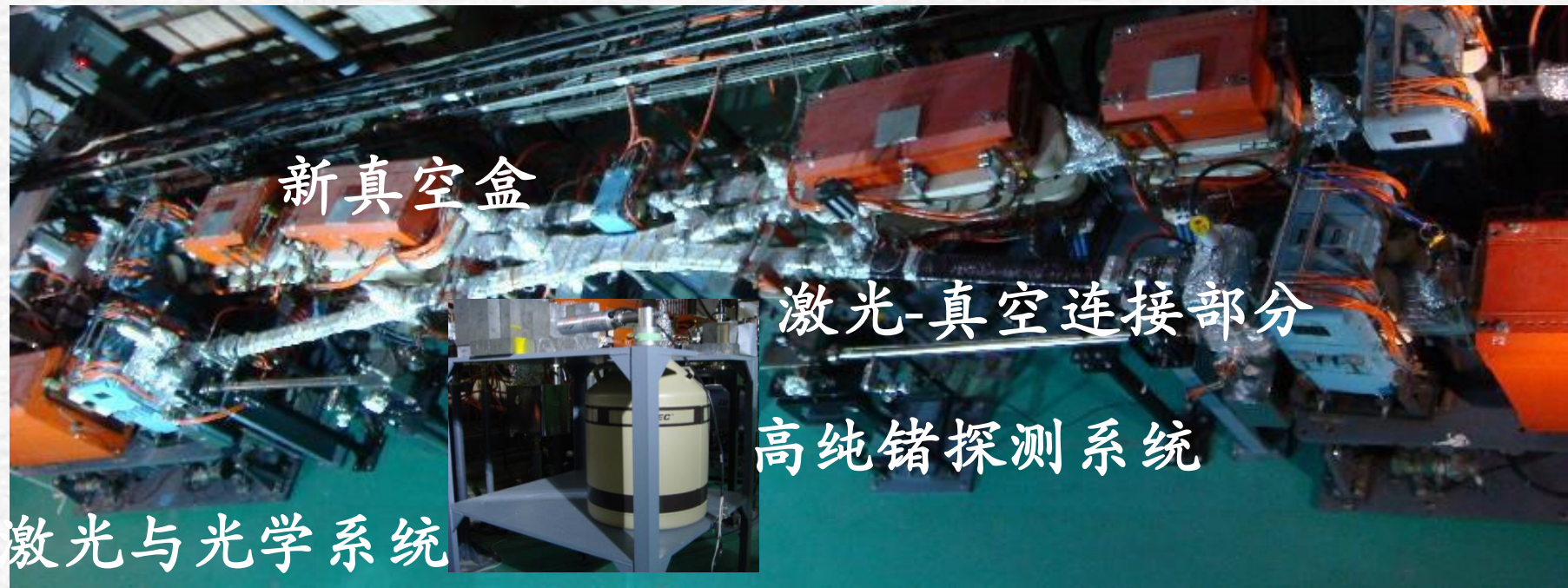
**Pump  
Installation**



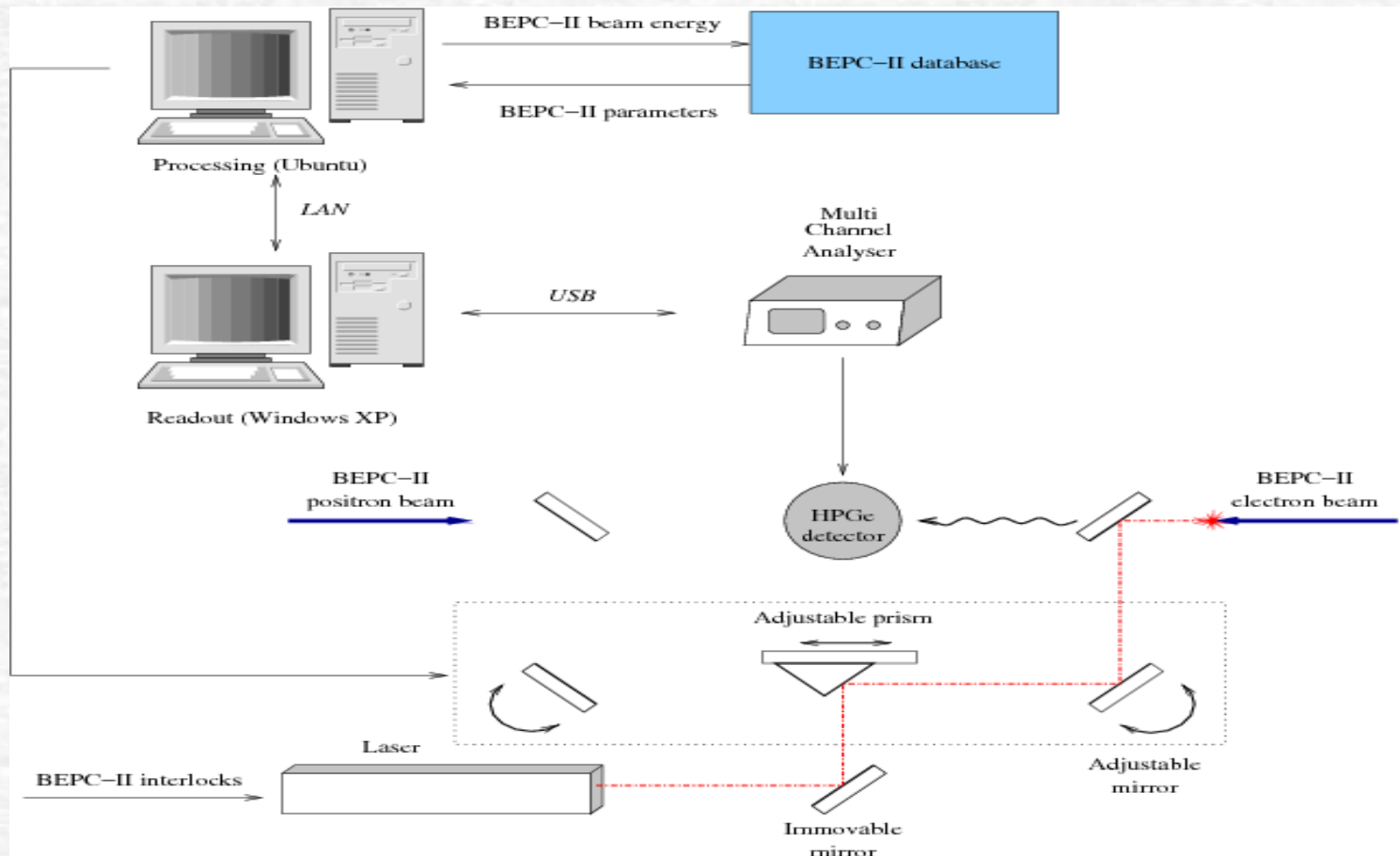
**Alignment**



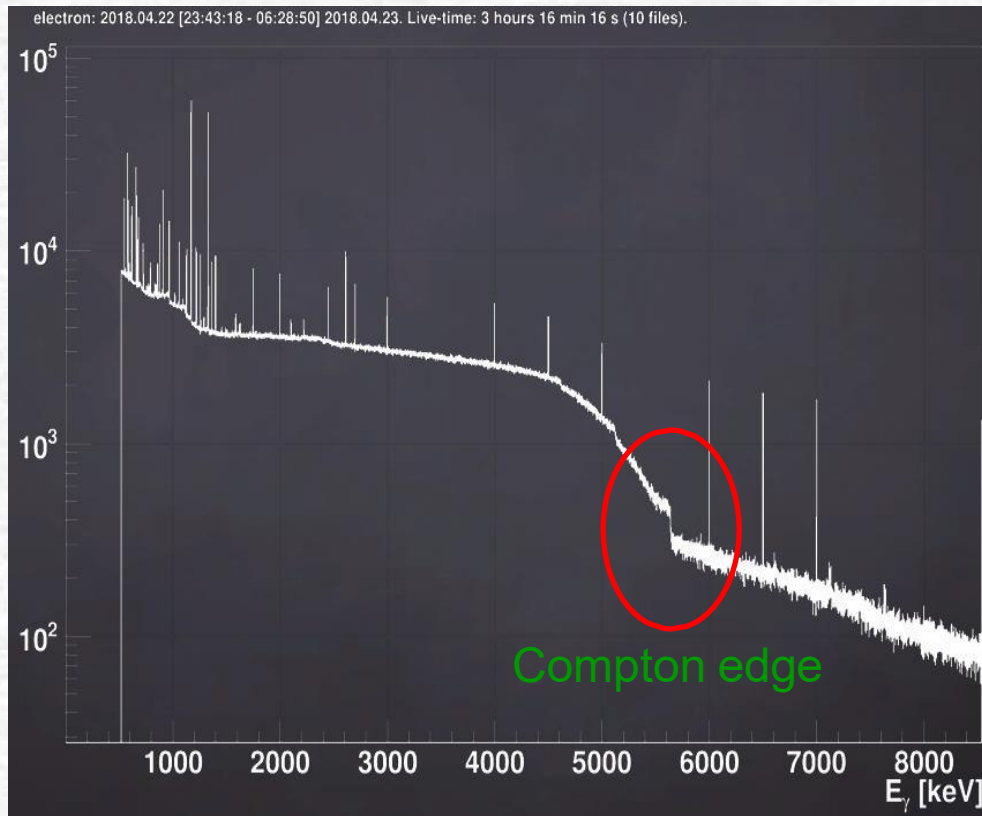
# BEMS总装图



# BEMS数据获取系统

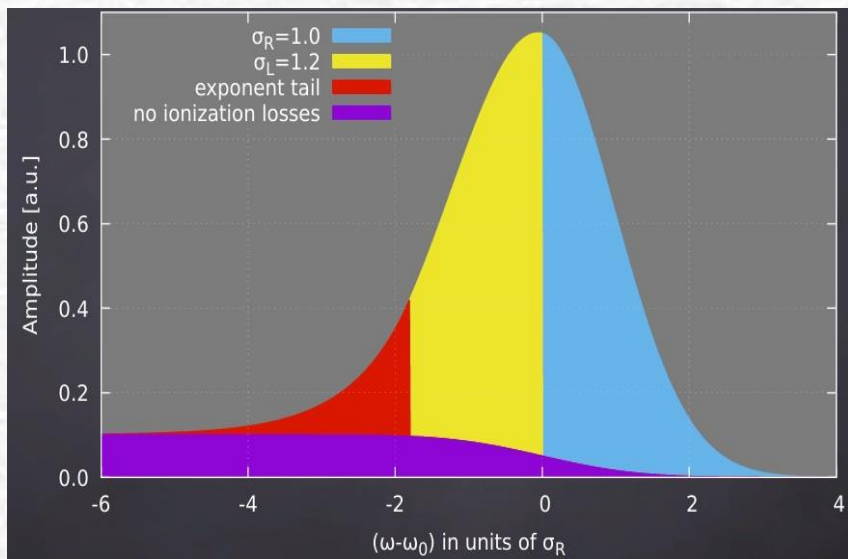


# 能谱与刻度



Source	$\gamma$ -rays energies, keV	Reference *
$^{137}\text{Cs}$	$661.657 \pm 0.003$	vol.4, 2008
$^{60}\text{Co}$	$1173.228 \pm 0.003$	vol.4, 2008
	$1332.492 \pm 0.004$	
$^{228}\text{Ac}$ ( $^{232}\text{Th}$ )	$911.209 \pm 0.006$	vol.6, 2011
$^{212}\text{Bi}$ ( $^{232}\text{Th}$ )	$727.330 \pm 0.030$	vol.2, 2004
	$1620.740 \pm 0.010$	
$^{208}\text{Tl}$ ( $^{232}\text{Th}$ )	$583.187 \pm 0.002$	vol.2, 2004
	$860.560 \pm 0.030$	
	$2614.511 \pm 0.010$	

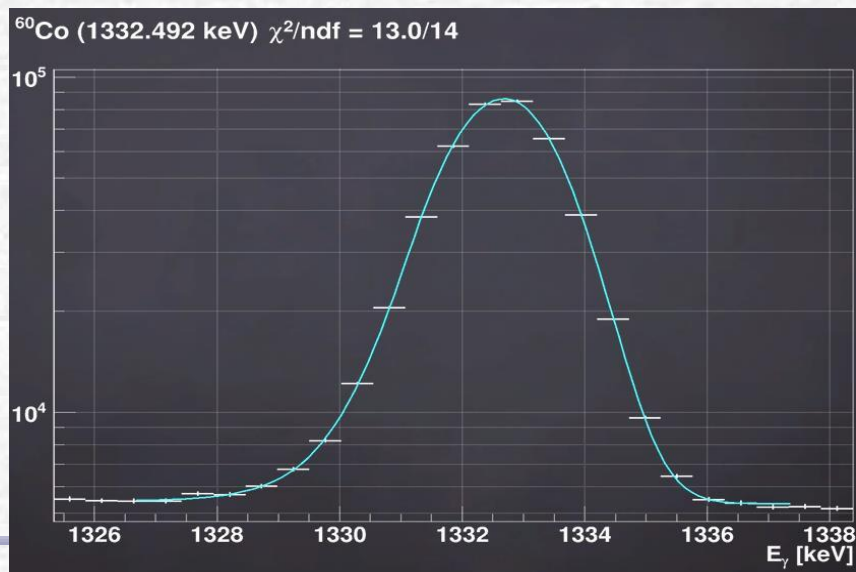
# 探测器刻度



$$f(x) = B + \frac{C}{2} \operatorname{erfc}\left(\frac{x}{\sqrt{2}\sigma_R}\right) + \frac{N}{N_1} \begin{cases} \exp\left(-\frac{x^2}{2\sigma_R^2}\right) & \text{if } x > 0; \\ \exp\left(-\frac{x^2}{2\sigma_L^2}\right) & \text{if } -\kappa\sigma_L < x \leq 0; \\ \exp\left(\frac{\kappa x}{\sigma_L} + \frac{\kappa^2}{2}\right) & \text{if } x \leq -\kappa\sigma_L. \end{cases}$$

$$N_1 = \sqrt{\frac{\pi}{2}}\sigma_R + \left\{ \frac{1}{\kappa} \exp\left(-\frac{\kappa^2}{2}\right) + \sqrt{\frac{\pi}{2}} \operatorname{erf}\left(\frac{\kappa}{\sqrt{2}}\right) \right\} \sigma_L$$

- 寻找并鉴别特征峰
- 通过响应函数与本底拟合特征峰
- 通过产生数据，获得MCA非线性特性
- 利用放射源，确定响应函数参数的能量依赖性



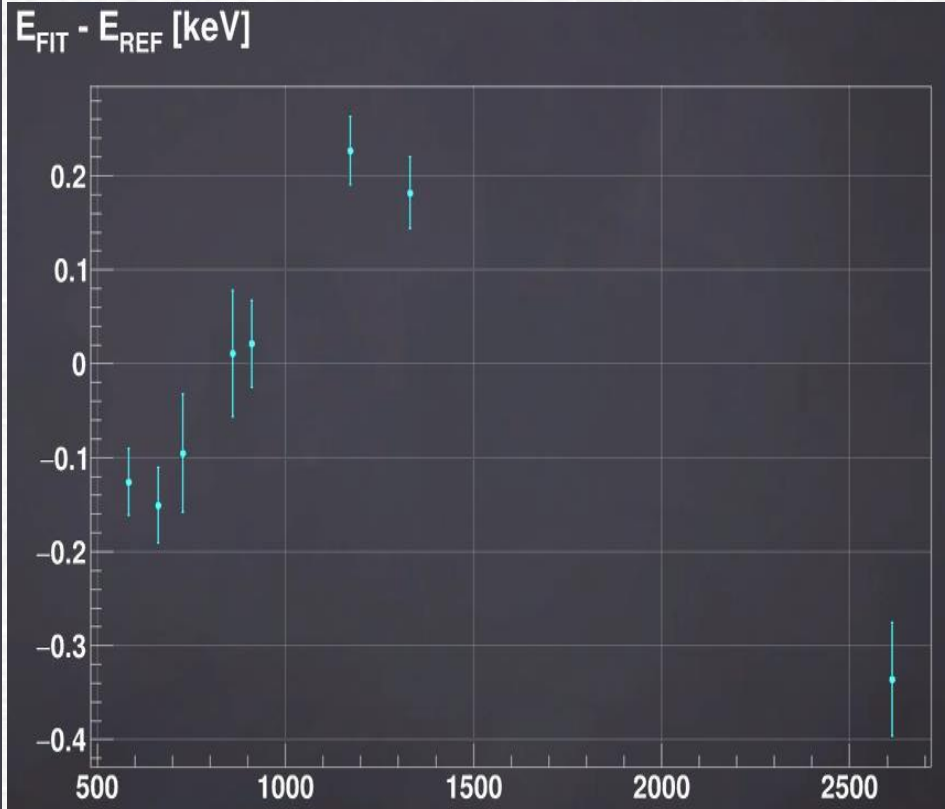
# 探测器刻度

Multichannel Analyzer:  
preamp & ADC  
ORTEC® DSPEC Pro™:



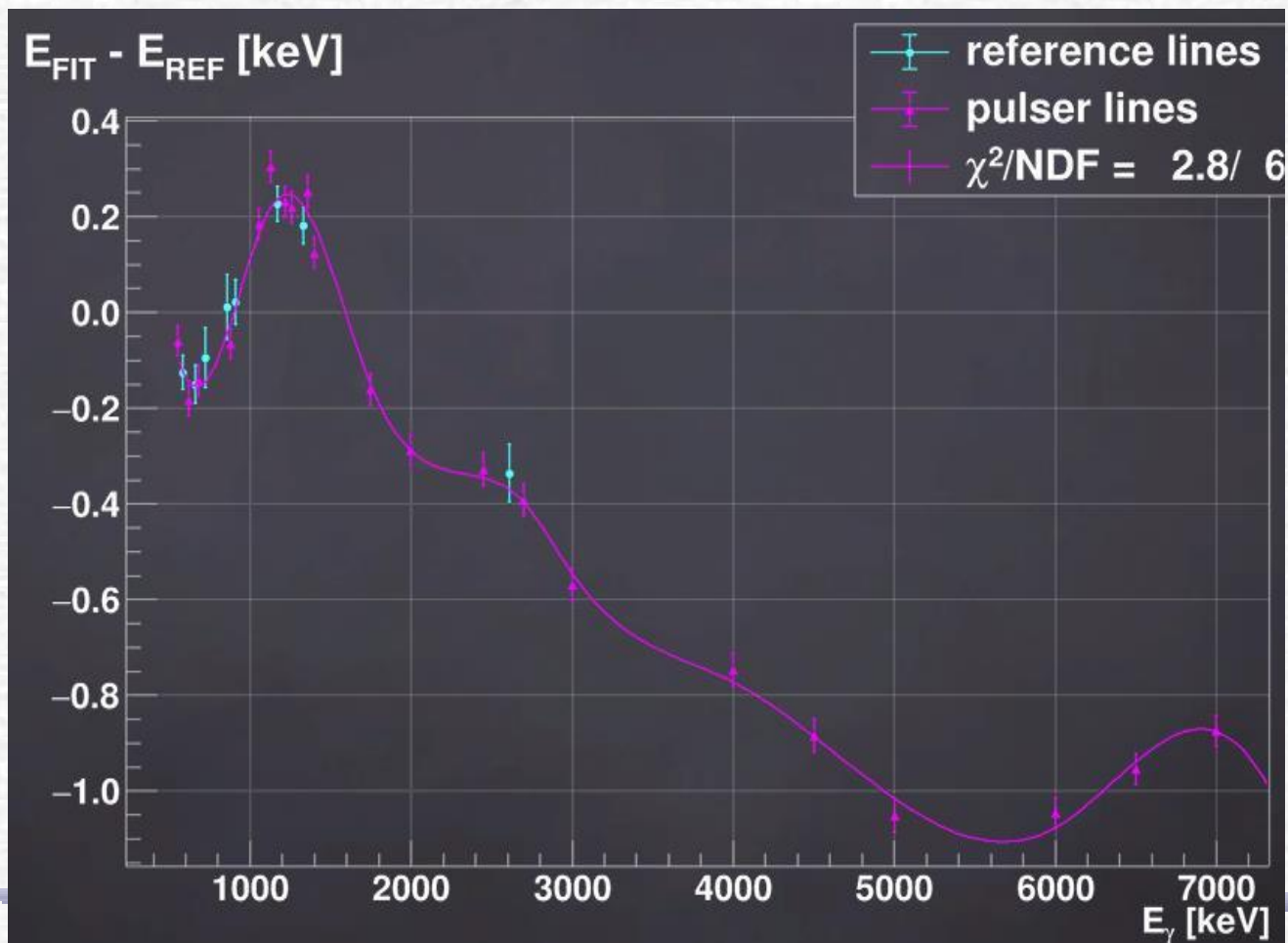
integral nonlinearity:  
 $\pm 250$  ppm

([www.ortec-online.com](http://www.ortec-online.com))



Syst. error is:  $\frac{|\Delta E_{\gamma}|}{E_{\gamma}} \simeq \frac{1 \text{ keV}}{6000 \text{ keV}} \simeq 200 \text{ ppm}$

# 探测器刻度



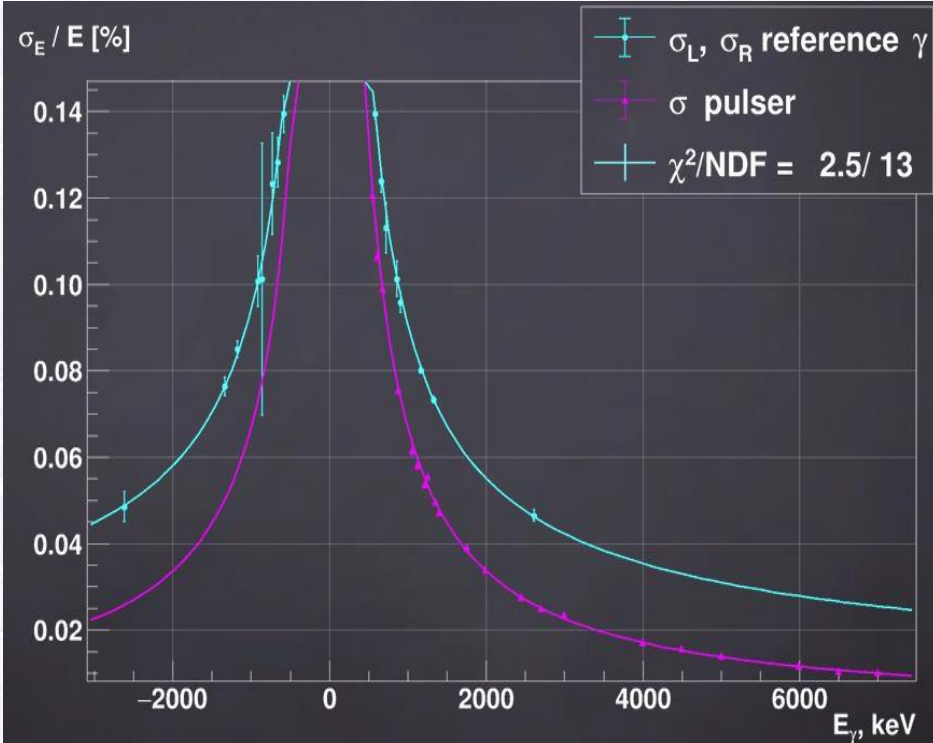
# 探测器的能量分辨

Combined fit for  $\sigma_R$  and  $\sigma_L$  dependence on  $E_\gamma$ :

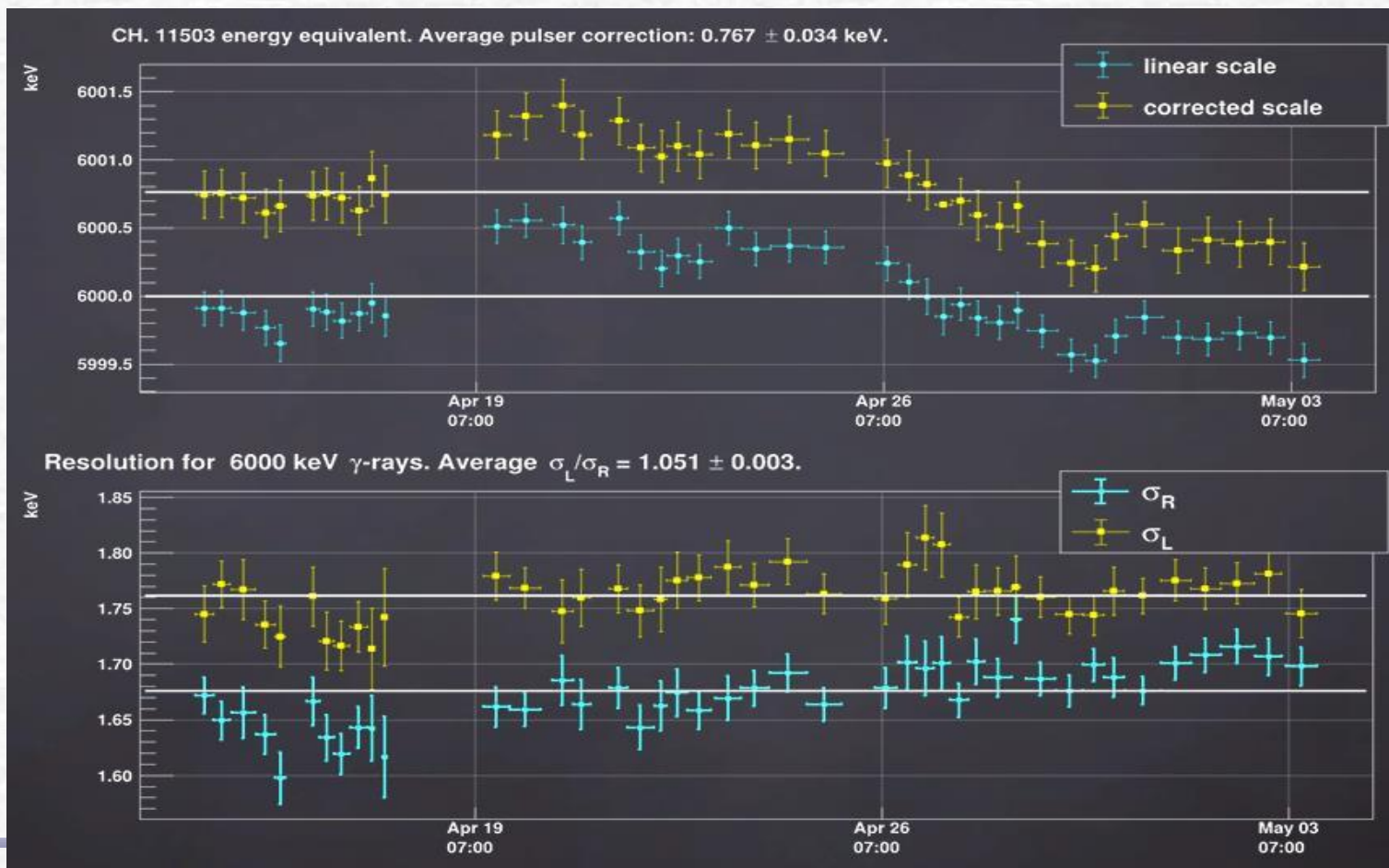
$$\sigma_R = \sqrt{p_0^2 + \epsilon f_R E_\gamma}$$

$$\sigma_L = \sqrt{p_0^2 + \epsilon f_L E_\gamma}$$

- ▶  $\sigma_R$  and  $\sigma_L$  are in [keV],
- ▶  $p_0$  is the noise impact to the resolution,
- ▶  $\epsilon = 2.96$  eV is the e-hole pair creation energy in Ge,
- ▶  $f_R, f_L$  - dimensionless parameters (Fano factor).



# 探测器的能量分辨



# 数据处理-康普顿edge拟合

$$S_2(x, x_0, \sigma, \sigma_s, \xi) = \int_x^{+\infty} S_1(y, x_0, \sigma, \sigma_s, \xi) dy + p_1(x)$$

$$\theta(x_0 - x) = \begin{cases} 0, & x < x_0 \\ 1, & x > x_0 \end{cases}$$

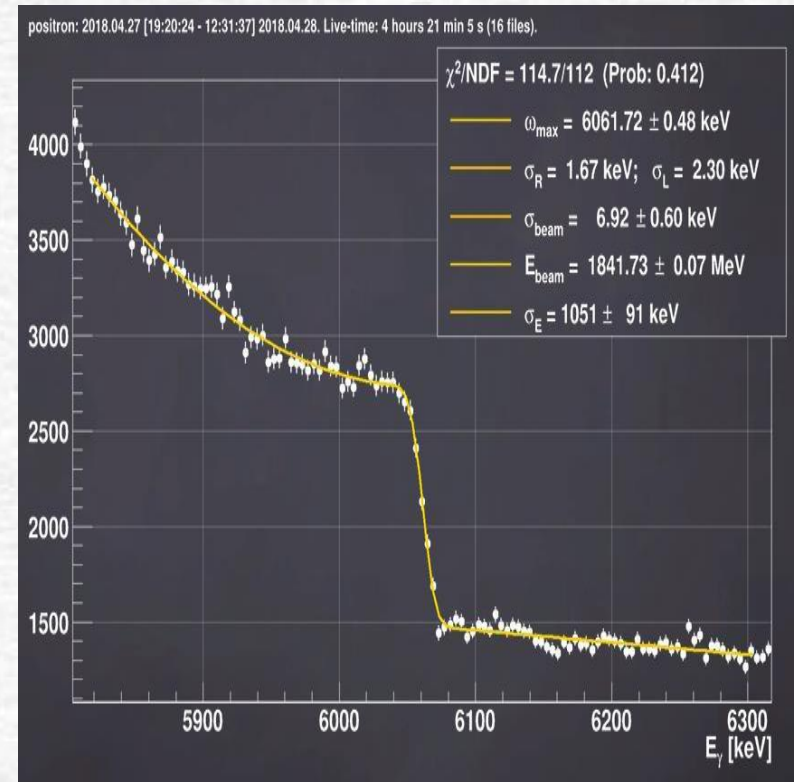
$$g(x, x_0, \sigma_s) = \frac{1}{\sqrt{2\pi}} \sigma_s \exp\left\{-\frac{(x-x_0)^2}{2\sigma_s^2}\right\}$$

$$S_1(x, x_0, \sigma, \sigma_s, \xi) = \frac{N}{2\sqrt{2\pi}} \times \left[ \frac{1}{\sigma} \exp\left(\frac{\xi^2}{2}\left(1 + \frac{\sigma_s^2}{\sigma^2}\right) + \frac{\xi x}{\sigma}\right) \cdot \operatorname{erfc}\left(\frac{\xi(\sigma^2 + \sigma_s^2) + x\sigma}{\sqrt{2}} \sigma_s\right) + \frac{1}{\sqrt{\sigma^2 + \sigma_s^2}} \exp\left(-\frac{x^2}{2(\sigma^2 + \sigma_s^2)}\right) \cdot \operatorname{erfc}\left(-\frac{\xi(\sigma^2 + \sigma_s^2) + x\sigma}{\sqrt{2(\sigma^2 + \sigma_s^2)}} \sigma_s\right) \right]$$

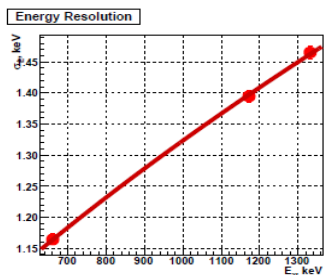
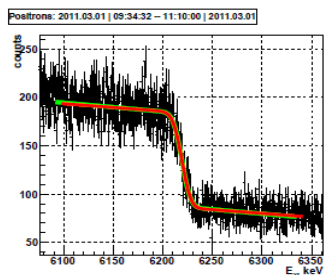
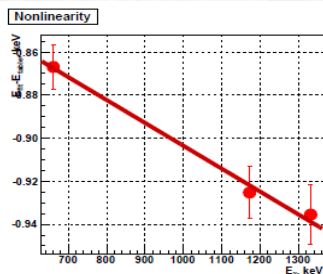
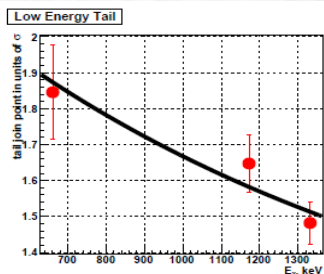
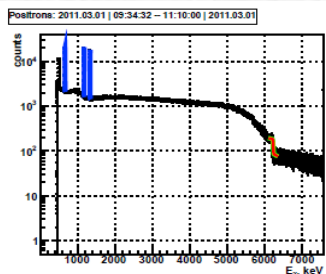
$$\varepsilon = \frac{\omega_{max}}{2} \left[ 1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{max}}} \right].$$

考虑到由北交叉点到IP的同步辐射:

$$\varepsilon_{sip} (MeV) = \varepsilon_{nip} (MeV) + 4.75 \cdot 10^{-3} \times (0.001 \cdot \varepsilon_{nip} (MeV))^4$$



# BEMS测量结果-验收



Zero = 0.23900 keV  
 Gain = 0.46142 keV/Ch  
 "Fano" = 0.395 ± 0.017  
 "Noise" = 0.582 ± 0.049 keV  
 $E_{\text{edge}} = 6220.999 \pm 0.441 \text{ keV}$   
 $\sigma_{E_{\text{edge}}} = 6.15 \pm 0.72 \text{ keV}$   
 $E_{\text{beam}} = 1887.065 \pm 0.067 \text{ MeV}$   
 $\sigma_{E_{\text{beam}}} = 932.1 \pm 109.3 \text{ keV}$   
 time from: 09:34:32 / 2011.03.01  
 time upto: 11:10:00 / 2011.03.01

正电子

测量的相对误差

实测结果:  $3.55 \times 10^{-5}$

设计指标:  $5 \times 10^{-5}$

$$E_{\text{edge}} = 6220.999 \pm 0.441 \text{ keV}$$

$$\sigma_{E_{\text{edge}}} = 6.15 \pm 0.72 \text{ keV}$$

$$E_{\text{beam}} = 1887.065 \pm 0.067 \text{ MeV}$$

$$\sigma_{E_{\text{beam}}} = 932.1 \pm 109.3 \text{ keV}$$

负电子

测量的相对误差

实测结果:  $4.29 \times 10^{-5}$

设计指标:  $5 \times 10^{-5}$

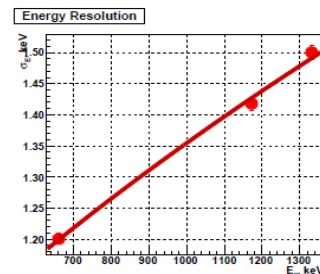
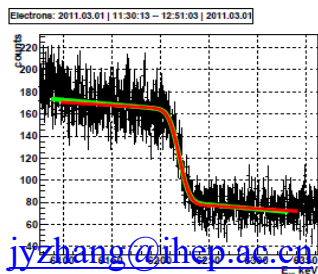
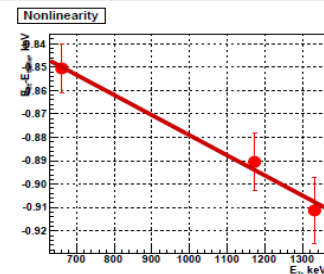
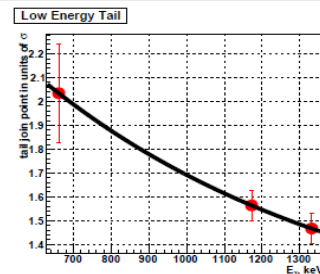
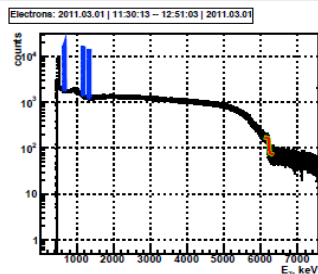
$$E_{\text{edge}} = 6221.178 \pm 0.535 \text{ keV}$$

$$\sigma_{E_{\text{edge}}} = 7.80 \pm 0.89 \text{ keV}$$

$$E_{\text{beam}} = 1887.092 \pm 0.081 \text{ MeV}$$

$$\sigma_{E_{\text{beam}}} = 1183.6 \pm 135.2 \text{ keV}$$

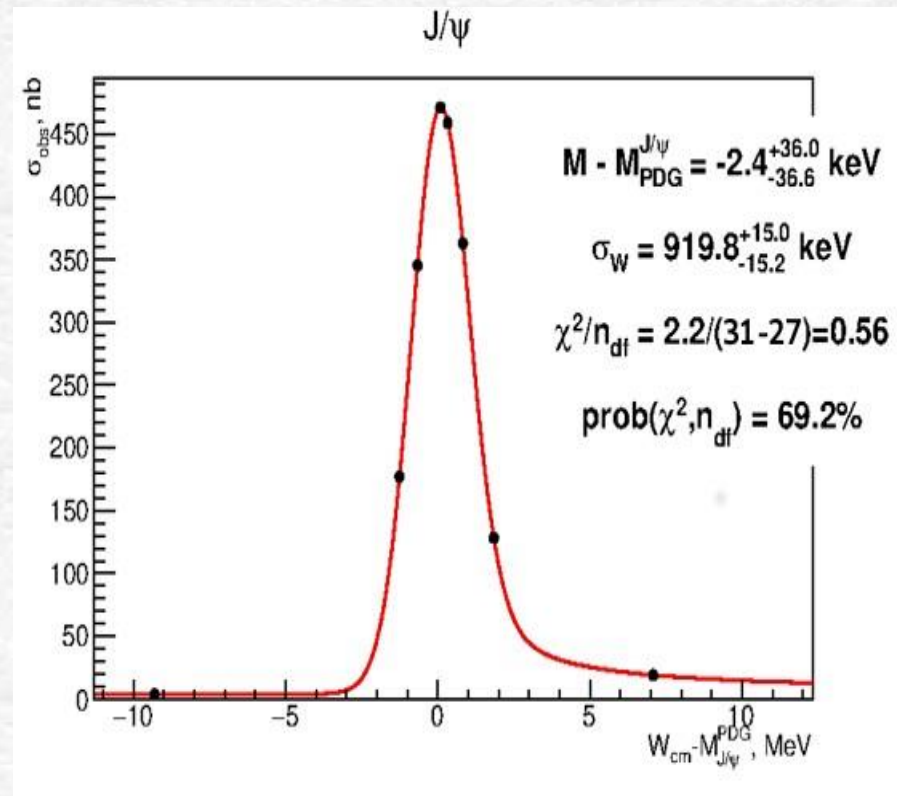
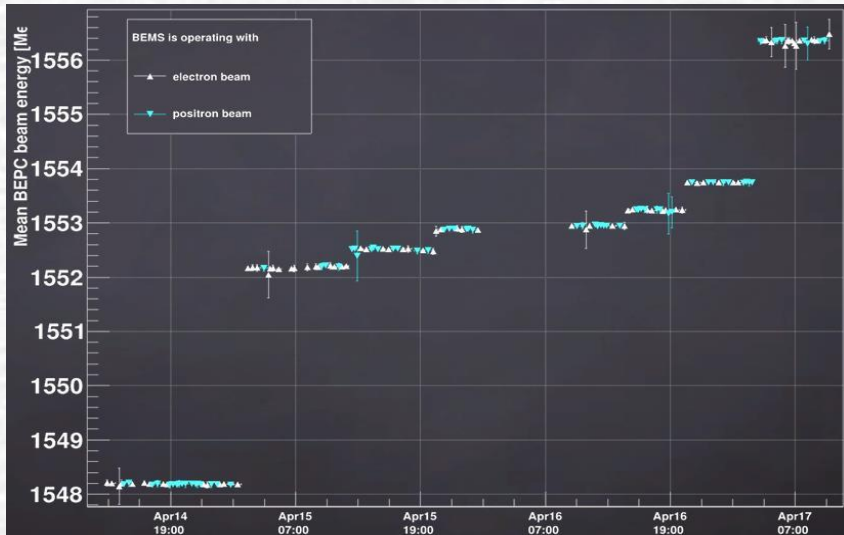
2026/7/2



Zero = 0.23900 keV  
 Gain = 0.46142 keV/Ch  
 "Fano" = 0.395 ± 0.018  
 "Noise" = 0.665 ± 0.052 keV  
 $E_{\text{edge}} = 6221.178 \pm 0.535 \text{ keV}$   
 $\sigma_{E_{\text{edge}}} = 7.80 \pm 0.89 \text{ keV}$   
 $E_{\text{beam}} = 1887.092 \pm 0.081 \text{ MeV}$   
 $\sigma_{E_{\text{beam}}} = 1183.6 \pm 135.2 \text{ keV}$   
 time from: 11:30:13 / 2011.03.01  
 time upto: 12:51:03 / 2011.03.01

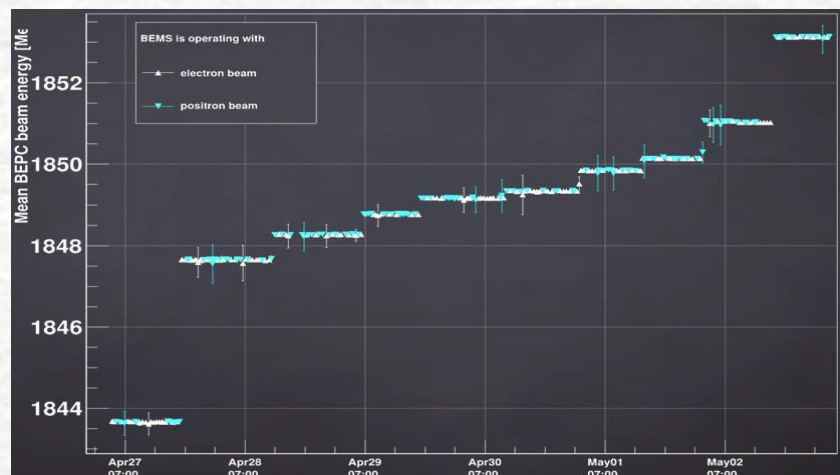
jy Zhang@ihep.ac.cn

# J/ψ扫描

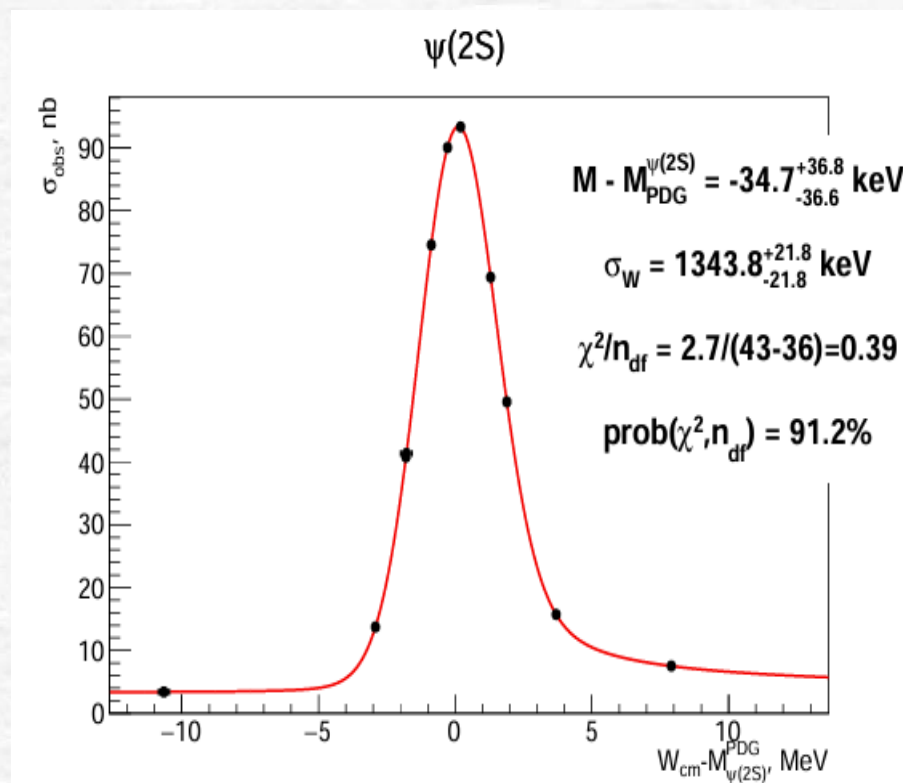


point	$W^{\text{BEMS}}$ , MeV	$L^{\text{online}}$ , pb <sup>-1</sup>	BES3 runs
1	3087.593 ± 0.125	2.46390	55060–55065
2	3095.726 ± 0.077	3.02796	55066–55073
3	3096.203 ± 0.069	5.22500	55074, 55079–55083
4	3096.986 ± 0.083	3.18454	55084–55088
5	3097.226 ± 0.099	1.76280	55089–55091
6	3097.654 ± 0.082	4.78633	55092–55097
7	3098.728 ± 0.078	5.61725	55098–55103
8	3104.000 ± 0.082	5.71792	55104–55109

# $\Psi(2S)$ 扫描



point	$W^{\text{BEMS}}$ , MeV	$L_{\text{online}}$ , $\text{pb}^{-1}$	BES3 runs
1	$3675.442 \pm 0.191$	5.17638	55258–55263
2	$3683.193 \pm 0.096$	15.60458	55264–55276
4	$3684.193 \pm 0.115$	2.18118	55286, 55288
3	$3684.393 \pm 0.201$	3.30610	55278–55285
5	$3685.306 \pm 0.101$	4.62110	55289–55294
6	$3685.833 \pm 0.095$	7.38168	55295–55308
7	$3686.302 \pm 0.096$	6.12081	55309–55318
8	$3687.305 \pm 0.101$	5.13150	55319–55325
9	$3687.993 \pm 0.096$	5.08032	55326–55332
10	$3689.773 \pm 0.098$	5.97002	55333–55339
11	$3694.027 \pm 0.098$	5.03245	55340–55346

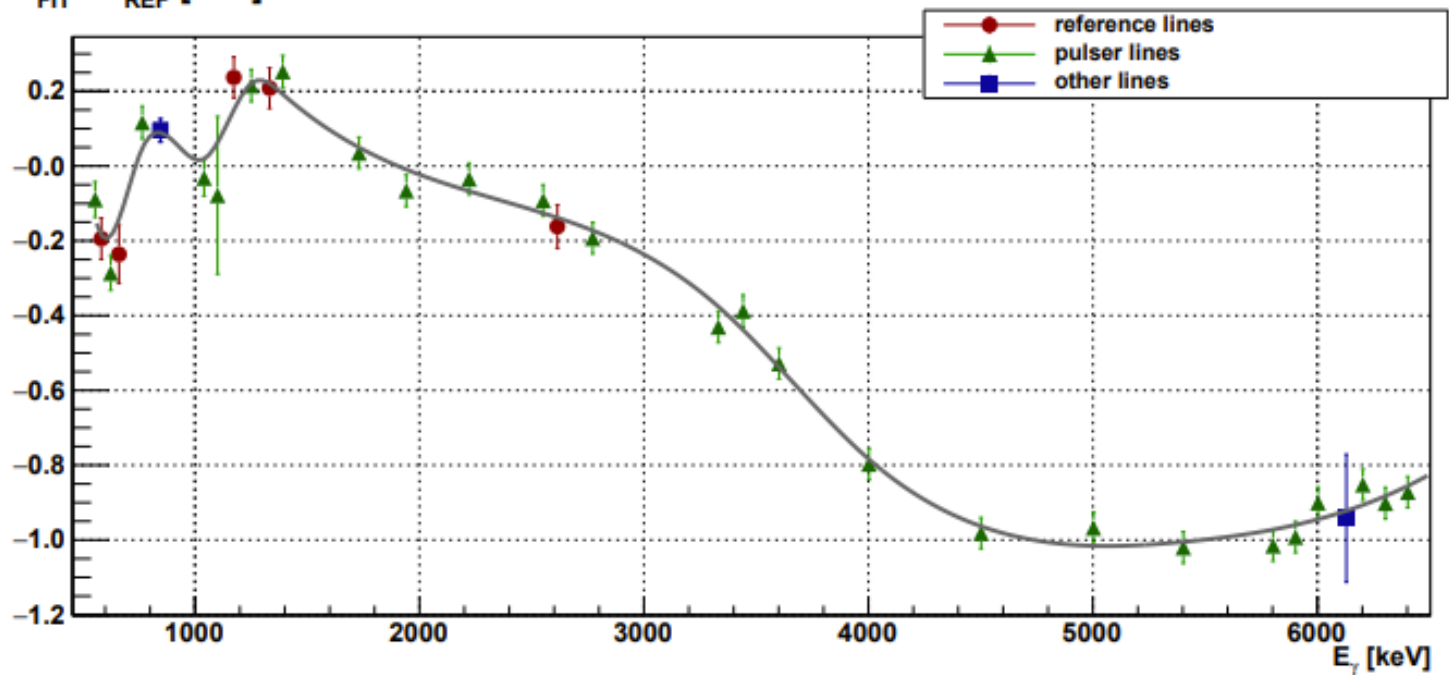


# 总结

- 利用康普顿背散射原理在**BEPCII**上研制了束流能量测量系统
- BEMS**测试结果好于设计指标
- 束流能量的精度约为**30 keV**

谢谢！

$E_{FIT} - E_{REF}$  [keV]



# Limitation of BEMS

- No radiation sources are available for detector calibration
- Detection efficiency are much lower, detection time is longer

	1548.5MeV	1777MeV	1843MeV	2000MeV	2800MeV
10.59 $\mu$ m	4.29MeV	5.64MeV	6.07MeV	7.14MeV	13.98MeV

Relative eff.	1.33MeV	9MeV	15MeV
30%	$3.5 \times 10^{-4}$	$4.4 \times 10^{-7}$	$2.7 \times 10^{-7}$

During tau scan, about half time (~10 days) spent in psi(3686) scan

# Possible solution to BEMS

Laser:

Increase the laser wave length

Laser wave length now: 10.59  $\mu\text{m}$

If wave length  $\sim 20 \mu\text{m}$ :

	1548.5MeV	1777MeV	1843MeV	2800MeV
10.59 $\mu\text{m}$	4.29MeV	5.64MeV	6.07MeV	13.98MeV
$\sim 20 \mu\text{m}$	2.27MeV	2.99 MeV	3.22MeV	7.43MeV

Cost of upgrade laser, 400,000 RMB

Continuous type to pulse type, need to match BII

# Solution to the crisis of BEMS

## HPGe detector

Increase the volume of the detector, to increase detection efficiency

Relative eff.	1.33MeV	9MeV	15MeV	Price
30%	$3.5 \times 10^{-4}$	$4.4 \times 10^{-7}$	$2.7 \times 10^{-7}$	52KUSD
60%	$1.8 \times 10^{-3}$	$6.8 \times 10^{-7}$	$3.9 \times 10^{-7}$	104.3KUSD
100%	$1.5 \times 10^{-3}$	$4.8 \times 10^{-6}$	$4.0 \times 10^{-6}$	182.8KUSD