STCF初态辐射的零角度探测

王雅迪

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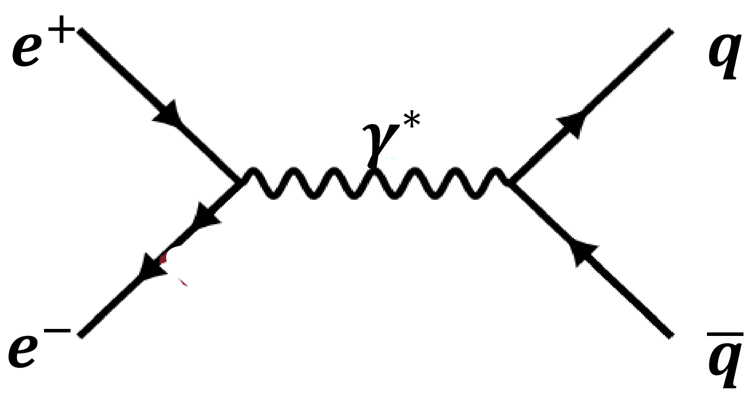
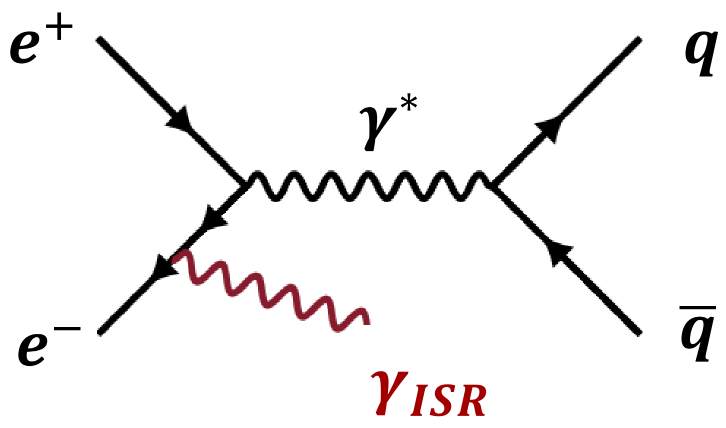
合肥，中国科学技术大学

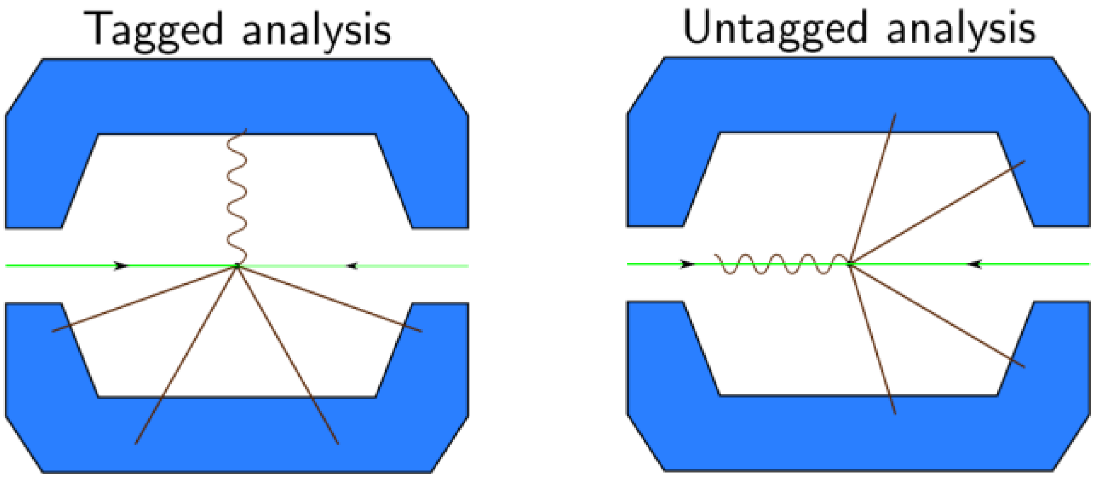
Outline

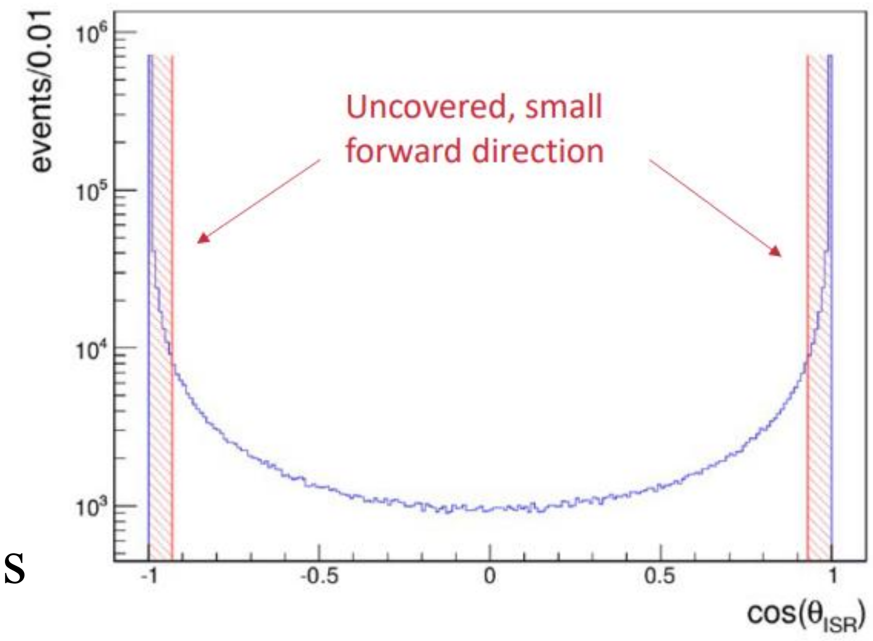
- ISR technique
- Related physics:
  - Muon $g-2$
  - Baryon EM form factors
  - …
- Zero Degree Detector at BESIII
- Some fast simulation results

ISR technique





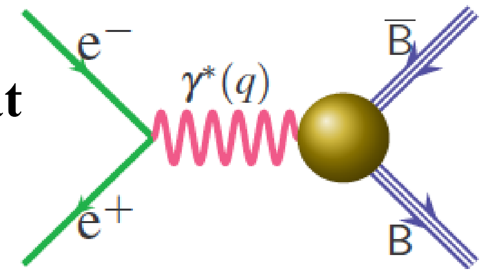




- ➢ Most ISR photons emitted at small angles
- ➢ ISR outside of spectrometer acceptance

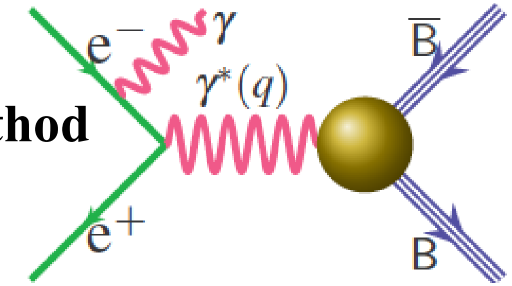
Energy scan VS ISR experiment

- **Energy scan method at discrete c.m.energies**

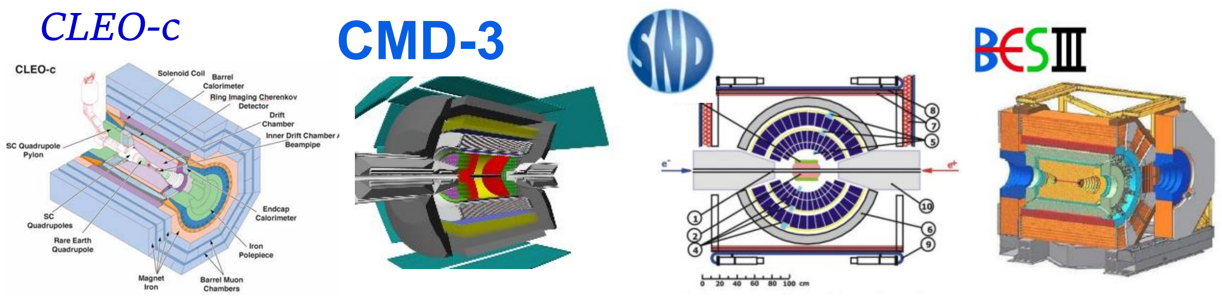


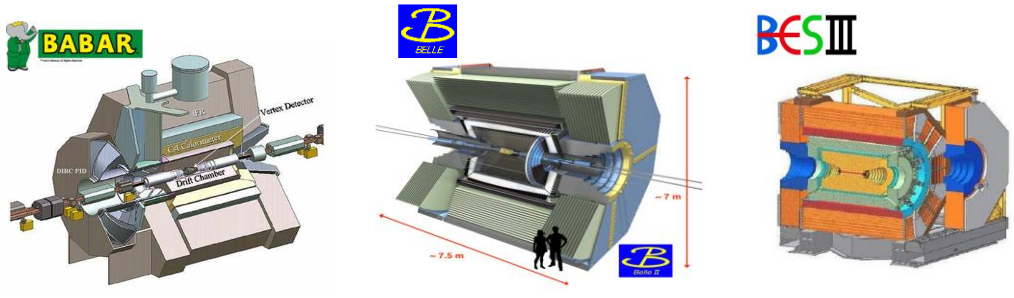
  - ➢ 质心系能量确定， 低本底
  - ➢ 能量分辨率好
  - ➢ 能量不连续， 不能形成连续的截面谱

- **Initial state radiation method at a fixed c.m.energy**



  - ➢ 可固定在一个束流能量下取数， 质心系能量可从低于质心系能量的阈值到 $\sqrt{s}$
  - ➢ 各个点的系统误差可以协调一致的方式处理
  - ➢ 需要大统计量的数据
  - ➢ 较高的本底水平

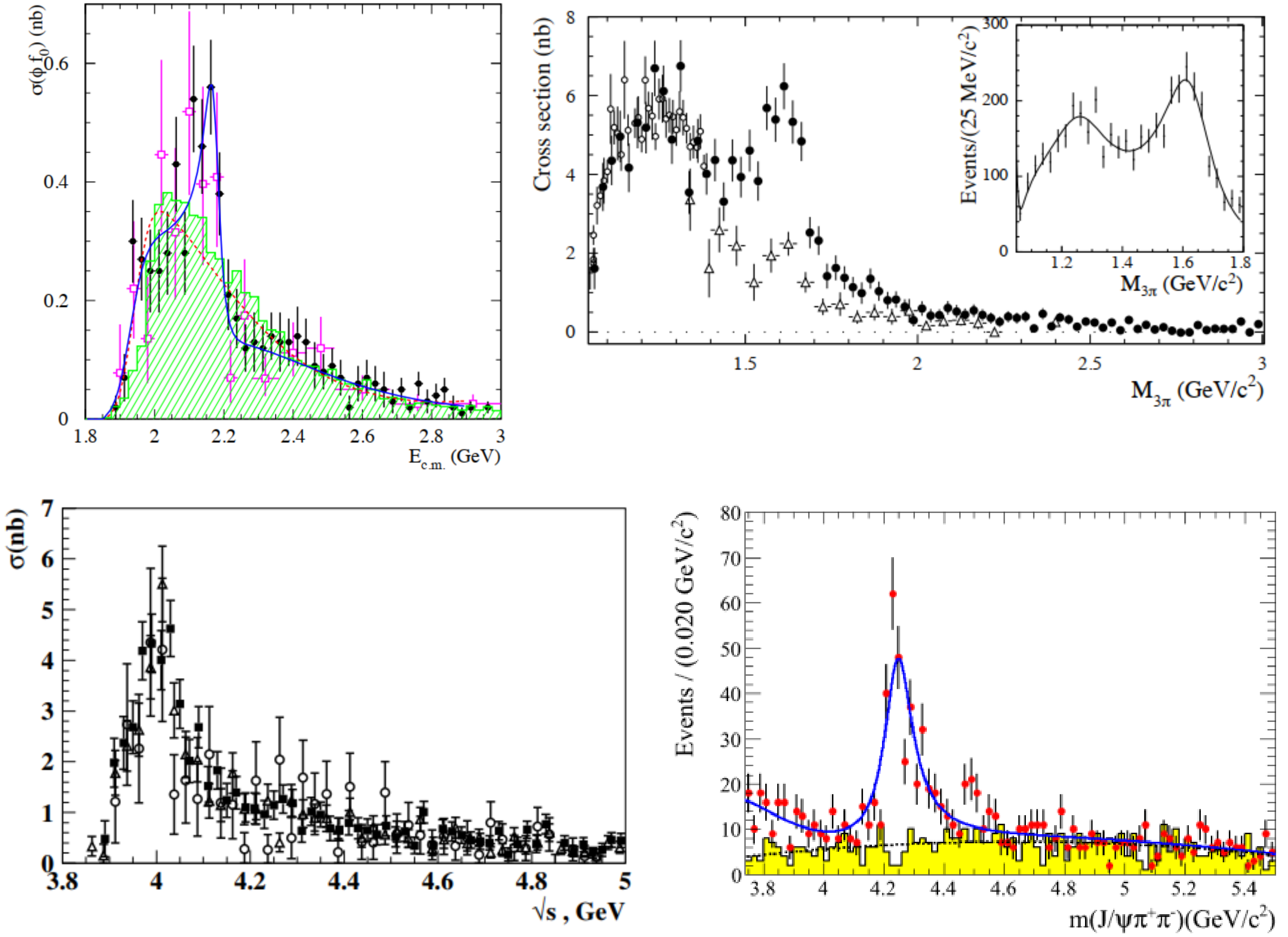




Both techniques can be used at BESIII

Fruitful physics with ISR technique

- Measurement of $e^+e^- \to \pi^+\pi^-(\gamma)$
- Light meson spectroscopy
- Measurement of baryon EMFF
- Measurement of exclusive $D^{(*)+}D^{(*)-}$production
- Three-body charm final states
- $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ production
- XYZ family states in ISR
- Dark force searches: dark photon, dark gauge bosons, dark Higgs bosons



From Babar, EPJC74(2014)3026

Anomalous Magnetic Moment $a_\mu = \frac{g-2}{2} \sim 0.1\%$

Physics Reports 887 (2020) 1–166

Contribution	Value $\times 10^{11}$
Experiment (E821)	116 592 089(63)
HVP LO (e^+e^-)	6931(40)
HVP NLO (e^+e^-)	−98.3(7)
HVP NNLO (e^+e^-)	12.4(1)
HVP LO (lattice, *udsc*)	7116(184)
HLbL (phenomenology)	92(19)
HLbL NLO (phenomenology)	2(1)
HLbL (lattice, *uds*)	79(35)
HLbL (phenomenology + lattice)	90(17)
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Difference: $\Delta a_\mu := a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	279(76)

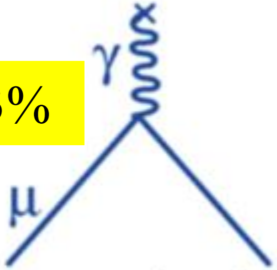
3.7σ difference!

New physics?

Anomalous Magnetic Moment $a_\mu = \frac{g-2}{2} \sim 0.1\%$

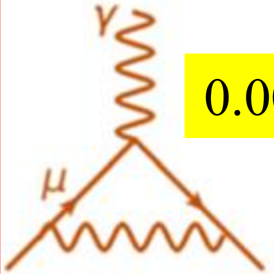
$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm weak} + a_\mu^{\rm had}$$

99.993%

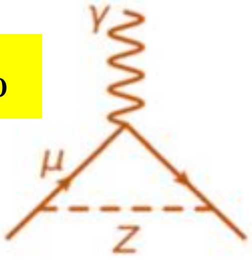


tree-level contribution

0.0002%

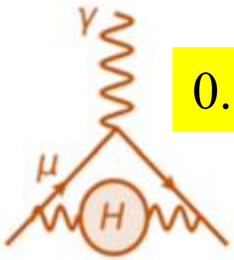


QED

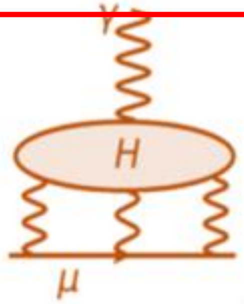


weak

0.006%



hadronic vacuum polarization

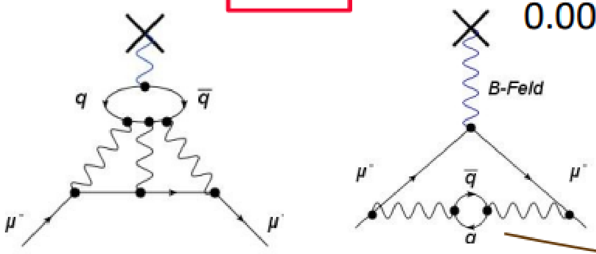


hadronic light-by-light scattering

$$a_\mu^{\rm HVP,\,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{s_{\rm thr}}^{\infty} ds \frac{\hat{K}(s)}{s^2} R_{\rm had}(s)$$

$$R_{\rm had}(s) = \frac{3s}{4\pi\alpha^2}\sigma[e^+e^- \to \text{hadrons}(+\gamma)]$$

QCD

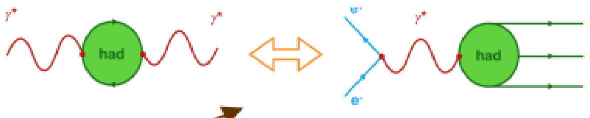


2%

0.006%

98%

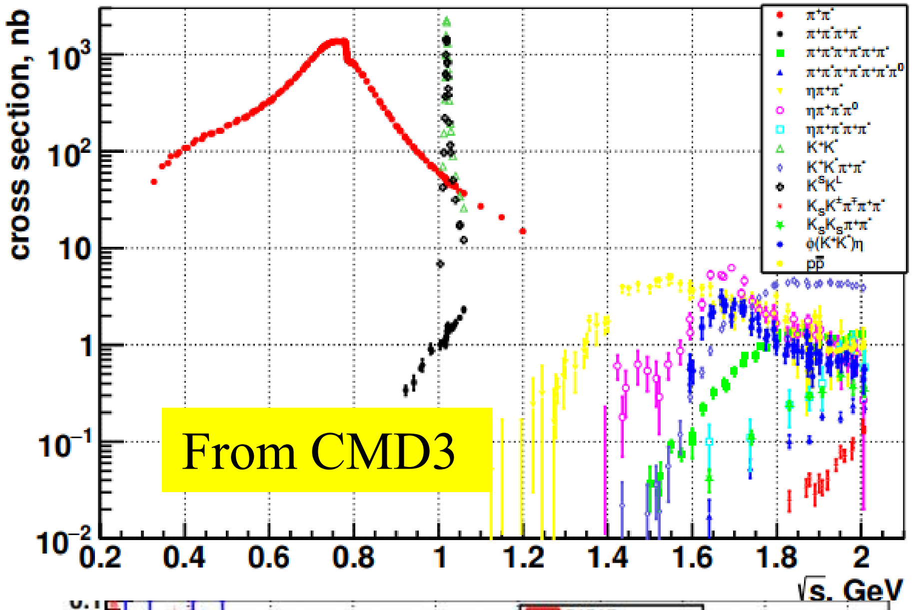
$$a_\mu^{\rm HVP} = \frac{1}{4\pi}\int_{4m_\pi^2}^{\infty} K(s)\,\sigma_{e^+e^-\to \rm had}\,ds$$

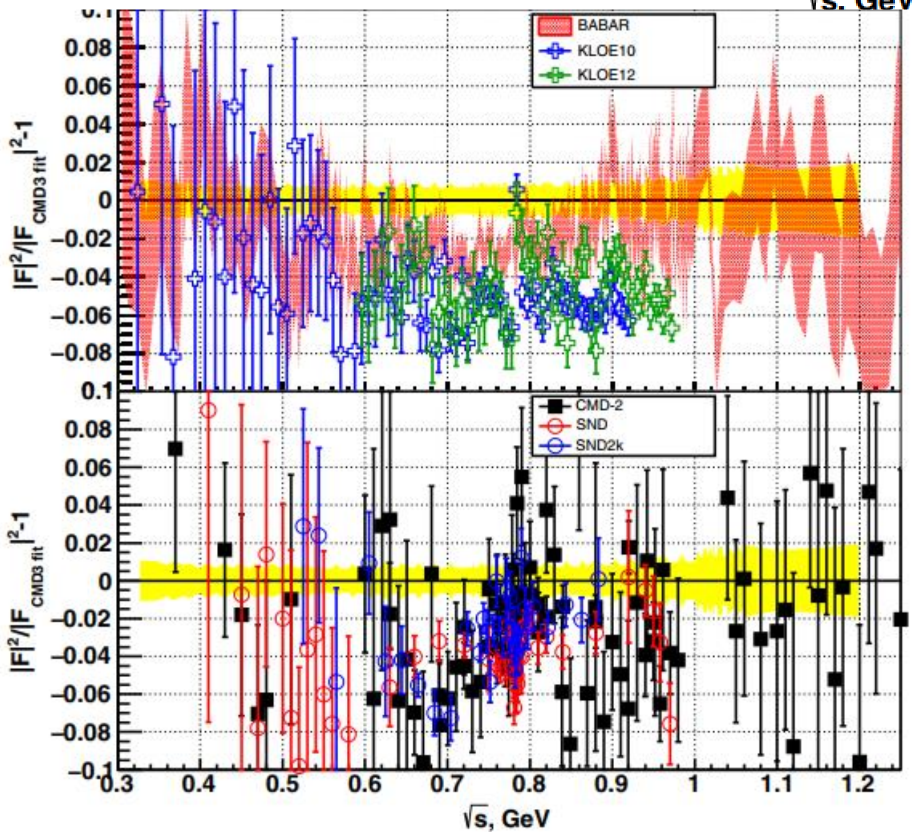


Dispersive
(or LQCD)

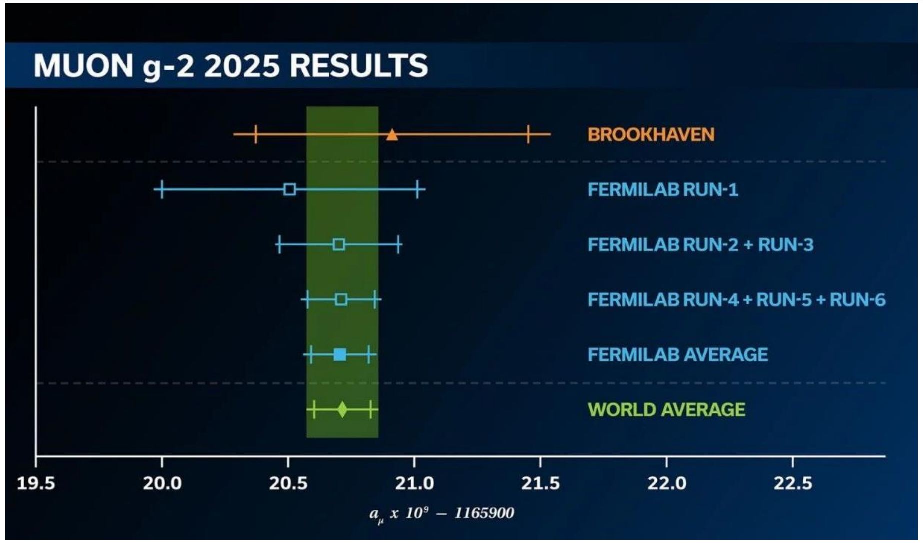
$\sigma(e^+e^- \to \pi^+\pi^-)$

- $\sigma(e^+e^- \to \pi^+\pi^-)$ contributes more than 70% of $\boldsymbol{a_\mu^{HVP,LO}}$.
- Babar and KLOE experiments claim a precision of better than 1% in the energy range below 1 GeV.
- A discrepancy ~3% on ρ resonance is observed, and even increasing towards higher energies.
- Measurement from BESIII has larger uncertainty (0.9%) and consistent with Babar.
- New measurement by CMD-3 increases the tensions among data-driven dispersive evaluations of the LO HVP contribution.





New results from MUON g-2



The newest experimental results:

$a_\mu^{exp} = 116\,592\,0705(148) \times 10^{-12} (127\ ppb)$

arXiv:2506.03069

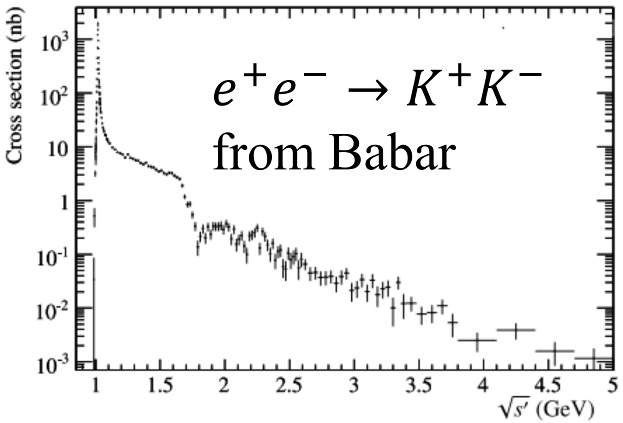
New measurements $\sigma(e^+e^- \to hadrons)$ and $\sigma(e^+e^- \to \pi^+\pi^-)$ with 0.2% precision are highly desirable.

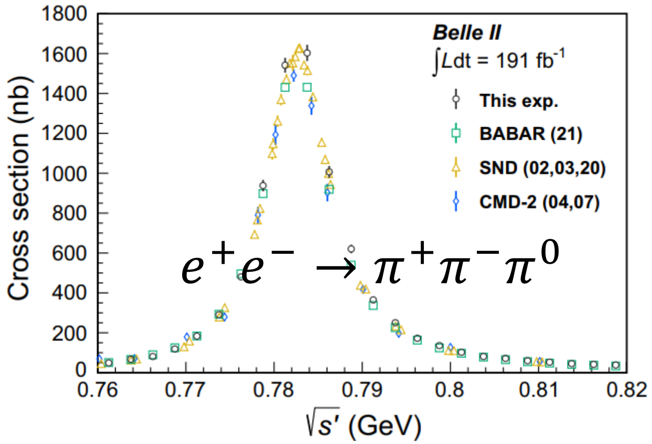
Contribution	arXiv:2505.21476	Value $\times 10^{11}$
Experiment (E989, E821)		116 592 071.5(14.5)
HVP LO (lattice)		7132(61)
HVP LO (e^+e^-, τ)		Estimates not provided
HVP NLO (e^+e^-)		−99.6(1.3)
HVP NNLO (e^+e^-)		12.4(1)
HLbL (phenomenology)		103.3(8.8)
HLbL NLO (phenomenology)		2.6(6)
HLbL (lattice)		122.5(9.0)
HLbL (phenomenology + lattice)		112.6(9.6)
QED		116 584 718.8(2)
EW		154.4(4)
HVP LO (lattice) + HVP N(N)LO (e^+e^-)		7045(61)
HLbL (phenomenology + lattice + NLO)		115.5(9.9)
Total SM Value		116 592 033(62)
Difference: $\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM}$		38(63)

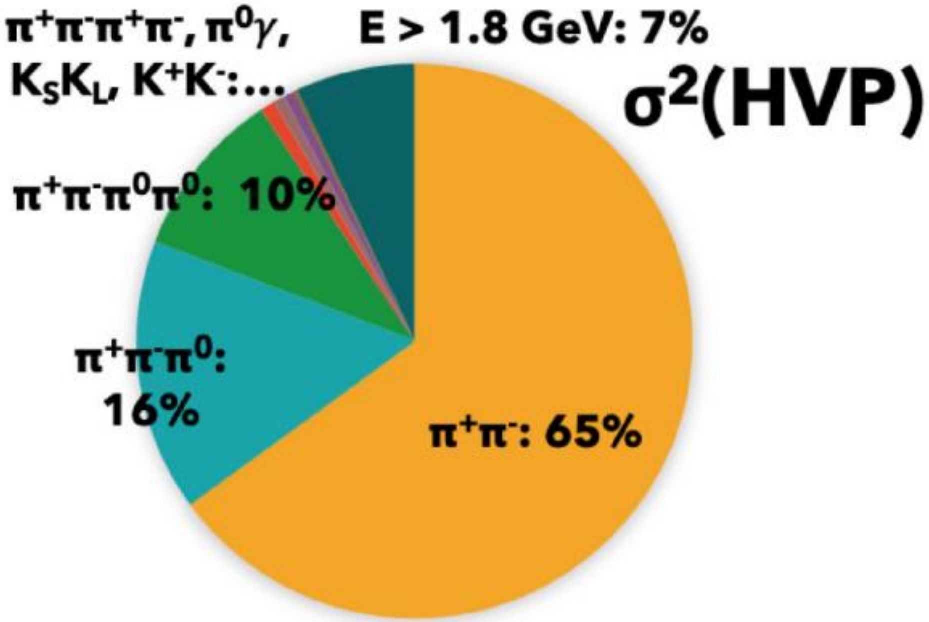
Consistency between the SM and experiment?

More

- The resolution of the tensions among data-driven dispersive evaluations of the LO HVP contribution will be a key element in this endeavor.
- Other hadronic modes are also important, e.g., $\pi^+\pi^-\pi^0$,$2(\pi^+\pi^-)$, $\pi^+\pi^-2\pi^0, K^+K^-, \pi^+\pi^-\eta, \eta\pi^+\pi^-\pi^0, \eta 4\pi, K^+K^-\pi^+\pi^-, K_S K_L \pi^0$, etc.
- Measurement at high energies are rare
- Missing channels based on isospin constraints.







[Data from: Phys.Rep 887 (2020) 1-166]

Baryon form factor and cross section

- 非点状散射截面 = 点状散射截面*形状因子

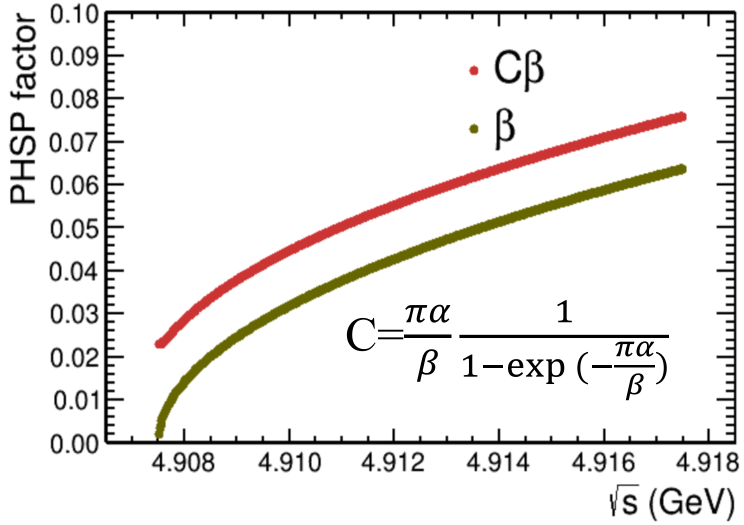
$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} F(Q^2) \rightarrow$$ 代表与点状粒子的偏离程度

- 形状因子与电荷密度构成傅里叶变换 $F(q^2) = \int d^3r' e^{i\vec{q}\cdot\vec{r}'} \rho(\vec{r}')$

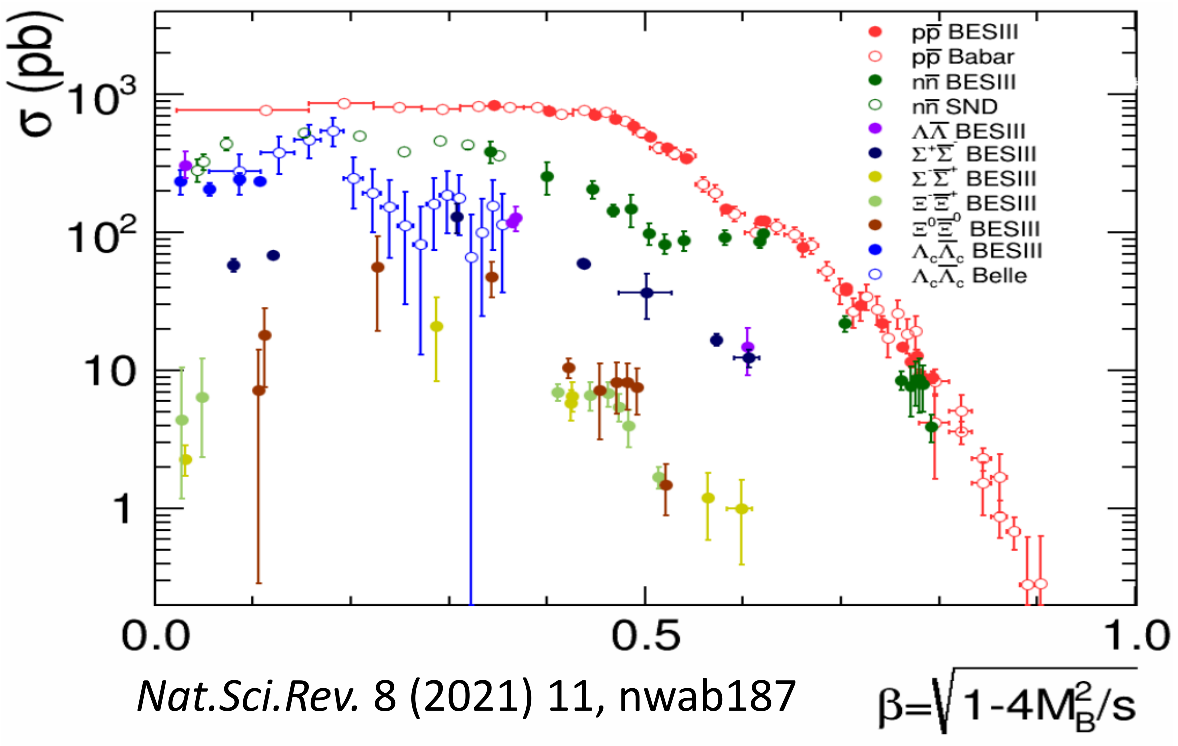
- Interaction of final states, lead to a non-zero cross section for charged baryon at threshold (Andrei D Sakharov *Sov. Phys. Usp.* **34** 375(1991))

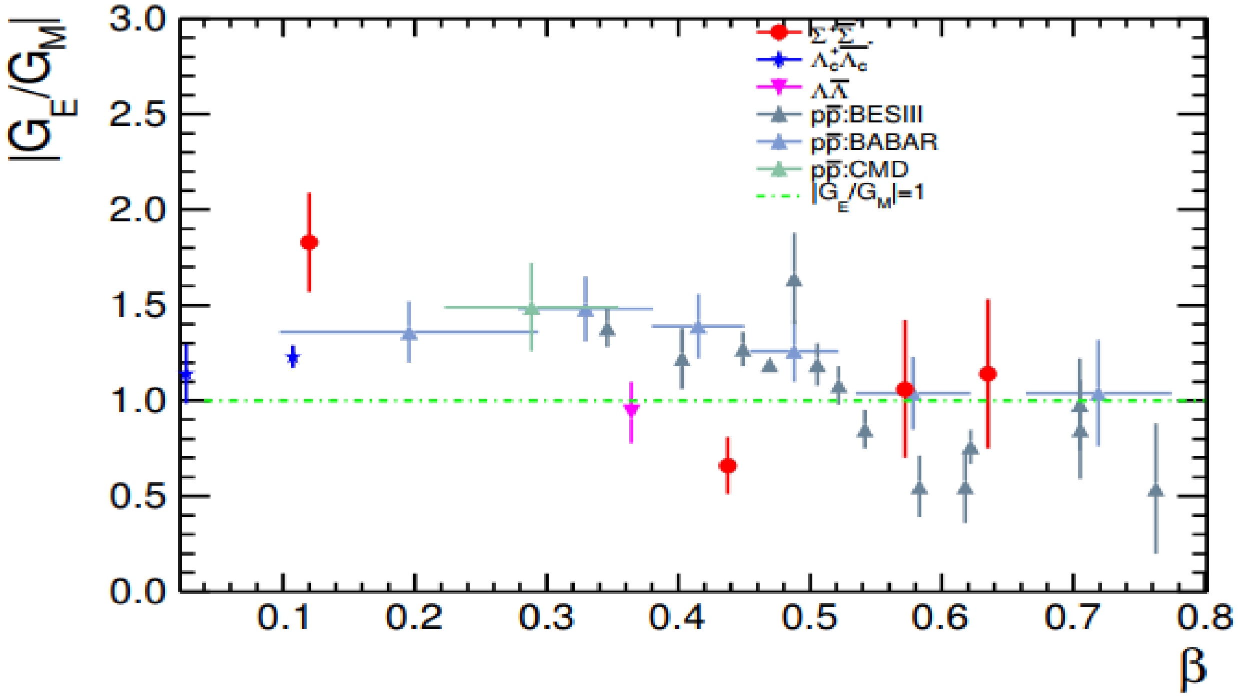
$$\frac{\mathrm{d}\sigma_{B\bar{B}}}{\mathrm{dcos}\theta} = \frac{\pi\alpha^2 C\beta}{2q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}|G_E|^2\sin^2\theta\right], \tau = \frac{q^2}{4m_B^2}$$

Integrated version: $\sigma_{B\bar{B}} = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right]$



Baryon form factor and cross section

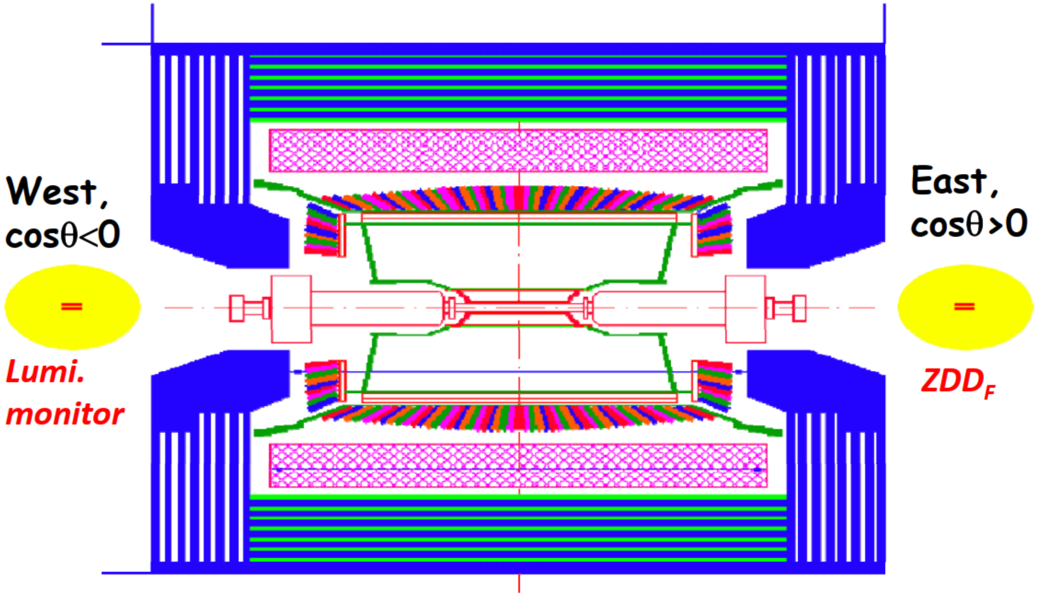


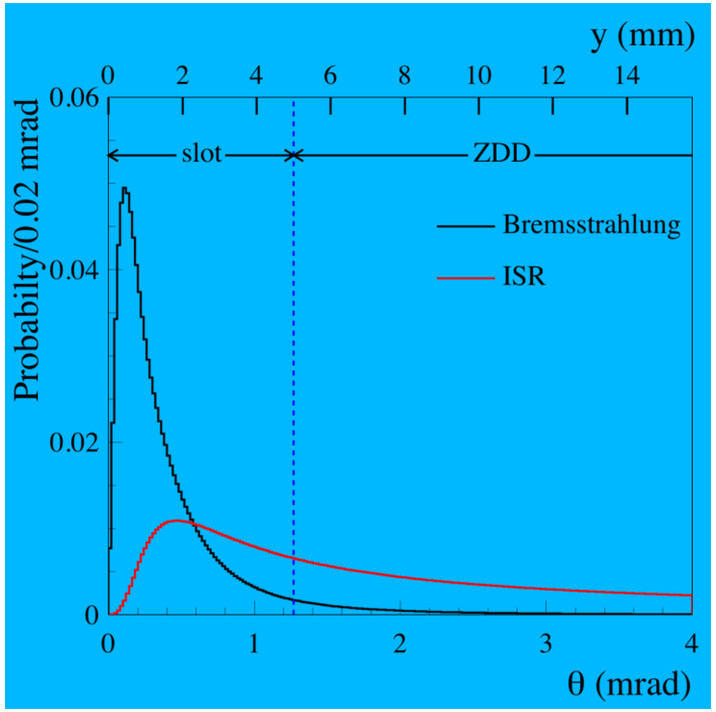


- Abnormal threshold effects observed in various baryon pair production: $p\bar{p}$, $\Lambda\bar{\Lambda}$, $\Lambda_c^+\bar{\Lambda}_c^-$ …
- Oscillation structures observed in $p\bar{p}$, $n\bar{n}$
- $|G_E/G_M|$ ratio significantly larger than 1 at low beta for p, Λ_c^+, Σ^+, indicating large D-wave near threshold
- Relative phase angle of form factor $\Delta\phi$ ($\sin\Delta\phi$) measured for Λ, Σ^+, Λ_c^+

Zero Degree Detector (ZDD) by INFN

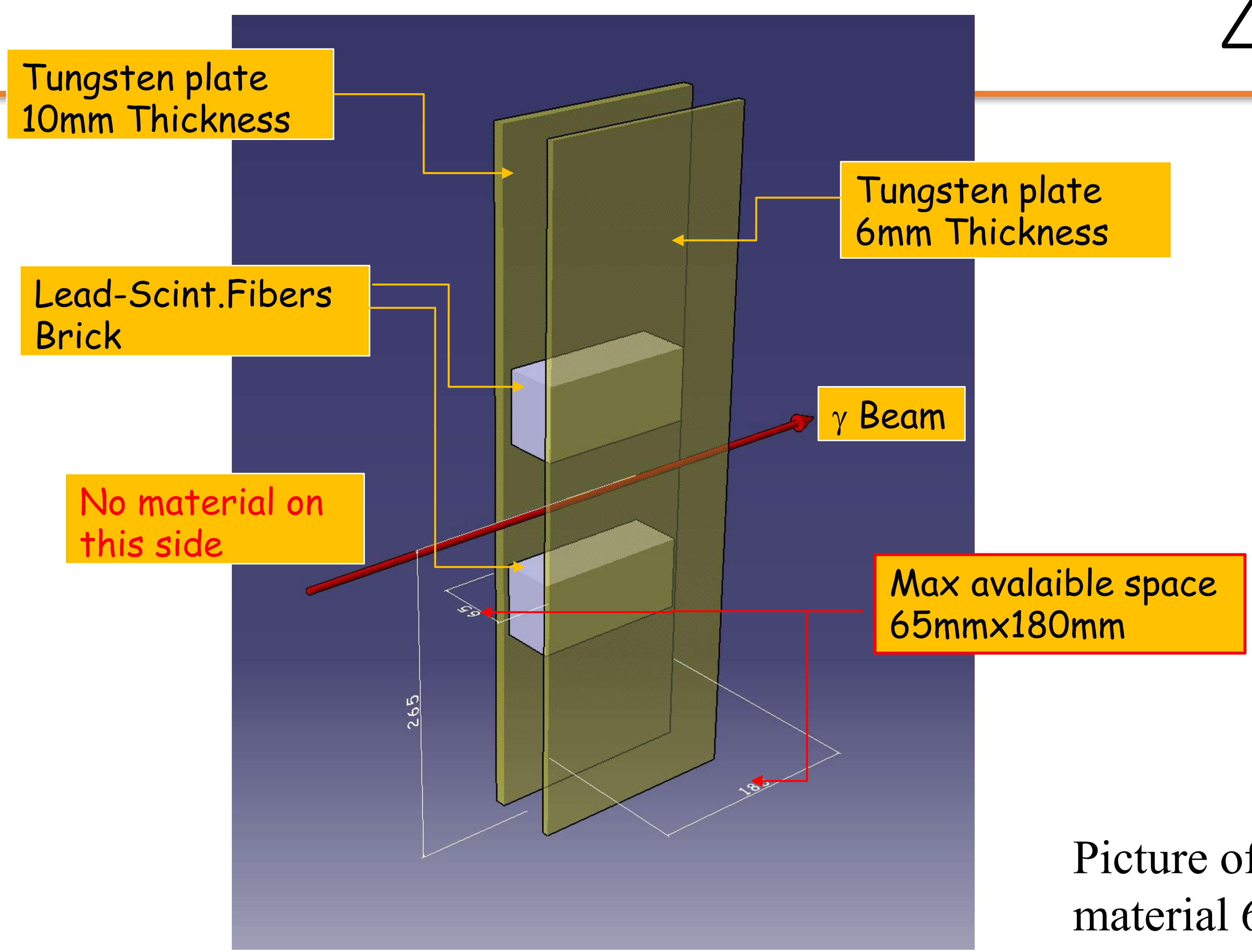
- Two detectors are developed to tag ISR photons at small angles @BESIII

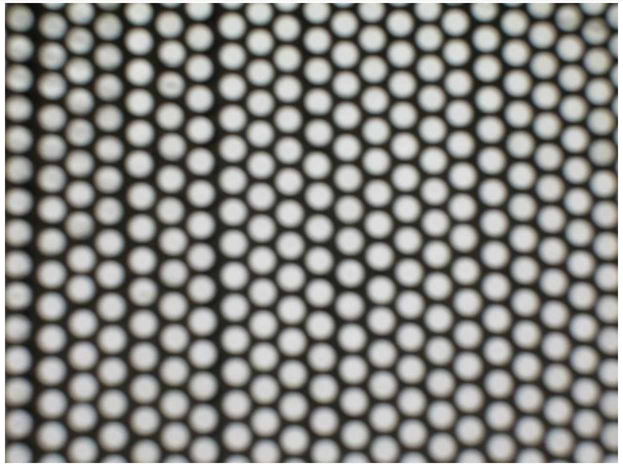




ZDD proposal by INFN: substitution of one luminometer with a mini-calorimeter based on the KLOE Pb/Scintillating fibers technique

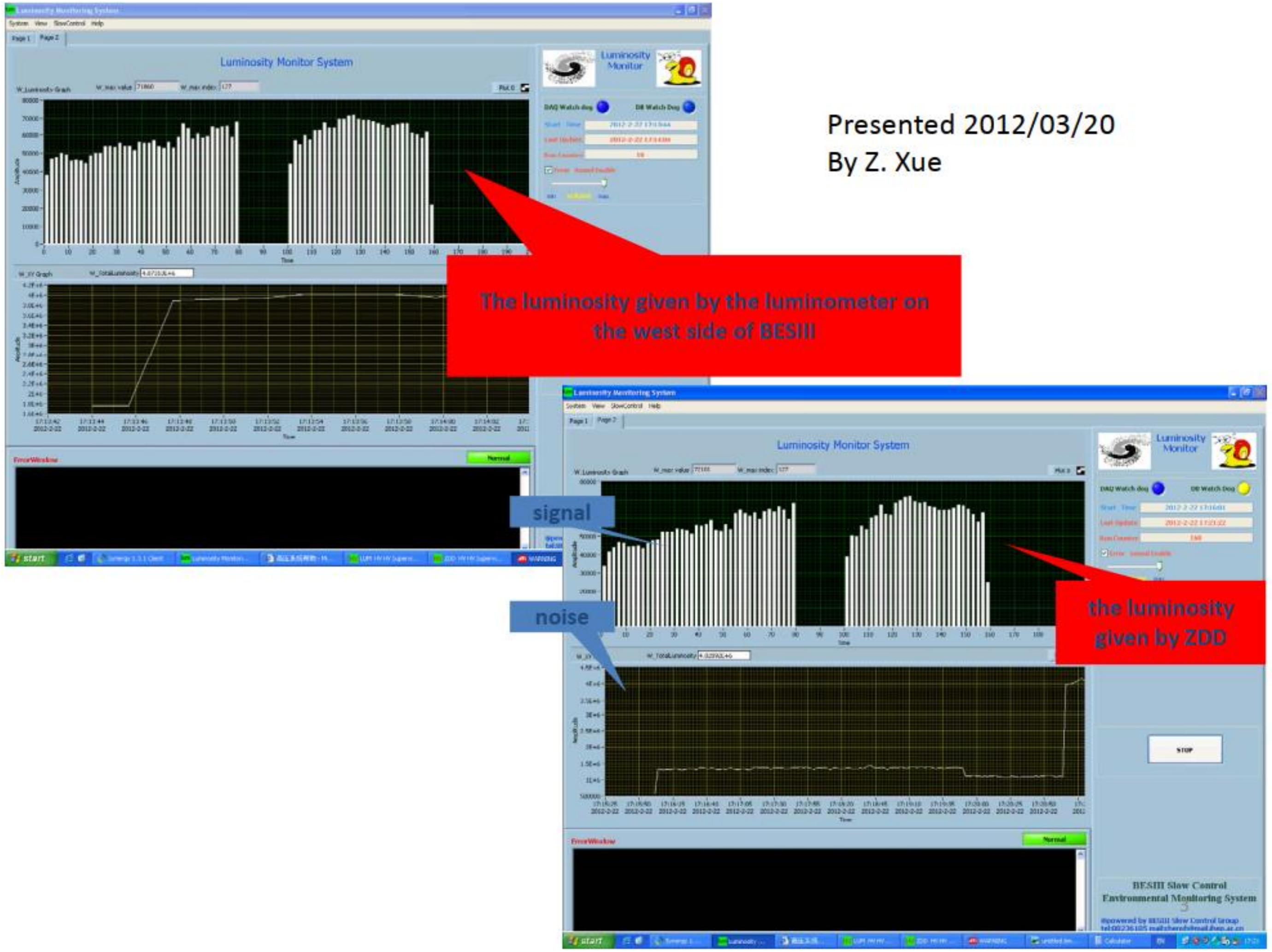
ZDD by INFN



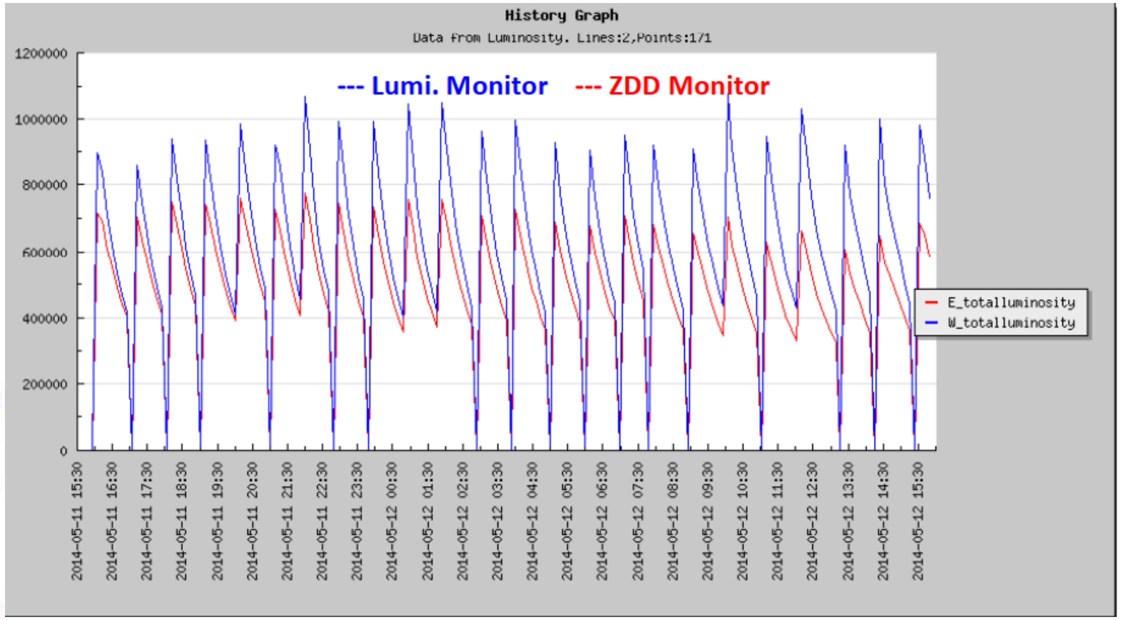


Picture of Pb/Sci.Fi. Array, scintillating material 60% of total (in volume)

Zero Degree Detector (ZDD) by INFN

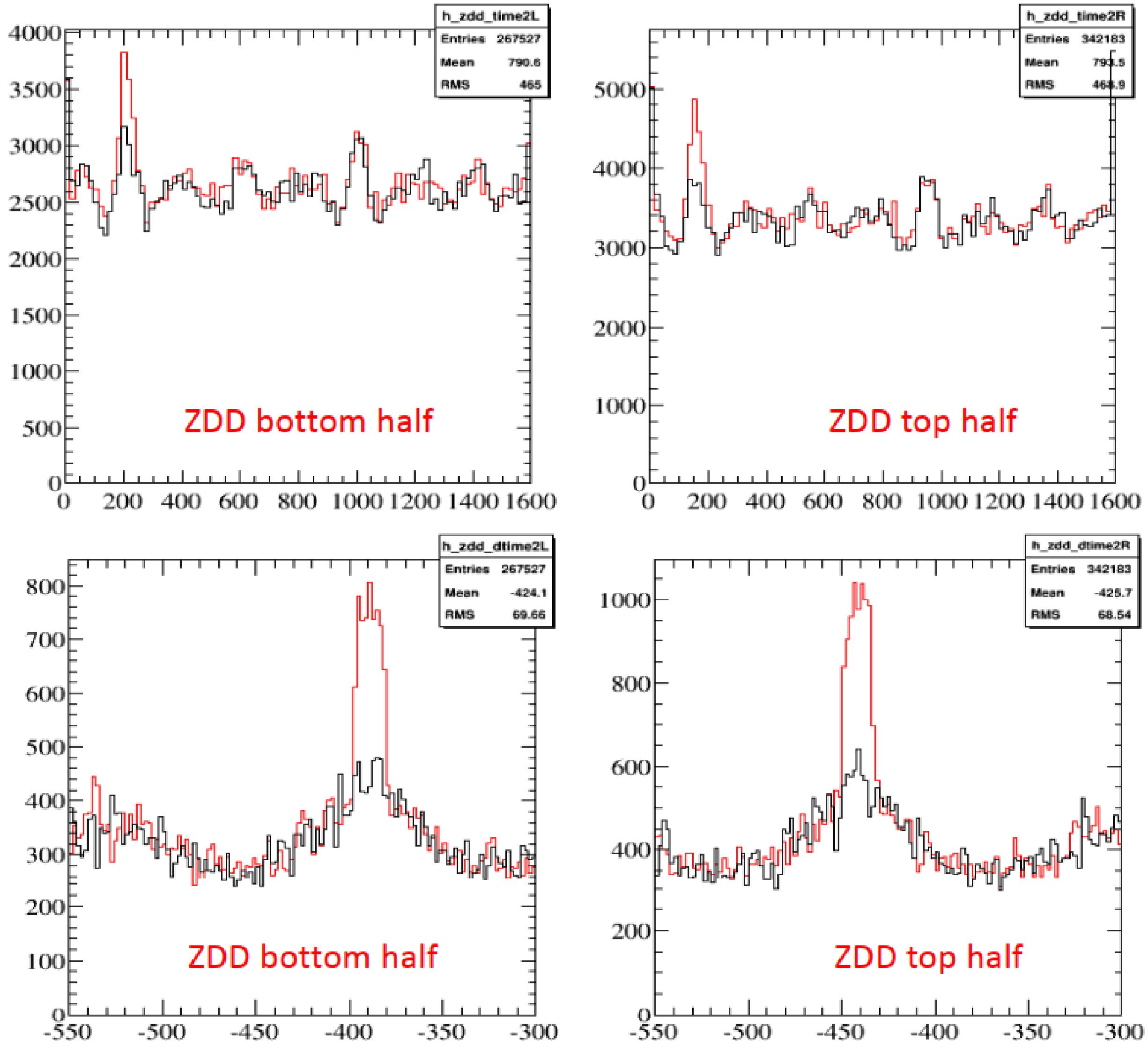


Presented 2012/03/20
By Z. Xue

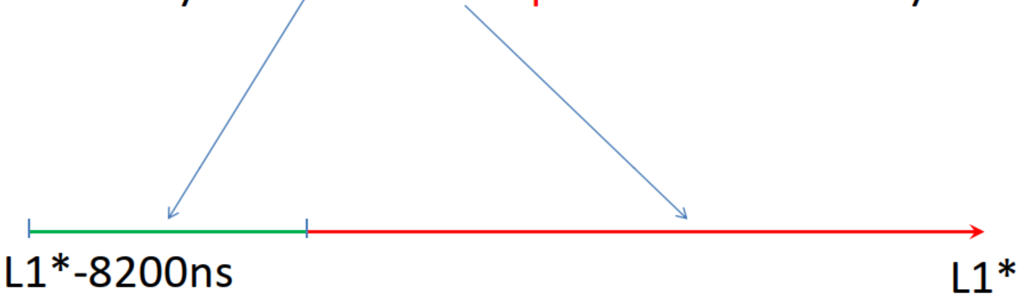


- Detect radiation photon
- Detect Bhabha for luminosity

Zero Degree Detector (ZDD) by INFN



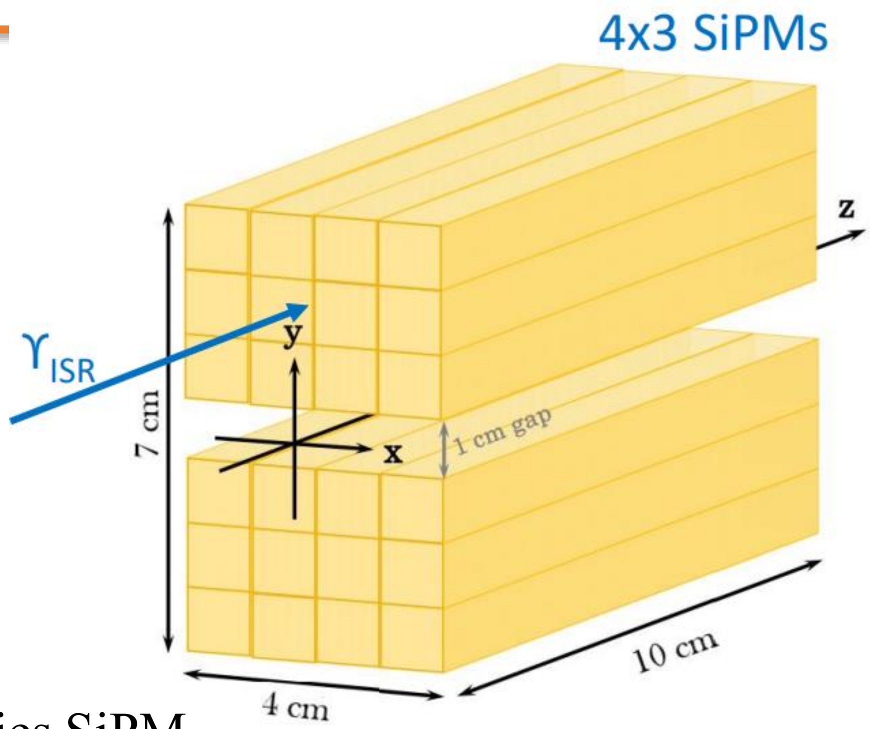
- This time is relative to the start of the ZDD data buffer, so (indirectly) to L1*, that closes the buffer
- Only the first part of the buffer, 1600 ns, is analyzed. The second part is thrown away.



- Calibration was done with Bhabha events.
- After correcting the timing by subtracting the BESIII “Event start time”, the signal is clearer.
- Later on, there appear a problem about the DAQ, and the ZDD was not used for ISR detection.

crystal Zero Degree Detector (cZDD) by JGU

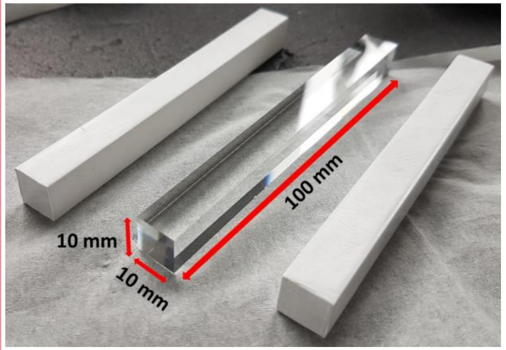
- ➢ Two arrays of 4x3 crystals with polar angle acceptance of $0.1° < \theta < 0.7°$
- ➢ 1 cm gap due to Bremsstrahlung at small angles
- ➢ SiPMs collect light output
- ➢ cZDD signal used by electronics for event correlation with BESIII trigger



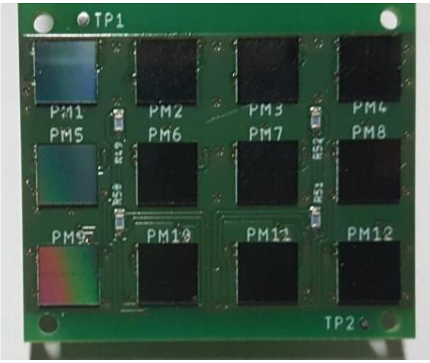
Advantage

- High density (≈ 7.2 g/cm²)
- Molière radius (≈ 2.1 cm)
- Fast decay time (≈ 42 ns)
- Radiation hardness (> 10^8 rad)
- Maximal emission wavelength of 420 nm
- High light output

LYSO Crystals



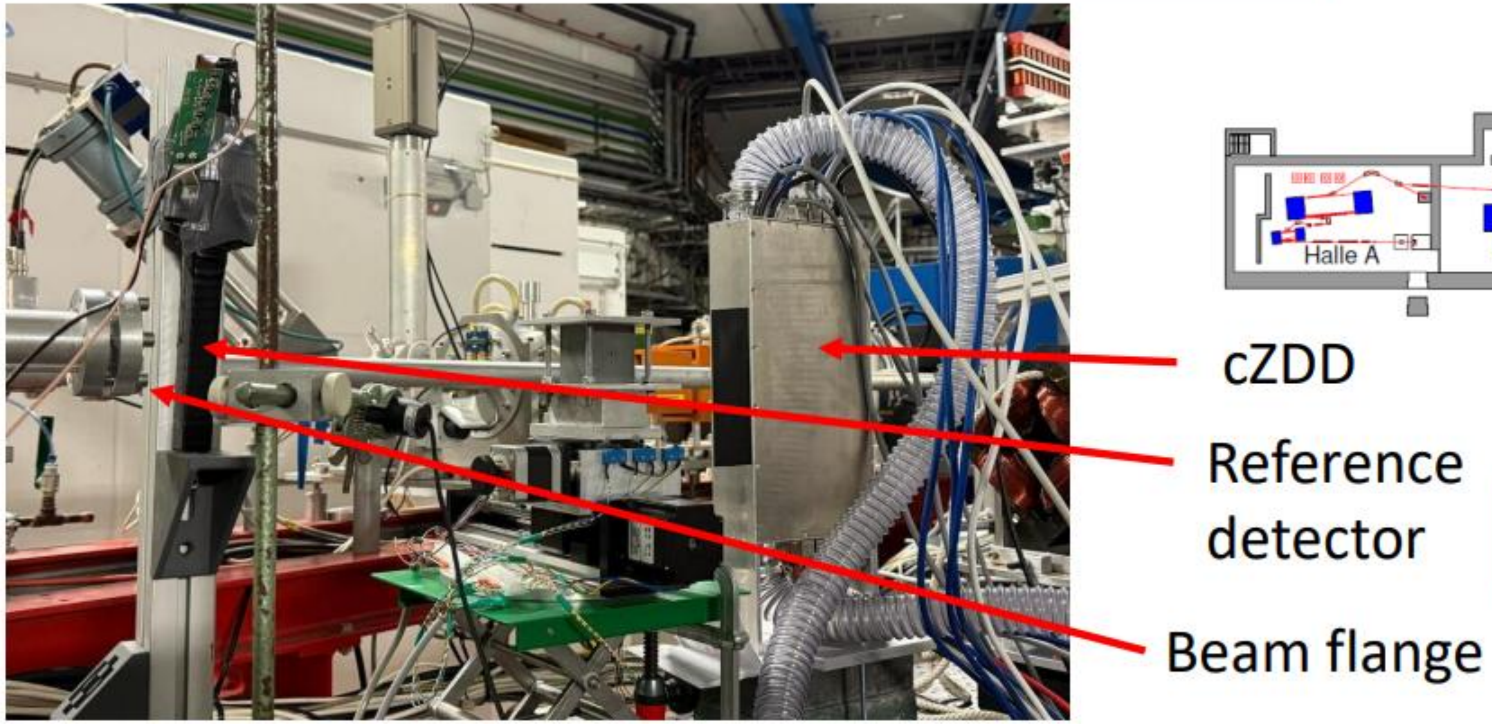
J-Series SiPM

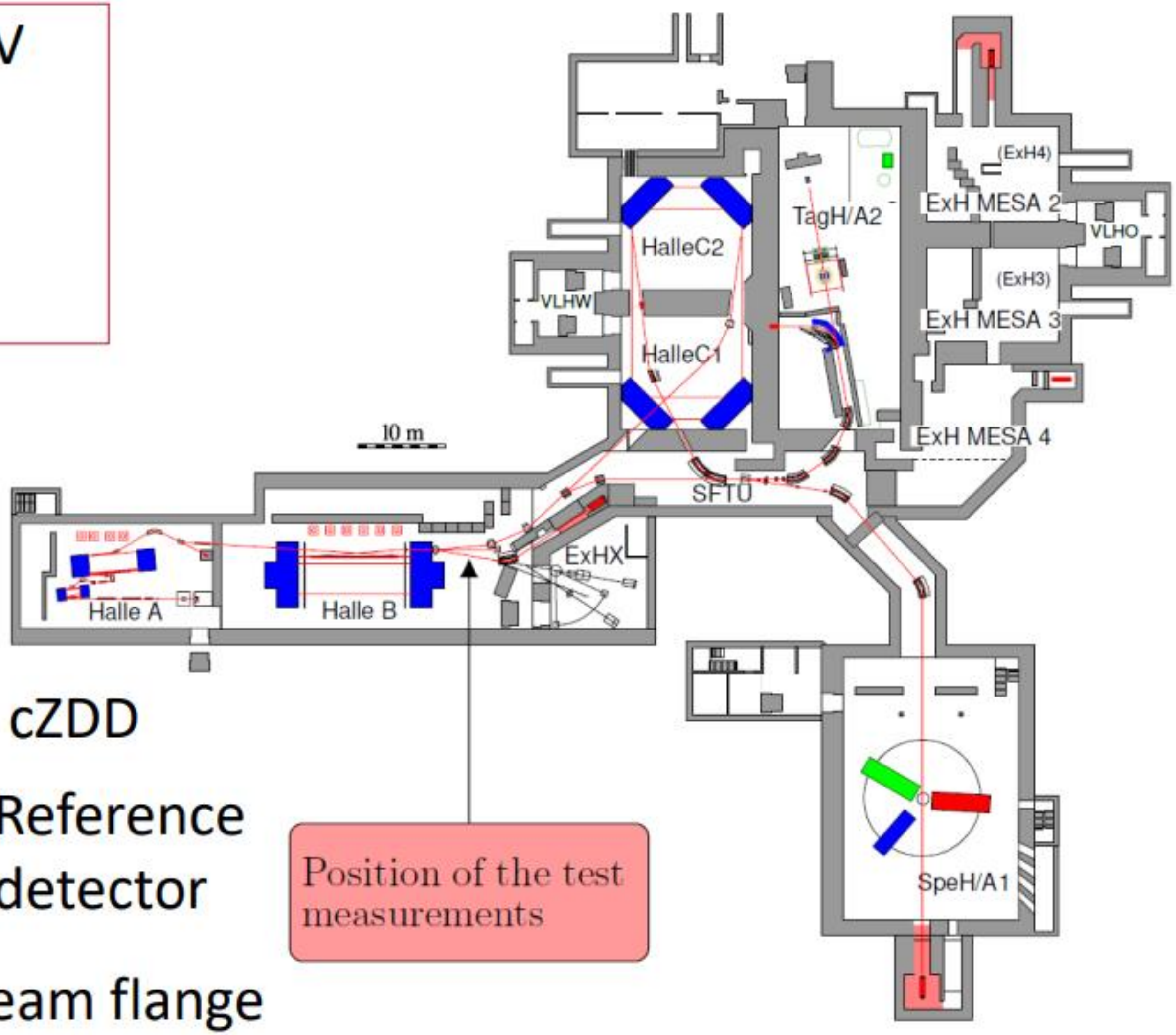


- Insensitive to magnetic fields
- Photon Detection Efficiency larger than 50 % for 420 nm
- RC charging time constant of 50 ns
- Total of 22,292 pixels on active area of (6 x 6) mm²
- Dark count rate temperature dependent (~ MHz)

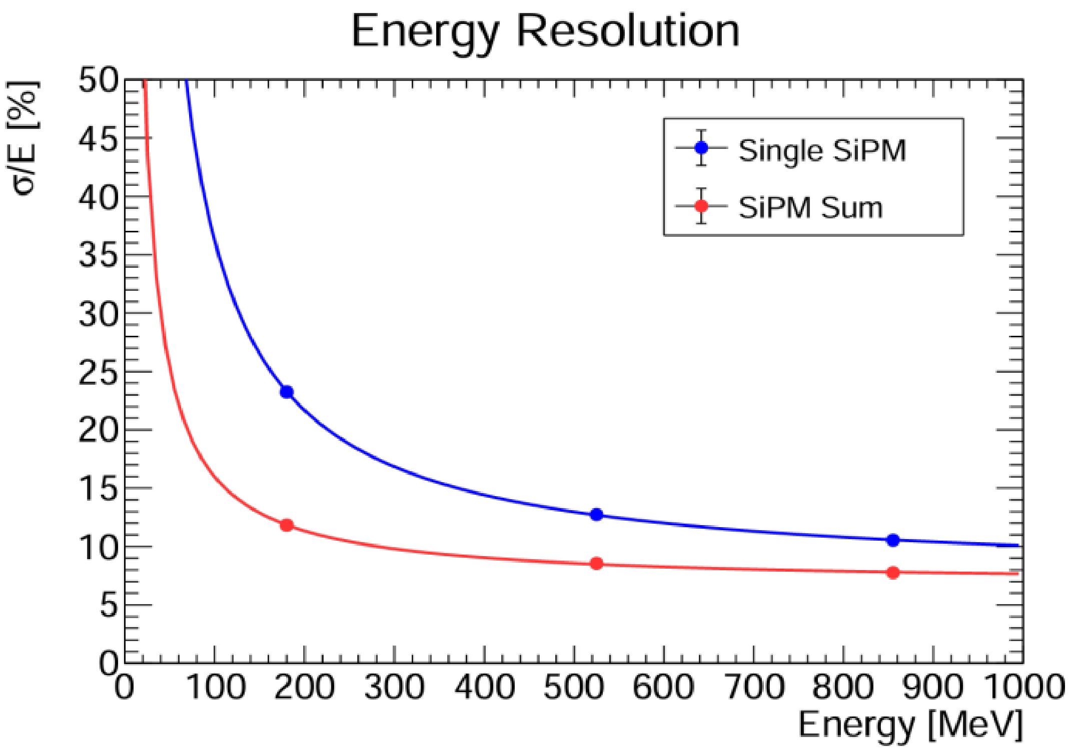
cZDD beam test @ MAMI – Mainz Microtron

- Electron beam energy up to 1.6 GeV (180MeV to 855 MeV at RTM3)
- Maximal cw current of ≈ 100 µA
- Small beam with high intensity

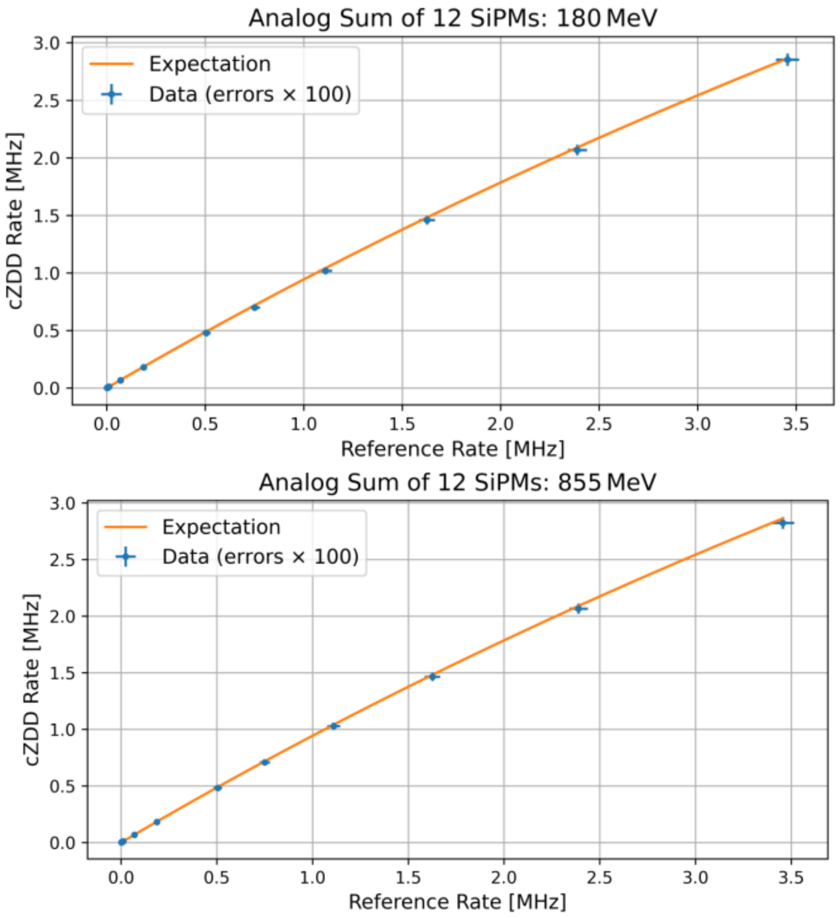




cZDD beam test results



➔ Precise energy resolution allows to tag ISR photons



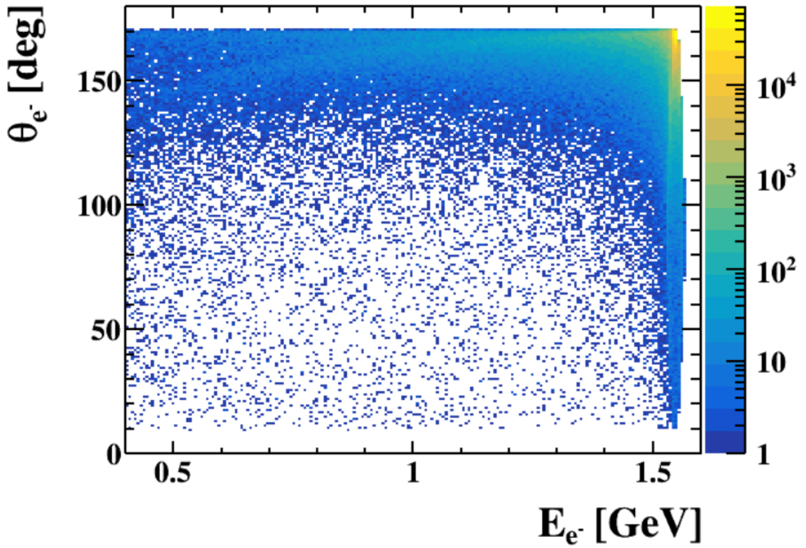
Had been successfully installed in this summer!

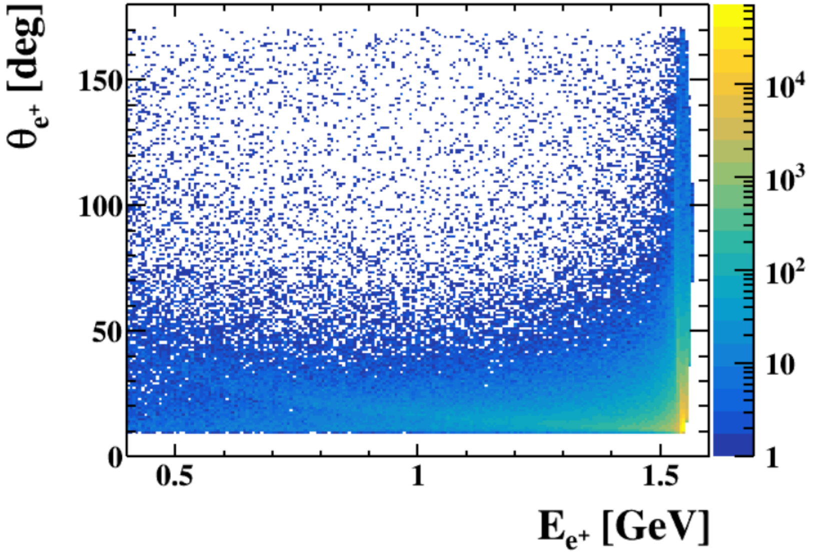
- Predicted background rate of about 1MHz at 200 MeV
- Expected relation based on different dead times: $R_{cor} = R/(1 + R \cdot \tau)$
  →Reliable detection of rates up to at least 3MHz

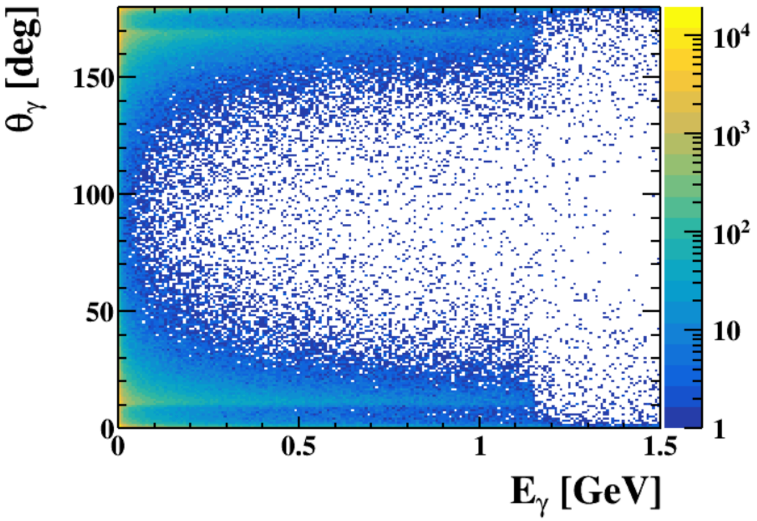
ISR at STCF

- The ISR physics is expected to be more precision than before.
- The better precision needs a "ZDD" detector with high energy and time resolutions.
- Due to high background from Bhabha(e^+e^-), it is needed to have an ability to identify e/γ in "ZDD".

Simulation of Bhabha with BabaYaga

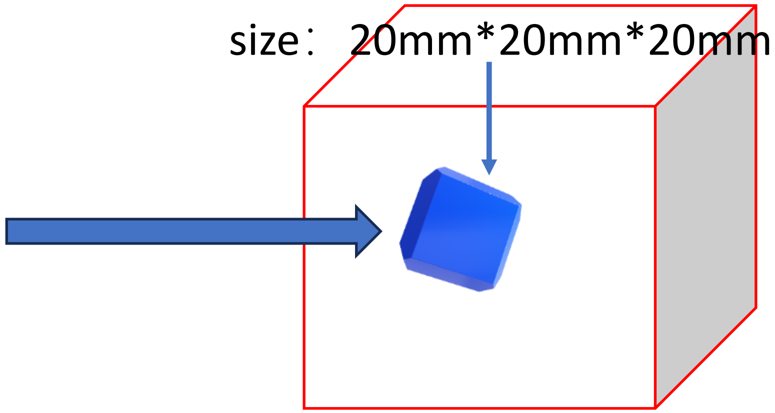


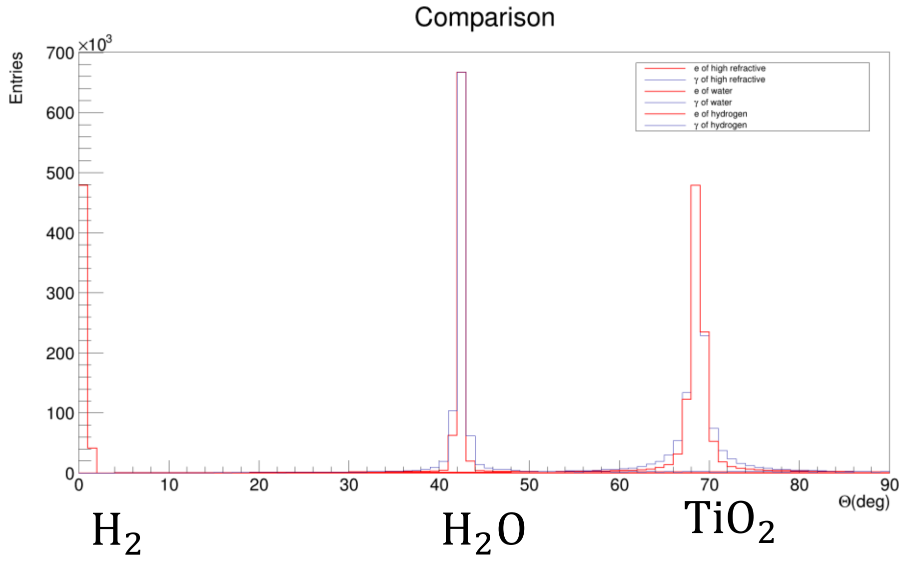




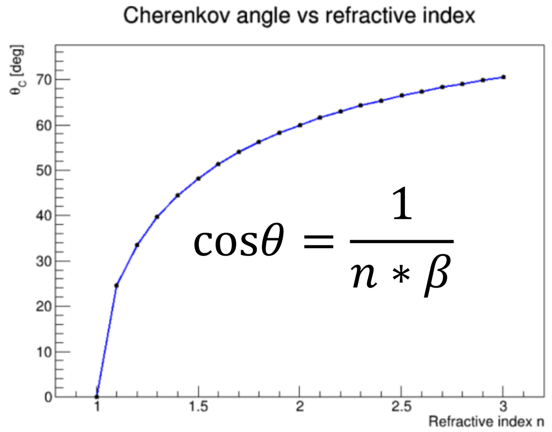
Bhabha 事例中，光子与电子的角分布基本一致；能量方面，电子对集中于高能段，光子则主要落在中低能区。

尝试用切伦科夫探测器



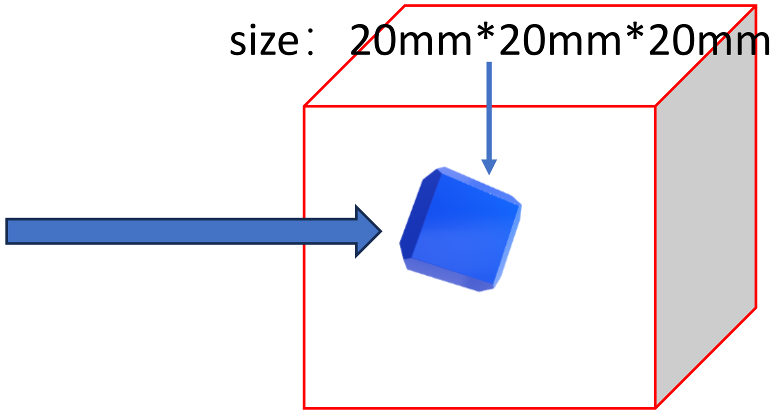


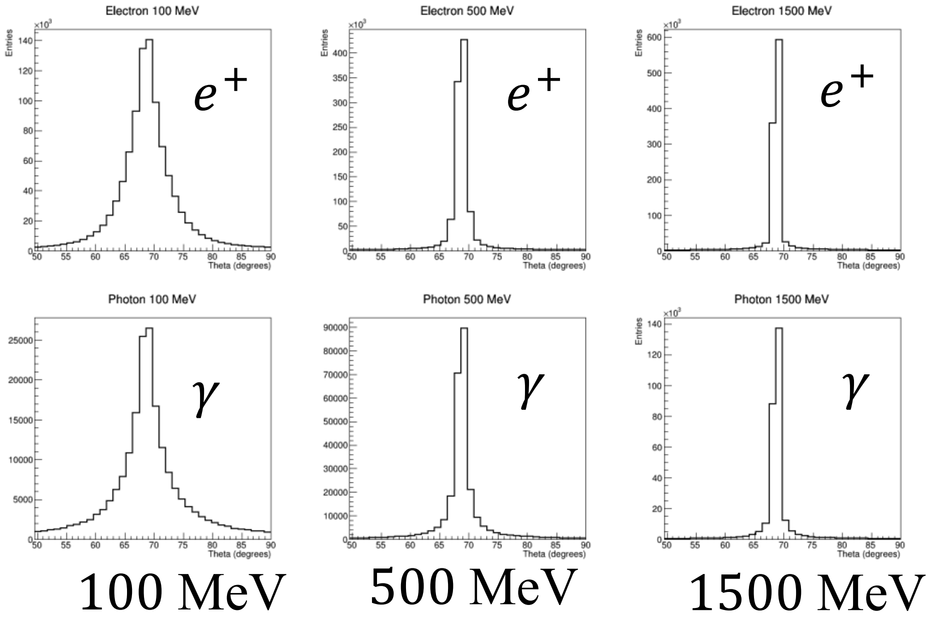
在坐标轴中心放置一个边长 20 mm 的立方体，将其折射率分别设为高(TiO_2)、中(H_2O)、低(H_2)三档，随后向立方体依次发射 500 MeV 的电子与光子，观测切伦科夫光子的产额与分布。



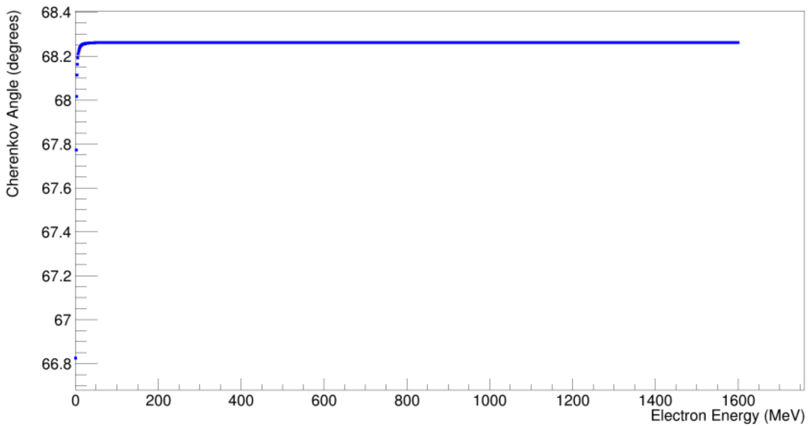
- 在固定能量下，切伦科夫角随折射率增大而单调增大。
- 由于光子进入介质后先通过康普顿散射等过程打出带电粒子，再由这些带电粒子辐射切伦科夫光，因此 500 MeV 光子与 500 MeV 电子最终产生的切伦科夫角几乎相同

尝试用切伦科夫探测器



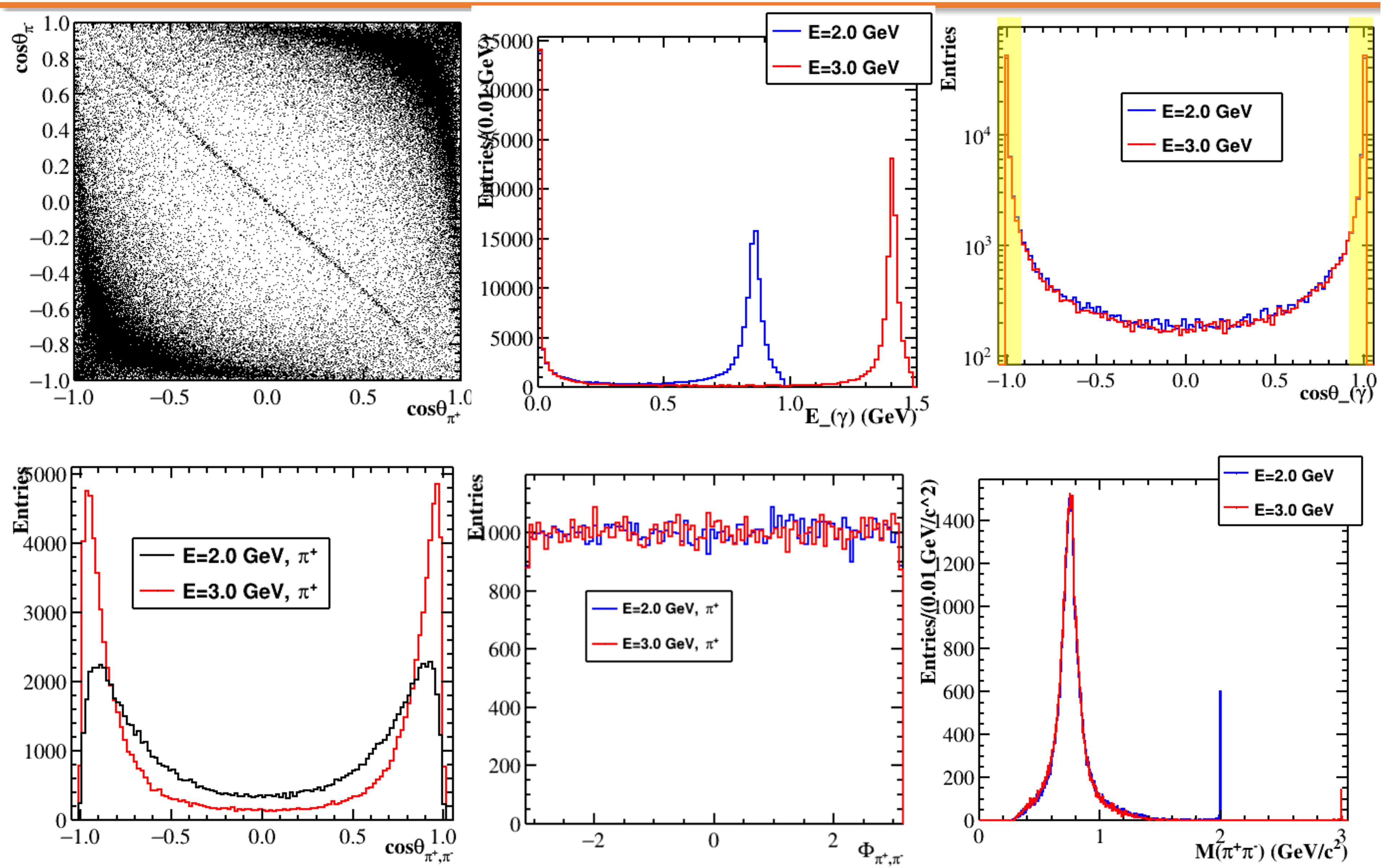


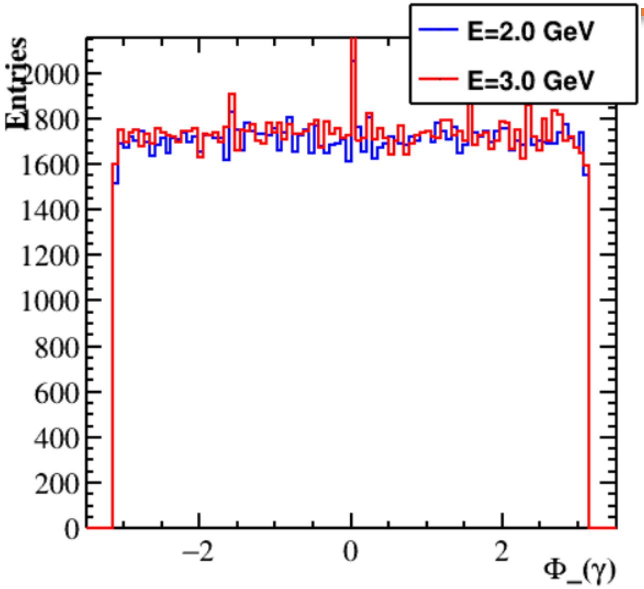
固定立方体材料为高折射率，依次沿束流向其中注入 100 MeV、500 MeV 和 1500 MeV 的电子与光子，比较三种能量下切伦科夫光子的产额及空间分布



- 在高折射率介质中，一旦能量远高于切伦科夫阈，100 MeV 以上电子的 相对论 因子已十分接近，β≈1，导致切伦科夫角几乎不再随能量变化，趋于恒定值

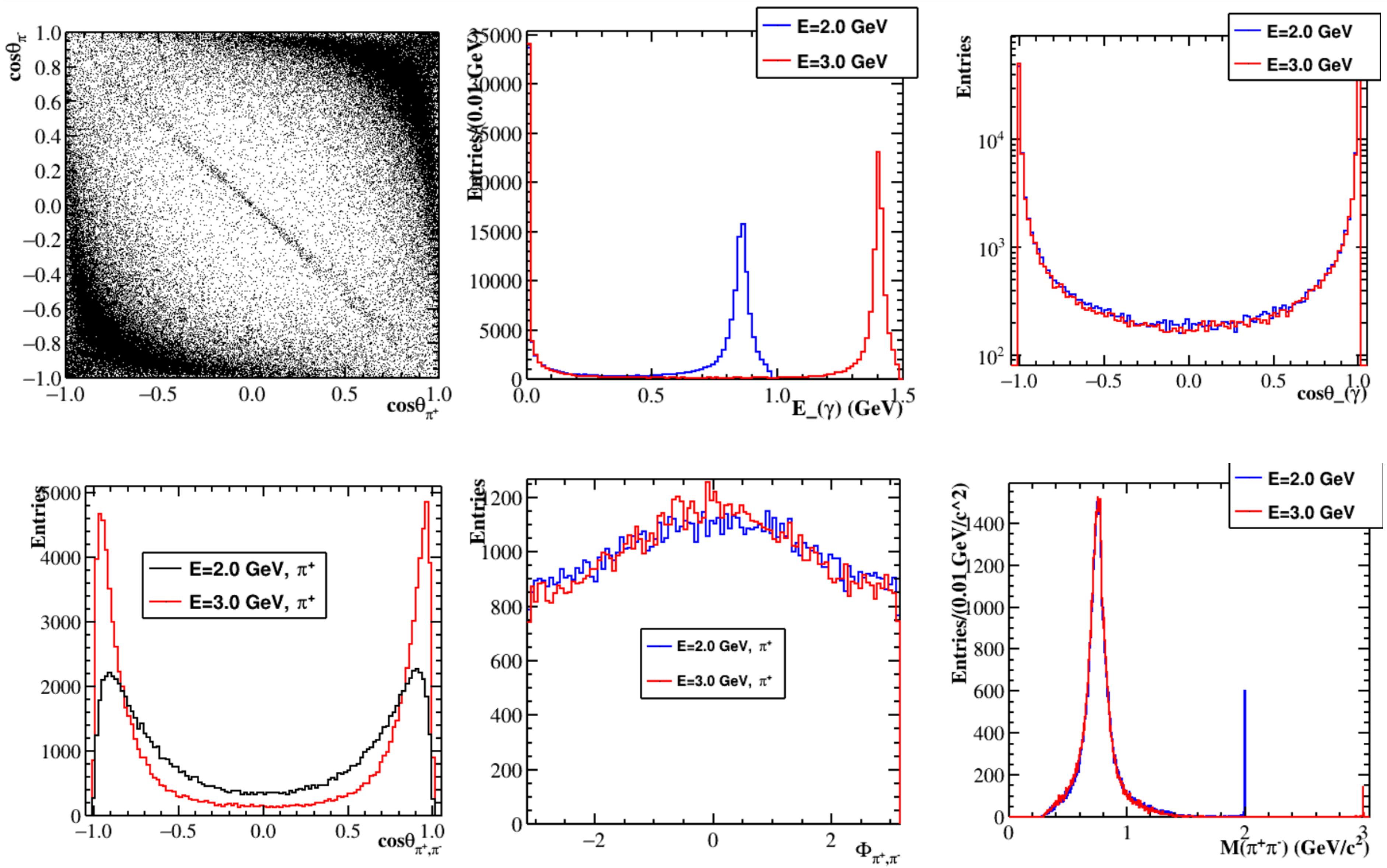
MC simulation with BabaYaga for $e^+e^- \to (\gamma_{ISR})\pi^+\pi^-$





The radiation direction doesn't change according to beam energy.

MC simulation with BabaYaga for $e^+e^- \to (\gamma_{ISR})\pi^+\pi^-$ boosted to lab. Frame (X(0.060*ecms, 0, 0, ecms);)



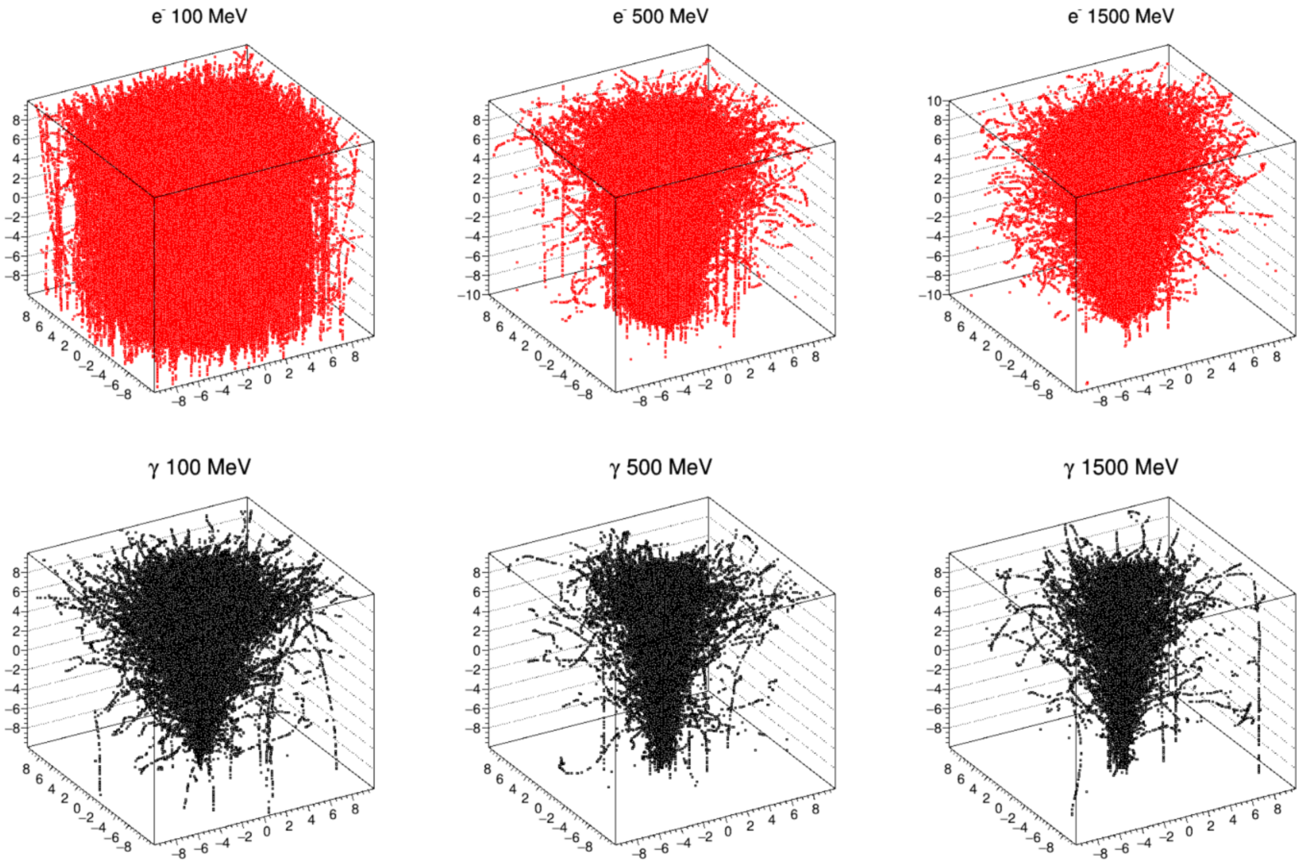
After boost to lab, the radiation centered in a certain ϕ direction.

ISR at STCF

- The ISR physics is expected to be more precision than before.
- The better precision needs a "ZDD" detector with high energy and time resolutions.
- Due to high background from Bhabha(e^+e^-), it is needed to have an ability to identify e/γ in "ZDD".
- To find a way to identify e/γ is needed for ZDD construction.
- One possible method of putting anther layer of plastic scintillator before ZDD proposed by Prof. Jin Li will be tested.
- **Si wafer + LYSO** for identification of e/γ proposed by Prof. Hou is also a nice idea.

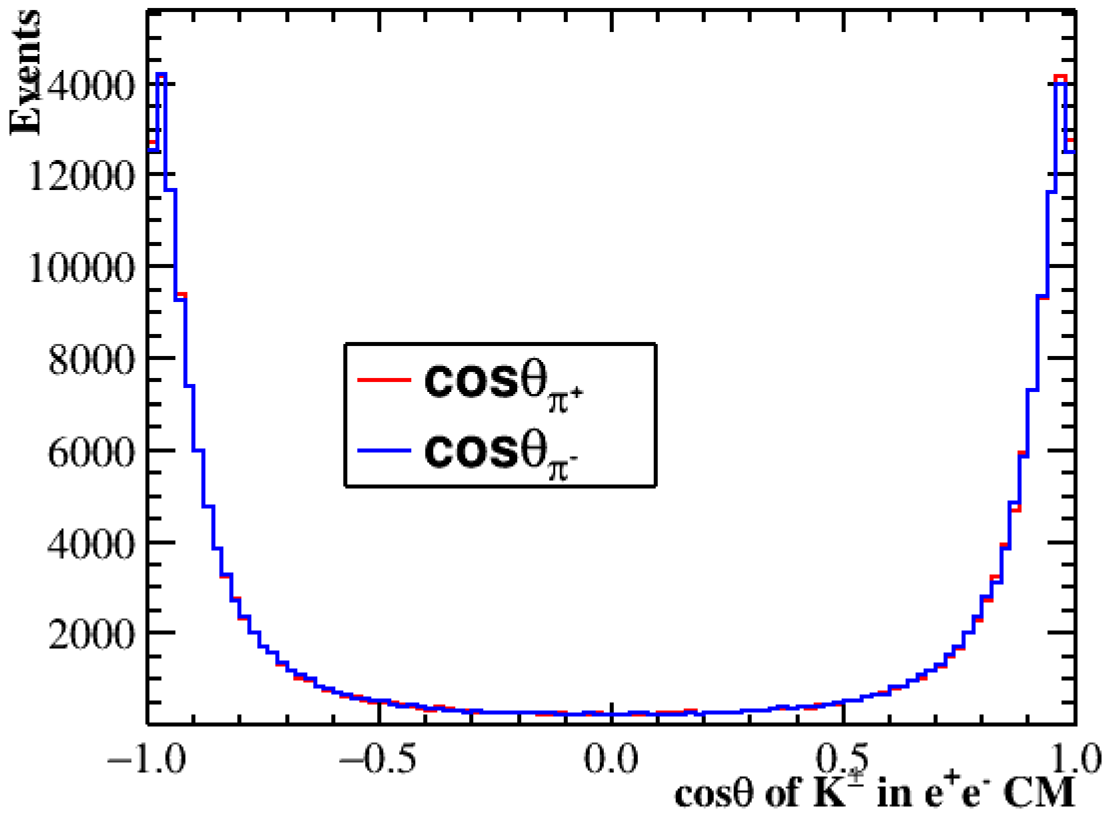
Thanks for your attention!

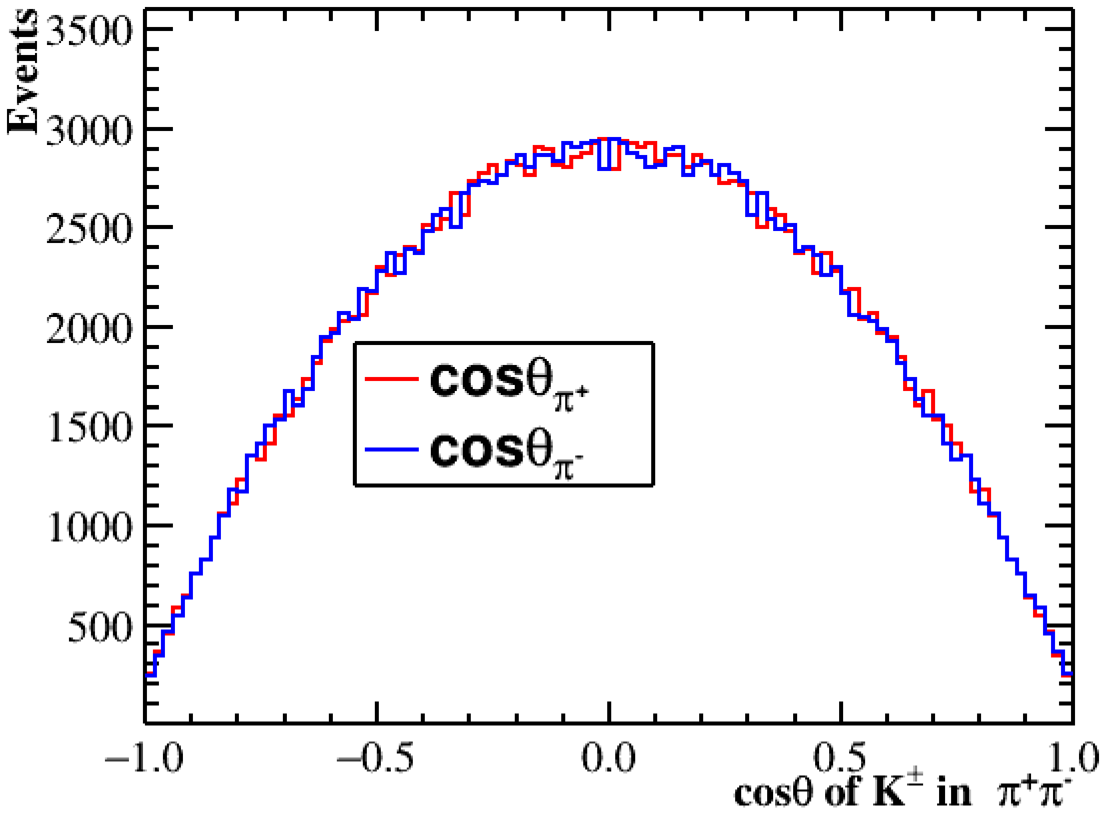
尝试用切伦科夫探测器



粒子能量越高、速度越接近光速，穿过同样尺寸介质的时间越短，可辐射距离随之缩短；因此，只要高于阈能，能量越高切伦科夫光子产额反而越低——产额与“停留时间”成正比。

MC simulation with BabaYaga for $e^+e^- \to (\gamma_{ISR})\pi^+\pi^-$





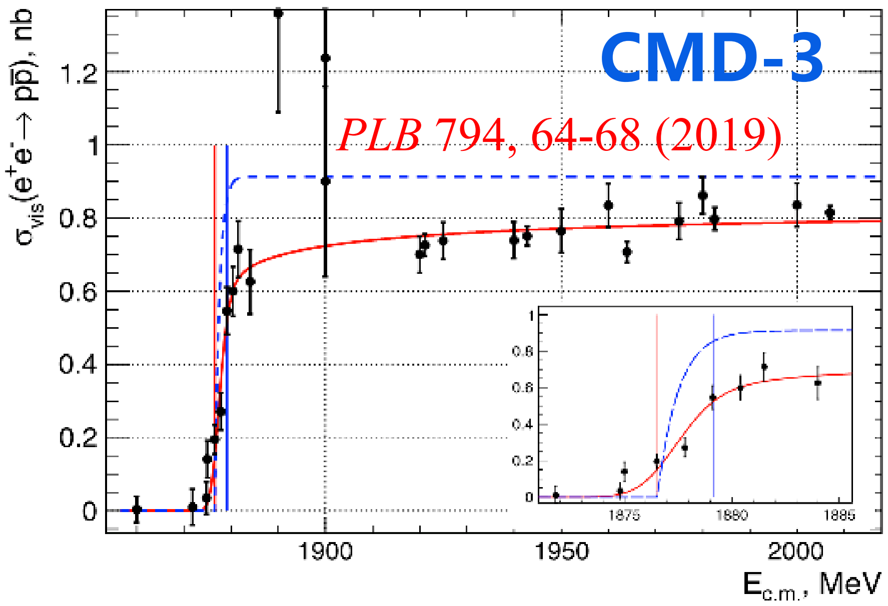
Threshold behavior

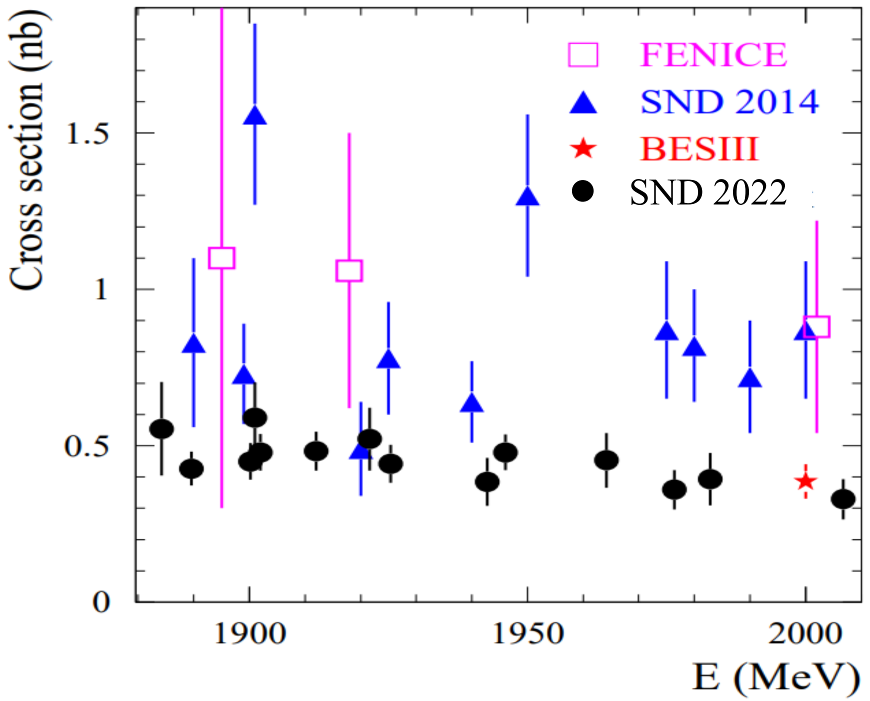
- From CMD-3, $\sigma(e^+e^- \to p\bar{p})$ is described with

$$\sigma_{\text{Born}}(\text{E}_{\text{c.m.}}) = \text{A} + \text{B}\left[1 - \exp\left(-\frac{(\text{E}_{\text{c.m.}} - \text{E}_{\text{thr}})}{\sigma_{\text{thr}}}\right)\right]$$

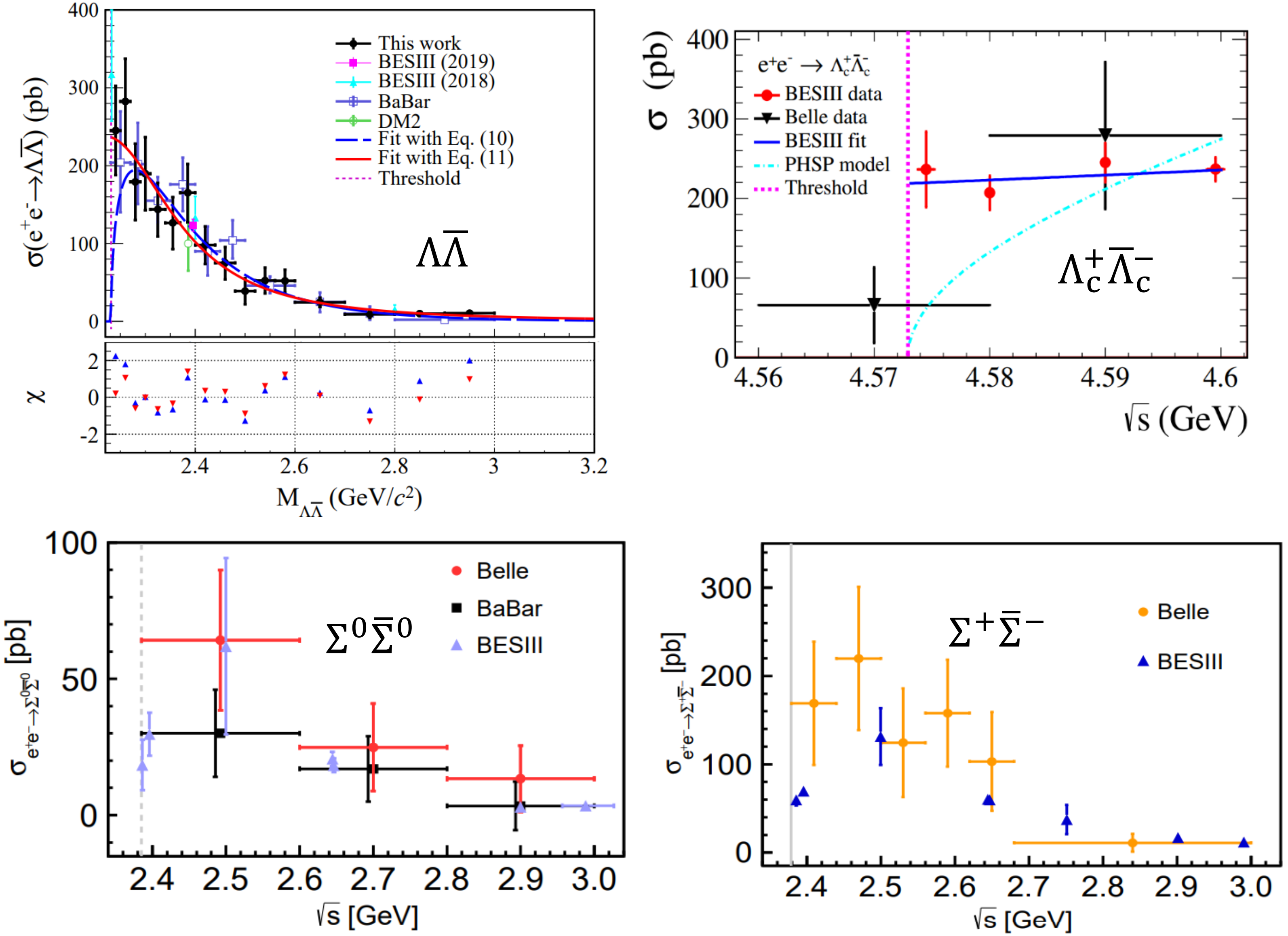
Reac.	A, nb	B, nb	E_{thr}, MeV	σ_{thr}, MeV	χ^2/ndf
$p\bar{p}$	0 – fxd	0.91±0.02	1877.1±0.2	0.18±0.27	29/26
$p\bar{p}$	0 – fxd	0.91±0.02	1876.54-fxd	0.76±0.28	31/27

- From SND, $e^+e^- \to n\bar{n}$ from 1.884 to 2.007 GeV, ~40 pb^{-1}
- $\sigma \approx 0.4$ nb below 2 GeV. Possible threshold effect

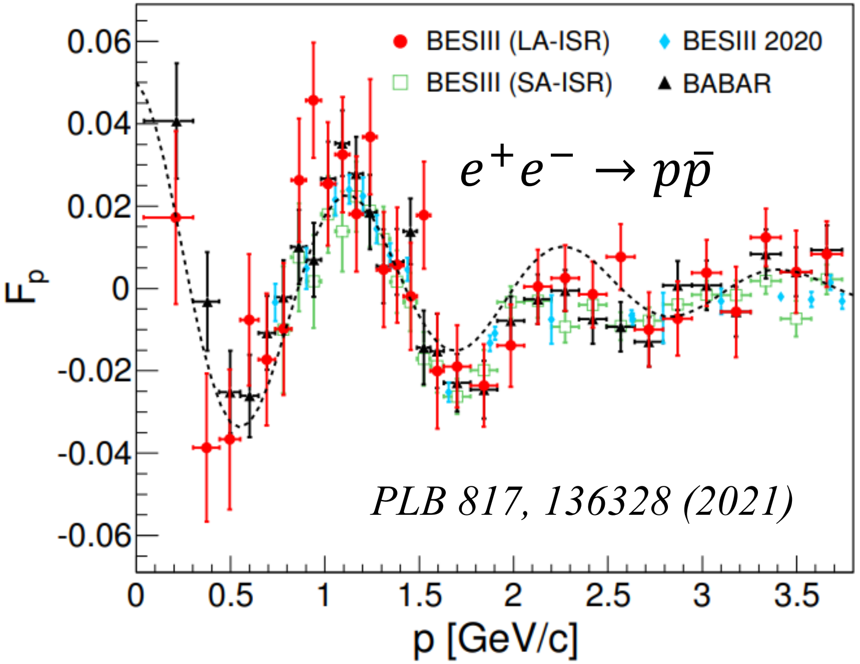


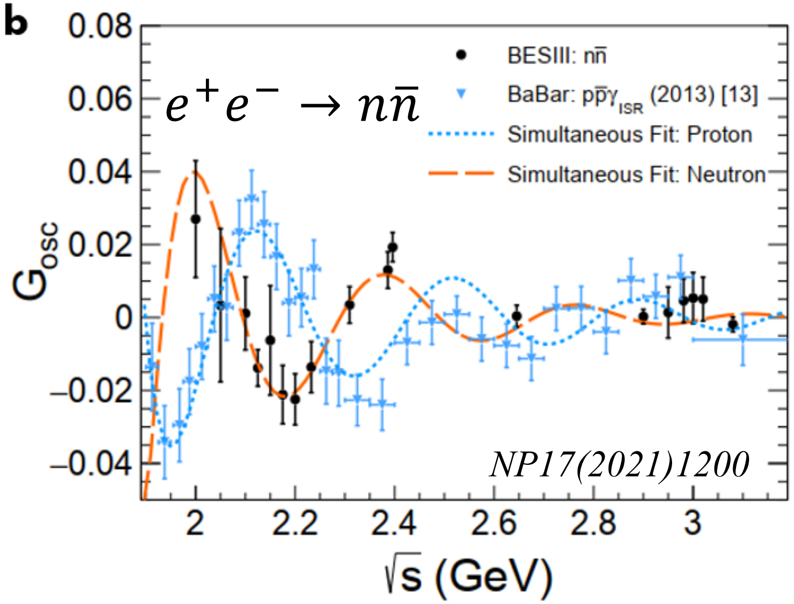


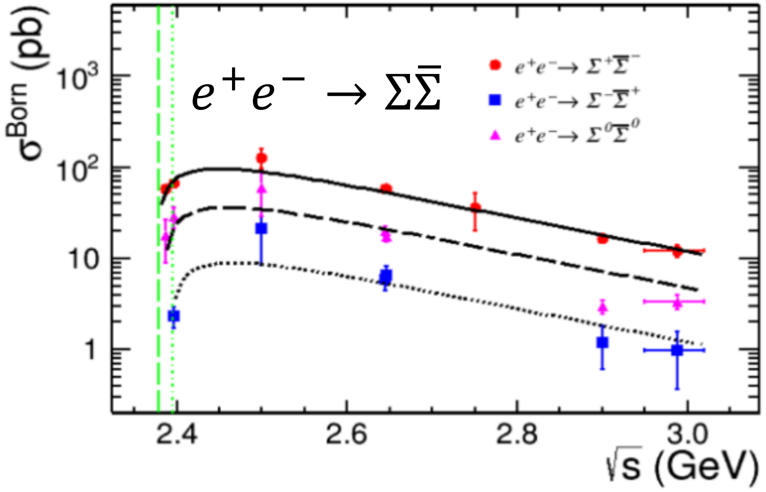
Threshold behavior

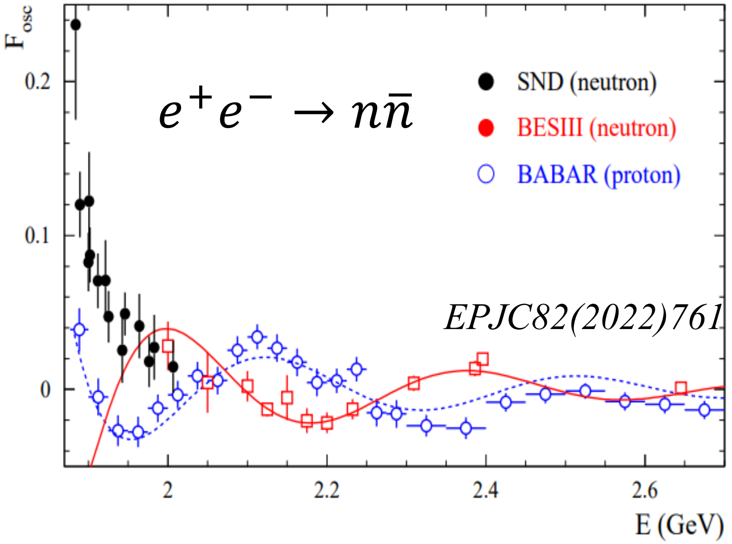


Oscillation behavior





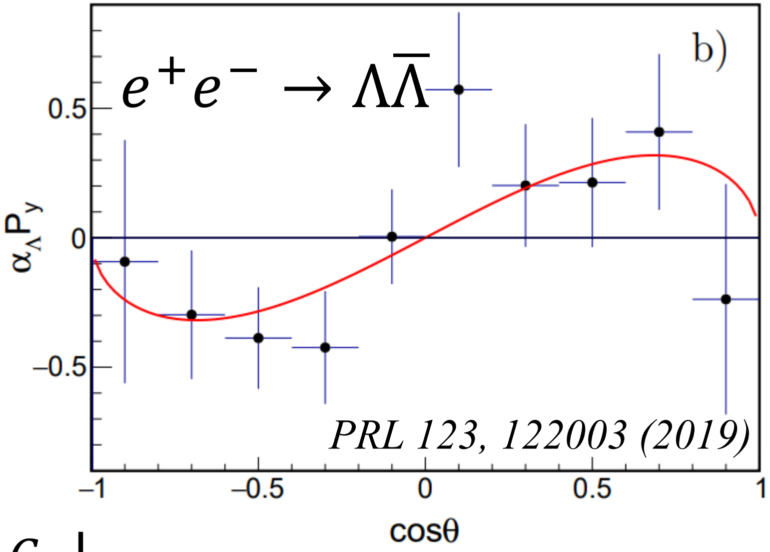




Complete measurement of baryon EMFF

Nuov Cim A **109**, 241–256 (1996)

$$P_y = -\frac{\sin 2\theta \, \mathrm{Im}[G_E G_M^*]/\sqrt{\tau}}{\frac{|G_E|^2 \sin^2\theta}{\tau} + |G_M|^2(1+\cos^2\theta)}$$

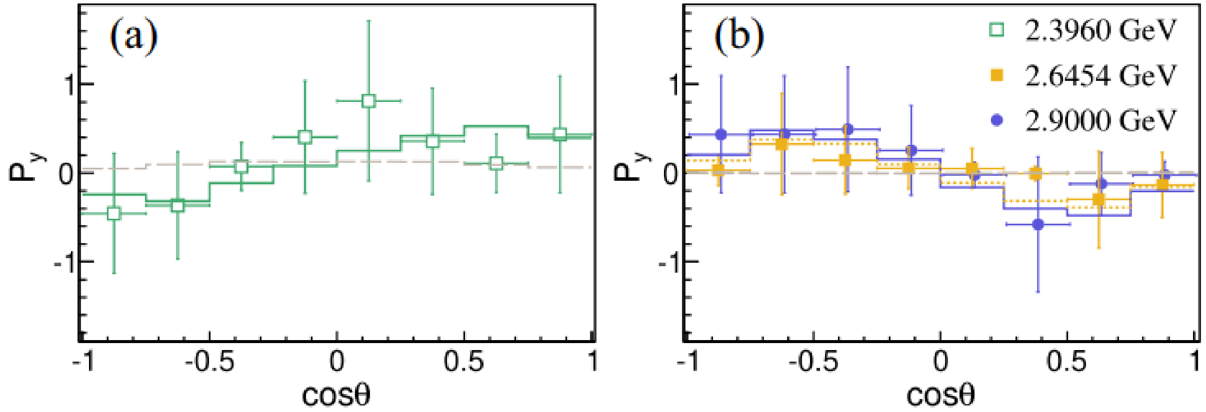


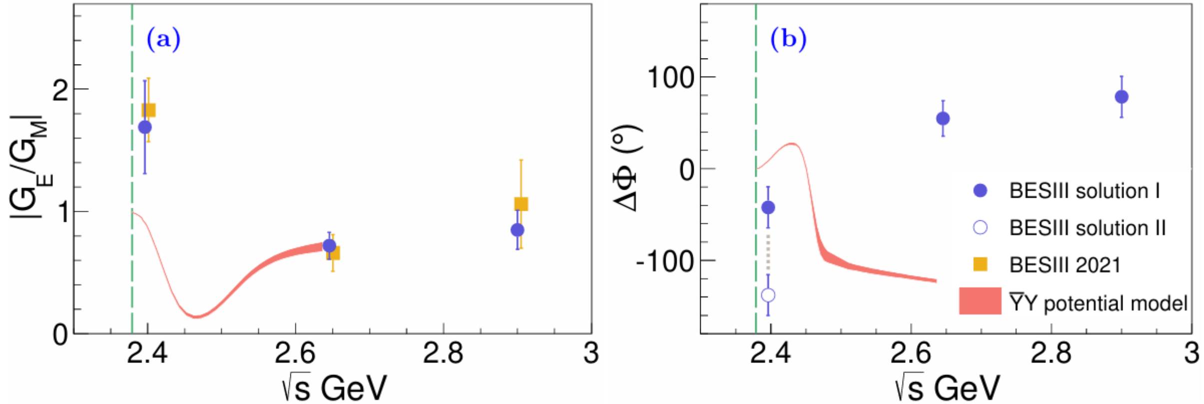
$$\left|\frac{G_E}{G_M}\right| = 0.96 \pm 0.14(\mathrm{stat.}) \pm 0.02(\mathrm{sys.})$$

$$\Delta\Phi = 37^\circ \pm 12^\circ(\mathrm{stat.}) \pm 6^\circ(\mathrm{sys.})$$

(Confirm the complex form of EMFFs)

$e^+e^- \to \Sigma^+\bar{\Sigma}^-$





$\sqrt{s}$ (GeV)	2.3960	2.6454	2.9000
α	$-0.47 \pm 0.18 \pm 0.09$	$0.41 \pm 0.12 \pm 0.06$	$0.35 \pm 0.17 \pm 0.15$
$\Delta\Phi(^\circ)$	$-42 \pm 22 \pm 14$ $(-138 \pm 22 \pm 14)$	$55 \pm 19 \pm 14$	$78 \pm 22 \pm 9$
$\sin \Delta\Phi$	$-0.67 \pm 0.29 \pm 0.18$		
$\lvert G_E/G_M \rvert$	$1.69 \pm 0.38 \pm 0.20$	$0.72 \pm 0.11 \pm 0.06$	$0.85 \pm 0.16 \pm 0.15$