Measuring space-time properties of baryon resonances around 1 GeV using intensity interference

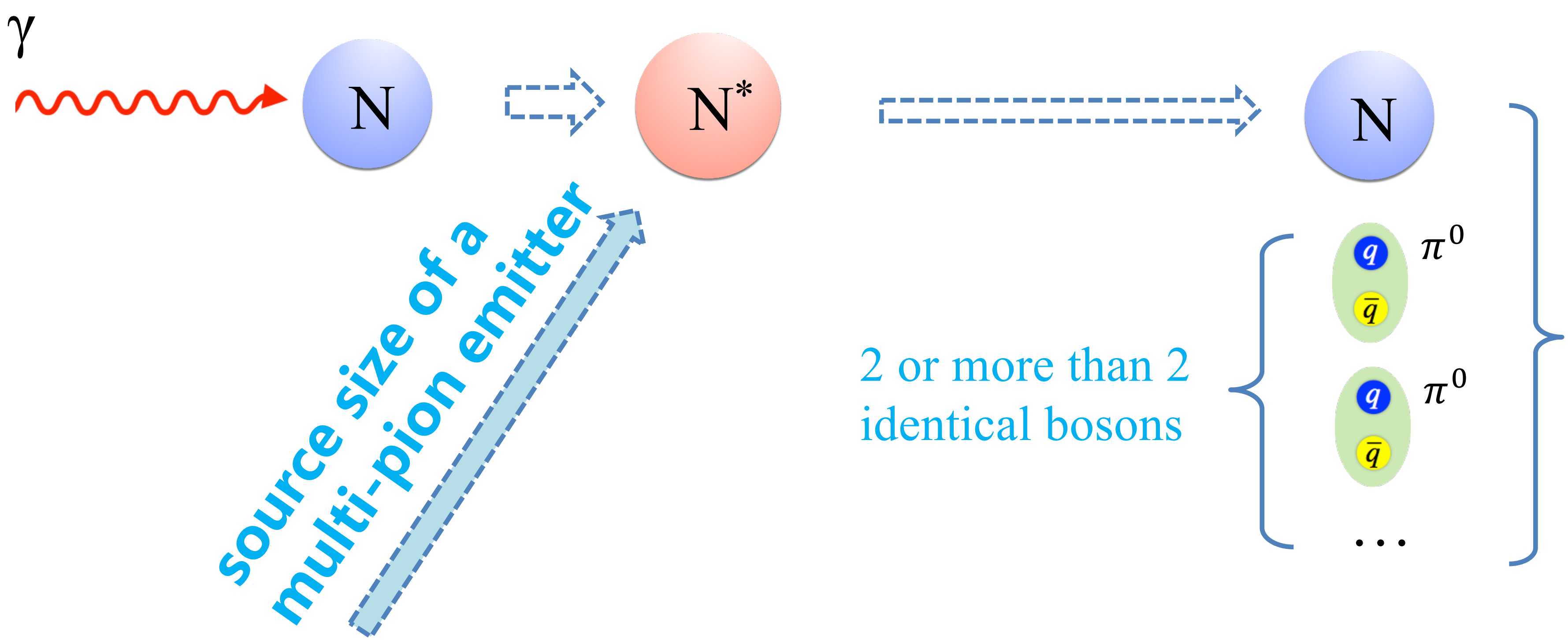
Qinghua HE for FOREST Collaboration

E-mail: heqh@nuaa.edu.cn

1 Department of Nuclear Science and Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

2 Research Center for Electron Photon Science, Tohoku University, Sendai 982-0826, Japan

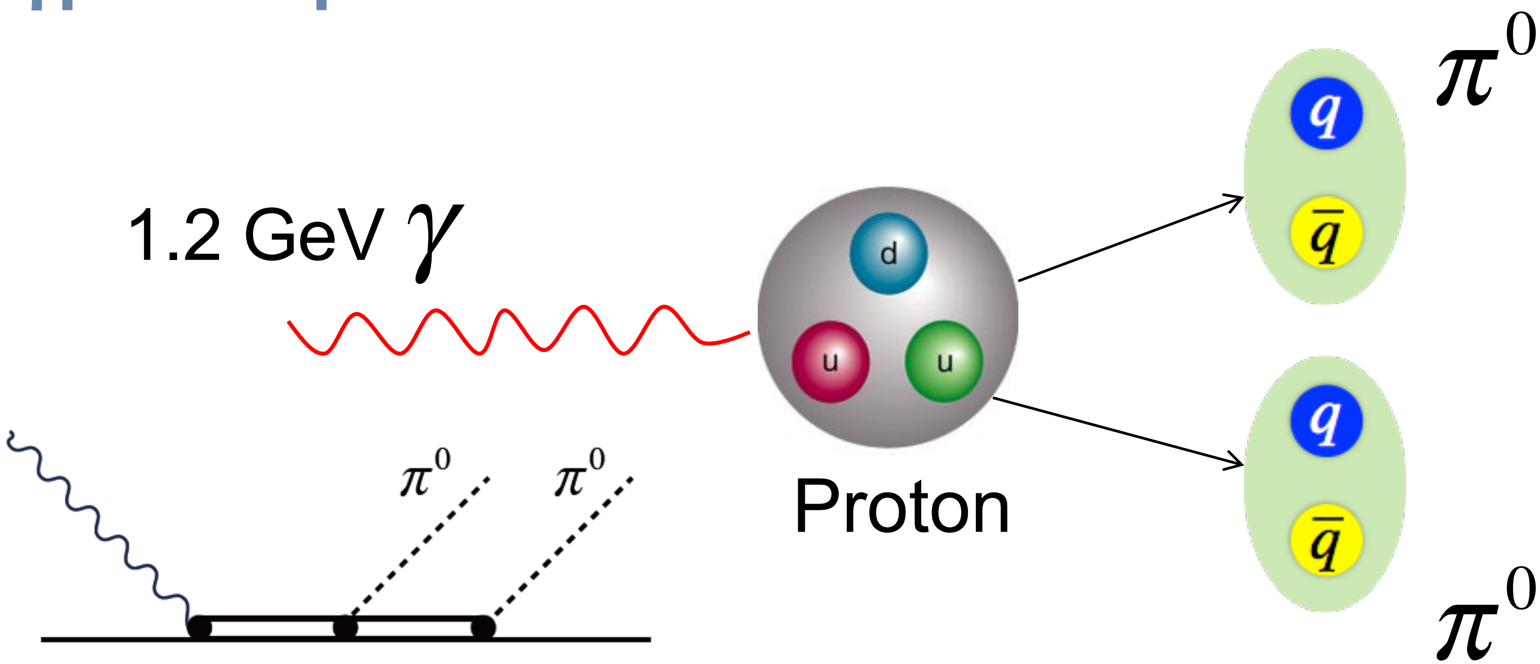
Motivation



Intensity interference between identical particles (**HBT effects**) provides a tool to measure the space-time properties of the particle emission source.

Motivation

Is that possible to measure space-time properties of Δ(1232) resonance using $\pi^0\pi^0$ correlations in $\gamma p \to \pi^0\pi^0 p$?



$\gamma p \to \pi^0 \Delta \to \pi^0\pi^0 p$ process is dominant in $\gamma p \to \pi^0\pi^0 p$

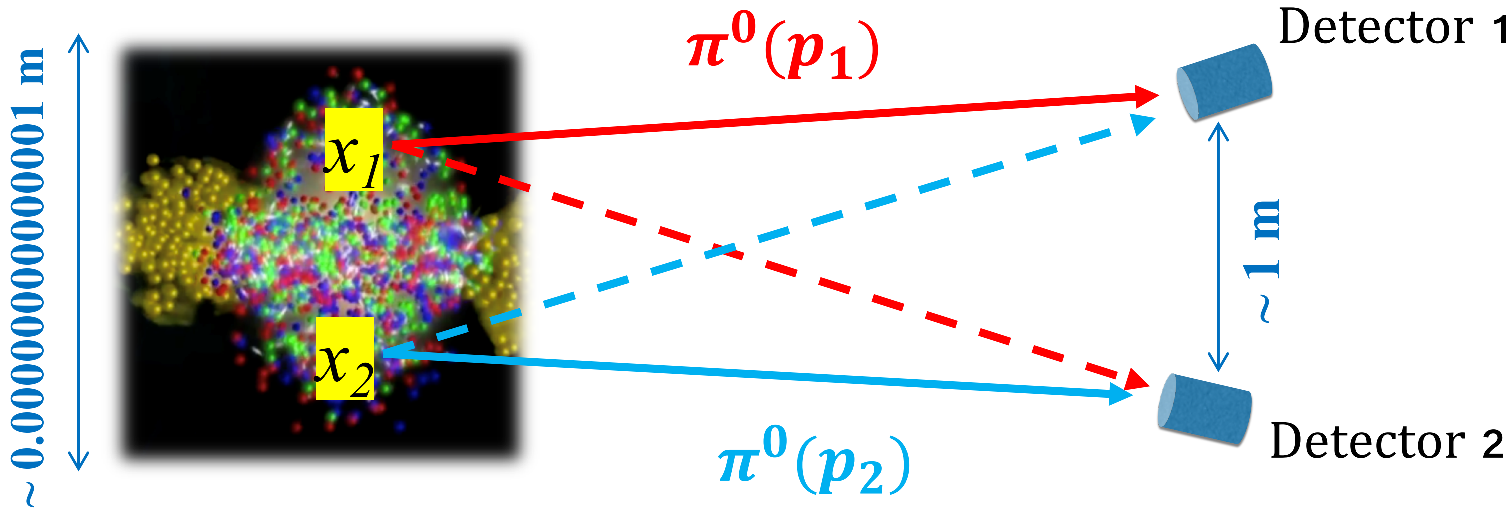
Using FOREST data @ ELPH

Intensity interference of bosons:

Bose-Einstein correlations (BEC)

space-time properties ⇔ enhancement

Size ?



Symmetrized two-particle wave function

$$\psi^s = \frac{1}{\sqrt{2}}\left[e^{-i(p_1(d_1-x_1)+p_2(d_2-x_2))} + e^{-i(p_1(d_1-x_2)+p_2(d_2-x_1))}\right]$$

(assume plane wave function of propagation)

This **symmetrization** results in an **enhanced probability** $(P_{12}(p_1,p_2) = \langle \psi^{s*}\psi^S \rangle)$ of emission if the two bosons have similar momenta.

Correlation function

Intensity interference is measured in terms of a **correlation function:**

$$C_2(p_1,p_2) \equiv \frac{P_{12}(p_1,p_2)}{P_1(p_1)P_2(p_2)}$$

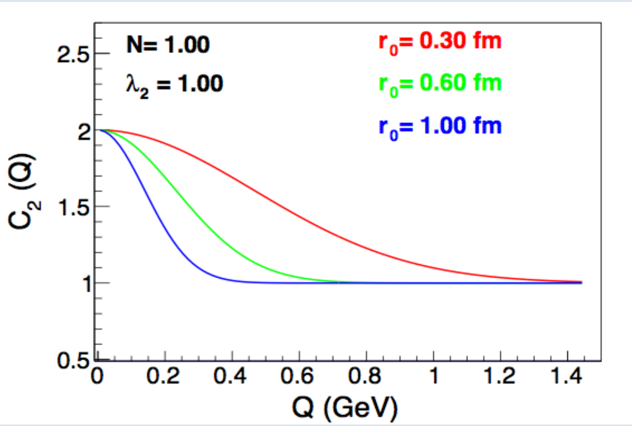
completely chaotic:

$$C_2(p_1,p_2) = 1 + \left|\hat{\rho}(Q)\right|^2$$

completely coherent:

$$C_2(p_1,p_2) = 1$$

$$C_2(Q) \equiv N(1 + \lambda_2 e^{-r_0^2 Q^2})$$



$Q^2 = -(p_1 - p_2)^2$

$p_{1,2}$: four momentum of the two identical particles.

Assume the particle emitting source has a Gaussian profile of density distribution

$$\rho(x) = \rho(0)e^{-x^2/2r_0^2}$$

$\hat{\rho}(Q)$: Normalized Fourier transform of source density ρ(x):

$$\hat{\rho}(Q) = \int dx \rho(x) e^{i(p_1-p_2)x} \qquad \left|\hat{\rho}(Q)\right|^2 = e^{-r_0^2 Q^2}$$

N: normalized factor

r_0 : emitter radius

λ_2 : chaoticity parameter ($0 \leqq \lambda_2 \leqq 1$)

0: completely coherent case

1: totally chaotic limit

How to measure correlation function

Measure the spectra of Q (momenta difference) and compared it to that in a **reference sample** free of BE effects

$$C_2(Q) = \frac{P_{BE}(Q)}{P_{noBE}(Q)} = \frac{\rho_{BE}(Q)}{\rho_{noBE}(Q)}$$

signal sample

reference sample

$$Q^2 = -(p_1 - p_2)^2 = (p_1 + p_2)^2 - 4\mu^2$$

A valid reference sample should be identical to the real data (signal sample) in all aspect but free of BEC.

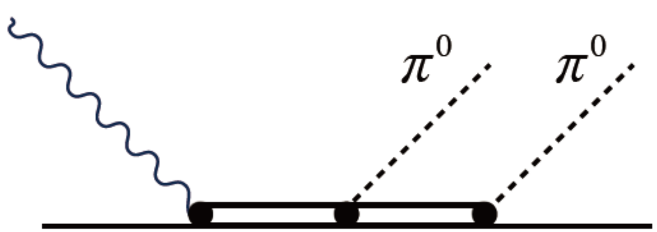
The reference sample is constructed by taking two π^0 from different events, namely **event mixing**

Challenges in BEC analysis at low energies with low multiplicities

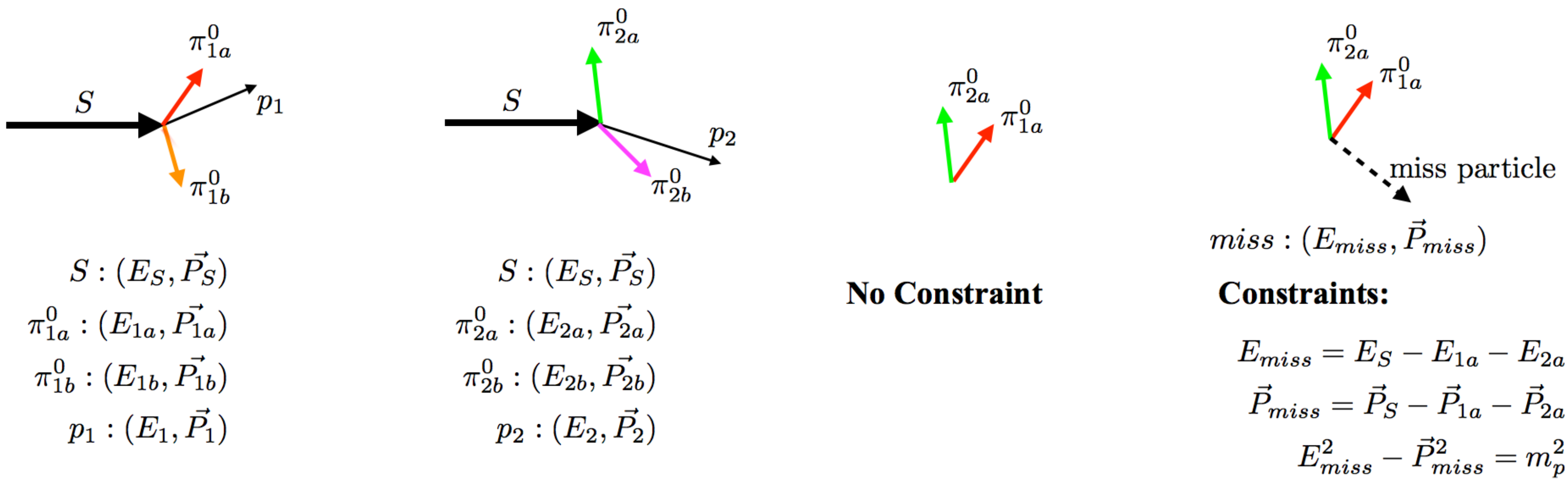
(1) Event mixing method

low energies low multiplicities	high energies high multiplicities
strongly disturbed by non-BEC factors of exclusive reactions with a low multiplicity such as global conservation laws and decays of resonances	weakly disturbed by non-BEC factors such as global conservation laws
Complicated kinematical constraints	Simple kinematical constraints

(2) Resonance decay effects



Event Mixing Technique

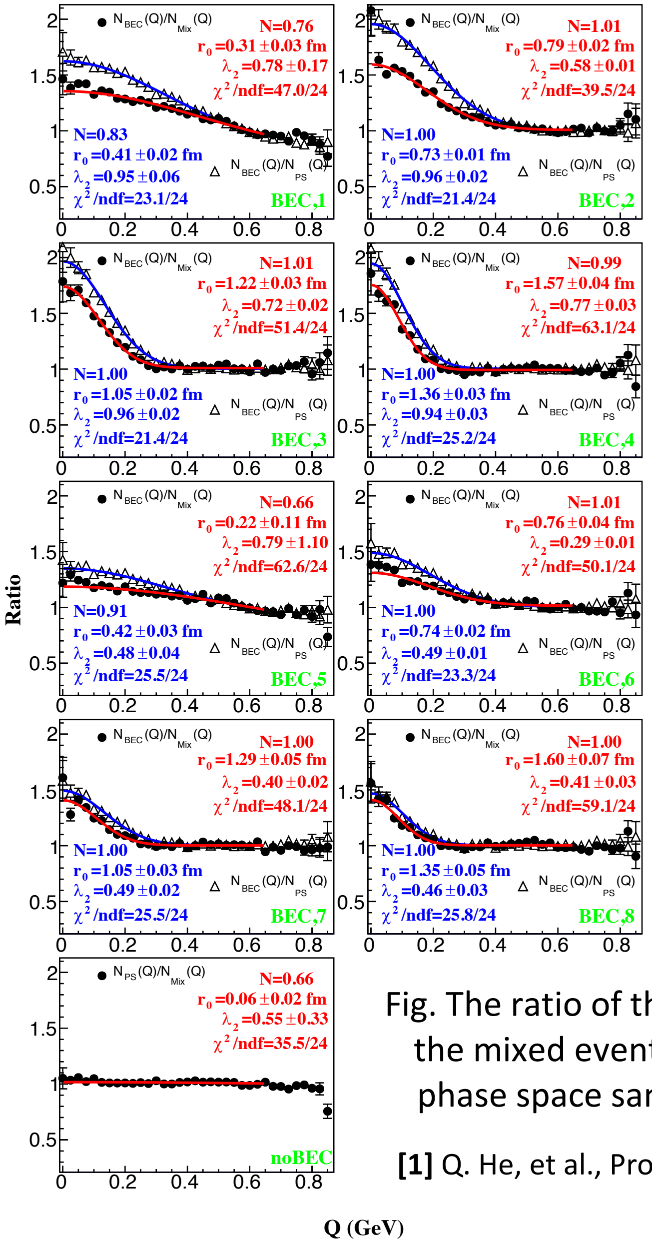


(a) Event 1 (b) Event 2 (c) Mixed Event (d) Mixed Event

Appropriate mixing cuts should be applied in the mixing

- **Missing mass consistency (MMC) cut :** $|m_X^{mix} - m_X^{ori}| < M_{cut}$
- **Pion energy (PE) cut:** events with pion energy higher than a given level are rejected
- **Energy sum order (ESO) cut:** $\mathbf{min}(E_{sum}^{ori,1}, E_{sum}^{ori,2}) < E_{sum}^{mix} < \mathbf{max}(E_{sum}^{ori,1}, E_{sum}^{ori,2})$
- **no overlapping photon clusters** (used to correct the detection efficiency)
- ……

Event Mixing Technique



Appropriate mixing cuts in event mixing: MMC + PE cuts

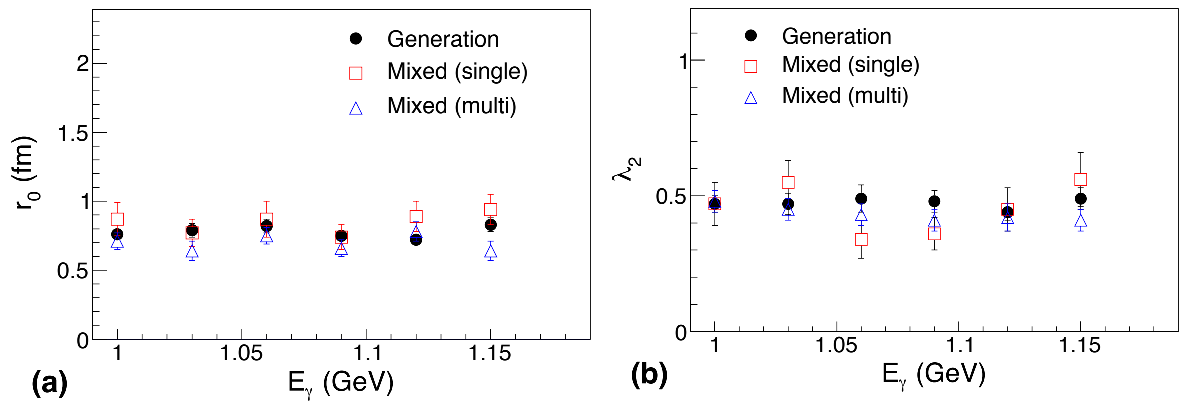


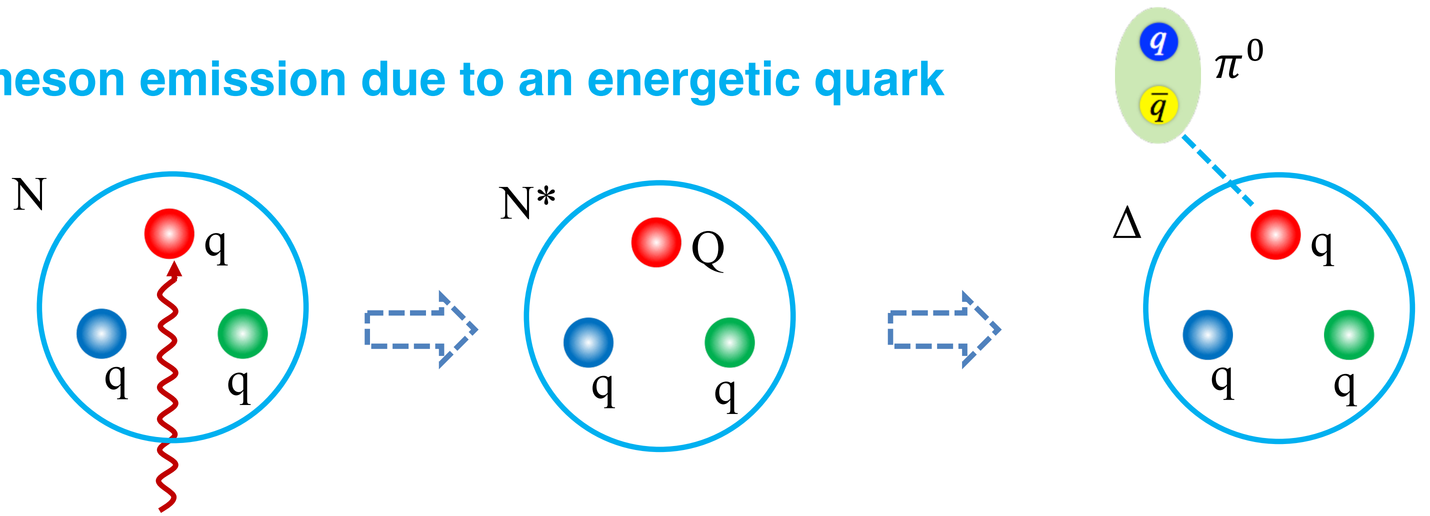
Fig. Fitted values of r_0 (a) and λ_2 (b) obtained by event mixing in a single-and a multi mixing (up to 10 times) mode at six incident photon energies E_γ=1.0, 1.03, 1.06, 1.09, 1.12, and 1.15 GeV for the $\gamma p \rightarrow \pi^0\pi^0 p$ events. For comparison, the values of r_0 and λ_2 for the generated sample with BEC effects are also shown.

Fig. The ratio of the Q distribution of the generated BEC/noBEC sample, $N_{BEC}(Q)$, to that from the mixed events, $N_{Mix}(Q)$ (filled circles). The ratio of $N_{BEC}(Q)$ to the Q distribution of pure phase space sample, $N_{PS}(Q)$, is also shown (open triangles) in each panel for comparison.

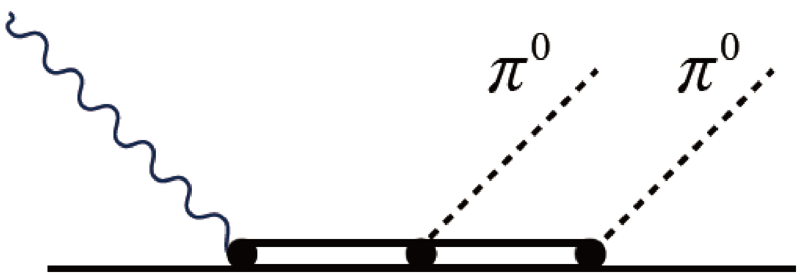
[1] Q. He, et al., Prog. Theor. Exp. Phys. **2017**, (2017); **[2]** Q.-H. He, et al., Chinese Phys. C **40**, 114002 (2016).

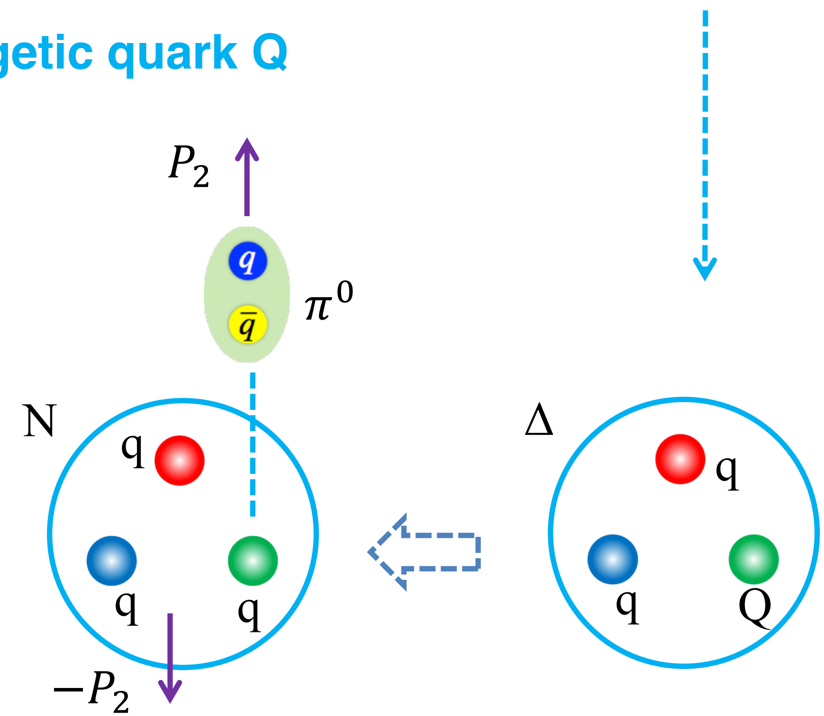
Resonance decay effects correction

- S wave meson emission due to an energetic quark



- $\Delta \rightarrow \pi^0 N$ decay originated by an energetic quark Q





H. Shimizu, ELPH Annual Report, 2017

Resonance decay effects correction

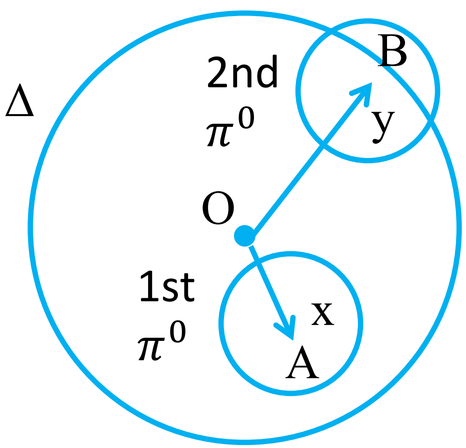
3-d correlation function

$$C_{BEC}(q,p_2) = 1 + \lambda \exp\left(-\frac{\alpha^2 q^2}{2}\right) \exp\left(-\frac{\alpha^2 q_z^2}{2}\right) J_0(\beta q_r)$$

$$= 1 + \lambda \exp(-\alpha^2 q_z^2) \exp\left(-\frac{\alpha^2 q_r^2}{2}\right) J_0(\beta q_r)$$

$\boldsymbol{\alpha}$: Gaussian radius

$\boldsymbol{\lambda}$: correlation strength



Space-time coordinates of Δ at rest

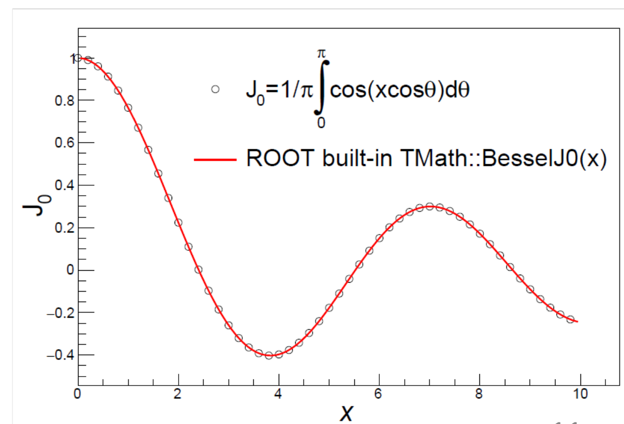
$\boldsymbol{q}$: relative momentum of two pions in the frame of Δ at rest

$\vec{q} = (q_r, 0, q_z)$ in cylindrical coordinates $q^2 = q_r^2 + q_z^2$

$$\boldsymbol{\beta} = \frac{1}{2p_2}$$

$\boldsymbol{p_2}$: Δ decayed pion 3-d momentum in the frame of Δ at rest

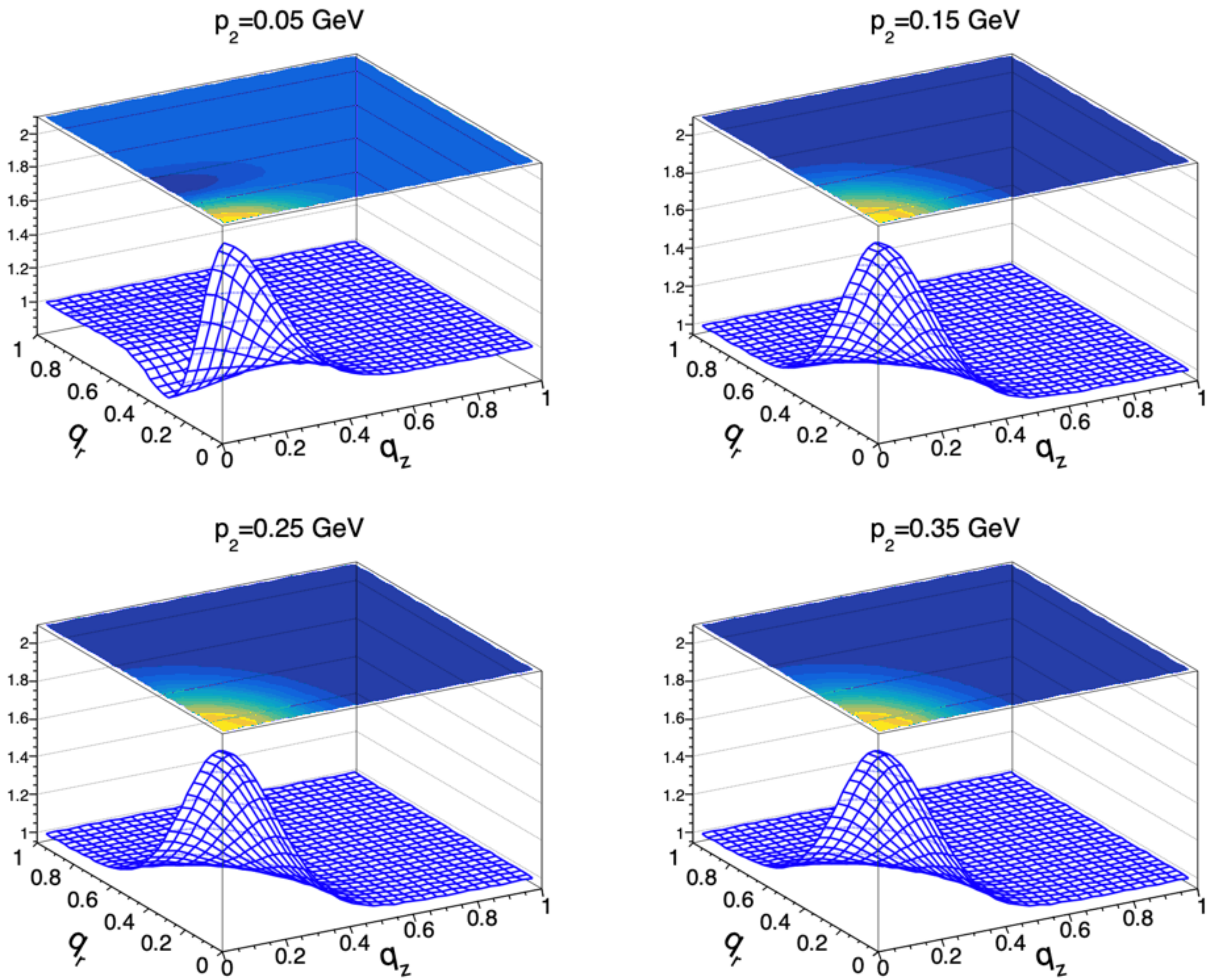
$\boldsymbol{J_0(\beta q_r)}$:
0th-order Bessel function



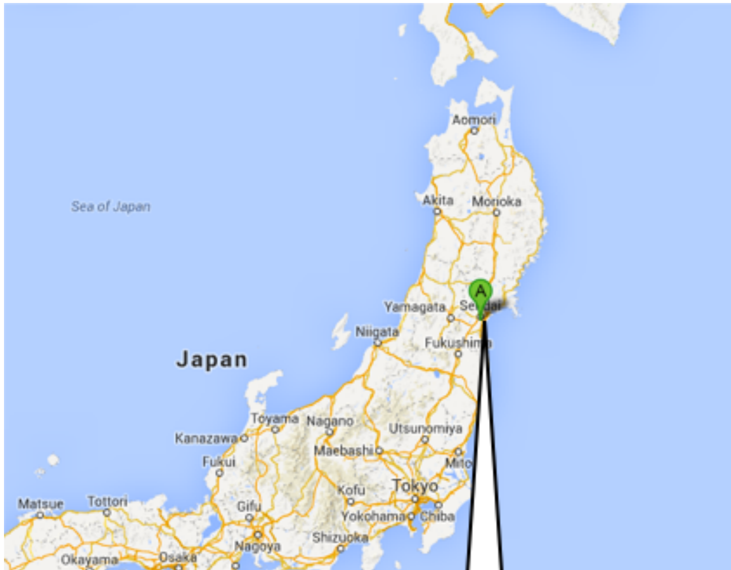
H. Shimizu, ELPH Annual Report, 2017

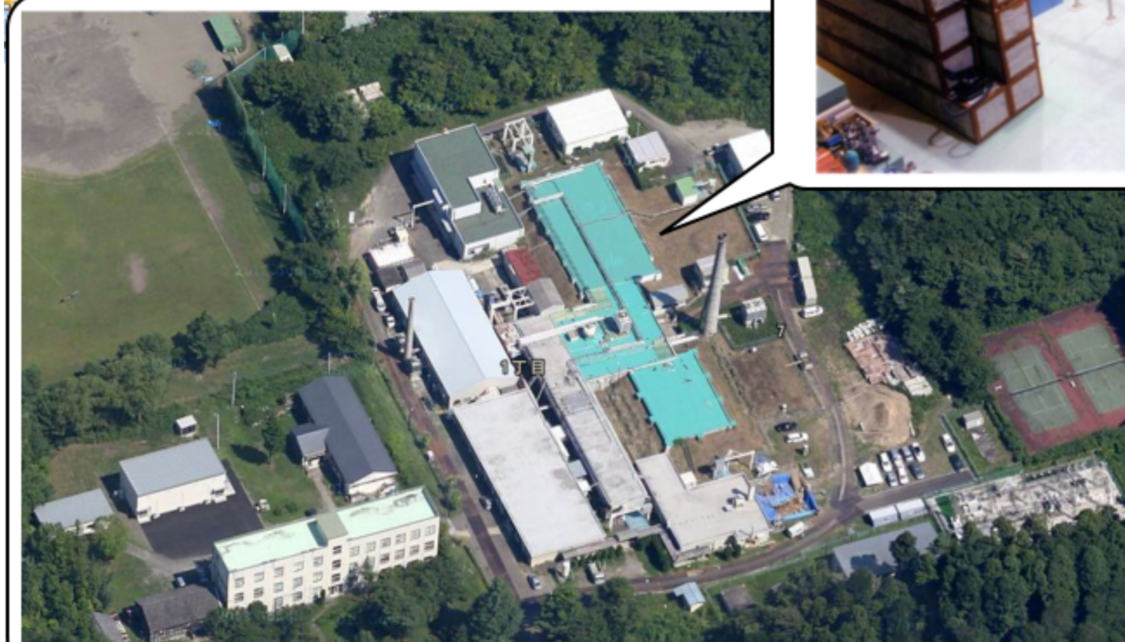
Correlation functions at different p_2

$$C_{BEC}(q, p_2) = 1 + \lambda \exp(-\alpha^2 q_z^2) \exp\left(-\frac{\alpha^2 q_r^2}{2}\right) J_0\left(\frac{q_r}{2p_2}\right)$$



FOREST Experiment

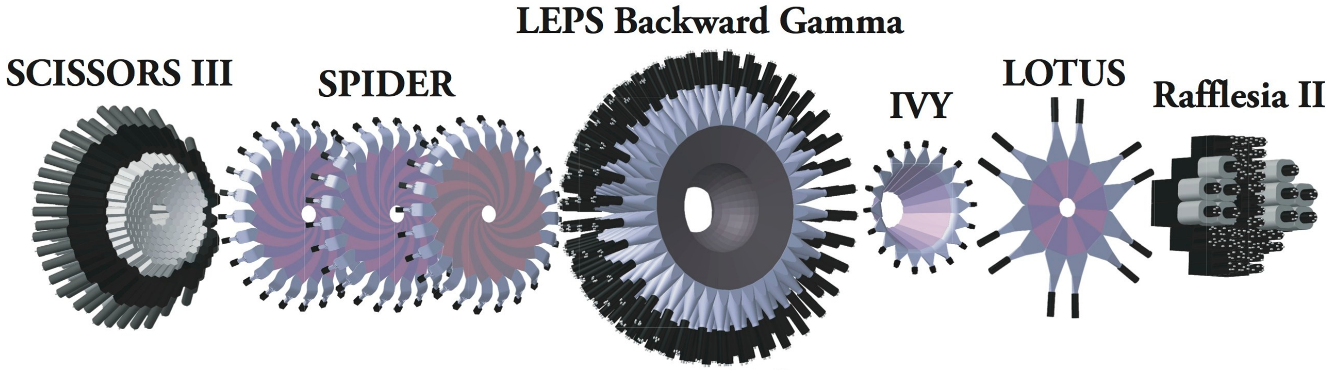


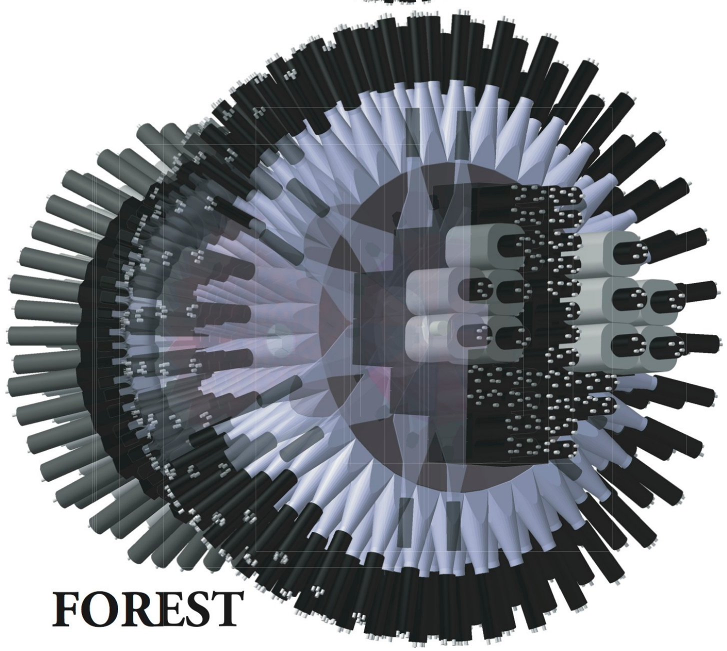


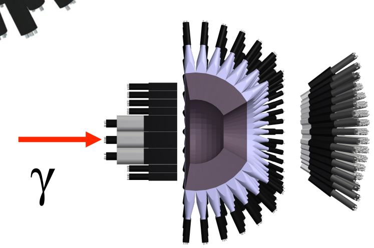
0.5-1.2 GeV
photon beam

$$\gamma p \rightarrow \pi^0 \pi^0 p$$

4π Electromagnetic detector complex FOREST







EM Calorimeter

SCISSORS III
192 CsI; θ: 4°-24°, φ:full
Res. : 3% @ 1GeV

Backward Gamma
252 Lead/Scintillating fiber modules;
θ: 30°-100°, φ:full
Res. : 7% @ 1GeV

Rafflesia II
62 Lead Glass modules;
Res. : 5% @ 1GeV

Plastic Scintillator

SPIDER (2 layers × 24 modules

IVY (18 modules)

LOTUS (12 modules)

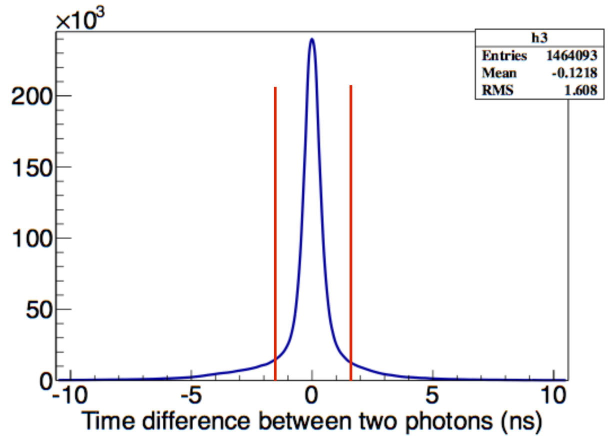
Identification of $\gamma p \rightarrow \pi^0 \pi^0 p$

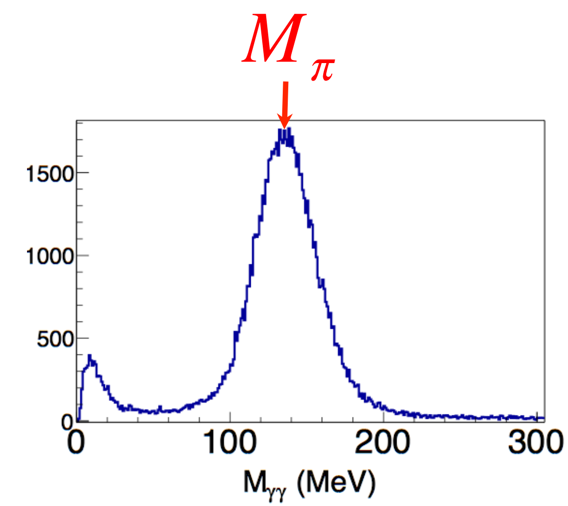
π^0

$\pi^0 \rightarrow 2\gamma$

- Two **neutral clusters** with $\Delta t = [-1.5, 1.5]$ ns.
- Invariant mass = $M_{\pi 0}$

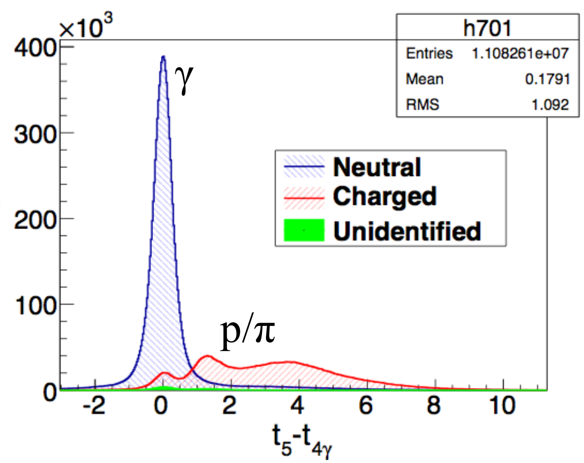
$m^2_{\gamma\gamma} = 2E_{\gamma 1}E_{\gamma 2}(1 - \cos\theta_{\gamma 1 \gamma 2})$

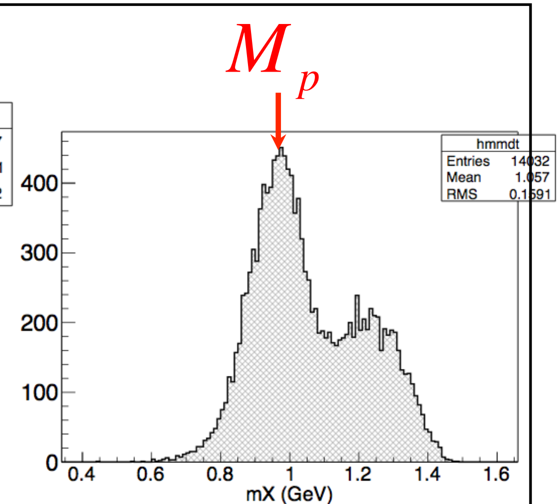




Proton

- Delayed **charged cluster** wrt. the average time of the selected 2 pairs of coincident photons (**$t_{4\gamma}$**)
- Miss mass Mx of $\gamma p \rightarrow \pi^0 \pi^0 X$ is equal to the proton mass

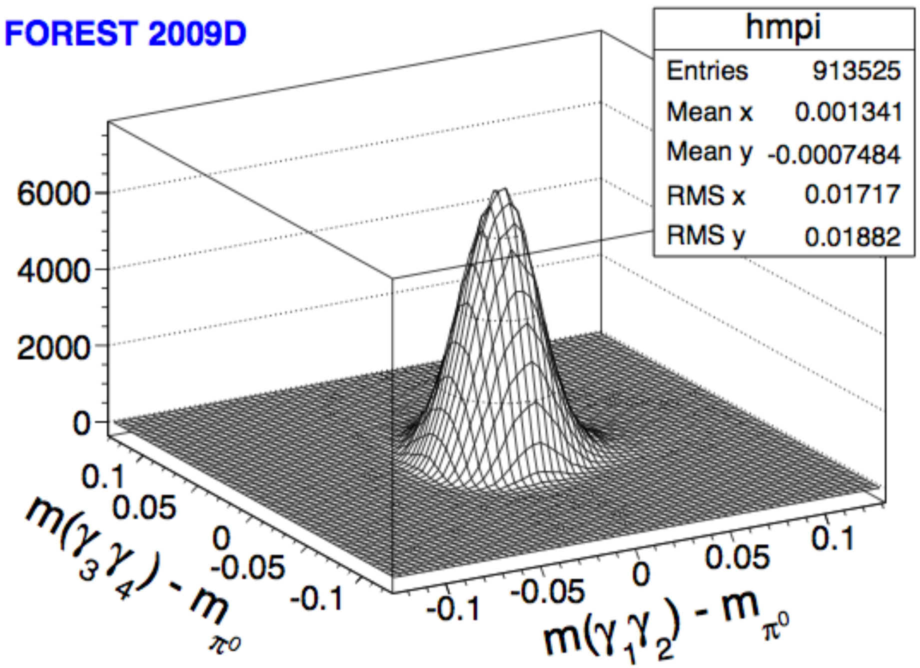


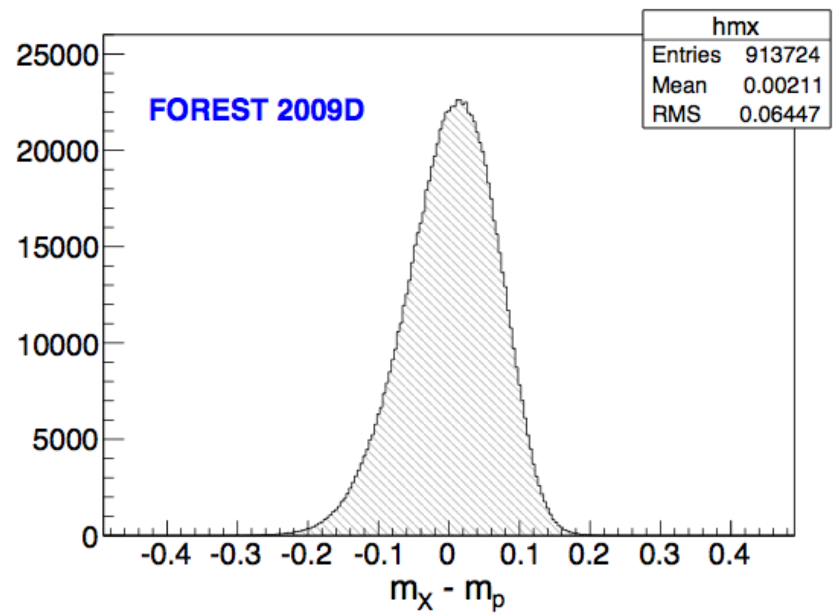


Invariant mass and missing mass

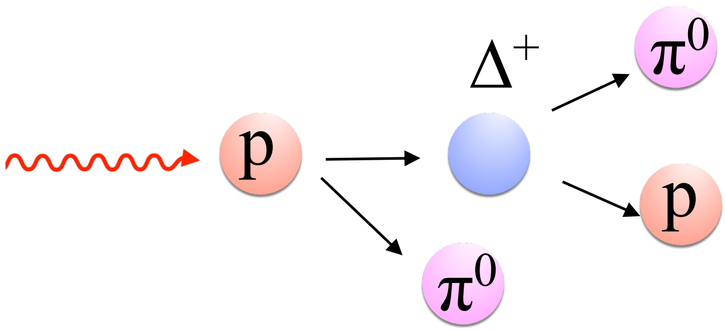
The best combinations of the two paris of photons

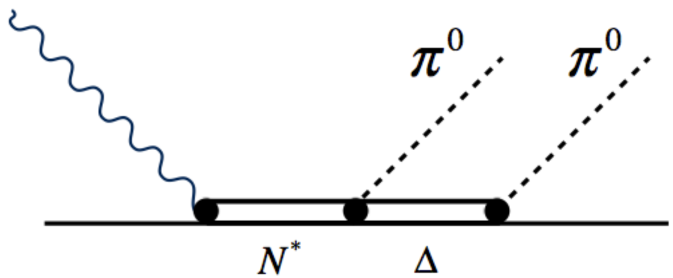
Missing mass distribution of the hypothesis $\gamma p \rightarrow \pi^0 \pi^0 X$

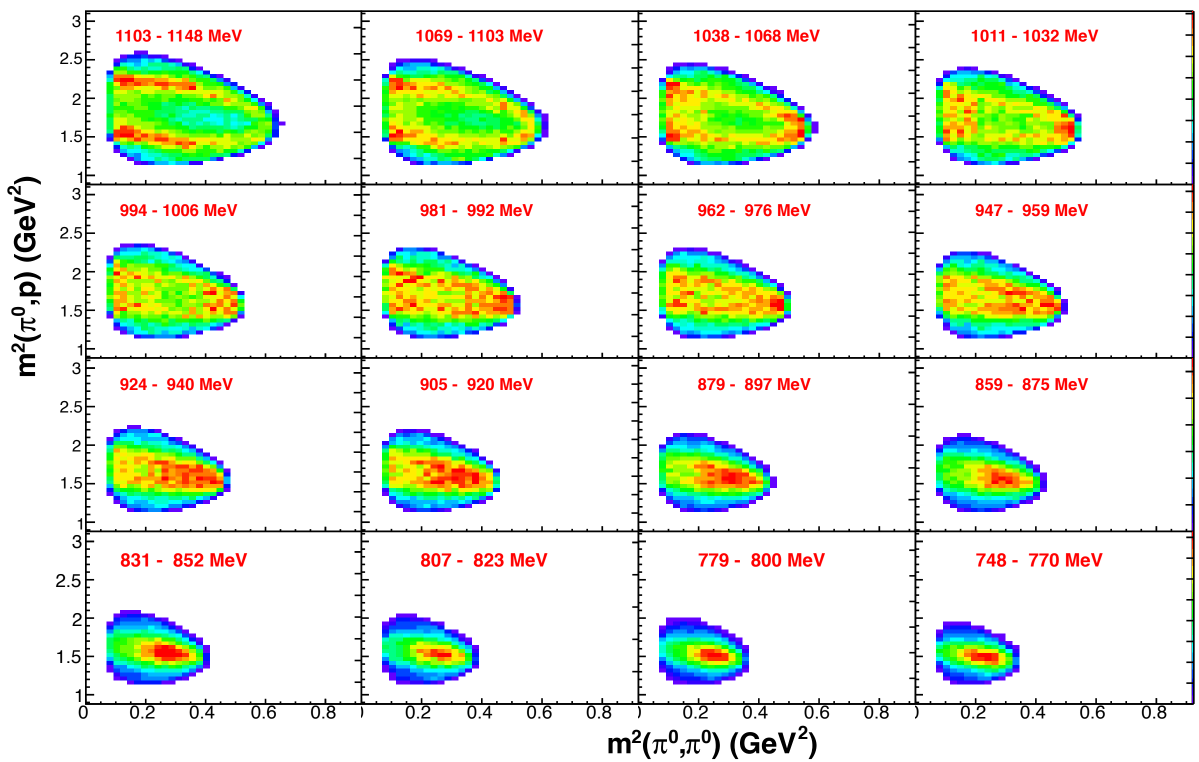




$\gamma p \to \pi^0 \Delta \to \pi^0 \pi^0 p$ process is dominant in $\gamma p \to \pi^0 \pi^0 p$







Q. He, PhD Thesis, Tohoku University, 2014

Preliminary results of experimental $\pi^0\pi^0$ correlation functions for reaction $\gamma p \to p\pi^0\pi^0$

p_2: 0.2-0.3 GeV

Preliminary

E_γ (GeV)	N	λ	α (fm)	χ^2/ndf
1.13-1.15	0.71±0.07	1.00±0.84	0.44±0.10	84.7/44
1.11-1.13	0.81±0.03	1.00±0.08	0.59±0.06	60.2/44
1.09-1.11	0.79±0.03	1.00±0.05	0.58±0.05	76.9/44
1.07-1.09	0.82±0.03	1.00±0.03	0.61±0.04	63.3/44
1.05-1.07	0.82±0.02	1.00±0.02	0.65±0.04	81.5/44
1.03-1.05	0.85±0.02	1.00±0.05	0.70±0.05	42.5/43
1.01-1.03	0.84±0.03	1.00±0.04	0.68±0.05	38.2/42
0.99-1.01	0.84±0.03	0.94±0.15	0.69±0.07	52.3/42
Ave.	0.83±0.01	1.00±0.01	0.63±0.02	
Mean square radius x (fm) ($\langle x^2\rangle = 3\alpha^2$)			**x=1.09±0.03**	

Fit: $C_{BEC}(q,p_2) = N(1+\lambda\exp(-\alpha^2 q_z^2)\exp\left(-\frac{\alpha^2 q_r^2}{2}\right)J_0(q_r/2p_2))$

Double ratio method is used (Geant4 simulation data are used to correct the experimental correlation function)

λ: fit limits: [0,1]

Fit range: q_z:[0,0.7] GeV; q_r:[0,0.7] GeV

p_2 is fixed to be 0.25 GeV

Summary and discussion

- Preliminary BEC results on FOREST experiments shows the mean square radius of the intermediate state ($\Delta(1232)$ resonance is dominant) in $\gamma p \to \pi^0\pi^0 p$ at $E_\gamma \sim 1\ GeV$ is about 1.09±0.03 fm

- Still need to refine this analysis to get BEC results from pure $\Delta(1232)$ events and to estimate the systematic errors…

- Appropriate event mixing method for low-multiplicity BEC analysis is required

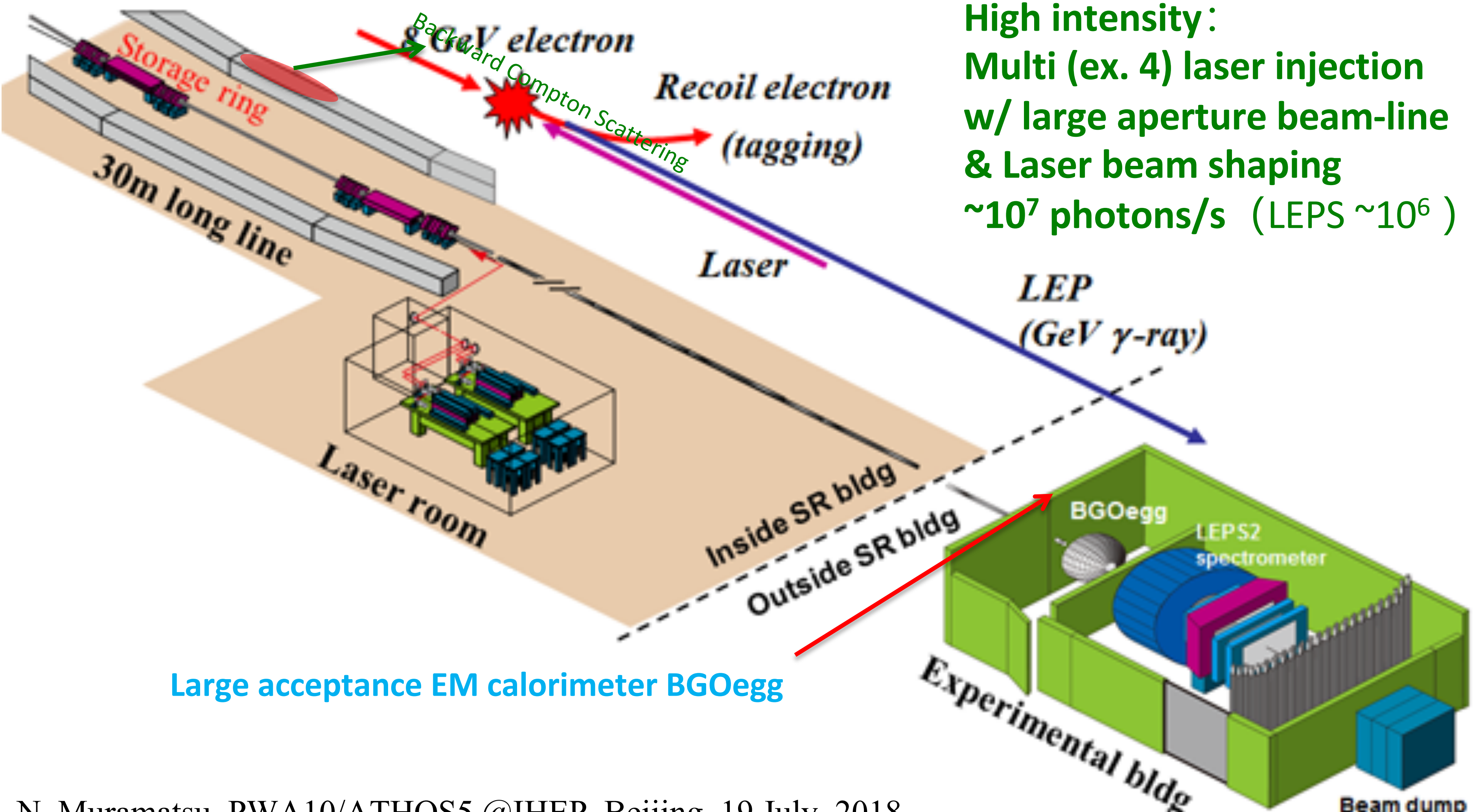
- BEC analysis for BGOegg experimental data is on the way

Future plan

BGOegg data is better

LEPS2/BGOegg @ Spring-8

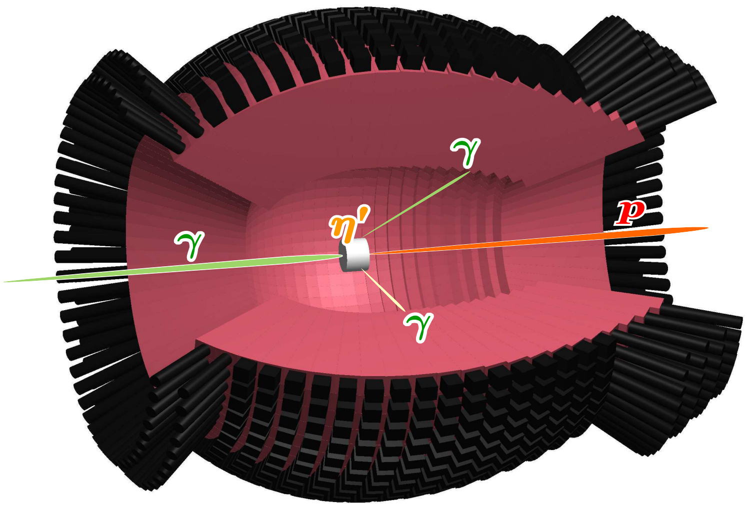
High intensity：
Multi (ex. 4) laser injection
w/ large aperture beam-line
& Laser beam shaping
~10^7 photons/s （LEPS ~10^6 ）



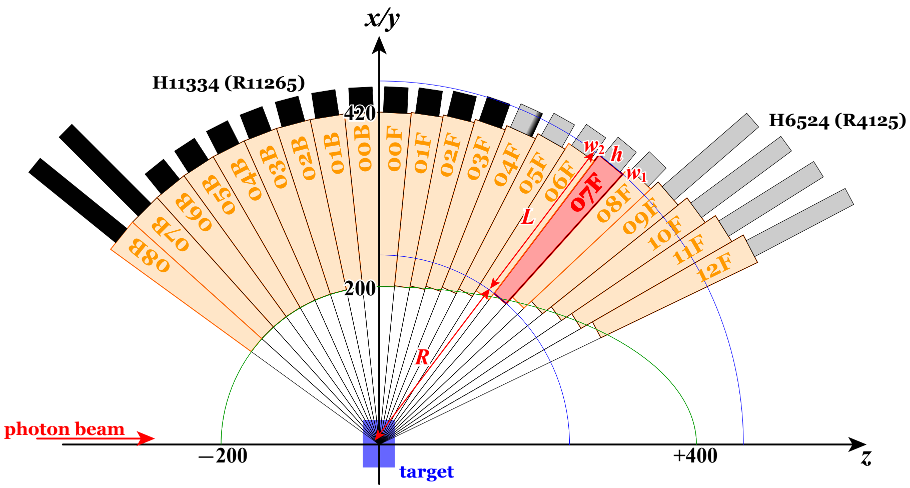
Large acceptance EM calorimeter BGOegg

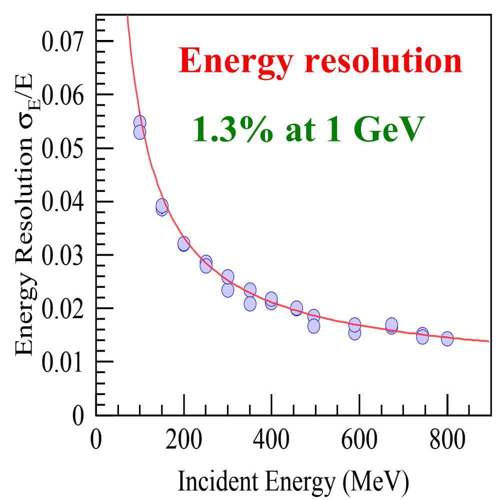
Future plan

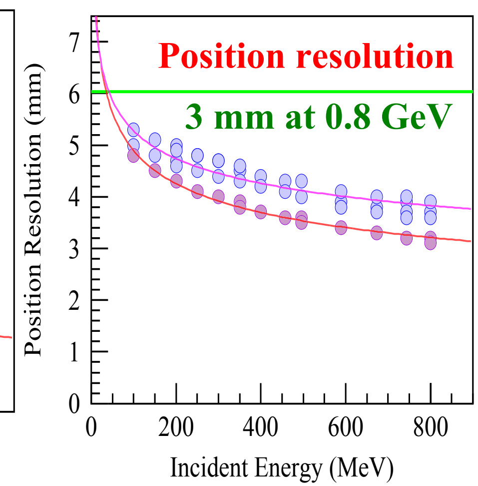
LEPS2/BGOegg @ Spring-8



- 1320 BGO crystals （60*22 layers）
- coverage： 24º-156º
- BGO crystal length: 220 mm (20X_0)







Thanks for your attention