How to measure the size of Δ

H. Shimizu
Research Center for Electron Photon Science
Tohoku University

Seminar @ JAEA Hadron Nuclear Physics
Oct. 10, 2017

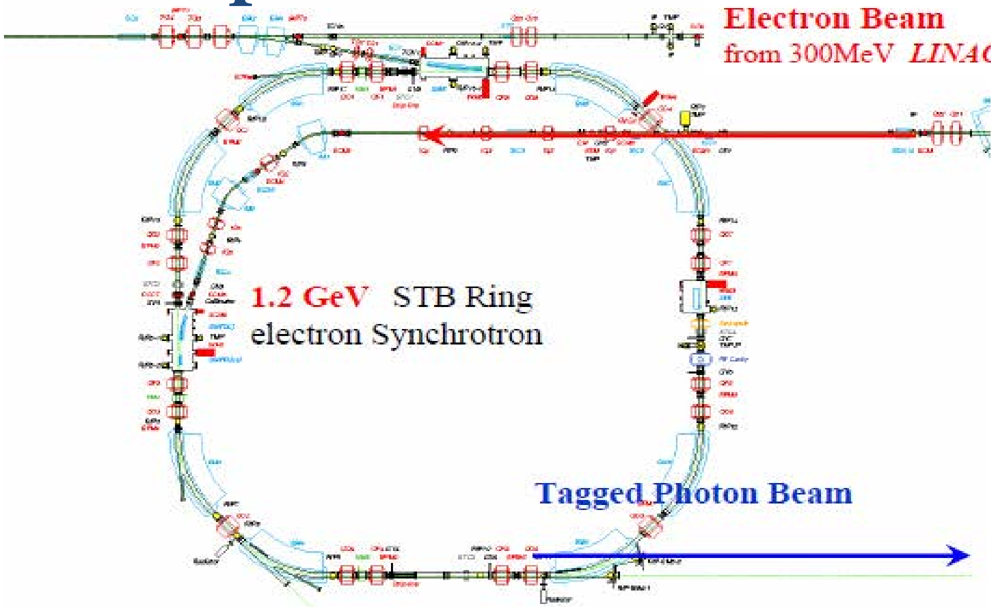
CONTENTS

- prologue
  - <Experiments before the disaster>
    - experimental apparatus
    - FOREST data
- an attempt to measure the Δ radius
- present status of ππ BEC experiments
- measurements of BEC parameters
    - event mixing methods
    - obtained BEC parameters
- 4-D source distribution
- more on the Δ size
- epilogue
    - BGOegg experiments

Experiments before 3.11

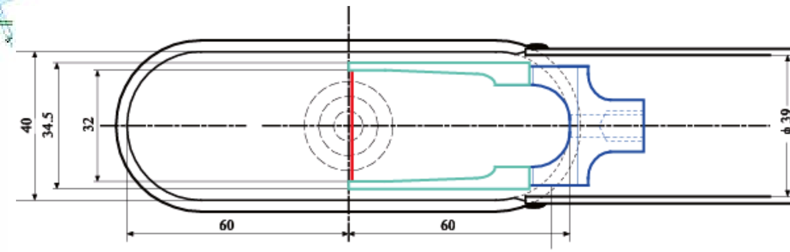
Experimental apparatus
at ELPH

<GeV photon beam>



GeV γ experiments at LNS

internal radiator



carbon fiber 11 μmφ
for Bremsstrahlung photons

high intensity photon beam

tagging counters

radiator

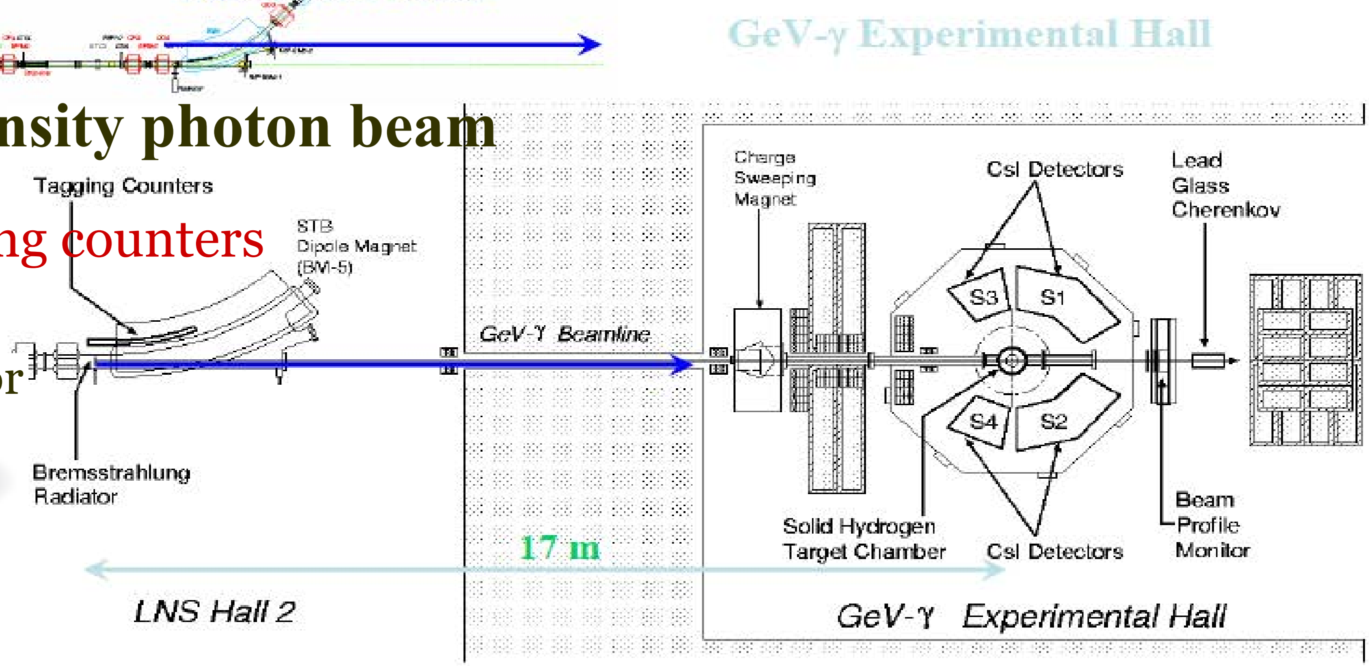


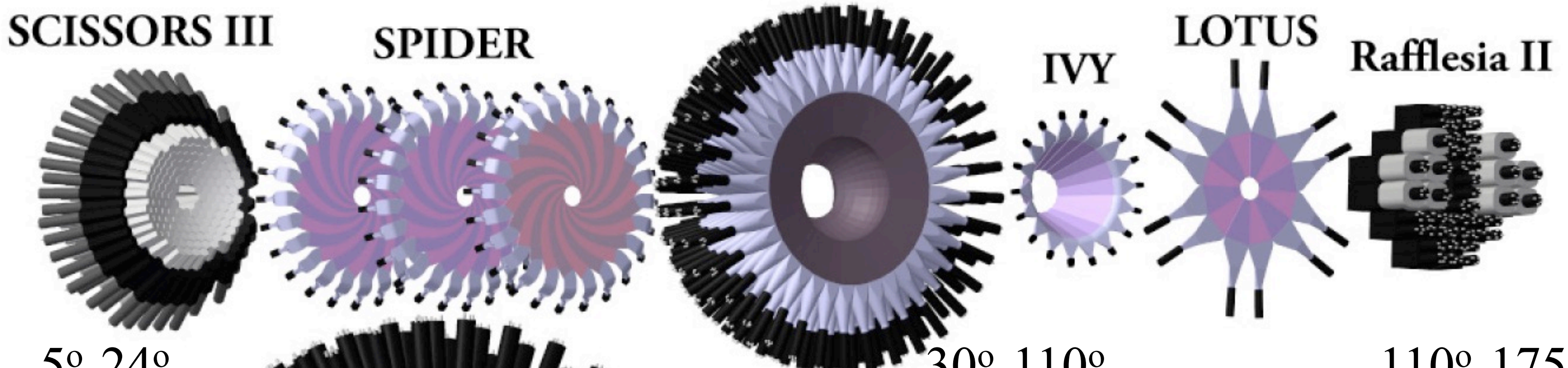
image of
circulating electrons

No other labs employ this method for Brems. photons.

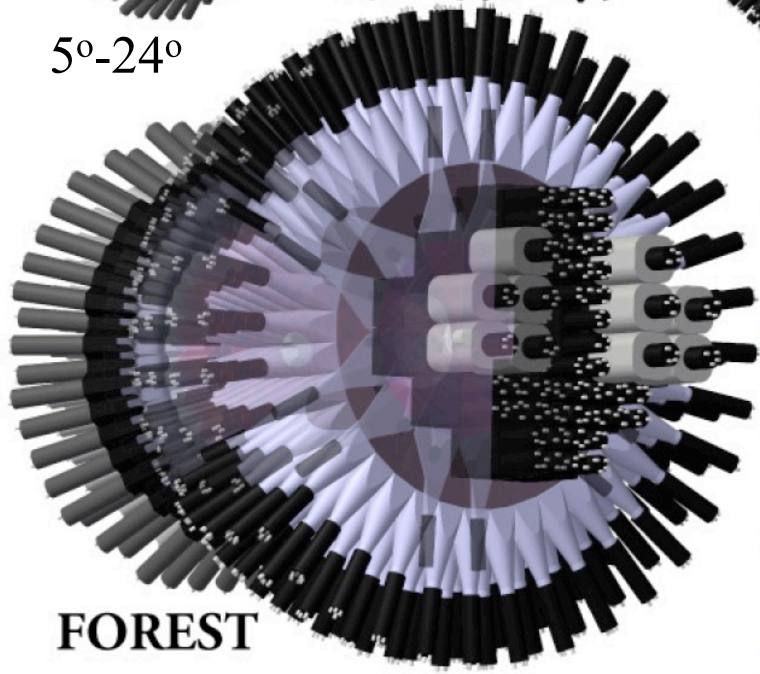

4π EM calorimeter
FOREST

4π EM calorimeter FOREST assembly of detectors

BG



5°-24° 30°-110° 110°-175°

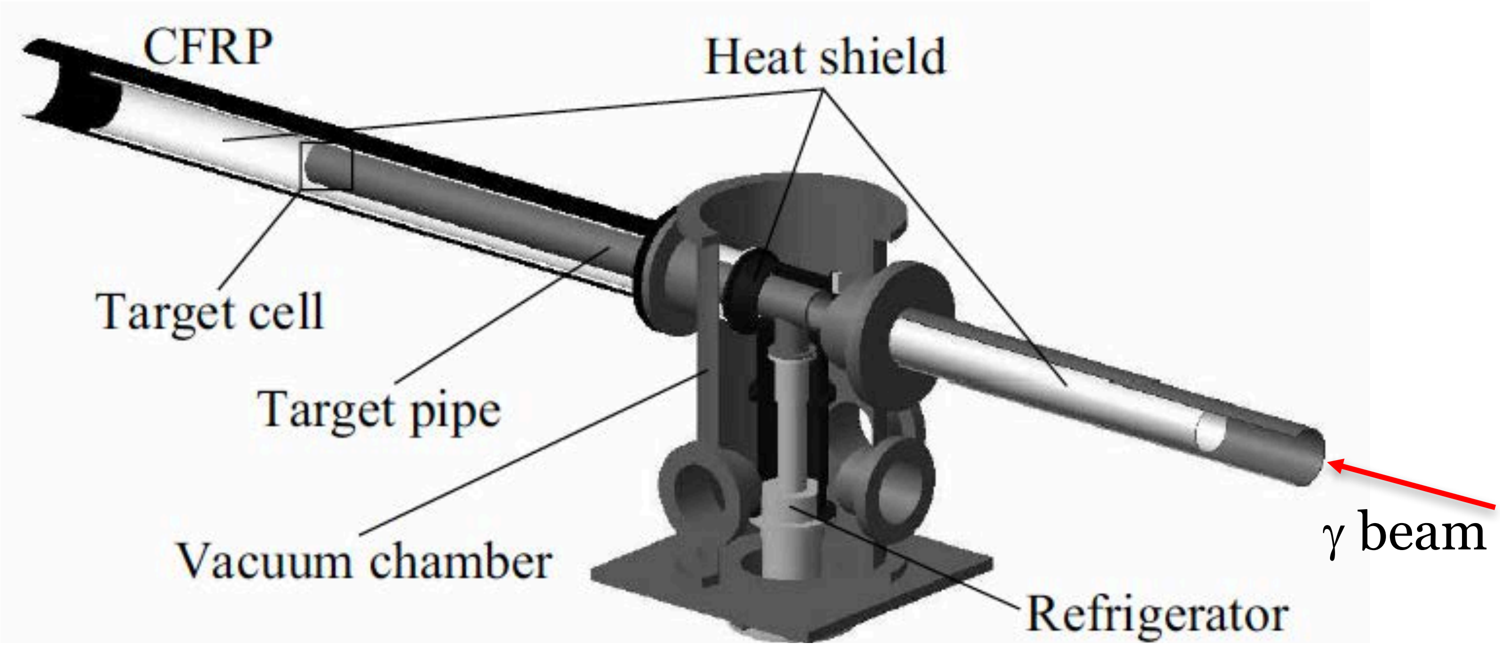


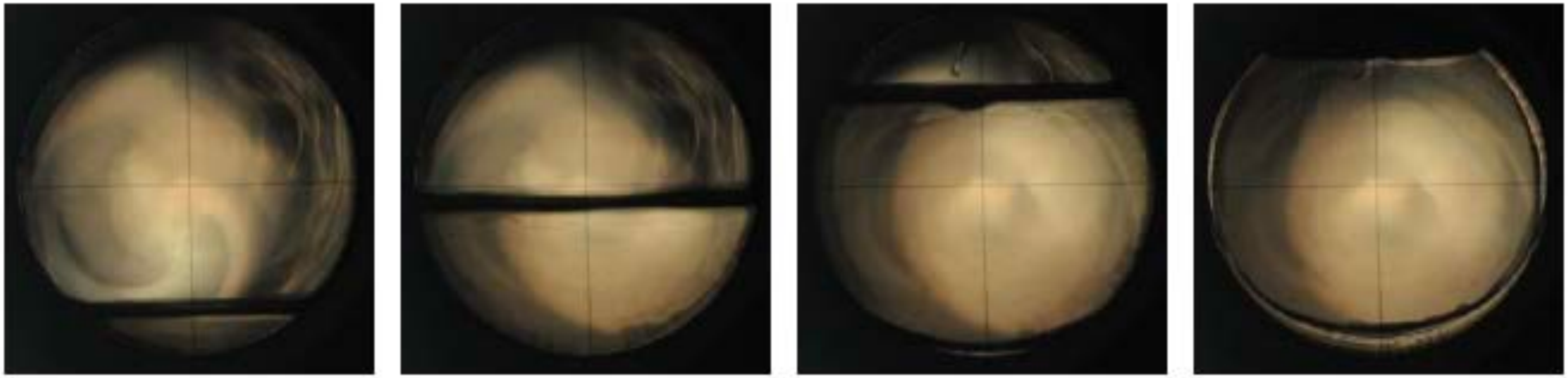
S3: 206 pure CsI crystals
2.3%@1GeV rearrangement of S2
SPIDER: 72 PSs

BG: 252 Lead/Scifi blocks
7.2%@1GeV from SPring-8
IVY: 18 PSs

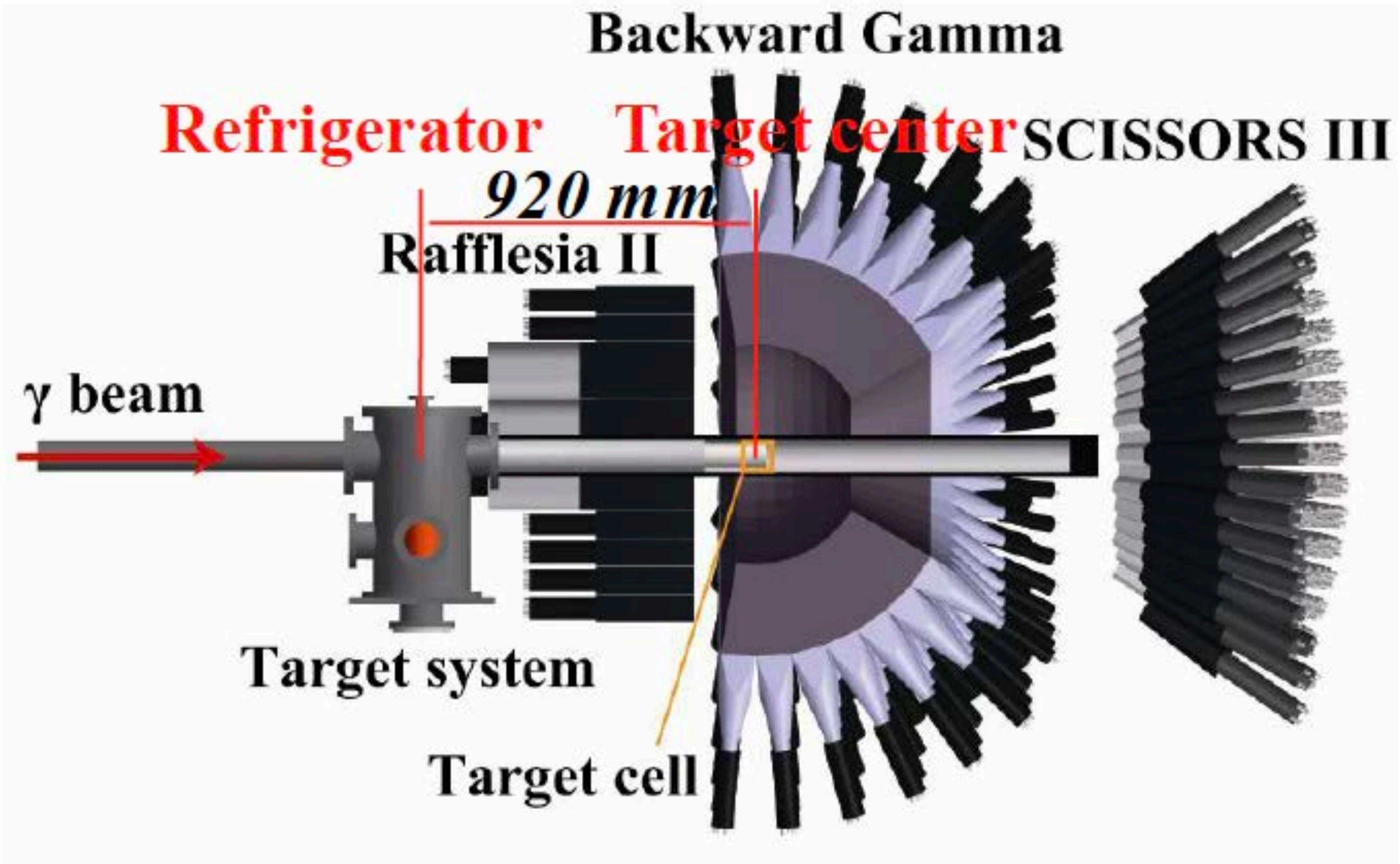
Raf: 62 lead glasses
4.9%@1GeV from KEK
LOTUS: 12 PSs

Solid/Liquid Hydrogen Target





FOREST cross sectional view

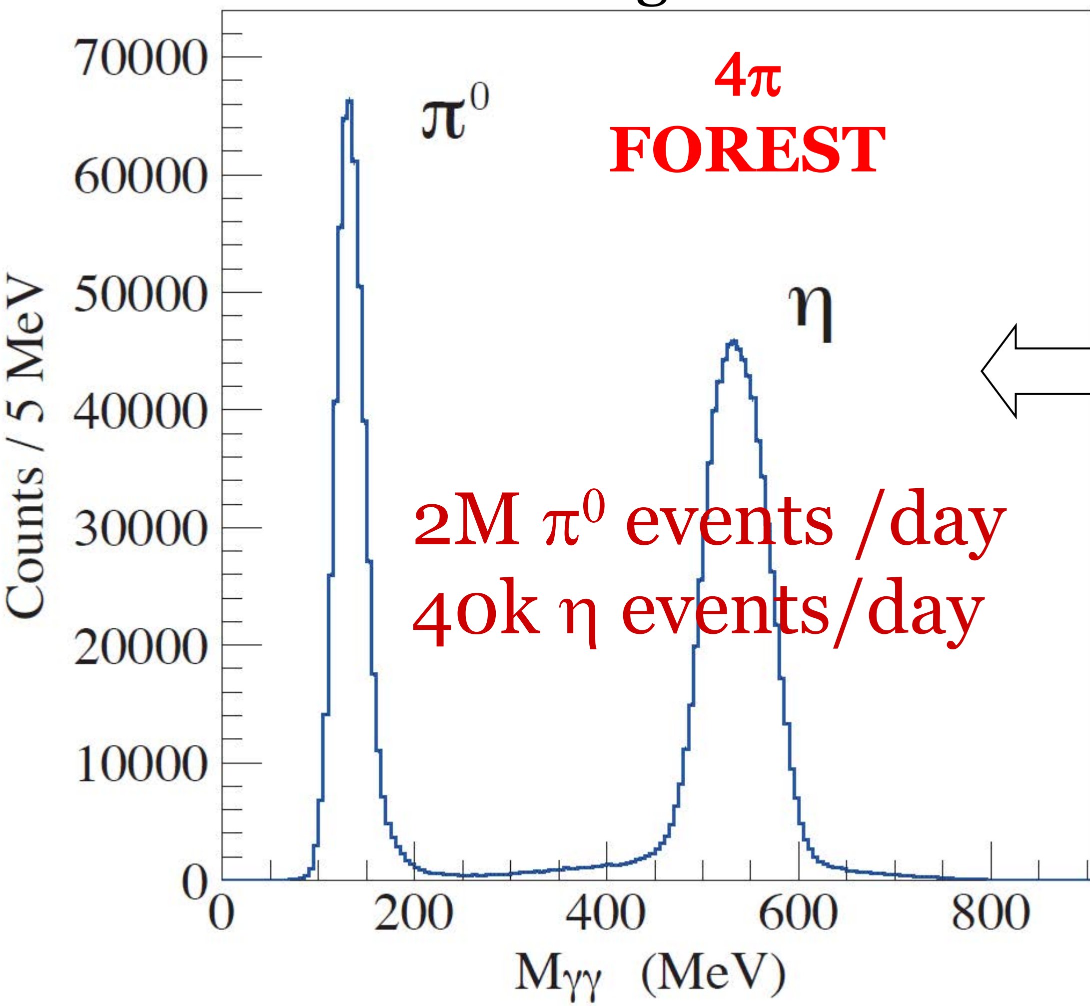


Standard FOREST data obtained before 3.11

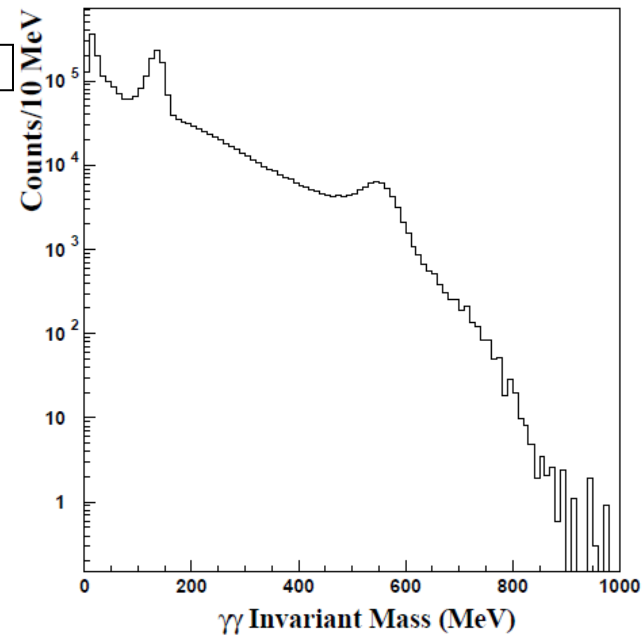
2γ invariant mass

Fast DAQ system
efficiency of 76%
trigger rate: 2kHz
for the data size of
2.6kB/event

clear signals!



previously obtained data with SCISSORS2



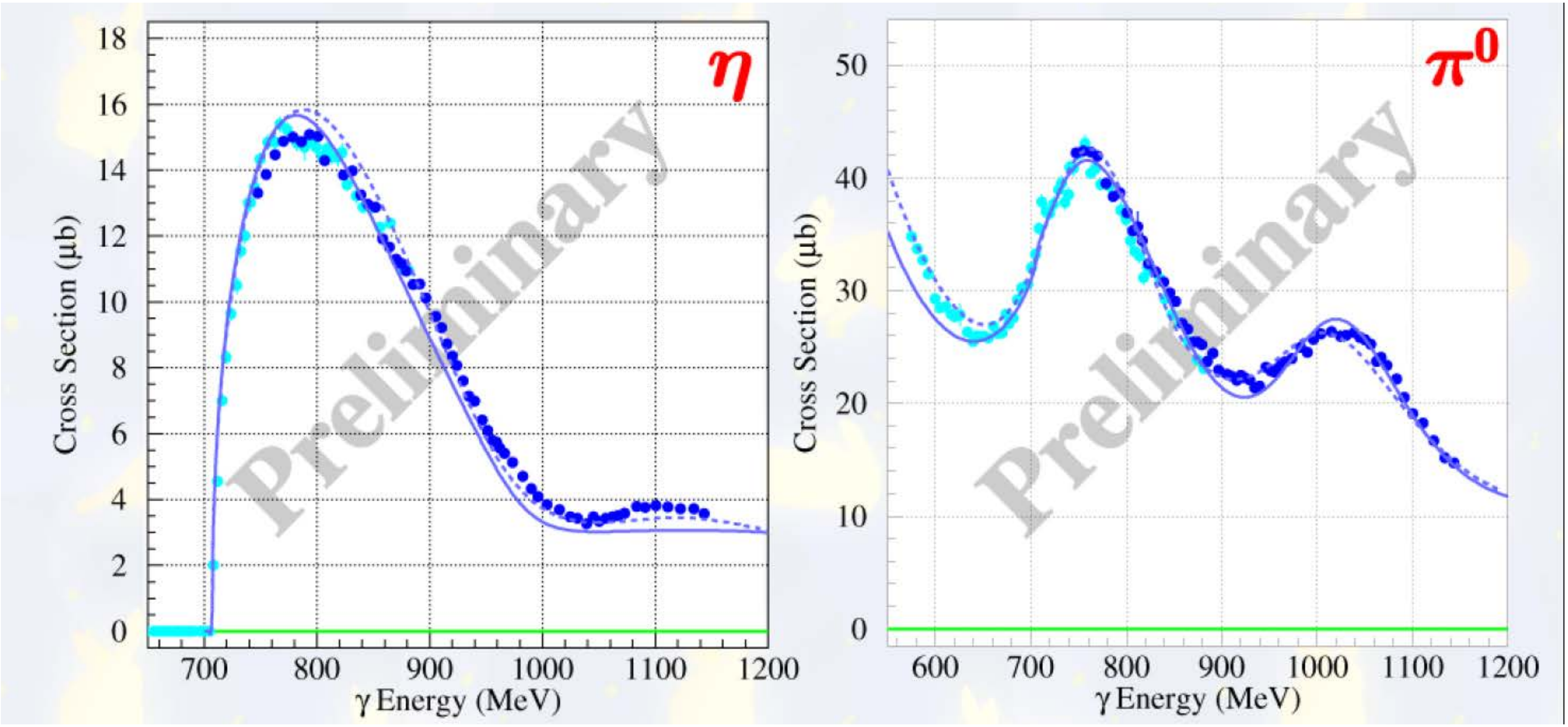
BG: 2 neutrals, S3: 0 or 1 particle, Raf: 0, Missing mass: nucleon
Data obtained in a 3 week run with a H2 target

Single meson photoproduction

ELPH
T. Ishikawa

Total cross section
(basic data)

$\gamma p \to \eta p$ $\gamma p \to \pi^0 p$



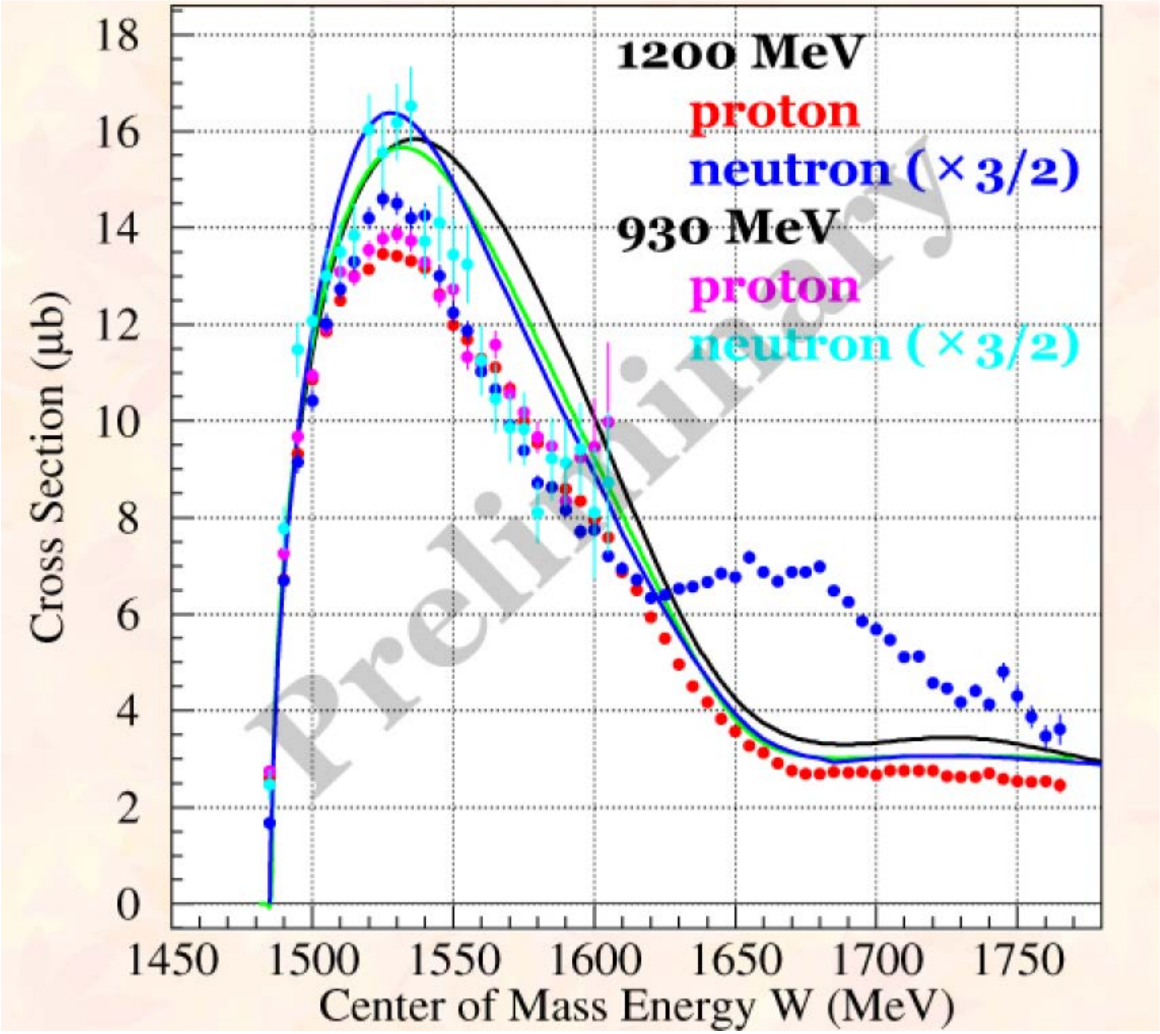
FOREST works well!

FOREST data with a D_2 target

Preliminary:

- Outgoing *p's* or *n's* were detected with FOREST.

ELPH
T. Ishikawa



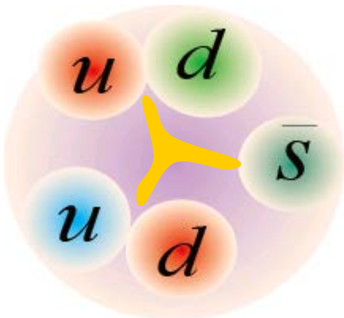
neutron data

$$\gamma d \rightarrow \eta n p_{sp}$$

proton data

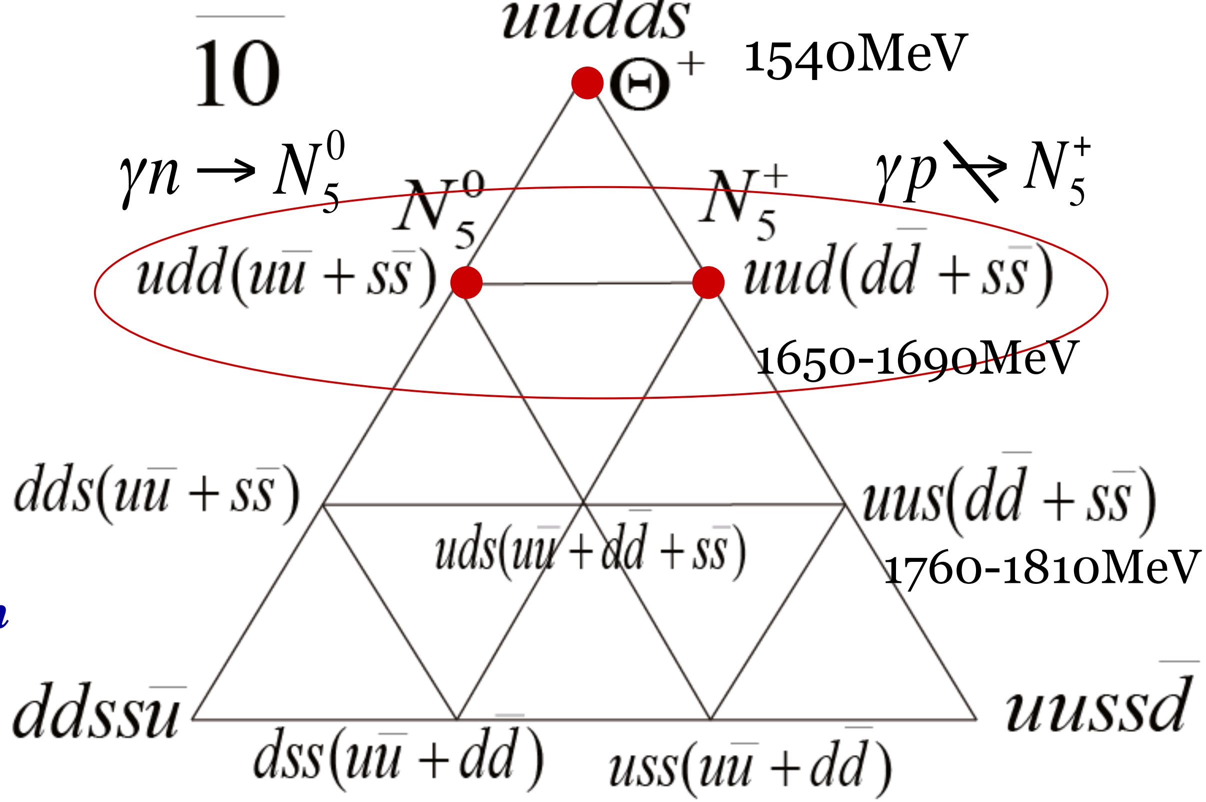
$$\gamma d \rightarrow \eta p n_{sp}$$

Search for hidden-strange pentaquark baryons



$\Theta^+(uudd\bar{s})$

quantum number (S=+1) impossible to be built-up with any 3q system

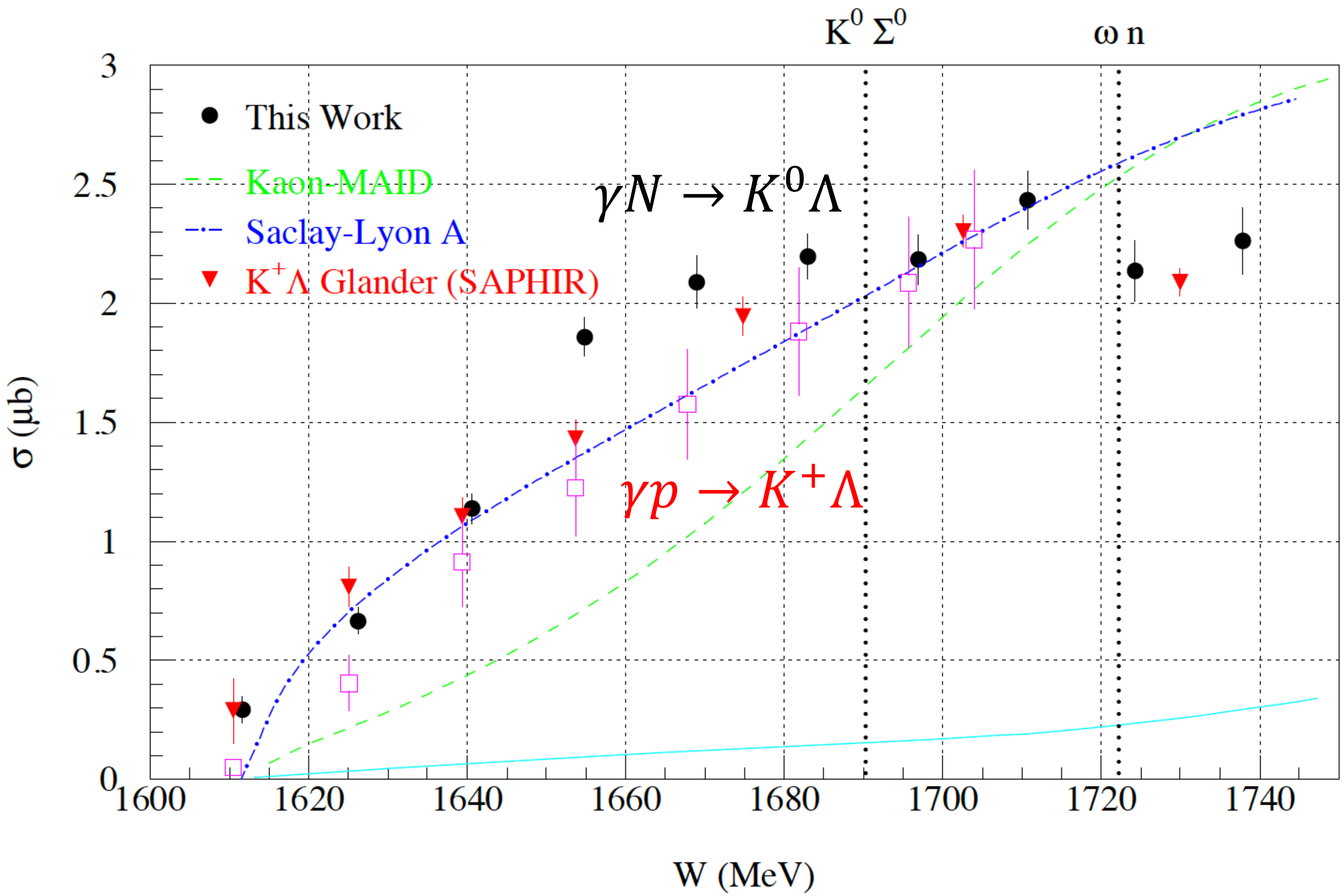


anti-decuplet members

Investigation of N*(1670) through η channel

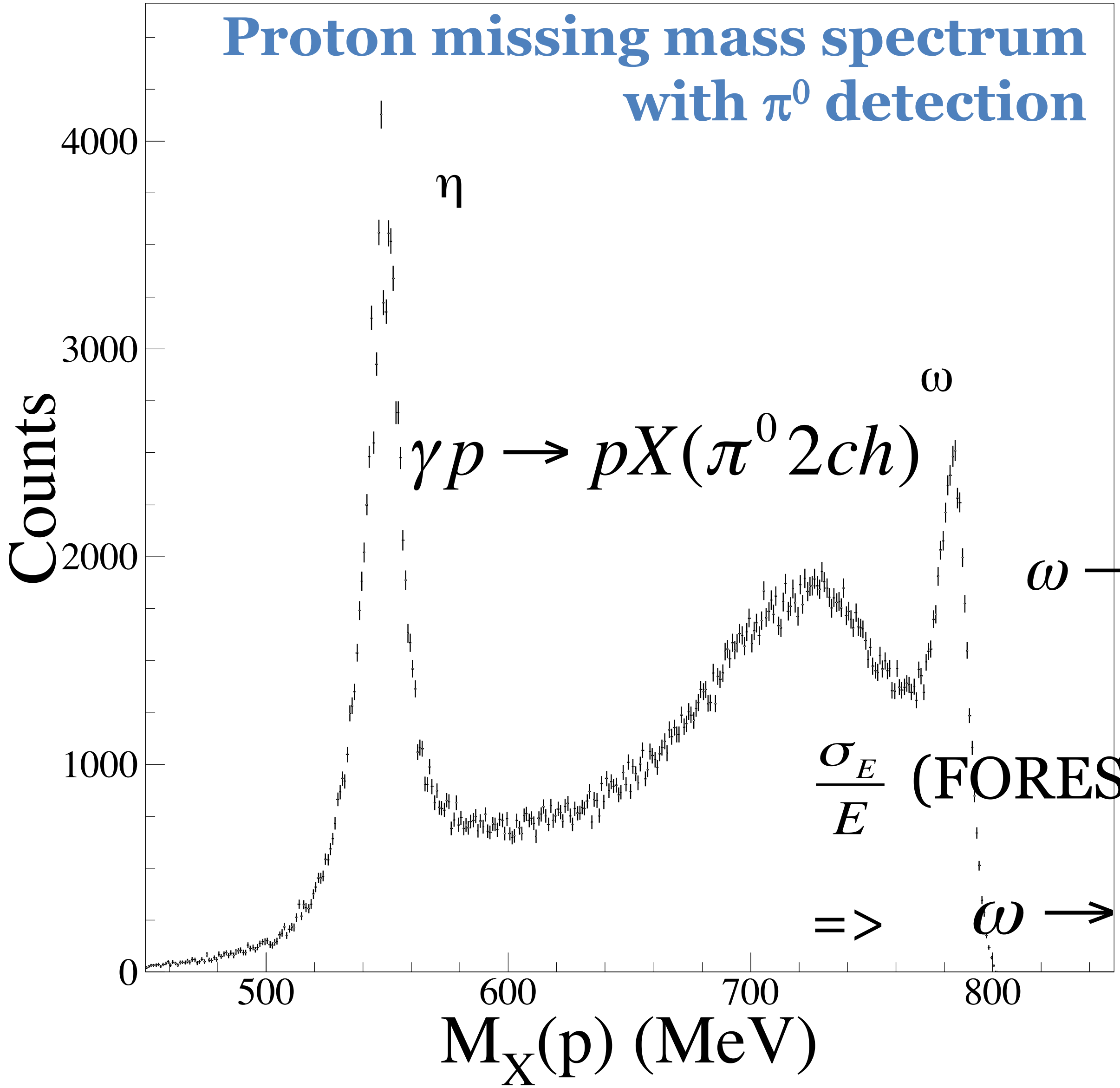
FOREST data in $K^0\Lambda$ channel

ELPH
Y. Tsuchikawa



Background reduction

Proton missing mass spectrum with π^0 detection



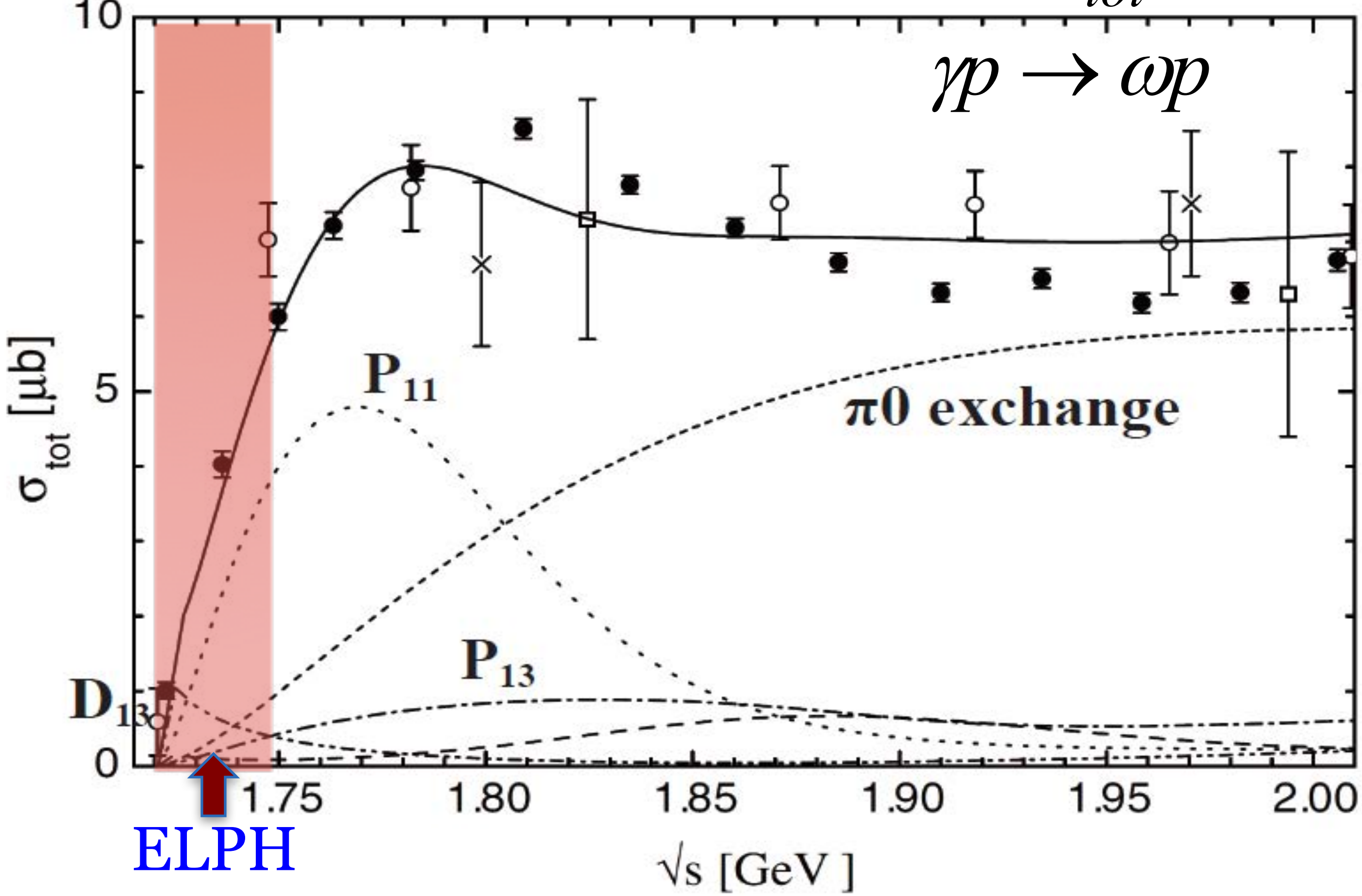
ELPH
R. Hashimoto

$\omega \rightarrow \pi^+ \pi^- \pi^0$

$\frac{\sigma_E}{E}$ (FOREST): NG

=> $\omega \rightarrow \pi^0 \gamma$: NG

World available data for σ_{tot}

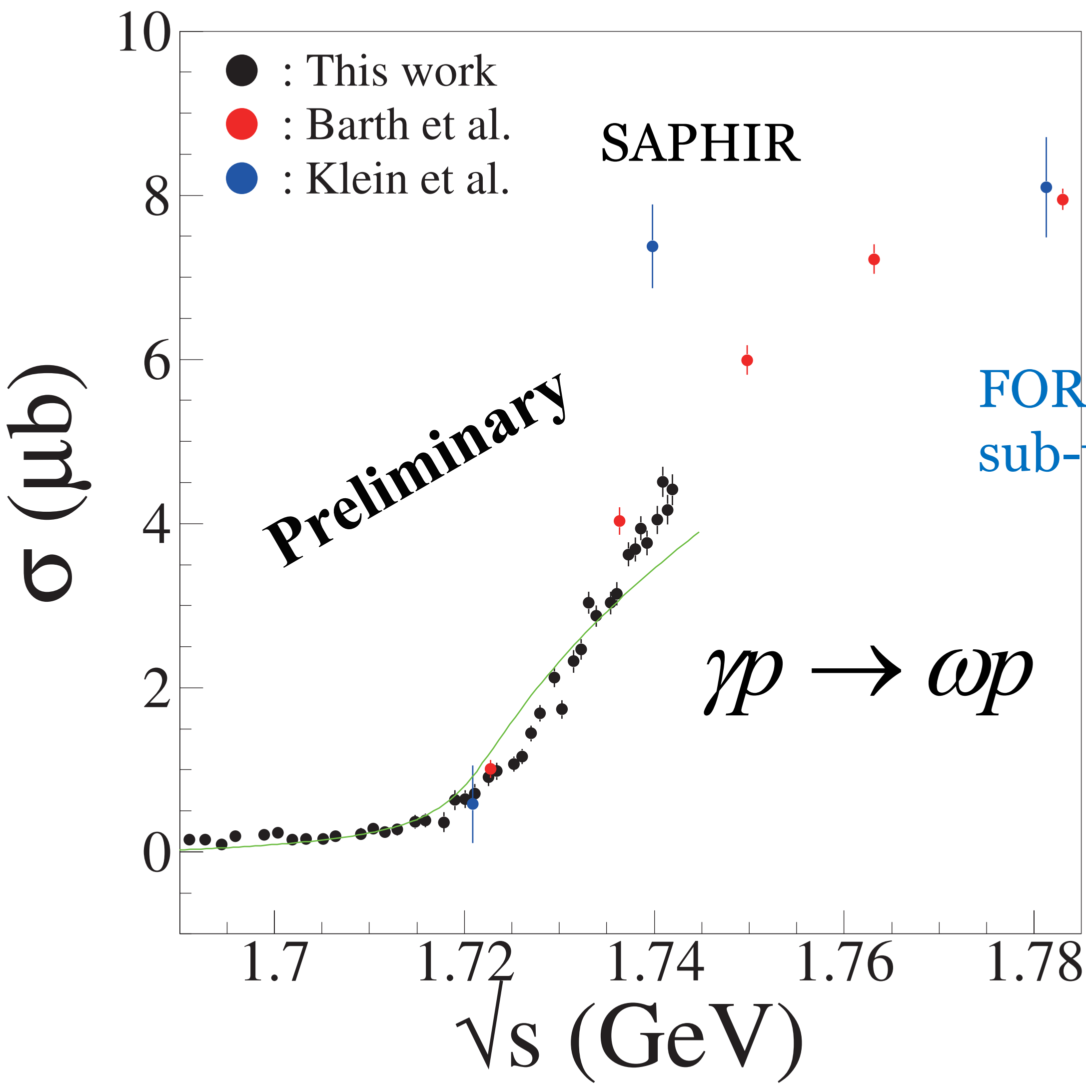


● : SAPHIR(2003) ○ : SAPHIR × : ABBHHM

□ : Brown-Harvard-MIT-Padova-Weizmann Institute Bubble Chamber Group

Curves : G. Penner and U. Mosel, Phys. Rev. C 66, 055212 (2002)

Determination of the ωN scattering length



ELPH
R. Hashimoto

FOREST data including sub-threshold ω production

An attempt to measure
the size of Δ(1232)
with FOREST data

How to measure the size of particles

- **Electron scattering**

  $$\langle r_p^2 \rangle = -6 \frac{dG_E}{dQ^2}\bigg|_{Q^2=0}$$

  electron-proton elastic scattering

  Orsay, Stanford, Saskatoon, Mainz

  $$G_E = 1 - \frac{1}{6} Q^2 r_p^2 + \frac{1}{120} Q^4 r_p^4 + \cdots$$

  (model indep. expansion)

- **Hydrogen spectroscopy**

  $$E(nS) \approx -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}, \qquad L_{1S} \approx (8172 + 1.56 r_p^2) MHz$$

  $$r_p^e = 0.8775(51)\, fm$$

- **Muonic hydrogen**

  2S-2P Lamb Shift

  $$r_p^\mu = 0.84087(39)\, fm$$

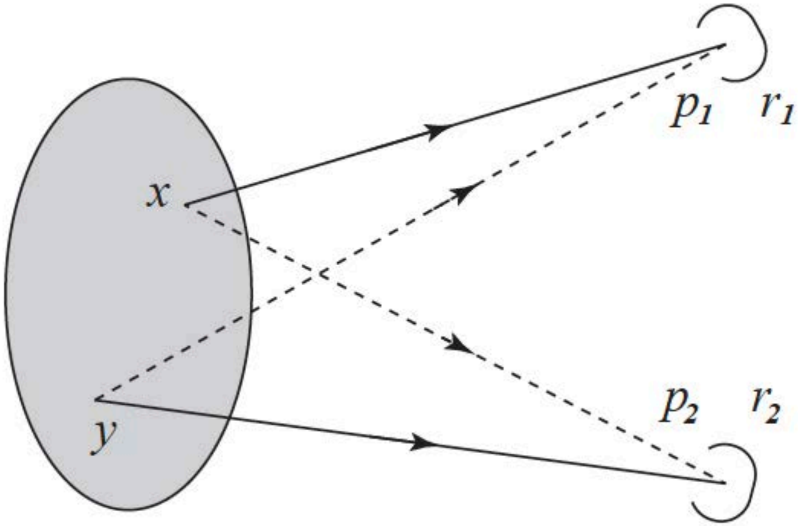
- **Hadron scattering**

  $\sigma_{pp} \approx 40\, mb \approx 2\pi a^2$ at high energies up to $\sqrt{s} \approx 50$ GeV

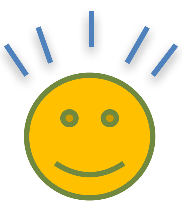
  $\Rightarrow$ $a \approx 0.8\, fm$

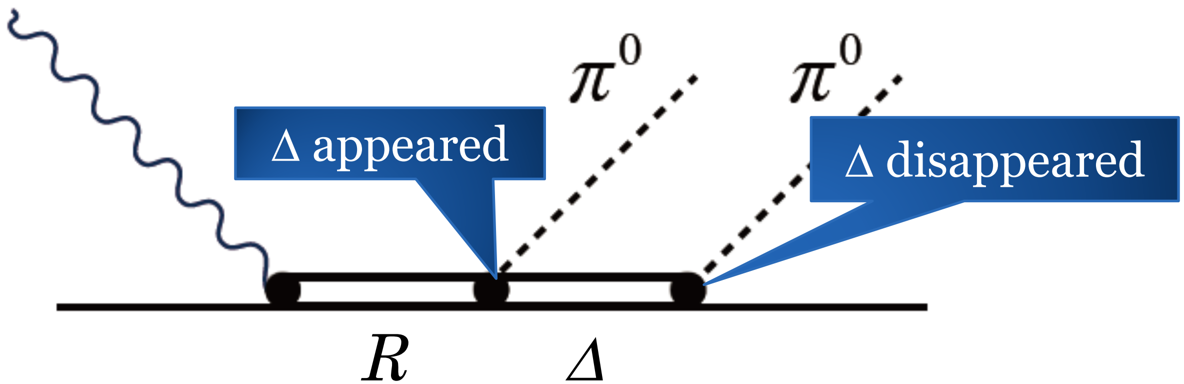
Source size of a multi-pion emitter

$\pi^{\pm}\pi^{\pm}$
$\pi^{0}\pi^{0}$ Bose-Einstein Correlation



$\Delta \nrightarrow \pi\pi N$

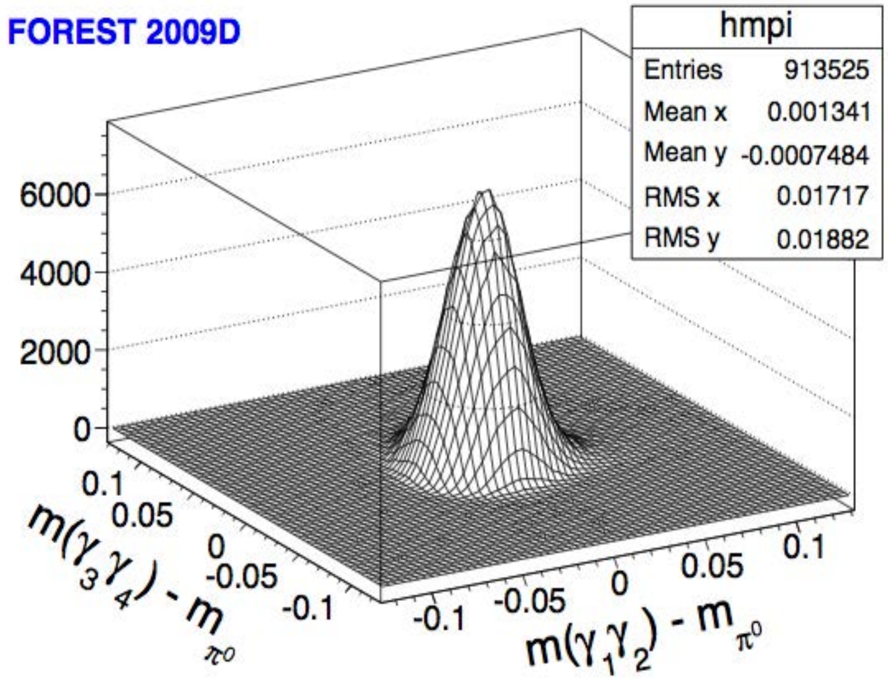




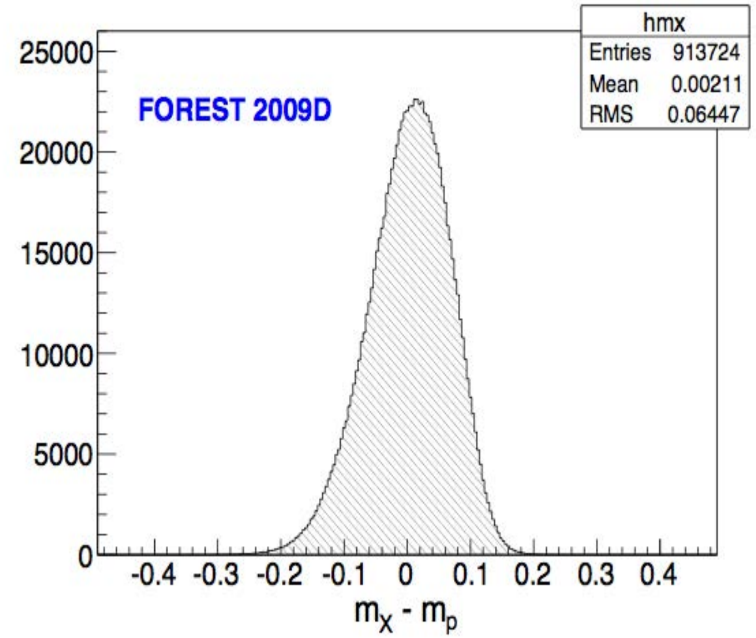
Δ sequential decay process

Data analysis with kinematical fit

best combinations of two pairs of photons

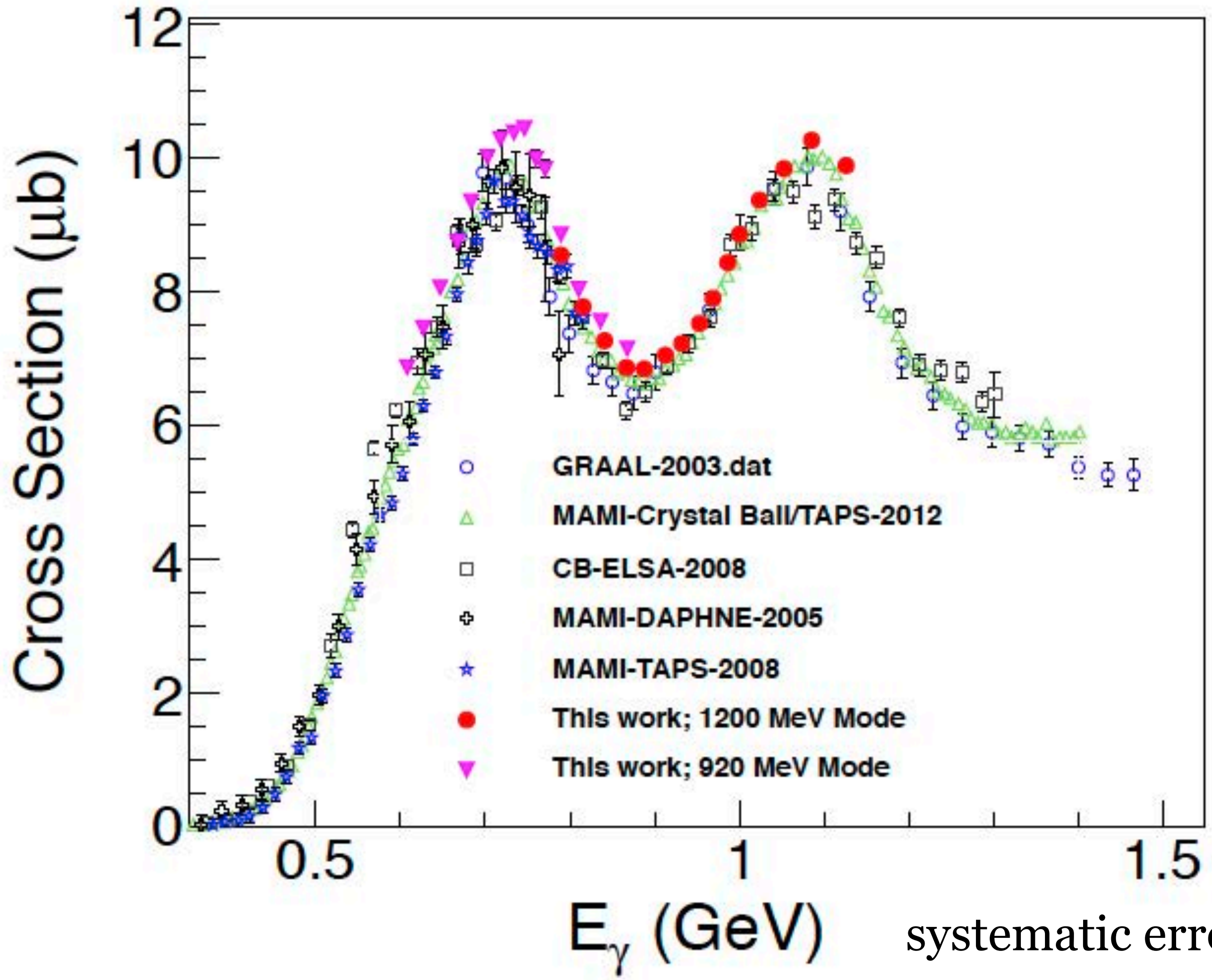


missing mass spectrum assumed $\gamma p \to \pi^0 \pi^0 p$



Total cross section

$\gamma p \rightarrow 2\pi^0 p$



ELPH
Q. He

systematic error: 11%

Dominant processes at 1 GeV

2^{nd} resonance region

- **Saclay model**

$$P_{11}(1440) \rightarrow p(\pi^0\pi^0)_S^{I=0}$$

- **Valencia model**

$$D_{13}(1520) \rightarrow \Delta\pi^0 \rightarrow p\pi^0\pi^0$$ **dominant process**

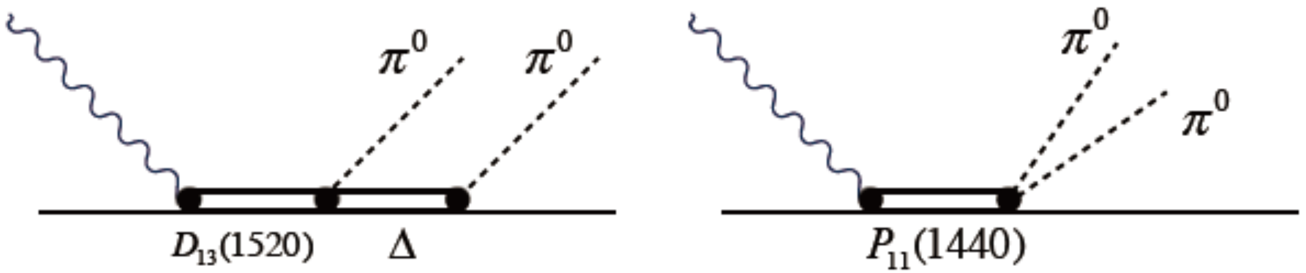
$$+\ P_{11}(1440) \rightarrow p(\pi^0\pi^0)_S^{I=0}$$

3^{rd} resonance region

- **Mainz model**

$$F_{15}(1680) \rightarrow \Delta\pi^0 \rightarrow p\pi^0\pi^0$$

$2\pi^0$ photoproduction at ~1 GeV is dominated by $\Delta\pi$

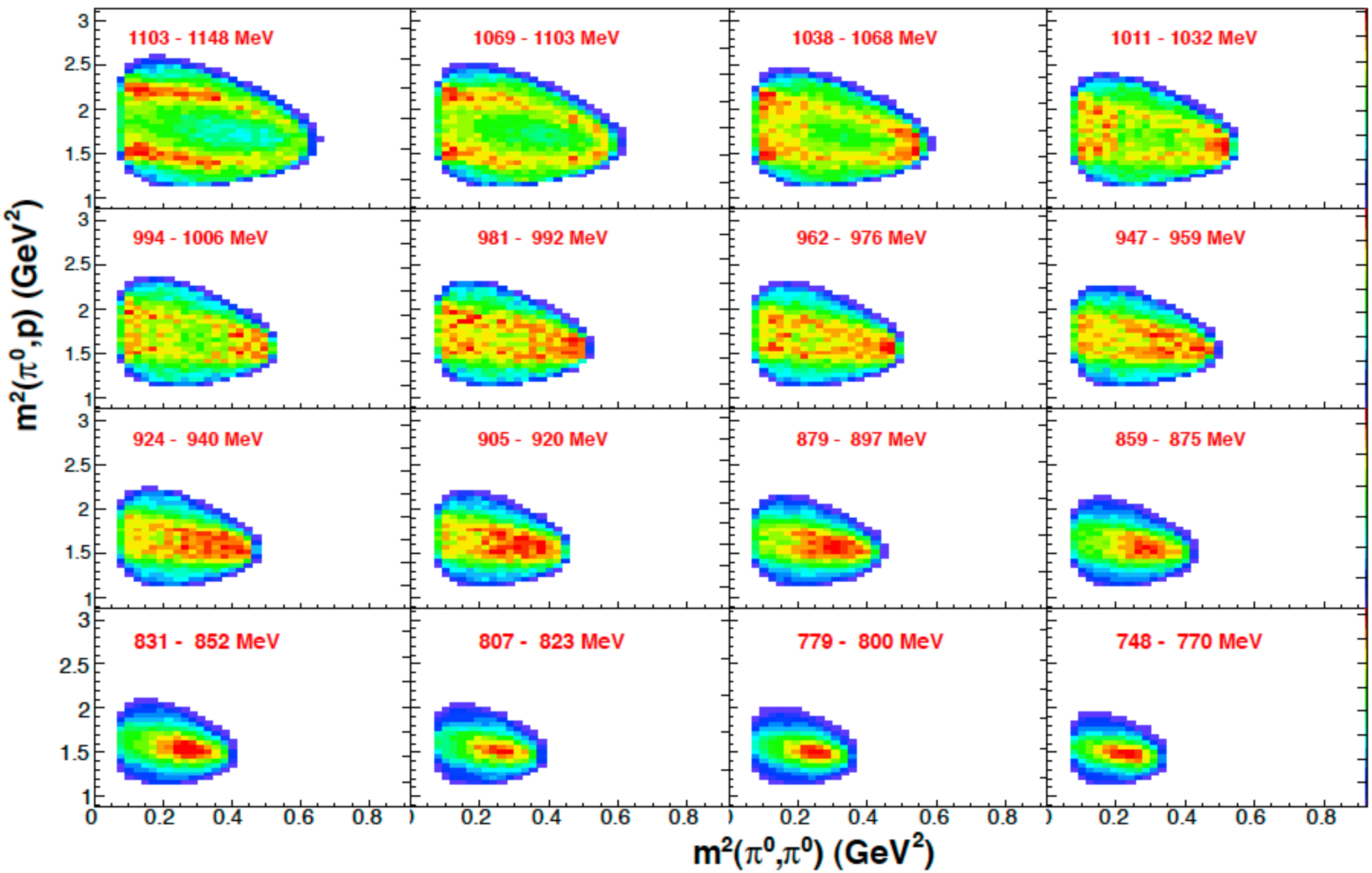


FOREST data

Dalitz plots

$\gamma p \to 2\pi^0 p$

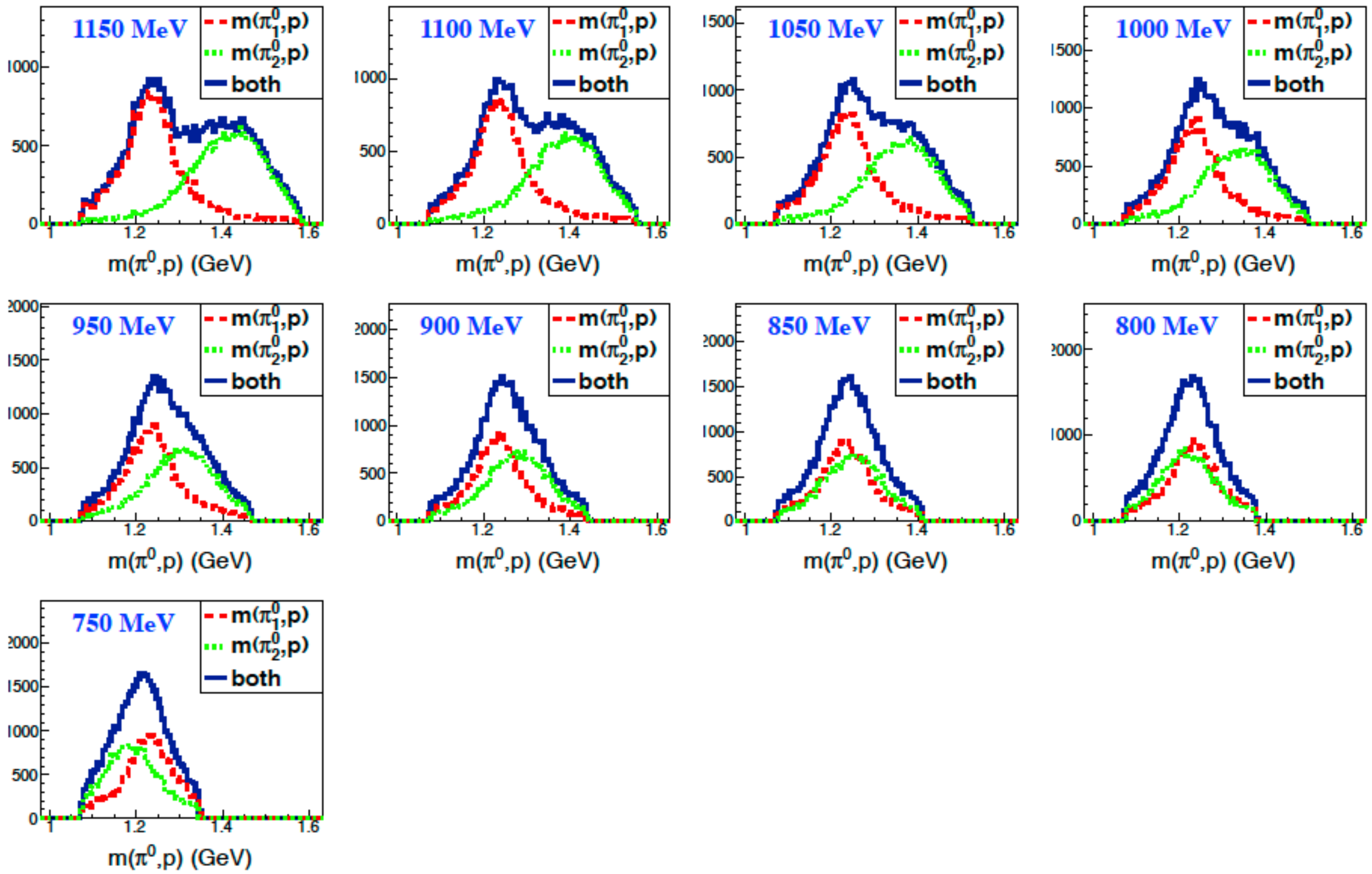
2009D



Δ production dominance

simulation

$\pi^0 p$ invariant mass

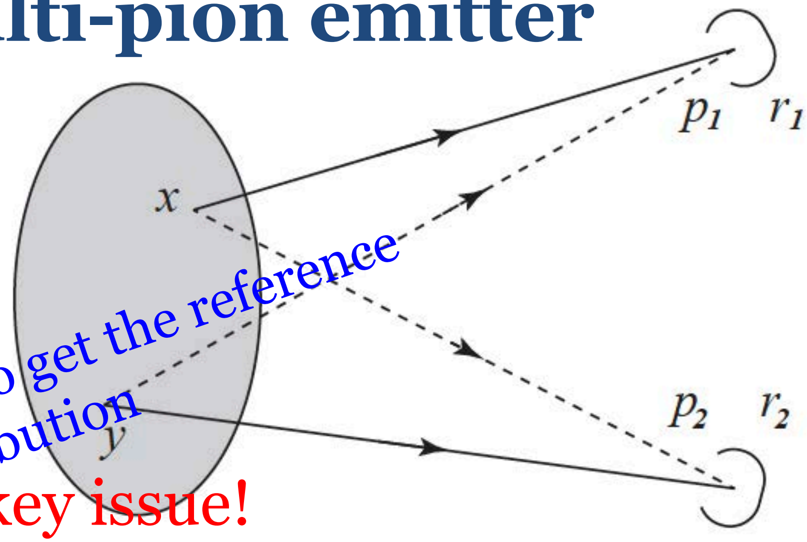


$\pi\pi$ BEC experiments

Present status

Source size of a multi-pion emitter

$\pi^{\pm}\pi^{\pm}$
$\pi^{0}\pi^{0}$ Bose-Einstein Correlation



$$C_{BEC}(p_1,p_2) = \frac{P_{BEC}(p_1,p_2)}{P_0(p_1,p_2)}$$

How to get the reference distribution

key issue!

$$P_{BEC}(p_1,p_2) = \int d^4x d^4y |\psi_2(p_1,p_2)|^2 \rho(x)\rho(y)$$ 2 particle probability density

$$\psi_2(p_1,p_2) = \frac{1}{\sqrt{2}}\left[e^{-ip_1(r_1-x)}e^{-ip_2(r_2-y)} + e^{-ip_1(r_1-y)}e^{-ip_2(r_2-x)}\right]$$

4-dimensional Gaussian

$$\rho(x) = N\exp\left(\frac{-(x^2-x_0^2)}{2\alpha^2}\right)$$

emitter source density

space-like Gaussian distribution

$$f(q) = \int d^4x e^{-iqx}\rho(x)$$

$$C_{BEC}(Q) = 1 + \lambda|f(Q)|^2 = 1 + \lambda e^{-\alpha^2 Q^2}$$

$$Q^2 \equiv -q^2$$

experimental condition

$$q^2 = (p_1-p_2)^2 = 2m_\pi^2 - 2p_1p_2 = 4m_\pi^2 - M^2 < 0$$

$$M^2 = (p_1+p_2)^2$$

$\pi\pi$ Bose-Einstein correlation experiments

in elementary processes

System	Reaction	$E_{cm}(GeV)$	$r_0(fm)$	λ_2
$\pi^\pm\pi^\pm$	$e^+e^- \to h$ [184]	29	0.75 ± 0.05^a	0.28 ± 0.04^a
			0.97 ± 0.11^b	0.27 ± 0.04^b
$\pi^\pm\pi^\pm$	$e^+e^- \to h$ [185]	29	0.65 ± 0.06^b	0.50 ± 0.04^b
$\pi^\pm\pi^\pm$	$e^+e^- \to h$ [186]	34	0.82 ± 0.07^a	0.35 ± 0.03^a
$\pi^\pm\pi^\pm$	$e^+e^- \to h$ [187]	58	0.73 ± 0.21^a	0.47 ± 0.07^a
			0.58 ± 0.06^b	0.39 ± 0.05^b
$\pi^\pm\pi^\pm$	$e^+e^- \to h$ [188]	91	0.82 ± 0.04^a	0.48 ± 0.03^a
			0.52 ± 0.02^b	0.30 ± 0.01^b
$\pi^\pm\pi^\pm$	$e^+e^- \to h$ [189]	91	0.83 ± 0.03^a	0.31 ± 0.02^a
			0.47 ± 0.03^b	0.24 ± 0.02^b
$\pi^\pm\pi^\pm$	$e^+e^- \to h$ [190]	91	0.46 ± 0.02^b	0.29 ± 0.03^b
$\pi^\pm\pi^\pm$	$e^+e^- \to h$ [183]	91	0.96 ± 0.02^a	0.67 ± 0.03^a
			0.79 ± 0.02^b	0.58 ± 0.01^b
$\pi^\pm\pi^\pm$	$\gamma\gamma \to h$ [184]	5	1.05 ± 0.08	1.20 ± 0.13
$\pi^\pm\pi^\pm$	$\gamma\gamma \to 6\pi^\pm$ [193]	1.6-7.5	0.54 ± 0.22	0.59 ± 0.20
$\pi^\pm\pi^\pm$	$\nu(\bar{\nu})N \to h$ [194]	8-64	0.64 ± 0.16	0.46 ± 0.16
$\pi^\pm\pi^\pm$	$\mu p \to h$ [195]	23	0.65 ± 0.03	0.80 ± 0.07
$\pi^\pm\pi^\pm$	$\pi^+ p \to h$ [196]	21.7	0.83 ± 0.06	0.33 ± 0.02
$\pi^\pm\pi^\pm$	$pp \to h$ [197]	26	1.02 ± 0.20	0.32 ± 0.08
$\pi^\pm\pi^\pm$	$pp \to h$ [198]	27.4	1.20 ± 0.03	0.44 ± 0.01
$\pi^\pm\pi^\pm$	$pp \to h$ [199]	63	0.82 ± 0.05	0.40 ± 0.03
$\pi^\pm\pi^\pm$	$\bar{p}p \to h$ [200]	1.88	1.04 ± 0.01	1.96 ± 0.03
$\pi^\pm\pi^\pm$	$\bar{p}p \to h$ [201]	200-900	0.73 ± 0.03	0.25 ± 0.02
$\pi^\pm\pi^\pm$	$ep \to eh$ [202]	$2.45 < Q_\gamma < 10$	0.68 ± 0.06	0.52 ± 0.20
$\pi^\pm\pi^\pm$	$ep \to eh$ [203]	$10.5 < Q_\gamma$	0.67 ± 0.04	0.43 ± 0.09
$\pi^0\pi^0$	$e^+e^- \to h$ [190, 191]	91	0.31 ± 0.10^b	0.16 ± 0.09^b
$\pi^0\pi^0$	$e^+e^- \to h$ [192]	91	0.59 ± 0.11^b	0.55 ± 0.15^b
$k^\pm k^\pm$	$ep \to eh$ [204]	$E_e : 27.5; E_p : 820$	$0.37 \pm 0.07^{+0.09}_{-0.08}$	$0.57 \pm 0.09^{+0.15}_{-0.08}$
$k^0_S k^0_S$	$ep \to eh$ [204]	$E_e : 27.5; E_p : 820$	$0.70 \pm 0.19^{+0.28+0.38}_{-0.08-0.52}$	$0.63 \pm 0.09^{+0.07+0.09}_{-0.08-0.02}$

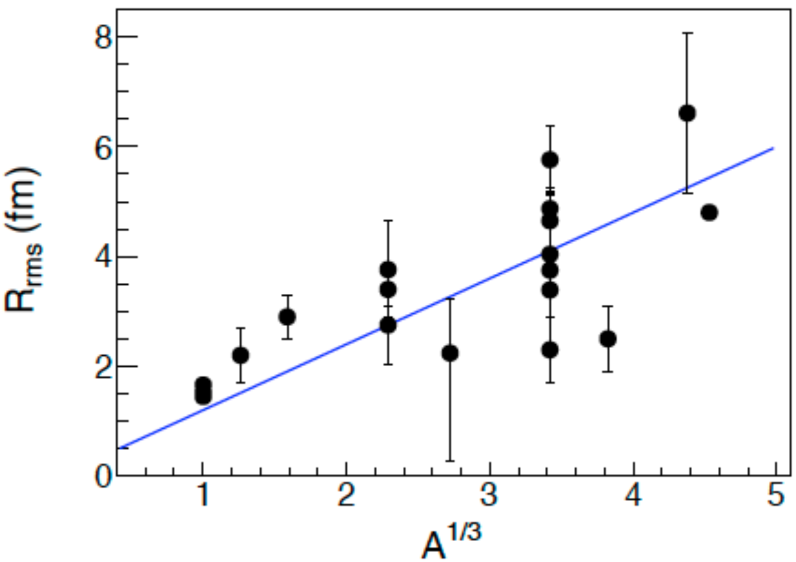
- BEC parameter ranges $\boxed{0.3 \le r_0 \le 1.2(fm)}$
- Different results from the same experiment
- Two $\pi^0\pi^0$ BEC experiments at LEP (L3, OPAL)

$a: \pi^+\pi^-$
$b: MC\ or\ EM$

$\pi\pi$ Bose-Einstein correlation experiments

in heavy ion collisions

BE System	Projectile	Target	E(GeV/nucleon)	$R_{rms}(fm)$	Ref.
$\pi^{\pm}\pi^{\pm}$	p	H	200	1.66 ± 0.04	[206]
$\pi^{\pm}\pi^{\pm}$	p	Xe	200	1.53 ± 0.13	[206]
$\pi^{\pm}\pi^{\pm}$	p	Xe	200	1.45 ± 0.11	[206]*
$\pi^{\pm}\pi^{\pm}$	d	Ta	3.4	2.20 ± 0.50	[207]
$\pi^{\pm}\pi^{\pm}$	He	Ta	3.4	2.90 ± 0.40	[207]
$\pi^{-}\pi^{-}$	C	C	4.2	2.75 ± 0.73	[208]
$\pi^{-}\pi^{-}$	C	C	4.2	3.76 ± 0.88	[208]*
$\pi^{\pm}\pi^{\pm}$	C	Ta	3.4	3.40 ± 0.30	[207]
$\pi^{+}\pi^{+}$	Ar	KCl	1.8	4.10 ± 0.4	[211]
$\pi^{-}\pi^{-}$	Ar	KCl	1.8	$2.77^{+0.6}_{-0.9}$	[211]
$\pi^{-}\pi^{-}$	Ne	NaF	1.8	2.80 ± 0.30	[211]
$\pi^{-}\pi^{-}$	Ar	KCl	1.5	4.91 ± 0.50	[213]
$\pi^{-}\pi^{-}$	Ar	KCl	1.2	3.8 ± 0.50	[210]*
$\pi^{-}\pi^{-}$	Ar	BaI_2	1.8	3.05 ± 1.10	[209]
$\pi^{-}\pi^{-}$	Ar	Pb_3O_4	1.8	3.30 ± 0.93	[209]
$\pi^{-}\pi^{-}$	Ar	Pb_3O_4	1.8	3.98 ± 0.78	[209]*
$\pi^{-}\pi^{-}$	Ar	KCl	1.8	2.3 ± 0.6	[205]
$\pi^{-}\pi^{-}$	Fe	Fe	1.7	2.5 ± 0.6	[205]
$\pi^{\pm}\pi^{\pm}$	Kr	RbBr	1.2	6.61 ± 1.47	[212]
$\pi^{-}\pi^{-}$	Nb	Nb	1.5	4.8 ± 0.1	[205]
$\pi^{-}\pi^{-}$	Ar	Pb	1.8	5.53 ± 0.38	[214]



$$R_{rms} = 1.2 A^{1/3}\, fm$$

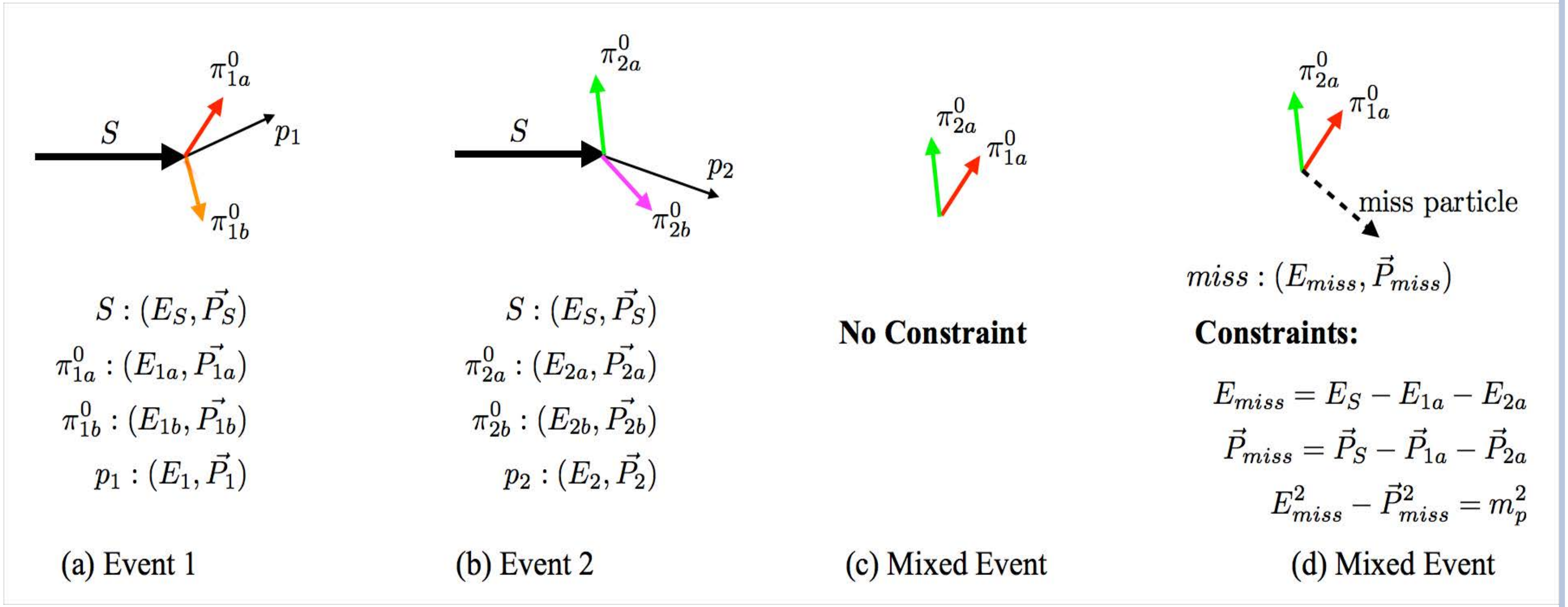
at high energies and no $\pi^0\pi^0$

1) No $\pi\pi$ BEC experiment at low energies (baryon resonance region)
2) No $\pi^0\pi^0$ BEC data obtained in heavy ion collisions
3) All $\pi\pi$ BEC effects in high multiplicity experiments

$\pi\pi$ BEC in low energies

How to get the reference for low-multiplicity data

Event mixing method for a reference distribution



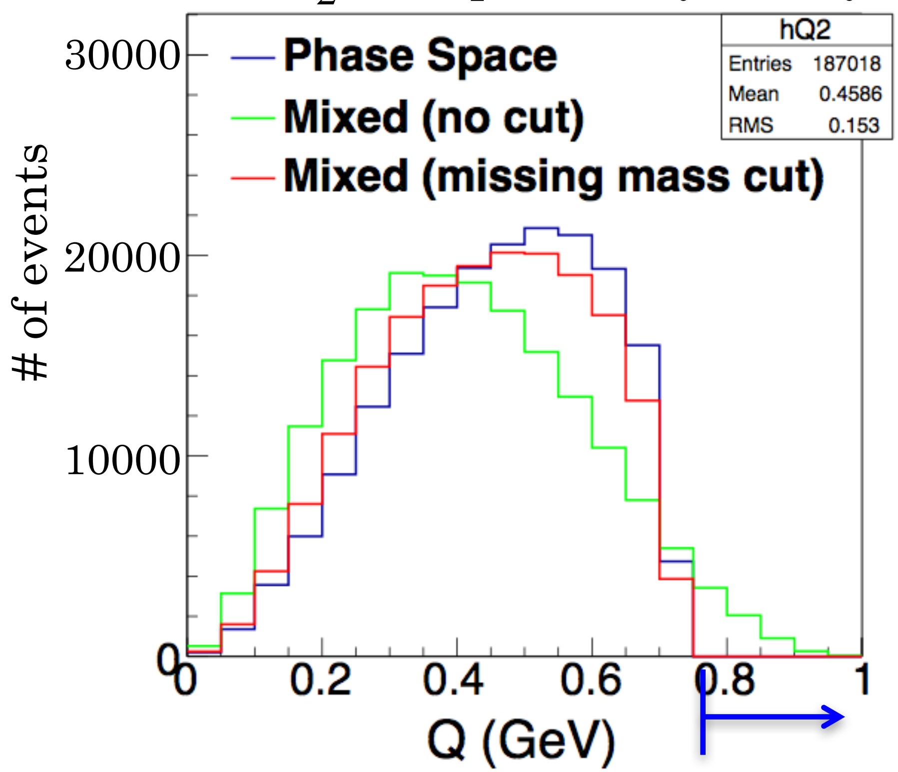
Appropriate kinematical requirements should be made in the mixing procedure.

An event mixing method was developed for $\gamma p \rightarrow 2\pi^0 p$ and then extended to $\gamma p \rightarrow 2\pi^0 X$ and $\gamma d \rightarrow 2\pi^0 X$.

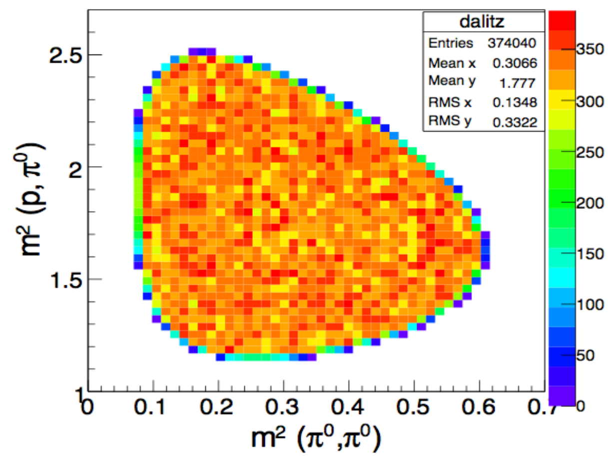
simulation

Requirements on missing mass

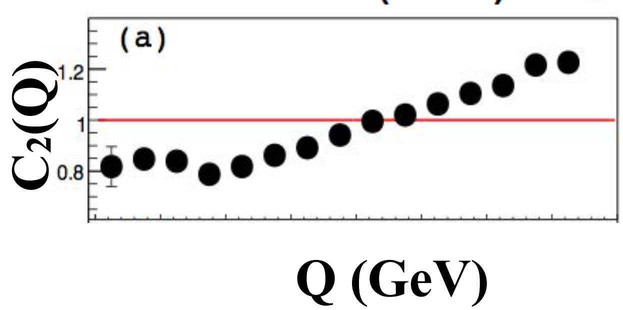
$P_2(Q)$ probability density



generated phase space
$\gamma p \rightarrow 2\pi^0 p$ events



unphysical region



C_2 should be flat.

Kinematical requirements

- **missing mass**

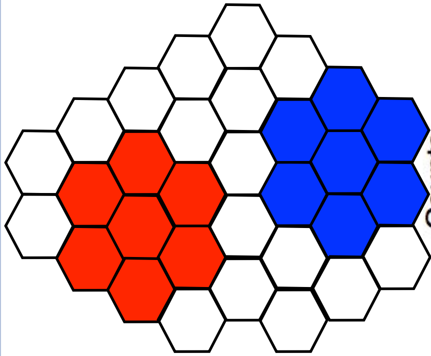
  The mass of the third particle in a mixed event should be the same as the original one.
- **pion energy**

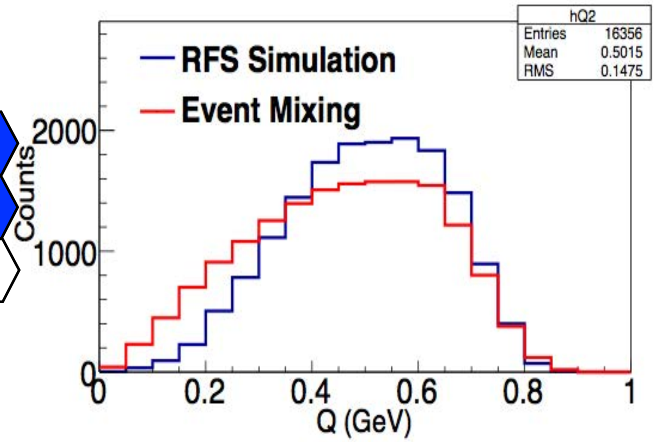
  The energy of pions should have an upper limit.
- **photon clusters**

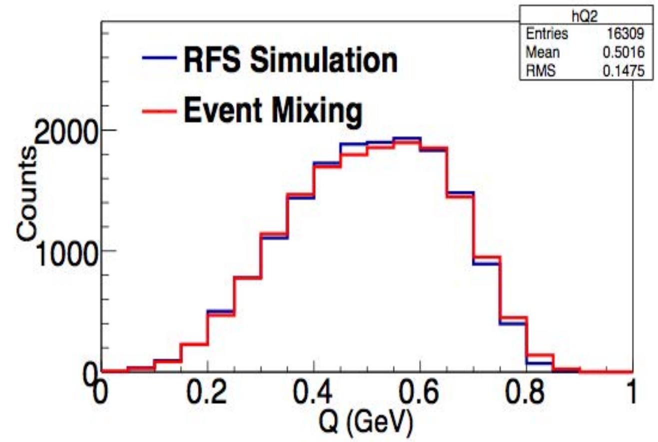
  There should be no overlapping photon clusters. (an acceptance issue)

simulation

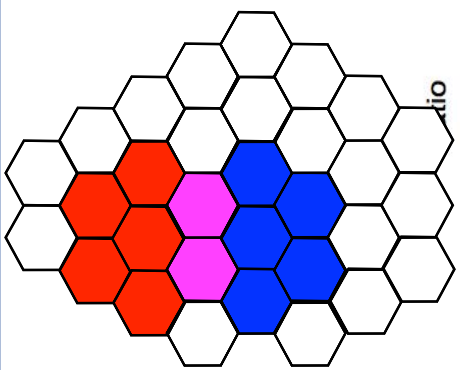
Treatments for cluster overlapping

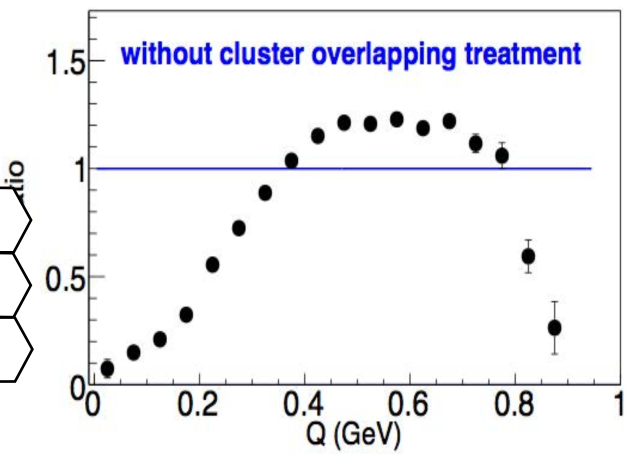


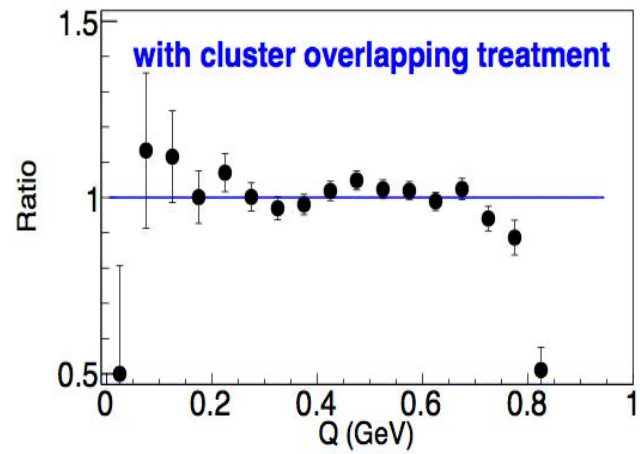




two clusters







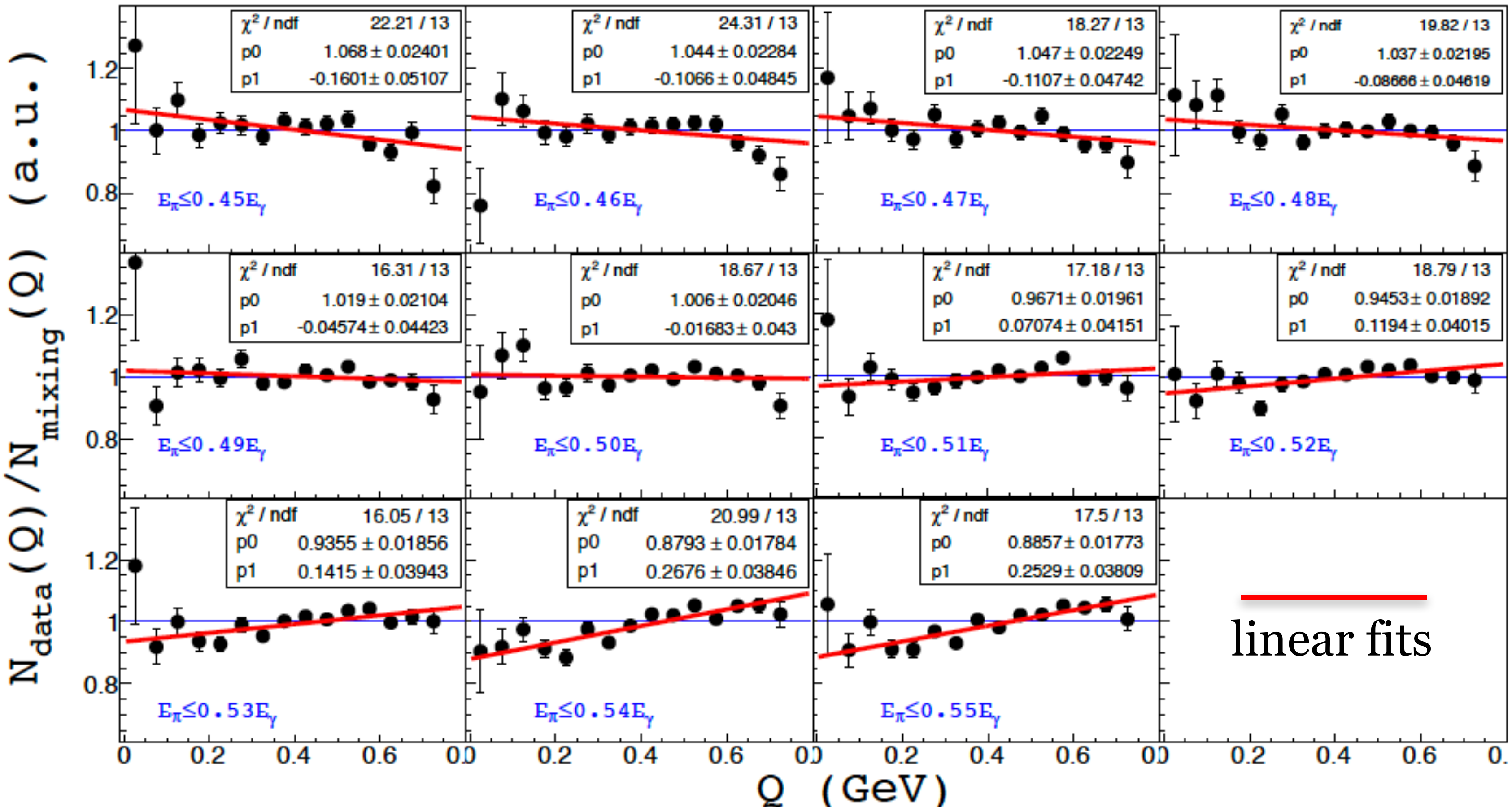
overlaping clusters

w/o clusters overlapped

simulation

Requirements on pion energies

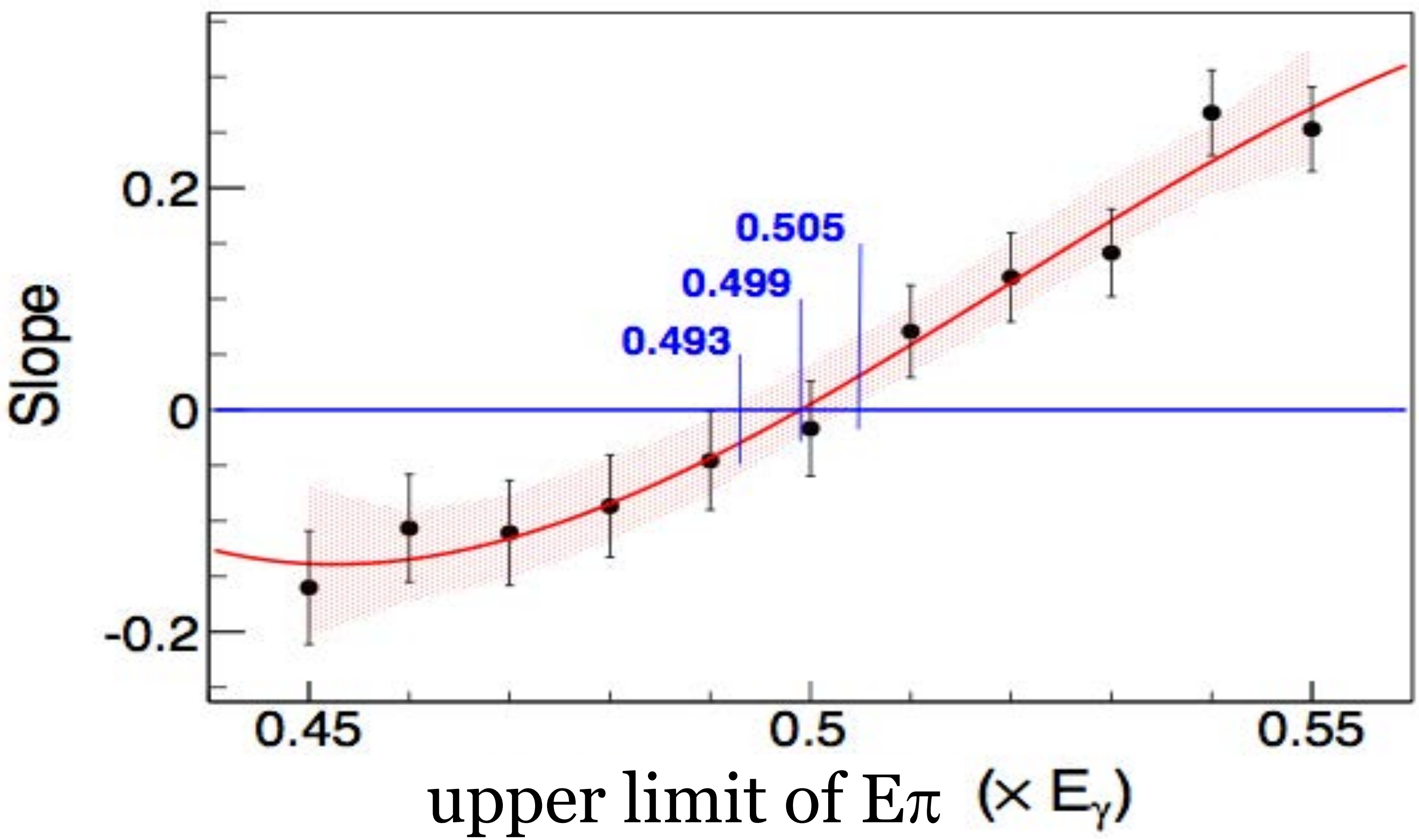
C2(Q) depending on the upper limit of Eπ
with missing mass requirements full filled



$\gamma p \rightarrow 2\pi^0 p$

simulation

Optimization for upper limits of Eπ



$\gamma p \rightarrow 2\pi^0 p$

Test of the method *w* MC simulation

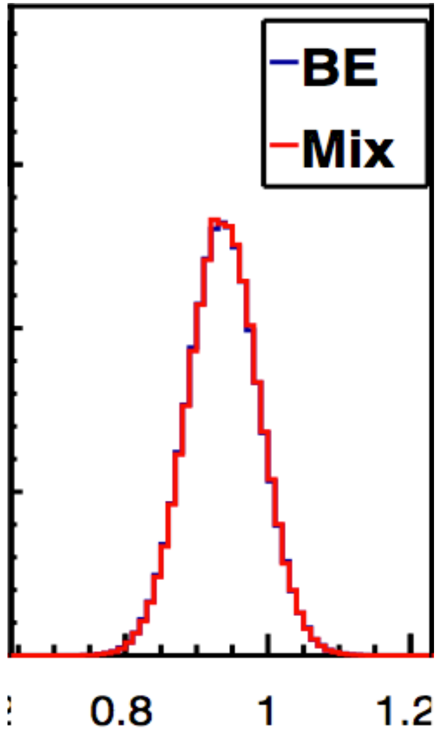
BEC events are produced by weighting the phase space events with the correlation function:

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

λ_2 and r_0

for Monte Carlo samples of $\gamma p \rightarrow \pi^0 \pi^0 X$

Event Sample	E_γ (GeV)	r_0 (fm)	λ_2
noBE	1.1	−−	−−
BE,1	1.1	0.4	1.0
BE,2	1.1	0.7	1.0
BE,3	1.1	1.0	1.0
BE,4	1.1	1.3	1.0
BE,5	1.1	0.4	0.5
BE,6	1.1	0.7	0.5
BE,7	1.1	1.0	0.5
BE,8	1.1	1.3	0.5



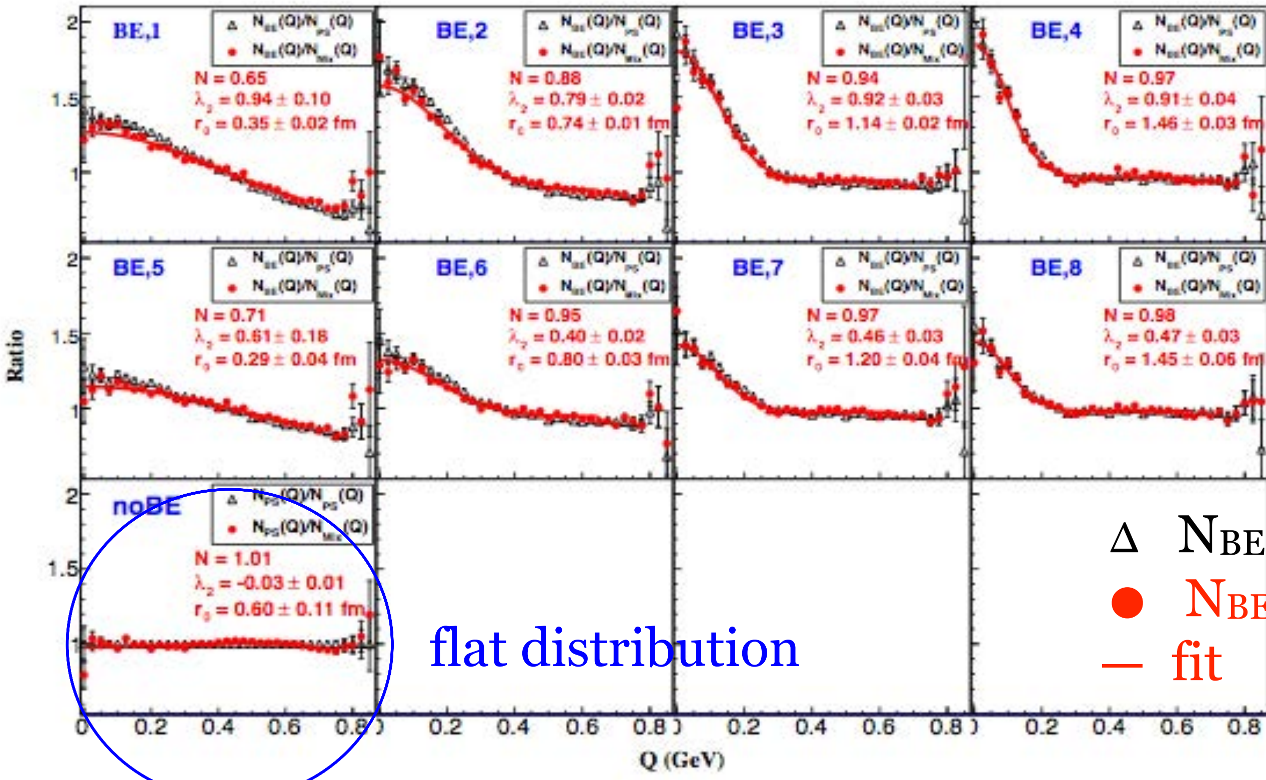
mass of X

μ=mp σ=50MeV

simulation

Test results for phase space events

$E\gamma$=1.1GeV

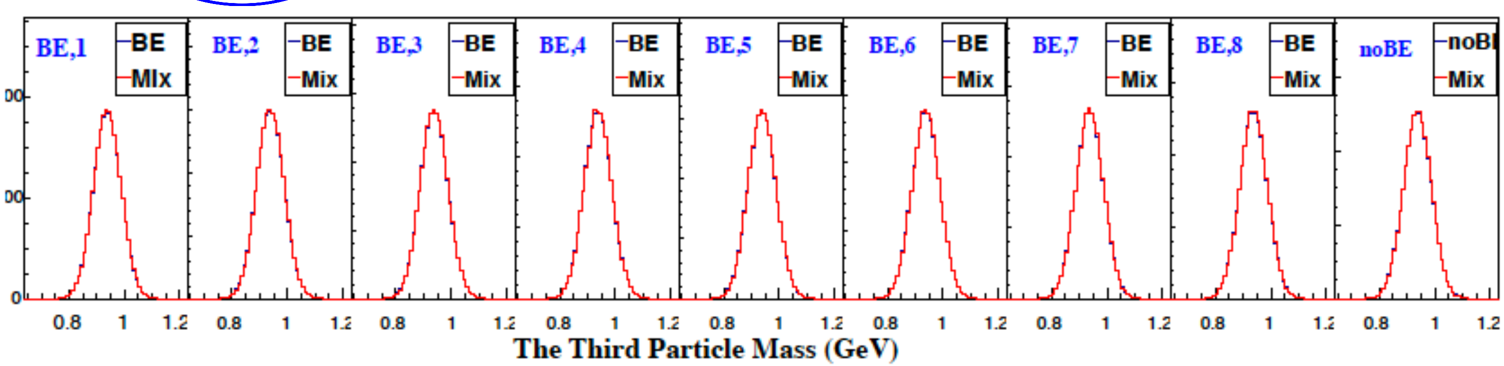


flat distribution

△ $N_{BE}(Q)/N_{ps}(Q)$

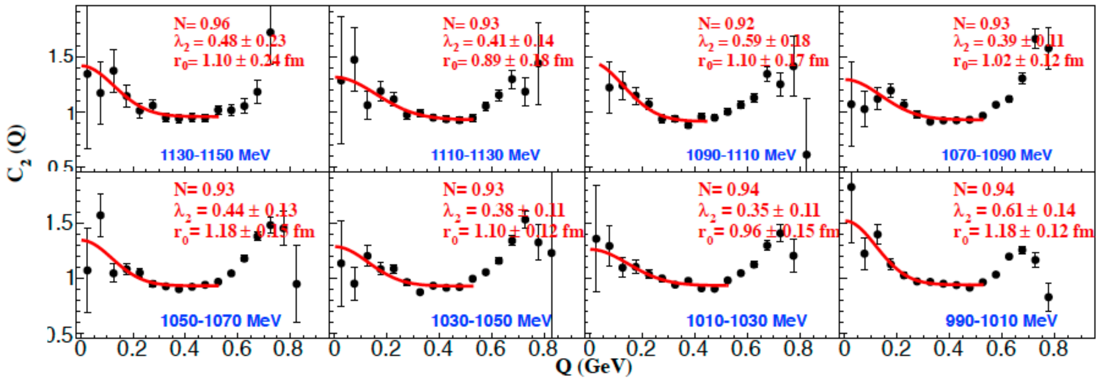
● $N_{BE}(Q)/N_{mix}(Q)$

— fit

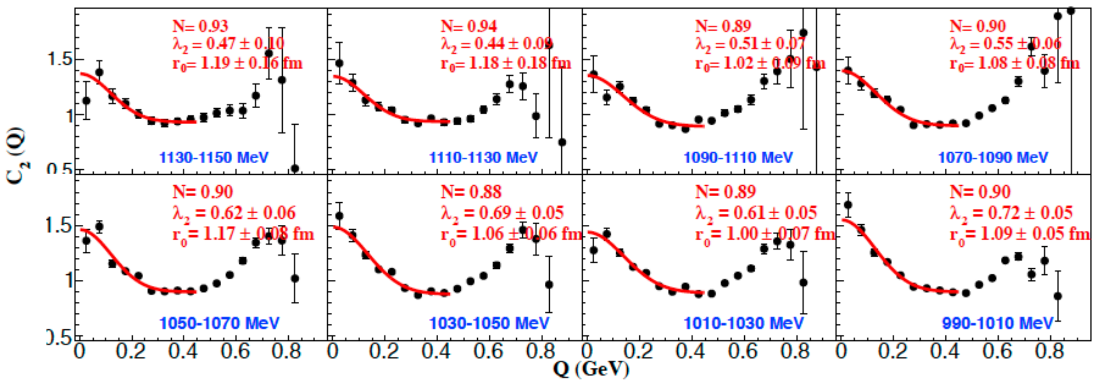


FOREST data

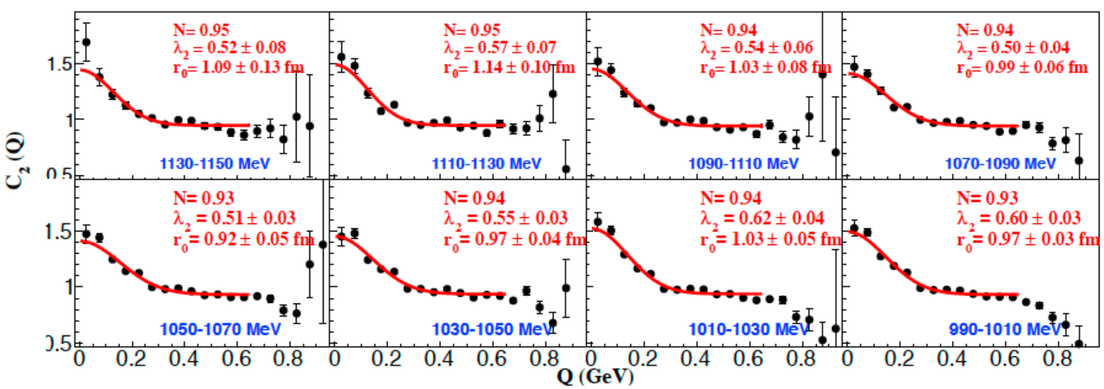
Results of C2 Q distribution



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



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

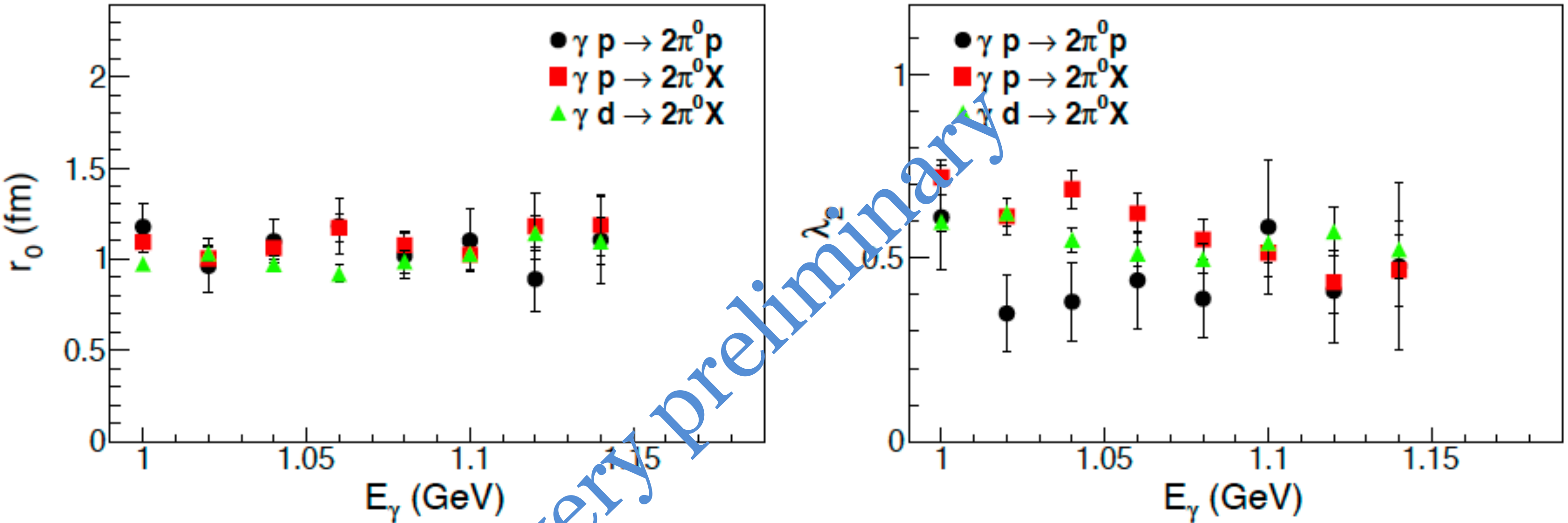


$$\gamma d \rightarrow \pi^0 \pi^0 X$$

FOREST data

Obtained BEC parameters

ELPH
Q. He



	$r_0(fm)$	λ_2
$\gamma p \to \pi^0\pi^0 p$	1.07 ± 0.05	0.43 ± 0.05
$\gamma p \to \pi^0\pi^0 X$	1.08 ± 0.03	0.61 ± 0.02
$\gamma d \to \pi^0\pi^0 X$	0.99 ± 0.02	0.56 ± 0.01

average:

$$r_0 = (1.02 \pm 0.01)\, fm$$

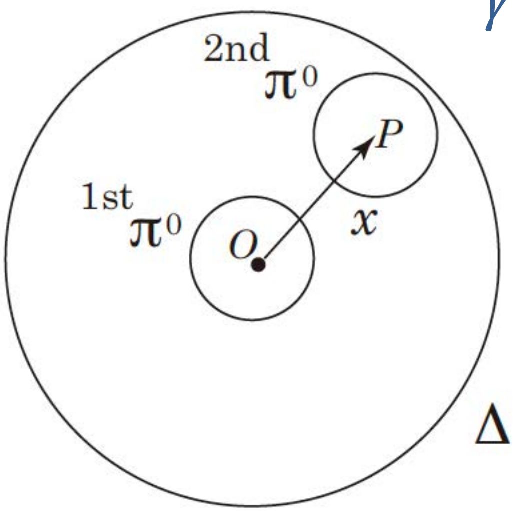
$$\lambda_2 = 0.57 \pm 0.01$$

$\pi\pi$ *BEC in low energies*

RMS radius of Δ
with 4D distribution

Where is the original point of a generated π^0?

$\gamma N \to \pi^0 \Delta$ process



4-D Gaussian distribution

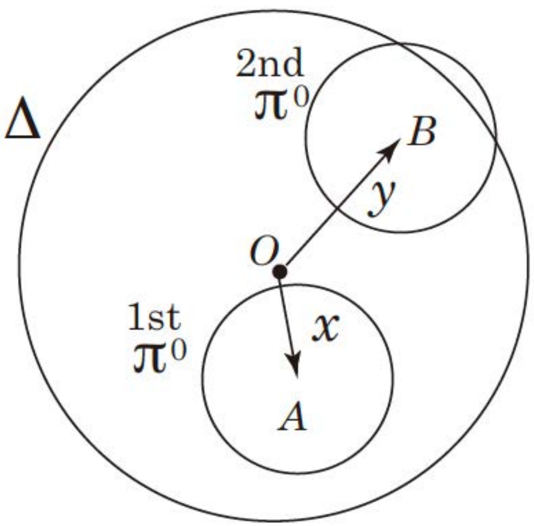
$$\rho(x) = N \exp\left(\frac{-(\boldsymbol{x}^2 - x_0^2)}{2\alpha^2}\right)$$

case I) 1st π^0 appears at the same place of Δ

$$C_{BEC}(Q) = 1 + \lambda f(Q) = 1 + \lambda e^{-\frac{\alpha^2 Q^2}{2}}$$

$$R^2 = \langle \boldsymbol{x}^2 \rangle_3 = \int \boldsymbol{x}^2 \rho_3(\boldsymbol{x}) d^3x$$

RMS radius of Δ if $\rho_3(\boldsymbol{x})$ is known



case II) 1st π^0 appears somewhere in Δ

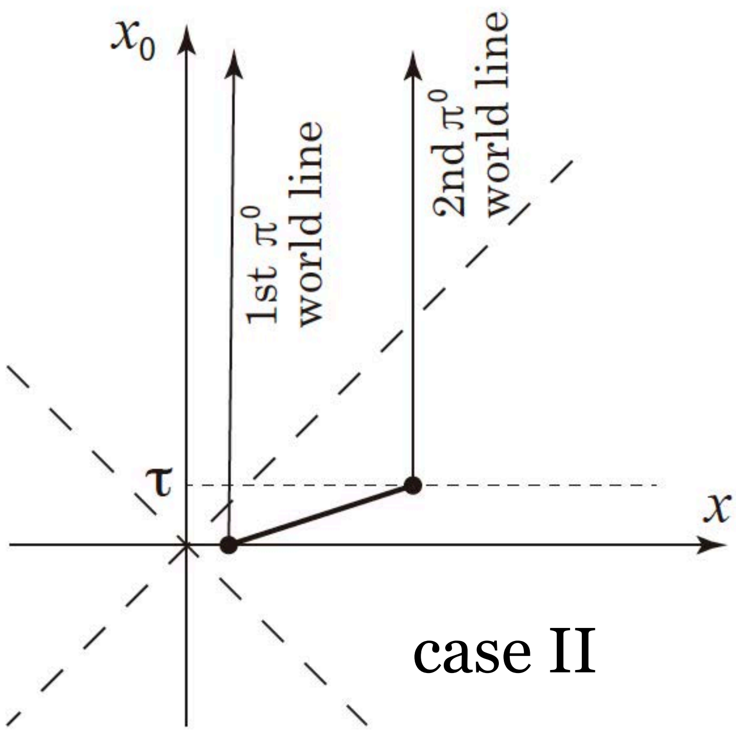
$$C_{BEC}(Q) = 1 + \lambda |f(Q)|^2 = 1 + \lambda e^{-\alpha^2 Q^2}$$

$$D^2 \equiv \langle (\boldsymbol{x} - \boldsymbol{y})^2 \rangle_3 = \int (\boldsymbol{x} - \boldsymbol{y})^2 \rho_3(\boldsymbol{x}) \rho_3(\boldsymbol{y}) d^3x d^3y = 2R^2$$

$2\pi^0$ in space-time coordinates of Δ at rest

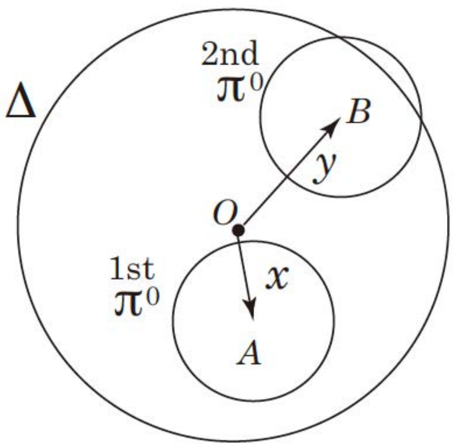
Expectation:

Space components of $(x-y)^2$ give information on the size in the Δ rest frame.



Space-like intervals between $2\pi^0$ at the original space-time points subject to the 4D Gaussian distribution parametrized by α and λ

$$C_{BEC}(Q) = 1 + \lambda |f(Q)|^2 = 1 + \lambda e^{-\alpha^2 Q^2}$$



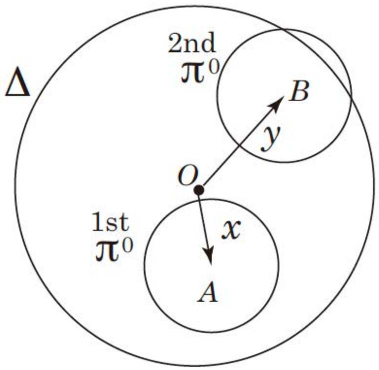
RMS radius *R* of Δ

<correlation function>

$$C_{BEC}(Q) = 1 + \lambda |f(Q)|^2 = 1 + \lambda e^{-\alpha^2 Q^2}$$

<Gaussian form factor in Euclidean coordinates>

$$\rho_E(x) = \frac{1}{(\sqrt{2\pi}\alpha)^4} \exp\left(-\frac{x_E^2}{2\alpha^2}\right)$$



<mean square space-time interval>

$$\langle (x_E - y_E)^2 \rangle = \int (x_E - y_E)^2 \rho_E(x) \rho_E(y) d^4x d^4y = 8\alpha^2$$

<Δ mean square radius *R*>

$$2R^2 = \int (\boldsymbol{x} - \boldsymbol{y})^2 \rho_3(\boldsymbol{x}) \rho_3(\boldsymbol{y}) d^3x d^3y$$

<mean square decay time>

$$\tau = \langle x_0 \rangle = \frac{1}{\Gamma} = \frac{1}{117\text{MeV}} = 1.68\text{fm}$$

$$\langle (x_0 - y_0)^2 \rangle_t = \frac{1}{\tau} \int t^2 e^{-\frac{t}{\tau}} dt = 2\tau^2$$

<assumption>

$$\langle (x_E - y_E)^2 \rangle = \langle (\boldsymbol{x} - \boldsymbol{y})^2 \rangle_3 + \langle (x_0 - y_0)^2 \rangle_t$$

$$\Rightarrow \quad R^2 = 4\alpha^2 - \tau^2 = 1.2\ \text{fm}^2 \qquad \text{if } \alpha^2 \sim 1\ \text{fm}^2$$

Summary up to here

- $\pi^0\pi^0$ Bose-Einstein correlations were observed for the first time in the baryon resonance region.
- One dimensional BEC parameters were preliminary obtained:

$$r_0 = (1.02 \pm 0.01)\, fm$$

$$\lambda_2 = 0.57 \pm 0.01$$

  by fitting a 2 particle correlation function

$$C_2(p_1, p_2) = \frac{P_2(p_1, p_2)}{P_0(p_1, p_2)} = 1 + \lambda_2 e^{-Q^2 r_0^2}$$

  to the FOREST $2\pi^0$ photoproduction data.
- More work is necessary to improve the event-mixing method.
- Assuming $r_0 = 1$ fm, we find 1.1 fm for the RMS radius of Δ.
- Some other applications of BEC are conceivable to get space-time information on $\Delta\Delta$ production.
- More detailed study on BEC will be made in BGOegg experiments.

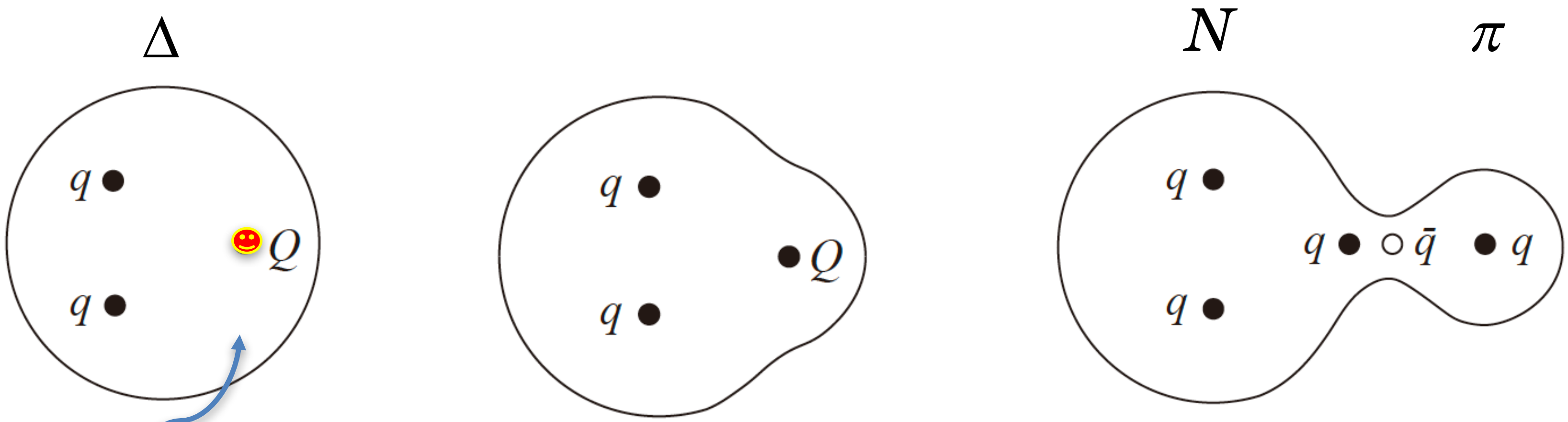
ππ BEC in low energies

Return back to
3D distribution

Where does π^0 originate from?

- size of hadrons = the range of existence of quarks

comprised of quarks

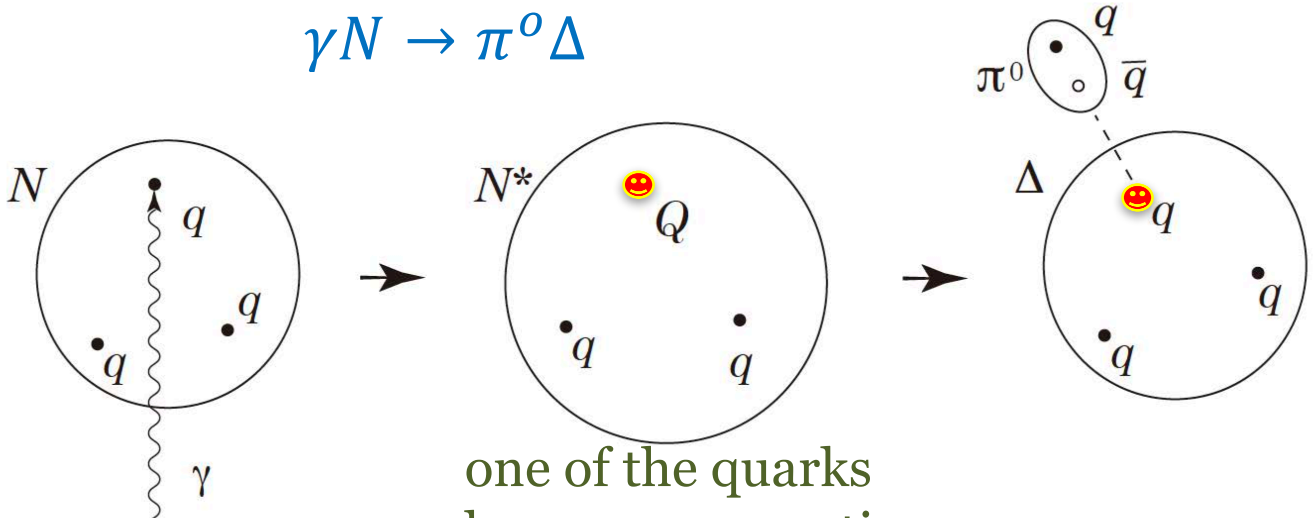


energetic quark

- place of the π originating point
  = place of the energetic quark

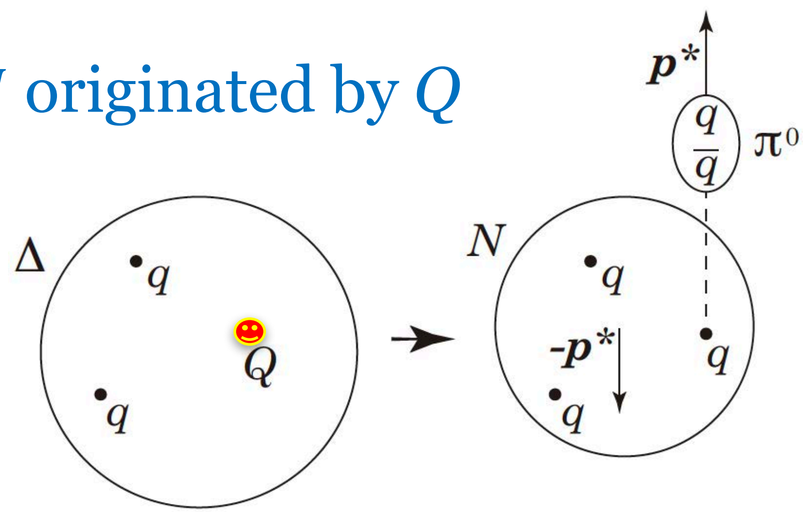
Originating places of pions

$\gamma N \to \pi^o \Delta$



one of the quarks
becomes energetic.

$\Delta \to \pi^0 N$ originated by Q



Considerations of the Δ size

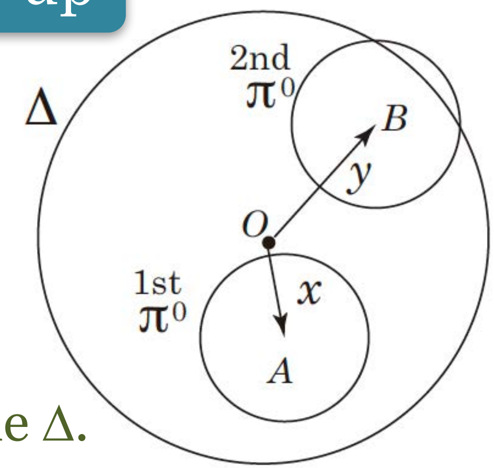
space-time points of 1st π and Δ showing up

- simultaneous production (time)

  1st π and Δ are produced at the same time

  in the $\gamma N \to \pi\Delta$ reaction.
- wave functions overlapped (place)

  the center of 1st π appears somewhere within the Δ.



space-time coordinates of ππ in the Δ rest frame

- the center of Δ: the origin of coordinates, O

  1st π: A(0,$\boldsymbol{x}$)

  2nd π: B(τ, $\boldsymbol{y}$) τ: proper time
- the MS radius of Δ: R

  $$\langle(\boldsymbol{x}-\boldsymbol{y})^2\rangle = 2R^2$$

3D treatments in the Δ rest frame

- 3D source density distribution

$$\rho(\boldsymbol{x}) = \frac{1}{(\sqrt{2\pi}\alpha)^3} \exp\left(\frac{-\boldsymbol{x}^2}{2\alpha^2}\right)$$

- BEC function

$$C_{BEC}(q) = 1 + \lambda f(q) = 1 + \lambda \exp\left(-\alpha^2 \boldsymbol{q}^2\right)$$

$$q^2 = \boldsymbol{q}^2 = (\boldsymbol{p}_1 - \boldsymbol{p}_2)^2$$

- MS radius of Δ

$$\langle \boldsymbol{x}^2 \rangle = \frac{1}{(\sqrt{2\pi}\alpha)^3} \int \boldsymbol{x}^2 \exp\left(\frac{-\boldsymbol{x}^2}{2\alpha^2}\right) d^3x = 3\alpha^2$$

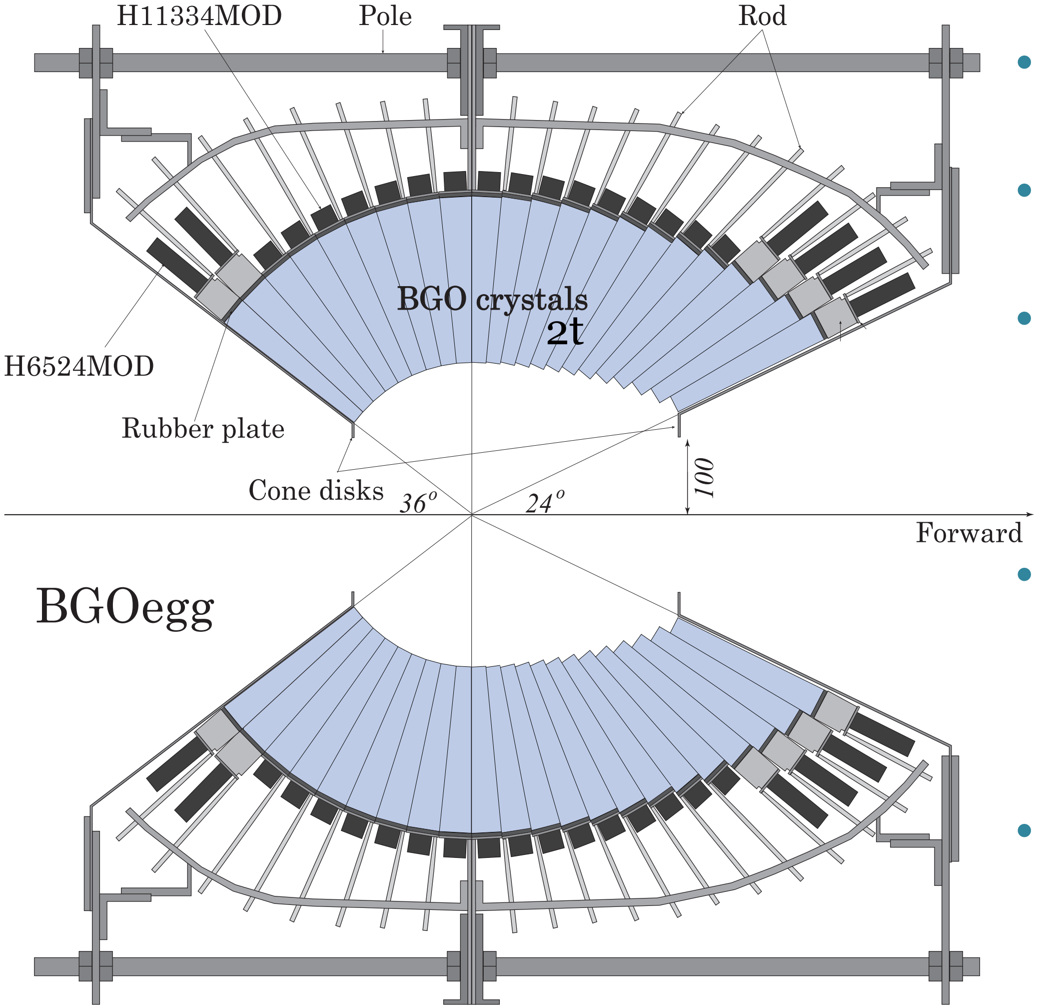
Experiments after

new

4π EM calorimeter

BGOegg

Construction of BGOegg

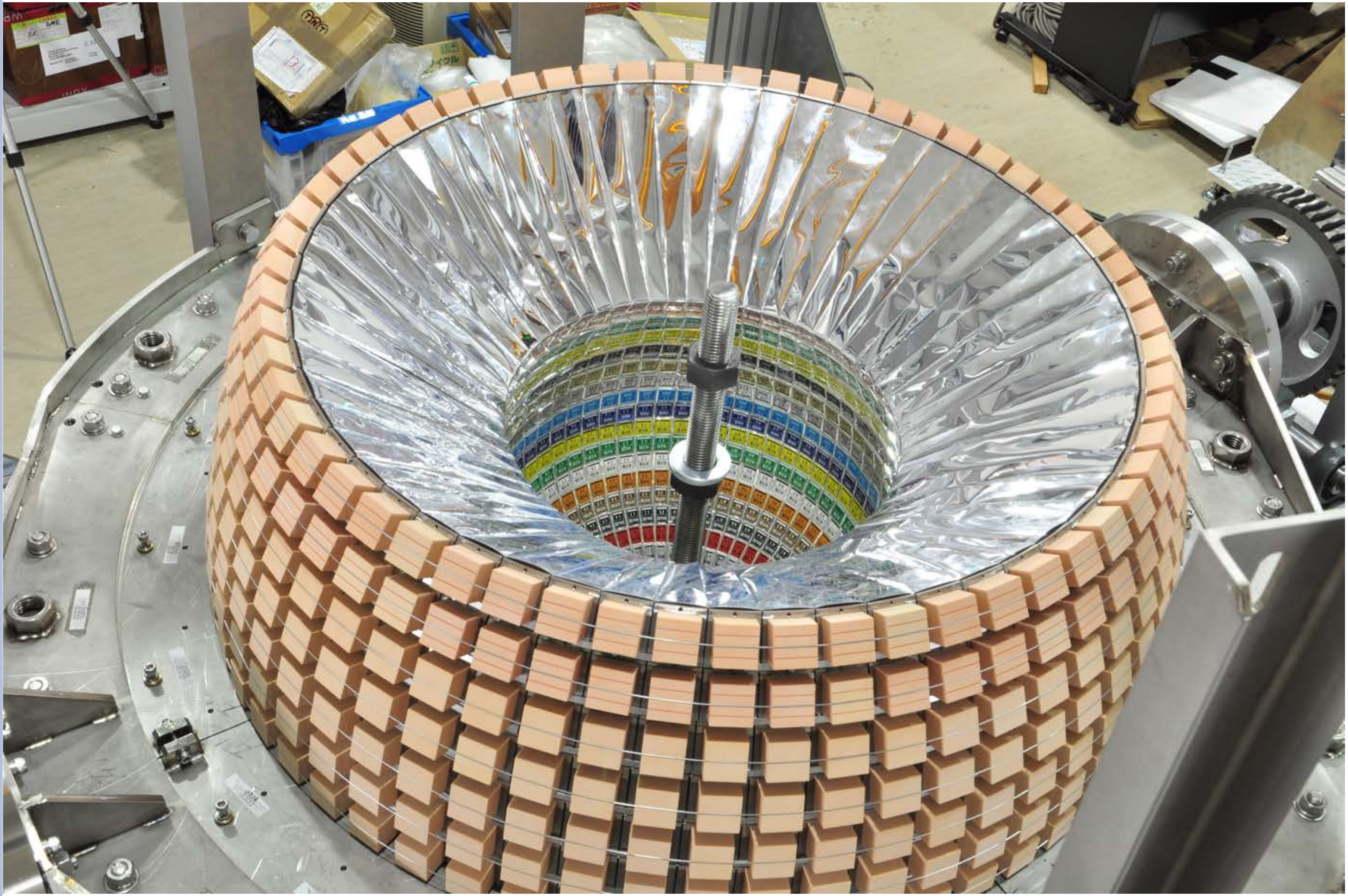


cross sectional view

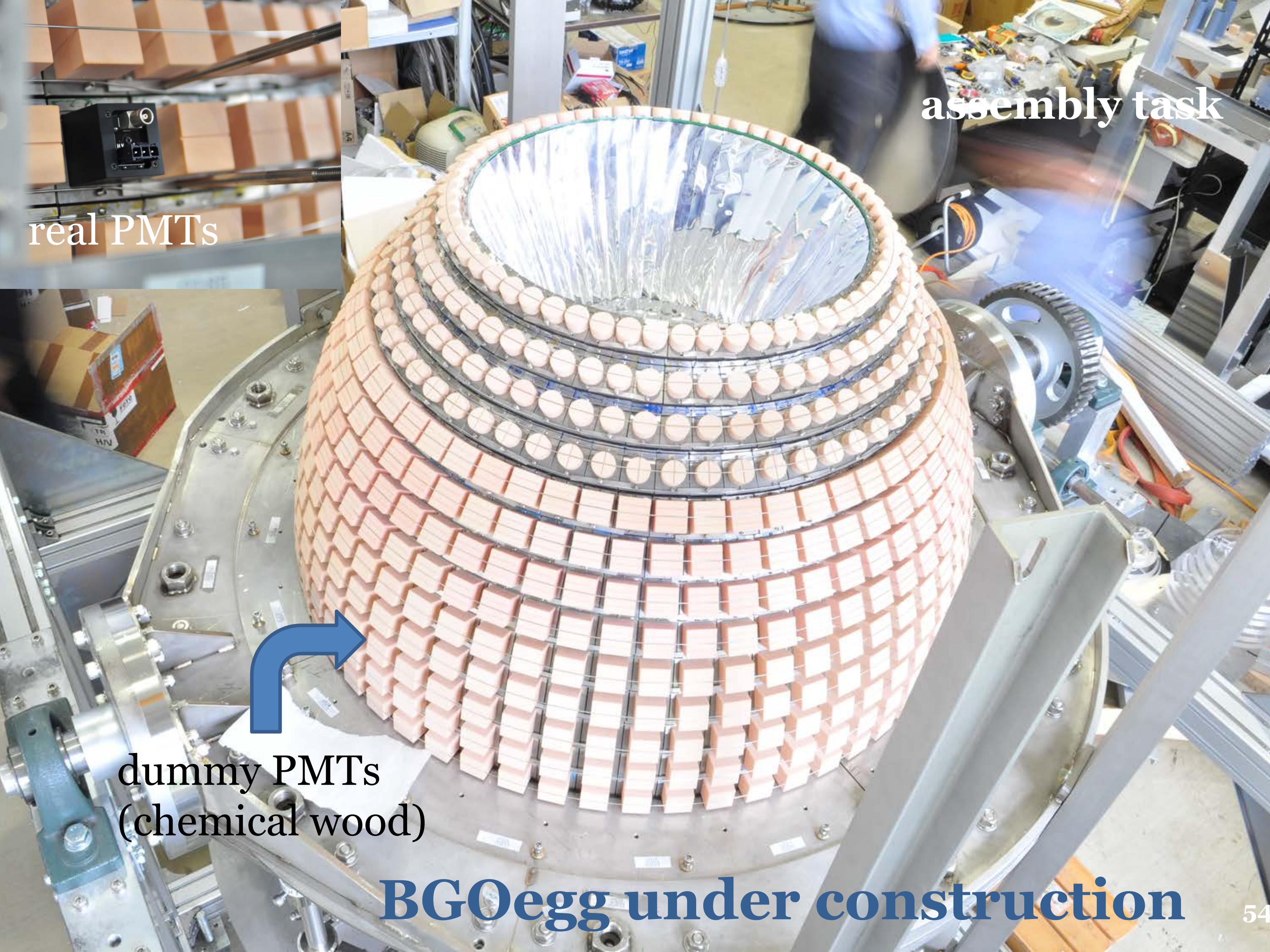
- egg-shape assembly of 1320 BGO crystals
- polar angles $24° \leq \theta \leq 144°$ (86% of 4π sr)
- good segmentation of ~6° sufficient thickness of 220 mm ($20X_0$)

- self-supporting structure to hold the whole crystals of about 2t in weight w/o insensitive area
- world highest energy-resolution of 1.3% for 1 GeV photons

not the maximum instantaneous value but obtainable everywhere in BGOegg



on the way of mounting 1320 BGO crystals

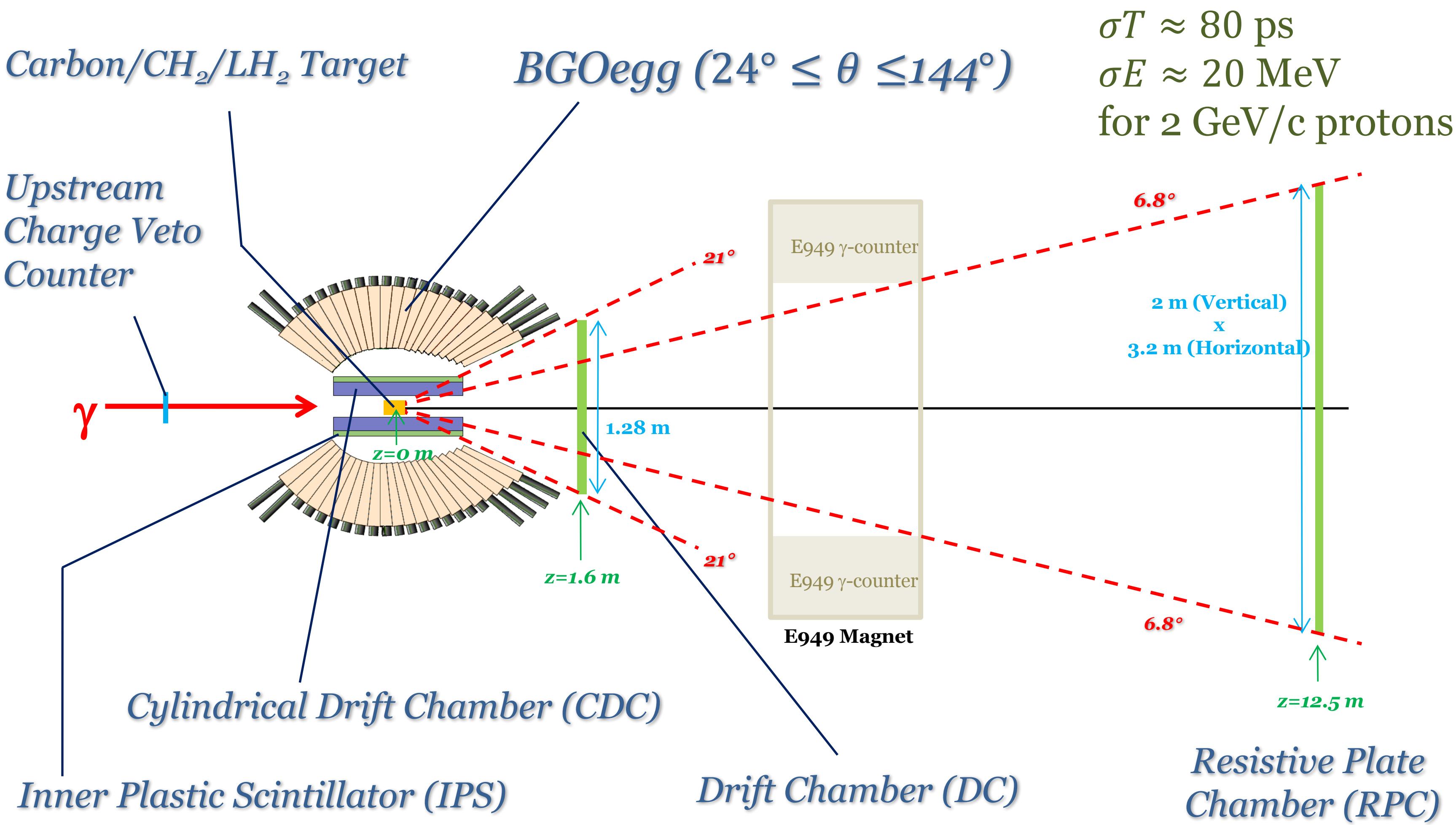


BGOegg under construction

Transportation of BGOegg from Sendai to SPring-8 by truck

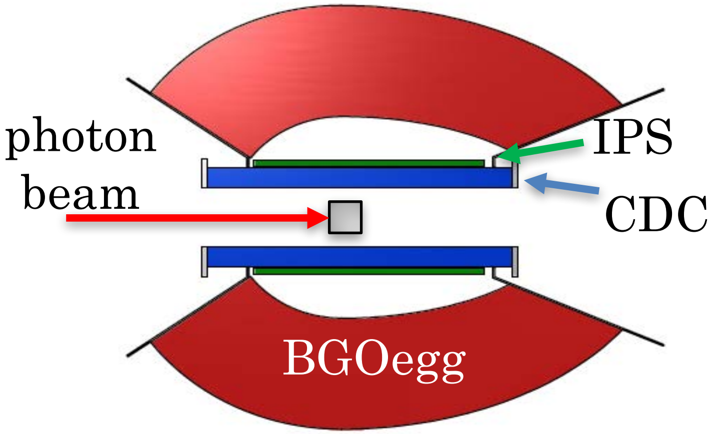
BGOegg @ SPring-8

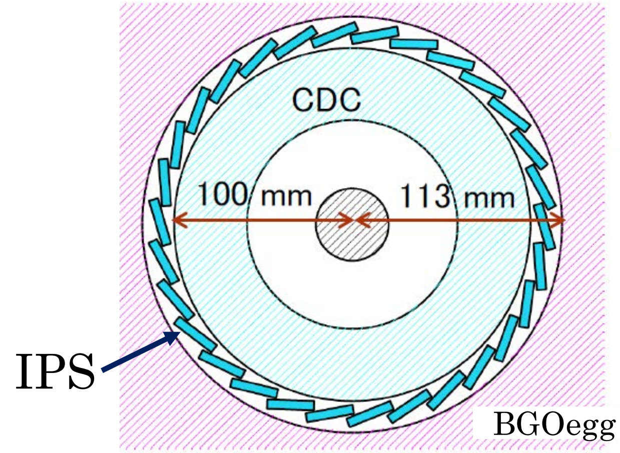
Layout of BGOegg experiments at LEPS2



Charged particle detection

with Inner Plastic Scintillator (IPS) and Cylindrical Drift Chamber (CDC) inside BGOegg

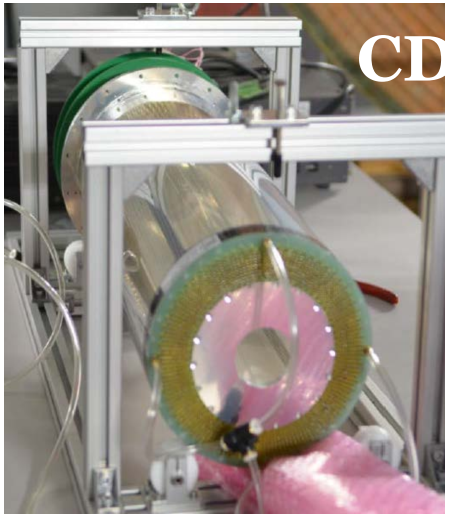




specifications

IPS: 30 plastic scintillator
453 mm x 26 mm x 5 mm
Multi Pixel Photon Counter(MPPC)
are placed only on one edge

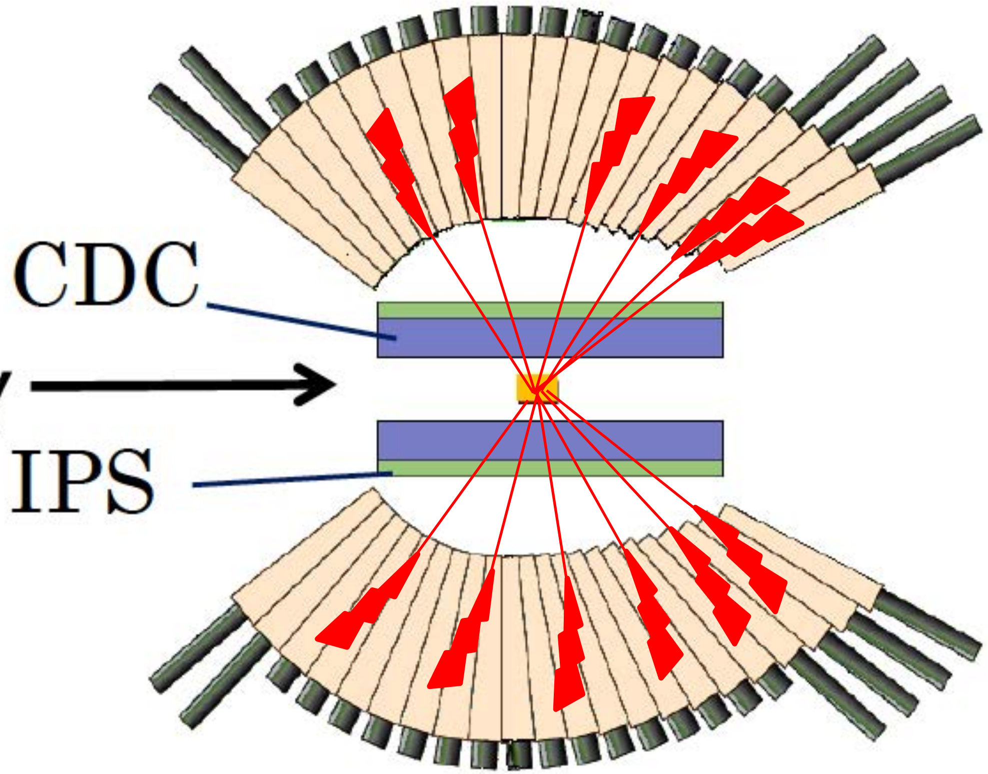
CDC: 72 stereo wires, 4 layers
inner diameter = 116 mm
outer diameter = 196 mm
chamber length = 550 mm
thickness = 40 mm

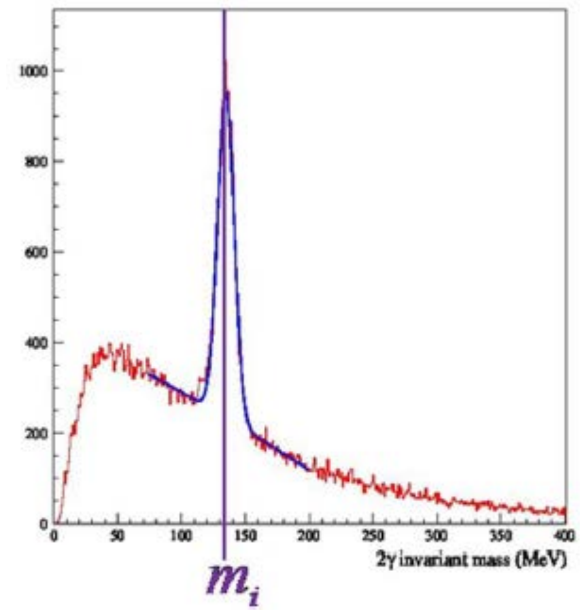


Energy calibration of BGOegg

most important job!

- Huge amounts of $\pi^0 \to \gamma\gamma$ events were used.
- Calibration was made so as to get π^0 mass just on the right place.
- Iterations are necessary to reach the final calibration result.
- All the $\gamma\gamma$ events are assumed to be generated at the center of the target.





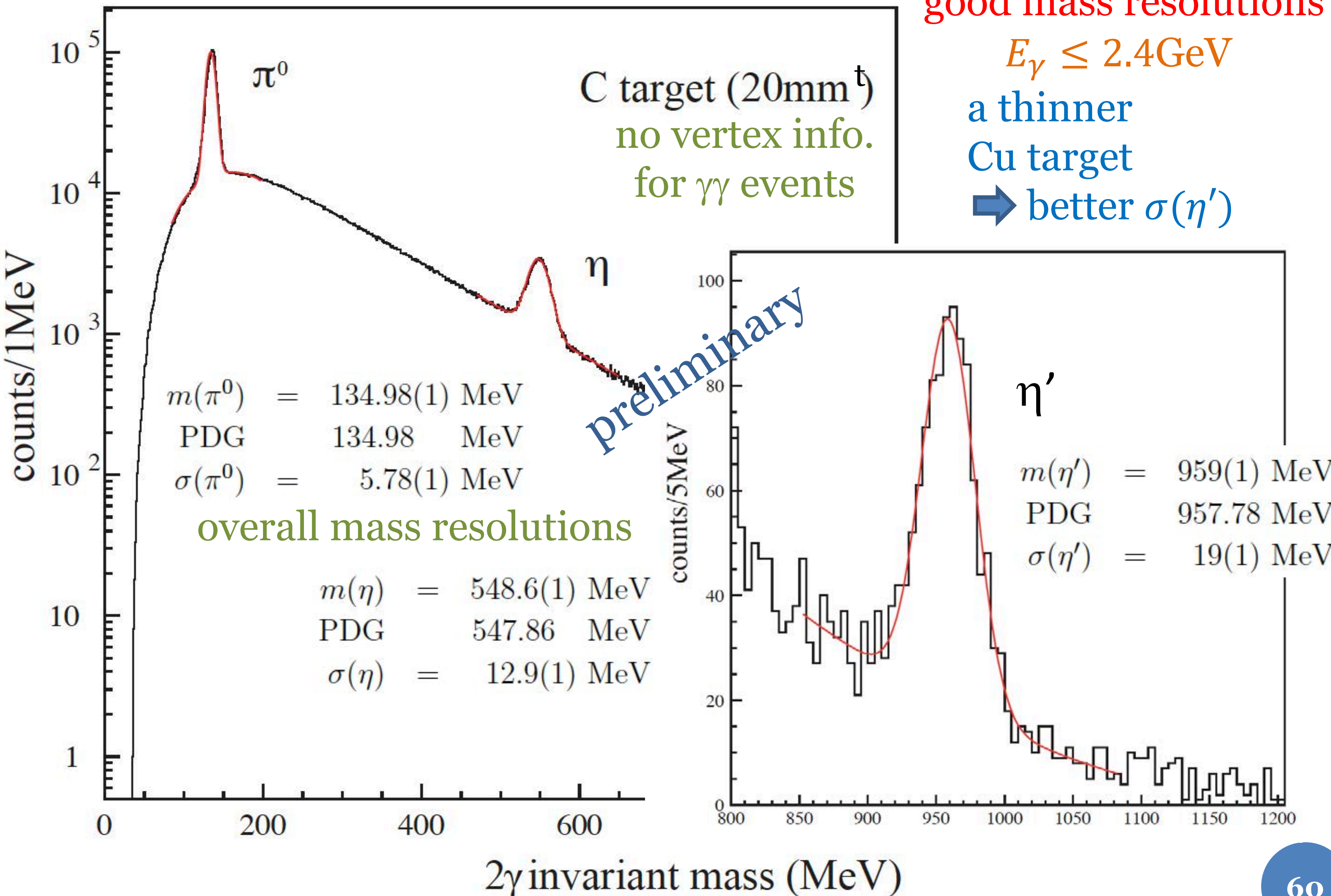
$m_i \to m_\pi = 134.98\ \mathrm{MeV}$

Calibration results (2γ invariant mass)

good mass resolutions

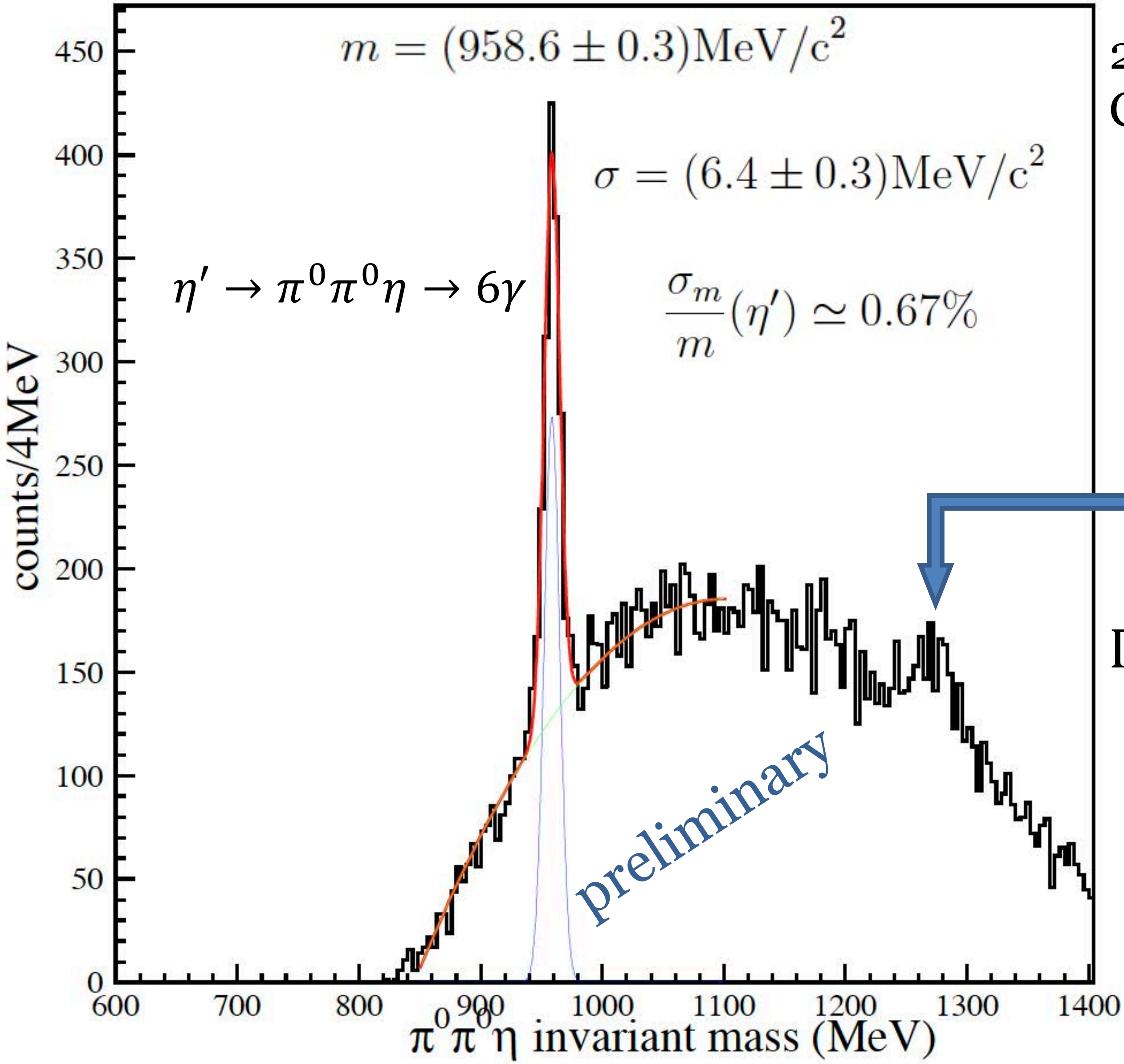
$E_\gamma \leq 2.4\mathrm{GeV}$

a thinner Cu target ➡ better $\sigma(\eta')$



$\pi^0\pi^0\eta$ invariant mass

with kinematical fit



20 mm^t
C target

$f_1(1285)$
1^{++}
$\Gamma = 24\,\mathrm{MeV}$

Summary for BGOegg experiments

- BGOegg experiments have been conducted at SPring-8/LEPS2.
- Goals of BGOegg experiments:

  to measure the spectral function of η' via $\eta' \rightarrow \gamma\gamma$

  in the nuclear medium

  to search for an η' mesic nucleus

~6 months
(effective data taking time)

- Data are accumulated for 2 years. (Liq.H_2 and C)
- Precise energy calibration was made for BGOegg.

  obtained $\gamma\gamma$ mass resolutions so far:

  $\sigma(\pi^0) \approx 5.8MeV, \quad \sigma(\eta) \approx 13MeV, \quad \sigma(\eta') \approx 19MeV$ (20mm^t C)

  intrinsic energy resolution of BGOegg: $\sigma(\gamma)/E_\gamma \approx 1.3\%@1GeV$
- Ready for analyzing data for physics.

  including Δ radius measurements