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The New Frontier of Neutral Color-Singlet $q\bar{q}$ Quark matter

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Author

Introduction to High-Energy Heavy-Ion Collisions
高能重离子碰撞导论，黄卓然著张卫宁译.

About the speaker: Cheuk-Yin Wong (黄卓然）

- born in Guangdong Province, China in 1941（广东梅县人）
- grew up in Hong Kong
- B.A. Princeton University, 1961
- Ph.D.Princeton University, 1966
- Oak Ridge National Laboratory, 1966 – now
- Research Fellow, Niels Bohr Institute, Denmark, 1968 – 1969
- Fellow of American Physical Society, 1979
- Visiting Scientist, M.I.T. 1982-1883
- Visiting Professor, University of Tokyo, 1988
- ……..

Neutral color-singlet $q\bar{q}$ quark matter is an important new frontier

- A new form of matter
- Consistent with existence of X17
- A window on confinement
- Connection to dark matter

Contents

I Color-singlet quark matter

II QED mesons as signature for neutral color-singlet quark matter

III Theoretical predictions of QED meson masses, at ~17 and ~38 MeV

IV Experimental observations of anomalous bosons by ATOMKI, DUBNA, and HUS, , at ~17 and ~38 MeV

V Theoretical support & experimental evidence suggest possible existence of QED mesons, as quanta of neutral color-singlet quark matter, pending confirmation.

CYWong,PRC81,064903(2010);arxiv:1001.1691
CYWong,JHEP2020(8),165;arxiv:2001.04864
CYWong,EPJA58,100(2020);arxiv:2010.13948
CYWong,FrontPhys18,64401(2023),arxiv:2208.09920
CYWong & A.Koshelkin,EPJA59,285(2024) arxiv:2111.14933
CYWong, in Proceedings of ISMD23, arxiv:2401.04142.
CYWong,Ukr.J.Phys.71,151(2026),arxiv:2601.01879

Quark matter and gauge fields in color space

q		$\bar{q}$					g	γ
3	$\otimes$	$\underline{3}$	$=$	8	$+$	1	8	1
q^3	$\otimes$	$\bar{q}^{\underline{3}}$	$=$	$[q\bar{q}]^8$	$+$	$[q\bar{q}]^1$		

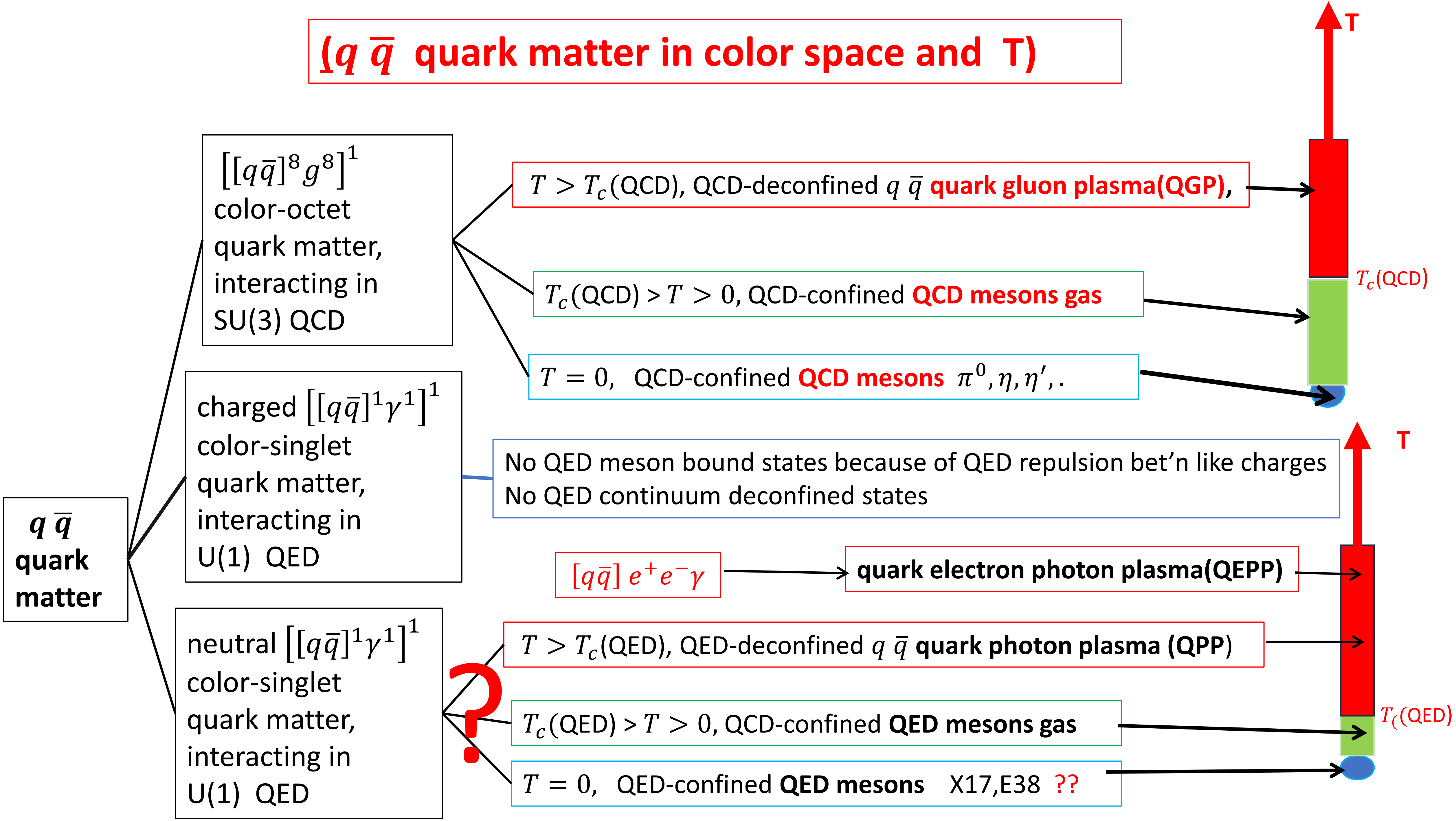
Principle of colorless observable entities:

An observable complex must be a colorless, color-singlet entity

- **color-octet quark matter in which q and $\bar{q}$ couple to color octet and interact in color-octet SU(3) gauge interaction,** $[[q\,\bar{q}]^8 g^8]^1$.

- **color-singlet quark matter in which q and $\bar{q}$ couple to color singlet and interact in color-singlet U(1) gauge interaction,** $[[q\,\bar{q}]^1 \gamma^1]^1$.

$(q\,\bar{q}$ quark matter in color space and T)



$q\,\bar{q}$ quark matter

$[[q\bar{q}]^8 g^8]^1$ color-octet quark matter, interacting in SU(3) QCD

$T > T_c$(QCD), QCD-deconfined $q\,\bar{q}$ **quark gluon plasma(QGP),**

T_c(QCD) > $T > 0$, QCD-confined **QCD mesons gas**

$T = 0$, QCD-confined **QCD mesons** $\pi^0, \eta, \eta', .$

charged $[[q\bar{q}]^1 \gamma^1]^1$ color-singlet quark matter, interacting in U(1) QED

No QED meson bound states because of QED repulsion bet'n like charges
No QED continuum deconfined states

$[q\bar{q}]\ e^+e^-\gamma$ → **quark electron photon plasma(QEPP)**

neutral $[[q\bar{q}]^1 \gamma^1]^1$ color-singlet quark matter, interacting in U(1) QED

?

$T > T_c$(QED), QED-deconfined $q\,\bar{q}$ **quark photon plasma (QPP)**

T_c(QED) > $T > 0$, QCD-confined **QED mesons gas**

$T = 0$, QED-confined **QED mesons** X17,E38 ??

Quark current $\boldsymbol{j^\mu(x,t)_{ij}}$ and gauge fields $\boldsymbol{A^\mu(x,t)_{ij}}$

- The **quark currents** $(\boldsymbol{j^\mu(x,t)})_{ij} = \langle\overline{\psi_i}\,\gamma^\mu\psi_j\rangle$ and **the gauge fields** $(\boldsymbol{A^\mu(x,t)})_{ij}$ are 3 × 3 matrices with 9 matrix elements in color space, at each space-time point (x,t)

- A general 3 × 3 color matrix can be represented by 9 basic matrices: $t^0, t^1, t^2, \ldots, t^8$,

  $t^0 = \frac{1}{\sqrt{6}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$ for **U(1)** , $t^1, t^2, \ldots, t^8$ the 8 Gell-Mann matrices for **SU(3)**,

  and 2 tr{ $t^i\, t^j] = \delta^{ij}$

- color-singlet current (electric current) $\boldsymbol{j^\mu_{color-singlet}} = \boldsymbol{j^\mu_{(0)}}\,(x,t)\ \ t^0$

  QED

  color-singlet QED gauge interaction (U(1) gauge interaction) $\boldsymbol{A^\mu_{color-singlet}} = \boldsymbol{A^\mu_{(0)}}(x,t)\ \ t^0$

  color–octet current (color current): $\boldsymbol{j^\mu_{color-octet}} = \boldsymbol{\sum_{i=1}^{8} j^\mu_{(i)}}(x,t)\ \ t^i$

  QCD

  color-octet QCD gauge interaction (SU(3) gauge interaction) $\boldsymbol{A^\mu_{color-octet}} = \boldsymbol{\sum_{i=1}^{8} A^\mu_{(i)}}(x,t)\ \ t^i$

Study of QED mesons

1) Schwinger showed in 1962 that **massless e^- and e^+** are **confined in QED in (1+1)D**.

2) q and $\bar{q}$ are approximately massless, and q and $\bar{q}$ reside predominantly in (1+1)D

3) therefore, **q and $\bar{q}$** are **confined in QED in (1+1)D** as a **$q\bar{q}$ QED meson in (1+1)D** .

4) **$q\bar{q}$ QED mesons in (1+1)D** may represent **physical QED mesons in (3+1)D**,

when the flux tube radius is taken into account, (CYWong,PRC81,064903(2010),JHEP2020(165))

5) The existence of $\boldsymbol{q\bar{q}}$ QED mesons in (3+1)D may explain many anomalies:

- soft photons anomaly: whenever hadrons are produced,

  soft photons in the form of excess e^+e^- are always produced
- neutral boson anomaly at ~ 17 MeV and ~38 MeV observed at ATOMKI, Dubna, and HUS

What is the nature of color-singlet quark matter in U(1) QED in (3+1)D ?

- Lattice gauge calculations using a Wilson loop confinement probe, indicates that $(e^- \text{ and } e^+)$ and $(\, q \text{ and } \bar{q})$ are deconfined in compact QED in (3+1)D at T=0

- Deconfinement of $(e^+ \text{ and } e^+)$ in (3+1)D QED is in agreement with observations

- However, lattice gauge theory prediction of deconfinement of $(q \text{ and } \bar{q})$ in (3+1)D QED appear to be inconsistent with the absence of fractional charges, when $(q \text{ and } \bar{q})$ can be produced with pair invariant mass $\sqrt{s_{pair}}$ within $2m_q < \sqrt{s_{pair}} < m_\pi$.

Likely possibilities

- The **U(1) gauge interaction between e^- and e^+** may be different from the **U(1) gauge interaction between q and $\bar{q}$** in the color-singlet quark fluid, because the U(1) interaction in **q and $\bar{q}$** is part of the U(3) = U(1)⨁SU(3) interaction.

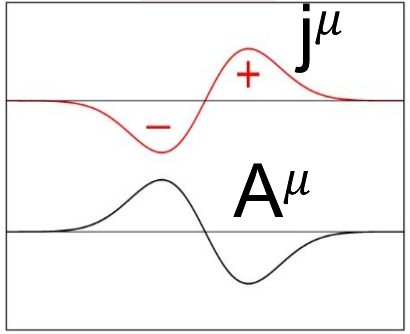
- q and $\bar{q}$ in neutral color-singlet quark matter may be confined and there may be QED mesons in the range $2m_q < \sqrt{s_{pair}} < m_\pi$.

We need to study 1) QED meson for neutral color-singlet quark matter
& 2) lattice gauge calculations for neutral color-singlet quark matter
in U(1)⨁ SU(3) with dynamical quarks in a flux tube

Schwinger confinement mechanism for massless $q\bar{q}$ in QED in (1+1)D

See Chapter6,CYWong'Intro.toHigh-EnergyHeavy-IonCollisions'

QED



- Consider the vacuum of massless quarks filling completely states below the Dirac sea in (1+1)D
- Introduce a QED gauge field A^μ acting on all quark states ψ

Dirac equation $\gamma_\mu(p^\mu\text{-}g_{2D}A^\mu)\psi = 0$

- The solution ψ generates a current, $j^\mu = \bar{\psi}\gamma^\mu\psi$, (Schwinger, 1962):

(1) $j^\mu = -\frac{g_{2D}}{\pi}(A^\mu - \partial^\mu \frac{1}{\partial^\lambda\partial_\lambda}\partial_\nu A^\nu)$, gauge-invariant under $(A^\nu)' = A^\nu - \partial^\nu\Lambda$

This second term needed to maintain gauge invariance

- The current j^μ generates a new gauge field $\tilde{A}^\mu$ through the Maxwell equation

(2) Maxwell equation: $\partial_\nu F^{\nu\mu} = \partial_\nu(\partial^\nu\tilde{A}^\mu - \partial^\mu\tilde{A}^\nu) = g_{2D}\, j^\mu$

- Stable collective motion is possible when $\tilde{A}^\mu = A^\mu$

$A^\mu \xrightarrow{\text{Dirac eq.}} j^\mu \xrightarrow{\text{Maxwell eq.}} \tilde{A}^\mu \to j^\mu \to A^\mu \to j^\mu \to \cdots$ (***A j A* non-linearity**)

- When $\tilde{A}^\mu = A^\mu$, Equations (1) and (2) are the same as (3) and (4) below

(3) $\partial_\nu\partial^\nu A^\mu + \frac{(g_{2D})^2}{\pi}A^\mu = 0$

(4) $\partial_\nu\partial^\nu j^\mu + \frac{(g_{2D})^2}{\pi}j^\mu = 0$

- Eqs. (3) and (4) are the Klein-Gordon equation for a stable boson, **QED meson in (1+1)D**, with a mass

$$m = \frac{g_{2D}}{\sqrt{\pi}}$$

Generalize Schwinger gauge theory in 1+1 dimesions from QED to (QED+QCD)

Consider massless quarks ψ in a gauge field A^μ in (1+1)D.

A^μ acts on ψ.

The Dirac equation is $\gamma_\mu(p^\mu\text{-}g_{2D}A^\mu)\psi = 0.$

ψ generates current $j^\mu = -\frac{g_{2D}}{\pi}\left(A^\mu - \partial^\mu \frac{1}{\partial^\lambda\partial_\lambda}\partial_\nu A^\nu\right)$

current j^μ generates A^μ through the Maxwell equation

$$\partial_\nu F^{\nu\mu} = \partial_\nu(\partial^\nu A^\mu - \partial^\mu A^\nu) = g_{2D}\, j^\mu$$

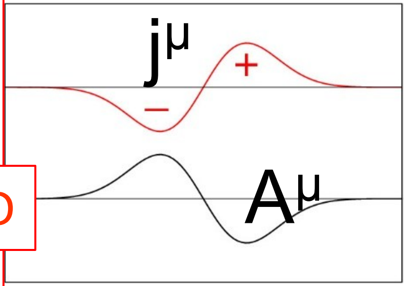
Stable collective motion occurs when A^μ and j^μ are self-

$$A^\mu \xrightarrow{\text{Dirac eq.}} j^\mu \xrightarrow{\text{Maxwell eq.}} A^\mu \rightarrow j^\mu \rightarrow \cdots$$ (***AjA* non-linearity**)

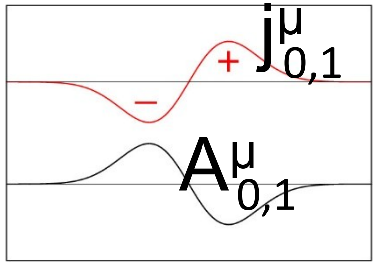
Then we get
$$\partial_\nu\,\partial^\nu A^\mu + \frac{(g_{2D})^2}{\pi} A^\mu = 0\,,$$
$$\partial_\nu\,\partial^\nu j^\mu + \frac{(g_{2D})^2}{\pi} j^\mu = 0\,,$$

which are the Klein-Gordon equations for a boson with a mass $m = \frac{g_{2D}}{\sqrt{\pi}}$

QED



$$\psi = \begin{pmatrix}\psi_{red}\\ \psi_{blue}\\ \psi_{green}\end{pmatrix}$$



(QED+QCD)

$$A^\mu = \sum_{i=0,1,2,..,8.} A_i^\mu t^i$$

$t^0 = \frac{1}{\sqrt{6}}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix}$ for color-singlet matrix

$t^1, t^2, \ldots, t^8$ color-octet Gell-Mann matrices

Consider the restricted variation that will lead to localized stable QCD bosons

$$A^\mu = A_0^\mu\tau^0 + A_1^\mu\tau^1$$ **quasi-Abelian approximation**

$$\tau^0 = t^0$$
$$\tau^1 = \sum_{i=1}^{8} n^i\, t^i$$

τ^1, a unit vector in SU(3) generator space.

Similarly, $j^\mu = j_0^\mu\tau^0 + j_1^\mu\tau^1$

We get $m^{QED} = \frac{g_{2D}^{QED}}{\sqrt{\pi}},\quad m^{QCD} = \frac{g_{2D}^{QCD}}{\sqrt{\pi}}$

How a $q\bar{q}$ meson in (1+1)D may represent a physical $q\bar{q}$ meson in (3+1)D ?

- In (3+1)D, the flux tube has a structure with a radius R_T, and the coupling constant g_{4D} is dimensionless.
- In (1+1)D, the open string has no structure, but the coupling constant g_{2D} has the dimension of a mass.

By reducing the Dirac equation for quarks from (3+1)D in a flux tube to the Dirac equation (1+1)D, we find that the information on the fluxtube radius R_T in (3+1)D is encoded into the coupling constant g_{2D} in (1+1)D:

$$(g_{2D})^2 = \frac{(g_{4D})^2}{\pi R_T^2}.$$

C.Y.Wong,PRC80,054917(2009)[arxiv:0903.3879]

- Thus, from fluxtube radius R_T and dimensionless 4D coupling constant g_{4D}, we get g_{2D} and the boson mass:

$$m^2 = \frac{(g_{2D})^2}{\pi} = \frac{(g_{4D})^2}{\pi^2 R_T^2} = \frac{4\alpha_{4D}}{\pi R_T^2}, \qquad \text{where } \alpha_{4D} = \frac{(g_{4D})^2}{4\pi}.$$

How a $q\bar{q}$ meson in (1+1)D may represent a physical $q\bar{q}$ meson in (3+1)D ?

$$m_{QCD}^2 = \frac{4\alpha_{4D}^{QCD}}{\pi R_T^2}, \qquad m_{QED}^2 = \frac{4\alpha_{4D}^{QED}}{\pi R_T^2}.$$

- If the flux tube radius R_T is an intrinsic property of the quark, then

$$\frac{(QCD\ meson\ mass\ m_{QCD})}{(QED\ meson\ mass\ m_{QED})} = \sqrt{\frac{\alpha_{qcd}}{\alpha_{qed}}} \approx \sqrt{\frac{0.7}{1/137}} \approx 10 \approx \frac{(hundreds\ MeV)}{(tens\ MeV)}, \qquad \frac{(QCD\ meson\ length)}{(QED\ meson\ length)} \approx \frac{1}{10}.$$

Two equivalent views of a QED or QCD meson in (3+1)D

- **Fundamental quantum field** theory viewpoint:

  A meson is a quanta of the quark fluid at T=0,

  a stable localized, collective, periodic space-time vibration

  of the quark current $j^\mu(x,t)$ and the gauge field $A^\mu\ (x,t)$.

QCD mesons: $\pi^0, \eta, \eta', ..$ are quanta of the color-octet quark fluid at T=0

QED mesons (yet to be uncovered) are quanta of the color-singlet quark fluid at T=0

- **Phenomenological, approximate, two-body viewpoint:**

  A meson is a bound state of a valence quark and a valance antiquark

  interacting with a phenomenological effective confining interaction.

meson masses with 2 flavors

$$m_i^2 = \left[\sum_{j=1}^{N_f} D_{ij}\, Q_j\right]^2 \frac{4\alpha_{4D}}{\pi R_T^2},$$

where the physical state $\Phi_i = \sum_{j=1}^{N_f} D_{ij}\varphi_j$, $\varphi_1 = |u\bar{u}>, \varphi_2 = |d\bar{d}>$,

$$\begin{pmatrix}\Phi_{isovector}\\ \Phi_{isoscalar}\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}1 & -1\\ 1 & 1\end{pmatrix}\begin{pmatrix}|u\bar{u}>\\ |d\bar{d}>\end{pmatrix}, \qquad \begin{pmatrix}m^2_{isovector}\\ m^2_{isoscalr}\end{pmatrix} = \frac{1}{2}\begin{pmatrix}(Q_u - Q_d)^2\\ (Q_u + Q_d)^2\end{pmatrix}\frac{4\alpha_{4D}}{\pi R_T^2}$$

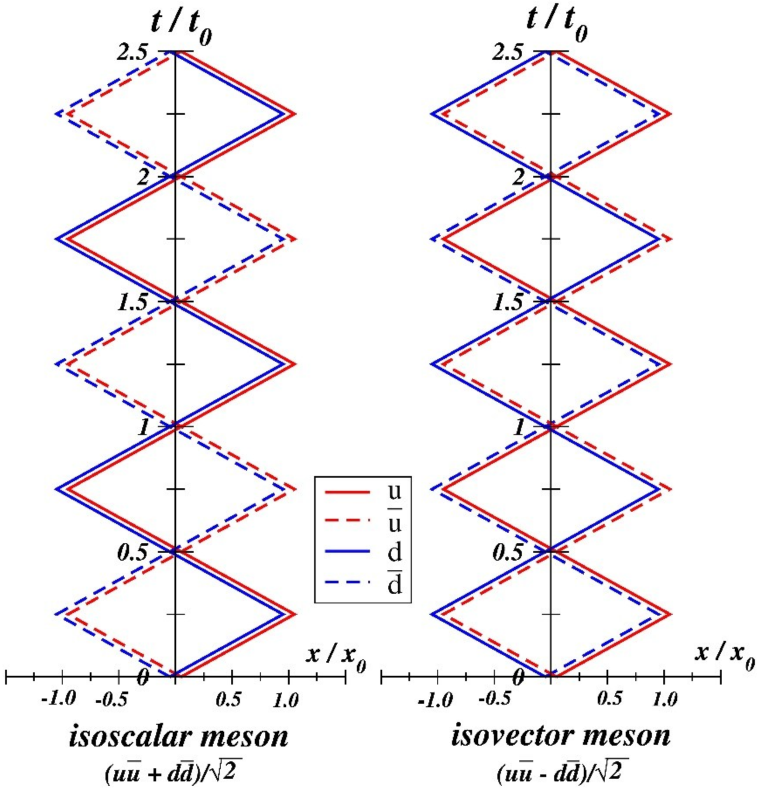
(i) for QCD, the color charges are $Q_u^{QCD} = Q_d^{QCD} = 1$

(iii) for QED, the electric charges are $Q_u^{QED} = \frac{2}{3}$, $Q_d^{QED} = -\frac{1}{3}$

C.Y.Wong,PRC80,054917(2009)[arxiv:0903.3879]
CYWong,JHEP08(2020)165,[arxiv:2001.04864

QED and QCD meson masses with 2 flavor

$$\Phi_{I=0,I_3=0}=\frac{1}{\sqrt{2}}(|u\bar{u}>+|d\bar{d}>)$$
$$\Phi_{I=1,I_3=0}=\frac{1}{\sqrt{2}}(|u\bar{u}>-|d\bar{d}>)$$



CYWong,PRC81,064903(2010),[arxiv:1001.1691]
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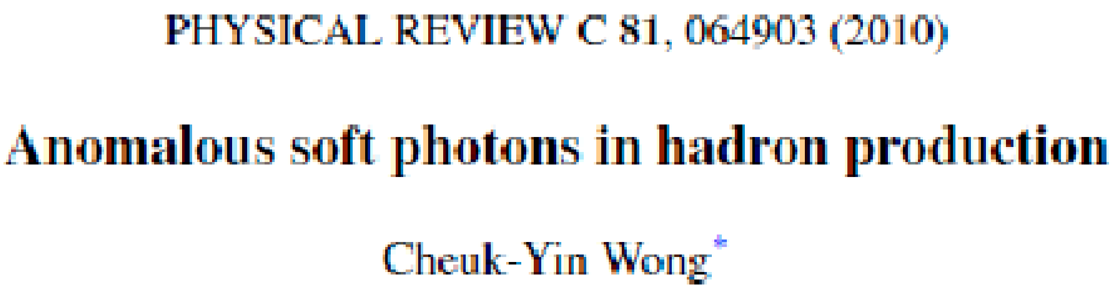


PHYSICAL REVIEW C 81, 064903 (2010)

Anomalous soft photons in hadron production

Cheuk-Yin Wong*

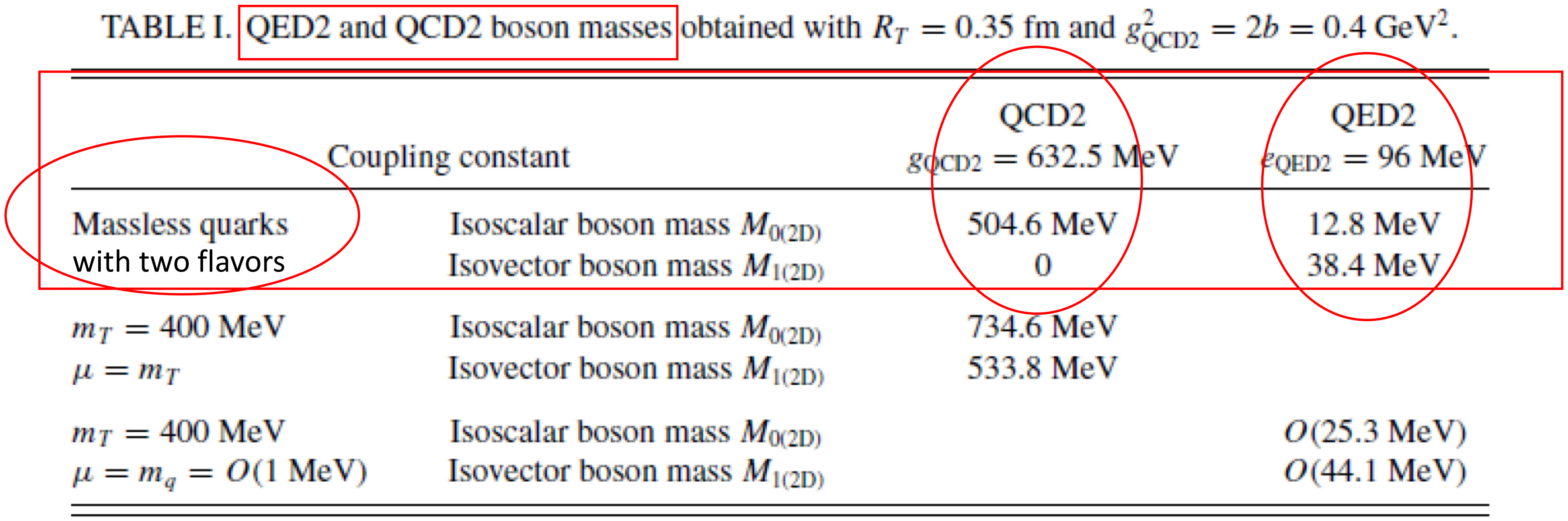


TABLE I. QED2 and QCD2 boson masses obtained with $R_T = 0.35$ fm and $g^2_{\rm QCD2} = 2b = 0.4\ {\rm GeV}^2$.

Coupling constant		QCD2 $g_{\rm QCD2} = 632.5$ MeV	QED2 $e_{\rm QED2} = 96$ MeV
Massless quarks with two flavors	Isoscalar boson mass $M_{0(2D)}$	504.6 MeV	12.8 MeV
	Isovector boson mass $M_{1(2D)}$	0	38.4 MeV
$m_T = 400$ MeV	Isoscalar boson mass $M_{0(2D)}$	734.6 MeV	
$\mu = m_T$	Isovector boson mass $M_{1(2D)}$	533.8 MeV	
$m_T = 400$ MeV	Isoscalar boson mass $M_{0(2D)}$		$O(25.3\ {\rm MeV})$
$\mu = m_q = O(1\ {\rm MeV})$	Isovector boson mass $M_{1(2D)}$		$O(44.1\ {\rm MeV})$

QCD mesons with 3 flavors

For quantitative descriptions of QCD and QED mesons, we must take into account

(i) color charges, $Q_u^{QCD} = Q_d^{QCD} = Q_s^{QCD} = 1$ for QCD

(ii) electric charges, $Q_u^{QED} = \frac{2}{3}$, $Q_d^{QED} = -\frac{1}{3}$ for QED

(iii) flavor mixture D_{ij} of the physical states $\Phi_i = \sum_{j=1}^{N_f} D_{ij}\,|q_j\bar{q}_j>$

(iv) the quark condensate and the quark masses m_u , m_d , and m_s

$$m_i^2 = \frac{4\alpha_{4D}}{\pi R_T^2}\left[\sum_{j=1}^{N_f} D_{ij}\, Q_j\right]^2 + m_\pi^2 \frac{\alpha_{4D}}{\alpha_{4D}^{QCD}} \sum_{j=1}^{N_f} \frac{m_f}{(m_u+m_d)/2} \left(D_{ij}\right)^2$$

the mass of a confined meson, as inferred from the Schwinger confinement mechanism

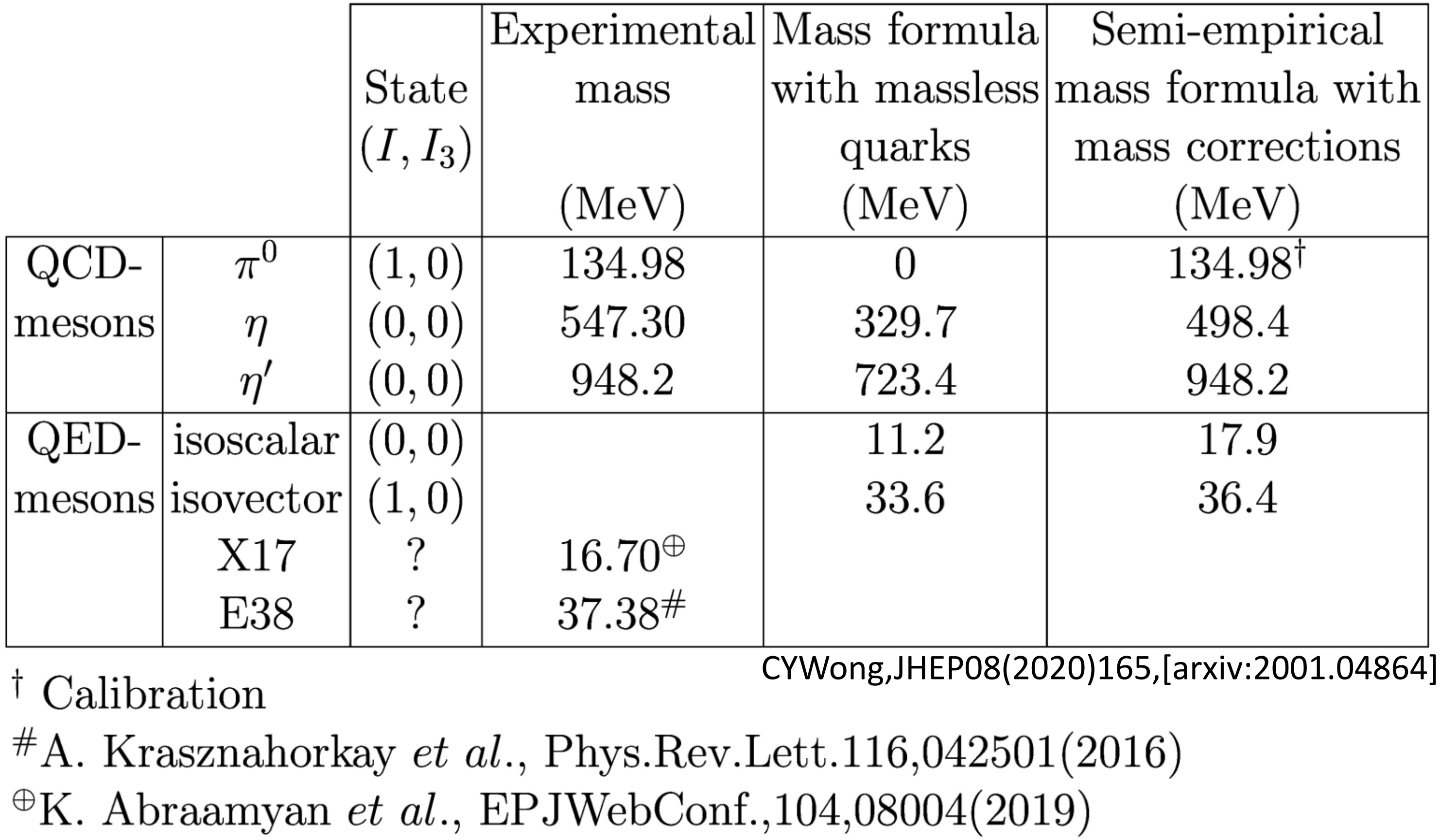
CYWong,JHEP(2020),165,arxiv:2001.04864

QCD mesons with 3 flavors

$$m_i^2 = \frac{4\alpha_{4D}}{\pi R_T^2}\left[\sum_{j=1}^{N_f} D_{ij}\, Q_j\right]^2 + m_\pi^2 \frac{\alpha_{4D}}{\alpha_{4D}^{QCD}} \sum_{f=1}^{N_f} \frac{m_f}{(m_u+m_d)/2} \left(D_{ij}\right)^2 ,$$

for the physical state $\Phi_i = \sum_{j=1}^{N_f} D_{ij} |q_j\, \bar{q}_j >$,

with D_{ij} and m_j from PDG Tables, $R_T = 0.4$ fm, $\alpha_{4D}^{QCD} = 0.68$, $\alpha_{4D}^{QED} = \frac{1}{137}$.



		State (I, I_3)	Experimental mass (MeV)	Mass formula with massless quarks (MeV)	Semi-empirical mass formula with mass corrections (MeV)
QCD-mesons	π^0	$(1,0)$	134.98	0	$134.98^\dagger$
	η	$(0,0)$	547.30	329.7	498.4
	η'	$(0,0)$	948.2	723.4	948.2
QED-mesons	isoscalar	$(0,0)$		11.2	17.9
	isovector	$(1,0)$		33.6	36.4
	X17	?	$16.70^\oplus$		
	E38	?	$37.38^\#$		

† Calibration

A. Krasznahorkay *et al.*, Phys.Rev.Lett.116,042501(2016)

⊕ K. Abraamyan *et al.*, EPJWebConf.,104,08004(2019)

CYWong,JHEP08(2020)165,[arxiv:2001.04864]

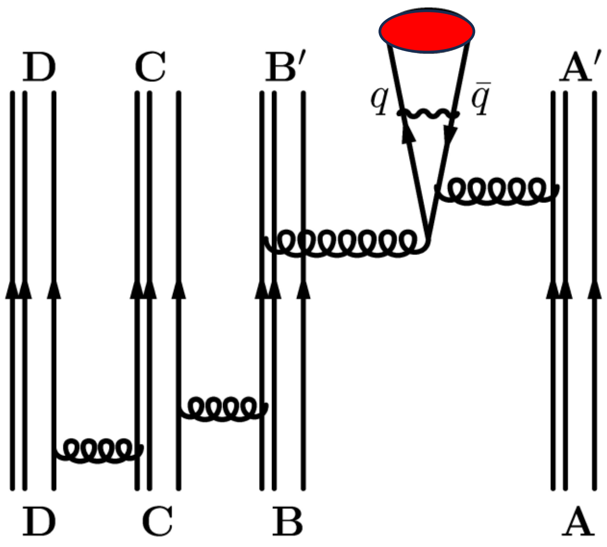
QCD mesons
& QED mesons
are reasonable
concepts!

Confrontation of theoretical QED meson predictions with experiment

We need

1. to produce QED mesons
2. to detect QED mesons by their decays
3. and measure the invariant mass of the decay products

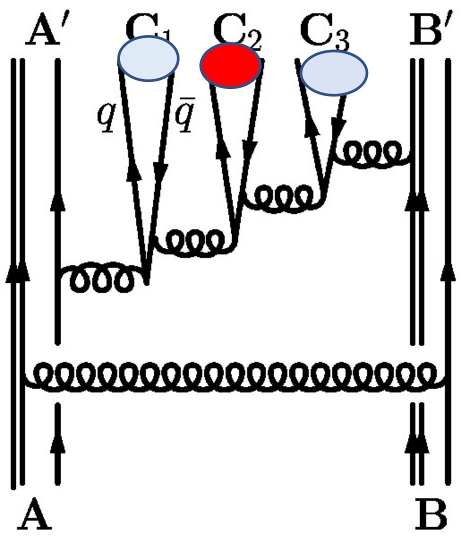
QCD meson (○) and QED mesons (●) can be produced in hadron-hadron colliisons



(a)

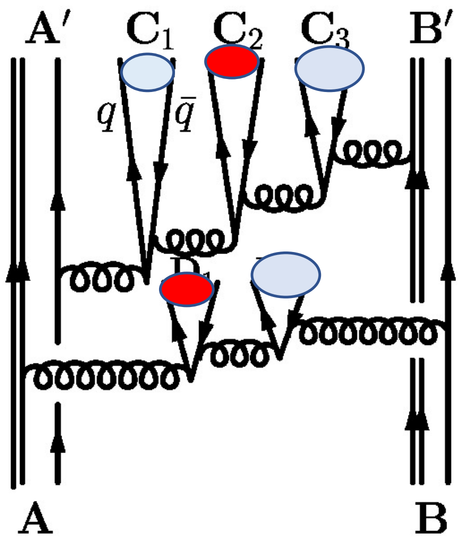
(i) Low excitation energies below pion mass threshold
(ATOMKI experiments)

(ii) Peripheral high-energy parton-parton collisions



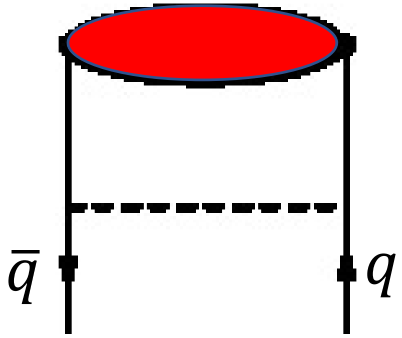
(b)

Intermediate energy hadron-hadron and nucleus-nucleus collisions above pion mass threshold
(Anomalous soft photons, Dubna experiments.)



(c)

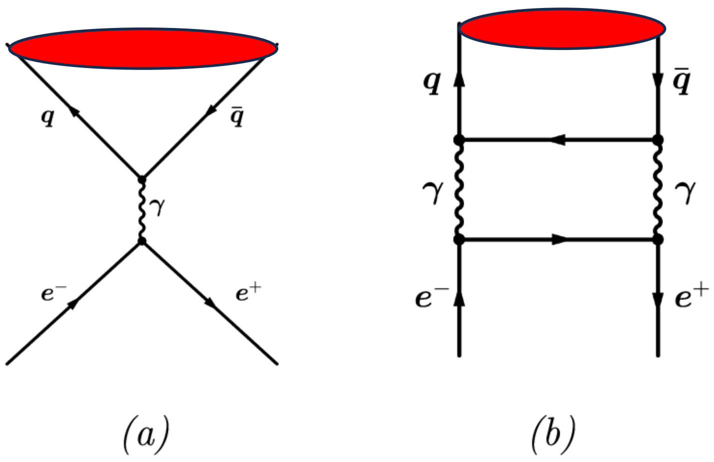
High energies central AA Collisions (RHIC and LHC experiments)



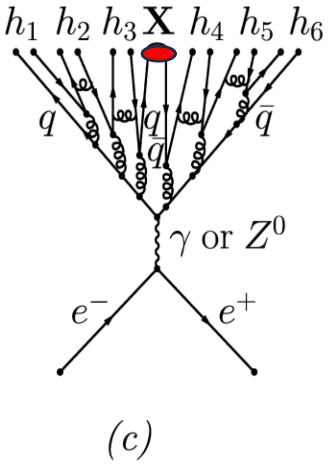
(d)

Coalescence during deconfinement-to confinement QGP phase transition in high energies central AA collisions
(RHIC & LHC experiments)

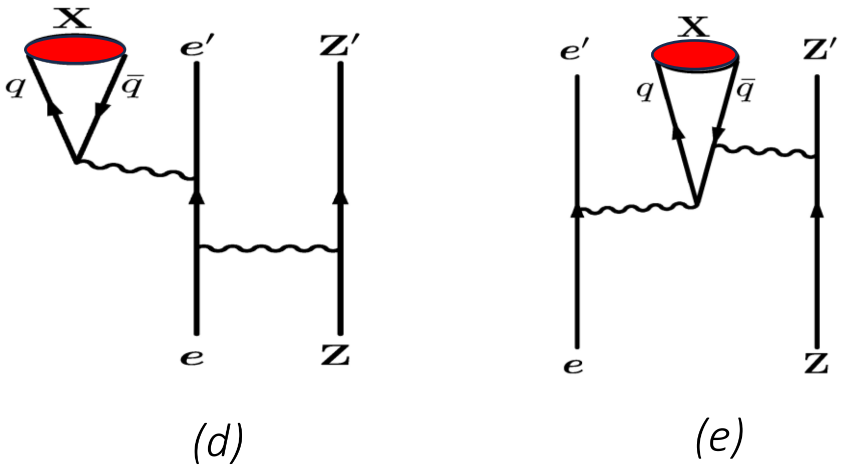
QCD mesons and QED mesons can be produced in e^+- e^- and e-A collisions



QED meson production by low-energy e^+e^- annihilation below pion mass threshold, $\sqrt{s_{e^+e^-}} \le m_\pi$
(inverse ATOMKI experiment)



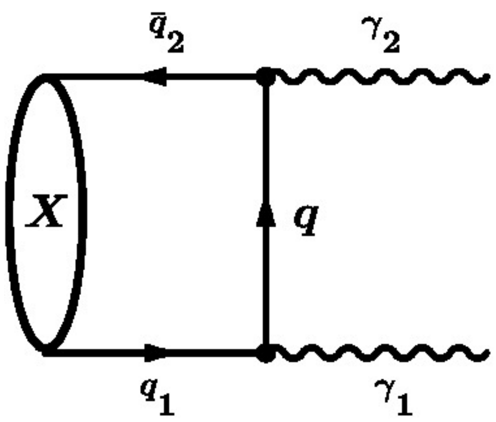
QED meson production
by high-energy e^+e^- annihilation
(DELPHI,PADME experiments,…)



QED meson production by electron-nucleus bremsstrahlung-type reactions
(JLAB experiment,…)

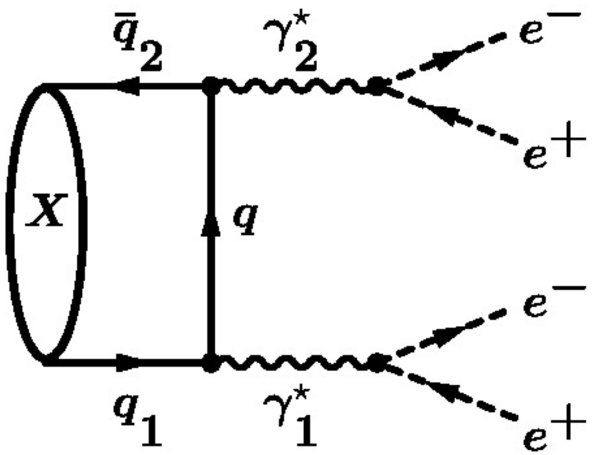
QED meson decay and decay products

QED mesons can be detected by (a) $\gamma\gamma$, (b) $\gamma^*\gamma^*$, and (c) e^+e^-



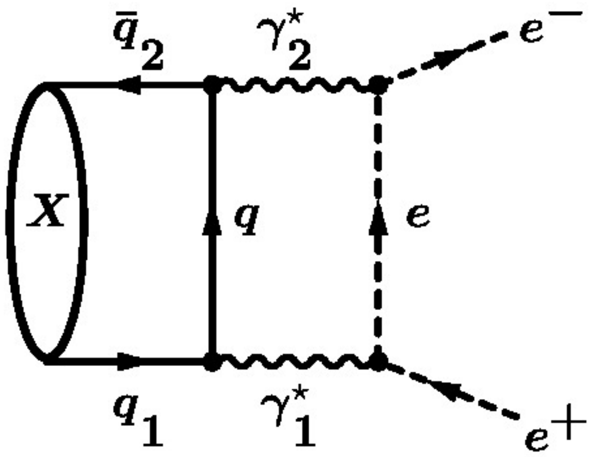
(a)

Detection using the invariant mass of two real photons
-- Dubna



(b)

Detection using the invariant mass of two virtual photons
-- RHIC?



(c)

Detection using invariant mass of e^+e^-
-- ATOMKI
Excess e^+e^- -- anomalous soft photons

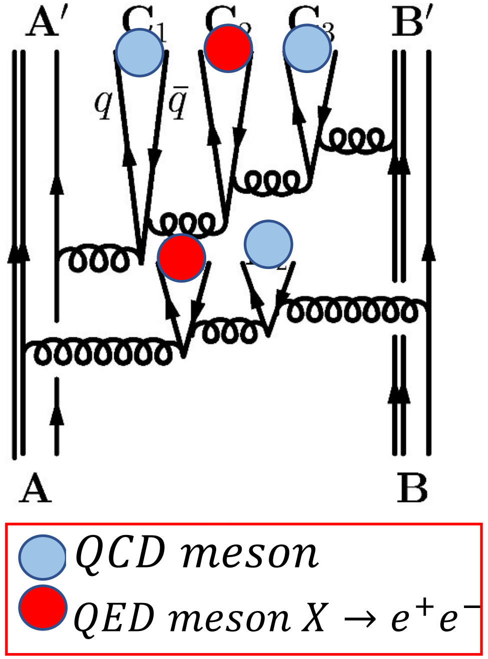
Experimental evidence for anomalous photons with pT < 60 MeV/c

How may QED mesons be produced?

Anomalous soft photons (excess e+e-) are always produced whenever hadrons are produced. They are not produced when hadrons are not produced.

Experiment	Collision Energy	Photon pT	Photon/Brems Ratio
Exclusive measurements with knowledge of all particle momenta to determine bremmstrahlung contributions			
K$^+$ p, CERN WA27,BEBC(1984)	70 GeV/c	PT < 60 MeV/c	4.0 ± 0.8
K$^+$ p, CERN NA22, EHS (1993) π$^+$ p, CERN NA22, EHS (1997)	250 GeV/c 250 GeV/c	PT < 40 MeV/c PT < 40 MeV/c	6.4 ± 1.6 6.9 ± 1.3
π$^-$ p , CERN WA83,OMEGA(1997)	280 GeV/c	PT < 10 MeV/c	7.9 ± 1.4
π$^-$ p , CERN WA91,OMEGA(2002)	280 GeV/c	PT < 20 MeV/c	5.3 ± 0.9
p p , CERN WA102,OMEGA(2002)	450 GeV/c	PT < 20 MeV/c	4.1 ± 0.8
e+e-→hadrons CERN DELPHI(2010) with hadron production	~91 GeV (CM)	PT < 60 MeV/c	~4.0
e+e- →μ+μ- CERN DELPHI(2008) with no hadron production	~91 GeV (CM)	PT < 60 MeV/c	~1.0

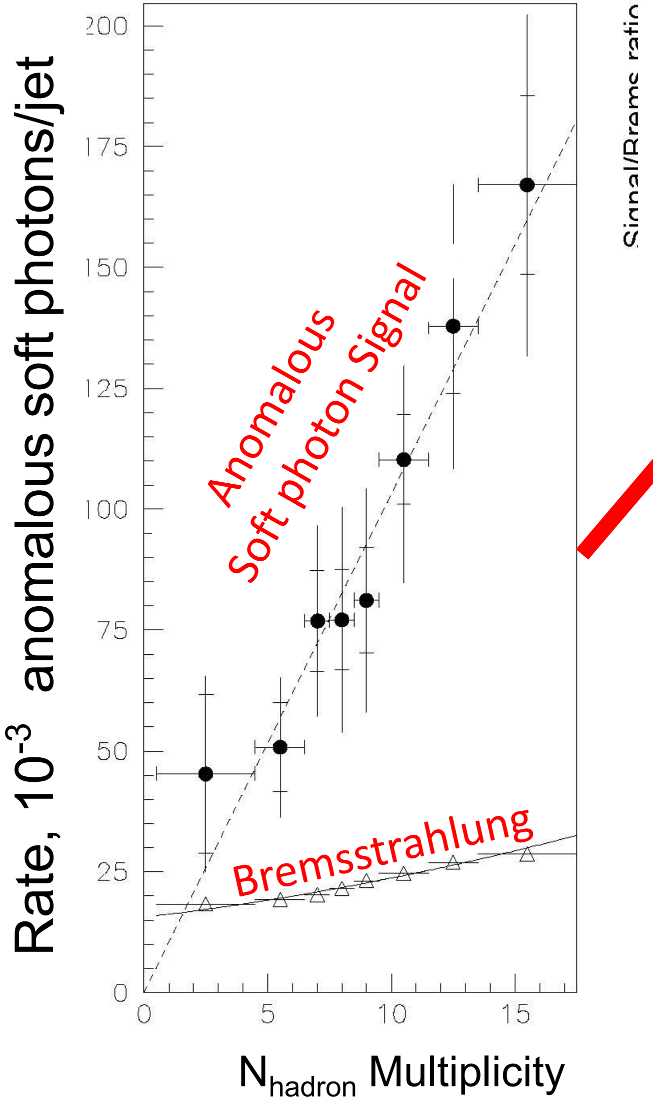
(Table compiled by V. Perepelitsa, 2009)



Anomalous soft photon yield is proportional to the hadron yield

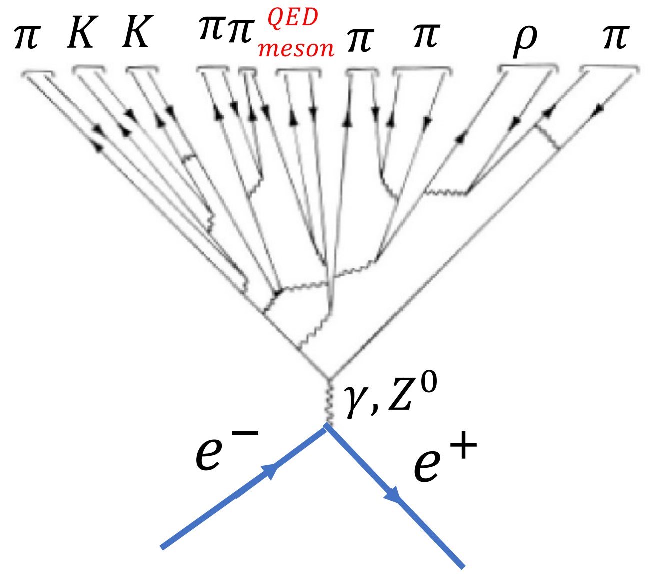
e+e- annihilation at Z0 decay (~ 91 GeV)

DELPHI (EPJ 2010) arXiv:1004.1587

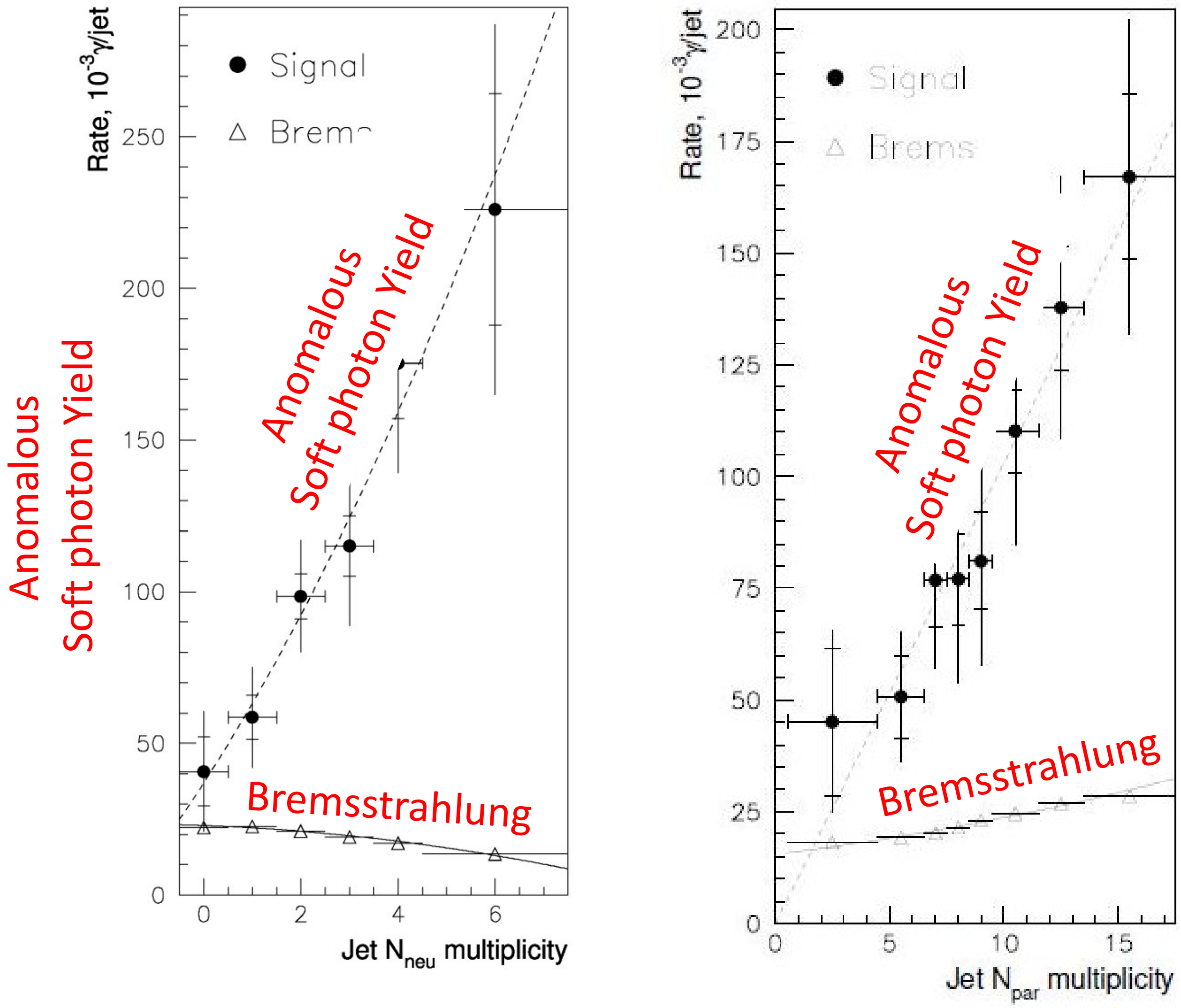


$$\frac{\text{Number of anomalous soft photons}}{\text{Number of produced hadrons}} \approx \frac{150 \times 10^{-3}}{15} \approx \frac{1}{100}$$

CYWong,PRC81,064903(2010);arxiv:1001.1691



Anomalous soft photons (ASP) and QCD mesons arise likely from similar $q\bar{q}$ production mechanisms



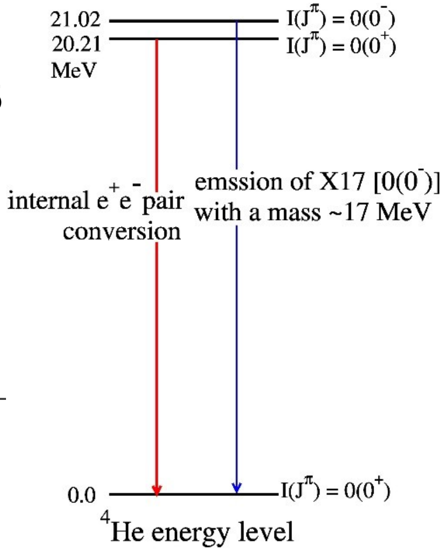
Anomalous soft photons are produced in a neutral charged environment!

This is consistent with:
1) QED mesons are quanta of a neutral color-singlet quark matter
2) no QED mesons are produced in a charged color-singlet quark matter.

Experimental evidence for anomalous bosons with masses ~17 MeV and ~38 MeV

X17 particle observed in decay of ^{4}He* at Atomki

Krasznahorkay et al, PRC104,044003(2021) arxiv:2104.10075



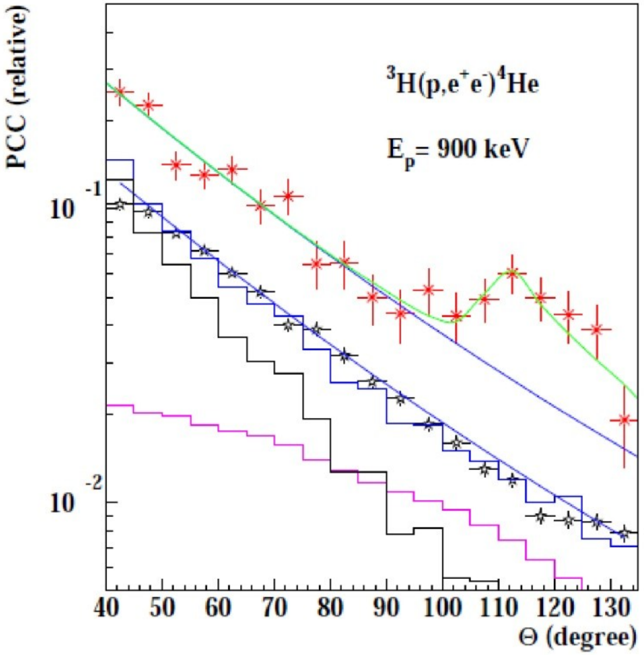


FIG. 2. *Angular correlations for the* e^+e^- *pairs measured the* $^3H(p,\gamma)^4He$ *reaction at the* E_p*=900 keV.*

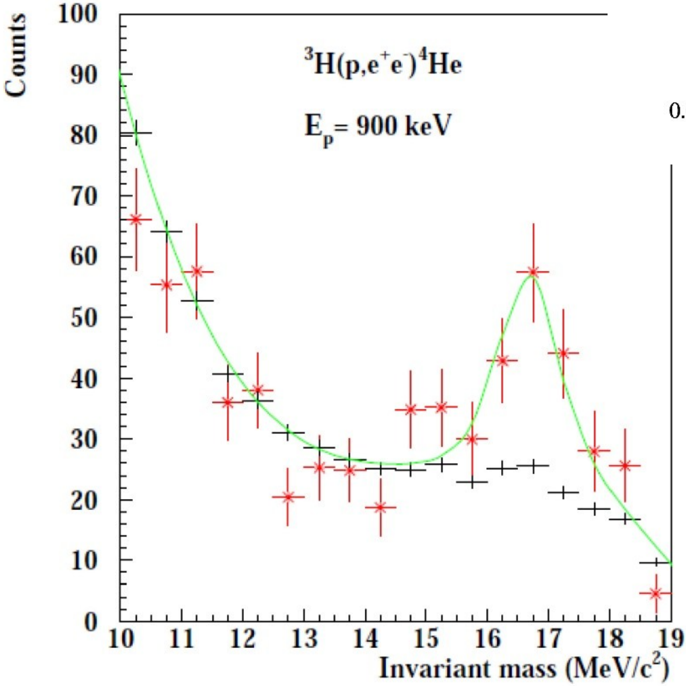
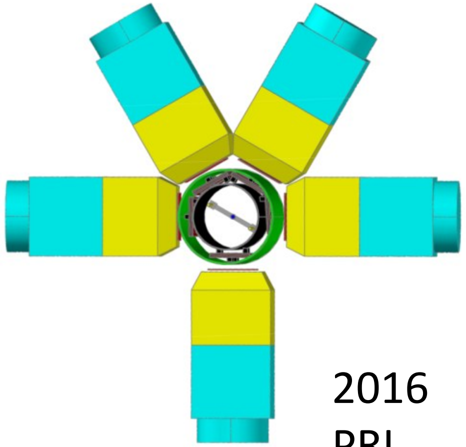


FIG. 3. *Invariant mass distribution derived for the 20.49 MeV transition in* ^4He.

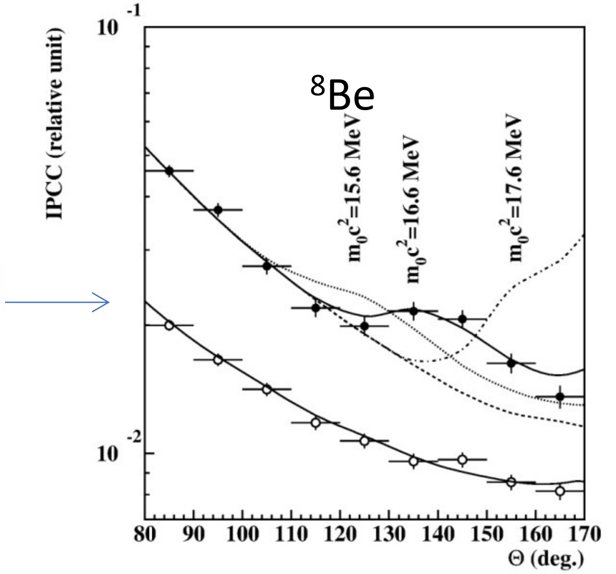
ATOMKI experimental results

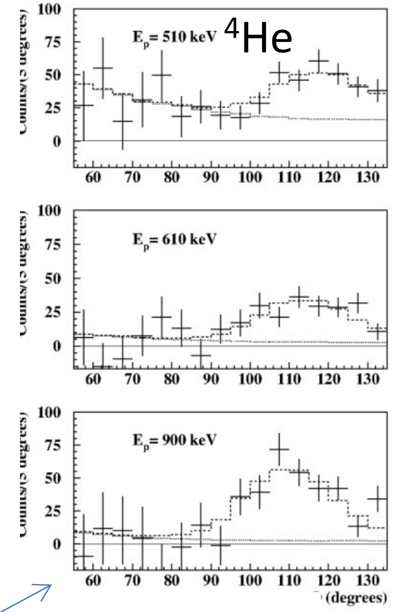
Krasznahorkay et al, ISMD2023



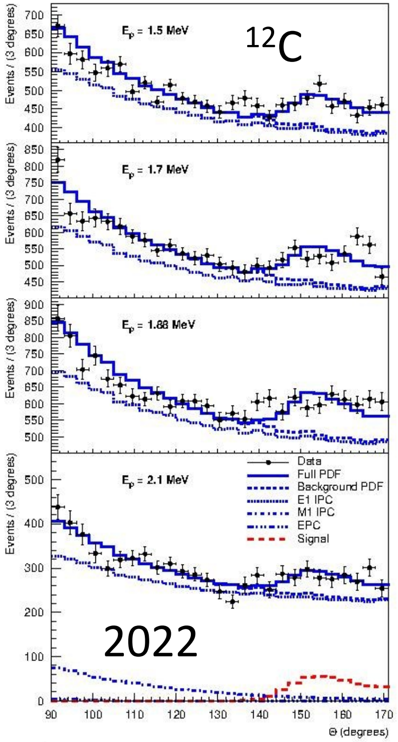
2016

PRL

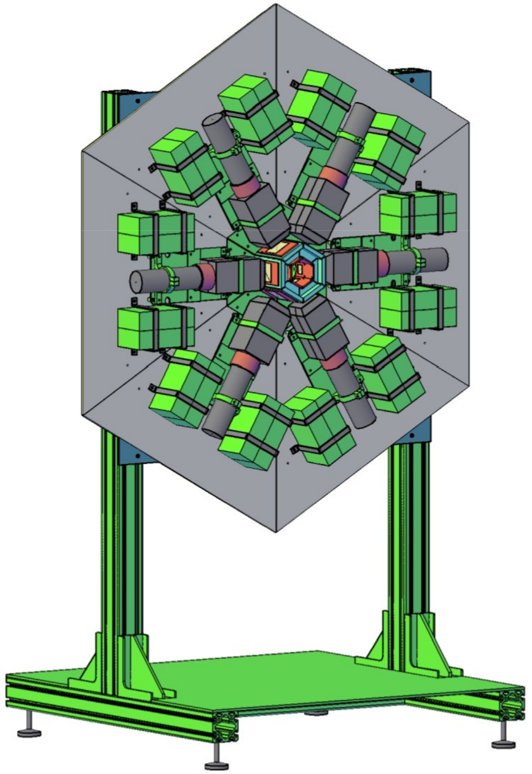




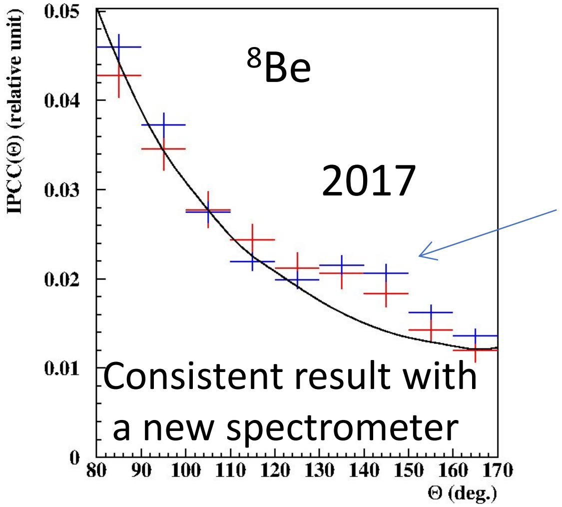
2021



2022

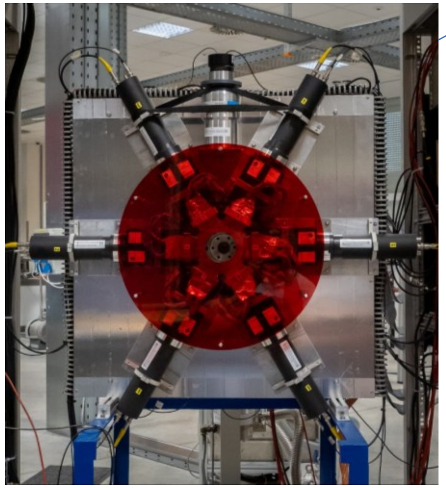


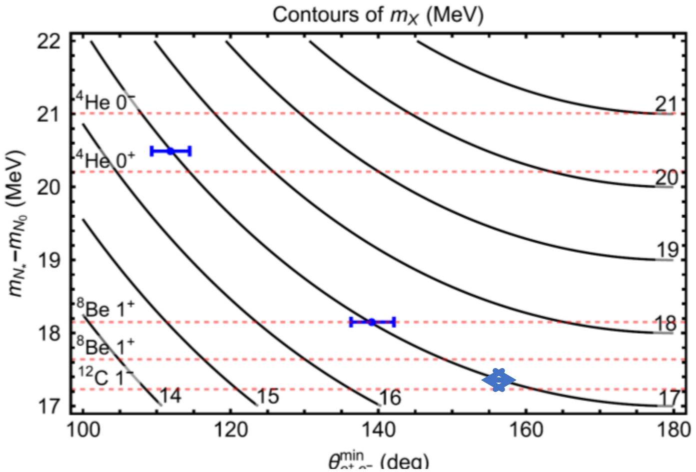
The newest version of the spectrometer



2017

Consistent result with a new spectrometer





- **Kinematical evidence for the X17 particle**
- **Vector character of X17 is supported**
- **Ejected with L=1 in ^{8}Be**

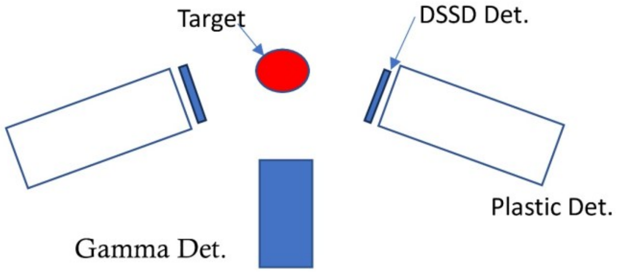
Tran et al, ISMD2023

Hanoi University of Science (HUS)

Experiment Setup

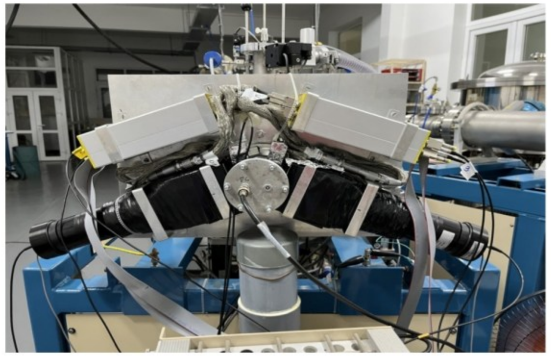
We used p-beam with different energies to bombard the Li-target to populate 18.15 and 17.6 MeV ^{8}Be excited states with resonant proton capture.

$^{7}Li(p,e^{-}e^{+})^{8}Be$

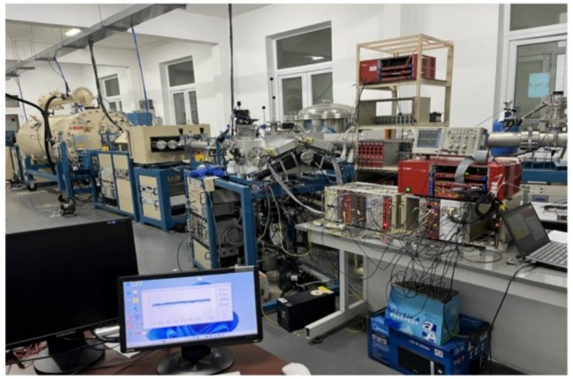


Why did we arrange the Det-system like this?

Detector setup to measure the energies and the angle between the e^{+} e^{-} particles.

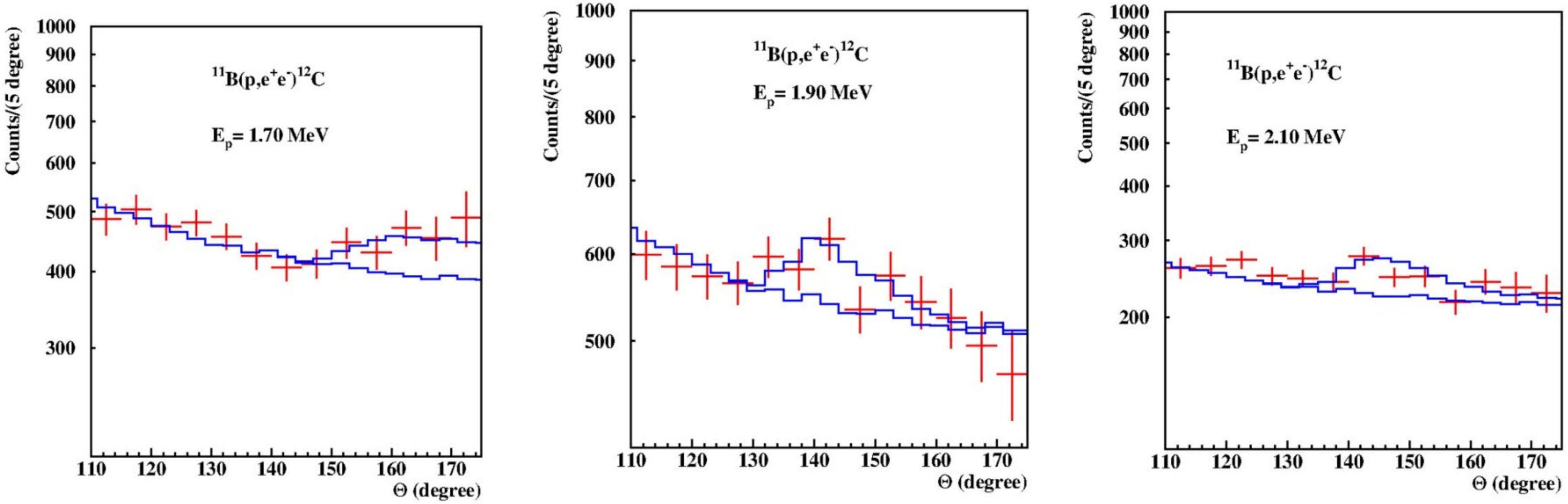


Picture in lab of the detector system and the DAQ connected to Pelletron



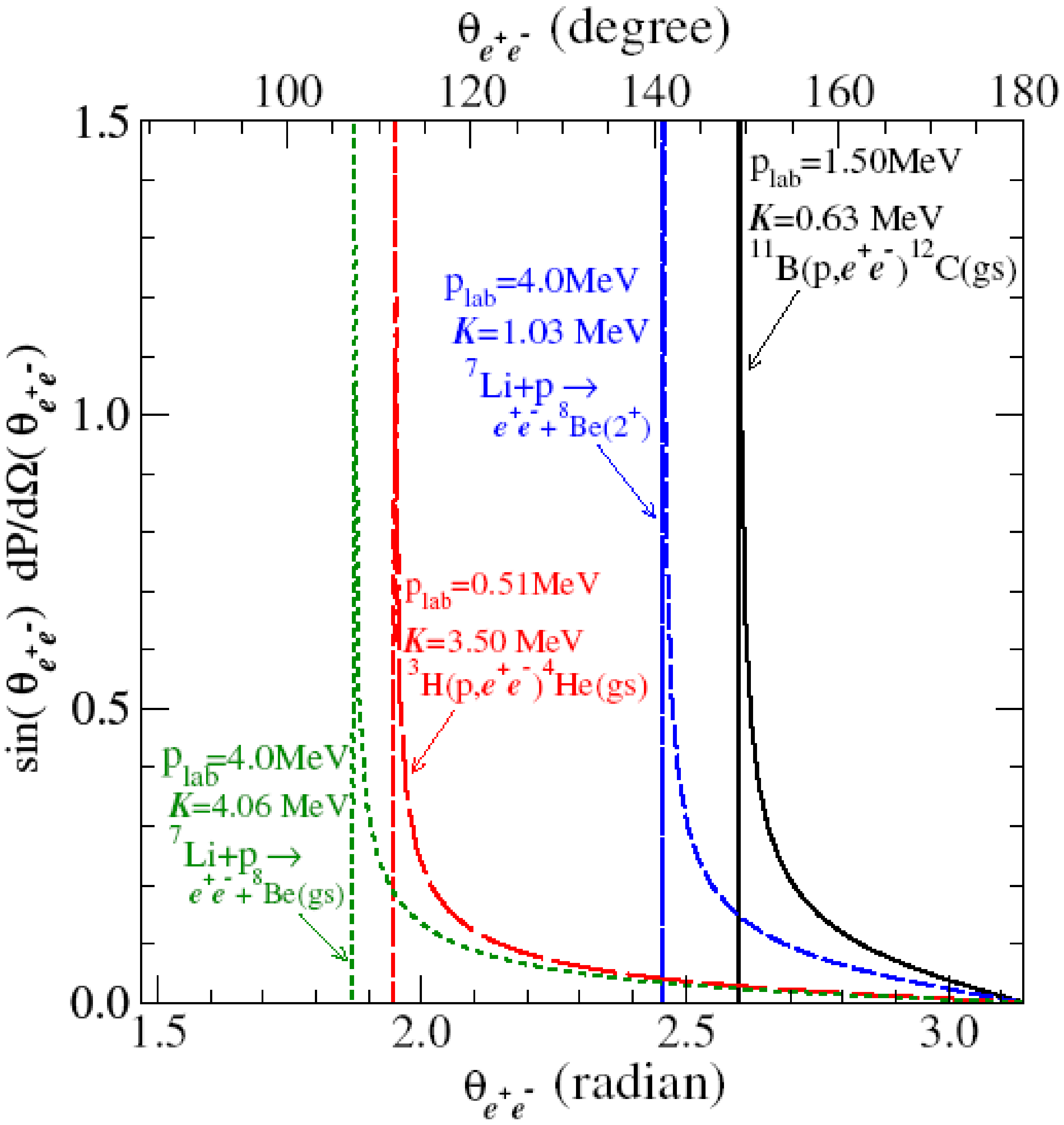
Preliminary results for $^{11}B(p, e^+ e^-)^{12}C$ reaction

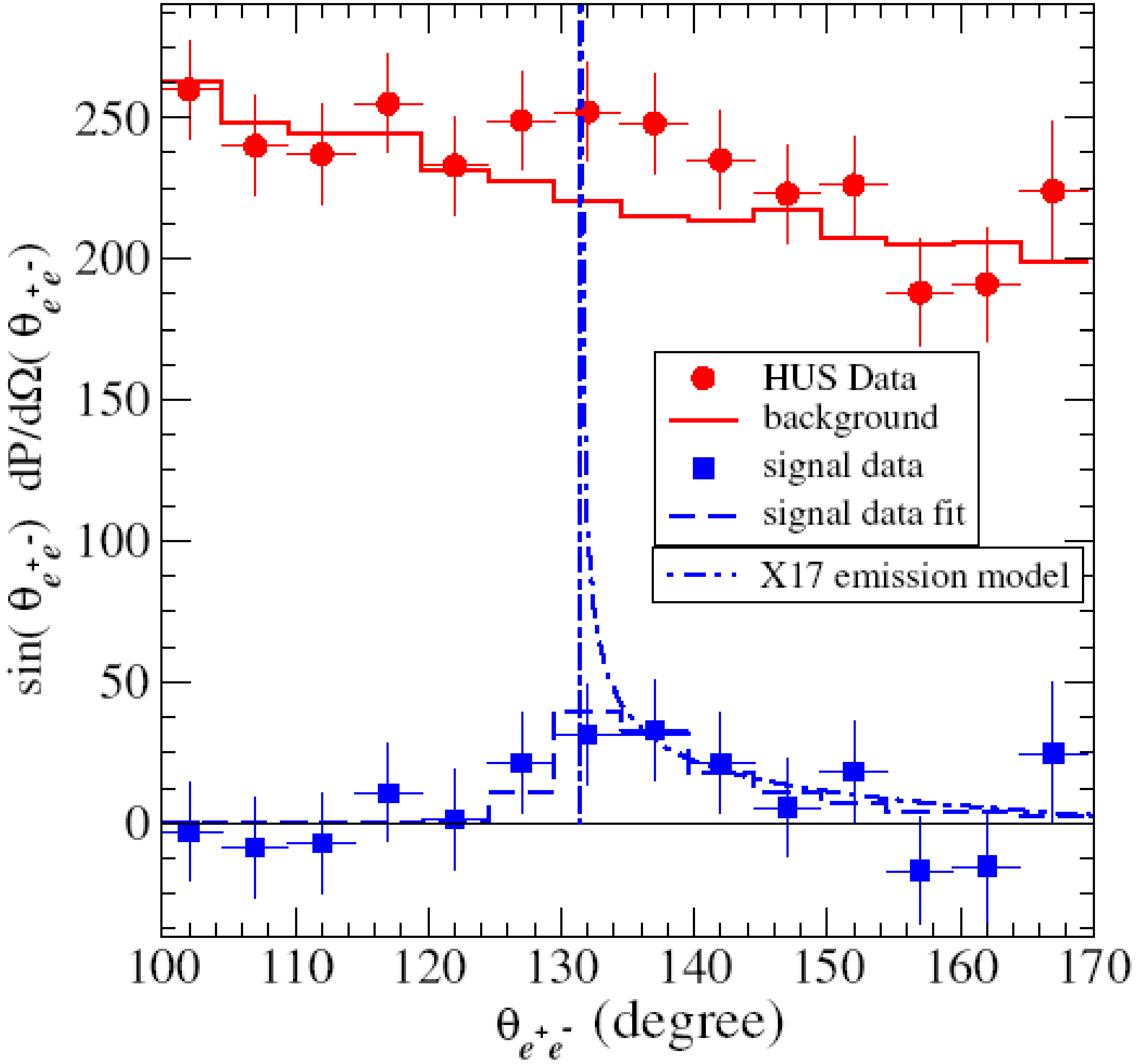
Preliminary angular correlations for ^{12}C



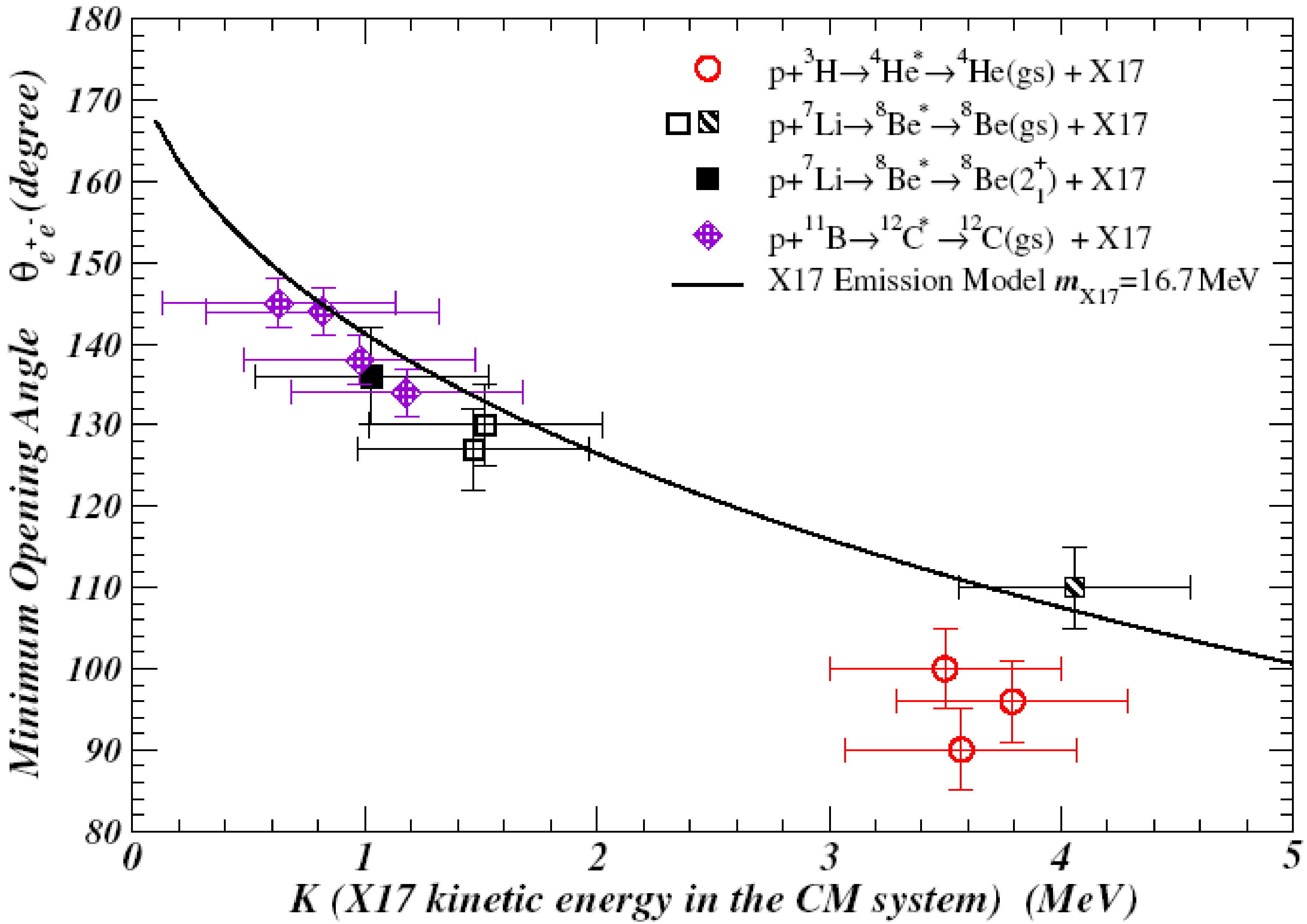
Agreement with ATOMKI result (2022) (*)

(*) A. J. Krasznahorkay et al, Phys. Rev. C 106, L061601 (2022)


$\theta_{e^+e^-}$ (degree)
100
120
140
160
180
p_{lab}=1.50MeV
K=0.63 MeV
^{11}B(p,e^+e^-)^{12}C(gs)
p_{lab}=4.0MeV
K=1.03 MeV
^{7}Li+p →
e^+e^- + ^{8}Be(2$^+$)
p_{lab}=0.51MeV
K=3.50 MeV
^{3}H(p,e^+e^-)^{4}He(gs)
p_{lab}=4.0MeV
K=4.06 MeV
^{7}Li+p →
e^+e^- + ^{8}Be(gs)
sin($\theta_{e^+e^-}$) dP/dΩ($\theta_{e^+e^-}$)
1.5
1.0
0.5
0.0
1.5
2.0
2.5
3.0
$\theta_{e^+e^-}$ (radian)



HUS Data
background
signal data
signal data fit
X17 emission model
$\sin(\theta_{e^+e^-})\ dP/d\Omega(\theta_{e^+e^-})$
$\theta_{e^+e^-}$ (degree)
0
50
100
150
200
250
100
110
120
130
140
150
160
170

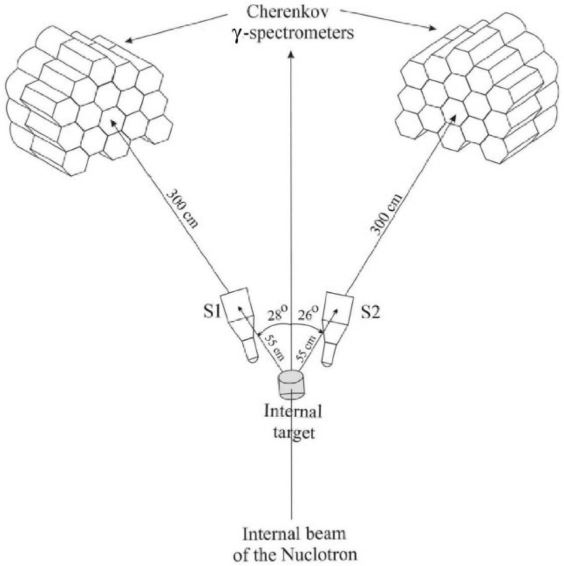

180
170
160
150
140
130
120
110
100
90
80
0
1
2
3
4
5
Minimum Opening Angle $\theta_{e^+e^-}$ (degree)
K (X17 kinetic energy in the CM system) (MeV)
$p+{}^3H \rightarrow {}^4He^* \rightarrow {}^4He(gs) + X17$
$p+{}^7Li \rightarrow {}^8Be^* \rightarrow {}^8Be(gs) + X17$
$p+{}^7Li \rightarrow {}^8Be^* \rightarrow {}^8Be(2^+_1) + X17$
$p+{}^{11}B \rightarrow {}^{12}C^* \rightarrow {}^{12}C(gs) + X17$
X17 Emission Model m_{X17}=16.7 MeV

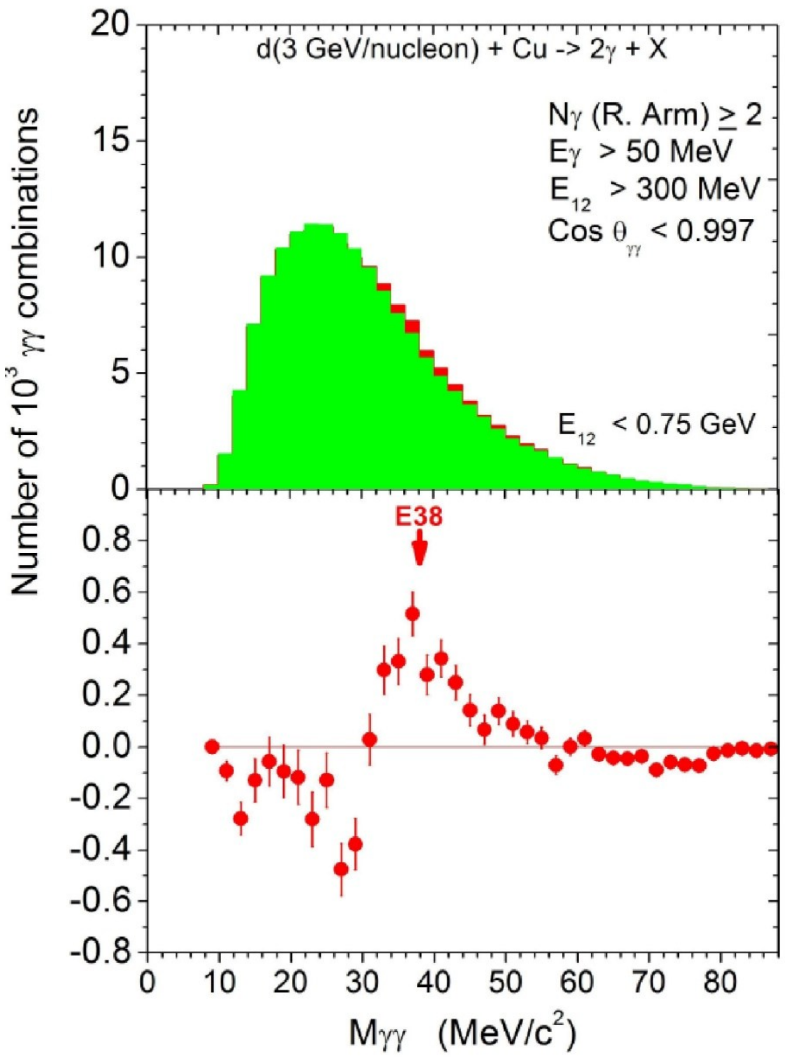
理论研究简介

- **“疏质子型第五力”(protophobic fifth force)：** 即该粒子与质子耦合极弱、而与中子及轻子耦合适中，这能解释仅在某些偶素核中出现信号的特性。这一思路由美国加州大学尔湾分校Jonathan L. Feng等人提出。 $\mathcal{L} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu - X^\mu J_\mu$, $J_\mu = \sum_f e\varepsilon_f \bar{f}\gamma_\mu f$. $-0.067 < \frac{\varepsilon_p}{\varepsilon_n} < 0.078.$
- **类轴子(Axion-like particle, ALP)：** 将X17视为轻质量的类轴子或CP-odd粒子，其拉格朗日量中包含电磁场对偶张量项，从而与轴子暗物质理论建立联系。这一解释在美国阿拉莫斯国家实验室Daniele. S. M. Alves等人的工作中得到了详细发展，其优势在于统一暗物质与低能核物理信号的可能性。
- **新的U(1)'规范对称性+双Higgs二重态模型：** 英国卢瑟福·阿普顿实验室 Luigi Delle Rose等人认为X17可能是一种由额外U(1)′ 规范对称性结合双Higgs二重态模型产生的轻矢量玻色子。
- **类QED介子：** 美国橡树岭国家实验室Cheuk-Yin Wong等人提出X17可类比为类QED介子，具有非常窄的质量和特定选择性耦合，能同时描述X17粒子以及E38粒子。
- **12夸克隐色Fock态：** 美国杰斐逊国家实验室Valery Kubarovsky等人通过QCD Fock态模型, 提出X17信号可能源于原子核内12夸克隐色Fock态(“hexadiquark”态)产生的新激发模式，而非新基本粒子。他们的研究强调需要独立实验验证ATOMKI结果并建议专门研究α团簇核的新激发态以确认这一潜在新现象。
- **传统核物理效应：** 美国华盛顿大学Xilin Zhang, Gerald A. Miller还提出X17可能并非基本粒子，而是核电磁跃迁干涉效应等对特定偶素核跃迁产生的增强。等

PRL 117(2016)071803; PRD 95(2017)035017; PRD 103(2021)055018; JHEP 08(2020)165; JHEP 11(2016)039; JHEP 07(2018)092; PRD 96(2017)115024; PRC 111(2025)024320; PLB 858(2024)139031;PRL119(2017)141803; PLB 773(2017)159; JHEP 10(2024)086; JHEP 06(2025)182; PRD 108(2023)015009; PRD 108(2023)055011; …

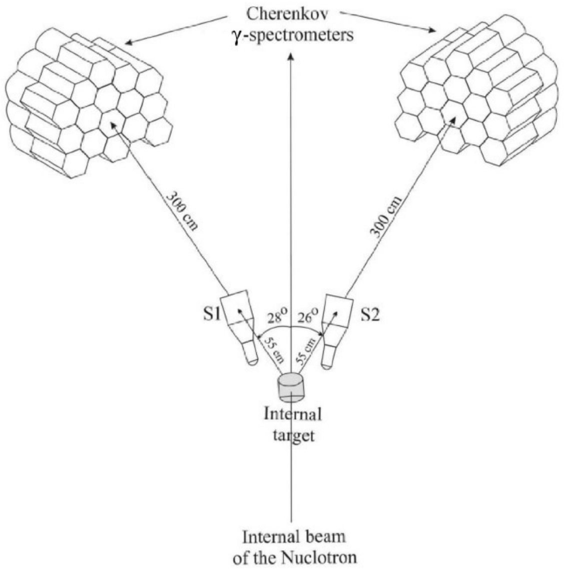
Observation of the E38 boson at Dubna

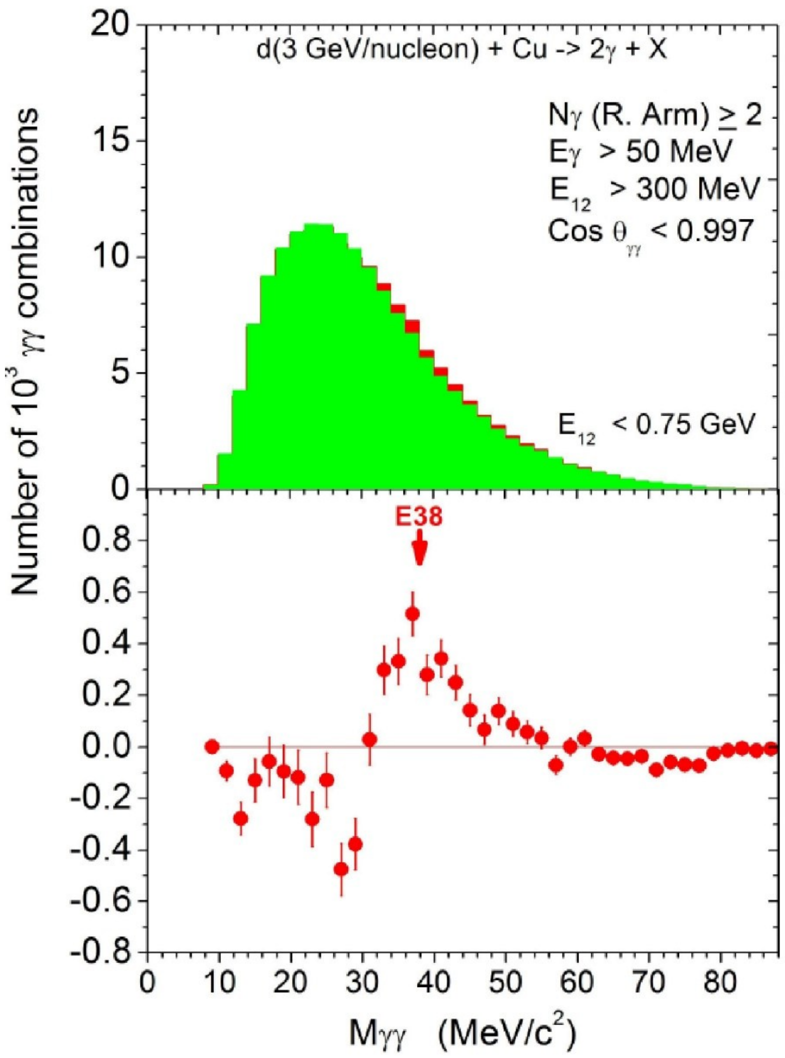




Abraamyan et al. arxiv:1208.3829(2012)
EPJWebConf204,08004(2019)

Observation of the E38 boson at Dubna

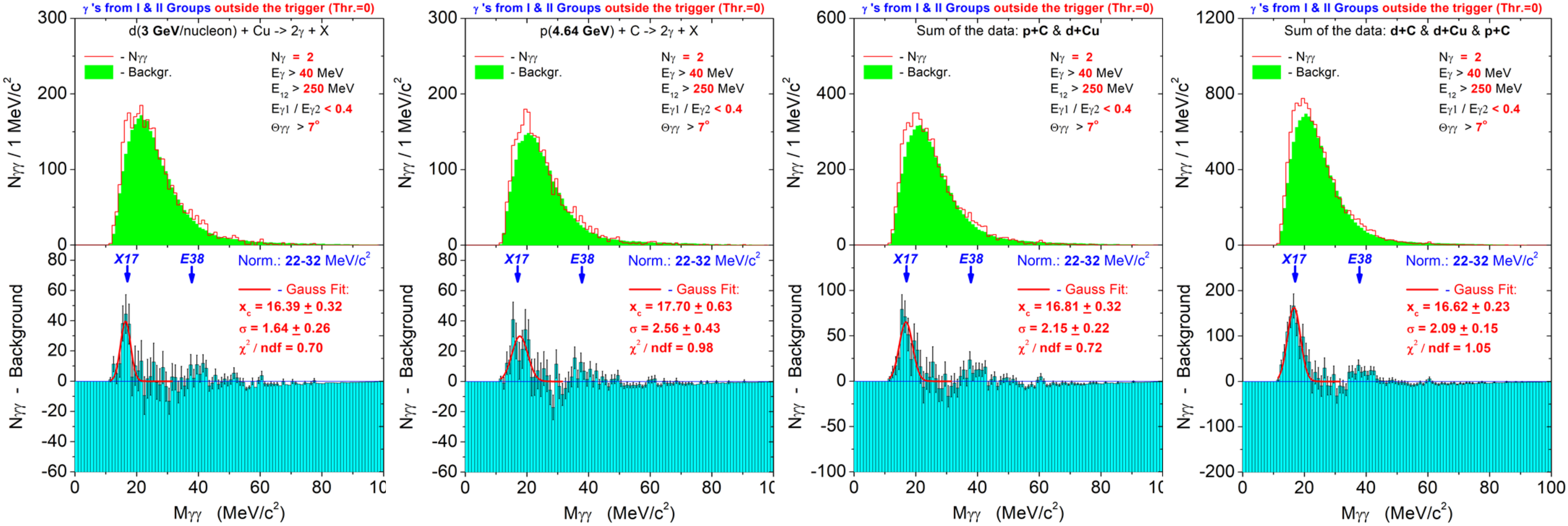




Abraamyan et al. arxiv:1208.3829(2012)
EPJWebConf204,08004(2019)

Results of the search for a signal at an invariant mass of photon pairs of about 17 MeV/c² and about 38 MeV

Abraamyan Kh.U. et al., ISMD2023



Invariant mass distributions of *γγ* pairs satisfying criteria (i)-(iii) without (upper panels) and with (bottom panels) the background subtraction obtained for the *d*+C, *d*+Cu and *p* + C reactions. The backgrounds are normalized by the numbers of pairs in the range (22, 32) MeV/c².

Other hints of anomalous particles in regions of many tens of MeV

(i) Anomalous soft photons (excess e^+e^-) in high-energy hadron-hadron and e^+e^- annihilations, with $p_T < 60$ MeV/c^2

(ii) COMPASS hadron-hadron collisions, with $\gamma\gamma$ invariant mass at $\sim$17 and $\sim$38 MeV

(iii) Pb collisions on Photographic Emulsion at RHIC, with e^+e^- invariant mass at $\sim$18 MeV

(iv) CMS anomalous low-mass diphoton structure at $\sim$40 MeV in Pb-Pb collisions at LHC

We need new experimental measurements to search for X17 and E38.

ATOMKI, DUBNA, and HUS experiments provide promising evidence for QED mesons, pending further confirmations.

Implications of the possible existence of the QED mesons in (3+1)D

1. Color-singlet quark matter may exist, with possible neutral QED mesons at T=0. There may then be QED meson gas at T< T_c(QED), and quark photon plasma above T_c(QED).
2. There may be a new family of QED-confined $q\bar{q}$ composite particles at T=0 that are composite in nature, with additional degrees of freedom in spin-spin, spin-orbit, collective vibrations, collective rotations, molecular states, …
3. Confinement occurs for q and $\bar{q}$ not only in QCD but also in neutral color-singlet quark matter in QED. The group of gauge interaction may be a broken U(3) group with U(3) = U(1) $\oplus$ SU(3).
4. Confinement may be an intrinsic property of the quarks or colors of quarks.
5. Quarks and antiquarks may interact with different interactions, including weak and gravitational interactions, to lead to confined $q\bar{q}$ composite particles.

6 The QED interaction between a quark and an antiquark may be predominantly linear. In such a case, there may be a stable d-u-d QED neutron, whereas the corresponding u-d-u QED proton is unstable. The QED neutron may be a good candidate for dark matter.

Neutral color-singlet $q\bar{q}$ quark matter is an important new frontier

- A new form of matter
- Consistent with the existence of X17
- A window on confinement
- Connection to dark matter

CONCLUSIONS

1. Theoretical and experimental observations point to the possible existence of color-singlet quark matter at T=0, with stable quanta of QED mesons, pending further confirmations.

2. The possible existence of QED mesons has important implications on the fundamental color properties of the quark matter and its interactions.