X17 Workshop, Rome
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$q\bar{q}$ QED Meson Description of X17 and other Anomalous Particles

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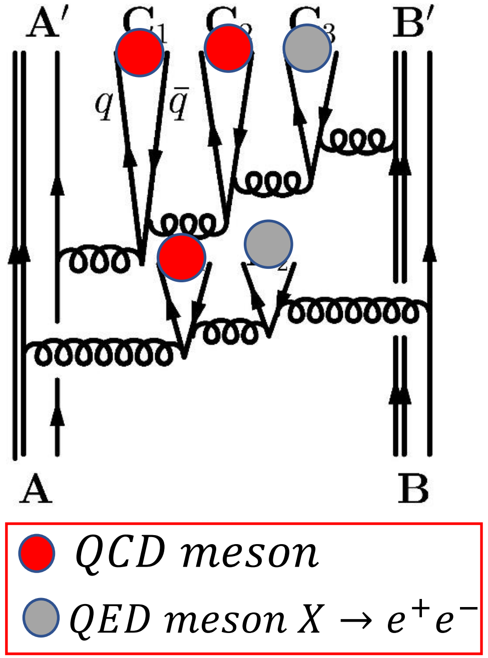
1. Introduction: ✶ QED mesons
   ✶ anomalous soft photons (ASP), X17, and E38
2. Frequent objections on QED mesons and their resolutions
3. Masses of QED mesons
4. How are QED mesons produced and detected ?
5. Encouraging pieces of experimental evidence for the QED mesons

CYWong,PRC81,064903(2010),[arxiv:1001.1691]
CYWong,JHEP08(2020)165,[arxiv:2001.04864]
CYWong,arxiv:2010.13948.
C.Y.Wong,arxiv:2108.00959.

Anomalous soft photons (excess e+e-) are produced whenever hadrons are produced

Experiment	Collision Energy	Photon pT	Photon/Brems Ratio
K^+ p, CERN WA27,BEBC(1984)	70 GeV/c	PT < 60 MeV/c	4.0 ± 0.8
K^+ p, CERN NA22, EHS (1993)	250 GeV/c	PT < 40 MeV/c	6.4 ± 1.6
π^+ p, CERN NA22, EHS (1997)	250 GeV/c	PT < 40 MeV/c	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)



Low Theorem (1958)

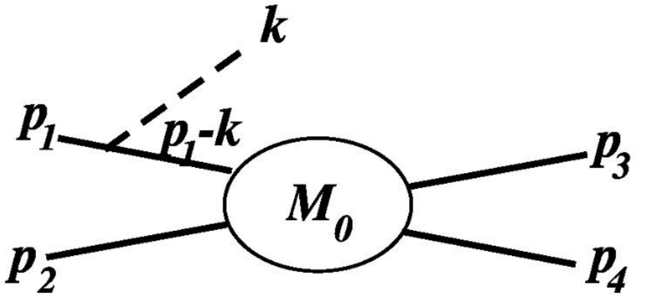
Consider $p_1 + p_2 \to p_3 + p_4 + k$

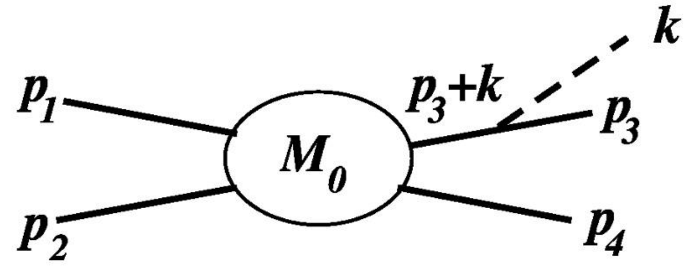
$$M(p_1 p_2;\ p_3 p_4 k) = M_0(p_1 p_2;\ p_3 p_4)\left[\frac{e_1 p_1 \cdot \varepsilon}{(p_1 - k)^2} + \frac{e_3 p_3 \cdot \varepsilon}{(p_3 + k)^2}\right]$$

$$= M_0(p_1 p_2;\ p_3 p_4)\left[\frac{-e_1 p_1 \cdot \varepsilon}{2 p_1 \cdot k} + \frac{e_3 p_3 \cdot \varepsilon}{2 p_3 \cdot k}\right]$$

$$= M_0(p_1 p_2;\ p_3 p_4)\left[\sum_i^{\text{all charged particles}} \frac{\eta_i e_i p_i \cdot \varepsilon}{2 p_i \cdot k}\right]$$

$\eta_i = +1$ for a final particle, $\eta = -1$ for an initial particle





This can be generalized to

$$M(p_1 p_2;\ p_3 p_4 \ldots p_N k) = M_0(p_1 p_2;\ p_3 p_4 .. p_N)\left[\sum_i^{N+2} \frac{\eta_i e_i p_i \cdot \varepsilon}{2 p_i \cdot k}\right]$$

$$|M(p_1 p_2;\ p_3 p_4 \ldots p_N k)|^2 = |M_0(p_1 p_2;\ p_3 p_4 .. p_N)|^2 \left[\sum_i^{N+2} \frac{\eta_i e_i p_i \cdot \varepsilon}{2 p_i \cdot k}\right]^2$$

$$(p_i \cdot \varepsilon)(p_j \cdot \varepsilon) = -(p_i \cdot p_j)$$

$$|M(p_1 p_2;\ p_3 p_4 \ldots p_N k)|^2 = |M_0(p_1 p_2;\ p_3 p_4 .. p_N)|^2 \left[\sum_{i,j}^{N+2} \frac{\eta_i \eta_j e_i e_j (p_i \cdot p_j)}{4(p_i \cdot k)(p_j \cdot k)}\right]$$

$$\boxed{\frac{dN_\gamma}{d^3k} = \frac{\alpha}{2\pi k_0} \int d^3p_3 d^3p_4 \ldots d^3p_N \sum_{i,j=1}^{N+2} \frac{\eta_i \eta_j e_i e_j (p_i \cdot p_j)}{4(p_i \cdot k)(p_j \cdot k)} \frac{dN_{\text{hadron}}}{d^3p_3 d^3p_4 \ldots d^3p_N}}$$

$\eta_i = 1$ for a final particle, $\eta = -1$ for an initial particle

Gribov's question: Where to find soft photons?

Consider $p_1 + p_2 \to p_3 + p_4 + p_5 + \ldots + p_N + k$

$$\frac{dN_\gamma}{d^3k} = \frac{\alpha}{2\pi k_0} \int d^3p_3 d^3p_4 \ldots d^3p_N \sum_{i,j=1}^{N+2} \frac{\eta_i \eta_j e_i e_j (p_i \cdot p_j)}{4(p_i \cdot k)(p_j \cdot k)} \frac{dN_{\text{hadron}}}{d^3p_3 d^3p_4 \ldots d^3p_N}$$

$\eta_i = 1$ for a final particle, -1 for an initial particle

Contributions are large when

$$p_i \cdot k = p_{i0} k (1 - \cos\theta) = p_{i0} k \frac{\theta^2}{2}$$

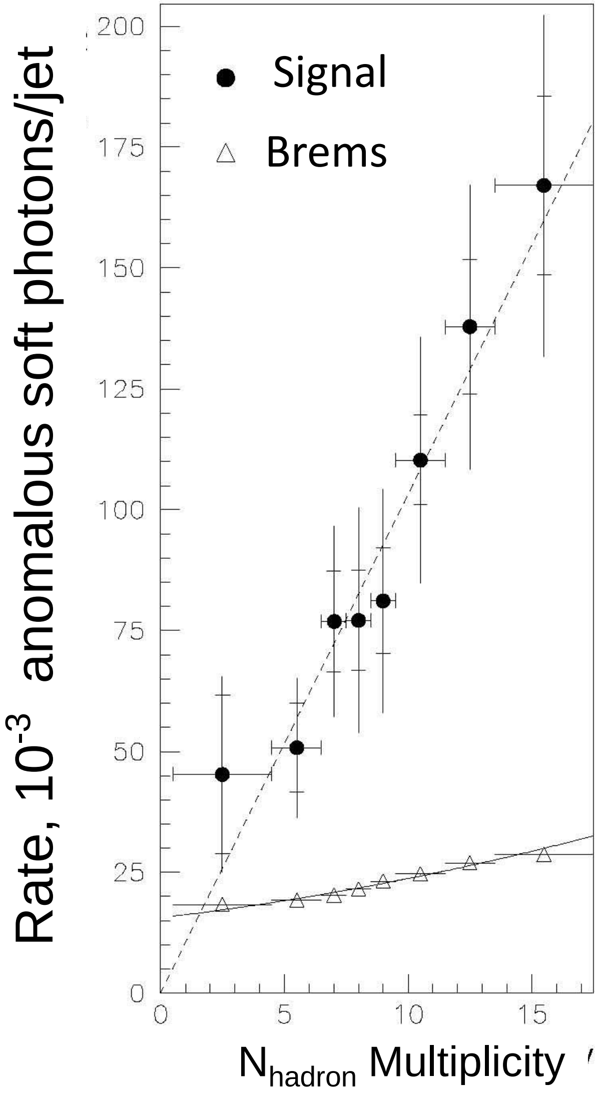
$$= p_{i0} k_T \frac{\theta}{2} \text{ is very small.}$$

So, experimental measurements have been focusing on the region of small k_T, and small θ.

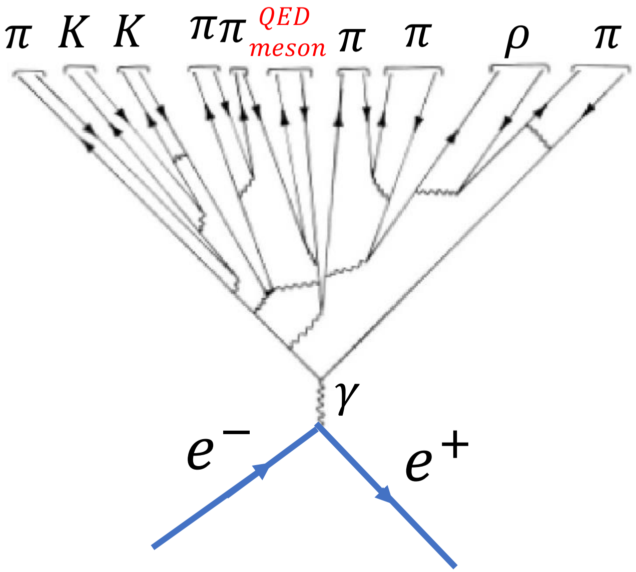
Anomalous soft photon yield is proportional to the hadron yield

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

DELPHI (EPJ 2010) arXiv:1004.1587



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



Do anomalous soft photons (ASP) and QCD mesons arise from the similar $q\bar{q}$ production mechanism?

Anomalous soft photons (excess e^+e^-pairs with p_T<60 MeV/c) are proportionally produced along with hadrons.

A parent particle of an anomalous soft photon (ASP) must contain some elements of the hadrons sector, such as a q-$\bar{q}$ pair.

The q-$\bar{q}$ pair interact in QCD and QED interactions.

The q-$\bar{q}$ pair cannot interacting in the QCD interaction, because the QCD interaction would endow the q-$\bar{q}$ pair with a mass greater or equal to m_π.

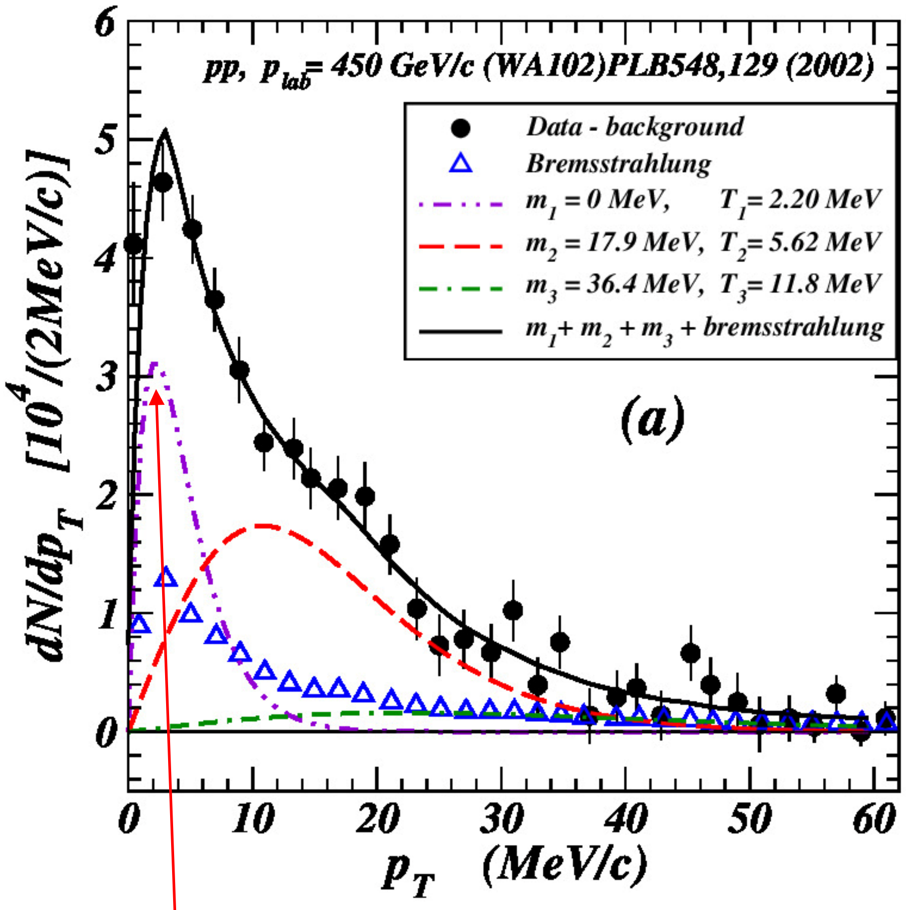
We are left with the q-$\bar{q}$ pair interacting only in the QED interaction.

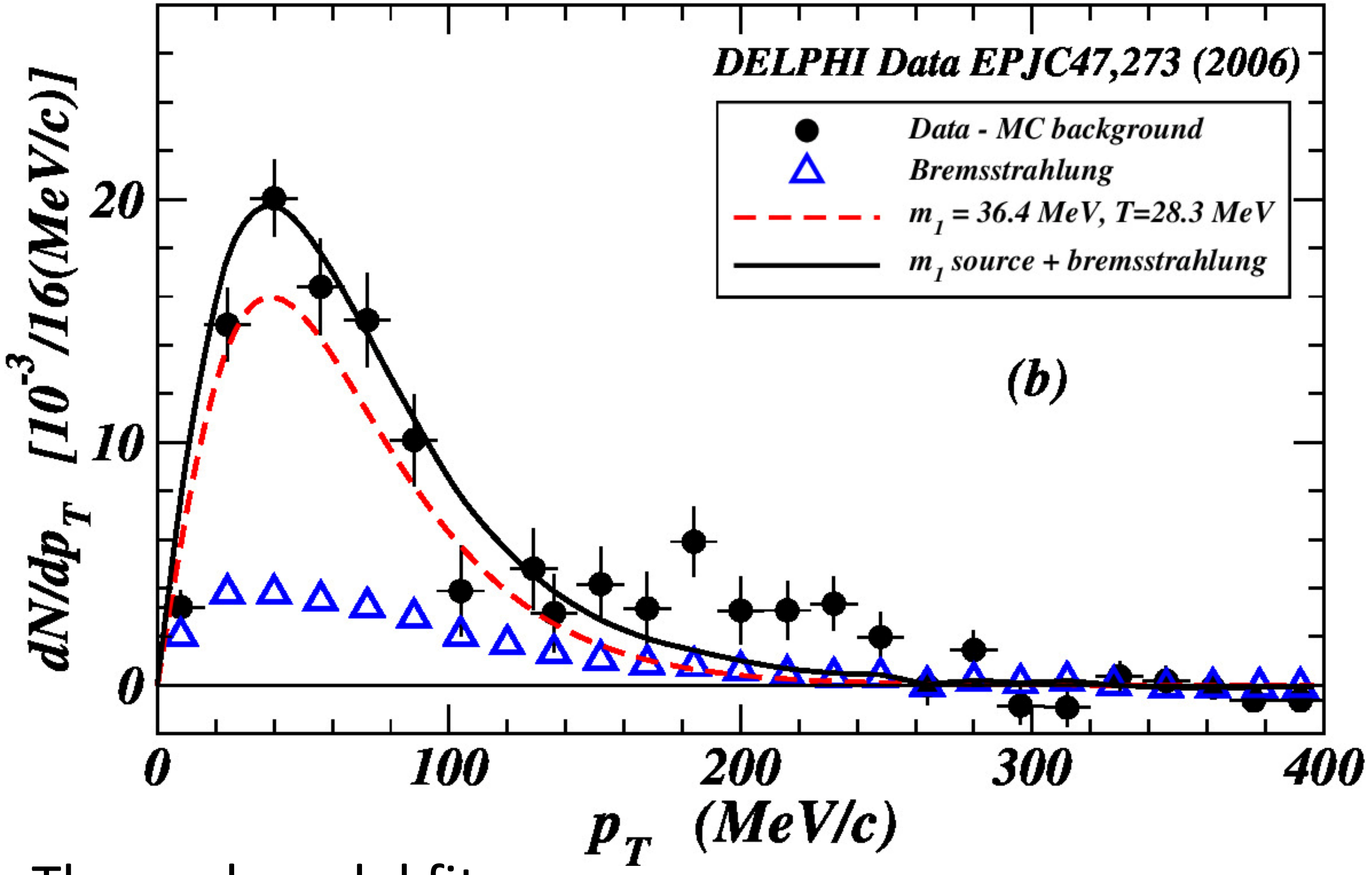
Such a QED possibility is re-inforced by Schwinger′s result that the mass of a confined q-$\bar{q}$ QED pair is proportional to the QED coupling constant, $m = g/\sqrt{\pi}$.

The lowest-energy QED mesons have masses about 20 and 40 MeV.

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

pT spectrum of anomalous soft photons (ASP) hints at boson masses of ~18 and ~36 MeV





Suggests the production of real photons from the decay of the anomalous soft photons

Thermal model fit:

$$\frac{dN}{p_T dp_T} = \sum_{i=1}^{3} A_i e^{-\sqrt{m^2+p_T{}^2}/T_i}$$

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

The proposal of stable and confined $q\bar{q}$ QED mesons raises serious objections.

Debate between the Wise Guy (大智) and the Old Fool (愚公)

Wise Guy
DaZhi(大智）
raises
objections :

- Quarks interact in QCD and QED simultaneously.
- When quarks oscillates, the color charges and electric charges also oscillate simultaneously.
- Stable collective QED excitations of quarks cannot occur without the QCD interactions.

Old Fool
YuGong(愚公)
replies:

- Quark densities and gauge fields are not single-element quantities. They are 3×3 color matrices.
- They have 9 elements which breaks up into color-octet subgroup and color-singlet subgroups
- Quark currents and the gauge fields depend only on quantities within each subgroup.
- In the space-time arena, each subgroup can generate separate stable collective excitations.
- There are localized, stable QCD excitations in the color-octet subgroup → $\pi^0, \eta, \eta', K, \rho$...
- There can also be localized, stable QED excitations in the color-singlet subgroup → ASP, X17, E38,...

Debate between the Wise Guy (大智) and the Old Fool (愚公) (contd)

Wise Guy
DaZhi(大智）
raises
objections :

- Only non-Abelian QCD interactions can confine quarks
- The Abelian QED interaction does not confine electrons and positrons, so the QED interaction does not confine quarks and antiquarks

Old Fool
YuGong(愚公)
replies:

- Light quarks (and antiquarks) as massless fermions are confined in QED in 1+1D (Schwinger,1962)
- Confined $q\bar{q}$ in QED in 1+1D can be taken as idealization of confined $q\bar{q}$ in QED in 3+1D in a flux tube,
- Gribov showed that massless fermions in QED in 3+1D are confined (NPB206,103(1982))
- Lattice gauge calculations showed that fermions can be confined in QED in 3+1D under appropriate conditions.
- The open-string description of QCD+QED mesons gives correct π^0, η, η', X17, E38 masses (JHEP 08(2020)165,arxiv:2001.04864)

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

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

A gauge theory in 1+1 dimensions with massless fermions

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

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

The gauge field A^ν tells quark ψ how to move

The quark field ψ gives j^ν to tell the gauge field A^ν how to act.

For a stable configuration, A^ν couples j^ν self-consistently.

A gauge-invariant relation between j^ν and A^ν is

$$j^\nu = -\frac{(g_{2D})^2}{\pi}\left(A^\nu - \partial^\nu \frac{1}{\partial^\lambda\partial_\lambda}\partial_\mu A^\mu\right), \qquad \widetilde{A^\mu} = A^\mu\text{-}\,\partial^\mu\lambda$$

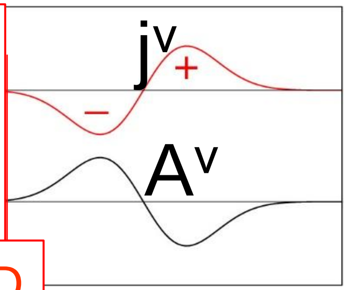
We substitute this into the Maxwell equation, and we get

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

This is the Klein-Gordon equation for a stable boson with mass

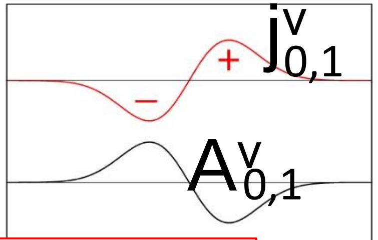
$$m = \frac{g_{2D}}{\sqrt{\pi}}$$

QED



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

(QED+QCD)



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

$$t^0 = \frac{1}{\sqrt{6}}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix}$$ 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

$$A^\nu = A_0^\nu \tau^0 + A_1^\nu \tau^1$$

$$\tau^0 = t^0$$

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

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

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

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

CYWong,PRC81,064903(2010),[arxiv:1001.1691]
CYWong,JHEP08(2020)165,[arxiv:2001.04864]

A localized boson in 1+1D can approximate a localized meson in 3+1D

- In 1+1D, the open string has no structure, but the coupling constant g_{2D} has the dimension of a mass.
- In 3+1D, the flux tube structure has a radius R_T, but the coupling constant g_{4D} is dimensionless.
- In going from 3+1D to 1+1D, fluxtube radius R_T information is stored in the coupling constant g_{2D} in 1+1D,

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

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

Koshelkin and Wong,[PRD86,125026(2012)]

- By such a relationship, a localized boson in 1+1D can be used to approximate a localized meson in 3+1D as

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

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

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

$$\frac{(QCD\ meson\ mass\ m_{QCD})}{(QED\ meson\ mass\ m_{QED})} = \sqrt{\frac{\alpha_{4D}^{QCD}}{\alpha_{4D}^{QED}}} \approx \sqrt{\frac{0.7}{1/137}} \approx 10 \approx \frac{(hundreds\ MeV)}{(tens\ MeV)}, \qquad \frac{(QCD\ meson\ linear\ length)}{(QED\ meson\ linear\ length)} \approx \frac{1}{10}.$$

The simple results

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

are only order-of-magnitude estimates.

For quantitative descriptions, we must take into account

(i) flavor mixture D_{ij} of the physical states

(ii) flavor independence of the color charges, $Q_u^{QCD} = Q_d^{QCD} = Q_s^{QCD} = 1$

(iii) flavor dependence of the electric charges, $Q_u^{QED} = \frac{2}{3}$, $Q_d^{QCD} = -\frac{1}{3}$

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

QED and QCD meson masses with 2 flavor

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

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

$$\boxed{m_I^2 = \left[\frac{Q_u + (-1)^I Q_d}{\sqrt{2}}\right]^2 \frac{4\alpha_{4D}}{\pi R_T^2} + m_\pi^2 \frac{\alpha_{4D}}{\alpha_{4D}^{QCD}}}$$

Effective charge = $\frac{Q_u + (-1)^I Q_d}{\sqrt{2}}$

$I = 0$, $I_3=0$

Effective charge

QCD: $\frac{1+1}{\sqrt{2}}$

QED: $\frac{1}{\sqrt{2}}\left[\left(\frac{2}{3}\right) + \left(-\frac{1}{3}\right)\right]$

$I = 1$, $I_3=0$

QCD: $\frac{1-1}{\sqrt{2}} = 0$

QED: $\frac{1}{\sqrt{2}}\left[\left(\frac{2}{3}\right)\left(-\frac{1}{3}\right)\right]$

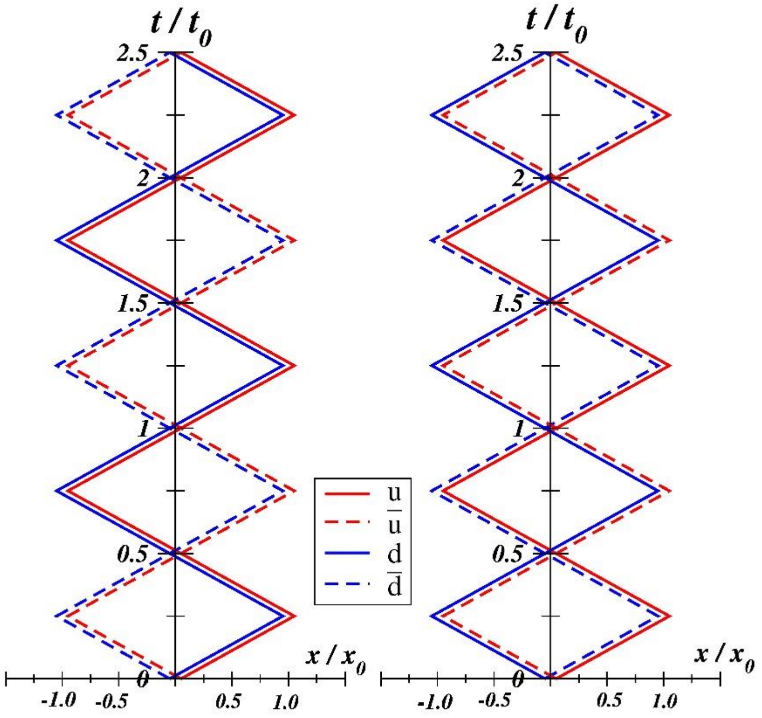
$$Q_u^{QCD} = Q_d^{QCD} = 1$$

$$Q_u^{QED} = 2/3, \quad Q_d^{QED} = -1/3$$

$$R_T = 0.4 \text{ fm}$$

$$\alpha_{4D}^{QCD} = 0.68$$

$$\alpha_{4D}^{QED} = \frac{1}{137}$$



isoscalar meson $(u\bar{u} + d\bar{d})/\sqrt{2}$

isovector meson $(u\bar{u} - d\bar{d})/\sqrt{2}$

The mass of the $I = 1$ isovector QCD meson is m_π.

The mass of the $I = 0$ isoscalar QCD meson m_η is 663 MeV.

The mass of the $I = 1$ isovector QED meson is m_{E38} is 36.4 MeV.

The mass of the $I = 0$ isoscalar QED meson m_{X17} is 17.9 MeV.

CYWong,PRC81,064903(2010),[arxiv:1001.1691]
CYWong,JHEP08(2020)165,[arxiv:2001.04864

QCD meson masses with 3 flavor

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

where the physical state $\Phi_i = \sum_{f=1}^{N_f} D_{ij}\varphi_j$

$\varphi_1 = |u\bar{u} >, \varphi_2 = |d\bar{d} >, \varphi_1 = |s\bar{s} >,$

D_{ij} and m_f from PDG table,

Parameters are α_{4D}^{QCD} and R_T

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

QCD and QED meson masses

		$[I(J^\pi)]$	Experimental mass (MeV)	Semi-empirical mass formula (MeV)
QCD meson	π^0	$[1(0^-)]$	134.9768±0.0005	134.9[‡]
	η	$[0(0^-)]$	547.862±0.017	498.4±39.8
	η'	$[0(0^-)]$	957.78±0.06	948.2±99.6
QED meson	X17	$[0(0^-)]$	16.94±0.24[#]	17.9±1.5
	E38	$[1(0^-)]$	37.38±0.71[⊕]	36.4±3.8

[‡] Calibration mass

[#] A. Krasznahorkay *et al.*, arxiv:2104.10075

[⊕] K. Abraamyan *et al.*, EPJ Web Conf 204,08004(2019)

$\alpha_{4D}^{QCD}=0.68\pm0.08$,
$R_T = 0.4 \pm 0.04$ fm

$\alpha_{4D}^{QED}=\frac{1}{137}$

QCD mesons
& QED mesons
are reasonable
concepts!

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

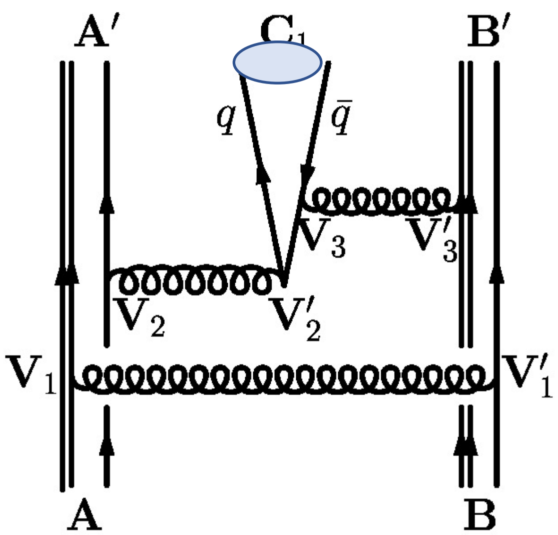
Search for QED mesons with masses in 10s MeV region

We need to know

(1) How QED mesons (and QCD mesons) are produced.

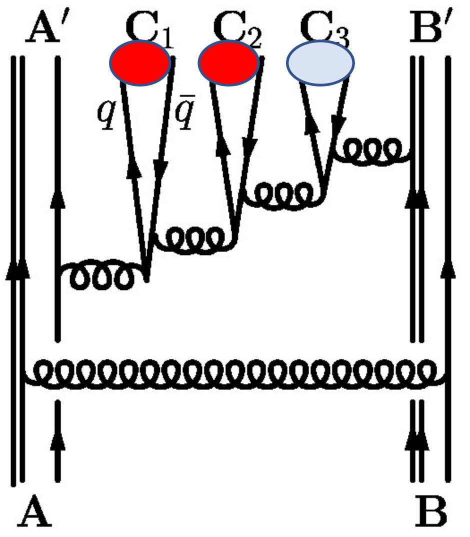
(2) How QED mesons decay and be detected.

QCD meson (🔴) and QED mesons (⚪) can be produced by $q\bar{q}$ pair production in hadron-hadron colliisons



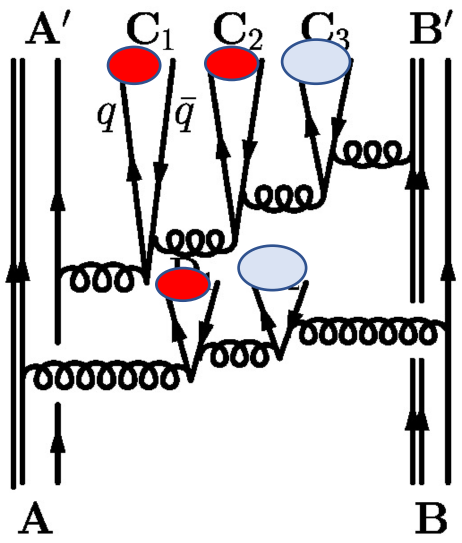
(a)

(i) Low energies
below pion mass
threshold
(ATOMKI experiments)
(ii) Peripheral
parton-parton
collisions



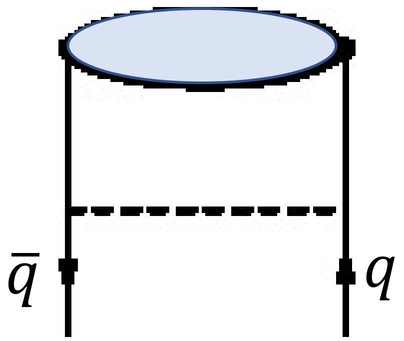
(b)

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



(c)

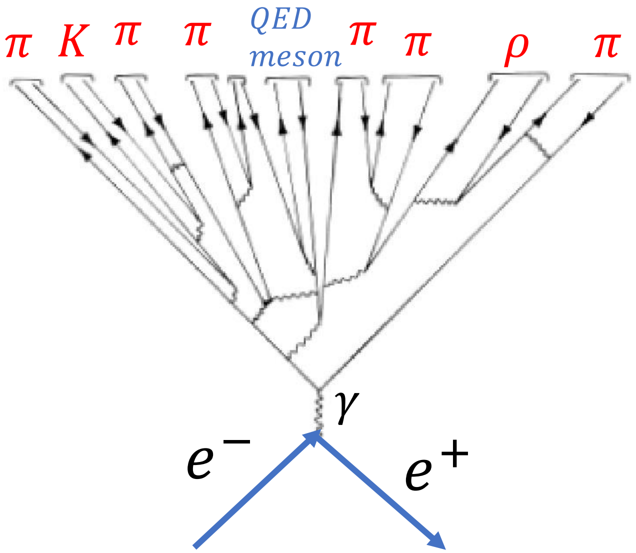
High energies
central AA
Collisions
(RHIC and
LHC experiments)



(d)

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

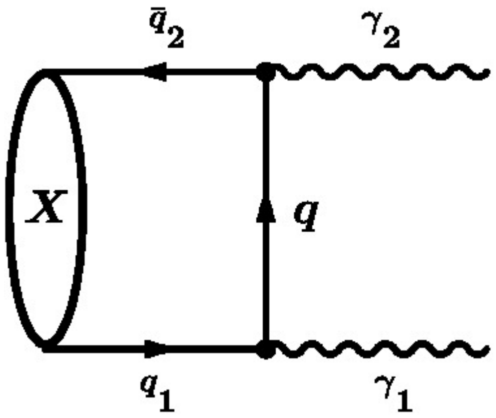
QCD meson and QED mesons can be produced by $q\bar{q}$ pair production in $e^+ - e^-$ anninihiations



(DELPHI experiments, PADME, …)

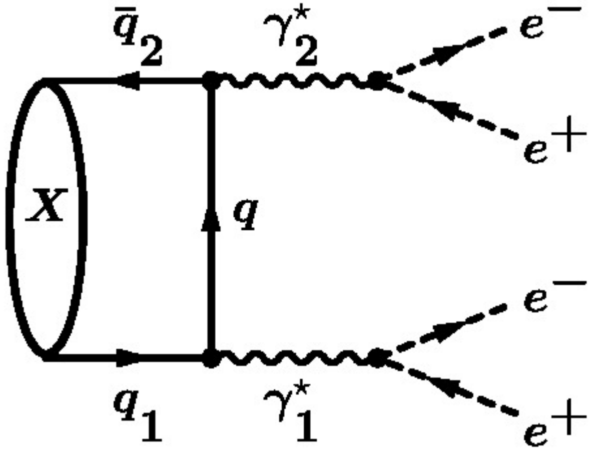
Decay and detection of a QED meson

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



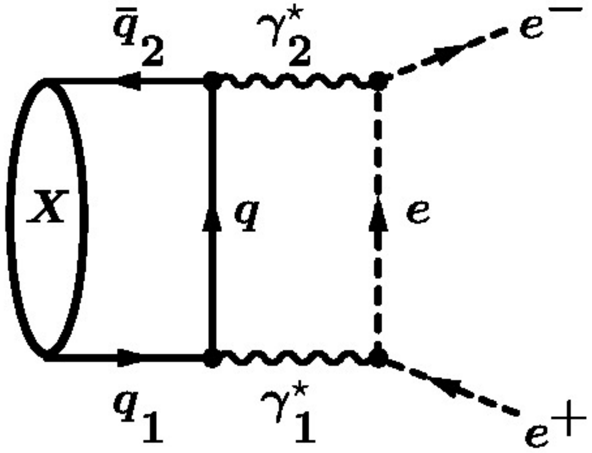
(a)

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



(b)

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

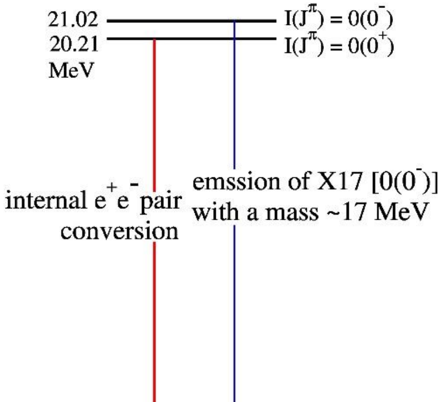


(c)

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

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

Krasznahorkay et al arxiv:1910.10459



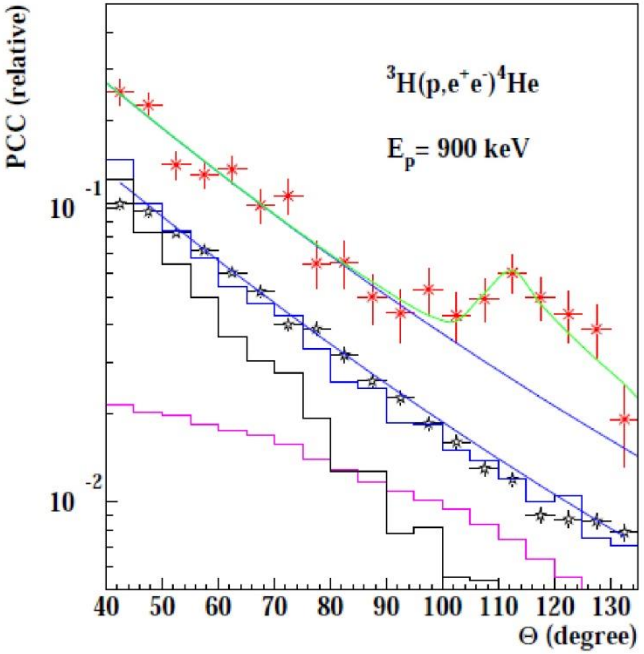


FIG. 2. *Angular correlations for the e^+e^- pairs measured the $^3H(p,\gamma)^4He$ reaction at the E_p=900 keV.*

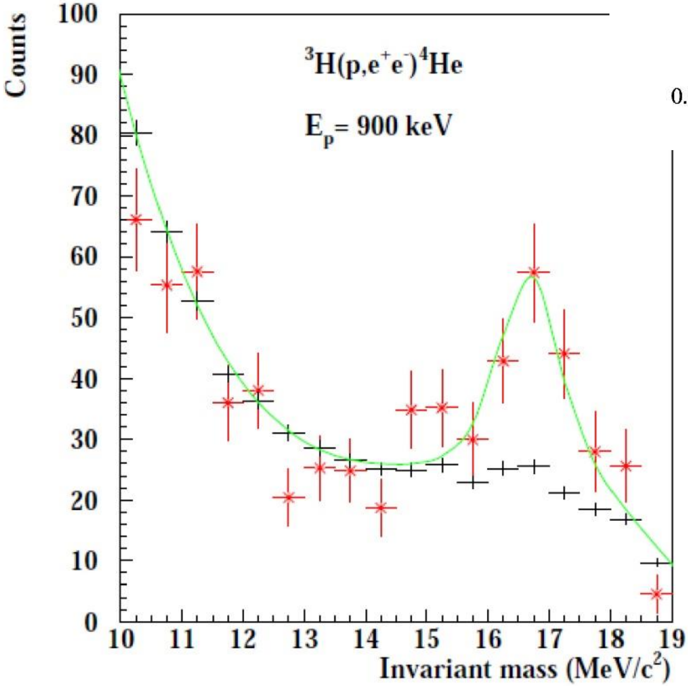
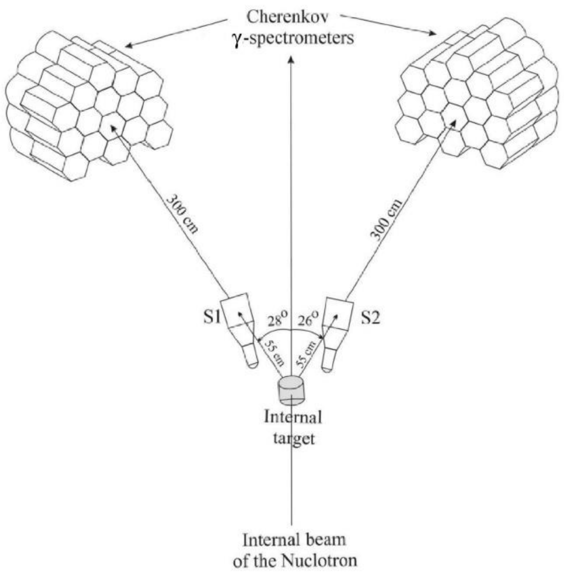
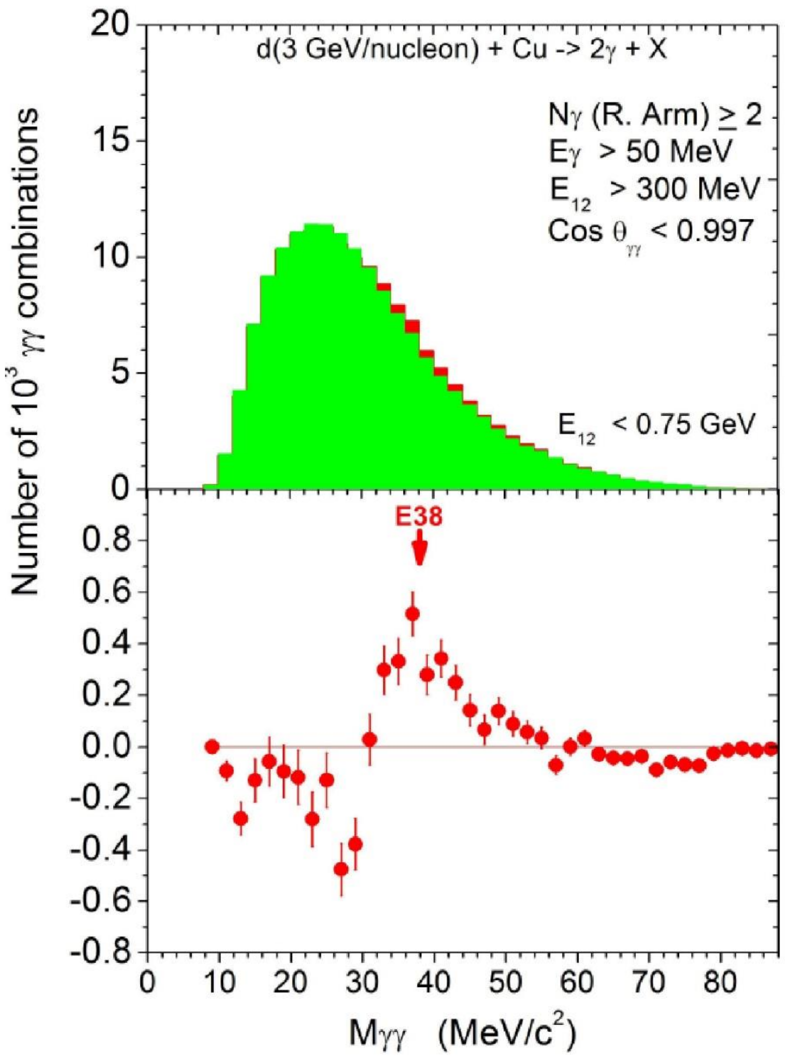


FIG. 3. *Invariant mass distribution derived for the 20.49 MeV transition in ^4He.*

Observation of the E38 boson at Dubna





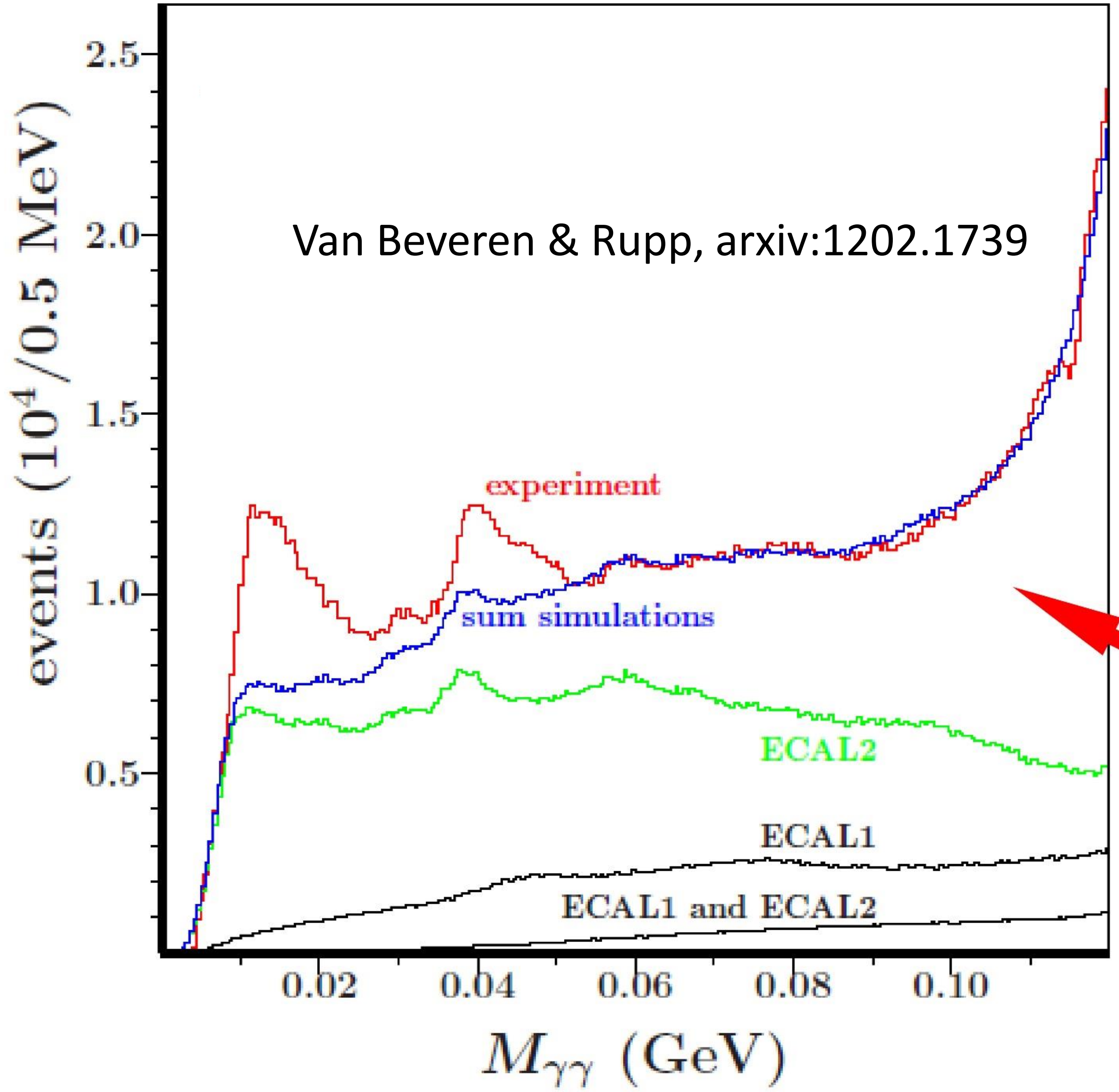
Abraamyan et al. arxiv:1208.3829(2012)
EPJWebConf204,08004(2019)

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

(i) COMPASS hadron-hadron collisions, with $\gamma\gamma$ invariant mass,

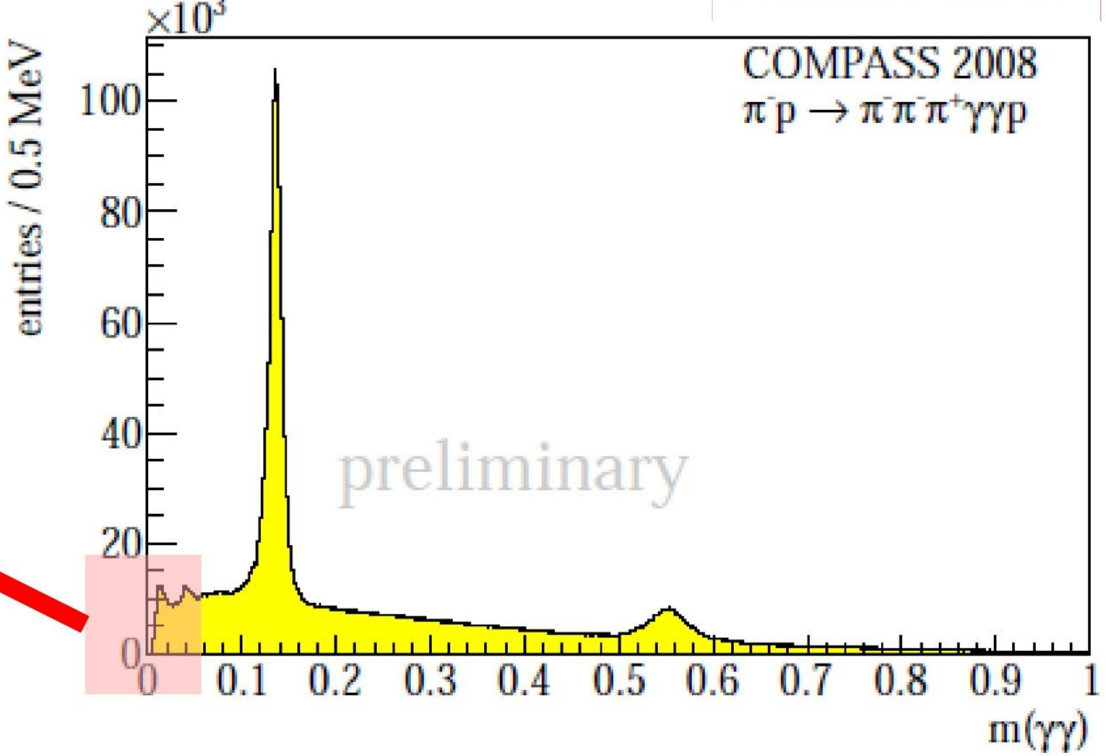
(ii) Pb collisions on Photographic Emulsion at RHIC, with e^+e^- invariant mass

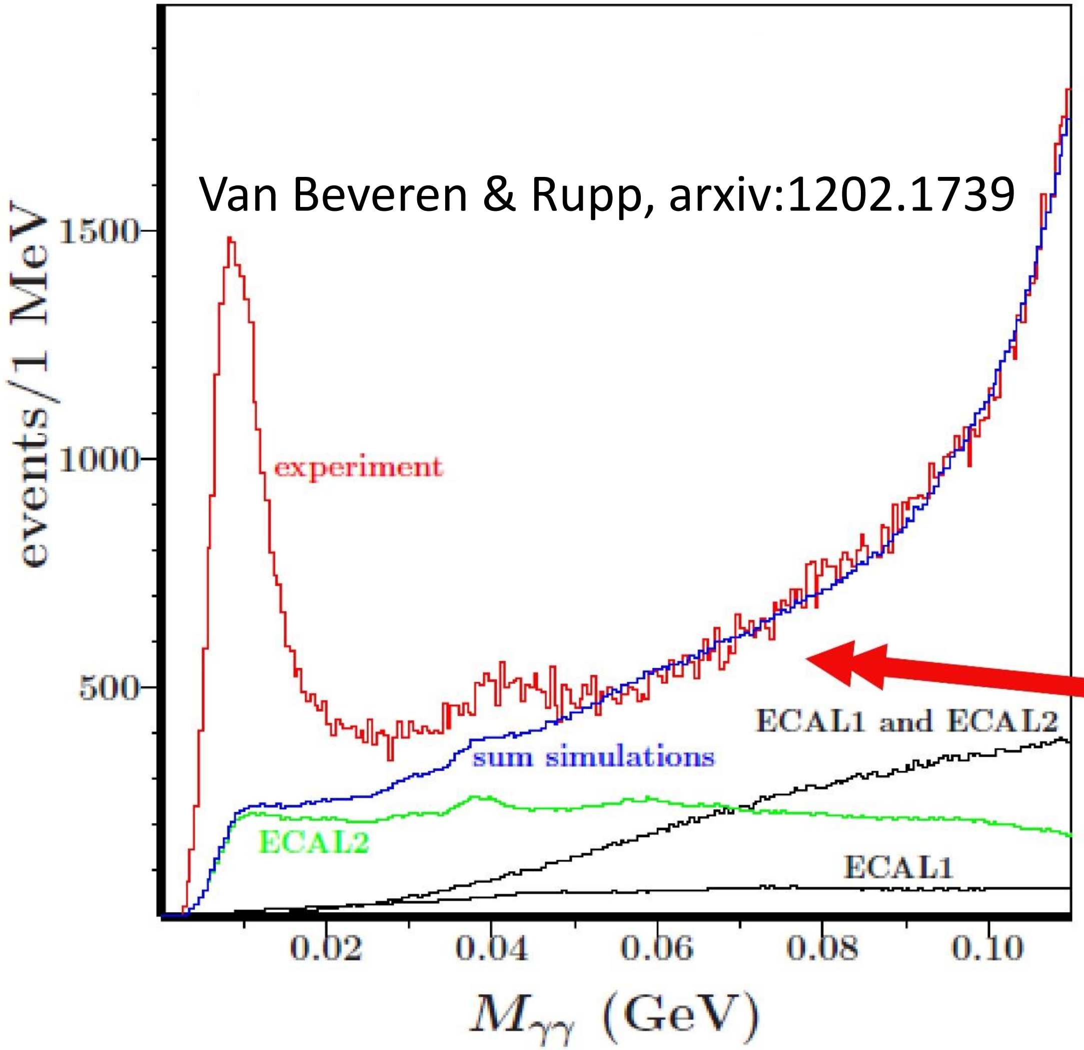
(iii)ALICE pPb collisions, $\gamma\gamma$ invariant mass.



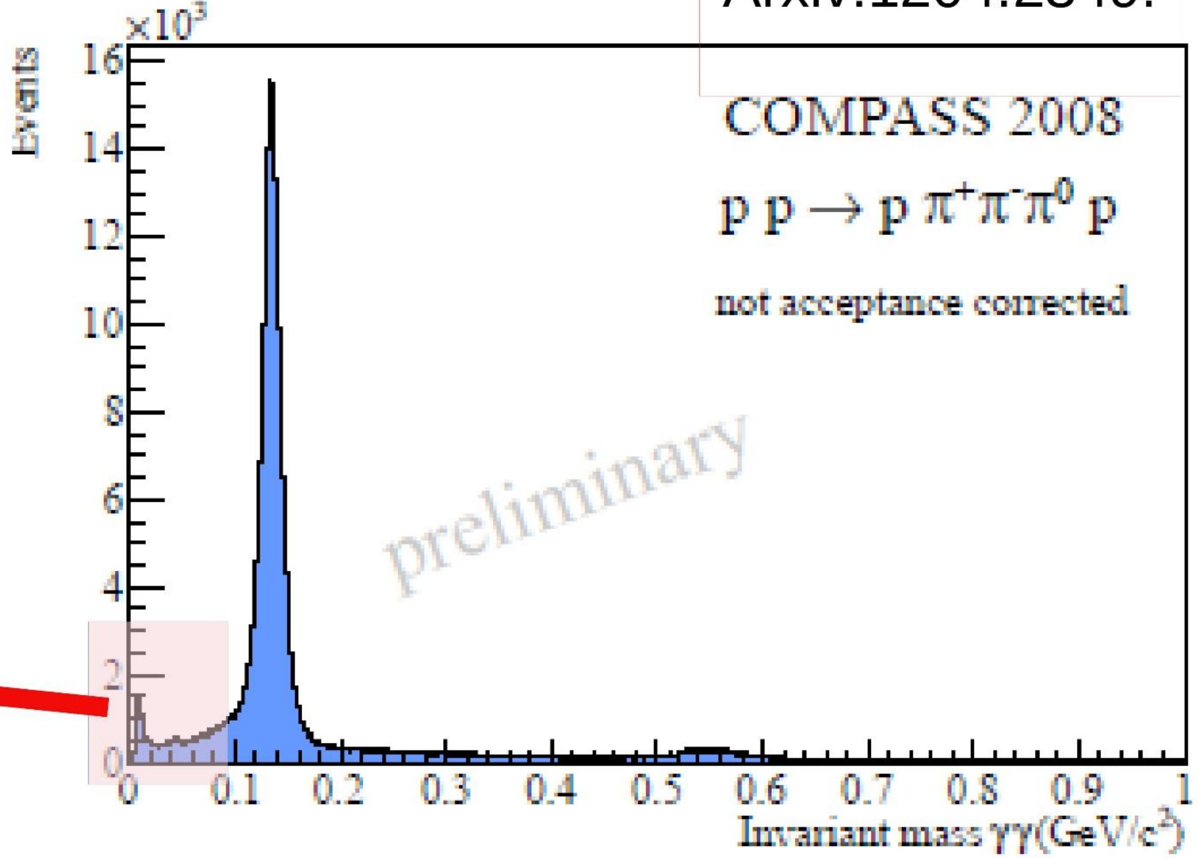
Van Beveren & Rupp, arxiv:1202.1739

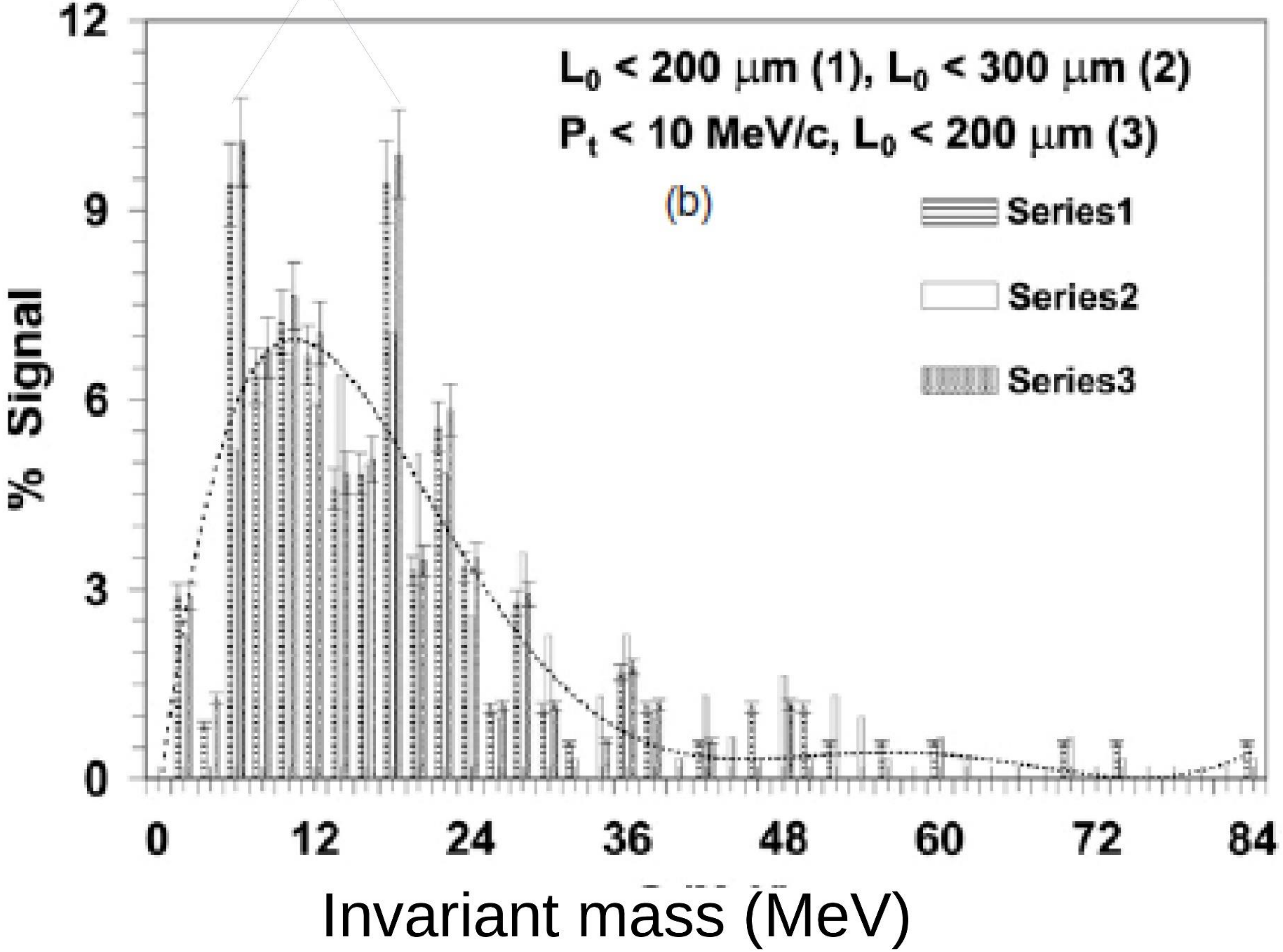
Bernhard et.al
Arxiv:1204.2349




Van Beveren & Rupp, arxiv:1202.1739

Bernhard et.al
Arxiv:1204.2349.



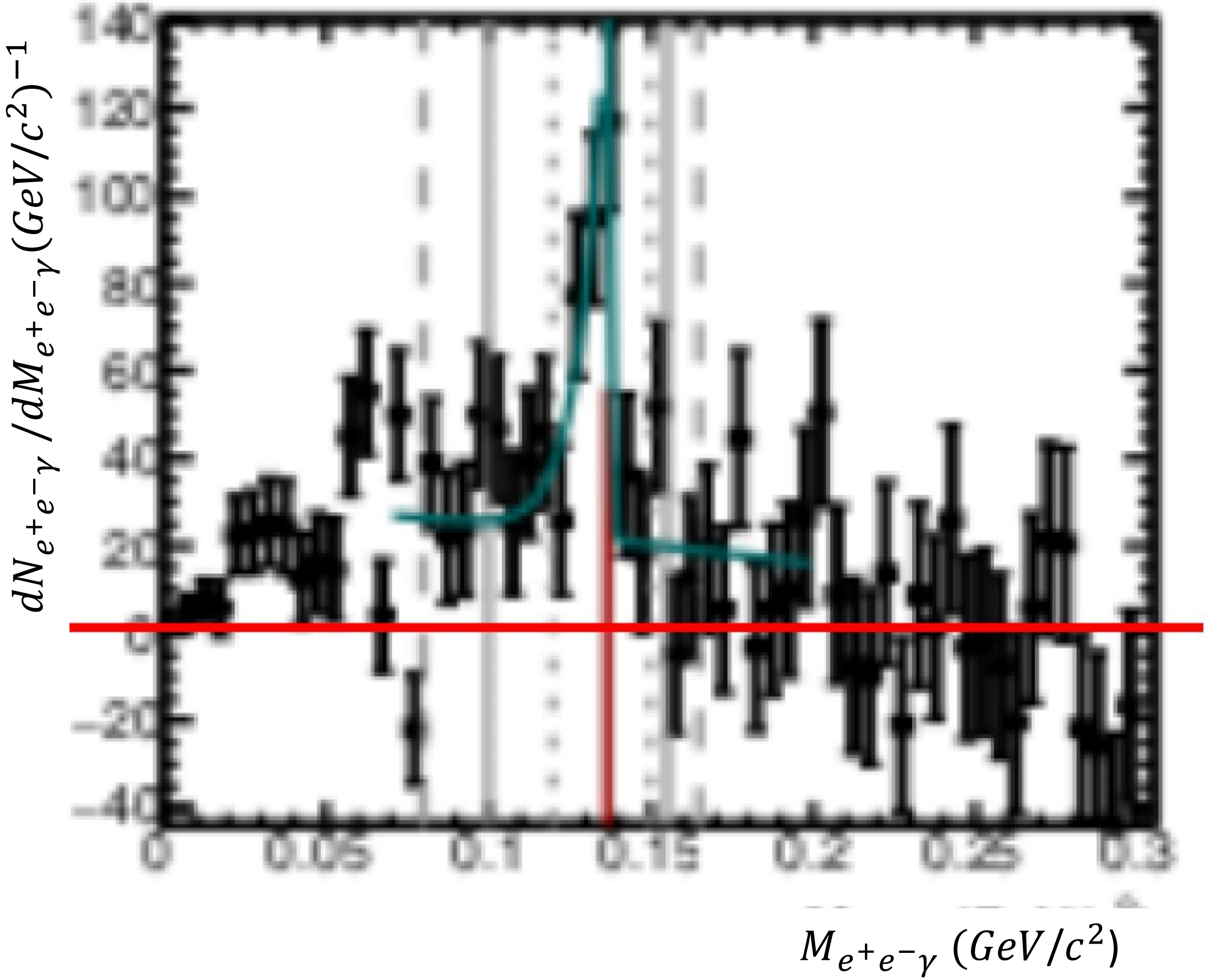


Peaks

Jain & Singh
J.Phys.G134,129(2007)

Pb Beam at 160A GeV
on photographic emulsion

0.60 GeV/c < $p_T < 0.7$ GeV/c



ALICE pPb at $\sqrt{s_{NN}}$ =5.02 TeV

From P G. Zamora, Ph.D. Thesis, Univ. Complutense de Madrid, 2017

There are many encouraging pieces of evidence for QED mesons :

(1) anomalous soft photons (excess e^+e^- pairs when producing hadrons)

(BEBC,WA27,NA22,WA83,WA91,WA102,DELPHI,...from 1984 to 2010)

(2) X17 particle (Krasznahorkay et.al., Atomki)

(3) E38 particle (Abraamyan et al., Dubna)

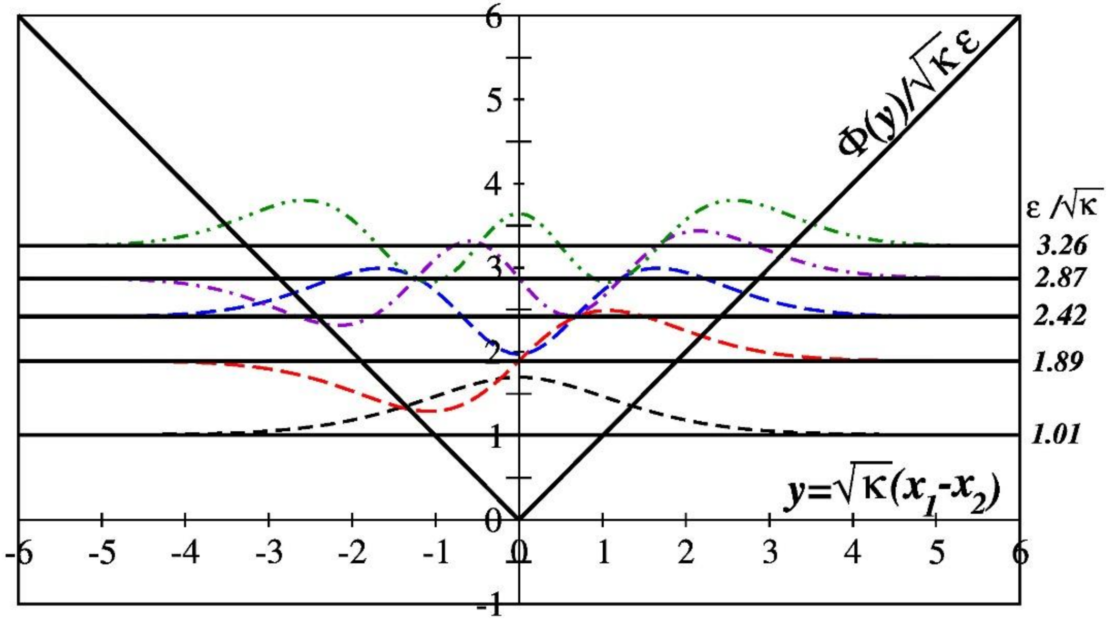
(4) X17, E38, and π^0 in (p,d)+A at a few GeV/nucleon collisions (Dubna,?)

(5) many states using virtual $\gamma^*\gamma^*$ [(e^+e^-)-(e^+e^-)] invariant mass in RHIC collisions(STAR,?)

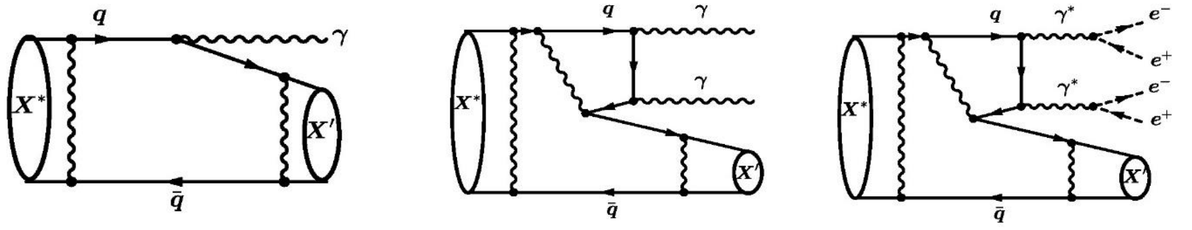
(6) other hints of anomalous particles ...

Excited states of QED mesons

Excited states of the QED string



Decay of higher excited states of a QED meson

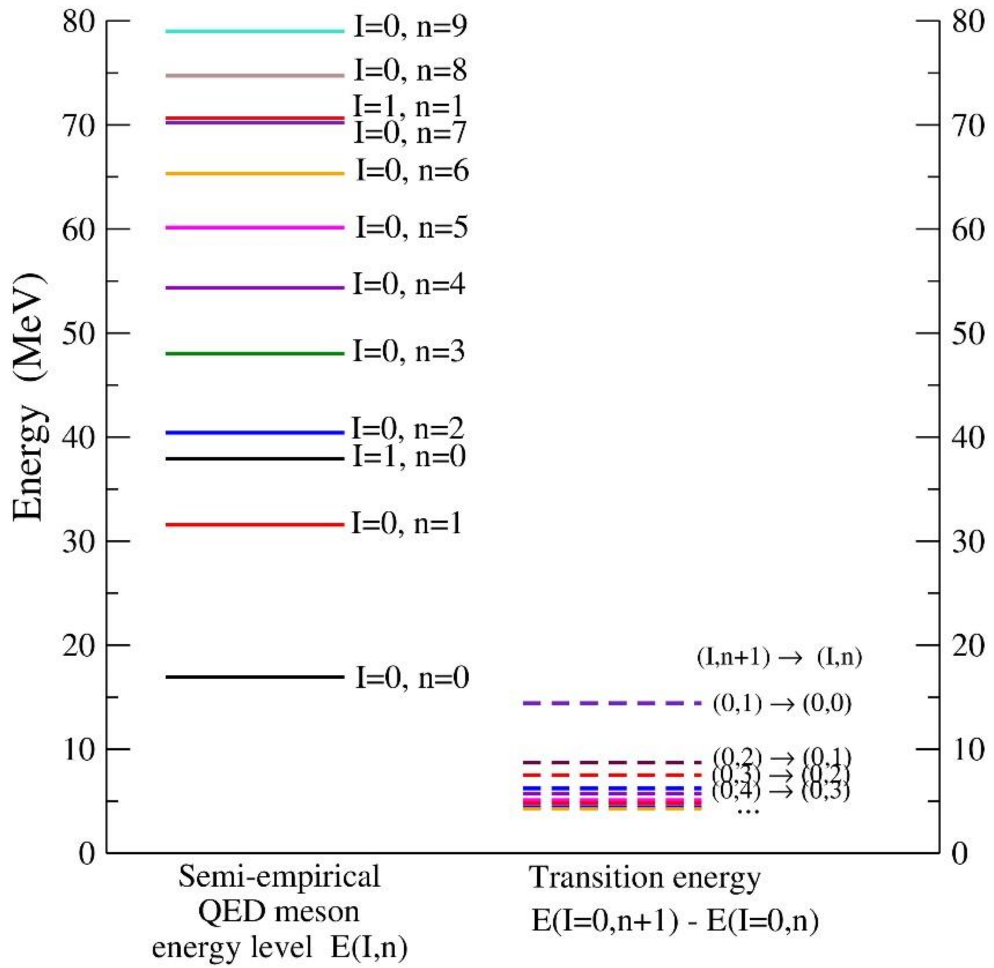


(a) $X^* \rightarrow X' + \gamma$

(b) $X^* \rightarrow X' + \gamma\,\gamma$

(c) $X^* \rightarrow X' + \gamma^*\gamma^*$

Semi-empirial spectrum of the QED string



The QED meson has a complex spectrum!

CYWong,arxiv:2010.13948.

Conclusions

- Excitation of the quark-QCD-QED system leads to independent QCD and QED excitations.
- These QCD and QED excitations give rise to QCD mesons and QED mesons.
- There are encouraging pieces of evidence for the occurrence of QED mesons in the mass region of many tens of MeV. On-going searches are continuing.