SQM2021, BNL
May 18-23, 2021

Quarks and antiquarks interacting in Electromagnetic Interactions

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1. The QCD string and the QED string between a valence q and its antiquark $\bar{q}$?
2. Consequences of the QED strings: $q\bar{q}$ QED mesons
3. Encouraging pieces of evidence for QED mesons: anomalous soft photons, X17, E38,...
4. Prospects of searching for QED mesons using $\gamma\gamma$ and (e^+e^-)-(e^+e^-) pairs.
5 QED d-u-d neutron as a candidate for dark matter
6. Conclusions

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

Stable QCD and QED string excitations above the QCD-QED vacuum

- The QCD-QED vacuum consists of quarks, QCD, and QED gauge fields filling up the Dirac sea
- A local disturbance creates a valence quark q and a valence antiquark $\bar{q}$ and their excitations
- There can be stable QCD string excitations which give rise to π, ρ, η, η', …
- There can be stable QED string excitations which give rise to

(1) anomalous soft photons (excess e^+e^- pairs when producing hadrons)
(BC,BEBC,WA27,NA22,WA83,WA91,WA102,DELPHI,…from 1979 to 2010)

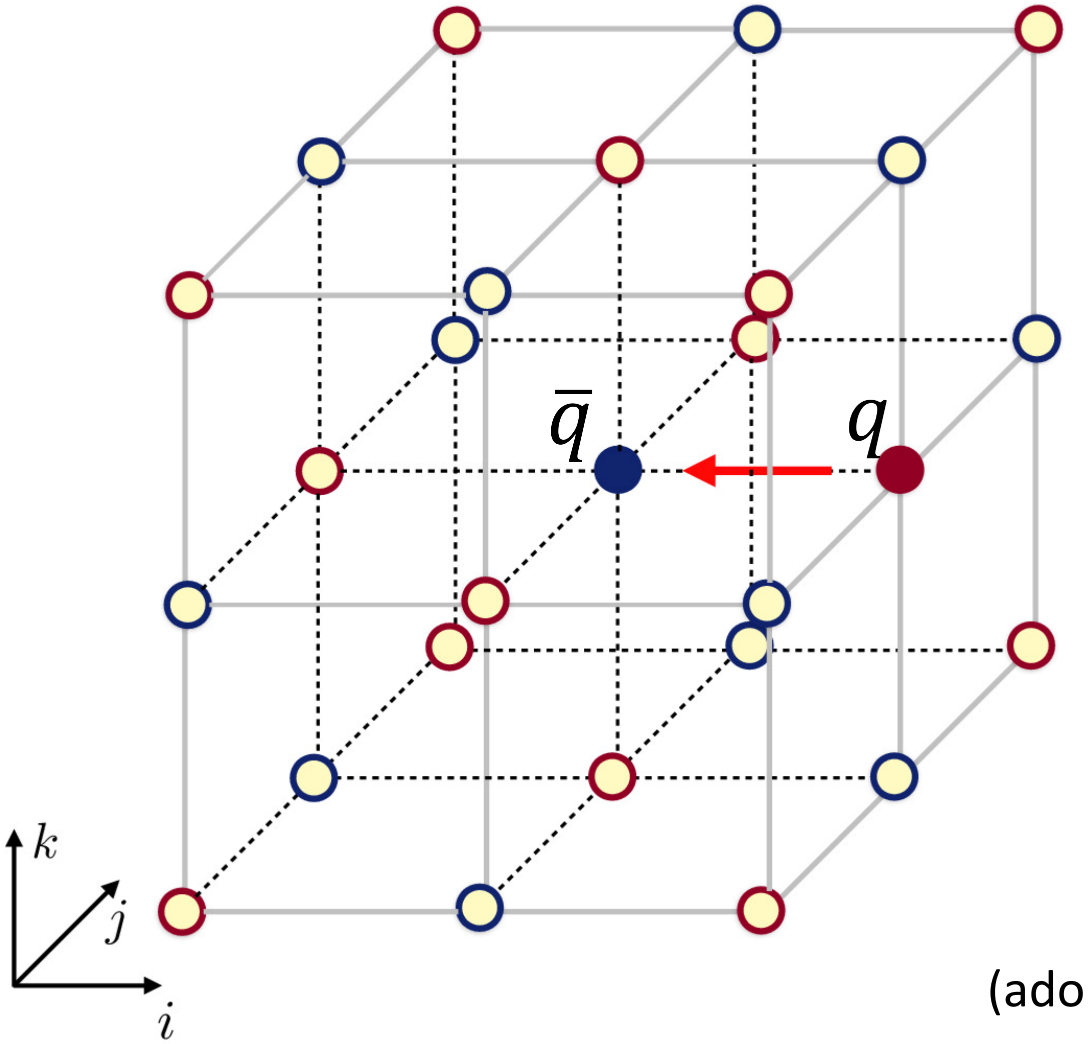
(2) X17 particle (Atomki)

(3) E38 particle (Dubna)

(4) X17, E38, and π^0 in same high energy heavy ion measurements (?)

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

A lattice illustration of background quarks, gauge fields, and valence particles



Quark Fields

$(-1)^{i+j+k} = +1:$
- $= \not\subset$ background quark under Dirac sea
- $= q$ a valence quark above Dirac sea

$(-1)^{i+j+k} = -1:$
- $= \not\subset$ background quark under Dirac sea
- $= \bar{q}$ valence antiquark, a hole below Dirac sea

QCD & QED Gauge Fields

$E_{x,\mu_x} =$
- $= |\rightarrow\rangle$ QCD & QED gauge fields bet'n q-$\bar{q}$
- $= |\varnothing\rangle$ background QCD & QED gauge fields
- $= |\leftarrow\rangle$ QCD & QED gauge fields bet'n q-$\bar{q}$

(adopted from Magifico et al., arxiv:2011.10658, with modifications)

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

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

Consider a gauge theory in 1+1 dimensions with massless fermions

$$\gamma^\mu(p_\mu - g_{2D}A_\mu)\,\psi = 0$$

QED

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

A small disturbance in $A^\nu \Rightarrow$ A small disturbance in j^ν

$\Rightarrow$ A small disturbance in A^ν

Therefore, j^ν must be a self-consistent function of A^ν

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

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

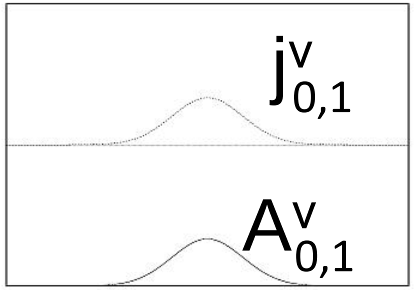
When we substitute this into the Maxwell equation, we get

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

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

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

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



(QED+QCD)

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

$$t^0 = \frac{1}{\sqrt{6}}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix}$$ for QED U(1) gauge field

$t^1, t^2, \dots, t^8$ for QCD SU(3) gauge field

Consider the restricted variation that will lead to stable QCD bosons

$$g_{2D}A^\nu = g_{2D}^{QED}A_0^\nu\tau^0 + g_{2D}^{QCD}A_1^\nu\tau^1$$

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

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

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

Theoretical support for the 2-string description of q-$\bar{q}$ excitations

- We consider Schwinger's 1+1D string as an idealization of a fluxtube with a radius R_T in 3+1D.

  The fluxtube has a structure in 3+1D. Its idealized string has no structure In 1+1D. The information on the fluxtube structure in 3+1D is stored in the idealized string in 1+1D as the coupling constant g_{2D},

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

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

- The physical mass in 3+1D is then related to the physical coupling constant g_{4D} by

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

- Therefore there are two kinds of string excitation between a valence q and its antiquark $\bar{q}$

  a QCD string and a QED string: $$m_{QCD}^2 = \frac{4\alpha_{4D}^{QCD}}{\pi R_T^2}, \quad m_{QED}^2 = \frac{4\alpha_{4D}^{QED}}{\pi R_T^2}.$$

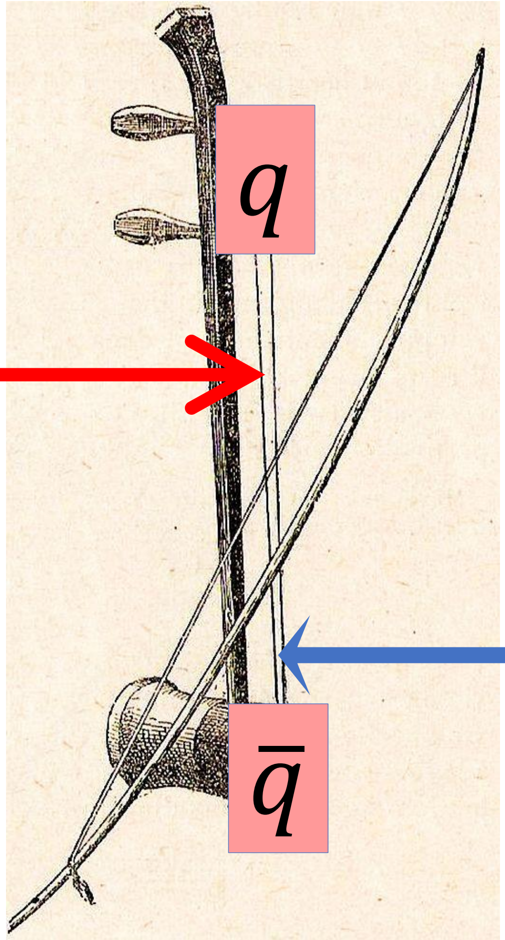
- If the flux tube radius R_T is an intrinsic property of the quark, then

$$\frac{(QCD\ boson\ mass\ m_{QCD})}{(QED\ boson\ mass\ m_{QED})} = \sqrt{\frac{\alpha_s}{\alpha_c}} \approx \sqrt{\frac{0.7}{1/137}} \approx 10 \approx \frac{(hundreds\ MeV)}{(tens\ MeV)}, \qquad \frac{(QCD\ boson\ length)}{(QED\ boson\ length)} \approx \frac{1}{10}.$$

The two-string (erhu 二胡) description of $q\bar{q}$ excitations

A QCD string excitation that generates $\pi, \rho, \eta, \eta', \ldots$

$$m^2_{QCD} = \frac{4\alpha^{QCD}_{4D}}{\pi R^2_T}$$



A QED string excitation that generates
(i) anomalous soft photons,
(ii) X17 particle,
(iii) E38 particle,
and ...

$$m^2_{QED} = \frac{4\alpha^{QED}_{4D}}{\pi R^2_T}$$

Additional theoretical support for q-$\bar{q}$ QED strings

- Many gauge calculations show that fermions in compact QED U(1) gauge theory in 3+1D have a confining phase for strong coupling and a non-confining phase for weak coupling:

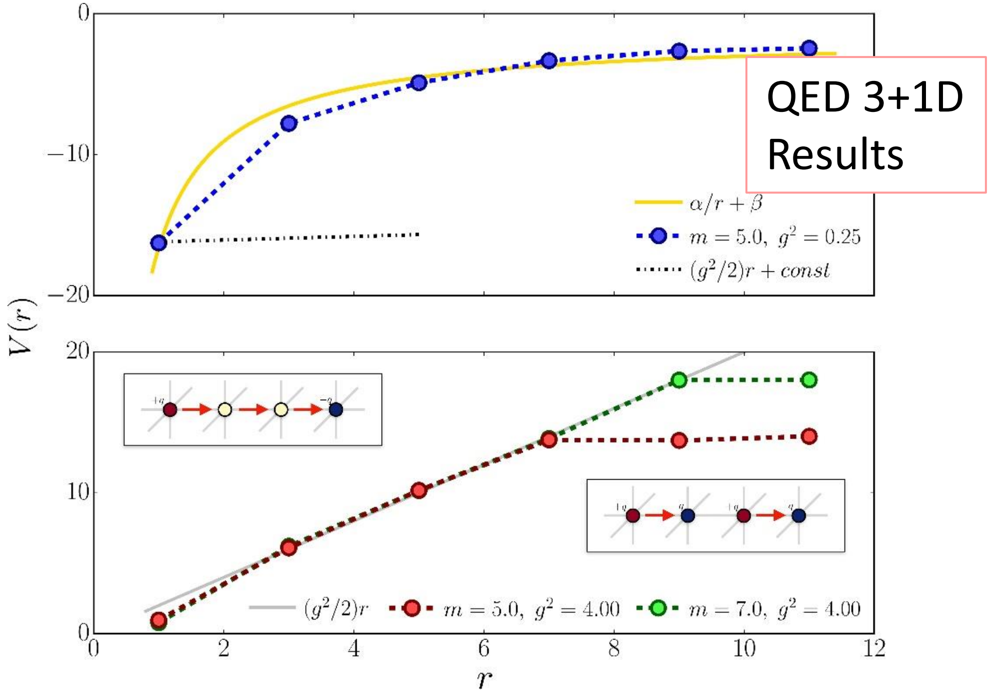
  Wilson(72), Polyakov(75), t'Hooft (74),

  Kogut&Suskind(75), Mandelstam(1975),

  Banks(77),Glimm&Jaffe(77),Peskin(78),

  Guth(80),Kondo(98),Magnifico(2011).

- It is therefore reasonable to consider q-$\bar{q}$ can also be confined in QED interactions.



Magnifico et al. (arxiv:2011.10658)

We are motivated to search for evidences of q-$\bar{q}$ **QED** string excitations.

By extrapolating from$q$-$\bar{q}$ **QCD** strings to q-$\bar{q}$ **QED** strings?

We study first the QCD meson masses with 3 flavor in QCD string model

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

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}, m_f from PDG tables

The unknown parameters are α_{4D}^{QCD} and R_T.

Fitting π, η, η' masses gives α_{4D}^{QCD}=0.68 and R_T=04 fm.

We then extrapolate to QED mesons with 2 flavor in QED string model

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

$I = 0,$ for isoscalar QED meson

$I = 1,$ for isovector QED meson

$Q_u=2/3, \quad Q_d=-1/3$

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

Lowest-energy QCD & QED I_3=0 meson masses

		I	S	$[I(J^\pi)]$	Experimental mass (MeV)	Semi-empirical mass formula (MeV)
QCD meson	π^0	1	0	$[1(0^-)]$	134.9768±0.0005	$134.9^{\ddagger}$
	η	0	0	$[0(0^-)]$	547.862±0.017	498.4±39.8
	η'	0	0	$[0(0^-)]$	957.78±0.06	948.2±99.6
QED meson	isoscalar	0	0	$[0(0^-)]$		17.9±1.5
	isovector	1	0	$[1(0^-)]$		36.4±3.8
Possible QED meson candidates	X17			(1^+)?	$16.70\pm0.35\pm0.5^{\dagger}$	
	X17			(0^-)?	$16.84\pm0.16\pm0.20^{\#}$	
	E38			?	$37.38\pm0.71^{\oplus}$	
	E38			?	$40.89\pm0.91^{\ominus}$	
	E38			?	$39.71\pm0.71^{\otimes}$	

$\ddagger$ Calibration mass

$\dagger$ A. Krasznahorkay *et al.*, Phys.Rev.Lett.116,042501(2016), ^{8}Be* decay

$\#$ A. Krasznahorkay *et al.*, arxiv:1910.10459, ^{4}He* decay

$\oplus$ K. Abraamyan *et al.*, EPJ Web Conf 204,08004(2019),dCu$\to\gamma\gamma X$

$\ominus$ K. Abraamyan *et al.*, EPJ Web Conf 204,08004(2019),pCu$\to\gamma\gamma X$

$\otimes$ K. Abraamyan *et al.*, EPJ Web Conf 204,08004(2019), dC$\to\gamma\gamma X$

α_{4D}^{QCD}=0.68±0.08 ,
R_T = 0.4 ± 0.04 fm

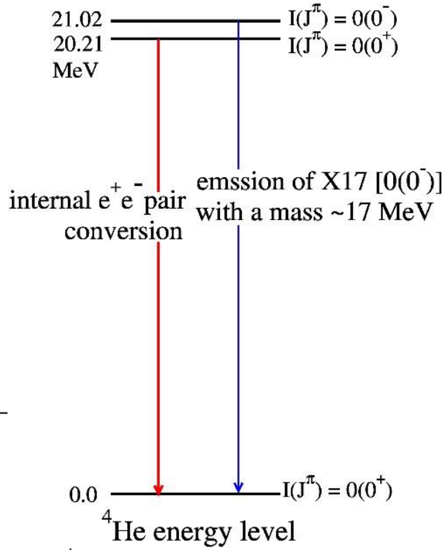
$$\alpha_{4D}^{QED}=\frac{1}{137}$$

We find that
QCD string & QED strings
are reasonable concepts!

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

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

Krasznahorkay et al arxiv:1910.10459



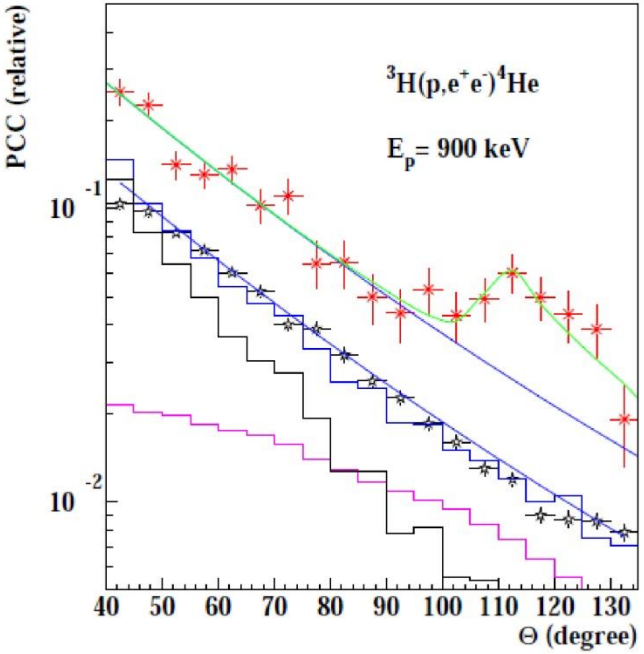


FIG. 2. *Angular correlations for the e^+e^- pairs measured the $^3H(p,\gamma)^4He$ reaction at the E_p=900 keV.*

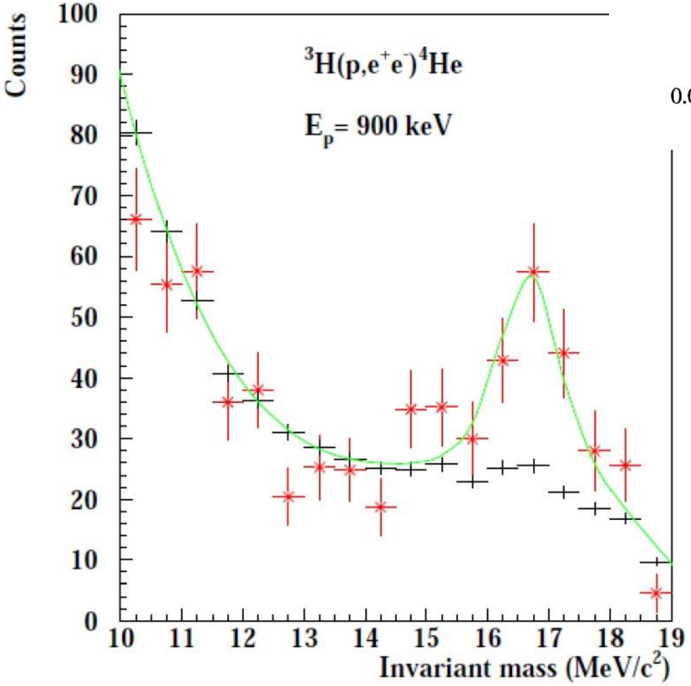
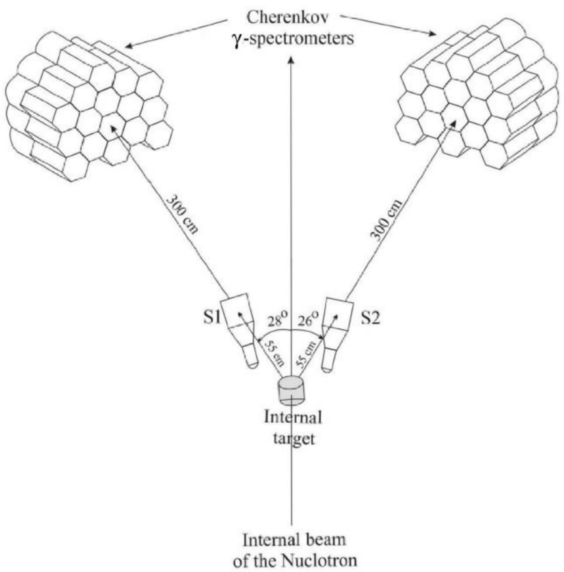
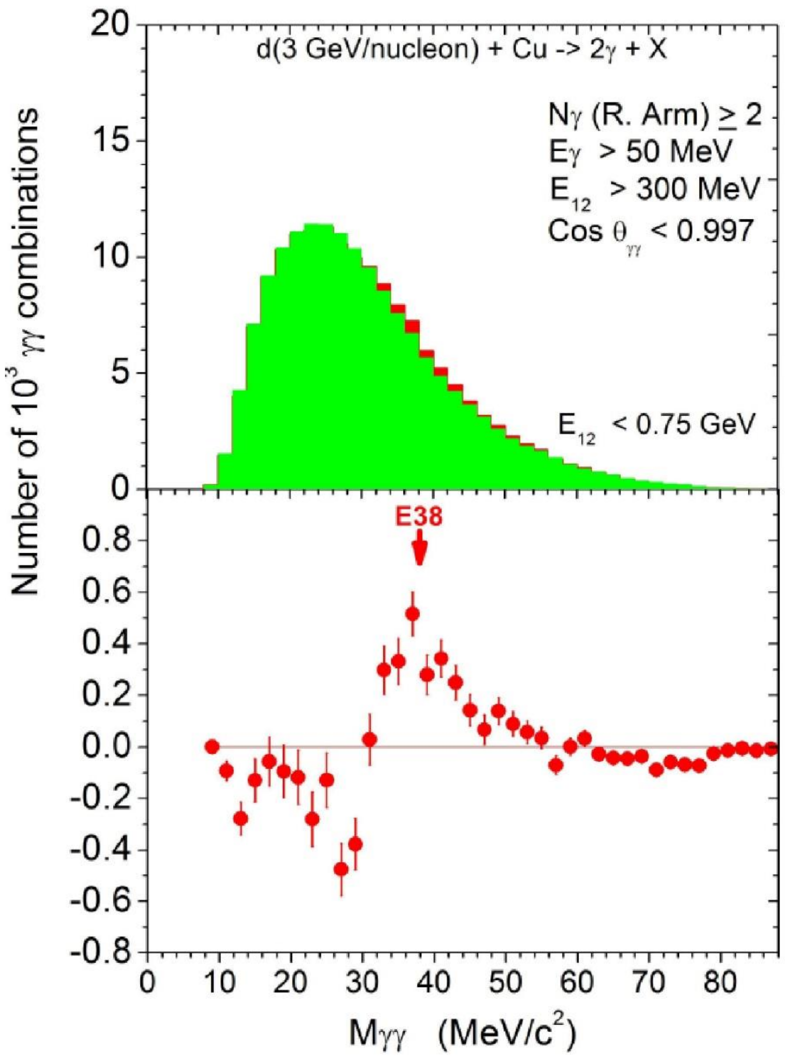


FIG. 3. *Invariant mass distribution derived for the 20.49 MeV transition in ^4He.*

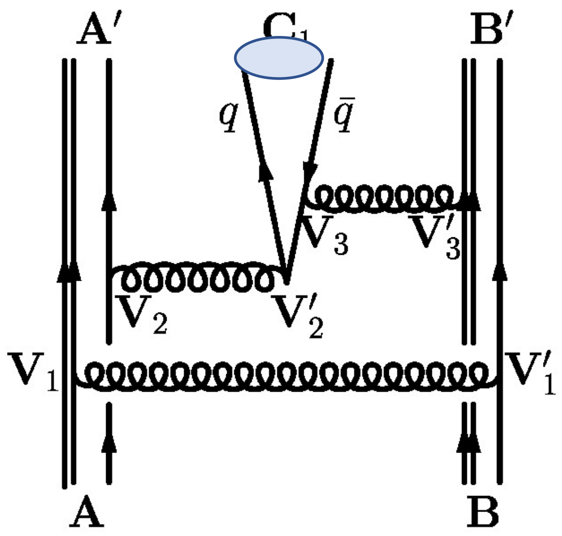
Observation of the E38 boson at Dubna



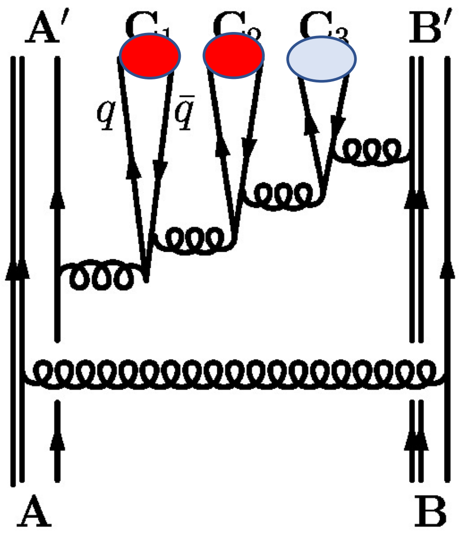


Abraamyan et al. arxiv:1208.3829(2012)
EPJWebConf204,08004(2019)

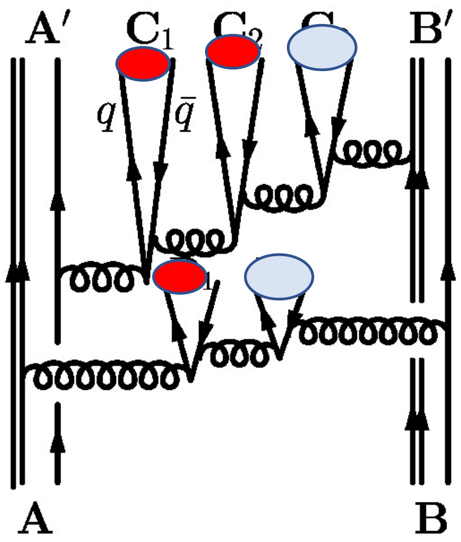
How are QCD and QED mesons produced?



(a)
Low energies



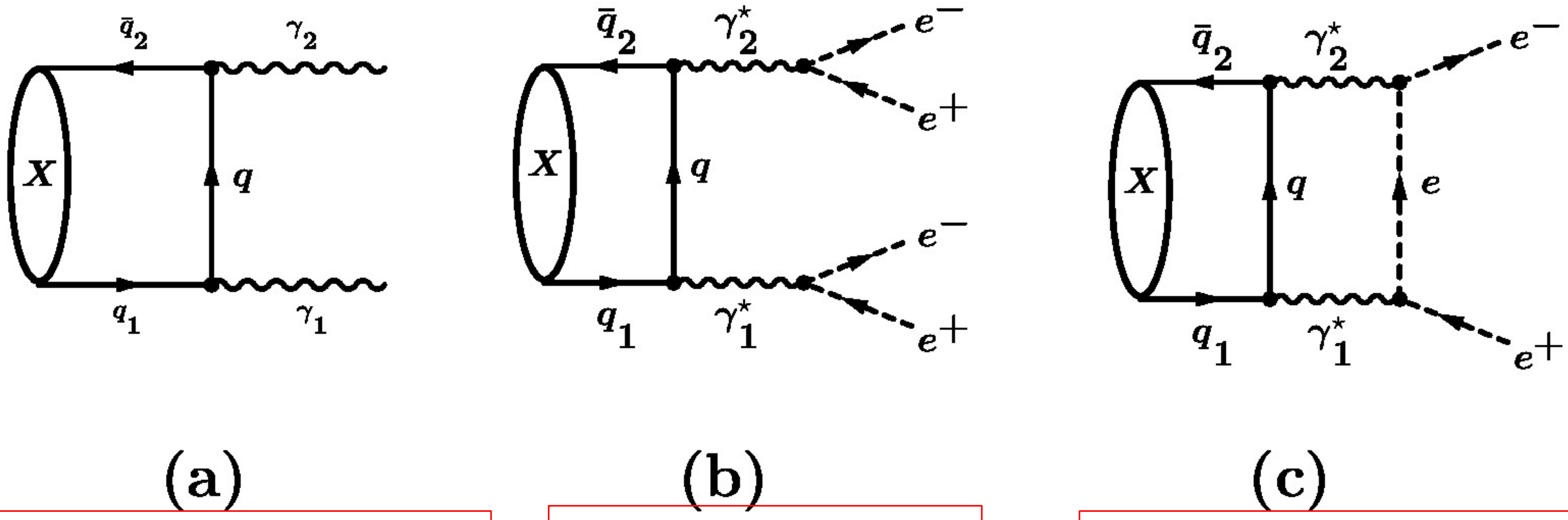
(b)
Intermediate energies



(c)
High energies

In the collision process, a large number of $q\bar{q}$ pairs are produced. Most become QCD mesons, but some may become QED mesons, which decay as X17, E38, or anomalous soft photons.

Decay and detection of QED mesons



Detection using diphoton invariant mass -- Dubna

Detection using invariant mass two virtual photons -- RHIC?

Detection using dilepton invariant mass -- Atomki

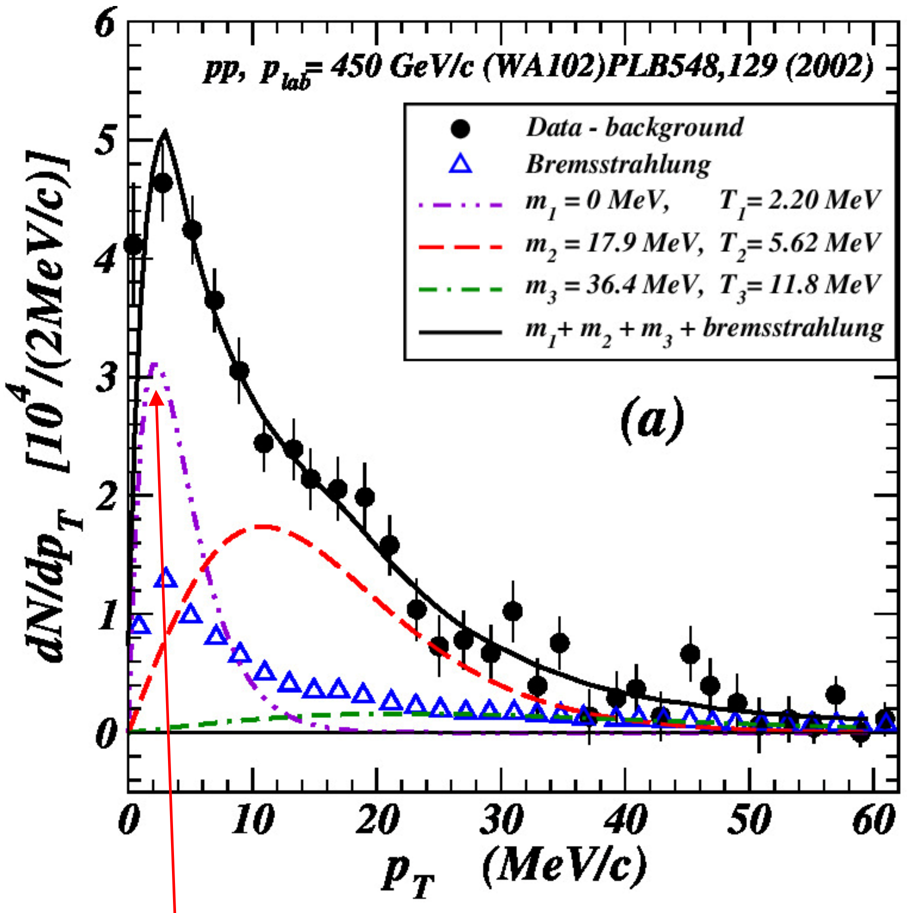
Anomalous soft photons are produced when hadrons are produced

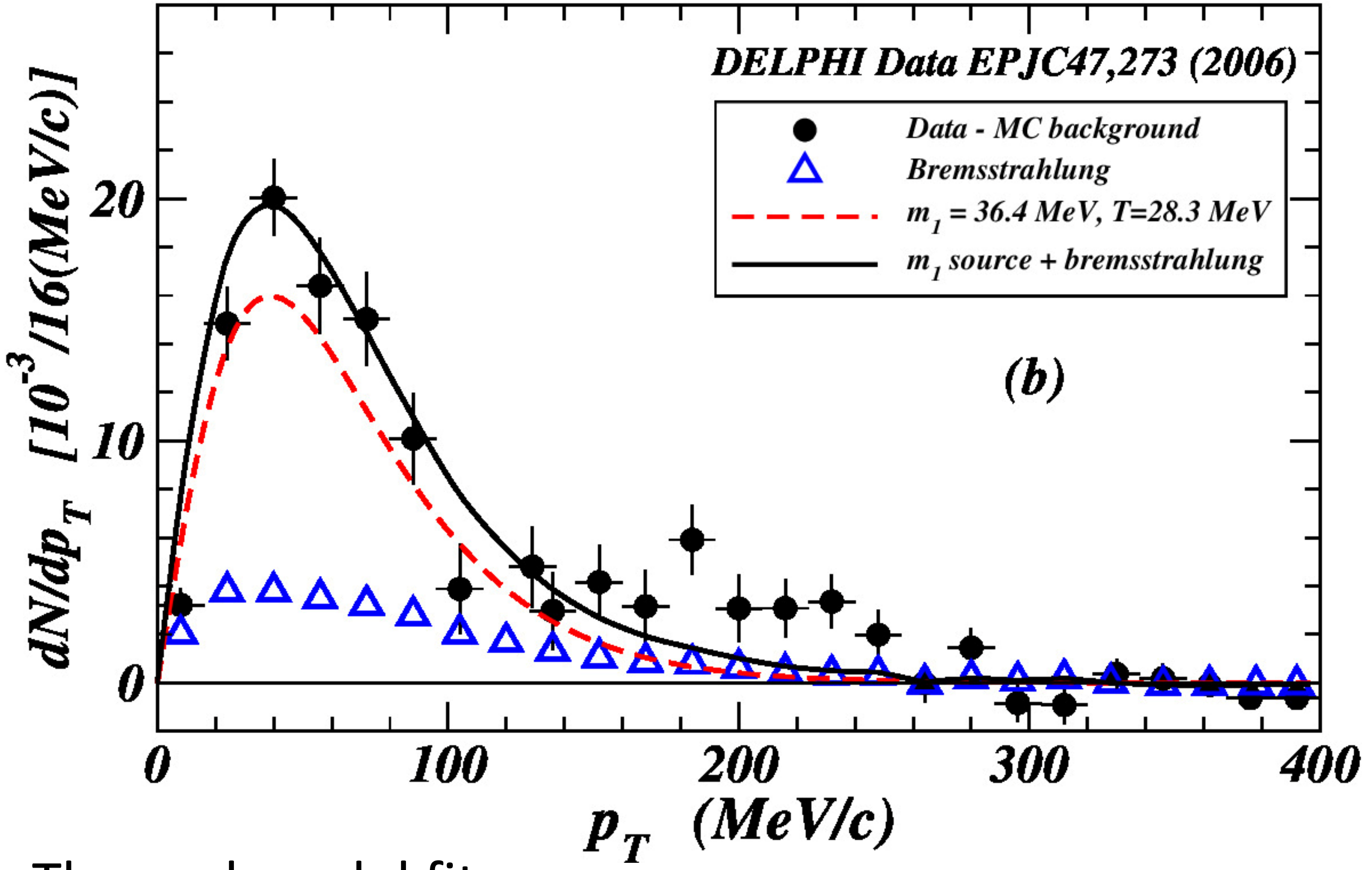
Experiment	Collision Energy	Photon pT	Photon/Brems Ratio
π^+ p, SLAC, BC (1979)	10.5 GeV/c	p_T < 20 MeV/c	1.25 ± 0.25
K^+ p, CERN WA27,BEBC(1984)	70 GeV/c	p_T < 60 MeV/c	4.0 ± 0.8
K^+ p, CERN NA22, EHS (1993) π^+ p, CERN NA22,EHS (1997)	250 GeV/c 250 GeV/c	p_T < 40 MeV/c p_T < 40 MeV/c	6.4 ± 1.6 6.9 ± 1.3
π^- p , CERN WA83,OMEGA(1997)	280 GeV/c	p_T < 10 MeV/c	7.9 ± 1.4
π^- p , CERN WA91,OMEGA(2002)	280 GeV/c	p_T < 20 MeV/c	5.3 ± 0.9
p p , CERN WA102,OMEGA(2002)	450 GeV/c	p_T < 20 MeV/c	4.1 ± 0.8
$e^+e^- \to$ hadrons CERN DELPHI(2010) with hadron production	~91 GeV (CM)	p_T < 60 MeV/c	~4.0
$e^+e^- \to \mu^+\mu^-$ CERN DELPHI(2008) with no hadron production	~91 GeV (CM)	p_T < 60 MeV/c	~1.0

(Table compiled by V. Perepelitsa)

- Anomalous soft photons are low-p_T photons (p_T<60 MeV).
- They are in excess of what is expected from EM bremsstrahlung.
- They occur only when hadrons are produced.

Large e^+e^- excess in pp and e^+e^- annihilations when hadrons are produced





High-energy pp collisions produce large numbers of virtual photons as $m \sim 0$, (e^+e^-) pairs.

Thermal model fit:

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

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)

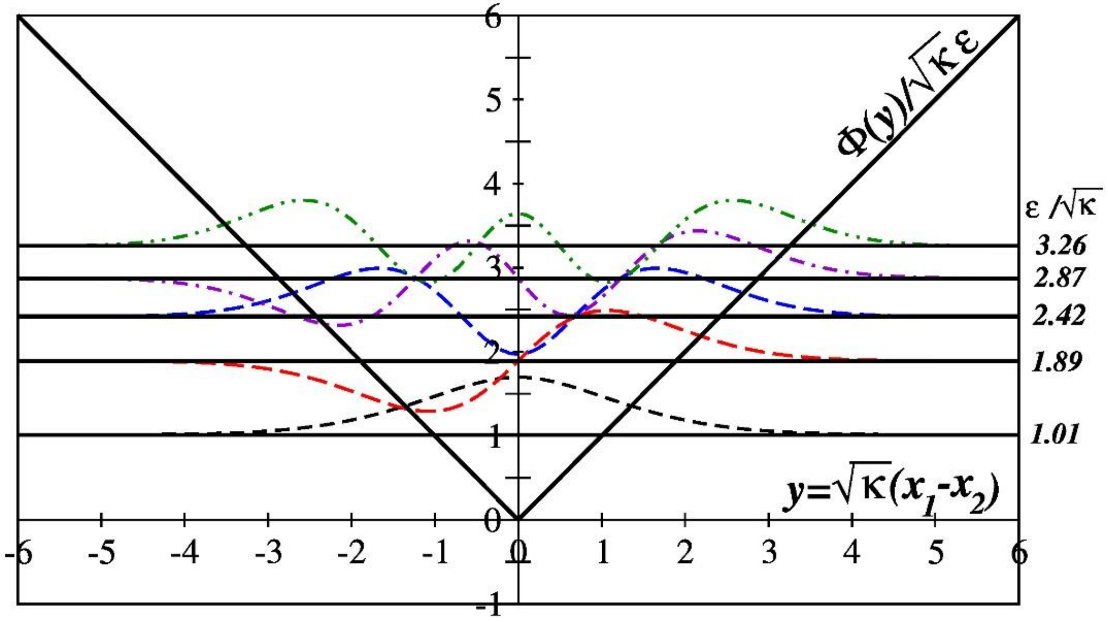
(3) E38 particle (Abraamyan et al., Dubna)

(4) X17, E38, and π^0 in same high energy heavy ion measurements (?)

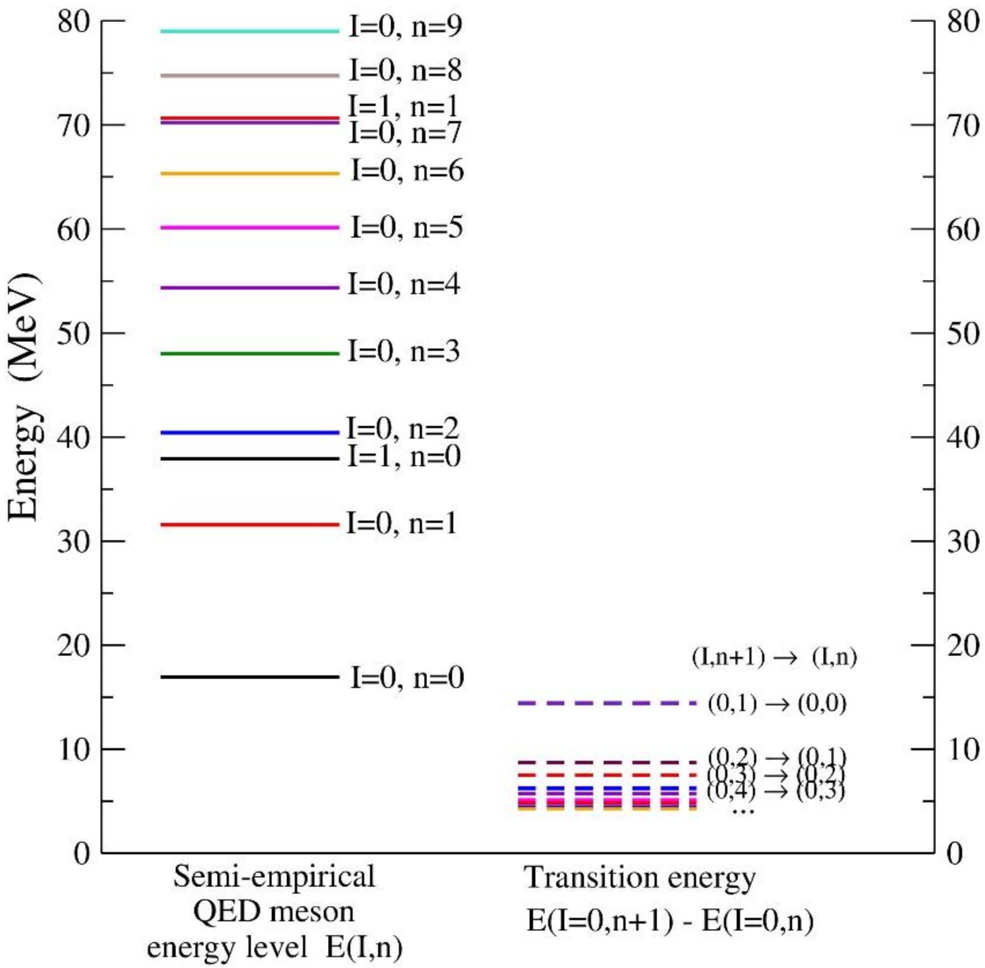
(5) many states using virtual $\gamma^*\gamma^*$ [(e^+e^-)-(e^+e^-)] invariant mass in RHIC collisions(?)

Excited states of QED mesons

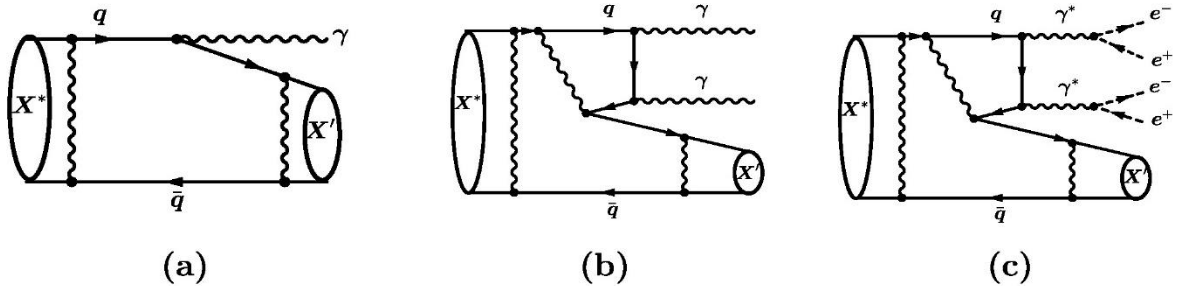
Excited states of the QED string



Semi-empirial spectrum of the QED string



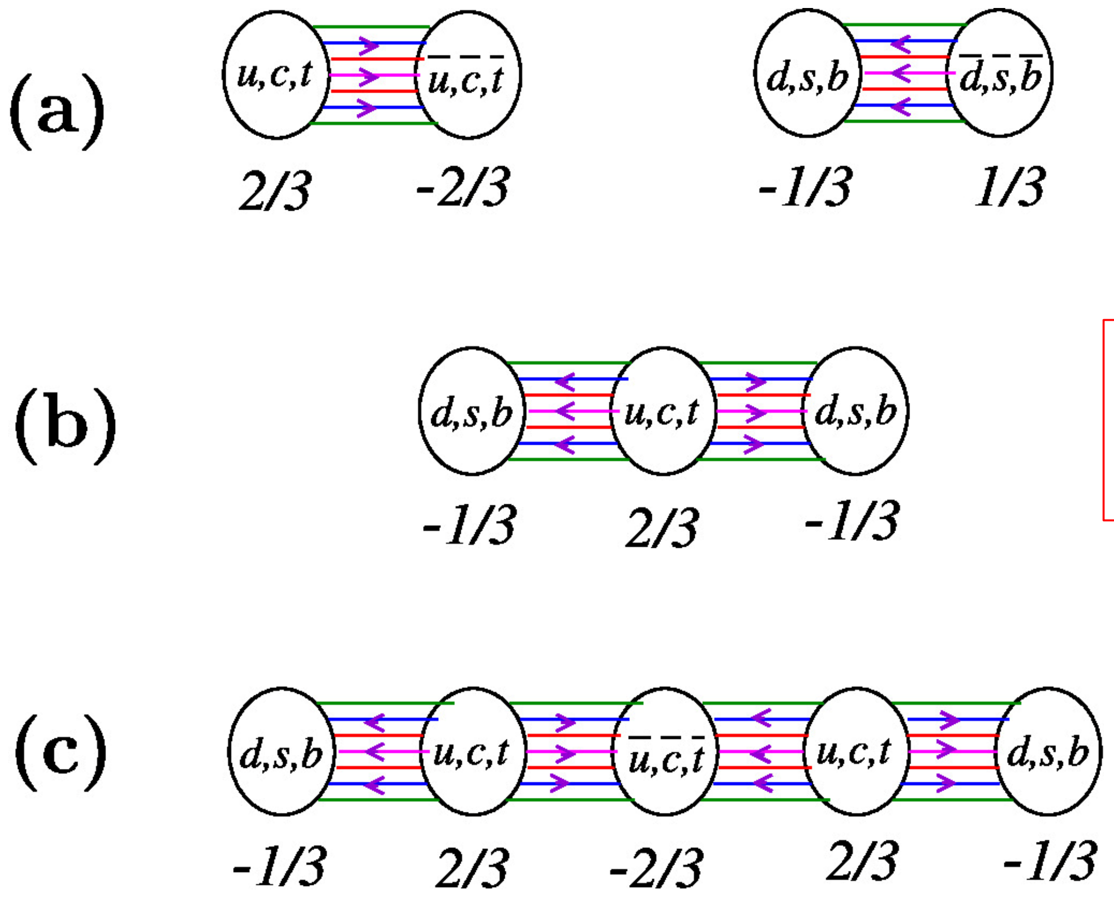
Decay of higher excited states of a QED meson



$X^* \to X' + \gamma$ $\quad$ $X^* \to X' + \gamma\,\gamma$ $\quad$ $X^* \to X' + \gamma^*\gamma^*$

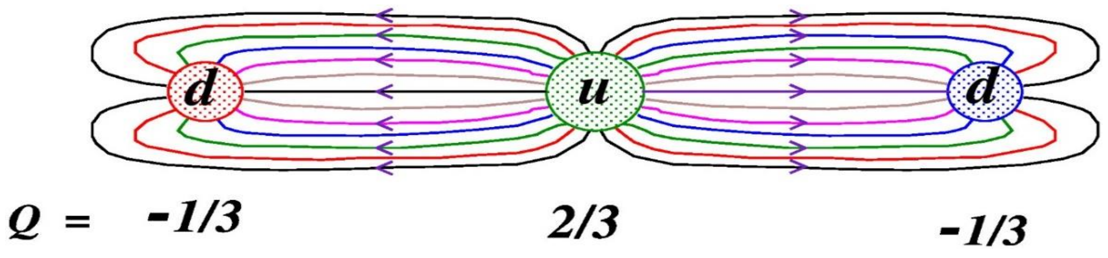
Other possible quark and antiquark states bound by QED forces

Other possible QED quark composite particles

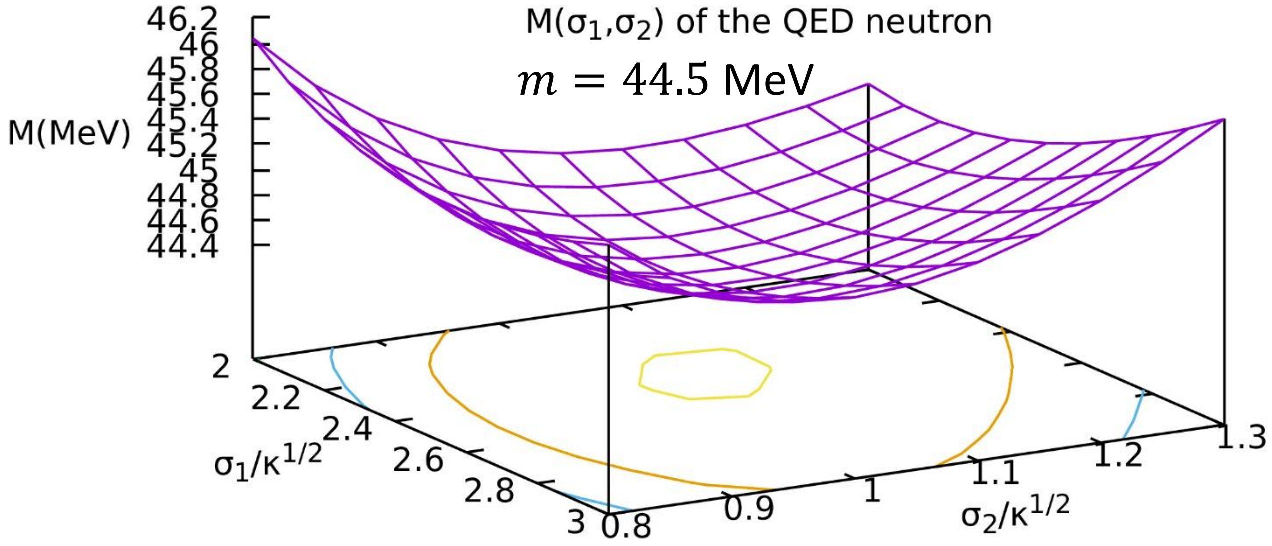


The connecting lines show the electric field lines of force

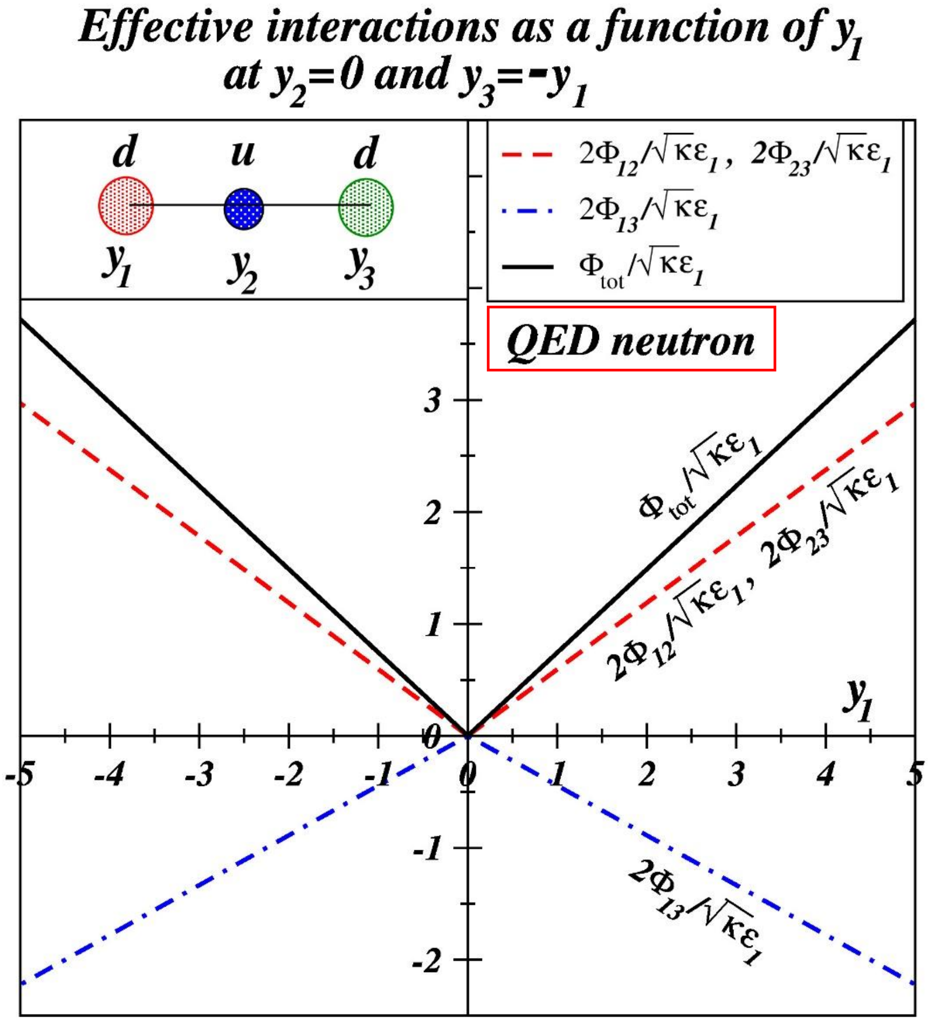
d-u-d QED neutron may be a stable particle



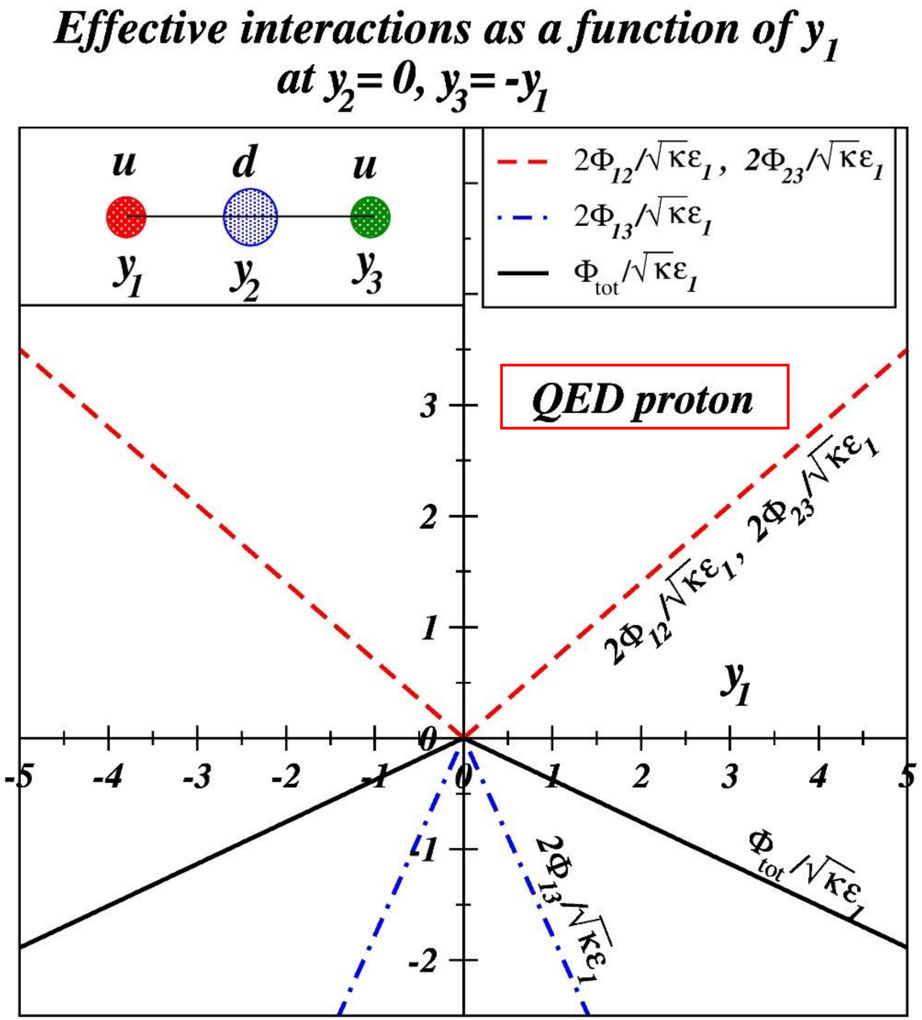
In a d-u-d neutron in QED interactions, the sum of the attractive forces between the d-u pairs are predicted to be greater than the repulsive force between the d-d pair to stabilize the QED neutron.



CYWong,arxiv:2010.13948.



The QED neutron is predicted to be stable because of sum attractive QED forces are greater than the repulsive force.



The QED proton is predicted to be unstable because of sum attractive QED forces are less than the repulsive force.

Important implications of the QED neutron

- QED neutron is stable against weak decay because there is no bound or continuum QED proton state for it to decay into.
- QED neutron cannot be dissociated because the quarks in the QED neutron are confined and are not isolatable
- QED neutron therefore has a very long lifetime. It can decay only through a baryon number changing process which presumably has a very long lifetime
- QED neutron may be produced by the coalescence of deconfined quarks during the deconfinement-to-confinement phase transition of the QGP
- QED neutron may be a good candidate particle for a part of the dark matter during the deconfinement-to-confinement phase transition of the QGP in the evolution of the early Universe

QED mesons and QED neutron produced by coalescence of deconfined quarks

- Coalescence of deconfined quarks and antiquarks during the deconfinement-to-confinement stage of the QGP phase transition can produce QED mesons and their excited states, depending on the invariant mass of the coalescing pair.

- QED neutron and its excited states can be produced by deconfined d, u and d quarks with low total invariant mass of the coalescing composite system during the deconfinement-to-confinement stage of the QGP phase transition.

Conclusions

- Excitation of the QCD-QED vacuum can lead to QCD and QED string excitations
- QED string excitations give rise to QED mesons and the possible QED neutron which may be a good candidate particle for the dark matter
- There are encouraging evidences for the occurrence of QED mesons in the region of many tens of MeV. On-going searches are continuing.
- Measurements of the invariant masses of real and virtual photon pairs at RHIC offer a good opportunity to study the states of QED mesons and the de-excitation of the QED neutron.