Paris, May 20, 2013

An Overview of the Anomalous Soft Photons in Hadron Production

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1. Introduction
   -- Why do we want to study soft photons in hadron production?
   -- What are the anomalous soft photons?

2. Many models to explain the anomalous soft photon phenomenon

3 Peculiar properties in anomalous soft photon production

4. Proposed quantum field theory explanation
   -- Bound QCD & QED states in the flux-tube environment
   -- Production of these bound states in the flux-tube environment
   -- Evolution of these flux tube-states

5 Conclusions

Why study soft photon in a hadron production?

Soft photons in hadron production involves
QED, QCD, & possible QCD effects in QED processes

Conventional theory of QED bremsstrahlung

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

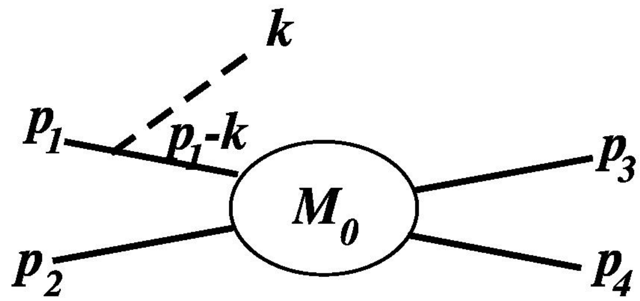
The spectrum of bremsstrhlung soft photons can be obtained from exclusive measurements of the momenta of all initial and final charged particles

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

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

Low Theorem

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



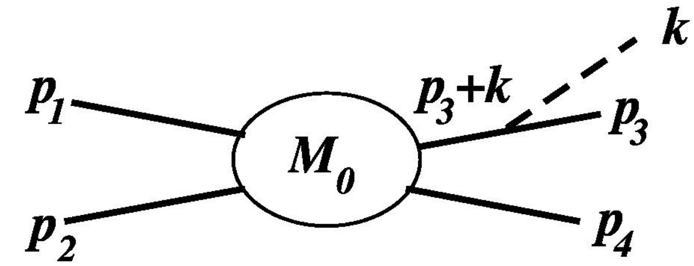
$$M(p_1p_2;\ p_3p_4k) = M_0(p_1p_2;\ p_3p_4)\left[\frac{e_1p_1\cdot\varepsilon}{(p_1-k)^2}+\frac{e_3p_3\cdot\varepsilon}{(p_3+k)^2}\right]$$

$$= M_0(p_1p_2;\ p_3p_4)\left[\frac{-e_1p_1\cdot\varepsilon}{2p_1\cdot k}+\frac{e_3p_3\cdot\varepsilon}{2p_3\cdot k}\right]$$

$$= M_0(p_1p_2;\ p_3p_4)\left[\sum_i^{\text{all charged particles}}\frac{\eta_ie_ip_i\cdot\varepsilon}{2p_i\cdot k}\right]$$

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

This can be generalized to



$$M(p_1p_2;\ p_3p_4...p_Nk) = M_0(p_1p_2;\ p_3p_4..p_N)\left[\sum_i^{N+2}\frac{\eta_ie_ip_i\cdot\varepsilon}{2p_i\cdot k}\right]$$

$$|M(p_1p_2;\ p_3p_4...p_Nk)|^2 = |M_0(p_1p_2;\ p_3p_4..p_N)|^2\left[\sum_i^{N+2}\frac{\eta_ie_ip_i\cdot\varepsilon}{2p_i\cdot k}\right]^2$$

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

$$|M(p_1p_2;\ p_3p_4...p_Nk)|^2 = |M_0(p_1p_2;\ p_3p_4..p_N)|^2\left[\sum_{i,j}^{N+2}\frac{\eta_i\eta_je_ie_j(p_i\cdot p_j)}{4(p_i\cdot k)(p_j\cdot k)}\right]$$

$$\frac{dN_\gamma}{d^3k} = \frac{\alpha}{2\pi k_0}\int d^3p_3d^3p_4...d^3p_N\sum_{i,j=1}^{N+2}\frac{\eta_i\eta_je_ie_j(p_i\cdot p_j)}{4(p_i\cdot k)(p_j\cdot k)}\frac{dN_{\text{hadron}}}{d^3p_3d^3p_4...d^3p_N}$$

$\eta_i = 1$ 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.

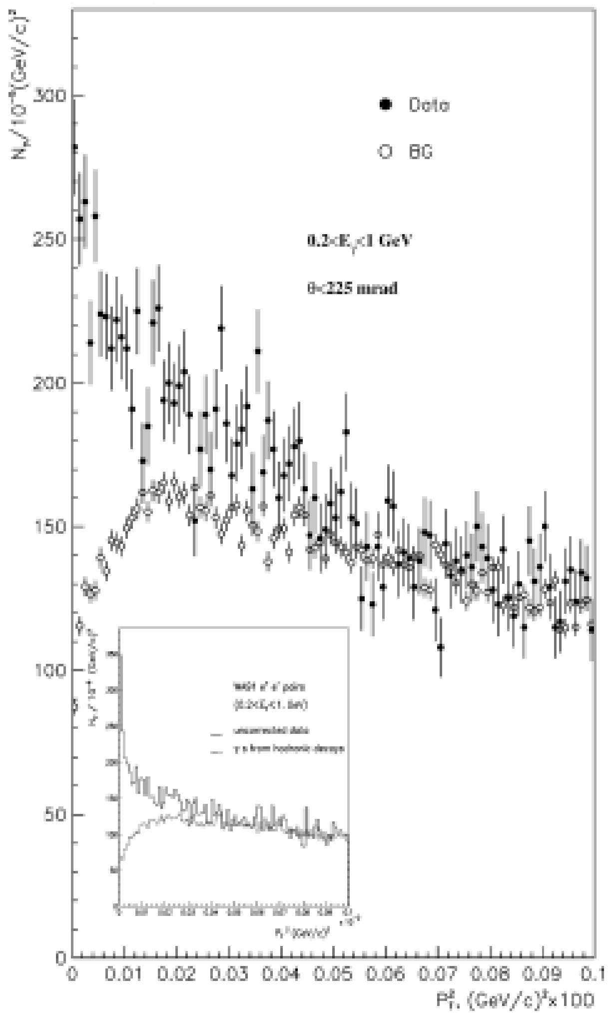
(Table compiled by V. Perepelitsa)

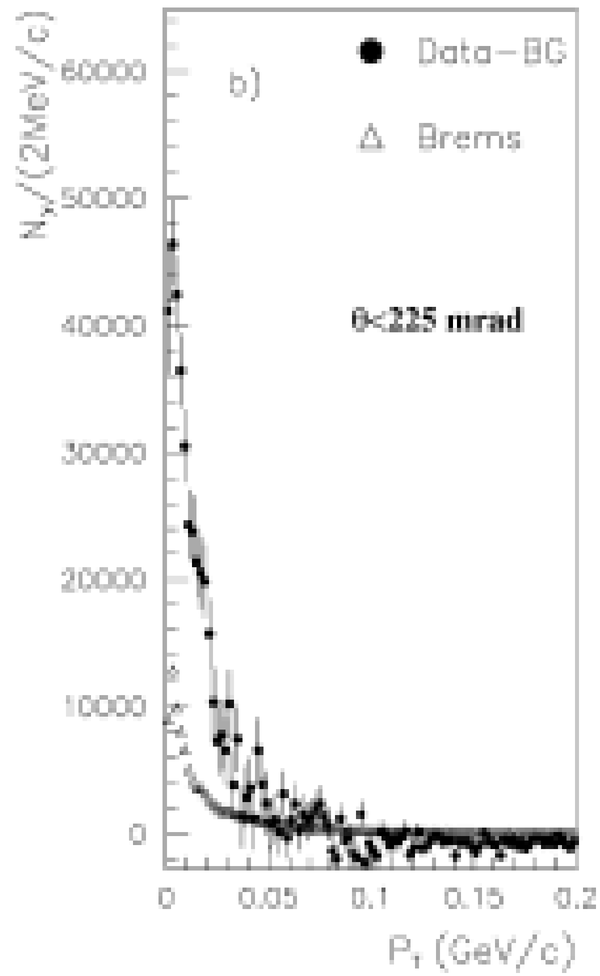
Experiment	Collision Energy	Photon pT	Photon/Brems Ratio
π^+ p, SLAC, BC (1979)	10.5 GeV/c	p_T < 20 MeV/c	1.25 ± 0.25
K^+ p, CERN WA27,BEBC(1984)	70 GeV/c	p_T < 60 MeV/c	4.0 ± 0.8
K^+ p, CERN NA22, EHS (1993) π^+ p, CERN NA22,EHS (1997)	250 GeV/c 250 GeV/c	p_T < 40 MeV/c p_T < 40 MeV/c	6.4 ± 1.6 6.9 ± 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-→hadrons CERN DELPHI(2010) with hadron production	~91 GeV (CM)	p_T < 60 MeV/c	~4.0
e+e- →μ+μ- CERN DELPHI(2008) with no hadron production	~91 GeV (CM)	p_T < 60 MeV/c	~1.0

- 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.

WA102 data for pp collisons at 450 GeV(fixed target)

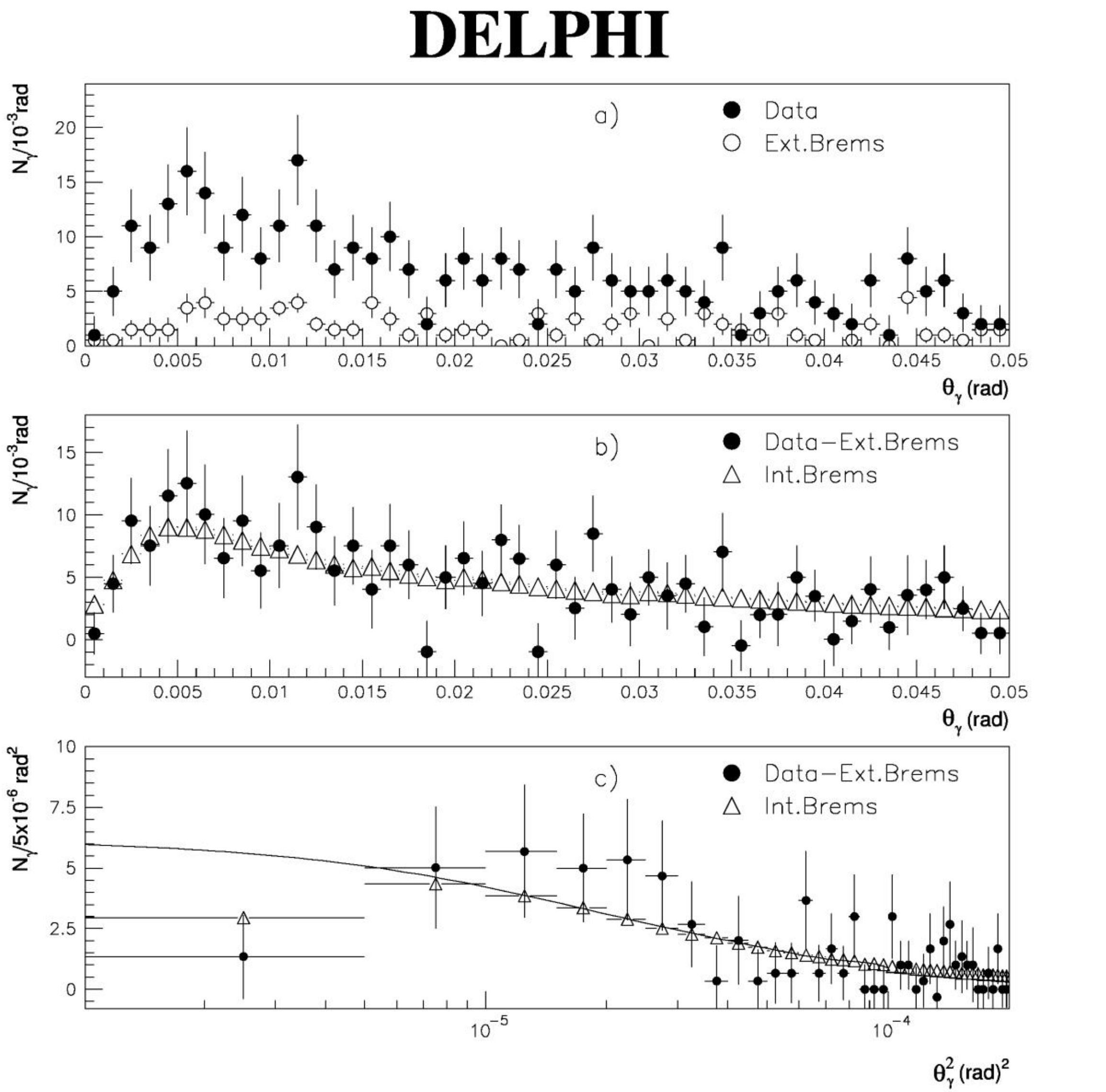
A. Belogianni et al. / Physics Letters B 548 (2002) 129–139



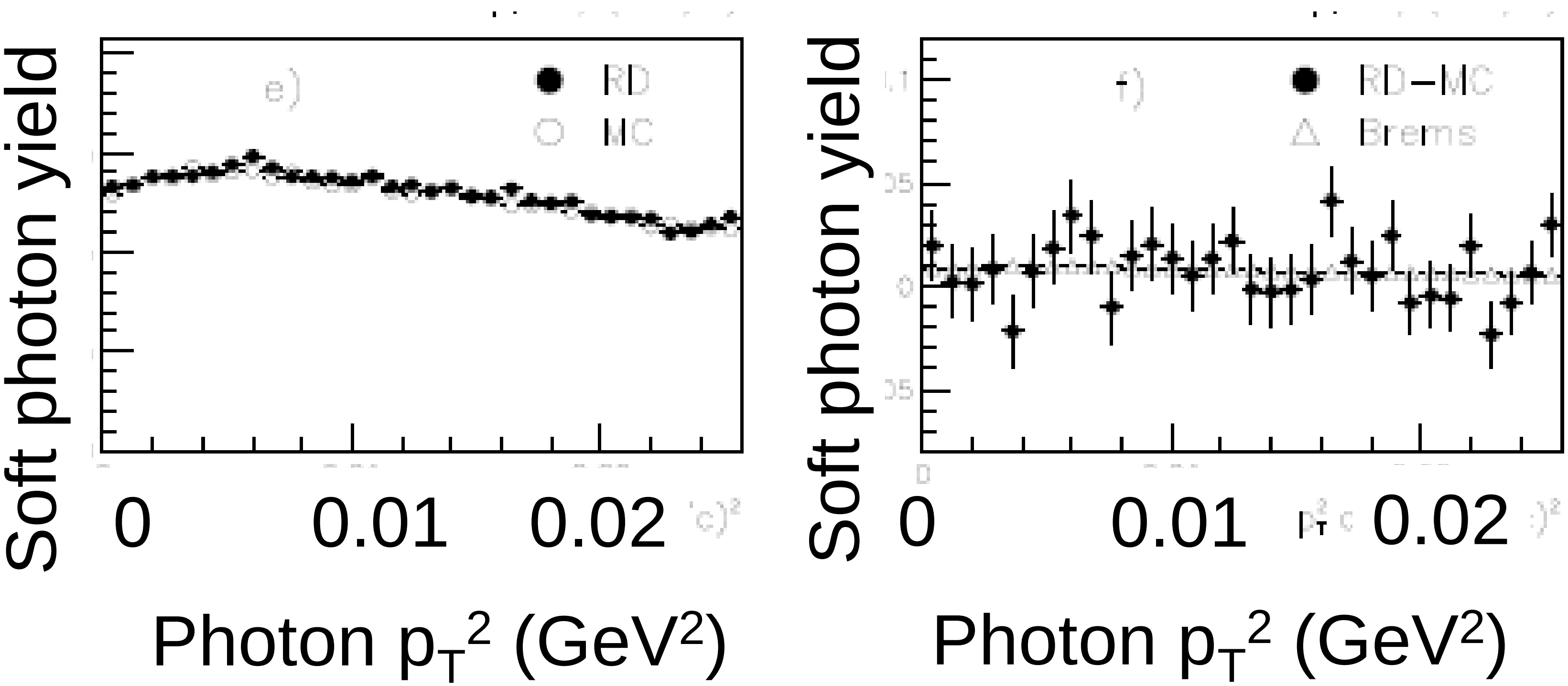


No anomalous soft photons in

$$e^+ + e^+ \rightarrow \mu^+ + \mu^- + n\gamma$$



DELPHI “Zero” experiment, using a distant jet as axis



Models of Anomalous Photons (I)

- Van Hove (Ann.Phys.192,66(1989))

  Van Hove & Lichard (PLB245,605(1990))

Partons at end of virtuality evolution form a glob of cold quark-gluon system of low temperature of

T~10 – 30 MeV.

Soft photons may be produced by $q + \bar{q} \rightarrow \gamma + g$

$$g + q \rightarrow \gamma + q$$

Models of Anomalous Photons (II)

- Barshay (PLB227,279(1989))

pions propagate in pion condensate and emit soft photons during the propagation. Rate of soft photon emission depends on the square of pion multiplicity

- Shuryak (PLB231,175 (1989))

Soft photons are produced by pions reflecting from a boundary under random collisions. Hard reflections lead to no effect, but soft pion collisions on wall leads to large enhancement in soft photon yield.

Models of Anomalous Photons (III)

- Czyz & Florkowski (ZFPC61,171(1994))

Soft photons are produced by classical bremsstrahlung, with parton trajectories following string breaking in a string fragmentation.

Photon emissions along the flux tube agree with the Low limit.

Photon emissions perpendicular to the flux tube are enhanced over the Low limit.

Models of Anomalous Photons (IV)

- Nachtmann et al (ZFPC67,143 (1995))

Soft photons produced by synchrotron radiation from quarks in the stochastic QCD vacuum.

- Hatta and Ueda (Nucl.Phys. B837 (2010) 22-39)

Soft photons are produced in ADS/CFT supersymmetric Yang-Mills theory.

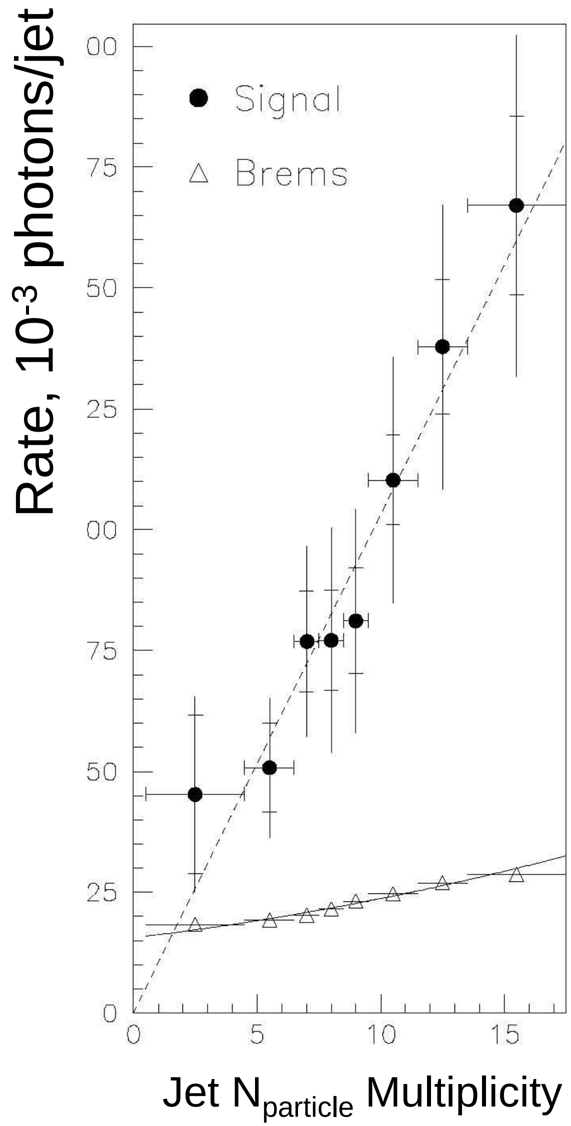
Properties of anomalous soft photons:

Anomalous soft photons, in excess of what is expected from EM bremsstrahlung, have been observed in K^+p, π^+p, π^-p, pp, and e^+e^- collisions at high energies.

1. They are produced only in association with hadron production. They are not produced in $e^+ + e^- \rightarrow \mu^+ + \mu^-$.
2. Total anomalous soft photon yield is proportional to total hadron yield.
3. Transverse momentum of anomalous soft photons $p_T \sim 2$ to 50 MeV.
4. Anomalous soft photon yield increase faster with increasing neutral hadron multiplicity N_{neu} than with charged hadron multiplicity N_{ch}.

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

Anomalous soft photon yield is proportional to the particle (hadron) multiplicity

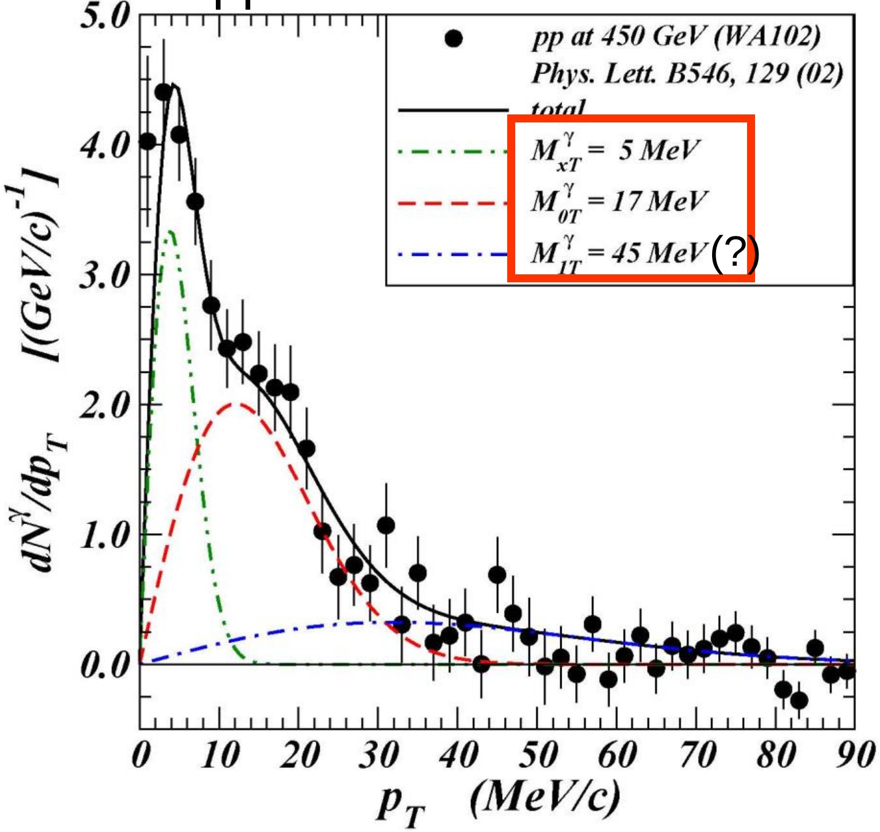


DELPHI (EPJ 2010) arXiv:1004.1587

Anomalous soft photons come in groups

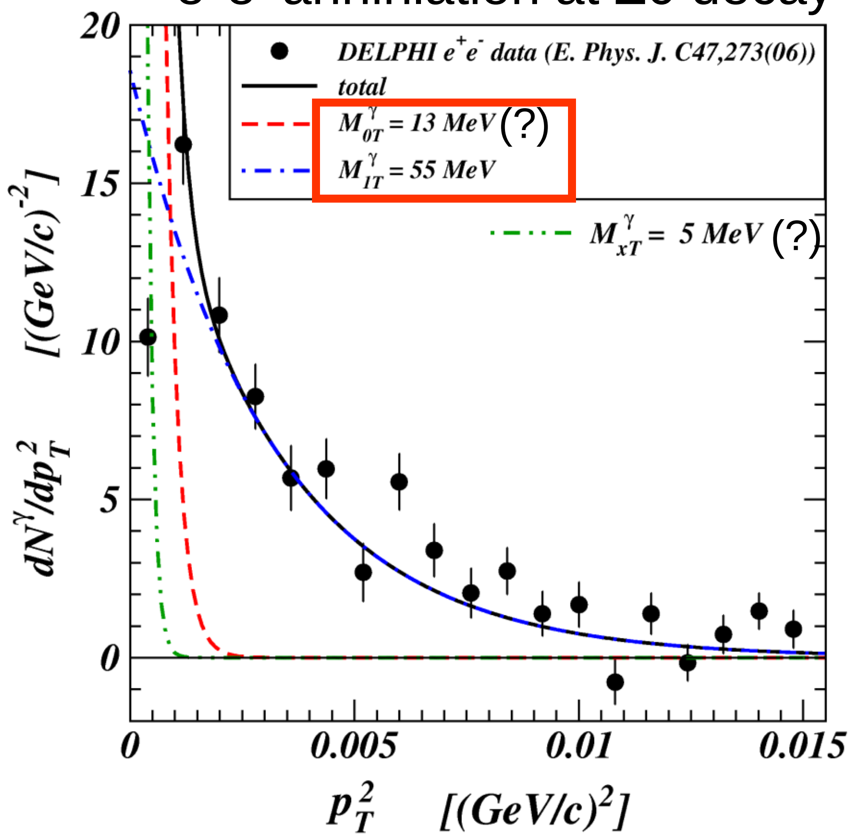
$$\frac{dN^{\gamma}}{dp_T} = \sum_{\alpha} N_{\alpha}^{\gamma}\ 2\pi p_T \exp\left\{-\frac{p_T^2}{(M_{\alpha T}^{\gamma})^2}\right\}, \qquad \frac{dN^{\gamma}}{dp_T^2} = \sum_{\alpha} N_{\alpha}^{\gamma} \exp\left\{-\frac{p_T^2}{(M_{\alpha T}^{\gamma})^2}\right\}$$

pp collisions at 450 GeV



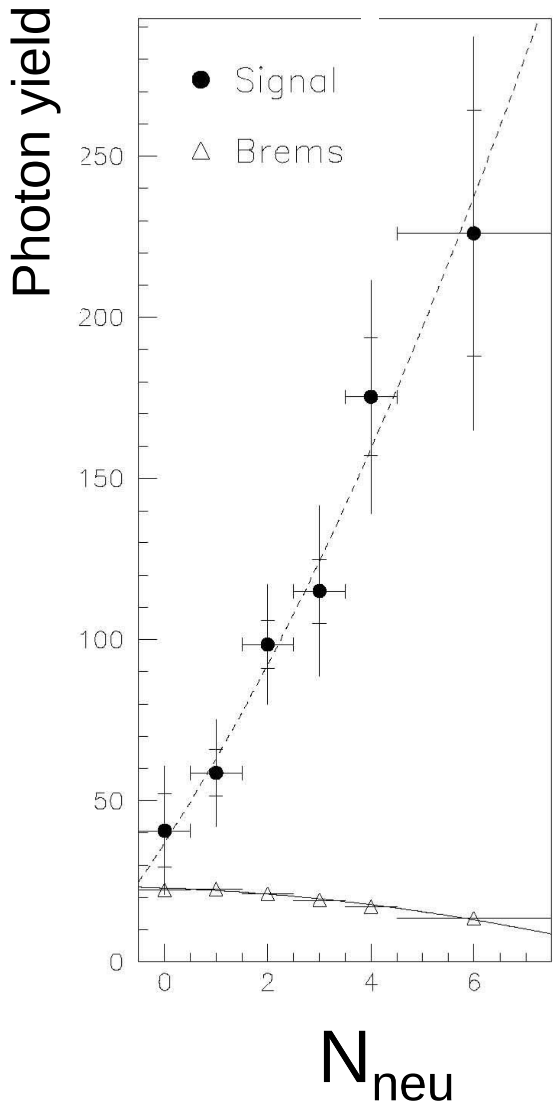
Experimental Δp_T uncertainty ~ 2 MeV

e^+e^- annihlation at Z0 decay



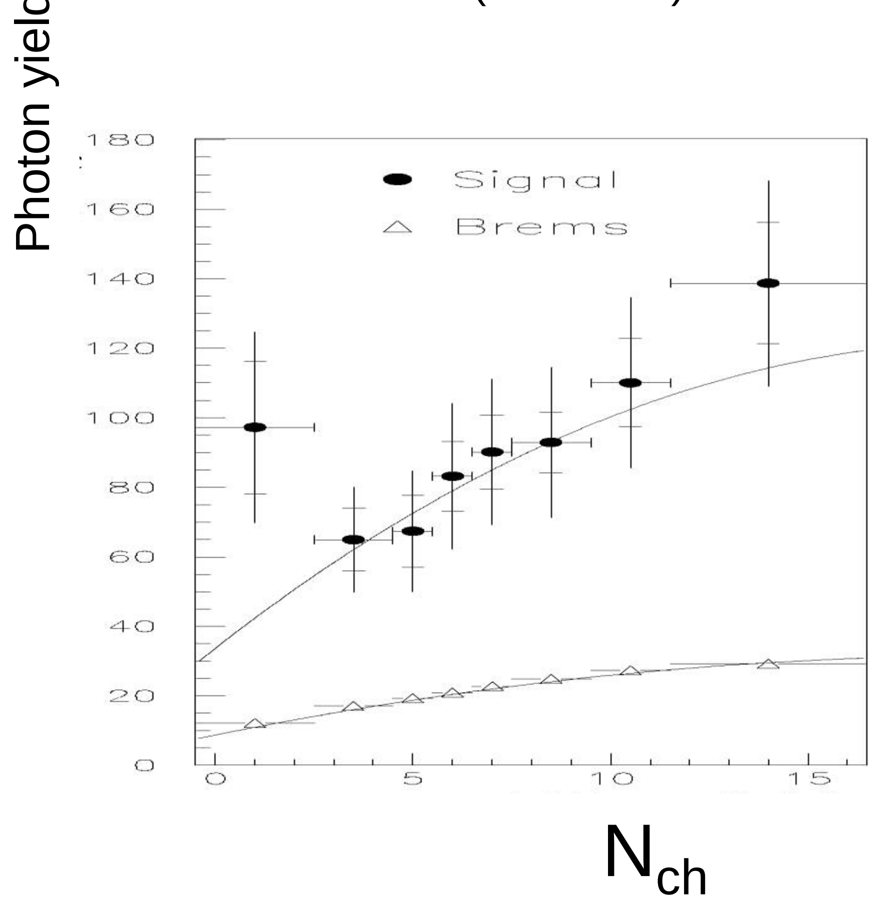
Experimental Δp_T uncertainty ~ 10 MeV

$$\frac{\text{Soft photon yield}}{N_{neu}} \gg \frac{\text{Soft photon yield}}{N_{ch}}$$



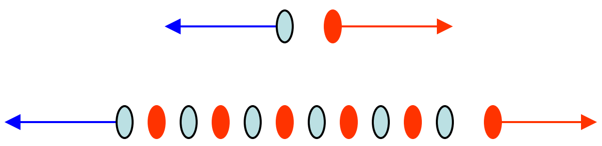
e+e- annihilation at Z0 decay (~91 GeV)

DELPHI (EPJ 2010) arXiv:1004.1587



Quantum field theory of meson and photon production

- Mesons are bound states of vacuum oscillations in a flux tube
- When a quark pulls away from an antiquark at high energies, the vacuum is polarized
- Polarization causes the color charges of the quarks in the vacuum to oscillate
- Oscillations of the color charges of the quarks in the vacuum produces mesons
- Oscillations of the color charges of the quarks in the vacuum are accompanied by the oscillations of the electric charges of quarks in the vacuum
- Oscillations of the electric charges of the quarks in the vacuum produces photons in the flux tube environment



Color charges oscillations →meson production
Electric charges oscillations →photon production

Such a model can explain:

1. Photon production accompanies by meson production
2. Photon yield is proportional to meson yield

We need to explain the other two features of the anomalous soft photon phenomenon:

3. Why $p_T \sim$ 10-50 MeV?
4. Why anomalous soft photon yield increase much faster with increasing neutral particle multiplicity than with charged multiplicity?

Schwinger QED2 quantum field theory model is a complete model of particle production

- It shows how the produced particles with a mass $m = e/\sqrt{\pi}$ are stable quanta of the underlying QED2 quantum field

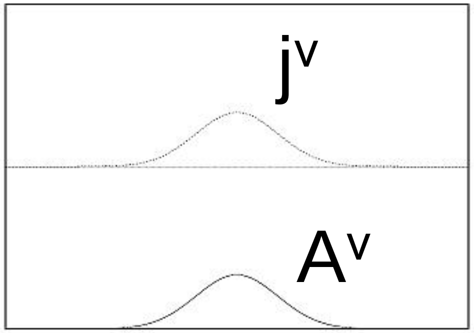
- It shows how particles are produced, when a quark pulls away from an antiquark at high energies

Schwinger QED2 quantum field theory

Quantum electrodynamics in 1+1 dimensions with massless fermions

$$\gamma^\mu (p_\mu - eA_\mu)\psi = 0$$

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



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

$\Rightarrow$ A small disturbance in A^ν

Therefore, j^ν is a self-consistent function of A^ν.

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

$$j^\nu = \frac{e}{\sqrt{\pi}}\left(A^\nu - \partial^\nu \frac{1}{\partial_\lambda \partial^\lambda}\partial_\mu \partial^\mu A^\nu\right)$$

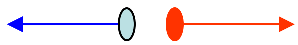
When we substitute this into the Maxwell equation, we get

$$\partial_\mu \partial^\mu A^\nu + \frac{e^2}{\pi} A^\nu = 0$$

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

$$m = \frac{e}{\sqrt{\pi}}$$

Flux tube environemnt is peculiar



$q\bar{q}$

When a q pulls away from a $\bar{q}$ at high energies,

QCD4$\times$QED4 can be approximated by QCD2$\times$QED2,

with the formation of a flux tube between the q and the $\bar{q}$.

The flux tube can be idealized as a string between the q and the $\bar{q}$.

The coupling constants in the 4D and 2D theories are related by

$$g_{2D}^2 = \frac{g_{4D}^2}{\pi R_T^2}, \qquad R_T = \text{flux tube radius.}$$

We need to study the bound states and their production in QCD2$\times$QED2.

C. Y. Wong, Phys. Rev.C81,064903(2010)

Bound states in QCD2XQED2 (1)

C. Y. Wong, Phys. Rev.C81,064903(2010)

1. $QCD2 \times QED2$ Lagrangian density is

$$\mathcal{L} = \overline{\psi}[\gamma^{\mu}(i\partial_{\mu} + gA_{\mu}) - m_T]\psi - \frac{1}{4} F_{\mu\nu}F^{\mu\nu}$$

$QCD2 \times QED2$ can be studied with the U(3) group which is the product of $\mathrm{U}(1) \times \mathrm{SU}(3)$.

2. The U(3) group has 9 generators :

$$\underbrace{t^0 = \frac{1}{\sqrt{6}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix},}_{\substack{U(1)\ \text{generator} \\ QED}} \qquad \underbrace{t^1, t^2, t^3, \ldots, t^8,}_{\substack{SU(3)\ \text{generators} \\ QCD}} \qquad \mathrm{tr}\{\, t^{\alpha} t^{\beta} \,\} = \frac{\delta^{\alpha\beta}}{2}$$

$$(gA_{\mu}\psi)^b = \sum_{f=u,d} \sum_{c=1,2,3} \sum_{a=0}^{8} g_f^a \, A_{\mu}^a \, (t^a)^{bc} \, \psi_f^c$$

3. The different coupling constants g_f^a depend on the generator and on the flavor

$$\left.\begin{array}{ll} g_u^0 = -Q_u e_{QED2} & Q_u = \dfrac{2}{3} \\ g_d^0 = -Q_d e_{QED2} & Q_d = -\dfrac{1}{3} \end{array}\right\} QED$$

$$g_u^{(1,2,3,\ldots,8)} = g_d^{(1,2,3,\ldots,8)} = g_{QCD2} \qquad QCD$$

Bound states in QCD2XQED2 (2)

Bound state masses can be obtained by non - Abelian bosonization.

Bosonization should be carried out in such a way to give stable bosons.

We bosonize an element u_f (flavor f) of the $U(3)$ group by φ_f^0 and φ_f^1

$$u_f = \exp\left\{ i\sqrt{2\pi}\sum_{a=0}^{1}\varphi_f^a t^a \right\}$$

We obtain the boson hamiltonian for φ_f^0 and φ_f^1,

$$2\mathcal{H} = N\sum_{a=0}^{1}\left\{ \sum_{f=u,d}\left[\frac{1}{2}\left(\Pi_f^a\right)^2 + \frac{1}{2}\left(\partial_1\varphi_f^a\right)^2\right] + \frac{1}{2\pi}\left[\sum_{f=u,d} g_f^a \varphi_f^a\right]^2 \right\} + V_{m_T}$$

We construct isospin I states with $(I_3 = 0)$,

$$\varphi_I^a = \frac{1}{\sqrt{2}}\left[\varphi_u^a + (-1)^I \varphi_d^a\right] \quad \text{and} \quad \Pi_I^a = \frac{1}{\sqrt{2}}\left[\Pi_u^a + (-1)^I \Pi_d^a\right]$$

Then, $$2\mathcal{H} = N\sum_{a=0}^{1}\left\{ \sum_{I=0,1}\left[\frac{1}{2}\left(\Pi_I^a\right)^2 + \frac{1}{2}\left(\partial_1\varphi_I^a\right)^2\right] + \frac{1}{2}\left[\sum_{I=0,1}\frac{g_u^a + (-1)^I g_d^a}{\sqrt{2\pi}}\varphi_I^a\right]^2 \right\} + V_{m_T}$$

Meson and photon masses depend on isospin

Isospin is a good quantum number in QCD2

isoscalar meson -- η^0 (I=0, I_3= 0)

isovector mesons –- π^+, π^0, π^- (I=1, I_3=1,0,-1)

Isospin is not a good quantum number in QED2

isoscalar photon (I=0, I_3=0)

isovector photon (I=1, I_3=0)

isovector QED (I=1, I_3=$\pm$1) states unlikely to be stable

Meson and photon masses for $I_3=0$ states

$$(M_I^a)^2 = \left[\frac{g_u^a + (-1)^I g_d^a}{\sqrt{2\pi}}\right]^2 + \begin{pmatrix} 1 & \text{for QCD2} \\ \frac{2}{3} & \text{for QED2} \end{pmatrix} e^{\gamma} m_T \mu$$

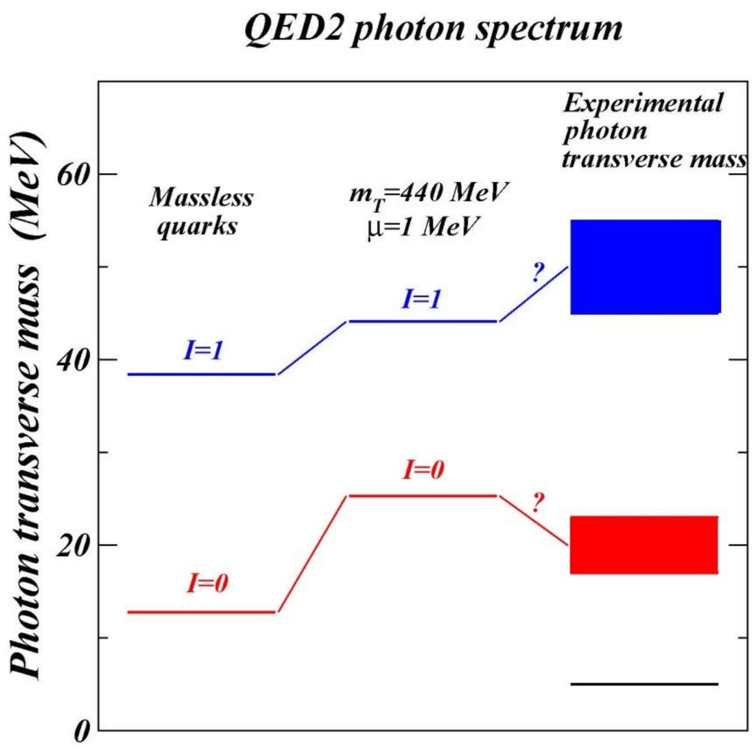
$$\gamma \;\; = \text{the Euler constant} = 0.5772$$

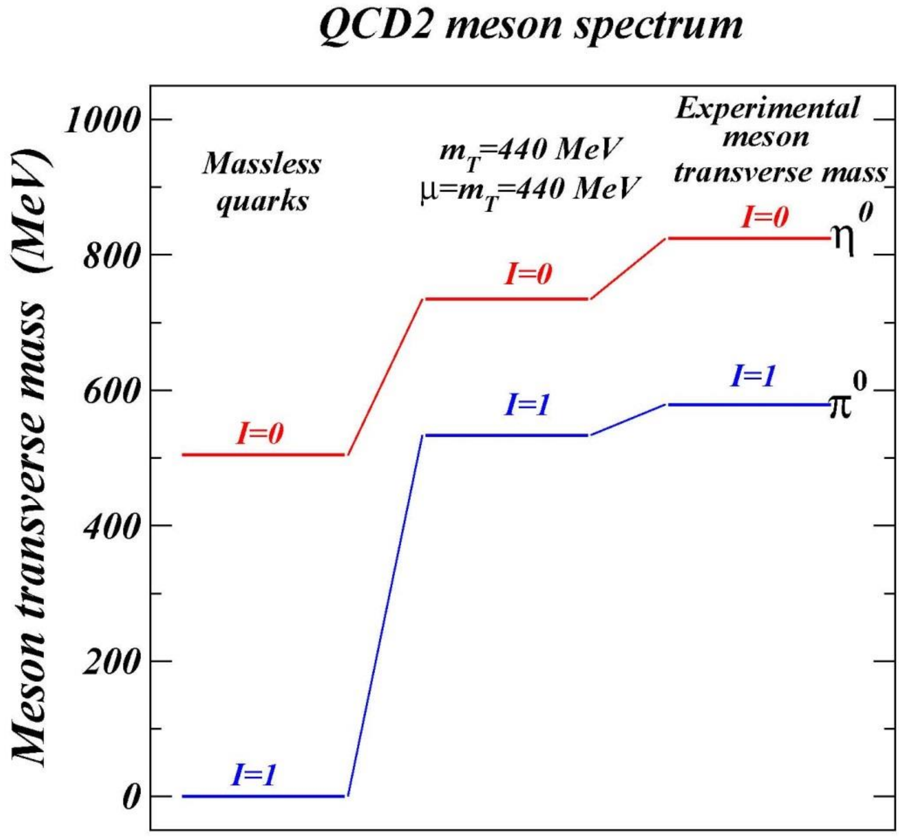
$$m_T = \text{quark transverse mass} \approx 1/R_T \approx 440\,\text{MeV},$$

$$\mu \;\; = \text{normal-ordering mass scale (interaction-depedent)}$$

$$\begin{cases} \mu(QCD) \approx \Lambda_{QCD} \approx m_T \approx 440\,\text{MeV} \\ \mu(QED) \approx \text{current quark rest mass} \approx O(1\,\text{MeV}) \end{cases}$$

Meson and photon masses for I_3=0





Evolution of a flux-tube QCD2, QED2 state

Inside the tube, a bound QCD2 or QED2 state exists

with a mass M, obeying

$$E^2 = p_z^2 + M^2$$

Outside the tube, the state come on the mass shell

with a mass m, obeying

$$E^2 = p_z^2 + p_T^2 + m^2$$

Energy and p_z preservation imply that after flux tube fragments,

$$p_T^2 + m^2 = M^2$$

For hadrons, hadron transverse mass can be identified with M

$$m_T(\text{hadron}) = M(\text{QCD2})$$

For soft photons, m=0, and

$$p_T^2 = M^2 \qquad \text{pT(soft photon)=M(QED2)}$$

Soft photon p_T can be identified with QED2 mass M.

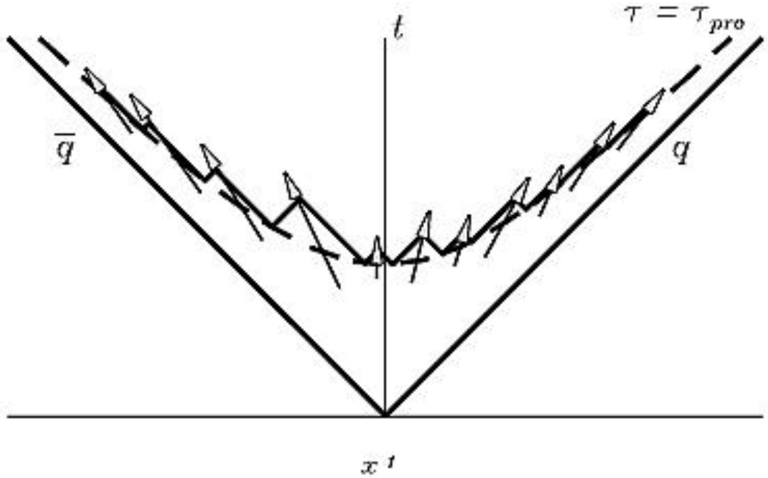
Quantum field theory of particle production in QED2

Casher,Kogut,Susskind,Phy.Rev.D10,732('74)
Bjorken,Phy.Rev.D27,140 ('83)
Wong, Phys. Rev. C80, 054917 ('09)

For a quark pulling away from an antiquark at infinite energies,

$$j^0_{ext}(x,t) = +e_{\bar{q}} \quad \delta(x+t) \ + e_q \quad \delta(x-t)$$

$$j^1_{ext}(x,t) = +e_{\bar{q}} v_{\bar{q}} \delta(x+t) + e_q v_q \delta(x-t),$$



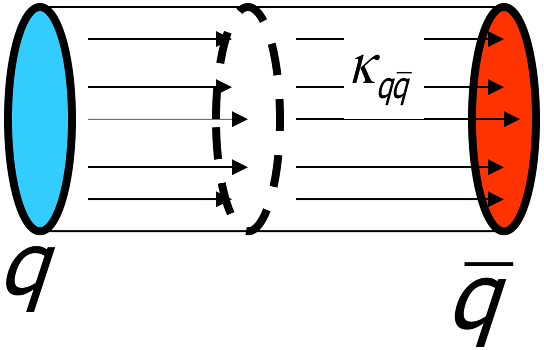
stable bosons are produced.

dN/dy of the produced bosons is boost-invariant.

For a finite energy, dN/dy becomes a rapidity plateau.

Meson and photon production rates

Schwinger pair production mechanism:

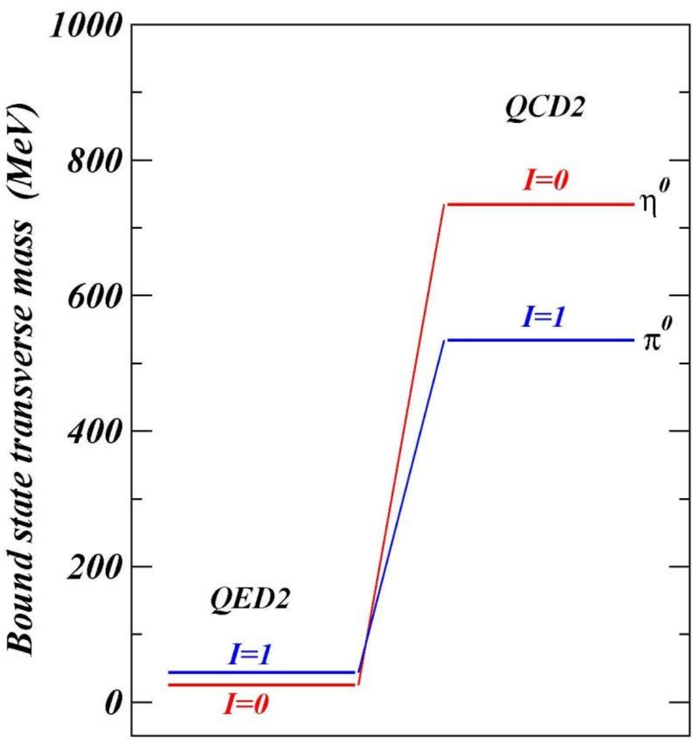


$$\frac{dN_I}{dz\,dt} = A\sum_{q\bar{q}} P_{q\bar{q}}\kappa_{q\bar{q}} \exp\left\{-\frac{\pi(M_{IT}/2)^2}{\kappa_{q\bar{q}}}\right\}$$

where $\kappa_{q\bar{q}} = g^2_{QCD2}/2$ for meson production

$\kappa_{q\bar{q}} = g^2_{QED2}/2$ for photon production

Correlation of anomalous soft photon yield with N_{neu} & N_{ch}



$$\frac{(I=0)\ \text{photon yeild}}{\eta^0(I=0)\ \text{meson yeild}} > \frac{(I=1)\ \text{photon yeild}}{\pi^0(I=1)\ \text{meson yeild}}$$

η^0 meson decay predominantly to neutral hadrons

π^0 meson is associated with the production of charged π^+ and π^-

Therefore, (photon yield) / N_{neu} >> (photon yield) / N_{ch}.

Predictions:

- Rapidity distribution of anomalous soft photons should have a plateau structure similar to hadron rapdity distribution
- The transverse momentum distribution of the isoscalar (I=0) anomlous soft photons associated with a large N_{neu} should be smaller (with m_T~15 MeV) than those associated with large N_{ch} (with I=1 and m_T~50 MeV)

Conclusion

- Soft photon in hadron production indicates the presence of QCD effects in QED processes
- Many models have been suggested
- Anomalous soft photons may arise from electric charge oscillations that accompany the color charge oscillations of the quarks in the vacuum, during the hadron production process.