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Anomalous Soft Photons associated with Hadron Production in String Fragmentation

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1. Introduction
   -- What are anomalous soft photons?
   -- What are their properties?
2. Explanation of the anomalous soft photon phenomenon
   -- Bound QCD & QED states in the flux tube (string) environment
   -- Production of these bound states in the flux tube environment
3. Conclusions

C. Y. Wong, Phys. Rev. C81, 064903 (2010), [arXiv:1001.1691]

- 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.

Experiment	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

(Table compiled by V. Perepelitsa)

Bremsstrahlung calculations

$$\frac{dN_\gamma}{d^3\vec{k}} = \frac{\alpha}{(2\pi)^2}\frac{1}{E_\gamma}\int d^3\vec{p}_1 ... d^3\vec{p}_N \sum_{i,j} \eta_i\eta_j \frac{-(P_iP_j)}{(P_iK)(P_jK)}\frac{dN_{hadrons}}{d^3\vec{p}_1 ... d^3\vec{p}_N} \, ,$$

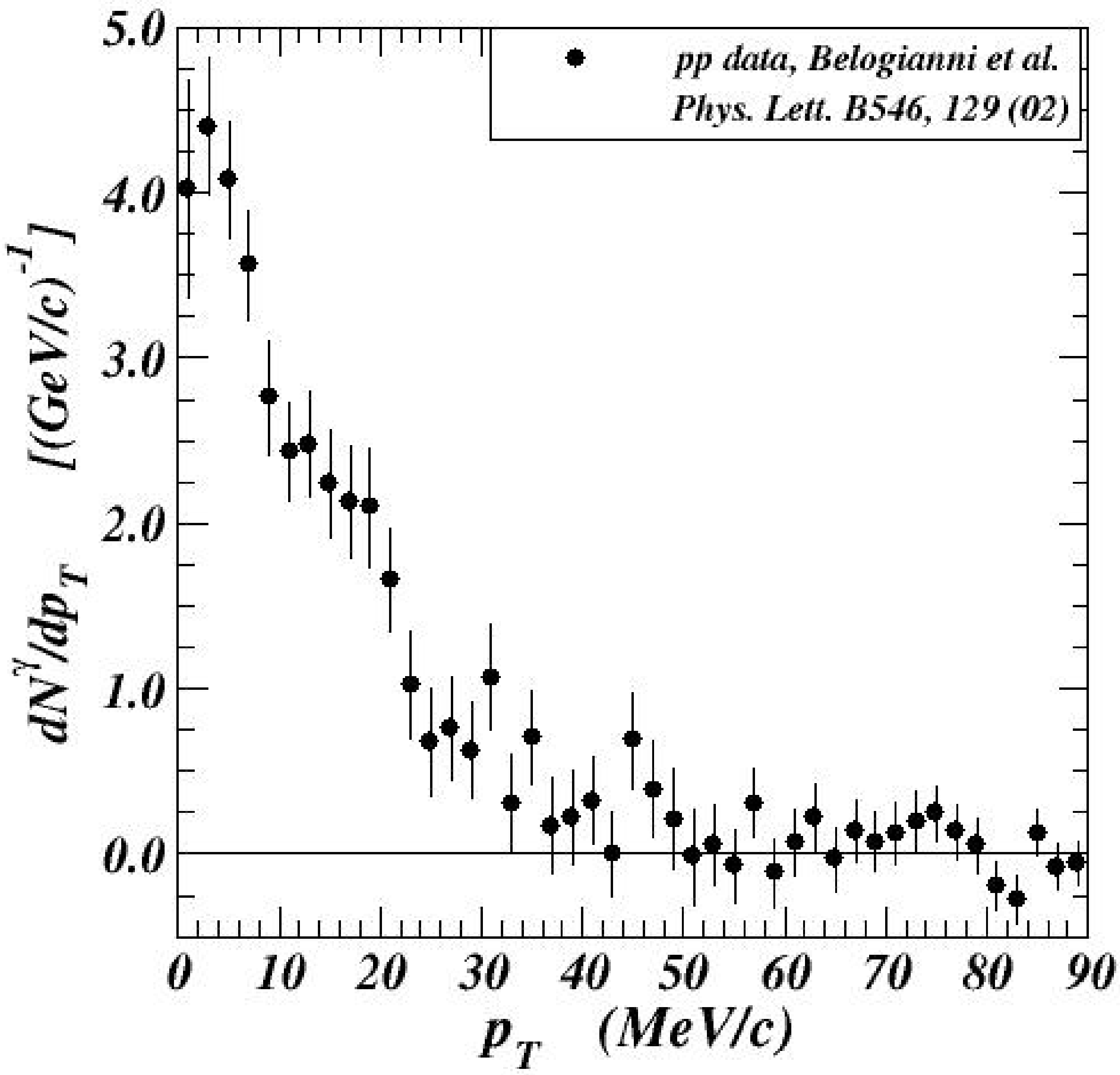
where K and k denote photon four- and three-momenta, P are the four-momenta of all the charged particles participating in the reaction. η = +1 for negative incoming and for positive outgoing particles, η = -1 for positive incoming and negative outgoing particles, and the sum is extended over all the N + 2 charged particles involved. The last factor in the integrand is a differential hadron production ratio.

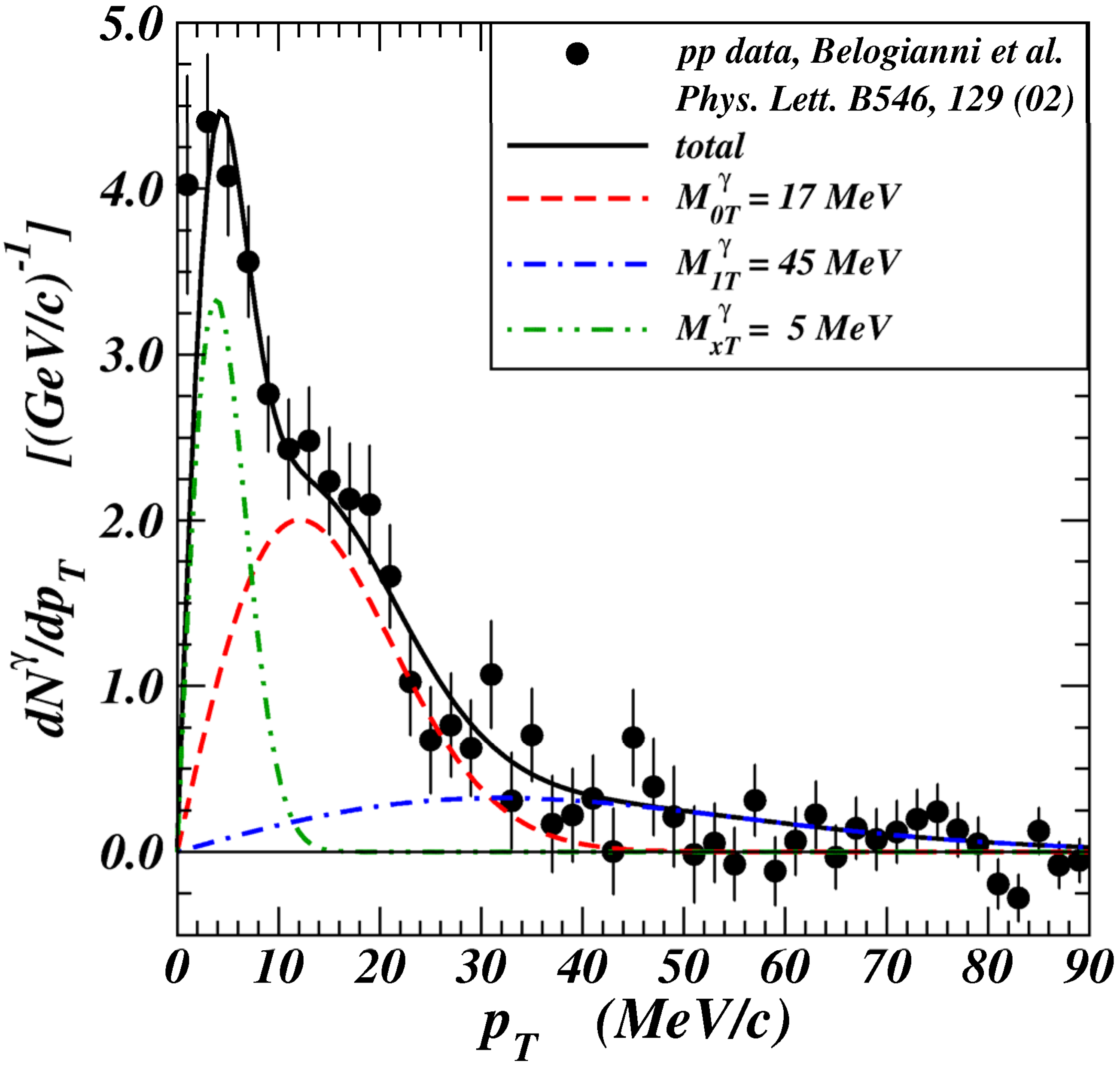
Properties of anomalous soft photons:

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 when there is no hadron production, 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}.

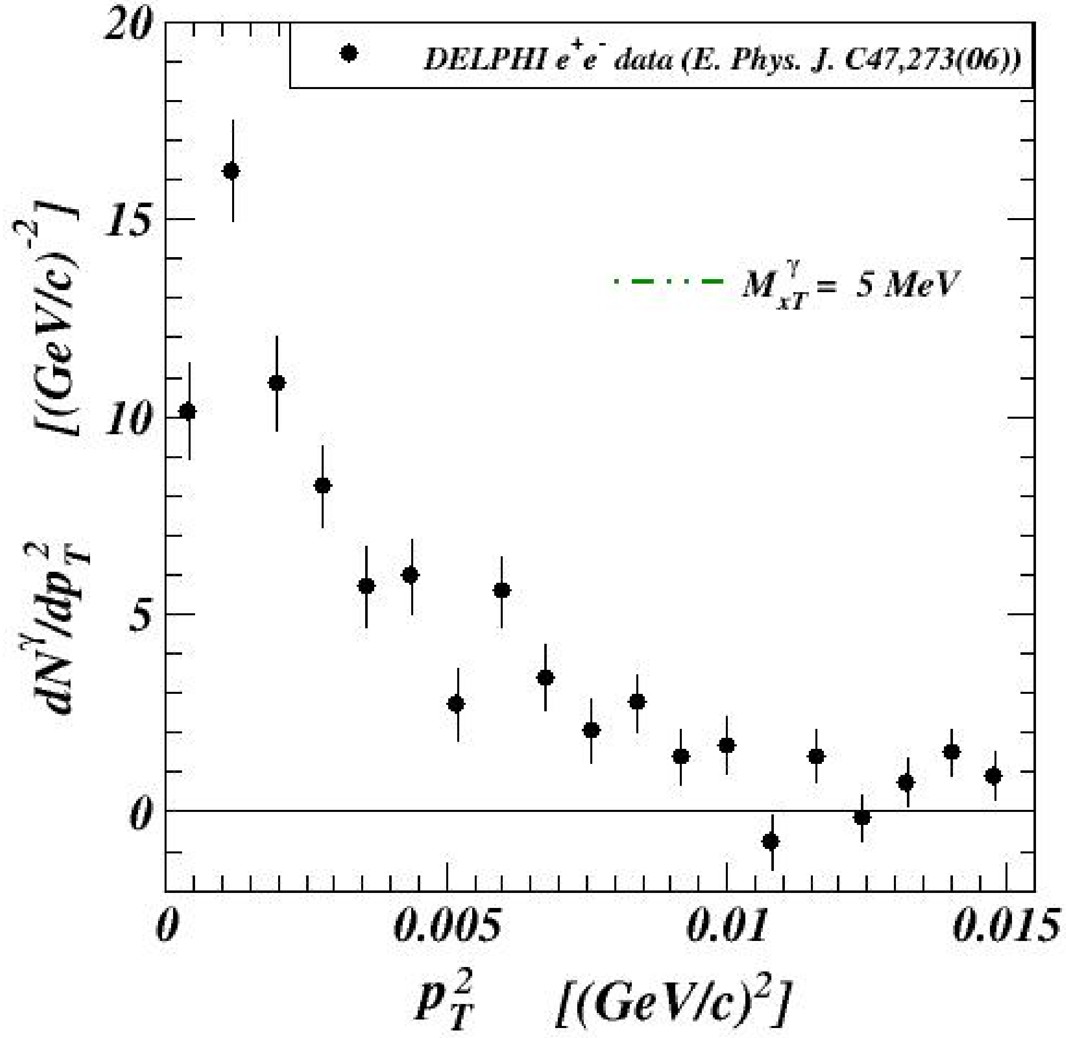
WA91 pp at 450 GeV

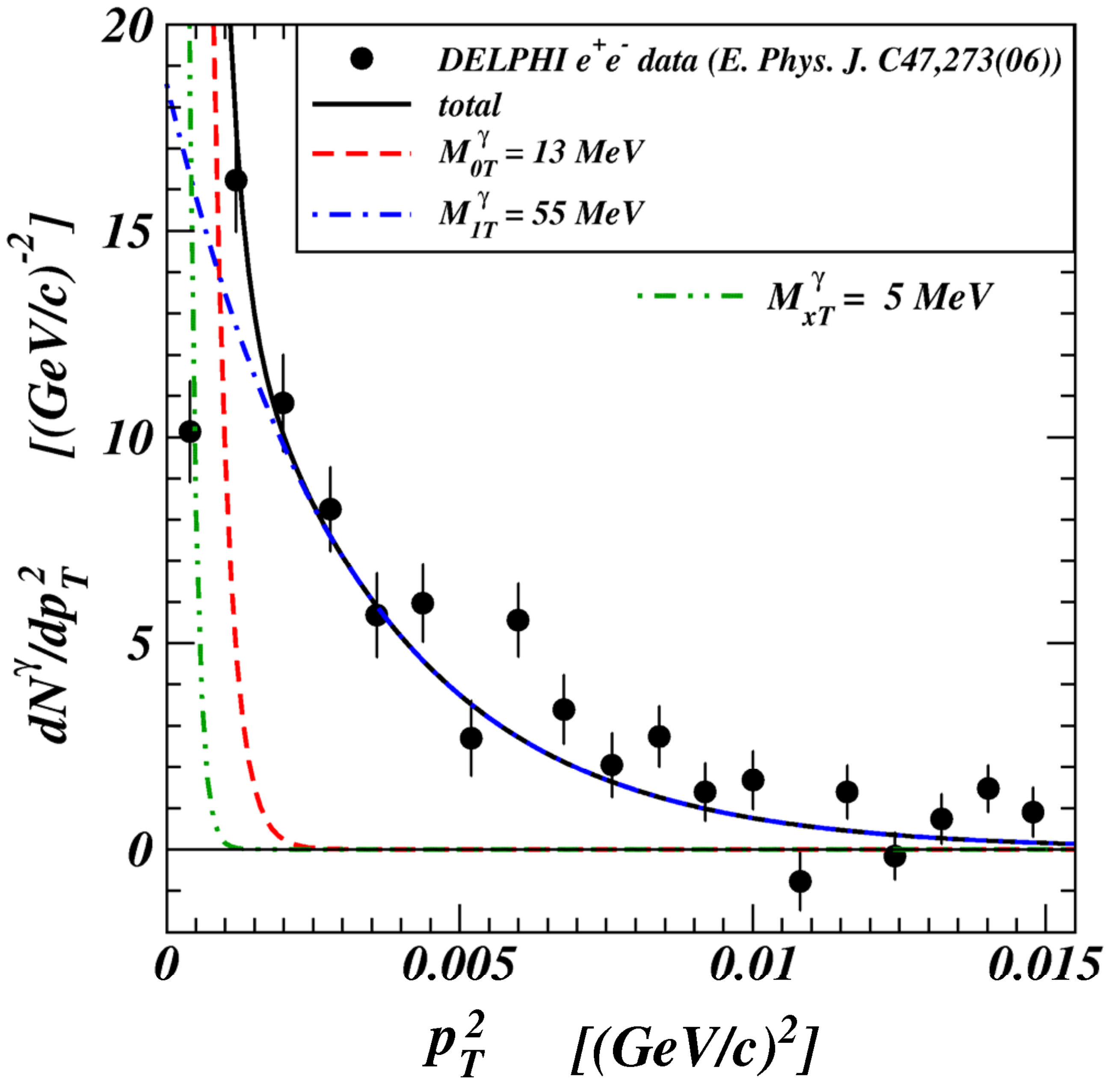




5.0
4.0
3.0
2.0
1.0
0.0
0
10
20
30
40
50
60
70
80
90
pp data, Belogianni et al.
Phys. Lett. B546, 129 (02)
total
M_{0T}^{γ} = 17 MeV
M_{1T}^{γ} = 45 MeV
M_{xT}^{γ} = 5 MeV
dN^{γ}/dp_T $[(GeV/c)^{-1}]$
p_T (MeV/c)

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



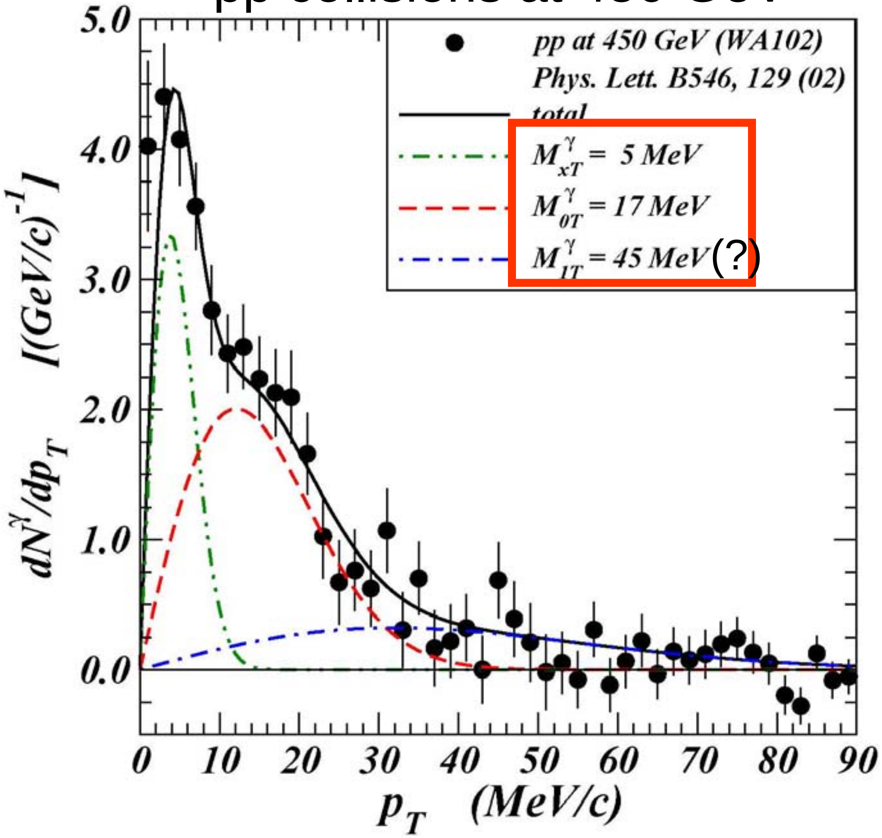


DELPHI e+e- data (E. Phys. J. C47,273(06))
total
M_{0T}^{γ} = 13 MeV
M_{1T}^{γ} = 55 MeV
M_{xT}^{γ} = 5 MeV
dN^{γ}/dp_T^2 $[(GeV/c)^{-2}]$
p_T^2 $[(GeV/c)^2]$
0
0.005
0.01
0.015
20
15
10
5
0

Anomalous soft photons come in groups

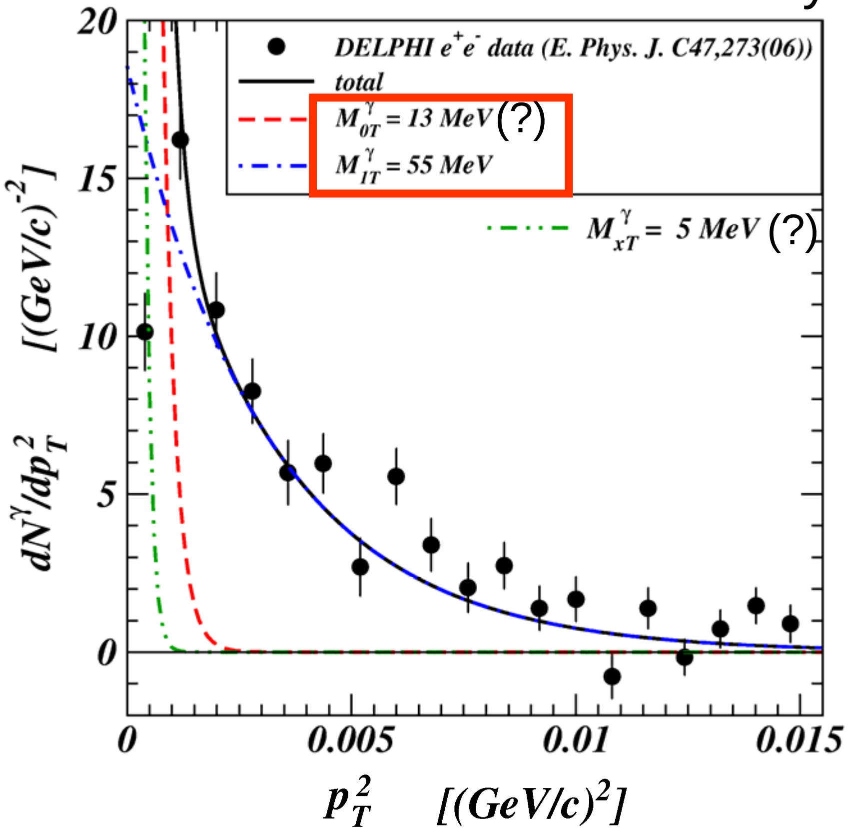
$$\frac{dN^{\gamma}}{dp_T} = \sum_{\alpha} N_{\alpha}^{\gamma}\ 2\pi p_T \exp\left\{-\frac{p_T^2}{(M_{\alpha T}^{\gamma})^2}\right\}, \qquad \frac{dN^{\gamma}}{dp_T^2} = \sum_{\alpha} N_{\alpha}^{\gamma} \exp\left\{-\frac{p_T^2}{(M_{\alpha T}^{\gamma})^2}\right\}$$

pp collisions at 450 GeV



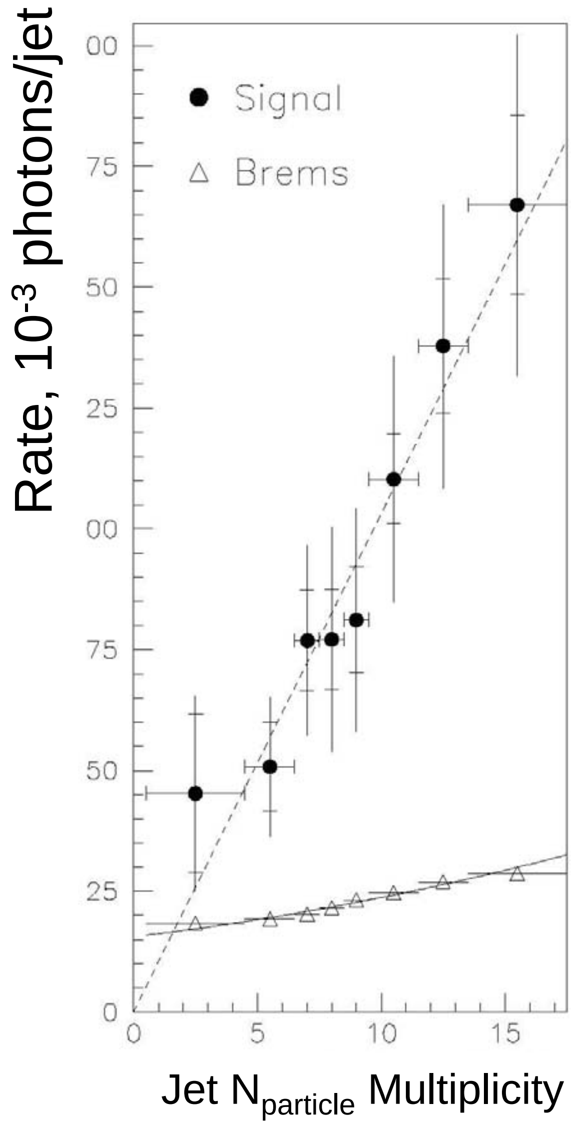
Experimental Δp_T uncertainty ~ 2 MeV

e^+e^- annihlation at Z0 decay



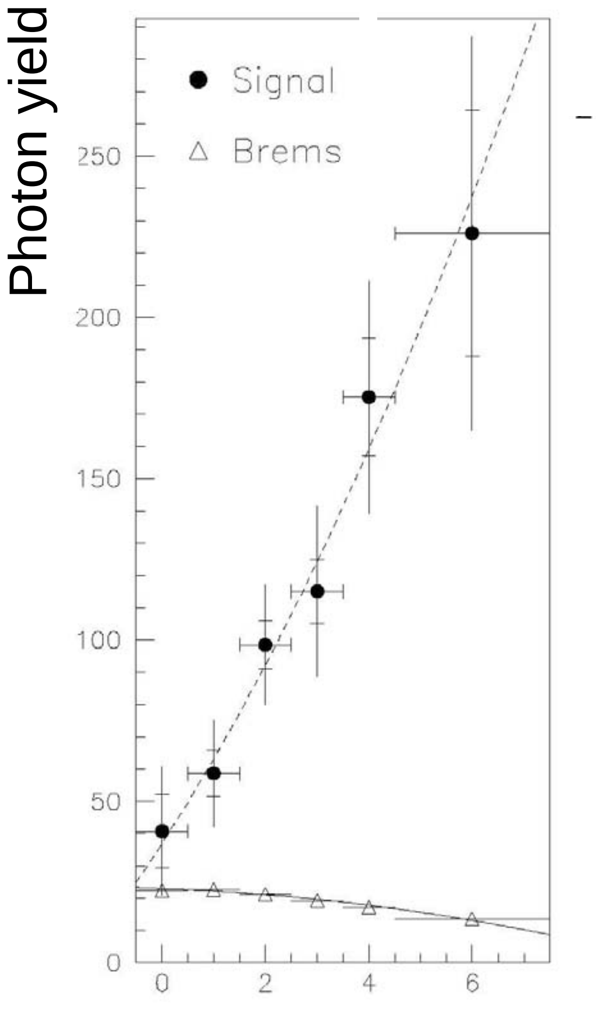
Experimental Δp_T uncertainty ~ 10 MeV e+e- annihilation at Z0 decay (~91 GeV)

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



DELPHI (EPJ 2010) arXiv:1004.1587

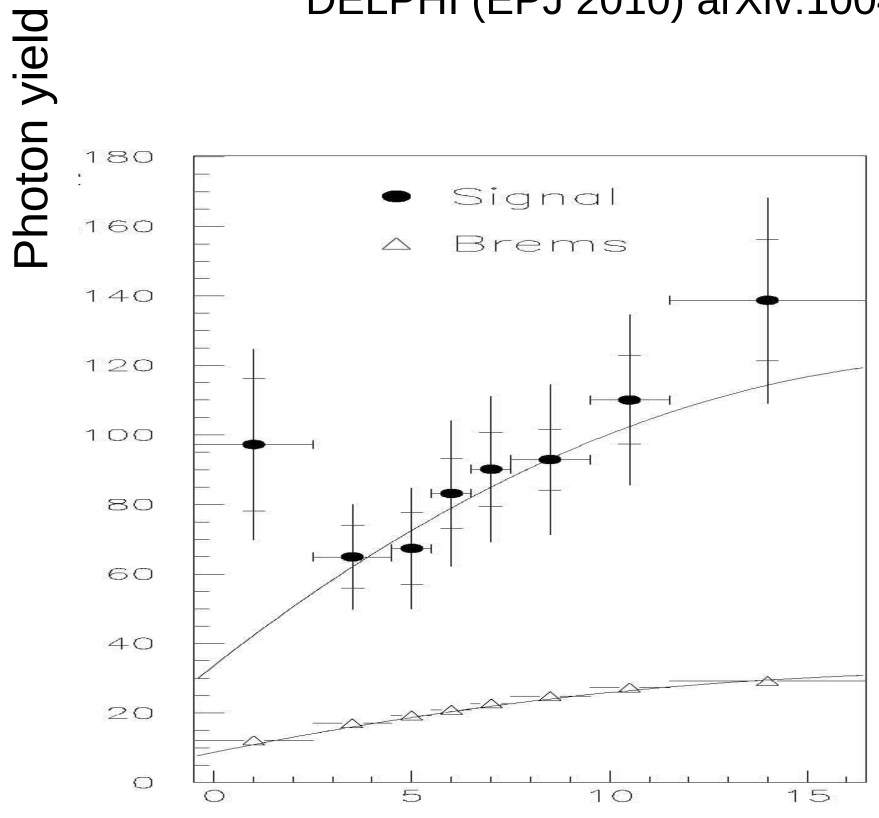
$$\frac{\text{Soft photon yield}}{N_{neu}} \gg \frac{\text{Soft photon yield}}{N_{ch}}$$



N_{neu}

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

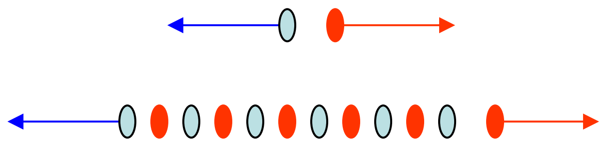
DELPHI (EPJ 2010) arXiv:1004.1587



N_{ch}

Quantum field theory of meson and photon production

- 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



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

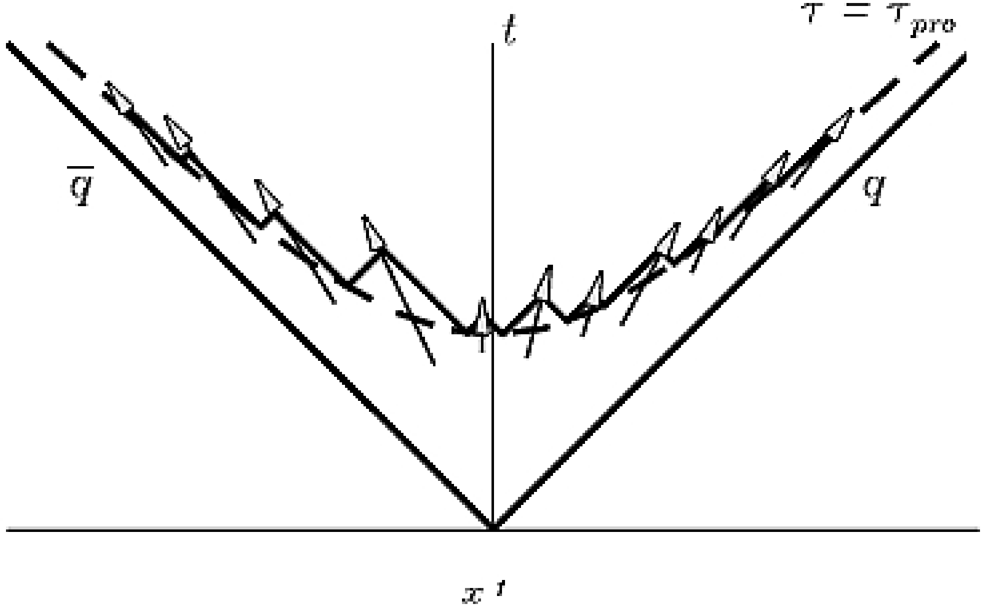
Such a model can explain:

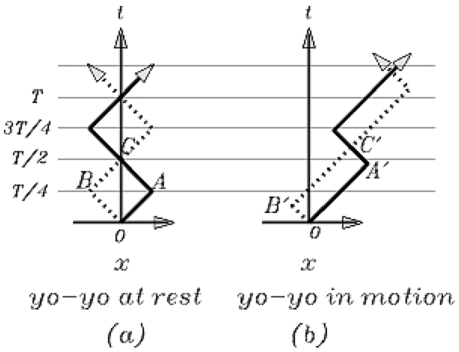
1. Photon production accompanies by meson production
2. Photon yield is proportional to meson yield

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

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

The classical Lund model of particle production is only a part of a complete model





In the Lund model, the stability of the produced particles is determined by other theories.

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

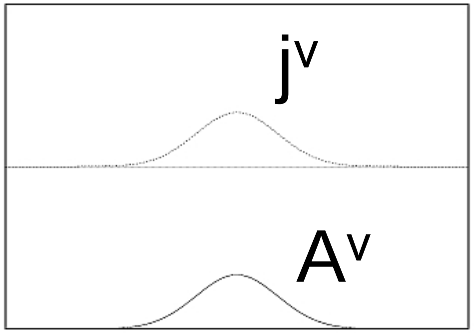
- It shows how particles are produced, when a quark pulls away from an antiquark at high energies

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^{ν} $\Rightarrow$ 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

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

Schwinger particle production in QED2

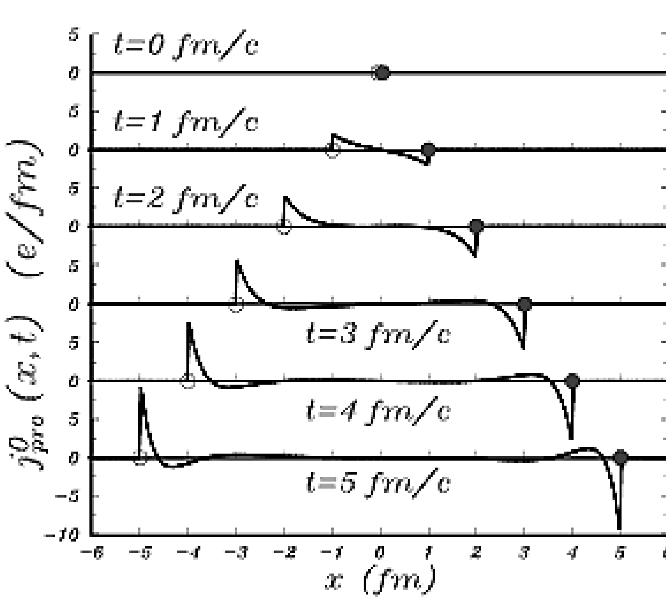
Casher,Kogut,Susskind,Phy.Rev.D10,732('74)

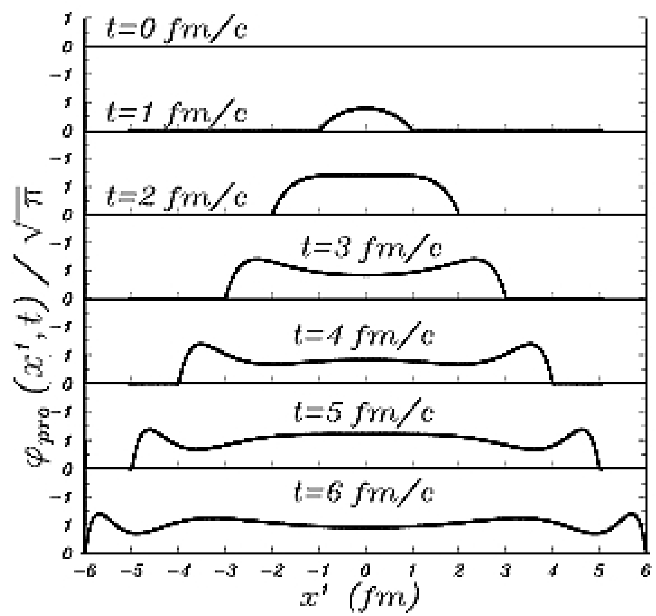
Given the external source current

$$j^0_{ext}(x,t) = -e\delta(x+t) + e\delta(x-t)$$

$$j^1_{ext}(x,t) = +e\delta(x+t) + e\delta(x-t)$$

The produced fermion and boson densities are





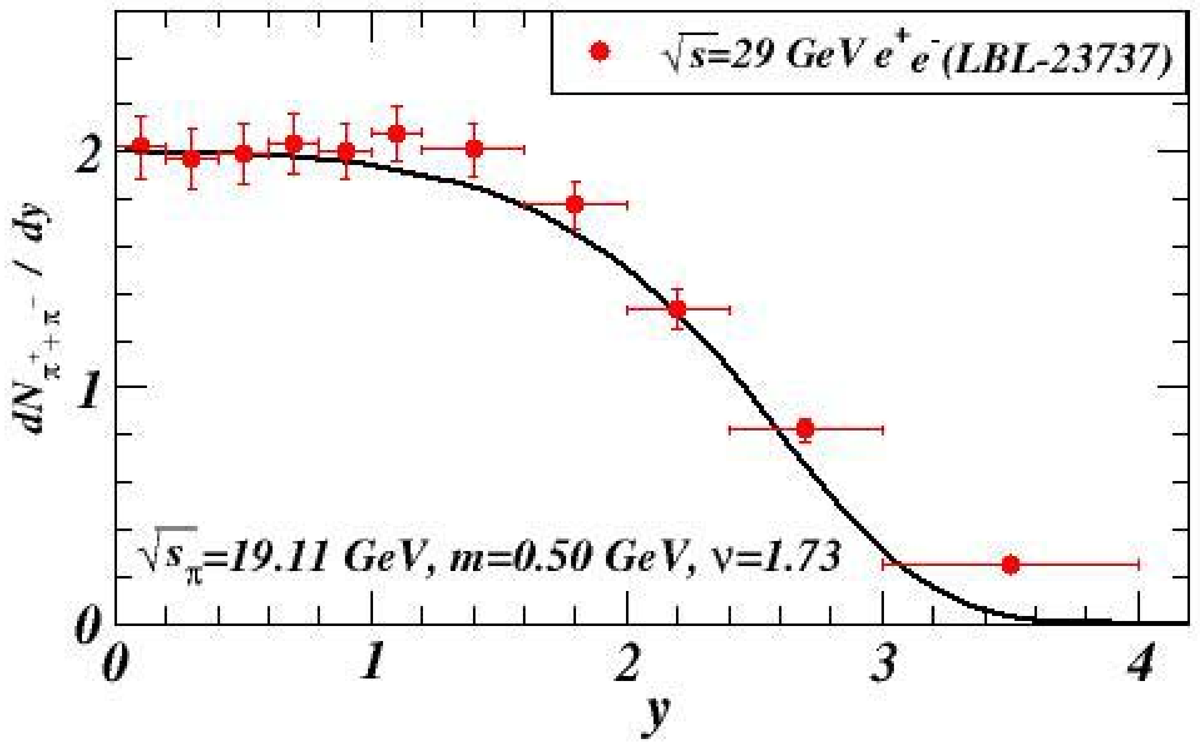
Summary of QED2 particle production model

- Stable boson particles with mass $m=e/(\pi)^{1/2}$ are quanta of the system
- dN/dy is boost invariant when a quark pulls from an antiquark at infinte energy
- For finite energy, dN/dy becomes a rapidity plateau with the plateau distribution

$$\frac{dN}{dy} = \frac{\nu^2 \xi^2}{\sinh^2 \xi}$$

$$\xi = \frac{\nu^2 \pi^2 m \sinh y}{3\sqrt{s}}$$

Comparsion of QED2 model of particle production with data



QED2 model gives a good description of particle production

C.Y.Wong, Phys. Rev. C80,054917 ('09)

Flux tube environemnt

$$q\bar{q}$$

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

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

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 $\mathrm{QCD2} \times \mathrm{QED2}$.

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

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

$QCD2 \times QED2$ 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:

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

QED QCD

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

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

$$g_u^0 = -Q_u e_{QED2} \qquad Q_u = \frac{2}{3}$$

$$g_d^0 = -Q_d e_{QED2} \qquad Q_d = -\frac{1}{3}$$

} QED

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

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

$$(M_I^a)^2 = \left[\frac{g_u^a + (-1)^I g_d^a}{\sqrt{2\pi}}\right]^2 + \begin{pmatrix} 1 & \text{for } a = 1\,(\text{QCD2}) \\ \frac{2}{3} & \text{for } a = 0\,(\text{QED2}) \end{pmatrix} e^{\gamma} m_T \mu$$

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

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

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

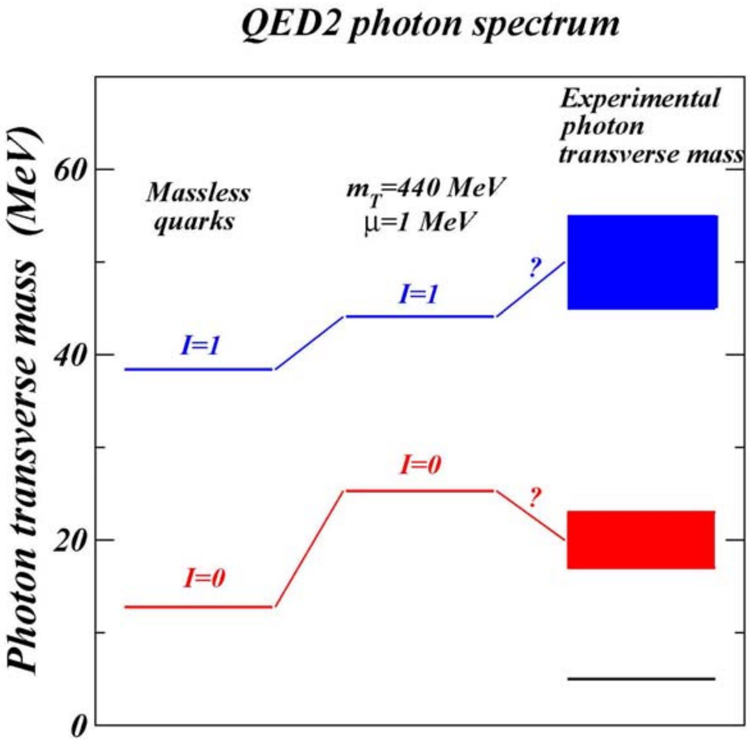
$$\begin{cases} \mu(QCD) \approx \Lambda_{QCD} \approx m_T \approx 440\text{ MeV} \\ \mu(QED) \approx \text{current quark rest mass} \approx O(1\text{ MeV}) \end{cases}$$

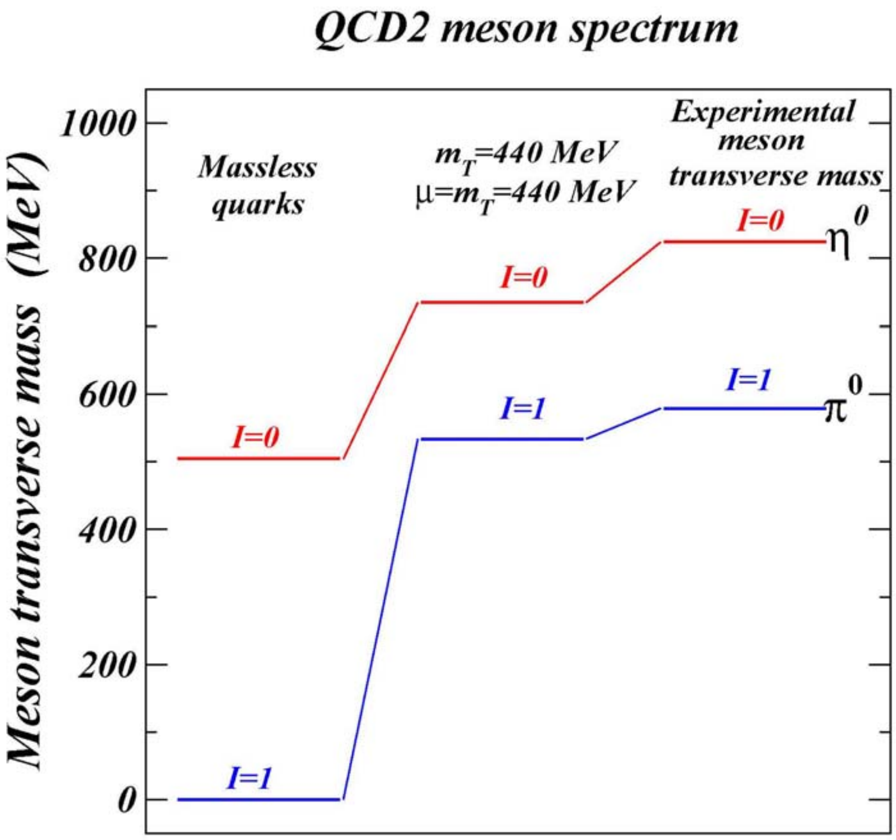
Meson and photon masses for I_3=0 in QCD2xQED2

($g^2_{\mathrm{QCD2}}=2b=0.4\ \mathrm{GeV}^2$, and $R_T=0.35$ fm)

		QCD2	QED2
Coupling Constant		$g_{\mathrm{QCD2}}=632.5$ MeV	$e_{\mathrm{QED2}}=96$ MeV
massless quarks	isoscalar $I=0$	504.6 MeV	12.8 MeV
	isovector $I=1$	0	38.4 MeV
$m_T=400$ MeV	isoscalar $I=0$	734.6 MeV	
$\mu=m_T$	isovector $I=1$	533.8 MeV	
$m_T=$ 400 MeV	isoscalar $I=0$		$O(25.3$ MeV$)$
$\mu=m_q=O(1$ MeV$)$	isovector $I=1$		$O(44.1$ MeV$)$

Meson and photon masses for I_3=0

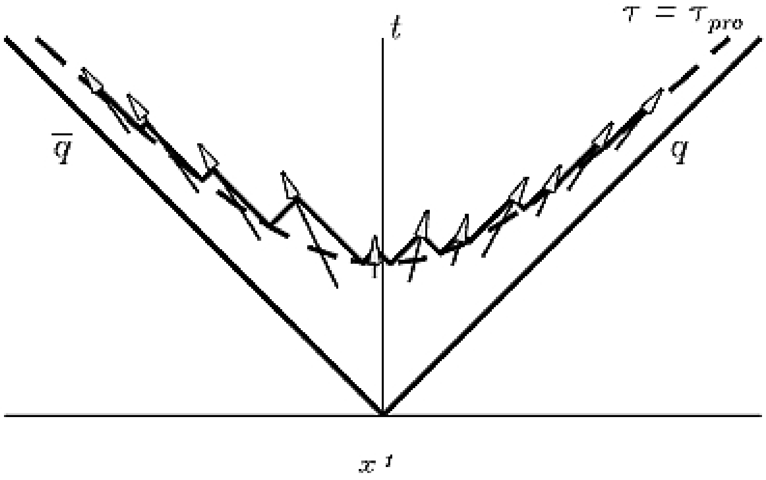




Quantum field theory of particle production in QED2

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,



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

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

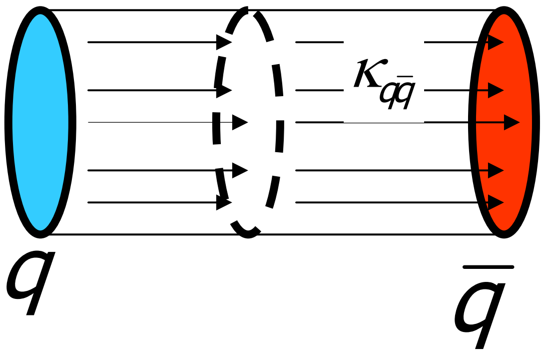
stable bosons are produced.

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:



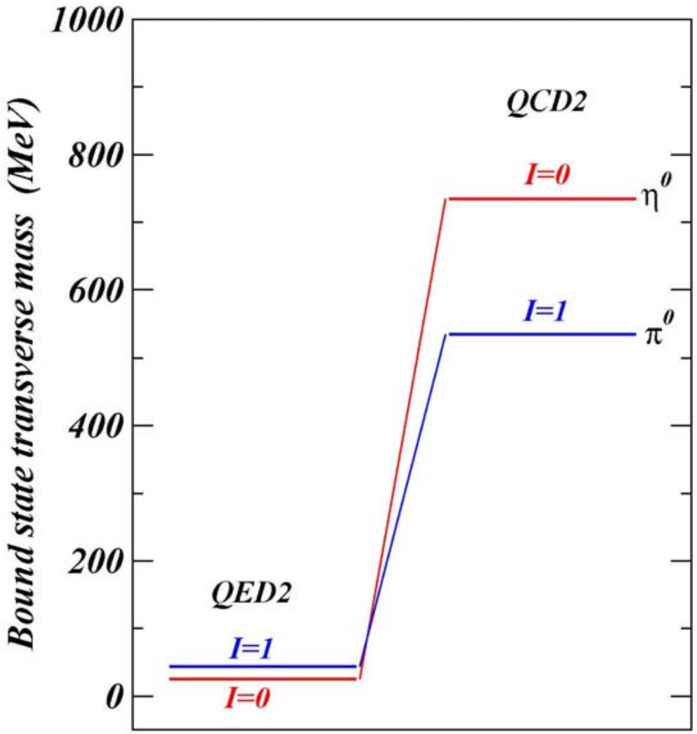
$$\frac{dN_I}{dz\,dt} = A \sum_{q\bar{q}} P_{q\bar{q}} \kappa_{q\bar{q}} \exp\left\{ - \frac{\pi (M_{IT}/2)^2}{\kappa_{q\bar{q}}} \right\}$$

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

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

Quantities	QED2 Model	Experimental Anomalous Soft Photon Data
$N_{I=0}^{\gamma} / N_{I=1}^{\gamma}$	2.75	1.8 - 2.4
$N^{\gamma} / N_{\mathrm{par}}$	7.91×10^{-3}	9.1×10^{-3}
$N^{\gamma} / N_{\mathrm{neu}}$	49.1×10^{-3}	37.7×10^{-3}
$N^{\gamma} / N_{\mathrm{ch}}$	3.71×10^{-3}	6.9×10^{-3}

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 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 m_T~50 MeV)

Conclusion

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.