The Low theorem for diffractive bremsstrahlung and soft photon puzzle

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Soft photon puzzle

Brief history of the soft photon puzzle

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Fixed-target experiments

Bubble chamber experiments

1983–1984 Beginning of the puzzle (WA27, K^++p@70 GeV/*c*: signal/brems ≈ 4)

1993 Confirmed by EHS-NA22

"Fully electronic experiments":

1985–1992 Excess confirmed by SOPHIE/WA83 (π-p@280 GeV/*c*)

1993 Antos et al. (modified HELIOS setup, p-Be@450 GeV/*c*): consistent with classical bremsstrahlung calculation

e^+e^- at Z^0 resonance (DELPHI):

2006 $e^+e^- \to$ 2 jets: excess above bremstrahlung calc. (signal/brems ≈ 4)

2008 $e^+e^- \to \mu^+\mu^-$: consistent with bremsstrahlung calc.

Observed photon excess spectrum often has same shape as bremsstrahlung spectrum

Soft photons: an experimental overview | K. Reygers

Soft photon puzzle

Collection of Klaus Reygers

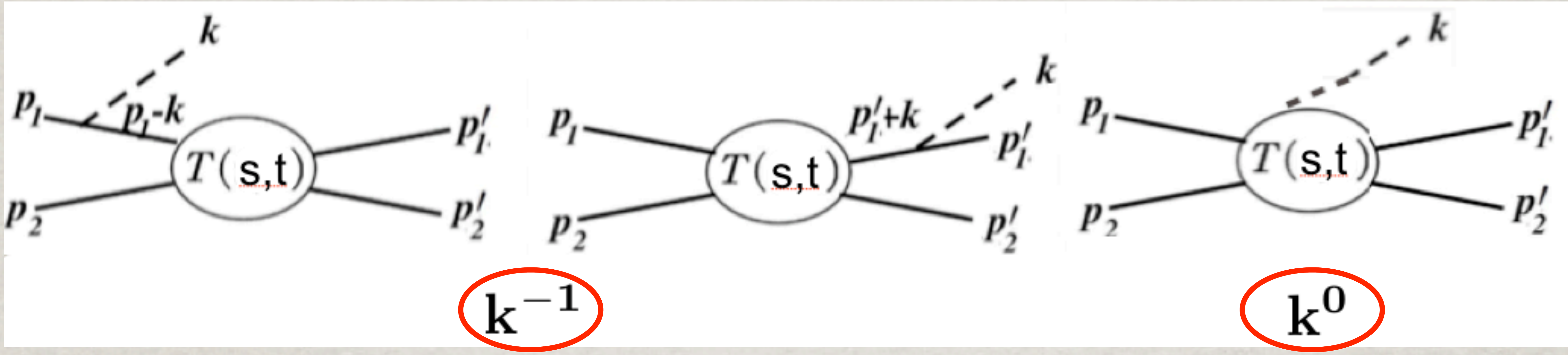
Experiment	Year	Collision energy	Photon p_T	Photon / Brems Ratio	Detection method	Reference
π^+p	1979	10.5 GeV	$p_T < 30$ MeV/c	~ 1	bubble chamber	Goshaw et al., Phys. Rev. Lett. 43, 1065 (1979)
K^+p WA27, CERN	1984	70 GeV	$p_T < 60$ MeV/c	4.0 ± 0.8	bubble chamber (BEBC)	Chliapnikov et al., Phys. Lett. B 141, 276 (1984)
π^+p CERN, EHS, NA22	1991	250 GeV	$p_T < 40$ MeV/c	6.4 ± 1.6	bubble chamber	Botterweck et al., Z. Phys. C 51, 541 (1991)
K^+p CERN, EHS, NA22	1991	250 GeV	$p_T < 40$ MeV/c	6.9 ± 1.3	bubble chamber	Botterweck et al., Z. Phys. C 51, 541 (1991)
π^-p, CERN, WA83, OMEGA	1993	280 GeV	$p_T < 10$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	7.9 ± 1.4	calorimeter	Banerjee et al., Phys. Lett. B 305, 182 (1993)
p-Be	1993	450 GeV	$p_T < 20$ MeV/c	< 2	pair conversion, calorimeter	Antos et al., Z. Phys. C 59, 547 (1993)
p-Be, p-W	1996	18 GeV	$p_T < 50$ MeV/c	< 2.65	calorimeter	Lissauer et al., Phys.Rev. C54 (1996) 1918
π^-p, CERN, WA91, OMEGA	1997	280 GeV	$p_T < 20$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	7.8 ± 1.5	pair conversion	Belogianni et al., Phys. Lett. B 408, 487 (1997)
π^-p, CERN, WA91, OMEGA	2002	280 GeV	$p_T < 20$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	5.3 ± 1.0	pair conversion	Belogianni et al., Phys. Lett. B 548, 122 (2002)
pp, CERN, WA102, OMEGA	2002	450 GeV	$p_T < 20$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	4.1 ± 0.8	pair conversion	Belogianni et al., Phys. Lett. B 548, 129 (2002)
$e^+e^- \to$ 2 jets CERN, DELPHI	2006	91 GeV (CM)	$p_T < 80$ MeV/c	4.0 ± 0.3 ± 1.0	pair conversion	DELPHI, Eur. Phys. J. C 47, 273 (2006)
$e^+e^- \to \mu^+\mu^-$ CERN, DELPHI	2008	91 GeV (CM)	$p_T < 80$ MeV/c	~ 1	pair conversion	DELPHI, Eur. Phys. J. C57, 499 (2008)

Soft photons | K. Reygers

Low theorem, revisited

$$\mathbf{h_1 + h_2 \to h_1' + \gamma + h_2'}$$

F. Low, Phys. Rev. 110, 974 (1958)



$$\mathbf{M_\mu = M_\mu^{ext} + M_\mu^{int}}$$

The infra-red divergent term reads

$$\mathbf{M_\mu^{ext} = \left(\frac{p'_{1\mu}}{p'_1 k} - \frac{p_{1\mu}}{p_1 k}\right) T(s,t)},$$

The two terms are related by gauge invariance

$$\mathbf{k_\mu M_\mu = 0}$$

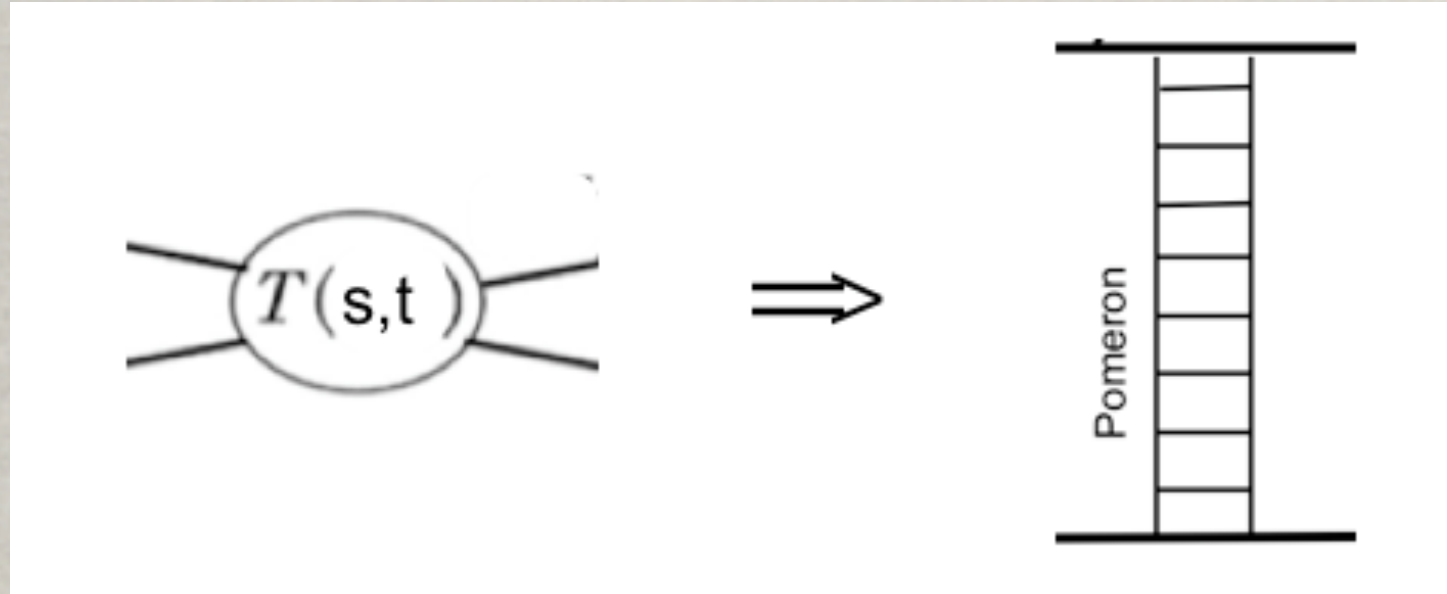
Therefore $\mathbf{M^{int}}$ is not divergent at $\mathbf{k \to 0}$

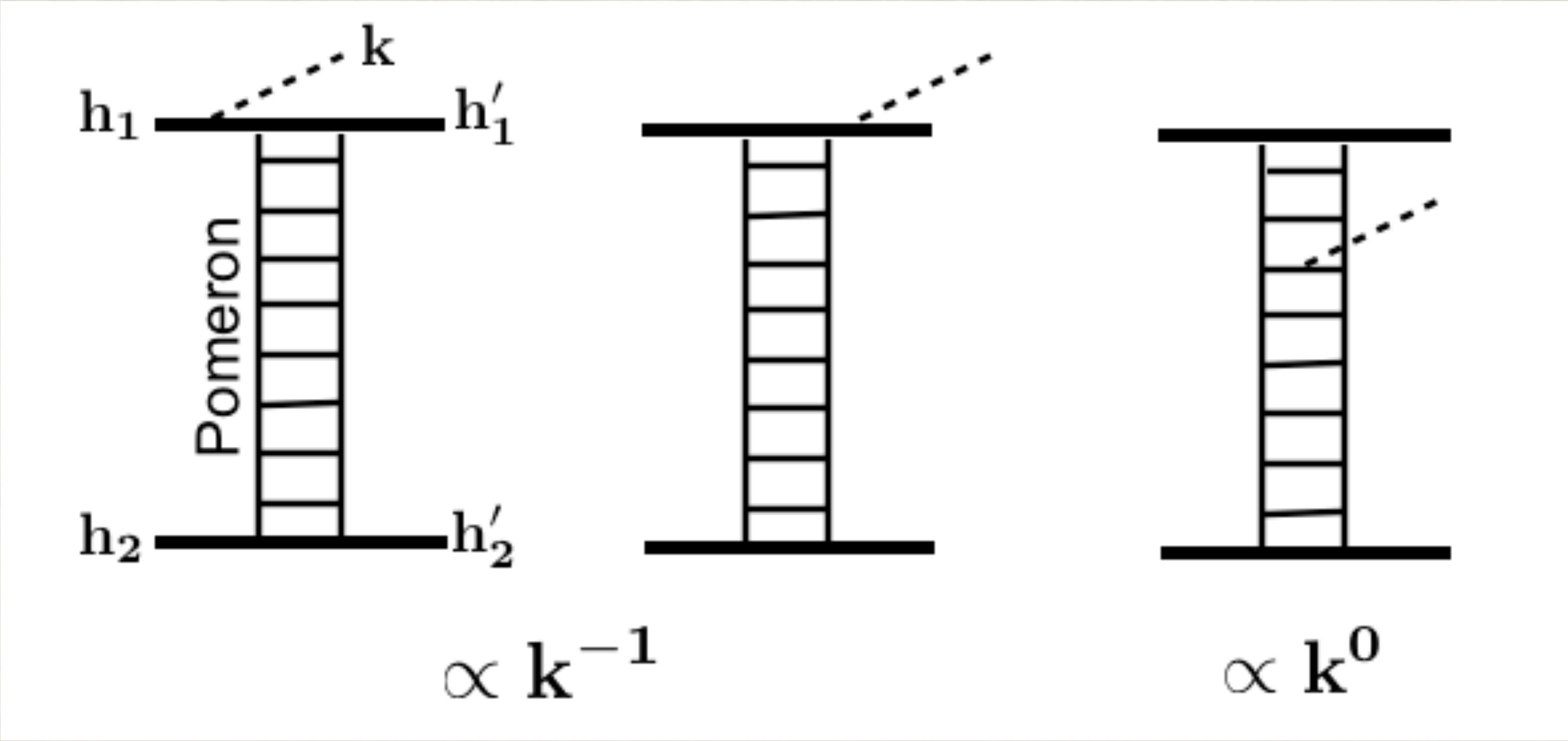
Is the photon radiated before or after the interaction? - both

The Low theorem is a formal proof of the Landau-Pomeranchuk principle (1953) : any variations of the EM current do not affect photons with much longer radiation (coherence) length. In the target rest frame

$$l_c^\gamma = \frac{2E_1 x_1(1-x_1)}{k_T^2 + x_1 m_h^2}. \qquad x_1 = \frac{k_+^\gamma}{p_+^{h_1}}$$

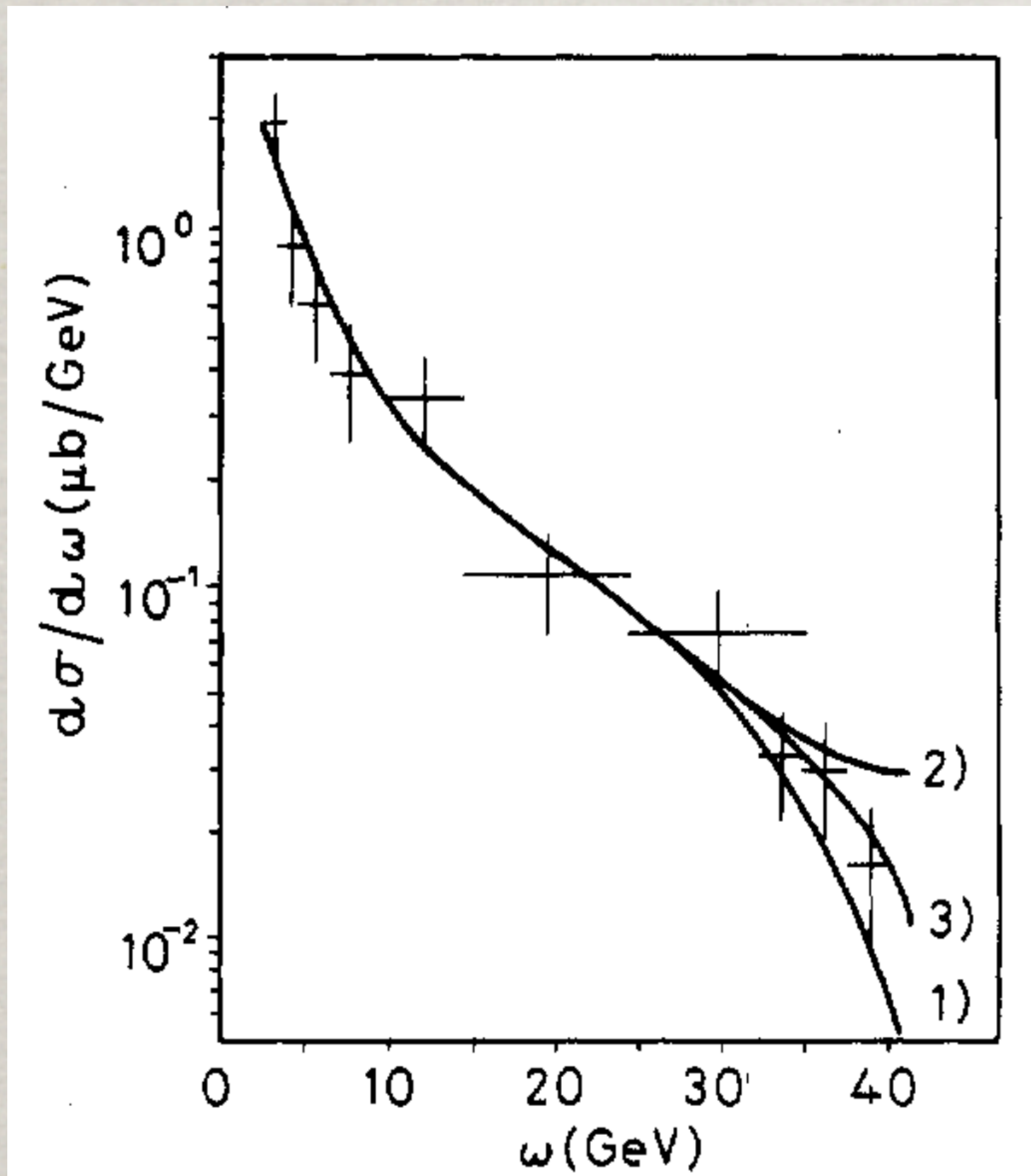
At high **energies** in terms of the Regge phenomenology radiation is treated as diffractive excitation of the projectile hadron h1 → h1+γ, so is dominated by the Pomeron exchange.





The Low theorem was successfully tested experimentally for the radiative process $\pi^- p \to \pi^- \gamma p$ at 43 GeV

Yu. M. Antipov et al. Europhys. Lett., 11 (8),725(1990)



$$\frac{\mathbf{d}\sigma}{\mathbf{d}\omega} = \frac{\sigma_\mathbf{0}}{\omega} + \sigma_\mathbf{1} + \ldots$$

σ_0 is elastic pion-proton cross section, well measured at this energy.

$$\sigma_\mathbf{1} = \mathbf{12.0 \pm 1.2_{stat} \pm 1.3_{syst}}\ \mu\mathbf{b}$$

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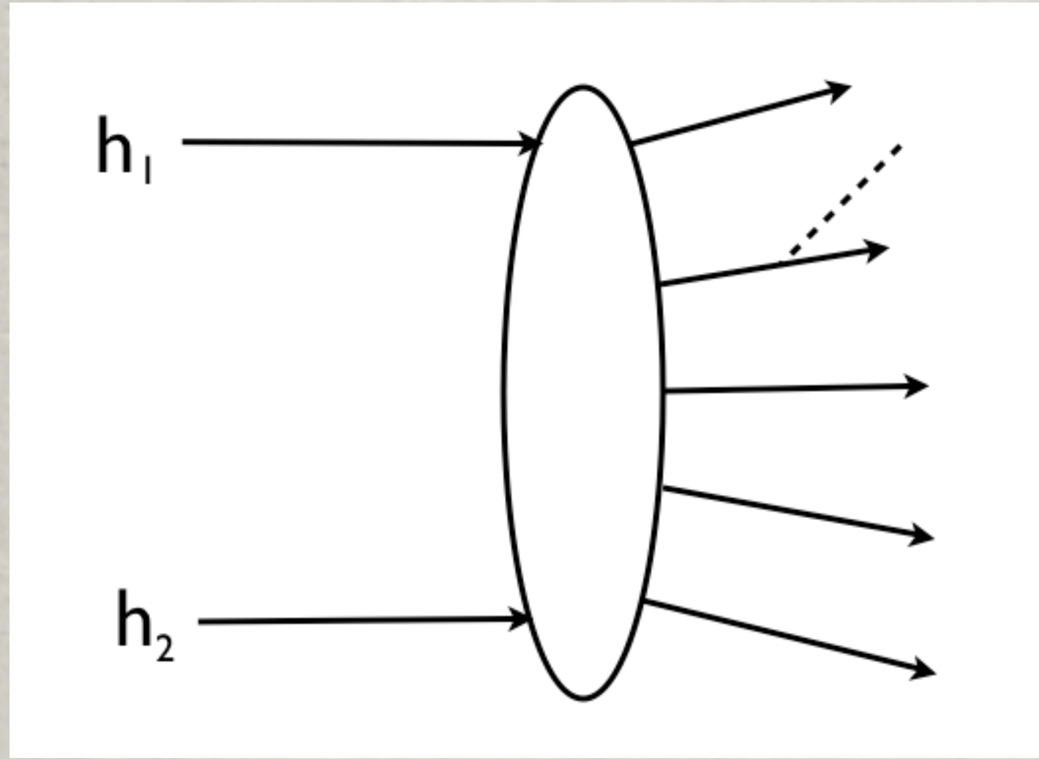
Photon production in inelastic collisions

The so-called bremsstrahlung model (BM) pretends to extend the Low theorem from the radiation in elastic scattering to inelastic collisions with multi-particle production



Photons are assumed to be radiated by participating charge particles, either the incoming, or outgoing.

$$\mathbf{M(p_1, p_2; p_3 ... p_N k) = M_0(p_1, p_2; p_3 ... p_N)} \left(\sum_{\mathbf{i}}^{\mathbf{charged}} \frac{\eta_\mathbf{i} \mathbf{e_i p_i \cdot \epsilon}}{\mathbf{2p_i \cdot k}} \right)$$

where $\eta_i = \pm 1$ for outgoing and incoming particles respectively, and M_0 is the amplitude of $2 \to N$ inelastic collision without radiation.

$\eta_\mathbf{i} = -1$ for incoming hadrons

$\eta_i = +1$ for outgoing hadrons

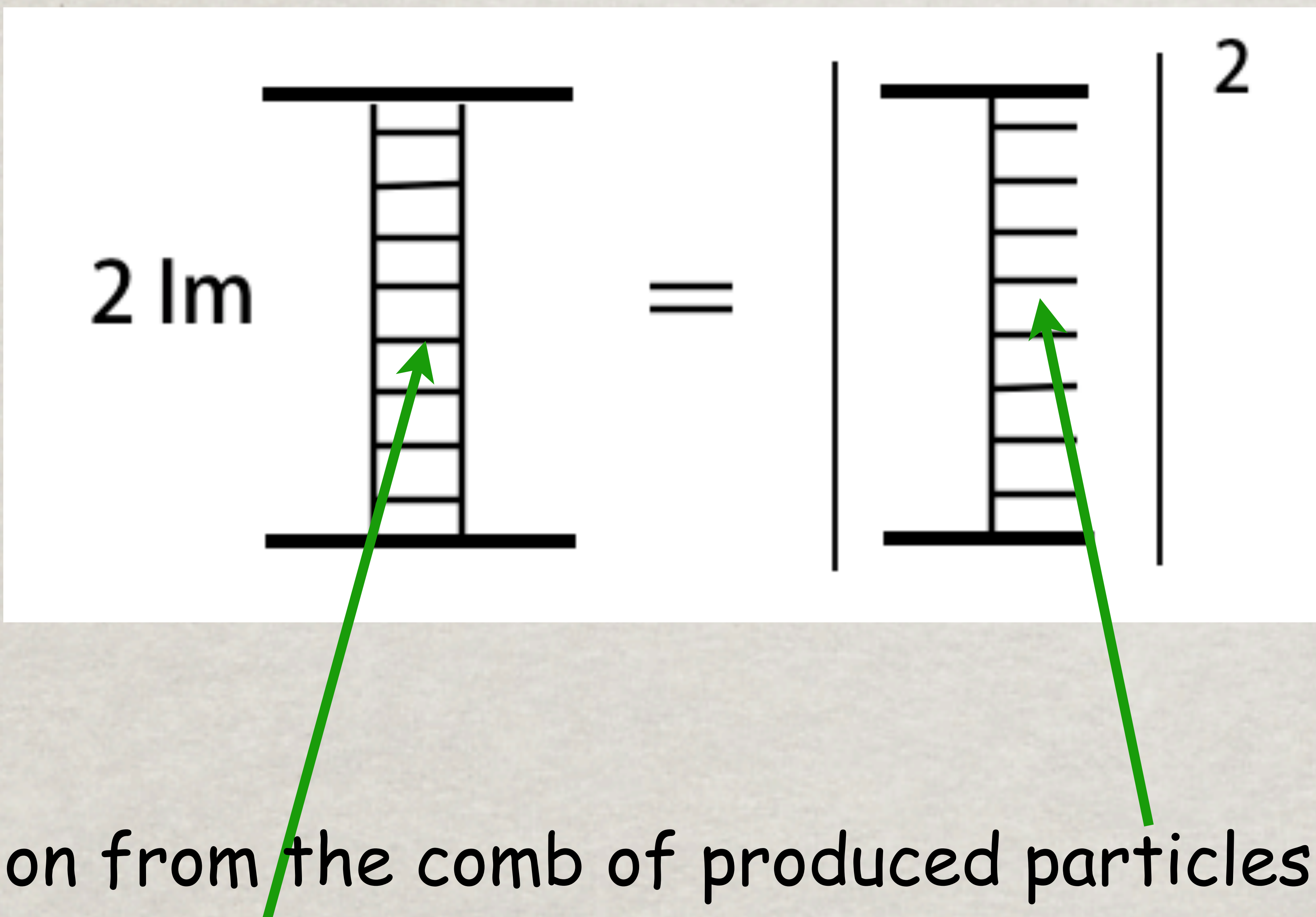
A.T. Goshaw et al., PRL 43(1079)1065

. . .

Such an "extension" of the Low theorem is not only unjustified, but strictly contradicts the Low theorem

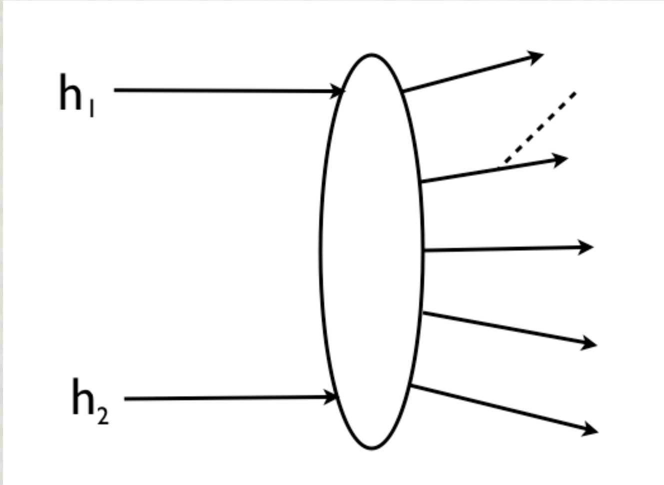
Unitarity relation

Optical theorem relates the imaginary part of the forward elastic amplitude with inelastic processes



Photon radiation from the comb of produced particles, corresponds to intrinsic radiation $\mathbf{M}_{\mu}^{\mathbf{int}}$ from the Pomeron ladder in the l.h.s. of this equation. That was shown by Low to be suppressed. On the contrary to the claim that the BM is an extended version of the Low theorem, in fact it strictly contradicts Low.

One might wonder what is concretely wrong in BM, why Feynman rules cannot be applied to the graph

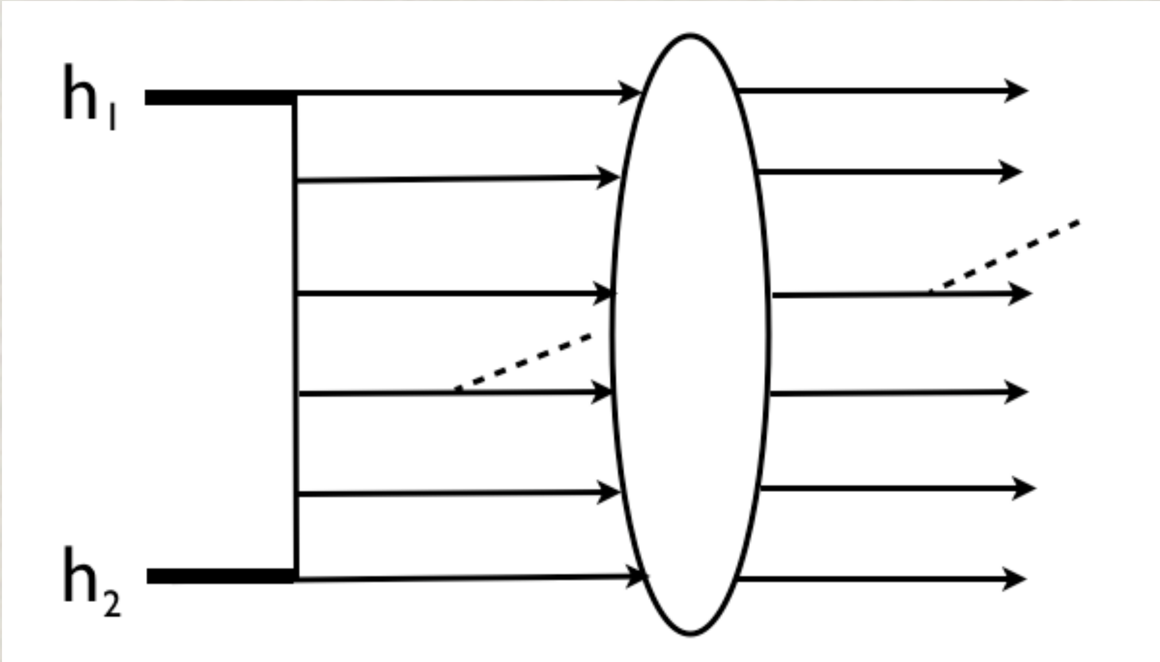


?

Infra-red divergency of the propagator means infinitely long radiation length.

$$\sum_{i}^{\mathbf{charged}} \frac{\eta_i e_i p_i\cdot\epsilon}{2p_i\cdot k} \longrightarrow \frac{1}{p^2-m_h^2} = \frac{x_1(1-x_1)}{k_T^2+x_1 m_h^2} = \frac{l_c^\gamma}{2E_1}$$

Thus, the process cannot be treated as radiation from two incoming and N outgoing charges, but N->N



This explains the observed contradiction between BM and the Low and optical theorems.

Conclusions

The observed enhancement of low-kT photons in comparison with incorrect calculations, should not be treated as a puzzle.

The paper by Low considered a large rapidity gap process of diffractive excitation of a hadron, $\mathbf{h} \to \mathbf{h} + \gamma$, which has little to do with multiple hadron production spanning all over the rapidity interval between colliding hadrons.

According o the unitarity relation what is treated by BM as final state external radiation corresponds to internal radiation in the elastic amplitude, which was proven by Low to be suppressed