Soft photon study in hadron interactions

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How Soft Photons are determined

Quark-quark (qq), quark-gluon(qg), and gluon-gluon (gg) interactions lead to the emission of photons, which are called direct ones. The information about that early stage of the qg-system development is especially valuable and it can be available by direct photon study.

The photon probes provide us complementary information to hadronic ones. Photons with low transverse $p_T \lesssim 70$ MeV/c and longitudinal momenta $x_F \lesssim 0.005$ (accordingly, with low energies in the c.m.s.) are called Soft Photons (SPs). They deserves special attention. We are aimed at studying of photons with $10 < p_T < 50$ MeV/c.

Why are we interested in SP?

The main sources of photons in hadron or nuclear interactions are the decay products of unstable particles (including resonances). Another source is bremsstrahlung (the scattering of charged particles).

Photons interact with the surrounding matter only electromagnetically. Their cross sections are much smaller than hadronic. Hadrons scatter many times, their spectrum reflects the state of the system only at the final stage of its expansion.

Photons with a high probability leave their system without scattering and, therefore, they carry information about the properties of the medium where they were born.

Why are we interested in SPs?

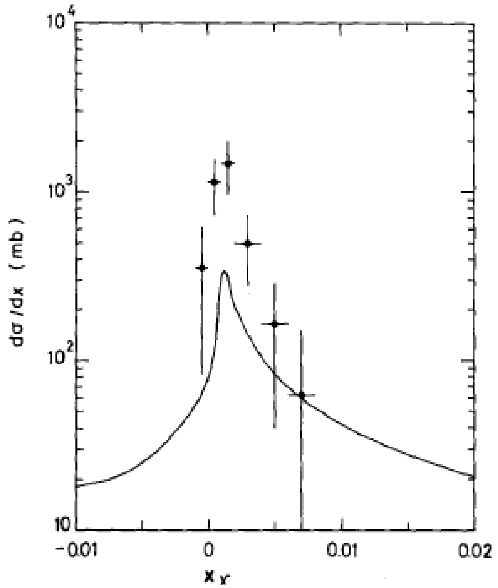
- Excess of the soft photon (SP) yield is observed in the different hadron & nuclear interactions in a wide energy region. There is still no comprehensive explanation of the nature of this phenomenon.
- In accordance to the Gluon Dominance Model (GDM) soft gluons can be sources of SPs.
- The region of the SP formation lies outside pQCD (hadronization region).
- Investigate the connection between the pion (Bose-Einstein, BEC) condensate and an excess SP yield.

Why are we interested in SPs?

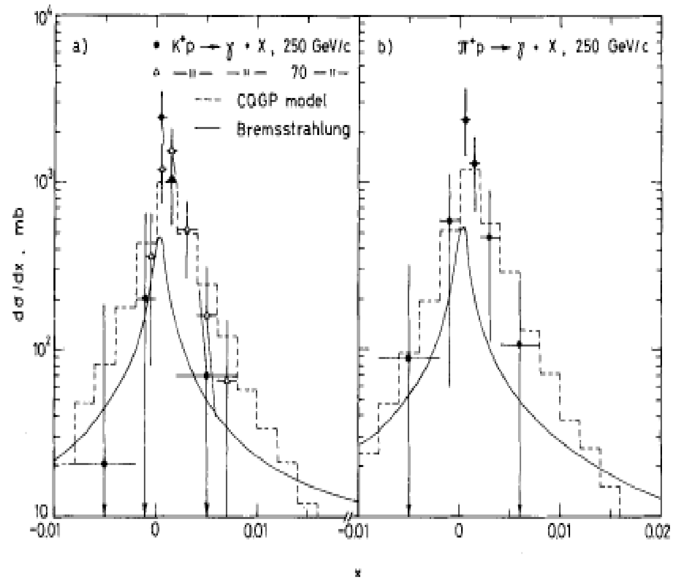
- The relevance of a gluon component for the nucleon structure study.
- γ- femtometry.
- Search for *P*-parity violation effect in events with high p_T and etc.
- An indication of increased yield of η^0-mesons in AA-interactions compared with nucleon interactions was obtained.
- Coherence of SP by measurement of flow v_2 (T. Kodama and T. Koide).
- Search for QED (QCD) mesons that can be sources of SP and soft e^+e^- pairs (new particles in the system of two γ-quanta (X17 and E38); etc.

Experiments corroborating SP excess

The first indication of weak signal: SLAC, bubble chamber, 1979, the process $\pi^+ p \to \gamma + X$ at 10.5 GeV/*c*.



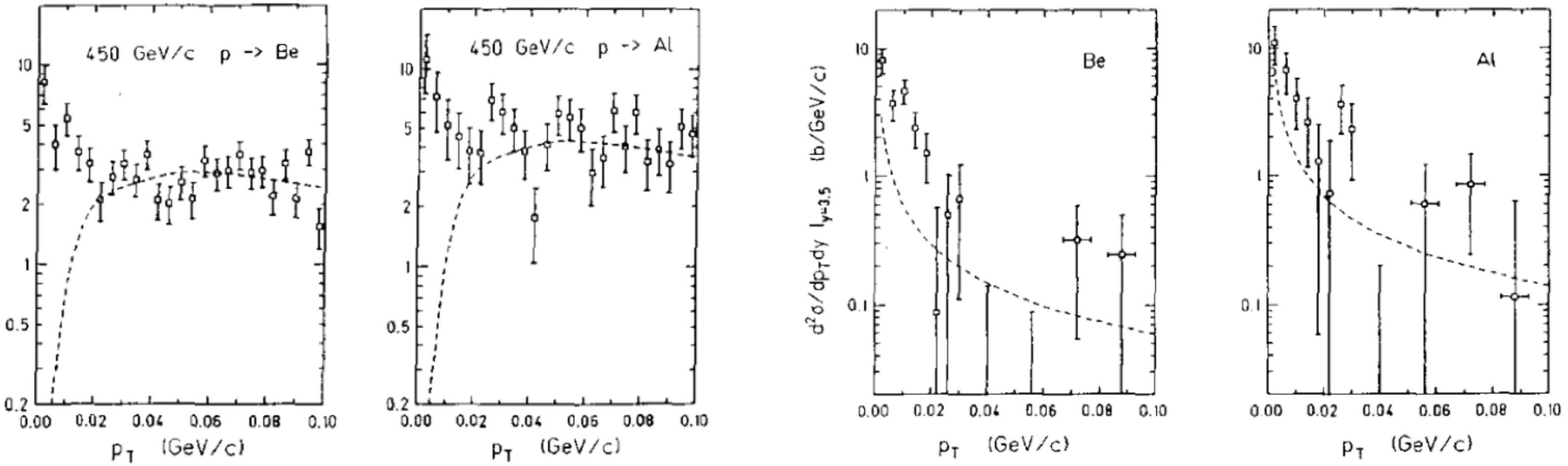
CERN, BEBC
$K^+p \to \gamma$ +..., 70 GeV/*c*,
solid line – bremsstrahlung, 1984



SPS, NA22. $K^+p \to \gamma$ +... , $\pi^+ p \to \gamma + X$,
K^+ and π^+ beams - 250 GeV/*c*, 1991

Experiments corroborating SP excess

CERN, SPS, HELIOS (WA34) Coll. 1989. pp, pBe, pAl, ^{32}S+W, 450 GeV/c interactions. One of the possible signals for qg-matter formation is an enhanced production of electromagnetic radiation in the form of real or virtual photons (low-p_T γ's or low-m_T lepton pairs). (J. Schukraft)



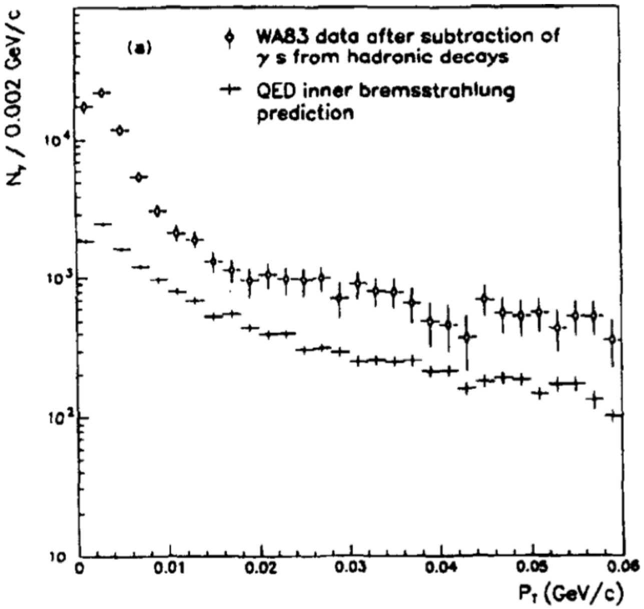
Left: γ's converted in a thin iron plate are identified in a DCh, their energy is measured in a 6x6 matrix of BGO. The dashed line represents the contribution from hadronic decays. Right: Background-subtracted spectra in p-Be and p-Al. The line corresponds to the calculated of hadronic bremsstrahlung.

Experiments corroborating SP excess

J. Schukraft, HELIOS Coll.:

"The SP excess presents an anomaly, because at the very low p_T the wavelength is large compared to the hadronic interact. region, bremsstrahlung from initial- and final-state particles is the conceivable source of SPs (Low's theorem). In this regime, processes confined within the interaction region with its typical size (and lifetime) of 1 fm. We might have to consider the presence of much larger scales (≈ 5-20 fm) than usually thought to exist in hadronic interactions."

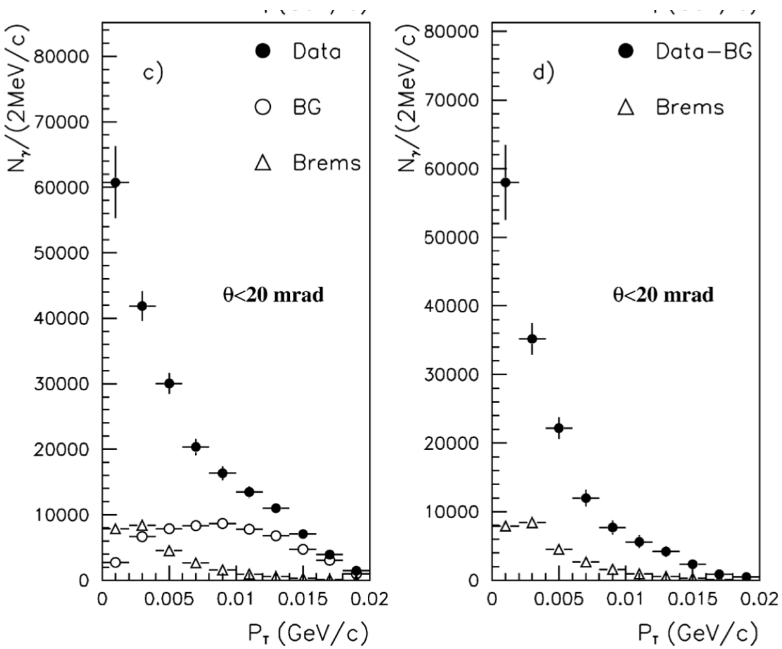
SOPHIE/WA83 Coll.
π^- + p, at 280 GeV/c, 1993



p_T distribution of γ's remaining after subtraction of hadronic γ's compared with QED inner bremsstrahlung.

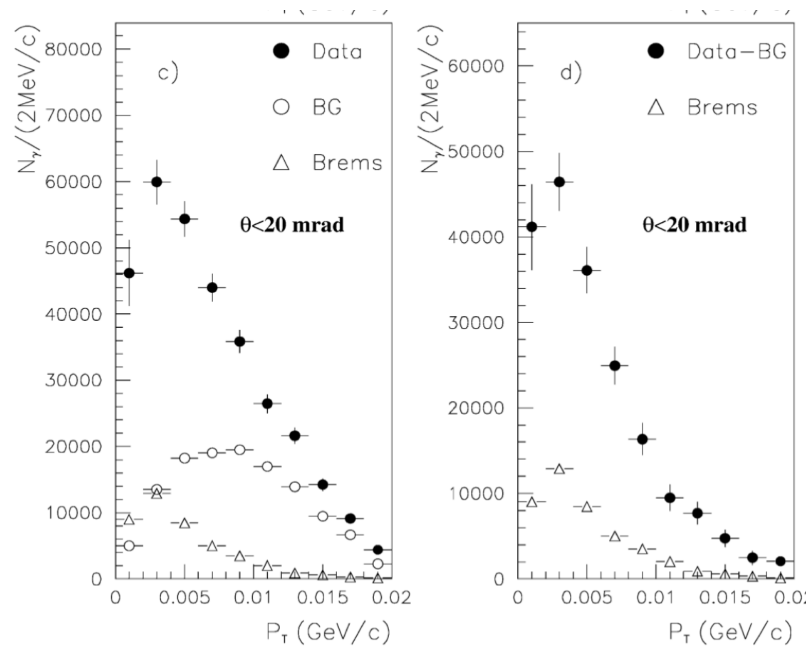
Experiments corroborating SP excess

CERN, WA91, OMEGA spectr.,
$\pi^- p$ inter. at 280 GeV/c (2002)



The re-calculated ratio of the observed direct SP signal to the expected hadronic inner bremsstrahlung, which is found to be 5.3 ± 1.0.

CERN, WA102, OMEGA spectr.,
pp inter. at 450 GeV/c (2002)



p_T distribution for γ's with $0.2 < E_\gamma < 1$ GeV, corrected for detection efficiency. “Brems” - for the inner hadronic bremsstrahlung.

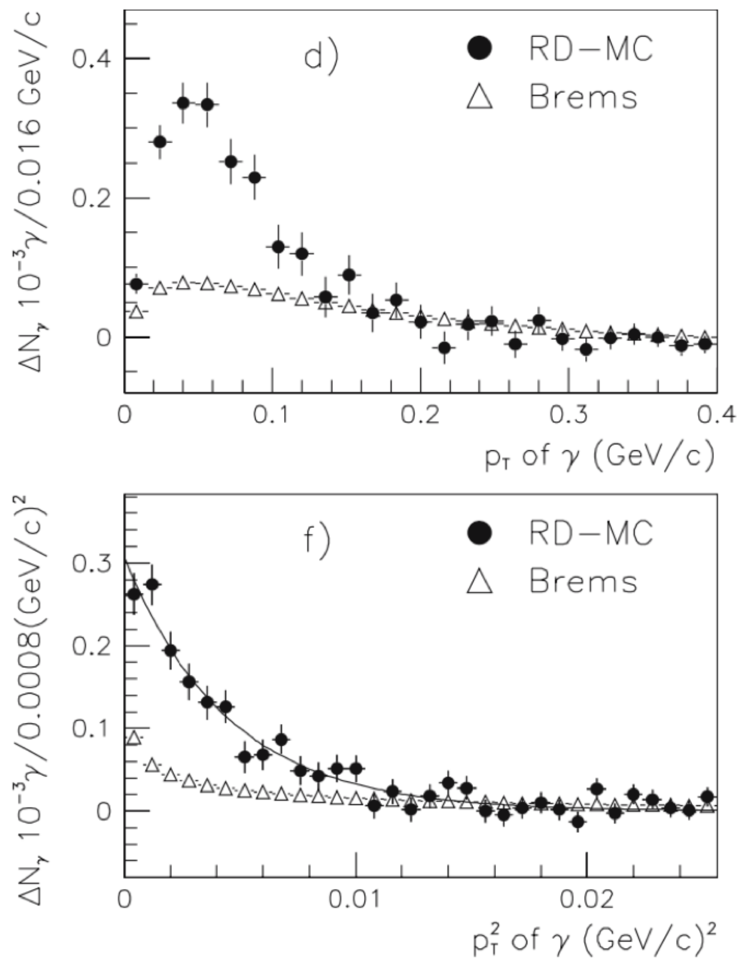
Experiments corroborating SP excess

CERN, DELPHI, 2009-2011.

An excess of SP's in hadronic decays of Z^0 at e^+e^- annihilation .

The ratio of the excess to the predicted bremsstrahlung rate is then (3.4±0.2±0.8), which is similar in strength to the anomalous SP signal observed in fixed target experiments with hadronic beams.

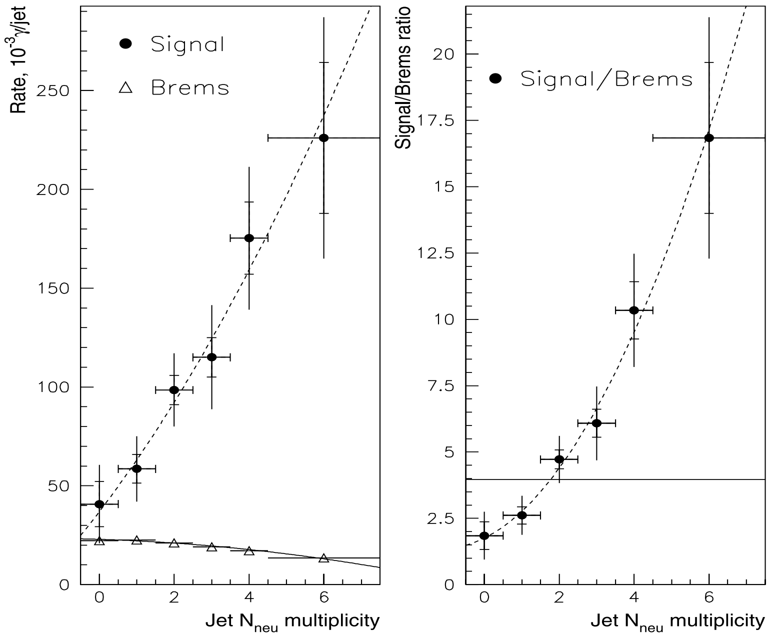
Figs.: the difference between the RD (Real Data) and MC distributions. "Brems" corresponds to the inner hadronic bremsstrahlung predictions. The errors are statistical.



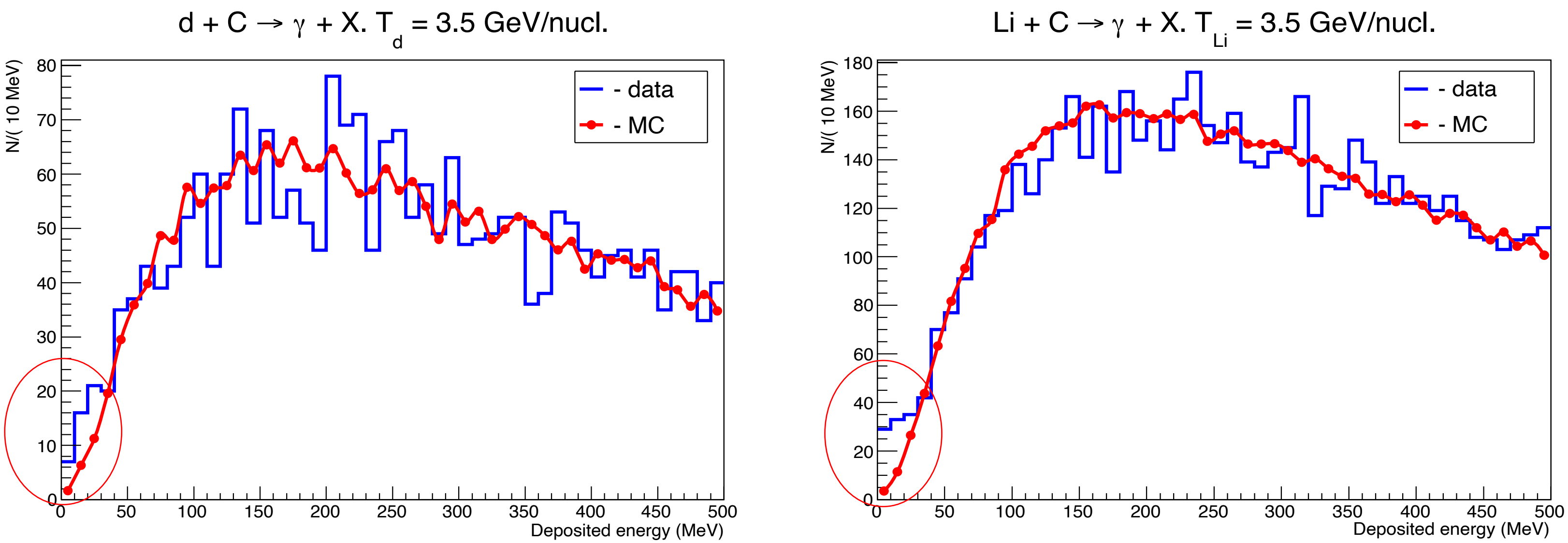
Experiments corroborating SP excess

CERN, DELPHI, 2010.
An excess of SP's in hadronic decays of Z^0 at e^+e^- annihilation for neutral pions.

The ratios of the signal rates to those of the inner bremsstrahlung. The whole vertical bars give the statistical and systematic errors combined in quadrature.



Experiments corroborating SP excess



Data and MC spectra of energy release in ECal & a pre-shower with 3.5A GeV/*c* d (left) and Li (right) beams, 50th and 51st Nuclotron's runs. SVD-2 Coll.

Criterions of selection: 1) E in the front veto-counter < 0.3 MIPs; 2) E in pre-shower 0.5 < *E* < 4 MIPs; 3)ToF -1200 < $t\text{-}t_{\gamma}$ <600ps; 4) more than 2 MeV it is registered in 1 BGO crystal; 5) location of shower in crystal must overlay throughout vertical with the triggered pre-shower counter; 6) E deposition in the outer BGO layer should be ≤ 1/3 of a total to prevent significant leakages

Gluon Dominance Model

Gluon Dominance Model (GDM) describes multiparticle production in two stages. It presents itself the convolution of qg-cascade (pQCD) and hadronization (phenomenological scheme). GDM confirms the fragmentation mechanism of hadronization for e^+e^- annihilation and recombination one in hadron and nuclear interactions.

It evidences the main sources of secondaries are active gluons, valence quarks are staying in the leading particles. The rest of gluons, ~ 50%, can't turn into hadrons - it's insufficient of energy, we call them soft gluons (2015). They are picked up by newly born quarks with following dropping of energy by emission of SP: $g + q \to \gamma + q$ or $q + \bar{q} \to \gamma$.

Gluon Dominance Model

We estimated the emission region of SPs in the case of almost the equilibrium state using the black body emission spectrum for interaction *pp* -> hadrons + γ's (SP) at U70. For estimation we used for this region the simplified shape, a cube. Its linear size exceeds the typical size of hadronization region (1 fm) and reaches a value about 4-6 fm. Density of SP: ρ(T)=n(T)/V

SP: $p_t \le 0.1 GeV/c,\ x \le 0.01$

σ(SP), 5-8 more then from QED

$$\sigma_\gamma \approx 4mb,\ \sigma_{in} \approx 40mb,\ \sigma_\gamma \approx n_\gamma(T)\cdot\sigma_{in} \to n_\gamma \approx 0.1 \qquad \frac{dn_\gamma}{d\nu} = \frac{8\pi}{c^3}\frac{\nu^3}{e^{\frac{h\nu}{T}}-1}.$$

$$n_\gamma(T) = n_\gamma(T_r)\cdot\left(\frac{T}{T_r}\right)^3,\ \rho(T) = n_\gamma(T)/V = 4.112\cdot10^8\cdot10^{-6}\cdot10^{-39}\left(\frac{T}{T_r}\right)^3 fm^{-3}$$

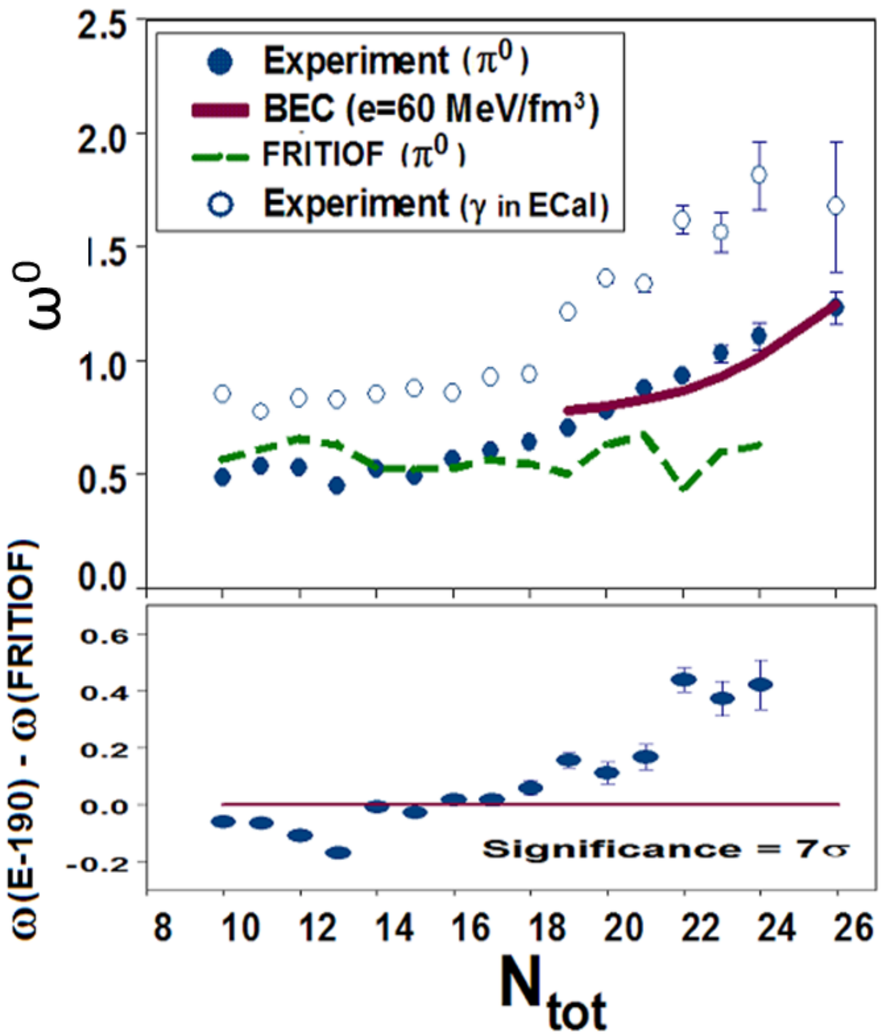
$$T = p \approx p_t\cdot\sqrt{2} \qquad L^3\cdot\rho(T) \approx n_\gamma \to L(T)$$

Fluctuations of the π^0's number in the region of high total multiplicity

Begun and Gorenstein (2007, 2008) predicted the pion or Bose-Einstein (BEC) condensate formation in *pp* interactions at U-70 in a region of high total multiplicity, HM, $N_{tot} = N_{ch} + N_0$, in the framework of the ideal pion gas model. HM: N >> <N>.
They proposed us to measure the scaled variance of the neutral pion number $\omega^0 = D/\langle N_0(N_{tot})\rangle$, $D = \langle N_0^2\rangle - \langle N_0\rangle^2$, with growth of N_{tot}. Sharp abrupt its rise would be signal of BEC (thermodynamic limit). In the case of the restricted pion system, ω^0 approaches to final value (12). MC and Poisson give $\omega^0 \approx 1$.
SVD-2 setup registered photons at ECal. Using original method, we have retrieved number of events with defined multiplicity of π^0's at given N_{ch}.

$$\frac{T_C(\pi)}{T_C(A)} \approx \frac{m_A}{m}\left(\frac{r_A}{r_\pi}\right)^2 \cong \frac{m_A}{m}10^{10}.$$

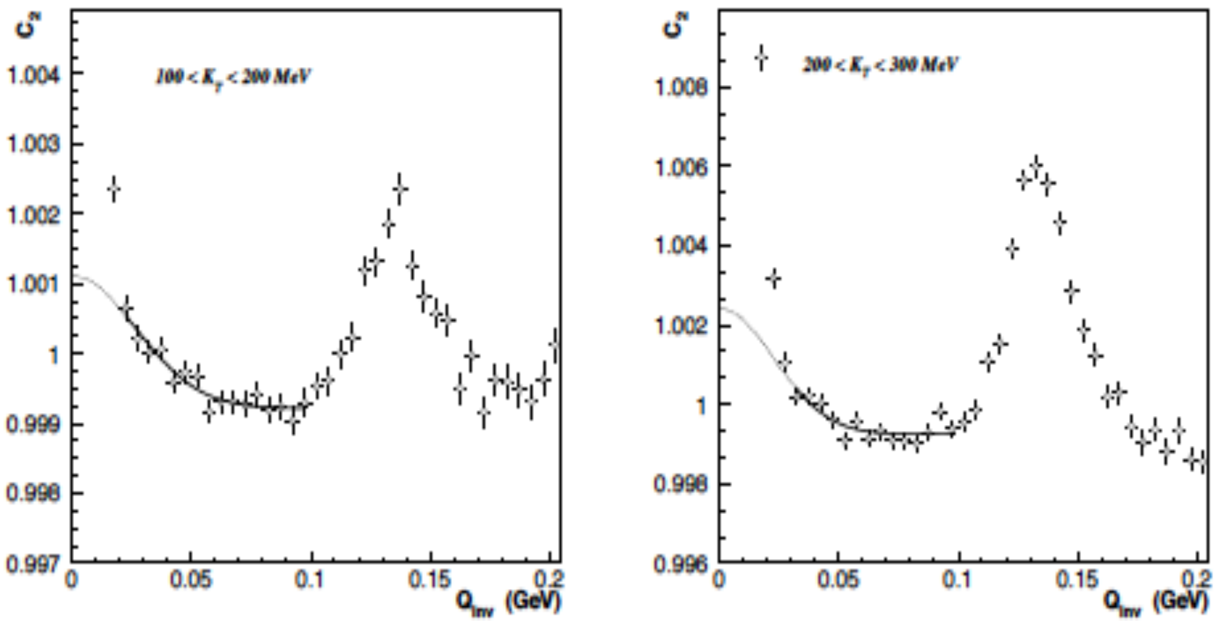
Fluctuations of the π^0's number in the HM region



ω^0 (exp)/ ω^0 (MC) gets 7 standard deviations at N_{tot}~ 25 (SVD Coll., 2012).

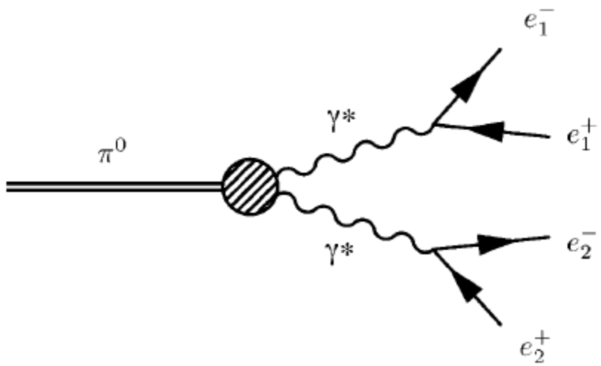
There are models that explain an enhanced yield of SPs by BEC formation.

gamma femtometry



Two-γ correlation function calculated for the 10% most central $^{298}Pb+^{298}Pb$ collisions at 158 AGeV. "All" PID criterion is used and cut on minimal distance L_{12} > 20 cm is imposed (WA98 Coll. (2004)

Search for *P*-parity violation effect in events with high p_T



B.A.Robson (2011)

The angle distribution on ϕ between planes of e^+e^--pairs has been gotten in FNAL experiment KTeV-E799 by using of 30000 events. Contribution of the positive parity state, factor *b* in expression for the angle distribution, consisted ≤ 3.3 %:

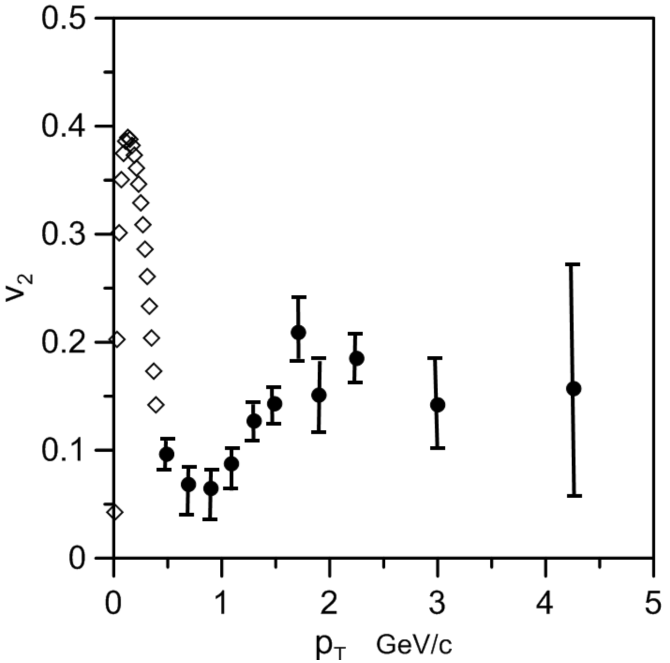
$$\frac{dF}{d\phi} = 1 + a\cos(2\phi) + b\sin(2\phi)$$

Yield of η^0-mesons in NN and NA-interactions

η^0 production is much higher in p ^{20}Ne interactions [R(η^0/π^0)=0.66+/-0.12 for n_p > 2] than in pN interactions [R (η^0 /π^0)=0. 06+0.04]. Strong correlations between ‹n_γ› and n_p, the number of secondary protons, are observed, primarily from the central and target fragmentation regions. …"

B.S. Yuldashev (1991)

Testing of coherent emission of SPs by means of flow v_2



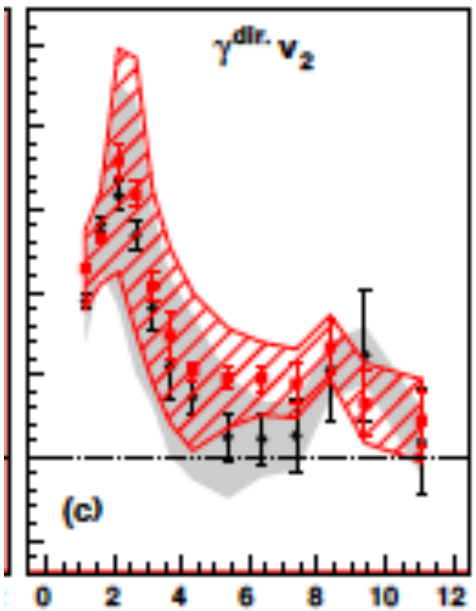
Flow v_2 as function of p_T for γ-spectra

Prediction for flow, v_2, from Direct Photons (empty diamonds). Squares denote the results with the effects of incoherent with p = 0.2 GeV. Filled circles indicate the experimental data from PHENIX T.Koide, T. Kodama. (2016)

Measurement of flow v_2 for Direct Photons

$$v_2^{\gamma,dir} = \frac{R_\gamma(p_T)v_2^{\gamma,inc} - v_2^{\gamma,bg}}{R_\gamma(p_T) - 1}$$

$R_\gamma(p_T)$ = $N^{inc}(p_T)/N^{bg}(p_T)$ with $N^{inc}=N^{meas}-N^{hadr}$, the number of inclusive γ's, while $N^{bg}(p_T)$ is the number of γ's attributed to hadron decay. Values of $R_\gamma(p_T)$ above 5 GeV/*c* are taken from real photon data with the PHENIX ECal and below that from the more accurate, but p_T-range limited internal conversion measurement of direct photons. PHENIX, 2012.



Open string QED meson description

Proposal of Cheuk-Yin Wong, PD Oak Ridge NL, (2001.04864v4)

q and $\bar{q}$ can't be isolated, the intrinsic motion of this $q\bar{q}$ system In its lowest-energy state lies predominantly in 1+1 dimensions, as in open string with q and $\bar{q}$ at its two ends. He studies these energy states of the open string $q\bar{q}$ system in QCD and QED in 1+1 dimensions and shows that π^0, η, and η' can be adequately described as open string $q\bar{q}$ QCD mesons.

By extrapolating into the $q\bar{q}$ QED sector in which q and $\bar{q}$ interact with QED interaction, he finds an open string isoscalar $I(J^\pi)=0(0^-)$ QED meson state at 17.9±1.5MeV and isovector ($I(J^\pi)=1(0^-)$, $I_3=0$) QED meson state at 36.4 ± 3.8 MeV.

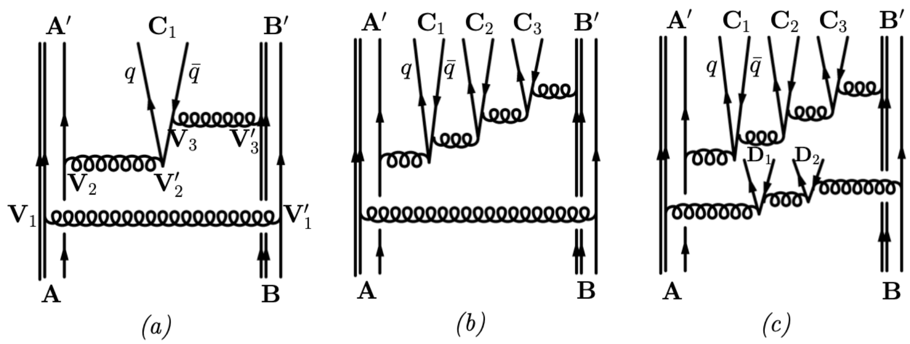
Open string QED meson description

The predicted masses of the isoscalar and isovector QED mesons are close to the masses of the hypothecal X17 [1] and E38 [2] particles observed recently, making them good candidates for these particles has generated a great deal interest [3]. Evidence for X17 reported in the decay of the excited $I(J^{\pi})=0(0^{-})$ state of ^{4}He [4].

[1] A.J. Krasznahorkay et al. Observation of anomalous internal pair creation in ^{8}Be: a possible indication of a light neutral boson. Phys. Rev. Lett. 116 (2016) 042501.
[2] K. Abraamyan et al. Check of the structure in photon pairs spectra at the invariant mass of about 38 MeV/c^{2}. EPJ, 2019.
[3] D. Banerjee et al. (NA64 Coll.) Search for a hypotical 16.7 MeV gauge boson and dark photons in the NA64 Experiment at CERN. Phys. Rev. Lett. 120 (2018) 231803.
[4] A.J. Krasznahorkay et al. arXiv: 1910.10459 (2019).

Open string QED meson description

The decay products of QED mesons may show up as excess *e+e-* and γγ pairs in the anomalous SP phenomenon associated with hadron production in high-energy hadron-proton collisions and e+e- annihilation.
Measurements of the invariant masses of excess *e+e-* and γγ pairs will provide tests for the exsistence of the open string $q\bar{q}$ QED mesons.



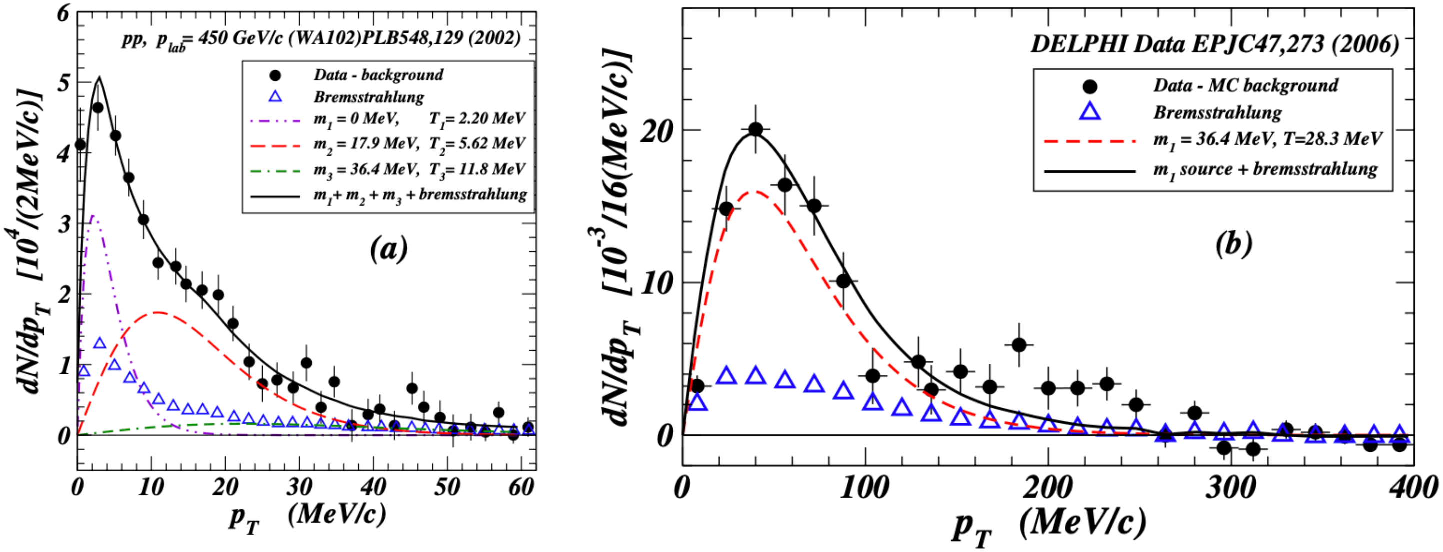
Feynman diagrams for the production of QCD and QED mesons (a) *A* + B at low energies, (b) *A* + B at intermediate energies, (c) *A* + B at high energies. The double lines represent a diquark in the case of a baryon or an antiquark in the case of a meson.

Open string QED meson description

Table. Comparison of experimental and theoretical masses of neutral, I_3=0, and S=0 QCD and QED mesons obtained with the semi-empirical mass formula for QCD mesons and for QED mesons, with α =1/137, α =0.68±0.08, and R =0.40±0.4 fm.

		I	S	$[I(J^\pi)]$	Experimental mass (MeV)	Semi-empirical mass formula (MeV)	Meson mass in massless quark limit (MeV)
QCD meson	π^0	1	0	$[1(0^-)]$	134.9768 ± 0.0005	$134.9^\ddagger$	0
	η	0	0	$[0(0^-)]$	547.862 ± 0.017	498.4 ± 39.8	329.7 ± 57.5
	η'	0	0	$[0(0^-)]$	957.78 ± 0.06	948.2 ± 99.6	723.4 ± 126.3
QED meson	isoscalar	0	0	$[0(0^-)]$		17.9 ± 1.5	11.2 ± 1.3
	isovector	1	0	$[1(0^-)]$		36.4 ± 3.8	33.6 ± 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			?	$39.71\pm0.71^\otimes$		

Open string QED meson description



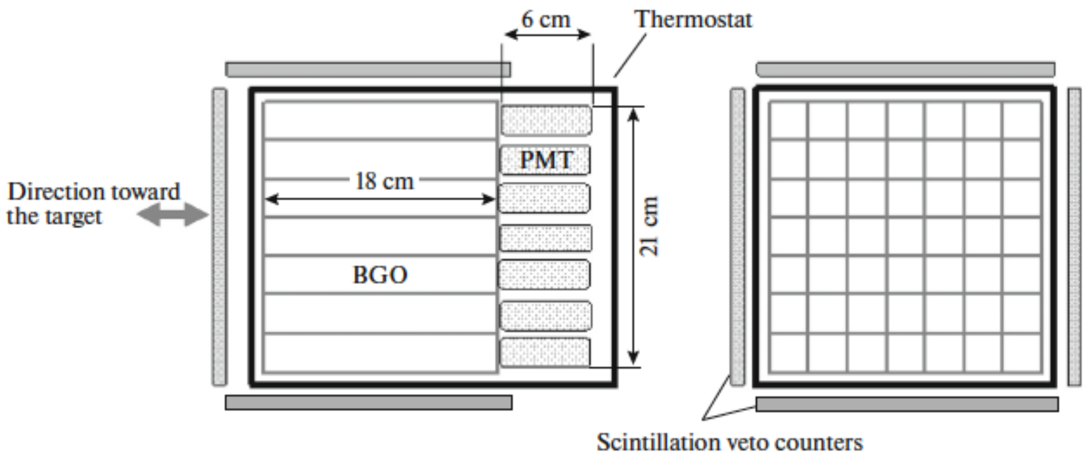
(a) Anomalous SP data from pp at p_{lab}=450 GeV/c Belogianni et al.
(b) SP data from the DELPHI Coll. for e+e− at Z^0 mass. The solid points represent the data after subtracting the experimental background, and triangle points represent the deduced bremsstrahlung contributions. The total theoretical yields in the thermal model from produced bosons and the additional bremsstrahlung contributions are shown as solid curves. The component yields from different masses of the thermal model are shown as separate curves.

Open string QED meson description

An assembly of graviting QED mesons are expected to emit *e+e-* and γγ rays and their decay, energies will be midified by their gravitational binding energies. Therefore, a self-gravitating isoscalar QED meson assembly whose mass M and radious R satisfy $(M/M_{\odot})/R/R_{\odot}) \gtrsim 4.71\times10^5$ will not produce *e+e-* pairs and γγ rays and may be a good candidate for the primordial dark matter.

An assembly of A number of m_X QED mesons of mass M_A=M and we add a test QED m_X meson at the surface of the assembly at radius R, the mass M_{A+1} of the combined system is $M_{A+1} = M_A + m_X - GM_Am_X / Rc^2$.
$Q((A+1)\text{->}A+2\gamma)=m_Xc^2 - GM_Am_X / Rc^2$. The QED meson m_X will not decay into 2γ when M and R satisfy $M/R > c^2/G$.

SP registration by ECal at Nuclotron



ECal scheme

A general view of ECal based on BGO crystals with veto-detectors at NIS-GIBS setup, 2015 (Nuclotron, JINR)

Expect parameters of ECal's

We would like to fill a niche between heterogeneous structures "shashlik"
for region 10-50 MeV (SP) with
light yield ~ 3-6 ph/MeV and crystal detectors – light yield ~10,000 -40,000 ph/MeV.

We're aimed at creation of "heavy" ECal's:
- scintillation decay time ~ 90 ns;
– light yield ~ 2000-3000 ph/MeV;
– price about $25-35/cm³ of volume;
– radiation resistance.

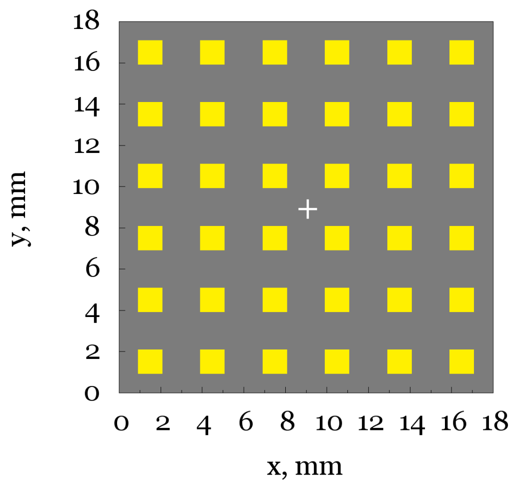
Comparison of scintillator properties

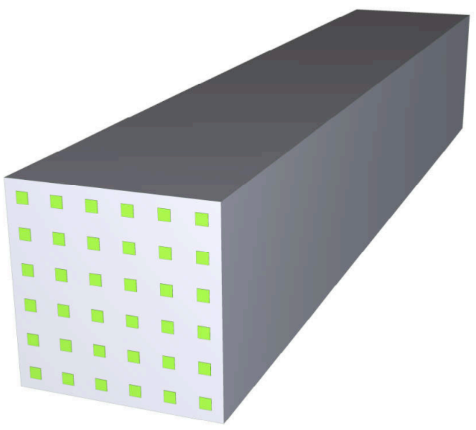
Parameters	$Gd_3Al_2Ga_3O_{12}$	$Bi_4Ge_3O_{12}$	NaI:Tl
light yield, 10^3ph/MeV	57	8	4,5
energy resolution, (%@662кeV)	5,2	12	7,1
decay time, ns	88	300	250
hygroscopicity	-	-	+
Density, g/cm^3	6,63	7,13	3,67
Radiation peak, nm	520	480	415

SpaCal scheme

The prototype detector cell is an assembly of W+Cu composite plates and rods, and GaGG: Ce rods, with shape of a rectangular parallelepiped: 18 × 18 × 100 mm^3. It has of 6x6 (1×1×100 mm^3) scintillator rods surrounded by absorber. The surfaces of plates and absorber rods are coated with a 10 µm polymer dim white reflector. We test 2 such assemblies.

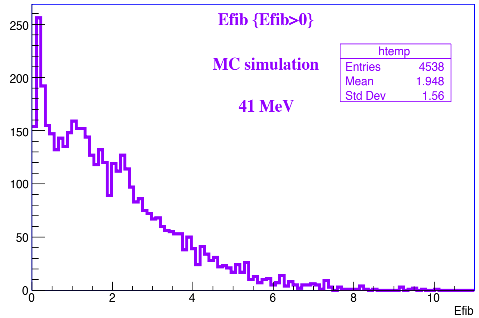
Detector cell with yellow/green rods, and grey plates.

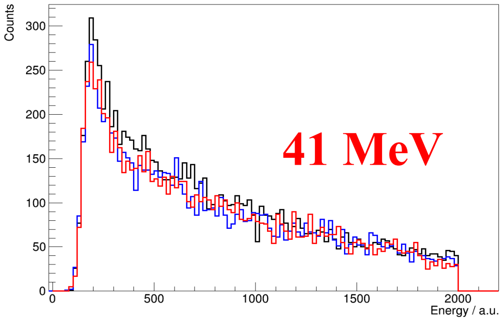


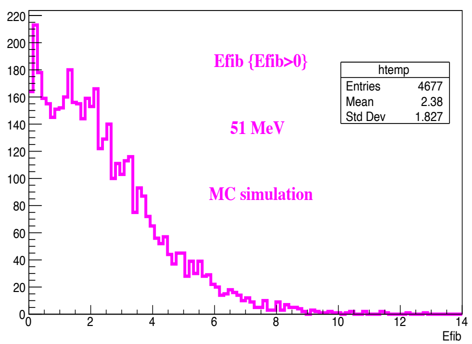


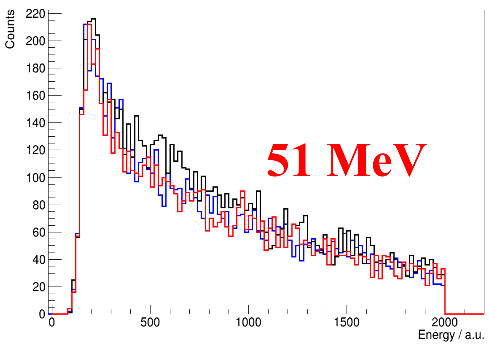
MC simulation

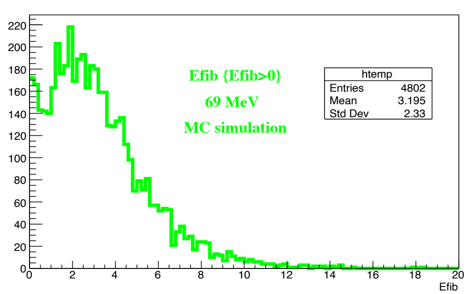
Data, Jun-2019

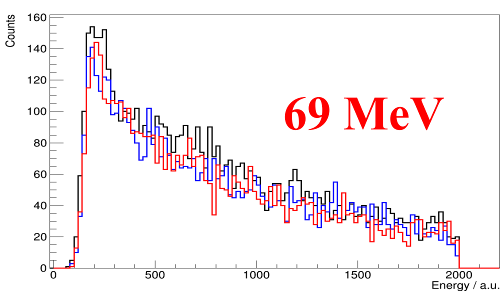






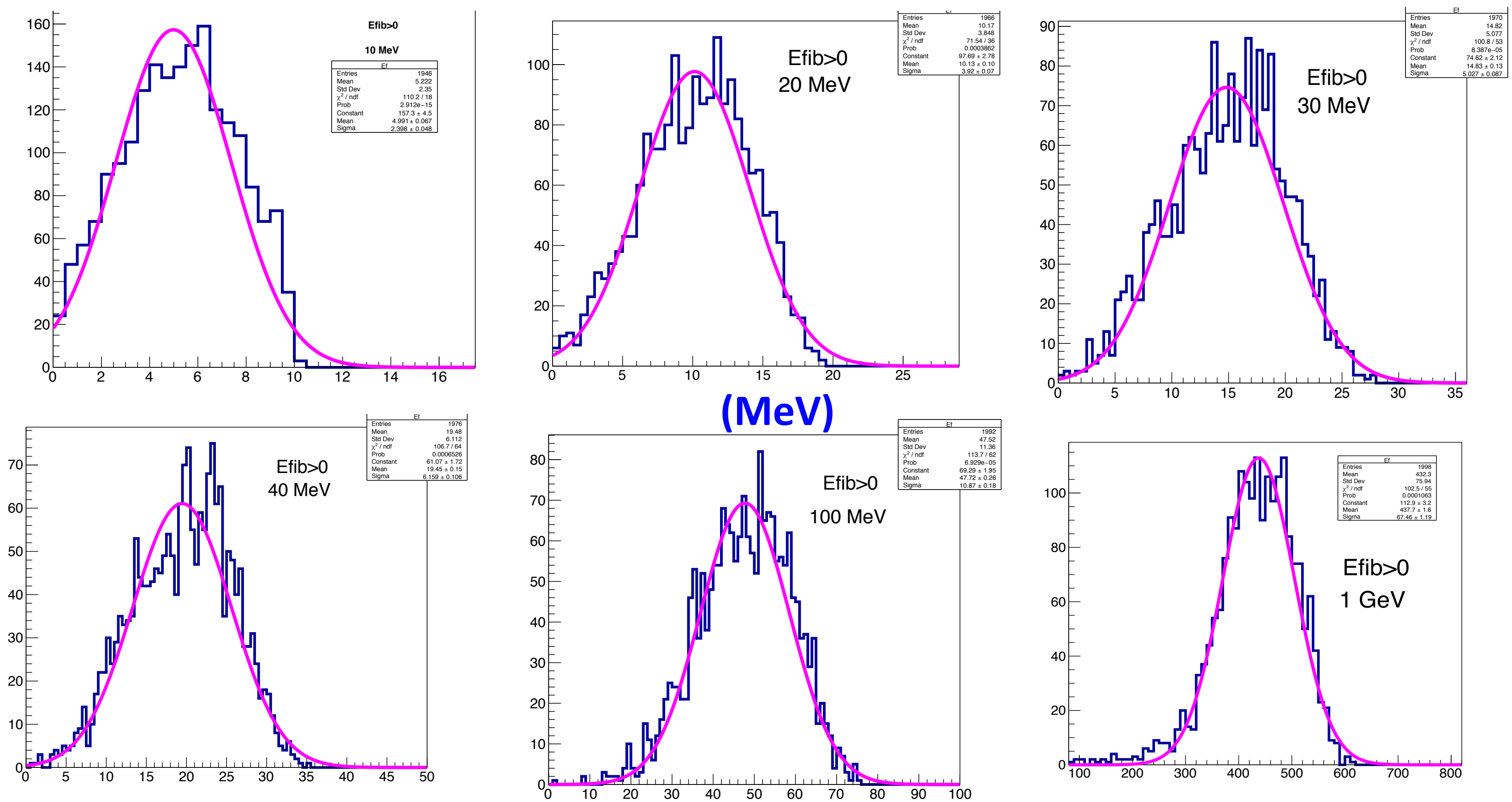






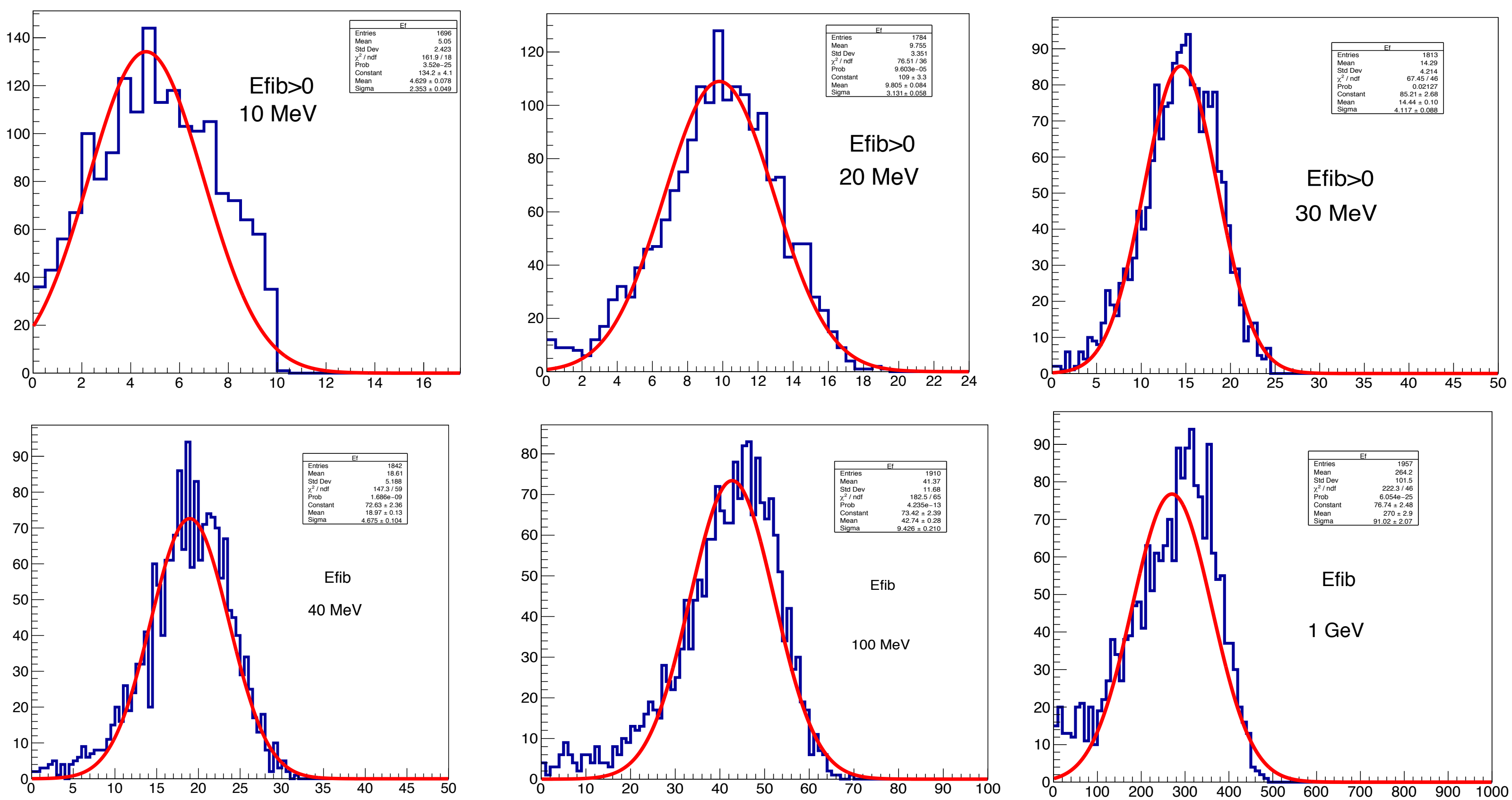
MC simulation of SpaCal

WCu(1/19),25x25 rods GaGG (3x3 mm^2), 1mm-gape, 101x101x150 mm^3

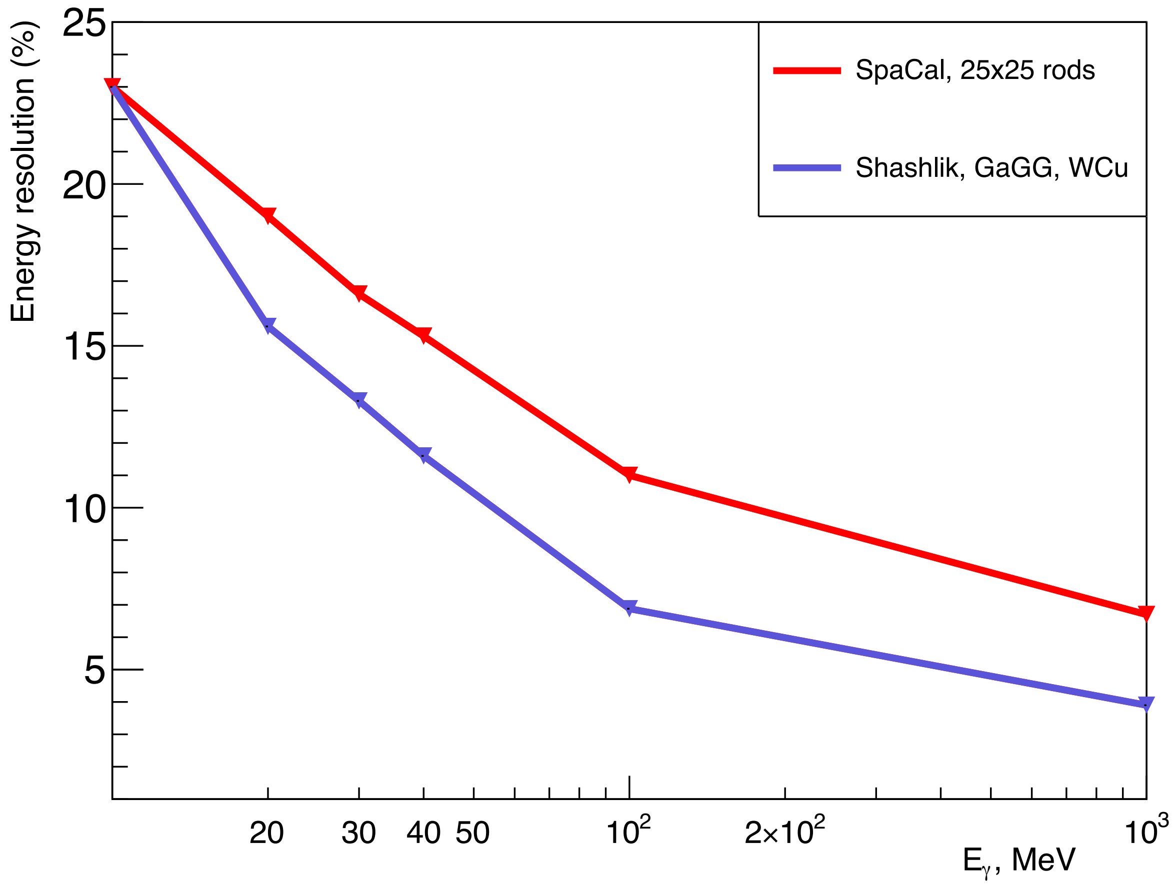


MC simulation of Shashlyk

16 plates GaGG (100x100x3 mm^3), 15 plates of 2mm-absorber WCu(1/19), thickness – 78mm



Energy resolution SpaCal vs Shashlyk



Our plans

For SpaSal ER will be 10 % and better for photons with E_γ above 50 MeV with SiPMs and the correct scheme for transporting of light to a photo detector.

MC simulation and experiment with prototype of Shashlyk with GaGG scintillator and W/Cu absorber to demonstrate better ER at low energy then with SpaCal's. In progress.

We also learn possibilities of using of Glass and Glass Ceramic Stoichiometric and Gd^{3+} heavy loaded BaO*2SiO2:Ce(DSB:Ce) scintillation material for ECal application.

Thank you for attention