

«SIMULATION OF DIRECT PHOTON PRODUCTION PROCESS»



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First $pp \rightarrow \gamma + X$ experiments were done at CERN:

at ISR (pp - collider, $E_{cm} = 31, 45, 53$ GeV):

- × R412 experiment (Darriulat et. al., 1976);
- × R107 (Amaldi et. al., 1978); ...and many others.

Also started at Fermilab and BNL:

- × E557 (Baltrusaitis et. al. 1979, pBe, $E_{cm} = 19.4, 23.7$ GeV)
 - × E629 (McLaughlin et. al. 1983, pC, $E_{cm} = 19.4$ GeV)
- ... and then continued in many other experiments at higher energies

Dpp has also been studied in **pion-proton**, **pion-nucleus**, **proton-nucleus** and in **heavy-ion collisions**, also at LEP and HERA

In addition, the direct photon production in the relativistic heavy ions collisions has also played a very important role in finding out of a new form of matter by the experimental confirmation of the existence of a new phase of strongly interacting matter - quark-gluon plasma QGP. This kind of measurements of heavy ions collisions was started at CERN by WA80 and WA98 collaborations and now is under investigations at RHIC and at the LHC.

- × Precision test of pQCD;
- × Serves to calibrate jet energy;
- × Dpp is complementary to DIS and DRELL-YAN for studying the structure of hadrons;
- × Dpp contributes significantly to the measurement of the gluon distributions in hadrons.

The energy region $1 < E_{\text{beam}} < 15$ GeV which can be covered by antiproton beam at the accelerator center FAIR (GSI, Darmstadt) is of interest for research because it is much less investigated as compared to those regions which were studied at the accelerators having the higher energies. Also the region of intermediate beam energy is important for searches of expected deviations from the perturbative QCD.

Our Physical goal: To estimate the possibility of getting *the information about* **proton structure functions** $f(x, Q^2)$.

Main interest: To estimate the size of the x - Q^2 kinematical region in which the **structure functions** *can be measured*.

In $p\bar{p} + p \rightarrow \text{gamma} + X$ process

(choosing $p\bar{p}$ beam direction as the z-axis)

the role of the transferred momentum Q

plays the **photon transverse momentum**, i.e.

$$p_T^\gamma = Q$$

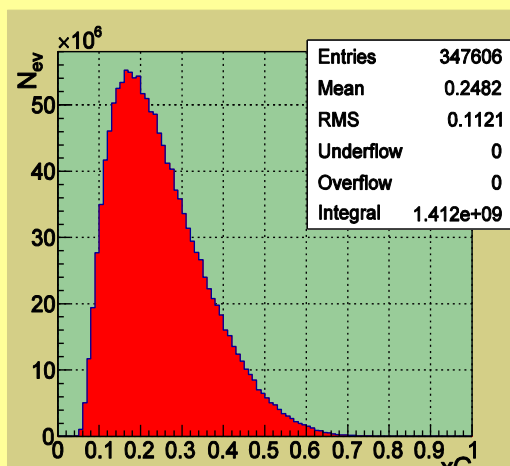
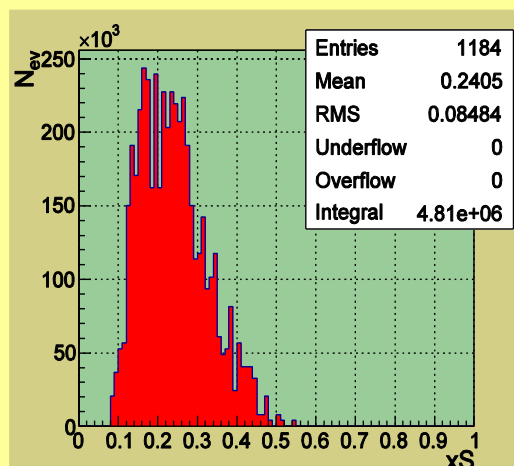
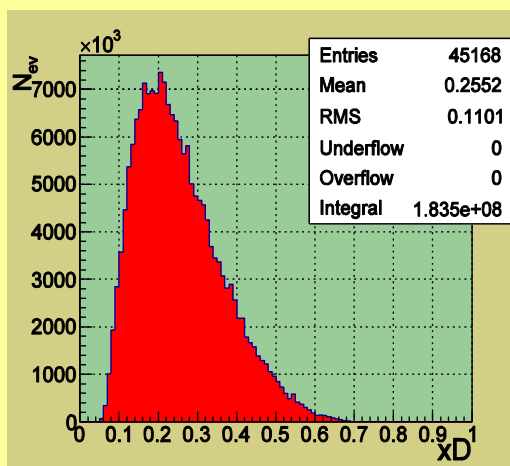
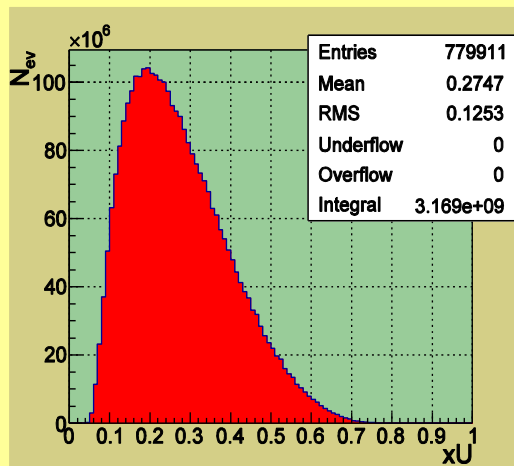
As it will be shown below, at $E_{\text{beam}} = 15 \text{ GeV}$

we can expect $p_T^\gamma < 2.3 \text{ GeV}$, i.e.,

$$Q^2 = (p_T^\gamma)^2 < 5.3 \text{ GeV}^2$$

This region is under study now at HERA and JLab .

Bjorken x distributions



From these quark distributions we see that at PANDA energy ($E_{\text{beam}}=15$ GeV) PYTHIA6.4 (with CTEQ3L parameterization) predicts that the Bjorken x -variable can cover the region

$$0.05 < x < 0.7$$

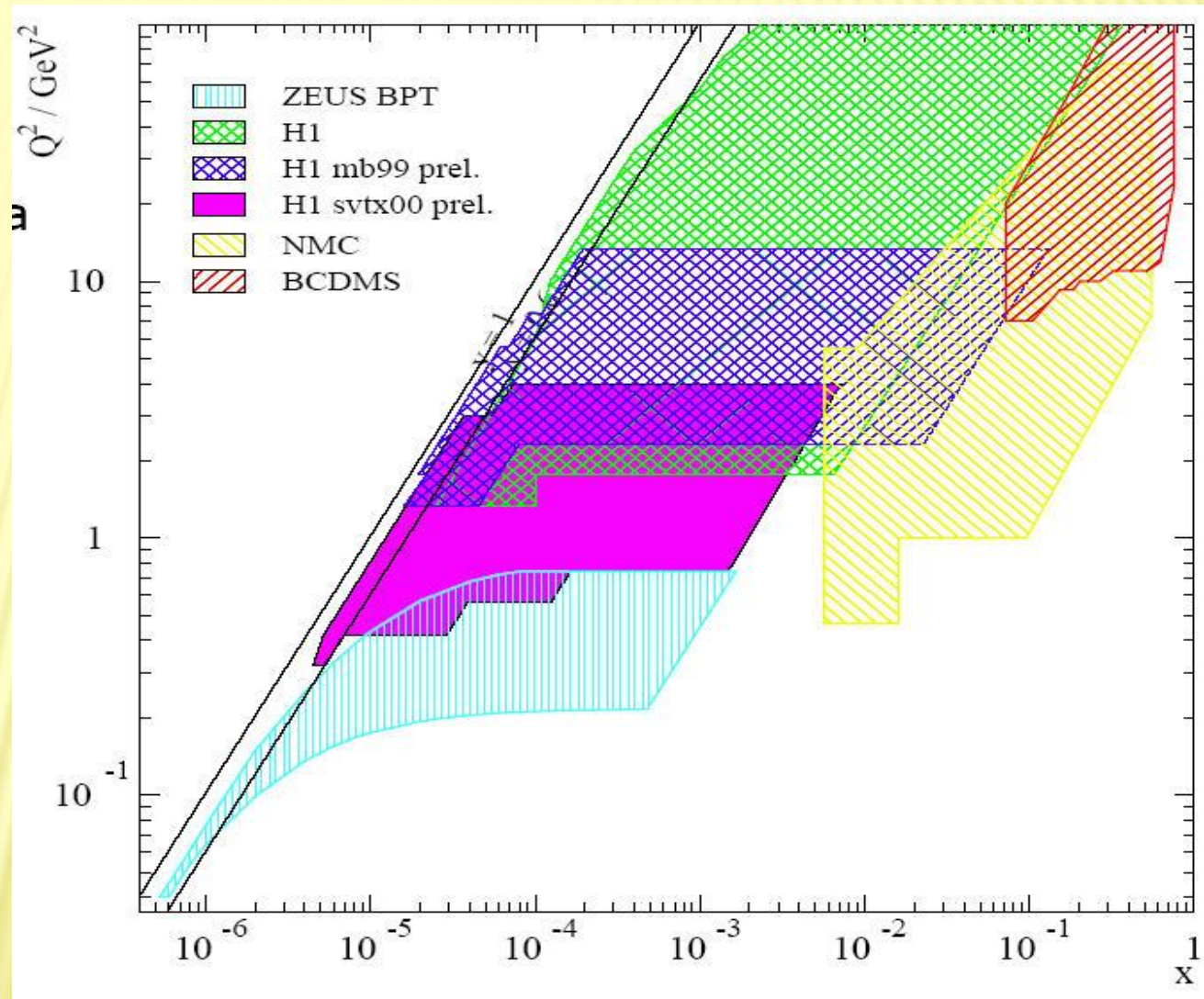
x - Q^2 plane

Regions
covered by

Structure
Function
measurements

in **DIS**
experiments

at low Q^2



Nowadays
there are new
measurements

at low Q^2

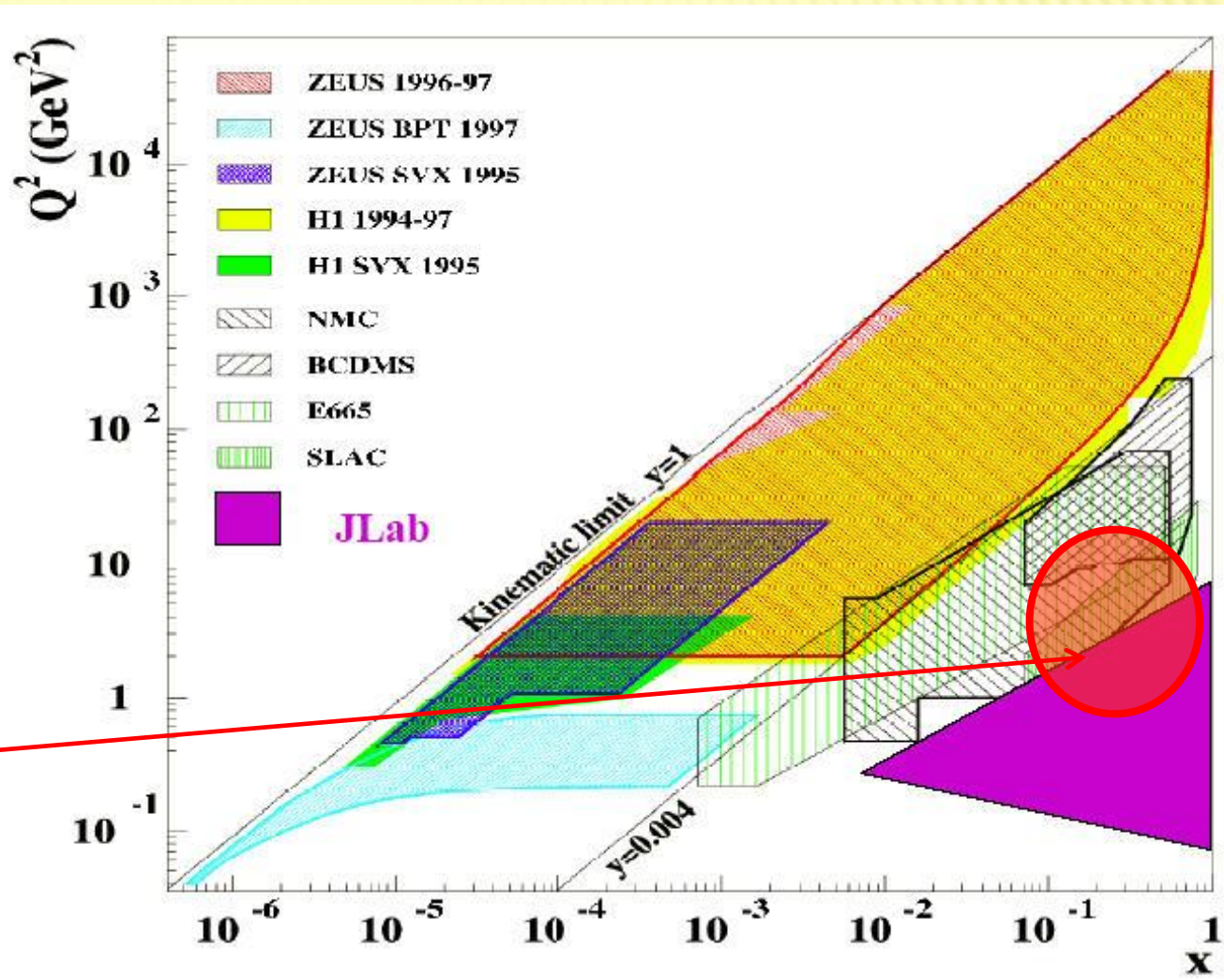
at JLab

$0.1 < Q^2 < 8.0 \text{ GeV}^2$

for PANDA

$0.05 < x < 0.7$

$1 < Q^2 < 5.3 \text{ GeV}^2$



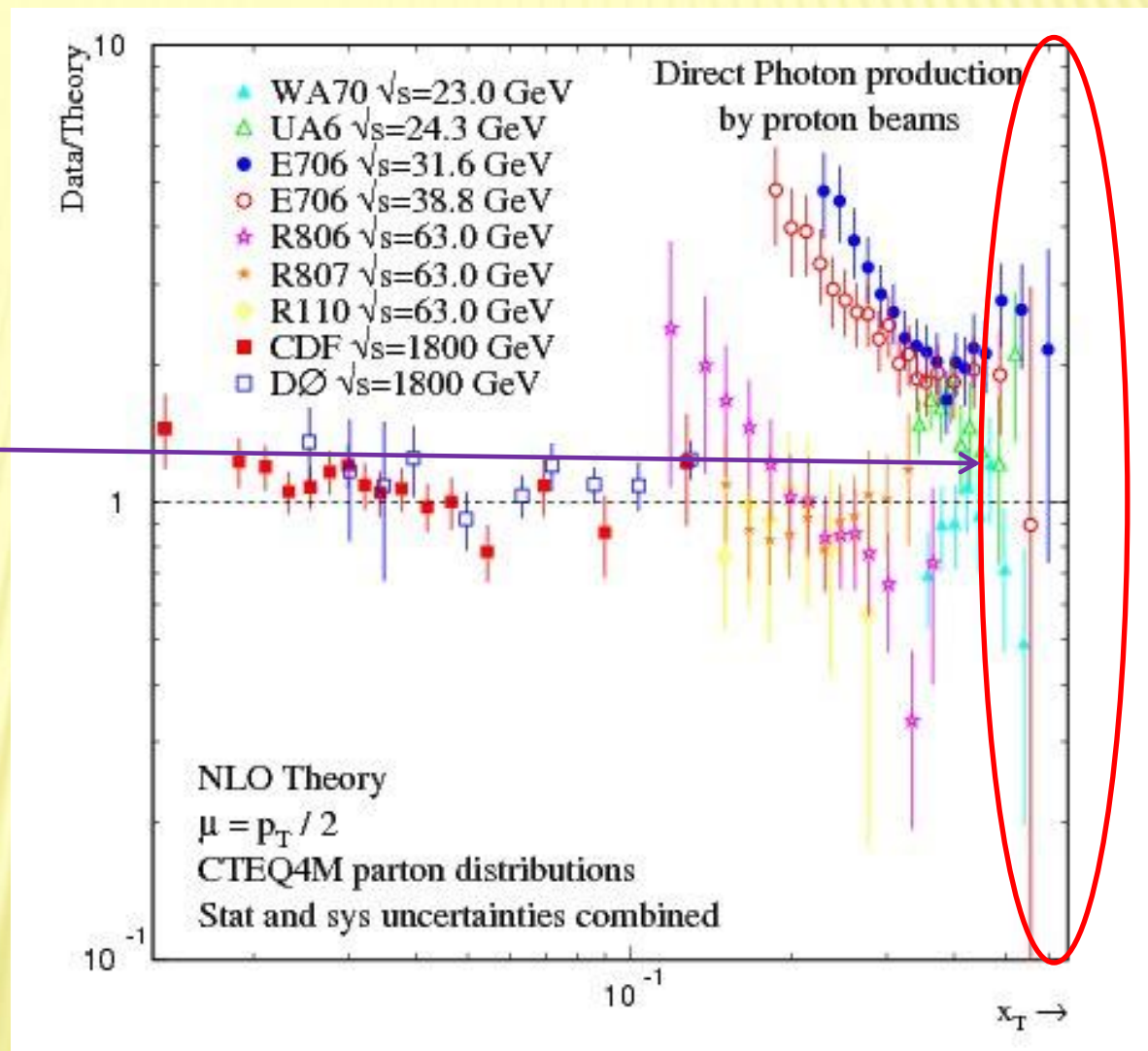
$$X_T = 2p_T / \sqrt{s}$$

for PANDA

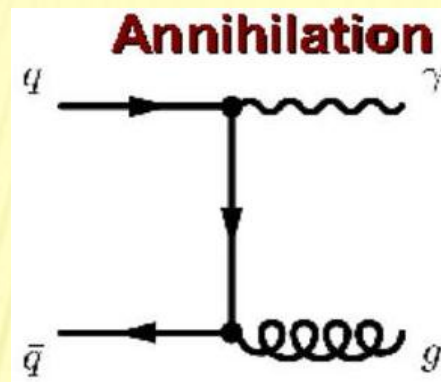
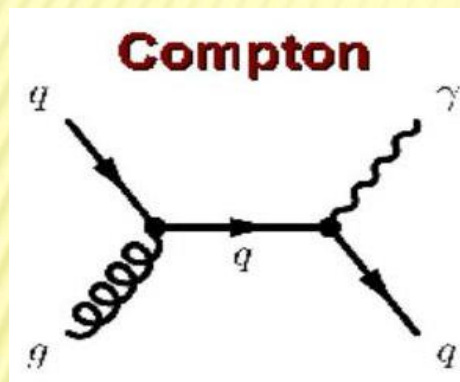
$$0.39 < X_T < 0.85$$

(with account of further
background restrictions)

and possibly higher for the
smaller E_{beam}
(and correspondingly \sqrt{s})



The $p\bar{p} + p \rightarrow \text{gamma} + X$ process (different to DIS scattering) is mainly defined by **LO QCD** diagrams:

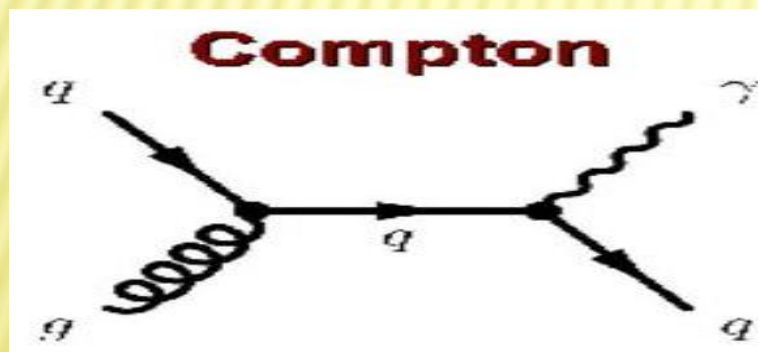


The “**QCD Compton**” diagram contribution makes **the cross section of $p\bar{p} + p \rightarrow \text{gamma} + X$** process to be sensitive to the gluon distribution $g(x, Q^2)$.

The hadrons are build of quarks which are interconnected by gluons. None of them can be detected as the final states of hadron-hadron or lepton-hadron collisions due to the so called "partons confinement". Nowadays, the physics deals mainly with the structure functions which model the distributions of partons in hadrons.

The information about such structure functions is extracted from the experimentally measured cross sections (defined as the ratio of the Number of events to the beam Luminosity, i.e. N_{ev} / Lum) by fitting the parameters of different models of structure functions to the cross sections data.

The contributions of both diagrams to the total cross section



Cross Sections

Total: $\sigma = 2.34 \cdot 10^{-3} \text{ mb}$

$q + q\text{bar} \rightarrow \text{gluon} + \gamma$ (65%)
 $\sigma = 1.53 \cdot 10^{-3} \text{ mb}$

$\text{gluon} + q \rightarrow q + \gamma$ (35%)
 $\sigma = 8.18 \cdot 10^{-4} \text{ mb}$

$\text{gluon} + \text{gluon} \rightarrow \text{gluon} + \gamma$
 (0.09%)
 $\sigma = 2.3 \cdot 10^{-7} \text{ mb}$

At the maximum luminosity one can expect up to 4×10^9 signal events per year.

Simulation of photon kinematical characteristics was done with use of PandaRoot (oct14) & Geant 4 (presented by pink histograms) with the initial set of **10 000 events** simulated by PYTHIA6.4 for the case of beam energy $E_{\text{beam}} = 15 \text{ GeV}$.

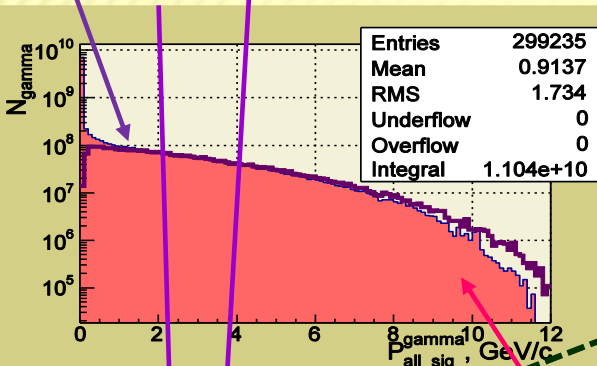


The corresponding initial distributions done with use of the PYTHIA6.4 alone are superimposed for comparison (violet line).

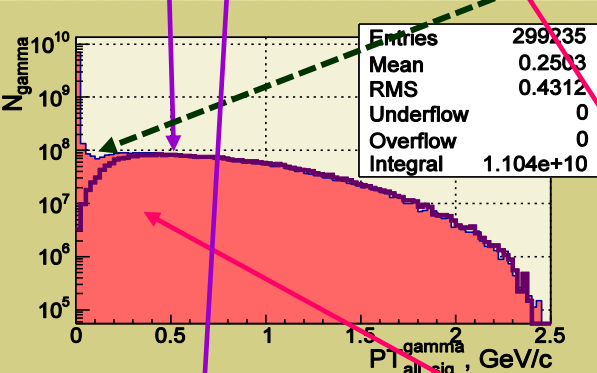


The following kinematical distributions over different variables will show the number of produced signal photons per year (supposing the full year of operation with the highest luminosity $2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$)

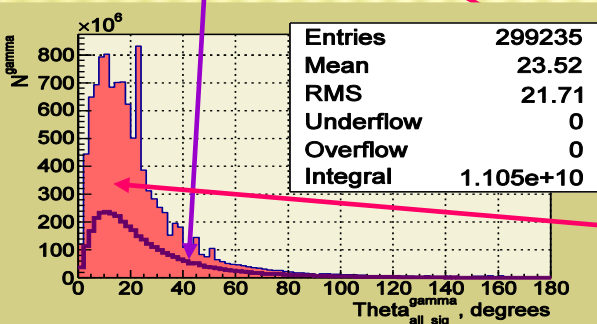
PYTHIA6.4



Py



PTy



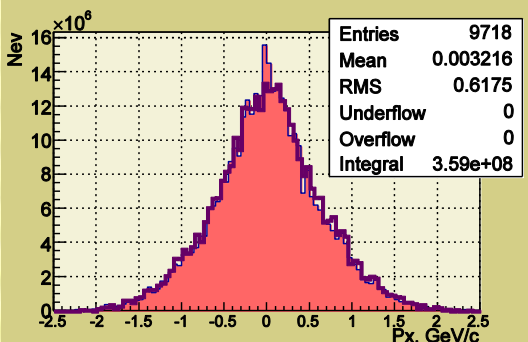
Theta

The kinematical distributions in the logarithmic scale of *all the produced photons* in signal events show significant excess of their number over initially generated photons in the region of very low momentum components and some loss of events in the region of highest momentum $P > 8 \text{ GeV/c}$.

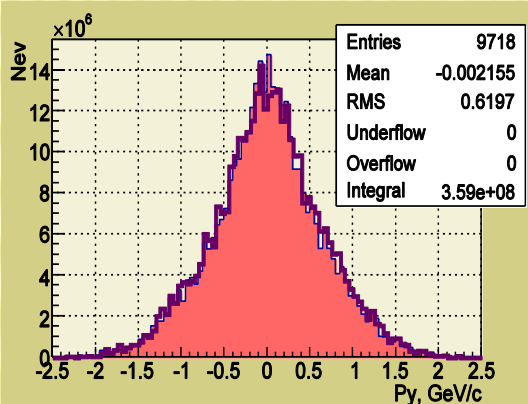
The first can be explained by the production of a big amount of secondary photons as a result of interaction of the particles with detector volume and some hadron decays.

Angle θ distribution follows the initial one with the excess in the number of particles.

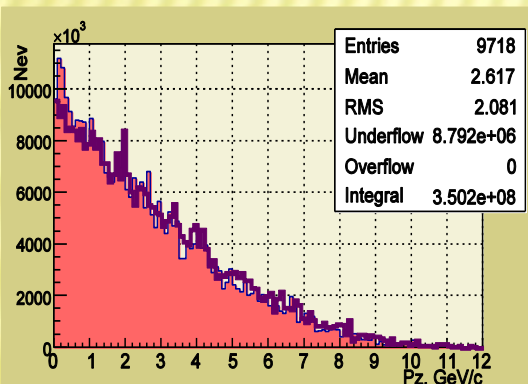
PANDARoot & Geant4



P_x



P_y



P_z

Here are presented the distributions of the signal photons with $P > 0.1$ GeV.

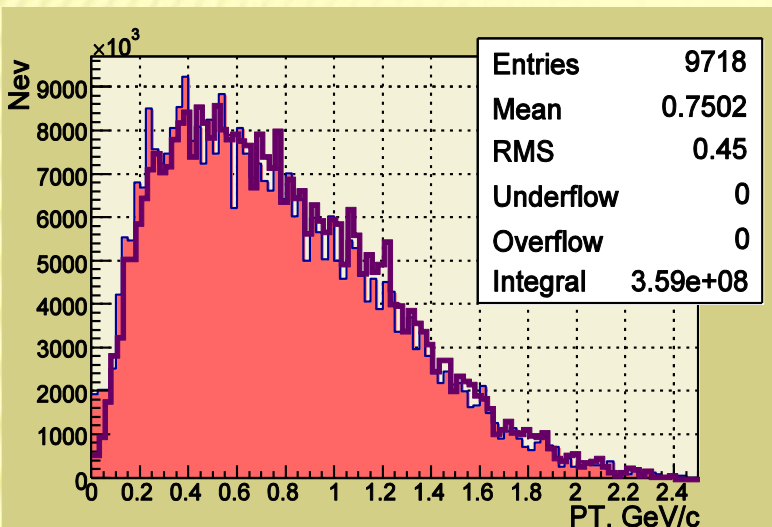
The number of such the “registered” photons is 9718 for generated 10000, i.e. **97.18%**.

These distributions in general follow the initial distributions of the photon, obtained at the level of PYTHIA simulation, except some excess of the number of the photons in the region of the low momentum components

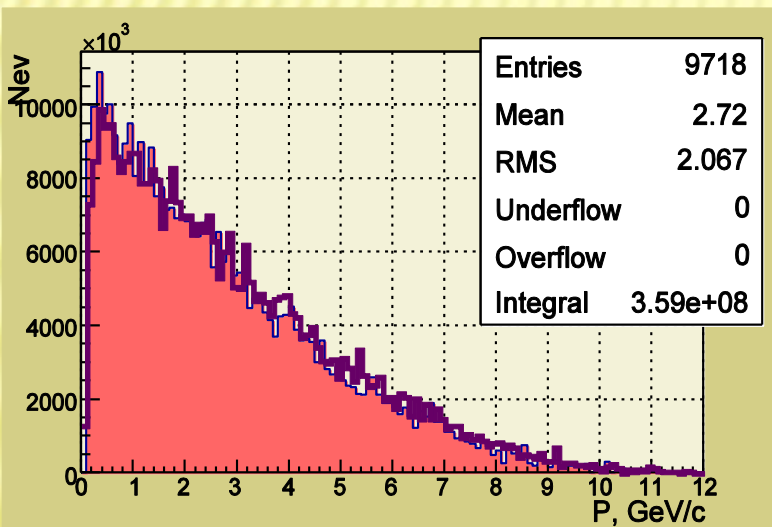
$P_x (P_y) < 0.1$ GeV/c, $P_z < 0.5$ GeV/c.

$-2.5 \leq P_x, P_y \leq 2.5$ GeV/c

$P_z \leq 11.6$ GeV/c, $\langle P_z \rangle = 2.62$ GeV/c



PT γ



P γ

Distributions of the signal photons with the momentum $P > 0.1$ GeV/c.

PandaRoot distributions practically coincide with Pythia histograms, except

some small excess of the number of final photons from PandaRoot simulation in the region of

$PT\gamma < 0.1$ GeV/c

&

some negligible loss of events.

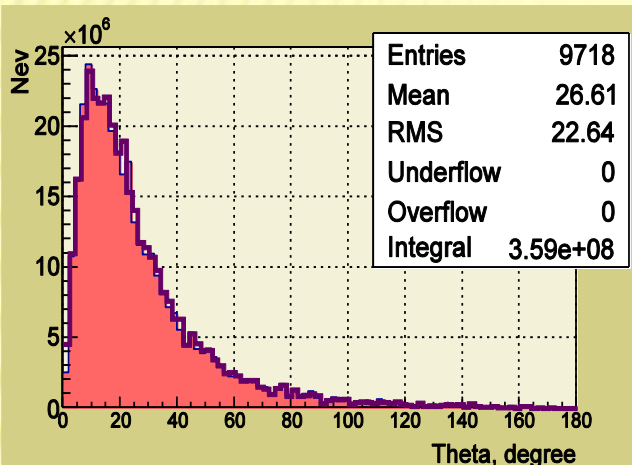
$0 \leq PT\gamma \leq 2.4$ GeV/c,

$\langle PT\gamma \rangle = 0.76$ GeV /c

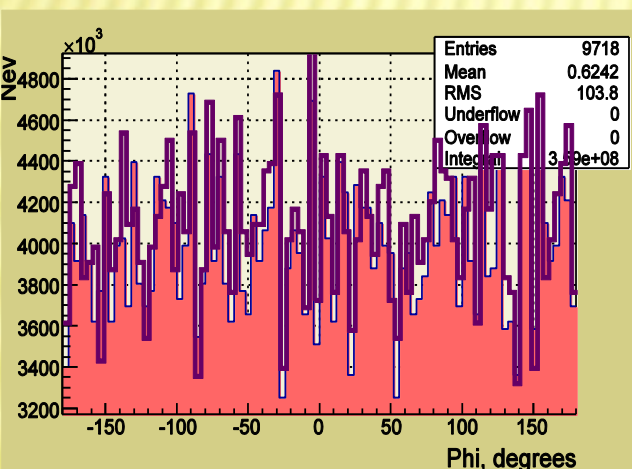
$0 \leq P\gamma \leq 11$ GeV/c,

$\langle P\gamma \rangle = 2.72$ GeV /c

Polar angle θ



Azimuth angle φ



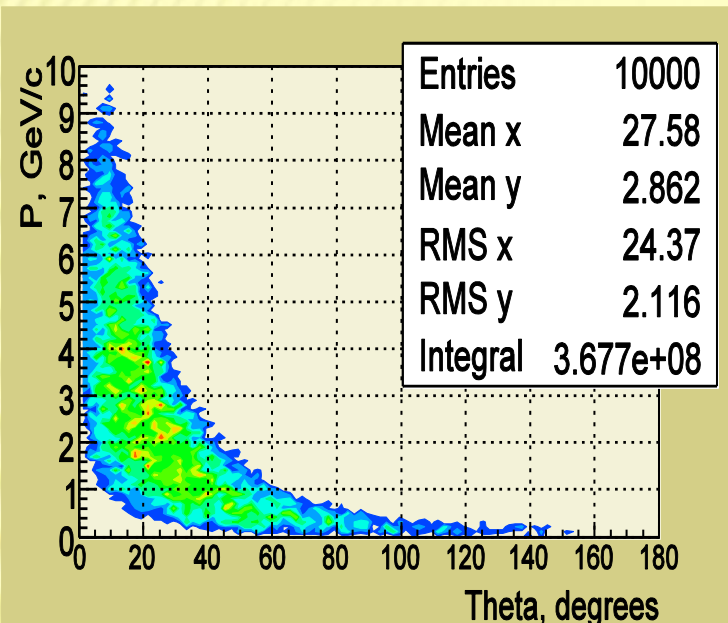
Distributions of the signal photons over the polar angle θ (top) and azimuth angle φ (bottom).

Both of the distributions mainly repeat the initial distributions, obtained by PYTHIA.

- For the polar angle θ the distribution shows
- the evident prevalence in the region of $5^\circ < \theta < 40^\circ$ &
 - complete loss of the signal (visible on the logarithmic scale) in the regions of $142^\circ < \theta < 148^\circ$ and $164^\circ < \theta$.

$$0 \leq \theta \leq 180 \text{ degrees, } \langle \theta \rangle = 26.6 \text{ degree}$$

With account of the statistical errors, the distribution over the azimuth angle φ has the uniform character.



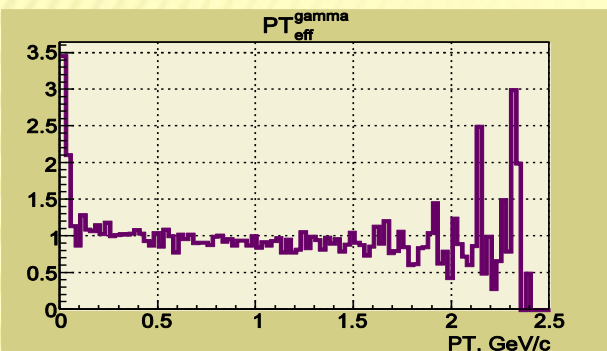
The Figure shows the projection of 3-D correlation distribution of the number of the signal photons over their full momentum P and polar angle θ .

The maximum of the distribution of the number of events belongs to the region of $0.1 < P < 4 \text{ GeV/c}$ over the full momentum and $10^\circ < \theta < 40^\circ$ over the polar angle.

The next slide will demonstrate the efficiencies of prompt photon registration over different kinematical variables.

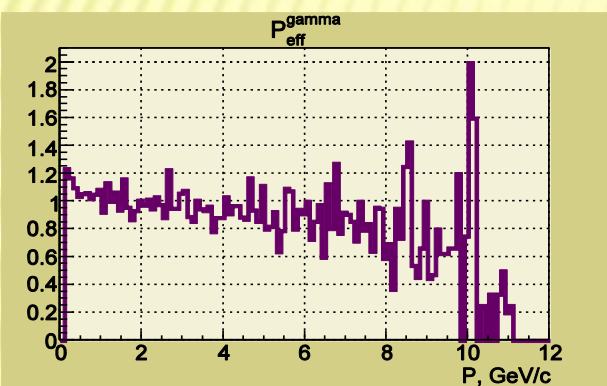
Registration efficiency Eff is calculated as a ratio of the number of the photons “registered” in a definite momentum and angle region while modeling *in PandaRoot* to the ones initially generated in the same momentum region *in PYTHIA*.

P, PT & θ REGISTRATION EFFICIENCY OF THE SIGNAL γ



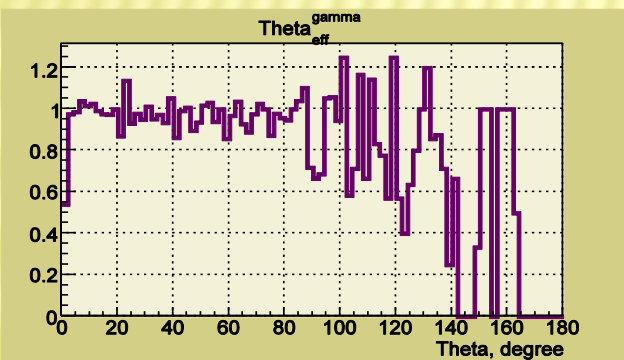
PT_{γ}^{eff}

From the upper plot one can see that at the **low values of $PT_{\gamma} < 0.1 \text{ GeV/c}$** , the registration efficiency over the transverse momentum is $Eff_{PT}^{\gamma} > 1$, that can be caused by the production of some additional low energetic γ in a result of interaction with the detector environment. At the **higher transverse moment values $0.1 < PT_{\gamma} < 2.4 \text{ GeV/c}$** the registration efficiency with account of the statistical errors is about $Eff_{PT}^{\gamma} \approx 0.9$ and stops at **$PT = 2.4 \text{ GeV/c}$** .



P_{γ}^{eff}

The middle plot of the registration efficiency over the full momentum shows that at **$P < 0.5 \text{ GeV/c}$** the registration efficiency $Eff_P^{\gamma} > 1$, that can be explained by the reason described above. Meanwhile at **$0.8 < P_{\gamma} < 6.5 \text{ GeV/c}$** the efficiency of the registration, with taking in account the statistical errors, is about $Eff_P^{\gamma} \approx 0.9$, after that it falls practically linearly up to $Eff_P^{\gamma} = 0.3$ at the value of **$P_{\gamma} = 11 \text{ GeV/c}$** .



$\theta_{\gamma}^{\text{eff}}$

The bottom plot of the registration efficiency over the polar angle θ shows the value close to $Eff_{\theta}^{\gamma} \approx 0.97$ in the region of **$\theta < 90^{\circ}$** , after that it is falling down up to $Eff_{\theta}^{\gamma} \approx 0.7$ with the clear gap ($Eff_{\theta}^{\gamma} = 0$) in the region of **$142^{\circ} < \theta < 148^{\circ}$** . At **$\theta > 164^{\circ}$** the efficiency $Eff_{\theta}^{\gamma} = 0$.

Process

Cross section, mb

×	95	Low-pT scattering	3. 368 E+ 01
×	92	Single diffractive (XB)	1. 719 E+ 00
×	93	Single diffractive (AX)	1. 719 E+ 00
×	94	Double diffractive	2. 479 E- 01
×	28	$f + g \rightarrow f + g$	1. 670 E- 02
×	11	$f + f' \rightarrow f + f'$ (QCD)	8. 756 E- 03
×	68	$g + g \rightarrow g + g$	4. 887 E- 03
×	12	$f + \bar{f} \rightarrow f' + \bar{f}$	1. 111 E- 03
×	13	$f + \bar{f} \rightarrow g + g$	1. 074 E- 03
×	53	$g + g \rightarrow f + \bar{f}$	1. 296 E- 04

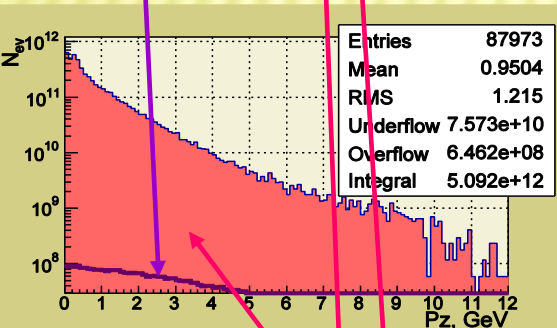
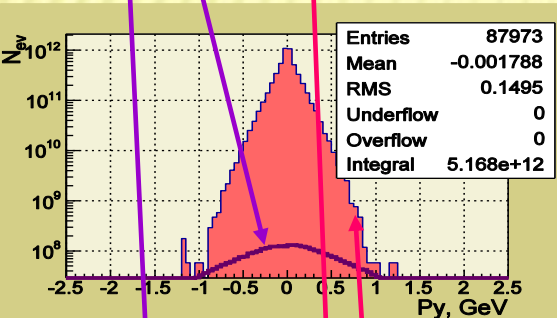
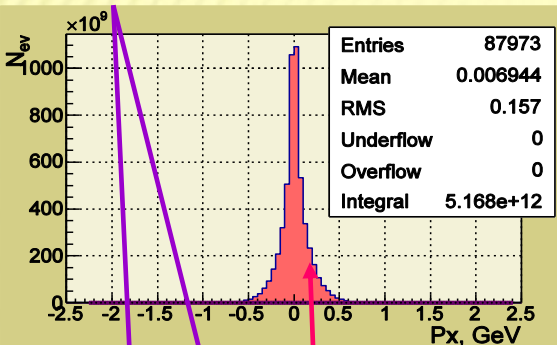
Signal processes - *total cross section is 4 order less than the cross section of “minimum-bias” processes*

×	14	$f + \bar{f} \rightarrow g + \gamma$	1. 533 E- 03
×	29	$f + g \rightarrow f + \gamma$	8. 181 E- 04
×	115	$g + g \rightarrow g + \gamma$	2. 280 E- 07

According to predictions of Monte-Carlo generator PYTHIA6.4 the total cross section at the energy of antiproton beam $E_{\text{beam}} = 15$ GeV for the processes of the leading photon is **2.35×10^{-3} mb**. At the same time the total cross section for the background processes is **37.4 mb**.

Thus the initial ratio of the signal to background is **$S/B = 6.283 \times 10^{-5}$** and one signal event corresponds to about **16000** background ones.

P_x, P_y, P_z distributions from 10^5 mini-bias background events



Background

Pink histograms - photon distributions of the hardest photons from background events.

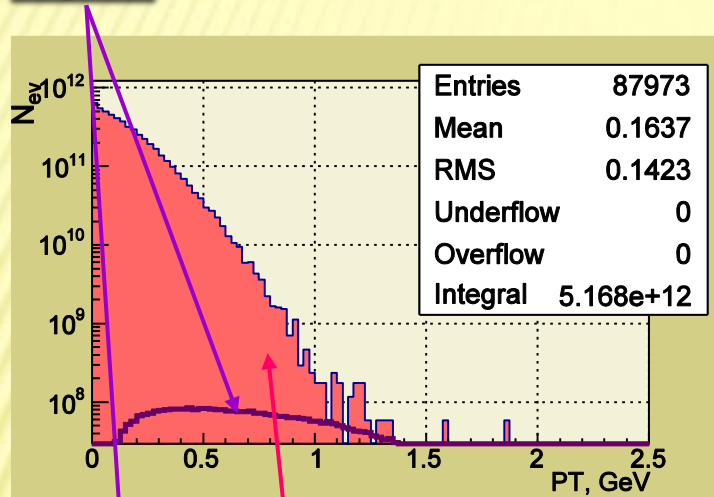
P_x Violet lines on the same pictures for comparison – photons distributions from signal events with account of the corresponding cross sections

As the distributions over P_x and P_y are identical to each other, for comparison the distributions over P_x are done in linear and P_y – in logarithmic scale.

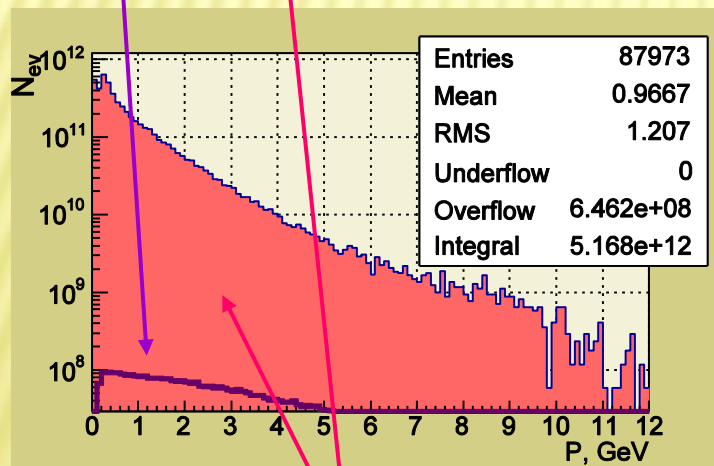
The values of the transverse momenta P_x and P_y of the *background photons* coincide with the corresponding values of the *signal photons* with a clear tendency – **the lower the value of transverse momentum, - the higher order of magnitude is the suppression of the signal by the background.**

P_z From the distributions over the longitudinal components of momentum P_z it is seen that the values of the corresponding components of the background photons strongly overlap the signal ones.

Signal



PT



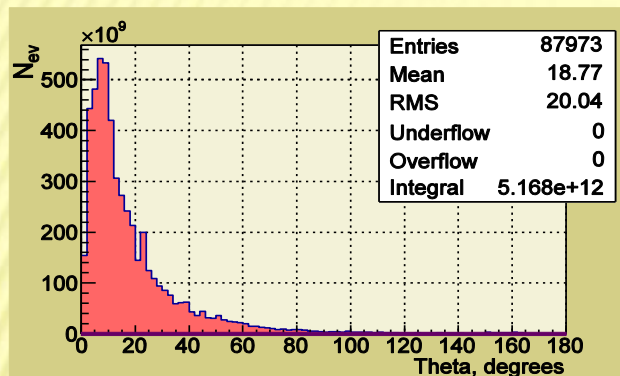
P

Background

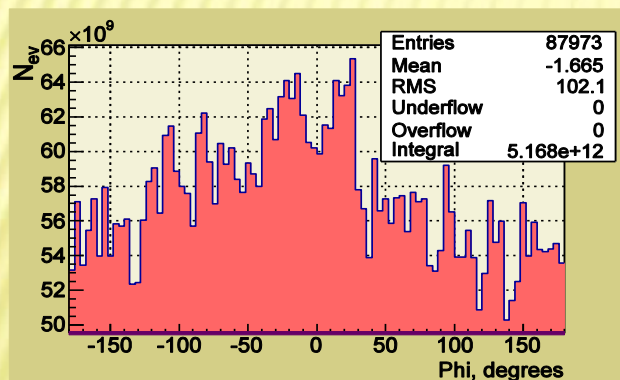
Comparative distributions of the signal and background photons over their transverse momentum PT and full momentum P

The *values of the transverse momentum PT* of the background photons do coincide with the corresponding ones of the signal photons. Obviously - the lower the value of transverse momentum, the higher order of magnitude is the suppression of the signal by the background.

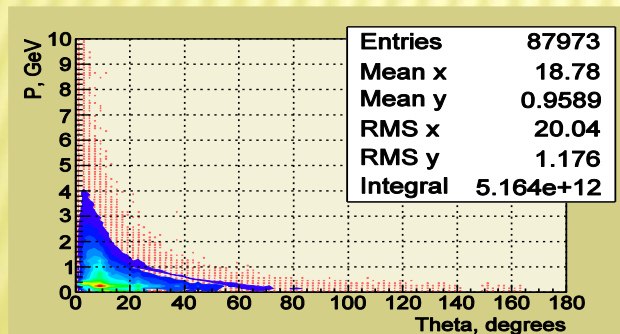
From the distributions over the *full momentum P* it is seen that the *values* of the corresponding components of the background photons strongly overlap the signal ones.



Distribution of the number of background photons over their polar angle θ shows that the most part of them are produced at the angles $5^\circ < \theta < 20^\circ$.



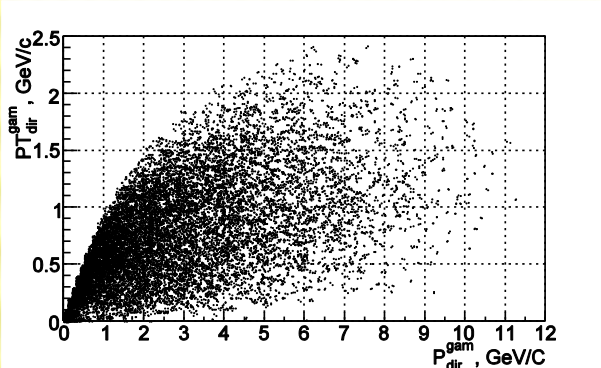
Distribution over the azimuth angle φ , with account of statistics, shows relatively uniform character with some prevalence in direction of $-30^\circ < \varphi < 30^\circ$.



Two-dimensional plot of background photons distributions over their momentum P_T and polar angle θ shows that the most energetic photons fly predominantly in the forward direction, while the rest ones are spread at the angles $\theta < 80^\circ$ and more.

The correlative distributions over transverse momentum PT^γ (x axis) and full momentum P^γ (y axis) show the influence of kinematical restriction on the leading photon. From these distributions one can see, that the *values of the full photon momentum P^γ* are placed at the same range both for the signal and the background. Thus the use of single momentum P separation criterion obviously **will not help** for background suppression, that is shown in the table below.

direct photon



background photon

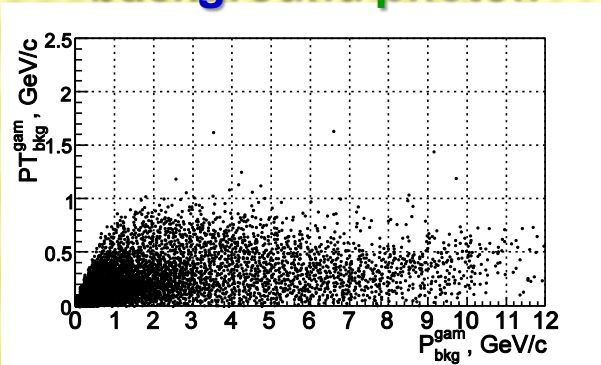


Table 1. Selection by the full momentum P^γ together with the transverse momentum criterion $PT^\gamma > 0.5 \text{ GeV}$

Criterion	Efficiency for background, %	Efficiency for the signal, %	Signal to background ratio S/B
$P_{\text{gamma}} > 0.5 \text{ GeV}$	17.76	80.41	2.845×10^{-4}
$P_{\text{gamma}} > 1.0 \text{ GeV}$	12.62	69.44	3.457×10^{-4}
$P_{\text{gamma}} > 1.5 \text{ GeV}$	8.883	59.55	4.212×10^{-4}
$P_{\text{gamma}} > 2.0 \text{ GeV}$	6.292	50.59	5.046×10^{-4}
$P_{\text{gamma}} > 2.5 \text{ GeV}$	4.442	42.45	6.004×10^{-4}
$P_{\text{gamma}} > 3.0 \text{ GeV}$	3.185	35.19	6.942×10^{-4}
$P_{\text{gamma}} > 3.5 \text{ GeV}$	2.321	28.74	7.780×10^{-4}
$P_{\text{gamma}} > 4.0 \text{ GeV}$	1.733	23.31	8.452×10^{-4}
$P_{\text{gamma}} > 4.5 \text{ GeV}$	1.333	18.52	8.729×10^{-4}
$P_{\text{gamma}} > 5.0 \text{ GeV}$	1.041	14.45	8.722×10^{-4}

But over transverse momentum PT^γ they are overlapped not completely that can be used for signal and background separation

Table 2. Selection by the transverse momentum PT_{γ}

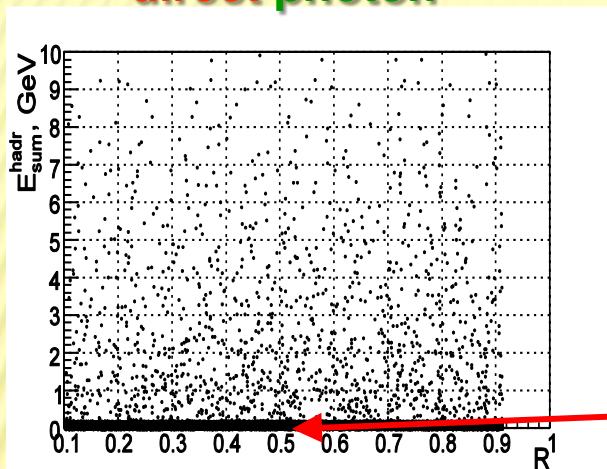
Criterion	Efficiency for background, %	Efficiency for the signal, %	Signal to background ratio S/B
$PT_{\gamma} > 0.25 \text{ GeV}$	19.825	85.19	2.700×10^{-4}
$PT_{\gamma} > 0.3 \text{ GeV}$	13.753	81.01	3.701×10^{-4}
$PT_{\gamma} > 0.4 \text{ GeV}$	6.212	71.94	7.277×10^{-4}
$PT_{\gamma} > 0.5 \text{ GeV}$	2.619	63.01	1.512×10^{-3}
$PT_{\gamma} > 0.6 \text{ GeV}$	1.053	54.47	3.250×10^{-3}
$PT_{\gamma} > 0.7 \text{ GeV}$	0.408	46.55	7.169×10^{-3}
$PT_{\gamma} > 0.8 \text{ GeV}$	0.150	39.06	1.636×10^{-2}
$PT_{\gamma} > 0.9 \text{ GeV}$	0.056	32.46	3.642×10^{-2}
$PT_{\gamma} > 1.0 \text{ GeV}$	0.023	26.42	7.218×10^{-2}
$PT_{\gamma} > 1.1 \text{ GeV}$	0.011	20.94	1.196×10^{-1}
$PT_{\gamma} > 1.2 \text{ GeV}$	0.0055	16.32	1.864×10^{-1}
$PT_{\gamma} > 1.3 \text{ GeV}$	0.00325	12.56	2.428×10^{-1}
$PT_{\gamma} > 1.4 \text{ GeV}$	0.00205	9.46	2.899×10^{-1}
$PT_{\gamma} > 1.5 \text{ GeV}$	0.00155	6.91	2.801×10^{-1}
$PT_{\gamma} > 1.6 \text{ GeV}$	0.00115	4.83	2.639×10^{-1}
$PT_{\gamma} > 1.7 \text{ GeV}$	0.00090	3.26	2.275×10^{-1}
$PT_{\gamma} > 1.8 \text{ GeV}$	0.00065	2.08	2.011×10^{-1}
$PT_{\gamma} > 1.9 \text{ GeV}$	0.00035	1.26	2.262×10^{-1}
$PT_{\gamma} > 2.0 \text{ GeV}$	0.00025	0.73	1.835×10^{-1}

$PT_{\gamma} \text{ cut} > 1.1 \text{ GeV}$

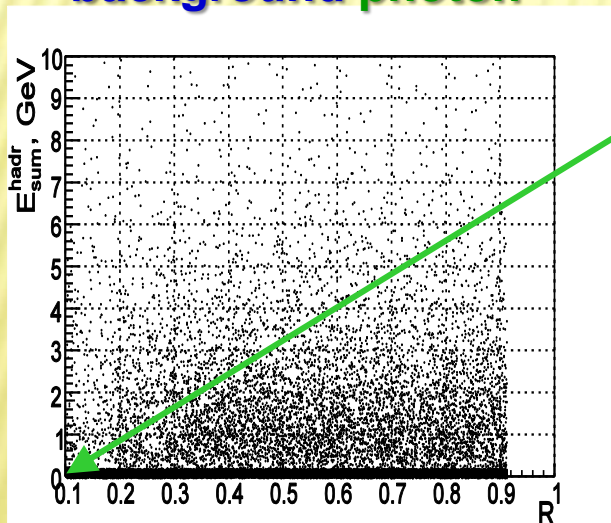
doesn't influence much on S/B ratio and doesn't have physical sense since it rejects strongly the signal.

The used statistics is 2000000 events generated in Pandaroot

direct photon



background photon



Different kind of taken separately isolation criteria were considered. It was determined that the best suppression of background events gives the criterion of events selection with the summarized energy $E_{\text{sum}} < 0.25 \text{ GeV}$ of all the charged particles inside the cone of radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$ in $\eta - \phi$ space around the leading photon momentum direction

(here $\Delta\phi = \phi_1 - \phi_2$ is the difference between the azimuth angles of the photon and the charged particle, $\Delta\eta = \eta_1 - \eta_2$ is the difference of the pseudorapidities of the photon and the charged particles).

Such a criterion allows to **suppress 47.8% of background** with **the loss of only 6% of the signal**.

Axis **x**: R (0.1, 0.2...0.9) – radius of the cone around direction of the leading photon momentum.

Axis **y**: E_{sum} - summarized energy of all the charged particles inside this cone.

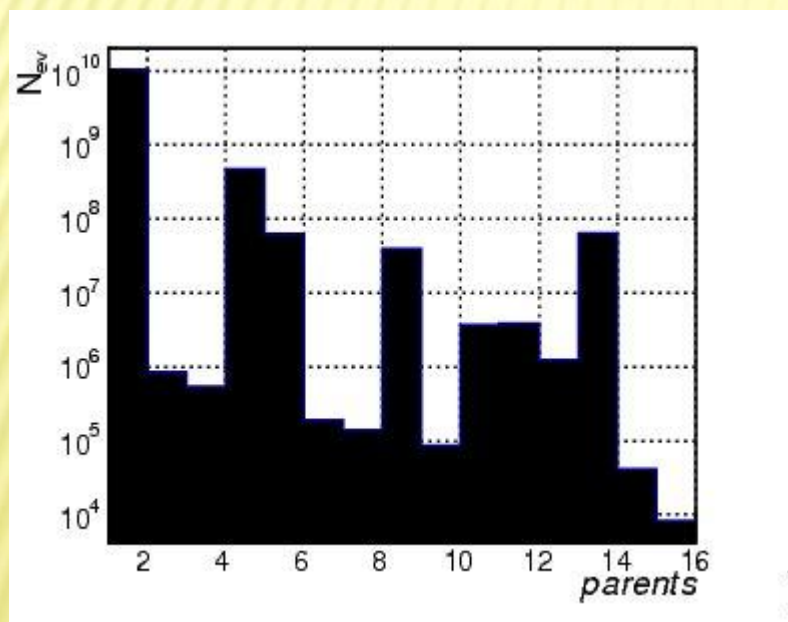
Table 3. Selection by the transverse momentum PT_{γ} together with the isolation criterion $E_{sum} < 0.25$ GeV in the cone with the radius $R=0.5$

Criterion	Efficiency for background, %	Efficiency for the signal, %	Signal to background ratio S/B
$PT_{\gamma} > 0.25$ GeV	13.717	83.41	3.821×10^{-4}
$PT_{\gamma} > 0.3$ GeV	9.774	79.51	5.111×10^{-4}
$PT_{\gamma} > 0.4$ GeV	4.650	70.95	9.587×10^{-4}
$PT_{\gamma} > 0.5$ GeV	2.038	62.34	1.922×10^{-3}
$PT_{\gamma} > 0.6$ GeV	0.848	54.02	4.003×10^{-3}
$PT_{\gamma} > 0.7$ GeV	0.333	46.27	8.731×10^{-3}
$PT_{\gamma} > 0.8$ GeV	0.123	38.86	1.985×10^{-2}
$PT_{\gamma} > 0.9$ GeV	0.048	32.31	4.229×10^{-2}
$PT_{\gamma} > 1.0$ GeV	0.017	26.33	9.732×10^{-2}
$PT_{\gamma} > 1.1$ GeV	0.0085	20.88	1.543×10^{-1}
$PT_{\gamma} > 1.2$ GeV	0.0043	16.28	2.379×10^{-1}
$PT_{\gamma} > 1.3$ GeV	0.0023	12.54	3.426×10^{-1}
$PT_{\gamma} > 1.4$ GeV	0.00155	9.44	3.827×10^{-1}
$PT_{\gamma} > 1.5$ GeV	0.00120	6.89	3.607×10^{-1}
$PT_{\gamma} > 1.6$ GeV	0.00080	4.82	3.785×10^{-1}
$PT_{\gamma} > 1.7$ GeV	0.00060	3.26	3.414×10^{-1}
$PT_{\gamma} > 1.8$ GeV	0.00050	2.08	2.614×10^{-1}
$PT_{\gamma} > 1.9$ GeV	0.00035	1.26	2.262×10^{-1}
$PT_{\gamma} > 2.0$ GeV	0.00005	0.73	9.174×10^{-2}

The analysis of the given pictures and tables shows that among all the possible kinematical variables the most effective is the selection of events by the transverse momentum PT of the leading photon together with the use of isolation criterion. These criteria allow to achieve the background suppression up to 50000 times and to get the signal to background ratio at the level of $S/B = 0.36$ at the restrictive condition for $PT_{\gamma} > 1.5$ GeV, that is nevertheless is not enough for the signal separation

The rest of the background can be rejected by calculation of invariant masses of the mesons, which can produce those background photons.

Their proportion distribution (for the signal events) according to Lund fragmentation model implemented in PYTHIA:



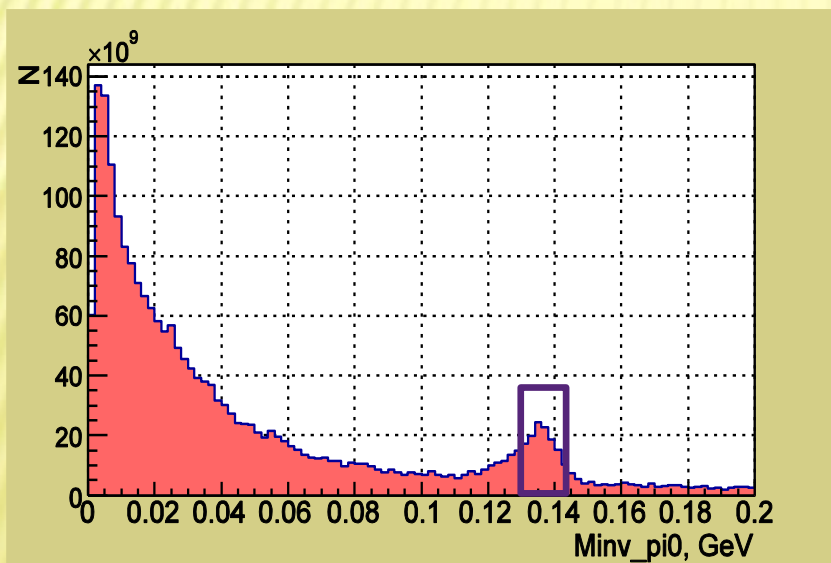
Bin number	Name of γ 's parent particle
1	π^0
2	ρ^0
3	ρ^+
4	η
5	ω
6	K^{*0}
7	K^{*+}
8	η'
9	ϕ
10	Δ^0
11	Δ^+
12	Λ^0
13	Σ^0
14	Σ^+
15	Ξ^0

The similar picture is expected for the backgrounds

98.8% $\pi^0 \rightarrow \gamma\gamma$

1.2% $\pi^0 \rightarrow \gamma e^+e^-$

Distribution of 2γ invariant mass, where the 1st γ is the one with the highest P in event.



Supposing **0.130 GeV** < π^0 mass < **0.145 GeV**, according to GEANT fragmentation, the number of background events, where the most energetic γ originates from π^0 decay is about 45% (without any other cuts). Thus S/B improves by a factor of 1.8.

Namely, the final results are:

Table 4. Selection by the transverse momentum $PT_{\gamma\text{gamma}}$ together with the *isolation criterion* $E_{\text{sum}} < 0.25 \text{ GeV}$ in the cone with the radius $R=0.5$

Criterion	Signal to background ratio S/B
$PT_{\gamma\text{gamma}} > 0.5 \text{ GeV}$	3.45×10^{-3}
$PT_{\gamma\text{gamma}} > 1.0 \text{ GeV}$	1.75×10^{-1}
$PT_{\gamma\text{gamma}} > 1.4 \text{ GeV}$	0.69

Analogous study can be done for the other kind of meson decays

Conclusion

The simulation with PYTHIA6.4 & PandaRoot (with Geant4) has shown that at PANDA energy $E_{beam} = 15 \text{ GeV}$

1. We can separate the most part of fake and background photons contribution, which comes from decays of neutral pions and other mesons.
2. PANDA can make the measurement of proton structure functions in the regions of
 $1 < Q^2 = (P_T^\gamma)^2 < 5.3 \text{ GeV}^2$ and $0.05 < x < 0.7$
3. This measurement can have an advantage as it is very sensitive to gluon distribution.

- **Signal events:** comparison with PYTHIA8, CompHEP generators; separation of the fake photons
- **Background events:** comparison with PYTHIA8, DPM generators; study of the contribution of the other different meson decays

& Recalculation with the latest PandaRoot version

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THANKS FOR YOUR ATTENTION !