«FEASIBILITY STUDY OF DIRECT PHOTON PRODUCTION AT FAIR»

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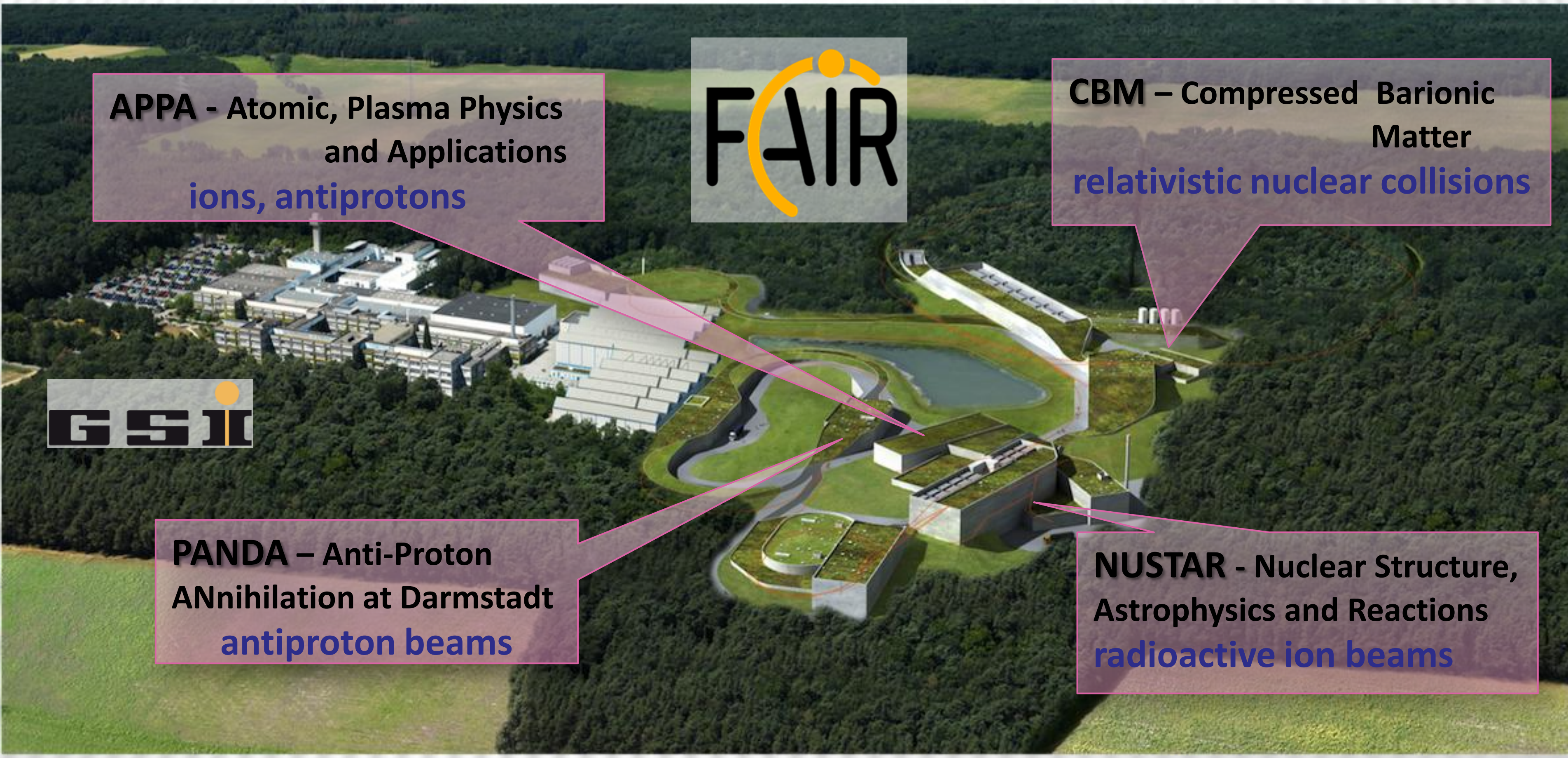
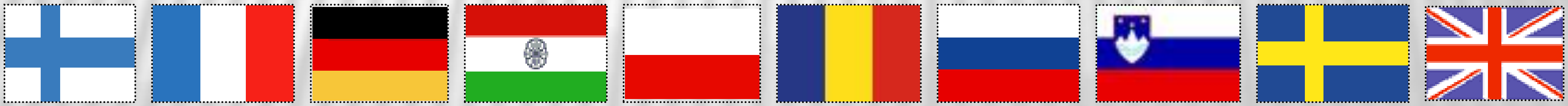
THE FAIR PROJECT





ROADMAP EXPERIMENTS AND INTEGRATED PROJECT TIME SCHEDULE: FAIR BUILDINGS, ACCELERATORS & EXPERIMENTS

	Name	Duration	Start	Finish
0	**Level 1 - FAIR Integrated Master Schedule**	**226,22 mons**	**08.08.2008**	**11.12.2025**
1	**FAIR Buildings**	**72,1 mons**	**08.06.2017**	**16.12.2022**
2	T110 SIS100	68,75 mons	08.06.2017	16.12.2022
11	G004 Transfer Building/T104N Transfer SIS100/T112N Trar	62,55 mons	29.11.2017	16.12.2022
20	G017A Cryo Compressor Building	43,25 mons	27.06.2019	16.12.2022
29	G017.1 Main Supply Building North	45,6 mons	23.04.2019	16.12.2022
36	G014 CBM/T112S Transfertunnel SIS100-CBM	48,75 mons	24.01.2019	16.12.2022
45	G004A Transfer Supply/T101 Transfer Line SIS18	30,4 mons	08.07.2020	16.12.2022
54	G018 SFRS/T103N Transfer SFRS-Experimente/T113N Tran	39 mons	24.10.2019	16.12.2022
64	G020 p-linac	26,5 mons	26.10.2020	16.12.2022
73	G017.2 Main Supply Building South/G006 SFRS HE-Cave/G	49,55 mons	17.12.2018	16.12.2022
88	G007 CR/T106 Transfer CR-HESR	47,55 mons	27.02.2019	16.12.2022
97	G009 HESR PANDA/T108 HESR	34,4 mons	18.03.2020	16.12.2022
107	G021 Storage	21,65 mons	01.04.2021	16.12.2022
114	G120 Supply Line	32,6 mons	07.05.2020	16.12.2022
120	**SIS100**	**174,17 mons**	**17.10.2011**	**20.02.2025**
121	SIS 100 procurement phase	128,25 mons	17.10.2011	13.08.2021
126	SIS 100 installation into tunnel, commissioning without beam phase	45,6 mons	31.12.2020	28.06.2024
132	SIS100 commissioning with beam	8,42 mons	28.06.2024	20.02.2025
135	**SuperFRS**	**143,92 mons**	**02.06.2014**	**12.06.2025**
136	SuperFRS procurement phase	114,45 mons	02.06.2014	09.03.2023
141	SuperFRS installation into tunnel, commissioning without beam	30,4 mons	06.10.2021	02.02.2024
148	SuperFRS commissioning with beam	17,67 mons	02.02.2024	12.06.2025
151	**pLINAC**	**192,43 mons**	**06.01.2011**	**08.10.2025**
152	pLinac procurement phase	138,2 mons	06.01.2011	11.08.2021
157	pLinac installation + commissioning with beam	15 mons	25.10.2021	16.12.2022
161	pLinac installation after HBO, commissioning with beam	36,63 mons	19.12.2022	08.10.2025
162	**p-bar separator**	**150,5 mons**	**05.09.2013**	**20.03.2025**
163	p-bar procurement phase	103,93 mons	05.09.2013	24.08.2021
168	p-bar installation into tunnel, commissioning without beam phase	34,34 mons	24.08.2021	10.04.2024
174	p-bar commissioning with beam	12,28 mons	10.04.2024	20.03.2025
177	**Collector Ring**	**183,57 mons**	**24.08.2011**	**18.09.2025**
178	CR procurement phase	134,85 mons	24.08.2011	24.12.2021
183	CR installation into tunnel, commissioning without beam	28,05 mons	16.06.2021	09.08.2023
188	CR commissioning with beam	27,51 mons	09.08.2023	18.09.2025
191	**HESR**	**218,02 mons**	**26.03.2009**	**11.12.2025**
192	HESR procurement phase	113,8 mons	26.03.2009	15.12.2017
197	HESR installation into tunnel, commissioning without beam	20,1 mons	18.11.2021	02.06.2023
203	HESR commissioning with beam	32,92 mons	02.06.2023	11.12.2025
206	**HEBT**	**138,77 mons**	**02.01.2014**	**22.08.2024**
207	HEBTprocurement phase	92,8 mons	02.01.2014	11.02.2021
224	HEBT installation and commissioning without beam	45,52 mons	25.02.2021	22.08.2024
240	**CBM**	**152,67 mons**	**08.07.2013**	**20.03.2025**
241	CBM procurement phase	130,25 mons	08.07.2013	30.06.2023
245	CBM installation and commissioning without beam	33,55 mons	01.12.2021	26.06.2024
250	CBM commissioning with beam	9,52 mons	26.06.2024	20.03.2025
253	**APPA**	**199,07 mons**	**16.12.2009**	**20.03.2025**
254	APPA procurement phase	172,65 mons	16.12.2009	10.03.2023
259	APPA installation into tunnel, commissioning without beam	36,6 mons	31.12.2020	20.10.2023
271	APPA commissioning with beam	18,42 mons	20.10.2023	20.03.2025
274	**NUSTAR**	**141,17 mons**	**15.09.2014**	**10.07.2025**
275	NUSTAR procurement phase	120 mons	15.09.2014	27.11.2023
278	NUSTAR installation into cave or tunnel phase	38,85 mons	17.06.2021	07.06.2024
288	NUSTAR commissioning with beam	14,17 mons	07.06.2024	10.07.2025
291	**PANDA**	**226,22 mons**	**08.08.2008**	**11.12.2025**
292	PANDA procurement phase	173,1 mons	08.08.2008	15.11.2021
297	PANDA installation and commissioning without beam	26,2 mons	19.10.2021	20.10.2023
303	PANDA commissioning with beam	27,92 mons	20.10.2023	11.12.2025

LEVEL_1

LEVEL_1

FAIR is in good shape for full completion by 2025.

Installation incl. commissioning of the experiments is planned during 2021-2024

GSI/FAIR Research Strategy towards 2025:

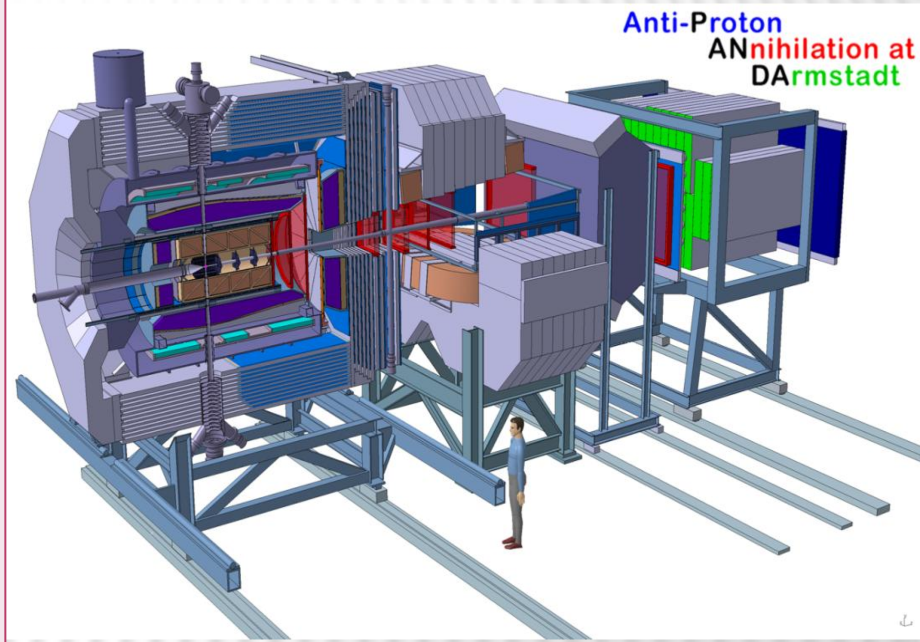
- **R&D for and construction of the FAIR experiments**
- **FAIR phase 0 – intermediate research program** bridging the construction phase from 2018 until commissioning of the FAIR accelerators and experiments.

THE PANDA DETECTOR

- $\bar{p}p$, $\bar{p}A$ collisions $p_{\bar{p}}$ = 1.5 – 15 GeV/c ,
  ($\sqrt{s}$ from 2.25 up to 5.46 GeV)
- $\bar{p}$ beam with unprecedented degree of monochromaticity $\delta p/p \le 4 \cdot 10^{-5}$
- Luminosity up to $2 \cdot 10^{32}$ $cm^{-2}s^{-1}$
- Capability to detect events with high rate (up to $2 \cdot 10^{7}$ s^{-1} interactions)
- Nearly 4π solid angle for large acceptance
- Tracking : ~50 μm vertex resolution
- Different PID techniques:
  $\pi^{\pm}$, $K^{\pm}$, $e^{\pm}$, $\mu^{\pm}$, γ identification

Photon detection from 10 MeV to 10 GeV

- Efficient event selection & good momentum resolution



It will continue and extend the successful physics program performed in the past at facilities like LEAR at CERN and the antiproton accumulator ring at FNAL

Previous experiments

First **pp -> γ + 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

Direct photon production (Dpp) has also been studied in pion-proton, pion-nucleus, proton-nucleus and in heavy-ion collisions, also at LEP and HERA

Motivation for studying Dpp in hadronic collisions

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

Motivation for studying dpp in hadronic collisions

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.

Our interests

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 ***pbar + p → γ + X process***

(choosing pbar 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 shall be shown below, at ***E_{beam} = 15 GeV***

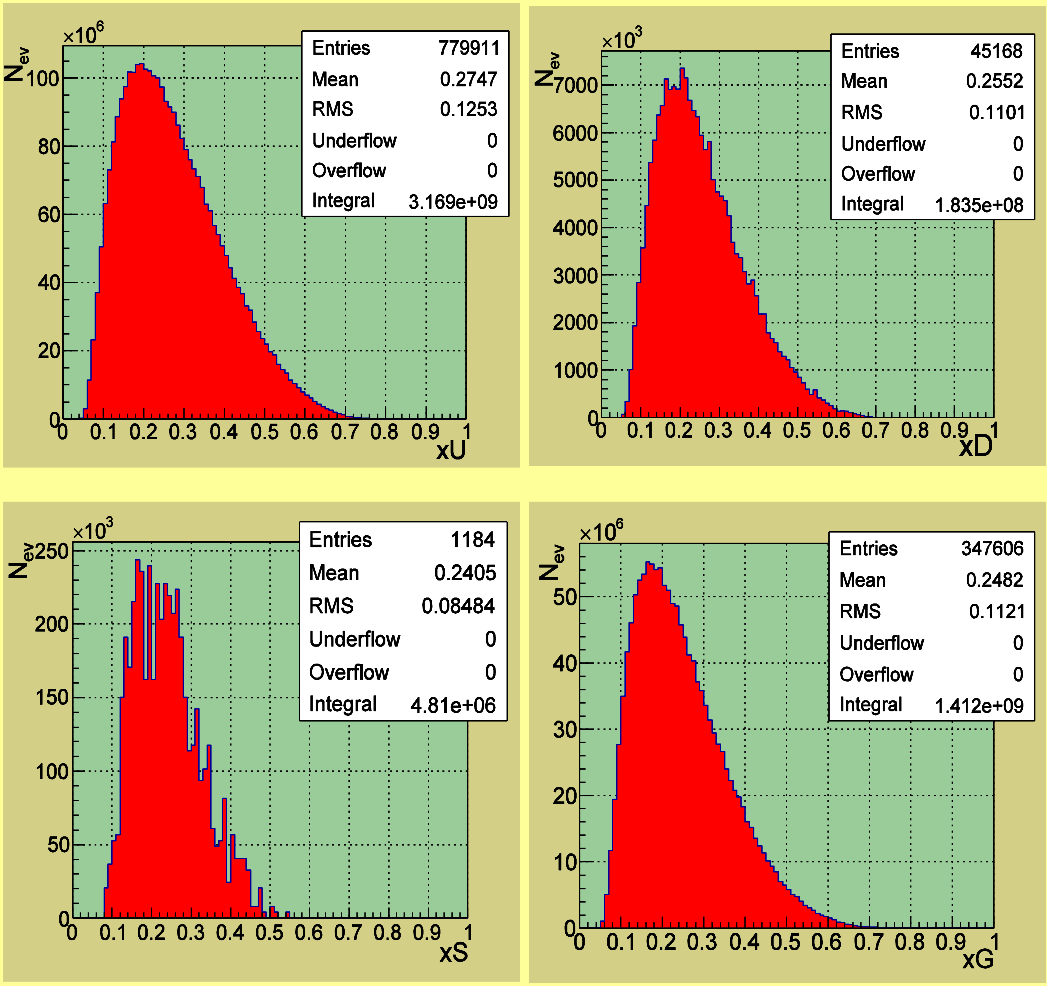
we can expect p_T^{γ} ***< 2.3 GeV, i.e***

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

This region is under study now at HERA and JLab .

Structure functions distributions

Bjorken x distributions



From these quark distributions we see that at PANDA energy (E_{beam}=15 GeV) PYTHIA (with CTEQ3L parametrization) predicts that the Bjorken *x* - variable can cover the region

$0.05 < x < 0.7$

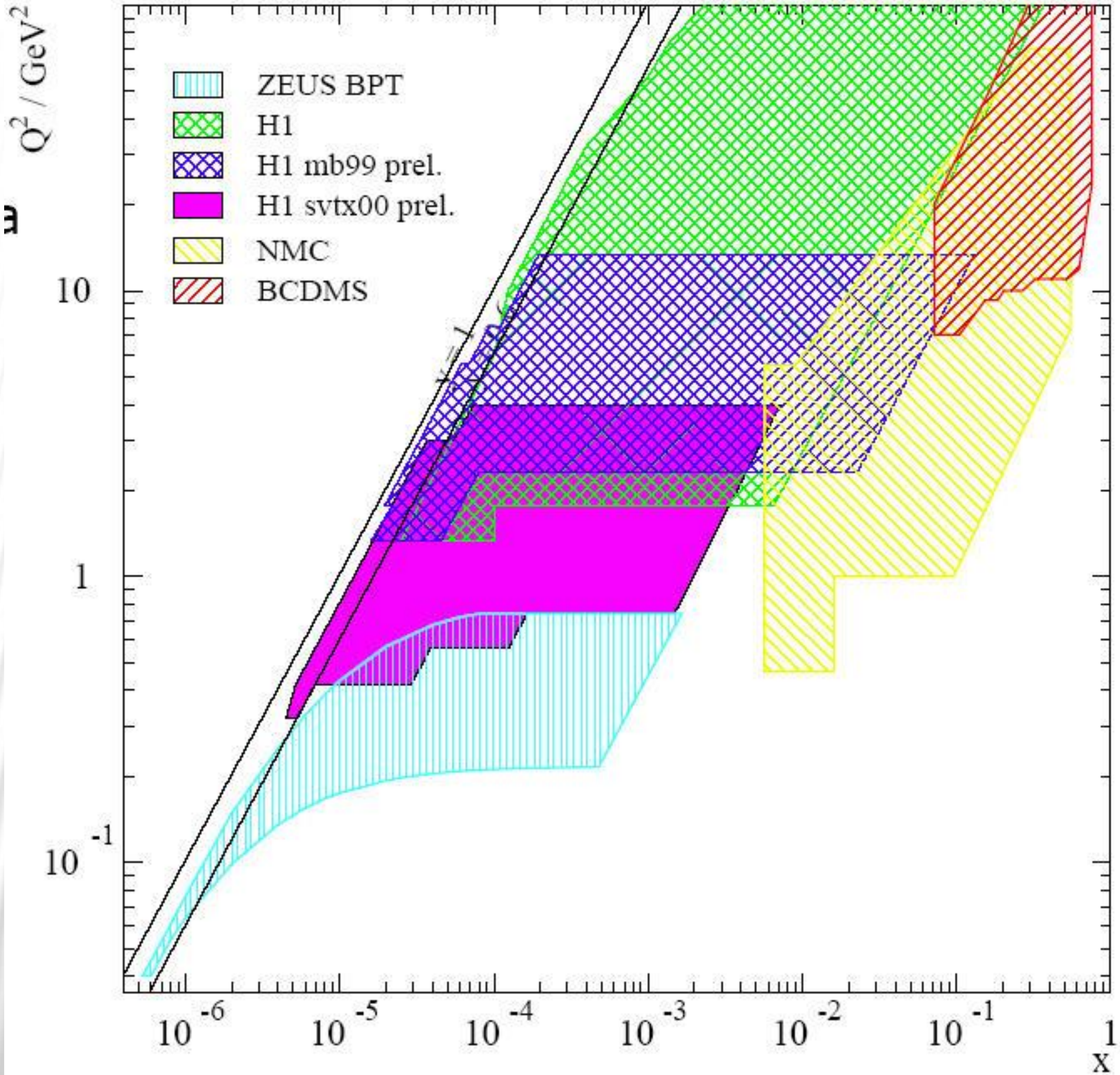
x-Q^2 plane

Regions covered by

Structure Function measurements

in **DIS** experiments

at low Q^2



Previous experiments

Nowadays

there are new

measurements

at low Q^2

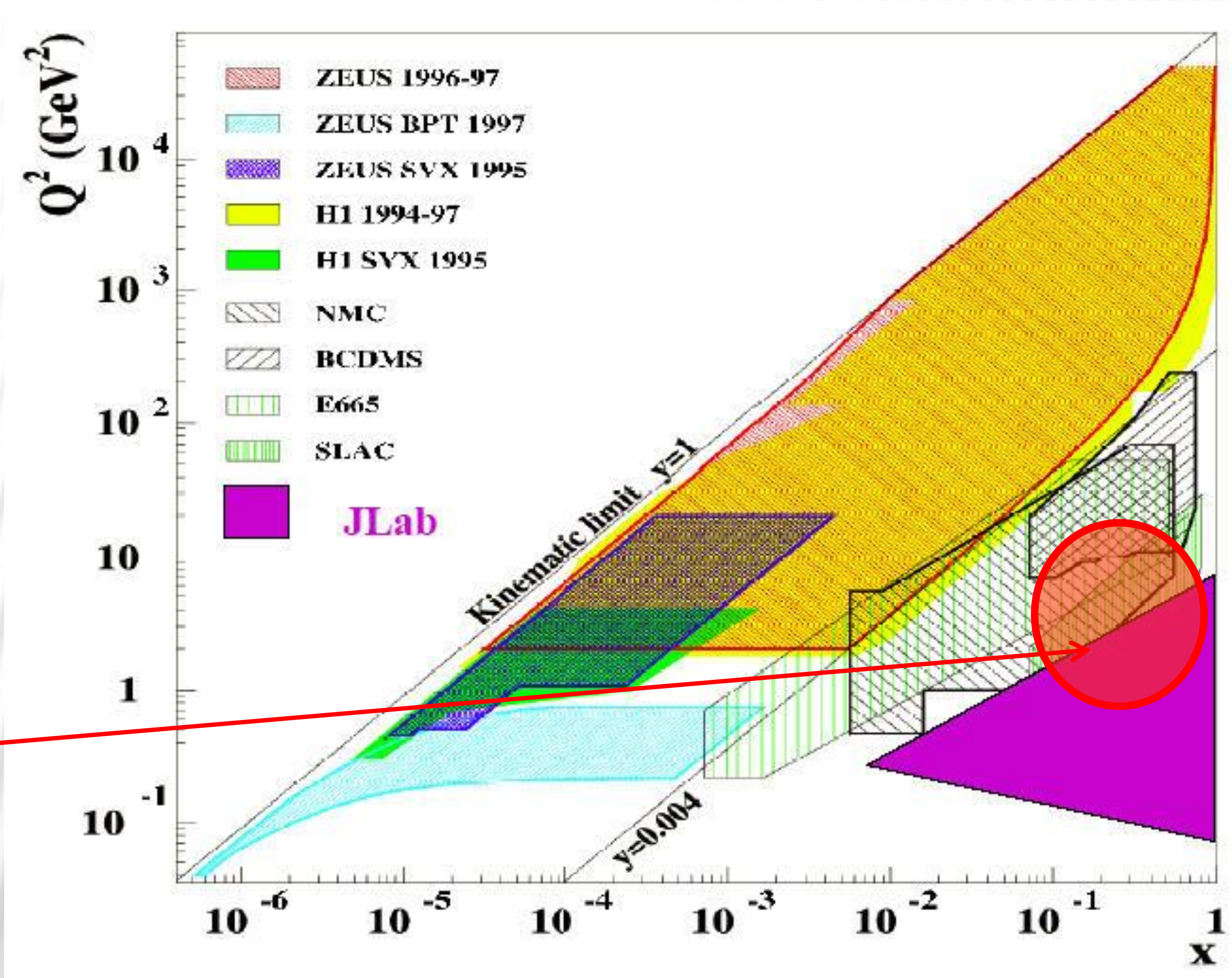
at **JLab**

$0.1 < Q^2 < 8.0$ GeV^2

for PANDA

$0.05 < x < 0.7$

$1 < Q^2 < 5.3$ GeV^2



Previous experiments

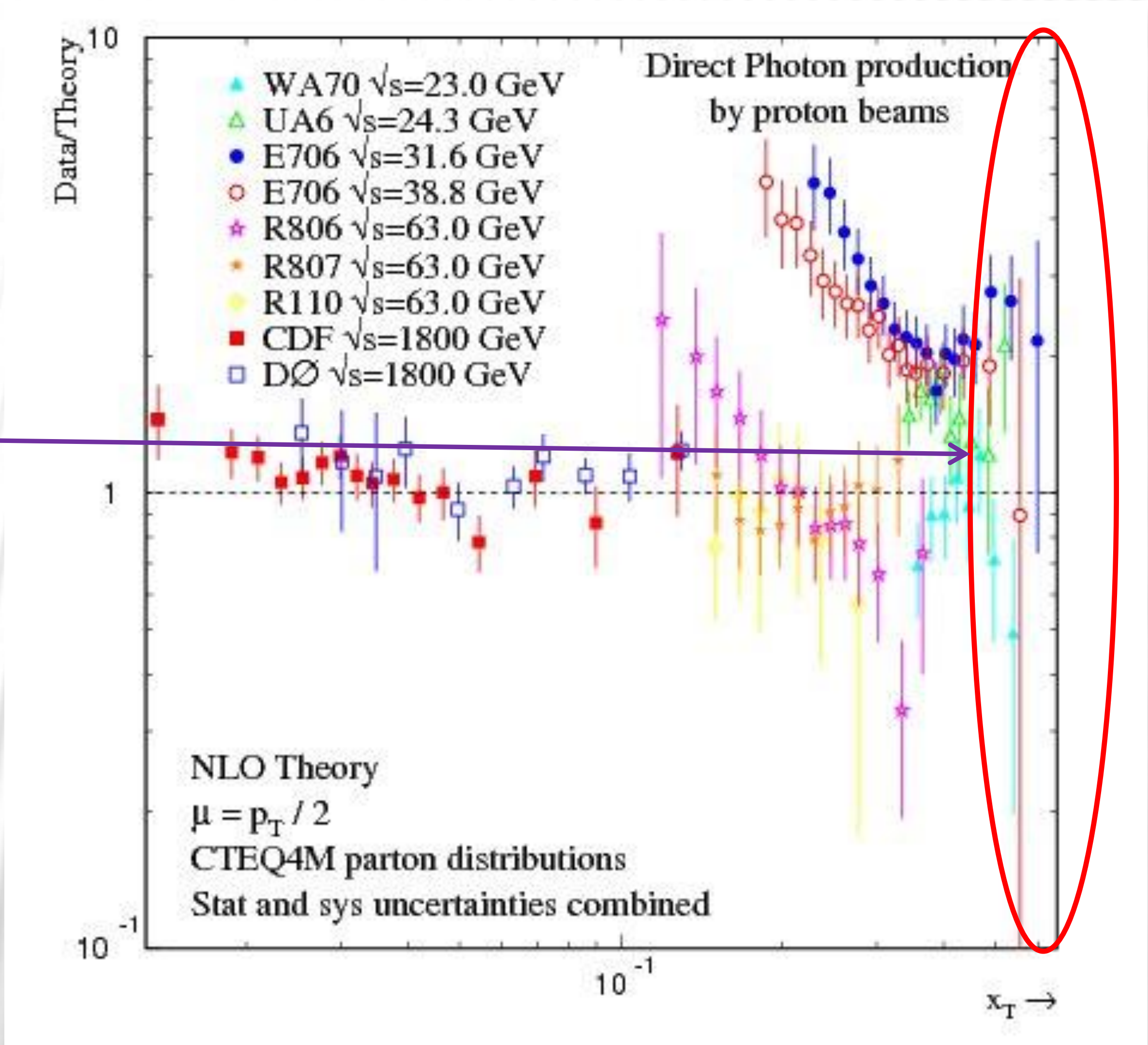
$X_T = 2PT/\sqrt{s}$

for PANDA

$0.39 < X_T < 0.85$

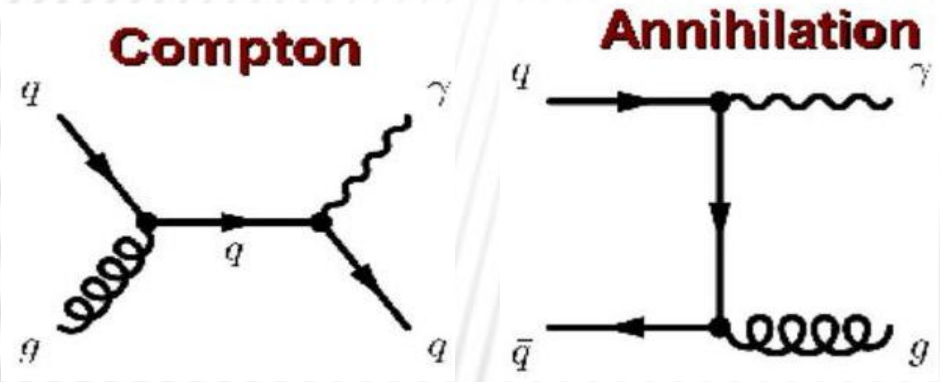
(with account of further background restrictions)

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



Direct photon production: definition

The ***pbar + p → gamma + X*** process (different to DIS scattering) is mainly defined by ***LO QCD*** diagrams:



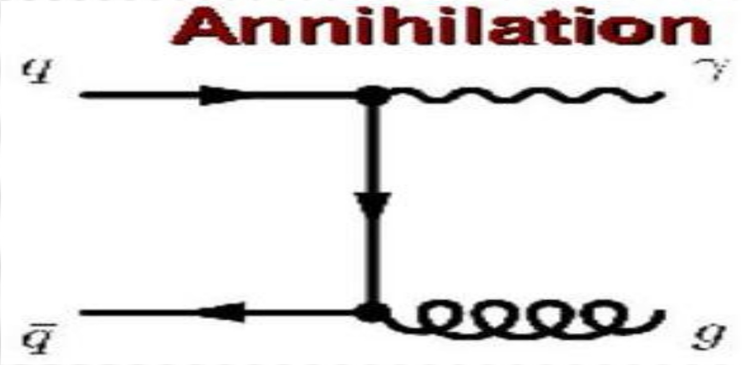
The "***QCD Compton*** " diagram contribution makes ***the cross section of pbar + p → gamma + X*** process to be sensitive to the gluon distribution ***g (x, Q²).***

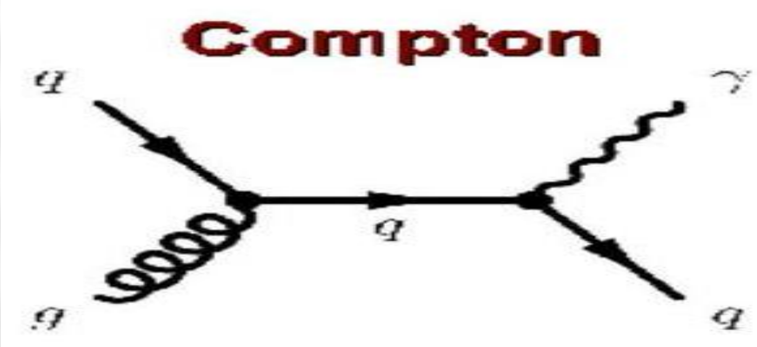
The hadrons are build of quarks which are interconnected by gluons. None of them can be detected as the final states of hadron-hadron or lepton-hadron collisions due to the so called "partons confiement". Nowdays, the physics deals mainly with the structure functions which model the distributions of 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. Nev /Lum) by fitting the parameters of different models of structure functions to the cross sections data.

The diagrams contribution

The contributions of both diagrams to the total cross section





Cross Sections

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

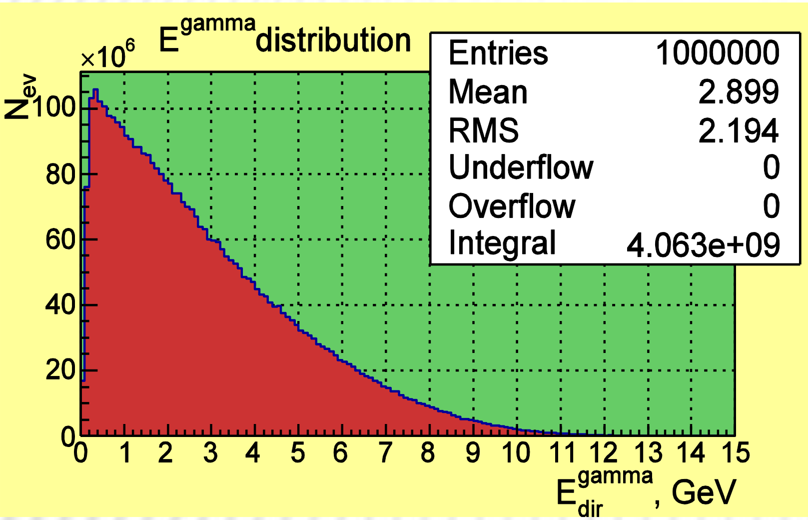
q + qbar → gluon + γ **(65%)**
$\sigma = 1.53*10^{-3}$ **mb**

gluon + q → q + γ **(35%)**
$\sigma = 8.18*10^{-4}$ **mb**

gluon + gluon → gluon + γ
(0.09%)
$\sigma = 2.3*10^{-7}$ **mb**

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

Signal photons distributions

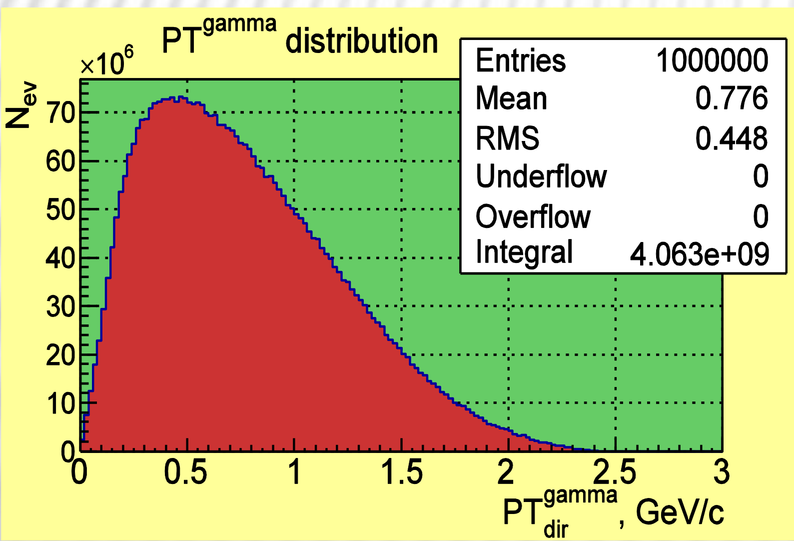


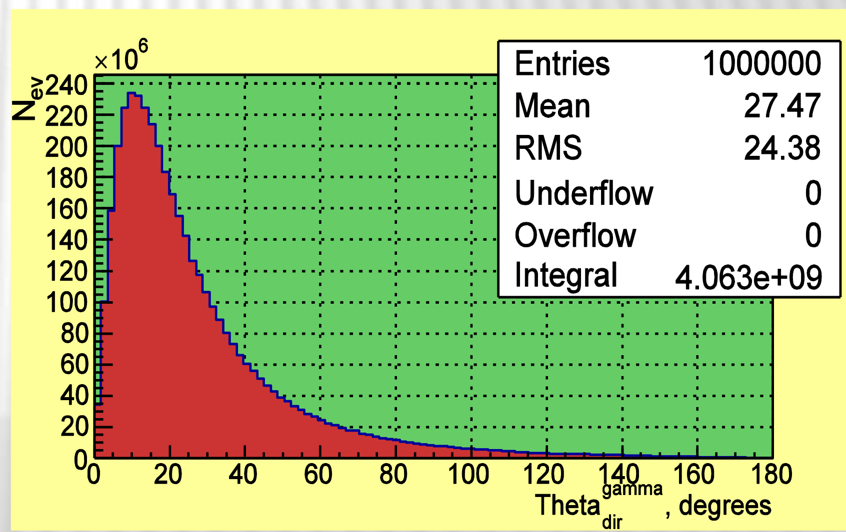
0 ≤ **E γ** ≤ 10 GeV, <**E γ**> = 2.9 GeV

0 ≤ **PT γ** ≤ 2.3 GeV, <**PT γ**> = 0.77 GeV

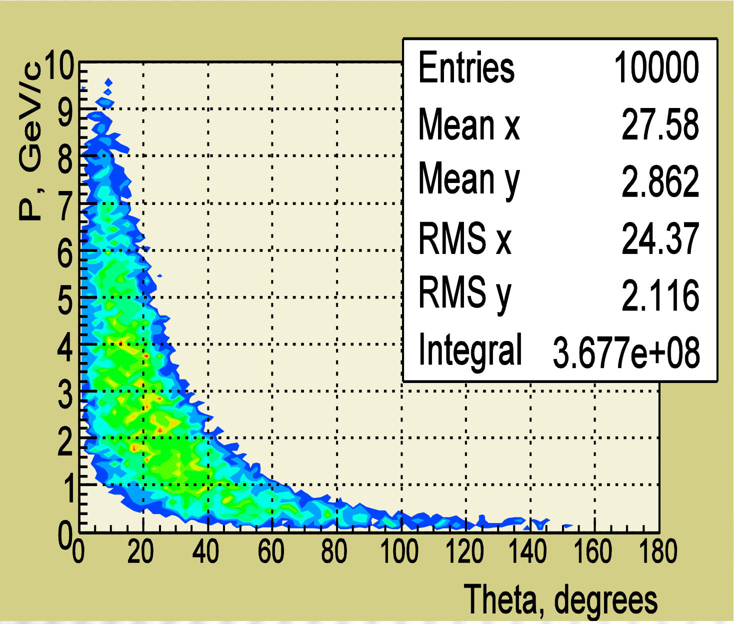
0 ≤ **Θ γ** ≤ 180 °, <**Θ γ**> = 27.5°

some **Θ γ** > 90°





Correlation distributions of polar angle θ and momentum P

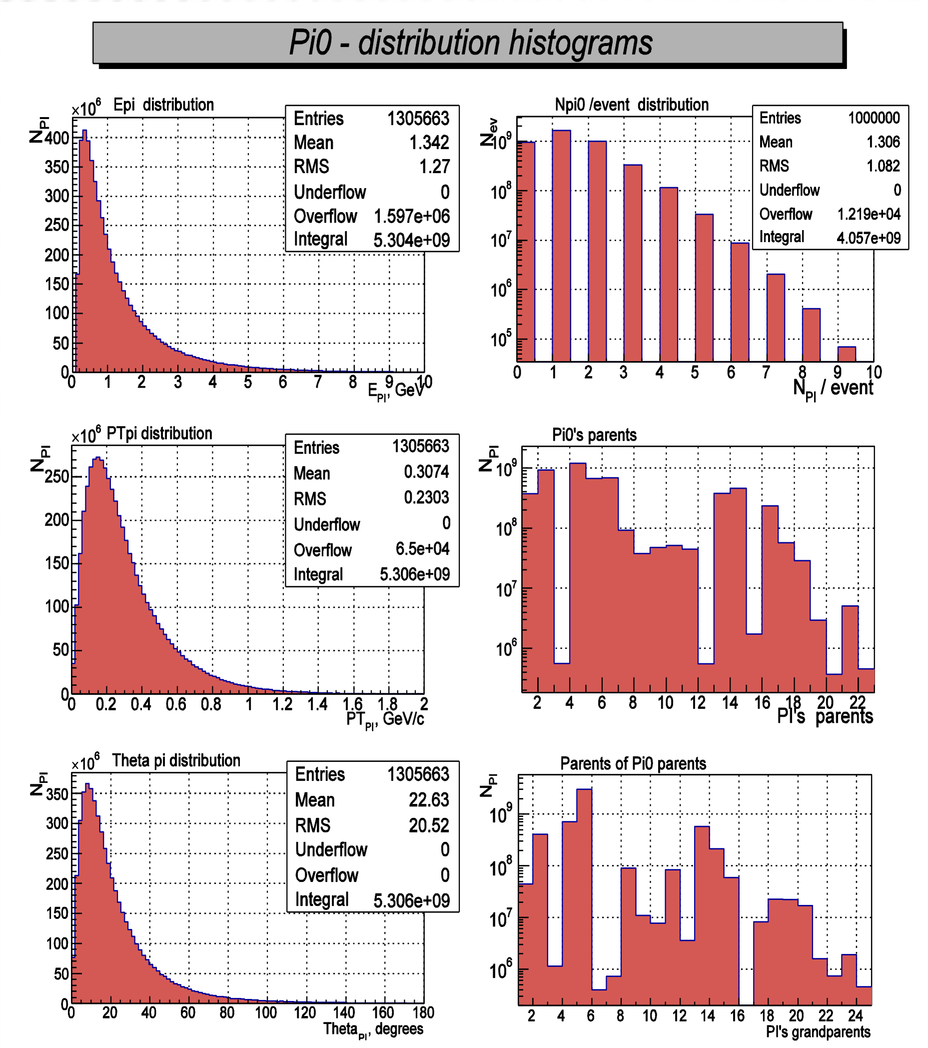


The Figure shows the projection of 3-D correlation distribution of the number of the signal photons over their full momentum P and polar angle θ.

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

All the presented kinematical distributions over different variables show the number of produced at beam energy E_{beam} = 15 GeV events per year (supposing the full year of operation with the highest luminosity $2 \cdot 10^{32}$ cm^{-2} s^{-1})

Neutral pions distributions in signal events



$0 \leq E\gamma \leq 6$ GeV, $<E\gamma> = 1.3$ GeV

$0 \leq PT\gamma \leq 1.3$ GeV, $<PT\gamma> = 0.3$ GeV

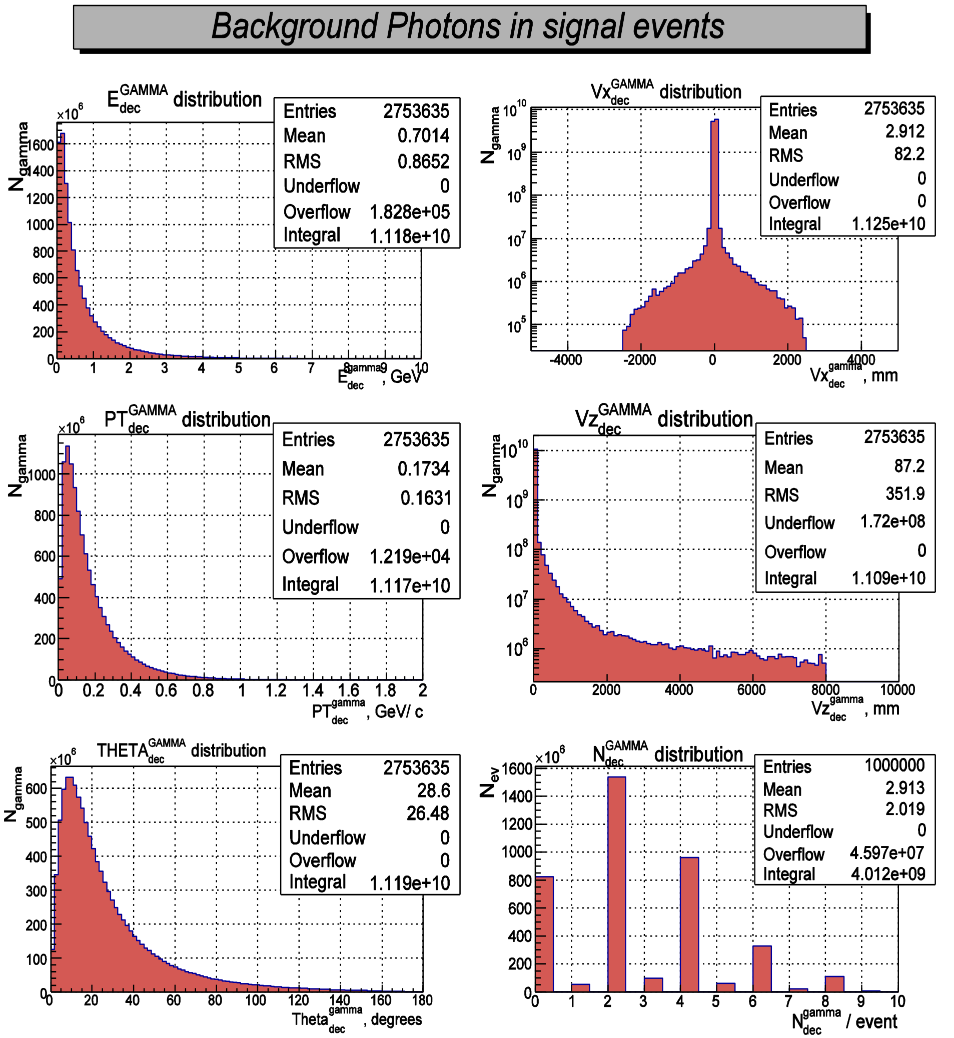
$0 \leq \Theta\gamma \leq 180°$, $<\Theta\gamma> = 22.6°$
some $\Theta\gamma > 90°$

Up to 9 (and more) neutral pions in signal event.

Distribution of $N\pi^o$/event well explains distributions of $N\gamma$/event (with $\pi^o \rightarrow 2\gamma$).

The most probable parents of π^o are η, $\rho+$, strings and Δ^0

Fake photons in signal events distributions



$0 \le E\gamma \le 3.5$ GeV, $\langle E\gamma \rangle = 0.7$ GeV

$0 \le PT\gamma \le 1$ GeV, $\langle PT\gamma \rangle = 0.17$ GeV

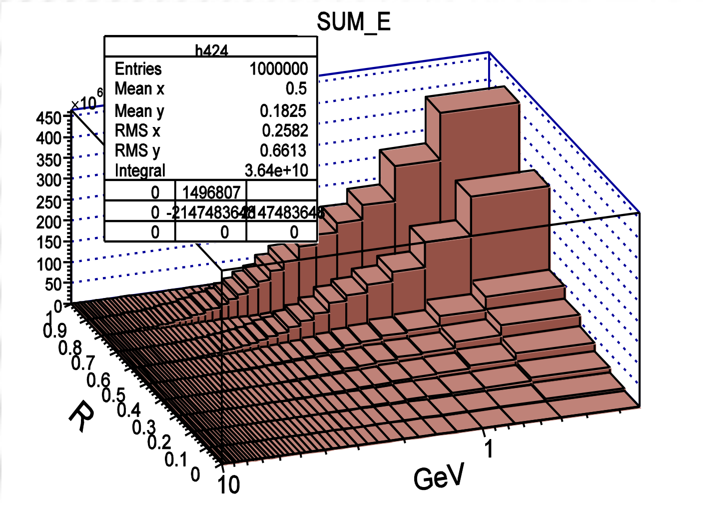
$0 \le \Theta\gamma \le 180°$, $\langle \Theta\gamma \rangle = 28.6°$
some $\Theta\gamma > 90°$

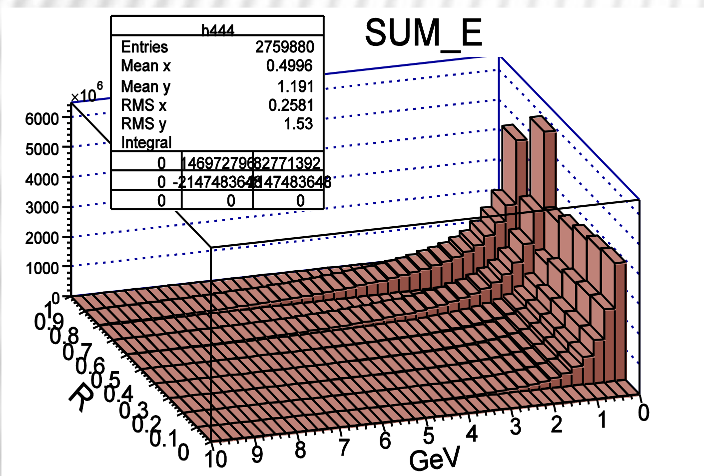
Vx, Vy, Vz **distributions (in log scale) show mostly zero value**

Up to 10 background photons in a signal event (in some few events up to 14)

The main source are π^o and (in 1-2 order of magnitude lower) *η, η`, ω* and Σ^0

Gamma isolation criteria





The plots show the distributions over ***summed energy*** of charged stable particles in the cones of radius $R = \sqrt{\eta^2+\varphi^2}$ respect to direction of the

upper plot → **direct** photon

bottom plot → **fake** photon

Isolation criteria **E** **(of charged particles)** **<0.25 GeV** in the cone of radius $R= \sqrt{\Delta\eta^2+\Delta\varphi^2} = 0.2$ allows to kill **67%** of fake photons with loss of **1.2%** of signal events

(here $\Delta\varphi = \varphi_1 - \varphi_2$ 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).

Background suppression in signal process

- The second cut $PT\gamma \geq 0.2$ GeV allows to reduce the background to 1.3 % thus achiving the ratio S/B = 73.9 by the additional loss of 6.5% signal events.

- The second cut $PT\gamma \geq 0.25$ GeV **allows to kill completely** the background (fake photons) in signal events.

The additional study in Pandaroot framework (full GEANT simulation) is needed.

Background processes

Process	Cross sections, mb
95 Low-pT scattering	3. 368 *10
92 Single diffractive (XB)	1. 719
93 Single diffractive (AX)	1. 719
94 Double diffractive	2. 479 $*10^{-1}$
28 f + g -> f + g	1. 670 $*10^{-2}$
11 f + f' -> f + f' (QCD)	8. 756 $*10^{-3}$
68 g + g -> g + g	4. 887 $*10^{-3}$
12 f + fbar -> f' + fbar	1. 111 $*10^{-3}$
13 f + fbar -> g + g	1. 074 $*10^{-3}$
53 g + g -> f + fbar	1. 296 $*10^{-4}$

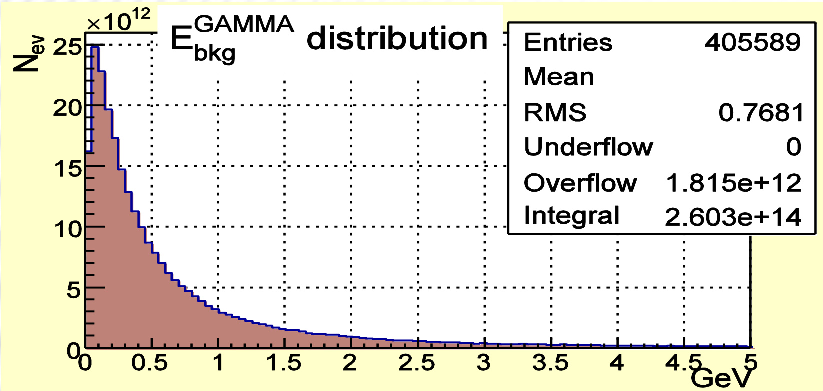
Signal processes - *total cross section is 5 order less than the cross section of "minimum-bias" processes*

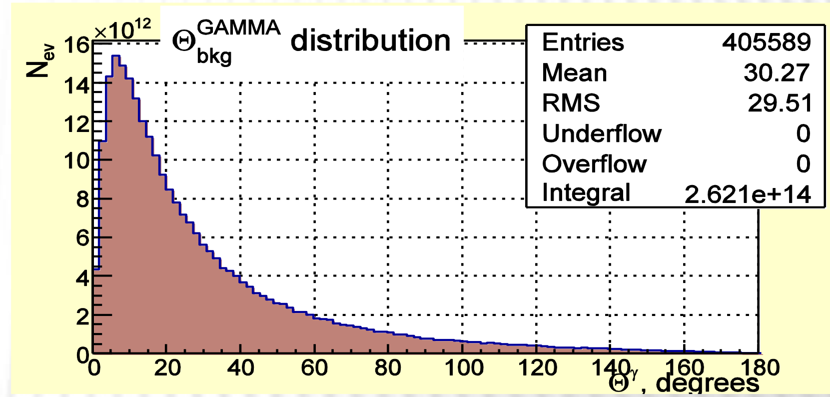
14 f + fbar -> g + gamma	1. 533 $*10^{-3}$
29 f + g -> f + gamma	8. 181 $*10^{-4}$
115 g + g -> g + gamma	2. 280 $*10^{-7}$

According to predictions of MC generator PYTHIA6.4 the total cross section at the energy of antiproton beam E_{beam} = 15 GeV for the processes of the prompt photons is 2.35 x 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 x 10^{-5} and one signal event corresponds to about 16000 background ones.

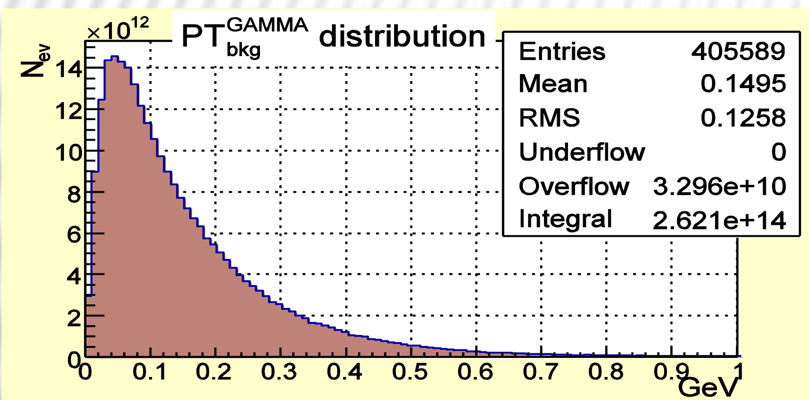
Background photons distributions

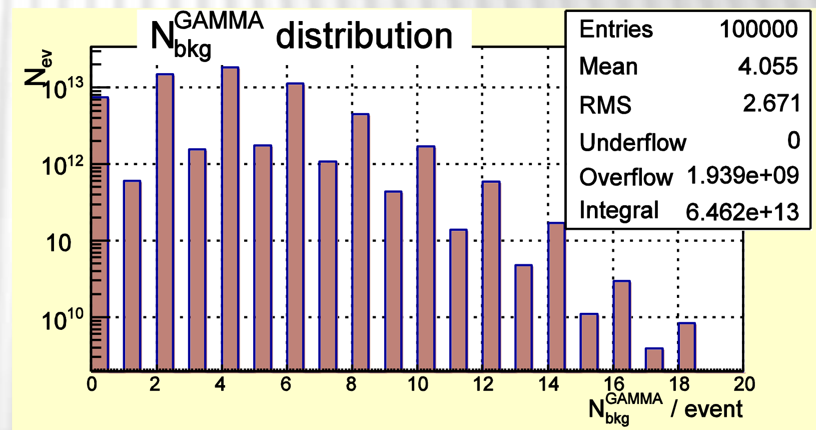




0 ≤ **E γ** ≤ 4 GeV, <**E γ**> = 0.64 GeV

0 ≤ **Θ γ** ≤ 180 °, <**Θ γ**> = 30.3 °





0 ≤ **PT γ** ≤ 0.7 GeV, <**PT γ**> = 0.15 GeV

Up to 18 bkg photons per event

Background elimination

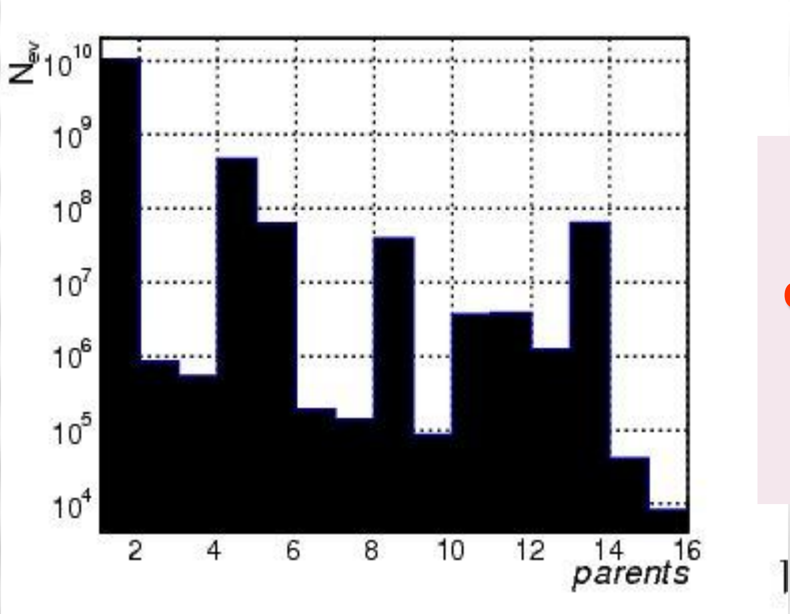
Cut	Rejected events
1. *Events without photons*	11.2 %
2. *Isolation criteria for the photon with the largest energy in event* *E (of charged particles) > 0.25 GeV in the R=0.2*	83.7 %
3. *PT < 0.25 GeV of the photon with the largest energy*	4.9 %

The rest of background events is < 0.2 %

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

Additional background elimination

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



Pions give 1.5 order higher contamination comparing to the other mesons

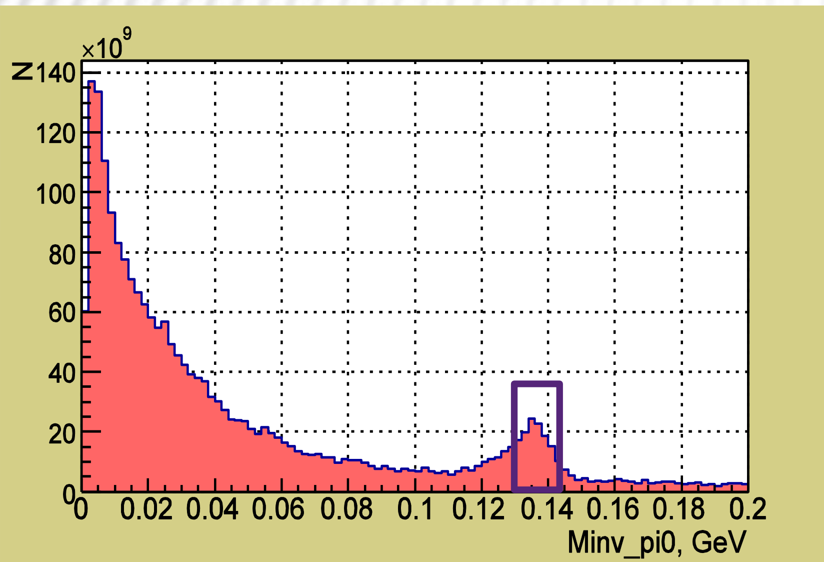
Bin number	Name of γ's parent particle
1	π^0
2	ρ^0
3	ρ^+
4	η
5	ω
6	K^{*0}
7	K^{*+}
8	η'
9	ϕ
10	Δ^0
11	Δ^+
12	Λ^0
13	Σ^0
14	Σ^+
15	Ξ^0

The similar picture is expected for the gamma`s parents in the background events

Background elimination

98.8% $\pi^0 \rightarrow \gamma\gamma$
1.2% $\pi^0 \rightarrow \gamma e^+e^-$

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



Supposing **0.130 GeV < π^0 mass < 0.145 GeV**, the number of background events, where the most energetic ɣ 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 . Selection by the transverse momentum PT_{gamma} together with the isolation criterion E_{sum} < 0.25 GeV in the cone with the radius R=0.5

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

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

Conclusion.

The simulation with PYTHIA6.4 (used as the first approximation) has shown that at PANDA energy *$Pbar_{beam}$ = 15 GeV*

1. **We can separate the most part of fake and background photons contribution, which comes from decays of pions and other neutral mesons.**

2. **PANDA can make the measurement of proton structure functions in the regions of**

$$0 < Q^2 = (P_T^{\gamma})^2 < 5.3\ \mathrm{GeV}^2 \quad \text{and} \quad 0.05 < x < 0.7$$

3. **This measurement can have the advantage as it is very sensitive to gluon distribution.**

THANKS FOR YOUR ATTENTION

The proton-antiproton cross section ($\sigma \equiv \sigma^{p\bar{p}}$)

in quark-parton model is expressed as follows:

$$\sigma = \int\int\int \mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}\hat{t}\, f_1(x_1, Q^2)\, f_2(x_2, Q^2)\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}$$

Here ***f(x, Q²)*** are the ***structure functions,*** $d\hat{\sigma}/d\hat{t}$ ***is***

the *2 → 2* ***parton*** *level (* $p_1 + p_2 = p_3 + p_4$ *) cross section ;*

$\hat{t} \equiv (p_3 - p_1)^2 = -Q^2$ *is the square of transferred momentum,*

$x_{1,2}$ *is the energy fraction carried by a quark in a proton.*

In our case, $d\hat{\sigma} \equiv d\sigma^{gq->\gamma q}$, *(or* $\equiv d\sigma^{q\bar{q}->\gamma g}$ *) and* $Q^2 = (p_T^\gamma)^2$