JOINT INSTITUTE
FOR NUCLEAR RESEARCH

AMBER
Apparatus for Meson and Baryon Experimental Research

Study of the kaon partonic structure with high-pT prompt photon production process at the AMBER experiment at CERN

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On behalf of the AMBER collaboration

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Hadron mass

1) Proton is built of 3 valence quarks ($|uud\rangle$), $m_p = 0.938$ GeV
2) ρ-meson contains a valence quark and a valence anti-quark ($|u\bar{d}\rangle$):

$$m_\rho = 0.770 \text{ GeV} \approx \frac{2}{3} m_p$$

3) $\pi^\pm-$meson contains a valence quark and a valence anti-quark ($|u\bar{d}\rangle$, $|\bar{u}d\rangle$):

$m_\pi = 0.140 \text{ GeV} \approx \frac{1}{7} m_p \neq \frac{2}{3} m_p -$ **mass problem: we can not predict hadron mass basing on masses of their constituent quarks.**

What the QCD can propose?

Hadron mass

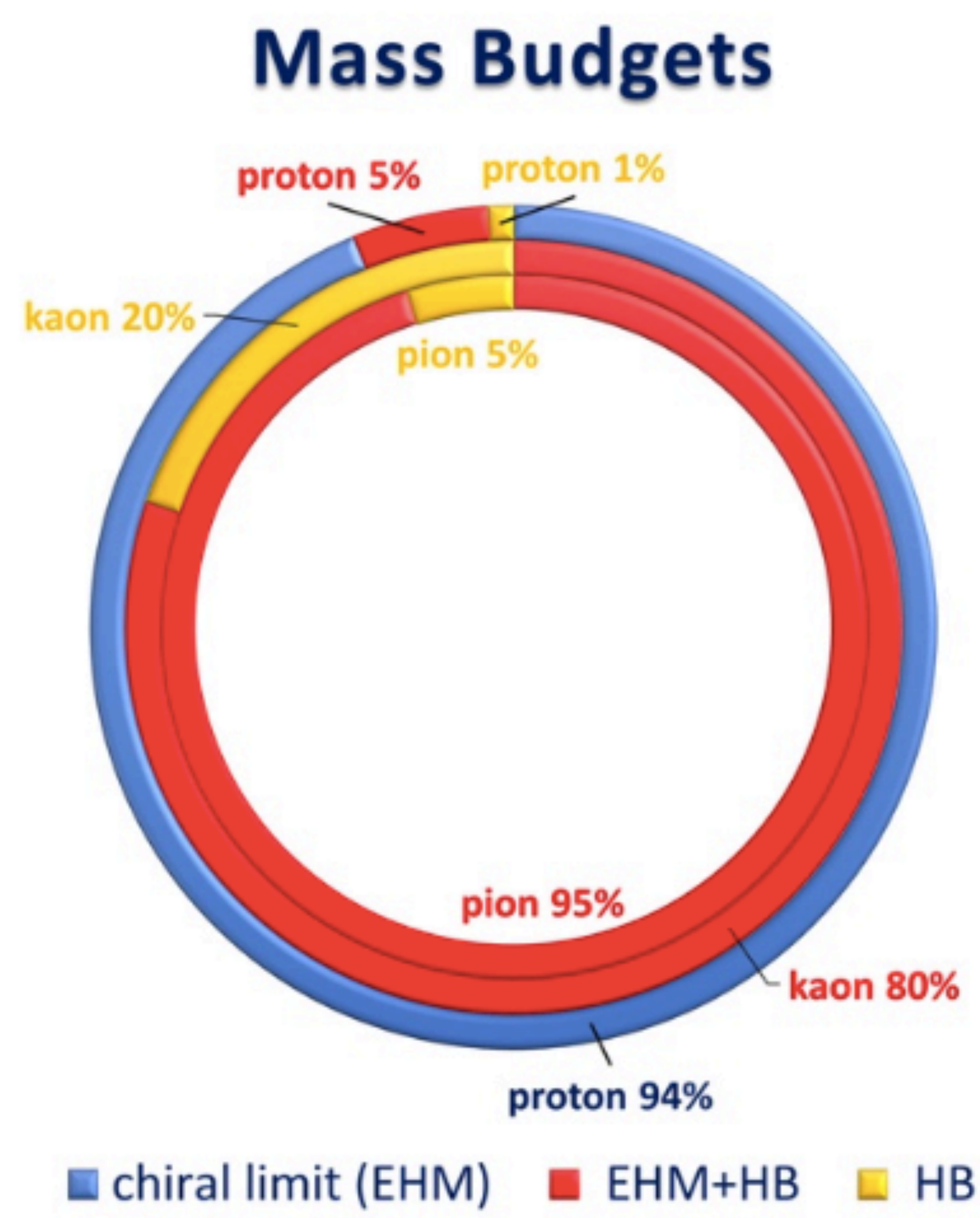
Higgs mechanism:

- generates quark mass
- responsible for ~1% of p mass

and for 5-20% of π and K mass.

In chiral limit:

- π and K are Goldstone bosons — $m_{\pi,\,K} = 0$;
- most of p mass is generated by gluons.



Hadron mass

$$\mathcal{L}_{\rm QCD} = \sum_{f=u,d,s,\ldots} \bar{q}_f[\gamma\cdot\partial + ig\tfrac{1}{2}\lambda^a\gamma\cdot A^a + m_f]q_f + \tfrac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu},$$

In chiral limit of QCD, the hadron mass in the Lagrangian arises through the energy-momentum tensor trace anomaly:

$$\langle p(P)|T_{\mu\nu}|p(P)\rangle = -P_\mu P_\nu \Rightarrow \langle p(P)|T_{\mu\mu}|p(P)\rangle = -P_\mu P_\mu = m^2_{\rm proton} = \langle p(P)|\Theta_0|p(P)\rangle.$$

Θ_0 — gluon self-interactions in proton.

For the pion (the Goldstone boson), the binding energy and masses of the "dressed" quarks cancel each other:

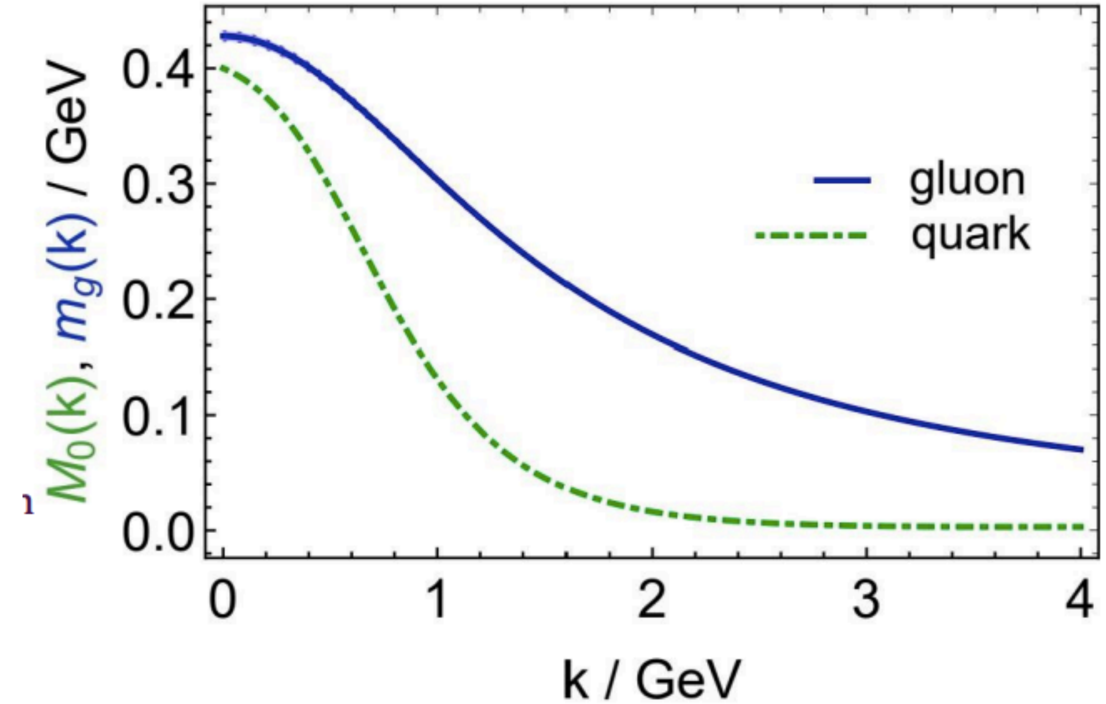
$$\langle \pi(q)|T_{\mu\nu}|\pi(q)\rangle = -q_\mu q_\nu \Rightarrow \langle \pi(q)|T_{\mu\mu}|\pi(q)\rangle = -q_\mu q_\mu = m^2_\pi = 0 = \langle \pi(q)|\Theta_0|\pi(q)\rangle.$$

The explanation of the origin of the proton mass is possible only if the origin of the pion mass is explained at the same time.

Mass generation in QCD

Gluons acquire running mass: self-interacting gluons become gluon quasi-particles described by a mass function that is large in infrared momenta:

$$m_0 = 0.43(1)\ GeV \approx \frac{m_{proton}}{2}$$



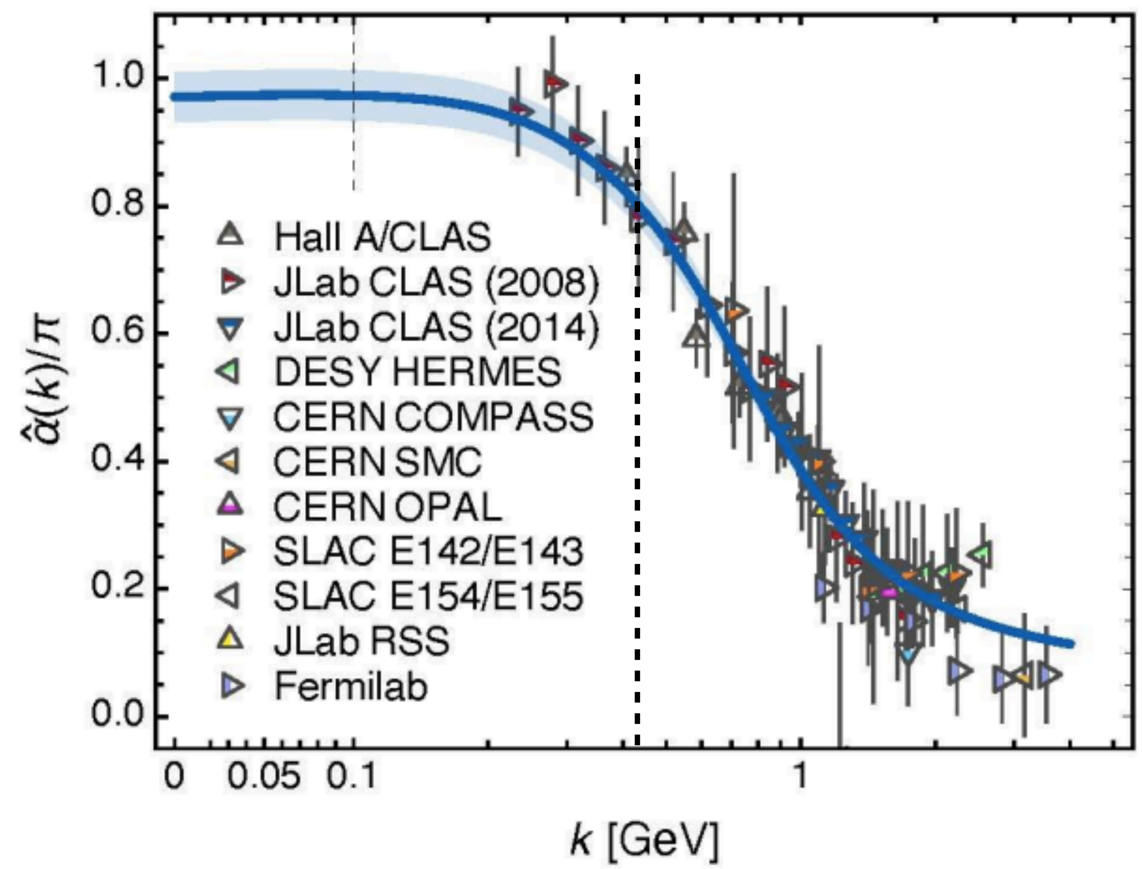
A. Deur, S. J. Brodsky and G. F. de Teramond, Prog. Part. Nucl. Phys. 90 (2016) 1-74

Quarks obtain mass due to dynamic chiral symmetry breaking, through interaction with their own gluon field.

Process independent effective charge

$$\alpha(k^2) = \frac{\gamma_m \pi}{ln k^2/\Lambda^2_{QCD}}\text{: at } k \ \le \frac{m_{proton}}{2}$$

interactions are independent of scale.



Hadron mass calculation still is a complex task for QCD.

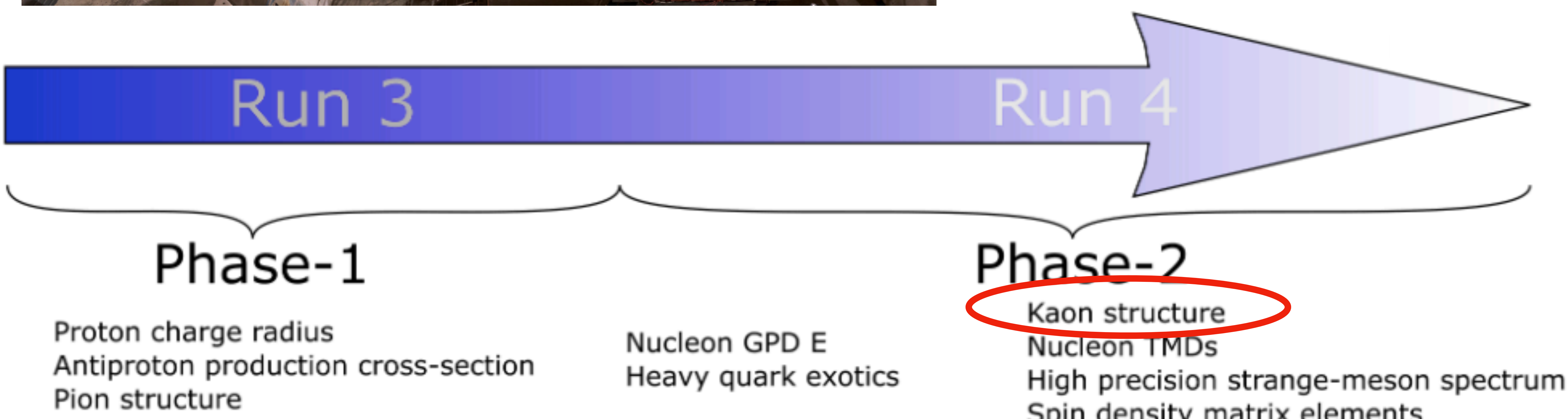
Observables

- Hadron charge radius;
- Parton density functions (PDF): almost unknown for pion and kaon;
- Hadron spectroscopy: precise mass measurement, new hadron states;
- Baryon spectroscopy: excited proton states could contain pseudo scalar and vector diquark correlations;
- Electromagnetic form-factors of pion an kaon.

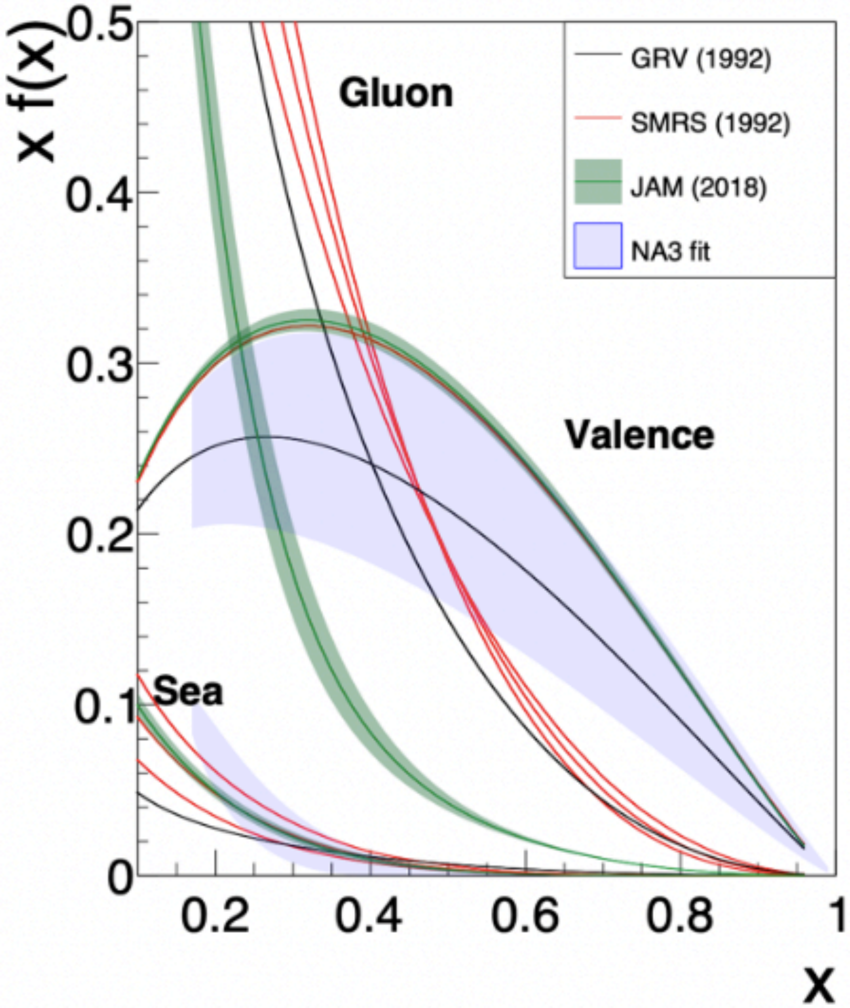
AMBER experiment at CERN plans to perform measurements of these observables to understand hadron mass generation mechanisms.

Apparatus for Meson and Baryon Experimental Research AMBER (NA66) experiment at CERN

- Successor of the COMPASS experiment (1999—…).
- ~150 members from ~30 institutes.
- Data taking has started in 2023.

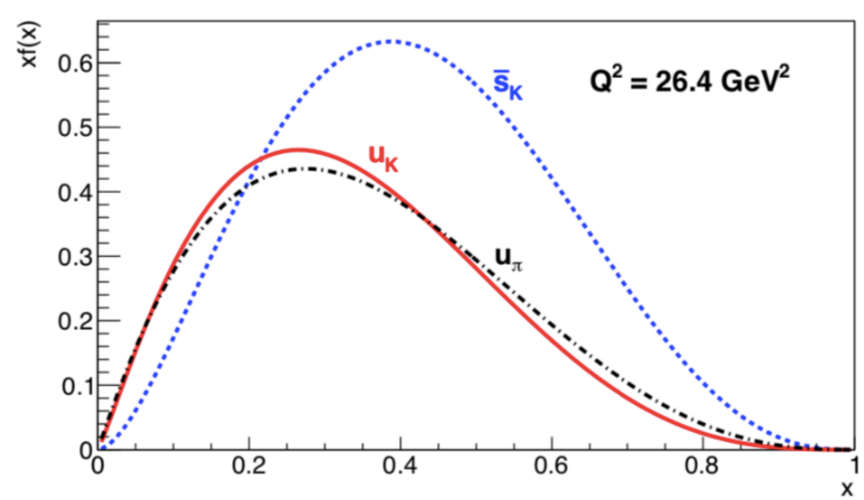


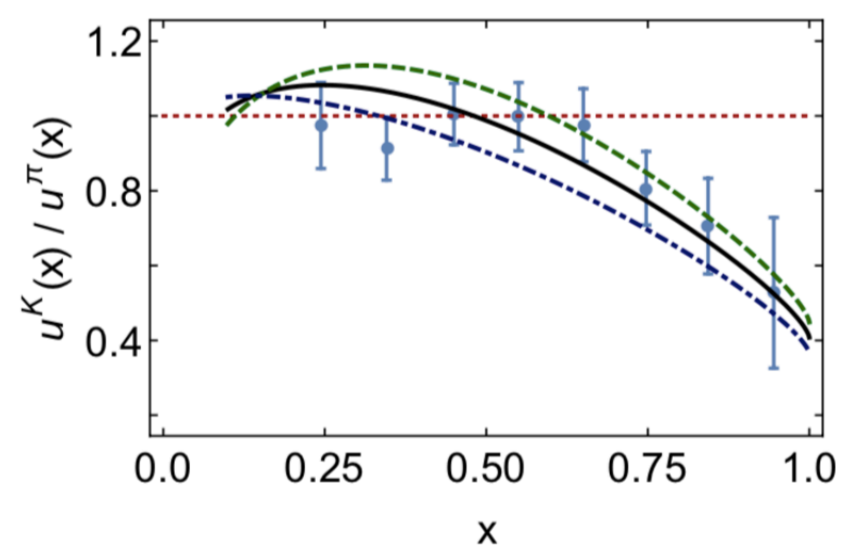
Available global fits to PDF data-sets



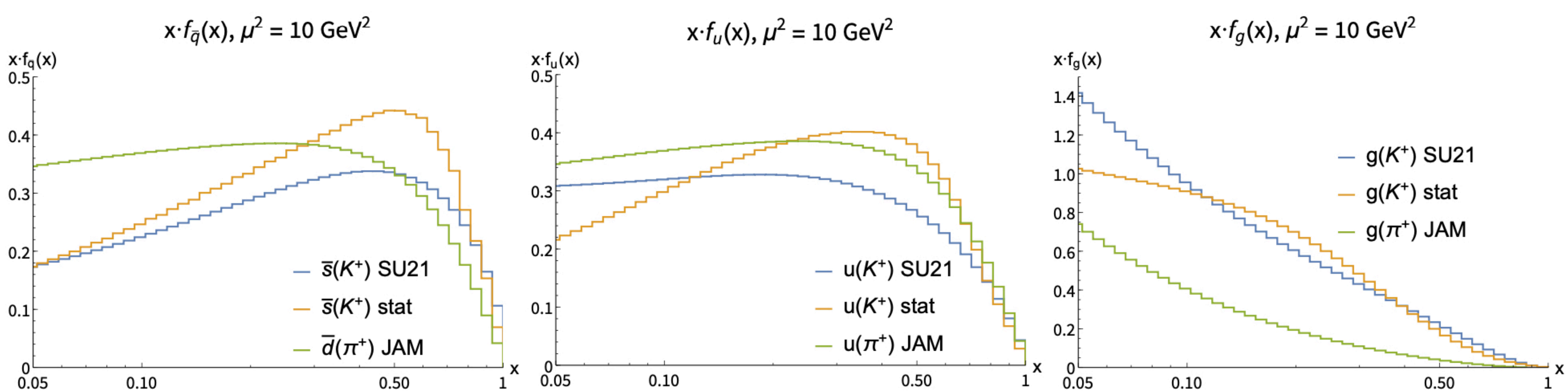
Available PDF sets:

SMRS (1992), GRV (1992): Drell-Yan, charmonia and prompt photon production (**E615, NA10, WA70, NA24**).
JAM (2018): + results on production of leading neutrons at HERA (**ZEUS, H1**).



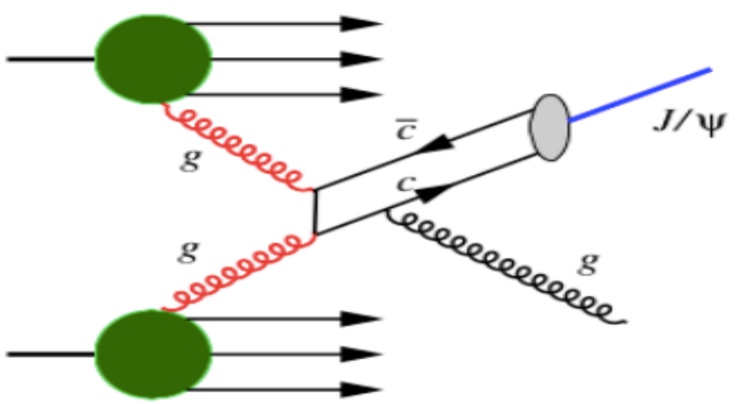


SU21: based on 700 kaon induced DY events at **NA3**



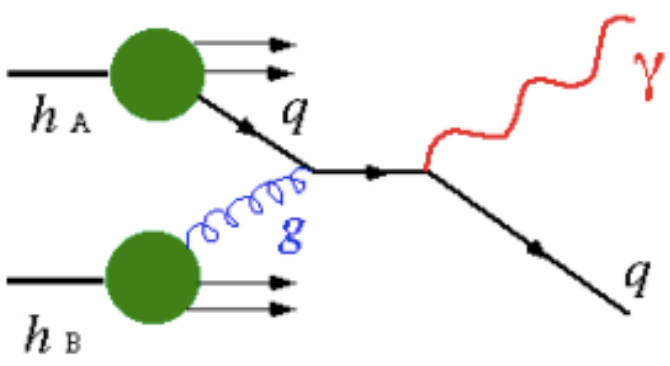
Ways to access quark and gluon structure of hadron

- Charmonia production



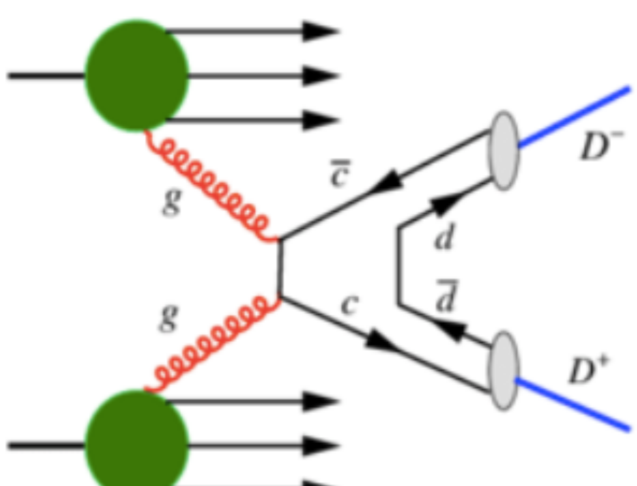
Good signal
Model dependence

- Prompt photon production



Direct access to gluons through $gq \rightarrow q\gamma$
Huge background from π^0 and η

- Open charm production

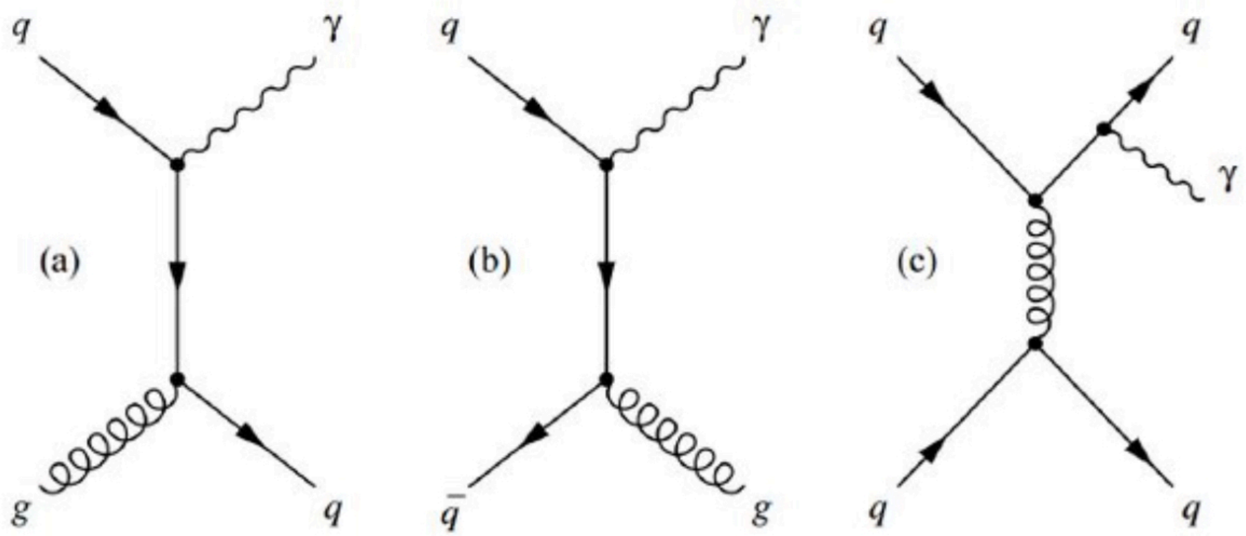


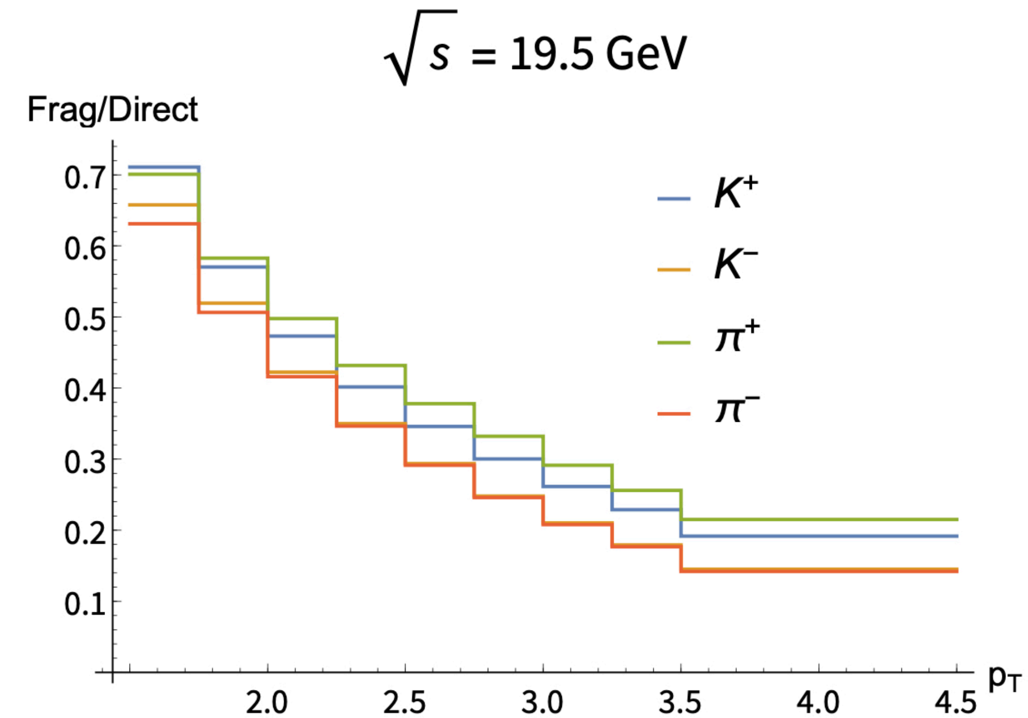
Problematic signal

Prompt photon production

$$d\sigma = d\sigma^{dir}_{LO} + d\sigma^{dir}_{NLO} + d\sigma^{frag}_{NLO} + \mathcal{O}\left(\alpha_s^2\alpha\right)$$

LO **LO** **NLO**





$$d\sigma^{dir}_{LO} = \sum_{a,b,c} \int dx_a f_a(x_a,\mu^2) \int dx_b f_b(x_b,\mu^2) d\hat{\sigma}(ab \to \gamma c) + \mathcal{O}\left(\Lambda^2_{QCD}/\mu^2\right)$$

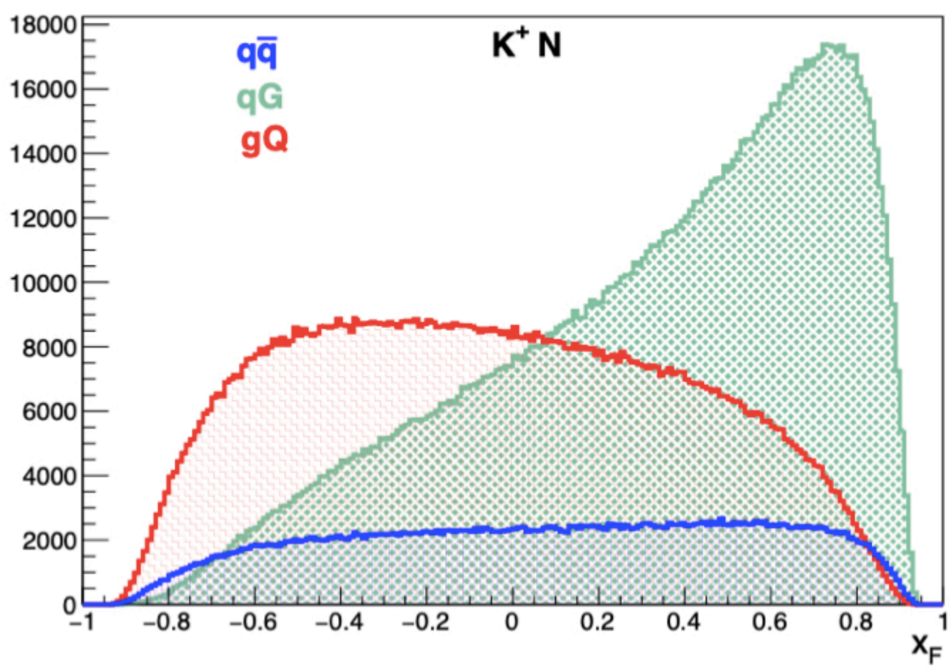
$$d\sigma^{frag}_{NLO} = \int dx_a f_a(x_a,\mu^2) \int dx_b f_b(x_b,\mu^2) \times \sum_{a,b,c,d} \int \frac{dz}{z^2} D_{c,d\to\gamma}(z,\mu^2) d\hat{\sigma}(ab \to cd)$$

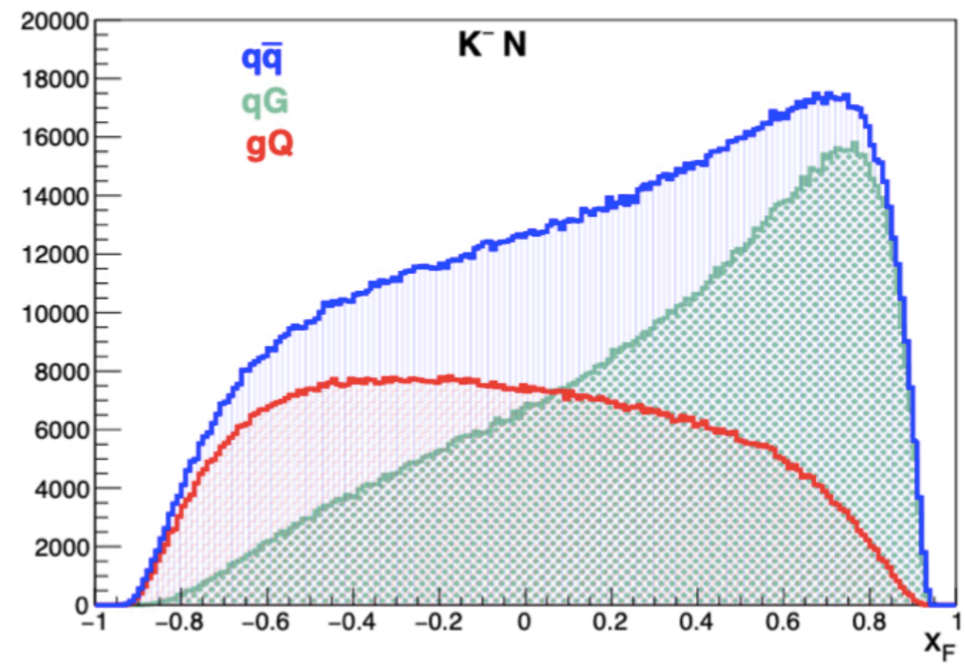
Experiment	Year	$\sqrt{s}$, GeV	Beam	Target	x_T-range	y or x_F range
E7629 [18]	1983	19.4	π^+	C	$0.22< x_T <0.52$	$-0.75< y <0.2$
NA3 [19]	1986	19.4	$\pi^\pm$	C	$0.26< x_T <0.62$	$-0.4< y <1.2$
NA24 [20]	1997	23.75	$\pi^\pm$	p	$0.23< x_T <0.59$	$-0.65< y <0.52$
WA70 [21]	1988	22.96	$\pi^\pm$	p	$0.35< x_T <0.61$	$-0.35< x_F <0.55$
E706 [22]	1992	30.63	π^-	Be	$0.20< x_T <0.65$	$-0.7< y <0.7$

Access to kaon PDF through prompt photon production

LO: $\sigma_{\pi/KN\to\gamma X} = [\bar{q}Q + q\bar{Q}] + [gQ + qG]$

NLO: K=1.4 for p_T>4 GeV/c





$$g_K = g_\pi$$

$p_T > 3$ GeV/c

σ, nb	K^+p	K^-p	K^+n	K^-n	K^+N	K^-N
$\bar{q}Q$	0.5	5.3	0.3	2.4	0.4	3.8
$q\bar{Q}$	0.2	0.1	0.3	0.1	0.2	0.1
gQ	2.4	2.4	1.5	1.5	2.0	2.0
qG	2.4	2.4	2.4	2.4	2.4	2.4
Total	5.5	10.2	4.5	6.4	5.0	8.3

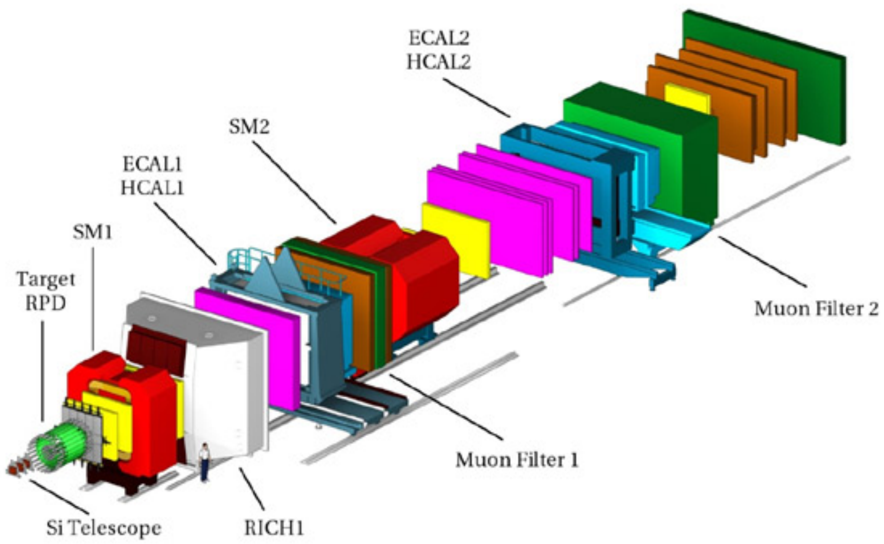
$$\sigma_{K^+N}|_{x_F<0} \sim \ldots + g_K$$

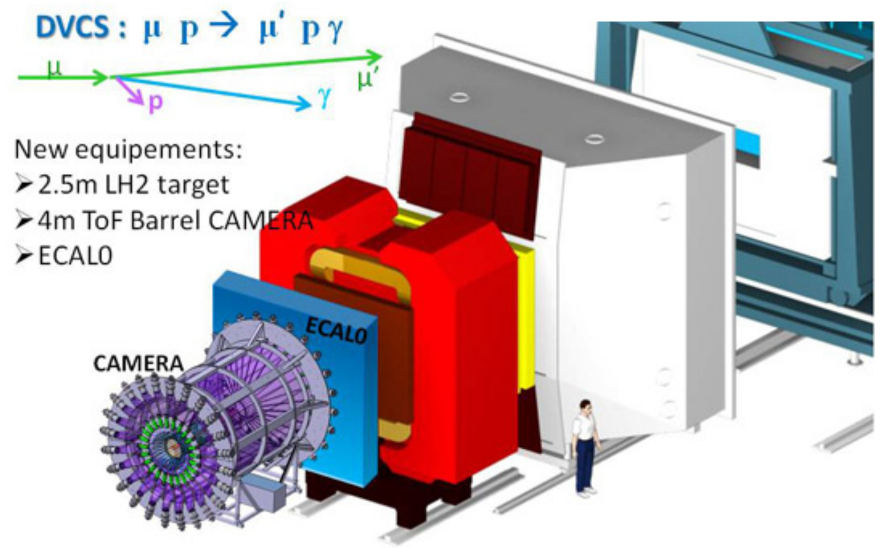
$$\sigma_{K^-N} - \sigma_{K^+N} \sim u_{val}$$

COMPASS 2017

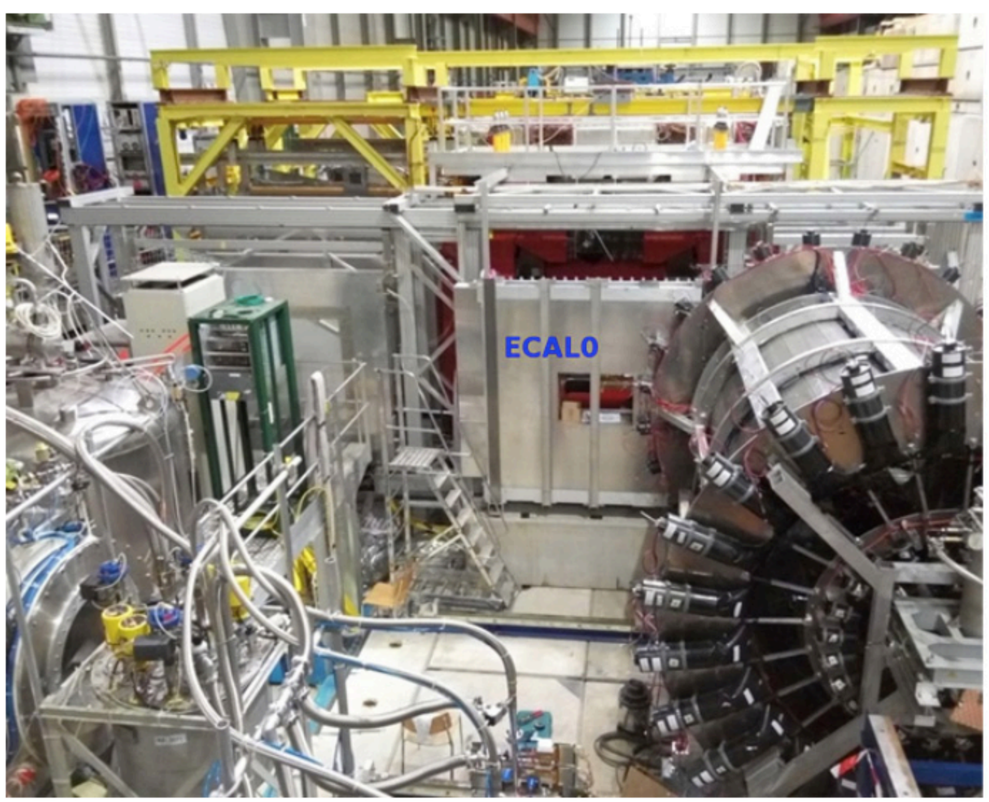
Particle fractions for a 190 GeV hadron beam

Particles	Positive	Negative
Pions	0.240	0.968
Kaons	0.014	0.024
Protons	0.746	0.008





- Possibility to use different meson and hadron beams of different energies;
- System of 3 electromagnetic calorimeters;
- > 300 detecting planes.



Analysis procedure

Signal events (photons with $p_T > 3\ GeV$):

- kaons from the hadron beam are identified by CEDAR detectors;
- ECAL clusters are not associated with charged tracks;
- primary vertex is reconstructed in the target.

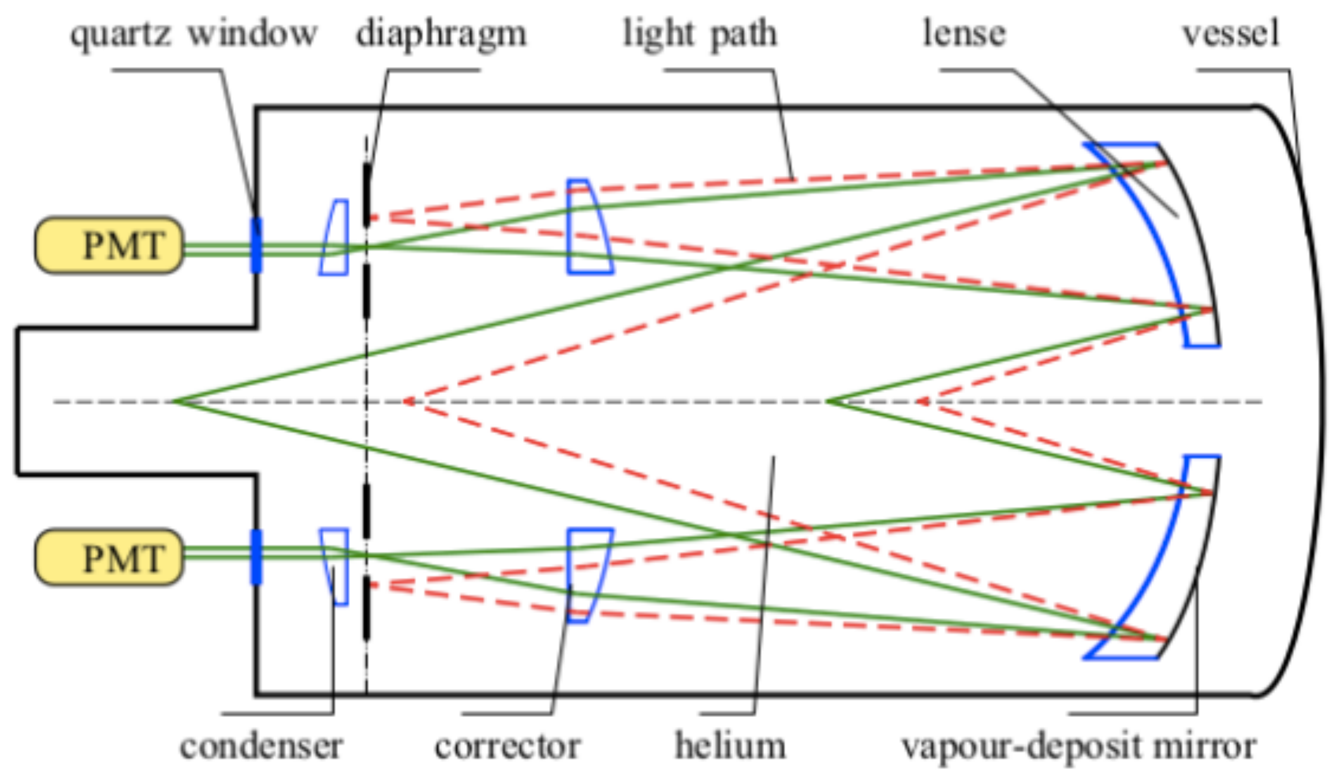
Background events:

- clusters from decays of π^0 and η mesons;
- unseparated clusters from decays of π^0 and η mesons;
- clusters from decays of other neutral particles ($\omega \to \pi^0\gamma,\ BR = 8.35\,\%$);
- photons produced upstream the target;
- noise of ECAL electronics.

Beams and target

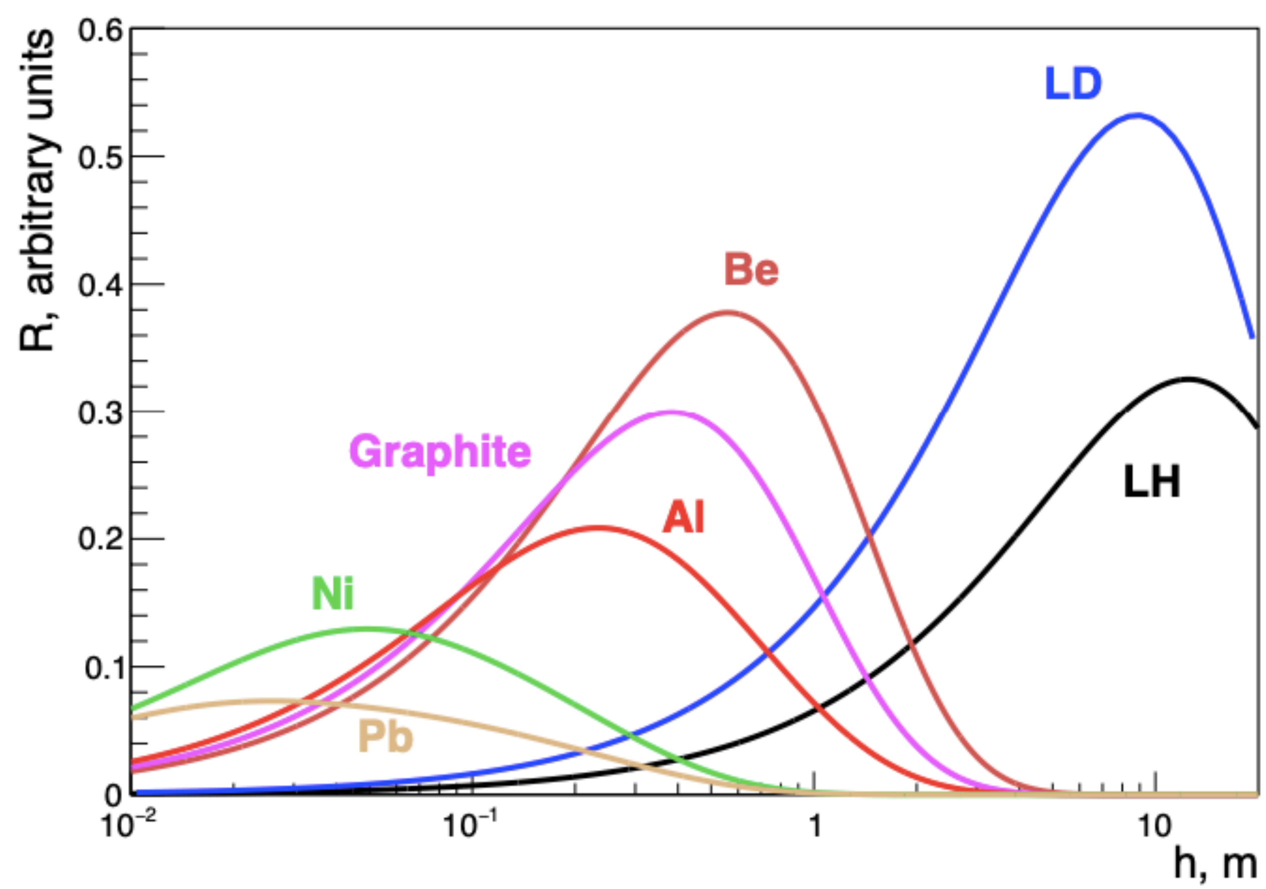
Cherenkov Detector with Achromatic Ring focus (CEDAR):

- hadron beam 190 GeV/c with intensity of 10^8 /spill.
- pion and proton background suppression by 1000 times;
- kaon identification efficiency al level of 90%.

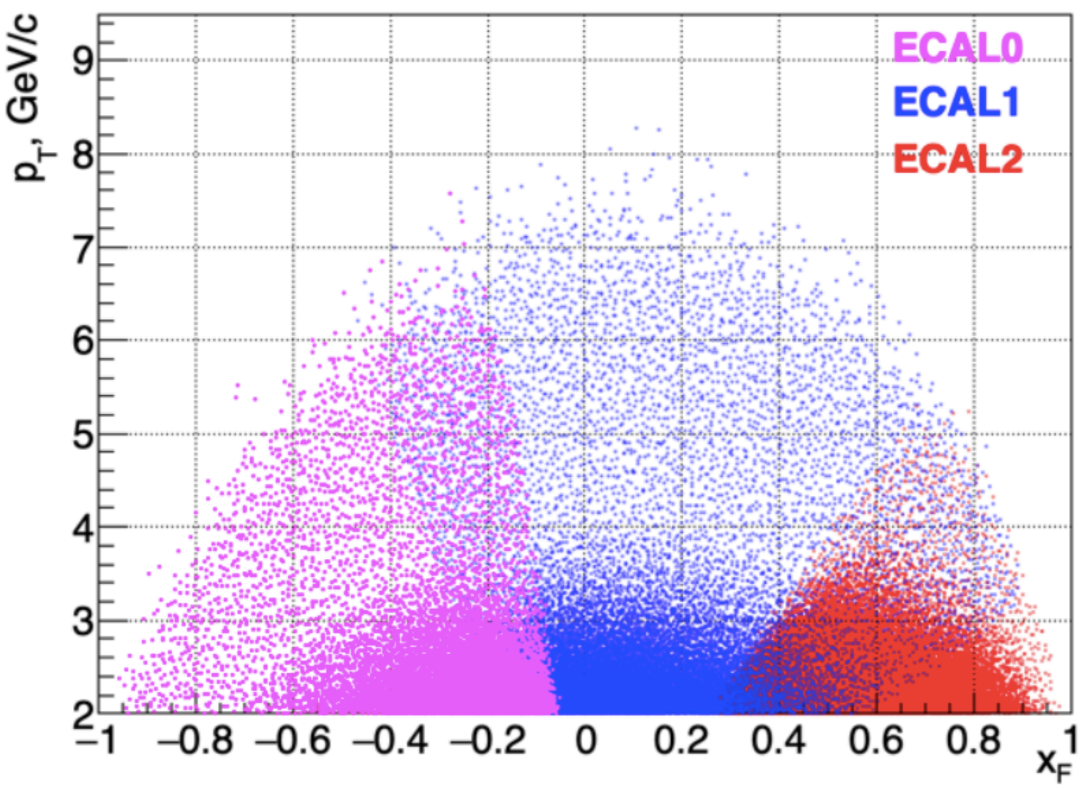


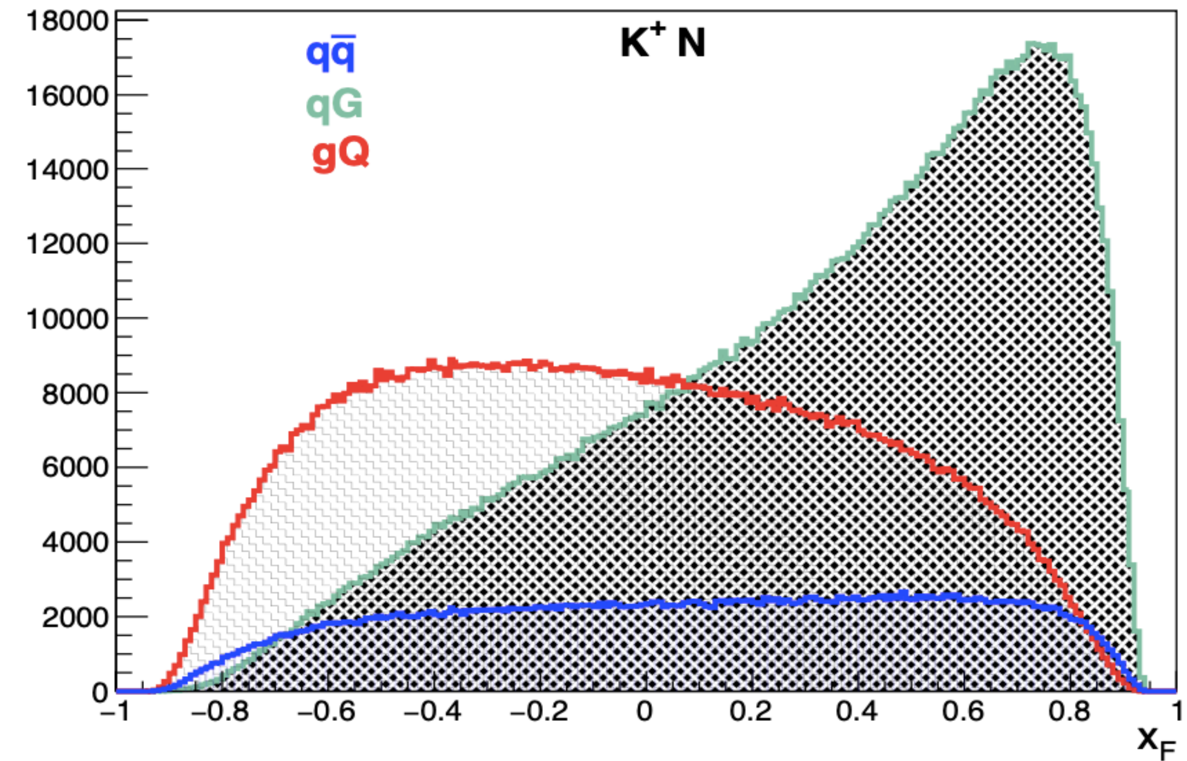
$$R \sim \frac{\lambda_K \lambda_\gamma}{\lambda_K - \lambda_\gamma} \times (e^{-h/\lambda_K} - e^{-h/\lambda_\gamma}) \times \frac{\rho\sigma(A)}{A}$$

- 40 cm graphite target (ρ=1.8 g/cm^3), D=4 cm.
- Target could be replaced with a segmented target.

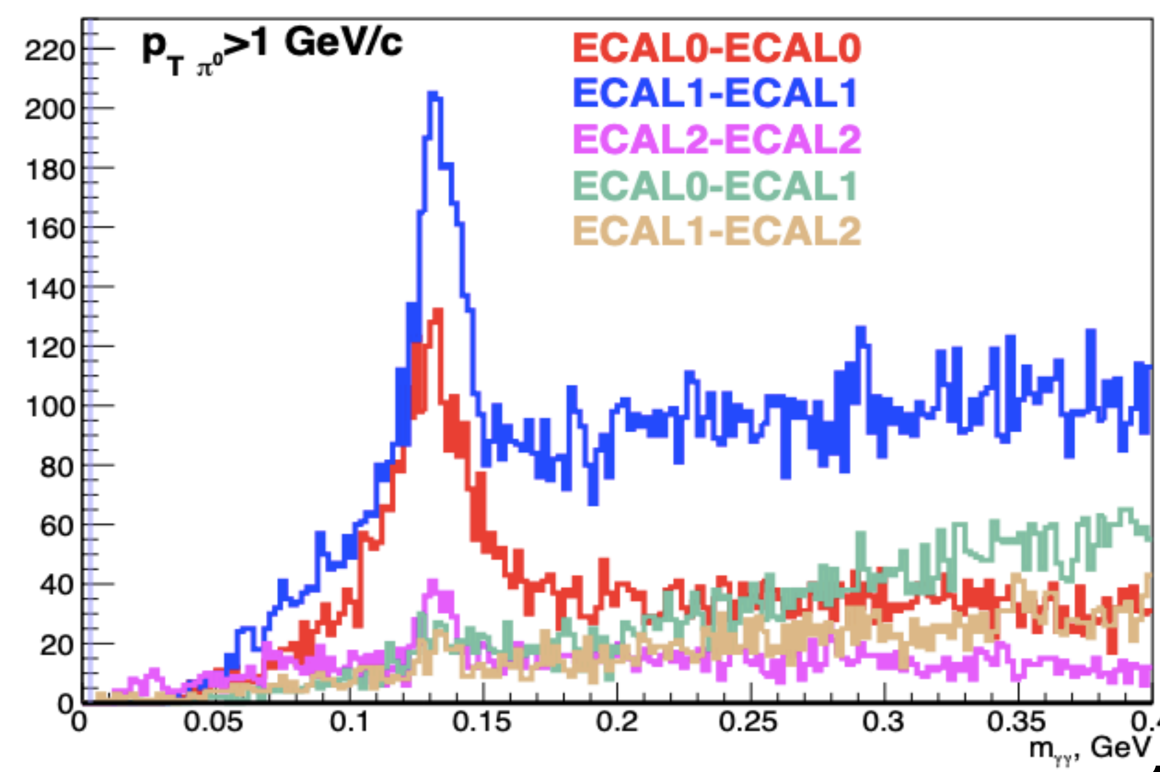


ECALs



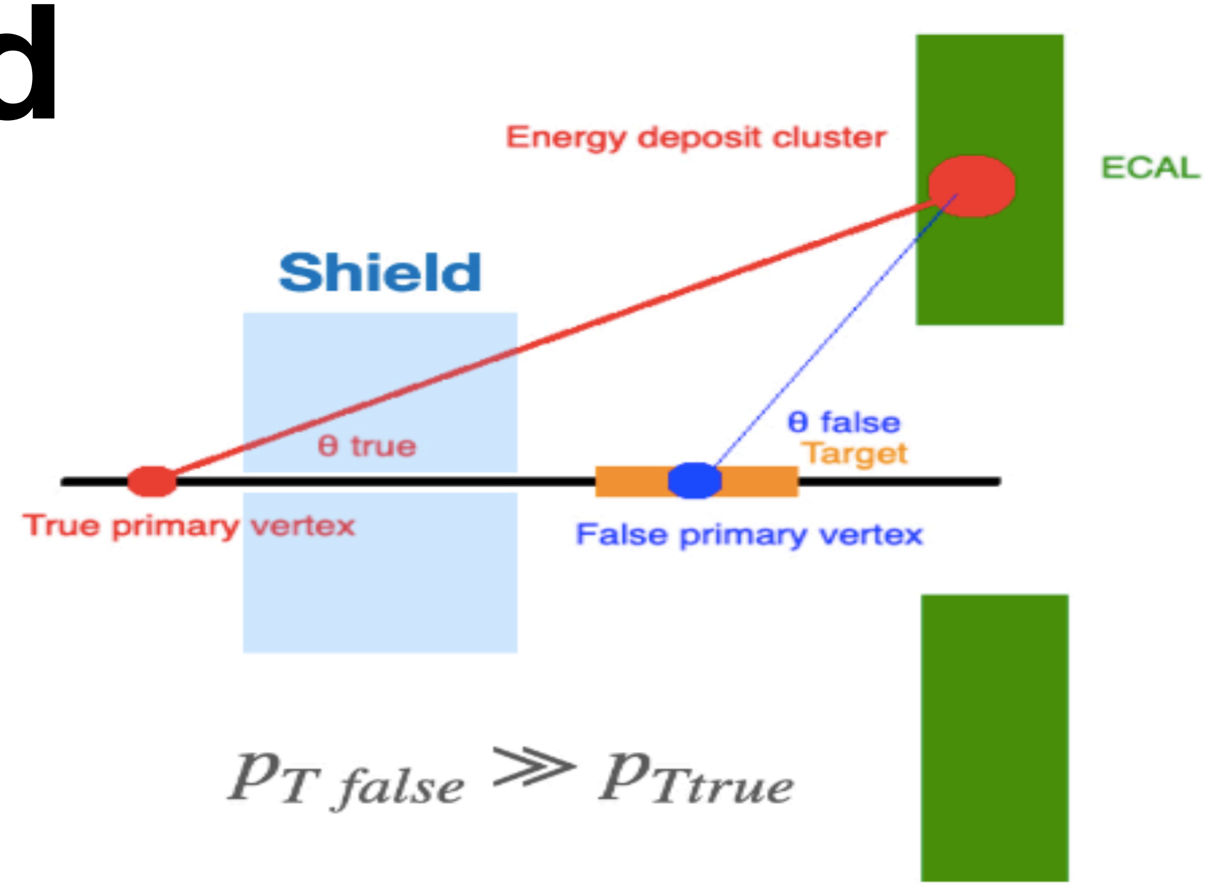


- ECAL0 and ECAL1 are main detectors in the setup.
- ECAL0 gives access to negative x_F region.

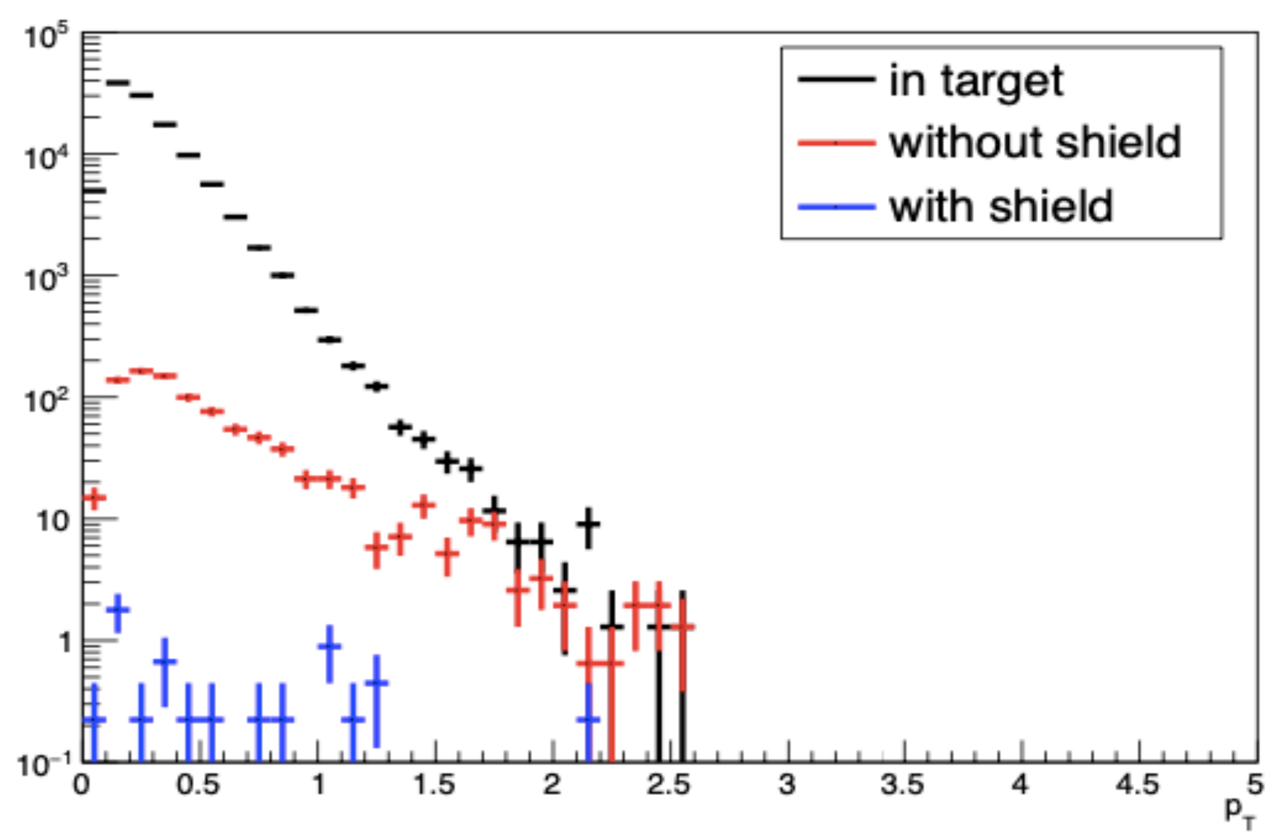


Upstream shield

Steel shield
 40x40x40 cm,
~500 kg,
4 cm hole for the beam.

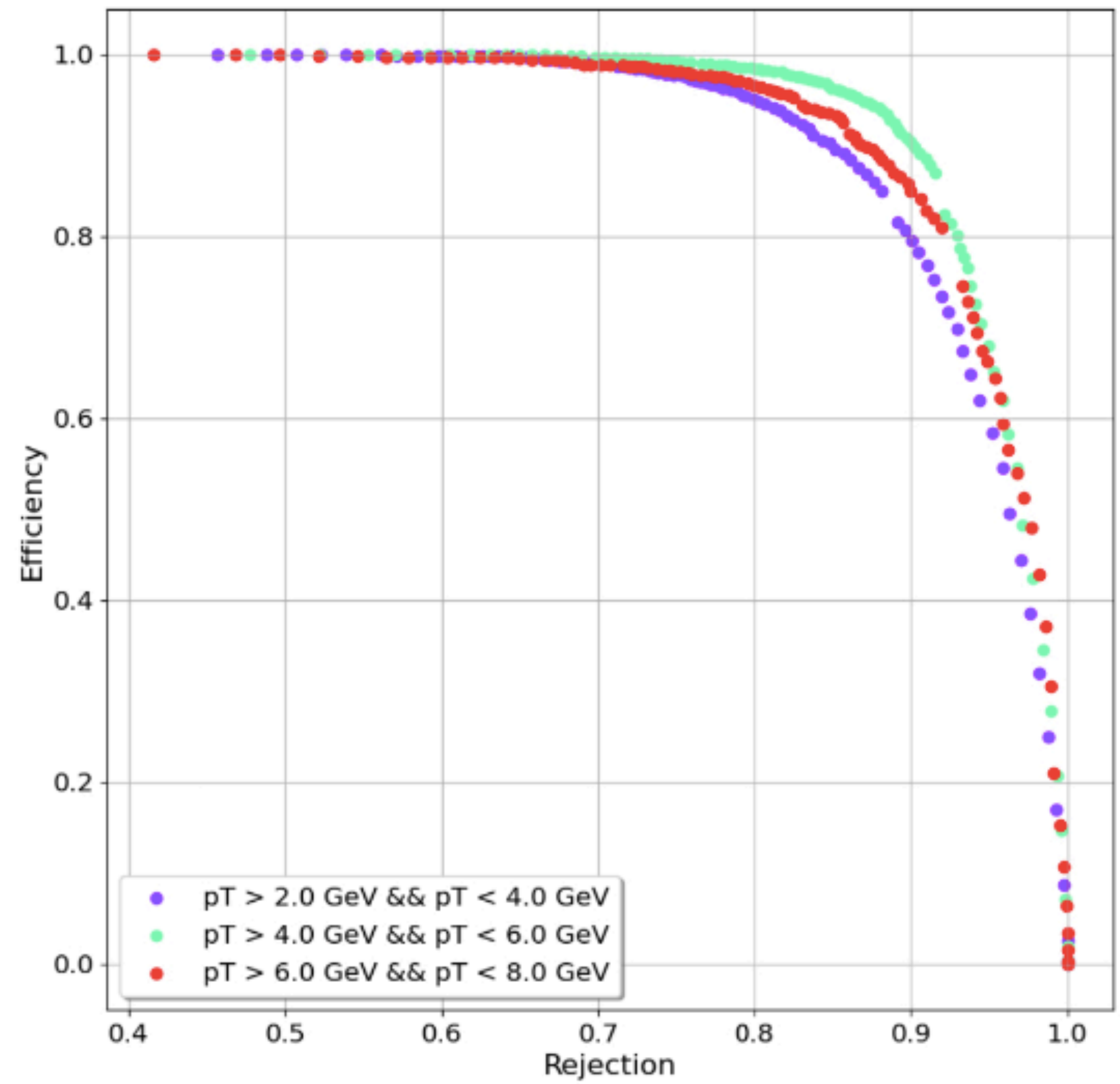


Other options for protection against photons generated in front of the target can be considered.

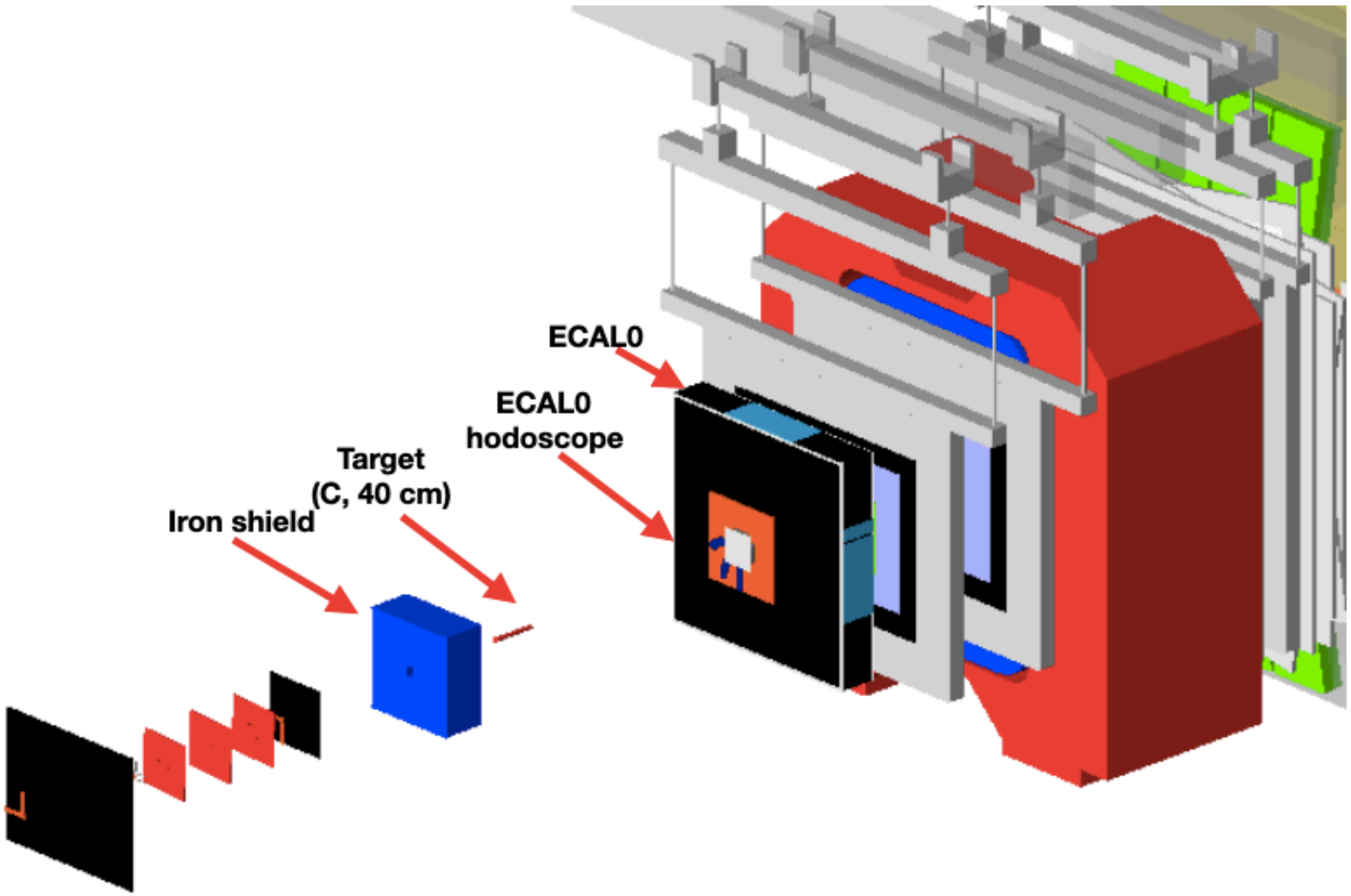


$\pi^0 \to 2\gamma$ cluster suppression

- Two-layer neural network with 64 neurons in a layer.
- 13 parameters dealing with cluster geometry and energy dependence.
- NN separates 1γ and 2γ clusters with 85% efficiency.



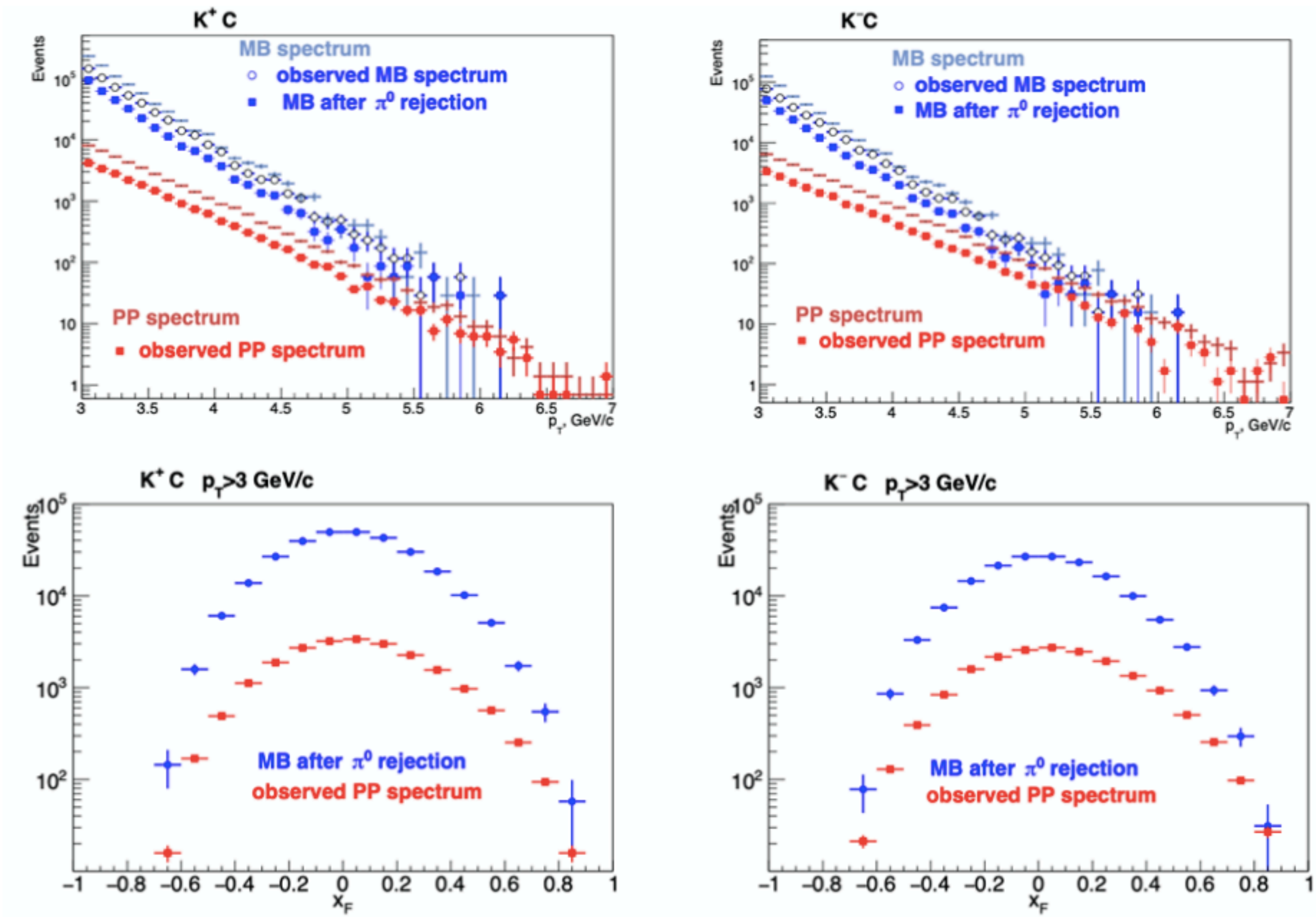
Proposed setup



Expected results

A data-driven MC-based background subtraction procedure:

$$N_{PP}(p_T, x_F) = N_\gamma(p_T, x_F) - N_{rem.bkg.}(p_T, x_F) = N_\gamma(p_T, x_F) - C_{MC}(p_T, x_F) \times N_{\gamma/\pi^0}(p_T, x_F).$$

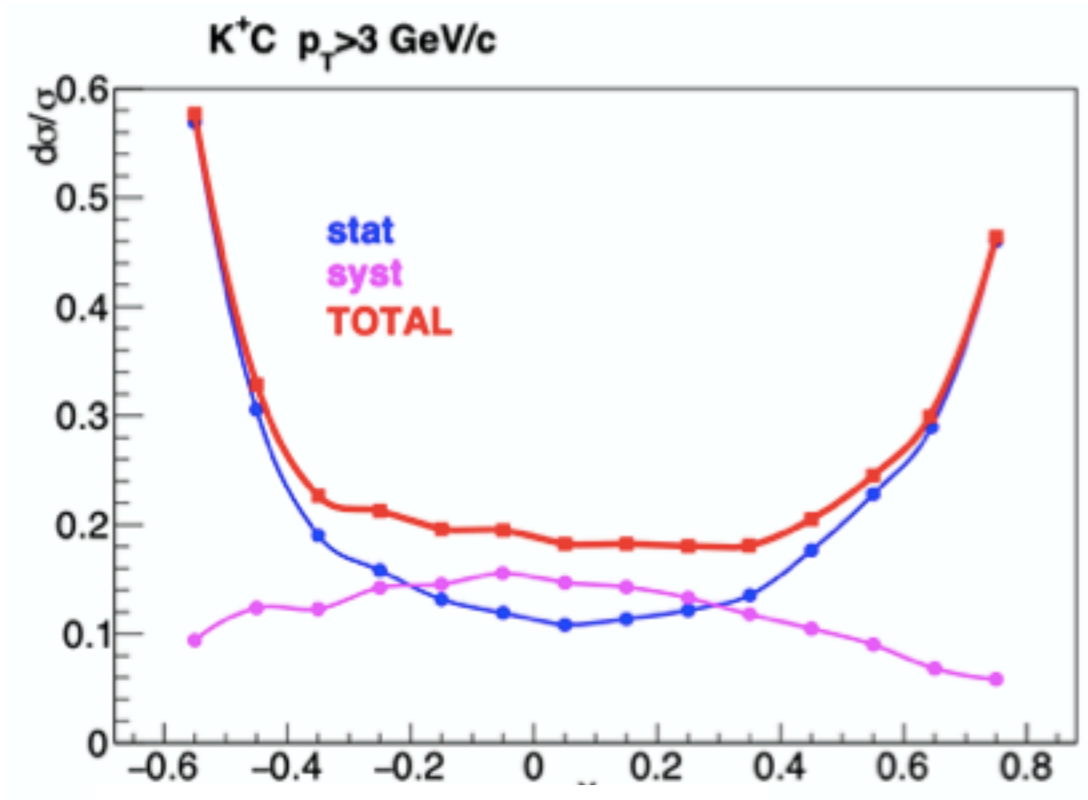


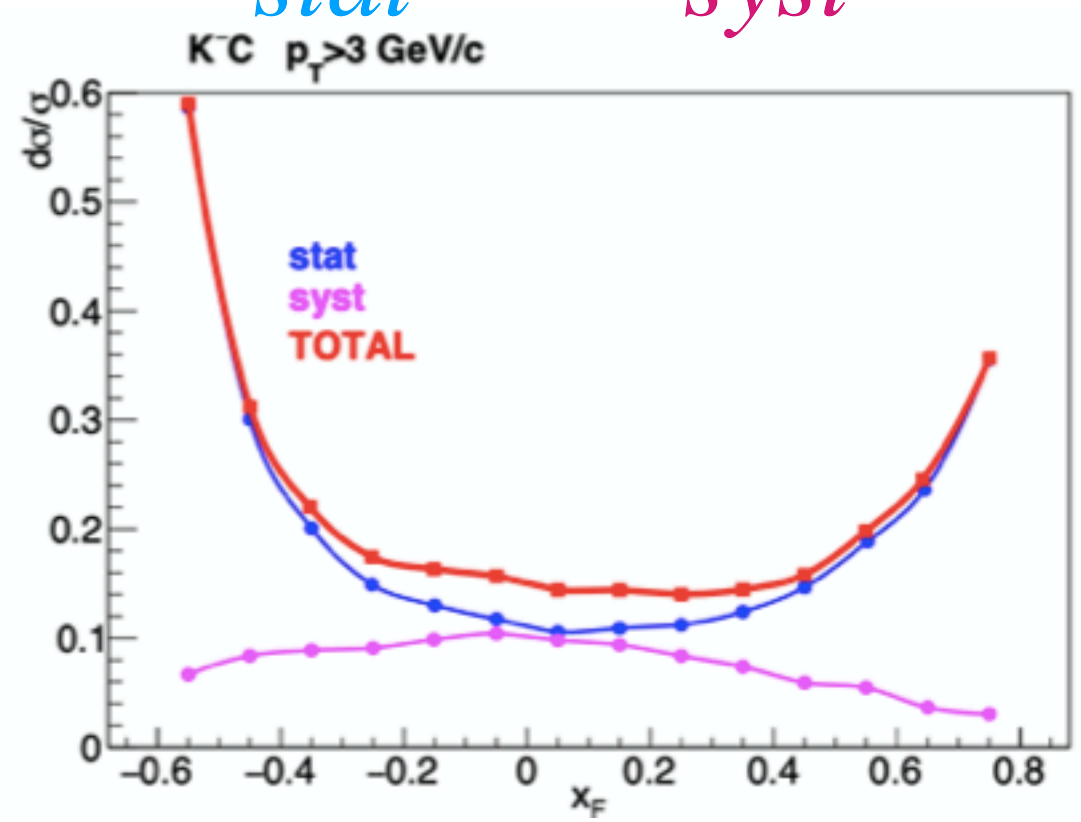
$$C_{MC}(p_T, x_F) \approx 3$$

Expected results

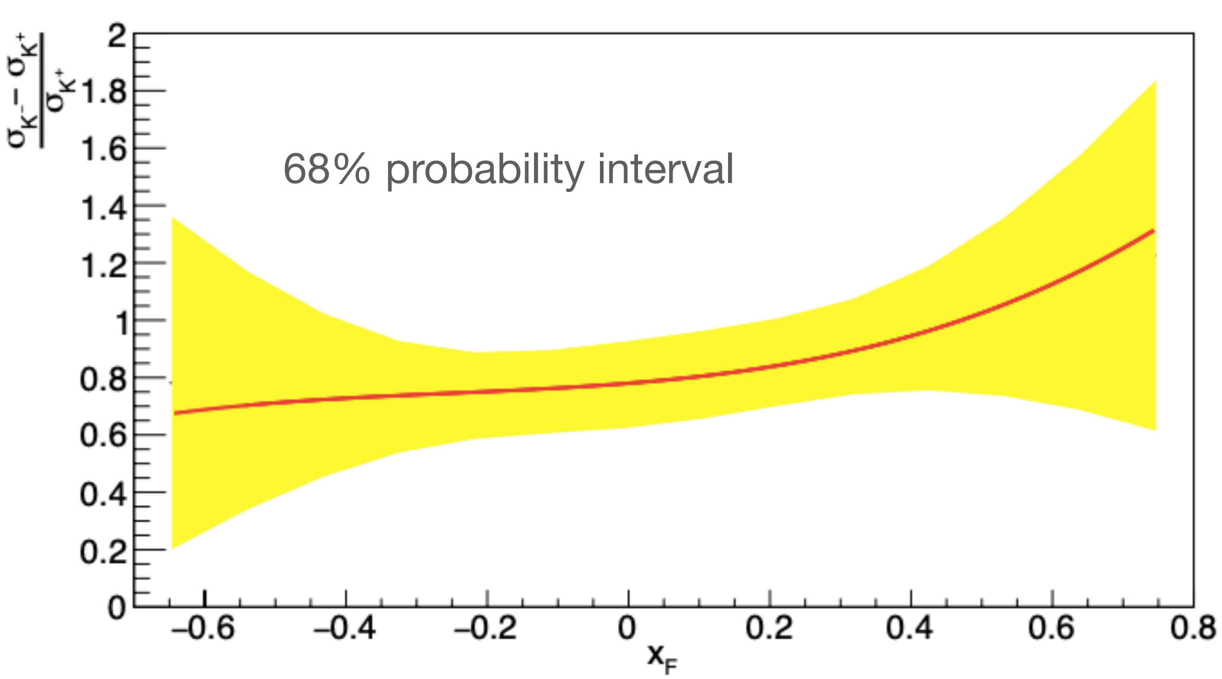
$$N_{PP}(p_T, x_F) = N_\gamma(p_T, x_F) - N_{rem.bkg.}(p_T, x_F) = N_\gamma(p_T, x_F) - C_{MC}(p_T, x_F) \times N_{\gamma/\pi^0}(p_T, x_F).$$

σ_{stat} σ_{syst} σ_{stat}





$+\sigma_{beam\ flux\ syst} \sim 5\%$



Uncertainty of cross section measurement: $\sigma_{K^\pm N \to \gamma X}$ for $p_T > 3$ GeV/c:

14.5% for K^+

10% for K^-

Conclusions

- Prompt photon production is an instrument that allows to get an access to kaon parton structure.
- Prompt photon cross section could be measured with uncertainty of 10-15% after one year of data taking.
- Additional data on prompt photon production with proton, antiproton and pion beams will be collected.
- Proposed measurement could be performed together with other planned measurements (DY, Primakoff).

Thank you for your attention