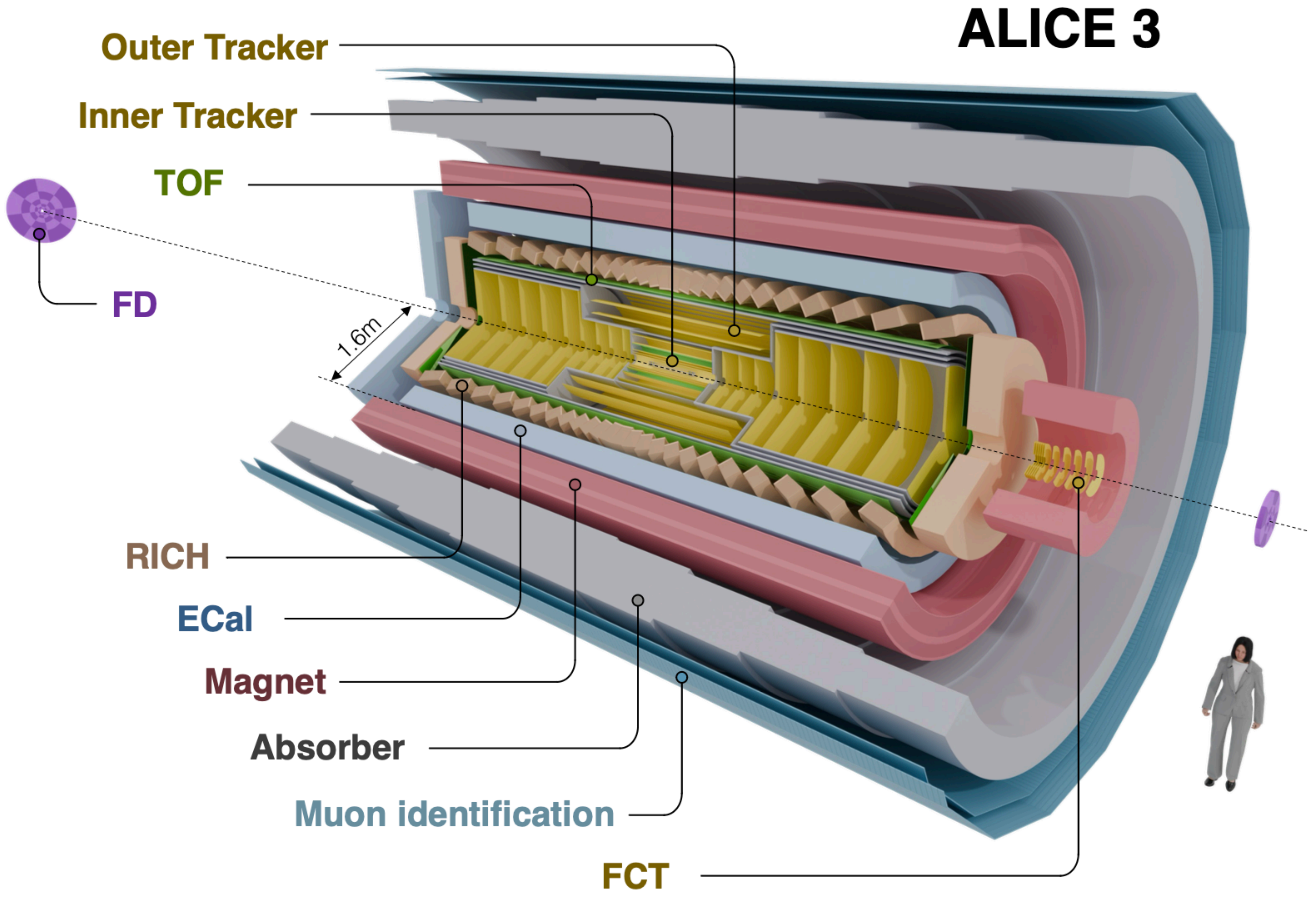
The ALICE 3 Forward Conversion Tracker (FCT)

EMMI workshop:
Soft Photons –
the higher orders

26 May 2025, Heidelberg

Klaus Reygers
Universität Heidelberg



“EMMI RRTF paper":
Anomalous soft photons: Status and perspectives,
Physics Reports 1097 (2024), 1–40”

Doctoral thesis Cas van Veen:
Simulation Studies for Measuring the Soft-Photon Spectrum with the ALICE 3 Forward Conversion Tracker, May 2025

Further references:

K.R.: *Status and Prospects: Experimental tests of Low's theorem*, EMMI RRTF

Peter Braun-Munzinger
- EMMI seminar, Feb. 2021, *Soft photons, the Low theorem, and ALICE 3*
- *Quark Matter 2022 student lecture*

Martin Völkl,
Prospects for testing Low’s theorem with ALICE3

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Anomalous soft photons: Status and perspectives

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ABSTRACT

This report summarizes the work of the EMMI Rapid Reaction Task Force on “Real and Virtual Photon Production at Ultra-Low Transverse Momentum and Low Mass at the LHC”. We provide an overview of the soft-photon puzzle, i.e., of the long-standing discrepancy between experimental data and predictions based on Low’s soft-photon theorem, also referred to as “anomalous” soft photon production, and we review the current theoretical understanding of soft radiation and soft theorems. We also focus on low-mass dileptons as a tool for determining the electrical conductivity of the medium produced in high-energy nucleus–nucleus collisions. We discuss how both topics can be addressed with the planned ALICE 3 detector at the LHC.

Motivation for the ALICE 3 Forward Conversion Tracker

Soft photon puzzle:
Striking discrepancies between predictions and experimental measurements.

No agreement exists on their possible origin, despite > 40 years of research.

Last measurement: 2006 and 2008 (DELPHI)

Significant progress in detector technology in the meantime

High time for new experiment(s)!

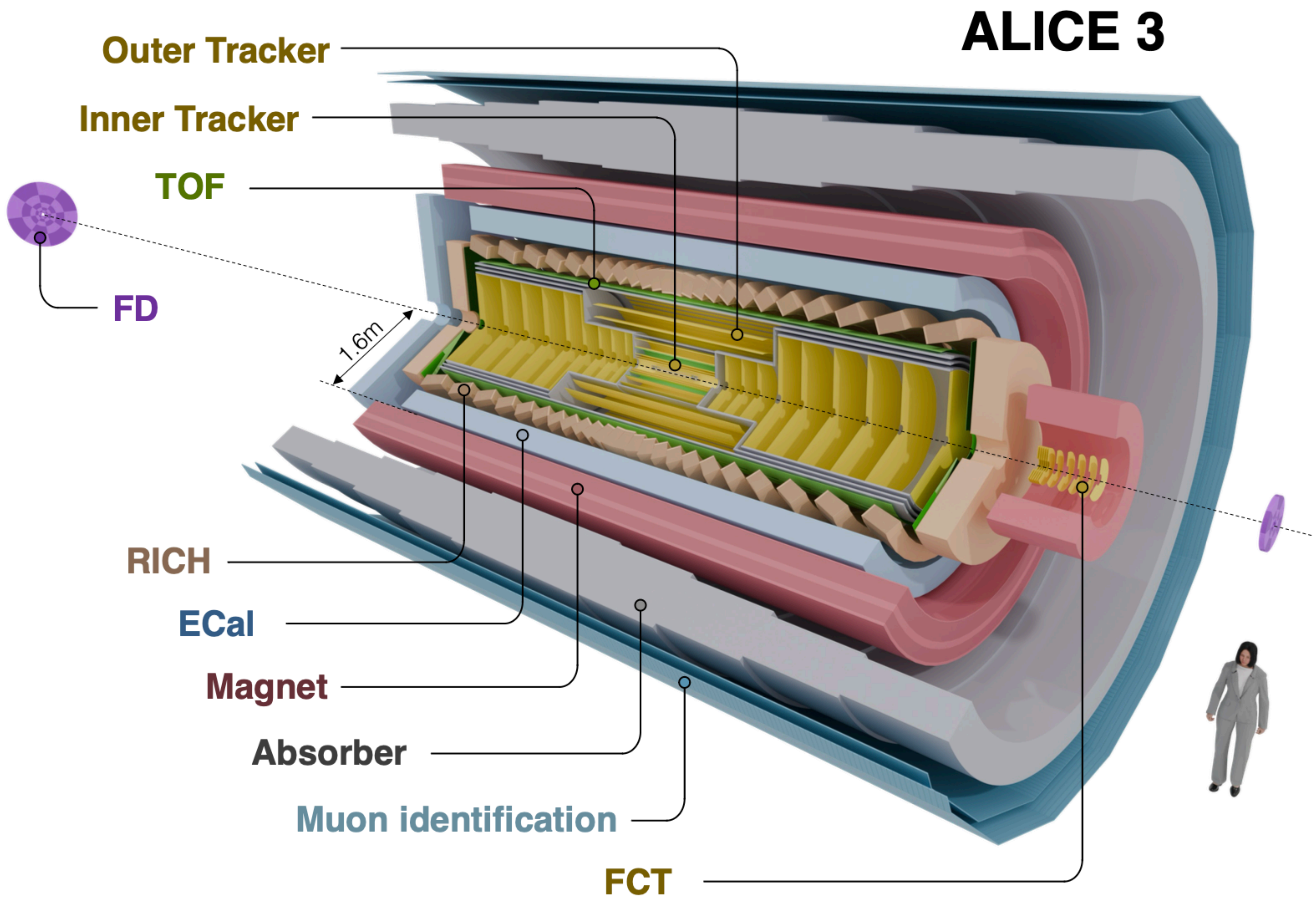
The ALICE 3 Forward Conversion Tracker (FCT)

11 consecutive silicon disks with monolithic pixel trackers

Dipole magnet with a magnetic field of ~ 0.25 T

Pseudorapidity range: $4 < \eta < 5$

Cost: ~ 5 M CHF



The Low divergence: defining the observable

Leading power expression for Low photons:

$$\frac{dN_\gamma}{d^3\vec{k}} = \frac{\alpha}{(2\pi)^2} \frac{-1}{\omega} \int d^3\vec{p}_1 \dots d^3\vec{p}_N \left(\sum_i \frac{\eta_i e_i p_i}{p_i k} \right)^2 \frac{dN_{\text{hadrons}}}{d^3\vec{p}_1 \dots d^3\vec{p}_N}$$

$\omega \equiv |\vec{k}|$

transverse momentum of the photon w.r.t. the direction of the charged particle

The photon production amplitude has a pole whenever $p \cdot k$ vanishes:

$$pk = \omega E - |\vec{k}||\vec{p}| \cos\theta$$

For $E \approx p$: $pk \approx \omega E(1 - \cos\theta) \approx \omega E \frac{\theta^2}{2} = k_T E \frac{\theta}{2}$

In the rest frame of the charged particle:
Photon energy must be much smaller than the mass of the charged particle to approach the Low limit.

In the laboratory frame:
Low limit is approached for $\theta \to 0$. Implies divergence for $k_T \to 0$.

V.N. Gribov, "Bremsstrahlung of hadrons at high energies", Sov.J.Nucl.Phys. 5 (1967) 280

k_T w.r.t. the beam axis or jet axis as a proxy

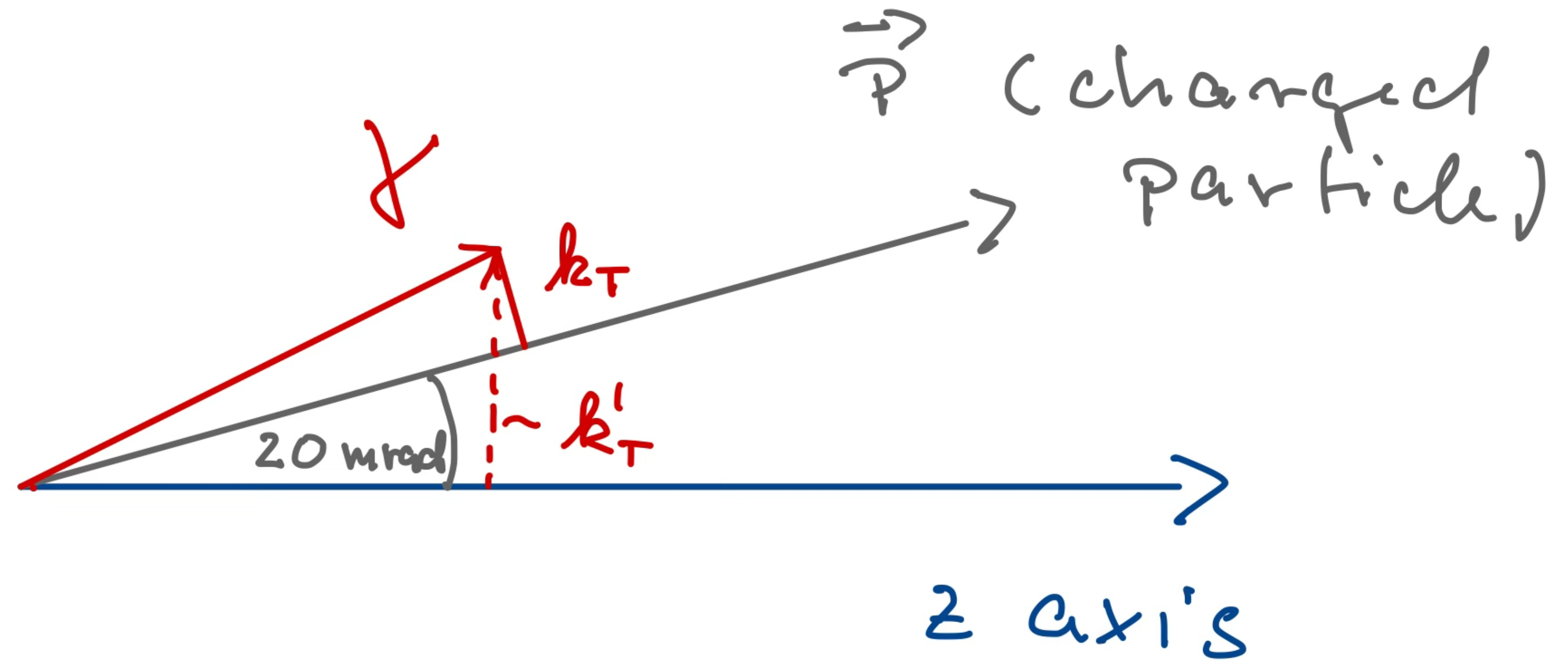
WA91/102 (fixed target experiments): measured photon k_T w.r.t. beam axis

DELPHI ($e^+e^- \rightarrow n$ jets): measured photon k_T w.r.t. jet axis

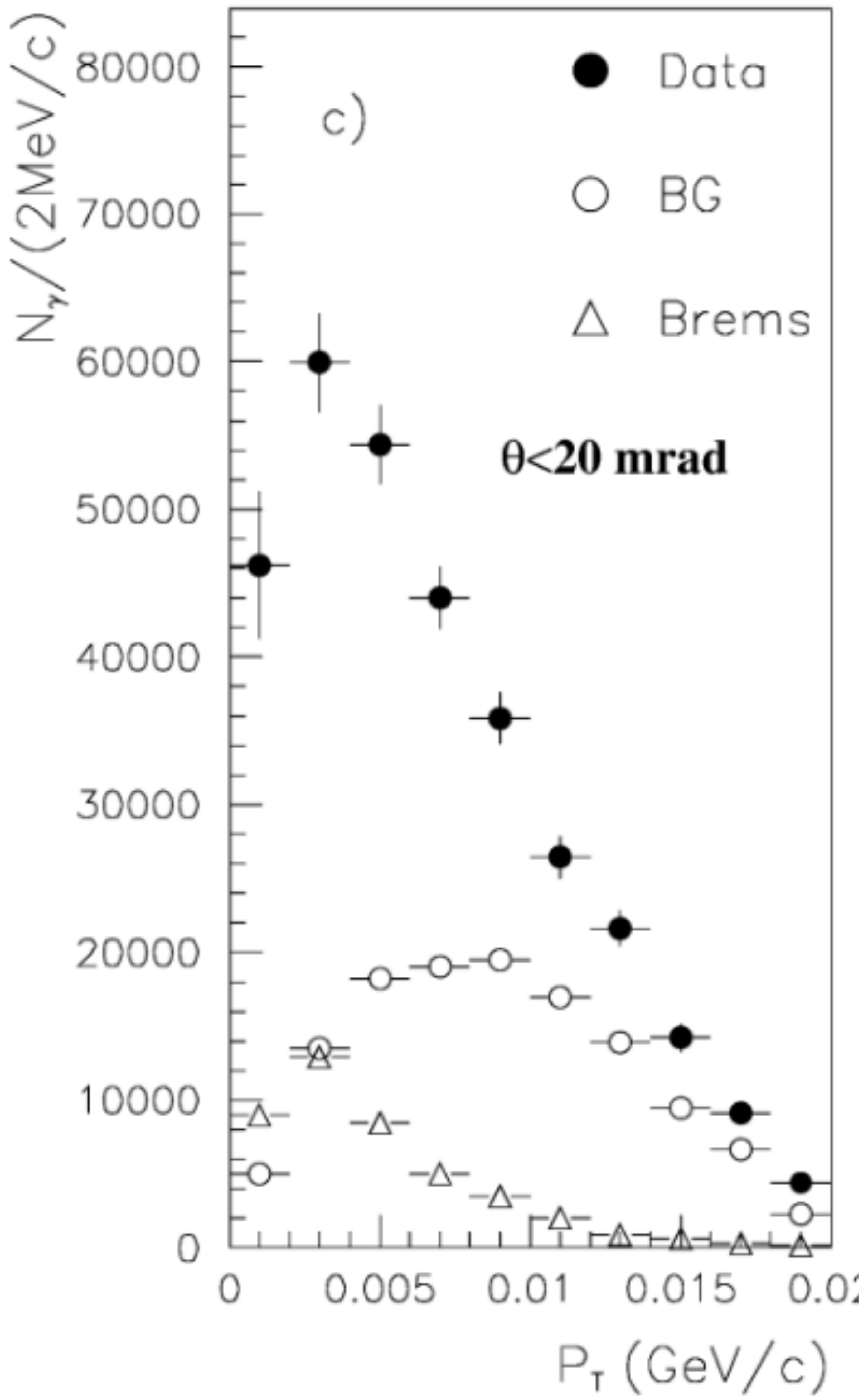
WA91/102: Excess concentrated at $\theta < 20$ mrad

Typical pion ($p_T \approx 400$ MeV/c) with $\theta = 20$ mrad: $\gamma \approx 142$.
Most likely photon emission angle: $\theta_\gamma \approx \sqrt{3}/\gamma = 12$ mrad

For WA91/102 taking the k_T w.r.t to the beam axis and not w.r.t the particle direction does not have a major effect.



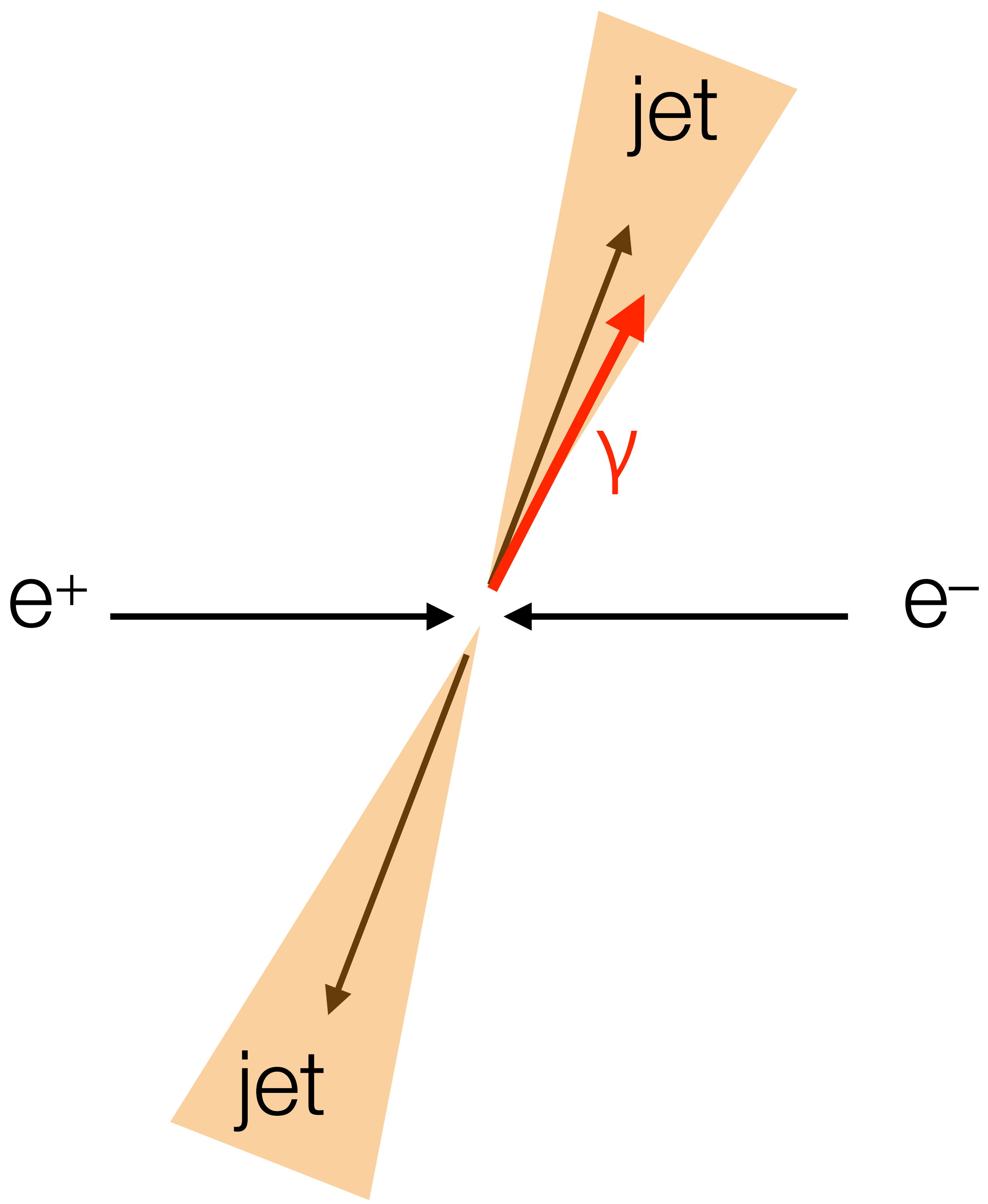
WA102, pp, p_{beam} = 450 GeV/c



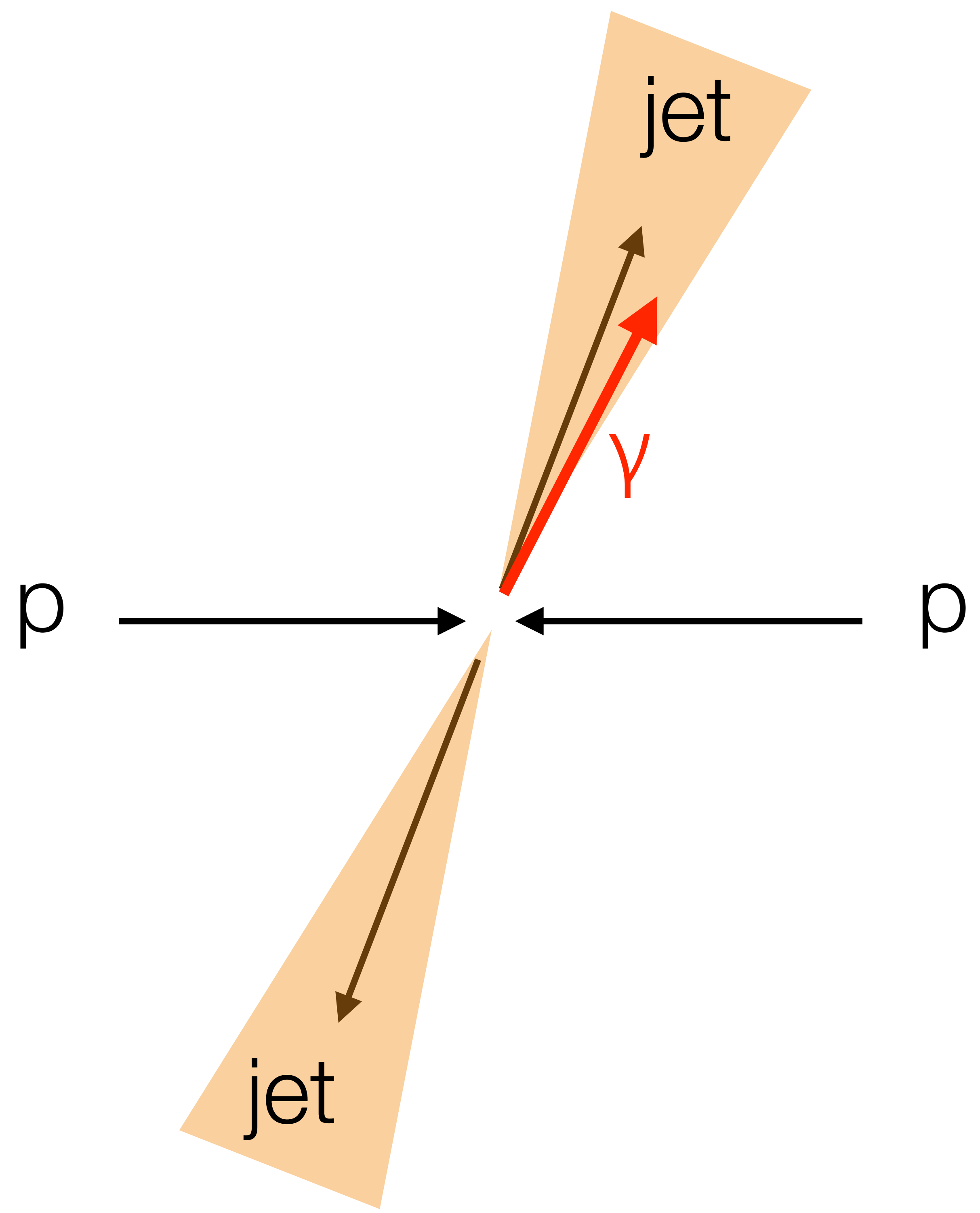
A soft photon detector – basic considerations

Low photon measurement at midrapidity w.r.t. a charged trigger particle?

DELPHI



ALICE 3?



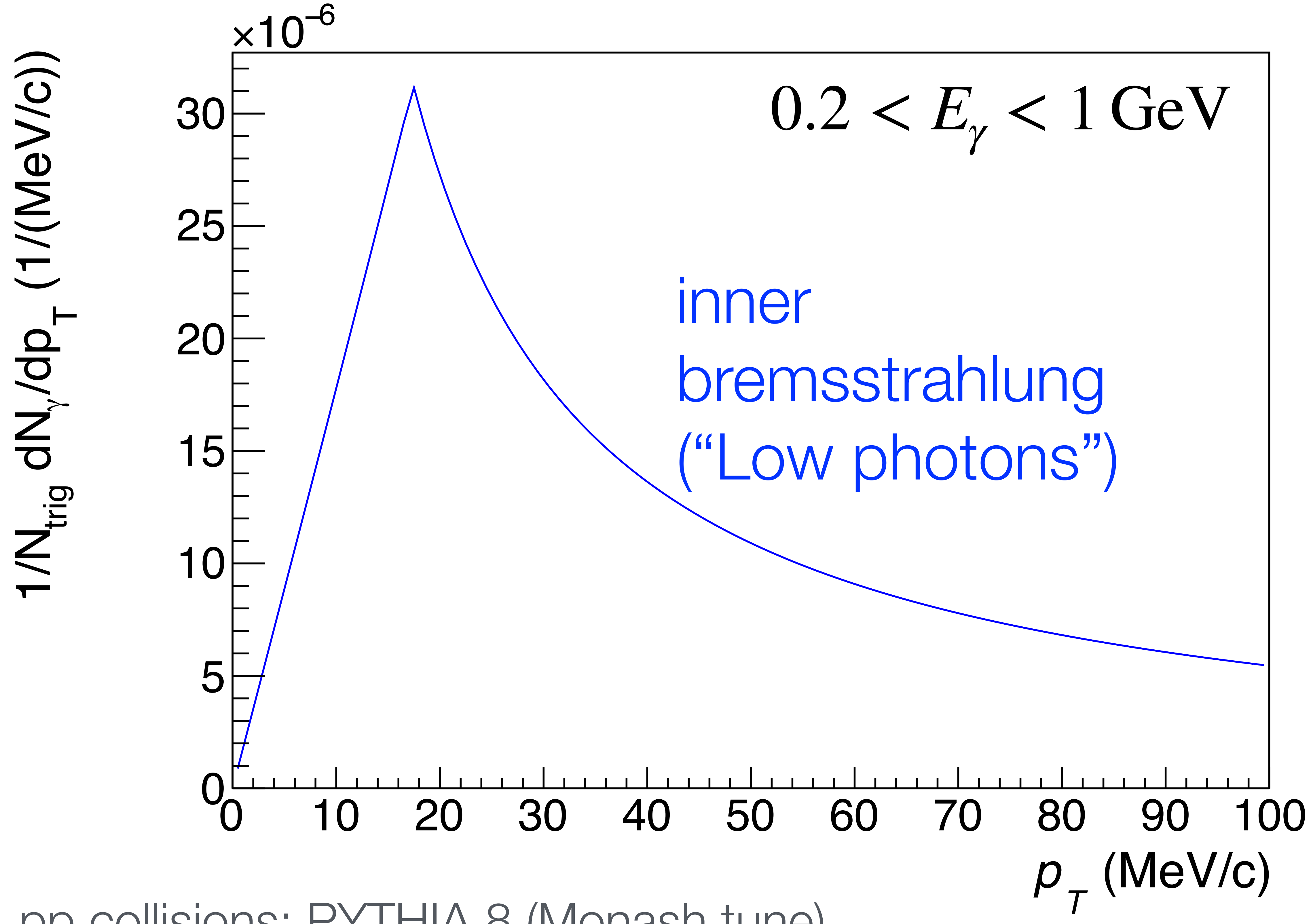
Need to study decay photon background from π^0's and η's of the underlying event

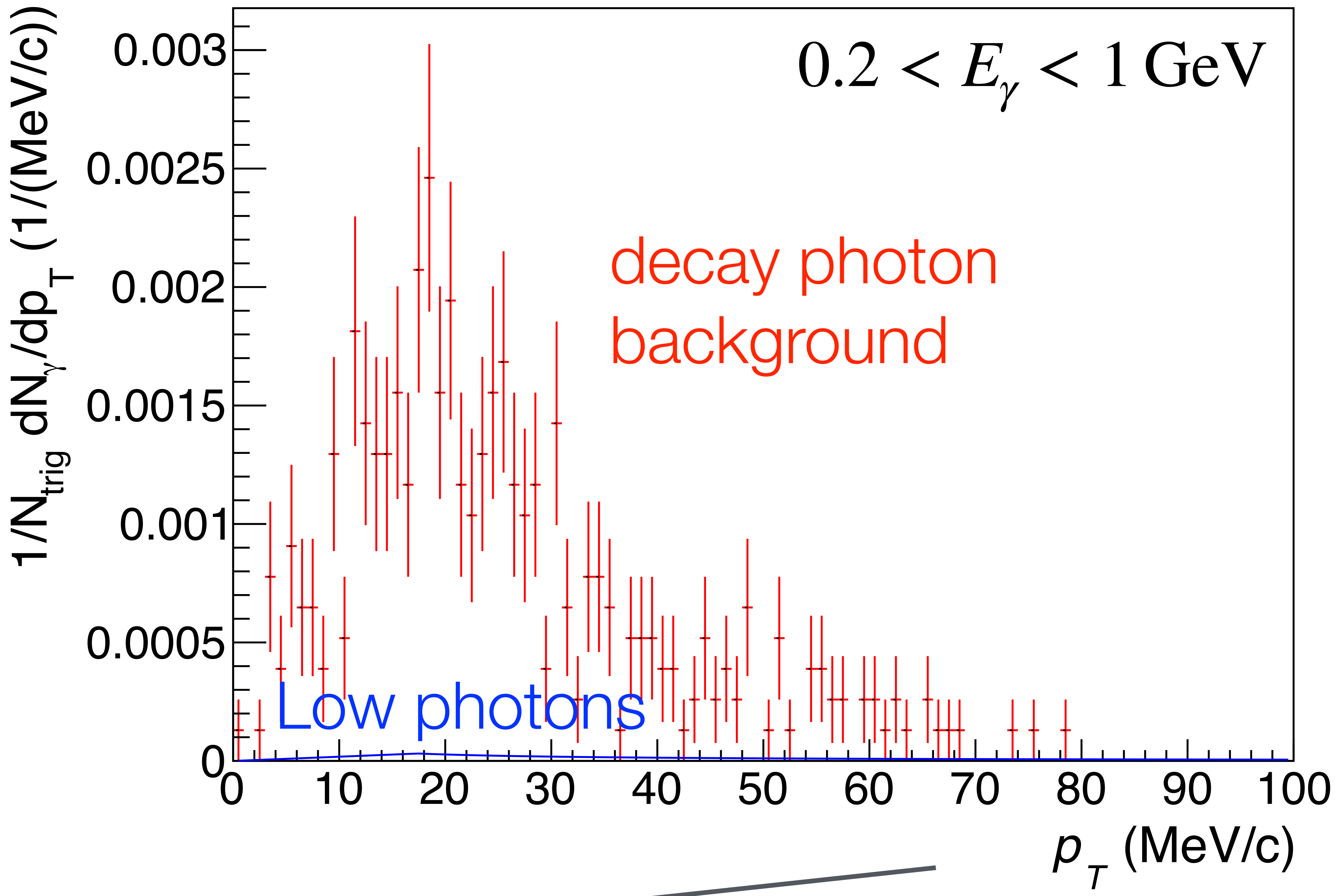
A DELPHI-style measurement in pp at η ≈ 0 is not feasible with ALICE 3

trigger particle:
- $-0.5 < \eta < 0.5$
- $p_T > 5$ GeV/c
- charged

photon:
- $\theta_{max} = 5°$ w.r.t. trigger particle
- $0.2 < E_\gamma < 1$ GeV

Low photons overwhelmed by decay photons

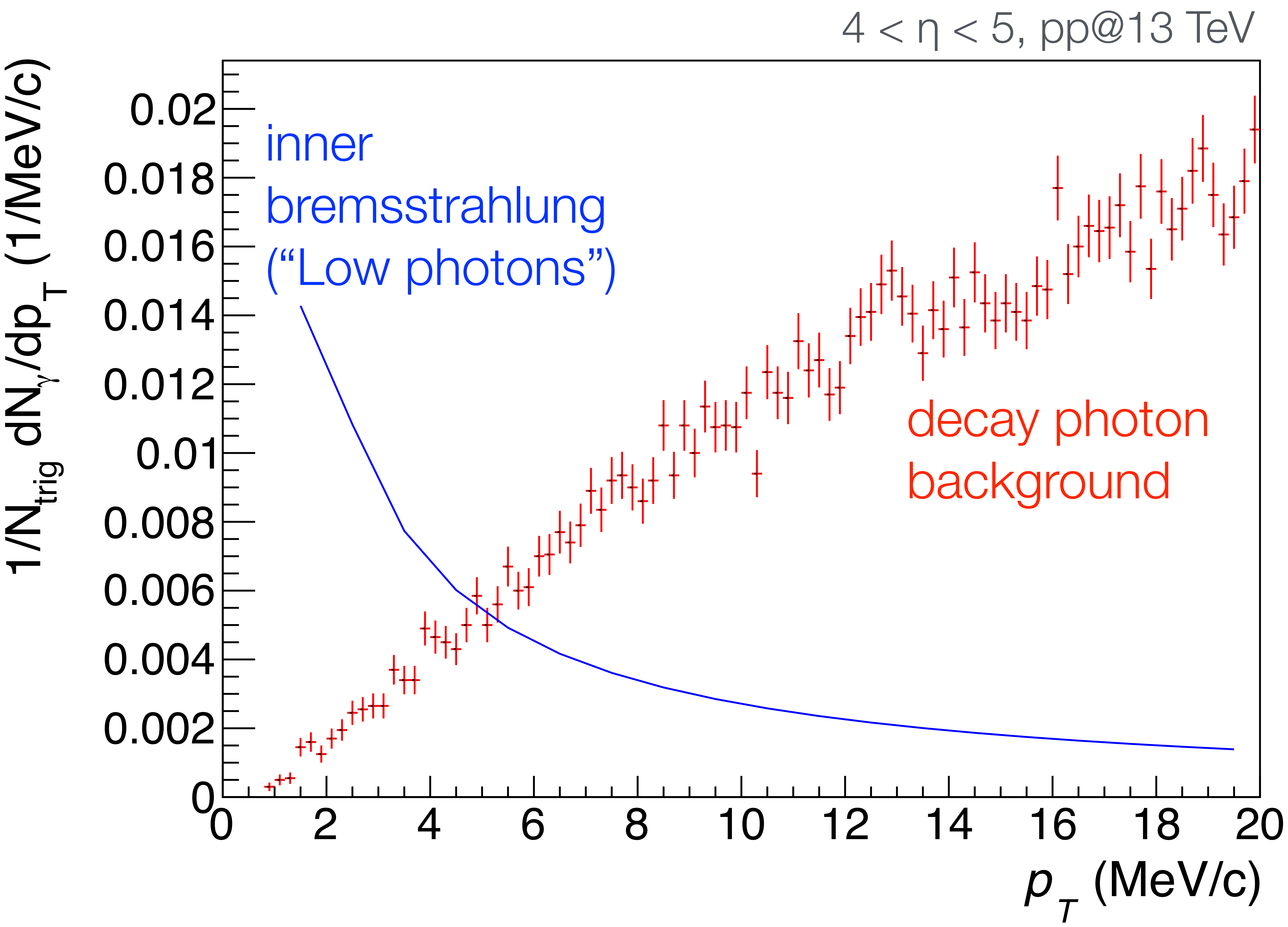




pp collisions: PYTHIA 8 (Monash tune)

w.r.t. trigger particle

Making use of the “Jacobian peak” is essential



Neutral pion with $p_{T,\text{pion}} = 0$:

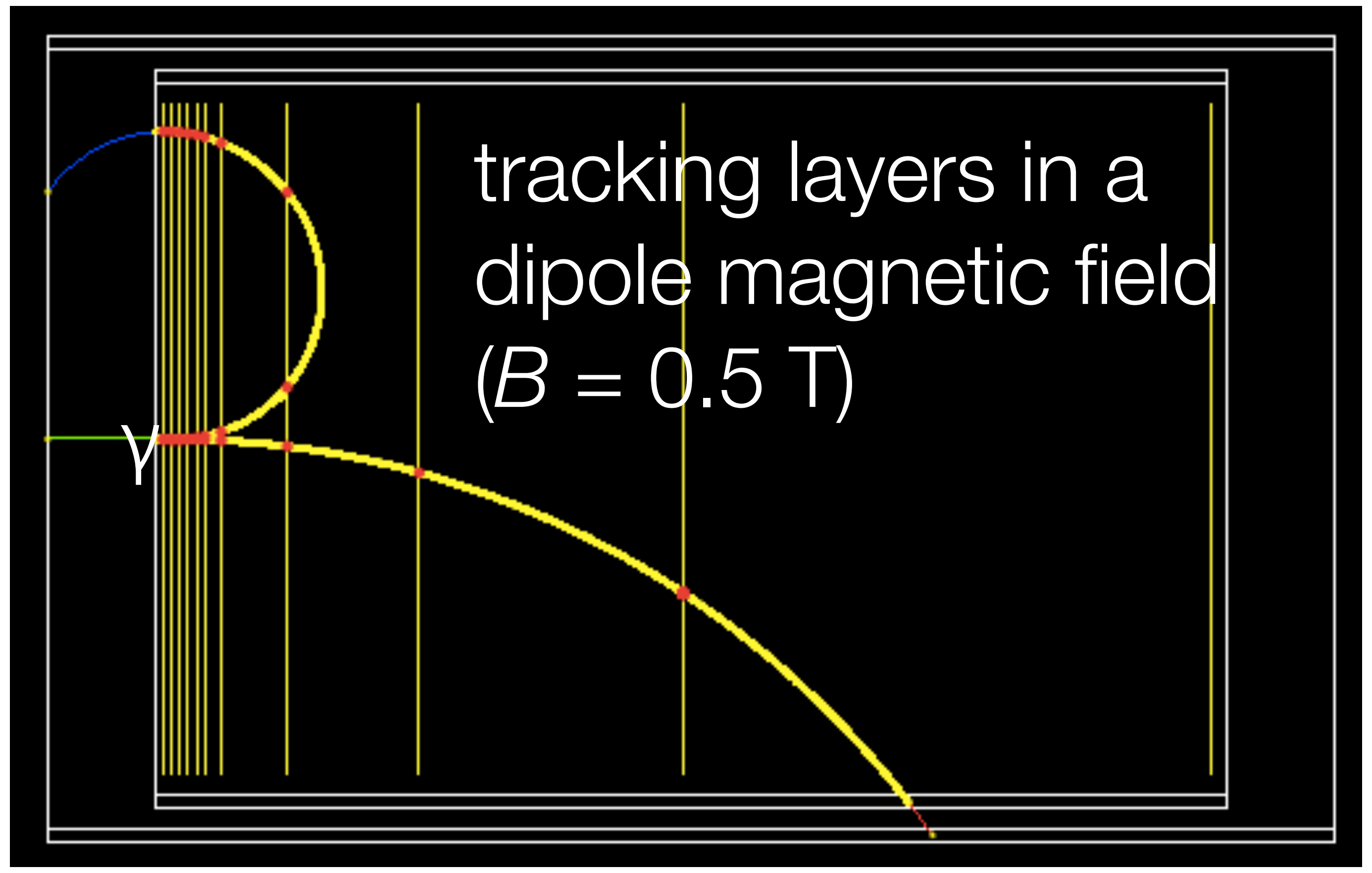
$$\frac{dN_\gamma}{dp_T} = \frac{2p_T}{m_{\pi^0}} \frac{1}{\sqrt{\left(\frac{m_{\pi^0}}{2}\right)^2 - p_T^2}}$$

The inner bremsstrahlung signal dominates over the decay photon background for $p_T \lesssim 5$ MeV/c.

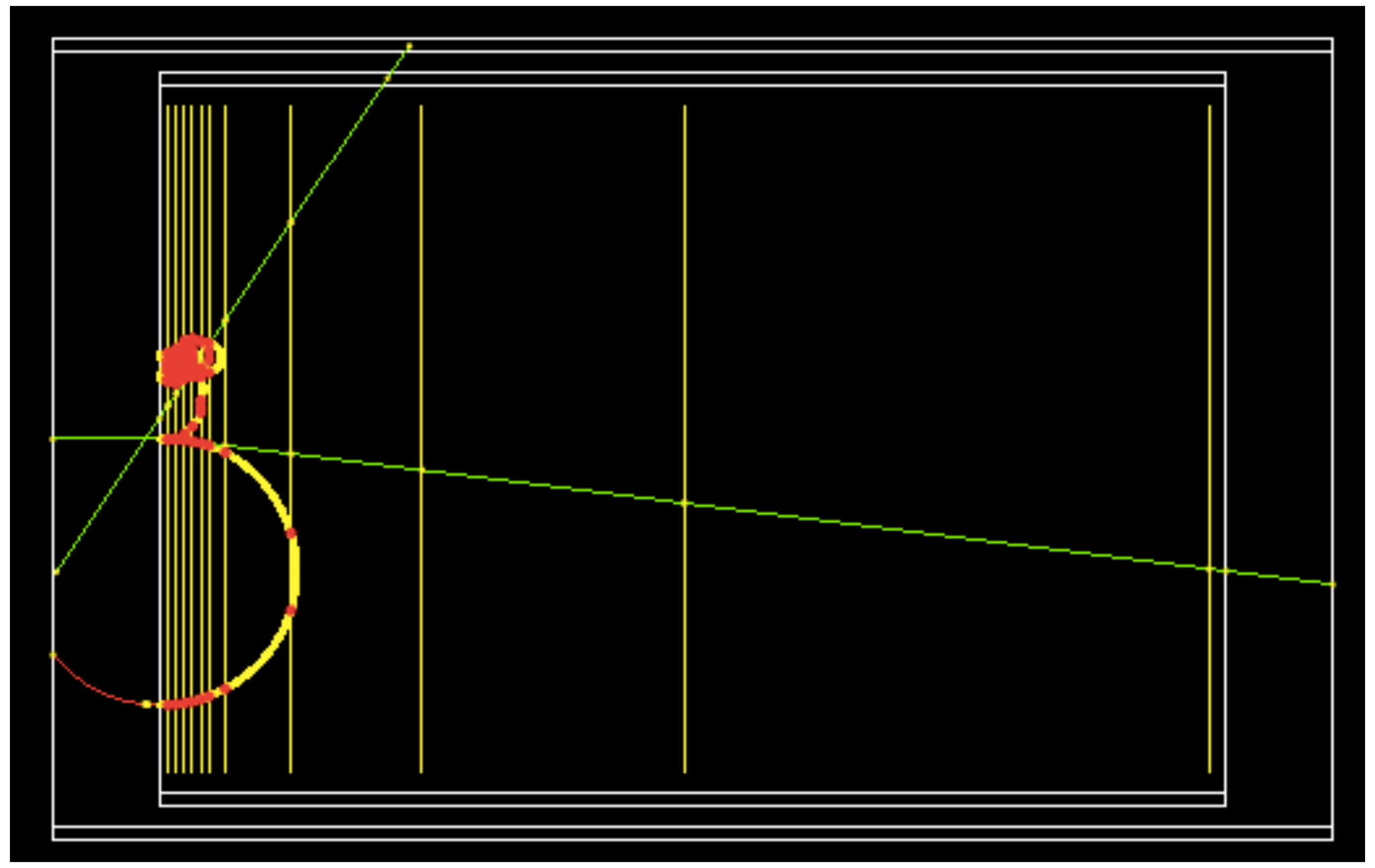
The 1–10 MeV/c k_T range is only accessible at forward rapidities

γ reconstruction via conversions:

E_γ = 100 MeV: easy



E_γ = 20 MeV: not so easy



~ 32 cm

Photon conversion measurement possible for $E_\gamma \gtrsim$ 50–100 MeV.

$$p_T = \frac{E_\gamma}{\cosh \eta}, \quad \cosh \eta \approx 10,\ 27,\ 74 \text{ for } \eta = 3,\ 4,\ 5$$

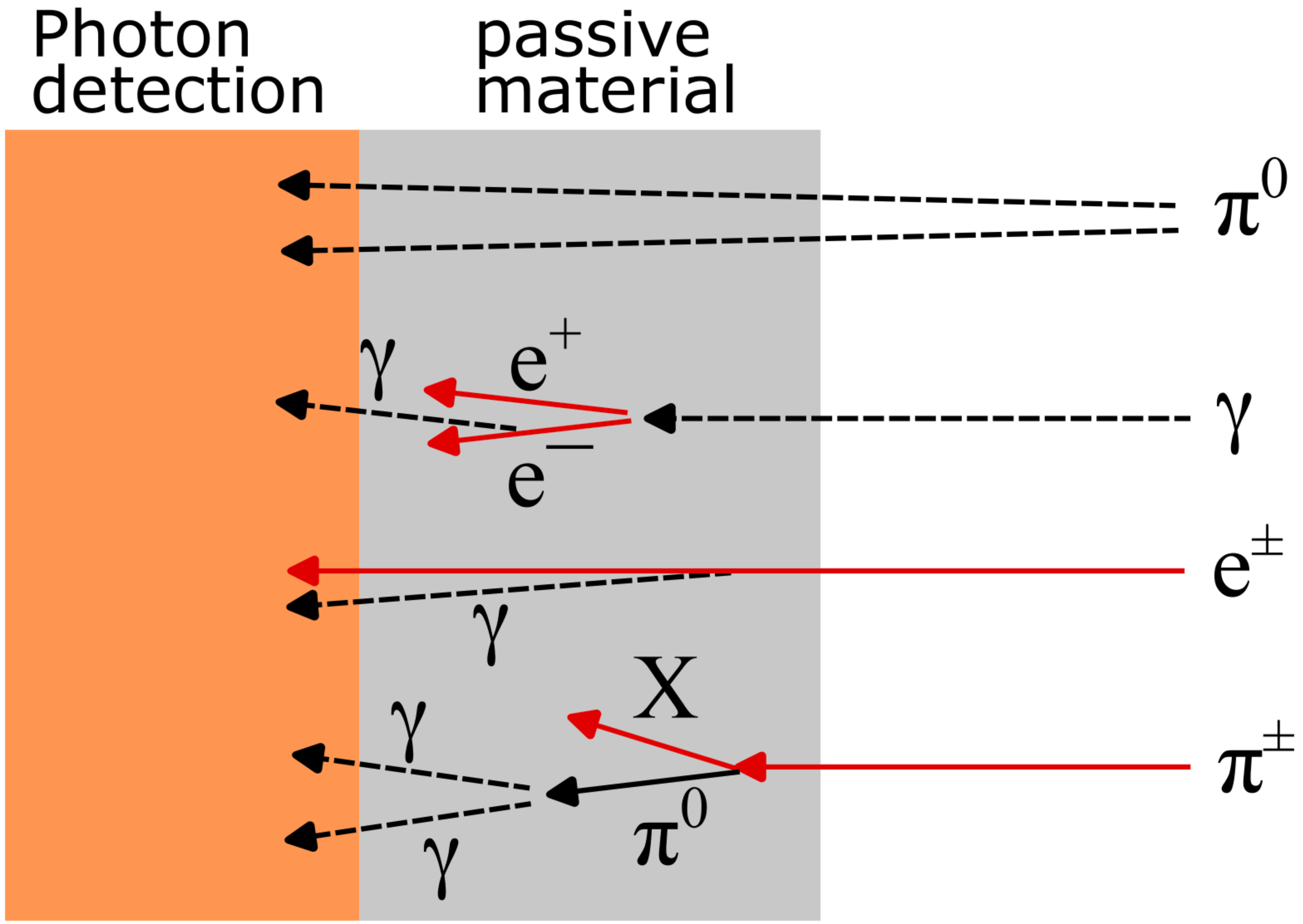
$E_\gamma = 100\,\text{MeV}$:

η	3	4	5
p_T (MeV/c)	10	3.7	1.3

Need to measure photons at η ≈ 4–5 to reach sufficiently low photon p_T.

Requires **dipole magnetic field** for accurate $e^\pm$ momentum reconstruction.

Effective background suppression is key to a successful measurement



Main background sources:

Decay photons (π^0, $\eta \rightarrow \gamma\gamma$)

External bremsstrahlung from $e^\pm$ (from photo conversion and primary $e^\pm$)

Decay photons of π^0's and η's produced in **secondary interactions**

A useful pocket formula for the background from photon conversions

$$\frac{dN_\gamma^{\mathrm{ext.brems}}}{d\omega} \approx \frac{4}{3}\frac{x}{X_0}\frac{1}{\omega} \qquad p_{\mathrm{conv}} \approx \frac{7}{9}\frac{x}{X_0}$$

"EMMI RRTF paper":
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Physics Reports 1097 (2024), 1–40"

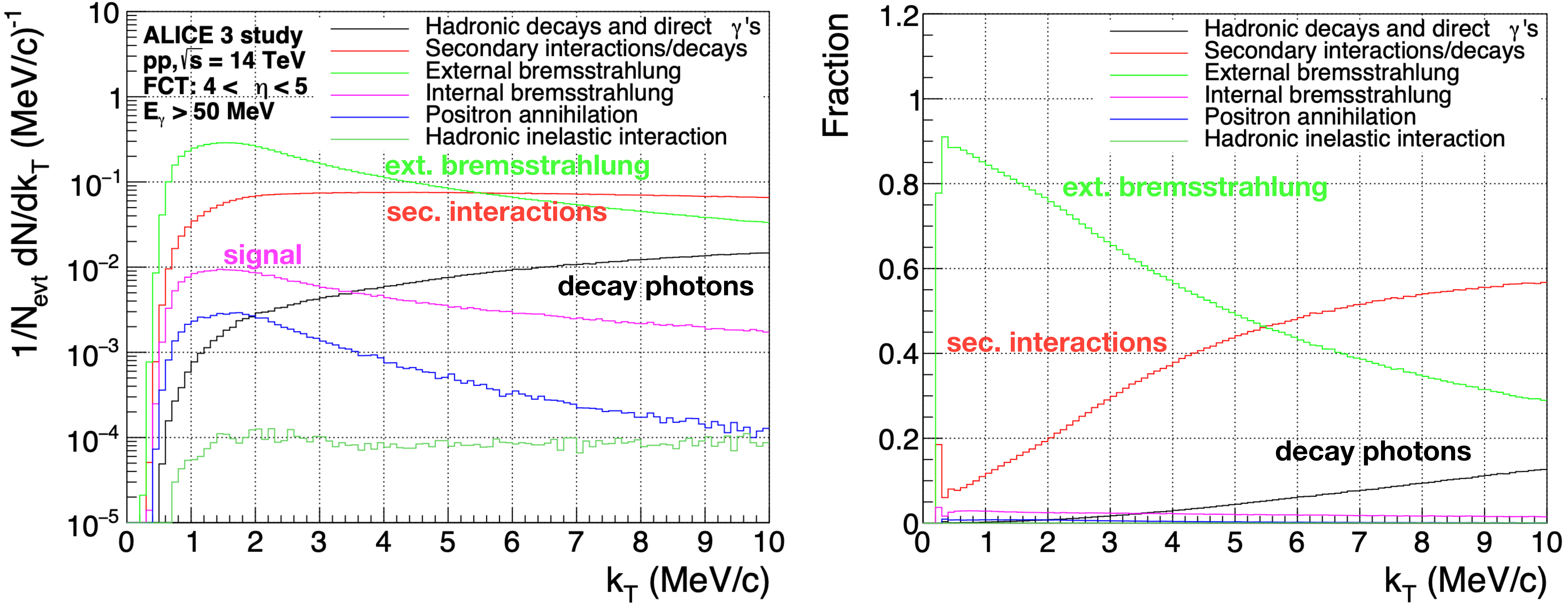
$$\Rightarrow \quad \frac{dN_\gamma^{\mathrm{ext.brems}}}{dk_T\, d\eta} \approx \frac{28}{27}\frac{dN_\gamma^{\mathrm{decay}}}{d\eta}\left(\frac{x}{X_0}\right)^2\frac{1}{k_T}$$

confirmed by full GEANT simulation to be an accurate approximation

Background of external bremsstrahlung from conversations of decay photons **increases quadratically** with the material in front of the photon detector.

Need to **minimize material** in front of the photon detector.

In the absence of background suppression, the signal is overwhelmed



Background reduction strategies

Pointing angle cut – require reconstructed photons to point to the vertex

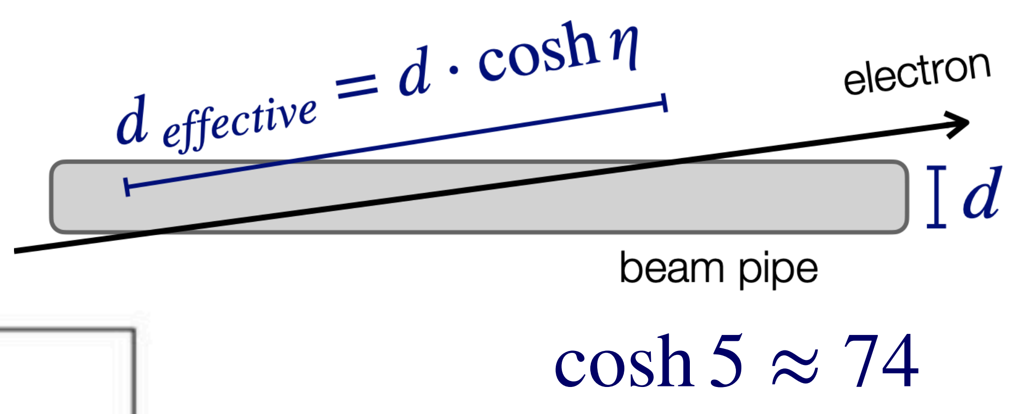
Cut on the distance to the closest charged particle track at the entrance of the FCT. Removes external bremsstrahlung produced relatively close to the FCT so that corresponding charged track is still close to bremsstrahlung photons.

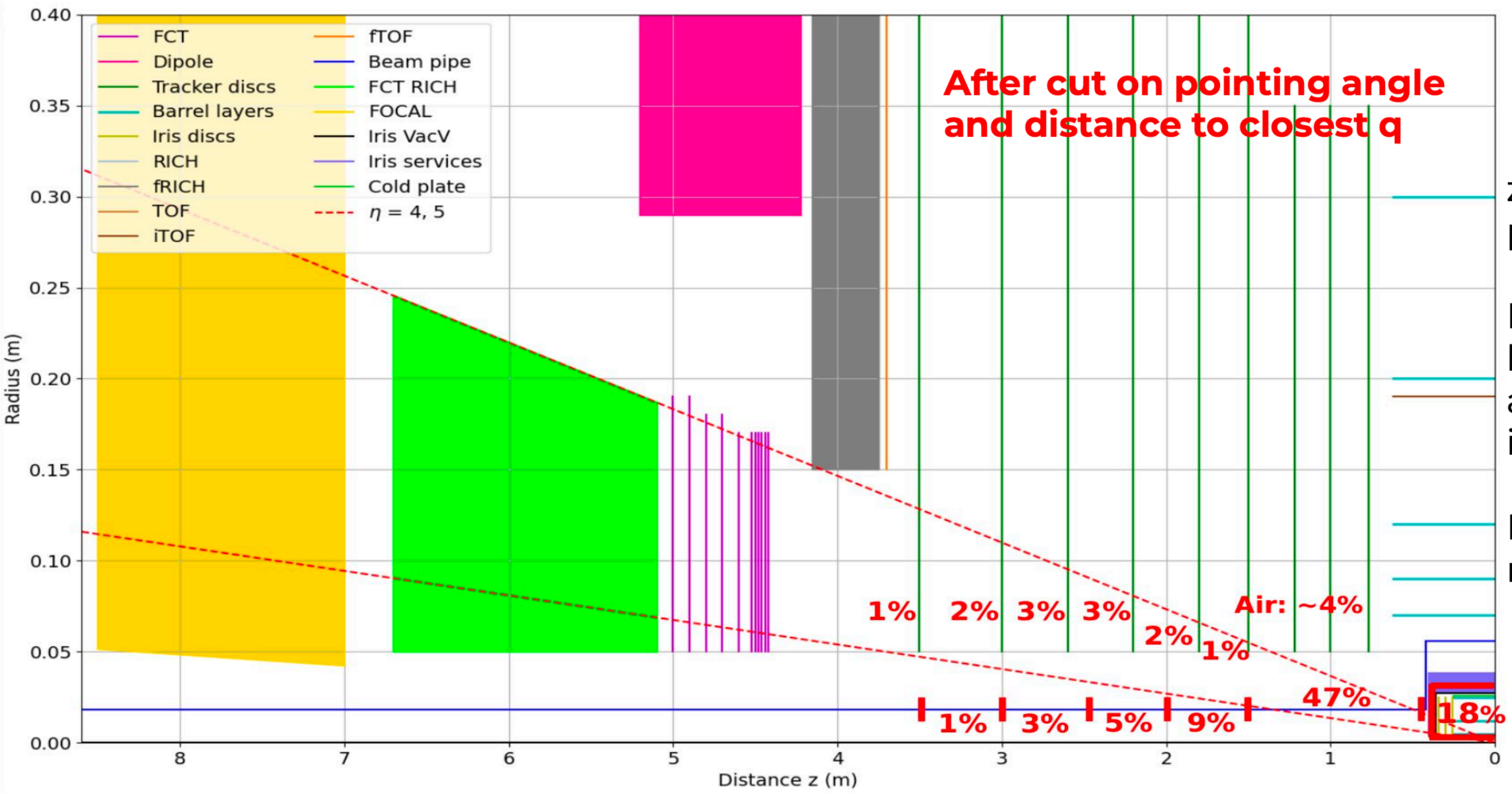
Window in the beam pipe to reduce material budget

RICH to veto events with $e^{\pm}$ (like DELPHI). Studied extensively, but turned out to be hard to realize.

Pointing angle and track proximity cuts are not sufficient;
a beampipe window is necessary.

Relative background contributions by detector component



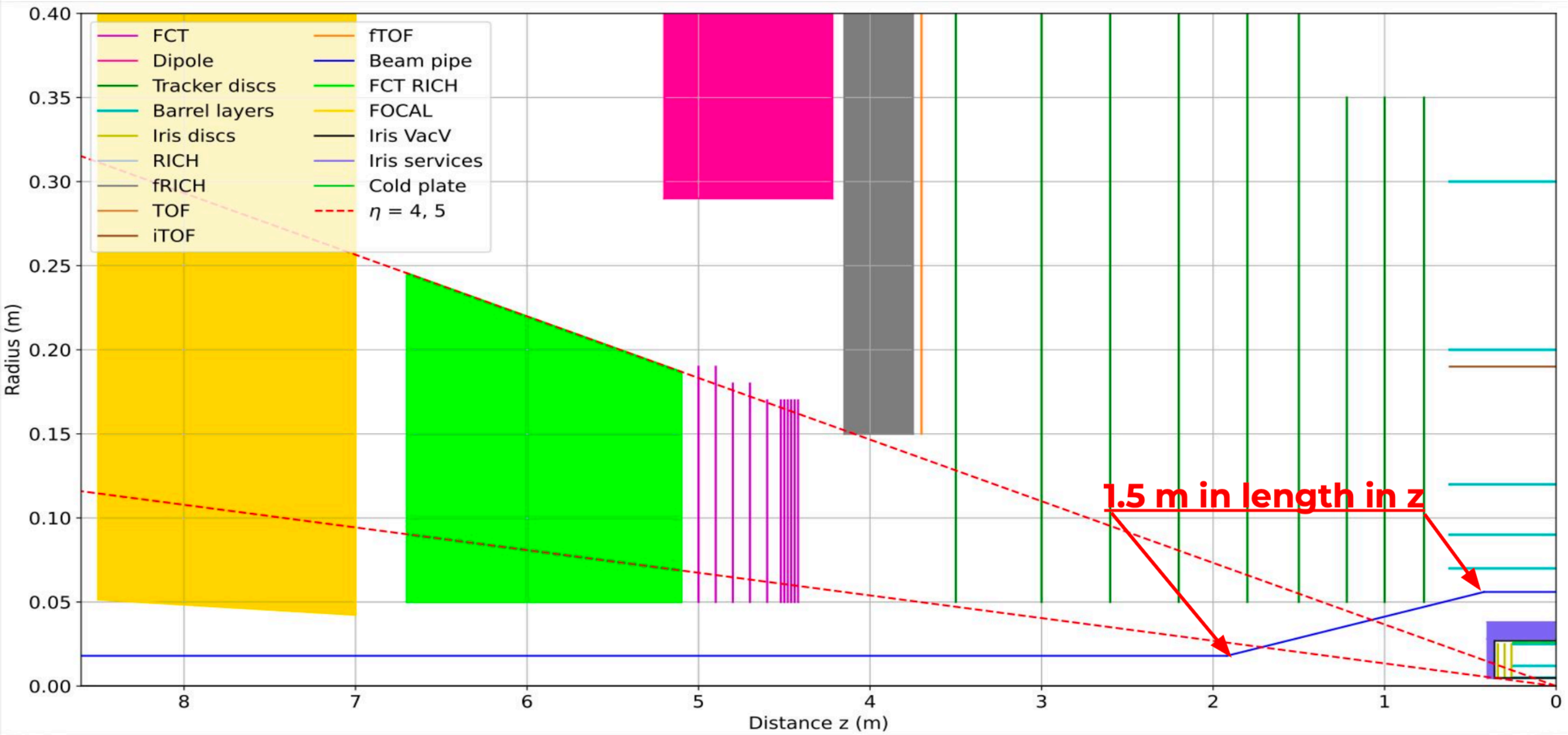


z-origin of photons plotted

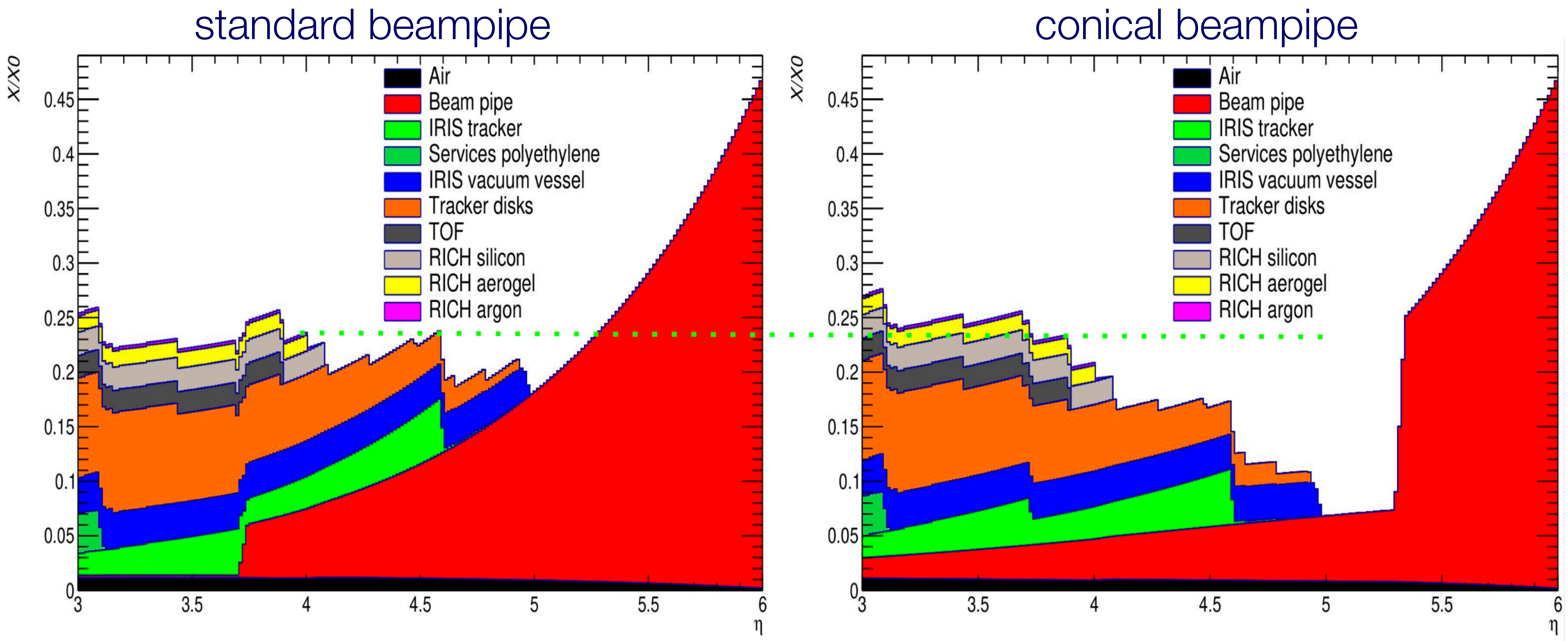
External bremsstrahlung and secondary interactions.

Hadron decay not included.

Background reduction with a conical beampipe



Material budget: standard vs. conical beampipe



Relative background contributions by detector component (conical beampipe)

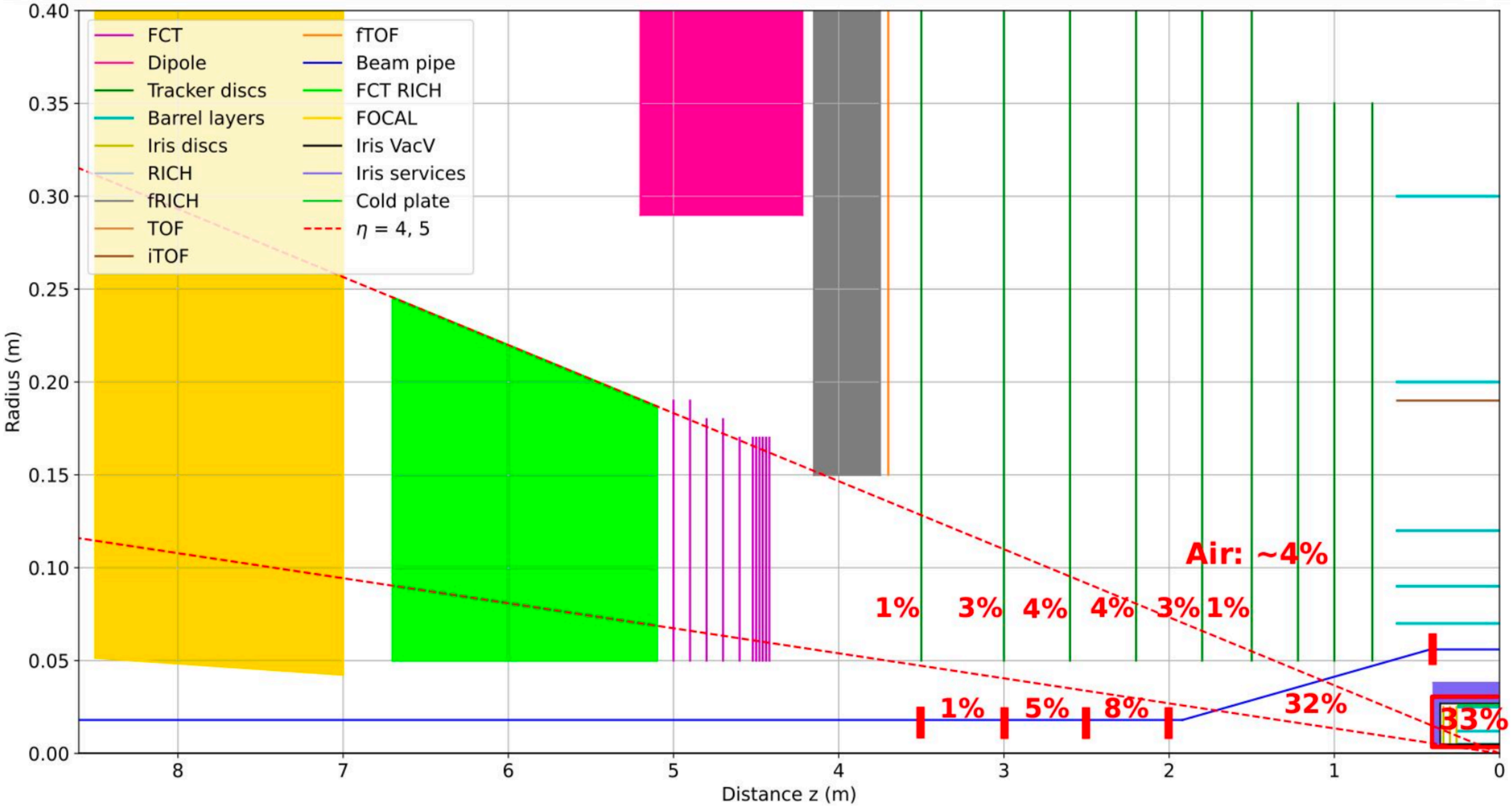
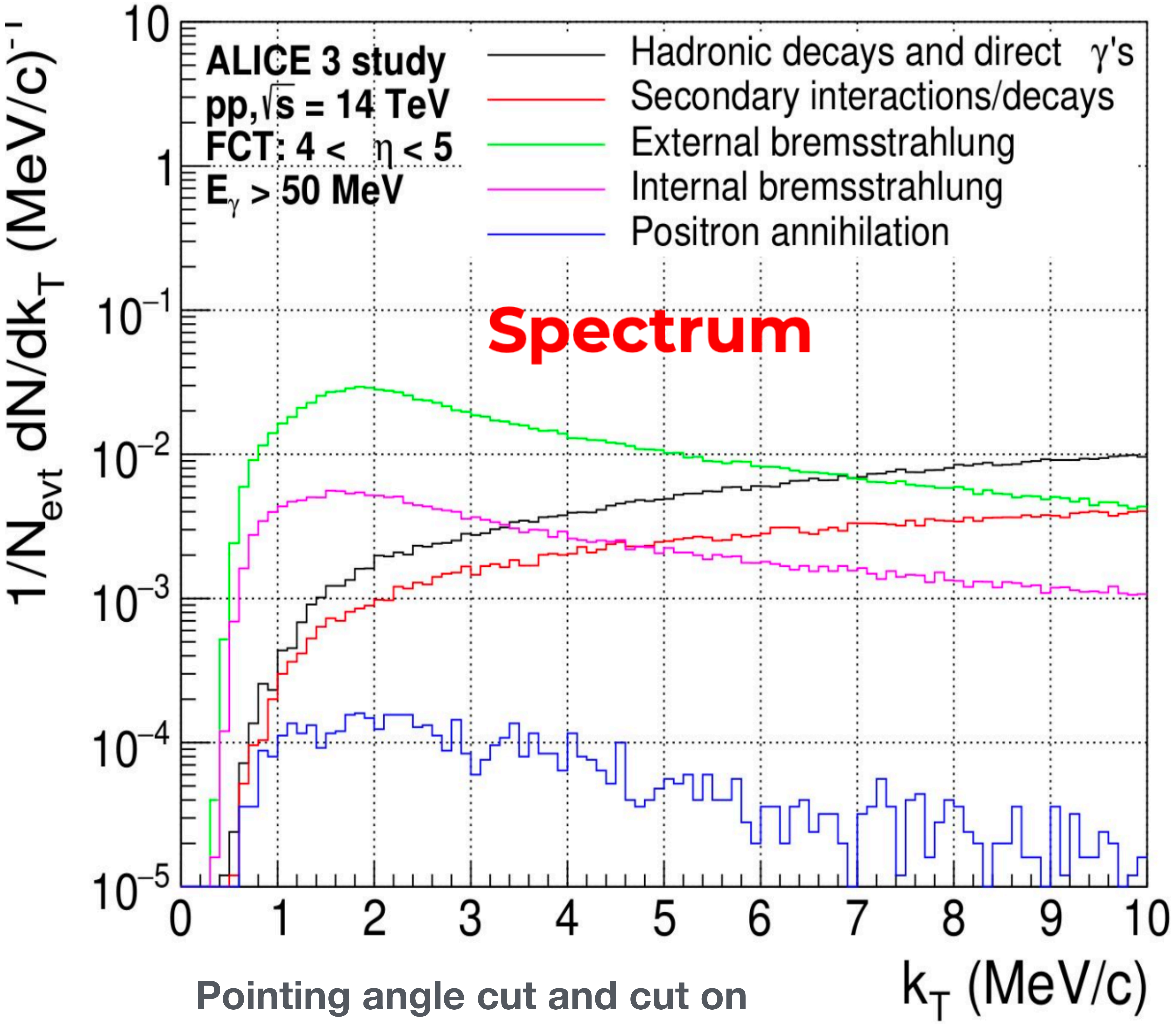
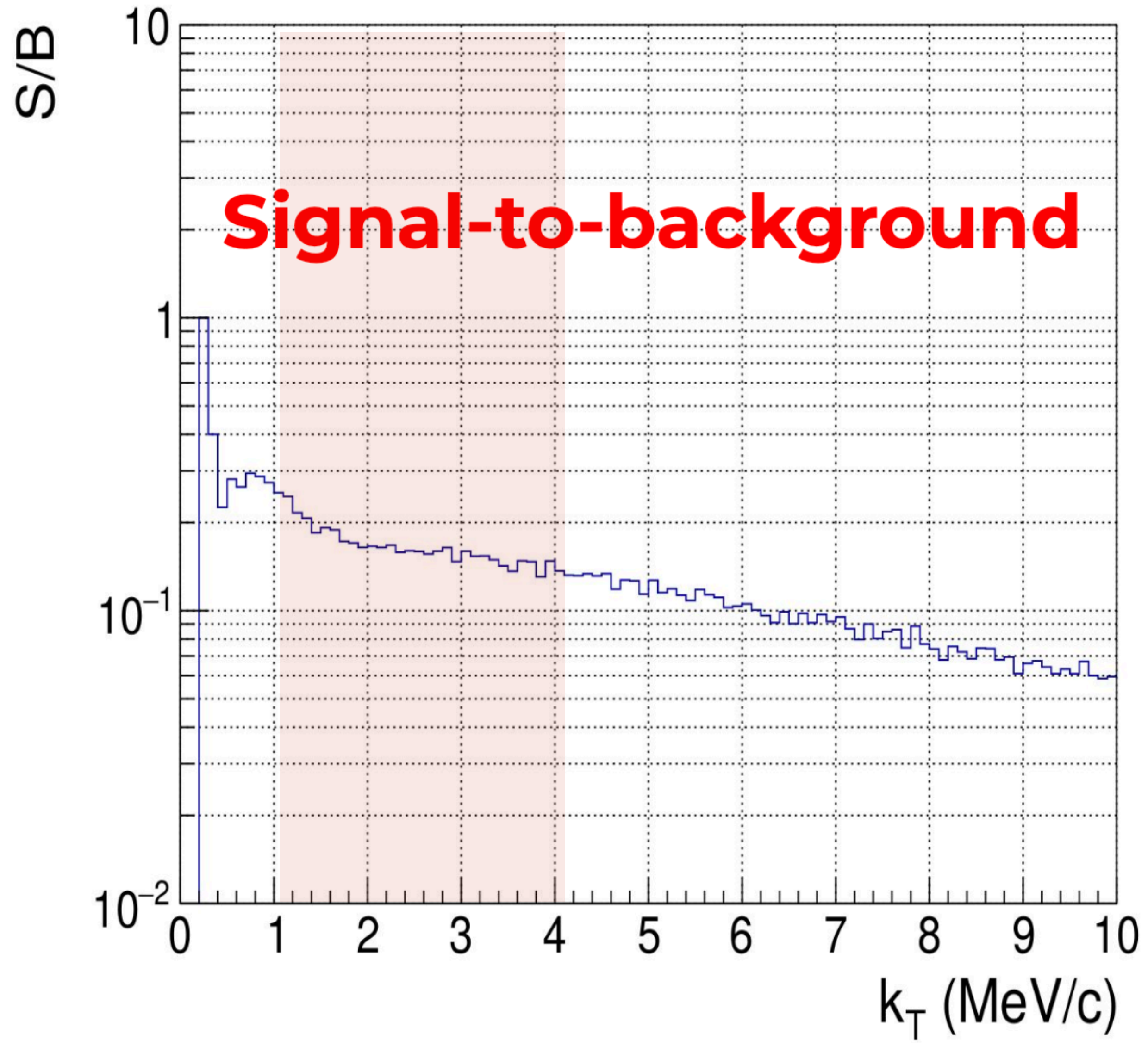


Figure does not show drop in magnitude, just percentages

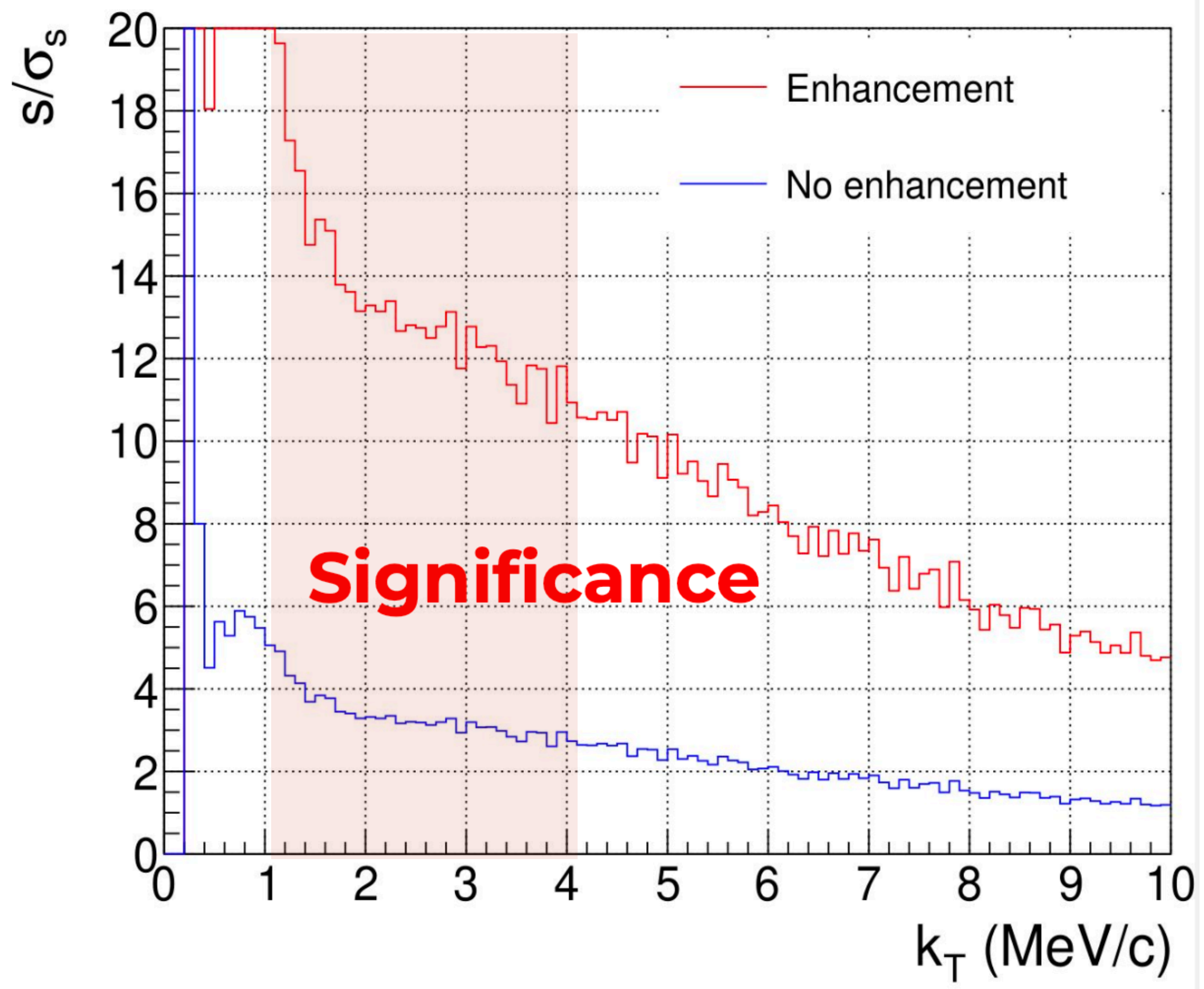
Low photons: Reasonable significances with cuts & conical beampipe



Pointing angle cut and cut on distance to closest track applied



S/B ≈ 0.1–0.2 (no enhancement)



Significance assuming material budget known to 5%

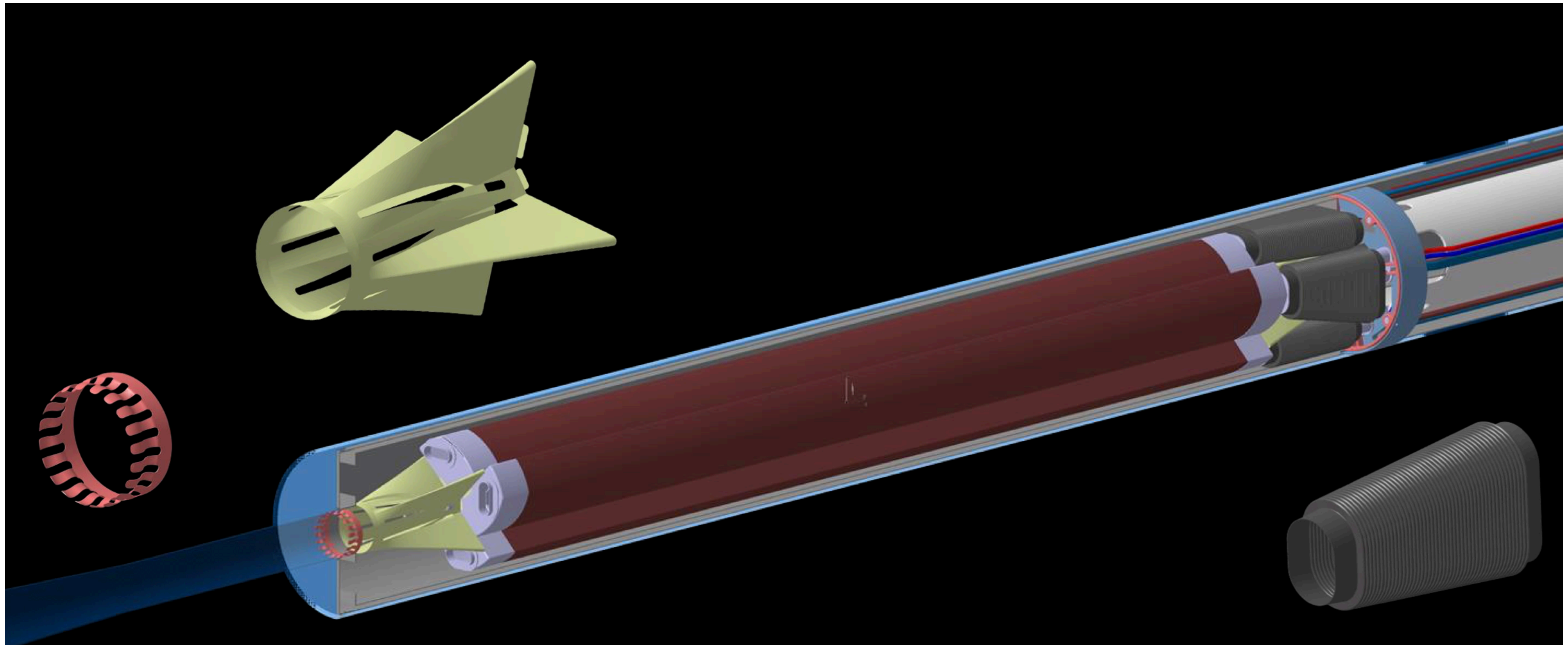
× 4 enhancement: 10–14σ significance

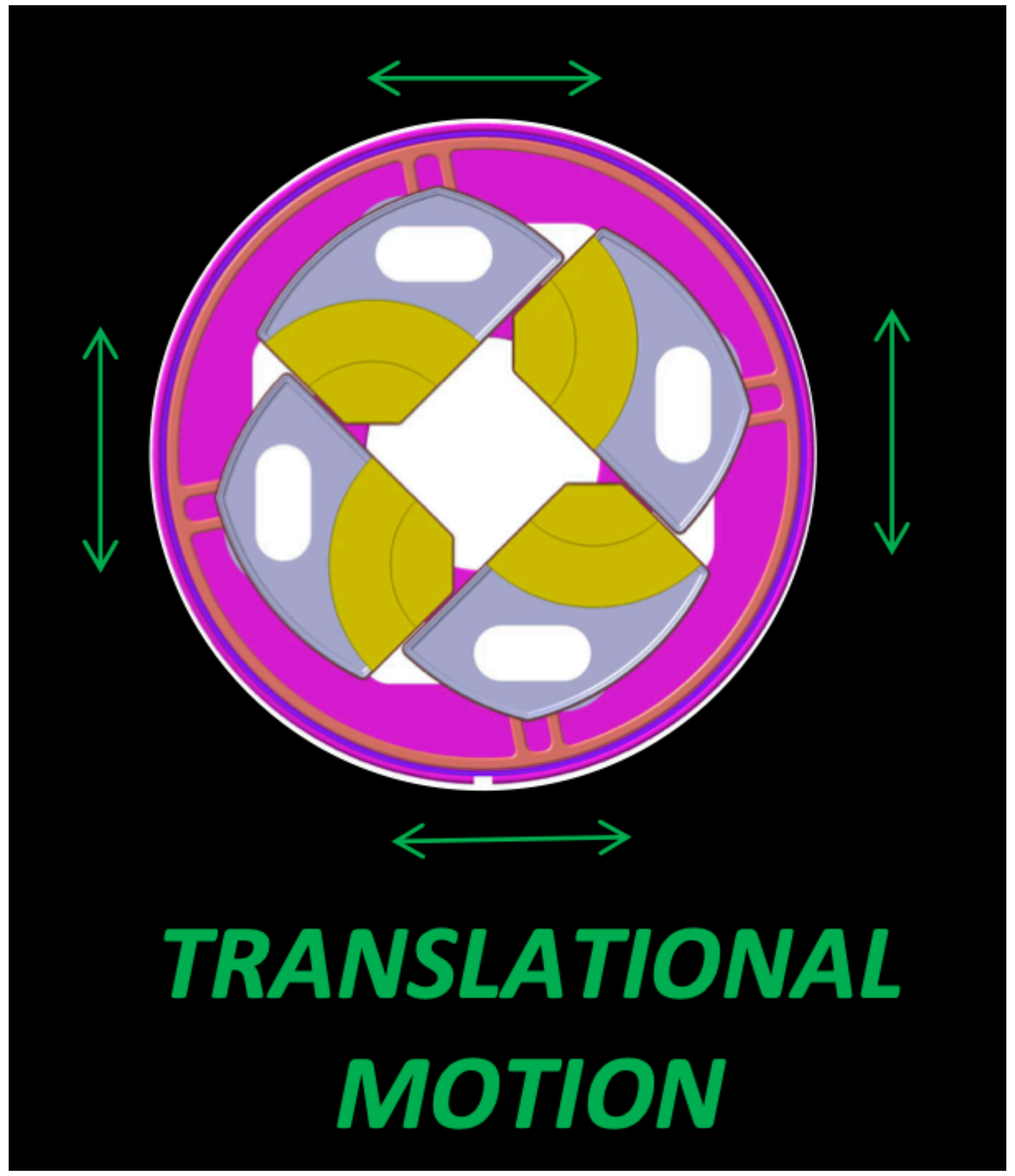
No enhancement: 2–4 σ significance

ALICE 3 FCT: Similar or improved signal-to-background ratio for Low photon measurements compared to previous experiments

	Photon k_T	$\gamma_{meas}/\gamma_{brems}$	S/B ($\gamma_{brems}/\gamma_{bkg}$)
pp CERN,WA102, OMEGA	k_T < 20 MeV/c (0.2 < Eγ < 1 GeV)	4.1 ± 0.8	0.38
$e^+e^- \rightarrow n$ jets CERN, DELPHI	k_T < 80 MeV/*c* (0.2<Eγ <1GeV)	4.0 ± 0.3 ± 1.0	0.036–0.013
ALICE 3	k_T < 10 MeV/*c*	?	0.1–0.2

Measuring the background from the ALICE 3 IRIS tracker

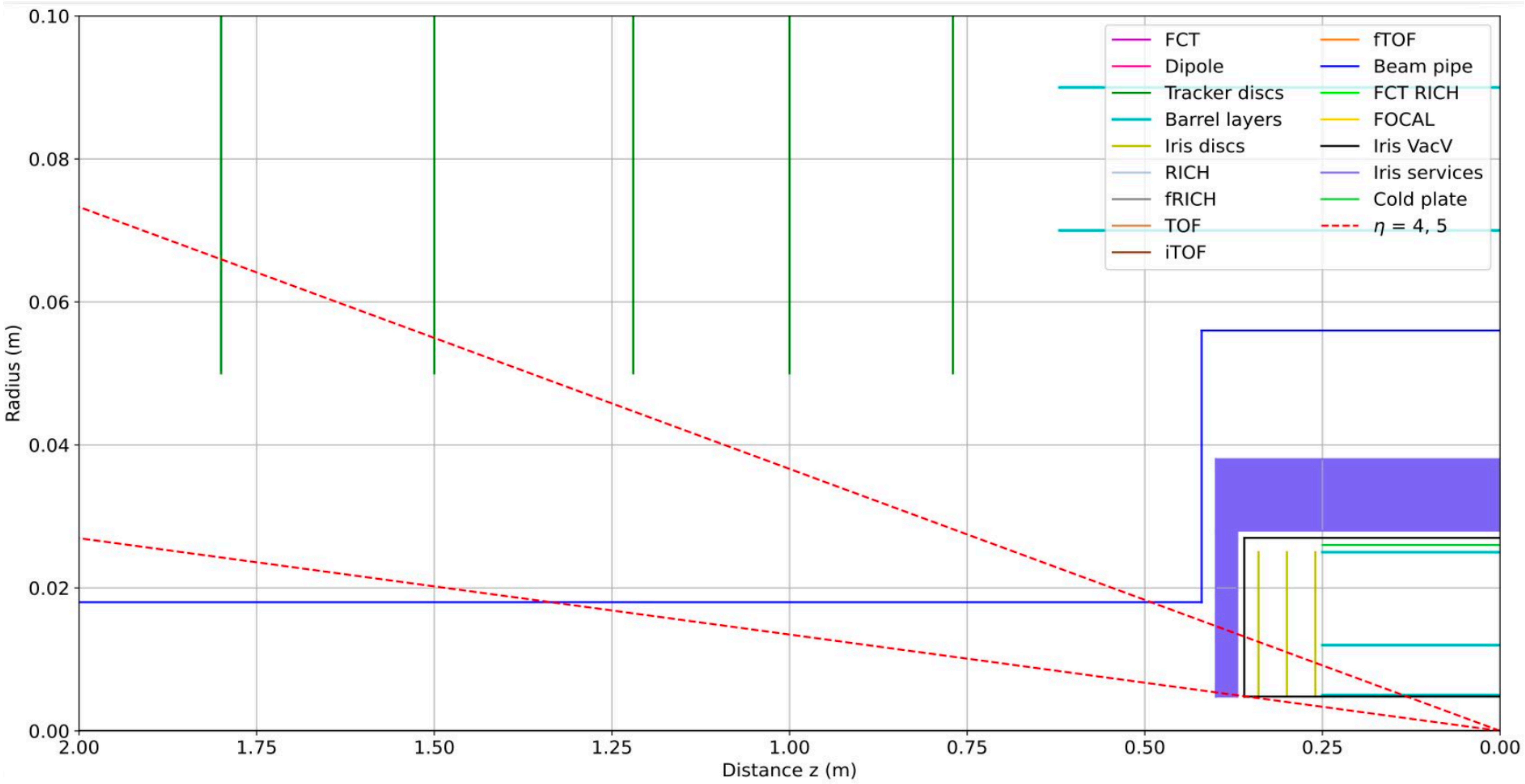




Soft photon measurements in both open and closed configurations of the IRIS tracker can assist in background reduction.

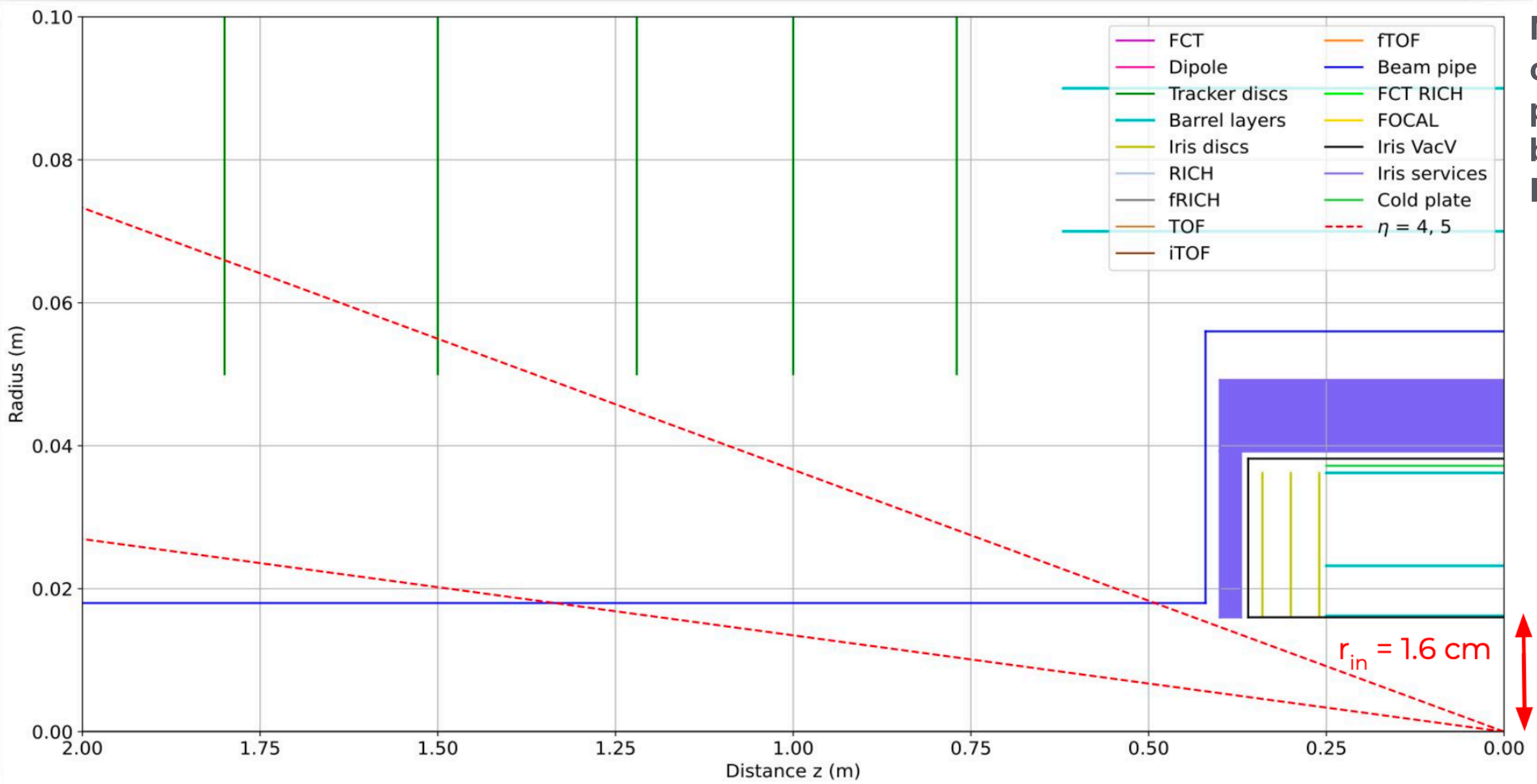
Further ideas for background reduction: Measuring the background from the ALICE 3 IRIS tracker

Closed IRIS tracker configuration



Closed position: configuration for standard data taking

Open IRIS tracker configuration



Measures photons in open and closed position to determine background from IRIS tracker

Conclusions

ALICE 3 Forward Conversion Tracker + dipole magnet the the LHC
→ access to ultra-soft photons (low-k_T regime)

Signal/background ratio: comparable or better than previous experiments.

Conical beampipe essential; no RICH needed behind FCT.

Expected significances for ultra-soft photon measurements ($1 \lesssim k_T \lesssim 4$ MeV/c):

- 2–4 σ (no enhancement)
- 10–14 σ (× 4 enhancement)

Further improvements underway.