Photon measurements with ALICE 3

ALICE 3 workshop, 18-19 October 2021

Klaus Reygers
Universität Heidelberg

Outline

Ultra-soft photons ($p_T \lesssim 50$ MeV/c): Low’s theorem and the soft photon puzzle

Photons in the O(100 MeV+) range: QGP temperature and dynamics + electrical conductivity

Beyond the Standard Model: Search for axion-like particles

A long-standing puzzle

Peter Braun-Munzinger, EMMI seminar, Feb. 2021
“Soft photons, the Low theorem, and ALICE 3”

In 1958, Francis Low wrote a seminal paper on how to relate hadron production in a high energy collision to the production of soft photons. Francis E. Low, Phys.Rev.Lett. 110 (1958) 468

Striking discrepancies were found between predictions and experimental measurements.
No agreement exists on their possible origin, despite > 40 years of research.

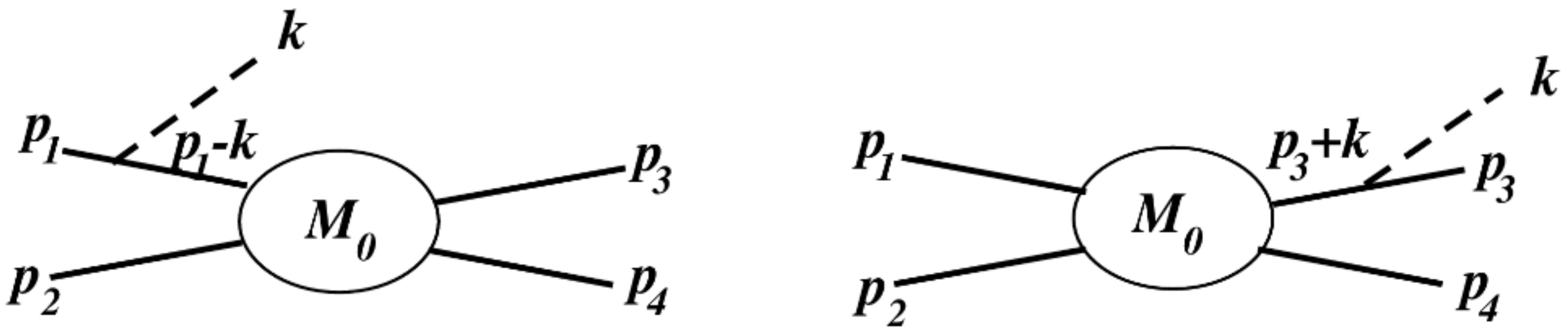
Low’s theorem is an example of a soft theorem in QFT. Considerable theoretical interest as soft theorems are related to **symmetries reflecting infrared structure of gravity and gauge theory**.*
V. Lysov, S. Pasterski and A. Strominger, Phys. Rev. Lett. 113 (2014)

With the **ALICE 3 Forward Conversion Tracker** we have come up with a concept for a detector that can provide a soft-photon measurement in the range $p_T < 10$ MeV/c to test Low’s theorem.

* “*These theorems tell us that a surprisingly large — in fact, infinite — number of soft particles are produced in any physical process, but in a highly controlled manner that is central to the consistency of quantum field theory*”, A. Strominger, arXiv:1703.05448

Relating soft photon to charged hadron production

$$p_1+p_2 \rightarrow p_3+p_4+k$$



External propagator contains term $\dfrac{1}{(p \pm k)^2 - m^2} = \dfrac{1}{\pm 2p \cdot k}$.

Amplitude of the process with a bremsstrahlung photon has a pole whenever $p \cdot k \rightarrow 0$.
Internal propagators are never on-shell → no pole → negligible contribution to photon yield.

Soft photon emission related by a simple factor to process without photon emission:

$\eta_i = +1$ for outgoing hadron,
$\eta_i = -1$ for incoming hadron,

polarization

$$M(p_1 p_2; p_3 p_4 \ldots p_N k) = M_0(p_1 p_2; p_3 p_4 \ldots p_N) \left(\sum_{i}^{\text{all charged particles}} \frac{\eta_i e_i p_i \cdot \varepsilon}{2 p_i \cdot k} \right)$$

Low’s formula as used by experiments

Photon momentum spectrum (“inner bremsstrahlung”):

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

$\sum_i$: sum over $N+2$ particles (2 incoming, N outgoing)

$K, \vec{k}$: photon four- and three momentum ($E_\gamma \equiv |\vec{k}|$)

$P_i, \vec{p}_i$: four- and three momentum of particle i

$e_i = 1$ for positive particle, $e_i = -1$ for negative particle

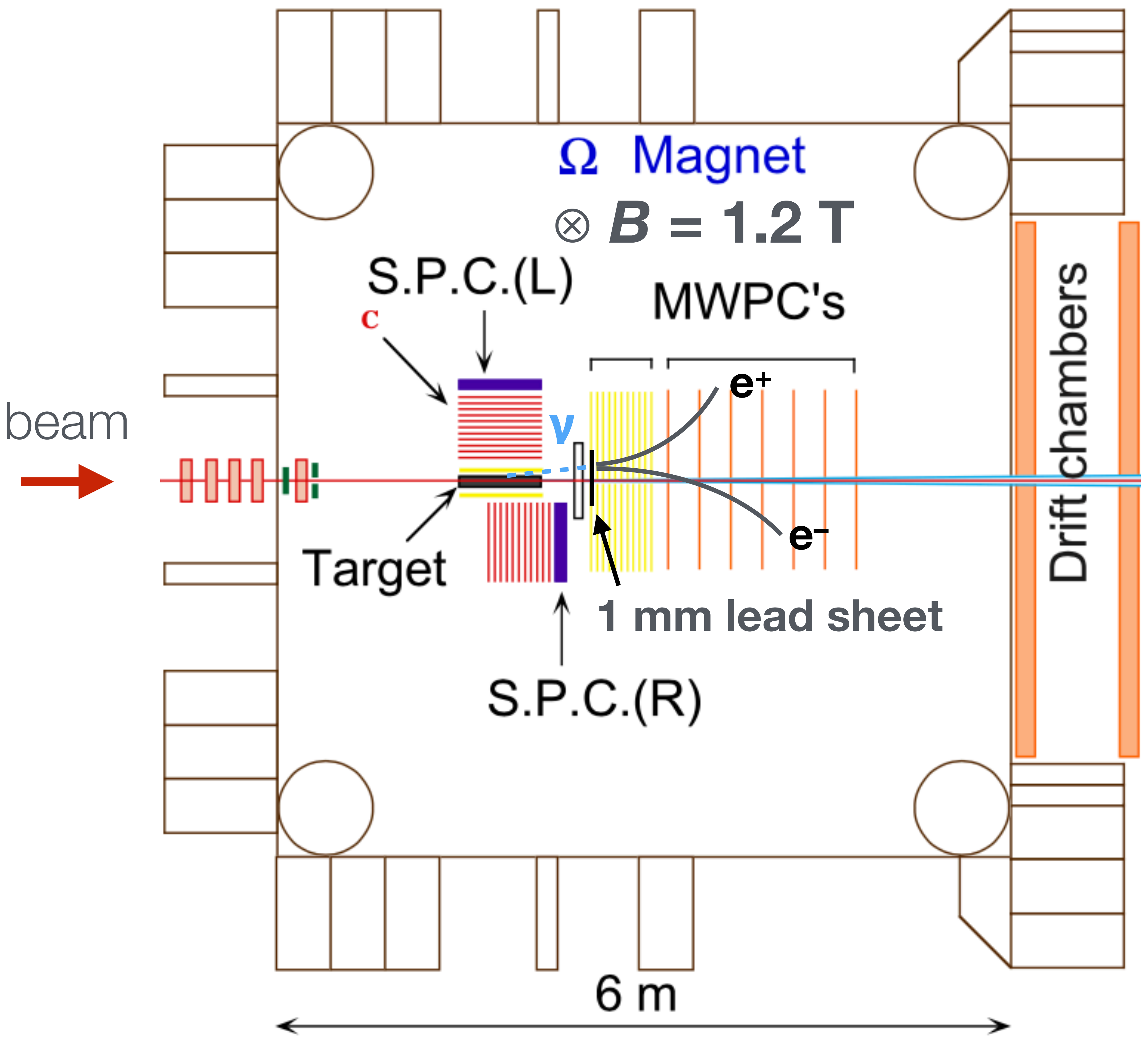
$\eta_i = 1$ for outgoing particle, $\eta_i = -1$ for incoming particle

Low’s formula for photon production is **“tree-level exact”**, i.e., it does not receive any loop corrections

First explicitly shown in
Goshaw et al.,
Phys. Rev. Lett. 43, 1065 (1979)

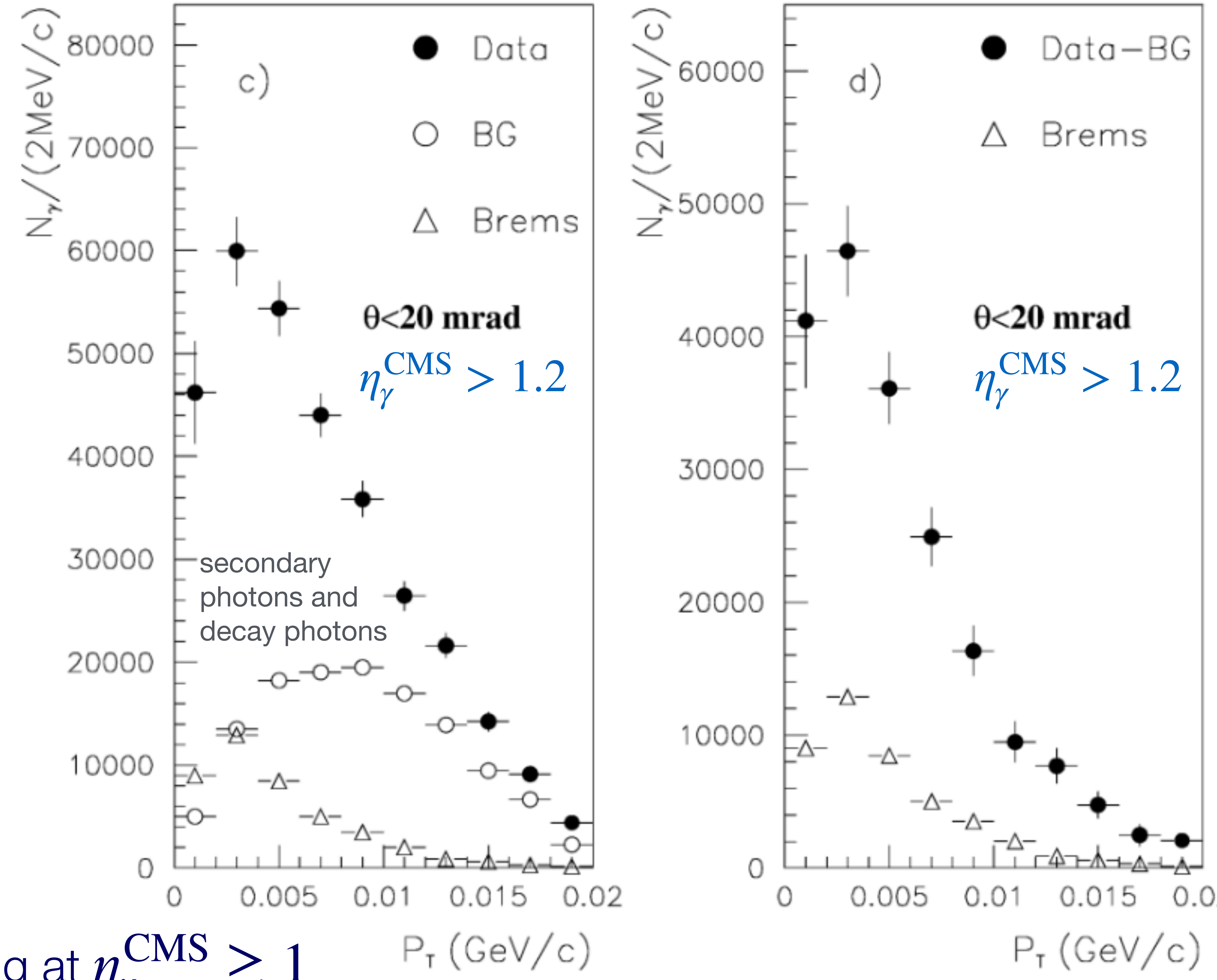
see also
Belogianni et al. (WA102), Phys. Lett. B 548, 129 (2002)
DELPHI, Eur. Phys. J. C 47, 273 (2006)

Example 1: Omega spectrometer – WA102



p+p fixed target experiment at $p_{\mathrm{beam}} = 450$ GeV/c

4×10^6 events (with less than 8 charged tracks)



Most of the excess above inner bremsstrahlung at $\eta_\gamma^{\mathrm{CMS}} \gtrsim 1$

Example 2: e^+e^- → 2 jets (DELPHI)

Photon range:

$$0.2 < E_\gamma < 1\,\mathrm{GeV}$$

$$p_T < 80\,\mathrm{MeV}/c$$

Expected from inner bremsstrahlung:

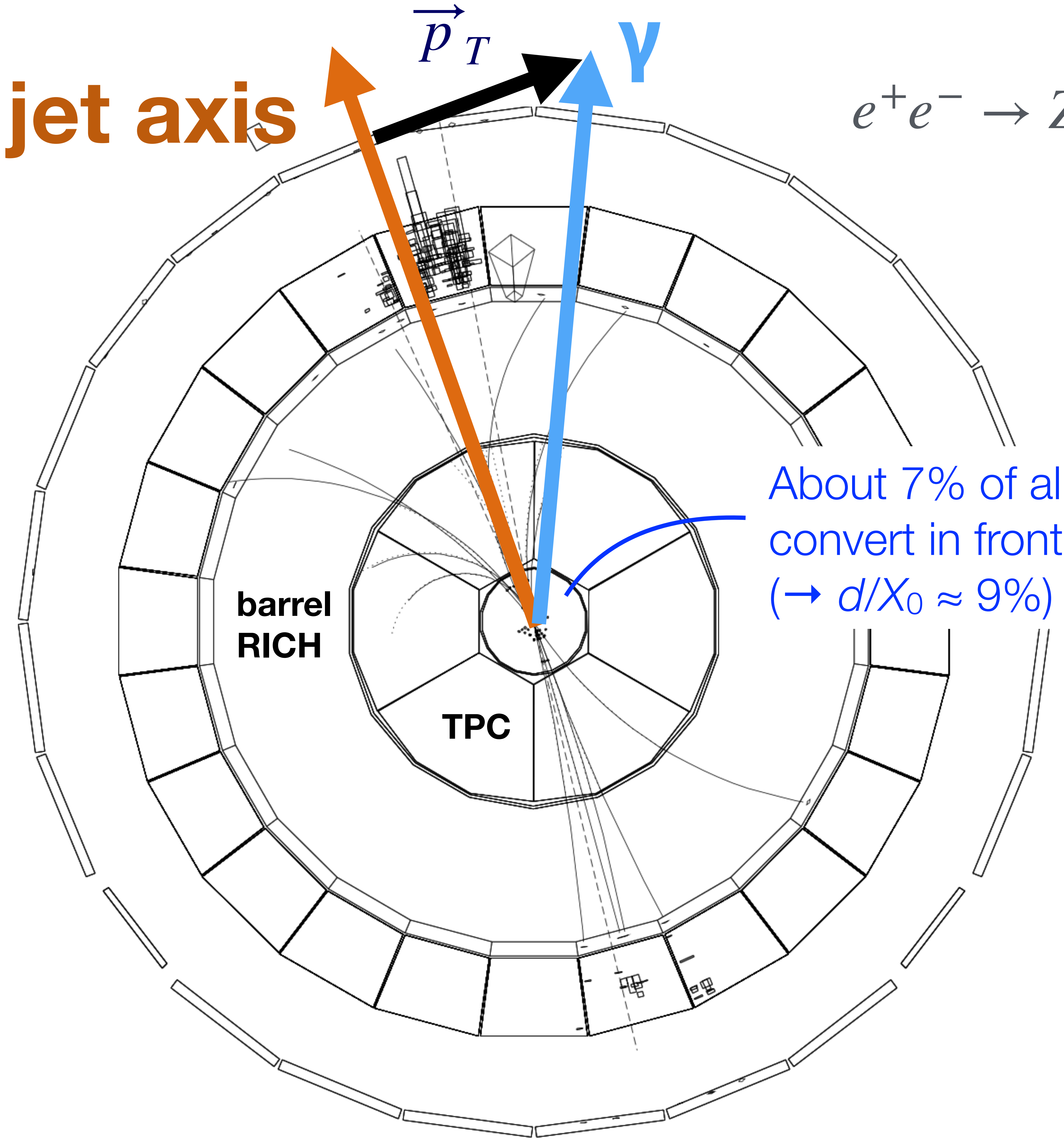
$$(17.1 \pm 0.01 \pm 1.21) \times 10^{-3}\,\gamma/\mathrm{jet}$$

Observation:

$$(69.1 \pm 4.5 \pm 15.7) \times 10^{-3}\,\gamma/\mathrm{jet}$$

Ratio:

$$4.0 \pm 0.3 \pm 1.0$$



$e^+e^- \rightarrow Z^0 \rightarrow 2$ jets

$B = 1.23$ T

About 7% of all photons convert in front of the TPC (→ $d/X_0 \approx 9\%$)

Anomalous soft photon production

Factor 2 – 5 excess w.r.t. Low's formula

Experiment	Year	Collision energy	Photon p_T	Photon / Brems Ratio	Detection method	Reference (click to go to paper)
π^+p	1979	10.5 GeV	$p_T < 30$ MeV/c	1.25 ± 0.25	bubble chamber	Goshaw et al., Phys. Rev. Lett. 43, 1065 (1979)
K^+p WA27, CERN	1984	70 GeV	$p_T < 60$ MeV/c	4.0 ± 0.8	bubble chamber (BEBC)	Chliapnikov et al., Phys. Lett. B 141, 276 (1984)
π^+p CERN, EHS, NA22	1991	250 GeV	$p_T < 40$ MeV/c	6.4 ± 1.6	bubble chamber (RCBC)	Botterweck et al., Z. Phys. C 51, 541 (1991)
K^+p CERN, EHS, NA22	1991	250 GeV	$p_T < 40$ MeV/c	6.9 ± 1.3	bubble chamber (RCBC)	Botterweck et al., Z. Phys. C 51, 541 (1991)
π^-p, CERN, WA83, OMEGA	1993	280 GeV	$p_T < 10$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	7.9 ± 1.4	calorimeter	Banerjee et al., Phys. Lett. B 305, 182 (1993)
p-Be	1993	450 GeV	$p_T < 20$ MeV/c	< 2	pair conversion, calorimeter	Antos et al., Z. Phys. C 59, 547 (1993)
p-Be, p-W	1996	18 GeV	$p_T < 50$ MeV/c	< 2.65	calorimeter	Lissauer et al., Phys.Rev. C54 (1996) 1918
π^-p, CERN, WA91, OMEGA	1997	280 GeV	$p_T < 20$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	7.8 ± 1.5	pair conversion	Belogianni et al., Phys. Lett. B 408, 487 (1997)
π^-p, CERN, WA91, OMEGA	2002	280 GeV	$p_T < 20$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	5.3 ± 1.0	pair conversion	Belogianni et al., Phys. Lett. B 548, 122 (2002)
pp, CERN, WA102,	2002	450 GeV	$p_T < 20$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	4.1 ± 0.8	pair conversion	Belogianni et al., Phys. Lett. B 548, 129 (2002)
$e^+e^- \rightarrow$ 2 jets CERN, DELPHI	2006	91 GeV (CM)	$p_T < 80$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	4.0 ± 0.3 ± 1.0	pair conversion	DELPHI, Eur. Phys. J. C 47, 273 (2006)
$e^+e^- \rightarrow \mu^+\mu^-$ CERN, DELPHI	2008	91 GeV (CM)	$p_T < 80$ MeV/c ($0.2 < E_\gamma < 1$ GeV)	~ 1	pair conversion	DELPHI, Eur. Phys. J. C57, 499 (2008)

ALICE 3 soft-photon strategy

Establish a baseline by studying a “clean” exclusive process: $pp \to pp\,\pi^+\pi^-\gamma$

Precise models for $pp \to pp\pi^+\pi^-$ exist. We expect $\lim_{\omega \to 0} \frac{d\sigma_{\text{exp}}/d\omega}{d\sigma_{\text{exact}}/d\omega} = 1$.

“A violation of these relations would mean a terrible crisis for QFT! ”
(Lebiedowicz, Nachtmann, Szczurek, arXiv:2107.10829)

Another interesting channel: $pp \to pp\,J/\psi\,\gamma$ with $J/\psi \to e^+e^-, \mu^+\mu^-$

Study soft-photon production in inelastic (non-diffractive) pp collisions

Requirements in terms of statistics are moderate:
1% stat. uncertainty in $5 < p_T < 6$ MeV bin for $3 < \eta < 5$ with 1% conversion probability obtained with 160×10^6 pp collisions @ 13 TeV

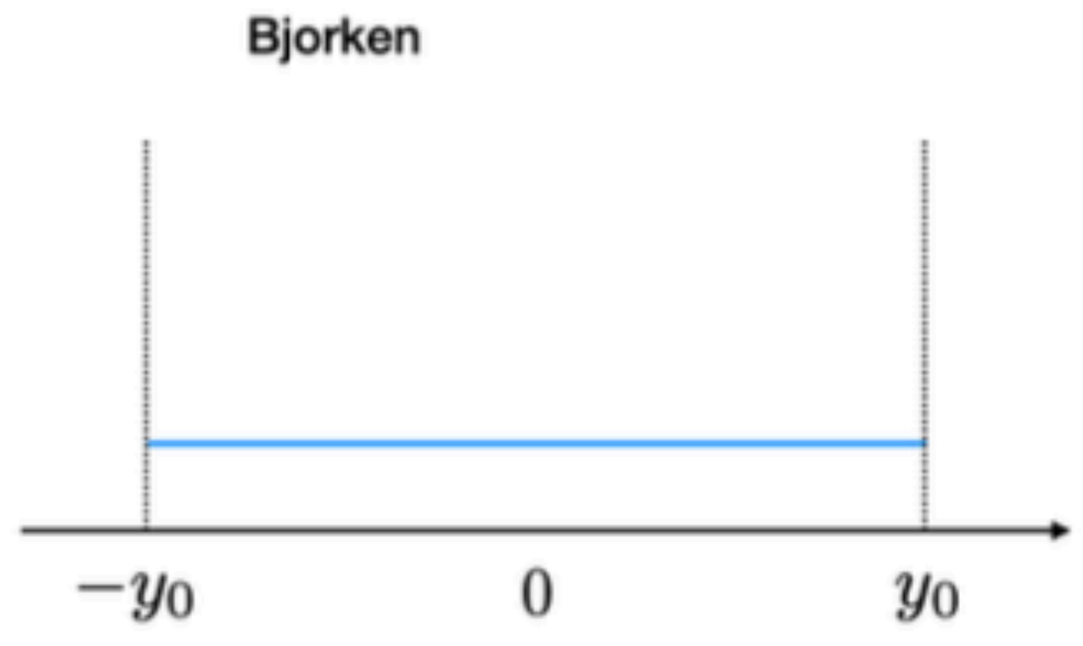
Extend study to reactions/systems with higher charged particle multiplicities

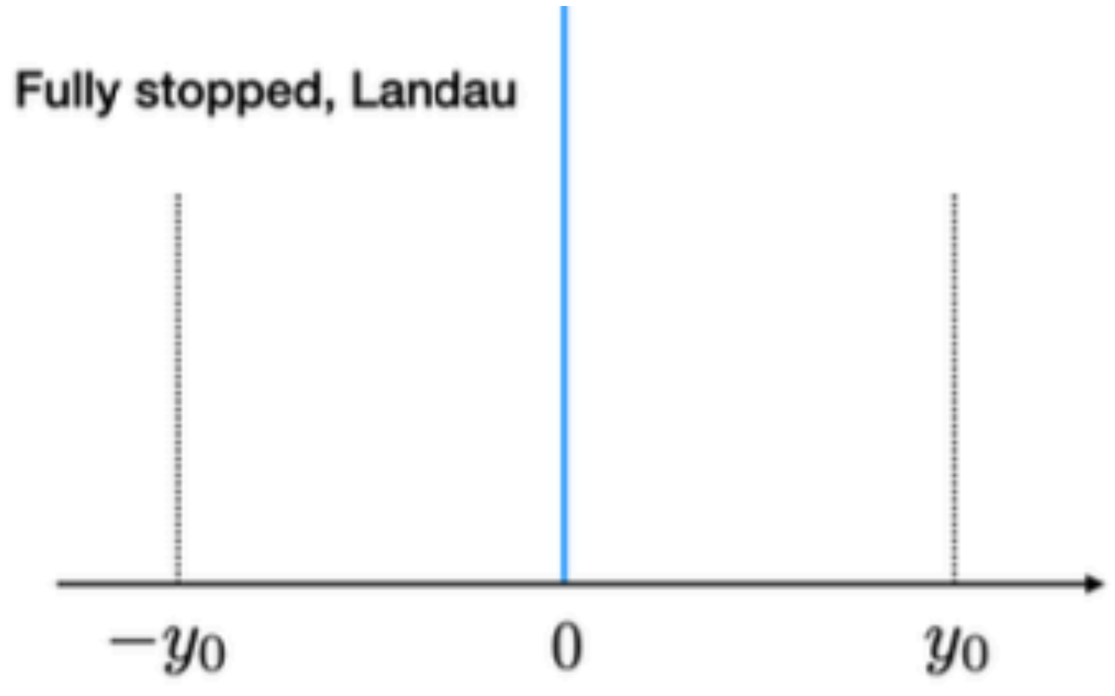
Bremsstrahlung photons from stopping in heavy-ion collisions

Sohyun Park, Urs Achim Wiedemann, Phys. Rev. C 104, 044903 (arXiv:2107.05129)

“As of today, forward bremsstrahlung from stopping of incoming charges remains a generally expected physics effect that has never been measured experimentally in heavy-ion collisions.”

see also J. I. Kapusta, Phys. Rev. C 15 (1977), 1580-1582
A. Dumitru, L. D. McLerran, H. Stoecker, W. Greiner, Phys. Lett. B 318 (1993), 583-586





Low’s theorem is a general quantum formulation of soft bremsstrahlung

A classical formulation should apply for sufficiently long wavelength:

$$\frac{d^2 I}{d\omega\, d\Omega} = |\mathbf{A}|^2, \quad \mathbf{A}(\mathbf{n},\omega) = \int dt \int d^3x\, \mathbf{n} \times (\mathbf{n} \times \mathbf{J}(\mathbf{x},t))\, e^{i\omega(t-\mathbf{n}\cdot\mathbf{x})}$$

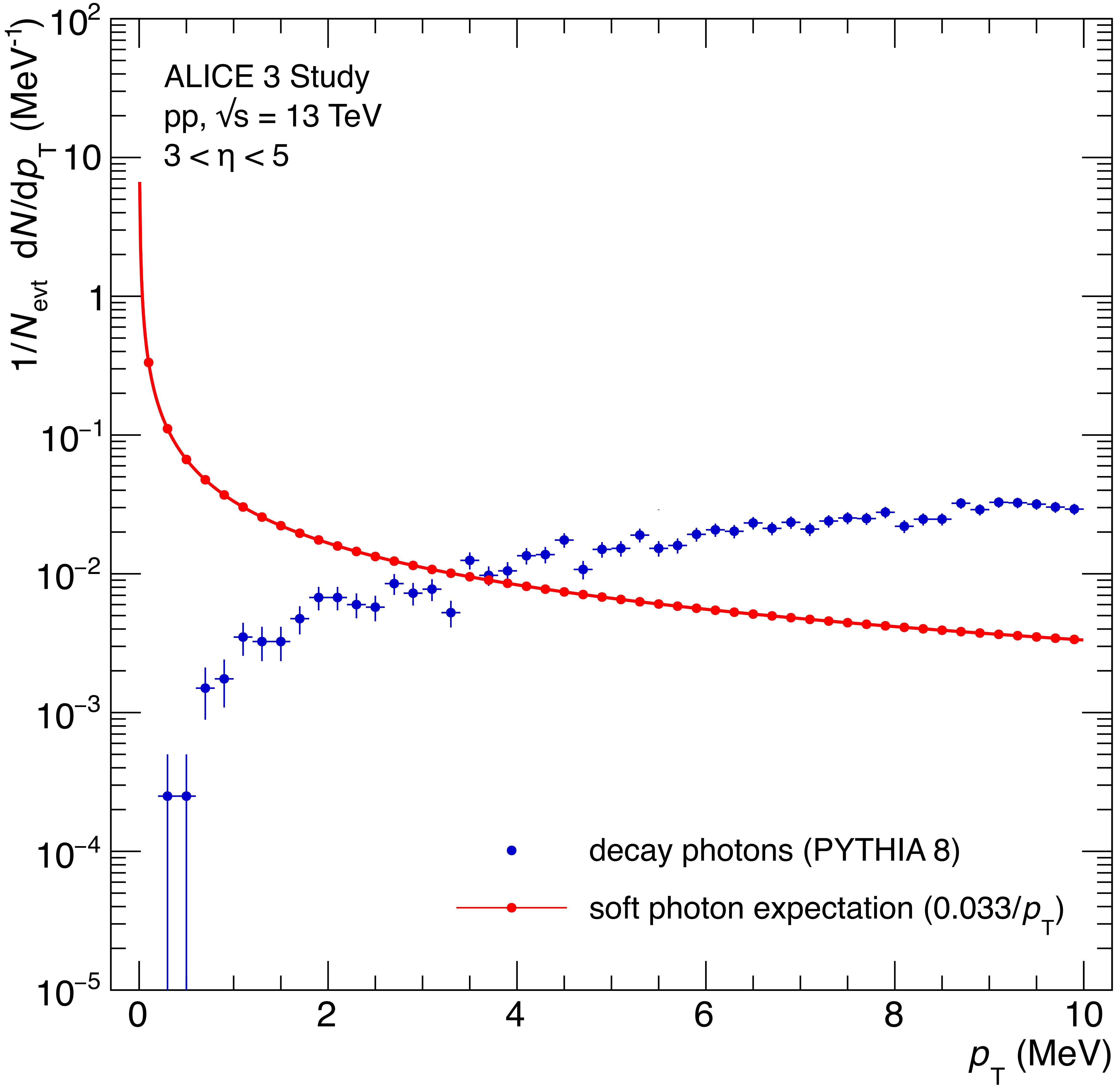
Eq. (14.67) in Jackson, *Classical Electrodynamics* (1998) 3rd ed.

$\mathbf{n}$: direction of the outgoing photon

$\mathbf{J} = \mathbf{J}_+^{(in)} + \mathbf{J}_-^{(in)} + \mathbf{J}^{(out)}$: incoming and outgoing currents

Soft photons with ALICE 3

Decay photon background small for $p_T \lesssim 5$ MeV/*c*



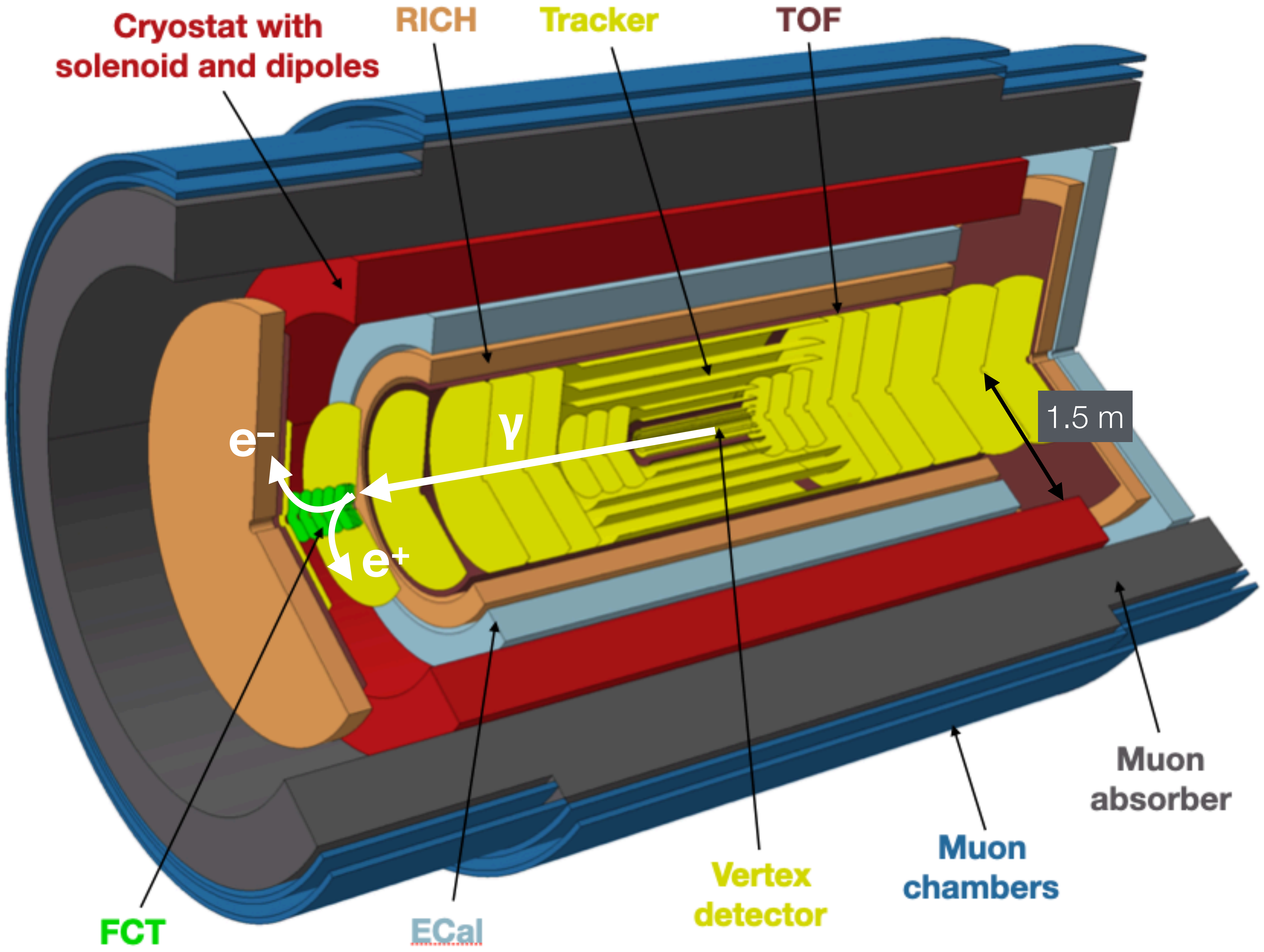
The 1 – 10 MeV/*c* transverse momentum range is accessible at forward rapidities

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

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

η	3	4	5
p_T (MeV/c)	10	3.7	1.3

Forward Conversion Tracker (FCT)

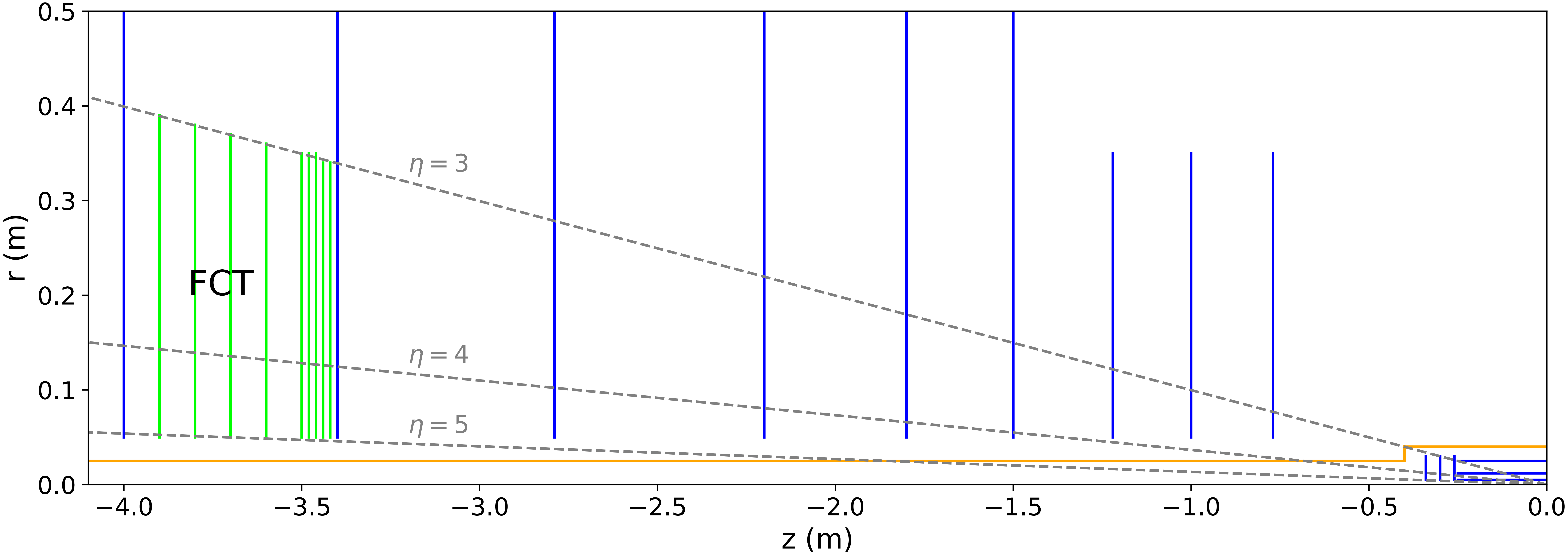


Tracking of electrons/positrons from photon conversions directly in front FCT

Dipole field required for good momentum resolution

Soft photons with ALICE 3

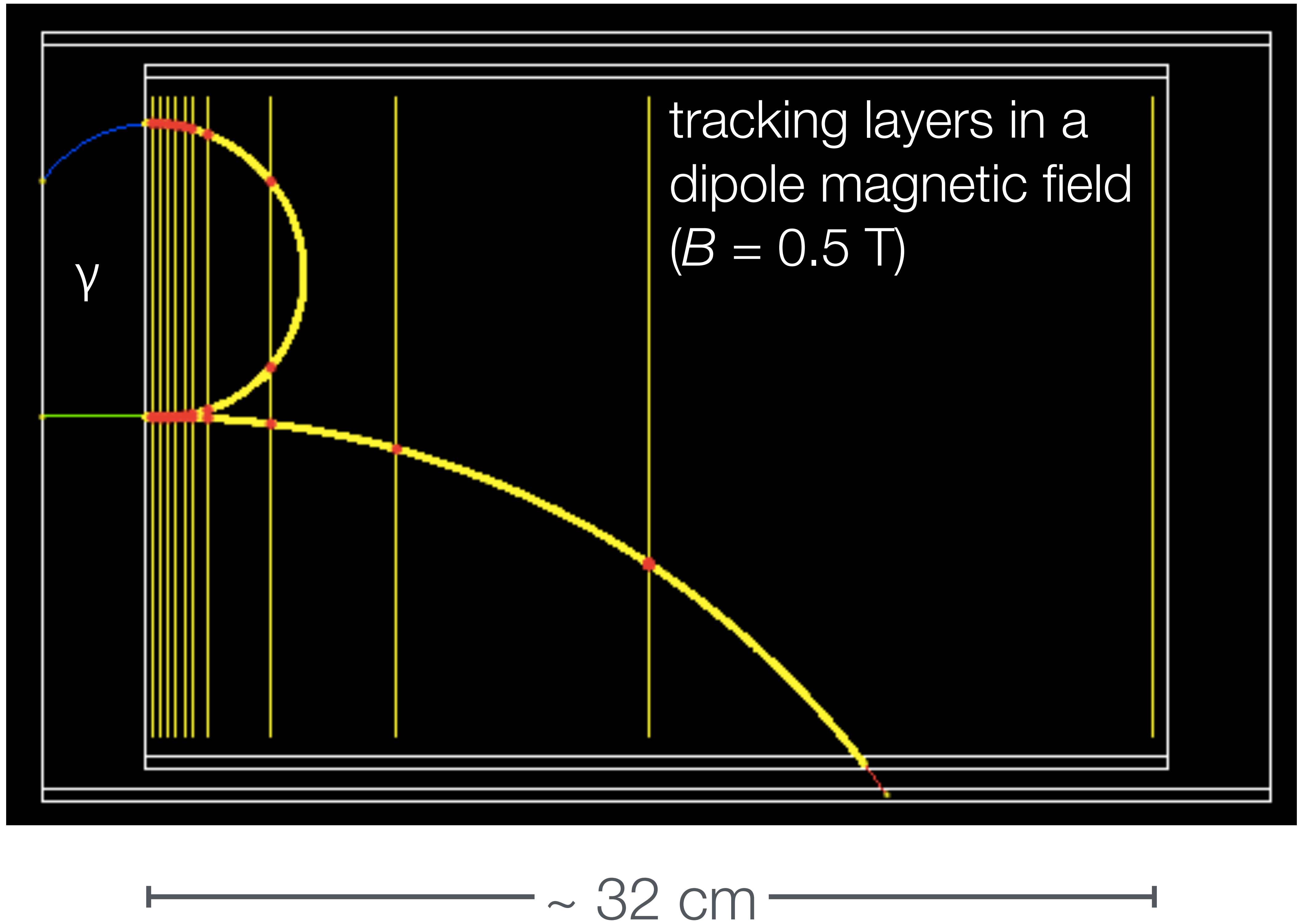
Forward Conversion Tracker (FCT)



Measuring soft photons through conversion

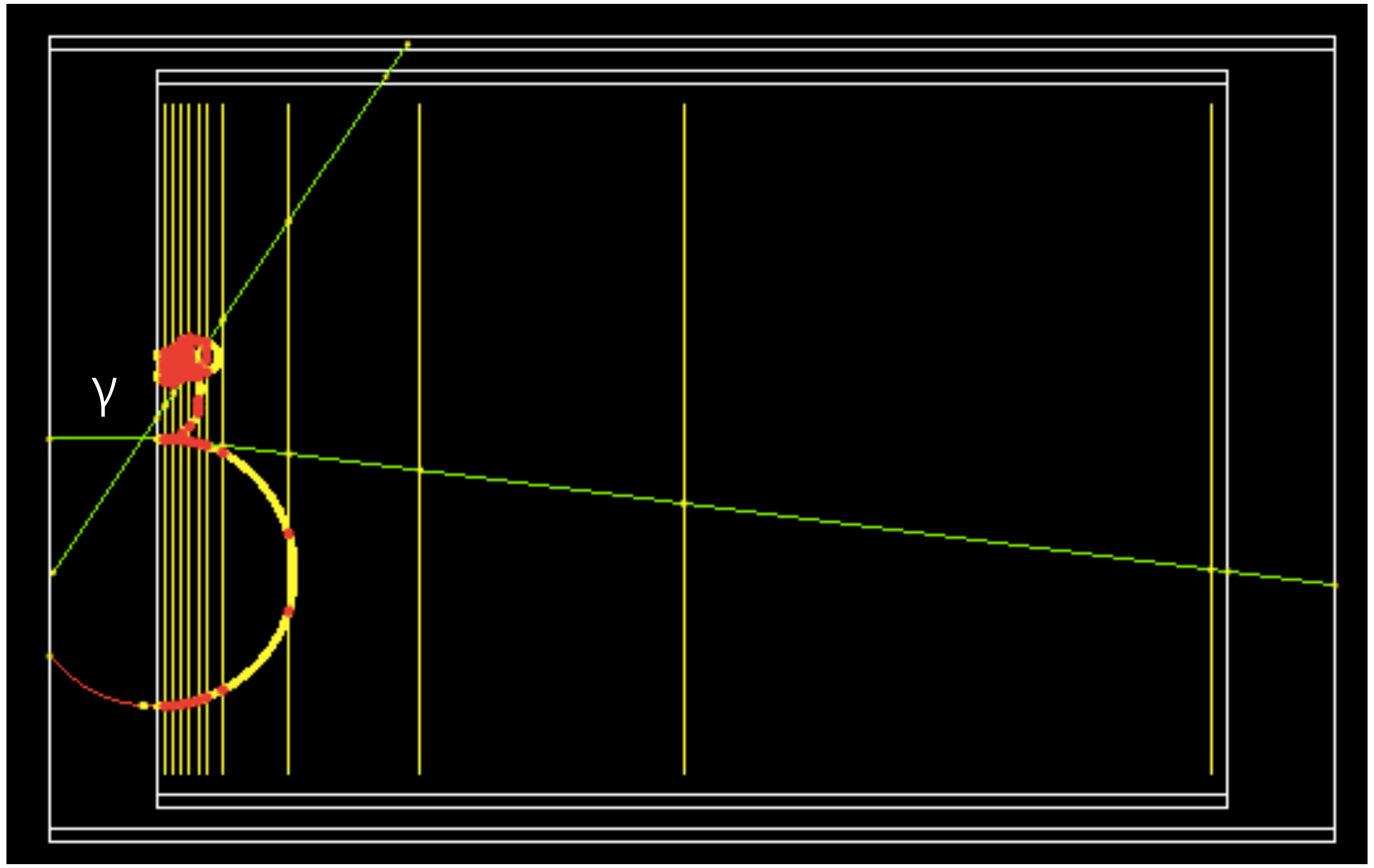
Can measure photons through conversions down to E_γ = 50-100 MeV

E_γ = 100 MeV: easy



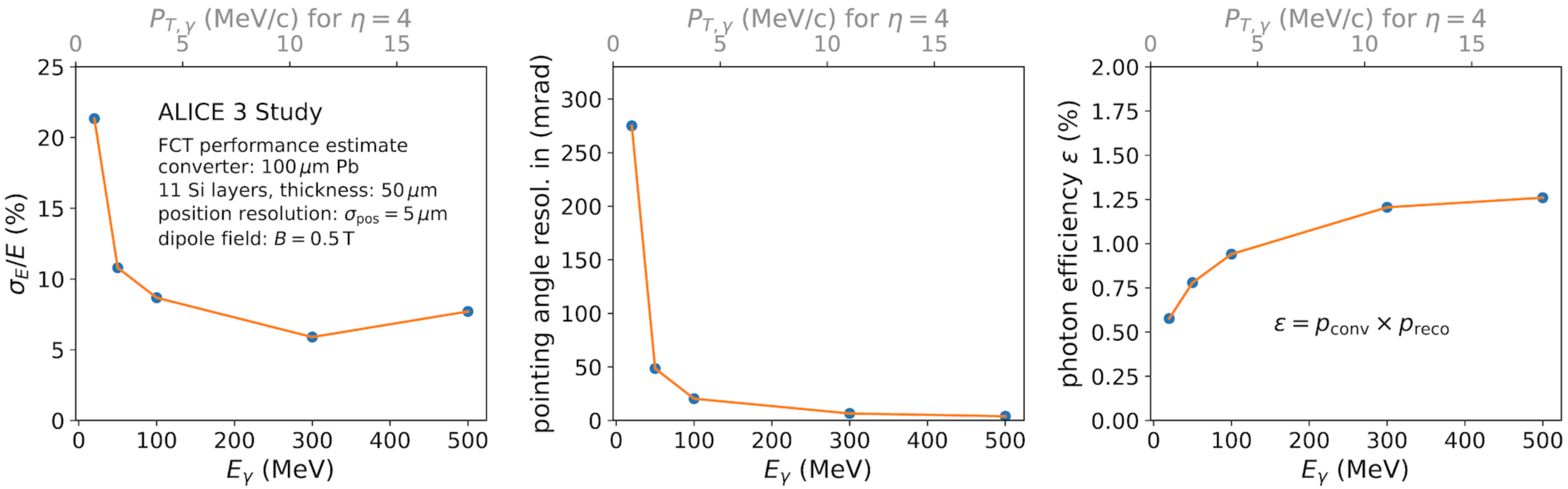
tracking layers in a dipole magnetic field (B = 0.5 T)

E_γ = 20 MeV: not so easy



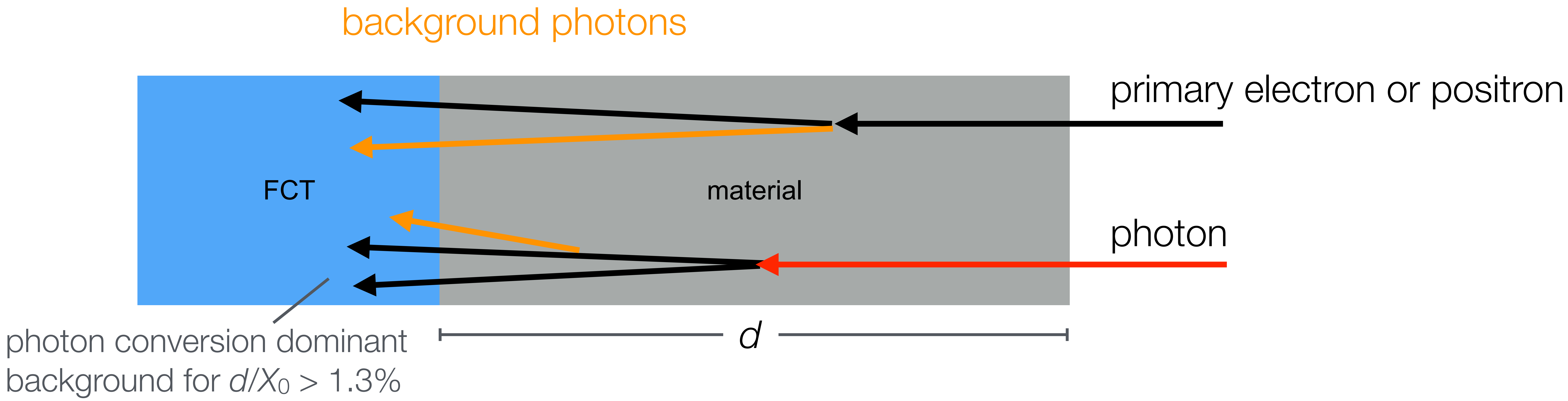
FCT performance estimate:

Energy resolution, pointing resolution and efficiency



ALI-SIMUL-492506

Background photons from primary e⁺/e⁻ and from conversion e⁺/e⁻



photon conversion dominant background for $d/X_0 > 1.3\%$

General strategy: minimize material in front of FCT

Avoid crossing of beampipe at shallow angles ($d = d_\perp \cosh \eta$)

Useful background estimate can be obtained analytically:

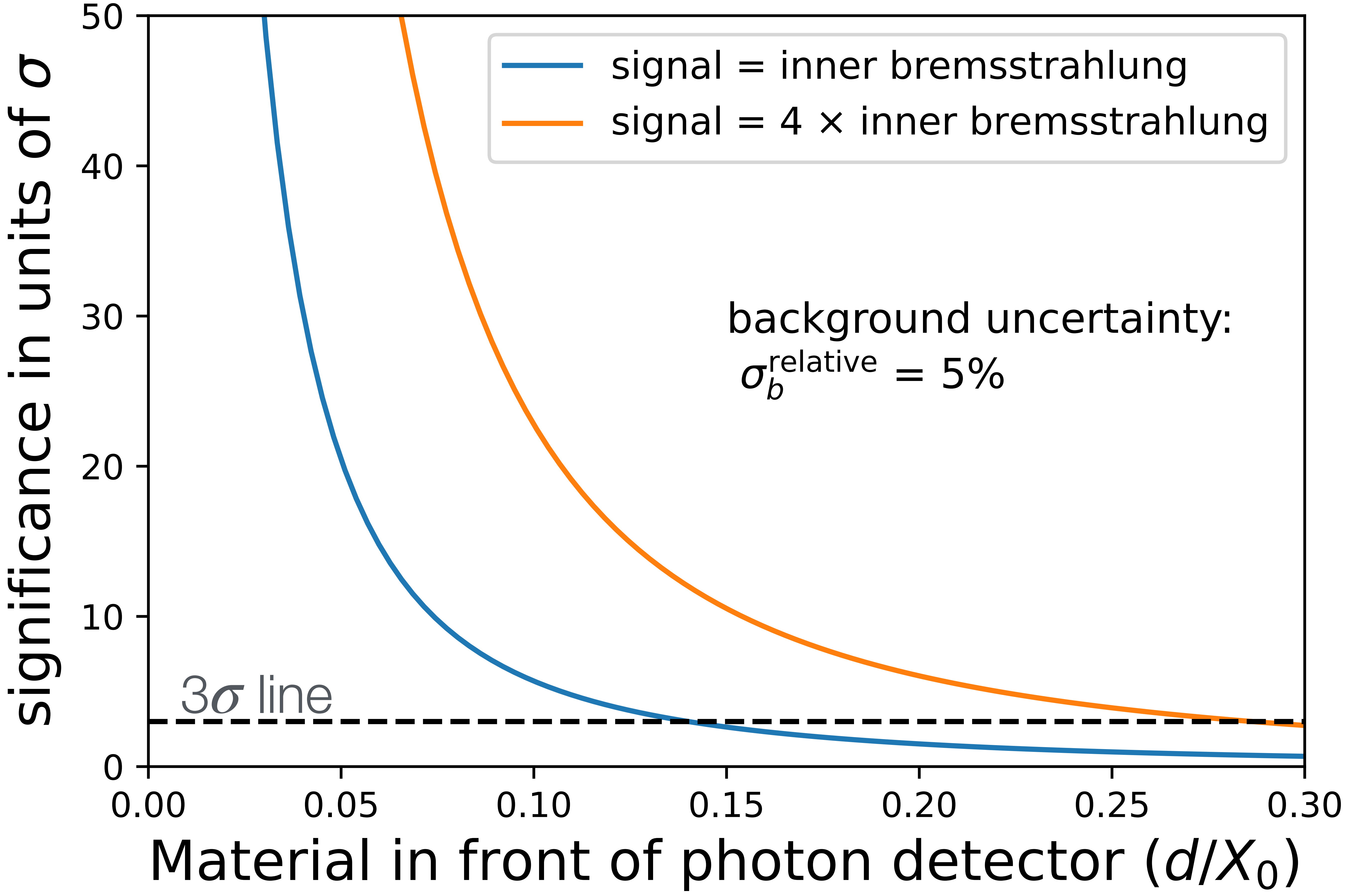
$$\frac{dN_\gamma^{\text{bck. per electron}}}{dk} \approx \frac{4}{3} \frac{d}{X_0} \frac{1}{k} \quad \text{for } k \ll E_e$$

photon energy

electron energy

Background due to external bremsstrahlung

Need to limit material in front of FCT to about 14% X_0 or less



Inner bremsstrahlung (pp, 13 TeV, based on charged particles from PYTHIA 8):

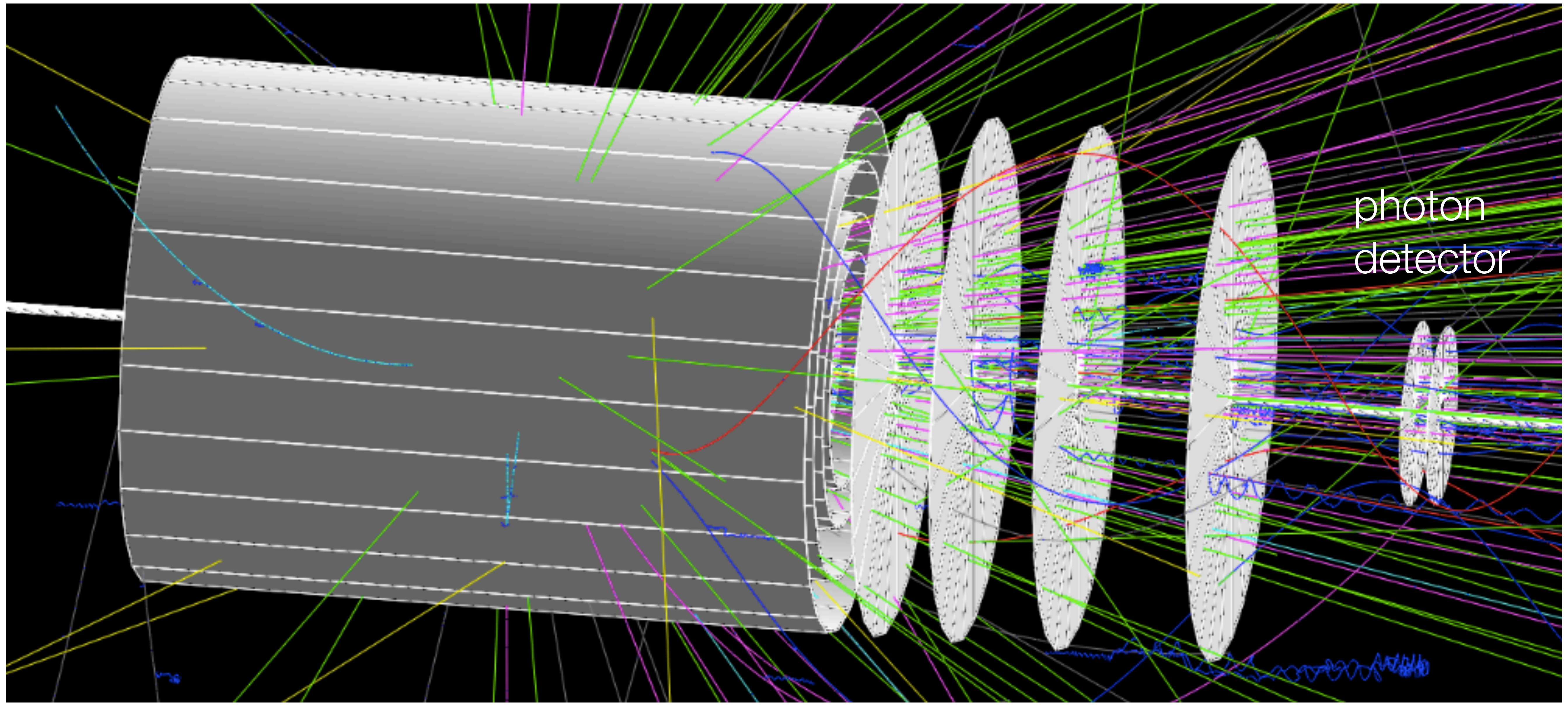
$$\frac{dN_{\text{signal}}}{dk_T} = \frac{0.034}{k_T} \quad \text{for } 3 < \eta < 5$$

Signal = background for $\dfrac{d}{X_0} \approx 5\,\%$

Significance (background subtraction):

$$\text{significance} = \frac{s}{\sigma_b^{\text{relative}} \cdot b}$$

Geant 4 simulation of background photons



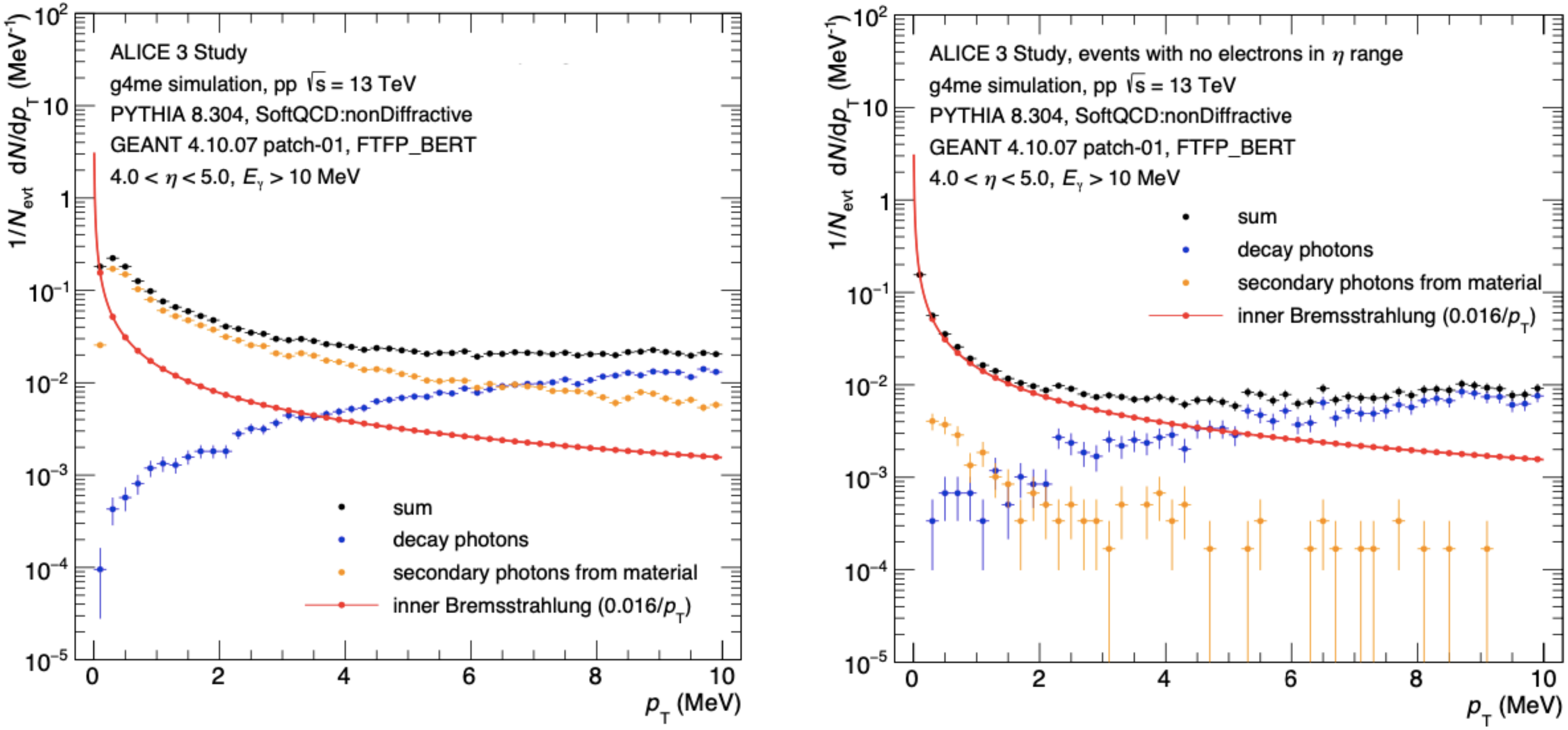
Compare background photons for two cases

1. all events
2. events without electrons/positrons in the pseudorapidity range of the FCT

Background due to external bremsstrahlung

Identification and/or rejection of e⁺/e⁻ in the η range of the FCT is key

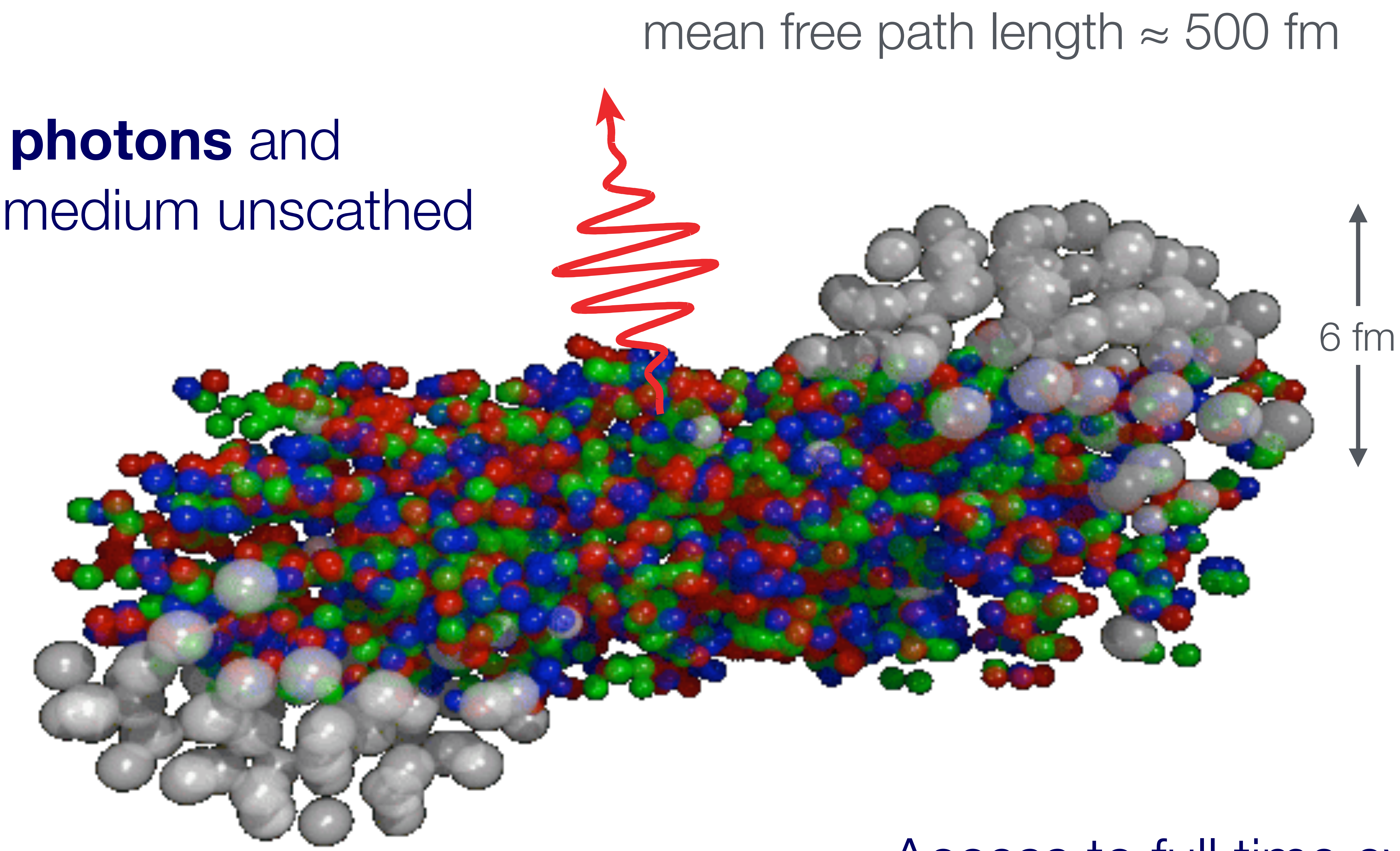
All events **Events without an e⁺ or e⁻ in FCT η range**



Promising. Further simulations needed to optimize detector, refine analysis cuts, and estimate significance.

Why photons in AA collisions?

Once produced, **photons** and **dileptons** leave medium unscathed



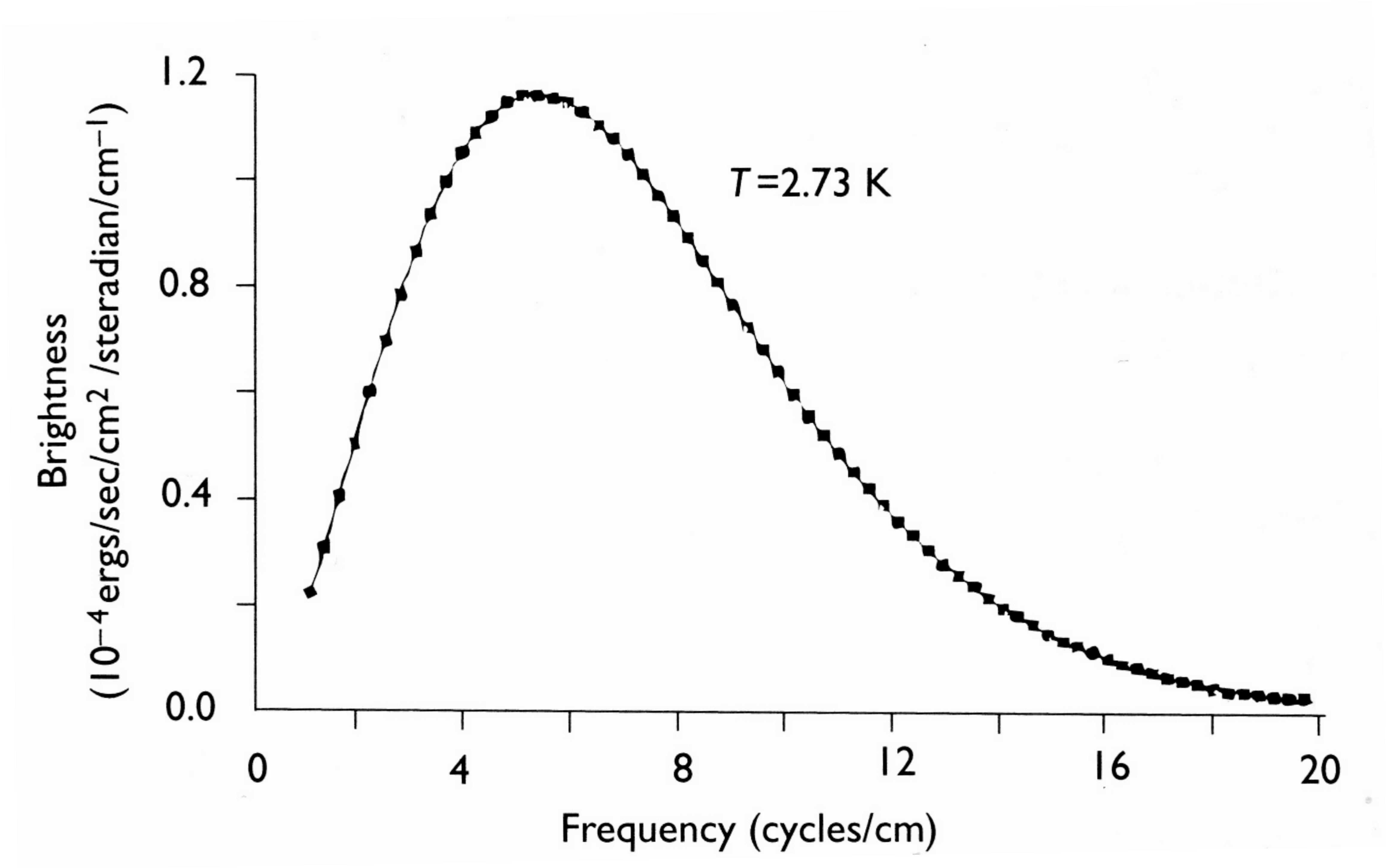
Sensitive to electrical conductivity of the QGP

Access to full time evolution of the system: pre-hydro and hydro phase

Photons from equilibrated medium: temperature

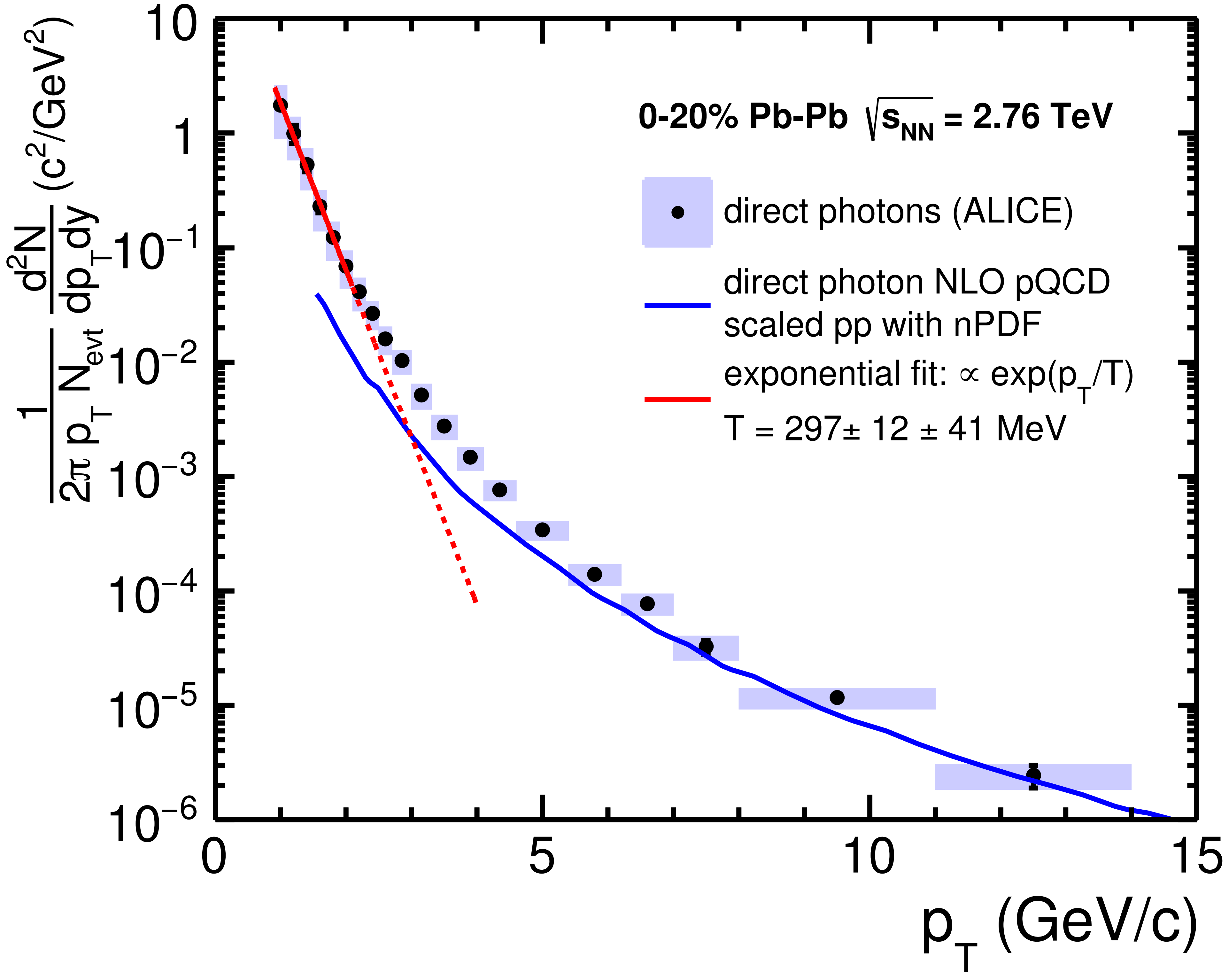
Temperature through the measurement of photons

CMB black-body spectrum (COBE)



Direct photons in Pb-Pb (ALICE)

ALICE, arXiv:1509.07324



A start. Significance so far below 3σ.
Expect ultimate measurement at LHC from ALICE 3.

Complementarity of real and virtual photons

Combine information from real and virtual photons to extract properties of hydro and pre-hydro phase in A-A collisions

Real and virtual photons rates closely related:

$$\omega \frac{dR}{d^3p} = \frac{1}{(2\pi)^3} n_B(\omega)\, \rho(\omega, |\vec{p}\,|) \qquad \frac{dR}{d^4p} = \frac{\alpha^2}{3\pi^2}\frac{1}{M^2} n_B(\omega)\, \rho(\omega, |\vec{p}\,|) \left(1 + \frac{2m^2}{M^2}\right)\sqrt{1 - \frac{4m^2}{M^2}}\,\Theta(M^2 - 4m^2)$$

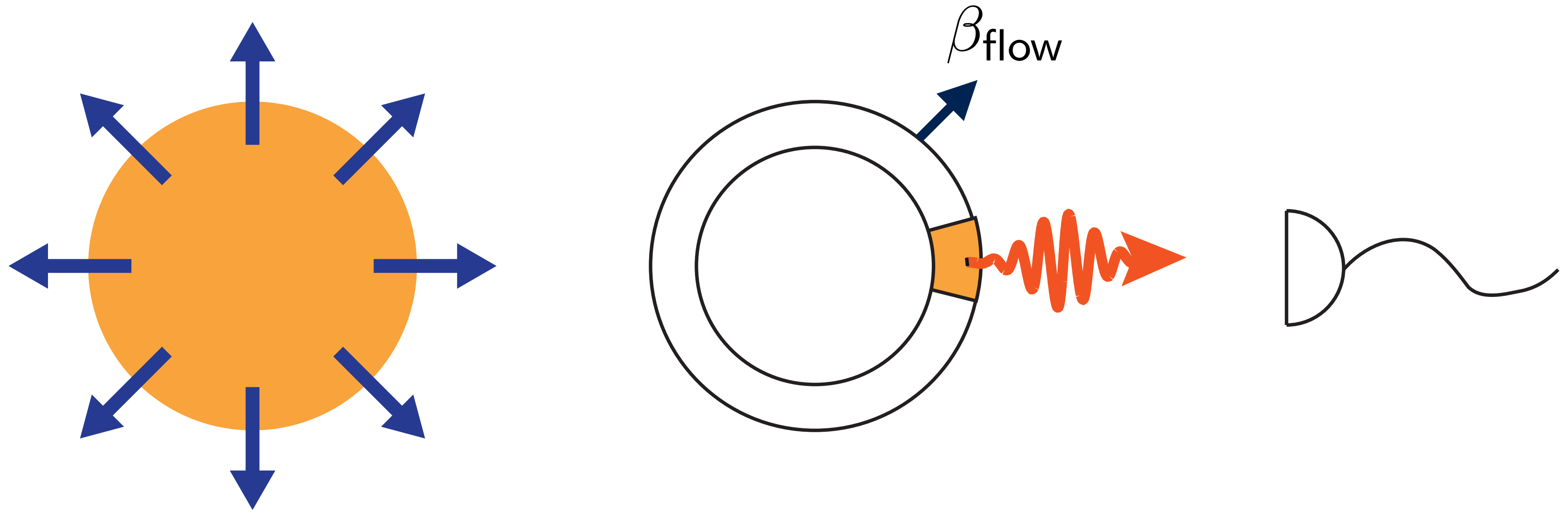
p_T spectrum of **real photons**:

- (effective) temperature + flow dynamics
- sensitive to pre-hydro phase

M_inv spectrum of **virtual photons**:

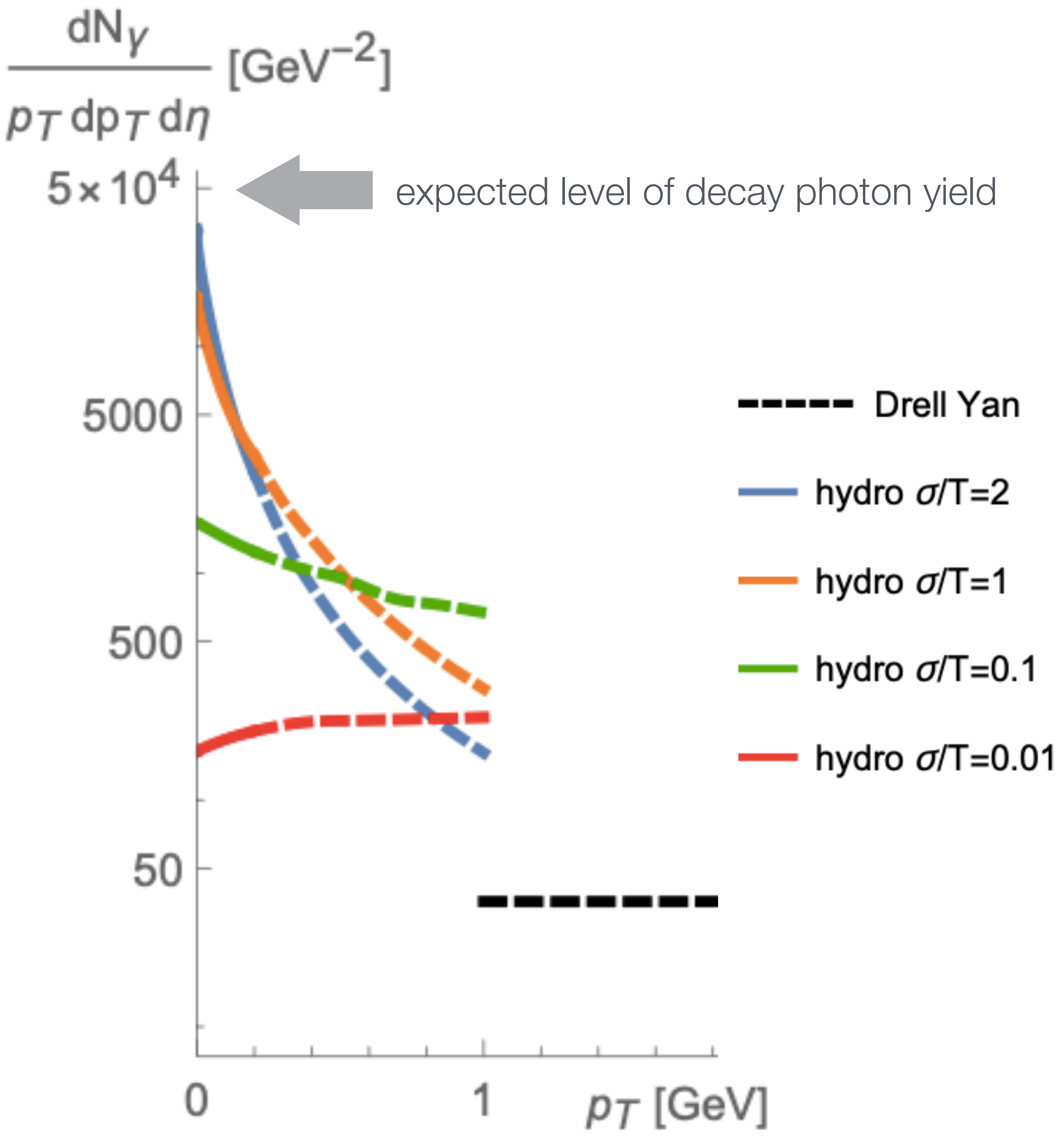
- (effective) temperature, not affected by flow
  $dN/dM \propto M^{3/2} \times \exp(-M/T)$ for $M > 1$ GeV
- sensitive to pre-hydro phase

Doppler blue-shift for real photons



$$E_\gamma \frac{d^3N_\gamma}{d^3p_\gamma} \propto e^{-E_\gamma/T_\mathrm{eff}} \qquad T_\mathrm{eff} = \underbrace{\sqrt{\frac{1+\beta_\mathrm{flow}}{1-\beta_\mathrm{flow}}}}_{2 \text{ for } \beta_\mathrm{flow}=0.6} \times T$$

Decay photons are a significant background



Electrical conductivity is a fundamental transport property (like, e.g., viscosity)

Low-p_T direct photon yields related to electrical conductivity σ:

$$\lim_{p_T \to 0} \frac{dN}{p_T\,dp_T} \propto \sigma$$

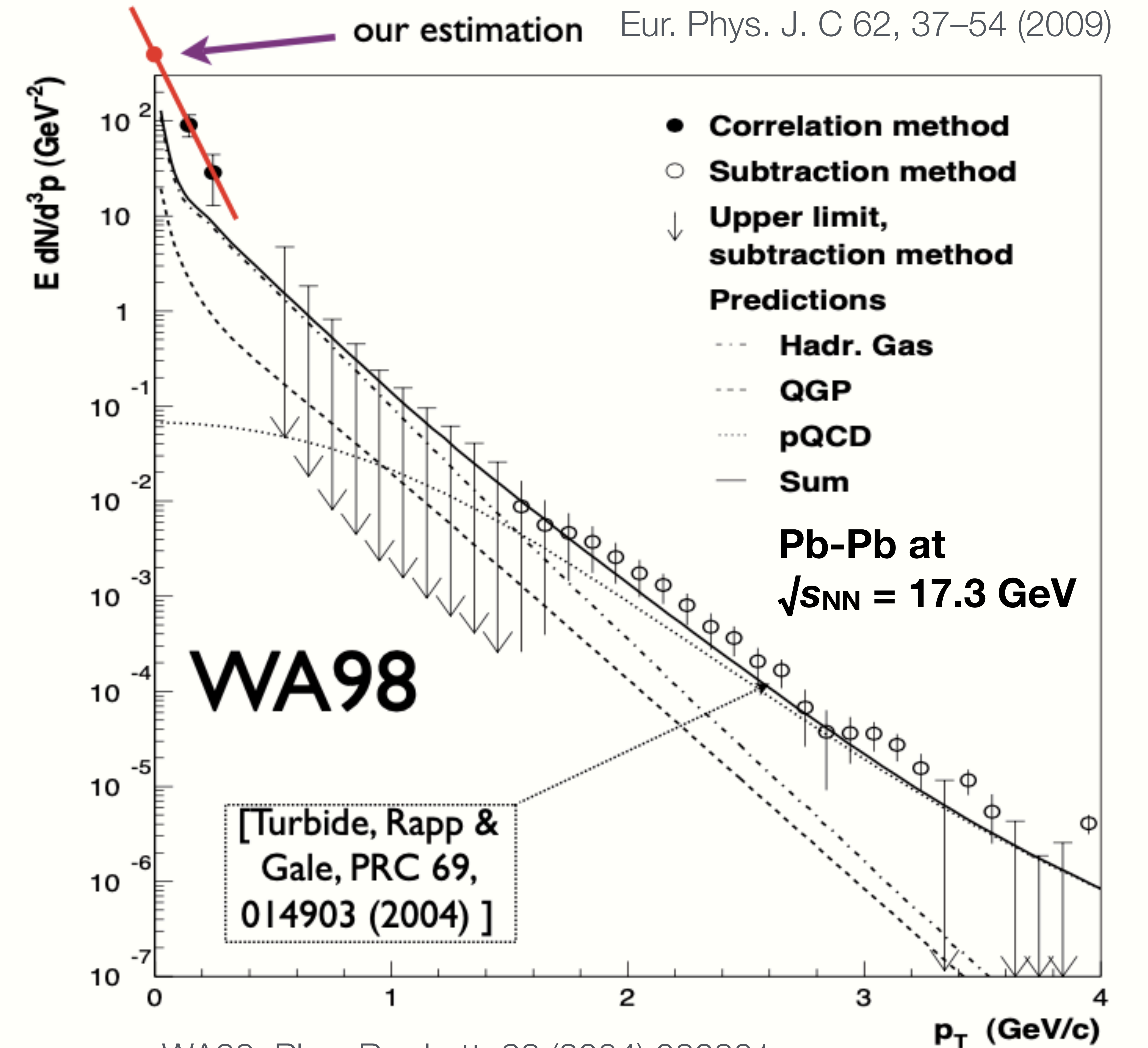
Spectral function with conductivity peak folded with space-time evolution (FluiduM)

Decay photon background ($\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, …) is expected to be large

C. Gebhardt, EMMI Rapid Reaction Task Force (RRTF), *"Signals of Electric Conductivity"*

Promising experimental approach: photon interferometry

D. Fernandez-Frailea and A. Gomez Nicola,
Eur. Phys. J. C 62, 37–54 (2009)



WA98, Phys.Rev.Lett. 93 (2004) 022301

WA98 measured low-p_T photons yields through Hanbury Brown-Twiss (HBT) correlations of photons:

$$N_\gamma^{\mathrm{direct}} / N_\gamma^{\mathrm{total}} = \sqrt{2\lambda} \approx 8\,\%$$

Direct-photon yields without decay-photon cocktail

Model for electrical conductivity of a meson gas consistent with WA98 data

Promising method for ALICE 3

- Sufficient statistics
- Can combine conversion photon with ECal photon

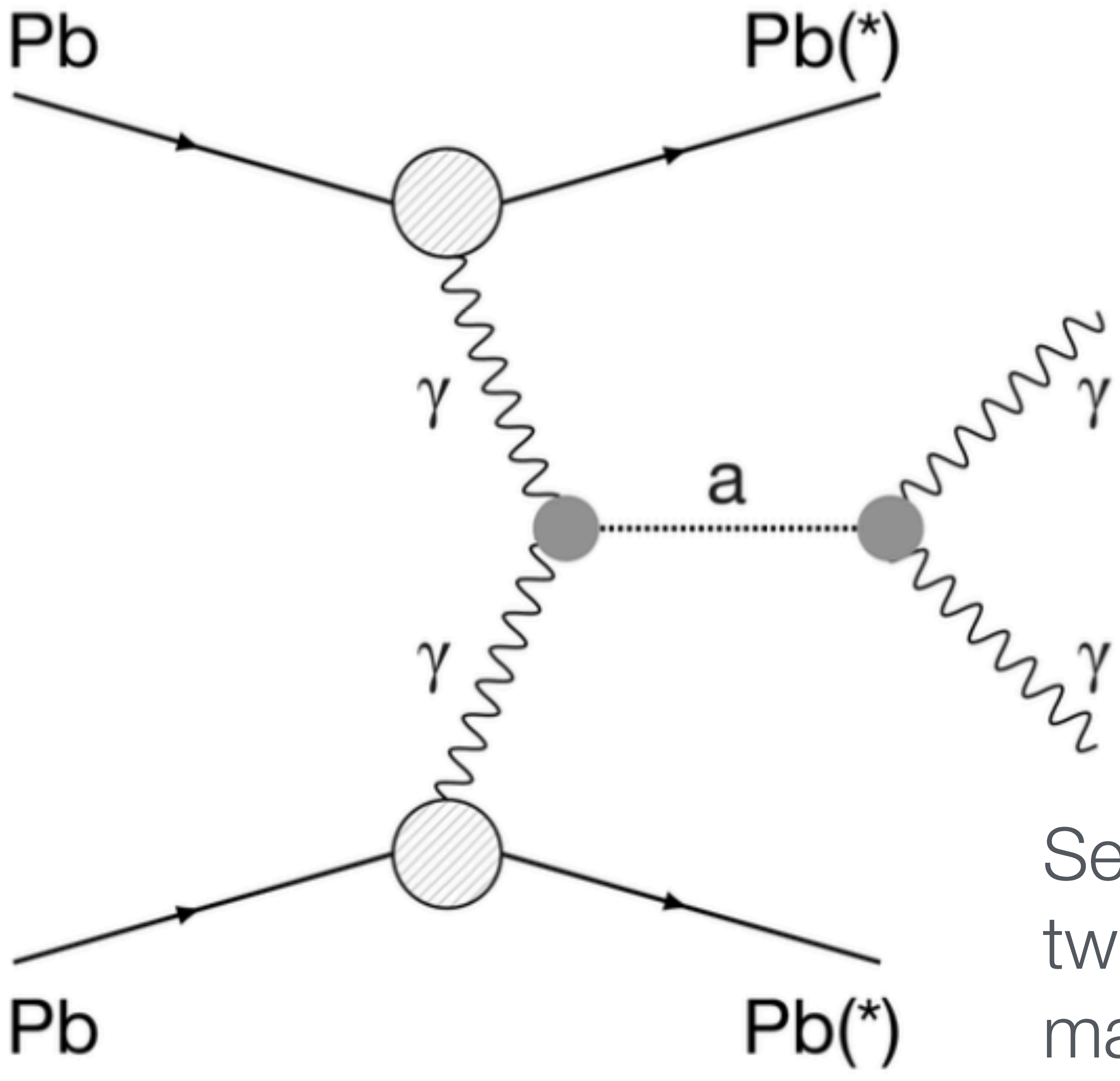
Search for axion-like particles

Low two-photon invariant masses accessible with ALICE 3

BSM studies with ALICE 3 include

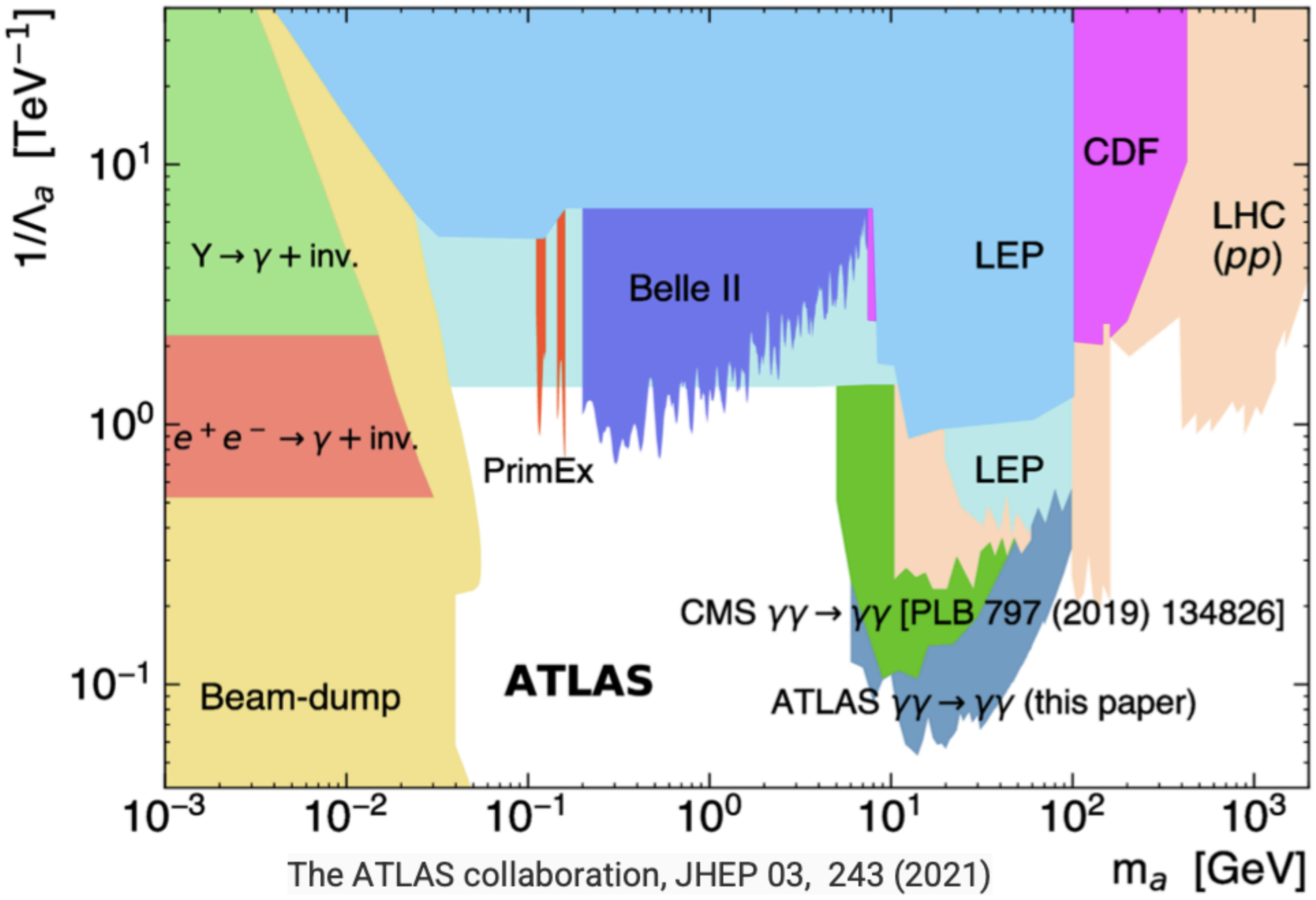
- axion-like particles (ALPs) searches
- τ *g*–2
- dark photon search

ALP searches in ultra-peripheral collisions:



Search for peaks in the two-photon invariant mass spectrum

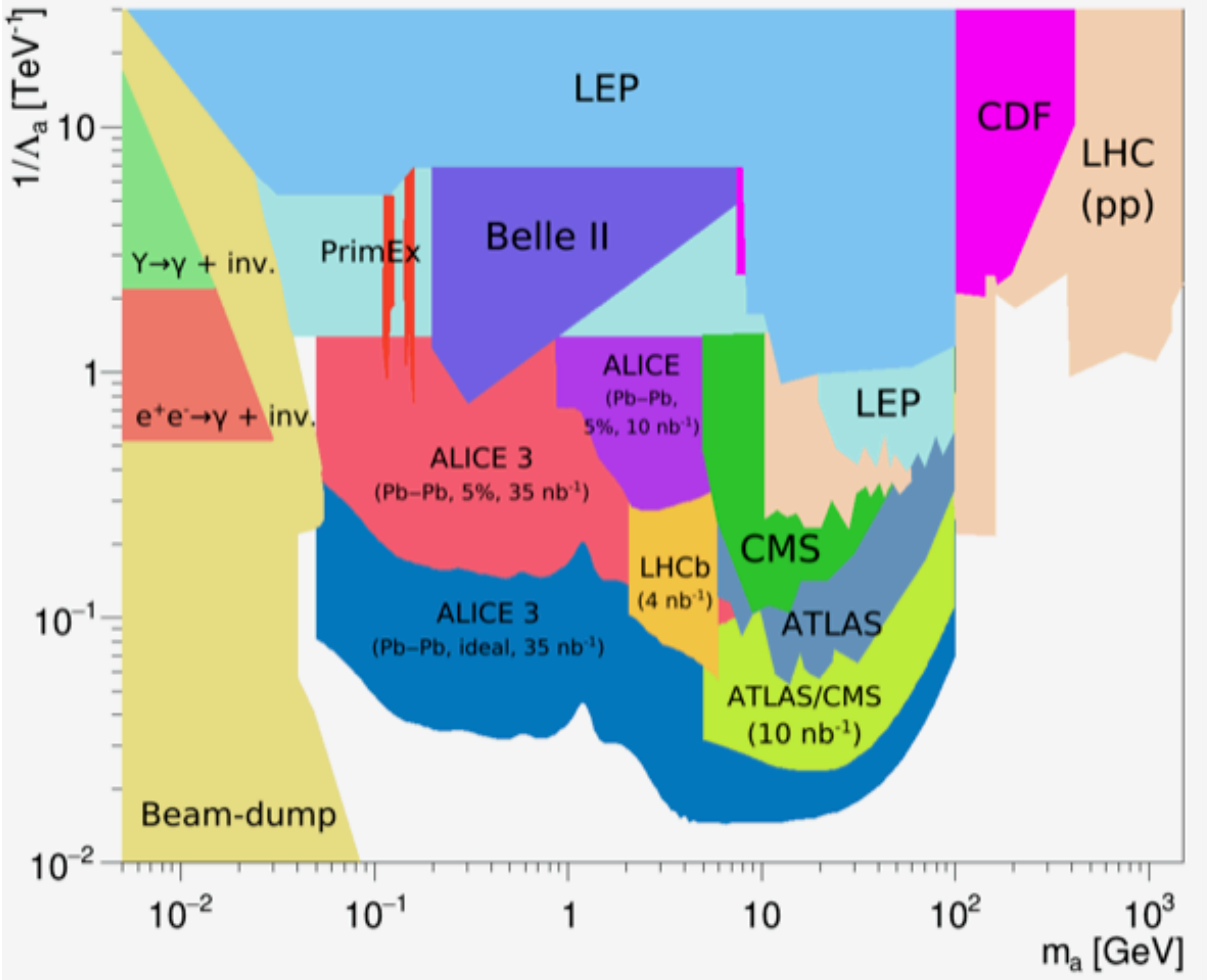
Existing constraints on ALP mass and ALP-photon coupling (from JHEP 12 (2017) 044)



The ATLAS collaboration, JHEP 03, 243 (2021)

Search for axion-like particles

ALICE 3 has the potential to fill the mass gap from 0.05 to 5 GeV



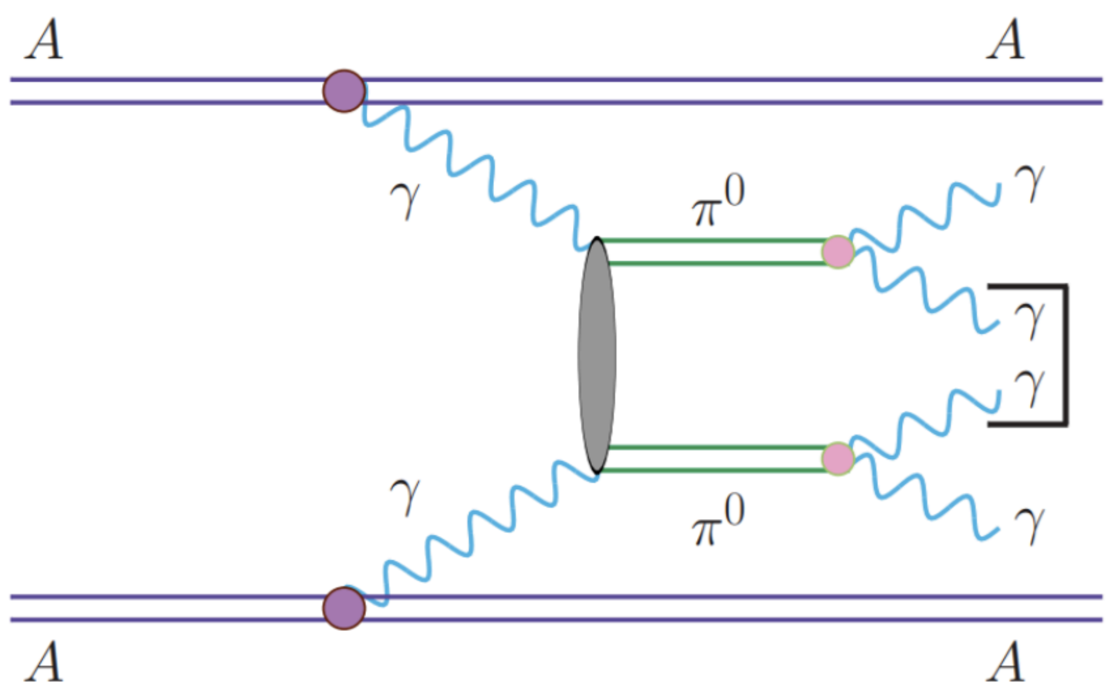
Existing limits from ATLAS, JHEP 03, 243 (2021)
Projections for ATLAS/CMS from PRL 118 (2017), 171801
Projections for LHCb from Goncalves et al. EPJC 81 (2021), 522

ALICE 3 projections for ALP exclusion limits assuming 35/nb Pb-Pb (6 years of data taking)

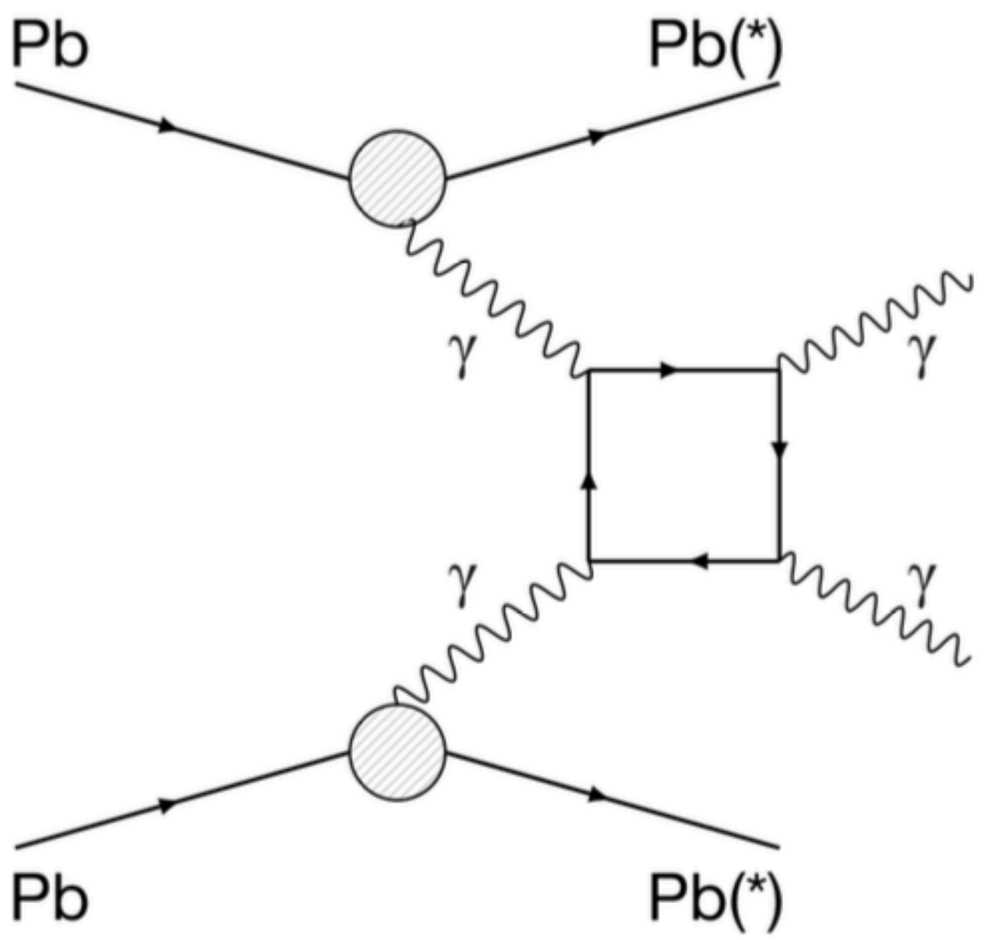
Signal ALPs from STARLight generator

Background includes:

$\pi^0\pi^0$ photoproduction



Light-by-light scattering



Evgeny Kryshen, EMMI RRTF meeting, Sep. 2021
"Light-by-light measurements, ALP searches, and tau g-2 constraints with UPCs"

Conclusions: Photons with ALICE 3

Ultra-soft photons: ALICE 3 Forward Conversion Tracker

- Access to ultra-soft photons in the $p_T < 10$ MeV/c range
- Resolve soft-photon puzzle
- Relation to infrared structure of quantum field theories

Real photons in the O(100 MeV+ range) with ALICE 3

- Photon conversion method and ECal measurement
- Combine information from real and virtual photons for best possible information about pre-hydro and hydro phase
- Electrical conductivity accessible through photon Hanbury Brown-Twiss correlations

Beyond standard model physics: ALPs searches, τ g–2, dark photon searches

- ALICE 3 can fill the gap in the ALP mass range from 50 MeV to 5 GeV