Anomalous Soft Photons：Status and Perspectives

heavily based on what I learnt from Klaus Reygers's talk at ISMD2025

Chia-Ming Kuo
NCU, Taiwan

Low's theorem

- Francis Low derived a universal formula for soft-photon emission in scattering processes
- It was first applied to 2→2 and later generalized to n→m reactions with an additional low-energy photon
- Based only on Gauge invariance, Lorentz invariance and Local relativistic QFT
- Model-independent result

$$\sigma(with\, soft\, \gamma) = \frac{\sigma_0}{\omega_\gamma} + \sigma_1 + \omega_\gamma \sigma_2 + \ldots$$

- Determined only by external charged legs and the non-radiative amplitude

The Soft Photon Puzzle

- Experiments in hadron collisions observed：
    - Soft photon production rate significantly above Low-theorem prediction
- Seen in：
    - hadron-hadron collisions
    - fixed-target experiments
    - hadrnoic Z decays (LEP)

Why It Matters

- Low's theorem is theoretically robust
- Discrepancy persists across experiments
- No widely accepted explanation after decades
- Possible origins proposed：
    - non-perturbative QCD,coherent radiation, hadronization effects, collective emission (but still unresolved)

Recent Reviews and New Experimental Push

- The soft photon puzzle is still an open problem, not just a historical anomaly
- A major 2024 review summarizes today's status and possible explanations
- An international task force (EMMI) is actively coordinating theory and experiment
- Dedicated workshops and seminar series (EMMI Soft Photon Day, focused lectures)
- New detectors (like ALICE 3) will directly test soft-photon production
- Both theory and experiment are being revisited in a systematic way

ELSEVIER

Physics Reports

Volume 1097, 18 December 2024, Pages 1-40

Anomalous soft photons: Status and perspectives

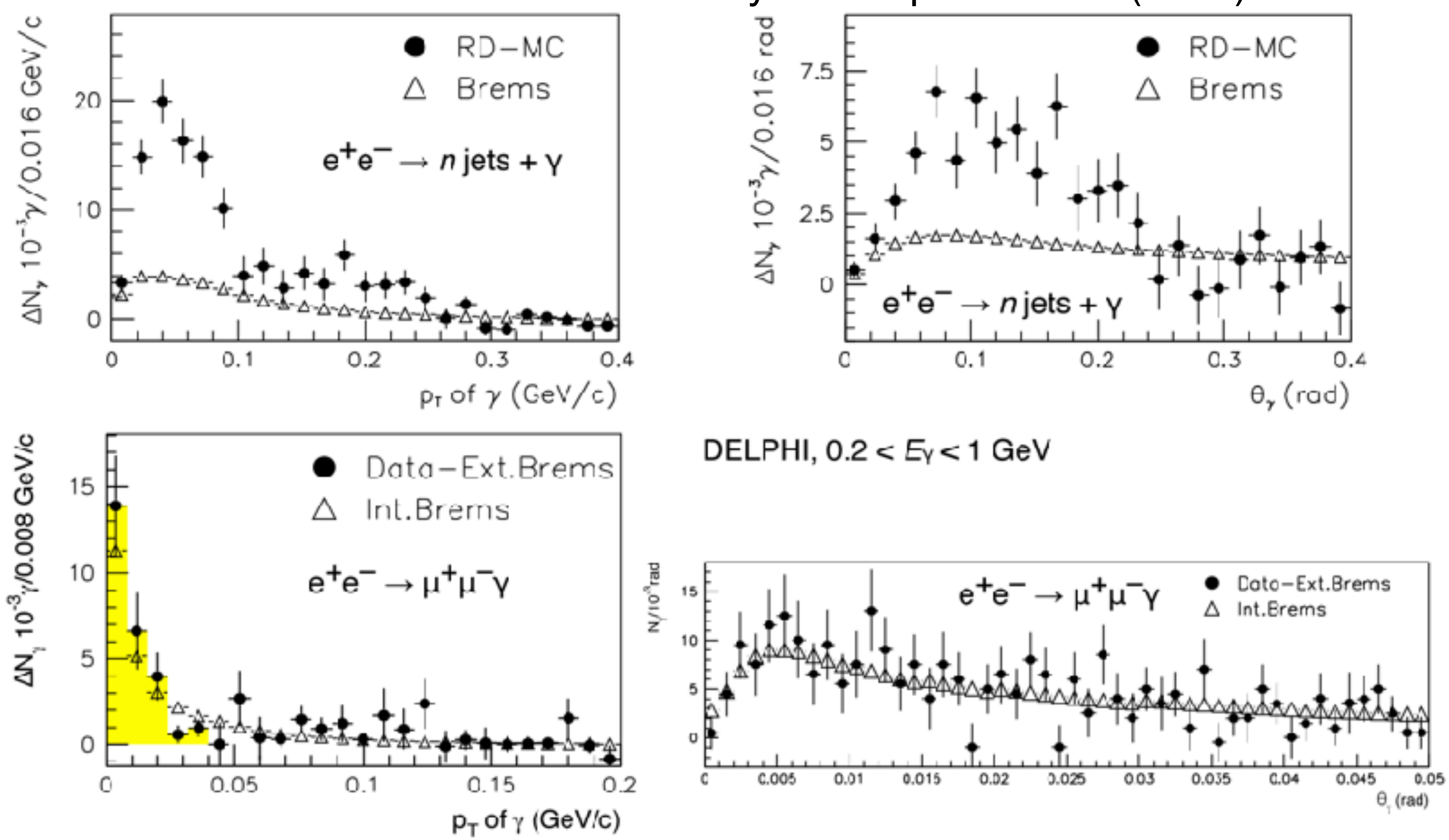
R. Bailhache [a], D. Bonocore [b], P. Braun-Munzinger [c], X. Feal [d], S. Floerchinger [e], J. Klein [f], K. Köhler [g], P. Lebiedowicz [h], C.M. Peter [c], R. Rapp [i], K. Reygers [g], W. Schäfer [h], H.S. Scheid [c], K. Schweda [c], J. Stachel [g], H. van Hees [j,k], C.A. van Veen [g], M. Völkl [g]

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.

Soft Photon Puzzle：Evidence from DELPHI

Physics Reports 1097 (2024) 1-40



- Soft photon excess appears only in hadronic environments

Soft Photon Measurements：Global Experimental Summary

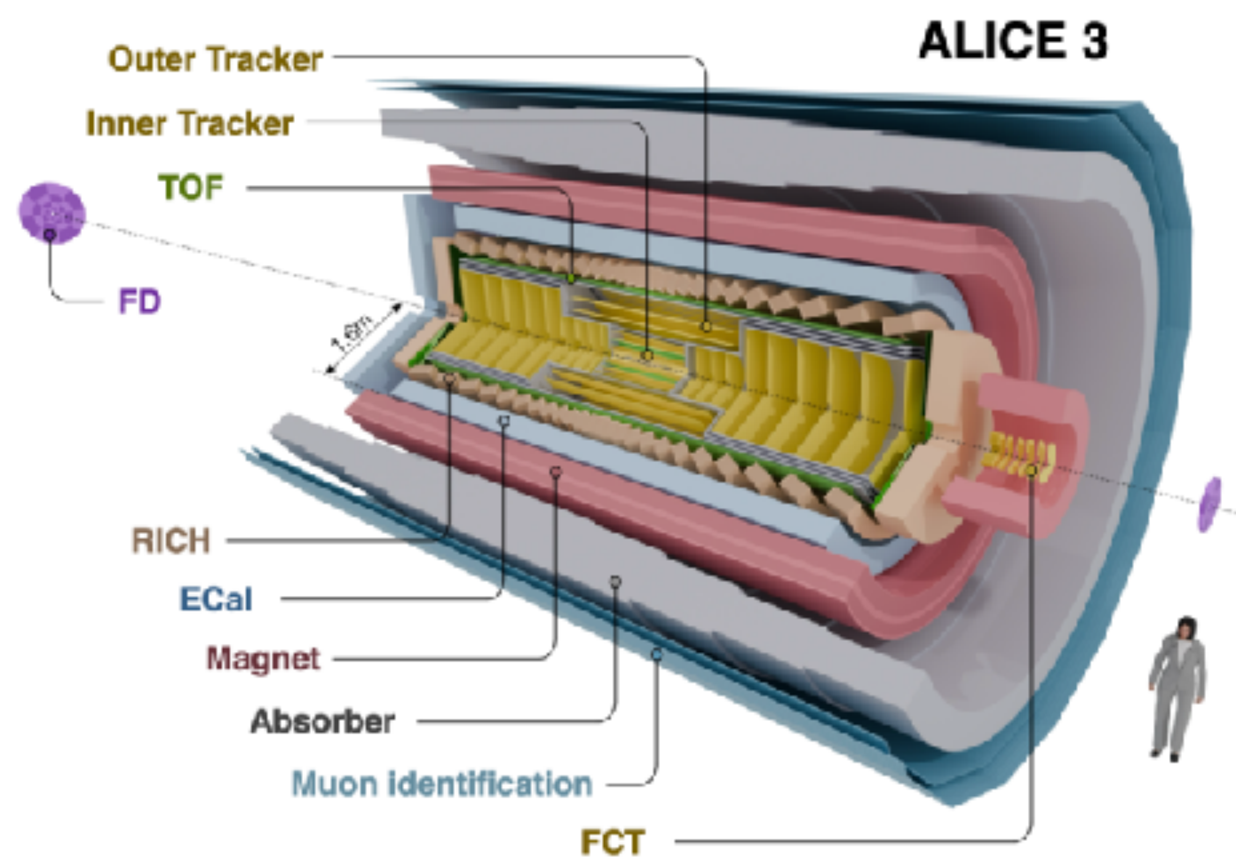
Physics Reports 1097 (2024) 1-40

Exp.	Year	p_{beam} or $\sqrt{s}$	Photon k_T	$\gamma_{meas}/\gamma_{brems}$	Method	Ref.
π^+p	1979	10.5 GeV/c	$k_T < 20$ MeV/c	1.25 ± 0.25	bubble chamber	Goshaw et al. [10]
K^+p WA27, CERN	1984	70 GeV/c	$k_T < 60$ MeV/c	4.0 ± 0.8	bubble chamber (BEBC)	Chliapnikov et al. [11]
π^+p CERN, EHS, NA22	1991	250 GeV/c	$k_T < 40$ MeV/c	6.4 ± 1.6	bubble chamber (RCBC)	Botterweck et al. [12]
K^+p CERN, EHS, NA22	1991	250 GeV/c	$k_T < 40$ MeV/c	6.9 ± 1.3	bubble chamber (RCBC)	Botterweck et al. [12]
π^-p CERN, WA83, OMEGA	1993	280 GeV/c	$k_T < 10$ MeV/c $(0.2 < E_\gamma < 1$ GeV)	7.9 ± 1.4	calorimeter	Banerjee et al. [13]
p–Be	1993	450 GeV/c	$k_T < 20$ MeV/c	$\lesssim 1.5$–3	pair conversion, calorimeter	Antos et al. [14]
p–Be, p–W	1996	18 GeV/c	$k_T < 50$ MeV/c	~ 1 (p–Be) < 2.65 (p–W)	calorimeter	Tincknell et al. [15]
π^-p CERN, WA91, OMEGA	1997	280 GeV/c	$k_T < 20$ MeV/c $(0.2 < E_\gamma < 1$ GeV)	7.8 ± 1.5	pair conversion	Belogianni at al. [16]
π^-p CERN, WA91, OMEGA	2002	280 GeV/c	$k_T < 20$ MeV/c $(0.2 < E_\gamma < 1$ GeV)	5.3 ± 1.0	pair conversion	Belogianni at al. [17]
pp CERN, WA102, OMEGA	2002	450 GeV/c	$k_T < 20$ MeV/c $(0.2 < E_\gamma < 1$ GeV)	4.1 ± 0.8	pair conversion	Belogianni at al. [6]
$e^+e^- \to n$ jets CERN, DELPHI	2006	91 GeV ($\sqrt{s}$)	$k_T < 80$ MeV/c $(0.2 < E_\gamma < 1$ GeV)	$4.0 \pm 0.3 \pm 1.0$	pair conversion	DELPHI [7,18]
$e^+e^- \to \mu^+\mu^-$ CERN, DELPHI	2008	91 GeV ($\sqrt{s}$)	$k_T < 80$ MeV/c $(0.2 < E_\gamma < 1$ GeV)	~ 1	pair conversion	DELPHI [19]

- Soft photon excess is a long-standing, cross-experiment effect tied to hadronic final states

The ALICE 3 Forward Conversion Tracker (FCT)

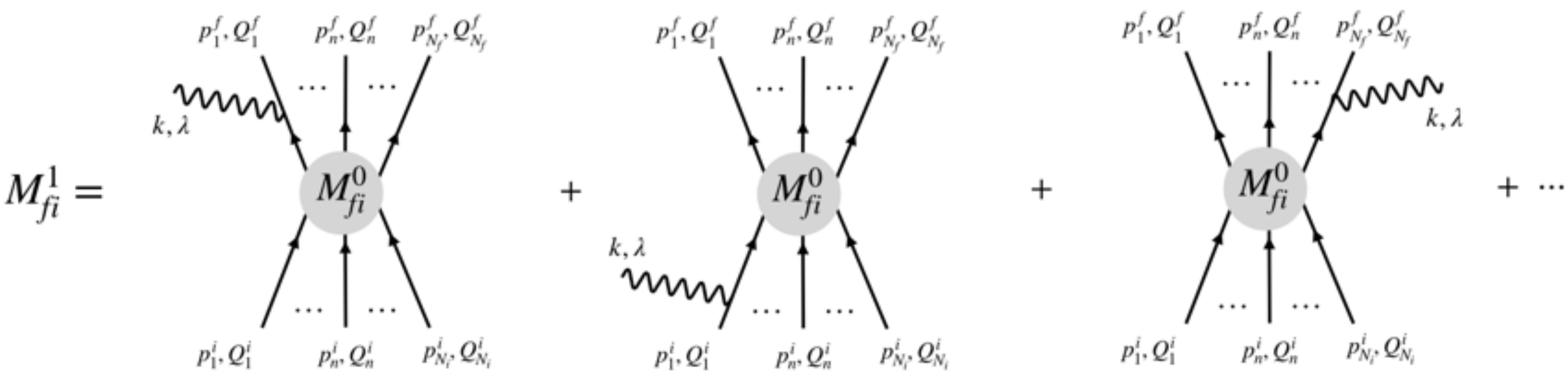
- A dedicated forward photon-conversion tracker for ALICE 3
- Aim to measure：
  - low-energy/soft photons
  - photon conversion→e^+e^- pairs
  - low-mass dileptons in the forward region
- 11 consecutive silicon disks with monolithic pixel sensors
- Dipole magnetic field：~0.25T
  - momentum measurement for e^+e^- pairs
- η coverage：$4 < \eta < 5$
- Planned for LHC Run 5 (~2035) with ALICE 3
- Estimated cost：5M CHF



FCT provides the forward, high-precision conversion measurement needed for next-generation soft-photon and low-mass dilepton studies.

Leading Soft Photon Theorem

- In the soft-photon limit (photon energy→0),
  Radiative amplitude = non-radiative amplitude x universal soft factor



$$M^1_f i = \frac{e}{\sqrt{2\omega_k}} \sum_{n=1}^{N_i+N_f} \eta_n Q_n \frac{\epsilon^*(\vec{k},\lambda)\cdot p_n}{k\cdot p_n} M^0_{fi} + O(\omega_k^0)$$

incoming particle : $\eta_n = -1$
outgoing particle : $\eta_n = +1$

soft factor

non-radiative amplitude of charged particles

Independent of internal loops (internal propagators are never on-shell → no pole)

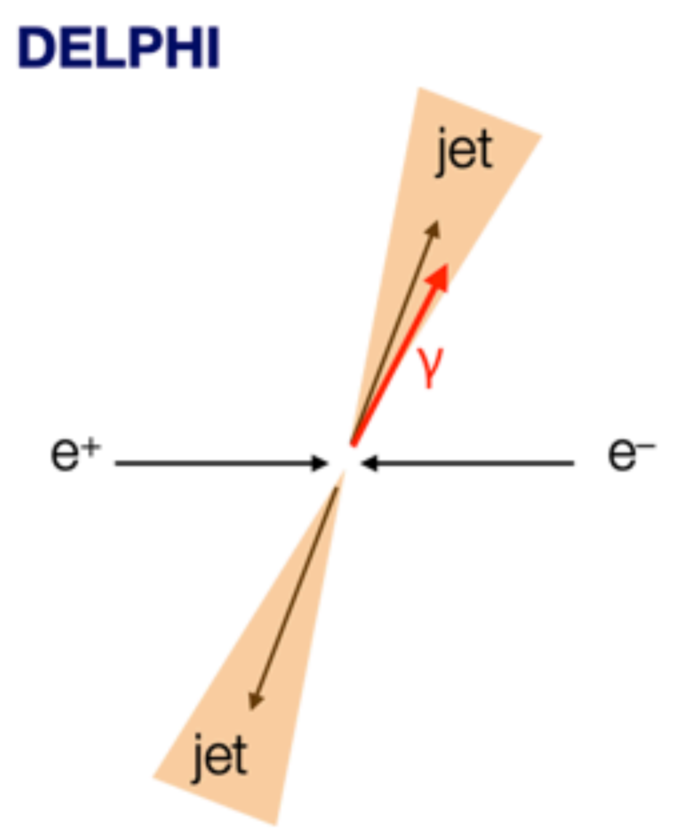
What Experiments Use

- The leading-power Low formula gives the soft-photon yield directly from charged-particle kinematics
- Photon production factorizes : $dN_{\gamma} = (soft\ \ factor)^2 \times dN_{hadrons}$
- Soft factor depends only on external charged-particle 4-momenta p_n, charged Q_n, photon 4-momentum k → independent of internal strong-interaction dynamics
- From the soft denominators $\dfrac{1}{p \cdot k}$: $\dfrac{dN_{\gamma}}{d\omega_k} \propto \dfrac{1}{\omega_k}, \ \dfrac{dN_{\gamma}}{dk_T} \propto \dfrac{1}{k_T}$
    - Very low-energy and low k_T photons are strongly enhanced
    - This defines the key phase space for soft-photon measurements
- Infrared (IR) behavior
    - Total photon yield： IR divergent; Total radiated energy： IR finite
- Bloch-Nordsieck mechanism：
    - IR divergences cancel when summing real + virtual soft photons
    - Observable quantities remain finite and measurable

What Does "Soft Photon" Mean Experimentally?

- Soft-photon enhancement occurs when the denominator in the amplitude becomes small：$p \cdot k \to 0$
- This is the true Low/soft divergence condition
- Not only when photon energy → 0, but whenever the photon is nearly parallel to a charged particle
- For a high-energy charged particle (E ≈ p):
    - $p \cdot k \approx \omega E(1 - cos\theta) \approx \omega E \frac{\theta^2}{2}$
    - Small angle (θ→0)
    - Implies small transverse momentum $k_T \approx \omega\theta \to 0$
    - Soft enhancement appears at the small angle/small k_T
- Frame dependence
    - Charged-particle rest frame：Soft = photon energy << particle mass
    - Laboratory frame： Low limit approached when θ→0 (collinear emission). Practical proxy： select photons with low k_T
- "Soft" photons are those with very small k_T (or small angle) relative to a charged particle. This is how the Low limit is identified in measurements.

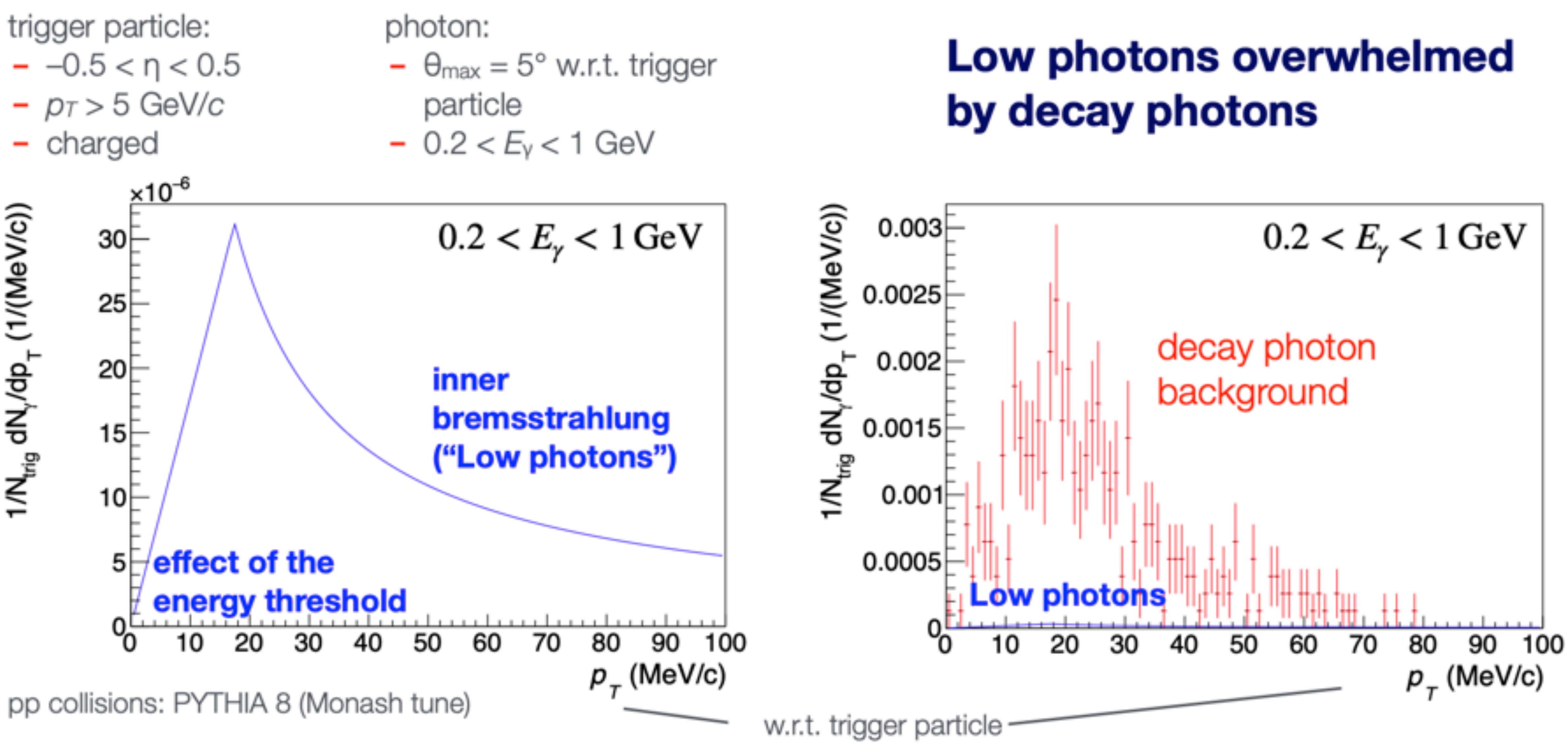
Can We Repeat DELPHI Measurements at the LHC?



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

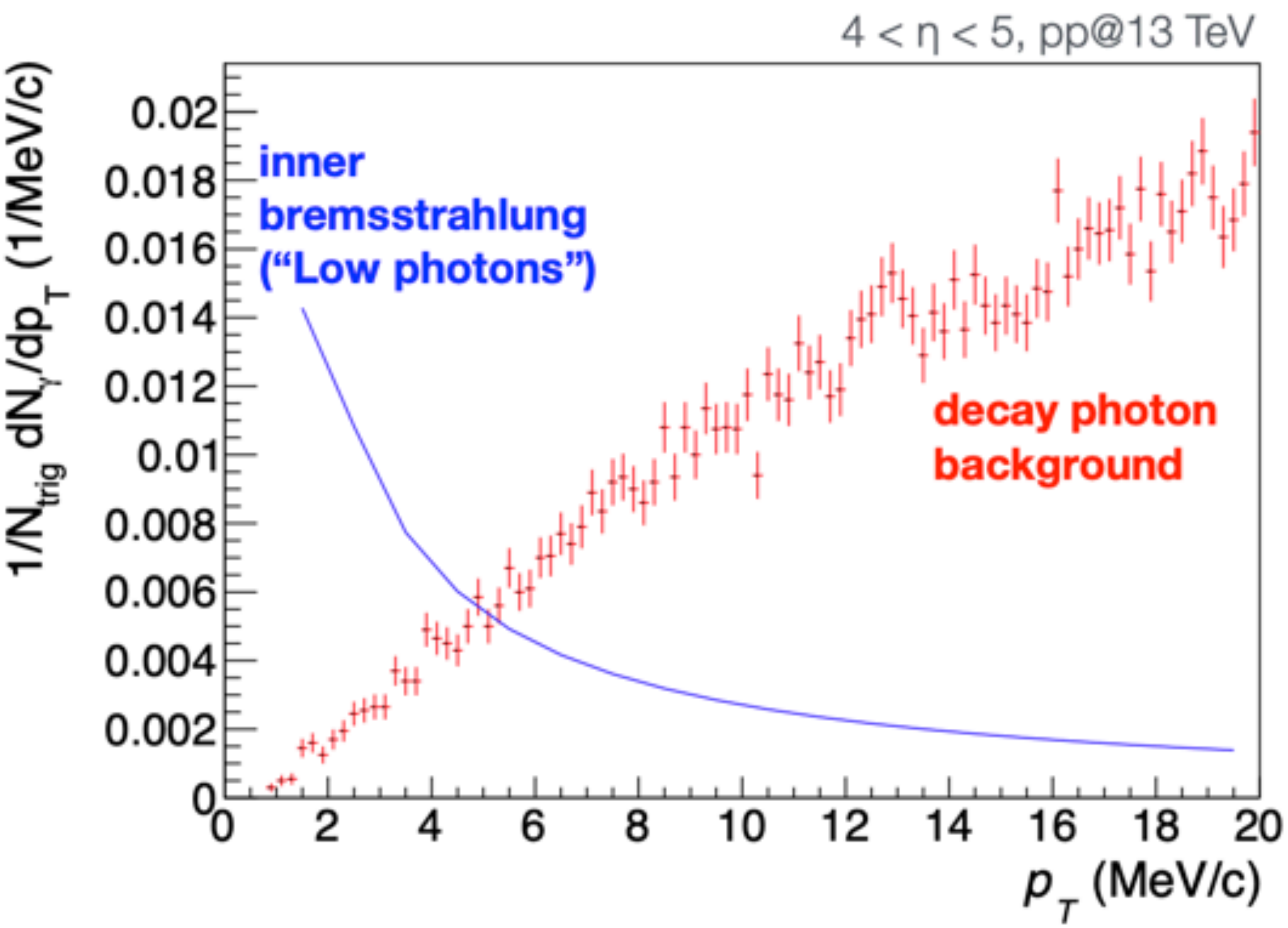
credit: Klaus Reygers's talk at ISMD2025

DELPHI-Style Measurement at η ≈ 0 Not Feasible with ALICE 3



credit: Klaus Reygers's talk at ISMD2025

From Background Dominance to Signal Window: The Role of the Jacobian Peak



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

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

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

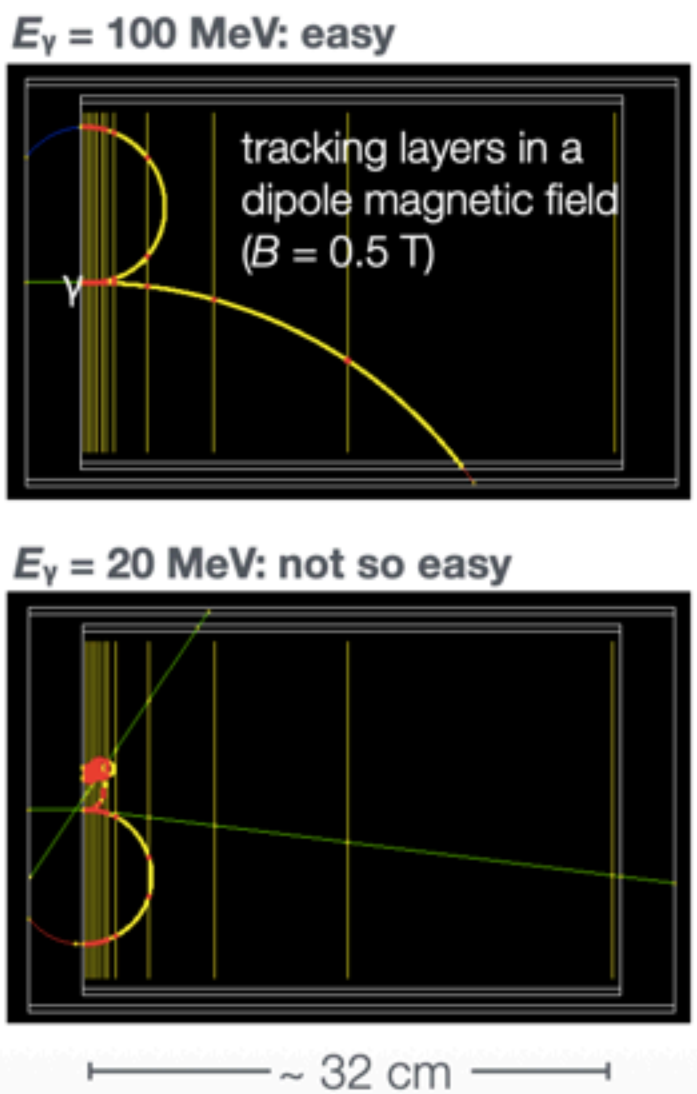
credit: Klaus Reygers's talk at ISMD2025

Ultra-Low k_T Photons Are Accessible Only at Forward Rapidity

A soft photon measurement at the LHC – basic considerations

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

γ reconstruction via conversions:



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

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

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

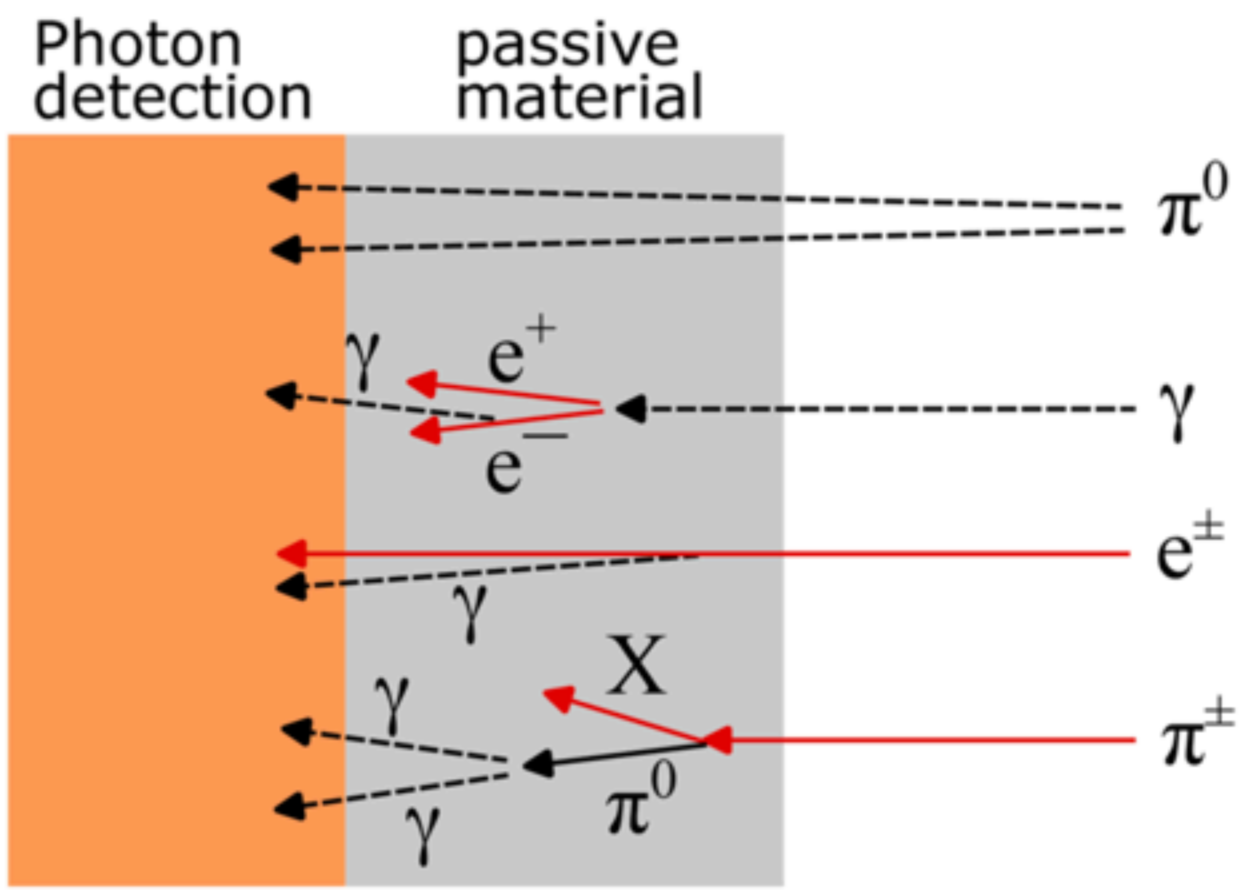
η	3	4	5
p_T (MeV/c)	10	3.7	1.3

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.

credit: Klaus Reygers's talk at ISMD2025

Effective Background Suppression is a Key



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**

credit: Klaus Reygers's talk at ISMD2025

Conversion Background Scales with Material

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

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

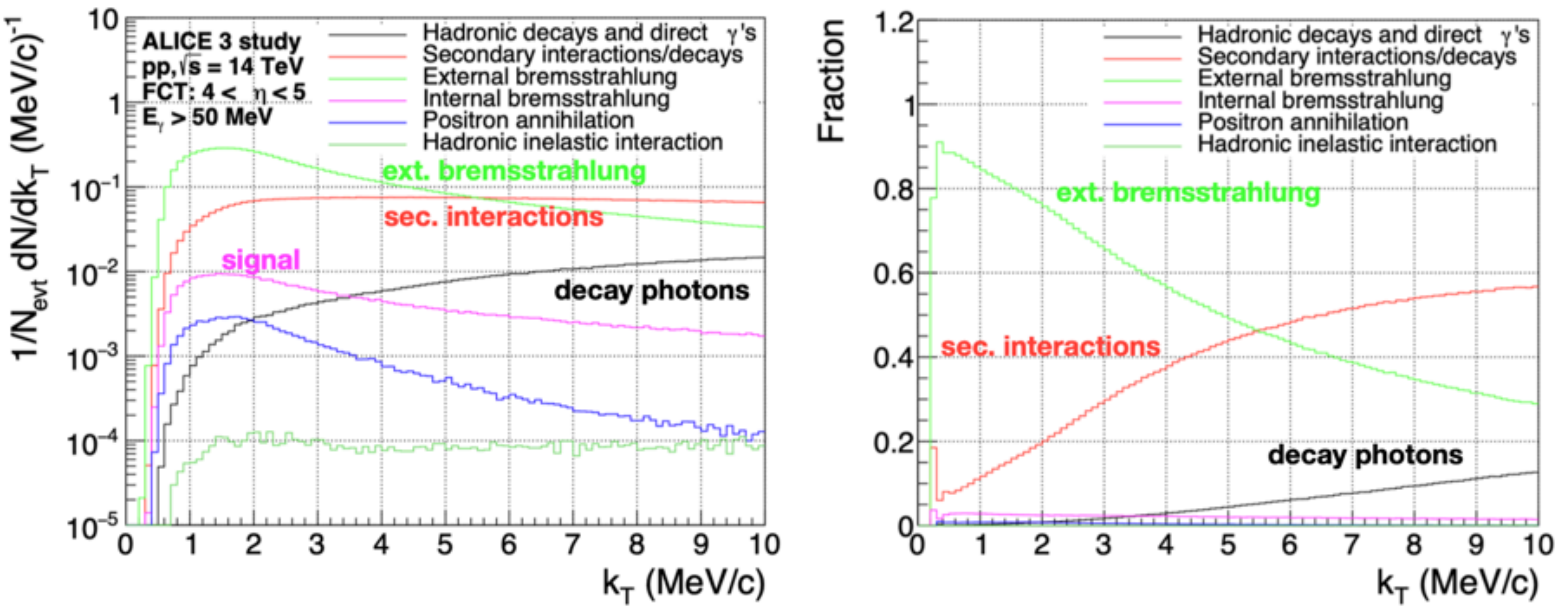
$$\Rightarrow \quad \frac{dN_\gamma^{\text{ext.brems}}}{dk_T\,d\eta} \approx \frac{28}{27}\frac{dN_\gamma^{\text{decay}}}{d\eta}\left(\frac{x}{X_0}\right)^2\frac{1}{k_T}$$

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.

Signal Overwhelmed Without Background Suppression



ALICE 3 FCT Performance

	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

Summary

- Soft photon puzzle remains a long-standing open problem in particle physics
- ALICE 3 Forward Conversion Tracker (FCT) enables access to the ultra-soft photon region (forward rapidity, conversion tracking, dipole field)
- Simulation studies show:
  - Signal-to-background ratio comparable to or better than previous experiments
  - Ultra-low k_T window ($\approx$ 1–4 MeV/c) becomes experimentally reachable
- Background control is the critical requirement
  - External bremsstrahlung and conversion backgrounds dominate without suppression
  - Low material budget + conical beampipe are essential design features
- Expected sensitivities:
  - ~2–4σ without enhancement
  - ~10–14σ for $\times$4 soft-photon enhancement
- If background is controlled, ALICE 3 FCT can provide a realistic path to testing and potentially resolving the soft-photon puzzle at the LHC.