Exploring the infra-red limit of quantum field theories with the measurement of ultra-soft photons at the LHC

pbm
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This presentation is based on work of the ALICE 3 Forward Conversion Tracker (FCT) team and on the publication in Phys. Rep. of a very recent EMMI Rapid Reaction Task Force (RRTF).

ALICE 3 Forward Conversion Tracker FCT

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EMMI RRTF

Phys. Rept. 1097 (2024) 1-40
arXiv:2406.17559 [nucl-ex]

Soft photons, the Low theorem, and ALICE 3

In 1958, Francis Low wrote a seminal paper* on how to relate hadron momenta produced in a high energy collision to the number of soft photons produced. The predictions from the resulting theorem have been repeatedly tested experimentally. In most cases, significant discrepancies were found between predictions and experimental measurements. Clearly, the measurement of very soft (MeV scale in transverse momentum) photons presents formidable difficulties. Nevertheless, the disrepancies are striking, and no agreement exists on their possible origin, despite > 40 years of research.

We review the current theoretical status and present a proposal how to make a precision test of the Low predictions in the framework of ALICE 3, the future ALICE detector to study novel QCD phenomena in the low transverse momentum region $p_T < 10$ GeV at LHC energies.

*F. Low,
Bremsstrahlung of very low-energy quanta in elementary particle collisions,"
Phys. Rev. 110 (1958), 974-977

Background

In all collisions among elementary particles, soft photons can be produced at any stage and without limits on their number by conservation laws etc. This was realized in the 1930ties when first QED calculations were performed, by Weisskopf, Bethe and Heitler and others. The consequences were worked out in systematic fashion in the by now famous paper by Bloch and Nordsieck,

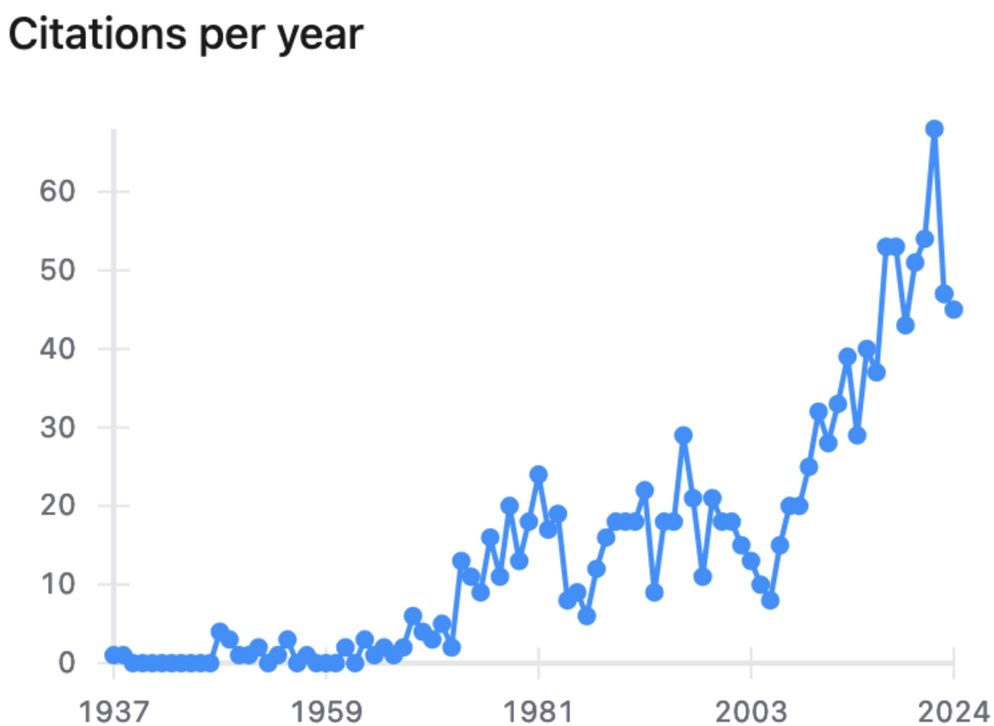
F. Bloch and A. Nordsieck,
Note on the Radiation Field of the electron, Phys. Rev. 52 (1937), 54-59

the conclusion by Bloch and Nordsieck is that the mean total number of light quanta radiated diverges, but the mean total energy radiated stays finite. see also H. Bethe and W. Heitler, Proc. Roy. Soc. A146 (1934) 83

This led to the work by Francis Low in the context of collisions between elementary particles.

A note on Arnold Nordsieck

Citations/year of the Bloch/Nordsieck paper, 1937 – 2024, one of the landmark papers in QFT (quantum field theory)



Arnold Nordsieck, 1911 – 1971, PhD 1935 with Robert Oppenheimer as supervisor, postdoc years at Leizig with Heisenberg and F. Bloch, published 3 papers, built the 1st US analog computer from WW2 spare parts, developed 1st inertial navigation system for nuclear submarines

Outline

1. on the derivation of the Low formula in y and k_t space

2. comments on implementation and application in the experimental context

3. ALICE 3
   - short overview
   - soft photon measurements

4. remarks

5. outlook

The Low theorem:
F. Low,
Bremsstrahlung of very low-energy quanta in elementary particle collisions,
Phys. Rev. 110 (1958), 974-977

The 'standard' derivation is based on the original article plus:

1. S. Weinberg, Phys. Rev. 140 (1965) B516 -- particularly clear exposition based on QED and gravitation theory,
see also S. Weinberg, The quantum theory of fields vol. 2
Cambridge University press, 2005

2. A.T. Goshaw et al., PRL 43 (1979) 1065, -- 1st experimental application

3. Delphi coll., Eur. Phys. J. C67 (2010) 343 -- measurement in jets

4. C.Y. Wong, arXiv:1404.0040, -- pedagogical introduction

5. A. Strominger, arXiv:1703.05448, -- introduction to soft theorems in general

6. A new, modern derivation developed in the context of a very recent EMMI Rapid Reaction task force, RRTF, see next slide

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 [a], R. Rapp [i], K. Reygers [g], W. Schäfer [h], H.S. Scheid [a], K. Schweda [c], J. Stachel [g], H. van Hees [j], C.A. van Veen [g], M. Völkl [g]

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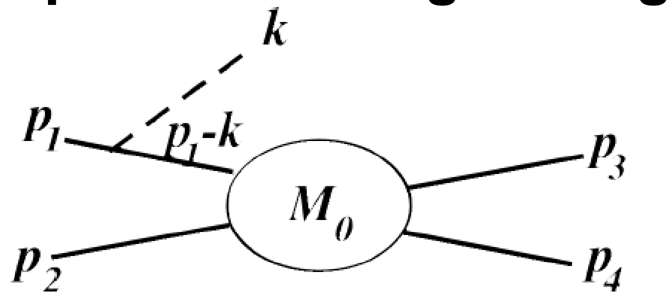
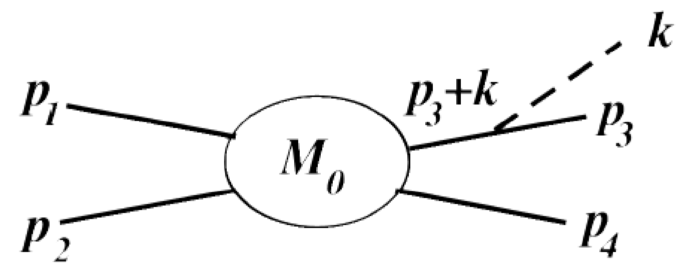
arXiv:2406.17559 [nucl-ex]

Feynman diagrams in leading order for a 'two body collision with soft photons' at high energy



note: the soft photon part is independent of particle identity, the factors e_i are particle charges and η_i are -/+ 1 for incoming and outgoing particles, respectively (interference!). For details see 2406.17559.



$$\mathcal{M}(p_1p_2;p_3p_4k) = \mathcal{M}_0(p_1p_2;p_3p_4)\left(\frac{e_1p_1\cdot\epsilon}{[(p_1-k)^2-m_1^2]} + \frac{e_3p_3\cdot\epsilon}{[(p_3+k)^2-m_3^2]}\right)$$

$$= \mathcal{M}_0(p_1p_2;p_3p_4)\left(\sum_i^{\text{all charged particles}} \frac{\eta_i e_i p_i\cdot\epsilon}{2p_i\cdot k}\right),$$

amplitude — 2-body part — photon part

all momenta are 4-vectors, ε is the 4-vector polarization of the photon

assumptions (1)

We first remark that, from Eq. (1), the photon production factor arises from the interference of photon production from incoming and outgoing charged particles. The resulting amplitude has a pole whenever $p \cdot k$ vanishes (in any reference frame). Importantly, one should recognize that, in this soft photon limit, all Feynman diagrams where the soft photon line is connected to an internal line corresponding to a virtual charged particle, yield a non-diverging and, therefore, negligible contribution to the soft photon production cross section. It is then not necessary to evaluate the contribution of all possible internal loops to the cross section: Low's leading term is 'tree-level' correct.

‘corrections’ to Low theorem

In addition to the standard Low term there is also a sub-leading term of order zero in k_t that was also computed in the original Low paper. Recently, it was shown [2], Lebiedowicz et al., that this term needs a correction due to the requirement to incorporate exact energy and momentum conservation at this order. Corrections to the leading-power expression for the soft photon yield were recently also studied in [1], Bonocore and Kulesza. Measurements in the sub-leading k_t range are important if one wants to study the approach to the Low limit as we plan to do with ALICE 3.

[1]
Domenico Bonocore and Anna Kulesza. Soft photon bremsstrahlung at next-to-leading power. *Phys. Lett. B*, 833:137325, 2022.
[2]
Piotr Lebiedowicz, Otto Nachtmann, and Antoni Szczurek. High-energy $\pi\pi$ scattering without and with photon radiation. *Phys. Rev. D*, 105(1):014022, 2022.

Many new theory developments, see Phys. Reports

Especially noteworthy:

Y. Ma, G. Sterman, A. Venkata

soft photon theorem in QCD with massless quarks

Phys. Rev. Lett. 132 (2024) 9, 091902

V. S. Fadin, V. A. Khoze

the Low soft photon theorem again

Eur.Phys.J.C 84 (2024) 3, 274,

Eur.Phys.J.C 84 (2024) 4, 376 (erratum)

assumptions (2)

Note that for all charged particles i the photon production factor $\frac{\eta_i e_i p_i \cdot \epsilon}{2p_i \cdot k}$ is independent of the mass of the radiating particle i. However, the photon production factor does depend on the (vector)-velocities of the charged particles, so in general, particle ID is necessary.

Here, e_i is the charge of p_i, and η_i is +1 for an outgoing hadron and -1 for an incoming hadron respectively. In obtaining the above equation, we have assumed

$$\mathcal{M}_0(p_1 - k \;\; p_2;\; p_3 \; p_4) \approx \mathcal{M}_0(p_1 \; p_2;\; p_3 + k \;\; p_4) \approx \mathcal{M}_0(p_1 \; p_2;\; p_3 \; p_4). \qquad (2)$$

The equations become exact in the limit (Low limit) in which the photon transverse momentum approaches zero. The amplitude $\mathcal{M}_0$ for the production of a soft photon is then independent of k and can be adequately represented by $\mathcal{M}_0(p_1 p_2; p_3 p_4)$, the Feynman amplitude for the production of only hadrons.

Beyond the Low limit, as discussed above, it becomes important and difficult to implement momentum conservation, see the very recent work of:
P. Lebiediwicz, O.Nachtmann, and A. Szczurek, Phys. Rev. D110 (2024) 094928

multi-particle reactions

We can generalize the above Eq. (1) to multi-particle production, i.e. to the process $p_1 + p_2 \to p_3 + p_4 + ... + p_{N+2} + k$ where N charged hadrons are produced with momenta p_3 to p_{N+2} and k is the 4-momentum of the soft photon. Of course the process can be accompanied by the production of neutral particles which are in general not detected. The Feynman amplitude is then, in the Low limit,

$$\mathcal{M}(p_1 p_2; p_3 p_4 ... p_{N+2} k) = \mathcal{M}_0(p_1 p_2; p_3 p_4 ... p_{N+2}) \left(\sum_i^{\text{all charged particles}} \frac{\eta_i e_i p_i \cdot \epsilon}{2 p_i \cdot k} \right). \quad (3)$$

photon k_t and Lorentz invariance

Since the total photon production factor $\left(\sum_i^{\text{all charged particles}} \frac{\eta_i e_i p_i \cdot \epsilon}{2 p_i \cdot k}\right)$ is here expressed in Lorentz-invariant form it becomes transparent that the photon production amplitude and cross section yields equivalent results in any Lorentz frame, in particular those corresponding to boosts along the beam direction. Note that the photon production factor contains the 'Low divergence'. Hence, it is appropriate to use photon rapidity y_k and transverse momentum k_t when investigation photon production in the Low regime.

for many more details, see the RRTF Phys. Rep. publication
in 2406.17559

the invariant yield

From the relation between Feynman amplitudes and cross sections, the above equation gives for the invariant yield [1]

$$N_{inv} = k_0 \frac{dN_\gamma}{d^3k} =$$

$$\frac{\alpha}{2\pi} \int d^3p_3 ... d^3p_{N+2} \sum_{i,j=1}^{N+2} \eta_i \eta_j e_i e_j \frac{-(p_i \cdot p_j)}{(p_i \cdot k)(p_j \cdot k)} \frac{dN_{\text{hadrons}}}{d^3p_3 ... d^3p_{N+2}}. \tag{4}$$

Then, as first derived in [1, 2], the momentum distribution of soft photons can be calculated from measurements of the distributions of the produced charged hadrons. Of course, the amplitude $\mathcal{M}$ additionally contains an arbitrary number of neutral hadrons which are immaterial for the photon production. Note that we explicitly ignore here as background the decay of neutral hadrons into photons although the elimination or strong reduction of this background is a major issue in all soft photon measurements.

We note from Eq. (4) that:

$$dN_{gamma}/dk_t \propto 1/k_t \tag{5}$$

for any reference frame centered at rapidity y (along the beam direction) due to the divergence in the photon production factor.

two versions of the Low formula

(a) original version

$$\frac{dN_\gamma}{d^3\vec{k}} = \frac{\alpha}{(2\pi)^2}\frac{1}{E_\gamma}\int d^3\vec{p}_1...d^3\vec{p}_N \sum_{i,j}\eta_i\eta_j \frac{-(P_iP_j)}{(P_iK)(P_jK)}\frac{dN_{hadrons}}{d^3\vec{p}_1...d^3\vec{p}_N}$$

(b) Haissinski version

$$\frac{dN_\gamma}{d^3\vec{k}} = \frac{\alpha}{(2\pi)^2}\frac{1}{E_\gamma}\int d^3\vec{p}_1...d^3\vec{p}_N \sum_{i,j}\eta_i\eta_j \frac{(\vec{p}_{i\perp}\cdot\vec{p}_{j\perp})}{(P_iK)(P_jK)}\frac{dN_{hadrons}}{d^3\vec{p}_1...d^3\vec{p}_N}$$

$\vec{p}_{i\perp} = \vec{p}_i - (\vec{n}\cdot\vec{p}_i)\cdot\vec{n}$ and $\vec{n}$ is the photon unit vector, $\vec{n} = \vec{k}/k$

both formulas are mathematically equivalent, but (b) is much preferred for e+e- collisions because of strong interference between incoming and outgoing particles

for pp or AA collisions with many outgoing particles the interference term between ingoing and outgoing particles is very small but for numerical applications (b) is more stable

experimental situation after 40 years of measurements

Exp.	year	p_{beam} or $\sqrt{s}$	photon k_T	$\gamma_{\mathrm{meas}}/\gamma_{\mathrm{brems}}$	method	Ref.
π^+p	1979	$10.5\,\mathrm{GeV}/c$	$p_T < 20\,\mathrm{MeV}/c$	1.25 ± 0.25	bubble chamber	Goshaw et al. [10]
K$^+$p WA27, CERN	1984	$70\,\mathrm{GeV}/c$	$k_T < 60\,\mathrm{MeV}/c$	4.0 ± 0.8	bubble chamber (BEBC)	Chliap-nikov et al. [11]
π^+p CERN, EHS, NA22	1991	$250\,\mathrm{GeV}/c$	$k_T < 40\,\mathrm{MeV}/c$	6.4 ± 1.6	bubble chamber (RCBC)	Botterweck et al. [12]
K$^+$p CERN, EHS, NA22	1991	$250\,\mathrm{GeV}/c$	$k_T < 40\,\mathrm{MeV}/c$	6.9 ± 1.3	bubble chamber (RCBC)	Botterweck et al. [12]
π^-p CERN, WA83, OMEGA	1993	$280\,\mathrm{GeV}/c$	$k_T < 10\,\mathrm{MeV}/c$ $(0.2 < E_\gamma < 1\,\mathrm{GeV})$	7.9 ± 1.4	calorimeter	Banerjee et al. [13]
p–Be	1993	$450\,\mathrm{GeV}/c$	$k_T < 20\,\mathrm{MeV}/c$	< 2	pair conversion, calorimeter	Antos et al. [14]
p–Be, p–W	1996	$18\,\mathrm{GeV}/c$	$k_T < 50\,\mathrm{MeV}/c$	< 2.65	calorimeter	Tincknell et al. [15]
π^-p CERN, WA91, OMEGA	1997	$280\,\mathrm{GeV}/c$	$k_T < 20\,\mathrm{MeV}/c$ $(0.2 < E_\gamma < 1\,\mathrm{GeV})$	7.8 ± 1.5	pair conversion	Belogianni at al. [16]
π^-p CERN, WA91, OMEGA	2002	$280\,\mathrm{GeV}/c$	$k_T < 20\,\mathrm{MeV}/c$ $(0.2 < E_\gamma < 1\,\mathrm{GeV})$	5.3 ± 1.0	pair conversion	Belogianni at al. [17]
pp CERN, WA102, OMEGA	2002	$450\,\mathrm{GeV}/c$	$k_T < 20\,\mathrm{MeV}/c$ $(0.2 < E_\gamma < 1\,\mathrm{GeV})$	4.1 ± 0.8	pair conversion	Belogianni at al. [6]
$e^+e^- \to n\,$jets CERN, DELPHI	2006	$91\,\mathrm{GeV}$ $(\sqrt{s})$	$k_T < 80\,\mathrm{MeV}/c$ $(0.2 < E_\gamma < 1\,\mathrm{GeV})$	$4.0 \pm 0.3 \pm 1.0$	pair conversion	DELPHI [7, 19]
$e^+e^- \to \mu^+\mu^-$ CERN, DELPHI	2008	$91\,\mathrm{GeV}$ $(\sqrt{s})$	$k_T < 80\,\mathrm{MeV}/c$ $(0.2 < E_\gamma < 1\,\mathrm{GeV})$	~ 1	pair conversion	DELPHI [18]

about 2/3 of all measurements are in significant excess of the 'Low' predictions

Table from Phys. Rept. 1097 (2024) 1-40

why test these 'divergencies' experimentally?

when the photon transverse momentum becomes very small, $k_t^{-1} >> d_{trans}$ the maximum conceivable transverse dimensions d_{trans}, then the structure of the system does not matter anymore

note: k_t = 1 MeV corresponds to k_t^{-1} = 200 fm

any deviation between between Low theorem predictions and experimental results for soft photon spectrum indicates:

a) a loophole in the theory argument

b) an experimental problem

or

c) something fundamentally not understood

a loophole in the theory?

the Low theorem has now been intensively studied by many scientists, for an exhaustive discussion see the review by A. Strominger, arXiv:1703.05448

the theorem has been derived in various ways and is considered, in the soft photon limit, tree-level exact, i.e. there are no loop corrections

are there possibly non-perturbative corrections?

I quote here again Andrew Strominger:

> to ask whether there can be nonperturbative corrections. To even talk about nonperturbative contributions to the soft theorem, one first needs a theory that exists nonperturbatively. QED — the theory of photons and electrons — does not exist due to the Landau pole. It must be embedded in some bigger theory — maybe one that is asymptotically free — that does exist nonperturbatively. To the best of my knowledge, all examples of such bigger theories contain magnetic monopoles.

clearly it is worthwhile to test the predictions of the Low theorem as best we can

experimental problems?

soft photons (E_{photon} << 100 MeV) are very difficult to measure in a collider environment

one also needs precise measurement of the momenta of all primary charged particles, over what phase space needs to be discussed

nearly all experimental tests so far have found large discrepancies between theoretical prediction and data, see below

thoughts about experimental approaches to test the Low theorem

1. currently, the direct photon spectrum in pp to Pb-Pb collisions is largely unknown for transverse momenta below 0.5 GeV

2. measurements in this kinematic region are exceedingly difficult because of the huge decay photon background

3. the soft photon spectrum in the very low k_t region can be computed with precision if one has on excellent measurement of the momenta of all charged primary particles with the least possible cut-offs

4. 1st focus should be on pp collisions at the highest available energy, both for exclusive channels and inclusive production

5. new at LHC energies is that one can make the number of outgoing charged particles large. this is a direct test of the multipicity dependence of soft photon production. It also will significantly change the interference pattern between incoming and outgoing particles, a unique possibility at high energy

6. to understand what is going on one needs to measure the range between k_t = 100 MeV to a few MeV MeV as well as possible before attempting to go into the MeV region

7. maybe the region below 5 MeV becomes simpler because of the suppression of meson decay photons via the Jacobi factor, see below

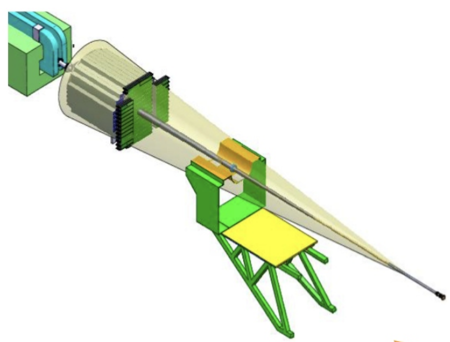
8. simultaneous measurement of low mass low p_t di-electrons is very important, although and especially because it is clear that there is nothing like a Low theorem and a divergence for virtual photons. Their total energy cannot be less than 2 m_e = 1.02 MeV.

See also the presentation by Harry Appelshaeuser on Friday, Jan. 31, 2025 in this meeting

ALICE future upgrades

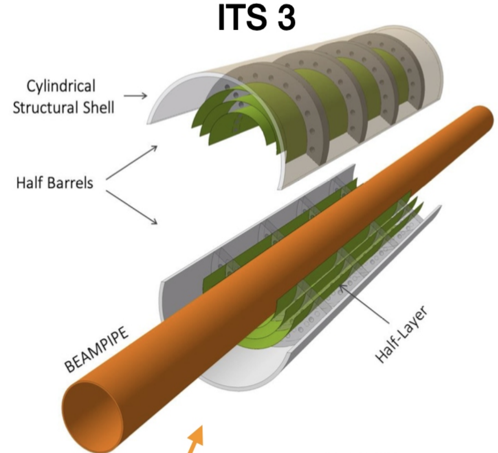
LS3 upgrades

Forward Calorimeter



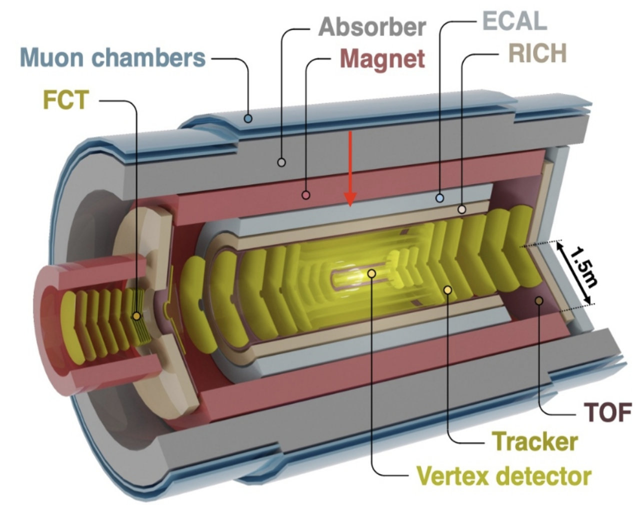
TDR approved

ITS 3

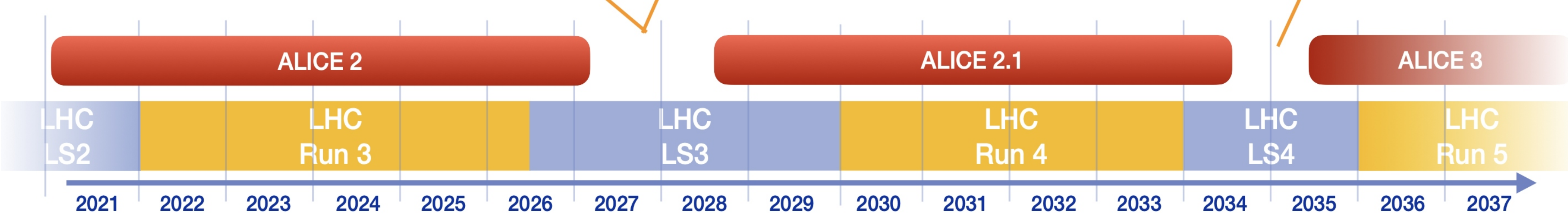


TDR approved

LS4: ALICE 3



ALICE 3 LoI: CERN-LHCC-2022-009



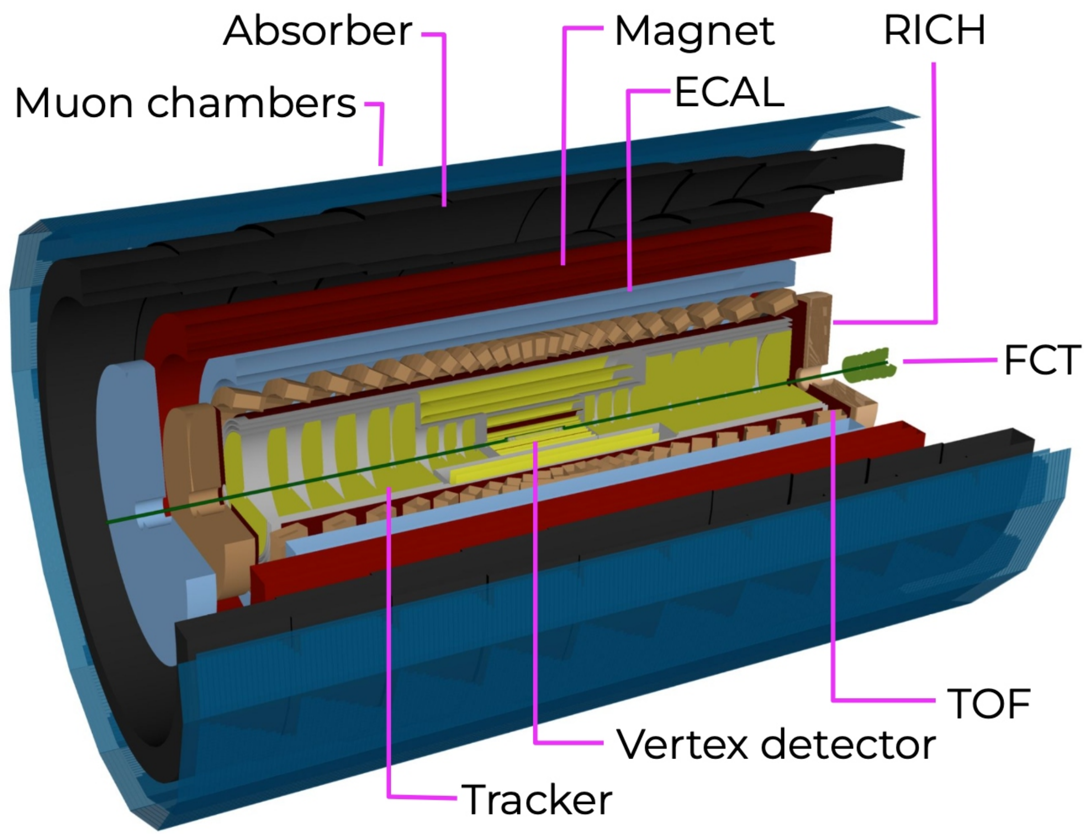
The FCT - A short overview

ALICE

Goal: Measure the soft photon spectrum predicted by Low's theorem

- 11 consecutive silicon discs with monolithic pixel trackers
- Pseudorapidity coverage: $4 < \eta < 5$
- Dipole magnet with a magnetic field of 0.25 T
- PID for e^+/e^- event veto

Cherenkov detector behind the FCT needed for good signal over background



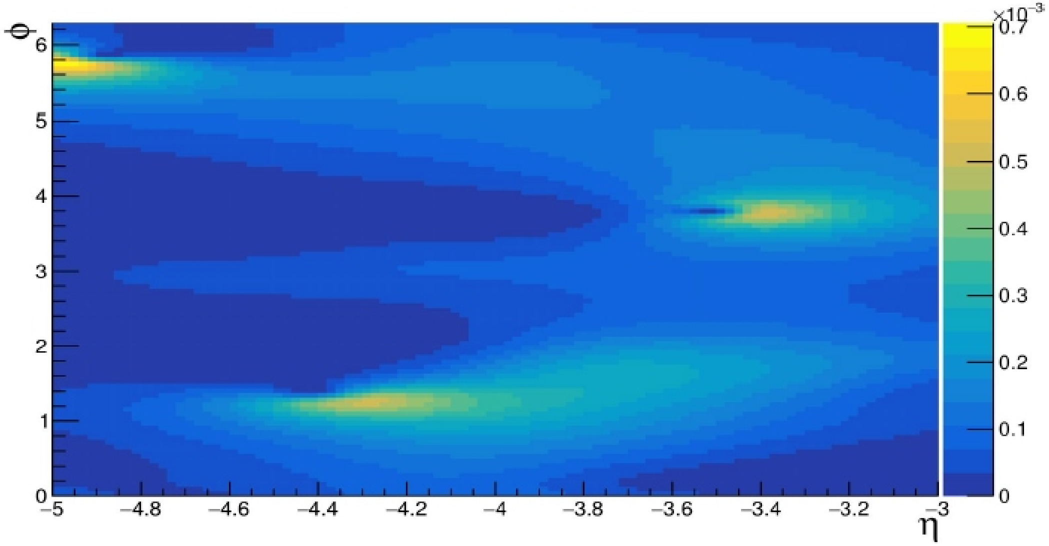
Monte Carlo generator of soft photons corresponding to the leading Low signal

The Low Photon Generator allows for the soft photon spectrum / inner bremsstrahlung spectrum to be added on top of PYTHIA 8.3.

It numerically calculates the expected amount of soft photons in a user defined pseudorapidity, azimuthal angle and photon energy range and samples the photons from the generated distribution.

These are the signal photons to arrive at the FCT.

With this, full event by event studies in O2 are possible.



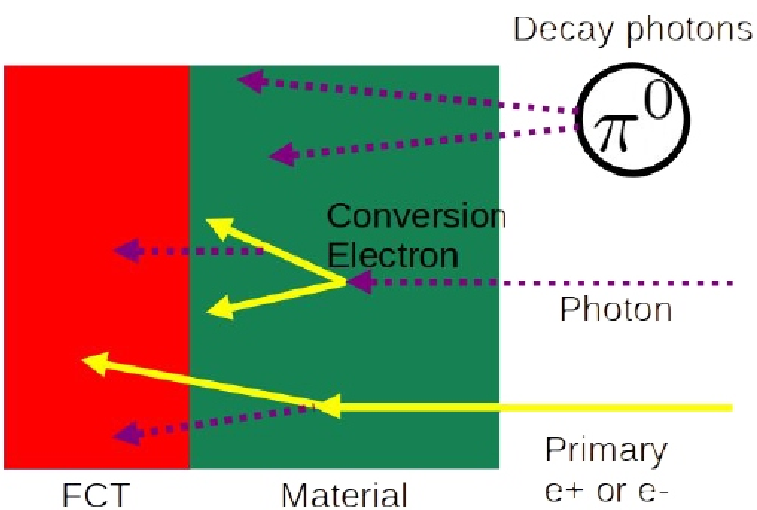
Cas van Veen

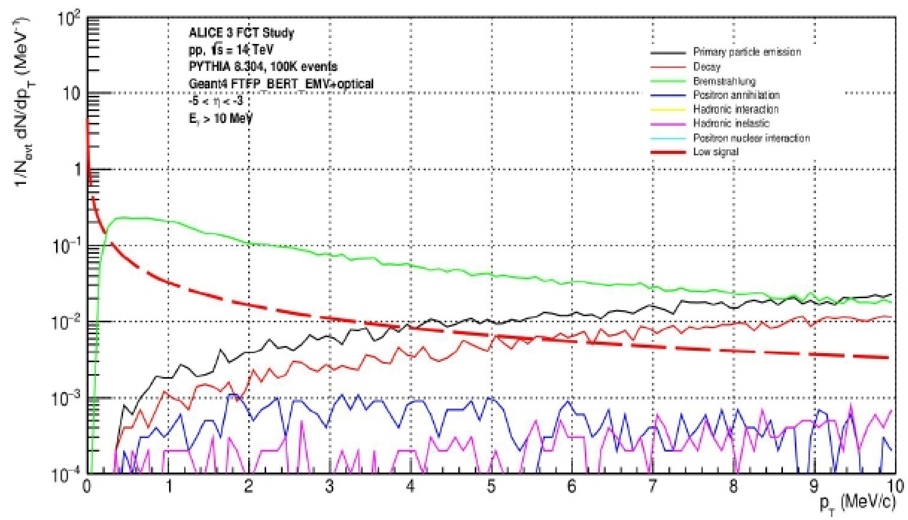
signal and background

without any cuts, the Low signal is buried under (external) bremsstrahlung, mainly from conversions in the material of the beam pipe

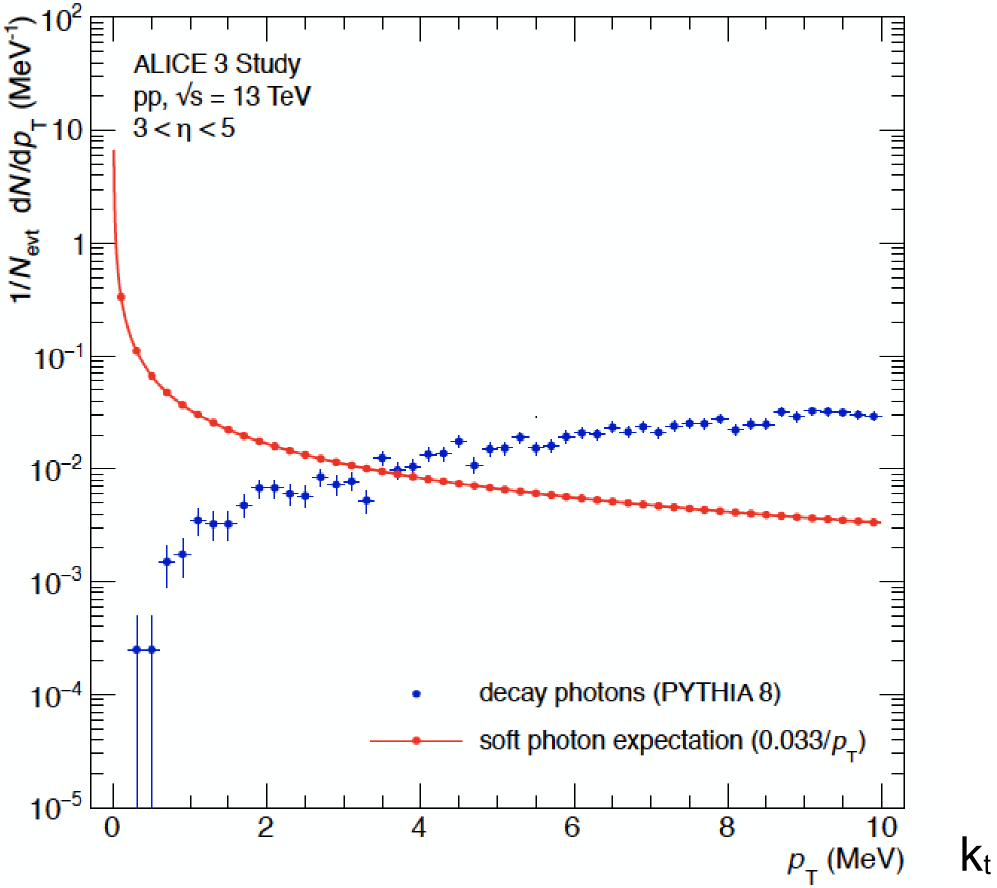
Full event by event studies allow us to quantify the amount of background versus the signal that will arrive at the FCT.

There is significant background
Especially material interactions form a huge source of background





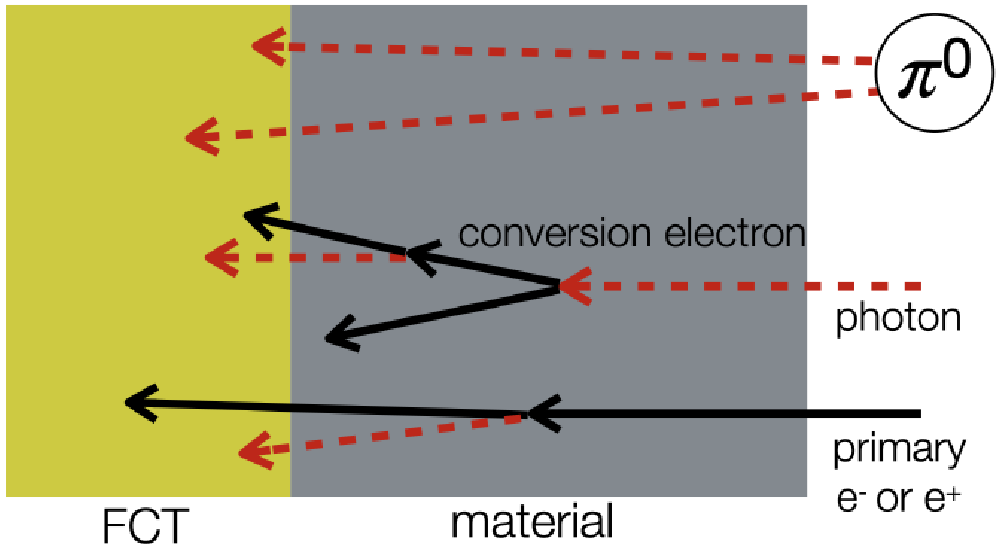
Jacobian suppression of pion decay photons in pp events generated with PYTHIA 8



window of opportunity at very low k_t and far forward rapidities

The experimental challenge

[figure by Tim Rogoschinski]



Main background:
External bremsstrahlung from electrons and positrons created in photon conversions

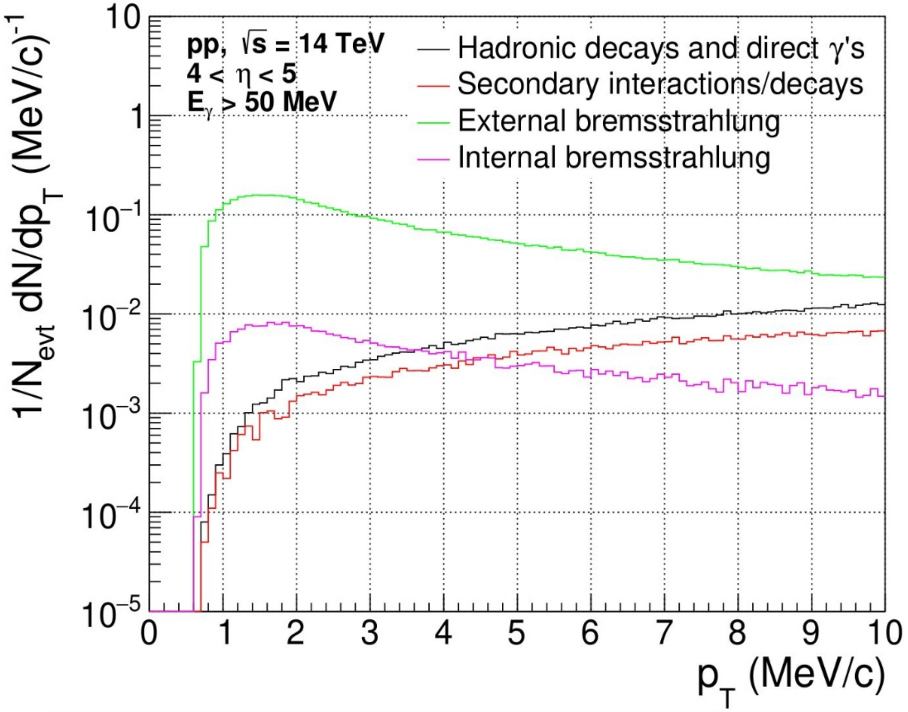
Current Status

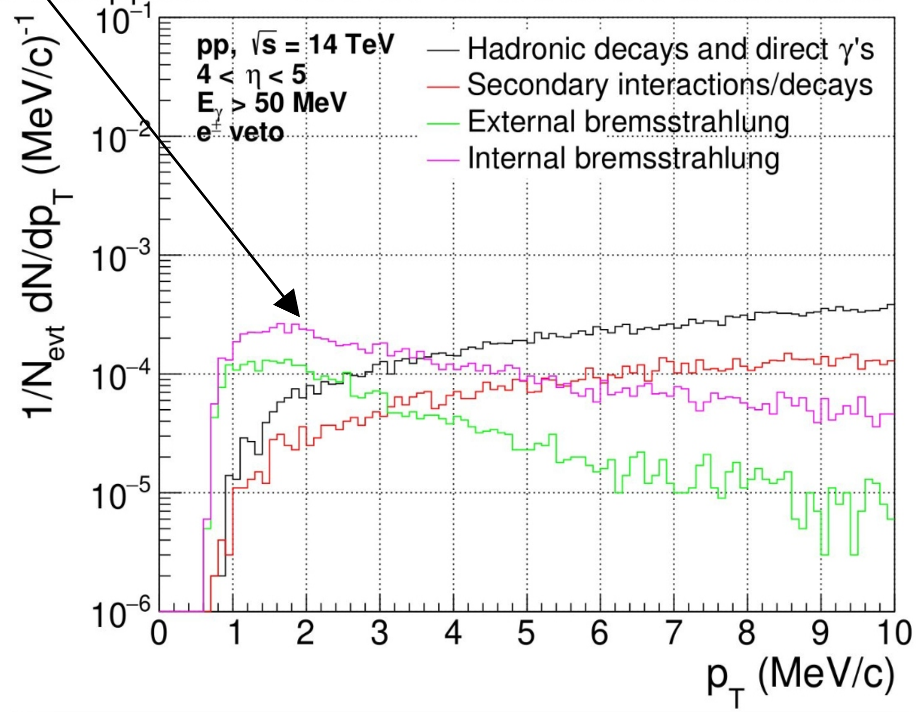
With electron veto, the Low signal, i.e. the internal bremsstrahlung photons, are well above external bremsstrahlung background.

No electron event veto

Both: Pointing angle cut applied

100% PID electron event veto





what can be done within ALICE 3

- photons, exclusive channels, do detailed evaluations of soft photon production
  - diffractive in pp collisions
  - exclusive channels within the tensor pomeron channel
  - UPC pp → (pp) J/psi, psi',..., + γ
- inclusive channels
  - pPb → γ dependence on y, p_t and charged particle multiplicity
  - pp → γ dependence on y, p_t and charged particle multiplicity
- di-leptons, dependence on mass, y, p_t and charged particle multiplicity

- evaluate rapidity window over which charged particle multiplicity should be measured

much of this can be prepared by simulations using Monte Carlo generators like Pythia coupled with the soft photon theorem/generator discussed above

With the ALICE FCT we can perform a precision measurement of the soft photon spectrum in pp collisions to test the QFT predictions for the infra-red limits of these theories. Sinced particle production at LHC energies extends to very large rapidities (η > 4) where the dominant (p^0) background can be effectively suppressed. This will either resolve the questions raised by many previous experiments or uncover new insights into the inner working of QFT.

We quote, e.g., from the paper of Nachtmann, Lebiedowicz and Szczurek, 2107.10829:

Then we could study, as an example, the ratio

$$R_{\text{exp}}(\omega) = \frac{d\sigma_{\text{exp}}/d\omega}{d\sigma_{\text{standard}}/d\omega}\,. \tag{6.1}$$

From the results of our present paper we know that the terms of order $1/\omega$ and ω^0 in the expansion of the standard amplitude are strict results from QFT without approximations, given the on-shell $\pi\pi \to \pi\pi$ amplitudes. Therefore, if QFT describes experiment we must have (see Appendix B for a detailed discussion)

$$\lim_{\omega\to 0} R_{\text{exp}}(\omega) = 1\,, \quad \lim_{\omega\to 0} \frac{dR_{\text{exp}}(\omega)}{d\omega} = 0\,. \tag{6.2}$$

A violation of these relations would mean a terrible crisis for QFT!

Summary

The measurement of ultra-soft photons with ALICE 3 will allow a new and sensitive test of the infra-red limit of QED/QCD. Previous measurements indicate significant differences between Low theorem predictions and data. If the Low theorem predictions are verified in the new measurements, this would remove a long-standing open issue.

I hate to think of what happens if the ‘violations’ persist....
... or maybe it would be super exciting

With ALICE 3 we can do the measurements!