Final Lecture – Future of QGP research

literature:

The ALICE experiment -- A journey through QCD,
eprint = "2211.04384"

Letter of intent for ALICE 3: A next-generation heavy-ion experiment at the LHC,
eprint = "2211.02491

Key physics areas for future QGP research beyond 2030

focus on physics at low transverse momentum

Heavy-flavour hadrons	$p_T \to 0$, $\lvert\eta\rvert < 4$
Dielectrons	$p_T \approx 0.05$ to $3\,\mathrm{GeV}/c$, $M_{ee} \approx 0.05$ to $4\,\mathrm{GeV}/c^2$
Photons	$p_T \approx 0.1$ to $50\,\mathrm{GeV}/c$, $-2 < \eta < 4$
Quarkonia and exotica	$p_T \to 0$, $\lvert\eta\rvert < 1.75$
→ Ultrasoft photons	$p_T \approx 1$ to $50\,\mathrm{MeV}/c$, $3 < \eta < 5$
Nuclei	$p_T \to 0$, $\lvert\eta\rvert < 4$

very large increase in integrated luminosity compared to LHC Run 3/Run4

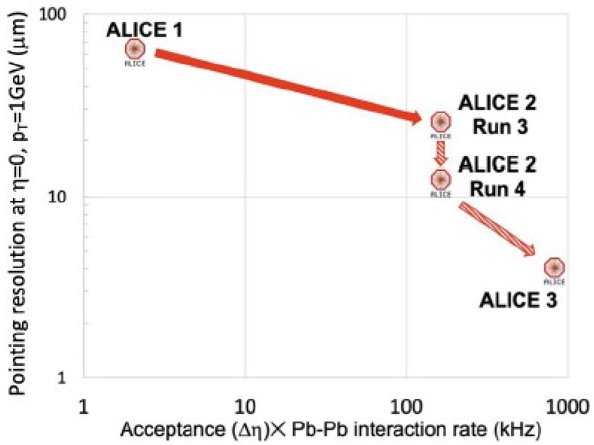
System	$\mathscr{L}^{\text{month}}$	$\mathscr{L}^{\text{Run5+6}}$
pp	$0.5\,\text{fb}^{-1}$	$18\,\text{fb}^{-1}$
pp reference	$100\,\text{pb}^{-1}$	$200\,\text{pb}^{-1}$
A–A		
Xe–Xe	$26\,\text{nb}^{-1}$	$156\,\text{nb}^{-1}$
Pb–Pb	$5.6\,\text{nb}^{-1}$	$33.6\,\text{nb}^{-1}$

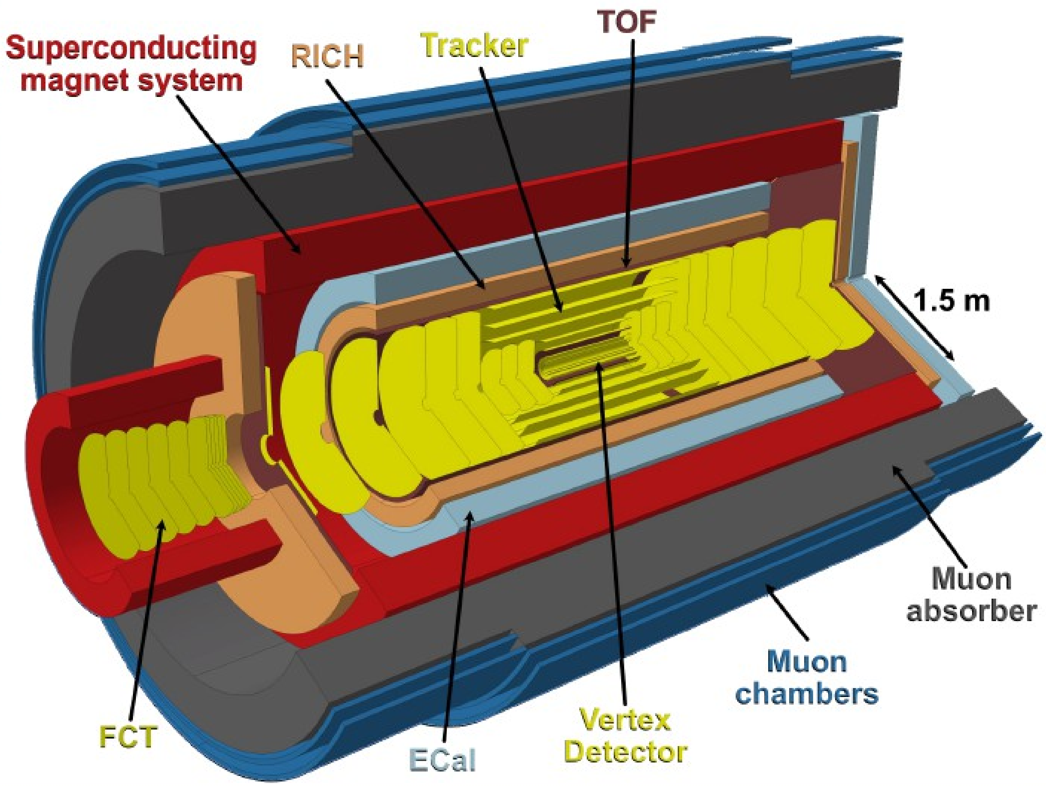
Integrated luminosities for different collision systems

ALICE 3 concept

➡ Novel and innovative detector concept

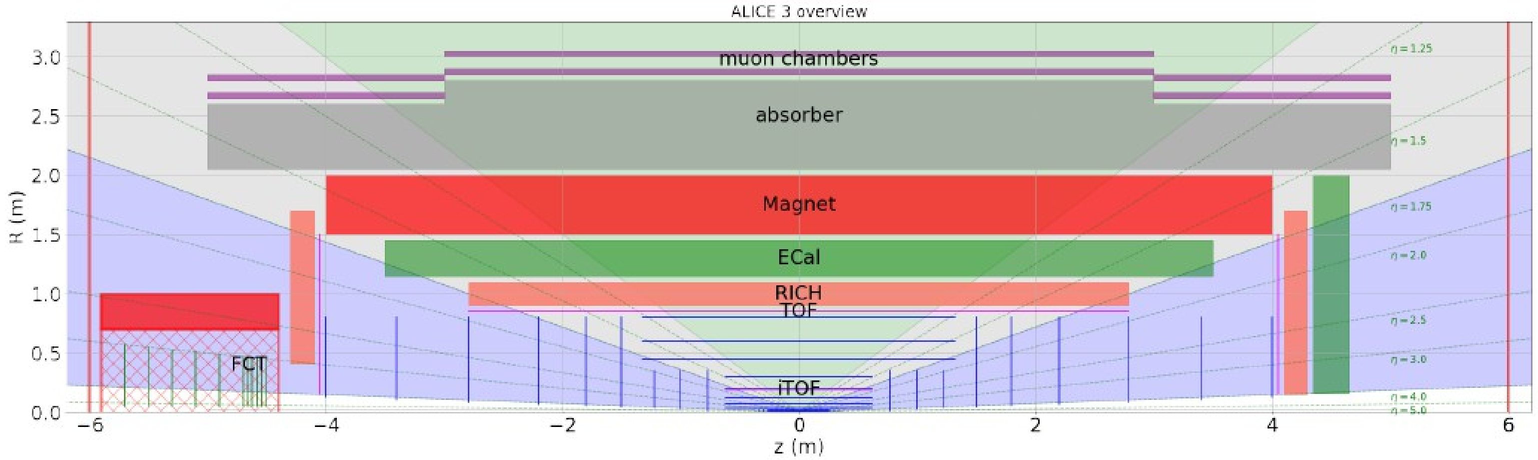
- Compact and lightweight all-silicon tracker
- Retractable vertex detector
- Extensive particle identification
- Large acceptance
- Superconducting magnet system
- Continuous read-out and online processing





innovative technologies relevant for future HEP experiments

Alice 3 – a compact and light-weight detector



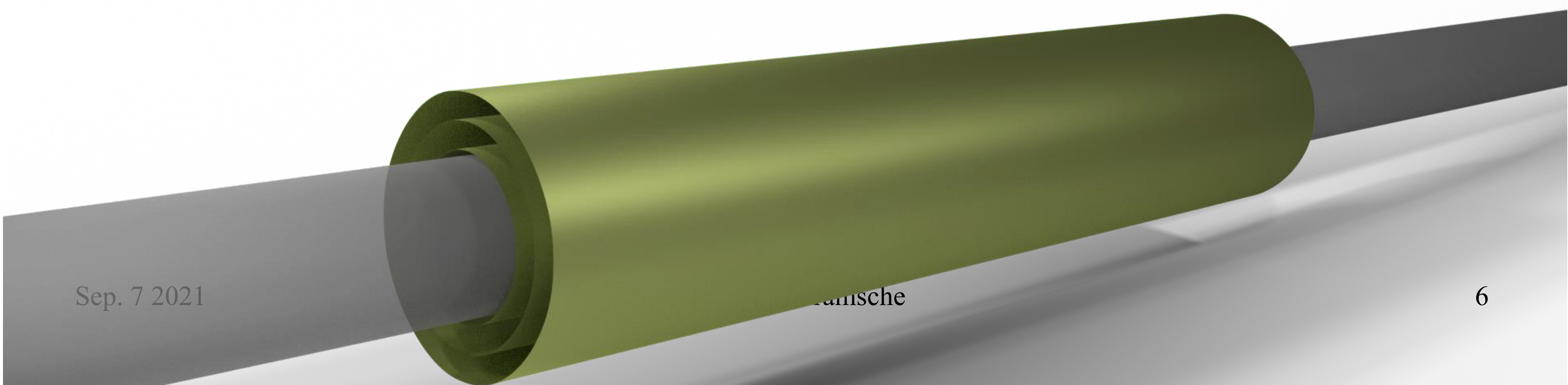
ALICE 3: a (nearly) massless detector for ALICE after LHC Run4 (2030+)

principle: surround the beam pipe by very thin (< 40 μm) Si pixel-chips bent into cylindrical shape

1st application: the ITS3 detector with 3 cylindrical layers, to be inserted into the current ALICE experiment after LHC Run3 (2026), see sketch below

baseline: monolithic active pixel (MAPS) sensors fabricated in the commercially available CMOS process

sensor and detector development currently underway in the framework of ITS3



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 present ideas how to make a precision test of the Low predictions in the framework of ALICE 3, the future (and futuristic) ALICE detector to study novel QCD phenomena in the low transverse momentum region pT < 10 GeV for colliding systems pp, pPb, OO, KrKr, XeXe, PbPb 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.

Outline

1. a simple 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 [1]

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

[2]. 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

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

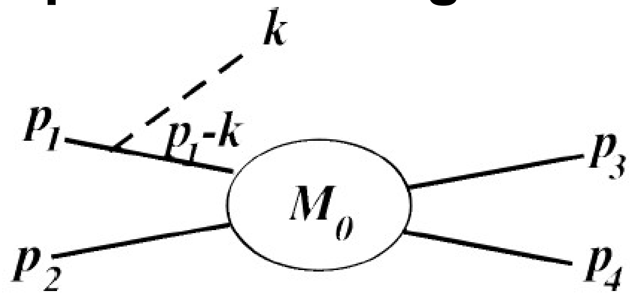
[4] Delphi coll., Eur. Phys. J. C67 (2010) 343 -- measurement in jets

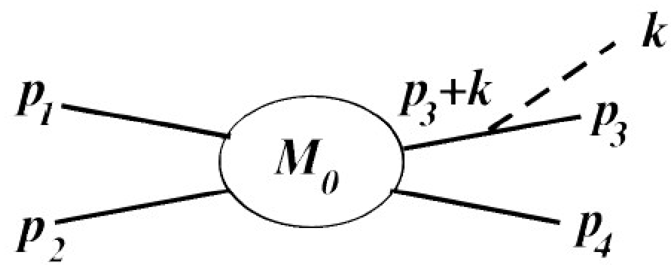
[5] C.Y. Wong, arXiv:1404.0040, -- pedagogical introduction

[6] A. Strominger, arXiv:1703.05448, -- introduction to soft theorems in general

[7] see also recent talks in the Oct. ALICE 3 meeting by Stefan Floerchinger and by Klaus Reygers, available from the authors

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

$$\mathcal{M}(p_1p_2;p_3p_4k) = \mathcal{M}_0(p_1p_2;p_3p_4)\left(\frac{e_1p_1\cdot\epsilon}{[(p_1-k)^2-m_1^2]}+\frac{e_3p_3\cdot\epsilon}{[(p_3+k)^2-m_3^2]}\right) \quad (1)$$

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

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.

assumptions (2)

Note that for all charged particles i the photon production factor $\frac{\eta_i e_i p_i \cdot \epsilon}{2 p_i \cdot k}$ 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.

multi-particle reactions

We can generalize the above Eq. (1) to multi-particle production, i.e. to the process $p_1 + p_2 \rightarrow p_3 + p_4 + ... + p_{N+2} + k$ 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.

the invariant yield

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

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

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

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:

$$dN_{gamma}/dk_t \propto 1/k_t \quad (5)$$

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

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.

Domenico Bonocore and Anna Kulesza. Soft photon bremsstrahlung at next-to-leading power. *Phys. Lett. B*, 833:137325, 2022.

Piotr Lebiedowicz, Otto Nachtmann, and Antoni Szczurek. High-energy $\pi\pi$ scattering without and with photon radiation. *Phys. Rev. D*, 105(1):014022, 2022.

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 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. 1^{st} 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

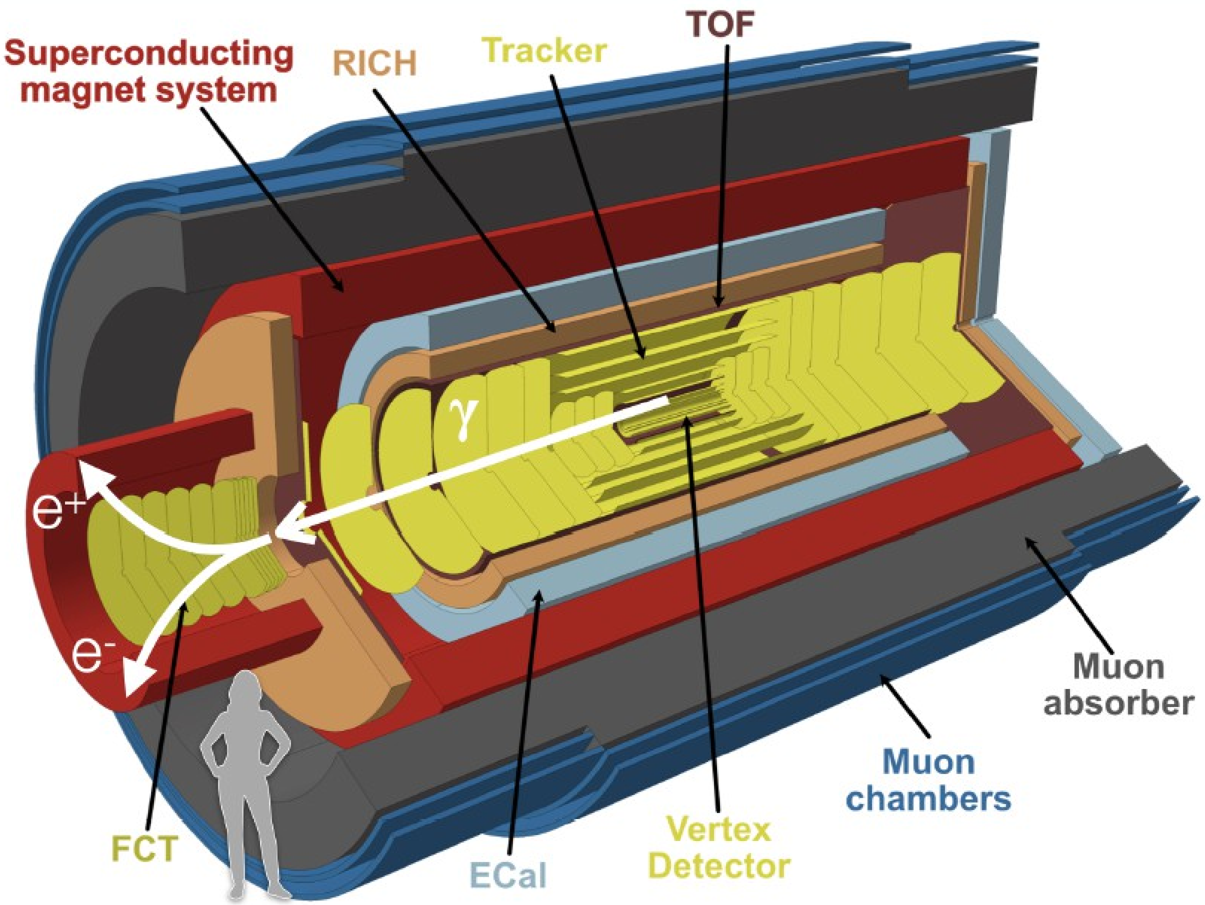
7. maybe the region below 5 MeV becomes simpler because of the suppression of meson decay photons via the Jacobi factor, see below

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.

ALICE 3 FCT team

P. Braun-Munzinger, N. Burmasov, H. Büsching, K. Reygers,
T. Rogoschinski, K. Schweda, J. Stachel, C.A. van Veen, M. Völkl

The Forward Conversion Tracker for ALICE 3



Ultra-soft photons

light-by-light scattering,
axion-like particles,
sexaquark searches(?)

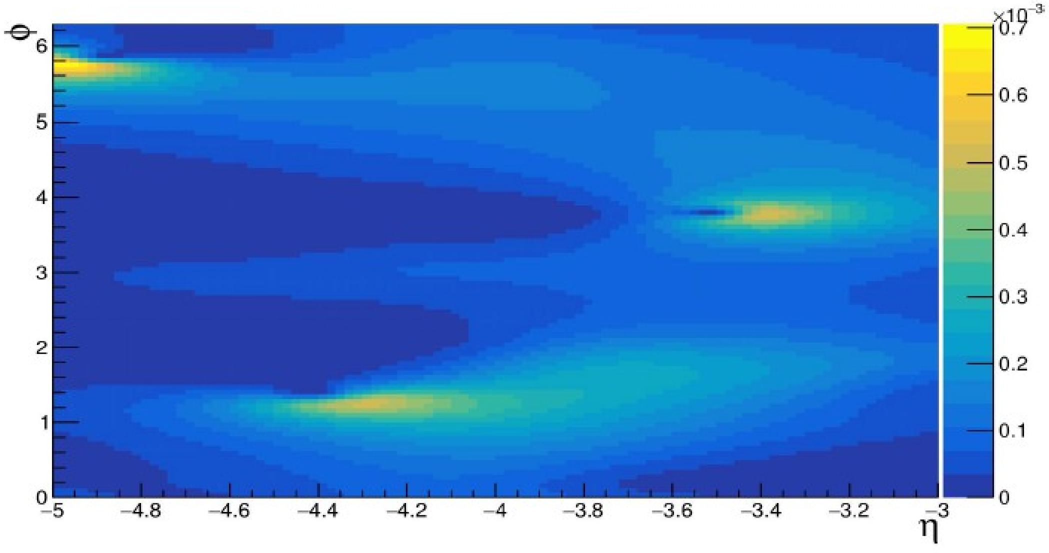
Monte Carlo generator of soft photons corresponding to the leading Low signal

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.



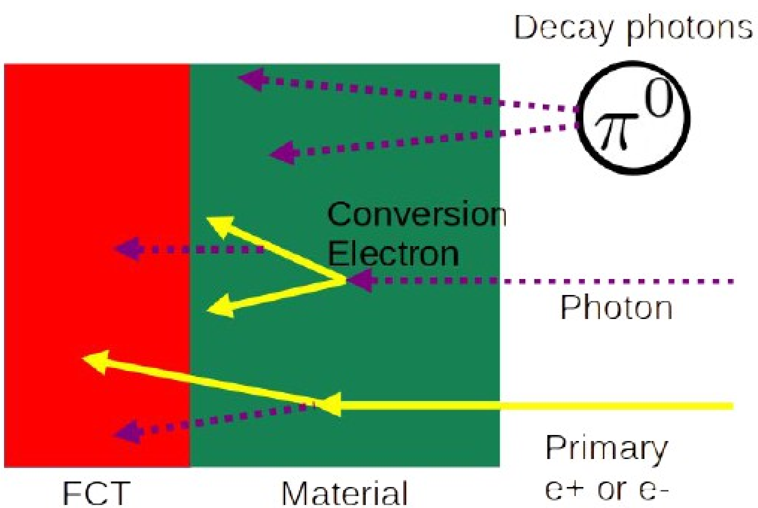
Cas van Veen

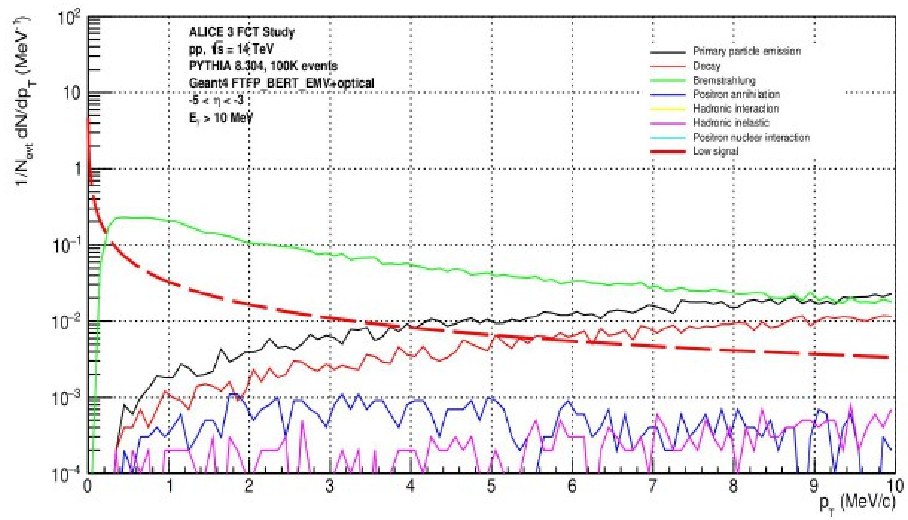
signal and background

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

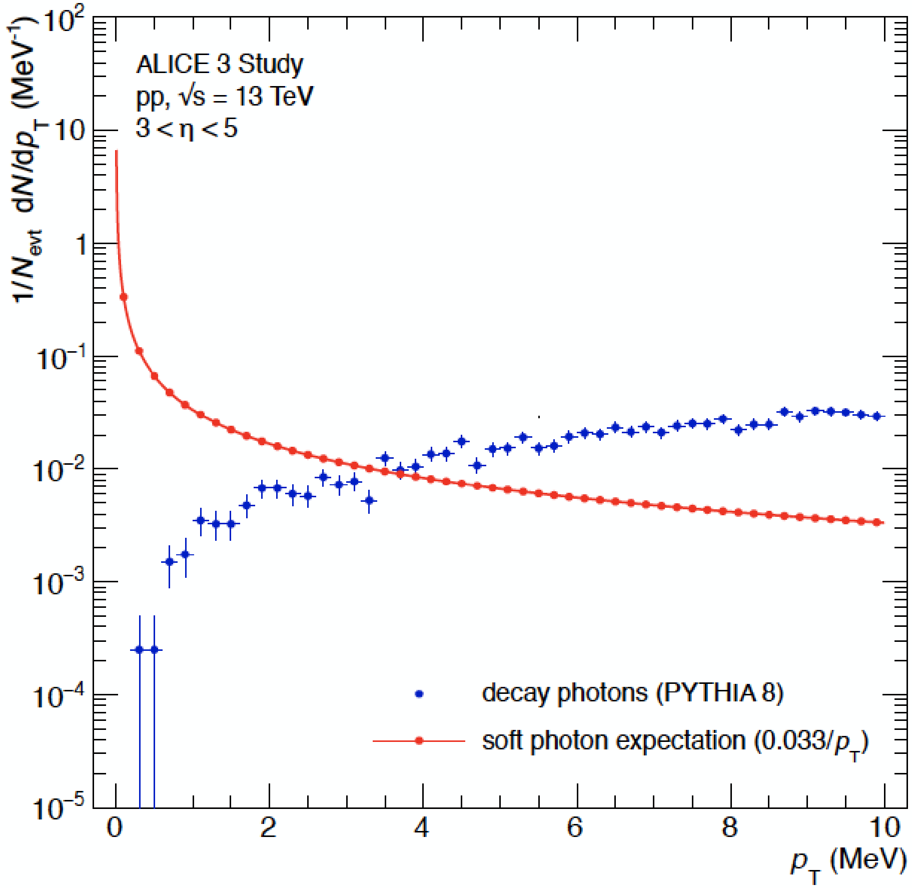
Full event by event studies allow us to quantify the amount of background versus the signal that will arrive at the FCT.

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





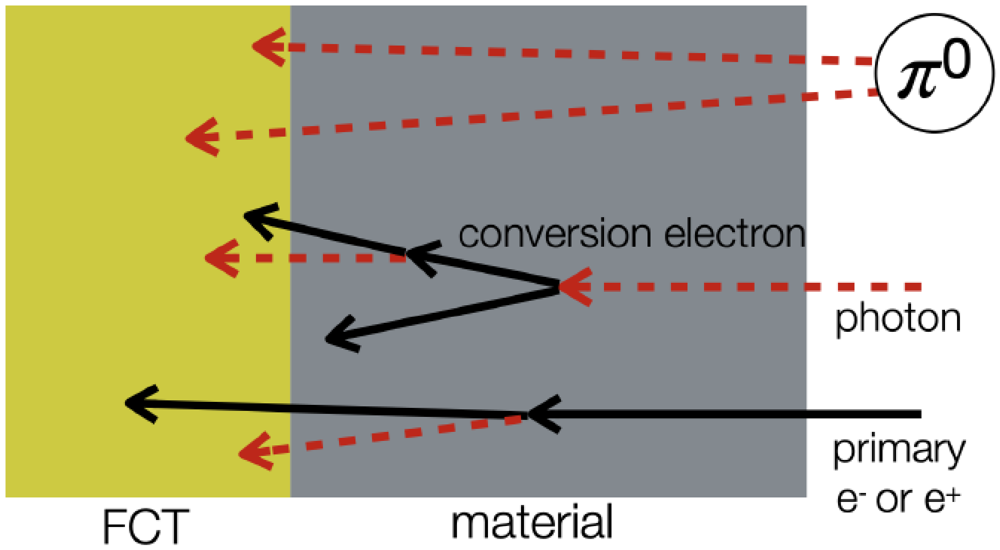
Jacobian suppression of pion decay photons in pp events generated with PYTHIA 8



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

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

the end