Soft photons, the Low theorem, and ALICE 3

(pbm, EMMI-RRTF, soft photons)
zoom meeting, Feb. 4, 2021

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

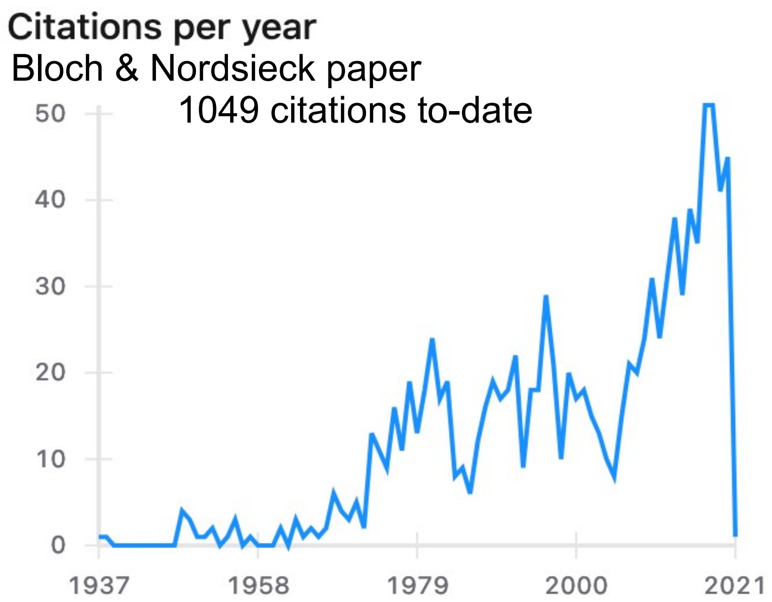
the conclusion by Bloch and Nordsieck is that the mean total number of light quanta radiated diverges, but the mean total energy radiated stays finite. see also H. Bethe and W. Heitler, Proc. Roy. Soc. A146 (1934) 83

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

an aside on Arnold Nordsieck

a man of many talents

- 1911 born in Marysville, Ohio
- 1935 PhD with Robert Oppenheimer, UCB, 'scattering of radiation by an electric field'
- 1935 – 1937 Guggenheim Fellow, worked in Leipzig, Germany with W. Heisenberg, paper with Felix Bloch
- 1947 – 1961 Prof. Physics UIUC, Urbana-Champaign
- 1950 built 1st analog computer out of WW2 surplus worth 700$, later copy was 1st computer at LLNL
- 1953 designed and built the 1st inertial Electrostatic Gyroscope System (EGS), served as inertial navigation system for US nuclear submarines
- 1950ties proposed the CORNFIELD system, a computer-based decision-making system for the air defense of ships using radar
- 1961 head of physics at General Research Corp., Santa Barbara, CA
- 1962 paper ' On numerical integration of ordinary differential equations ' Mathematics of Computation, vol.16 (1962) 22
- 1967 1st numerical solution of the full Boltzmann equation, with B.L Hicks
- 1971 died in St. Barbara



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

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

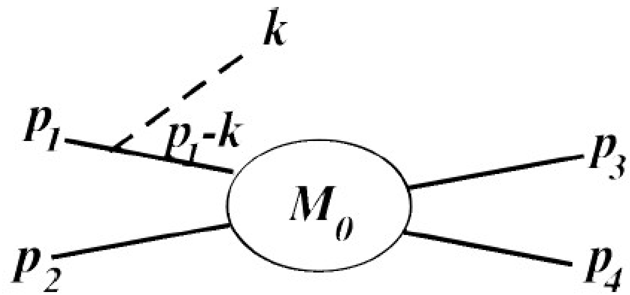
3. Delphi coll., Eur. Phys. J. C67 (2010) 343 -- measurement in jets

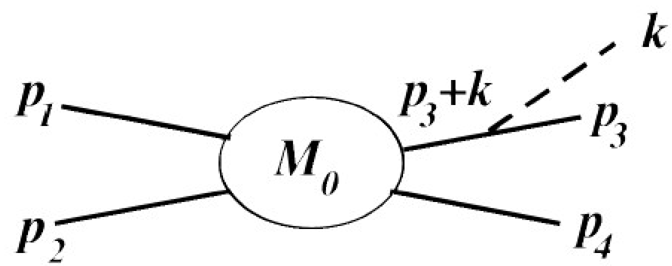
4. C.Y. Wong, arXiv:1404.0440, -- pedagogical introduction

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

6. 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

$$M(p_1p_2;p_3p_4k) = M_0(p_1p_2;p_3p_4)\left(\frac{e_1p_1\cdot\varepsilon}{(p_1-k)^2}+\frac{e_3p_3\cdot\varepsilon}{(p_3+k)^2}\right)$$

amplitude　　elastic part　　photon part

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

In the soft photon limit, summing over all incoming and outgoing charged particles, and neglecting hadron masses:

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

note the separation between the (uncalculable) elastic amplitude M_0 and the QED (perturbative) bremsstrahlung part. The sum above runs also over incoming particles.

e_i is the charge of p_i, and η_i is +1 for an outgoing hadron and -1 for an incoming hadron

for the more general case of

$$p_1 + p_2 \to p_3 + p_4 + ... + p_N + k$$

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

there are N-2 charged hadrons in the final state

soft factor

the Low formula slightly re-written

taking the absolute square of the amplitude M and putting in phase space factors one obtains the cross section or invariant distribution

$$\frac{dN_\gamma}{d^3k} = \frac{\alpha}{(2\pi)^2}\,\frac{1}{E_\gamma}\left(\int d^3p_3\, d^3p_4 \ldots d^3p_N \left[\sum_{i,j=1}^{N} \eta_i \eta_j e_i e_j \frac{(-p_i\cdot p_j)}{(p_i\cdot k)(p_j\cdot k)}\right] \times \frac{dN_{hadrons}}{d^3p_3 \ldots d^3p_N}\right)$$

the sum in the factor in the square brackets runs over all particles including the 2 initial particles. There are N-2 final state hadrons. This factor is a Lorentz invariant and is obtained from the measured momenta and charges. Note that η_i is +1 for an outgoing hadron and $\eta_i = -1$ for an incoming hadron.

this factor has dimension [1/E^2]
it contains interference between incoming and outgoing particles

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

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

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

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

Low formula in rapidity y and k_t space

$$E_\gamma = k_t \cdot \cosh y \qquad k_{\parallel} = k_t \cdot \sinh y$$

invariant yield of photons in the $k_t \to 0$ limit

$$E_\gamma \cdot \frac{d^3N_\gamma}{d^3k} = \frac{d^2N_\gamma}{2\pi k_t\, dk_t\, dy} = \frac{\alpha}{(2\pi)^2} \times$$

$$\left[\int d^3p_3 \dots d^3p_N \left(\sum_{i,j=1}^{N} \eta_i \eta_j e_i e_j \frac{(-p_i \cdot p_j)}{(p_i \cdot k)(p_j \cdot k)} \right) \frac{dN_{hadrons}}{d^3p_3 \dots d^3p_N} \right]$$

$$\Rightarrow \frac{d^2N_\gamma}{dk_t\, dy} = \frac{\alpha}{2\pi} \cdot k_t \left[\dots \right]$$

now: $p_i \cdot k = E_i \cdot k_t \cdot \cosh y - p_{\parallel,i} \cdot k_t \cdot \sinh y - p_{t,i} \cdot k_t$

$= k_t \cdot \beta_i(y), \quad \beta_i = E_i \cdot \cosh y - p_{\parallel,i} \sinh y - p_{t,i}$

$$\frac{d^2N_\gamma}{dk_t\,dy} = \frac{\alpha}{2\pi}\,\frac{1}{k_t}\int d^3p_3 \cdots d^3p_N \sum_{i,j=1}^{N} \eta_i\eta_j e_i e_j \frac{(-p_i p_j)}{\beta_i(y)\,\beta_j(y)}\,\frac{dN_{hadrons}}{d^3p_3 \cdots d^3p_N}$$

note the $\frac{1}{k_t}$ divergence, $k_t = \frac{E_\gamma}{\cosh y}$ sets the scale in every rapidity interval

so for collider energies it is advantageous to use y and k_t and boost E_γ while going with k_t as low as possible. note that at rapidity y = 4 and k_t = 10 MeV, E_γ = 273 MeV

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 1 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 100 MeV and 10 MeV as well as possible before attempting to go into the MeV region

7. maybe the region below 20 – 30 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.

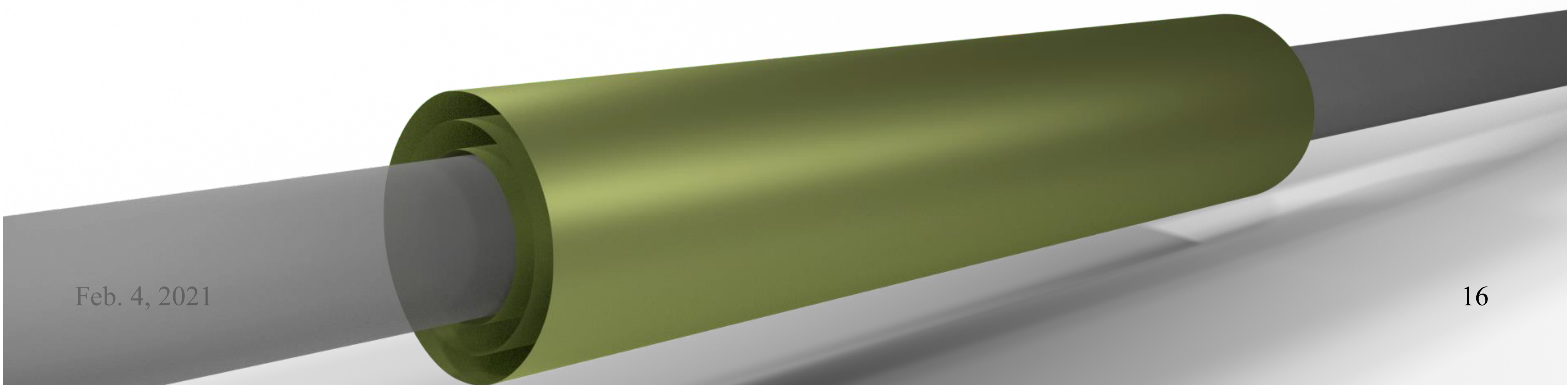
ALICE 3: a (nearly) massless detector for ALICE after LHC Run4 (2030+)

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



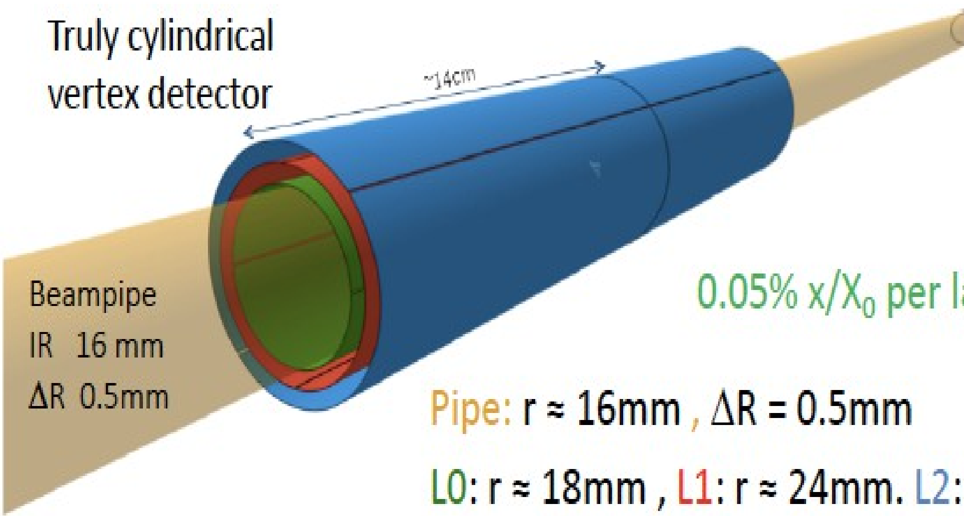
A new HI dedicated experiment at the LHC beyond LS4

- Idea for new dedicated heavy-ion experiment at the LHC developed within ALICE in the course of 2018/19
- Discussed at the Heavy-Ion Town meeting (CERN, Oct 2018)
- Expression of Interest submitted (Dec 2018) as input to the European Particle Physics Strategy Update (EPPSU) - arXiv:1902.01211
- Presented at the EPPSU Symposium (Granada workshop, May 2019)
  - Presentation Johanna Stachel
  - Summary Strong Interactions
  - Briefing Book 1910.11775 [hep-ex]
- Presented at several conferences
  - XXV Conference EPIPHANY Conference on Advance in Heavy Ion Physics, January 2019
    Luciano Musa
  - Strangeness in Quark Matter, June 2019
    Johanna Stachel, Luciano Musa
  - 3rd EMMI workshop on Exotica at the LHC, Wroclaw, Nov. 2019
    pbm

EoI for new ultra-light Inner Barrel in LS3 (CDS, ALICE-PUBLIC-2018-013)

Recent silicon technologies (ultra-thin wafer-scale sensors) allow

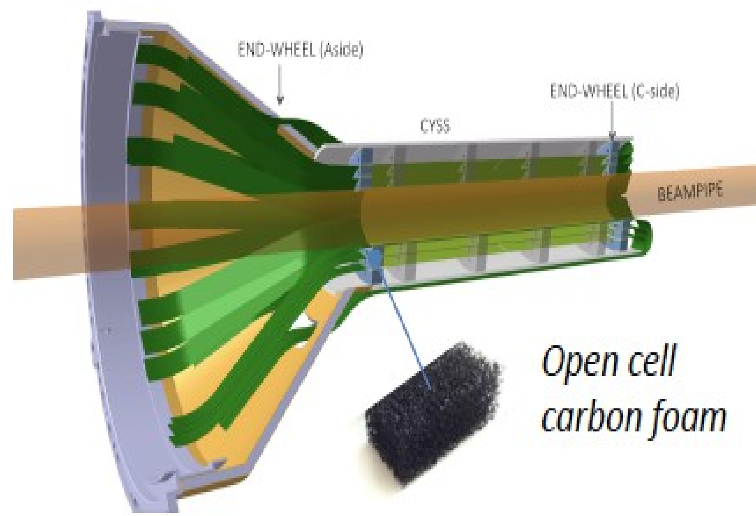
- Eliminate active cooling ⇨ possible for power < 20mW/cm^2
- Eliminate electrical substrate ⇨ Possible if sensor covers the full stave length
- Sensors arranged with a perfectly cylindrical shape ⇨ sensors thinned to ~30μm can be curved to a radius of 10-20mm



0.05% x/X_0 per layer

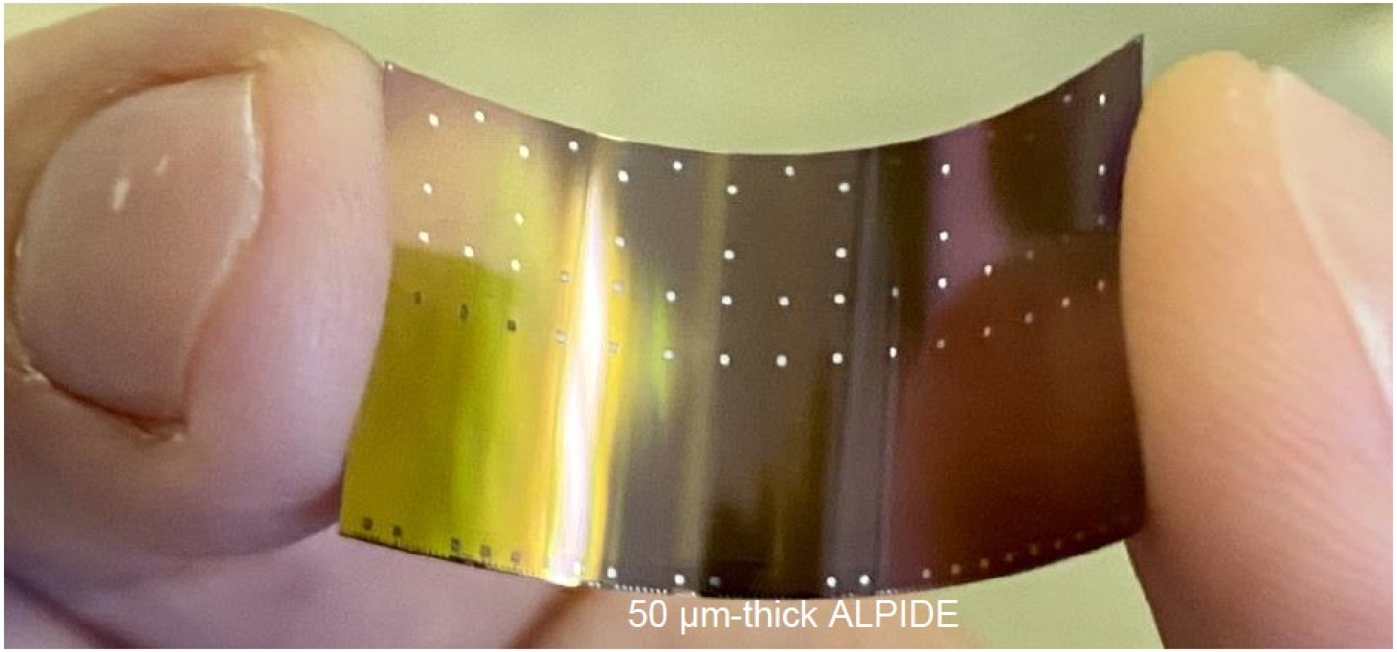
Pipe: r ≈ 16mm , ΔR = 0.5mm

L0: r ≈ 18mm , L1: r ≈ 24mm. L2: r ≈ 30 mm

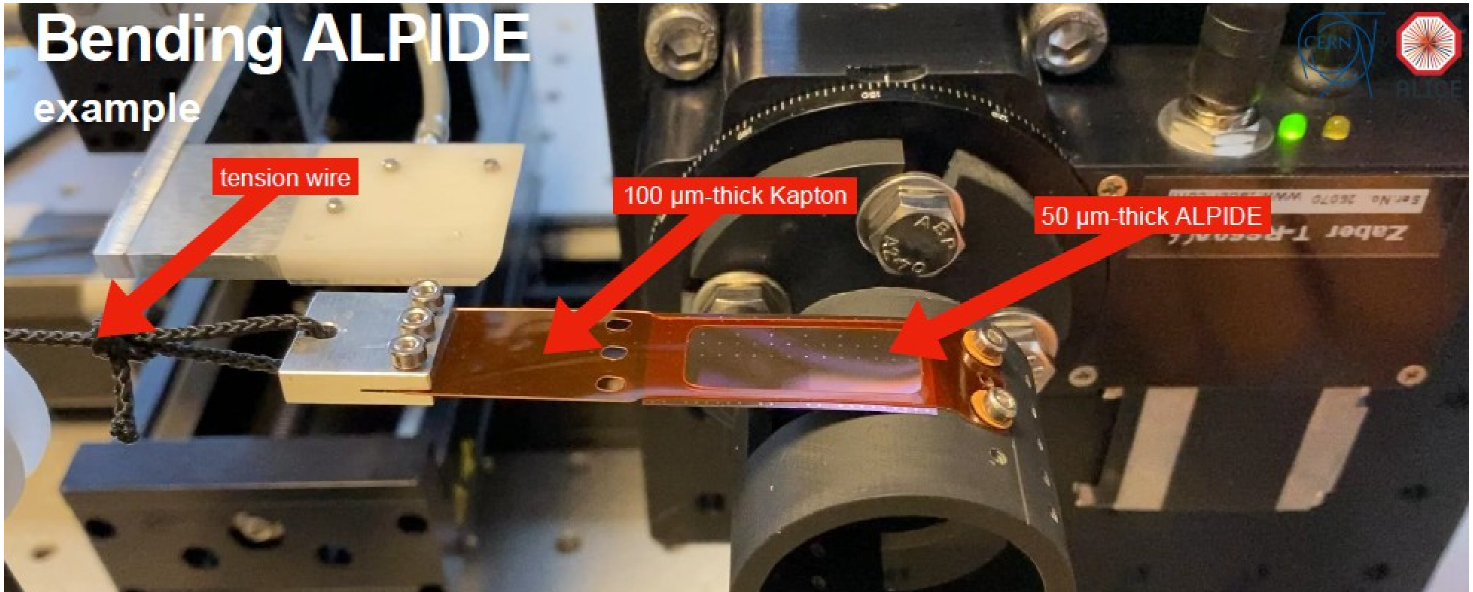


...now a few slides from Magnus Mager's talk at the CERN ALICE 3 workshop

Bent Silicon Detectors



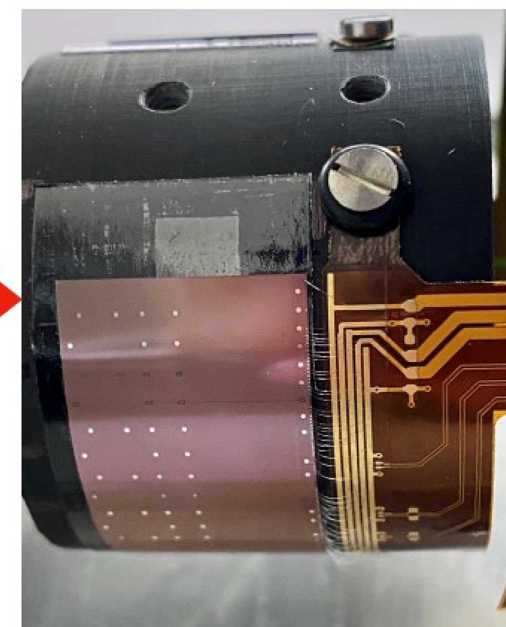
Magnus Mager (CERN) | ALICE 3 | 14.10.2020 25



Interconnection

wire-bonding after bending as example

- This is the current baseline for characterisation of bent MAPs
- We have a handful of these assemblies and they work
- Integration of the bonding on a (semi-)automatic process ongoing



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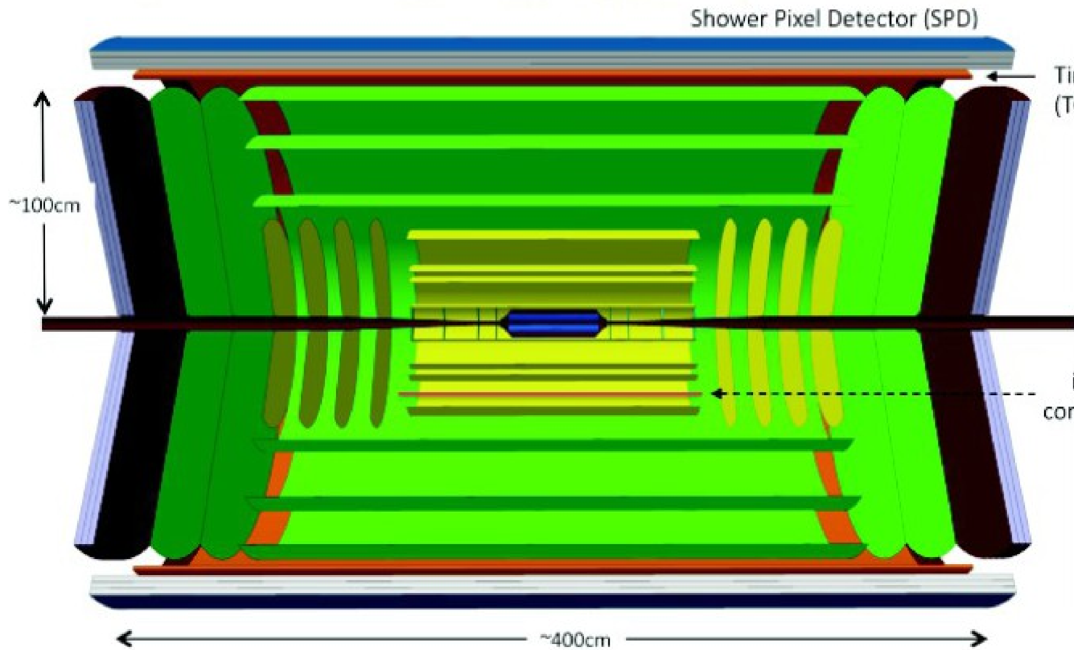
Next generation of AA/pA/pp experiment for installation beyond Run4 @ HL-LHC



proposal to replace ALICE

Ultra-thin chip (<50 um): flexible with good stability

Detector concept is an all Silicon detector:

- Pixel detector with fast and light CMOS MAPS
- High-rate capabilities of MAPS will allow the experiment to run at significantly higher luminosities (a factor 20 to 50), e.g. with lighter ions

Physics potential:

- QGP properties via precision measurements in heavy flavor sector
- Access to new low-p_T phenomena (γ & hadrons)
- Low mass di-leptons

1902.01211

experimental coverage: $-4 < y < 4$ $0 < p_t < 30$ GeV
particle ID via time-of-flight in the low p_t region < 4 GeV

Rich physics potential

- Heavy-flavor and quarkonia
  - Multiply Heavy Flavoured hadrons. e.g.: Ξ_{cc}, Ω_{cc}, Ω_{ccc}
  - $\chi_{c1,2}$ states
  - Ultimate precision on B mesons at low p_T
  - X, Y, Z charmonium-like states (e.g. X(3872))

→ Hadron formation from deconfined QGP

- Low-mass dielectrons
  - Precision measurement of the thermal dilepton continuum, $0 < m < 3$GeV

→ Chiral symmetry restoration ρ-a1 sector

- Real soft photons
  - down to 50MeV/c

→ QGP Radiation unchartered phase space region

- Real ultra-soft photons
  - Very low p_T photons: $1\text{MeV/c} < p_T^{\gamma} < 100\text{MeV/c}$
  - dedicated small forward spectrometer at $3.5 < |\eta| < 5$)

→ Test of soft theorems

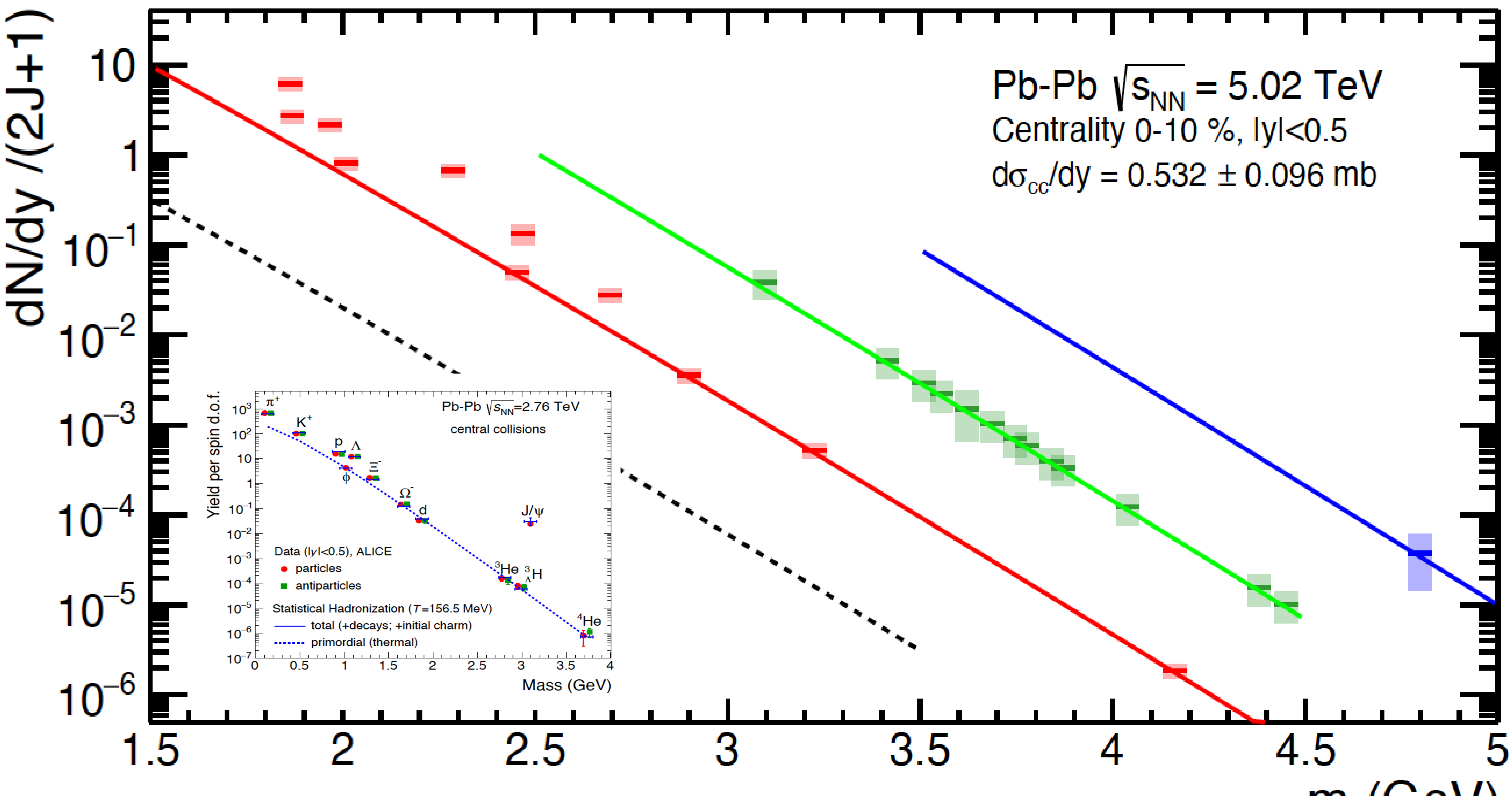
L. Musa (CERN) – Arbeitstreffen Kernphysik, Schleching 2020 a brief aside:

the charm hierarchy – prediction from the Statistical Hadronization Model

with ALICE 3, exotic multi-charm objects can be discovered shedding light on deconfinement of charm quarks

A. Andronic, pbm, K. Redlich, J. Stachel, Nature 561 (2018) 7723
A. Andronic, pbm, M. Koehler, K. Redlich, J. Stachel, Phys.Lett.B 797 (2019) 134836, 1901.09200 [nucl-th]
A. Andronic, pbm, M. Koehler, A. Mazeliauskas, K. Redlich, J. Stachel, V. Vislavicius, in preparation

yields/degeneracy for charm hadrons
grand-canonical, correction factor 0.84 for n_c = 3



red: single charm, green: double charm, blue: triple charm

lines: primordial SHM predictions

dashed line: SHM (u,d,s), red line: SHMC (1c), green line: SHMC (2c), blue line: SHMC (3c)

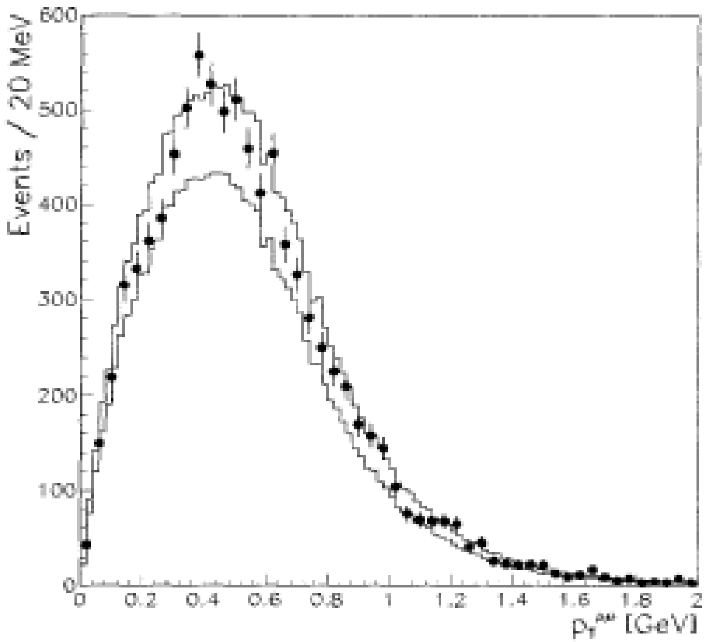
brief survey of experimental situation

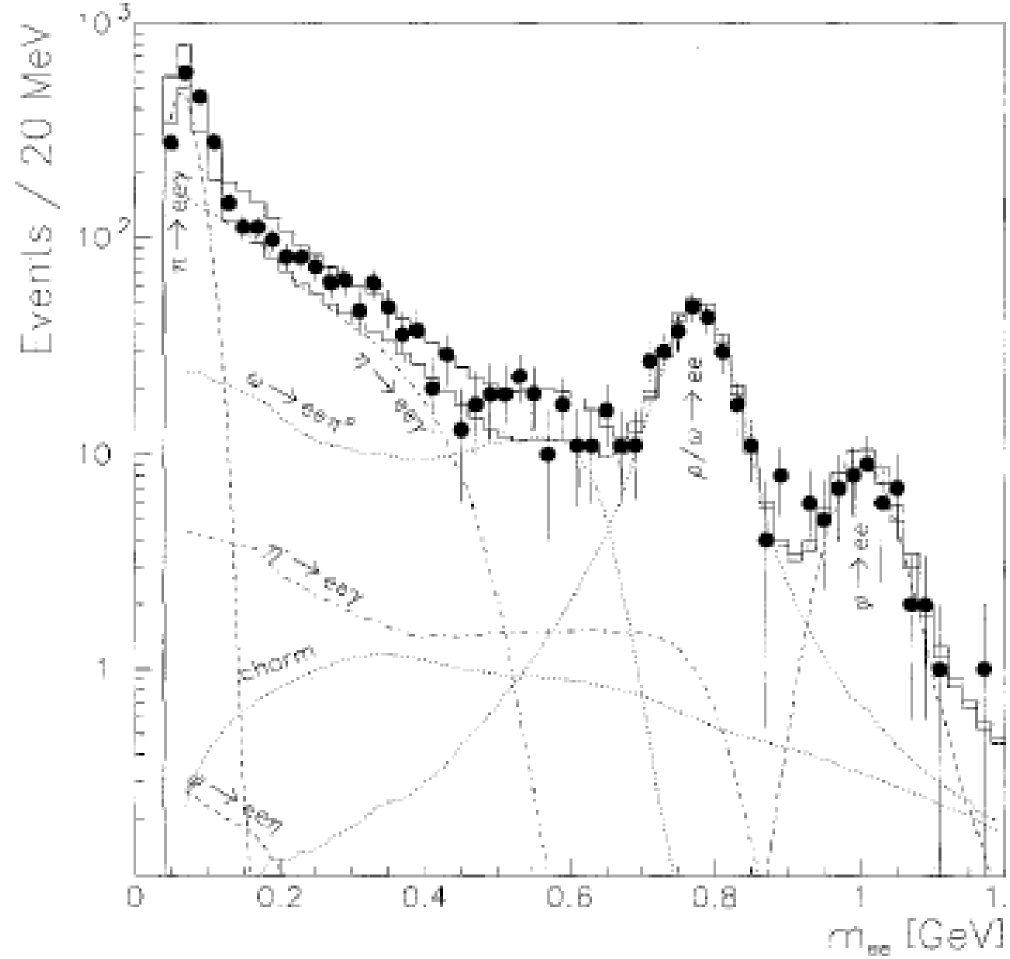
see also: K. Reygers, ALICE 3 workshop Oct. 13 – 15, 2020

Z. Phys. C 68, 47–64 (1995)

di-leptons at SPS

Low-mass lepton-pair production in p-Be collisions at 450 GeV/c

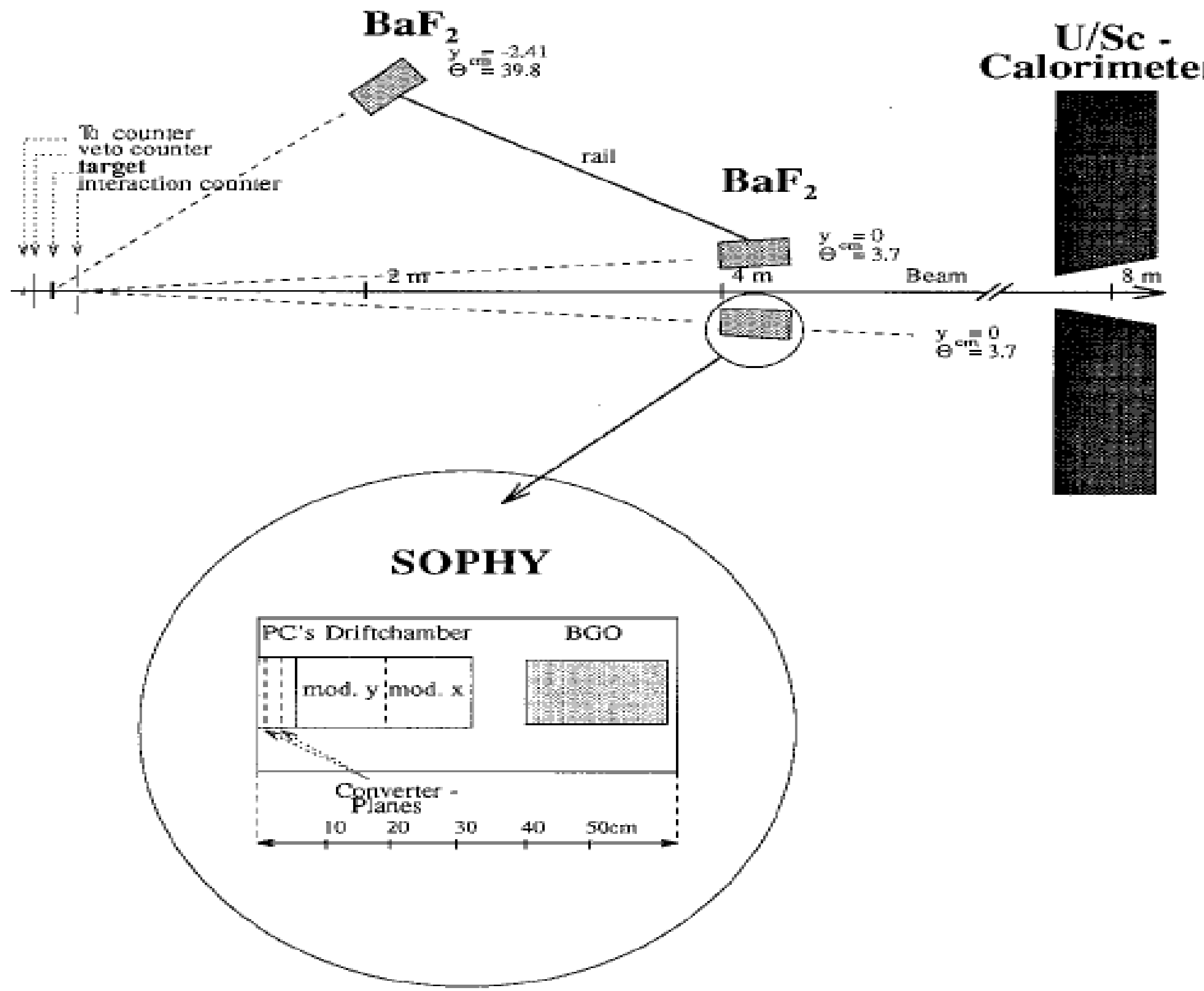




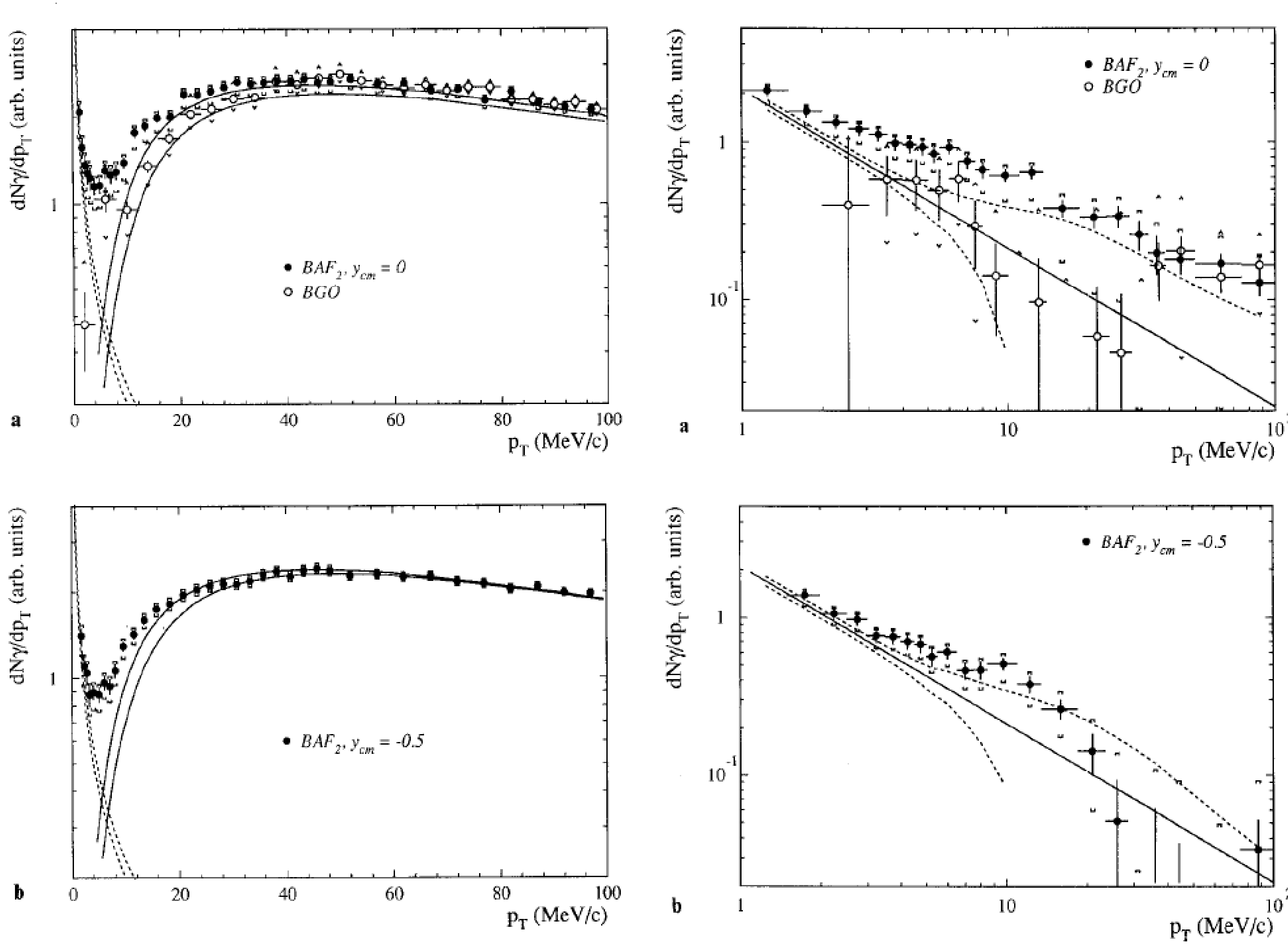
a few examples from the past, ...

Z. Phys. C 59, 547–553 (1993)

Soft photon production in 450 GeV/c p-Be collisions

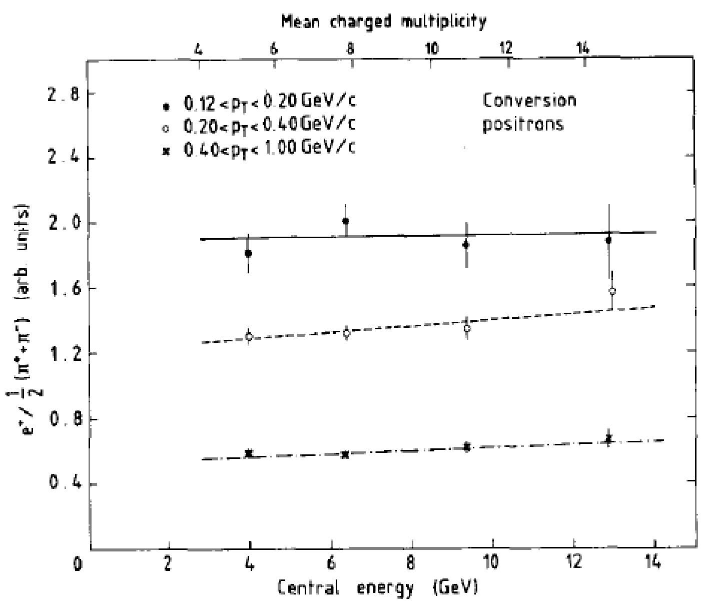


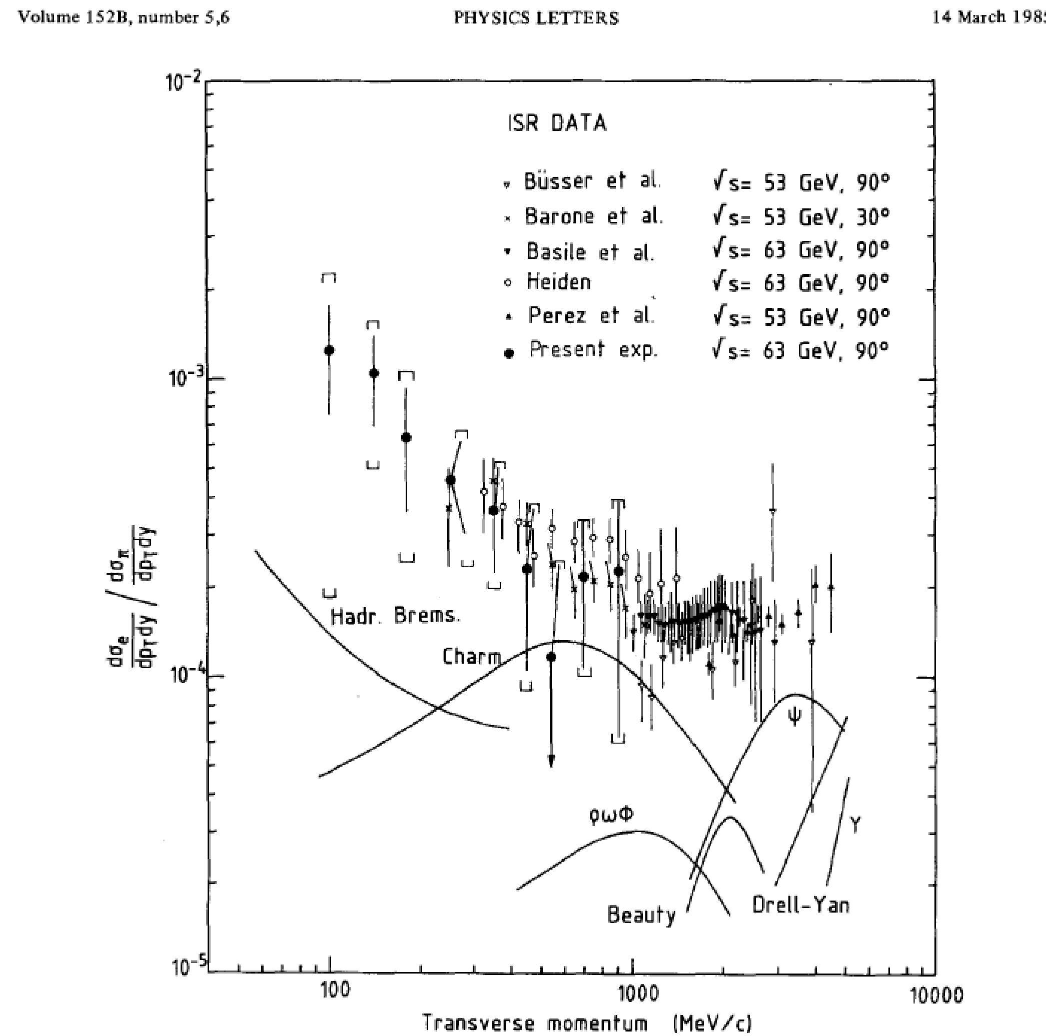
... there is life beyond the Jacobian peak



real photons down to the MeV scale, bremsstrahlung rise towards low p_T clearly observed, consistent with Low theorem, but charged particles were not measured, only simulated

single positrons at the ISR

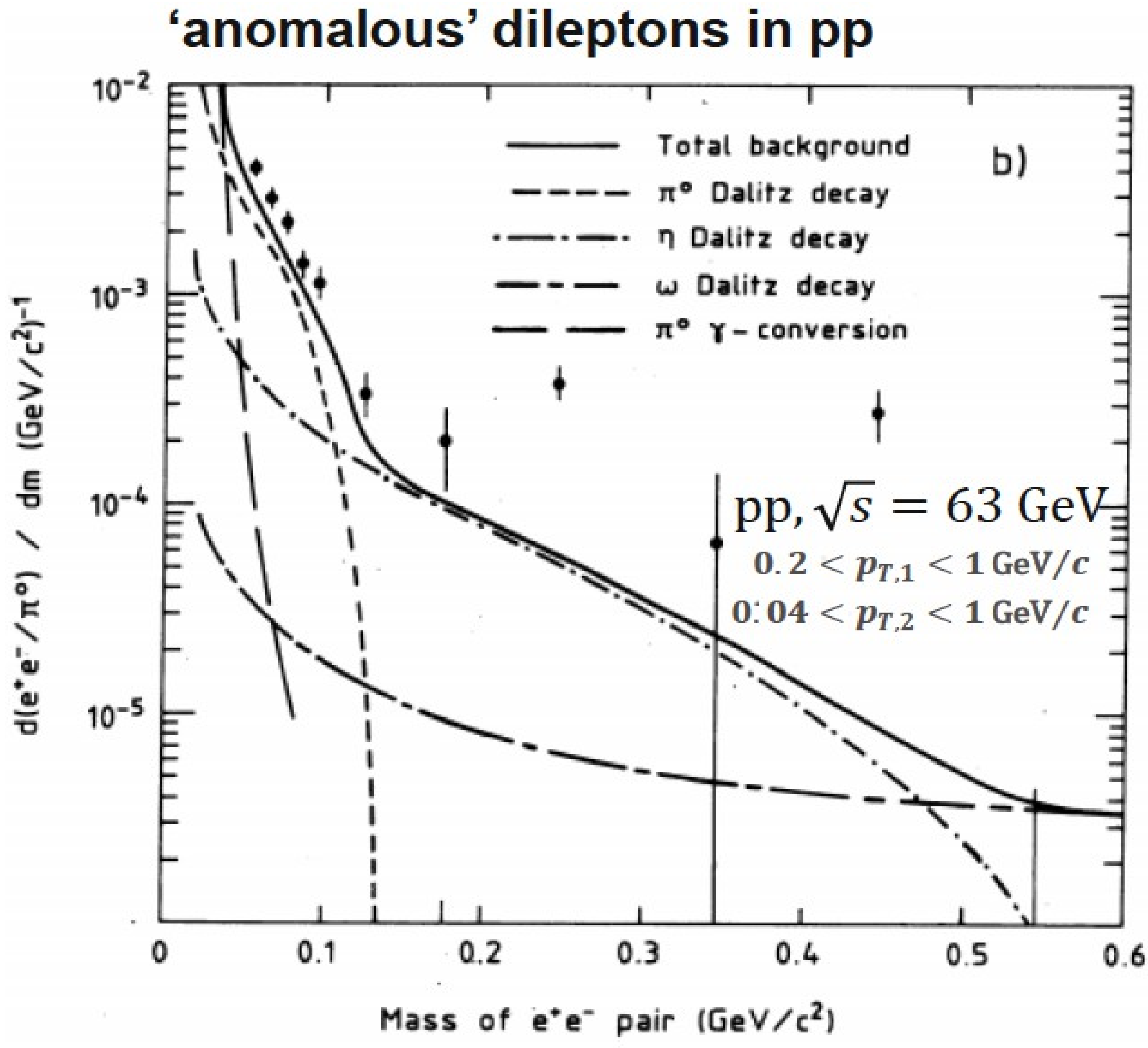




...the lonely anomaly left over from the ISR era

single positron measurements

ISR anomaly in di-electrons



soft photons in jets, DELPHI at LEP

DELPHI measurement:
Overview

Photon range:

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

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

Observation:

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

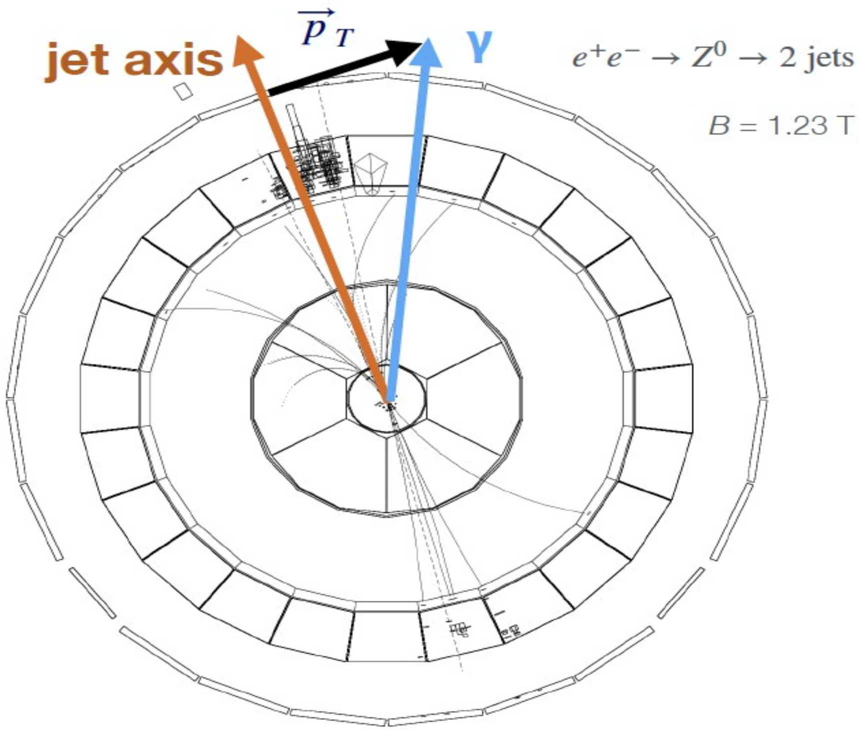
[→ probably very hard to do analysis in pp or AA due to underlying event]

Expected from bremsstrahlung:

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

Ratio:

$4.0 \pm 0.3 \pm 1.0$



picture taken from K. Reygers talk at ALICE 3 workshop, Oct. 2020

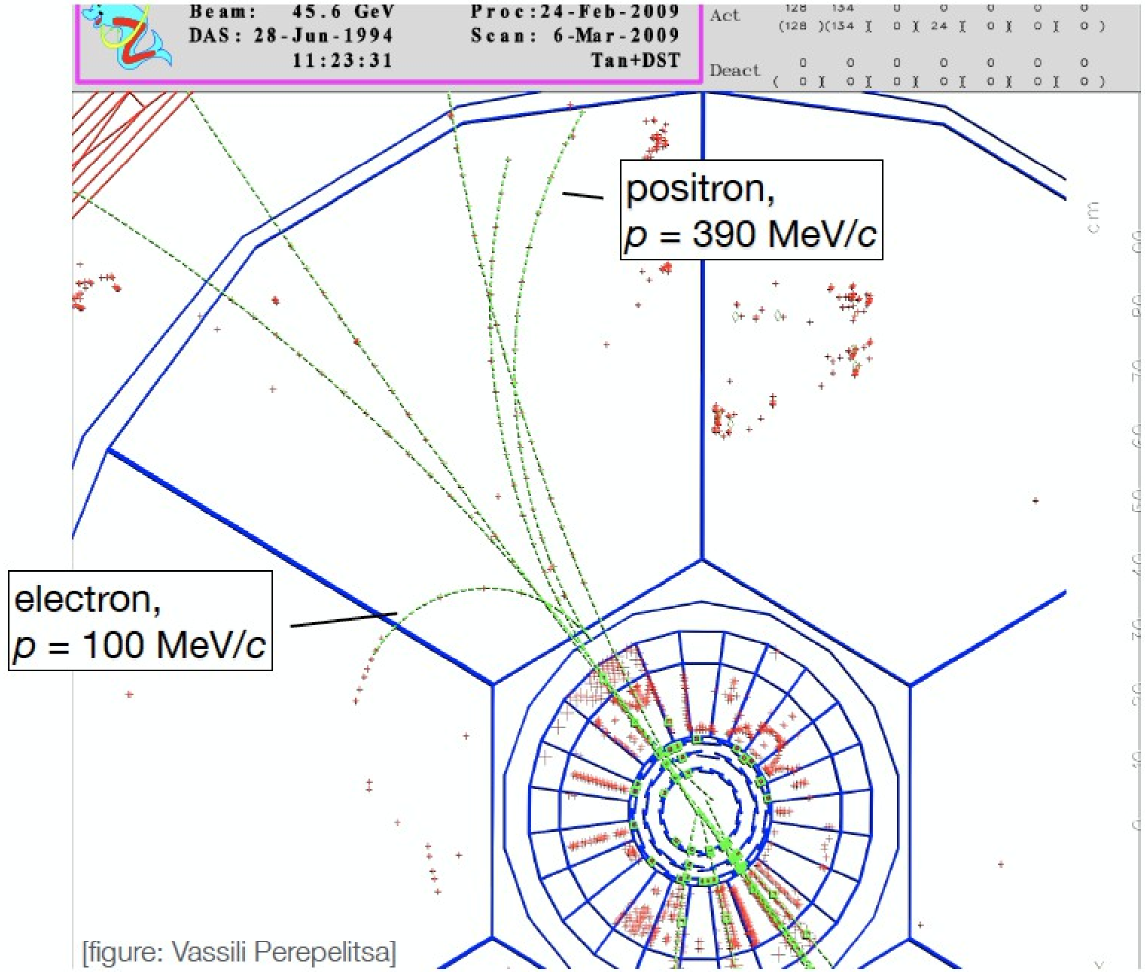
Delphi coll. Eur.Phys.J.C 67 (2010) 343-366, 1004.1587 [hep-ex]
Eur.Phys.J.C 47 (2006) 273-294, hep-ex/0604038 [hep-ex]

soft photon measurement using conversion method

DELPHI photon event

Conversion in front of TPC

Conversion probability: ~ 7%



picture taken from K. Reygers talk at ALICE 3 workshop, Oct. 2020

soft photon signal is enhanced by factor 4 over 'Low' prediction

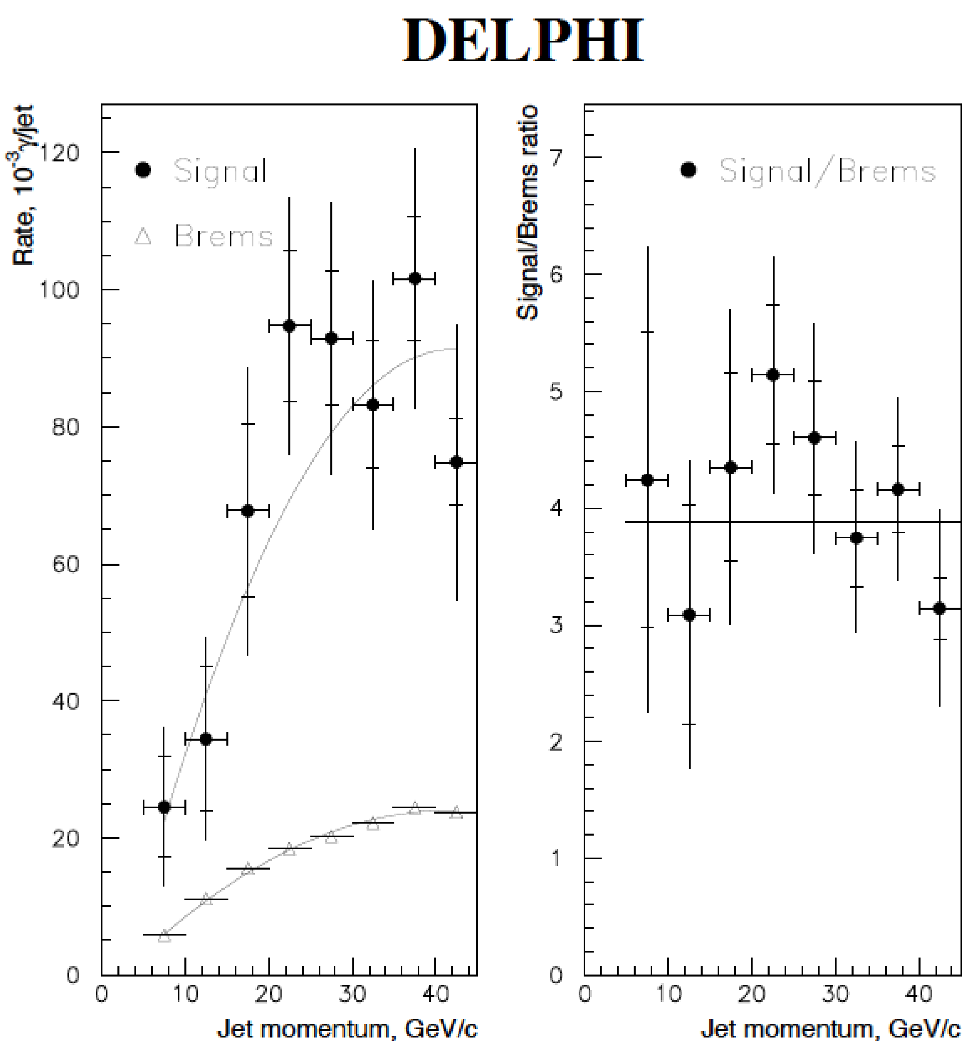


Figure 4: Dependence of the direct soft photon production on the jet momentum. Left panel: signal and predicted inner bremsstrahlung rates as a function of jet momentum. Right panel: ratios of the signal rates to those of the inner bremsstrahlung. The curves in the left panel are 2nd order polynomial fits produced to guide the eye; the bremsstrahlung points were fitted first, and then the bremsstrahlung curve was scaled by a factor of 4 giving a good approximation to the signal points. The inner vertical bars represent the statistical errors, while the whole vertical bars give the statistical and systematic errors combined in quadrature. The horizontal line in the right panel represents the statistical average over the signal-to-bremsstrahlung ratios.

very different jet multiplicity dependence for charged and neutral particles

...and muon bremsstrahlung is bang on the 'Low' prediction

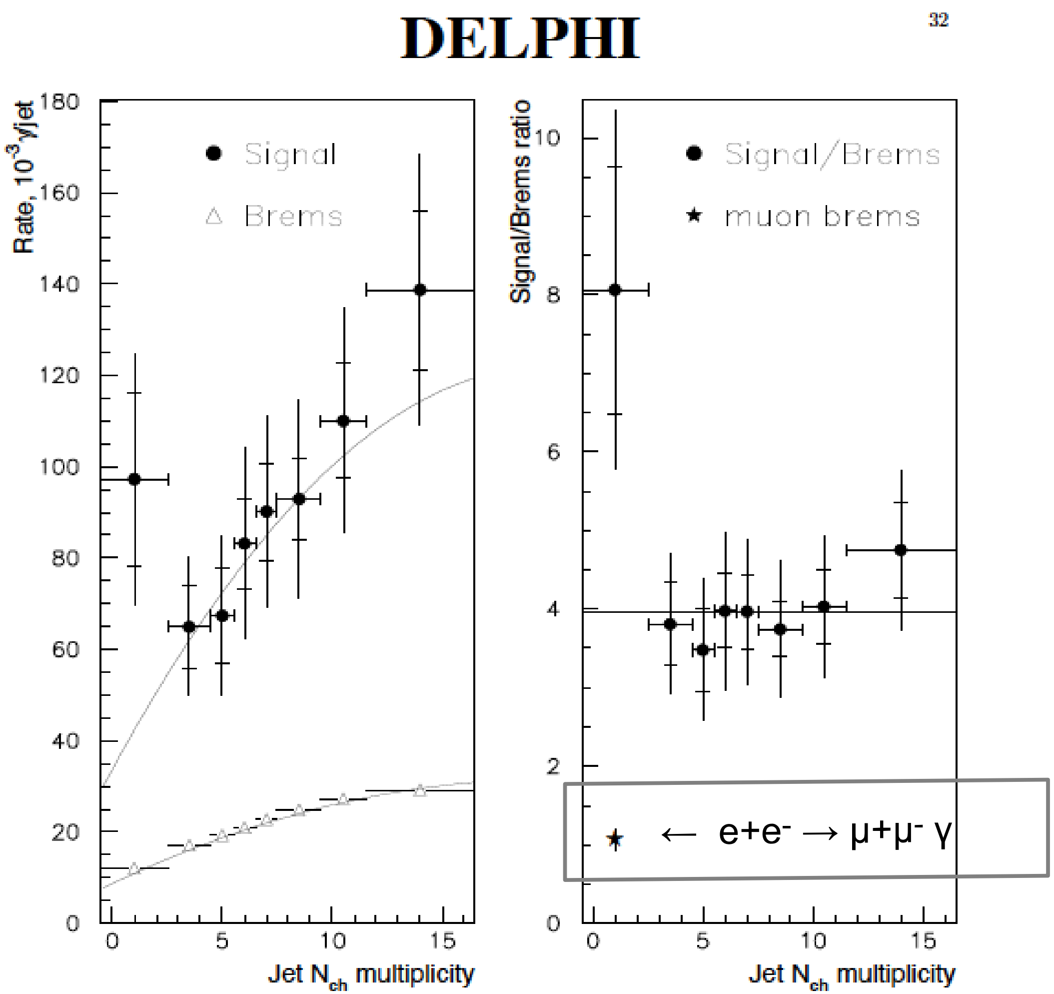


Figure 5: Dependence of the direct soft photon production on the jet charged multiplicity. Left panel: signal and predicted inner bremsstrahlung rates as a function of the jet charged multiplicity. Right panel: ratios of the signal rates to those of the inner bremsstrahlung. The curves in the left panel are 2nd order polynomial fits produced to guide the eye; the bremsstrahlung points were fitted first, and then the bremsstrahlung curve was scaled by a factor of 4, which satisfactorily approximates the signal points. The inner vertical bars represent the statistical errors, while the whole vertical bars give the statistical and systematic errors combined in quadrature. The horizontal line in the right panel represents the statistical average over the signal-to-bremsstrahlung ratios. The cut $p_{jet} \geq 20$ GeV/c is applied.

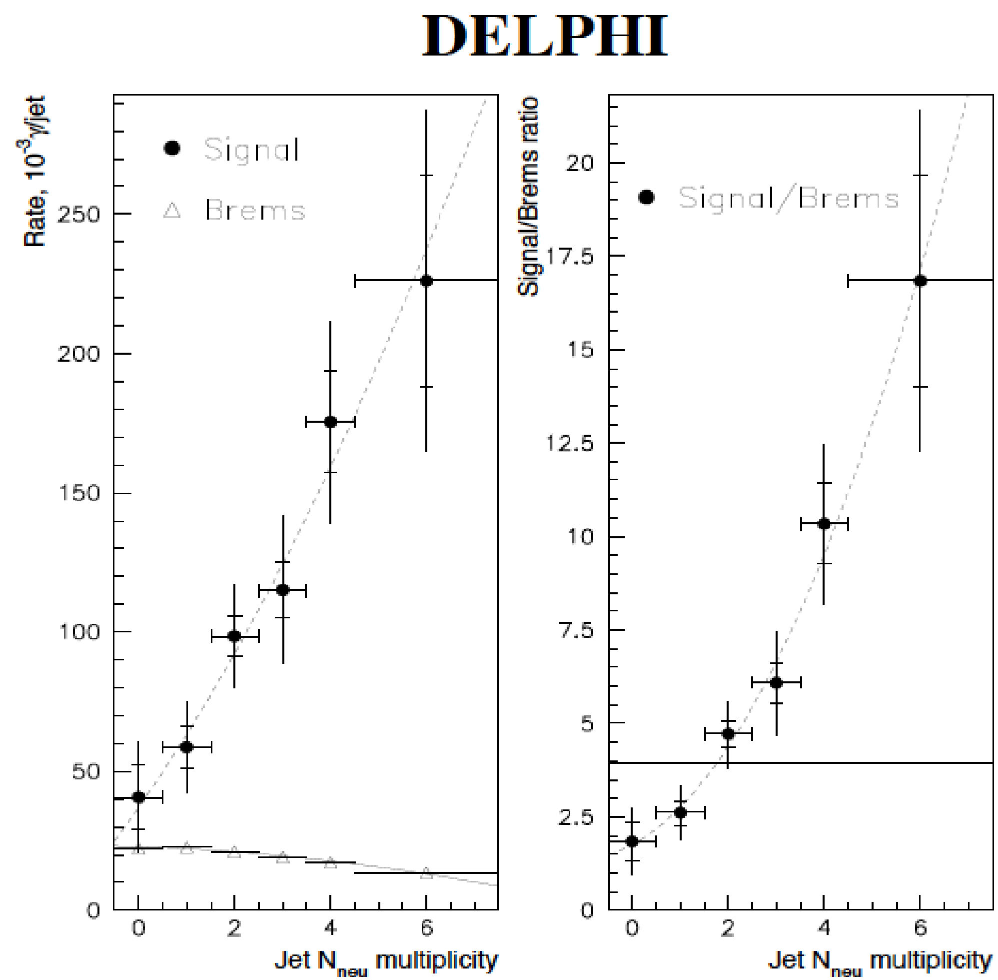


Figure 6: Dependence of the direct soft photon production on the jet neutral multiplicity. Left panel: signal and predicted inner bremsstrahlung rates as a function of the jet neutral multiplicity. Right panel: ratios of the signal rates to those of the inner bremsstrahlung. All the curves in the figure are independent 2nd order polynomial fits produced to guide the eye. The inner vertical bars represent the statistical errors, while the whole vertical bars give the statistical and systematic errors combined in quadrature. The horizontal line in the right panel represents the statistical average over the signal-to-bremsstrahlung ratios. The cut $p_{jet} \geq 20$ GeV/c is applied.

Delphi coll. Eur.Phys.J.C 67 (2010) 343-366, 1004.1587 [hep-ex]
Eur.Phys.J.C 47 (2006) 273-294, hep-ex/0604038 [hep-ex]

An analysis of the direct soft photon production rate as a function of the parent jet characteristics is presented, based on hadronic events collected by the DELPHI experiment at LEP1. The dependences of the photon rates on the jet kinematic characteristics (momentum, mass, etc.) and on the jet charged, neutral and total hadron multiplicities are reported. Up to a scale factor of about four, which characterizes the overall value of the soft photon excess, a similarity of the observed soft photon behaviour to that of the inner hadronic bremsstrahlung predictions is found for the momentum, mass, and jet charged multiplicity dependences. However for the dependence of the soft photon rate on the jet neutral and total hadron multiplicities a prominent difference is found for the observed soft photon signal as compared to the expected bremsstrahlung from final state hadrons. The observed linear increase of the soft photon production rate with the jet total hadron multiplicity and its strong dependence on the jet neutral multiplicity suggest that the rate is proportional to the number of quark pairs produced in the fragmentation process, with the neutral pairs being more effectively radiating than the charged ones.

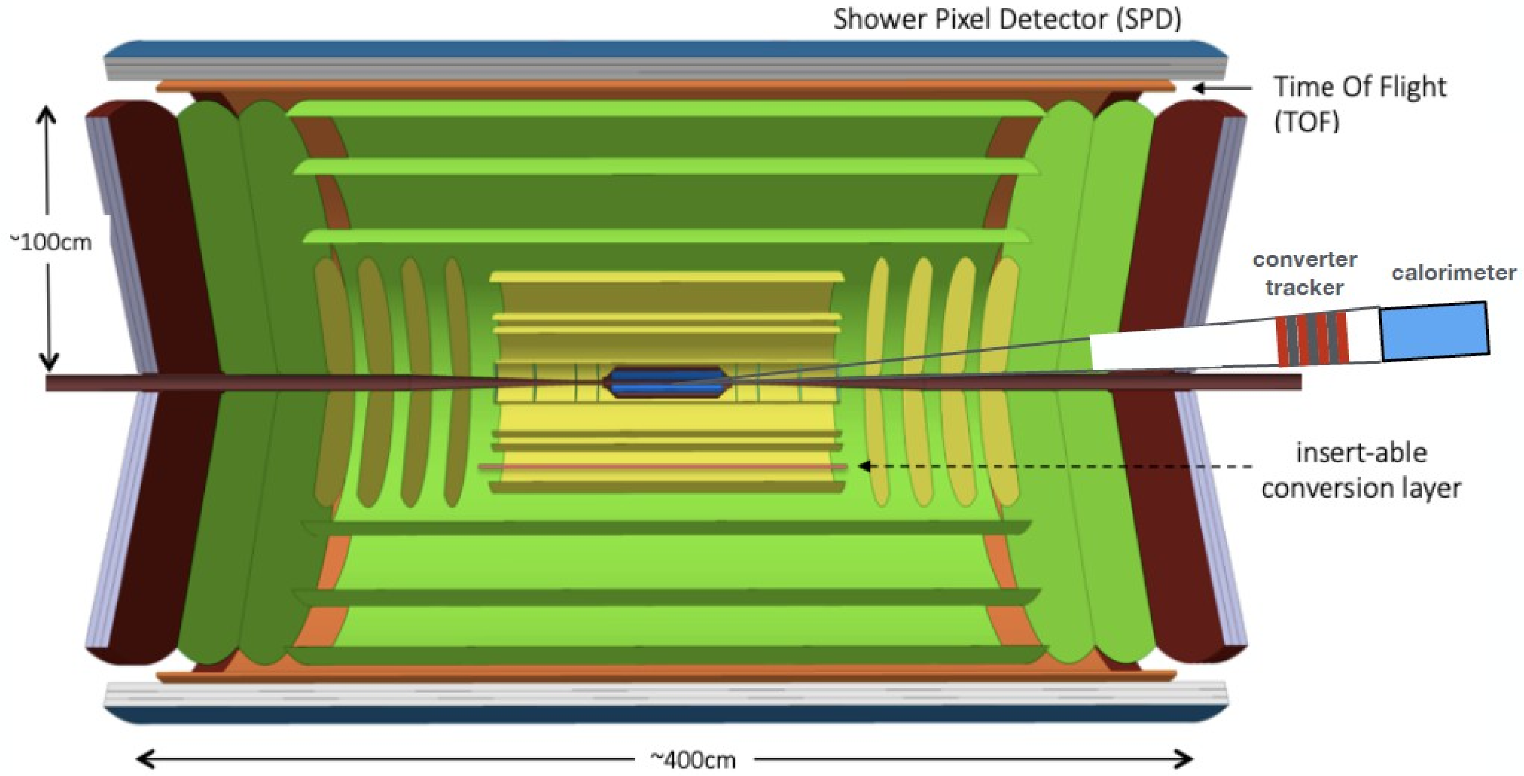
???

summary of most existing soft photon results, taken from K. Reygers, ALICE 3 workshop , Oct. 2020

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_γ < 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_γ < 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_γ < 1 GeV)	5.3 ± 1.0	pair conversion	Belogianni et al., Phys. Lett. B 548, 122 (2002)
pp, CERN, WA102, OMEGA	2002	450 GeV	$p_T < 20$ MeV/c (0.2 < E_γ < 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_γ < 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	~ 1	pair conversion	DELPHI, Eur. Phys. J. C57, 499 (2008)

soft photon measurement in ALICE 3

a possible forward detector sketch



such a forward photon detector is currently being simulated by the ALICE 3 photon team, advantage: very little material between collision vertex and photon detector

my list of to-do's for or better before the RRTF

- photons, exclusive channels, do detailed evaluations of soft photon production
  - diffractive in pp collisions
  - exclusive channels within the tensor pomeron channel
  - UPC pp $\rightarrow$ (pp) J/psi, psi',..., + γ
  - $e^+e^- \rightarrow \mu^+\mu^- \gamma$
  - $e^+e^- \rightarrow$ jet + γ, multiplicity dependence for charged and neutral particles
- inclusive channels
  - pPb $\rightarrow \gamma$ dependence on y, p_t and charged particle multiplicity
  - pp $\rightarrow \gamma$ 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 done by simulations using Monte Carlo generators like Pythia coupled with the sof photon theorems discussed above

additional slides

main assumptions and results

In the soft photon limit, k → 0, the matrix element M can be factorized into the hadron part M_0 and the photon emission part $\sum_i^{\text{all charged particles}} \frac{\eta_i e_i p_i \cdot \varepsilon}{2 p_i \cdot k}$

underlying this is the recognition that, for k → 0, and with the colliding hadrons in the GeV to TeV range, the following equality holds:

$$M_0(p_1 - k \;\; p_2;\; p_3 \;\; p_4) \sim M_0(p_1 \;\; p_2;\; p_3 + k \;\; p_4) \sim M_0(p_1 \;\; p_2;\; p_3 \;\; p_4)$$

since M_0 is just the amplitude for 'elastic' scattering, or in the general case, the amplitude for multi-hadron production, the number of soft photons is precisely predicted from the (measured) cross section for multiple production of charged hadrons

what about gauge invariance of the soft factor?

note that since $(\varepsilon+q)\cdot q = \varepsilon\cdot q$ for the massless photon 4-vector q ,the condition $\varepsilon\cdot q = 0$ fixes the polarization vector ε only up to multiples of q

what happens to the soft factor $\sum_{k=1}^{m} \frac{eQ_k^{\text{out}} p_k^{\text{out}} \cdot \varepsilon}{p_k^{\text{out}} \cdot q} - \sum_{k=1}^{n} \frac{eQ_k^{\text{in}} p_k^{\text{in}} \cdot \varepsilon}{p_k^{\text{in}} \cdot q}$

if we shift ε to ε+q? it get's a contribution $\sum_{k=1}^{m} eQ_k^{\text{out}} - \sum_{k=1}^{n} eQ_k^{\text{in}}$

but this contribution vanishes exactly because of charge conservation

so the soft factor is also, because of the connection between gauge invariance and charge conservation, a gauge invariant quantity