Soft photon measurements with ALICE 3

Never at Rest: A Lifetime Inquiry of QGP

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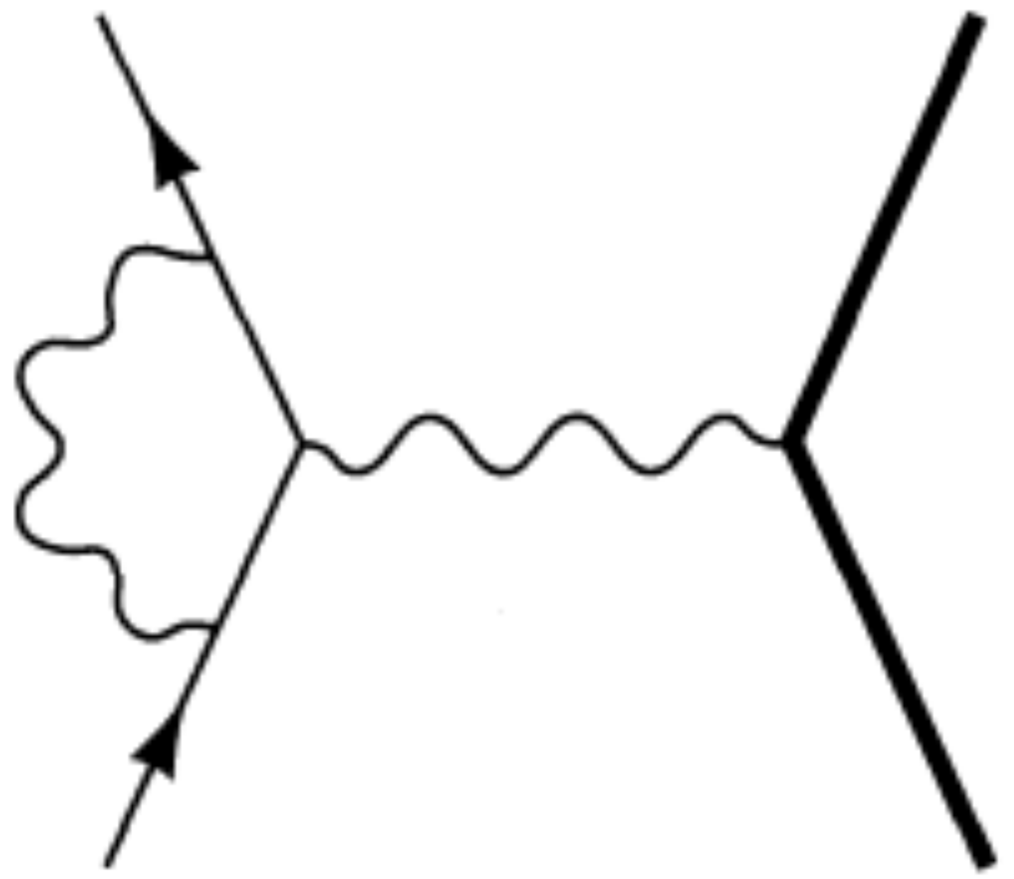
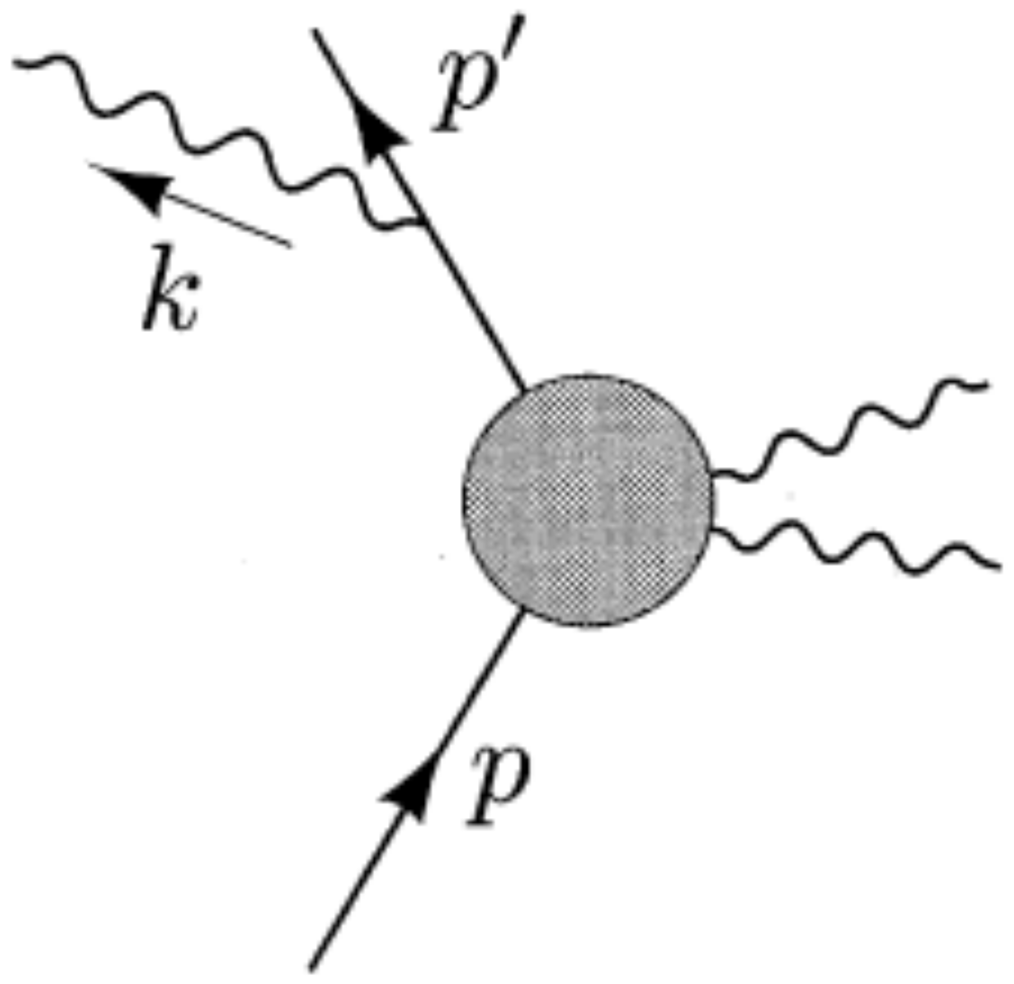
Infrared divergences

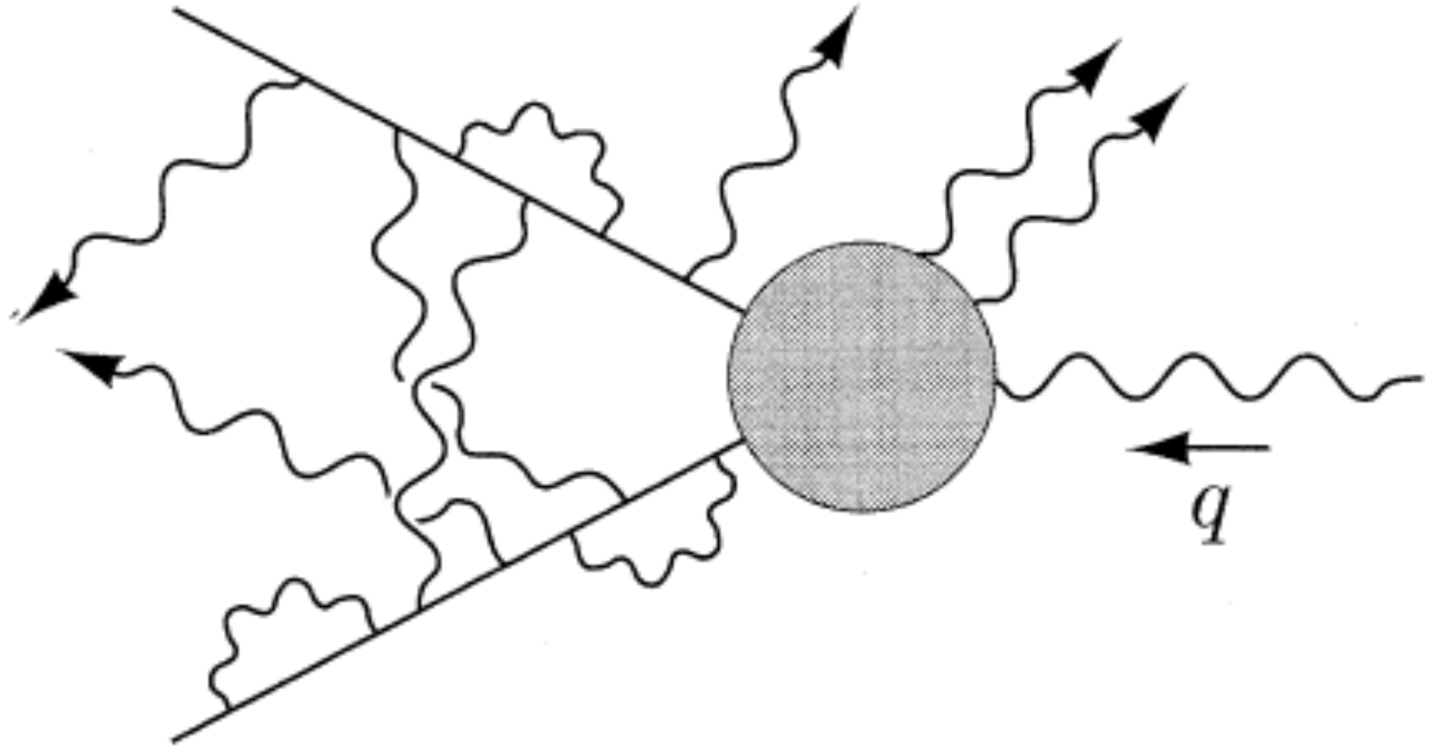
- QED corrections to processes let the cross section diverge (as $m_\gamma \to 0$):
  - Vertex correction $\sigma(p \to p')_{\text{corr}} \approx \sigma(p \to p') \cdot \left(1 - \frac{\alpha}{\pi} \log \frac{-q^2}{\mu^2} \log \frac{-q^2}{m^2}\right)$
  - Soft photon emission $\sigma(p \to p' + \gamma(k)) \sim \sigma(p \to p') \cdot \frac{\alpha}{\pi} \log \frac{-q^2}{\mu^2} \log \frac{-q^2}{m^2}$
- Interpretation: Cannot be experimentally distinguished for very low photon
- Sum of effects is finite
- Add up higher orders of corrections – divergencies still cancel (Bloch-Nordsiek theorem)
- Can we measure these photons?



Vertex correction

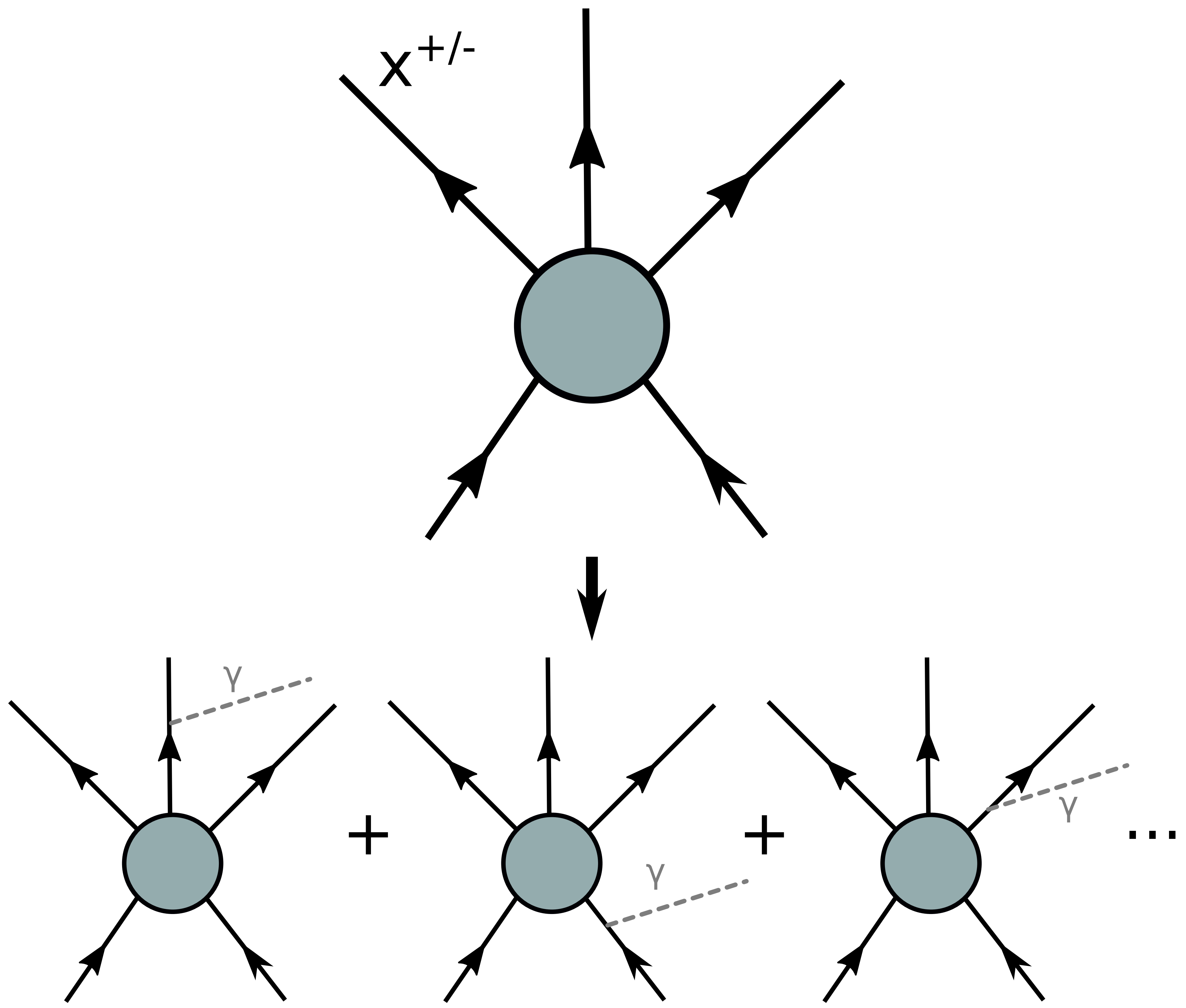


Soft photon emission



Low's theorem

- For interactions with charged particles: corresponding process producing photons
- Only external lines contribute in soft limit
- Extra propagator $\frac{1}{(p+k)^2 - m^2} = \frac{1}{2pk}$
- No change in momenta → blob stays the same → soft photon production in relation to hadronic cross section even without calculating the process
- Soft photon production/inner bremsstrahlung/hadronic bremsstrahlung
- Based on very fundamental principles; few uncertainties
- Soft theorems connected to fundamental conservation theorems (charge conservation)



Low's theorem

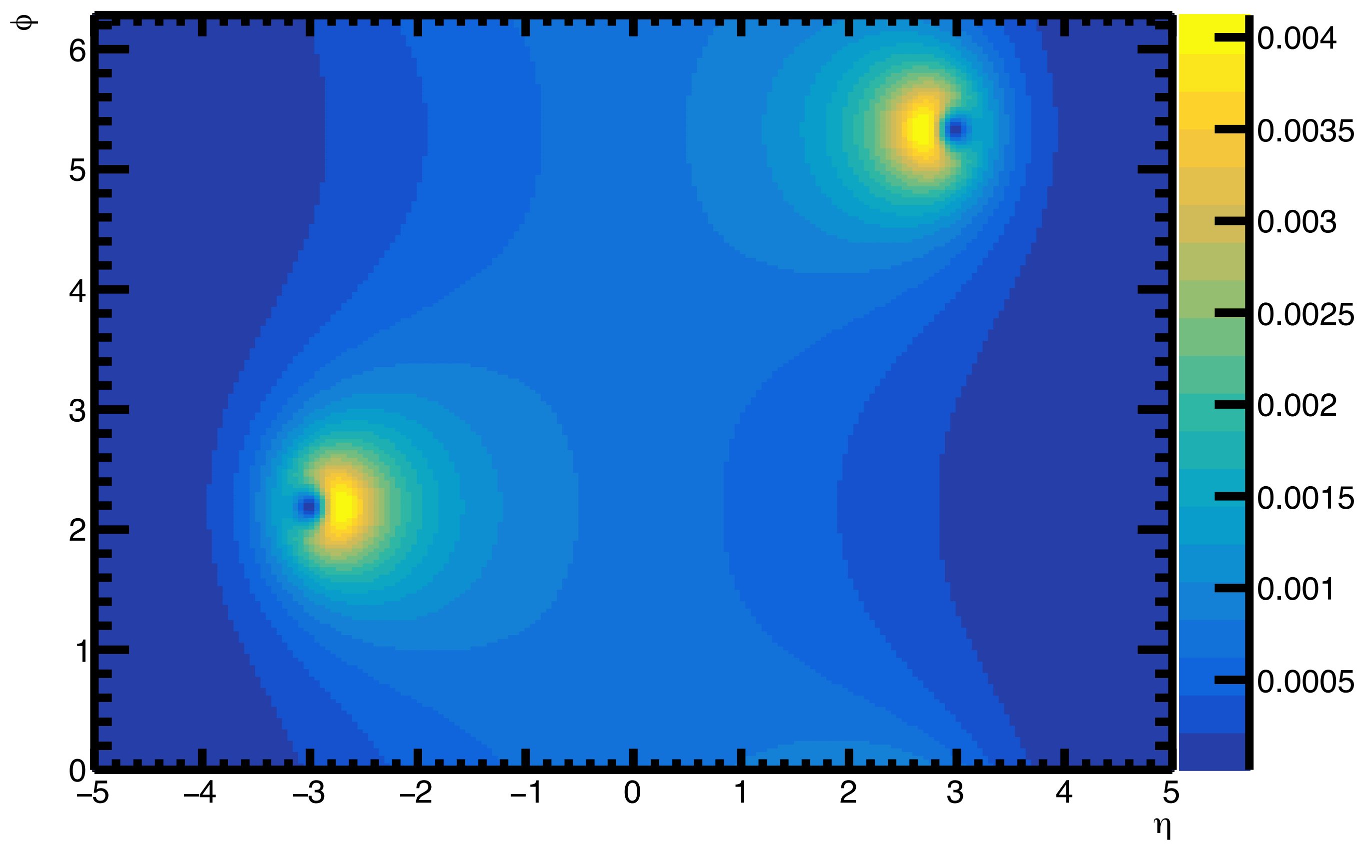
- Low's Theorem connects interaction of charged particles with 4-momenta $\mathbf{P_i}$ with expectation value for soft
- photon production (with 4-momentum $\mathbf{K}$):

$$\frac{\mathrm{d}N^\gamma}{\mathrm{d}^3k} = \frac{\alpha}{(2\pi)^2}\frac{-1}{E_\gamma}\int \left(\mathrm{d}^3p_1\ldots\mathrm{d}^3p_N\right)\left(\sum_{\text{Particle } i}\frac{\eta_i e_i \mathbf{P_i}}{\mathbf{P_i K}}\right)^2 \frac{\mathrm{d}N^{\mathrm{H}}}{\mathrm{d}^3p_1\ldots\mathrm{d}^3p_N}$$

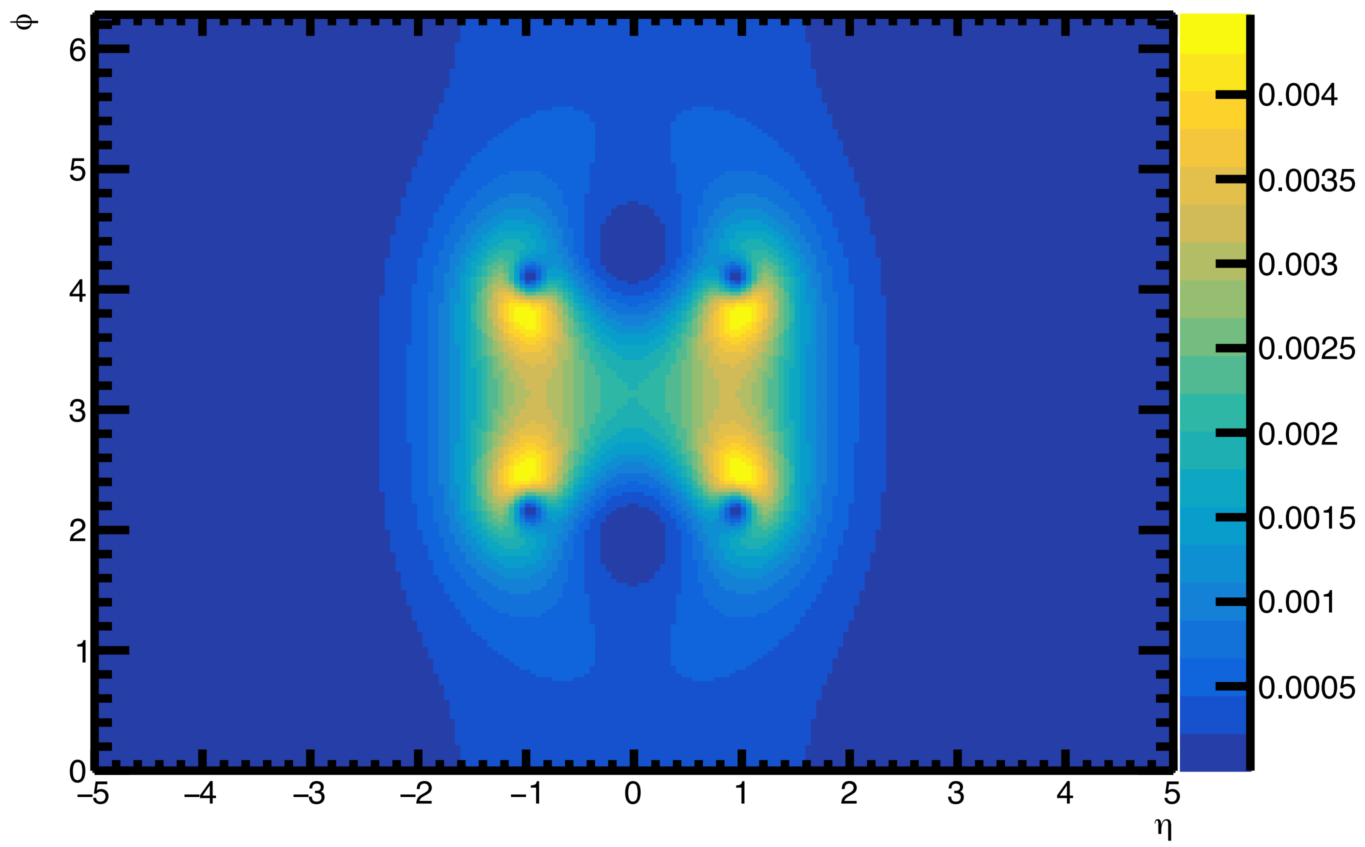
- For a single event:

$$\frac{d^3\mathrm{N}}{d|k|d\eta d\phi} = -\frac{\alpha}{(2\pi)^2}\cos(\vartheta/2)\sin(\vartheta/2)E_\gamma \sin\vartheta \left(\sum_{\text{Particle } i}\frac{\eta_i e_i \mathbf{P_i}}{\mathbf{P_i K}}\right)^2 \sim \frac{1}{E_\gamma}$$

Experimentalists seem to call this Low's theorem. Theorists use the name for the next order corrections

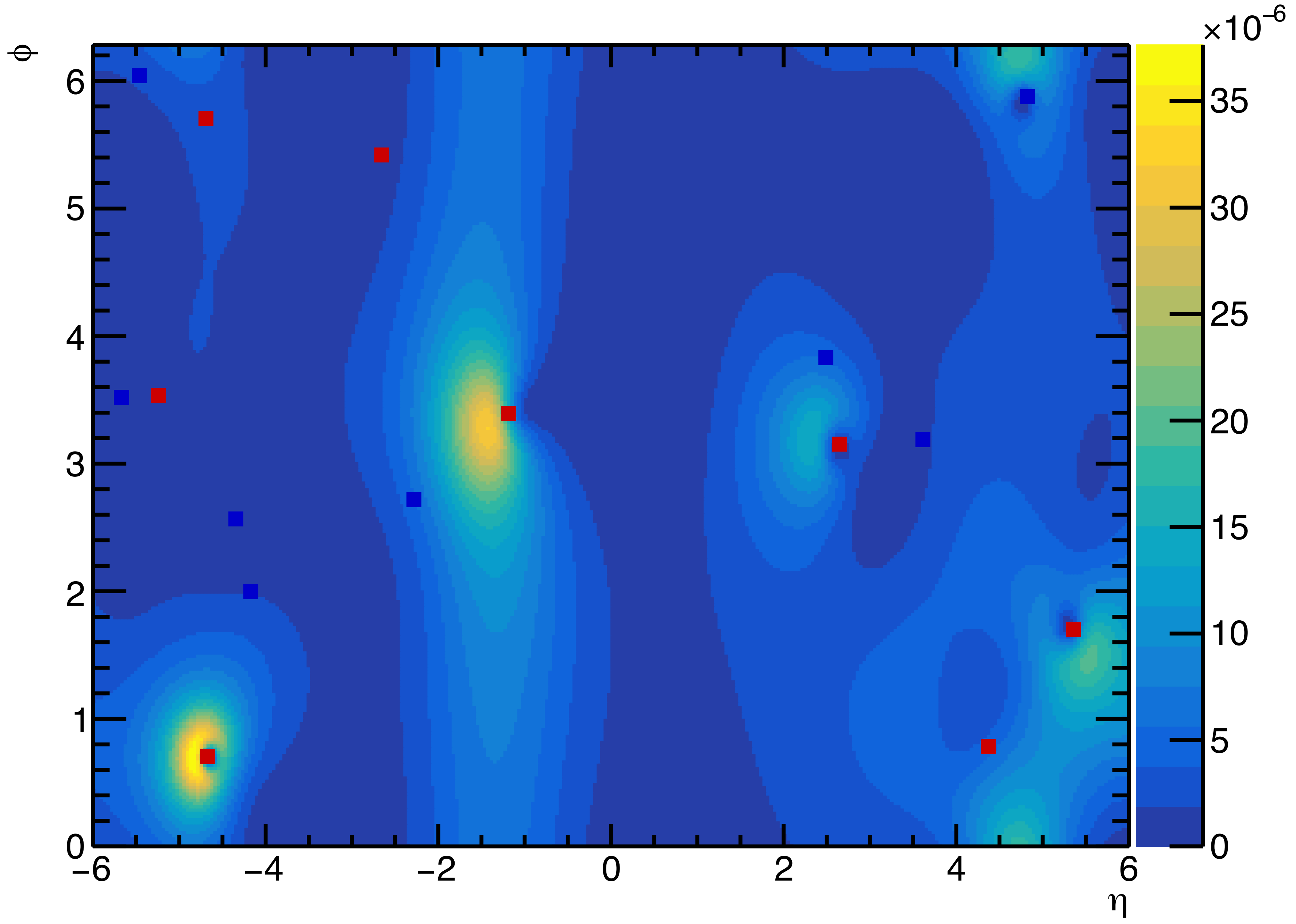


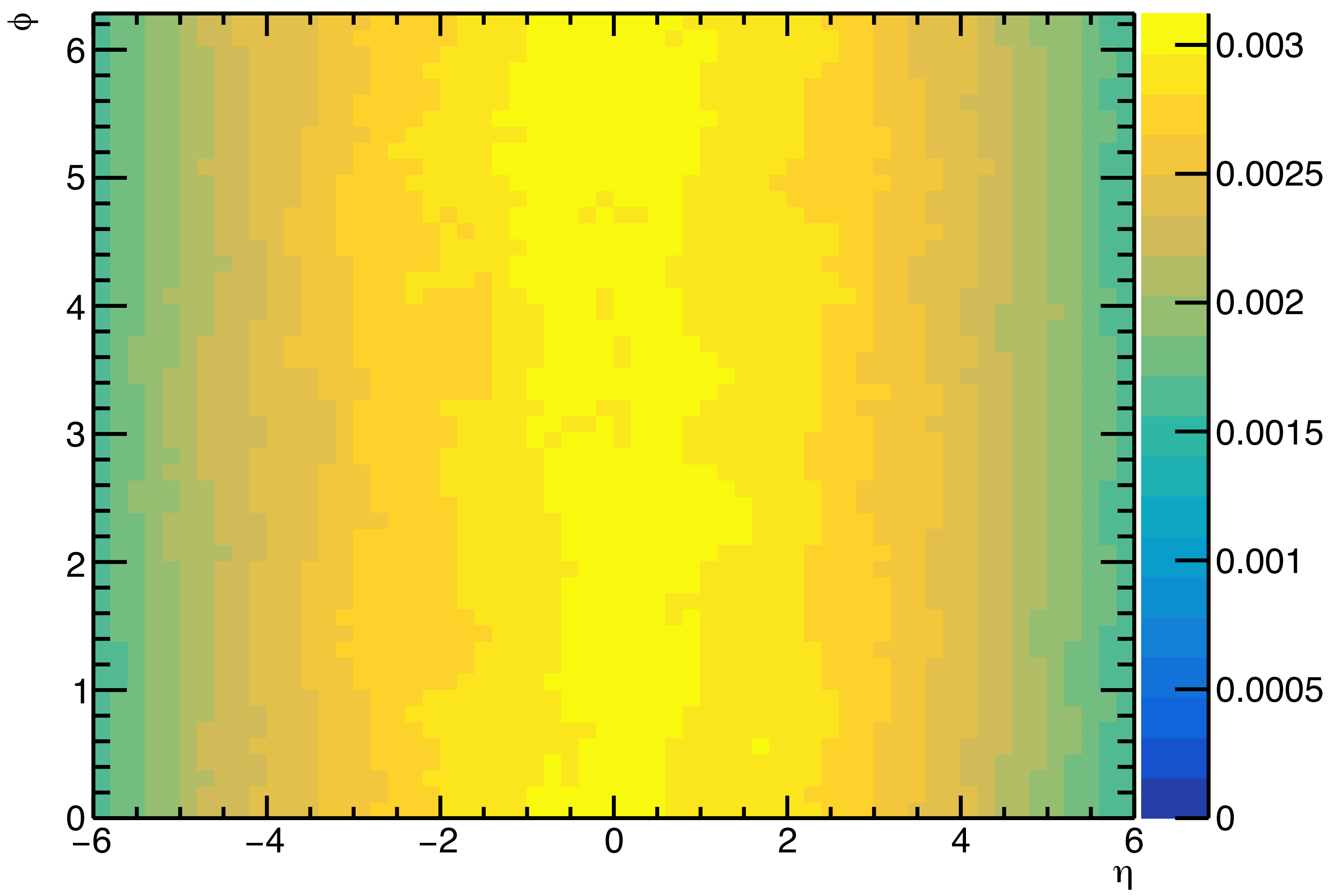
1 pos, 1 neg charged particle plus arbitrary neutral



2 pos, 2 neg charged particles plus arbitrary neutral

Estimating the soft photon signal

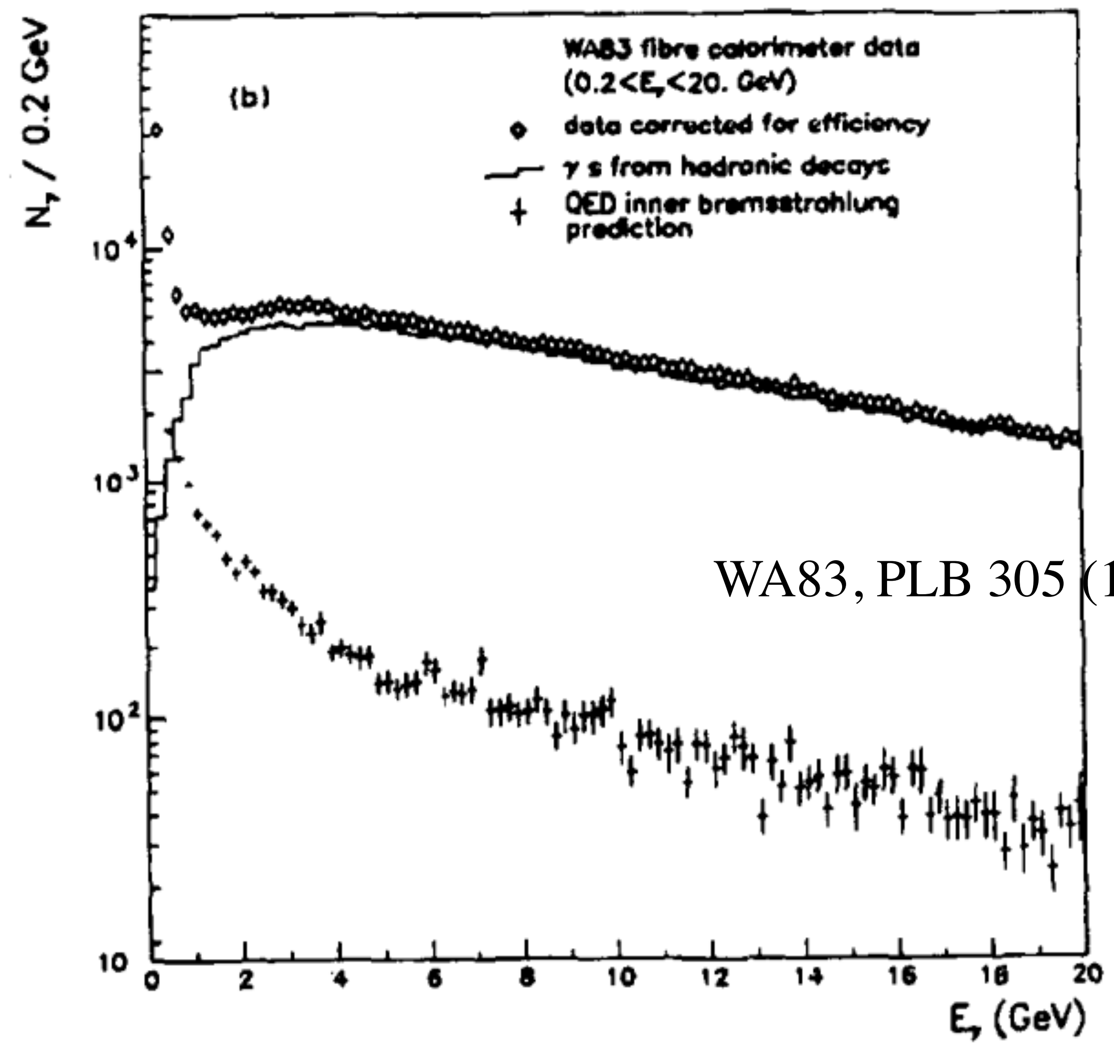




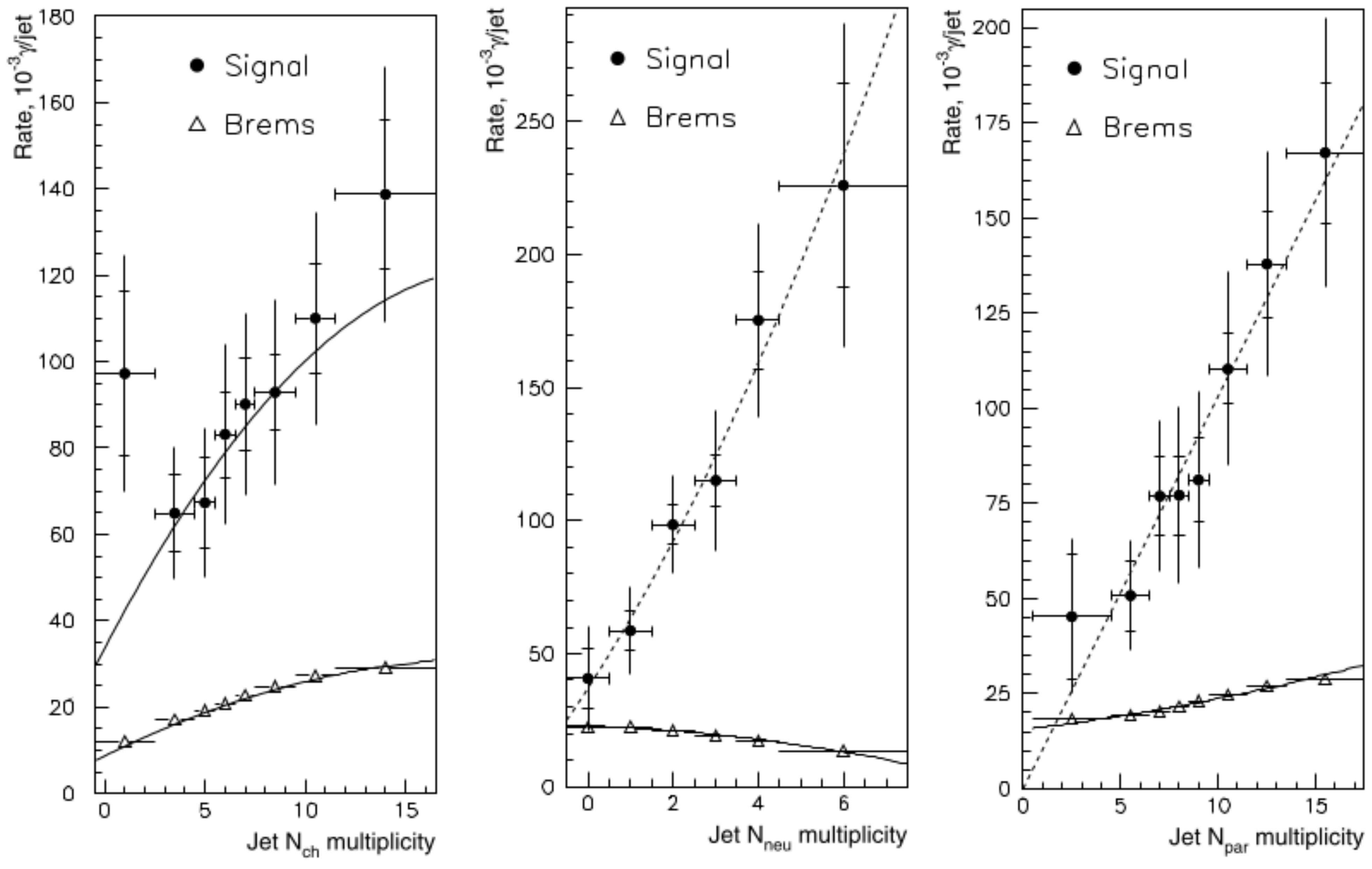
- Signal can be estimated from initial and produced charged particles
- Depends on $\beta\gamma$, difficulties without PID and with inefficiencies
- In previous experiments: estimated using event generators
- Signal turns out to be approximately constant per pseudorapidity for fixed E_γ and $p_{T,\gamma}$

Previous measurements of excess production

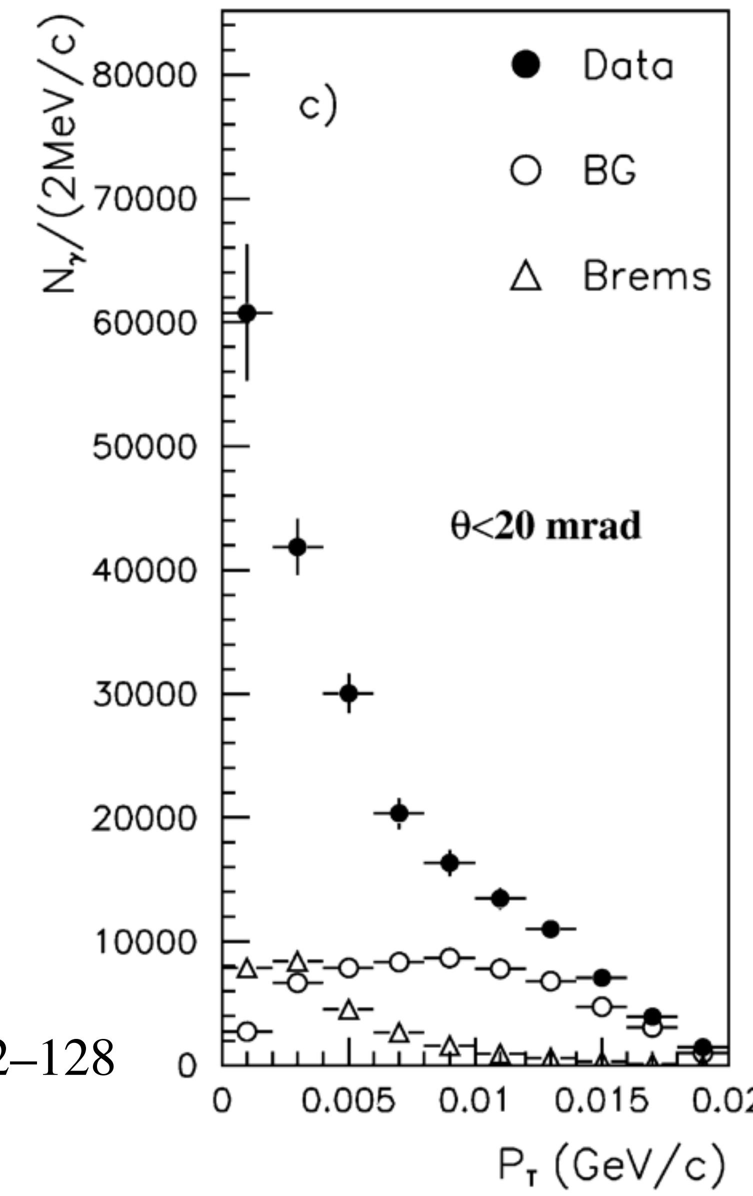
- Several measurements of soft photon production were performed previously
- Expected signal usually calculated from event generators
- Typically an enhancement of a factor~ 5 over the expected signal
- Typically $E_\gamma > 0.2$ GeV



WA83, PLB 305 (1993) 182-186



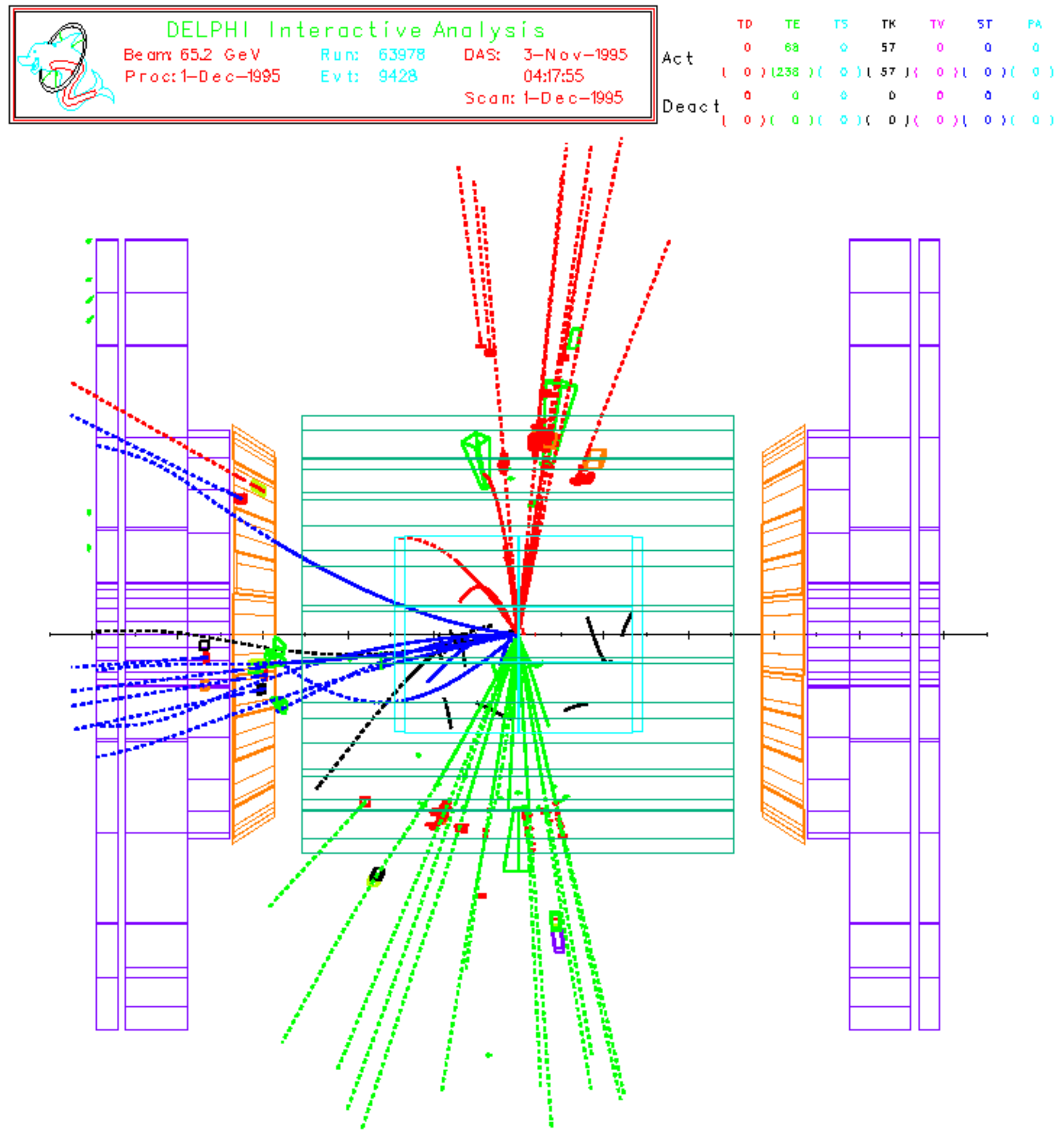
DELPHI, Eur. Phys. J. C (2010) 67: 343–366



WA91, PLB 548 (2002) 122–128

The soft photon puzzle

(from Klaus Reygers' talk at the ALICE 3 workshop)



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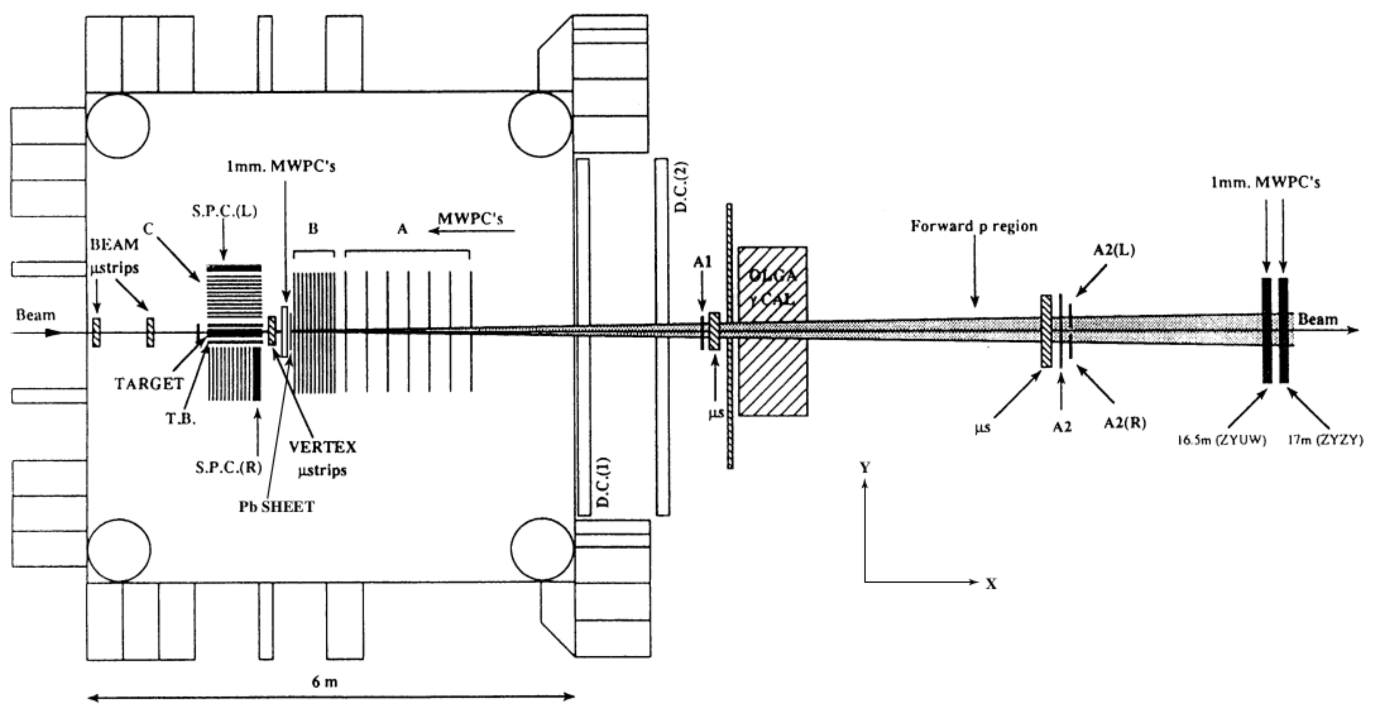
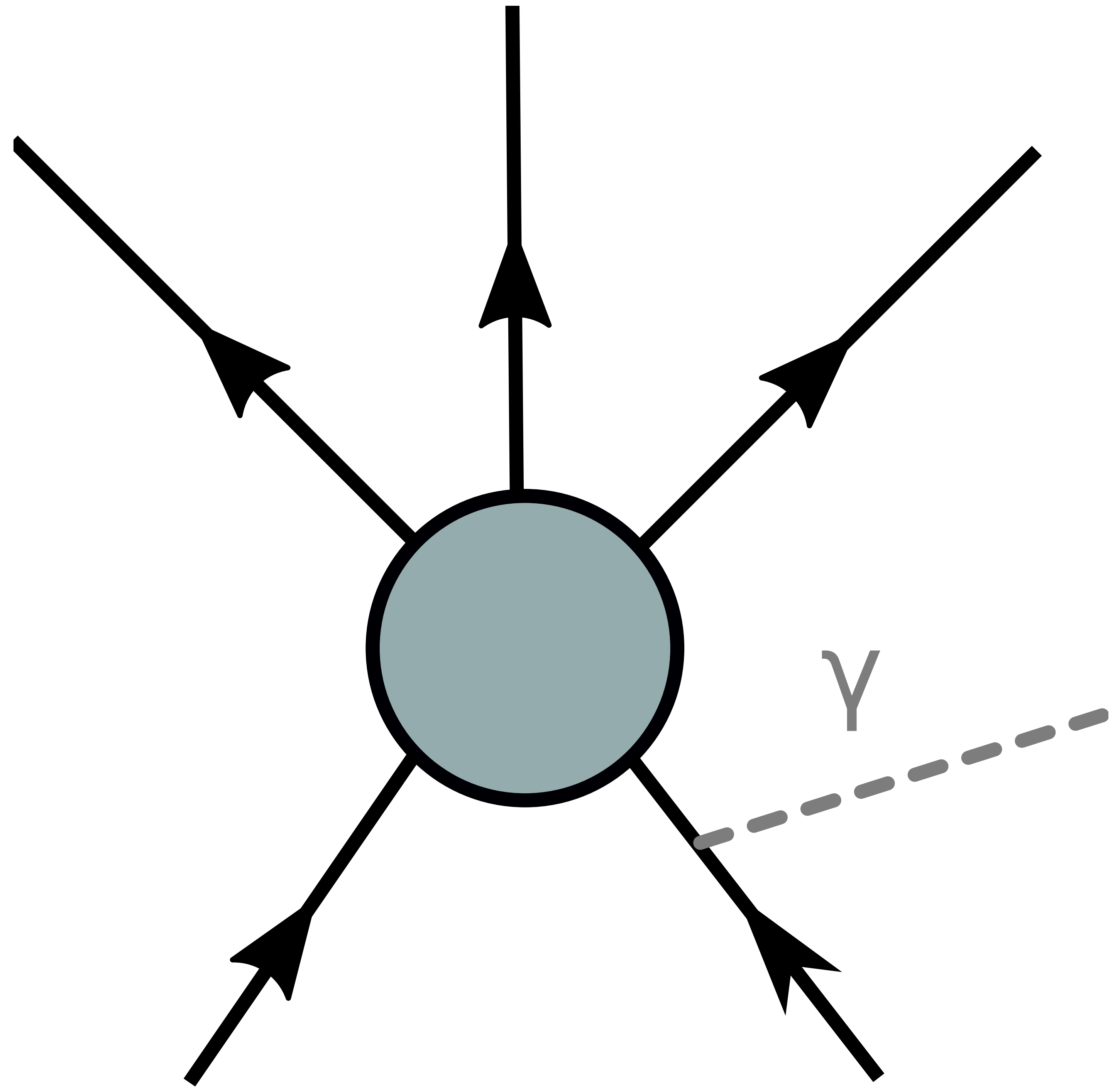
Ω LAYOUT FOR WA91 (1992 RUN)



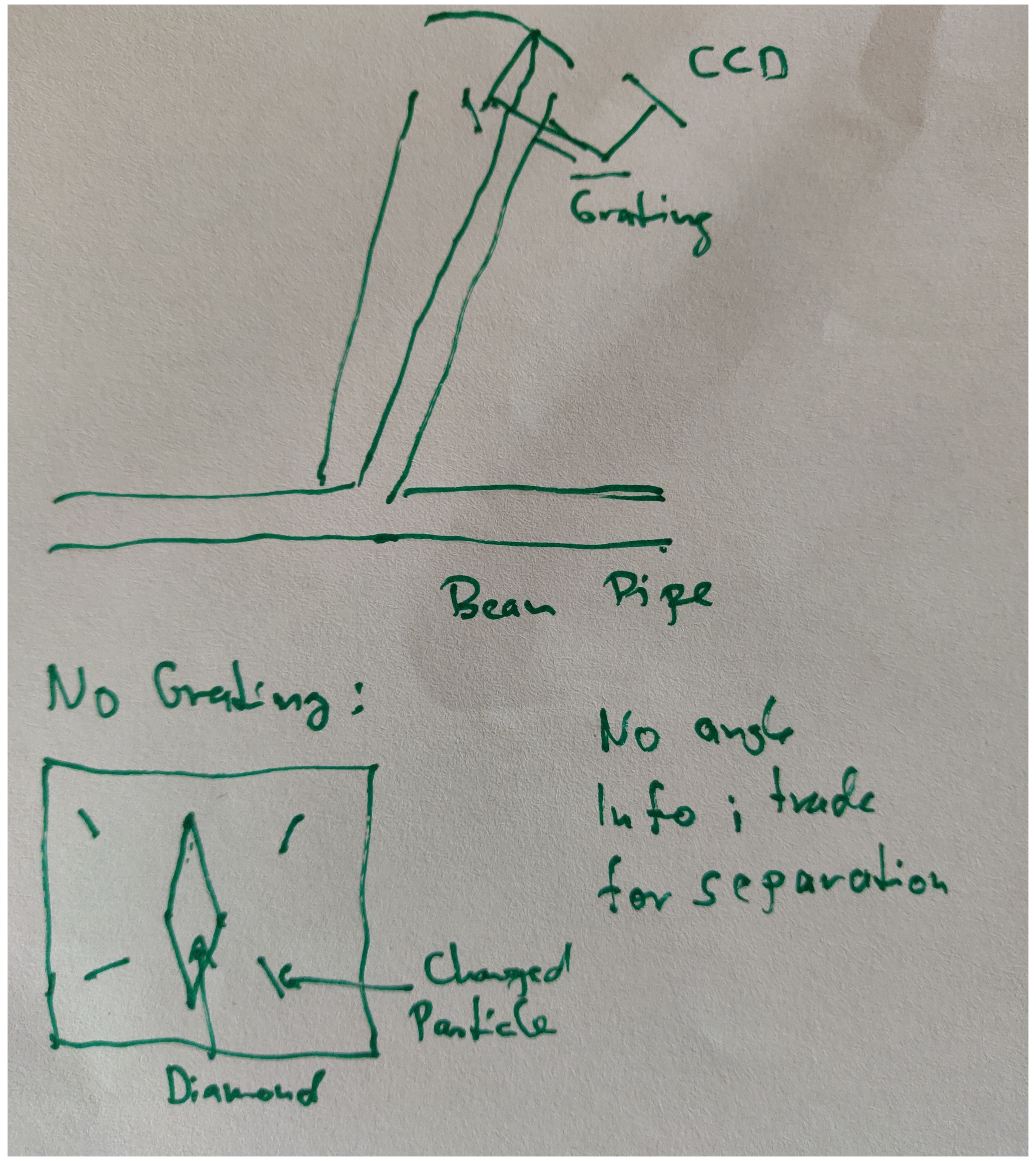
- Experiments with different setups
- Somewhat different analysis strategies
- Very simple signal estimate based on very fundamental principles...
- ... which is nevertheless off by a factor~5
- Also at LHC energies? And if so: why?

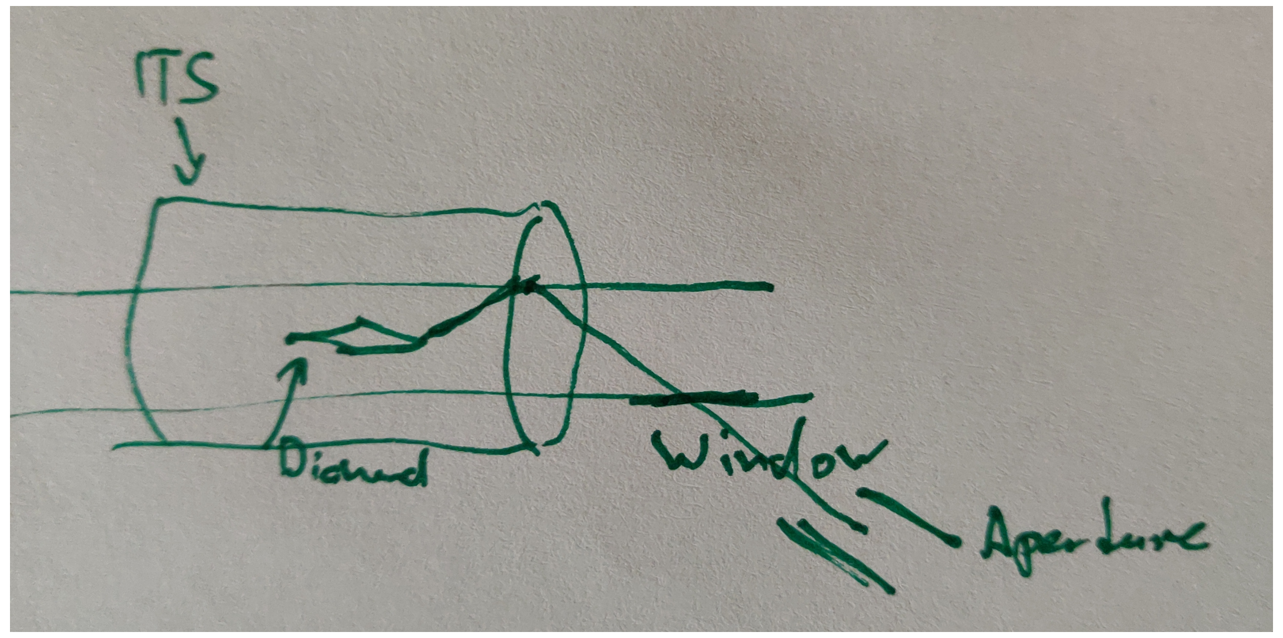
What is a soft photon anyways?

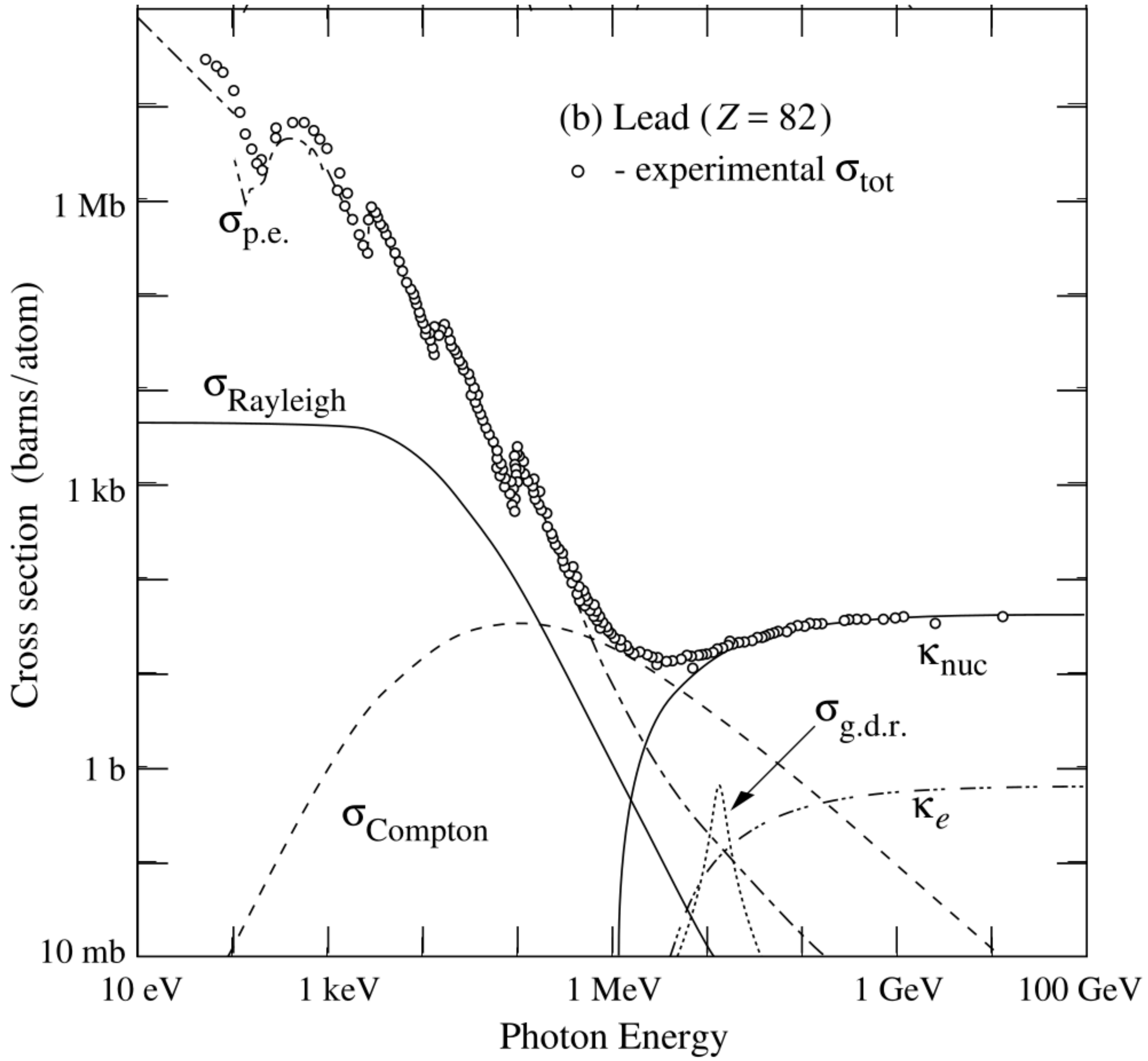
- Extra propagator $\frac{1}{p^2 - m^2}$, with the photon $\frac{1}{(p+k)^2 - m^2}$
- Divergence depending on how virtual the propagator is compared to photon energy
- Internal lines contribute if they are sufficiently close to on-shell
- Theorists: Calculate next order
- Experimentalists: softest we can measure



Early discussions

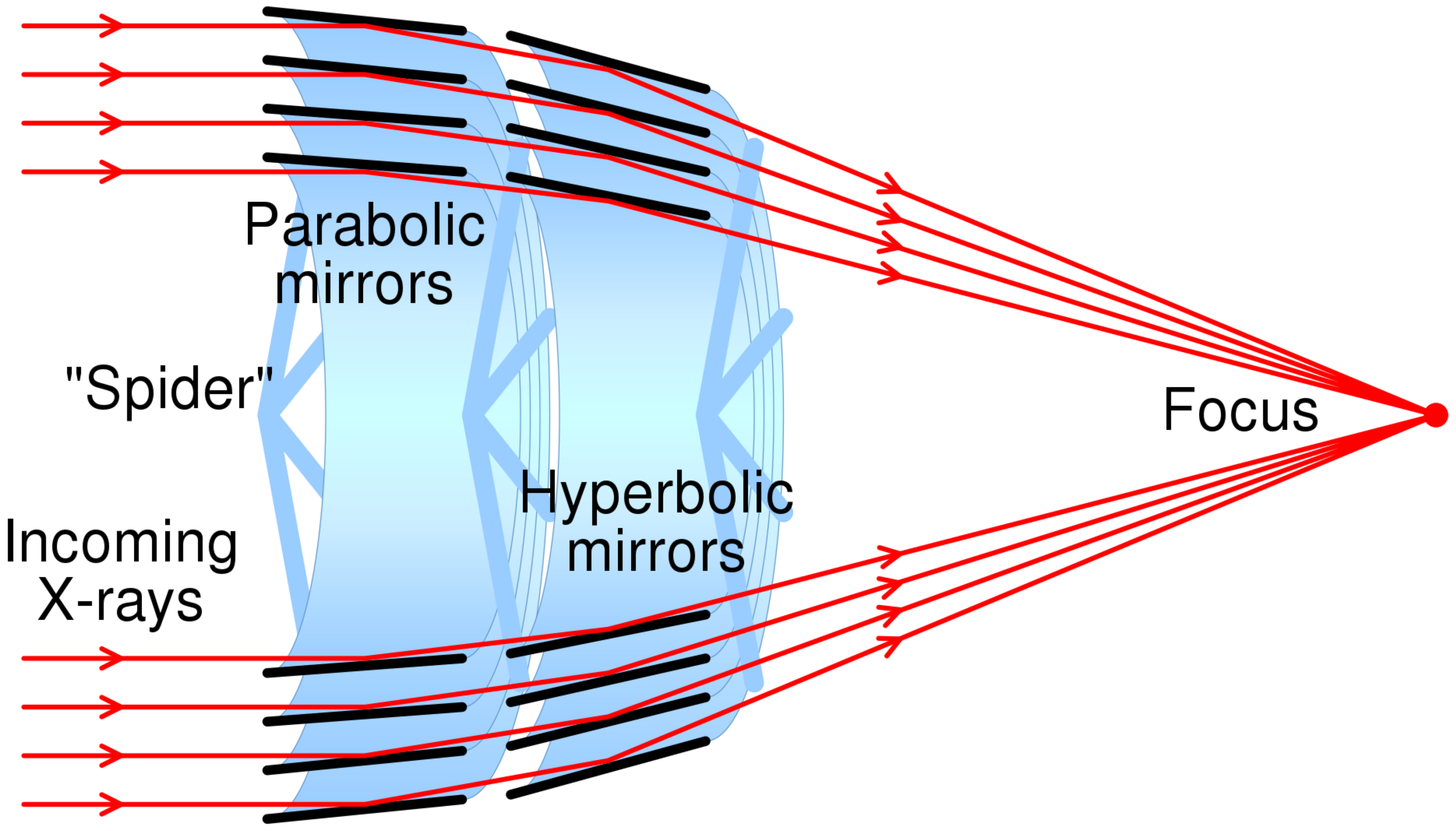


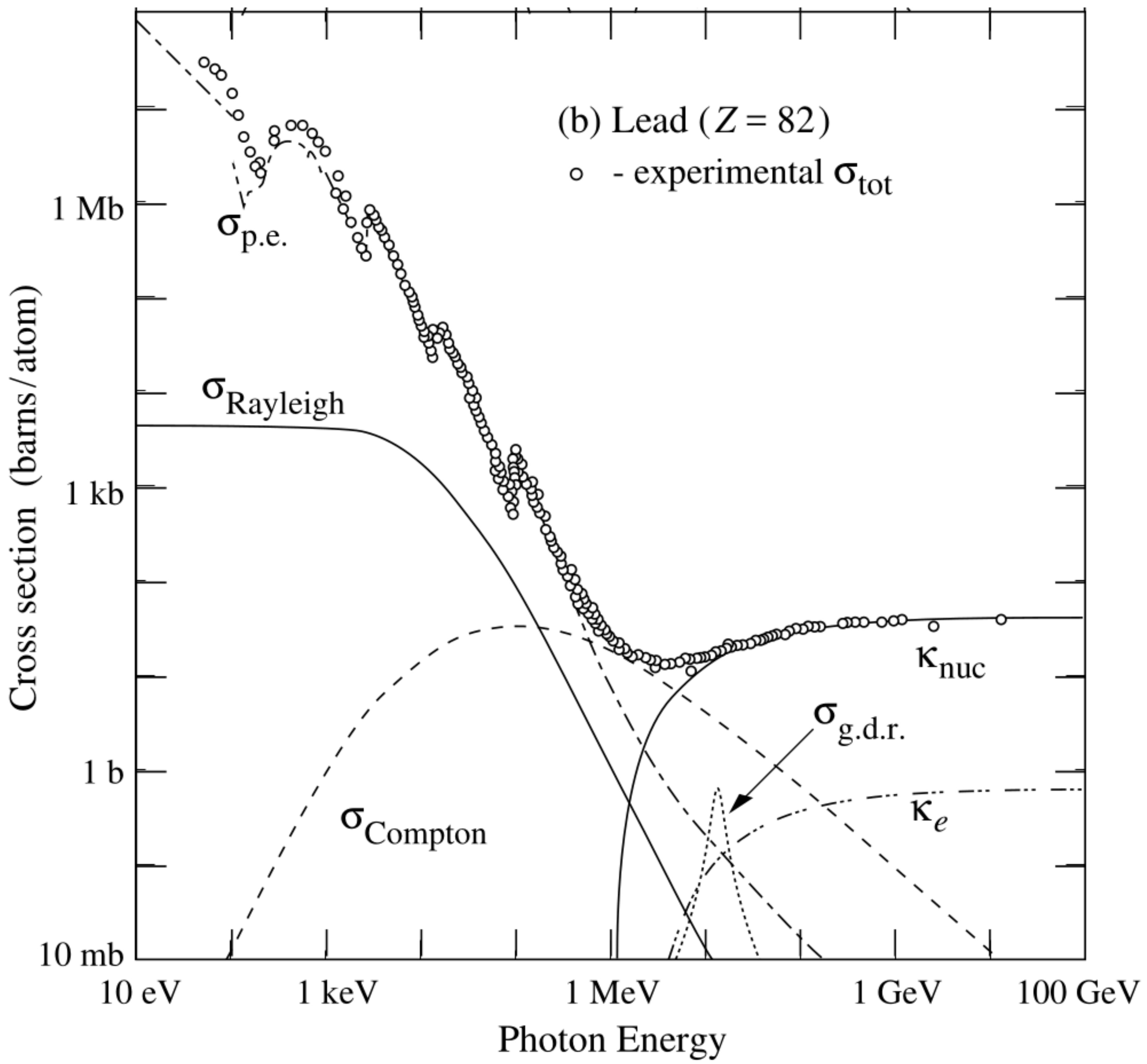




- What does the QGP collision look like to the eye? Can we put a telescope into the beam pipe?
- Virtual meetings during the pandemic

Early discussions (2)

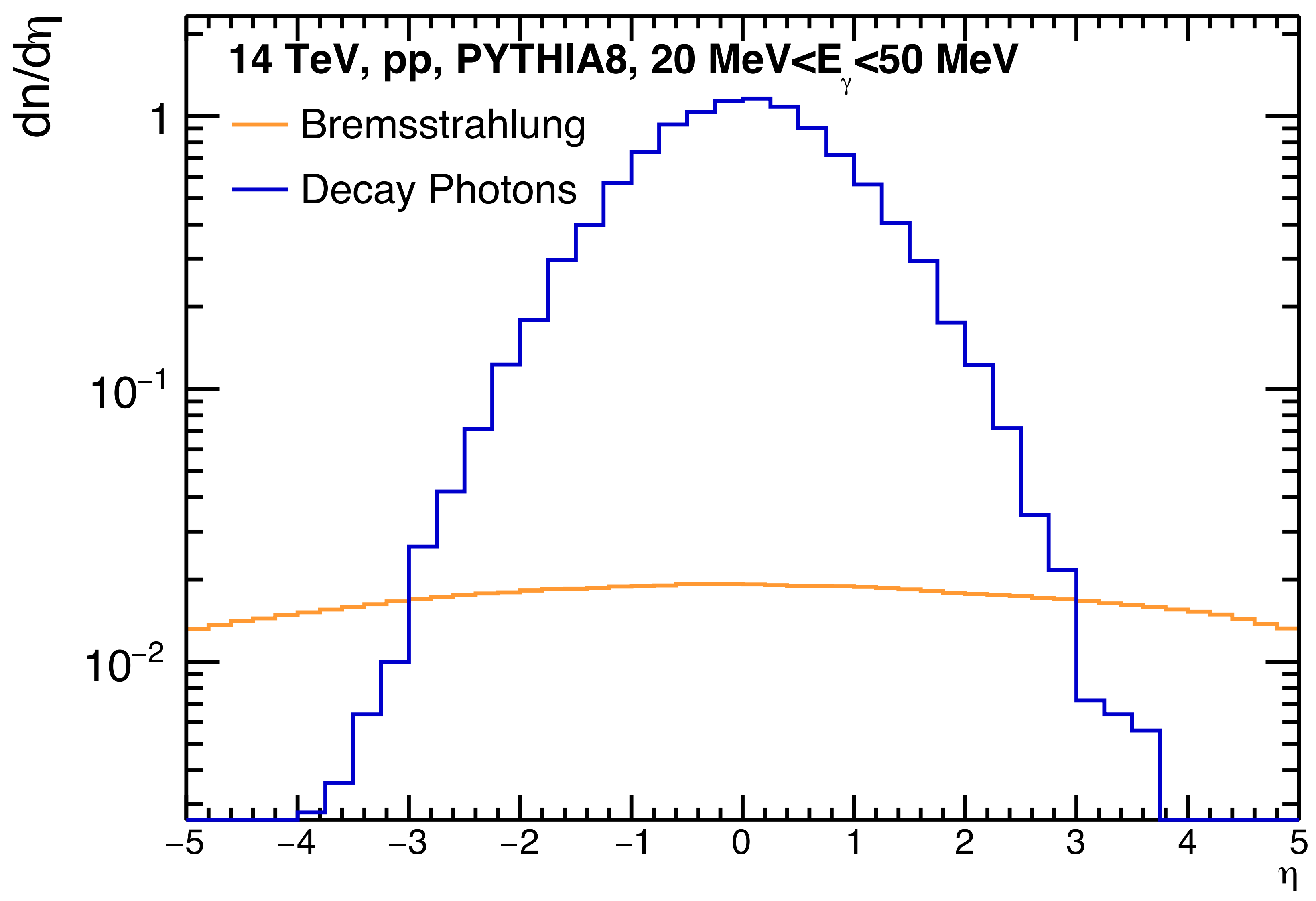


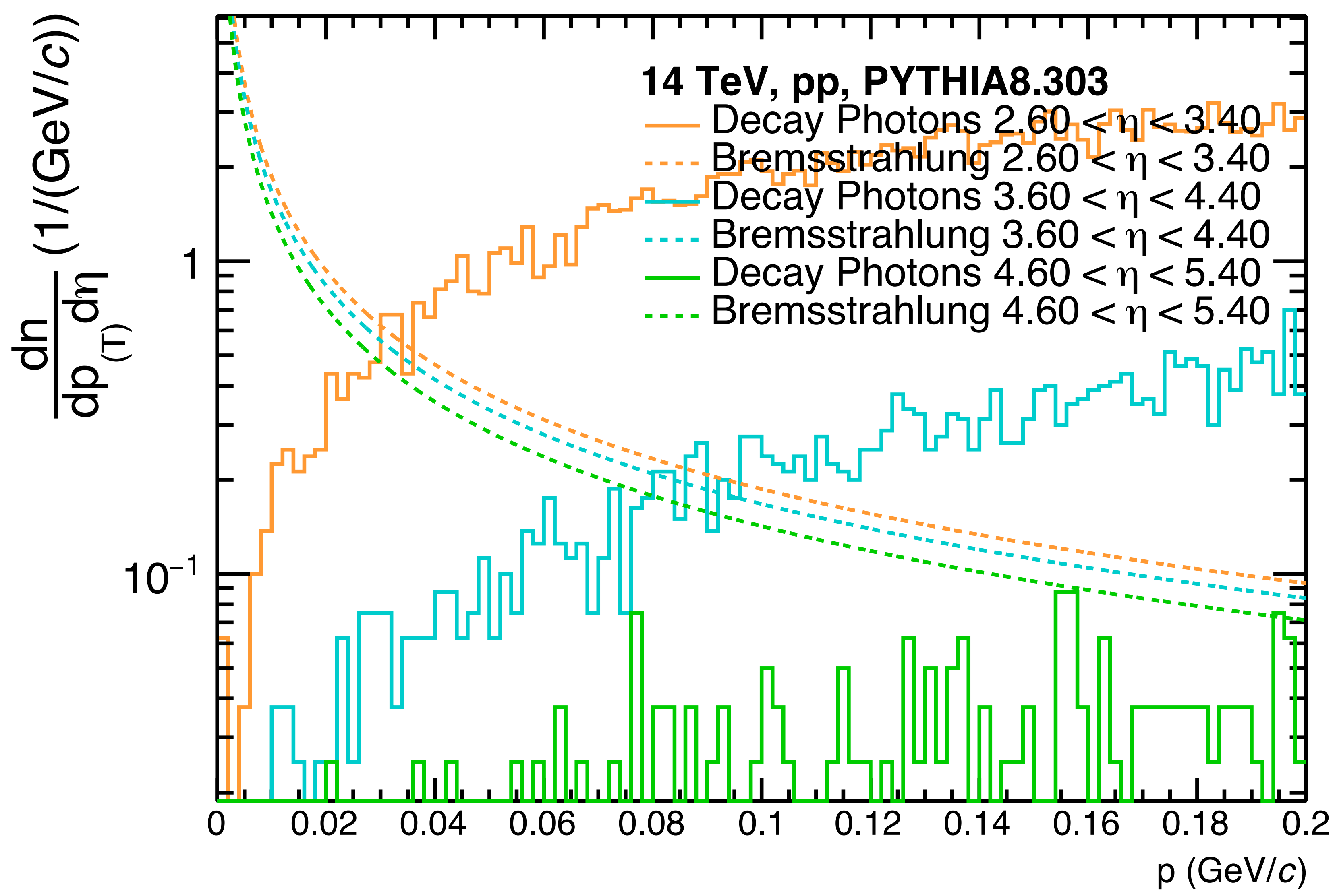


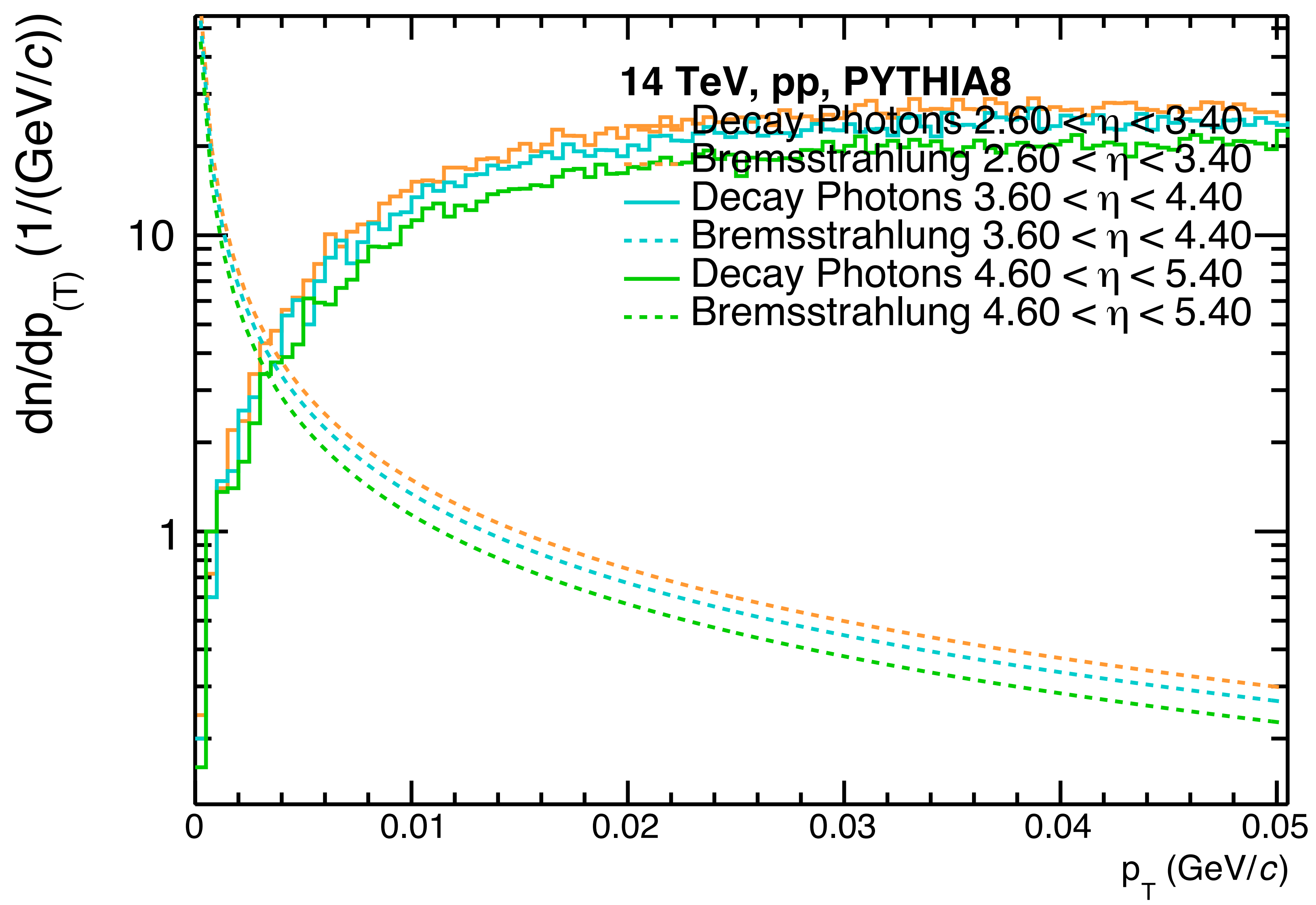
- X-ray optics?
- Can we reconstruct the photons after Compton scattering?
- Likely too many backgrounds that are hard to estimate

Photons at the MeV scale

- Substantial contribution from π^0 decays
- Boosted in forward direction - better signal/ background
- Plan for a photon detector in the forward direction

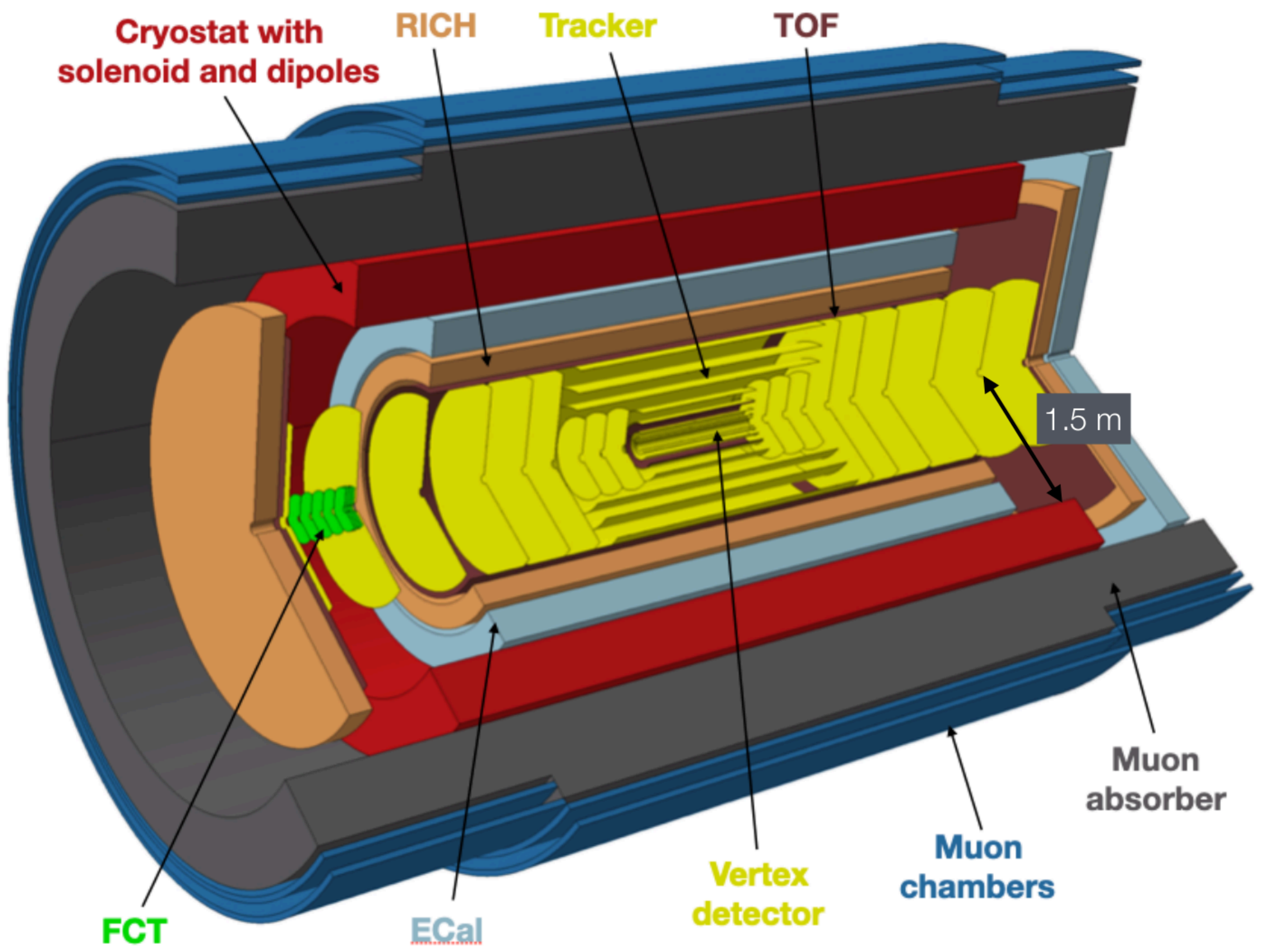


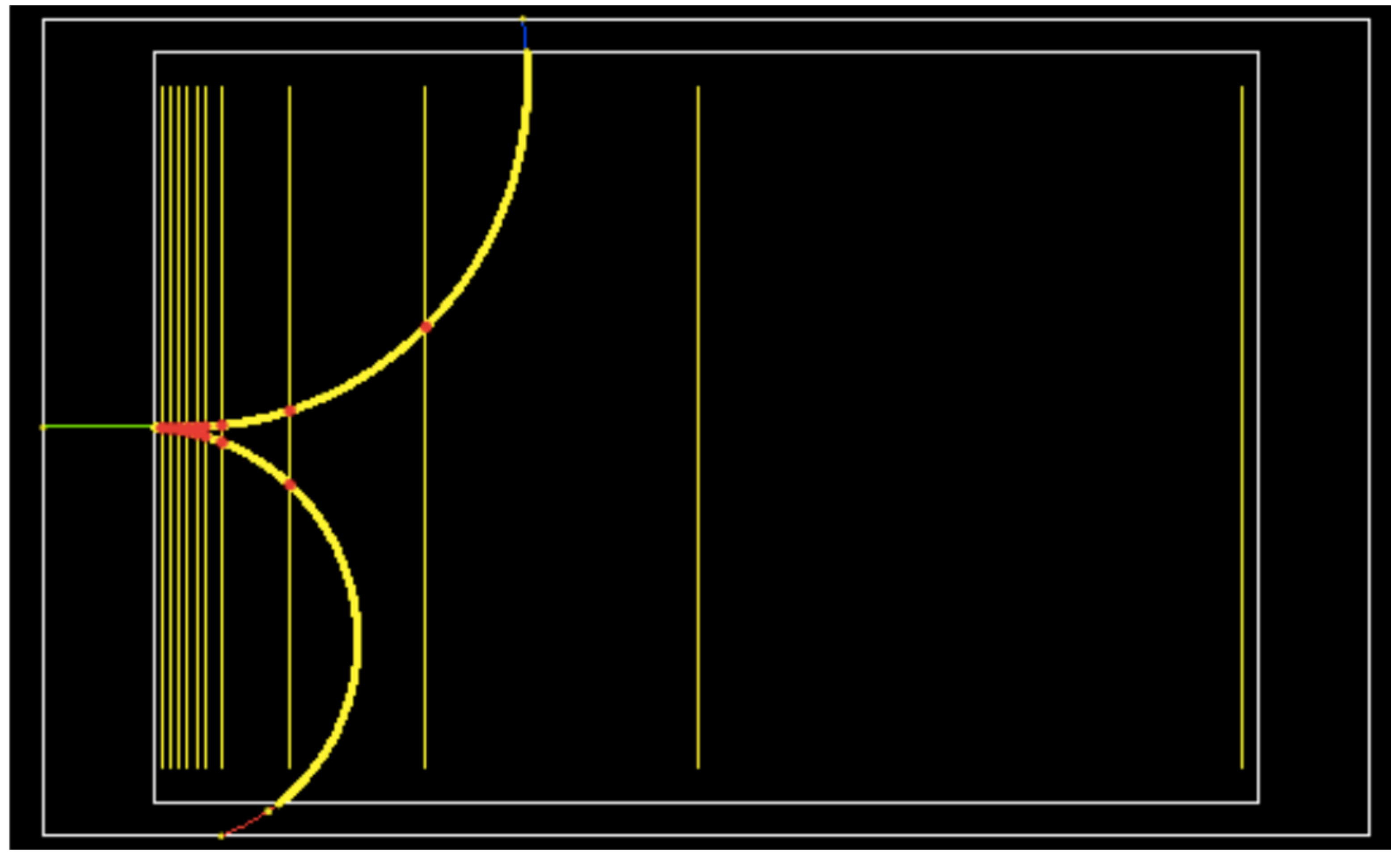


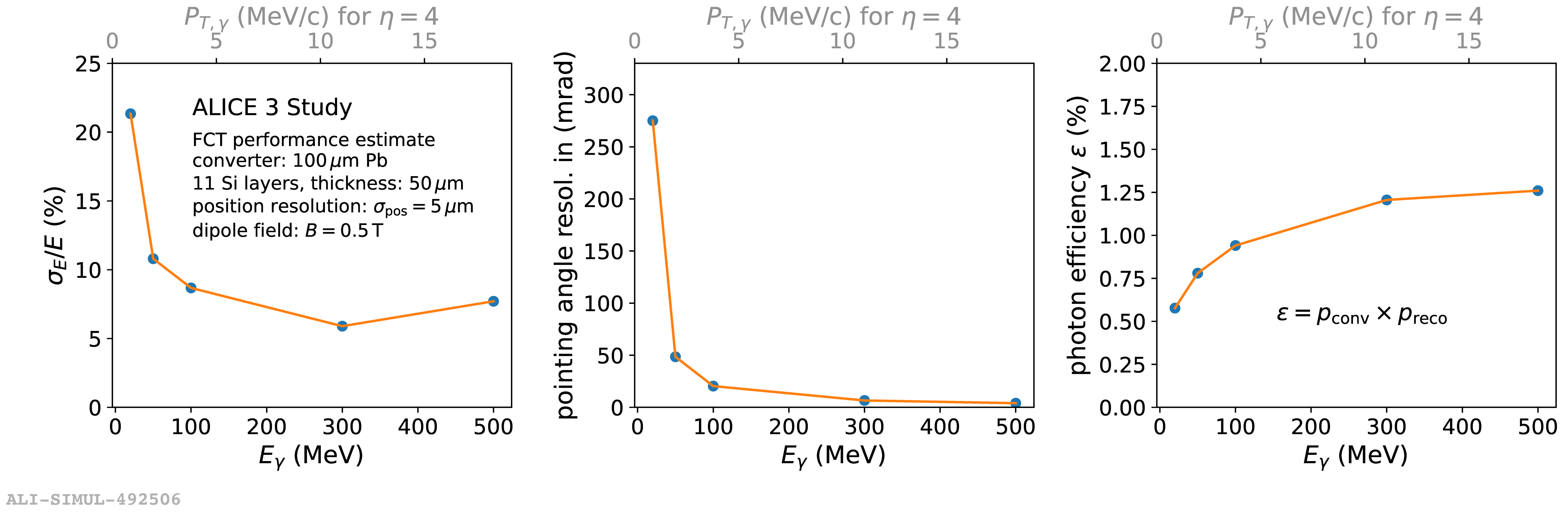


The Forward Conversion Tracker

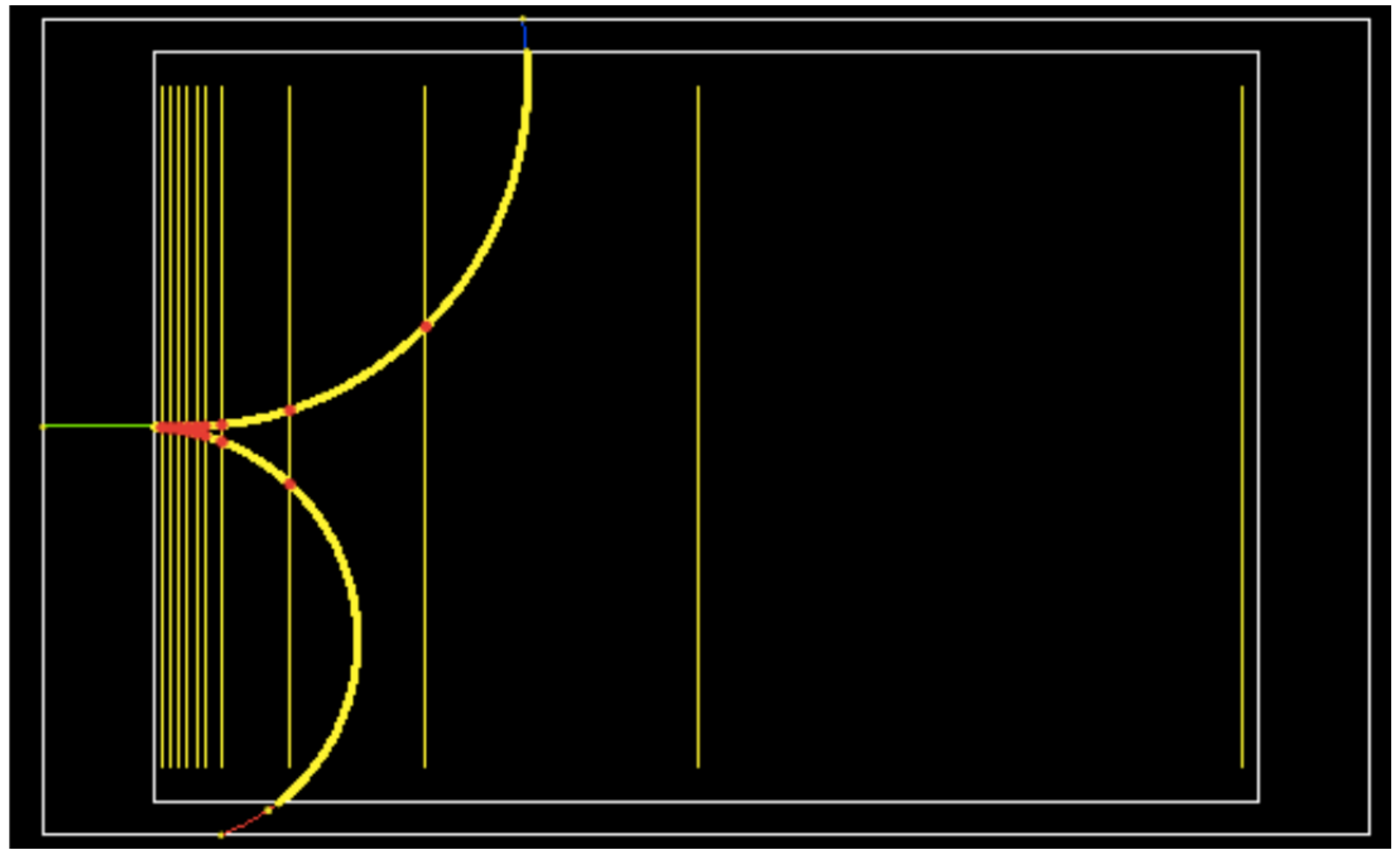
- Several layers of silicon tracker
- Measures photons via e^+e^--pairs from converter
- Energy from track bending in dipole field
- Tests with Geant4 suggest measurements from a few 10 MeV possible



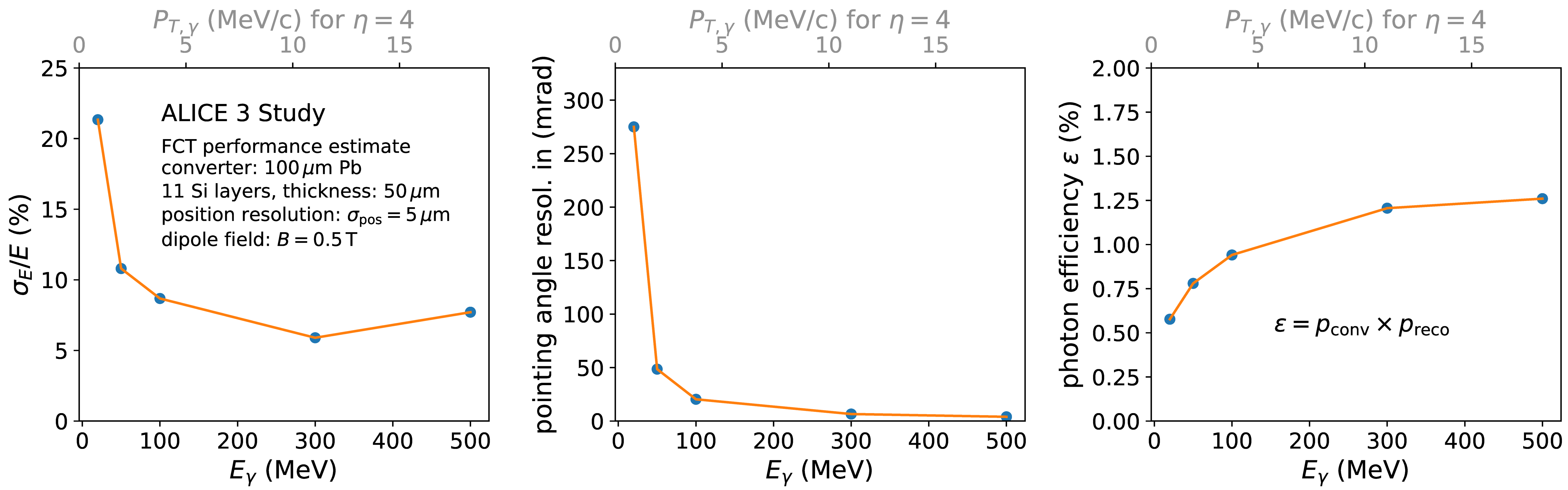




Magnetic field discussions



Dipole



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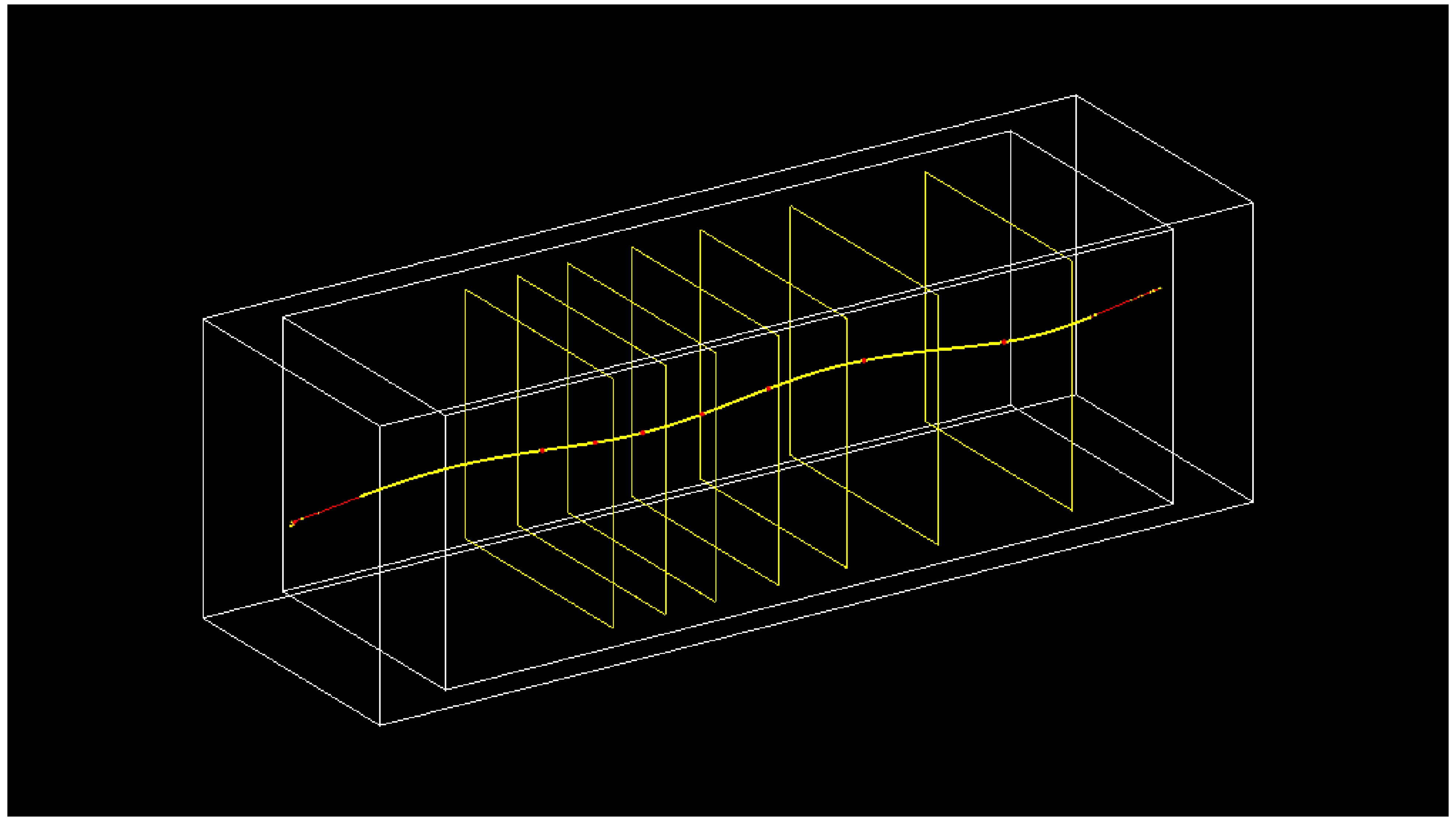
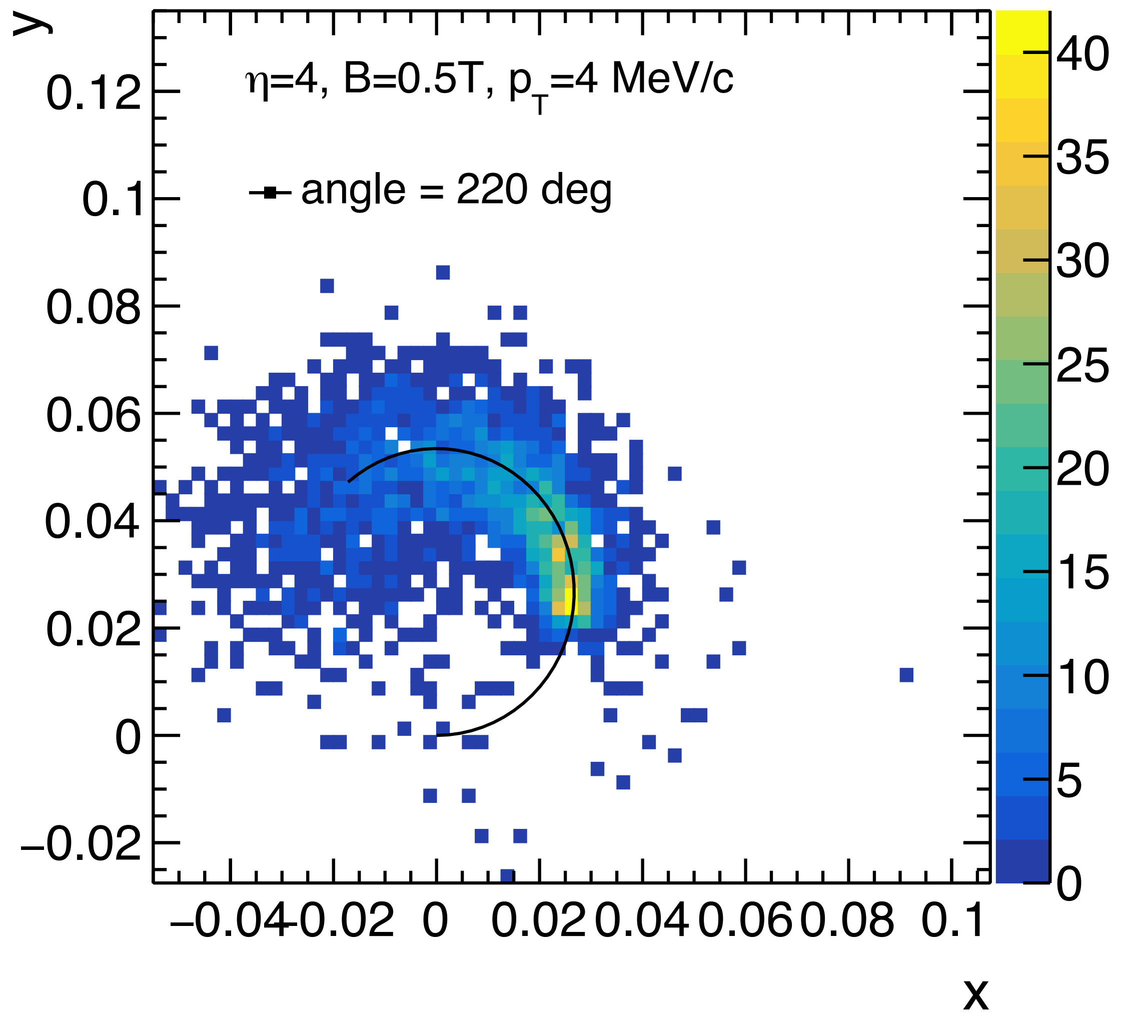
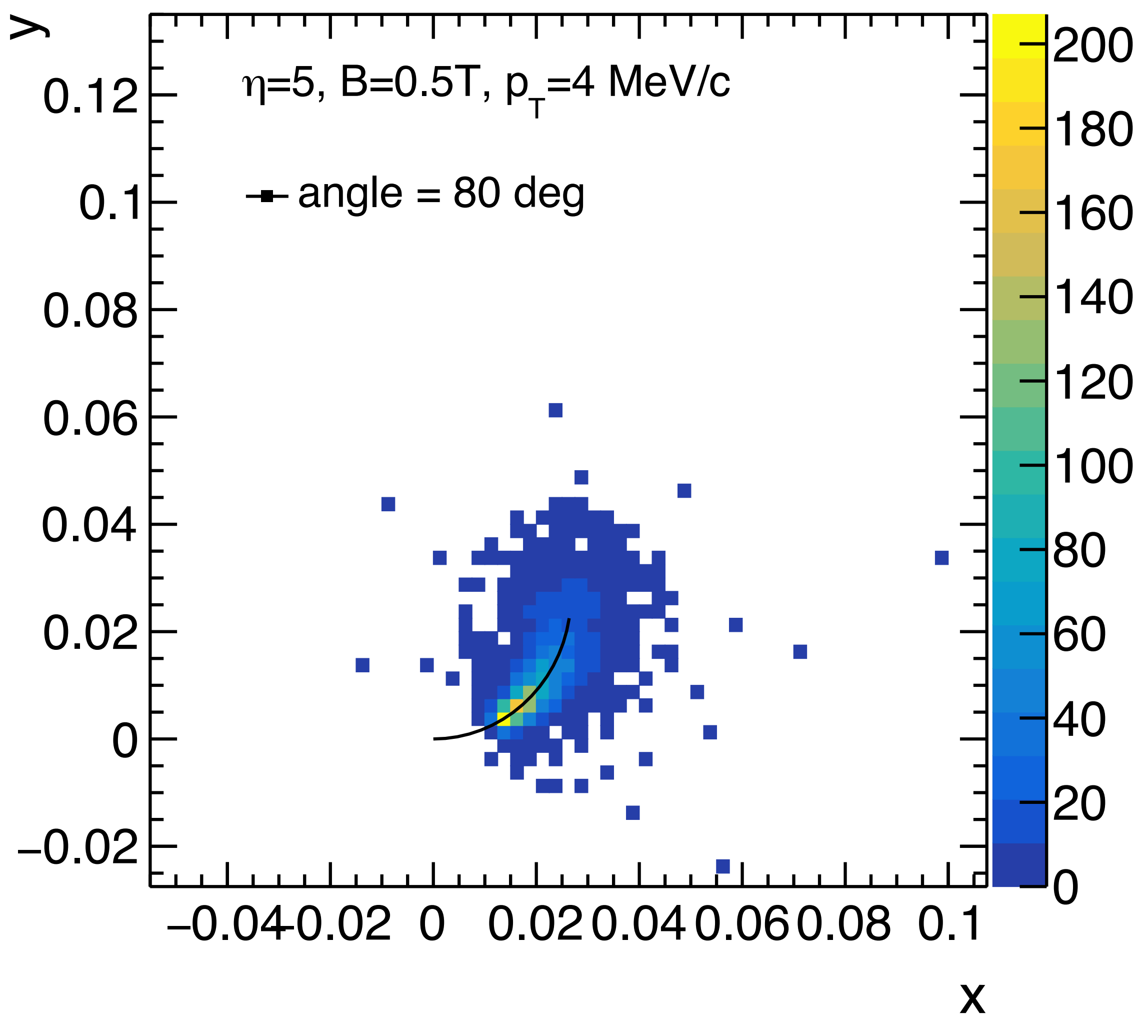
Solenoid







Are these photons soft?

- Low: $E_\gamma / E \ll 1$ - but for $2 \to 2$ scattering

- For theorists classically limit more important than region of applicability

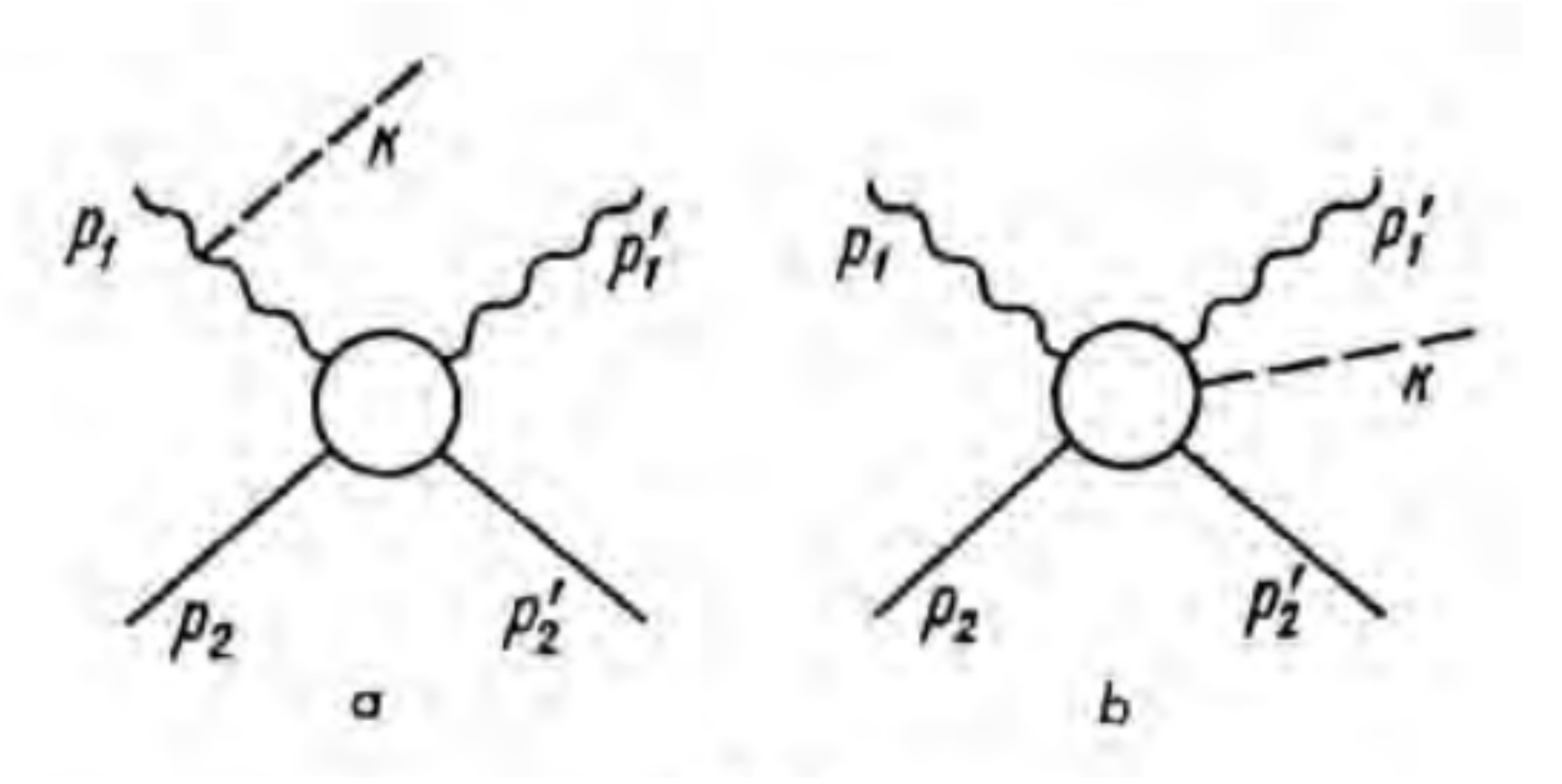
- D. Bonocore: $E_\gamma \ll m^2/Q$ receives no corrections at loop level - would mean $E_\gamma \ll 0.1\,\mathrm{MeV}$ for $e^+e^- \to \mu^+\mu^-$ - but was measured at 200.

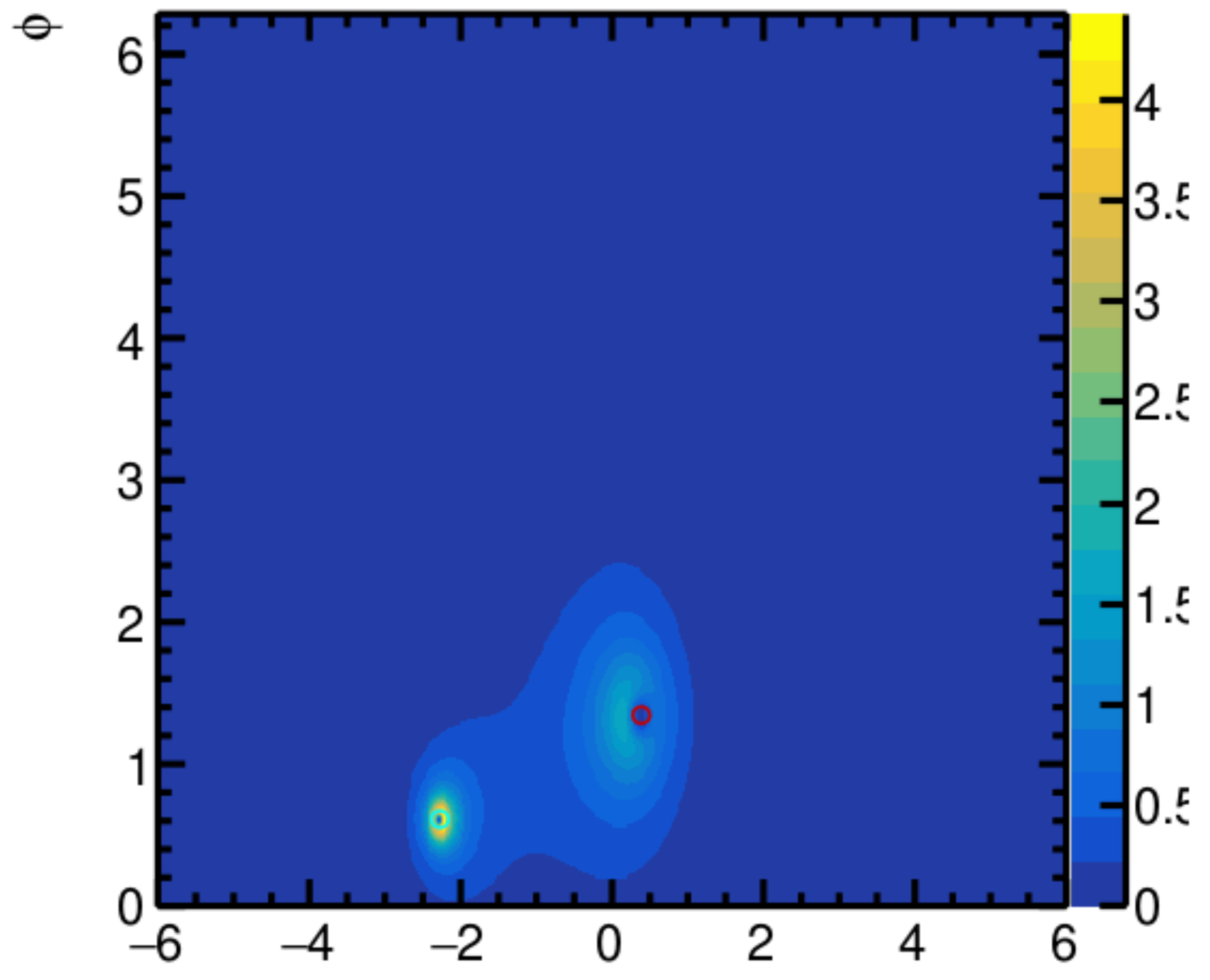
  Sov.J.Nucl.Phys. 5 (1967) 280

- Gribov (considering $2 \to 2$ processes) gives $k_T \ll m$ (RRTF paper: necessary but not sufficient condition)

  Phys.Rept. 1097 (2024) 1-40

- pp collisions give particle production in the forward direction as boosted version of particle production at mid-rapidity - does this mean that soft photons at mid rapidity are harder in the forward case?





$J/\psi \to \mu^+\mu^-$

Full calculation compared to Low

- Lebiedowicz, Nachtmann, and Szczurek found that here E_γ is the relevant expansion parameter
- Angles are relative to incoming pion axis

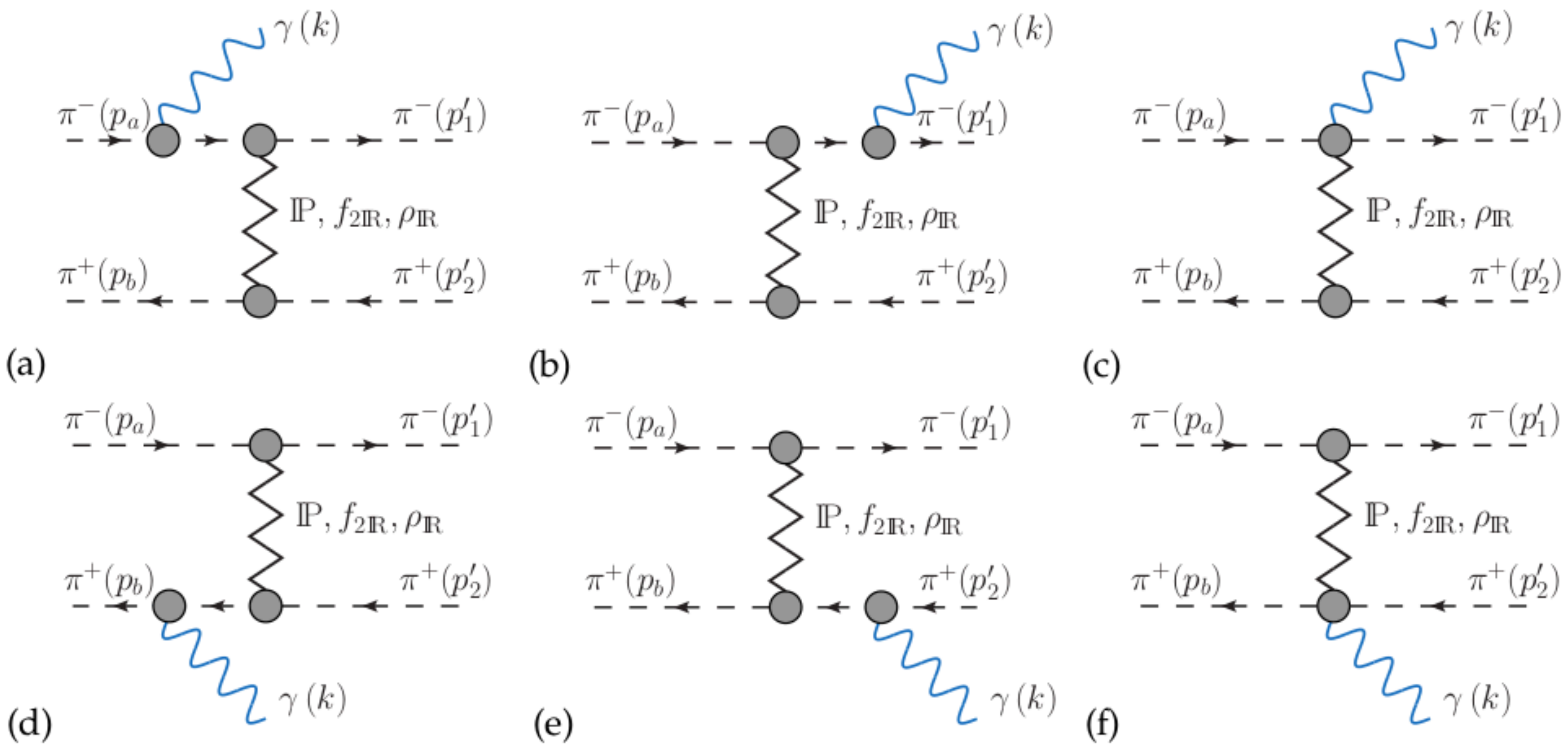
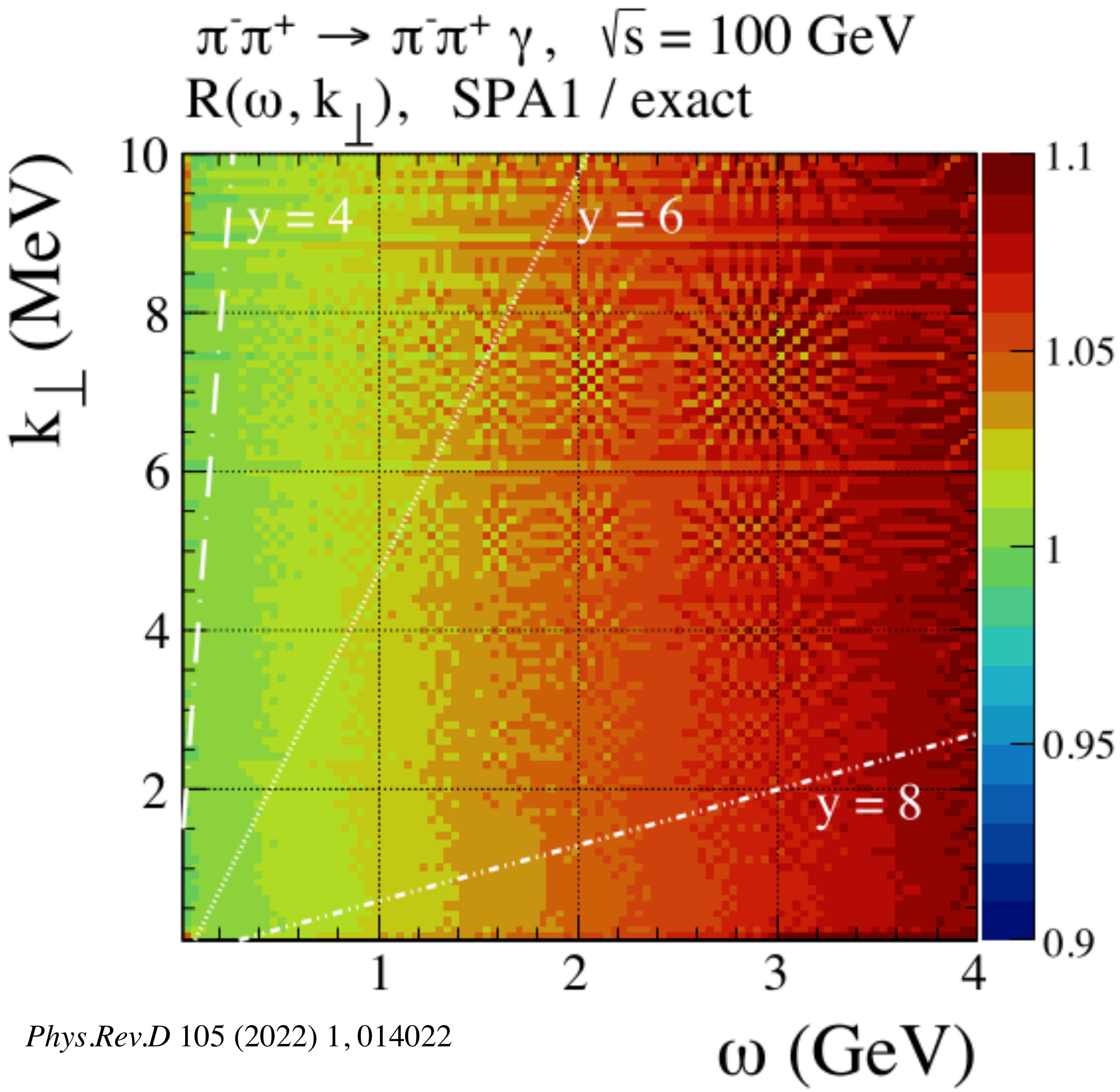


FIG. 6. Diagrams for the reaction $\pi^-\pi^+ \to \pi^-\pi^+\gamma$ with tensor-pomeron exchange.

- How does this relate to non-diffractive processes?



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Soft photon production and hadronisation

- The purely EM process does not show a photon excess
- Photons are produced by accelerated charges
- What if there are additional processes that accelerate charges?
- What if there are processes that take some time and cause decoherence between the contributions?
- Might be connected to hadronisation

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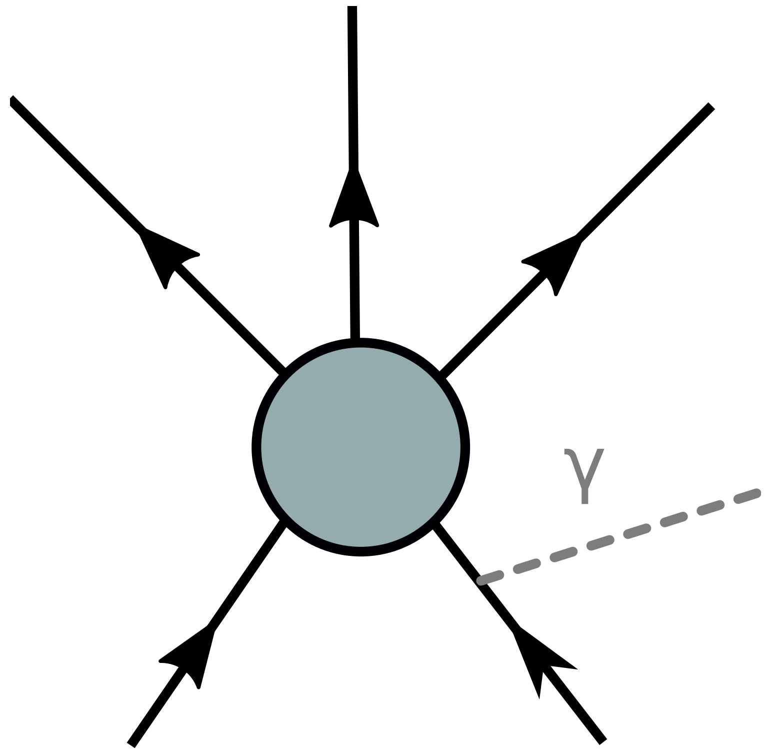
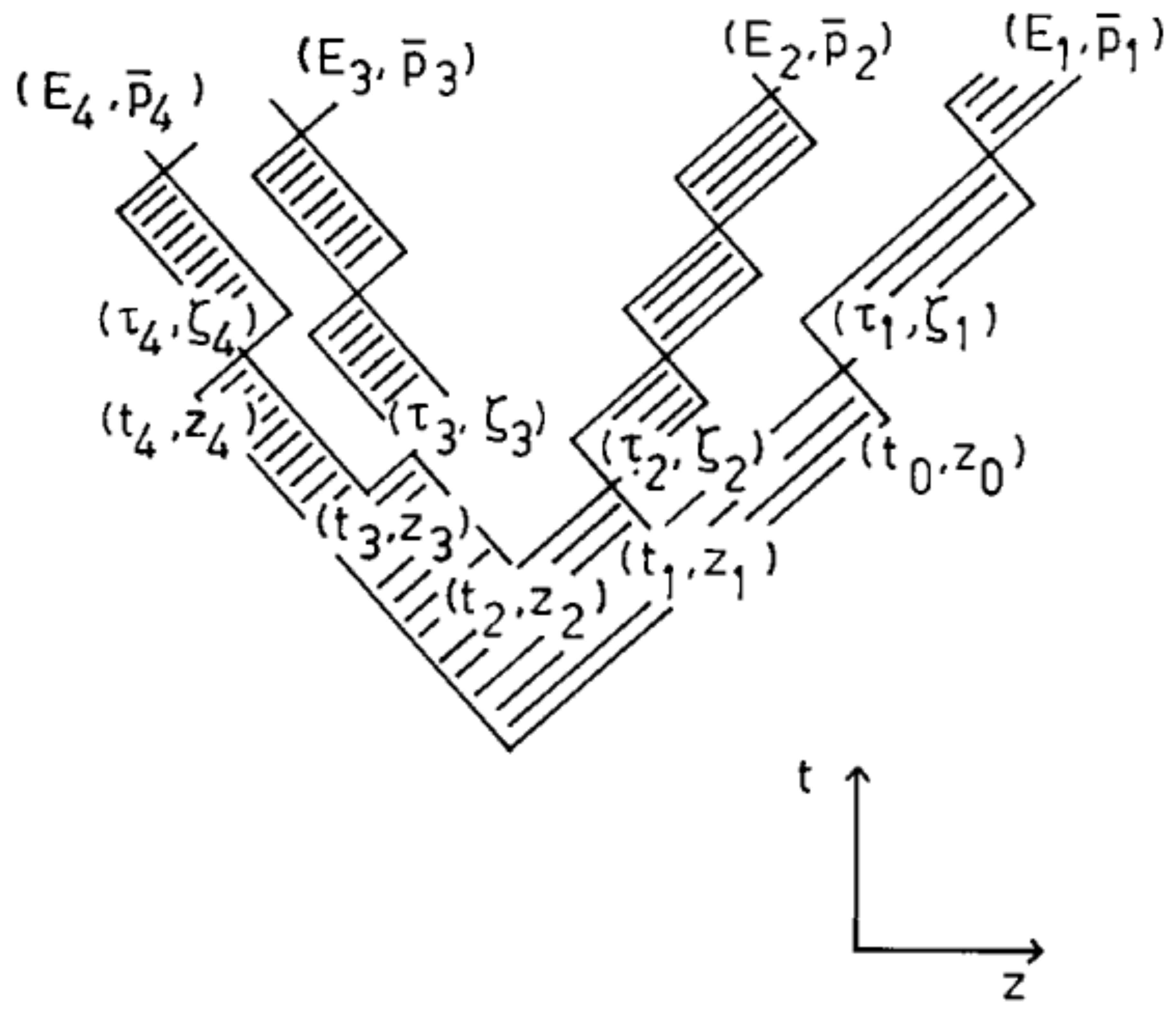
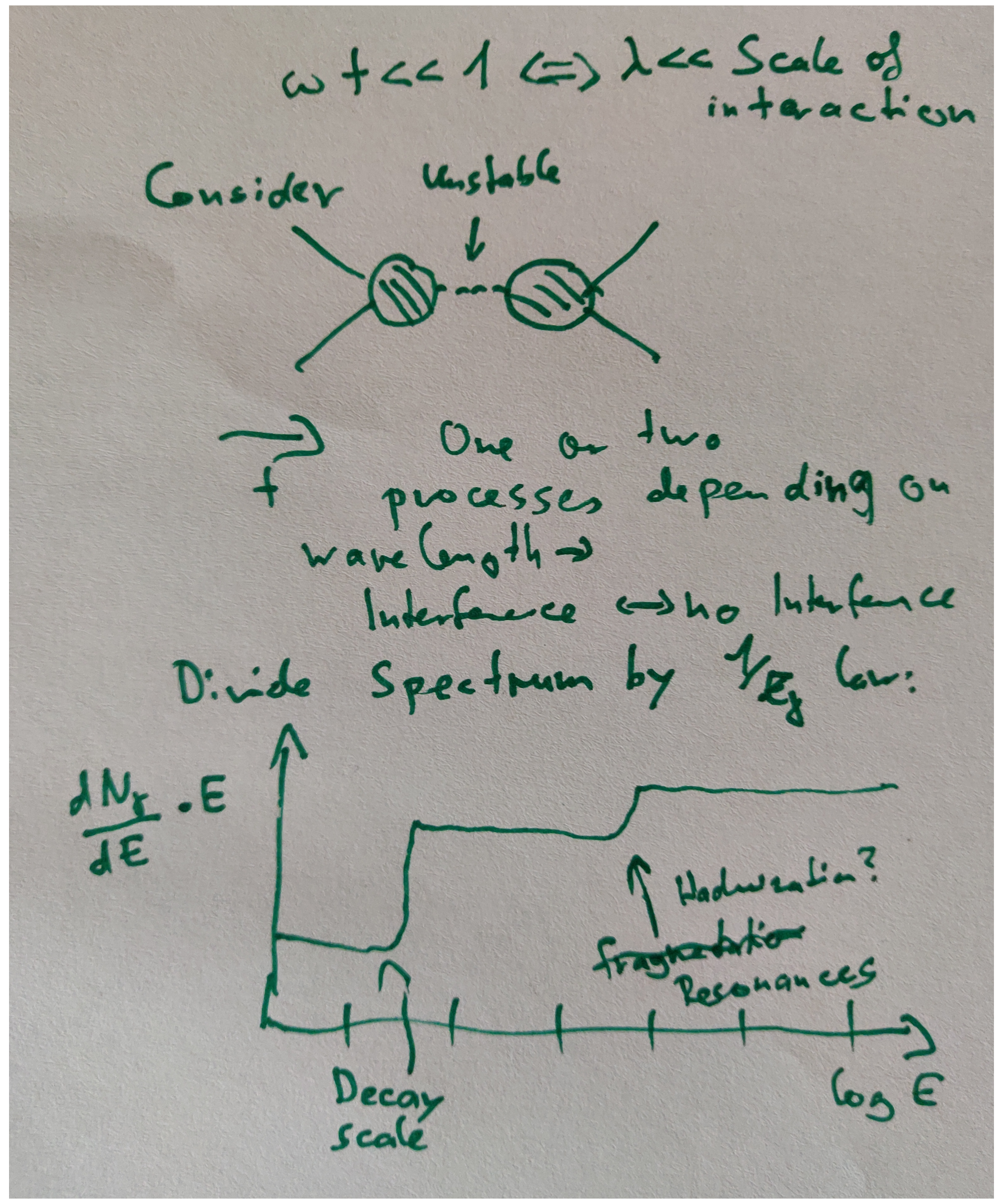


Hadronisation and soft photons



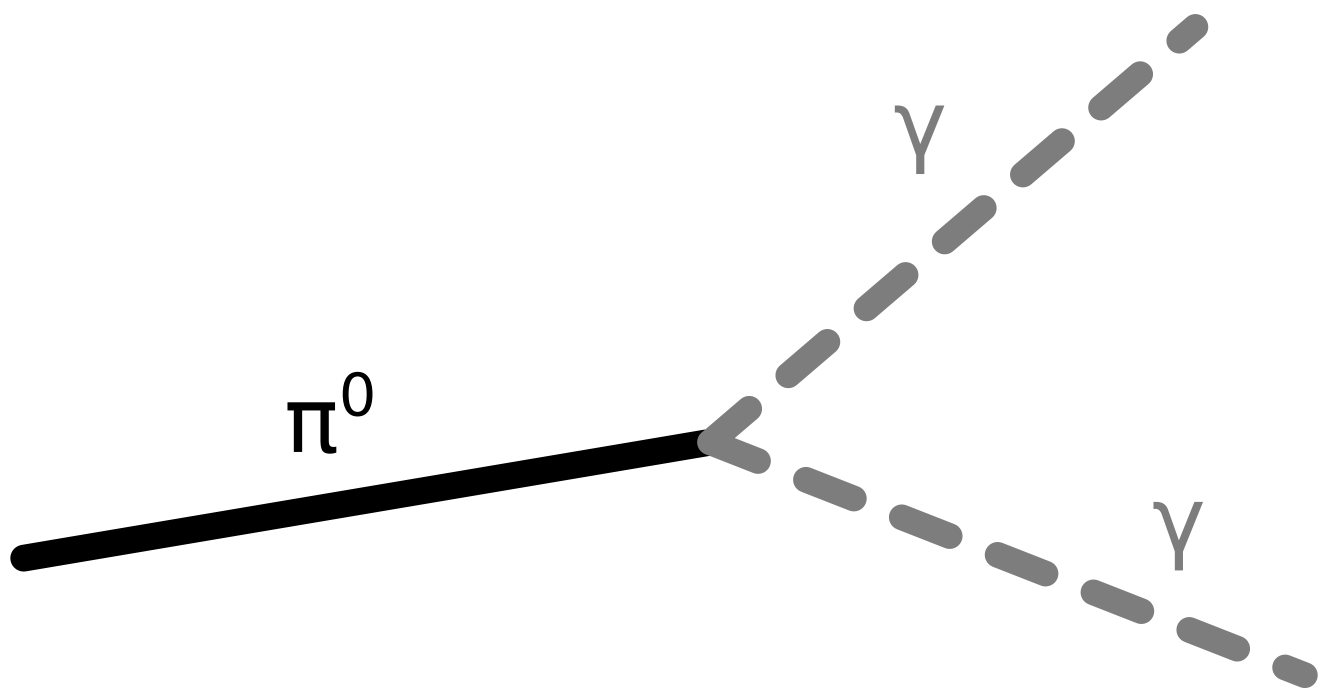


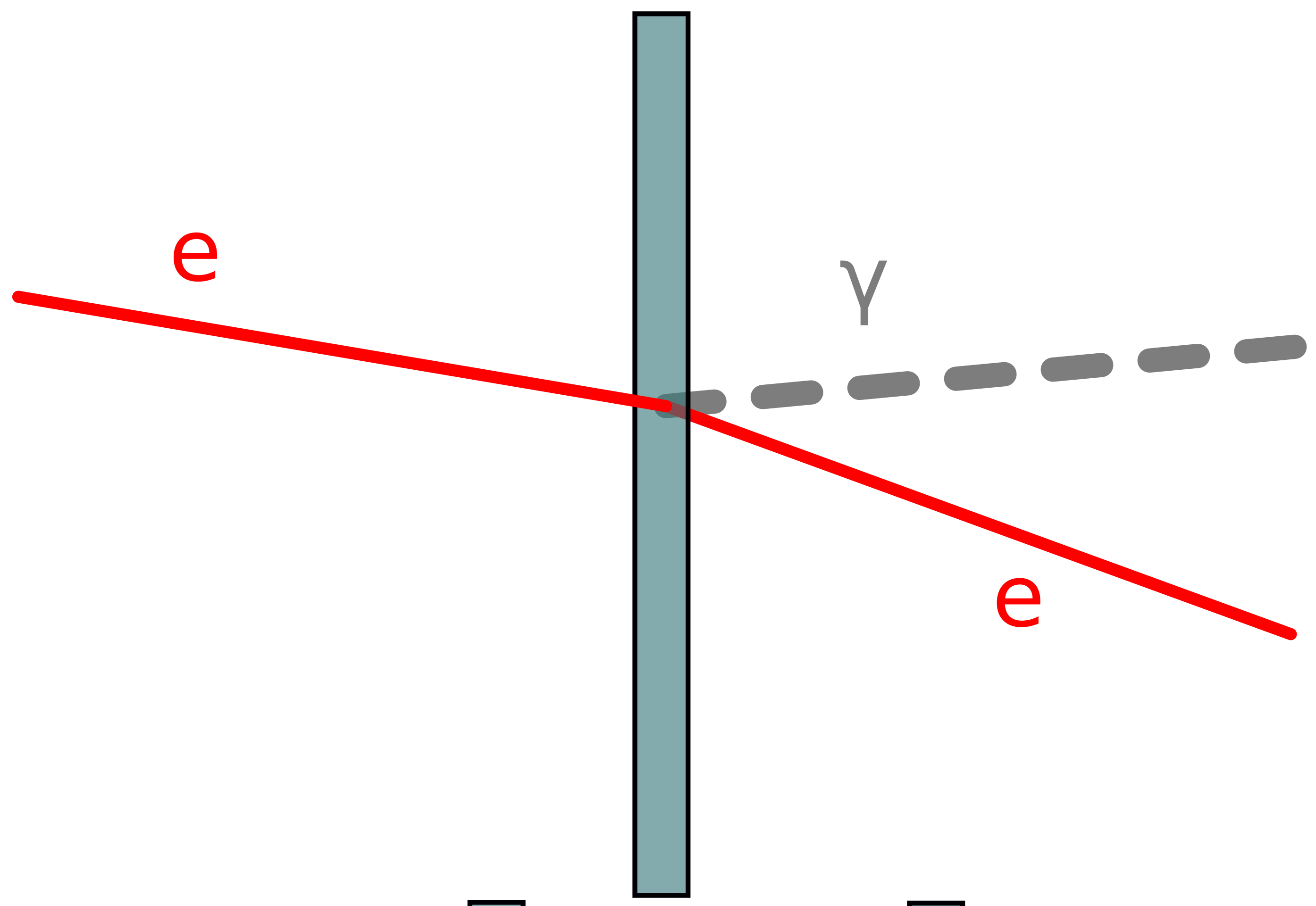
- Emission via rotating charged strings in the Lund model

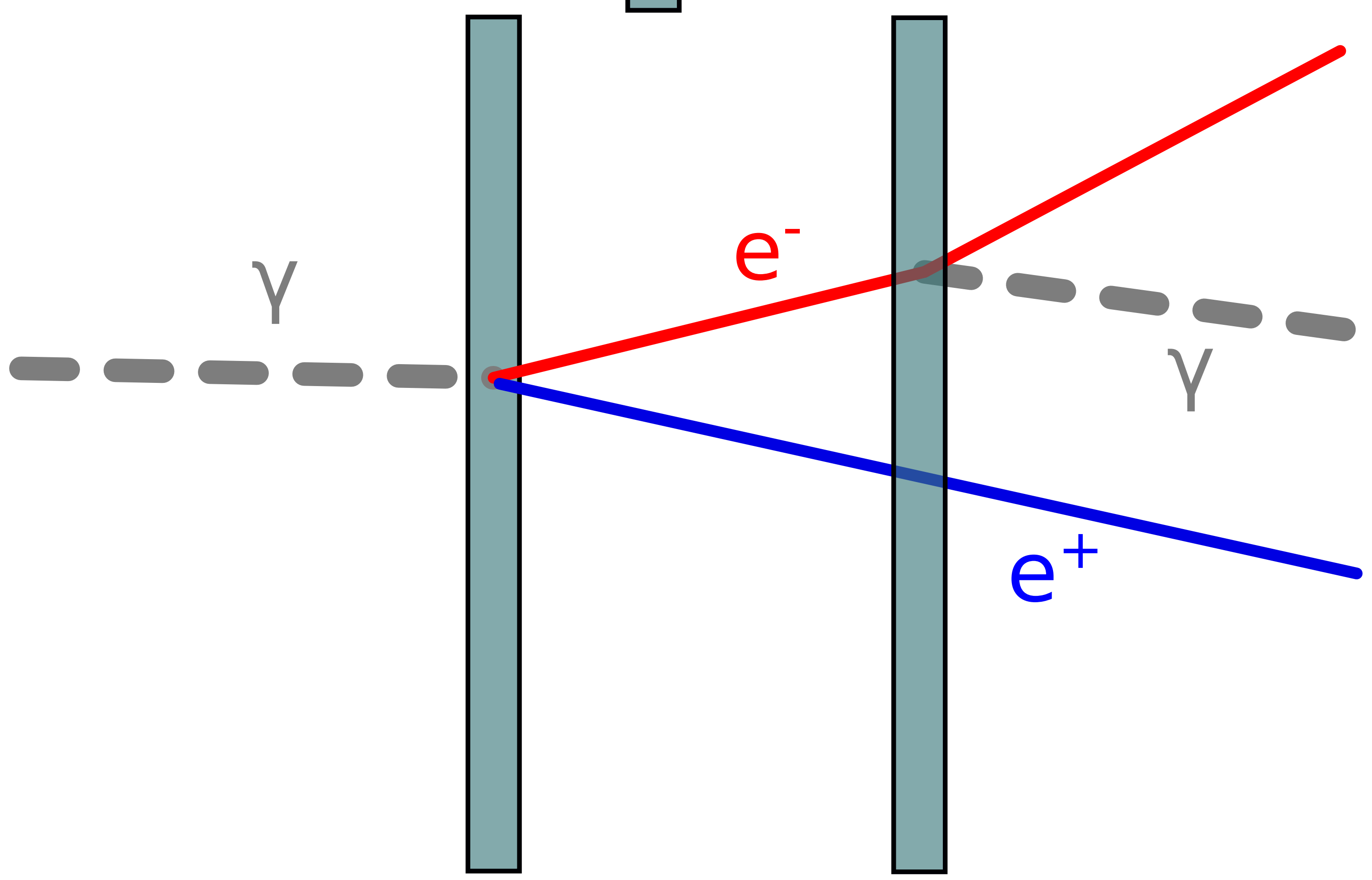
- If a hadron is produced via a resonance, is this one process or two?
- Does the answer depend on the soft photon energy

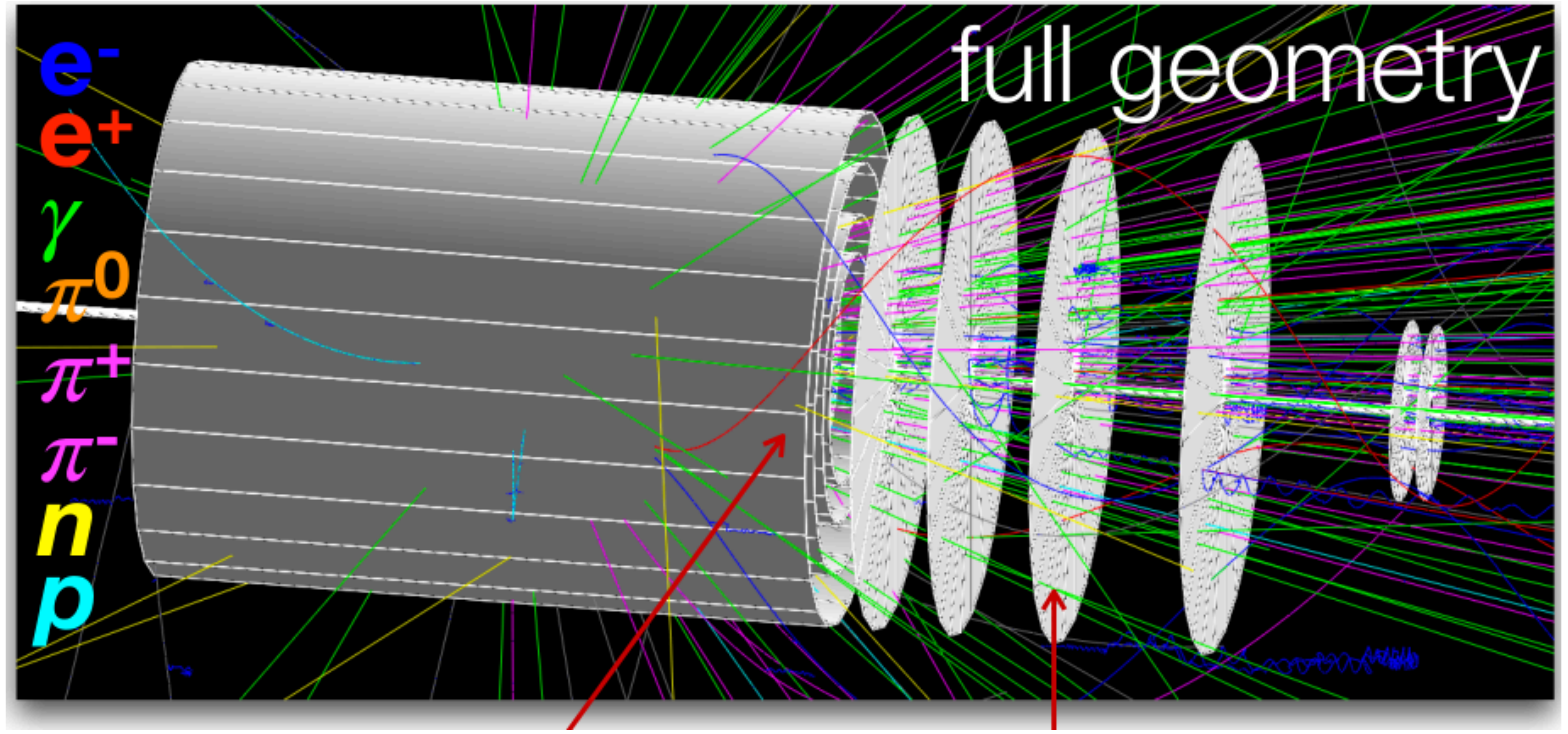
Background photons

- Decay photons independent of material
- Bremsstrahlung: Proportional to material budget
- Photon producing electrons-positron pair, these producing bremsstrahlung: Proportional to square of material budget



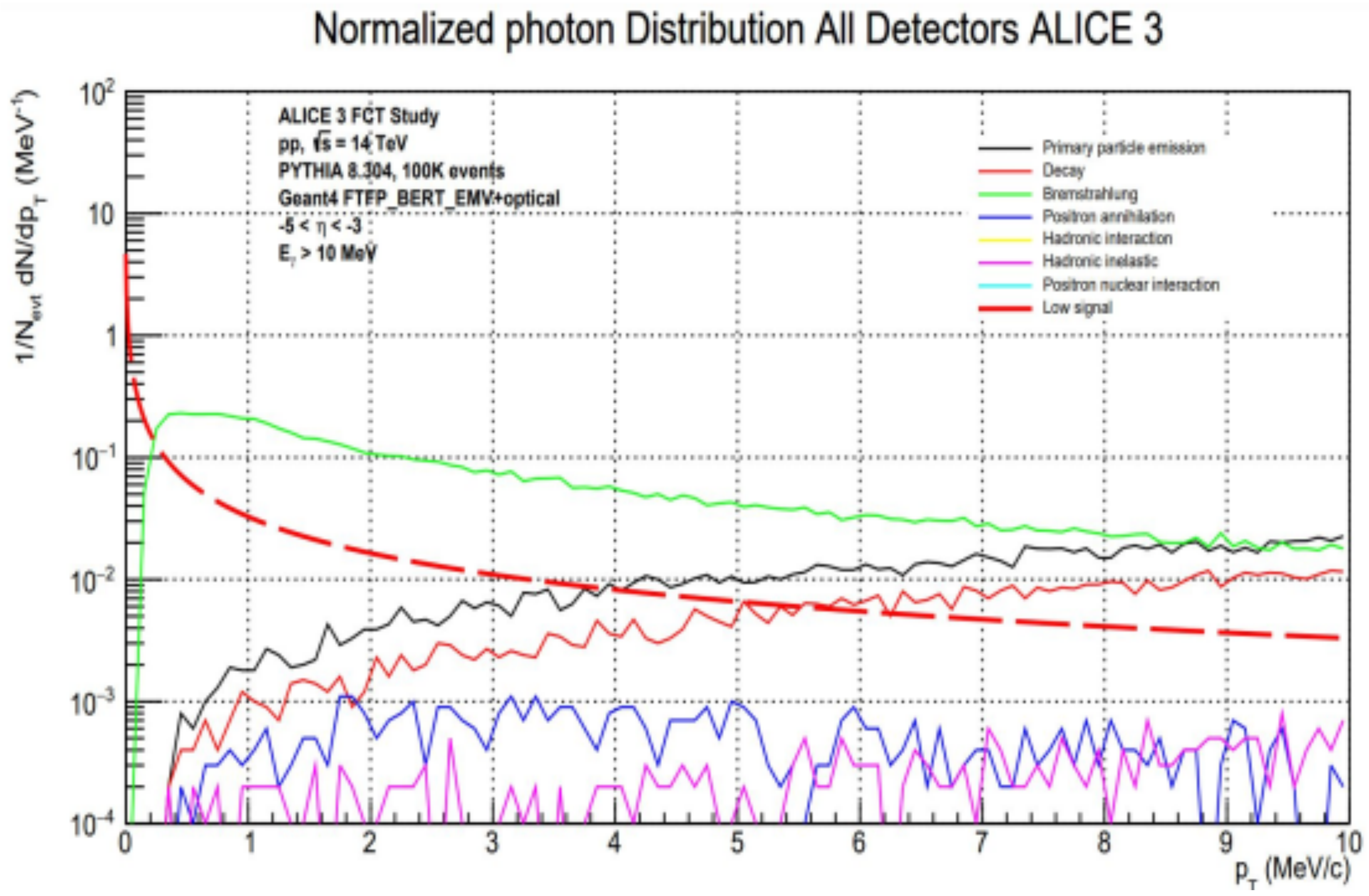


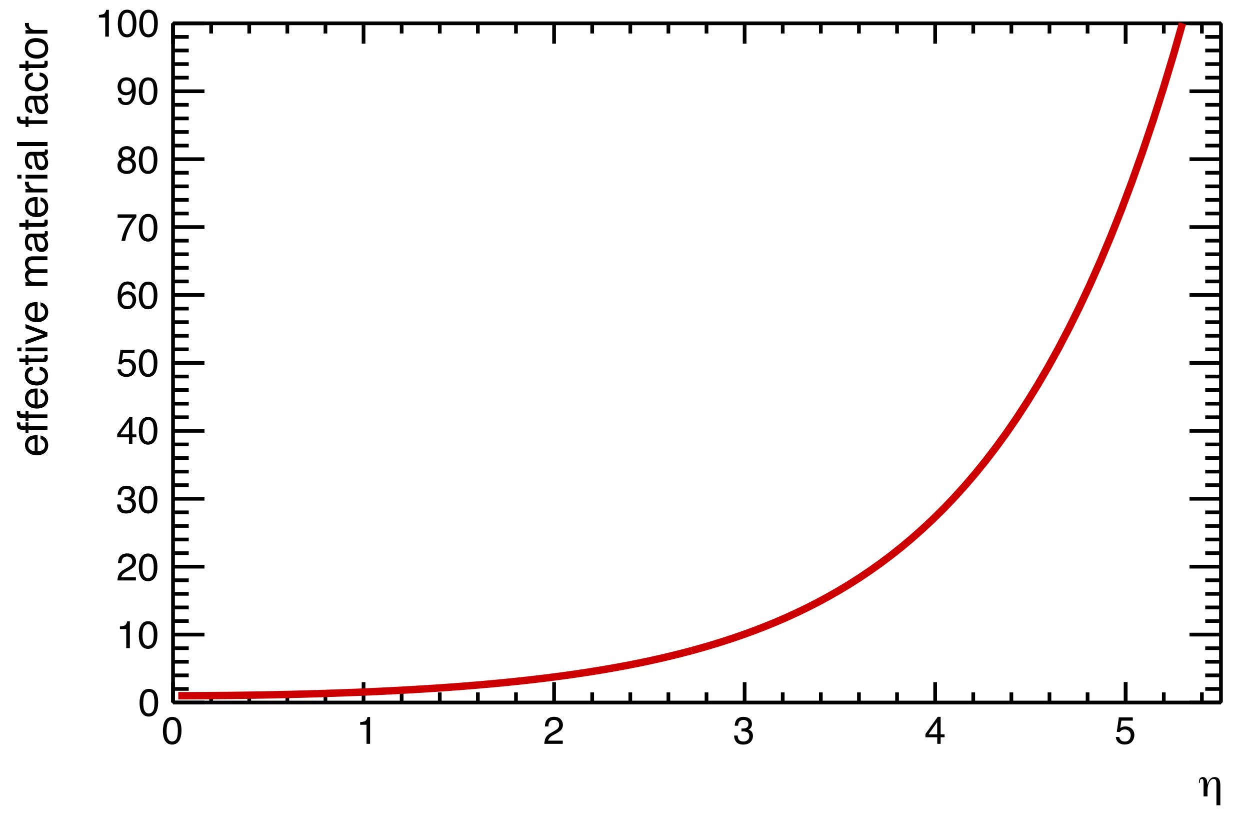


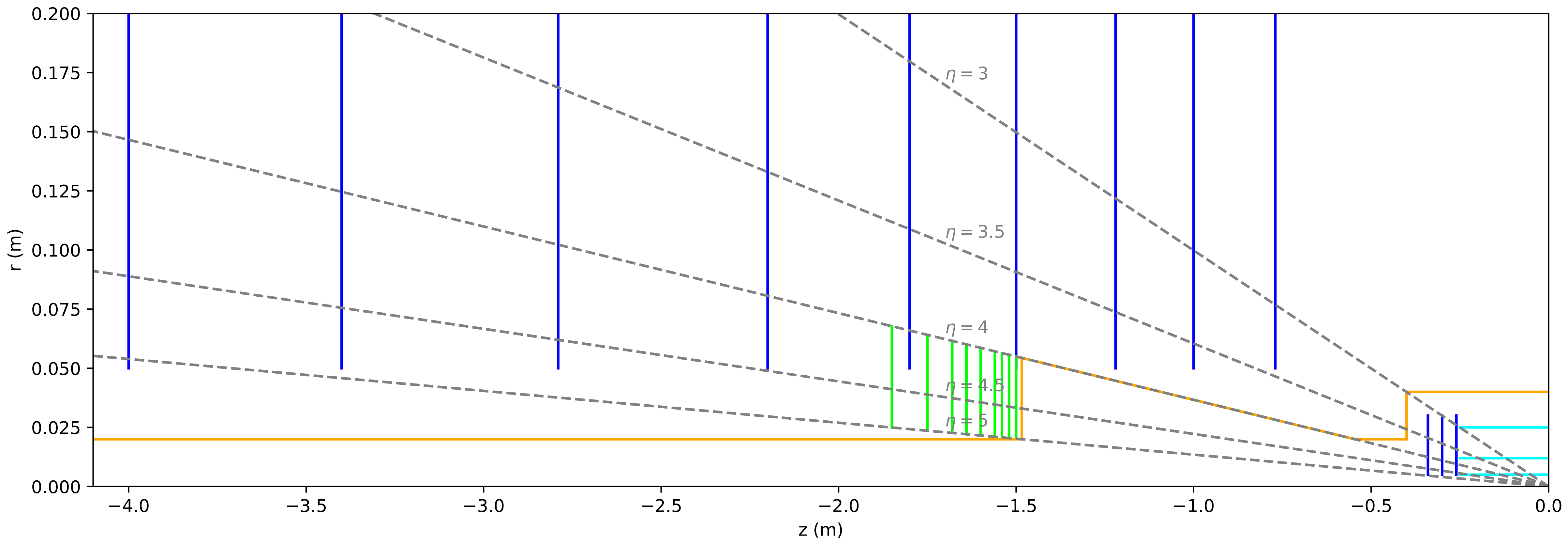


The challenges ahead for soft photon measurements

- Material budget between interaction diamond and forward detector not so small
- Bremsstrahlung has $1/E_\gamma$ distribution - just like the signal
- $\cosh \eta$ dependence of material budget for beam pipe
- Ideas:
  - Consider adapting geometry
  - Adding sufficient PID to veto signals from electrons

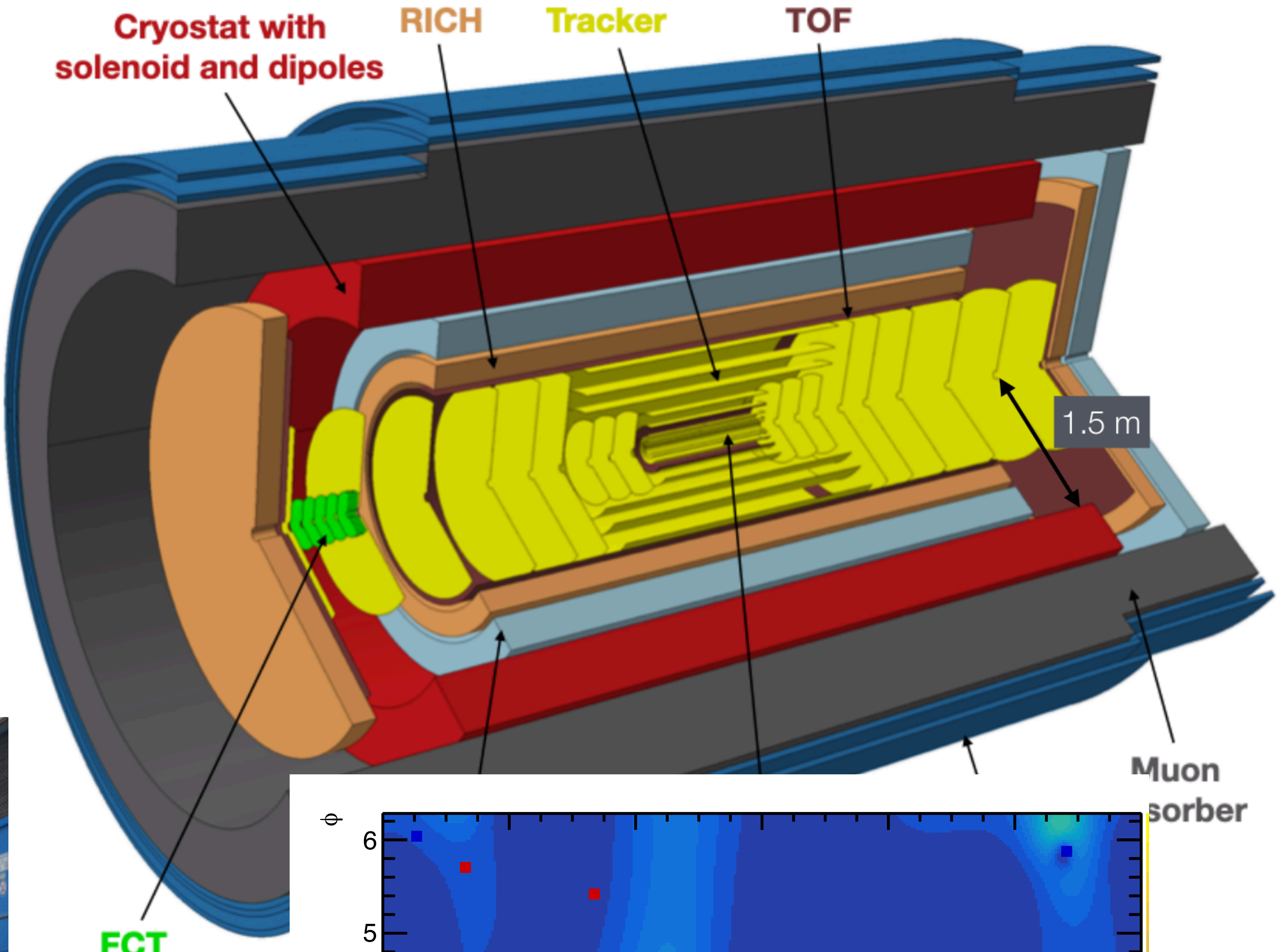


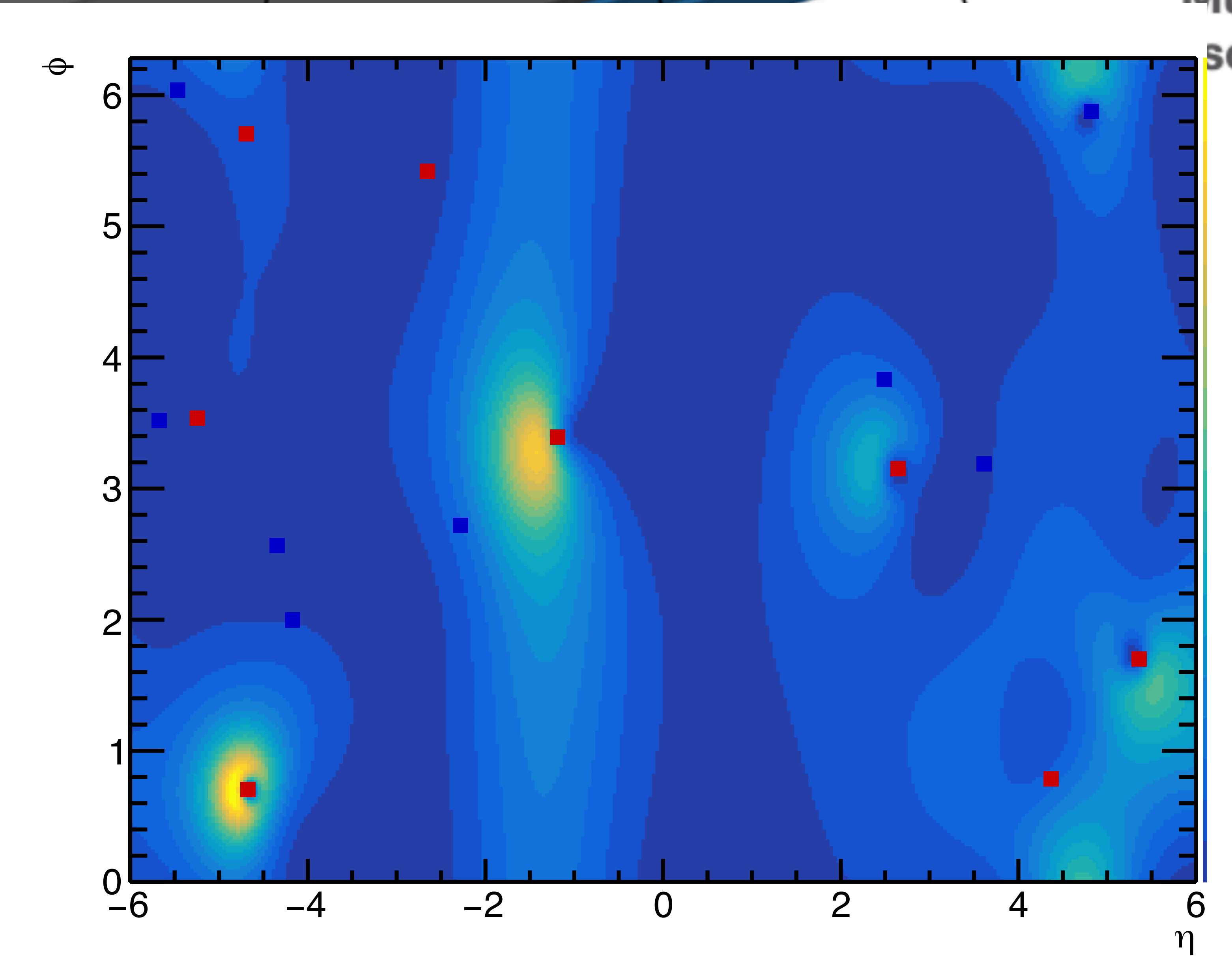




Summary

- More photons at low energies were measured than expected from soft divergences
- The production can be estimated even from generator events
- ALICE 3 will measure soft photons in the forward direction





Appendix

Direct calculation

- For specific processes, processes with and without photon emission may be calculated
- For hadronic processes usually model needed
- Here: Tensor pomeron exchange to model $\pi\pi$ scattering
- Unexpected: While $1/E_\gamma$ term appears as expected E_γ^0 term different from Low's result
- Similar calculations may be made for $pp \to pp + \gamma$ or $pp \to pp + \pi\pi + \gamma$
- Requires charged particles measured over large rapidity
- Process without leptons reduces background
- Events can be selected via double-gap

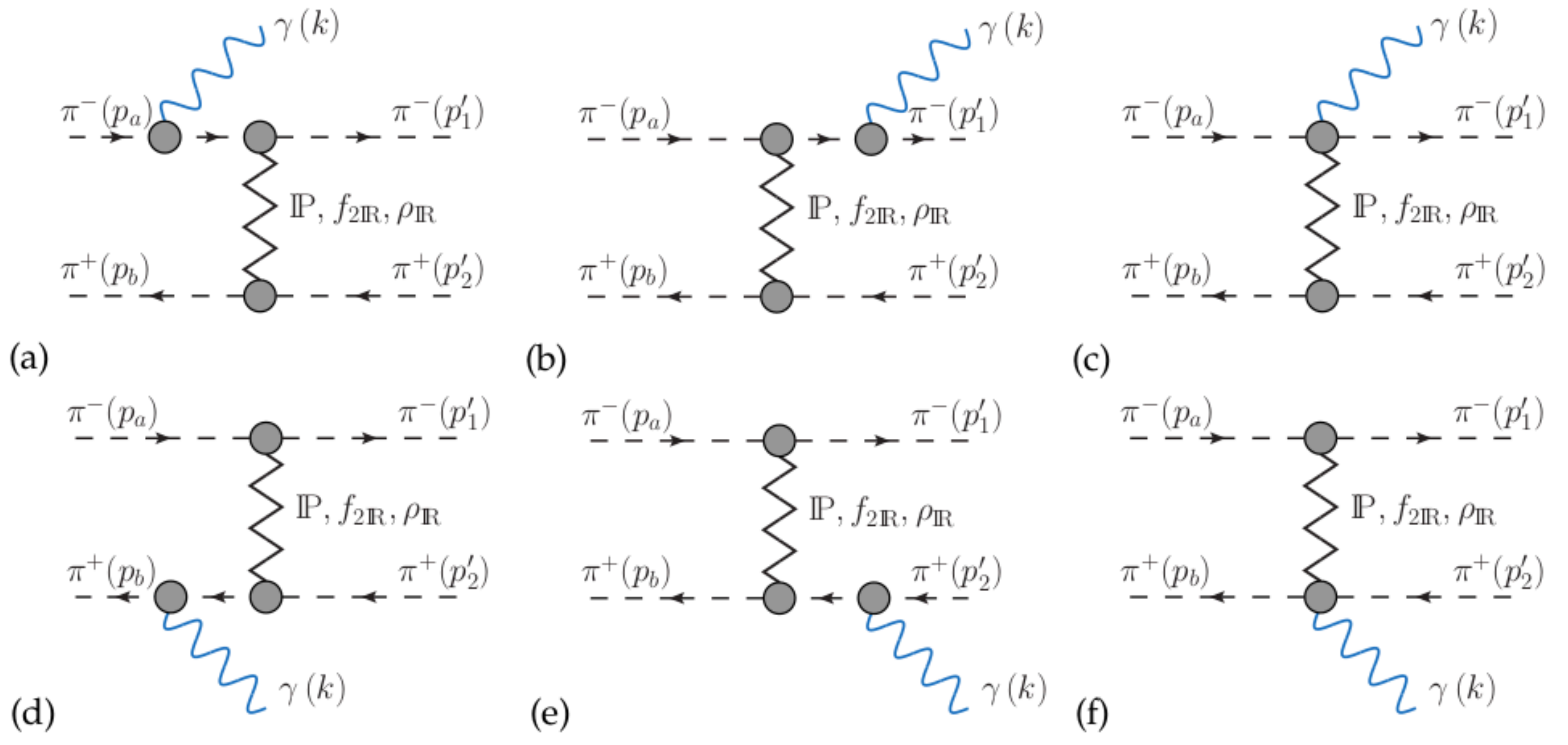
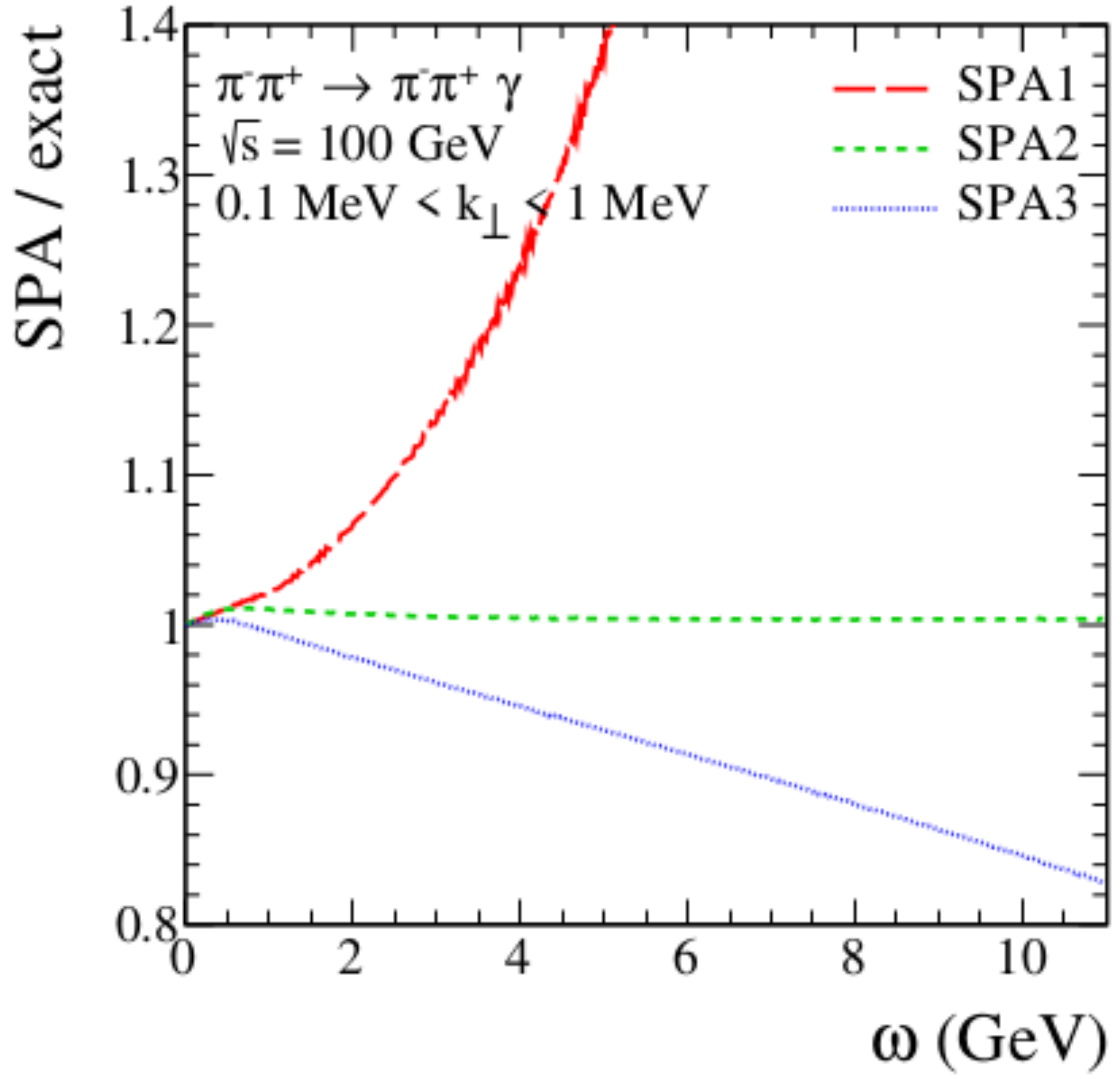


FIG. 6. Diagrams for the reaction $\pi^-\pi^+ \to \pi^-\pi^+\gamma$ with tensor-pomeron exchange.



SPA1 is the leading term only ("Low's theorem")

Separating contributions

$$\frac{\mathrm{d}N^{\gamma}}{\mathrm{d}^3k} \sim \frac{-1}{E_{\gamma}} \left(\sum_{\text{Particle } i} \frac{\eta_i e_i \mathbf{P_i}}{\mathbf{P_i K}} \right)^2$$

- Contributions from (individual particles)^2 and cross terms
- Total cross section is only positive if charges are conserved
- but we can rewrite:
  $$\frac{\mathrm{d}N^{\gamma}}{\mathrm{d}^3k} \sim \frac{-1}{E_{\gamma}} \left(\sum_{\text{Particle } i} \frac{\eta_i e_i \vec{\beta}_i \times \vec{k}}{1 - \vec{\beta}_i \cdot \vec{k}} \right)^2$$
  where squares are positive
- Is it enough to consider individual particles as the photon source sometimes? E.g. to measure the dead-cone?