Soft photon measurements with ALICE3

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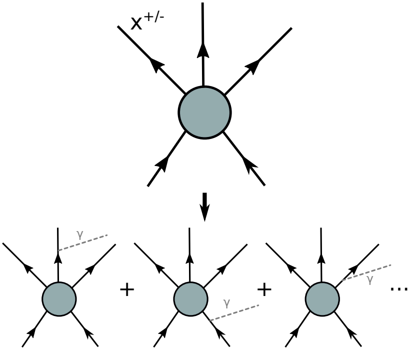
2022-08-03

Reminder: Soft Photon Production

- For interactions with charged particles: corresponding process producing photons
- Attaching photon line to each line of charged particles (incoming or outgoing)
- Low E_γ:
  - only on-shell propagators contribute – only consider external lines
  - No change in momenta $\rightarrow$ blob stays the same
- Calculate 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)
- Limit of approximation E_γ small not simple for general process ($\omega\tau \ll 1$, $|\vec{k}|d \ll 1$)

Low's theorem

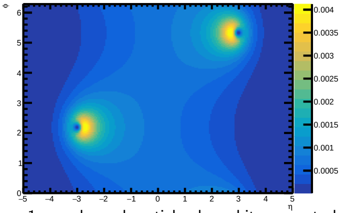
- Low's Theorem connects interaction of charged particles with 4-momenta $\mathbf{P_i}$ with expectation value for soft photon production (with 4-momentum $\mathbf{K}$):

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

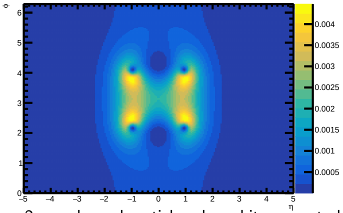
- Via the square, interference terms between the particles are created
- For a single event, this means

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

- In particular direction, always $1/E_\gamma$ spectrum
- Signal typically between + and − particles, depletion very close to particle
- Signal estimate usually done with input from event generators



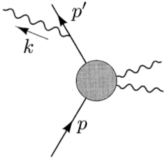
1 pos, 1 neg charged particle plus arbitrary neutral



2 pos, 2 neg charged particles plus arbitrary neutral

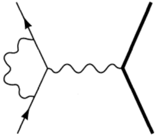
Infrared divergences

- When including single soft photon emission in scattering, cross-section diverges
- Can make finite with photon mass μ (*Sudakov double logarithm*):



$$\mathrm{d}\sigma(p \to p' + \gamma(k)) \underset{-q^2 \to \infty}{\approx} \sigma(p \to p') \cdot \frac{\alpha}{\pi} \log \frac{-q^2}{\mu^2} \log \frac{-q^2}{m^2}$$

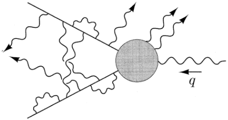
- Similar divergence from vertex correction:



$$\mathrm{d}\sigma(p \to p')_{\mathrm{corr}} \approx \sigma(p \to p') \cdot \left(1 - \frac{\alpha}{\pi} \log \frac{-q^2}{\mu^2} \log \frac{-q^2}{m^2}\right)$$

- Interpretation: Cannot be experimentally distinguished for very low photon energies – sum of effects is finite

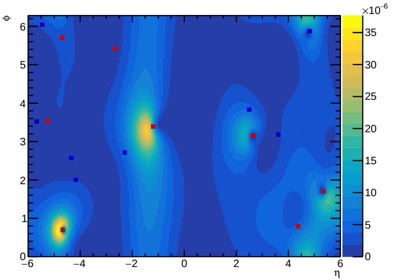
- Add up higher orders of corrections – divergencies still cancel (*Bloch-Nordsiek theorem*)
- Probability distribution of number of photons in energy range follows Poisson law – interpretation of emission probability divergence



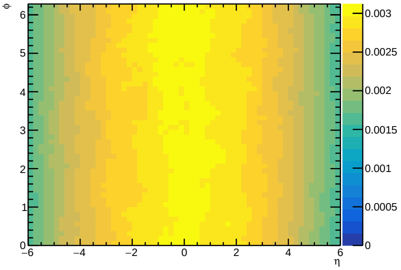
Region of validity

- Photon energy must be low in two places:
  - Energy removed by the photon from leg must not change cross section ($\mathbf{E}_\gamma \ll \mathbf{E}_{\mathbf{particles}}$)
  - In the propagator, e.g. $1/((p-k)^2 - m^2) \approx 1/(p^2 - m^2 - 2pk)$: If $p^2 - m^2 \neq 0$ then $2pk$ must be small compared to it – only then does the blob not contribute ($\mathbf{E}_\gamma \ll$ **off-shellness**)
- In addition, the contributions must be coherent: The size of the source must be small compared to the wavelength $\mathbf{E} \cdot \mathbf{l} \ll \mathbf{1}$ (Low argues from multipole radiation)
- Additionally: For coherent radiation, the timescale must be small compared to the frequency $\mathbf{E} \cdot \mathbf{t} \ll \mathbf{1}$
- In original paper: Elastic $2 \to 2$ scattering only – natural energy scale in COM energy
- More complex for pp/PbPb collisions: Soft particle production along with hard processes

Estimating the soft photon signal



PYTHIA8 event, particles with large $\beta\gamma$

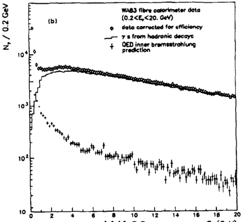


PYTHIA8 average over many events

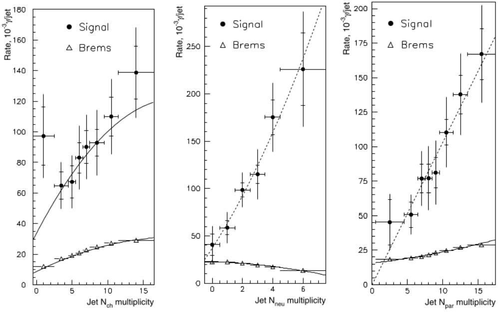
- Signal can be estimated from initial and produced charged particles
- Depends on $\beta\gamma$, difficulties without PID and with inefficiencies
- In previous experiments: estimated using event generators
- Signal turns out to be approximately constant per pseudorapidity for fixed E_γ and $p_{\mathrm{T}\gamma}$

Previous measurements of excess production

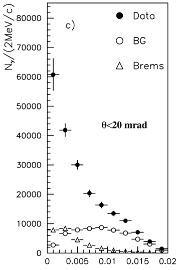
- Several measurements of soft photon production were performed previously
- Expected signal usually calculated from event generators
- Typically an enhancement of a factor ~ 5 over the expected signal
- Typically $E_\gamma > 0.2\,\mathrm{GeV}$



WA83

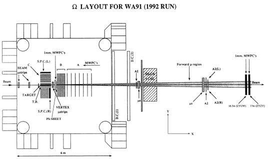


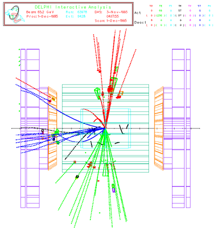
DELPHI



WA91

Previous measurements of excess production (2)





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

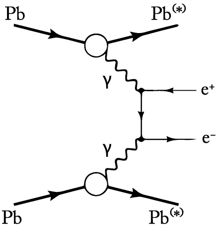
Experiment	Year	Collision energy	Photon p_T	Photon / Brems Ratio	Detection method	Reference (click to go to paper)
π^+p	1979	10.5 GeV	p_T < 30 MeV/c	1.25 ± 0.25	bubble chamber	Goshaw et al., Phys. Rev. Lett. 43, 1065 (1979)
K^+p WA27, CERN	1984	70 GeV	p_T < 60 MeV/c	4.0 ± 0.8	bubble chamber (BEBC)	Chliapnikov 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)
$e^+e^- \to$ 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)
$e^+e^- \to \mu^+\mu^-$ CERN, DELPHI	2008	91 GeV (CM)	p_T < 80 MeV/c	~ 1	pair conversion	DELPHI, Eur. Phys. J. C57, 499 (2008)

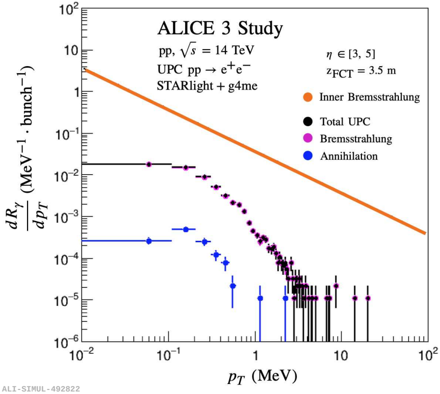
- Experiments with different setups
- Somewhat different analysis strategies
- Very simple signal estimate based on very fundamental principles . . .
- . . . which is nevertheless off by a factor ~ 5
- Also at LHC energies? And if so: why?

Background sources

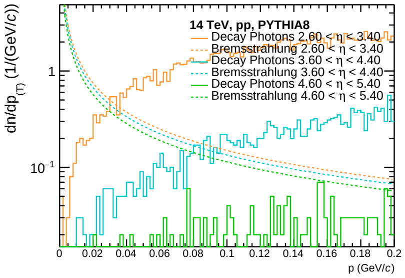
- For signal photons with E_γ a few 10 MeV
- Possible sources of background
  - **Decay Photons**
  - **Regular bremsstrahlung in the detector material**
  - **Ultraperipheral collisions**
  - Misidentified V0s
  - (Misidentified Dalitz decays)
  - Beam-gas interactions
  - Synchrotron radiation
  - Activated material
- Other sources probably smaller/can be suppressed

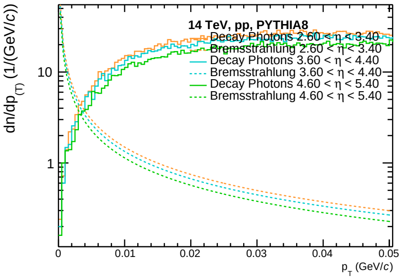
- Ultraperipheral collisions can produce e^+e^--pairs, which create bremsstrahlung
- Positrons can also annihilate with material
- Backgrounds small in pp collisions, but may be relevant in Pb–Pb





Study by Georgijs Skorodumovs

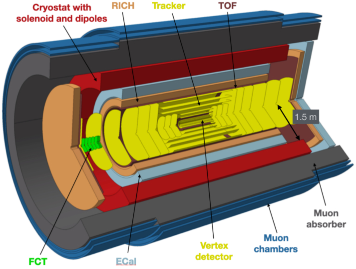


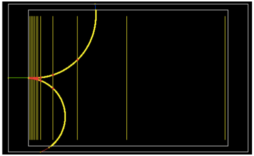


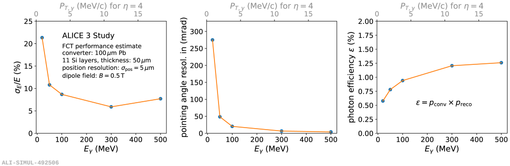
- Low-energy photons difficult to measure
- E.g. photon conversion only for $E_\gamma > 2m_e$
- Important background: Decay from light meson decays (e.g. $\pi^0 \to \gamma\gamma$)
- Crossover, at approximately constant p_T, signal can be measured below
- Minimum E_γ $\to$ easier to measure at forward rapidity

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



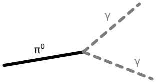


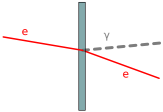


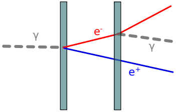
Study by Klaus Reygers

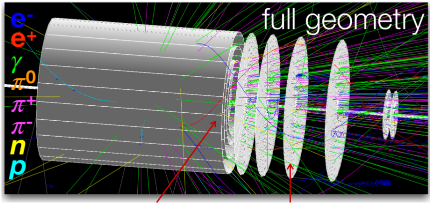
Background dependence on material

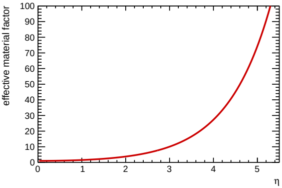
- Decay photons independent of material
- Charged electron/positron producing bremsstrahlung: Proportional to material budget
- Photon producing electrons-positron pair, these producing bremsstrahlung: Proportional to square of material budget
- π^0-decays mostly at primary vertex – same as signal
- Bremsstrahlung, photon conversion: typical angle of m_e/E, very small
- Problem: Cylindrical geometry gives $\cosh\eta$-dependence of effective material budget – large at forward rapidities ($\cosh 5 \approx 74$)
- Ideally $< 10\%$ effective material, possibly remove some material in front





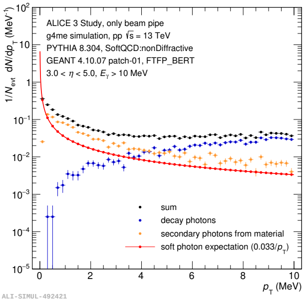


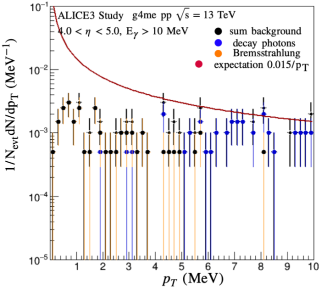


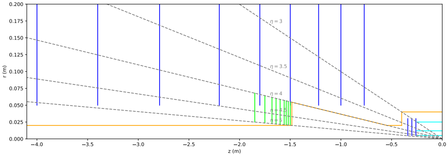


Background from bremsstrahlung

- Baseline: Material only the beampipe and Air
- Similar signal and background, same energy distribution
- Variation of beampipe shape could mitigate this – decreased background
- However: Constraints from mechanical stability, induced fields – requires detailed study
- Additional material from ITS3 tracking layers, support structures

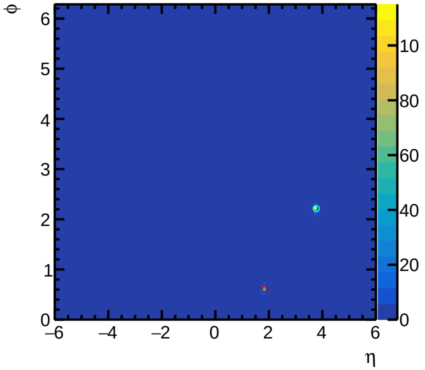






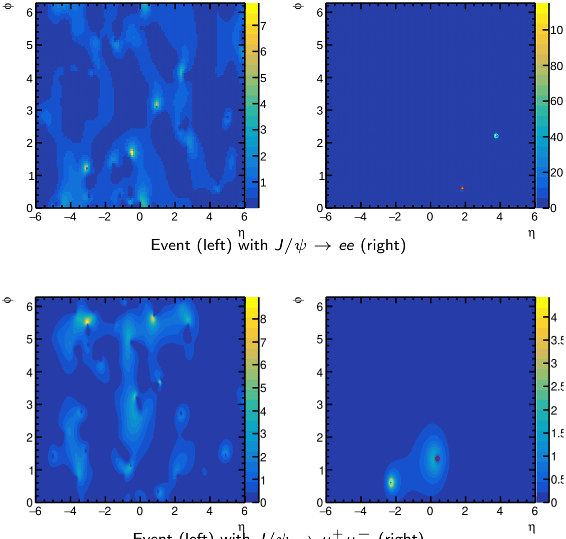
Radiation from J/ψ decays

- J/ψ decay is separate process; radiates independently
- Can reconstruct from e^+e^- or $\mu^+\mu^-$ pair
- For two-body decay: Definite and high energy scale – Low theorem assumptions more clearly fulfilled
- For boosted system: Blueshift increases scale further
- Simple signal but need to compare to background
- Signal near the tracks for electrons – this is where bremsstrahlung would also be
- EM process rather than hadronic collision



$J/\psi \to ee$ soft photon radiation pattern

- In single event signal clearly distinguishable from background soft photons
- S/B depends on selection of J/ψ
- Distribution wider for muons
- Bridge visible – specific for "inner" bremsstrahlung
- Can we measure $J/\psi \to \mu^+\mu^-$ at forward rapidities and distinguish it from $J/\psi \to e^+e^-$

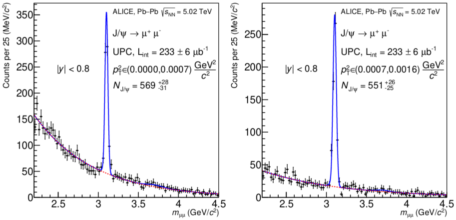


Event (left) with $J/\psi \to ee$ (right)

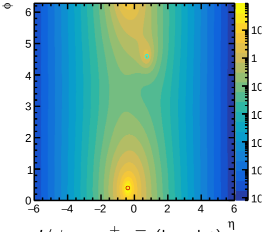
Event (left) with $J/\psi \to \mu^+\mu^-$ (right)

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

- In ultraperipheral collisions we can get a clean J/ψ signal
- Allows to associate soft photons and check if they follow the expected distribution



Phys. Lett. B 817 (2021) 136280



$J/\psi \to \mu^+\mu^-$ (log plot)

Direct calculations of soft photon production

- 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

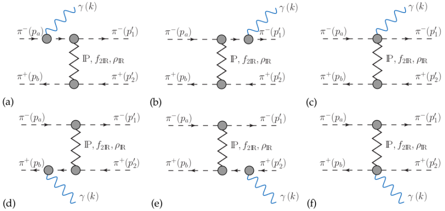
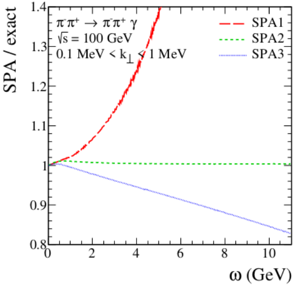


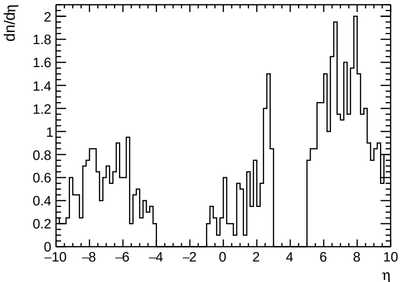
FIG. 6. Diagrams for the reaction $\pi^-\pi^+ \to \pi^-\pi^+\gamma$ with tensor-pomeron exchange.



Lebiedowicz, Nachtmann, Szczurek; ArXiv: 2107.10829

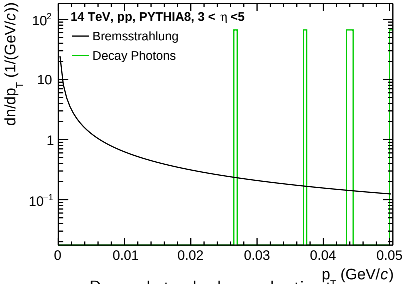
Central diffractive events with soft photons

- Central diffractive events selected using double-gap requirement
- FCT itself is forward detector, so gaps e.g. at $-4 < \eta < -1$ and $3 < \eta < 5$
- One positive and one negatively charged track in $-1 < \eta < 3$
- Require no neutral tracks. This assumes that a calorimeter catches them or they decay
- Veto > 2 photons with $E_\gamma > 0.2\ \mathrm{GeV}/c$ (could be detected by ECals)
- Very strongly suppresses non-diffractive pp events
- Less suppression for diffractive events
- No PID



Particles from diffractive events after double-gap requirement

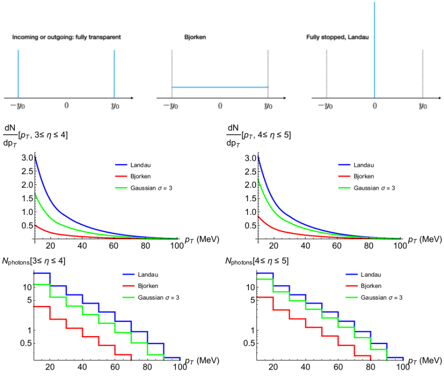
- Approach
  - Simulate Non-diffractive, diffractive and central events with PYTHIA
  - For events passing selections, calculate soft photons using Low's theorem
  - Scale signal events with cross section measured by CMS and efficiency of event selection (≈ 0.13)
  - Compare signal electron ratios
- These (idealized) selections would mean that the signal from central diffractive events would be about a factor 5 higher than from other diffractive events
- Non-diffractive contribution negligible; not enough statistics for the decay photons (probably negligible)
- About 2/3 central diffractive contribution from signal process; background e.g. $pp \to pp\pi^+\pi^-\pi^0$ or $pp \to ppp\bar{p}$)
- If these can be calculated as well, they would become signal



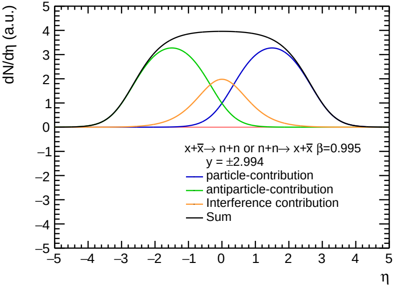
Decay photon background estimate

Inner bremsstrahlung from stopping of charges in a QGP

- In Pb–Pb collisions: Large number of charges suddenly stopped
- Coherent incoming charges accelerated $\rightarrow$ bremsstrahlung produced
- Spatial extent of system makes quantum mechanical calculation difficult
- Estimate instead via semiclassical calculation gives large photon yield
- Mostly independent of radial charge distribution for forward direction
- May allow to differentiate between different stopping scenarios
- Validity of approximation interesting question (ignores lifetime of medium, transverse momenta, quantized charges), but order of magnitude should be reasonable



Park, Wiedemann; ArXiv: 2107.05129



- Low's theorem contains the term ($\underline{P}$, $\underline{K}$ particle and photon 4-momentum)

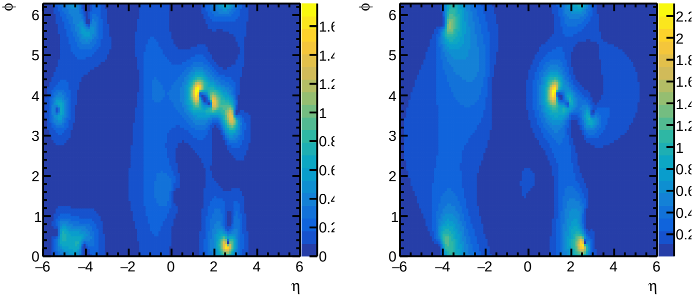
$$\left(\sum_i e_i \eta_i \frac{\underline{P}_i}{\underline{P}_i \underline{K}}\right)^2$$

- Redefine: Every incoming particle gets an outgoing particle of same mass at rest; every outgoing particle gets an incoming particle of same mass at rest:

$$\left(\sum_i e_i \eta_i \frac{\underline{P}_i}{\underline{P}_i \underline{K}} - \frac{(m_i, \vec{0})}{(m_i, \vec{0})\underline{K}}\right)^2$$

- If all particles are in the sum, this gives the same result as before, but for missing particles charge is always conserved
- Previously used to define radiation of individual particles and interference contributions

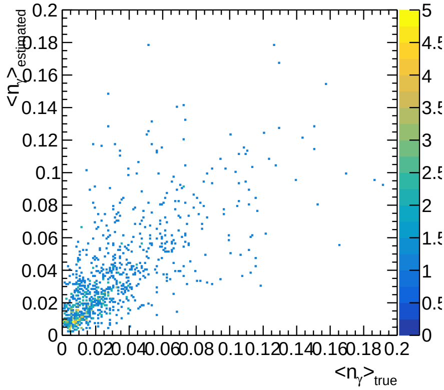
Estimated radiation pattern



left: Low theorem single event radiation pattern, right: estimate from "measurement"

- Estimate radiation pattern for single event from measured particles
- Here: All charged (primary) particles in $|\eta| < 5$
- Assume perfect $(p_{\mathrm{T}}, \eta, \phi)$-measurement
- Assume no PID – assume all particles are $\pi^{\pm}$
- Also include incoming protons with known mass and momentum

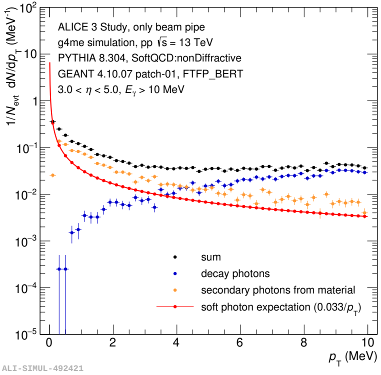
Performance of photon radiation estimator



- Integrate expected per-event yield over $3 < \eta < 5$
- Compare Low's theorem result with estimate using pions+acceptance
- Obvious correlation with true radiation expectation, but not great
- Can probably be optimized, certainly better with PID
- Next step would be to search specifically in the high-probability regions to verify shape
- Requires very low background (low material budget)

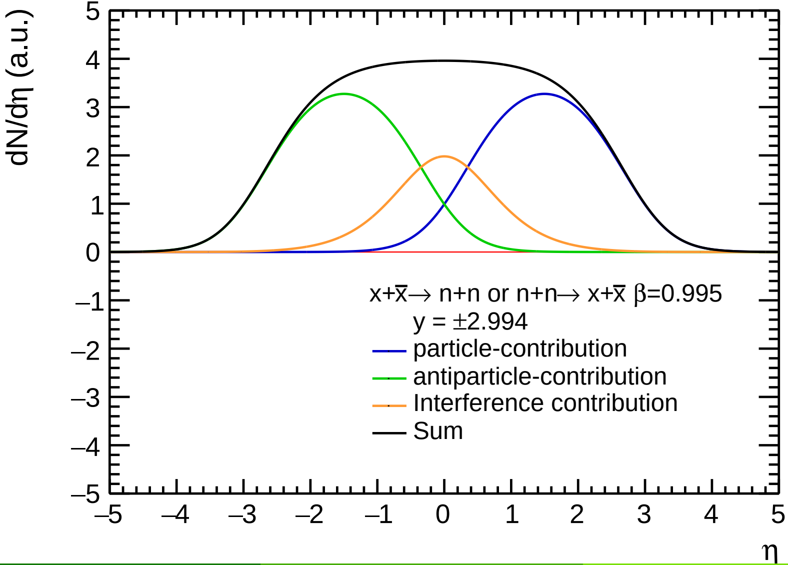
Conclusions

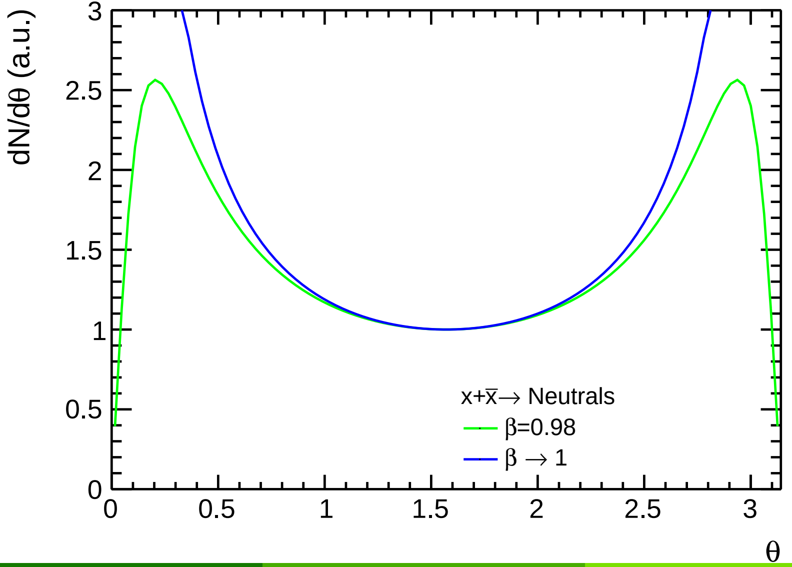
- Several measurements show deviation from expected soft photon limit in hadronic interactions
- Presents serious challenge to understanding of quantum field theory
- FCT may be capable of addressing this question
- Initially, measurement differential in p_{T}, η, multiplicity
- More differential signal shape could be estimated from measured particles
- Detector based on photon conversion in dipole field at forward rapidity feasible
- Background from material bremsstrahlung with similar p_{T}-shape; problematic if $X/X_0 > 10\%$
- Soft photon can provide insights in several further measurements



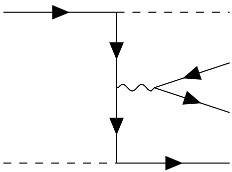
Appendix

Simple example




dN/dθ (a.u.)
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
θ
x+x̄→ Neutrals
β=0.98
β → 1

t-channel contribution 2→4 scattering



- Upper propagator has $P = (E^*, 0, p_\mathrm{T}, E^*)$
- Lower Propagator has $P = (-E^*, 0, p_\mathrm{T}, E^*)$ (extra momentum needs to be exchanged between incoming particles)
- Thus $p^2 \approx {p_\mathrm{T}}^2$ in both cases
- kp term for forward going photon gives $\pm E_\gamma E^* - p_\mathrm{T} k_t - E_\gamma E^*$
- The propagators give approximately: $\frac{1}{{p_\mathrm{T}}^2 + 4E_\gamma E^*}$ and $\frac{1}{{p_\mathrm{T}}^2 - 2p_\mathrm{T} k_t}$
- With $p_\mathrm{T} \approx E^*$, this leads to the conditions $E_\gamma \ll p_\mathrm{T}$ and $k_t \ll p_\mathrm{T}$
- The first condition means, that here the new scale is actually the relevant one
- However: The contribution from attaching to the second propagator should always be larger
- Is the dominance of the $1/E$ term really the correct condition at all?