Baryon stopping from bremsstrahlung photon spectrum

Sigurd Nese†, Joakim Nystrand‡

† University of Oslo, Oslo, Norway, ‡ University of Bergen, Bergen, Norway

Introduction

In ultra-relativistic heavy-ion collisions, the colliding nuclei are decelerated and kinetic energy is converted into new particles. This energy loss is referred to as baryon stopping, and the amount of baryon stopping can be quantified by the net proton rapidity distribution. At LHC energies, the only experimental constraints are at the central rapidity region, which has zero net protons. To investigate the net proton distribution beyond mid-rapidity at LHC energies, one can use the bremsstrahlung radiation emitted by the colliding nuclei as they slow down [1]. The yield and angular distribution of bremsstrahlung photons are sensitive probes of how much energy the incoming protons have lost.

1. The bremsstrahlung spectrum

To calculate the bremsstrahlung spectrum, one can follow a semi-classical approach. The starting point is the expression for the energy radiated per solid angle by a current $\mathbf{J}(\mathbf{r},t)$, given by

$$\frac{d^2I}{d\omega d\Omega} = \frac{\omega^2}{4\pi^2}\left|\int\int \overline{n}\times(\overline{n}\times\mathbf{J}(\mathbf{r},t))e^{i\omega(t-\overline{n}\cdot\mathbf{r}(t))}dtd^3\mathbf{r}\right|^2, \quad (1)$$

where $\overline{n}$ denotes the photon direction. To describe the currents for the incoming nuclei, note that they are Lorentz-contracted in the longitudinal direction to a size $\sim R/\gamma$, where R is the nuclear radius and γ is the Lorentz factor. Thus, the longitudinal extension can be ignored and the incoming currents are written as

$$\mathbf{J}_{\pm}(\mathbf{r},t) = \pm v_0\frac{e}{\sqrt{4\pi\epsilon_0}}\sigma(r_\perp)\delta(z\mp v_0t)\,\theta(-t)\hat{\mathbf{z}}, \quad (2)$$

where v_0 is the beam velocity, σ is the nuclear electric charge density in the transverse plane normalized to the beam atomic number Z, and $\theta(t)$ is the Heaviside step function. For the outgoing current, we assume the transverse charge distribution is the same as for the incoming nuclei. We write the outgoing current as

$$\mathbf{J}_f(\mathbf{x},t) = \sigma(r_\perp)\frac{e}{\sqrt{4\pi\epsilon_0}}\int_{-\infty}^{+\infty}\rho(y)v(y)\delta(z-v(y)t)dy\,\theta(t)\hat{\mathbf{z}}\,, \quad (3)$$

where $\rho(y)$ is the rapidity density of the outgoing protons normalized to 2, and $v(y)=\tanh(y)$ is the velocity as a function of rapidity.
The currents in Eqs. (2), (3) are inserted into Eq. (1) to calculate the bremsstrahlung spectrum. The time and z integrals are carried out using the approximation

$$e^{i\omega(t-\overline{n}\cdot\mathbf{r})} \approx e^{-i\omega x\sin\theta}, \quad (4)$$

which is justified since the time span of the process is small compared to the transverse size ($\Delta t \ll R$), and we consider low energy photons ($\omega \ll 1/\Delta t$). Then, the integral over $r_\perp$ can be performed, yielding

$$\frac{dN_\gamma}{d\omega d\Omega} = \frac{\alpha Z^2}{4\pi^2\omega}\sin^2(\theta)|F(\omega\sin(\theta))|^2\left[\int\frac{v(y)\rho(y)}{1-v(y)\cos(\theta)}dy - \frac{2v_0^2\cos(\theta)}{1-v_0^2\cos^2(\theta)}\right]^2, \quad (5)$$

where $F(Q)$ is the nuclear form factor encapsulating the transverse shape of the nuclei. Here, the following form factor is used:

$$F(Q) = \frac{4\pi\rho_0}{AQ^3}\left(\sin(QR_A)-QR_A\cos(QR_A)\right)\left[\frac{1}{1+a^2Q^2}\right], \quad (6)$$

which accurately reproduces the Fourier transform of a Woods-Saxon distribution.

2. Stopping scenarios

To obtain a photon spectrum, one must define the final state net-proton rapidity distribution, $\rho(y)$. This function characterizes the baryon stopping. Here, 4 stopping scenarios are considered: Net proton distributions as given by the event generators PYTHIA 8.3 [2, 3], SMASH-2.2 [4] and EPOS4 [5], and a phenomenological model which is consistent with measurements and has a considerable shift away from beam rapidity. These scenarios are shown in Fig. 1a).
For a given stopping scenario, one can integrate Eq. (5) over energy to obtain the angular bremsstrahlung photon distribution. This is shown in Fig. 1b) for $0.1 \leq \omega \leq 0.5\,\text{GeV}$, in terms of pseudorapidity. For all scenarios, the photon yield is peaked at large $|\eta|$. However, at lower pseudorapidities the yields differ significantly between scenarios, making them potentially discernible within experimental acceptances.

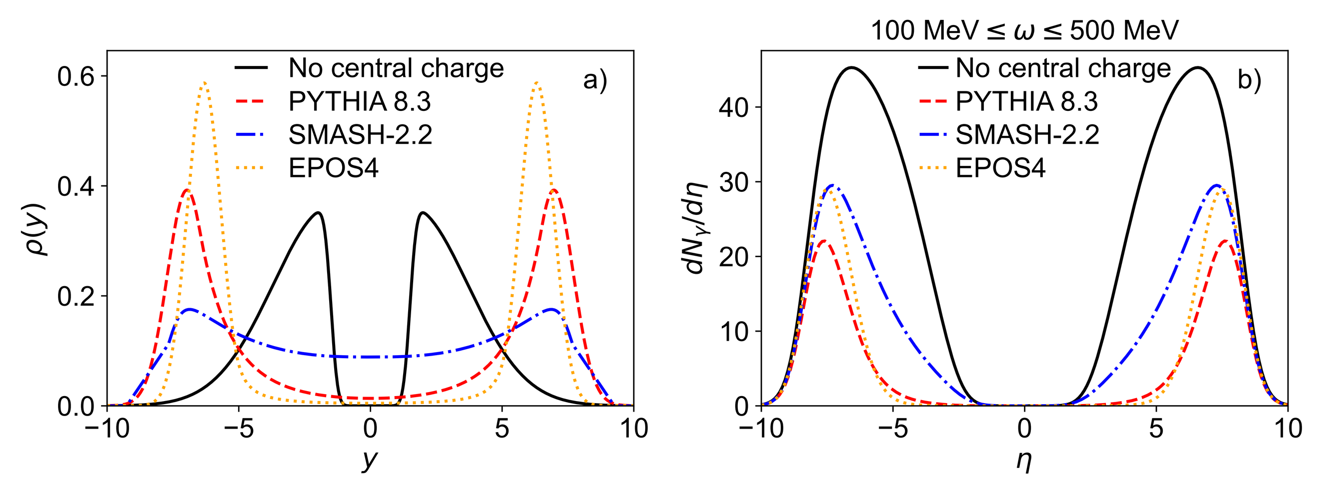

Fig. 1: a) Charge rapidity distribution in the various baryon stopping scenarios. b) The bremsstrahlung photon distribution integrated over the energy range 100 MeV to 500 MeV, as a function of pseudorapidity.

3. Results

In Pb+Pb collisions, hadronically produced photons will constitute a background for the bremsstrahlung radiation from stopping. To put the bremsstrahlung yield into context, it is compared to the photon yield from the 5% most central Pb+Pb collisions in PYTHIA 8.3. This is shown in Fig. 2. For a fair comparison, a correction factor corresponding to the average number of participating protons in the 5% most central collisions should be applied to the bremsstrahlung spectrum calculation. This correction is included in the blue, dashed histograms in the figure.
At low pseudorapidities, the background completely dominates, but the bremsstrahlung peak emerges in the very forward direction. The yield differs widely between scenarios, emphasizing the sensitivity of this probe to nuclear stopping.

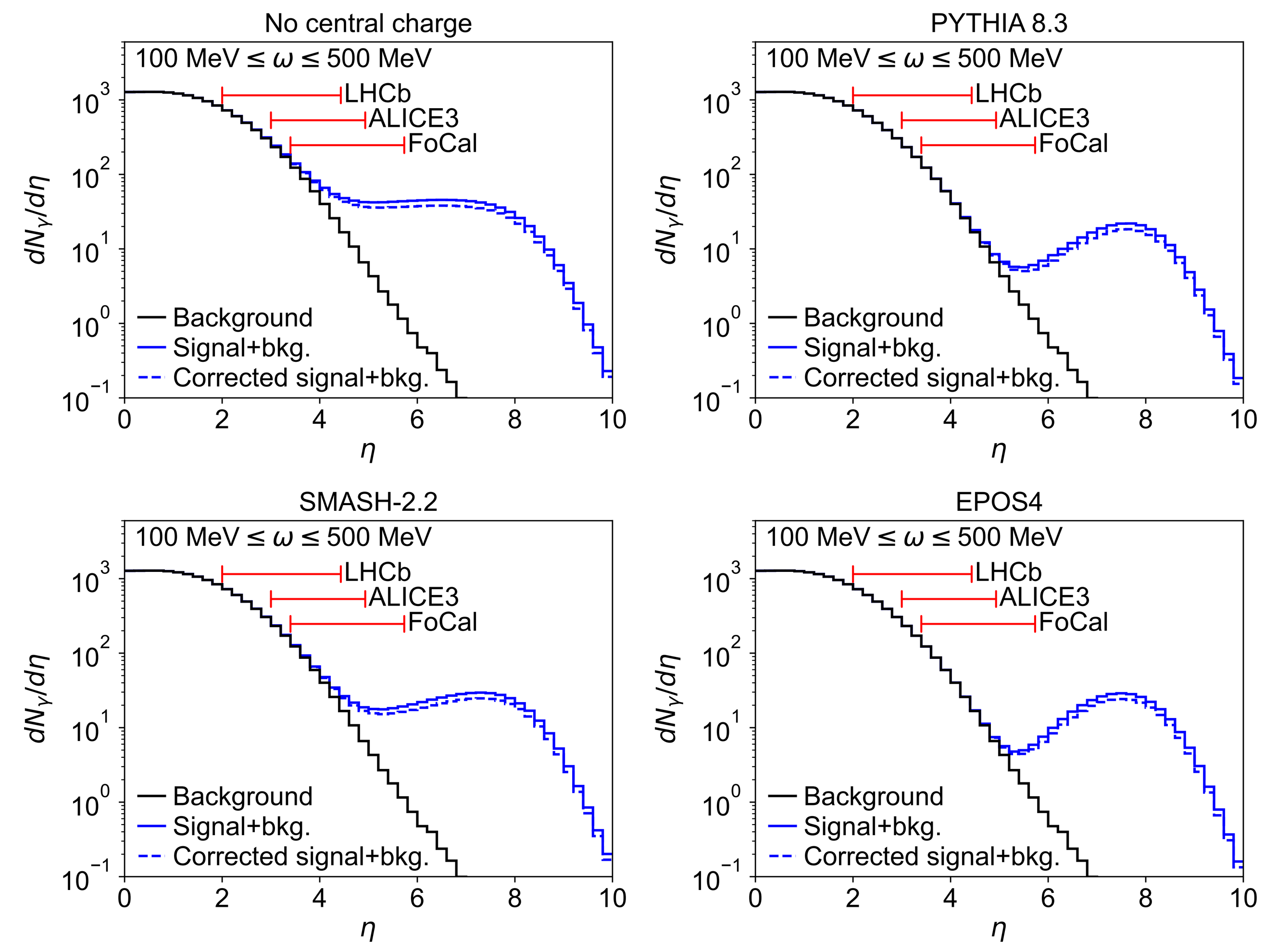

Fig. 2: The pseudorapidity distributions for photons with $0.1 \leq \omega \leq 0.5\,\text{GeV}$ integrated over the azimuthal angle.

In contrast to the hadronically produced photons, the bremsstrahlung spectrum increases rapidly with decreasing photon energy, approximately as $1/\omega$. Thus, even with a small amount of stopping, the signal is visible if one goes to low enough energies. This is illustrated in Fig. 3.

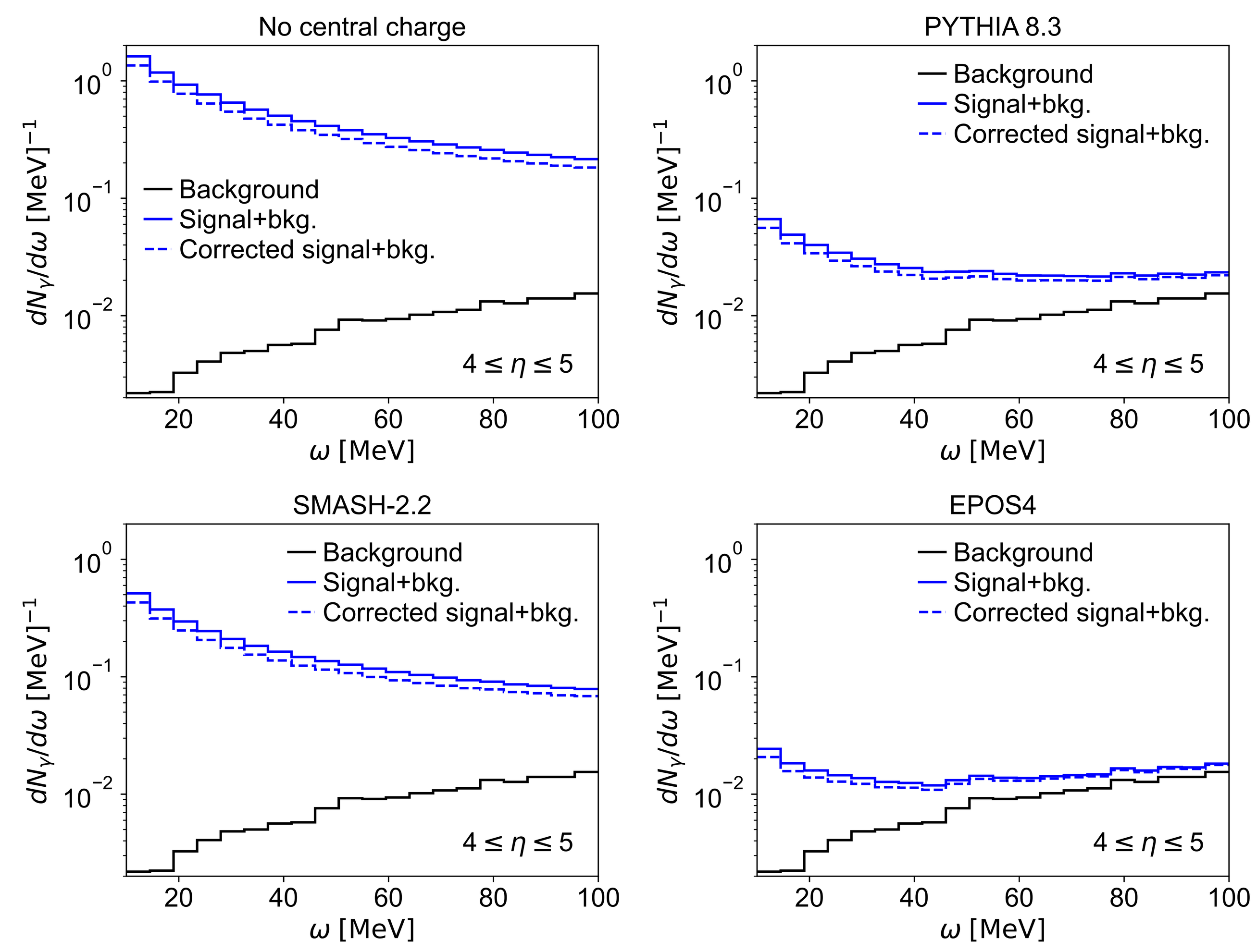

Fig. 3: The energy distributions for photons with $4.0 \leq \eta \leq 5.0$ integrated over azimuthal angle.

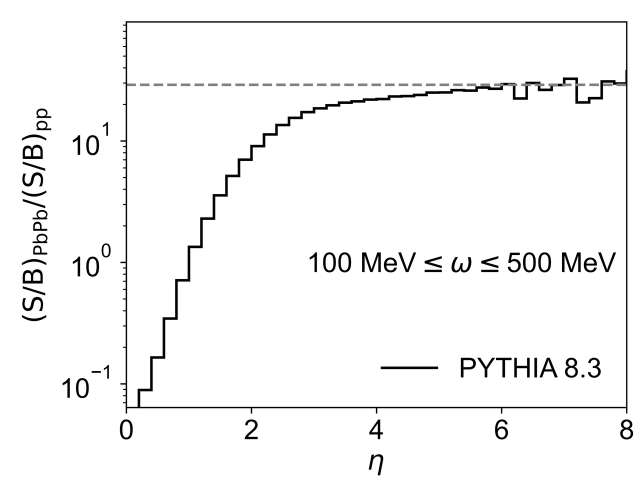

Fig. 4: Signal over background comparison for Pb+Pb collisions vs. proton-proton collisions, for photons with $4.0 \leq \eta \leq 5.0$. The dashed line is the result expected from rough scaling arguments.

Similarly to the case of Pb+Pb collisions, one can obtain $\rho(y)$ for proton-proton collisions from event generators, and obtain the corresponding bremsstrahlung photon yield. From Eq. (5), a suppression factor $1/Z^2$ is expected. The number of hadronic photons will decrease as well, scaling roughly as $N_{\gamma,\text{had}} \sim N_{p,\text{part}}$, where $N_{p,\text{part}}$ is the number of participating nucleons. A comparison of the signal-to-background ratio in Pb+Pb collisions and proton-proton collisions are shown in Fig. 4, using $\rho(y)$ from PYTHIA 8.3. From the above arguments one would expect an enhancement factor of $Z_{\text{Pb}}^2/A_{\text{Pb}} = 32$. This value, with a correction corresponding to 5% centrality in the PYTHIA background data, is indicated by the dashed line in Fig. 4.

References

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