Opportunities with ultra-soft photons: Bremsstrahlung from stopping

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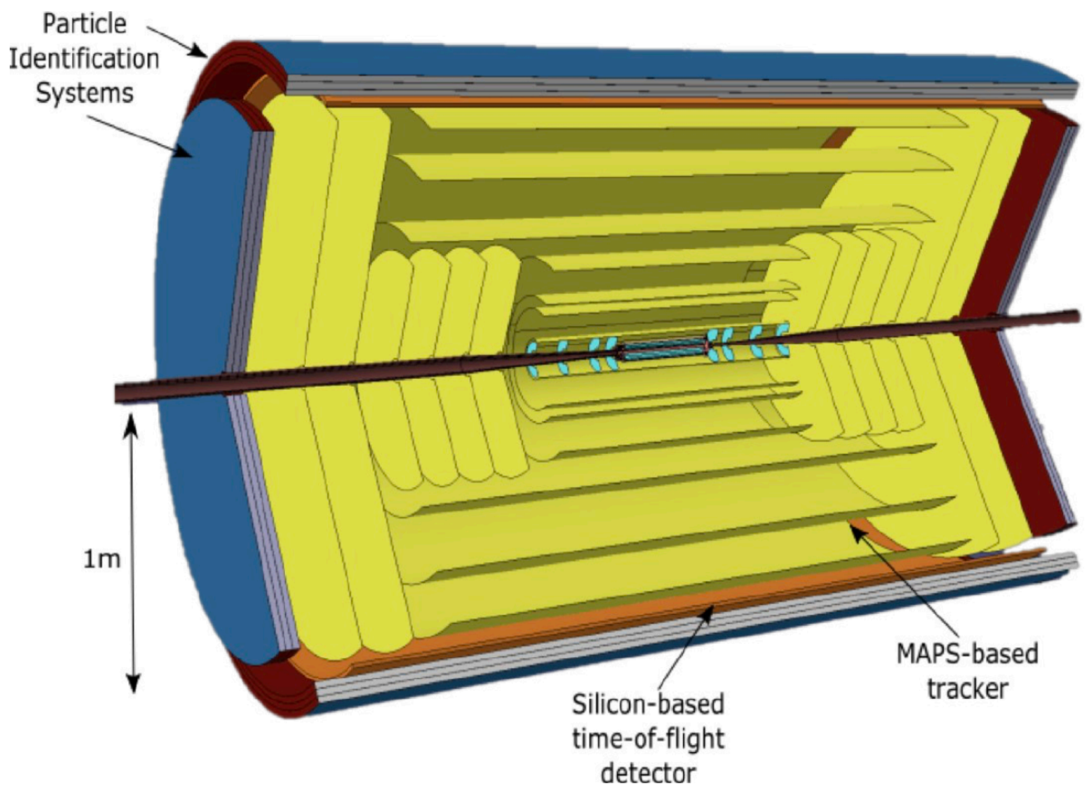
Based on arXiv: 2107.05129, PRC 104 (2021) 4, 044903

“A next-generation LHC heavy-ion experiment”

arXiv:1902.01211
ALICE 3 LOI: LHCC-2022-009



At LHC, a new detector ALICE 3 is planned for the 2030s.

One new capability of this detector design: measuring ultra-soft photons (pT ~ 10 MeV) at forward rapidity (up to rapidity 4)

Our plan:

- Calculate the spectrum of bremsstrahlung photons from stopping in PbPb@LHC.
- Ask whether this spectrum can be measured with ALICE 3.

An earlier proposal to measure bremsstrahlung from stopping

- This idea is not new but actually is as old as the field of heavy-ion physics:

  Kapusta 1977; Bjorken and McLerran 1985

- Calculations of classical electromagnetic bremsstrahlung in the late 1990s;
  The effect is measurable; Proposed a detector at RHIC but it was never realized

  Jeon, Kapusta, Chikanian and Sandweiss, 1998

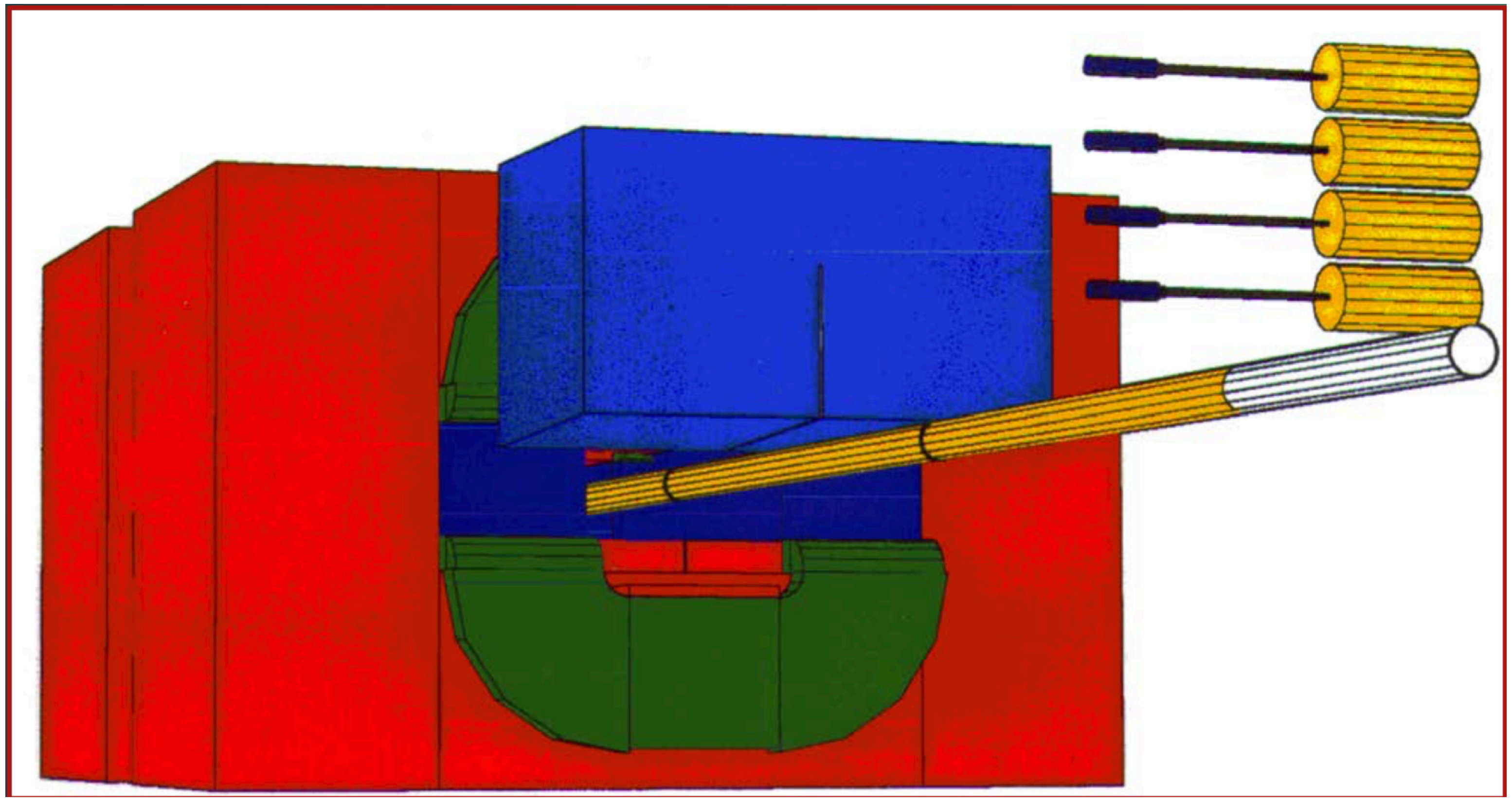


Image from Jack Sandweiss Memorial by Evan Finch at SQM 2021

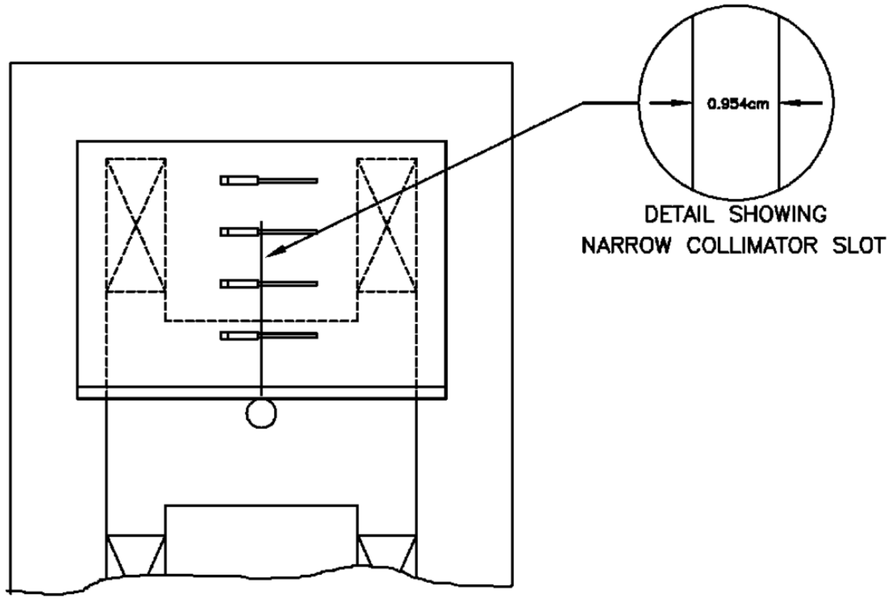


FIG. 7. View of the experiment along the beam, looking back from the detector side.

PRC 58 (1998), 1666
Jeon, Kapusta, Chikanian and Sandweiss

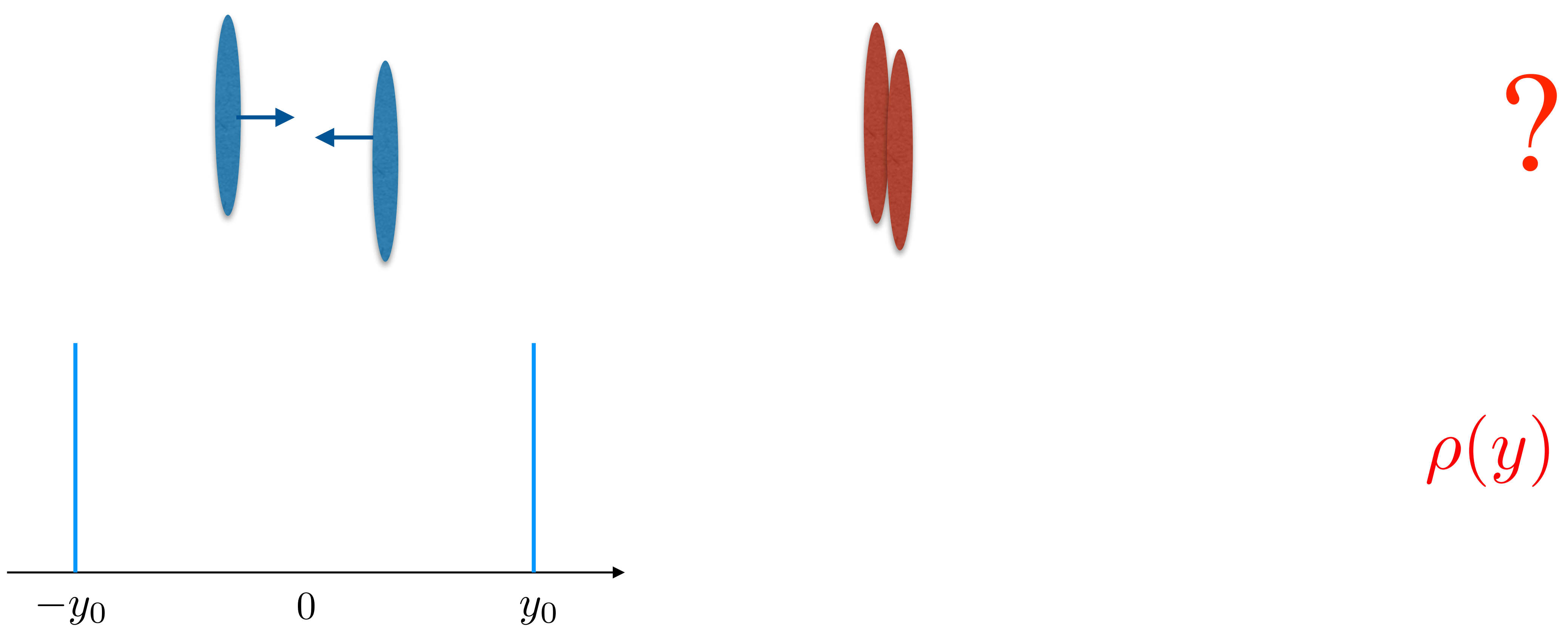
Bremsstrahlung from stopping

- Pb-ions are 82+ ⟶ each PbPb collision decelerates a net-charge 164+
- Classical Electrodynamics: charge deceleration ⟶ photon bremsstrahlung
- Why is this interesting?

  Robust prediction but never measured ⟶ experimental challenge

  Bremsstrahlung sensitive to the degree of longitudinal stopping

  Longitudinal stopping determines rapidity distribution of net electric charge



$$\rho(y) = ?$$

Classical bremsstrahlung

- The intensity of photons of energy ω in direction $\mathbf{n}$ from charge current $\mathbf{J} = \mathbf{J}_+^{(in)} + \mathbf{J}_-^{(in)} + \mathbf{J}^{(out)}$

$$\frac{d^2 I}{d\omega d\Omega} = |\mathbf{A}|^2\,,\;\; \mathbf{A}(\mathbf{n},\omega) = \int dt \int d^3x \mathbf{n} \times (\mathbf{n} \times \mathbf{J}(\mathbf{x},t)) e^{i\omega(t-\mathbf{n}\cdot\mathbf{x})}$$

Eq. (14.67) in Jackson, *Classical Electrodynamics* (1998) 3rd ed.

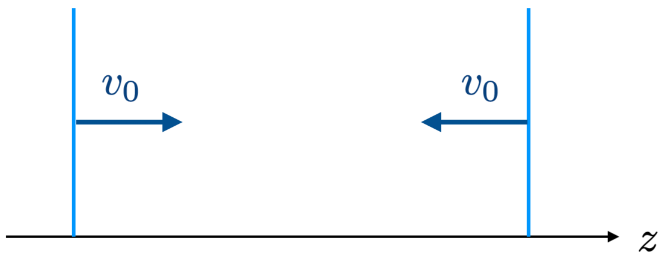
- Incoming current: incoming charges with projectile rapidity y_0 along the beam direction z

$$J_\pm^{(in)}(\mathbf{x},t) = \pm Z\, e\, \rho_{\text{in}}(r)\, v_0\, \delta(z \mp v_0 t)\, \Theta(-t)$$

$\rho_{\text{in}}(r)$: incoming charge density in the transverse plane

$v_0 = \tanh y_0$

$y_0 \simeq \ln\left(\frac{\sqrt{s_{\text{NN}}}}{m_N}\right)$



- Outgoing current at shifted velocity $v(y)$ after collision at time $t = 0$

$$J^{(out)}(\mathbf{x},t) = \Theta(t) \int_{-y_0}^{y_0} \rho(\mathbf{r},y,t)\, v(y)\, \delta\left(z - v(y)t\right)\, dy$$

$-v_0 < v(y) = \tanh y < v_0$

Applicability of classical bremsstrahlung formula

- Assume $\rho(\mathbf{r}, y, t) = \rho_{\text{in}}(\mathbf{r})\, \rho(y) \Theta(t)$ i.e., transverse profile is initialized

- The intensity of photons

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

Transverse form factor: $F(\omega R \sin\theta) = \int d^2 r_\perp \, \rho_{\text{in}}(r_\perp) e^{-i\omega \mathbf{n}\cdot\mathbf{r}_\perp} = \frac{3}{q^2}\left(\frac{\sin q}{q} - \cos q\right)$, $q = \omega R \sin\theta$

for a homogeneous sphere of radius R

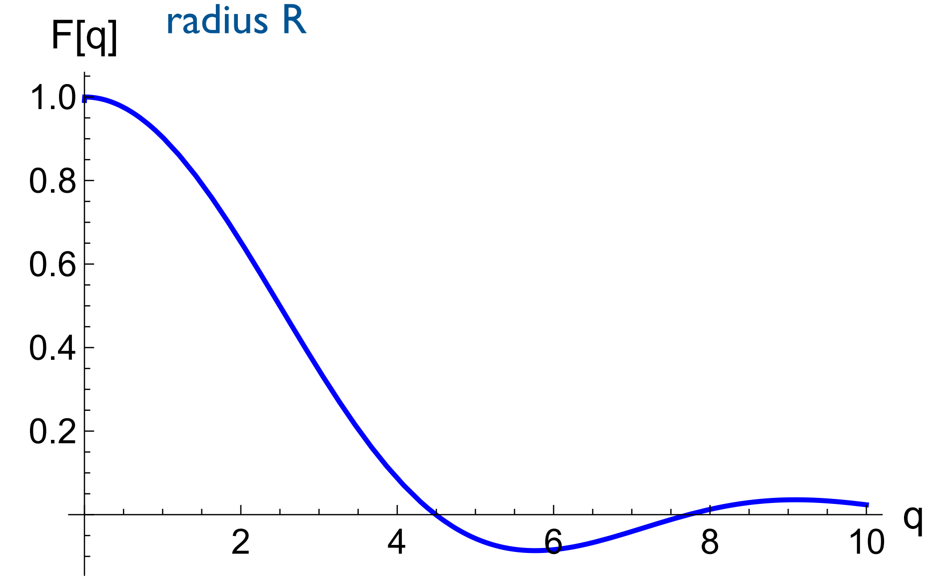
- For sufficiently soft and collinear photons

$$q = \omega R \sin\theta \lesssim 1$$

details of the transverse profile of the charge distribution are not resolved by the radiation.

The approximation breaks when $q \simeq 4$

If $R = 6.8\,\text{fm}\,,\ \omega = 1\,\text{GeV},\ \ \sin\theta = \frac{q}{\omega R} = 0.12 \ \Rightarrow\ \eta = 2.8$



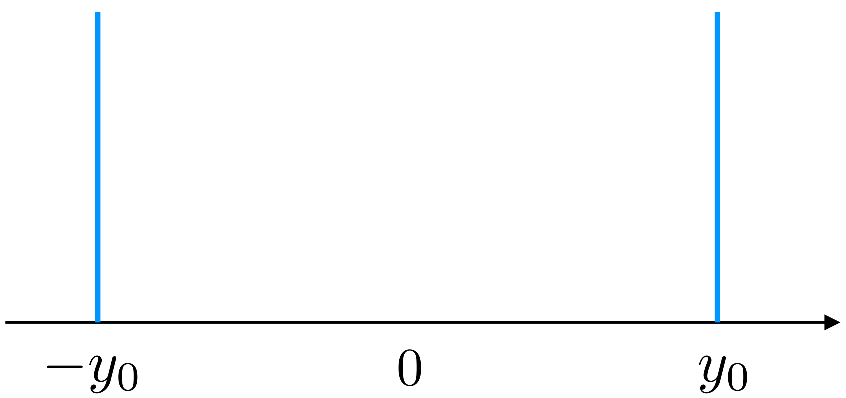
However, if $\omega \lesssim 200\,\text{MeV}\,, \eta \gtrsim 3 \ \Rightarrow\ q < 1,$ the intensity is insensitive to transverse profile.

Moreover, the photon spectrum is dominant for $q < 1$, hence we will work exclusively in this regime.

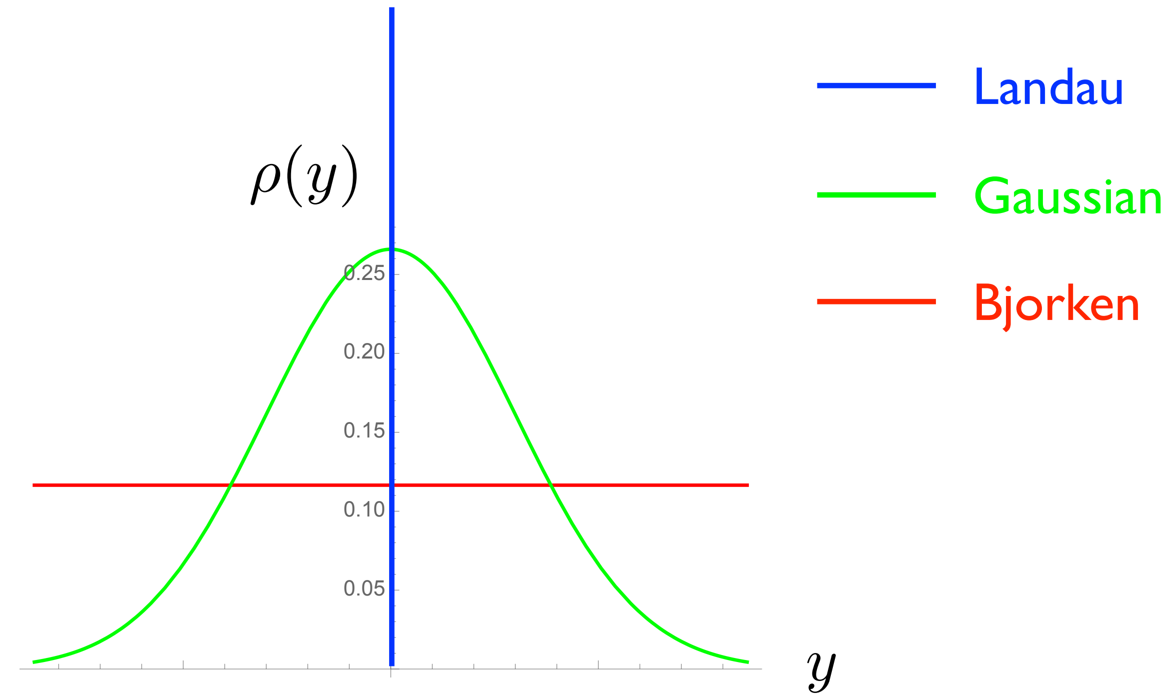
- Classical formula is sufficient for soft/collinear photons that do not resolve internal structure

Modelling charge-rapidity distribution $\rho(y)$

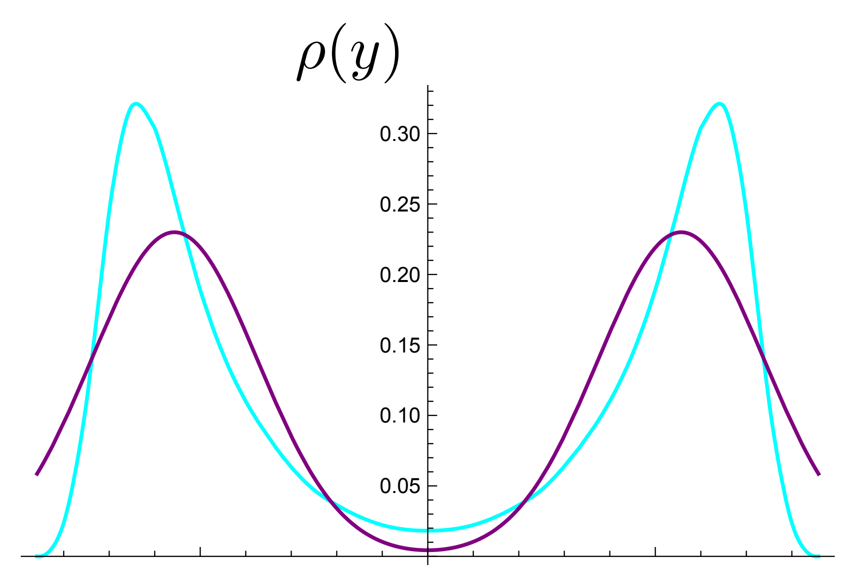
before collision

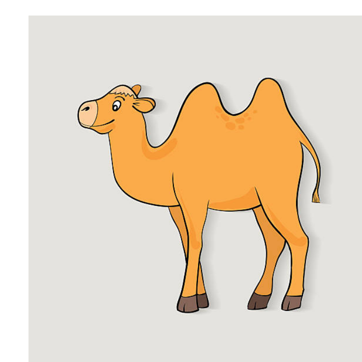


after collision



Each $\rho(y)$ is normalized by 2





camel 1

adopted from Mehtar-Tani and Wolschin
PRL 102 (2009) 182301, PRC 80 (2009) 054905

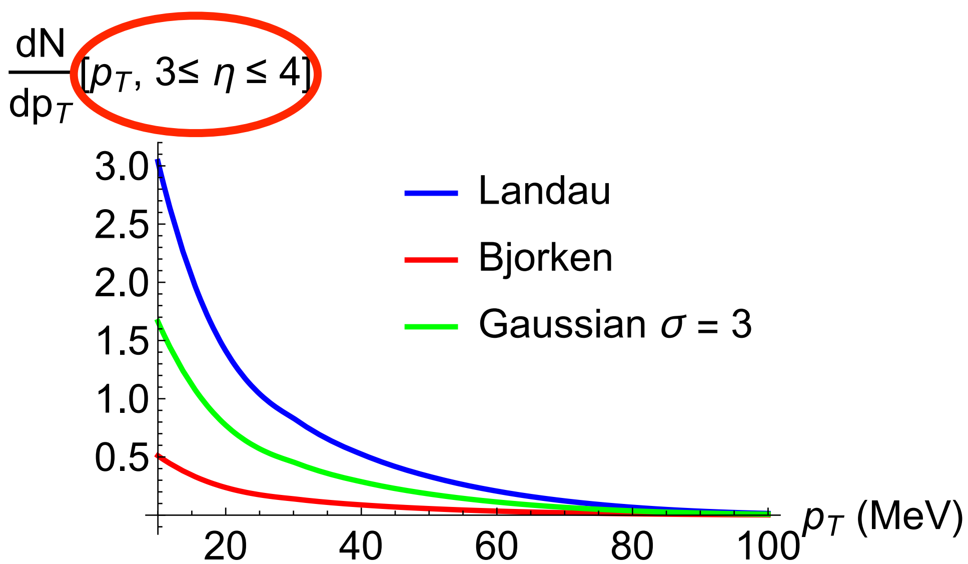
"Rapidity distribution of net baryons in central PbPb collisions at $\sqrt{s_{\rm NN}} = 5.52$ TeV"

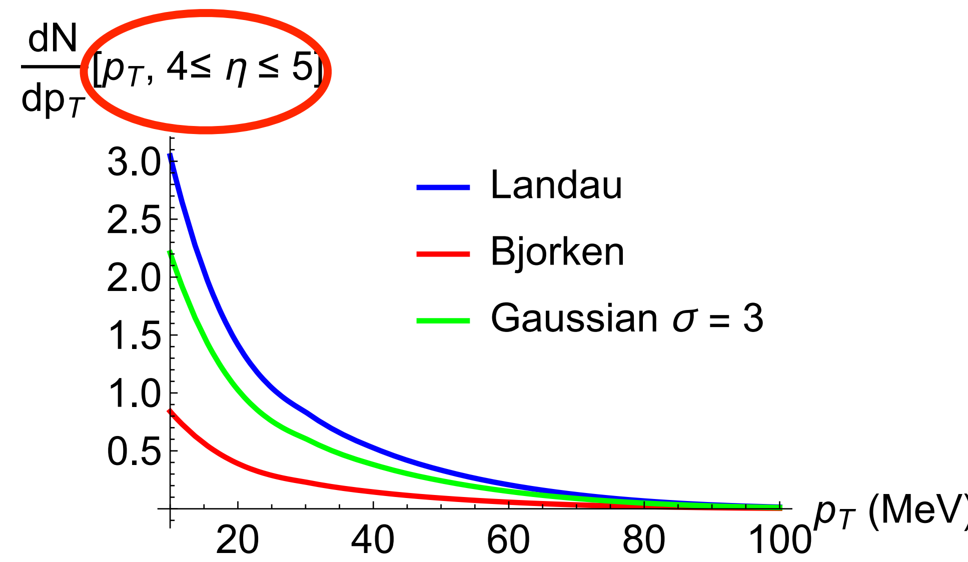
camel 2 $a \exp[-b\, y^2] \cosh[c\, y]$

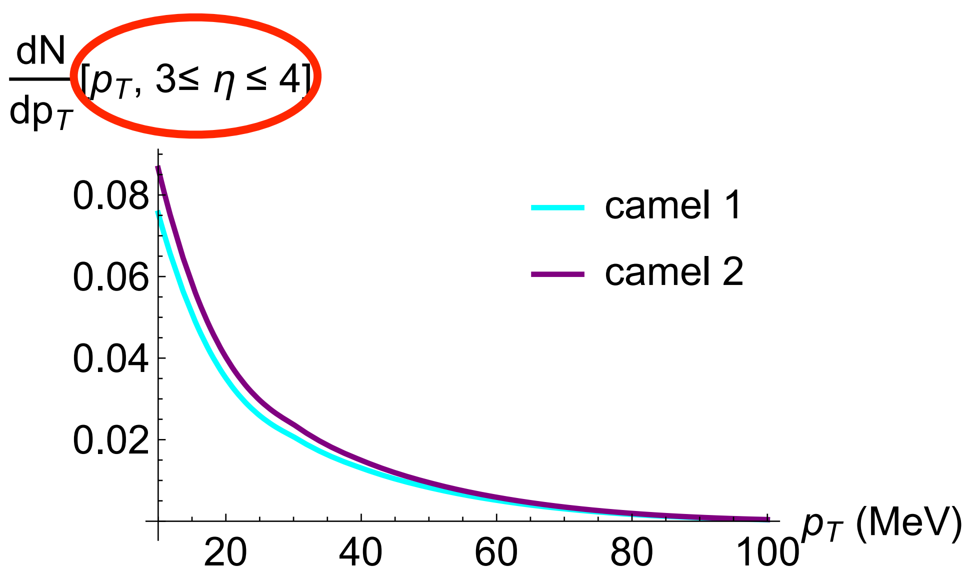
Number of photons per pT in pseudo-rapidity bins

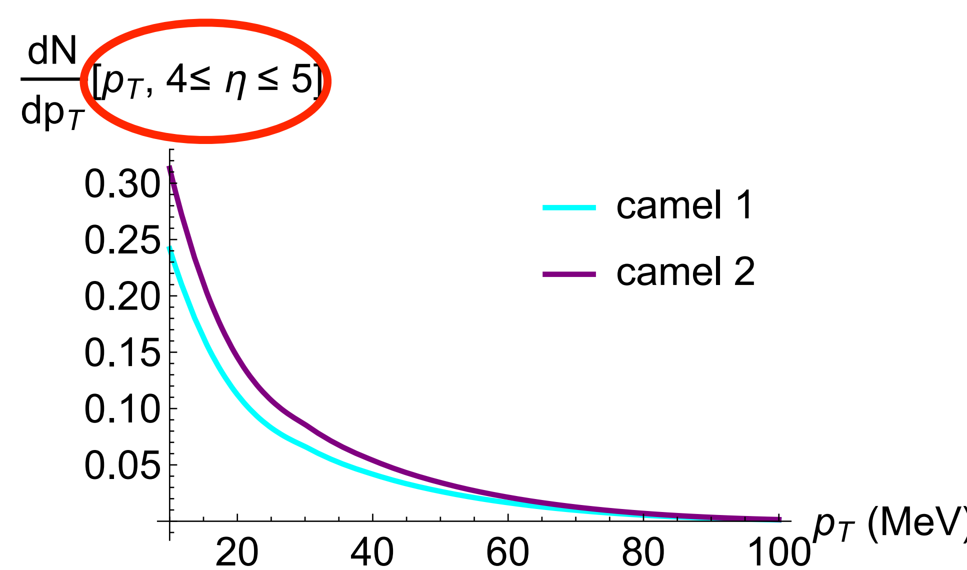
Input: charge-rapidity distribution $\rho(y)$ ➞ Output: photon spectrum $\frac{d^2 I}{d\omega d\Omega} \rightarrow \frac{d^2 I}{dp_T d\eta} \rightarrow \frac{d^2 N}{dp_T d\eta}$

Intensity — Number







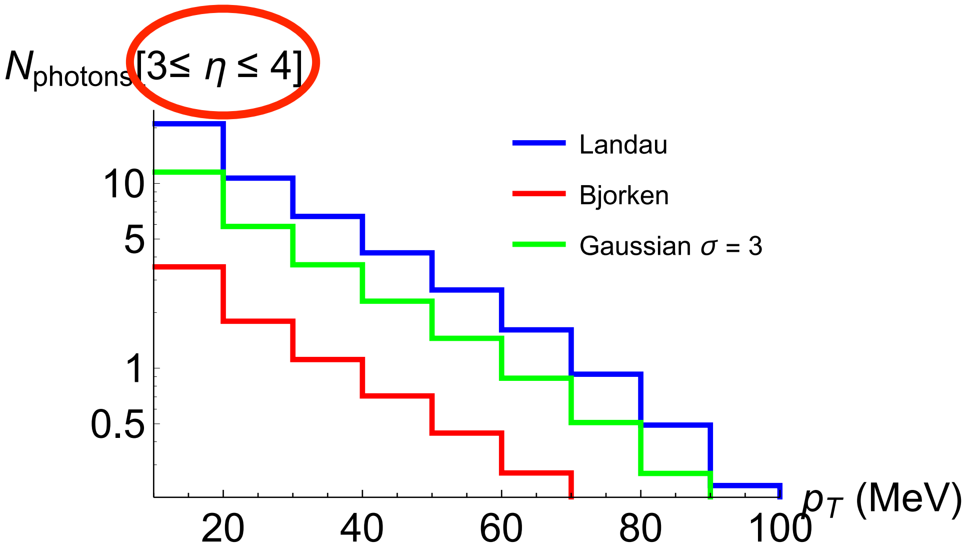


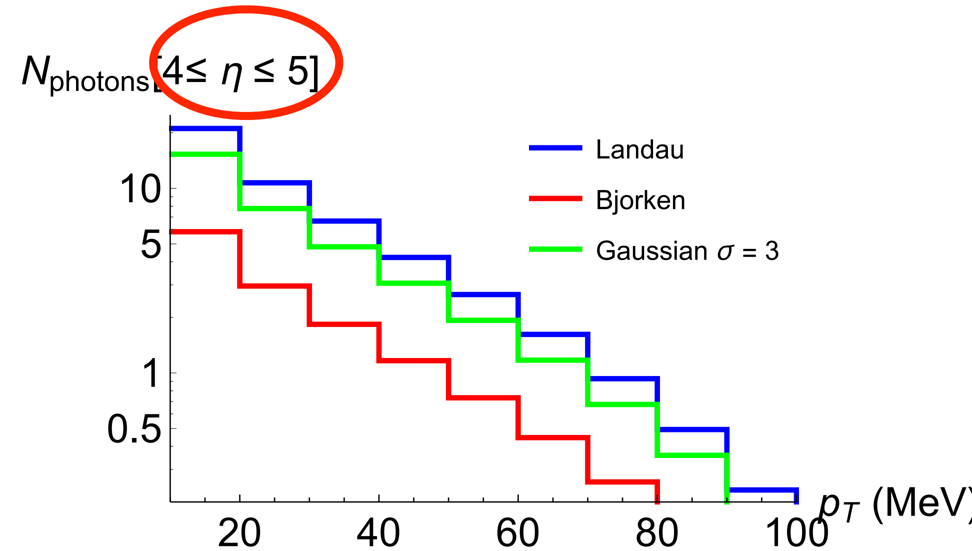
- Onset of soft 1/pT divergence (characteristic of photon bremsstrahlung) is visible

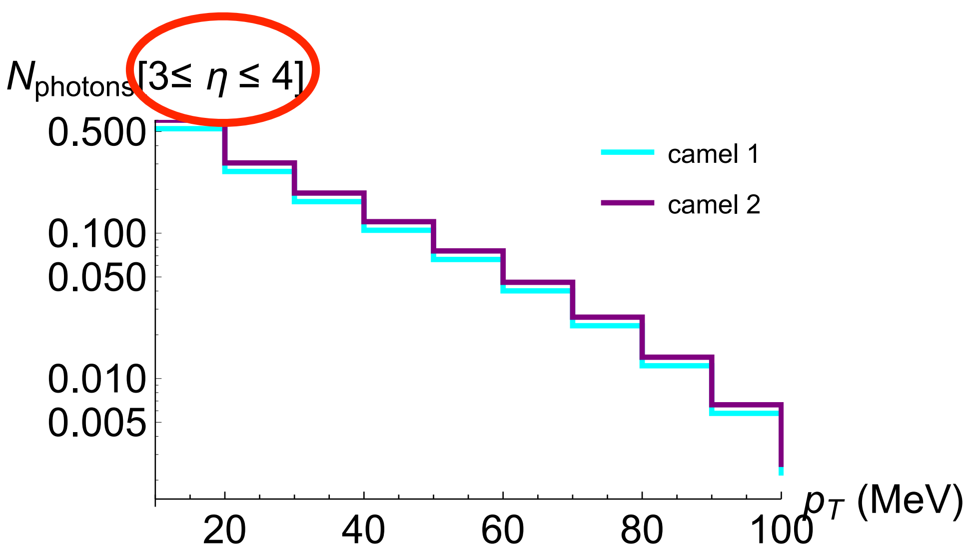
PbPb $\sqrt{s_{\mathrm{NN}}} = 5.02\mathrm{TeV}$

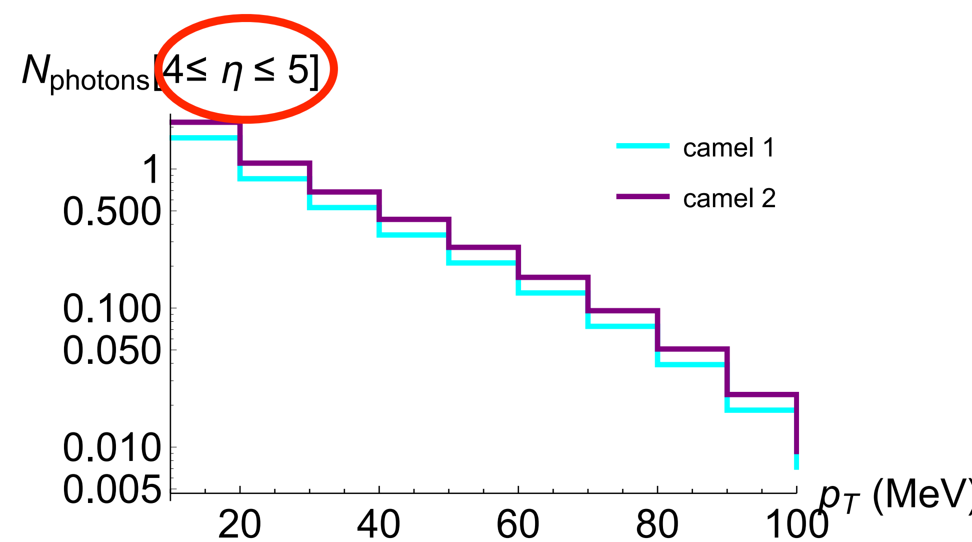
Expected photon yields per event in pT bins

- Is this detectable above background?







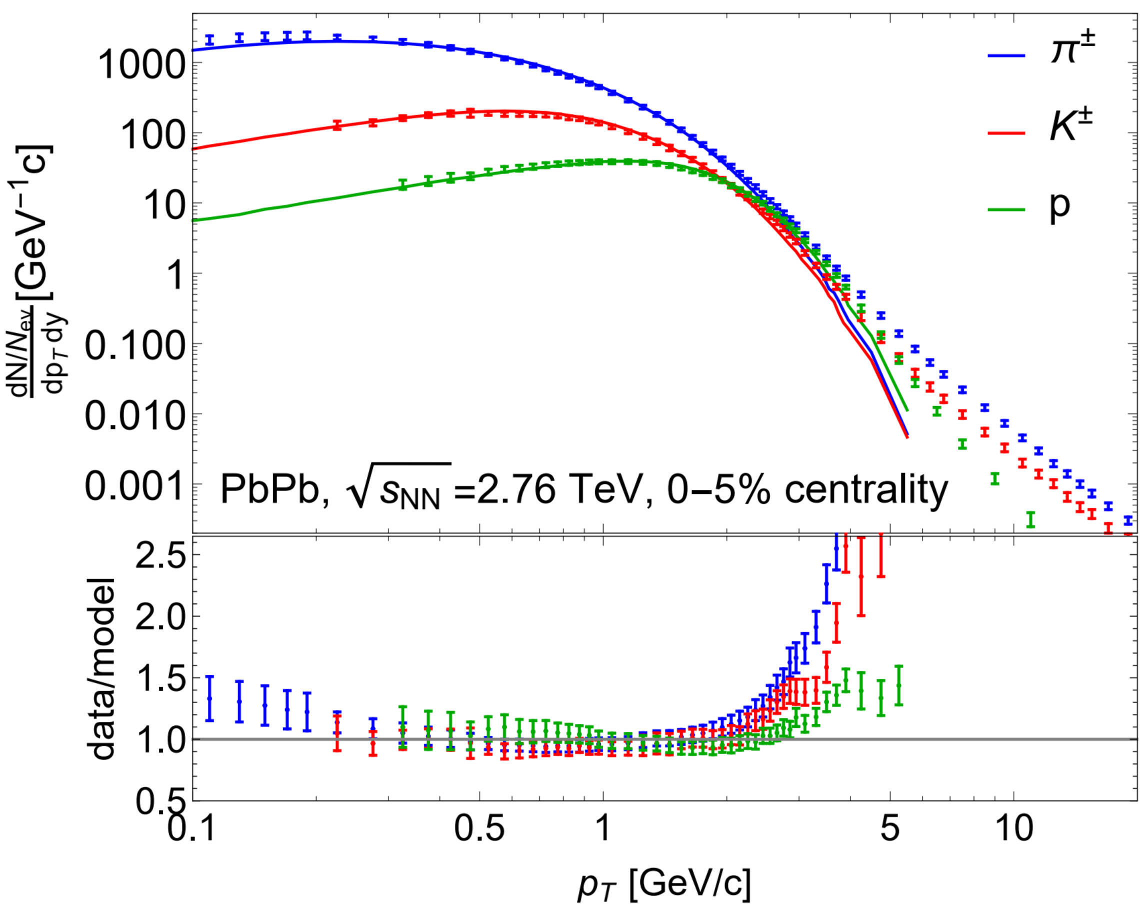


$\mathrm{PbPb}\ \sqrt{s_{\mathrm{NN}}} = 5.02\mathrm{TeV}$

Background photons

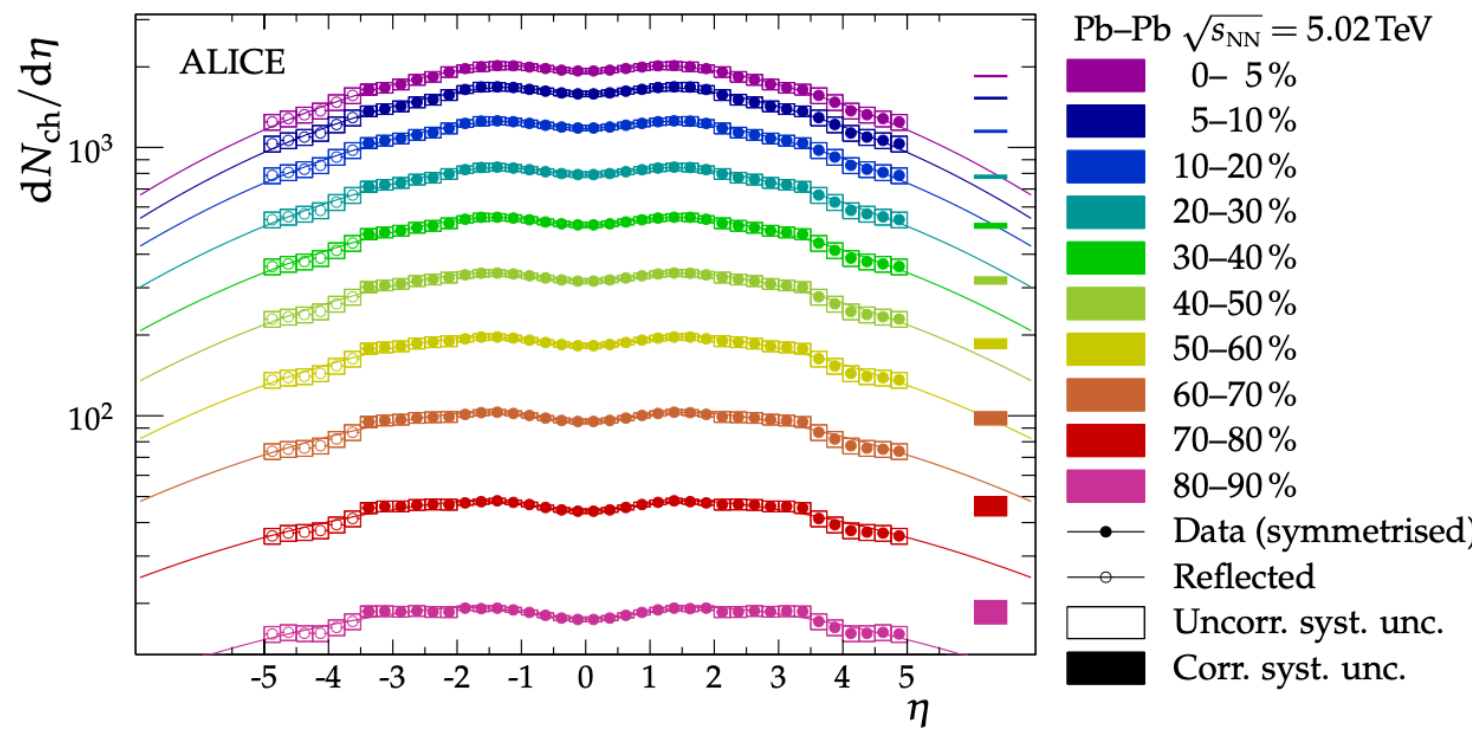
- Photons do not come only from electromagnetic bremsstrahlung
- π^0 decay photons are expected to be the dominant background
- How many? How are they distributed?

PRC 103 (2021) 054909
Nijs, van der Schee, Gursoy and Snellings



Soft $\frac{dN^{\pi^0}}{dp_T}$ is flat.

PLB 772 (2017) 567
ALICE Collaboration



$$\left.\frac{dN^{\pi^0}}{dp_T d\eta}\right|_{\eta=4} \simeq \frac{500}{\text{GeV}} = \frac{0.5}{\text{MeV}} \quad \rightarrow \quad \left.\frac{dN^{\gamma}}{dp_T d\eta}\right|_{\eta=4} \simeq \frac{1}{\text{MeV}}$$

$N^{\pi^0} \sim N^{\pi^\pm}$ $\qquad$ $\pi^0 \rightarrow \gamma + \gamma$

Can bremsstrahlung photons be separated from background?

- Signal-to-background

$$0.1 \lesssim \frac{S}{B} \lesssim 1 \quad \text{for} \quad p_T \lesssim 50\,\text{MeV} \quad \text{and} \quad \eta \gtrsim 3$$

- characteristically different pT dependence

$$\frac{dN^{\text{bgd}}}{dp_T} \simeq \text{const.} \quad \text{vs} \quad \frac{dN^{\text{brems}}}{dp_T} \propto \frac{1}{p_T}$$

- characteristically different centrality dependence

$$\frac{d^2N^{\text{bgd}}}{dp_T\,d\eta} \propto N_{\text{part}} \quad \text{vs} \quad \frac{d^2N^{\text{brems}}}{dp_T\,d\eta} \propto Z^2 \propto N_{\text{part}}^2$$

Conclusions

ALICE 3 is a new detector to have acceptance at very low-pT and rather forward rapidity.

We asked:

- What acceptance ALICE 3 should have to measure bremsstrahlung photons in PbPb @ LHC?

$\eta \gtrsim 3$ to be insensitive to transverse structure

$p_T \gtrsim 10$ MeV to see 1/pT shape

- Can bremsstrahlung photons be disentangled from the background of photons from meson decays?

Characteristically different pT & centrality dependence may help to separate bremsstrahlung photons

Proper study of background effects still needed

Thank you!