Femtoscopy and spectra of identified hadrons from CMS

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Motivation

$$\langle |\Psi|^2 \rangle$$

By measuring the correlation between hadrons emitted in high energy collisions of nucleons and nuclei we can learn a lot about the **spatial extent and shape of the created system**.

The **characteristic radii, the homogeneity lengths, of the particle emitting source can be extracted** with reasonable precision.

Let's analyze many systems, dimensions, with particle identification!

Results are public as CMS PAS HIN-14-013

Data analysis

- Elements
  - event selection: **double-sided trigger** (at least one HF tower with $>$ 3 GeV, both sides)
  - very **low bias tracking** ($p_{\mathrm{T}} >$ 0.1 GeV/c, at least two tracks)
  - pile-up: use bunch crossing if $N_{\mathrm{vtxs}} \leq 2$; take the vertex with the most tracks
  - pixel and strip chips: **gain calibration** for all datasets
  - datasets:

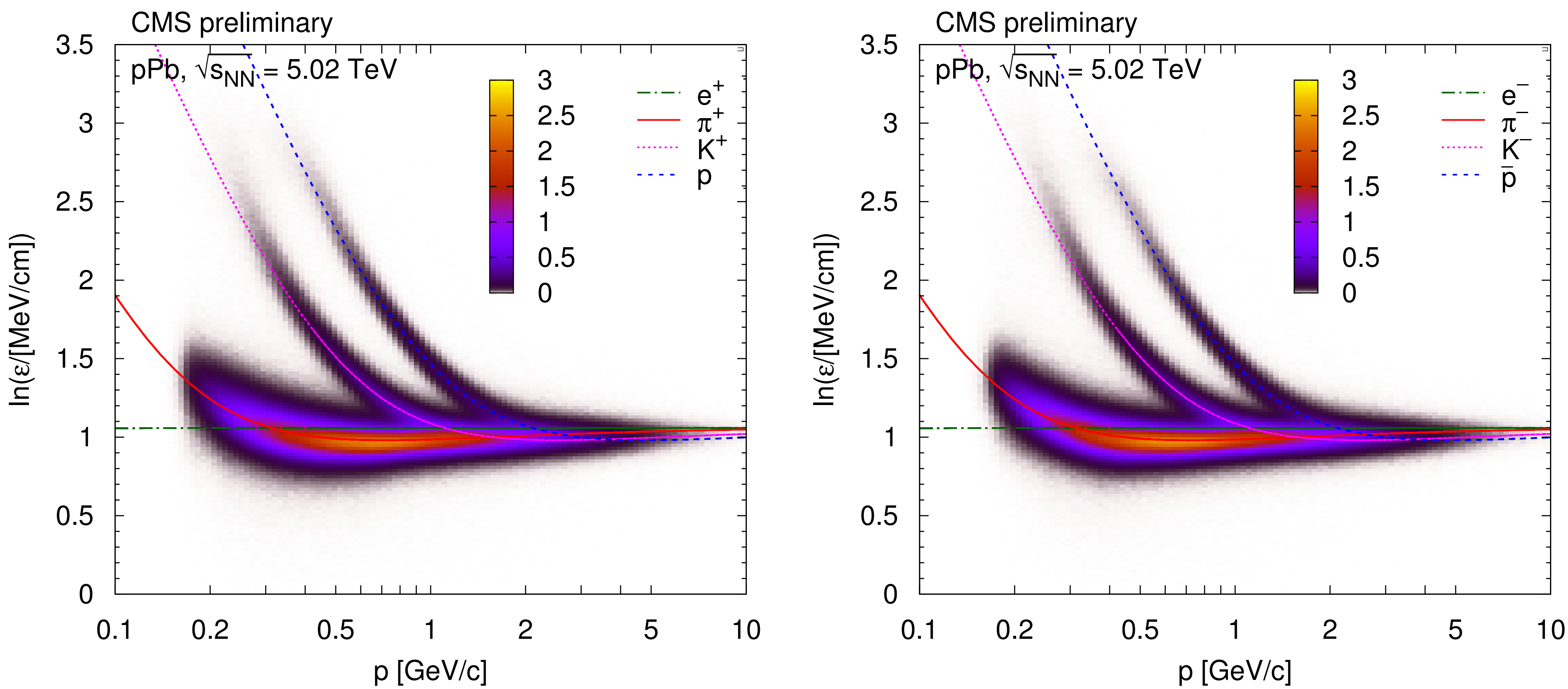
Collision	$\sqrt{s_{NN}}$	*Events*
pp	0.9 TeV	8.97 M
pp	2.76 TeV	9.62 M
pp	7 TeV	6.20 M
pPb	5.02 TeV	8.95 M
PbPb	2.76 TeV	3.07 M

PbPb 60-100% centrality covers the populated pp and pPb range very well

Methods are identical to the ones used in pp and pPb PID spectra paper

Measure of event "centrality": **number of reconstructed particles N_{rec} for $|\eta| < 2.4$**

Particle identification

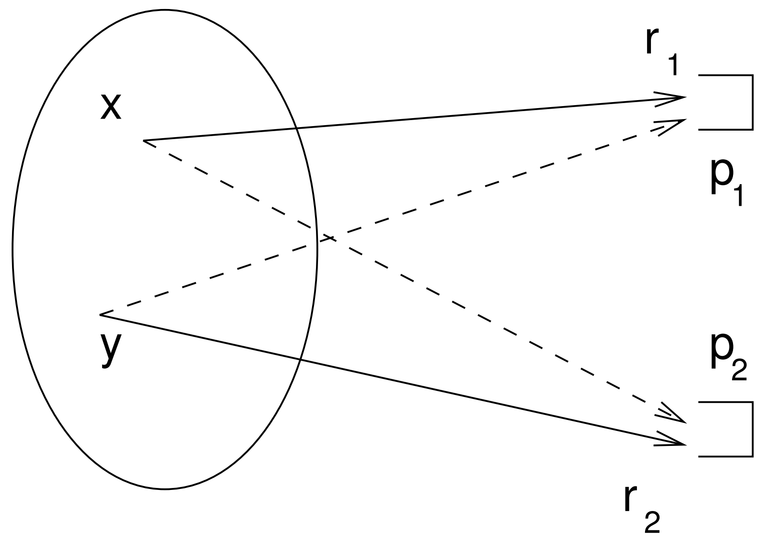


Particle-by-particle identification using specific ionization

In the momentum range $p < 1.15$ GeV/c for pions and kaons,
and $p < 2.00$ GeV/c for protons

Determine the **probability** of being a charged pion, kaons, proton, or electron

Bose-Einstein correlation – theory



The symmetrization of the joint wave function of identical bosons leads to correlations at low values of relative momenta q

$$C_{\mathsf{BE}}(q) \equiv P_{12} = \int d^4x d^4y |A_{12}|^2 \rho(x)\rho(y) =$$

$$= \int d^4x d^4y (1 + e^{iq(x-y)})\rho(x)\rho(y) = 1 + |\mathcal{F}(q)|^2$$

where $\mathcal{F}(q)$ is the Fourier transform of $\rho(r)$ density.

Since ρ is normalized, $\int d^4x\ \rho(x) = 1$, that is why $C_{\mathsf{BE}}(q=0) = 2$.

Correlated pairs: signal and background

- Collect pair distributions in
  - number of reconstructed charged particles N_{rec} in the event;
  - transverse pair momentum $k_{\text{T}} = |\boldsymbol{p}_{\boldsymbol{T},\mathbf{1}} + \boldsymbol{p}_{\boldsymbol{T},\mathbf{2}}|/2$;
  - relative momentum ($\boldsymbol{q}$) in the longitudinally co-moving system (LCMS):

    $q_{\text{inv}} = |\boldsymbol{q}|$ $\quad (q_{\text{l}}, q_{\text{t}})$ $\quad (q_{\text{l}}, q_{\text{o}}, q_{\text{s}})$

    (Here q_{o} is the component of $\boldsymbol{q}_{\text{t}}$ parallel to $\boldsymbol{k}_{\text{T}}$, q_{s} is the component of $\boldsymbol{q}_{\text{t}}$ perp to $\boldsymbol{k}_{\text{T}}$)

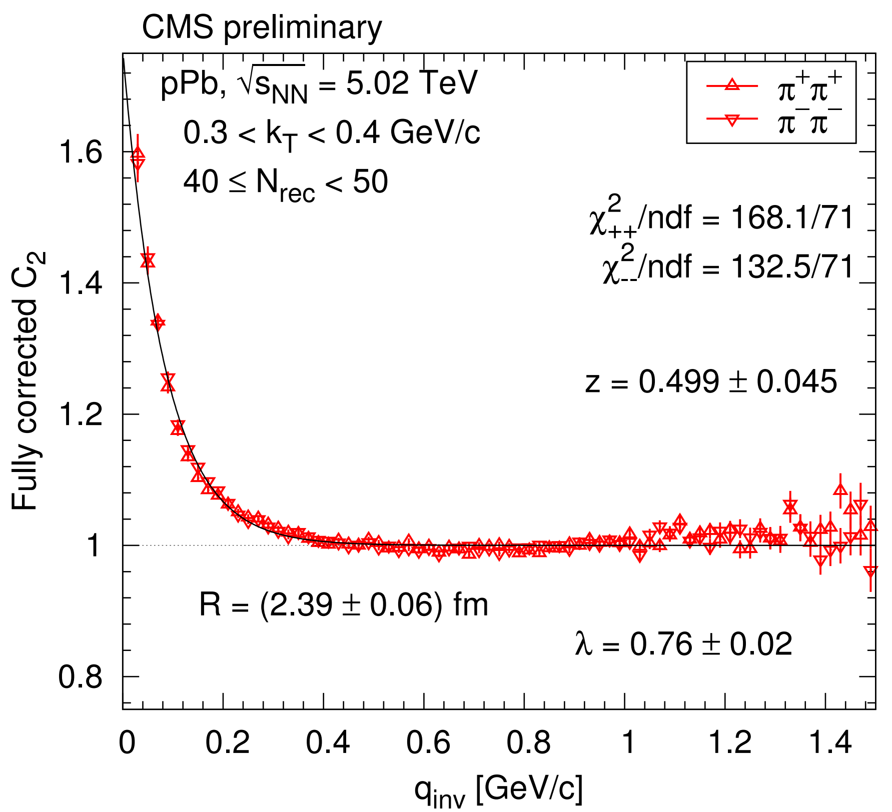
- Several choices for background

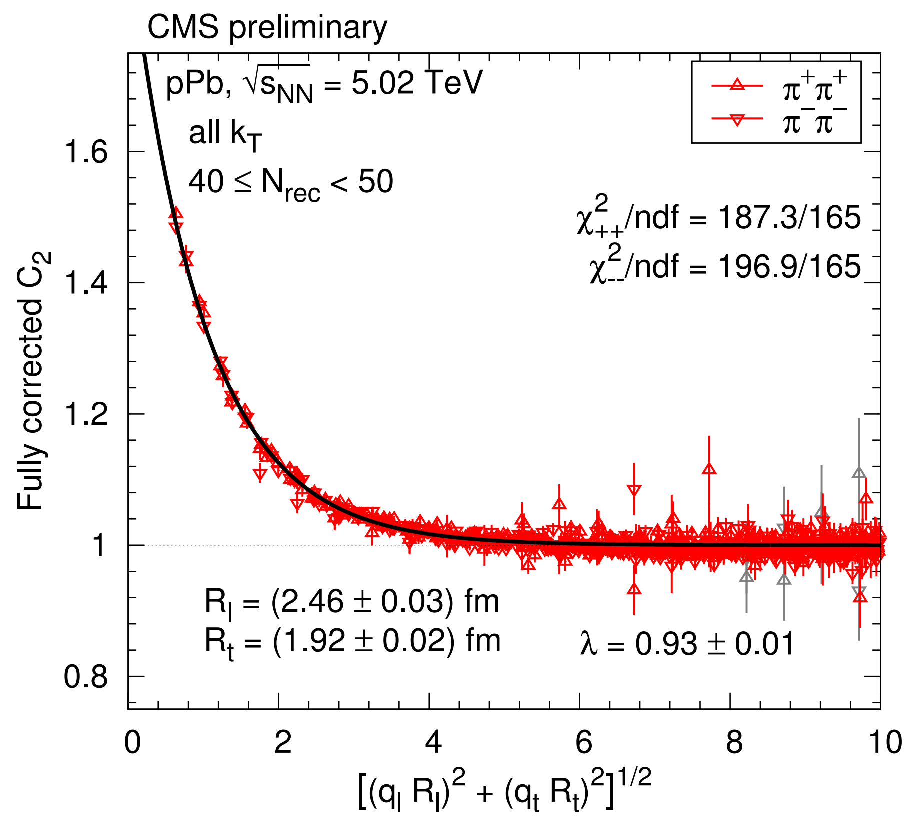
$$C_2(q) = \frac{N_{\text{signal}}(q)}{N_{\text{bckgnd}}(q)}$$

  - pair particles from the actual events with particles from some given number of preceding events (**"event mixing"**);
  - pair particles from the actual event, but rotate the laboratory momentum vector of the second particle around the beam axis by 90 degrees (**"rotated"**);
  - pair particles from the actual event, but negate the laboratory momentum vector of the the second particle (**"mirrored"**).

Took event mixing as central value, used the others for systematics

Some inspiration – Bose-Einstein





Fully corrected correlation function – exponential

Measured correlation – Bose-Einstein

- One dimension
  - Gaussian : $C_{\mathsf{BE}}(q) = 1 + \lambda \exp(-q^2 R^2) \Rightarrow \rho(r) = \frac{1}{R^3 (2\pi)^{3/2}} \exp\left(-\frac{r^2}{2R^2}\right)$
  - exponential : $C_{\mathsf{BE}}(q) = 1 + \lambda \exp(-qR) \Rightarrow \rho(r) = \frac{R}{2\pi^2} \frac{1}{[r^2 + (R/2)^2]^2}$.
- Multi-dimension
  - Our choice
    - Having tested several expressions, the “stretched exponential” parametrization does a very good job (χ^2/ndf) in one- and multi-dimensions
    - Theoretical studies show that for the class of **stable distributions**, with index of stability $0 < \alpha \leq 2$, the Bose-Einstein correlation function has a **stretched exponential** shape (Csörgő, Hegyi, Zajc, EPJC 36 (2004) 67)
    - In our case $\alpha \approx 1$, so in general the system is an **ellipsoid with Cauchy-type density distribution**. The functions to fit (modulo $\hbar c$)

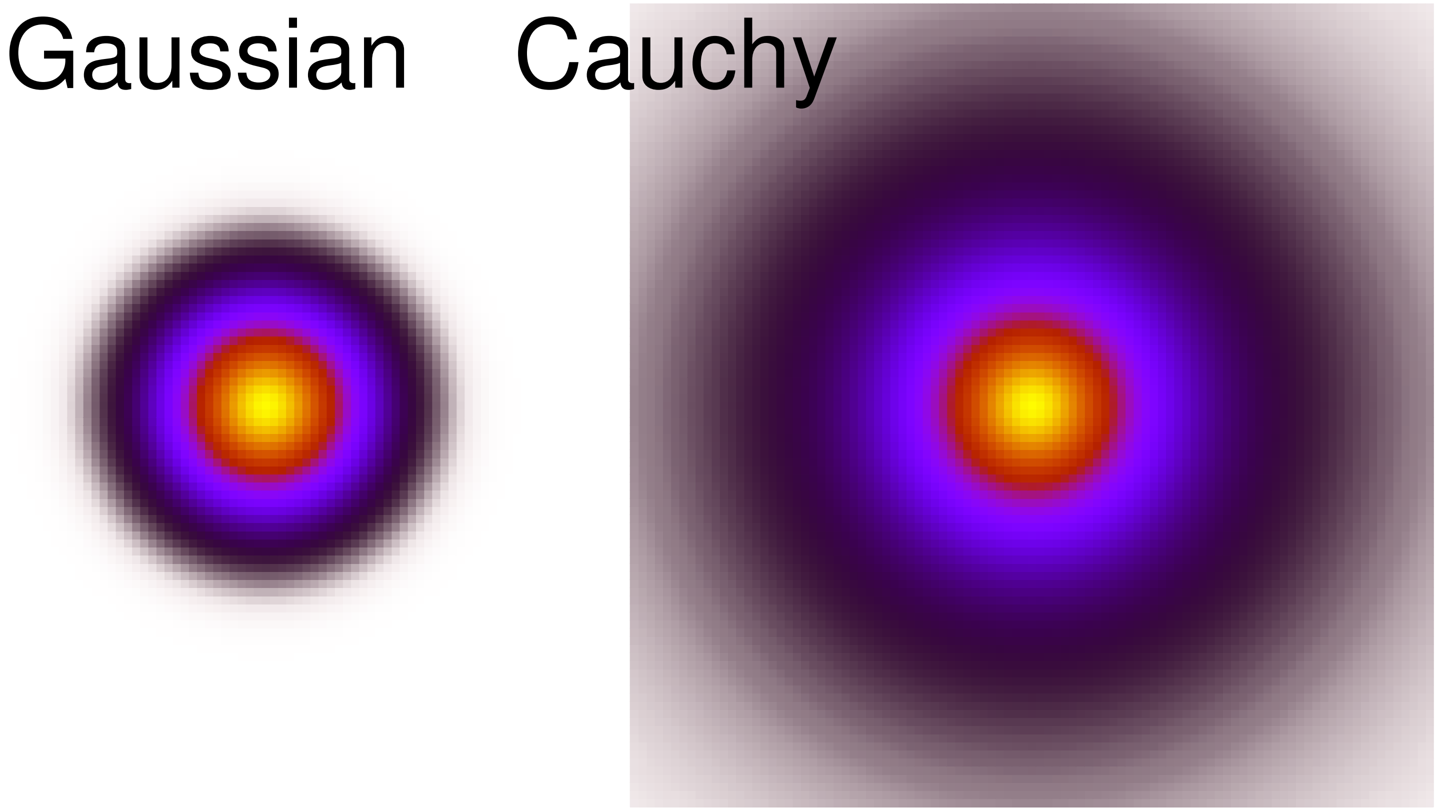
$$C_{\mathsf{BE}}(q_{\mathsf{inv}}) = 1 + \lambda \exp\left[-q_{\mathsf{inv}} R\right]$$

$$C_{\mathsf{BE}}(q_{\mathsf{l}}, q_{\mathsf{t}}) = 1 + \lambda \exp\left[-\sqrt{(q_l R_l)^2 + (q_t R_t)^2}\right]$$

$$C_{\mathsf{BE}}(q_{\mathsf{l}}, q_{\mathsf{o}}, q_{\mathsf{s}}) = 1 + \lambda \exp\left[-\sqrt{(q_l R_l)^2 + (q_o R_o)^2 + (q_s R_s)}\right]$$

All data can be projected onto a single (1D) variable!

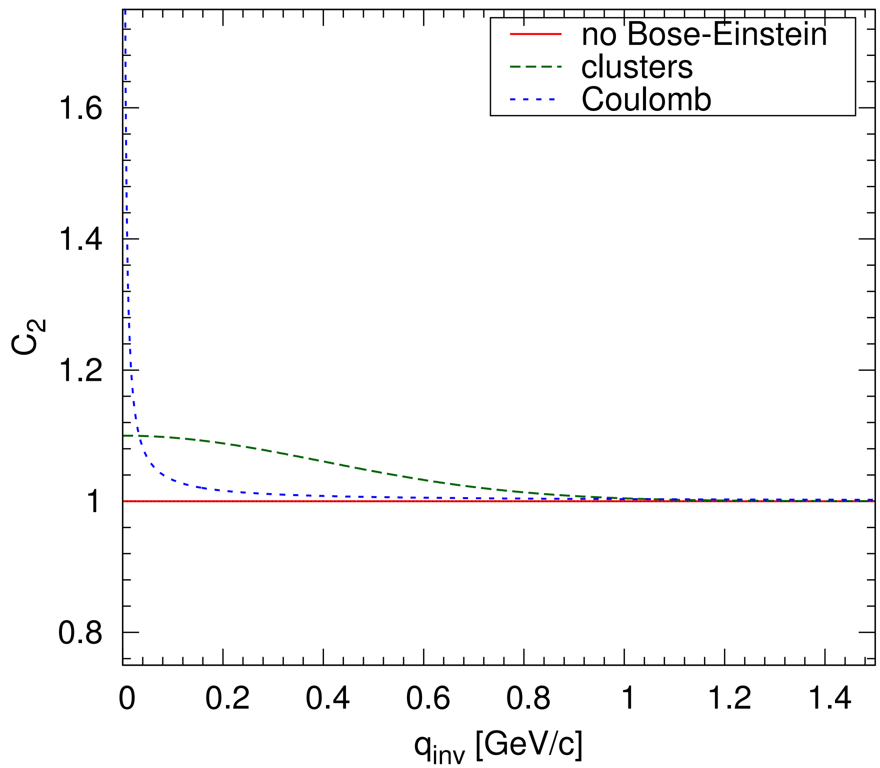
Measured correlation – Bose-Einstein



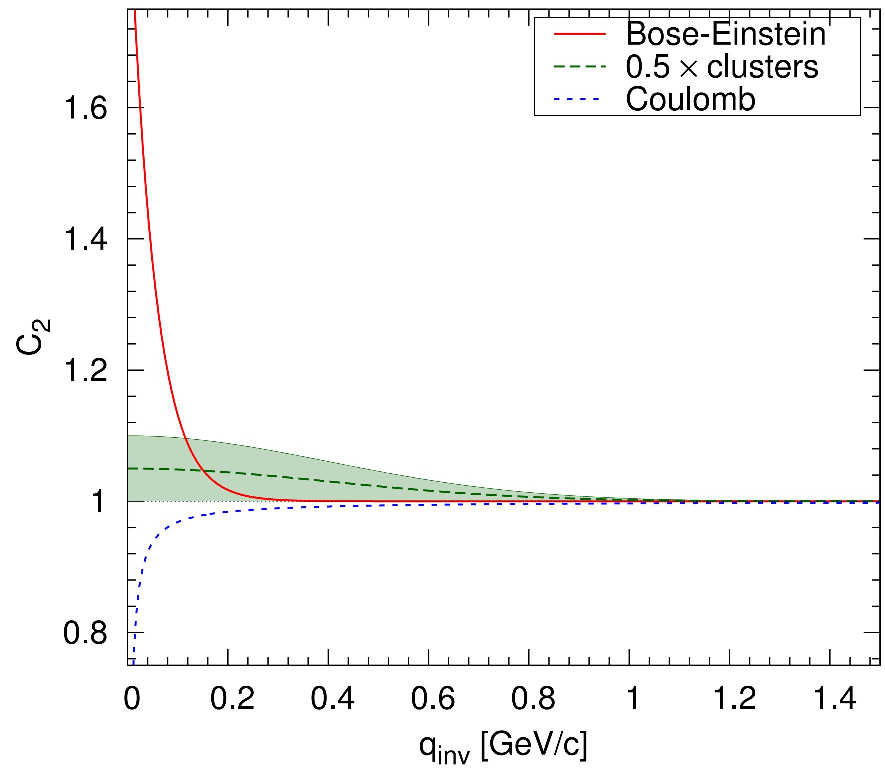
They describe quite different sources

Measured correlation – elements

Unlike-sign (+−)



Like-sign (++ and − −)



- Elements
  - Bose-Einstein correlation: $\Leftarrow$ This is what we are interested in
  - Contribution from correlated clusters: mini-jets, multi-body resonance decays
  - The effect of the Coulomb interaction (between the members of the pair)

Measured correlation – Coulomb correction

- Coulomb interaction
  - The Coulomb **relative wave function** is
    $\Psi(\boldsymbol{k},\boldsymbol{r}) = \Gamma(1+i\eta)\exp(-\pi\eta/2)\exp(i\boldsymbol{k}\cdot\boldsymbol{r})F\left[-i\eta, 1, i(kr-\boldsymbol{k}\cdot\boldsymbol{r})\right]$
  - The effect of the Coulomb interaction is
    $K(q_\mathrm{inv}) = \int d^3\boldsymbol{r}\ f(\boldsymbol{r})\ |\Psi(\boldsymbol{k},\boldsymbol{r})|^2$
  - For pointlike source, $f(\boldsymbol{r}) = \delta(\boldsymbol{r})$, the Gamow factor is
    $G(\eta) = |\Psi(r=0)|^2 = \frac{2\pi\eta}{\exp(2\pi\eta)-1}$

Deviations from point-like source seen for kaons

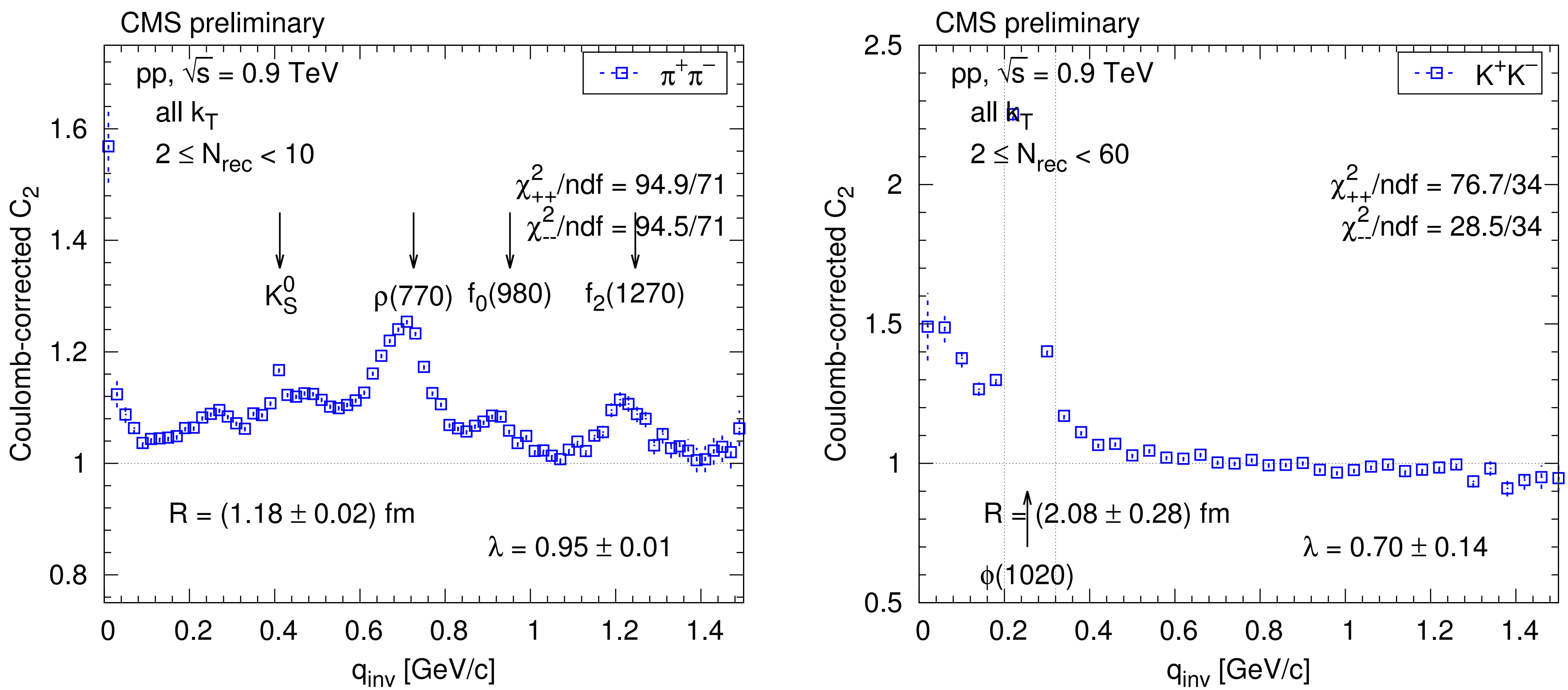
Do the **full calculation**, and plug in the **Cauchy density** distribution!

$$\underline{\underline{\int |F|^2 f(r) d^3 r}} = 1 + 2\eta \int_0^\infty \left[\frac{\cos(2kr)-1}{kr} + 2\,\mathrm{Si}(2kr)\right] \frac{R}{2\pi^2} \frac{1}{\left[r^2 + (R/2)^2\right]^2} 2\pi r^2 \mathrm{d}r \approx$$

$$\approx \underline{\underline{1 + \pi\eta \frac{q_\mathrm{inv} R}{1.26 + q_\mathrm{inv} R}}}$$

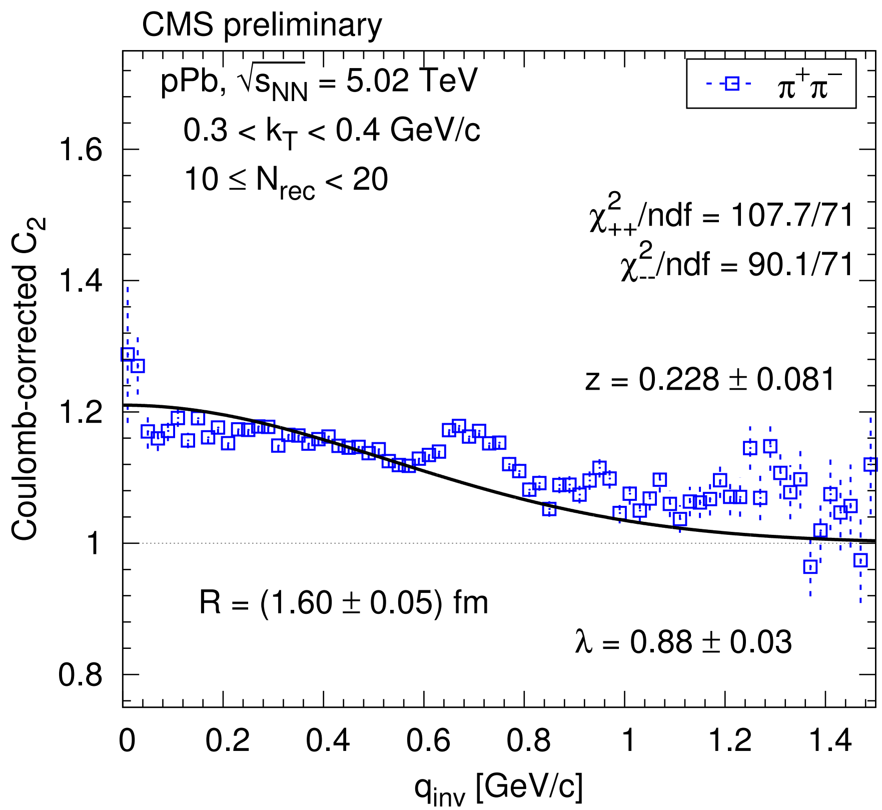
Analytic formula for Coulomb correction! No need for iterations on R

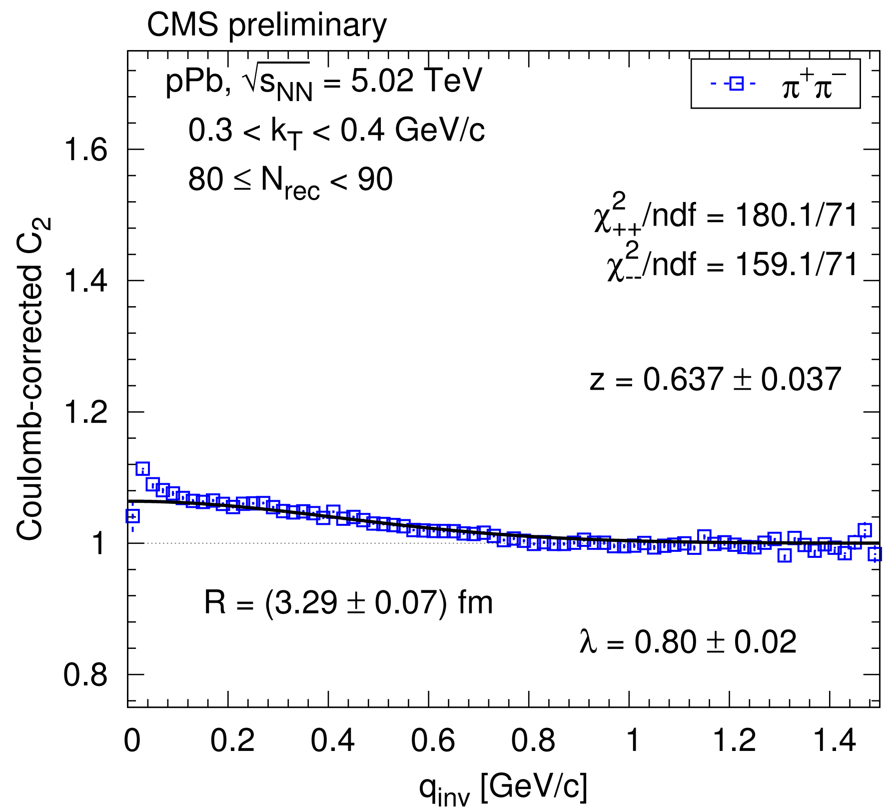
Measured correlation – resonances



- Unlike-sign
  - what are those **peaks**? ⇒ **two-body decays of known resonances**; their contribution diminishes as N_{rec} goes up; but does not matter for like-sign

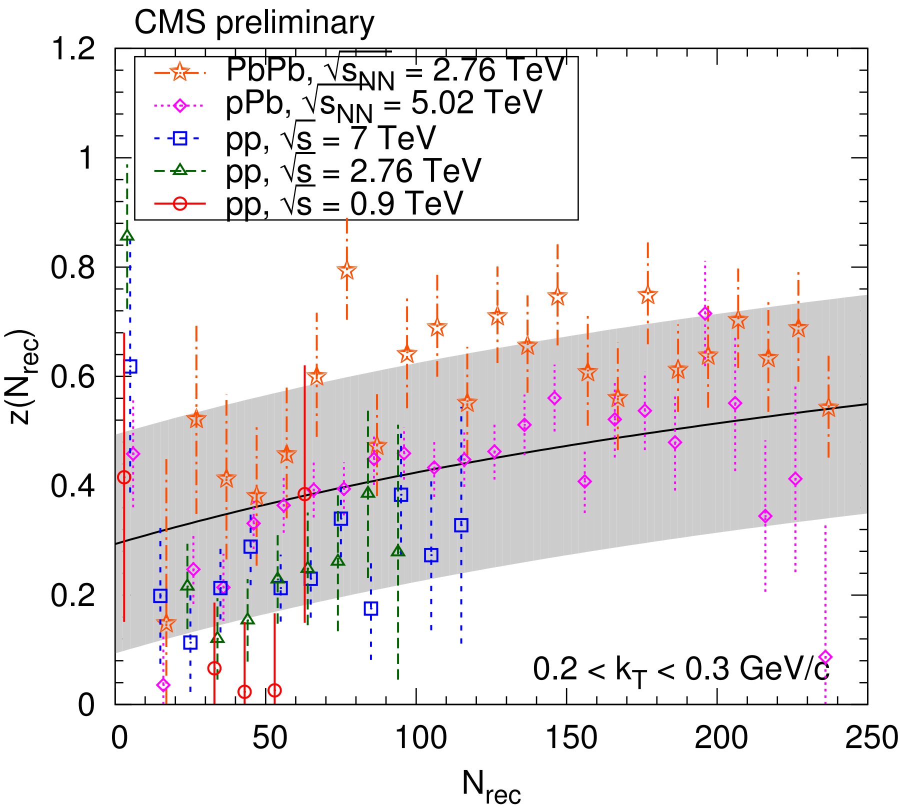
Measured correlation – clusters

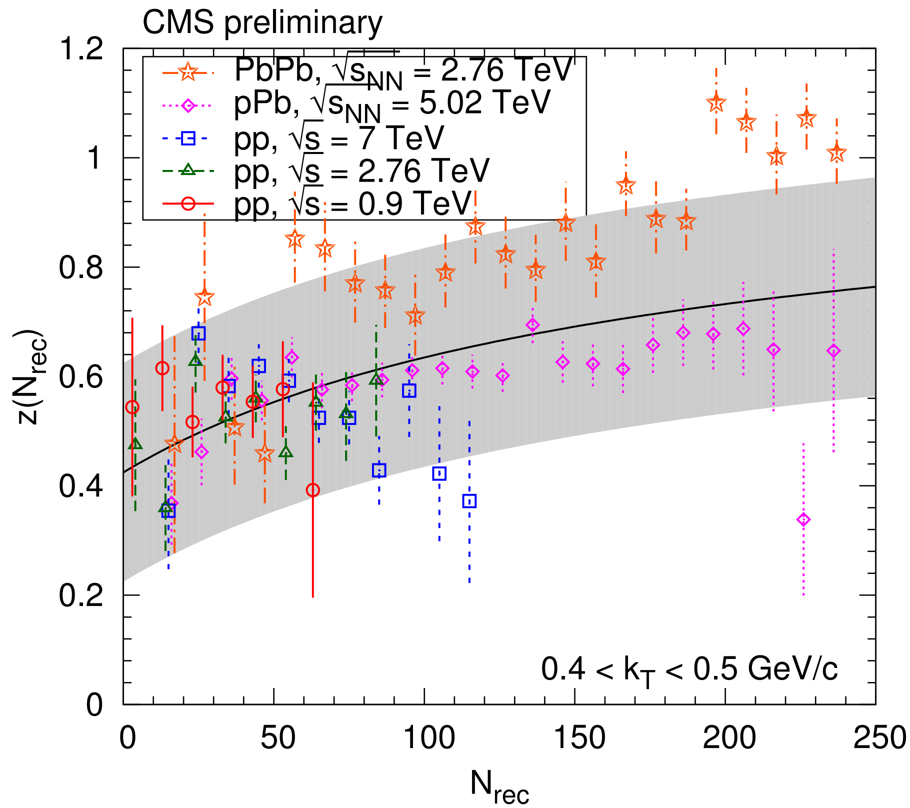




- Unlike-sign
  - what are those peaks? ⇒ two-body decays of known resonances; their contribution diminishes as N_{rec} goes up; but does not matter for like-sign
  - what is **Gaussian-like hump** at low q_{inv}? **cluster contribution (mini-jets and multi-body resonances decays)**; this is particularly annoying since these are present for like-sign as well; highly correlated with λ

Measured correlation – ratio of cluster contribution

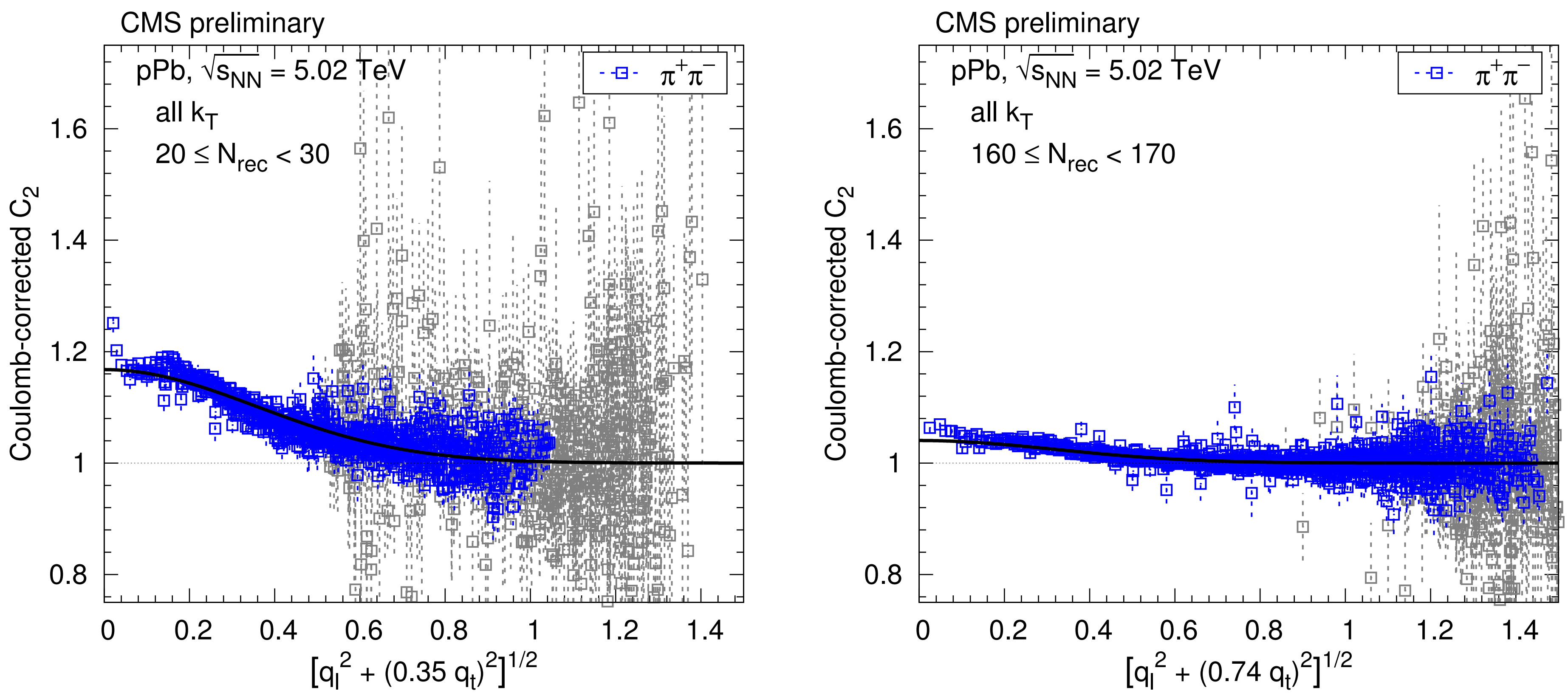




Ratio of cluster contribution for like-sign wrt unlike-sign pairs

Parametrize z as a function on k_{T} and N_{rec} for all reactions

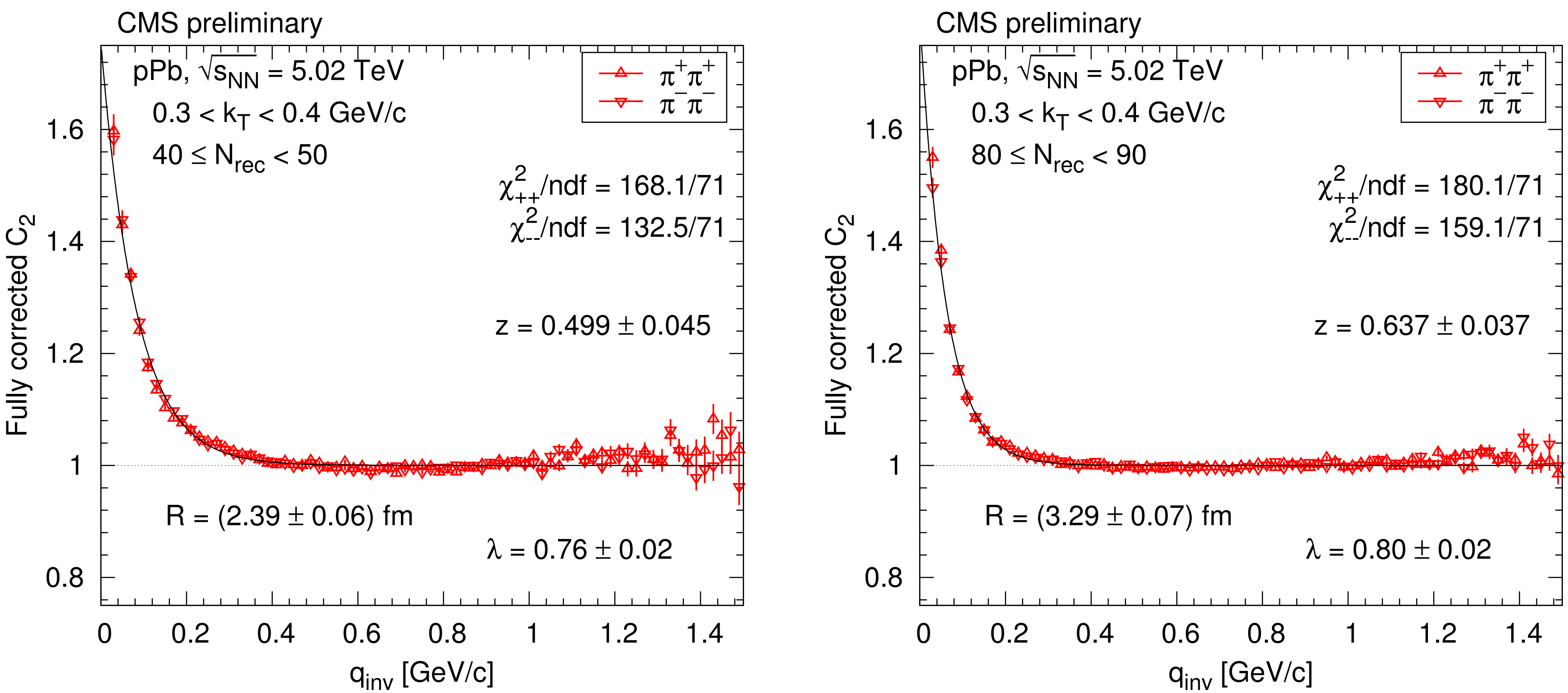
Measured correlation – unlike-sign – 2D



Using the parametrization of the cluster contribution

Looks good

Bose-Einstein correlation functions – q_{inv} – pions

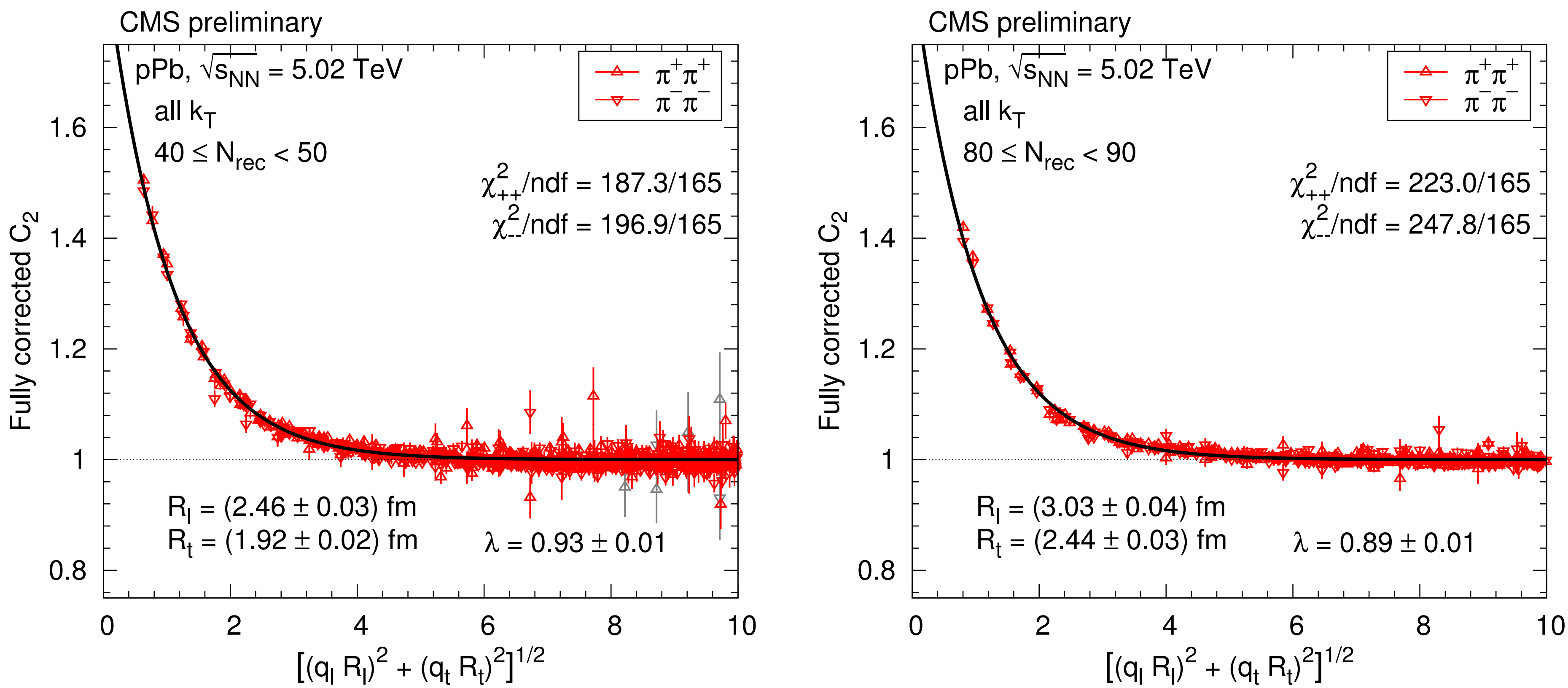


We will fit the following form to $++$ and $--$

$$C_2^{\pm\pm}(q_{\text{inv}}) = c\ K^{\pm\pm}(q_{\text{inv}})\ \left[1 + \boldsymbol{z(N_{\text{rec}}, k_{\text{T}})} \frac{b}{\sigma_b\sqrt{2\pi}} \exp\left(-\frac{q_{\text{inv}}^2}{2\sigma_b^2}\right)\right]\ C_{\text{BE}}(q_{\text{inv}})$$

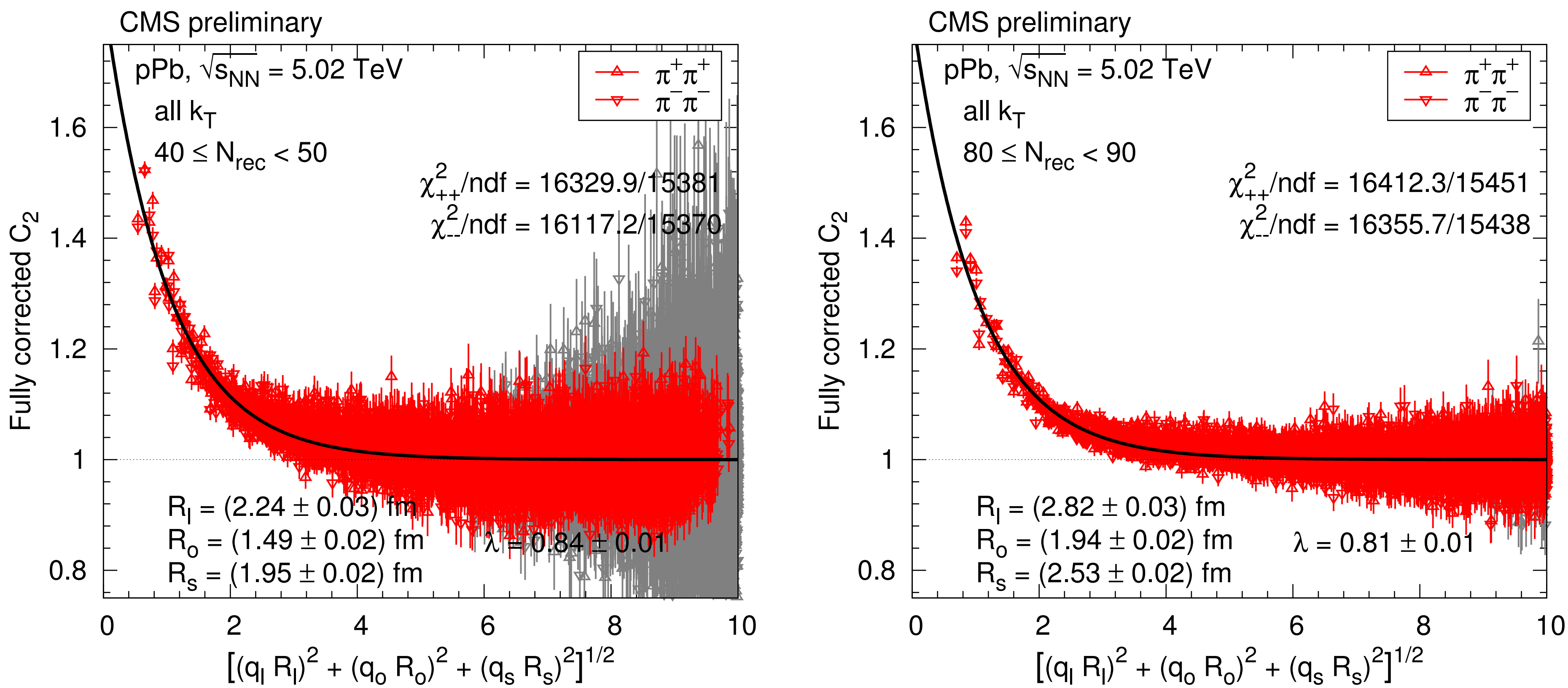
The exponential parametrization in $C_{\text{BE}}(q_{\text{inv}})$ is an excellent choice!

Bose-Einstein correlation functions – (q_l, q_t) – pions



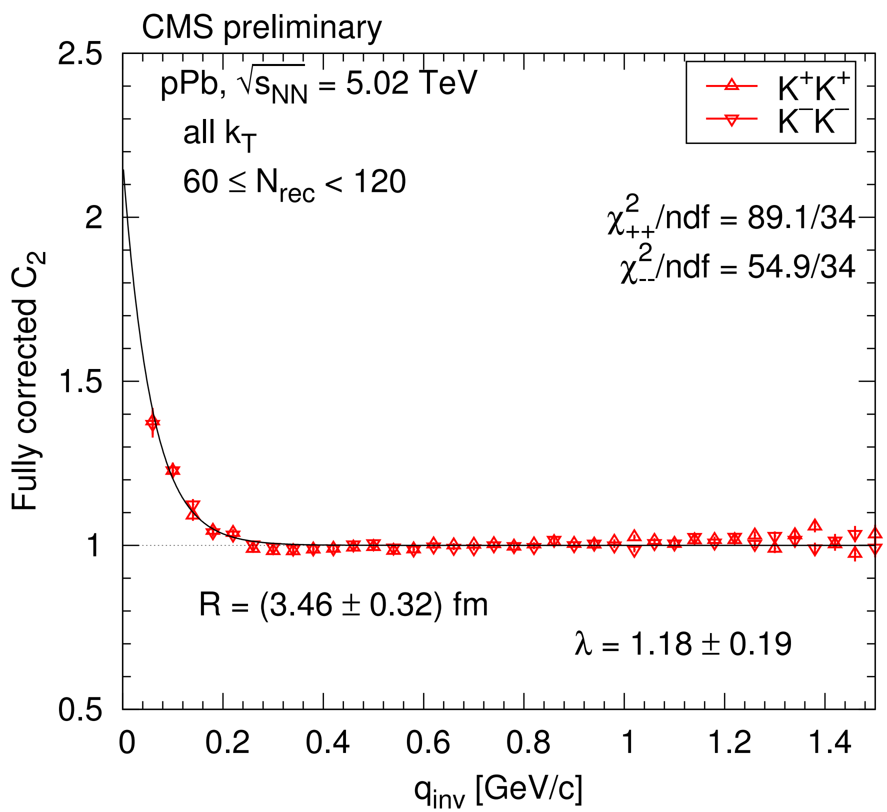
As a function of $\sqrt{(q_l R_L)^2 + (q_t R_T)^2}$

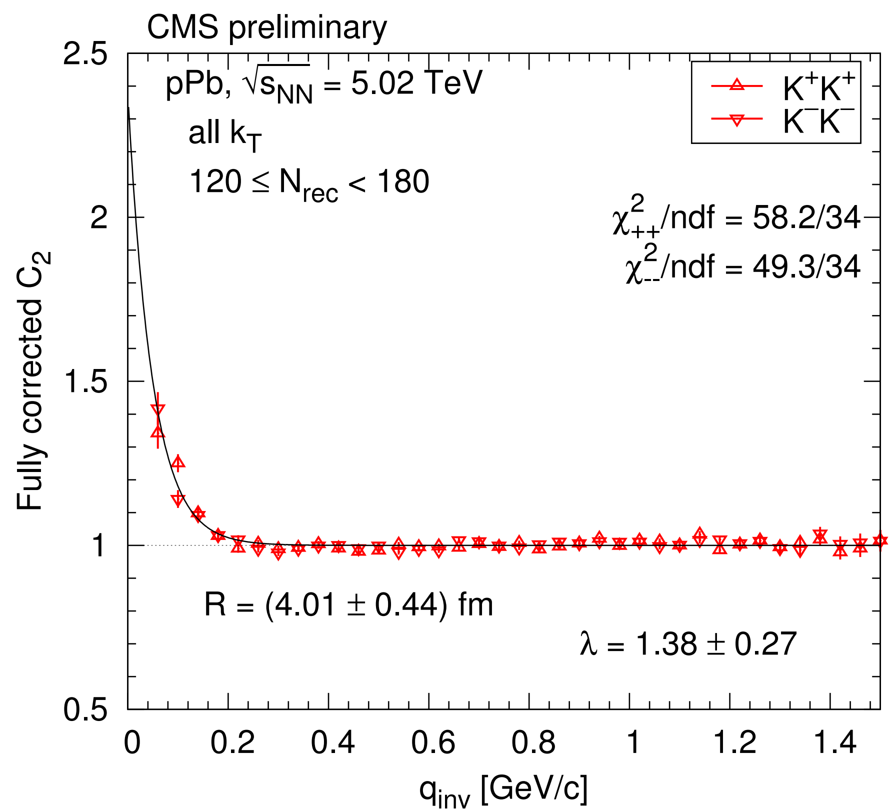
Bose-Einstein correlation functions – (q_l, q_o, q_s) – pions



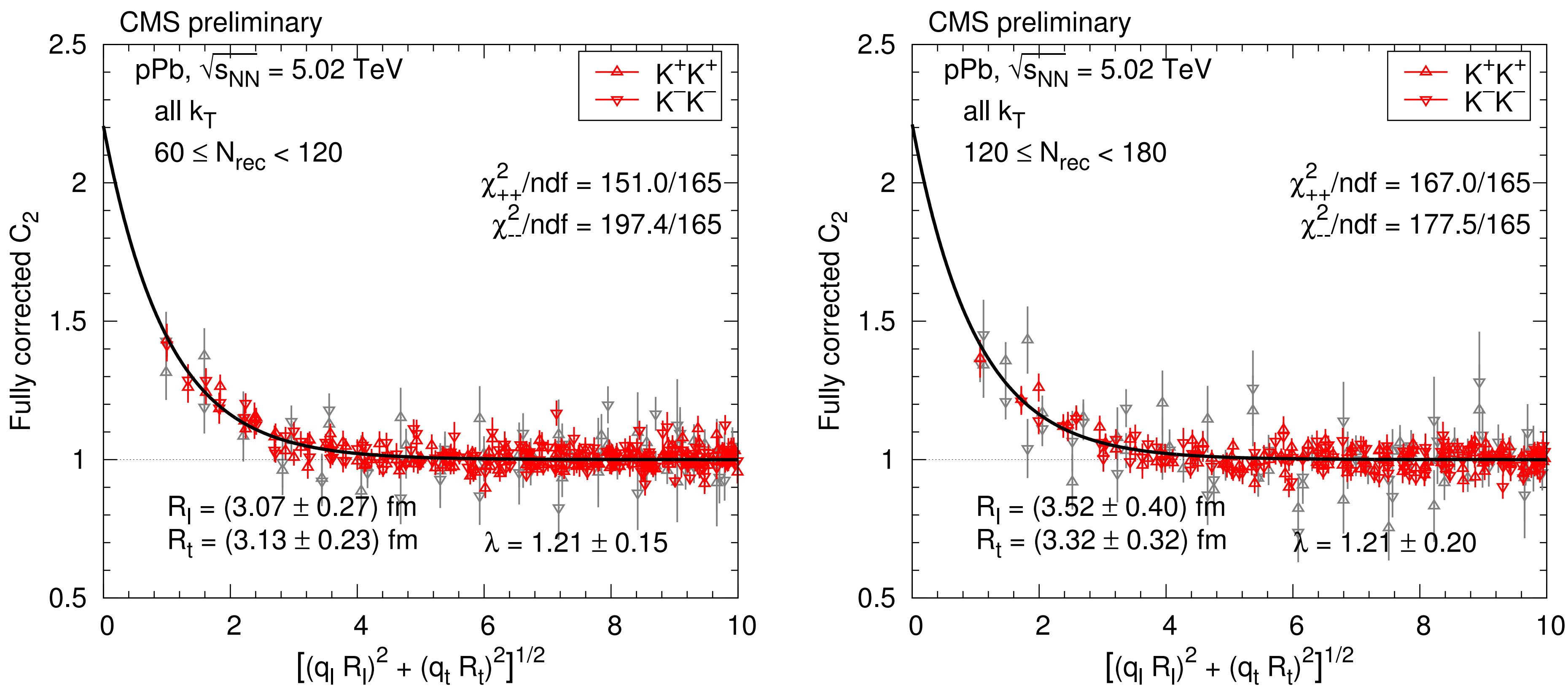
As a function of $\sqrt{(q_l R_l)^2 + (q_o R_o)^2 + (q_s R_s)^2}$

Bose-Einstein correlation functions – q_{inv} – kaons



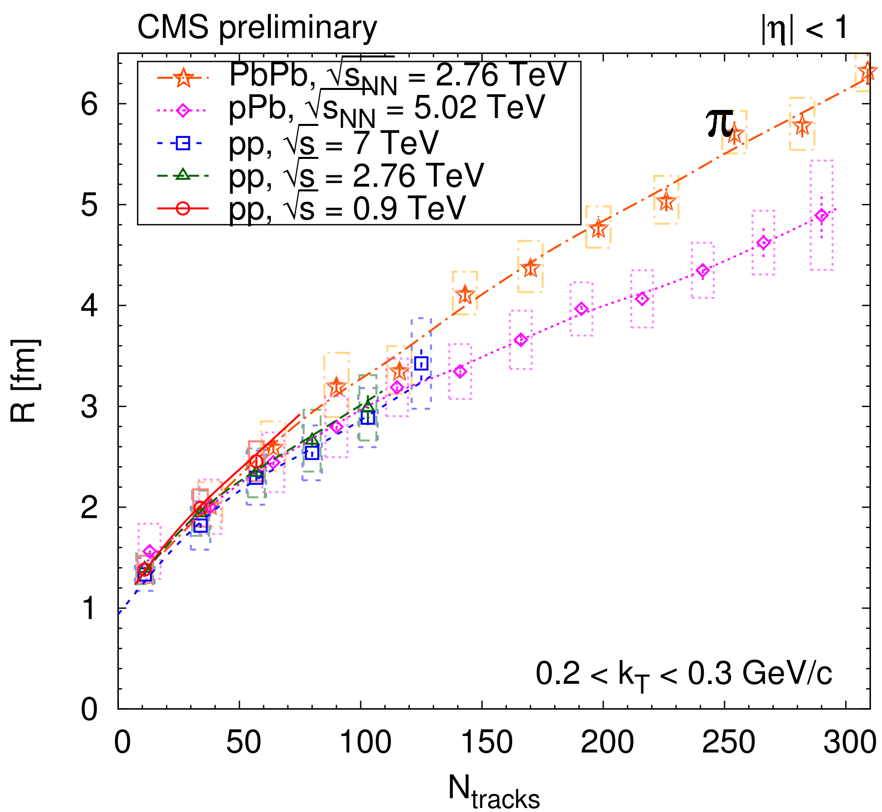


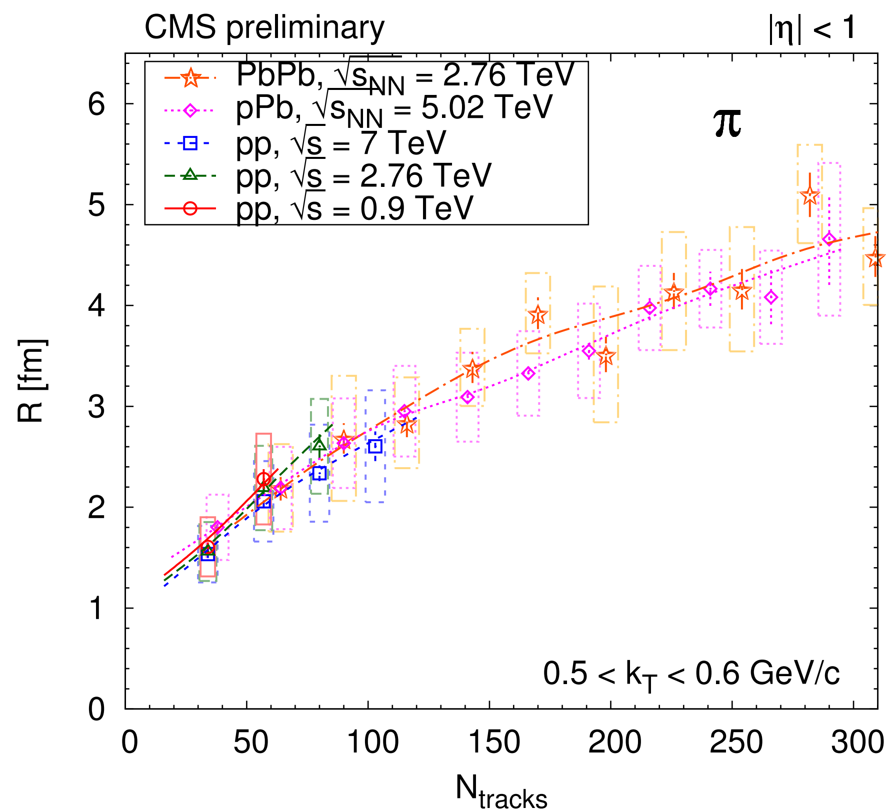
Bose-Einstein correlation functions – (q_l,q_t) – kaons



Looks good, λ is around 1

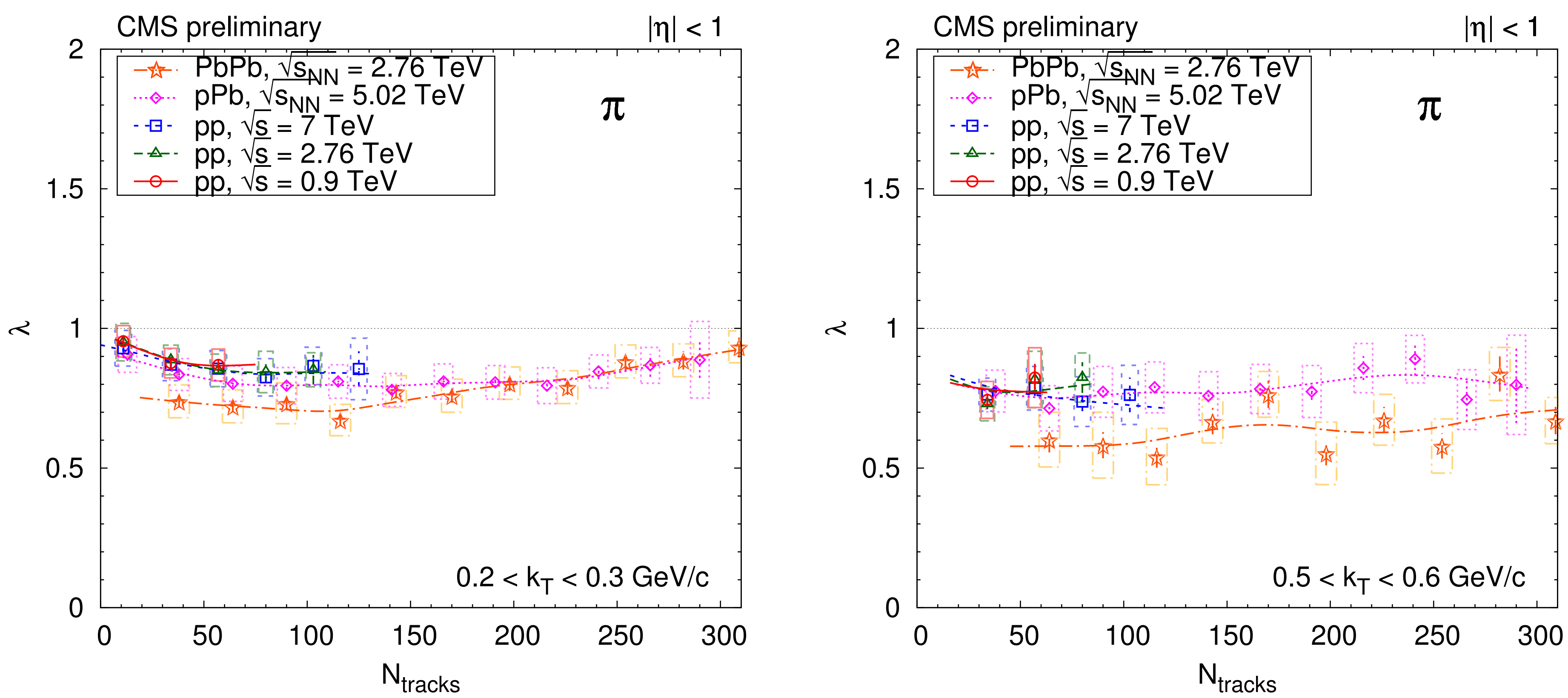
Results – radii – pions – 1D



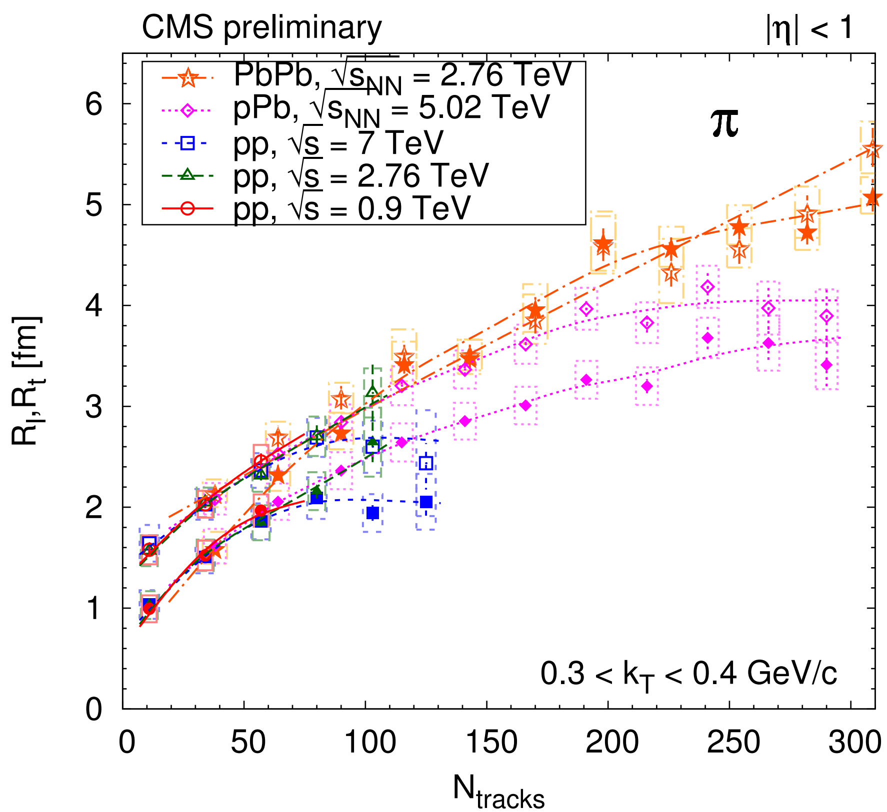


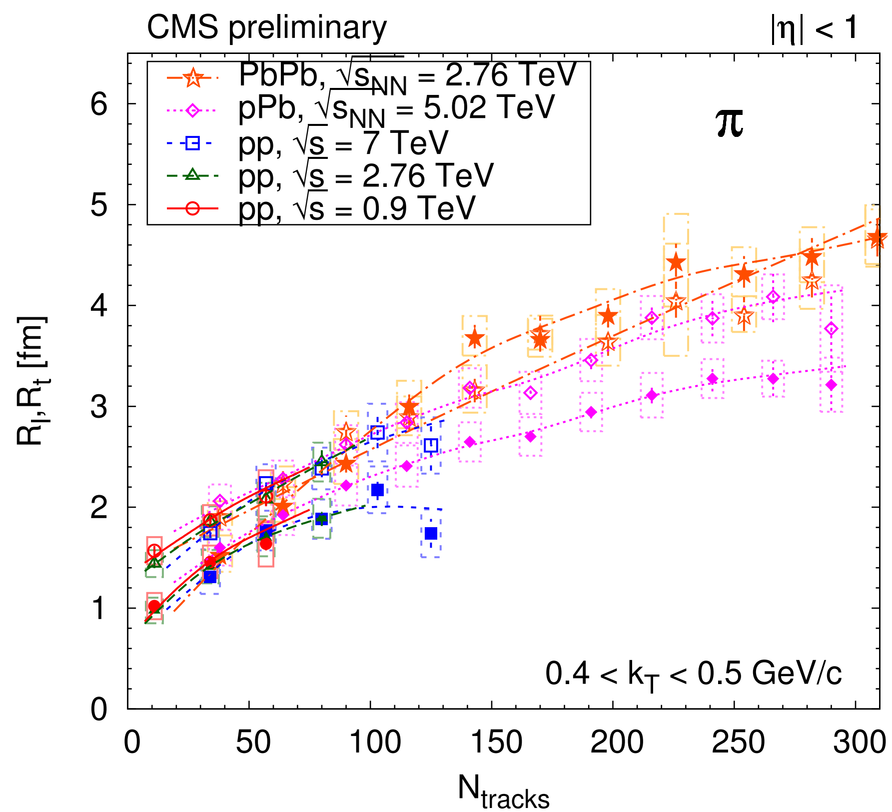
N_{tracks} dependence is **similar** for pp and pPb

Results – chaoticity – pions – 1D



Results – radii – pions – 2D

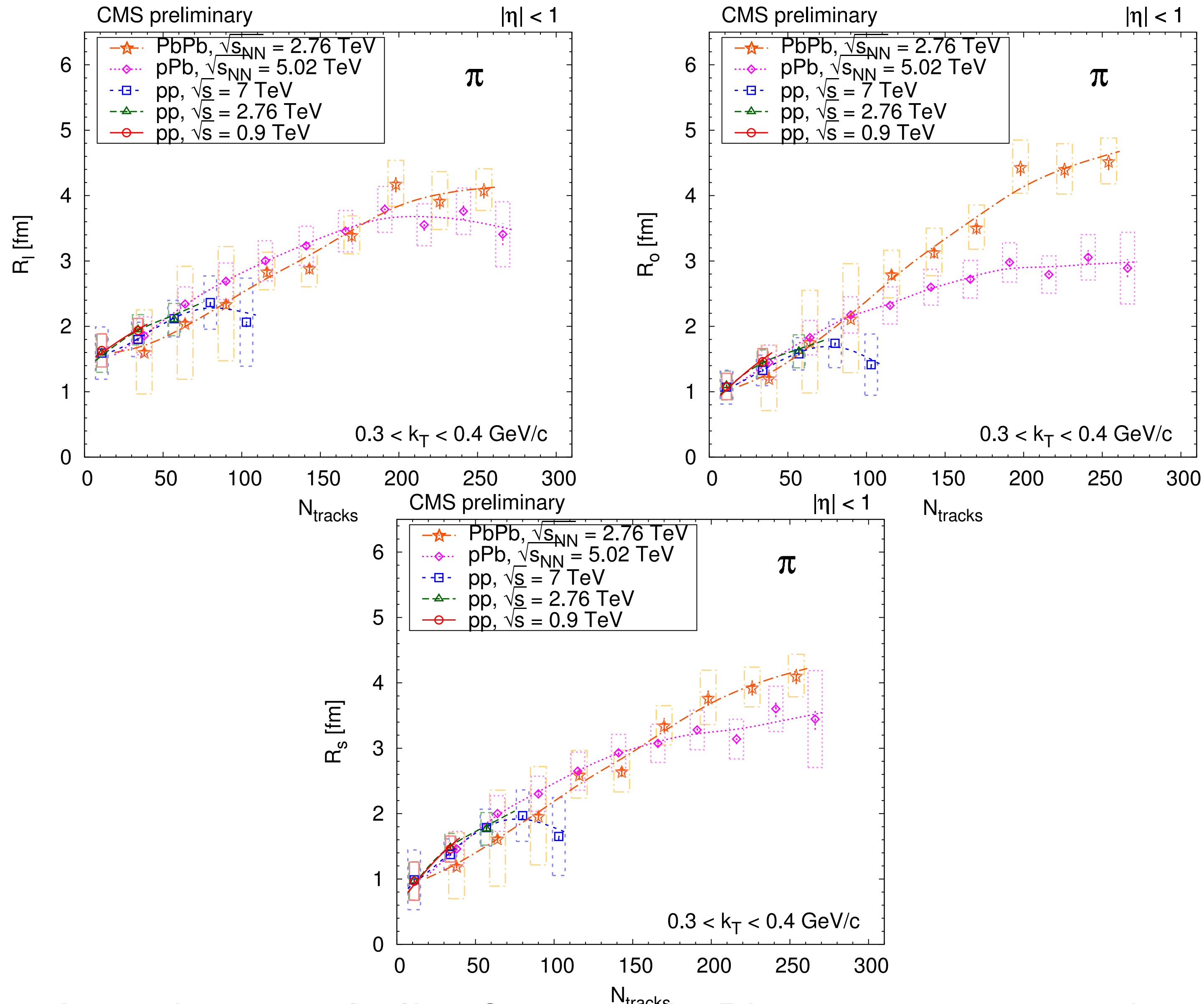




N_{tracks} dependence is **similar** for pp and pPb, $R_l > R_t$, **elongated**

In case of PbPb $R_l \approx R_t$, quite **symmetric**

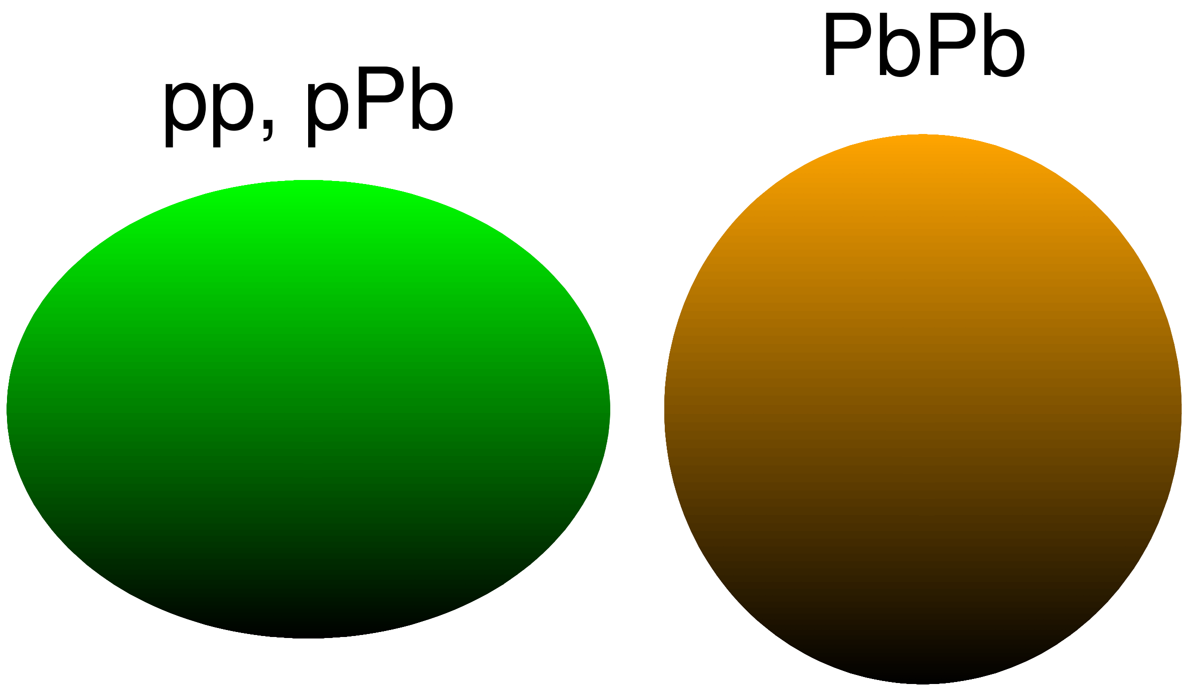
Results – radii – pions – 3D



N_{tracks} dependence is **similar** for pp and pPb, $R_l > R_s > R_o$, **elongated**

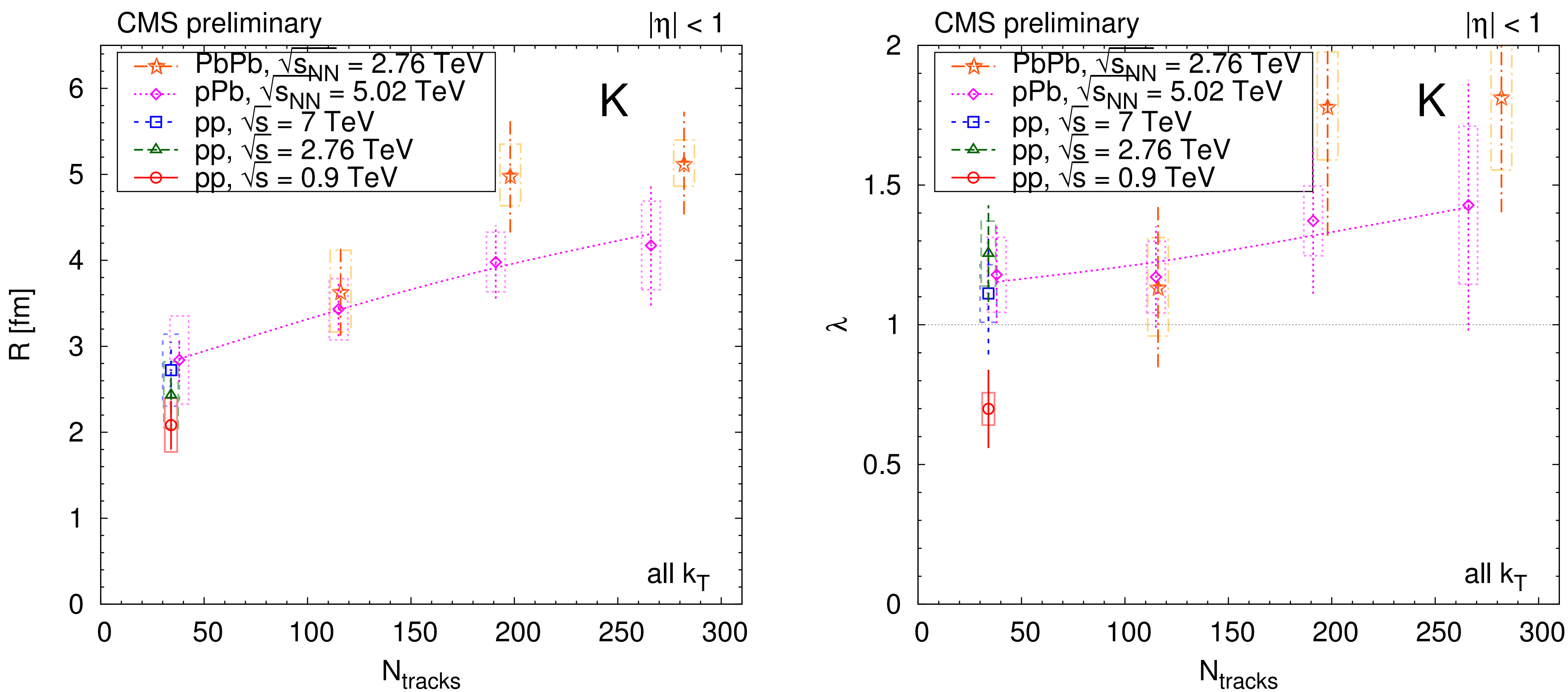
In case of PbPb $R_l \approx R_t \approx R_s$, **slightly different** N_{tracks} dependence

Results – radii – pions – 3D



Elongated vs spherical

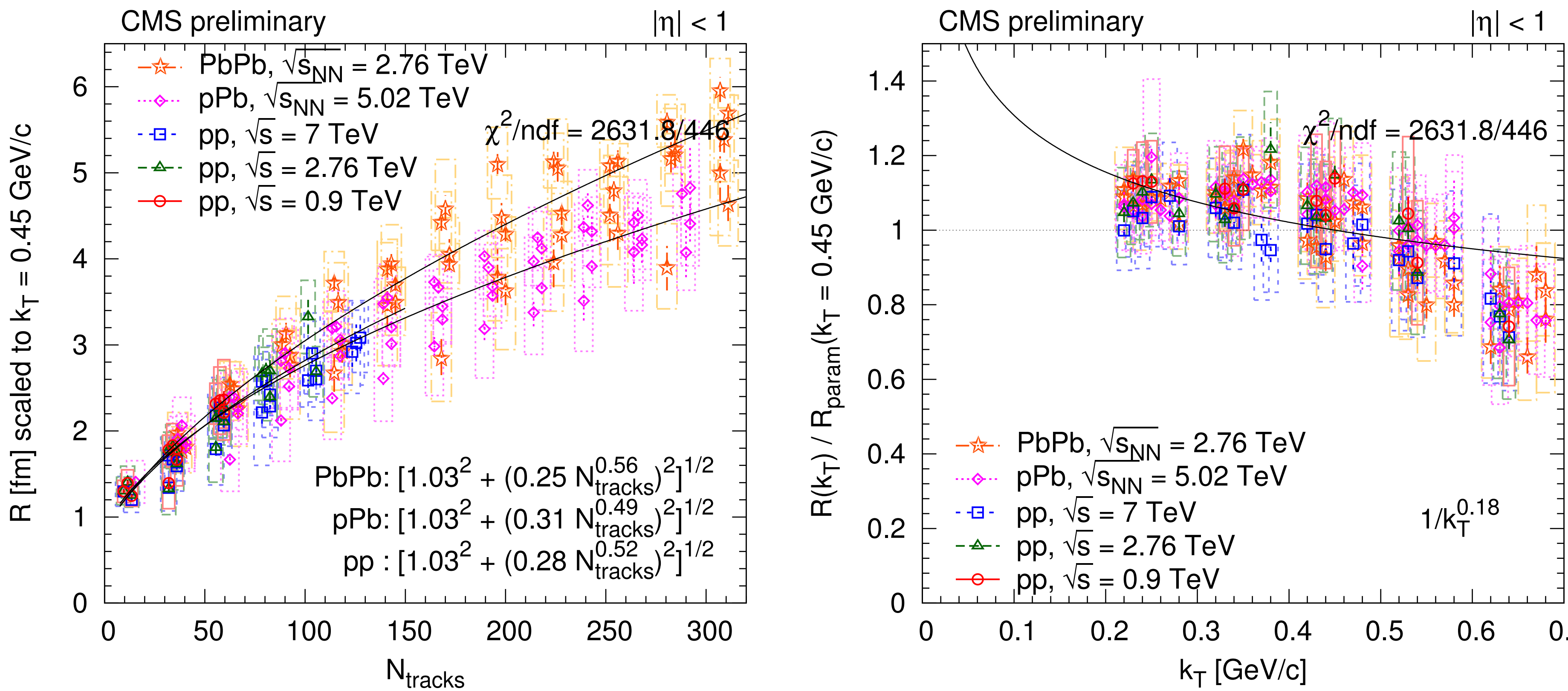
Results – kaons



Kaon radii increase with N_{tracks}, but with smaller slope

We measure the size of the system at last interactions
Role of resonances? Rescattering?

Scaling – q_{inv}



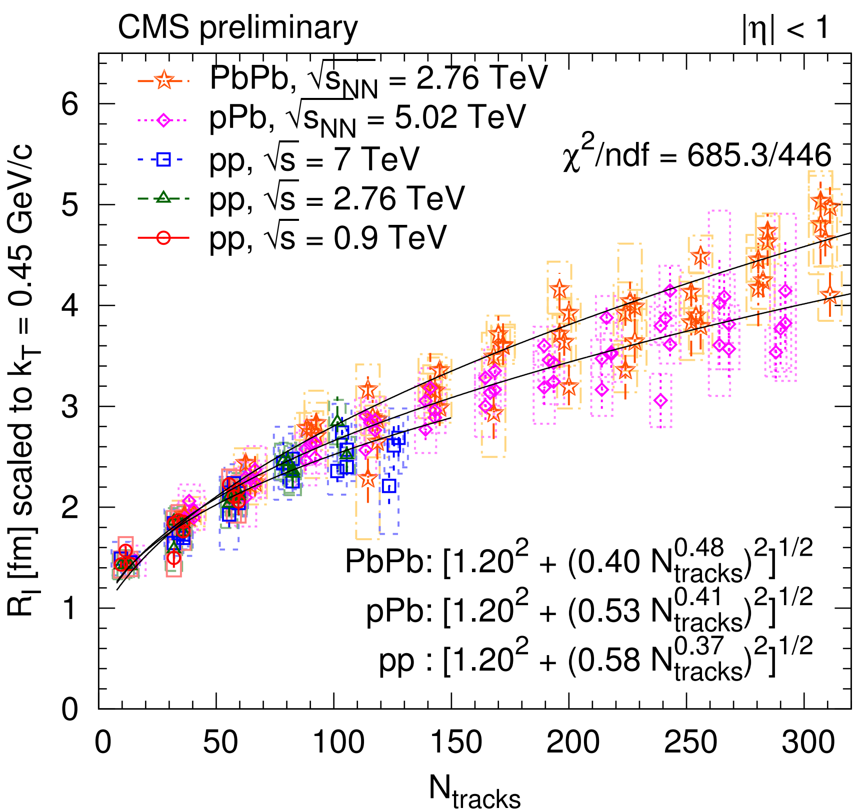
It seems that N_{rec} and k_{T} dependence of radii nicely **factorize**

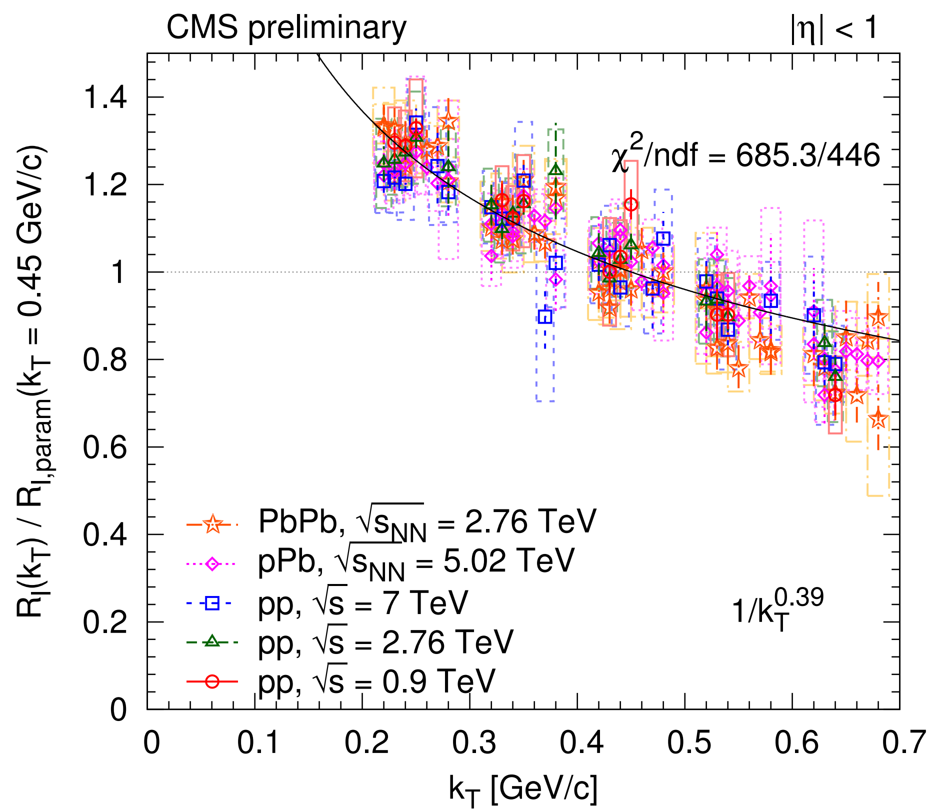
$$R_{\text{param}}(N_{\text{tracks}}, k_{\text{T}}) = \left[a^2 + (b N_{\text{tracks}}^{\beta})^2\right]^{1/2} \cdot (0.2\ \text{GeV}/c/k_{\text{T}})^{\gamma}$$

Can be motivated: **minimal radius a** can be connected to the size of the proton, the **power-law dependence on N_{tracks}** is attributed to the freeze-out density of hadrons

Quite similar for pp at several energies; PbPb slightly higher

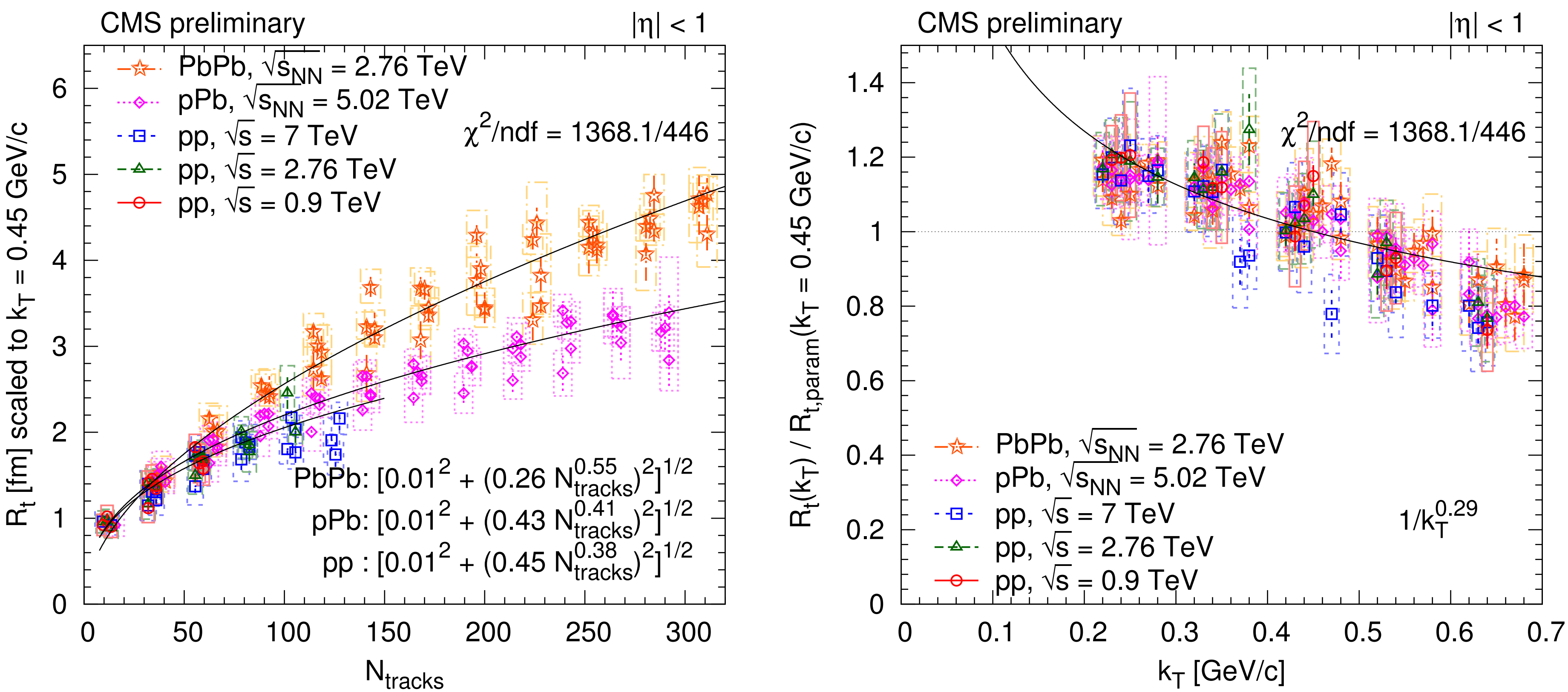
Scaling – 2D – q_l





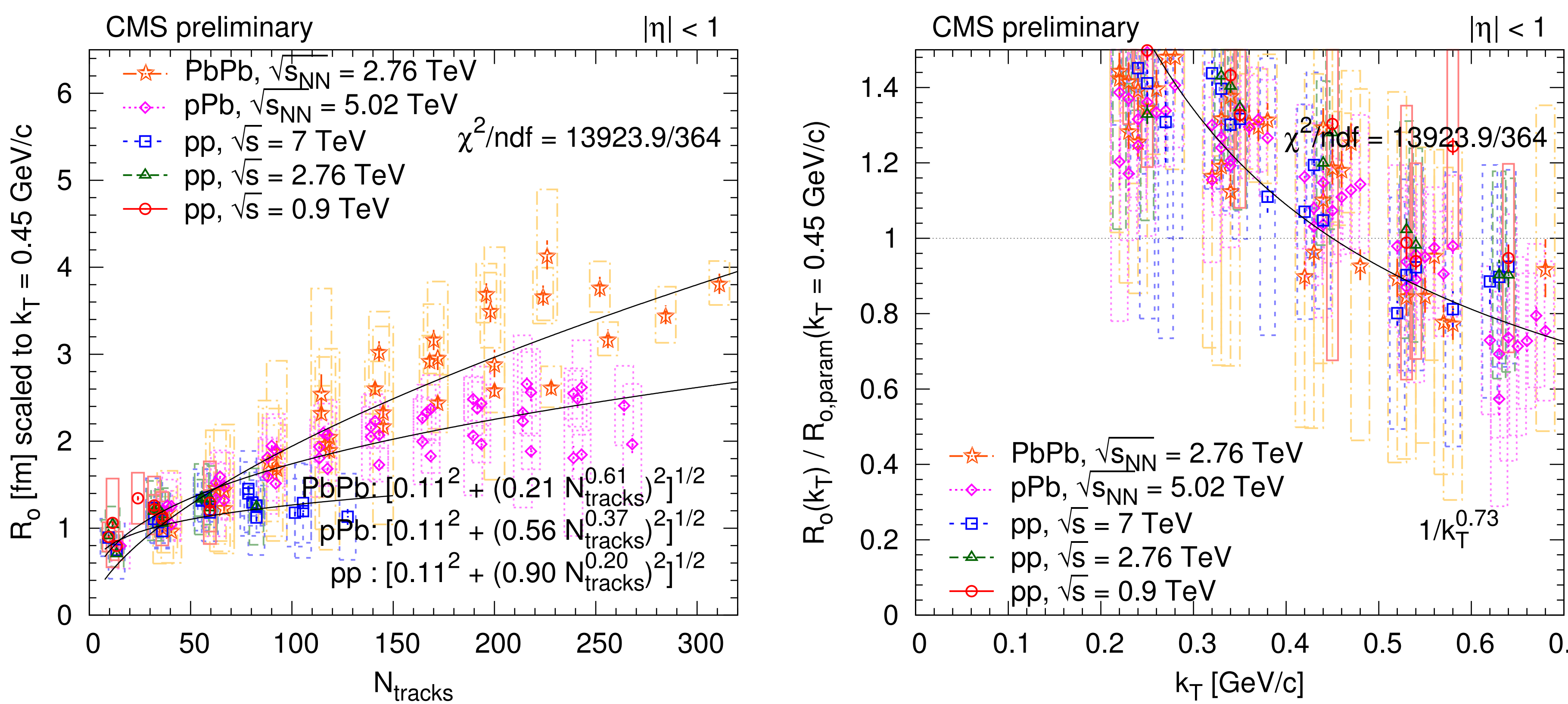
Nice scaling here!

Scaling – 2D – q_t



PbPb system is **larger in transverse** direction

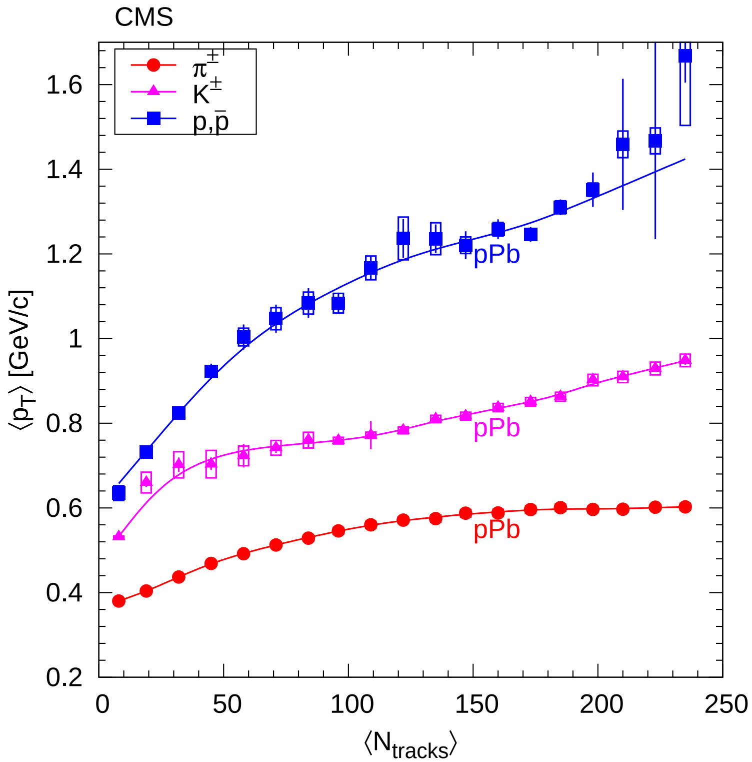
Scaling – 3D – q_o

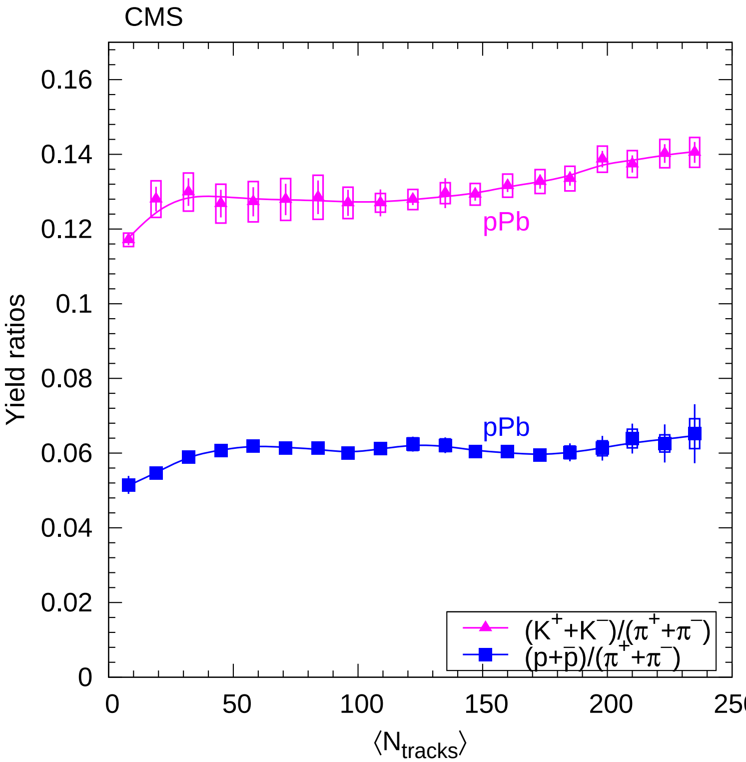


Systems are **different in out** direction

What is the seen N_{tracks} dependence for particle spectra? $\Rightarrow$

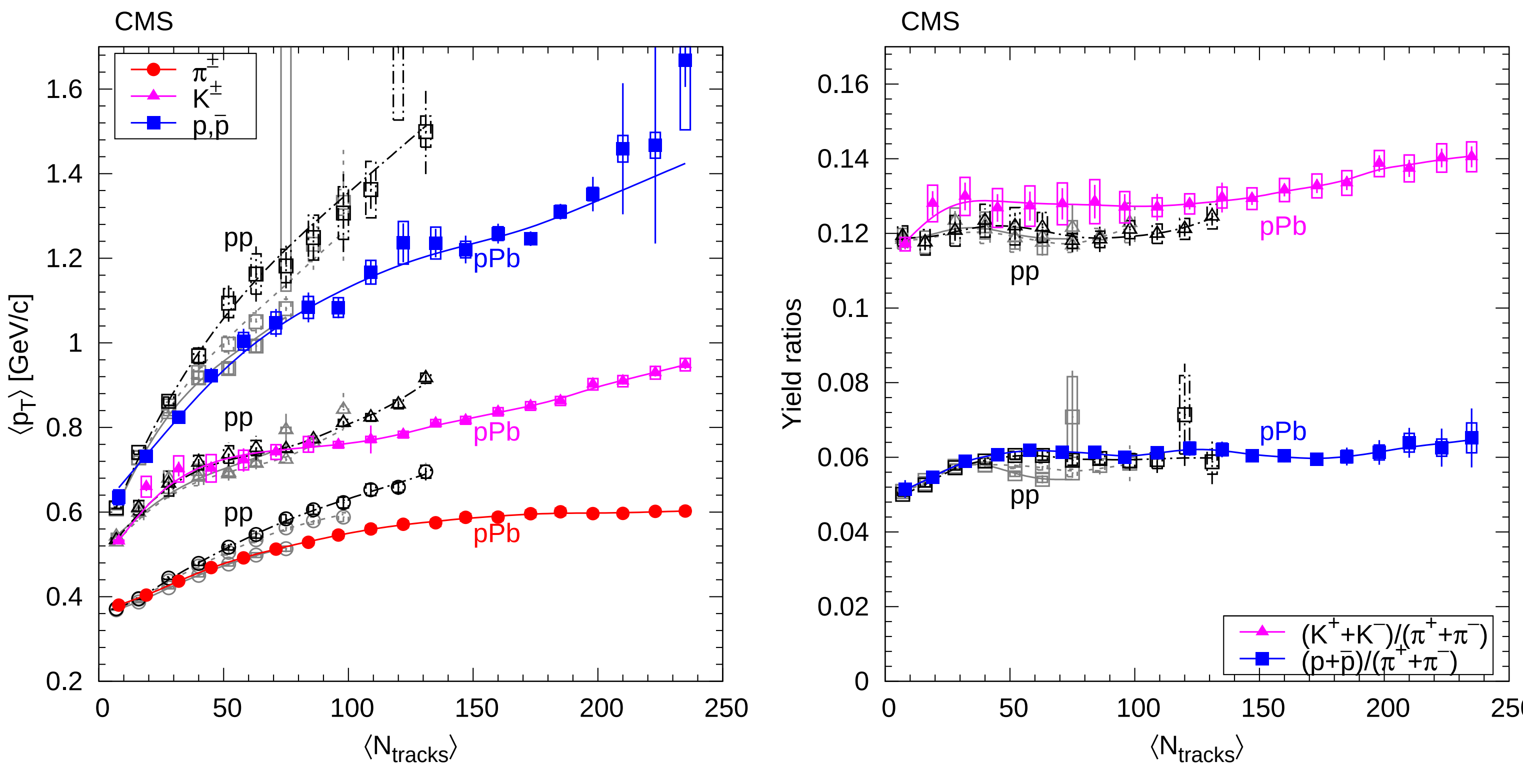
Comparisons – $\sqrt{s}$ dependence – pPb





CMS Coll, EPJC 74 (2014) 2847

Comparisons – $\sqrt{s}$ dependence – pp vs pPb

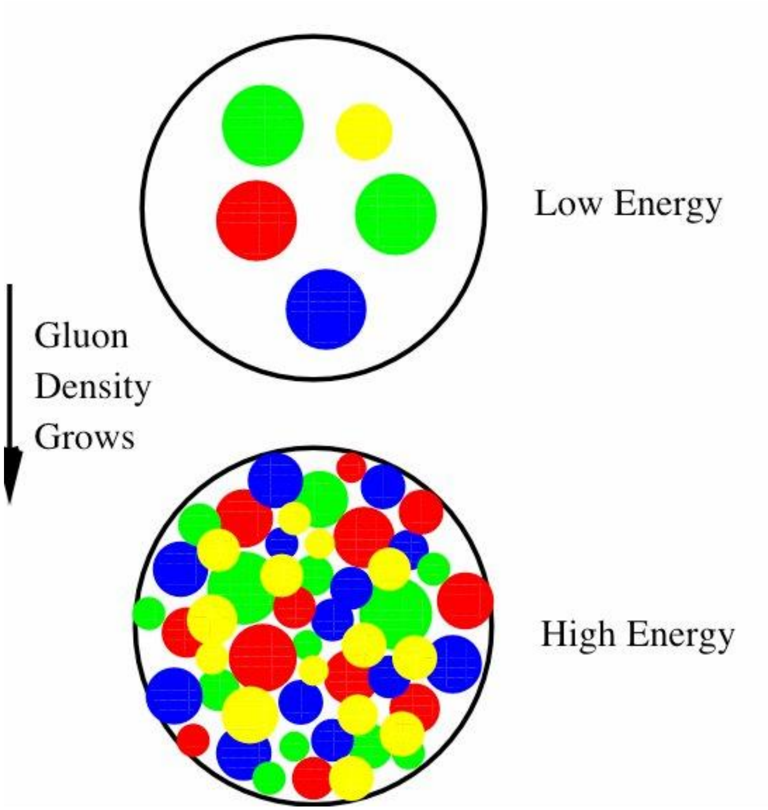


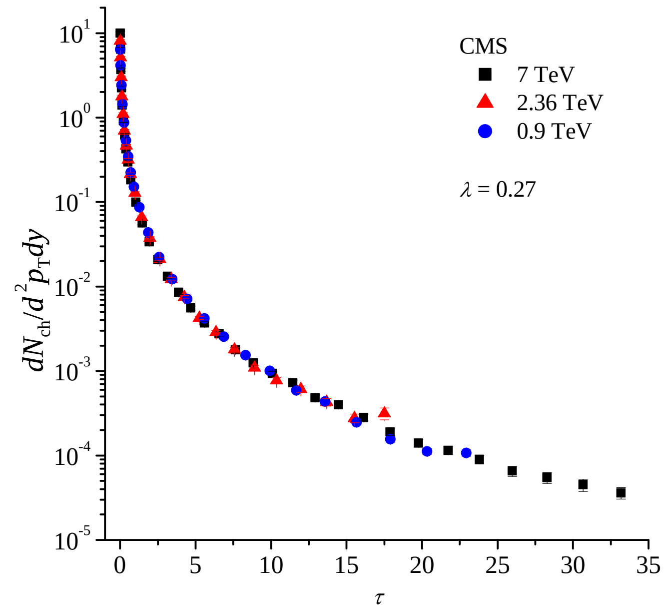
pp (0.9, 2.76, 7 TeV), pPb (5.02 TeV)

CMS Coll, EPJC 72 (2012) 2164

- Past conclusions
  - Particle production at LHC energies is strongly **correlated with event multiplicity in both pp and pPb,** rather than with the center-of-mass energy of the collision or with the masses of the colliding nuclei
  - Common underlying physics mechanism: at TeV energies, the characteristics of particle production are **constrained by** the amount of **initial parton energy** that is available in any given collision

Number of particles – number of gluons

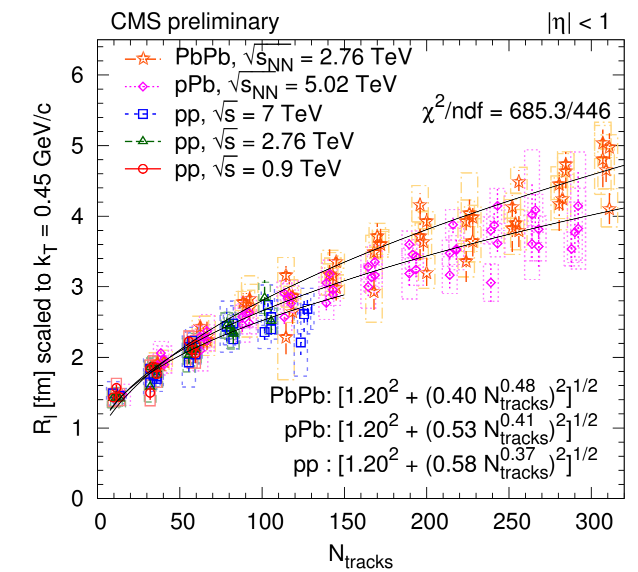


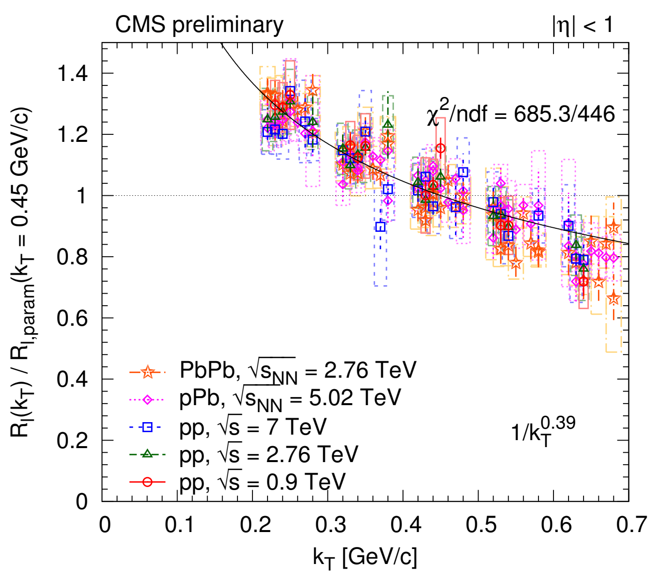


M. Praszalowicz, PRL 106 (2011) 142002

- Gluon saturation, geometrical scaling
  - the low x gluons can be described simply
  - their density grows as x decreases; reaches saturation
  - the spectra scale in $\tau = m_{\mathrm{T}}^{2+\lambda}/(Q_0^2\sqrt{s}^{\lambda})$

Summary





- Conclusions
  - Radii are in the range 1–5 fm
  - A large system exists in high multiplicity pPb (and corresponding PbPb)
  - Scaling with N_{rec}
    $\Rightarrow$ critical density, when hadrons disconnect
  - Scaling with k_{T}
    $\Rightarrow$ seen already for PbPb
  - Largely independent of system and $\sqrt{s_{NN}}$

- Status
  - Preliminary at CMS PAS HIN-14-013,
  - also, at arXiv:1411.6609 (hep-ex)
  - Plots at CMSPublic/PhysicsResultsHIN14013
  - Preparing for journal submission

Thank you for your attention!