Strangeness production vs. charged particle multiplicity with PYTHIA8 & Pion interferometry with CorAL

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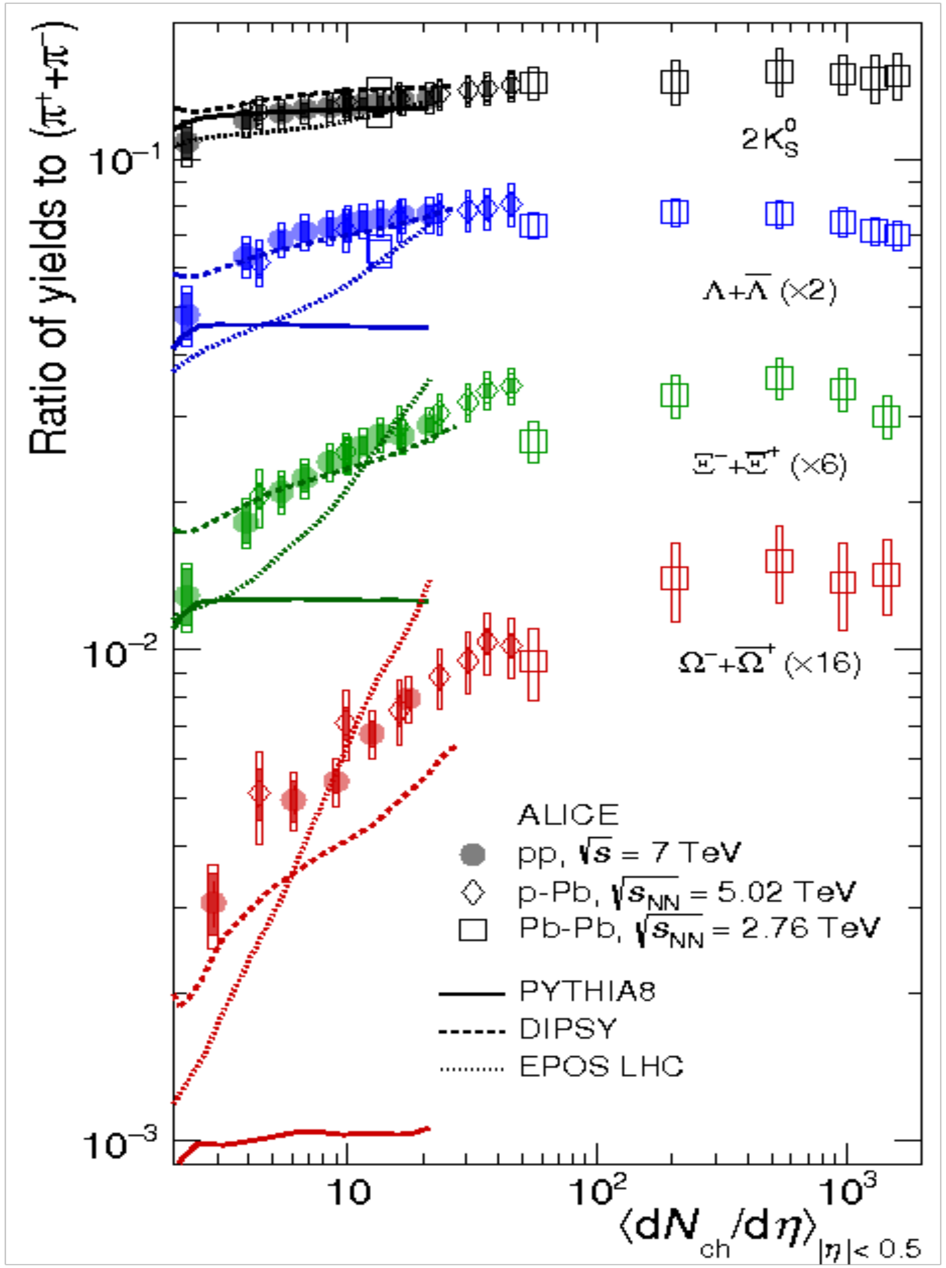
Overview

- **Investigation of Strangeness Enhancement at ALICE experiment using PYTHIA event generator**
- **Analysis of transverse momentum (p_T) distribution of strange hadrons using Tsallis-Weibull formalism**
- **Spherocity dependent study of Rope Hadronization for p-p collisions**
- **Analysis of the trend of enhanced production of Strange baryons in p-p collisions at $\sqrt{S}$ =7 TeV**
- **Pion interferometry with Correlation Algorithm Library (CorAL)**

Investigation of Strangeness Enhancement at ALICE experiment using PYTHIA



In heavy ion collisions, the enhanced production of strange particles in central and midcentral collisions have been attributed to the abundance of strange and anti-strange quarks in the deconfined QGP medium.

Rate of enhancement increases with the strangeness content of the Baryons

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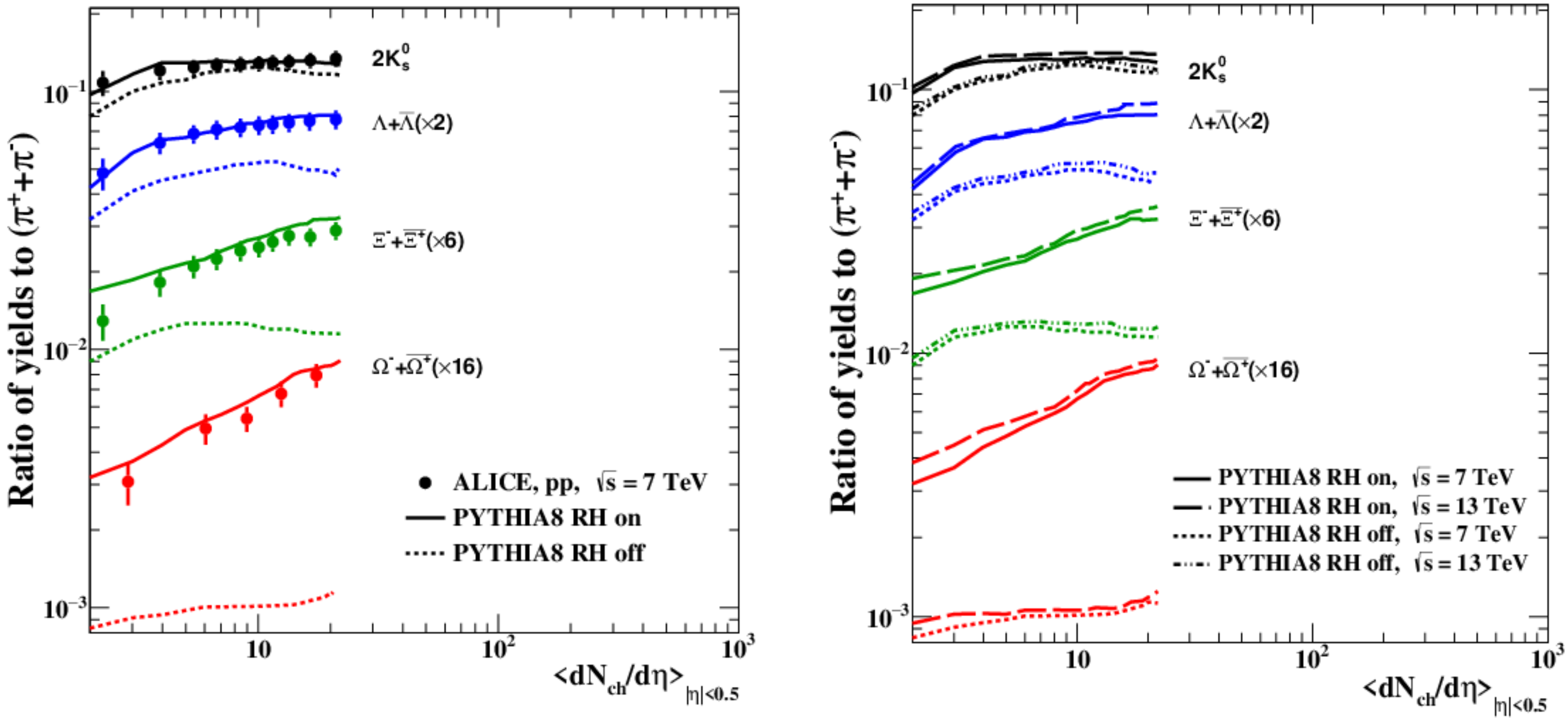
Color Reconnection and Rope Hadronization

- CR address the question: between which partons do strings form?
- Rope Hadronization is a model extending the Lund string hadronization model to describe environments such as high multiplicity pp collisions or AA collisions.
- The key point of the Rope Hadronization model, is the increase of local string tension.



https://doi.org/10.1103/PhysRevD.100.074023

Analysis of transverse momentum distribution of strange hadrons using Tsallis-Weibull formalism

Boltzmann-Gibbs Blast-Wave Model

Bulk properties of the system created in relativistic heavy-ion collisions can be studied via the transverse momentum (p_T) distribution through statistical approach.

Dynamical non-equilibrium effects :

- Hard QCD scattering processes in the initial stage of hadronisation

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} = \frac{gVm_T}{(2\pi)^3} exp\left(-\frac{m_T}{T}\right)$$

Assumptions：

– Local thermal equilibrium → Boltzmann distribution

– Longitudinal and transverse expansions (1+2)

– Temperature and $\langle \beta_T \rangle$ are global quantities

Limitations：

– Strong assumption on local thermal equilibrium

– Limited to low p_T regime

Tsallis-Weibull Distribution

Weibull Distribution

Processes governed by sequential branching and fragmentation is described by Weibull Distribution

$$P(x;\lambda,k) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k}$$

Tsallis q Statistics

Generalization of Gibbs-Boltzmann statistics

$$P_q(x;q,T) = \frac{1}{T}\, e_q^{-\left(\frac{x}{T}\right)},$$

where

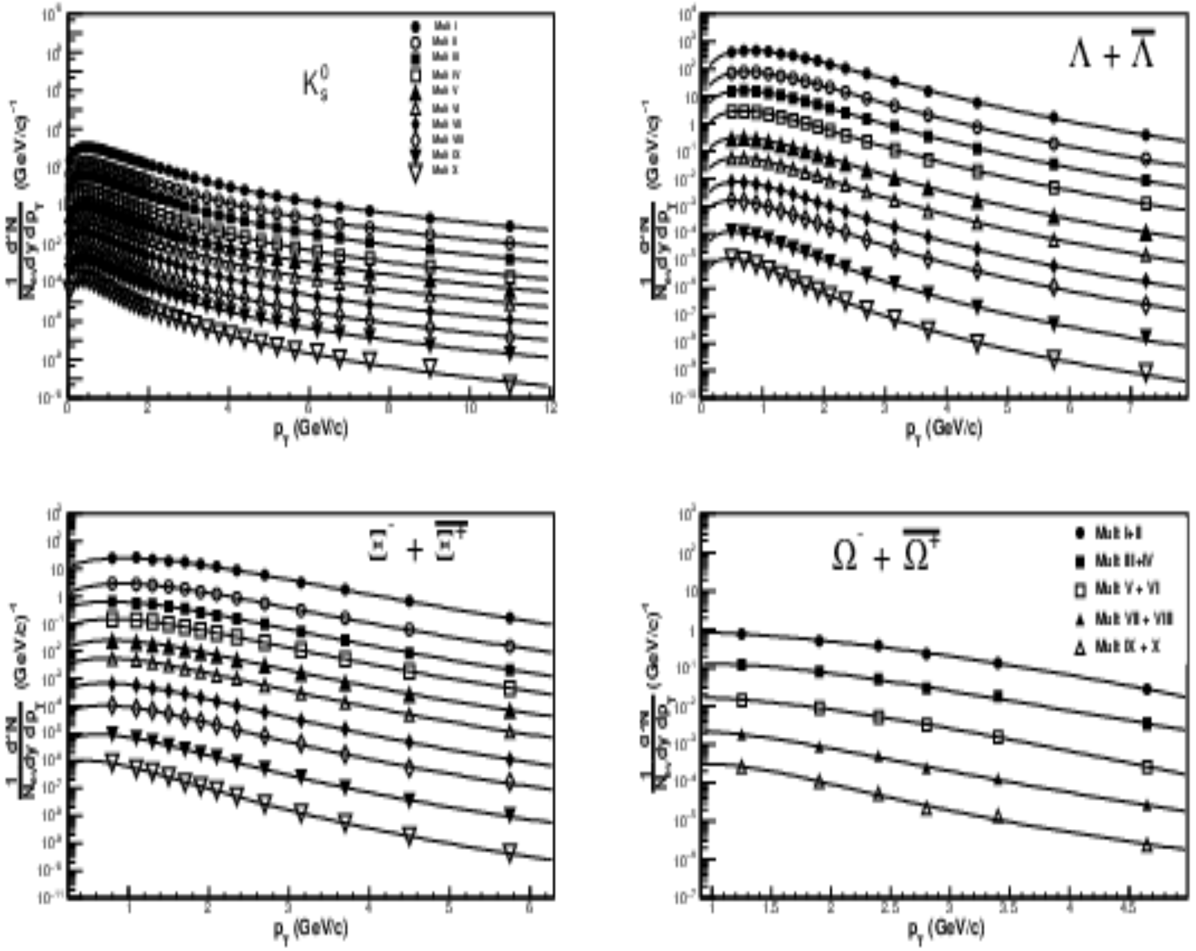
$$e_q^{-\left(\frac{x}{T}\right)} = \left(1-(1-q)\left(\frac{x}{T}\right)\right)^{\left(\frac{1}{1-q}\right)}$$

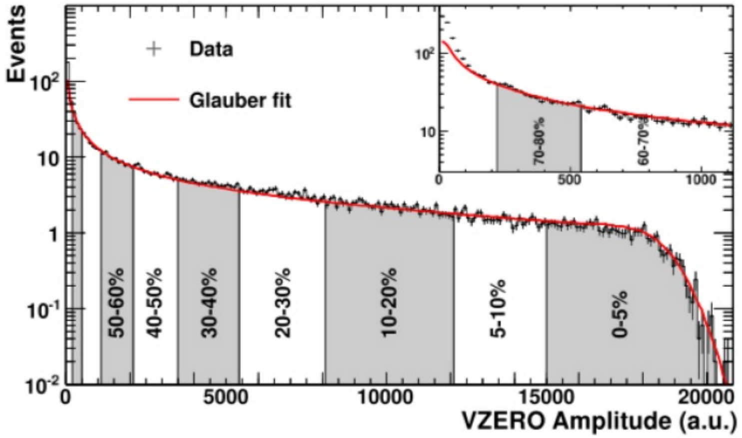
q-Weibull distribution

$$P_q(x; q, \lambda, k) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e_q^{-\left(\frac{x}{\lambda}\right)^k}$$

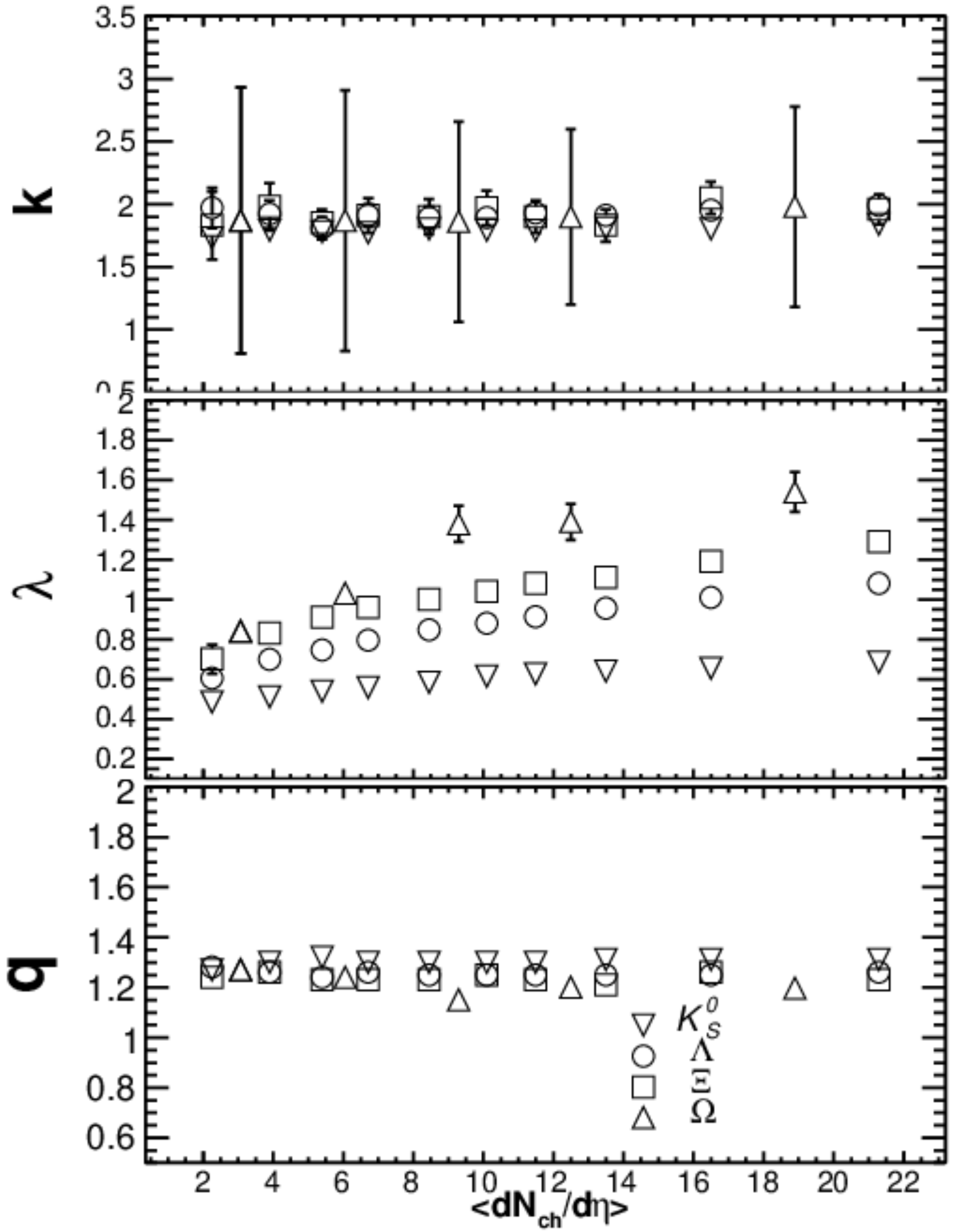
Where, $e_q^{-\left(\frac{x}{\lambda}\right)^k} = \left(1 - (1-q)\left(\frac{x}{\lambda}\right)^k\right)^{\left(\frac{1}{1-q}\right)}$

The transverse momentum (p_T) distribution of strange hadrons measured in p–p collisions at LHC energies has been studied for different **multiplicity classes**





Multiplicity class	$\langle dN_{ch}/d\eta \rangle$	Multiplicity class	$\langle dN_{ch}/d\eta \rangle$
I	21.5 ± 0.6	VI	8.45 ± 0.25
II	16.5 ± 0.5	VII	6.72 ± 0.21
III	13.5 ± 0.4	VIII	5.40 ± 0.17
IV	11.5 ± 0.3	IX	3.90 ± 0.14
V	10.1 ± 0.3	X	2.26 ± 0.12



For q ⟶ 1 and k = 1, the q-exponential

$$e_q^{-\left(\frac{x}{\lambda}\right)^k} = \left(1 - (1-q)\left(\frac{x}{\lambda}\right)^k\right)^{\left(\frac{1}{1-q}\right)}$$

becomes $e^{-\left(\frac{x}{\lambda}\right)}$ i.e. Gibbs-Boltzmann distribution. λ can be associated with the temperature of the system. q represents the deviation from thermal equilibrium.

λ shows an increment from peripheral to central collisions and mass hierarchy .

q > 1 ; ➡ collective expansion ➡ non-equilibrium

k almost constant ; ➡ Initial state effects

https://doi.org/10.1140/epja/s10050-020-00081-4

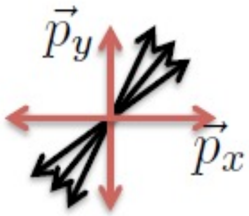
Spherocity dependent study of Rope Hadronization for p-p collisions

Transverse Spherocity

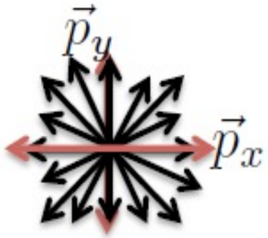
Spherocity is defined for a unit vector $\hat{n} = (n_x, n_y, 0)$

such that $$S_o = \frac{\pi^2}{4} \min_{\hat{n}=(n_x,n_y,0)} \left(\frac{\sum_i |\vec{p}_{Ti} \times \hat{n}|}{\sum_i p_{Ti}} \right)^2$$

Jetty (pencil like): $S_o \rightarrow 0$



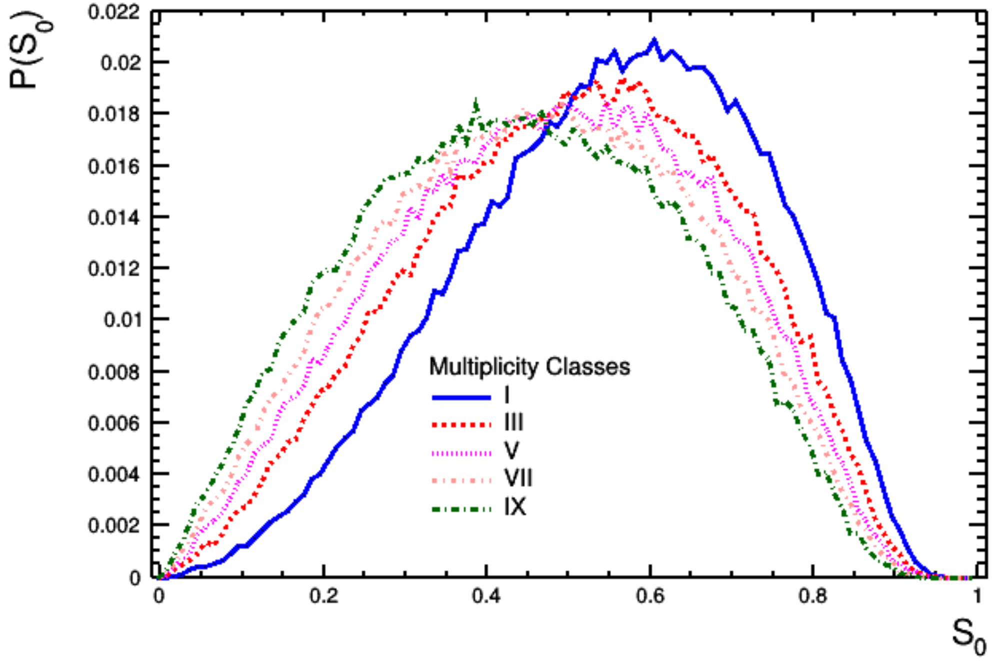
Isotropic (spherically symmetric): $S_o \rightarrow 1$

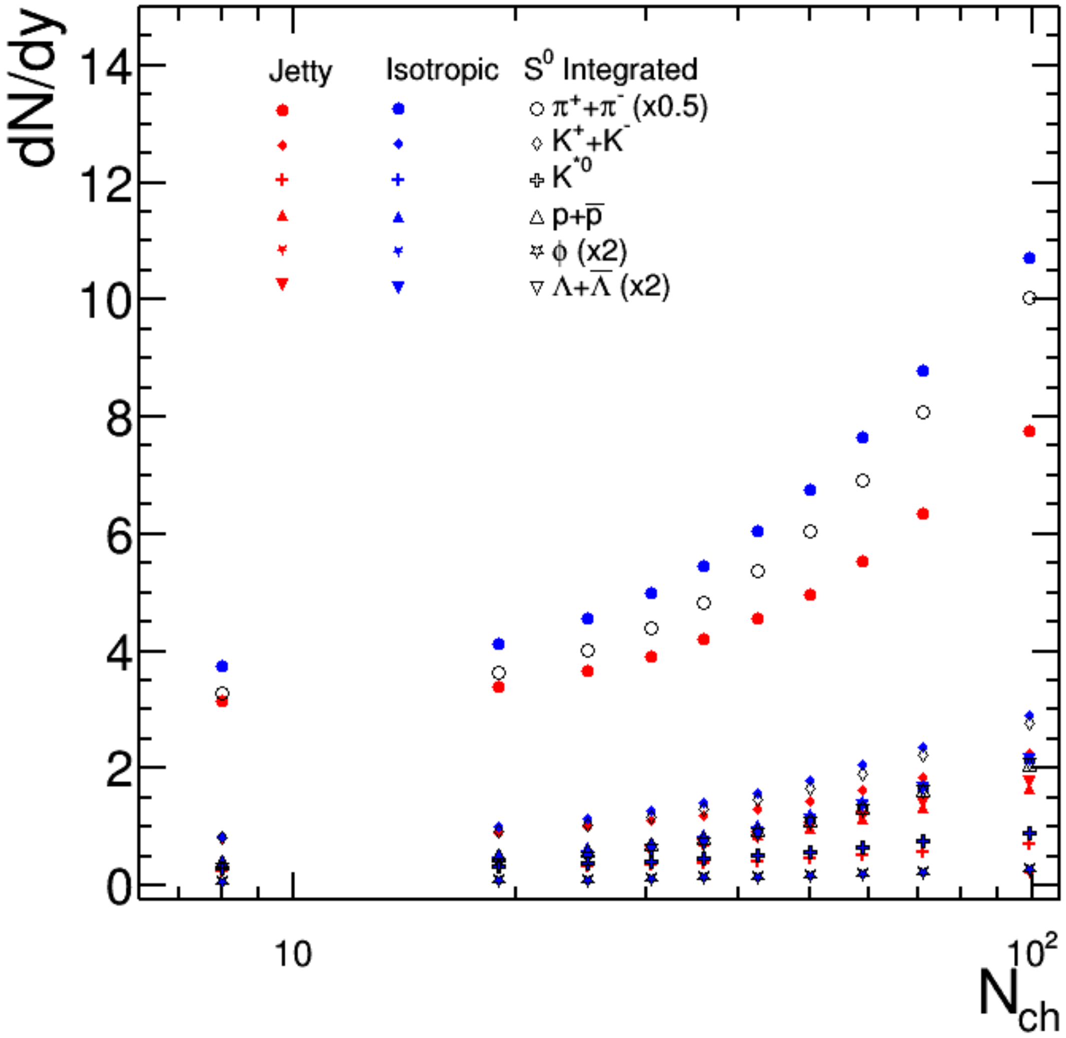


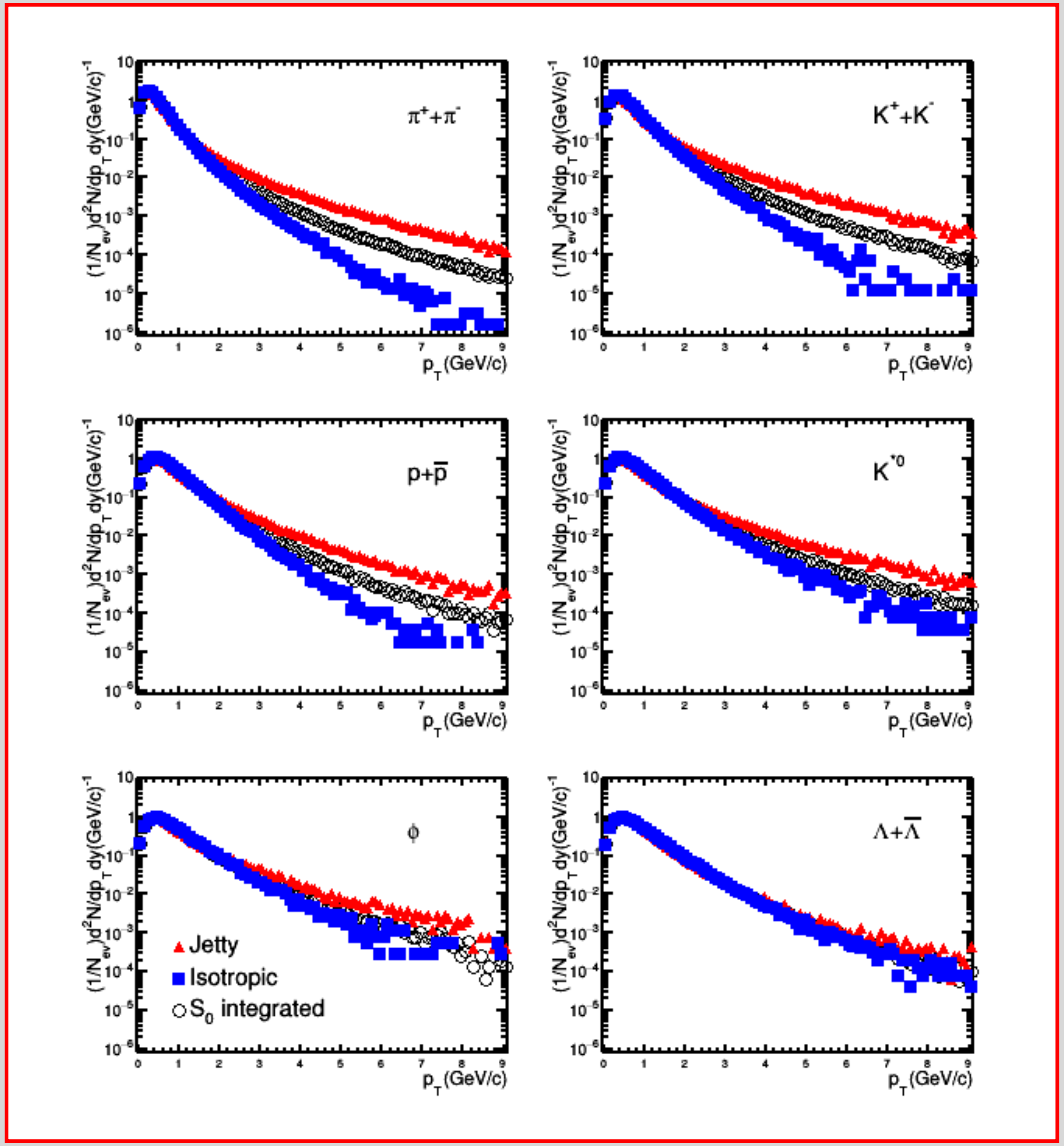
Spherocity can help to discriminate hard and soft processes.

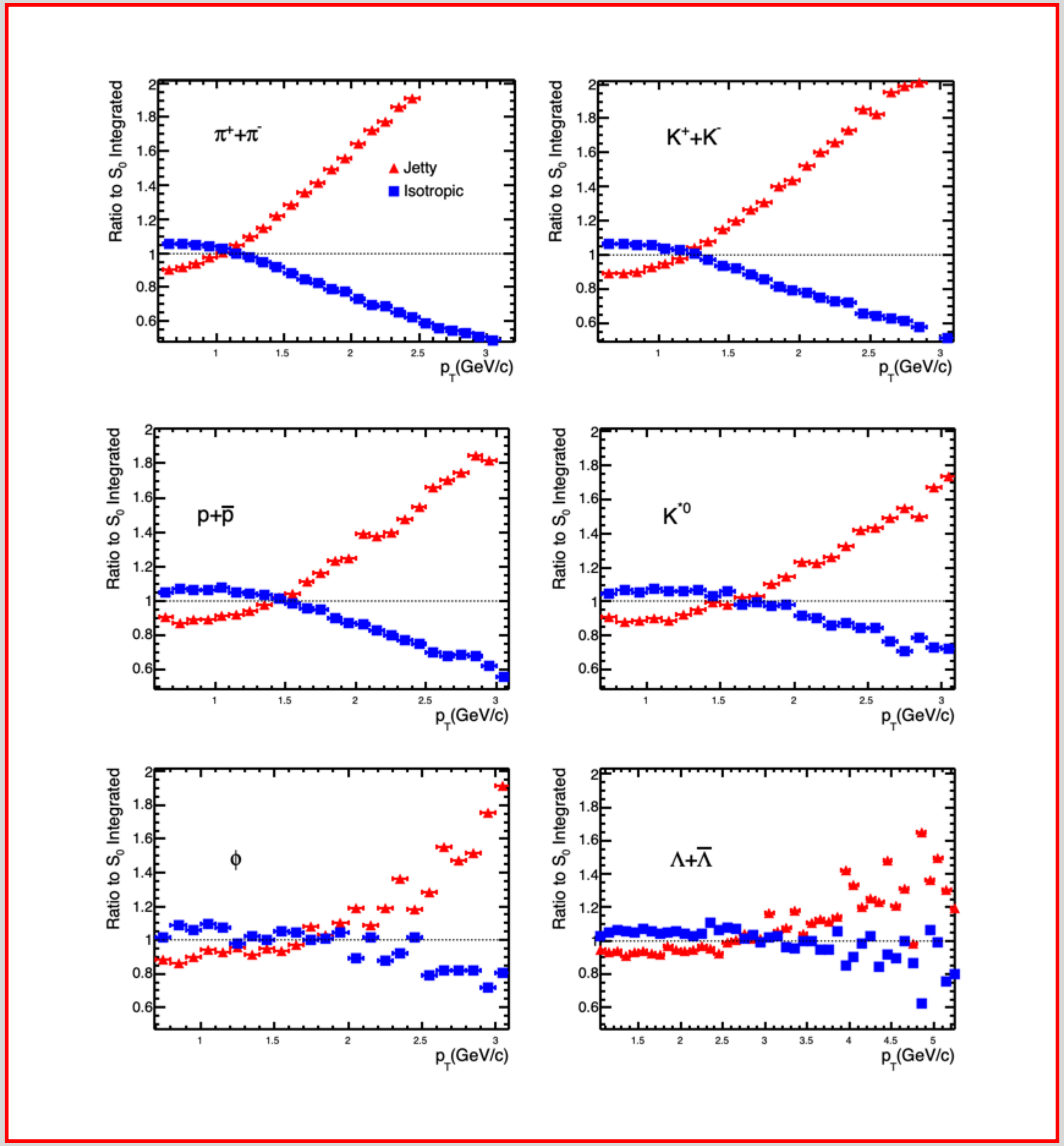
- Jetty events :
  hard QCD
  low multiplicity events

- Isotropic events :
  soft QCD
  high multiplicity events


P(S_0)
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
0.2
0.4
0.6
0.8
1
S_0
Multiplicity Classes
I
III
V
VII
IX

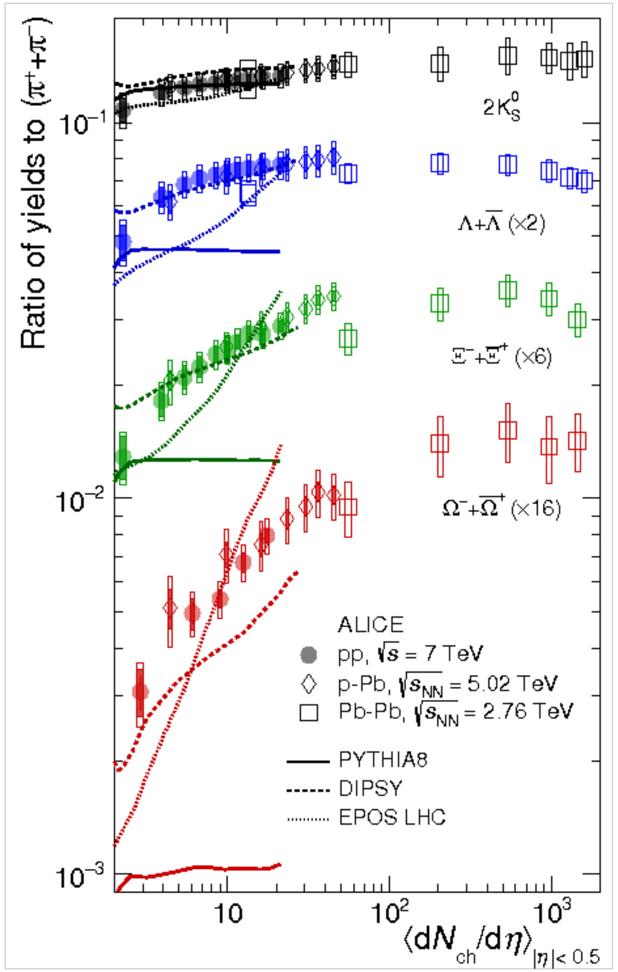

dN/dy
14
12
10
8
6
4
2
0
10
10^2
N_ch
Jetty
Isotropic
S^0 Integrated
π⁺+π⁻ (x0.5)
K⁺+K⁻
K*0
p+p̄
ϕ (x2)
Λ+Λ̄ (x2)


$\pi^{+}+\pi^{-}$
$K^{+}+K^{-}$
$p+\bar{p}$
K^{*0}
ϕ
$\Lambda+\bar{\Lambda}$
Jetty
Isotropic
S_0 integrated
$(1/N_{ev})d^2N/dp_T dy(GeV/c)^{-1}$
p_T(GeV/c)


$\pi^{+}+\pi^{-}$
$K^{+}+K^{-}$
$p+\bar{p}$
K^{*0}
ϕ
$\Lambda+\bar{\Lambda}$
Jetty
Isotropic
Ratio to S_0 Integrated
p_T(GeV/c)

Analysis of the trend of enhanced production of Strange baryons in p-p collisions at $\sqrt{S} = \mathbf{7\ TeV}$

Rate of enhancement increases with the strangeness content of the Baryons



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Yield Ratio Function

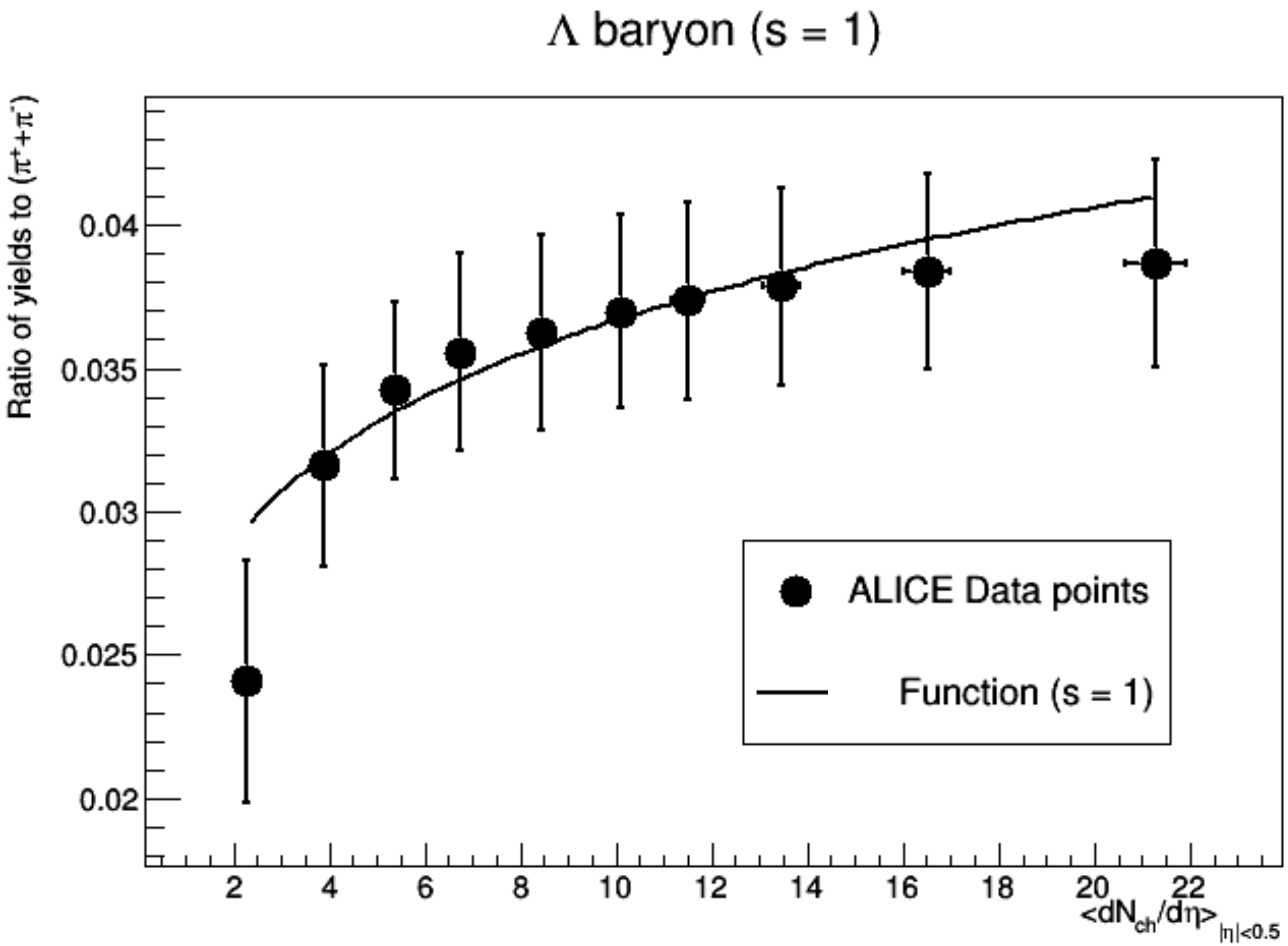
$$r = 0.37e^{-2.64s}\mathrm{N_{ch}}^{0.16s-0.001}$$

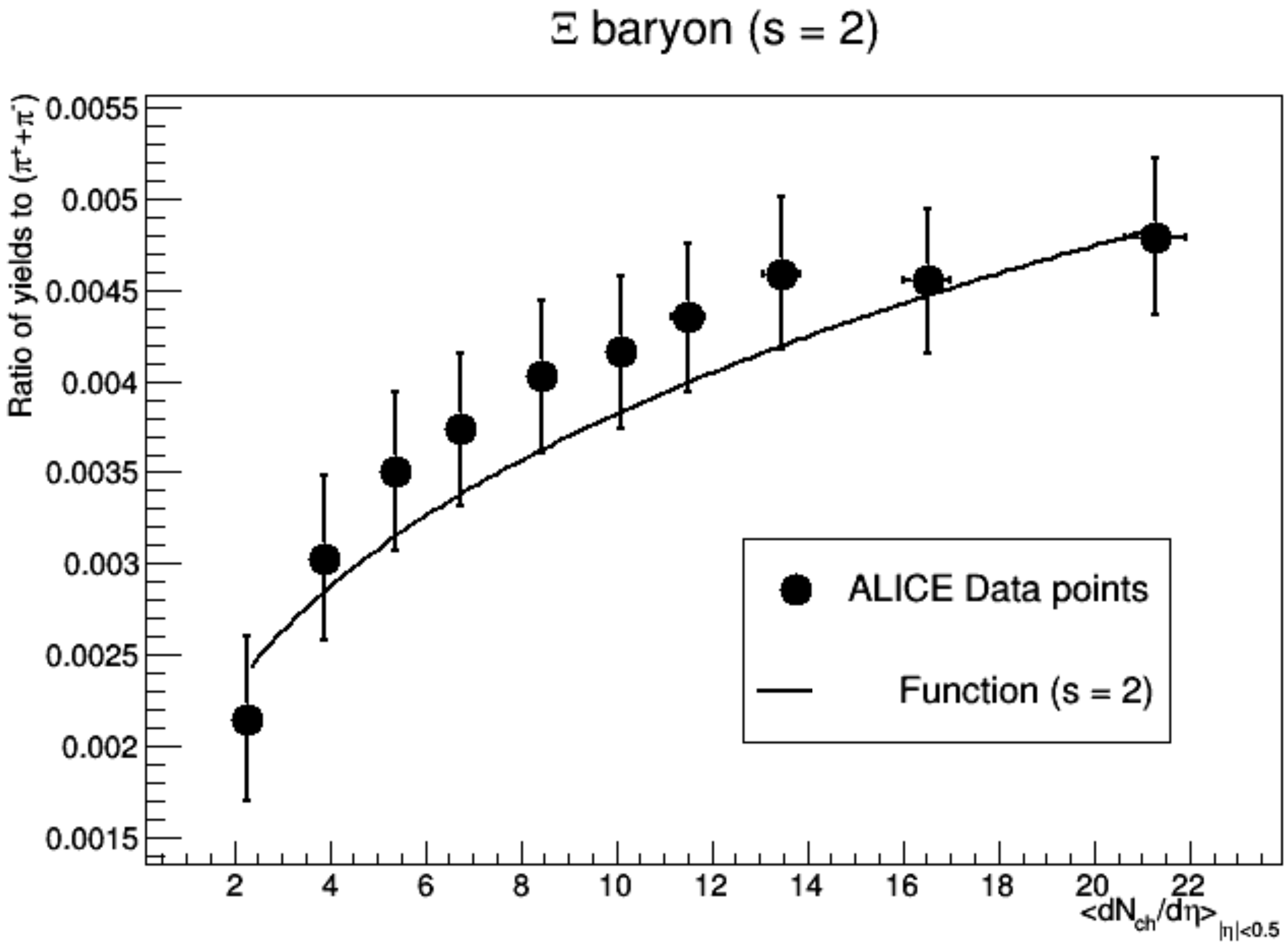
Where ,

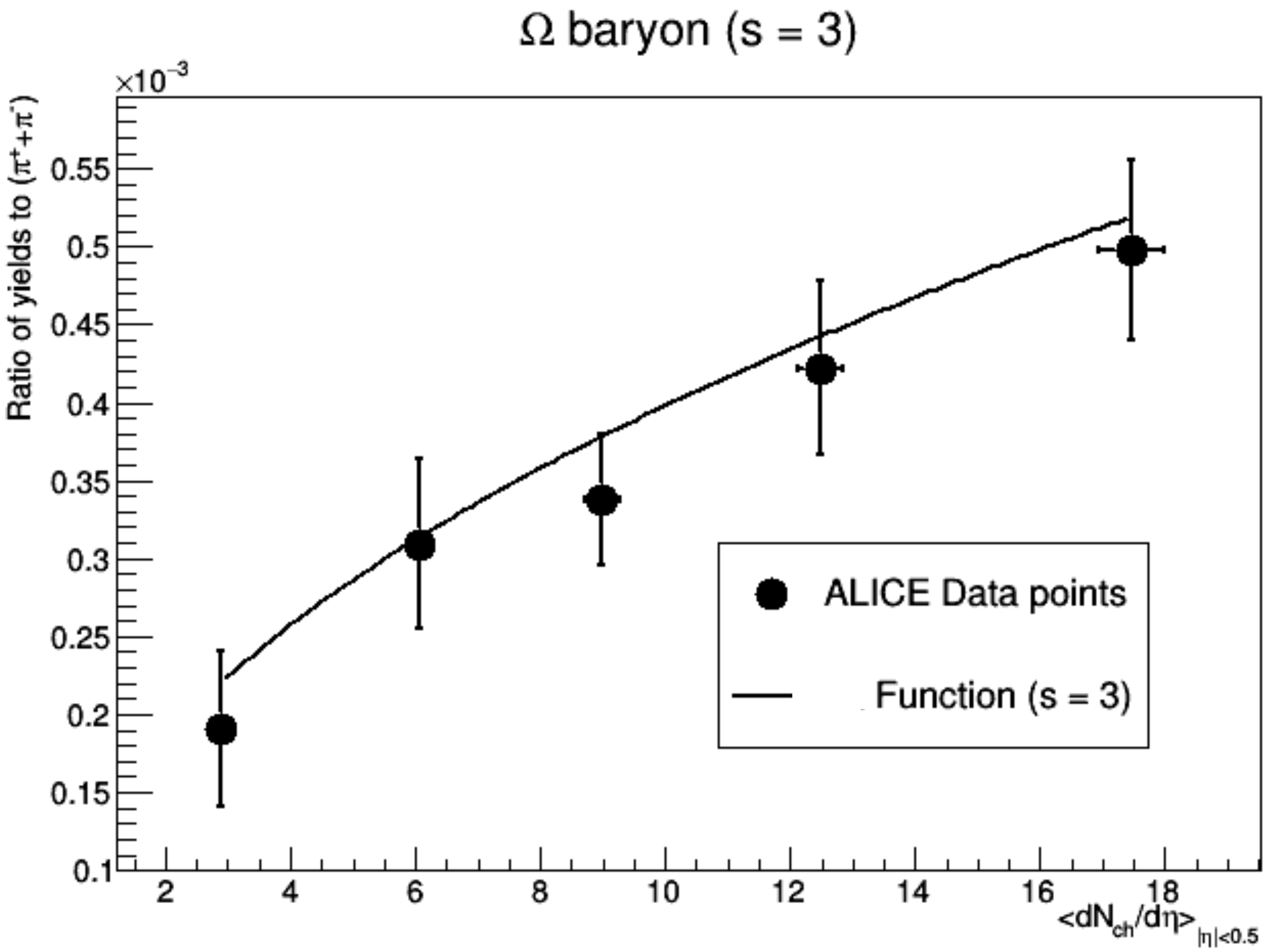
r is the ratio of yield of the Baryon to $(\pi^{+} + \pi^{-})$ measured at midrapidity

$\mathrm{N_{ch}}$ is the charged particle multiplicity of the event detected at midrapidity $(|\ \eta\ | < 0.5)$

s is the strangeness content of the Baryon


Λ baryon (s = 1)
Ratio of yields to (π⁺+π⁻)
0.04
0.035
0.03
0.025
0.02
2
4
6
8
10
12
14
16
18
20
22
<dN_ch/dη>_|η|<0.5
ALICE Data points
Function (s = 1)


Ξ baryon (s = 2)
Ratio of yields to ($\pi^+ + \pi^-$)
0.0055
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
2
4
6
8
10
12
14
16
18
20
22
$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$
ALICE Data points
Function (s = 2)


Ω baryon (s = 3)
×10⁻³
Ratio of yields to (π⁺+π⁻)
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
2
4
6
8
10
12
14
16
18
<dNch/dη>|η|<0.5
ALICE Data points
Function (s = 3)

HBT Inteferometry in Heavy-Ion collisions: Explore space-time evolution of system

Measuring the size of subatomic and nuclear collisions

What is Intensity Interferometry ?

Young's double slit Experiment

Interference of the amplitudes of two light waves from two slit openings which travel different paths to arrive at the same detection point

Intensity Interferometry

Interference of intensities when identical particles are detected at different points measured in coincidence.

When a particle has been detected in one detector, the probability for the detection of a second particle in coincidence is found to exhibit a correlation.

i.e. these two events may not be independent!!!

Correlation Function :

$$C_2(k_1, k_2) = \frac{P(k_1, k_2)}{P(k_1)\, P(k_2)}$$

$P\,(k_1, k_2)$ = probability of the coincidence of a particle pair with momentum k_1 and k_2.

$P\,(k_i)$ = probability of observing a particle with momentum k_i.

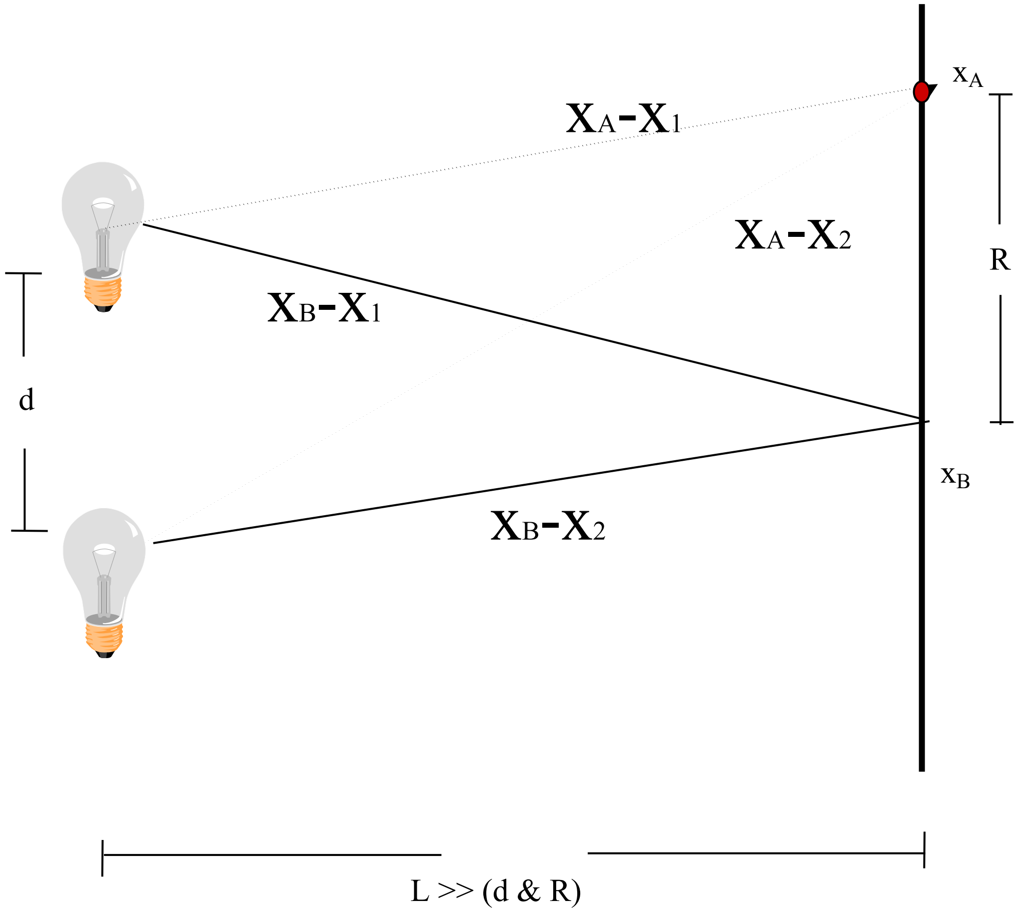
Probability amplitude for 2 particles with momenta k_1 and k_2, emitted from points x_1 and x_2 and detected at x_A and x_B is

$$A(k_1, k_2) = \frac{1}{\sqrt{2}}[e^{-ik_1.(x_A-x_1)}e^{i\phi_1}e^{-ik_2.(x_B-x_2)}e^{i\phi_2} \pm e^{-ik_1.(x_A-x_2)}e^{i\phi'_2}e^{-ik_2.(x_B-x_1)}e^{i\phi'_1}]$$

$$P_2(k_1, k_2) = \langle|A(k_1, k_2)|^2\rangle =$$

$$= \frac{1}{2}[2 \pm (e^{i(k_1-k_2).(x_1-x_2)}\langle e^{\pm i(\phi_1+\phi_2-\phi'_1-\phi'_2)}\rangle + c.c.)]$$

$$= 1 \pm \cos[(k_1 - k_2).(x_1 - x_2)]$$



Now, for the single particle momentum distribution, we have

$$A(k_i) = \frac{1}{\sqrt{2}}[e^{-ik_1.(x_A-x_1)}e^{i\phi_1} \pm e^{-ik_1.(x_A-x_2)}e^{i\phi_2}]$$

$$\langle e^{\pm i(\phi_1-\phi_2)} \rangle = 0$$

$$P_1(k_i) = \langle |A(k_i)|^2 \rangle = \frac{1}{2}[2 \pm e^{ik_i.(x_1-x_2)} \langle e^{\pm i(\phi_1-\phi_2)} \rangle + c.c.]$$

$$C(k_1,k_2) = \frac{P_2(k_1,k_2)}{P_1(k_1)P_1(k_2)} = 1 \pm \cos[(k_1-k_2).(x_1-x_2)]$$

For an extended source of emission, we have:

$$P(k_1, k_2) = \int dx_1 dx_2 \; \rho(x_1)\rho(x_2)|\Phi(k_1 k_2 : x_1 x_2 \to x_1' x_2')|^2$$

$$= P(k_1)P(k_2) + \left| \int dx e^{i(k_1 - k_2)\cdot x} \rho(x) A(k_1, x) A(k_2, x) \right|^2$$

$$\rho_{\text{eff}}(x; k_1, k_2) = \frac{\rho(x) A(k_1, x) A(k_2, x)}{\sqrt{P(k_1)P(k_2)}}$$

$$C_2(k_1, k_2) = 1 + |\tilde{\rho}_{\text{eff}}(q; k_1 k_2)|^2$$

ρ(x) is the normalised space-time distribution .

Gaussian profile :

$$\rho_{eff}(x) = e^{x^{\mu}x_{\mu}/(2R)^2}$$

$$C(k_1, k_2) = 1 \pm \lambda\, e^{-q^2 R^2}$$

$$\tilde{\rho}_{eff}(q) = e^{-q^2R^2/2}$$

$$C(p_1, p_2) = (1 \pm \lambda|\tilde{\rho}(q)|^2)$$

λ is called the chaoticity parameter.

Correlation Analysis Library (CorAL)

- ❑ Code base for analysis of 2-particle correlations at small relative momentum.
- ❑ Generate pions based on the Core-Halo picture of Bose-Einstein correlations.

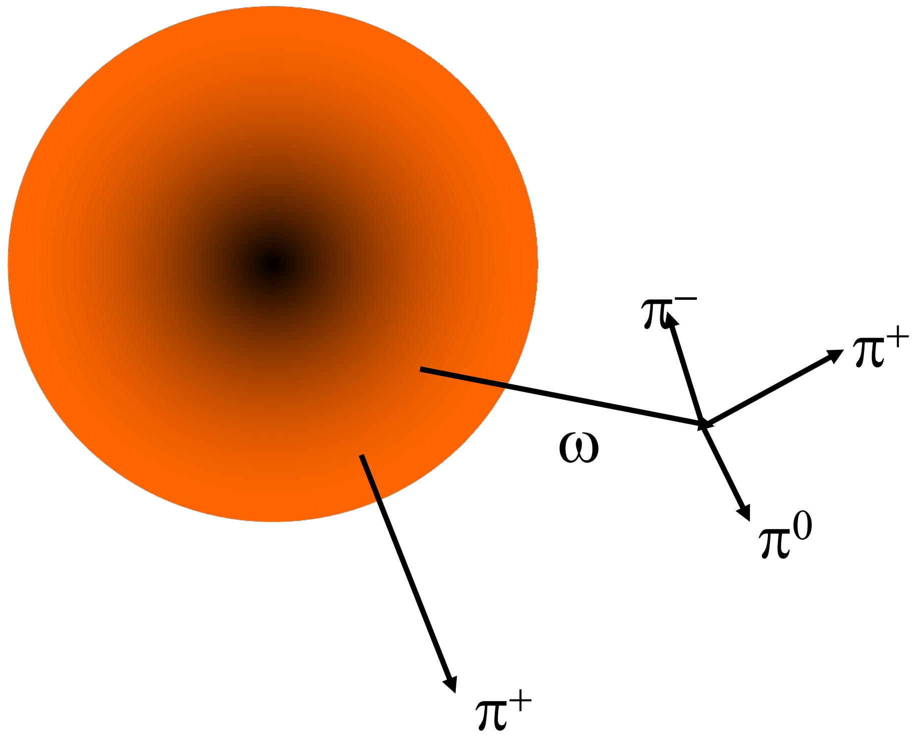
https://github.com/brown170/CorAL

Core Halo Model

Boson source is a superposition of central core and the surrounding extended halo.

$D\,(r,t,p) = fD_{core}\,(r,t,p) + (1\text{-}f)D_{halo}(r,t,p)$

Emission Function



$$S_{\vec{P}}(\vec{r'}) = \int dr'_0 \int d^4R\, D(R + r/2, \vec{P}/2)\; D(R - r/2, \vec{P}/2)$$

The *source function*, it gives the probability of producing a pair of total momentum *P* and a distance *r* apart.

$$C_P(\vec{q}) = \int d^3r\, |\Phi_{\vec{q}}(\vec{r})|^2 S_P(\vec{r})$$

The pair's final state wave-function, we can compute this if we know the interaction. This is called the kernel function *K(q,r)*.

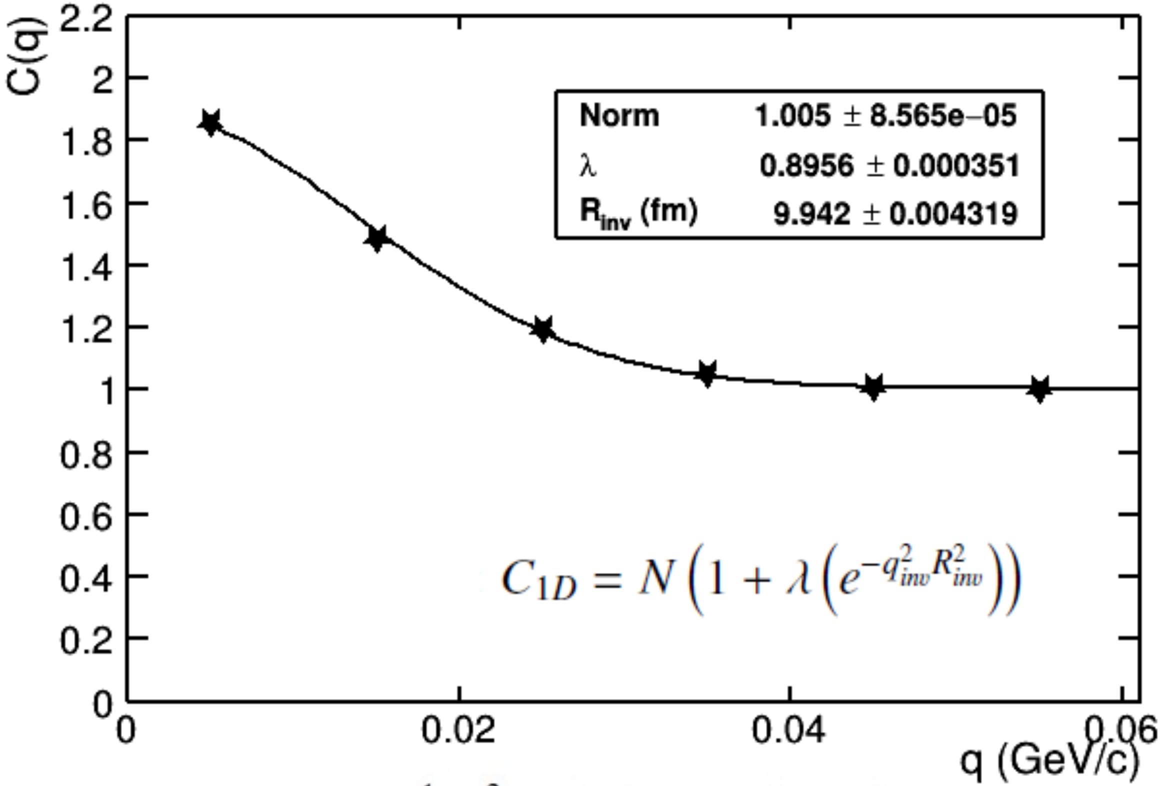
Kernel is affected by the interactions.

1-D Parameterization of the source

- Rx 4.00 fm
- Ry 3.00 fm
- Rz 6.00 fm
- Freeze-out time 13.00 fm/c
- f 0.8
- Temperature 100.0 MeV
- Flow-profile radial

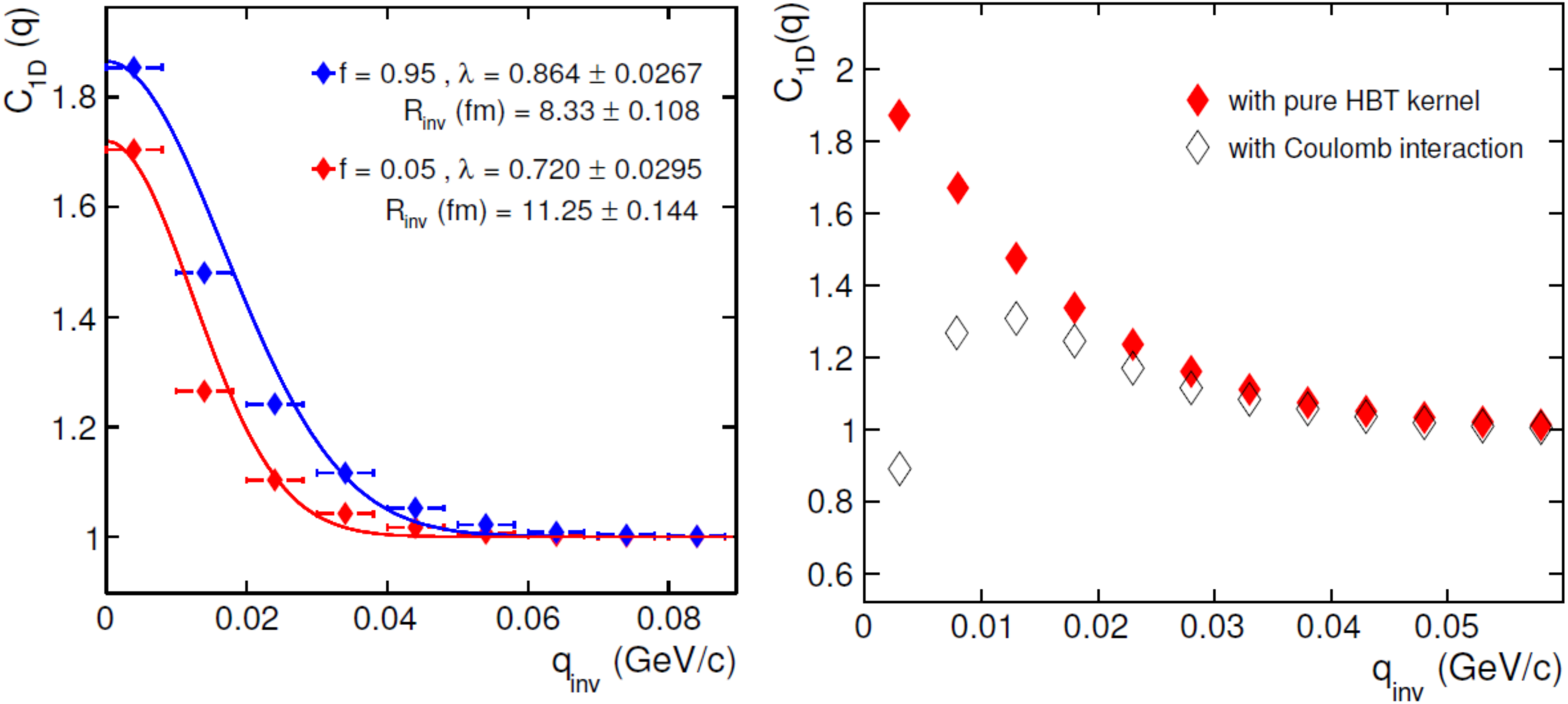
$$D_{\text{core}}(\mathbf{r}, t, \mathbf{p}) \propto e^{-p_\mu u^\mu/T - r_x^2/2R_x^2 - r_y^2/2R_y^2 - r_z^2/2R_z^2 - t/\tau_{fo}}$$

$$D_{\text{halo}}(\mathbf{r}, t, \mathbf{p}) \propto \int d\Delta t\, d^3 p_\omega\, P(\mathbf{p}_\omega, \mathbf{p}) e^{-\Delta t/\tau_\omega} \times D_{\text{core}}\left(\mathbf{r} - \frac{\mathbf{p}_\omega}{E_\omega}\Delta t, t - \Delta t, \mathbf{p}_\omega\right)$$



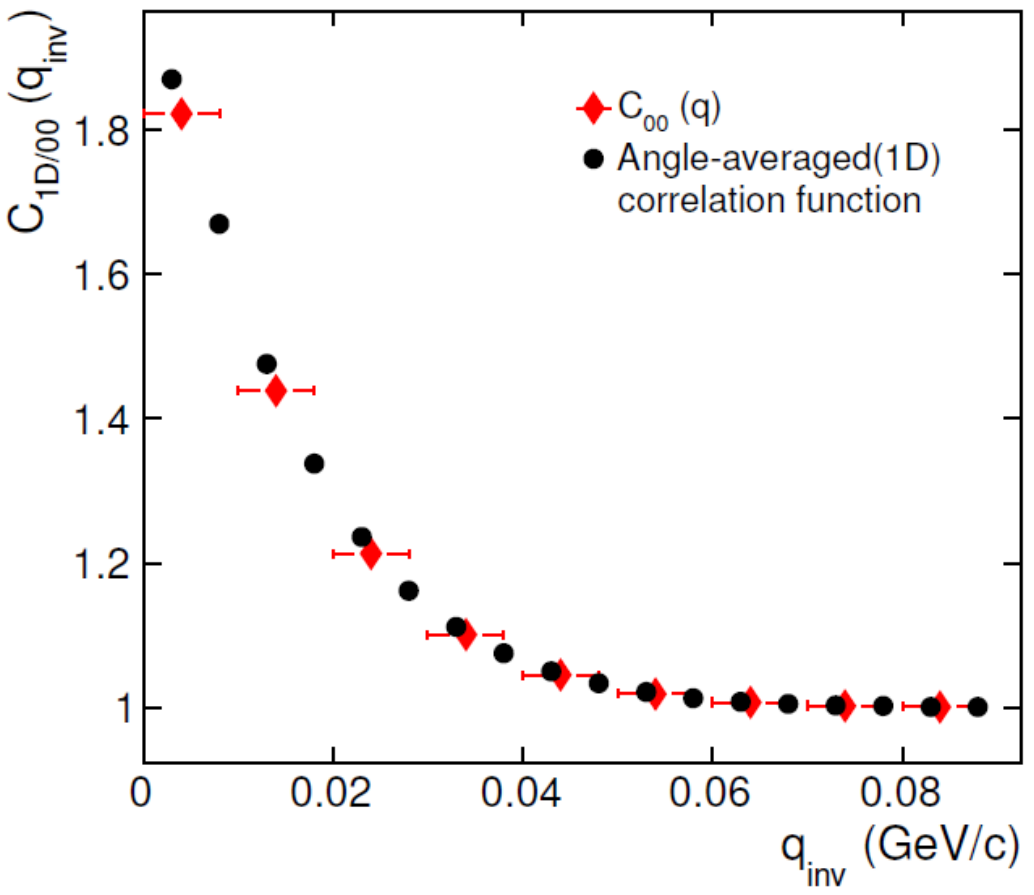
$$C_{1D}(q) = \frac{1}{4\pi}\int_{-1}^{1}\int_0^{2\pi} C\left(\vec{q}\right) d\phi_{\hat{q}} d\left(\cos\theta_{\hat{q}}\right)$$

$$S_{1D}(r) = \frac{1}{4\pi}\int_{-1}^{1}\int_0^{2\pi} S\left(\vec{r}\right) d\phi_{\hat{r}} d\left(\cos\theta_{\hat{r}}\right)$$


f = 0.95 , λ = 0.864 ± 0.0267
R_inv (fm) = 8.33 ± 0.108
f = 0.05 , λ = 0.720 ± 0.0295
R_inv (fm) = 11.25 ± 0.144
C_1D (q)
q_inv (GeV/c)
with pure HBT kernel
with Coulomb interaction
C_1D(q)
q_inv (GeV/c)

$$C\left(\vec{q}\right) = \sqrt{4\pi}\sum_{l_1,m_1} C_{l_1,m_1}(q)\, Y_{l_1,m_1}\left(\Omega_{\hat{q}}\right)$$
$$S\left(\vec{r}\right) = \sqrt{4\pi}\sum_{l_2,m_2} S_{l_2,m_2}(r)\, Y_{l_2,m_2}\left(\Omega_{\hat{r}}\right)$$

$$\sqrt{4\pi}\, C_{lm}(q) = \int_{-1}^{1}\int_{0}^{2\pi} Y^{*}_{l,m}\left(\Omega_{\hat{q}}\right) C\left(\vec{q}\right) d\phi_{\hat{q}} d\left(\cos\theta_{\hat{q}}\right)$$
$$C_{00}(q) = \frac{1}{\sqrt{4\pi}}\int_{-1}^{1}\int_{0}^{2\pi} Y^{*}_{0,0}\left(\Omega_{\hat{q}}\right) C\left(\vec{q}\right) d\phi_{\hat{q}} d\left(\cos\theta_{\hat{q}}\right)$$
$$= \frac{1}{4\pi}\int_{-1}^{1}\int_{0}^{2\pi} C\left(\vec{q}\right) d\phi_{\hat{q}} d\left(\cos\theta_{\hat{q}}\right)$$

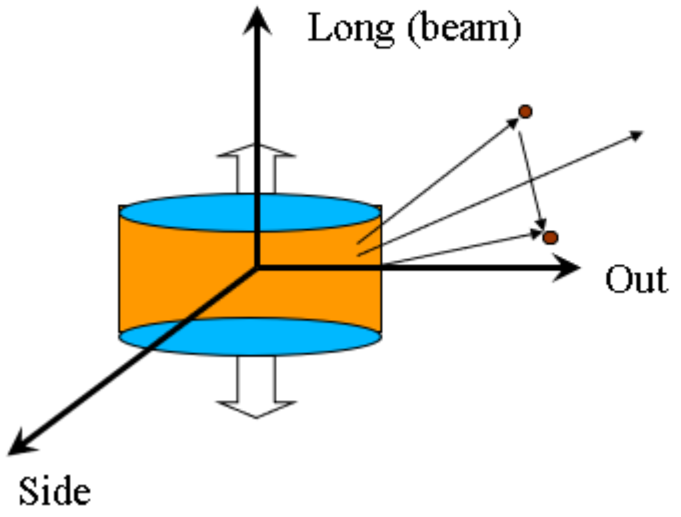


3D Parameterization

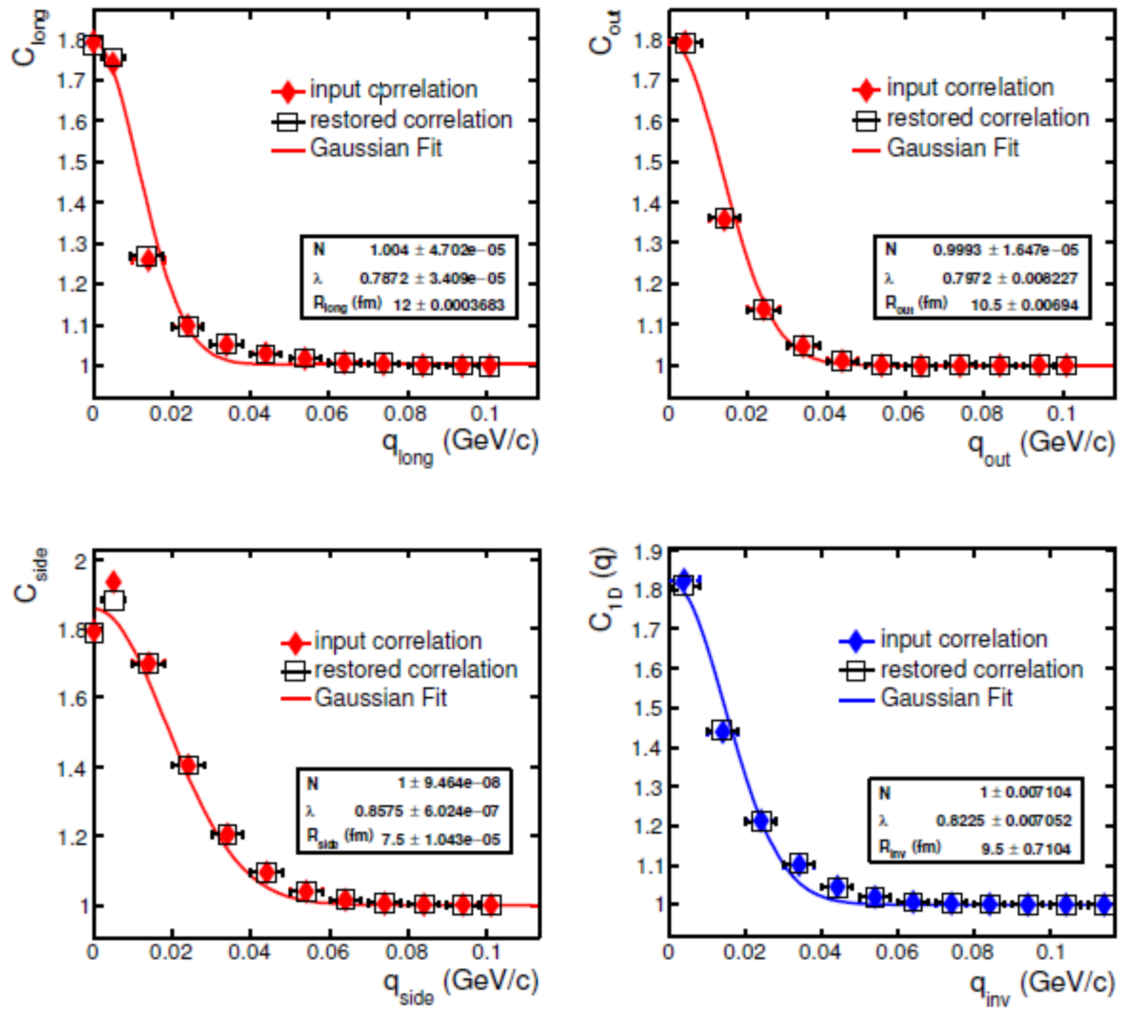
R_{long} – along beam direction

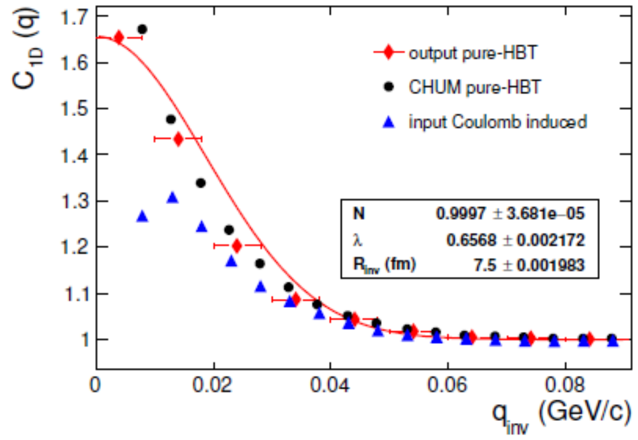
R_{out} – along "line of sight"

R_{side} – ⊥ "line of sight"



$$C(\vec{q}, \vec{K}) = 1 + \lambda(\vec{K})\ exp(-R^2_{out}(\vec{K})q^2_{out} - R^2_{side}(\vec{K})q^2_{side} - R^2_{long}(\vec{K})q^2_{long})$$





$$C_i = N\left(1+\lambda\left(e^{-q_i^2R_i^2}\right)\right)$$

Summary

- The combined effect of color reconnection and the Rope Hadronization was able to describe the enhanced production of strange hadrons in proton-proton collisions at ALICE.
- The q-Weibull function successfully describes the p_T distribution of the strange particles. And the strange particles were emitted from a source which is not fully equilibrated.
- In low-multiplicity classes, the effect of spherocity is minimal, whereas towards higher-multiplicity classes, it starts playing a role in making a separation of jetty to isotropic events for all identified particles.
- At small relative momentum, long-range Coulomb repulsion effects caused a suppression of the correlation function for $(\pi^+ \pi^+)$ pair.

THANK YOU