# TESTING cc̄ CREATION PROPERTIES WITH CORRELATIONS AT THE CERN SPS

MG KIELCE

## BASED ON:

**Spatial correlations of charm and anticharm quarks at hadronisation**

Marek Gazdzicki (Frankfurt U., Inst. Kernphys. and Jan Kochanowski U.), Daniel Kikoła (Warsaw U. of Tech. (main)), Ivan Pidhurskyi (Frankfurt U., Inst. Kernphys. and Jan Kochanowski U. and CERN), Leonardo Tinti (Jan Kochanowski U.) (Apr 29, 2023)

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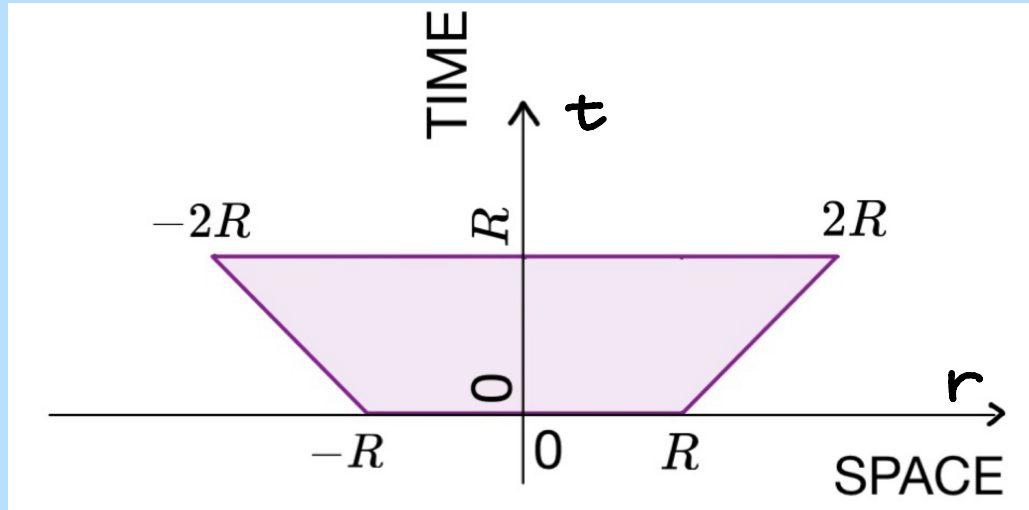**Apparent teleportation of indistinguishable particles**

Marek Gazdzicki (Jan Kochanowski U.), Daniel Kikola (Warsaw U. of Tech.), Ivan Pidhurskyi (Jan Kochanowski U. and CERN), Leonardo Tinti (Jan Kochanowski U.) (Mar 13, 2025)

e-Print: 2503.10565 [nucl-th]

CENTRAL Pb+Pb COLLISION WITH A SINGLE c c̄ PAIR

INITIAL STAGE

EXPANSION STAGE

HADRONISATION STAGE

c

c̄

QGP

D

D̄

D
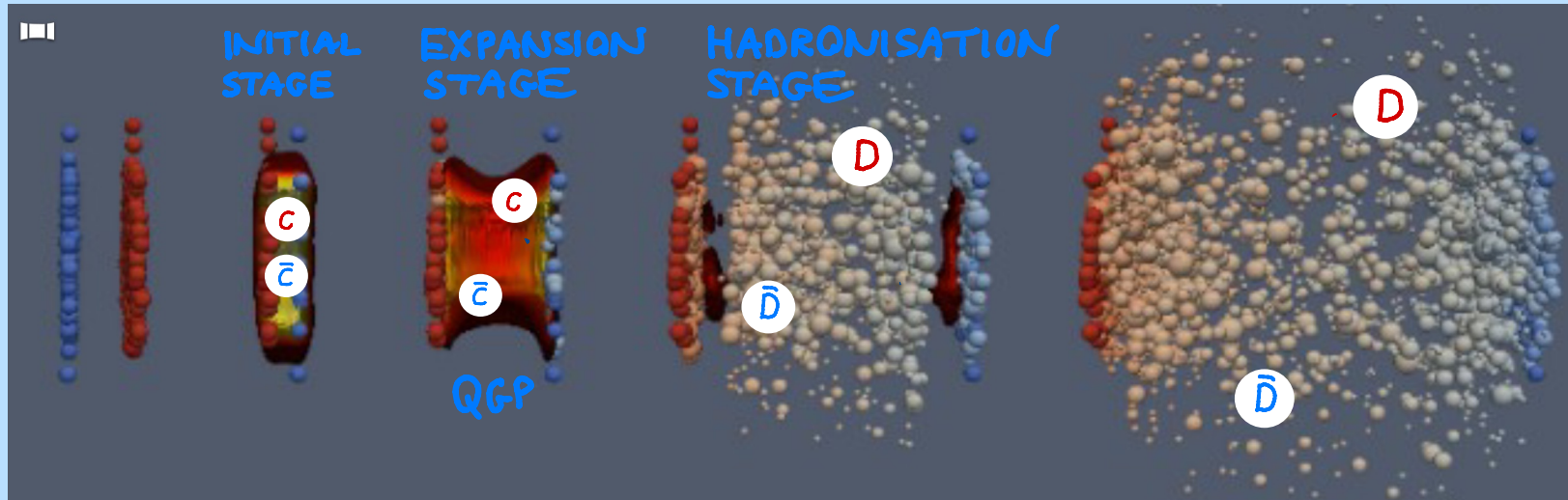
D̄

AND ASSUME:

$t = 0$: INITIAL STAGE: $-R < r < R$

$t = R$: HADRONISATION STAGE $-2R < r < 2R$

$0 < t < R$: EXPANSION STAGE →
COLLECTIVE FLOW AT HADRONISATION:
$\beta(t = R) = r/2R$, $(-1, 1)$

## TWO MODELS OF $c\bar{c}$ CREATION:

- CLASSICAL MODEL (CLA):
  - DISTINGUISHABLE (LABELLED) PARTICLES
  - SPECIAL RELATIVITY
  - CHARM-LABEL CONSERVATION

  → SAME-LABEL $c$ AND $\bar{c}$ APPEAR IN A COMMON SPACE-TIME POINT

  → THEIR EVOLUTION IS LIMITED BY THE COMMON LIGHT-CONE
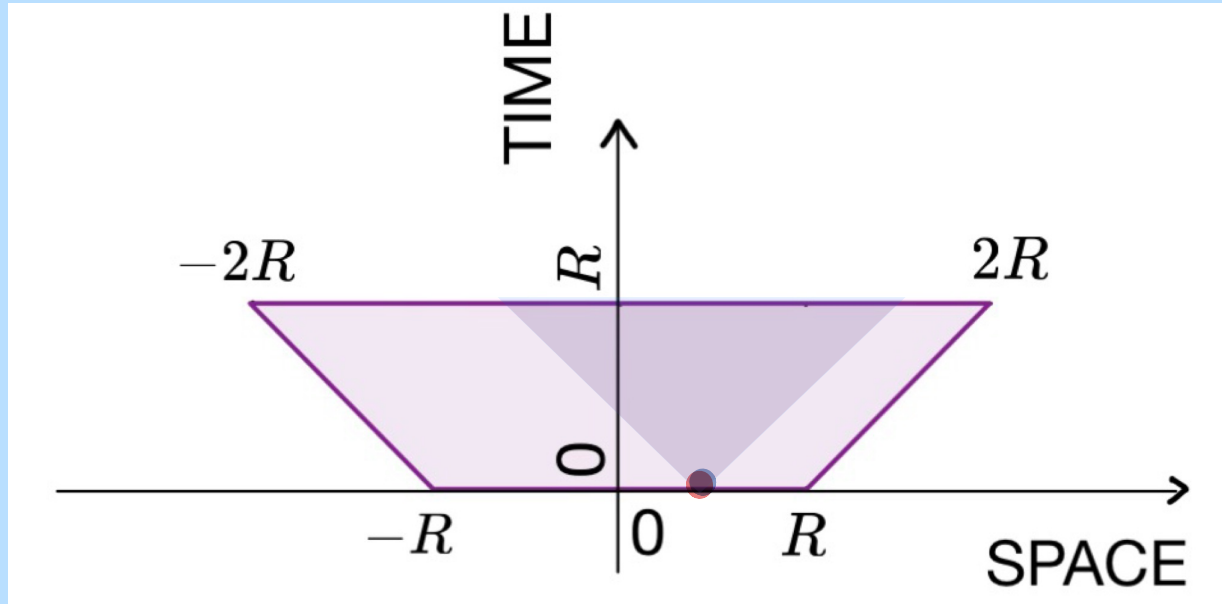
- QFT MODEL (QFT):
  - INDISTINGUISHABLE PARTICLES
  - LOCAL CREATION OF DELOCALISED $c\bar{c}$ STATE

  → $c$ AND $\bar{c}$ APPEAR IN SOMEWHAT DIFFERENT SPACE-TIME POINTS
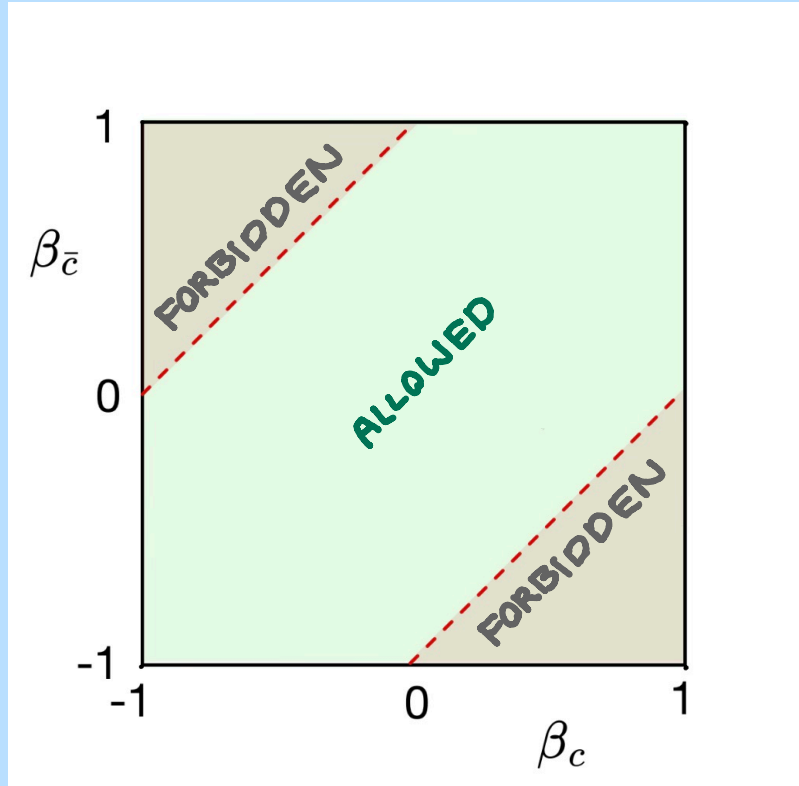
  → THEIR EVOLUTION IS LIMITED BY THE INDIVIDUAL LIGHT CONES

ASSUMING $c$ AND $\bar{c}$ VELOCITIES AT HADRONISATION
ARE GIVEN ONLY BY FLOW ONE GETS THAT ONLY PAIRS WITH

$|\beta_c - \beta_{\bar{c}}| \leqslant 1$ ARE ALLOWED

$\left( \beta(t=R) = r/2R , (-1,1) \right)$

THE CLASSICAL MODEL     $|\beta_c - \beta_{\bar{c}}| \leqslant 1$

## THE QFT MODEL

SCALES FOR THE $c\bar{c}$ CREATION, $p_c \approx m_c$, $\Delta p_c \approx m_c$:

- CREATION OF THE INITIAL $c\bar{c}$ STATE:

$$\Delta \tau^I \approx \hbar/m_c \approx 0.1 \text{ fm/c}$$

- DELOCALISATION OF THE INITIAL $c\bar{c}$ STATE:

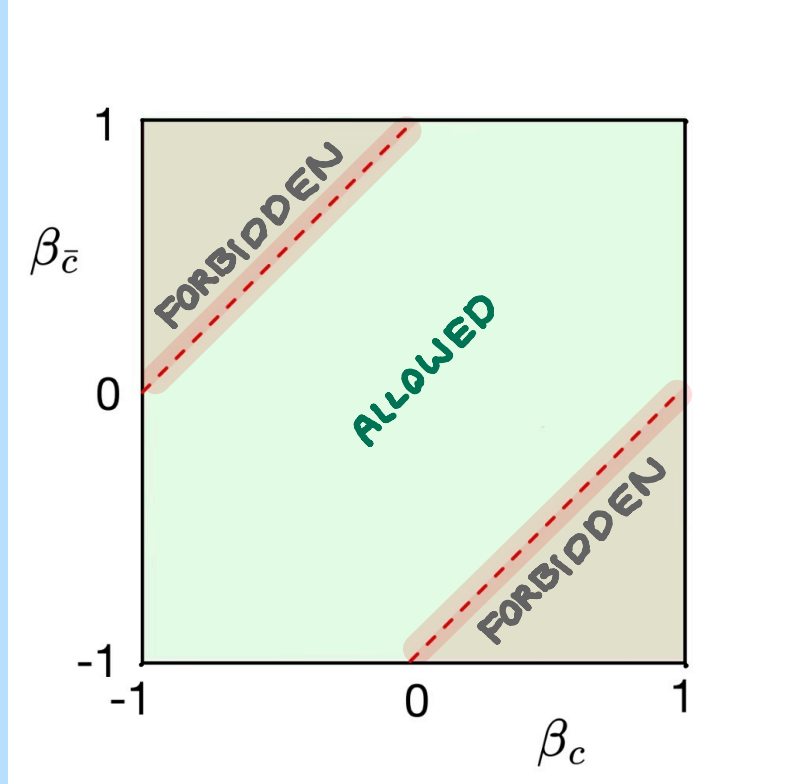$$\Delta x^I \approx \hbar/m_c \cdot c \approx 0.1 \text{ fm}$$

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$\Delta \tau^I$ AND $\Delta x^I$ << NUCLEAR COLLISION SCALES

( EXPANSION TIME $\approx$ 10 fm/c AND INITIAL SIZE $\approx$ 10 fm )

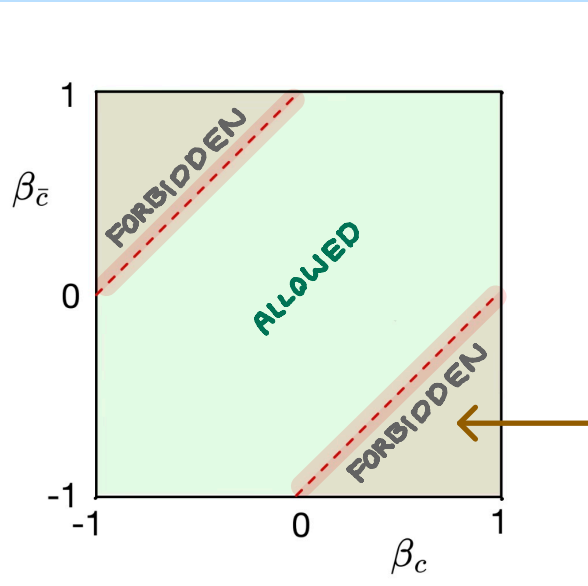THE QFT MODEL   $|\beta_c - \beta_{\bar{c}}| \lesssim 1$



$\rightarrow$ QFT SOMEWHAT SMEARS THE CLASSICAL-MODEL'S SHARP BOUNDARIES

OBSERVING EVENTS IN FORBIDDEN REGIONS WOULD INDICATE PRESENCE OF EFFECTS BEYOND NAIVE UNDERSTANDING OF QFT.

WE REFER TO THESE HYPOTHETICAL EFFECTS AS APPARENT TELEPORTATION

# COMMENT: APPARENT TELEPORTATION IN THE CELL MODEL

- MARKOV-CHAIN WITH $c\bar{c}$ CREATION AND ANNIHILATION,
  - OBEYS TRANSPORT LOCALITY AND CAUSALITY,
  - ALLOWS "GHOSTLY ACTION AT DISTANCE"!
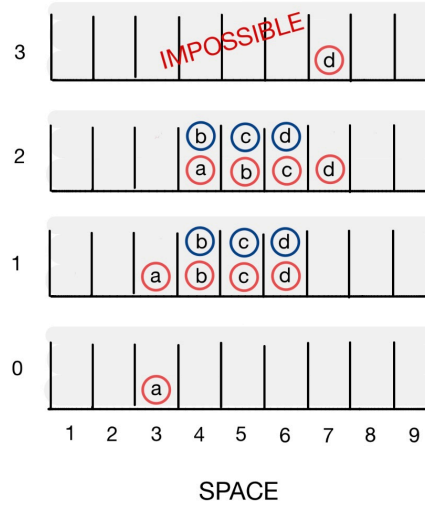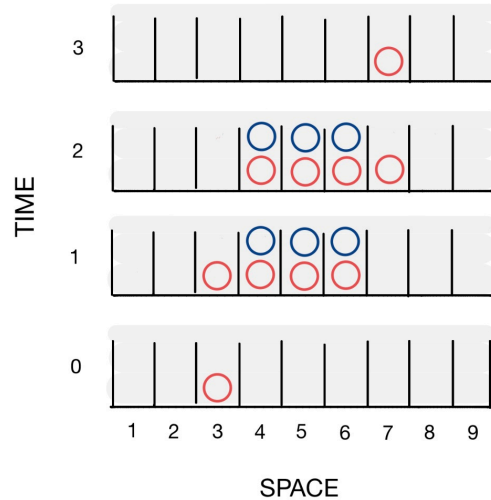
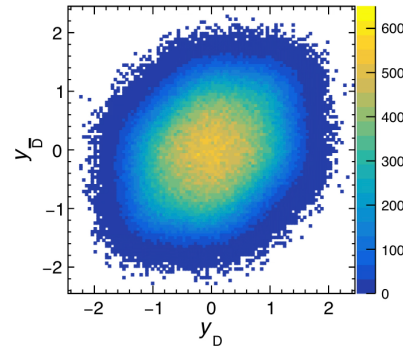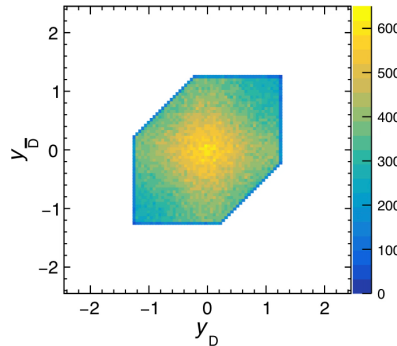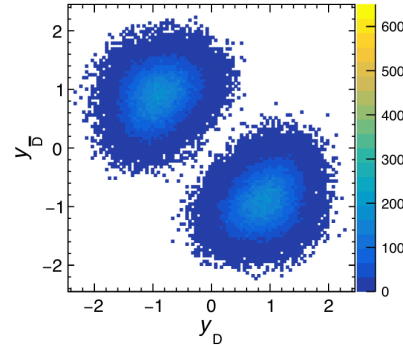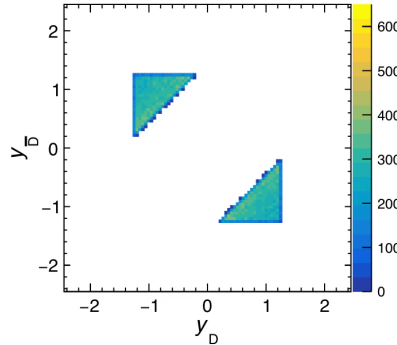$$\sum_{j=i}^{i+k} n_j^X \le \sum_{l=i-\Delta}^{i+k+\Delta} n_l^Y,$$

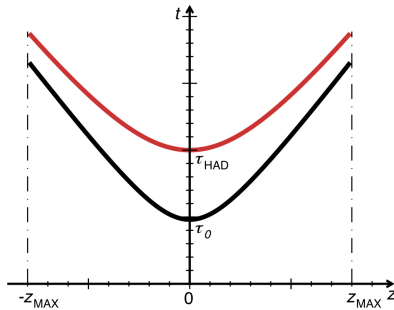$$\sum_{l=i}^{i+k} n_l^Y \le \sum_{j=i-\Delta}^{i+k+\Delta} n_j^X,$$

HERE $\Delta = 1$



APPARENT TELEPORTATION IS POSSIBLE FOR INDISTINGUISHABLE PARTICLES AND IMPOSSIBLE FOR LABELLED ONES.

TOWARDS MORE REALISTIC MODELLING (CLA):

1+1D + HUBBLE-LIKE FLOW + STATISTICAL HADRONISATION
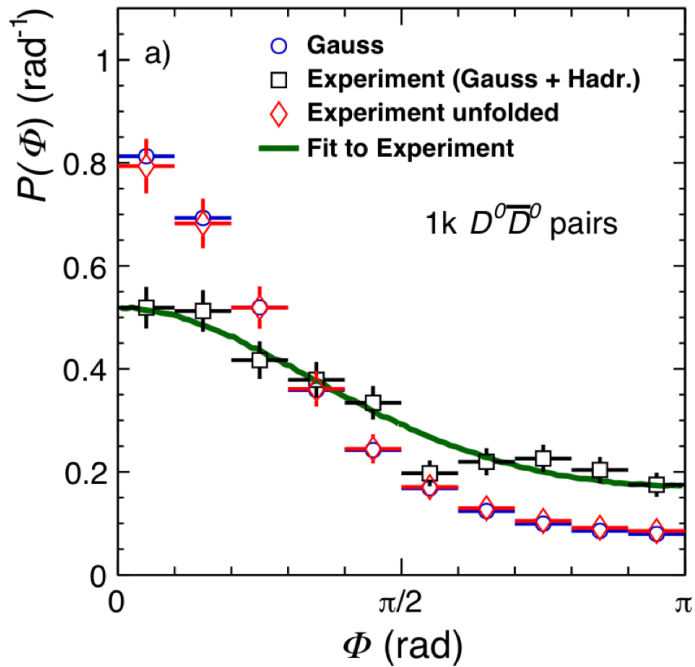
$t^2 = z^2 + \tau_{HAD}^2$

$\beta = z/t$

$y = \tanh^{-1}(\beta)$

$T_0 = 200$ MeV

$T_{HAD} = 150$ MeV

$R = 6$ fm

a)
○ Gauss
□ Experiment (Gauss + Hadr.)
◇ Experiment unfolded
— Fit to Experiment

1k $D^0\overline{D}^0$ pairs

$P(\Phi)$ (rad$^{-1}$)

$\Phi$ (rad)

AZIMUTHAL OPENING ANGLE

ASSUME GAUSS-LIKE ($\sigma = 2\,fm$) CORRELATION OF $c - \bar{c}$ HADRONISTATION POINTS

– POSSIBLE TO GENERALISE FOR UNFOLDING OF OTHER INDEPENDENT FOR $c$ AND $\bar{c}$ STOCHASTIC PROCESSES.

– INITIAL BACK-TO-BACK CORRELATIONS SHOULD APPEAR AS ENHANCEMENT AT $\phi = \pi$

## 1+3D + BLAST WAVE RADIAL FLOW (SPHERICAL SYMMETRY)

$$v(\bar{r}) = \bar{r}/(2R)$$

FOR c AND $\bar{c}$ HADRONISING ON A SPHERE WITH RADIUS $r = aR$, THE MAXIMUM OPENING ANGLE BETWEEN c AND $\bar{c}$ IN CLA IS:
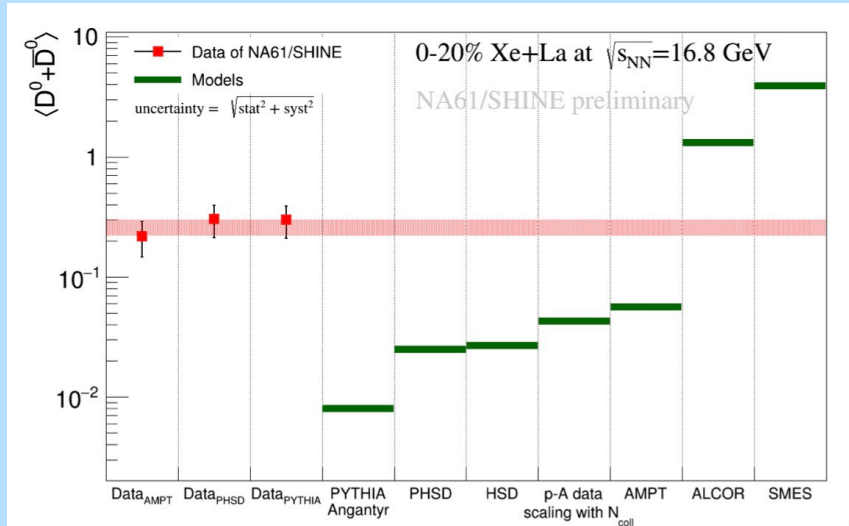
$$\theta_{MAX} = \pi - \cos^{-1}(1 - a^2/2)$$

(FOR c AND $\bar{c}$ HADRONISING IN THE SPHERE CENTRE $(a=0)$, NO LIGHT-CONE LIMITATION)

STUDIES WITHIN 3+1D REALISTIC HYDRO MODELS NEEDED

# IMPORTANCE OF HAVING AT MOST ONE c AND c̄ IN INDIVIDUAL COLLISIONS

FOR MORE THAN ONE $c\bar{c}$ PAIR OF INDISTINGUISHABLE CHARM QUARKS, TWO-QUARK CORRELATIONS DEPEND ON UNMEASURABLE MULTI-QUARK CORRELATIONS
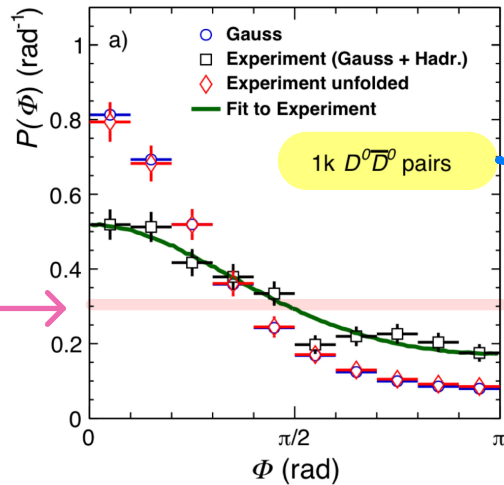


SEARCH FOR APPARENT TELEPORTATION AT THE CERN SPS, WHERE $\langle c\bar{c}\rangle \approx 1$.

## COMMENT:

IF APPARENT TELEPORTATION EXISTS, THERE IS A CHANCE TO HAVE FULLY UNCORRELATED D AND D̄ IN MOMENTUM SPACE:

$$g(\vec{P}_D, \vec{P}_{\bar{D}}) = g(\vec{P}_D) \cdot g(\vec{P}_{\bar{D}})$$

WHICH SEEMS TO BE EASY TO TEST EXPERIMENTALLY:

CENTRAL Pb+Pb AT THE CERN SPS
NA61/SHINE VD ACCEPTANCE



1k $D^0\bar{D}^0$ pairs

|  | $\langle c\bar{c}\rangle = 0.1$ | $\langle c\bar{c}\rangle = 0.2$ | $\langle c\bar{c}\rangle = 0.5$ | $\langle c\bar{c}\rangle = 1$ |
|---|---|---|---|---|
| 1 kHz | 300 days | 150 days | 62 days | 30 days |
| 10 kHz | 30 days | 15 days | 6 days | 3 days |
| 100 kHz | 3 days | 1 day | <1 day | <1 day |
| $N_{pair}/N_{comb}$ | 91% | 83% | 66% | 50% |

S∿INE

CERN

July 14, 2025

**Proposal from the NA61/SHINE Collaboration
for update of European Strategy for Particle Physics**

The NA61/SHINE Collaboration

**2032+:**

**SILICON PIXEL DETECTOR SUPPLEMENTED
WITH LARGE AREA GAS DETECTORS FOR
BETTER MOMENTUM RESOLUTION**