Hidden strangeness shines in NA61/SHINE

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Introduction

\( \phi = s\bar{s} \) meson according to PDG 2014

- Mass \( m = (1019.461 \pm 0.019) \text{ MeV} \)
- Width \( \Gamma = (4.266 \pm 0.031) \text{ MeV} \)
- \( \mathcal{BR}(\phi \rightarrow K^+K^-) = (48.9 \pm 0.5) \% \)

Goal of the analysis

- Differential \( \phi \) multiplicities in p+p collisions measured in NA61/SHINE
  - as function of rapidity \( y \) and transverse momentum \( p_T \)
  - from tag-and-probe invariant mass spectra fits in \( \phi \rightarrow K^+K^- \) decay channel

Motivation

- To constrain hadron production models
  - \( \phi \) interesting due to its hidden strangeness \((s\bar{s})\)
- Reference data for Pb+Pb at the same energies
NA61/SHINE detector

directly — only charged particles!

**TPC → particle tracks in 3D**
- curvature → charge and momentum
- energy loss (dE/dx) → mass

**Performance**
- total acceptance \( \sim 80\% \)
- momentum resolution \( \sigma(p)/p^2 \sim 10^{-4} \text{ GeV}^{-1} \)
- track reconstruction efficiency \( \geq 95\% \)
Analysis methodology overview

**Event selection**
- inelastic
- in the target
- with well measured main vertex

**TPC track selection**
- from main vertex
- well reconstructed
- number of points in TPCs → accurate dE/dx and momentum
- PID cut: \( \frac{dE}{dx} \sim K^\pm \)

**Signal extraction**
- invariant mass spectra in \( y, p_T \) bins
- tag-and-probe fits with background templates from event mixing
Goal: to remove bias of $N_\phi$ due to PID cut efficiency $\varepsilon$

Simultaneous fit of 2 spectra:
- tag $\rightarrow N_t = N_\phi \varepsilon (2 - \varepsilon)$
- probe $\rightarrow N_p = N_\phi \varepsilon^2$

Imperfect description of the background with event mixing $\rightarrow$ 5\% correction and 5\% systematic uncertainty contribution from Monte Carlo study
Double differential spectra: p+p @ 158 GeV

$\sqrt{s_{NN}} = 17.3$ GeV
Double differential spectra: \( p+p @ 158 \, \text{GeV} \)

\( \sqrt{s_{NN}} = 17.3 \, \text{GeV} \)

\[ \frac{d^2N}{dp_T^2 dy} \, [\text{GeV}] \]

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail

MC normalization: \( \int \text{model} = \int \text{data} \)
Double differential spectra: p+p @ 158 GeV

\[ \sqrt{s_{NN}} = 17.3 \text{ GeV} \]

**MC normalization:**
\[ \int \text{model} = \int \text{data} \]

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail
- Fit \( p_T e^{-m_T/T} \) → extrapolation to \( p_T = \infty \) → tail < 1%
Double differential spectra: p+p @ 158 GeV

\[ \sqrt{s_{NN}} = 17.3 \text{ GeV} \]

MC normalization: \( \int \text{model} = \int \text{data} \)

- First 2D (\( y \) vs \( p_T \)) \( \phi \) production measurements for p+p @ 158 GeV

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail

- Fit \( p_T e^{-m_T/T} \rightarrow \) extrapolation to \( p_T = \infty \rightarrow \) tail < 1%
Double & single differential spectra: 80 GeV & 40 GeV

\[ \sqrt{s_{NN}} = 12.3 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 8.8 \text{ GeV} \]

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail
- Fit \( p_T e^{-m_T/T} \rightarrow \) extrapolation to \( p_T = \infty \rightarrow \) tail < 4% & < 1%
Double & single differential spectra: 80 GeV & 40 GeV

\[ \sqrt{s_{NN}} = 12.3 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 8.8 \text{ GeV} \]

- First ever differential (2D) \( \phi \) measurements for p+p @ 80 GeV
- First ever differential (2\times1D) \( \phi \) measurements for p+p @ 40 GeV

- MC normalization: \( \int \text{model} = \int \text{data} \)

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail

- Fit \( p_T e^{-m_T/T} \) → extrapolation to \( p_T = \infty \) → tail < 4\% & < 1\%
Transverse mass spectra at midrapidity

\[ \sqrt{s_{NN}} = 17.3 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 12.3 \text{ GeV} \]

Thermal fit results

<table>
<thead>
<tr>
<th>( p_{\text{beam}} ) [GeV]</th>
<th>( T_\phi ) [MeV]</th>
<th>( T_{\pi^-} ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>158</td>
<td>150 ± 14 ± 8</td>
<td>159.3 ± 1.3 ± 2.6</td>
</tr>
<tr>
<td>80</td>
<td>148 ± 30 ± 17</td>
<td>159.9 ± 1.5 ± 4.1</td>
</tr>
</tbody>
</table>
Rapidity

\[ \text{p+p @ 158 GeV} \]

\[ \text{p+p @ 80 GeV} \]

\[ \text{p+p @ 40 GeV} \]

\[ \sqrt{s_{NN}} = 17.3 \text{ GeV} \]

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- NA61/SHINE consistent with NA49
  
Rapidity

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- EPOS and UrQMD shape comparable to data, Pythia slightly narrower
Rapidity

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\[ \sqrt{s_{NN}} = 8.8 \text{ GeV} \]

- NA61/SHINE consistent with NA49 \( S. \text{ Afanasie} \text{v et al., Phys. Lett. B 491, 59 (2000)} \)
- EPOS and UrQMD shape comparable to data, Pythia slightly narrower
- Fit Gaussian \( e^{-y^2/2\sigma_y^2} \rightarrow \) extrapolation to \( y = \infty \rightarrow \) tails: 3 % for 158 GeV, 7 % for 80 GeV, 5 % for 40 GeV

MC normalization: \( \int_{\text{model}} = \int_{\text{data}} \)
Reference data for Pb+Pb: \( \sigma_y = \text{width of } dn/dy \)

Comparison of particles / reactions

- All but \( \phi \) in Pb+Pb:
  - \( \sigma_y \) proportional to \( y_{beam} \) with the same rate of increase
- two new \( \phi \) points in p+p emphasize peculiarity of \( \phi \) in Pb+Pb
Reference data for Pb+Pb: $\sigma_y = \text{width of } dn/dy$

**Comparison of particles / reactions**

- All but $\phi$ in Pb+Pb:
  - $\sigma_y$ proportional to $y_{\text{beam}}$ with the same rate of increase
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Comparison of particles / reactions

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  - two new $\phi$ points in p+p emphasize peculiarity of $\phi$ in Pb+Pb

Coalescence

- Not compatible with production through $K^+ K^-$ coalescence, but p+p closer
Reference data for Pb+Pb: total yield

- $\phi/\pi$ ratio increases with collision energy
- Production enhancement in Pb+Pb about $3 \times$, independent of energy
- Enhancement systematically larger than for kaons, comparable to $K^+$
  - For $K^-$ consistent with strangeness enhancement in parton phase
  (square of $K^-$ enhancement)

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Comparison with world data and models

\[ \sqrt{s_{NN}} \text{ [GeV]} \]

**p+p → \( \phi + X \)**

- NA61/SHINE preliminary
- World data

**p+p world data**

\[ \frac{dN}{dy} (y = 0) \]

- NA61/SHINE results consistent with world data, much more accurate
Comparison with world data and models

\[ p+p \to \phi + X \]

- NA61/SHINE preliminary
- World data

Models

- EPOS close to data, Pythia underestimates experimental data, UrQMD underestimates \( \sim 2 \times \), HRG (thermal) overestimates \( \sim 2 \times \)
- EPOS rises too fast with \( \sqrt{s_{NN}} \)

\[ \frac{dN}{dy} (y = 0) / \text{d}N \]

- NA61/SHINE preliminary
- World data

\[ \sqrt{s_{NN}} \text{ [GeV]} \]

- EPOS 1.99
- Pythia 6
- UrQMD 3.4
- HRG

V. Blobel et al., PLB 59 (1975)
ACCMOR, NPB 186 (1981)
D. Drijard et al., ZPC 9 (1981)
LEBC-EHS, ZPC 50 (1991)
NA49, PLB 491 (2000)

HRG: PRC 93 (2016)

Hidden strangeness shines in NA61/SHINE
Quark Matter 2018, May 16
Summary

Results

- Differential multiplicities of $\phi$ mesons in p+p:
  - 158 GeV: first 2D ($y$ and $p_T$)
  - 80 GeV: 2D, first at this energy
  - 40 GeV: $2 \times 1D$, first at this energy

Comparison with experimental data

- Results consistent with p+p world data, showing superior accuracy
- Non-trivial system size dependence of width of rapidity distribution ($\sigma_y$), contrasting with that of other mesons → needs study in Be+Be, Ar+Sc, Xe+La
- Confirm enhancement in Pb+Pb, independent of energy in considered range, similar to kaons

Comparison with models

- Each describes well either $p_T$ or $y$ shape, but not both
- None is able to describe total yields
Acknowledgements

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- and the Foundation for Polish Science — MPD program, co-financed by the European Union within the European Regional Development Fund
BACKUP
NA61/SHINE experiment

Fixed target experiment in the North (experimental) Area of CERN SPS
Successor of NA49
Beams
- hadrons (secondary)
- ions (secondary and primary)

~150 physicists
Physics active since 2009
Physics programme

SHINE = SPS Heavy Ion and Neutrino Experiment

Heavy ion physics
- spectra, correlations, fluctuations
- critical point
- onset of deconfinement
  - EM interactions with spectators

Cosmic rays and neutrinos
- precision measurements of spectra
- cosmic rays: Pierre Auger Observatory, KASCADE
- neutrinos: T2K, Minerva, MINOS, NOνA, LBNE

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Data selection

**Events**
- inelastic
- in the target
- with well measured main vertex

**TPC tracks**
- from main vertex
- well reconstructed
- number of points in TPCs → accurate dE/dx and momentum
- with dE/dx corresponding to kaons (PID cut)

Probe: $y \in [0.0, 0.21)$, $p_T \in [0.0, 1.6]$ GeV

![Graph showing entries vs. invariant mass](image)
Selection done with dE/dx
Accept tracks in ±5% band around kaon Bethe-Bloch curve (area between black curves in right picture)
Losses due to efficiency of this selection corrected with tag-and-probe method
Signal extraction
phase space binning, invariant mass spectrum

Probe: $y \in [0.0, 2.1)\), $p_T \in [0.0, 1.6)\) GeV

Entries = 11681

$\Gamma = 4.27$ MeV
$\sigma = 0.991 \pm 0.098$ MeV
$N_{\text{bkg}} = 9187 \pm 79$
$N_p = 2494 \pm 53$
$m_y = 1019.623 \pm 0.071$ MeV
$q = 1.50$
$\chi^2/\text{ndf} = 1.6$

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Signal extraction
phase space binning, invariant mass spectrum

**Signal**
Convolution of:
- relativistic Breit-Wigner
  \[ f_{\text{relBW}}(m_{\text{inv}}; m_\phi, \Gamma) \]
  resonance shape
- q-Gaussian \[ f_{qG}(m_{\text{inv}}; \sigma, q) \]
  broadening due to detector resolution

**Background**
Obtained with the event mixing method:
- Kaon candidate taken from the current event is combined with candidates from previous 500 events to create \( \phi \) candidates in the mixed events spectrum

**Fitting function**
\[
f(m_{\text{inv}}) = N_p \cdot (f_{\text{relBW}} \ast f_{qG})(m_{\text{inv}}; m_\phi, \Gamma, \sigma, q) + N_{\text{bkg}} \cdot B(m_{\text{inv}})
\]
Goal: to remove bias of $N_\phi$ due to PID cut efficiency $\varepsilon$

Simultaneous fit of 2 spectra:
- tag — at least one track in the pair passes PID cut
  $N_t = N_\phi \varepsilon (2 - \varepsilon)$
- probe — both tracks pass PID cut
  $N_p = N_\phi \varepsilon^2$
Normalization and corrections

\[ \frac{d^2n}{dp_T \ dy} = \frac{N_\phi}{N_{ev} \Delta p_T \Delta y} \times \frac{c_\infty \cdot c_{bkg} \cdot c_{MC}}{\mathcal{BR}(\phi \to K^+K^-)} \]

- \( c_\infty \sim 1.06 \) — extrapolation of the resonance curve
- \( c_{bkg} = 1.05 \) — unaccounted-for effects in the background description by event mixing

Monte Carlo correction

\[ c_{MC} = \frac{N^\text{gen}_\phi}{N^\text{sel}_{ev}} \frac{N^\text{sel}_\phi}{N^\text{gen}_{ev}} \]

- registration efficiency
- trigger bias
- losses due to vertex cuts
- reconstruction efficiency
Uncertainties

**Statistical**

MINUIT/HESSE (symmetric)

**Systematic bin-independent**

<table>
<thead>
<tr>
<th>Source</th>
<th>value [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}\mathcal{R}(\phi \rightarrow K^+K^-)$</td>
<td>1</td>
</tr>
<tr>
<td>fitting constraints</td>
<td>2</td>
</tr>
<tr>
<td>resonance theory</td>
<td>3</td>
</tr>
<tr>
<td>background</td>
<td>5</td>
</tr>
<tr>
<td>Total (quadratic)</td>
<td>6</td>
</tr>
</tbody>
</table>

Total systematic uncertainty $= \sqrt{\sum \sigma_i^2}$

For p+p @ 40 GeV additional bin-independent 3 % due to $c_{MC}$ averaging

Statistical uncertainty dominates