φ meson production in proton-proton collisions at 158 GeV in the NA61/SHINE experiment at CERN SPS

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Introduction

- $\phi$ ($ss$) meson according to PDG 2012:
  - Mass $m = 1019.455 \pm 0.020$ MeV
  - Full width $\Gamma = 4.26 \pm 0.04$ MeV
  - $\text{BR}(\phi \rightarrow K^+K^-) = (48.9 \pm 0.5)\%$

- The goal is to measure $\phi$ multiplicities in pp collisions for 5 energies available in NA61 by means of invariant mass spectra fits in the $\phi \rightarrow K^+K^-$ decay channel.

- Motivation: to constrain hadron production models

- $\phi$ especially interesting due to its hidden strangeness ($ss$)

  e.g. Statistical Hadronization Model of Becattini et al.:

  $$\frac{dN}{dp} \sim \gamma_S n_s e^{-\left(\sqrt{p^2+m^2} - \mu \cdot q\right)/T}$$

  $0$ strangness neutral

  $2$ two strange quarks
Statistical Hadronization Model

- Pb+Pb at beam energies 20A-158A GeV

\[ n_s(\phi) = 2 \]
NA49 results
single differential spectra of $p_T (m_T)$ and $y$


- Goal of my analysis:
  - repeat measurement for the same energy and better statistics
  - add new energy points for $p+p$: 20, 31, 40, 80 GeV
NA49 results
single differential spectra of $p_T$ ($m_T$) and $y$


- My p+p data will serve as reference for NA49 Pb+Pb to conclude about strangness-related phenomena in Pb+Pb
Other experiments also measure $\phi$


Detector

BPDs: for each beam particle:
*straight line trajectory*

TPCs: for each charged particle:
*charge, momentum, mass (dE/dx)*

TOFs: for each charged particle:
*mass (tof)*

PSD: for all particles:
*total energy*
Roadmap of the analysis

1) Data selection

2) Signal extraction
   - signal shape parametrisation
   - background shape parametrisation

3) Corrections for known detector and physics effects
   - kaon selection efficiency
   - geometrical and kinematical acceptance
   - track reconstruction efficiency
   - background from off-target interactions
   - trigger bias

4) Systematic uncertainties studies
**p+p data collected in 2009**

<table>
<thead>
<tr>
<th>beam energy</th>
<th>number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2M</td>
</tr>
<tr>
<td>31</td>
<td>3M</td>
</tr>
<tr>
<td>40</td>
<td>6M</td>
</tr>
<tr>
<td>80</td>
<td>4M</td>
</tr>
<tr>
<td>158</td>
<td>4M</td>
</tr>
</tbody>
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**Liquid Hydrogen Target**

selection ➔ **1.7M**
Data selection

Event level cuts

- Standard trigger for inelastic interaction
- Beam particle trajectory well measured (signals from detector positioned close to the target)
- Main interaction vertex fitted using beam and TPC tracks, z position within 20 cm from centre of the target
Data selection

Track level cuts

- Momentum measured (fit converged)
- Track impact parameters in x and y directions smaller than 4 cm
Kaon candidate selection

- Tracks in detector acceptance passing quality selection
- Accept tracks in +/- 5% band around Kaon Bethe-Bloch curve; area between black curves (PID cut) is accepted as Kaons

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

- Signal is parametrised with Voigt ($V$) function to take into account Lorentz ($L$) shape of resonance and Gaussian ($G$) broadening due to detector resolution:

\[
V(x; \sigma, \Gamma) = \int_{-\infty}^{\infty} G(x'; \sigma)L(x - x', \Gamma) \, dx'
\]

- Invariant mass spectrum is fitted with:

\[
f(m_{\text{inv}}) = N_\phi V(m_{\text{inv}} - m_\phi; \sigma, \Gamma) + N_{\text{bg}} B(m_{\text{inv}})
\]

- Background $B(m_{\text{inv}})$ is 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
Invariant mass spectra in NA49 binned phase space
Invariant mass spectra in NA49 binned phase space
Kaon selection efficiency correction

- Not all $K$ accepted by the cut → loss in $\varphi$ yield
- Correction method used by NA49
  - $\sigma$ → Gaus fits
  - cut: Bethe-Bloch +/- $n\sigma$
  - e.g. for $n=1.5$, efficiency $\varepsilon = 87\%$
  - correction $= 1/\varepsilon^2$
- The other method is the tag and probe method (next slide)

Depends strongly on quality of dE/dx calibration → big systematic errors:

1% bias in Bethe-Bloch → 4% bias in correction, 5% bias in $\sigma$ → 5% in correction
The tag and probe method

Assuming:

\[ N_\phi \] — true number of resonances, \( \epsilon \) — PID cut efficiency

Yields in both samples:

\[ N_t(N_\phi, \epsilon) = 2N_\phi \epsilon(1 - \epsilon) + N_\phi \epsilon^2 \]
\[ N_p(N_\phi, \epsilon) = N_\phi \epsilon^2 \]

Fit is done simultaneously to both distributions with:

\[
f(m_{inv}) = \begin{cases} 
N_t(N_\phi, \epsilon) V(m_{inv} - m_\phi; \sigma, \Gamma) + N_{bkg,t} B_t(m_{inv}) & \text{tag sample} \\
N_p(N_\phi, \epsilon) V(m_{inv} - m_\phi; \sigma, \Gamma) + N_{bkg,p} B_p(m_{inv}) & \text{probe sample}
\end{cases}
\]
Closure test with EPOS MC

• To check whether my implementation of the method works, I implemented a PID cut in MC:
  – PID cut passes for reconstructed tracks matched to MC kaons in 90% times – this 90% should be returned by the method
  – To get some background contamination from misidentifications, PID cut passes also for 5% of pions or protons
Closure test with EPOS MC

- NA61 EPOS generates $\phi$ with $\Gamma=0$ → peak fitted with Gaus instead of Voigt
- Fit done in range 990:1060 MeV
- Gives correct efficiency 90.3% +/- 1.7%, but incorrect yield → need to change the fit function for further studies (next slides).
Tag sample bump toy MC study

- **Method:**
  
  generate resonance decay → smear product momenta → calculate $m_{inv}$ with Kaon mass hypothesis for both products

- **Smearing of momenta → $\phi$ peak with similar Voigt shape as in data**

- **Conclusion for NA61 EPOS MC**
  
  The bump in EPOS is due to misidentified $K^*$ with $\Gamma=0$

- **Strategy for data on treatment of misidentified $K^*$**
  
  include in systematic uncertainty or use toy MC shape in the fit to take out the systematic effect.
Choice of signal parametrisation for EPOS

- \( q \)-Gaussian

\[
1 - \left( 1 - q \right) \frac{(x - m_\phi)^2}{2\sigma^2} \left[ \frac{1}{1-q} \right]
\]

- \( \phi \) invariant mass spectrum from NA61 EPOS \((\Gamma=0)\)
- Conclusion for MC fit with \( q \)-Gaussian unbiased
- Strategy for data
  Add \( q \)-Gaussian ansatz of detector resolution effect to systematic uncertainty studies
Improving Tag and Probe method

- Problem:
  huge background in Tag sample $\rightarrow$ huge statistical errors

- Solution:
  require second track in the Tag sample to be within wider (+/-12%) PID band, which preserves 100% kaons
Improving Tag and Probe method

standard T&P

the same

improved T&P
Example of “difficult” bin

\[ y \in [-0.31, -0.01), \quad p_T \in [0.2, 0.4) \]

Standard T&P

Improved T&P

the same

\[ y \in [-0.31, -0.01), \quad p_T \in [0.2, 0.4) \]
Example of “good” bin

\[ y \in [0.59, 0.89), \ p_T \in [0.6, 0.8) \]

Tag: \( y \in [0.59, 0.89), \ p_T \in [0.6, 0.8) \text{ GeV} \)  Entries = 5207

Probe: \( y \in [0.59, 0.89), \ p_T \in [0.6, 0.8) \text{ GeV} \)  Entries = 481

\[ \Gamma = 4.26 \text{ MeV} \]
\[ \sigma = 0.99 \text{ MeV} \]
\[ \varepsilon = 0.90 \pm 0.11 \]
\[ N_0 = 168 \pm 36 \]
\[ N_{\text{bkg,p}} = 353 \pm 29 \]
\[ N_{\text{bkg,t}} = 4963 \pm 100 \]
\[ m_0 = 1019.64 \text{ MeV} \]
\[ N_0 / \sigma(N_0) = 4.7 \]

standard T&P

the same

improved T&P
Fitted $\phi$ yields

standard T&P

\begin{align*}
\text{y} \in [-0.31, -0.01] & & \\
\text{y} \in [-0.01, 0.29] & & \\
\text{y} \in [0.29, 0.59] & & \\
\text{y} \in [0.59, 0.89] & & \\
\text{y} \in [0.89, 1.49] & & \\
\end{align*}

\begin{align*}
\text{fitted yield} & & \\
\text{fitted yield} & & \\
\text{fitted yield} & & \\
\text{fitted yield} & & \\
\end{align*}

- uncorrected
- corrected for PID (T&P)
Fitted $\phi$ yields

improved T&P

$y \in [-0.31, -0.01)$

$y \in [-0.01, 0.29)$

$y \in [0.29, 0.59)$

$y \in [0.59, 0.89)$

$y \in [0.89, 1.49)$

\[ \bullet \text{ uncorrected} \]

\[ \text{red} \text{ corrected for PID (T&P)} \]
Cross-check with NA49

- NA49 – fully corrected (PID, acceptance, reconstruction, off-target, trigger bias)
- uncorrected – from fit to probe sample
- corrected for PID – from Tag and Probe method

**improved T&P**

Conclusion

- Measurement very interesting for hadron production models
- All data already collected; under final calibration process
- Analysis in progress (preparing corrections)
  - Completed PID efficiency correction measurement
  - Next step: geometrical and kinematical acceptance
General info

**SHINE – SPS Heavy Ion and Neutrino Experiment**

- Fixed target experiment in the north area of the CERN SPS
- Beams:
  - Ions (secondary: Be, primary: Ar and Xe) at 13A - 158A GeV/c
- Based on the upgraded NA49 detector
- Proposal November 2006, pilot run 2007, first physics run 2009, further runs in 2010-2013
- Collaboration of ~150 physicists, 28 institutes, 16 countries
NA61/SHINE physics program

Hadron production in p+p, p+A, h+A, A+A at various energies

• **Heavy ion program - spectra, fluctuations, correlations**
  - search for the critical point of strongly interacting matter
  - study of the properties of the onset of deconfinement
  - study high $p_T$ particles (energy dependence of nuclear modif. factor)

• **Neutrino and cosmic-ray physics programs - precision data on hadron production (spectra)**
  - reference measurements of p+C interactions for the T2K experiment for computing initial neutrino fluxes at J-PARC
  - reference measurements of p+C, p+p, p+C, and K+C interactions for cosmic-ray physics (Pierre-Auger and KASCADE experiments) for improving air shower simulations

• **Considered extensions beyond the approved program**
  - measurements of Pb+Pb collisions for the ion program
    (+ open charm and multi-strange particles, high pT spectra)
  - measurements for the Fermilab neutrino program
  - measurements for the CERN (LBNO) neutrino program
Status of the NA61 data taking within the heavy ion program

- high stat. with new vertex detector
  - 2017/18/19

- detailed scan with existing detector
  - Pb+Pb
  - Xe+La
  - Ar+Ca
  - Be+Be
  - p+Pb
  - p+p

- momentum (A GeV/c)
  - 13, 20, 30, 40, 80, 158

- Considered extension of n-program for CERN (LAGUNA-LBNO) and US experiments (MINERnA, MINOS, NOνA and future LBNE)

Status of the NA61 data taking within the neutrino and CR programs

- p+A
  - A=C, Be, Al, etc.
- K−+C
- π−+C
- p+C(LT)
- p+C

- momentum (GeV/c)
  - 9 - 120

- planned data (approved)
- pilot (test) data
- recorded data
- beyond the approved program

- 2012
- 2009/12
- 2007-10
- 2007/09/12
Detector – particle identification

ToF – low momenta

\( \sigma(p)/p^2 \approx 10^{-4} \ (\text{GeV/c})^{-1} \)

\( \sigma(\text{ToF}) \approx 60-120 \ \text{ps} \)

\( \sigma(\text{dE/dx})/\langle\text{dE/dx}\rangle \approx 4\% \)

dE/dx – very low and high momenta

combined ToF and dE/dx – medium momenta
Possible sources of systematic uncertainty

- signal extractions ambiguities:
  - Lorentz: relativistic or not
  - detector resolution: gaus, q-Gaus, crystal ball (probably irrelevant)
  - background: event mixing or analytical
  - fitting range, parameter constraints
- associated with corrections?
- ?
NA49 results
single differential spectra of $p_T$ ($m_T$) and $y$


- My p+p data will serve as reference for NA49 Pb+Pb to conclude about strangeness-related phenomena in Pb+Pb