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

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Introduction

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

- The goal is to obtain $\phi$ multiplicities in pp collisions for 5 available energies

- Motivation: to constrain hadron production models – various types of models predict certain scaling properties for multiplicities of hadrons if we change energy or size of the colliding system. $\phi$ especially interesting due to its hidden strangeness (s$\bar{s}$) – should it be treated as a strangeness-neutral hadron which production is governed solely by the mass, or assuming that 2 strange quarks need to be produced and coalesced what might be influenced by strangeness suppression/enhancement, or … ?

- NA49 published results for pp,pPb @ 158 GeV, as well as PbPb at 20,30,40,80,158 GeV.

- First I will obtain results for pp@158GeV to cross check with NA49 – available only single differential spectra of $p_T$ and $y$.

- Analysis by means of invariant mass spectra fits in the $\phi \rightarrow K^+K^-$ decay channel. Available about 1.7M preselected pp@158GeV events.
Kaon candidate selection

- No PID selection for kaons – no $\phi$ peak in the spectrum
- accept tracks in +/- 5% band around Kaon Bethe-Bloch curve; area between black curves is accepted as Kaons
Signal extraction

- Background is parametrised using 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

- Signal is parametrised with Voigt function to take into account Lorentz shape of resonance and Gaussian 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:

\[
f(m) = N_\phi \cdot V(m - m_\phi; \sigma, \Gamma = 4.26 \, \text{MeV}) + \beta \cdot \text{Mixed}(m)
\]
Unbinned phase space matching to NA49

- Fit with Voigt + mixed event spectrum*β

\[ y \in [-0.31, 1.49), \quad p_t \in [0.0, 1.2) \text{ GeV} \]

Entries = 19802

\[ \Gamma = 4.26 \text{ MeV} \]
\[ \sigma = 0.91 \pm 0.16 \text{ MeV} \]
\[ N_\phi = 3355 \pm 92 \]
\[ N_{bkg} = 16813 \pm 195 \]
\[ m_\phi = 1019.614 \pm 0.081 \text{ MeV} \]

pp@158GeV
Binning (2D based on NA49 2x1D binning) - pp@158GeV
Binning (2D based on NA49 2x1D binning) - pp@158GeV
Tag & Probe method
The method

- It is used by others (e.g. LHCb, ATLAS) to correct for number of resonances lost due to rejecting of daughter tracks by PID cut – PID cut efficiency

- One needs 2 data samples:
  - Probe
    - Both kaon candidates need to pass PID cut for kaon (this was used up to now)
  - Tag
    - At least one of kaon candidates need to pass PID cut for kaon

- Assuming true number of resonances in data is $N_\phi$ and PID cut efficiency is $\epsilon$, numbers of observed resonances:

$$N_{tag} = 2N_\phi\epsilon(1 - \epsilon) + N_\phi\epsilon^2$$

$$N_{probe} = N_\phi\epsilon^2$$
Test with EPOS MC

- To check whether my implementation of the method works, I implemented a PID cut in MC:
  - reconstructed VertexTrack is matched to MC track
  - PID cut passes in 90% times when matched MC track is kaon – this 90% should be returned by the method
  - To get some background from misidentification, PID cut passes also for 5% of pions or protons
Test with EPOS MC

- **Width of Lorentz is set to zero, because EPOS has no physical mass distribution**
- **Bump at m>1060MeV – probably misidentified K^*\to K,\pi**
- **Fit done in range 990-1060 MeV**
- **Obtained efficiency: 90.3% +/- 1.7%**
Data in unbinned phase space matching to NA49
Examples of binned fits
Binned fit results
Comparison to NA49 – uncorrected spectrum
Conclusion

- Uncorrected spectrum looks reasonable.
- Analysis in progress, several corrections to be done.
- Need to move to newly reconstructed, better calibrated data and incorporate proper kaon candidate selection using fitted Bethe-Bloch.
- Check if it is possible to reduce tag&probe statistical uncertainty using a second band in the tag sample to remove pions/protons without changing efficiency for kaons.
BACKUP
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
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
NA61/SHINE at CERN SPS

+Z detector, +A detector
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 $p_T$ 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

<table>
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<th>Year</th>
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<th>Xe+La</th>
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Considered extension of n-program for CERN (LAGUNA-LBNO) and US experiments (MINERnA, MINOS, NOnA and future LBNE)

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

- p+A
  - A=C, Be, Al, etc.
- K^+C
- \(\pi^-C\)
- p+C(LT)
- p+C

- 9 - 120 GeV/c
Detector – particle identification

ToF – low momenta

\[ \sigma(p)/p^2 \approx 10^{-4} \ (\text{GeV}/c)^{-1} \]
\[ \sigma(\text{ToF}) \approx 60-120 \ \text{ps} \]
\[ \sigma(dE/dx)/<dE/dx> \approx 4\% \]

dE/dx – very low and high momenta

combined ToF and dE/dx – medium momenta
Data collected in 2009 for physics of strongly interacting matter

- p+p at 158 GeV/c: 4M events
- p+p at 80 GeV/c: 4M events
- p+p at 40 GeV/c: 6M events
- p+p at 31 GeV/c: 3M events
- p+p at 20 GeV/c: 2M events
No PID selection - no $\phi$ peak

massHisto

- Entries: $7.780441 \times 10^7$
- Underflow: $2.373 \times 10^5$
- Overflow: $5.357 \times 10^7$
Fig. 2. (a) Transverse-mass distributions of $\phi$-mesons (averaged over rapidity) for Pb+Pb (3.0 < $y$ < 3.8) and p+p (2.9 < $y$ < 4.4). (b) Rapidity distributions of $\phi$-mesons for Pb+Pb and p+p. Full symbols represent measured points, open ones are reflected at midrapidity ($y_{\text{cm}}$ = 2.9).

Fig. 3. $\phi/\pi$ ratio measured for Pb+Pb in comparison with p+p data (NA49 and previous work [18]) as a function of the square of the center-of-mass energy per nucleon pair. $\pi$ yields in p+p were taken from [21].

Produced particles, e.g., pions and kaons. From a fit with a Gaussian ($dn/dy \propto \exp(-(y - y_{\text{cm}})^2/2\sigma_y^2)$) one obtains for the widths $\sigma_y = 0.89 \pm 0.06$ (p+p) and 1.22 ± 0.16 (Pb+Pb). This difference is remarkable in view of the fact that the shape of the distributions of charged pions and kaons is very similar in both reactions (e.g., $\sigma_y(\pi) = 1.5$ [4]).

By integrating the fit functions discussed before over the whole kinematical range one obtains for the total average $\phi$-multiplicities
- for p+p (inelastic): $\langle \phi \rangle = 0.012 \pm 0.0015$,
- for Pb+Pb (central): $\langle \phi \rangle = 7.6 \pm 1.1$.

The error estimates include contributions from statis-
NA49 results

Fig. 4. (a) Multiplicity dependence of the $\phi/\pi$ ratio in p+p. The cross-section weighted average is indicated by the horizontal dashed line. (b) Centrality dependence of the $\phi/\pi$ ratio in the forward hemisphere in p+Pb normalized to the average p+p value. The minimum-bias value is indicated by the horizontal dashed line. Vertical dashed lines indicate bin sizes in the abscissa.

4. Dis

When it appears, a naive approach for the p+p comparisons of Pb+1 factor:

$$\langle \phi \rangle / \langle \pi \rangle$$

de where

$$\langle \pi \rangle =$$

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Roadmap

1) Binned phase space – preliminary done using 2x1D NA49 binning

2) Event/track selection – preliminary

3) Signal extraction:
   signal & background parametrisation – done

4) correction for PID efficiency of kaons:
   based on knowledge of PID variables distributions or Tag&Probe method –
   possible innovation with respect to NA49 and current NA61 methods

5) correction for acceptance and decay of kaons:
   on flat space MC

6) correction for reconstruction efficiency:
   MC model or embedding, but expected 100% based on NA49 experience

7) correction for EMPTY target contribution

8) correction for trigger bias due to S4 killing good events:
   MC model

9) systematic uncertainties studies

10) optimisations and reiteration
Possible sources of systematic uncertainty

- signal extractions ambiguities:
  - Lorentz: relativistic or not
  - detector resolution: gaus or e.g. crystal ball (probably irrelevant)
  - background: event mixing or analytical
  - fitting range, parameter constraints
- associated with corrections?
- ?