Progress on hadron production in NA61/SHINE

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Layout:
• Introduction to the NA61/SHINE experiment
• Calibration status
• $\phi$ meson production
• Tag&Probe method
• Conclusion
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 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
  - 2017/18/19
  - 20: 2017
  - 40: 2016
  - 158: 2015

- detailed scan with existing detector
  - 2017
  - 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, NOnA and future LBNE)

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

- p+A
  - A=C, Be, Al, etc.
  - 9 - 120 GeV/c
  - 2012
  - 2009/12
  - 2007-10
  - 2007/09/12

- K⁻+C
- π⁻+C
- p+C (LT)
- p+C

- momentum (GeV/c): 31, 120, 158, 350, 400

Legend:
- recorded data
- planned data (approved)
- pilot (test) data
- beyond the approved program
BPD calibration Status

- BPD alignment was performed for the whole data set up to 2013. Identified 42 settings of the BPD geometry.
- BPD-TPC alignment was done for 2010 pC and pp, 2011 BeBe.
- A general-purpose production management system was developed, which allowed for significant automation of above steps.
dE/dx calibration status

• Calibration consists of several steps – time dependence, y-dependence, Bethe-Bloch and sector constants calibrations; 2 latter steps are iterative. Initially was done largely manually, so that a single iteration took up ~2 weeks; procedure very error prone.

• Developed method for simultaneous fitting of Bethe-Bloch curve and sector constants.

• Automated one of legacy substeps, speeding it up from ~1 week to ~10 minutes, so that single iteration went down to ~2 days.

• Learnt to operate the whole chain. Parallelized and automated it – after fixing Bethe-Bloch curve, the whole chain with 10 iterations of sector constants calibration takes ~3 days of CPU and ~1h of human attention.
$\phi$ meson production
Introduction

- The goal is to obtain $\phi$ multiplicities in pp collisions for available energies.
- Analysis by means of invariant mass spectra fits in the $\phi \rightarrow K^+K^-$ decay channel (which includes about 50% of all $\phi$'s produced).
- 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 $y$. 
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

**pp@158GeV**

**positive particles**

**negative particles**
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:

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

- Fit with Voigt + mixed event spectrum*β

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

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<td>( m_0 )</td>
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<td>( \sigma )</td>
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\( \text{pp@158GeV} \)
Binning (2D based on NA49 2x1D binning) - pp@158GeV
Binning (2D based on NA49 2x1D binning) - pp@158GeV
Not normalized, not corrected $\phi$ spectra in pp@158GeV
Roadmap

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

2) Event/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
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 $\varepsilon$, numbers of observed resonances:

  \[ N_{tag} = 2N_\phi\varepsilon(1 - \varepsilon) + N_\phi\varepsilon^2 \]

  \[ N_{probe} = N_\phi\varepsilon^2 \]

- This yields

  \[ \varepsilon = 1 - \frac{N_{tag} - N_{probe}}{N_{tag} + N_{probe}} \]
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
- Fit done in range 990:1060 MeV
- Obtained efficiency: 90.2% +/- 1.6%
Test with EPOS MC

- Tag & probe method seems to work
- Need to compare with cut in data done with dE/dx distributions widths
- Need to understand bump in MC for m>1060MeV
- Need to calculate properly and compare statistical errors coming from tag & probe and classical methods
- Need to make systematic studies – can tag & probe give proper number of phi's if we make a band cut?
Conclusions

- Calibration almost finished
- Did a lot of automation
- Making steady progress in the $\phi$ production analysis
BACKUP
PhD thesis status

- Procedure started in May 2012
- Title: "Proton and antiproton production in proton-proton collisions in the NA61/SHINE experiment at CERN SPS"; requires change “Proton and antiproton” to “Phi meson”
- Table of contents:
  1. Introduction
  2. NA61/SHINE experiment
  3. BPD calibration and reconstruction
  4. dE/dx calibration
  5. Data analysis
  6. Results and their discussion
  7. Summary and conclusions
NA61/SHINE at CERN SPS

+Z detector, +A detector
Detector – particle identification

ToF – low momenta

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

Combination of ToF and dE/dx – medium momenta

dE/dx – very low and high 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 $\varphi$ peak

- **Entries**: $7.780441e+07$
- **Underflow**: $2.373e+05$
- **Overflow**: $5.357e+07$
NA49 results

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 ($dn/dy \propto \exp\left(-\left(y-y_{\text{cm}}\right)^2/2\sigma_y^2\right)$) one obtains for the widths $\sigma_y = 0.89 \pm 0.06$ ($p+p$) and $1.22 \pm 0.16$ (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 statisti-
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. Discussion

When interpreting the results, it is important to consider the contribution from peripheral Pb+Pb collisions and the centrality dependence. The ratio $\langle \phi \rangle / \langle \pi \rangle$ and $\langle \phi \rangle / \langle \pi \rangle$ is found to be consistent with the expected behavior for the central Pb+Pb collisions.
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?
- ?