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

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Białasówka, 28 April 2017
Outline

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2 Analysis methodology

3 Results

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Introduction

**φ = s\bar{s}** meson according to PDG 2014

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

Goal of the analysis

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

Motivation

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

General info

- Fixed target experiment in the North (experimental) Area of CERN SPS
- Successor of NA49
- Beams
  - hadrons (secondary)
  - ions (secondary and primary)
- \( \sim 150 \) physicists \( \rightarrow \) IFJ PAN group (6 people) since June 2016
- 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, Minerνa, MINOS, NOνA, LBNE

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production in p+p in NA61/SHINE

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**Physics programme**

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

If not stated otherwise, pictures for $p+p @ 158 \text{ GeV} \rightarrow \sqrt{s_{NN}} = 17.3 \text{ GeV}$.

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

**Cosmic rays and neutrinos**
- precision measurements of spectra
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Production in $p+p$ in NA61/SHINE

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NA61/SHINE detector

directly — only charged particles!

TPC $\rightarrow$ particle tracks in 3D
- curvature $\rightarrow$ charge and momentum
- energy loss (dE/dx) $\rightarrow$ mass

Performance
- total acceptance $\sim 80\%$
- momentum resolution $\sigma(p)/p^2 \sim 10^{-4} \text{ GeV}^{-1}$
- track reconstruction efficiency $\geq 95\%$
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: $y \in [0.0, 2.1)$, $p_T \in [0.0, 1.6)$ GeV

- no PID cut
- with PID cut

entries

$10^4$

$10^3$

$10^2$

$10$

$1$

1000 1020 1040 1060 1080

$m_{\text{inv}}(K^+, K^-) \text{ [MeV]}$
Kaon candidate selection — PID cut

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
$N_{\text{bkg}} = 9187 \pm 79$
$N_p = 2494 \pm 53$
$m_\phi = 1019.623 \pm 0.071$ MeV
$q = 1.50$
$\chi^2/\text{ndf} = 1.6$

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.
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**

\[ f(m_{\text{inv}}) = N_p \cdot (f_{\text{relBW}} \ast f_{qG})(m_{\text{inv}}; m_\phi, \Gamma, \sigma, q) + N_{bkg} \cdot B(m_{\text{inv}}) \]
Signal extraction

**tag-and-probe method** → ATLAS, LHCb

- **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
    
    $$N_p = N_\phi \varepsilon^2$$

**Simultaneous fit of 2 spectra:**

- **Tag:**
  - $y \in [0.0, 2.1]$, $p_t \in [0.0, 1.6]$ GeV
  - Entries = 128572
  - $\chi^2$/ndf = 1.9

- **Probe:**
  - $y \in [0.0, 2.1]$, $p_t \in [0.0, 1.6]$ GeV
  - Entries = 11681
  - $\Gamma = 4.27$ MeV
  - $\sigma = 0.70 \pm 0.12$ MeV
  - $\varepsilon = 0.899 \pm 0.031$
  - $N_b = 2952 \pm 183$
  - $N_{bkg,p} = 9746 \pm 154$
  - $N_{bkg,t} = 123748 \pm 504$
  - $m_q = 1019.566 \pm 0.083$
  - $q = 1.50$
  - $\chi^2$/ndf = 2.0

**Tag:**

- at least one K pass PID

**Probe:**

- both K pass PID
Monte Carlo correction

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

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

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

\(c_{\infty} \sim 1.06\) — extrapolation of the resonance curve

\(c_{\text{bkg}} = 1.05\) — unaccounted-for effects in the background description by event mixing
Uncertainties

Statistical
MINUIT/HESSE (symmetric)

Systematic bin-independent

<table>
<thead>
<tr>
<th>Source</th>
<th>value [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{BR}(\phi \rightarrow K^+K^-)$</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
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 \((y \text{ vs } p_T)\) \(\phi\) production measurements for p+p @ 158 GeV
- +1 bin in \(y\), +1 bin in \(p_T\) compared to \(2 \times 1D\) NA49

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

- Fit \(p_T e^{-m_T/T} \rightarrow \text{extrapola} \quad \text{tion to } p_T = \infty \rightarrow \text{tail} < 1\% \)
Double differential spectra: p+p @ 80 GeV

$\sqrt{s_{NN}} = 12.3$ 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 $p_T e^{-m_T/T} \rightarrow$ extrapolation to $p_T = \infty \rightarrow$ tail $< 4\%$
Double differential spectra: p+p @ 80 GeV

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

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

- First \( \phi \) production measurements for p+p @ 80 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 \( p_T = \infty \rightarrow \text{tail} < 4\% \)
Rapidity

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

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

- EPOS and UrQMD shape comparable to data, Pythia slightly narrower
- Fit Gaussian \( e^{-y^2/2\sigma_y^2} \) → extrapolation to \( y = \infty \) → tails: 3\% for 158 GeV, 7\% for 80 GeV
- NA61/SHINE consistent with NA49
Transverse mass spectra at midrapidity

\[ p+p @ 158 \text{ GeV} \]
\[ y \in [0.0,0.3) \]
\[ m_T - m_0 \text{ [GeV]} \]
\[ \sqrt{s_{NN}} = 17.3 \text{ GeV} \]

\[ p+p @ 80 \text{ GeV} \]
\[ y \in [0.0,0.3) \]
\[ m_T - m_0 \text{ [GeV]} \]
\[ \sqrt{s_{NN}} = 12.3 \text{ GeV} \]

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**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>
Single differential spectra: p+p @ 40 GeV

\[ \frac{d^2n}{dp_T dy} \] [GeV]

\[ T_p \]

0 0.5 1

-1

\[ y \in [0.0, 1.5) \]

\[ \int_{model} = \int_{data} \]

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

MC normalization:

Pythia agrees best, UrQMD similar, EPOS spectrum too short tail

extrapolation tail < 1 %

UrQMD agrees with data, EPOS bit too narrow, Pythia even narrower

extrapolation tail 5 %
Single differential spectra: p+p @ 40 GeV

$\sqrt{s_{NN}} = 8.8$ GeV

MC normalization:
$\int_{model} = \int_{data}$

- First $\phi$ production measurements for p+p @ 40 GeV

$P_T$
- Pythia agrees best, UrQMD similar, EPOS spectrum too short tail
- extrapolation tail $< 1\%$

$y$
- UrQMD agrees with data, EPOS bit too narrow, Pythia even narrower
- extrapolation tail $5\%$
Reference data for Pb+Pb: $\sigma_y = \text{width of } dn/dy$

![Graphs showing particle yields vs. collision energy and rapidity.]

**Comparison of particles / reactions**

- All but $\phi$ in Pb+Pb:
  - $\sigma_y$ proportional to $y_{\text{beam}}$ with the same rate of increase
- Two new $\phi$ points in p+p emphasize peculiarity of $\phi$ in Pb+Pb

**Coalescence**

- For p+p only 40 GeV compatible with production through $K^+ K^-$ coalescence
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)
Comparison with world data and models

p+p world data
- Results consistent with world data, much more accurate

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 $\sqrt{s_{NN}}$
Summary

Results

- Differential multiplicities of $\phi$ mesons in p+p:
  - 158 GeV: first 2D ($y$ and $p_T$), more accurate than $2 \times 1D$ ($y$ or $p_T$) NA49
  - 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, but much more accurate!
- Emphasize peculiarity of longitudinal expansion ($\sigma_y$) in Pb+Pb
- 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
BACKUP
Vertex $z$ cut choice

**loose vertex $z$ cut**
- Accepts windows of LHT.
- Small $c_{\text{MC}}$ $\rightarrow$ no in-target events removed due to vertex $z$ resolution.
- Requires EMPTY target subtraction to remove background from windows.

**tight vertex $z$ cut**
- Removes interactions in windows of LHT.
- Large $c_{\text{MC}}$ $\rightarrow$ in-target events removed due to vertex $z$ resolution.
- Negligible EMPTY target contribution (no windows) $\rightarrow$ no EMPTY subtraction.
EMPTY target subtraction requires division of these stats in the same bins as for FULL target analysis → clearly not feasible.
Example 1D $y$ binning fit to constrain $\varepsilon$

Tag: $y \in [0.9, 1.5)$, $p_t \in [0.0, 1.6)$ GeV

Entries = 30559

probe: $y \in [0.9, 1.5)$, $p_t \in [0.0, 1.6)$ GeV

Entries = 3362

- $\Gamma = 4.27$ MeV
- $\sigma = 0.99$ MeV
- $\varepsilon = 0.973 \pm 0.056$
- $N_y = 768 \pm 82$
- $N_{bkg,p} = 2804 \pm 80$
- $N_{bkg,t} = 29559 \pm 247$
- $m_q = 1019.62$ MeV
- $q = 1.50$

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Example 2D binning fits

Tag: $y \in [0.9, 1.5)$, $p_t \in [0.2, 0.4)$ GeV  
Entries = 7880

Probe: $y \in [0.9, 1.5)$, $p_t \in [0.2, 0.4)$ GeV  
Entries = 786

$\Gamma = 4.27$ MeV  
$\sigma = 0.99$ MeV  
$\varepsilon = 0.980 \pm 0.048$  
$N_q = 185 \pm 23$  
$N_{bkg,p} = 610 \pm 37$  
$N_{bkg,t} = 7570 \pm 116$  
$m_q = 1019.62$ MeV  
$q = 1.50$

$N_q/\sigma(N_q) = 7.9$

Tag: $y \in [0.9, 1.5)$, $p_t \in [1.2, 1.6)$ GeV  
Entries = 931

Probe: $y \in [0.9, 1.5)$, $p_t \in [1.2, 1.6)$ GeV  
Entries = 146

$\Gamma = 4.27$ MeV  
$\sigma = 0.99$ MeV  
$\varepsilon = 0.974 \pm 0.055$  
$N_q = 23.2 \pm 7.1$  
$N_{bkg,p} = 133 \pm 17$  
$N_{bkg,t} = 908 \pm 40$  
$m_q = 1019.62$ MeV  
$q = 1.50$

$N_q/\sigma(N_q) = 3.2$
Integral value vs integration cut-off

- \(N\) — integral using given limit, \(N_{\text{ref}}\) — integral using edges of \(m_{\text{inv}}\) histogram as limits.
- Fits with \(y_\infty - a/|x - m_\phi|^b\) to obtain \(y_\infty\) — value of relative difference when limit is infinite. This allows to calculate correction / bias of the integral for each value of limit.

\[
c_R = \frac{N_{\text{ref}} + N_R}{N_{\text{ref}}} = \frac{y_\infty}{100\%} + 1
\]

\[
c_L = \frac{N_L + N_{\text{ref}}}{N_{\text{ref}}}
\]

- Reference lower limit for rel. Breit-Wigner already gives at least \(\%\) accuracy.
Bias / correction due to integration cut-off

\[ c_\infty = \frac{N_\infty}{N_{\text{ref}}} = \frac{N_L + N_{\text{ref}} + N_R}{N_{\text{ref}}}, \]

\[ = \frac{N_L + N_{\text{ref}} + N_R + N_{\text{ref}} - N_{\text{ref}}}{N_{\text{ref}}}, \]

\[ = c_L + c_R - 1. \]
Biases in this analysis may arise as consequence of

1. wrong choice of analytical parametrizations for resonance shape and detector resolution effect
2. choice of integration range of signal parametrization curve to obtain the yield
3. unaccounted effects in background description
4. constraints used in fitting
5. wrong assumptions associated with kaon selection efficiency
6. improper MC corrections of detector effects

First 2 points — methods used up to now are changed (changes central values): Voigtian + integration in broad range → q-Gaussian ⊗ relativistic Breit-Wigner + correction to integral

Other points — systematic uncertainties are estimated using improved methods for signal extraction.
Initially used Voigtian = Gaus⊗BW due to technical convenience
Using MC decided to change Gaussian → q-Gaussian (explained later)
For $\phi$ relativistic Breit-Wigner (used in NA49) better than non-relativistic, which yields couple % sub-threshold production.
Change in $\chi^2 / \text{ndf}$ due to effects in background (explained later)
Yields are corrected integrals in \((-\infty, +\infty)\) (explained later).

- Old parametrization yielded up to 10\% underestimated results.
- About 2\% due to detector resolution model
- About 5\% due to resonance model
Underestimation of background for high $m_{\text{inv}}$ in Tag $\rightarrow K^*0$

Underestimation for low $m_{\text{inv}}$, overestimation of background for high $m_{\text{inv}}$ in Probe $\rightarrow$ electrons

Using MC (next slides) — up to 10% systematic effect
Mock PID cuts tuned in MC (top) to have similar shapes as in data (bottom).
In cleaned sample (no electrons, nothing from $K^{-\ast 0}$) no background problems observed.
Source of low $m_{\text{inv}}$ effect in MC — electrons

- Picture compatible with correlation due to Coulomb interaction (studied e.g. as background effect in HBT correlations for kaons and pions)
- Effect stronger for electrons as compared to hadrons due to lower mass of electrons?
• Up to 10% systematic effect coming mostly from $K^{*0}$ → assign 10% systematic uncertainty bin independent

• Although in most bins effect about 5%, assigning bigger uncertainty possibly takes into account mismatches between MC and data
Resolution model

- MC with $\Gamma = 0$ (20M pp@158 events) provides insight into the effect of detector resolution on $m_{\text{inv}}$.
- It turns out that the default choice of Gaussian model is not optimal $\rightarrow$ tested also Lorentz and q-Gaussian:

\[
\begin{align*}
\text{Gaussian:} & \quad \sigma = 0.8318 \pm 0.0089 \quad m_\phi = 1019.475 \pm 0.01 \quad \chi^2/\text{ndf} = 5.2 \\
\text{Breit-Wigner:} & \quad \sigma = 1.049 \pm 0.022 \quad m_\phi = 1019.484 \pm 0.01 \quad \chi^2/\text{ndf} = 8.2 \\
\text{q-Gaussian:} & \quad q = 1.390 \pm 0.030 \quad m_\phi = 1019.475 \pm 0.01 \quad \chi^2/\text{ndf} = 0.7
\end{align*}
\]

- Black dots are the same in all 3 pictures.
- Each model has a location parameter $m_\phi$ and width parameter $\sigma$.
- q-Gaussian has additional shape parameter $q$:
  - $q = 2 \Leftrightarrow$ shape = Lorentz
  - $q \rightarrow 1$ shape $\rightarrow$ Gaussian
q-Gaussian clearly favoured.
Weighted sample standard deviation 7–9% $\sigma$ fitted in full phase space, depending on model, with smallest for Gaussian.

These values used to estimate systematic uncertainties ($\approx 1\%$) associated with assumption of invariant $\sigma$ in phase space bins.
Parameters stability: $q$ (only for q-Gaussian)

- Weighted sample standard deviation 6% $q$ fitted in full phase space.
- These value used to estimate systematic uncertainties (< 2%) associated with assumption of invariant $q$ in phase space bins.
- $q$ needs to be fixed to MC average value of 1.5 in fits to data due to background distortions (q-Gaussian can adapt its shape via $q$ to fit background as signal)
Parameters stability: $m_\phi$

- Weighted sample standard deviation $\approx 0.5\% \Gamma$, $0.002\% m_\phi$ fitted in full phase space, for all models.
- Translates into $< 0.5\%$ systematic uncertainty.
Systematics due to constraints on parameters

- "+", "-" superscripts — fits redone with listed fixed parameters increased/decreased by factors obtained from MC study from previous slides
- Also shown refits with fixed parameters shifted by their statistical errors from fits in full phase space
- Systematic uncertainty: 2%, bin independent or should sum up, or bin by bin?
Tag-and-probe systematics

- Known sources of systematic error in tag-and-probe:
  - non-constant value of PID efficiency ($\varepsilon$) within phase space bins
  - constraints on $\varepsilon$ in $(y, p_T)$ bins fits if $\varepsilon$ non-constant between bins

- Known and unknown effects studied by variation of window size around Bethe-Bloch (range +/- 30% of default/reference window size = $\pm 5\%$ Bethe-Bloch value)

- Done for 2 cases of fitting strategy:
  - default — value of $\varepsilon$ fitted in $y$ bin in full $p_T$ range is used to soft-constrain fits in $(y, p_T)$ bins
  - free $\varepsilon$ in $(y, p_T)$ bins fits to validate these strategies
Fit results: $\epsilon$ in „constrained” strategy

- Apart from one case in the last $y$ bin, $\epsilon$ changes monotonically with window size
- agrees with expectation
Fit results: $\varepsilon$ in „free” strategy

- Visible problems with monotonic dependence of $\varepsilon$ on window size
- contrary to expectation — fit instabilities?
Fit results: $N_\phi$ in „constrained” strategy

- Differences between $N_\phi$ values for the given and the reference cut as percentage of results for reference cut
- If no systematic error → all points should cluster at zero; standard deviation = measure of systematic uncertainty
Differences between $N_\phi$ values for the given and the reference cut as percentage of results for reference cut

If no systematic error → all points should cluster at zero; standard deviation = measure of systematic uncertainty

Clearly more spread than in „constrained” case
„constrained” strategy yields smaller systematic uncertainties than „free”

Above, together with better behaviour of $\varepsilon$ and smaller statistical uncertainties clearly favours „constrained” strategy over the „free” one.
Differences between normalized and corrected yield values for the given and the reference cut as percentage of results for reference cut = 18 cm

If no systematic error → all points should cluster at zero; standard deviation = measure of systematic uncertainty
Systematic uncertainty due to vertex Z position cut

- Magnitude similar to tag-and-probe systematics
Differences between normalized and corrected yield values for the given and the reference cut as percentage of results for reference cut = $n_{\text{all}} > 30$, $n_{\text{VTPC}} > 15$

- $n_{GAP-TPC} > 4$ not varied; also shown result after removing Bx,By cut
- If no systematic error $\rightarrow$ all points should cluster at zero; standard deviation = measure of systematic uncertainty
Systematic uncertainty due to track quality cuts

- Magnitude smaller than for tag-and-probe and vertex cut systematics
Model dependence of MC correction

MC correction may depend on:
- $\phi$ model — shape of generated $\phi$ spectrum
- event model — distributions of other particles and correlations between particles
- detector model — geometry, materials, models of interactions with material

Removing $\phi$ model dependence:
- calculate correction is small bins; on application level use
  - weighting of entries with the correction
  - averaging of correction with fit of data spectrum (NA49)
- reweight existing MC (Antoni’s pp h- paper)

Reducing systematic uncertainty of correction:
- detector model dependence unavoidable; can only improve the model
- event model $\rightarrow$ find better one, or
- factorize correction into accurate large part that doesn’t depend on event model and smaller that depends
Single correction is calculated and applied to data, but one can look how different effects contribute to this correction.

Breakdown realised by sequentially applying selection cuts. For $\phi$ it means that both $K$ need to pass the given track cut.

Conditions probably are not statistically independent, so change of cuts sequence may change the breakdown.

Overall systematic uncertainty might be reduced if correction factorized into dominant, accurate part and subdominant, less accurate part.
Breakdown of MC correction

registration efficiency

Correction

\[ c_{\text{geom}} = \left( \frac{n_{\text{reg}}}{n_{\text{gen}}} \right)^{-1} \]

where \( n_{\text{reg}} \) — spectrum of generated (SimEvent) tracks that pass the cuts:

- Number of GEANT points in all TPCs > 30
- Number of GEANT points in VTPCs > 15 or GTPC > 4

- Supposed to correct for particle registration efficiency (geometry, interactions with detector, K decays)
- Probably does not take into account correctly the K decay effect
- No dependence on the model of event production → candidate to factorize out and calculate from large statistics, well binned, flat phase space MC
Breakdown of MC correction
trigger bias

Correction

$$c_{T2} = \left( \frac{n_{T2}}{n_{\text{reg}}} \right)^{-1}$$

where $n_{T2}$ — spectrum of generated (SimEvent) tracks that pass the cut $\text{reg}$ and events with T2 trigger (no GEANT hits in S4).

- Corrects for trigger bias due to S4 killing inelastic events
- Expected to be bigger at high energies (many high momentum tracks) and smaller at low energies
- Depends on the model of event production
**Correction**

$$c_{\text{Vertex}} = \left( \frac{n_{\text{ver}}}{n_{T2}} \right)^{-1}$$

where $n_{\text{ver}}$ — spectrum of generated (SimEvent) tracks that pass the cut $\text{reg, } T2$ and events pass all vertex cuts

- Corrects for bias due to vertex cuts — removal of low multiplicity events
- Expected to be smaller at high energies (large track multiplicities) and bigger at low energies
- Depends on the model of event production
Correction

\[ c_{\text{Track}} = \left( \frac{n_{\text{sel}}}{n_{\text{ver}}} \right)^{-1} \]

- Corrects for reconstruction efficiency and bin migration, since \( n_{\text{sel}} \) binned according to the reconstructed momentum
- Reconstruction efficiency
  - expected to be small for proton-proton due to low track multiplicities
  - depends on the model of event production
- Bin migration
  - depends on momentum resolution
Breakdown of MC correction

\[ y \in [0.0, 0.3) \]

\[ y \in [0.3, 0.6) \]

\[ y \in [0.6, 0.9) \]

\[ y \in [0.9, 1.5) \]

\[ y \in [1.5, 2.1) \]