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

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Outline

Introduction

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

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

Goal of the analysis

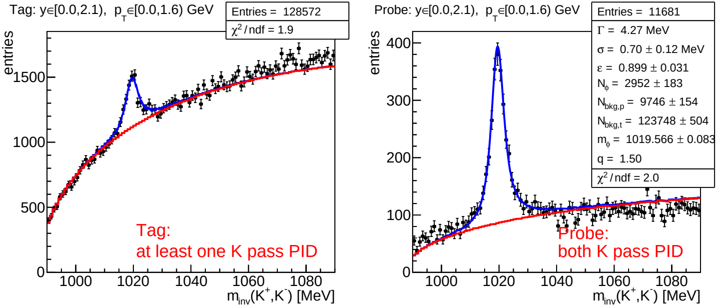
- Differential ϕ multiplicities in p+p collisions measured in NA61/SHINE
  - $\rightarrow$ from invariant mass spectra fits in $\phi \to K^+K^-$ decay channel
  - $\rightarrow$ as function of rapidity y and transverse momentum p_T

Motivation

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

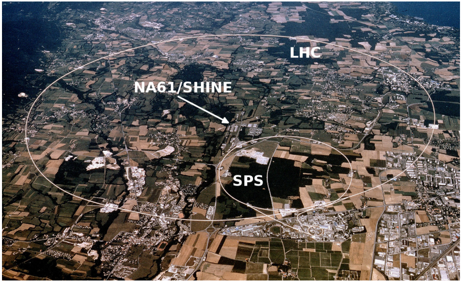
New development

- Preliminary results released > 2 years ago, basis of my PhD, presented on several conferences, e.g. Quark Matter, also on IFJ PAN seminar
- While drafting the paper a question of background description with event mixing came back



- For preliminary estimated 5 % correction and 5 % systematic uncertainty due to this misdescription; used MC with these structures mocked by misidentified K^* daughters and e^+, e^- (improbable in dE/dx selected data, rather f_0 / a_0)
- We can do better: let's fit it!

NA61/SHINE experiment

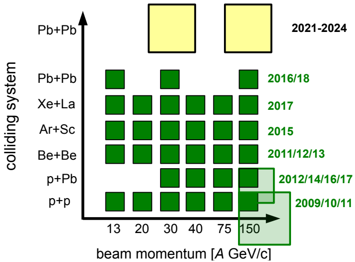


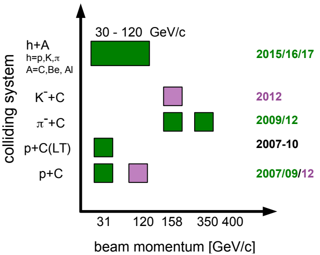
General info

- Fixed target experiment in the North (experimental) Area of CERN SPS
- Successor of NA49
- Beams
  - hadrons (secondary)
  - ions (secondary and primary)
- ∼150 physicists → 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

Physics programme

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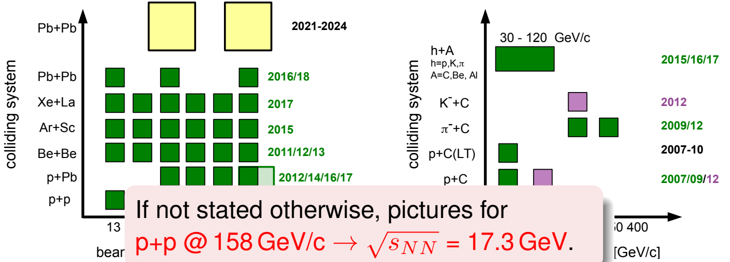

If not stated otherwise, pictures for
p+p @ 158 GeV/c $\rightarrow \sqrt{s_{NN}}$ = 17.3 GeV.

Heavy ion physics

- spectra, correlations, fluctuations
- critical point
- onset of deconfinement
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Cosmic rays and neutrinos

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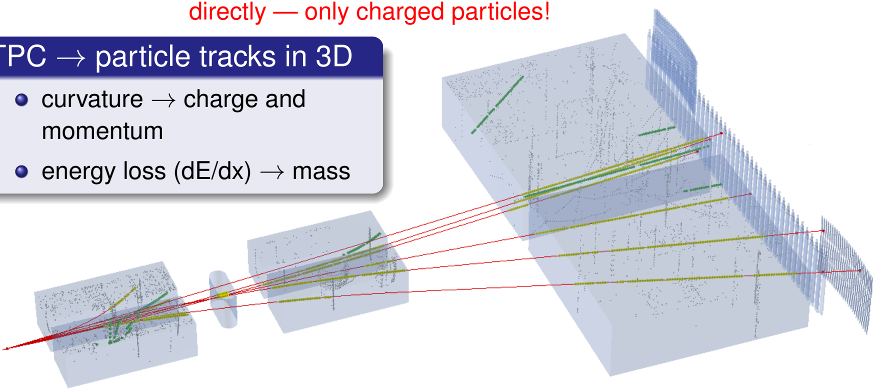
NA61/SHINE detector

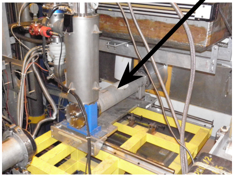
directly — only charged particles!

TPC → particle tracks in 3D

- curvature → charge and momentum
- energy loss (dE/dx) → mass



liquid H_2 target



Performance

- total acceptance $\sim 80\,\%$
- momentum resolution $\sigma(p)/p^2 \sim 10^{-4}\,\mathrm{GeV}^{-1}$
- track reconstruction efficiency $> 95\,\%$

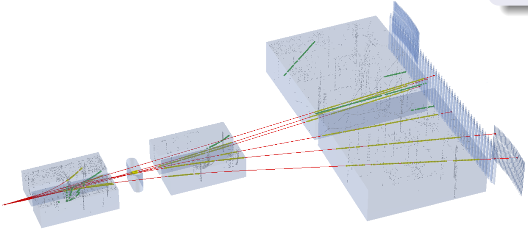
Data selection

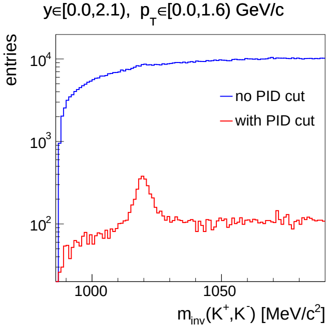
Events

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

TPC tracks

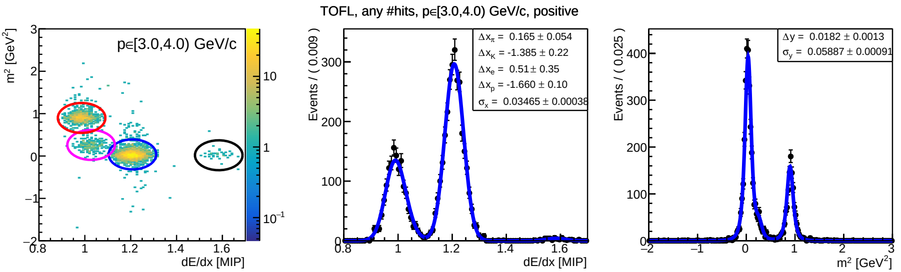
- from main vertex
- well reconstructed
- number of points in TPCs → accurate dE/dx and momentum
- particle identification of kaon candidates (PID cut)





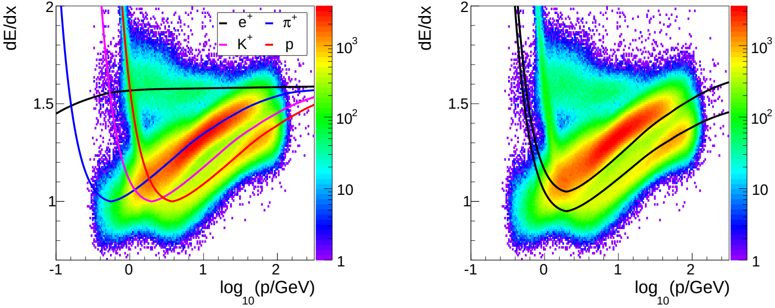
Non-biasing TOF-dE/dx background reduction cut

New with respect to preliminary / PhD analysis



- Possible only in limited number of total momentum bins (TOF acceptance / resolution)
- dE/dx fit with Gaussian, m^2 fit with q-Gaussian
- Cut on 3σ to remove other particles without removing any kaons (rejects tracks if unambiguously non-kaons)

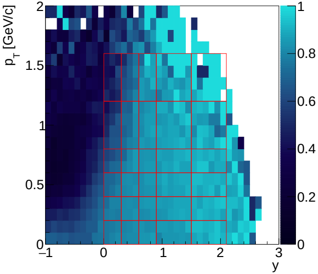
Biasing dE/dx kaon selection cut

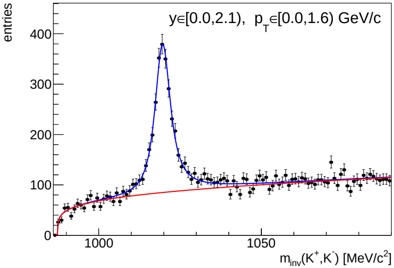


- Selection done with dE/dx
- Accept tracks in $\pm 5\,\%$ band around kaon Bethe-Bloch curve (area between black curves in right picture)
- Losses due to efficiency of this selection corrected with tag-and-probe method

Signal extraction

phase space binning, invariant mass spectrum





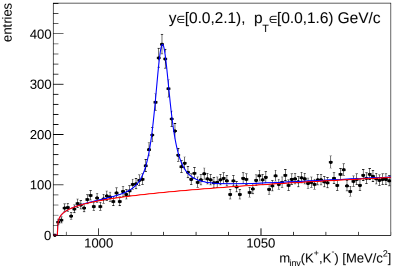
Signal extraction

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 $f_{\text{qG}}(m_{\text{inv}}; \sigma, q)$ broadening due to detector resolution



Background

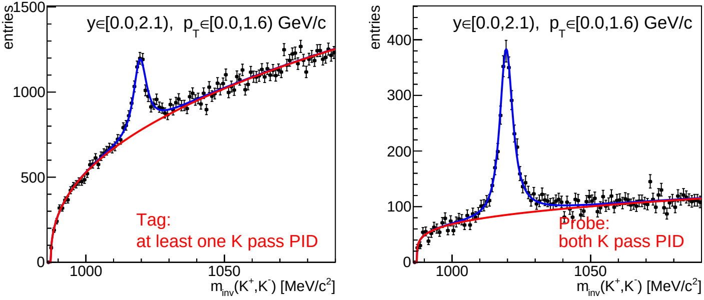
Previously event mixing. Now main result with modified generalised ARGUS distribution $f_{\text{ARGUS}}(m_{\text{inv}}; k, p)$ and for systematic uncertainty estimation also mixing + K^* template + f_0 resonance fit

Fitting function

$$f(m_{\text{inv}}) = N_{\text{p}} \cdot (f_{\text{relBW}} * f_{\text{qG}})(m_{\text{inv}}; m_\phi, \Gamma, \sigma, q) + N_{\text{bkg}} \cdot f_{\text{ARGUS}}(m_{\text{inv}}; k, p)$$

Signal extraction

tag-and-probe method → ATLAS, LHCb



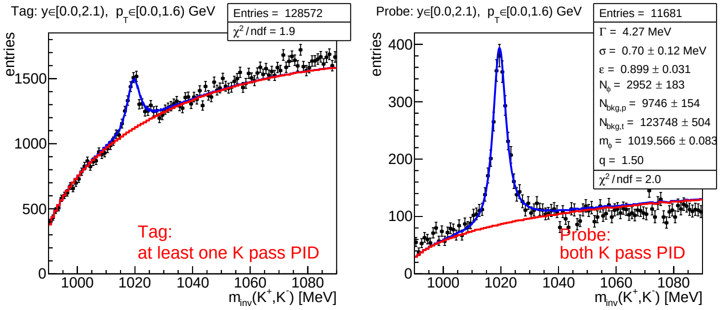
- Goal: to remove bias of N_ϕ due to PID cut efficiency ε
- Simultaneous fit of 2 spectra:
  - tag — at least one track in the pair passes PID cut

$$N_{\mathrm{t}} = N_\phi \varepsilon (2 - \varepsilon)$$

  - probe — both tracks pass PID cut

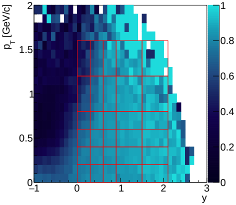
$$N_{\mathrm{p}} = N_\phi \varepsilon^2$$

Comparison with PhD results



- Background reduced in Tag sample thanks to TOF-dE/dx cut
- Fitting down to kaon threshold
- Background actually fitted in both samples

Normalization and corrections



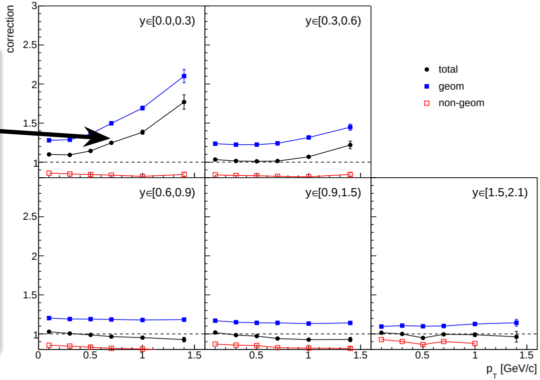
$$\frac{d^2 n}{dp_T\, dy} = \frac{N_\phi}{N_{\text{ev}}\, \Delta p_T\, \Delta y} \times \frac{c_\infty \cdot c_{\text{MC}}}{\mathcal{BR}(\phi \to K^+ K^-)}$$

- $c_\infty \sim 1.06$ — extrapolation of the resonance curve

Monte Carlo correction

$$c_{\text{MC}} = \frac{N_\phi^{\text{gen}}}{N_{\text{ev}}^{\text{gen}}} \Big/ \frac{N_\phi^{\text{sel}}}{N_{\text{ev}}^{\text{sel}}}$$

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



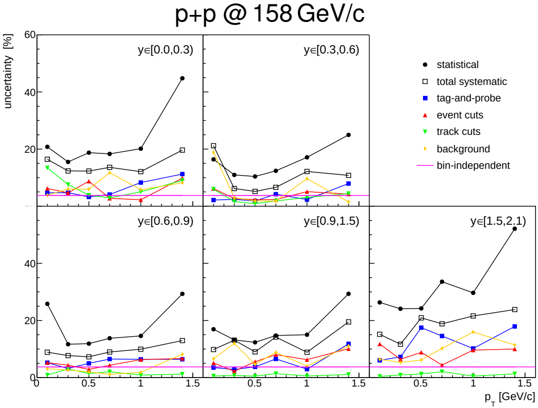
Uncertainties

Statistical

MINUIT/HESSE (symmetric)

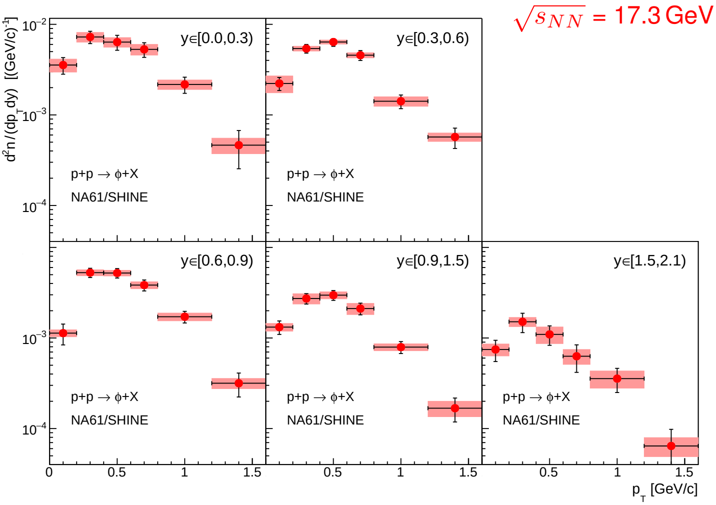
Systematic bin-independent

Source	value [%]
$\mathcal{BR}(\phi \to K^+K^-)$	1
fitting constraints	2
resonance theory	3
Total (quadratic)	4



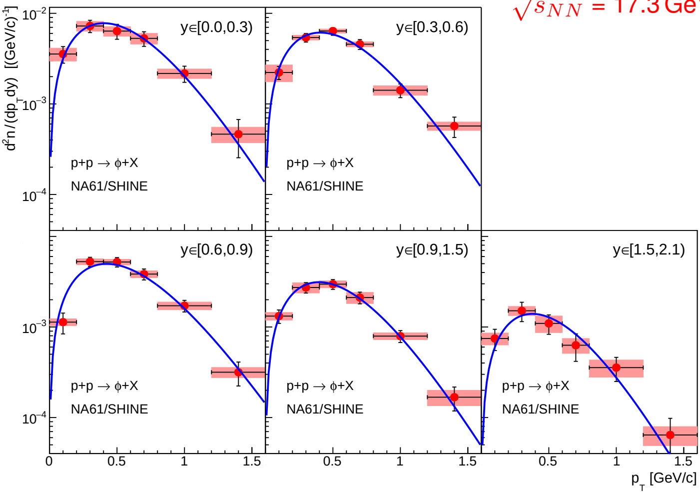
- Total systematic uncertainty $= \sqrt{\sum \sigma_i^2}$
- For p+p @ 40 GeV/c additional bin-independent 3 % due to c_{MC} averaging
- Statistical uncertainty dominates

Double differential spectra: p+p @ 158 GeV/c



Double differential spectra: p+p @ 158 GeV/c

$\sqrt{s_{NN}}$ = 17.3 GeV



- Fit $p_T e^{-m_T/T}$ → extrapolation to $p_T = \infty$ → tail $< 1\,\%$

Double differential spectra: p+p @ 158 GeV/c

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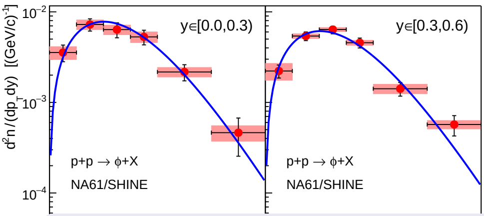
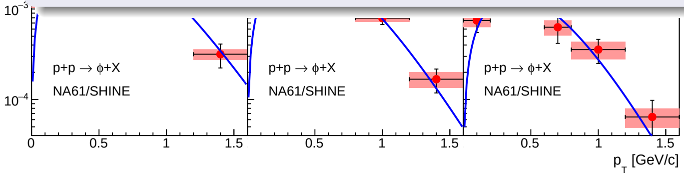


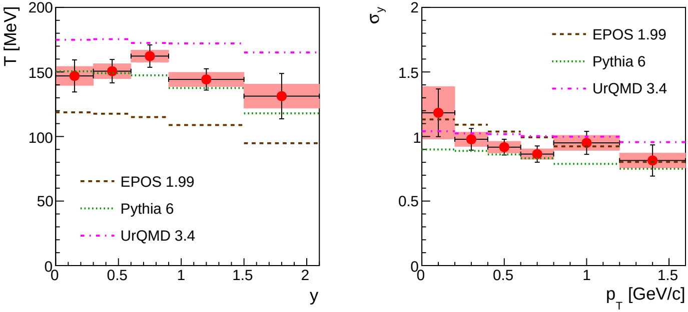
- First 2D (y vs p_T) ϕ production measurements for p+p @ 158 GeV/c



- Fit $p_T e^{-m_T/T}$ $\rightarrow$ extrapolation to $p_T = \infty$ $\rightarrow$ tail $< 1\,\%$

Double differential spectra: p+p @ 158 GeV/c

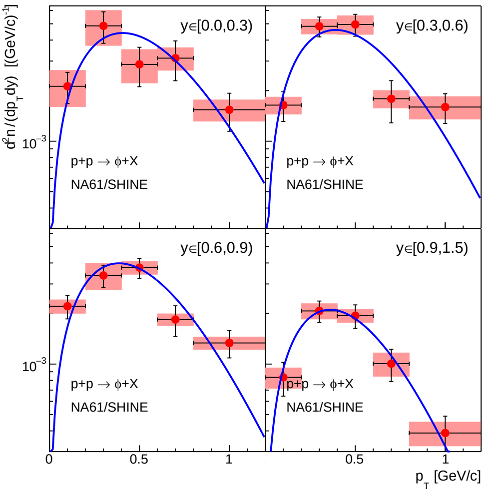
Shape parameters compared to models



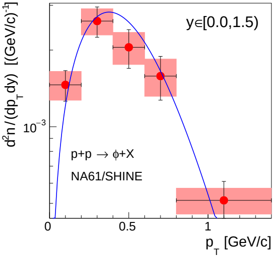
- Pythia describes p_T spectra shapes best, UrQMD and EPOS fail
- Pythia gives slightly too narrow y distributions, while EPOS and UrQMD closer to each other and data

Double & single differential spectra: 80 GeV/c & 40 GeV/c

$\sqrt{s_{NN}}$ = 12.3 GeV

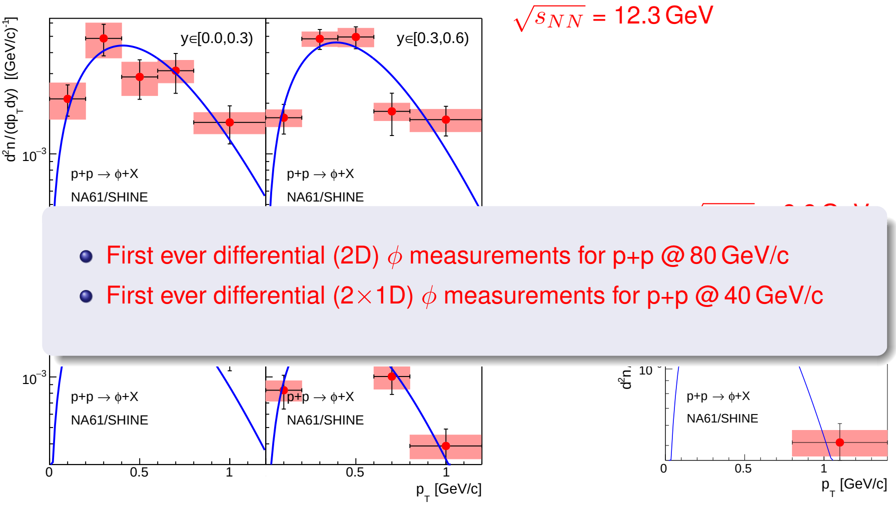


$\sqrt{s_{NN}}$ = 8.8 GeV



- Fit $p_T e^{-m_T/T}$ → extrapolation to $p_T = \infty$ → tail $< 4\,\%$ & $< 1\,\%$

Double & single differential spectra: 80 GeV/c & 40 GeV/c



- First ever differential (2D) ϕ measurements for p+p @ 80 GeV/c
- First ever differential (2×1D) ϕ measurements for p+p @ 40 GeV/c

- Fit $p_T e^{-m_T/T}$ → extrapolation to $p_T = \infty$ → tail $< 4\,\%$ & $< 1\,\%$

Double differential spectra: p+p @ 80 GeV/c

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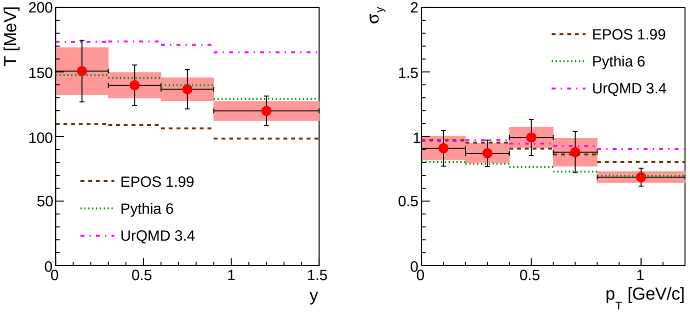

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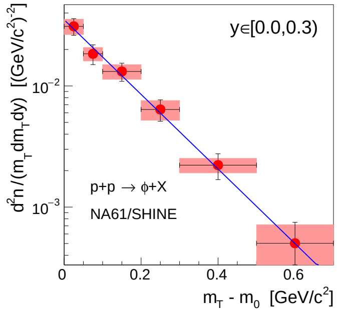
Transverse mass spectra at midrapidity

p+p @ 158 GeV/c



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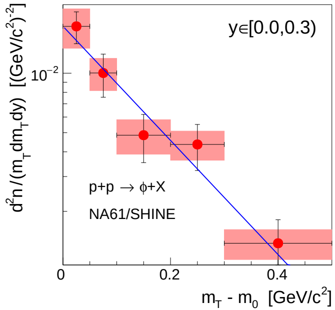
p+p @ 80 GeV/c

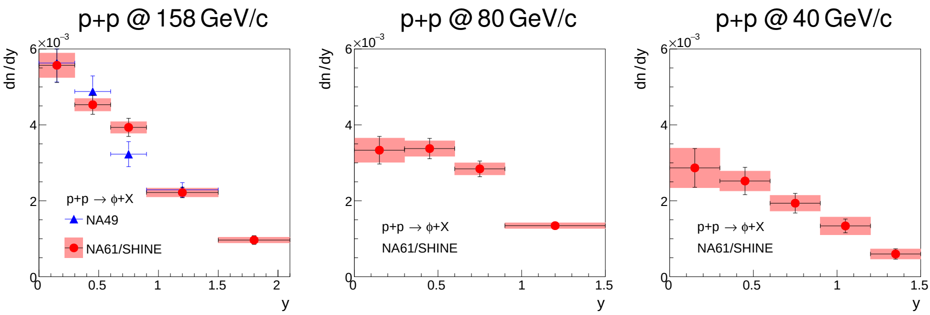


$\sqrt{s_{NN}}$ = 12.3 GeV

Thermal fit results

p_{beam} [GeV]	T_ϕ [MeV]	T_{π^-} [MeV]
158	$141 \pm 12 \pm 9$	$159.3 \pm 1.3 \pm 2.6$
80	$150 \pm 24 \pm 20$	$159.9 \pm 1.5 \pm 4.1$

Rapidity



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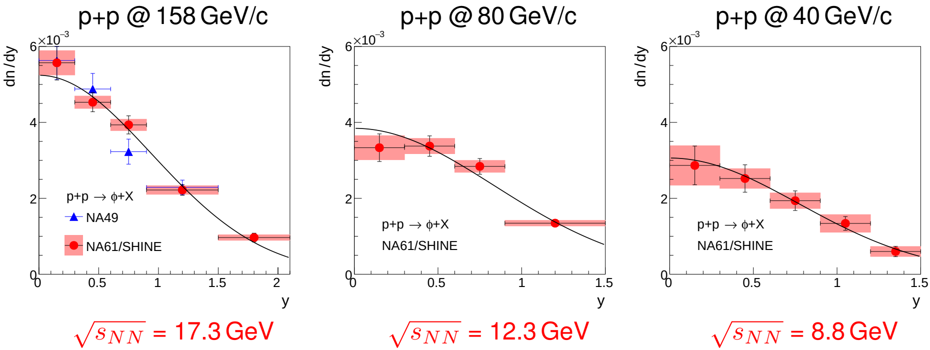
- NA61/SHINE consistent with NA49 S. Afanasiev et al., Phys. Lett. B **491**, 59 (2000)
- Midrapidity, especially for 158 GeV/c, higher than in PhD due to TOF-dE/dx cut

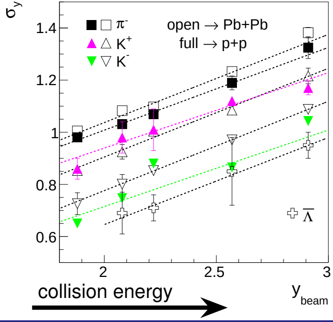
Rapidity



- NA61/SHINE consistent with NA49 S. Afanasiev et al., Phys. Lett. B **491**, 59 (2000)
- Midrapidity, especially for 158 GeV/c, higher than in PhD due to TOF-dE/dx cut
- Fit Gaussian $e^{-y^2/2\sigma_y^2}$ → extrapolation to $y = \infty$ → tails: $3\,\%$ for 158 GeV, $7\,\%$ for 80 GeV, $5\,\%$ for 40 GeV

Reference data for Pb+Pb: σ_y = width of dn/dy

NA49: PLB 491 (2000), PRC 66 (2002), PRL 93 (2004), PRC 77 (2008), PRC 78 (2008)



Comparison of particles / reactions

- All but ϕ in Pb+Pb:
  σ_y proportional to y_{beam} with the same rate of increase
- two new ϕ points in p+p emphasize peculiarity of ϕ in Pb+Pb

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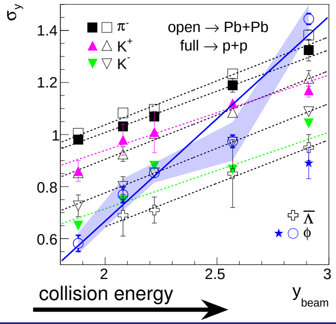

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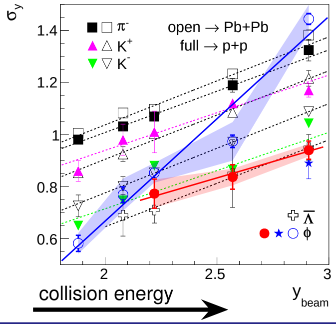

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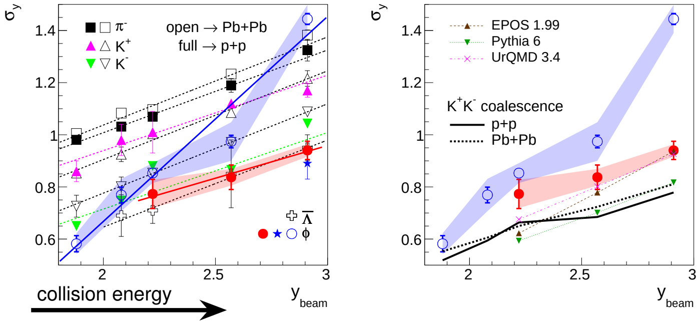

Comparison of particles / reactions

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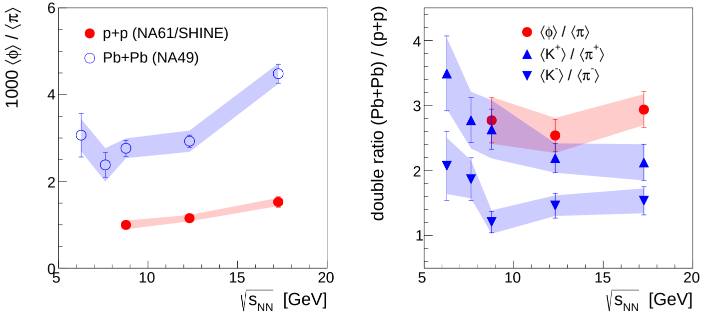
Coalescence

- Not compatible with production through $K^+\,K^-$ coalescence, but p+p closer

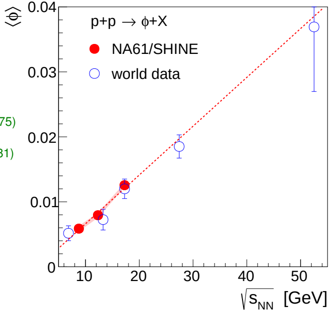
Reference data for Pb+Pb: total yield

NA49: PRC 66 (2002), PRC 77 (2008), PRC 78 (2008)



- ϕ/π ratio increases with collision energy
- Production enhancement in Pb+Pb about 3×, 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)

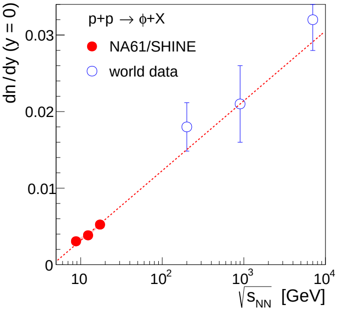
Comparison with world data and models



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)

STAR: PRC 79 (2009), ALICE: EPJC 71 (2011), EPJC 72 (2012)



p+p world data

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

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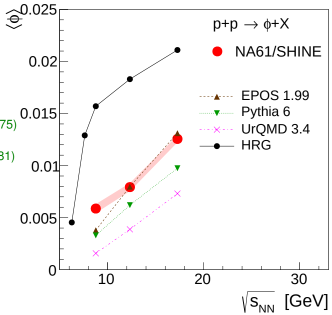

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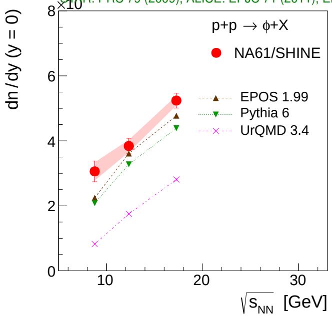

p+p world data

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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 ϕ mesons in p+p:

158 GeV	first 2D (y and p_T)
80 GeV	2D, first at this energy
40 GeV	2×1D, 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 (σ_{y}), contrasting with that of other mesons $\rightarrow$ 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

Modified generalized ARGUS distribution

$$f(x;k,p) = \begin{cases} 0 & \text{for } x \leq 2m_K \\ z(x) \cdot \left(1 - \frac{z^2(x)}{x^2_{\text{max}}}\right)^p \cdot \exp\left\{k\left(1 - \frac{z^2(x)}{x^2_{\text{max}}}\right)\right\} & \text{for } x > 2m_K \end{cases}, \quad \text{(1a)}$$

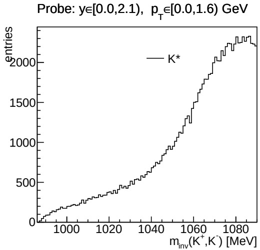
with

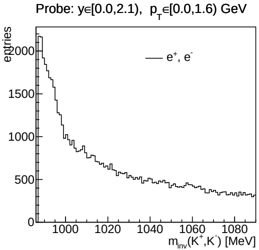
$$z(x) = 2m_K + x_{\text{max}} - x\,, \quad \text{(1b)}$$

where k is a shape parameter corresponding to $-\frac{1}{2}\chi^2$ in the Wikipedia formula for the ARGUS distribution, p is the power as in the generalized ARGUS distribution, m_K is the kaon mass and x_{max} is the right boundary of the m_{inv} histogram. Note that in this parametrization, based on ROOFIT's `RooArgusBG`, k can be any real number, while the original ARGUS formula assumed it to be negative.

Contributions on top of event mixing

- Templates from MC:





- f_0 resonance fit instead of e^+, e^-: