Hidden strangeness shines in NA61/SHINE

Antoni Marcinek for the NA61/SHINE Collaboration

Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland

Quark Matter 2018,
16 May 2018, Lido di Venezia, Italy

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
  - $\rightarrow$ as function of rapidity y and transverse momentum p_T
  - $\rightarrow$ from tag-and-probe invariant mass spectra fits in $\phi \to K^+K^-$ decay channel

Motivation

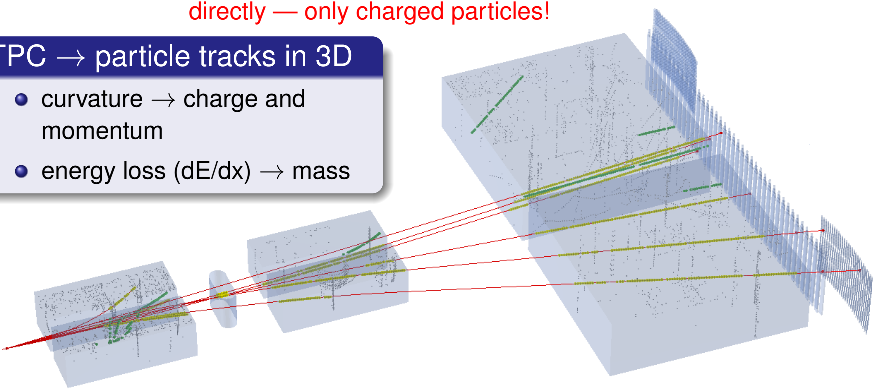
- To constrain hadron production models
  - $\rightarrow$ ϕ interesting due to its hidden strangeness ($s\bar{s}$)
- Reference data for Pb+Pb at the same energies

NA61/SHINE detector

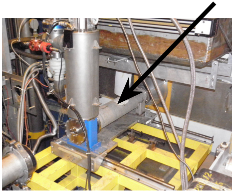
directly — only charged particles!

TPC $\rightarrow$ particle tracks in 3D

- curvature $\rightarrow$ charge and momentum
- energy loss (dE/dx) $\rightarrow$ 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 $> 95\,\%$

Analysis methodology overview

Event selection

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

Signal extraction

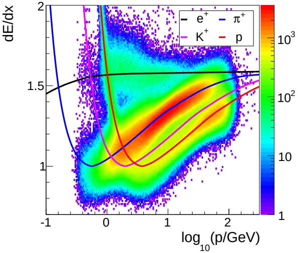
- invariant mass spectra in y, p_T bins
- tag-and-probe fits with background templates from event mixing

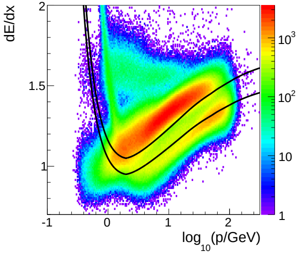
TPC track selection

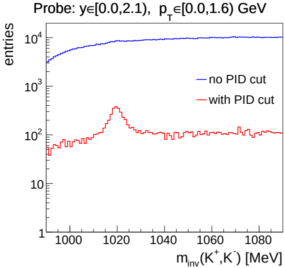
- from main vertex
- well reconstructed
- number of points in TPCs $\rightarrow$ accurate dE/dx and momentum
- PID cut: dE/dx $\sim K^{\pm}$

$\downarrow$

$\leftarrow$ loss of ϕ due to cut efficiency

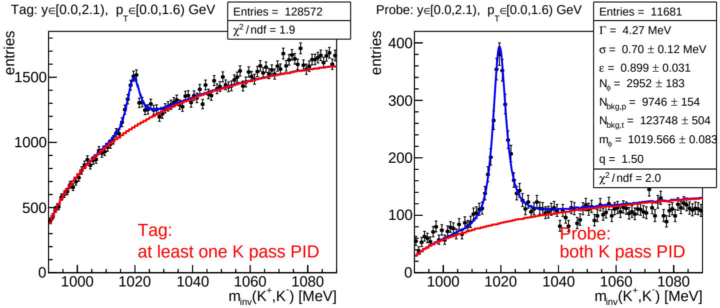






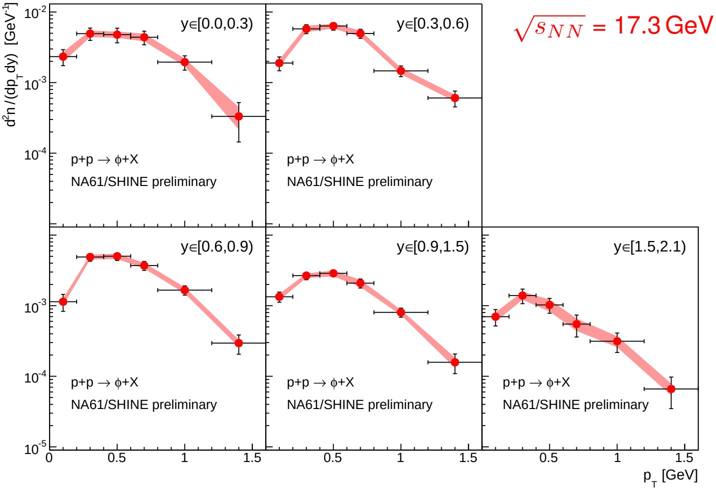
Signal extraction

tag-and-probe method → ATLAS, LHCb

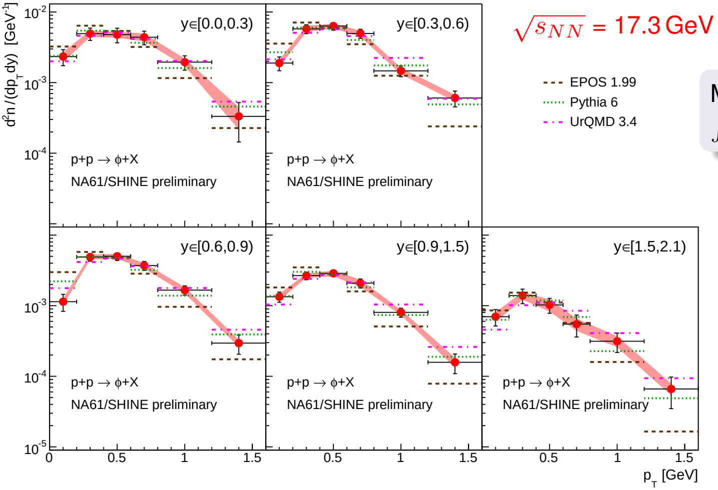


- Goal: to remove bias of N_ϕ due to PID cut efficiency ε
- Simultaneous fit of 2 spectra:
  - tag → $N_\mathrm{t} = N_\phi \varepsilon (2 - \varepsilon)$
  - probe → $N_\mathrm{p} = N_\phi \varepsilon^2$
- Imperfect description of the background with event mixing → 5 % correction and 5 % systematic uncertainty contribution from Monte Carlo study

Double differential spectra: p+p @ 158 GeV



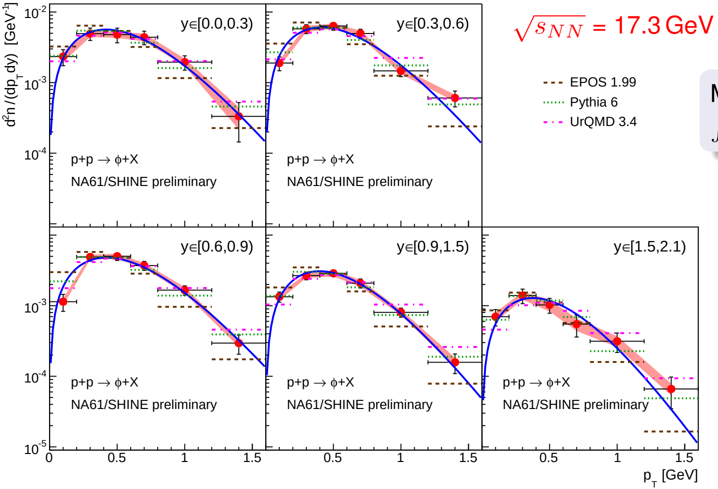
Double differential spectra: p+p @ 158 GeV



MC normalization:
$\int$ model $= \int$ data

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

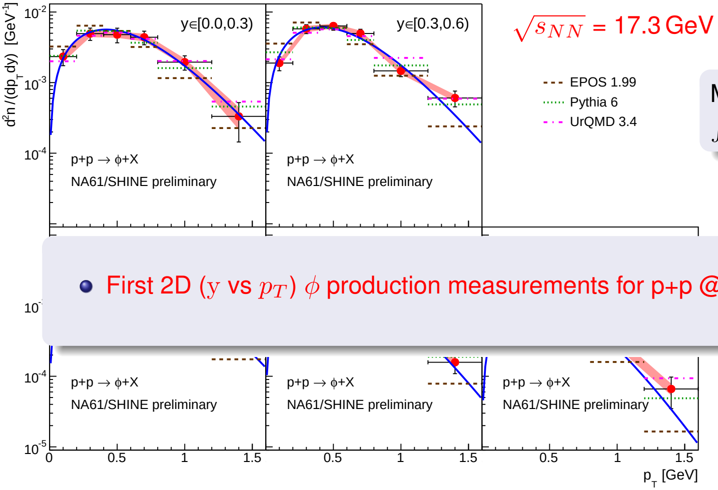
Double differential spectra: p+p @ 158 GeV



MC normalization:
$\int$ model $= \int$ 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 $< 1\,\%$

Double differential spectra: p+p @ 158 GeV

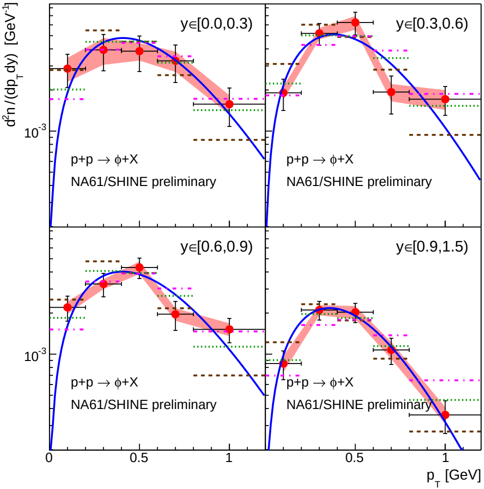


MC normalization:
$\int$ model $= \int$ data

- First 2D (y vs p_T) ϕ production measurements for p+p @ 158 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 $p_T = \infty \rightarrow$ tail $< 1\,\%$

Double & single differential spectra: 80 GeV & 40 GeV

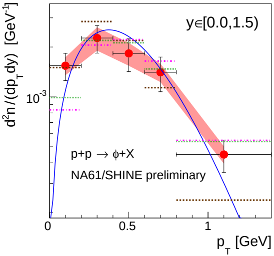


$\sqrt{s_{NN}}$ = 12.3 GeV

- - - EPOS 1.99
······ Pythia 6
- · - UrQMD 3.4

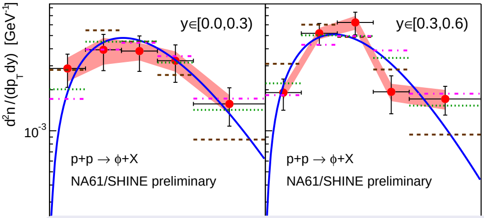
MC normalization:
$\int$ model $= \int$ data

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



- 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 $< 4\,\%$ & $< 1\,\%$

Double & single differential spectra: 80 GeV & 40 GeV



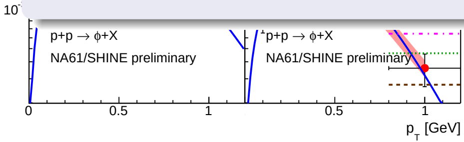
$\sqrt{s_{NN}}$ = 12.3 GeV

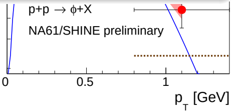
- - - EPOS 1.99
······ Pythia 6
-·-· UrQMD 3.4

MC normalization:
$\int$ model $= \int$ data

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

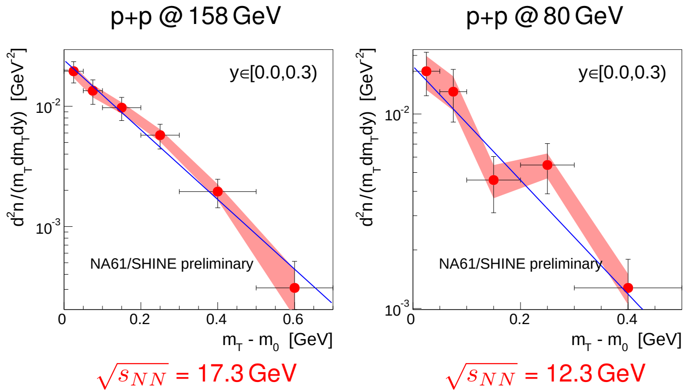
- First ever differential (2D) ϕ measurements for p+p @ 80 GeV
- First ever differential (2×1D) ϕ measurements for p+p @ 40 GeV





- 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 $p_T = \infty \rightarrow$ tail $< 4\,\%$ & $< 1\,\%$

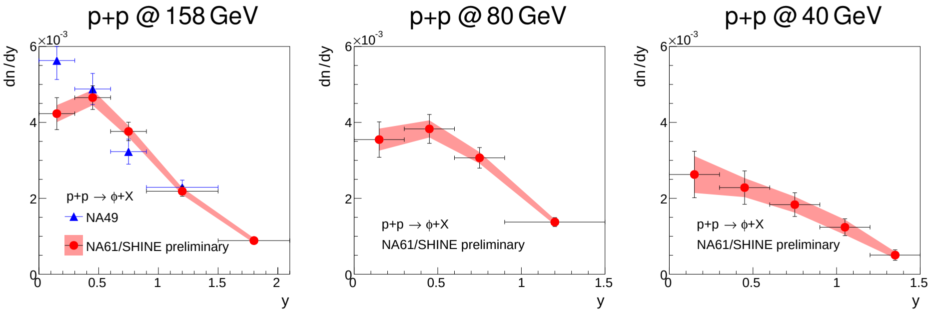
Transverse mass spectra at midrapidity



Thermal fit results

p_{beam} [GeV]	T_ϕ [MeV]	T_{π^-} [MeV]
158	$150 \pm 14 \pm 8$	$159.3 \pm 1.3 \pm 2.6$
80	$148 \pm 30 \pm 17$	$159.9 \pm 1.5 \pm 4.1$

Rapidity

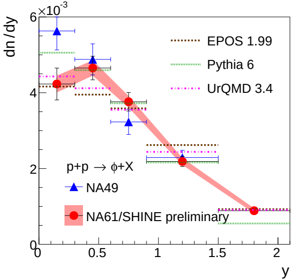


$\sqrt{s_{NN}}$ = 17.3 GeV $\sqrt{s_{NN}}$ = 12.3 GeV $\sqrt{s_{NN}}$ = 8.8 GeV

- NA61/SHINE consistent with NA49 S. Afanasiev et al., Phys. Lett. B **491**, 59 (2000)

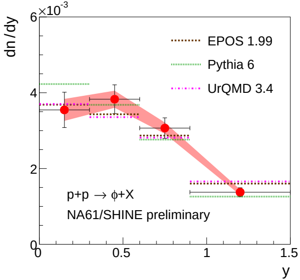
Rapidity

p+p @ 158 GeV



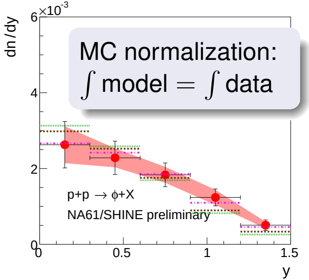
$\sqrt{s_{NN}}$ = 17.3 GeV

p+p @ 80 GeV



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

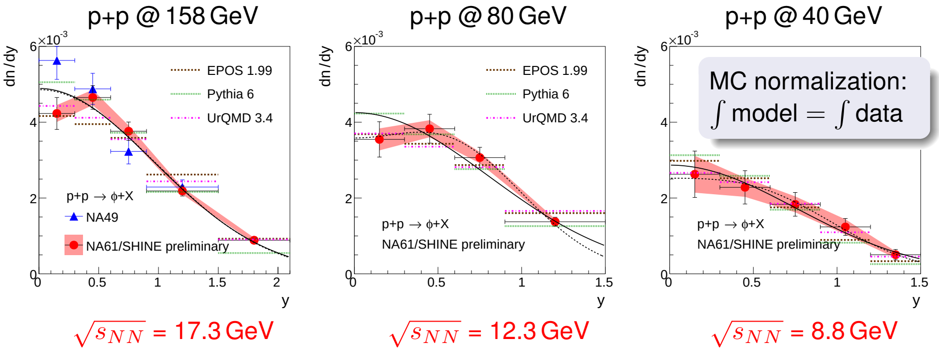
p+p @ 40 GeV



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

- NA61/SHINE consistent with NA49 S. Afanasiev et al., Phys. Lett. B **491**, 59 (2000)
- EPOS and UrQMD shape comparable to data, Pythia slightly narrower

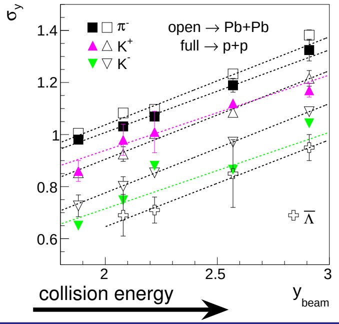
Rapidity



- NA61/SHINE consistent with NA49 S. Afanasiev et al., Phys. Lett. B **491**, 59 (2000)
- EPOS and UrQMD shape comparable to data, Pythia slightly narrower
- Fit Gaussian $e^{-\mathrm{y}^2/2\sigma_\mathrm{y}^2}$ $\rightarrow$ extrapolation to $\mathrm{y} = \infty$ $\rightarrow$ tails: $3\,\%$ for 158 GeV, $7\,\%$ for 80 GeV, $5\,\%$ for 40 GeV

Reference data for Pb+Pb: σ_{y} = width of $\mathrm{d}n/\mathrm{dy}$

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

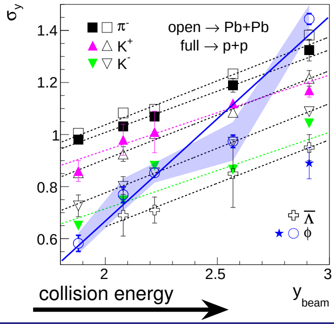


Comparison of particles / reactions

- 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

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)

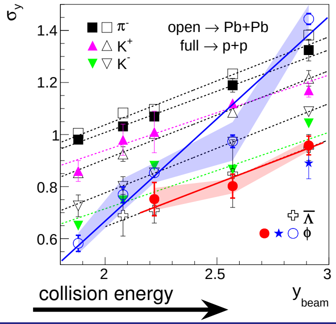


Comparison of particles / reactions

- 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

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)

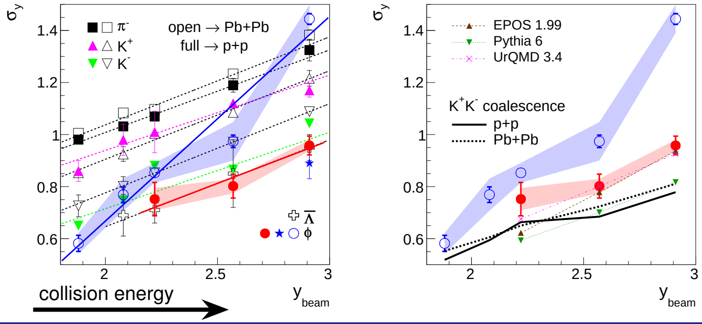


Comparison of particles / reactions

- 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

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

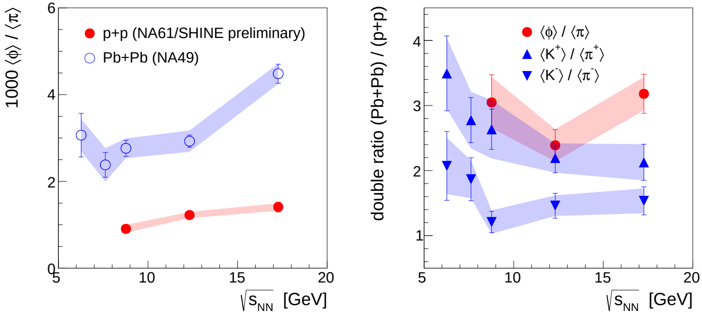
- All but ϕ in Pb+Pb:
  σ_y proportional to y_{beam} with the same rate of increase
- two new ϕ points in p+p emphasize peculiarity of ϕ in Pb+Pb

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)



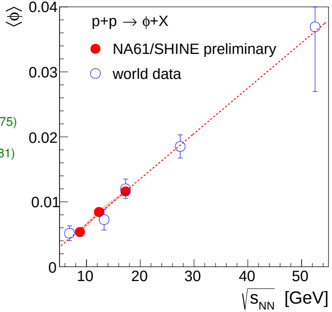
- ϕ/π ratio increases with collision energy
- Production enhancement in Pb+Pb about 3×, independent of energy
- Enhancement systematically larger than for kaons, comparable to K^+
  - → for K^- consistent with strangeness enhancement in parton phase (square of K^- enhancement)

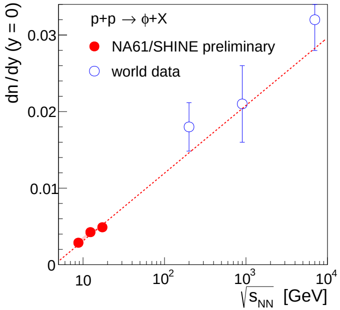
Comparison with world data and models

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

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)

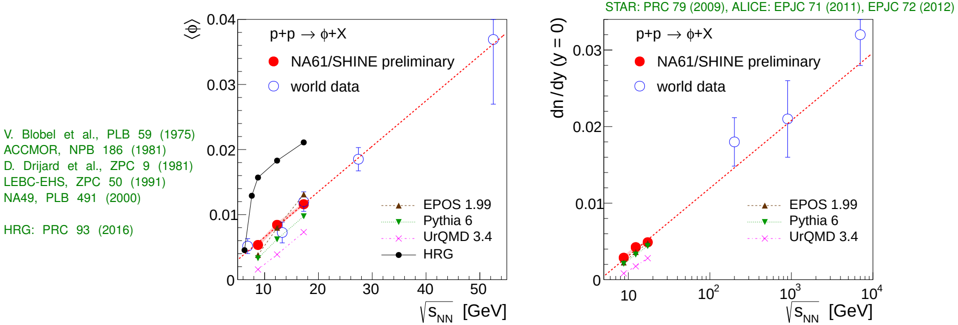




p+p world data

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

Comparison with world data and models



p+p world data

- NA61/SHINE 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 ϕ mesons in p+p:

158 GeV	first 2D (y and p_T)
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, 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

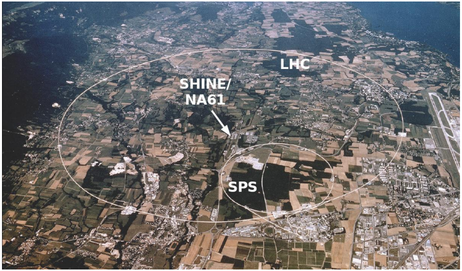
- Each describes well either p_T or y shape, but not both
- None is able to describe total yields

Acknowledgements

- This work was supported by the National Science Centre, Poland (grant numbers: 2014/14/E/ST2/00018, 2015/18/M/ST2/00125)
- and the Foundation for Polish Science — MPD program, co-financed by the European Union within the European Regional Development Fund

BACKUP

NA61/SHINE experiment

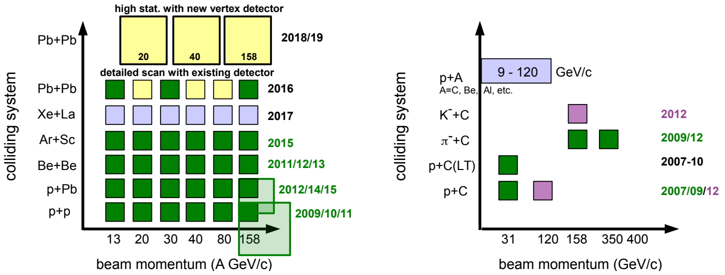


General info

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

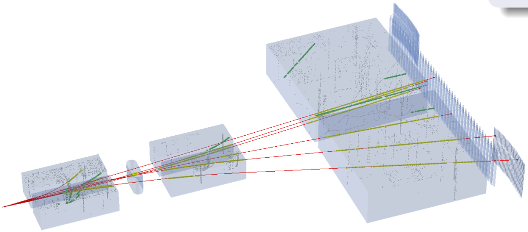
Data selection

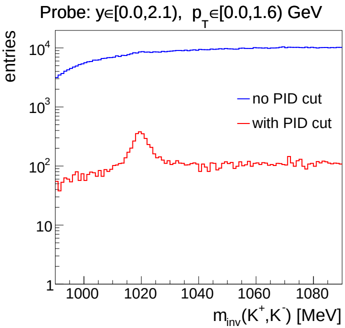
Events

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

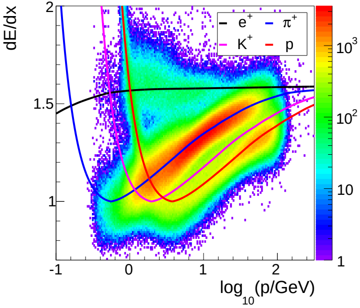
TPC tracks

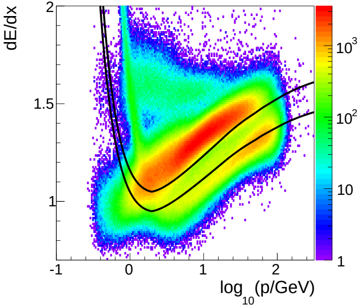
- from main vertex
- well reconstructed
- number of points in TPCs $\rightarrow$ accurate dE/dx and momentum
- with dE/dx corresponding to kaons (PID cut)





Kaon candidate selection — PID cut

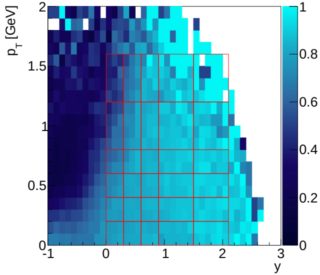


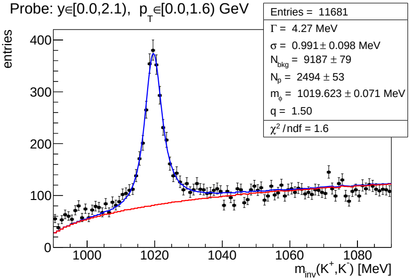


- Selection done with dE/dx
- Accept tracks in $\pm 5\,\%$ band around kaon Bethe-Bloch curve (area between black curves in right picture)
- Losses due to efficiency of this selection corrected with tag-and-probe method

Signal extraction

phase space binning, invariant mass spectrum





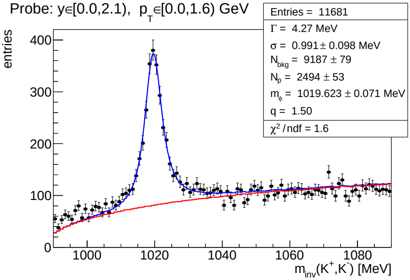
Signal extraction

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

Obtained with the event mixing method:

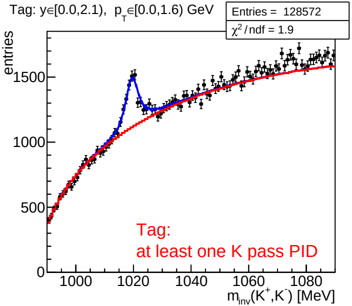
- Kaon candidate taken from the current event is combined with candidates from previous 500 events to create ϕ candidates in the mixed events spectrum

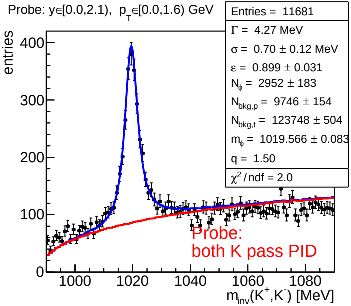
Fitting function

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

Signal extraction

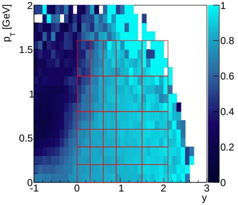
tag-and-probe method → ATLAS, LHCb





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

Normalization and corrections



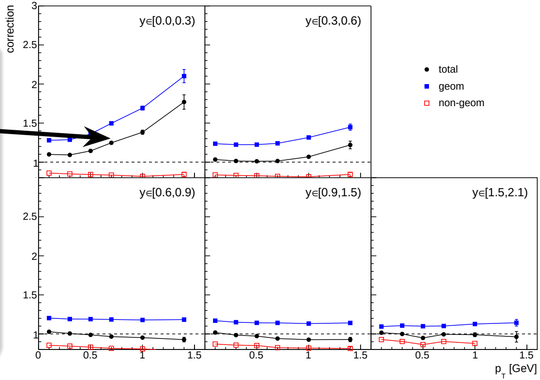
$$\frac{d^2 n}{dp_T\, dy} = \frac{N_\phi}{N_{\text{ev}}\, \Delta p_T\, \Delta y} \times \frac{c_\infty \cdot c_{\text{bkg}} \cdot c_{\text{MC}}}{\mathcal{BR}(\phi \to K^+K^-)}$$

- $c_\infty \sim 1.06$ — extrapolation of the resonance curve
- $c_{\text{bkg}} = 1.05$ — unaccounted-for effects in the background description by event mixing

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

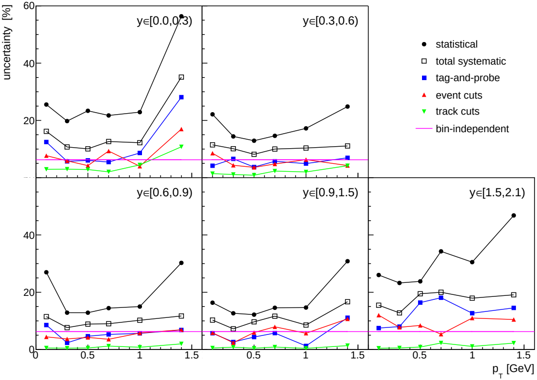
Statistical

MINUIT/HESSE (symmetric)

Systematic bin-independent

Source	value [%]
$\mathcal{BR}(\phi \to K^+K^-)$	1
fitting constraints	2
resonance theory	3
background	5
Total (quadratic)	6

p+p @ 158 GeV



- 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