Mesons in NA61/SHINE

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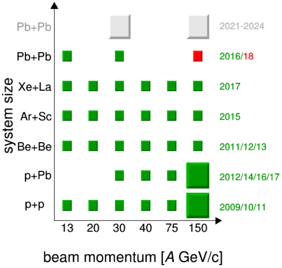
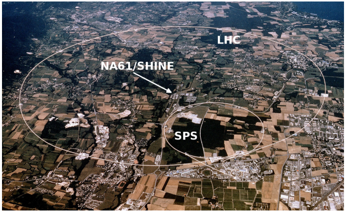
15th International Workshop on Meson Physics (MESON 2018),
11 June 2018, Kraków, Poland

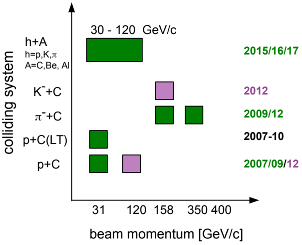
Outline

NA61/SHINE experiment

SHINE = SPS Heavy Ion and Neutrino Experiment







$\sqrt{s_{NN}}$ = 5.1–17.3(27.4) GeV

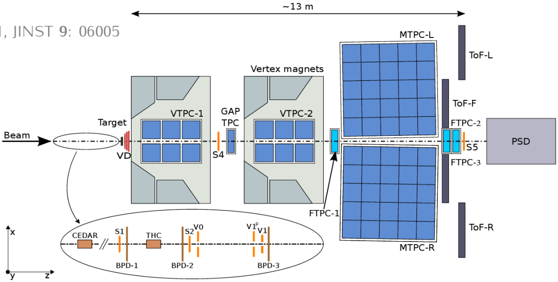
Heavy ion physics

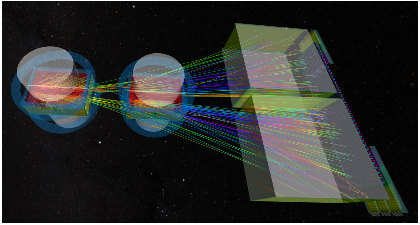
- spectra, correlations, fluctuations
- critical point
- onset of deconfinement
- ⋆ EM interactions with spectators

Cosmic rays and neutrinos

- precision measurements of spectra
- cosmic rays: Pierre Auger Observatory, KASCADE
- neutrinos: T2K, Minerνa, MINOS, NOνA, LBNE

NA61/SHINE detector



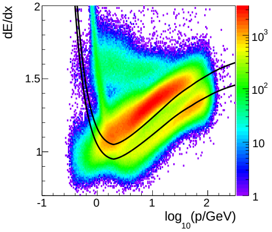


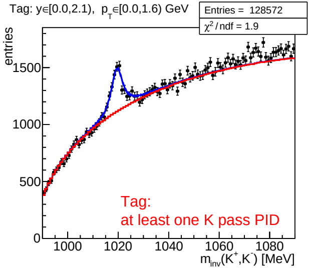
NA61/SHINE in virtual reality: `http://shine3d.web.cern.ch/shine3d`

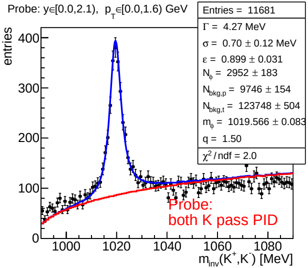
- large acceptance: full forward hemisphere, down to $p_T = 0$
- directly $\rightarrow$ only charged particles
- identification via dE/dx in Time Projection Chambers and via ToF
- centrality via forward energy in Projectile Spectator Detector
- momentum resolution $\sigma(p)/p^2 \sim 10^{-4}\,\mathrm{GeV}^{-1}$
- track reconstruction efficiency $> 95\,\%$

ϕ (1020) meson in p+p

tag-and-probe method → ATLAS, LHCb

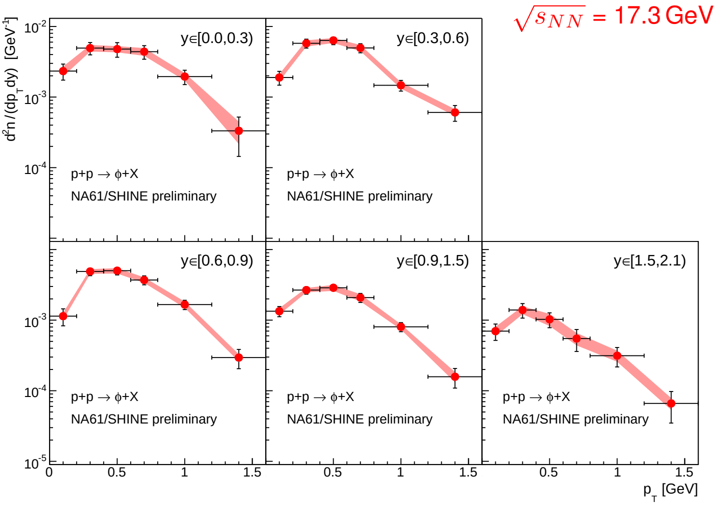






- Goal: to remove bias of N_ϕ due to PID cut efficiency ε
- Simultaneous fit of 2 spectra:
  - tag → $N_{\text{t}} = N_\phi \varepsilon (2 - \varepsilon)$
  - probe → $N_{\text{p}} = N_\phi \varepsilon^2$
- Imperfect description of the background with event mixing → 5 % correction and 5 % systematic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

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



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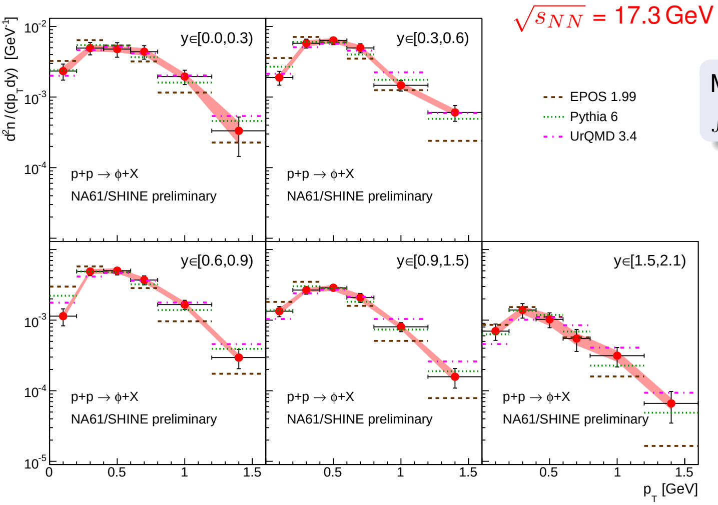
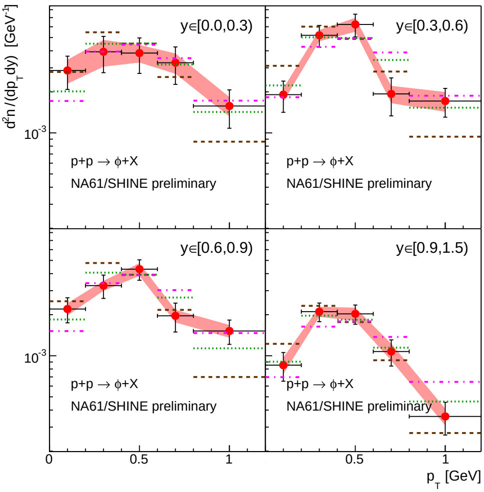


MC normalization:
$\int$ model $= \int$ data

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

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

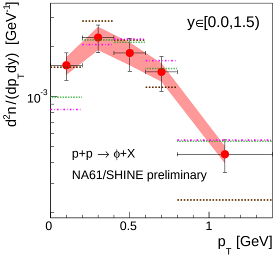
$\sqrt{s_{NN}}$ = 12.3 GeV



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

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

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



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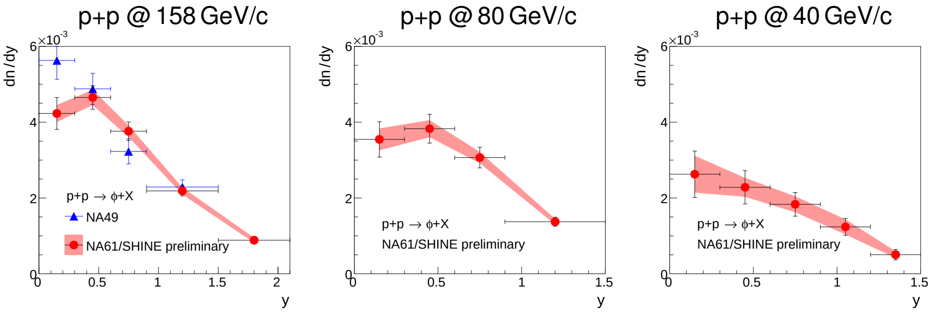
Rapidity



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

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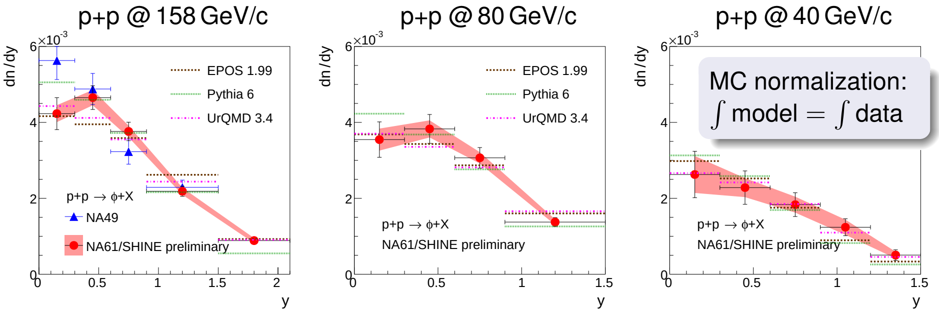

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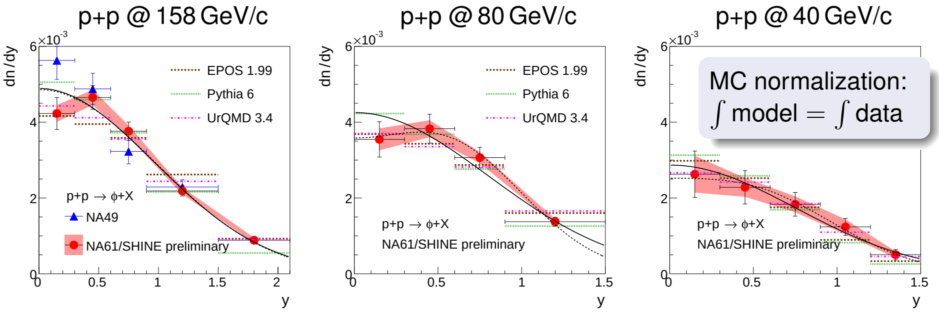

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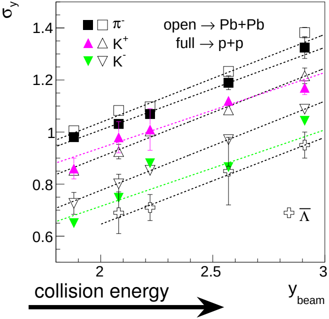
- EPOS and UrQMD shape comparable to data, Pythia slightly narrower
- Fit Gaussian $e^{-\mathrm{y}^2/2\sigma_{\mathrm{y}}^2} \rightarrow \sigma_{\mathrm{y}}, \frac{\mathrm{d}n}{\mathrm{dy}}(\mathrm{y}=0)$, extrapolation to $\mathrm{y}=\infty$, $\rightarrow$ tails: $3\,\%$ for 158 GeV, $7\,\%$ for 80 GeV, $5\,\%$ for 40 GeV

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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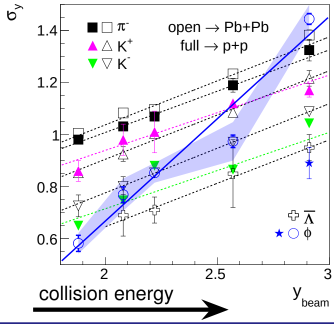

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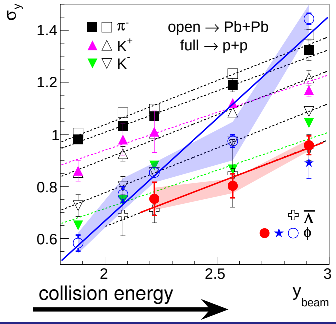

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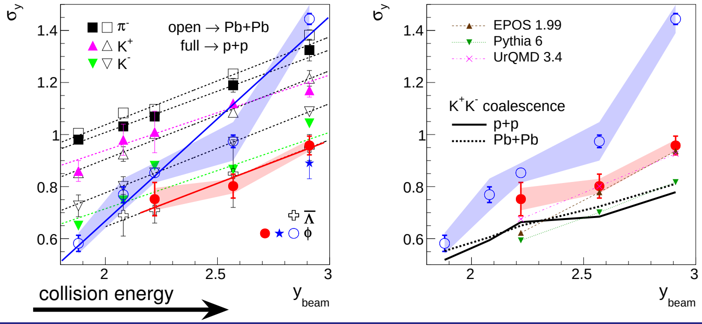

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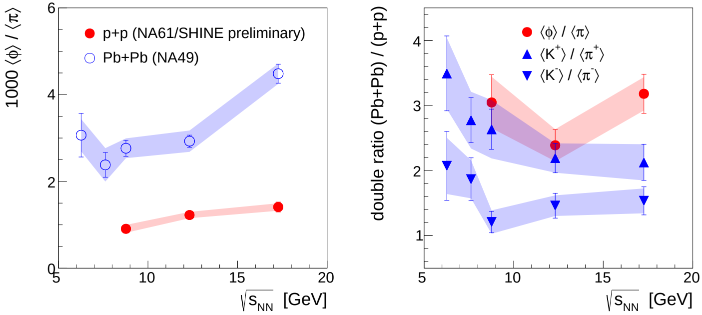
Coalescence

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

Strangeness enhancement

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)
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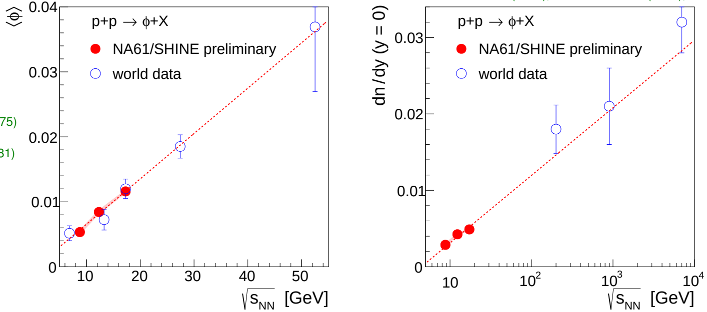
HRG: PRC 93 (2016)

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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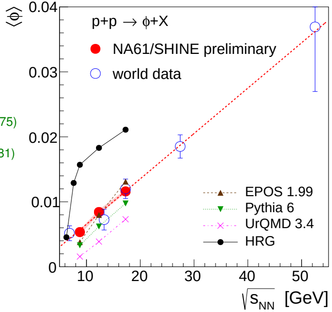

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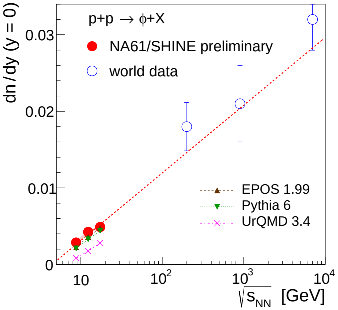


p+p world data

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

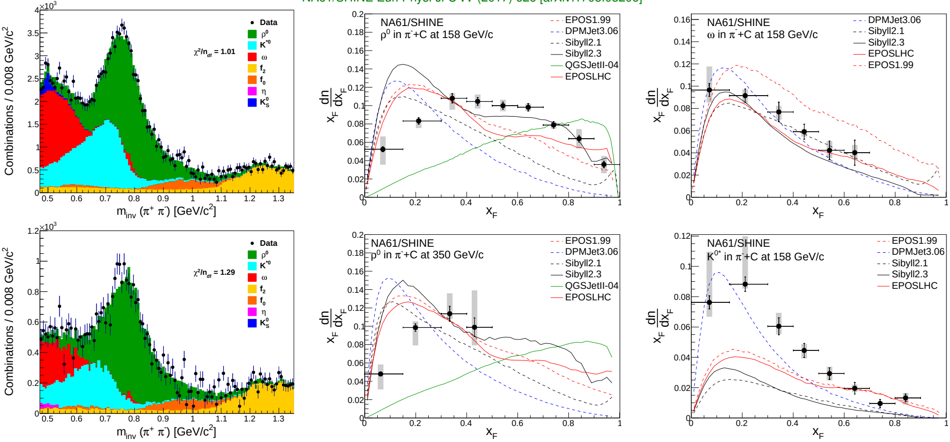
Models

- EPOS close to data, Pythia underestimates experimental data, UrQMD underestimates $\sim 2\times$, HRG (thermal) overestimates $\sim 2\times$
- EPOS rises too fast with $\sqrt{s_{NN}}$

Meson resonances in $\pi^- + C$

cocktail fit method

NA61/SHINE Eur. Phys. J. C **77** (2017) 626 [arXiv:1705.08206]



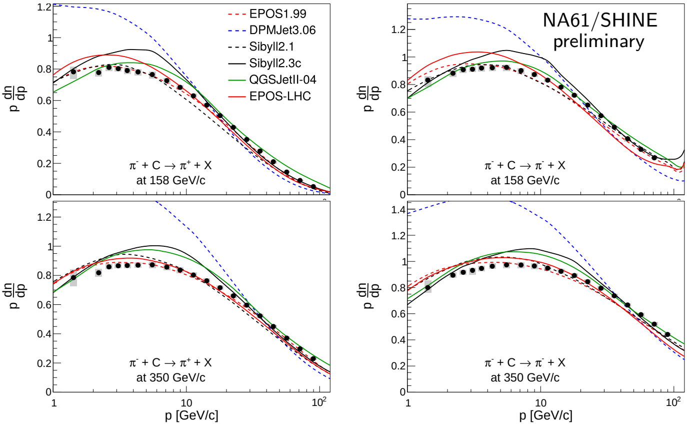
$$x_F = \frac{p_L}{p_{beam}} \text{(c.m.s.)}$$

- Models fail to describe ρ^0 and K^{*0} production
- Important input for modelling of cosmic ray air showers

Charged mesons in $\pi^- + C$

dE/dx spectra fits

$$\pi^- + C \rightarrow \pi^{\pm} + X$$

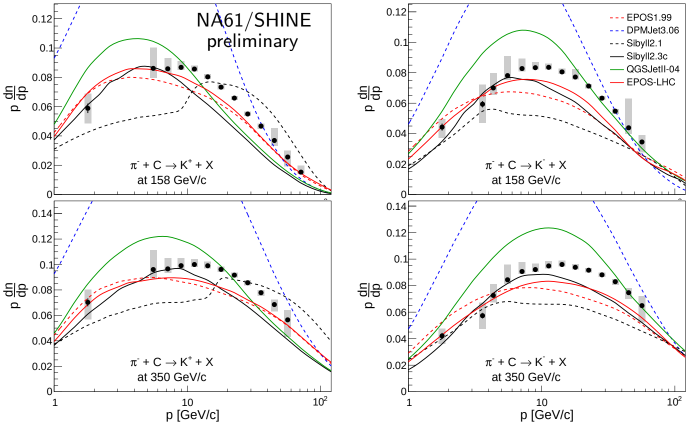


- Fairly well described by EPOS

Charged mesons in $\pi^- + C$

dE/dx spectra fits

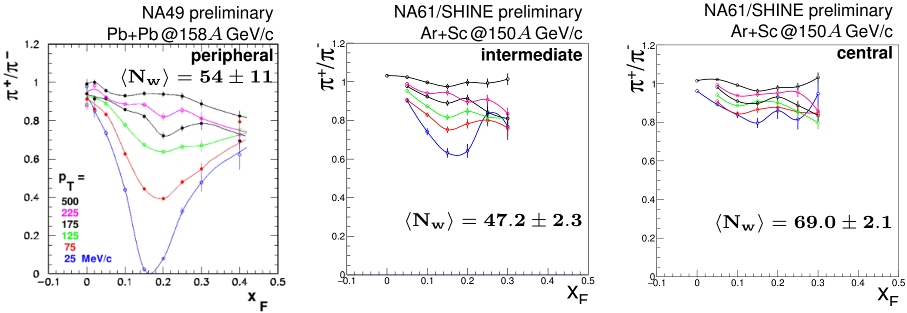
$$\pi^- + C \to \mathbf{K^\pm} + X$$



- Again models fail

Spectator-induced EM effects in $\pi^\pm$ production

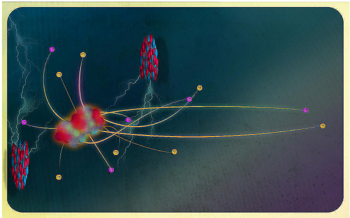
A. Rybicki, Acta Phys. Polon. **B42**, 867 (2011)



$$x_F = \frac{p_L}{p_{beam}} \text{(c.m.s.)}$$

- Peripheral Pb+Pb ($Q_{spectator} \approx 70$ e.u.)
  $\rightarrow$ large EM effect, $\pi^+/\pi^- \approx 0$
- Intermediate Ar+Sc ($Q_{spectator} \approx 8$ e.u.)
  $\rightarrow$ visible EM effect, breaks isospin symmetry
- Central Ar+Sc ($Q_{spectator} \approx 3$ e.u.)
  $\rightarrow$ still visible shadow of EM effect

plot by I. Sputowska



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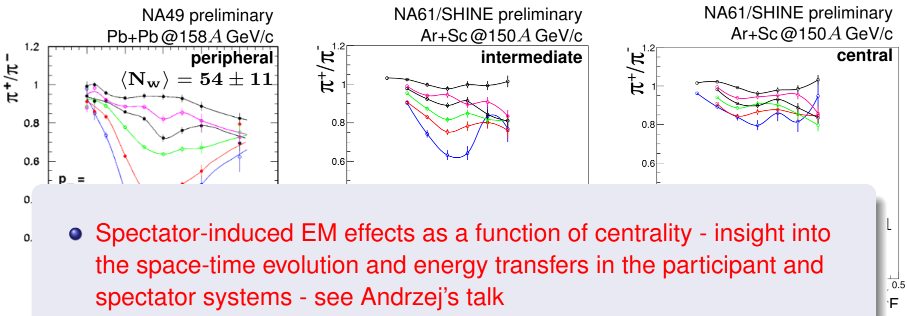

- Spectator-induced EM effects as a function of centrality - insight into the space-time evolution and energy transfers in the participant and spectator systems - see Andrzej's talk

- Peripheral Pb+Pb ($Q_{\text{spectator}} \approx 70$ e.u.)
  $\rightarrow$ large EM effect, $\pi^+/\pi^- \approx 0$
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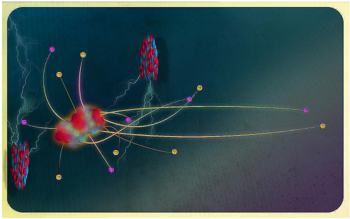


Summary and outlook

Summary

- NA61/SHINE allows measurement of meson production in various reactions.
- First differential multiplicities of ϕ mesons in p+p at SPS energies show superior accuracy, allowing to put constraints on hadron production models.
- Non-trivial system size dependence of width of rapidity distribution (σ_{y}) of ϕ mesons, contrasting with that of other hadrons
  $\rightarrow$ calls for study in Be+Be, Ar+Sc, Xe+La
- First measurements of π^{-}+C collisions at SPS energies contribute to understanding of cosmic-ray air showers.
- Spectator-induced EM effects in charged pion production give insight to space-time properties of the system created in heavy ion collisions.

Outlook

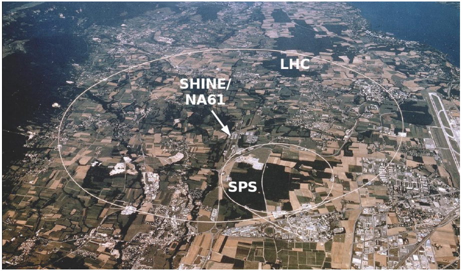
- New Vertex Detector broadens the catalogue of accessible mesons
  $\rightarrow$ open charm mesons for QGP studies

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

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

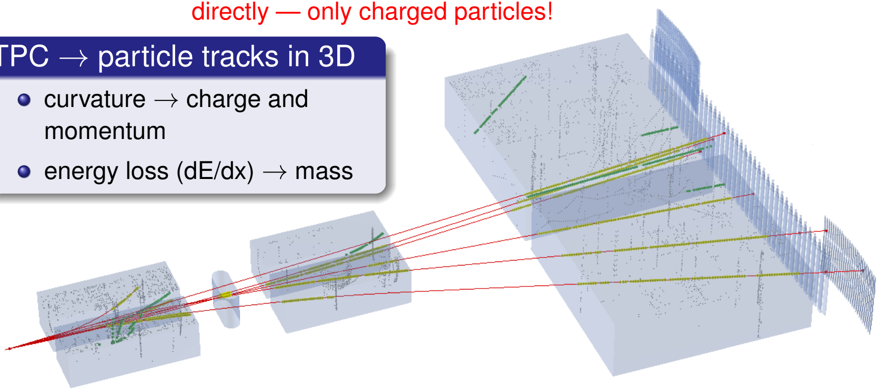
- Differential ϕ multiplicities in p+p collisions measured in NA61/SHINE
  - $\rightarrow$ as function of rapidity y and transverse momentum p_T
  - $\rightarrow$ from tag-and-probe invariant mass spectra fits in $\phi \to K^+K^-$ decay channel

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

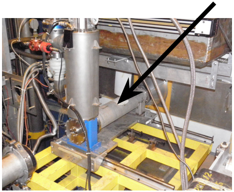
directly — only charged particles!



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 $> 95\,\%$

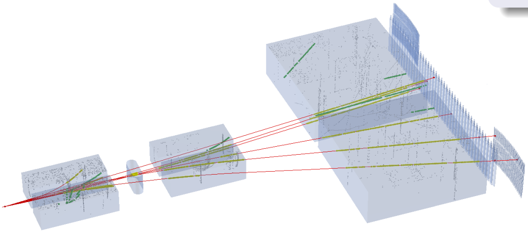
Data selection

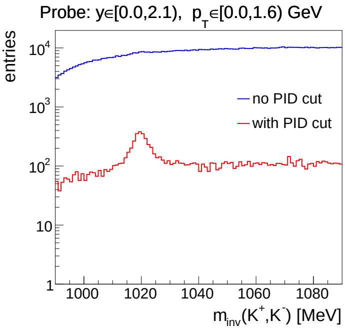
Events

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

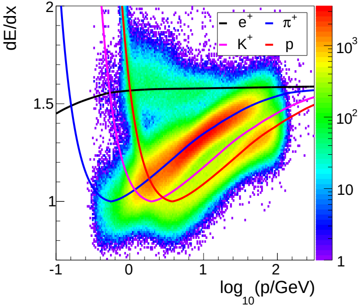
TPC tracks

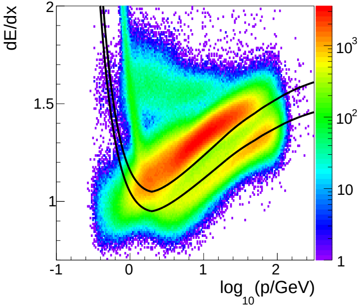
- from main vertex
- well reconstructed
- number of points in TPCs $\rightarrow$ accurate dE/dx and momentum
- with dE/dx corresponding to kaons (PID cut)





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

Analysis methodology overview

Event selection

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

Signal extraction

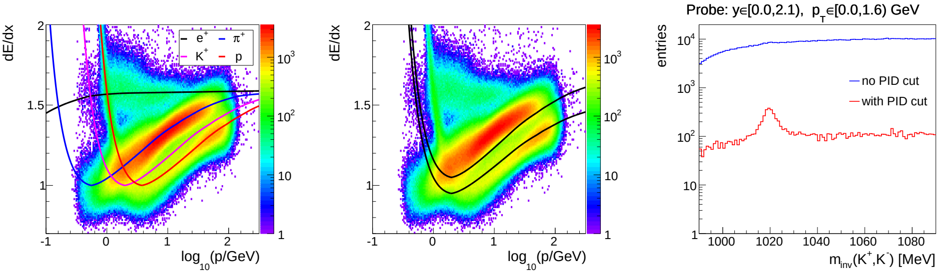
- invariant mass spectra in y, p_T bins
- tag-and-probe fits with background templates from event mixing

TPC track selection

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

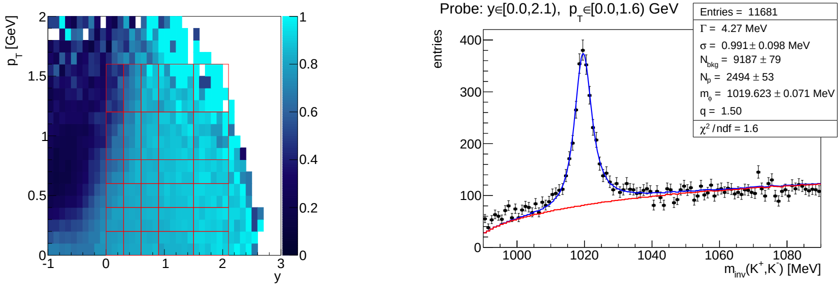
$\downarrow$

$\leftarrow$ loss of ϕ due to cut efficiency



Signal extraction

phase space binning, invariant mass spectrum



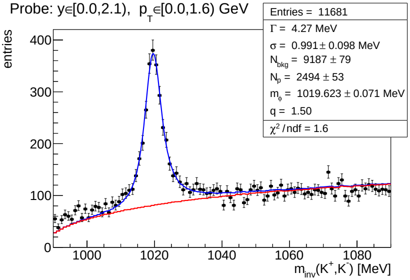
Signal extraction

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:

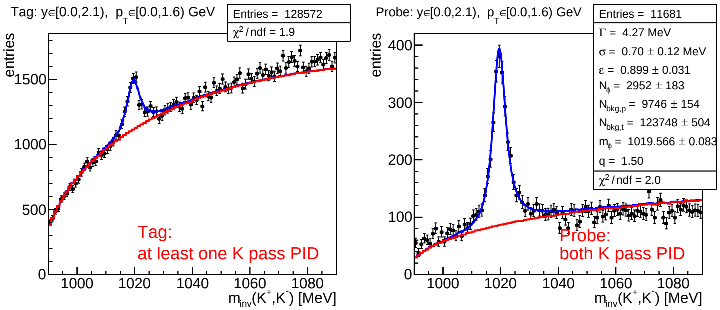
- Kaon candidate taken from the current event is combined with candidates from previous 500 events to create ϕ candidates in the mixed events spectrum

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

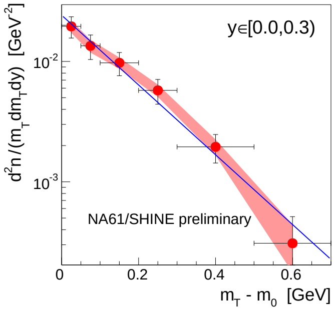
$$N_\mathrm{t} = N_\phi \varepsilon (2 - \varepsilon)$$

  - probe — both tracks pass PID cut

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

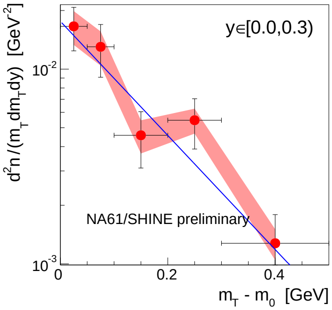
Transverse mass spectra at midrapidity

p+p @ 158 GeV/c



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

p+p @ 80 GeV/c

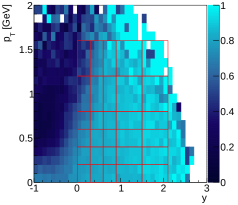


$\sqrt{s_{NN}}$ = 12.3 GeV

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	$148 \pm 30 \pm 17$	$159.9 \pm 1.5 \pm 4.1$

Normalization and corrections



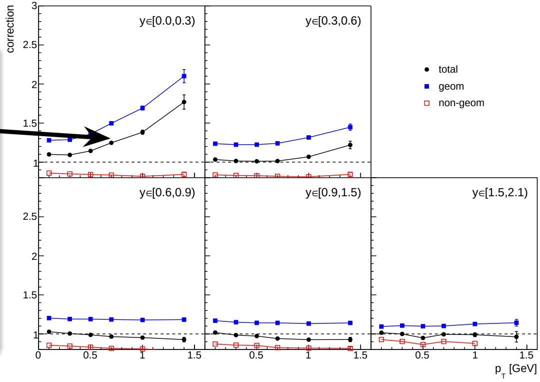
$$\frac{d^2 n}{dp_T\, dy} = \frac{N_\phi}{N_{\text{ev}}\, \Delta p_T\, \Delta y} \times \frac{c_\infty \cdot c_{\text{bkg}} \cdot c_{\text{MC}}}{\mathcal{BR}(\phi \to K^+K^-)}$$

- $c_\infty \sim 1.06$ — 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



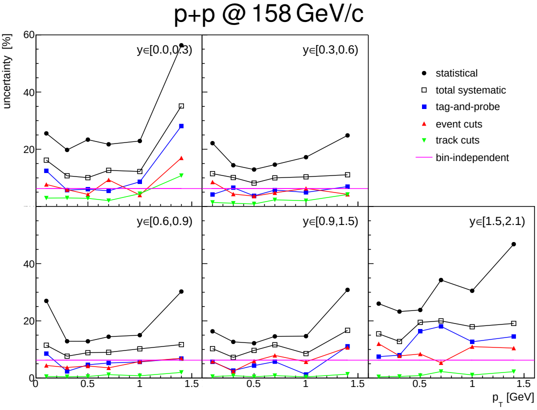
Uncertainties

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



- 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