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INTERNATIONAL PHD PROJECTS IN APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES

This project is supported by the Foundation for Polish Science – MPD program, co-financed by the European Union within the European Regional Development Fund

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

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Białasówka, 28 April 2017

Outline

Introduction

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

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

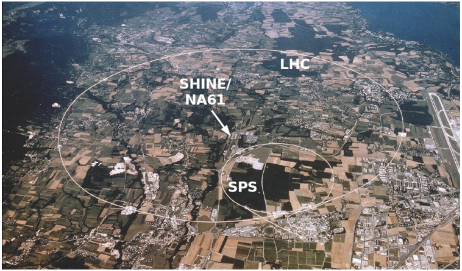
Goal of the analysis

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

Motivation

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

NA61/SHINE experiment

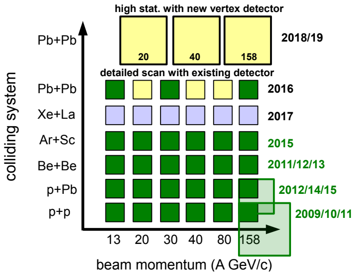


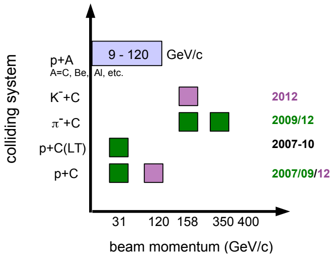
General info

- 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

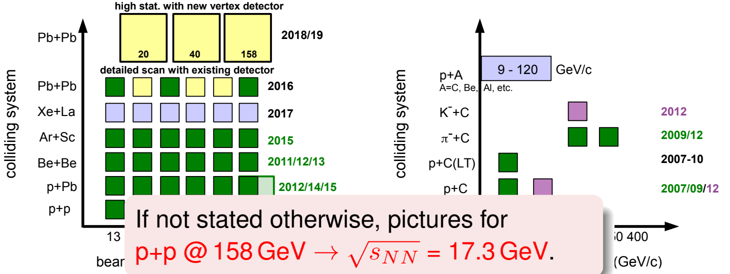
- spectra, correlations, fluctuations
- critical point
- onset of deconfinement
- ⋆ EM interactions with spectators

Cosmic rays and neutrinos

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

Physics programme

SHINE = SPS Heavy Ion and Neutrino Experiment



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

Heavy ion physics

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

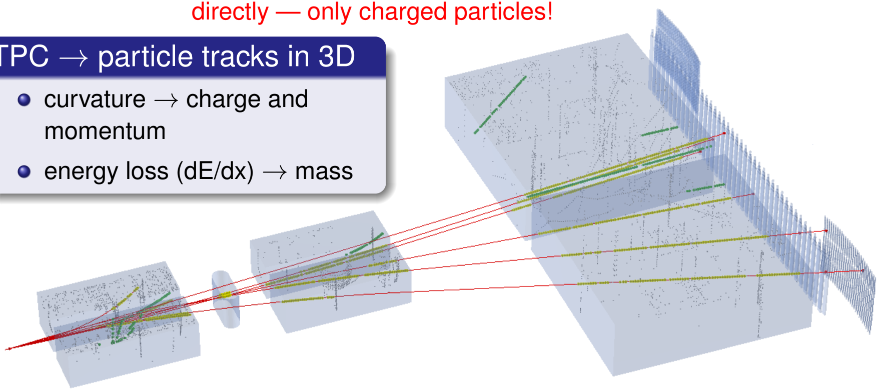
- precision measurements of spectra
- cosmic rays: Pierre Auger Observatory, KASCADE
- neutrinos: T2K, Minerνa, MINOS, NOνA, LBNE

NA61/SHINE detector

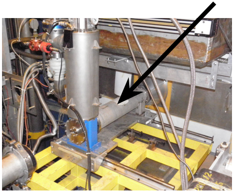
directly — only charged particles!

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 $> 95\,\%$

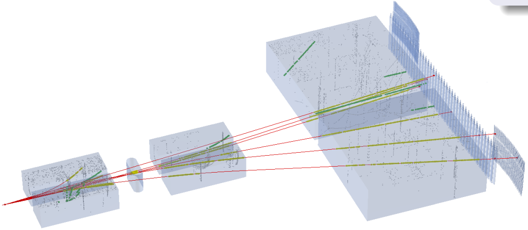
Data selection

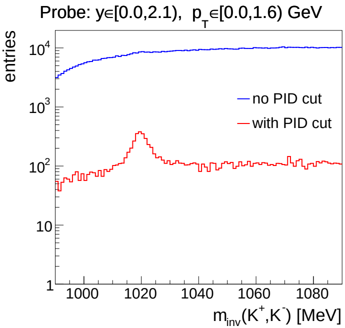
Events

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

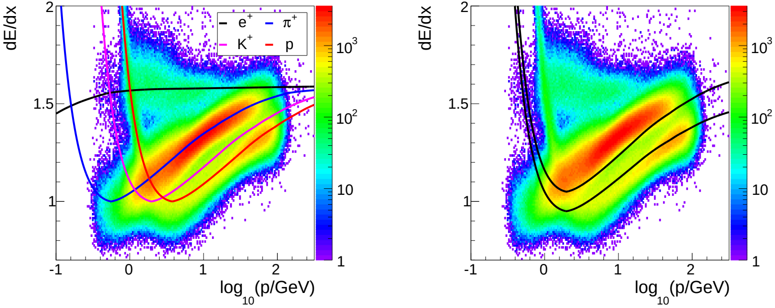
TPC tracks

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





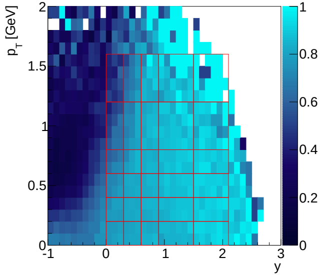
Kaon candidate selection — PID cut

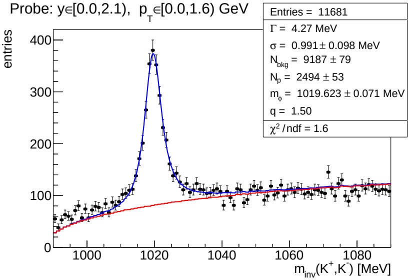


- Selection done with dE/dx
- Accept tracks in $\pm 5\,\%$ band around kaon Bethe-Bloch curve (area between black curves in right picture)
- Losses due to efficiency of this selection corrected with tag-and-probe method

Signal extraction

phase space binning, invariant mass spectrum





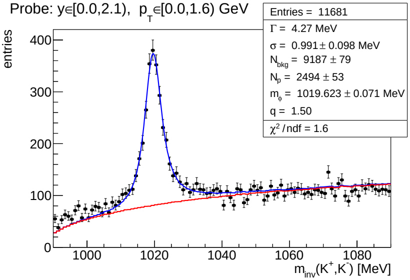
Signal extraction

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:

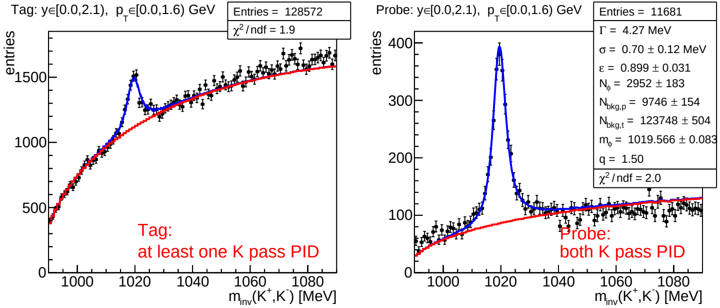
- Kaon candidate taken from the current event is combined with candidates from previous 500 events to create ϕ candidates in the mixed events spectrum

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

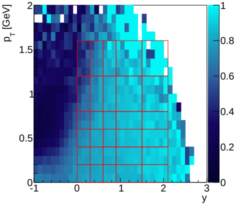


- Goal: to remove bias of N_ϕ due to PID cut efficiency ε
- Simultaneous fit of 2 spectra:
  - tag — at least one track in the pair passes PID cut

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

  - probe — both tracks pass PID cut

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



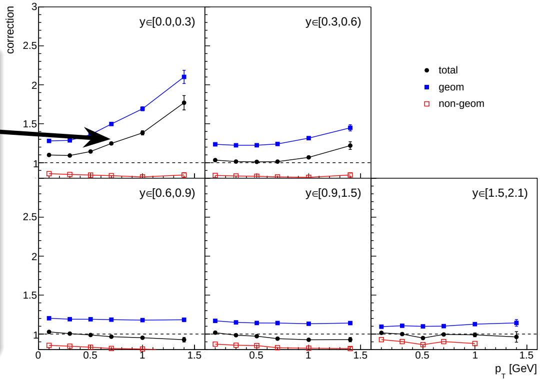
$$\frac{d^2 n}{dp_T\, dy} = \frac{N_\phi}{N_{\text{ev}}\, \Delta p_T\, \Delta y} \times \frac{c_\infty \cdot c_{\text{bkg}} \cdot c_{\text{MC}}}{\mathcal{BR}(\phi \to K^+K^-)}$$

- $c_\infty \sim 1.06$ — 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



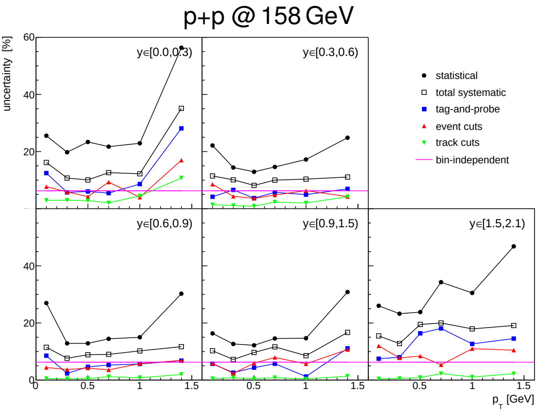
Uncertainties

Statistical

MINUIT/HESSE (symmetric)

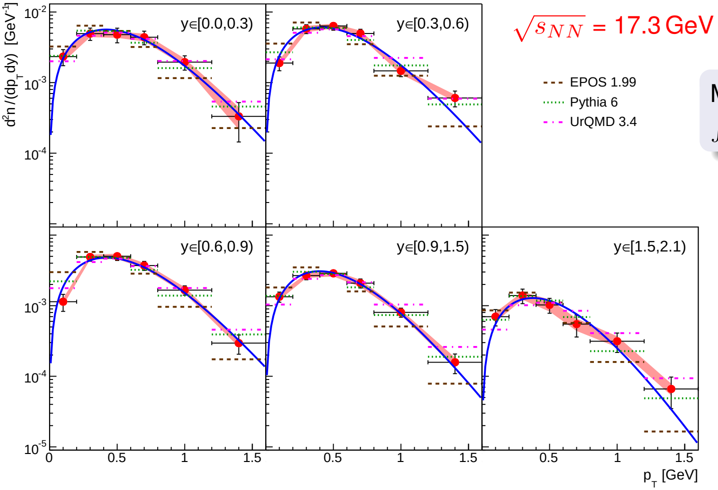
Systematic bin-independent

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 additional bin-independent 3 % due to c_{MC} averaging
- Statistical uncertainty dominates

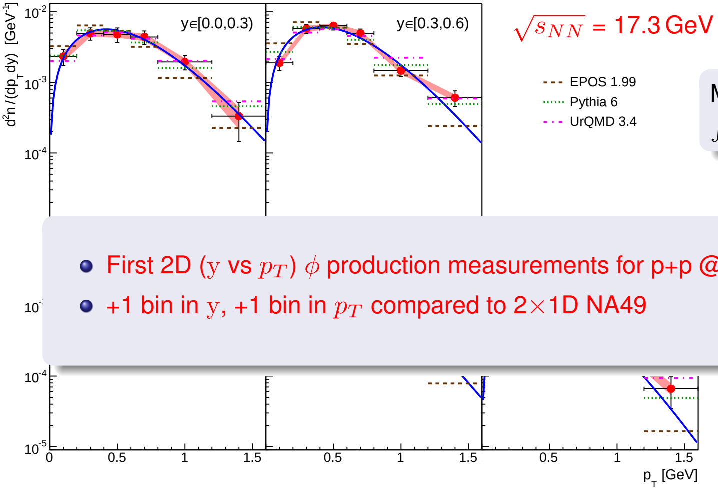
Double differential spectra: p+p @ 158 GeV



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

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail
- Fit $p_T e^{-m_T/T}$ → extrapolation to $p_T = \infty$ → tail $< 1\,\%$

Double differential spectra: p+p @ 158 GeV

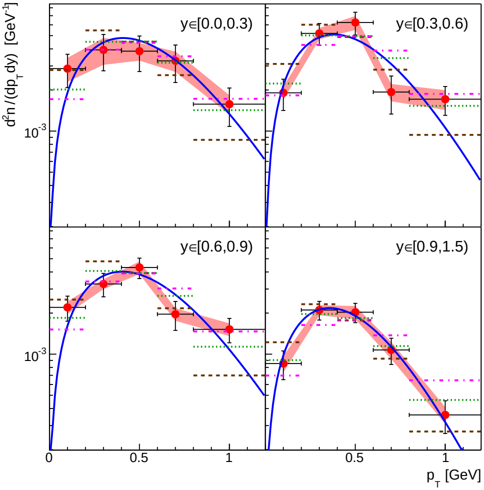


MC normalization:
$\int$ model $= \int$ data

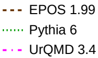
- First 2D (y vs p_T) ϕ production measurements for p+p @ 158 GeV
- +1 bin in y, +1 bin in p_T compared to 2×1D NA49

- Pythia describes spectra shapes best, UrQMD slightly too long tail, EPOS clearly too short tail
- Fit $p_T e^{-m_T/T}$ $\rightarrow$ extrapolation to $p_T = \infty \rightarrow$ tail $< 1\,\%$

Double differential spectra: p+p @ 80 GeV



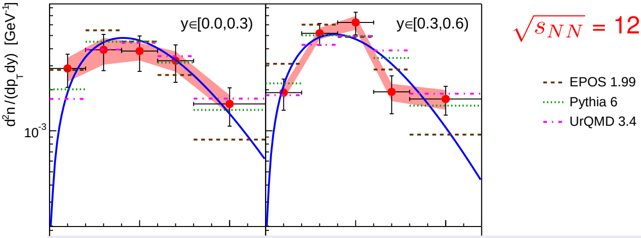
$\sqrt{s_{NN}}$ = 12.3 GeV



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 $< 4\,\%$

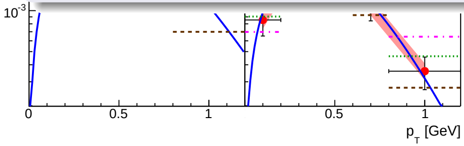
Double differential spectra: p+p @ 80 GeV



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

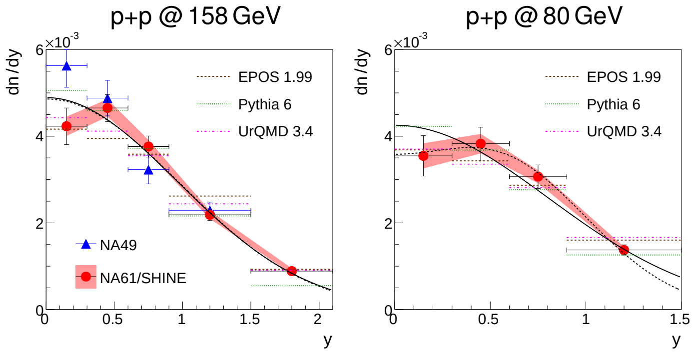
MC normalization:
$\int$ model $= \int$ data

- First ϕ 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 $p_T = \infty \rightarrow$ tail $< 4\,\%$

Rapidity



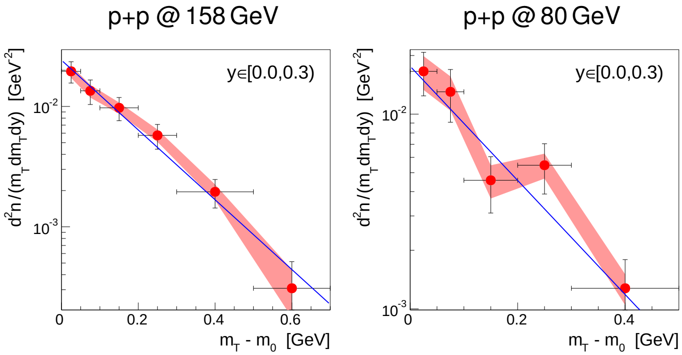
$\sqrt{s_{NN}}$ = 17.3 GeV

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

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

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

Transverse mass spectra at midrapidity



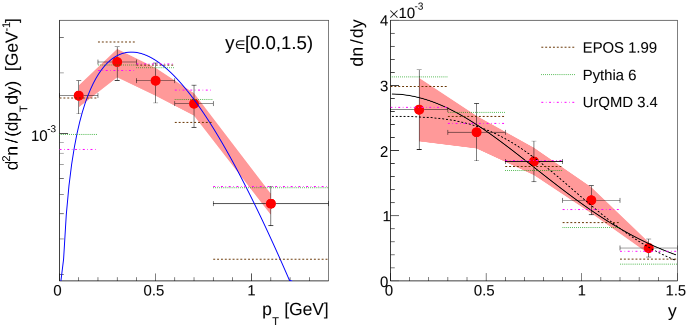
$\sqrt{s_{NN}}$ = 17.3 GeV

$\sqrt{s_{NN}}$ = 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	$148 \pm 30 \pm 17$	$159.9 \pm 1.5 \pm 4.1$

Single differential spectra: p+p @ 40 GeV



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

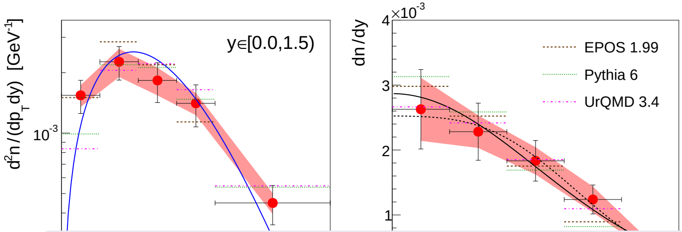
MC normalization:
$\int$ model $=$ $\int$ data

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 $5\,\%$



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

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

- First ϕ production measurements for p+p @ 40 GeV

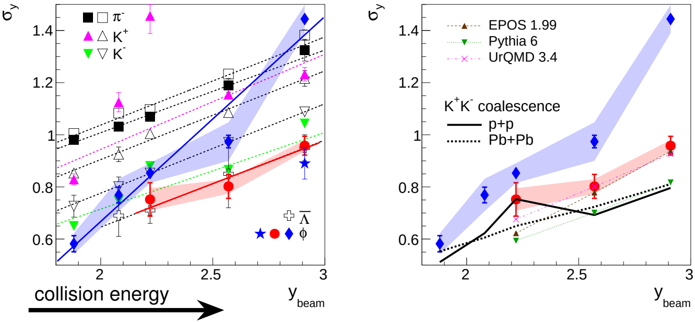
p_T

- 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: σ_y = width of dn/dy



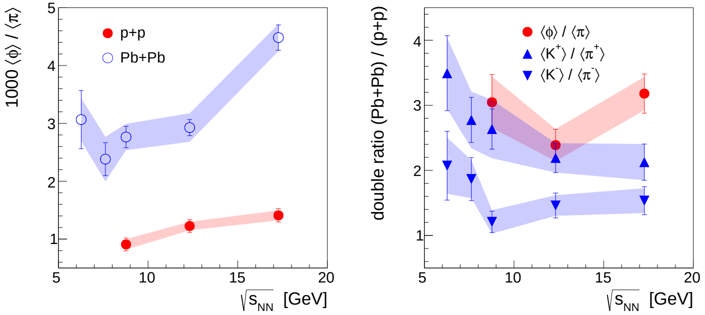
Comparison of particles / reactions

- 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

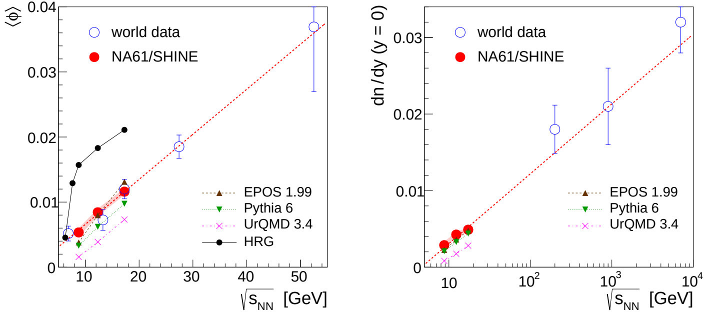
- For p+p only 40 GeV compatible with production through $K^+ K^-$ coalescence

Reference data for Pb+Pb: total yield



- 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^+
  - $\rightarrow$ 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 ϕ 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

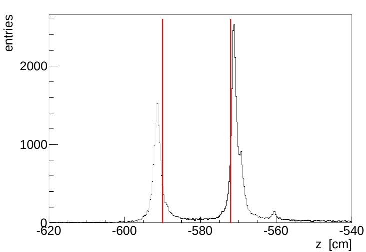
- Results consistent with p+p world data, but much more accurate!
- Emphasize peculiarity of longitudinal expansion (σ_{y}) in Pb+Pb
- Confirm enhancement in Pb+Pb, independent of energy in considered range, similar to kaons

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



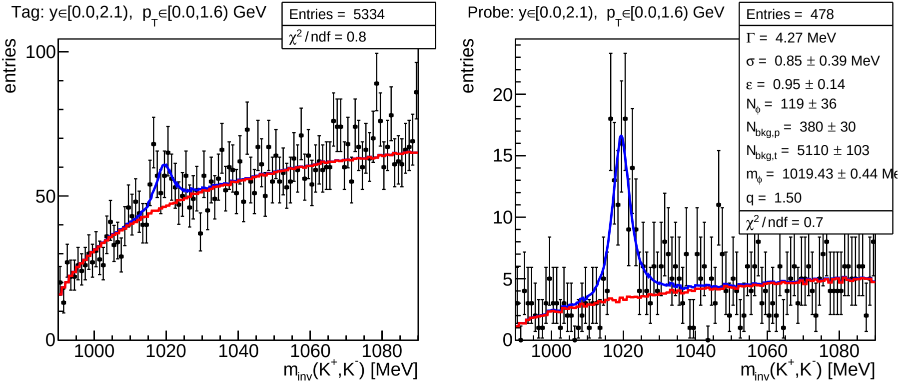
loose vertex z cut

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

tight vertex z cut

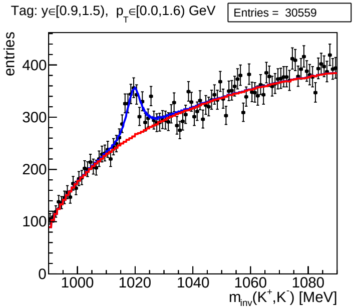
- Removes interactions in windows of LHT.
- Large $c_{\mathrm{MC}} \rightarrow$ in-target events removed due to vertex z resolution.
- Negligible EMPTY target contribution (no windows) $\rightarrow$ no EMPTY subtraction.

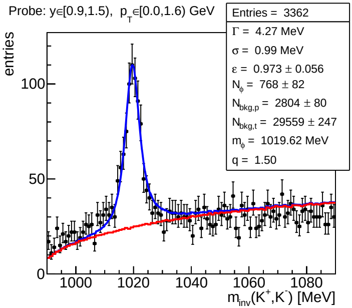
Empty target statistics — 158 GeV



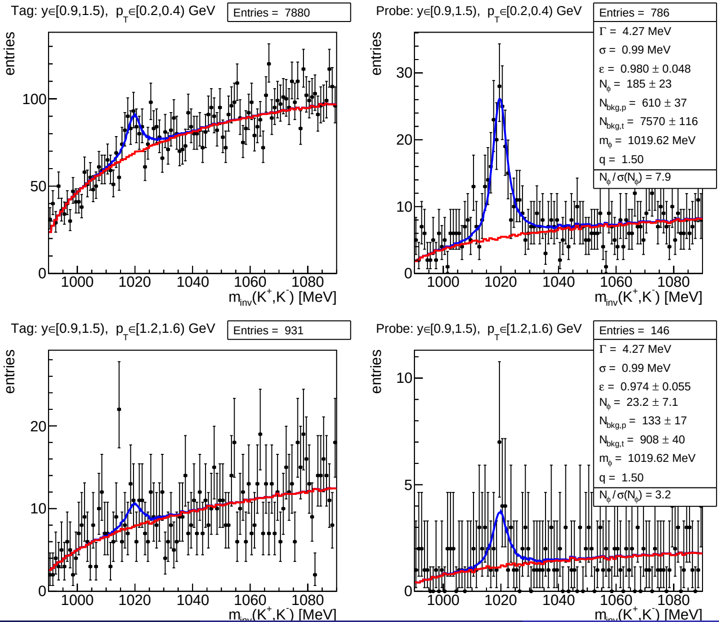
- EMPTY target subtraction requires division of these stats in the same bins as for FULL target analysis $\rightarrow$ clearly not feasible.

Example 1D y binning fit to constrain ε

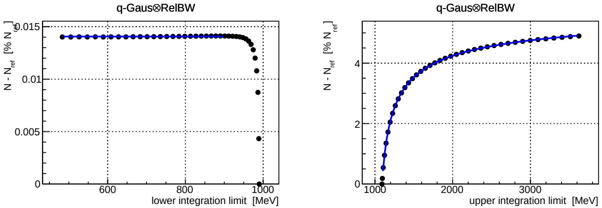




Example 2D binning fits



Integral value vs integration cut-off

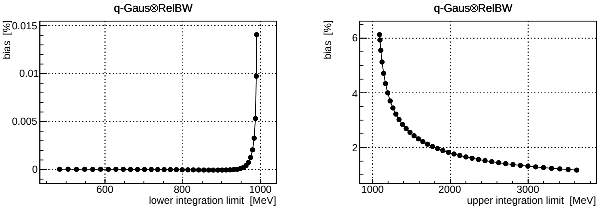


- N — integral using given limit, N_{ref}— integral using edges of m_{inv} histogram as limits.
- Fits with $y_\infty - a/|x - m_\phi|^b$ to obtain y_∞— value of relative difference when limit is infinite. This allows to calculate correction / bias of the integral for each value of limit.

$$c_{\text{R}} = \frac{N_{\text{ref}} + N_{\text{R}}}{N_{\text{ref}}} = \frac{y_\infty}{100\,\%} + 1 \qquad c_{\text{L}} = \frac{N_{\text{L}} + N_{\text{ref}}}{N_{\text{ref}}}$$

- Reference lower limit for rel. Breit-Wigner already gives at least ‰ accuracy.

Bias / correction due to integration cut-off



$$c_\infty = \frac{N_\infty}{N_{\text{ref}}} = \frac{N_{\text{L}} + N_{\text{ref}} + N_{\text{R}}}{N_{\text{ref}}}$$

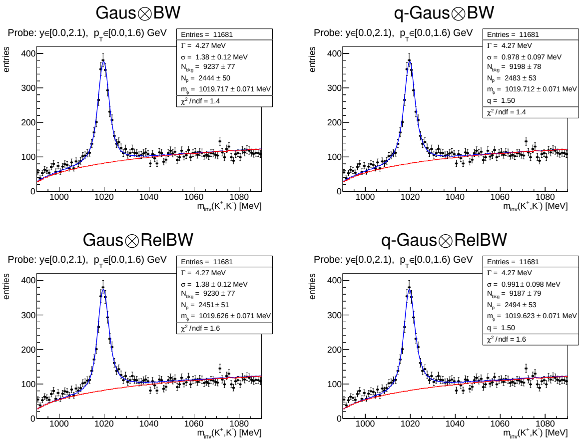
$$= \frac{N_{\text{L}} + N_{\text{ref}} + N_{\text{R}} + N_{\text{ref}} - N_{\text{ref}}}{N_{\text{ref}}}$$

$$= c_{\text{L}} + c_{\text{R}} - 1\,.$$

Introduction to systematic studies

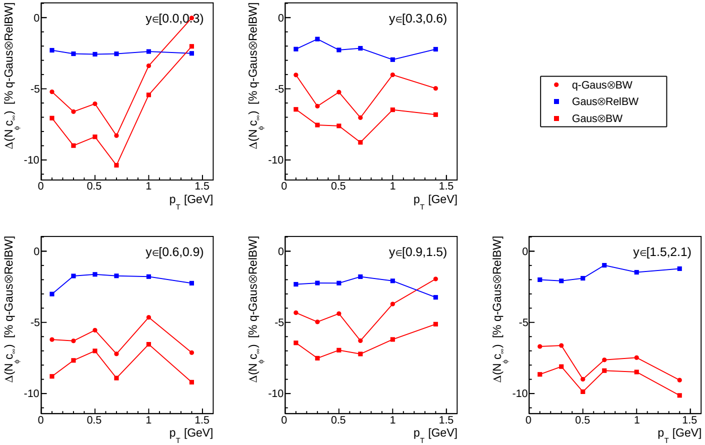
- Biases in this analysis may arise as consequence of
  1. wrong choice of analytical parametrizations for resonance shape and detector resolution effect
  2. choice of integration range of signal parametrization curve to obtain the yield
  3. unaccounted effects in background description
  4. constraints 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 $\rightarrow$ q-Gaussian $\otimes$ relativistic Breit-Wigner + correction to integral
- Other points — systematic uncertainties are estimated using improved methods for signal extraction.

Signal parametrization choice



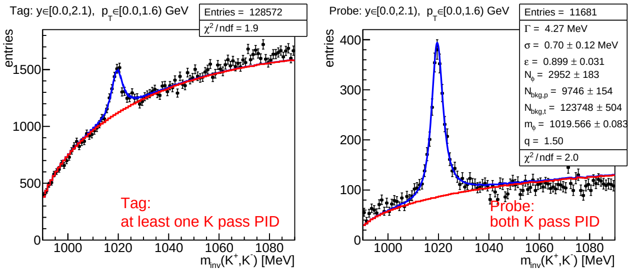
- Initially used Voigtian = Gaus⊗BW due to technical convenience
- Using MC decided to change Gaussian $\rightarrow$ q-Gaussian (explained later)
- For ϕ relativistic Breit-Wigner (used in NA49) better than non-relativistic, which yields couple % sub-threshold production.
- Change in χ^2 / ndf due to effects in background (explained later)

Quantitative comparison of signal parametrizations



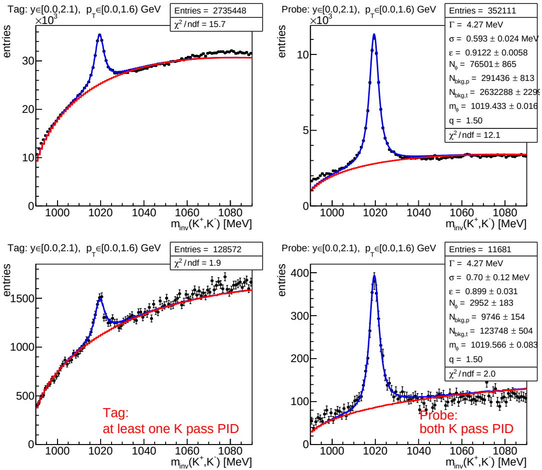
- Yields are corrected integrals in $(-\infty, +\infty)$ (explained later)
- Old parametrization yielded up to 10% underestimated results.
- About 2% due to detector resolution model
- About 5% due to resonance model

Background distortions



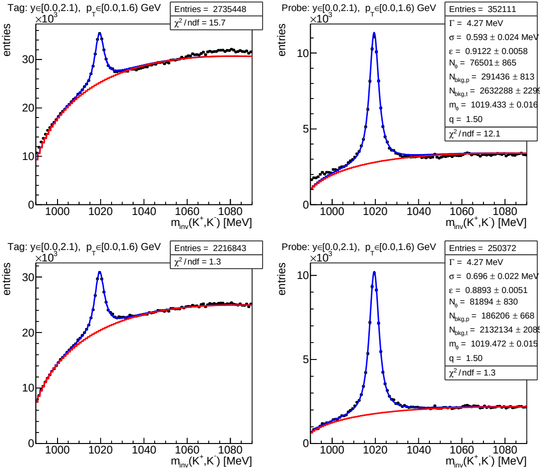
- Underestimation of background for high m_{inv} in Tag $\rightarrow K^{*0}$
- Underestimation for low m_{inv}, overestimation of background for high m_{inv} in Probe $\rightarrow$ electrons
- Using MC (next slides) — up to 10% systematic effect

MC vs data



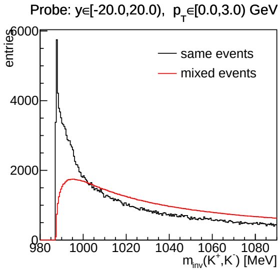
- Mock PID cuts tuned in MC (top) to have similar shapes as in data (bottom).

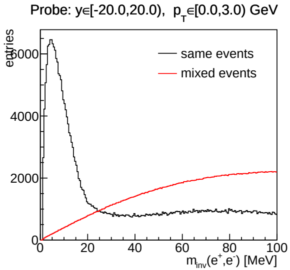
MC dirty vs clean



- In cleaned sample (no electrons, nothing from K^{*0}) no background problems observed.

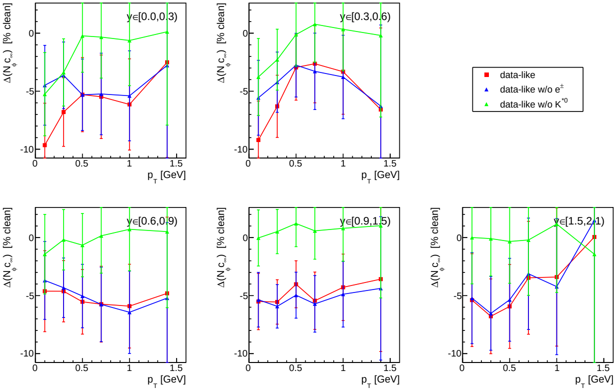
Source of low m_{inv} effect in MC — electrons





- 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?

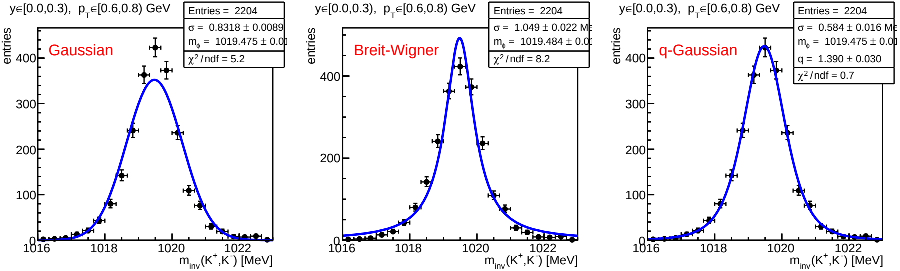
Systematics



- 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

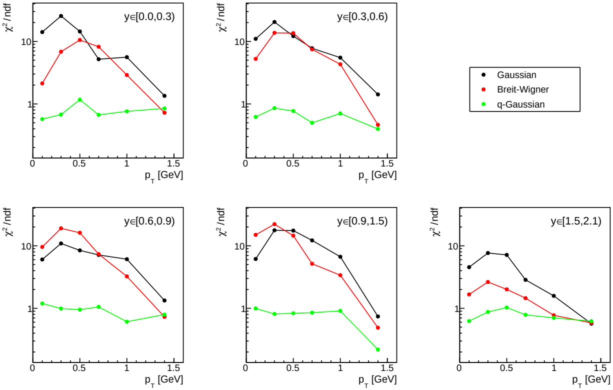
Resolution model

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



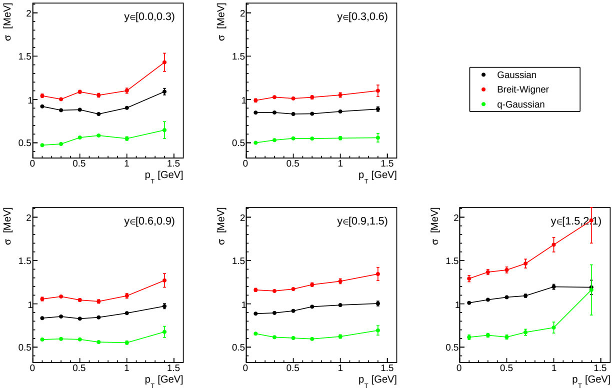
- Black dots are the same in all 3 pictures.
- Each model has a location parameter m_ϕ and width parameter σ.
- q-Gaussian has additional shape parameter q:
  - $q = 2 \Leftrightarrow$ shape = Lorentz
  - $q \rightarrow 1$ shape $\rightarrow$ Gaussian

Choice of model



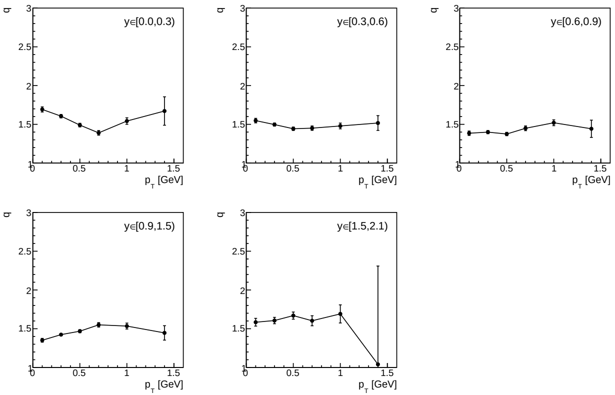
- q-Gaussian clearly favoured.

Parameters stability: σ

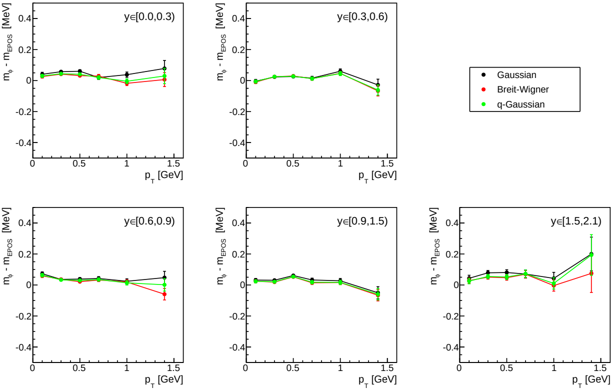


- Weighted sample standard deviation 7–9$\%$ σ fitted in full phase space, depending on model, with smallest for Gaussian.
- These values used to estimate systematic uncertainties ($\approx 1\%$) associated with assumption of invariant σ in phase space bins.

Parameters stability: q (only for q-Gaussian)

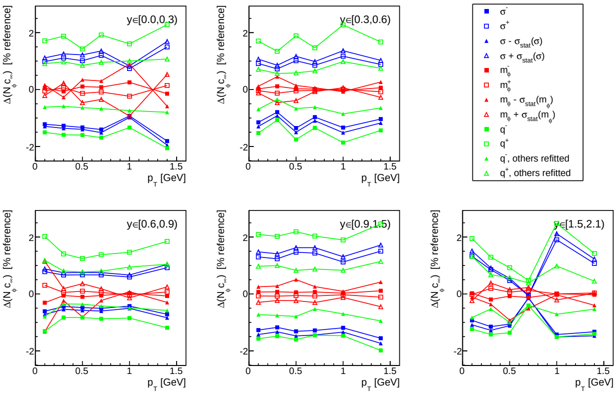


- Weighted sample standard deviation 6% q fitted in full phase space.
- These value used to estimate systematic uncertainties ($< 2\%$) associated with assumption of invariant q in phase space bins.
- q needs to be fixed to MC average value of 1.5 in fits to data due to background distortions (q-Gaussian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



- 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



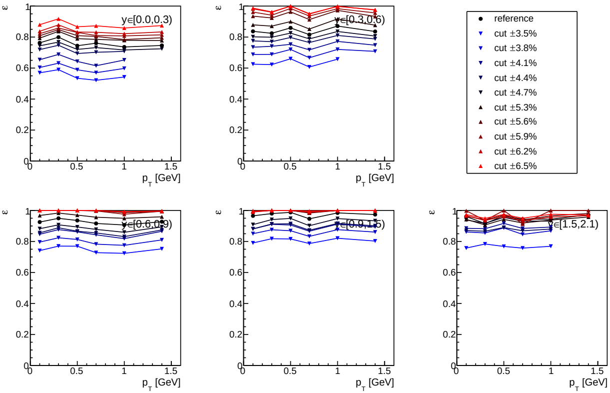
- „+“, „-“ superscripts — fits redone with listed fixed parameters increased/decreased by factors obtained from MC study from previous slides
- Also shown refits with fixed parameters shifted by their statistical errors from fits in full phase space
- Systematic uncertainty: 2%, bin independent or should 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 (ε) within phase space bins
  - constraints on ε in (y, p_T) bins fits if ε 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 ε fitted in y bin in full p_T range is used to soft-constrain fits in (y, p_T) bins
  - free ε in (y, p_T) bins fits

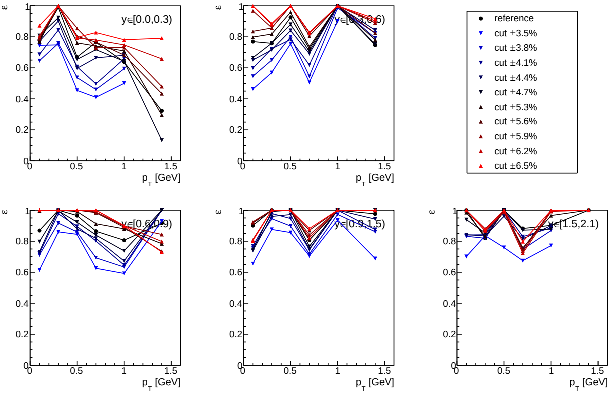
  to validate these strategies

Fit results: ε in „constrained” strategy



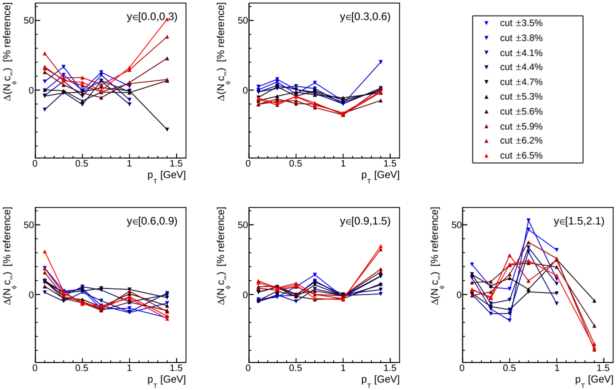
- Apart from one case in the last y bin, ε changes monotonically with window size
- agrees with expectation

Fit results: ε in „free” strategy



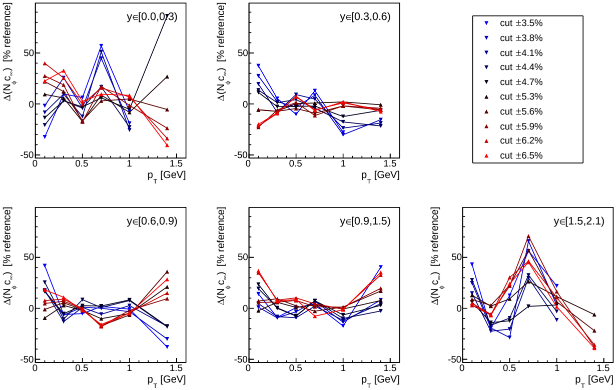
- Visible problems with monotonic dependence of ε on window size
- contrary to expectation — fit instabilities?

Fit results: N_ϕ in „constrained” strategy



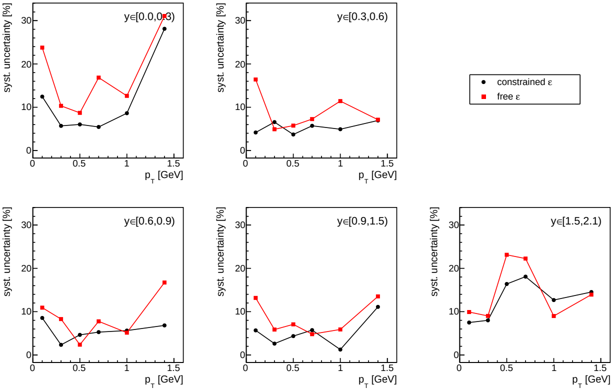
- Differences between N_ϕ values for the given and the reference cut as percentage of results for reference cut
- If no systematic error $\rightarrow$ all points should cluster at zero; standard deviation = measure of systematic uncertainty

Fit results: N_ϕ in „free" strategy



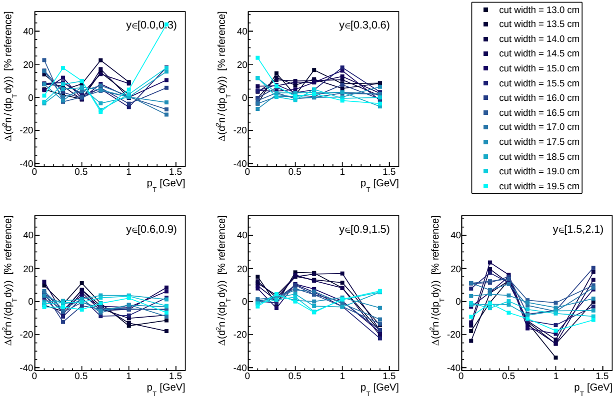
- Differences between N_ϕ values for the given and the reference cut as percentage of results for reference cut
- If no systematic error $\rightarrow$ all points should cluster at zero; standard deviation = measure of systematic uncertainty
- Clearly more spread than in „constrained" case

Tag-and-probe systematic uncertainties



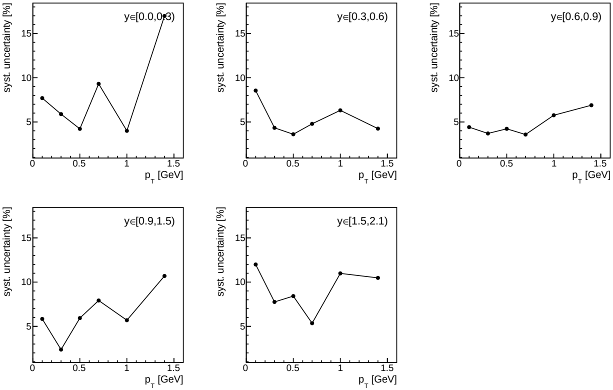
- „constrained” strategy yields smaller systematic uncertainties than „free”
- Above, together with better behaviour of ε and smaller statistical uncertainties clearly favours „constrained” strategy over the „free” one.

Main vertex Z position cut variations



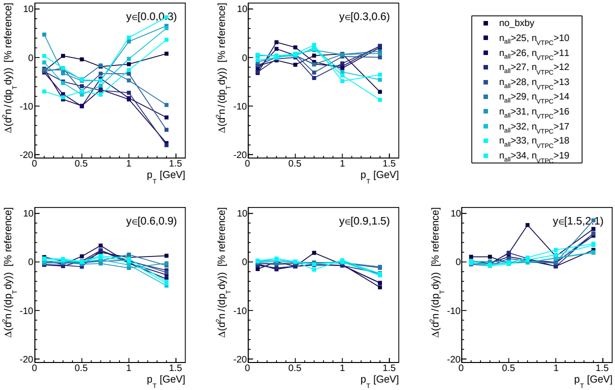
- Differences between normalized and corrected yield values for the given and the reference cut as percentage of results for reference cut = 18 cm
- If no systematic error $\rightarrow$ all points should cluster at zero; standard deviation = measure of systematic uncertainty

Systematic uncertainty due to vertex Z position cut



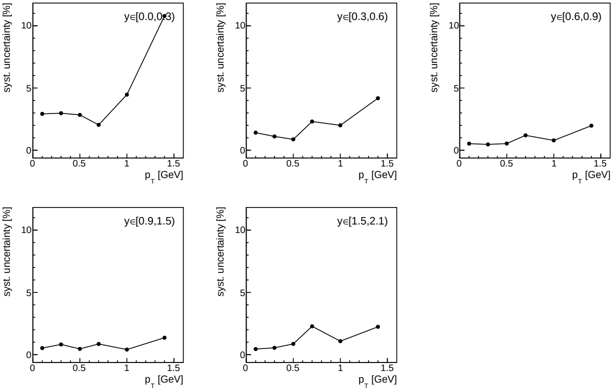
- Magnitude similar to tag-and-probe systematics

Number of TPCs points cuts variations



- Differences between normalized and corrected yield values for the given and the reference cut as percentage of results for reference cut = $n_{all} > 30, n_{VTPC} > 15$
- $n_{GAP-TPC} > 4$ 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 to tag-and-probe and vertex cut systematics

Model dependence of MC correction

MC correction may depend on

- ϕ model — shape of generated ϕ spectrum
- event model — distributions of other particles and correlations between particles
- detector model — geometry, materials, models of interactions with material

Removing ϕ 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

Breakdown of the MC correction

- 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 ϕ 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_{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 $\rightarrow$ candidate to factorize out and calculate from large statistics, well binned, flat phase space MC

Breakdown of MC correction

trigger bias

Correction

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

where n_{T2} — spectrum of generated (SimEvent) tracks that pass the cut 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

Breakdown of MC correction

vertex cuts bias

Correction

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

where n_{ver} — spectrum of generated (SimEvent) tracks that pass the cut 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

Breakdown of MC correction

track cuts bias

Correction

$$c_{\mathrm{Track}} = \left(\frac{n_{\mathrm{sel}}}{n_{\mathrm{ver}}}\right)^{-1}$$

- Corrects for reconstruction efficiency and bin migration, since n_{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