Low Mass Dimuon Production in Proton-Nucleus Collisions with the NA60 Apparatus

Outline:

- Introduction

  Motivation

  NA60 apparatus; setup in 2002; data reconstruction and selection

  Detector performance: Phase space coverage

  Dimuon mass resolution and

  Signal-to-background ratio
- Monte Carlo generation and comparison to data
- Extraction of physics results and discussion

  Elementary (pp) production cross-sections of η, ρ, ω and ϕ

  Nuclear dependence of the η, ρ/ω and ϕ production cross-sections

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Motivation

The study of low mass dilepton production in nuclear collisions provides a window of opportunity to learn about several interesting physics topics:

- Medium effects on the mass and width of the ρ vector meson (less for ω and ϕ)
  → which might be due to the approach to chiral symmetry restoration
- Thermal virtual photon production from the earliest stages of the collision
  → which would constitute direct evidence of a quark-gluon-plasma phase
- Strangeness enhancement, through the ϕ meson
  → link to general strangeness enhancement in deconfined phase

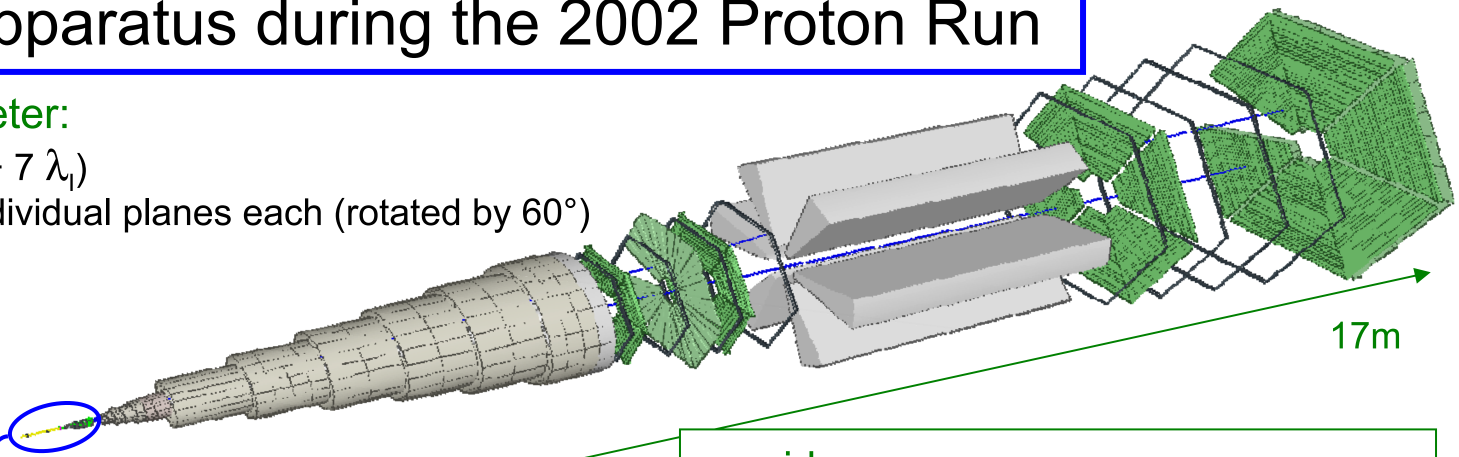
Such “new physics” studies must be built on top of a solid understanding of low mass dilepton production in proton-nucleus collisions, which provide a reference baseline with respect to which the heavy-ion specific phenomena can be extracted.

NA60 is presently taking a high statistics proton-nucleus data sample with seven different nuclear targets, at 400 and 158 GeV. The present talk reports on results obtained from a much smaller data sample collected in 2002.

The NA60 Apparatus during the 2002 Proton Run

The muon spectrometer:

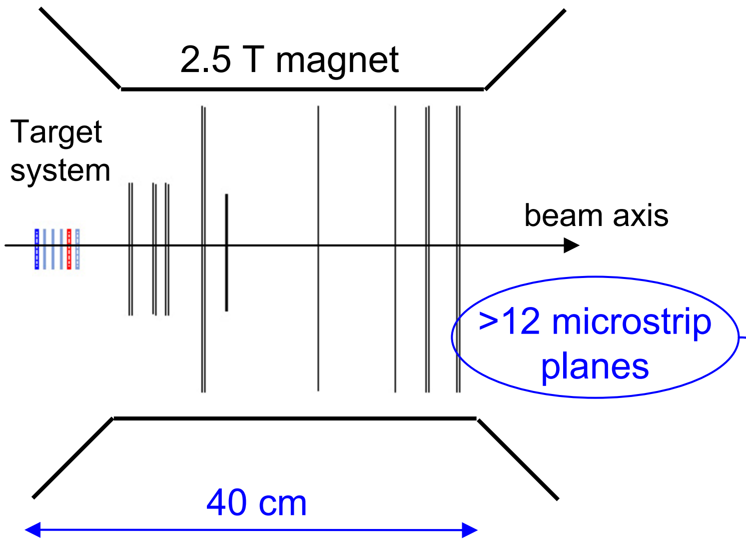
- Hadron absorber (13 + 7 λ_I)
- 4+4 MWPCs with 3 individual planes each (rotated by 60°)
- 4 trigger hodoscopes
- Toroidal magnet



provides:

- Muon identification
- Highly selective dimuon trigger
- Track reconstruction of two muons
  however: affected by multiple scattering and energy loss induced by the hadron absorber

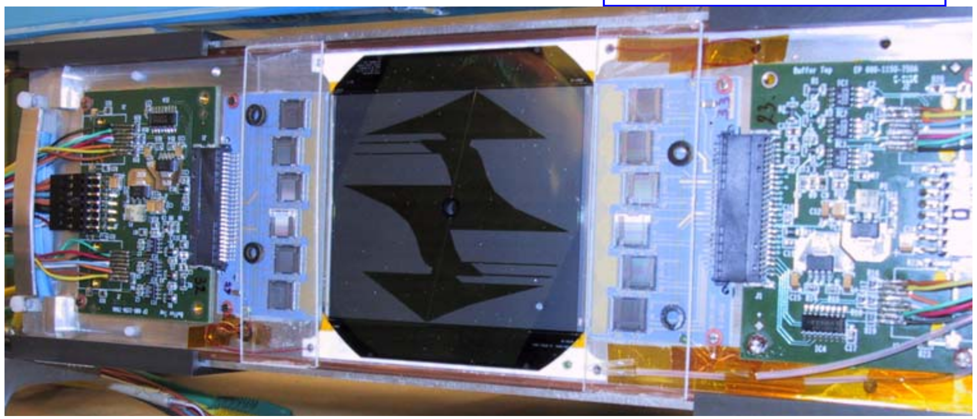
The vertex region:



provides:

- Tracking of charged particles
- Target identification
- Improved dimuon kinematics via track "matching"

microstrip plane



Strip segmentation adapted to the highly inhomogeneous particle production across the sensor surface.

Data Taking, Reconstruction and Event Selection

1) Data Taking

- 400 GeV proton beam incident on Be, In and Pb targets (2%, 0.9% and 1.2% λ_{Int} respectively)
- All targets were simultaneously placed in the beam to reduce systematic effects in the extraction of the nuclear dependence of the production cross-sections
- During 4 days in 2002: 600 000 dimuons collected (at “low” beam intensity: 1–3 · 10^8 protons/burst)

2) Data Reconstruction and Event Selection

- Reconstruct tracks in the muon spectrometer and build dimuons of all charge combinations
- Reconstruct the charged particle tracks in the vertex telescope
- Reconstruct the primary interaction vertex
- Select events with only one reconstructed vertex in the target region to reject pile-up
- Match the two muons to vertex telescope tracks, in coordinate and momentum space

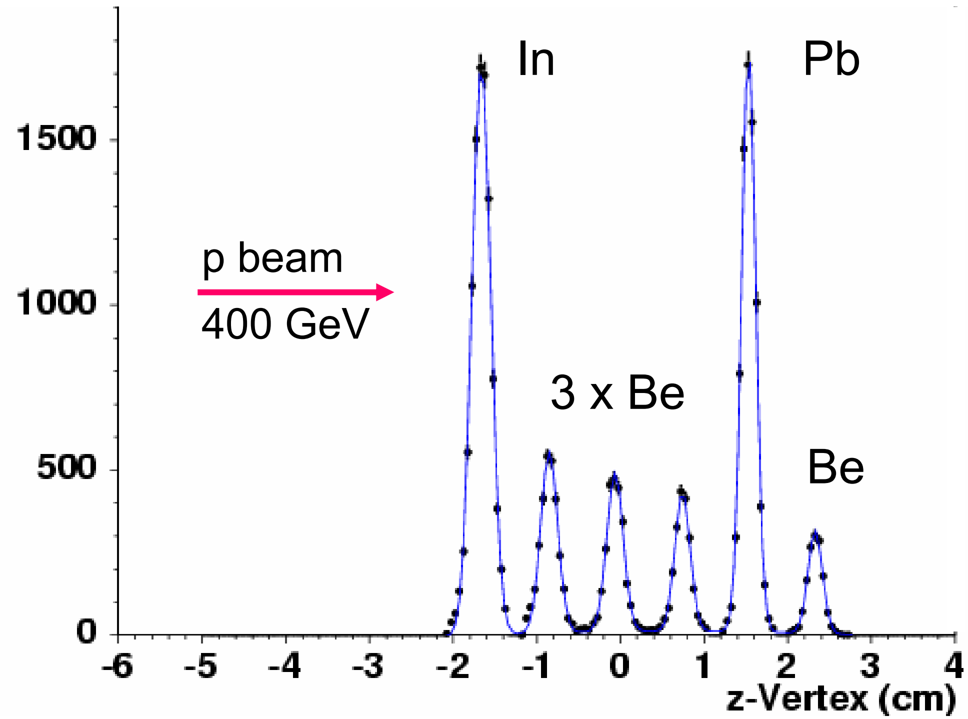
Like Sign (LS) dimuons:
used to evaluate the “combinatorial background” from π, K decays through a mixed event technique

Opposite Sign (OS) dimuons:
used for the physics data analysis

- Select matched dimuons in a well defined phase space window
- After the full reconstruction, vertex selection and phase space cuts we are left with ~ 15 000 OS dimuons

Target Identification

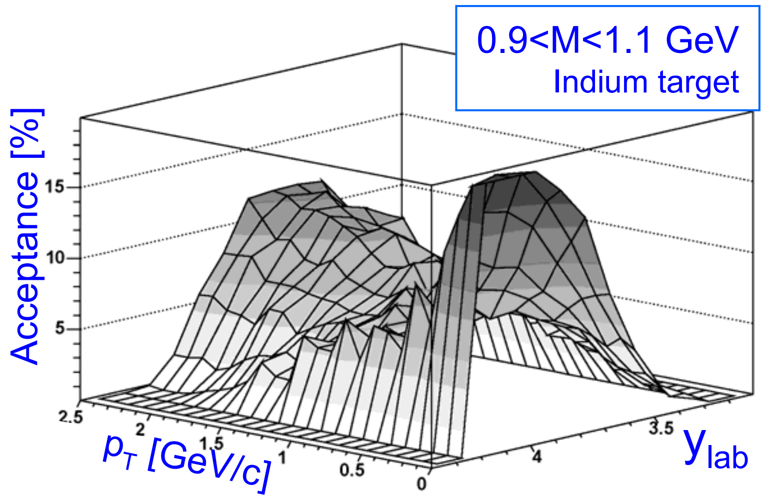
- Z-vertex resolution ~ 600–900 μm depending on the target position
  ⇒ allows us to clearly separate the individual targets (2 mm thick, 8 mm interspacing)
- Vertexing algorithm tuned through MC simulation
  ⇒ in only ~2% of all generated events the collision vertex is reconstructed in a wrong target



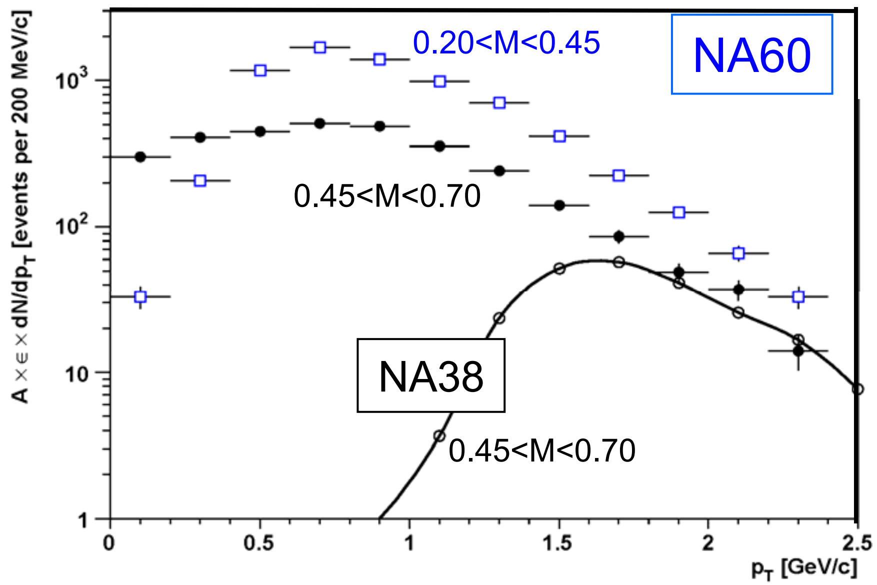
The use of 3 target materials with very different mass numbers (Be, In, Pb) allows us to extract the nuclear dependence of the particle production cross-sections.

Phase Space Window & Acceptances

Dimuon phase space
$3.3 < y_{lab} < 4.2$
$|\cos \theta_{CS}| < 0.5$
$m_T > 0.4 + 0.7\,(y - 4.2)^2$ GeV

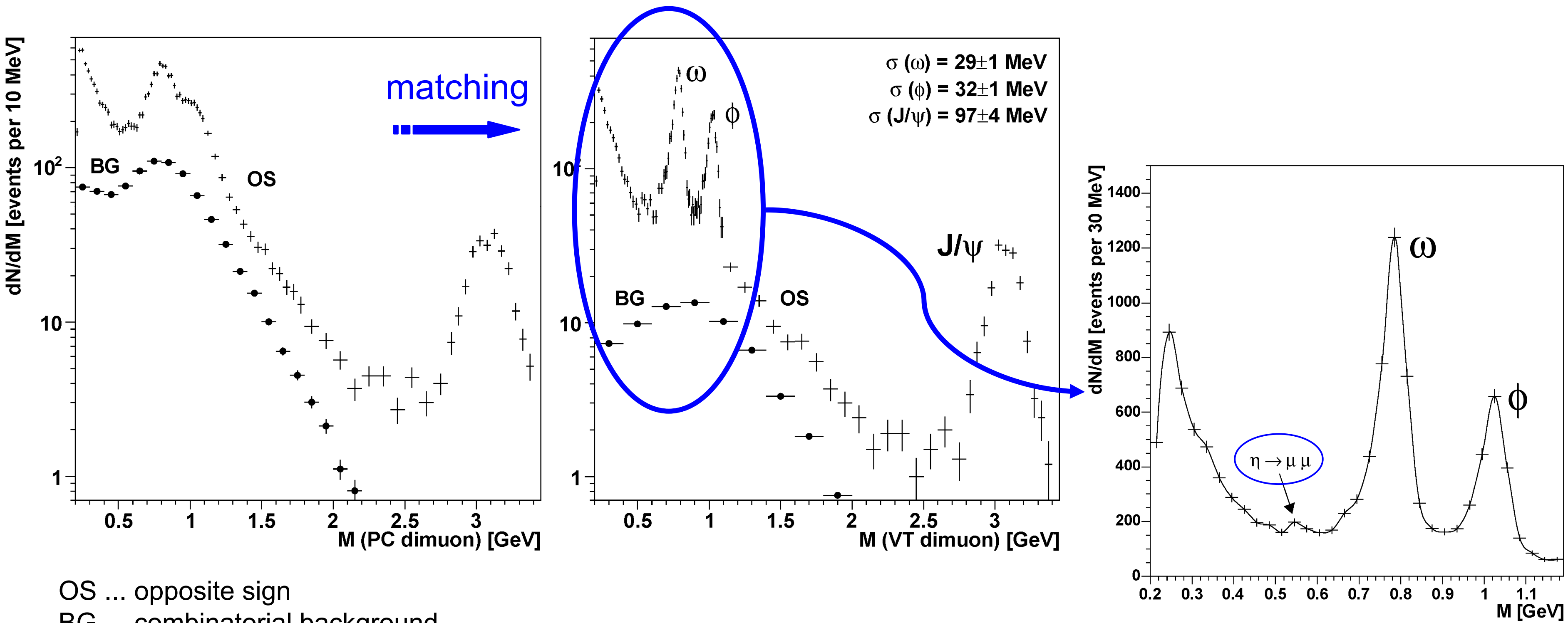


- The phase space window was tuned to keep most of the dimuons collected in the ω and ϕ mass windows.
- Apart from the dimuon selection cuts (y_{lab}, cosθ and m_T) we also apply an angular single muon cut to stay away from the "beam-hole" of the strip sensors: $\eta(\mu) < 4.2$
- Acceptances: ρ ~ 3.3%, ω ~ 3.6%, ϕ ~ 6.5 %
  (the exact value depending on the target position)
- The dipole magnetic field in the vertex region improves significantly the acceptance for low mass and low p_T opposite sign dimuons



Mass Resolution and Signal / Background

- Measuring the muons before they suffer multiple scattering and energy loss in the hadron absorber, thanks to our silicon vertex telescope, allows us to achieve a mass resolution on the ω and ϕ resonances of around 30 MeV. That is exactly the value expected from our MC simulations.
- Through the matching procedure the signal to background ratio improves by a factor of 4.

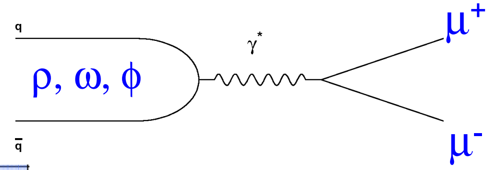


OS ... opposite sign
BG ... combinatorial background

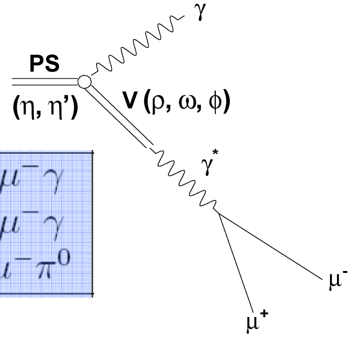
The mass resolution is even sufficient to see the η in the $\mu\mu$ decay channel!

(These figures show the statistics collected from all targets)

MC Generation of Light Meson Decays



2-body		
	η	$\mu^+\mu^-$
	ρ	$\mu^+\mu^-$
	ω	$\mu^+\mu^-$
	ϕ	$\mu^+\mu^-$

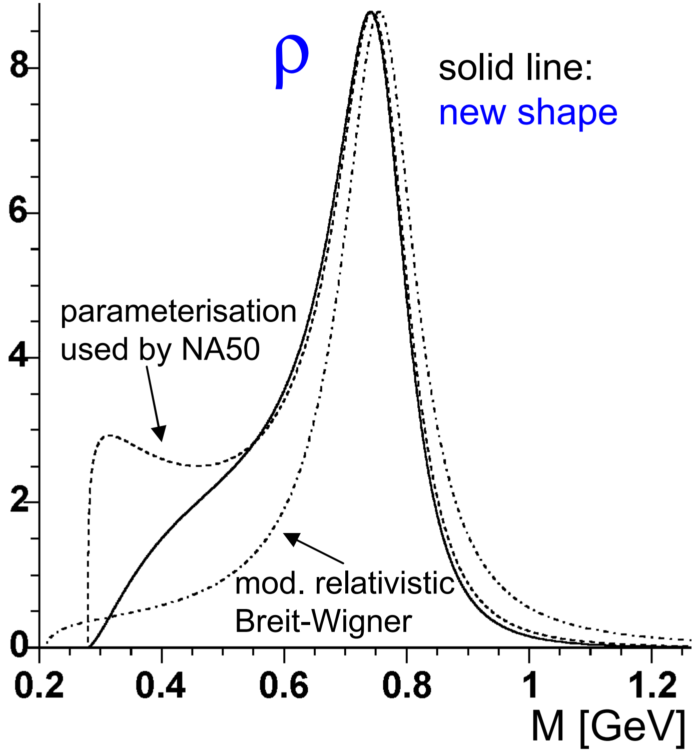


Dalitz		
	η	$\mu^+\mu^-\gamma$
	η'	$\mu^+\mu^-\gamma$
	ω	$\mu^+\mu^-\pi^0$

- The η, η', ρ, ω and φ mesons were generated with
  - p_T distributions: $$\frac{1}{p_T}\cdot\frac{dN}{dp_T}=\frac{1}{m_T}\cdot\frac{dN}{dm_T}=m_T K_1\left(\frac{m_T}{T}\right)$$
  - y distributions: $$\frac{dN}{dy}\propto\frac{1}{\cosh^2(a(y-y^*))}$$

    the y width scales with $y_{max}=\ln(\sqrt{s}/m)$
  - mass distributions: Gounaris-Sakurai parameterisation
  - ρ mass line shape modified to include phase space effects:

$$\frac{\mathrm{d}R(M)}{\mathrm{d}M}=\frac{\alpha^2 m_\rho^4}{3(2\pi)^4}\frac{\left(1-\frac{4m_\pi^2}{M^2}\right)^{3/2}\sqrt{1-\frac{4m_\mu^2}{M^2}}\left(1+\frac{2m_\mu^2}{M^2}\right)}{(M^2-m_\rho^2)^2+M^2\Gamma_{\rm tot}^2}(2\pi MT)^{3/2}e^{-M/T}$$



- Dimuon mass distributions of Dalitz decays:
  Kroll-Wada form multiplied with transition form factors (Lepton-G data)
- Branching ratios from PDG04;

  we use $\omega\to ee$ instead of $\omega\to\mu\mu$ because it is known more accurately ("lepton universality")

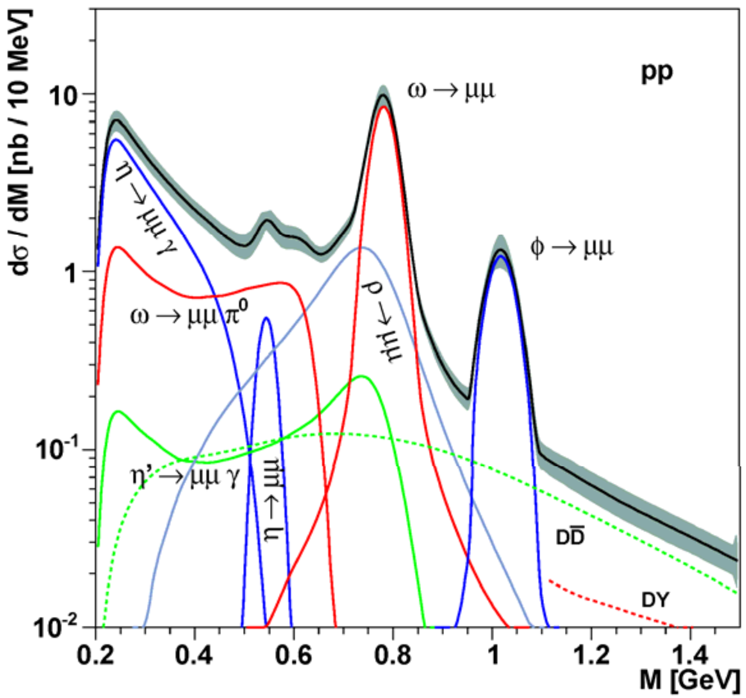
MC Simulation of Hard Processes

Events generated with Pythia 6.2

<u>Open Charm ($D\bar{D}$): semi-muonic decays of two D mesons</u>

- Generation done with CTEQ6L PDFs
- Branching Ratios taken from PDG04
- Normalisation:

  $\sigma(c\bar{c}) \sim 20\ \mu b$ (from a compilation of charm measurements)
  Linear A-dependence, including nuclear effects on the PDFs



<u>Drell-Yan (DY)</u>

- Generated with MRS-A Low Q^2 to obtain events with low masses
- K factor = 1.4 (to reproduce NA3 data: p-Pt at 400 GeV)

  $\sigma(DY)_{pp}$ = 17 nb, $\sigma(DY)_{pn}$ = 15 nb
- Linear scaling with the number of nucleons:

  $\sigma(DY)_{p\text{-}A} = Z \cdot \sigma_{pp} + (A-Z) \cdot \sigma_{pn}$

Reconstruction:

- All generated muon pairs are immersed in an underlying hadronic event, using VENUS, to correctly reproduce the reconstruction efficiencies.
- Particle tracking through the apparatus done via GEANT.
- The reconstruction was done with the same settings as the real data
  → gives particle acceptances and detector smearing effects.

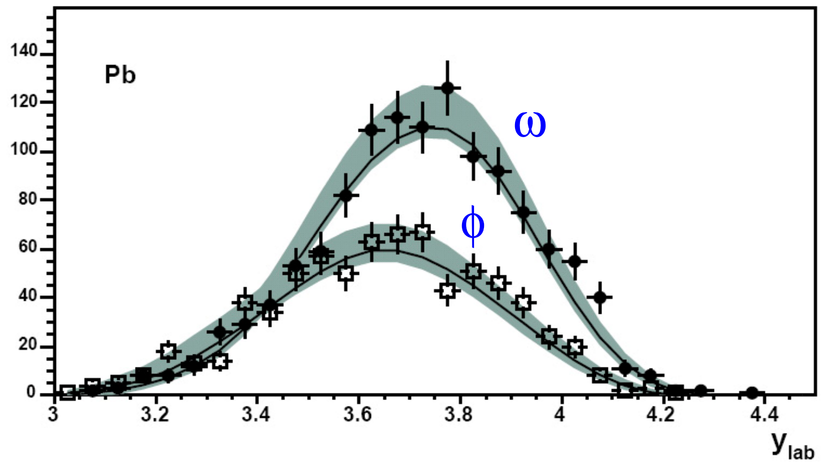
Reconstructed MC vs. Data

• Before extracting physics results from the data *using* our MC simulations, we must ensure that the data's kinematical distributions are reproduced.

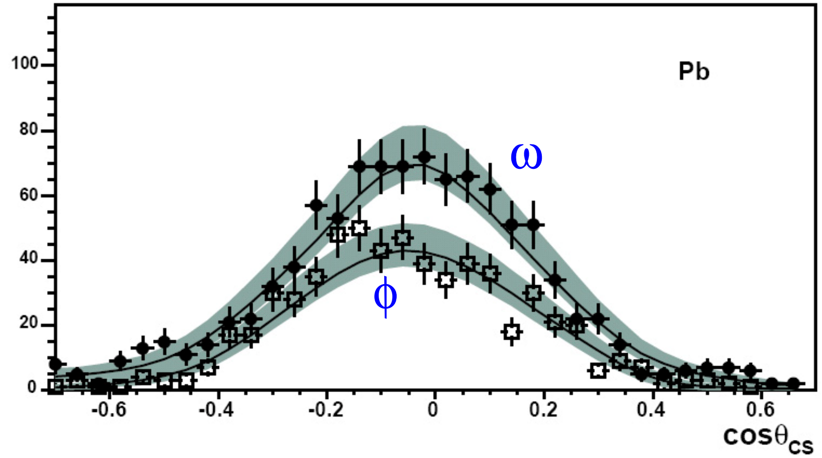
• Among other variables, we compare the rapidity, the decay angle and the transverse momentum distributions of various mass windows, where the comparison is performed on the raw data level.

• Within the statistics available in the ω and ϕ mass windows we see good agreement between reconstructed MC and data.

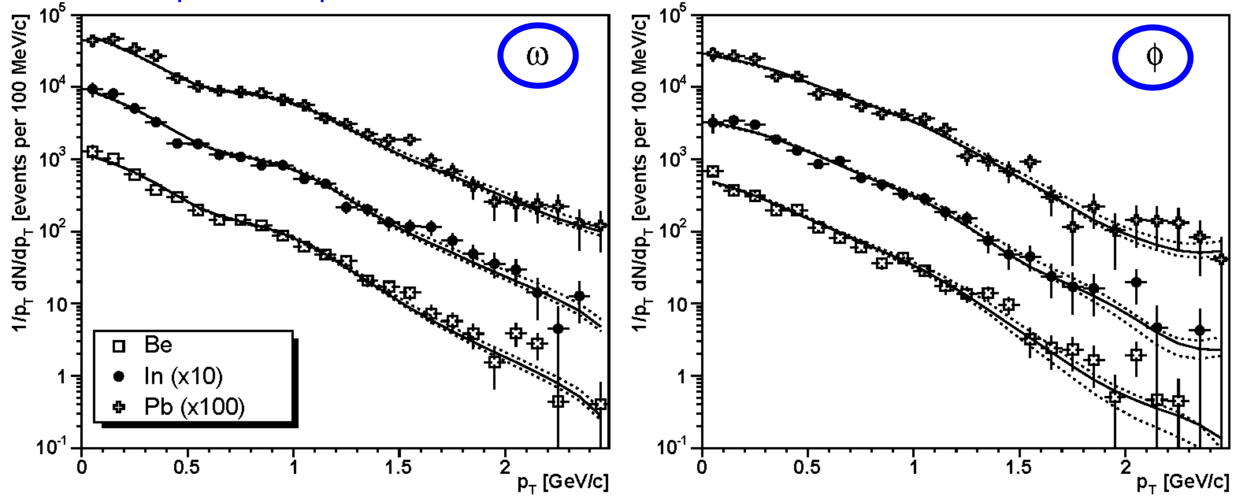
rapidity:



$\cos\theta_{CS}$:



$1/p_T \cdot dN/dp_T$:



Fitting the OS Dimuon Mass Spectrum

- Background fixed by a mixed event technique using single muons from the measured like-sign dimuons.
- Open charm and Drell-Yan production cross-sections fixed from previous measurements (describes nicely the region between the ϕ and the J/ψ peaks).

- The ω and ϕ cross-sections can be extracted from the resonance peaks.
- The good mass resolution allows us to extract the ρ normalisation independently of the ω.
- The η cross-section is essentially determined from the mass region below 0.45 GeV, where its Dalitz decay is the dominating process (the η 2-body peak does not have enough statistics to influence the fit).

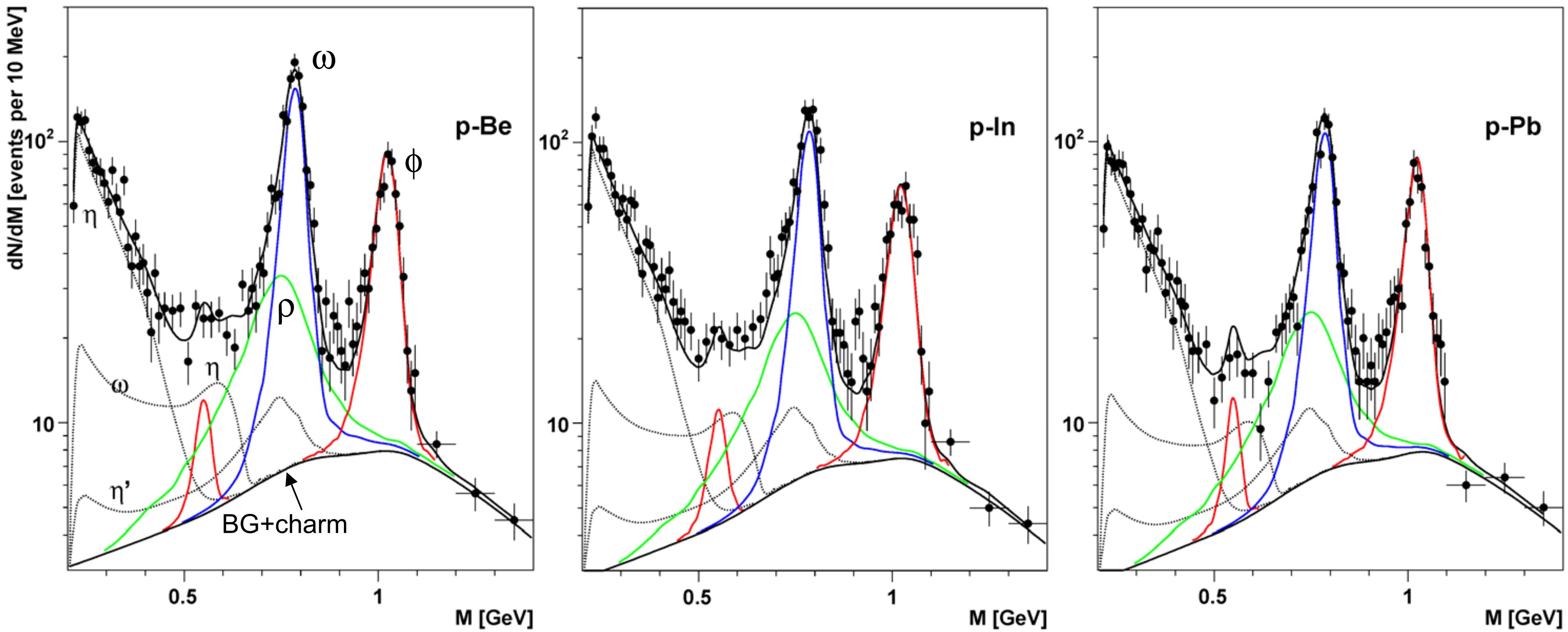
- From a simultaneous fit of the 3 data samples (Be, In and Pb), we can extract the dependence of the η, ρ/ω and ϕ cross-sections with A.

$$\sigma_{pA} = \sigma_0 \cdot A^{\alpha}$$

$$\sum_{i=Be,In,Pb} \frac{\mathrm{d}N_i^{OS}}{\mathrm{d}M} = \sum_{i=Be,In,Pb} \frac{\mathrm{d}N_i^{BG}}{\mathrm{d}M} + \mathcal{L}_i \Bigg(\frac{\mathrm{d}\sigma_{pA_i}^{D\overline{D}}}{\mathrm{d}M} +$$
$$B^{\eta_D}\sigma_0^{\eta}\mathrm{A}_i^{\alpha^{\eta}}\frac{\mathrm{d}N_i^{\eta_D}}{\mathrm{d}M} + B^{\eta'_D}\sigma_0^{\eta'}\mathrm{A}_i^{\alpha^{\eta'}}\frac{\mathrm{d}N_i^{\eta'_D}}{\mathrm{d}M} + B^{\omega_D}\sigma_0^{\omega}\mathrm{A}_i^{\alpha^{\omega}}\frac{\mathrm{d}N_i^{\omega_D}}{\mathrm{d}M} +$$
$$B^{\eta}\sigma_0^{\eta}\mathrm{A}_i^{\alpha^{\eta}}\frac{\mathrm{d}N_i^{\eta}}{\mathrm{d}M} + B^{\rho}\sigma_0^{\rho}\mathrm{A}_i^{\alpha^{\rho}}\frac{\mathrm{d}N_i^{\rho}}{\mathrm{d}M} + B^{\omega}\sigma_0^{\omega}\mathrm{A}_i^{\alpha^{\omega}}\frac{\mathrm{d}N_i^{\omega}}{\mathrm{d}M} + B^{\phi}\sigma_0^{\phi}\mathrm{A}_i^{\alpha^{\phi}}\frac{\mathrm{d}N_i^{\phi}}{\mathrm{d}M} \Bigg)$$

- Fit parameters: σ_0^{η}, σ_0^{ρ}, σ_0^{ω}, σ_0^{ϕ}, α^{η}, α^{ω}, α^{ϕ}
- Assuming: $\alpha^{\rho} = \alpha^{\omega}$; $\alpha^{\eta'} = \alpha^{\eta}$ and $\sigma^{\eta'} = 0.15 \cdot \sigma^{\eta}$ [Eur. Phys. J. C4 (1998) 231]
- The fit is performed in the mass window 0.2–1.1 GeV.

Fitting p-Be, p-In and p-Pb simultaneously



• The fitting procedure (7 free parameters) describes the low mass dimuon spectra of the three data samples without additional sources (like in HELIOS-1 and CERES).

• From these fits we can derive the number of ω's and ϕ's present in our data samples:

• The ϕ peak increases relatively to the ω, from p-Be to p-Pb.

	N^{ω}	N^{ϕ}
Be	966	575
In	676	464
Pb	660	511

Results I: Nuclear dependence of production cross-sections

The fit gives the nuclear dependence of the η, ω and φ cross-sections:

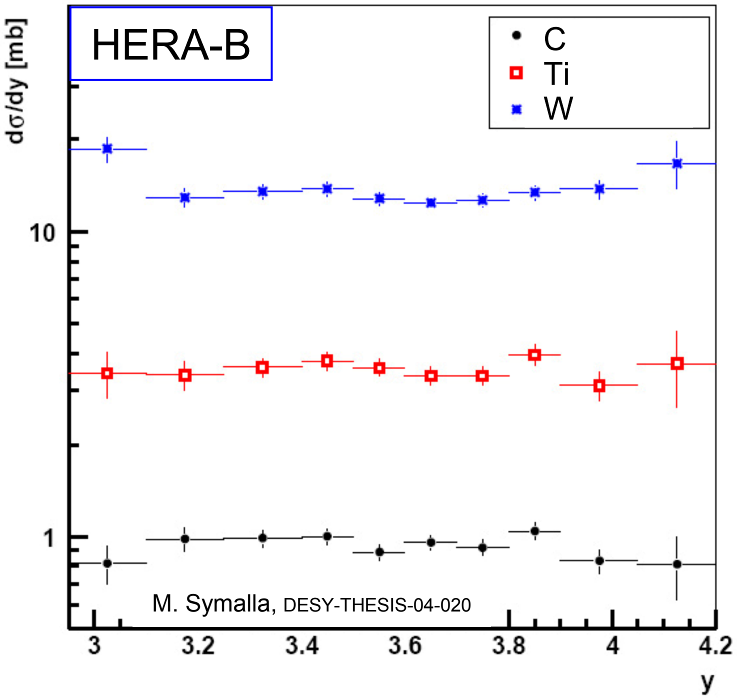
$$\sigma_{pA} = \sigma_0 \cdot A^{\alpha}$$

α^{η}	0.93±0.02
α^{ω}	0.82±0.01
α^{ϕ}	0.91±0.02

(statistical error only)

- The η and φ production cross-sections scale faster with A than the ω.
  This should be kept in mind when interpreting data collected in heavy ion collisions.

- No previous measurements are worth comparing to, except with HERA-B, which measured



$\alpha(\phi)$ = 1.01 ± 0.01 ± 0.06

in p-C, Ti, W at 920 GeV, in the $\phi \rightarrow K^+K^-$ decay channel

Phase space domain:

$0.5 < p_T^2 < 12.1$ (GeV/c)^2
$2.95 < y_{lab} < 4.2$
(i.e. $-0.85 < y^* < 0.4$)

note that α decreases with x_F and increases with p_T

Results II: Elementary 4π production cross-sections

We have extracted the absolute production cross-sections of the η, ρ, ω and ϕ mesons in elementary p-nucleon collisions at E_{lab} = 400 GeV.

The extrapolation to 4π requires assuming certain kinematical distributions outside of our phase space window. For the decay angle distributions of the 2-body decays we have two reasonable options: $1+\cos^2\theta$ or uniform

σ_0 [mb]	$1+\cos^2\theta$	uniform
ρ	11.6±1.0	8.9±0.7
ω	10.5±0.6	8.0±0.5
ϕ	0.53±0.05	0.40±0.03
η	9.5±0.6	10.2±0.6

(statistical errors only)

Looking at the results:

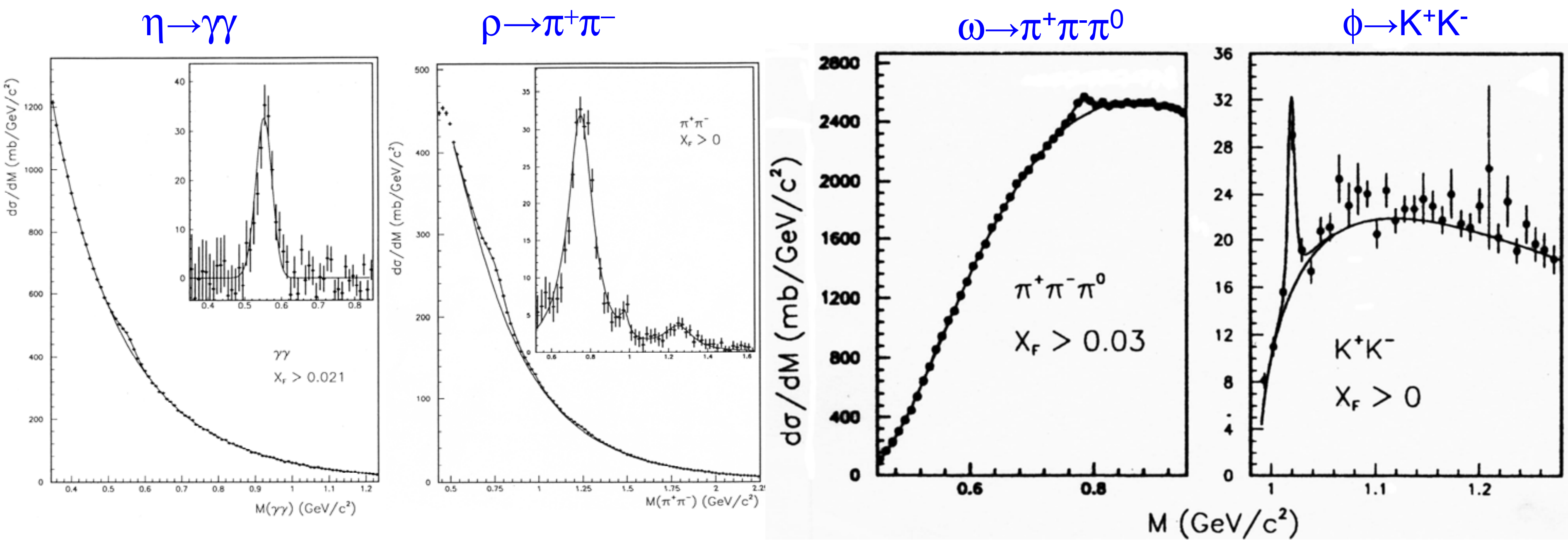
(a) $$\left(\sigma_0^{\rho} / \sigma_0^{\omega}\right)_{\mu\mu} = 1.1 \pm 0.1$$

(b) $$\left(\sigma_0^{\rho} + \sigma_0^{\omega}\right)_{\mu\mu} = \begin{cases} 22.1 \pm 1.2 \text{ mb for } 1+\cos^2\theta \\ 16.9 \pm 0.9 \text{ mb for uniform} \end{cases}$$

(c) $$\left(\frac{\sigma_0^{\eta}}{\sigma_0^{\rho} + \sigma_0^{\omega}}\right)_{\mu\mu} = \begin{cases} 0.43 \pm 0.04 \text{ for } 1+\cos^2\theta \\ 0.60 \pm 0.05 \text{ for uniform} \end{cases}$$

How do these results compare to previous measurements ?

NA27



NA27 measured the elementary η, ρ, ω and φ full phase space production cross-sections in pp @ 400 GeV
[Z. Phys. C50 (1991) 405]

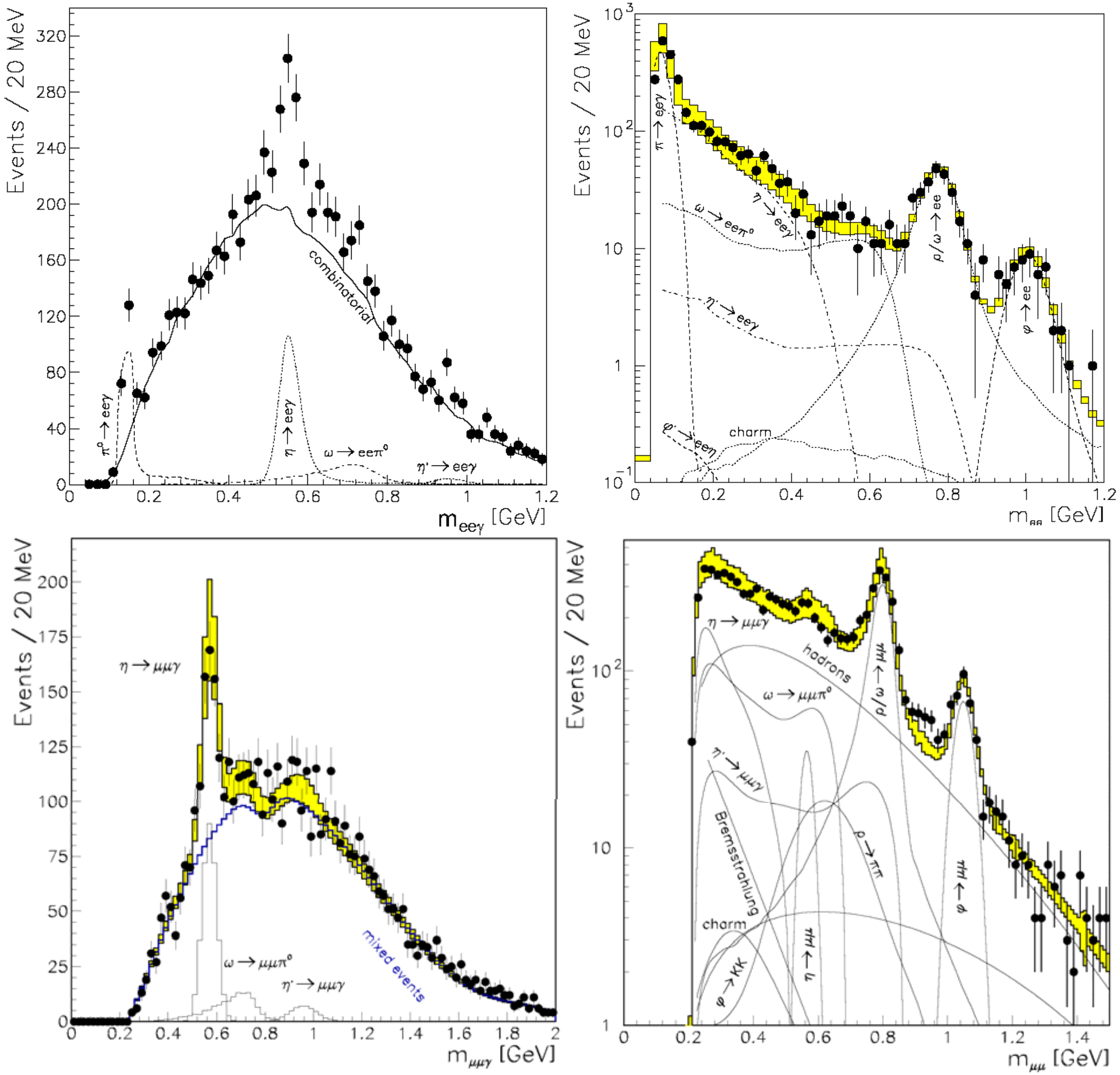
Phase space coverage: $x_F > 0$

HELIOS-1

fully reconstructed Dalitz modes — dilepton spectra

electrons

muons



- HELIOS-1 measured di-electron and dimuon spectra in p-Be @ 450 GeV
  [Z. Phys. C68 (1995) 47.]

- The η yield in the dilepton spectra was fixed from the independent $l^+l^-\gamma$ measurement

Comparison to NA60:

- similar phase space coverage:

  $+0.25 < y^* < +1.50$ e^+e^-

  $-0.25 < y^* < +1.25$ $\mu^+\mu^-$

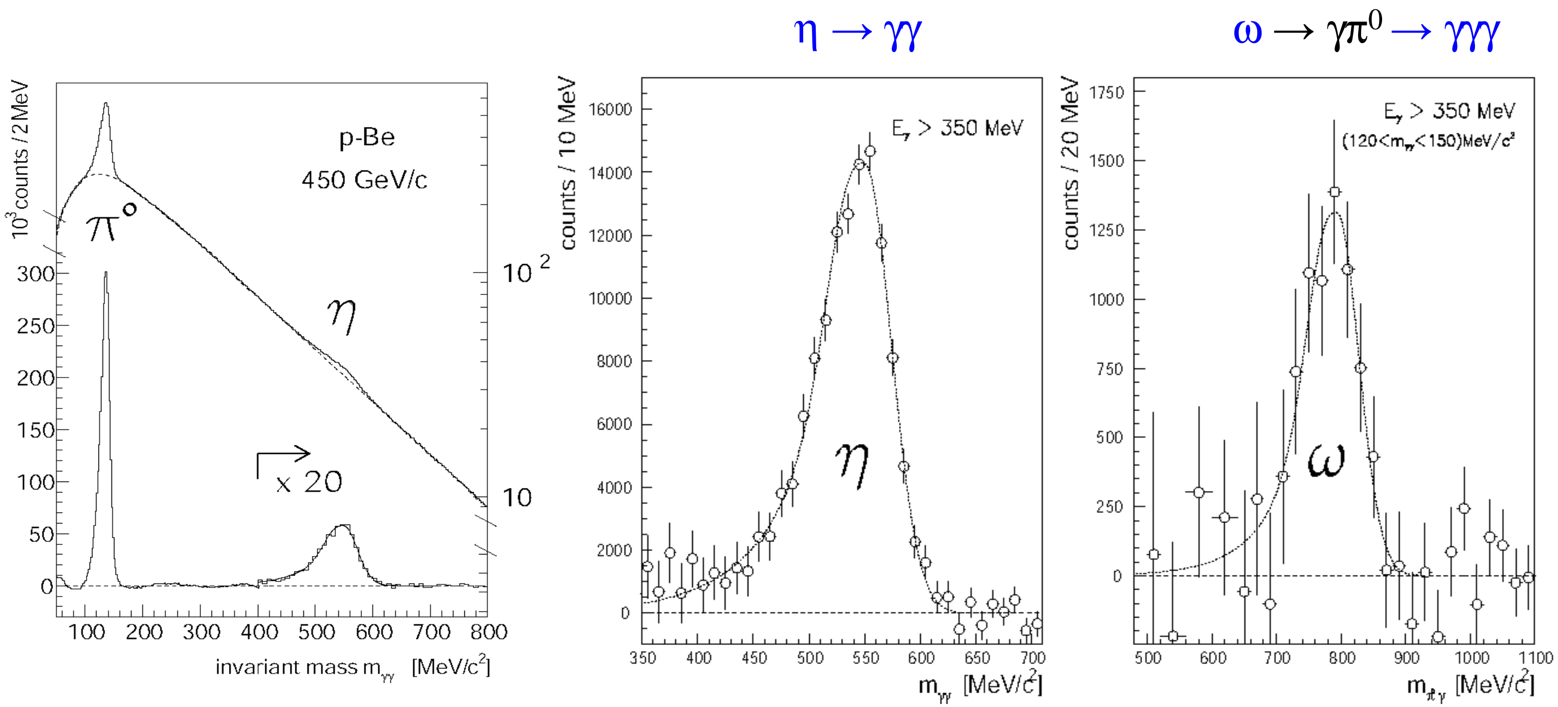
  $-0.75 < \cos\theta < 0.75$

  $m_T > 0.25$ GeV e^+e^-

  $m_T > 0.4$ GeV $\mu^+\mu^-$

- same mass resolution
- higher background

CERES-TAPS



- CERES-TAPS measured η and ω production in p-Be and p-Au collisions @ 450 GeV [Eur. Phys. J. C4(1998) 249].
- Phase space coverage: $3.1 < y < 3.7$
- Published particle ratios (no absolute cross-sections) in their phase space window.

Absolute cross-sections: ($\sigma_0^\rho+\sigma_0^\omega$), σ_0^η and σ_0^ϕ

To compare our ρ and ω cross-sections with measurements done in independent decay channels, we must take into account the interference effect in our data (→ overlapping mass; measurement in the same decay channel). HELIOS-1 found in their analysis a negative interference effect, giving a total $\sigma^{\rho/\omega}$ 15% smaller than their sum, measured in independent channels, $\sigma^\rho+\sigma^\omega$.

	NA27
σ_0^η [mb]	9.8±0.6
σ_0^ρ [mb]	12.6±0.6
σ_0^ω [mb]	12.8±0.8
σ_0^ϕ [mb]	0.62±0.06

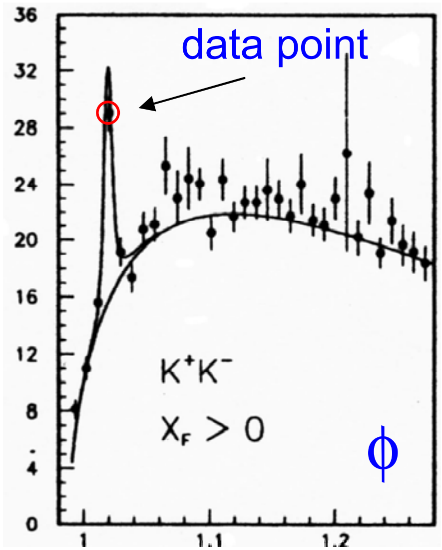
$\sigma_0^\rho+\sigma_0^\omega$ (NA27) = 25.4 ± 1.0 mb

NA60

	$1+\cos^2\theta$	uniform
σ_0^η [mb]	9.5±0.6	10.2±0.6
$\sigma_0^\rho+\sigma_0^\omega$ [mb]	25.4±1.3	19.4±1.0
σ_0^ϕ [mb]	0.53±0.05	0.40±0.03

- The cross-sections $\sigma_0^\rho+\sigma_0^\omega$ measured by NA27 and NA60 agree perfectly if the $1+\cos^2\theta$ decay angle distribution is used for NA60's extrapolation to 4π.
- The η cross-sections of NA27 and NA60 also agree very well with $1+\cos^2\theta$.
- The ϕ cross-section measured by NA60 is lower than NA27's, but maybe the NA27 value is slightly overestimated.

- The comparisons of absolute cross-sections indicate that the $1+\cos^2\theta$ decay angle distribution is the more appropriate one.



The $\eta/(\rho+\omega)$ cross-section ratio in p-nucleon collisions

In order to compare apples with apples:

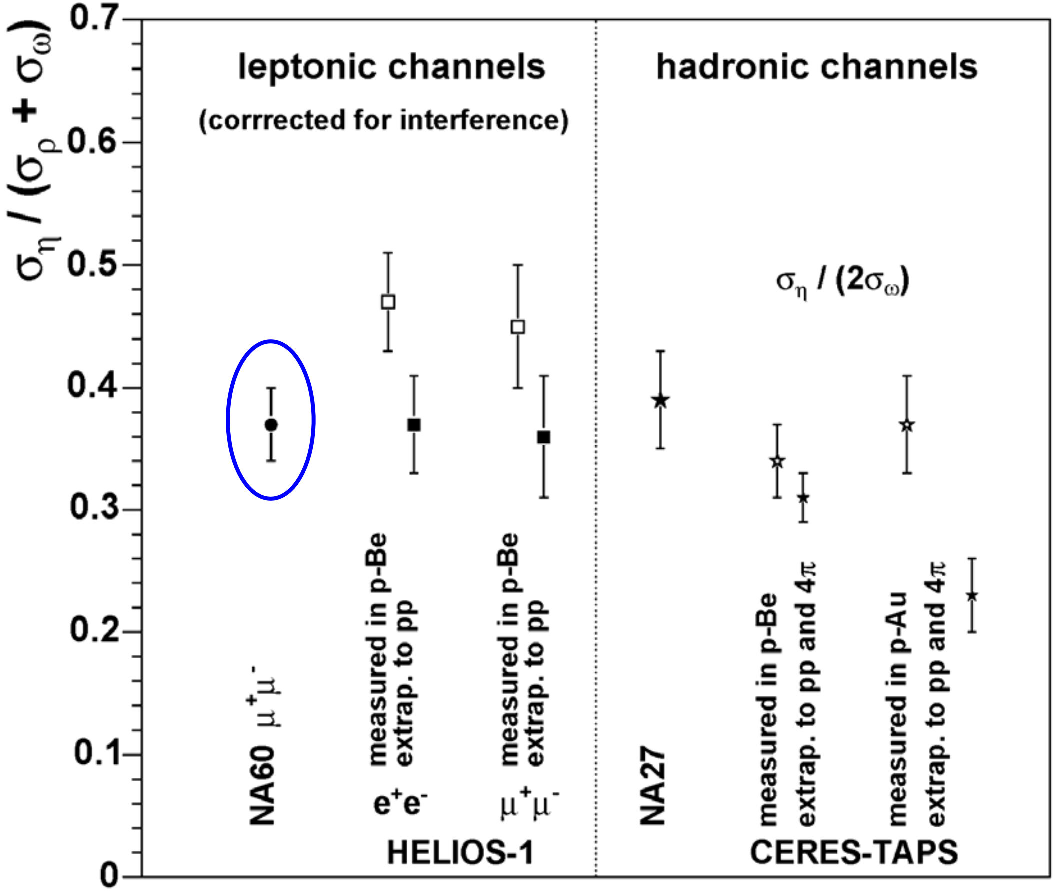
1. Correct the measurements in leptonic decay channels (HELIOS-1 and NA60) for the ρ/ω interference, and use the results obtained with $1+\cos^2\theta$.

2. Extrapolate the HELIOS-1 and CERES-TAPS measurements to elementary p-nucleon collisions (using our α^η and $\alpha^\rho = \alpha^\omega$).

3. Extrapolate the CERES-TAPS measurement to full phase space.

Note: CERES-TAPS assumed $\sigma^\rho=\sigma^\omega$ for the calculation of $\eta/(\rho+\omega)$.

→ The NA60 value agrees with these previous measurements.



The open (closed) symbols show the measurements before (after) extrapolating to 4π and p-nucleon collisions

Summary and Outlook

- Although the proton 2002 run had limited statistics, we achieved
  - a good mass resolution (~30 MeV at 1 GeV)
  - a good signal-to-background ratio
- This performance allowed us to
  - clearly separate the ω and ϕ peaks and
  - estimate the ρ normalisation independently of the ω
- Having 3 target materials with very different mass numbers, we extracted the nuclear dependence of the production cross-sections for the η, ω and ϕ mesons.

- The extracted elementary proton-nucleon 4π cross-sections for the η, ρ, ω and ϕ mesons are in good agreement with existing measurements (NA27, HELIOS-1 and CERES)

- The observed faster scaling of the η and ϕ mesons with respect to the ω should be taken into account when interpreting the heavy-ion data.

Outlook:

NA60 is currently collecting a large data sample with a proton beam at 400 GeV incident on 7 nuclear targets (Be, Al, Cu, In, W, Pb, U) to collect further reference data.