Vector meson measurements through dielectron: planned experiment at J-PARC

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- Introduction
- Results of KEK-PS E325 experiment
  - observation of vector meson mass modification in nuclei
- J-PARC Hadron experimental facility
- Future: J-PARC E16 experiment
  - systematic study of mass modification of phi meson
Mass and chiral symmetry in nuclear matter

- Origin of hadron mass: spontaneous breaking of chiral symmetry
- In hot/dense matter, chiral symmetry is expected to be restored
  - hadron modification is also expected
  - many theoretical predictions, related CS restoration (or not); meson mass decreasing, width broadening, and so on.

W. Weise, NPA553(93)59
linear dependence on density

\[ m^*/m_0 \sim (\langle \bar{q}q \rangle^*/\langle \bar{q}q \rangle)^{1/2} \]

mass 'dropping'
- 16(±6)% for \( \rho/\omega \)
- 0.15(±0.05)*\( \phi \)
  =2~4% for \( \phi \)
  for \( y=0.22 \)

at the normal nuclear density

Bronwn-Rho scaling
PRL 66(91)2720, etc

\[ \frac{m^*_\rho}{m_\rho} \sim \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \]

effective Lagrangian (chiral SU(3)+VMD)
Klinge,Kaiser,Weise,
NPA 624(97)527

QCD sum rule
Hatsuda and Lee, PRC 46(92)R34, PRC 52(95)3364

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Klingle,Kaiser,Weise,
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Hatsuda and Lee, PRC 46(92)R34, PRC 52(95)3364

Hatsuda and Lee, PRC 46(92)R34, PRC 52(95)3364
dispersion (mass VS momentum) in dense matter

- S.H.Lee (PRC57(98)927)
  - $m^*/m_0 = 1 - k \rho/\rho_0$
  - $\rho/\omega : k = 0.16 \pm 0.06 + (0.023 \pm 0.007)(p/0.5)^2$
  - $\phi : k = 0.15(\pm 0.05)y$
    - $(0.0005 \pm 0.0002)(p/0.5)^2$
  - for $p<1$GeV/c

- Harada & Sasaki (PRC80(09)054912)

- Post & Mosel (NPA699(02)169)

- Kondratyuk et al. (PRC58(98)1078)
**Experiment KEK-PS E325**

- $12\text{GeV} \ p+A \to \rho/\omega/\phi \ +X \ (\ \rho/\omega/\phi \to e^+e^-, \ \phi \to K^+K^-)$

- Experimental key issues:
  - Very **thin target** to suppress the conversion electron background (typ. 0.1% interaction/0.2% radiation length of C)
  - To compensate the thin target, **high intensity** proton beam to collect high statistics (typ. $10^9\ \text{ppp} \to 10^6\text{Hz interaction}$)
  - Large acceptance spectrometer to detect **slowly moving** mesons, which have larger probability decaying inside nuclei ($1<\beta\gamma<3$)

**Collaboration**

History of E325

- 1993 proposed
- 1994 R&D start
- 1996 construction start
- '97 data taking start
- '98 first ee data
  - PRL86(01)5019 $\rho/\omega$ (ee)
- 99,00,01,02....
  - x100 statistics
  - PRL96(06)092301 $\rho/\omega$ (ee)
  - PRC74(06)025201 $\alpha$ (ee)
  - PRL98(07)042501 $\phi$ (ee)
  - PRL98(07)152302 $\phi$ (KK),$\alpha$
- '02 completed
- spectrometer paper
  - NIM A457(01)581
  - NIM A516(04)390
E325 Results (1)

$e^+ e^- \text{ invariant mass spectra}$

M. Naruki et al.,
PRL 96 (2006) 092301
R.Muto et al.,
PRL 98 (2007) 042501
measured kinematic distribution of $\omega/\phi \rightarrow e^+e^-$

- $0 < P_T < 1, \ 0.5 < y < 2 \quad (y_{CM}=1.66)$

- $1 < \beta \gamma (=p/m) < 3 \quad (0.8<p<2.4\text{GeV/c for } \omega, \ 1<p<3 \text{ GeV/c for } \phi)$
**Expected Invariant mass spectra in $e^+e^-$**

- smaller FSI in $e^+e^-$ decay channel
- double peak (or tail-like) structure:
  - second peak is made by inside-nucleus decay (modified meson): amount depend on the nuclear size and meson velocity
  - could be enhanced for slower mesons & larger nuclei

**longer-life meson($\omega$ & $\phi$)cases : Schematic picture**

- outside decay (natural)
- inside decay (modified)
- expected to be observed
E325 observed the meson modifications

- in the $e^+e^-$ channel

- below the $\omega$ and $\phi$, statistically significant excesses over the known hadronic sources including experimental effects
Fitting results ( $\rho/\omega$ )

- 1) excess at the low-mass side of $\omega$
  - To reproduce the data by the fitting, we have to exclude the excess region: 0.60-0.76 GeV

- 2) $\rho$ meson component seems to be vanished. ($\rho/\omega = 1.0 \pm 0.2$ in a former experiment)
$e^+e^-$ spectra of $\phi$ meson (divided by $\beta\gamma$)

$\beta\gamma<1.25$ (Slow)  \quad 1.25<\beta\gamma<1.75  \quad 1.75<\beta\gamma$ (Fast)
e^+e^- spectra of φ meson (divided by βγ)

- βγ<1.25 (Slow)
- 1.25<βγ<1.75
- 1.75<βγ (Fast)

Only slow/Cu is not reproduced in 99% C.L.
**Discussion : modification parameters**

- MC type model analysis to include the nuclear size/meson velocity effects
  - generation point: uniform for $\phi$ meson
  - from the measured $A$-dependence
  - measured momentum distribution
  - Woods-Saxon density distribution
  - decay in-flight: linearly dependent on the density of the decay point
    - dropping mass: $M(\rho)/M(0) = 1 - k_1 (\rho/\rho_0)$
    - width broadening: $\Gamma(\rho)/\Gamma(0) = 1 + k_2 (\rho/\rho_0)$
  - consistent result with the predictions by Hatsuda & Lee ($k_1$), Oset & Lamos ($\Gamma$)

\[
\begin{align*}
  k_1 &= 0.034^{+0.006}_{-0.007} \\
  k_2^{\text{tot}} &= 2.6^{+1.8}_{-1.2}
\end{align*}
\]

For $\phi$, 3.4% mass reduction (35MeV) 3.6 times width broadening (15MeV) at $\rho_0$
**Discussion** ($\rho/\omega$)

Free param.: - scales of background and hadron components for each C & Cu
- modification parameter $k$ for $\rho$ and $\omega$ is common to C & Cu

From the fit: $k=0.092 \pm 0.002$ : ~ 9% reduced at normal nuclear density

$\rho/\omega$ production ratio: $0.7 \pm 0.1$ (C), $0.9 \pm 0.2$ (Cu): ... $\rho$ meson returns.

Note: if $k_\omega$ is assumed to be 0 (i.e. not modified), $k_\rho$ could be smaller.
E325 Results (2)

KK invariant mass / branching ratio

F. Sakuma et al., PRL98(2007)152302
tendency of KK branch enhancement

Production Cross sections

T.Tabaru et al., PRC74(2006)025201
nuclear dependence of CS :
\( \alpha_\omega = 0.710 \pm 0.021(\text{stat.}) \pm 0.037(\text{syst.}) \)
\( \alpha_\phi = 0.937 \pm 0.049(\text{stat.}) \pm 0.018(\text{syst.}) \)
measured production CS by E325

- values for the CM backward
- consistent w/ the former measurement for ρ meson by Blobel (PLB48(1974)73)
- Nuclear dependence $\alpha_\phi = 0.937$ corresponds to about $\sigma_{\phi N} = 3.7 \text{mb}$ (Sibirtsev et.al. EPJA 37(2008)287)

  - additional $\Gamma = 12 \text{ MeV}$ for 2 GeV/c $\phi$ ($\beta = 0.9$) : consistent with $\Gamma = 15^{+8}_{-5} \text{ MeV}$ (i.e. $k^2 = 2.6^{+1.8}_{-1.2}$)
- Remark:
  $\Gamma_\phi = 15 \text{MeV}$ at $m_\phi = 985 \text{MeV}$ is consistent with Oset & Ramos (NPA679(2001)616)
Summary (1)

- E325 observed mass modification of vector mesons in nuclear matter
  - in $\rho/\omega \rightarrow e^+e^-$
    - in the $e^+e^-$ channel, $\rho$ and $\omega$ cannot be distinguished
  - in $\phi \rightarrow e^+e^-$
    - only one histogram has significance
  - in $\phi \rightarrow K^+K^-$, there is a hint in the branching ratio, but not significant

- Next step in the invariant-mass approach
  - $\phi \rightarrow e^+e^-$: less uncertain than the $\rho/\omega$ case
    - $\rho$'s broad and complicated shape, $\rho-\omega$ interference, $\rho/\omega$ ratio, etc.
  - systematic study of the mass modification
    - matter-size dependence: larger/smaller nuclei, impact parameter
    - momentum dependence: never measured
  - check the interpretation models
**J-PARC E16 experiment**

Systematic study of the modification of vector meson spectra in nuclei to approach the chiral symmetry restoration

**Collaboration**
- RIKEN: S.Yokkaichi, H. En'yo, F. Sakuma, K. Aoki, J. Kanaya
- U-Tokyo: K. Ozawa, K. Utsunomiya, Y.S. Watanabe, Y.Komatsu, S.Masumoto

**Proposal**

Scientific approval : 2007/3
... Detector R&D is on going (already supported)
... production is dependent on budget status
... beamline is also : budget requested by KEK/J-PARC
Goal of construction : 2012/autumn
Collect high statistics for the systematic study

- For the statistics 100 times as large as E325, **new spectrometer is required.**
  - To cover larger acceptance: \( x \sim 5 \)
  - Higher energy beam (12 → 30/50 GeV): \( x \sim 2 \) of production
  - Higher intensity beam (\( 10^9 \rightarrow 10^{10} /\text{spill (1sec)} \)): \( x \times 10 \) (→ ~10MHz interaction on targets)

**Proposed Spectrometer**
J-PARC : Japan Proton Accelerator Research Complex

- High Intensity Proton accelerator (3GeV and 50GeV rings) -> secondary beams
  - material & life science using neutron and muon beams
  - nuclear and hadronic physics using pion, kaon anti-proton and primary proton beams
  - neutrino beam to Kamioka
- At Tokai village, 2 hours from Tokyo by train and taxi
Hadron experimental facility in J-PARC

- 50GeV Main Ring (MR) is operated in 30GeV, first acceleration in 2008/12
- first slow extraction to Hadron experimental facility in 2009/1
  - first physics experiment (E19: penta quark search), using 1.9GeV/c pion beam, is planned in 2010/10
Location of E16: High-momentum beam line

SM1: branched by 5°
Vertical Bend
3.9°
5.8° x3

Experimental Area
beam dump

Beam dump and shields are for $10^{10}$ protons/s

by R. Muto
Already the spectrometer magnet has been moved to Hadron Hall.

Budget being requested.

R&D for the actual beam line is underway.

by R. Muto
Proposed spectrometer

- Spectrometer Magnet: reuse E325's
  - remodeling the pole / repairing the coil
  - stronger field for compact detector size
- GEM (Gas electron multiplier) Tracker
  - cope with high rate (5kHz/mm²)
- Two-stage Electron ID (∼10⁻⁴ π rejection)
  - Hadron Blind Detector (Gas Cherenkov)
    - GEM+CsI photocathode
    - hexagonal pad readout (∼36mm φ)
  - Leadglass EMC: reuse of TOPAZ
- ∼70K Readout Channels (in 26 segments)
  - cf. E325: 3.6K, PHENIX: ∼300K (w/o VTX)
- Cost: ∼$5M (including ∼$2M electronics)
  - cf. E325: $2M not including electronics
**Detector R&D**

Beam test results of the Prototype Detector Module

**GEM Chamber:**
required position resolution (\(\sim 100 \mu m\)) is achieved

**Hadron Blind Detector:**
UV Cherenkov photons from the electron beam are detected by CsI-GEM in CF4

**GEM & GEM chamber schematics**

**HBD (Hadron Blind Gas Cherenkov Detector) schematics**
Achievement in beam tests

• GEM Tracker
  – GEM(PI 50um) by Raytech.Co.
    • 100mmx100mm, 200mm x 200mm, 300mm x300mm
  – R/O double sided strip PCB (PI 25um) by Raytech.Co
  – position resolution (using ArCO2/350um pitch strip) for angled tracks
    • 100um (for 0deg/15deg) – 140um(30deg) in 100mm x 100mm GEM
    • larger GEMs have enough gain, resolution will be checked in next beam test( 2010/Nov. )

• HBD
  – developed thanks to Weizmann/Stony Brook
  – GEM(LCP 100um: higher gain) by Scienergy.Co.
  – CsI evaporaiton by Hamamatsu
  – 5-6 photoelectrons detected (cf. PHENIX ~20 p.e.)
    • gas purity and CsI q.eff. should be improved
Expected signals in E16 high statistics
velocity and nuclear size dependence

- velocity dependence of excesses ('modified' component)
- E325 only one data point for $\phi$ (slow/Cu) has significant excess
**Velocity and Nuclear Size Dependence**

- Velocity dependence of excesses ('modified' component)
- E325 only one data point for $\phi$ (slow/Cu) has significant excess
- Systematic study: all the data should be explained by the interpretation model

- Establish the modification
**velocity and nuclear size dependence**

- velocity dependence of excesses ('modified' component)
- E325 only one data point for $\phi$ (slow/Cu) has significant excess
- systematic study: all the data should be explained the interpretation model

- establish the modification
- check the interpretation model with shape analysis for each histogram
dispersion relation (mass VS momentum)

- prediction for $\phi$ by S.H.Lee ($p<1\text{GeV}/c$)
- current E325 analysis neglects the dispersion (limited by the statistics)
dispersion relation (mass VS momentum)

- prediction for $\phi$ by S.H. Lee ($p<1\text{GeV/c}$)
- current E325 analysis neglects the dispersion (limited by the statistics)

\[ \phi \text{ mass (1020)} \]
\[ \Delta M \approx 35\text{MeV} \]
dispersion relation (mass VS momentum)

- prediction for $\phi$ by S.H.Lee ($p<1\text{GeV/c}$)
- current E325 analysis neglects the dispersion (limited by the statistics)
- fit with common shift parameter $k_1(p)$, to all nuclear targets in each momentum bin
dispersion relation (mass VS momentum)

- prediction for $\phi$ by S.H.Lee($p<1\text{GeV/c}$)
- current E325 analysis neglects the dispersion (limited by the statistics)
- fit with common shift parameter $k_1(p)$, to all nuclear targets in each momentum bin
mass resolution requirement

- mass resolution should be kept less than \( \sim 10\text{MeV} \)

Fast

\[
\sigma = 11\text{MeV} \quad \sigma = 5\text{MeV} \quad \sigma = 20\text{MeV}
\]

\[\beta_y > 3\]

Slow

\[\beta_y < 1.5\]

(model calc. for the Cu target)
mass resolution requirement

- mass resolution should be kept less than ~10MeV
- Very ideal case: very slow mesons w/ best mass resolution:

\[
\phi(1020) \\
\text{Cu } \beta\gamma < 1.25
\]

\[
\beta\gamma < 0.5, \sigma = 5 \text{ MeV}
\]
50GeV is necessary for charmonium @E16

- charmonium mass is governed by the gluon condensate
  - small modification is expected for J/ψ
    - even narrow width (no in-medium decays)
  - width broadening (~10MeV) for χc, ψ(2s) and mass decreasing (~10-100MeV)

- very rough estimation w/ the production CS ratio

<table>
<thead>
<tr>
<th></th>
<th>φ</th>
<th>J/ψ</th>
<th>ratio</th>
<th>ψ (3686)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pp</td>
<td>70ub</td>
<td>0.01ub</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pCu</td>
<td>1mb</td>
<td>5mb</td>
<td>0.5ub</td>
<td>1/10000</td>
</tr>
<tr>
<td>ee branch</td>
<td>0.03%</td>
<td>6%</td>
<td>200</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

- *1 : JAM & empirical formula, from 12GeV data
- *2 : nuclear dependence ~A, from pp
- 10¹⁰ ppp, 0.1% int. target
Summary(2) : J-PARC E16

- Main goal: collect $\sim 1-2 \times 10^5 \phi \rightarrow e^+e^-$ for each target in 5 weeks using 30 (or 50) GeV $p + A (C/CH_2/Cu/Pb)$ reactions

  - statistics: $\sim 100$ times as large as E325

  - systematic study of the modification
    - velocity & nuclear size (0~10 fm) dependence
      - proton/Pb targets / collision geometry (impact parameter)
    - momentum dependence (dispersion relation)
    - mass resolution: $< 10$ MeV (E325: 10.7 MeV for $\phi$)
      - double peak structure with $\sigma \sim 5$ MeV, selecting $\beta \gamma < 0.5$ (very slow)

- Confirm the modification observed in E325, and provide new information about the mass of hadrons
Backup slides...
meson bound state in nuclei

- $\omega$ bound state (P26 Ozawa)
  - missing mass spectroscopy in $\pi^- + A$ reaction – select the bound state
    - elementary: $\sim 2$ GeV/c $\pi^- + p \rightarrow \omega + n$
    - and measure the $\omega$ decay to $\pi^0 \gamma$
  - $P_\omega$ is low, and decay in nuclear matter

theoretical predictions of missing mass and invariant mass
Analysis: Fitting with known sources

- Hadronic sources of $e^+e^-$:
  - $\rho/\omega/\phi \rightarrow e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-$, $\eta \rightarrow \gamma e^+e^-$
  - relativistic Breit-Wigner shape (without any modifications, but internal radiative corrections are included)
  - Geant4 detector simulation
    - multiple scattering and energy loss of $e^+/e^-$ in the detector and the target materials
    - chamber resolutions
    - detector acceptance, etc.
- Combinatorial background: event mixing method
- Relative abundance of these components are determined by the fitting
experimental effects on the BW shape (E325)

- E325 Detector Sim.
  - target material is negligible for ~0.5% radiation length ($X_0$)
  - detectors : up to 4.5% $X_0$ in the tracking region

![Graphs showing experimental effects on BW shape with C and Cu targets.]

- $0.21\% \lambda_1$
- $0.43\% X_0$
- $0.054\% \lambda_1$
- $0.57\% X_0$
Experimental effects on the BW shape (E325)

- E325 Detector Sim.
  - target material is negligible for \( \sim 0.5\% \) radiation length \((X_0)\)
  - detectors: up to 4.5 % \(X_0\) in the tracking region

- In the case of the thick targets: \(1\text{g/cm}^2\)
  - bremsstrahlung in target is so large for the Cu case

\[
\begin{align*}
\text{C} & : 0.21\% \lambda_1, 0.43\% \lambda_0 \\
\text{Cu} & : 0.054\% \lambda_1, 0.57\% \lambda_0 \\
\text{C} & : 1.0\% \lambda_1, 1.9\% \lambda_0 \\
\text{Cu} & : 0.75\% \lambda_1, 8.0\% \lambda_0
\end{align*}
\]
To collect high statistics

- For the statistics 100 times as large as $E_{325}$, a new spectrometer is required.
  - To cover larger acceptance: $x \sim 5$
  - Higher energy beam ($12 \rightarrow 30/50$ GeV): $x \sim 2$ of production
  - Higher intensity beam ($10^9 \rightarrow 10^{10}$ /spill (1sec)): $x \times 10$ ($\rightarrow \sim 10$MHz interaction on targets)

**Target configuration**

<table>
<thead>
<tr>
<th>nuclei</th>
<th>interaction length(%)</th>
<th>radiation length(%)</th>
<th>thickness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.05</td>
<td>0.1</td>
<td>200</td>
</tr>
<tr>
<td>CH$_2$</td>
<td>0.05</td>
<td>0.1</td>
<td>400</td>
</tr>
<tr>
<td>Cu</td>
<td>0.05</td>
<td>0.5</td>
<td>80</td>
</tr>
<tr>
<td>Pb</td>
<td>0.01</td>
<td>0.3</td>
<td>20</td>
</tr>
</tbody>
</table>
**Expected Invariant mass spectra in e^+e^-**

- smaller FSI in e^+e^- decay channel
- double peak (or tail-like) structure:
  - second peak is made by inside-nucleus decay (modified meson): amount depend on the nuclear size and meson velocity
  - could be enhanced for slower mesons & larger nuclei

**shorter-life meson (ρ) case**

- outside decay (natural)
- inside decay (modified)

---

1) decay inside nuclei  
2) decay outside nuclei

---

expected to be observed
Experimental setup

- Spectrometer Magnet
  - 0.71T at the center
  - 0.81Tm in integral
- Targets
  - at the center of the Magnet
  - C & Cu are used typically
  - very thin: ~0.1% interaction length
- Primary proton beam
  - 12.9 GeV/c
  - ~1x10^9 in 2sec duration, 4sec cycle
Experimental setup

• Typical $e^+e^-$ Event
  - blue: electron
  - red: other
  - invariant mass and momentum of mother particle can be calculated

• Experimental condition
  - 1GHz proton beam, 1MHz interaction, 1K $\phi$ mesons, 0.3 $e^+e^-$ decays, 9% come into detector, 10% overall efficiency, ...
**K⁺K⁻ spectra of φ meson**

- mass modification is NOT statistically significant (very low statistics in βγ < 1.25 where modification is observed in φ → e⁺e⁻)
measured kinematic distribution
of $\phi \rightarrow K^+K^- \& \phi \rightarrow e^+e^-$

- $0.5 < y < 1.5$
- $1 < \beta \gamma < 3$
- $0.5 < P_T < 1.5$
- overlayed
  - $\phi \rightarrow K^+K^-$
  - $\phi \rightarrow e^+e^-$
mass modification and $\phi$ branching ratio

- small decay Q value ($= 32\text{MeV}$) for $\phi \rightarrow K^+K^-$
  - branching ratio is sensitive to $\phi$ and $K$ mass modification
    - when $\phi$ mass decrease : $\Gamma_{K^+K^-}$ decrease
    - when $K$ mass decrease : $\Gamma_{K^+K^-}$ increase
- change of the ratio : $\Gamma_{K^+K^-}/\Gamma_{e^+e^-}$ can be studied by measurement of parameter : the nuclear dependence of production cross section
  - measure both $\phi \rightarrow K^+K^- \& \phi \rightarrow e^+e^-$ simultaneously
  - $\Rightarrow$ NEXT
nuclear dependence $\alpha$ of the prod. CS of $\phi$ in $K^+K^-$ & $e^+e^-$ channel

- nuclear dependence $\alpha$:
  \[ \sigma(A) = \sigma_0 \times A^\alpha \]

- $\alpha$ and $\Gamma$ : for example
  - $\Gamma_{K^+K^-} / \Gamma_{e^+e^-}$ increases in nuclei, $N_{K^+K^-} / N_{e^+e^-}$ becomes larger
  - larger modification expected in larger nuclei
  - then, $\alpha_{K^+K^-} > \alpha_{e^+e^-}$, especially for slowly moving mesons

- ...looks such tendency but consistent within the errors
nuclear dependence $\alpha$ of the prod. CS of $\phi$ in $K^+K^-$ \& $e^+e^-$ channel

- nuclear dependence $\alpha$:
  - $\sigma(A) = \sigma_0 \times A^\alpha$

- $\alpha$ and $\Gamma$ : for example

- $\Gamma_{K^+K^-}/\Gamma_{e^+e^-}$ increases in nuclei, $N_{K^+K^-}/N_{e^+e^-}$ becomes larger

- larger modification expected in larger nuclei

- then, $\alpha_{K^+K^-} > \alpha_{e^+e^-}$, especially for slowly moving mesons

- ...looks such tendency of KK enhancement but consistent within the errors : $\alpha_{K^+K^-} - \alpha_{e^+e^-} = 0.14 \pm 0.12$

EM Probe @ECT* 2010Sep17 S.Yokkaichi
New nuclear targets with larger statistics

- Smaller nuclear target:
  - proton as reference ($\text{CH}_2 - \text{C}$ subtraction)
  - LH target cannot be used because of the materials

- Larger nuclear target as Pb
  - larger nuclear matter
  - collision geometry ("impact parameter") study using multiplicity (PRC60 024902 (18GeV p+A))
    - can be divided to at least two regions
    - another type of the matter size effect
  - larger radiation length for heavier target → more thinner foil target to keep S/N
    - high statistics capability is required.
Impact parameter cut

Cu

Pb

Pb central
\( \phi \rightarrow e^+e^- \) invariant mass spectra

- from 2001/02 run data
- C & Cu target
- acceptance uncorrected
- mass resolution : 10.7MeV
- fit with
  - simulated mass shape of \( \phi \)
  - polynomial curve background
**φ → e⁺e⁻ invariant mass spectra**

- from 2001/02 run data
- C & Cu target
- acceptance uncorrected
- mass resolution : 10.7MeV
- fit with
  - simulated mass shape of φ
    - (evaluated as same as ρ&ω)
  - polynomial curve background
- examine the 'excess' is significant or not.
  - → see the βγ dependence : excess could be enhanced for slowly moving mesons
Amount of excess

- To evaluate the amount of excess ($N_{\text{excess}}$), fit again excluding the excess region (0.95~1.01GeV) and integrate the excess area.
**Amount of excess**

- To evaluate the amount of excess ($N_{\text{excess}}$), fit again excluding the excess region ($0.95\sim1.01\text{GeV}$) and integrate the excess area.
Observed $e^+e^-$ invariant mass spectra

- from 2002 run data (~70% of total data)
- C & Cu target
- clear resonance peaks
- $m<0.2$ GeV is suppressed by detector acceptance
- acceptance uncorrected

→ fit the spectra with known sources
However, $\rho/\omega = 1.0 \pm 0.2$ in former experiment ($p+p$, 1974) suggests that the origin of excess is modified $\rho$ mesons.
**Discussion: fit with modification**

- Assumptions to include the nuclear size effect in the fitting shape
  - dropping mass: $M(\rho)/M(0) = 1 - k_1 \rho/\rho_0$
    (Hatsuda & Lee, $k=0.16 \pm 0.06$)
  - width broadening: $\Gamma(\rho)/\Gamma(0) = 1 + k_2 \rho/\rho_0$ (* Oset & Ramos *)
    (momentum dependence of modification is not taken into account this time)

<table>
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<th>$m^*/m$</th>
<th>$\rho$, $\omega$</th>
<th>$\phi$</th>
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<tbody>
<tr>
<td>$\Gamma^*/\Gamma$</td>
<td>$1 - k_1 \frac{\rho}{\omega} \rho/\rho_0$</td>
<td>$1 - k_1^\phi \rho/\rho_0$</td>
</tr>
<tr>
<td>generation point</td>
<td>surface</td>
<td>uniform</td>
</tr>
<tr>
<td>$\alpha (\sigma(A) \propto A^\alpha)$</td>
<td>$0.710 \pm 0.021$</td>
<td>$0.937 \pm 0.049$</td>
</tr>
</tbody>
</table>

- $[\text{PRC74}(06)025201]$
**Remark on the model fitting**

- **constraint at right side of peak**
  - Introducing the *width broadening* (x2 & x3) are rejected by this constraint
  - prediction of 'ρ mass increasing' is also not allowed.

- ρ (ω) decay inside nucleus: 46%(5%) for C, 61%(10%) for Cu
  - used spectrum is the sum of the modified and not-modified components.

- momentum dependence of mass shift is not included. (But typical p = 1.5GeV/c)
Fit using modified mass shapes

- MC type calc.: mesons are generated, filed and modified
  - observed momentum dist.
  - uniformly made in nuclei
    - measured $\alpha$ of $\phi$ production $\sim 1$
    - $m^*/m_0 = 1 - k_1 \rho/\rho_0$
      ($k_1 = 0.04$, Hatsuda & Lee, '92,'96)
    - To reproduce such amount of excess, linear-dependent width broadening is adopted:
      $\Gamma_{tot}^*/\Gamma_{tot}^0 = 1 + k_2 \rho/\rho_0$
    - $e^+e^-$ branching ratio is not changed
      - $\Gamma_{e^+e^-}/\Gamma_{tot}^0 = \Gamma_{e^+e^-}/\Gamma_{tot}^0$
      - fits were done with many combinations of $(k_1, k_2)$
Fit using modified mass shapes

- MC type calc.: mesons are generated, flown and modified
  - observed momentum dist.
  - uniformly made in nuclei
    • measured $\alpha$ of $\phi$ production ~ 1
    - $m^*/m_0 = 1 - k_1 \rho/\rho_0$
      ($k_1=0.04$, Hatsuda & Lee, '92,'96)
    - To reproduce such amount of excess, linear-dependent width broadening is adopted:
      $\Gamma_{tot}^*/\Gamma_{tot}^0 = 1 + k_2 \rho/\rho_0$
      • $e^+e^-$ branching ratio is not changed
        - $\Gamma_{e^+e^-}/\Gamma_{tot} = \Gamma_{e^+e^-}^0/\Gamma_{tot}^0$
    - fits were done with many combinations of $(k_1, k_2)$

$\beta\gamma<1.25$ (Slow) $k_1=0.04, k_2=2$

$\chi^2/ndf=69/50$
Model fitting: parameter $k_1$ and $k_2$

- To determine the shift parameters...
  - $m^*/m_0 = 1 - k_1 \rho/\rho_0$
  - $\Gamma_{\text{tot}}^*/\Gamma_{\text{tot}}^0 = 1 + k_2 \rho/\rho_0$

- We fit the observed 6 mass spectra (C/Cu, slow/mid/fast) with modified MC shapes and calculate the $\chi^2$ as the sum of 6 spectra

$$\begin{align*}
(k_1 = 0.04, k_2 = 2, \chi^2 = 316)
\end{align*}$$
Model fitting: parameter $k_1$ and $k_2$

- To determine the shift parameters...
  
  \[ \frac{m^*}{m_0} = 1 - k_1 \frac{\rho}{\rho_0} \]
  \[ \frac{\Gamma_{\text{tot}}^*}{\Gamma_{\text{tot}}^0} = 1 + k_2 \frac{\rho}{\rho_0} \]

- We fit the observed 6 mass spectra (C/Cu, slow/mid/fast) with modified MC shapes and calculate the $\chi^2$ as the sum of 6 spectra for each $(k_1, k_2)$ combination on the grid and make the $\chi^2$ contour.

**Best Fit Value:**

\[
\begin{align*}
  k_1 &= 0.034^{+0.006}_{-0.007} \\
  m^* &= 985\text{MeV} \\
  k_2^{\text{tot}} &= 2.6^{+1.8}_{-1.2} \\
  \Gamma_{\text{tot}}^* &= 15\text{MeV} \\
  (3.6 \text{ times width broadening at } \rho_0) \\
\end{align*}
\]