Coherent ω-Meson Photoproduction off Deuterium from CLAS

Submitted to PLB, arXiv:1802.06746

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CLAS COLLABORATION MEETING 2018

09 March, 2017

Department of physics + astronomy OHIO UNIVERSITY

Outline

- Physics Motivation
- Vector Meson Dominance
- Differential Cross Section
- Results
- Summary and Outlook

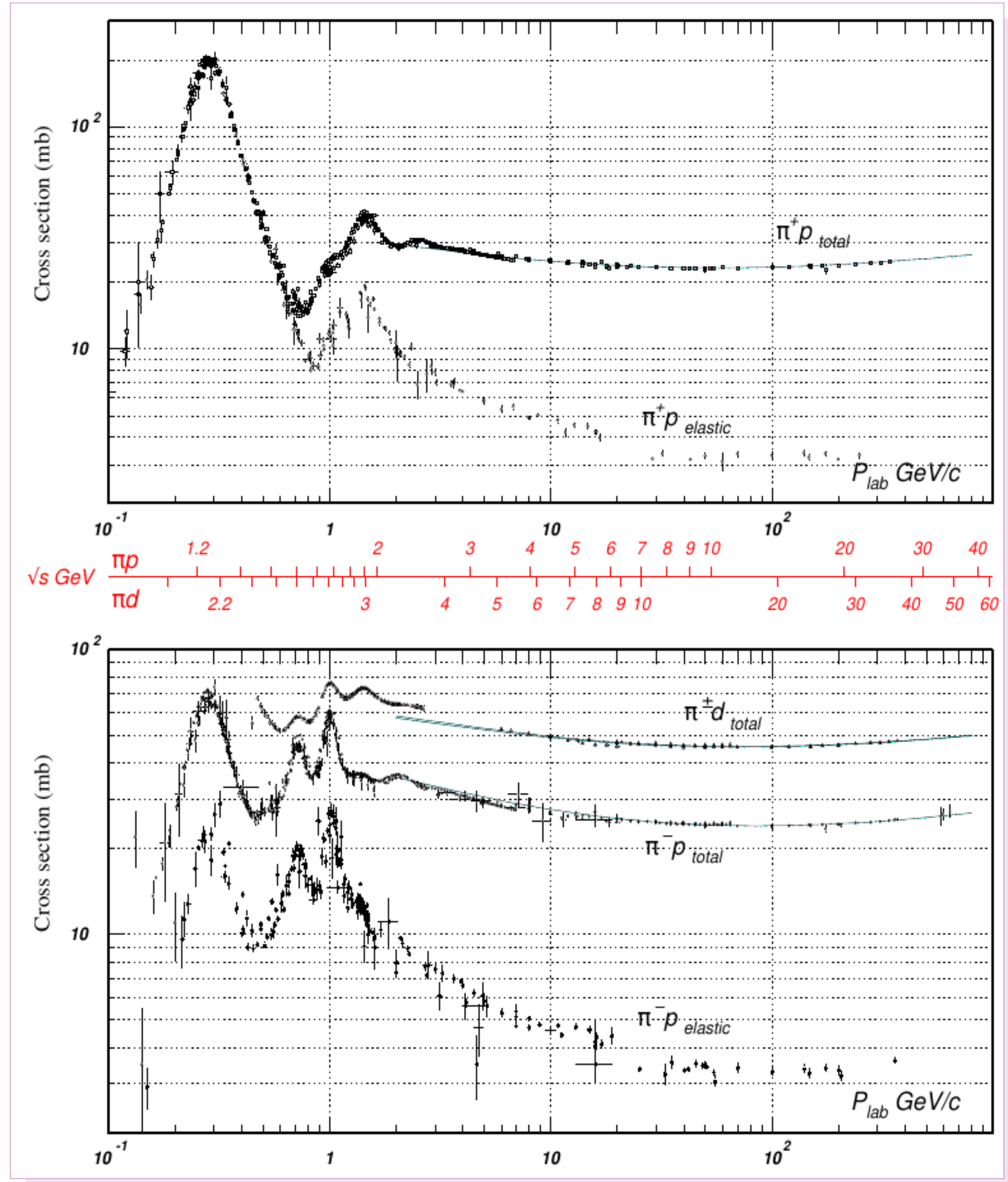
Goal

- π-**N** scattering provides access to fundamental questions
  - Baryonic spectrum of QCD.
  - Chiral dynamics of QCD.
  - Study of isospin violation.
  - Internal structure of the nucleon.

- Just imagine the possibilities with other mesons, say a vector meson!

- Experimental Challenge:
  - Short mean lifetimes ~10^{23} s
  - Vector meson beams cannot be produced in a lab.

- Extract ω-**N** cross section!
  - LQCD
  - Physics models



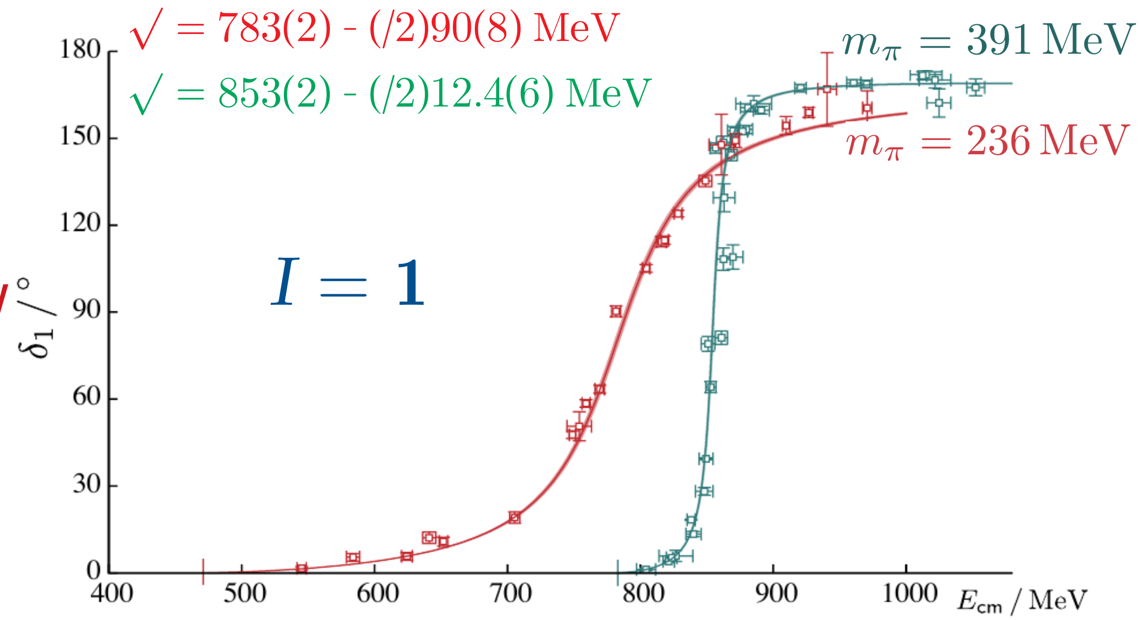
C. Patrignani et al. (Particle Data Group)
Chin. Phys. C, 40, 100001 (2016) and 2017 update

Scattering on the Lattice

- Lattice QCD
  - ➢ $\pi\pi$ scattering (ρ resonance)
- Meson-baryon scattering is now a possibility.
- ω is a good choice!!

  → Pions are heavy on the lattice.
- Jianwei pointed out the progress made by The Hadron Spectrum Collaboration on Wednesday's Plenary talk.

Elastic P-wave $\pi\pi$ phase shifts



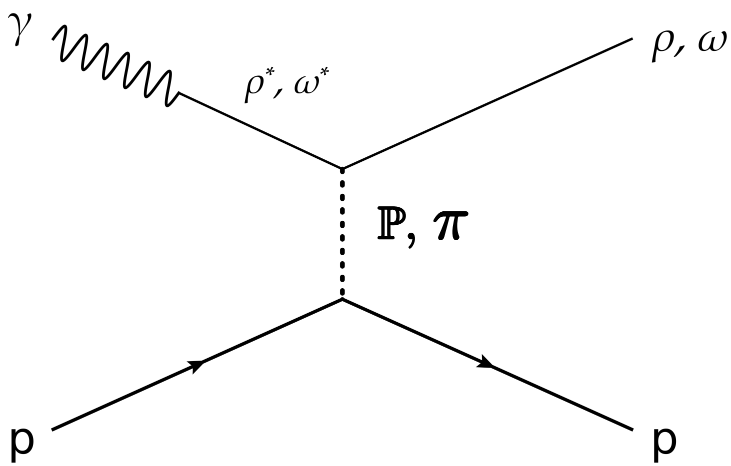
Breit-Wigner: $$t(s) = \frac{1}{\rho(s)} \frac{\sqrt{s}\Gamma(s)}{m_R^2 - s - i\sqrt{s}\Gamma(s)}$$

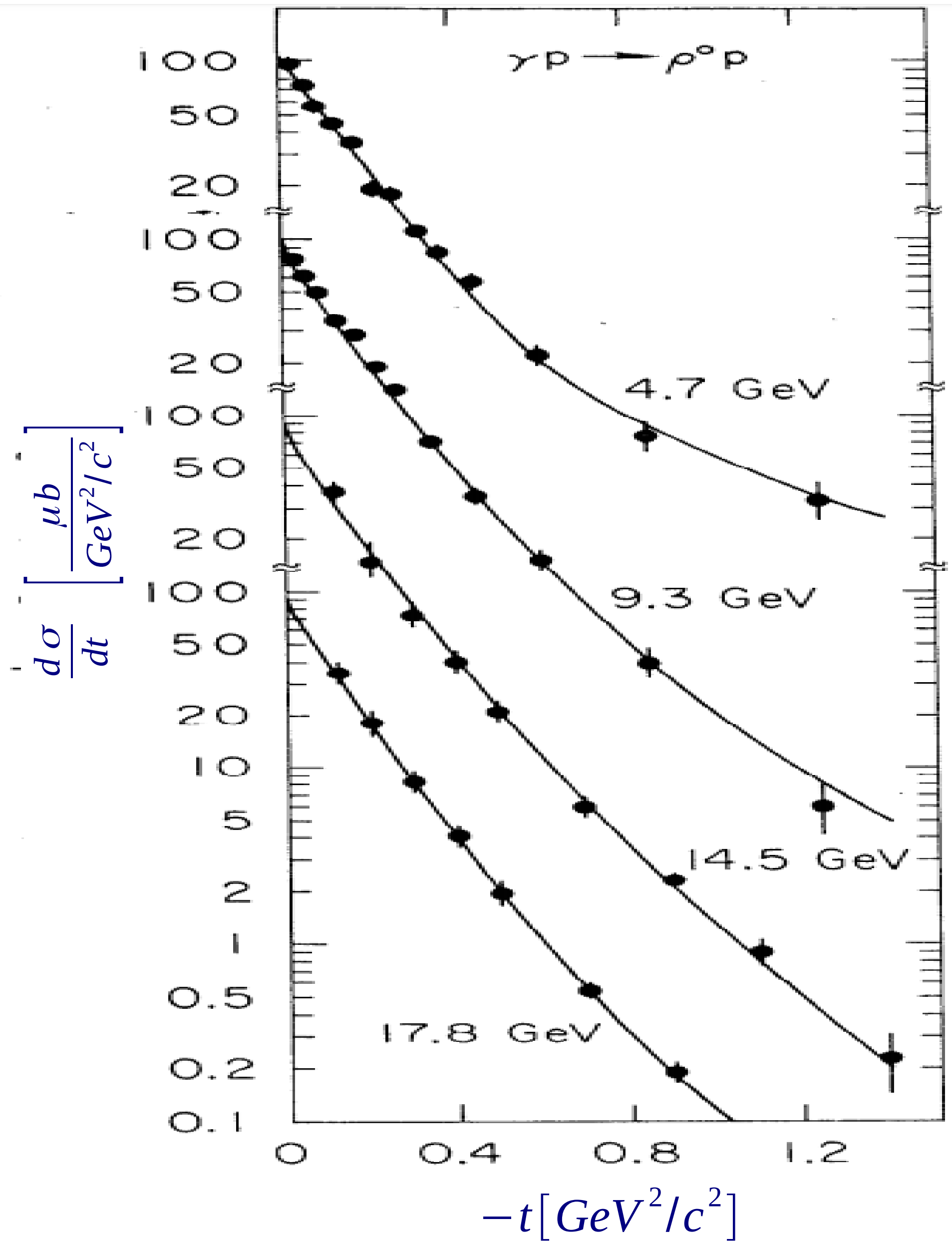
Energy dependent width: $$\Gamma(s) = \frac{g_R^2}{6\pi}\frac{k^3}{s}$$

Parameters: $$m_R = 0.13171(36)(6) \cdot a_t^{-1} \quad g_R = 5.691(70)(25) \quad \begin{bmatrix} 1 & 0.04 \\ & 1 \end{bmatrix}$$

D.J. Wilson, R.A. Briceño, J.J. Dudek, R.G. Edwards, C.E. Thomas
The Hadron Spectrum Collaboration
Phys. Rev. D 92, 094502 (2015)

Vector Meson Dominance (VMD)





Phenomenologically:

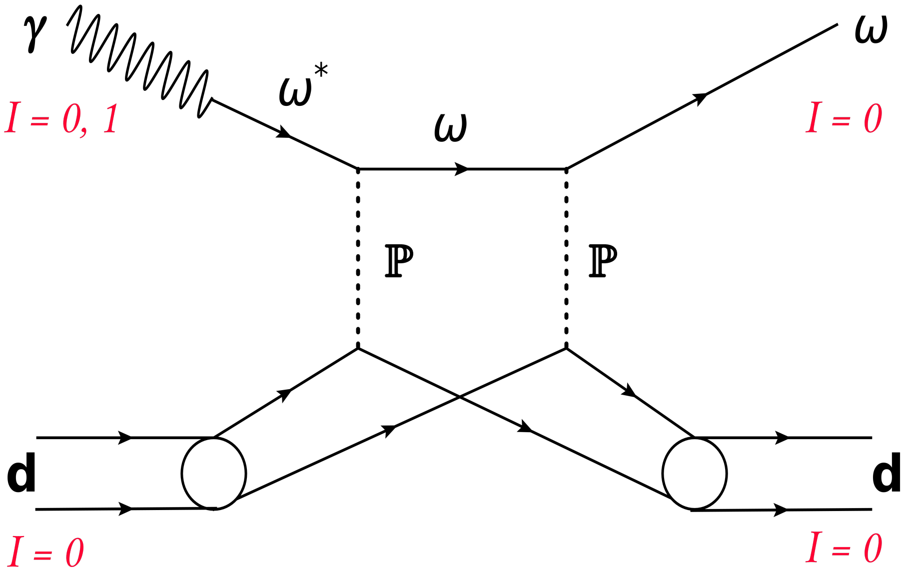
$$\frac{d\sigma}{dt} \propto e^{-bt}$$

b is the slope parameter

$$t = (P_{\gamma} - P_{\rho,\omega})^2$$

D. W. G. S. Leith, "High Energy Photoproduction: Diffractive Processes"
SLAC-PUB-1978

Vector Meson Dominance (VMD)



- Two processes:
  - $\gamma N \rightarrow \omega N$
  - $\omega N \rightarrow \omega N$
- Slope parameters:
  - $b_{\gamma N}$ and $b_{\omega N}$
- Ratio of Re(A) and Im(A):
  - $\alpha_{\gamma N}$ and $\alpha_{\omega N}$

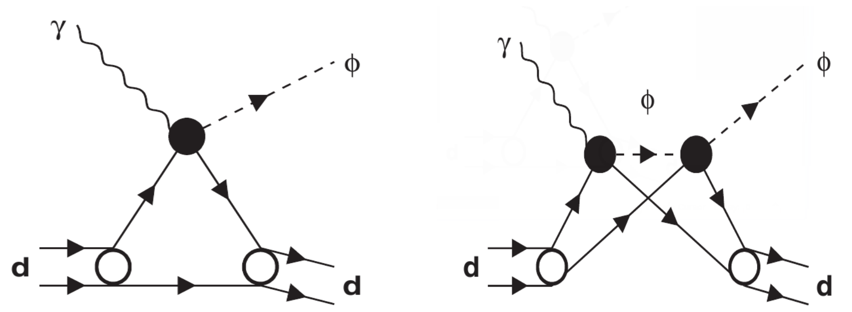
- Proton → $I = \mathbf{0}, \mathbf{1}$
- Deuteron acts as an Isospin filter for $I = \mathbf{0}$ only.
- Vector Meson off deuterium simplifies theoretical interpretations of the data.

Vector Mesons off deuteron in CLAS

$\gamma\, d \rightarrow \omega\, d$

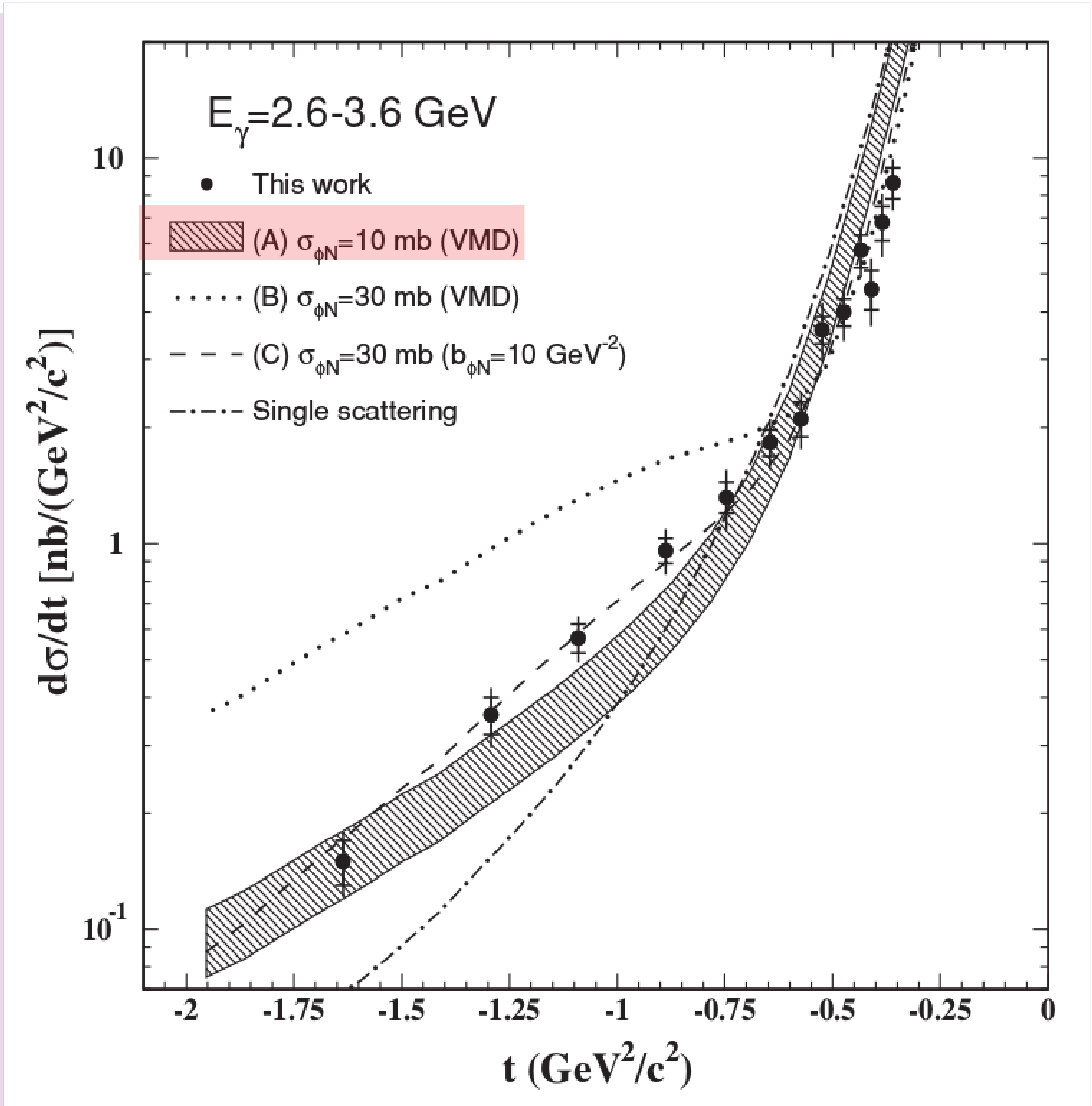
Single scattering

Double scattering



Highlights:

- *g*10 data
- A rescattering model is used.
- Within VMD, data is consistent with $\sigma_{\phi N}$ at about 10 mb.
- In the model, larger $\sigma_{\phi N}$ is possible by taking $b_{\gamma N} > b_{\phi N}$



T. Mibe *et al.*
CLAS Collaboration
Phys. Rev. C 76, 052202(R) (2007)

Previous Results: $\gamma\, d \rightarrow \omega\, d$

Limited World Data

- Mostly from Bubble Chamber experiments.
- Missing double scattering effect.

Experiment	Energy	Target	Measured quantities	$\|T_0^N\|^2$ (μb/GeV^2)	$\sigma_{\omega N}$ (mb)	$\hat{f}_\omega^2/4\pi$	Assumptions	Comments
SLAC–Berkeley Ballam *et al.* (1973)	9.3	H	$\left.\frac{d\sigma}{dt}\right\|_\omega$	11.4 ± 2.1	···	25.3 ± 4.7	$\sigma_{\omega N}=27$ mb $\alpha_\omega=-0.24$ $\left.\frac{d\sigma}{dt}\right\|_{t=0}=\|T_0^N\|^2$	No correction for A_2 exchange
Rochester Abramson *et al.* (1976)	8.3	D, Be, C, Al Cu, Pb	$\left.\frac{d\sigma}{dt}\right\|_{t=0}$	7.4 ± 0.5	25.4 ± 2.7	30.4 ± 4.8	$\alpha_{\omega N}=-0.24$	Corrected for A_2 exchange
Tel Aviv Alexander *et al.* (1975)	7.5	D	$\left.\frac{d\sigma}{dt}\right\|_\omega$	11.2 ± 2.5		25.7 ± 6.5	$\sigma_{\omega N}=27$ $\alpha_\omega=-0.24$	
Tel Aviv Alexander *et al.* (1975)	7.5	D	$\left.\frac{d\sigma}{dt}\right\|_{\rho,\omega}$ $\left.\frac{d\sigma}{dt}\right\|_\rho \Big/ \left.\frac{d\sigma}{dt}\right\|_\omega = 7.1^{+2.0}_{-1.2}$	···	···	$15.5^{+7.0}_{-2.8}$	$\hat{f}_\omega^2/\hat{f}_\rho^2=\left.\frac{d\sigma}{dt}\right\|_\rho \Big/ \left.\frac{d\sigma}{dt}\right\|_\omega$ $\hat{f}_\rho^2/4\pi=2.18$	The rho cross section was anomalously low
Pisa–Bonn Braccini *et al.* (1970)	5.7	C, Al, Zn, Ta, Ag, Pb	Smeared cross section	13.5 ± 3.3	$27.0^{+6.0}_{-5.5}$	22.0 ± 5.4	$\alpha_{\omega N}=-0.3$	Poor t resolution and uncertainties in background correction

T. H. Bauer, R. D. Spital, D. R. Yennie, and F. M. Pipkin
Rev. Mod. Phys. 50, 261(1978)

Previous Results: $\gamma\, d \to \omega\, d$

Limited World Data

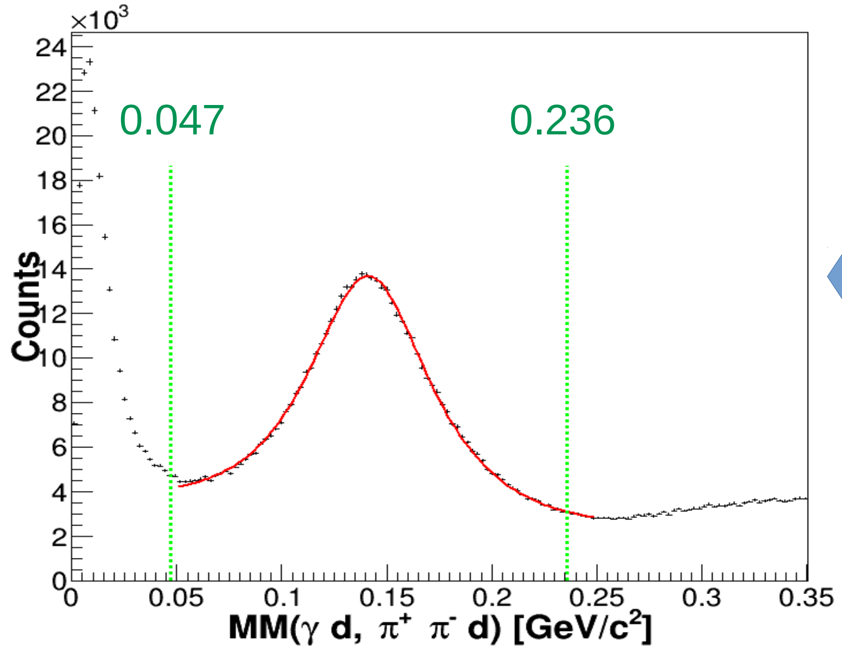
- Best data till date is from the Weizman Institute of Science

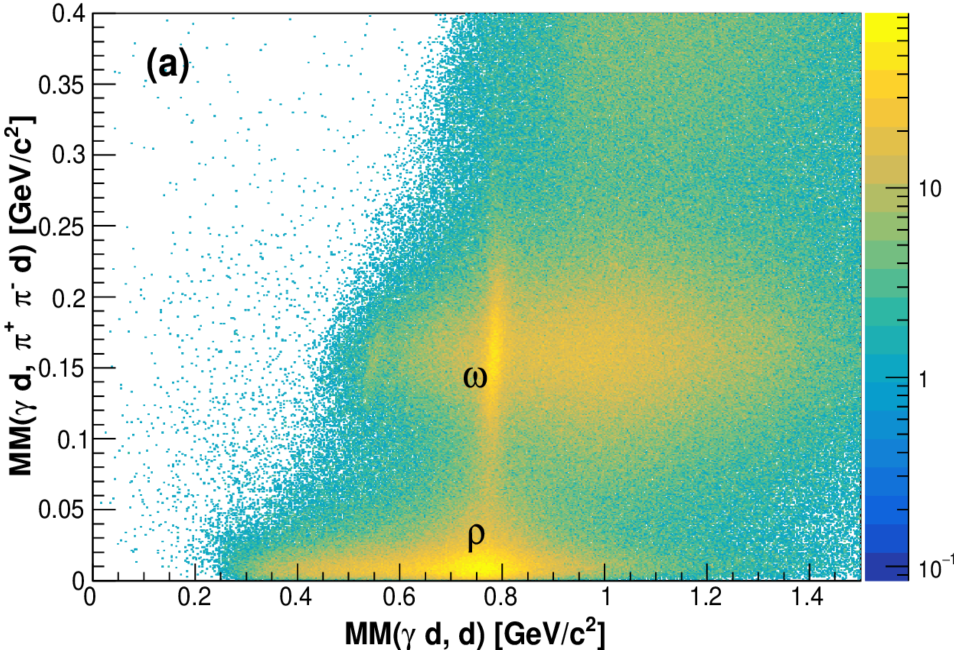
$E_\gamma = 4.3$ GeV and $|t| < 0.2$ GeV$^2/c^2$

Experiment	Energy	Target	Measured quantities	$\lvert T_0^N\rvert^2$ (μb/GeV^2)	$\sigma_{\omega N}$ (mb)	$\hat{f}_\omega^2/4\pi$	Assumptions	Comments
Weizmann Eisenberg *et al.* (1976)	4.3	D	$\left.\frac{d\sigma}{dt}\right\rvert_\omega$	18.5 ± 4.5	$\cdots$	15.6 ± 3.8	$\sigma_{\omega N} = 27$ mb $\alpha_{\omega N} = -0.24$	
Weizmann Eisenberg *et al.* (1976)	4.3	D	$\left.\frac{d\sigma}{dt}\right\rvert_\rho$ $\left.\frac{d\sigma}{dt}\right\rvert_\rho \Big/ \left.\frac{d\sigma}{dt}\right\rvert_\omega = 6.7^{+2.1}_{-1.3}$	$\cdots$	$\cdots$	$14.6^{+4.9}_{-3.0}$	$\hat{f}_\omega^2/\hat{f}_\rho^2 = \left.\frac{d\sigma}{dt}\right\rvert_\rho \Big/ \left.\frac{d\sigma}{dt}\right\rvert_\omega$ $\hat{f}_\rho^2/4\pi = 2.18$	
Harvard–CEA Gladding *et al.* (1973)	4.2	H	$\left.\frac{d\sigma}{dt}\right\rvert_{\rho,\omega}$ $\left.\frac{d\sigma}{dt}\right\rvert_\rho \Big/ \left.\frac{d\sigma}{dt}\right\rvert_\omega = 7.7 \pm 0.12$			16.8 ± 2.8	$\hat{f}_\omega^2/\hat{f}_\rho^2 = \left.\frac{d\sigma}{dt}\right\rvert_\rho \Big/ \left.\frac{d\sigma}{dt}\right\rvert_\omega$ $\hat{f}_\rho^2/4\pi = 2.18$	No correction for OPE or A_2 exchange
ABHHM Benz *et al.* (1974)	1.3–5.3	D	$\sigma_{\rho,\omega}$ $\frac{\sigma(\rho)}{\sigma(\omega)} = 7.2^{+2.7}_{-1.6}$			$15.7^{+6.2}_{-3.7}$	$\hat{f}_\omega^2/\hat{f}_\rho^2 = \frac{\sigma(\gamma d \to \rho d)}{\sigma(\gamma d \to \omega d)}$ $\hat{f}_\rho^2/4\pi = 2.18$	
Lancaster Morris *et al.* (1976)	3.9	D	$\left.\frac{d\sigma}{dt}\right\rvert_{\rho,\omega}$	14.5 ± 5.4		15.3 ± 6.4	$\hat{f}_\omega^2/\hat{f}_\rho^2 = \frac{\sigma(\gamma d \to \rho d)}{\sigma(\gamma d \to \omega d)}$ $\hat{f}_\rho^2/4\pi = 2.18$	Poor-resolution experiment
Colliding beams						18.4 ± 1.8		

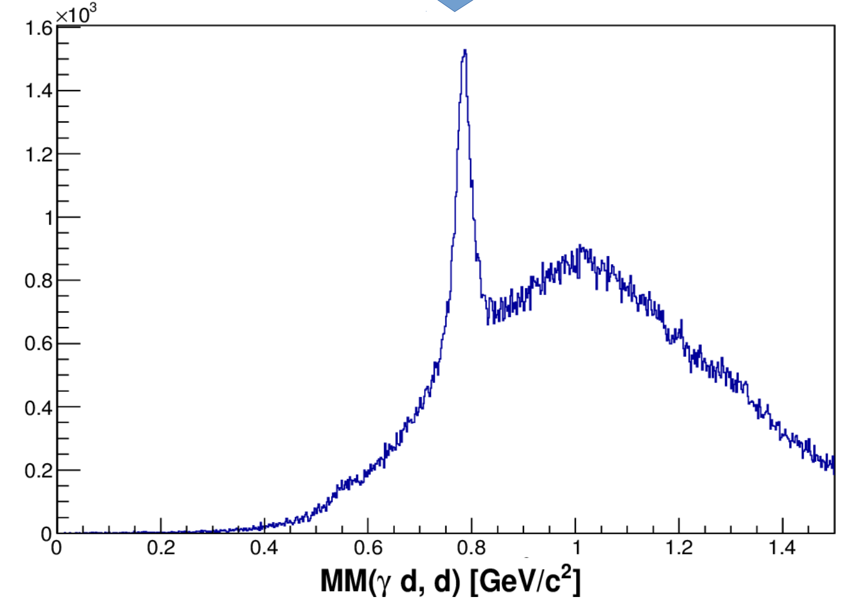
T. H. Bauer, R. D. Spital, D. R. Yennie, and F. M. Pipkin
Rev. Mod. Phys. 50, 261(1978)

Global Spectrum: $\gamma\, d \rightarrow \omega\, d$ ($g10$ dataset)

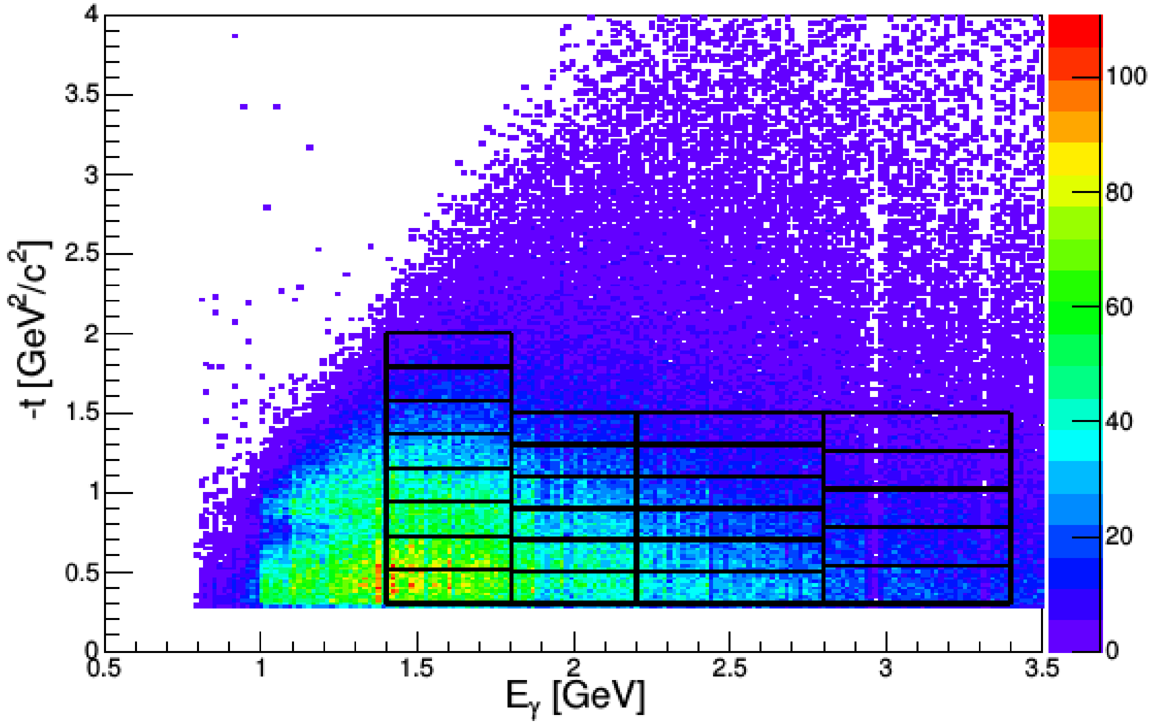




- Basic cuts to reduce background:
  - z-vertex cut
  - Fiducial cut
  - Minimum Momentum cut, etc.
- Corrections applied:
  - Momentum corrections
  - Energy loss corrections
- Signal over smooth background.



Binning

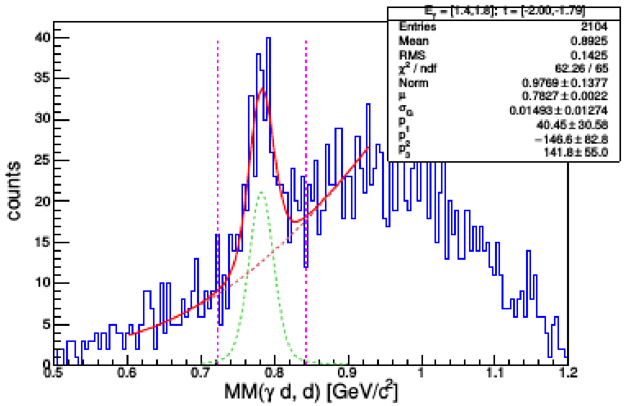


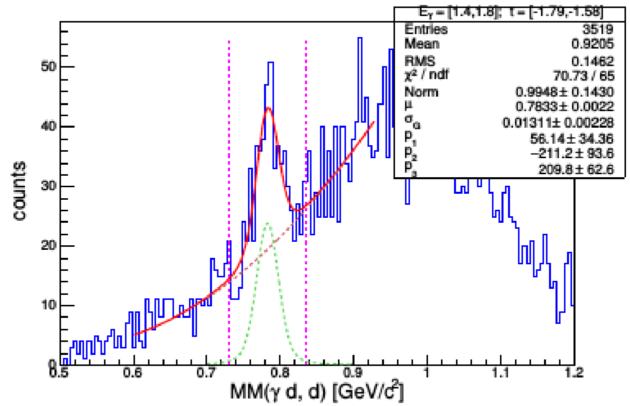
E_γ [GeV]	t-bins	$-t_{min}$ [GeV^2/c^2]	$-t_{max}$ [GeV^2/c^2]
1.4-1.8	8	2.0	0.3
1.8-2.2	6	1.5	0.3
2.2-2.8	6	1.5	0.3
2.8-3.4	5	1.5	0.3

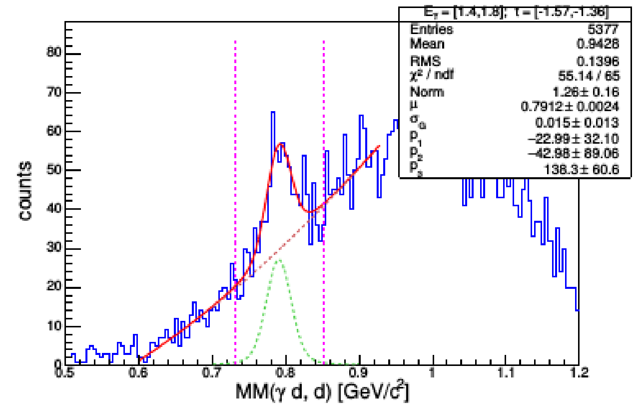
4 incident photon energy and variable 4-momentum transfer bins.

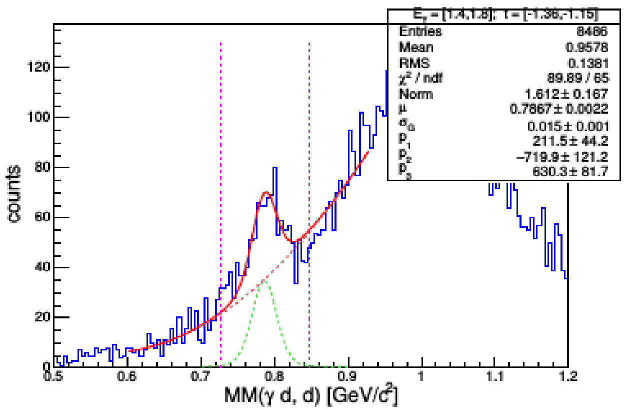
Yield Extraction

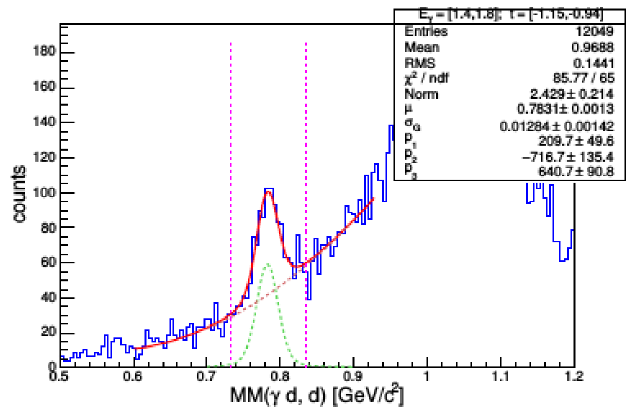
E = [1.4, 1.8] GeV

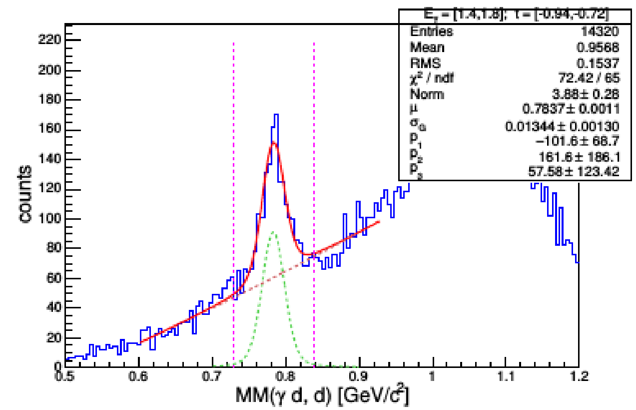




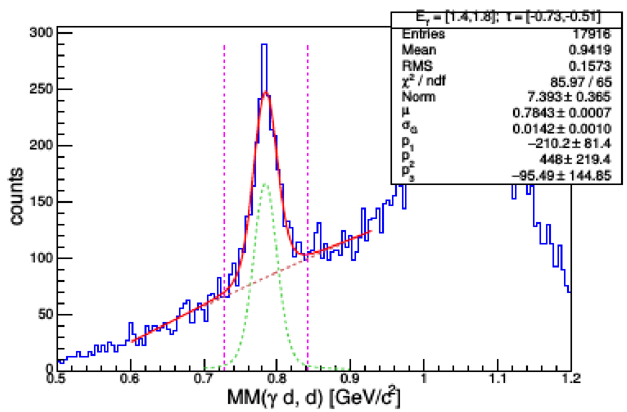


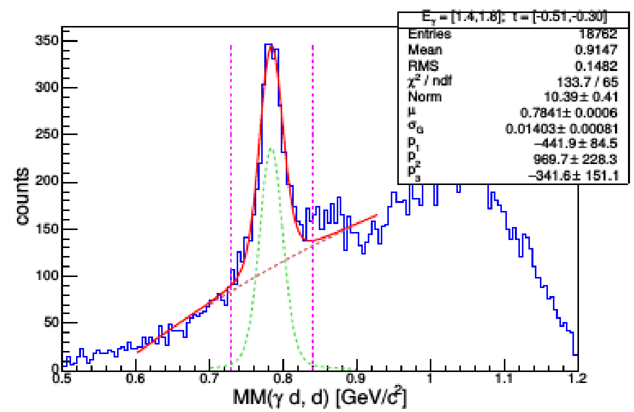






Yield is extracted by taking integral of the Voigt function





Fit Functions

Voigt

Pol2

Differential Cross section: $\gamma\, d \to \omega\, d$

$$\frac{d\sigma}{dt} = \frac{Y_D}{\Delta t A \mathscr{L}} \times \frac{\Gamma_\omega}{\Gamma_{\omega\to\pi^+\pi^-\pi^0}} \times \gamma_{corr}$$

A = Acceptance

Δt = Width of t-bin

Y_D = Signal Yield

γ_{corr} = Photon Multiplicity Correction factor

Luminosity,

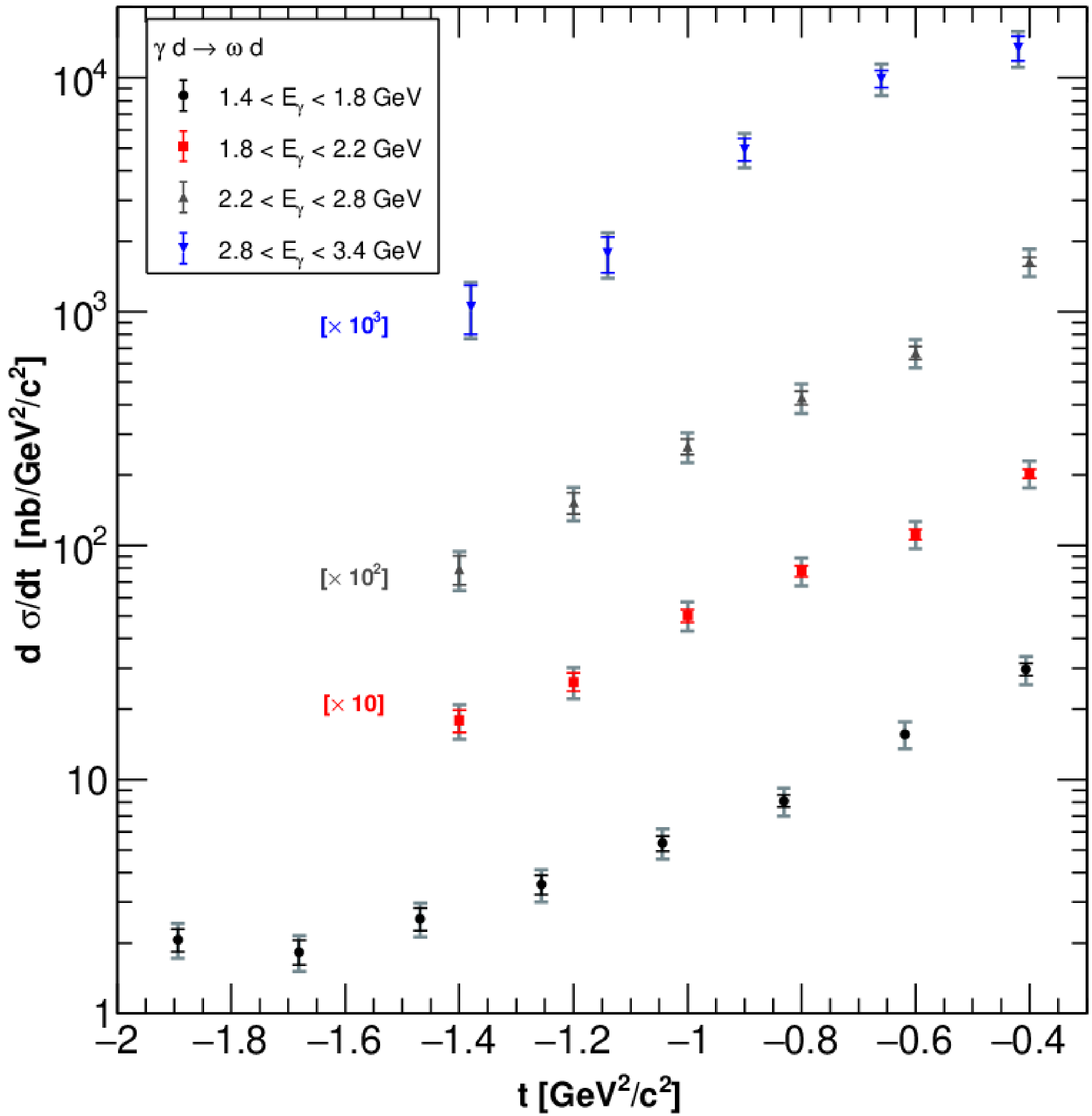
$$\mathscr{L}(E_\gamma) = \frac{\rho_T N_A l_T}{M_d} N_\gamma(E_\gamma)$$

$\rho_d = 0.169\, g cm^{-3}$

$l_d = 24\, cm$

$M_d = 2.014\, g\, mole^{-1}$

$N_\gamma(E_\gamma) =$ *Photon Flux*



Model Based on VMD: $\gamma\, d \rightarrow \omega\, d$

$$f^{\gamma N \to \omega N} = \sigma_{\gamma^* \omega}(i + \alpha_{\gamma N}) e^{\frac{-b_{\gamma N}}{2} t}$$

b → *p*: $b_{\gamma N}$ = *d*: $b_{\omega N}$

σ → *p*: $d\sigma/dt|_{t=0;\gamma N}$; *d*: $\sigma_{\omega N}$

$\alpha = \frac{Re(A)}{Im(A)}$ → *p*: $\alpha_{\gamma N}$; *d*: $\alpha_{\omega N}$

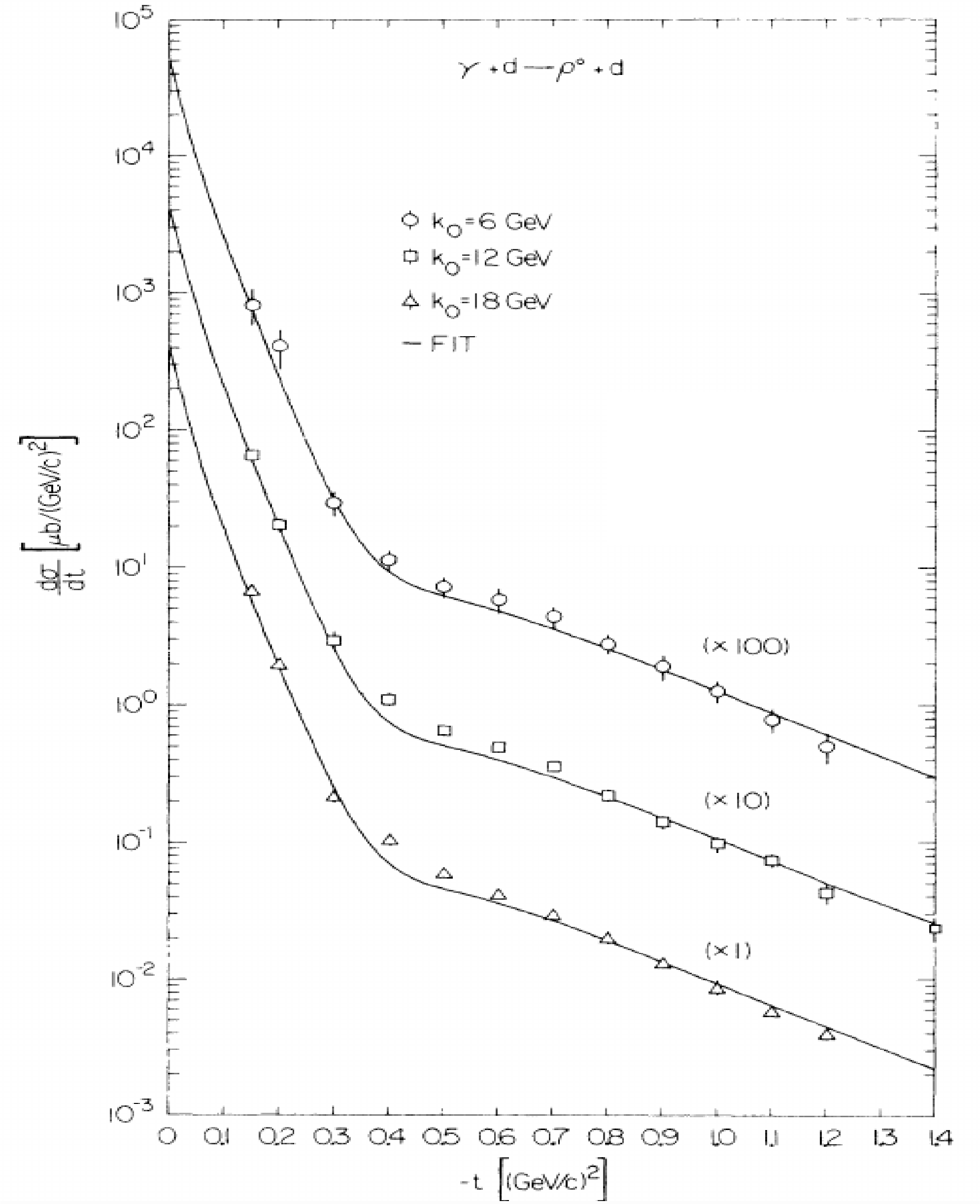
Calculation based on VMD
(provided by M. Sargsian, FIU)*

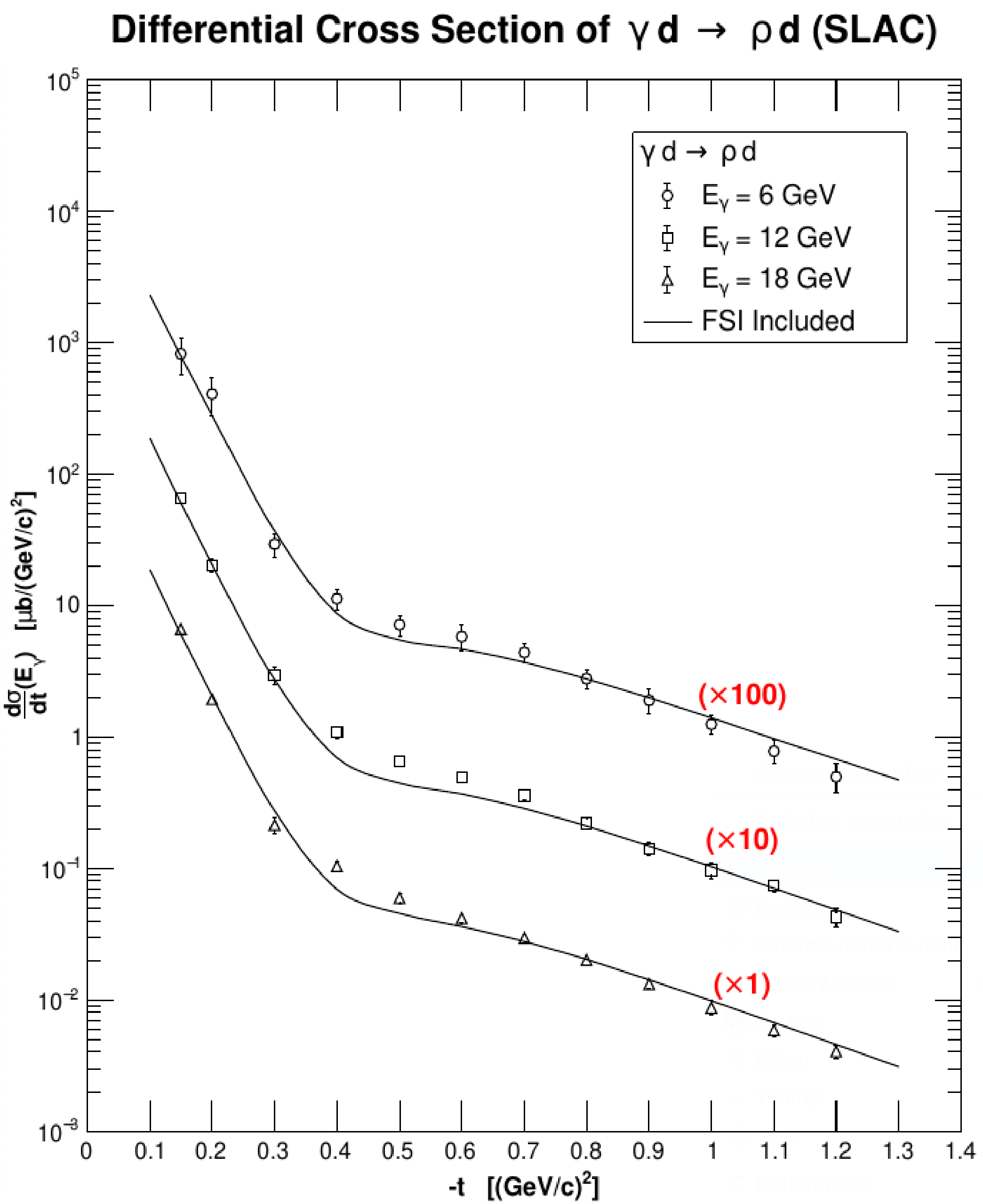
$\frac{d\sigma}{dt}$

Comparison with Data → $\sigma_{\omega N}$

* **Frankfurt et al**, Nucl.Phys. A622 (1997) 511-537

SLAC Data

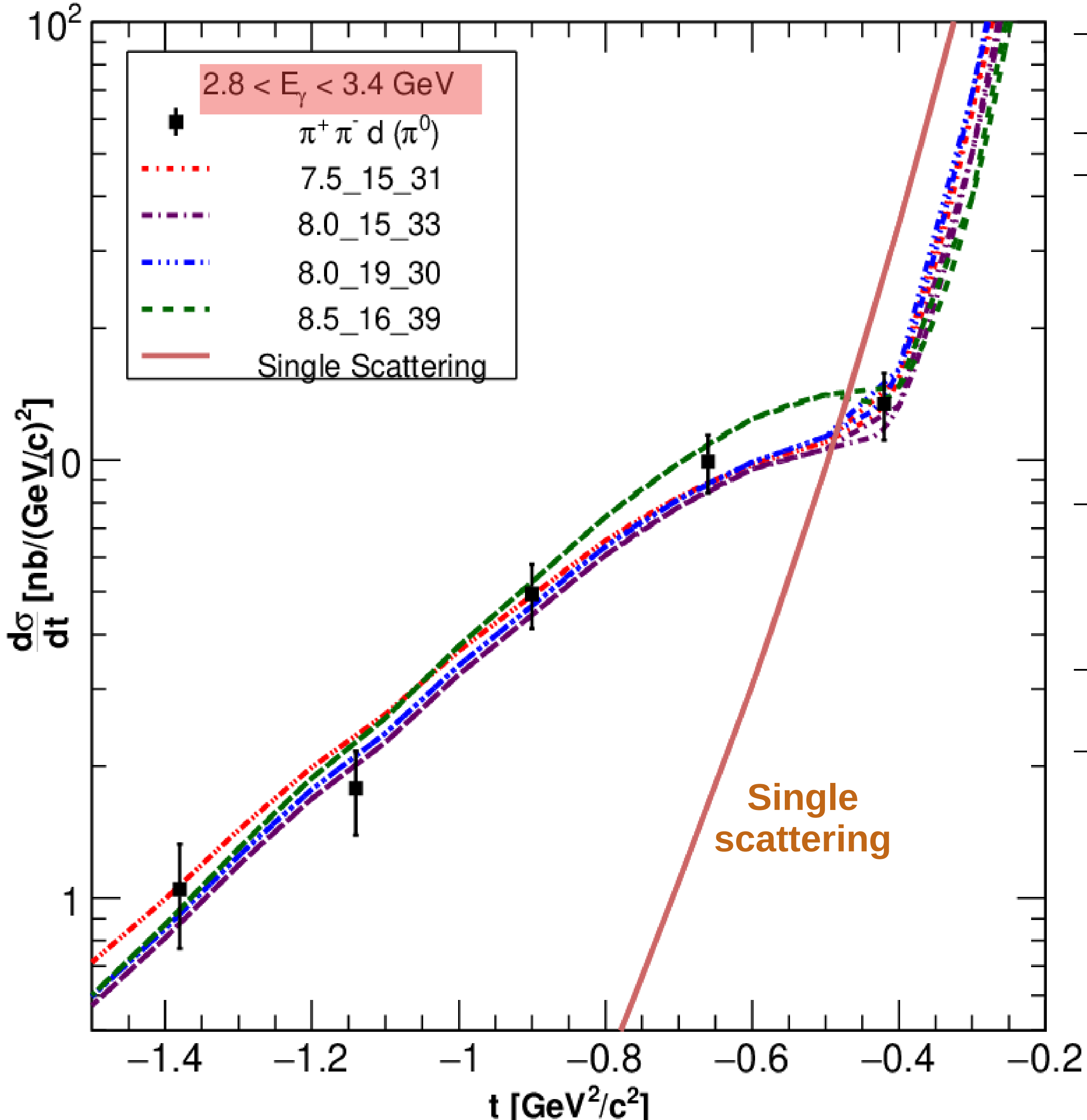




R.L.Anderson et al, Phys. Rev. D. 4, 3245, 1971

Using Calculations provided by M.Sargsian

Results: $\gamma\, d \to \omega\, d$



$b_{\gamma N} = b_{\omega N}$ $[GeV^{-2}/c^{-2}]$	$\frac{d\sigma}{dt}\big\|_{t=0,\gamma N}$ $[\mu b/(GeV^2/c^2)]$	$\sigma_{\omega N}$ $[mb]$	χ^2/NDF
7.5	15	31	1.13
8.0	14	34	1.15
8.0	15	33	1.01
8.0	16	32	0.96
8.0	17	31	1.00
8.0	18	30	1.15
8.0	19	30	0.91
8.0	19	31	0.87
8.0	20	30	1.03
8.5	16	35	1.11
8.5	16	39	1.00
8.5	17	34	1.05
8.5	18	33	1.07
9.0	19	39	0.89
9.0	20	38	0.87

$|\chi^2/F - 1.0| < 0.15$

$30 < \sigma_{\omega N} < 40$ mb

This range is typical of hadronic cross-sections in the energy range!

Click here to see animation!!

Summary

- Access to lower energy and larger momentum transfer to investigate ω-N scattering.

- First high statistics world data for the reaction: $\gamma\, d \rightarrow \omega\, d$

  Extracted $30 < \sigma_{\omega N} < 40$ mb using a rescattering model based on VMD for E_γ = [2.8, 3.4] GeV.

- The cross-section data provides sensitivity to the nucleon-scattering data in the energy and momentum transfer range mentioned.

Submitted to PLB, arXiv:1802.06746

Future work:

- *d** interference using the same final state detected particles.
  - $\gamma\, d \rightarrow \underline{d^{*+}\pi} \rightarrow \underline{d\pi^0}\, \pi^+\, \pi^-$
- Investigation of photocoupling ratio of light vector mesons.
- A2 meson exchange from proton data (T0 and T1 amplitudes).

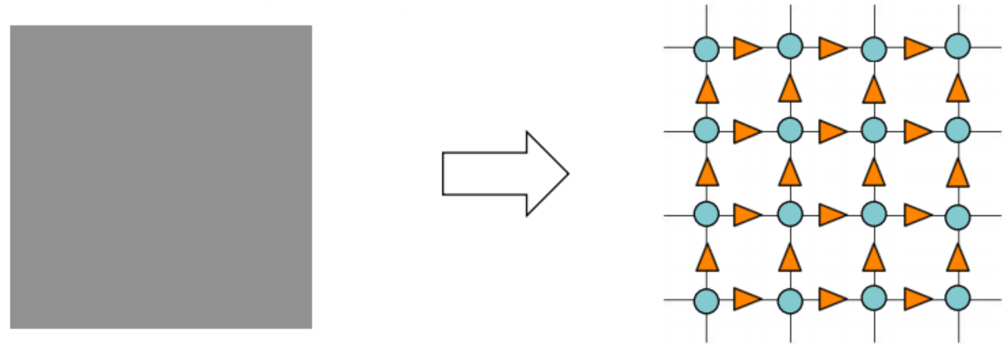
  f meson exchange or the $\mathbb{P}$ exchange in deuteron data provides T0 (natural isospin 0 transfer) amplitude.
  - Combining proton (pion extracted) and deuteron data, estimation of A2 is possible.

Thank you!

Any Questions?

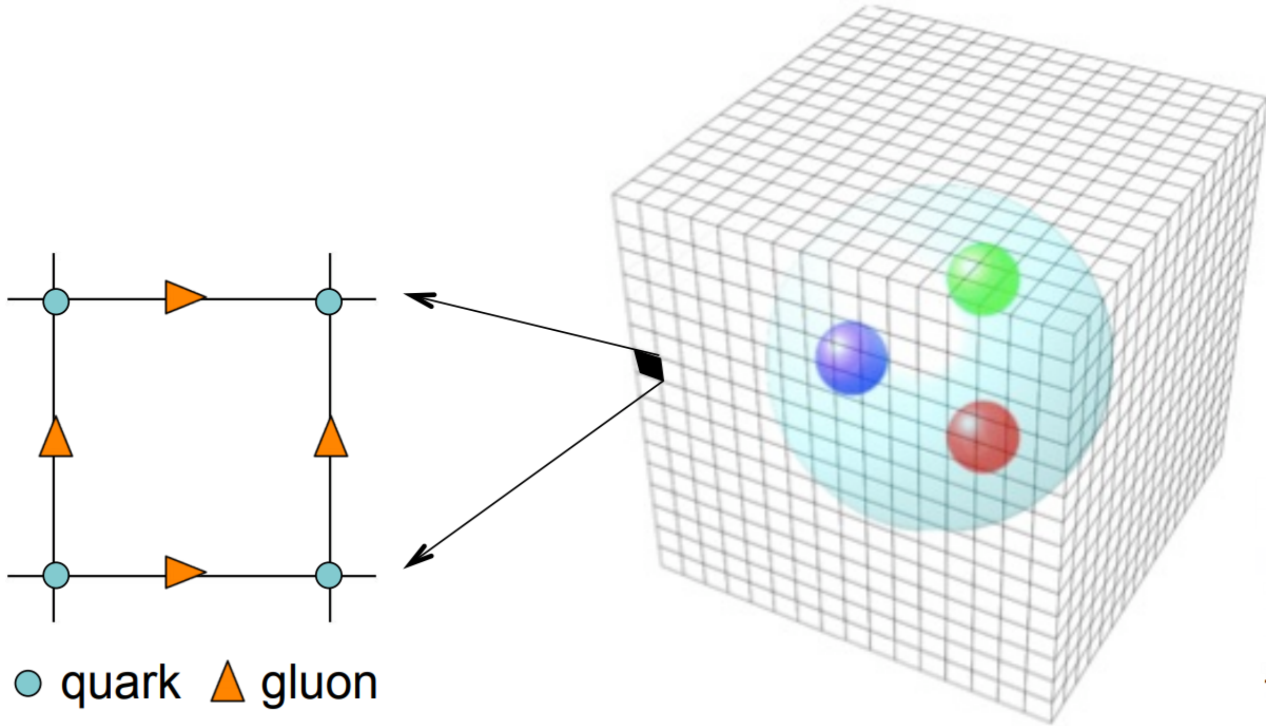
Extras

Lattice QCD (LQCD)



q(x) : quark field
$A_\mu(x)$: gauge field

q(n) : quark field
$U_\mu(n)$: SU(3) link variable



Investigated Channels

$$\gamma d \rightarrow \rho d \rightarrow \pi^+ \pi^- d$$

$\rho(770)$ [h]		$I^G(J^{PC}) = 1^+(1^{--})$	

Mass $m = 775.26 \pm 0.25$ MeV
Full width $\Gamma = 149.1 \pm 0.8$ MeV
$\Gamma_{ee} = 7.04 \pm 0.06$ keV

$\rho(770)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi\pi$	~ 100 %		363

$$\gamma d \rightarrow \omega d \rightarrow \pi^+ \pi^- d \ (\pi^0)$$

$\omega(782)$ — $I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 782.65 \pm 0.12$ MeV (S = 1.9)
Full width $\Gamma = 8.49 \pm 0.08$ MeV
$\Gamma_{ee} = 0.60 \pm 0.02$ keV

$\omega(782)$ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
$\pi^+\pi^-\pi^0$	(89.2 ± 0.7) %		327
$\pi^0\gamma$	(8.28 ± 0.28) %	S=2.1	380
$\pi^+\pi^-$	$(1.53^{+0.11}_{-0.13})$ %	S=1.2	366

Photon Coupling ratio of the vector mesons:

$$\gamma_\rho : \gamma_\omega : \gamma_\phi = 1 : 3 : -3/\sqrt{2}$$

- Assuming SU(3) and SU(6) symmetry.
- The coupling constants provide understanding for EM form factors of pseudo-scalar mesons and nucleons, EM meson decays, etc.

Diffractive DCS

Preliminary

Differential cross-section,

$$\frac{d\sigma}{dt} = \frac{Y_D}{\Delta t A \mathscr{L}} \times \frac{\Gamma_\omega}{\Gamma_{\omega\to\pi^+\pi^-\pi^0}} \times \gamma_{corr}$$

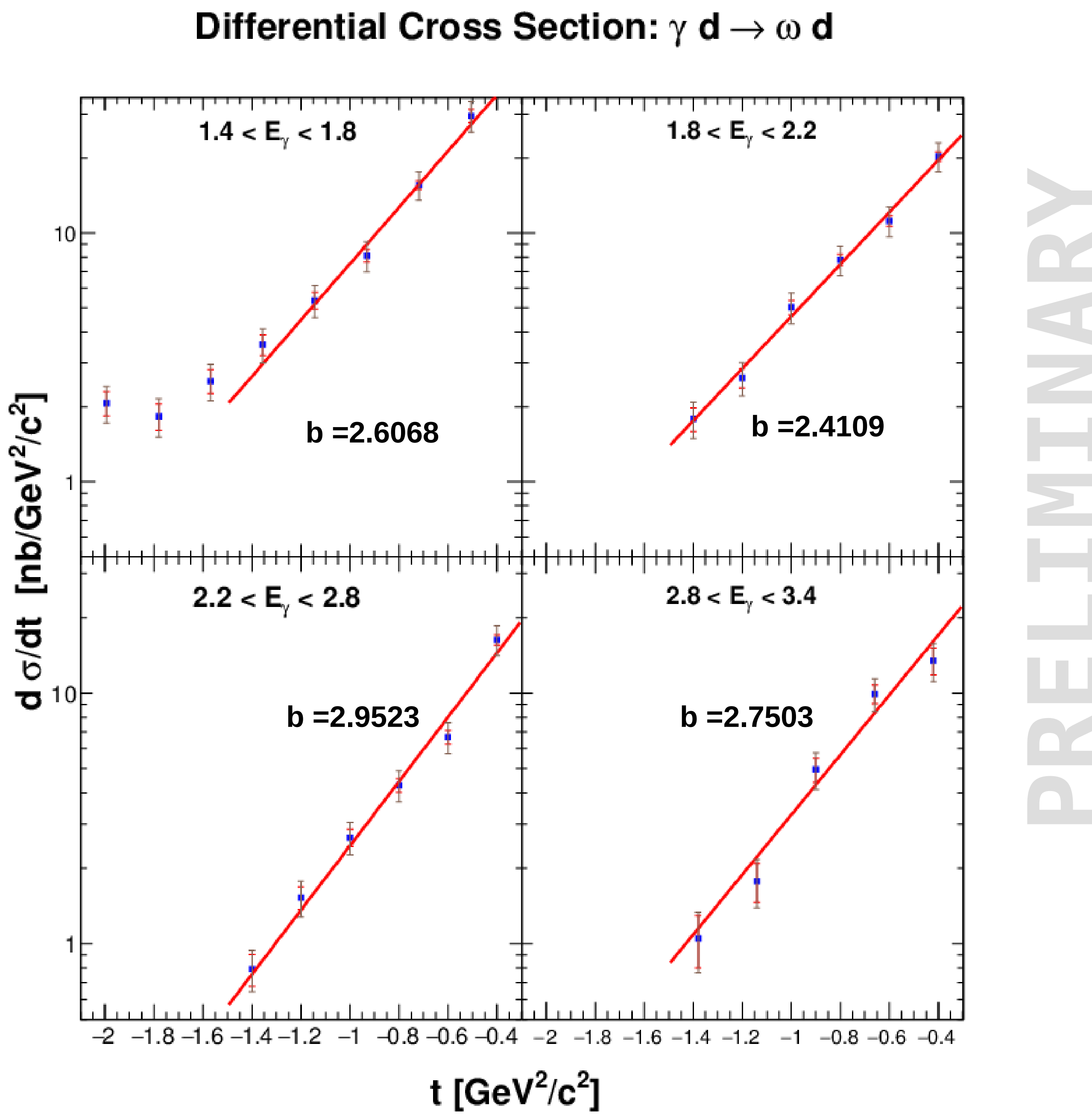
A = Acceptance
Δt = Width of t-bin
Y_D = Signal Yield
γ_{corr} = Photon Multiplicity Correction factor

Luminosity,

$$\mathscr{L}(E_\gamma) = \frac{\rho_T N_A l_T}{M_d} N_\gamma(E_\gamma)$$

$\rho_d = 0.169\, g cm^{-3}$
$l_d = 24\, cm$
$M_d = 2.014\, g\, mole^{-1}$
$N_\gamma(E_\gamma) =$ Photon Flux

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$



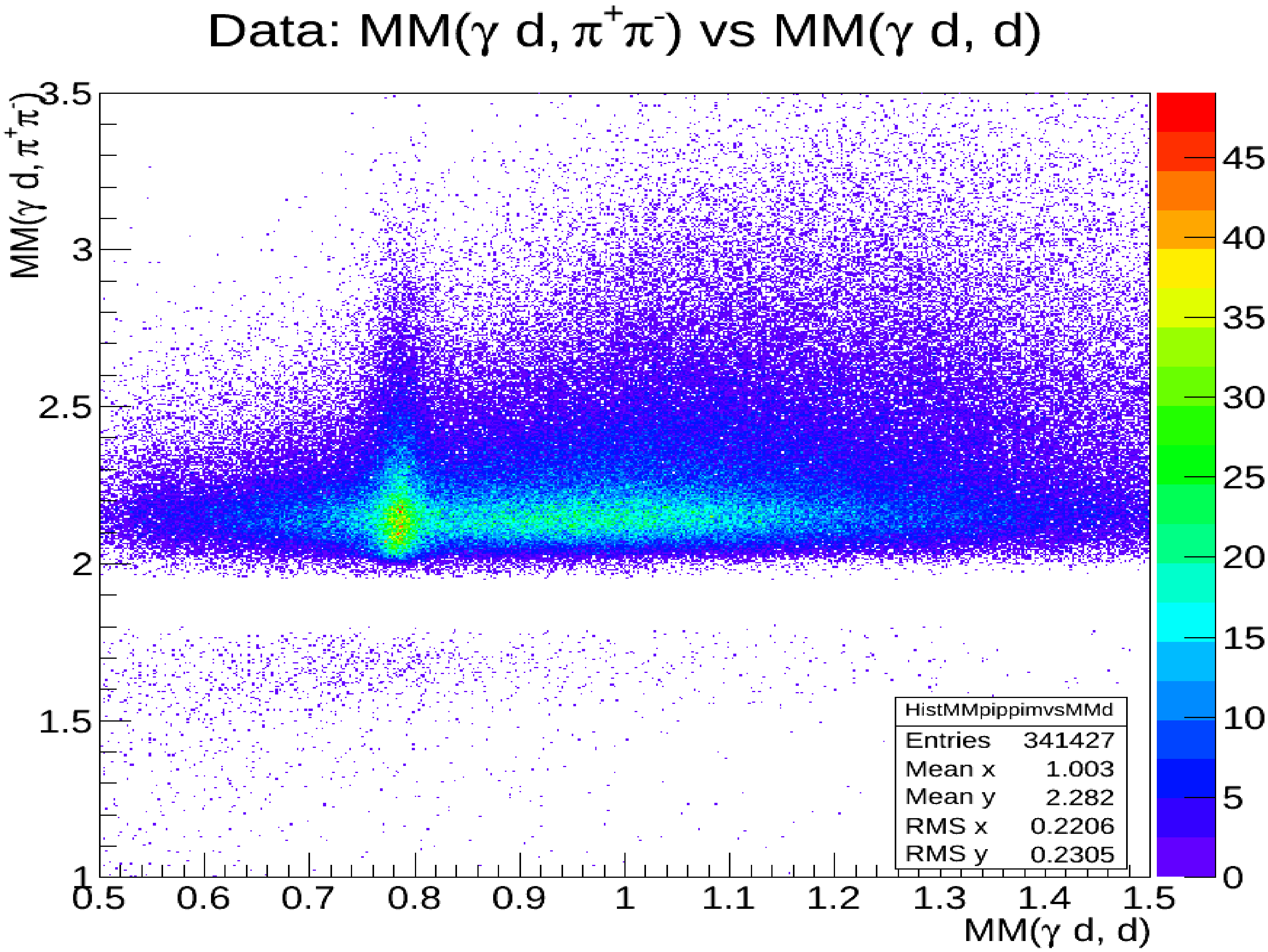
Systematic Uncertainties

Back-up

Source	Description	Uncertainty
Flux Consistency/Luminosity	Sec. 9.1	8.00%
t-slope dependence	Varied from $b = 2.5$ to $b = 0$	0.04%
Sector Dependence	Sec. 9.3	2.00%
Timing Cut	Varied from a 3σ to 3.5σ cut	0.60%
Minimum $\|p\|$ Cut	Removed	0.52%
Missing Mass Cut	Varied from a 3σ to 2.5σ cut	3.46%
z-Vertex Cut	Varied from $\|z + 25\| < 11$ to $\|z + 25\| < 11.5$	0.73%
Fiducial Cut	Varied from a 50% to a 100% cut	1.34%
Signal Integral Range	Varied from 4σ to 5σ	0.10%
Choice of Background function	Sec. 9.10	8.59%
Branching Ratio	Reference [5]	0.70%
Total Systematic Uncertainty (Added in quadrature)		**12.54%**

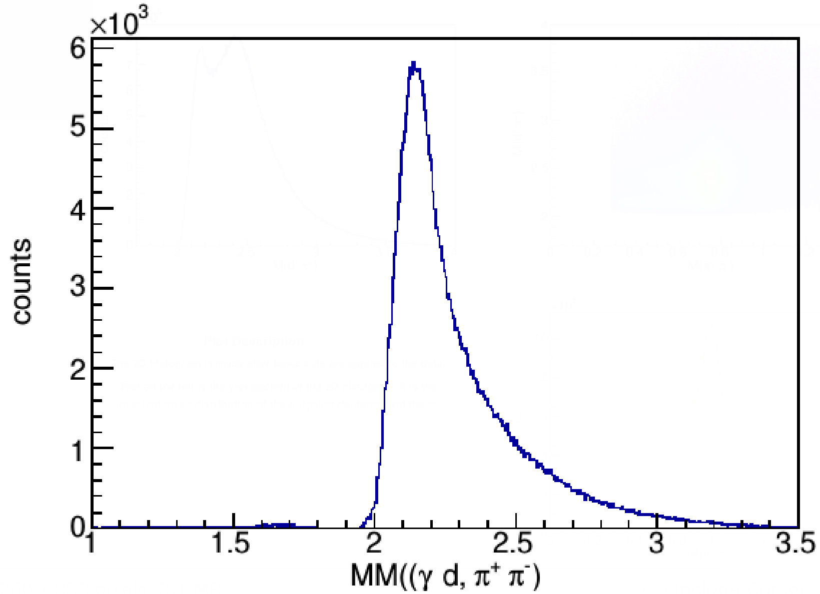
Interference

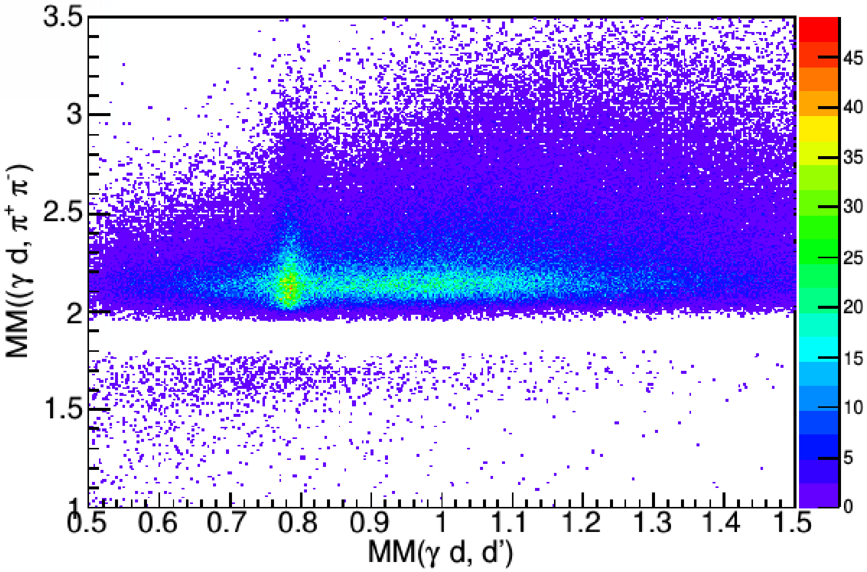
Back-up



Interference

Back-up





Plot Description

The 2D histogram is made after basic cuts are applied to the data.

Plot on the left is the y-projection of the 2D histogram. It is the mass distribution for the π^0 and the outgoing d.

Plot on the right is the x-projection of the 2D histogram. It is the mass distribution for $\pi^+ \pi^- \pi^0$ or the ω-meson distribution.