Analysis of Photoproduction Reactions

Vincent MATHIEU

Jefferson Lab
-
Joint Physics Analysis Center

CLAS Collaboration Meeting
Jefferson Lab - October 2017

INDIANA UNIVERSITY

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Motivation: The Factorization Hypothesis

Photoproduction of mesons at $E_\gamma = 6 - 12\ \mathrm{GeV}$

Study photoproduction of mesons

Search for exotic resonances

Special interest in mesons:

Does the target decouple at JLab energies ?

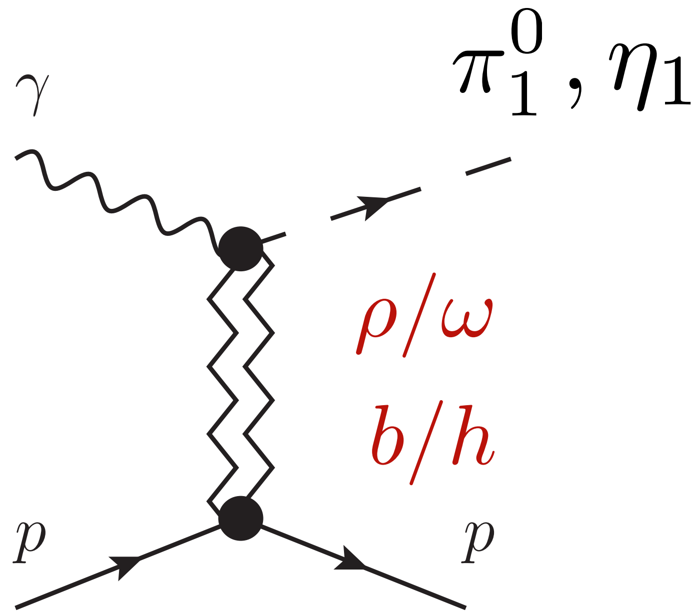
Production of ‘Exotica’

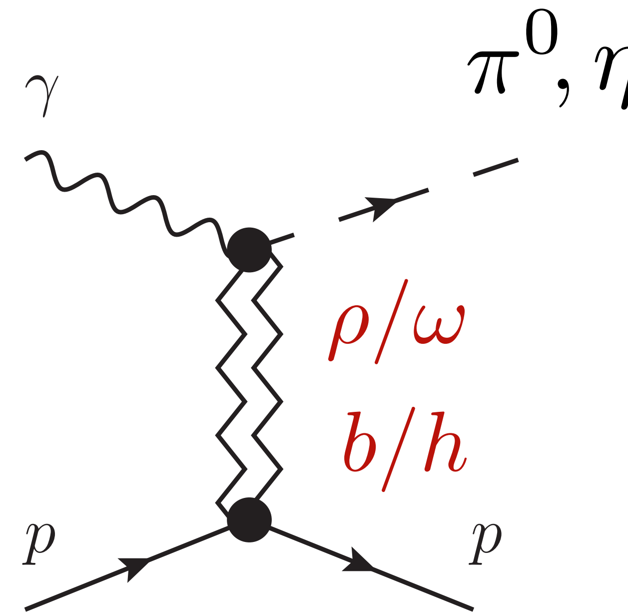
In photoproduction, the production of π_1 $\quad J^{PC} I^{G} = 1^{-+}1^{-}$
is similar to the production of π $\quad = 0^{-+}1^{-}$

Neutral partner

$C = -1$

$I = 0, 1$

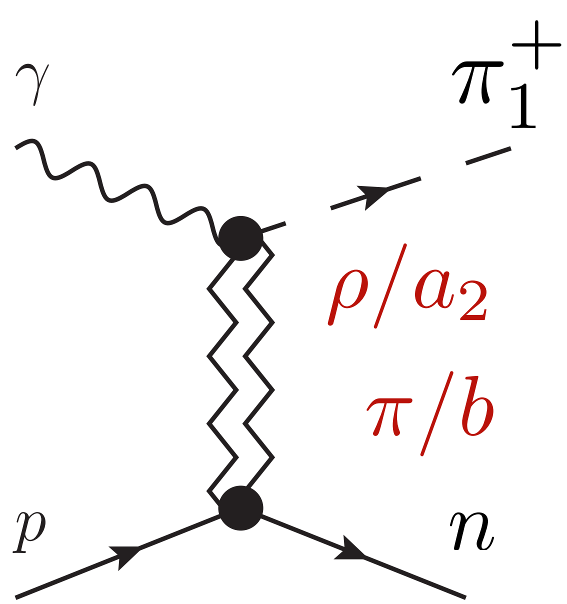


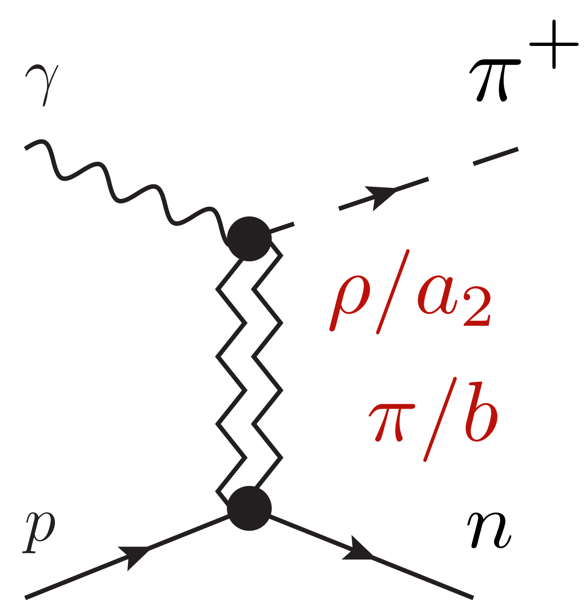


Charged partner

$C = \pm 1$

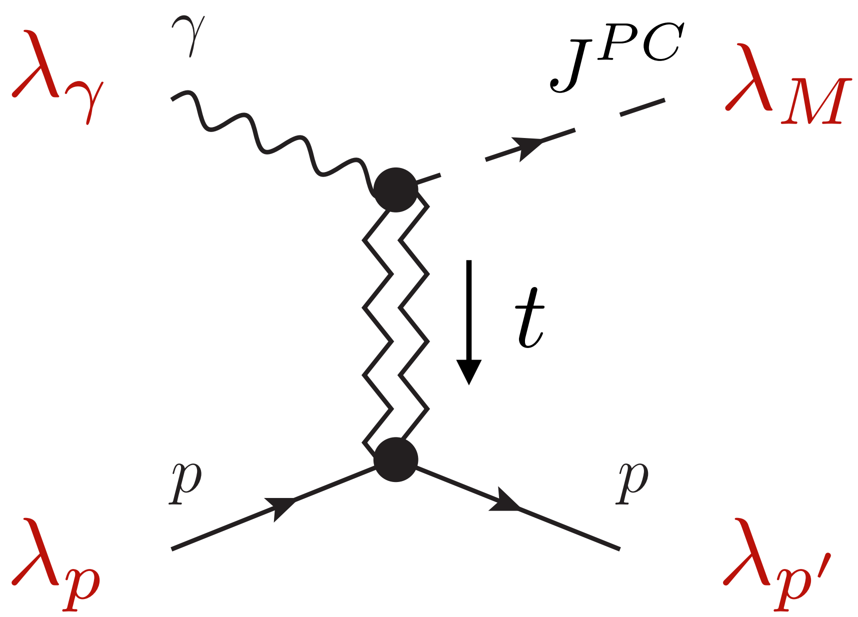
$I = 1$





start by photoproduction of pions

Factorization



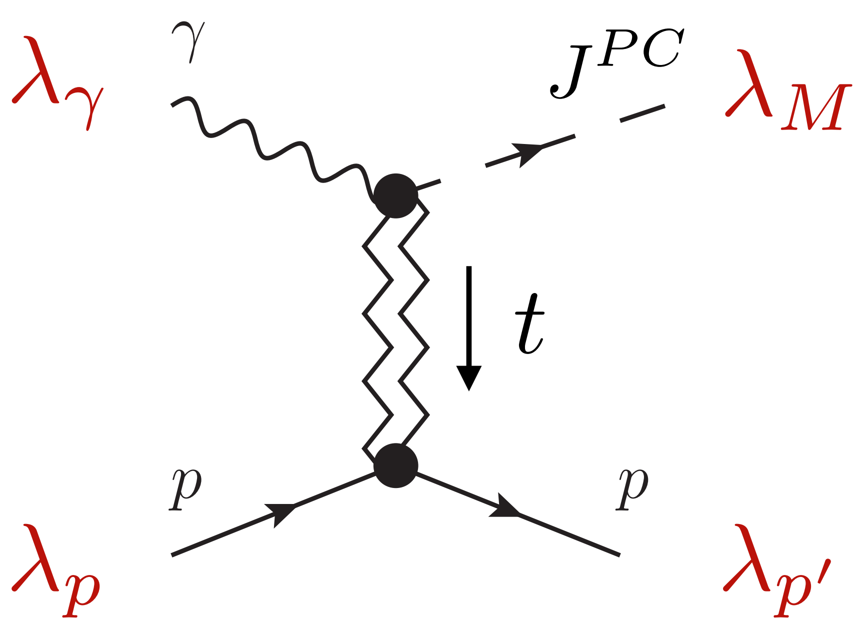
$\lambda_i =$ **s-channel helicity of particle i**

Trajectory

Angular momentum conservation for the reaction implies:

$$A^{\lambda_\gamma \lambda_M}_{\lambda_p \lambda_{p'}} = \gamma(t)(\sqrt{-t})^{|(\lambda_\gamma - \lambda_M)-(\lambda_p - \lambda_{p'})|} \times \frac{1 \pm e^{-i\pi\alpha(t)}}{2\sin\pi\alpha(t)} s^{\alpha(t)}$$

Factorization



$\lambda_i =$ **s-channel helicity of particle i**

Angular momentum conservation for the reaction implies:

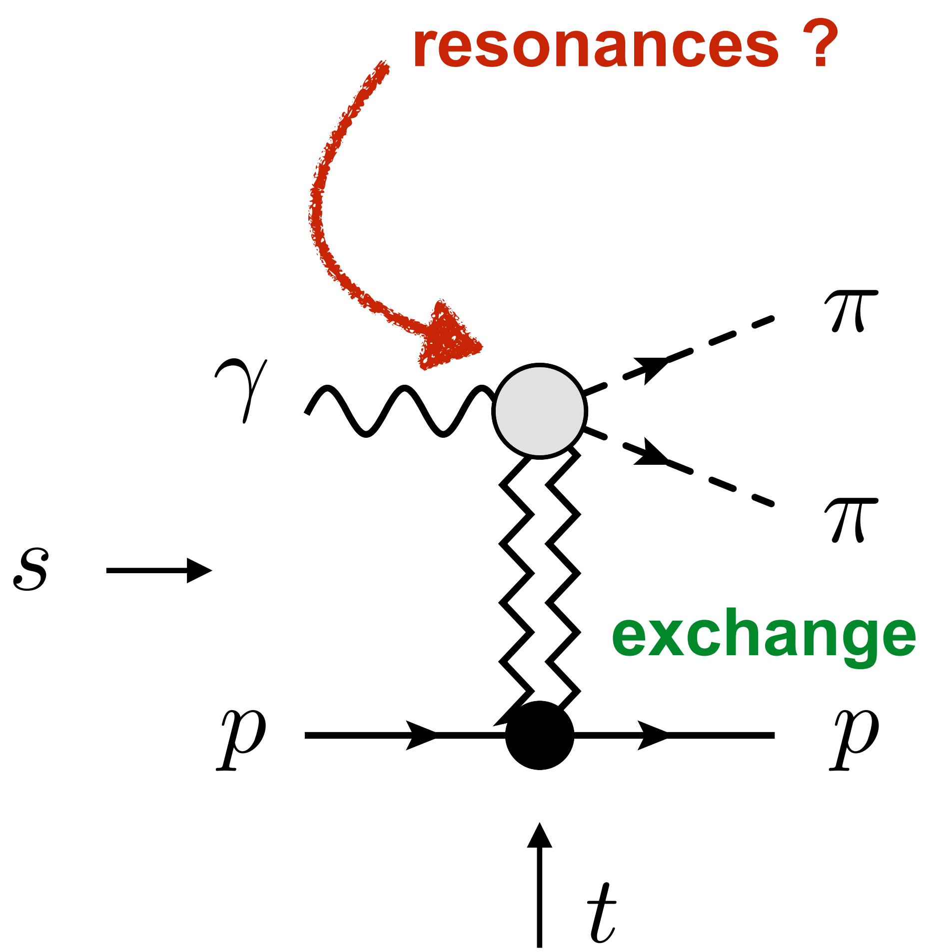
$$A^{\lambda_\gamma \lambda_M}_{\lambda_p \lambda_{p'}} = \gamma(t)(\sqrt{-t})^{|(\lambda_\gamma - \lambda_M) - (\lambda_p - \lambda_{p'})|} \times \frac{1 \pm e^{-i\pi\alpha(t)}}{2\sin\pi\alpha(t)} s^{\alpha(t)}$$

Trajectory

Factorization implies angular mom, conservation at each vertex:

$$A^{\lambda_\gamma \lambda_M}_{\lambda_p \lambda_{p'}} = \underbrace{\gamma(t)(\sqrt{-t})^{|\lambda_\gamma - \lambda_M|}}_{\text{top vertex}} \times \underbrace{(\sqrt{-t})^{|\lambda_p - \lambda_{p'}|}}_{\text{bottom vertex}} \times \frac{1 \pm e^{-i\pi\alpha(t)}}{2\sin\pi\alpha(t)} s^{\alpha(t)}$$

Production: A Simple Example

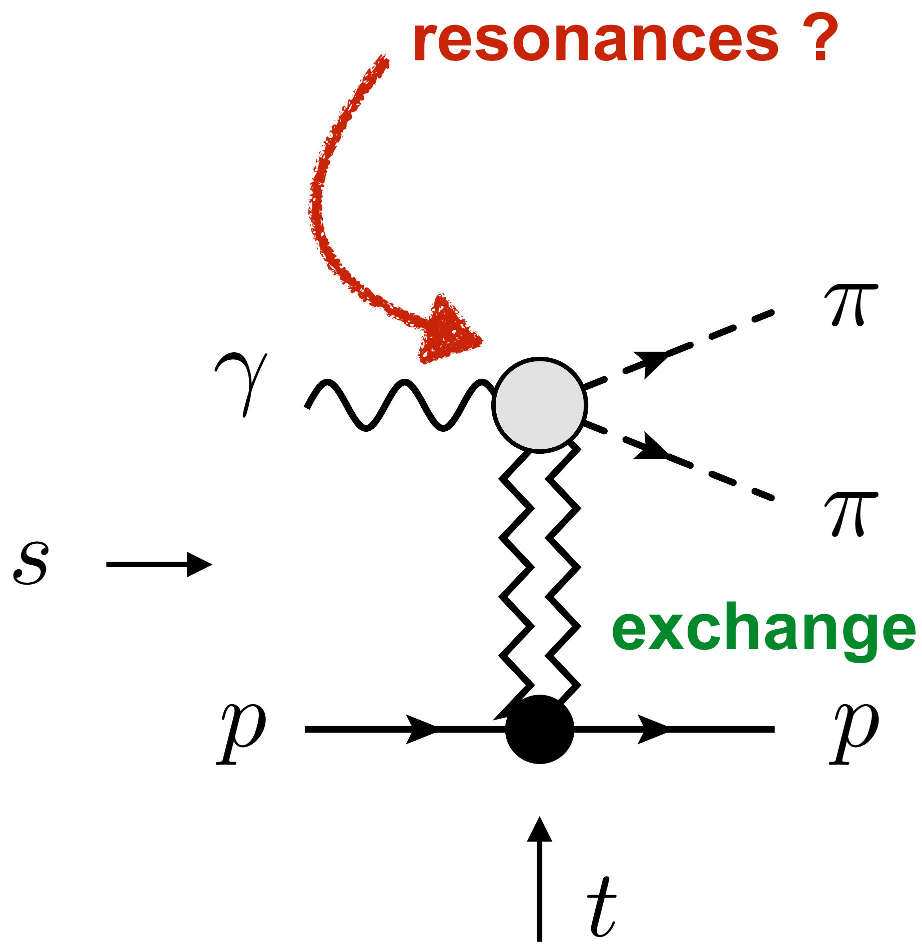


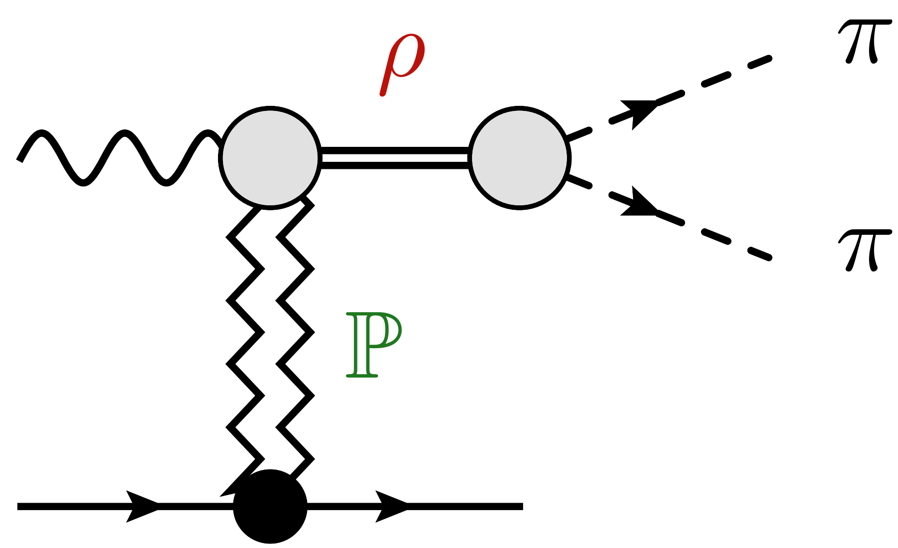
simple form for production
via Regge exchange

$$A \propto \beta(t) s^{\alpha(t)}$$

s = c.-of-mass energy squared
t = mom. transfered squared

Production: A Simple Example



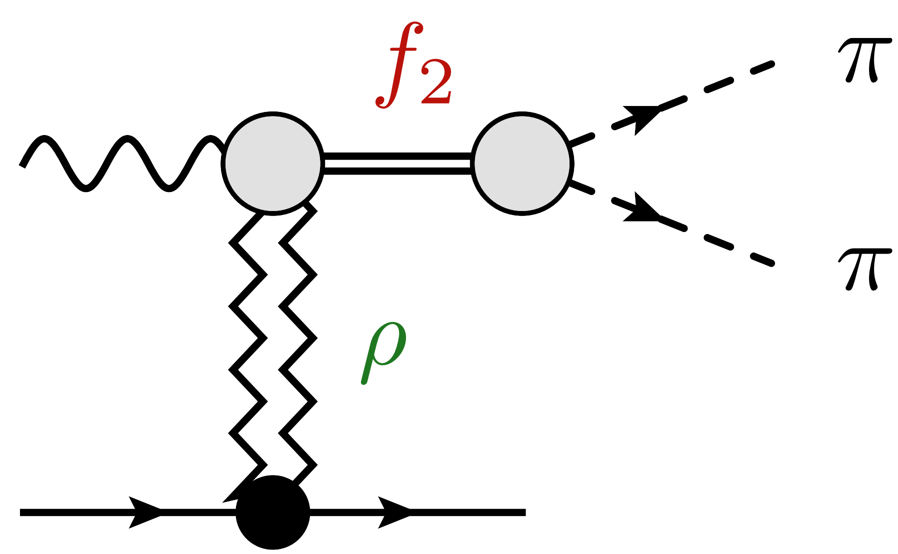


$$\sim s^{1+0.2t}$$

Pomeron exchange

simple form for production
via Regge exchange

$$A \propto \beta(t) s^{\alpha(t)}$$

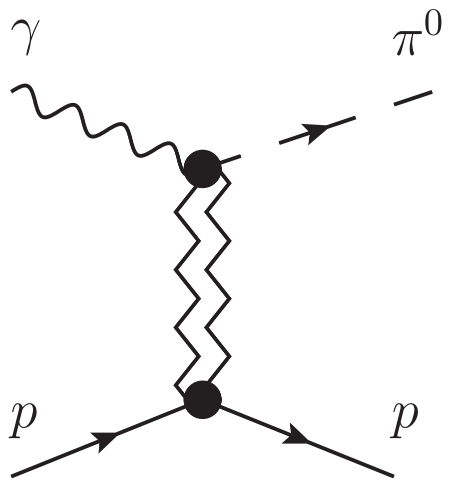


$$\sim s^{0.5+0.9t}$$

vector exchange

s = c.-of-mass energy squared
t = mom. transfered squared

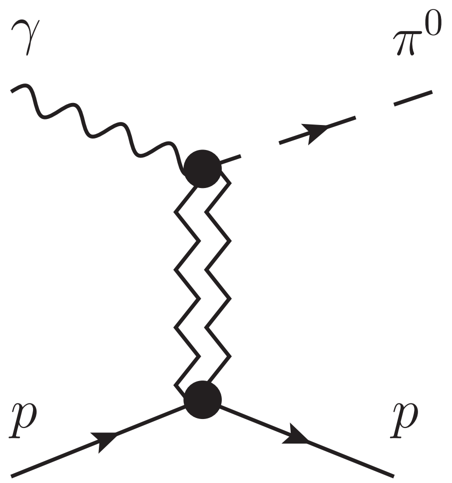
Effective Trajectory



$$A \propto \beta(t) s^{\alpha(t)}$$

$$\frac{d\sigma}{dt} \propto \frac{1}{p^2} \beta^2(t) s^{2\alpha(t)}$$

Effective Trajectory

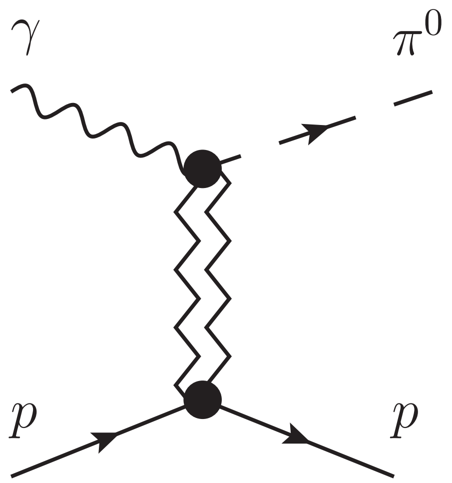


$$A \propto \beta(t) s^{\alpha(t)}$$

$$\frac{d\sigma}{dt} \propto \frac{1}{p^2} \beta^2(t) s^{2\alpha(t)}$$

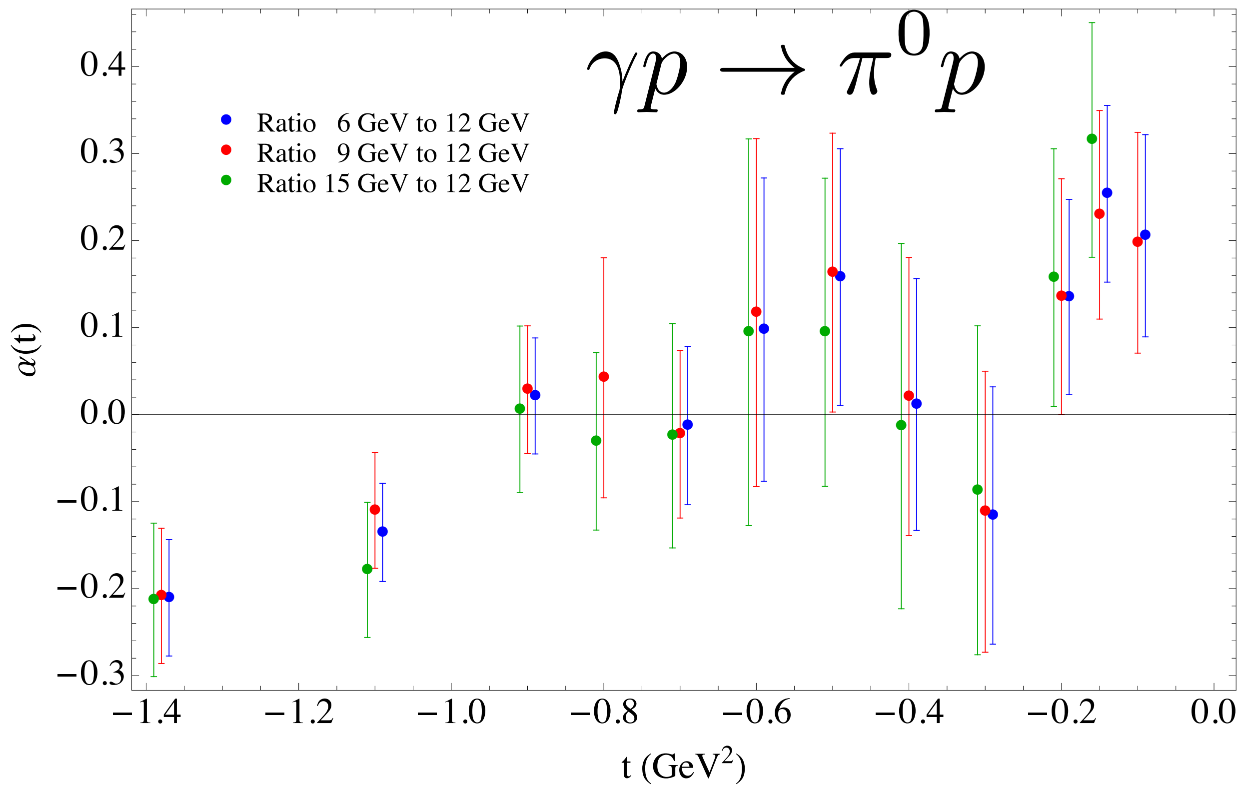
$$\alpha_{\text{eff}} = \frac{1}{2} \log \left(\frac{p^2 \frac{d\sigma}{dt}}{p_0^2 \frac{d\sigma_0}{dt}} \right) \log^{-1} \left(\frac{s}{s_0} \right)$$

Effective Trajectory



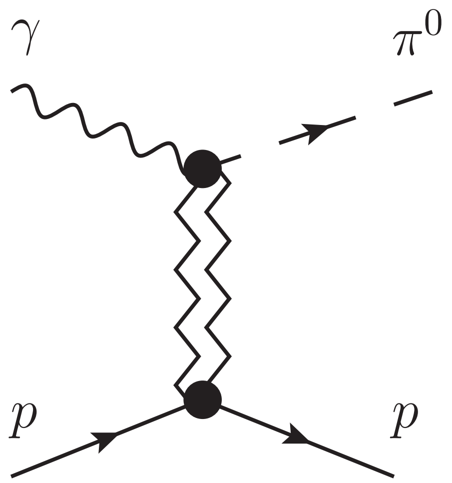
$$A \propto \beta(t) s^{\alpha(t)}$$

$$\frac{d\sigma}{dt} \propto \frac{1}{p^2} \beta^2(t) s^{2\alpha(t)}$$



$$\alpha_{\text{eff}} = \frac{1}{2} \log \left(\frac{p^2 \frac{d\sigma}{dt}}{p_0^2 \frac{d\sigma_0}{dt}} \right) \log^{-1} \left(\frac{s}{s_0} \right)$$

Effective Trajectory

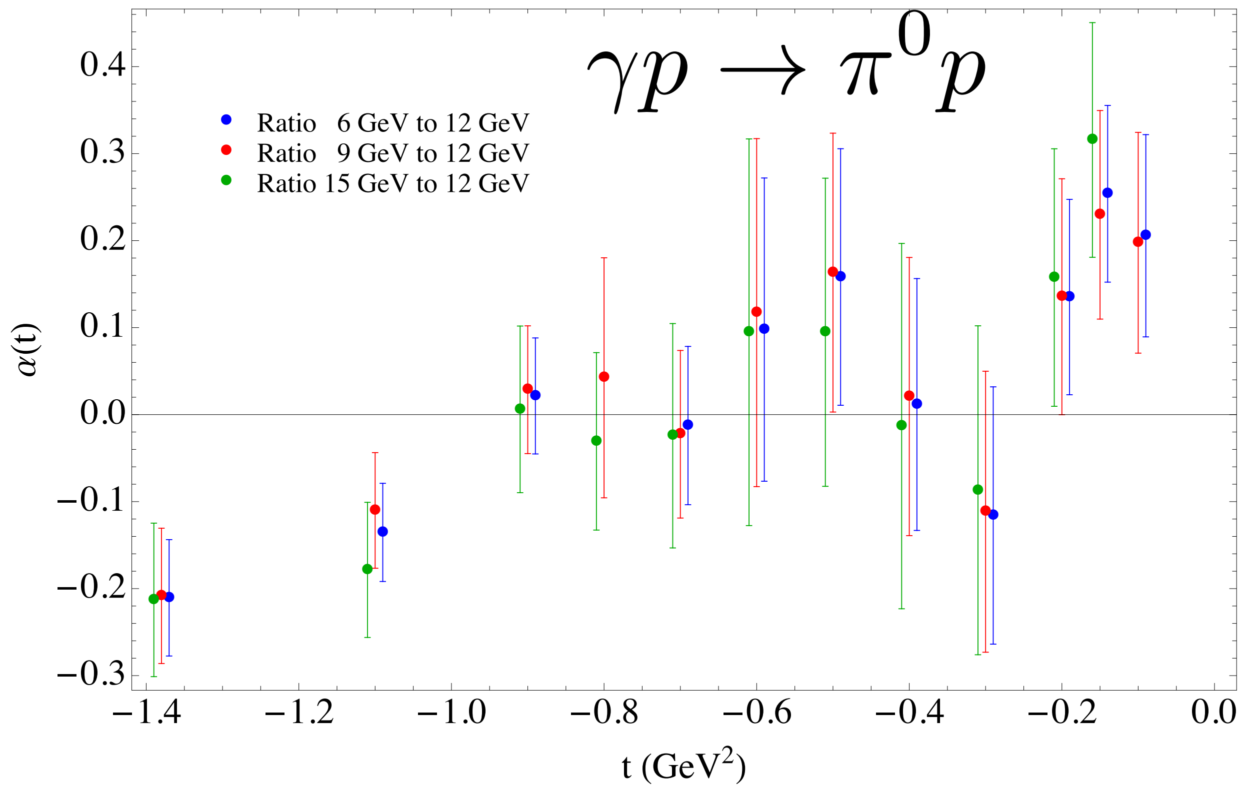


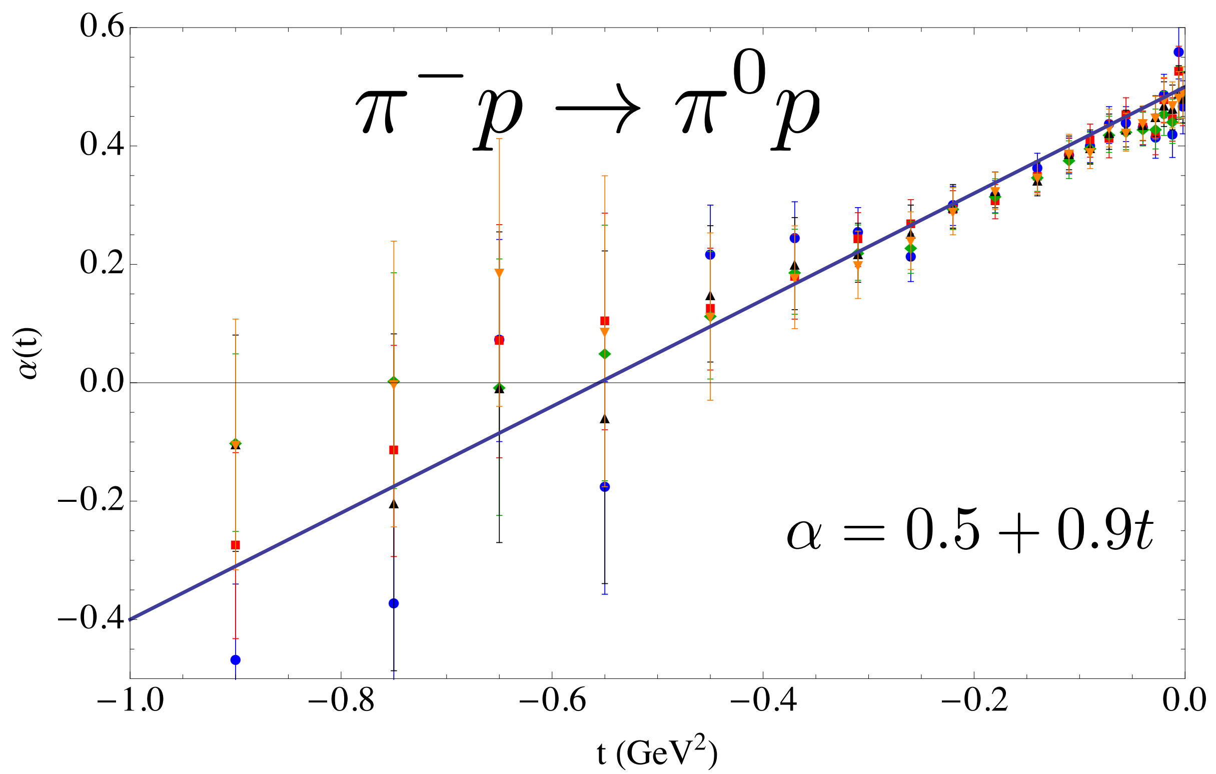
$$A \propto \beta(t) s^{\alpha(t)}$$

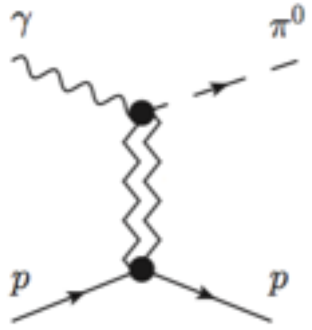
$$\frac{d\sigma}{dt} \propto \frac{1}{p^2} \beta^2(t) s^{2\alpha(t)}$$

$$\alpha_{\text{eff}} = \frac{1}{2} \log \left(\frac{p^2 \frac{d\sigma}{dt}}{p_0^2 \frac{d\sigma_0}{dt}} \right) \log^{-1} \left(\frac{s}{s_0} \right)$$

Correct energy dependence
BUT
multiple contributions

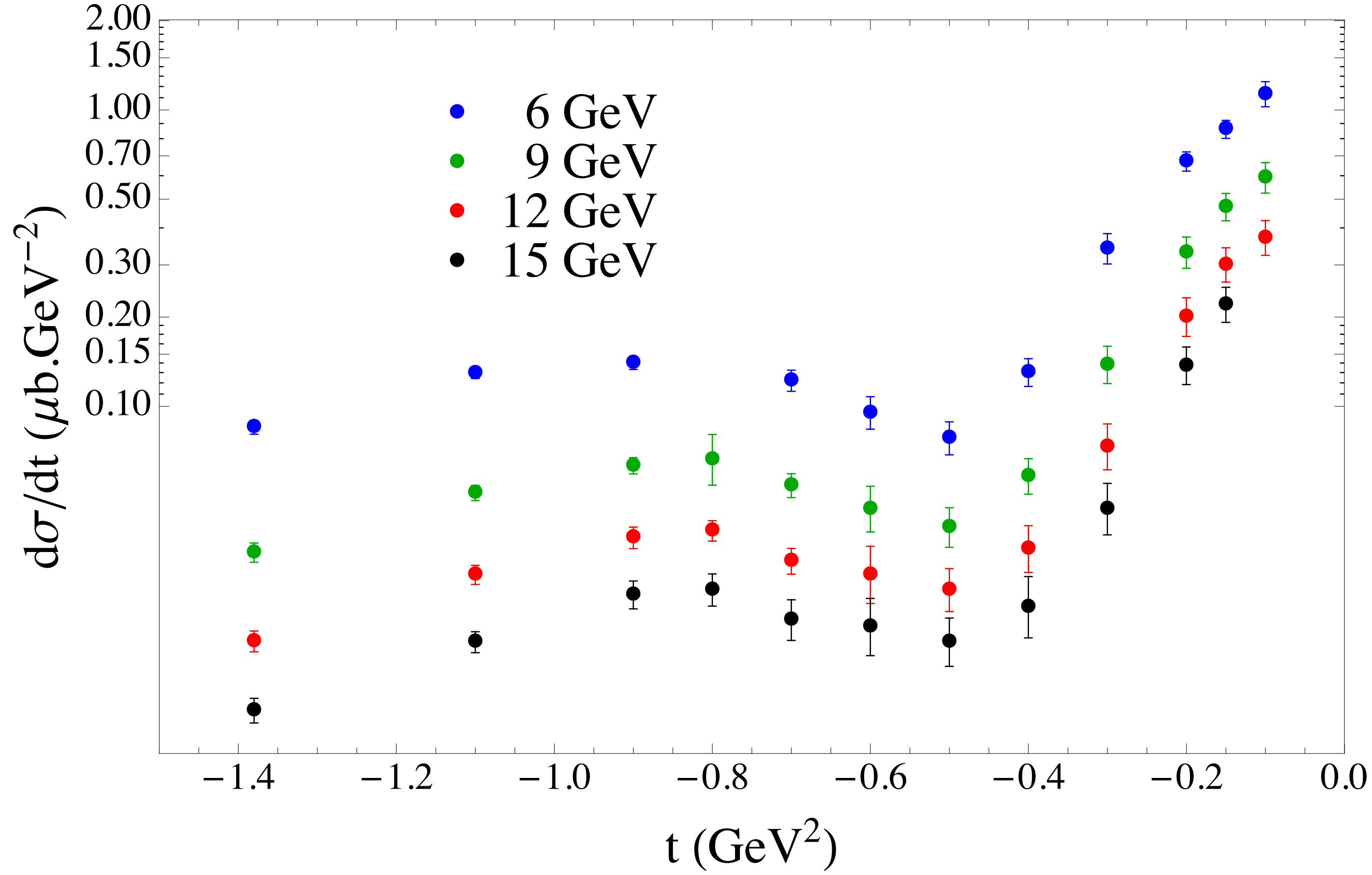






$$\gamma p \to \pi^0 p$$

diff cross section [SLAC Anderson et al. 1971]



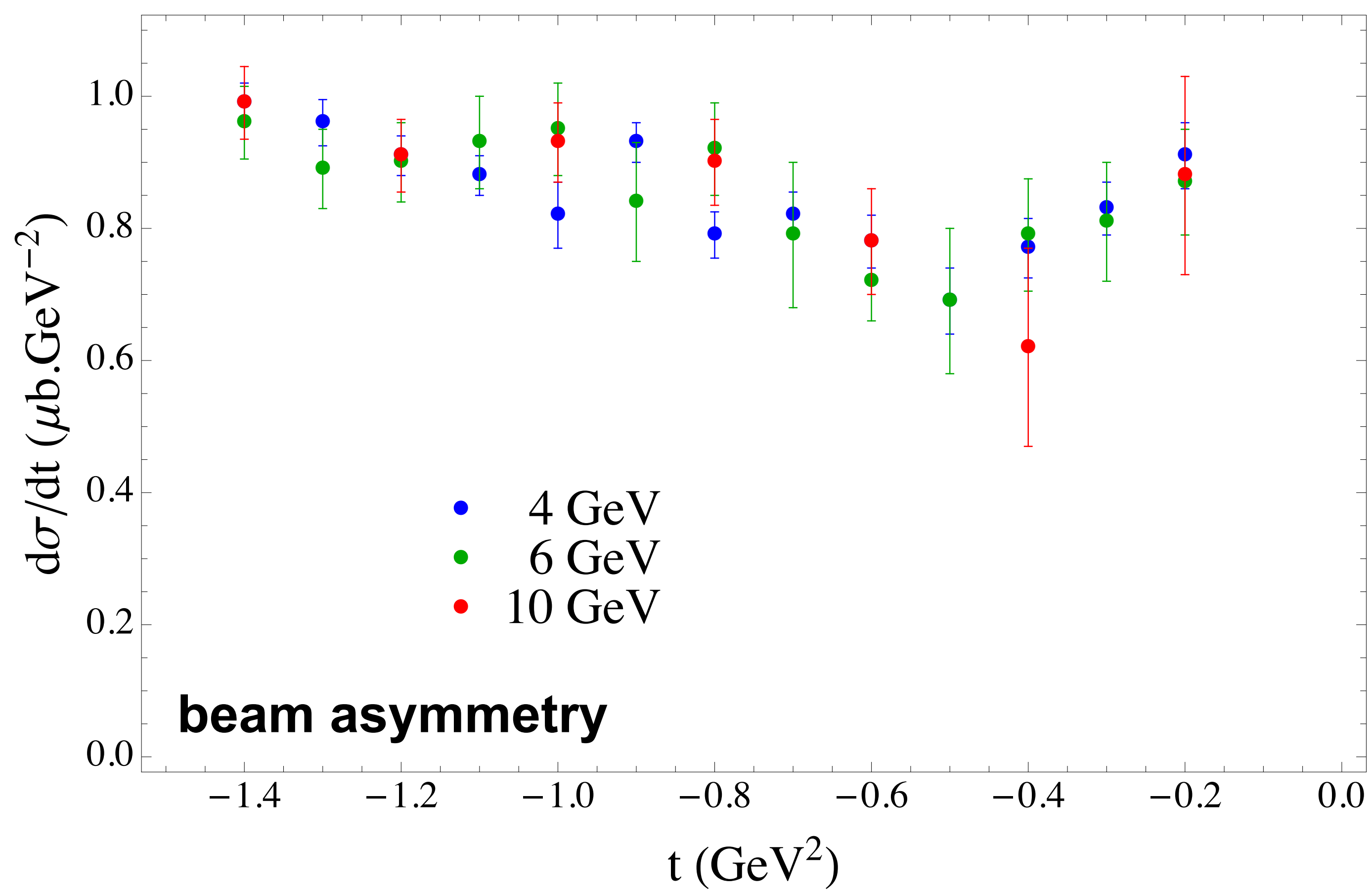
$$\frac{d\sigma}{dt} = \sigma_\perp + \sigma_\parallel = |\rho + \omega|^2 + |b + h|^2$$

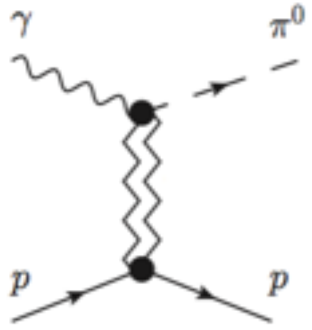
$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho + \omega|^2 - |b + h|^2}{|\rho + \omega|^2 + |b + h|^2}$$

both have dip at $t_0 \sim -0.5\ \mathrm{GeV}^2$

$$\alpha_{\rho,\omega}(t) \sim 0.5 + t$$

$$\alpha_{\rho,\omega}(t_0) = 0$$





$$\gamma p \to \pi^0 p$$

$$\frac{d\sigma}{dt} = \sigma_\perp + \sigma_\parallel = |\rho + \omega|^2 + |b + h|^2$$

$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho + \omega|^2 - |b + h|^2}{|\rho + \omega|^2 + |b + h|^2}$$

both have dip at $t_0 \sim -0.5\ \mathrm{GeV}^2$

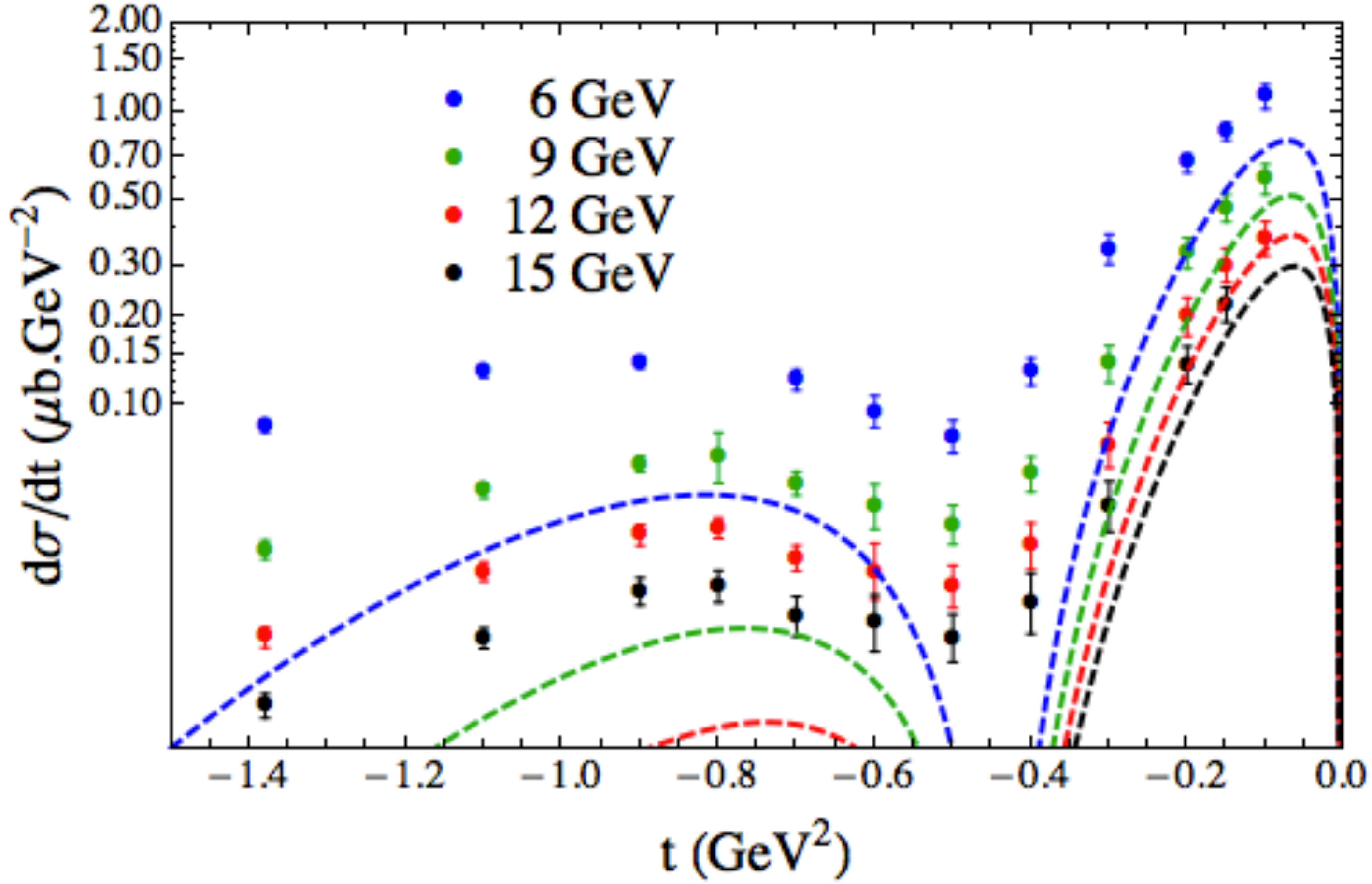
$$\alpha_{\rho,\omega}(t) \sim 0.5 + t$$

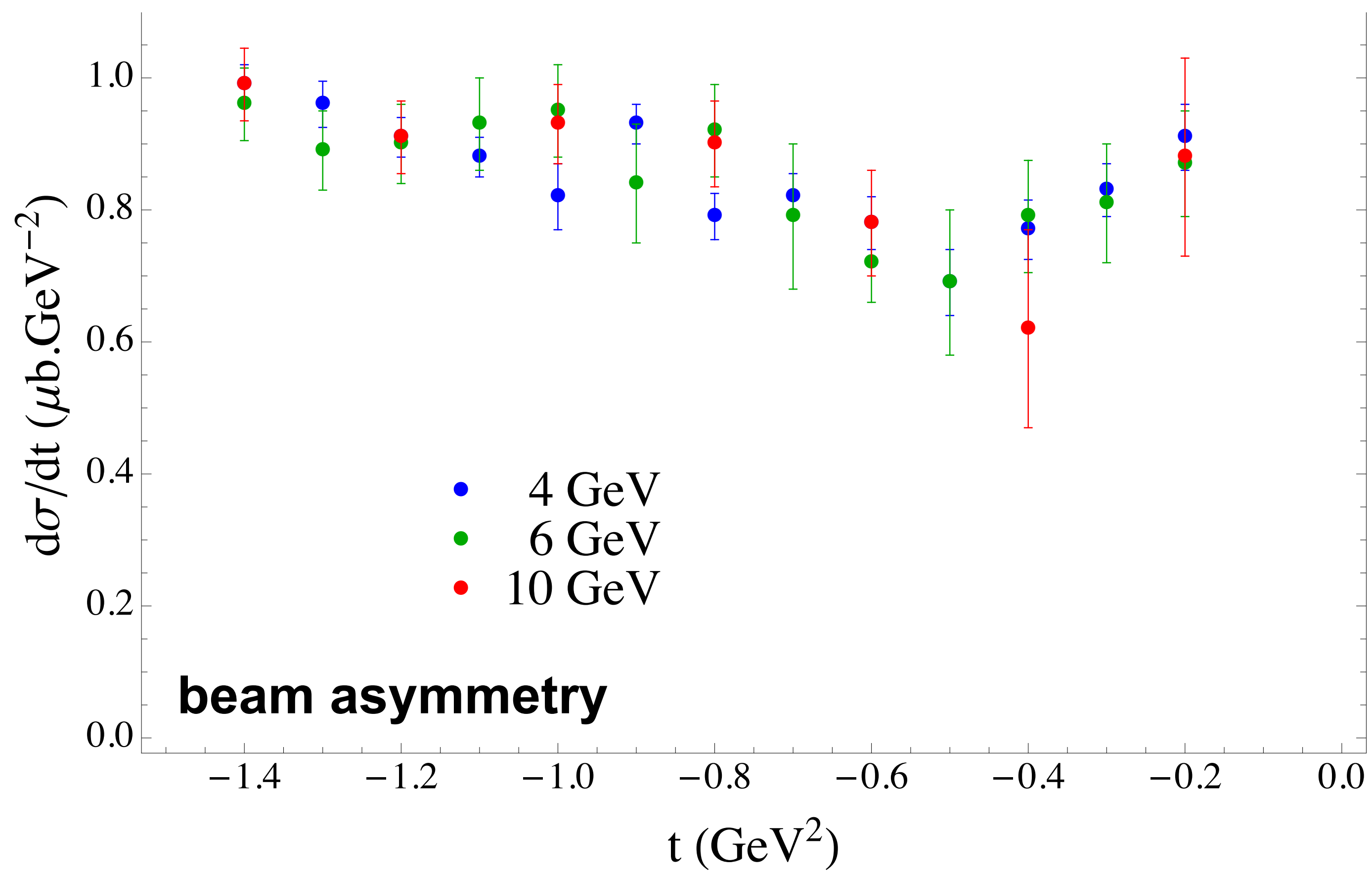
$$\alpha_{\rho,\omega}(t_0) = 0$$

Impose wrong signature zero

$$A^{\lambda_\gamma \lambda_\pi}_{\lambda_p \lambda_{p'}} = A^{10}_{\frac{1}{2}\frac{1}{2}} \propto \alpha(t)(\sqrt{-t})$$

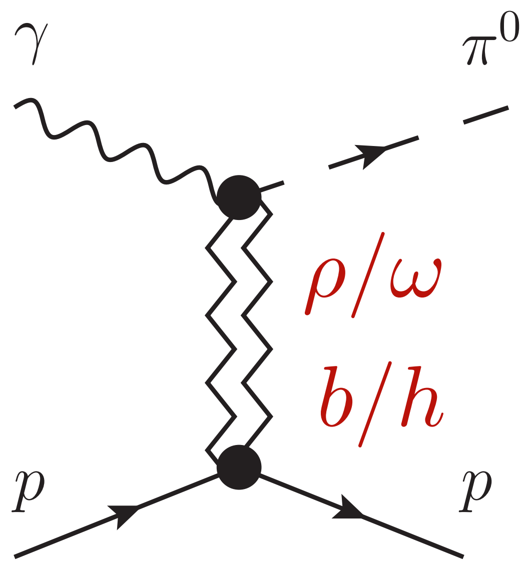
diff cross section [SLAC Anderson et al. 1971]





$$\gamma p \to \pi^0 p$$

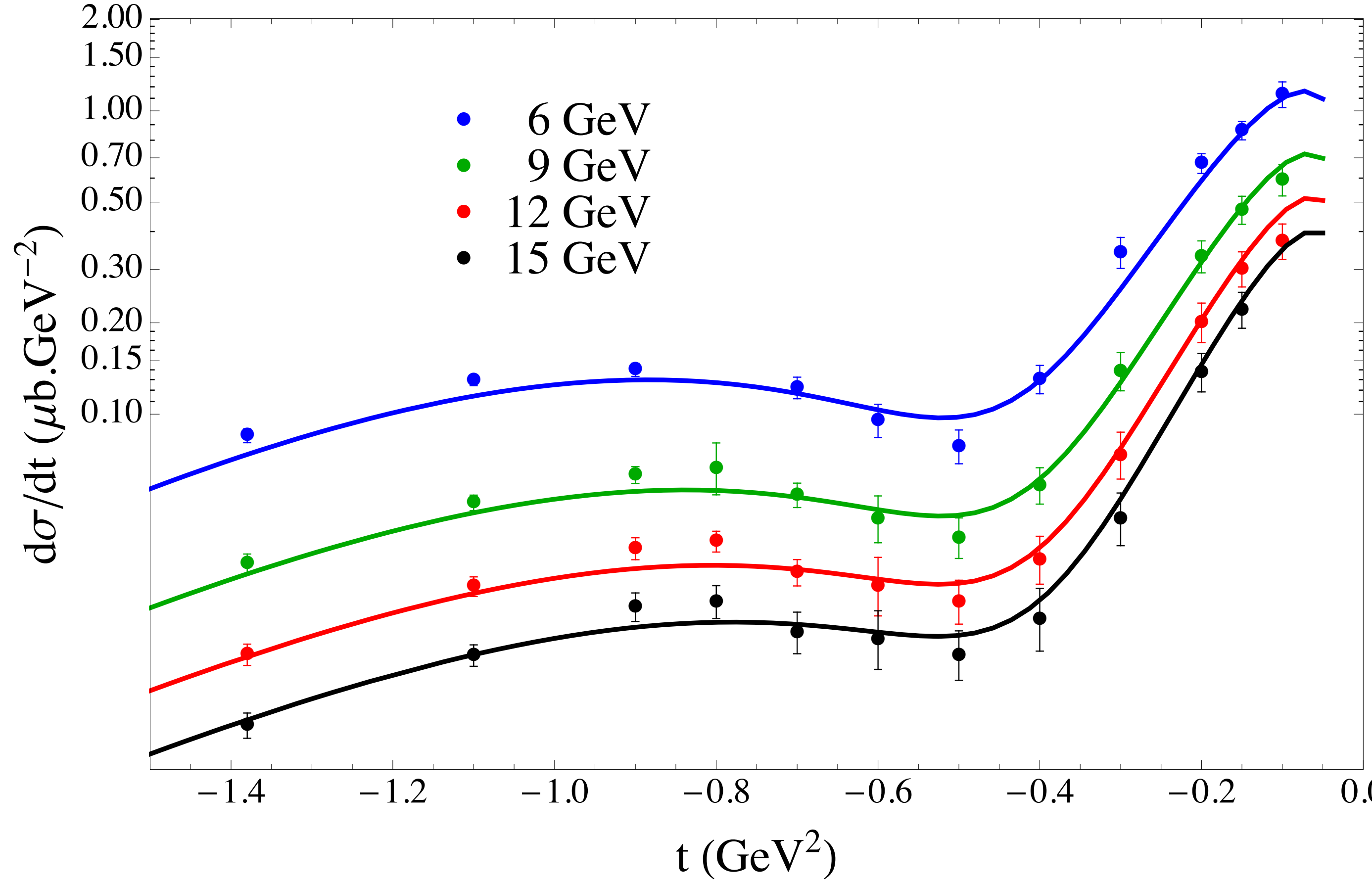
Model based on factorization with parameters fitted

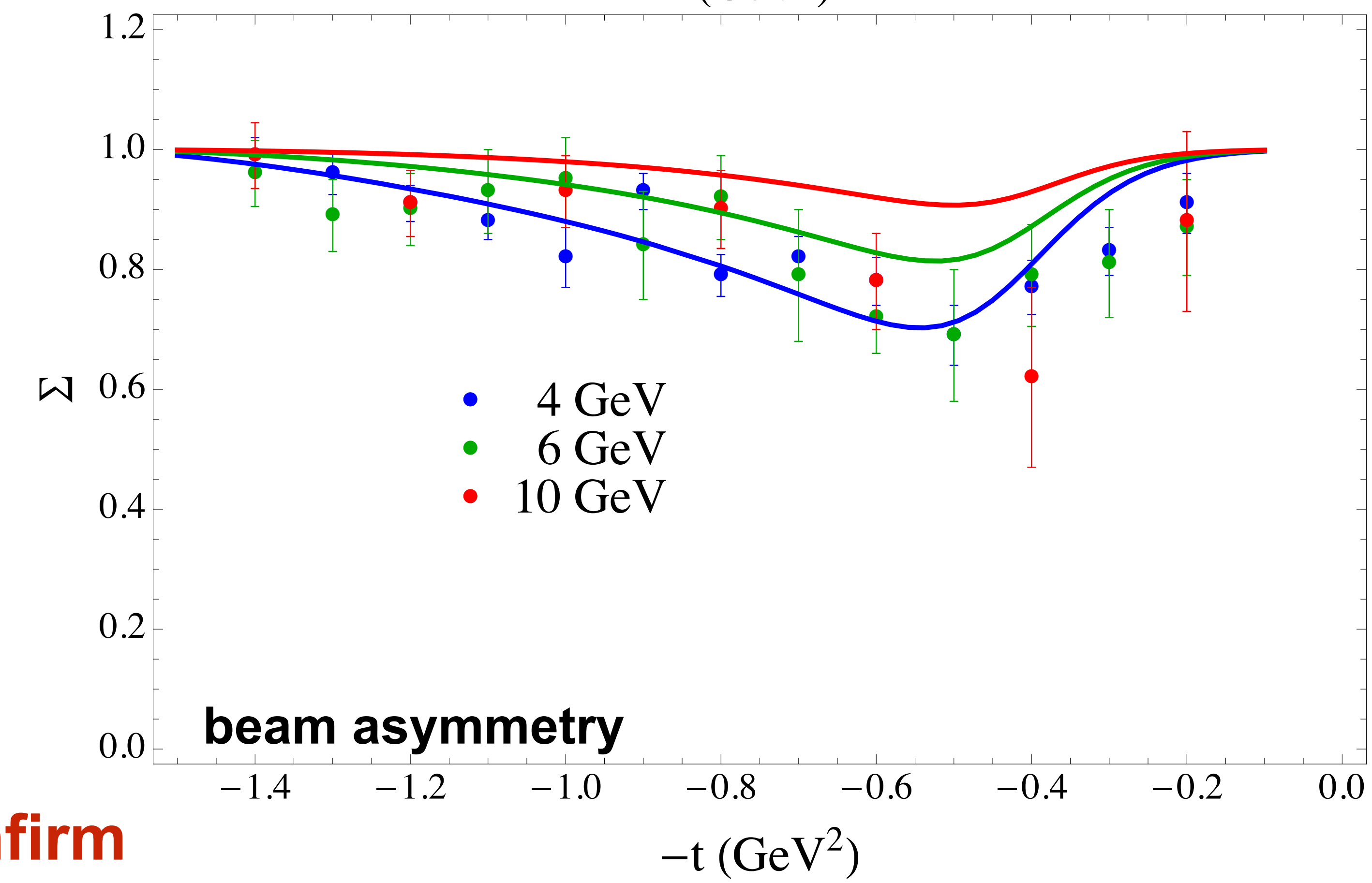


$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$

axial-vector exchanges strength decreases with energy

More precise data@JLAB could confirm

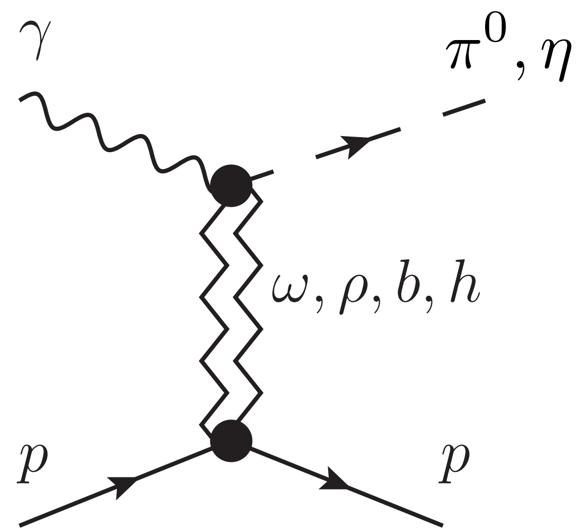


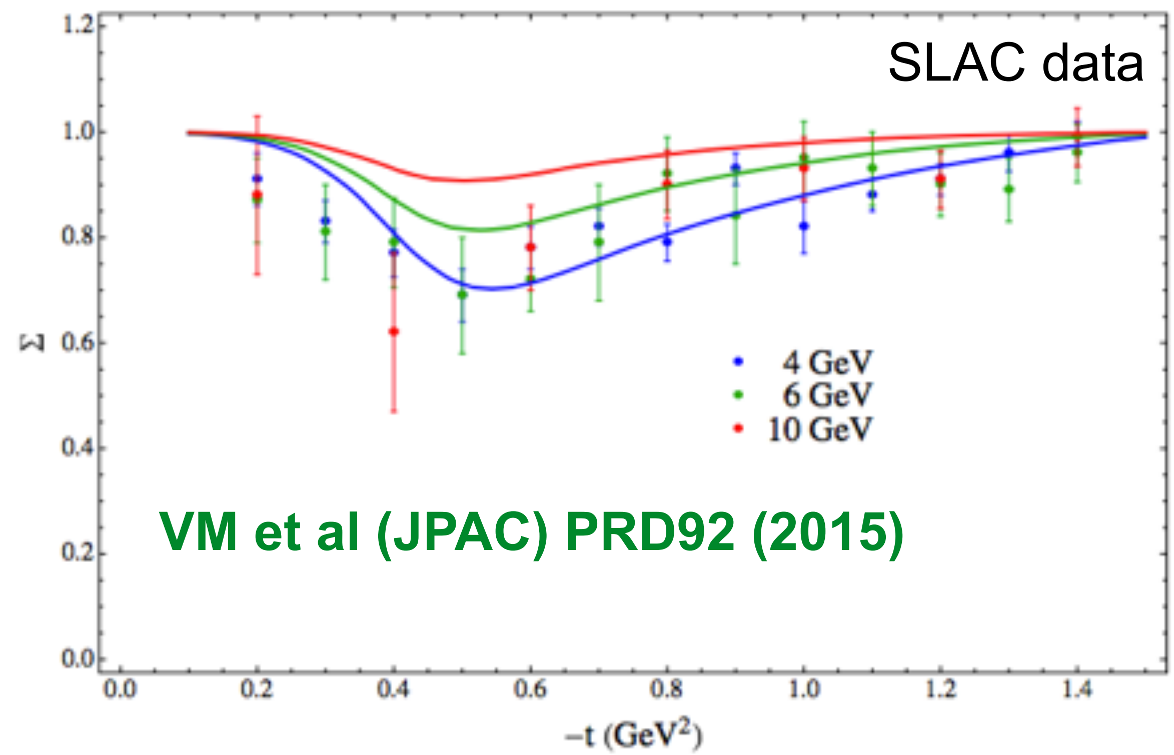


VM, Szczepaniak and Fox Phys. Rev. D. 92 074013

Beam Asymmetries @ GlueX

$\pi^0, \eta(0^{-+})$ **have same production as** $\pi_1^0, \eta_1(1^{-+})$

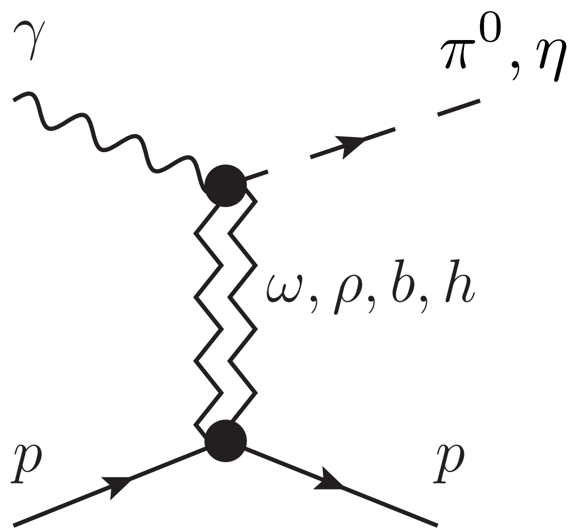


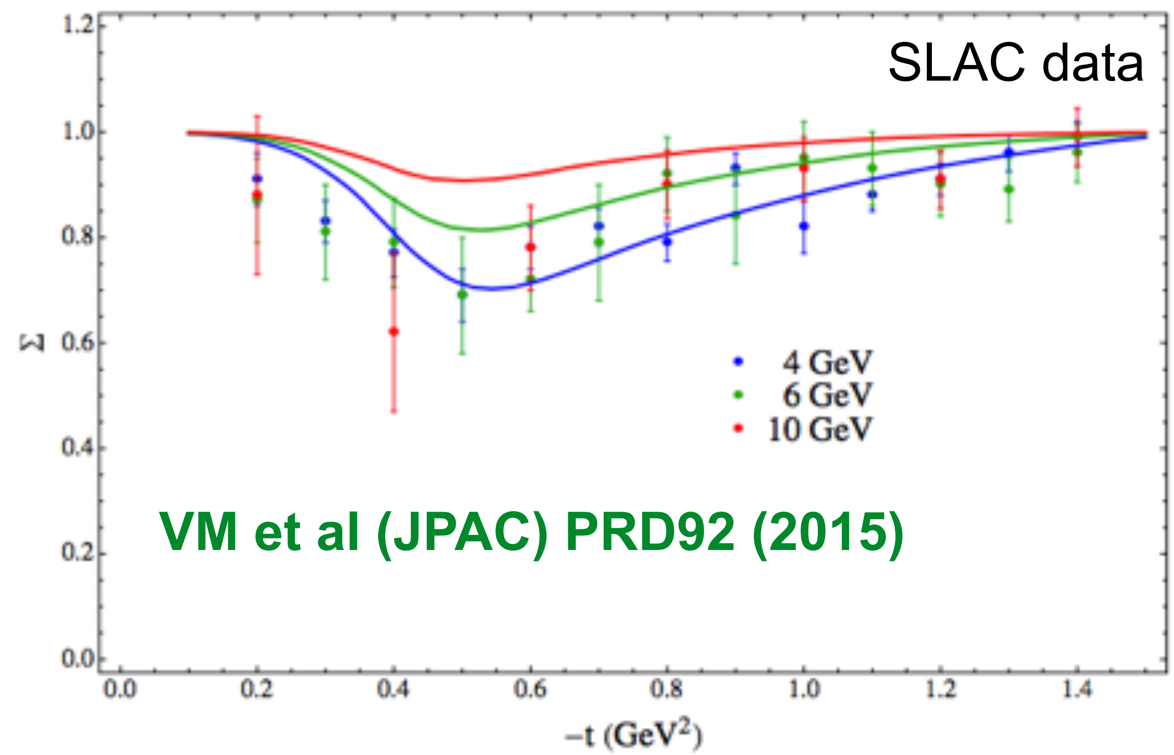


$$\Sigma = \frac{|\rho + \omega|^2 - |b + h|^2}{|\rho + \omega|^2 + |b + h|^2}$$

Beam Asymmetries @ GlueX

$\pi^0, \eta(0^{-+})$ **have same production as** $\pi_1^0, \eta_1(1^{-+})$





$$\Sigma = \frac{|\rho+\omega|^2 - |b+h|^2}{\boxed{|\rho+\omega|^2} + \boxed{|b+h|^2}}$$

grow with E_γ constant with E_γ

$\rho, \omega \sim s^{0.5}$ $b, h \sim s^{0.0}$

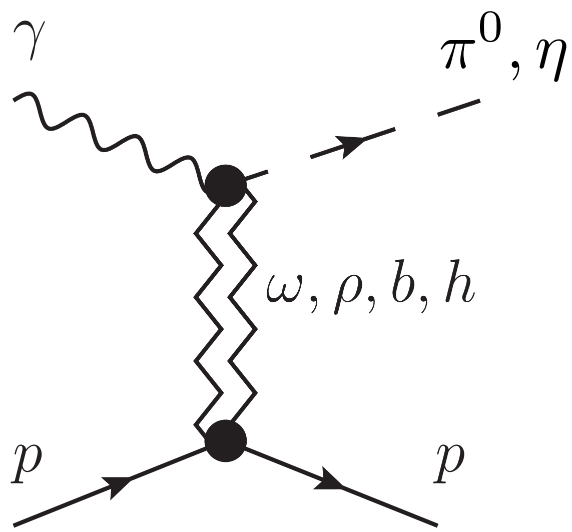
$\Sigma \to 1$ as E_γ increases

Beam Asymmetries @ GlueX

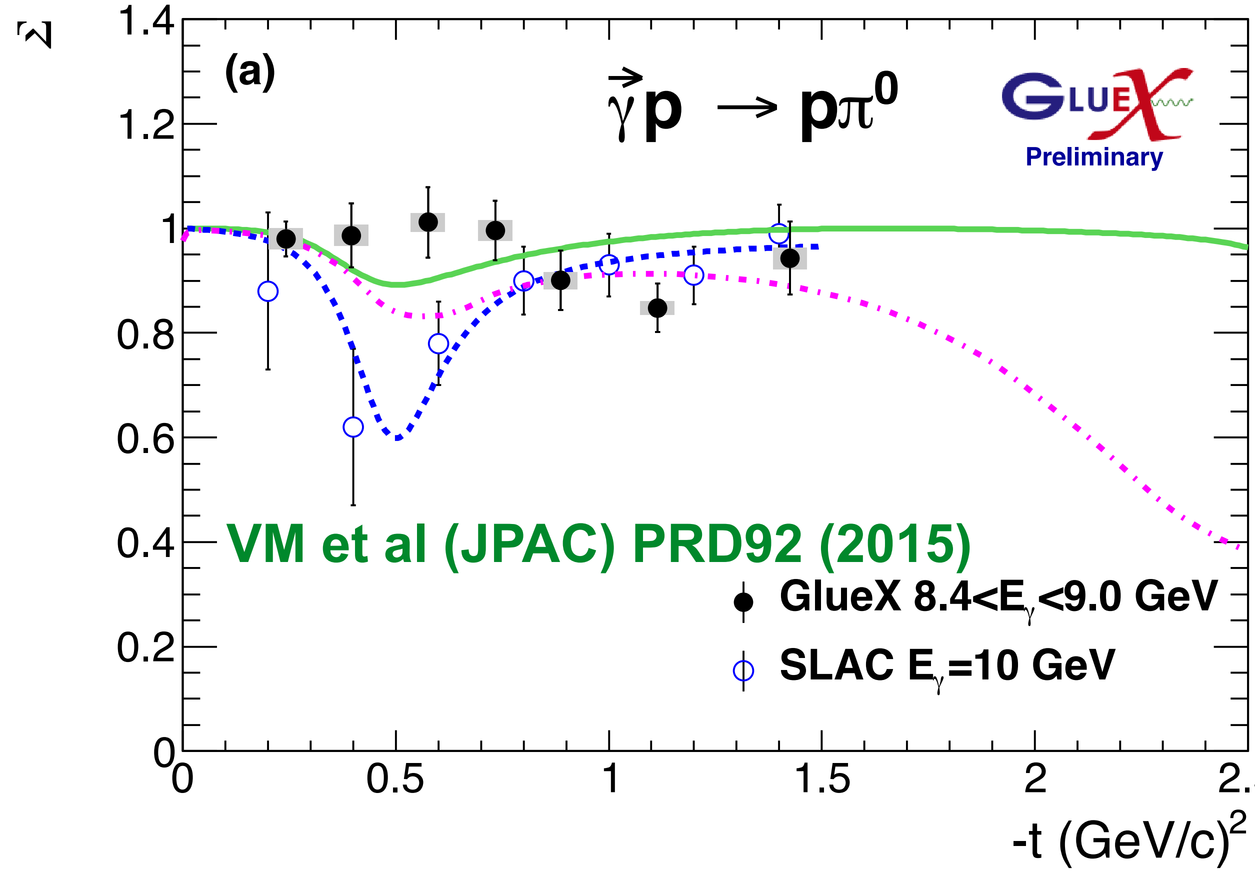
$\pi^0, \eta(0^{-+})$ **have**

same production as

$\pi_1^0, \eta_1(1^{-+})$



GlueX, VM and J. Nys PRC (2017)



$$\Sigma = \frac{|\rho + \omega|^2 - |b + h|^2}{|\rho + \omega|^2 + |b + h|^2}$$

grow with E_γ constant with E_γ

$\rho, \omega \sim s^{0.5}$ $b, h \sim s^{0.0}$

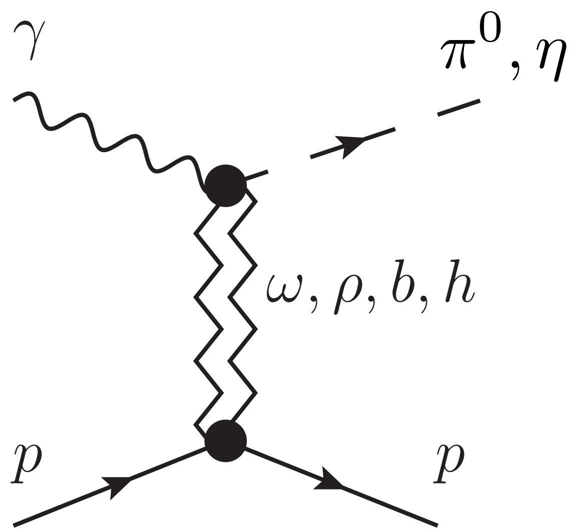
$\Sigma \to 1$ as E_γ increases

Beam Asymmetries @ GlueX

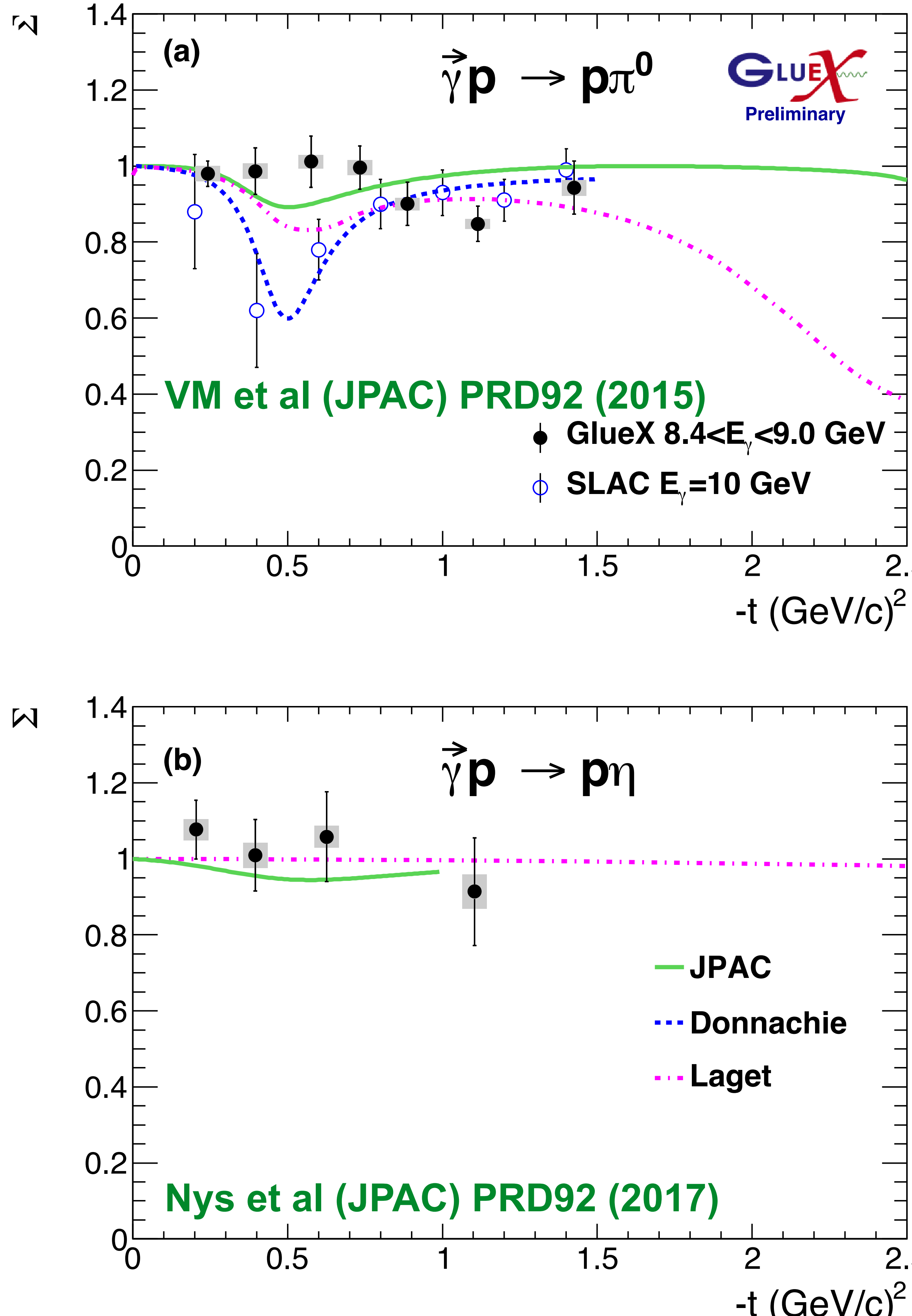
$\pi^0, \eta(0^{-+})$ **have**

same production as

$\pi_1^0, \eta_1(1^{-+})$



GlueX, VM and J. Nys PRC (2017)



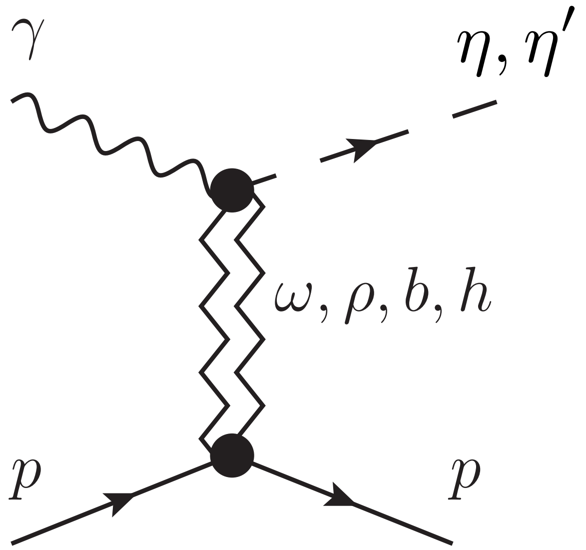
$$\Sigma = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$

grow with E_γ constant with E_γ

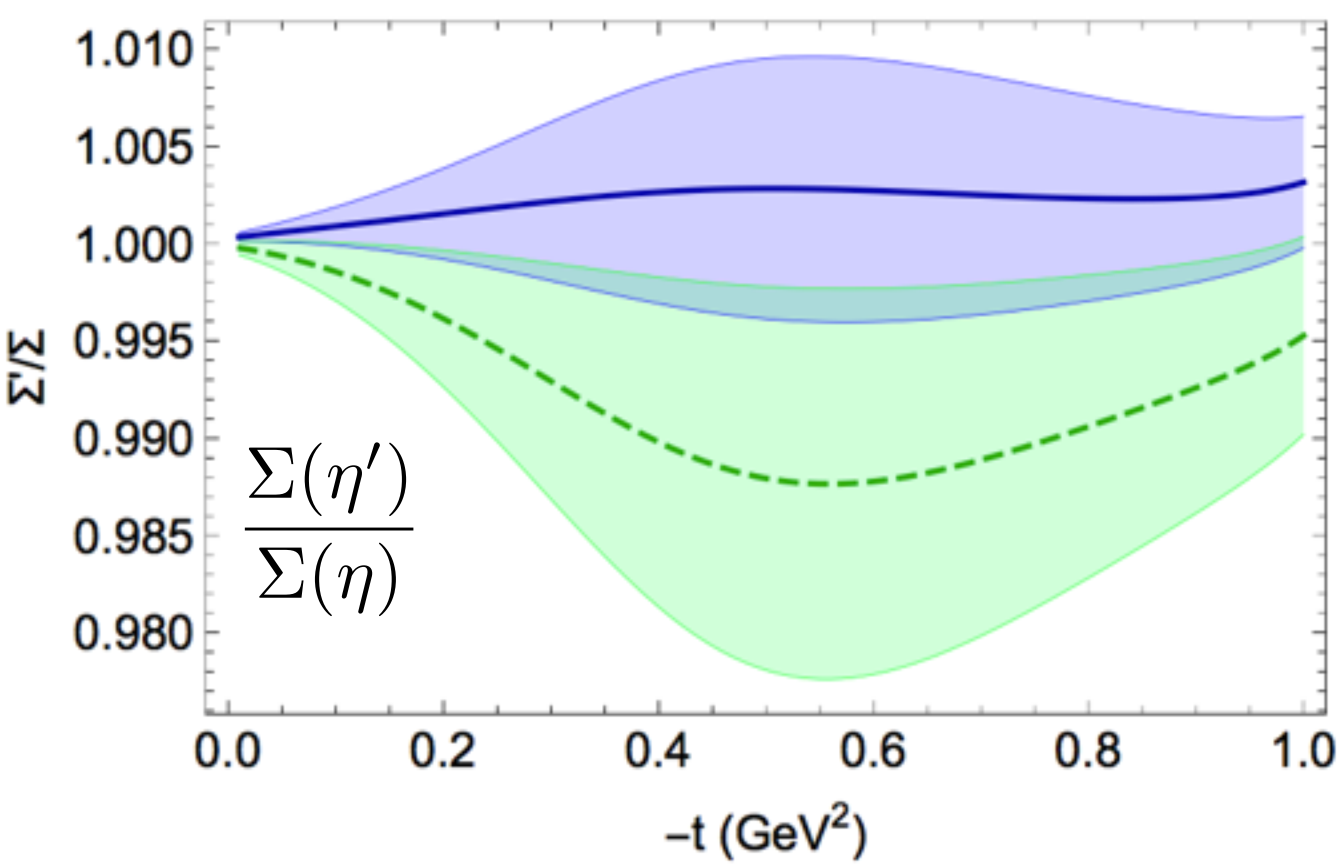
$\rho, \omega \sim s^{0.5}$ $b, h \sim s^{0.0}$

$\Sigma \to 1$ as E_γ increases

Beam Asymmetries @ GlueX



$$\Sigma(\eta) = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 - |b+h|^2}$$
$$= \Sigma(\eta')$$



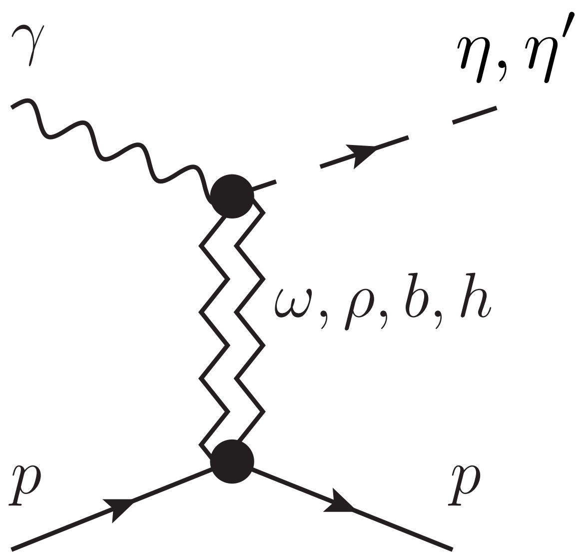
Beam asymmetry Difference probes strange exchanges contribution

blue and green models represent the estimation of systematic errors

GlueX Preliminary results expected at the APS meeting (October 25-27th 2017)

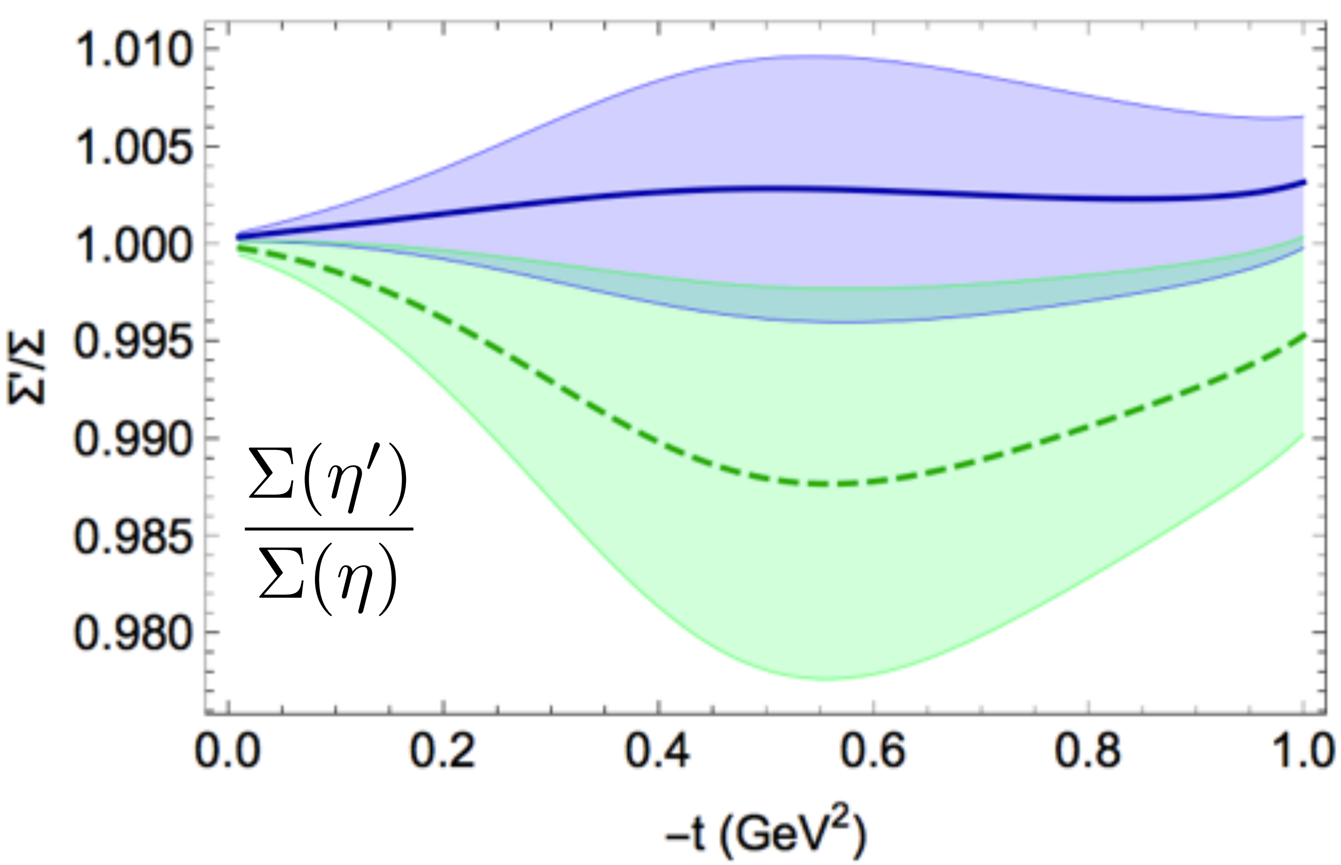
VM et al. (JPAC) arXiv:1704.07684

Beam Asymmetries @ GlueX



$$\Sigma(\eta) = \frac{|\rho + \omega + \phi|^2 - |b + h + h'|^2}{|\rho + \omega + \phi|^2 - |b + h + h'|^2}$$

$$\neq \Sigma(\eta')$$



Beam asymmetry Difference probes strange exchanges contribution

blue and green models represent the estimation of systematic errors

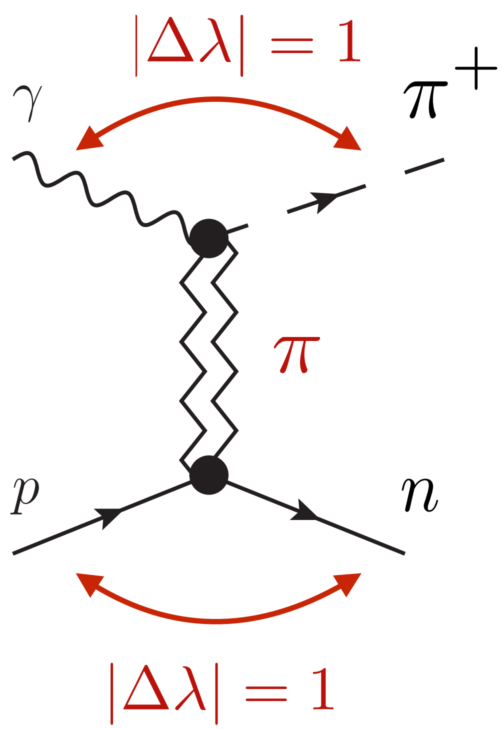
GlueX Preliminary results expected at the APS meeting (October 25-27th 2017)

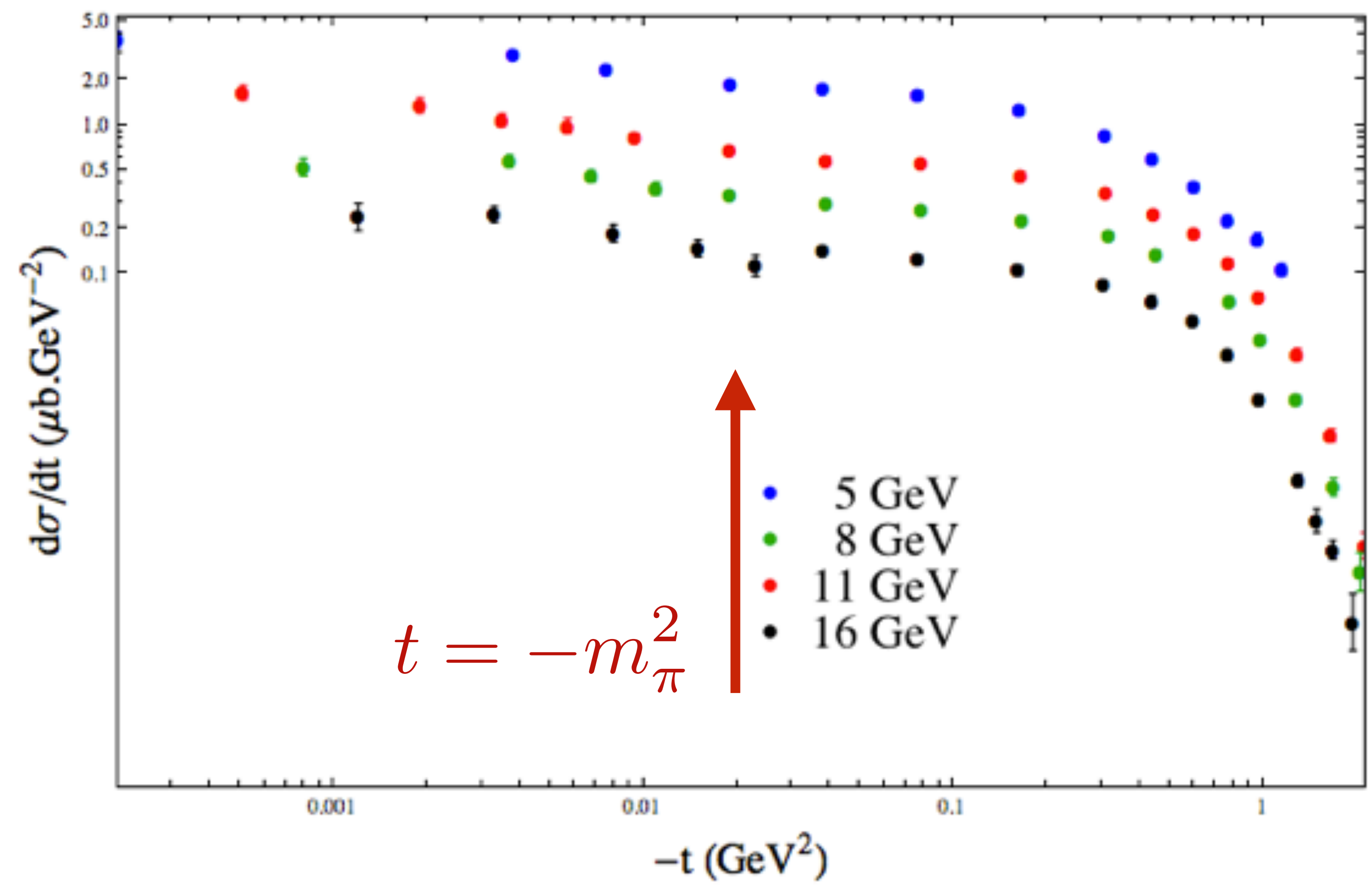
VM et al. (JPAC) arXiv:1704.07684

$\gamma p \to \pi^+ n$

Pion dominate very small |t| :

[Boyarski et al. 1968]





Factorization of Regge residues:

$(\lambda_\gamma, \lambda_\pi) = (1, 0)$ **and**

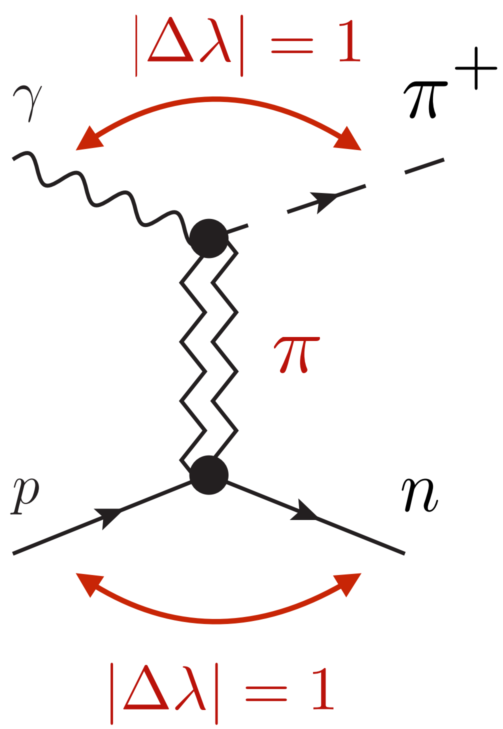
$$(\lambda_p, \lambda_n) = \left(-\frac{1}{2}, +\frac{1}{2}\right) \qquad A^{10}_{-\frac{1}{2}\,\frac{1}{2}} \propto \frac{-t}{m_\pi^2 - t}$$

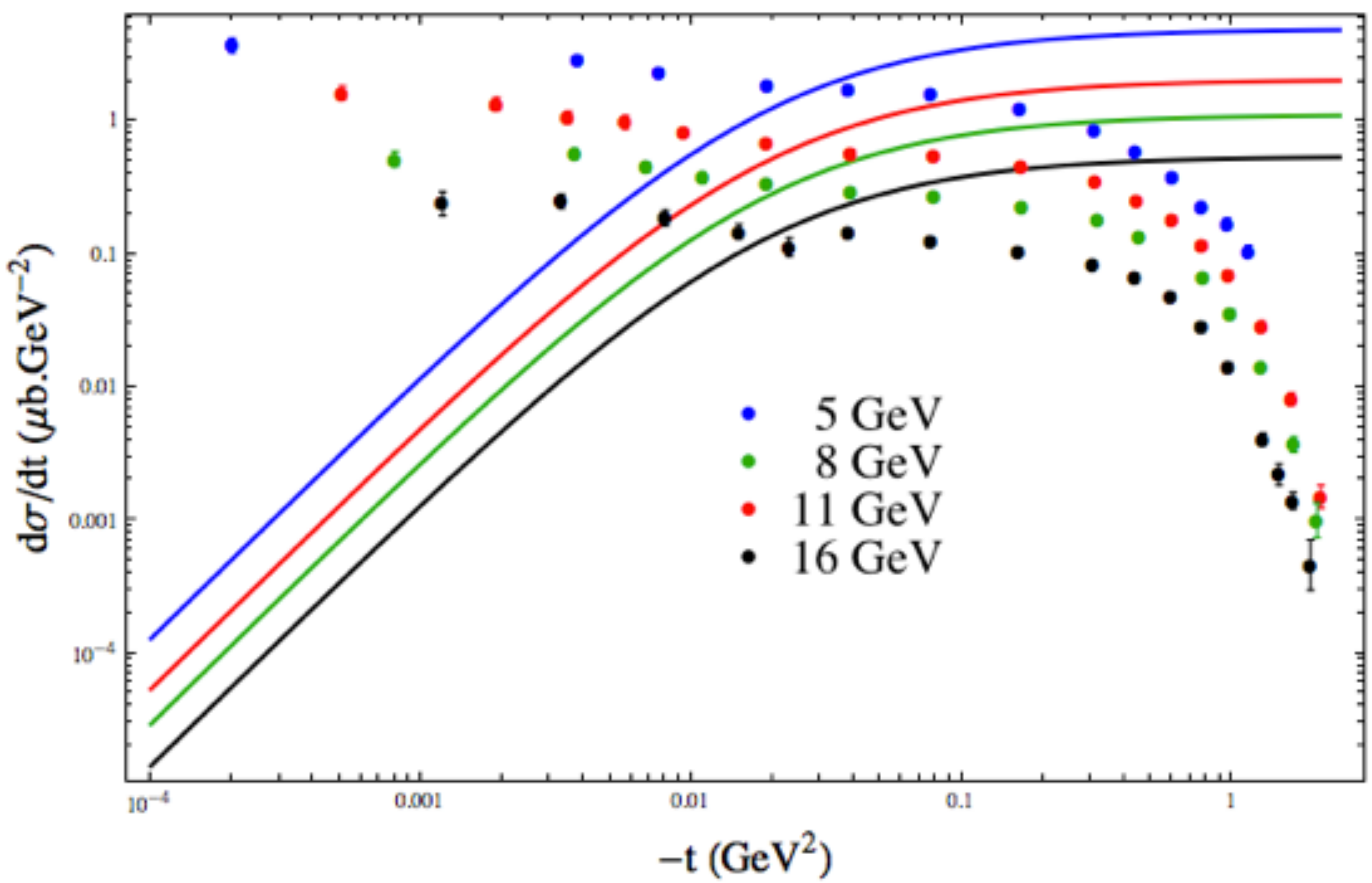
$$(\lambda_p, \lambda_n) = \left(+\frac{1}{2}, -\frac{1}{2}\right) \qquad A^{10}_{\frac{1}{2}-\frac{1}{2}} \propto \frac{-t}{m_\pi^2 - t}$$

$$\gamma p \to \pi^+ n$$

Pion dominate very small |t| :

[Boyarski et al. 1968]





Factorization of Regge residues:

$(\lambda_\gamma, \lambda_\pi) = (1, 0)$ **and**

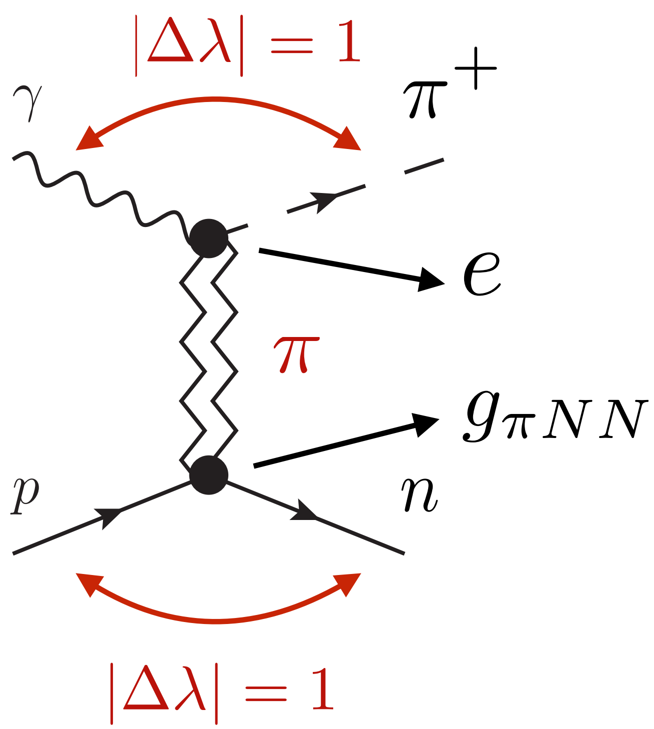
$$(\lambda_p, \lambda_n) = \left(-\frac{1}{2}, +\frac{1}{2}\right) \qquad A^{10}_{-\frac{1}{2}\,\frac{1}{2}} \propto \frac{-t}{m_\pi^2 - t}$$

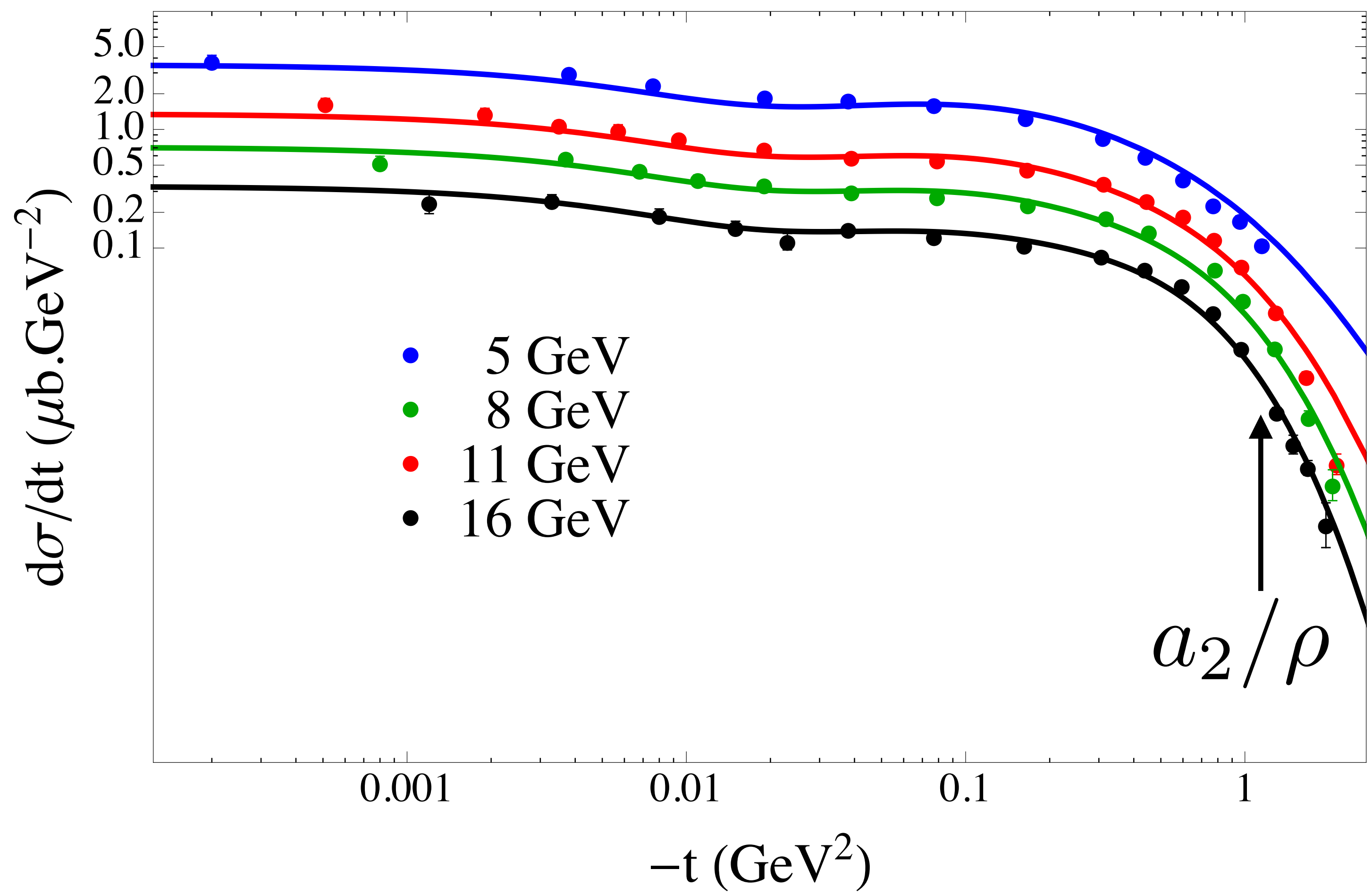
$$(\lambda_p, \lambda_n) = \left(+\frac{1}{2}, -\frac{1}{2}\right) \qquad A^{10}_{\frac{1}{2}\,-\frac{1}{2}} \propto \frac{-t}{m_\pi^2 - t}$$

$\gamma p \to \pi^+ n$

Pion dominate very small |t| :

[Boyarski et al. 1968]





Factorization of Regge residues:

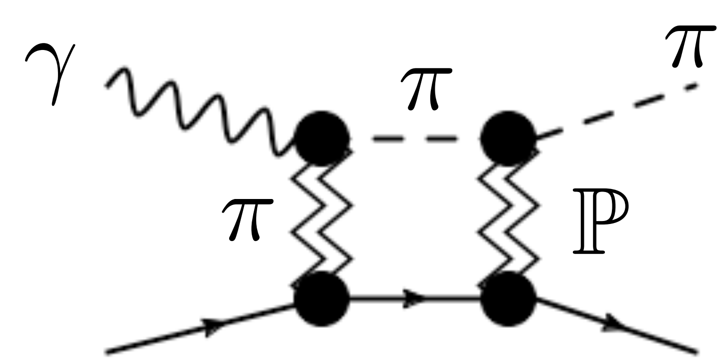
$(\lambda_\gamma, \lambda_\pi) = (1, 0)$ **and**

$$(\lambda_p, \lambda_n) = \left(-\frac{1}{2}, +\frac{1}{2}\right) \qquad A^{10}_{-\frac{1}{2}\frac{1}{2}} \propto \frac{-t}{m_\pi^2 - t}$$

$$(\lambda_p, \lambda_n) = \left(+\frac{1}{2}, -\frac{1}{2}\right) \qquad A^{10}_{\frac{1}{2}-\frac{1}{2}} \propto \frac{-t}{m_\pi^2 - t}$$

$$|(\lambda_\gamma - \lambda_p) - (\lambda_\pi - \lambda_{p'})| = 0$$

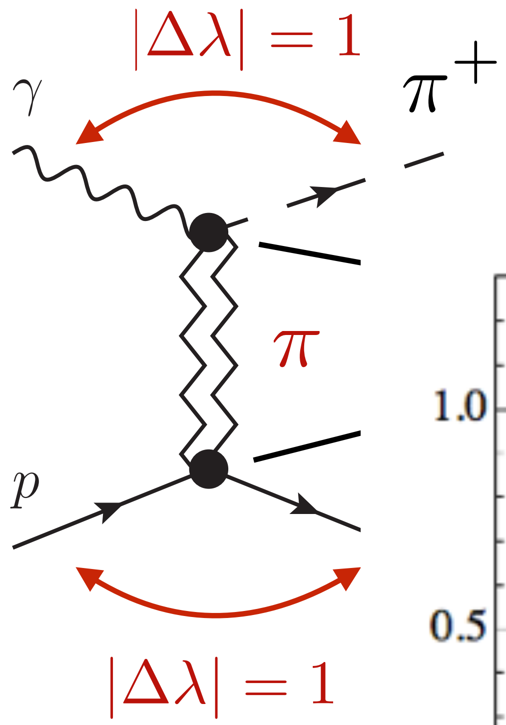
William's Poor man absorption: $\to \dfrac{-m_\pi^2}{m_\pi^2 - t}$

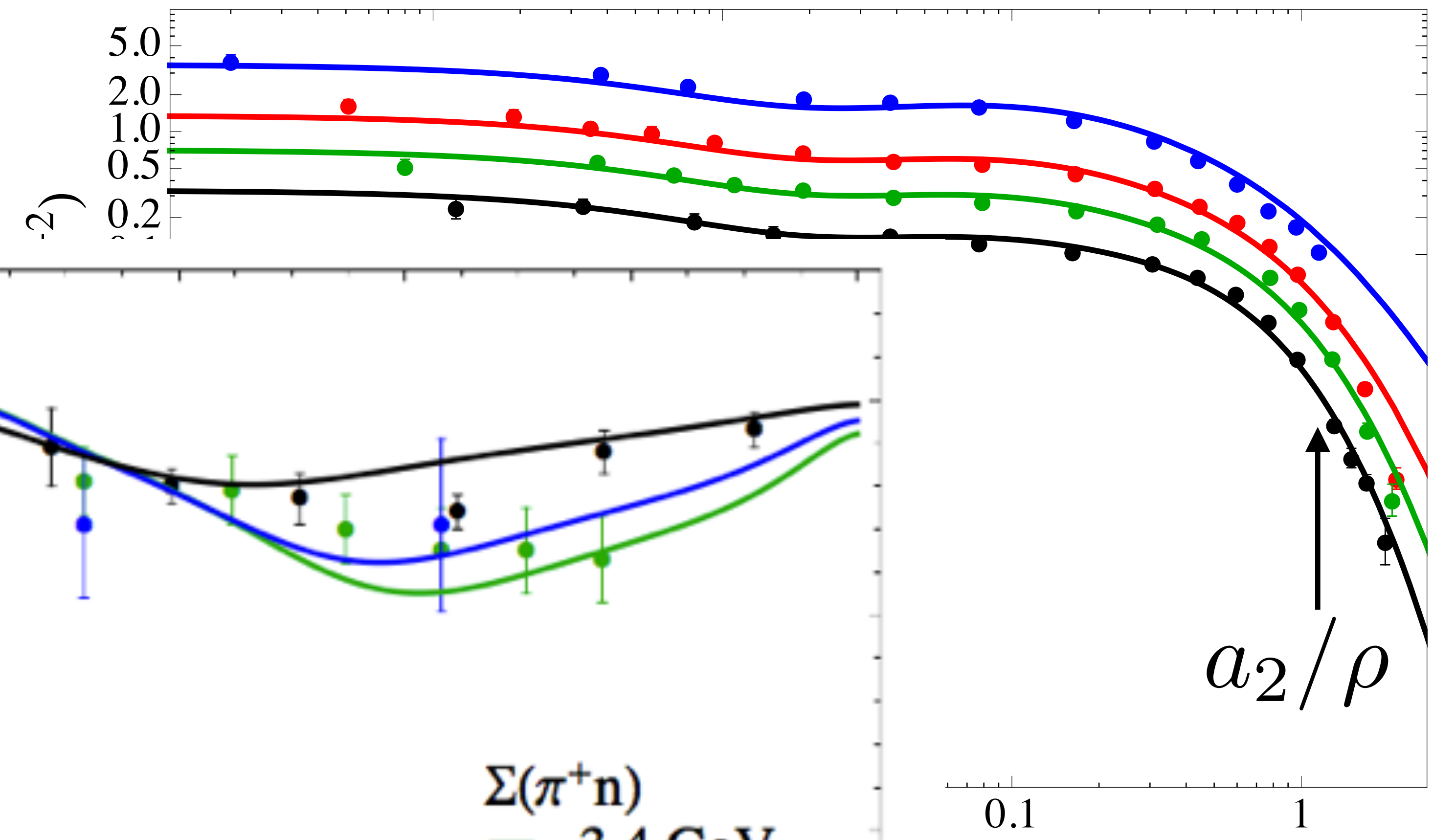


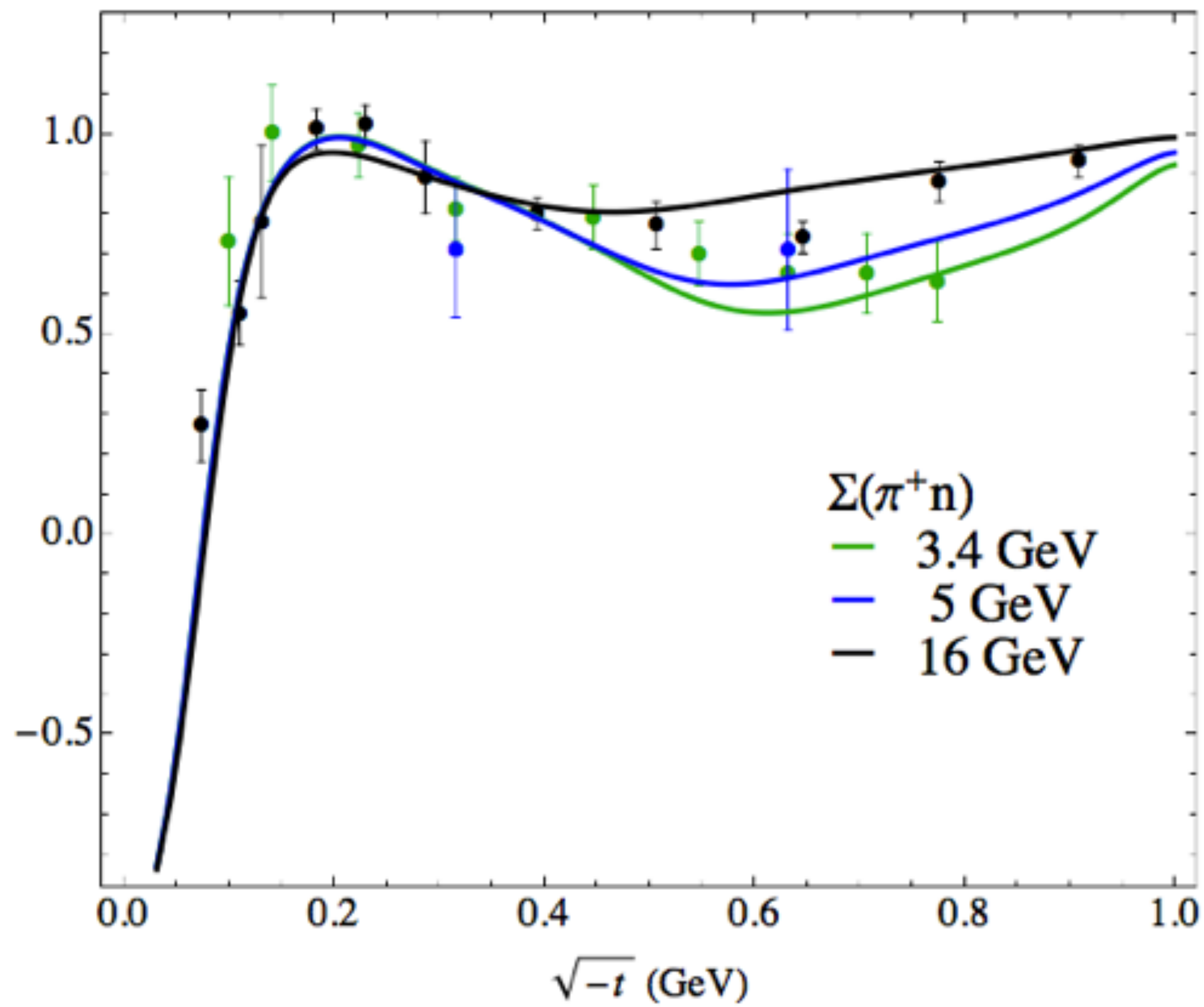
$\gamma p \to \pi^+ n$

Pion dominate very small |t| :

[Boyarski et al. 1968]







Factorization of Reg

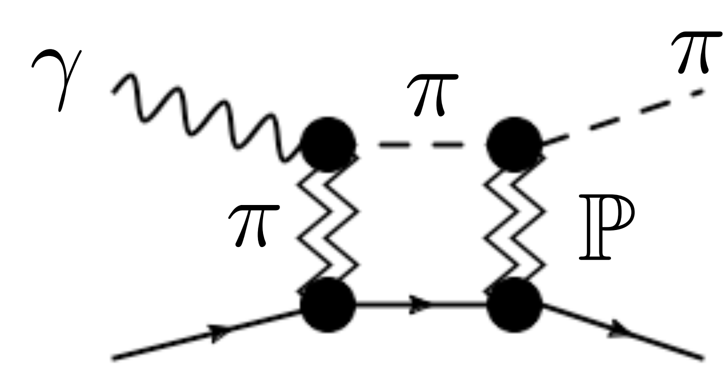
$(\lambda_\gamma, \lambda_\pi) = (1, 0)$ **and**

$$(\lambda_p, \lambda_n) = \left(-\frac{1}{2}, +\frac{1}{2}\right)$$

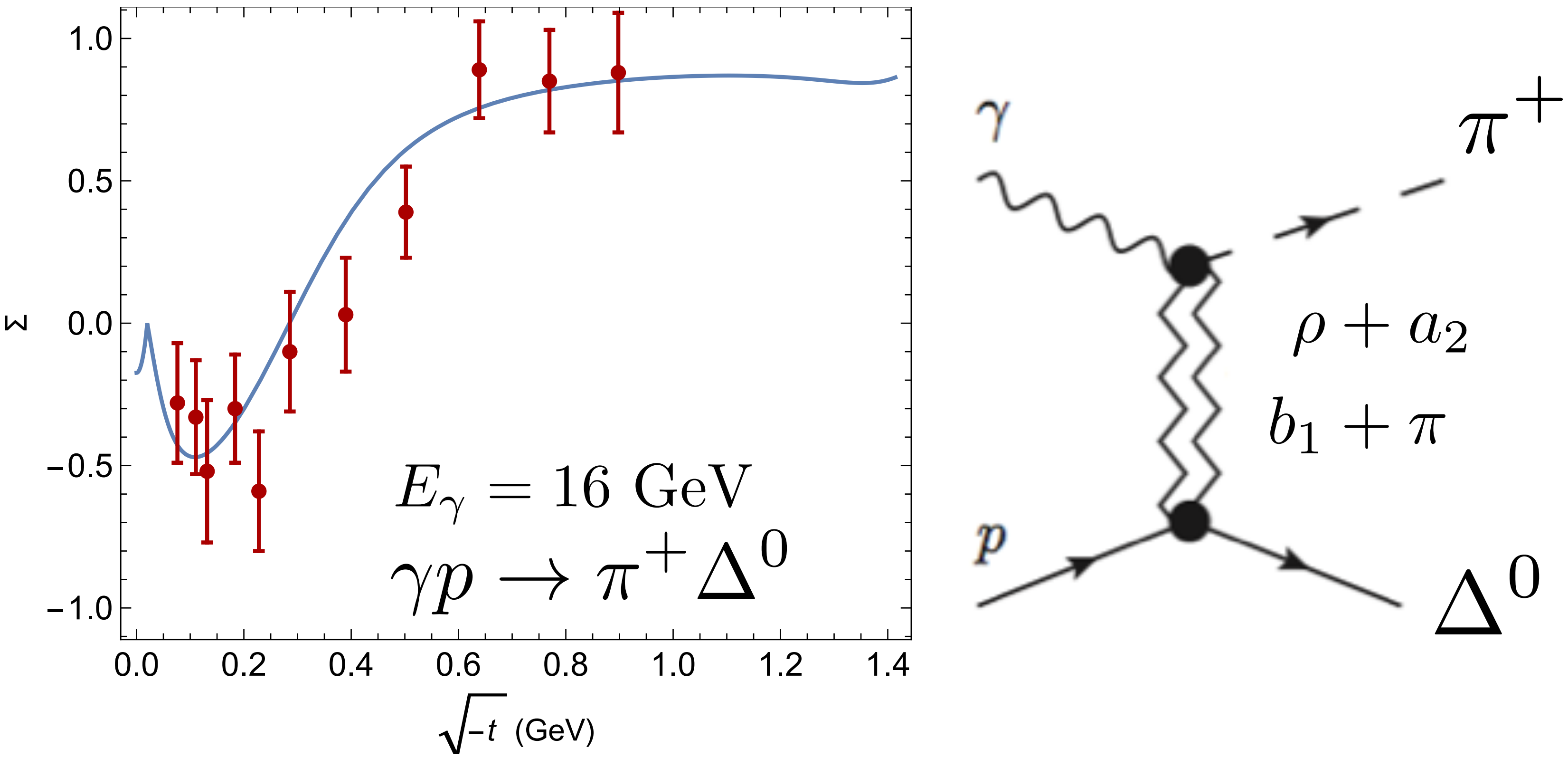
$$(\lambda_p, \lambda_n) = \left(+\frac{1}{2}, -\frac{1}{2}\right)$$

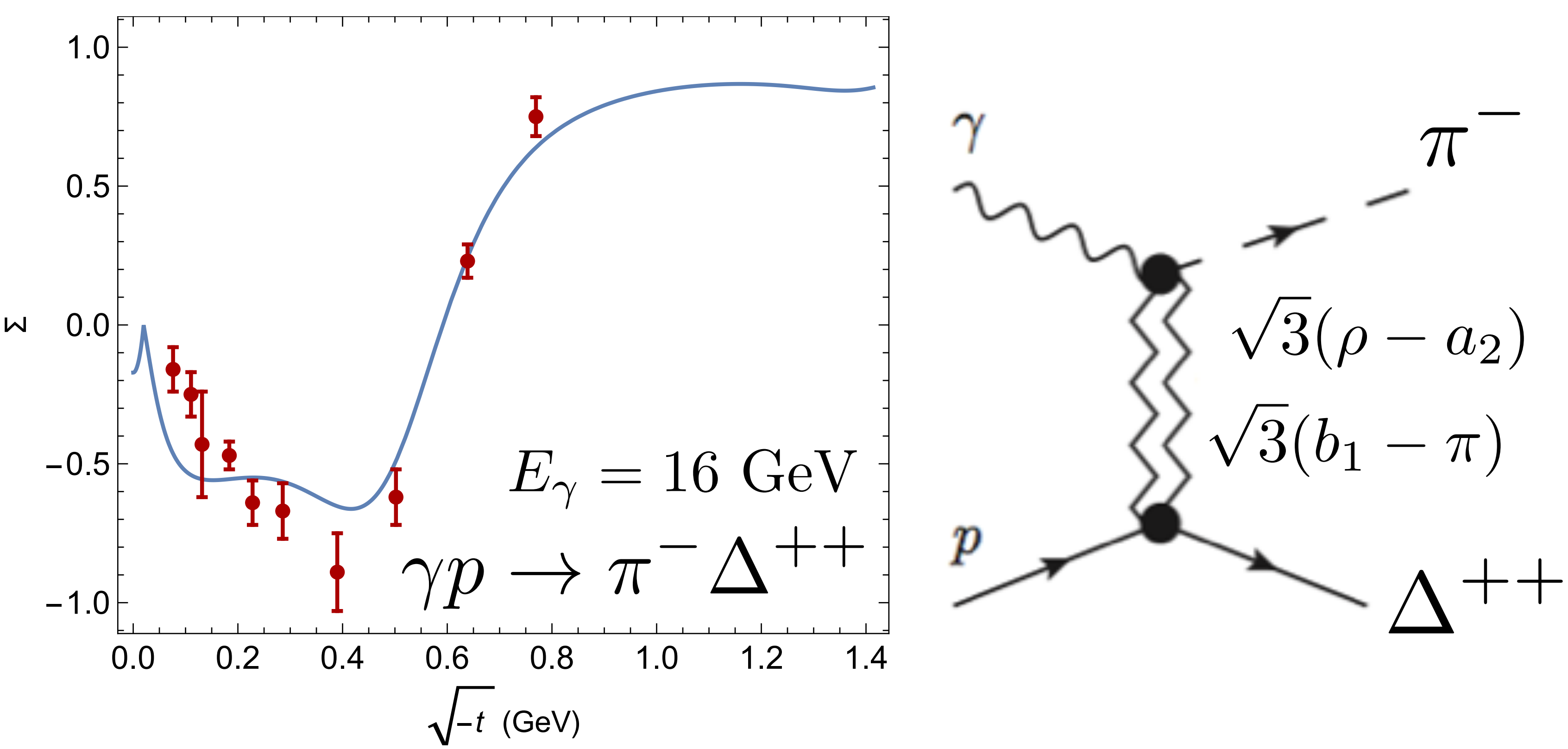
$\lambda_p) - (\lambda_\pi - \lambda_{p'})| = 0$

William's Poor man absorption: $\to \dfrac{-m_\pi^2}{m_\pi^2 - t}$

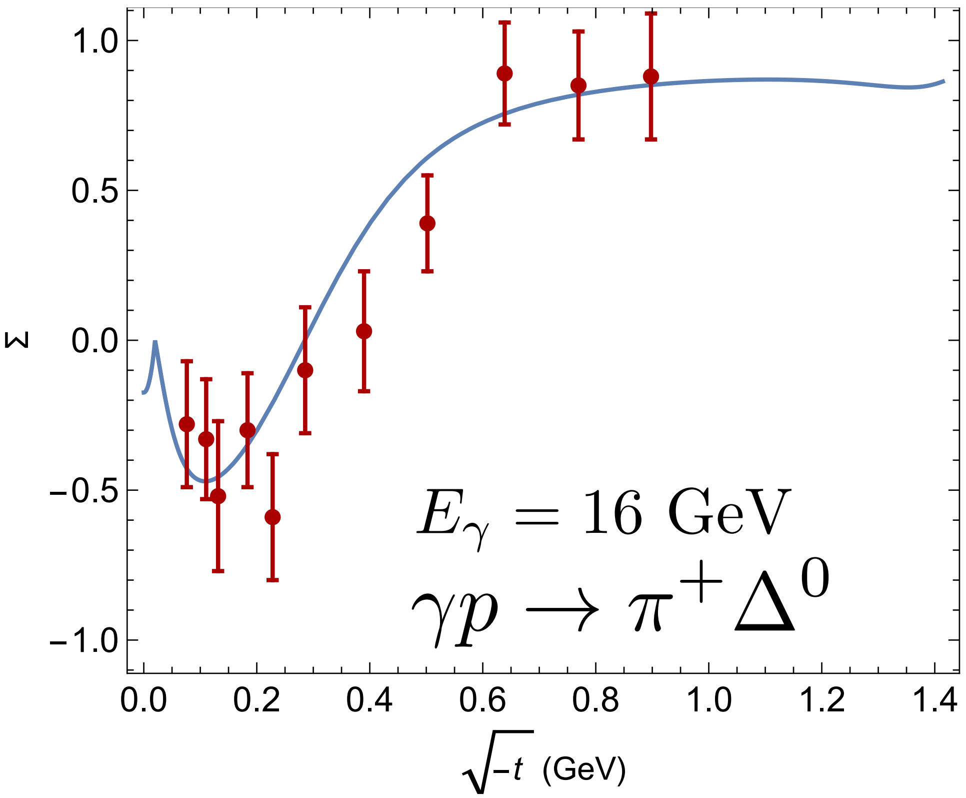


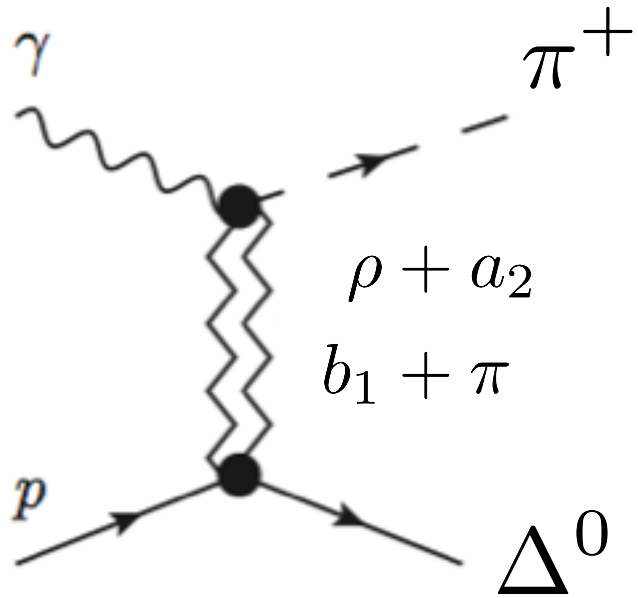
Courtesy of J. Nys



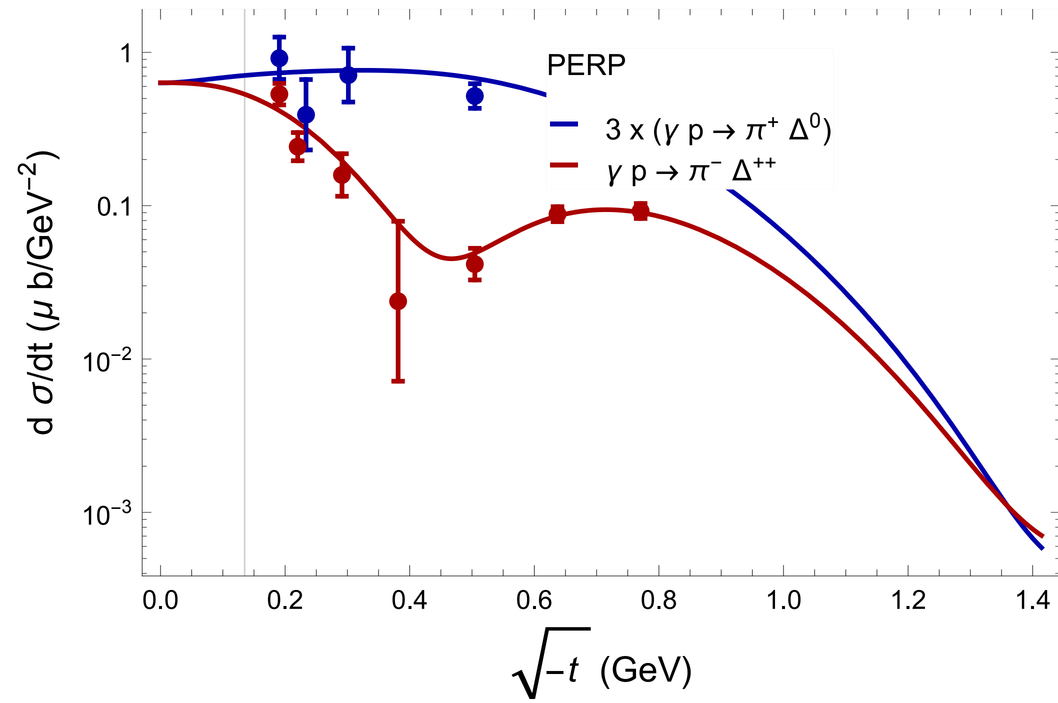


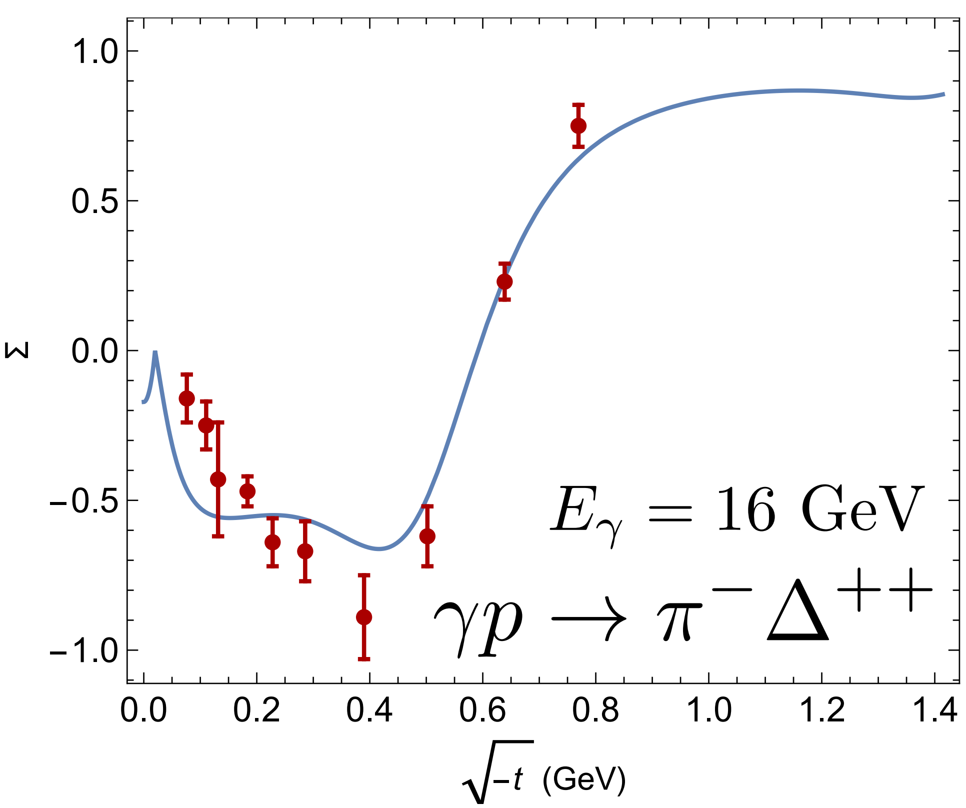
Courtesy of J. Nys

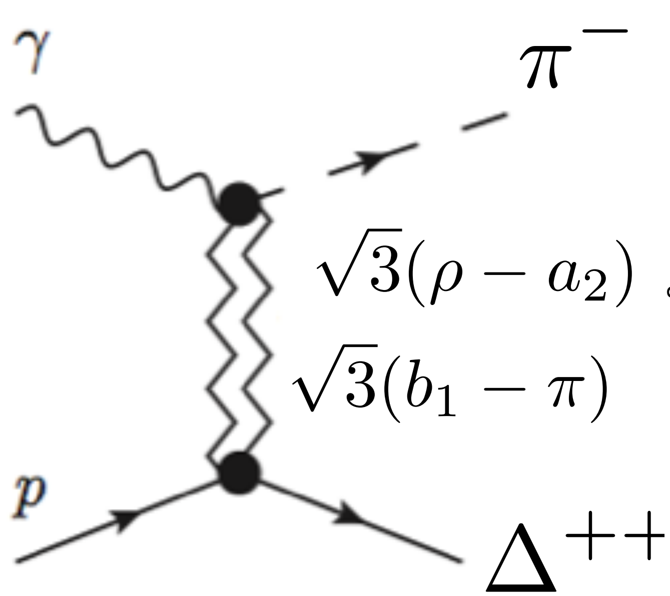




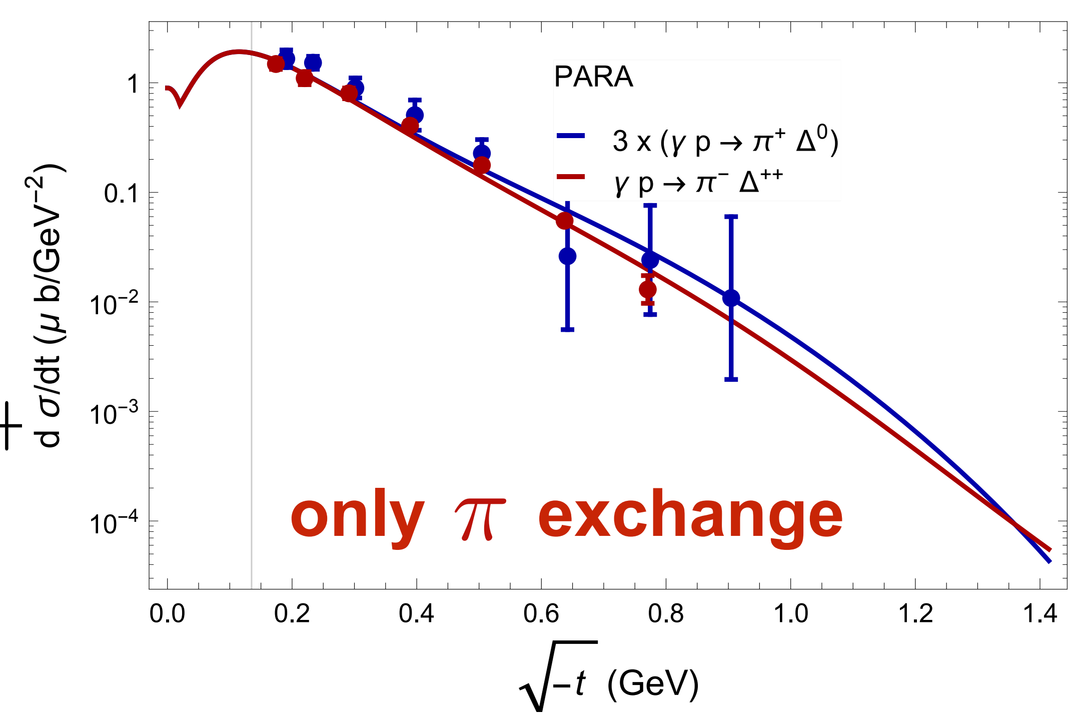
$\sigma_\perp : \rho \pm a_2$

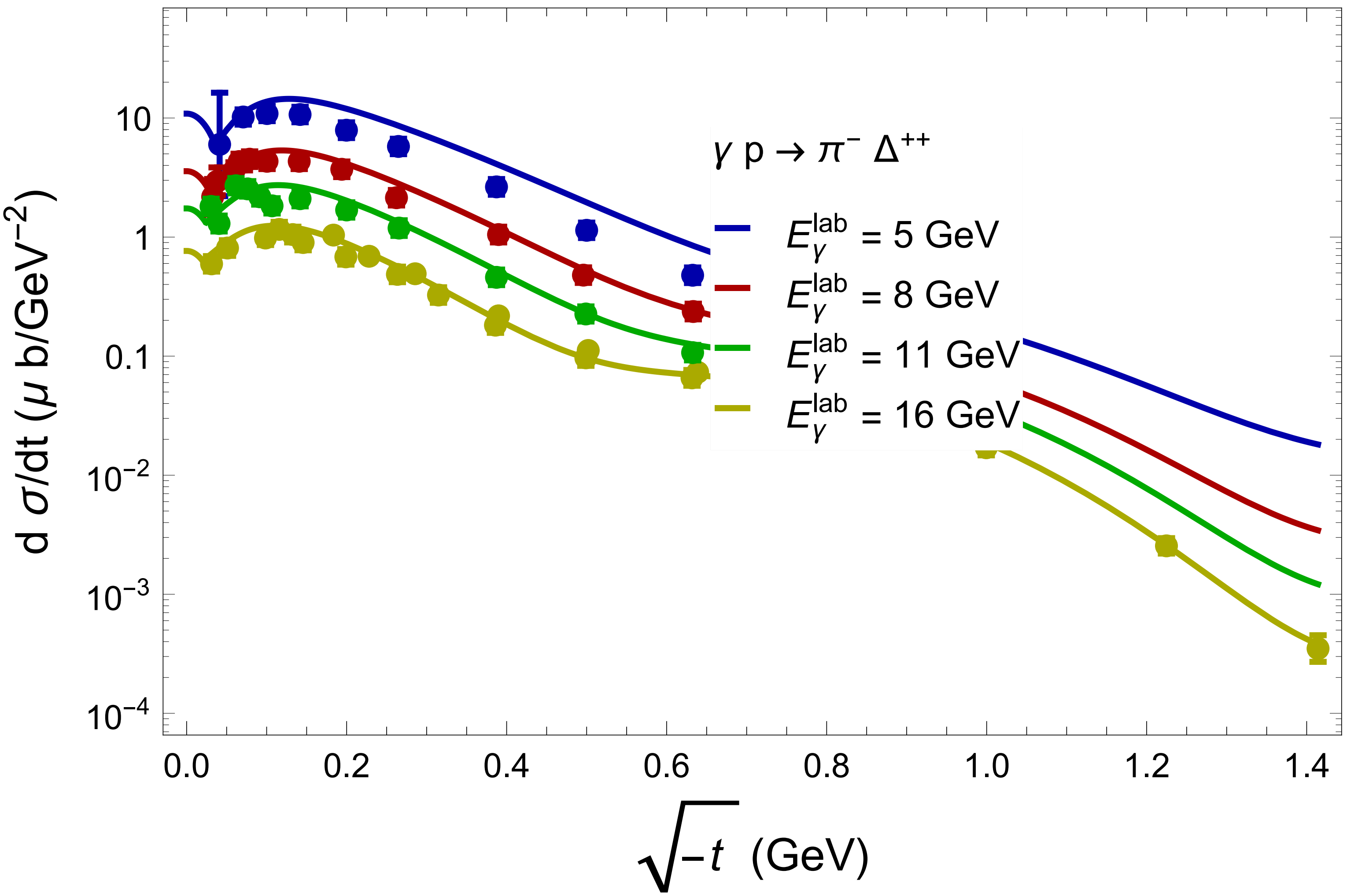




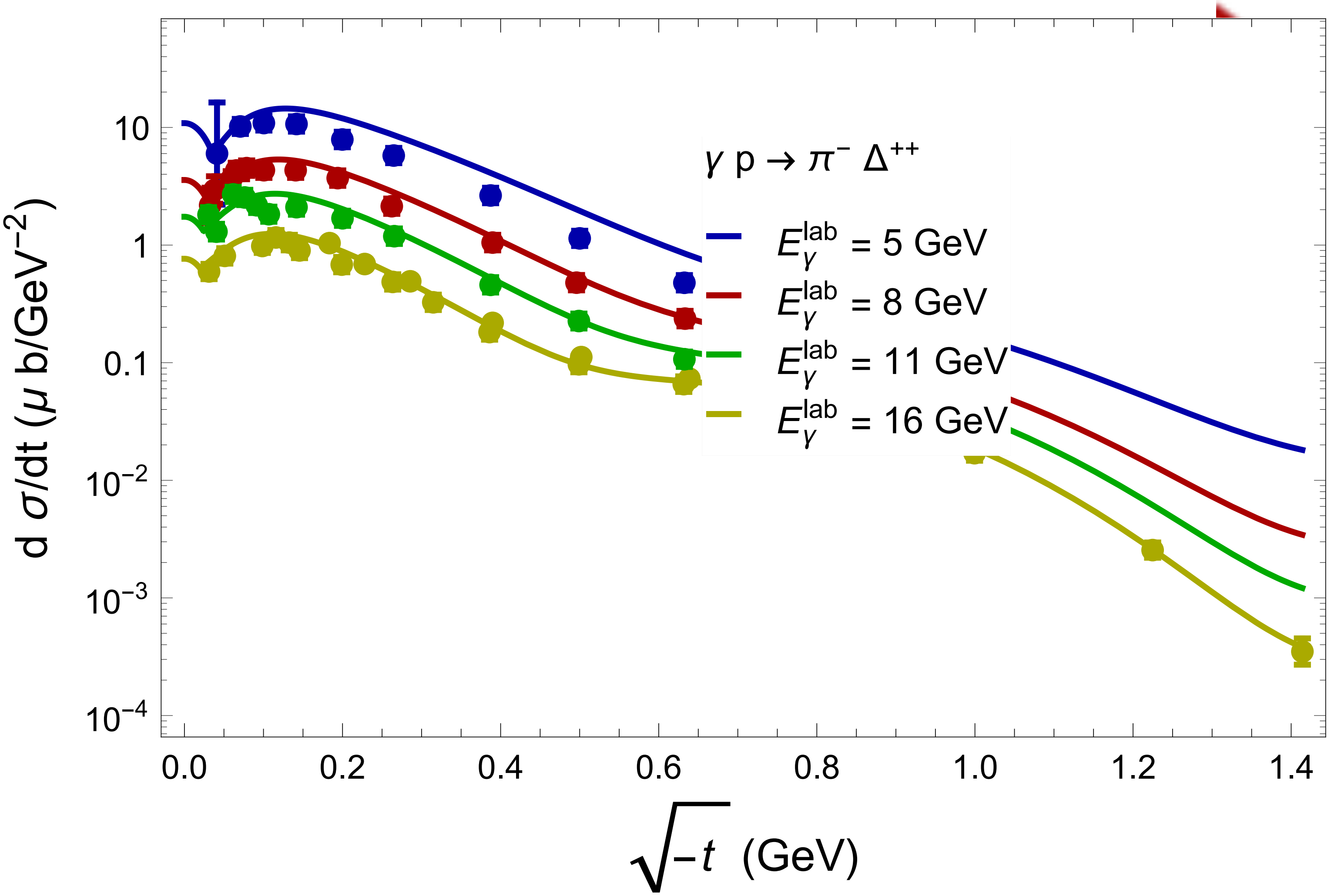


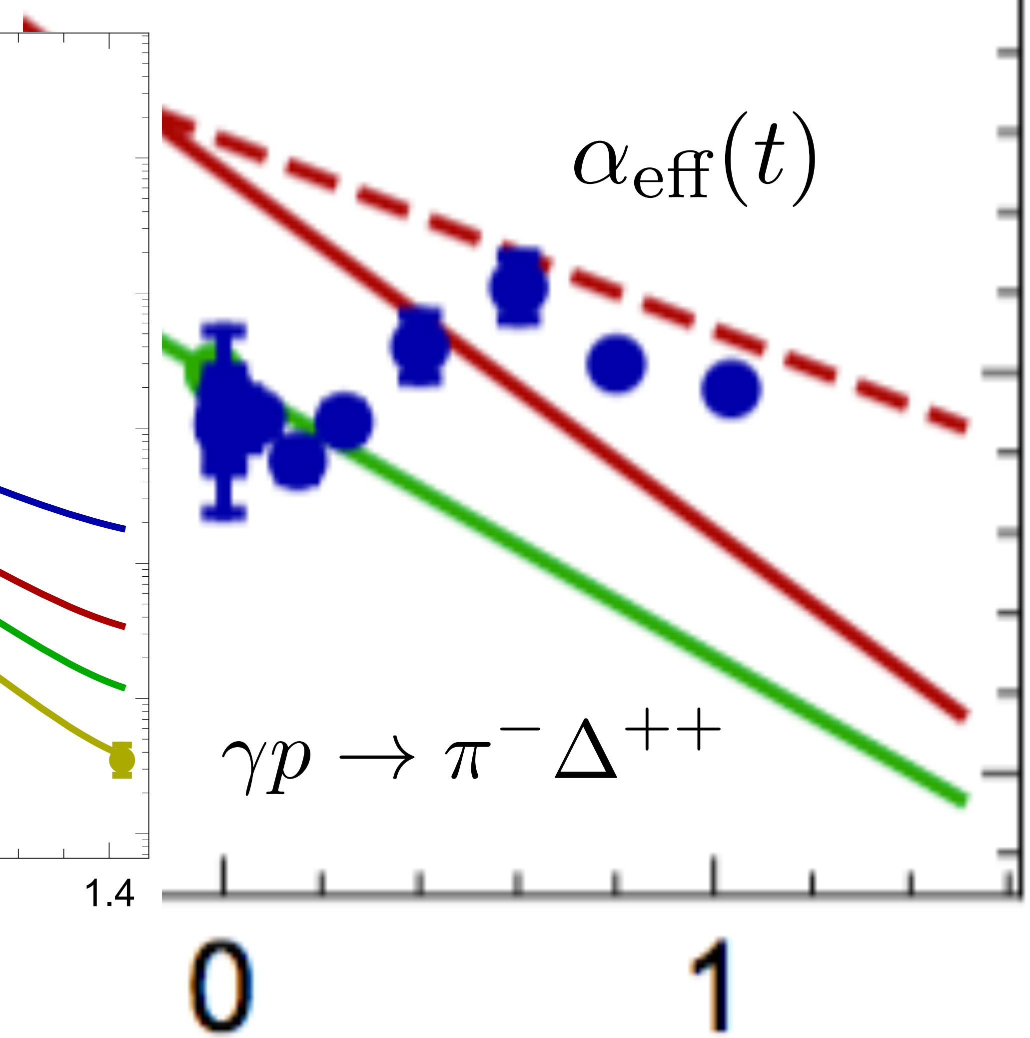
$\sigma_\parallel : b_1 \pm \pi$

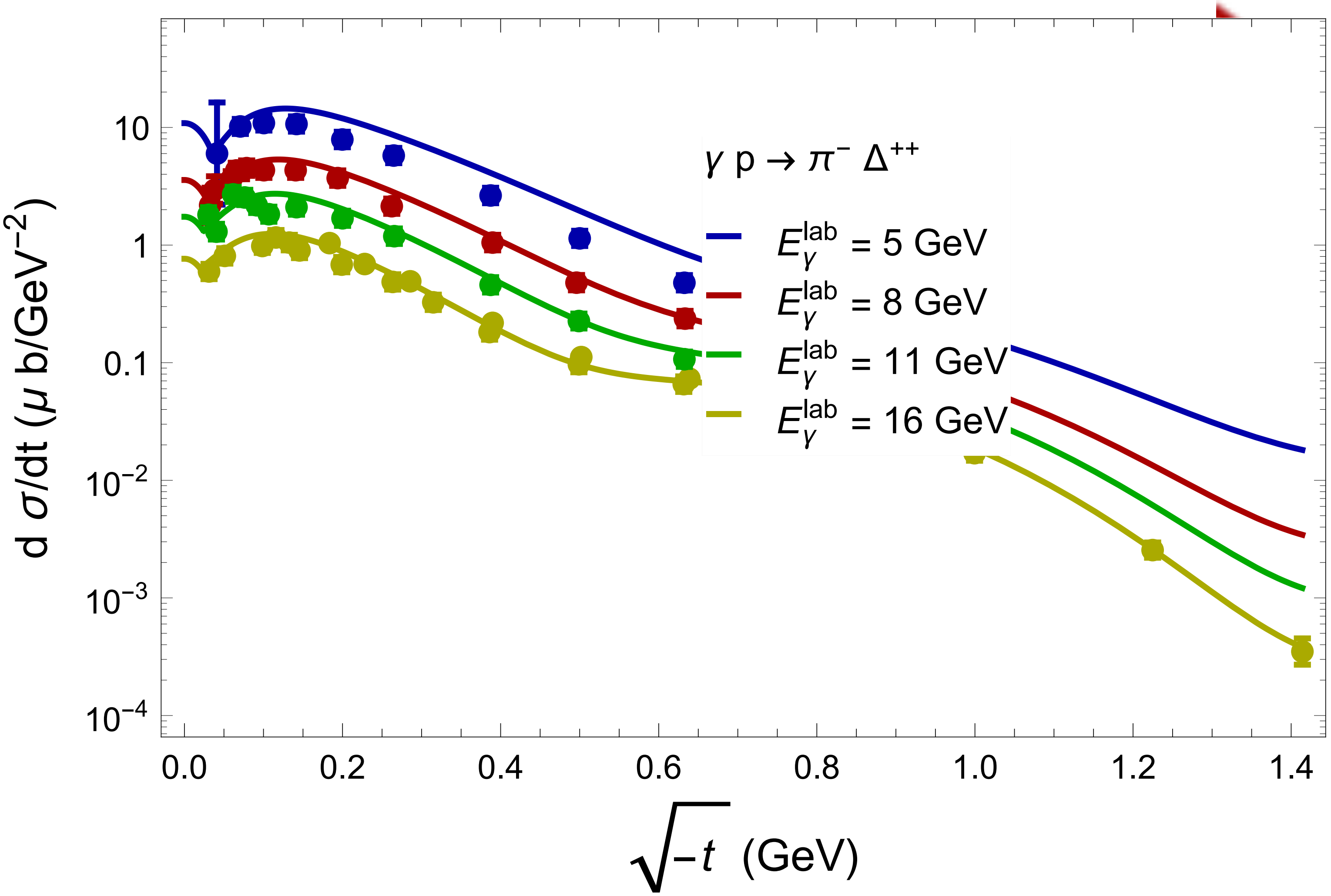


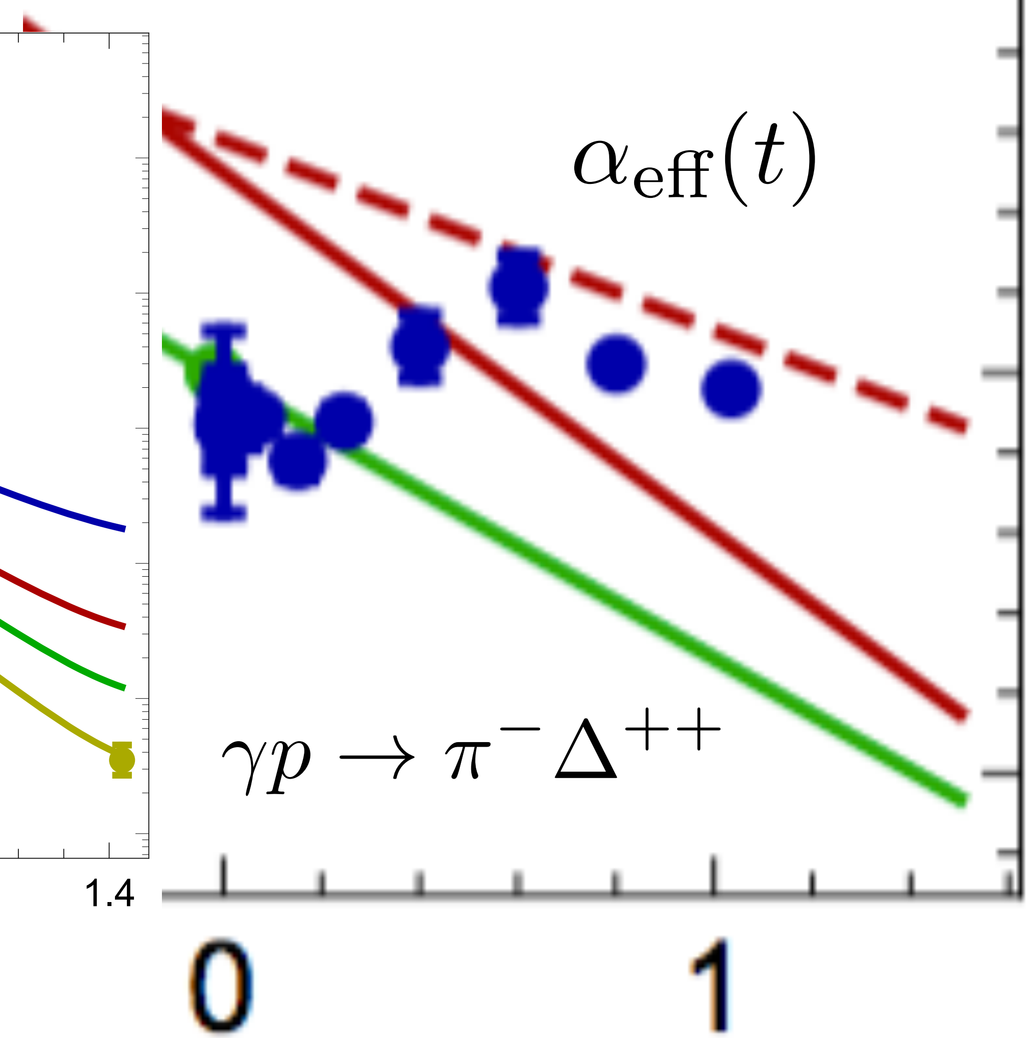


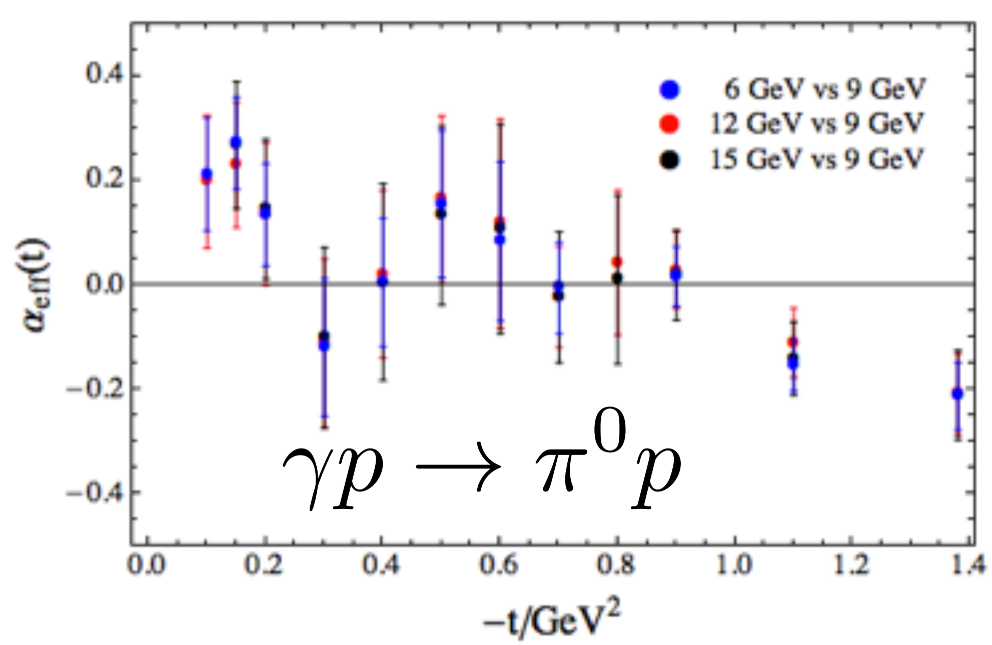
$\gamma\, p \to \pi^- \Delta^{++}$
E_γ^{lab} = 5 GeV
E_γ^{lab} = 8 GeV
E_γ^{lab} = 11 GeV
E_γ^{lab} = 16 GeV
d σ/dt (μ b/GeV^{-2})
$\sqrt{-t}$ (GeV)

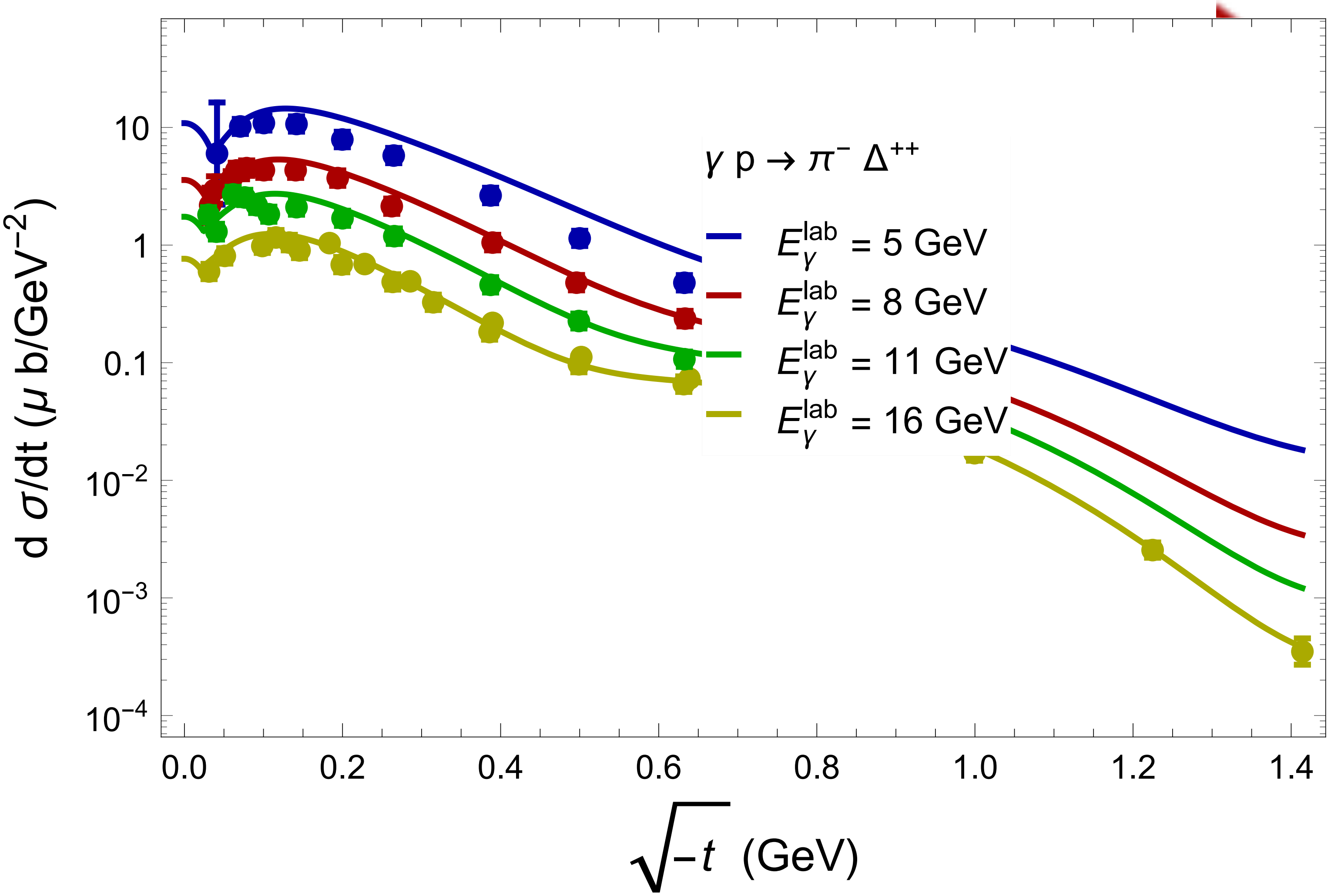

γ p → π⁻ Δ⁺⁺
E_γ^{lab} = 5 GeV
E_γ^{lab} = 8 GeV
E_γ^{lab} = 11 GeV
E_γ^{lab} = 16 GeV
d σ/dt (μ b/GeV⁻²)
$\sqrt{-t}$ (GeV)


$\alpha_{\text{eff}}(t)$
$\gamma p \to \pi^- \Delta^{++}$

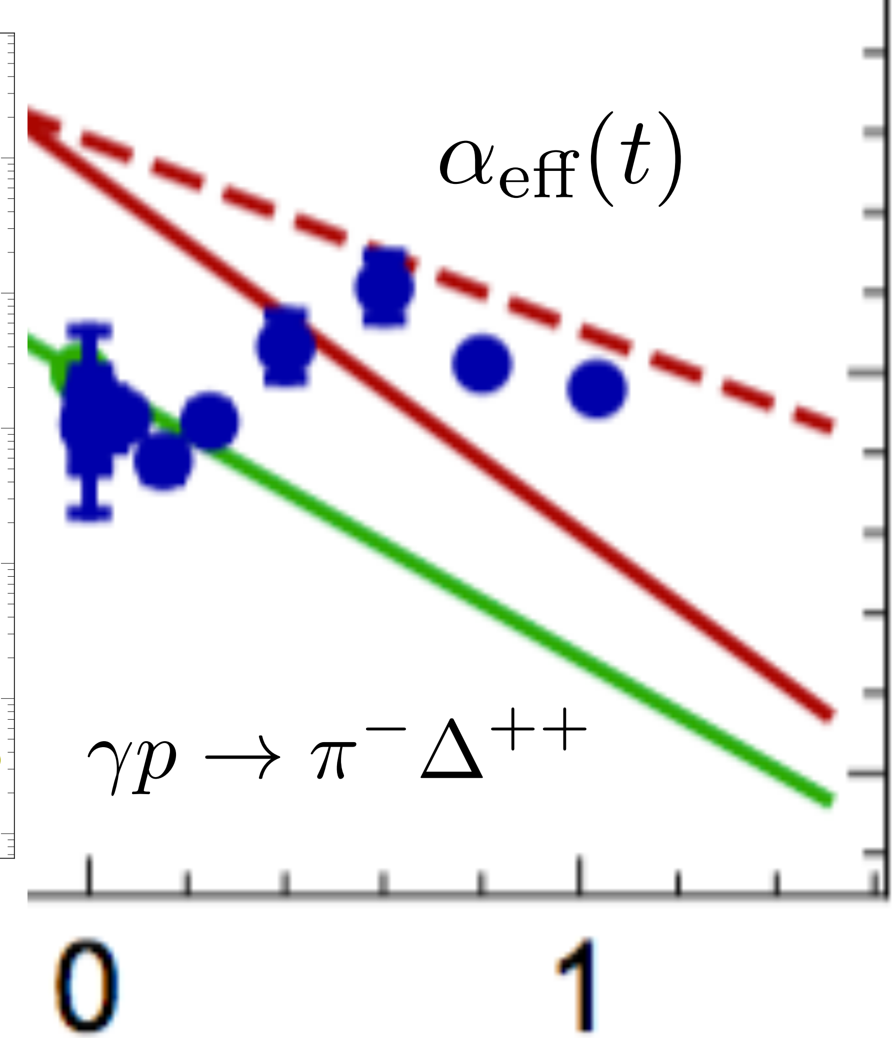

γ p → π⁻ Δ⁺⁺
E_γ^{lab} = 5 GeV
E_γ^{lab} = 8 GeV
E_γ^{lab} = 11 GeV
E_γ^{lab} = 16 GeV
d σ/dt (μ b/GeV⁻²)
$\sqrt{-t}$ (GeV)


$\alpha_{\rm eff}(t)$
$\gamma p \to \pi^- \Delta^{++}$
0
1

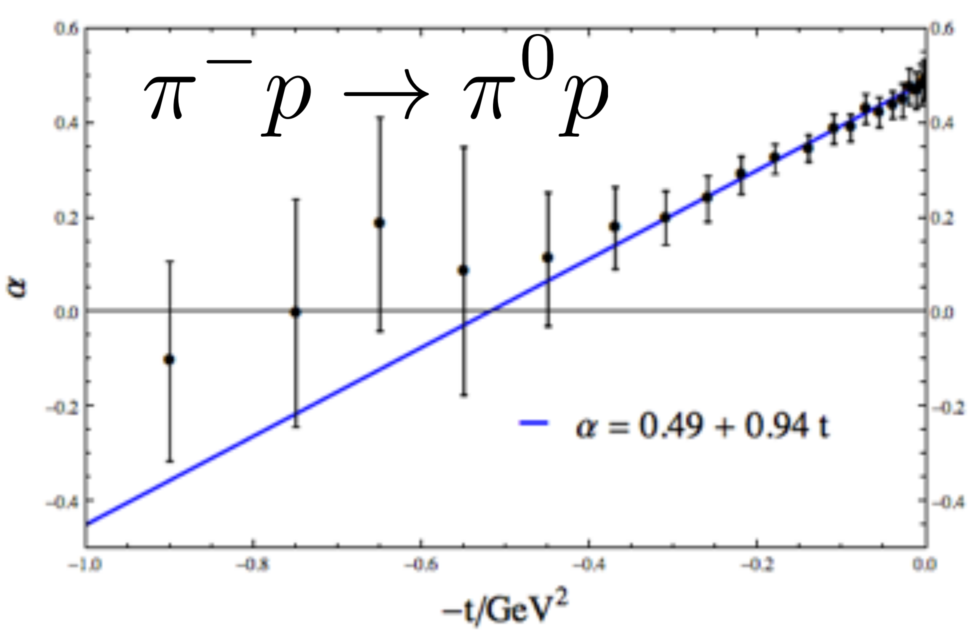

6 GeV vs 9 GeV
12 GeV vs 9 GeV
15 GeV vs 9 GeV
$\alpha_{\rm eff}(t)$
$\gamma p \to \pi^0 p$
$-t/\mathrm{GeV}^2$



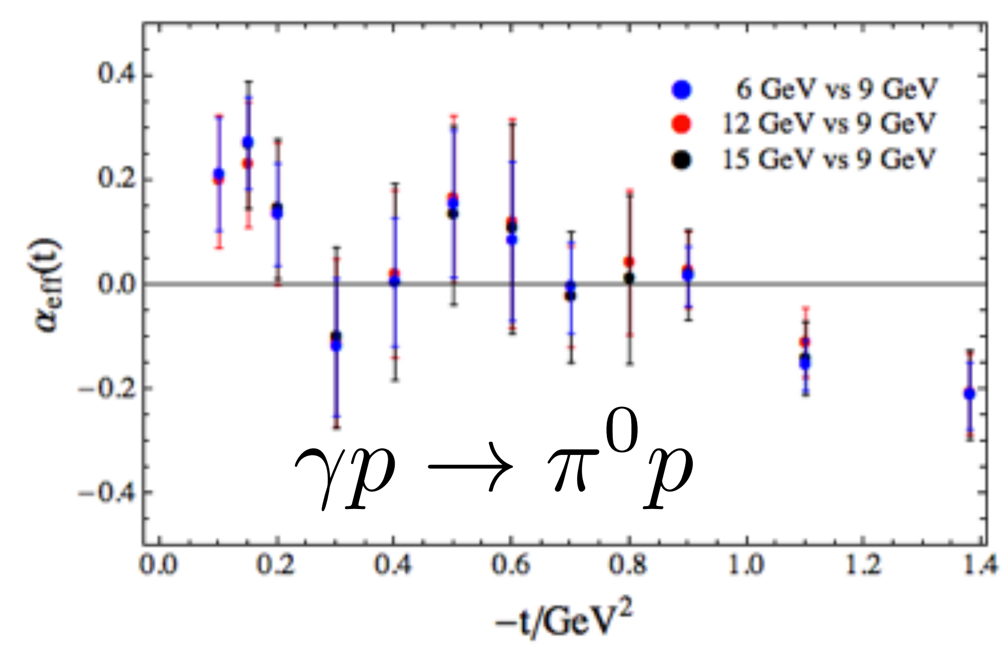
γ p → π⁻ Δ⁺⁺
E_γ^{lab} = 5 GeV
E_γ^{lab} = 8 GeV
E_γ^{lab} = 11 GeV
E_γ^{lab} = 16 GeV
d σ/dt (μ b/GeV⁻²)
$\sqrt{-t}$ (GeV)



$\alpha_{\rm eff}(t)$
$\gamma p \to \pi^- \Delta^{++}$
0
1



$\pi^- p \to \pi^0 p$
α = 0.49 + 0.94 t
α
−t/GeV²



6 GeV vs 9 GeV
12 GeV vs 9 GeV
15 GeV vs 9 GeV
$\gamma p \to \pi^0 p$
$\alpha_{\rm eff}(t)$
−t/GeV²

INDIANA UNIVERSITY BLOOMINGTON | Jefferson Lab Thomas Jefferson National Accelerator Facility | THE GEORGE WASHINGTON UNIVERSITY WASHINGTON, DC

Joint Physics Analysis Center

HOME PROJECTS PUBLICATIONS LINKS

U.S. DEPARTMENT OF ENERGY | National Science Foundation

JPAC acknowledges support from DOE and NSF

INDIANA UNIVERSITY

Interactive webpage: http://www.indiana.edu/~jpac/index.html

Indiana University

- **Adam Szczepaniak** Professor
- **Geoffrey Fox** Professor
- **Emilie Passemar** Professor
- **Tim Londergan** Professor
- **Ina Lorenz** Postdoctoral researcher
- **Andrew Jackura** PhD student

Jefferson Lab

- **Michael R. Pennington** Professor
- **Viktor Mokeev** Professor
- **Vincent Mathieu** Postdoctoral researcher
- **Alessandro Pilloni** Postdoctoral researcher

Universidad Nacional Autonoma de Mexico

- **Cesar Fernandez-Ramirez** Professor

Johannes Gutenberg University, Mainz

- **Igor Danilkin** Postdoctoral researcher
- **Astrid Hiller Blin** Postdoctoral researcher

Murcia University

- **Miguel Albaladejo** Postdoctoral researcher

George Washington University

- **Ron Workman** Professor
- **Michael Doring** Professor

Bonn University

- **Misha Mikhasenko** PhD student

Ghent University

- **Jannes Nys** PhD student

INDIANA UNIVERSITY BLOOMINGTON

Jefferson Lab
Thomas Jefferson National Accelerator Facility

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Joint Physics Analysis Center

HOME PROJECTS PUBLICATIONS LINKS

U.S. DEPARTMENT OF ENERGY

National Science Foundation

JPAC acknowledges support from DOE and NSF

INDIANA UNIVERSITY

Interactive webpage: http://www.indiana.edu/~jpac/index.html

Indiana University

- **Adam Szczepaniak** Pro
- **Geoffrey Fox** Professor
- **Emilie Passemar** Profes
- **Tim Londergan** Profess
- **Ina Lorenz** Postdoctoral
- **Andrew Jackura** PhD s

Jefferson Lab

- **Michael R. Pennington**
- **Viktor Mokeev** Professo
- **Vincent Mathieu** Postdo
- **Alessandro Pilloni** Post

Photoproduction:

1. High energy model for η' beam asymmetry photoproduction: $\gamma p \to \eta^{(\prime)} p$ page
2. High energy model for η photoproduction: $\gamma p \to \eta p$ page
3. High energy model for π^0 photoproduction: $\gamma p \to \pi^0 p$ page
4. High energy model for J/ψ photoproduction: $\gamma p \to J/\psi p$ page

Hadroproduction:

1. Pion-nucleon scattering:
   - Amplitudes $\pi N \to \pi N$ amplitude page
   - Finite energy sum rules $\pi N \to \pi N$ FESR page
2. Kaon-nucleon scattering: $\bar{K}N \to \bar{K}N$ page

Light meson Decay:

1. η meson into three pions: $\eta \to 3\pi$ page
2. vector meson into three pions: $\omega, \phi \to 3\pi$ page

Washington University

- **Workman** Professor
- **ael Doring** Professor

niversity

- **ha Mikhasenko** PhD student

University

- **nes Nys** PhD student

Interactive webpage: http://www.indiana.edu/~jpac/index.html

INDIANA UNIVERSITY

Resources

- **Publication:** [Nys16]
- **C/C++ observables:** C-code main, Input file, C-code source, C-code header, Eta-MAID 2001 multipoles
- **C/C++ minimal script to calculate the amplitudes:** C-code zip
- **Data:** Dewire , Braunschweig
- **Contact person:** Jannes Nys
- **Last update:** November 2016

$$\gamma p \to \eta p$$

Run the code

E_γ in GeV 9

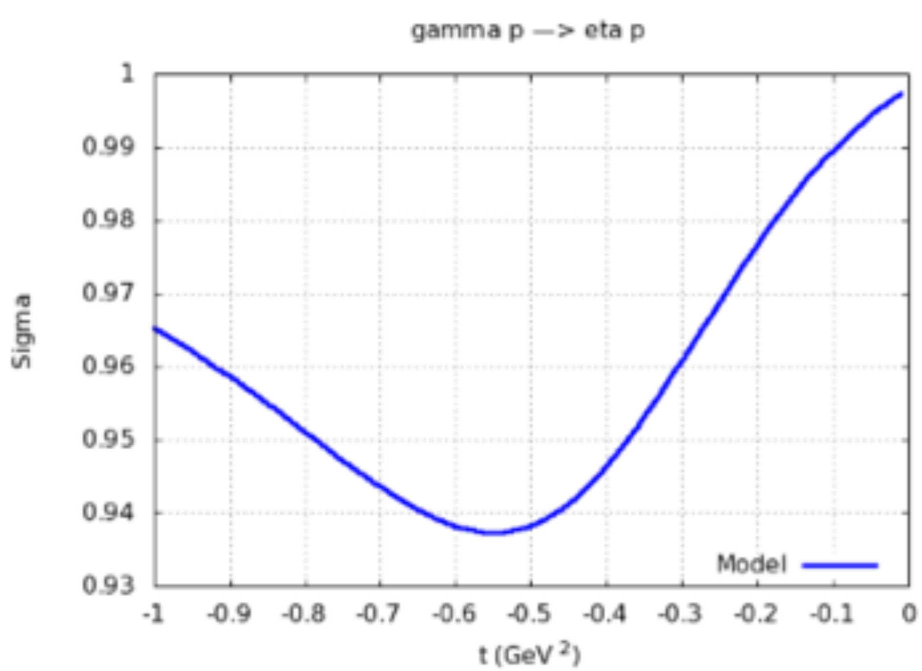
t cos

t in GeV^2 (min max step) -1 0 0.01

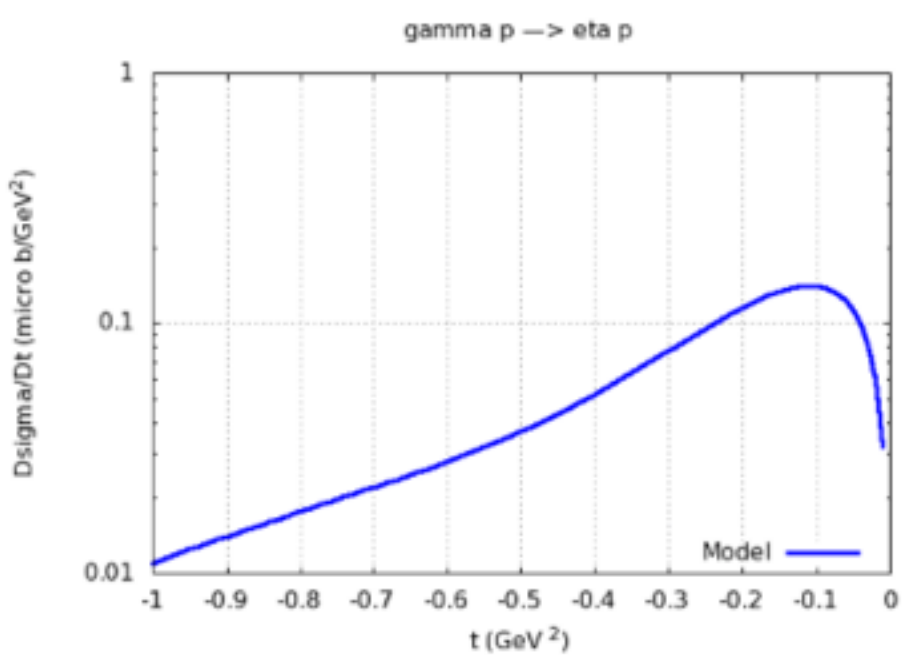
$\cos\theta$ (min max step) 0.85 1 0.01

Start reset

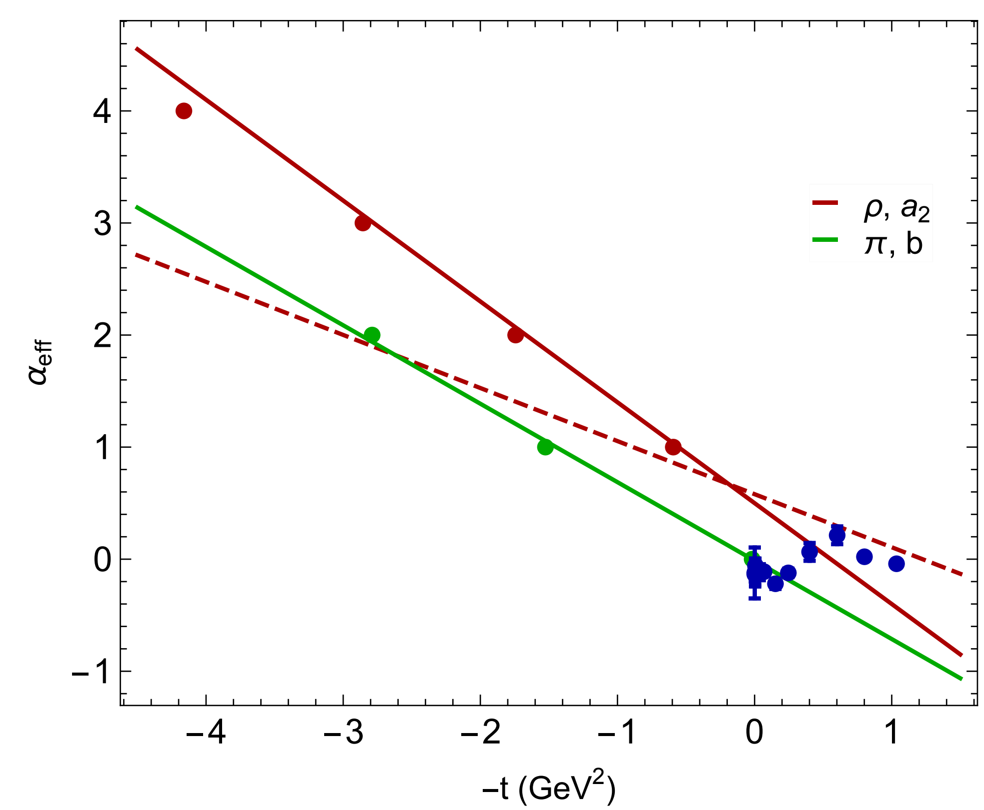
Observable: photon beam asymmetry
Download the the plot with Ox=t , the plot with Ox=cos .



Observable: differential cross section
Download the the plot with Ox=t , the plot with Ox=cos .

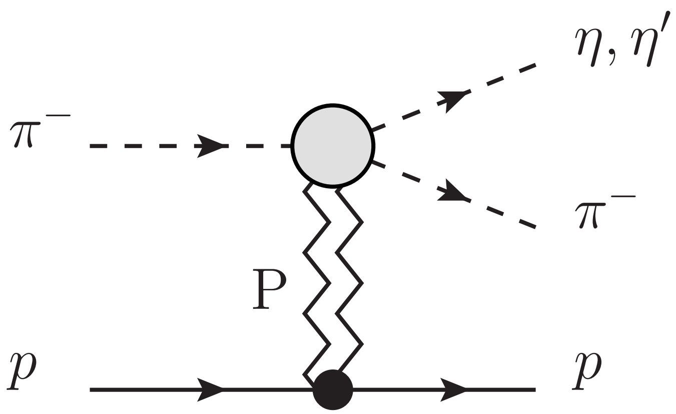


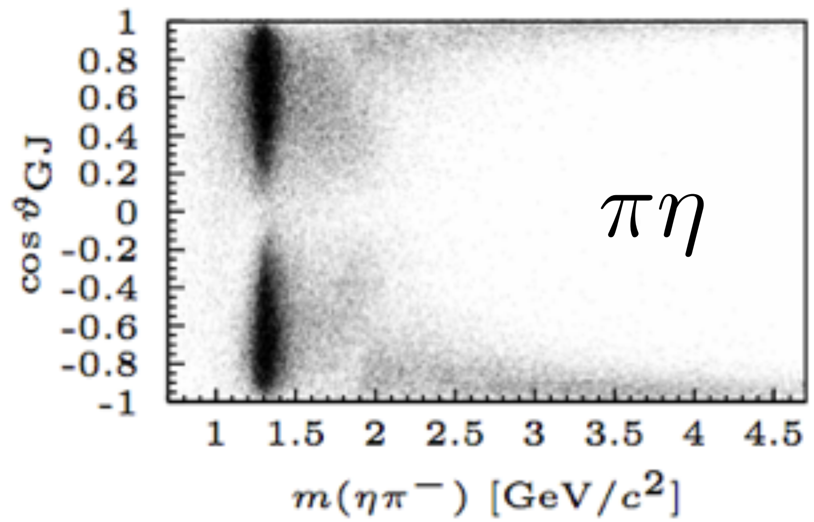
Backup Slides

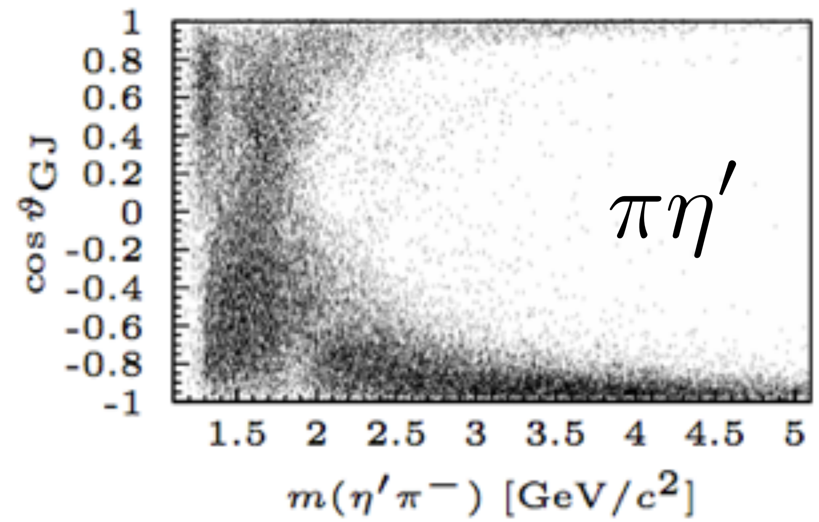


ρ, a_2
π, b
α_{eff}
−t (GeV^2)

Eta-Pi @COMPASS

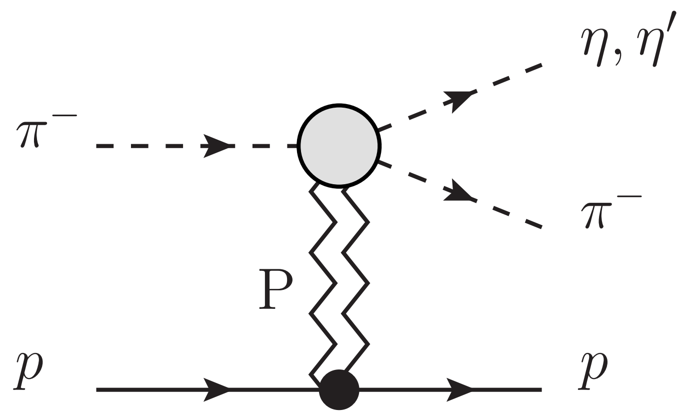


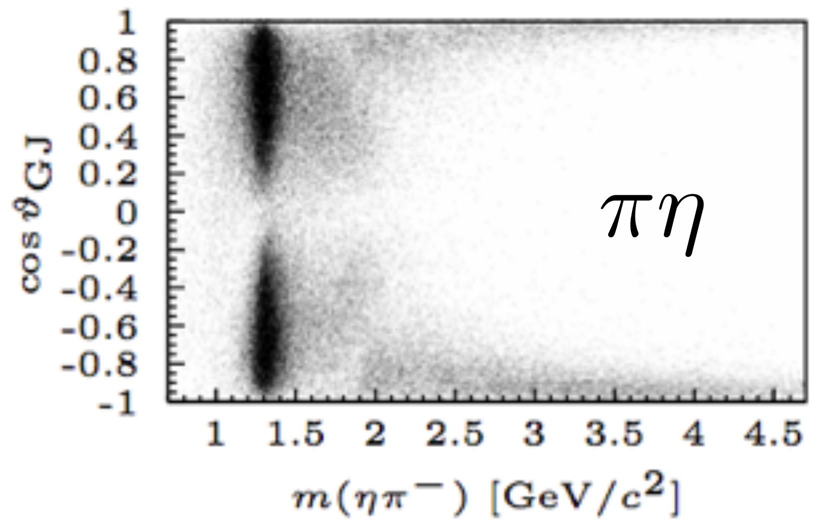


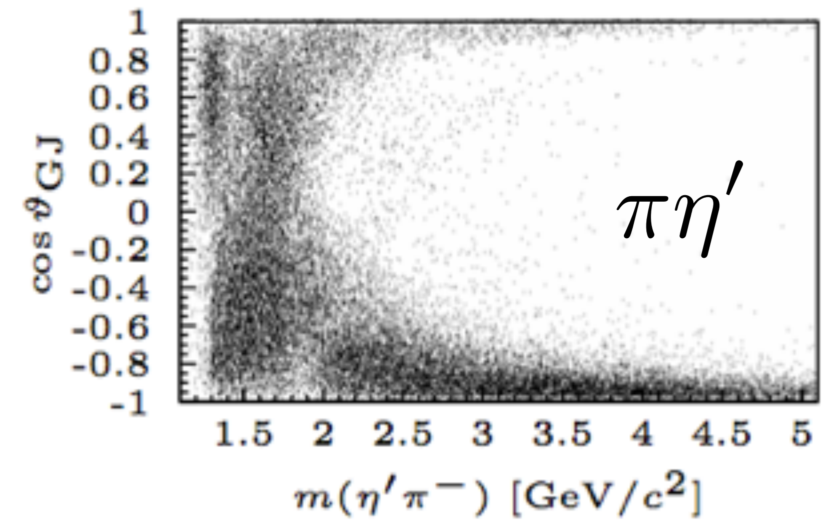


COMPASS Phys. Lett. B740 (2015)

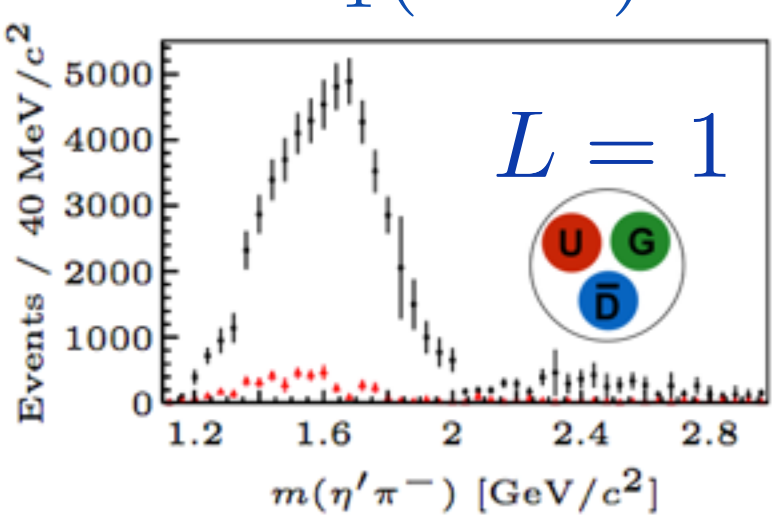
Eta-Pi @COMPASS



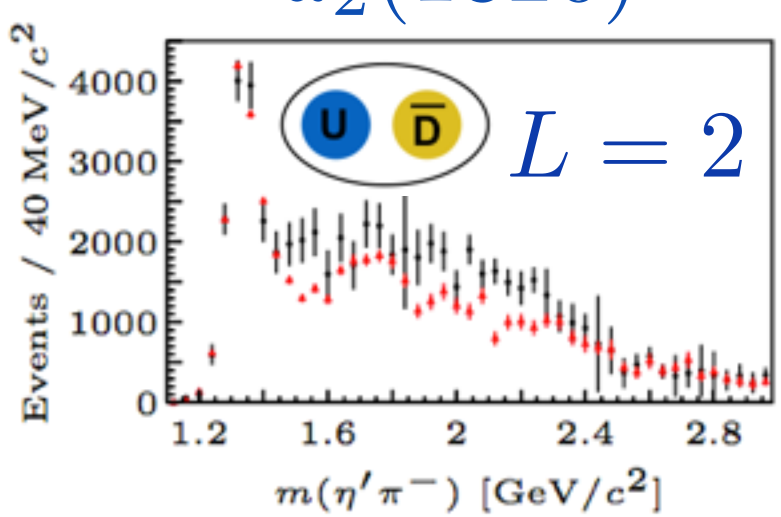




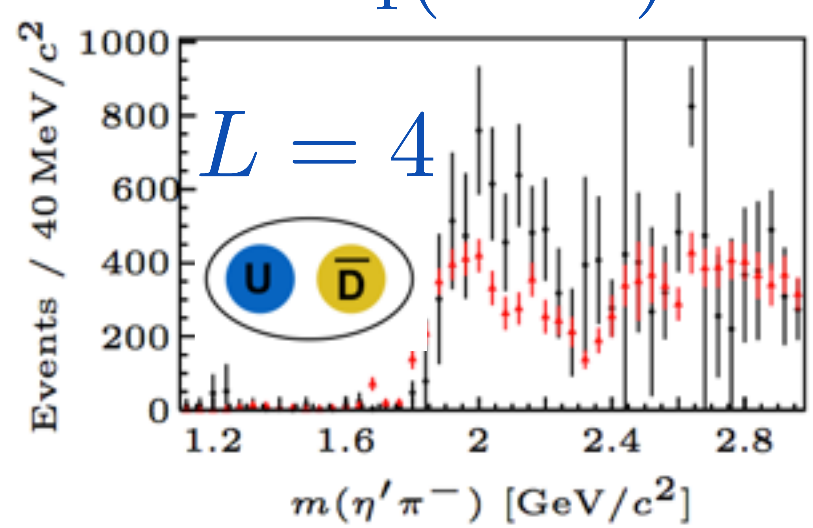
$\pi_1(1600)$?

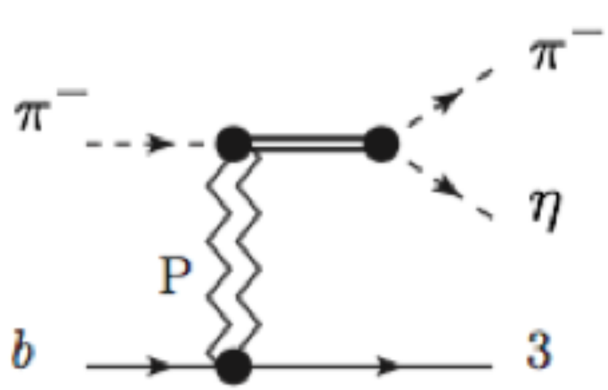


$a_2(1320)$



$a_4(2040)$





black: $\pi\eta'$

red: $\pi\eta$ **(scaled)**

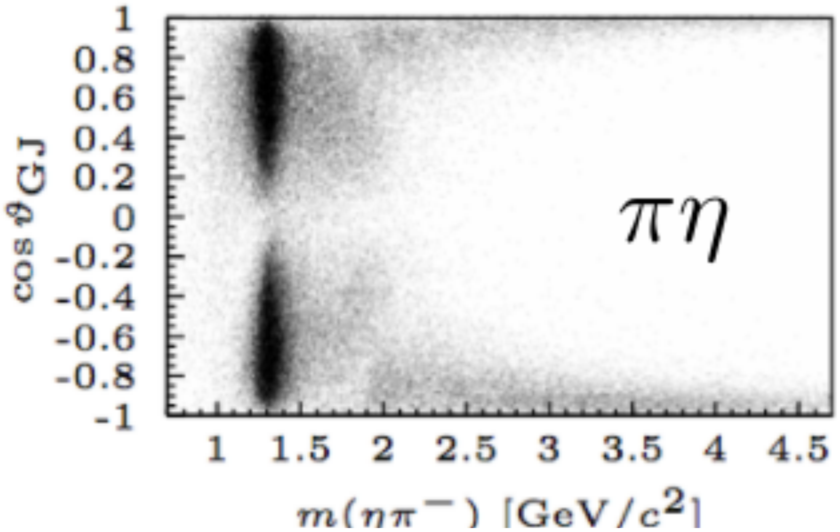
Resonance in angular mom. L = 1 ?

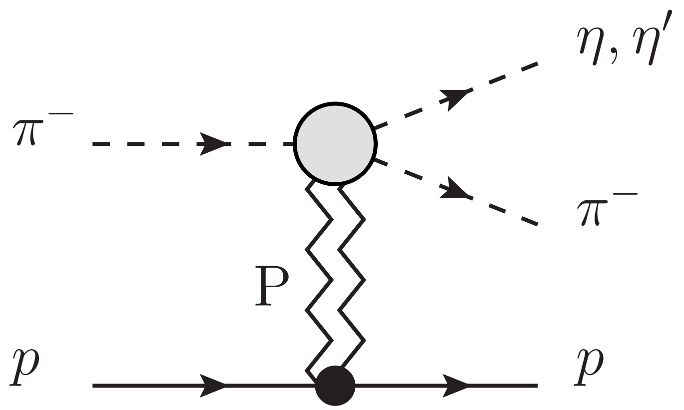
COMPASS Phys. Lett. B740 (2015)

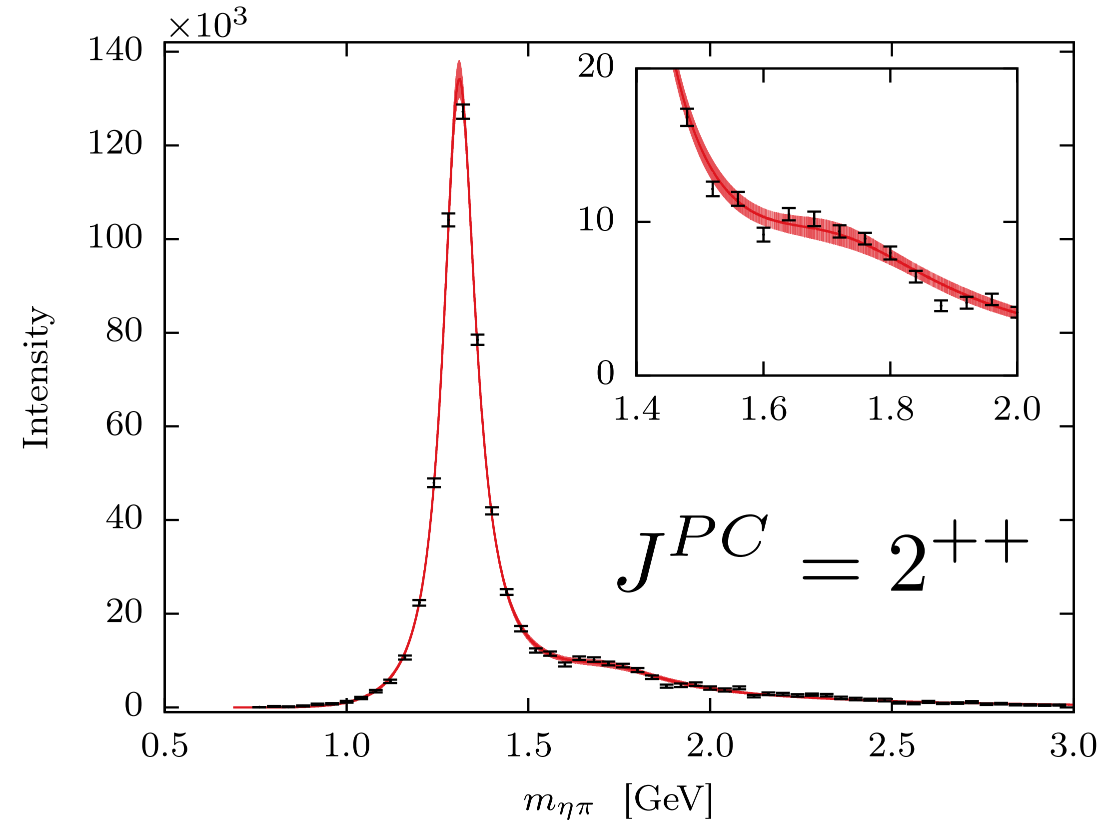
COMPASS PLB740 (2015)

Eta-Pi@COMPASS

A. Jackura et al (JPAC) and COMPASS, arXiv:1707.02848



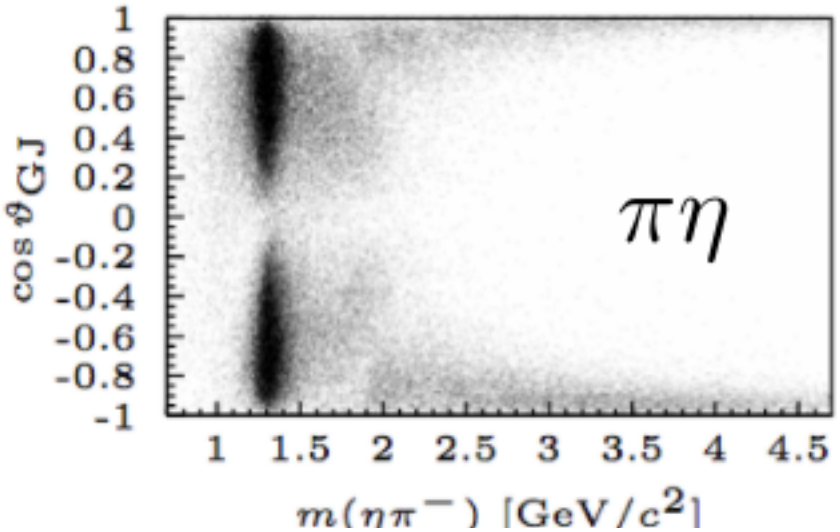


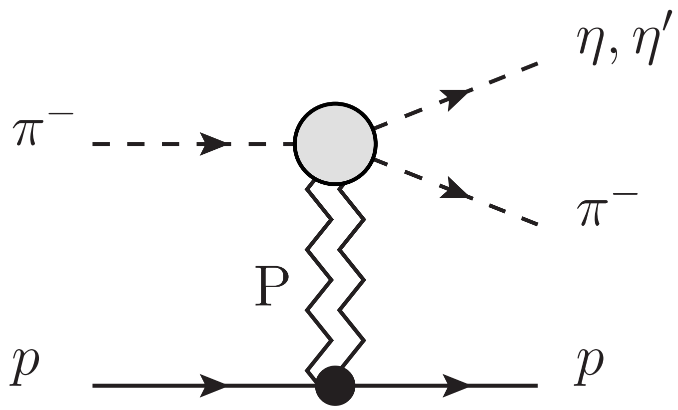


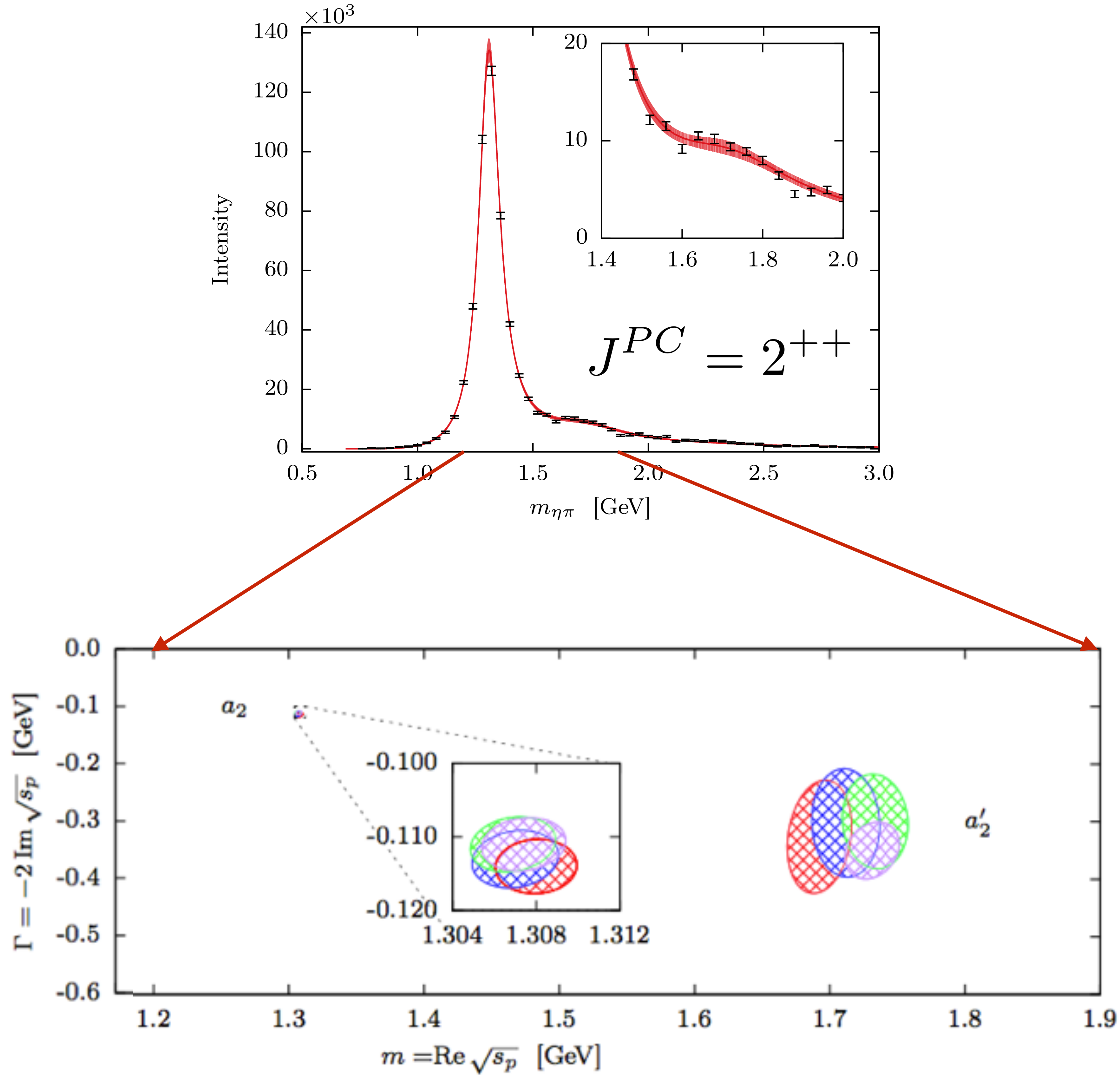
COMPASS PLB740 (2015)

Eta-Pi@COMPASS

A. Jackura et al (JPAC) and COMPASS, arXiv:1707.02848



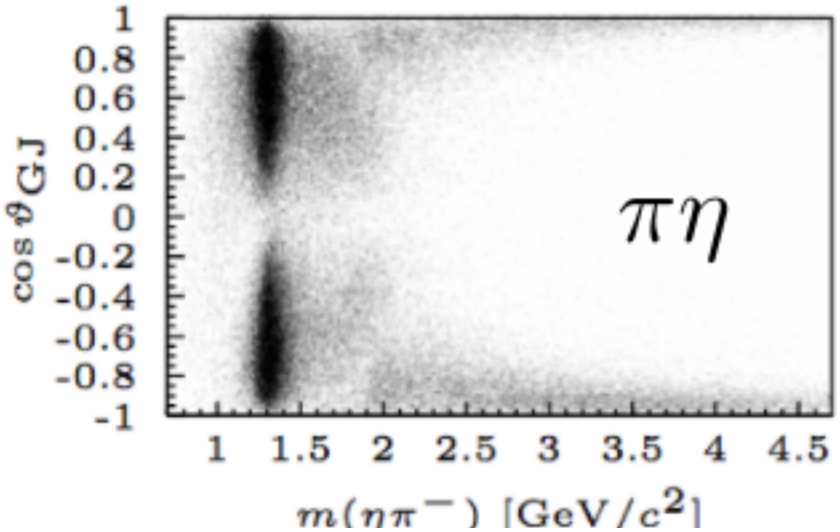


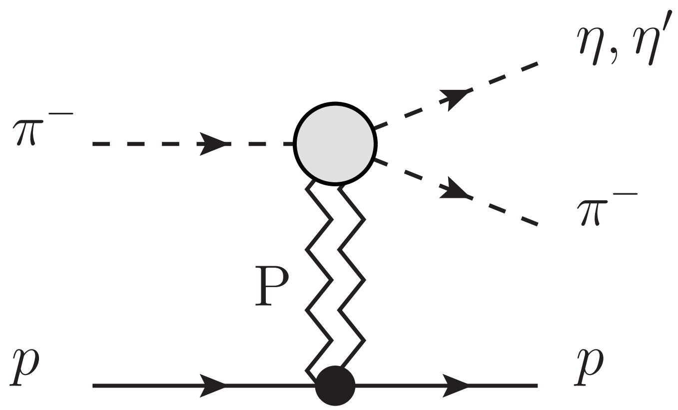


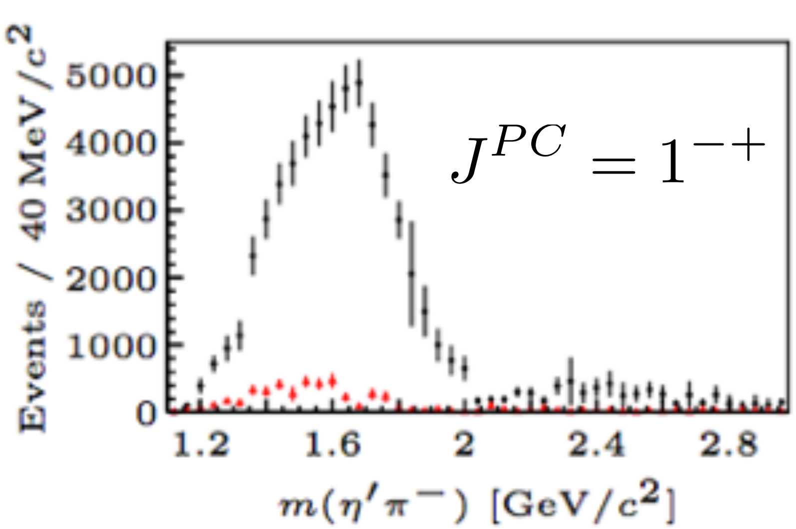
COMPASS PLB740 (2015)

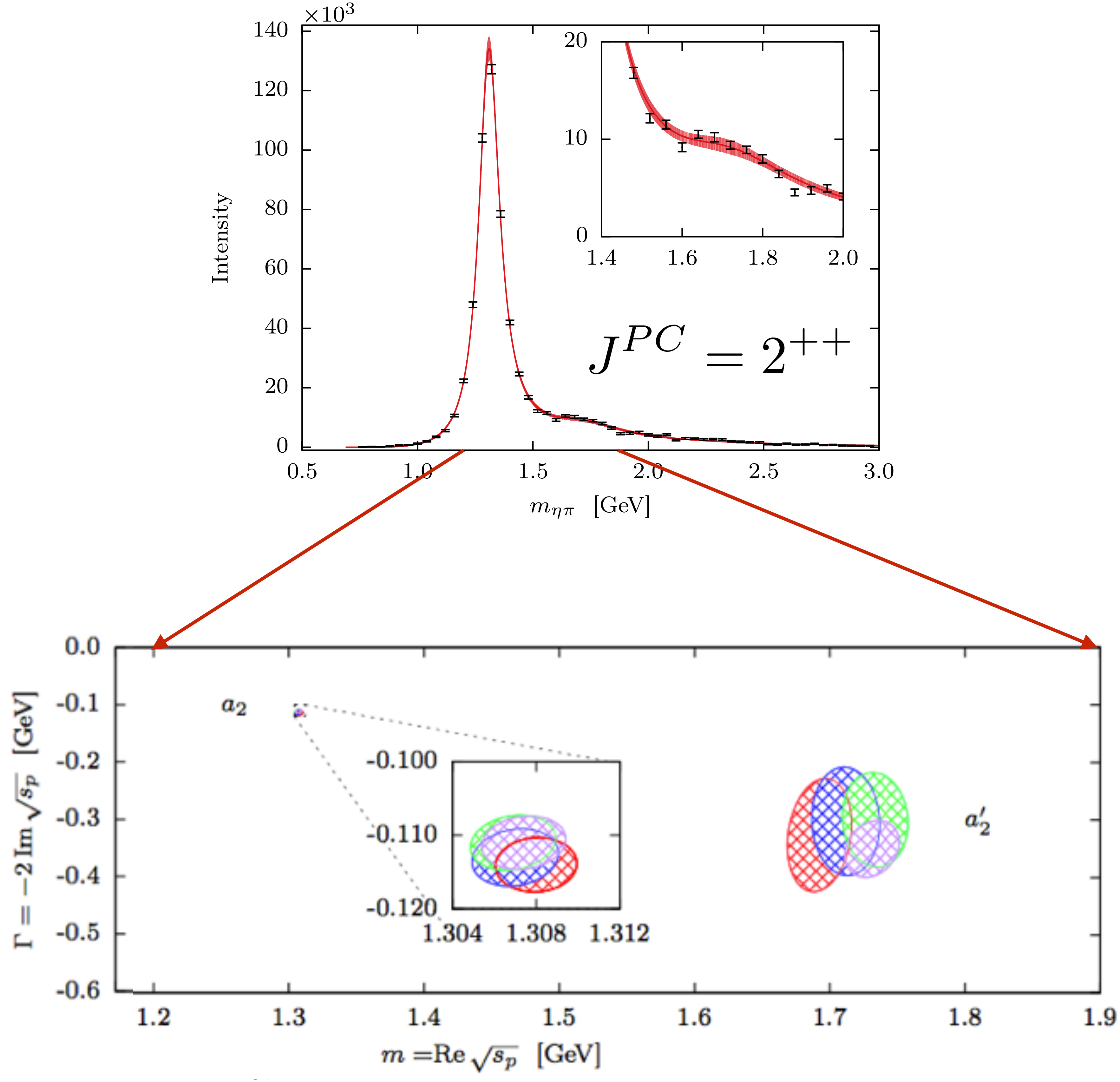
Eta-Pi@COMPASS

A. Jackura et al (JPAC) and COMPASS,
arXiv:1707.02848





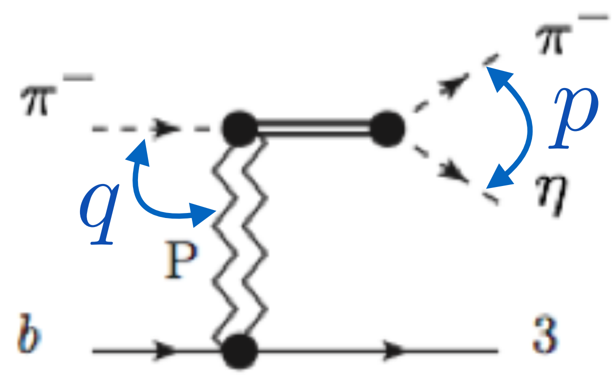


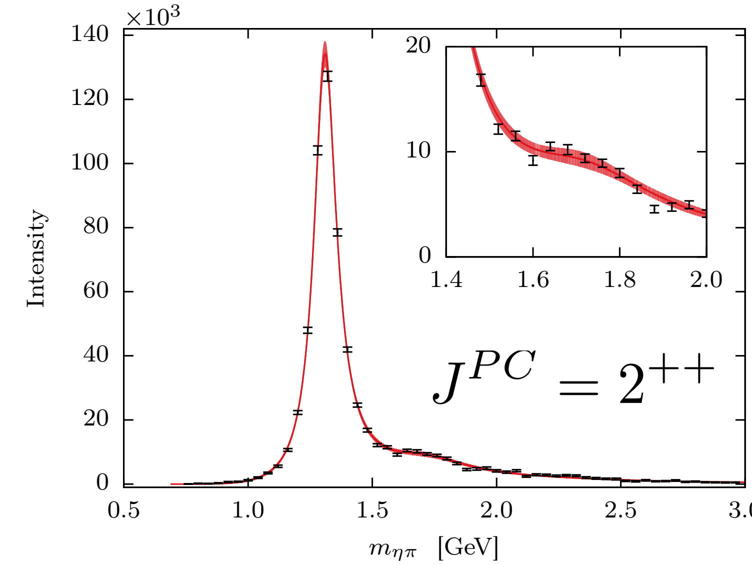


Eta-Pi@COMPASS

normalization

$$\frac{d\sigma}{d\sqrt{s}} = Np|a(s)|^2$$





Chebyshev polynomials

production

$$n(s) = \frac{q}{c_3 - s} \sum_n a_n T_n(\omega(s))$$

$$\omega(s) = \frac{s}{s + \Lambda}$$

$$a(s) = p^2 \frac{n(s)}{D(s)}$$

dynamics (poles)

$$D(s) = D_0(s) - \frac{1}{\pi} \int_{s_{th}}^{\infty} ds' \frac{\rho(s')N(s')}{s' - s}$$

real (masses)

imaginary (widths)

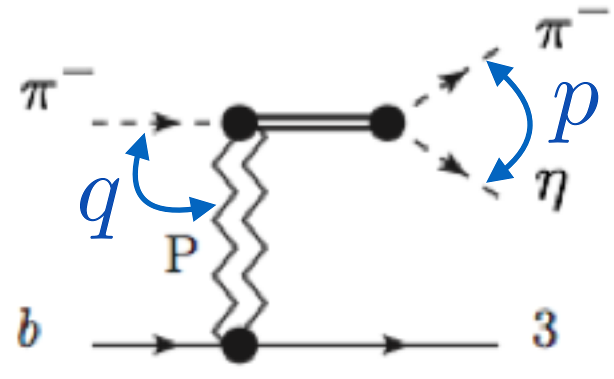
$$D_0(s) = c_0 - c_1 s - \frac{c_2}{c_3 - s}$$

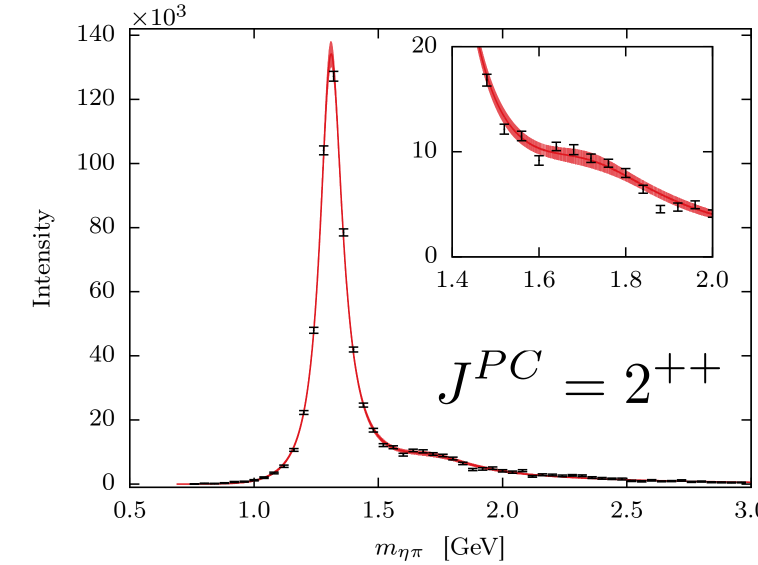
$$\rho(s)N(s) = g \frac{\lambda^{J+\frac{1}{2}}(s, m_\eta^2, m_\pi^2)}{(s + s_R)^{2J+3}}$$

Eta-Pi@COMPASS

normalization

$$\frac{d\sigma}{d\sqrt{s}} = N p |a(s)|^2$$





$$a(s) = p^2 \frac{n(s)}{D(s)}$$

production

Chebyshev polynomials

$$n(s) = \frac{q}{c_3 - s} \sum_n a_n T_n(\omega(s))$$

$$\omega(s) = \frac{s}{s + \Lambda}$$

cf. A. Jackura's talk
Wednesday 10am
Spectroscopy of Mesons

dynamics (poles)

$$D(s) = D_0(s) - \frac{1}{\pi} \int_{s_{th}}^{\infty} ds' \frac{\rho(s') N(s')}{s' - s}$$

real (masses)

imaginary (widths)

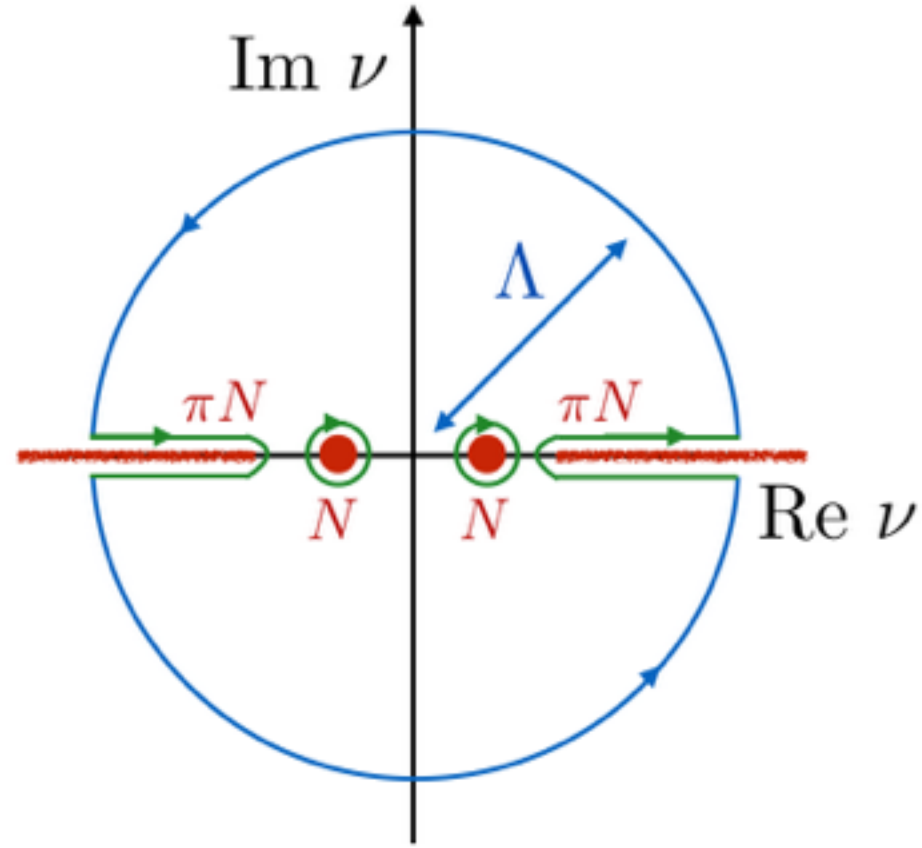
$$D_0(s) = c_0 - c_1 s - \frac{c_2}{c_3 - s}$$

$$\rho(s) N(s) = g \frac{\lambda^{J+\frac{1}{2}}(s, m_\eta^2, m_\pi^2)}{(s + s_R)^{2J+3}}$$

Finite Energy Sum Rules

Cauchy contour

$$\oint_C A(\nu,t)d\nu = 0$$

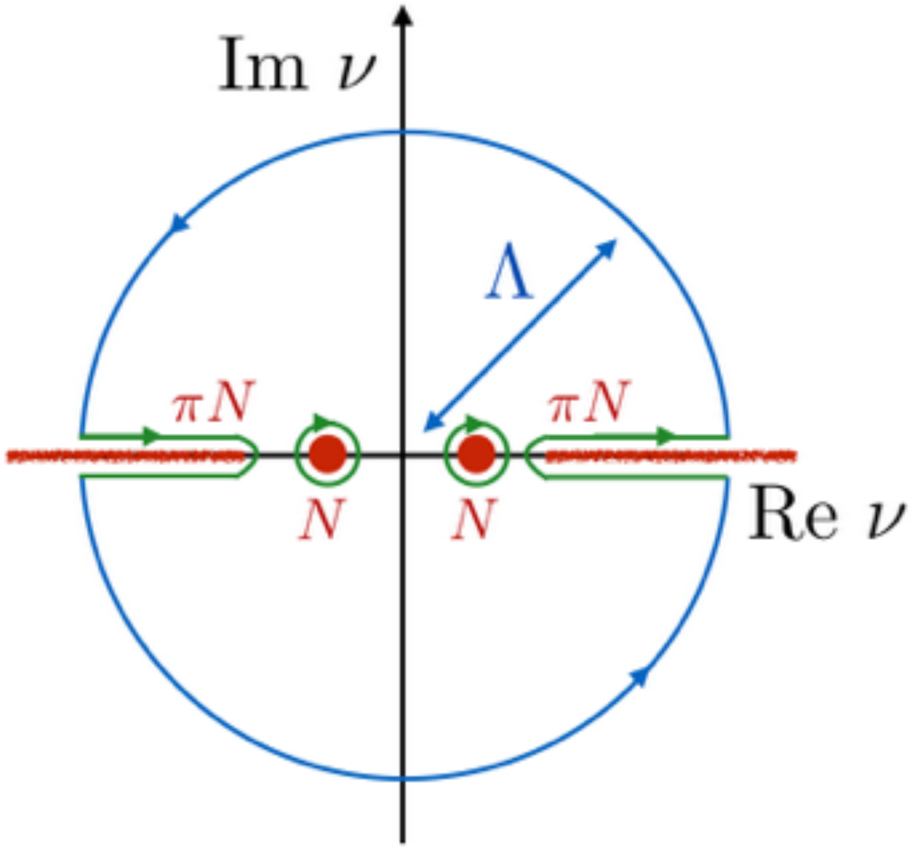


Finite Energy Sum Rules

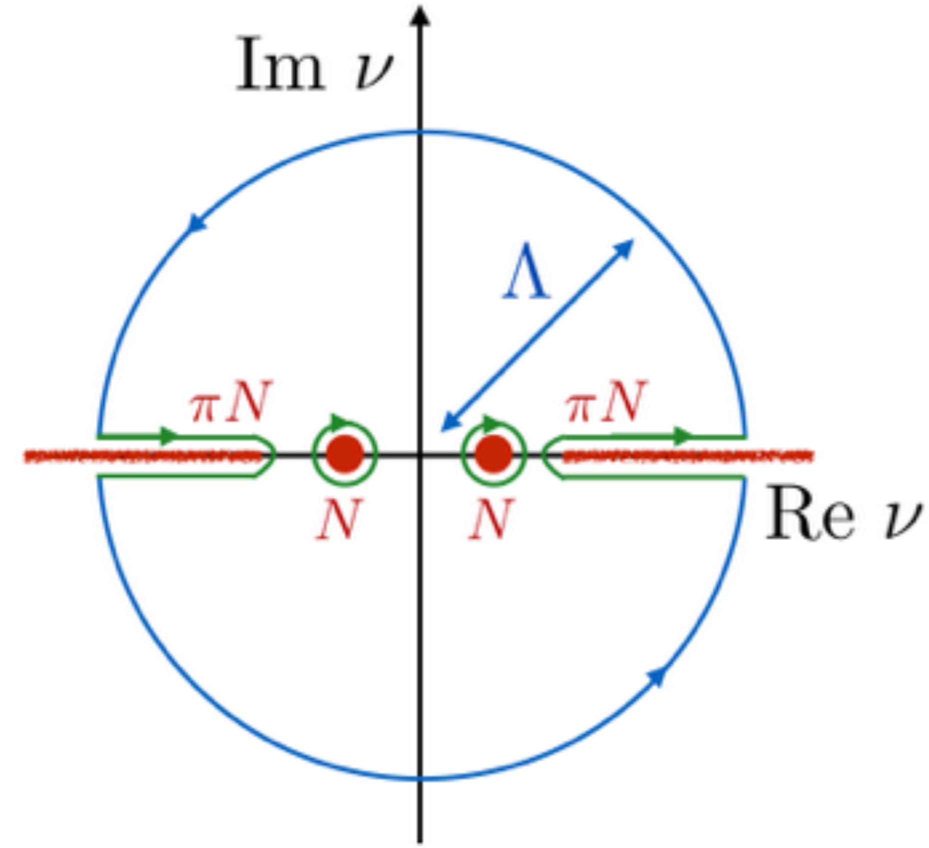
Cauchy contour

$$\oint_C A(\nu, t) d\nu = 0$$

$$2i \int_{\nu_0}^{\Lambda} \mathrm{Im}\ A(\nu, t) d\nu = - \oint_{C_\Lambda} A(\nu, t) d\nu$$



Finite Energy Sum Rules



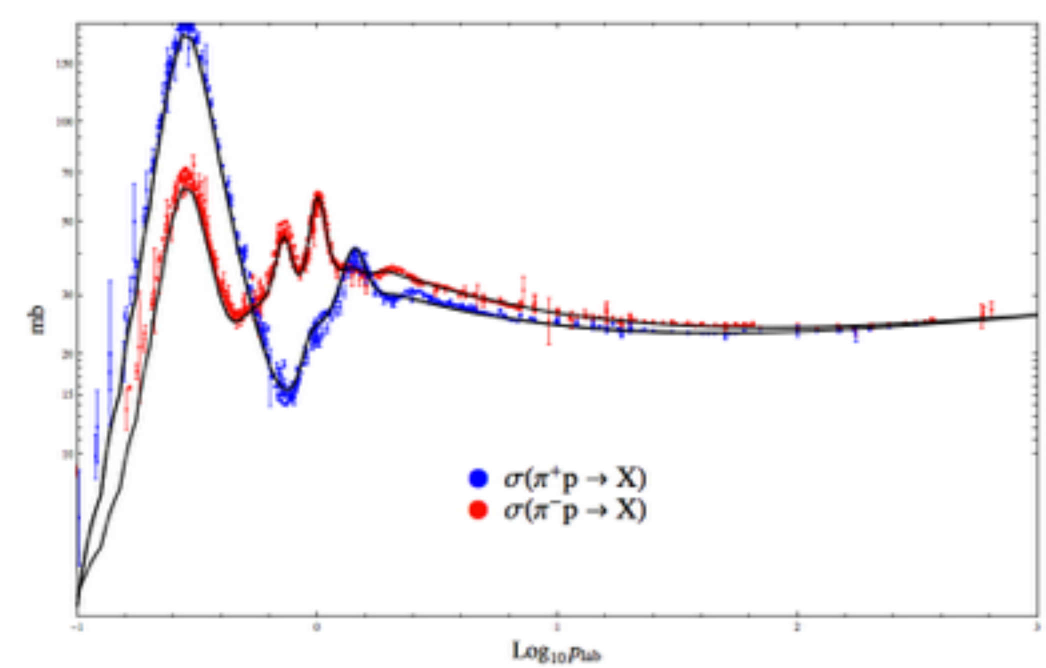
Cauchy contour

$$\oint_C A(\nu, t) d\nu = 0$$

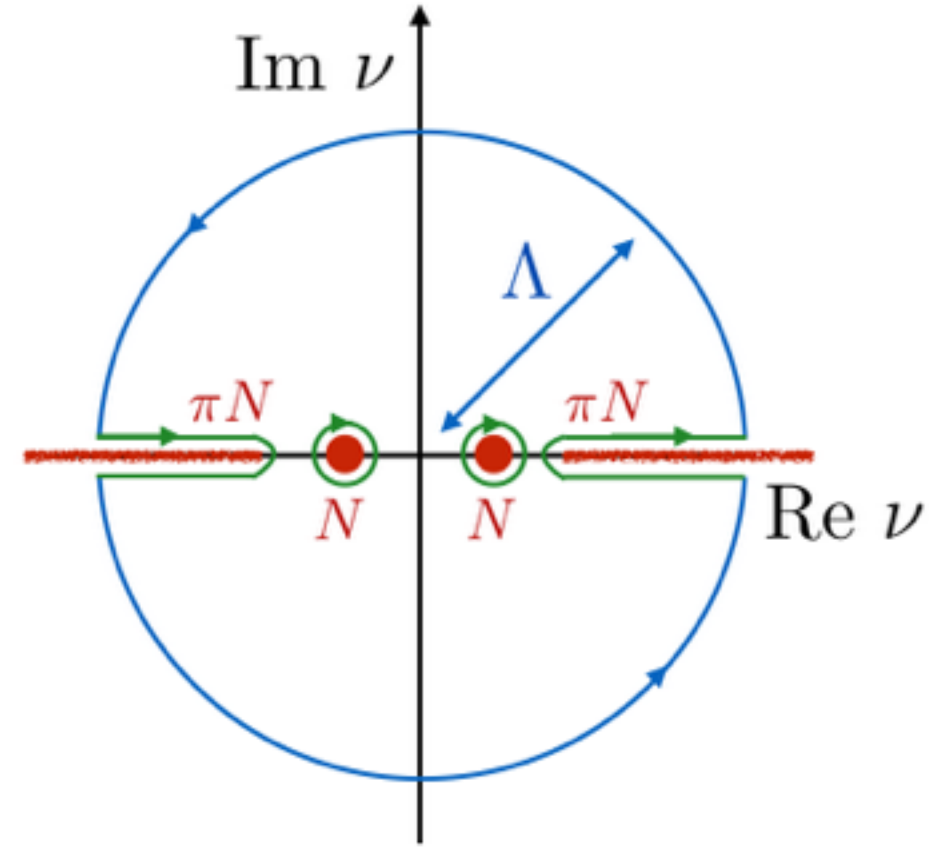
$$2i \int_{\nu_0}^{\Lambda} \text{Im } A(\nu, t) d\nu = - \oint_{C_\Lambda} A(\nu, t) d\nu$$

Assume Regge form at $\nu = \Lambda$ **:**

$$A(\nu, t) = \beta(t) \frac{\pm 1 - e^{-i\pi\alpha(t)}}{\sin \pi\alpha(t)} \nu^{\alpha(t)}$$



Finite Energy Sum Rules



Cauchy contour

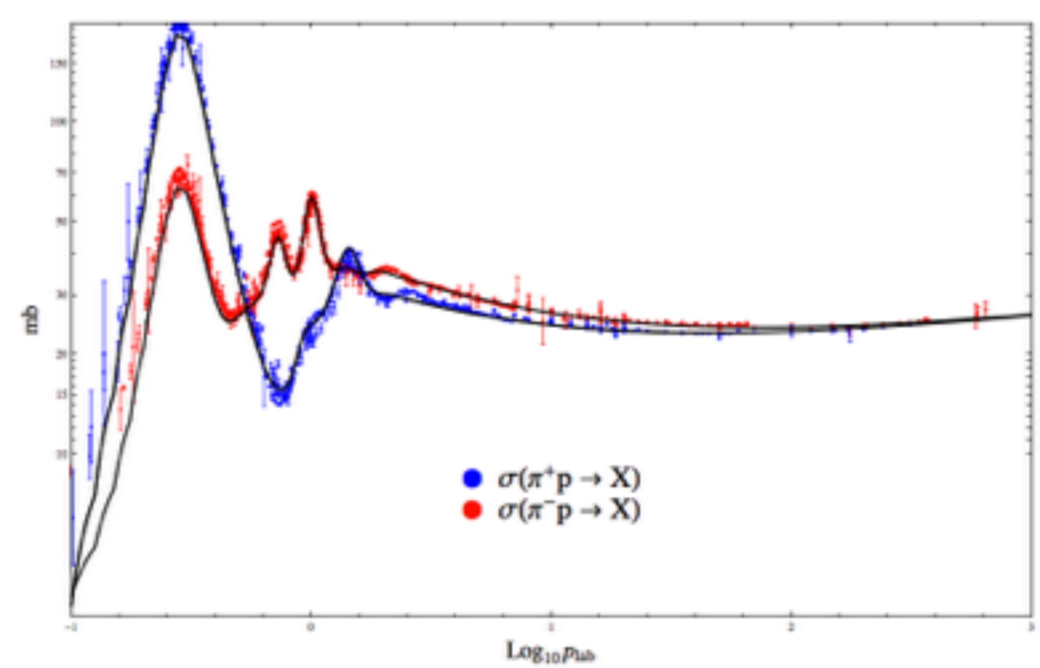
$$\oint_C A(\nu,t)d\nu = 0$$

$$2i\int_{\nu_0}^{\Lambda} \text{Im } A(\nu,t)d\nu = -\oint_{C_\Lambda} A(\nu,t)d\nu$$

Assume Regge form at $\nu = \Lambda$ **:**

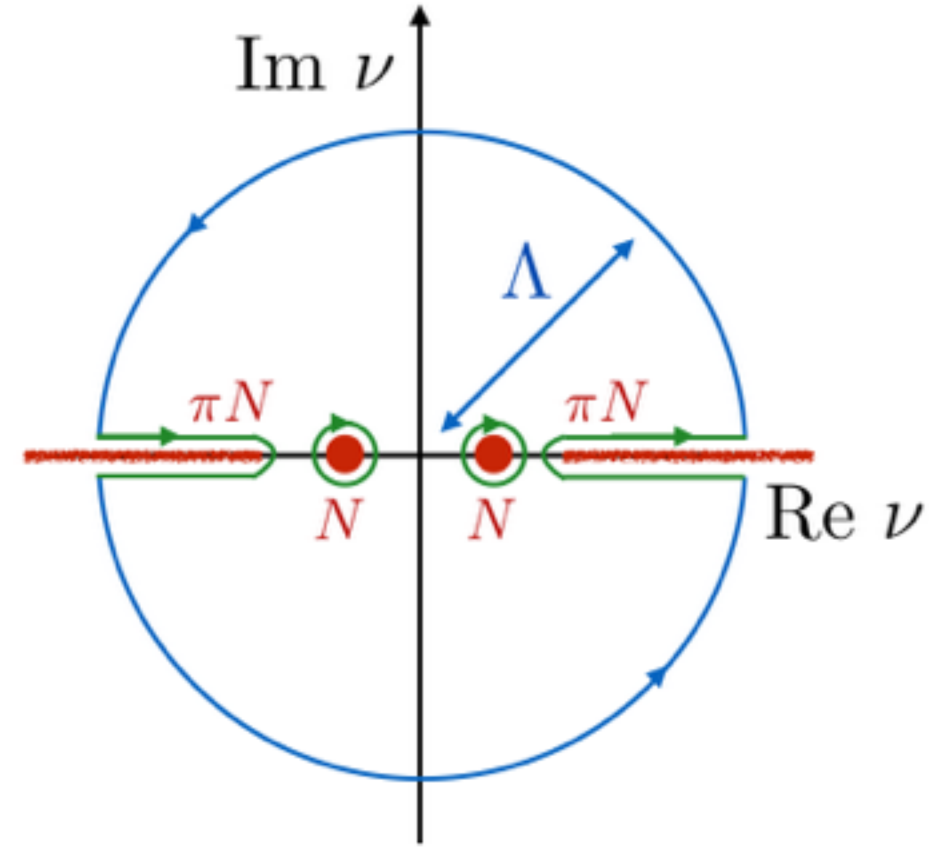
$$A(\nu,t) = \beta(t)\frac{\pm 1 - e^{-i\pi\alpha(t)}}{\sin \pi\alpha(t)}\nu^{\alpha(t)}$$

$$\int_{\nu_0}^{\Lambda} \text{Im } A(\nu,t)d\nu = \beta(t)\frac{\Lambda^{\alpha(t)+1}}{\alpha(t)+1}$$



t fixed

Finite Energy Sum Rules



Cauchy contour

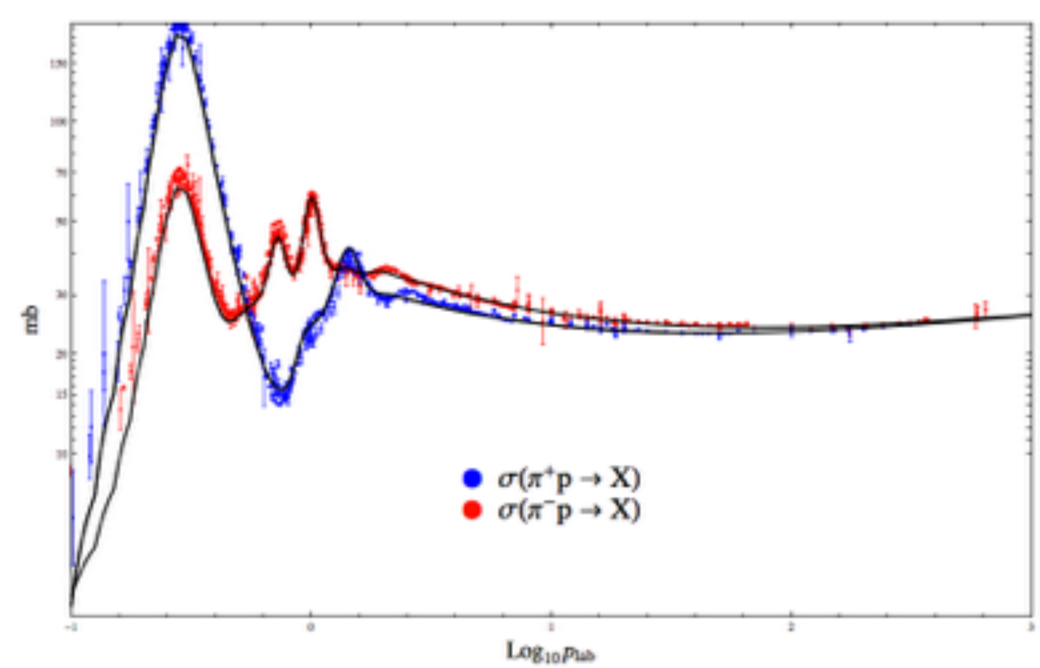
$$\oint_C A(\nu,t)\nu^k d\nu = 0$$

$$2i\int_{\nu_0}^{\Lambda} \mathrm{Im}\ A(\nu,t)d\nu = -\oint_{C_\Lambda} A(\nu,t)d\nu$$

Assume Regge form at $\nu = \Lambda$ **:**

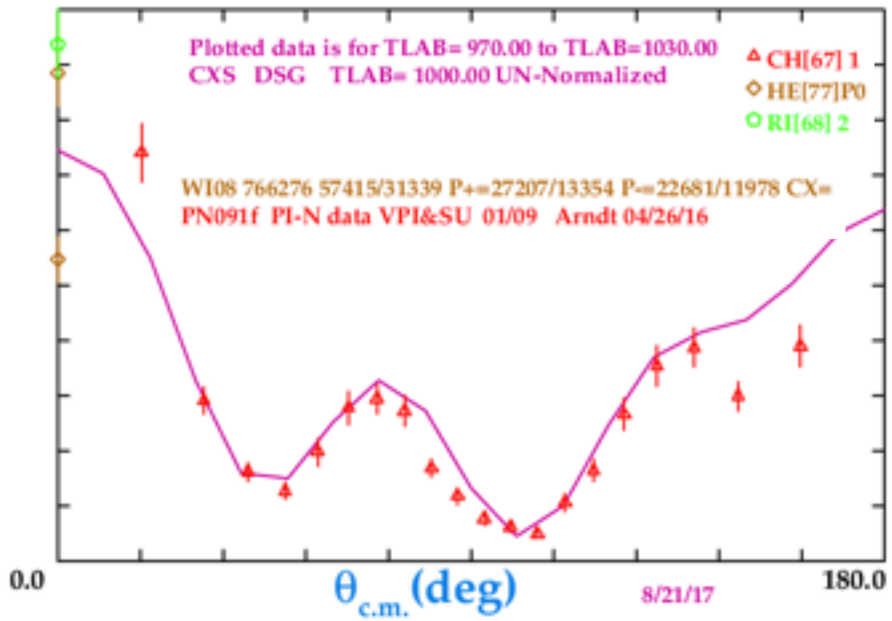
$$A(\nu,t) = \beta(t)\frac{\pm 1 - e^{-i\pi\alpha(t)}}{\sin\pi\alpha(t)}\nu^{\alpha(t)}$$

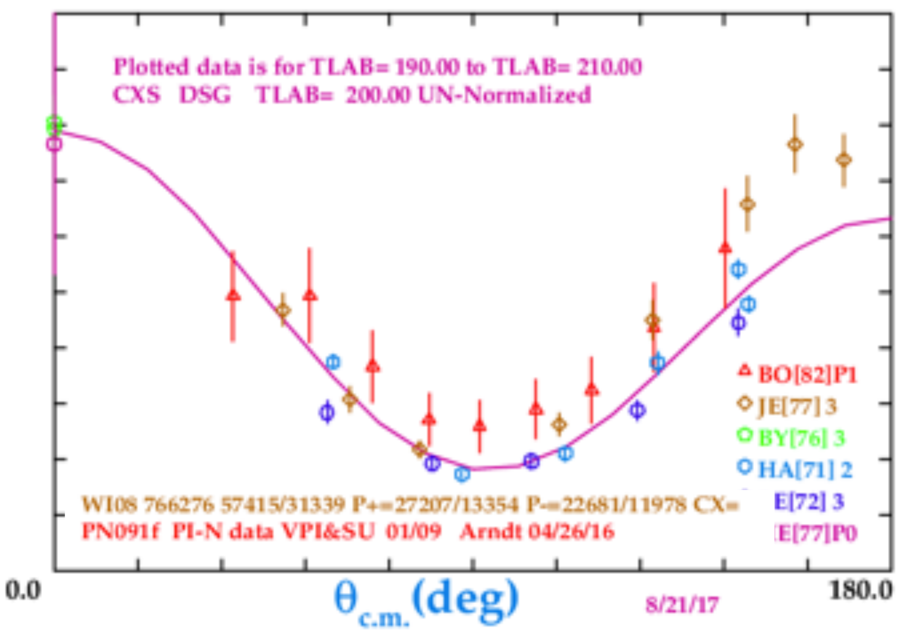
$$\boxed{\frac{1}{\Lambda^k}\int_{\nu_0}^{\Lambda} \mathrm{Im}\ A(\nu,t)\nu^k d\nu = \frac{\beta(t)\Lambda^{\alpha(t)+1}}{\alpha(t)+k+1}}$$



t fixed

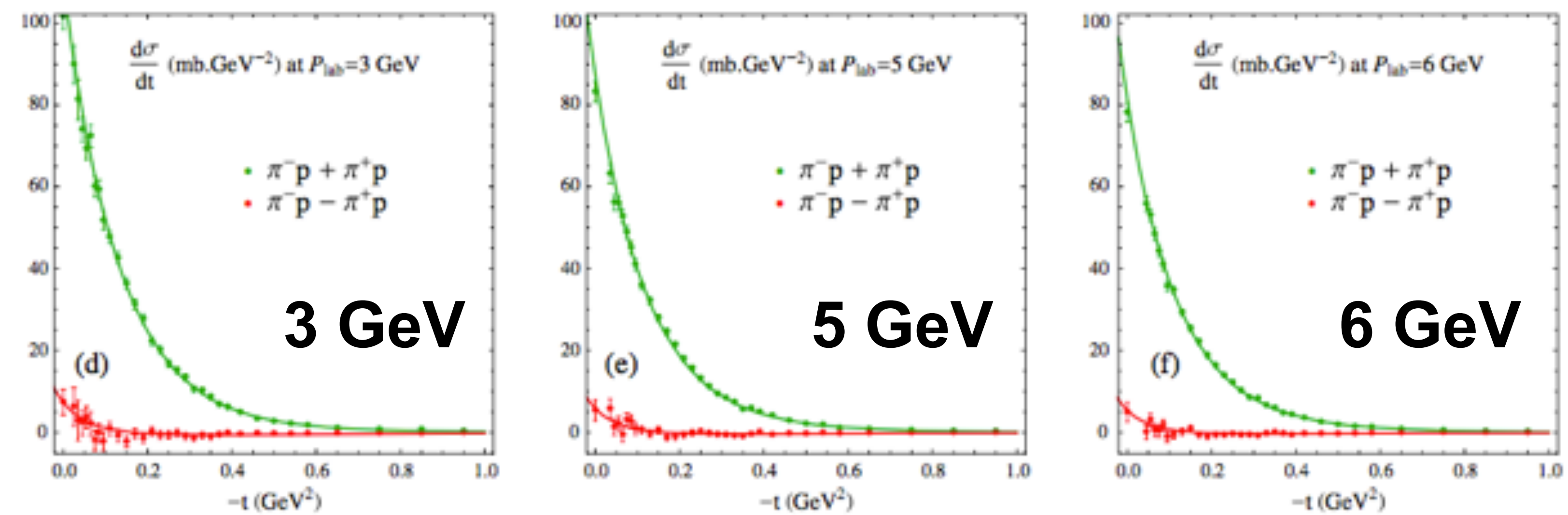
Low energy: SAID



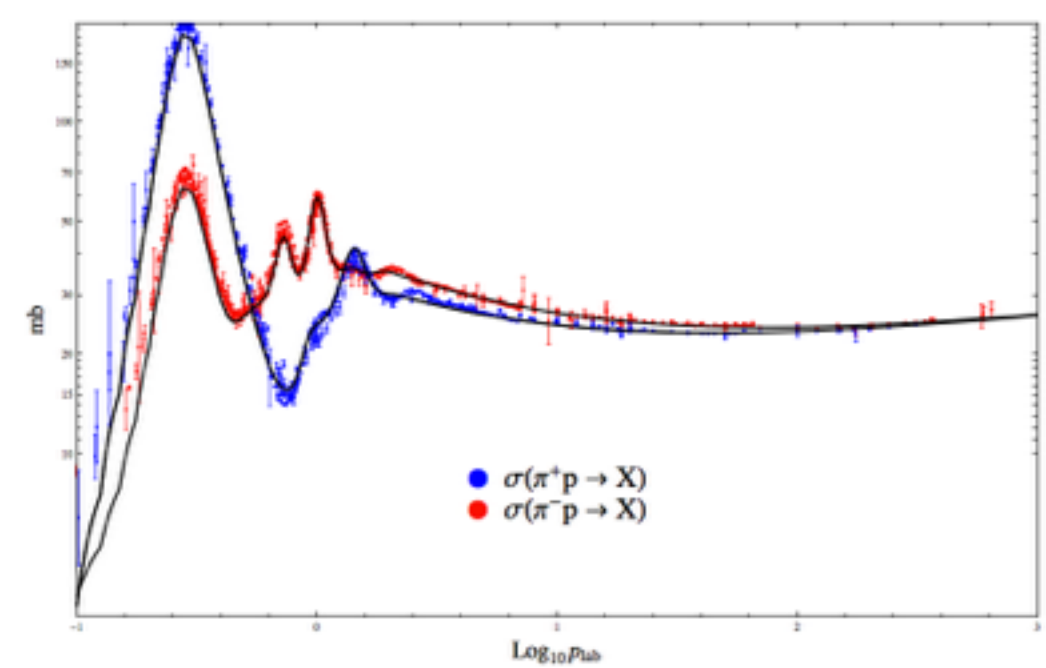


High energy: Regge

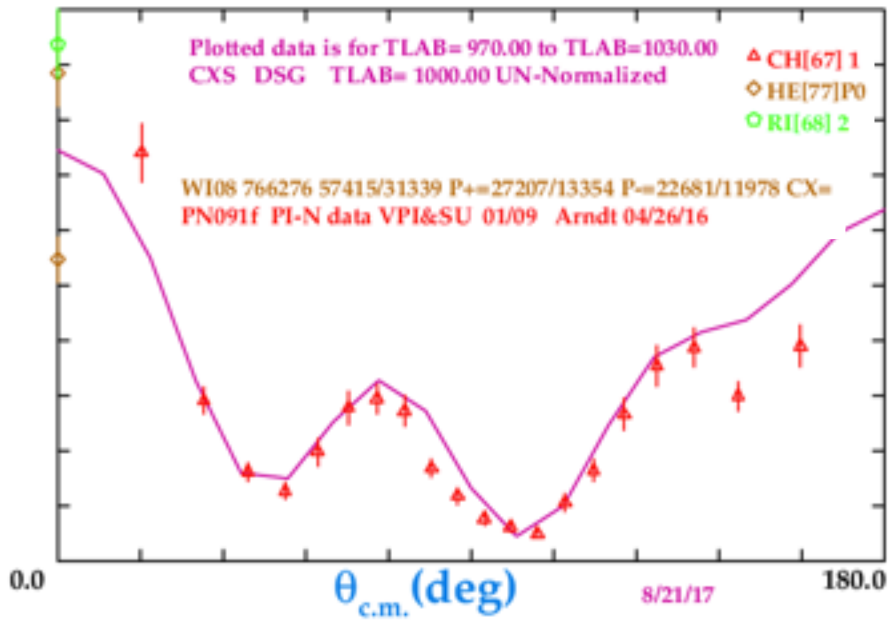
VM et al. (JPAC) PRD92 (2015)

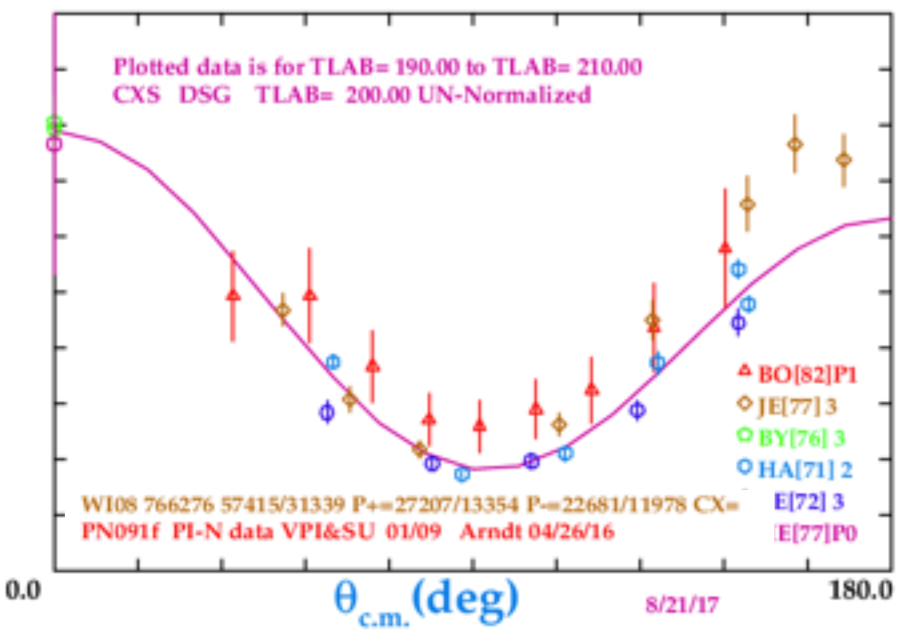


$$
\frac{1}{\Lambda^k}\int_{\nu_0}^{\Lambda} \mathrm{Im}\ A(\nu,t)\nu^k d\nu = \frac{\beta(t)\Lambda^{\alpha(t)+1}}{\alpha(t)+k+1}
$$



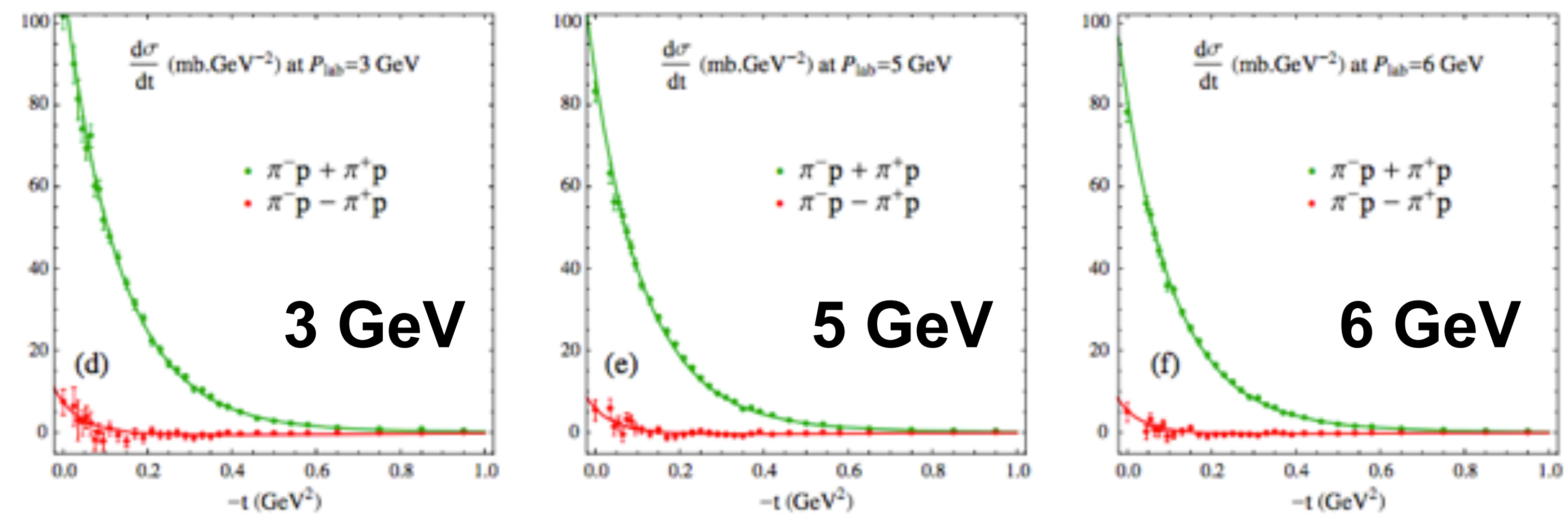
Low energy: SAID





High energy: Regge

VM et al. (JPAC) PRD92 (2015)



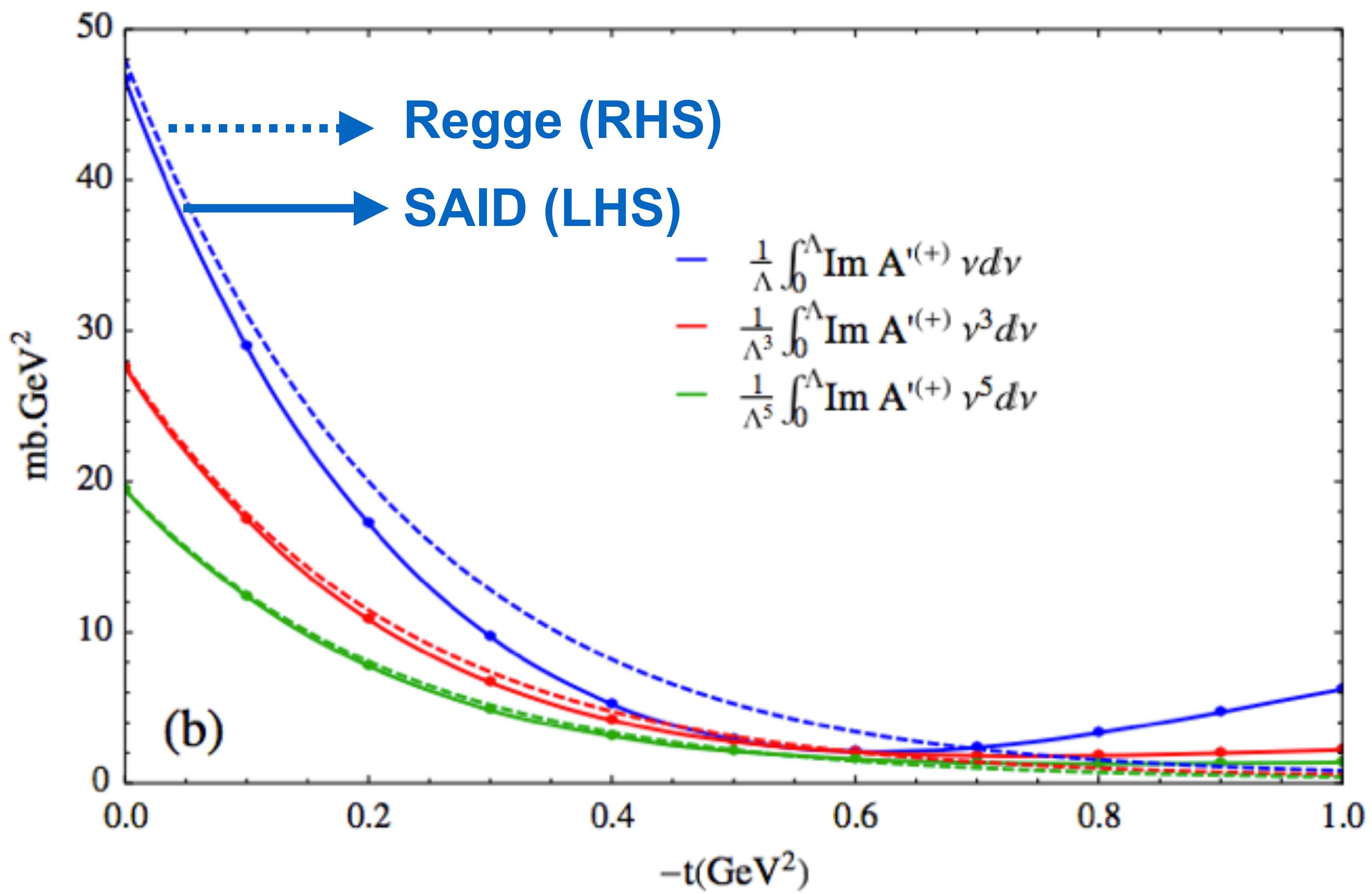
$$\boxed{\frac{1}{\Lambda^k}\int_{\nu_0}^{\Lambda} \mathrm{Im}\ A(\nu,t)\nu^k d\nu = \frac{\beta(t)\Lambda^{\alpha(t)+1}}{\alpha(t)+k+1}}$$

FESR provides constraint on the low energy fit (that determines resonances parameters)

High energy fit determines $\beta(t)$ **and** $\alpha(t)$

Let's compare both side of the sum rule

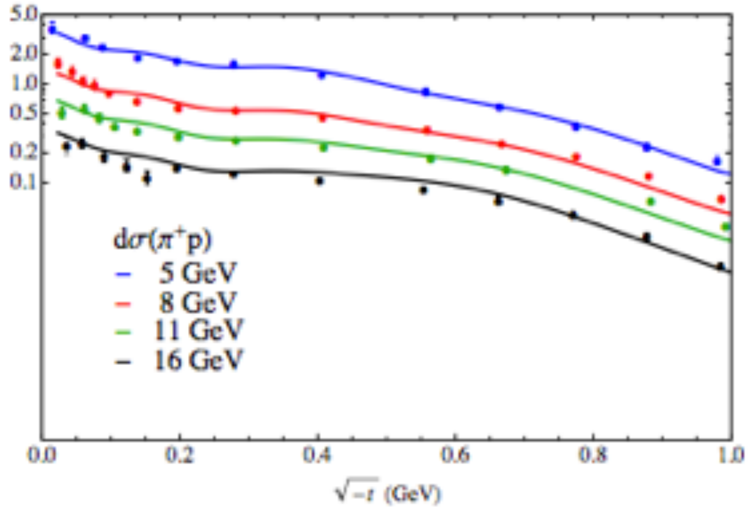
$$\pi^{\pm} p \to \pi^{\pm} p$$

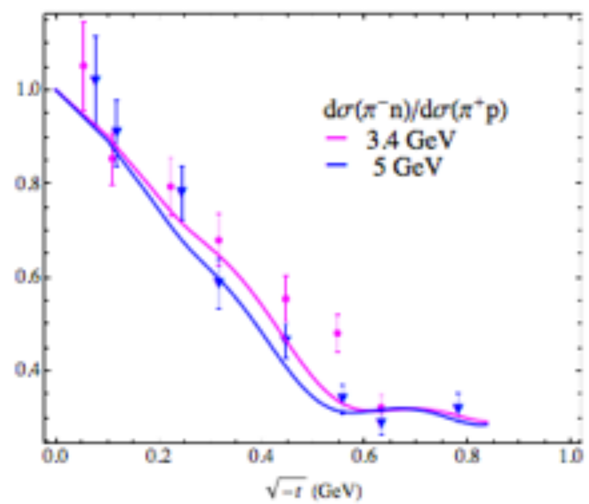


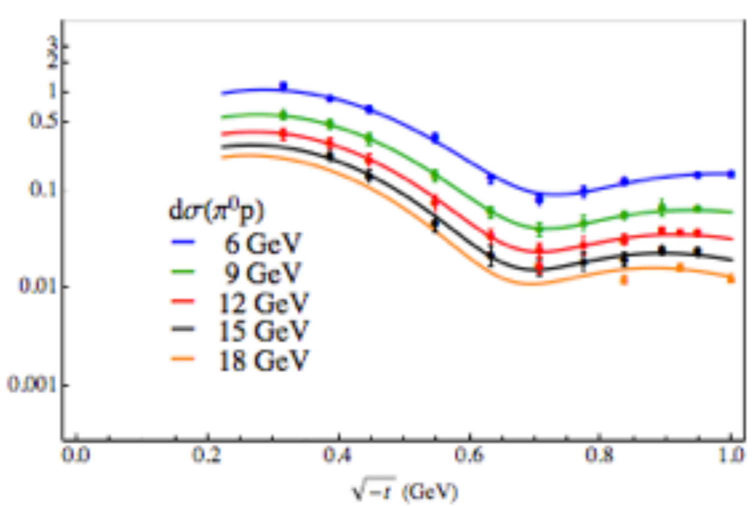
$$\boxed{\frac{1}{\Lambda^k}\int_{\nu_0}^{\Lambda} \mathrm{Im}\ A(\nu,t)\nu^k d\nu = \frac{\beta(t)\Lambda^{\alpha(t)+1}}{\alpha(t)+k+1}}$$

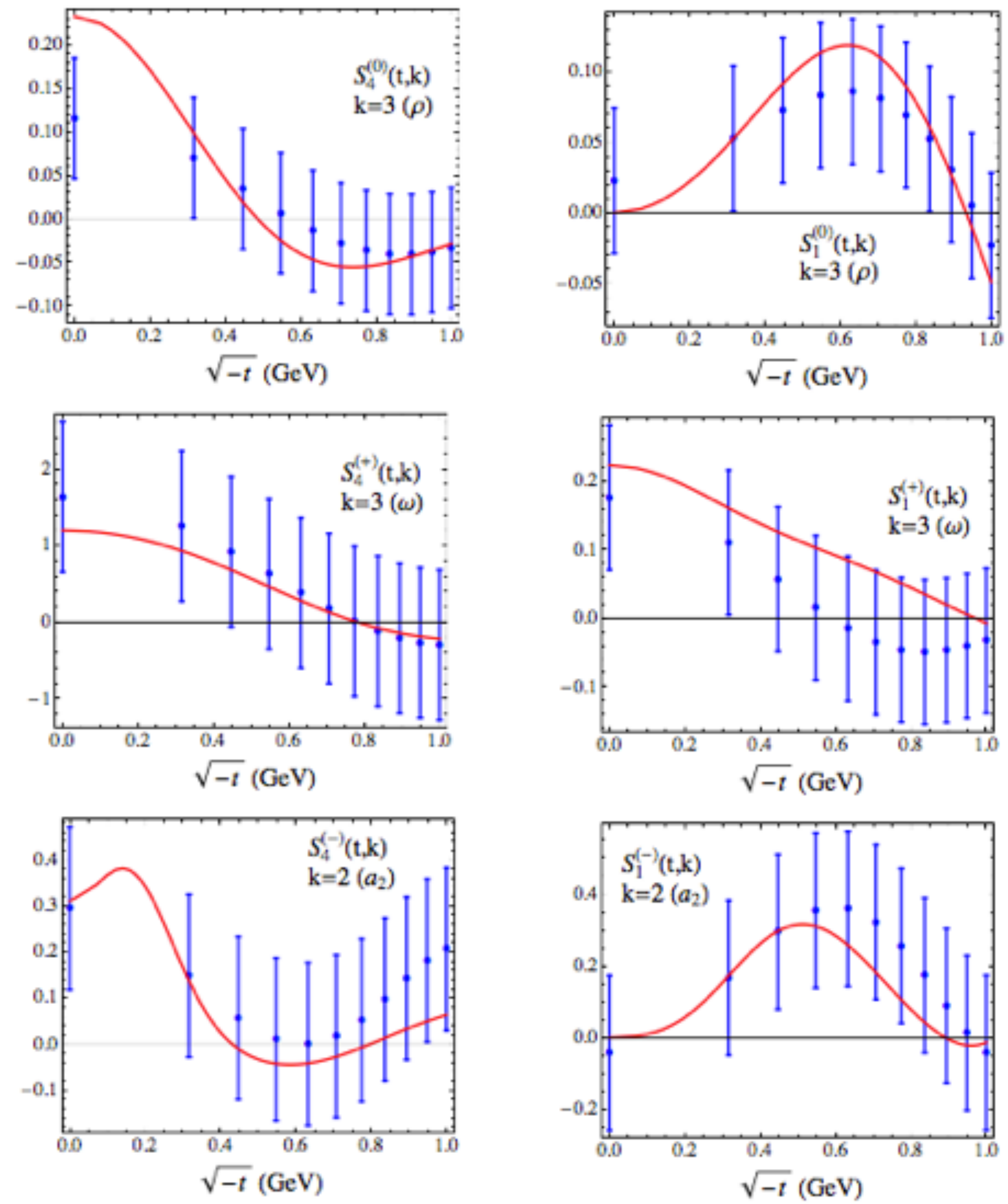
VM et al (JPAC) PRD92 (2015) ; arXiv:1506.01764

Combined Fit of FESR and Observables









$$\gamma N \to \pi N$$

$$\frac{1}{\Lambda^3}\int_0^\Lambda \mathrm{Im}\ A(\nu,t)\nu^3 d\nu = \beta(t)\frac{\Lambda^{\alpha(t)+1}}{\alpha(t)+4}$$

VM et al (JPAC) in preparation

Future Projects

J. Stevens et al.

$$\gamma p \to \omega p$$

$$\gamma p \to \pi \Delta$$

$$\gamma p \to \eta \pi^0 p$$

M. Mikhasenko et al.

$$\pi^- p \to \eta \pi^- p$$ **arXiv:1707.02848**

$$\pi^- p \to \pi^- \pi^+ \pi^- p$$

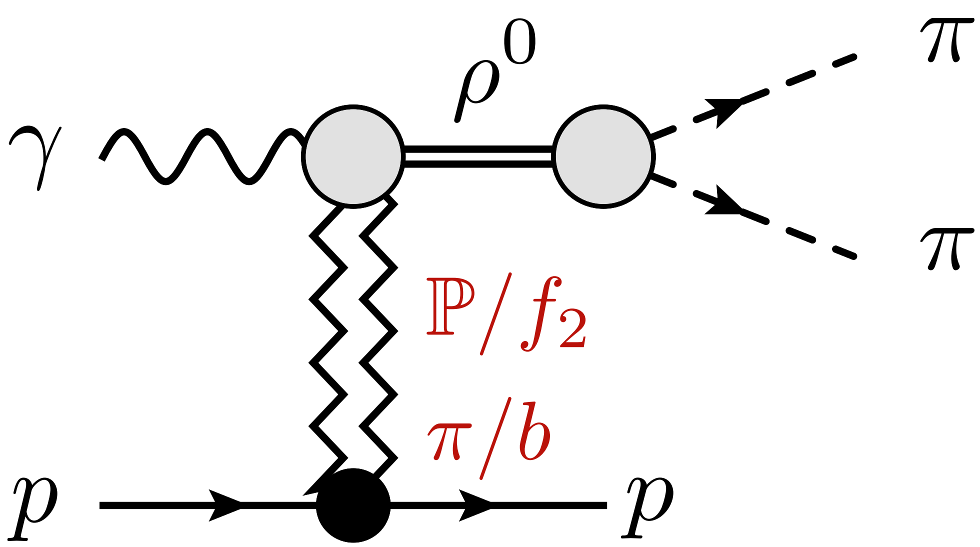
T. Skwarnicki et al.

$$\Lambda_b \to J/\psi K^- p$$

R. Mitchell et al.

$$e^+ e^- \to \pi^+ \pi^- J/\psi$$ **PLB772 (2017)**

$\gamma p \to \rho^0 p$



Use beam polarization to extract spin density matrix elements:

$$\rho^0_{MM'} = \frac{1}{N} \sum_{\lambda_\gamma \lambda_p \lambda_{p'}} A_{\lambda_\gamma \lambda_p \lambda_{p'}, M} A^*_{\lambda_\gamma \lambda_p \lambda_{p'}, M'}$$

$$\rho^1_{MM'} = \frac{1}{N} \sum_{\lambda_\gamma \lambda_p \lambda_{p'}} A_{\lambda_\gamma \lambda_p \lambda_{p'}, M} A^*_{-\lambda_\gamma \lambda_p \lambda_{p'}, M'}$$

$$N = \sum_\lambda |A_\lambda|^2$$

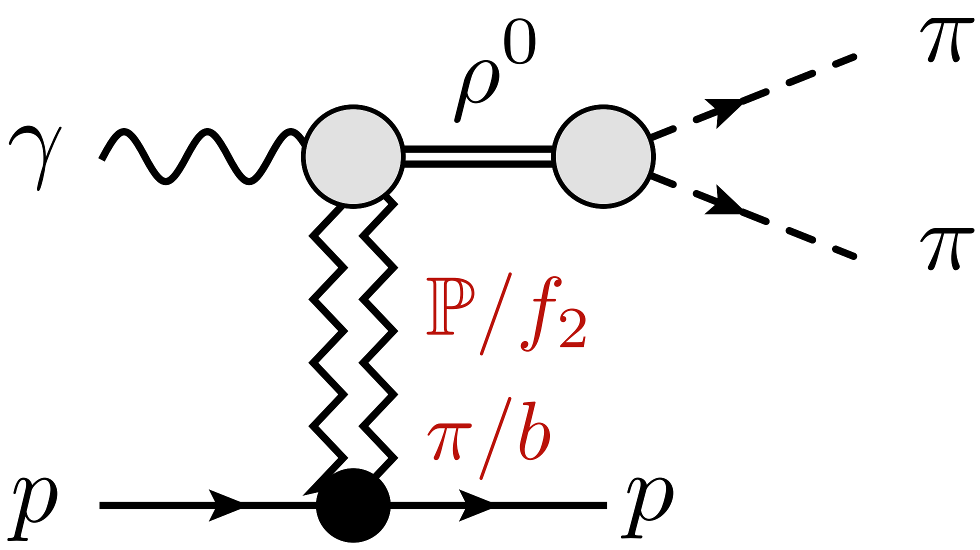
At leading s, one can separate natural and unnatural exchanges

natural exchange: Pomeron

$$\rho^N_{00} = \frac{1}{2}\left(\rho^0_{00} - \rho^1_{00}\right) \qquad \rho^N_{11} = \frac{1}{2}\left(\rho^0_{11} + \rho^1_{11}\right)$$

$$\rho^N_{10} = \frac{1}{2}\left(\rho^0_{10} - \rho^1_{10}\right) \qquad \rho^N_{1-1} = \frac{1}{2}\left(\rho^0_{1-1} + \rho^1_{11}\right)$$

$\gamma p \to \rho^0 p$



Use beam polarization to extract spin density matrix elements:

$$\rho^0_{MM'} = \frac{1}{N}\sum_{\lambda_\gamma\lambda_p\lambda_{p'}} A_{\lambda_\gamma\lambda_p\lambda_{p'},M} A^*_{\lambda_\gamma\lambda_p\lambda_{p'},M'}$$

$$\rho^1_{MM'} = \frac{1}{N}\sum_{\lambda_\gamma\lambda_p\lambda_{p'}} A_{\lambda_\gamma\lambda_p\lambda_{p'},M} A^*_{-\lambda_\gamma\lambda_p\lambda_{p'},M'}$$

$$N = \sum_\lambda |A_\lambda|^2$$

At leading s, one can separate natural and unnatural exchanges

natural exchange: Pomeron

$$\rho^N_{00} = \frac{1}{2}\left(\rho^0_{00} - \rho^1_{00}\right) \qquad \rho^N_{11} = \frac{1}{2}\left(\rho^0_{11} + \rho^1_{11}\right)$$

$$\rho^N_{10} = \frac{1}{2}\left(\rho^0_{10} - \rho^1_{10}\right) \qquad \rho^N_{1-1} = \frac{1}{2}\left(\rho^0_{1-1} + \rho^1_{11}\right)$$

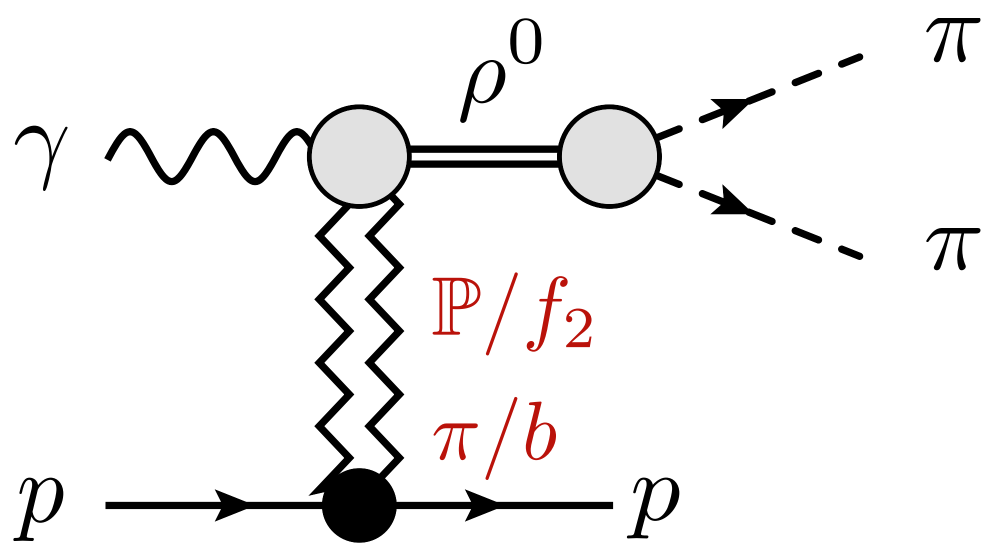
Factorization:
test t-dependence of top vertex

non-flip $\propto \beta_0\left(\sqrt{-t}\right)^0$

single-flip $\propto \beta_1\left(\sqrt{-t}\right)^1$

double-flip $\propto \beta_2\left(\sqrt{-t}\right)^2$

$\gamma p \to \rho^0 p$



Use beam polarization to extract spin density matrix elements:

$$\rho^0_{MM'} = \frac{1}{N} \sum_{\lambda_\gamma \lambda_p \lambda_{p'}} A_{\lambda_\gamma \lambda_p \lambda_{p'}, M} A^*_{\lambda_\gamma \lambda_p \lambda_{p'}, M'}$$

$$\rho^1_{MM'} = \frac{1}{N} \sum_{\lambda_\gamma \lambda_p \lambda_{p'}} A_{\lambda_\gamma \lambda_p \lambda_{p'}, M} A^*_{-\lambda_\gamma \lambda_p \lambda_{p'}, M'}$$

$$N = \sum_\lambda |A_\lambda|^2$$

At leading s, one can separate natural and unnatural exchanges

natural exchange: Pomeron

$$\rho^N_{00} = \frac{1}{2}\left(\rho^0_{00} - \rho^1_{00}\right) \qquad \rho^N_{11} = \frac{1}{2}\left(\rho^0_{11} + \rho^1_{11}\right)$$

$$\rho^N_{10} = \frac{1}{2}\left(\rho^0_{10} - \rho^1_{10}\right) \qquad \rho^N_{1-1} = \frac{1}{2}\left(\rho^0_{1-1} + \rho^1_{11}\right)$$

Factorization:
test t-dependence of top vertex

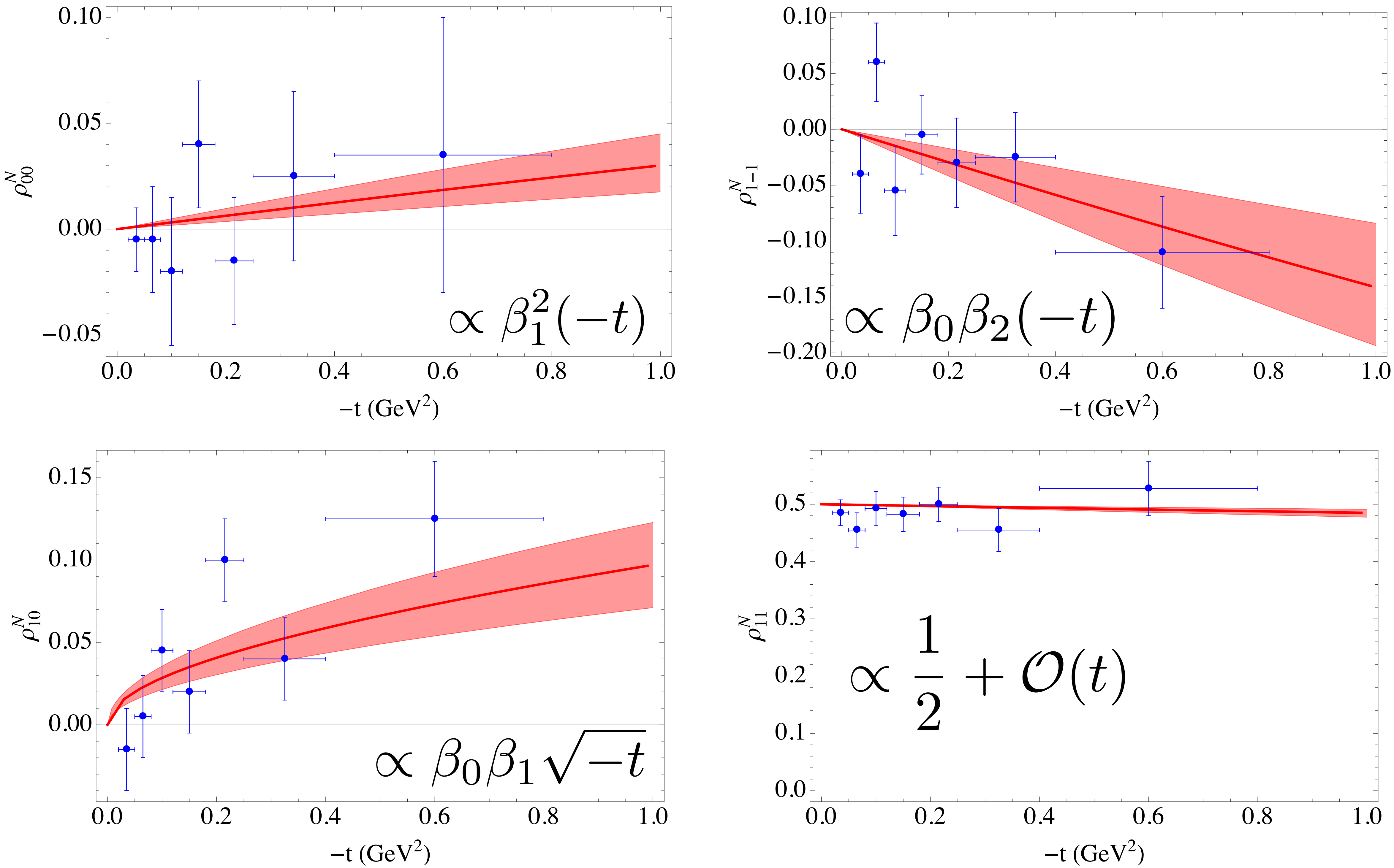
non-flip $\propto \beta_0 \left(\sqrt{-t}\right)^0$

single-flip $\propto \beta_1 \left(\sqrt{-t}\right)^1$

double-flip $\propto \beta_2 \left(\sqrt{-t}\right)^2$

Expectation: $\beta_0 > \beta_1 > \beta_2$

$\gamma p \to \rho^0 p$: SDME for Natural Exchange



[SLAC Ballam 1973 Eg = 9.3 GeV]

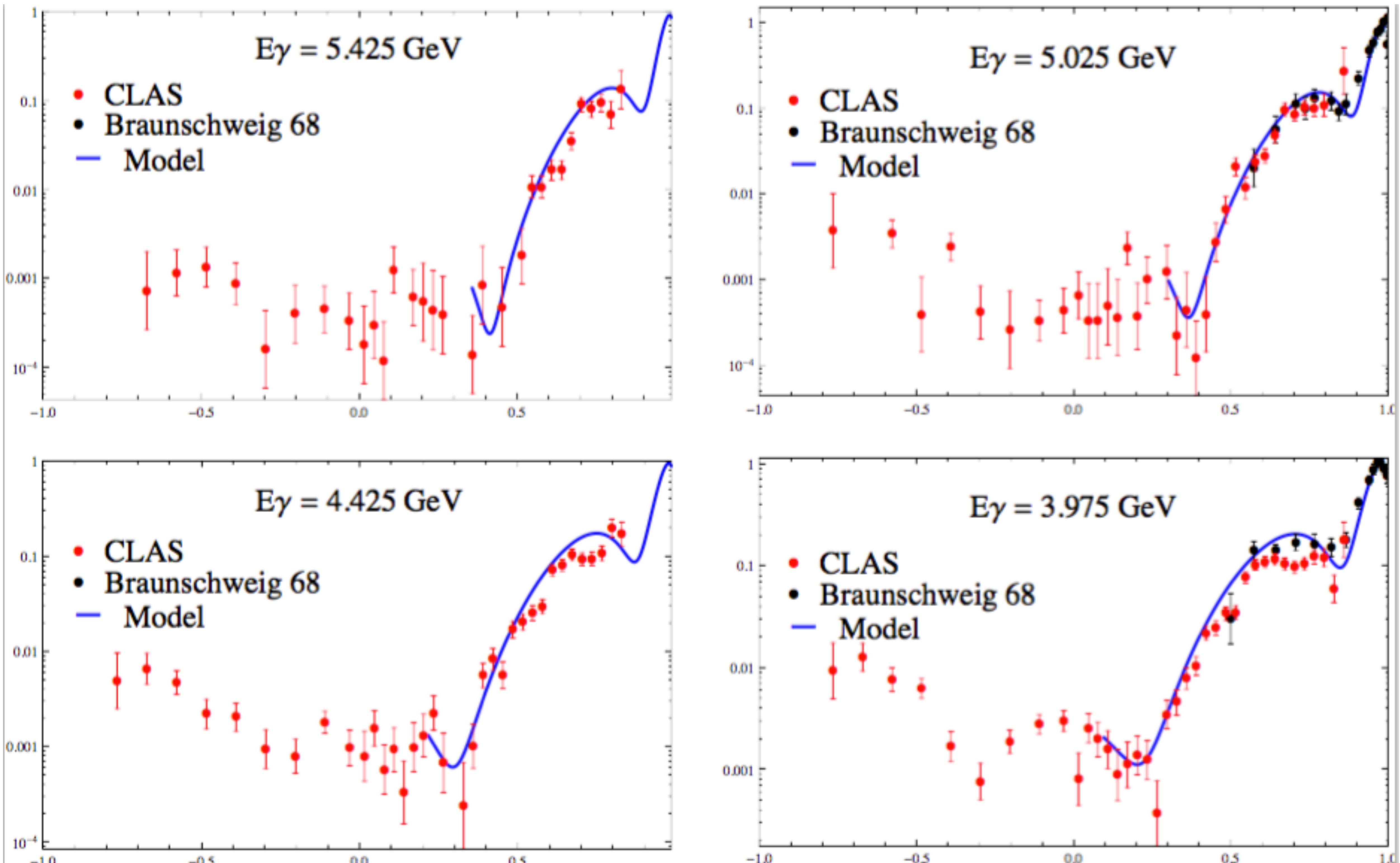
Expectation: $\beta_0 > \beta_1 > \beta_2$

Fit: $\beta_0 : \beta_1 : \beta_2 = 1.00 : 0.14 : -0.09$

$\gamma p \to \pi^0 p$

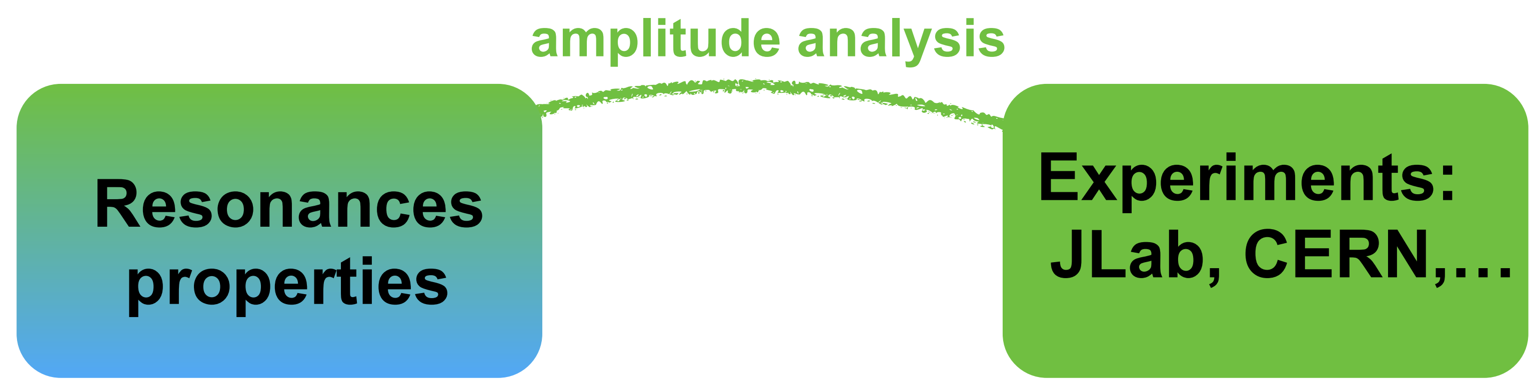
Blue line: Predictions from VM et al
Phys. Rev. D92 074013

Red points: Data from CLAS (preliminary)
Courtesy of M. Kunkel

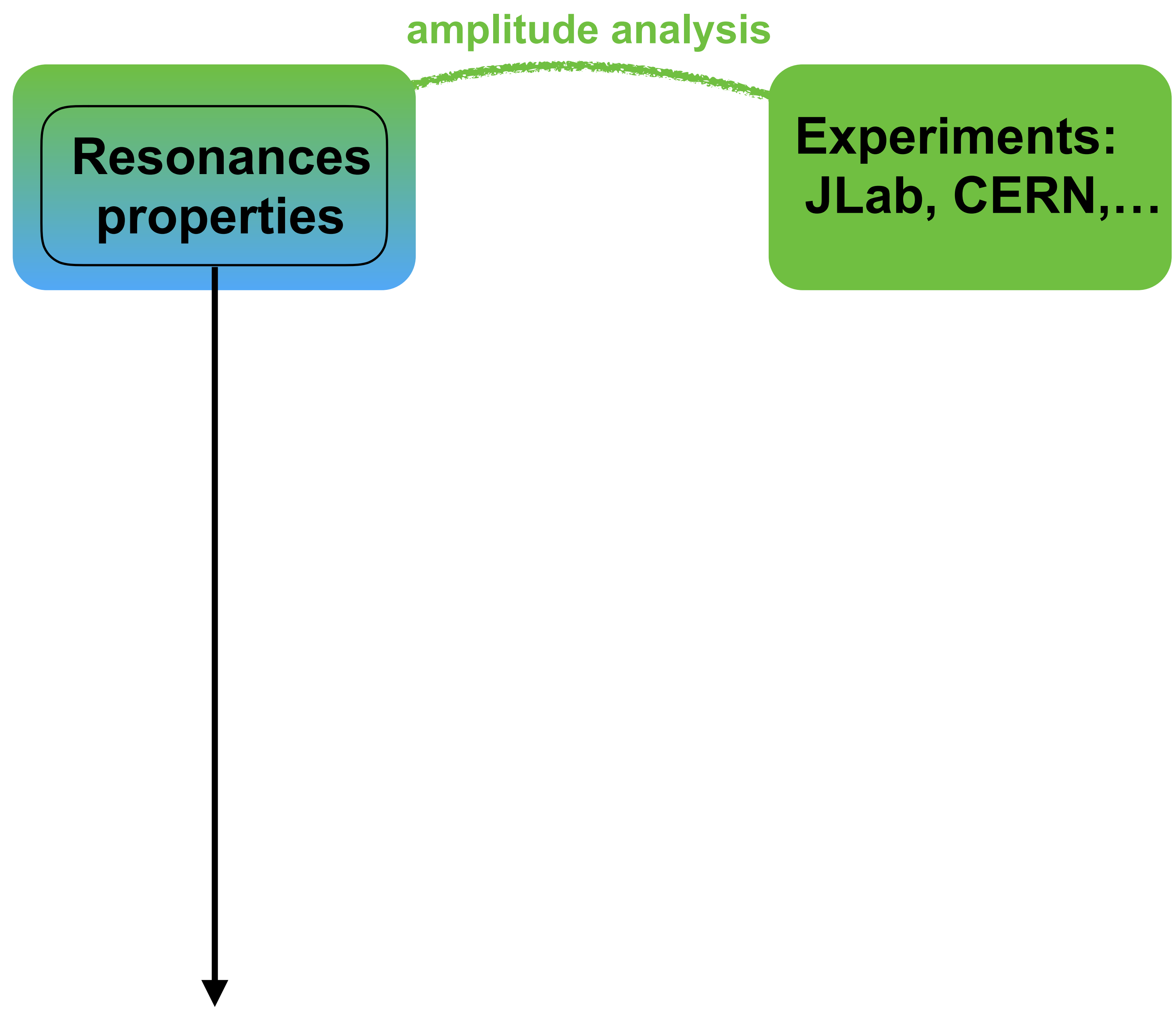


$\cos\theta$ $\cos\theta$

Extracting Resonance Properties



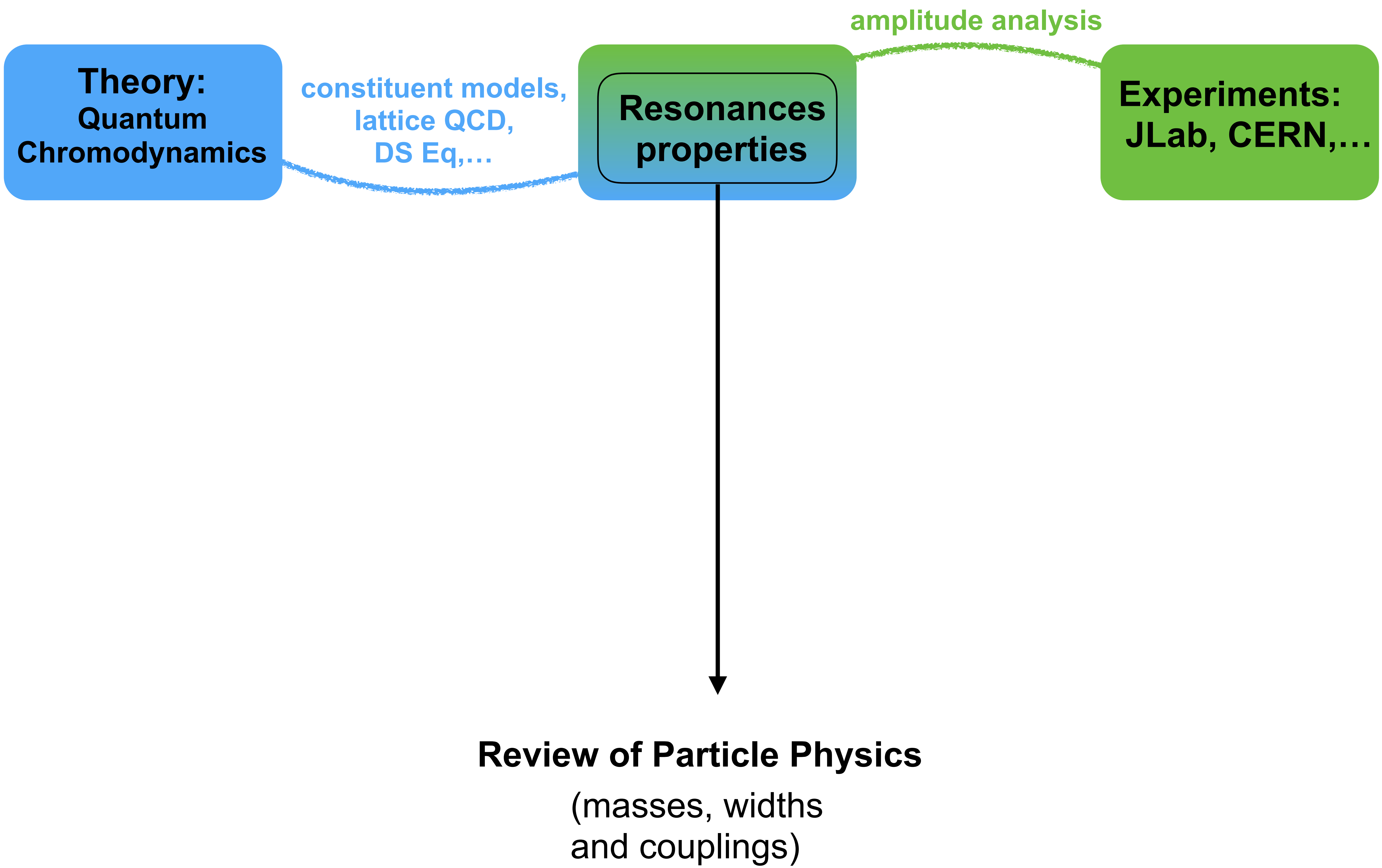
Extracting Resonance Properties



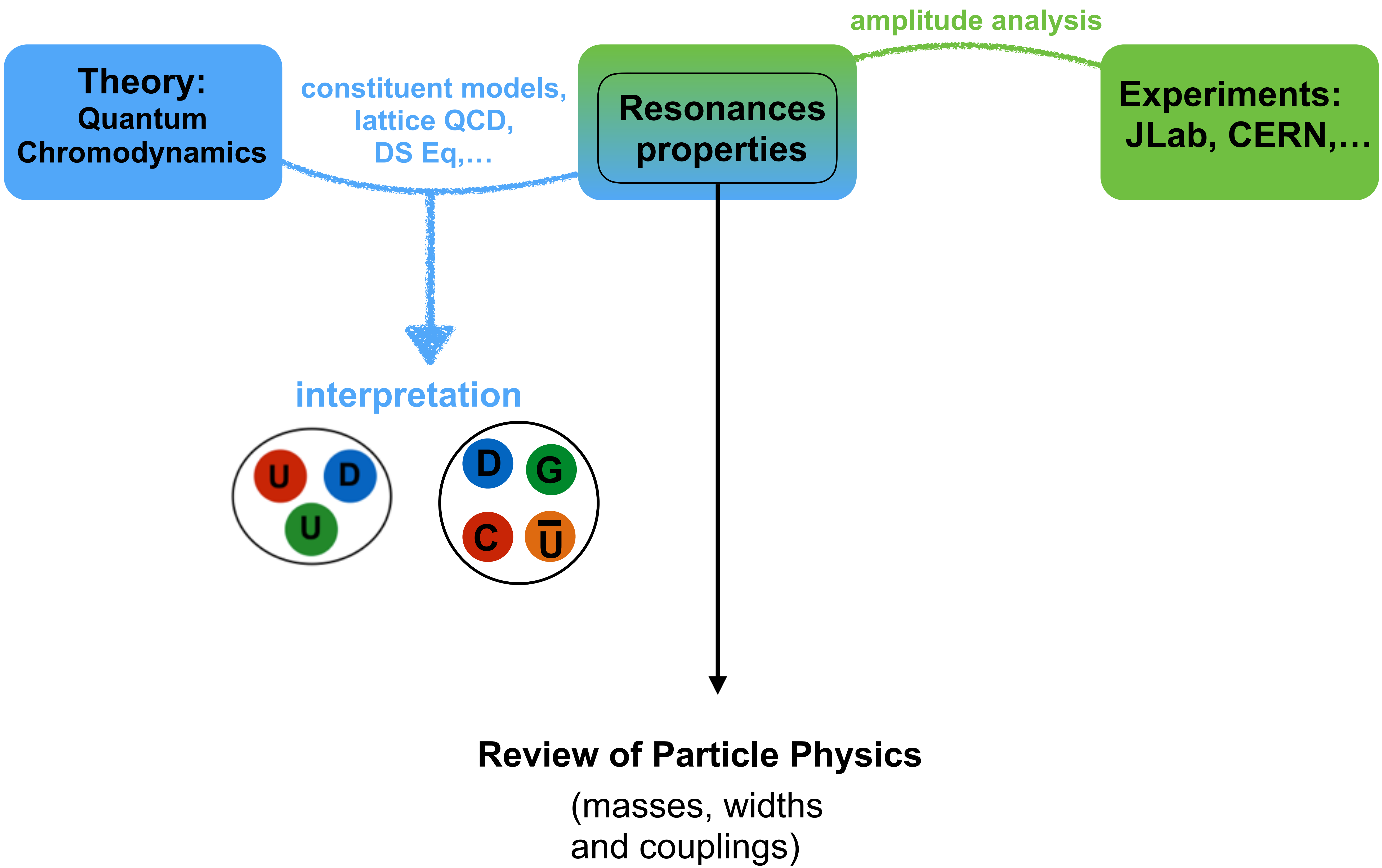
Review of Particle Physics

(masses, widths
and couplings)

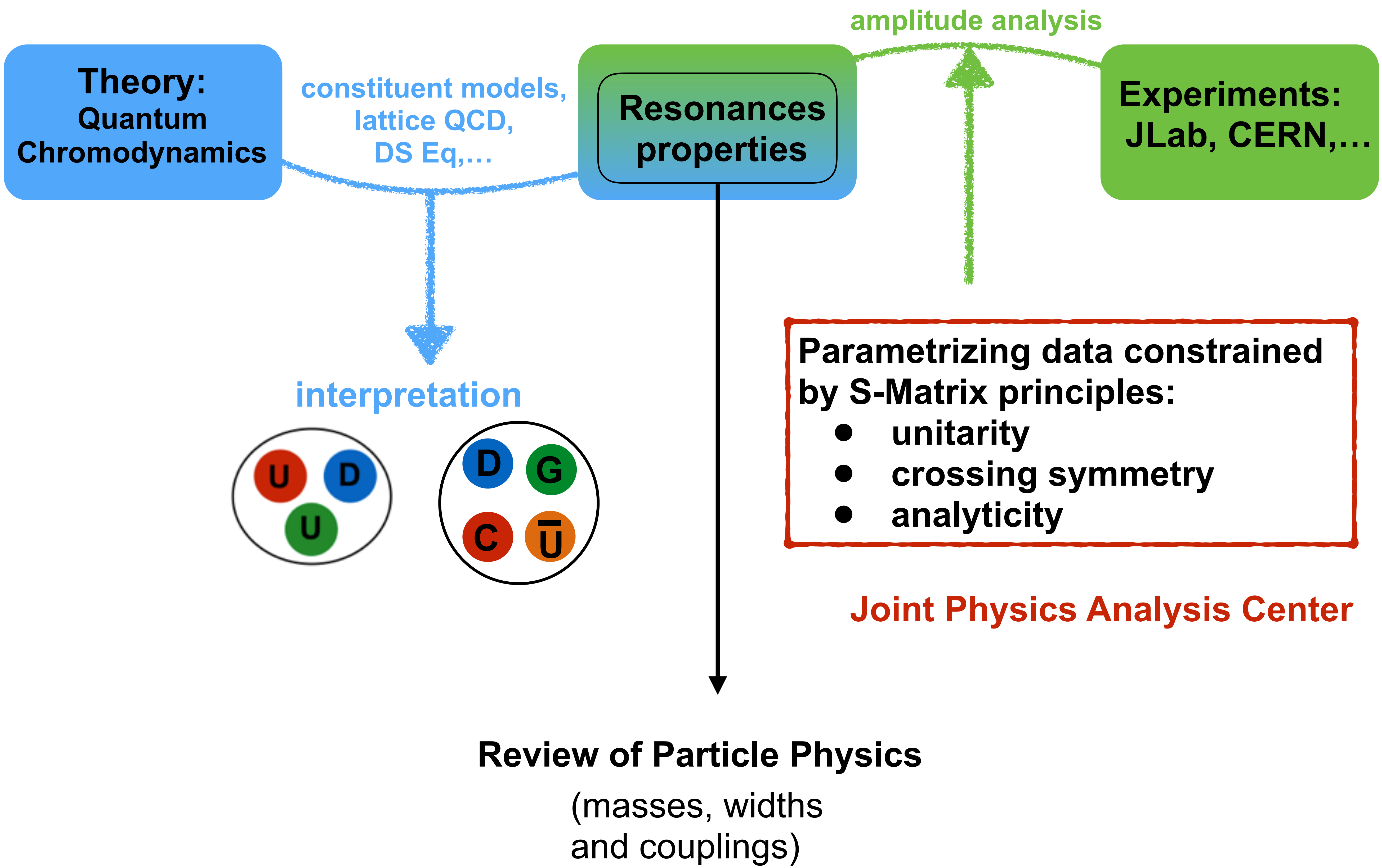
Extracting Resonance Properties



Extracting Resonance Properties



Extracting Resonance Properties



INDIANA UNIVERSITY BLOOMINGTON

Jefferson Lab
Thomas Jefferson National Accelerator Facility

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Joint Physics Analysis Center

HOME PROJECTS PUBLICATIONS LINKS

U.S. DEPARTMENT OF ENERGY

National Science Foundation

JPAC acknowledges support from DOE and NSF

INDIANA UNIVERSITY

Interactive webpage: http://www.indiana.edu/~jpac/index.html

Indiana University

- **Adam Szczepaniak** Professor
- **Geoffrey Fox** Professor
- **Emilie Passemar** Professor
- **Tim Londergan** Professor
- **Ina Lorenz** Postdoctoral researcher
- **Andrew Jackura** PhD student

Jefferson Lab

- **Michael R. Pennington** Professor
- **Viktor Mokeev** Professor
- **Vincent Mathieu** Postdoctoral researcher
- **Alessandro Pilloni** Postdoctoral researcher

Universidad Nacional Autonoma de Mexico

- **Cesar Fernandez-Ramirez** Professor

Johannes Gutenberg University, Mainz

- **Igor Danilkin** Postdoctoral researcher
- **Astrid Hiller Blin** Postdoctoral researcher

Murcia University

- **Miguel Albaladejo** Postdoctoral researcher

George Washington University

- **Ron Workman** Professor
- **Michael Doring** Professor

Bonn University

- **Misha Mikhasenko** PhD student

Ghent University

- **Jannes Nys** PhD student

INDIANA UNIVERSITY BLOOMINGTON

Jefferson Lab
Thomas Jefferson National Accelerator Facility

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Joint Physics Analysis Center

HOME PROJECTS PUBLICATIONS LINKS

U.S. DEPARTMENT OF ENERGY

National Science Foundation

JPAC acknowledges support from DOE and NSF

INDIANA UNIVERSITY

Interactive webpage: http://www.indiana.edu/~jpac/index.html

Photoproduction:

1. High energy model for η' beam asymmetry photoproduction: $\gamma p \to \eta^{(\prime)} p$ page
2. High energy model for η photoproduction: $\gamma p \to \eta p$ page
3. High energy model for π^0 photoproduction: $\gamma p \to \pi^0 p$ page
4. High energy model for J/ψ photoproduction: $\gamma p \to J/\psi p$ page

Hadroproduction:

1. Pion-nucleon scattering:
   - Amplitudes $\pi N \to \pi N$ amplitude page
   - Finite energy sum rules $\pi N \to \pi N$ FESR page
2. Kaon-nucleon scattering: $\bar{K}N \to \bar{K}N$ page

Light meson Decay:

1. η meson into three pions: $\eta \to 3\pi$ page
2. vector meson into three pions: $\omega, \phi \to 3\pi$ page

Indiana University

- **Adam Szczepaniak** Pro
- **Geoffrey Fox** Professor
- **Emilie Passemar** Profes
- **Tim Londergan** Profess
- **Ina Lorenz** Postdoctoral
- **Andrew Jackura** PhD s

Jefferson Lab

- **Michael R. Pennington**
- **Viktor Mokeev** Professo
- **Vincent Mathieu** Postdo
- **Alessandro Pilloni** Post

Washington University

- **Workman** Professor
- **ael Doring** Professor

niversity

- **ha Mikhasenko** PhD student

University

- **nes Nys** PhD student

Collaborations

$$\gamma p \to \pi\pi p$$ PRD80, PRL102 (2009)

$$\gamma p \to K\bar{K}p$$ under CLAS review

HASPECT (HAdron SPEctroscopy CenTer)
M. Battaglieri et al.

J. Stevens et al.

$$\gamma p \to \pi^0 p, \eta p$$ PRC95 (2017)

$$\gamma p \to \omega p$$

$$\gamma p \to \pi\Delta$$

M. Mikhasenko et al.

$$\pi^- p \to \eta\pi^- p$$ arXiv:1707.02848

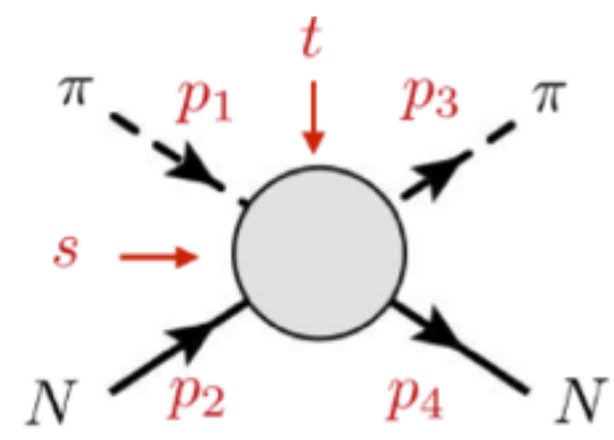
$$\pi^- p \to \pi^-\pi^+\pi^- p$$

T. Skwarnicki et al.

$$\Lambda_b \to J/\psi K^- p$$

INDIANA UNIVERSITY

Interactive webpage: http://www.indiana.edu/~jpac/index.html



Upload your partial waves: Choose File no file selected

Or choose a model: ◉ SAID ○ JuBo ○ BnGo ○ KH80 ○ ANL-O

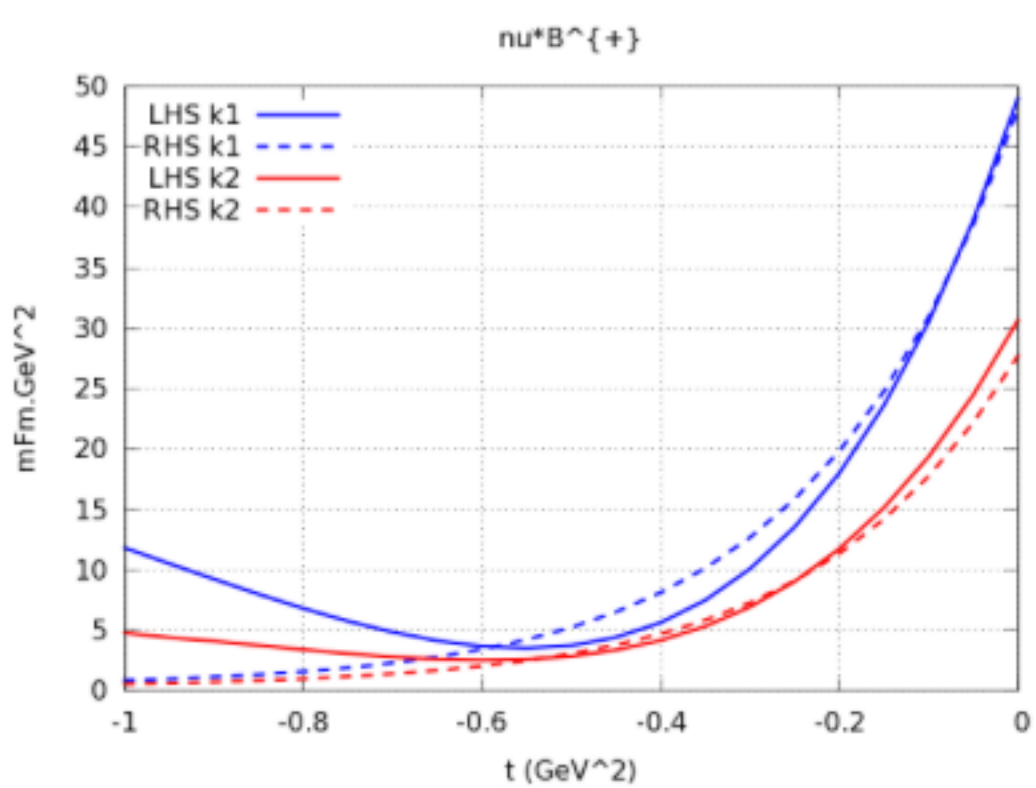
Range of t in GeV^2: min = -1.0 max = 0.0 step = 0.05

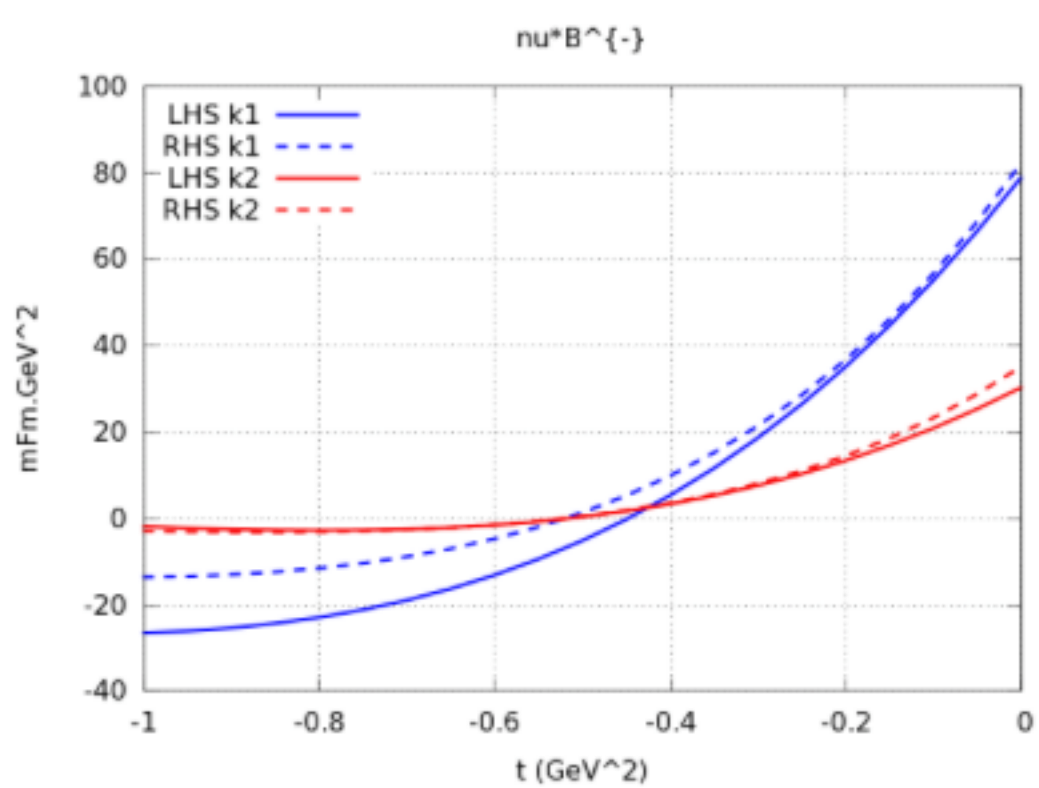
Cutoff: $E_{\rm lab}^{\rm max}$ = 2.00 GeV

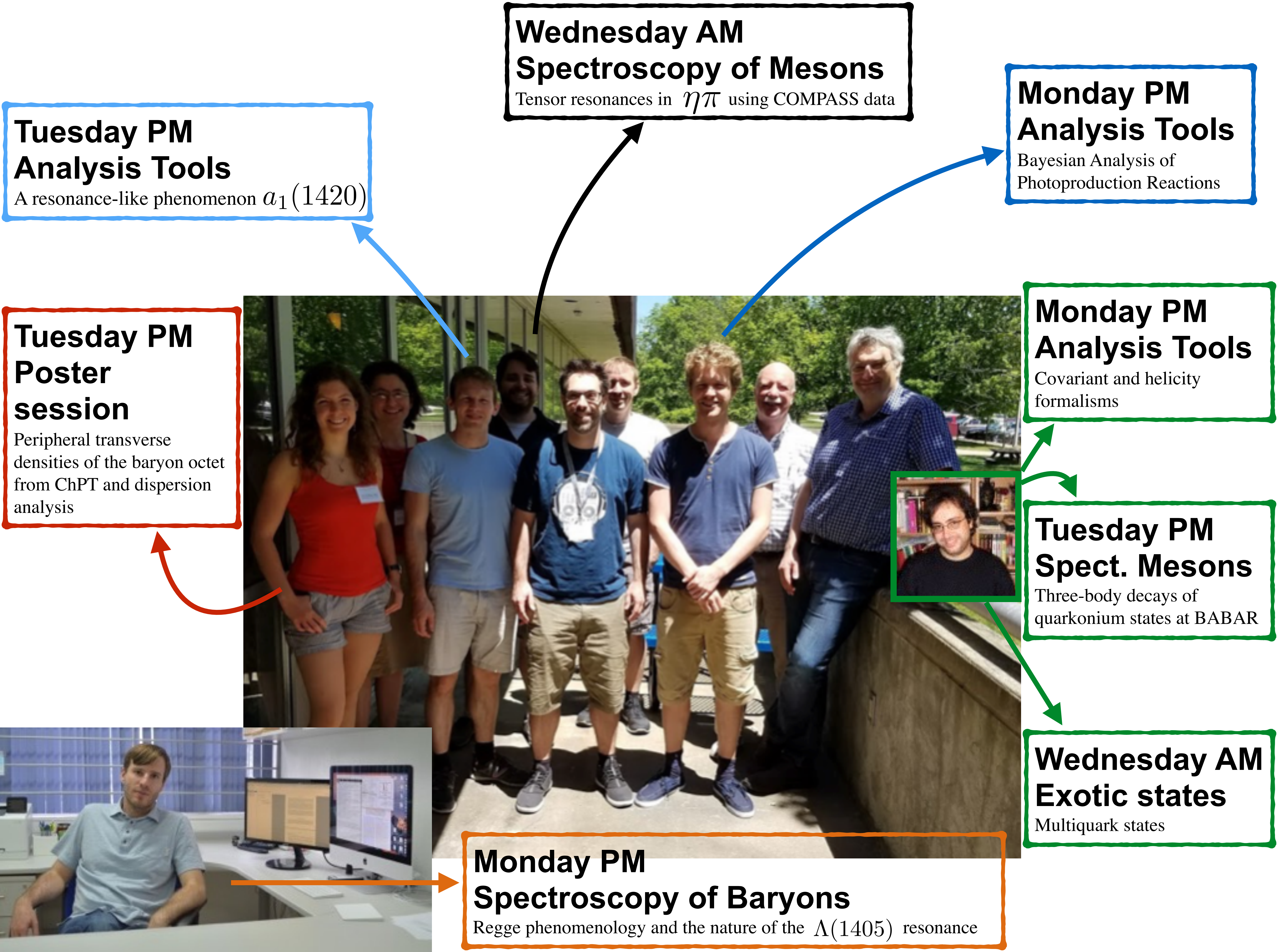
Moments: k1 = 0 k2 = 2

Regge parameters [show/hide]

Start






Wednesday AM
Spectroscopy of Mesons
Tensor resonances in $\eta\pi$ using COMPASS data
Tuesday PM
Analysis Tools
A resonance-like phenomenon $a_1(1420)$
Monday PM
Analysis Tools
Bayesian Analysis of Photoproduction Reactions
Tuesday PM
Poster session
Peripheral transverse densities of the baryon octet from ChPT and dispersion analysis
Monday PM
Analysis Tools
Covariant and helicity formalisms
Tuesday PM
Spect. Mesons
Three-body decays of quarkonium states at BABAR
Wednesday AM
Exotic states
Multiquark states
Monday PM
Spectroscopy of Baryons
Regge phenomenology and the nature of the $\Lambda(1405)$ resonance