Regge Models of meson photoproduction

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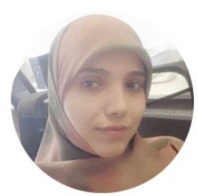

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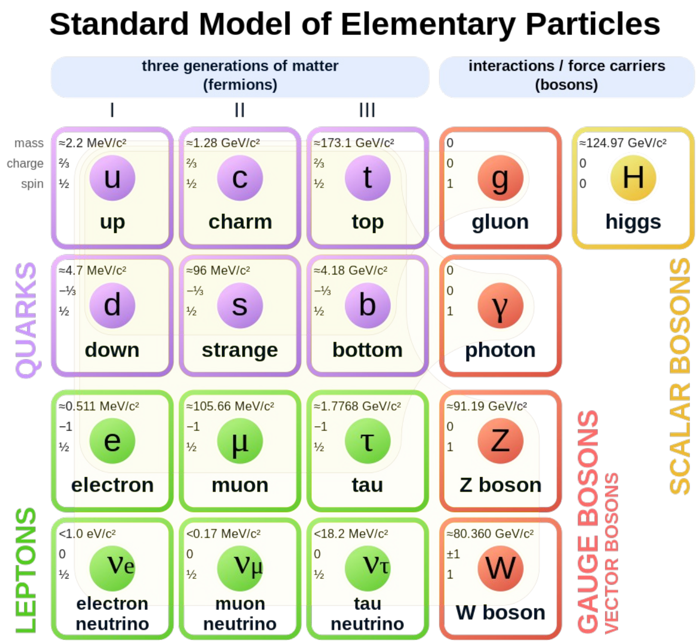
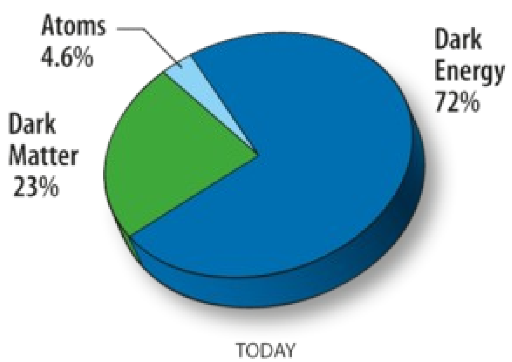
Motivation

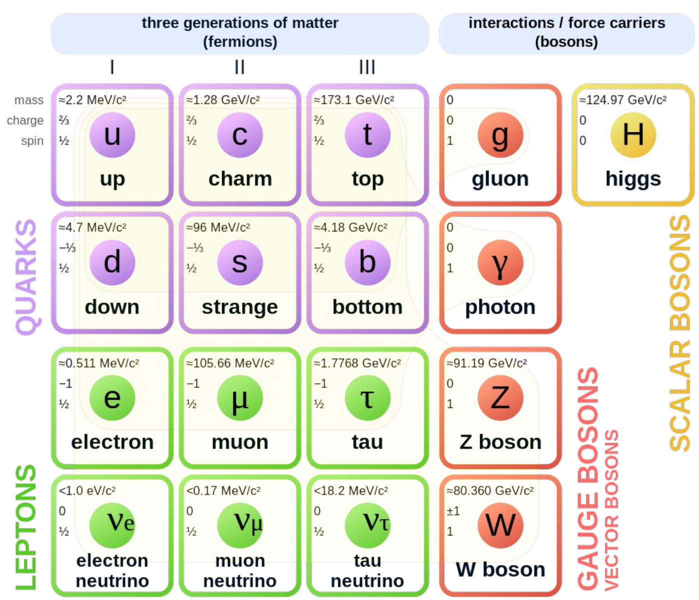


Beyond the Standard Model

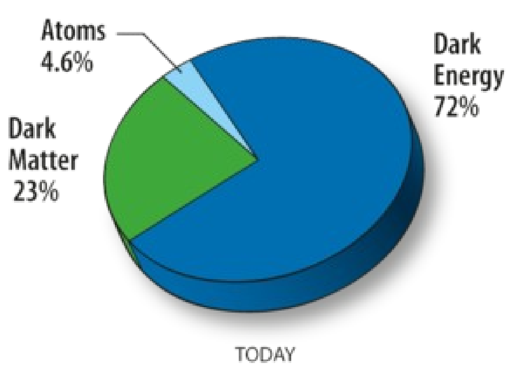


Motivation

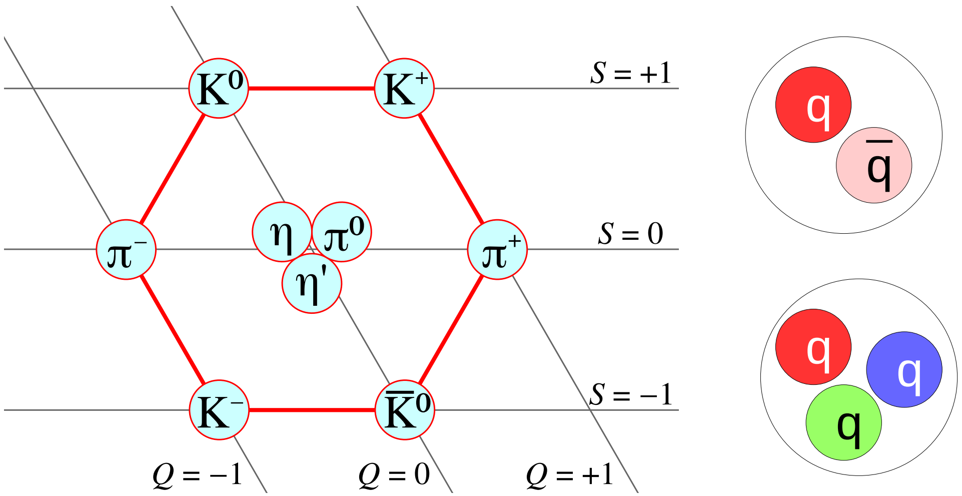
Standard Model of Elementary Particles



Beyond the Standard Model

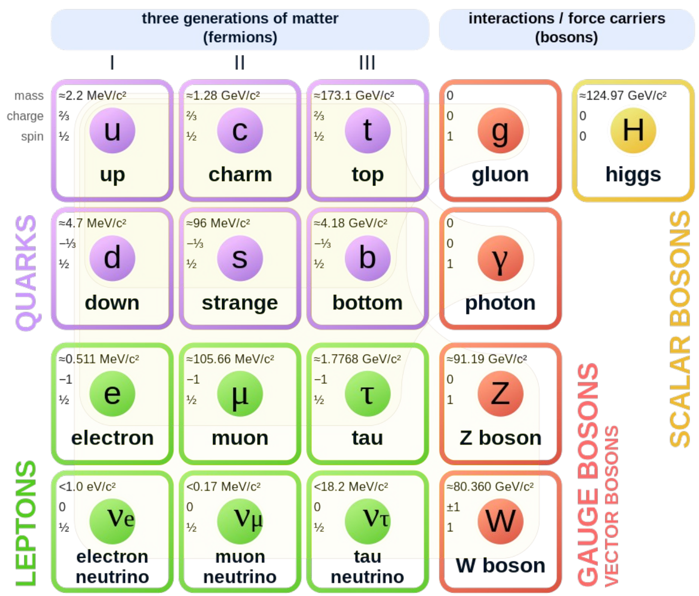


Standard (Quark) Model



Motivation

Standard Model of Elementary Particles



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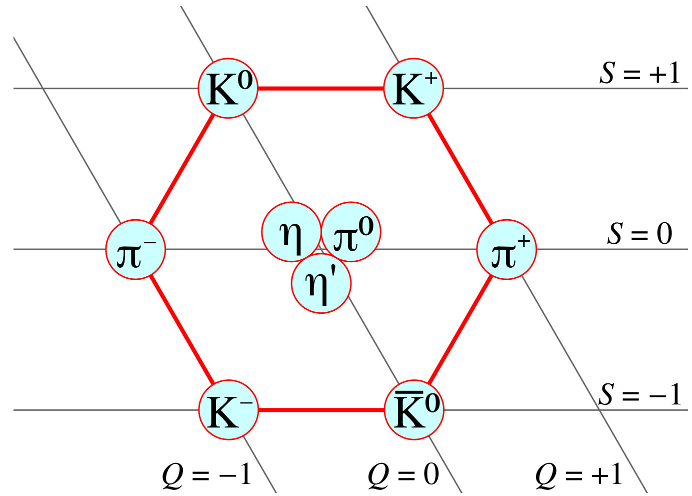
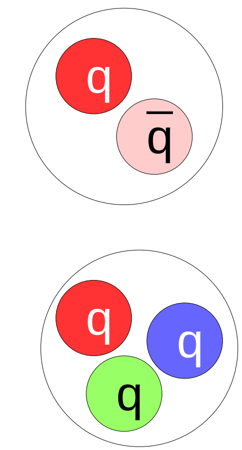
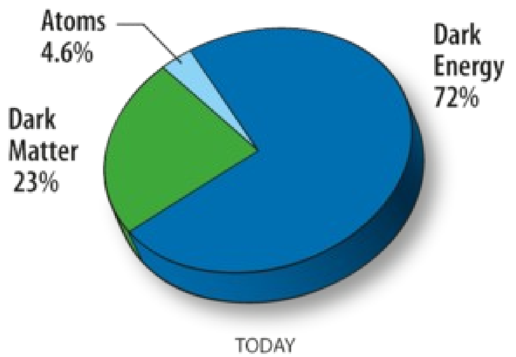
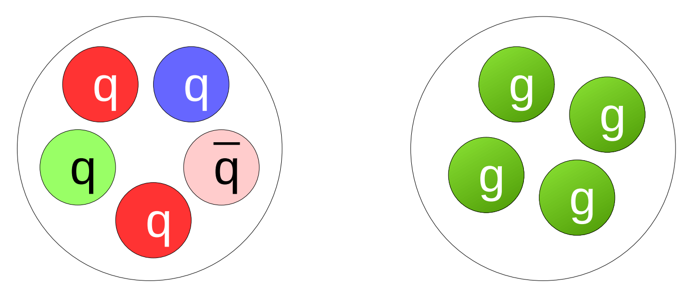




Beyond the Standard Model

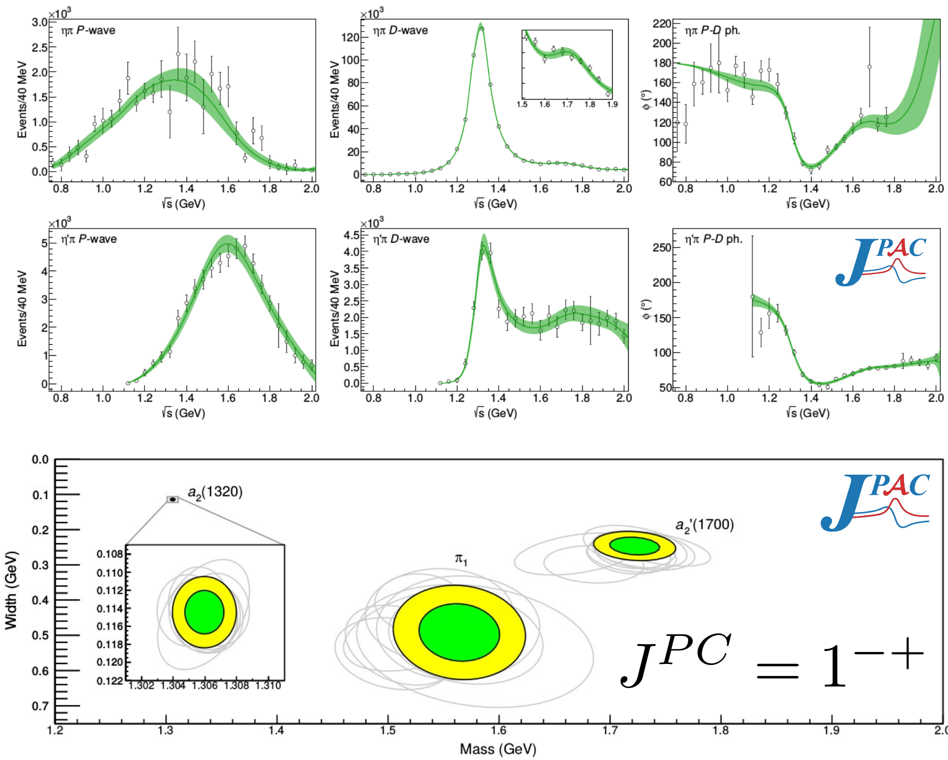


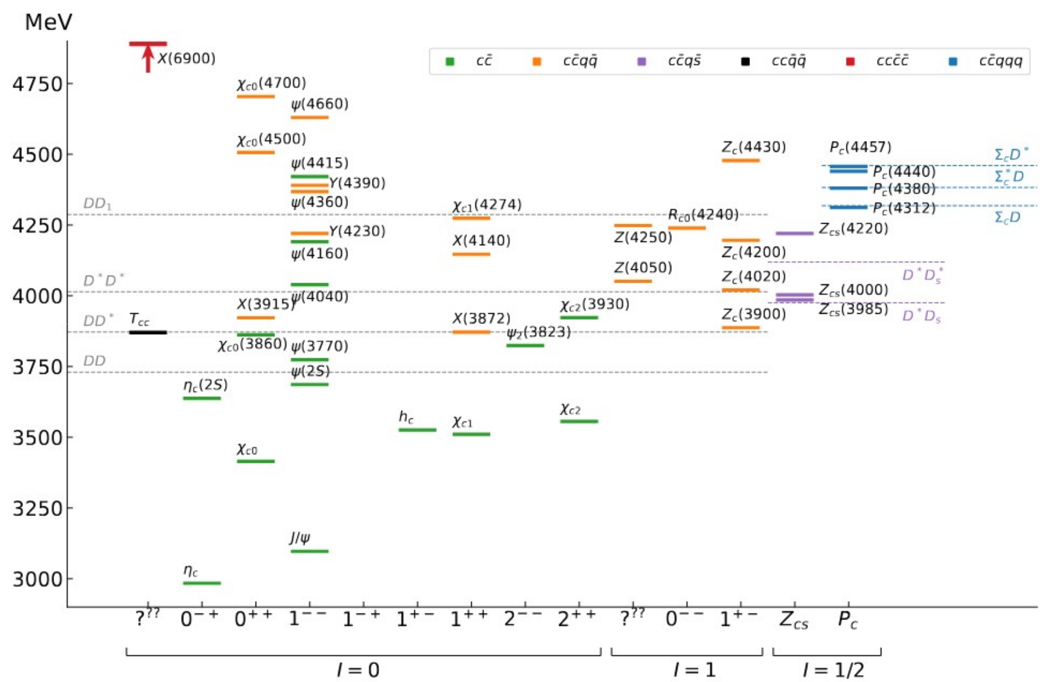
Beyond the Standard (Quark) Model



Evidence for BS(Q)M

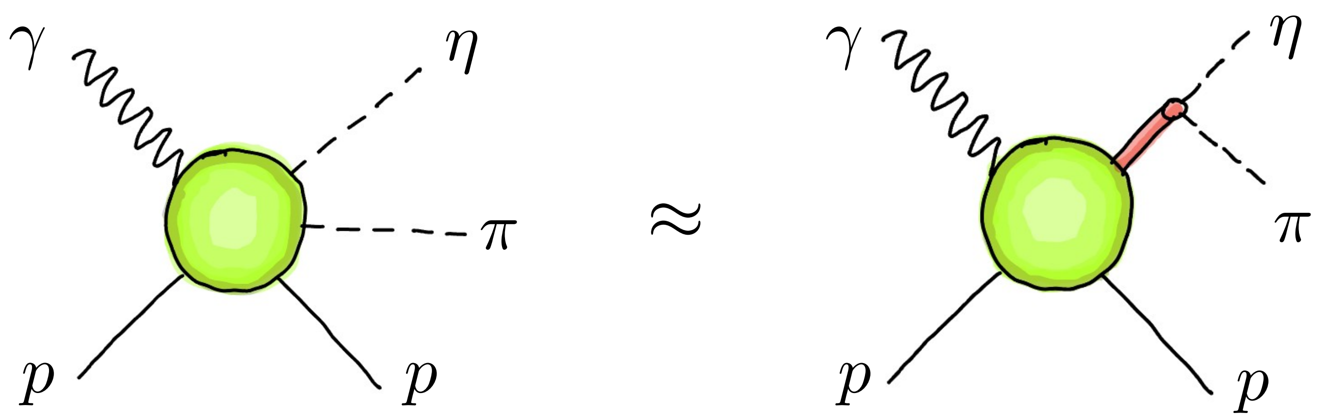
Evidence for BS(Q)M in the light **and** heavy sectors





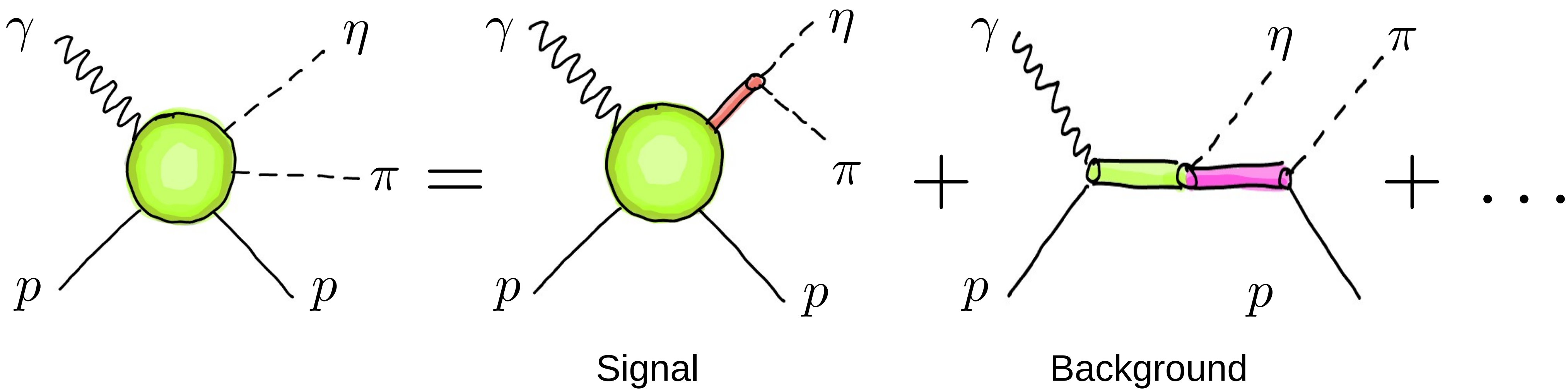
Photoproduction

- Use peripheral photoproduction to produce:



Reality is not so simple...

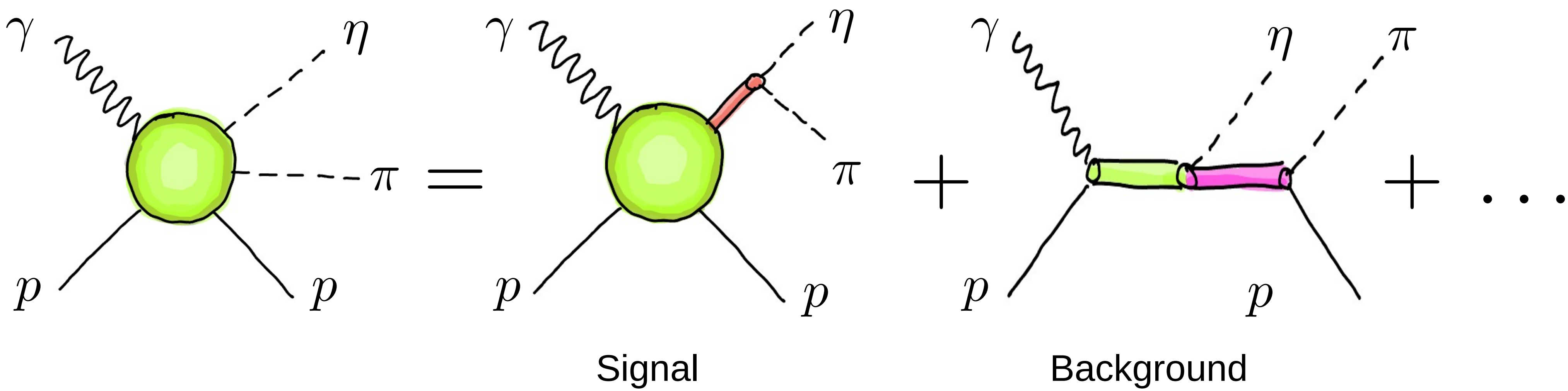
- QCD: All things not prohibited must happen:



- Understand relevant physics to isolate exotic meson signal
- What is effect of **background** on measurements?
- Theoretical input **critical...**

Reality is not so simple...

- QCD: All things not prohibited must happen:



- Understand relevant physics to isolate exotic meson signal
- What is effect of **background** on measurements?
- Theoretical input **critical...**

These requirements are mass-independent

Outline

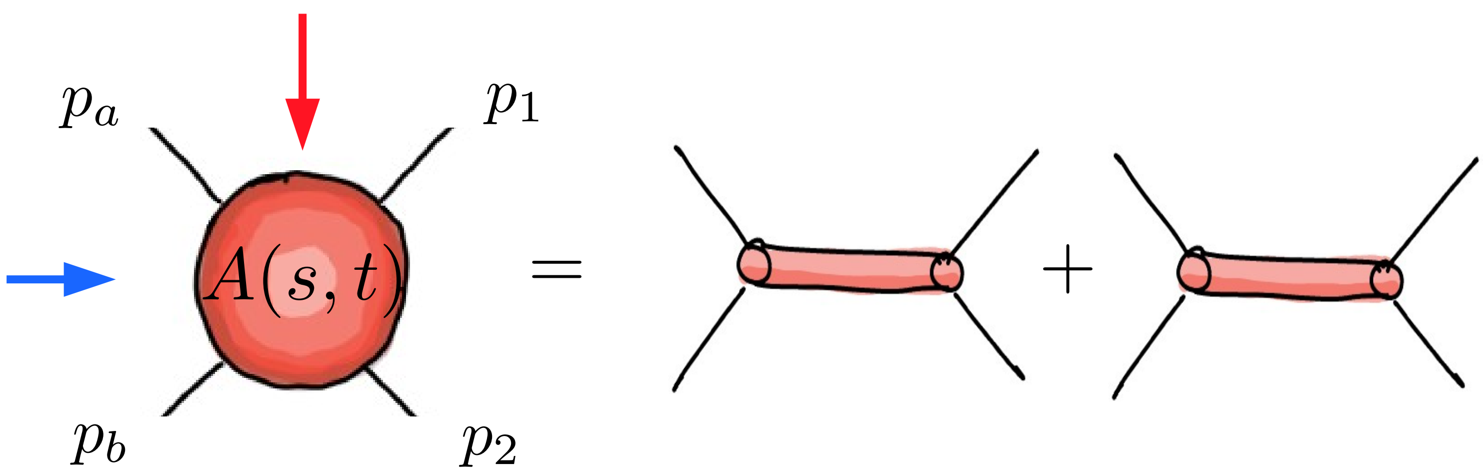
- Motivation
- Regge theory
- Applications of Regge theory
  - Two-pion photoproduction
  - XYZ photoproduction
- Conclusions

Regge Theory

- Consider scattering amplitude in limit s large, t small
- Re-summation infinite tower of states

$$t = (p_a - p_1)^2$$

$$s = (p_a + p_b)^2$$



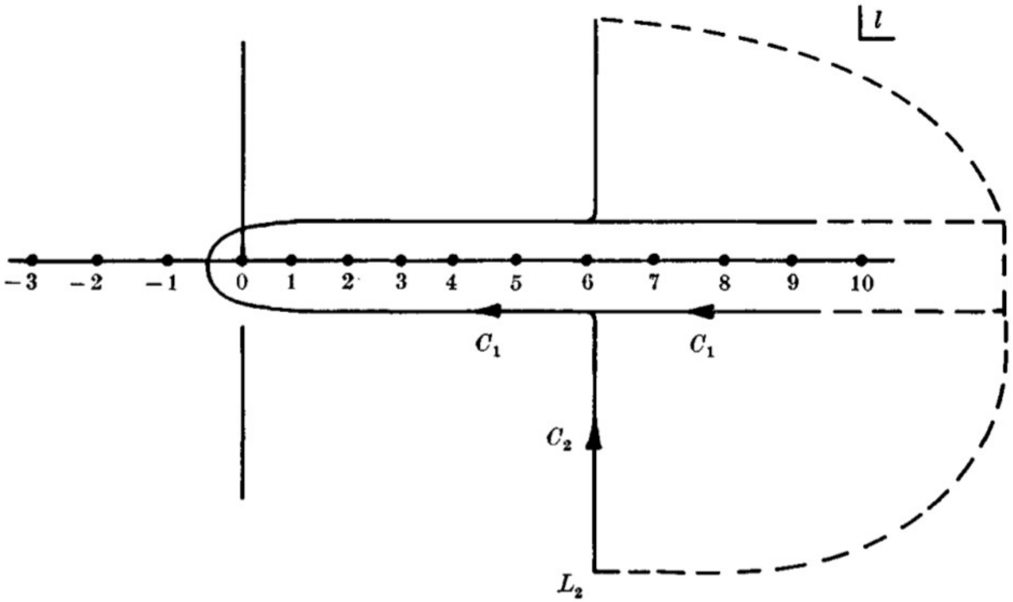
$$z_s = \cos\theta_s \approx 1 + \frac{t}{s}$$

$$A(s,t) = 16\pi \sum_{l=0}^{\infty} (2l+1) A_l(s) P_l(z_s) = 16\pi \sum_{l=0}^{\infty} (2l+1) A_l(t) P_l(z_t)$$

Regge Theory

- Maximal Analyticity of the second kind

$$A(s,t) = 16\pi \sum_{l=0}^{\infty}(2l+1)A_l(t)P_l(z_t) = -\frac{16\pi}{2i}\oint_C dl(2l+1)A_l(t)\frac{P_l(z_t)}{\sin \pi l}$$



Sommerfield-Watson Transform

Regge Theory

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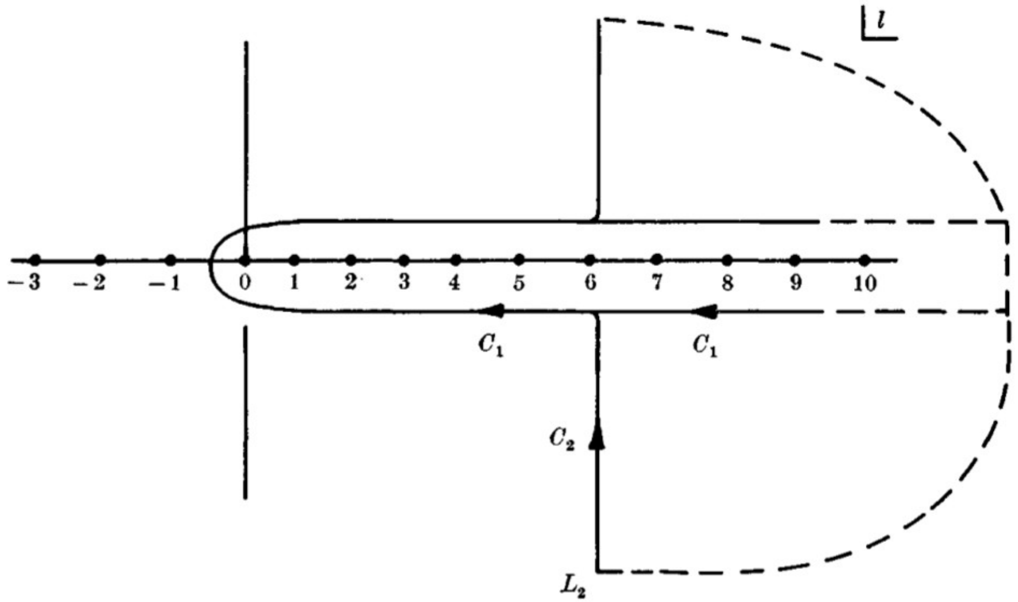

Sommerfield-Watson Transform

(Unconstrained) t-dep residue

$$A_l(t) \sim \frac{\beta(t)}{l - \alpha(t)}$$

Regge trajectory

Regge Theory

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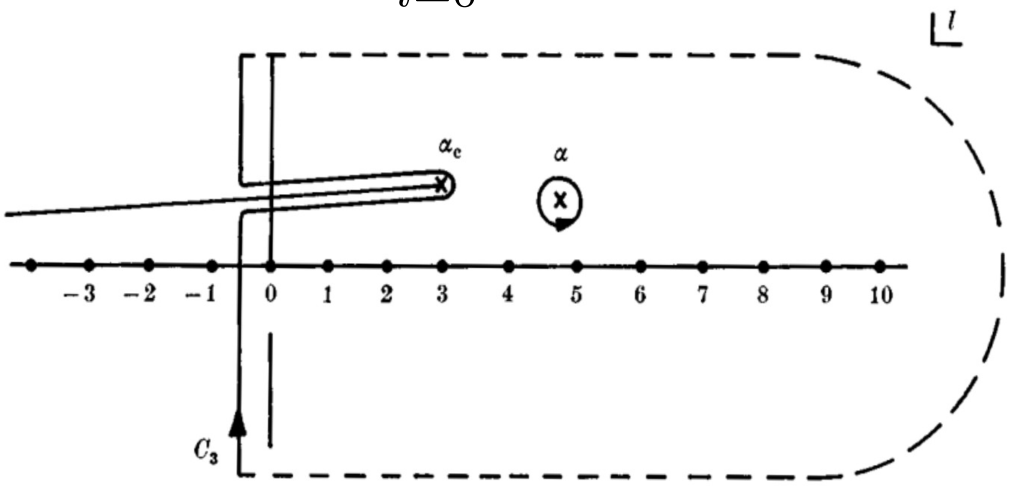

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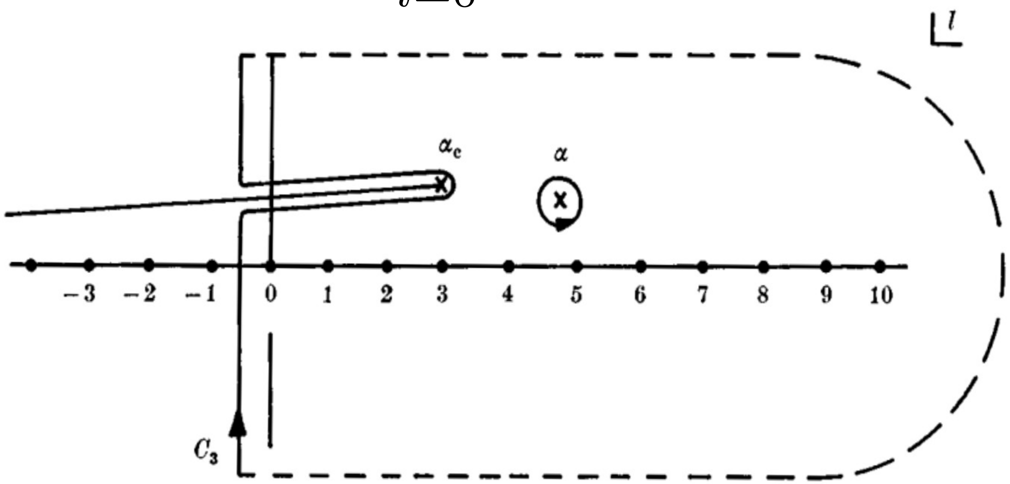

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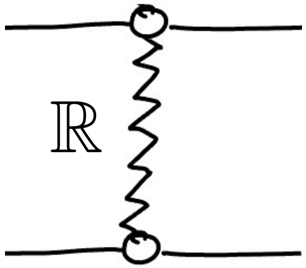
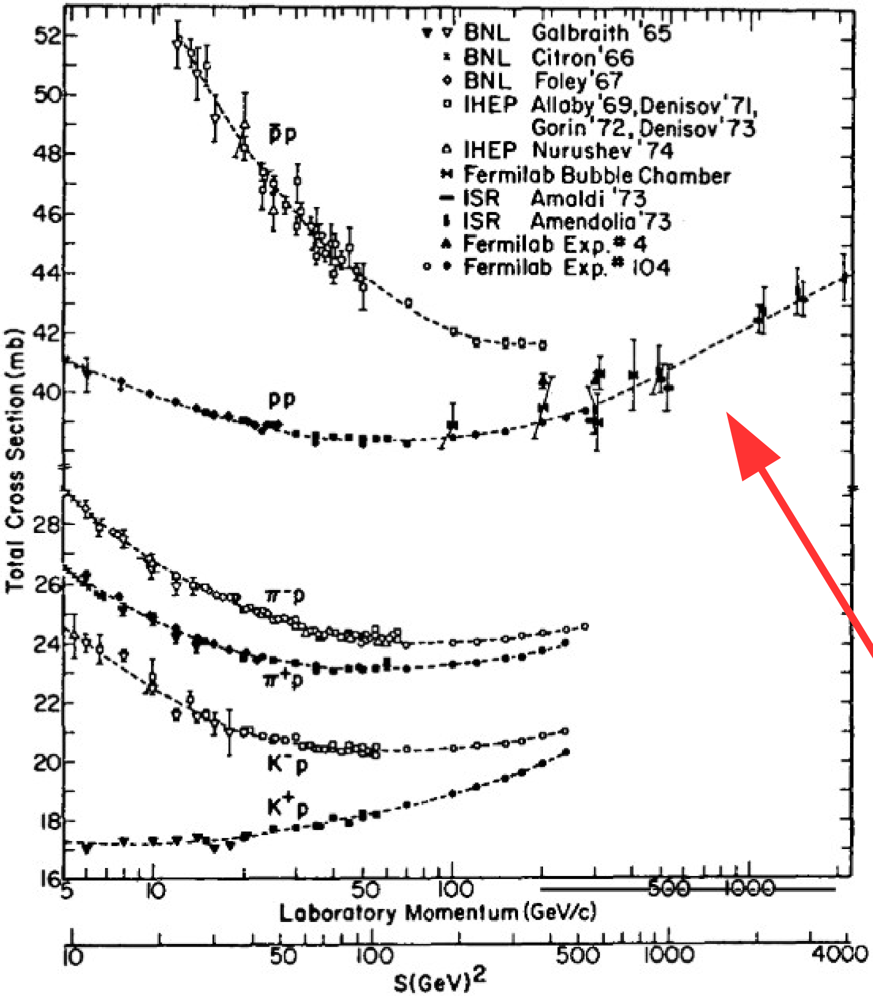


$$A(s,t) = \frac{1}{2}(1 + \tau e^{-i\pi\alpha(t)}) \frac{\beta(t)}{\sin(\pi\alpha(t))} \left(\frac{s}{s_0}\right)^{\alpha(t)}$$

Pomeron

A.C. Irving and R.P. Worden, Regge phenomenology



Minimal assumptions

$$\alpha(t) = \alpha_0 + \alpha_1 t + \ldots$$

Linear Regge trajectory

$$\alpha(t) = \alpha_0 + \alpha_1 t$$

Optical Theorem

$$\sigma(s) \sim \frac{1}{s} \mathrm{Im} A(s, 0) \sim \frac{1}{s} \left(\frac{s}{s_0} \right)^{\alpha(0)}$$

Pomeron has

$$\alpha(0) \approx 1$$

Povides explanation within Regge theory of logarithmic rise of total cross section

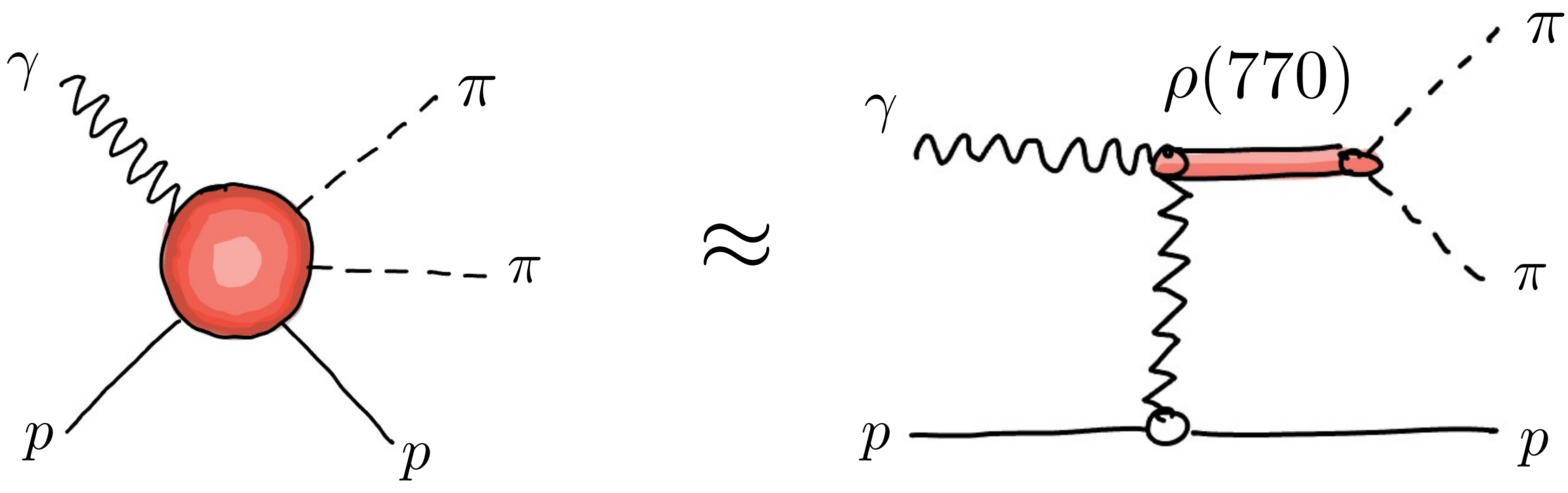
Benchmark Study

JPAC, Phys.Rev.D 111 (2025) 1, 014002

- How will we know predictions are reasonable?
- Benchmark modeling tools by developing framework first for "standard candle" process

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

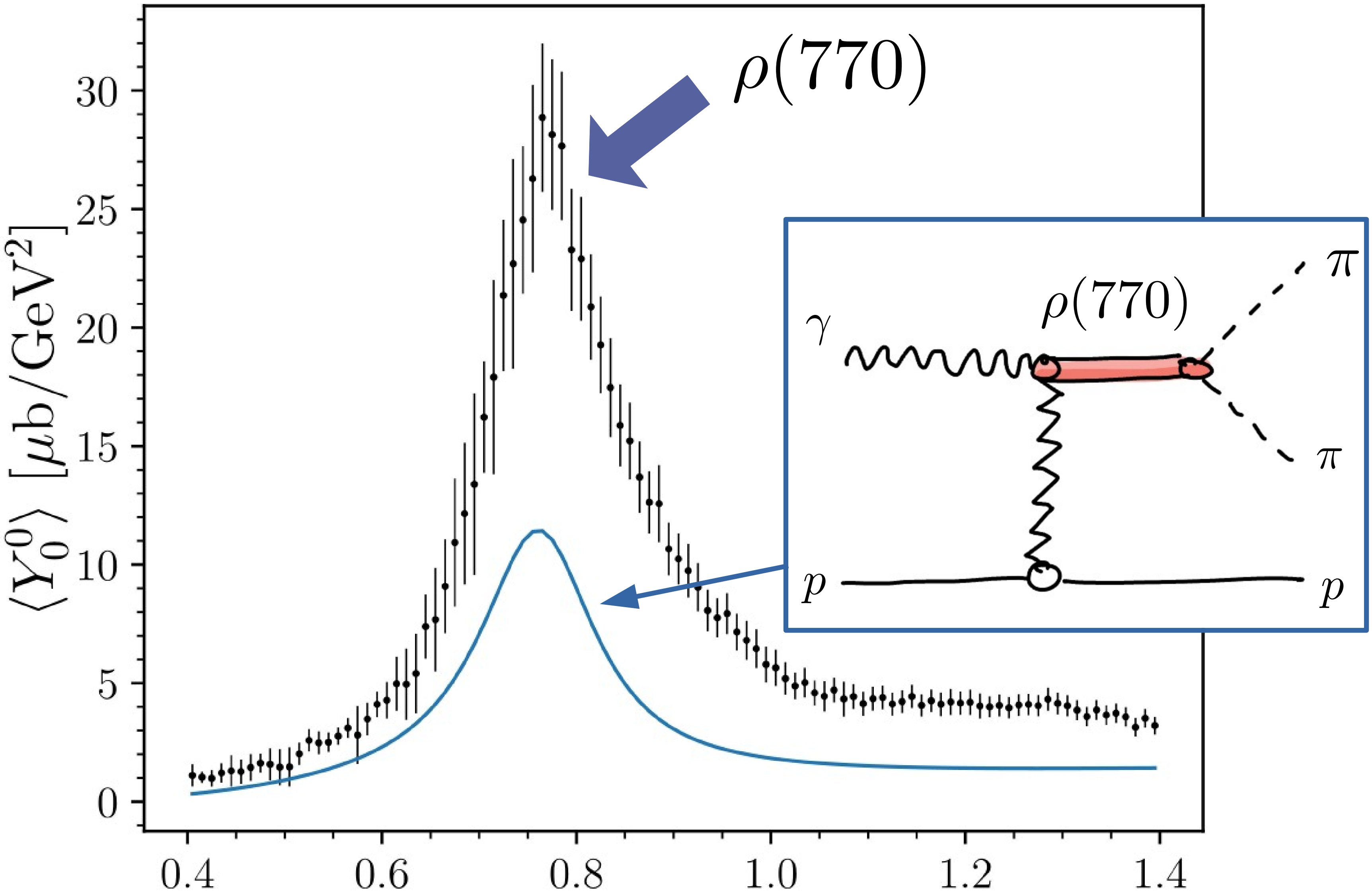
- Process is not sensitive to exotic meson, but interesting in own right.
- Two-pion spectrum dominated by the $\rho(770)$



CLAS Data

$$\langle Y_M^L \rangle = \sqrt{4\pi} \int d\Omega^{\mathrm{H}} \frac{d\sigma}{dt\, d\sqrt{s_{12}}\, d\Omega^{\mathrm{H}}} \mathrm{Re} Y_M^L(\Omega^{\mathrm{H}})$$

Data from **[Phys.Rev.D 80 (2009) 072005]**



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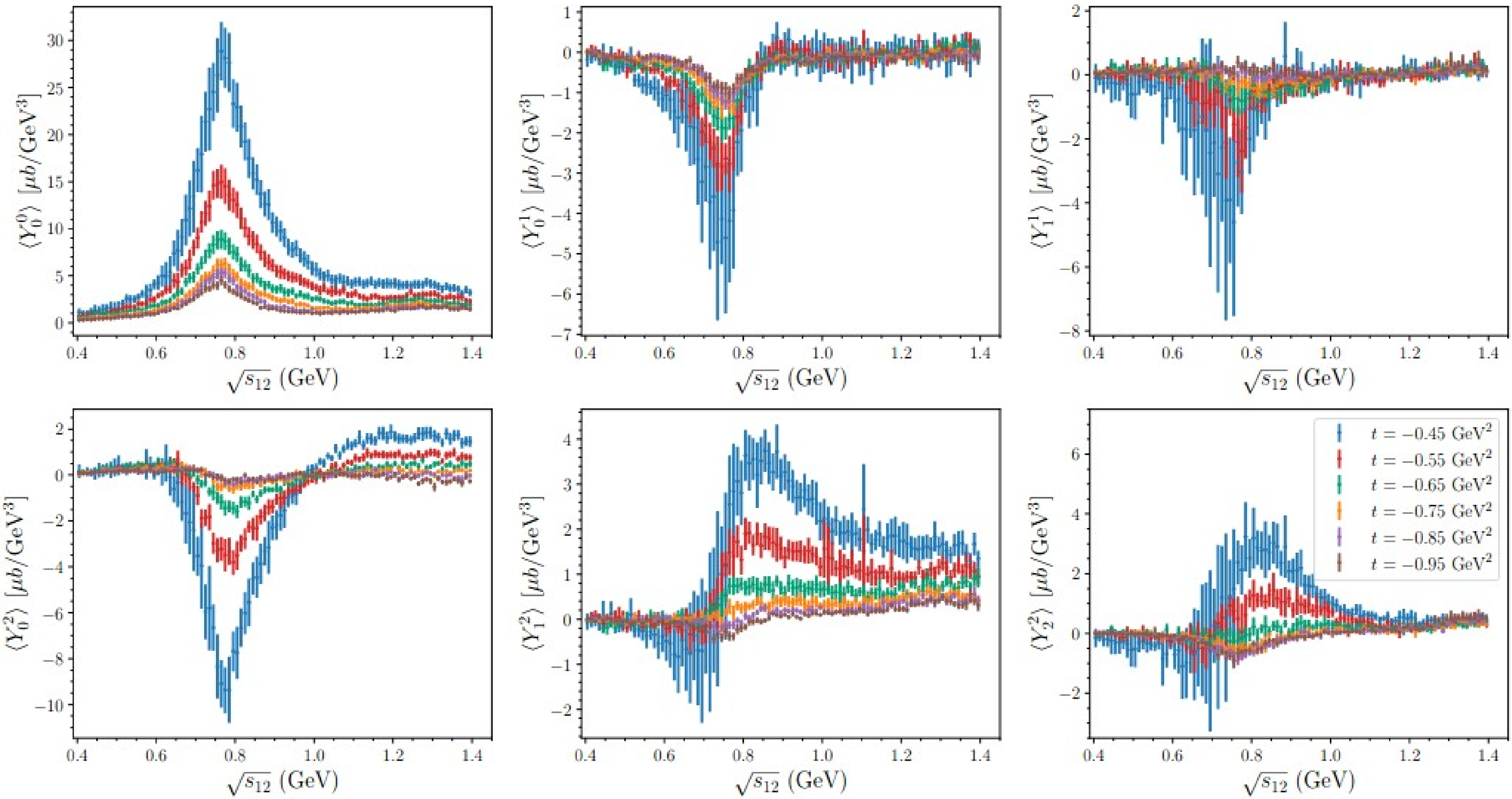
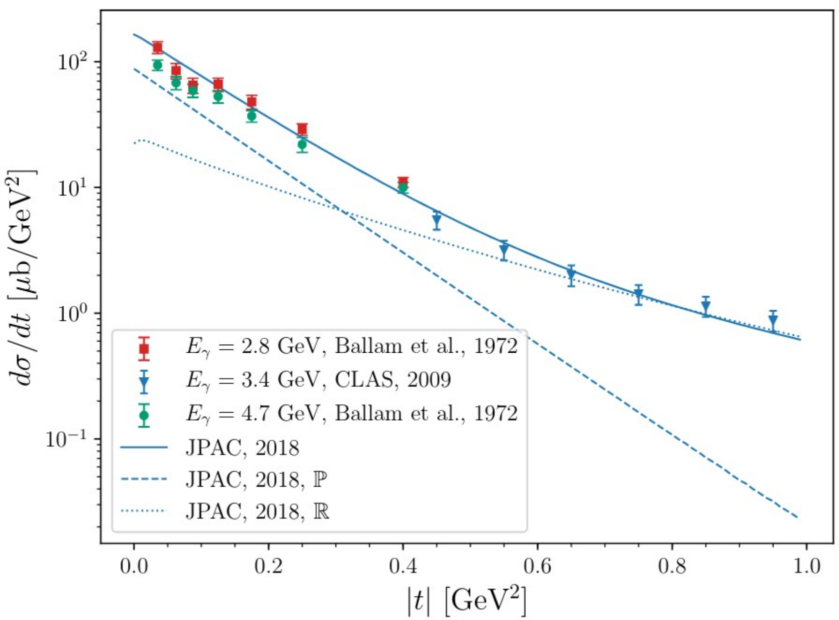
$$E_\gamma \in [3.0, 3.8]\ \mathrm{GeV}, \quad t \in [-0.4, 1.0]\ \mathrm{GeV}^2$$

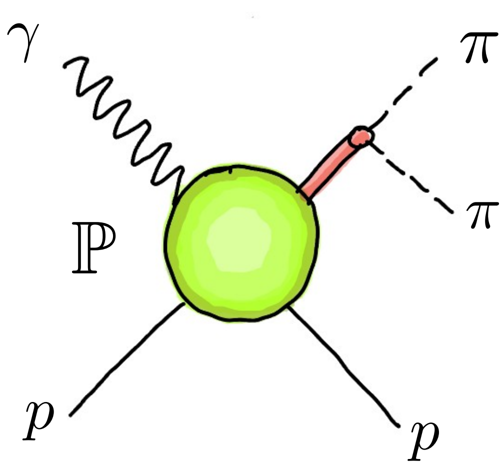


Phys.Rev.D 80 (2009) 072005

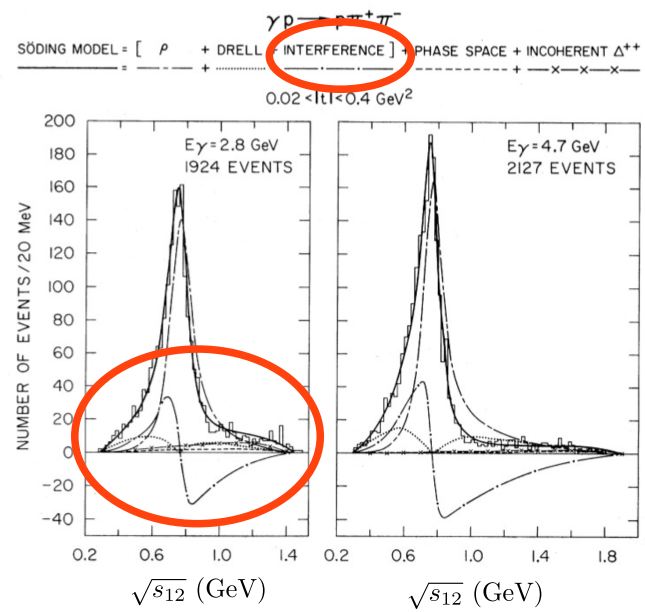
The two-pion final state is interesting in its own right...

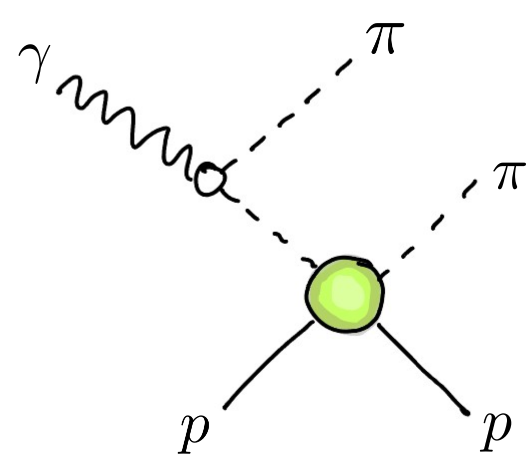
t-dependence of cross-section





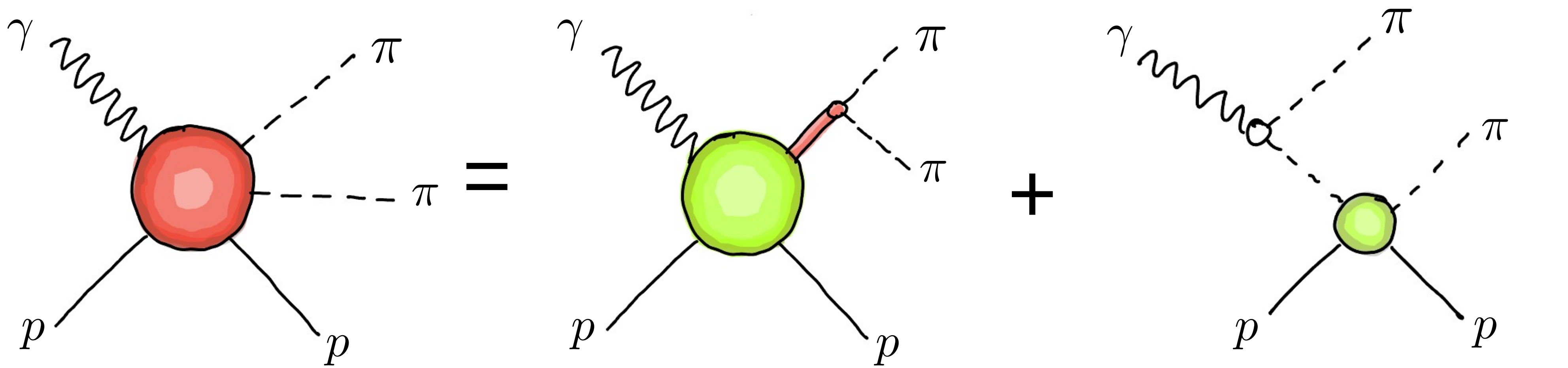
$\rho(770)$ lineshape





The Model

- 2 to 3 dynamics built from known dynamics in 2 to 2 subchannels.



Resonant Component　　Non-resonant component

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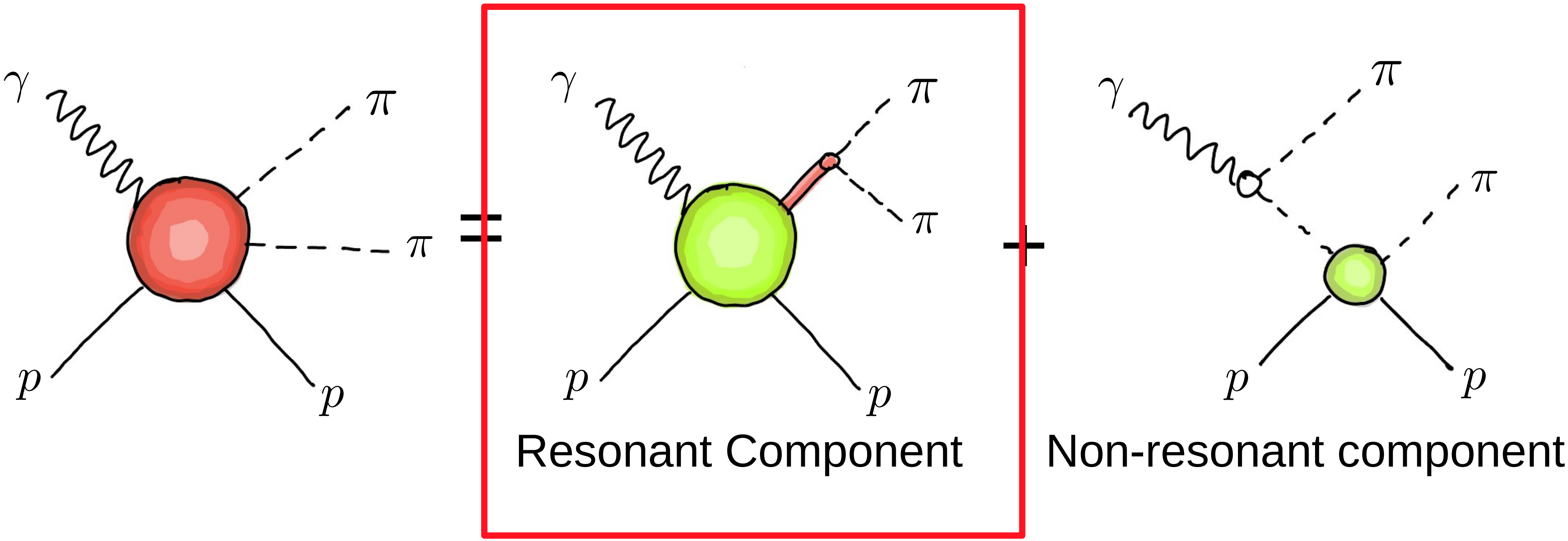
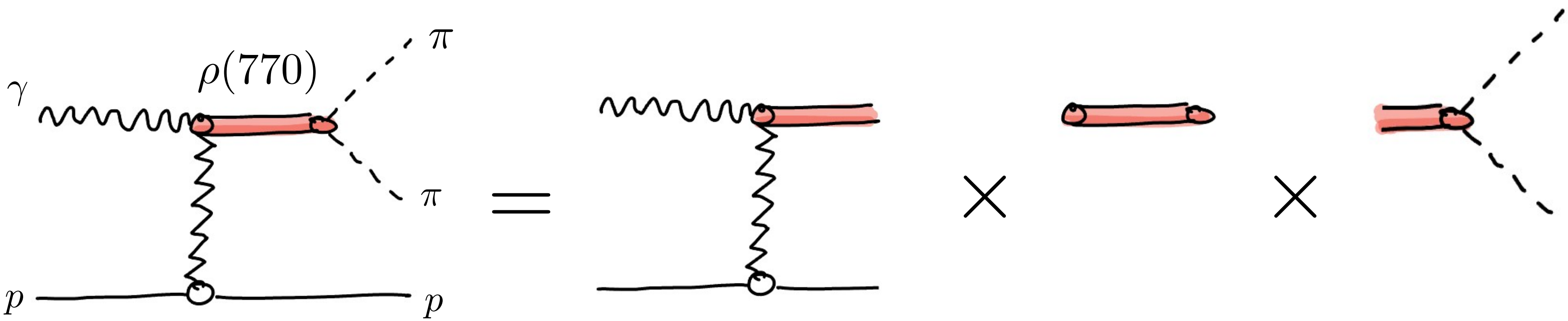


Resonant Component

- Process can be understood as product of probability amplitudes



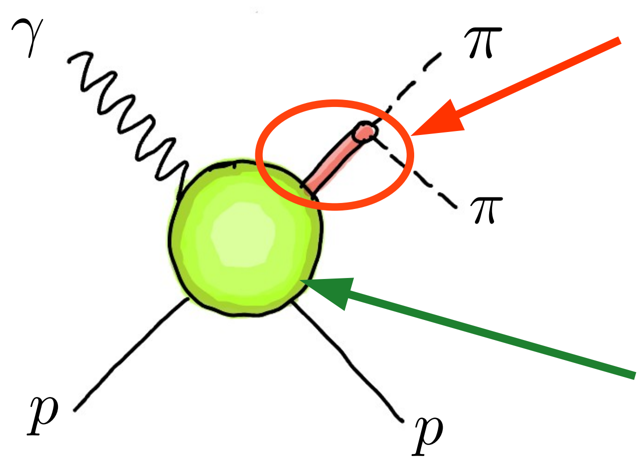
2-to-2 scattering (Regge Model) | propagator | resonance decay

$$\mathcal{M}^{\mathcal{R}}_{\lambda_\gamma \lambda_1 \lambda_2}(s, t, s_{12}, \Omega^{\mathrm{H}}) = \sum_{M=-J}^{J} \mathcal{M}^{\gamma p \to \mathcal{R} p}_{\lambda_\gamma \lambda_1 M \lambda_2}(s, t) \times A^{\mathcal{R}}(s_{12}) \times Y^J_M(\Omega^{\mathrm{H}}).$$

Sorry Eric!

Resonant Component

- Resonances are produced from sum of Regge exchanges
- Incorporate known two-pion resonances



$\mathcal{R}$	J	$m_{\mathcal{R}}$ [GeV]	$\Gamma_{\mathcal{R}}$ [GeV]
$f_0(500)$	0	0.500	0.450
$\rho(770)$	1	0.775	0.149
$f_0(980)$	0	0.990	0.055
$f_2(1270)$	2	1.2755	0.1867
$f_0(1370)$	0	1.370	0.350

E	τ^{E}	α_0^{E}	α_1^{E} [GeV^{-2}]
$\mathbb{P}$	$+1$	1.08	0.2
a_2/f_2	$+1$	0.5	0.9
ρ/ω	-1	0.55	0.8

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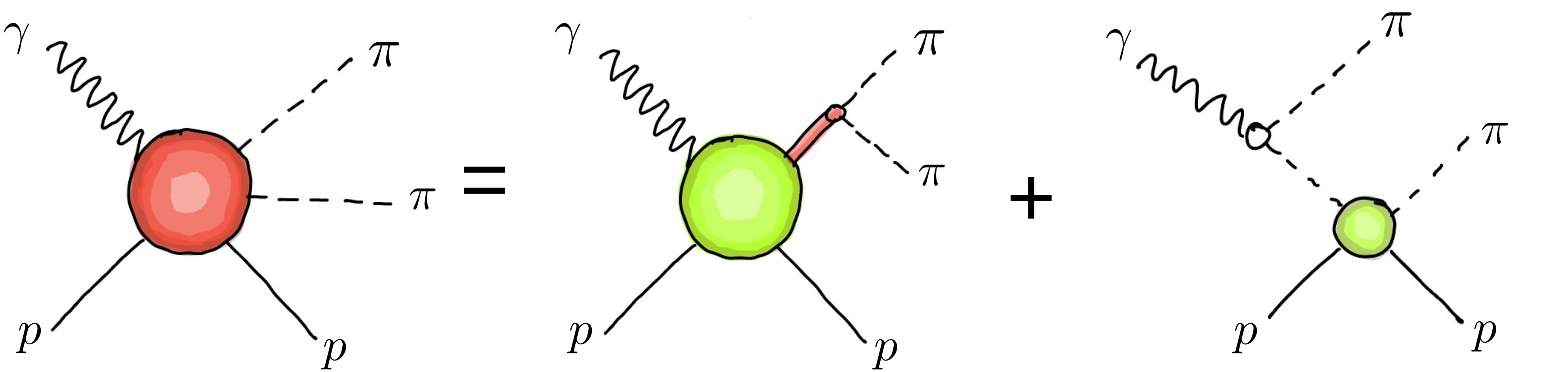
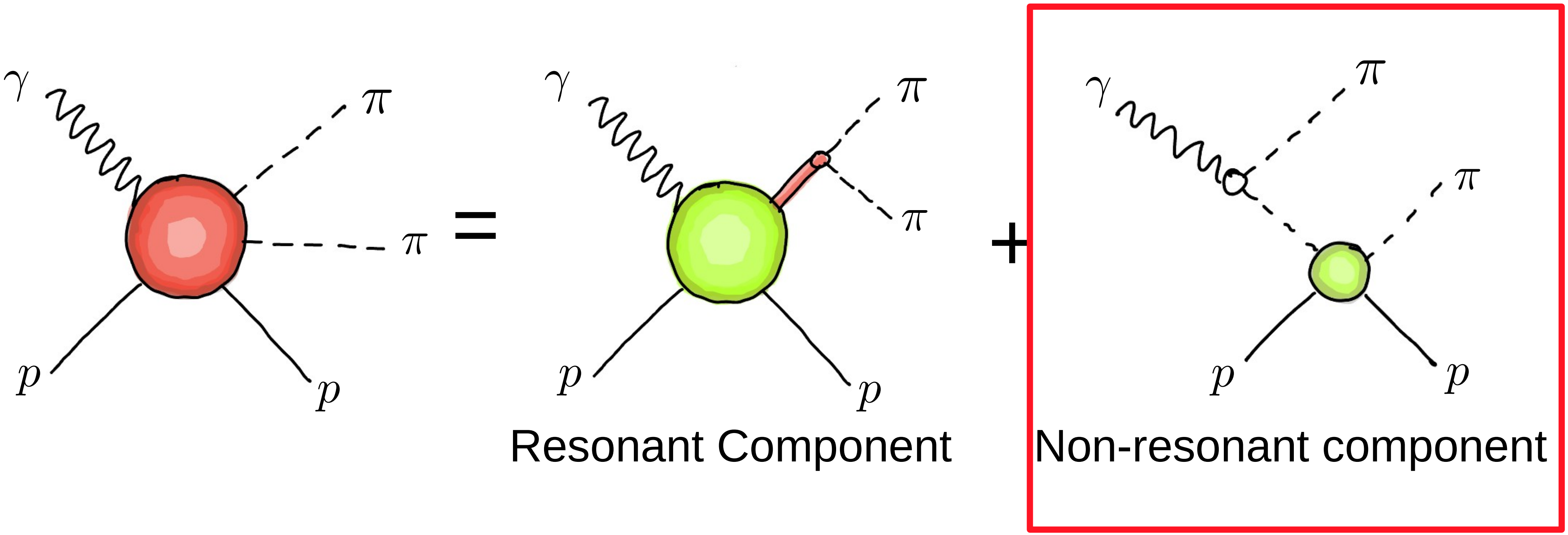


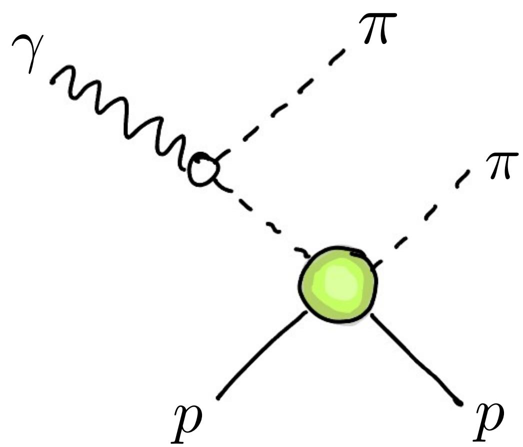
Resonant Component   Non-resonant component

The Model

- 2 to 3 dynamics built from known dynamics in 2 to 2 subchannels.

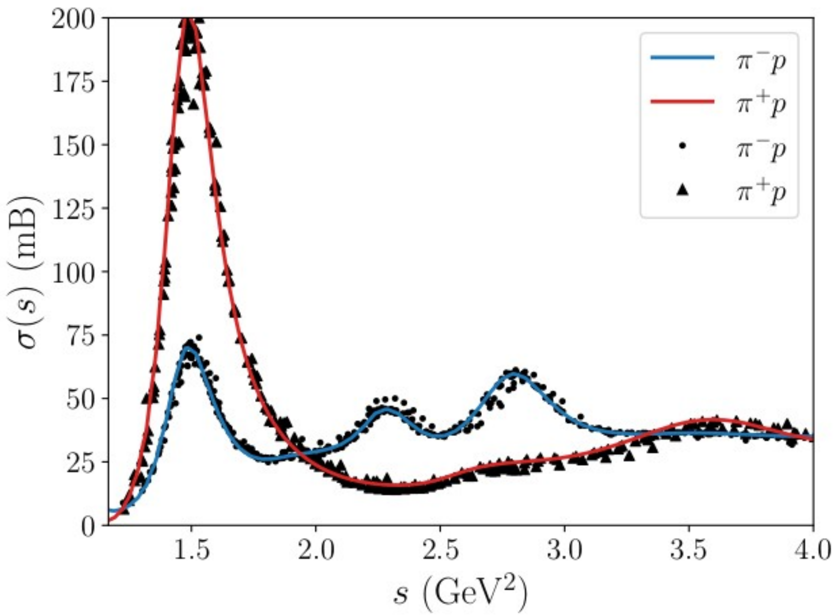


Leading Background: Deck Process

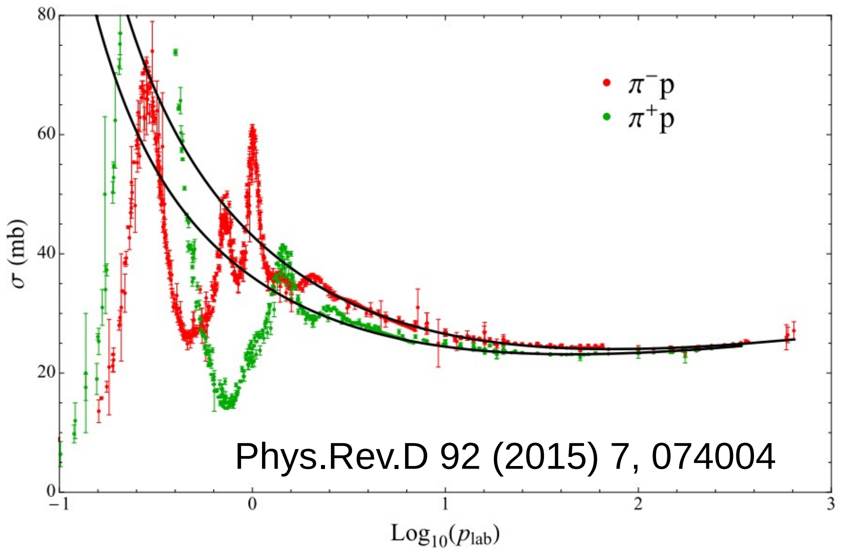


- Photon dissociates into two pions
- One recoils against nucleon target

$$\frac{\epsilon_{\lambda_\gamma}(q)\cdot(2k_1-q)}{u_1-m_\pi^2}\beta(u_1)M^{-}_{\lambda_1\lambda_2}(s_2,t;u_1)-\frac{\epsilon_{\lambda_\gamma}(q)\cdot(2k_2-q)}{u_2-m_\pi^2}\beta(u_2)M^{+}_{\lambda_1\lambda_2}(s_1,t;u_2)$$
$$+\mathcal{M}^{\text{cont.}}_{\lambda_\gamma\lambda_1\lambda_2}(s,t,s_{12},\Omega^{\mathrm{H}})$$

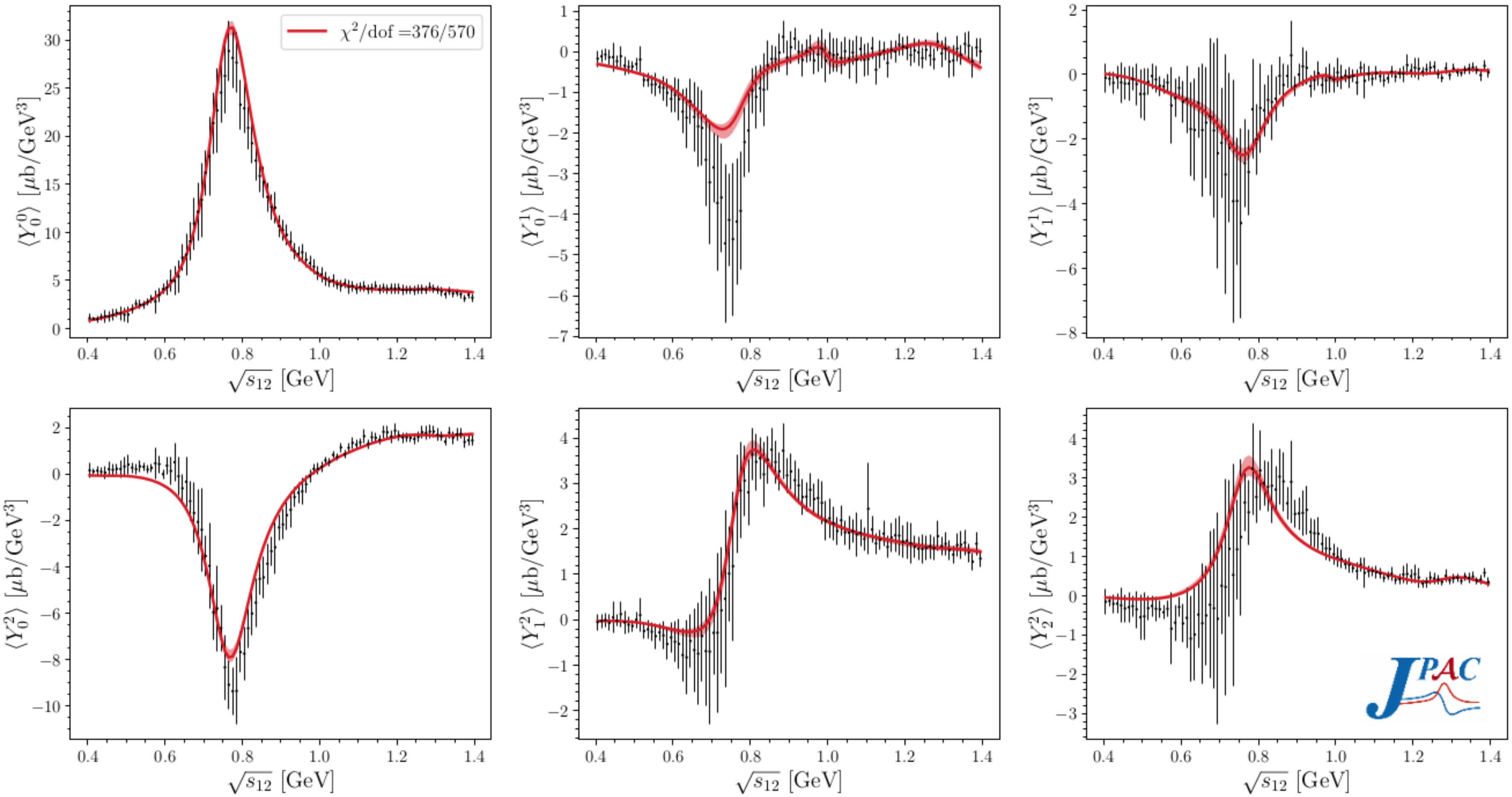


SAID



Regge

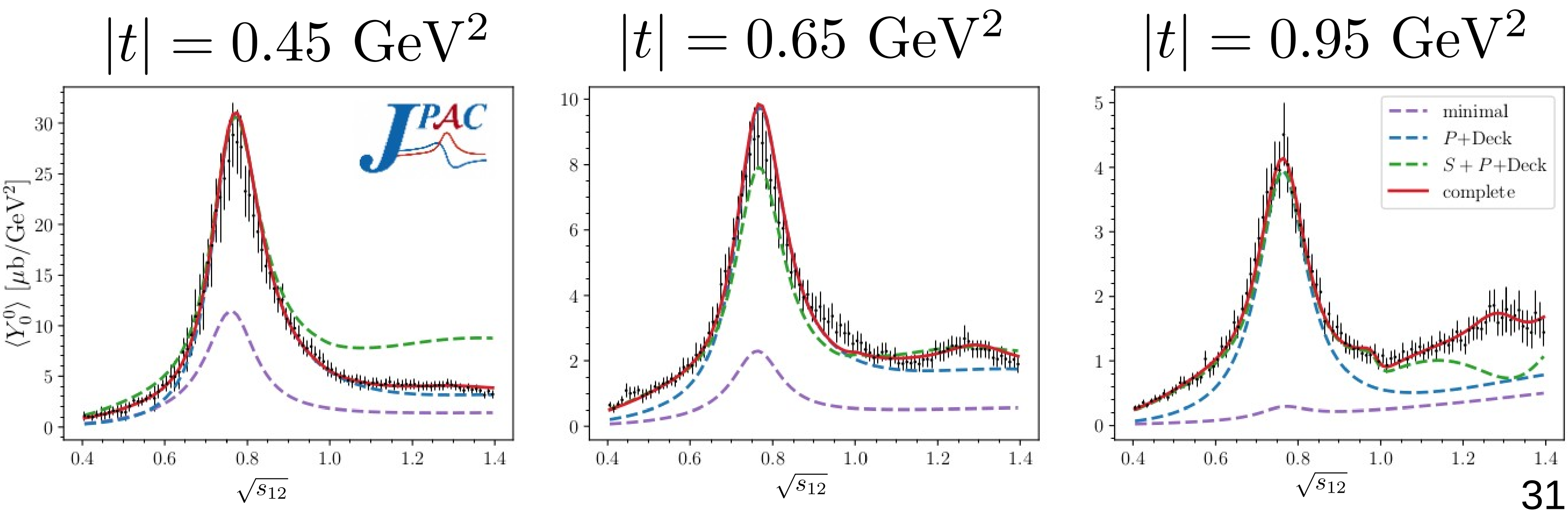
Results



$$E_\gamma = 3.7 \text{ GeV},\, t = -0.45 \text{ GeV}^2$$

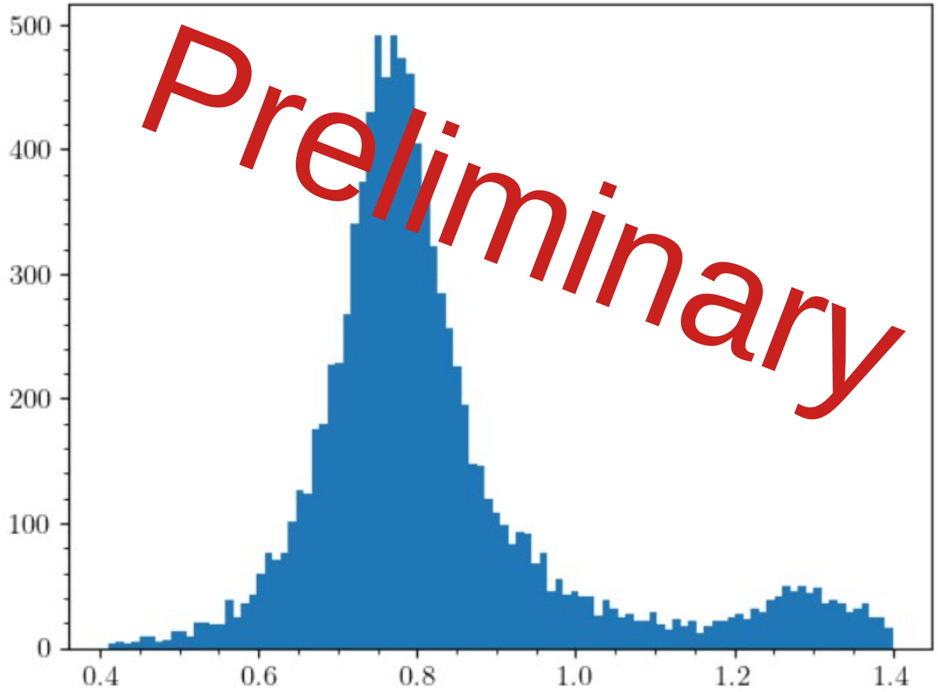
Decomposition

- Define ‘decompositions’:
  - “minimal”: Pomeron + Deck
  - P + Deck: Pomeron + a2/f2 + Deck
  - S + P + Deck: Pomeron + a2/f2 + rho/omega + Deck
  - Complete: Full model
- Clearly require more than “minimal” → evidence for other exchanges



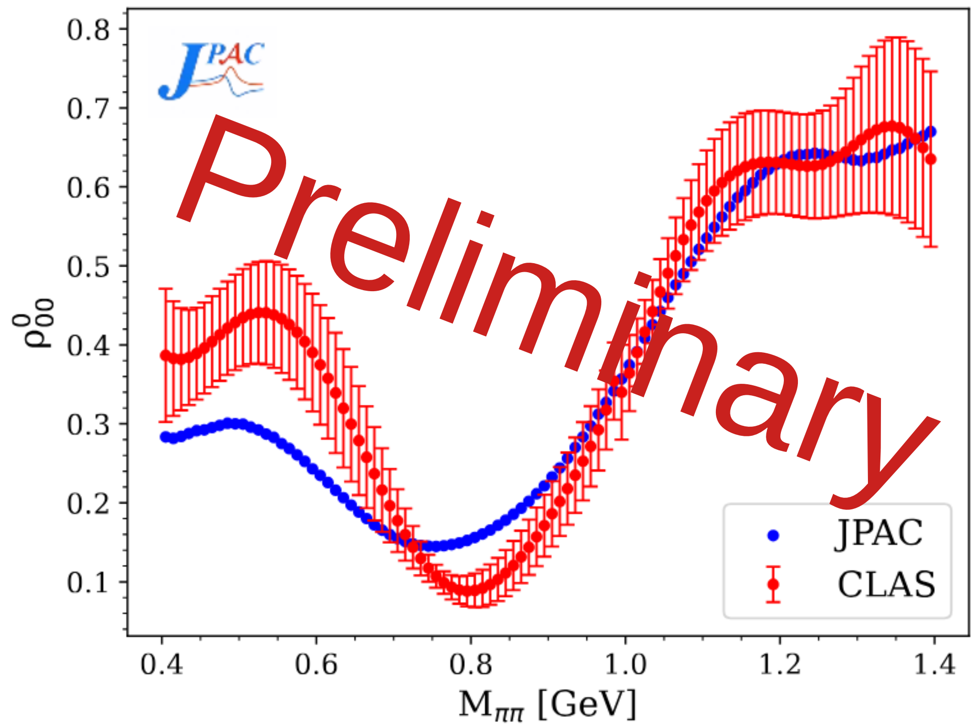
Applications of Model

Generate realistic MC for input-output studies



Courtesy of Łukasz Bibrzycki

Compute derived quantities: Rho, Delta SDMEs etc.



Courtesy of Nadine Hammoud

XYZ spectroscopy with photoproduction

Pro: New production process

Con: New production process:

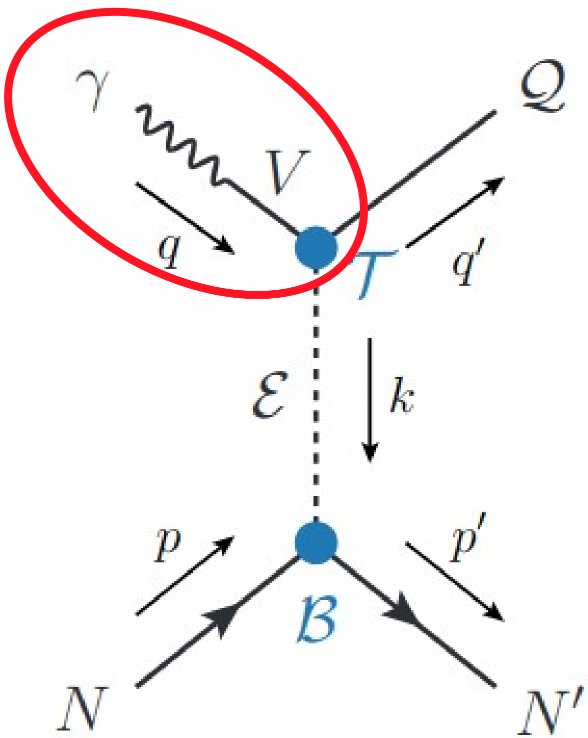
- Don’t know photocouplings

What can we do?

Vector Meson Dominance

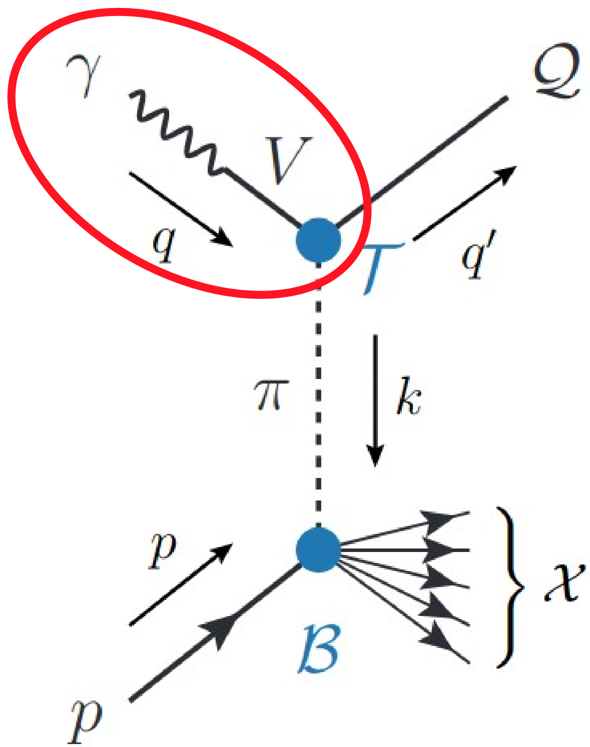
XYZ spectroscopy with photoproduction

Exclusive Processes



JPAC, Phys.Rev.D 102 (2020) 114010

Semi-inclusive Processes
Pion exchange



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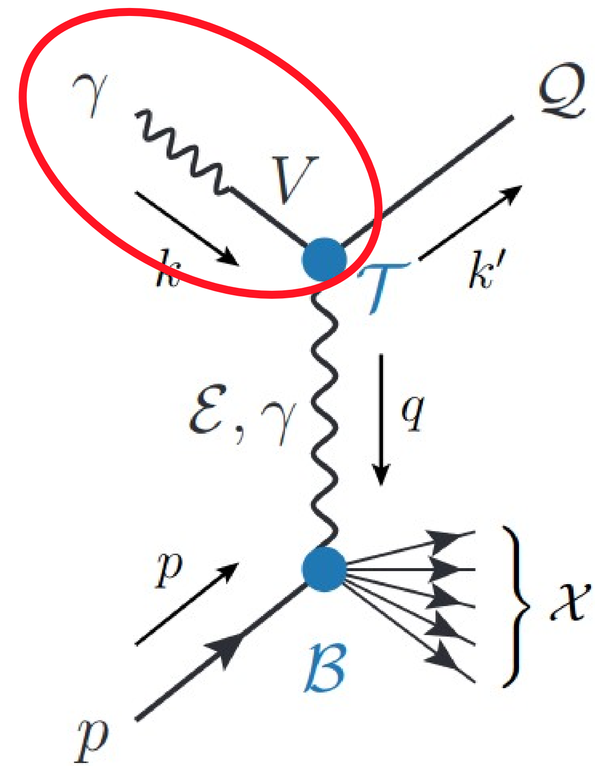
Semi-inclusive Processes
Vector exchange



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Formalism

Minimal model assumptions about XYZ states

Relates hadro- and photo-couplings

$$g_{\mathcal{Q}\gamma\gamma} = \sum_i \frac{g_{\mathcal{Q}i\gamma}}{\gamma_i} \,,$$

$$g_{\mathcal{Q}\gamma\mathcal{E}} = \sum_V \frac{g_{\mathcal{Q}V\mathcal{E}}}{\gamma_V} \,,$$

$$g_{\gamma NN} = \sum_{\mathcal{E}} \frac{g_{\mathcal{E}NN}}{\gamma_{\mathcal{E}}} \,,$$

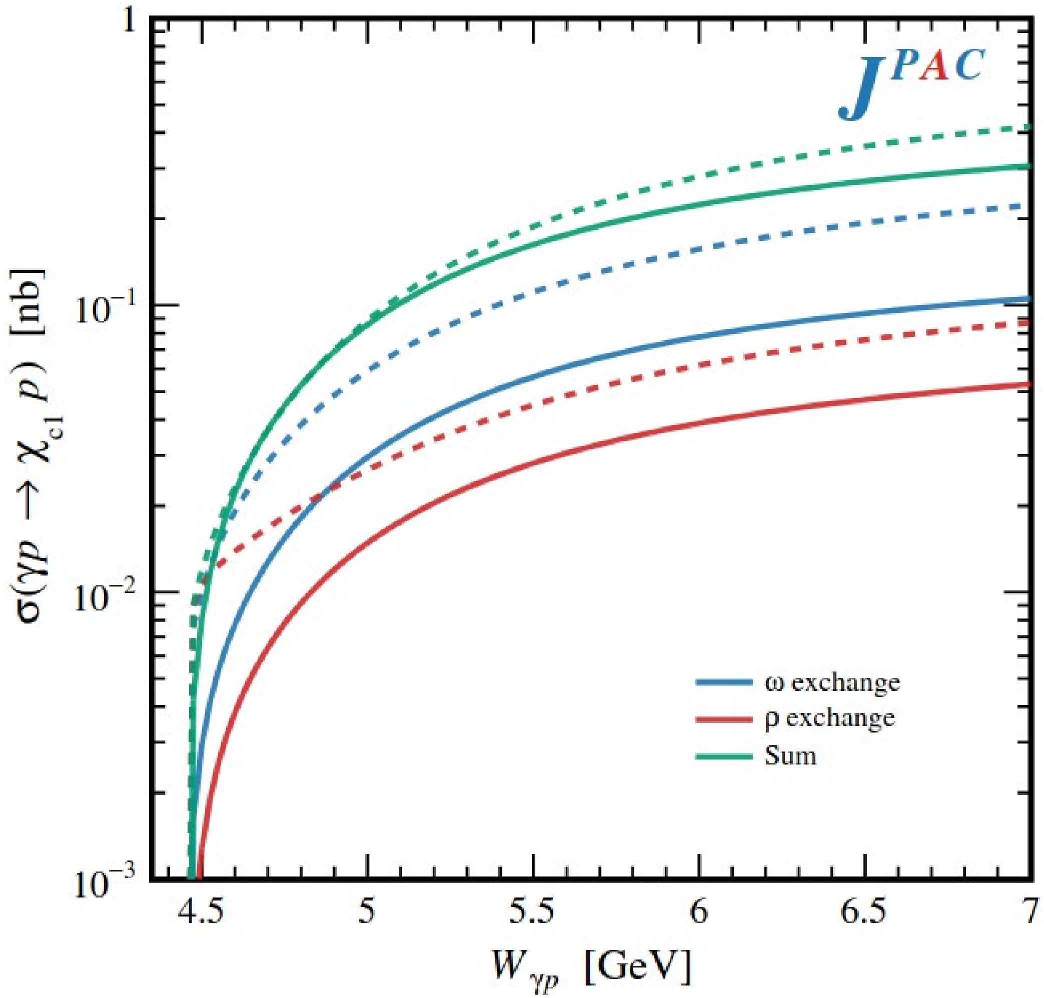
$$\frac{1}{\gamma_i} = \frac{e\, f_i}{m_i} \,.$$

Weakest aspect of model. Can we test the validity here?

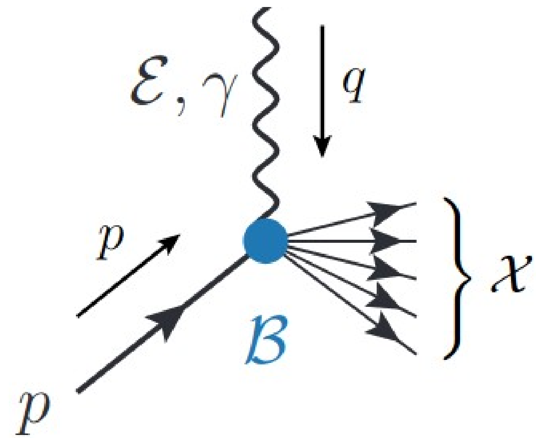
Validation of VMD

Confirm validity of VMD for photoproduction of regular charmonia

Dashed and solid should agree if VMD holds

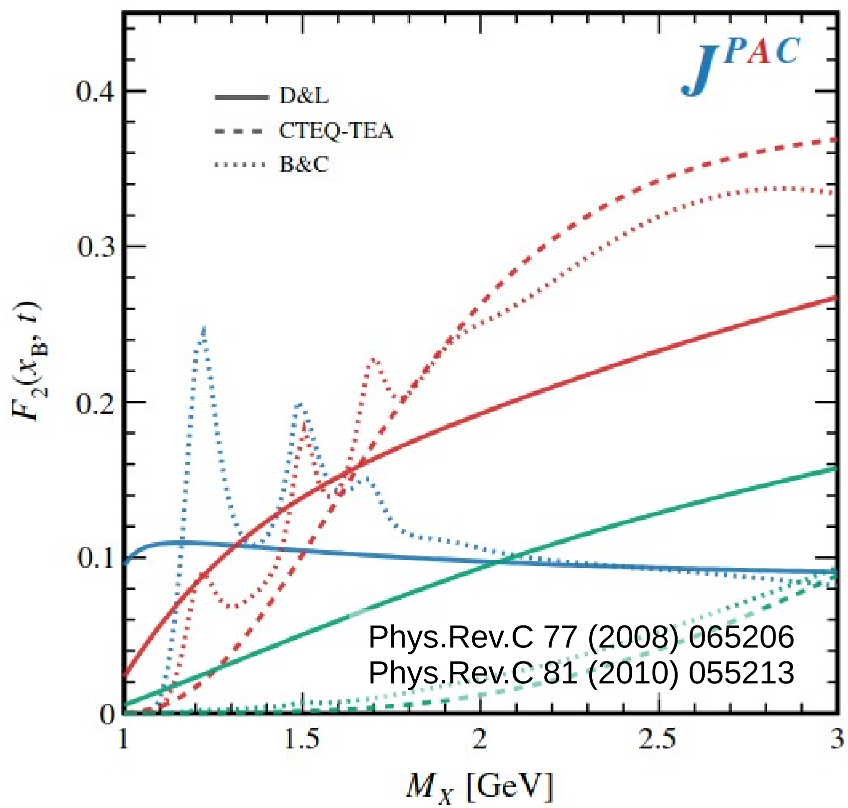


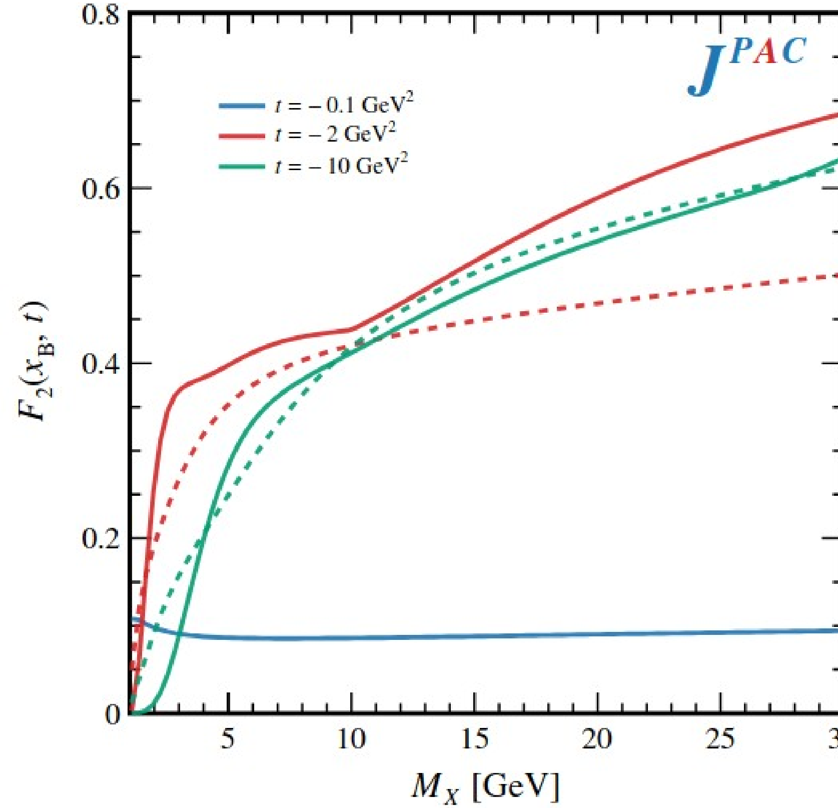
Lower Vertex



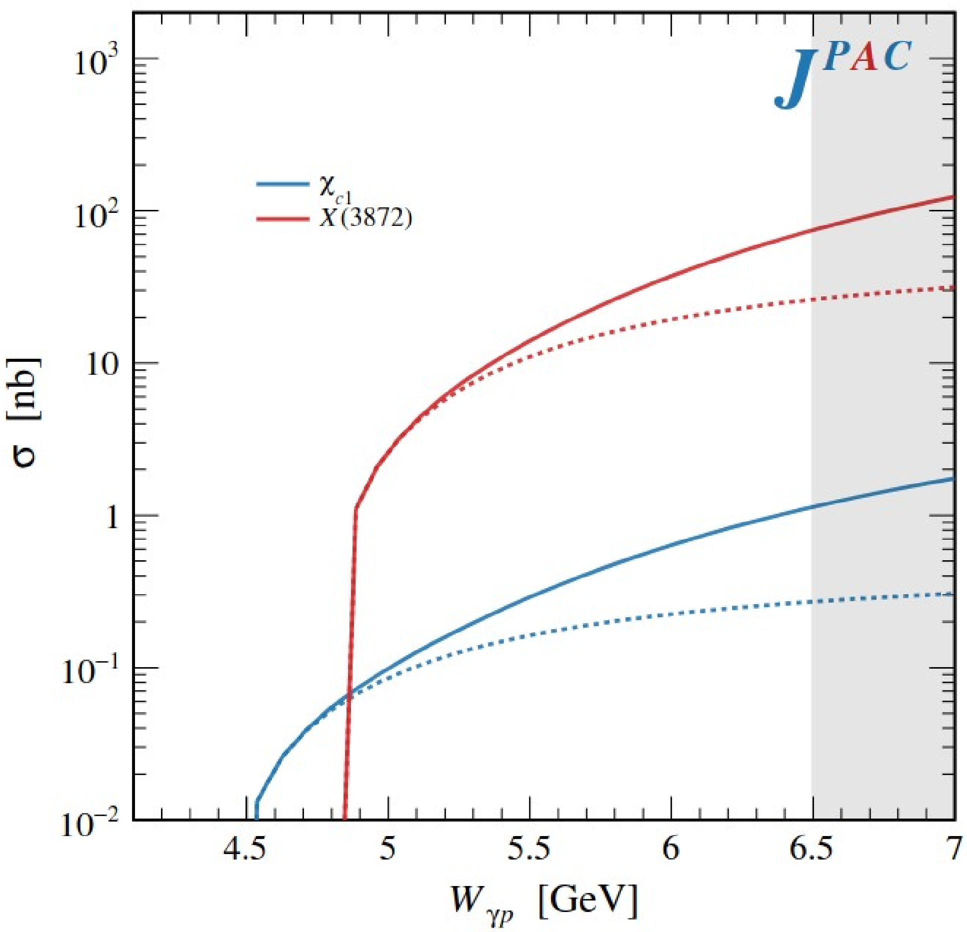
Empirical parameterization

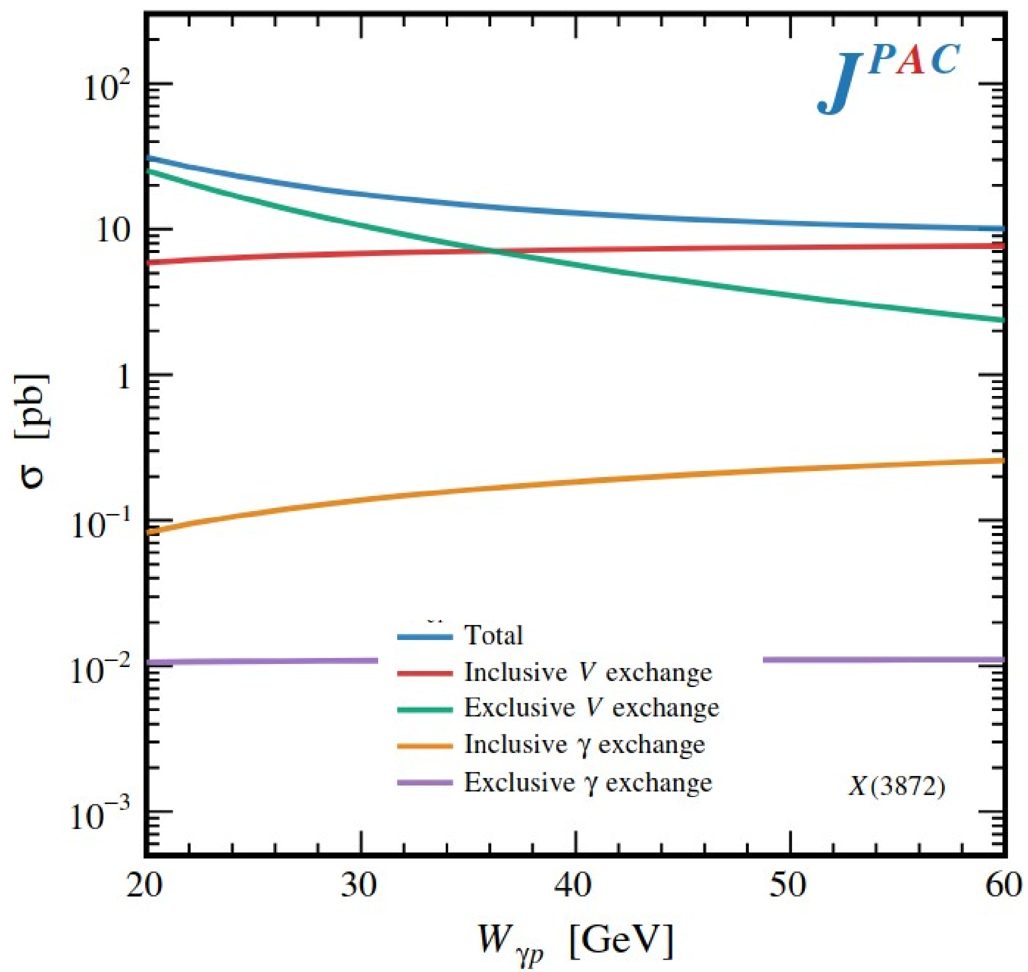
$$F_2(x_B, t) = \sum_k f_2^k(t)\ (1 - x_B)^{\epsilon_k}\ x_B^{1-\alpha_k(0)} .$$





Numerical Results





Conclusions

Before we can study states, we need to measure them

Need reliable estimates of cross sections

Regge theory and amplitude analysis techniques provide estimates of cross sections with minimal model assumptions