Exclusive Photoproduction of Vector Mesons

Lin Tang

Supervisor: Prof. Craig D. Roberts
Affiliation: INP, NJU

ICC Jeju, Korea
Nov 13, 2025
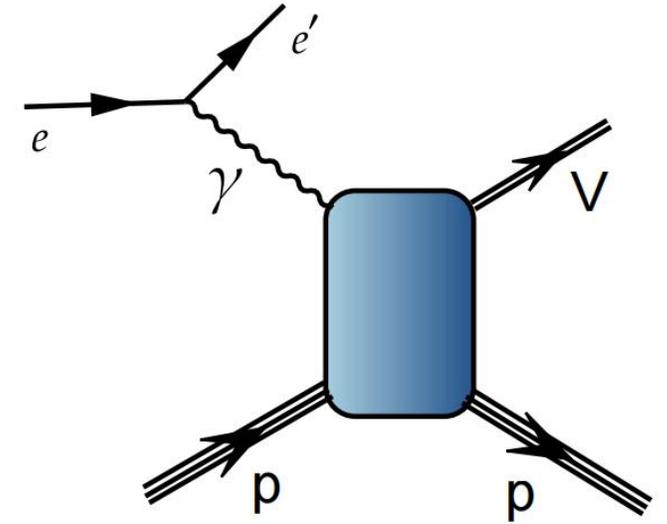
Introduction and motivation

➢ $e + p \rightarrow e' + V + p$ $(V = \rho, \varphi, J/\psi, \Upsilon)$

1.The incoming photon transform into the final state vector meson, while the proton remains intact. It is a clean and exclusive diffractive process.

2.Both photon and vector meson are colorless, thus it requires the exchange of a color-singlet object. This kind of scatter spans both non-perturbative (near-threshold) and perturbative (high-Q^2, heavy quarks) regimes.

3. The experiment reveals that cross section rise with W, it is contrdict to pQCD predictions.

Introduction and motivation

A. Donnachie & P. V. Landshoff (1984-1992):

➤ A. Donnachie and P. V. Landshoff have begun to study Pomeron in different process during 1980s to 1990s

[1] Donnachie, A., & Landshoff, P. V. (1984). Elastic scattering and diffraction dissociation. Nuclear Physics B, 244(2), 322-336.
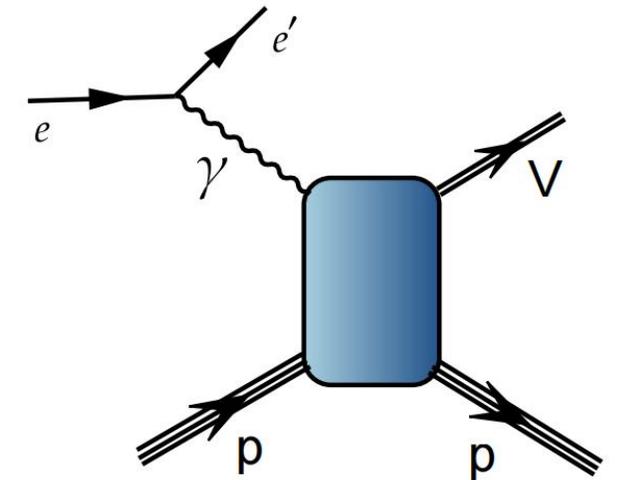
[2] Donnachie, A., & Landshoff, P. V. (1986). Dynamics of elastic scattering. Nuclear Physics B, 267(3-4), 690-701.

[3] Donnachie, A., & Landshoff, P. V. (1987). Exclusive rho production in deep inelastic scattering. Physics Letters B, 185(3-4), 403-406.

[4] Donnachie, A., & Landshoff, P. V. (1992). Total cross sections. arXiv preprint hep-ph/9209205.

➤ They fitted these data of Regge type. It provides an extremely simple and economical parameterisation of all total cross sections: $\sigma^{TOT} = Xs^{\epsilon}$.

➤ Soft Pomeron trajectory: $\alpha(t) = 1.08 + 0.25 * t$ ($\alpha_0 = 1.08, \alpha_1 = 0.25 \ GeV^{-2}$).

$$\frac{d\sigma}{dt} \sim \left(\frac{s}{m^2}\right)^{2[\alpha(t)-1]} \rightarrow \left(\frac{s}{\alpha'}\right)^{2[\alpha(t)-1]}.$$

Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.

Introduction and motivation
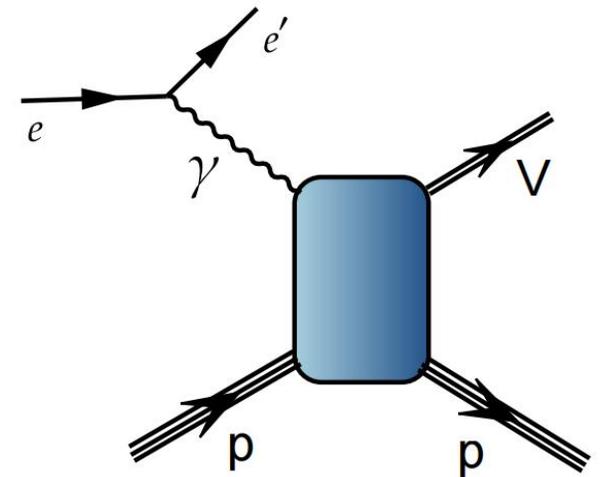
M. A. Pichowsky & T.-S. H. Lee (1996 – 1997) :

[1] Pichowsky, M. A., & Lee, T. S. (1996). Pomeron exchange and exclusive electroproduction of ϱ-mesons in QCD. Physics Letters B, 379(1-4), 1-6.

[2] Pichowsky, M. A., & Lee, T. S. (1997). Exclusive diffractive processes and the quark substructure of mesons. Physical Review D, 56(3), 1644.

➢ They provide a reaction model for exclusive diffractive processes involving Pomeron exchange. They obtain Pomeron quark coupling constant $\beta_{u/d}$ and Pomeron trajectory by fitting to πN elastic scattering data in the high-energy and small-momentum-transfer region,

$$\alpha_0 = 1.1, \alpha_1 = 0.33 GeV^{-2}$$

➢ These work inspires us to provide a model with more realistic quark propagator which can unify vector meson photoproduction.

Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.

Introduction and motivation

Table 2: Available data for vector meson photoproduction.

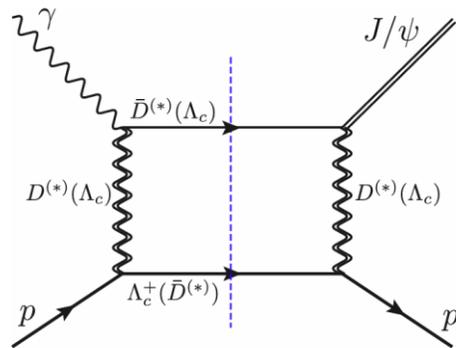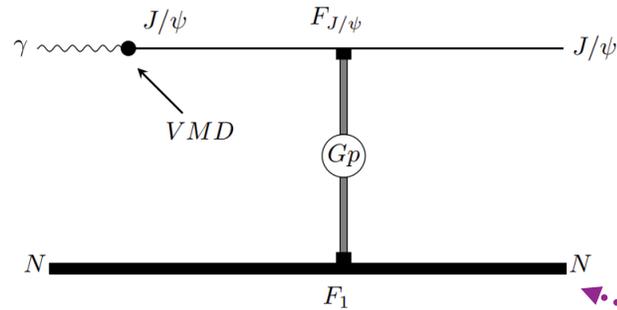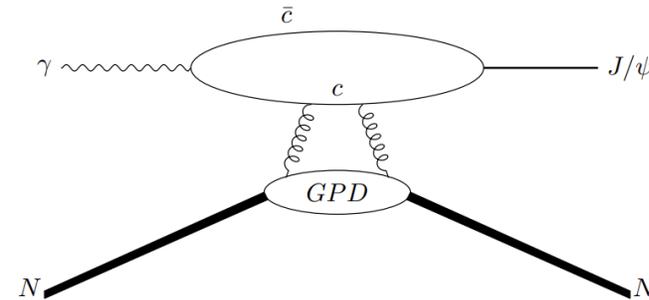| Meson	σ_{tot} EXPs	$d\sigma/dt$ EXPs
ρ^0	AHHM, SLAC, H1, Fermilab, CLAS	ZEUS
ϕ	E401, ZEUS, Fermilab, CLAS	CLAS, Daresbury, SAPHIR, LEPS
J/ψ	LHCb, ZEUS, GlueX, H1, ALICE	H1, ZEUS, GlueX, $J/\Psi - 007$
Υ	ZEUS, H1, LHCb, CMS	—

Table 1. Recent work of vector meson photoporduction.

Model	Articles
2-gluon/3-gluon exchange	[1] Zeng F, Wang X Y, Zhang L, et al. The European Physical Journal C, 2020, 80(11): 1-6. [2] Lee, T. -S. H. and Sakinah, S. and Oh, Yongseok. Eur.Phys.J.A 58 (2022) 12, 252.
GPD	[1] Guo, Yuxun, et al. Physical Review D, 108.3 (2023): 034003. [2] Guo, Y., Ji, X., Liu, Y. (2021). Physical Review D, 103(9), 096010.
VMD	[1] Lee, T. -S. H. and Sakinah, S. and Oh, Yongseok. Eur.Phys.J.A 58 (2022) 12, 252. [2] Sakinah, S. and Lee, T. -S. H. and Choi, Ho-Meoyng. Phys.Rev.C 109 (2024) 6, 065204.
Open charm coupled-channel	[1] Du, Meng-Lin and Baru, et al. Eur.Phys.J.C 80 (2020) 11, 1053.

> ➤ There are many work try to describe VMP based on different reaction model, especially for heavy meson (J/ψ). Table 1 shows some of recent work. Table 2 displays available measurements for VMP.

Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.

The reaction model

➤ We introduce a reaction model where the process is dynamically resolved into three core stages [1]:

➤ 1.Photon Fluctuation:

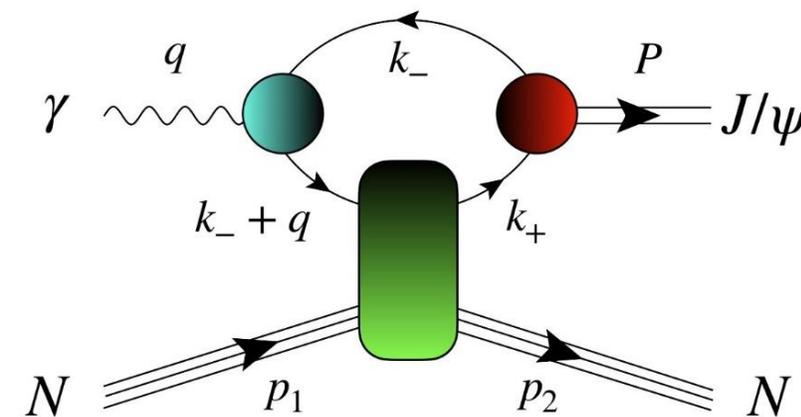The incoming photon fluctuates into a virtual quark-antiquark (q\bar{q}) pair.

➤ 2.Diffractive Scattering:

This q\bar{q} pair interacts with the proton via the exchange of a Pomeron .

➤ 3.Meson Formation:

The scattered q\bar{q} pair subsequently recombines into the final-state on-shell vector meson (V).

[1] J/ψ photoproduction: threshold to very high energy, Lin Tang (唐淋) et al., NJU-INP 089/24,e-Print: 2405.17675 [hep-ph]

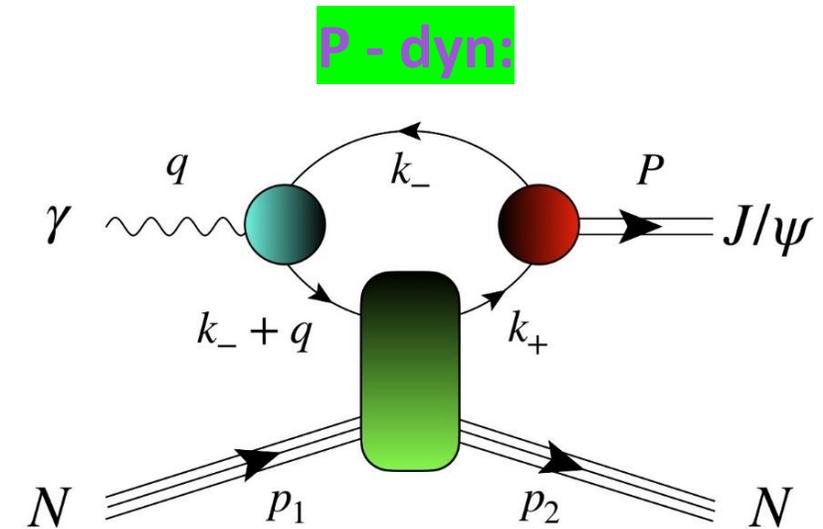*Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.*

The reaction model

➢ The Dynamical Transition Amplitude：

$$t_{\mu\alpha\nu}(q, P) = \beta_f N_c e_0 \mathrm{tr} \int \frac{d^4k}{(2\pi)^4} S(k_-)\Gamma_\mu(k_-, k_- + q)$$

$$\times S(k_- + q)\gamma_\alpha S(k_+)V_\nu(k_+, k_-),$$

➢ Key Elements: quark propagator $S(q)$;

vector meson BSA $V(k_+, k_-)$;

photon-quark vertex $\Gamma_\mu(k_-, k_- + q)$;

➢ Full photoproduction amplitude and cross section:

$$I_\mu(W, t) = \langle J(P; \lambda)p(p_2)|\bar{q}\gamma_\mu q|p(p_1)\rangle$$

$$= 2t_{\mu\alpha\nu}(q, P)\epsilon_\nu^\lambda(P)\bar{u}(p_2)\tilde{G}_\alpha(\omega^2, t)u(p_1)$$

$$\tilde{G}_\alpha(\omega^2, t) = \gamma_\alpha G_\mathbb{P}(\omega^2, t)3\beta_f F_0(t)$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi^2}\frac{m_p}{4W}\frac{|\vec{P}|}{k_W}\sum_{\text{proton spin}}(|I_1|^2 + |I_2|^2)$$

P - dyn:

Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.

The reaction model

➤ **NO nonperturbative inputs** .

➤ The Dynamical Transition Amplitude [1]: $\Gamma_{\alpha,\mu\nu} = q_\alpha \delta_{\mu\nu} - q_\mu \delta_{\alpha\nu}$.
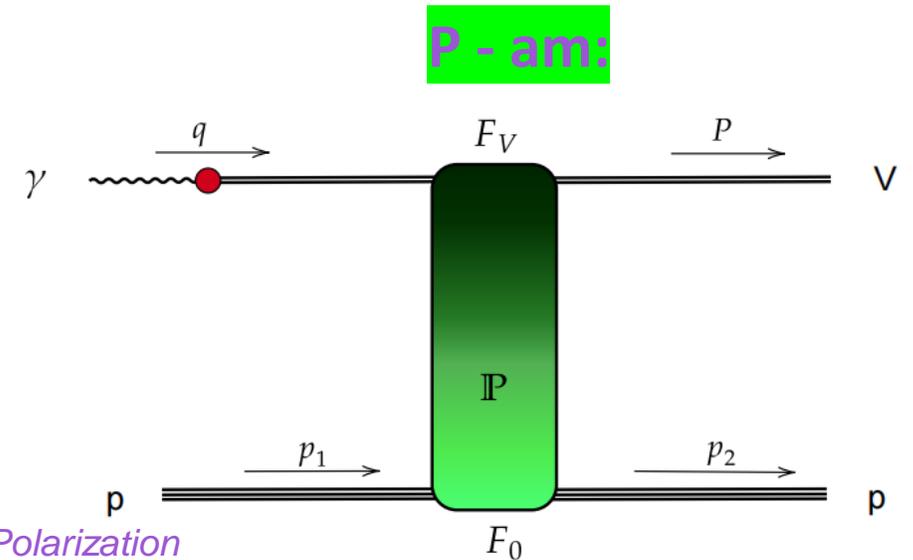
➤ P-Meson Form factor: $F_V(t) = \dfrac{1}{m_V^2 - t}\left(\dfrac{2\mu_0^2}{2\mu_0^2 + m_V^2 - t}\right)$

➤ Nucleon EM Form factor: $F_0(t) = \dfrac{4m_p^2 - 2.8t}{4m_p^2 - t}\dfrac{1}{(1 - t/t_0)^2}$

➤ The Full Photoproduction Amplitude:

$$\mathcal{I}_\mu(W,t) \propto \bar{u}(p_2)\gamma_\alpha u(p_1)\epsilon_\nu^\lambda(P)\Gamma_{\alpha,\mu\nu}G_\mathbb{P}(w^2,t)$$
$$\times [\beta_q F_V(t)][\beta_l F_0(t)],$$

[1] A. I. Titov, Y.-s. Oh, S. N. Yang, T. Morii, Photoproduction of phi meson from proton: Polarization observables and the strangeness in the nucleon, Phys. Rev. C 58 (1998) 2429–2449.

Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.

The reaction model

- A Foundation in QCD: Continuum Schwinger Methods
- The Qin-Chang Model:

$$g^2 D_{\mu\nu}(k) = D_{\mu\nu}^{\text{free}}(k)k^2 \mathscr{G}(k^2),$$

$$D_{\mu\nu}^{\text{free}}(k) = \frac{1}{k^2}(\delta_{\mu\nu} - \frac{k_\mu k_\nu}{k^2}).$$

$$\mathscr{G}(k^2) = D\frac{8\pi^2}{\omega^4}e^{-k^2/\omega^2} + \frac{8\pi\gamma_m\mathscr{F}(k^2)}{\ln[\tau + (1 + k^2/\Lambda_{QCD}^2)^2]}].$$
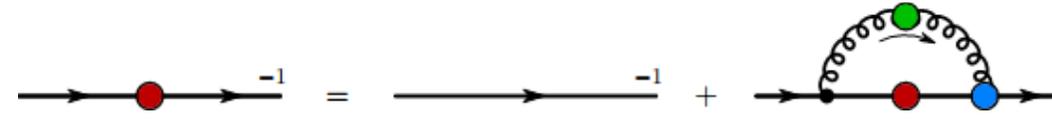
$$\mathscr{F}(k^2) = \frac{1 - \exp(-k^2/(4m_t^2))}{k^2}$$

$$m_t = 0.5\text{GeV}, \tau = e^2 - 1, \gamma_m = 12/(33 - 2N_f).$$

- Owing to the infinite coupling feature, it is necessary to truncate the DSEs and BSE at a certain level for practical calculations

- Ladder approximation: $\Gamma_\nu^a(q, p) = \frac{\lambda^a}{2}\gamma_\nu$

$$\Gamma(k; P) = -Z_2^2 \int \frac{d^4q}{(2\pi)^4}\mathscr{G}((k - q)^2)T_{\mu\nu}(k - q)\frac{\lambda^a}{2}\gamma_\mu S(q_+)\Gamma(q; P)S(q_-)\frac{\lambda^a}{2}\gamma_\nu.$$
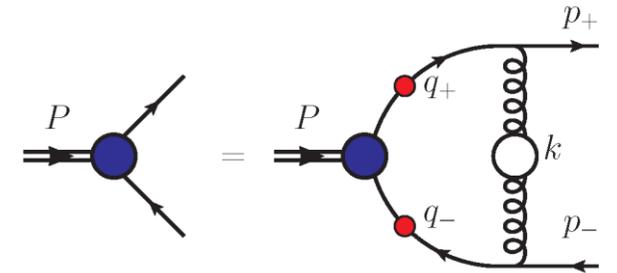
Dyson Schwinger equation

$$S(p)^{-1} = i\gamma \cdot p + m$$
$$+ \int \frac{d^4q}{(2\pi)^4}g^2 D_{\mu\nu}(p - q)\frac{\lambda^a}{2}\gamma_\mu S(q)\frac{\lambda^a}{2}\Gamma_\nu(q, p).$$
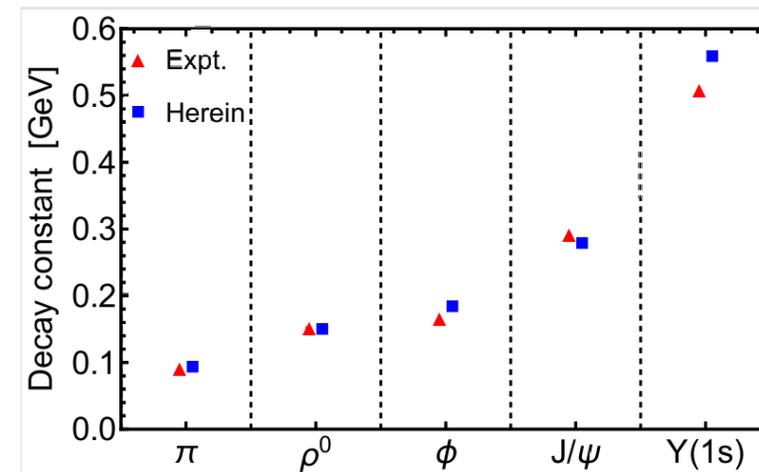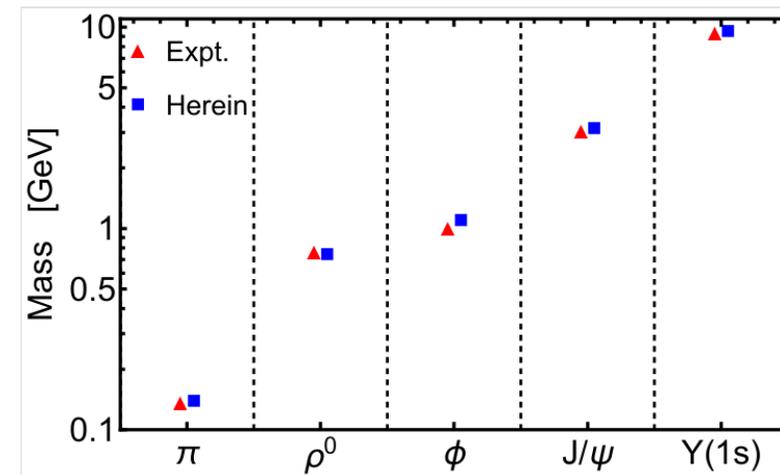
Homogeneous Bethe Salpeter equation

The reaction model

➢ Proven Success: This same interaction accurately predicts a wide range of ground-state hadron observables (masses, decay constants), as shown in our tables.

➢ This makes the P-dyn approach fundamentally more robust and predictive than phenomenological models.
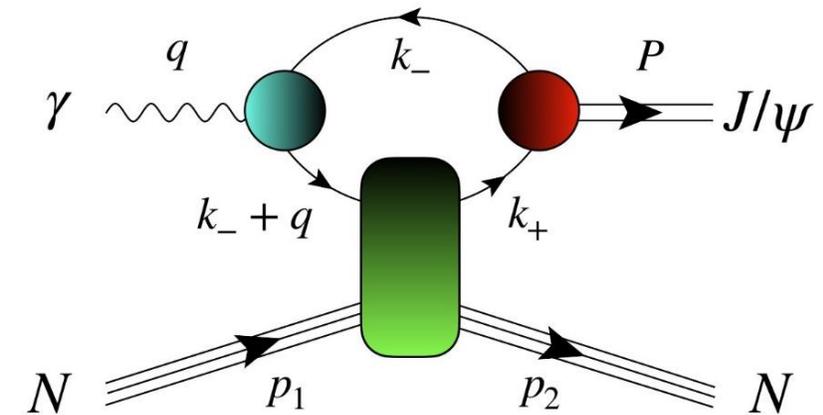

Meson	Mass [GeV]		Decay constant [GeV]	
	Herein	Expt.	Herein	Expt.
π	0.138	0.138	0.092	0.092
ρ^0	0.741	0.775	0.149	0.153
ϕ	1.086	1.019	0.183	0.168
J/ψ	3.123	3.097	0.278	0.294
$\Upsilon(1s)$	9.52	9.46	0.558	0.51

Result and Comparison

Meson	Gluon model					$\mathbb{P}$ trajectory		$\mathbb{P}-$dyn	$\mathbb{P}-$am
	$m_{\zeta_{19}}$ [GeV]	$D\omega$ [GeV^3]	ω [GeV]	N_f	$\Lambda_{\rm QCD}$ [GeV]	α_0	α_1 [GeV^{-2}]	β_q [GeV^{-1}]	β_q [GeV^{-1}]
ρ_ℓ^0	0.0034	0.8^3	0.5	4	0.234	1.1	0.33	3.5	1.96
ϕ_s	0.083	0.8^3	0.5	4	0.234	1.1	0.33	1.89	1.51
J/ψ_c	0.89	0.6^3	0.8	4	0.234	1.2	0.115	0.11	0.428
Υ_b	3.59	0.6^3	0.8	5	0.36	1.2	0.115	0.016	0.638

➢ Light Mesons (ρ, φ): $\alpha_0 = 1.1, \alpha_p' = 0.33 GeV^{-2}$ [1].

➢ Heavy Mesons (J/ψ, Υ): $\alpha_0 = 1.2, \alpha_p' = 0.115 GeV^{-2}$ [2].

➢ Only the Pomeron-quark couplings β_q are free parameters. Each β_q is determined by a fit to the high-energy (W > 10 GeV) data for its respective meson.

➢ *[1] M. A. Pichowsky and T. S. H. Lee. Phys. Rev. D, 56:1644–1662, 1997*

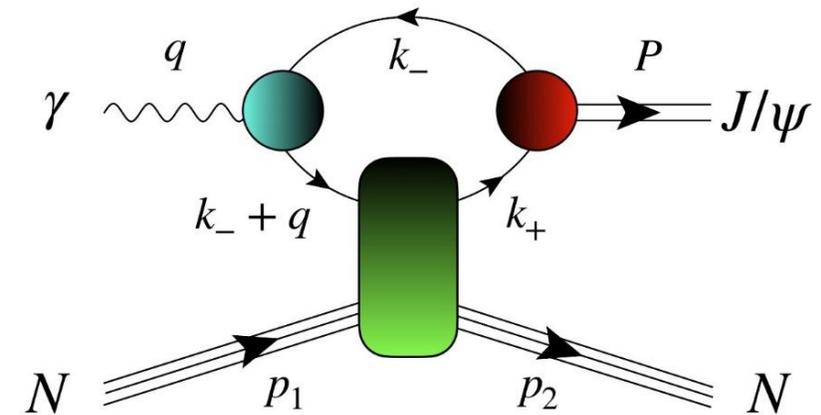➢ *[2] S. Chekanov et al. Exclusive photoproduction of J / psi mesons at HERA. Eur. Phys. J. C, 24:345–360, 2002*

Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.

10/22

Result and Comparison

Light Mesons (ρ, φ): $\alpha_0 = 1.1, \alpha_p' = 0.33 GeV^{-2}$.

Heavy Mesons (J/ψ, Y): $\alpha_0 = 1.2, \alpha_p' = 0.115 GeV^{-2}$.

➤ Only the Pomeron-quark couplings β_q are free parameters.

   – Pomeron + valence quark coupling:

      • $\beta_{u/d}$ … fixed by _HERA_ high-W $\gamma p \to \rho^0 p$ _differential_ cross-section

      • β_c … fixed by _HERA_ high-W $\gamma p \to J/\psi p$ _forward differential_ cross-section

      • β_s … fixed by _ZEUS_ high-W $\gamma p \to \varphi p$ _total_ cross-section

      • β_b … fixed by _ZEUS_ and _LHCb_ high-W $\gamma p \to \Upsilon p$ _total_ cross-section

➤ Crucially: All parameters are then fixed. All predictions for near-threshold kinematics and differential cross-sections are true predictions of the model. Once these parameters are set, the model produces predictions for all other energies and momentum transfers, especially the crucial near-threshold region. There is no further tuning.
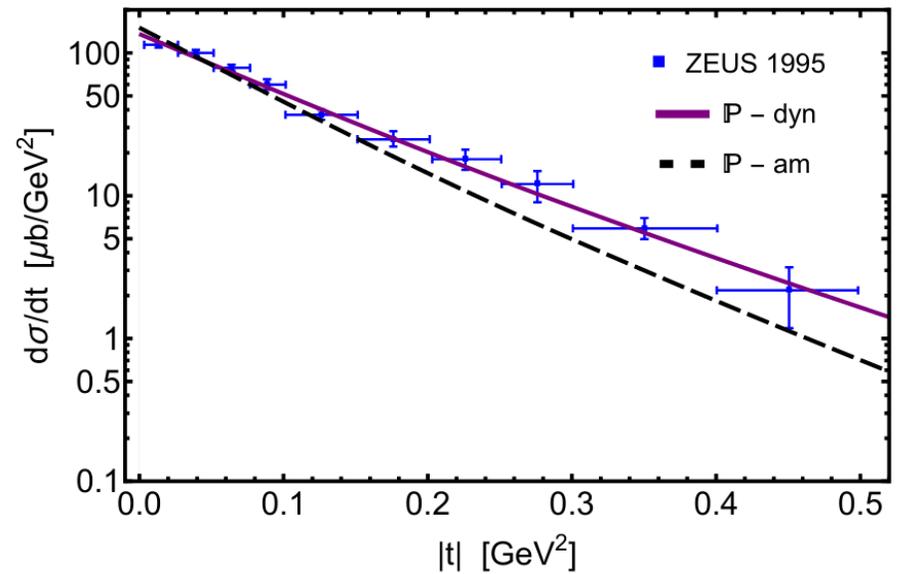
Result and Comparison[1]

➤ Success: Our P-dyn model describes the total cross-section well for W > 10 GeV.

➤ Discrepancy: It fails very close to threshold, where non-diffractive processes (meson exchange), not included here, dominate. This is expected as the ρ shares valence quarks with the proton.
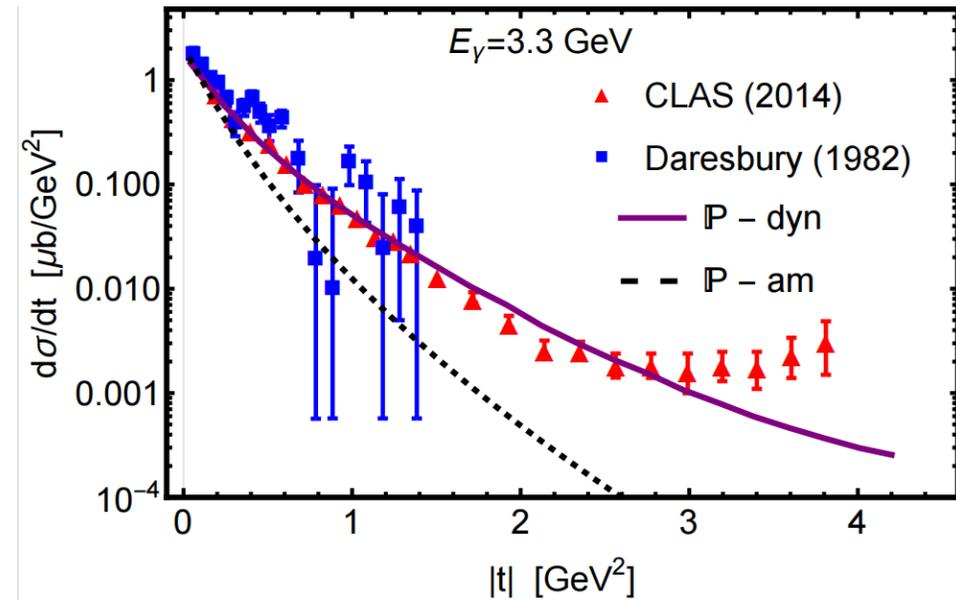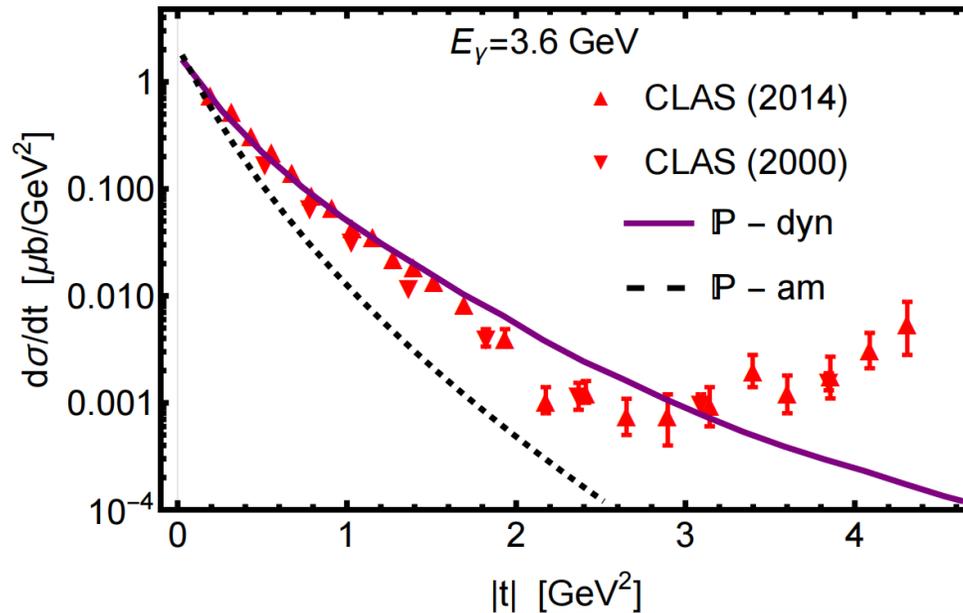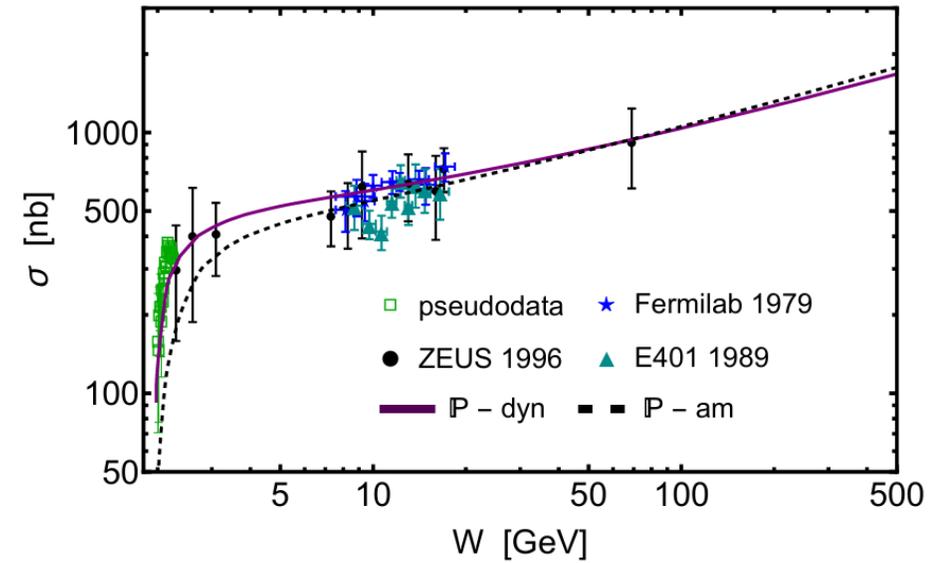
--> It should be the same case for ω meson.

--> While for other vector mesons, this reaction model can present reasonable curves.

[1] Exclusive photoproduction of light and heavy vector mesons: thresholds to very high energies, Lin Tang (唐淋) et al., NJU-INP 105-25, e-Print: 2510.08845 [hep-ph].
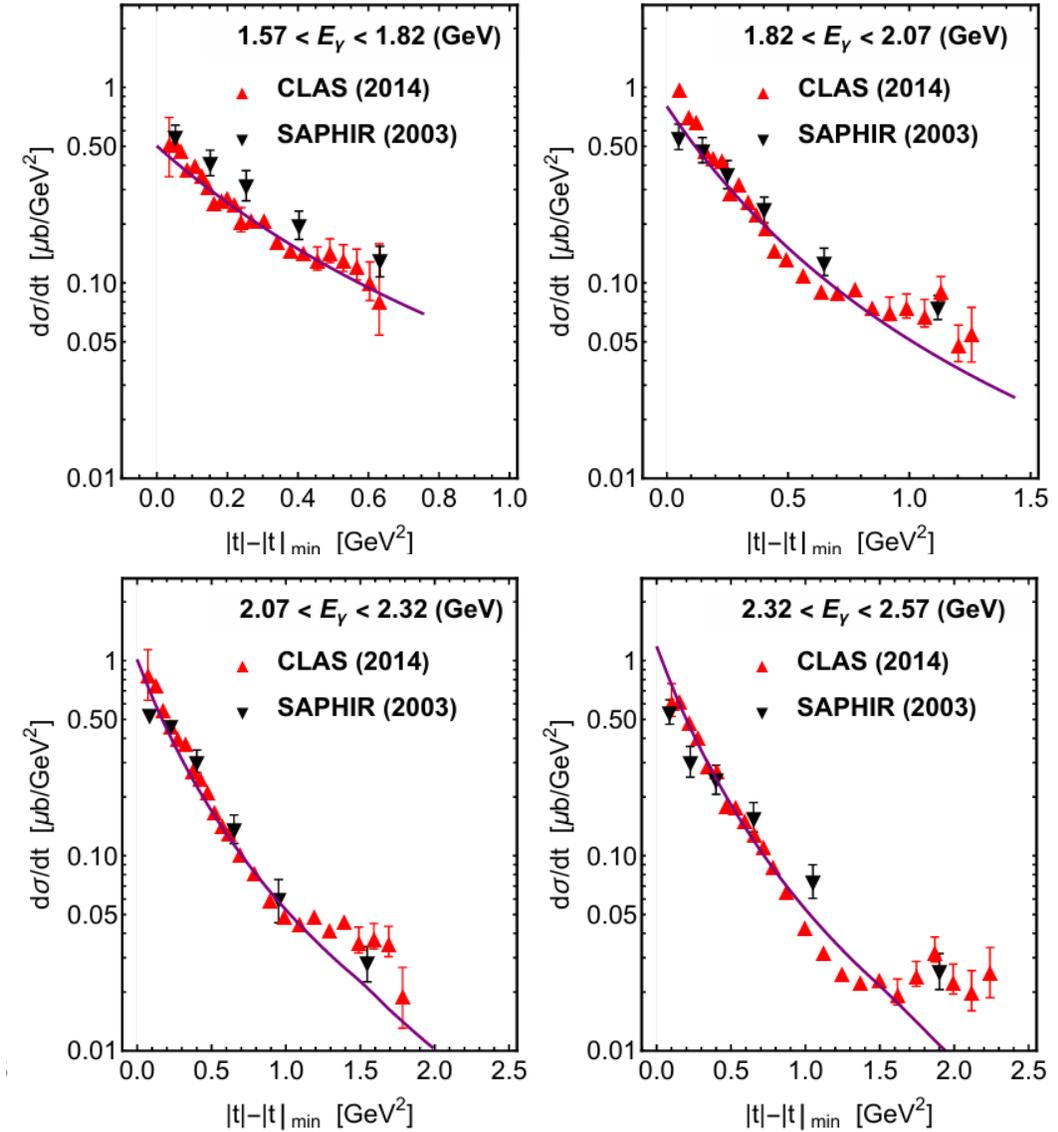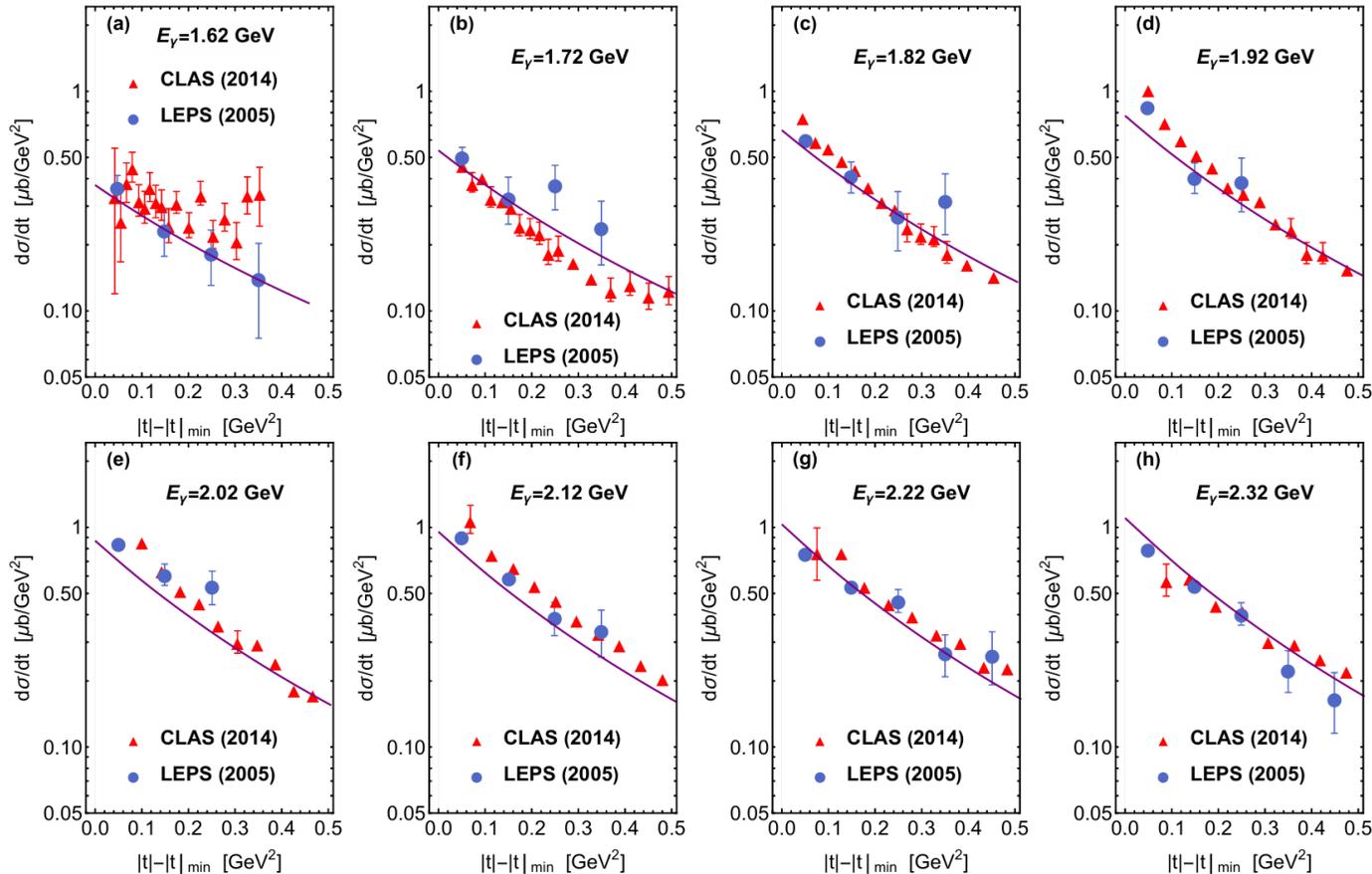
Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.

Result and Comparison

➢ The φ meson (s̄s) has no common valence quarks with the proton, making it a pure probe of the diffractive mechanism.

➢ *Finding:* Our P-dyn model provides an excellent description of both the total and differential cross-sections from threshold to high energies.

➢ The P-am model, which simplifies the quark loop, fails to capture the correct strength and shape, especially near threshold.
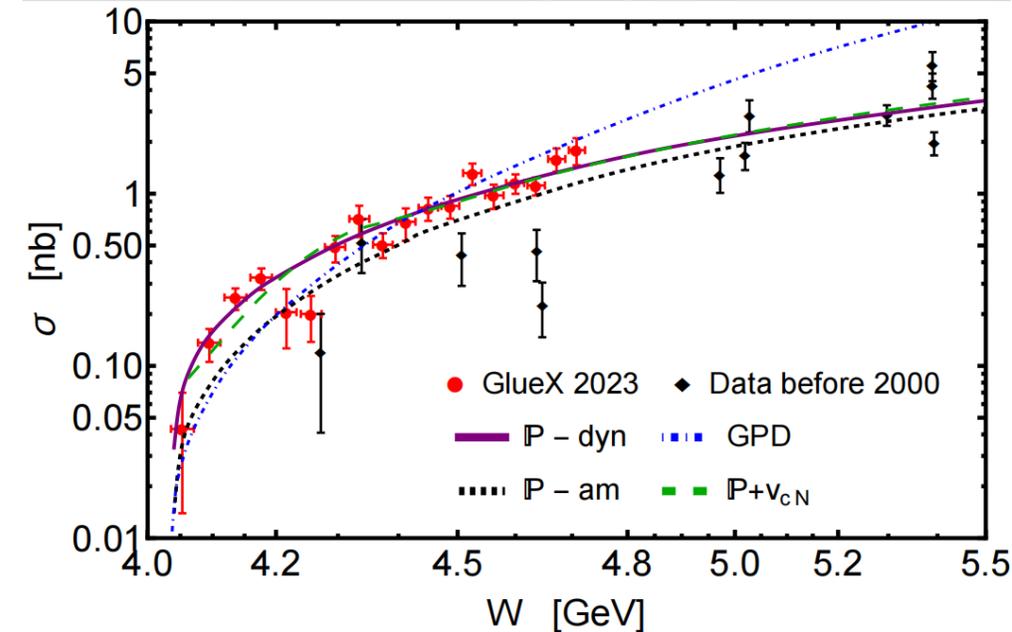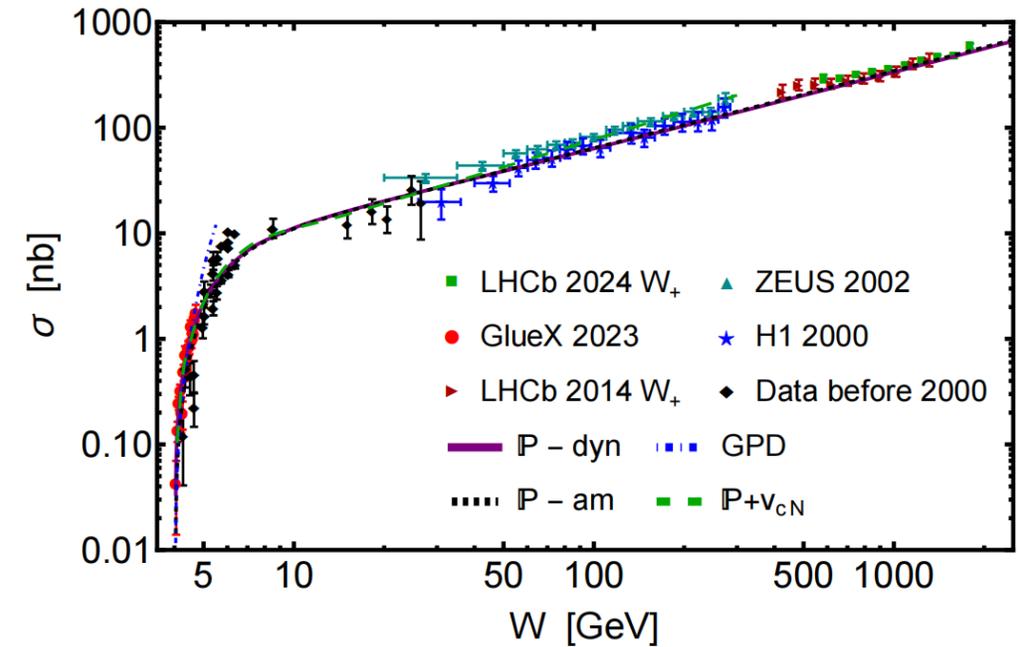
Result and Comparison

➤ *Conclusion:* The precise agreement for the φ meson gives us strong confidence in the validity of our dynamical

$\gamma \to q\bar{q} + P \to V$ treatment.

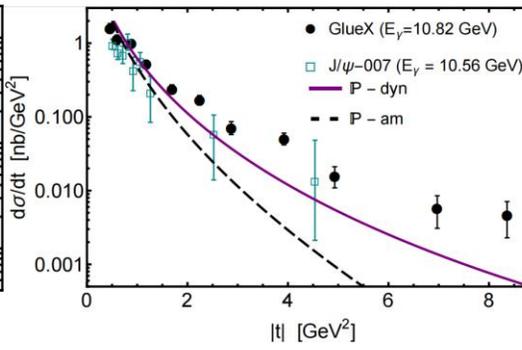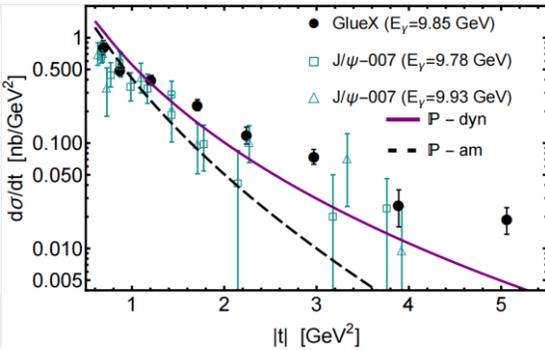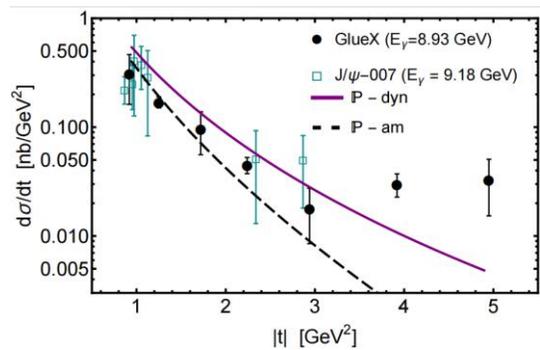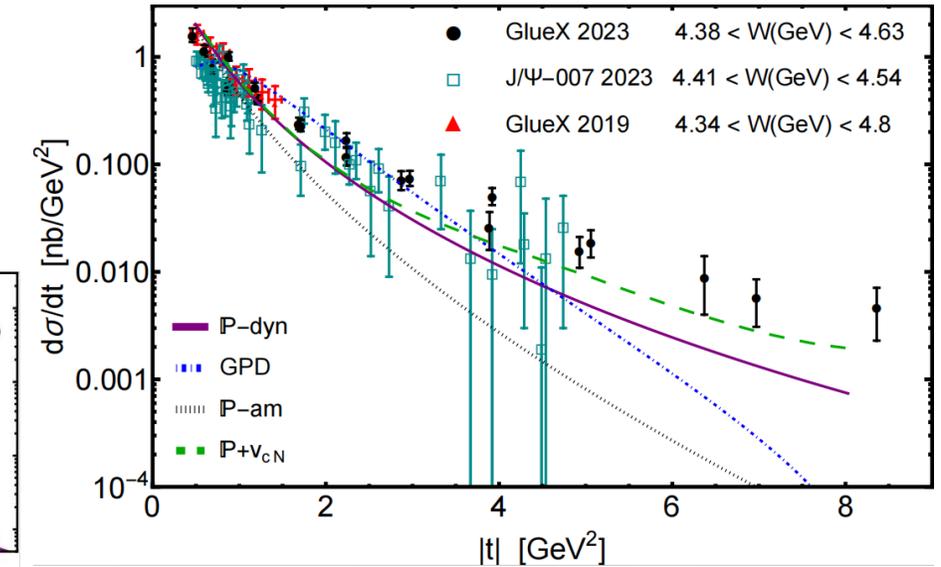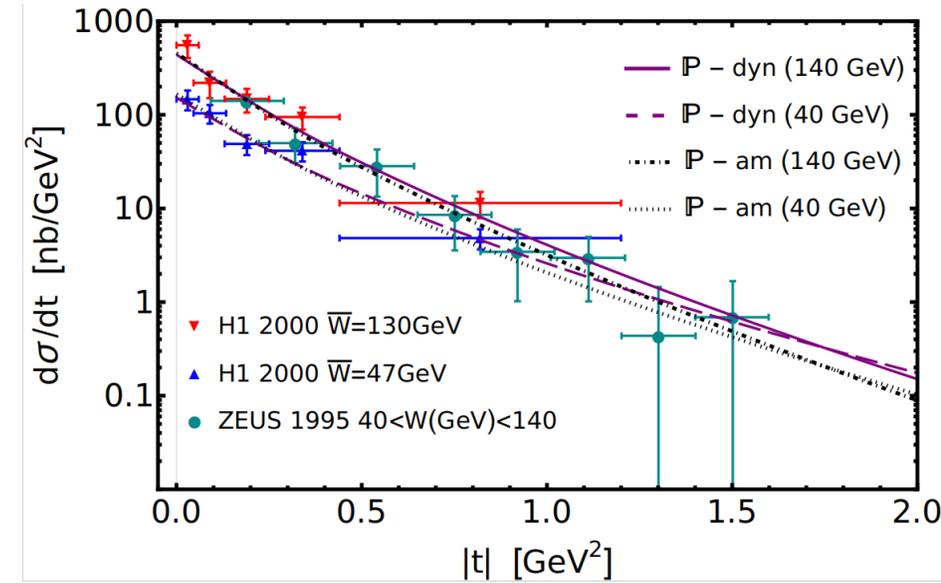Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.

Result and Comparison

➢ *J/ψ Total Cross-Section:* Our P-dyn model (solid purple curve) provides a unified description of all data, from the new GlueX near-threshold points to the high-W H1/ZEUS/LHCb data.

➢ *Differential Cross-Section:* Near threshold, P-dyn successfully describes the data convex shape. Other models (GPD, FSI) show different behaviors, but the reaction mechanism is not yet uniquely determined by data alone.

➢ *Key Message:* Our models are the only one that works across the entire kinematic range without changing parameters and introducting compensatory mechaism.
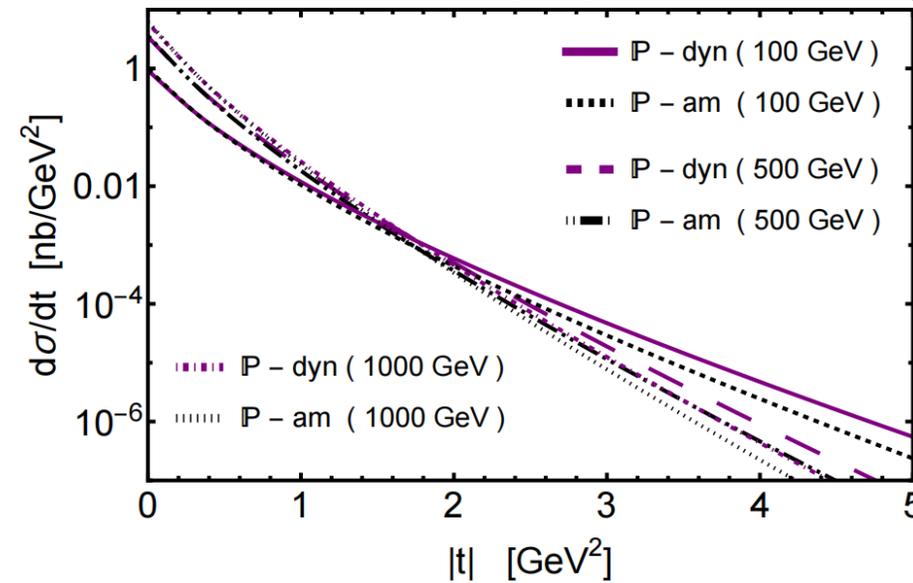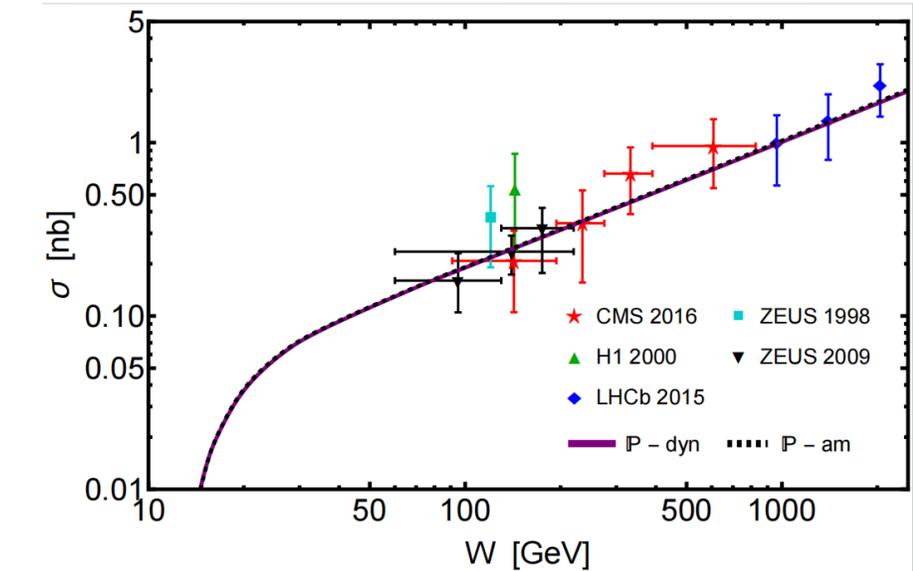
Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.

Result and Comparison

➢ *High W Differetial Cross-Section:* Our P-dyn model (solid purple curve) provides a unified description of all data, from the new GlueX near-threshold points to the high-W H1/ZEUS/LHCb data.

➢ *Low W Differential Cross-Section:* Near threshold, P-dyn successfully describes the data convex shape. The quark transition loop has a significant influence for near threshold reaction.

➢ *Two more curves:* Blue dot-dashed curve --> GPD based model; green long dashed curve --> VMD + FSI.

Result and Comparison

- ➤ Υ: Prediction and Confirmation

- ➤ *Total Cross-Section:* Our prediction is in excellent agreement with the available high-energy data.

- ➤ *Differential Cross-Section:* We provide predictions for future EIC/EICC measurements. The difference between P-dyn and P-am is clear, indicating that future precise data can distinguish the reaction mechanism.
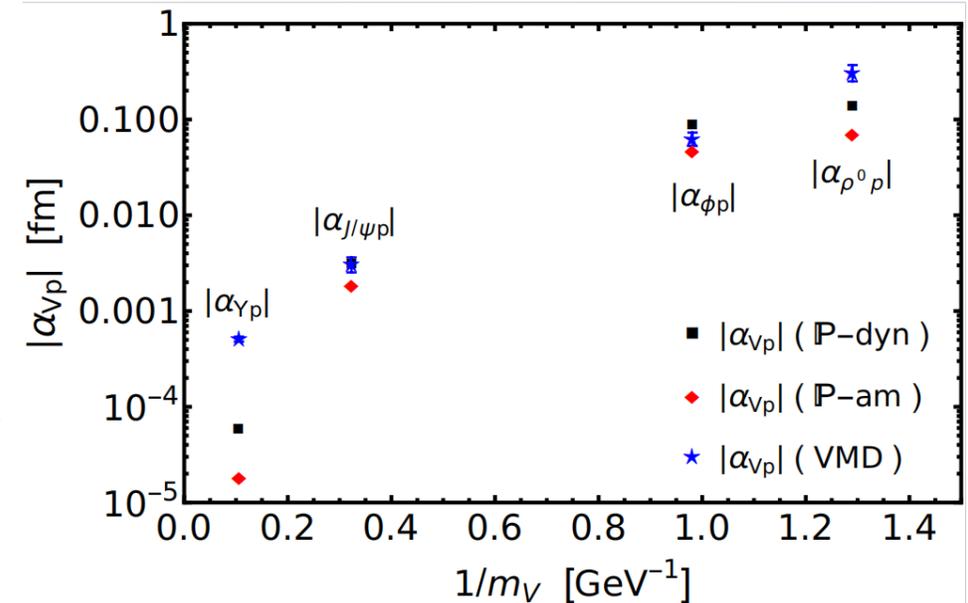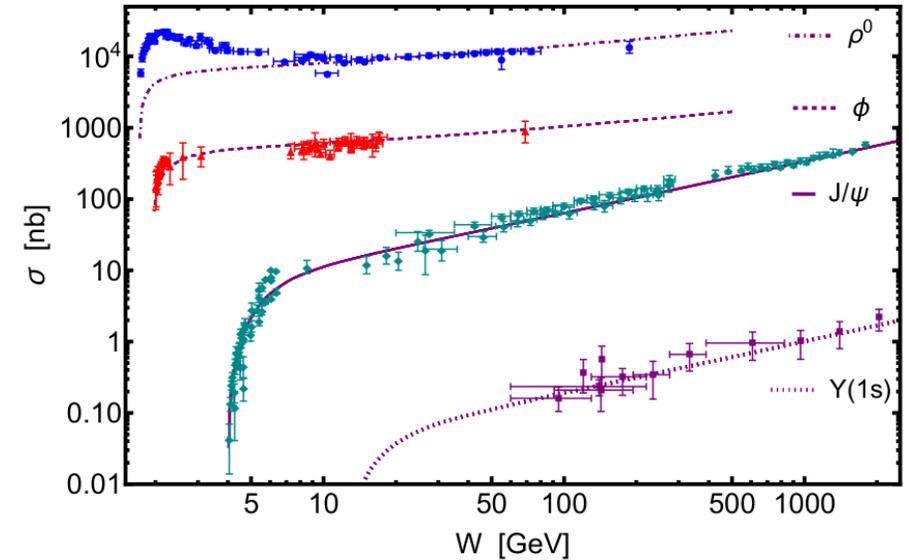
Result and Comparison

➤ A single calculation framework (P-dyn) describes the total cross-sections for four vector mesons across an enormous kinematic range.

➤ This is a powerful demonstration of the model's robustness and universality.

➤ Using a VMD-inspired relation, we extract a slope parameter |α_Vp| (scattering length) from our near-threshold differential cross-sections [1],

$$\frac{d\sigma^{\gamma p \to V p}}{d\Omega}\bigg|_{th} = \frac{|\vec{P}|}{|\vec{q}|}\frac{1}{64\pi}|T^{\gamma p \to V p}|^2,$$

$$= \frac{|\vec{P}|}{|\vec{q}|}\frac{\pi\alpha}{g_V^2}\frac{d\sigma^{V p \to V p}}{d\Omega}\bigg|_{th}$$

$$= \frac{|\vec{P}|}{|\vec{q}|}\frac{\pi\alpha}{g_V^2}|\alpha_{V p}|^2,$$

$$|\alpha_{\Upsilon p}| \ll |\alpha_{J/\psi p}| \ll |\alpha_{\phi p}| < |\alpha_{\rho^0 p}|.$$

[1] Threshold Upsilon-meson photoproduction at the EIC and EicC, Strakovsky, Igor et al., Phys. Rev. D.

Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.

Result and Comparison

- Near-Threshold Slope Parameters (Scattering Lengths)

- Using a VMD-inspired relation, we extract a slope parameter $|\alpha\_Vp|$ from our near-threshold differential cross-sections.

V	m_V/GeV	q_{th}/GeV	$\Gamma_{V \to e^+e^-}/\text{keV}$	$|\alpha_{Vp}^{\text{dyn}}|/\text{fm}$	$|\alpha_{Vp}^{\text{am}}|/\text{fm}$	$|\alpha_{Vp}^{\text{VMD}}|/\text{fm}$
ρ^0	0.775	0.6	6.97	0.136	0.072	0.23 ± 0.03 [63]
ϕ^0	1.019	0.75	1.27	0.087	0.048	0.063 ± 0.010 [61]
J/ψ	3.097	1.91	5.53	3.08×10^{-3}	1.88×10^{-3}	$3.08(55) \times 10^{-3}$ [60]
Υ	9.46	5.16	1.34	5.87×10^{-5}	1.86×10^{-5}	$0.51(3) \times 10^{-3}$ [62]

- [60] I. Strakovsky, D. Epifanov, L. Pentchev, J/ψp scattering length from GlueX threshold measurements, Phys. Rev. C 101 (4) (2020) 042201

- [61] I. I. Strakovsky, L. Pentchev, A. Titov, Comparative analysis of ωp, φp, and J/ψp scattering lengths from A2, CLAS, and GlueX threshold measurements, Phys. Rev. C 101 (4) (2020) 045201

- [62] I. I. Strakovsky, W. J. Briscoe, L. Pentchev,A. Schmidt, Threshold Upsilon-meson photoproduction at the EIC and EicC, Phys. Rev. D 104 (7)(2021) 074028.

- [63]I. I. Strakovsky, E. L. Isupov, V. Mokeev,A. Schmidt, ρ-Meson Nucleon Scattering Lengthfrom CLAS Threshold Photoproduction Measurements– arXiv:2509.04672 [nucl-th] .

$$|\alpha_{\Upsilon p}| \ll |\alpha_{J/\psi p}| \ll |\alpha_{\phi p}| < |\alpha_{\rho^0 p}|.$$
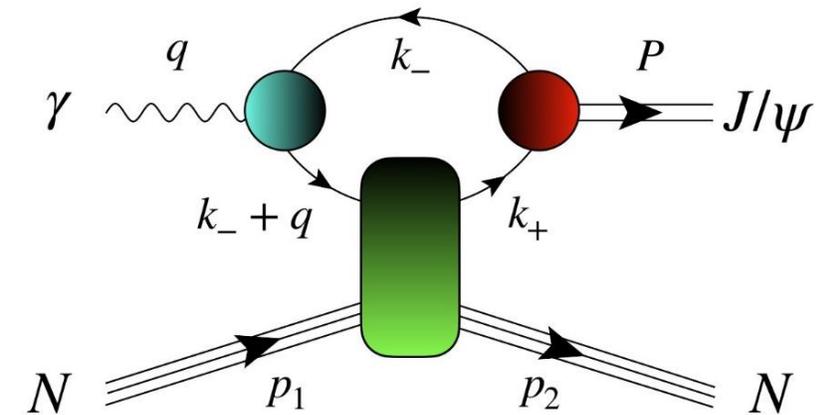
Conclusion

Methods:

➤ First-Principles Transition: We developed the P-dyn model, which for the first time incorporates a rigorous, CSM-based calculation of the full γ → qq̄ + P → V transition amplitude, moving beyond phenomenological approximations.

➤ Universal Pomeron Framework: This dynamical amplitude is coupled to the proton via a Pomeron exchange, using universal trajectories for light and heavy mesons.

➤ High-Energy Constraint: The model's minimal free parameters (β_q) are fixed exclusively with high-energy data.

Key Achievements:

☑ *Unified Description:* The model successfully describes total and differential cross-sections for ρ, φ, J/ψ, and Υ from threshold to TeV scales.

☑ *Role of Quark Dynamics:* The critical comparison between P-dyn and P-am provides direct evidence that quark loop dynamics are dominant in the near-threshold region. Simplifying this element degrades the description.

Email: lin-tang@smail.nju.edu.cn, Vector meson photoproduction.
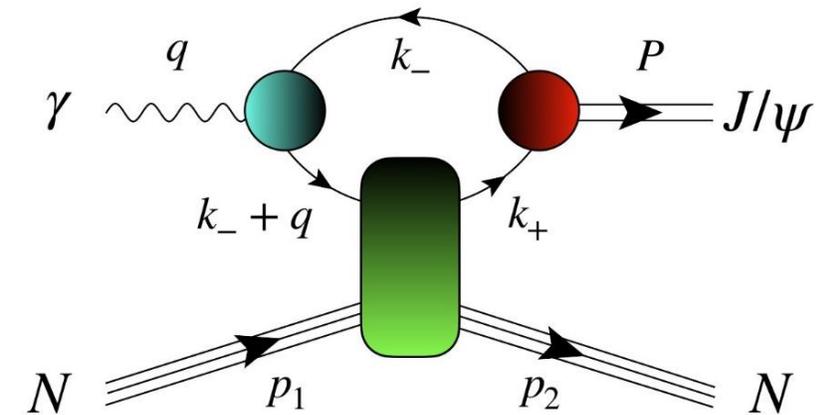
Conclusion

A Critical Implication:

The remarkable success of our quark-based P-dyn model serves as a strong counterpoint to other interpretations.

The reaction mechanism is not yet uniquely determined by existing data. Our model presents a viable and powerful alternative that does not rely on these specific mechanisms.Therefore, it is premature to directly link existing J/ψ data with detailed gluonic properties in proton.

The Path Forward:

Future experiments can check test our predictions, especially our differential cross-sections for J/ψ and Y near threshold.

Deviations from our P-dyn results will be possible to uncover signs of new physics or sub-dominant mechanisms.

Thankyou

ICC Jeju, Korea
Nov 13, 2025