Structure of multi-particle states

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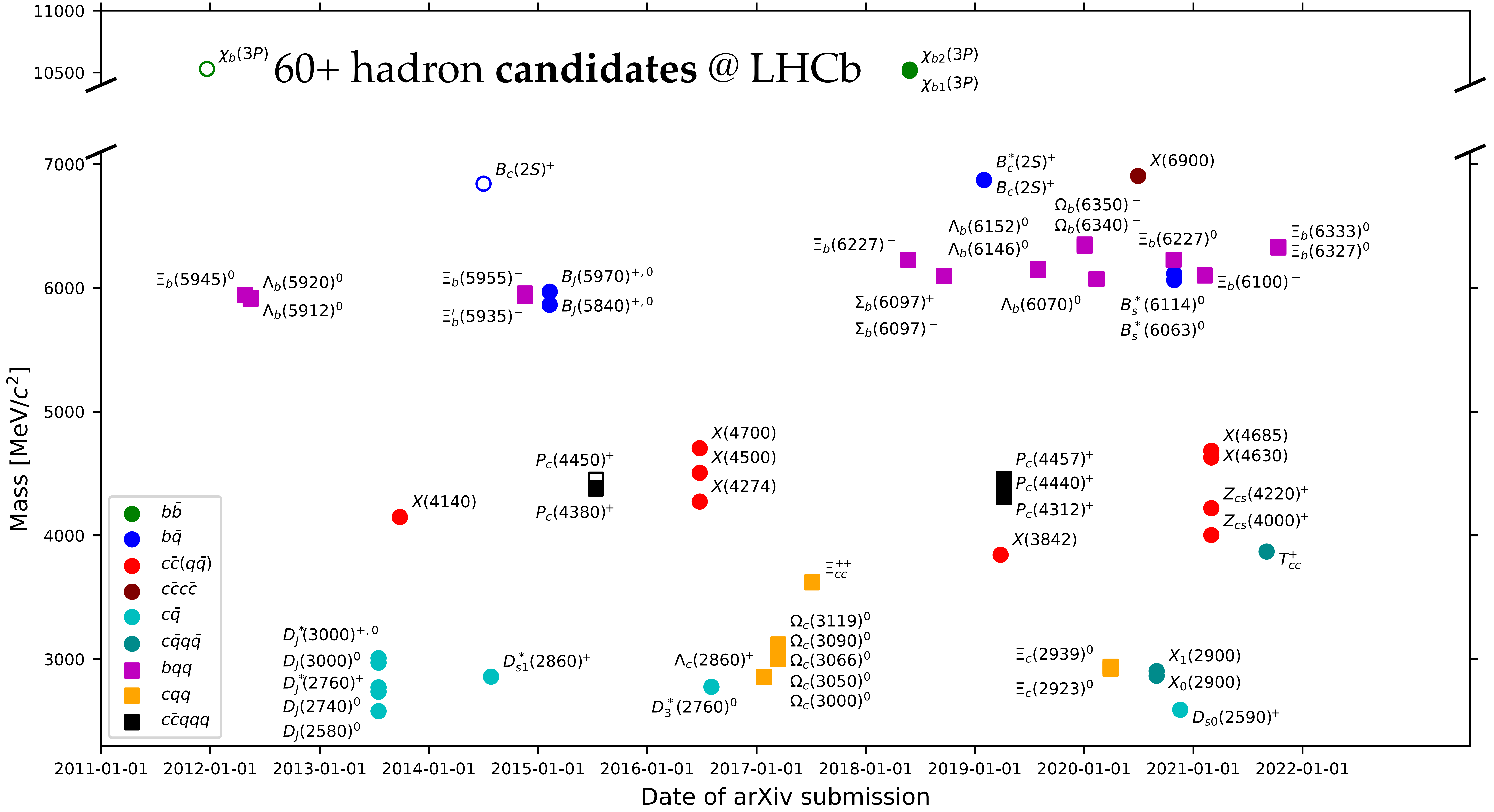
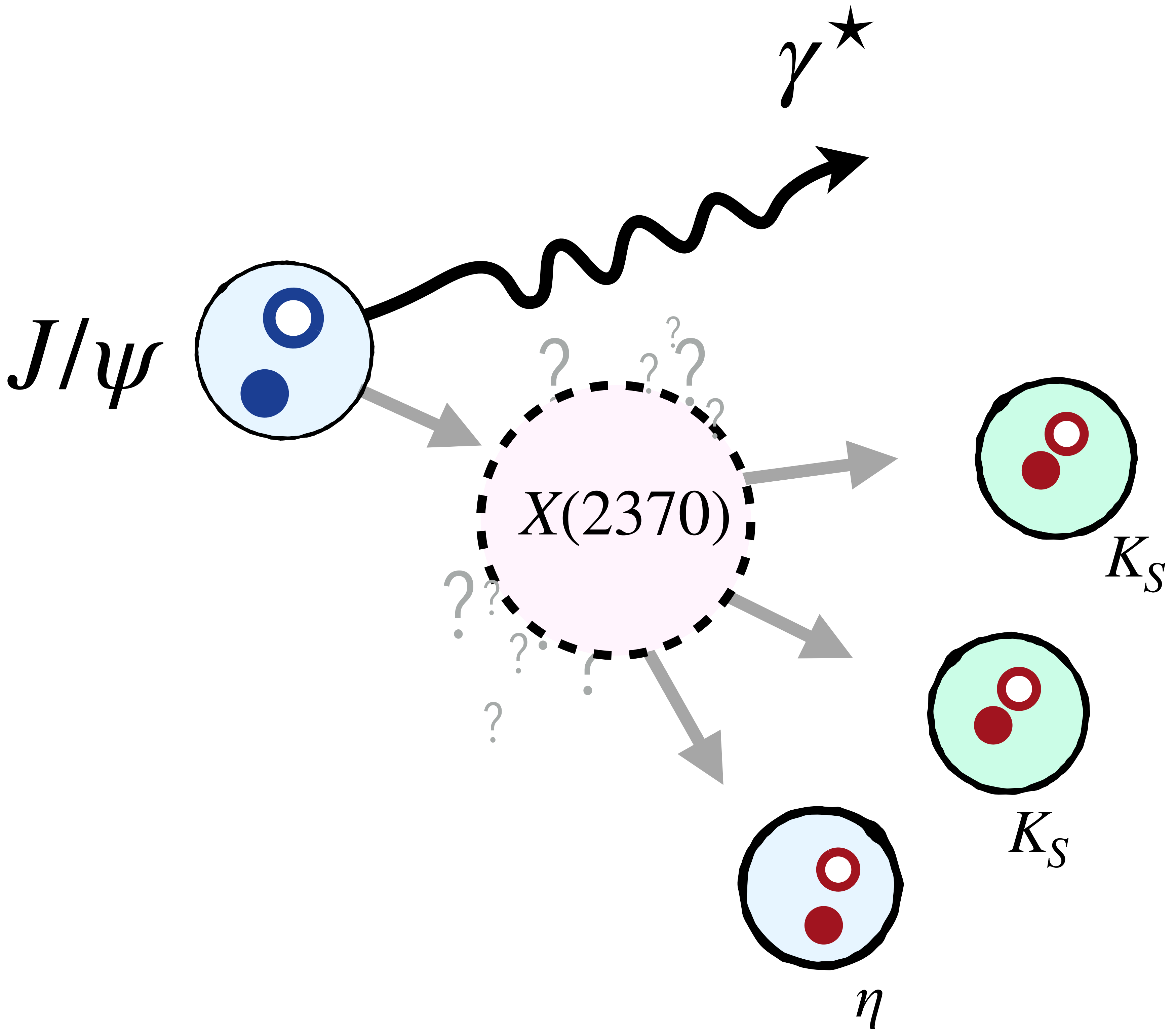
QCD is a rich forest with lots of trees deserving our attention

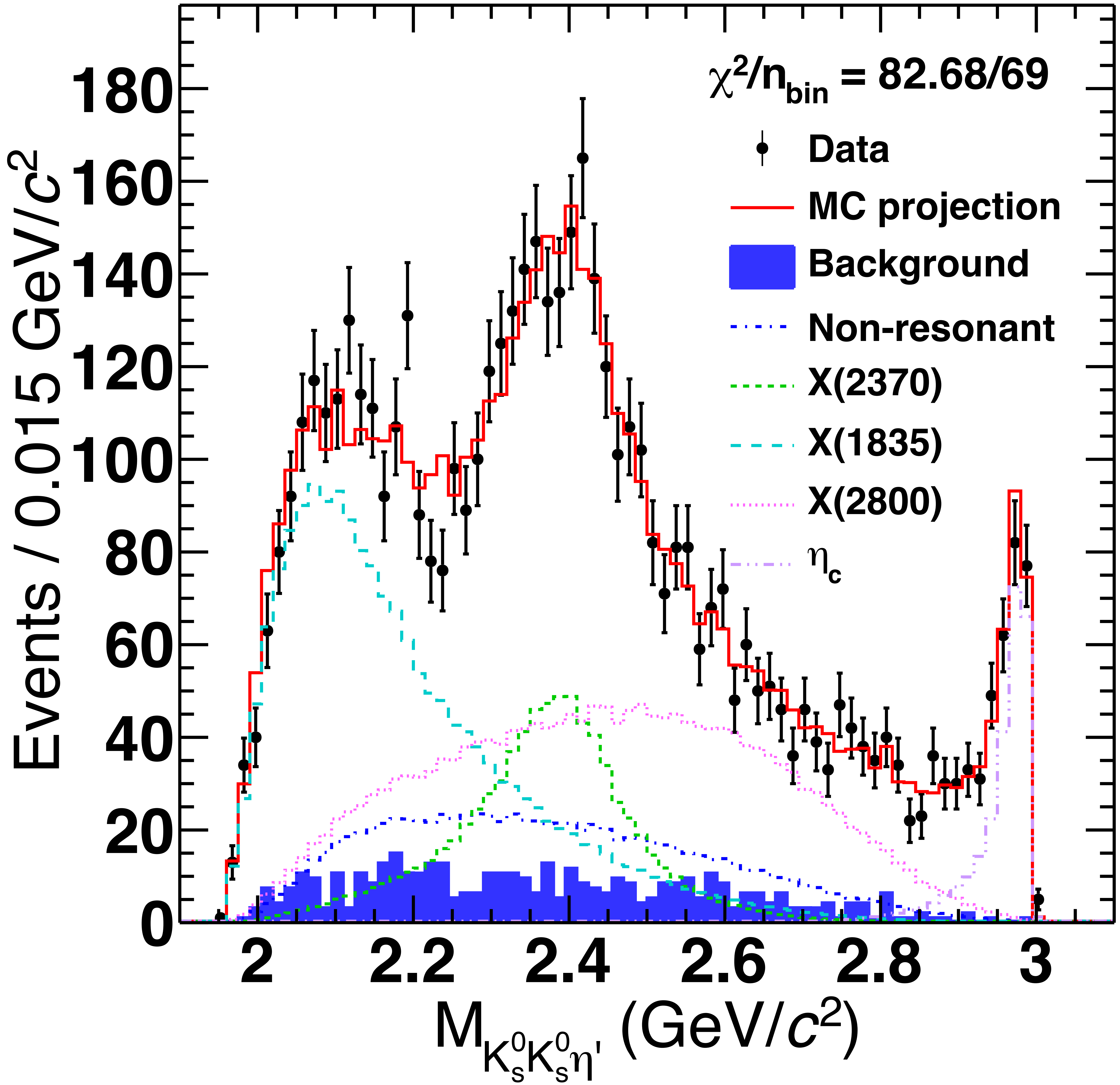
The particle zoo the remake



Numerous other experimental searches…

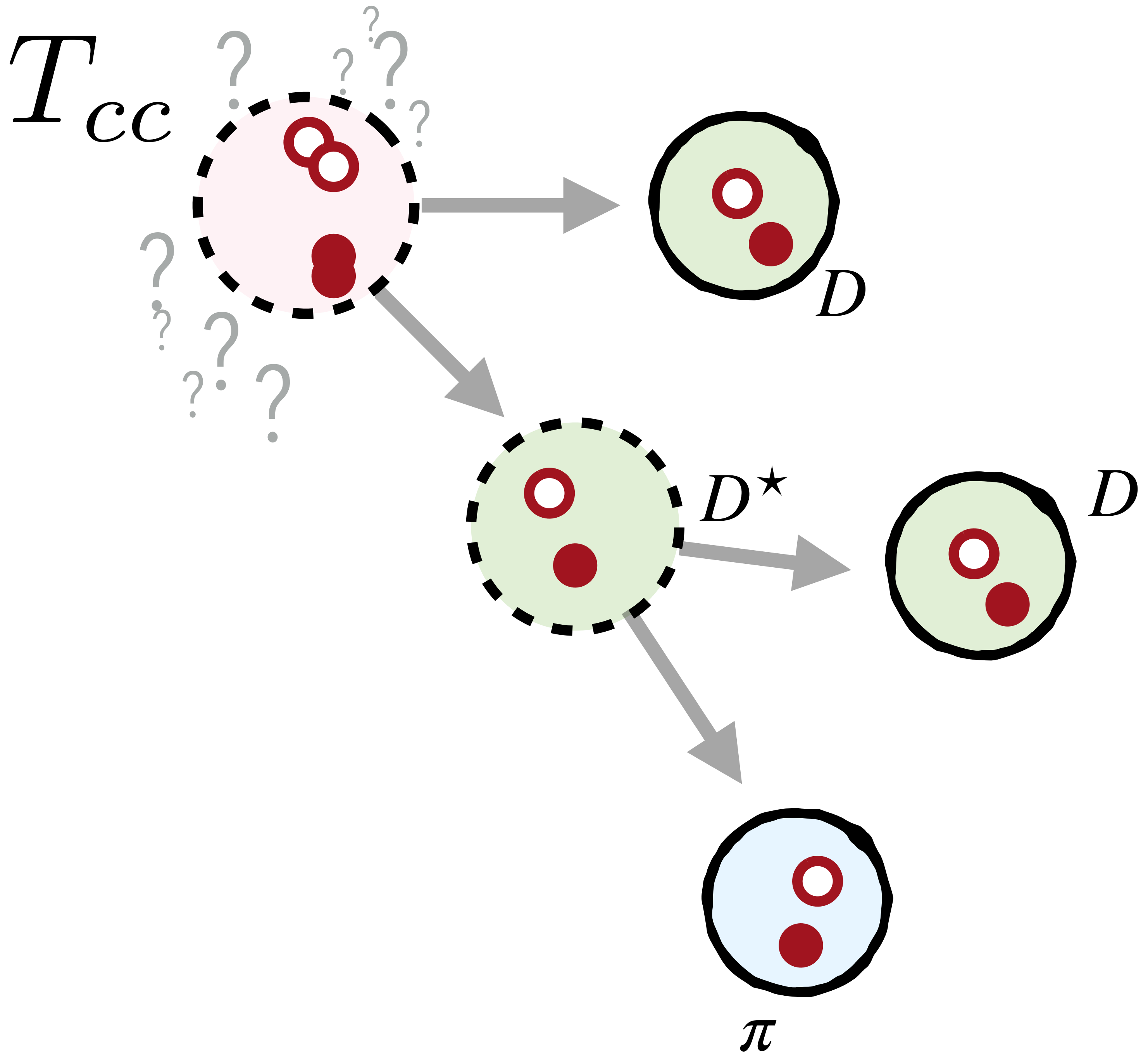
Glueballs?

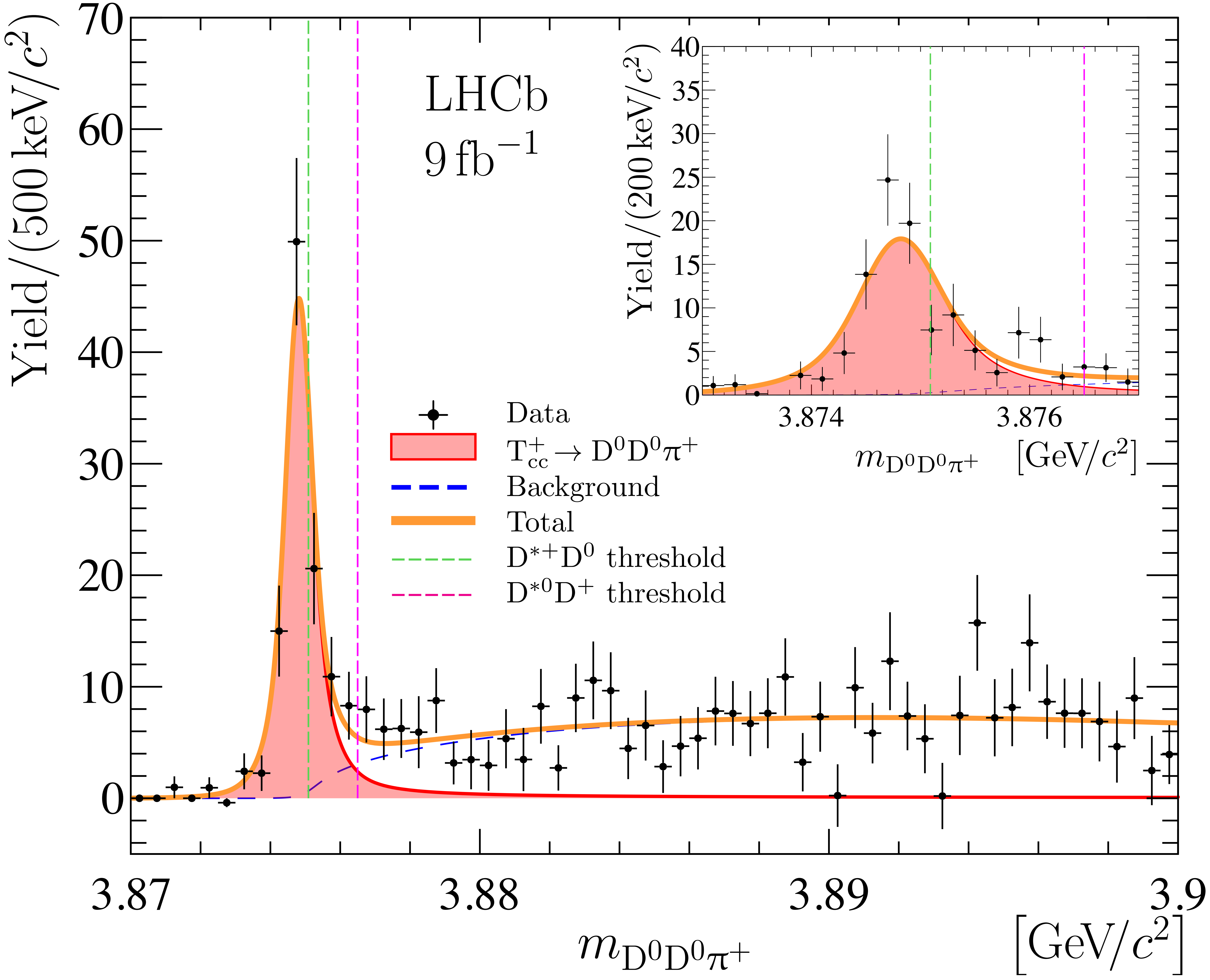




BESIII

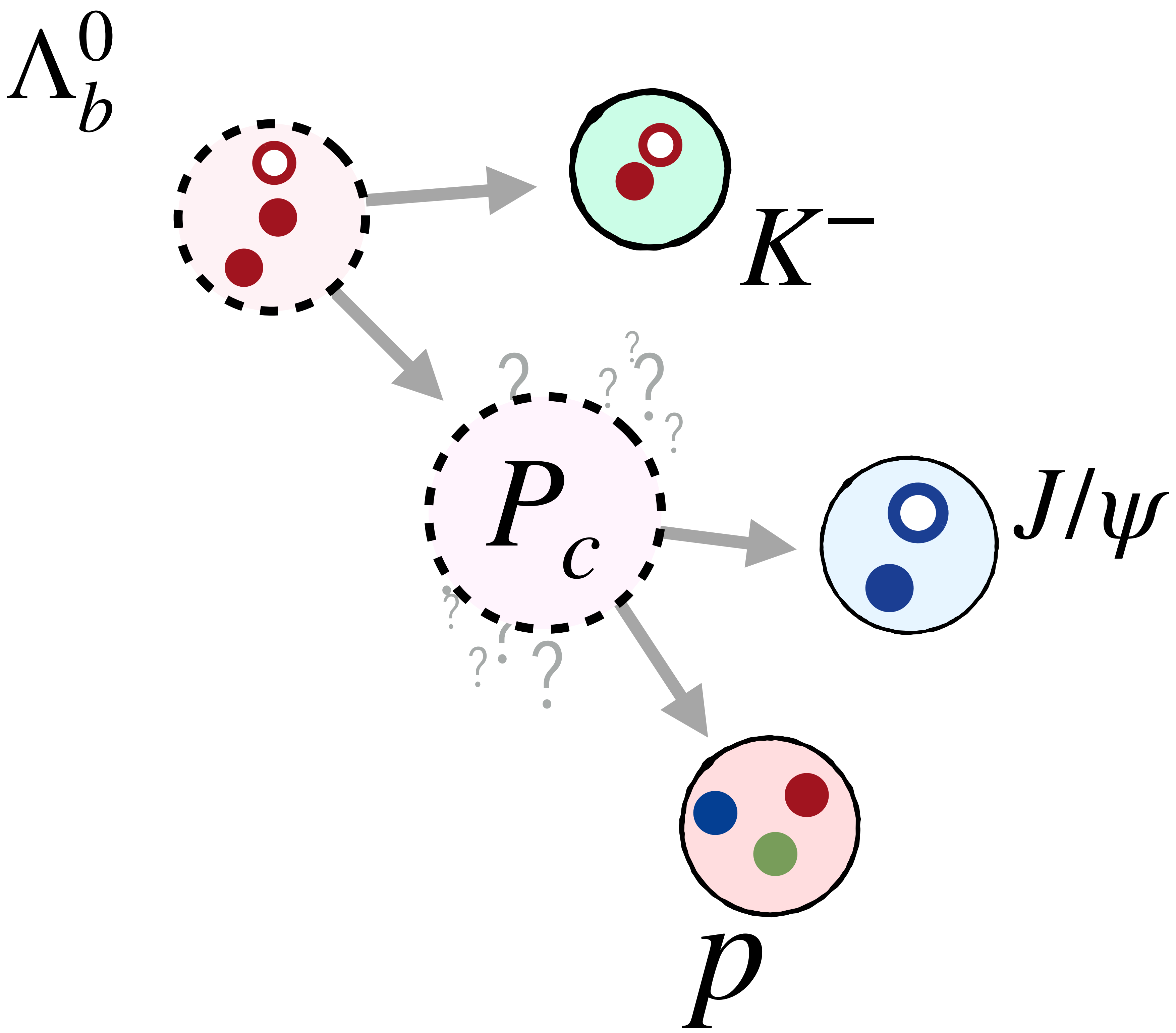
Tetraquarks?

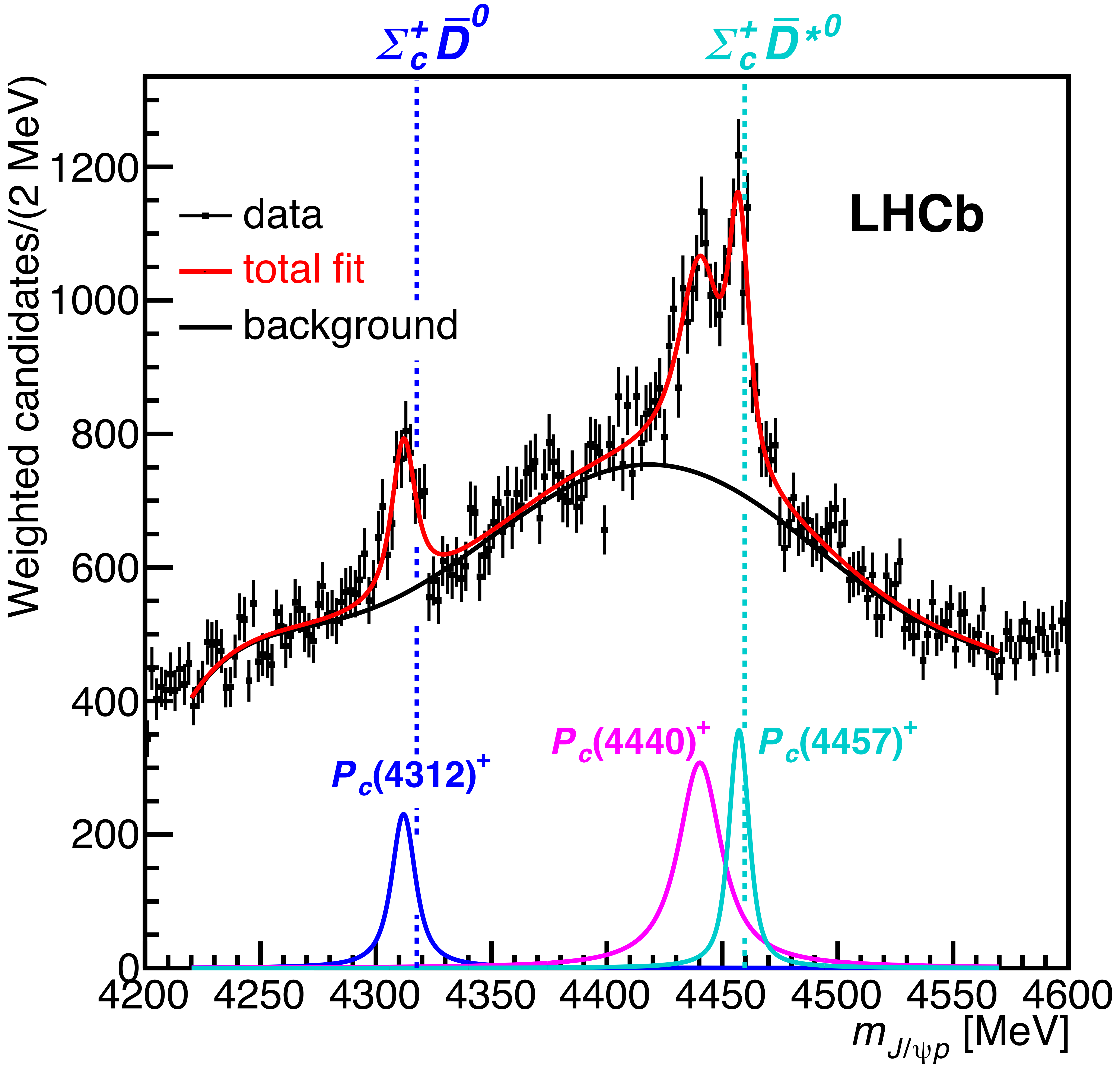




(2021)

Pentaquarks?





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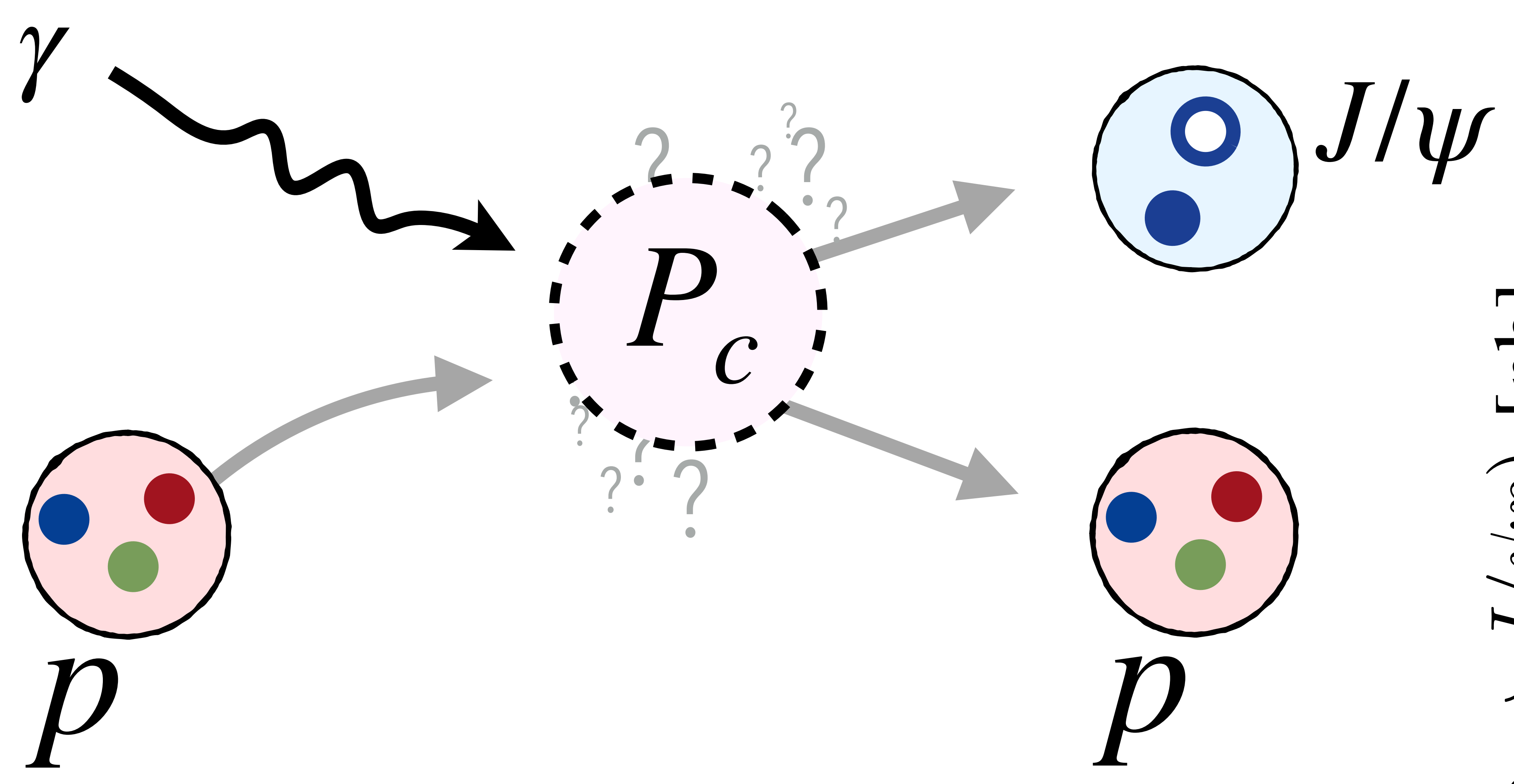
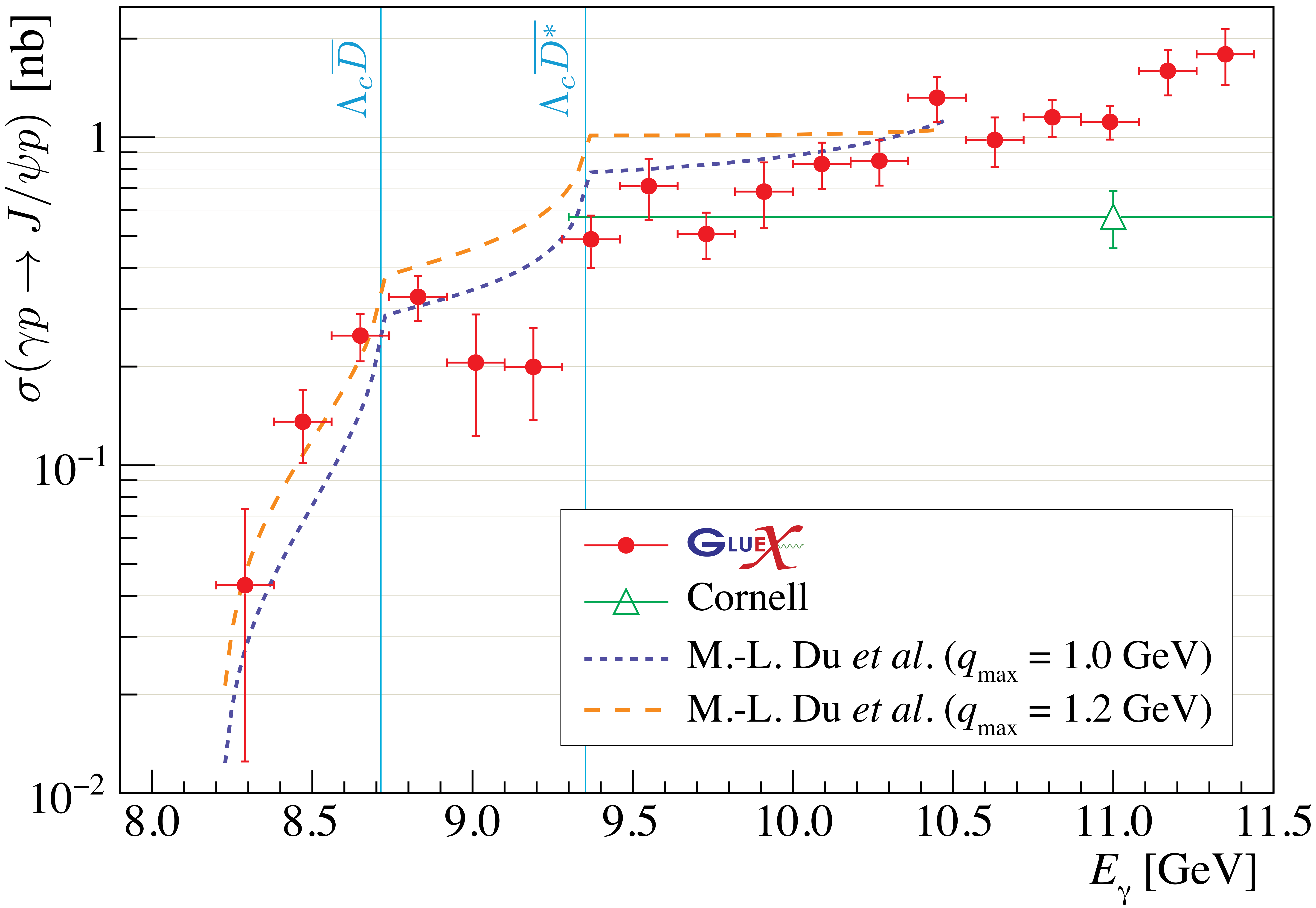
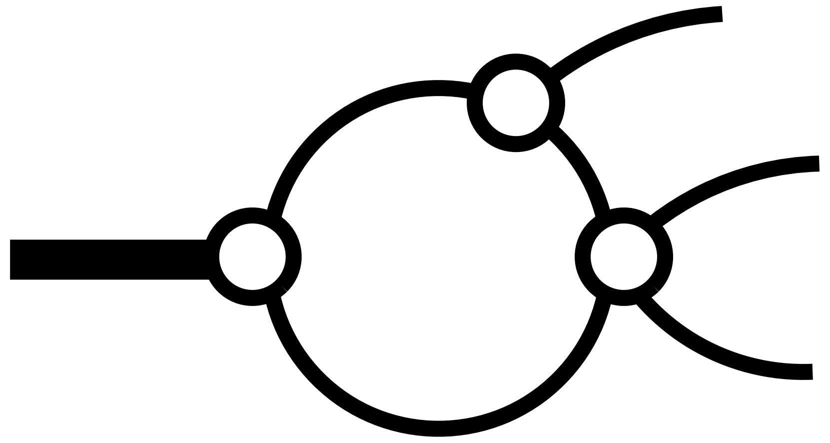




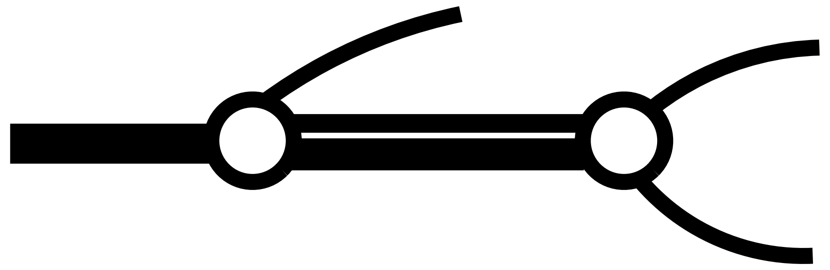
Key questions to answer

- [ ] Which enhancements in cross sections are actual resonances?



$\sim \log(s - s_t)$

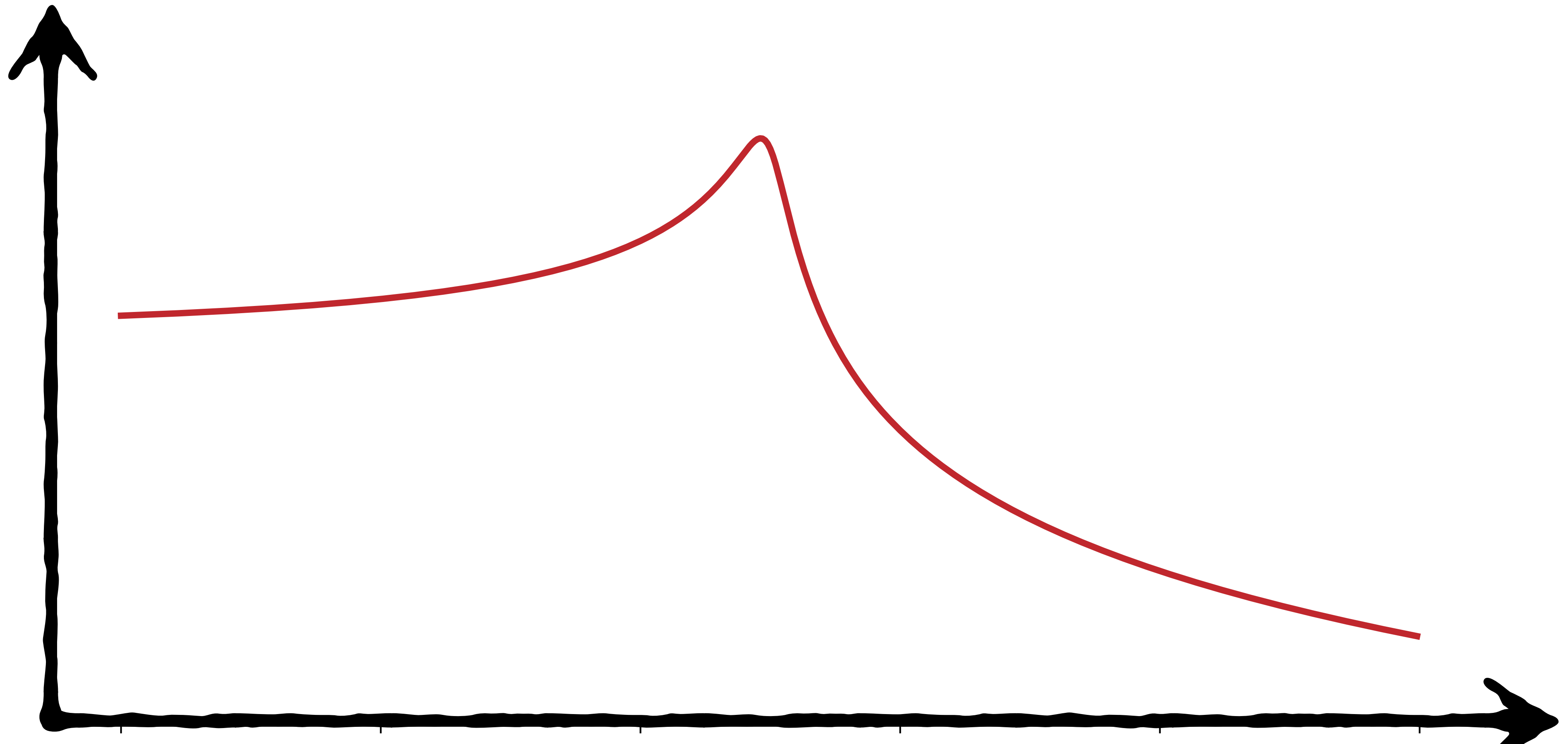
vs.

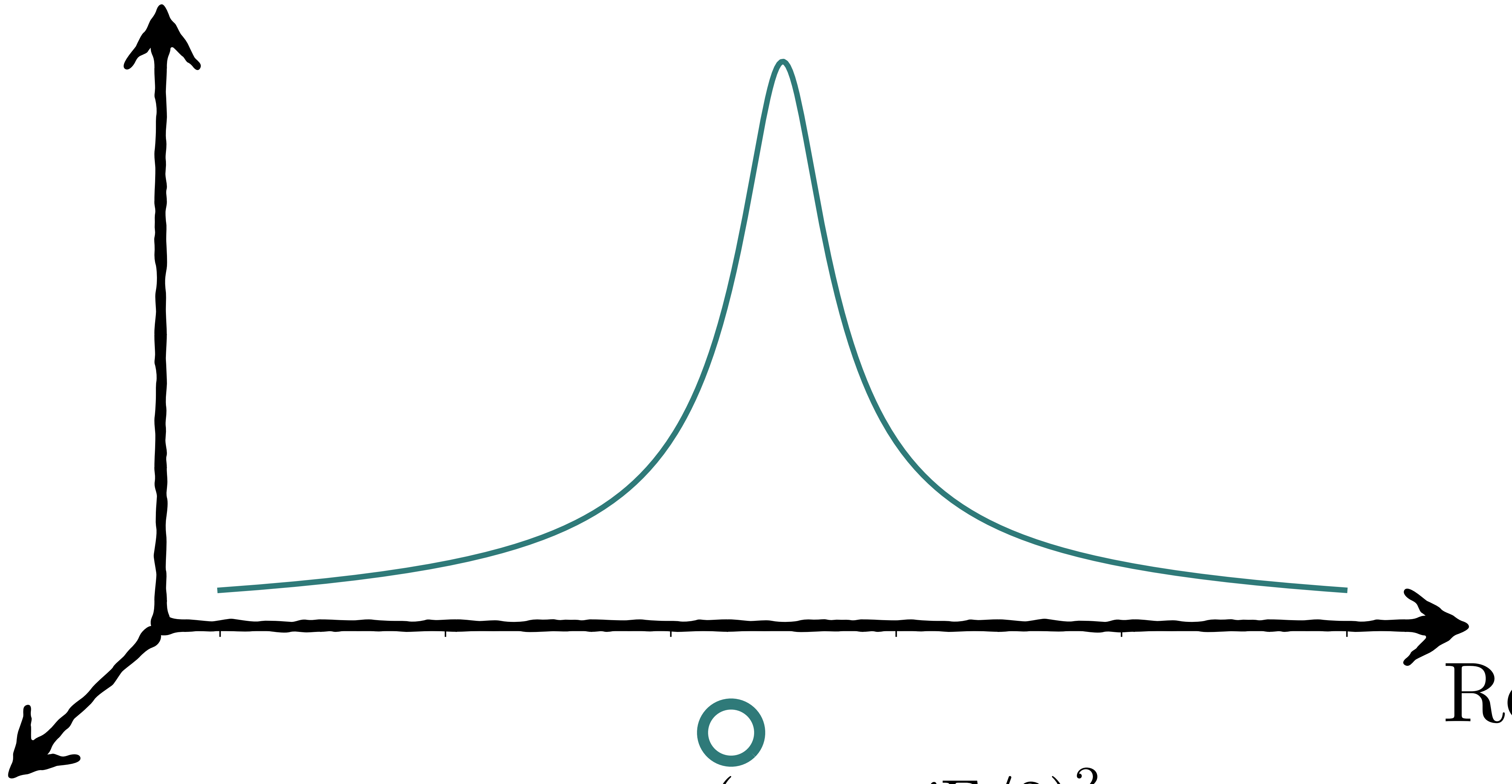


$$\sim \frac{1}{s - (m_R - \frac{i}{2}\Gamma)^2}$$

"just a poser"

"the real deal"





$s = E_{\text{cm}}^2$

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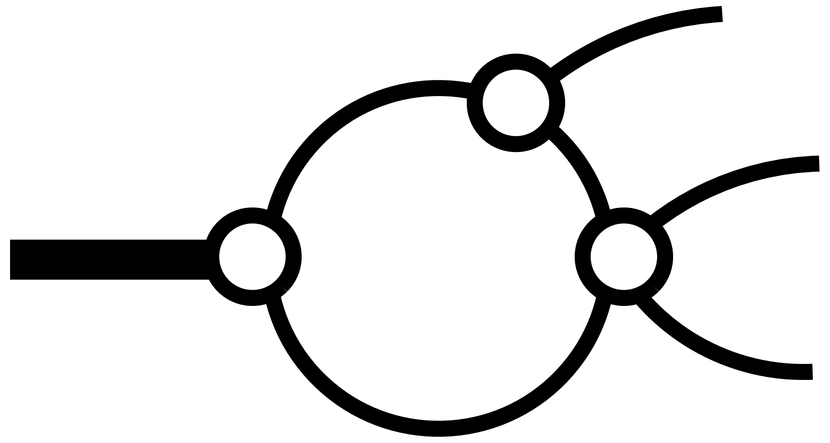
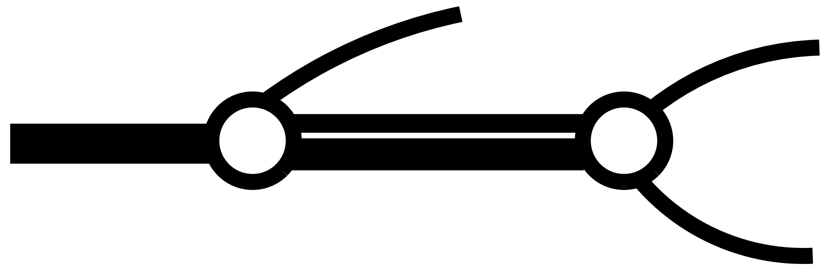


$\sim \log(s - s_t)$ vs.



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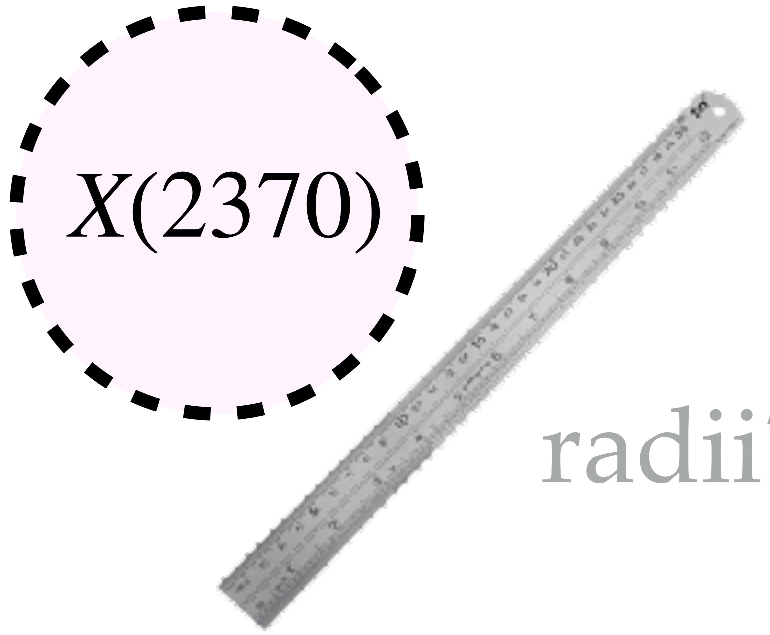
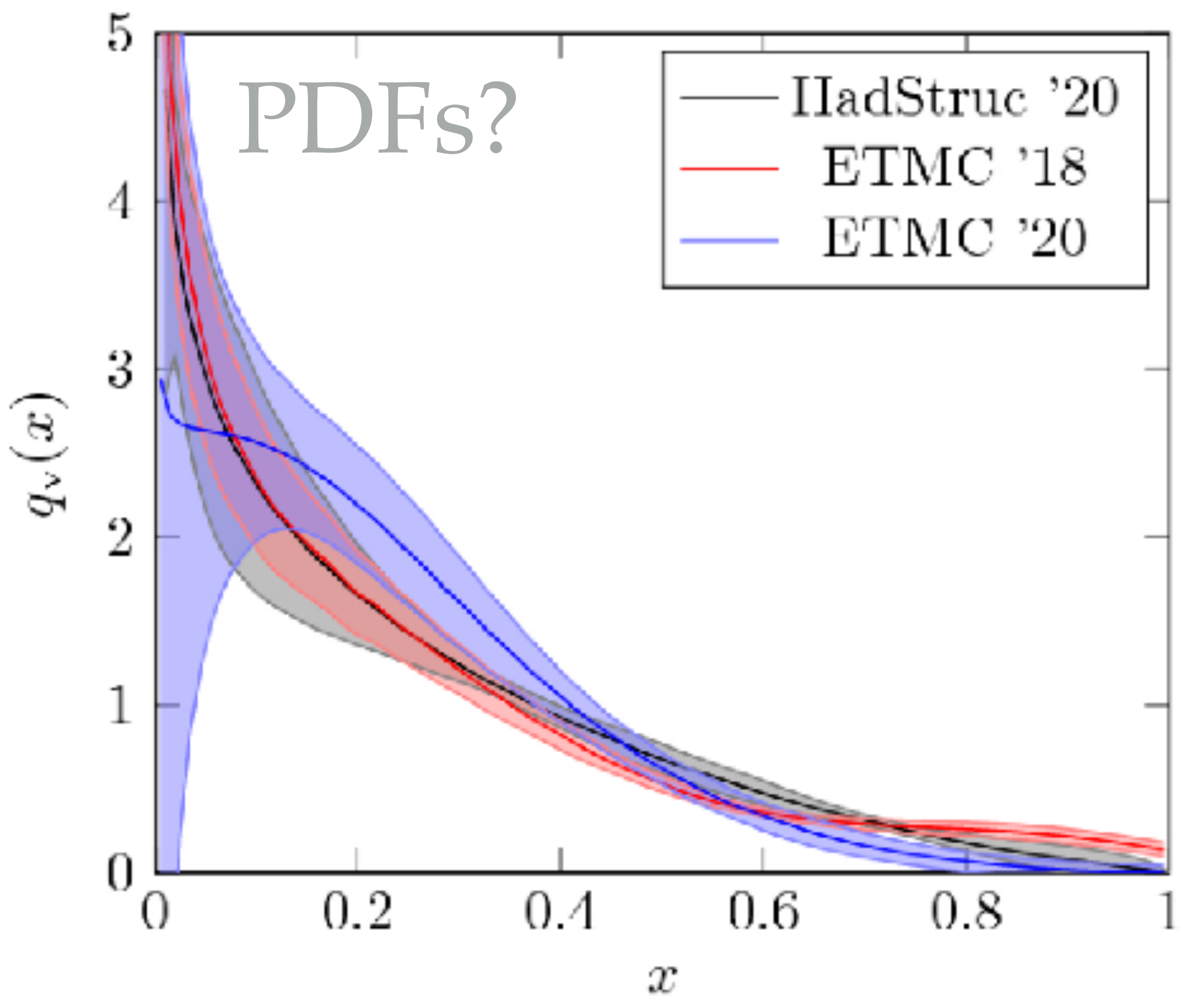
"just a poser" "the real deal"

- If a real resonance, what is its inner structure?



radii?



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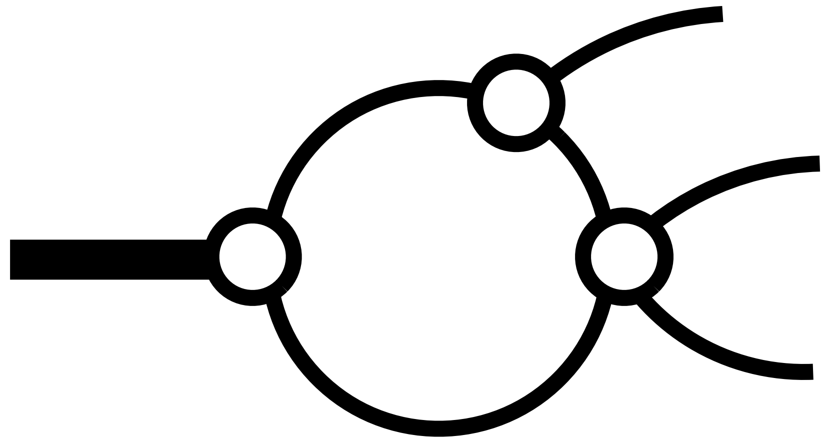
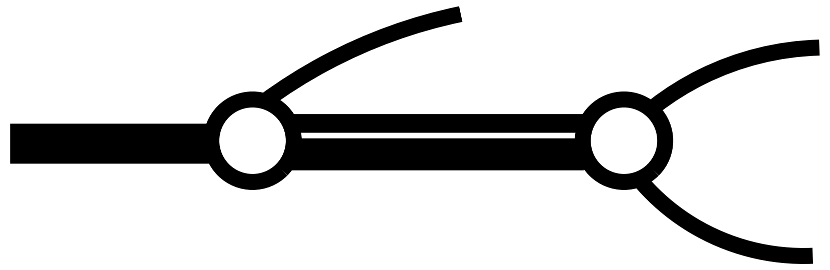


$\sim \log(s - s_t)$

“just a poser”

vs.



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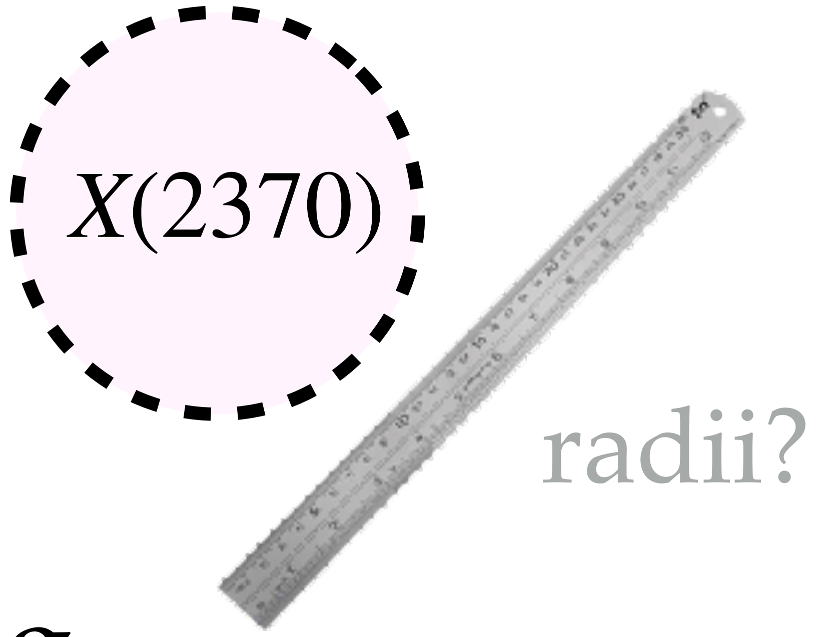
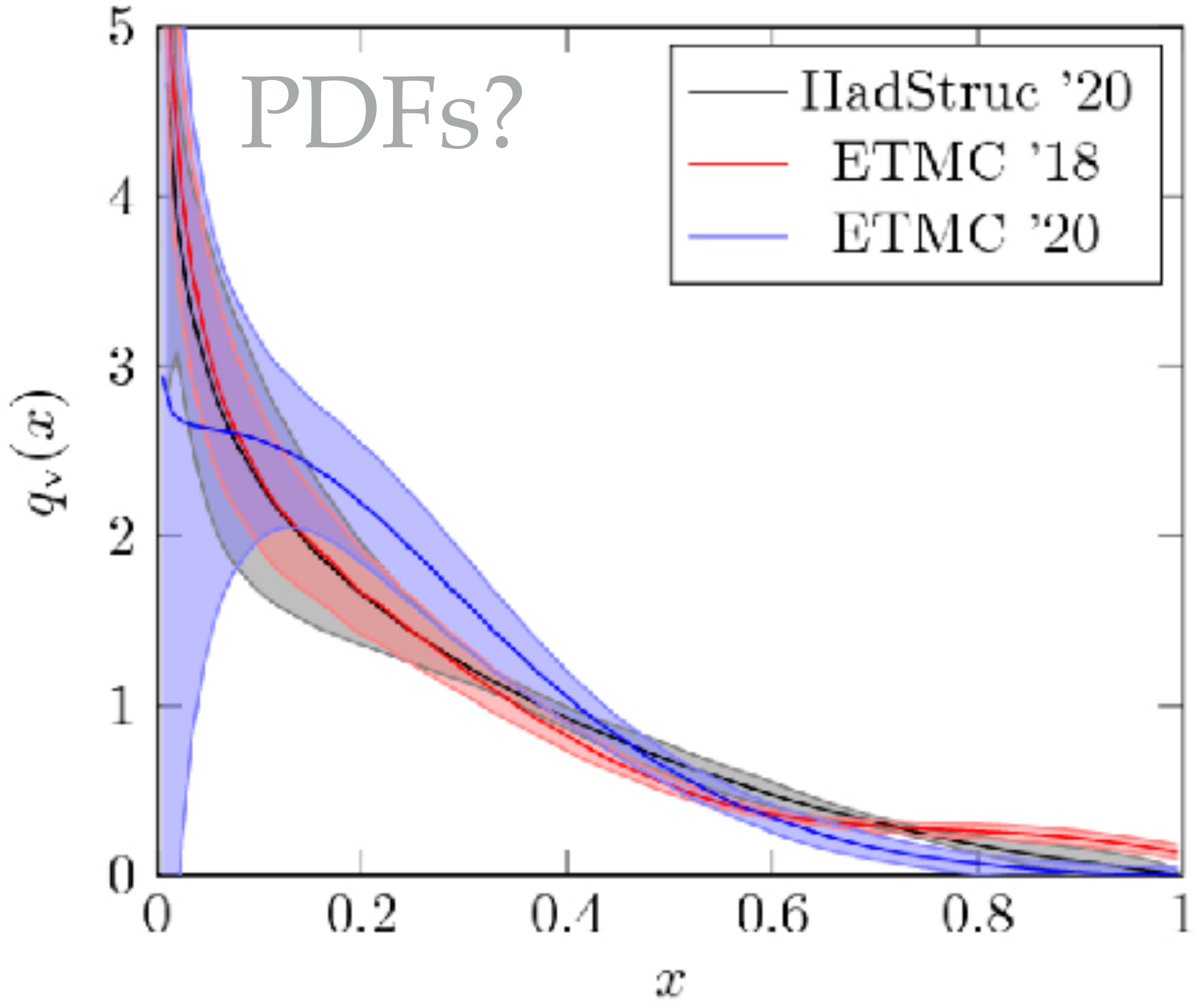
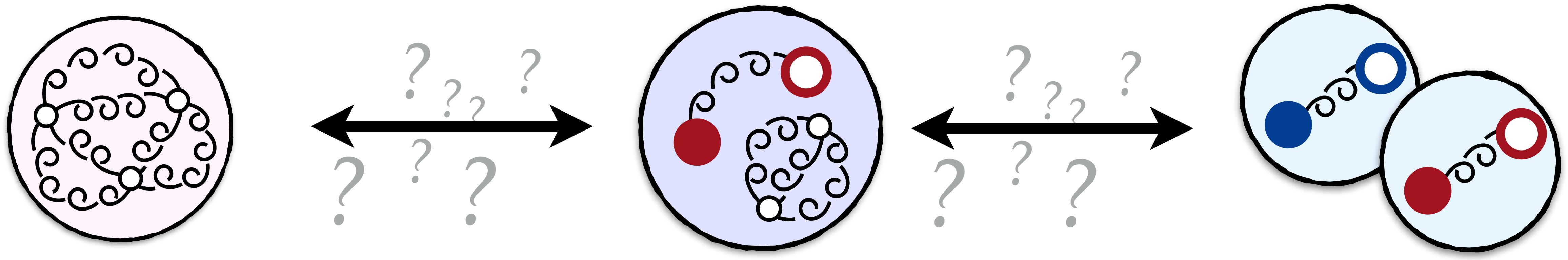




- Given structural information, can we say anything about the nature?



- Can we deduce general principles from the QCD spectrum?

Need for a Lattice QCD spectroscopy program

A Lattice QCD program running in parallel with experiments is critical.

- ☑ **Guide experimental searches**,
- ☑ **Confirm existence** [e.g. tetraquarks, pentaquarks],
- ☑ **Understand their nature** [*observations are not enough*!].

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- ☐ **resonances** or multi-body **bound states**,
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Challenges to overcome:

- ☐ scattering amplitudes are direct inaccessible via lattice QCD,
- ☐ formalism needed to access amplitudes,
- ☐ increasingly complicated correlators to evaluate,
- ☐ increasingly complicated amplitude analysis, }
- ☐ **warm bodies**,
- ☐ …

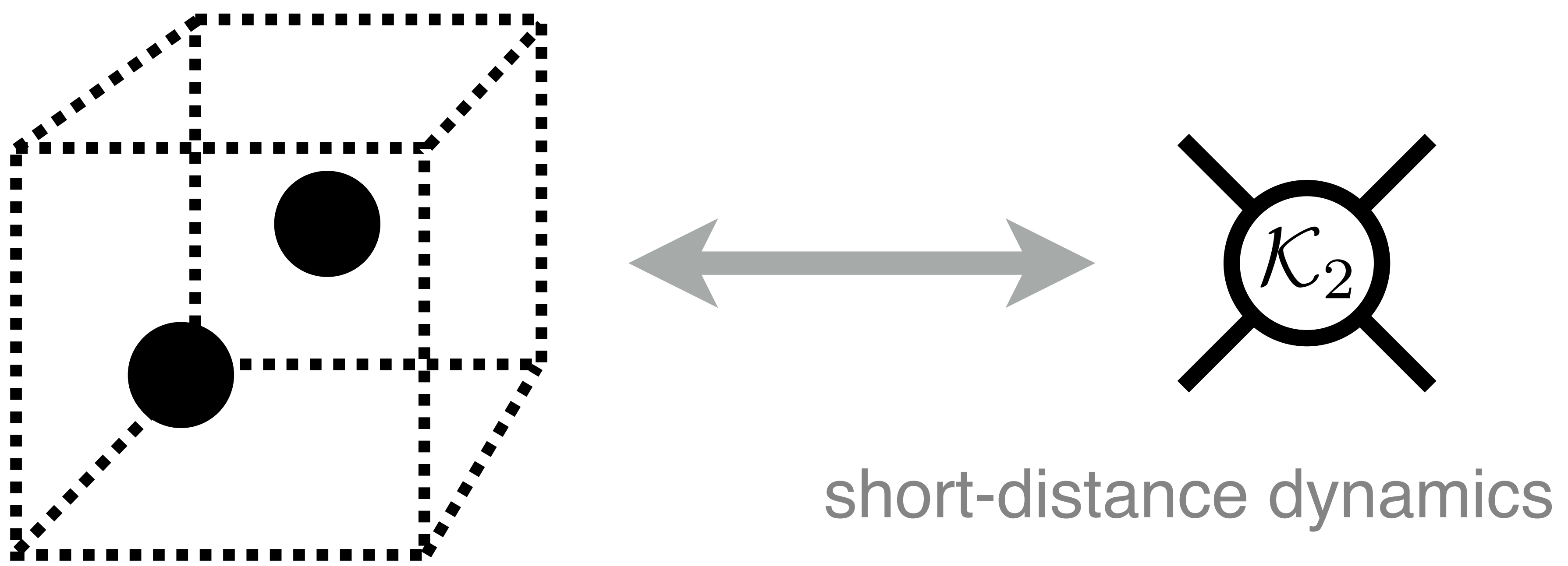
EXOHAD

EXOTIC HADRONS TOPICAL COLLABORATION

cross-pollination with experimental searches

LQCD is finally up to the challenge!

Tremendous formal progress:



$$\det\left[F^{-1}(P,L)+\mathcal{K}_2\right]=0$$

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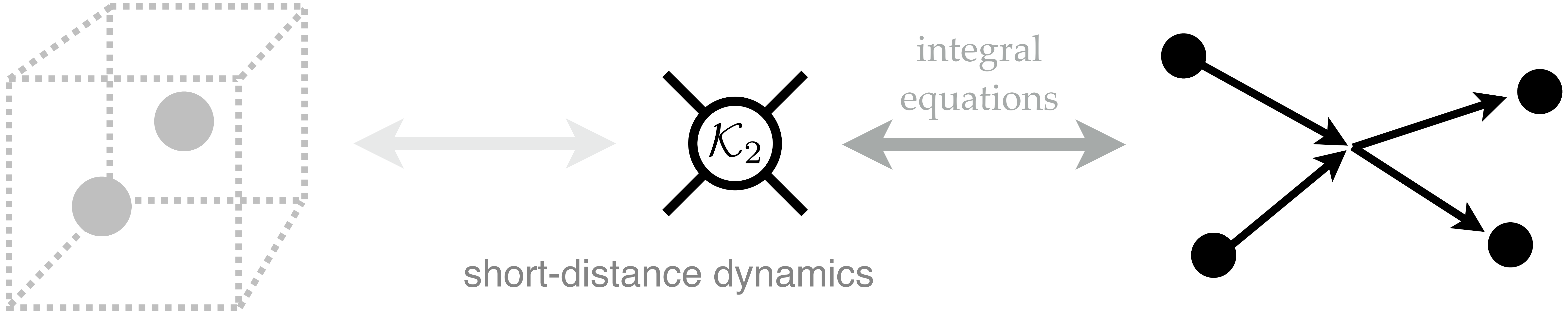

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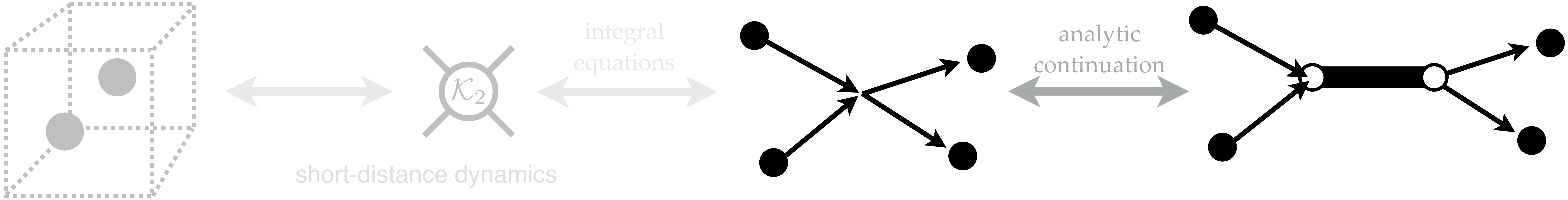

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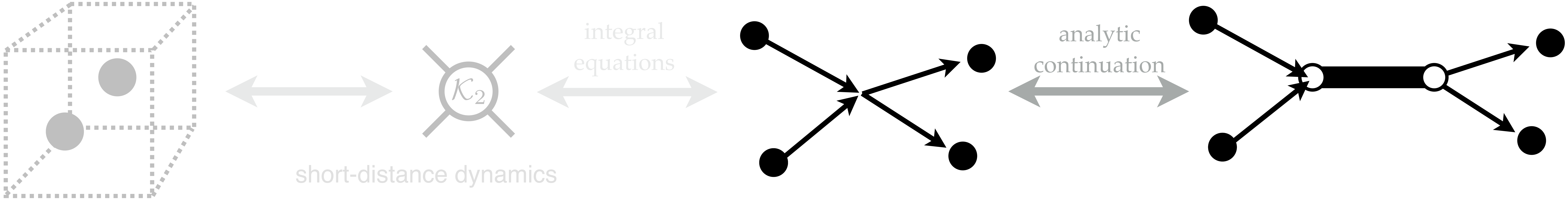

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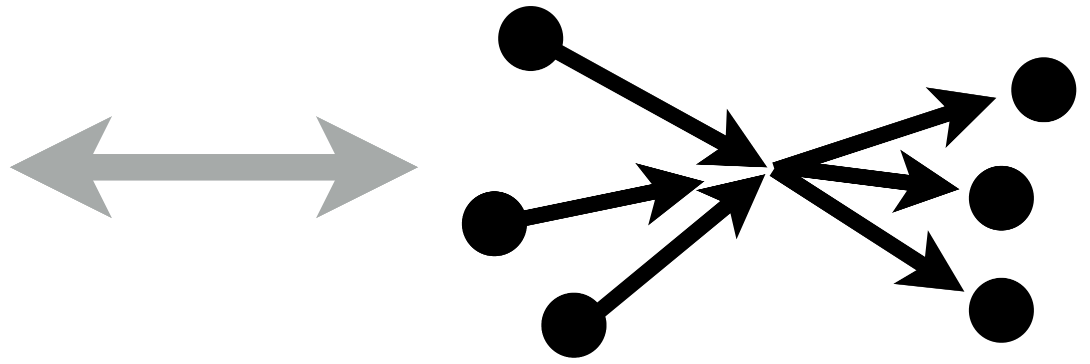
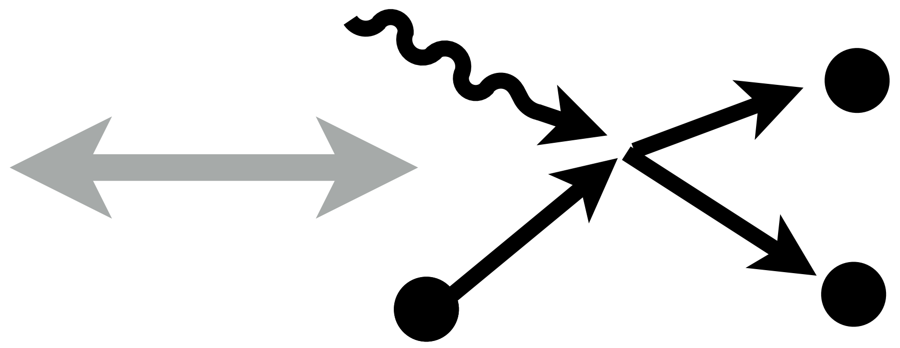
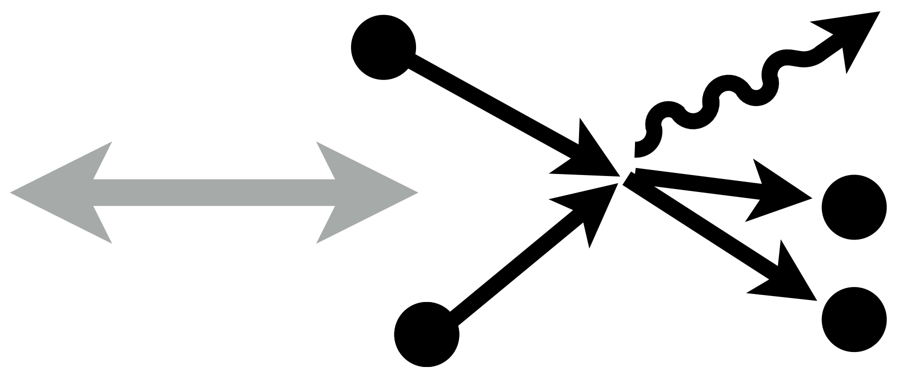
E_L 

Purely hadronic reactions

$\langle 1|\mathcal{J}|2\rangle_L$ 

Electroweak transitions

$\langle 2|\mathcal{J}|2\rangle_L$ 

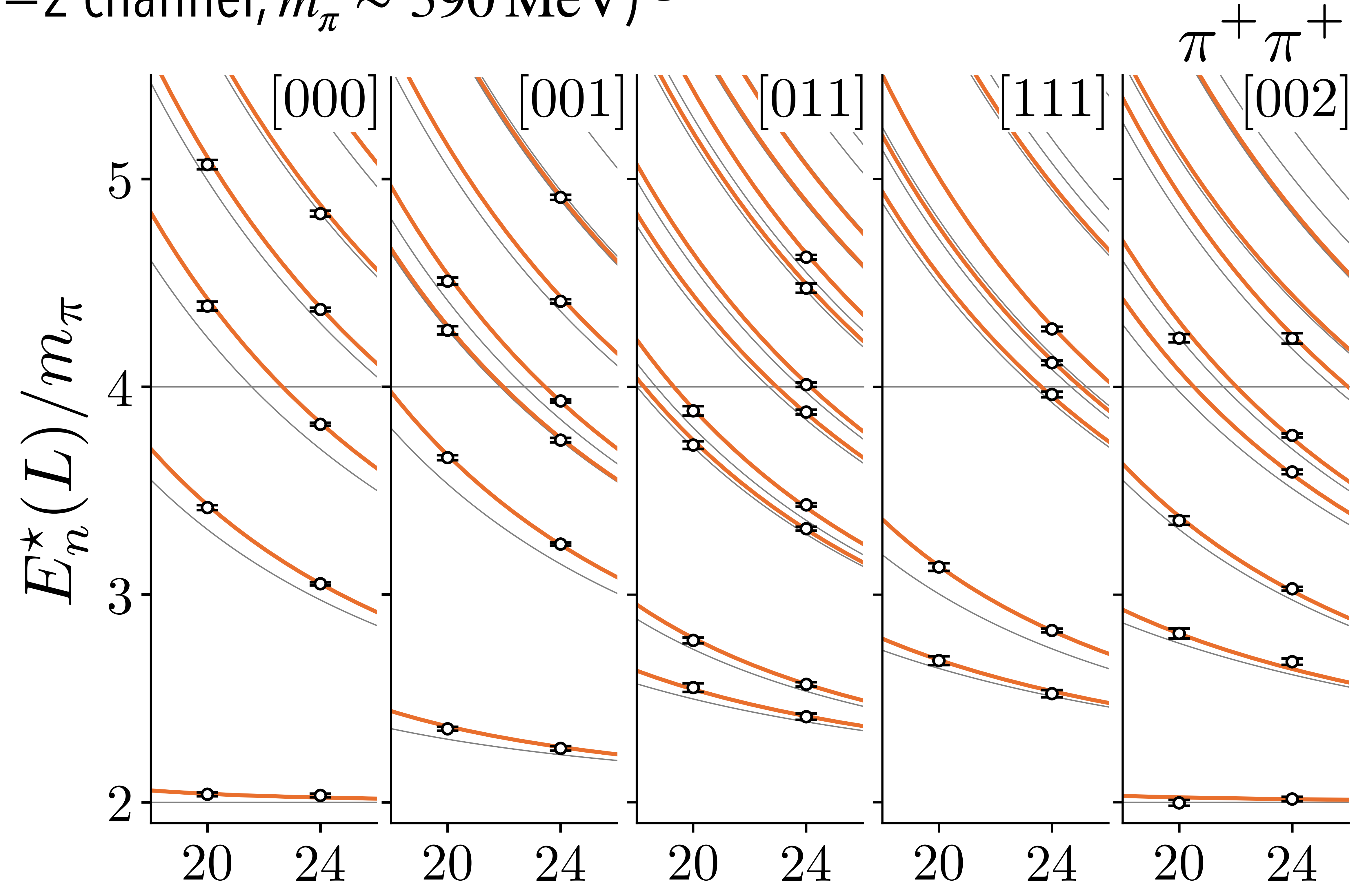
Structural information

LQCD is finally up to the challenge!

- ☑ Generalized eigenvalue problem (GEVP),
  - ☐ large basis: $\mathcal{O}_b \sim \bar{q}\,\Gamma_b\, q, \pi\pi\pi, \pi K\overline{K}, \ldots,$
  - ☐ contractions: $C^{2pt.}_{ab}(t, \mathrm{P}) \equiv \langle 0 | \mathcal{O}_b(t, \mathrm{P}) \mathcal{O}^{\dagger}_a(0,\mathrm{P}) | 0 \rangle = \sum_n Z_{b,n} Z^{*}_{a,n} e^{-E_n t}$
  - ☐ "diagonalization"
- ☐ It is now common to have $\mathcal{O}(100)$ kinematic points

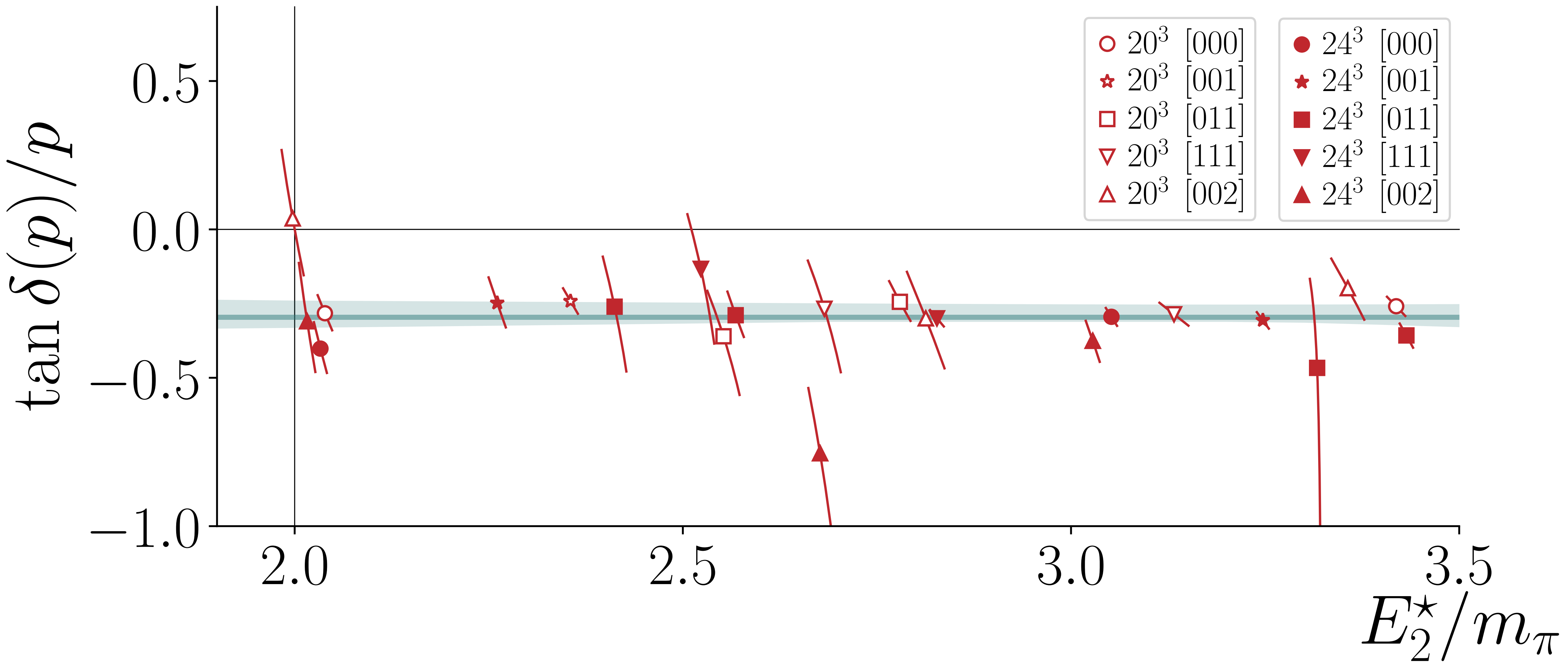
$\pi\pi$ scattering

(I=2 channel, $m_\pi \sim 390\,\mathrm{MeV}$)



$$\det[F^{-1}(P,L) + \mathcal{M}(P)] = 0$$

$$\mathcal{M} \sim \frac{1}{p\cot\delta - ip}$$



Hansen, RB, Edwards, Thomas, & Wilson (2020)

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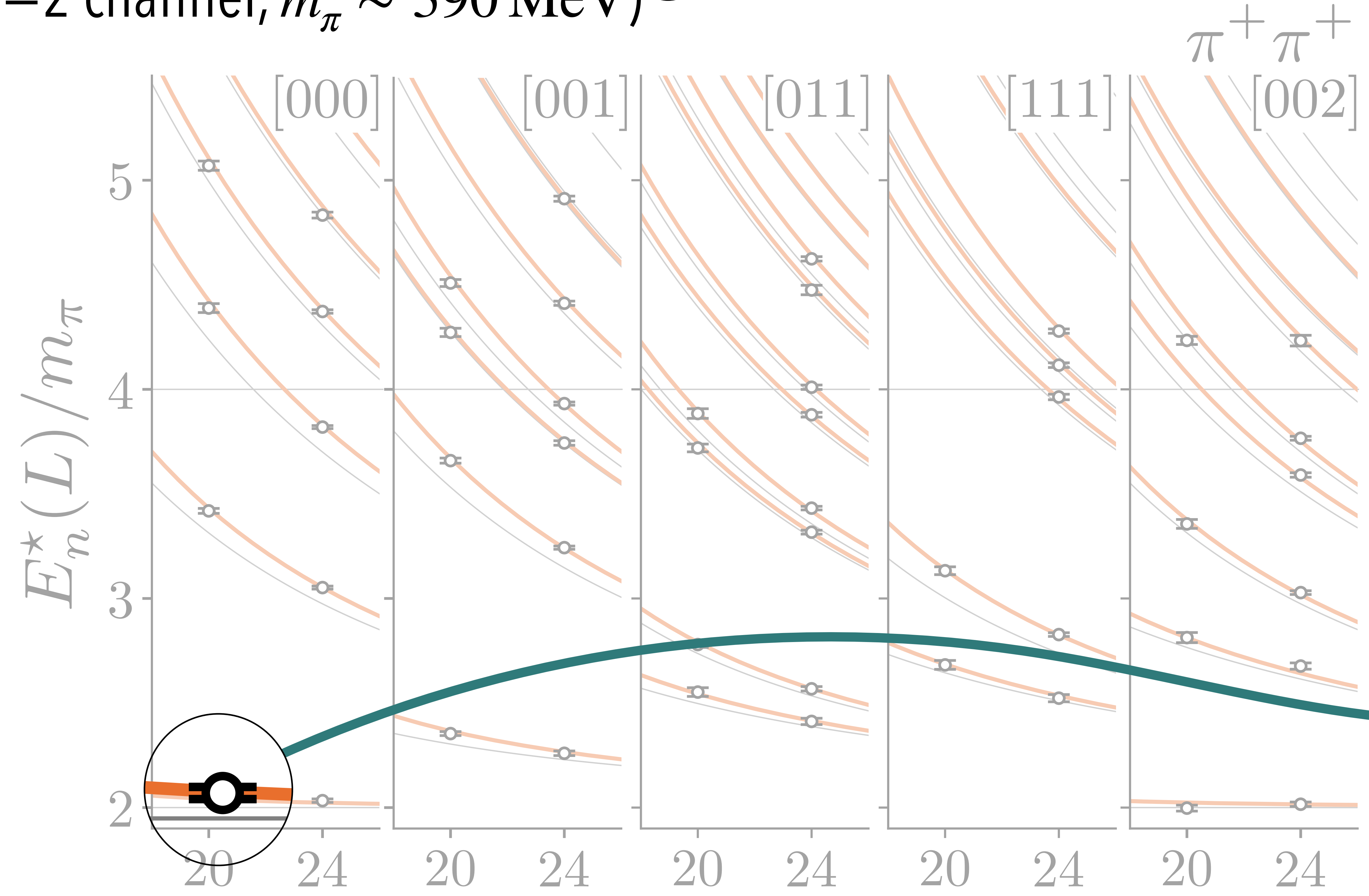

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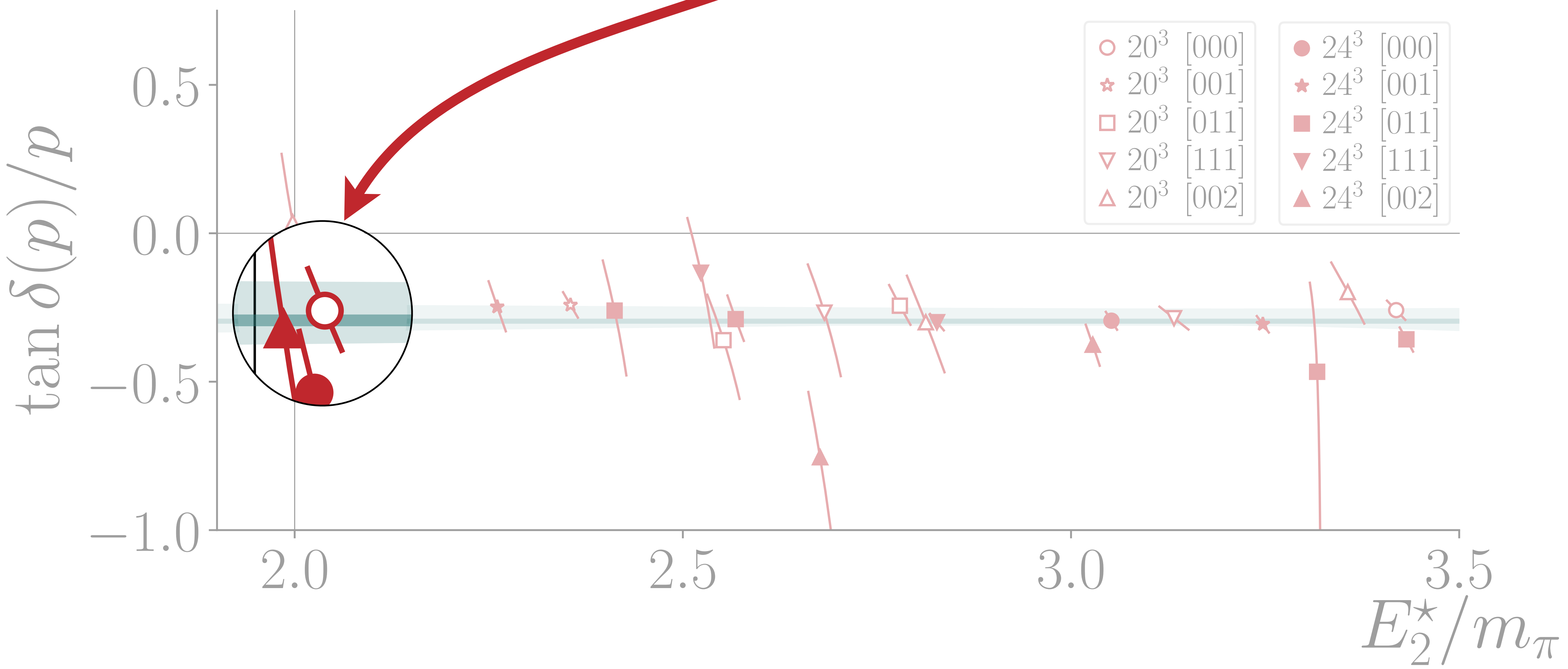
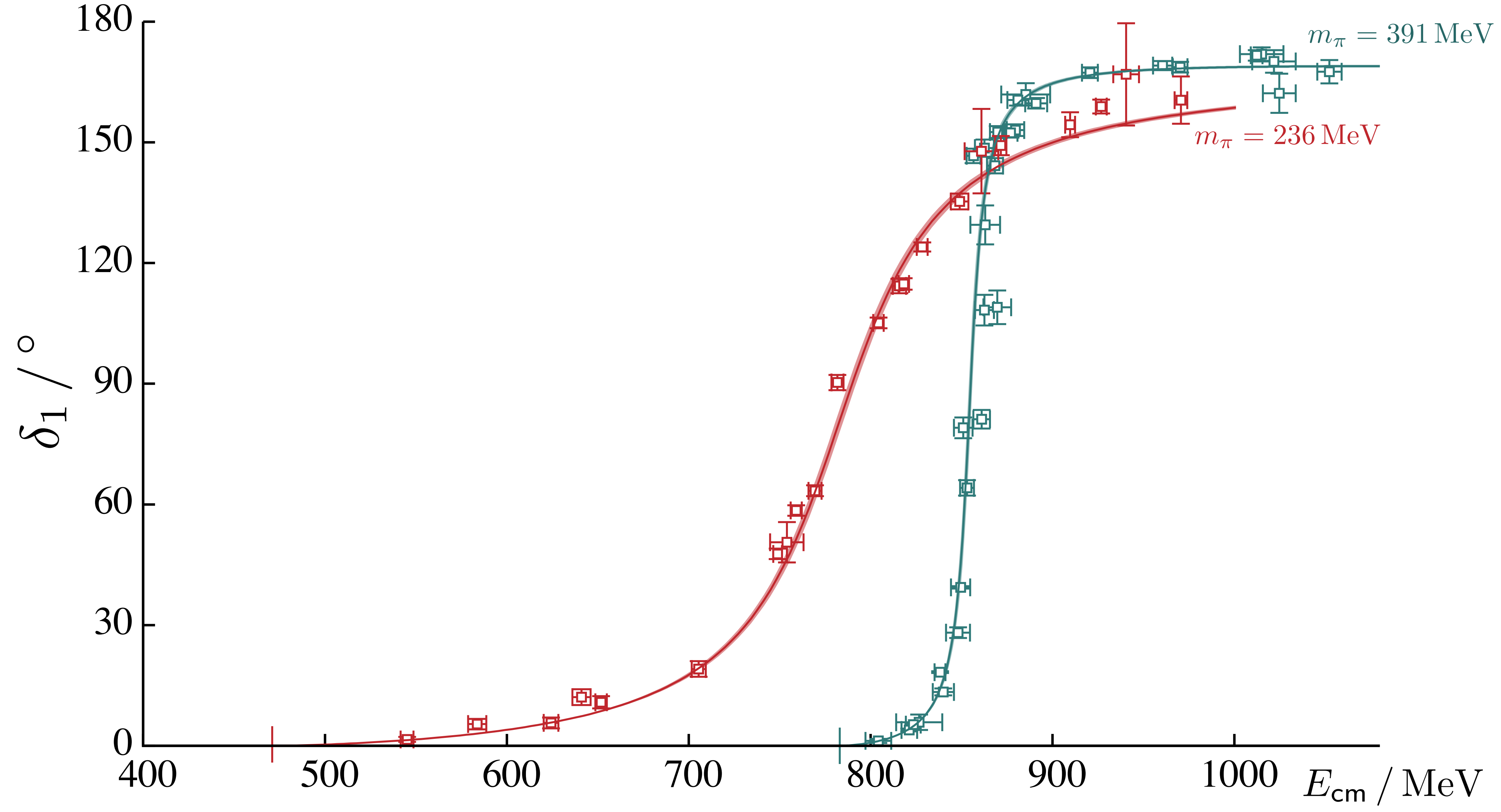


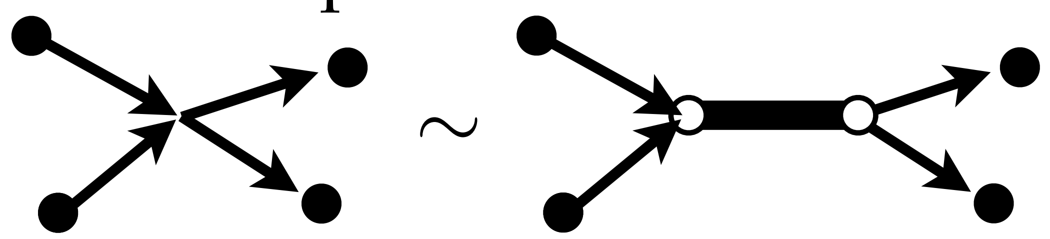
Hansen, RB, Edwards, Thomas, & Wilson (2020)

$\pi\pi$ scattering
(I=1 channel)



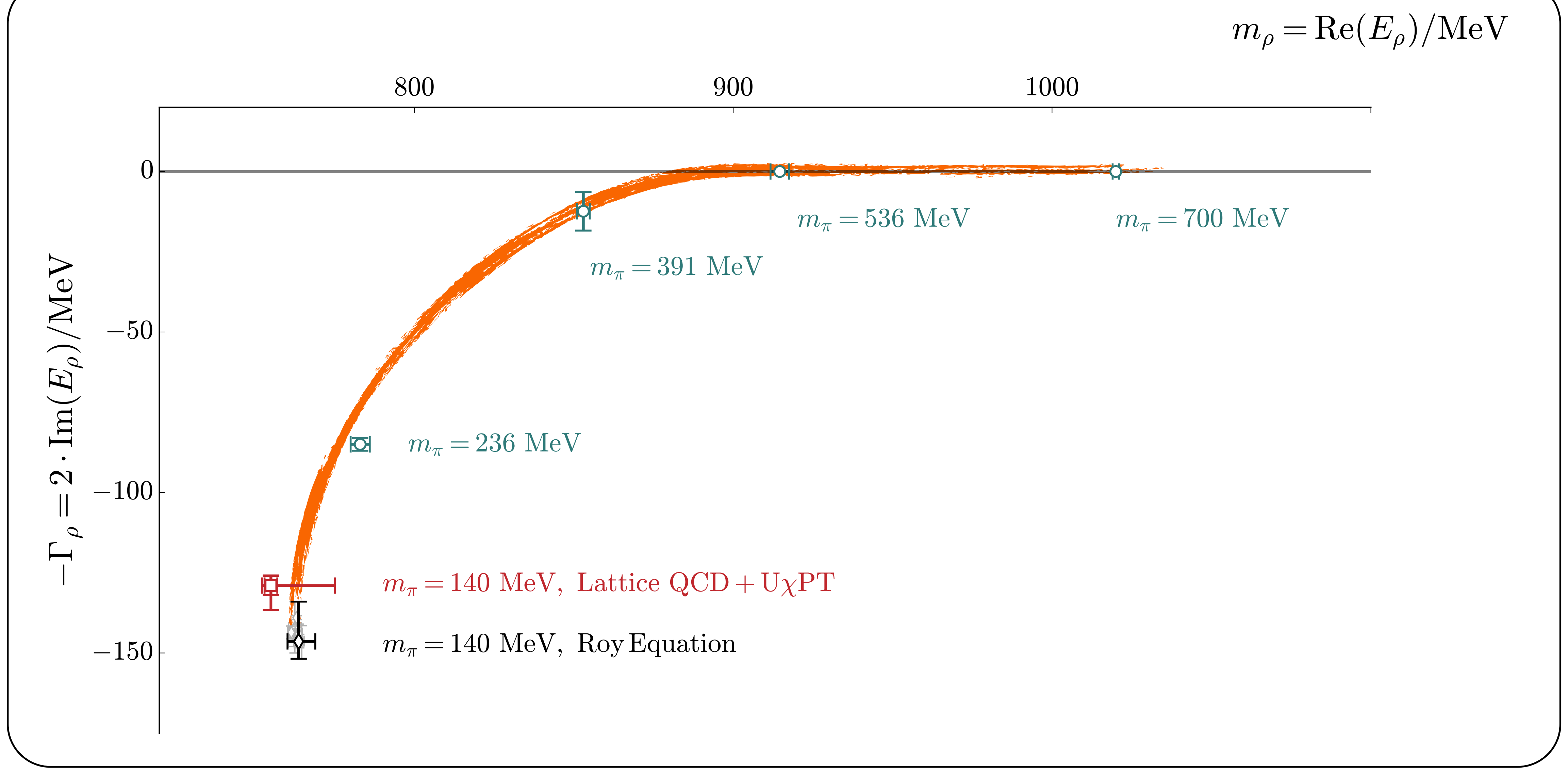
$$\mathcal{M} \sim \frac{1}{p \cot \delta - ip}$$

resonance pole



$$\sim \frac{1}{s - s_0}$$

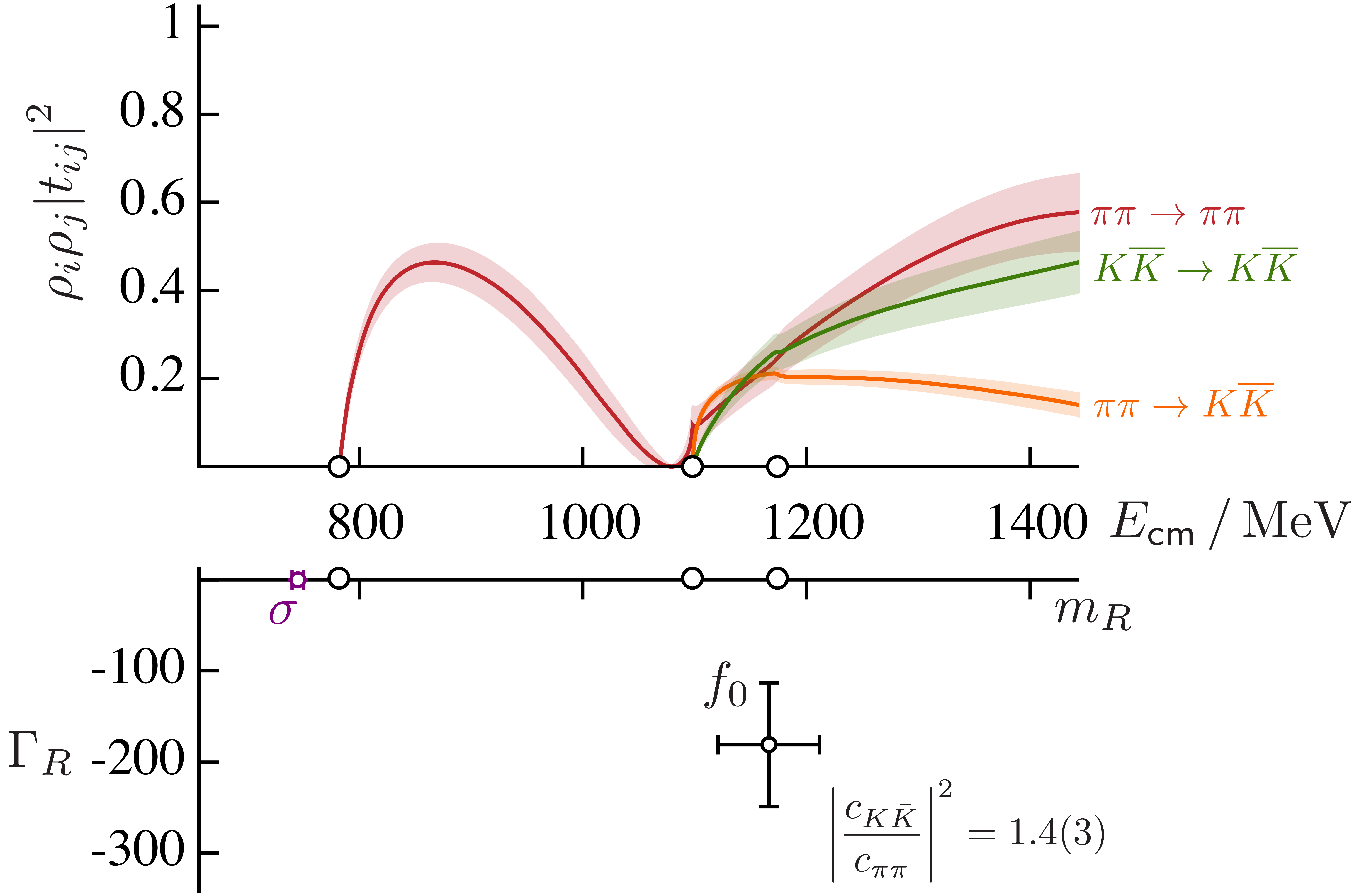
$$s_0 = (m_R - i\Gamma_R/2)^2$$



Dudek, Edwards, & Thomas (2012)

Wilson, RB, Dudek, Edwards, & Thomas (2015)

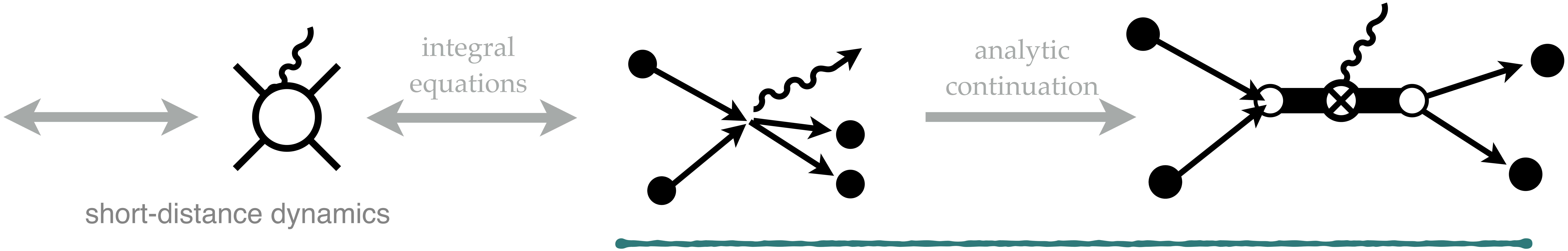
Coupled $\pi\pi$, $K\overline{K}$ and the f_0's



Structure of multi-particles states

An idea to wet your palette

$$\langle 2|\mathcal{J}^{\mu}|2\rangle_L$$



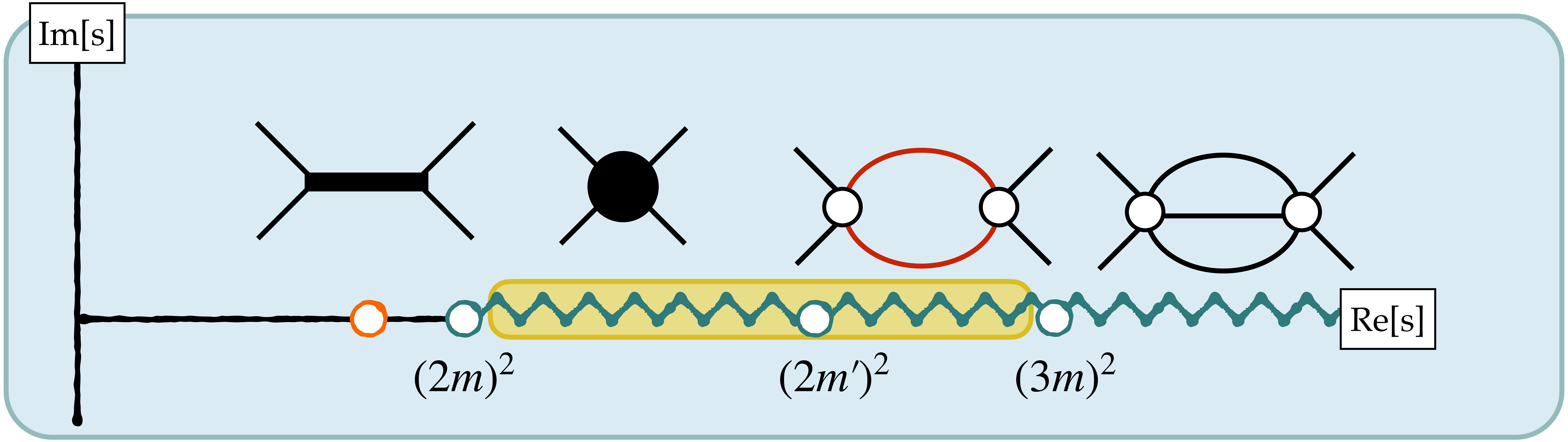
let us focus on this

RB, Jackura, Ortega-Gama, Sherman (2021)

$2 + \mathcal{J}^\mu \to 2$

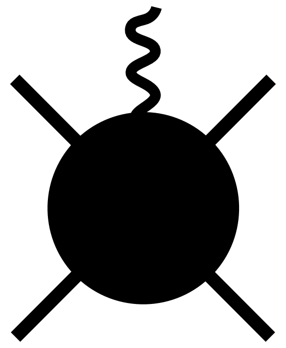
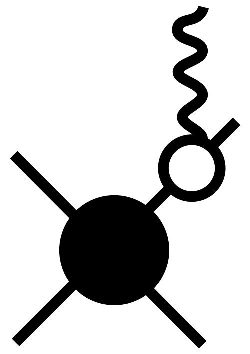
Goal: *isolated ALL kinematic singularities of amplitudes in a kinematic region.*

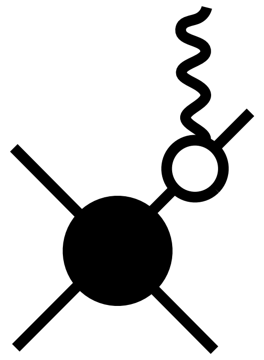
Observation: *kinematic singularities are due to intermediate particles goin on-shell.*

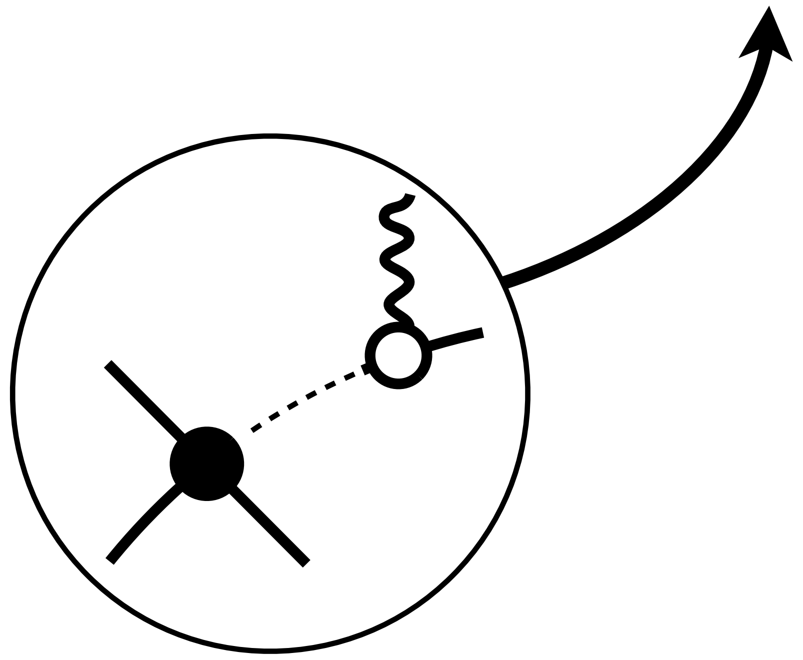


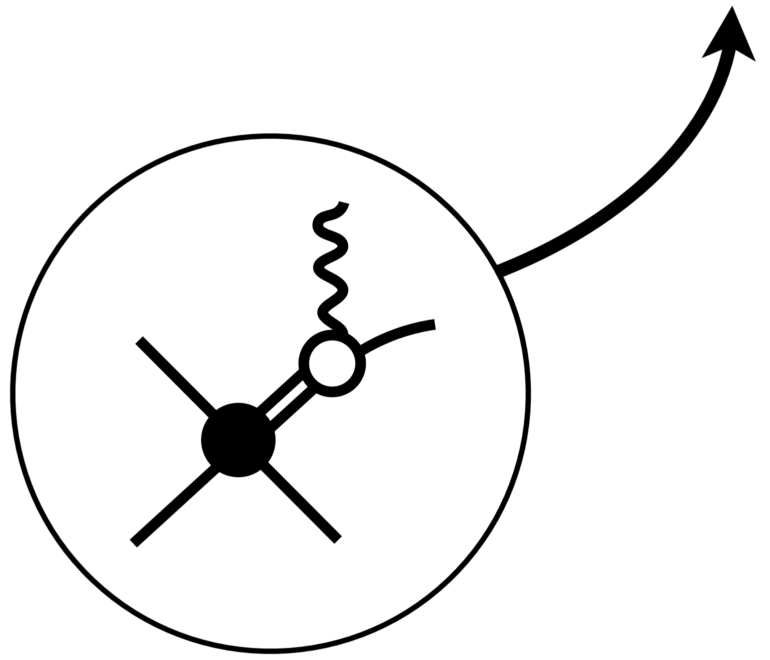
$2 + \mathscr{J}^\mu \to 2$

Let's isolate all possible singularities of…

$i\mathcal{W}^\mu =$  $=$  $+ \cdots$

 $= i\mathcal{M} \dfrac{i}{k^2 - m^2 + i\epsilon} i\omega^\mu + \text{“smooth”}$





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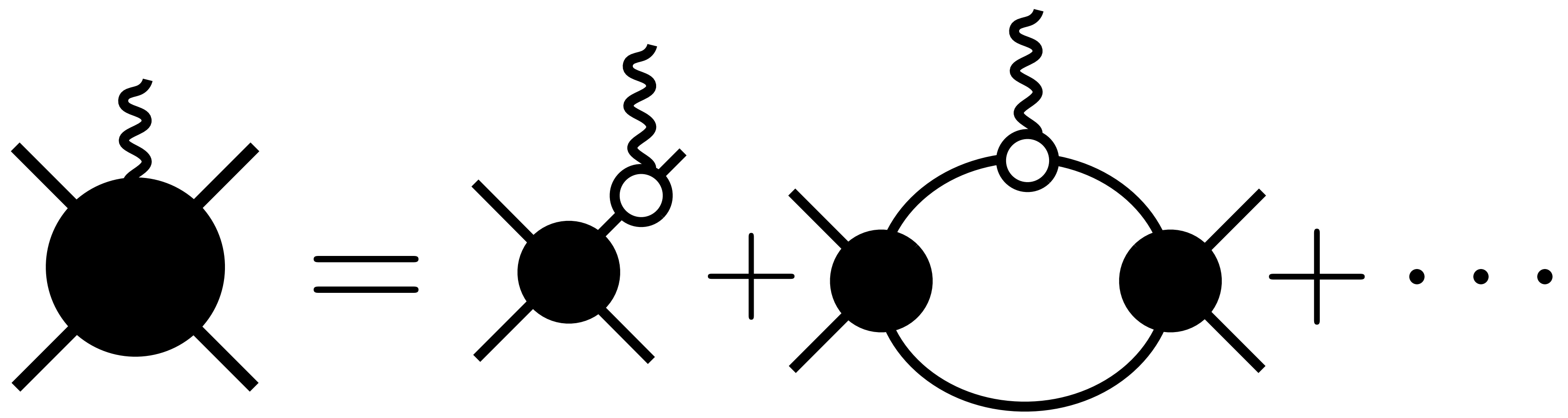
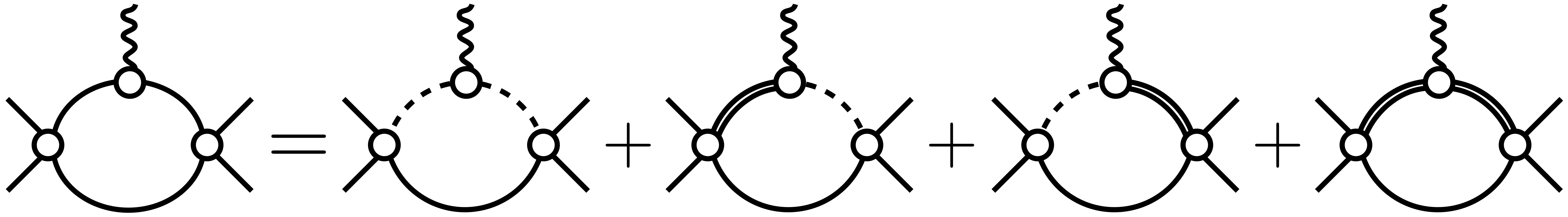
$i\mathcal{W}^\mu =$ 



Lorentz decomposition of off-shell $1 + \mathscr{J} \to 1$ amplitude:

$$\omega^\mu(k_f, k_i) = \sum_j K_j^\mu(k_f, k_i)\, f_j(Q^2, k_f^2, k_i^2)$$

Off-shell form factor

$$f_j(Q^2, k_f^2, k_i^2) = f_j(Q^2) \quad \text{[on-shell]}$$
$$+[f_j(Q^2, k_f^2, k_i^2) - f_j(Q^2, k_f^2, m^2)] \quad \text{[left-cut]}$$
$$+[f_j(Q^2, k_f^2, k_i^2) - f_j(Q^2, m^2, k_i^2)] \quad \text{[right-cut]}$$
$$+[f_j(Q^2, k_f^2, m^2) + f_j(Q^2, m^2, k_i^2) - f_j(Q^2, k_f^2, k_i^2) - f_j(Q^2, m^2, m^2)] \quad \text{[smooth]}$$

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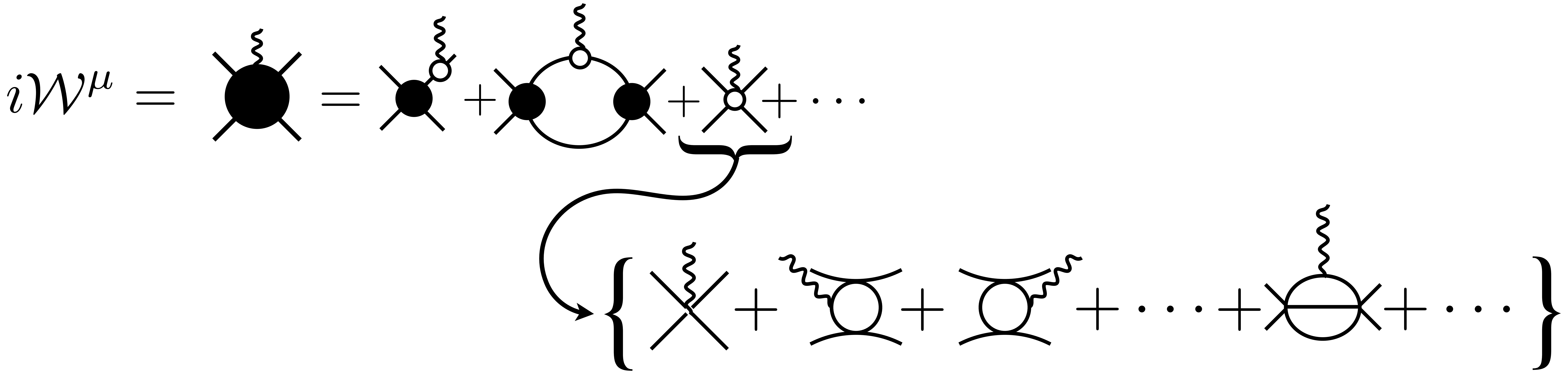

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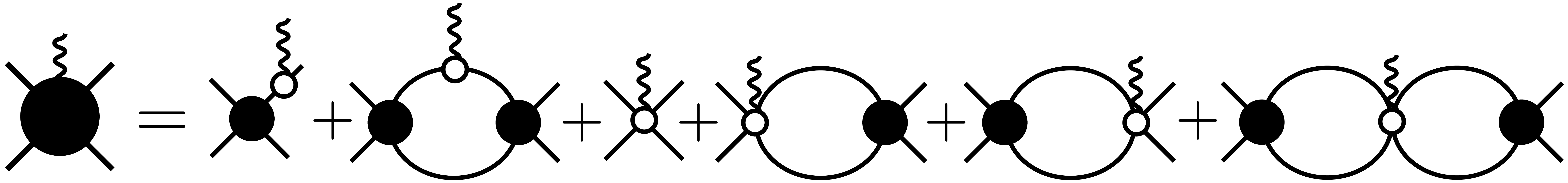
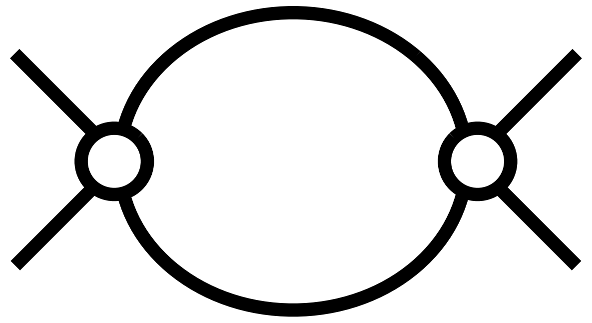
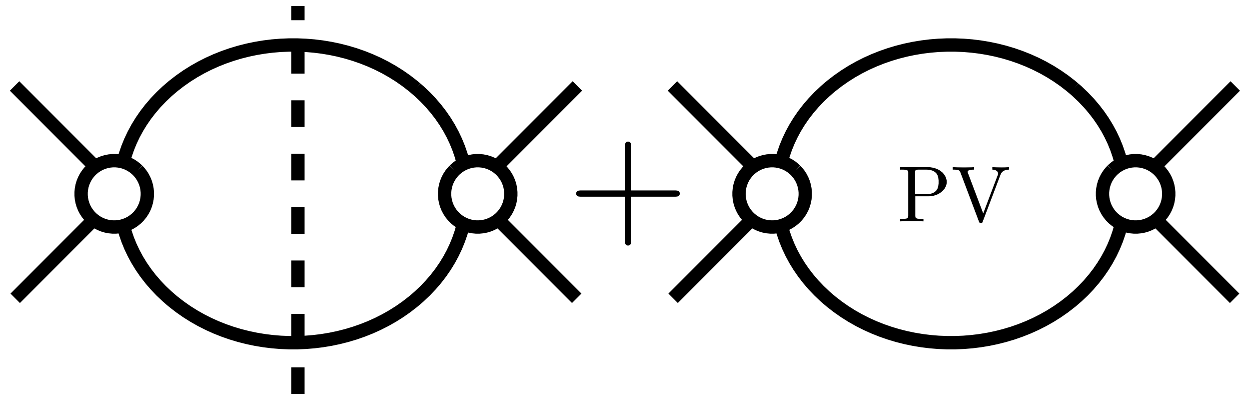
$i\mathcal{W}^\mu =$ 



$$= \int \frac{d^4k}{(2\pi)^4} [iB(k,P)]^2 \frac{i}{k^2 - m^2 + i\epsilon} \frac{i}{(P-k)^2 - m^2 + i\epsilon}$$

$$= \int \frac{d^3k}{(2\pi)^3} \frac{[iB(k,P)]^2}{(2\omega_k)^2} \pi\delta(E - 2\omega_k) + \text{“PV integral”}$$

$$= [iB_{on}]\rho\,[iB_{on}] + \text{“PV integral”}$$

$=$ 

$$\rho \equiv \frac{p}{8\pi E} \sim \sqrt{s - s_{th}}$$

square root singularity.

$2 + \mathscr{J}^\mu \to 2$

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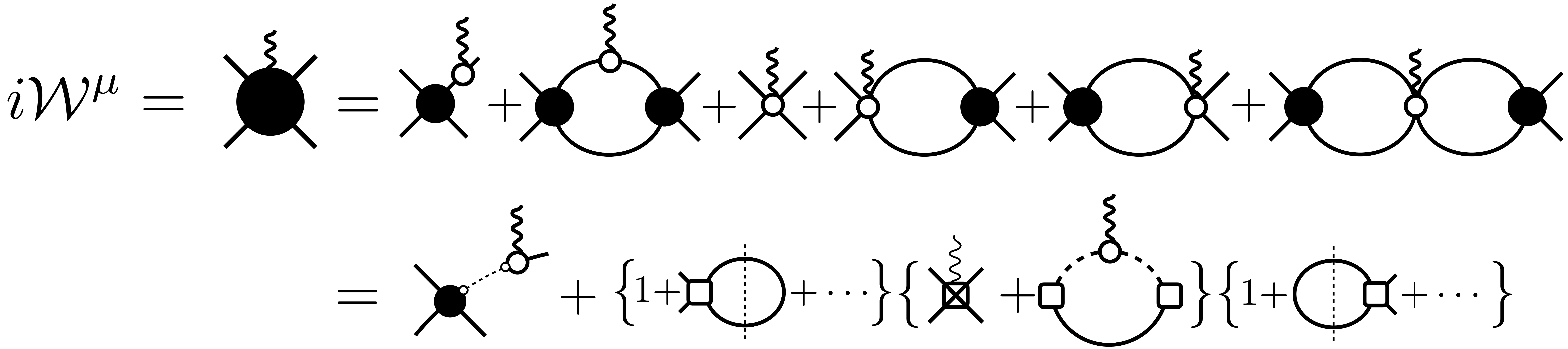

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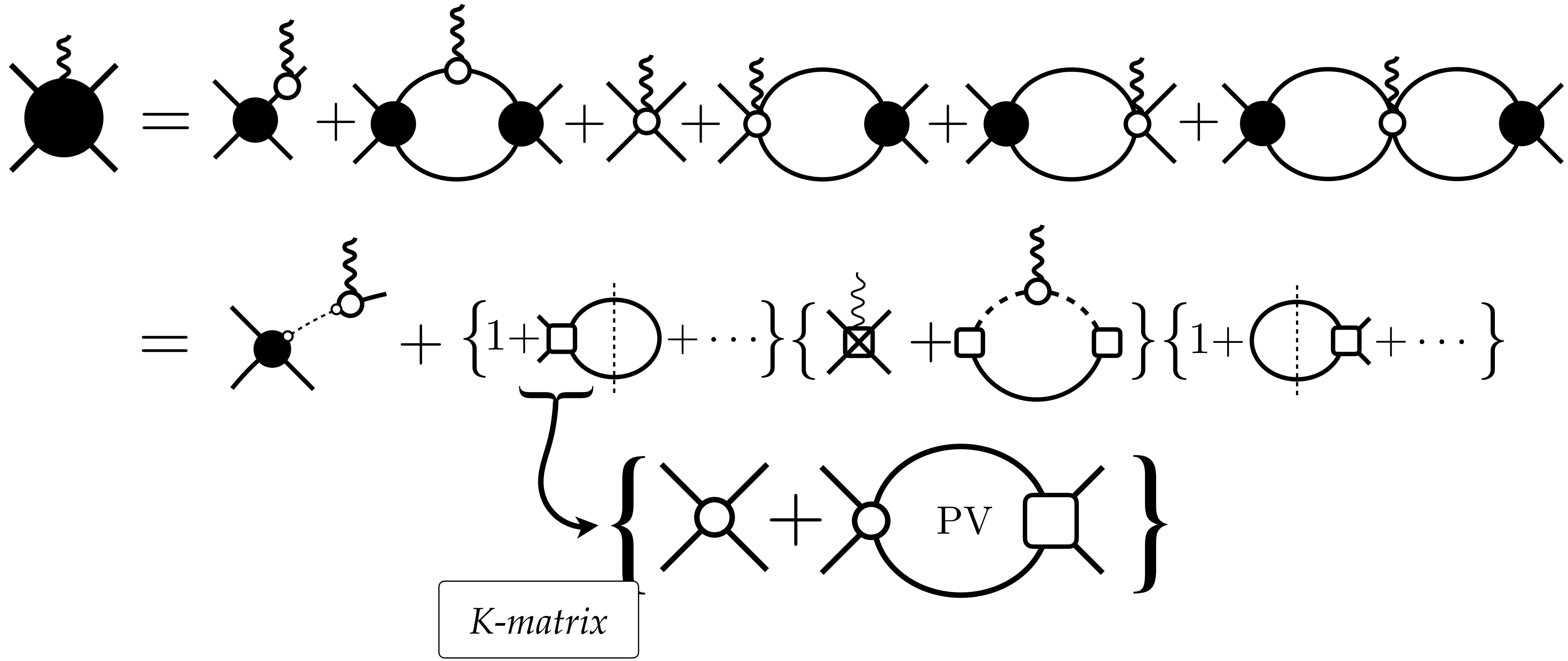
$i\mathcal{W}^\mu =$ 

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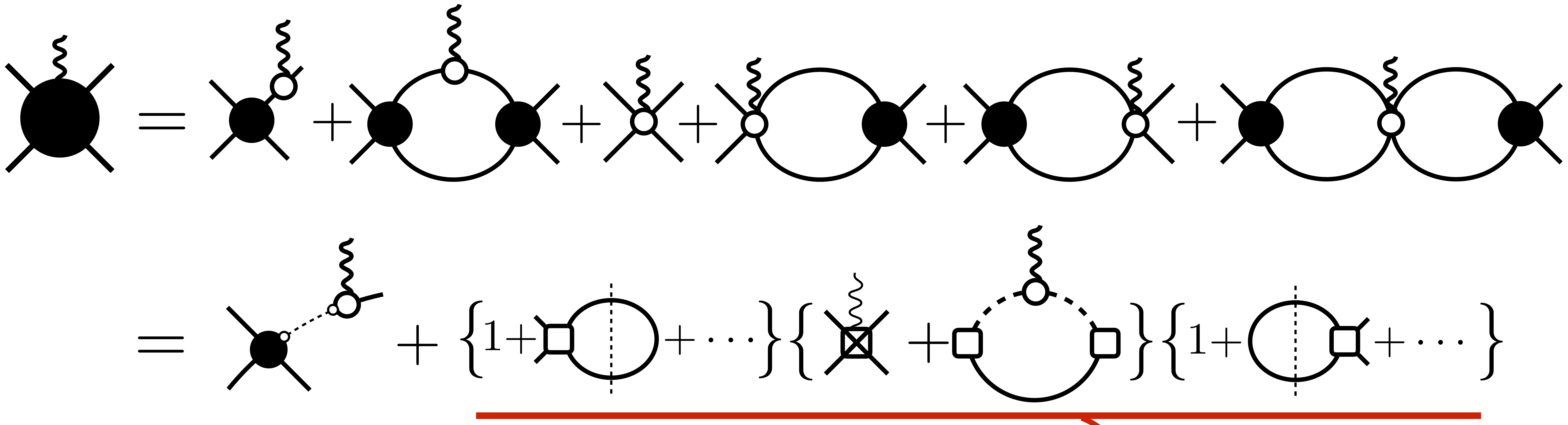
Let's isolate all possible singularities of…

$$i\mathcal{W}^\mu =$$

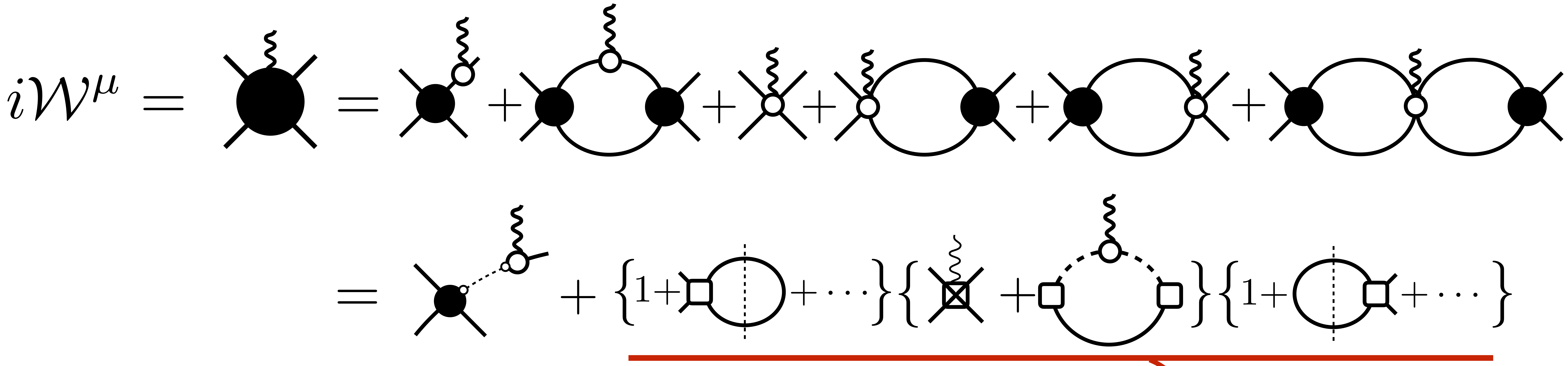


$$i\mathcal{W}^\mu_{\text{df}} = \mathcal{M} \cdot \left(i\mathcal{A}^\mu + i \sum_j f_j(Q^2)\mathcal{G}^\mu_j \right) \cdot \mathcal{M}$$

unknown real function, to be determined via lattice QCD

$2 + \mathcal{J}^\mu \to 2$

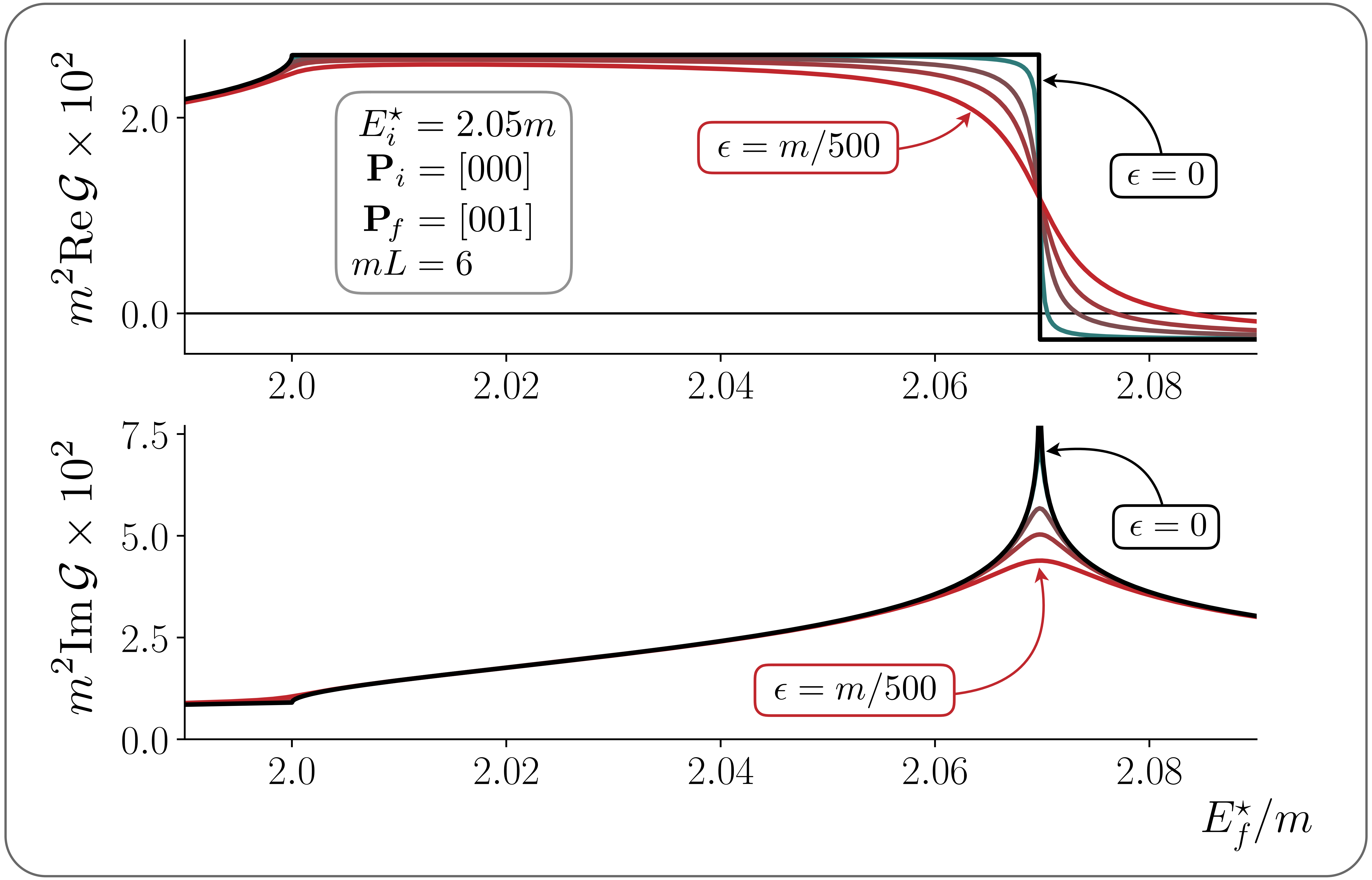
Let's isolate all possible singularities of…



$$i\mathcal{W}^\mu_{\text{df}} = \mathcal{M} \cdot \left(i\mathcal{A}^\mu + i \sum_j f_j(Q^2) \mathcal{G}^\mu_j \right) \cdot \mathcal{M}$$

$$\mathcal{G}^\mu_j = \int \frac{d^4k}{(2\pi)^4} \frac{\mathcal{Y}_f \; iK^\mu_j \; \mathcal{Y}_i}{(k^2 - m^2)\,((P_f - k)^2 - m^2)\,((P_i - k)^2 - m^2)}$$

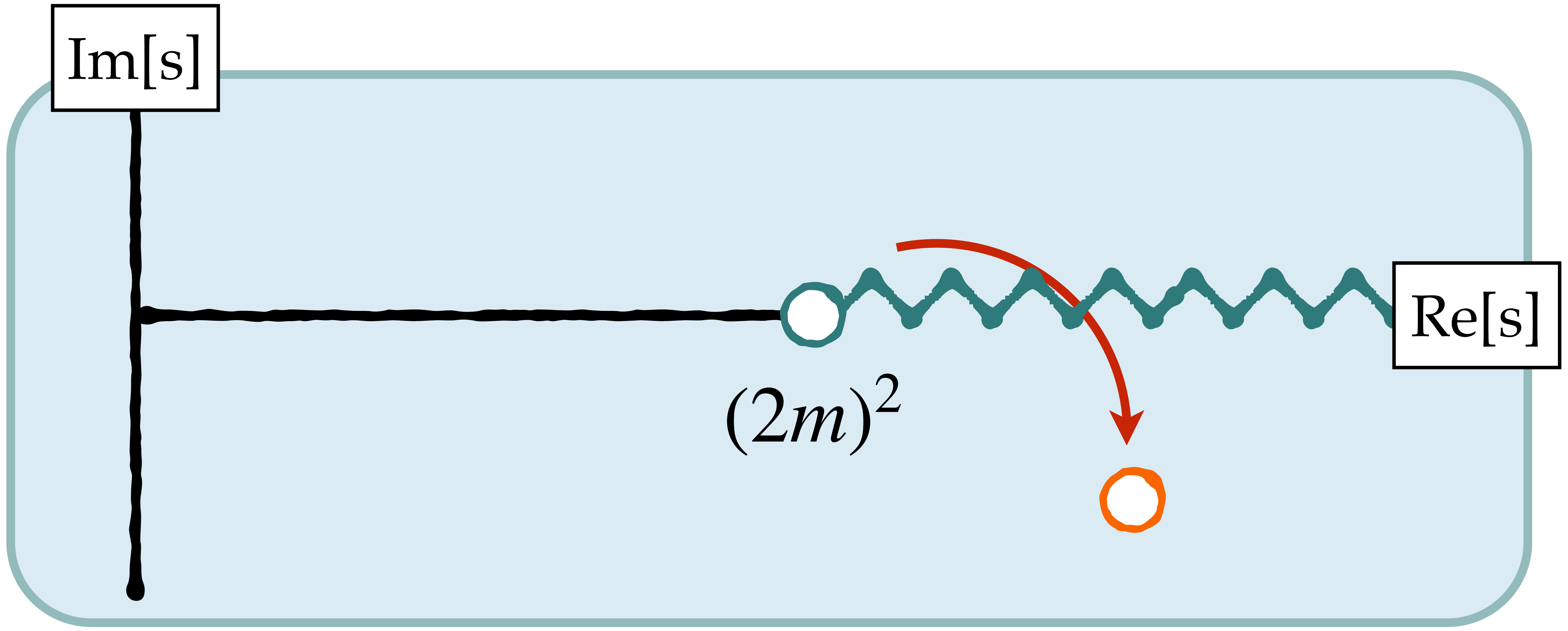
$2 + \mathcal{J}^\mu \to 2$



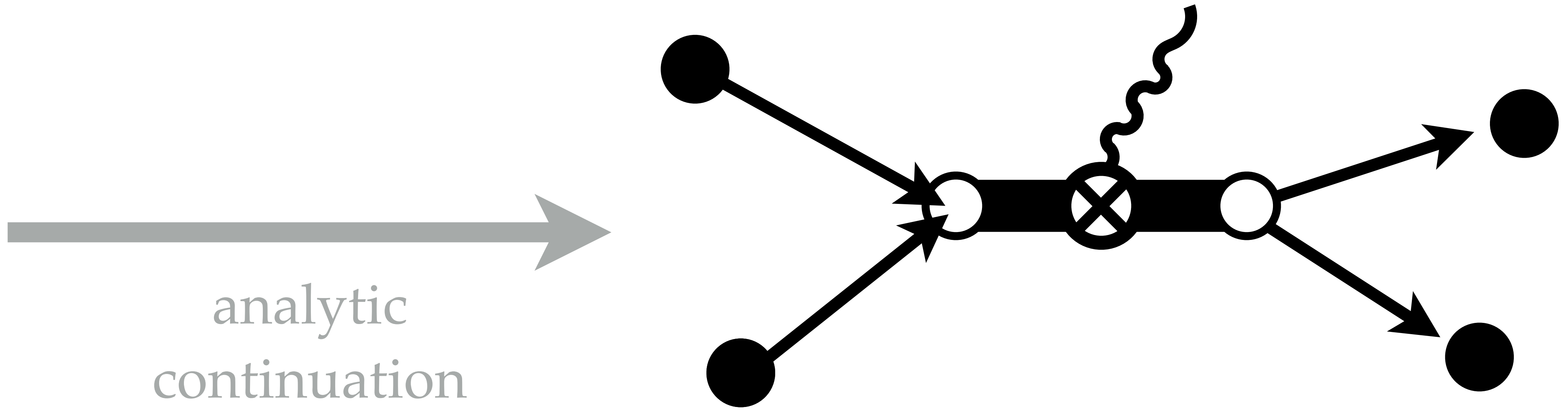
$$\mathcal{G}_j^\mu = \int \frac{d^4k}{(2\pi)^4} \frac{\mathcal{Y}_f \; iK_j^\mu \; \mathcal{Y}_i}{(k^2 - m^2)\,((P_f - k)^2 - m^2)\,((P_i - k)^2 - m^2)}$$

$$R + \mathcal{J}^\mu \to R$$

Analytic continuation towards resonance pole



$$i\mathcal{W}^\mu_{\rm df} = \mathcal{M} \cdot \left(i\mathcal{A}^\mu + i \sum_j f_j(Q^2)\mathcal{G}^\mu_j \right) \cdot \mathcal{M}$$

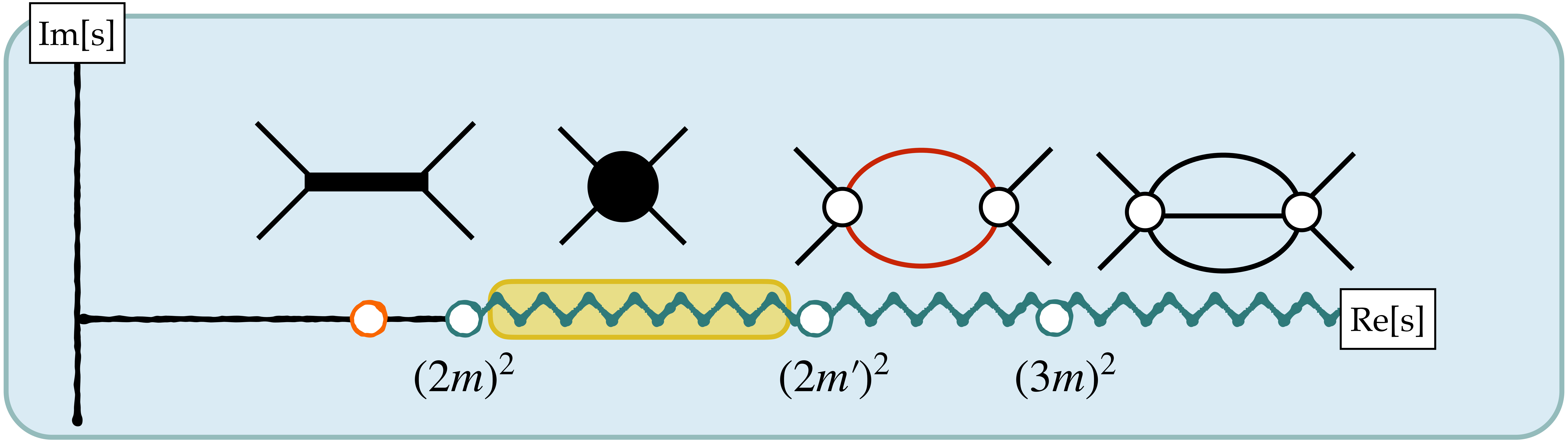


$$= g \frac{1}{s_f - s_R} iK^\mu F_R(Q^2) \frac{1}{s_i - s_R} g$$

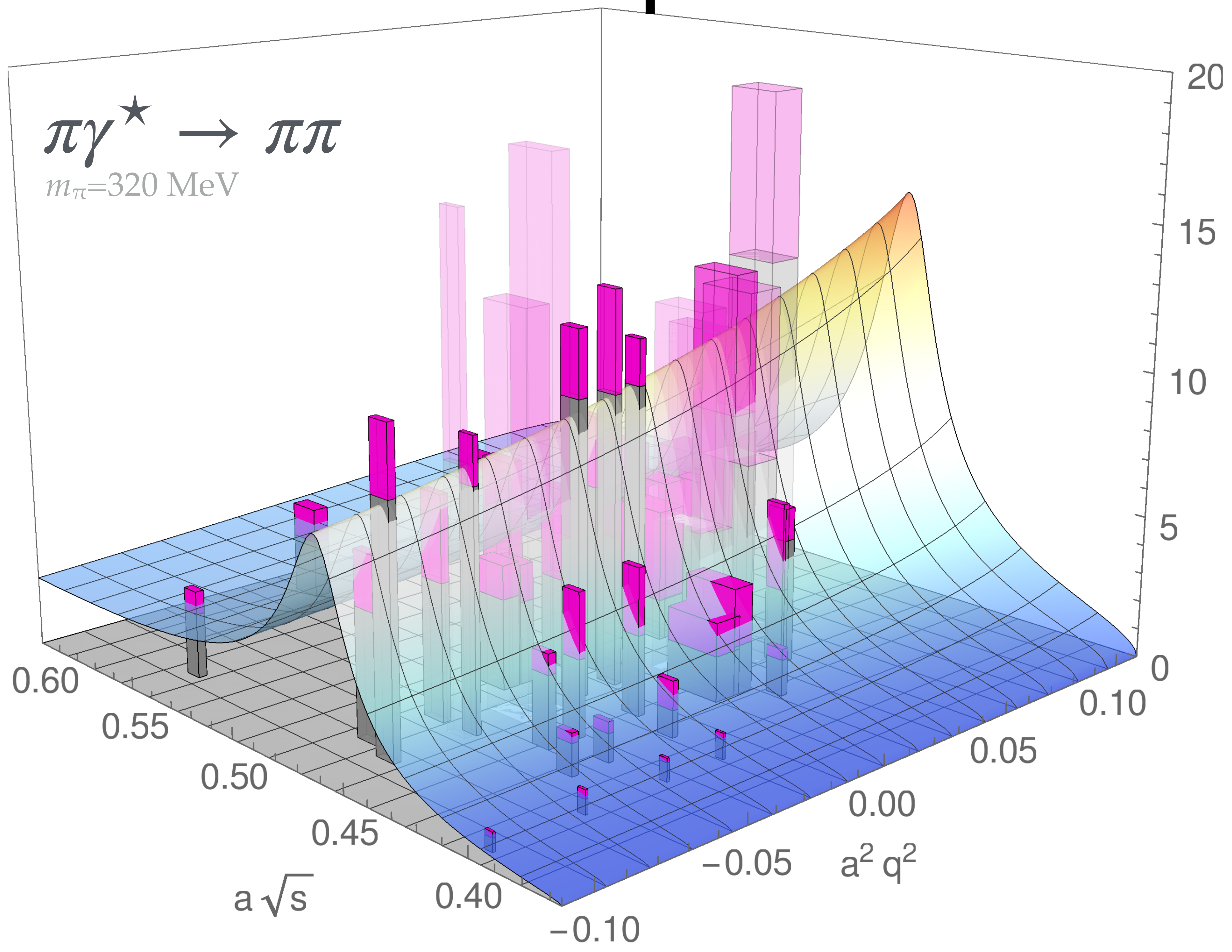
$2 + \mathcal{J}^\mu \to 2$

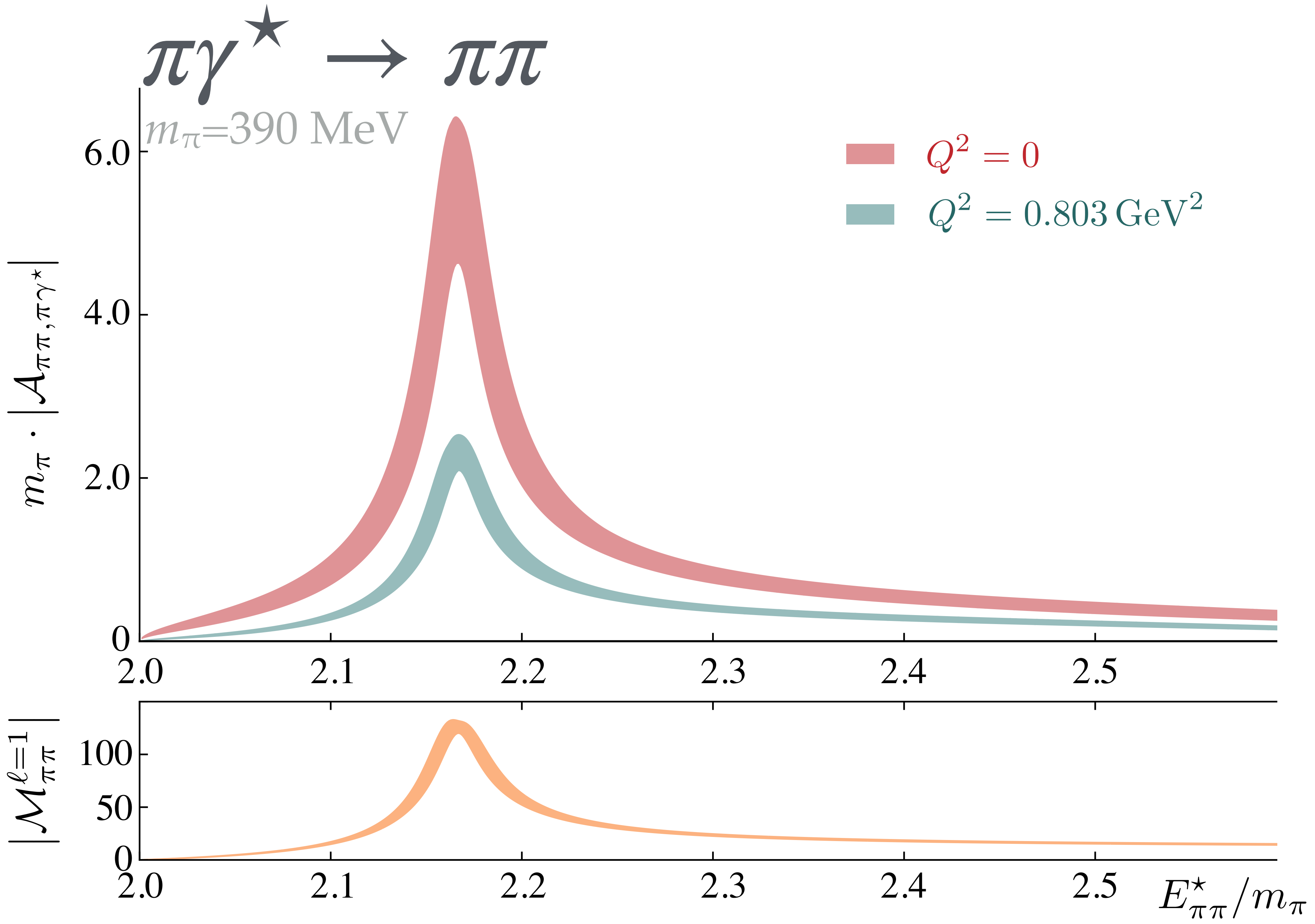
Goal: *isolated ALL kinematic singularities of amplitudes in a kinematic region.*

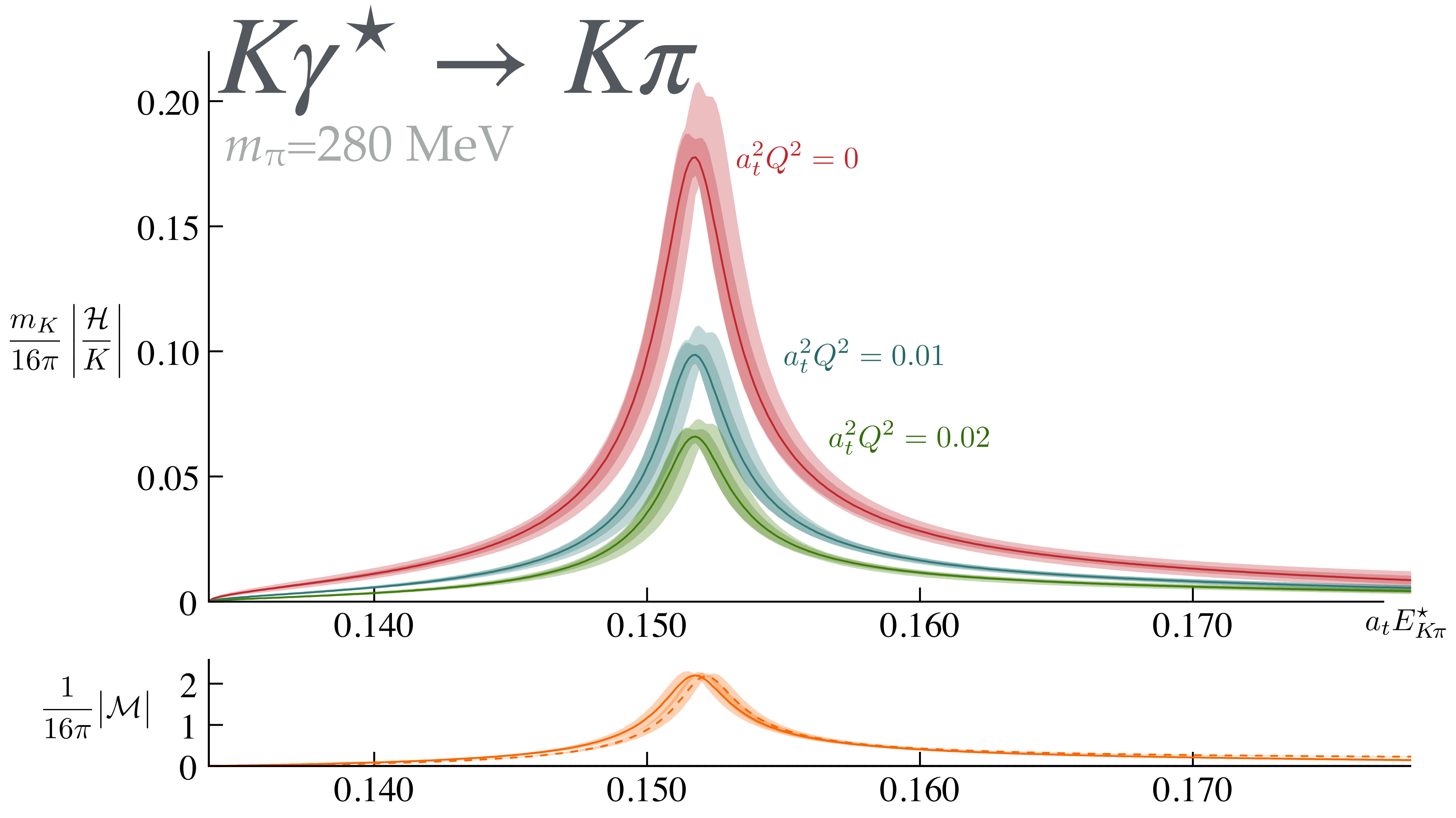
Observation: *kinematic singularities are due to intermediate particles goin on-shell.*



Transition amplitudes

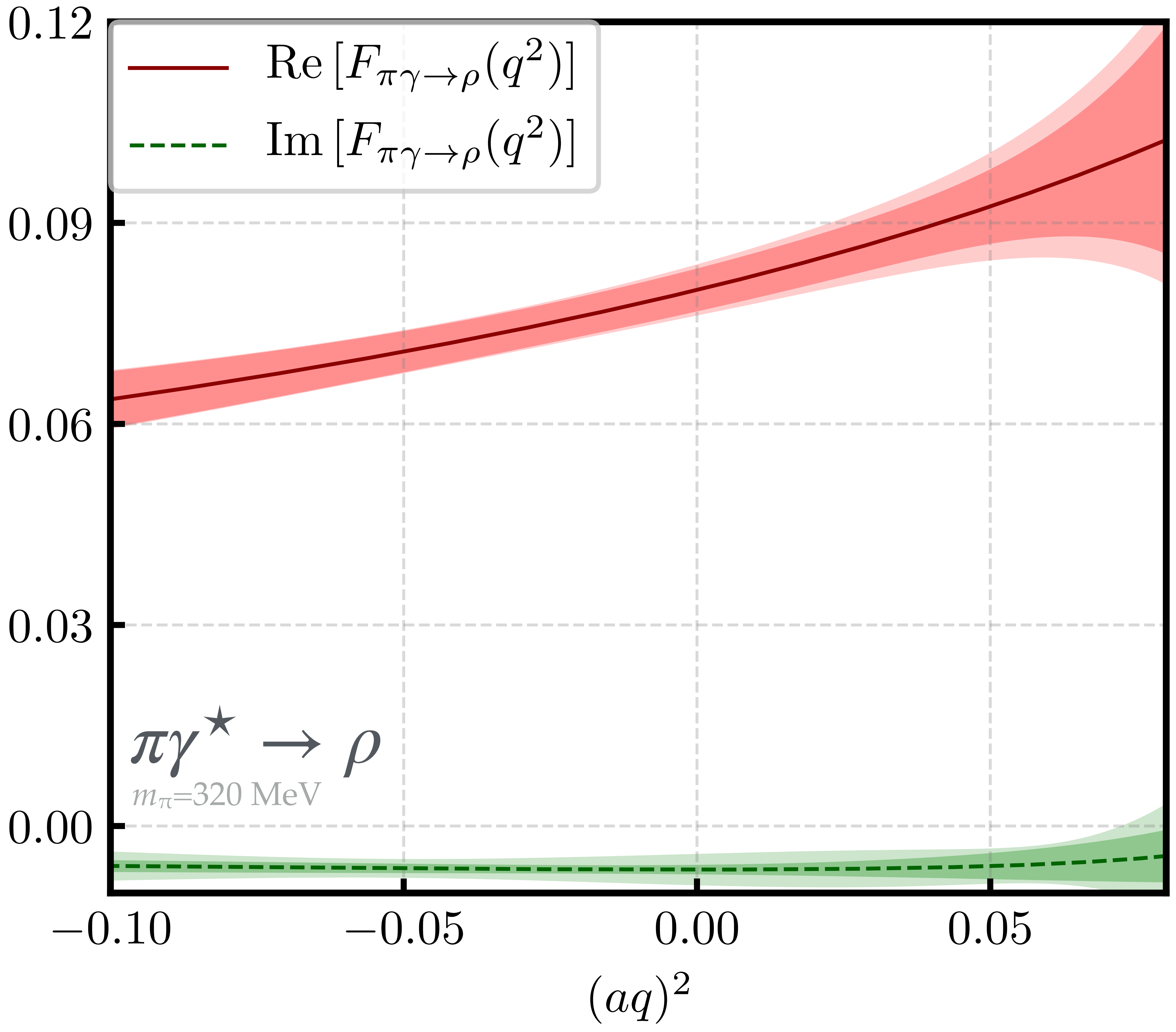


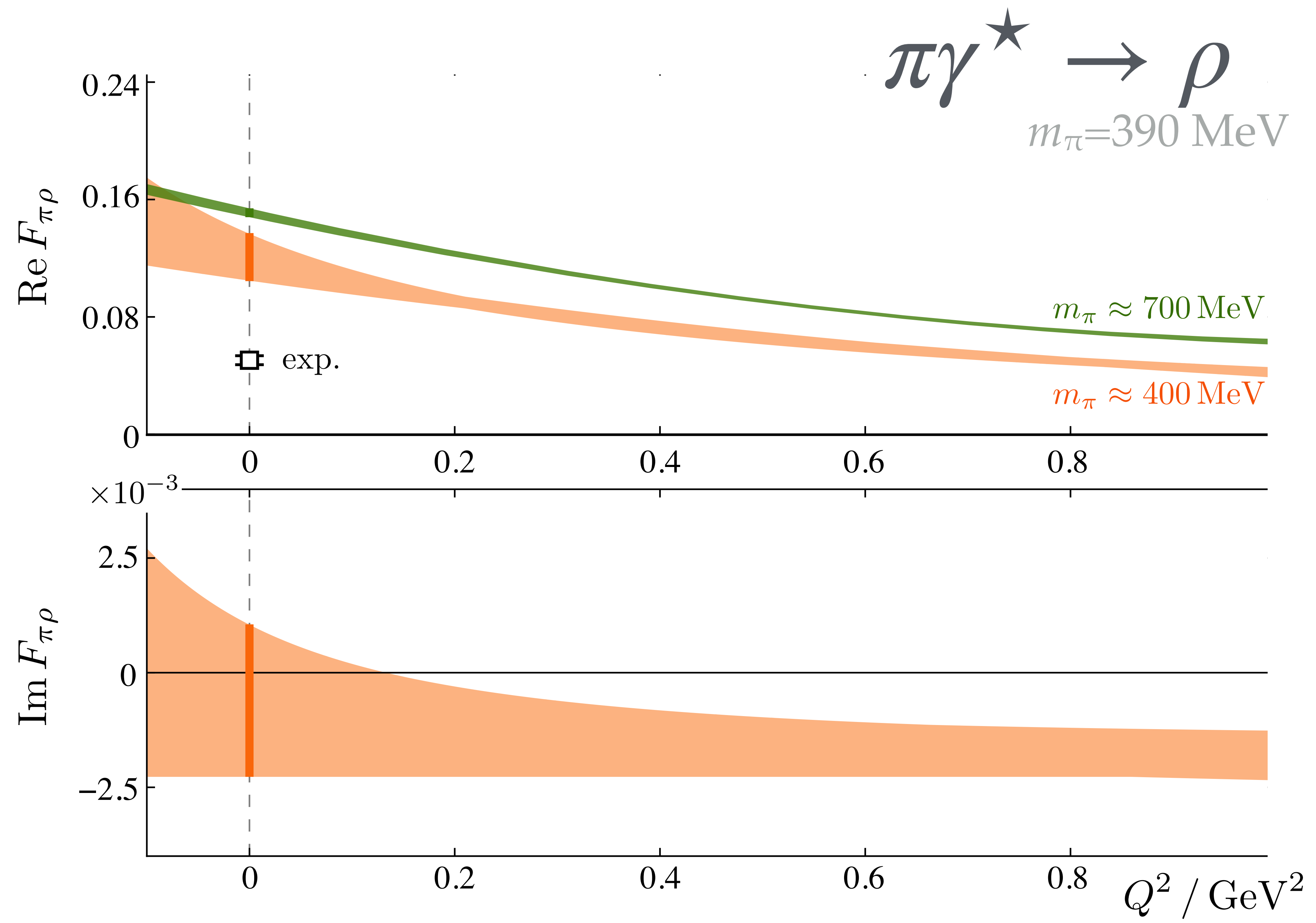


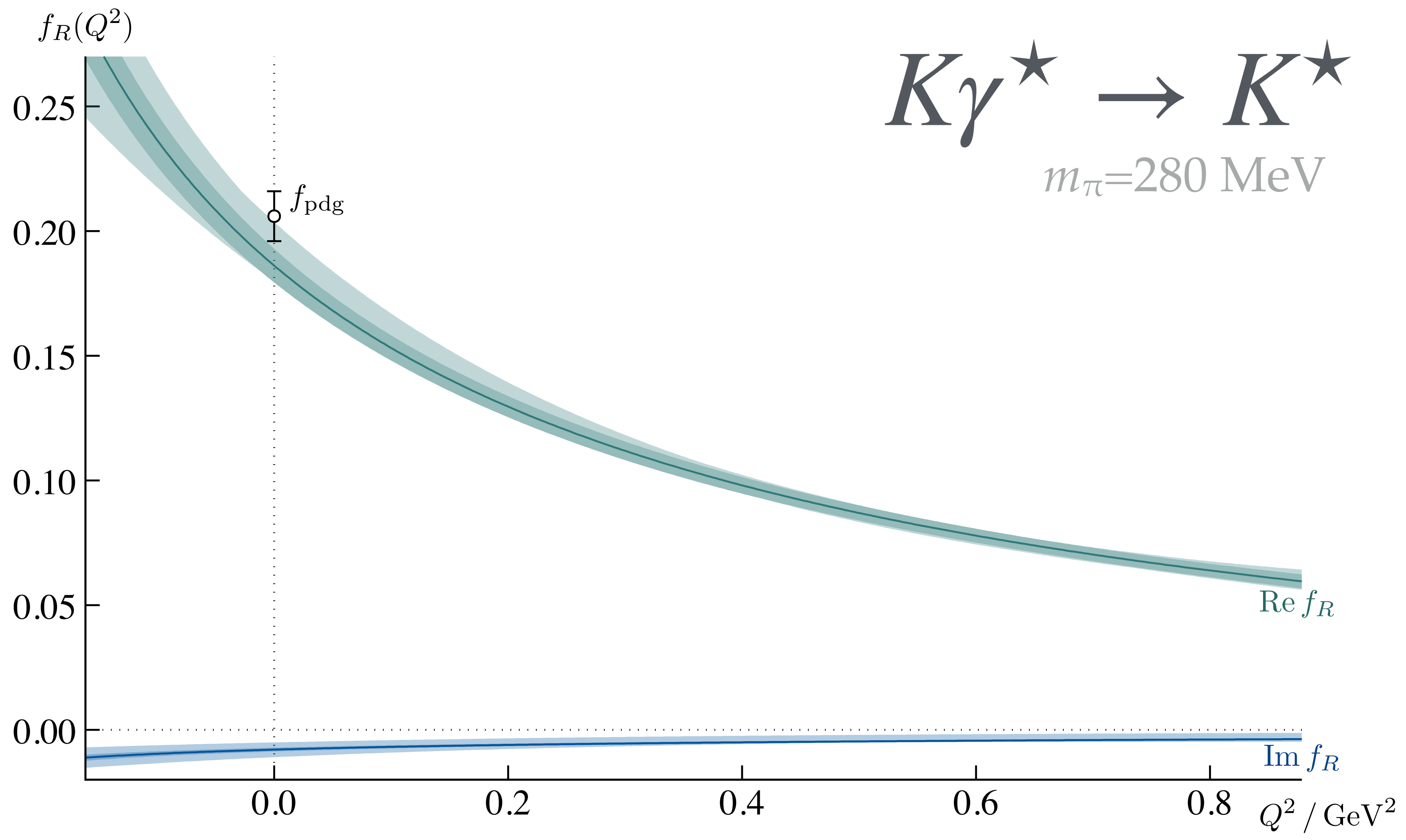


RB, Dudek, Edwards, Schultz, Thomas, Wilson (2016)
Radhakrishnan, Dudek, Edwards (2022)
Alexandrou, Leskovec, et al. (2018)

Transition form factors



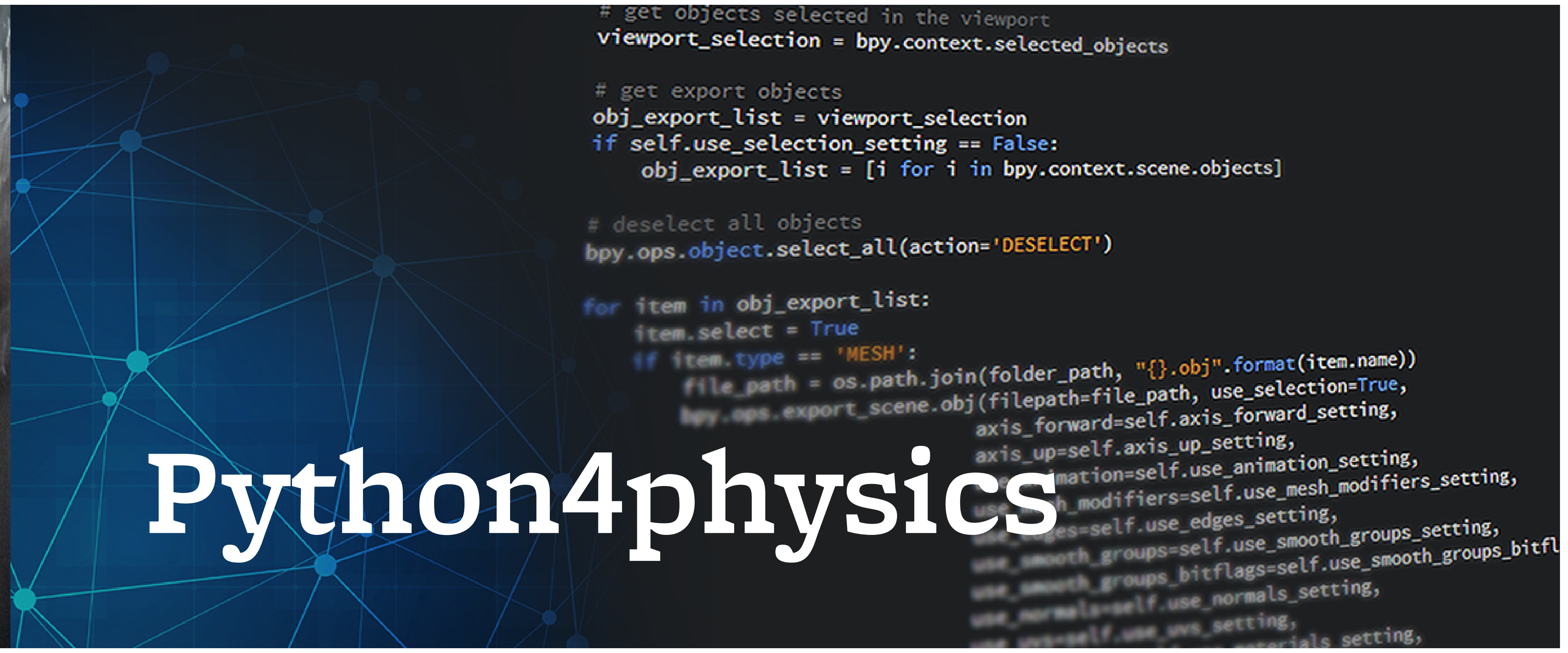




RB, Dudek, Edwards, Schultz, Thomas, Wilson (2016)
Radhakrishnan, Dudek, Edwards (2022)
Alexandrou, Leskovec, Meinel, et al. (2018)

QCD is a rich forest with lots of trees deserving our attention

Outreach & mentoring



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