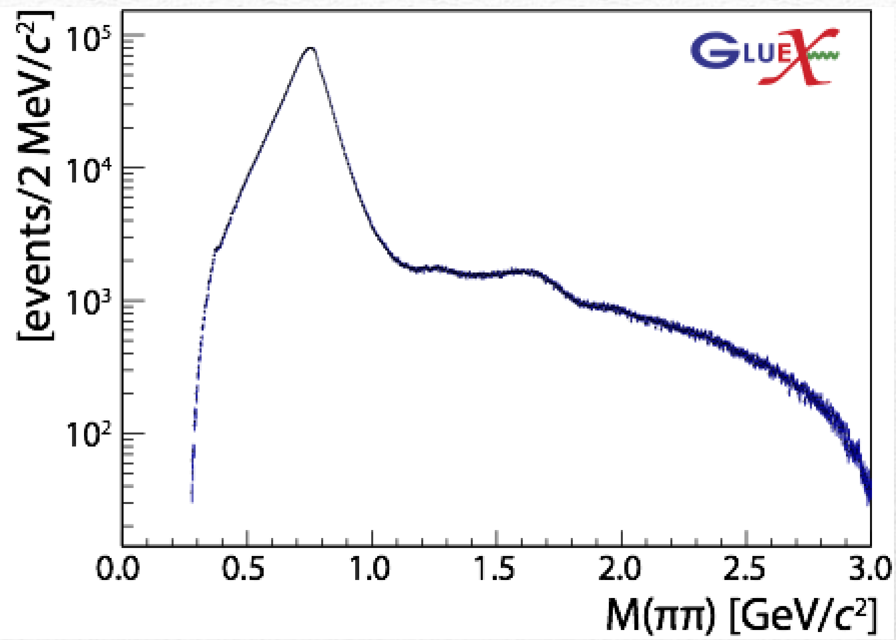
Amplitude analysis for exotic states at JPAC

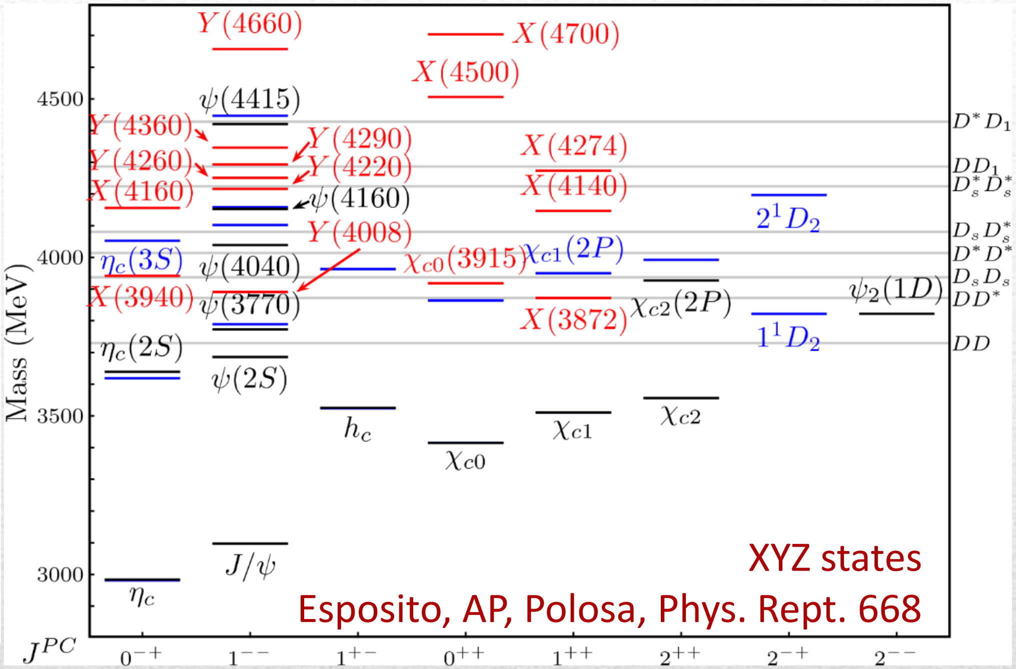
Alessandro Pilloni

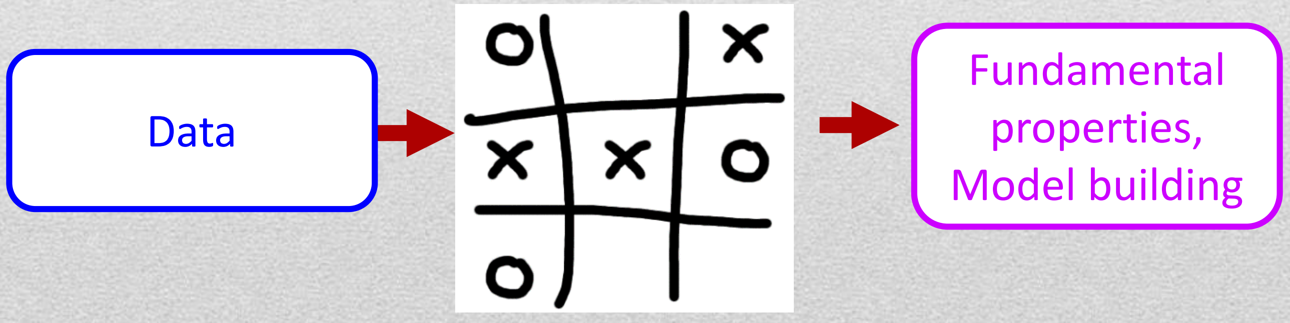
APS-DNP, Pittsburgh, October 27th, 2017

Jefferson Lab

Hadron Spectroscopy



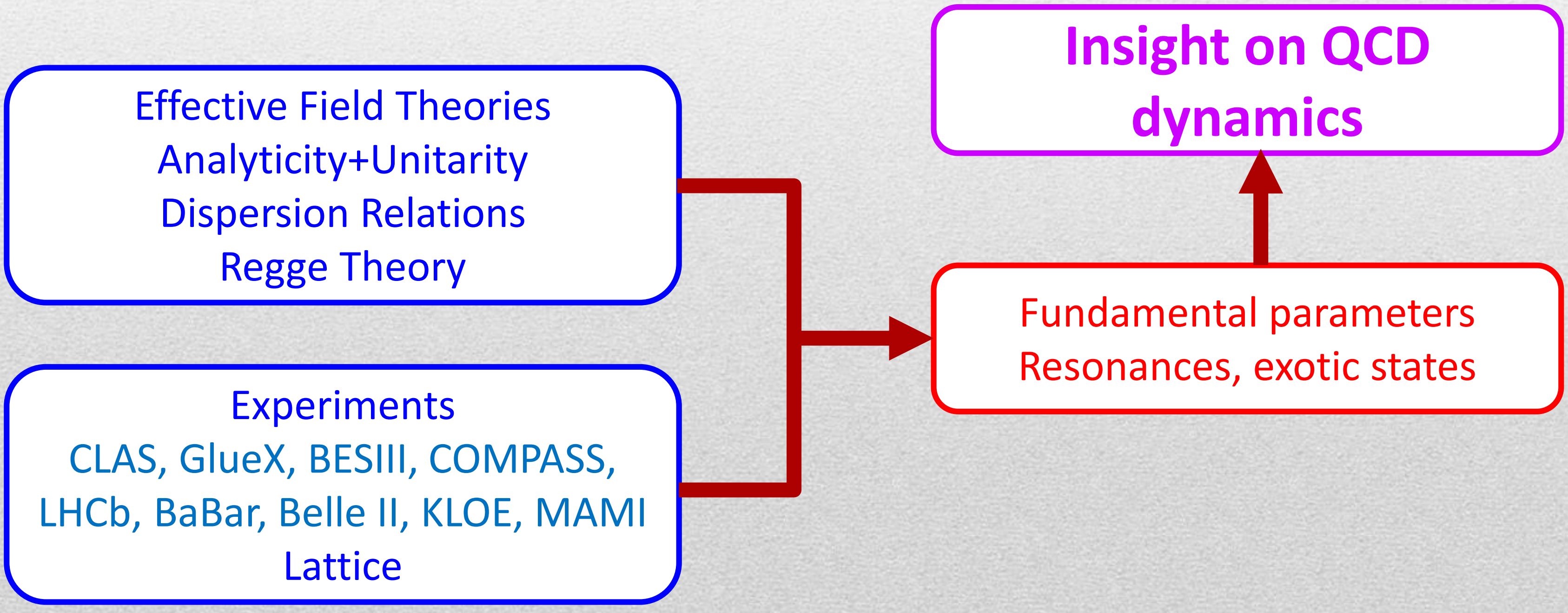




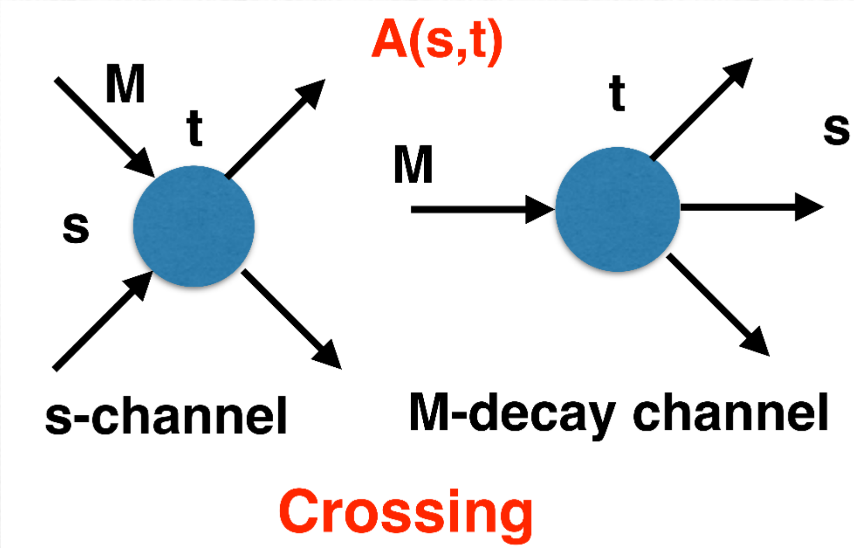
Improvement needed! With great statistics comes great responsibility!

Joint Physics Analysis Center

- Joint effort between theorists and experimentalists to work together to make the best use of the next generation of very precise data taken at JLab and in the world
- Created in 2013 by JLab & IU agreement
- It is engaged in education of further generations of hadron physics practitioners



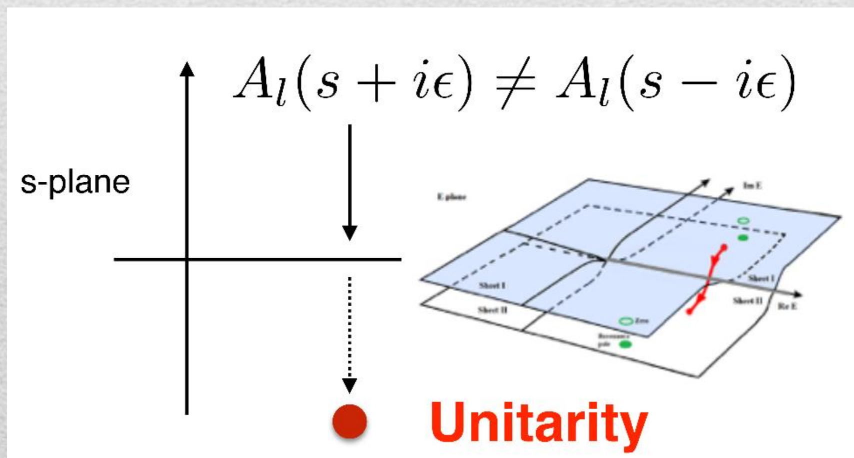
S-Matrix principles



$$A(s,t) = \sum_l A_l(s) P_l(z_s)$$

Analyticity

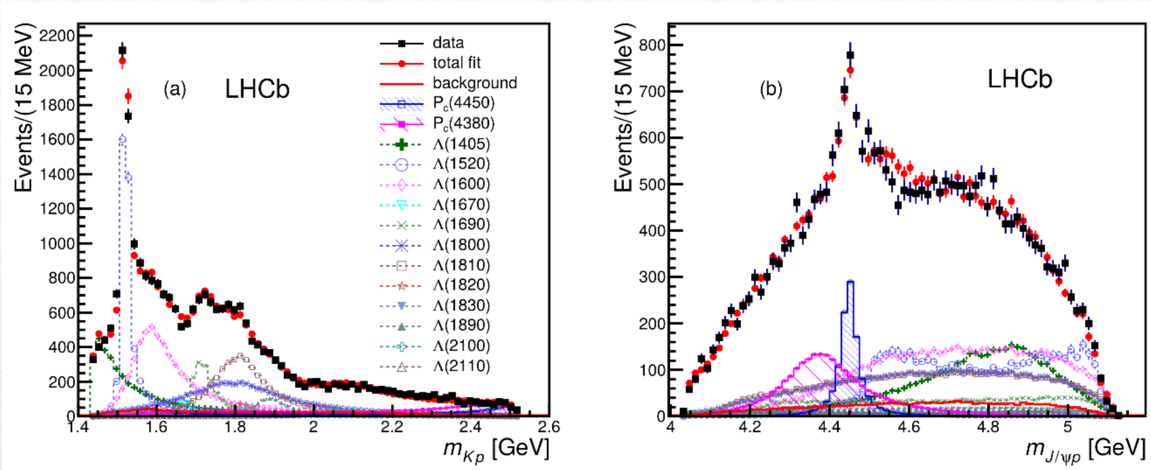
$$A_l(s) = \lim_{\epsilon\to 0} A_l(s+i\epsilon)$$



These are constraints the amplitudes have to satisfy, but do not fix the dynamics

Resonances (QCD states) are poles in the unphysical Riemann sheets

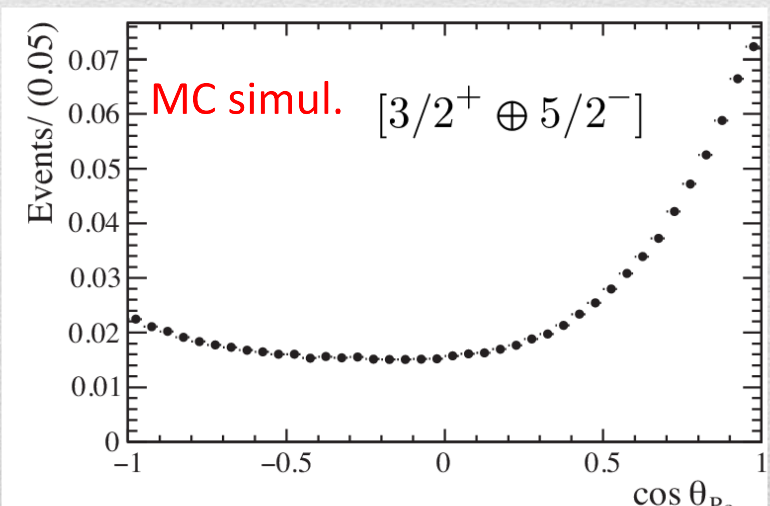
Pentaquarks!



LHCb, PRL 115, 072001
LHCb, PRL 117, 082003

Two states seen in $\Lambda_b \to (J/\psi\, p)\, K^-$, evidence in $\Lambda_b \to (J/\psi\, p)\, \pi^-$

$$M_1 = 4380 \pm 8 \pm 29 \text{ MeV}$$
$$\Gamma_1 = 205 \pm 18 \pm 86 \text{ MeV}$$
$$M_2 = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$$
$$\Gamma_2 = 39 \pm 5 \pm 19 \text{ MeV}$$



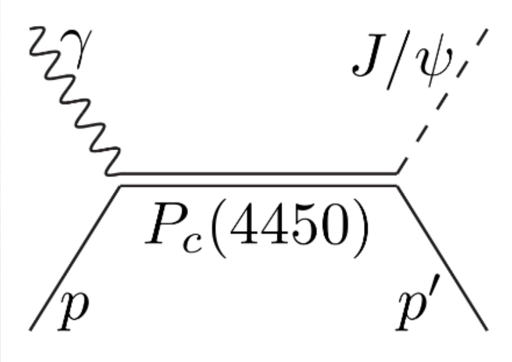
Quantum numbers

$$J^P = \left(\frac{3}{2}^-, \frac{5}{2}^+\right) \text{ or } \left(\frac{3}{2}^+, \frac{5}{2}^-\right) \text{ or } \left(\frac{5}{2}^+, \frac{3}{2}^-\right)$$

Opposite parities needed for the interference to correctly describe angular distributions, low mass region contaminated by Λ^* (model dependence?)

P_c photoproduction

To exclude any rescattering mechanism, we propose to search the $P_c(4450)$ state in photoproduction.



Hadronic vertex EM vertex

$$\langle\lambda_\psi\lambda_{p'}|\,T_r\,|\lambda_\gamma\lambda_p\rangle = \frac{\boxed{\langle\lambda_\psi\lambda_{p'}|\,T_{\text{dec}}\,|\lambda_R\rangle}\boxed{\langle\lambda_R|\,T^\dagger_{\text{em}}\,|\lambda_\gamma\lambda_p\rangle}}{M_r^2 - W^2 - \mathrm{i}\Gamma_r M_r}$$

Hadronic part

- 3 independent helicity couplings,
  → approx. equal, $g_{\lambda_\psi,\lambda_{p'}} \sim g$
- g extracted from total width and (unknown) branching ratio

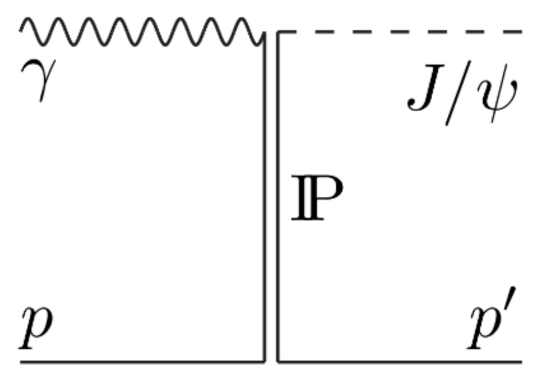
Vector meson dominance relates the radiative width to the hadronic width

$$\Gamma_\gamma = 4\pi\alpha\,\Gamma_{\psi p}\left(\frac{f_\psi}{M_\psi}\right)^2\left(\frac{\bar{p}_i}{\bar{p}_f}\right)^{2\ell+1}\times\frac{4}{6}$$

Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

Background parameterization

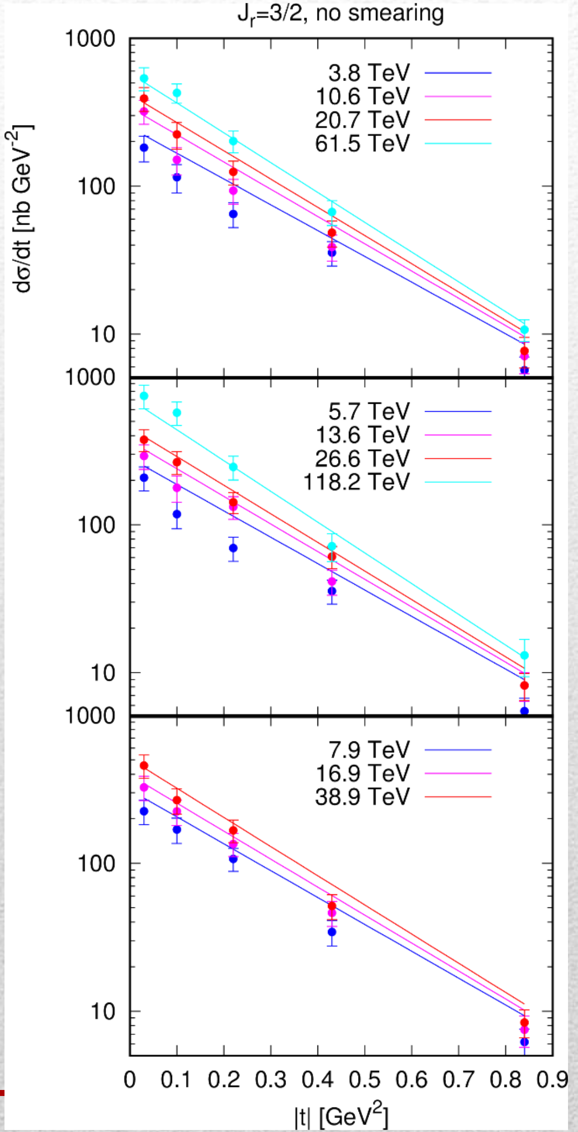
The background is described via an Effective Pomeron, whose parameters are fitted to high energy data from Hera



$$\langle \lambda_\psi \lambda_{p'} | T_P | \lambda_\gamma \lambda_p \rangle = iA \left(\frac{s - s_t}{s_0} \right)^{\alpha(t)} e^{b_0 (t - t_{\min})} \delta_{\lambda_p \lambda_{p'}} \delta_{\lambda_\psi \lambda_\gamma}$$

Asymptotic + Effective threshold

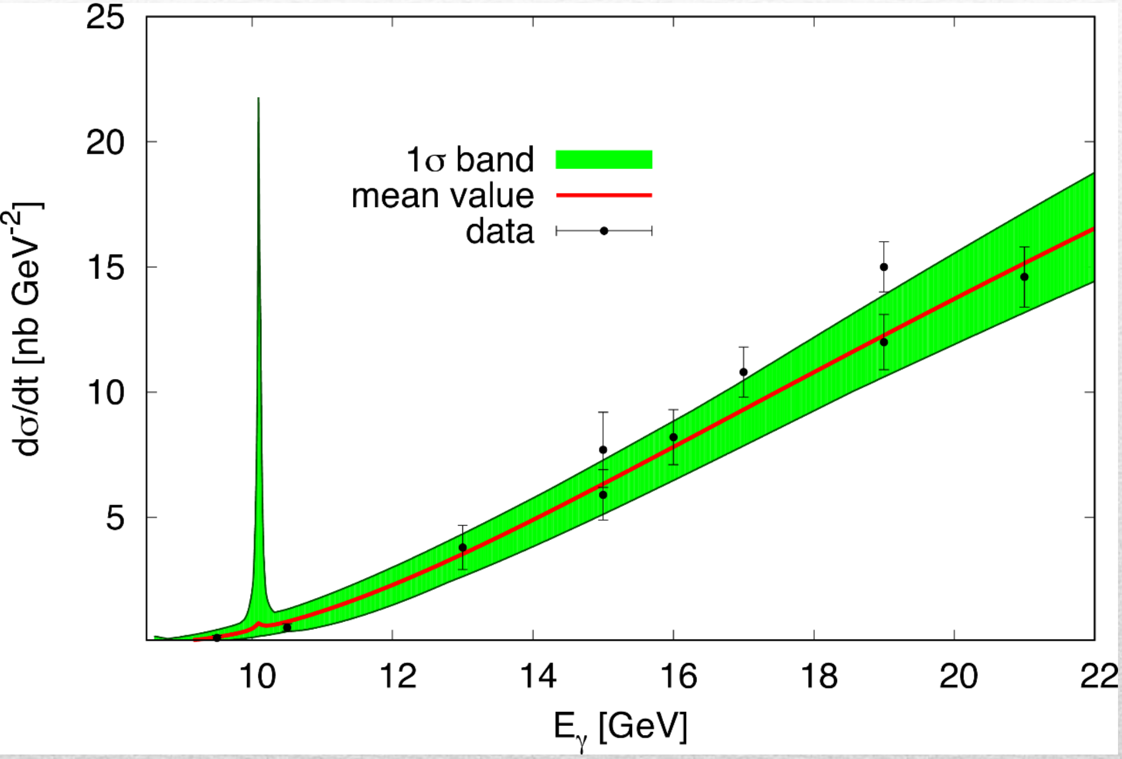
Helicity conservation



Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

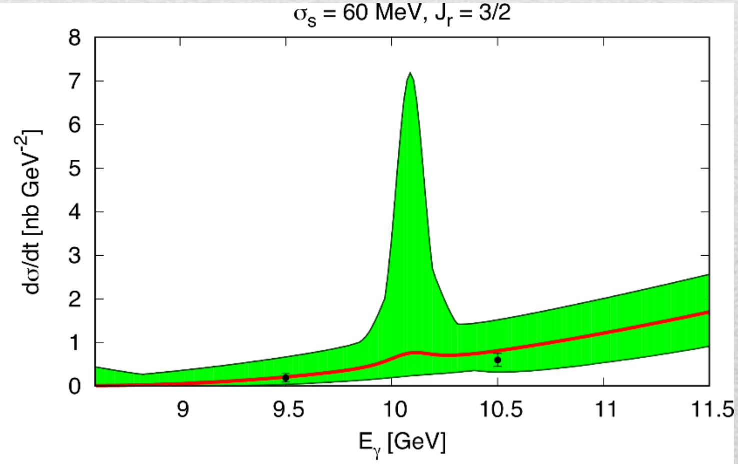
Pentaquark photoproduction

$J^P = (3/2)^-$



σ_s (MeV)	0	60
A	$0.156^{+0.029}_{-0.020}$	$0.157^{+0.039}_{-0.021}$
α_0	$1.151^{+0.018}_{-0.020}$	$1.150^{+0.018}_{-0.026}$
α' (GeV^{-2})	$0.112^{+0.033}_{-0.054}$	$0.111^{+0.037}_{-0.064}$
s_t (GeV^2)	$16.8^{+1.7}_{-0.9}$	$16.9^{+2.0}_{-1.6}$
b_0 (GeV^{-2})	$1.01^{+0.47}_{-0.29}$	$1.02^{+0.61}_{-0.32}$
$\mathcal{B}_{\psi p}$ (95% CL)	≤ 29 %	≤ 30 %

With smearing

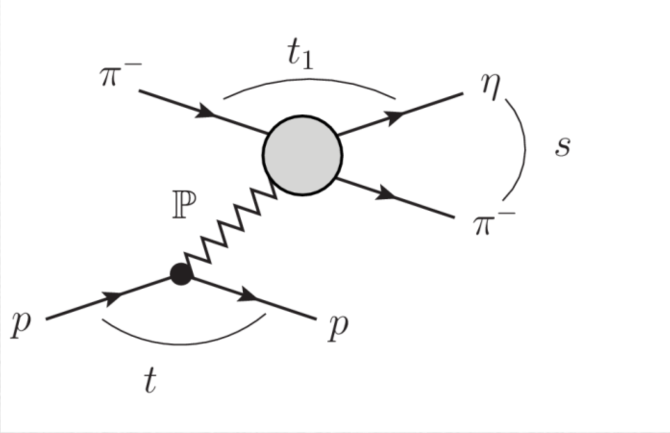


Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

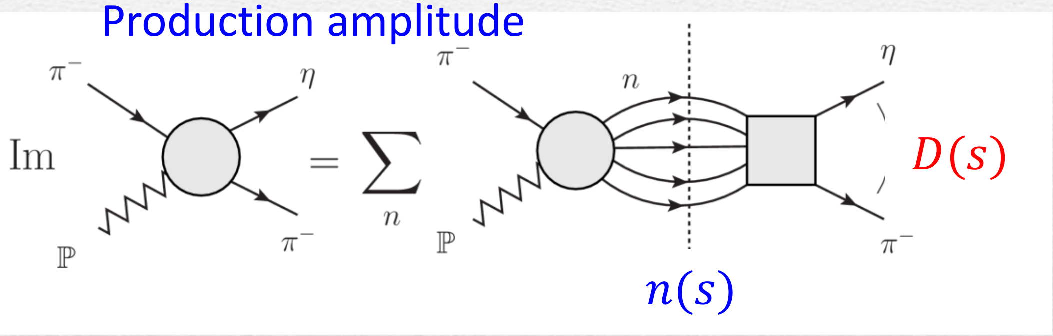
Searching for resonances in $\eta\pi$

- The $\eta\pi$ system is one of the golden modes for hunting hybrid mesons
- We build the partial waves amplitude according to the N/D method

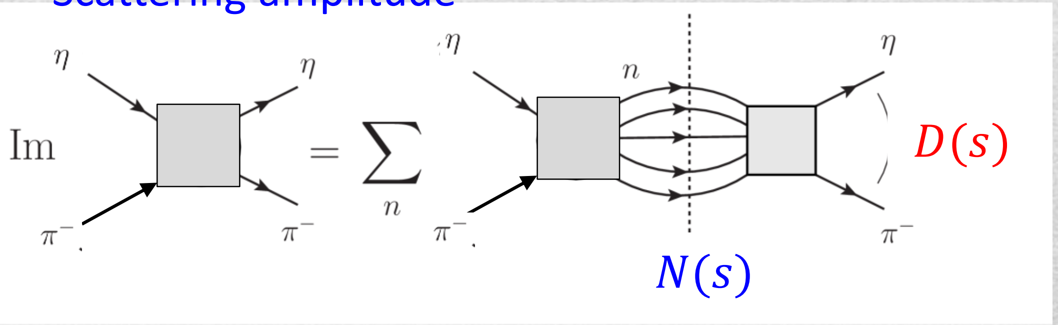
A. Jackura, *et al.* (JPAC & COMPASS), 1707.02848
see talk at 2:12pm



Production amplitude



Scattering amplitude



The denominator $D(s)$ contains all the Final State Interactions constrained by unitarity → universal
The numerator $n(s)$ depends on the exchanges → process-dependent, smooth

Searching for resonances in $\eta\pi$

The denominator $D(s)$ contains all the FSI constrained by unitarity → universal

$$D(s)_{ij} = (K^{-1})_{ij}(s) - \frac{s}{\pi}\int_{s_i}^{\infty} \frac{\rho_i(s')N_{ij}(s')}{s'\,(s'-s)} ds'$$

$$K_{ij}(s) = \sum_R \frac{g_i^R g_j^R}{M_R^2 - s}$$

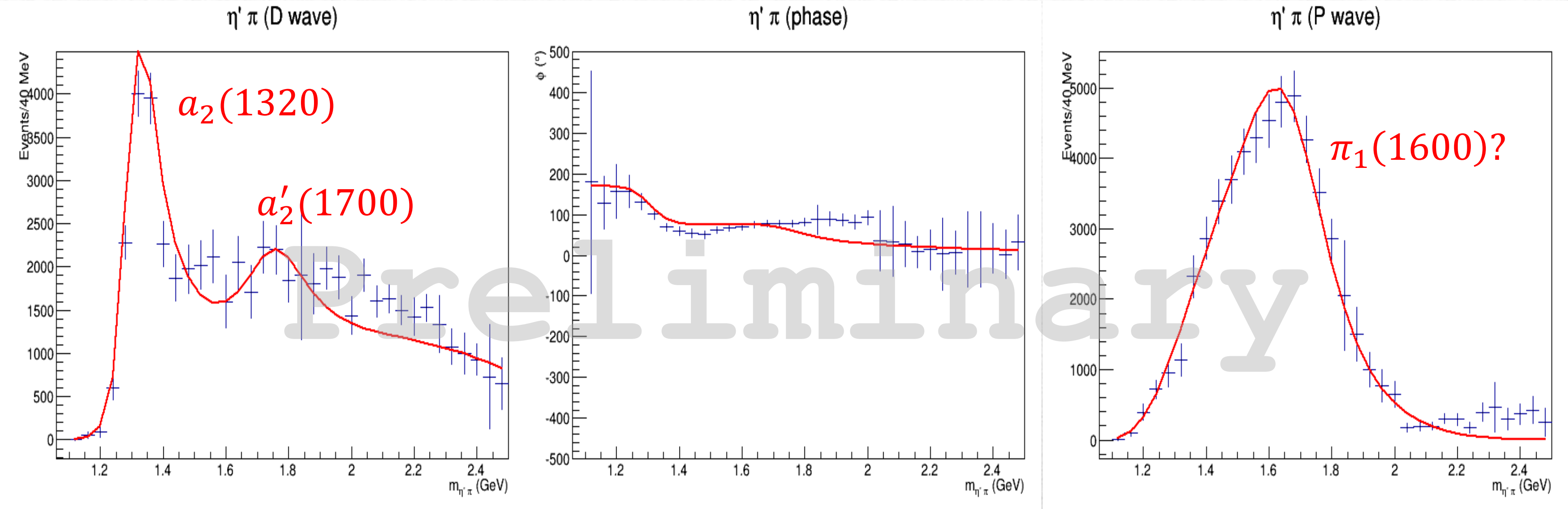
Standard K matrix,
with usual trick for
vanishing determinant

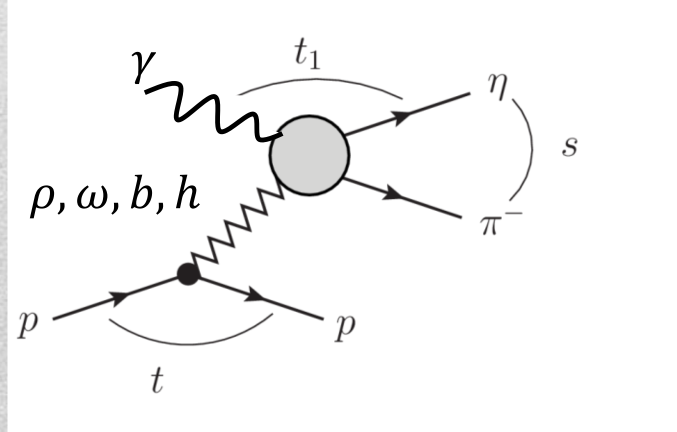
The numerator $n(s)$ depends on the exchanges → process-dependent, smooth

$$\rho_i(s)N_{ij}(s) = \frac{\lambda^{(2l+1)/2}\left(s, m_\pi^2, m_\eta^2\right)}{(s+\Lambda)^7}$$

Searching for resonances in $\eta\pi$

- The coupled channel analysis involving the $\eta\pi$ and $\eta'\pi$ for P- and D-wave is ongoing





- The extention to the GlueX production mechanism and kinematics is also ongoing
- Same $D(s)$, different numerator

Conclusions & prospects

- We aim at developing new theoretical tools, to get insight on QCD using first principles of QFT (unitarity, analyticity, crossing symmetry, low and high energy constraints,…) to extract the physics out of the data
- Many other ongoing projects (both for meson and baryon spectroscopy, and for high energy observables), with a particular attention to producing complete reaction models for the golden channels in exotic meson searches

A. Jackura, N. Sherrill, G. Fox, T. Londergan (IU), E. Passemar, A. Szczepaniak (IU/JLab)

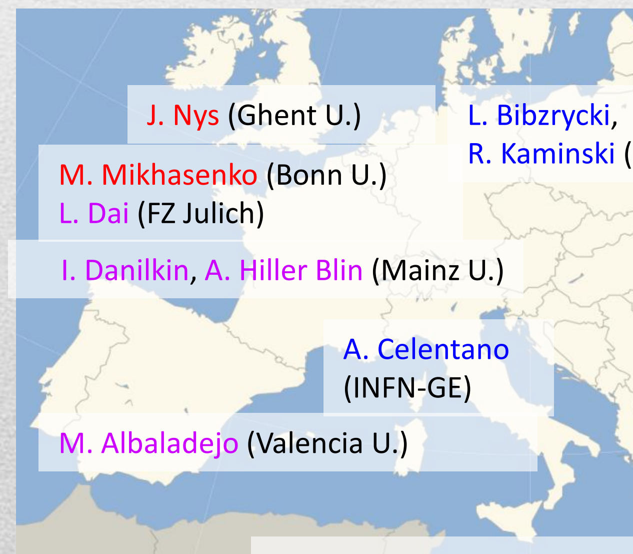
R. Workman (GWU), M. Döring (GWU/JLab)

V. Mathieu, A. Pilloni, V. Mokeev (JLab)

P. Guo (Cal. State U.)

J. Castro, C. Fernandez-Ramirez (UNAM)

Joint Physics Analysis Center



J. Nys (Ghent U.)

L. Bibzrycki, R. Kaminski (Krakow)

M. Mikhasenko (Bonn U.)
L. Dai (FZ Julich)

I. Danilkin, A. Hiller Blin (Mainz U.)

A. Celentano (INFN-GE)

M. Albaladejo (Valencia U.)

Students, Postdocs, Faculties

BACKUP

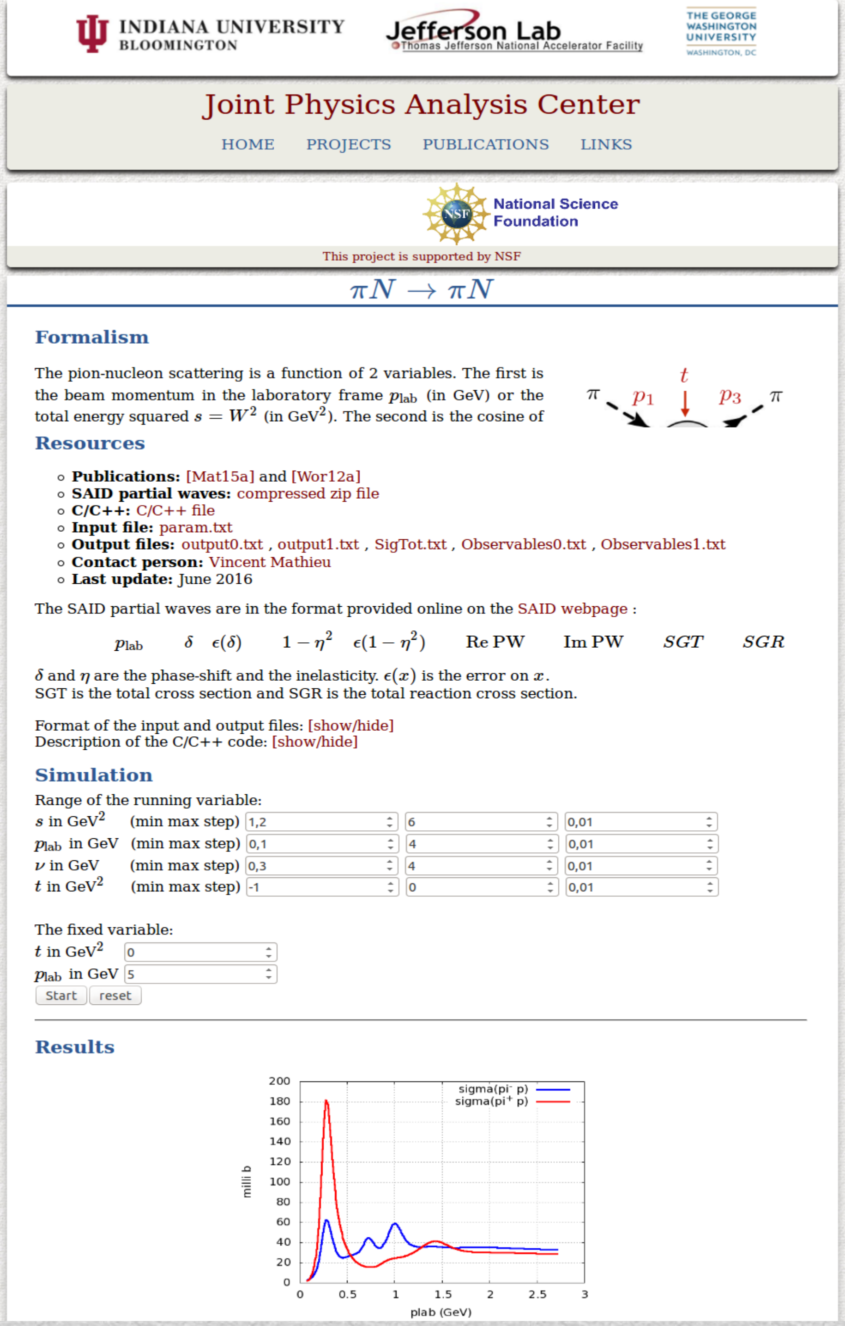
Production

- $>$ 40 Research Papers (Phys.Rev., Phys.Lett, Eur.J. Phys.)
- $\sim$120 Invited Talks and Seminars
- $O(10)$ ongoing analyses
- Summer Schools on Reaction Theory (IU, 2015 and 2017)
- Workshop “Future Directions in Hadron Spectroscopy” (JLab, 2014 and UNAM 2017)

$\gamma\, N \to \pi\, \Delta$	J. Nys *et al.*,	arXiv:1710.09394
FESR	V. Mathieu *et al.*,	arXiv:1708.07779
$\pi\, N \to \eta\, \pi\, N$	A. Jackura *et al.*,	arXiv:1707.02848
$\gamma\, N \to \eta\, N$ vs. $\to \eta'\, N$	V. Mathieu *et al.*,	arXiv:1704.07684
$Z_c(3900)$	A. Pilloni *et al.*,	PLB772, 200
$\gamma\, N \to \eta\, N$	J. Nys *et al.*,	PRD95, 034014
$\gamma\, p \to J/\psi\, p$	A. Blin *et al.*,	PRD94, 034002
$K\, N \to\ K\, N$	C. Fernandez-Ramirez *et al.*,	PRD93, 034029; PRD93, 074015
$\gamma\, p \to\ \pi^0\, p$	V. Mathieu *et al.*,	PRD92, 074013
$\pi\, N \to \pi\, N$	V. Mathieu *et al.*,	PRD92, 074004
$\eta \to \pi^+\, \pi^-\, \pi^0$	P. Guo *et al.*,	PRD92, 054016; PLB771, 497
$\omega, \phi \to \pi^+\, \pi^-\, \pi^0$	I. Danilkin *et al.*,	PRD91, 094029
$\gamma\, p \to\ K^+\, K^-\, p$	M. Shi *et al.*,	PRD91, 034007

Interactive tools

- Completed projects are fully documented on interactive portals
- These include description on physics, conventions, formalism, etc.
- The web pages contain source codes with detailed explanation how to use them. Users can run codes online, change parameters, display results.



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Joint Physics Analysis Center

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National Science Foundation

This project is supported by NSF

$\pi N \to \pi N$

Formalism

The pion-nucleon scattering is a function of 2 variables. The first is the beam momentum in the laboratory frame p_{lab} (in GeV) or the total energy squared $s = W^2$ (in GeV^2). The second is the cosine of

Resources

- **Publications:** [Mat15a] and [Wor12a]
- **SAID partial waves:** compressed zip file
- **C/C++:** C/C++ file
- **Input file:** param.txt
- **Output files:** output0.txt , output1.txt , SigTot.txt , Observables0.txt , Observables1.txt
- **Contact person:** Vincent Mathieu
- **Last update:** June 2016

The SAID partial waves are in the format provided online on the SAID webpage :

p_{lab} δ $\epsilon(\delta)$ $1-\eta^2$ $\epsilon(1-\eta^2)$ Re PW Im PW SGT SGR

δ and η are the phase-shift and the inelasticity. $\epsilon(x)$ is the error on x.
SGT is the total cross section and SGR is the total reaction cross section.

Format of the input and output files: [show/hide]
Description of the C/C++ code: [show/hide]

Simulation

Range of the running variable:

s in GeV^2	(min max step)	1,2	6	0,01
p_{lab} in GeV	(min max step)	0,1	4	0,01
ν in GeV	(min max step)	0,3	4	0,01
t in GeV^2	(min max step)	-1	0	0,01

The fixed variable:

t in GeV^2 0
p_{lab} in GeV 5

Start reset

Results

http://www.indiana.edu/~jpac/

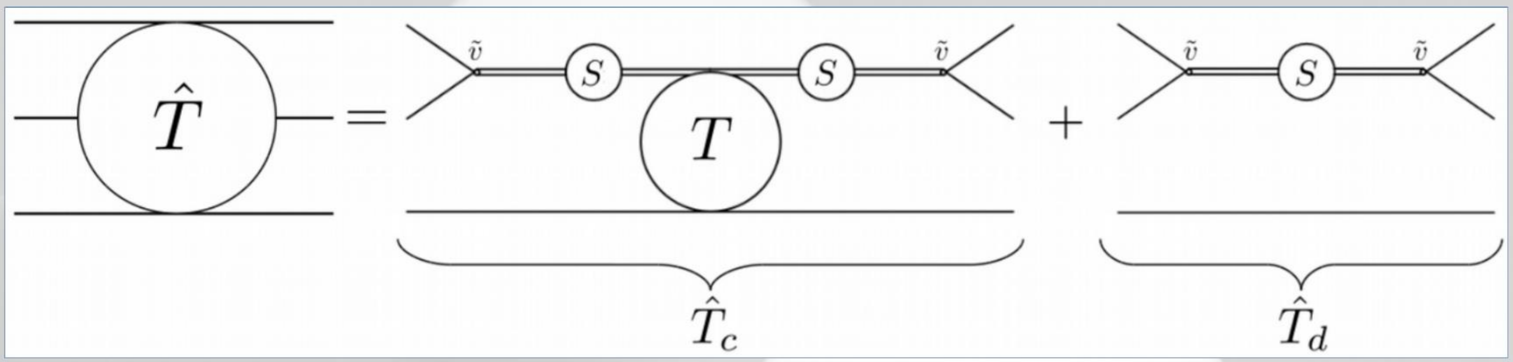
Three-Body Unitarity

Mai, Hu, Doring, AP, Szczepaniak, EPJA53, 9, 177

Original study by Amado/Aaron/Young **AAY(1968)**

- 3-dimensional integral equation from unitarity constraint & BSE ansatz
- valid below break-up energies ($E < 3m$)
- analyticity constraints unclear

One has to begin with asymptotic states



- v a general but cut-free (in the phys. region) function
- two-body interaction is parametrized by an *"isobar"*

= has definite QN and correct r.h.-singularities w.r.t invariant mass

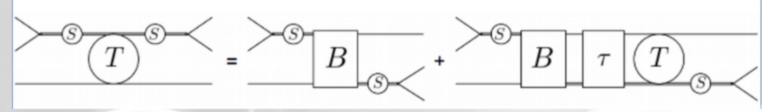
- ***S*** **and** ***T*** **are yet unknown functions**

M. Mai

Three-Body Unitarity

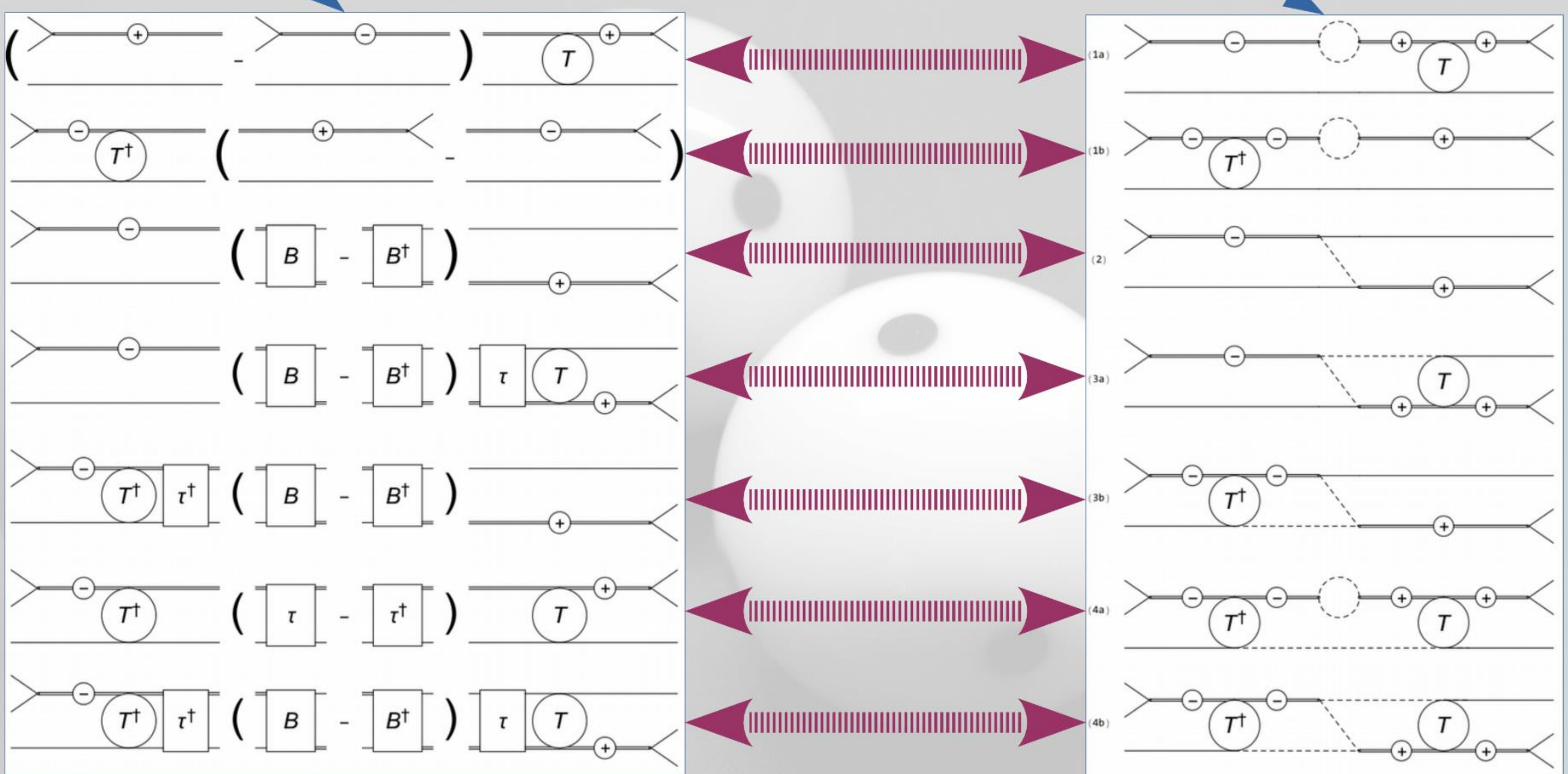
A general ansatz for the Isobar-spectator interaction

→ B & τ are unknown!!!



3-body Unitarity (normalization condition ↔ phase space integral)

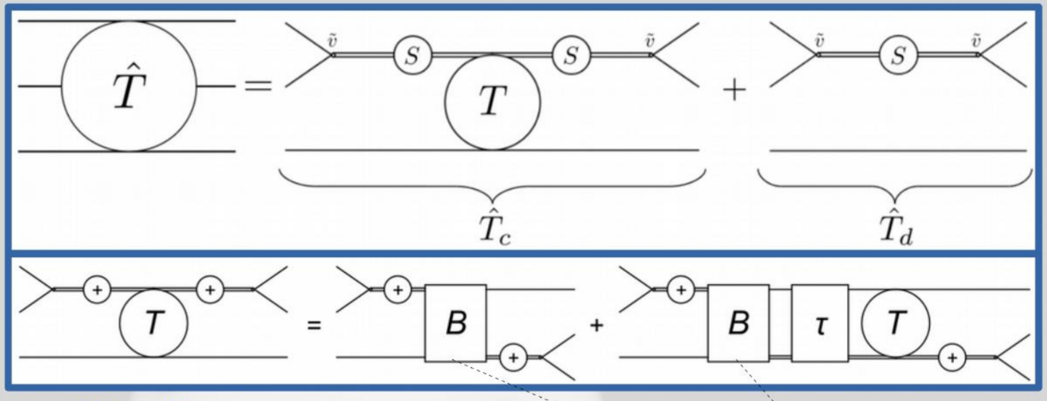
$$\langle q_1,q_2,q_3|(\hat{T}-\hat{T}^\dagger)|p_1,p_2,p_3\rangle \;=\; i\int_P \langle q_1,q_2,q_3|\hat{T}^\dagger|k_1,k_2,k_3\rangle\langle k_1,k_2,k_3|\hat{T}|p_1,p_2,p_3\rangle$$



M. Mai

Three-Body Unitarity

$3 \to 3$ scattering amplitude is a 3-dimensional integral equation



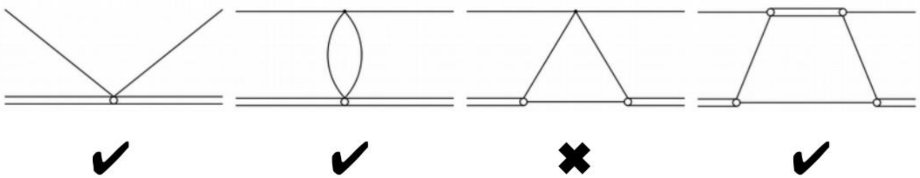
– Imaginary parts (***B, τ, S***) are fixed by **unitarity/matching**
For simplicity ***υ=λ*** (full relations available)

$$\tau(\sigma(k)) = (2\pi)\delta^+(k^2 - m^2)S(\sigma(k))$$

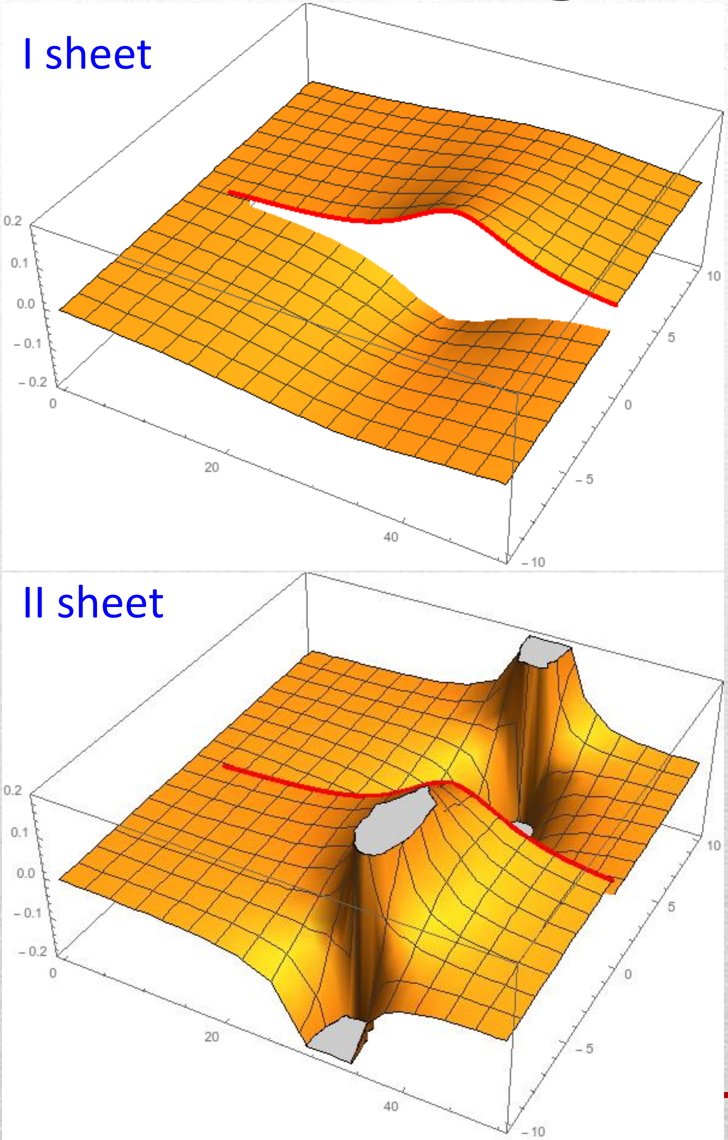
$$-\frac{1}{S(P^2)} = \sigma(k) - M_0^2 - \frac{1}{(2\pi)^3}\int d^3\ell \frac{\lambda^2}{2E_\ell(\sigma(k) - 4E_\ell^2 + i\epsilon)}$$

$$\langle q|B(s)|p\rangle = -\frac{\lambda^2}{2\sqrt{m^2+\mathbf{Q}^2}\left(E_Q - \sqrt{m^2+\mathbf{Q}^2} + i\epsilon\right)}$$

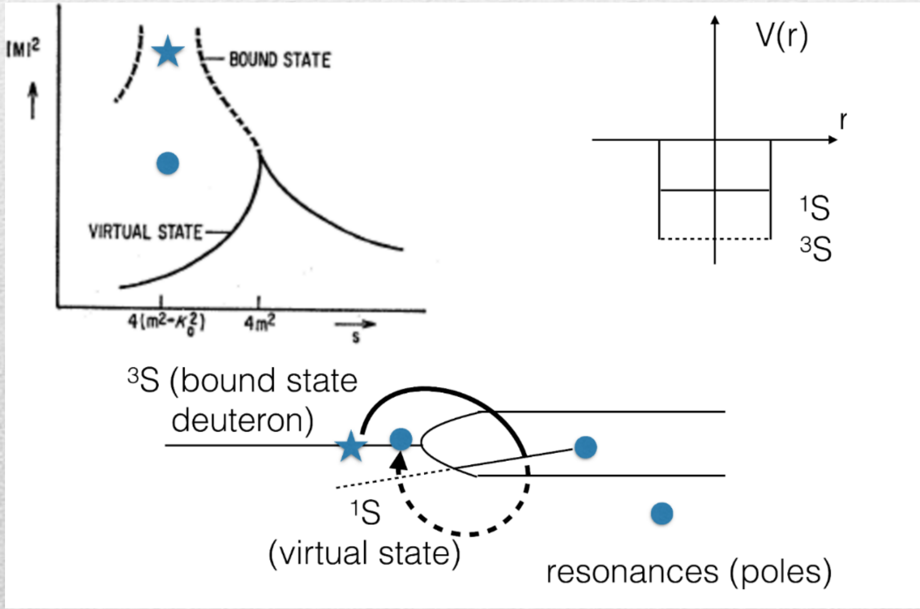
- un-subtracted dispersion relation
- one-π exchange in TOPT
- real contributions can be added to B



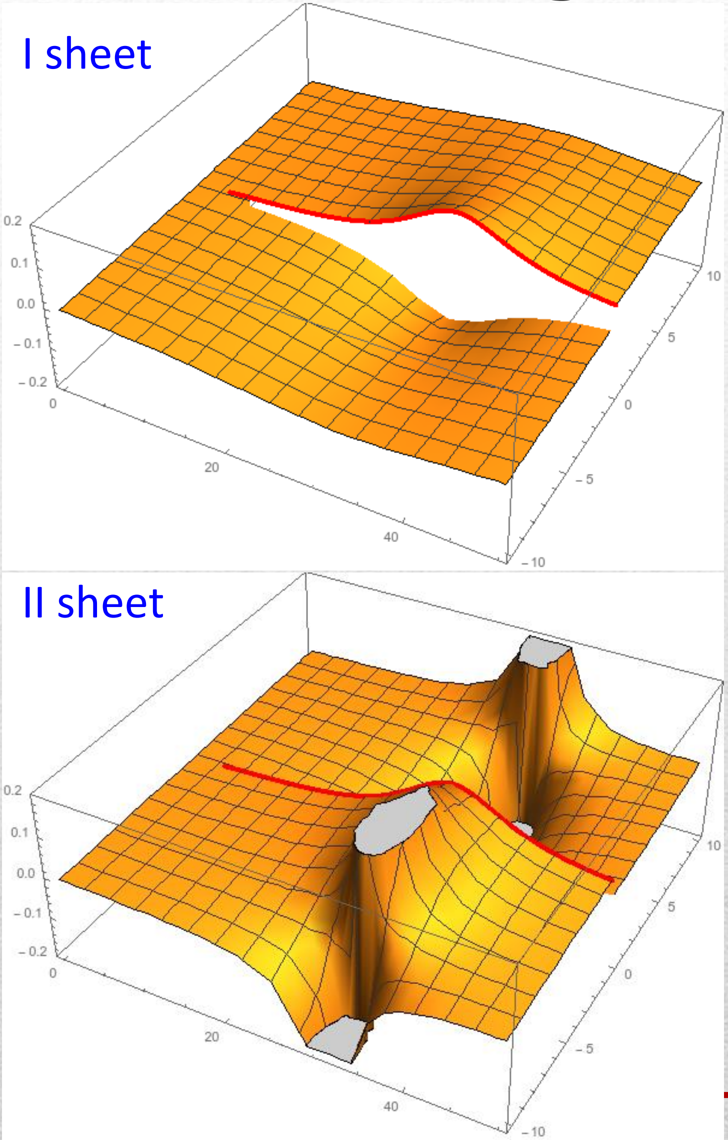
Pole hunting



Bound states on the real axis 1st sheet
Not-so-bound (virtual) states on the real axis 2nd sheet



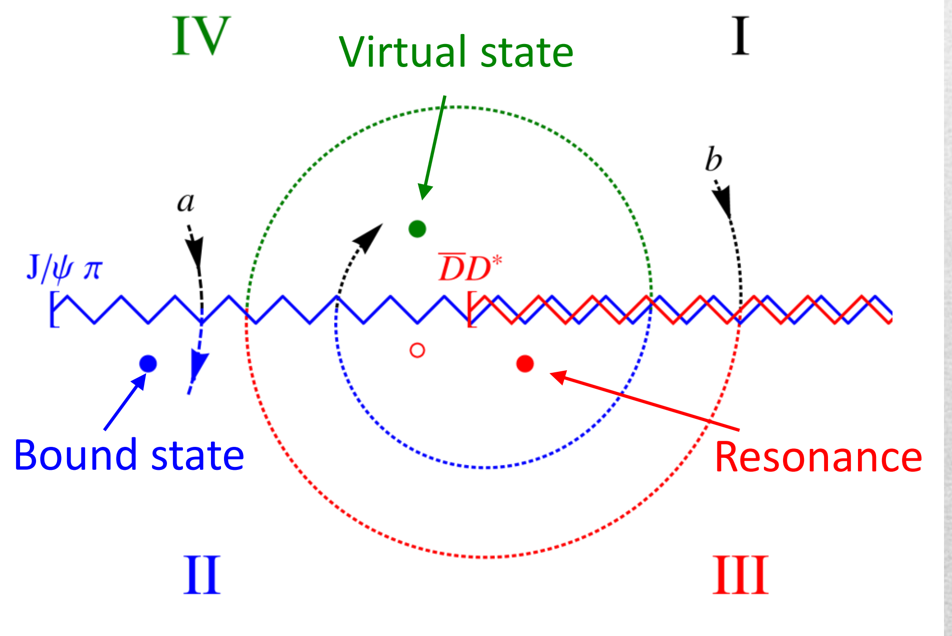
Pole hunting



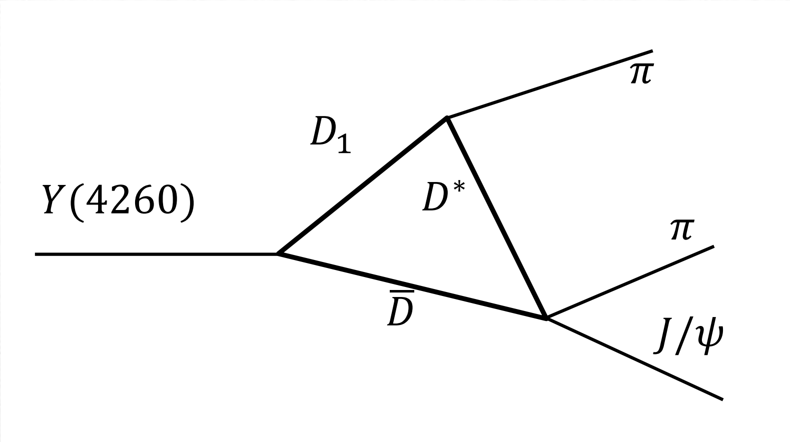
More complicated structure when more thresholds arise: two sheets for each new threshold

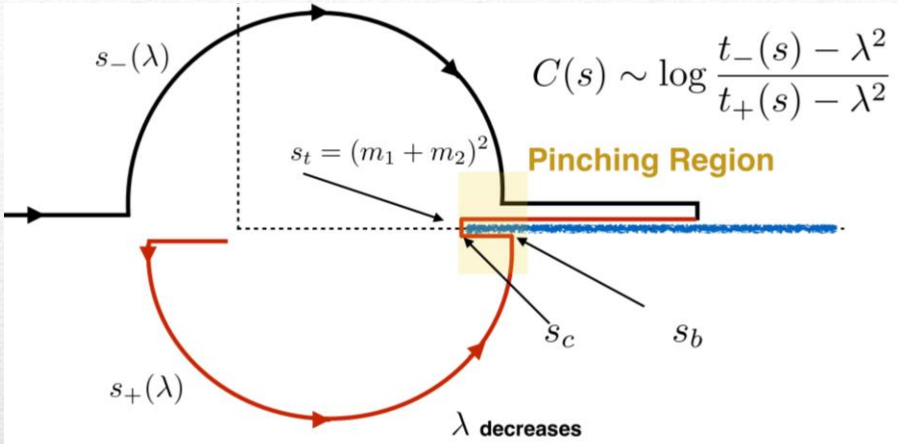
III sheet: usual resonances

IV sheet: cusps (virtual states)



Triangle singularity





- Logarithmic branch points due to exchanges in the cross channels can simulate a resonant behavior, only in very special kinematical conditions (Coleman and Norton, Nuovo Cim. 38, 438)
- However, this effects cancels in Dalitz projections, no peaks (Schmid, Phys.Rev. 154, 1363)
- But the cancellation can be spread in different channels, you might still see peaks in other channels!