THERMODYNAMICS OF COUPLED CHANNEL SYSTEM

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25 SEP 2022
XV POLISH WORKSHOP ON RELATIVISTIC HEAVY ION COLLISIONS

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Jean Cleymans

Natasha Sharma

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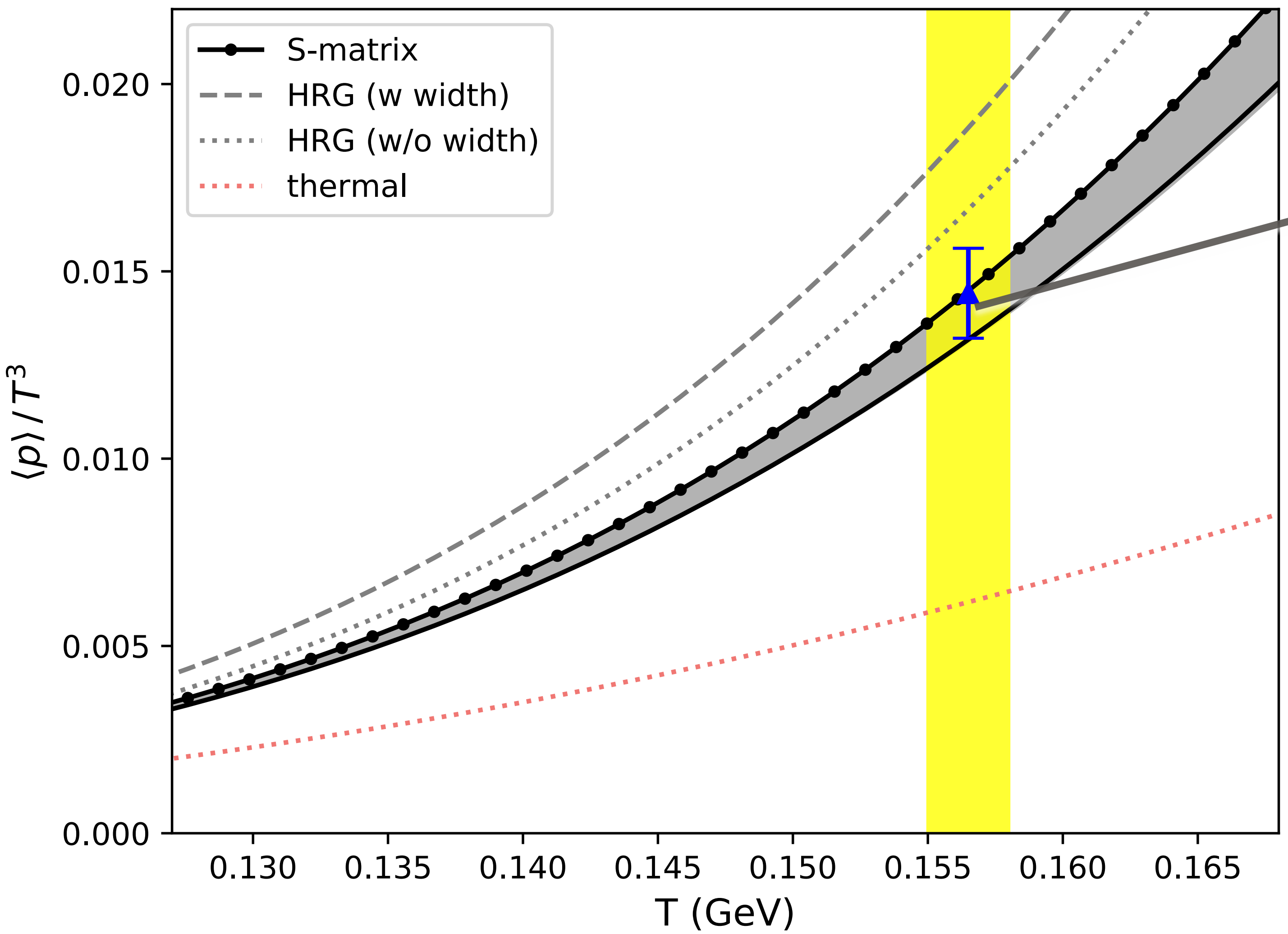
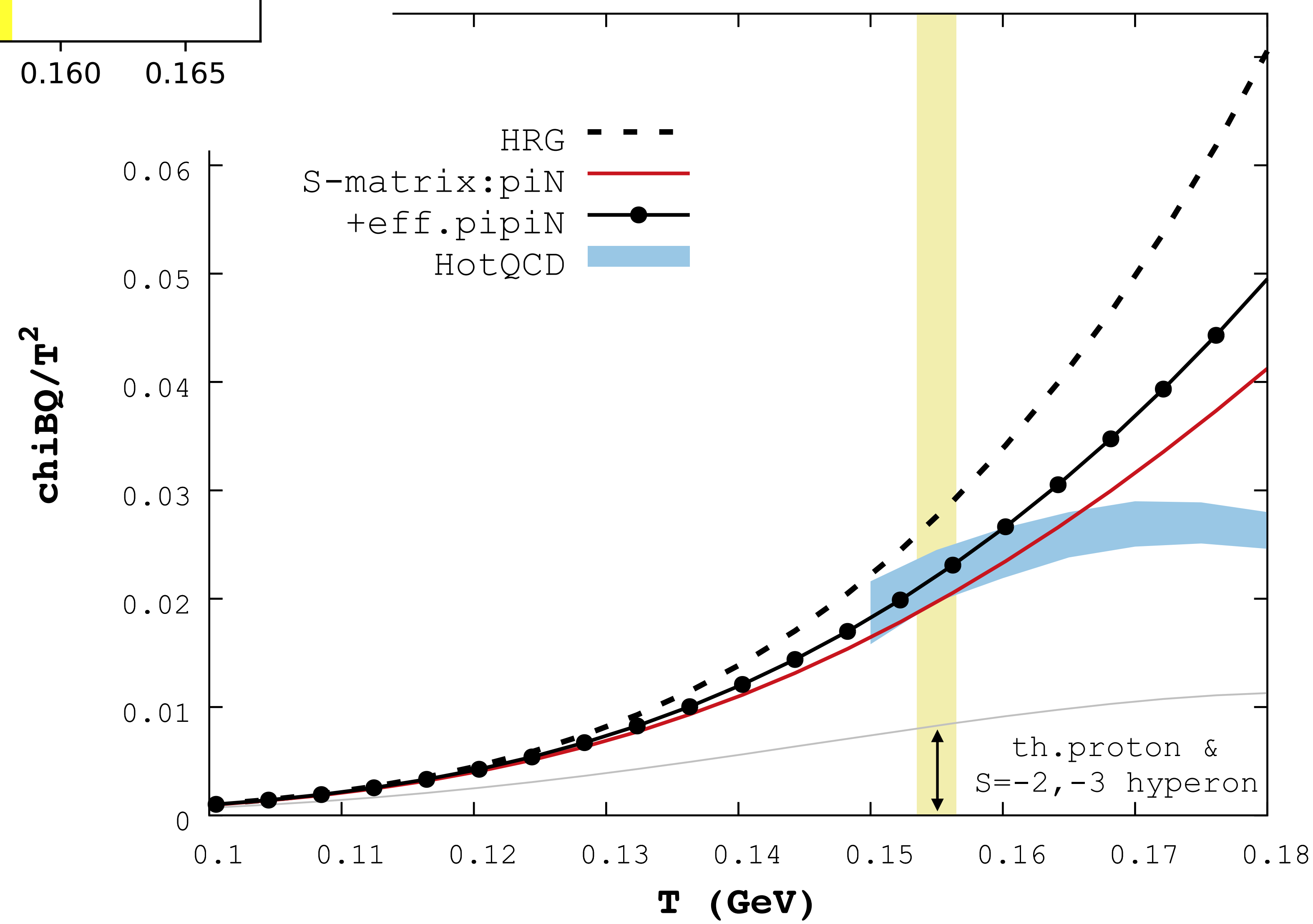
CONCLUSIONS



ALICE proton yield
Pb-Pb @ 2.76 TeV
thermal model est.

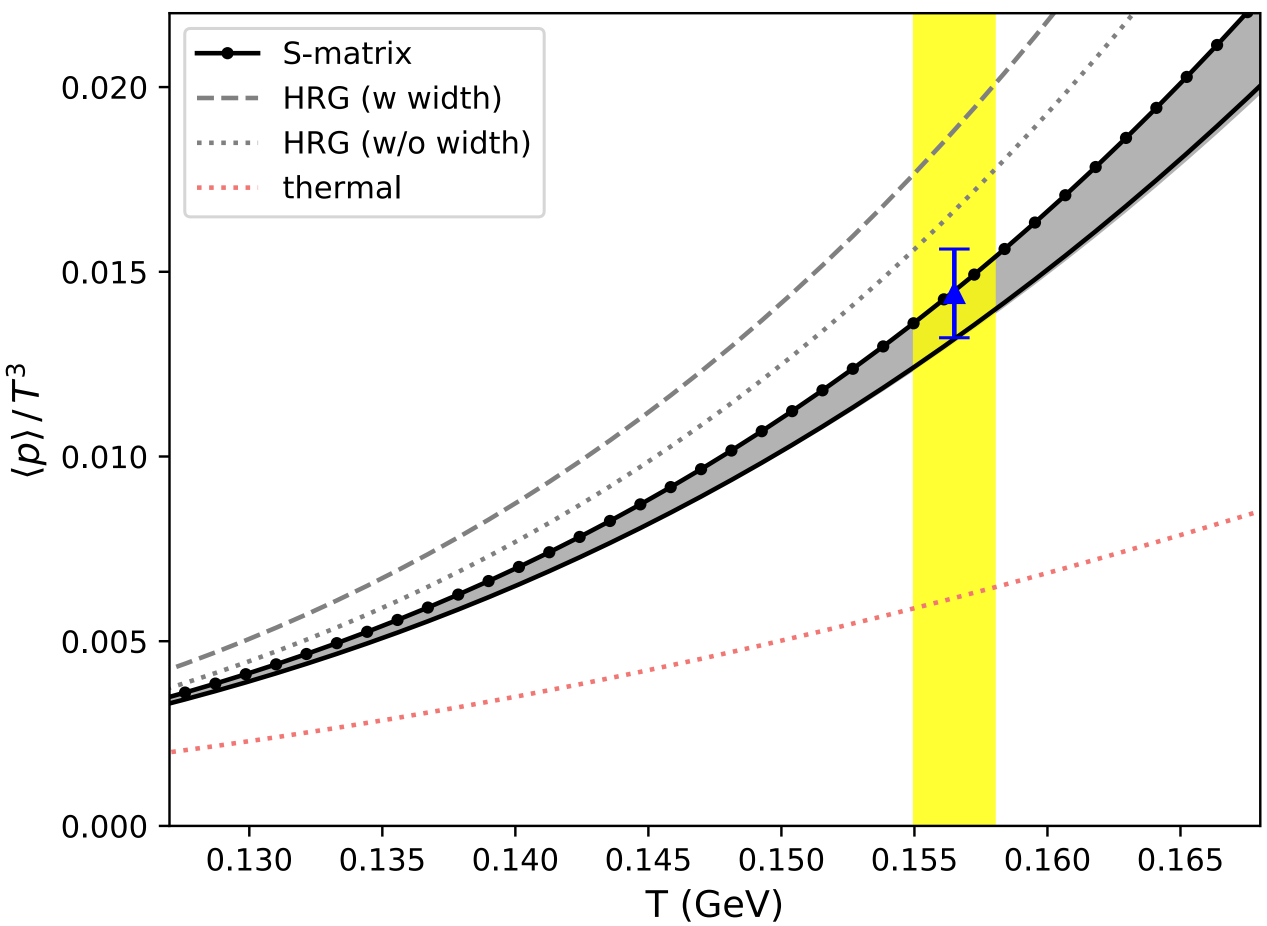


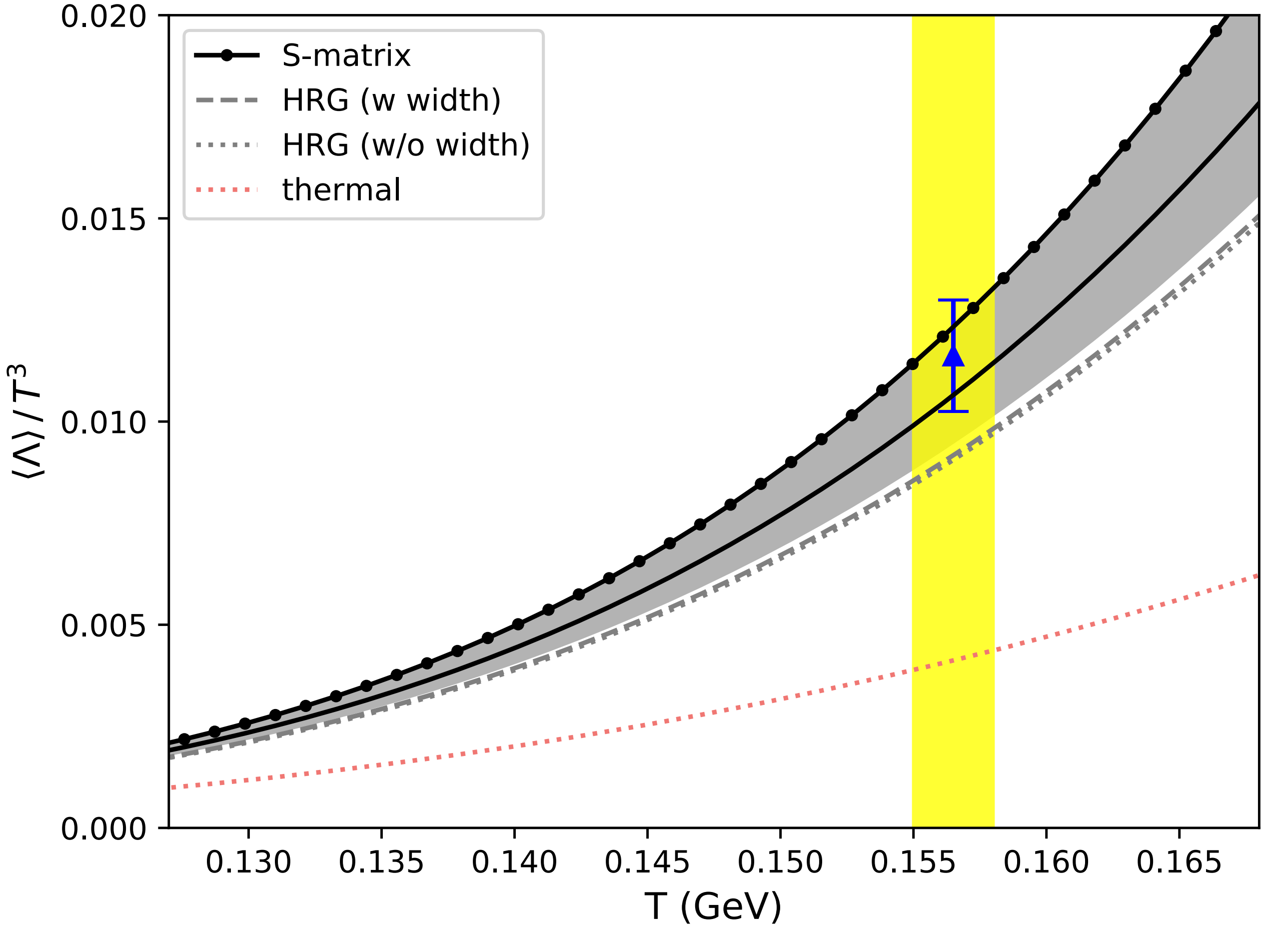
LQCD result on chiBQ

A. Bazavov, et al.,
Phys. Rev. D 86 (2012) 034509.

see also
Bellwied et al.
Phys. Rev. D 101, 034506 (2020)

S-matrix VS HRG





Jefferson Lab
Thomas Jefferson National Accelerator Facility

`piN phase shifts`
`pipiN BGs`
`hyperons`

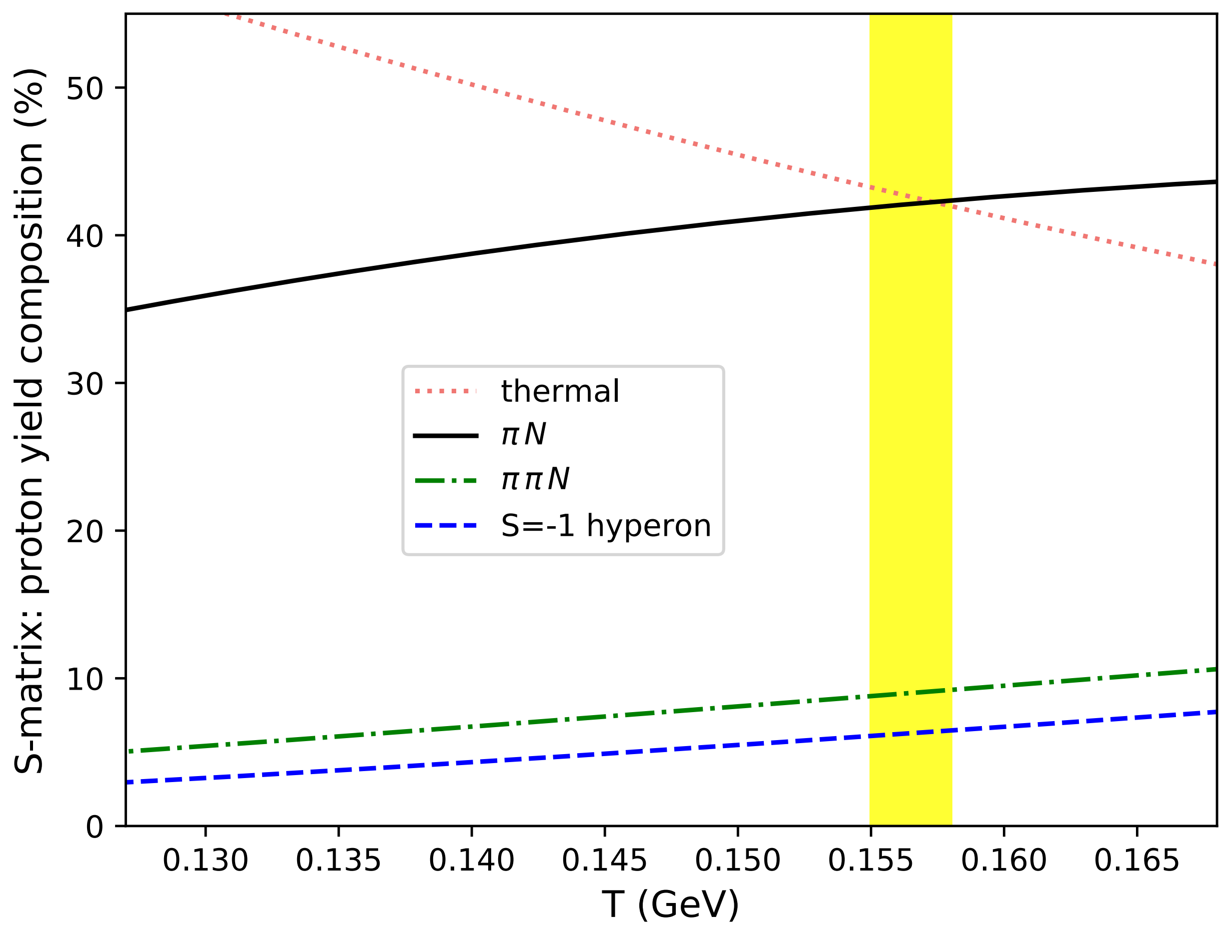
Coupled-Channel model:

$\bar{k}N, \pi\Lambda, \pi\Sigma, \ldots$

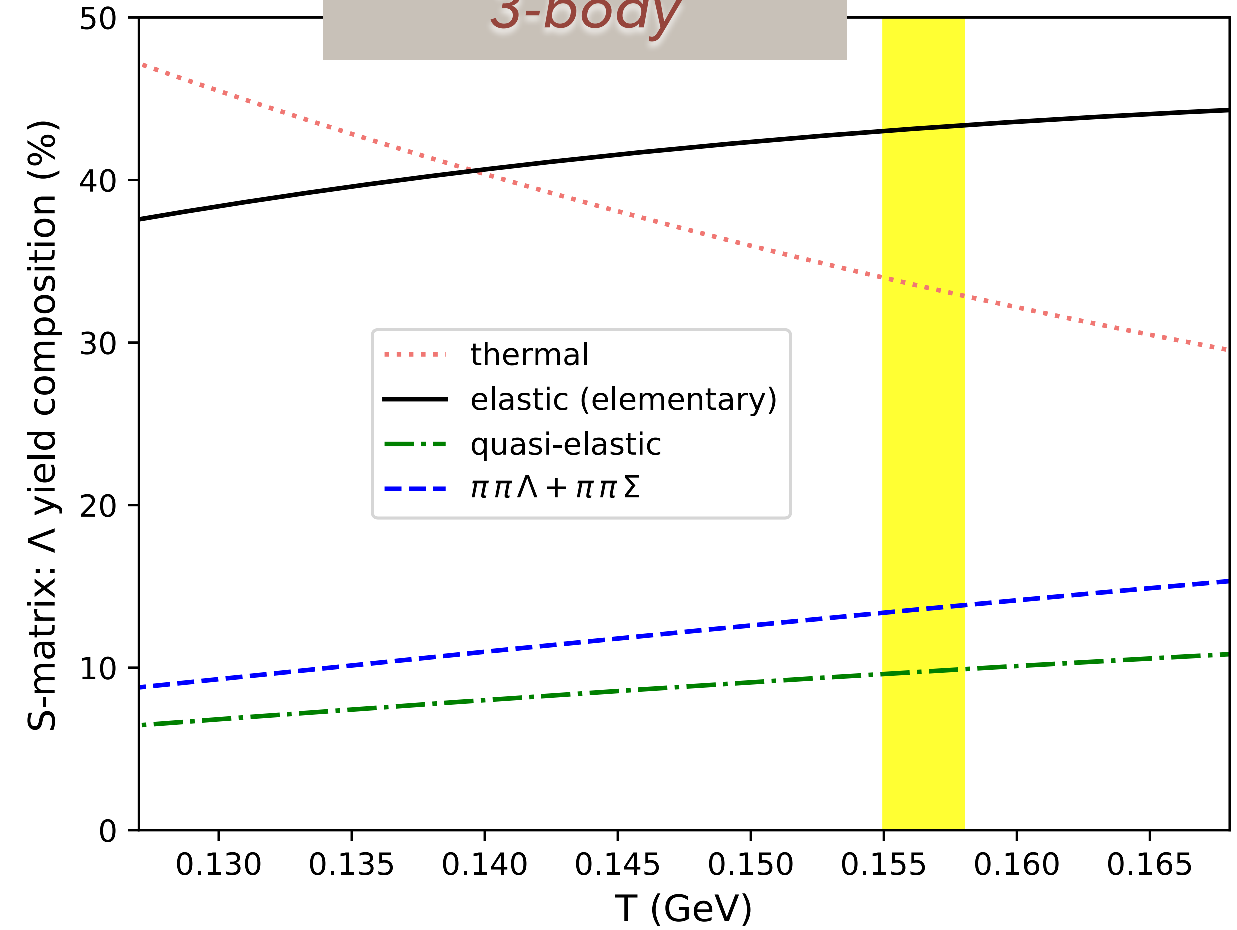
extra hyperon states beyond PDG

unitarity BGs

consistent treatment of res and non-res. int.



quasi-elastic +
3-body



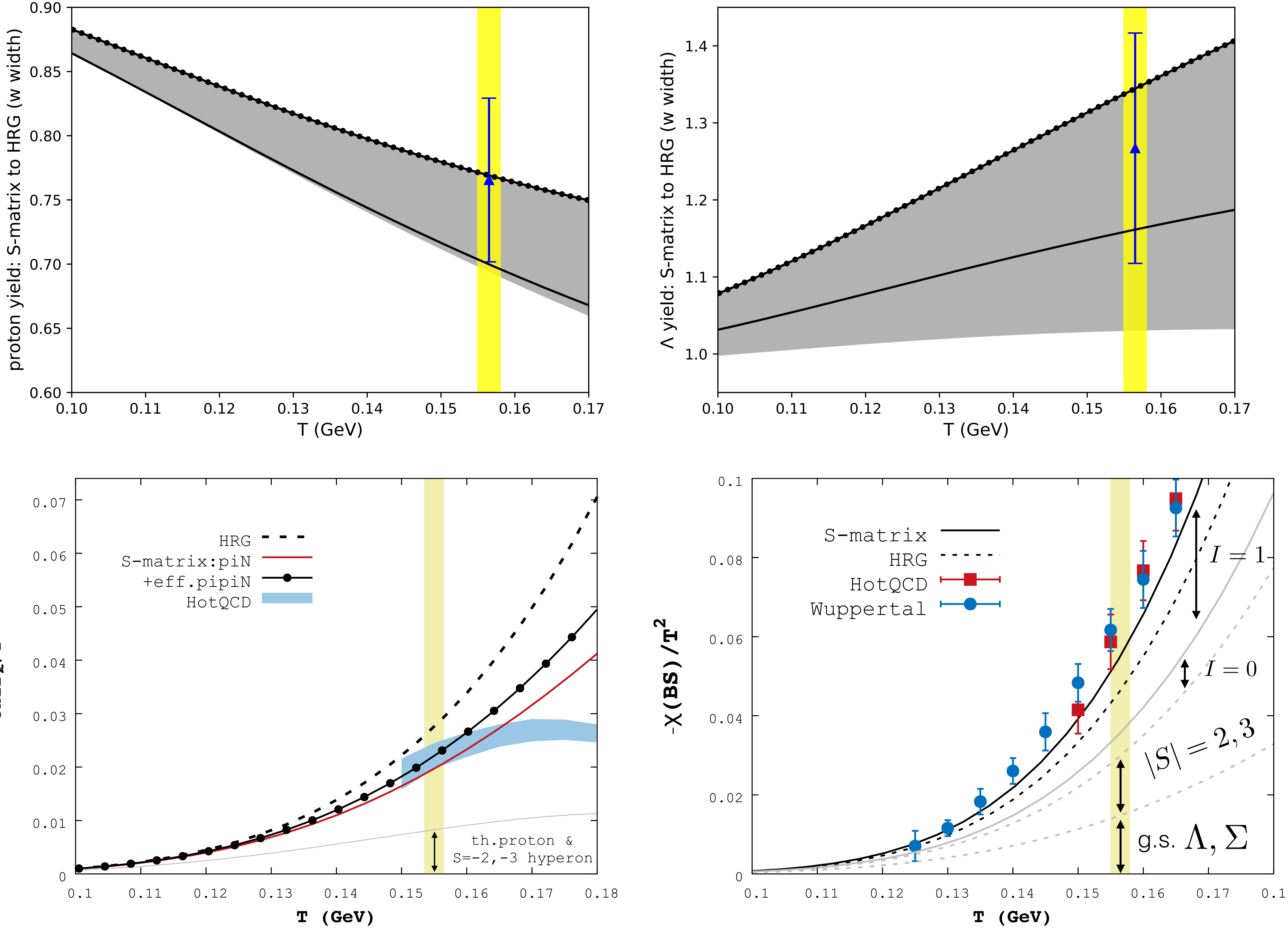
piN phase shifts
pipiN BGs
hyperons

Coupled-Channel system:

$$\bar{k}N, \pi\Lambda, \pi\Sigma, ...$$

extra hyperon states
beyond PDG
unitarity BGs

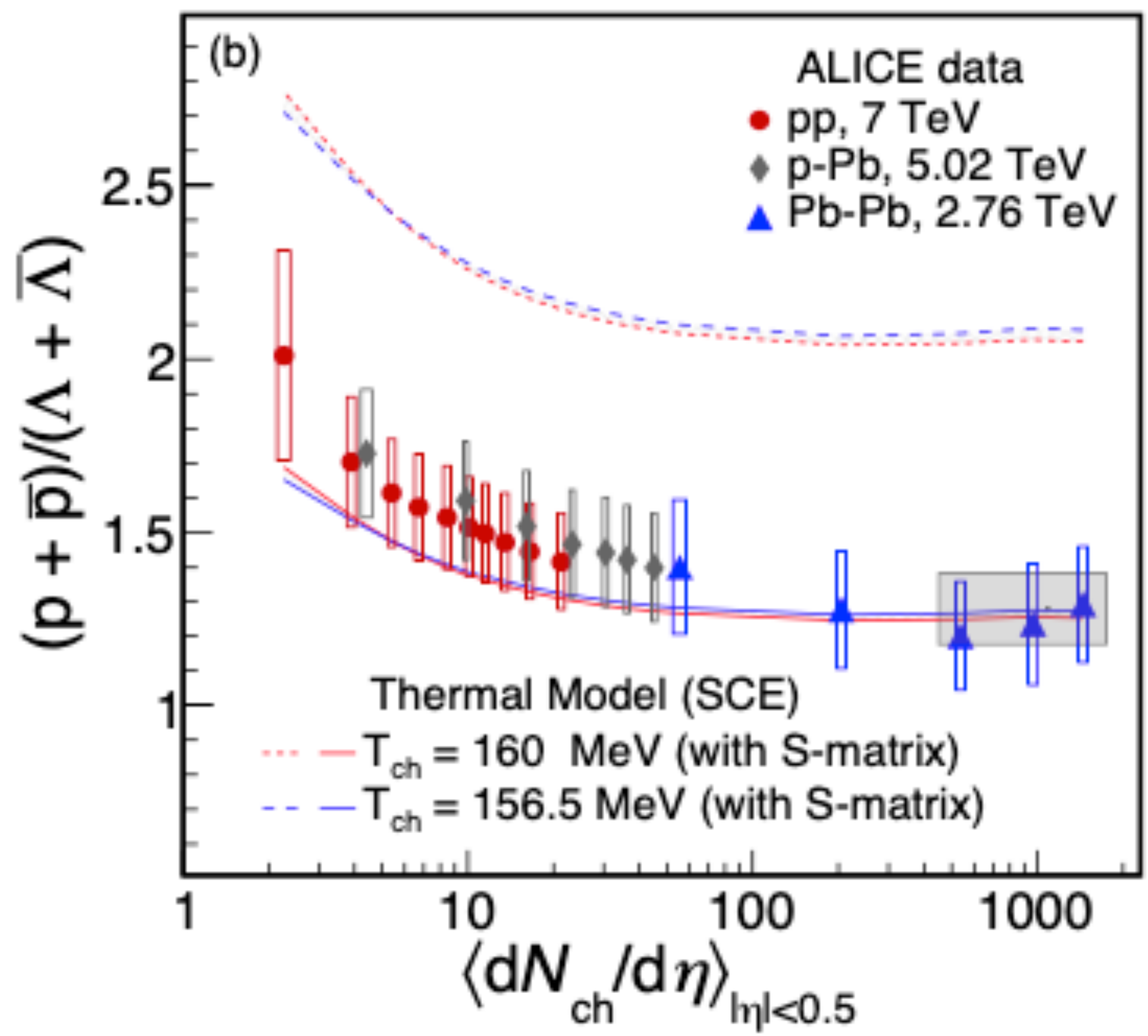
consistent treatment of res and non-res. int.



proton yield: S-matrix to HRG (w width)
T (GeV)
Λ yield: S-matrix to HRG (w width)
T (GeV)
chiBQ/T^2
HRG
S-matrix:piN
+eff.pipiN
HotQCD
th.proton &
S=-2,-3 hyperon
T (GeV)
-χ(BS)/T^2
S-matrix
HRG
HotQCD
Wuppertal
I = 1
I = 0
|S| = 2, 3
g.s. Λ, Σ
T (GeV)

less protons

more lambdas

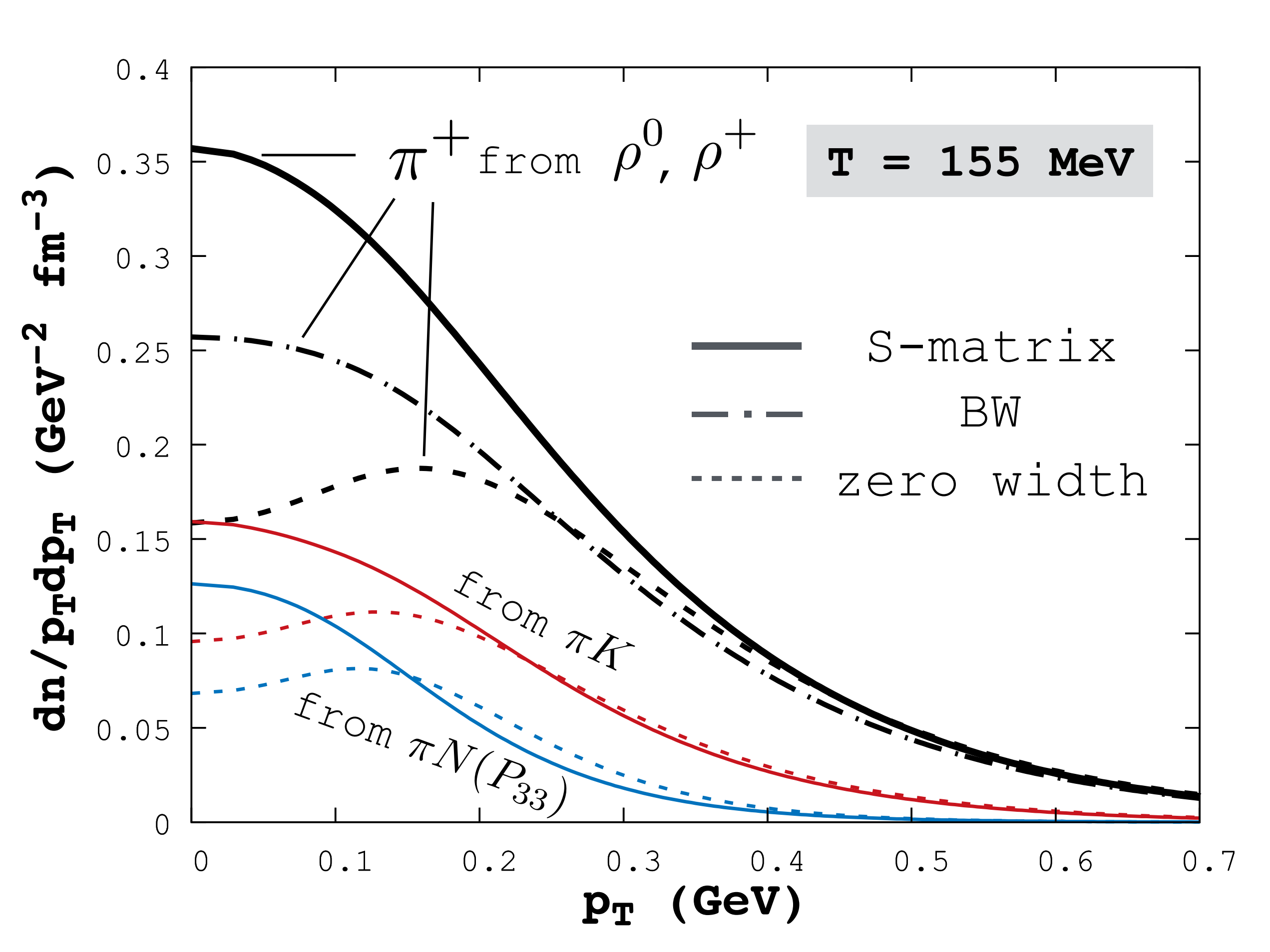


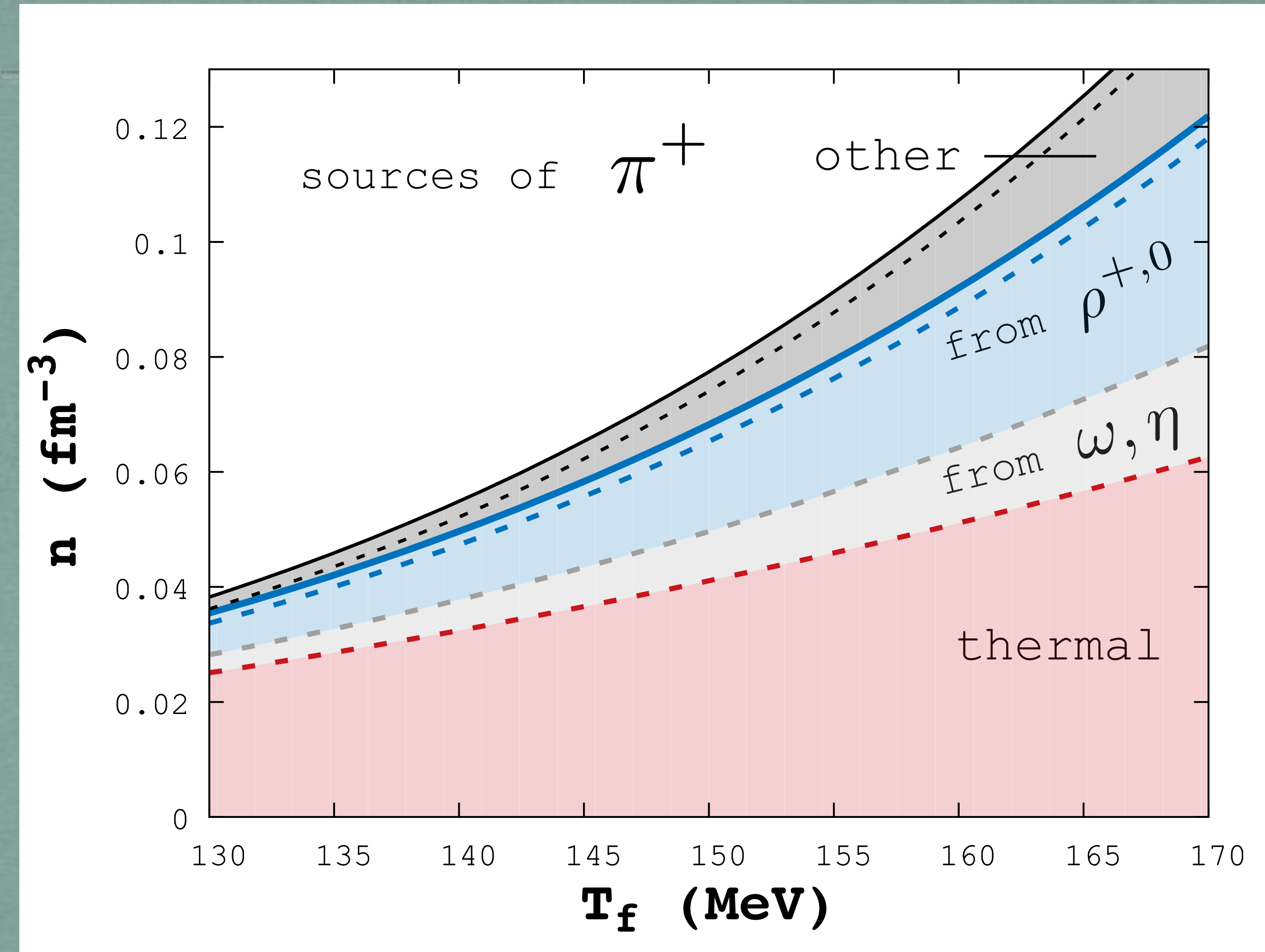
hrg

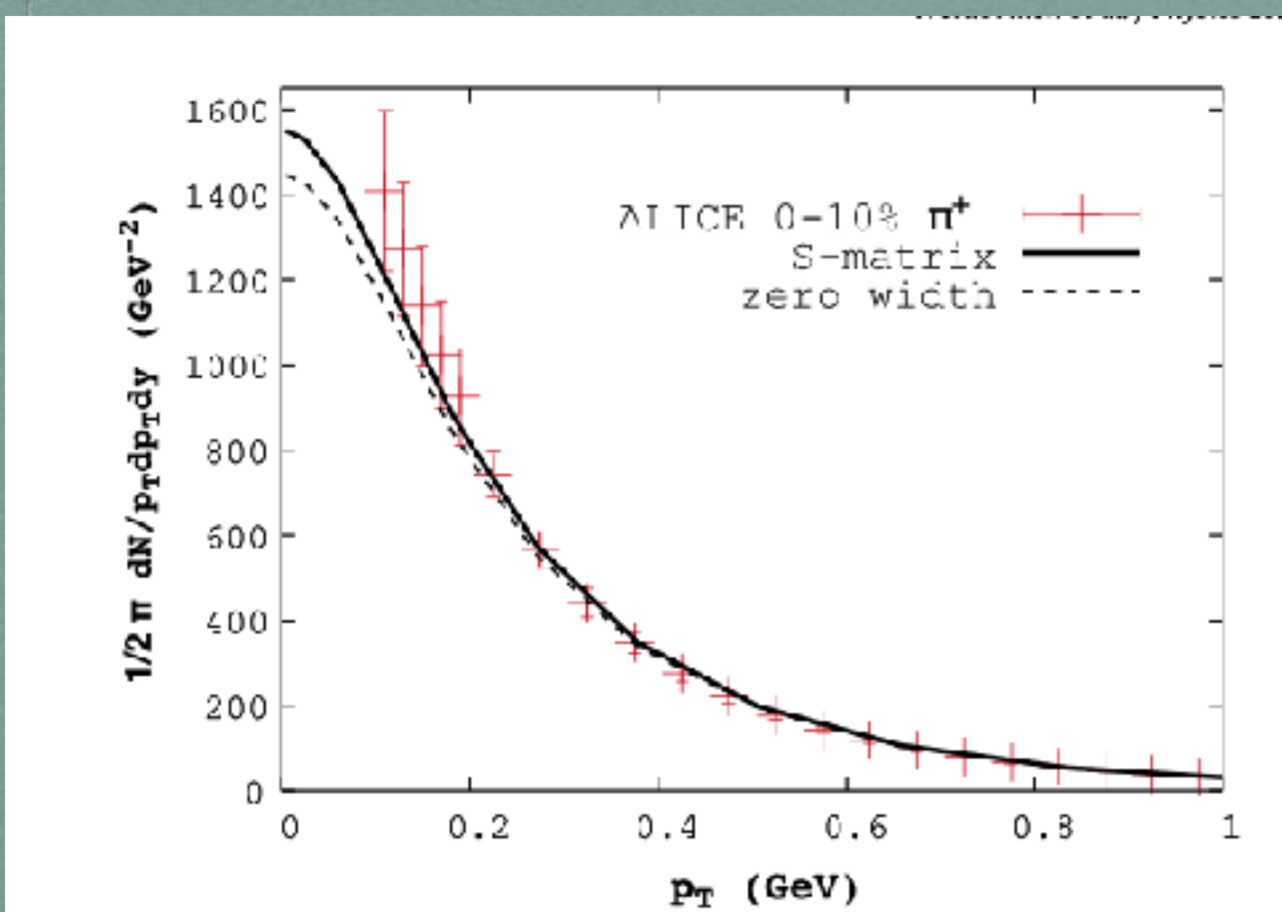
smat

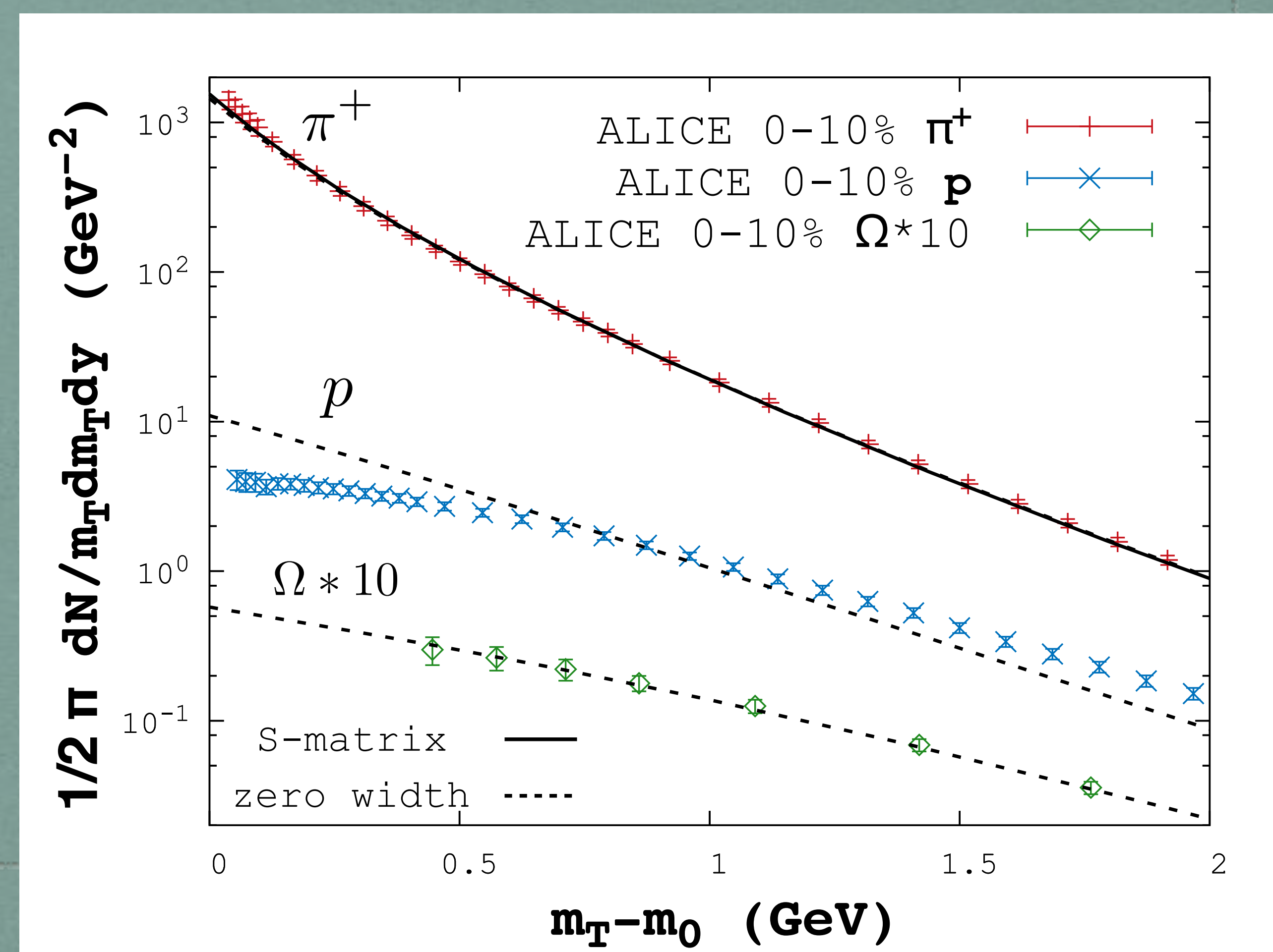
Phys. Rev. C 103, 014904 (2021).

Phys. Lett. B 792, 304 (2019).


π+ from ρ0, ρ+
T = 155 MeV
S-matrix
BW
zero width
from πK
from πN(P33)
dn/pTdpT (GeV-2 fm-3)
pT (GeV)

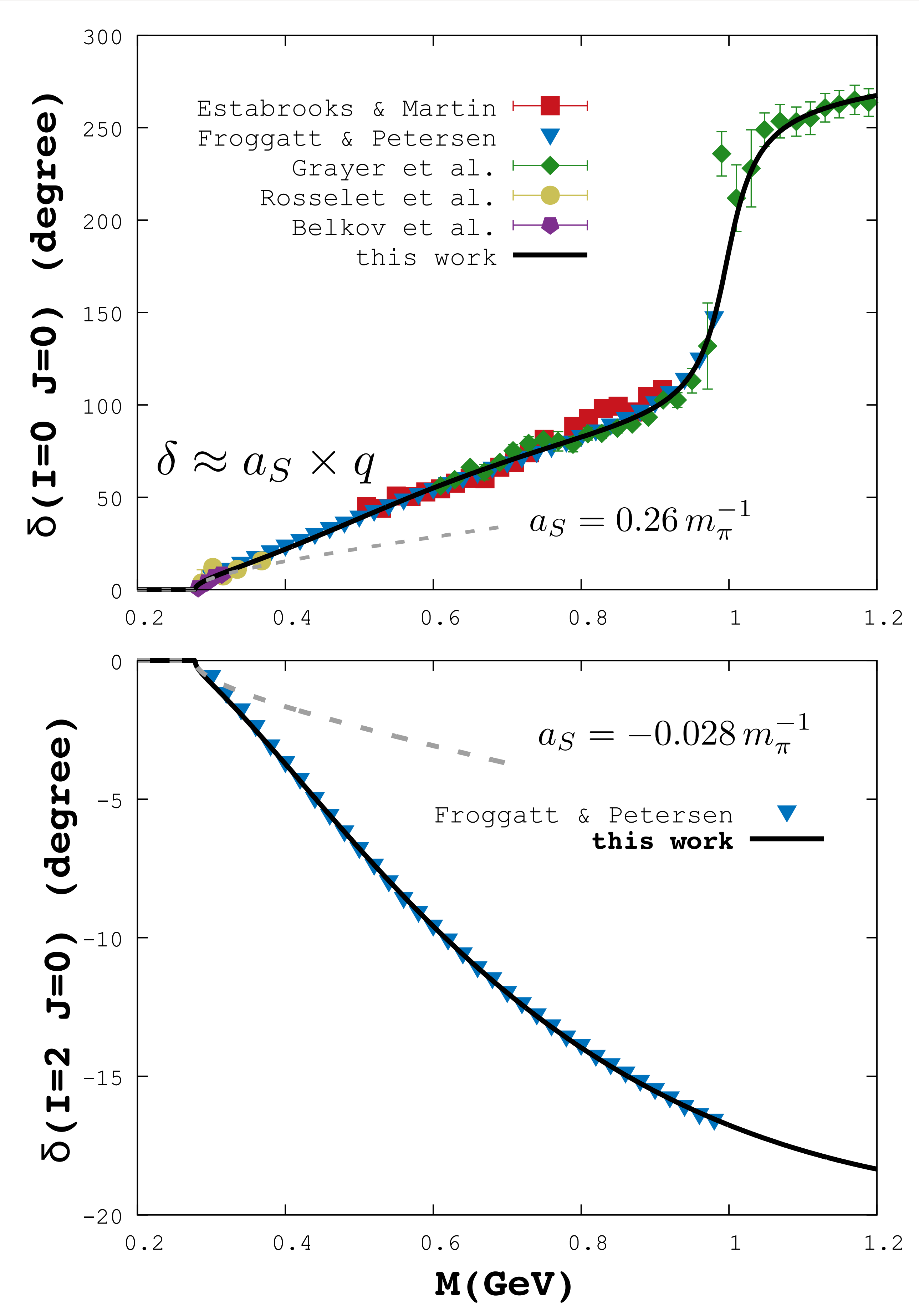

sources of π+
other
from ρ+,0
from ω, η
thermal
n (fm-3)
Tf (MeV)


ALICE 0-10% π+
S-matrix
zero width
1/2 π dN/pTdpTdy (GeV-2)
pT (GeV)


π+
ALICE 0-10% π+
ALICE 0-10% p
ALICE 0-10% Ω*10
p
Ω * 10
S-matrix
zero width
1/2 π dN/mTdmTdy (GeV-2)
mT-m0 (GeV)

phase shifts encode hadronic interactions.

- positive:
  - attractive forces
  - resonances formation
- negative:
  - repulsive forces
  - hard-core
  - channel opening up
  - resonance not as strong



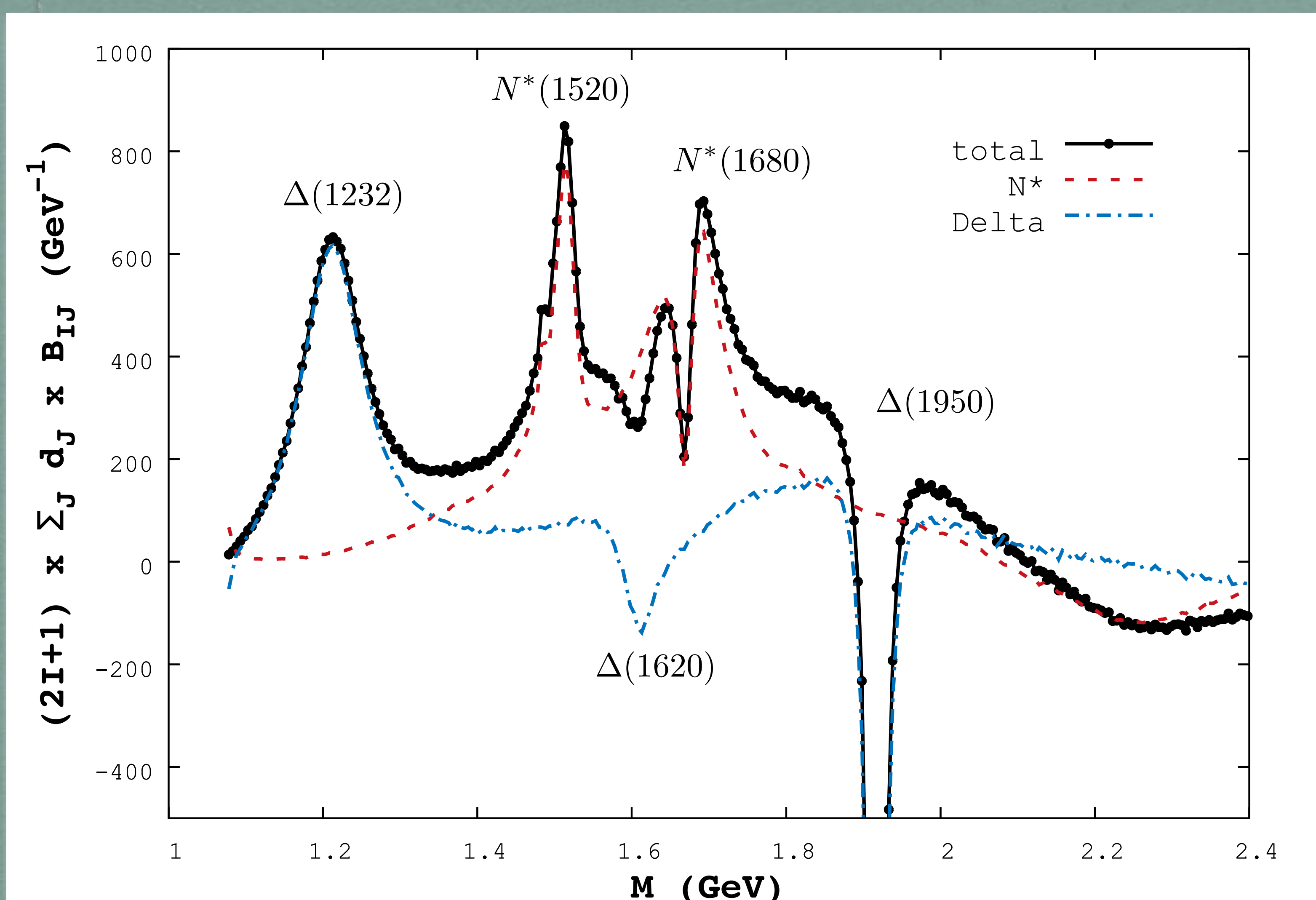
W. Broniowski, F. Giacosa and V. Begun, PRC **92**, 034905 (2015)

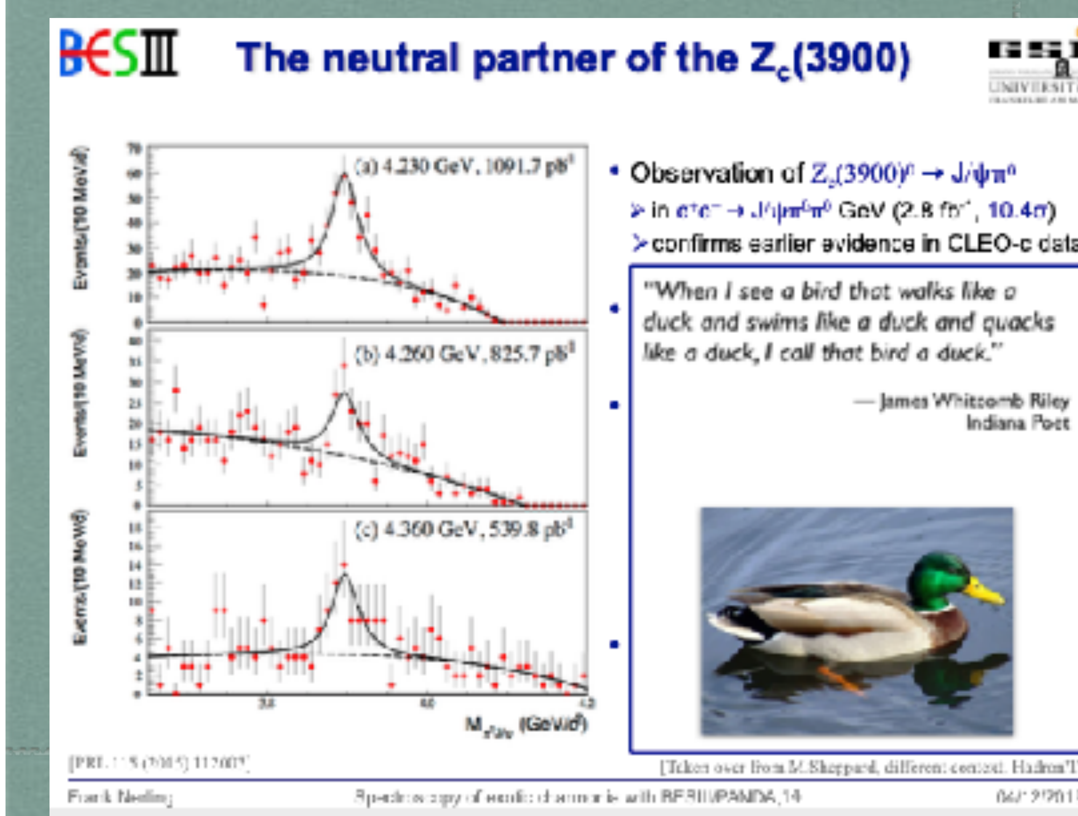
FACTS OF HADRON PHYSICS

- broad /overlapping resonances
- molecular states
- threshold effects /cusps

non-resonant interactions: +/-

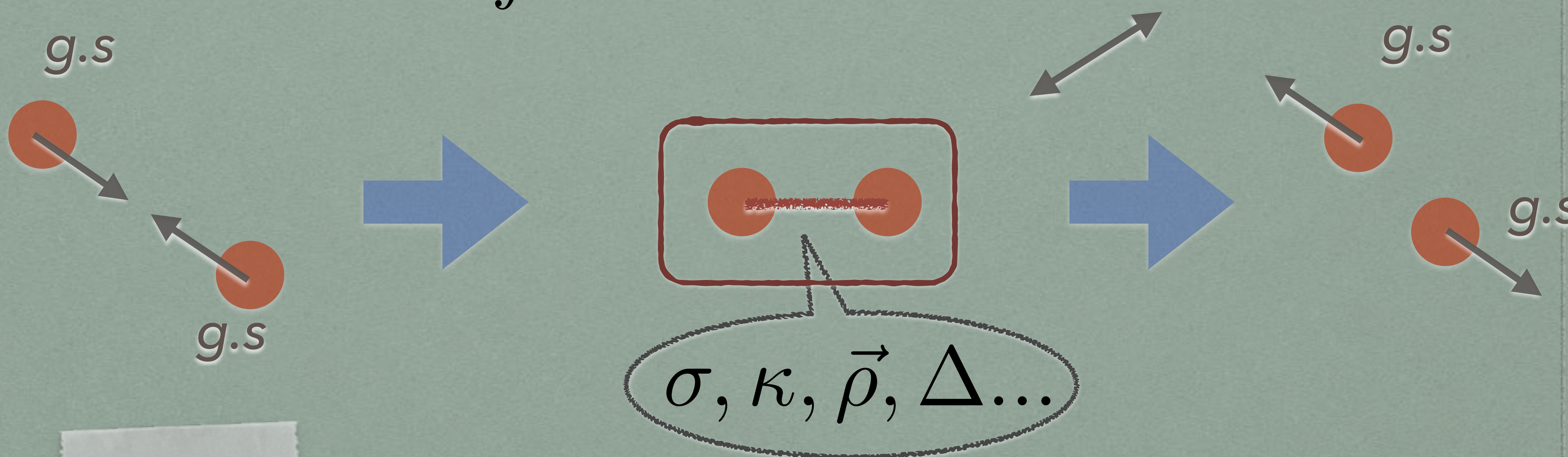
$$\pi N \to \Delta \to \pi N$$





S-MATRIX FORMULATION OF STATISTICAL MECHANICS

$$\Delta \ln Z = \int dE \, e^{-\beta E} \times \frac{1}{\pi} \frac{\partial}{\partial E} \mathrm{tr} \, (\delta_E) \, .$$



+ repulsions

PWA
X
S-matrix thermo.

$$\delta \longrightarrow \mathcal{Q}(M) \equiv \frac{1}{2} \, \mathrm{Im} \, (\mathrm{tr} \ln \mathrm{S})$$

S-MATRIX FORMULATION OF STATISTICAL MECHANICS

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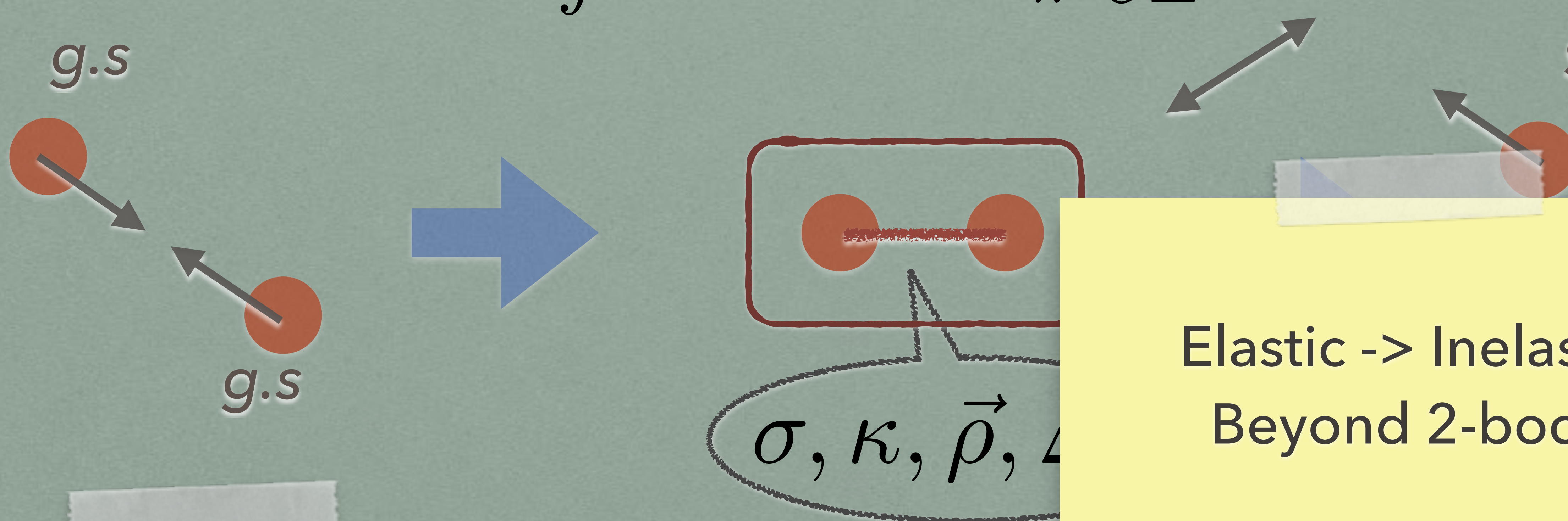


Elastic -> Inelastic
Beyond 2-body

+ *repulsions*

PWA
X
S-matrix thermo.

$$\delta \longrightarrow \mathcal{Q}(M) \equiv \frac{1}{2} \, \mathrm{Im} \, (\mathrm{tr} \ln \mathrm{S})$$

S-MATRIX FORMULATION OF THERMODYNAMICS

thermo-statistical ***dynamical***

$$\Delta \ln Z = \int dE \, e^{-\beta E} \frac{1}{4\pi i} \, \mathrm{tr} \left\{ S_E^{-1} \overleftrightarrow{\frac{\partial}{\partial E}} S_E \right\}_c$$

$$b_{\pi\pi}\xi_\pi^2 + b_{\pi K}\xi_\pi\xi_K + b_{\pi N}\xi_\pi\xi_N + b_{\pi\eta}$$

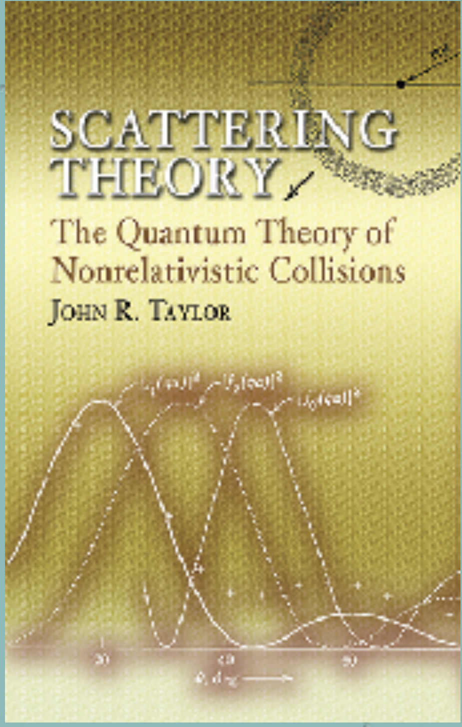
$$b_{\pi\pi} = b_{\pi\pi}^{I=0} + 3 \times 3 \times b_{\pi\pi}^{I=1} + 5$$

sum over eigenphases

$$\mathcal{Q} = \frac{1}{2} \, \mathrm{Im}\mathrm{Tr} \, \ln S = \sum_{\text{channels}} \lambda_i$$

Phys. Rev. C 103, 014904 (2021).

EXERCISE: QM SCATTERING OPERATOR



show that

$$S_E = G_0^* \, G^{*\,-1} \, G \, G_0^{-1}$$
$$= 1 - 2\pi i \times \delta(E - H_0) \times T_E$$

$$G = \frac{1}{E - H + i\epsilon}$$

Verify $$\Delta \ln Z = \int dE \, e^{-\beta E} \frac{1}{4\pi i} \mathrm{tr} \left\{ S_E^{-1} \frac{\overleftrightarrow{\partial}}{\partial E} S_E \right\}_c$$

Alternative way to obtain the Beth-Uhlenbeck result!

From Hamiltonian to Scattering Matrix

$$\frac{1}{E - \mathcal{H}_0 \pm i\delta}$$

$$\begin{aligned}\tilde{S} &= (I - G^0_-\,V)\,(I + G^0_+\,T) \\ &= I - G^0_-\,V + G^0_+\,T - G^0_-\,V\,G^0_+\,T \\ &= I - G^0_-\,V + G^0_+\,V + G^0_+\,V\,G^0_+\,T - G^0_-\,V\,G^0_+\,T \\ &= I + (G^0_+ - G^0_-)\,V + (G^0_+ - G^0_-)\,V\,G^0_+\,T \\ &= I + (G^0_+ - G^0_-)\,T \\ &\to I + 2\,i\,\mathrm{Im}\,(G^0_+) \times T.\end{aligned}$$

on-shell limit

WHY IT IS NOT A SUM OF BREIT-WIGNERS

WHAT'S IN A NAME? THAT WHICH WE CALL A RESONANCES?

- A resonance is MORE than a MASS and a **WIDTH**

$f_0(500)$ [g] $I^G(J^{PC}) = 0^+(0^{++})$

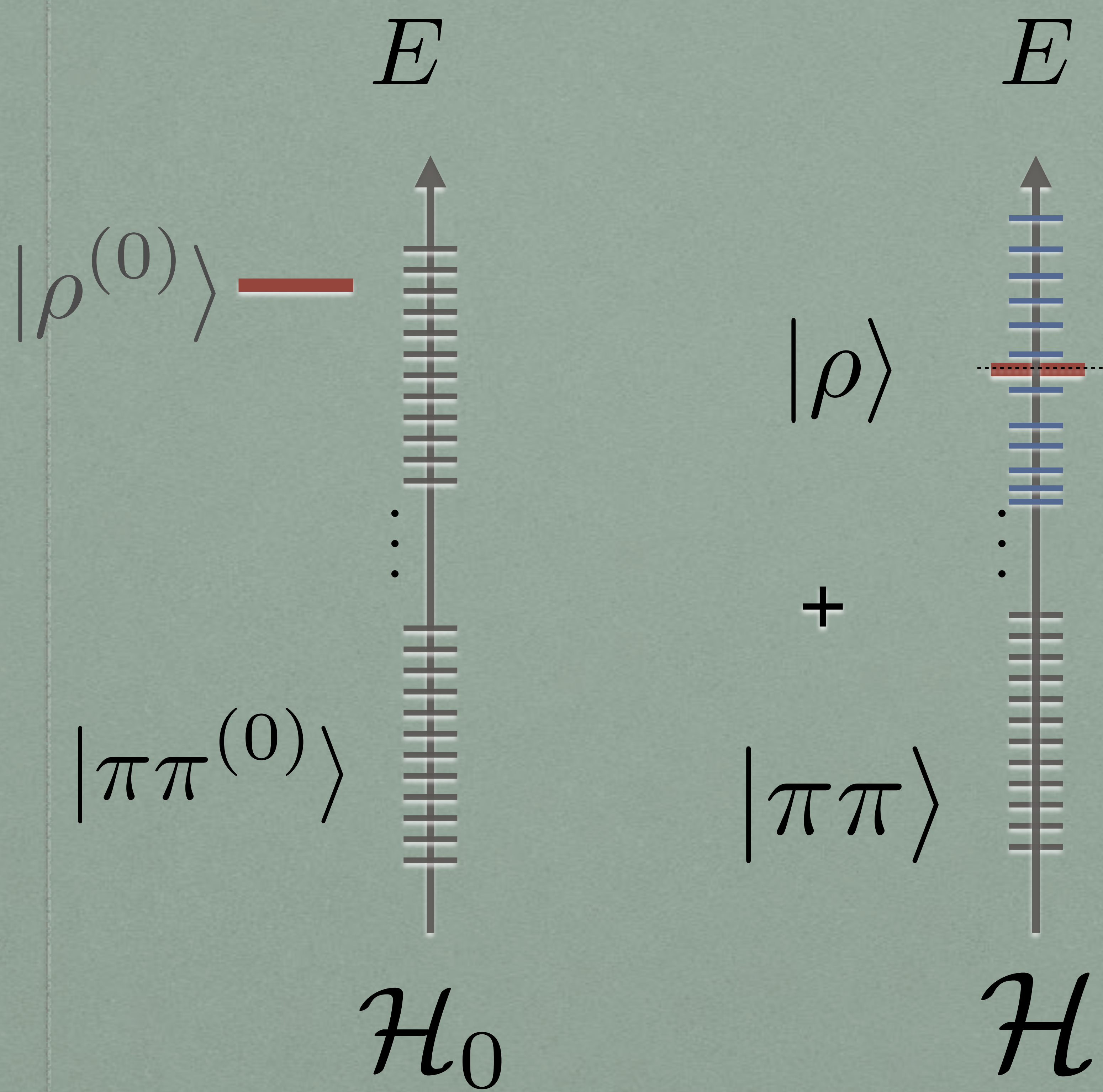
Mass (T-Matrix Pole $\sqrt{s}$) = (400–550)$-i$(200–350) MeV
Mass (Breit-Wigner) = (400–550) MeV
Full width (Breit-Wigner) = (400–700) MeV

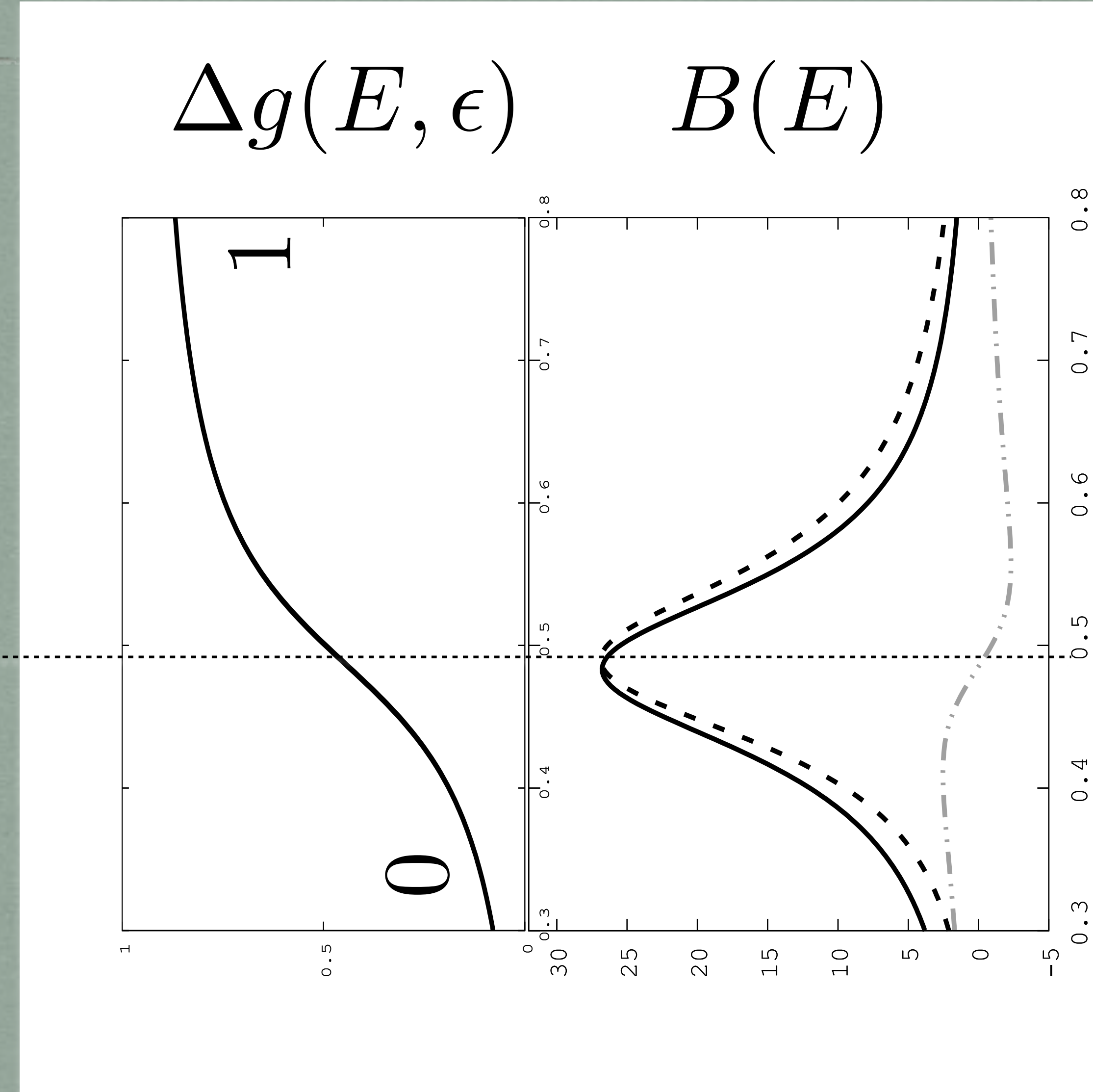
$\rho(770)$ [h] $I^G(J^{PC}) = 1^+(1^{--})$

Mass $m = 775.26 \pm 0.25$ MeV
Full width $\Gamma = 149.1 \pm 0.8$ MeV
$\Gamma_{ee} = 7.04 \pm 0.06$ keV

W. Weinhold, B. Friman, and W. Norenberg. PLB **433**:236-242 (1998)

PML, Francesco Giocosa EPJC **79**(2019)





$$\mathrm{Tr}\, e^{-\beta\mathcal{H}_0} \quad \textit{vs} \quad \mathrm{Tr}\, e^{-\beta\mathcal{H}}$$

$$g(E,\epsilon) = \sum_n \theta_\epsilon(E - E_n)$$

$$B(E) = 2\pi \frac{d}{dE}\Delta g(E,\epsilon)$$

$$= A_\rho + \Delta A_{\pi\pi}$$

PHYSICS OF B

$$\delta = -\mathrm{Im}\,\mathrm{Tr}\ln G_\rho^{-1}$$

physical interpretation:

$$B = 2\,\frac{\partial}{\partial E}\delta$$

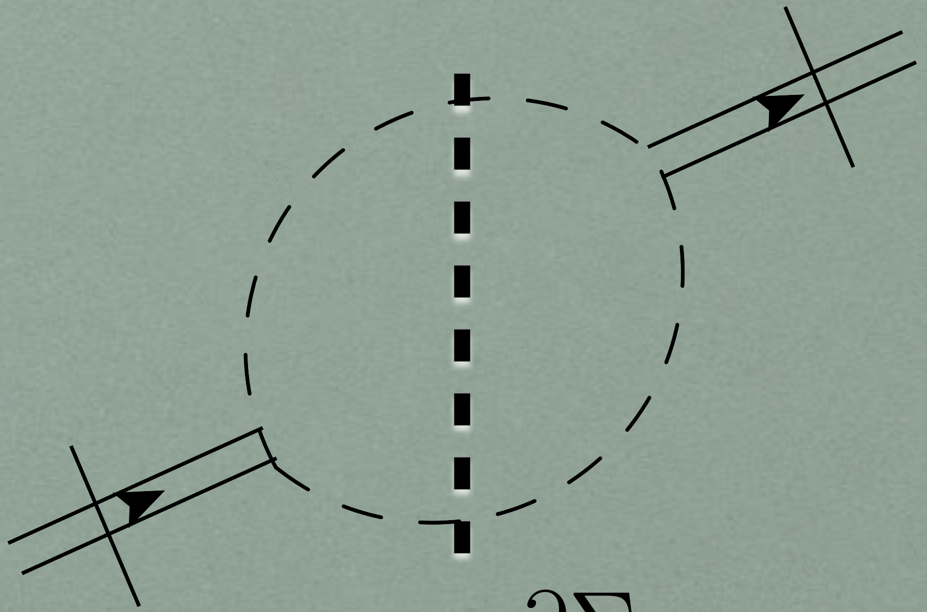
$$= -2\,\mathrm{Im}\frac{\partial}{\partial E}\ln G_\rho^{-1}$$

$$= -2\,\mathrm{Im}[G_\rho](2E) + 2\,\mathrm{Im}[\frac{\partial \Sigma_\rho}{\partial E}G_\rho]$$

$$= A_\rho(E) + \Delta A_{\pi\pi}$$

$$-\frac{\partial}{\partial E}\int d\phi_E\, T_{\mathrm{re}}$$ pipi -> pipi

contribution from
correlated pi pi pair



$$\frac{\partial \Sigma_\rho}{\partial E}$$

PHYSICS OF B

to rho or not to rho?
that's out of the question!

resonance's picture:

$$B(E) = A_\rho(E) + \Delta A_{\pi\pi}$$

rho

scattering picture:

$$B_1 = \frac{\partial}{\partial E}\,\mathrm{Tr}\,\hat{t}_{\rm re}$$

$$B_2 = \frac{1}{2}\,\mathrm{Im}\,\mathrm{Tr}\,\hat{t}^\dagger\,\overleftrightarrow{\partial_E}\,\hat{t}$$

pipi -> pipi

$$\delta = -\mathrm{Im}\,\mathrm{T}$$

$$B = 2\,\frac{\partial}{\partial E}\delta$$

$$= -2\,\mathrm{Im}\,\frac{\partial}{\partial E}$$

$$= -2\,\mathrm{Im}[G$$

$$= A_\rho(E) + \Delta A_{\pi\pi}$$

$$-\frac{\partial}{\partial E}\int d\phi_E\, T_{\rm re}$$

pipi -> pipi

$$\frac{\partial \Sigma_\rho}{\partial E}$$

on:

m

air

DYNAMICAL GENERATION OF BS / RESONANCES

- dynamical generation of bound states / resonances:
  f(980) close to K Kbar threshold
  f(500) dynamically generated
- coupling of open channels: pipi, kkbar with a $|q\bar{q}\rangle$ state

Locher, Markushin, Zheng, EPJC 4 (1998)
Kaminski, Lesniak, Loiseau, EPJC 9 (1999)

what you give ?=? what you get

1 in 5 out!

2 open channels

$$\frac{1}{E - \mathcal{H}_0} = \begin{bmatrix} \Pi_{\pi\pi}(E) & & \\ & \Pi_{K\bar{K}}(E) & \\ & & \frac{1}{E - m^0_{res}} \end{bmatrix}$$

$$V_{int} = \begin{bmatrix} g_{\pi\pi} & g_{\pi K} & g_{\pi R} \\ g_{\pi K} & g_{KK} & g_{KR} \\ g_{\pi R} & g_{KR} & \end{bmatrix}$$

$$G = G_0 + G_0 V_{int} G$$

TESTING THE ROBUSTNESS

$$\mathcal{Q}(E) = \frac{1}{2}\mathrm{Im}\mathrm{Tr}\{\ln S_E\}$$

Getting
Effective DOS
on
REAL Energy

effective DOS

$$B = 2\frac{d}{dE}\mathcal{Q}$$

what is being counted?

can it handle dynamically generated states?

TESTING THE ROBUSTNESS

$$\mathcal{Q}(E) = \frac{1}{2}\mathrm{Im}\mathrm{Tr}\{\ln S_E\}$$

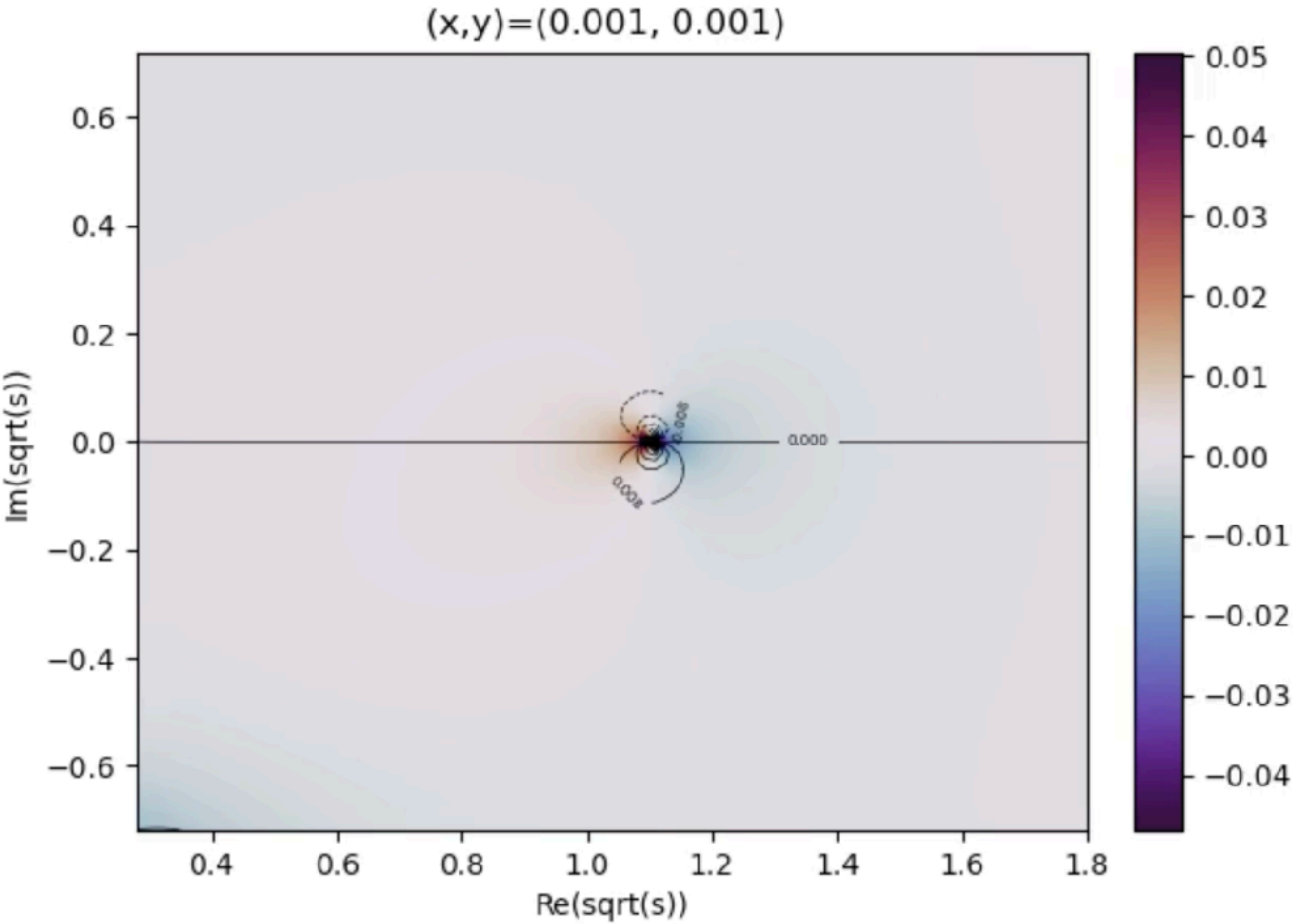
Getting Effective DOS on REAL Energy

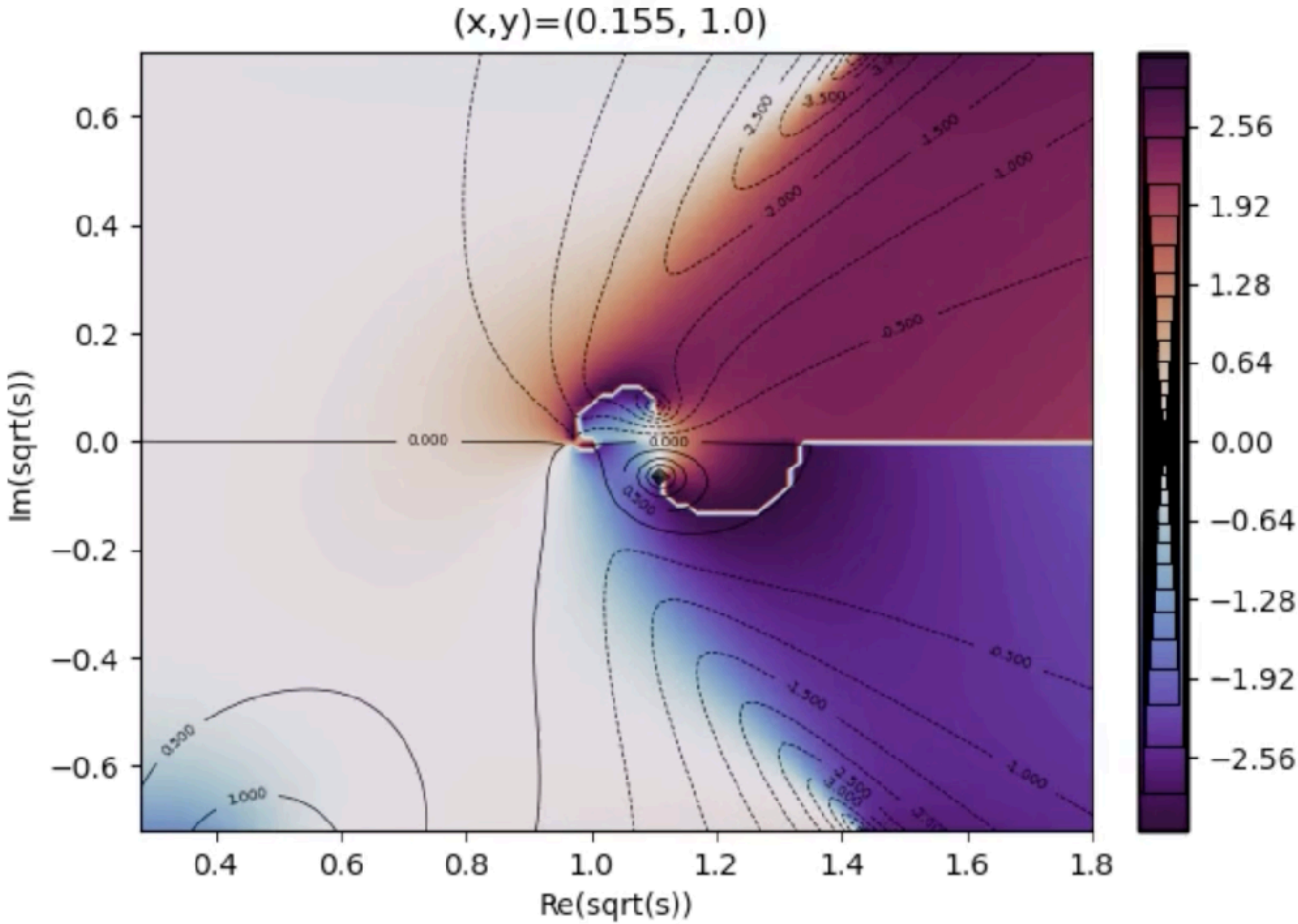
effective DOS

$$B = 2\frac{d}{dE}\mathcal{Q}$$

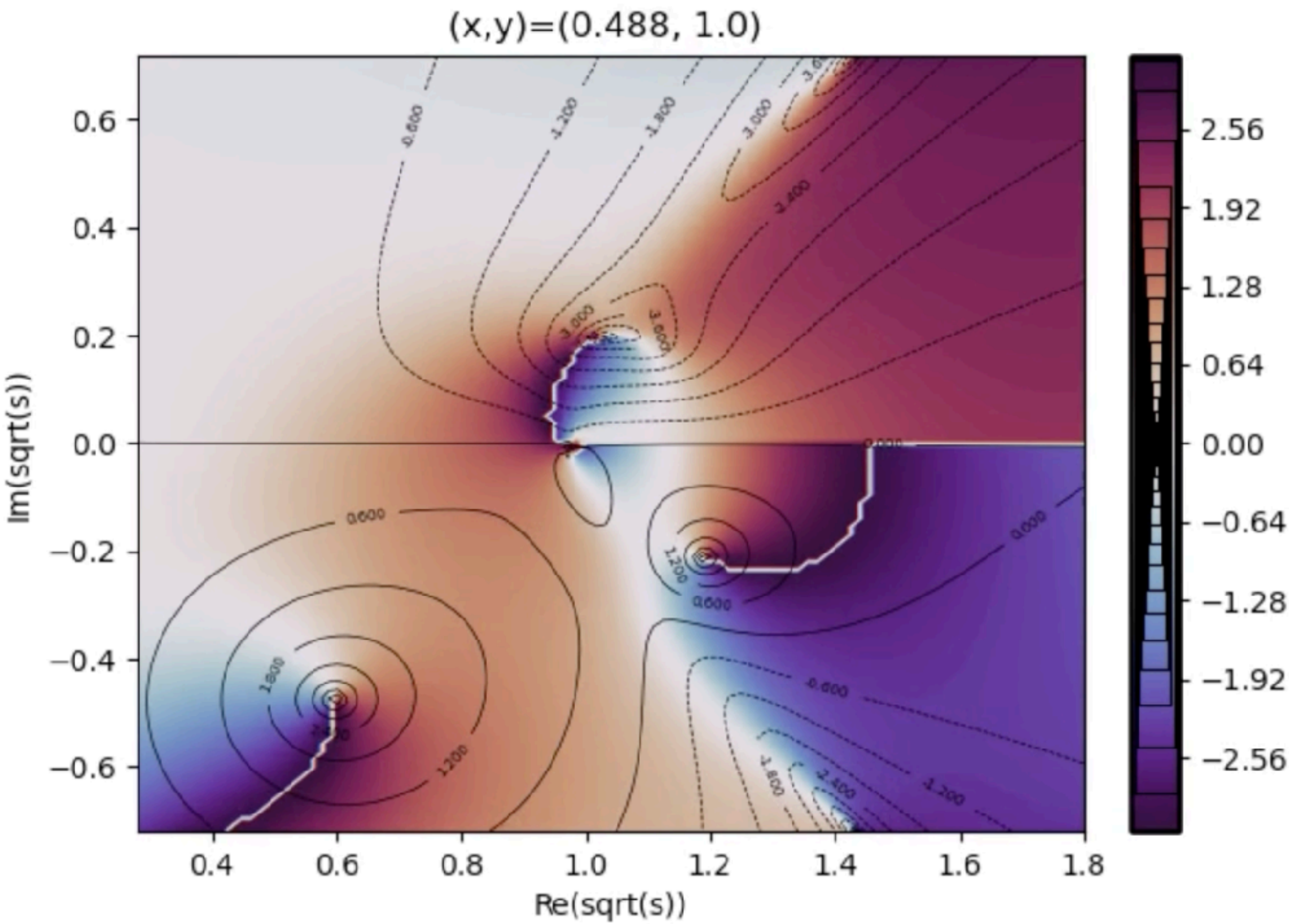
what is being counted?

can it handle dynamically generated st

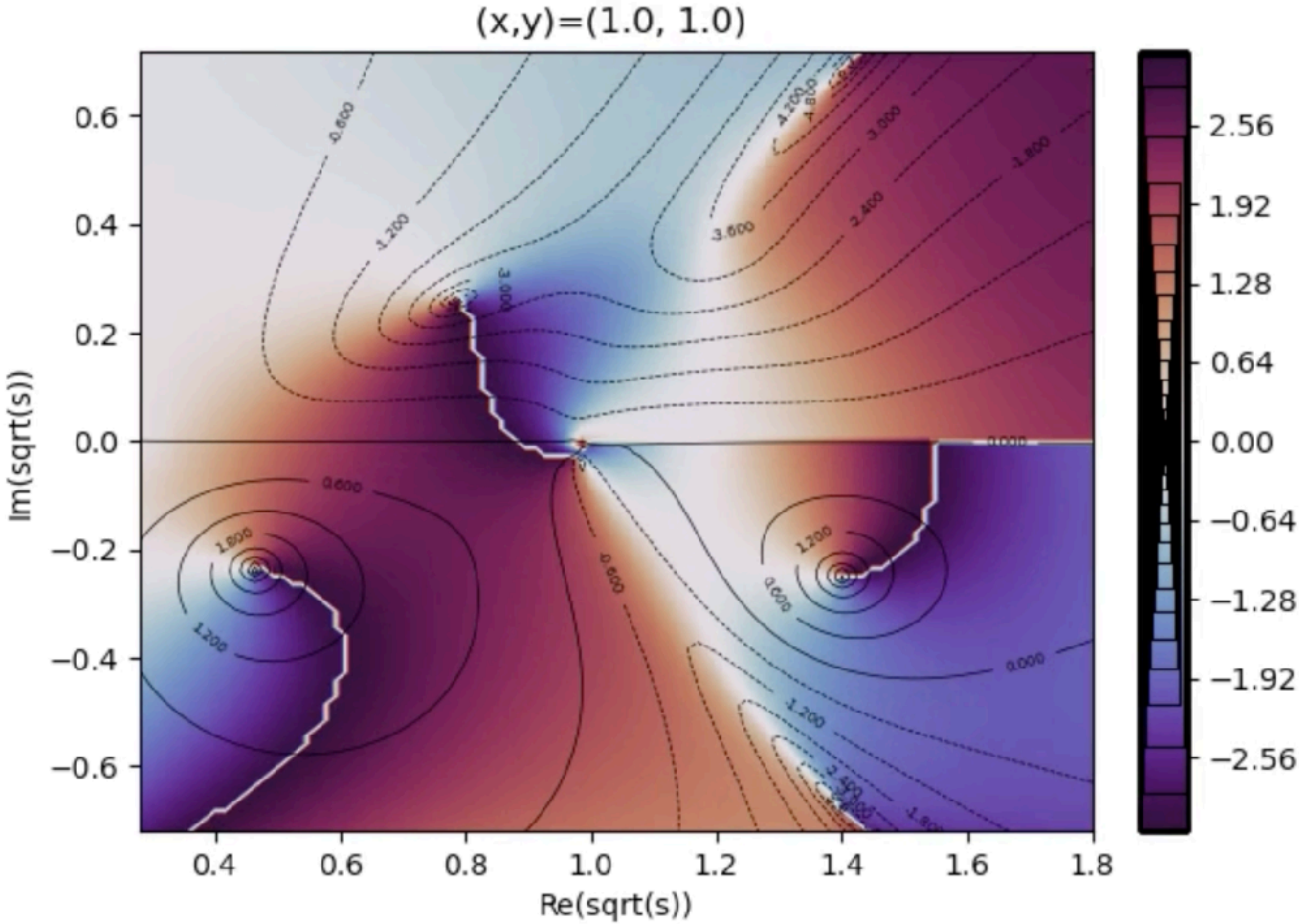

(x,y)=(0.001, 0.001)
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Im(sqrt(s))
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Re(sqrt(s))
0.000
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04

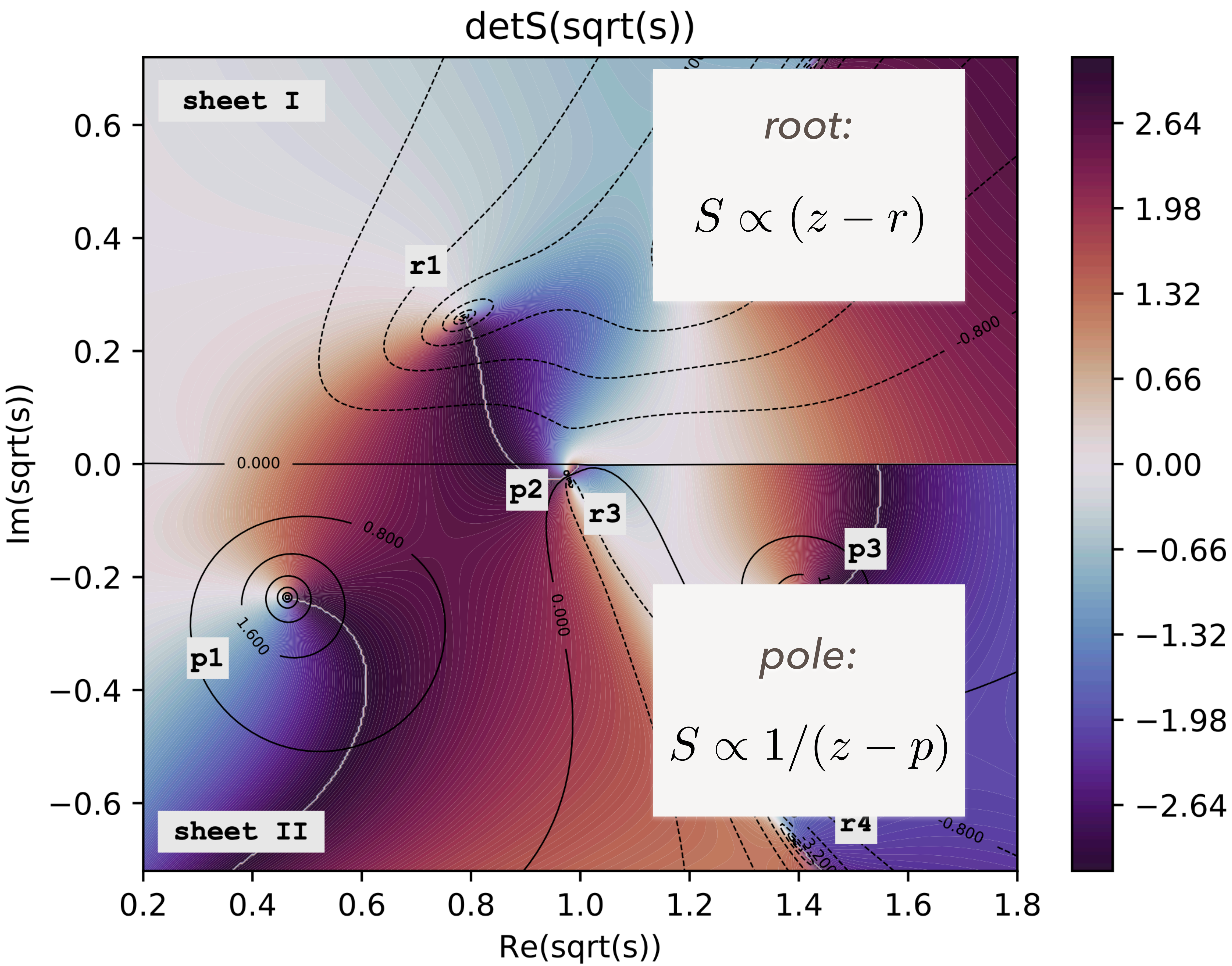


(x,y)=(0.155, 1.0)
Im(sqrt(s))
Re(sqrt(s))
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.56
1.92
1.28
0.64
0.00
−0.64
−1.28
−1.92
−2.56

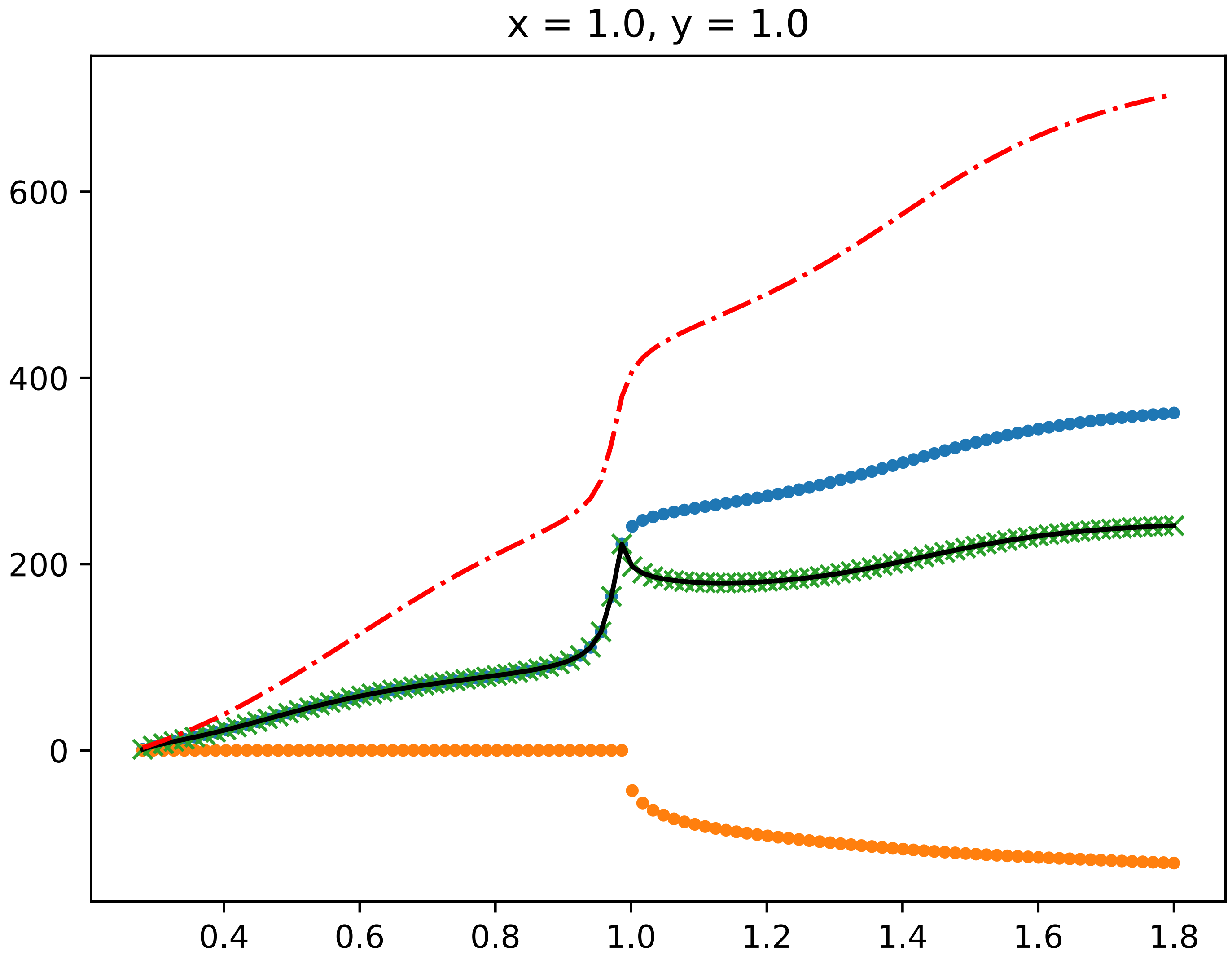


(x,y)=(0.488, 1.0)
Im(sqrt(s))
Re(sqrt(s))
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.56
1.92
1.28
0.64
0.00
−0.64
−1.28
−1.92
−2.56

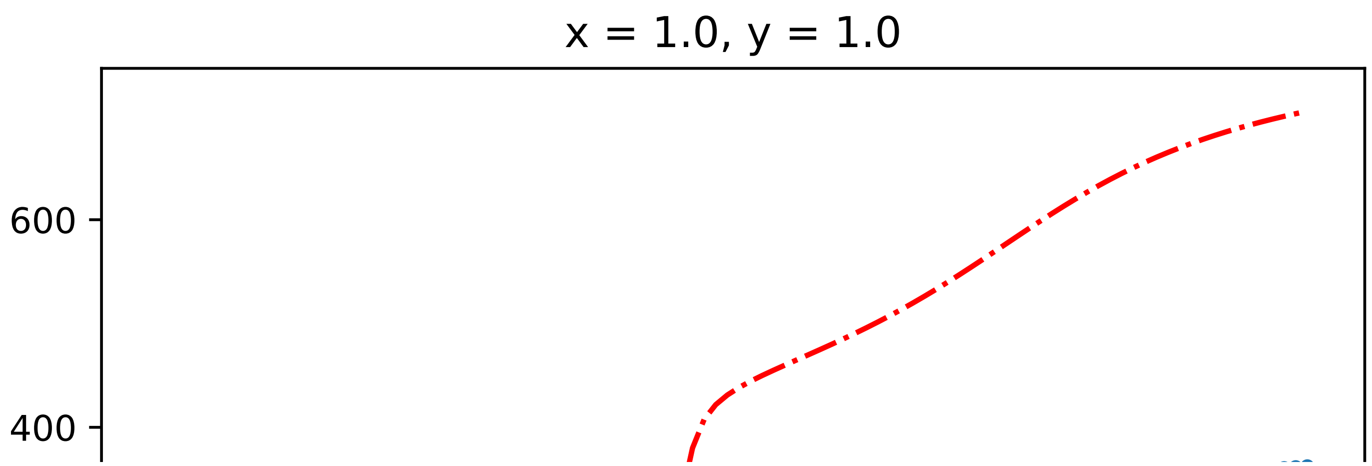

(x,y)=(1.0, 1.0)
Im(sqrt(s))
Re(sqrt(s))
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.56
1.92
1.28
0.64
0.00
−0.64
−1.28
−1.92
−2.56



detS(sqrt(s))
sheet I
sheet II
root:
$S \propto (z - r)$
pole:
$S \propto 1/(z - p)$
r1
r3
r4
p1
p2
p3
0.000
0.800
1.600
-0.800
Im(sqrt(s))
Re(sqrt(s))
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.64
1.98
1.32
0.66
0.00
−0.66
−1.32
−1.98
−2.64



	Re $\sqrt{s}$	Im $\sqrt{s}$	sheet
p1	0.4637	-0.2357	II
p2	0.975	-0.0164	II
p3	1.401	-0.249	II
p4	0.6654	-0.2263	III
p5	1.4176	-0.2640	III
r1	0.787	+0.259	I
r2	1.410	+0.691	I
r3	0.981	-0.032	II
r4	1.393	-0.669	II
r5	0.918	+0.248	IV



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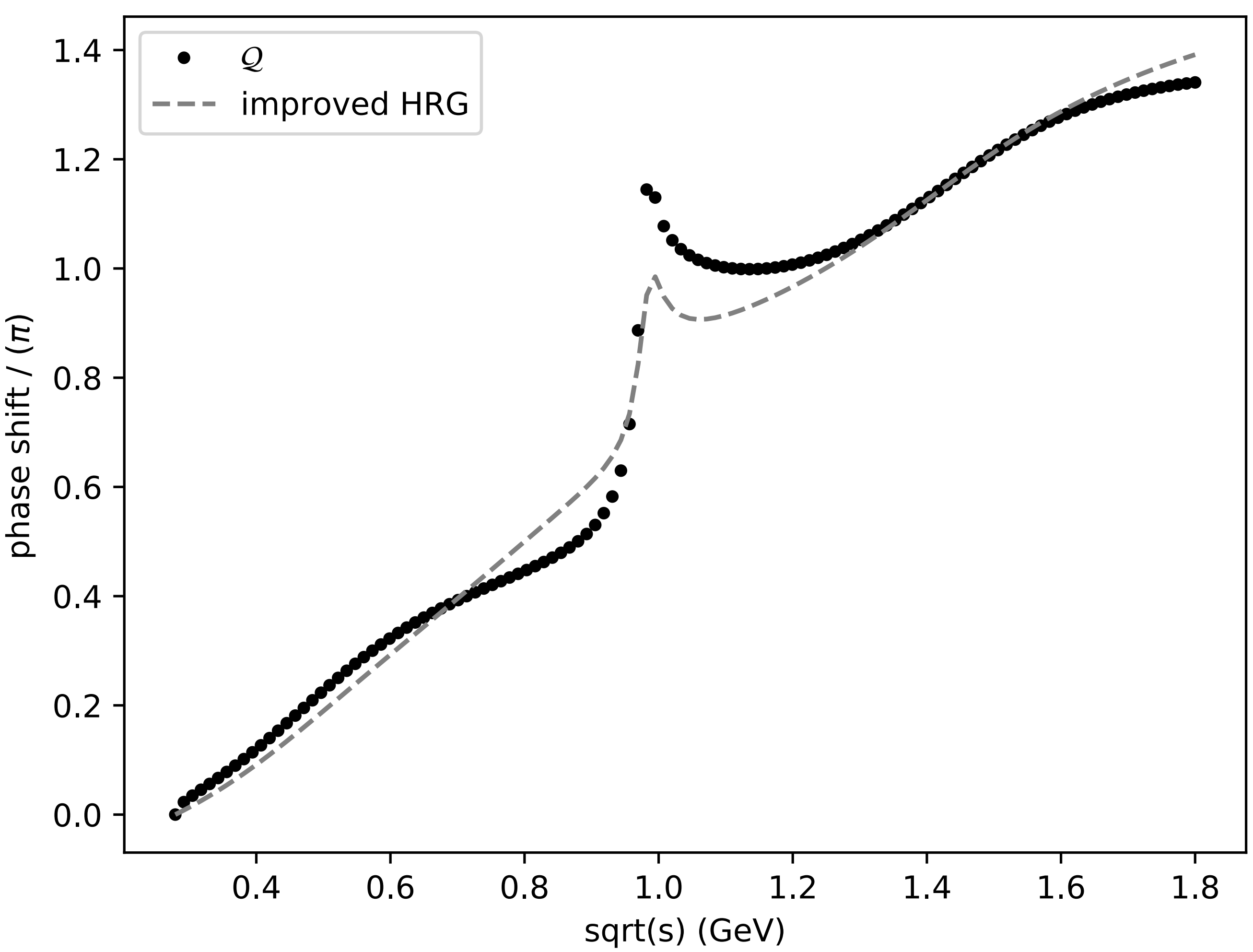
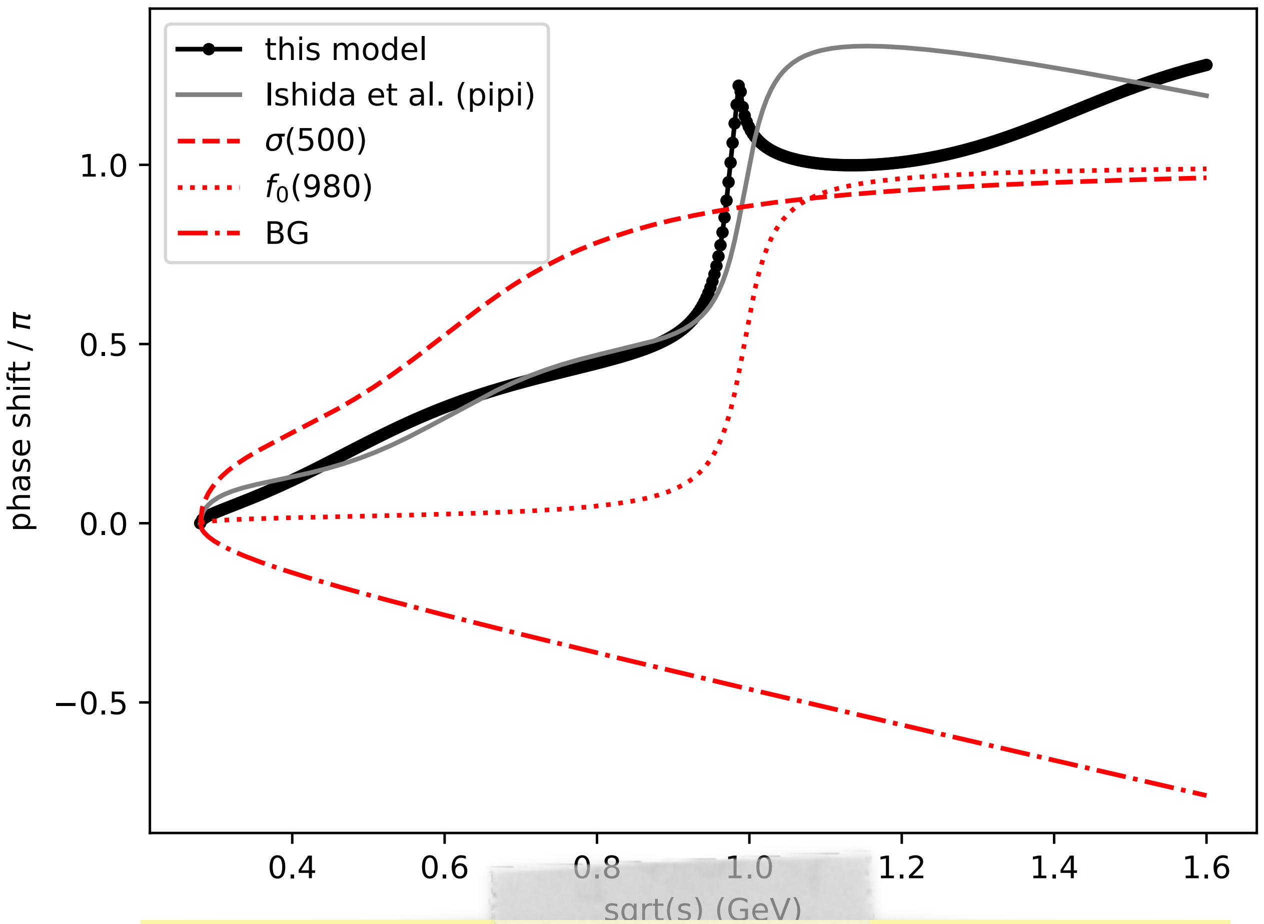


repulsive corrections in HRG-like scheme: via roots

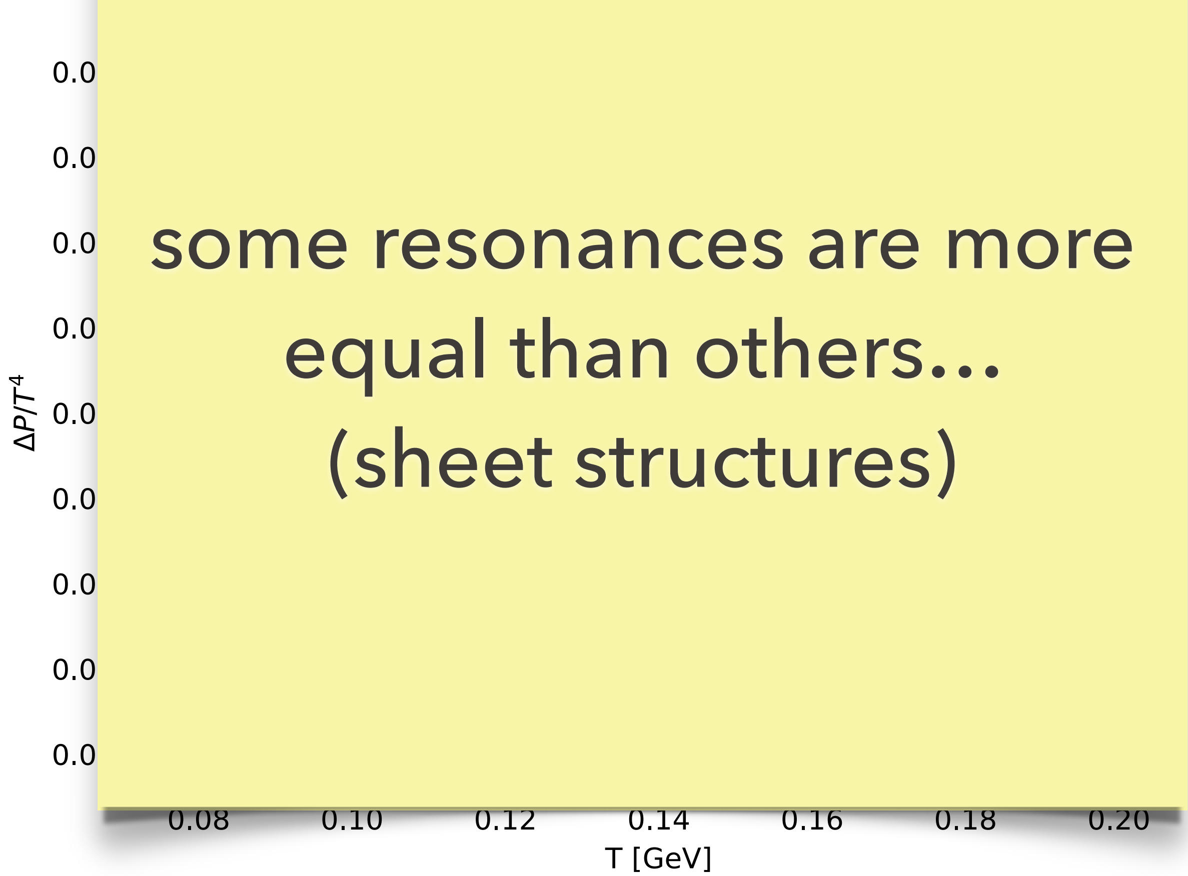
	$\mathrm{Re}\sqrt{s}$	$\mathrm{Im}\sqrt{s}$	sheet

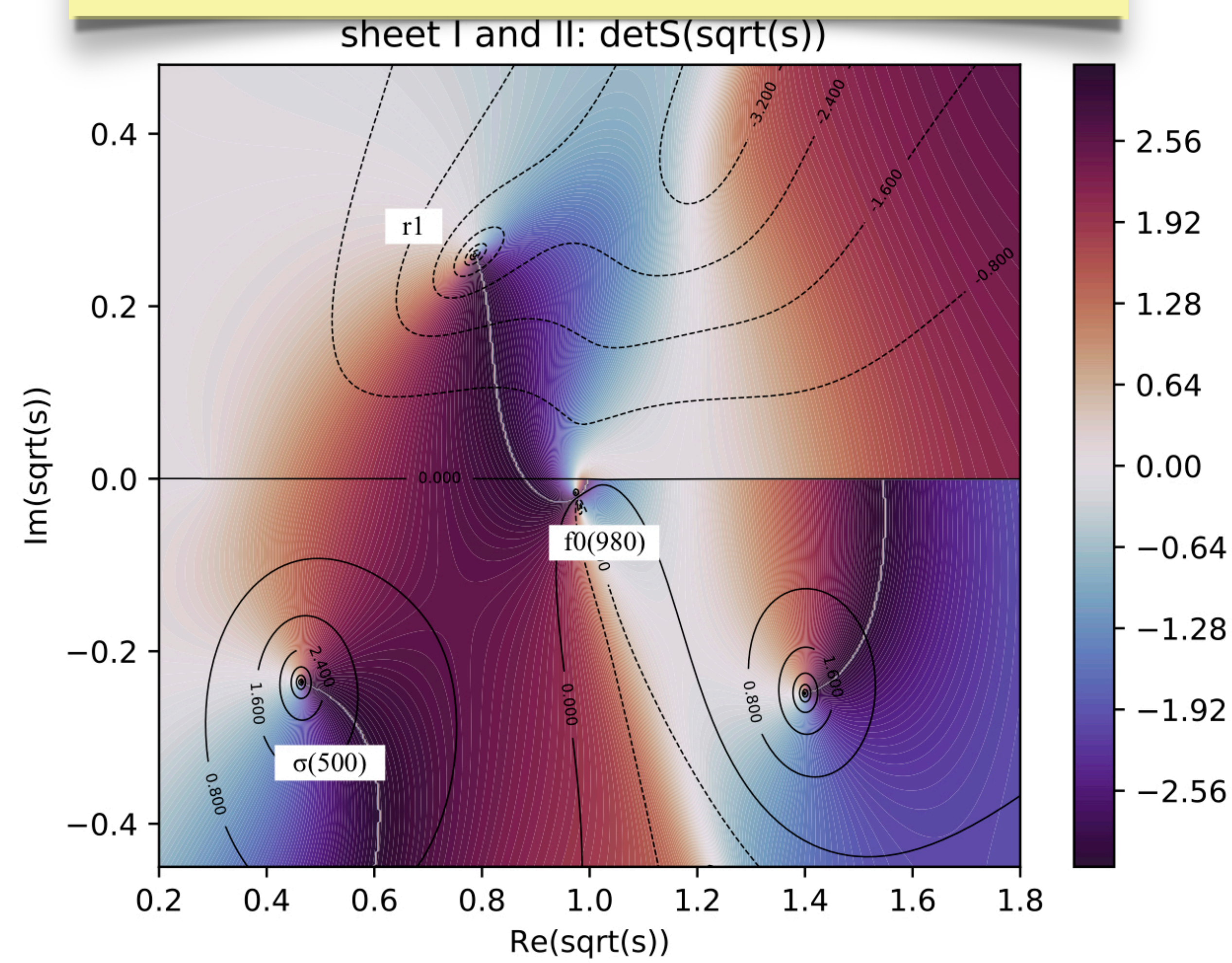


non-Briet-Wigner
=> poles and roots distribution

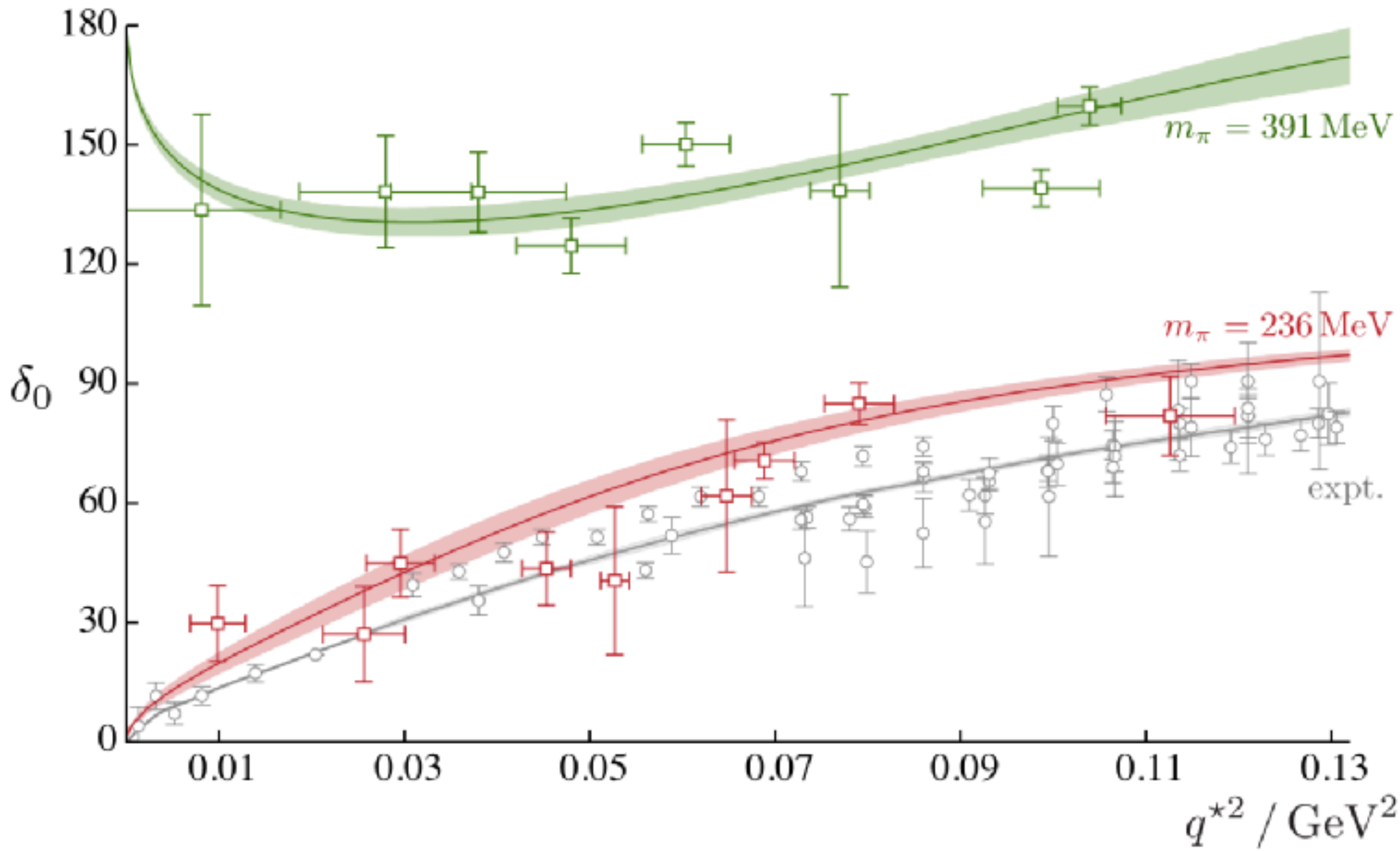
subtractive corrections

some resonances are more equal than others...
(sheet structures)





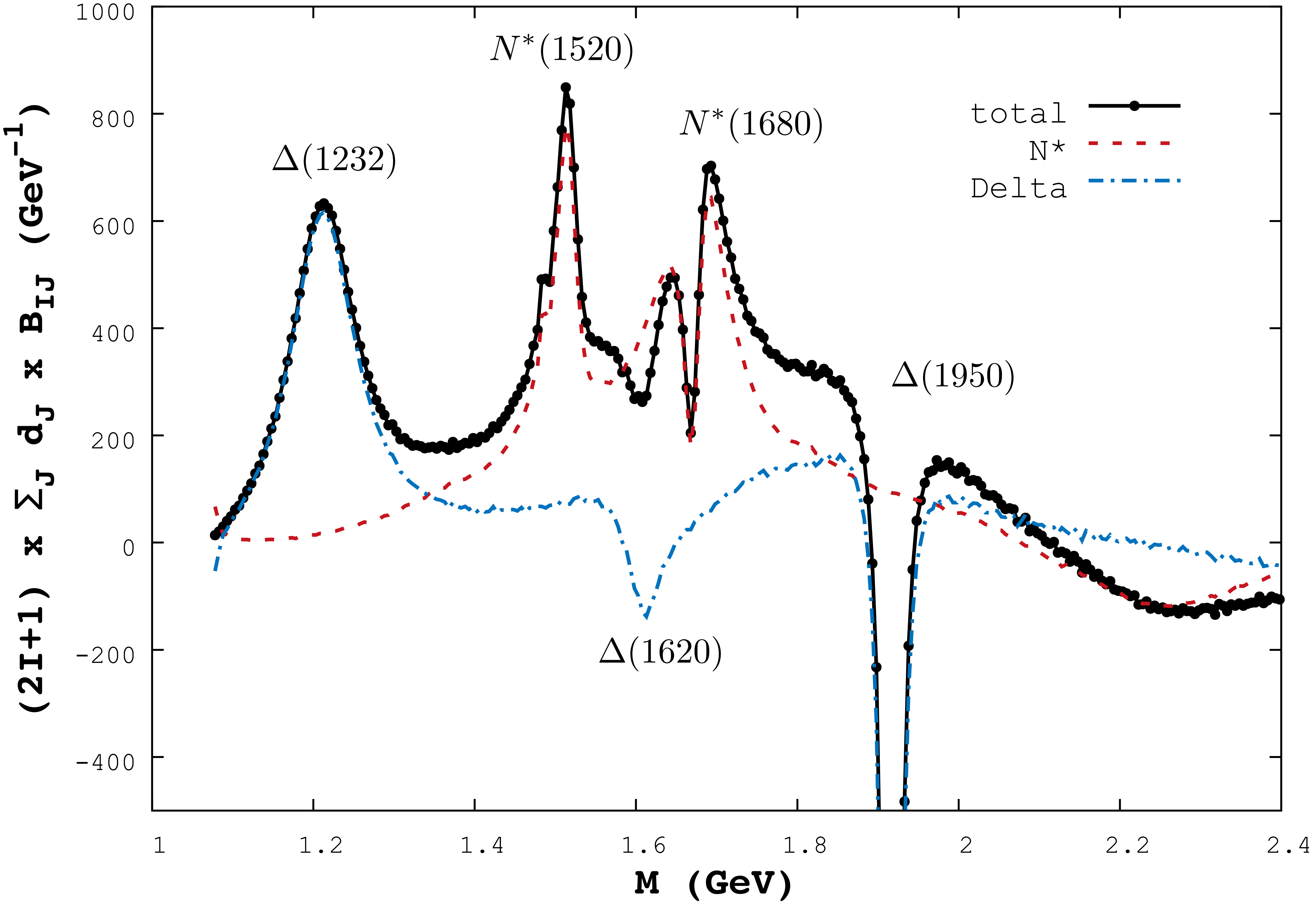
LATTICE COMPUTATIONS ON PHASE SHIFT



R. A. Briceno, J. J. Dudek and R. D. Young, arXiv:1706.06223 [hep-lat].

BARYON SPECTRUM IMPLEMENTATION STATUS

unflavored Baryons



PHASE SHIFT FROM PWA

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Coupled Channels partial wave calculator for KN scattering

by the Joint Physics Analysis Center (JPAC)

Version: September 1, 2015

--------------------------------------------------------------------------------
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Authors:

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Disclaimers:

1 - This code follows the 'garbage in, garbage out' philosphy. If your
parameters do not make sense, the output will not make sense either.
2 - You can use, share and modify this code under your own responsability.
3 - This code is distributed in the hope that it will be useful,
but WITHOUT ANY WARRANTY; without even the implied warranty of
MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.
4 - No PhD students or postdocs were severely damaged during the development
of this project.

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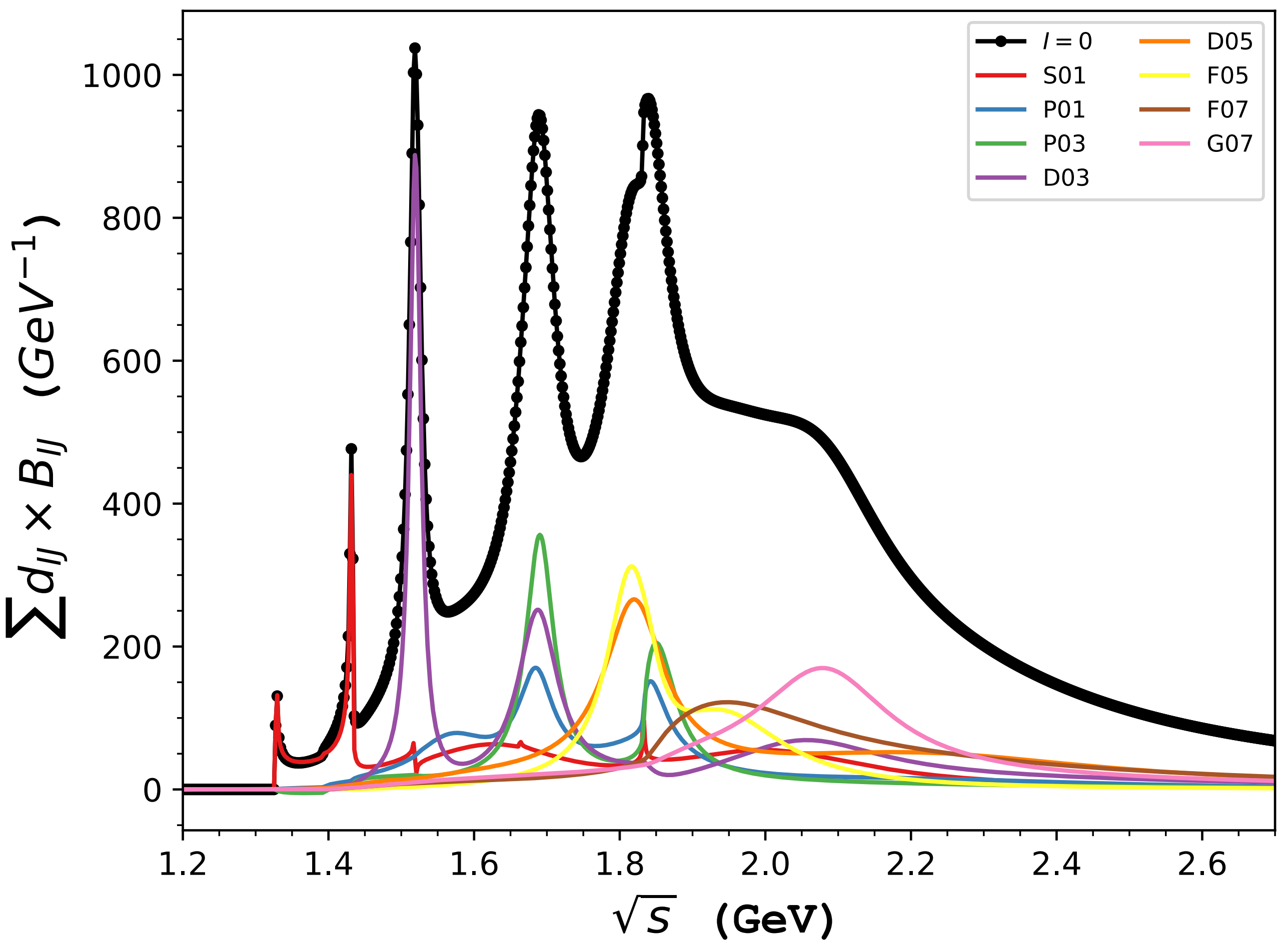
- $1 \to \bar{K}N$,
- $2 \to \pi\Sigma$,
- $3 \to \pi\Lambda$,
- $4 \to \eta\Lambda$,
- $5 \to \eta\Sigma$,
- $6 \to \bar{K}_1 N$,
- $7 \to [\bar{K}_3 N]_-$,
- $8 \to [\bar{K}_3 N]_+$,
- $9 \to [\pi\Sigma^*]_-$,
- $10 \to [\pi\Sigma^*]_+$,
- $11 \to [\bar{K}\Delta]_-$,
- $12 \to [\bar{K}\Delta]_+$,
- $13 \to [\pi\Lambda(1520)]_-$,
- $14 \to [\pi\Lambda(1520)]_+$,
- $15 \to \pi\pi\Lambda$,
- $16 \to \pi\pi\Sigma$.

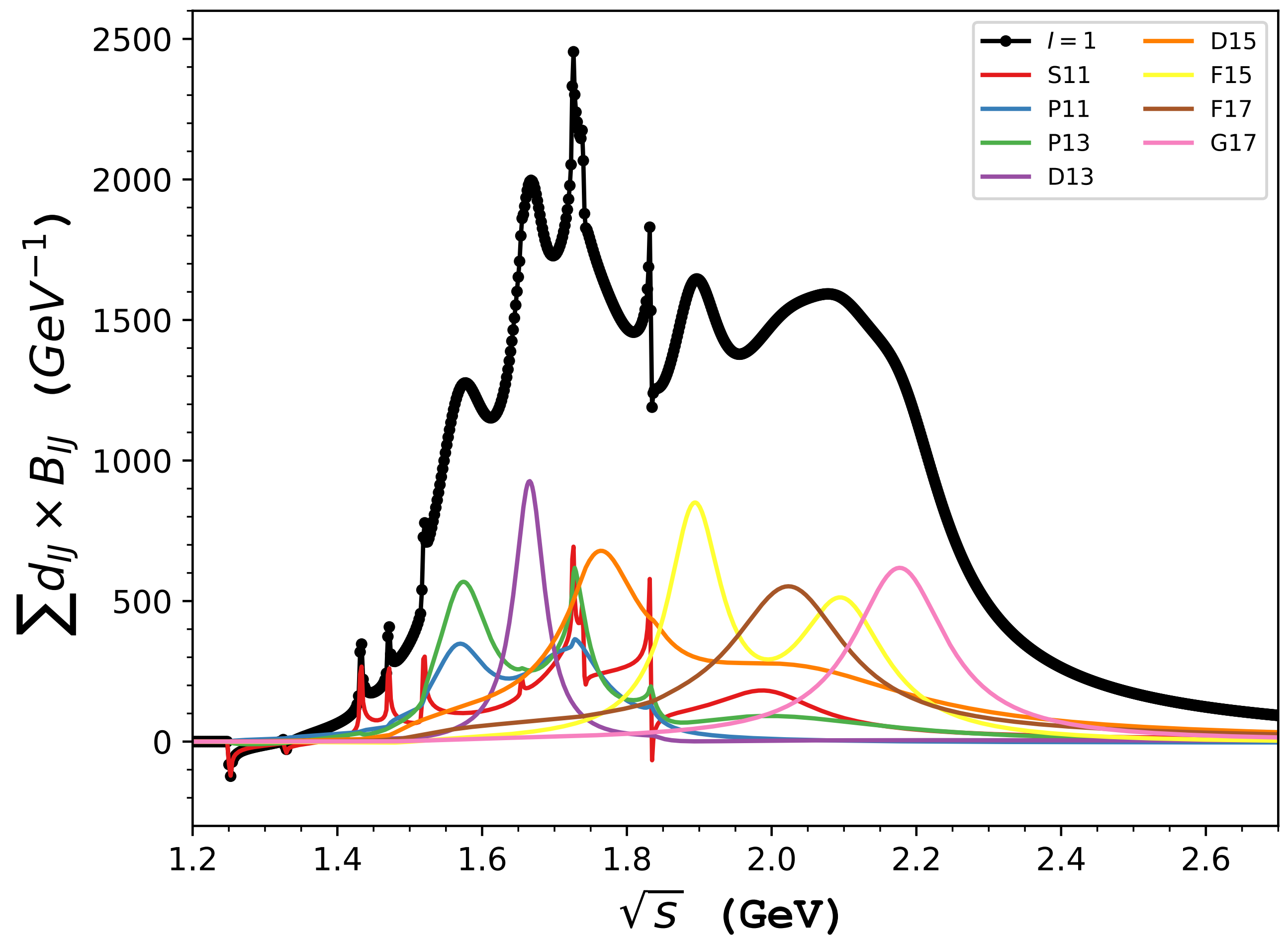
elastic scatterings (elementary)

quasi elastic scatterings

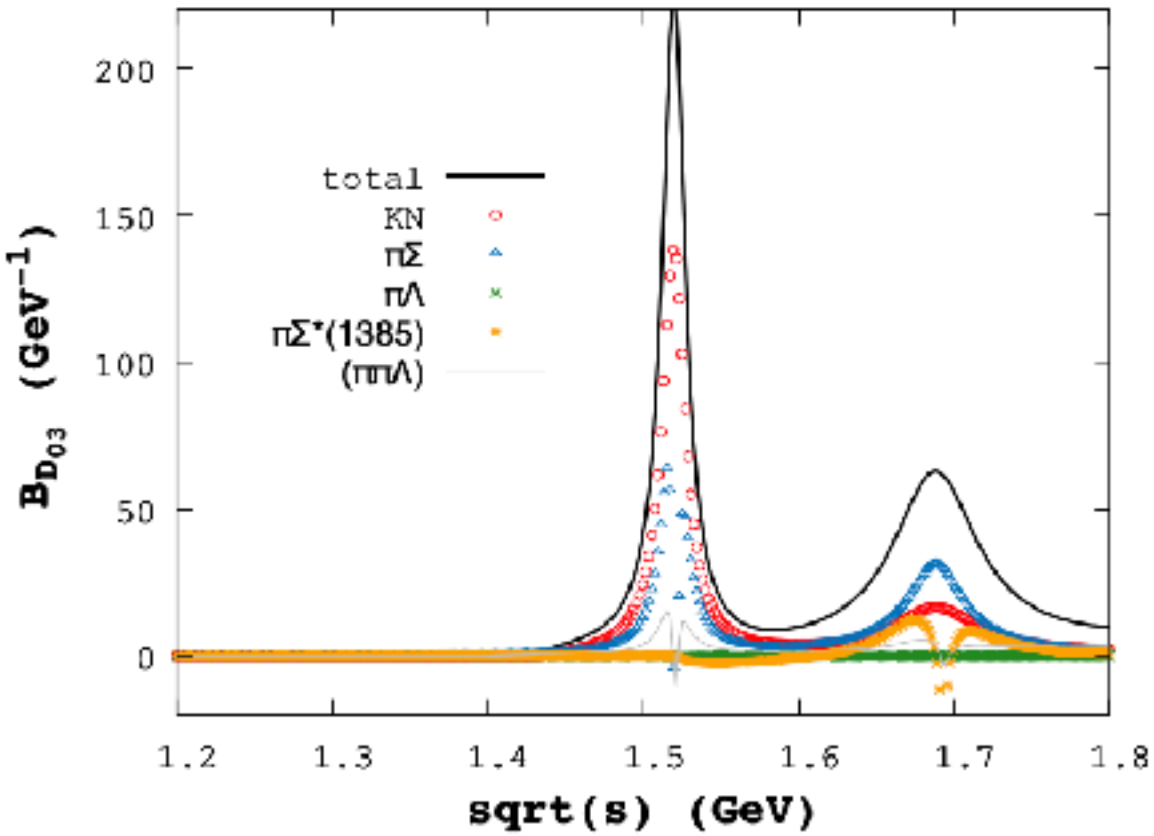
unitarity background

summing all channels…

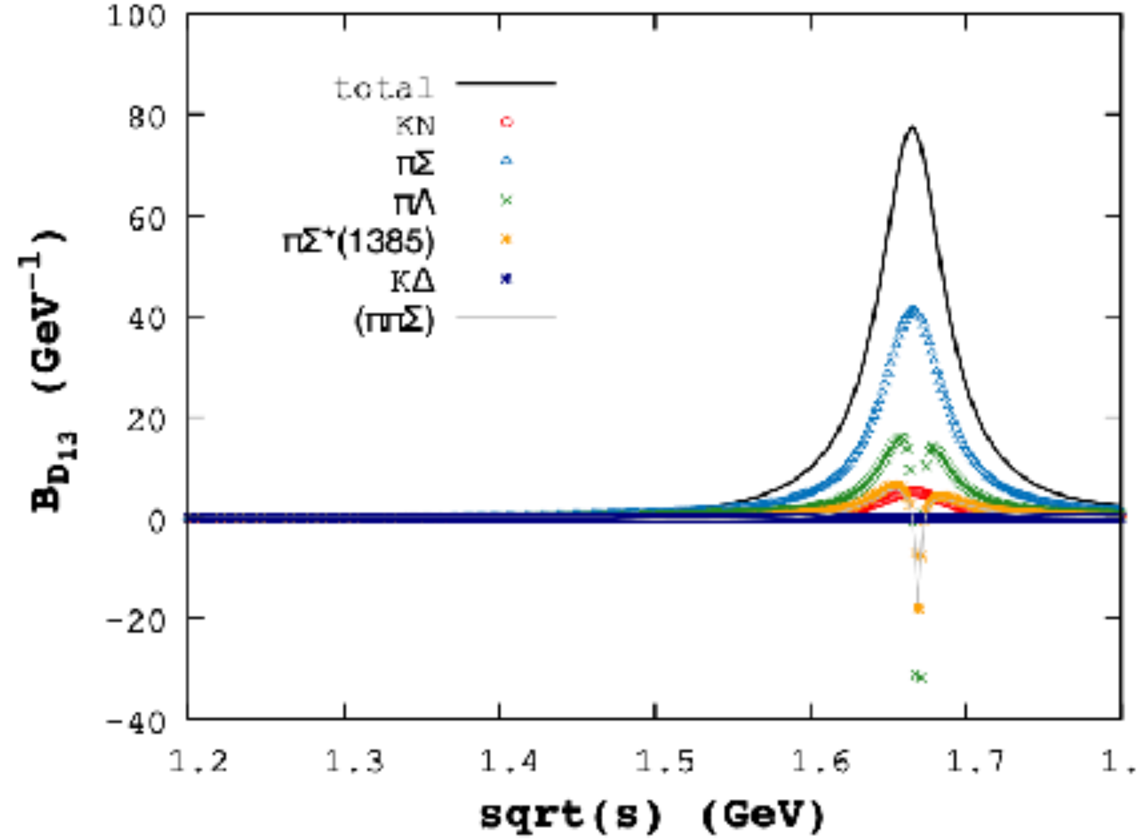




1520, 1690



1670



$\Lambda(1520)\ 3/2^-$ $I(J^P) = 0(\frac{3}{2}^-)$

Mass $m = 1519.5 \pm 1.0$ MeV [d]
Full width $\Gamma = 15.6 \pm 1.0$ MeV [d]
$p_{beam} = 0.39$ GeV/c $4\pi\lambda\!\!\!^{-2} = 82.8$ mb

Λ(1520) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	45 ± 1%	243
$\Sigma\pi$	42 ± 1%	268
$\Lambda\pi\pi$	10 ± 1%	259
$\Sigma\pi\pi$	0.9 ± 0.1%	169
$\Lambda\gamma$	0.85 ± 0.15%	350

$\Lambda(1690)\ 3/2^-$ $I(J^P) = 0(\frac{3}{2}^-)$

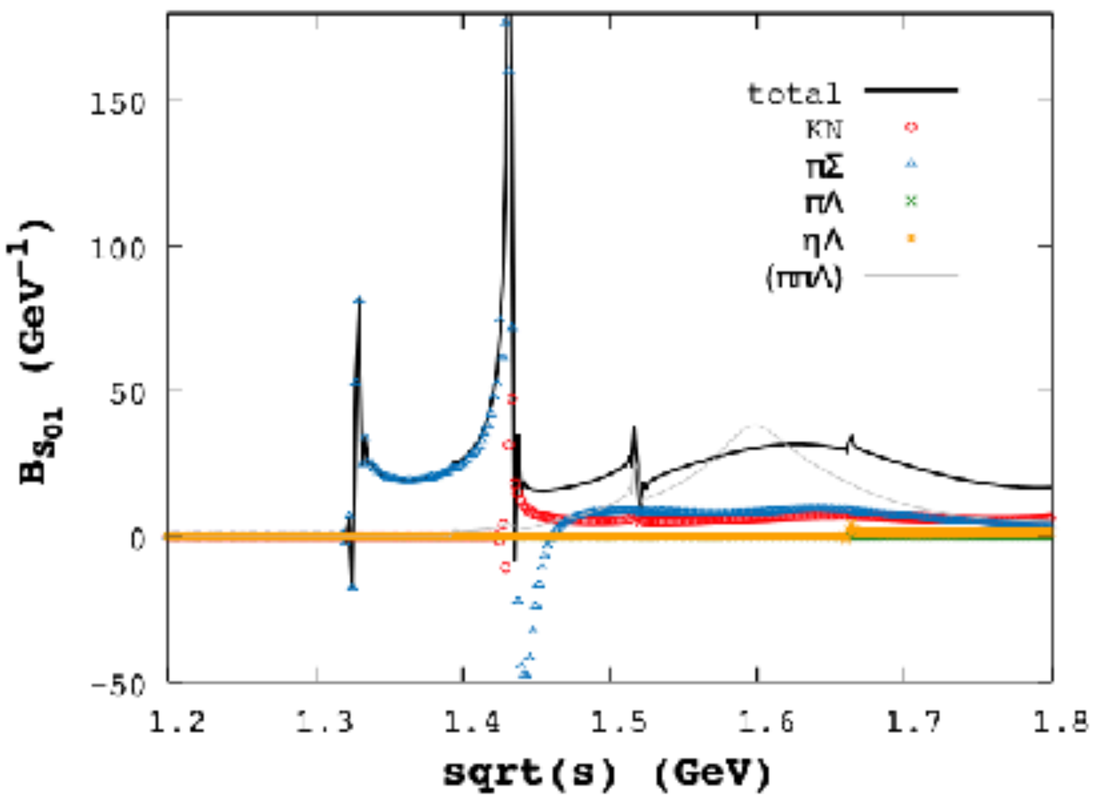
Mass $m = 1685$ to 1695 (≈ 1690) MeV
Full width $\Gamma = 50$ to 70 (≈ 60) MeV
$p_{beam} = 0.78$ GeV/c $4\pi\lambda\!\!\!^{-2} = 26.1$ mb

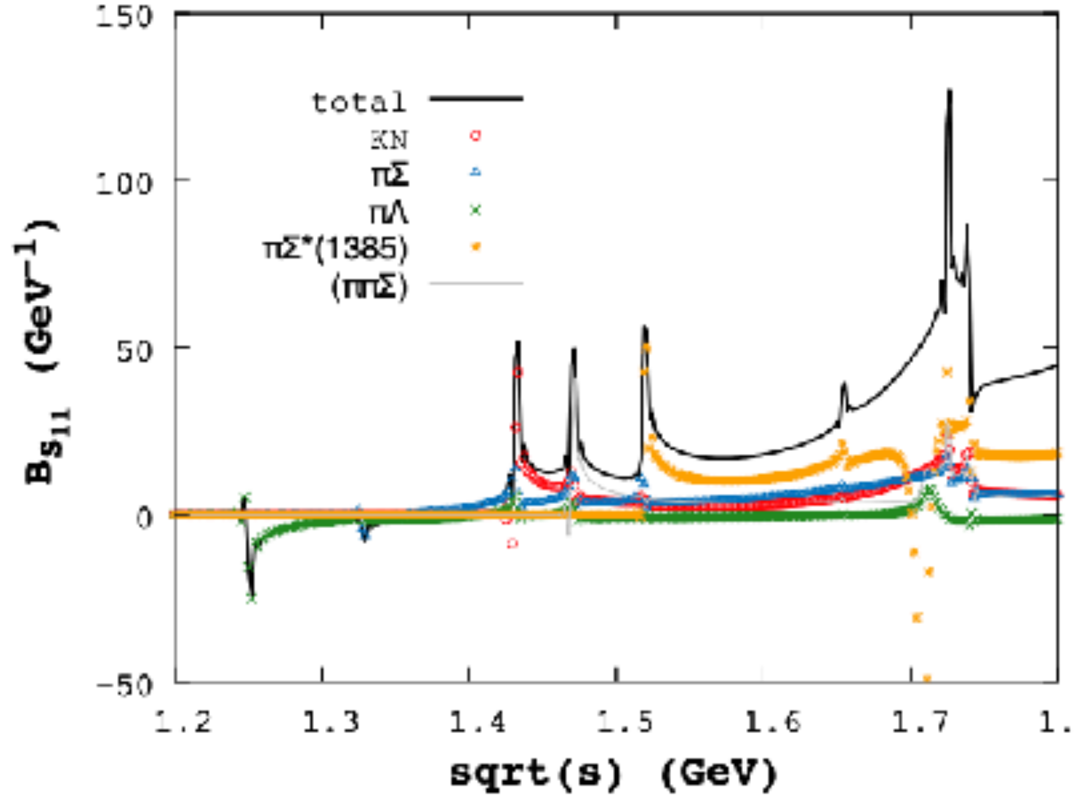
Λ(1690) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	20–30 %	433
$\Sigma\pi$	20–40 %	410
$\Lambda\pi\pi$	~ 25 %	419
$\Sigma\pi\pi$	~ 20 %	358

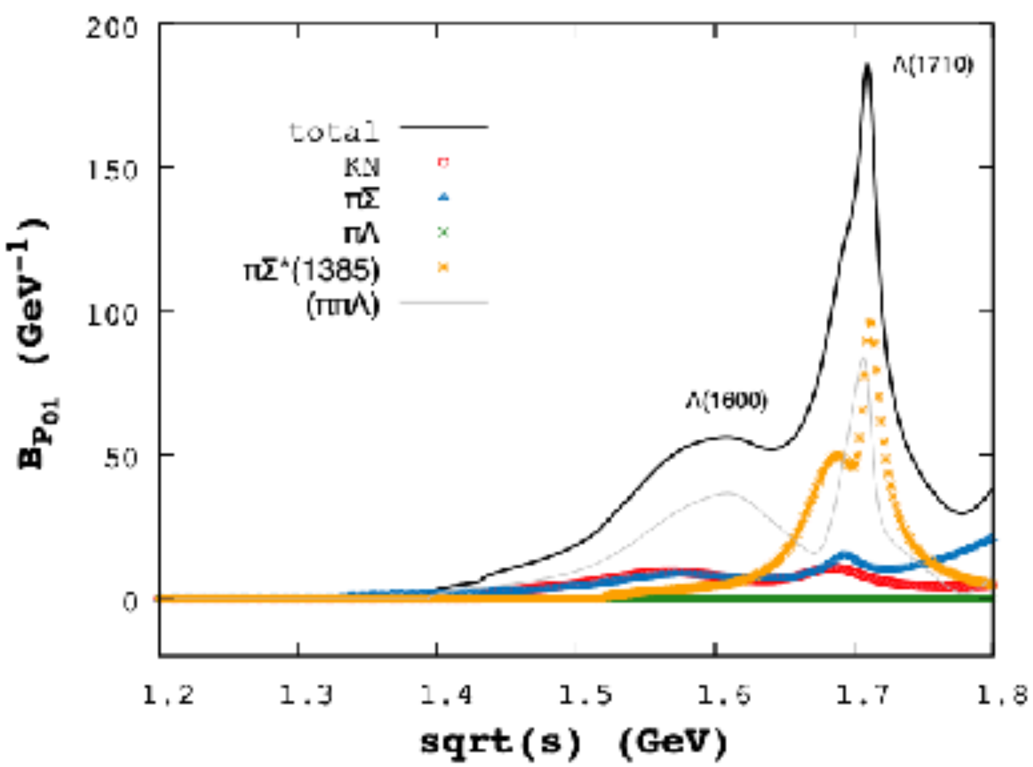
$\Sigma(1670)\ 3/2^-$ $I(J^P) = 1(\frac{3}{2}^-)$

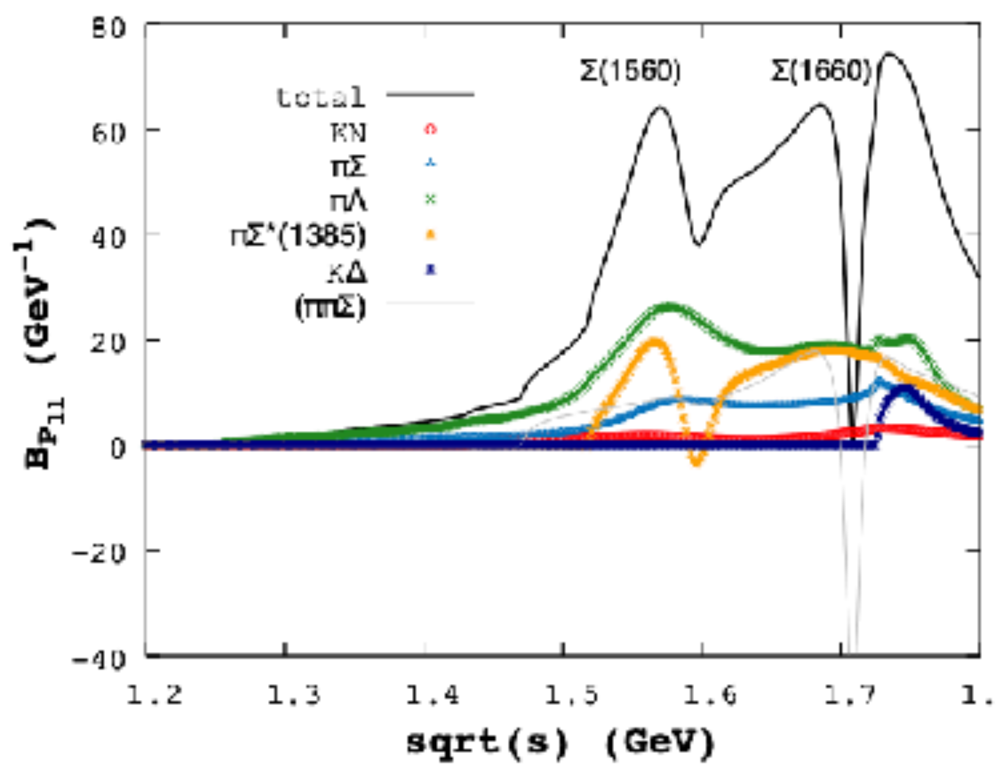
Mass $m = 1665$ to 1685 (≈ 1670) MeV
Full width $\Gamma = 40$ to 80 (≈ 60) MeV
$p_{beam} = 0.74$ GeV/c $4\pi\lambda\!\!\!^{-2} = 28.5$ mb

Σ(1670) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\overline{K}$	7–13 %	414
$\Lambda\pi$	5–15 %	448
$\Sigma\pi$	30–60 %	394









branching ratio?

STRANGENESS CONTENT IN A HADRON GAS

- K-N system requires a coupled channel analysis

$|\bar{K}N\rangle, |\pi\Sigma\rangle, |\pi\Lambda\rangle, |\eta\Lambda\rangle, \ldots$ *16 basis states*

$$\mathcal{Q}(M) \equiv \frac{1}{2}\,\mathrm{Im}\,(\mathrm{tr}\ln\,\mathrm{S}) = \frac{1}{2}\,\mathrm{Im}\,(\ln\,\det\,[\mathrm{S}]) = \delta_{\bar{K}N} + \delta_{\pi\Sigma} + \delta_{\pi\Lambda} + \ldots$$

recipe to extract eigenphases from PWA

COUPLED-CHANNEL PROBLEM

$$\{\gamma_1, \gamma_2, m_{\rm res}\} \longleftrightarrow \{\delta_1, \delta_2, \eta\}$$

$$S = \begin{pmatrix} \eta\, e^{2\,i\,\delta_I} & i\sqrt{1-\eta^2}\, e^{i\,(\delta_I+\delta_{II})} \\ i\sqrt{1-\eta^2}\, e^{i\,(\delta_I+\delta_{II})} & \eta\, e^{2\,i\,\delta_{II}} \end{pmatrix}$$

$$\begin{aligned} \mathcal{Q}(M) &\equiv \frac{1}{2}\,\mathrm{Im}\,(\mathrm{tr}\ln\ \mathrm{S}) \\ &= \frac{1}{2}\,\mathrm{Im}\,(\ln\ \det\,[\mathrm{S}]) \\ &= \delta_I + \delta_{II}. \end{aligned}$$

$a_0(980)$ *system*

$$\pi\eta \to \begin{pmatrix} \pi\eta \\ K\bar{K} \end{pmatrix} \to \pi\eta$$

$$K\bar{K} \to \begin{pmatrix} \pi\eta \\ K\bar{K} \end{pmatrix} \to K\bar{K}$$

WIGNER, EISENBUD, SMITH, …

$$S \to U^\dagger S_d U$$

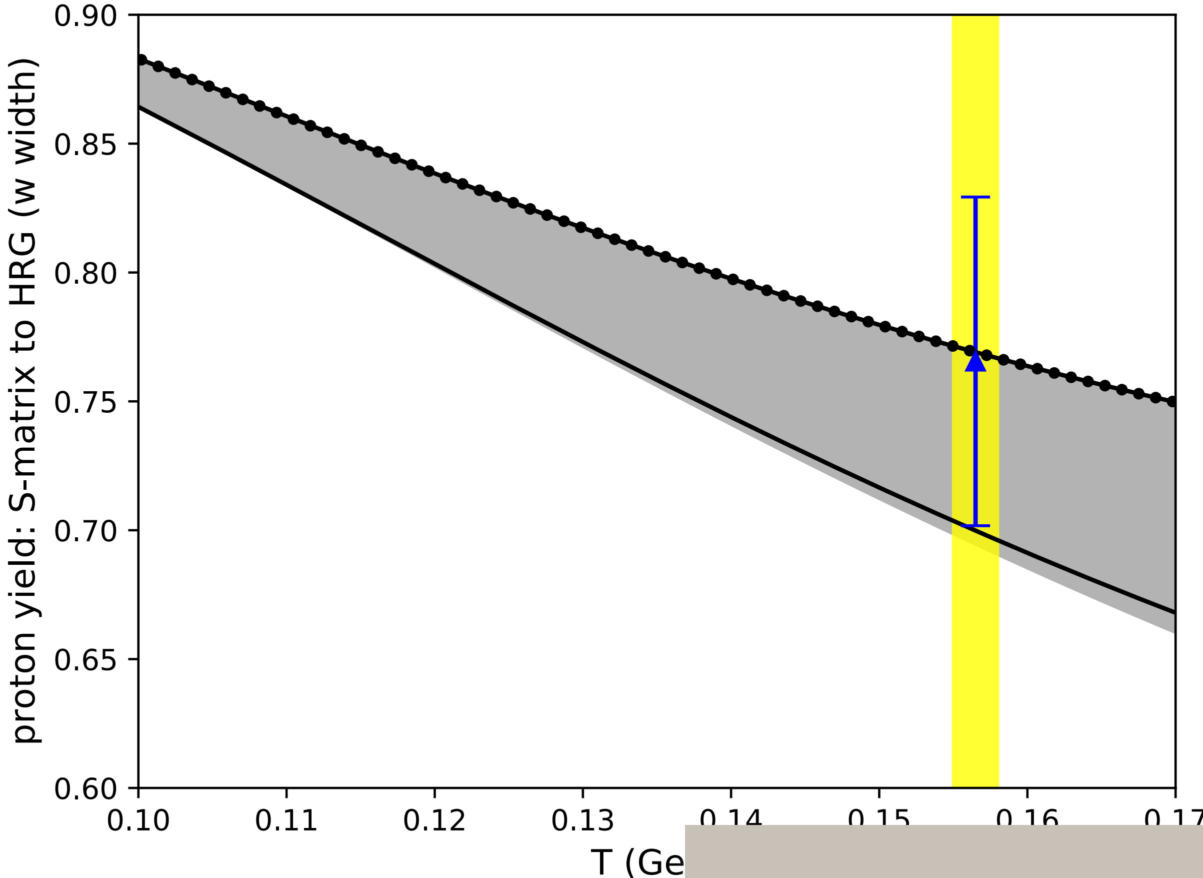
$$S_d = \begin{pmatrix} e^{2i\delta_{\rm res}(s)} & 0 \\ 0 & 1 \end{pmatrix},$$

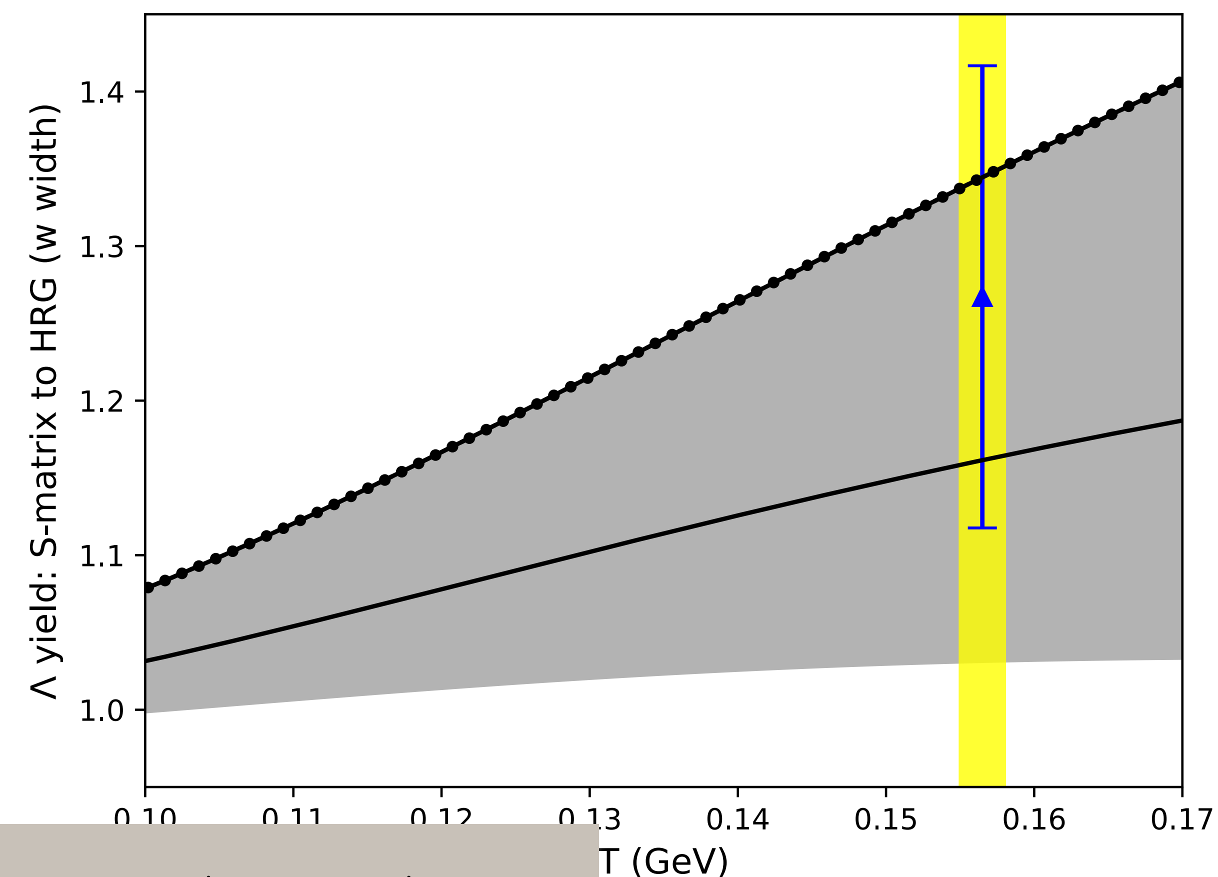
$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}.$$

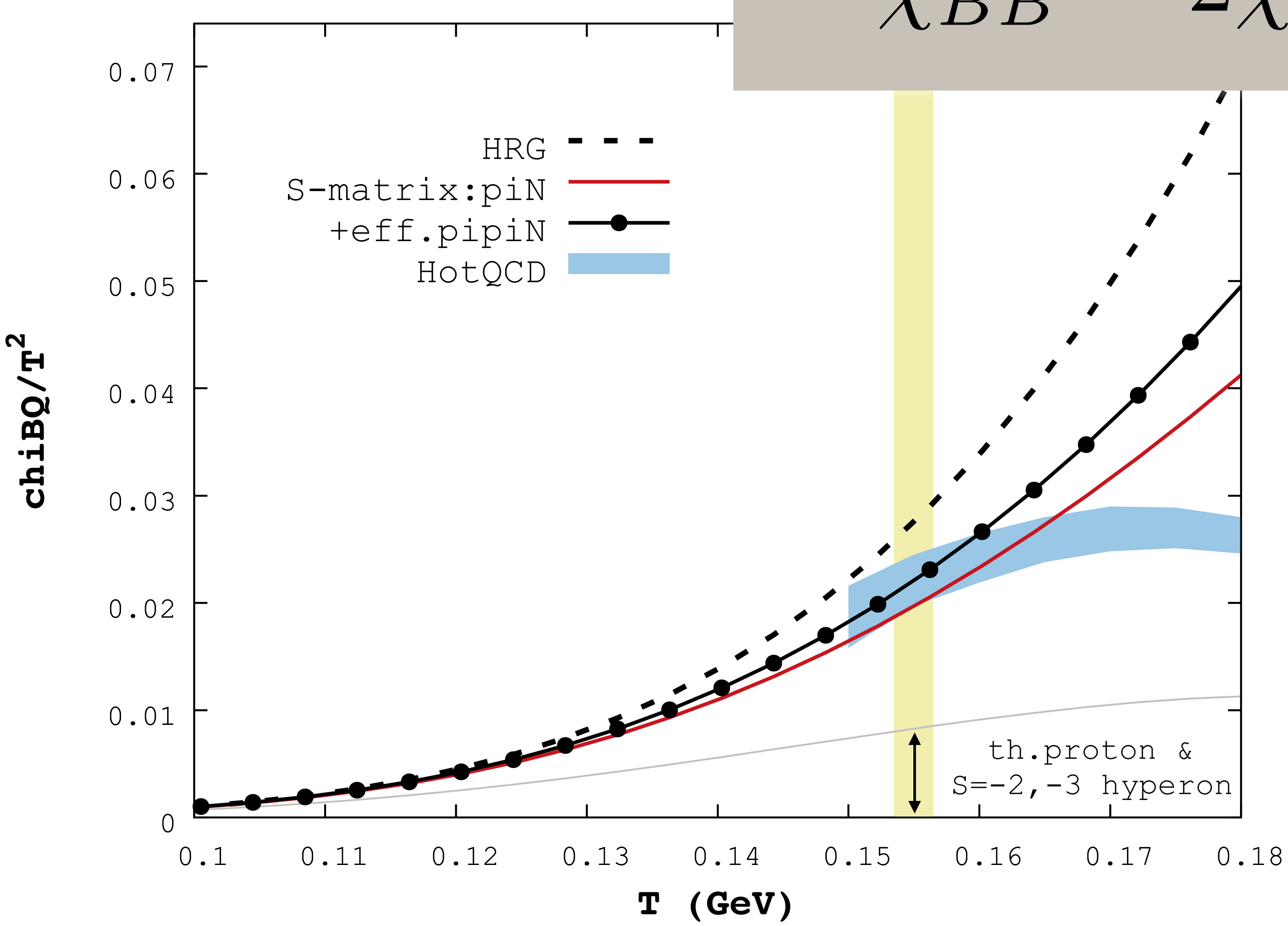
$$\mathrm{BR}_a = \cos^2\theta = \frac{g_a^2\,\phi_a}{g_a^2\,\phi_a + g_b^2\,\phi_b},$$

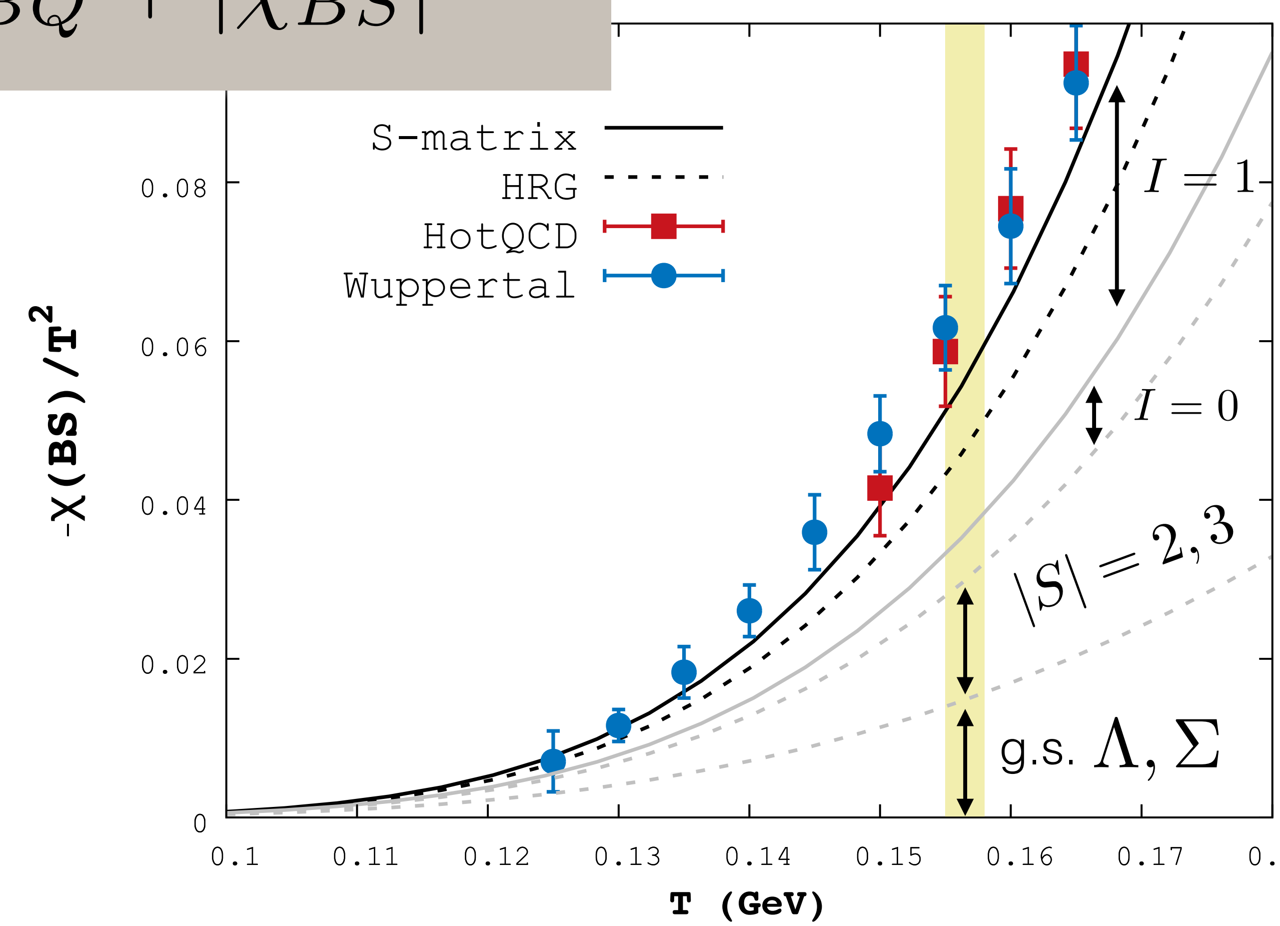
$$\mathrm{BR}_b = \sin^2\theta = \frac{g_b^2\,\phi_b}{g_a^2\,\phi_a + g_b^2\,\phi_b}.$$

$$\chi_{BB} = 2\chi_{BQ} + |\chi_{BS}|$$









indecently optimistic...

VOLUME 34, NUMBER 3 JULY, 1962

S-Matrix Theory of Strong Interactions without Elementary Particles*†

GEOFFREY F. CHEW
Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California

1. INTRODUCTION

IN this paper I present an indecently optimistic view of strong interaction theory. My belief is that a major breakthrough has occurred and that within a relatively short period we are going to achieve a depth of understanding of strong interactions that a few years ago I, at least, did not expect to see within my lifetime. I know that few of you will be convinced by the arguments given here, but I would be masking my feelings if I were to employ a conventionally cautious attitude in this talk. I am bursting with excitement, as are a number of other theorists in this game. tell me that this is a fetish, that field theory is an equally suitable language, but to me the basic strong-interaction concepts, simple and beautiful in a pure *S*-matrix approach, are weird, if not impossible, for field theory. It must be said, nevertheless, that my own awareness of these concepts was largely achieved through close collaboration with three great experts in field theory, M. L. Goldberger, Francis Low, and Stanley Mandelstam. Each of them has played a major role in the development of the strong interaction theory that I describe,[1] even though the language of my description may be repugnant to them. Murray Gell-Mann, also, although he has not actu-

PARTICLES AS S–MATRIX POLES; HADRON DEMOCRACY *

satisfy unitarity. There is no "reason" for any others. Similarly, as Feynman and Heisenberg have both emphasized, there is no reason why some particles should be on a different footing from others. The elementary particle concept is unnecessary, at least for baryons and mesons.

The second assumption may turn out to be closely related to the first, perhaps even a consequence, but

but some are more equal than the others?

Geoffrey F. Chew

Chew at his California home on July 2014

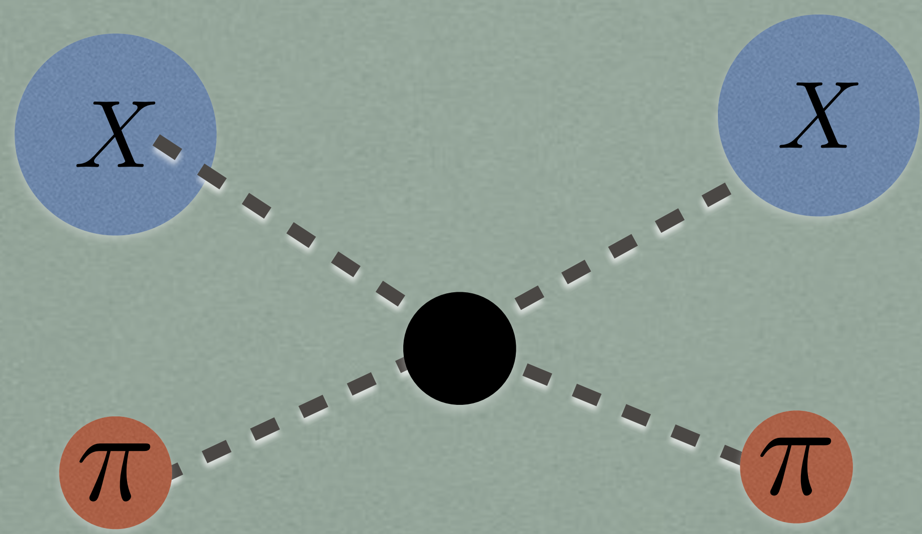
Born	June 5, 1924 Washington, D.C., United States
Died	April 12, 2019 (aged 94) Berkeley, California, United States
Nationality	American
Alma mater	University of Chicago
Known for	S-matrix theory, bootstrap theory, strong interactions, Chew–Frautschi plot
Awards	Hughes Prize (1962) Lawrence Prize (1969) Majorana Prize (2008)
Scientific career	
Fields	Theoretical physics
Institutions	University of Illinois UC Berkeley
Doctoral advisor	Enrico Fermi
Doctoral students	David Gross John H. Schwarz John R. Taylor

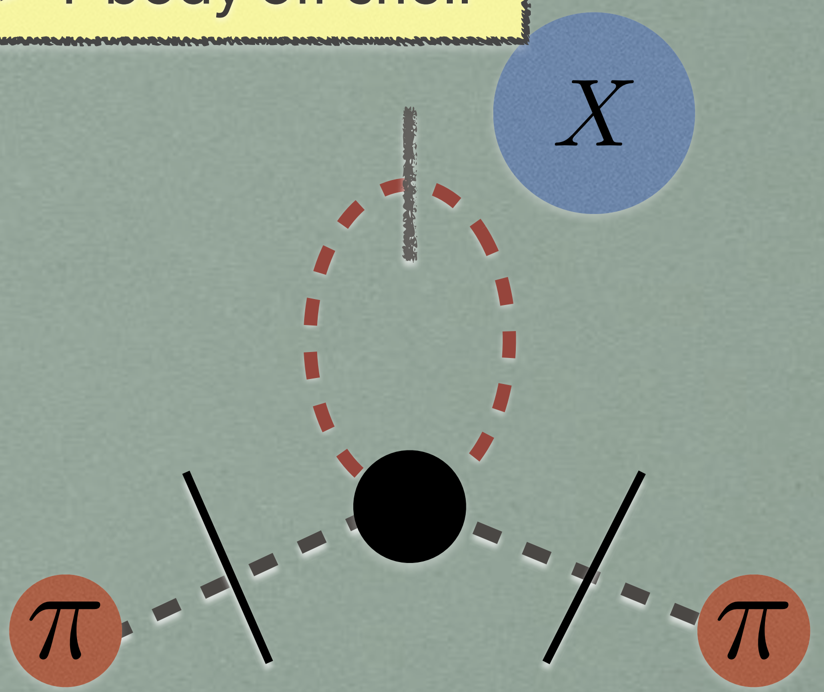
GOING FURTHER WITH S-MATRIX

- Theoretical development:
  N-body scattering: beyond 2->2; inelasticity
- In-medium effects with S-matrix
- Quark-Hadron Duality and QCD phase transition
- Equation of states for Dense Matter

IN-MEDIUM EFFECTS FROM S-MATRIX

2-body on-shell -> 1-body off-shell





$$\Delta P = \approx N_{\rm th}^{\pi}\, N_{\rm th}^{N} \times (-T_{\rm NR}).$$

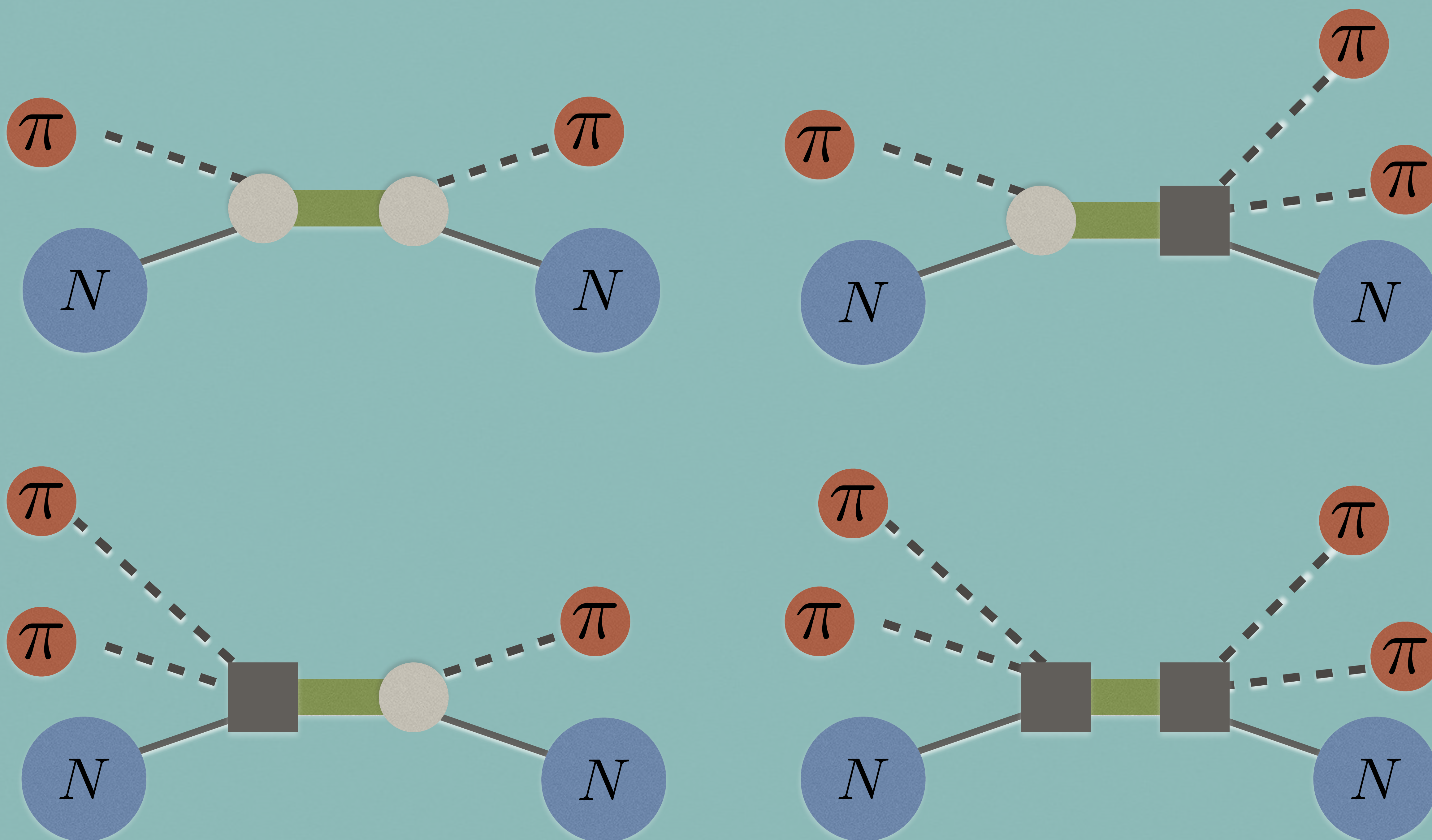
$$\Sigma_\pi \propto \int \frac{d^3q}{\omega_q}\, n_X\, T_{\pi X}(s)$$

forward amplitude

A. Schenk NPB 363(1991)

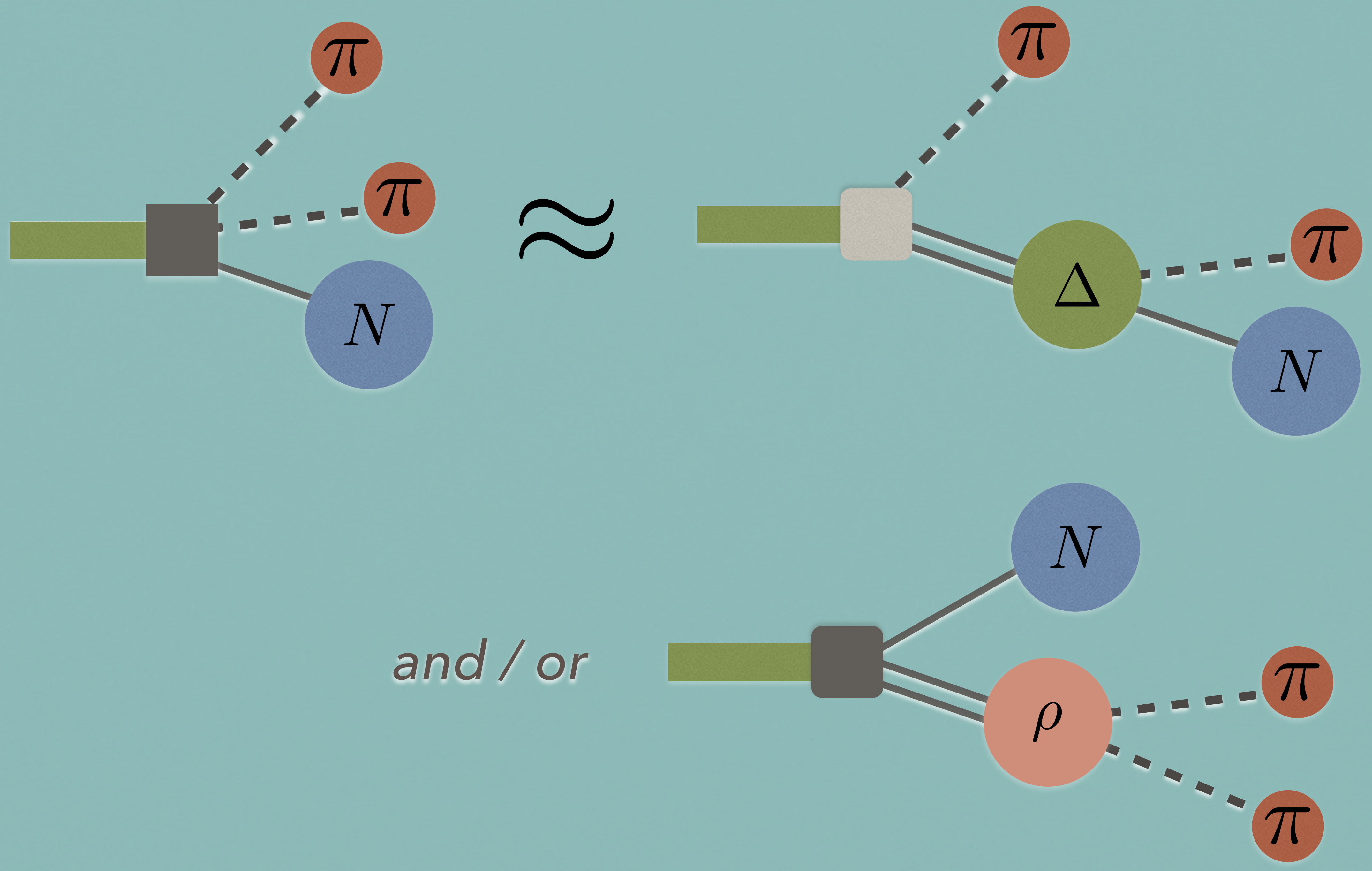
S. Jeon and P. J. Ellis PRD 58 045013 (1998)

ISOBAR MODEL



ISOBAR MODEL

sequential decay model



THANK YOU