Role of a triangular singularity in the $\gamma\, p \to p\, \pi^0 \eta$ reaction

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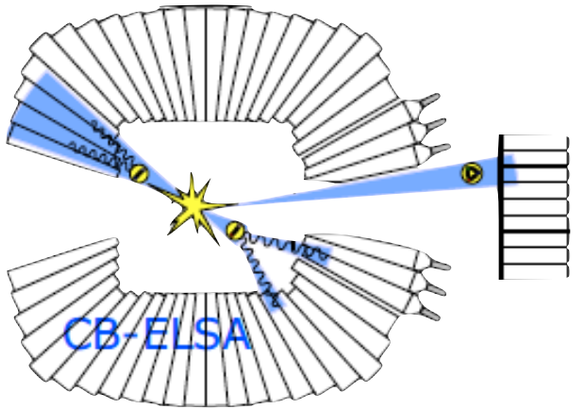
Outline:

- observation and characterisation of a structure at $M_{p\eta} \approx 1710$ MeV
- interpretation: triangular singularity at opening of the $\gamma\, p \to p\, a_0$ channel
- summary and conclusions

Experimental Physics II

Exotic Hadron Spectrsocopy 2023
April 19-21, 2022
Durham University, United Kingdom

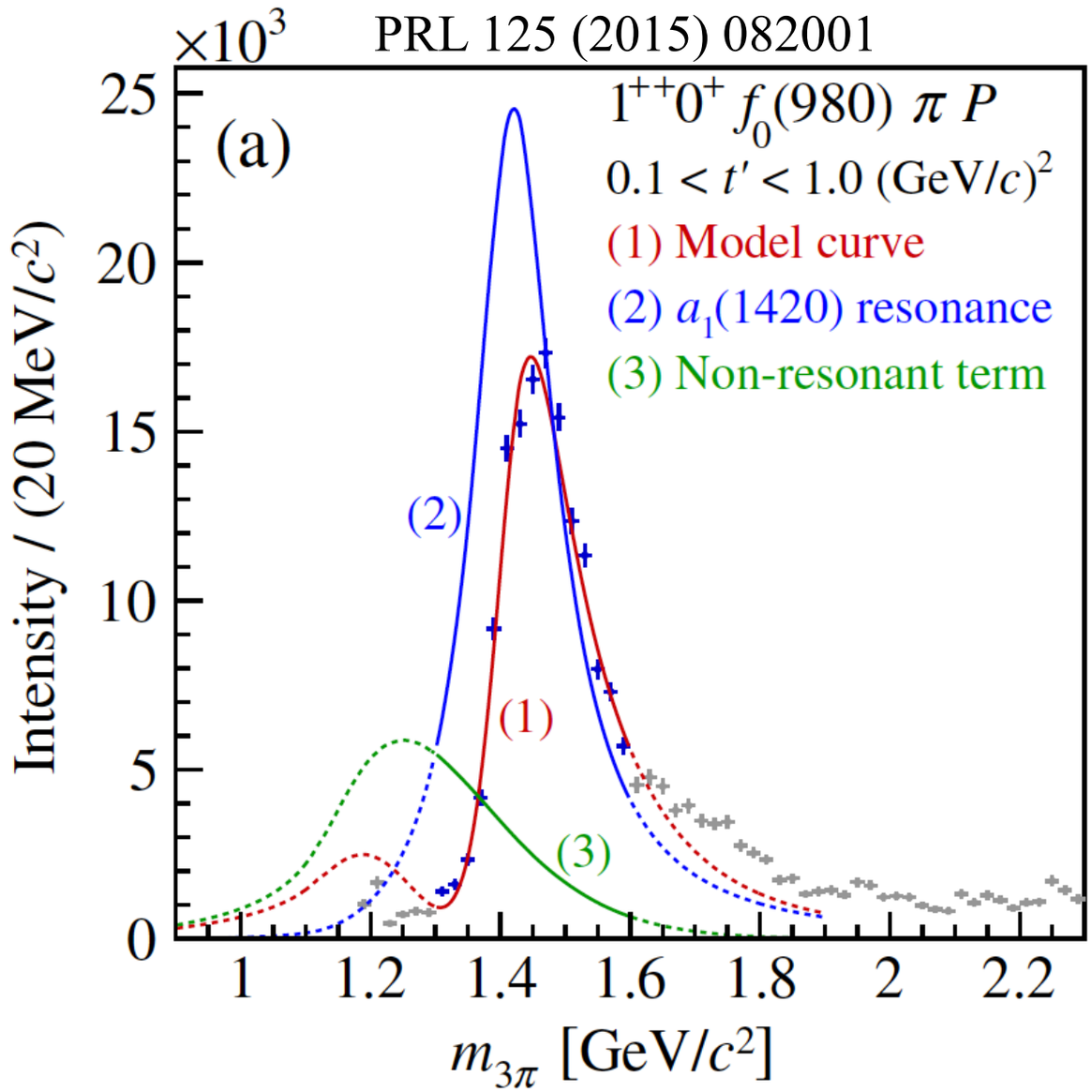


triangular singularities in hadronic reactions

diffractive π^- p scattering at 190 GeV

$\pi^- p \rightarrow p\, \pi^- \pi^+ \pi^-$

COMPASS collaboration
PRL 125 (2015) 082001



resonance like signal in $\pi^-\pi^-\pi^+$ final state

genuine new state: $a_1(1420)$??
difficult to explain within quark model
tetra-quark resonance ??

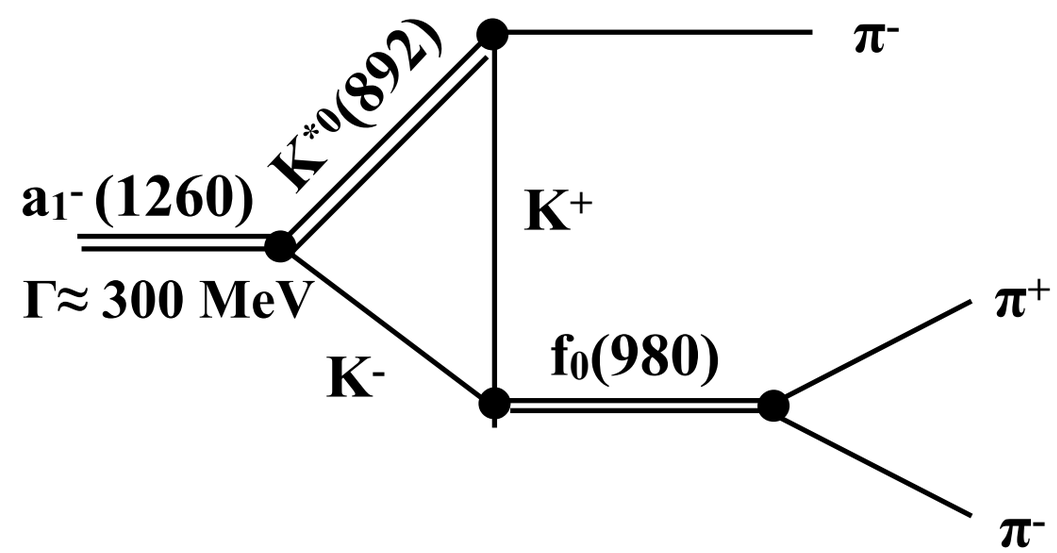
M. Mikhasenko, B. Ketzer, A Sarantsev
PRD 91 (2015) 094105

COMPASS collaboration
PRL 127 (2021) 082501

$\pi^- p \rightarrow a_1^-(1260)\, p$

$a_1^-(1260) \rightarrow \pi^- \pi^+ \pi^-$

triangular diagram

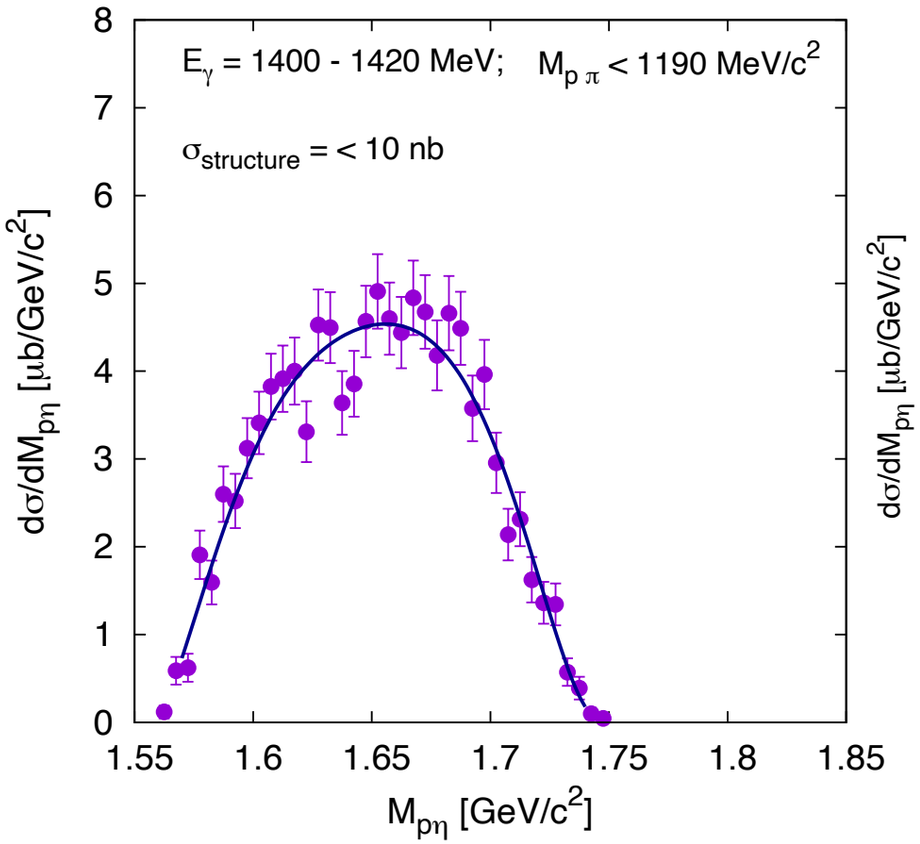


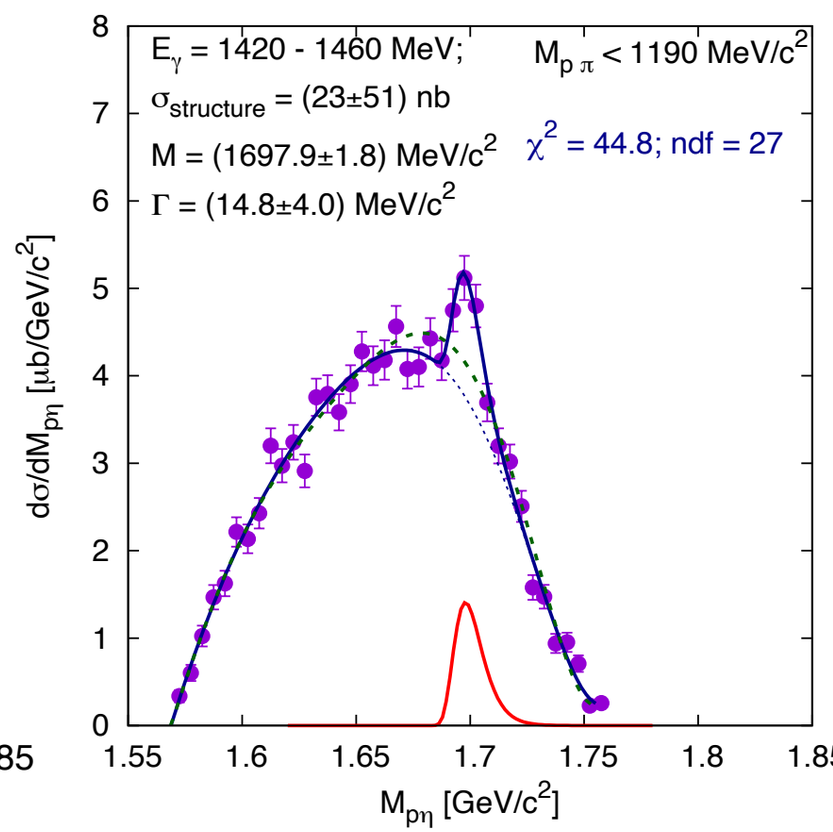
three point (triangular) loop generates structure (singularity) at $\sqrt{s}$ = 1420 MeV

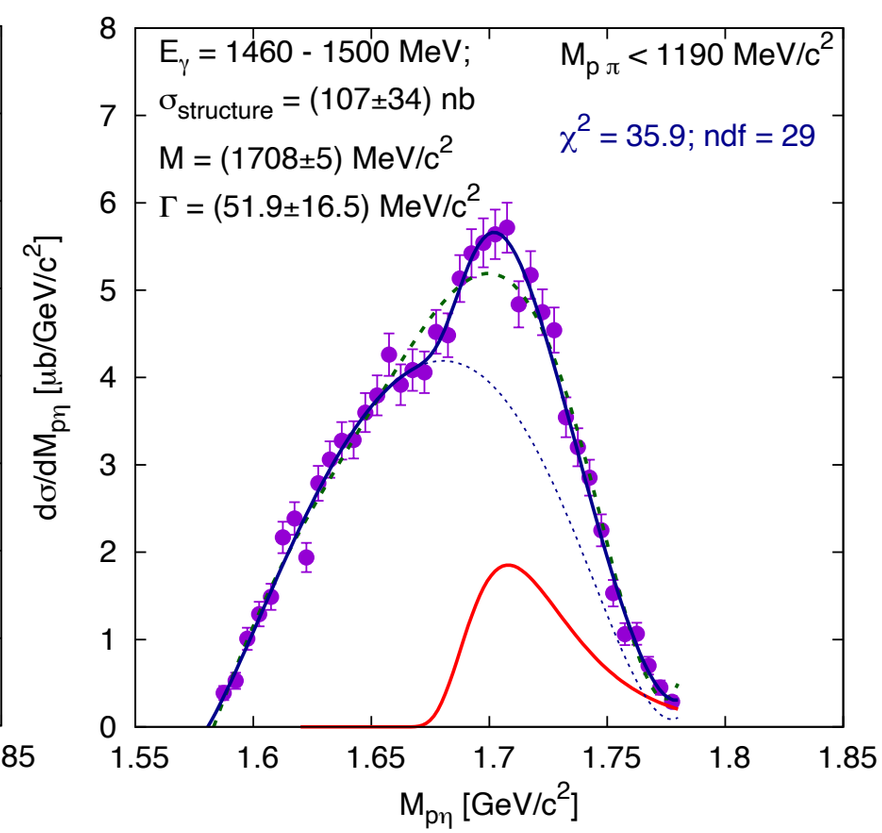
many other cases in meson sector:
F-K.Guo, X-H.Liu, S.Sakai
Prog. Part. Nucl. Phys. 112 (2020) 103757

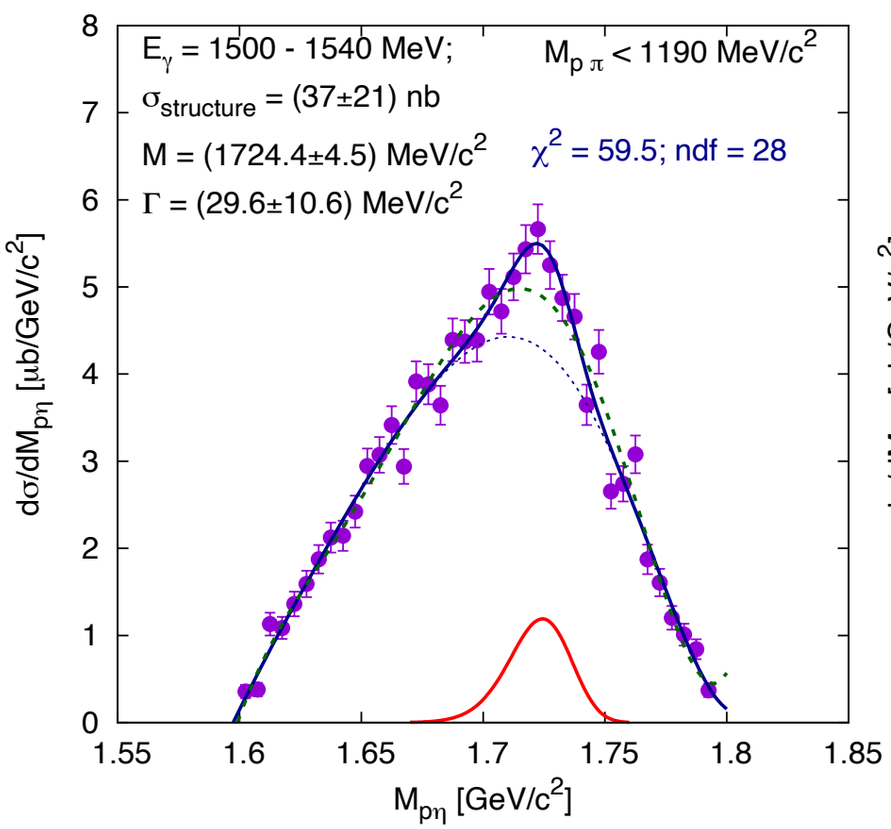
$\gamma\, p \rightarrow p\, \pi^0 \eta$; E_γ = 1400 - 1600 MeV

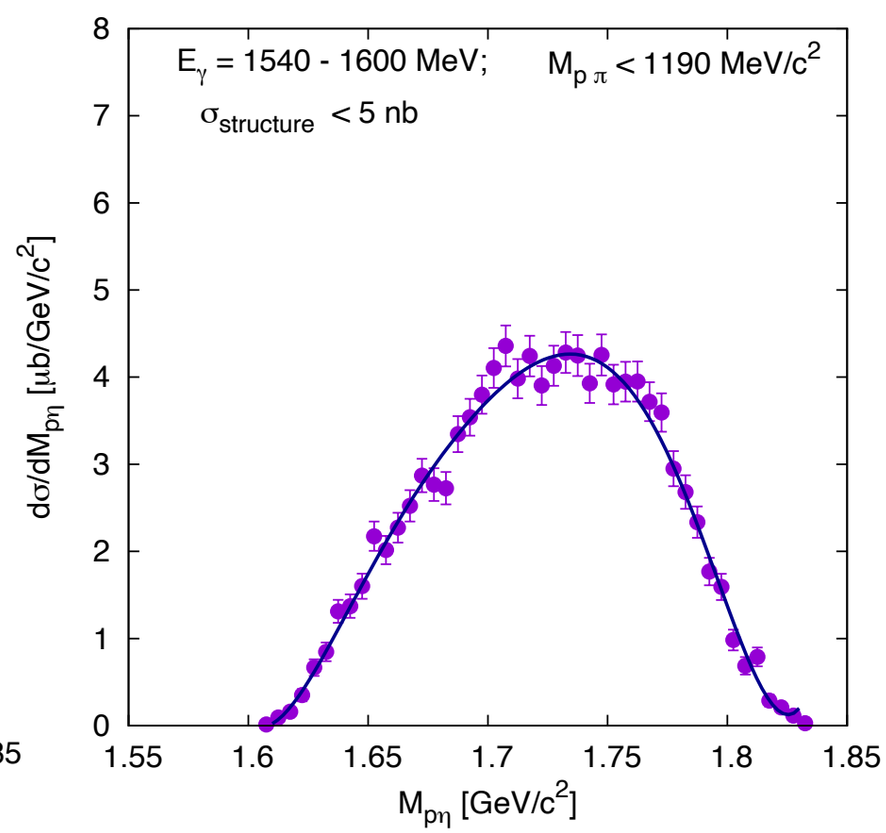
properties of structures as function of the incident photon energy











signal only seen for E_γ = 1420 - 1540 MeV

position and shape of signal vary with excitation energy !!

→ no genuine nucleon resonance

$\gamma\, p \rightarrow p\, \pi^0 \eta$; E_γ = 1420 - 1540 MeV

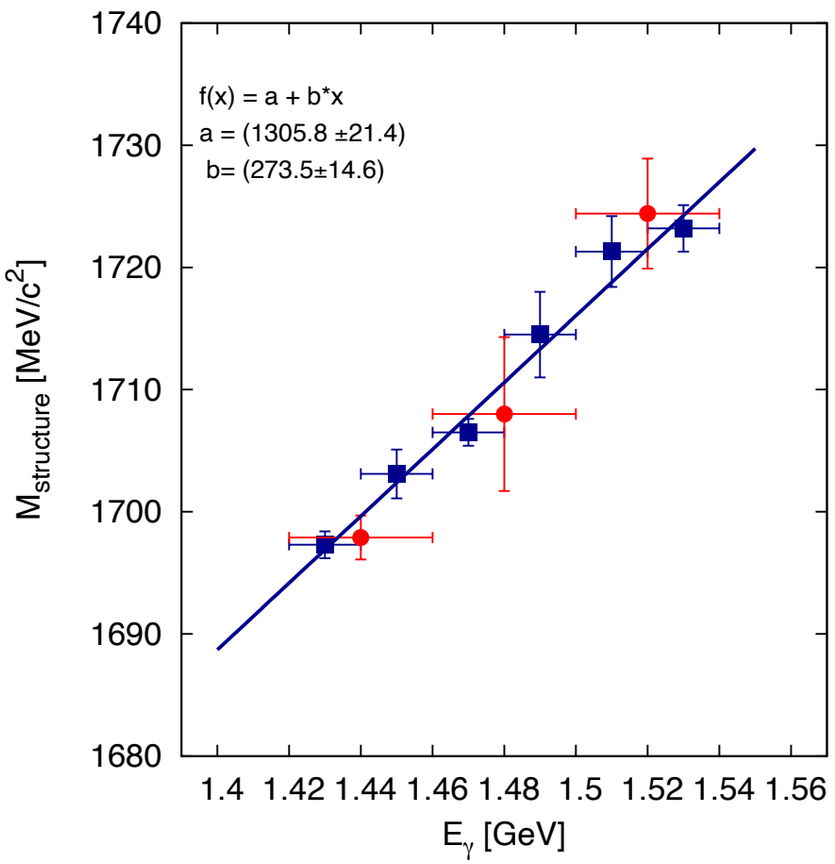
properties of the structure as function of the excitation energy

signal fitted with Novosibirsk function

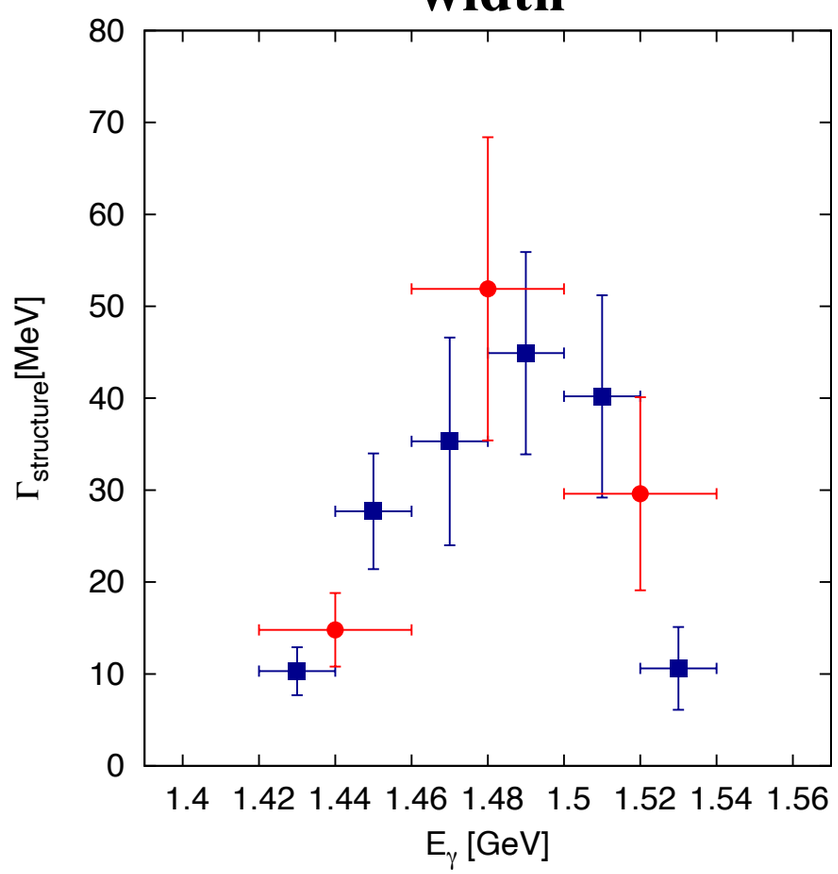
signal fitted with Gaussian function

systematic error of fits (different fit functions): $\leq$ 15%

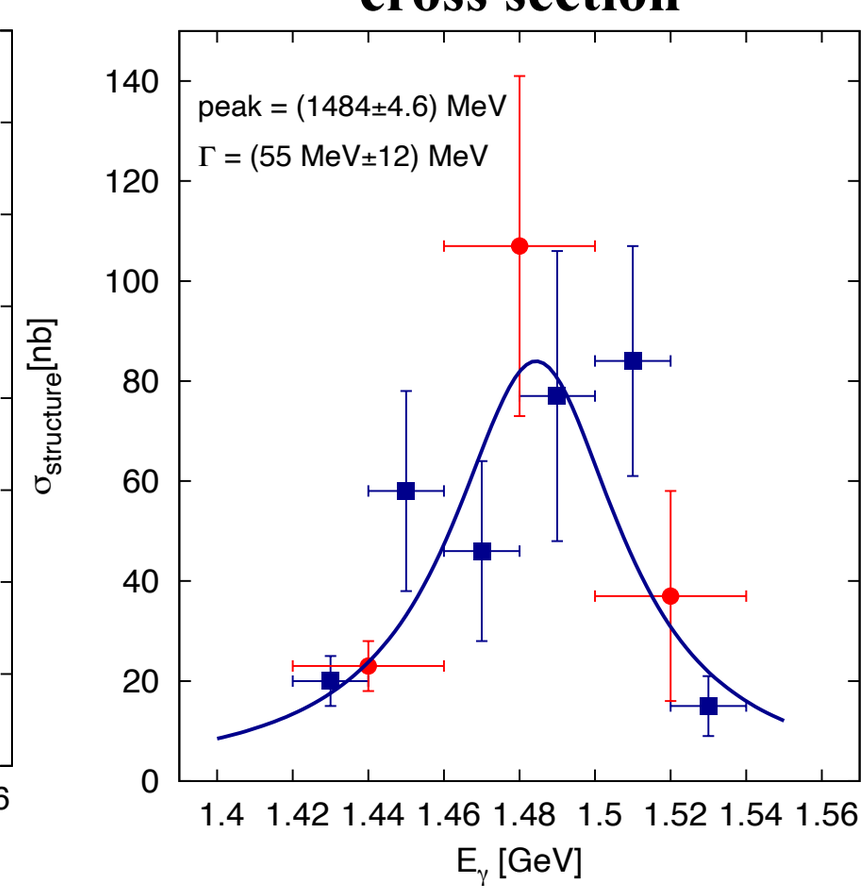
peak position



width



cross section



I. peak shifts with incident energy

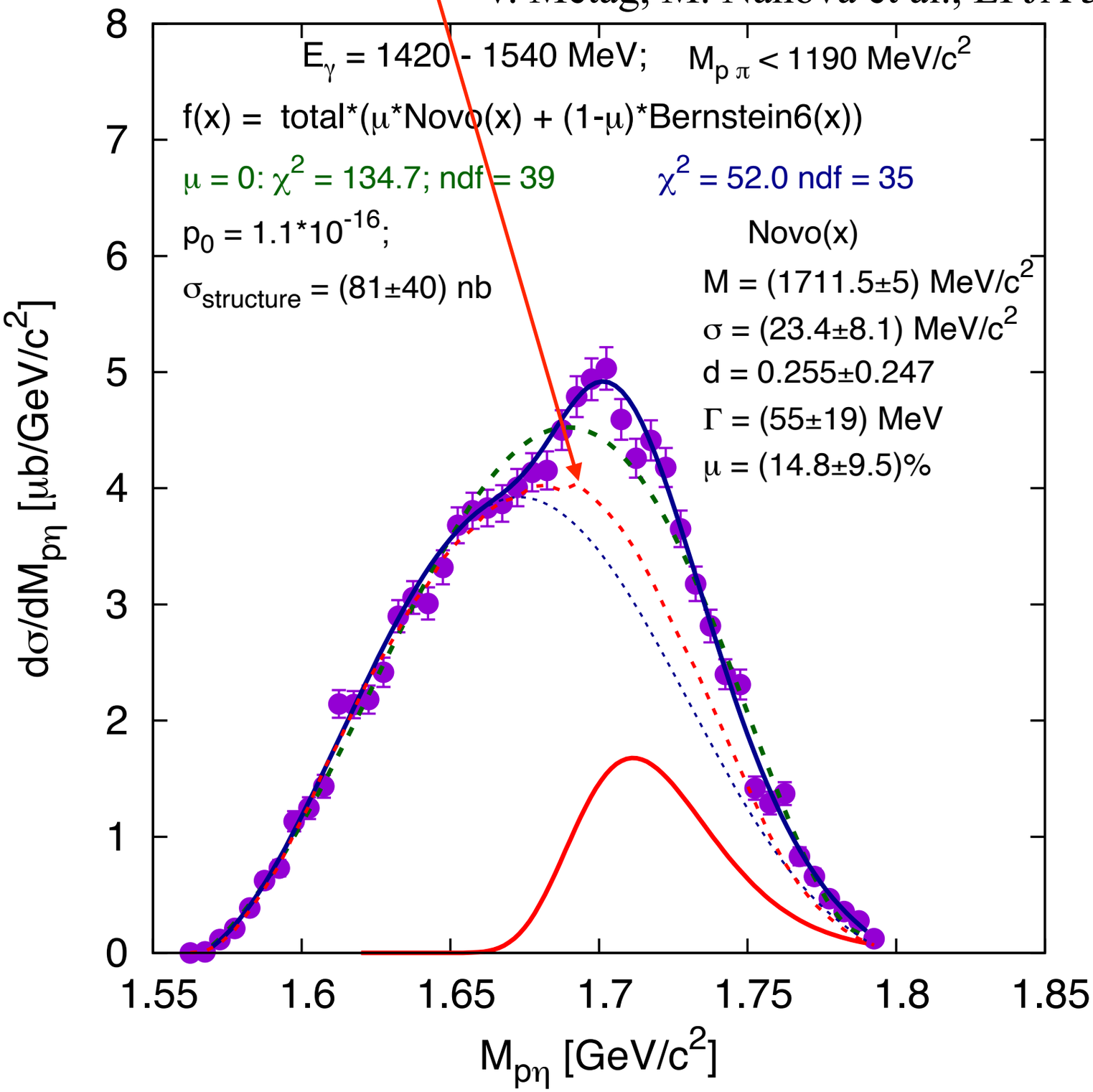
II. width: $\Gamma \leq 50$ MeV

III. resonance-like cross section peaking at
E_γ = 1490 MeV ($\gamma p \rightarrow p\, a_0 \rightarrow p\, \pi^0\, \eta$ threshold)

observation of a structure at $M_{p\eta} \approx 1710$ MeV in the $\gamma\, p \rightarrow p\, \pi^0 \eta$ reaction

comparison to PWA: BnGa 2016-02 (normalized to data in 1550 MeV < $M_{p\eta}$ < 1680 MeV)

V. Metag, M. Nanova et al., EPJA 57 (2021) 325



structure established with 6 σ

characterisation of structure: { 1.) by fit of signal
2.) by deviation from PWA

observation of a structure at $M_{p\eta} \approx 1710$ MeV in the $\gamma\, p \rightarrow p\, \pi^0 \eta$ reaction

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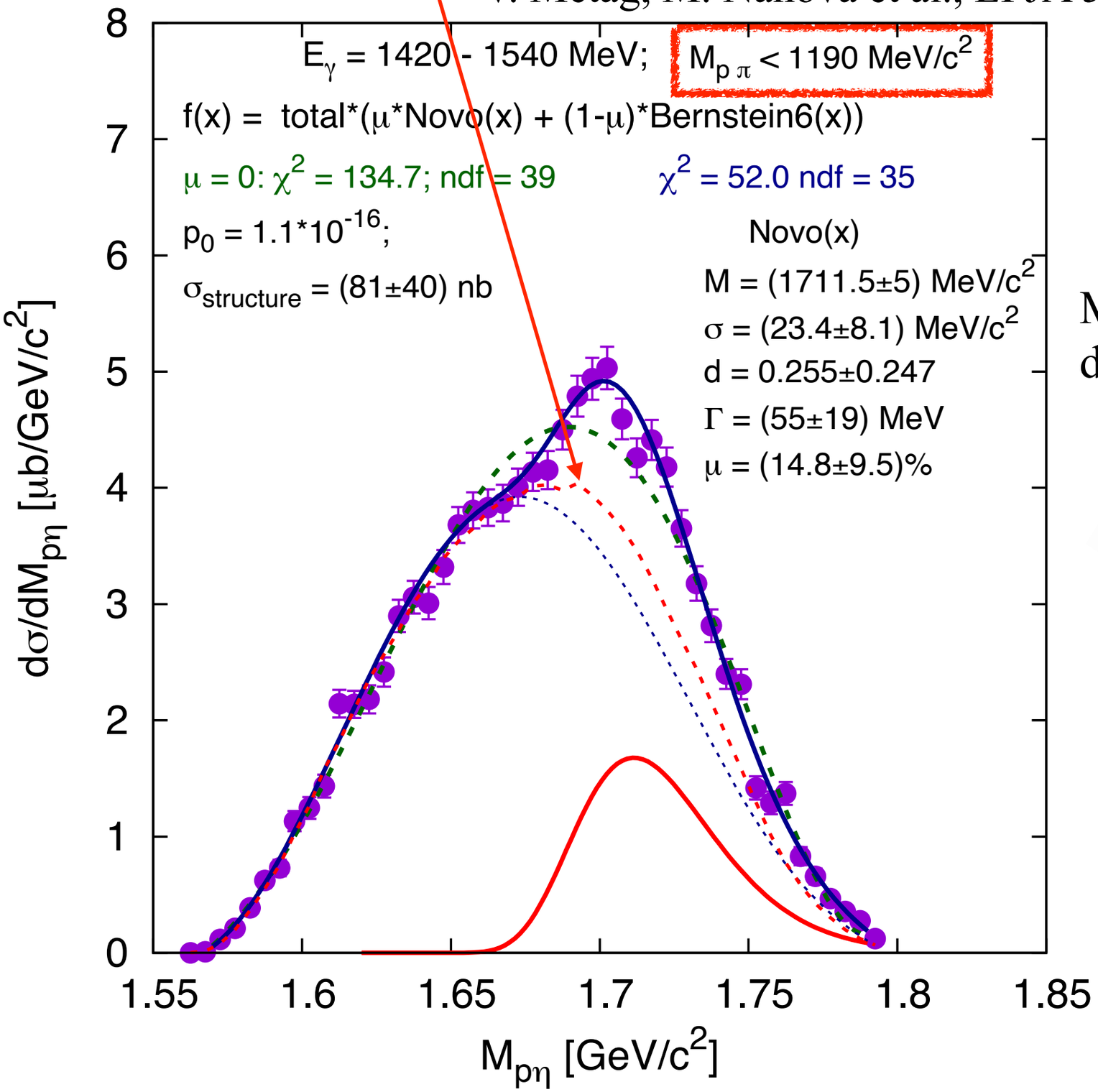
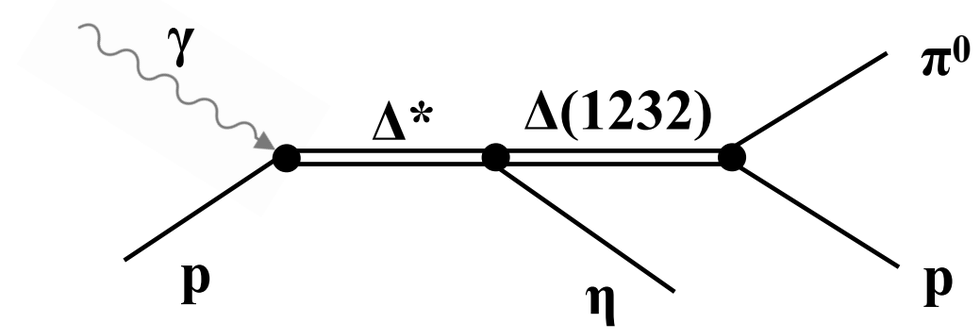


structure established with 6 σ

$M_{p\pi}$ cut applied to suppress dominant decay chain via the Δ (1232) resonance

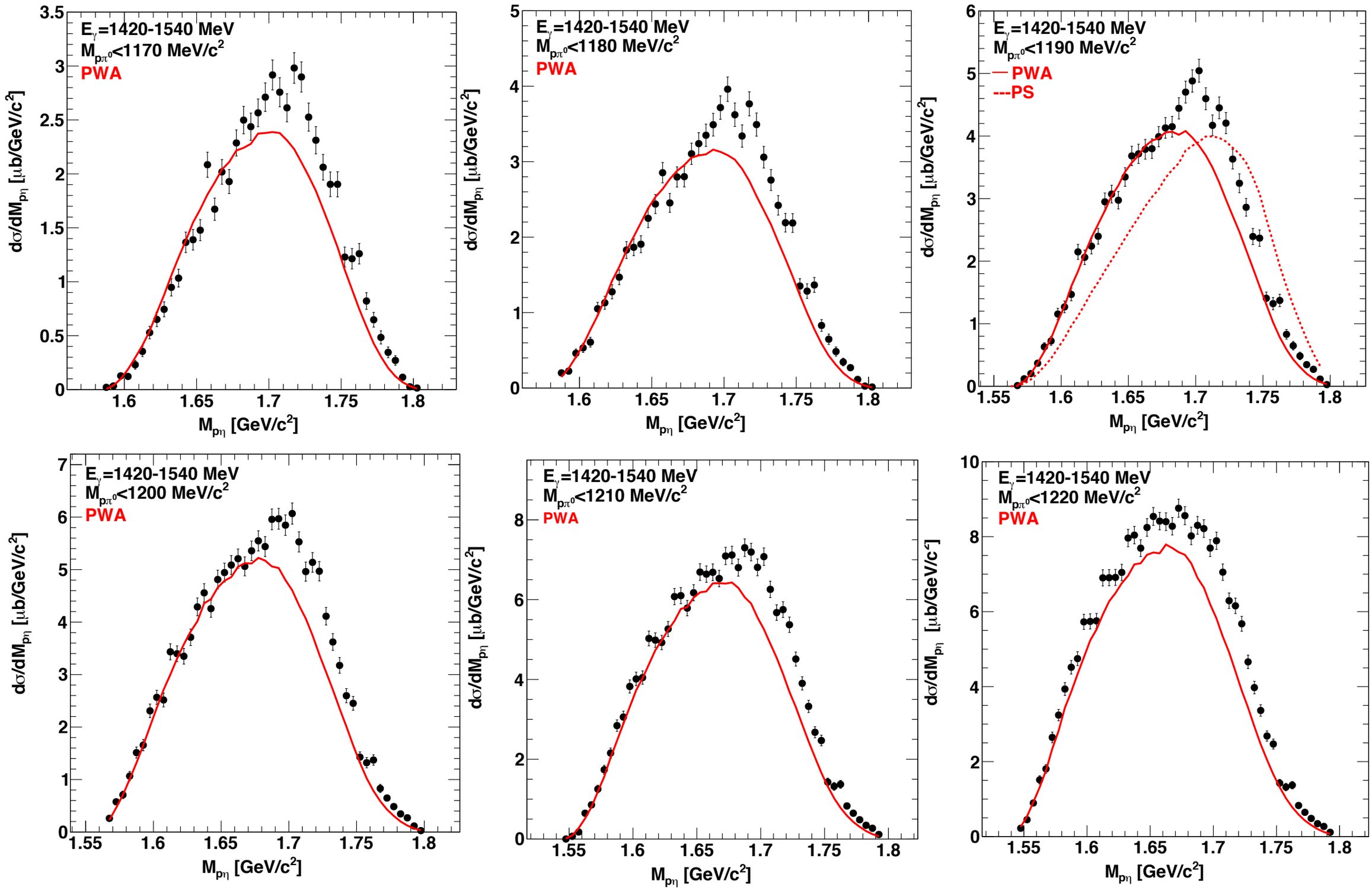
tree level diagram:



characterisation of structure: { 1.) by fit of signal
2.) by deviation from PWA

$\gamma\, p \rightarrow p\, \pi^0 \eta$; E_γ = 1420 - 1540 MeV

comparison to partial wave analysis (PWA) /and phase space distribution (PS)



structure not reproduced by PWA; excess also seen for different $M_{p\pi0}$ cuts

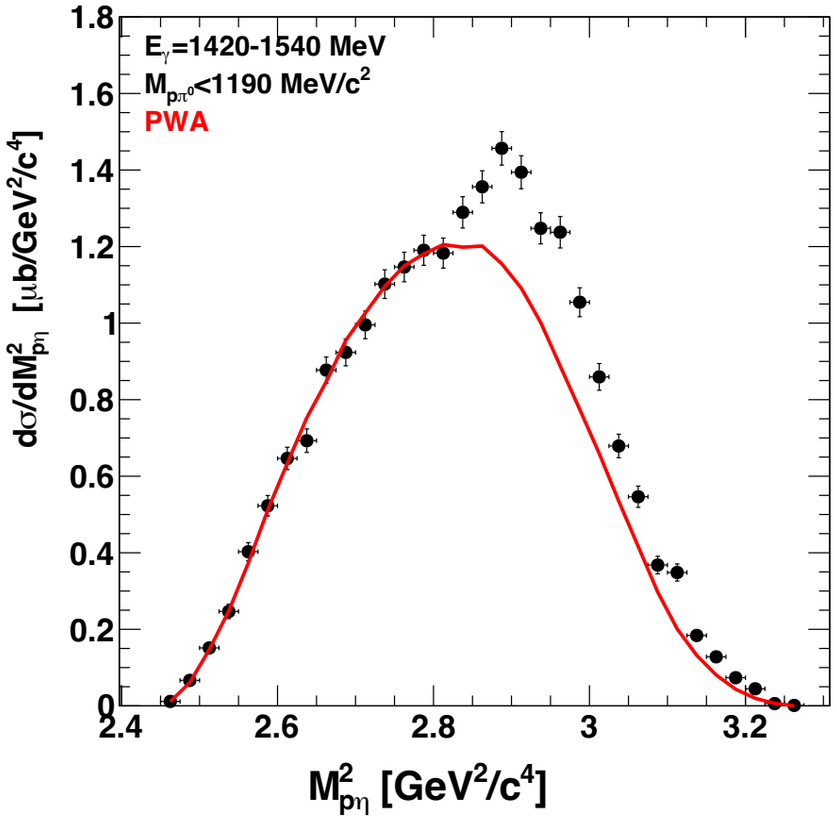
structure not caused by cut $M_{p\pi0} < 1190$ MeV

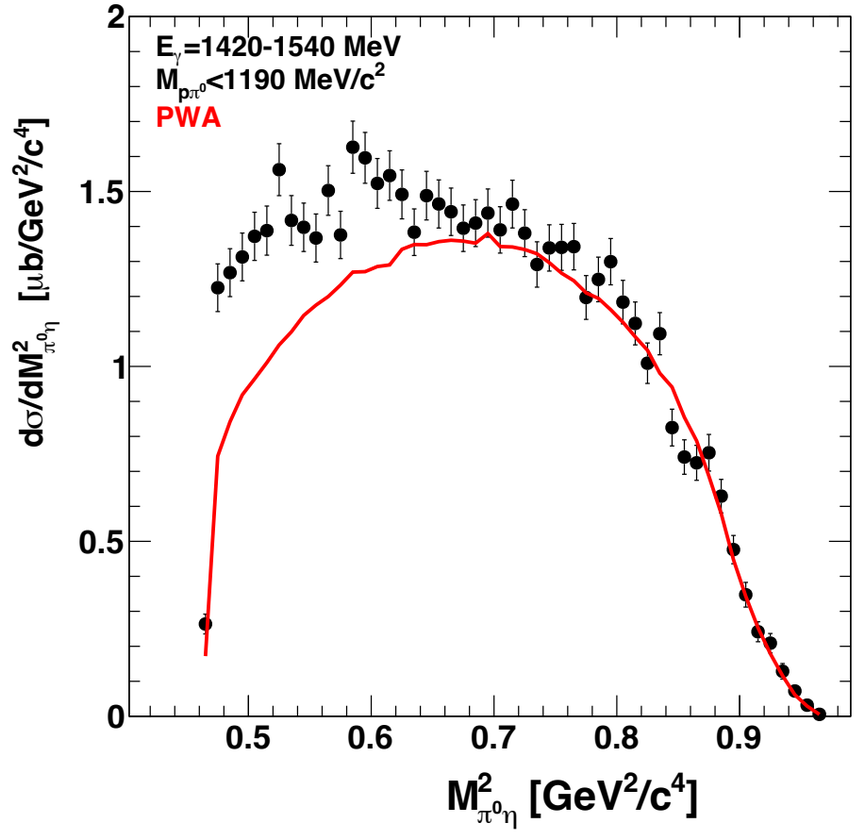
$M_{p\pi 0}$ < 1190 MeV

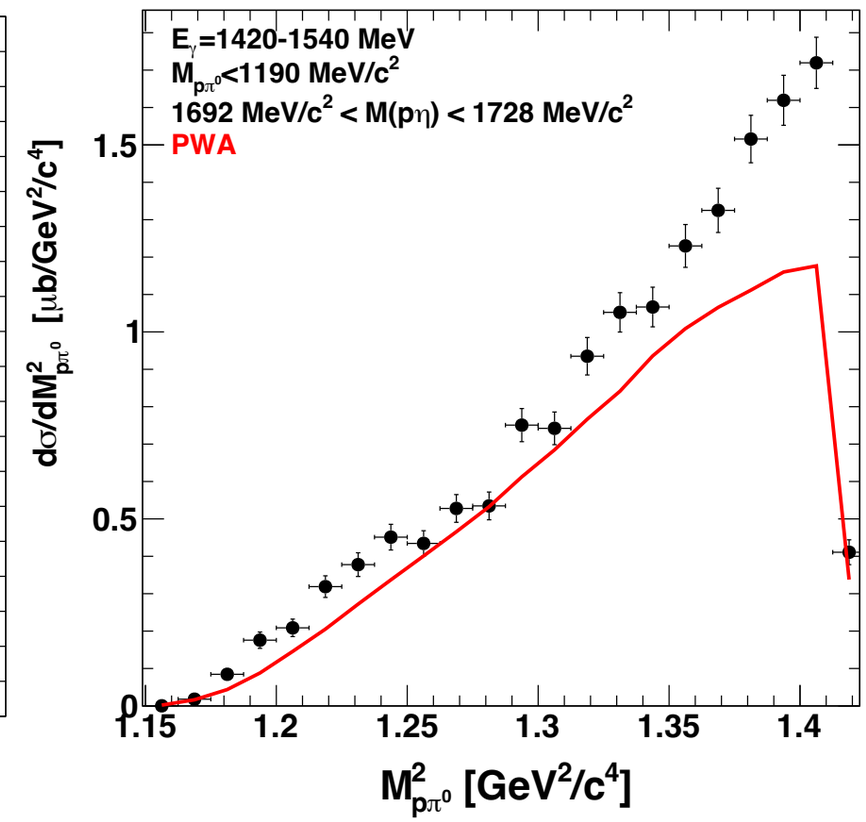
$\gamma\, p \rightarrow p\, \pi^0 \eta$; E_γ = 1420 - 1540 MeV

(1190 MeV)^2

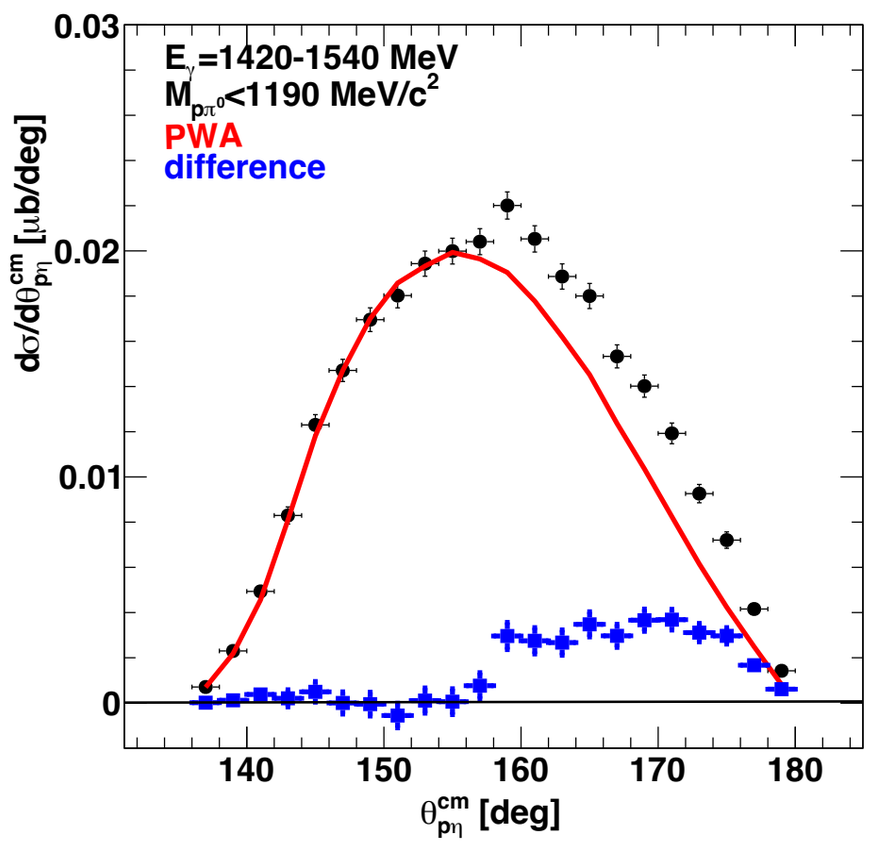
signal = deviation from PWA

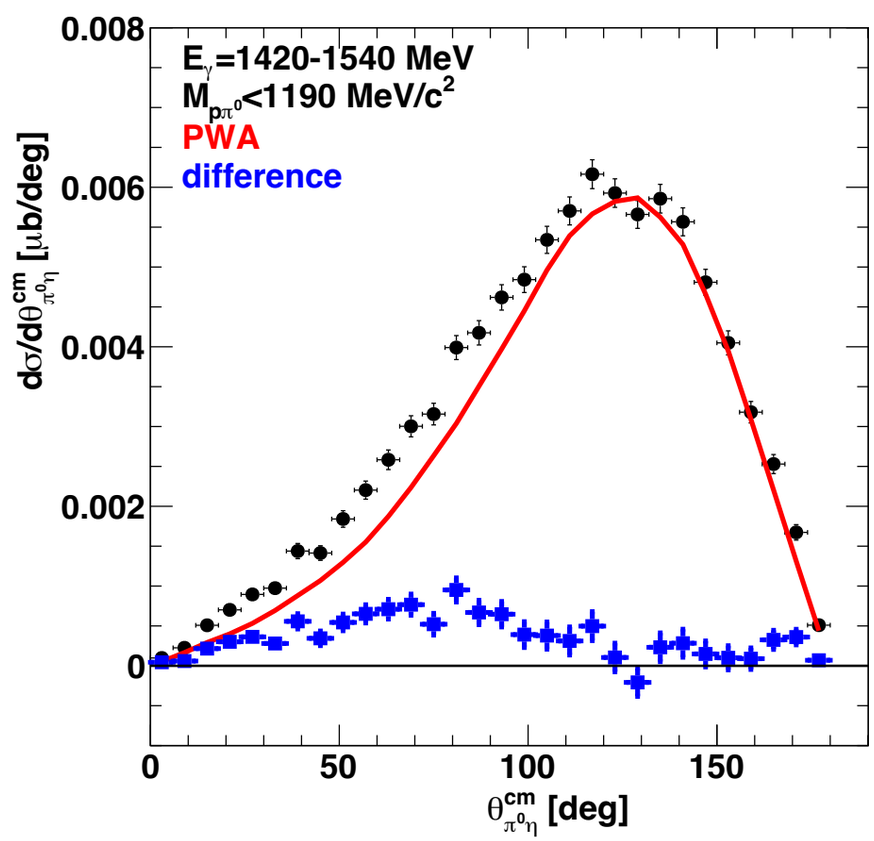






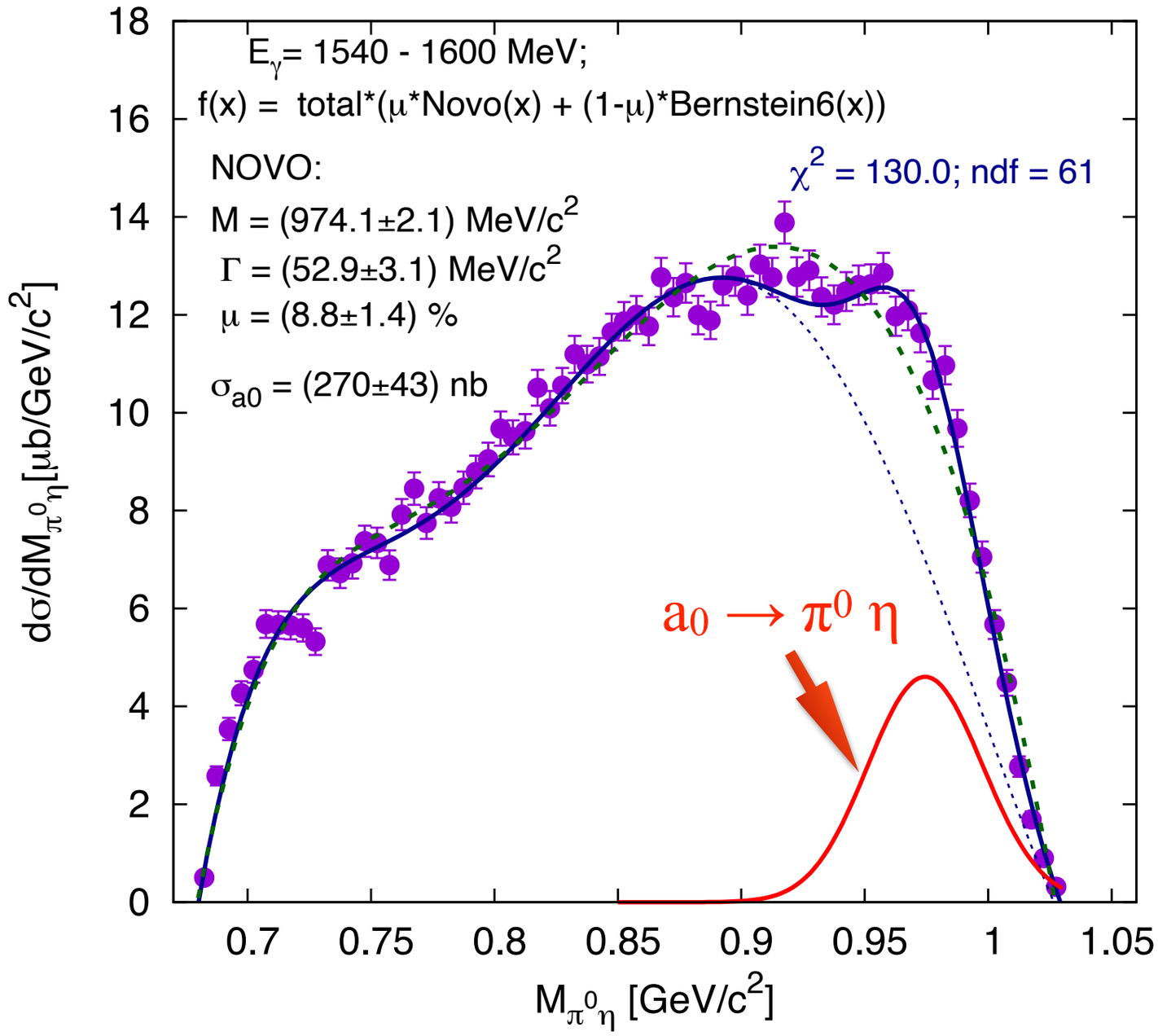
predominant back-to-back emission in γp-cm-system





deviation for $\theta_{\pi 0\eta} \approx 20^0$ - 90^0 γp-cm-system

$\gamma\, p \rightarrow p\, \pi^0 \eta$; direct observation of an a_0 signal



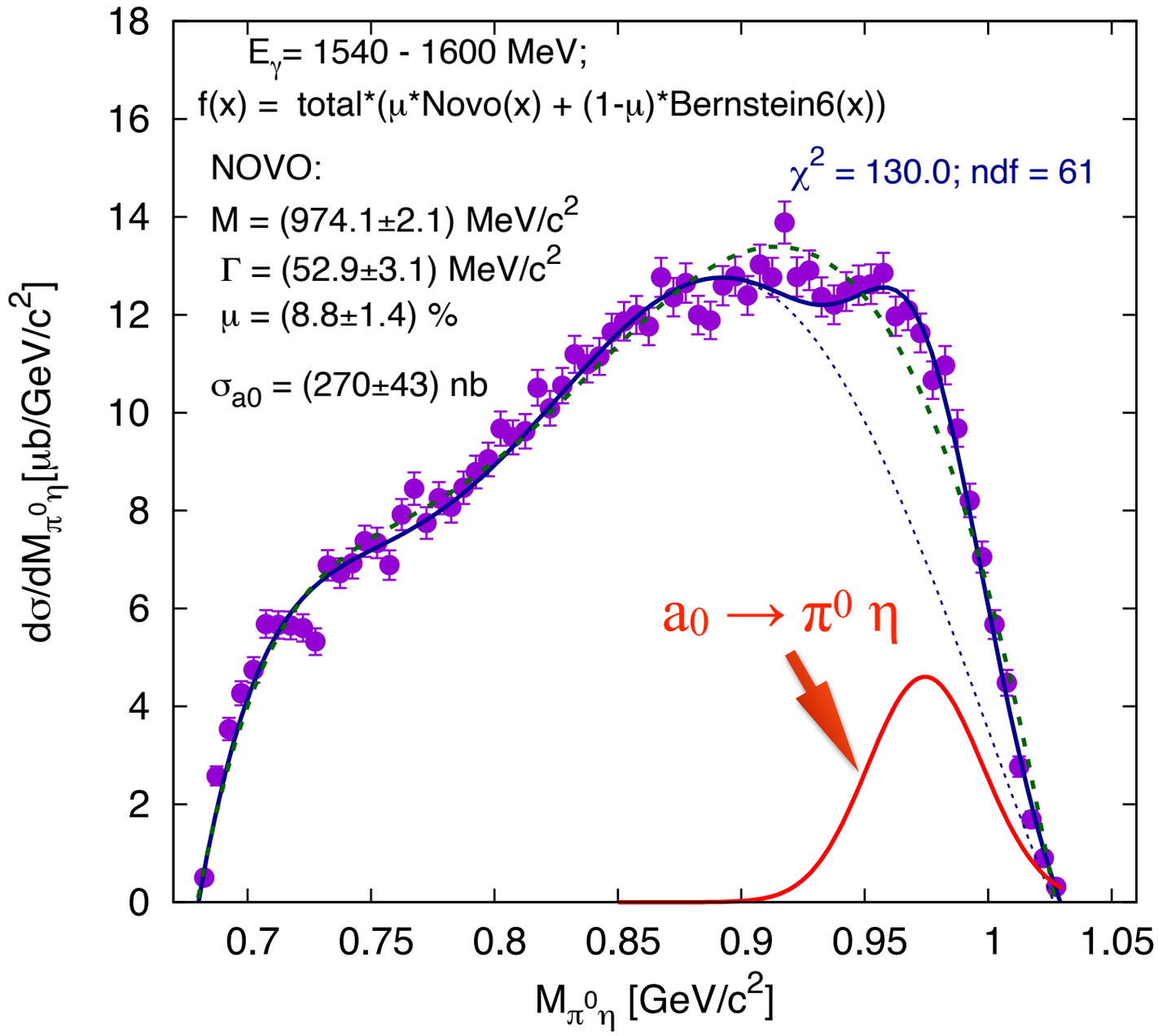
$m_{a0} = 974 \pm 2$ MeV ; $\Gamma_{a0} = 53 \pm 3$ MeV

PDG: $m_{a0} = 980 \pm 20$MeV ; $\Gamma_{a0} = 50$ - 100 MeV

$\sigma\_{a0} = 270 \pm 43$ nb; σ_{a0} (PWA) = 250 nb

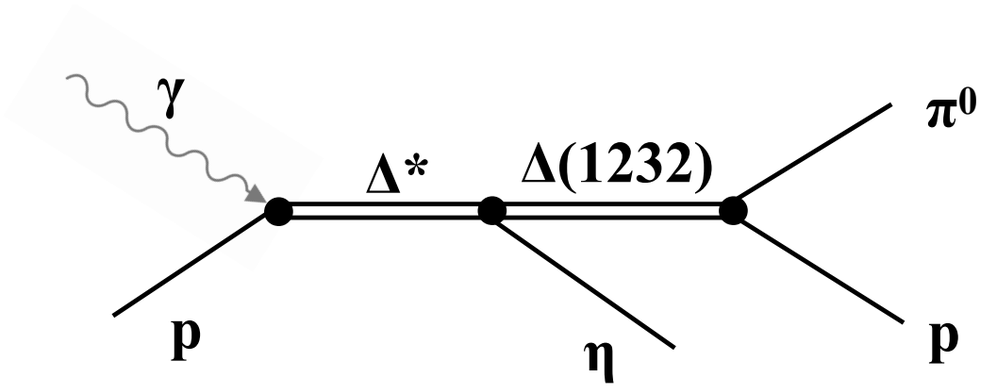
for $m\_a_0 > 990$ MeV $a_0 \rightarrow K^+K^-$ dominant

$\gamma\, p \rightarrow p\, \pi^0 \eta$; direct observation of an a_0 signal

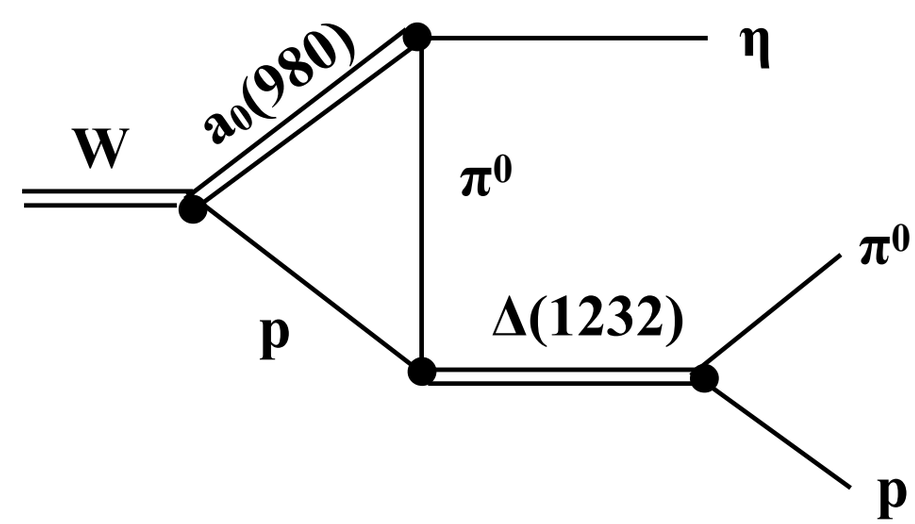


tree level diagram:

(suppressed by $M_{p\pi}$ < 1190 MeV cut)



triangular diagram:



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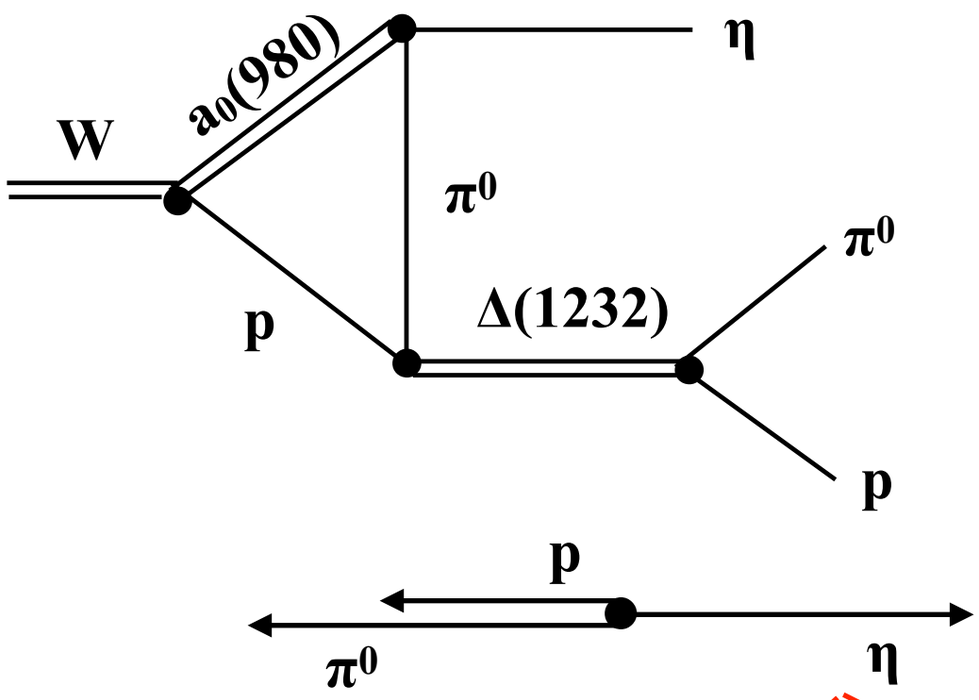
calculating triangular singularities

triangular diagram:

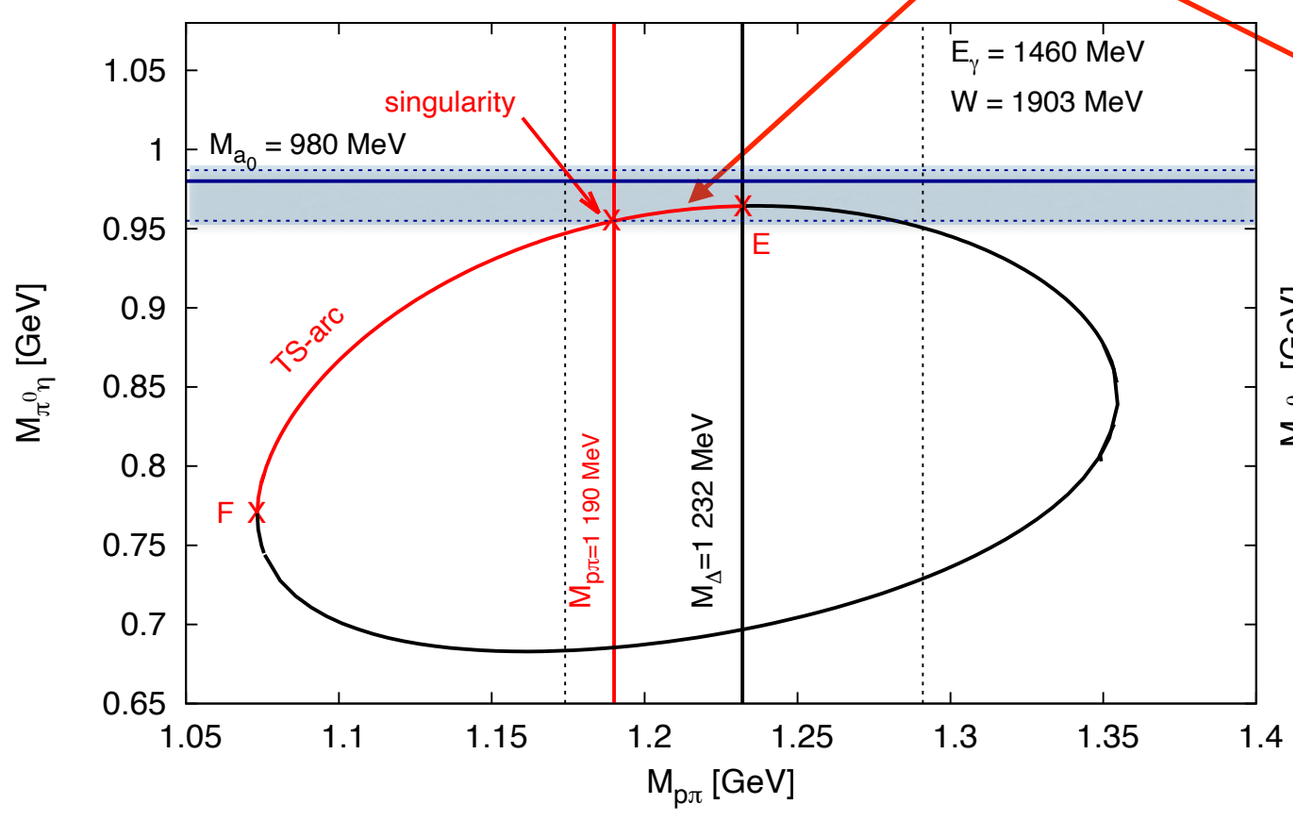


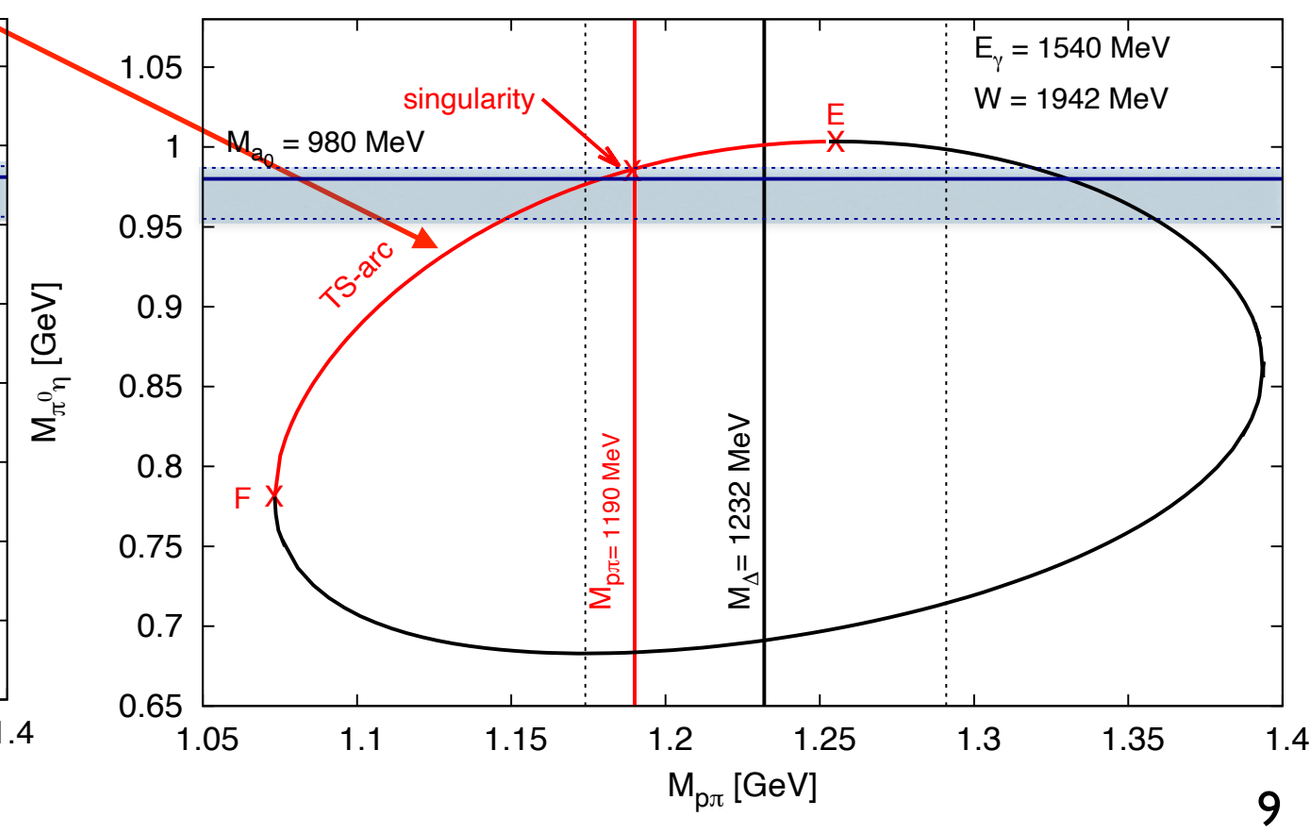
Bayar et al. PRD 94 (2016) 074039

the triangular diagram leads to
an enhancement at the a_0 threshold;

1.) energy/mom. balance: internal ↔ external
2.) all internal particles almost on mass shell
3.) p, π^0, η collinear:

F-K.Guo, X-H.Liu, S.Sakai
Prog. Part. Nucl. Phys. 112 (2020) 103757

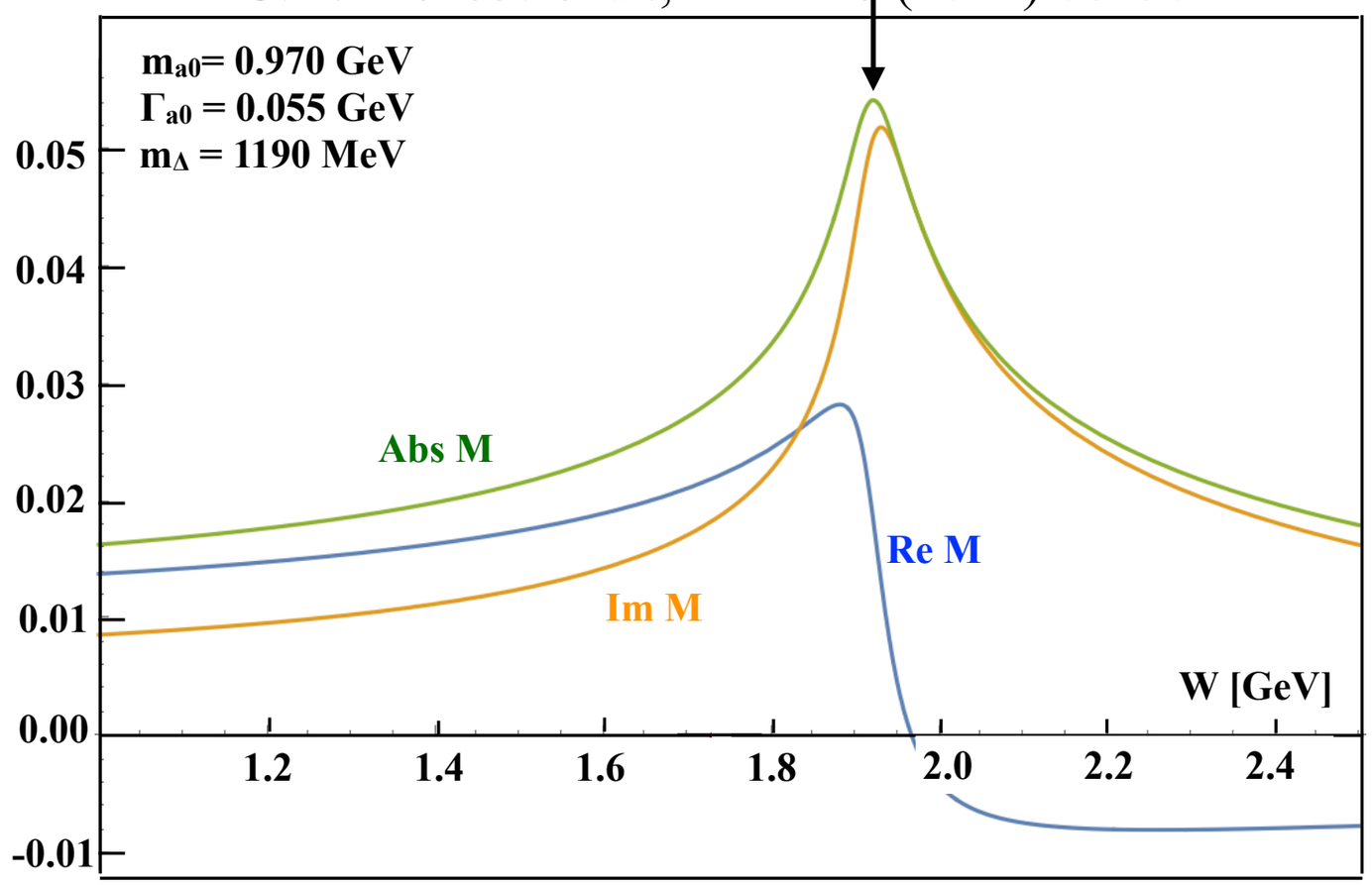




Calculation of triangular singularity strength

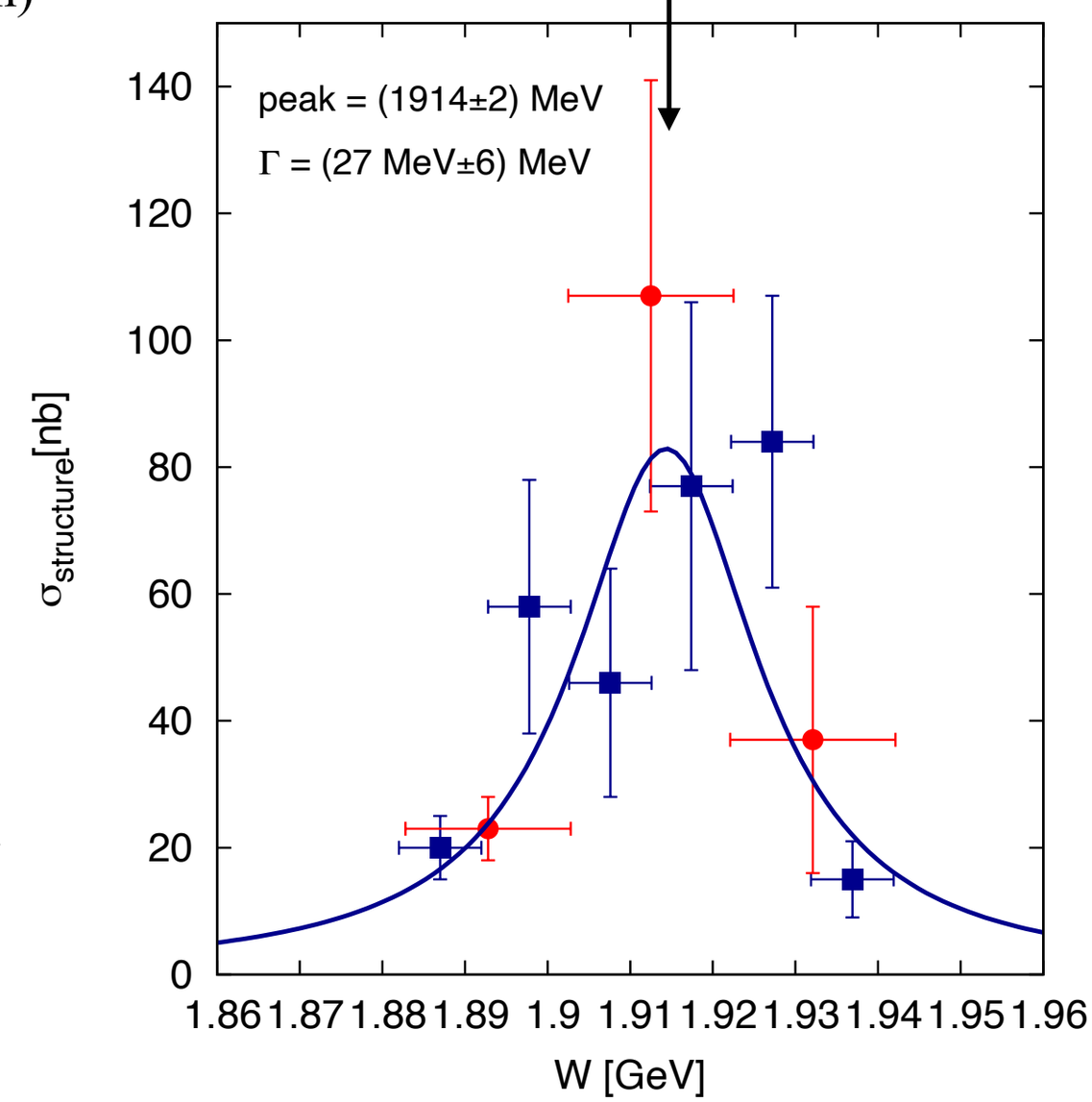
$m_p + m_{a0} = 1918$ MeV
W=1918 MeV
$E_\gamma = 1492$ MeV

thanks to Mathias Wagner and Bernhard Ketzer (Univ. Bonn)
M. Mikhasenko et al., PRD 91 (2015) 094015
G.D. Alexeev et al., PRL 127 (2021) 082501



comparison to data:

$m_p + m_{a0} = 1918$ MeV
W=1918 MeV
E_γ=1492 MeV

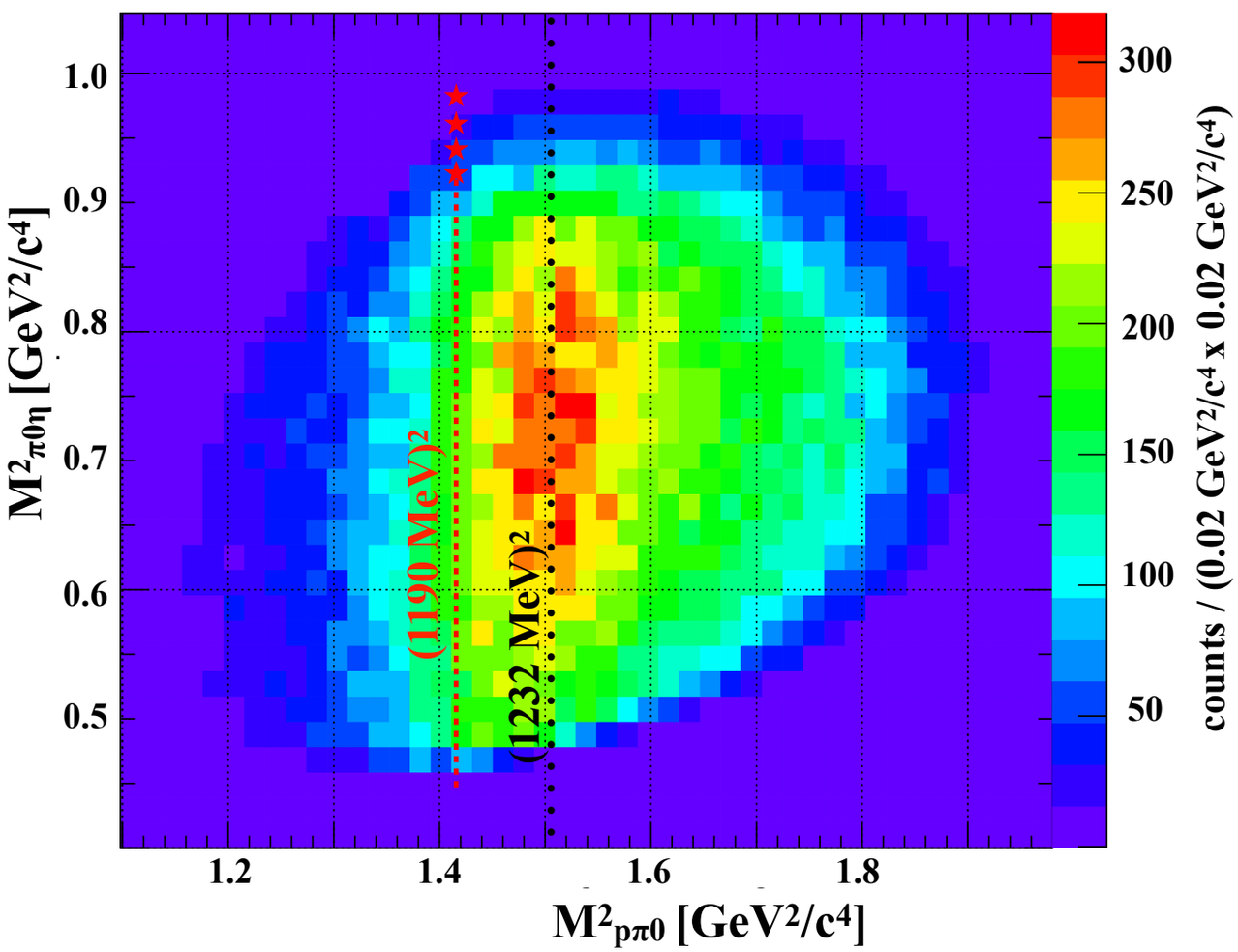


calculation shows enhancement at W=1918 MeV; E_γ= 1492 MeV
as observed experimentally

calculating triangular singularities

calculation of singularities for 4 incident energies near the a_0 threshold,
following Bayar et al. PRD 94 (2016) 074039

E_γ [MeV]	$M_{\pi 0\eta}$[MeV]	$M_{p\eta}$[MeV]	$M_{p\pi 0}$[MeV]
1549	990	1609	1190
1524	980	1601	1190
1498	970	1591	1190
1473	960	1583	1190



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γ p-cm-system:

p_p= 122.9 MeV; β_p=0.130

β_η = -0.590

p_π= 277.8 MeV; β_π=0.899

p_η= -400.7MeV

π^0 faster than p

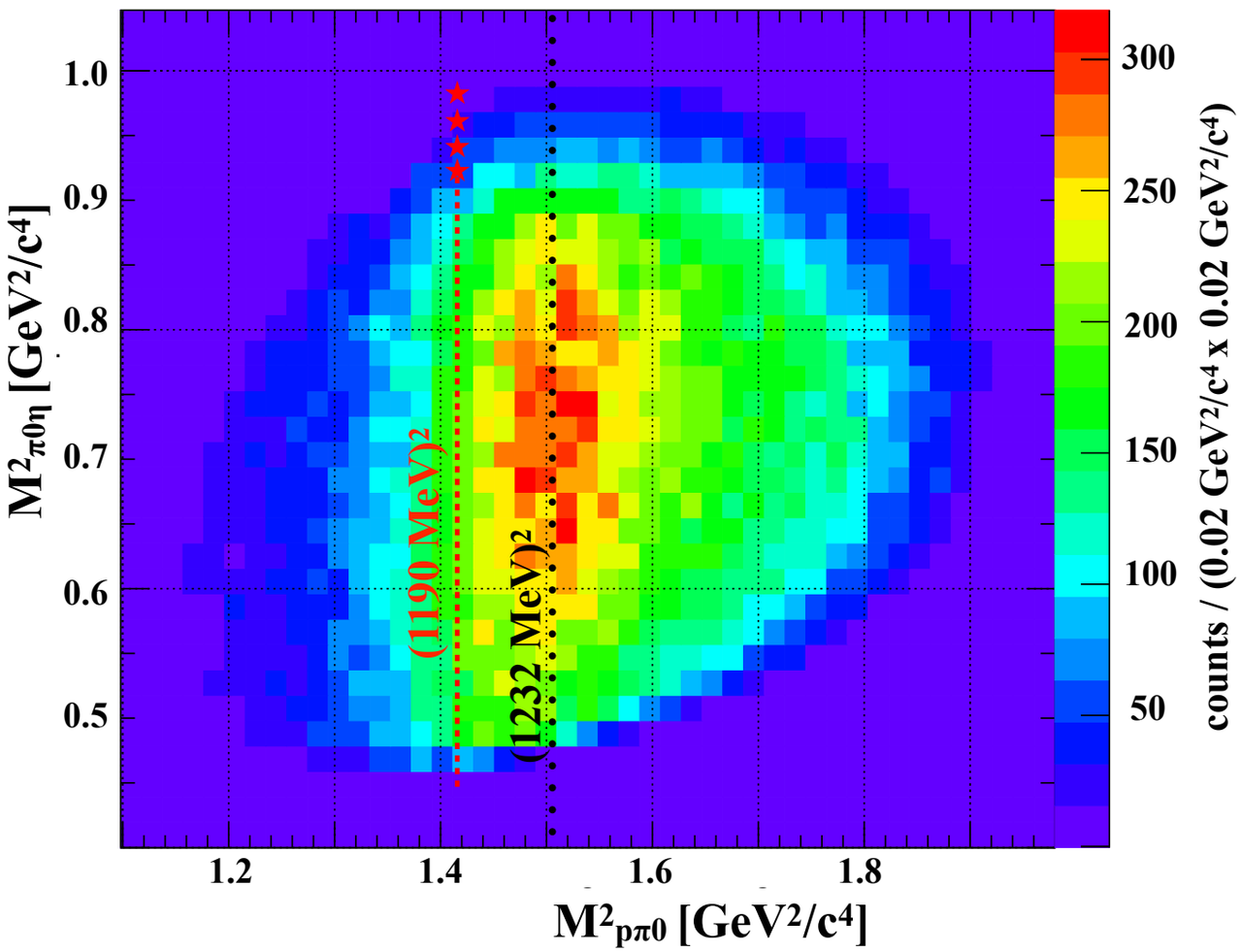
π^0-p rescattering:

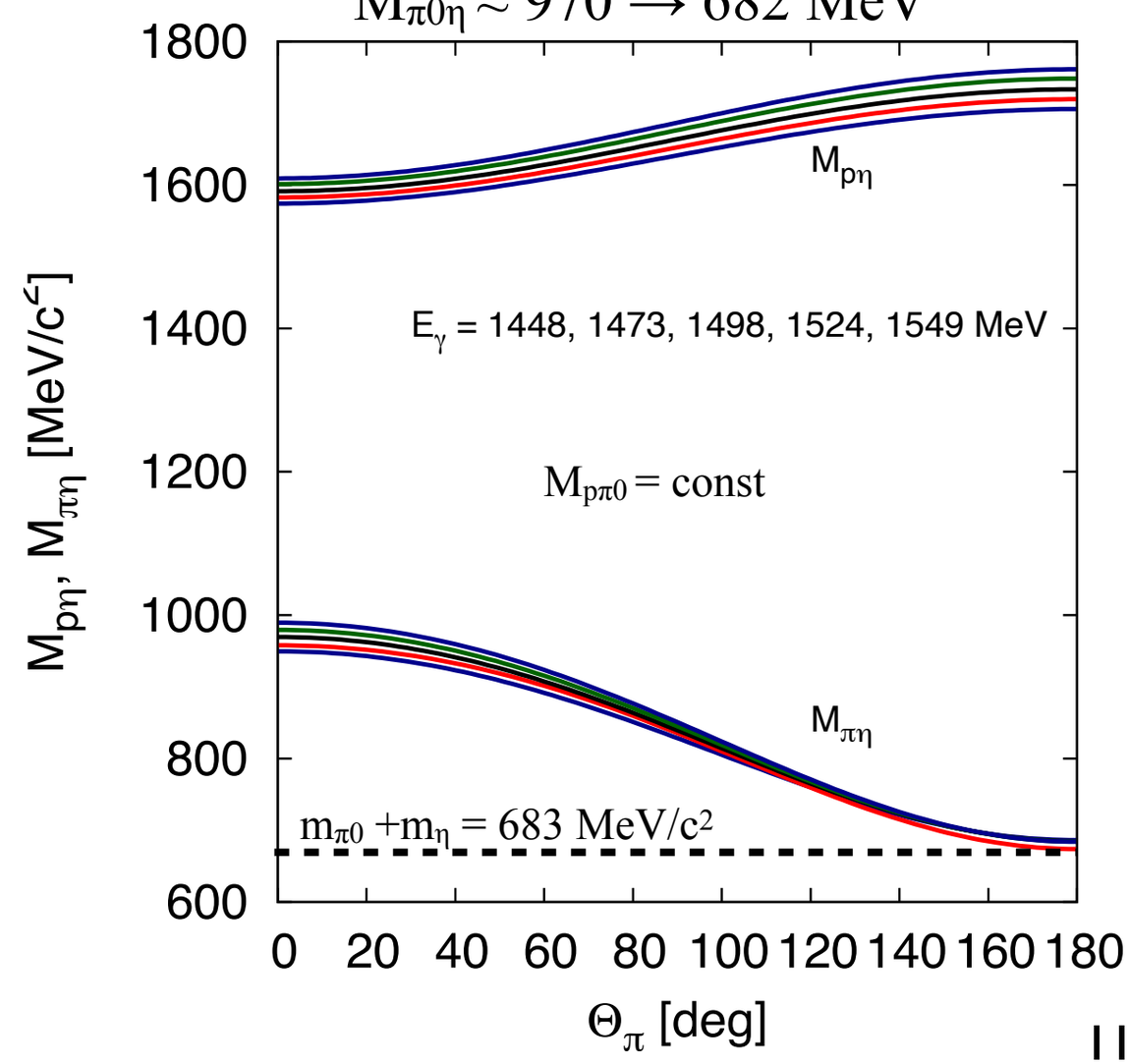
$M_{p\pi0}$ = const = 1190 MeV

$M_{p\eta} \approx$ 1600 → 1700 MeV

$M_{\pi0\eta} \approx$ 970 → 682 MeV

singularity events are re-distributed along the dashed red line by **π^0-p - rescattering**

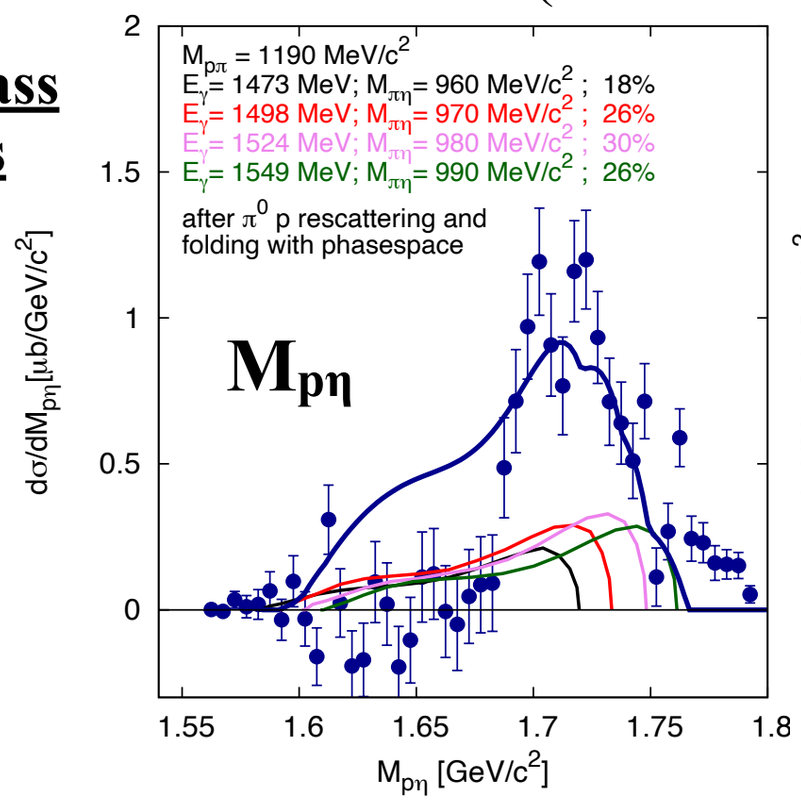


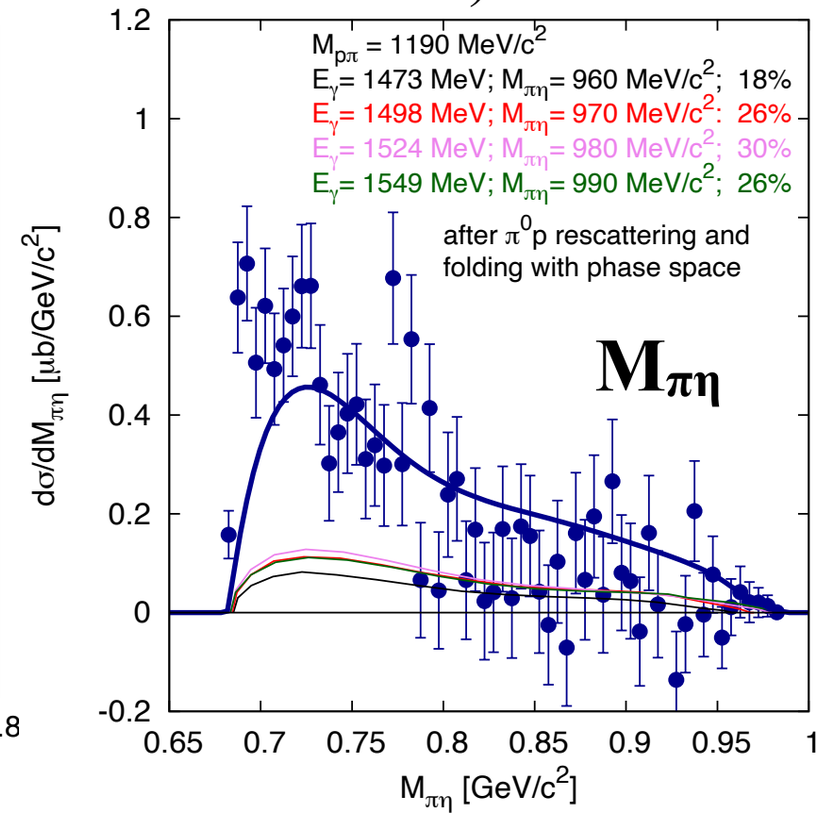


Comparison data (difference to PWA) ⟷ calculation

contributions of the 4 selected singularity points with weight given by a_0 line shape
blue curve (sum of the 4 contributions) fitted to the data

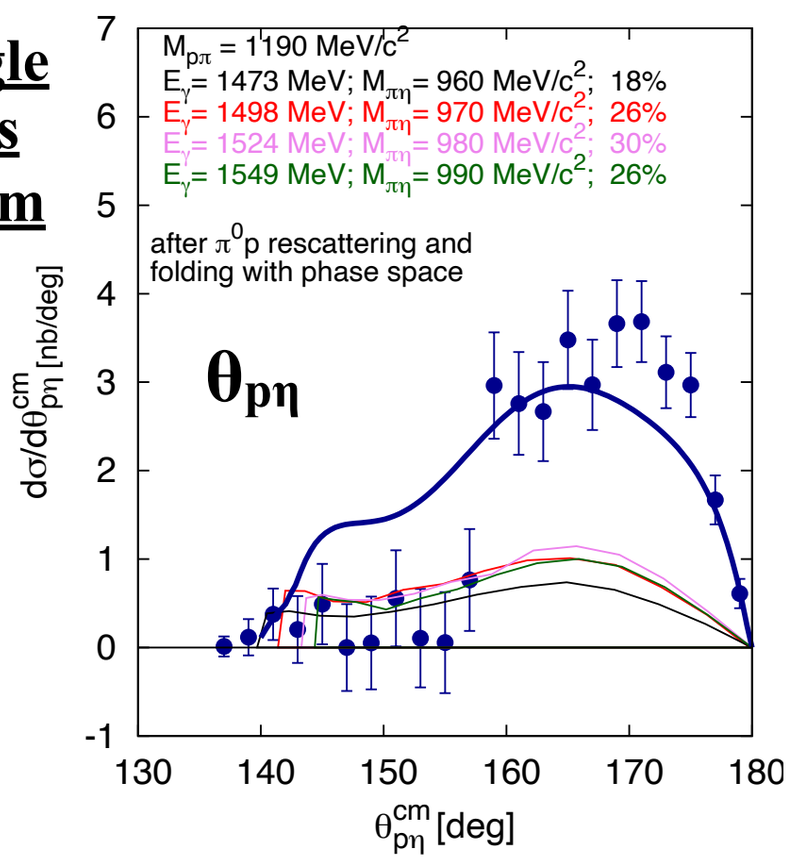
invariant mass distributions

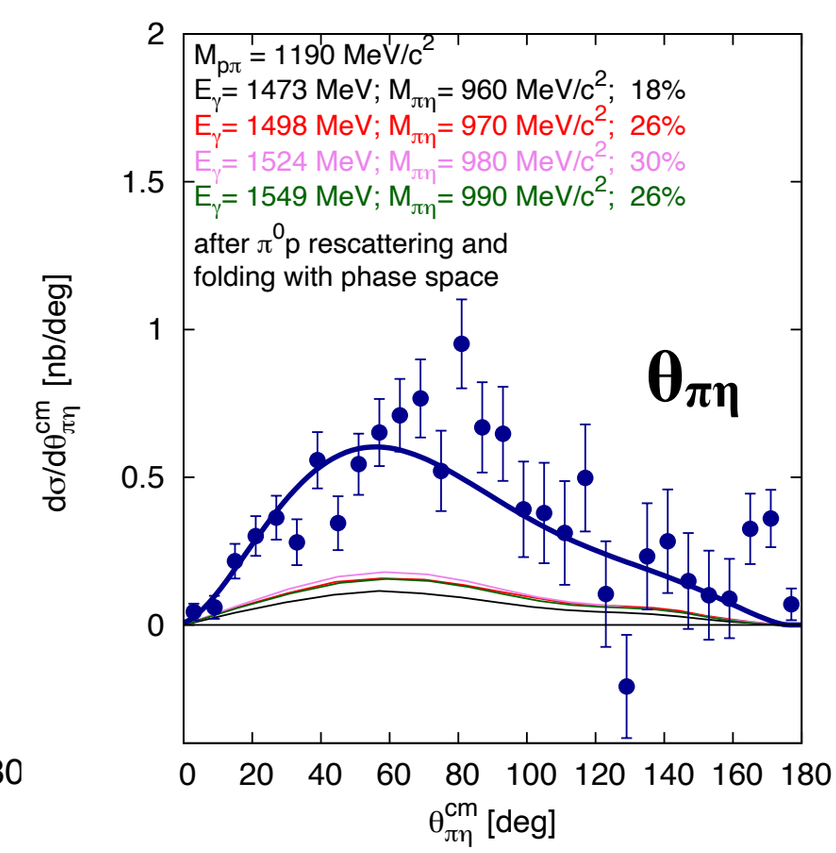




data qualitatively reproduced by calculations !!

opening angle distributions γp-cm-system

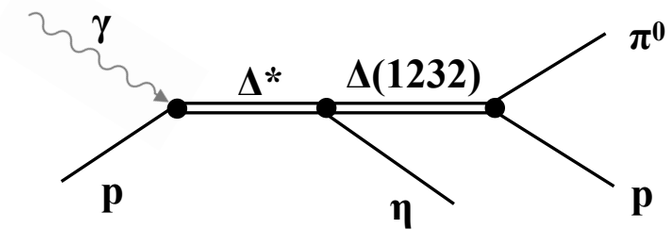




Interference of loop- (triangular) and tree-level amplitudes

thanks to Mathias Wagner (Univ. Bonn)

tree level diagram:

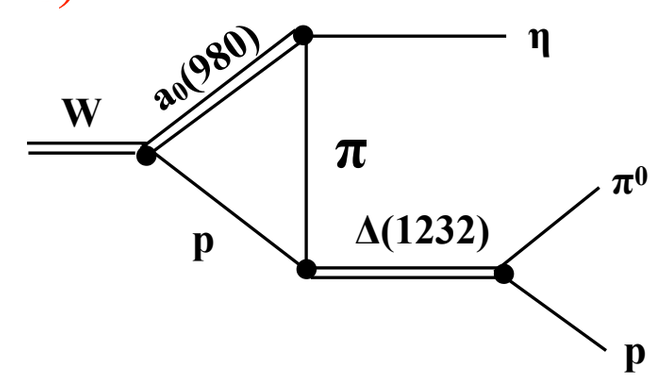


initially populated nucleon resonance (source of p, a_0):
$m_1 = 1.95$ GeV; $\Gamma_1 = 0.350$ GeV

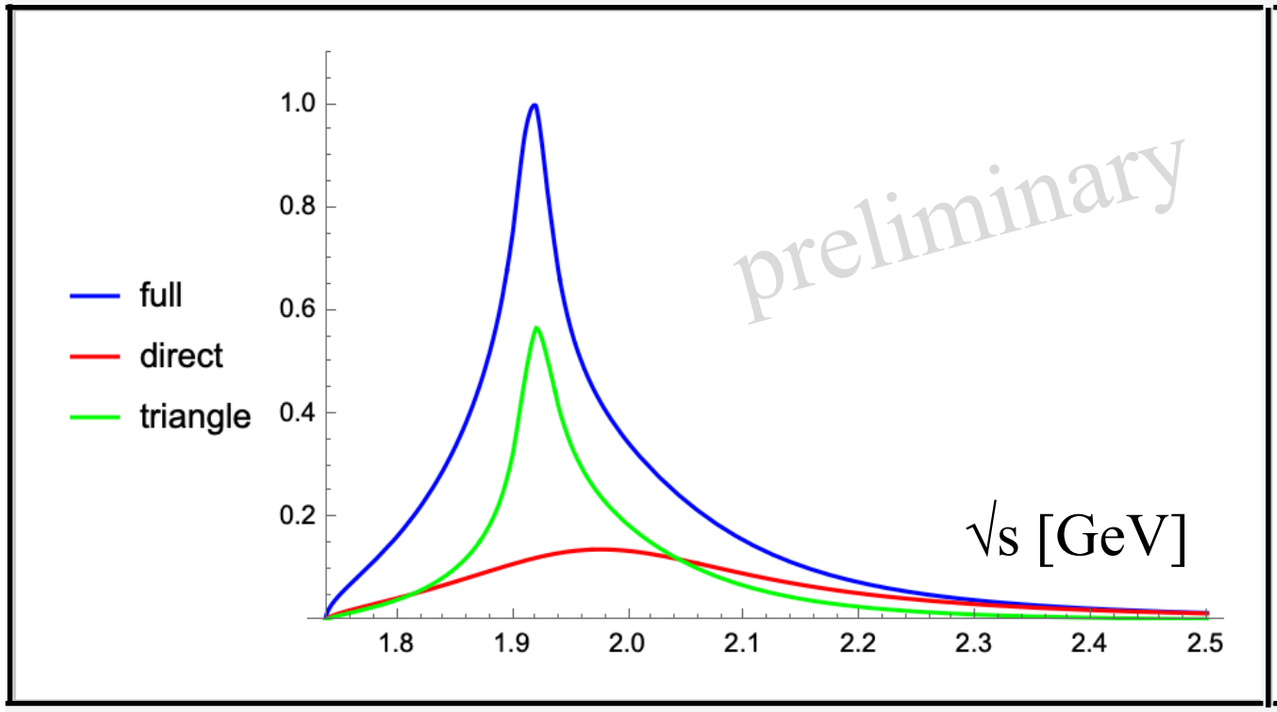
$f_{tot} = f_{tree} + f_{loop} = (rel + e^{i\varphi} * f_{triangle}(\sqrt{s}; \Gamma_{a0}, m_{a0}, m_\Delta)) * BW(\sqrt{s}; m_1, \Gamma_1)$

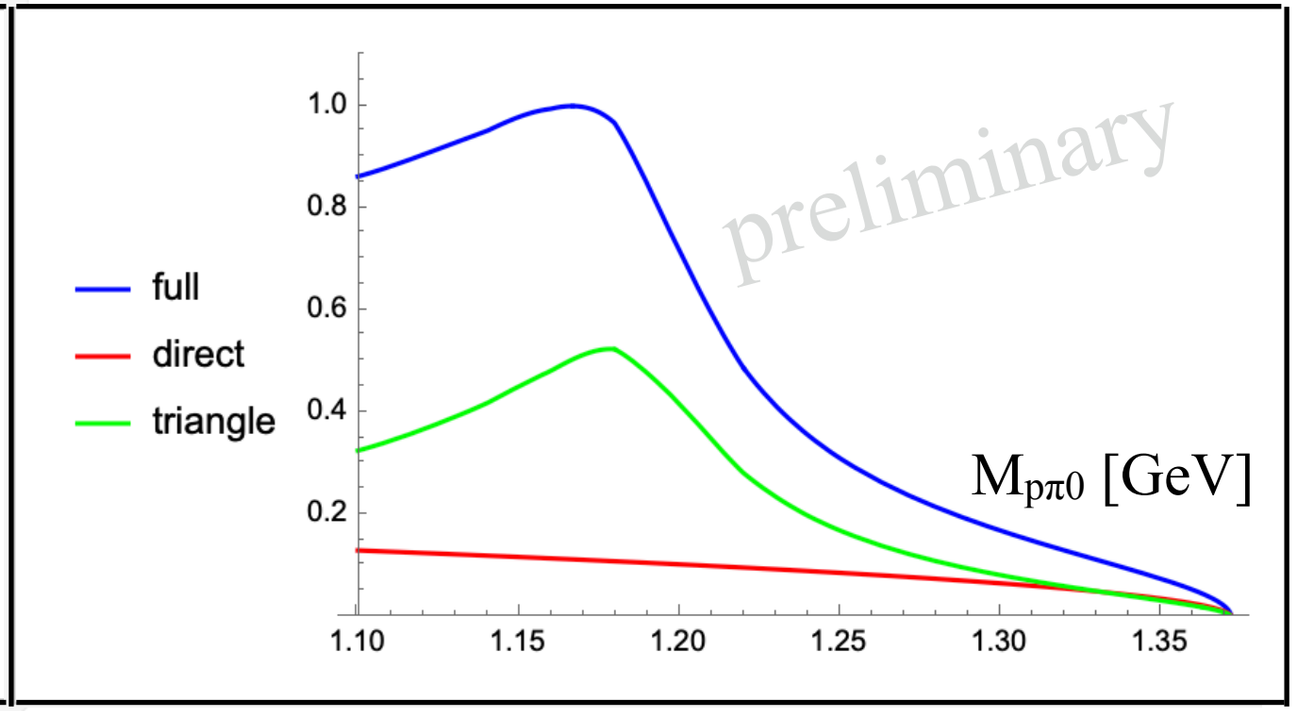
intensity = $|M|^2$*phasespace

triangular diagram:



experimentally observed excitation function and
$M_{p\pi 0}$ distribution reproduced for rel = 0.036; φ = - 0.5





more detailed studies require partial wave analysis !!

summary and conclusions

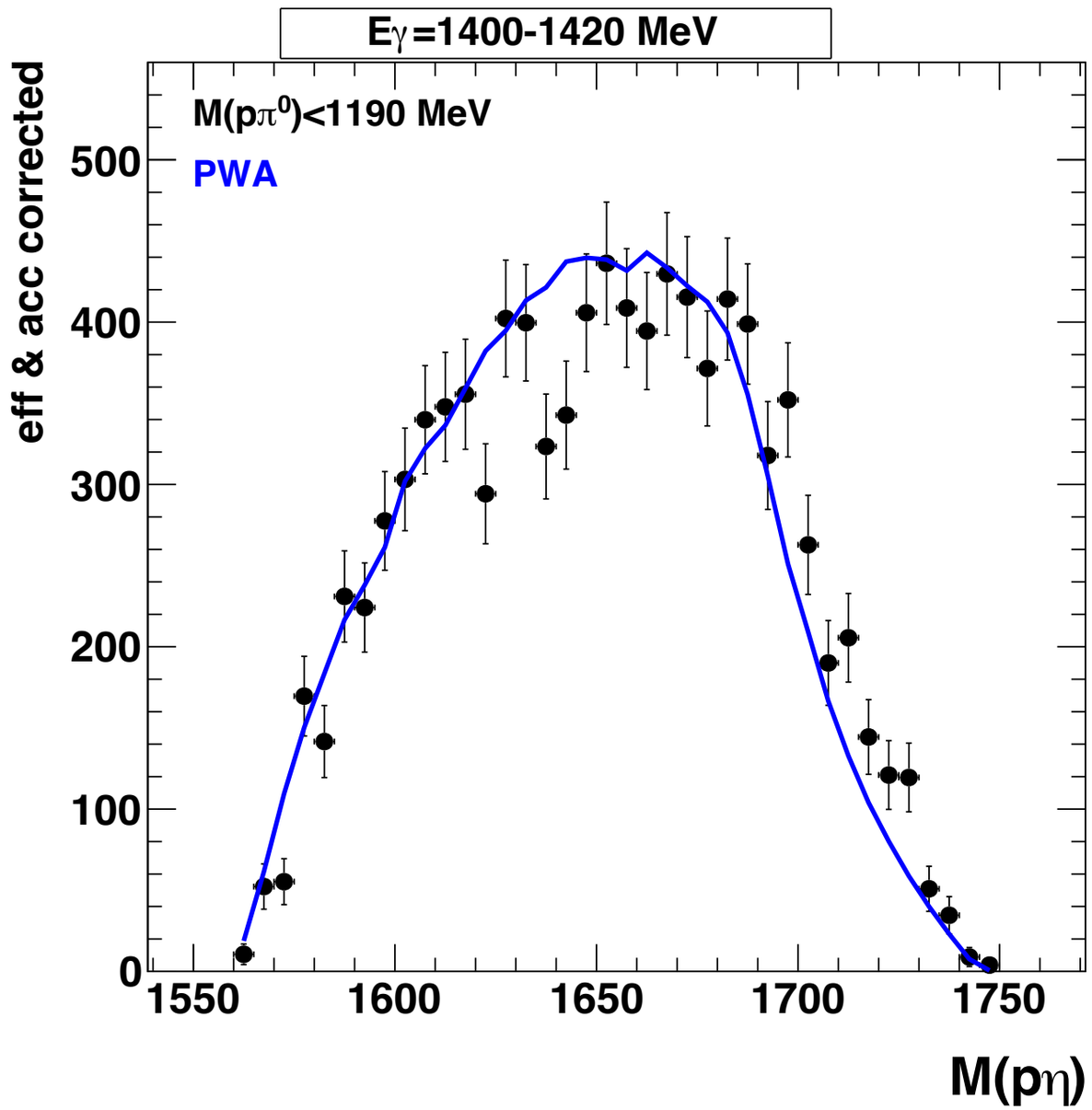
- structure at $M_{p\eta} \approx 1710$ MeV established in $\gamma\, p \rightarrow p\, \pi_0\, \eta$ reaction for $E_\gamma = 1400 - 1600$ MeV
- structure moves and changes shape with incident photon energy $\rightarrow$ no genuine nucleon resonance
- characteristics of structure qualitatively reproduced by calculation based on the triangular loop in the $\gamma\, p \rightarrow p\, a_0 \rightarrow p\, \pi_0\, \eta$ reaction; (EPJA 57 (2021) 325)
- loop diagrams and rescattering effects play an important role also in the **baryon sector** in the interpretation of structures in the excitation spectrum of the nucleon; important to distinguish kinematical singularities from genuine resonances
- not every bump in an invariant mass spectrum is a resonance !
- **<u>improvements:</u>**

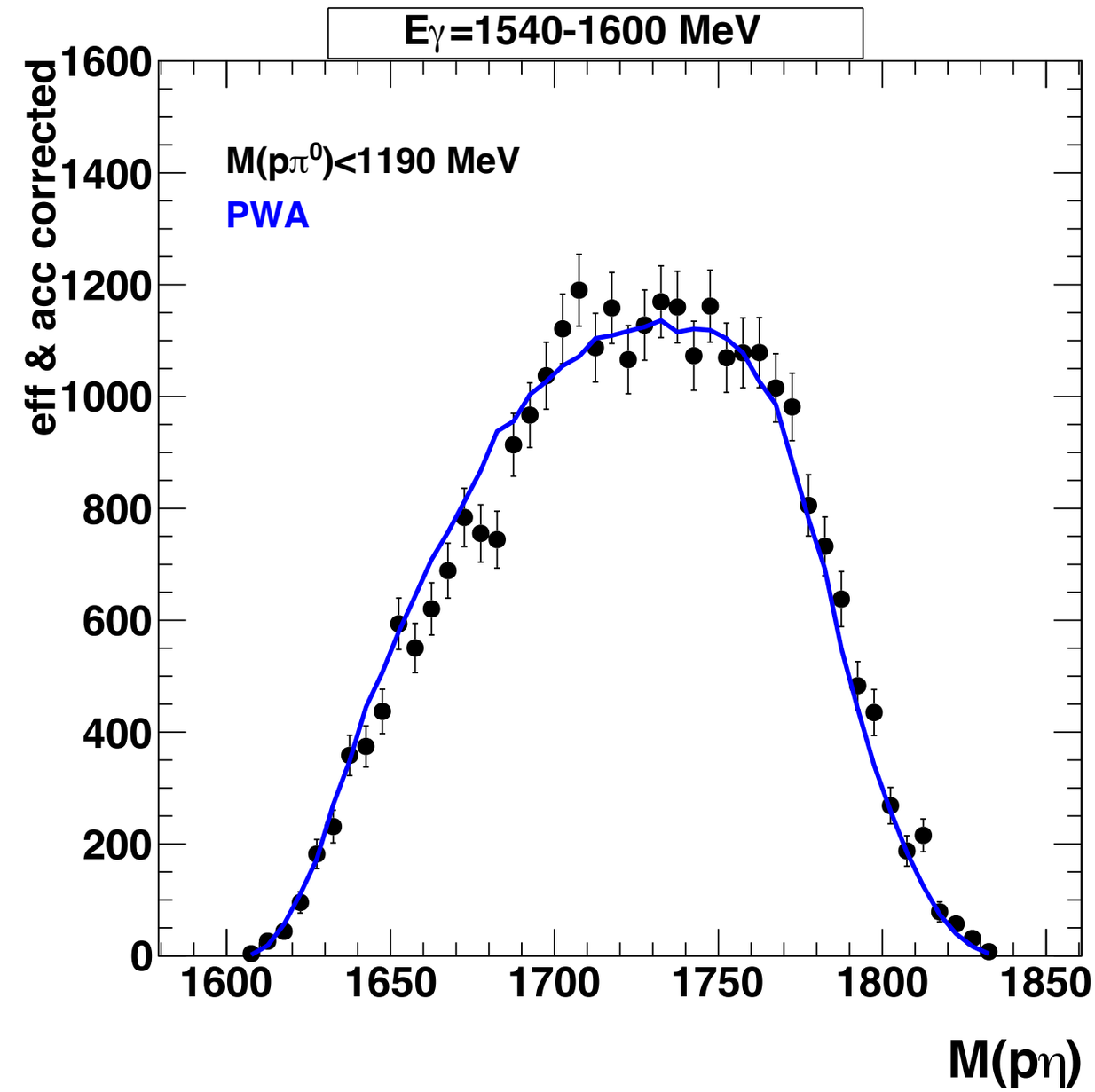
  calculation not only for 4 selected singularity points

  $\rightarrow$ **full partial wave analysis required including the present data**

backup

comparison data ⟷ PWA outside signal region

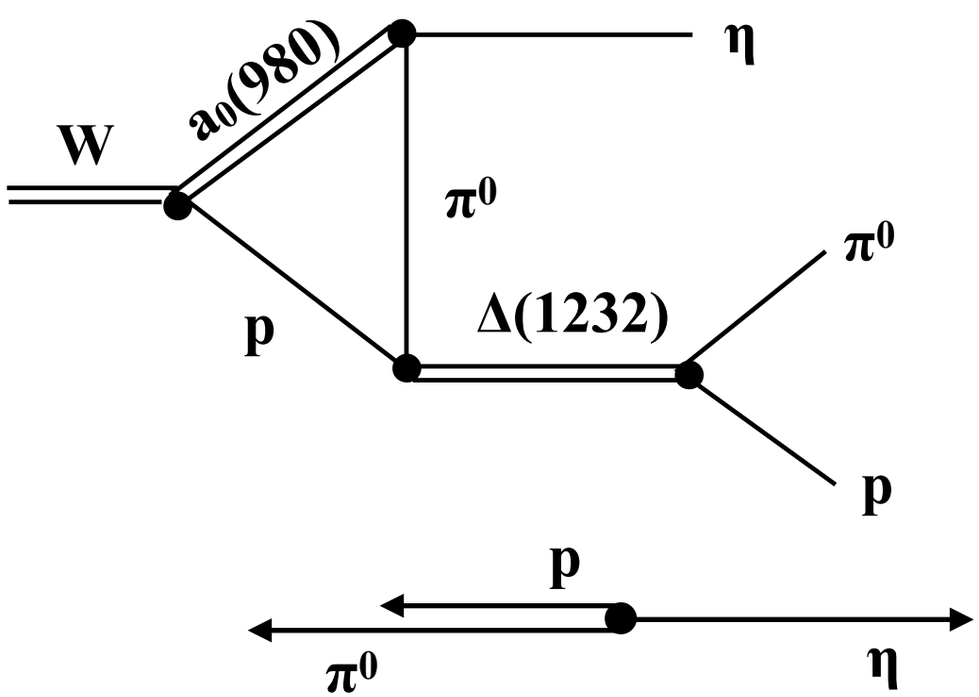




PWA describes data very well outside the signal region (E_γ = 1420 - 1540)

calculating triangular singularities

triangular diagram:

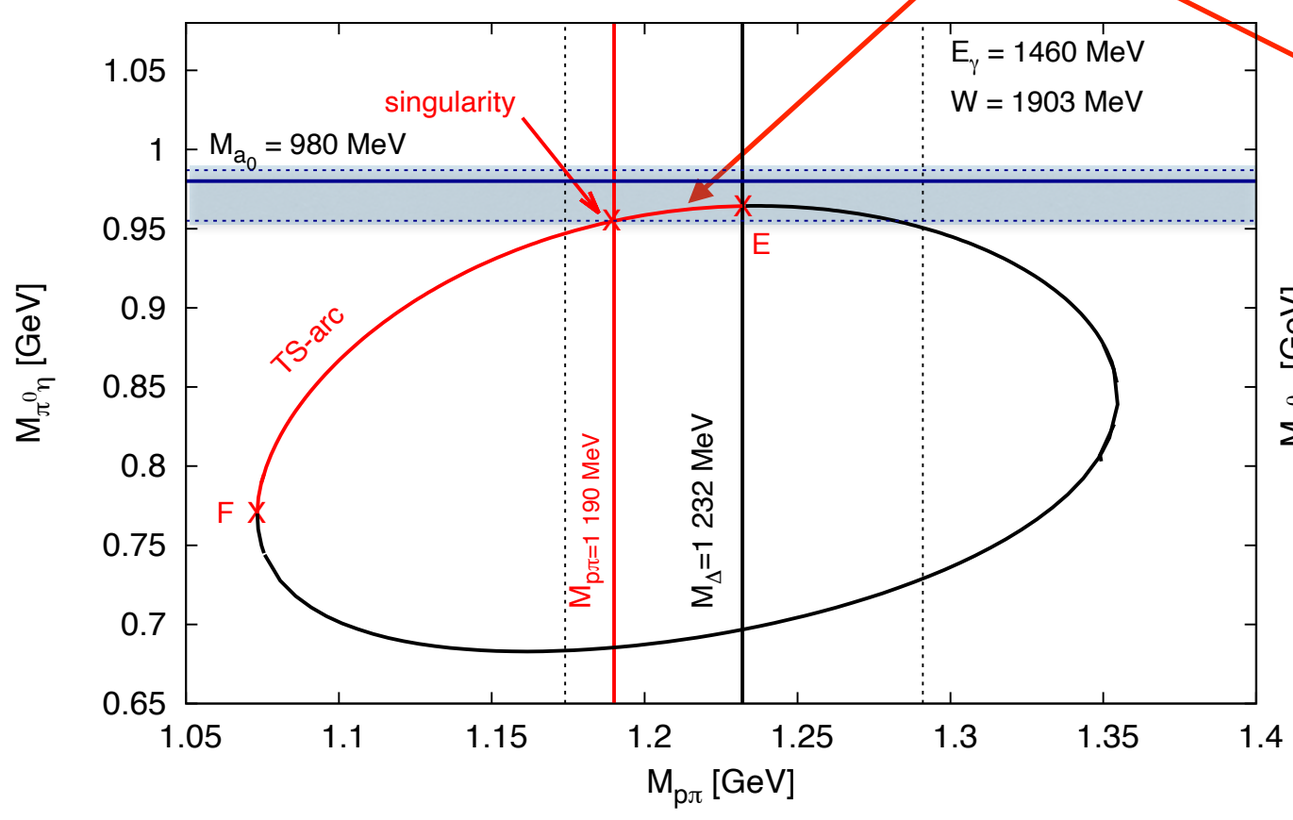


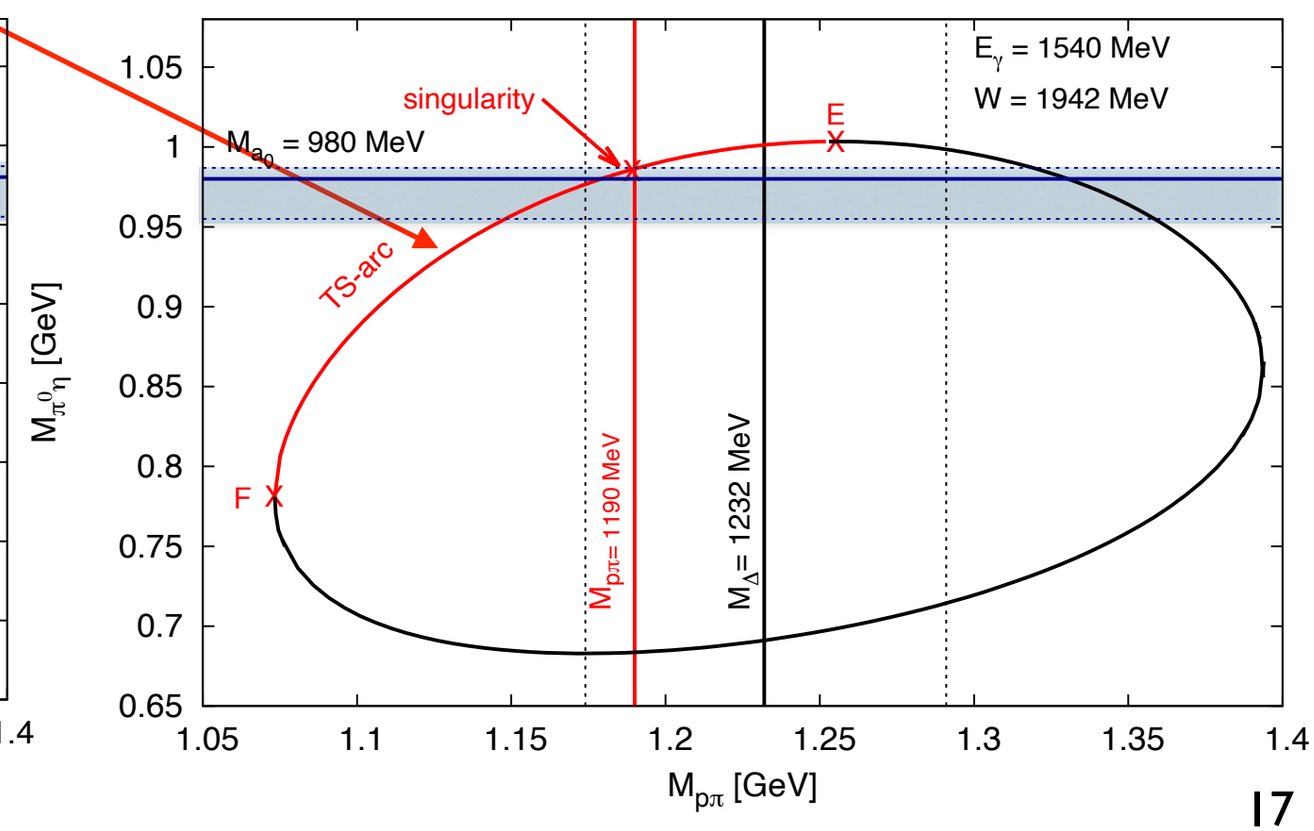
Bayar et al. PRD 94 (2016) 074039
energy-momentum balance within the loop has to match the energy-momentum balance of the initial and final state particles:

$$W = E_p(q) + E_\pi(q) + E_\eta$$
$$\underline{W = E_p(q) + E_{a0}(\mathbf{p_\eta - q})}$$
$$E_\eta + E_\pi(q) - E_{a0}(\mathbf{p_\eta - q}) = 0$$
$$E_\eta + E_\pi(q) - \sqrt{m_{a0}^2 + (\mathbf{p_\eta - q})^2} = 0$$

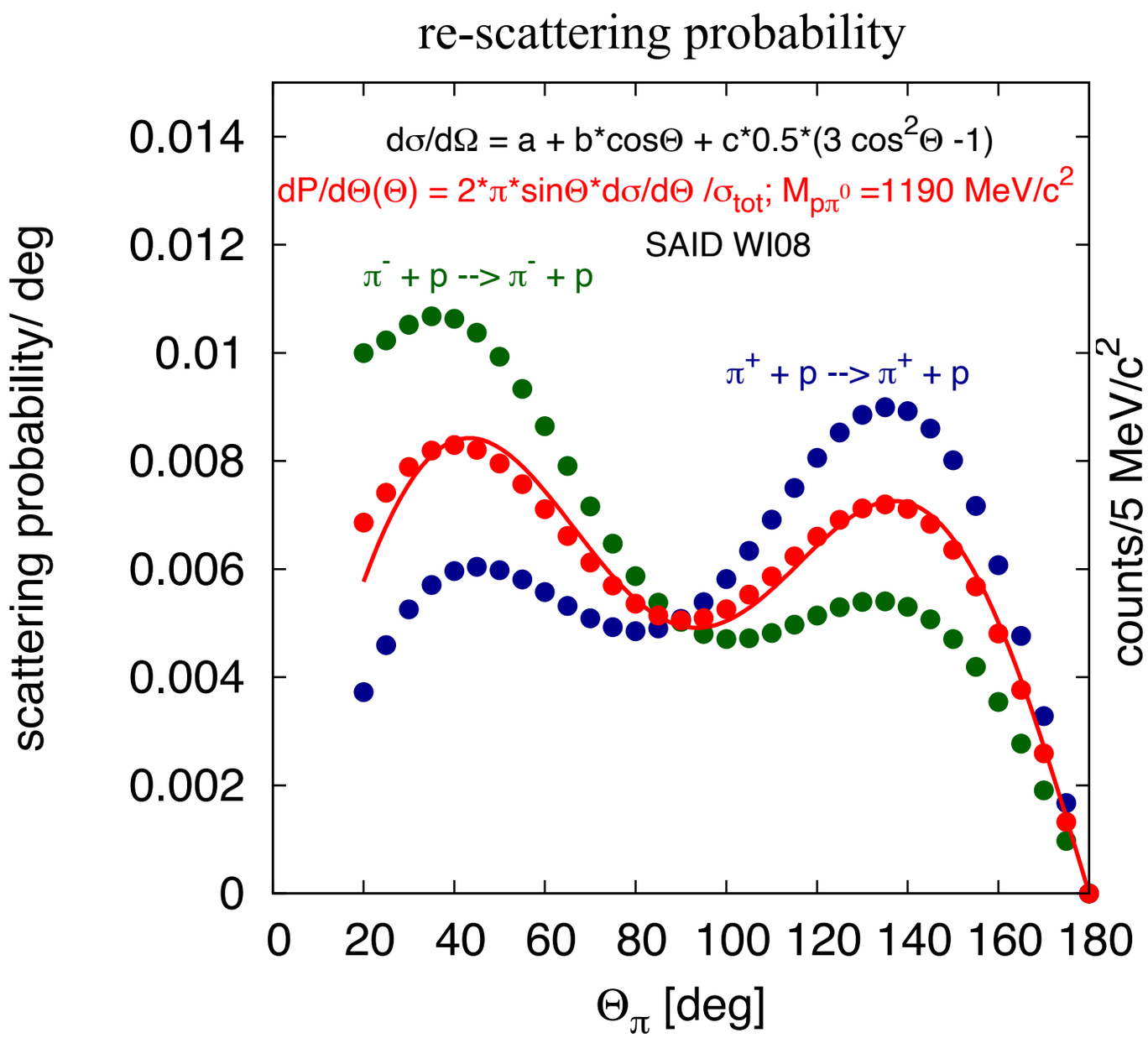
q = proton momentum in loop

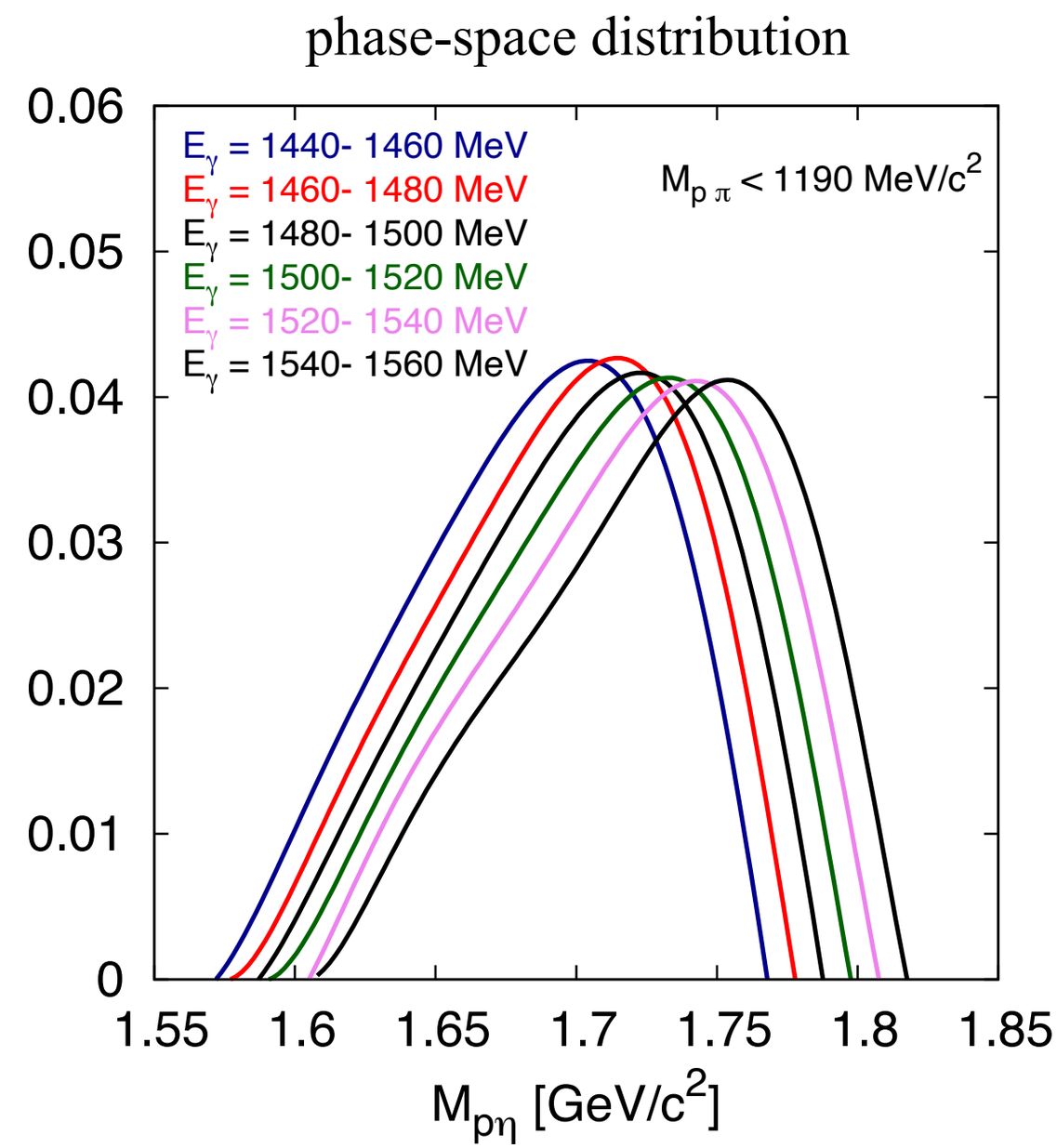
for given excitation energy W solutions only for certain ($M_{\pi 0\eta}$, $M_{p\pi 0}$) values and if all particles are almost on-mass shell and p, π^0, η are collinear



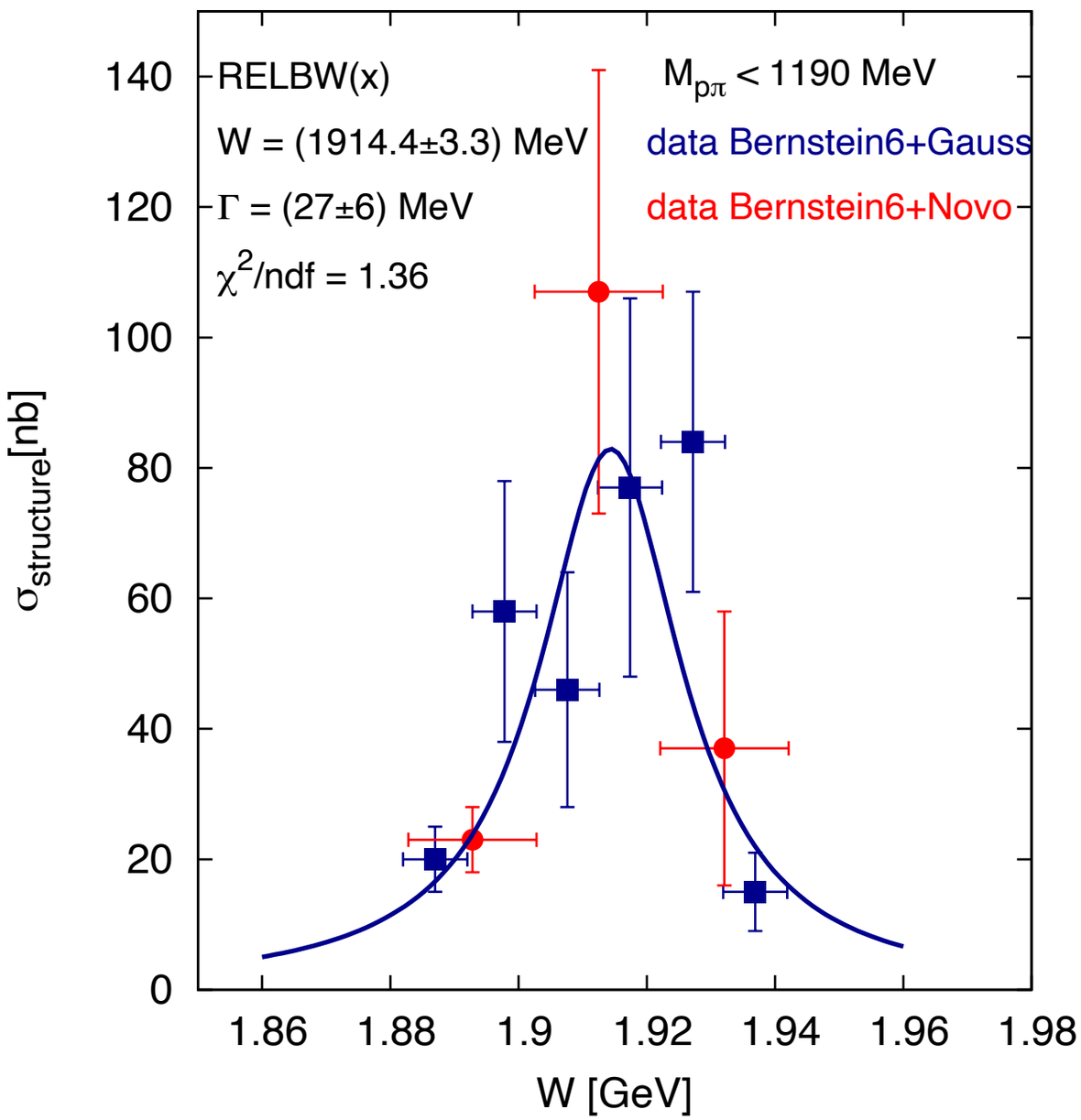


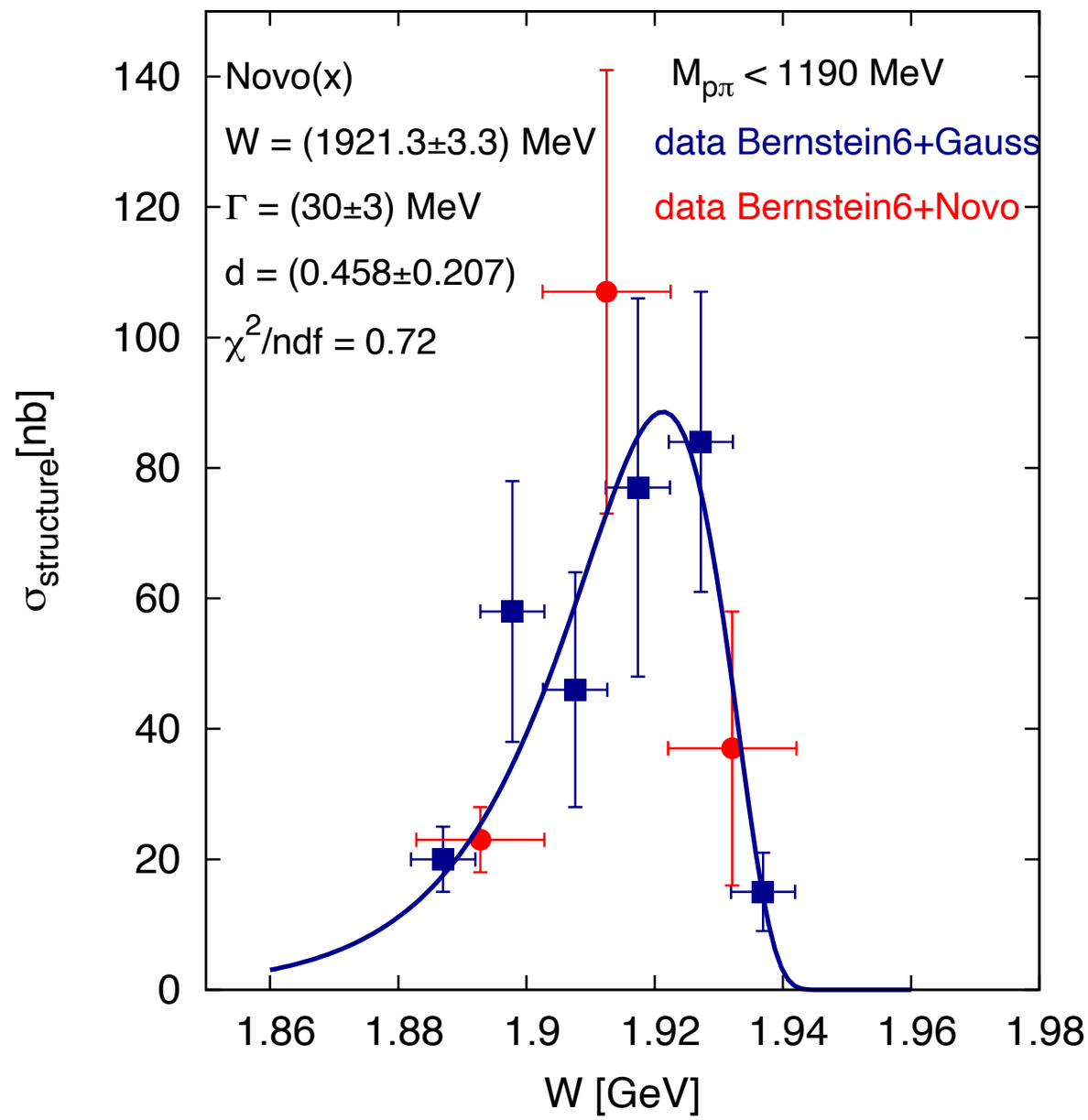
probability of π^0 - p rescattering





θ_π = scattering angle of π^0
in the π^0-p cm system

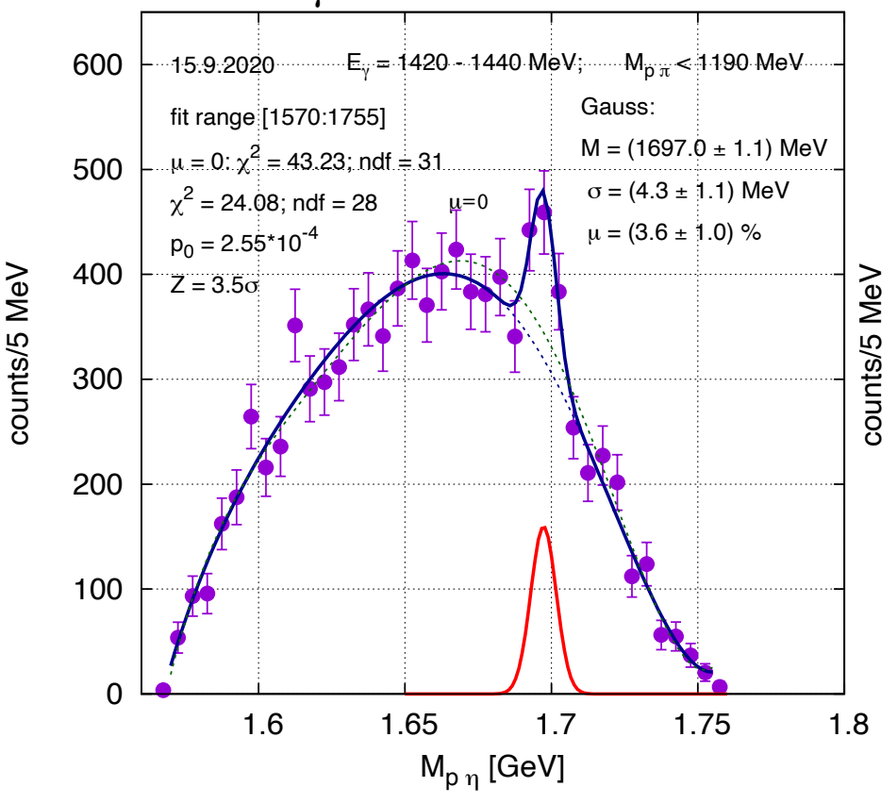

RELBW(x)
W = (1914.4±3.3) MeV
Γ = (27±6) MeV
χ²/ndf = 1.36
M_pπ < 1190 MeV
data Bernstein6+Gauss
data Bernstein6+Novo
σ_structure [nb]
W [GeV]
0
20
40
60
80
100
120
140
1.86
1.88
1.9
1.92
1.94
1.96
1.98


Novo(x)
W = (1921.3±3.3) MeV
Γ = (30±3) MeV
d = (0.458±0.207)
χ²/ndf = 0.72
M_pπ < 1190 MeV
data Bernstein6+Gauss
data Bernstein6+Novo
σ_structure [nb]
W [GeV]
0
20
40
60
80
100
120
140
1.86
1.88
1.9
1.92
1.94
1.96
1.98

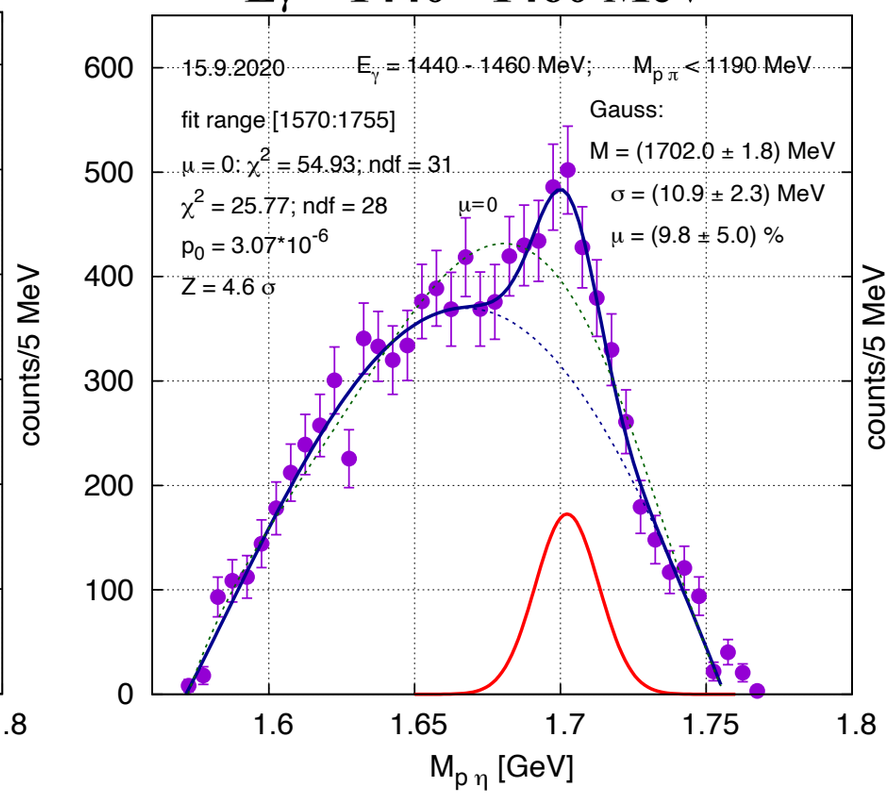
$\gamma\, p \rightarrow p\, \pi^0\, \eta$; E_γ = 1420 - 1540 MeV

properties of structure as function of the incident photon energy; fit: Gauss

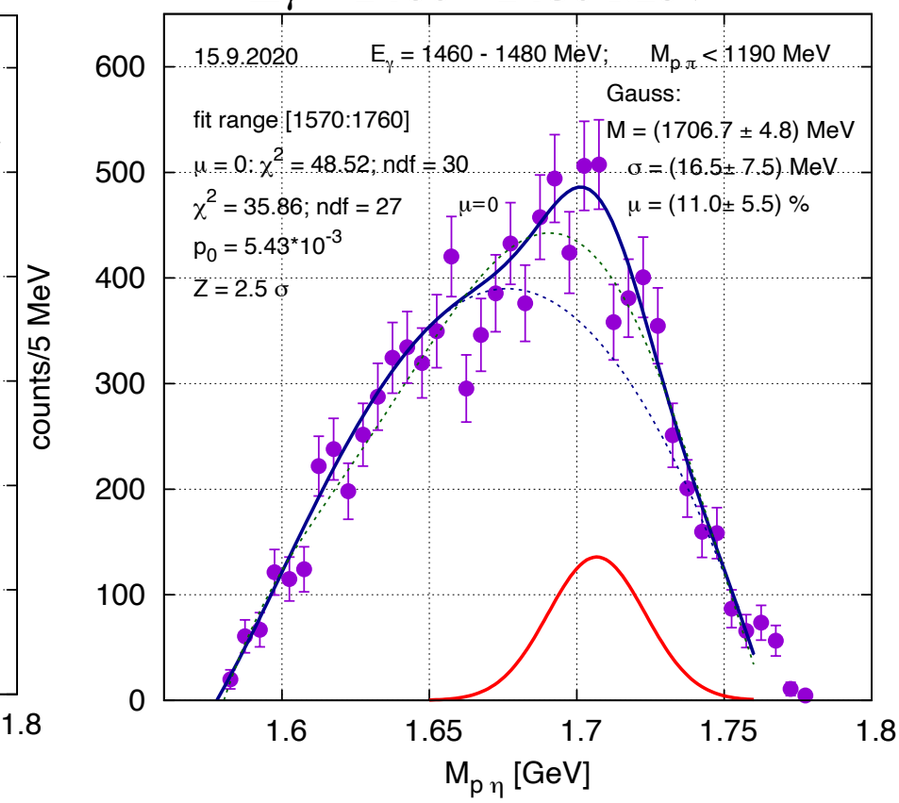
E_γ = 1420 - 1440 MeV



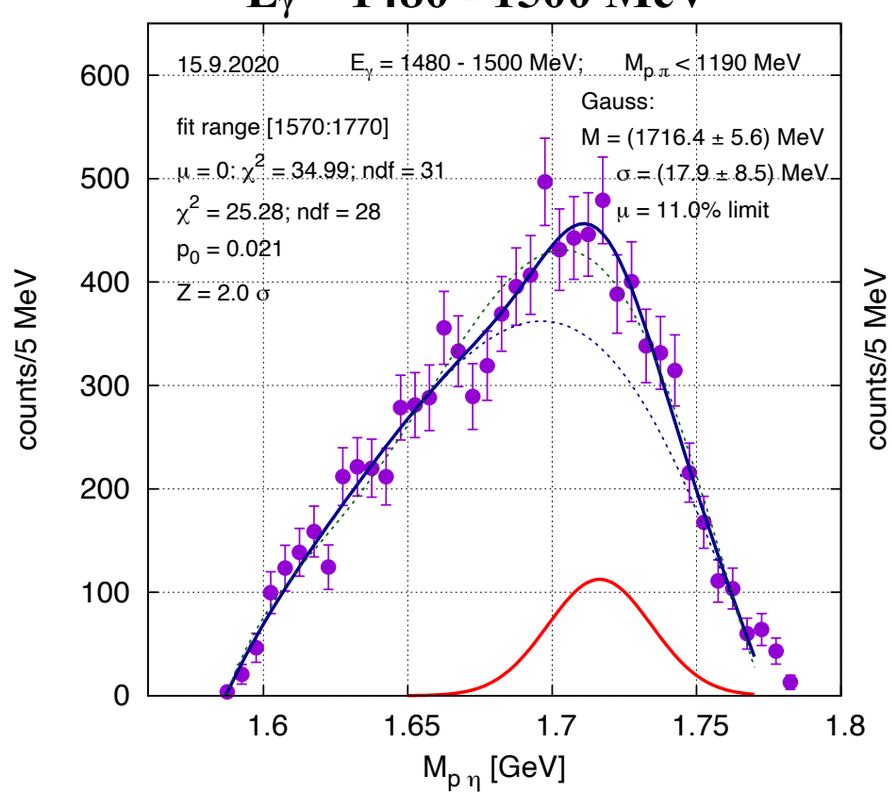
E_γ = 1440 - 1460 MeV



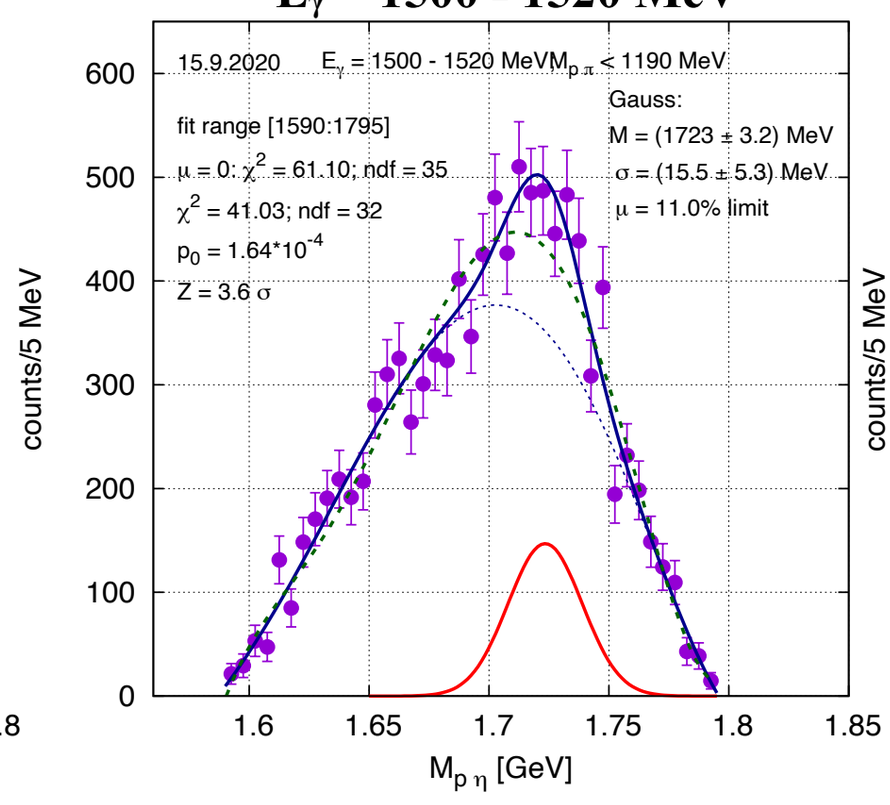
E_γ = 1460 - 1480 MeV



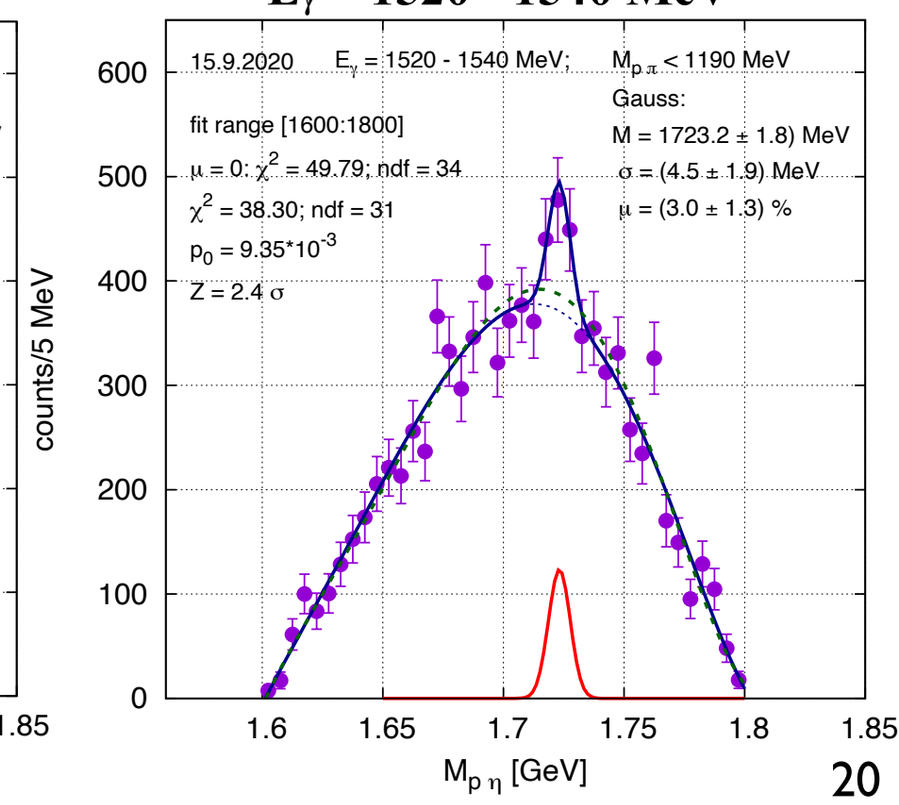
E_γ = 1480 - 1500 MeV



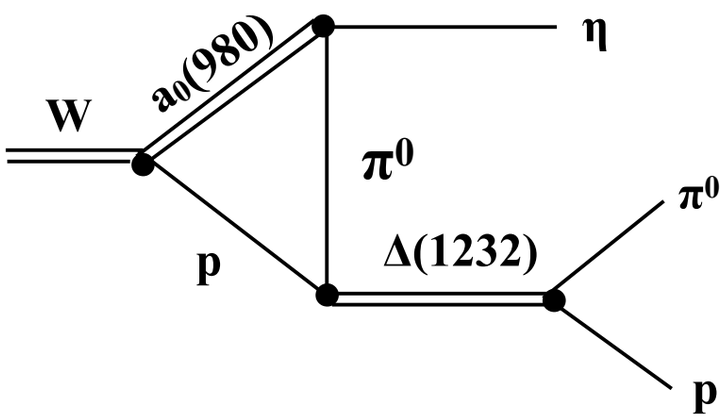
E_γ = 1500 - 1520 MeV



E_γ = 1520 - 1540 MeV

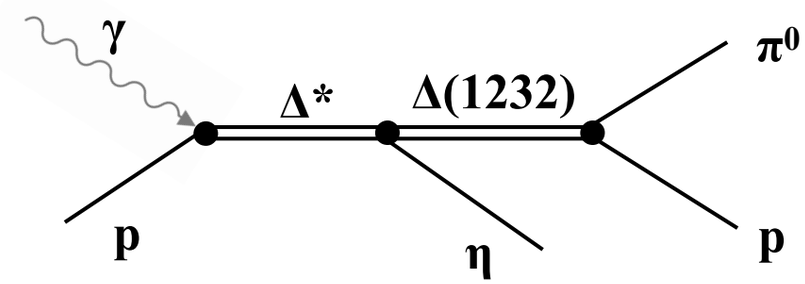


triangular diagram:



interference of tree-level and triangular amplitudes

tree level diagram:



resonance	I	J^P	mass[MeV]	width [MeV]	br(p a0)	br(η Δ(1232))	reference
N(1880)	1/2	$1/2^+$	1860	230	(3±2)%	——-	Gutz/PDG
Δ(1910)	3/2	$1/2^+$	1900	300	?	(5-13)%	Gutz/PDG
Δ(1920)	3/2	$3/2^+$	1920	300	(4±2)%	(5-17)%	Horn/PDG
Δ(1940)	3/2	$3/2^-$	2000	400	(2±1)%	(4-16)%	Horn/PDG

$N(1880)1/2^+ \ (1/2,1/2^+) \rightarrow a_0(1,0^+) + p(1/2,1/2^+)$; $L = 0$

$\Delta(1910)1/2^+ \ (3/2,1/2^+) \rightarrow a_0(1,0^+) + p(1/2,1/2^+)$; $L = 0$

$\Delta(1920)3/2^+ \ (3/2,3/2^+) \rightarrow a_0(1,0^+) + p(1/2,1/2^+)$; $L = 2$

$\Delta(1940)3/2^- \ (3/2,3/2^-) \rightarrow a_0(1,0^+) + p(1/2,1/2^+)$; $L = 1$

W = $N(1880)1/2^+$ (I=1/2) would imply isospin violation since η Δ(1232) has I=3/2 !!!

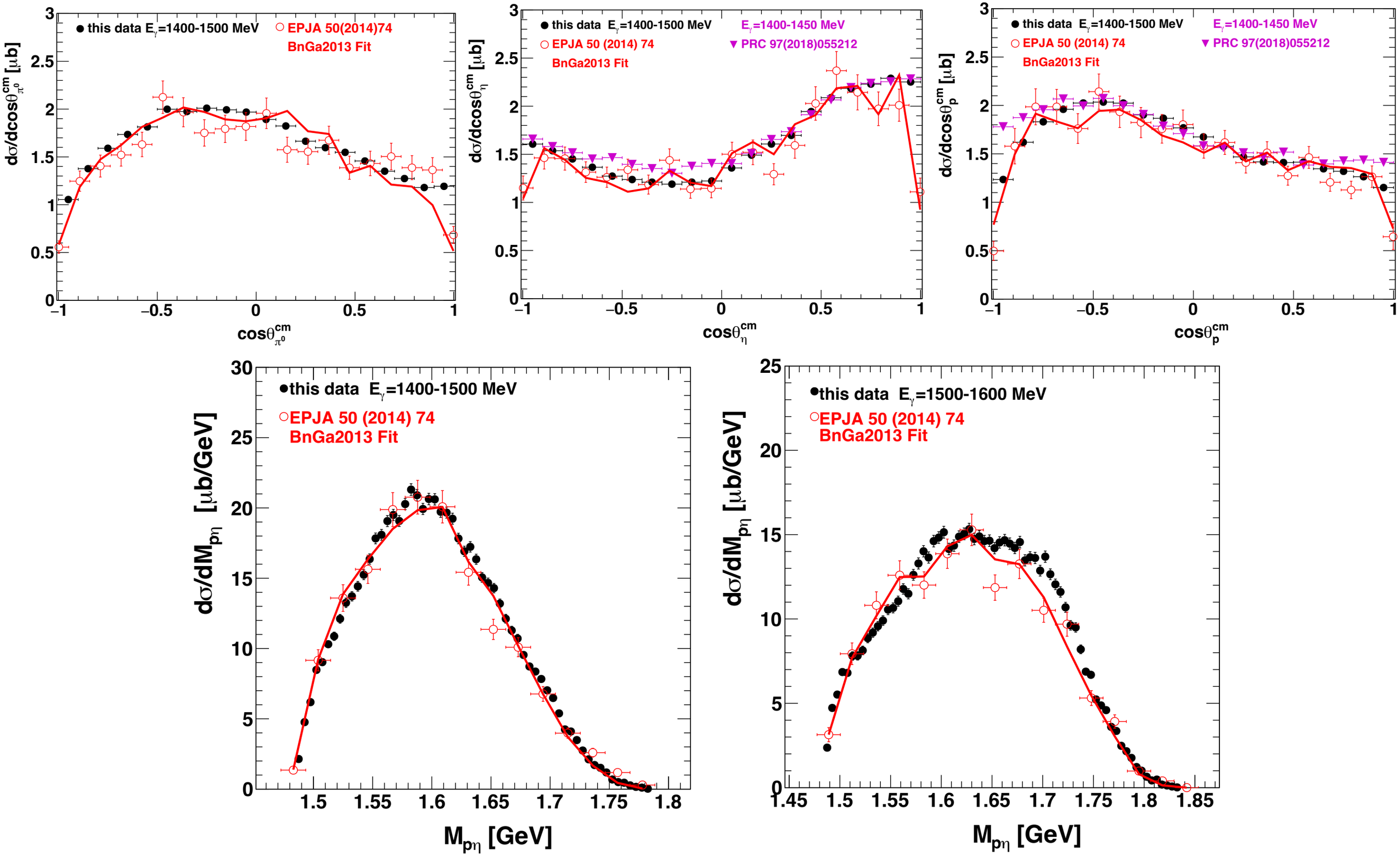
if W = $\Delta(1910)1/2^+$ I=3/2 interference with dominating tree level ($L_{\eta\Delta}$= 1; I=3/2); L_{pa0} = 0

if W = $\Delta(1920)3/2^+$ I=3/2 interference with dominating tree level ($L_{\eta\Delta}$= 1; I=3/2); L_{pa0} = 2

if W = $\Delta(1940)3/2^-$ I=3/2 interference with dominating tree level ($L_{\eta\Delta}$= 0,2; I =3/2); L_{pa0}= 1

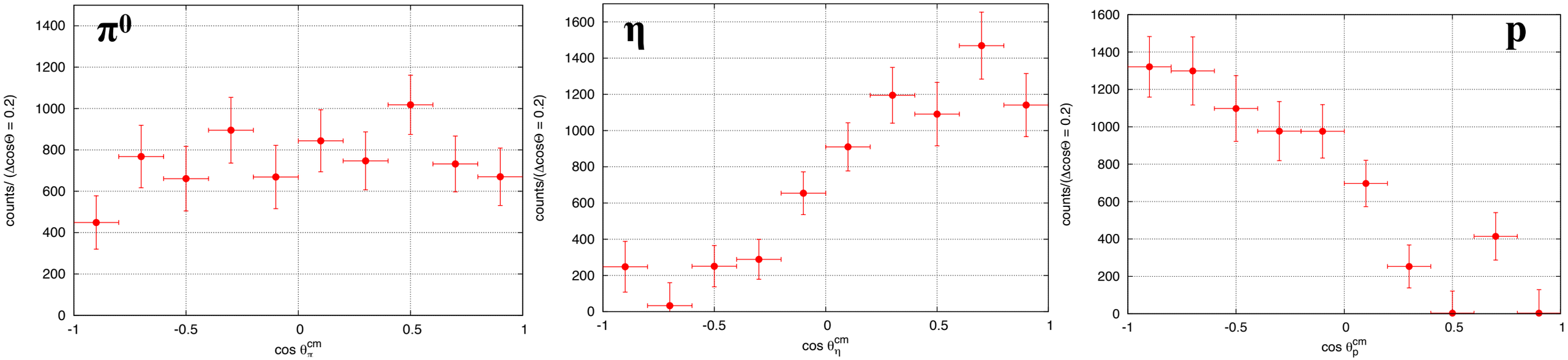
comparison to previous results

$\gamma\, p \rightarrow p\, \pi^0\, \eta$ E_γ= 1400 - 1500 MeV

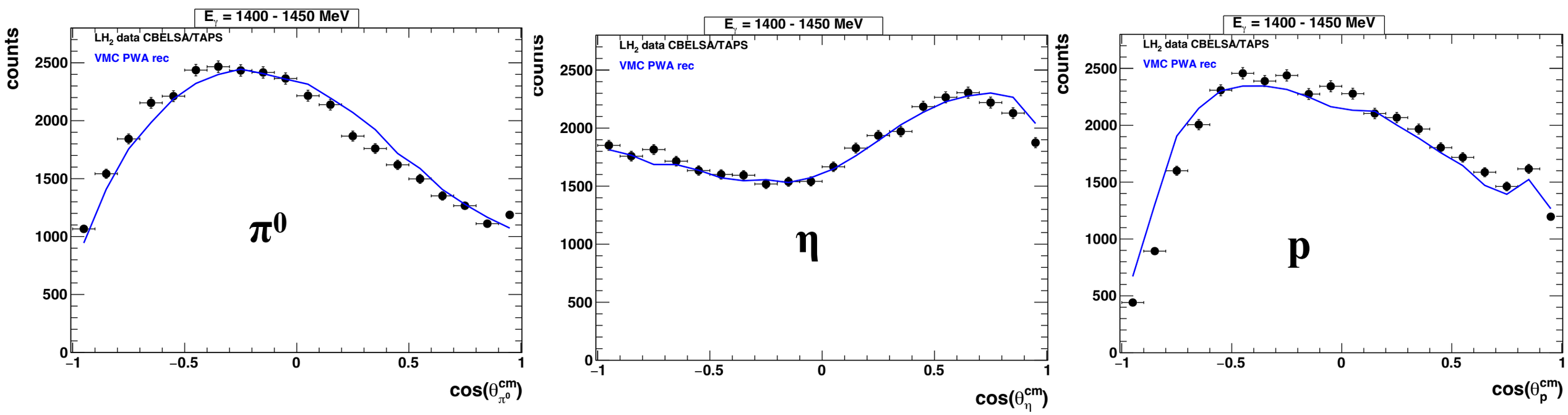


$\gamma p \rightarrow p\, \pi^0\, \eta$

angular distributions of events in structure for E_γ = 1420 - 1540 MeV and $M_{p\pi}$ < 1190 MeV in γp cm system



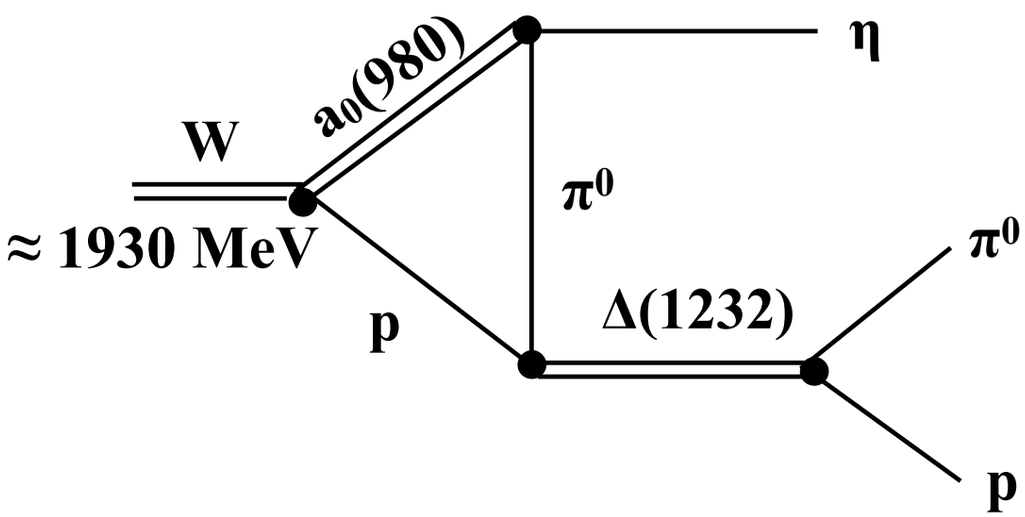
angular distributions for E_γ = 1400 - 1450 MeV without $M_{p\pi}$ cut



CBELSA/TAPS

$\gamma\, p \rightarrow p\, \pi^0\, \eta$

triangular diagram:



$a_0\,(980)$; $\Gamma \approx 50 - 100$ MeV

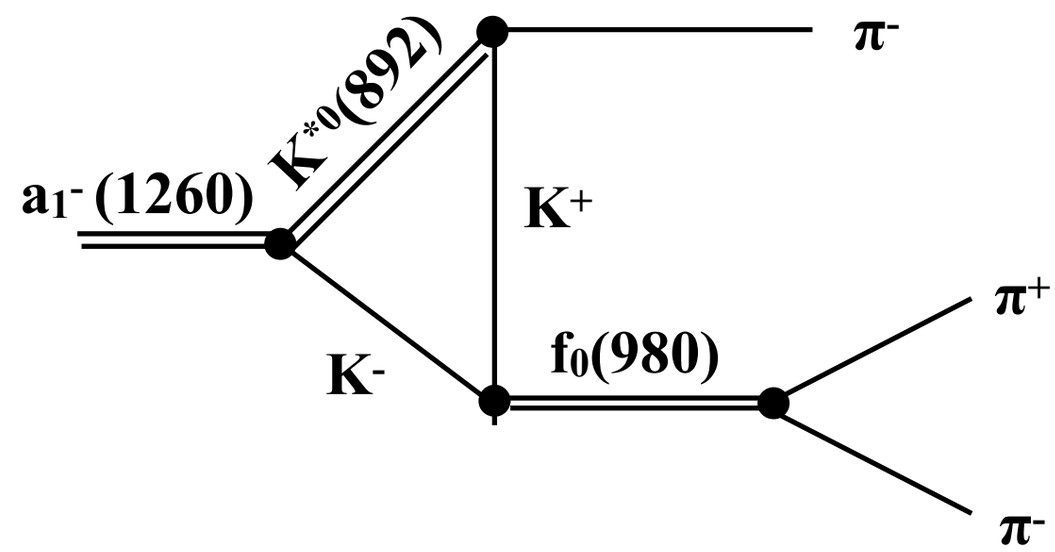
$\Delta\,(1232)$; $\Gamma \approx 117$ MeV

COMPASS

$\pi^-\, p \rightarrow a_1^-\,(1260)\, p$

$a_1^-\,(1260) \rightarrow \pi^-\, \pi^+\, \pi^-$

triangular diagram



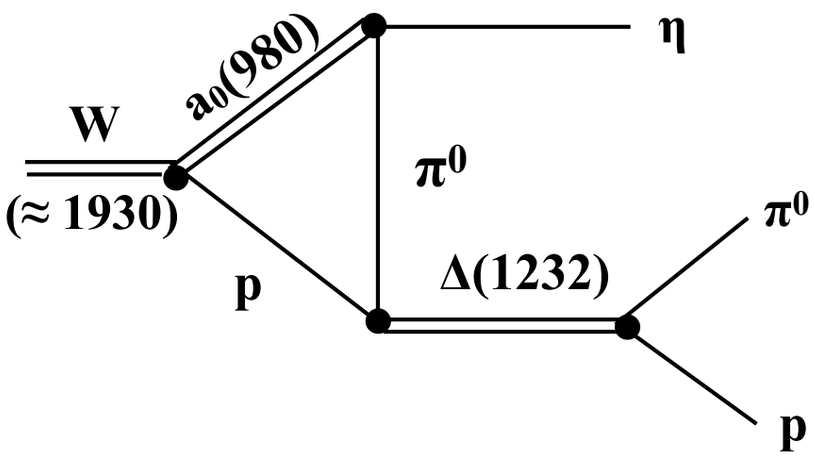
$K^{*0}\,(892)$; $\Gamma = 47.3 \pm 0.5$ MeV

$f_0\,(980)$; $\Gamma \approx 10 - 100$ MeV

triangular diagrams

CBELSA/TAPS

$\gamma\, p \rightarrow p\, \pi^0\, \eta$

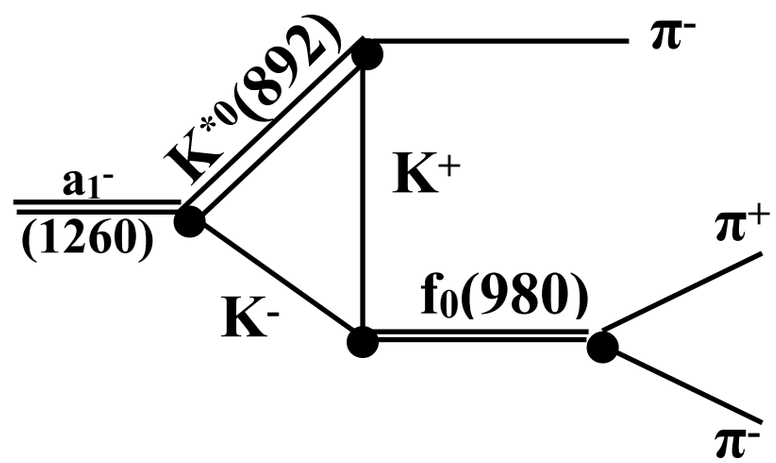


kinematics: singularity

COMPASS

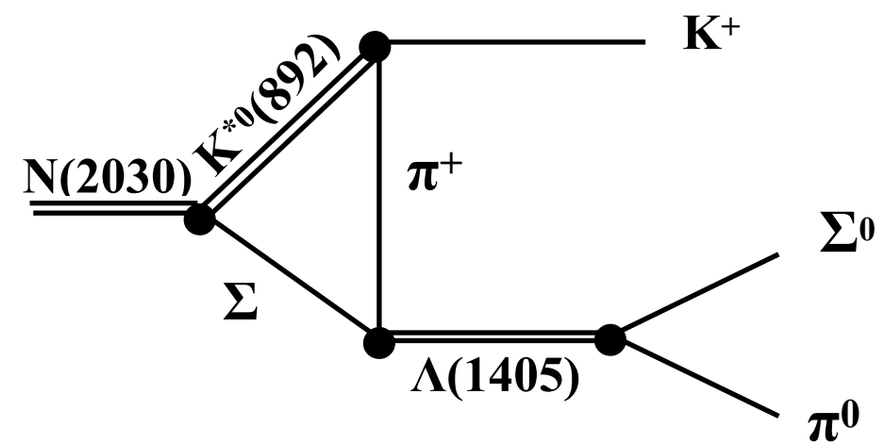
$\pi^-\, p \rightarrow a_1^-(1260)\, p$

$a_1^-(1260) \rightarrow \pi^-\, \pi^+\, \pi^-$



BGOOD

$\gamma\, p \rightarrow K^+\, \pi^0\, \Sigma^0$



$a_0(980)$; $\Gamma \approx 50 - 100$ MeV

$\Delta(1232)$; $\Gamma \approx 117$ MeV

$K^{*0}(892)$; $\Gamma = 47.3 \pm 0.5$ MeV

$f_0(980)$; $\Gamma \approx 10 - 100$ MeV

$K^{*0}(892)$; $\Gamma = 47.3 \pm 0.5$ MeV

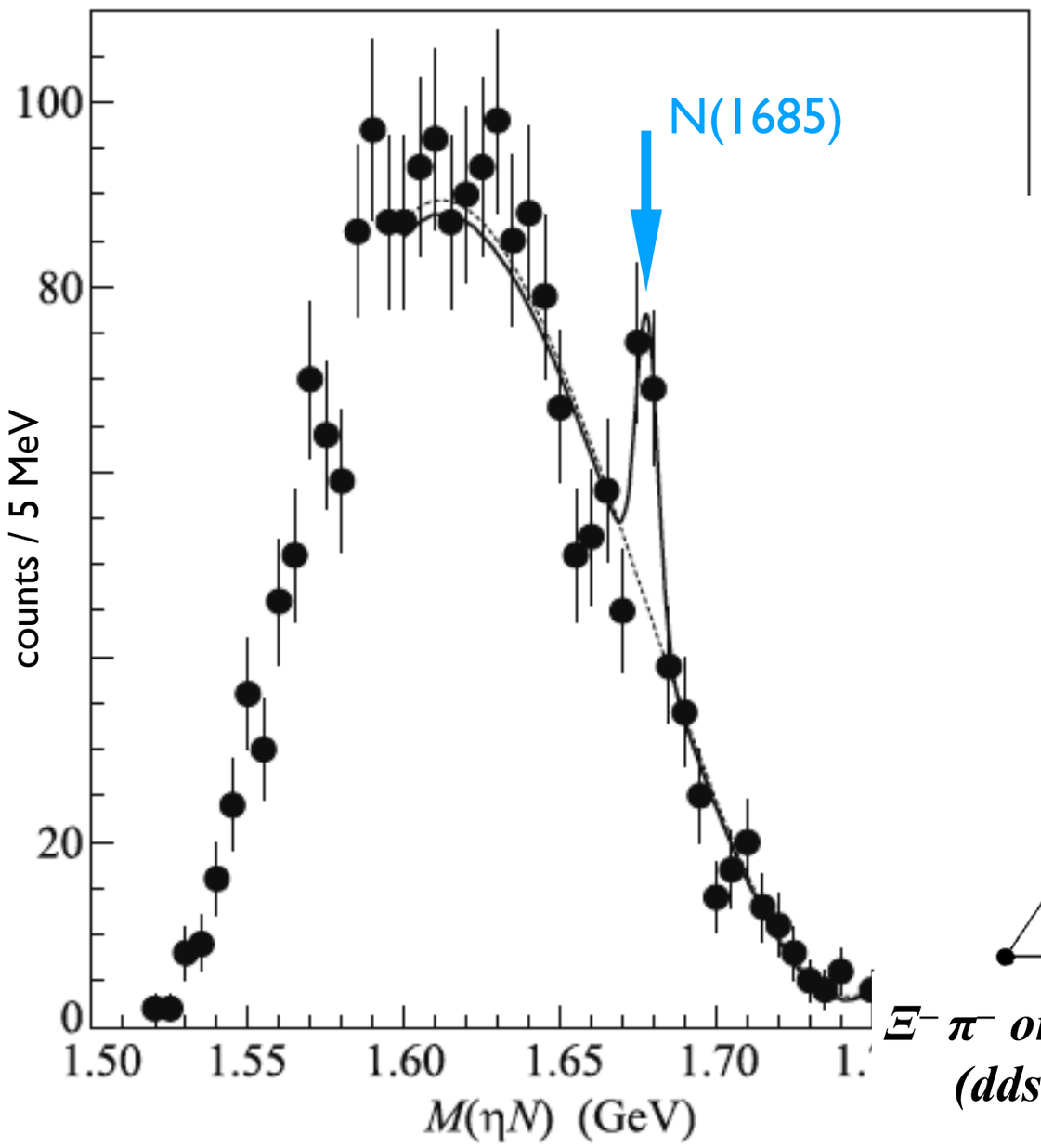
$\Lambda(1405)$; $\Gamma = 50.5 \pm 2.0$ MeV

motivation:
observation of narrow N(1685) resonances in γN→ηπN reactions

V. Kuznetsov et al., JETP Letters106 (2017) 692

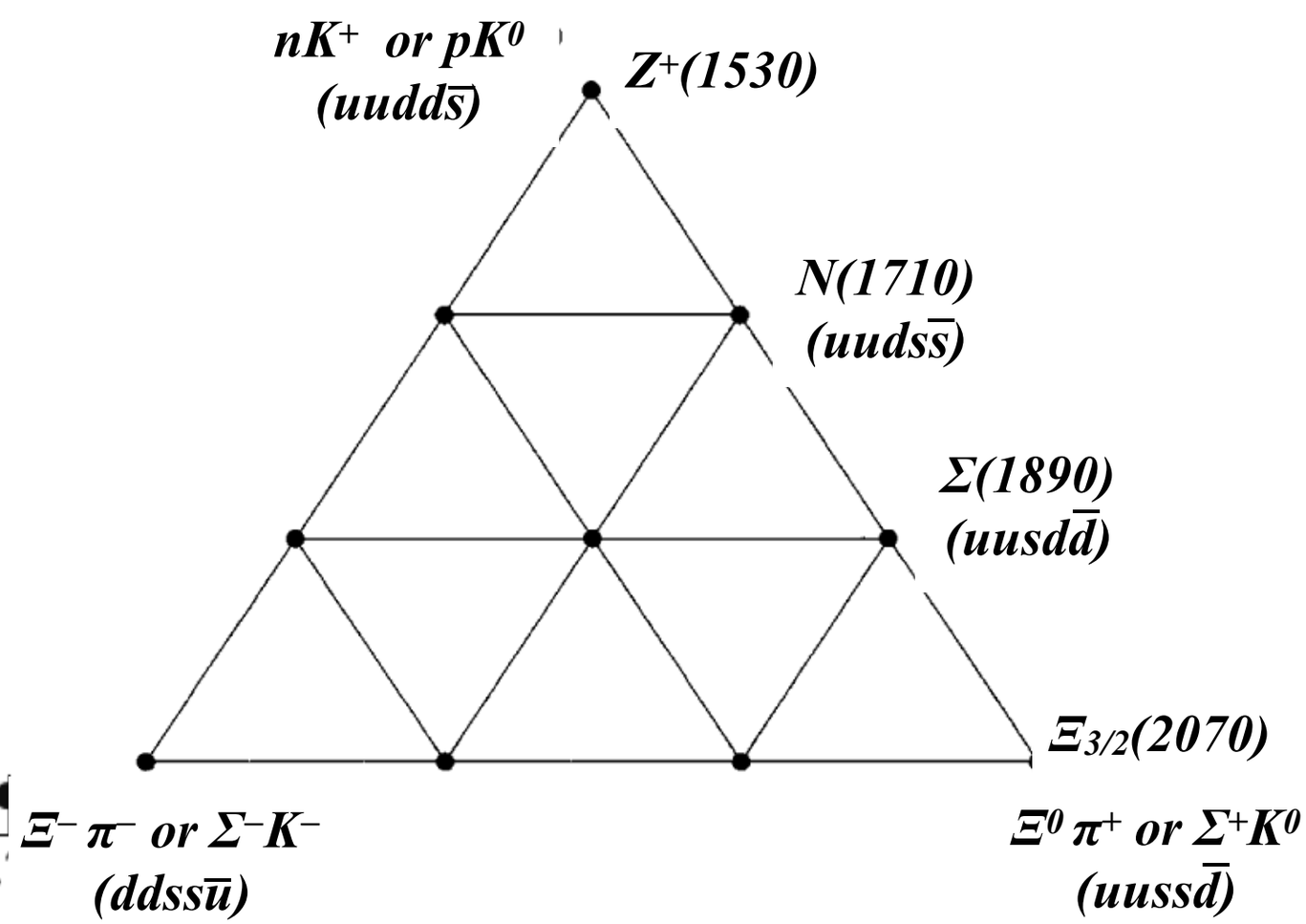
E_γ = 1400 - 1500 MeV

γN → π η N - sum of all channels



Anti-Decuplet of baryons
in the Chiral Soliton Model

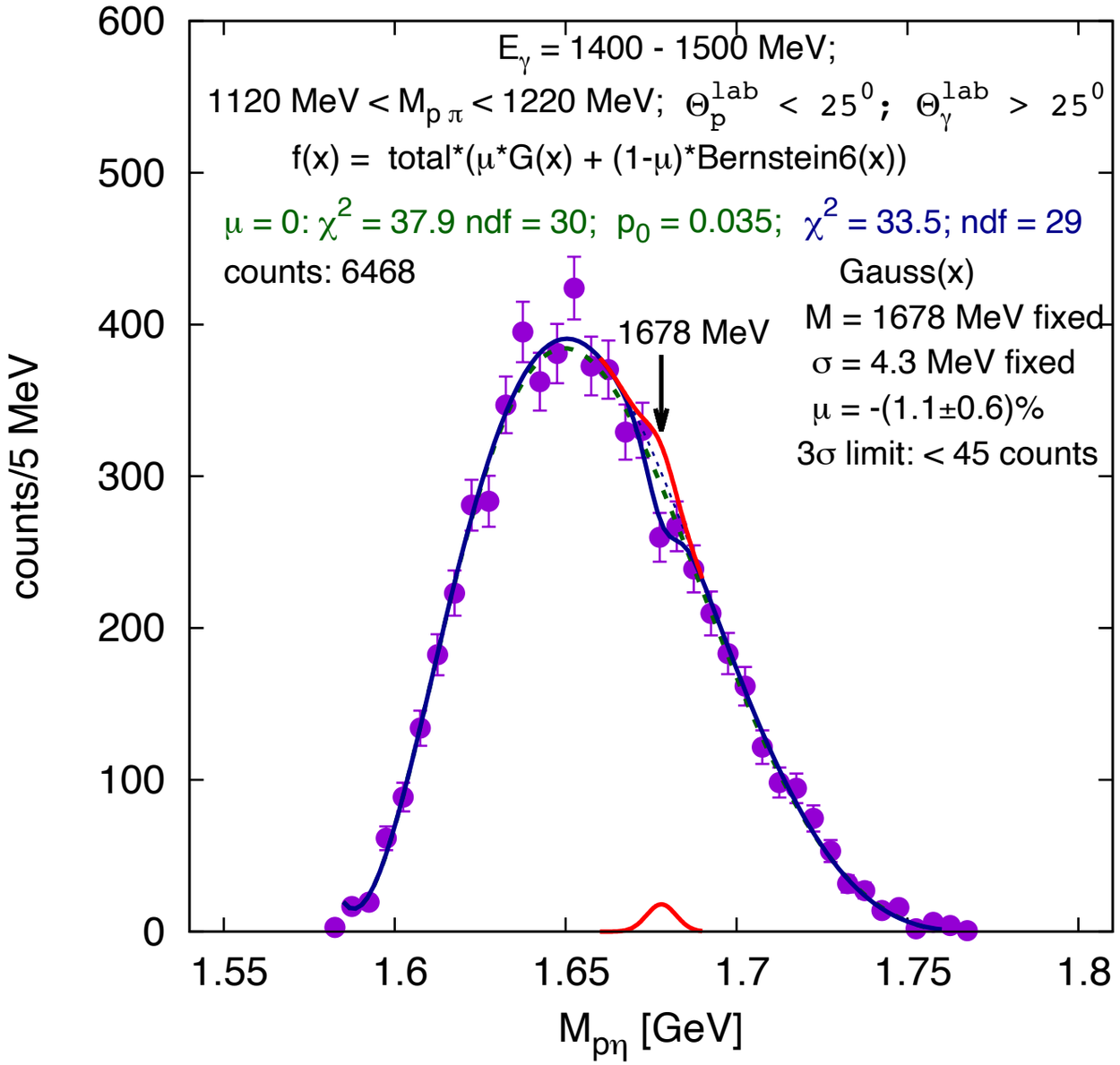
D. Diakonov, V. Petrov, and M.V. Polyakov,
Z. Phys. A 359 (1997) 305



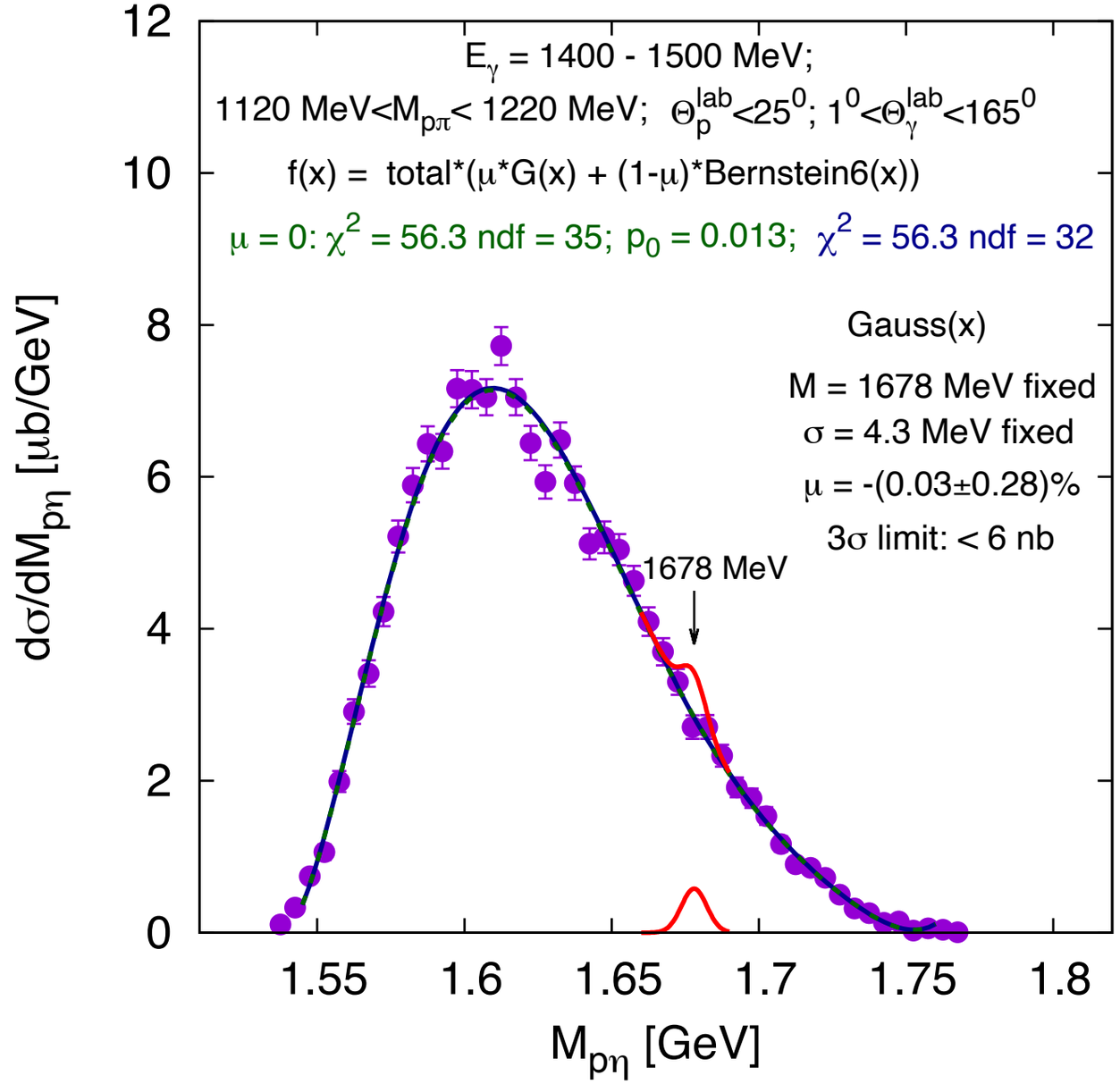
is the narrow structure in M(ηN) real?

search for a narrow structure in M(pη) distribution around 1678 MeV

identical cuts as in JETP 106



acceptance corrected; $\theta_\gamma > 1^0$



3 σ limit: < 45 counts

≈ 4 times higher statistics

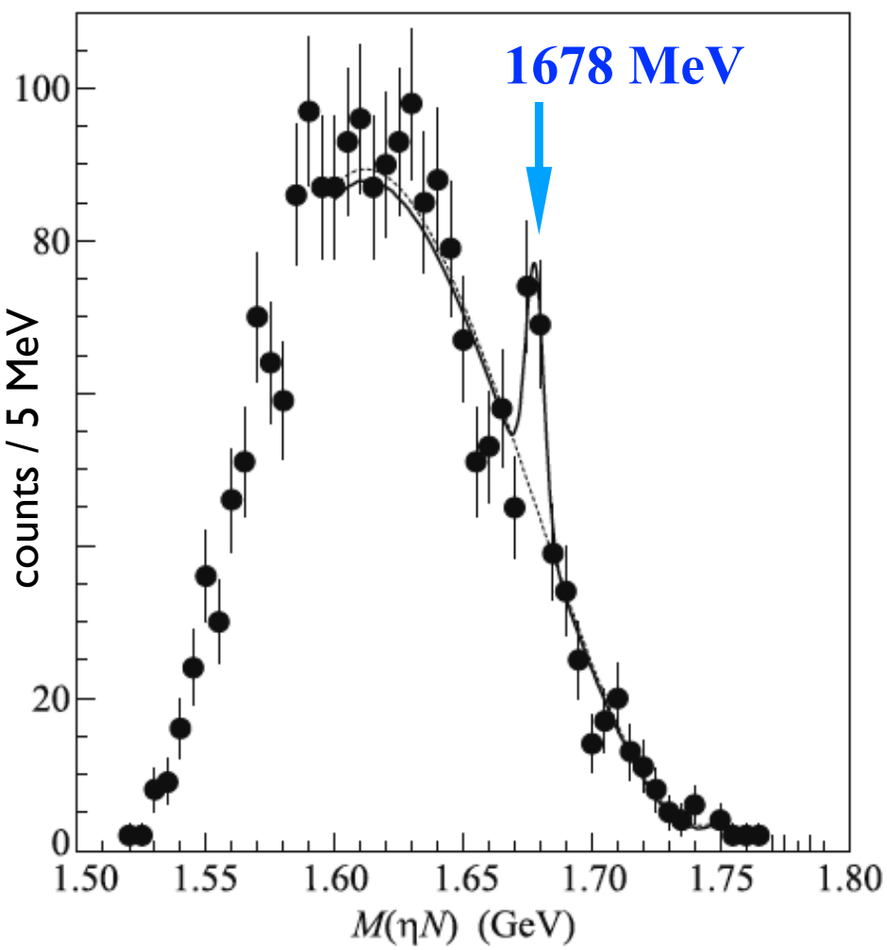
motivation:
observation of narrow N(1685) resonances in $\gamma N \rightarrow \eta\pi N$ reactions

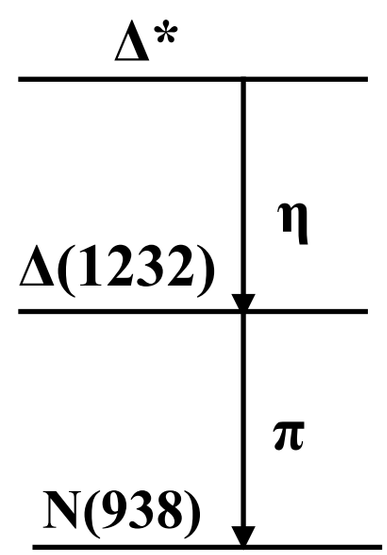
V. Kuznetsov et al.,
JETP Lett. 106 (2017) 693
exotic state predicted by
Chiral Soliton Model

D. Diakonov, V. Petrov, and M.V. Polyakov,
Z. Phys. A 359 (1997) 305

E_γ = 1400 - 1500 MeV
$\theta_p < 25^0$; $25^0 < \theta_\gamma < 155^0$

$1120 < M_{p\pi} < 1220$ MeV
to suppress
dominant decay





$M_{\eta N}$ = (1678±0.8(stat)±10(syst)) MeV;
Γ≈ 10 MeV; significance 4.6 σ

motivation:
observation of narrow N(1685) resonances in $\gamma N \rightarrow \eta\pi N$ reactions

V. Kuznetsov et al.,
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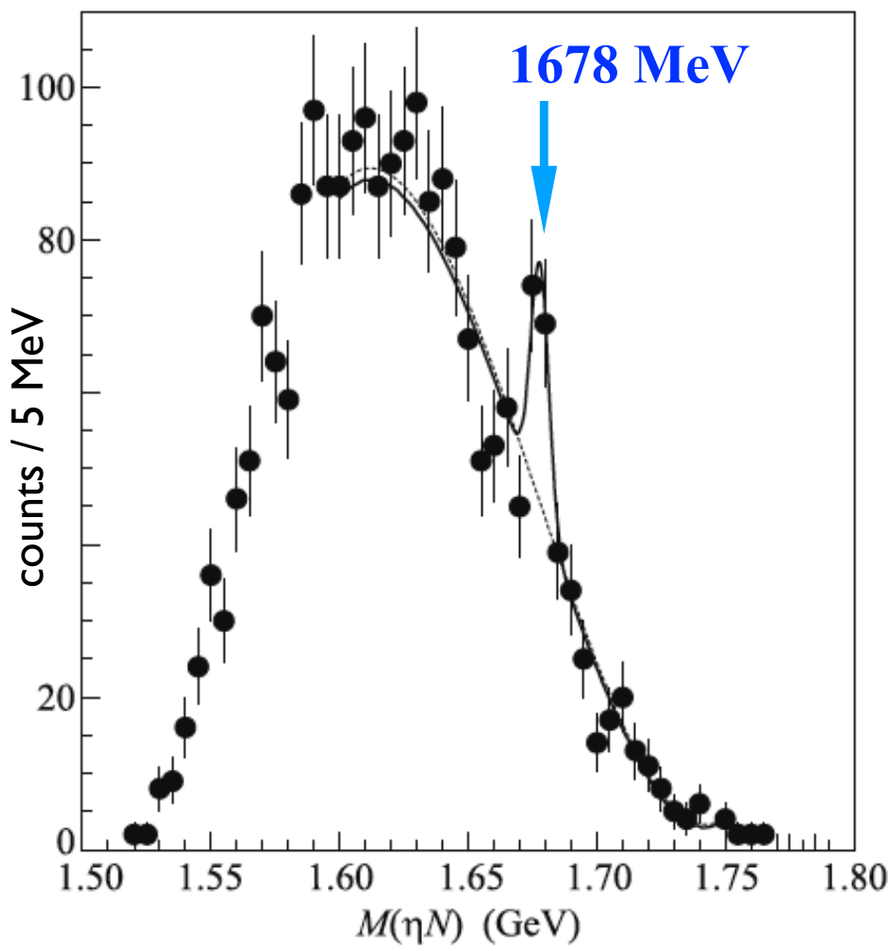

$M_{\eta N}$ = (1678±0.8(stat)±10(syst)) MeV;
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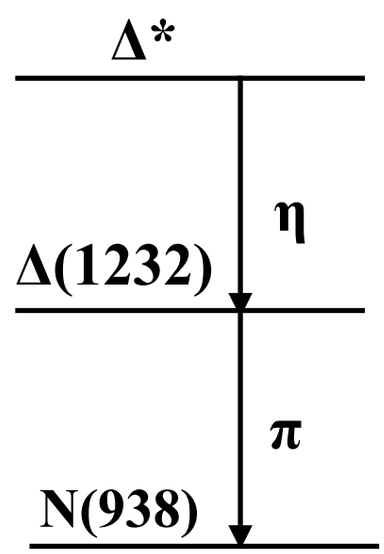
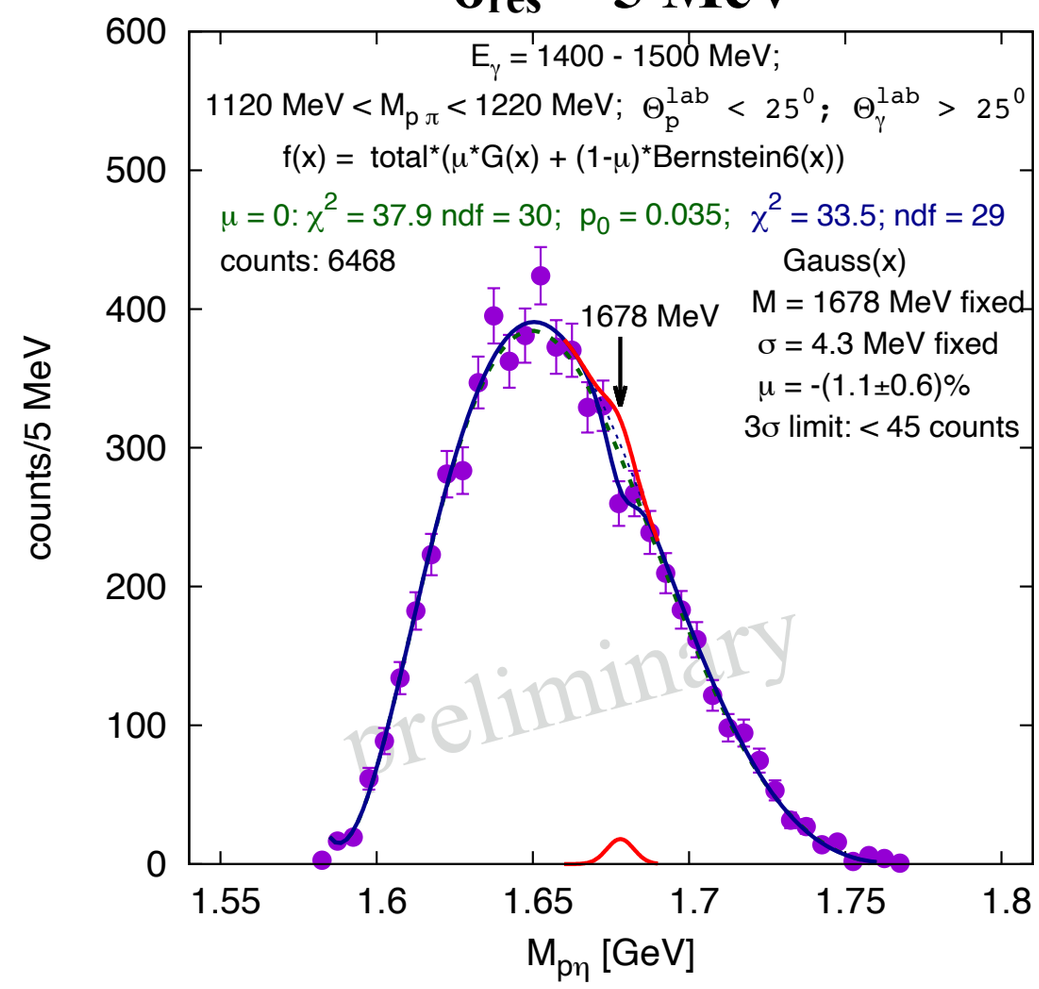


identical conditions:

$\gamma\, p \rightarrow p\, \pi^0\, \eta$
CBELSA/TAPS

4.5 times higher statistics;
σ_{res} = 5 MeV



< 45 counts: $\sigma_{structure}$ < 6 nb (3σ)

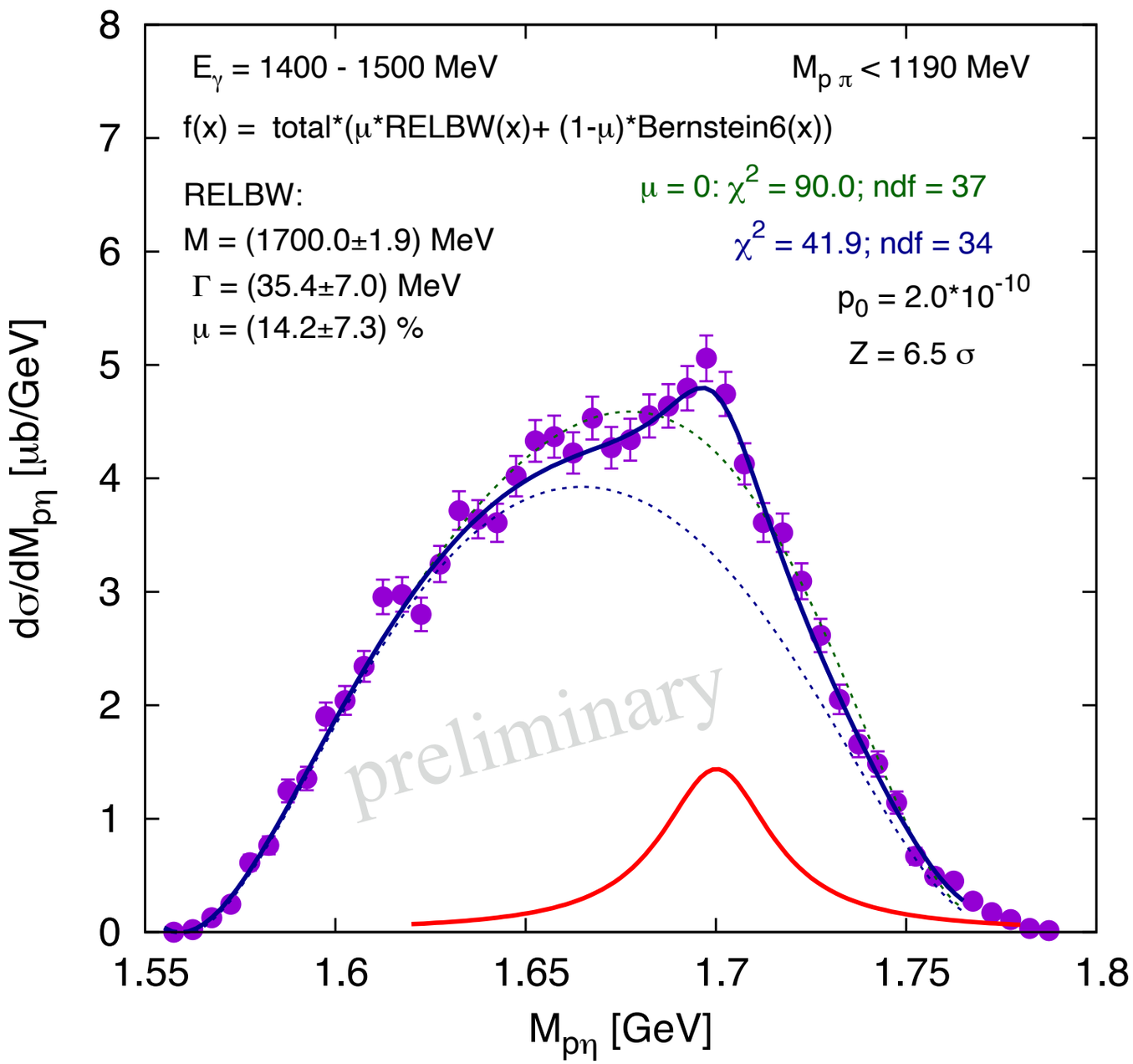
structure cannot be confirmed !!!

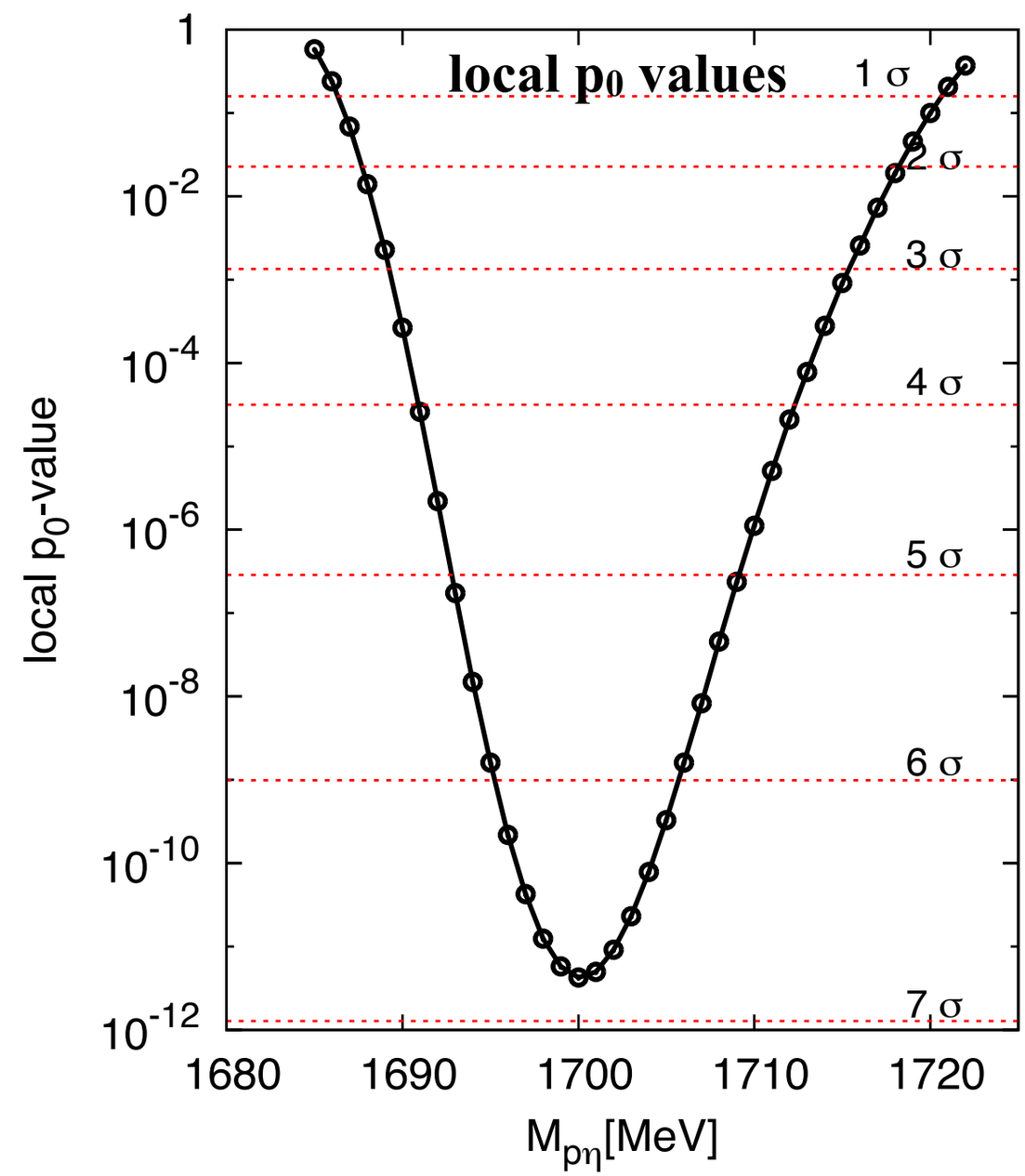
$\gamma\, p \rightarrow p\, \pi^0 \eta$

E_γ = 1400 - 1500 MeV

$M_{p\pi}$ < 1190 MeV

statistical significant structure observed at $M_{p\eta} \approx$ 1700 MeV





$M_{p\eta}$ = (1700±1.9) MeV; Γ = (35.4±7.0)MeV

structure established at 6.8 σ