Advances in Coupled Channel Approaches for N* Parameter Extraction

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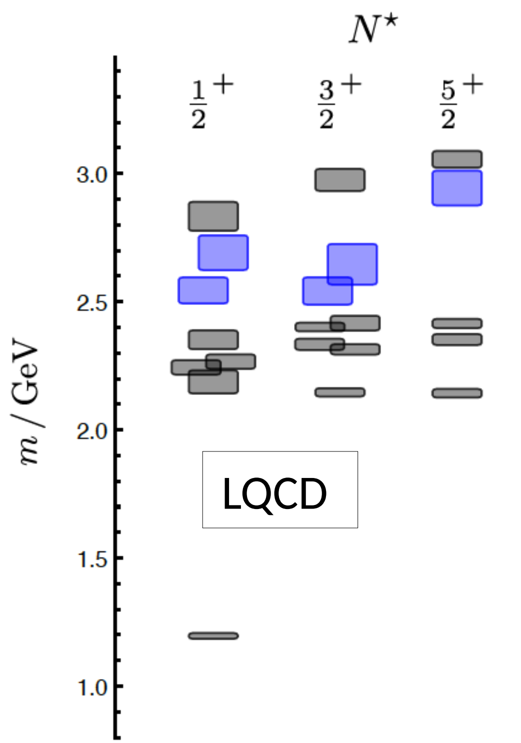
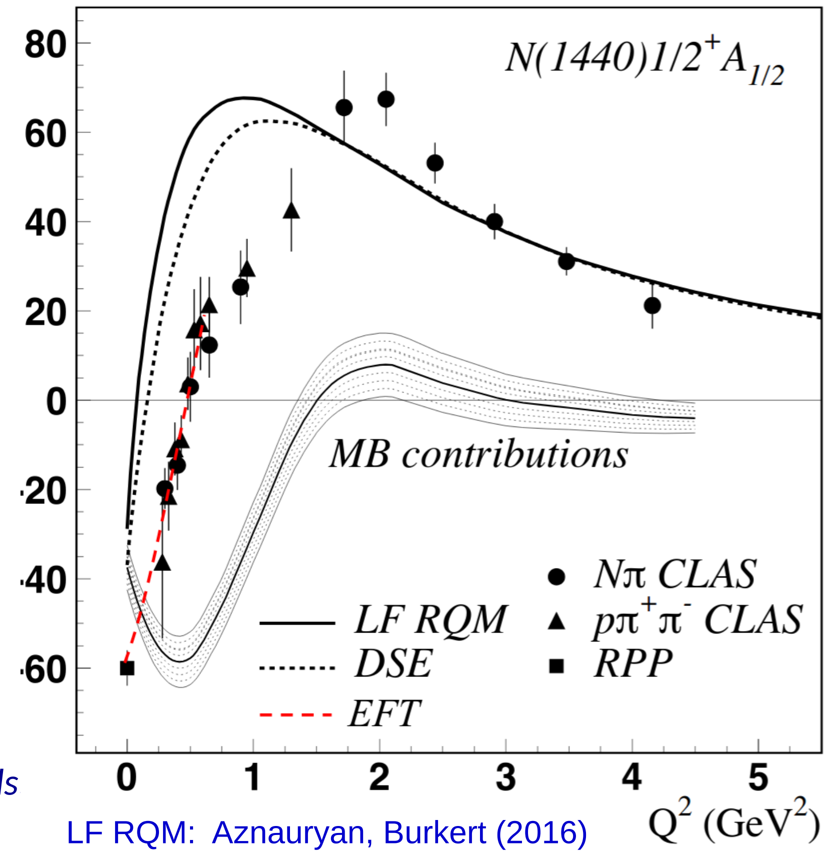
[several slides by
D. Rönchen and M. Mai]

Degrees of freedom: Quarks or hadrons?

Hybrid Baryons

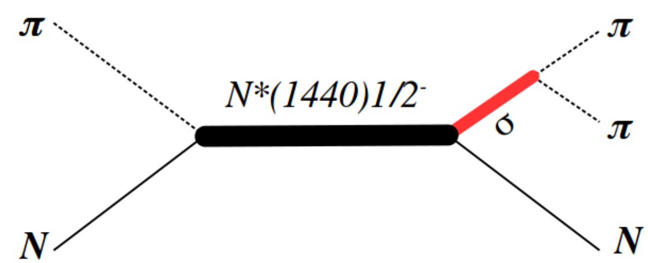


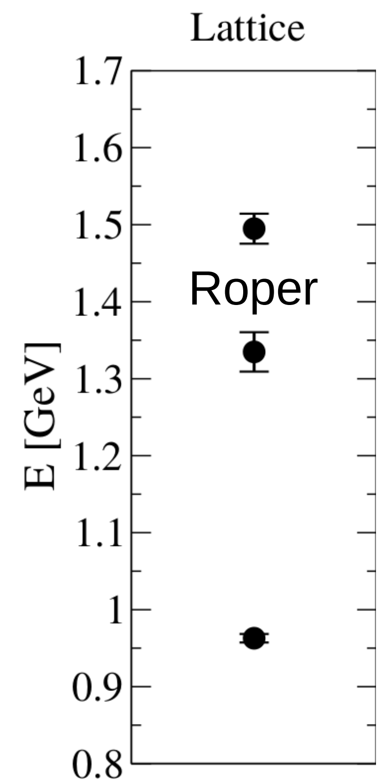
J.J. Dudek and R.G. Edwards
PRD85 (2012)



LF RQM: Aznauryan, Burkert (2016)
DSE: Segovia, Roberts, PRC (2016)
EFT: Bauer, Scherer, Tiator, PRC (2014)

$\pi N,\ \sigma(\pi\pi)N,\ \pi\Delta(\pi N)$





Data: [Lang et al., Phys.Rev. D95 (2017), 014510]

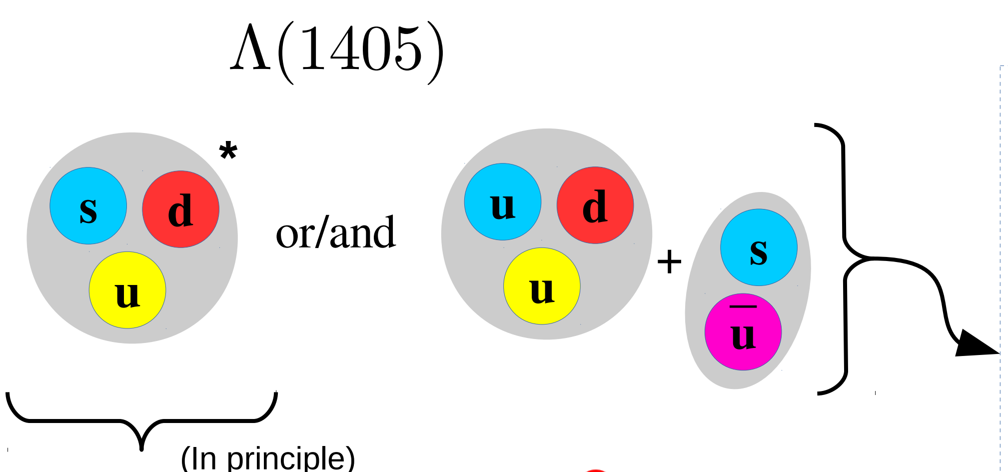
Hybrid states: same J^P values as q^3 baryons.
Identification? Measure Q^2 dependence of electro-couplings (**CLAS 12**)

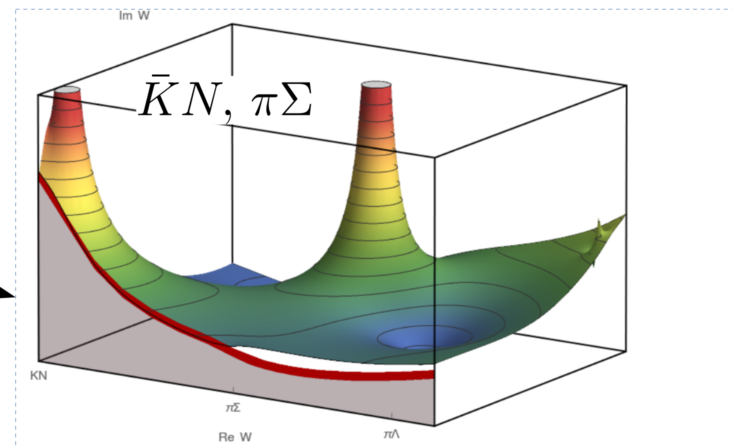
[parts of slide courtesy of V. Burkert]

- **QCD** at low energies → *mass generation & confinement*
- Non-perturbative dynamics → rich spectrum of excited states

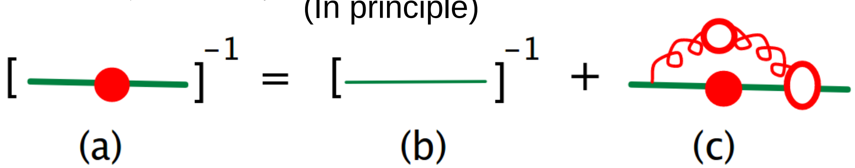
  Q1: how many are there? (missing resonance problem)

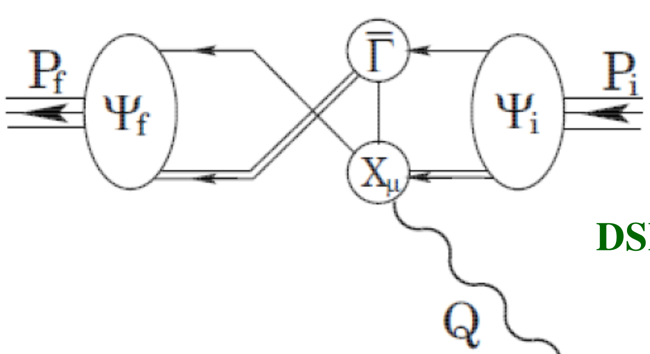
  Q2: what are they? (2-quark/3-quark, hadron molecules, exotics,...)





Oset, Ramos (1998)
Mai, Meißner (2015)
Sadasivan, Mai, M. D. (2019)



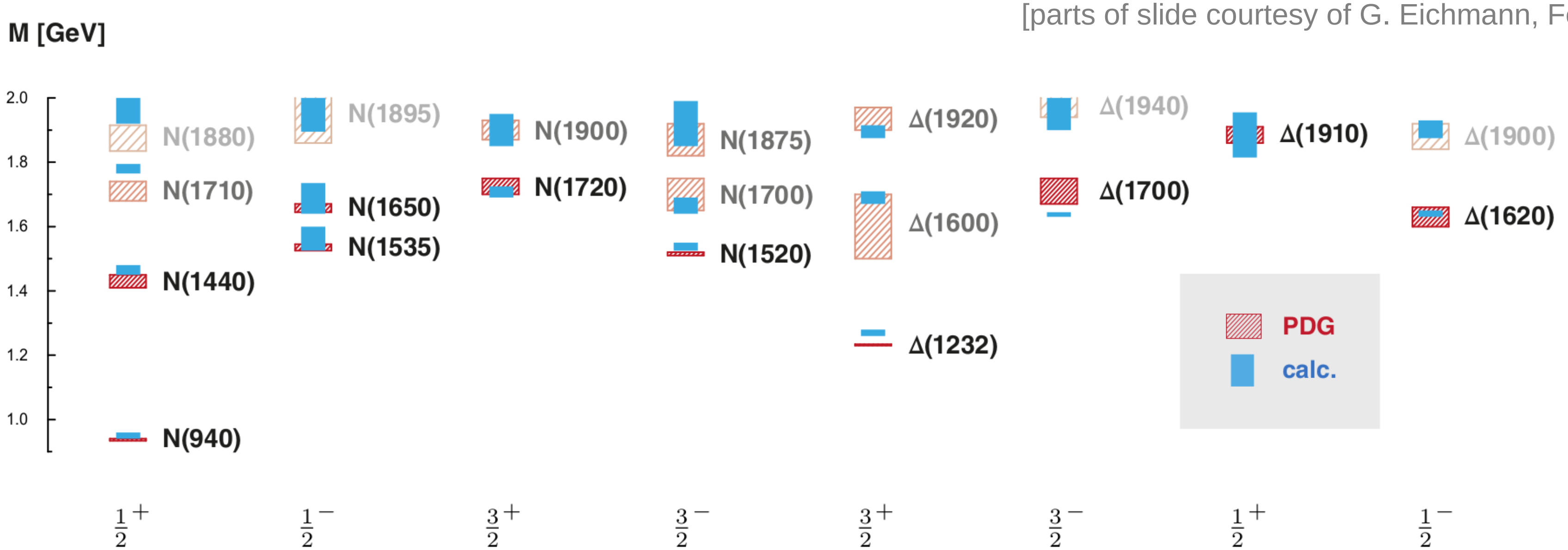


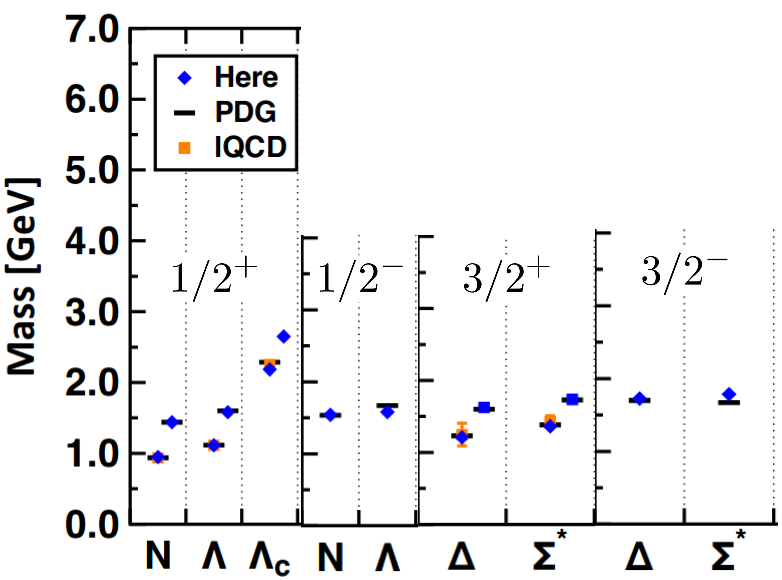
DSE (Wilson, Cloet, Chang, Roberts)

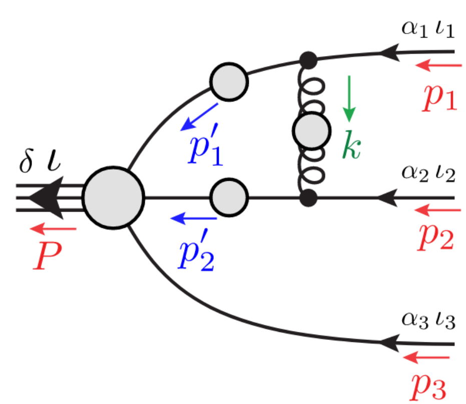
New results in dynamical quark picture

Quark-diquark with reduced pseudoscalar + vector diquarks: GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)

[parts of slide courtesy of G. Eichmann, Few Body 2018]





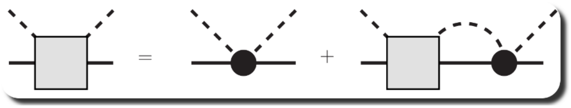


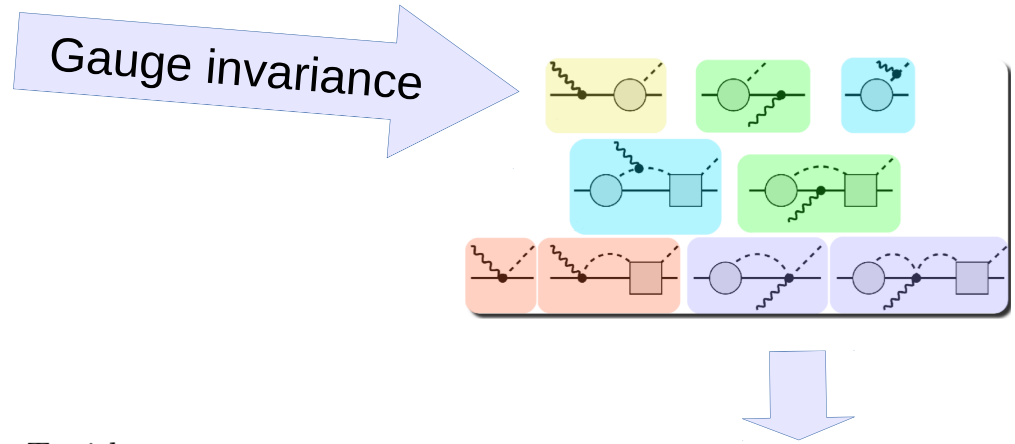
Poincaré-covariant analysis of heavy-quark baryons, Qin, Roberts, Schmidt, PRD (2018)
Spectrum of light- and heavy-baryons, Qin, Roberts, Schmidt, Few Body Syst. 60 (2019)

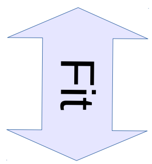
Using ONLY meson-baryon degrees of freedom (no explicit quark dynamics):

Manifestly gauge invariant approach based on full BSE solution

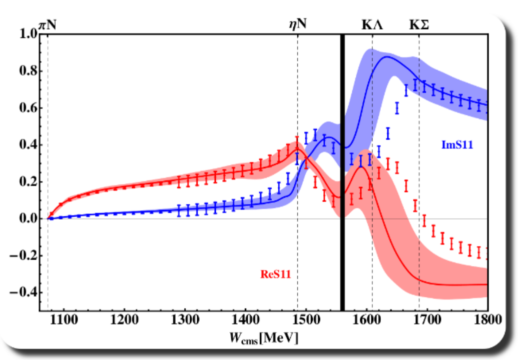
[Ruic, M. Mai, U.-G. Meissner PLB 704 (2011)]

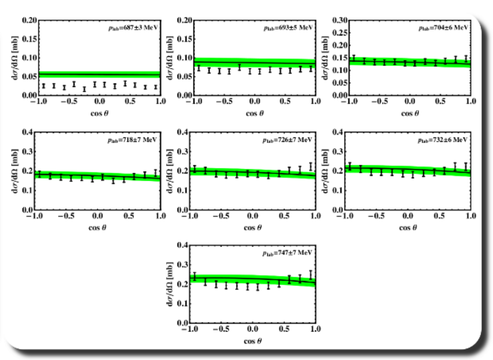


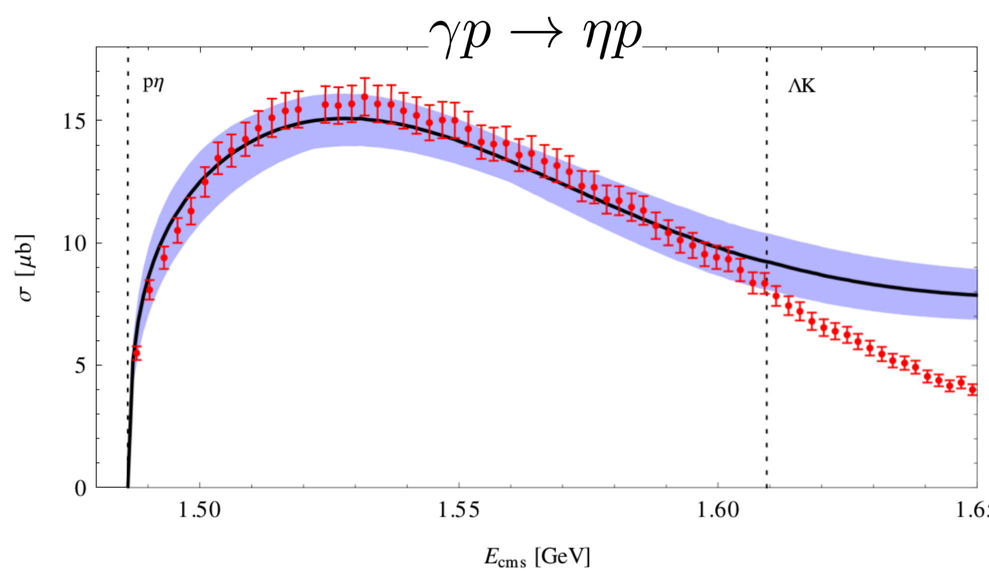




- Exact unitary meson-baryon scattering amplitude T with parameters, fixed to reproduce:
  - πN-partial wave S_{11} and S_{31} for $\sqrt{s} < 1560$ MeV
    Arndt et al. (2012)
  - $\pi^- p \to \eta n$ differential cross sections
    Prakhov et al. (2005)







→ Making the “Missing resonance problem” worse ?!

Phenomenology

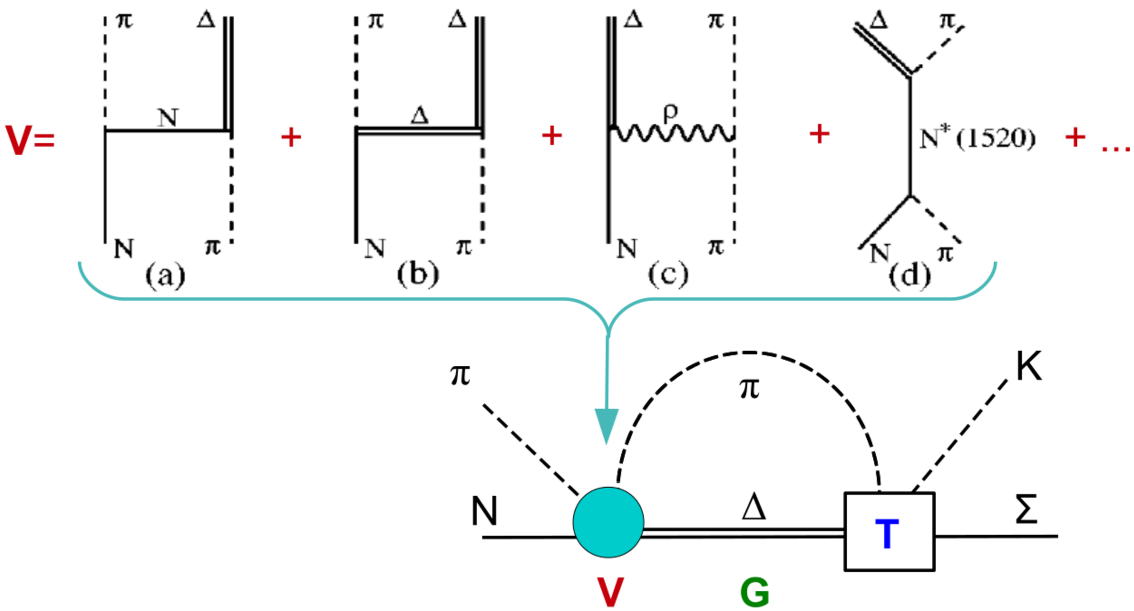
The Julich-Bonn Dynamical Coupled-Channel Approach

e.g. EPJ A 49, 44 (2013)

Dynamical coupled-channels (DCC): **simultaneous** analysis of different reactions

The scattering equation in partial-wave basis

$$\langle L'S'p'|T^{IJ}_{\mu\nu}|LSp\rangle = \langle L'S'p'|V^{IJ}_{\mu\nu}|LSp\rangle + \sum_{\gamma,L''S''}\int_0^\infty dq \quad q^2 \quad \langle L'S'p'|V^{IJ}_{\mu\gamma}|L''S''q\rangle \frac{1}{E-E_\gamma(q)+i\epsilon} \langle L''S''q|T^{IJ}_{\gamma\nu}|LSp\rangle$$



- potentials V constructed from effective $\mathcal{L}$
- s-channel diagrams: T^P

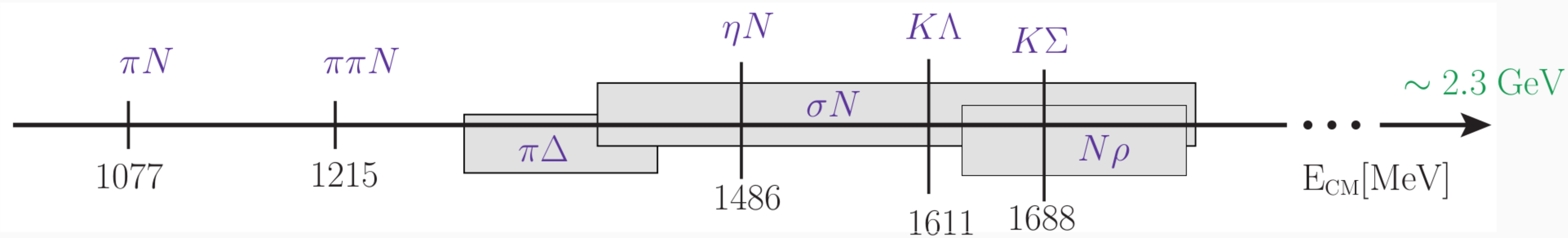
  genuine resonance states
- t- and u-channel: T^{NP}

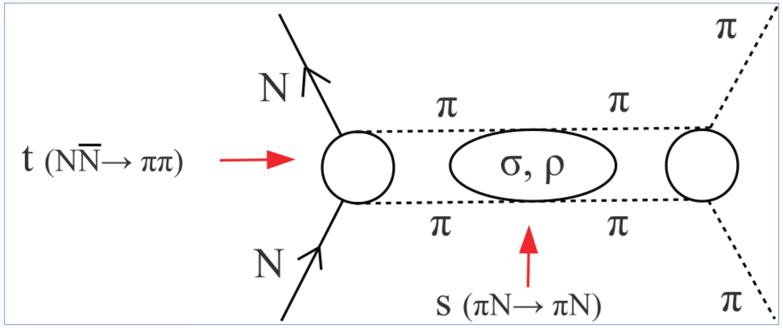
  dynamical generation of poles

  partial waves strongly correlated

JuBo: Channels and Analytic Structure

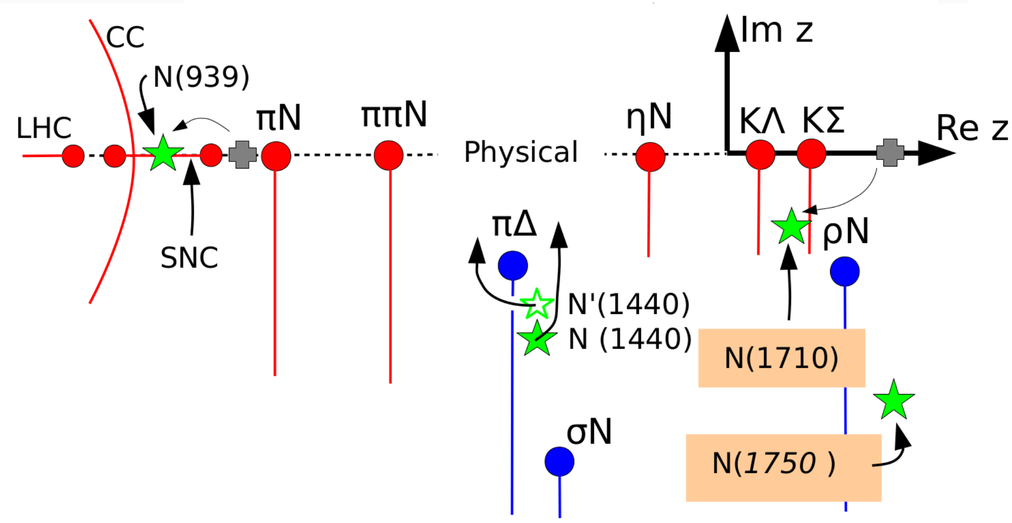
Channels included:





- (2-body) unitarity and analyticity respected
- 3-body $\pi\pi N$ channel:
  - parameterized effectively as $\pi\Delta$, σN, ρN
  - $\pi N/\pi\pi$ subsystems fit the respective phase shifts

  ↳ branch points move into complex plane



JuBo: Data base

- $\pi N \to X$: $>$ **7,000** data points ($\pi N \to \pi N$: GW-SAID WI08 (ED solution))
- $\gamma N \to X$:

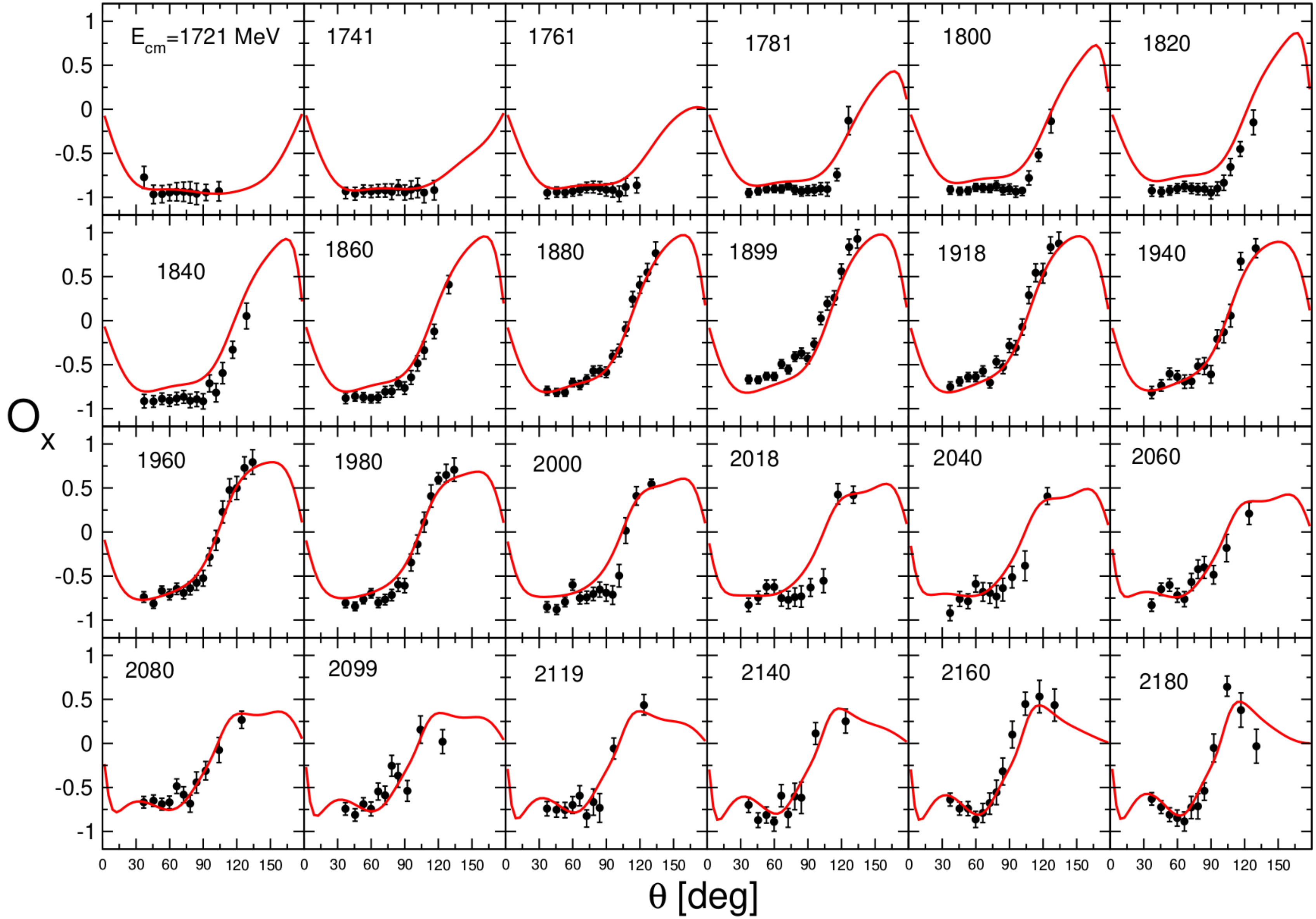
Reaction	Observables (# data points)	p./channel
$\gamma p \to \pi^0 p$	$d\sigma/d\Omega$ (18721), Σ (2927), P (768), T (1404), $\Delta\sigma_{31}$ (140),	
	G (393), H (225), E (467), F (397), $C_{x'_L}$ (74), $C_{z'_L}$ (26)	25,542
$\gamma p \to \pi^+ n$	$d\sigma/d\Omega$ (5961), Σ (1456), P (265), T (718), $\Delta\sigma_{31}$ (231),	
	G (86), H (128), E (903)	9,748
$\gamma p \to \eta p$	$d\sigma/d\Omega$ (9112), Σ (403), P (7), T (144), F (144), E (129)	9,939
$\boldsymbol{\gamma p \to K^+ \Lambda}$	$d\sigma/d\Omega$ (2478), P (1612), Σ (459), T (383),	
	$C_{x'}$ (121), $C_{z'}$ (123), $O_{x'}$ (66), $O_{z'}$ (66), O_x (314), O_z (314),	5,936
$\boldsymbol{\gamma p \to K^+ \Sigma^0}$	$d\sigma/d\Omega$ (4271), P (422), Σ (280), T (127), $C_{x',z'}$ (188), $O_{x,z}$ (254)	5,542
$\boldsymbol{\gamma p \to K^0 \Sigma^+}$	$d\sigma/d\Omega$ (242), P (78)	320
	in total	**57,027**

A new **SAID** interface [Video, R. Workman]

Selected Fit Results (I)

- $\gamma p \to K^+ \Lambda$:

http://collaborations.fz-juelich.de/ikp/meson-baryon/main



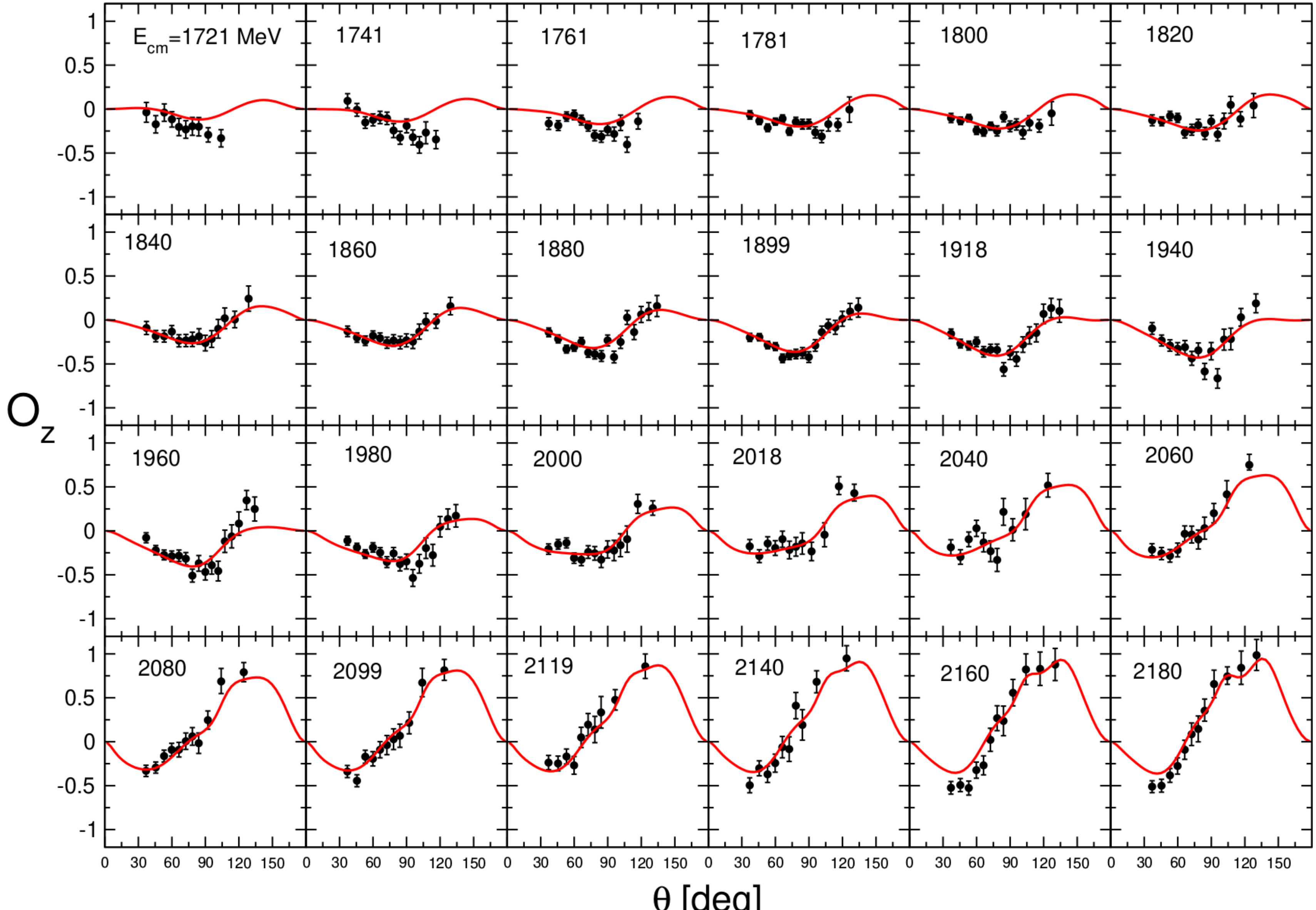
[D. Roenchen, M. D., U.-G. Meißner, EPJ A 54, 110 (2018)]

data: Paterson (CLAS) PRC 93, 065201 (2016), red line: fit JüBo2019

Selected Fit Results (II)

- $\gamma p \to K^+ \Lambda$:

http://collaborations.fz-juelich.de/ikp/meson-baryon/main



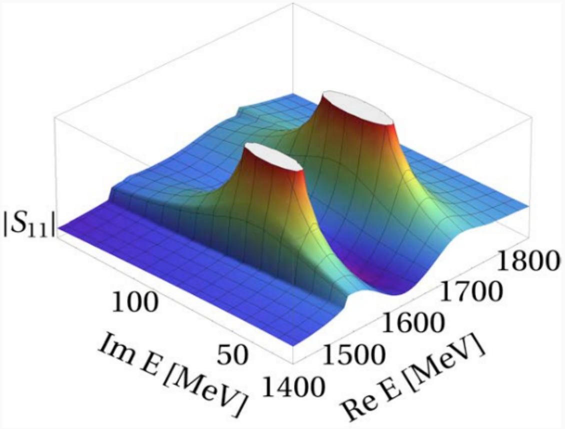
[D. Roenchen, M. D., U.-G. Meißner, EPJ A 54, 110 (2018)

data: Paterson (CLAS) PRC 93, 065201 (2016), red line: fit JüBo2019

Resonance Couplings

Resonance states: **Poles in the T-matrix** on the 2^{nd} Riemann sheet

[D. Roenchen, M. D., U.-G. Meißner, EPJ A 54, 110 (2018)]



- Re(E_0) = "mass", -2Im(E_0) = "width"
- elastic πN residue $(|r_{\pi N}|, \theta_{\pi N\to\pi N})$, normalized residues for inelastic channels $(\sqrt{\Gamma_{\pi N}\Gamma_\mu}/\Gamma_{tot}, \theta_{\pi N\to\mu})$
- photocouplings at the pole: $\tilde{A}^h_{pole} = A^h_{pole} e^{i\vartheta^h}$, $h = 1/2,\ 3/2$

Inclusion of $\gamma p \to K^+\Lambda$ in JüBo ("JuBo2017-1"): 3 additional states

	z_0 [MeV]	$\frac{\Gamma_{\pi N}}{\Gamma_{tot}}$	$\frac{\Gamma_{\eta N}}{\Gamma_{tot}}$	$\frac{\Gamma_{K\Lambda}}{\Gamma_{tot}}$	$\frac{\Gamma_{K\Sigma}}{\Gamma_{tot}}$
N(1900)$3/2^+$	$1923 - i\,108.4$	1.5 %	0.78 %	2.99 %	69.5 %
N(2060)$5/2^-$	$1924 - i\,100.4$	0.35 %	0.15 %	13.47 %	27.02 %
Δ(*2190*)$1/2^+$	$2191 - i\,103.0$	33.12 %			3.78 %

- N(1900)$3/2^+$: s-channel resonances, seen in many other analyses of kaon photoproduction (BnGa), 3 stars in PDG
- N(2060)$5/2^-$: dynamically generated, 2 stars in PDG, seen e.g. by BnGa
- Δ(*2190* $1/2^+$: dyn. gen., no equivalent PDG state

Electroproduction (preliminary)

C. Granados, M.D., H. Haberzettl, D. Rönchen, R. Workman et al.

Data & Analyses

Take advantage of multi-channel approach
→ analyze simultaneously final states $\pi N,\ \eta N,\ K\Lambda$

~10^6 pion electroproduction data

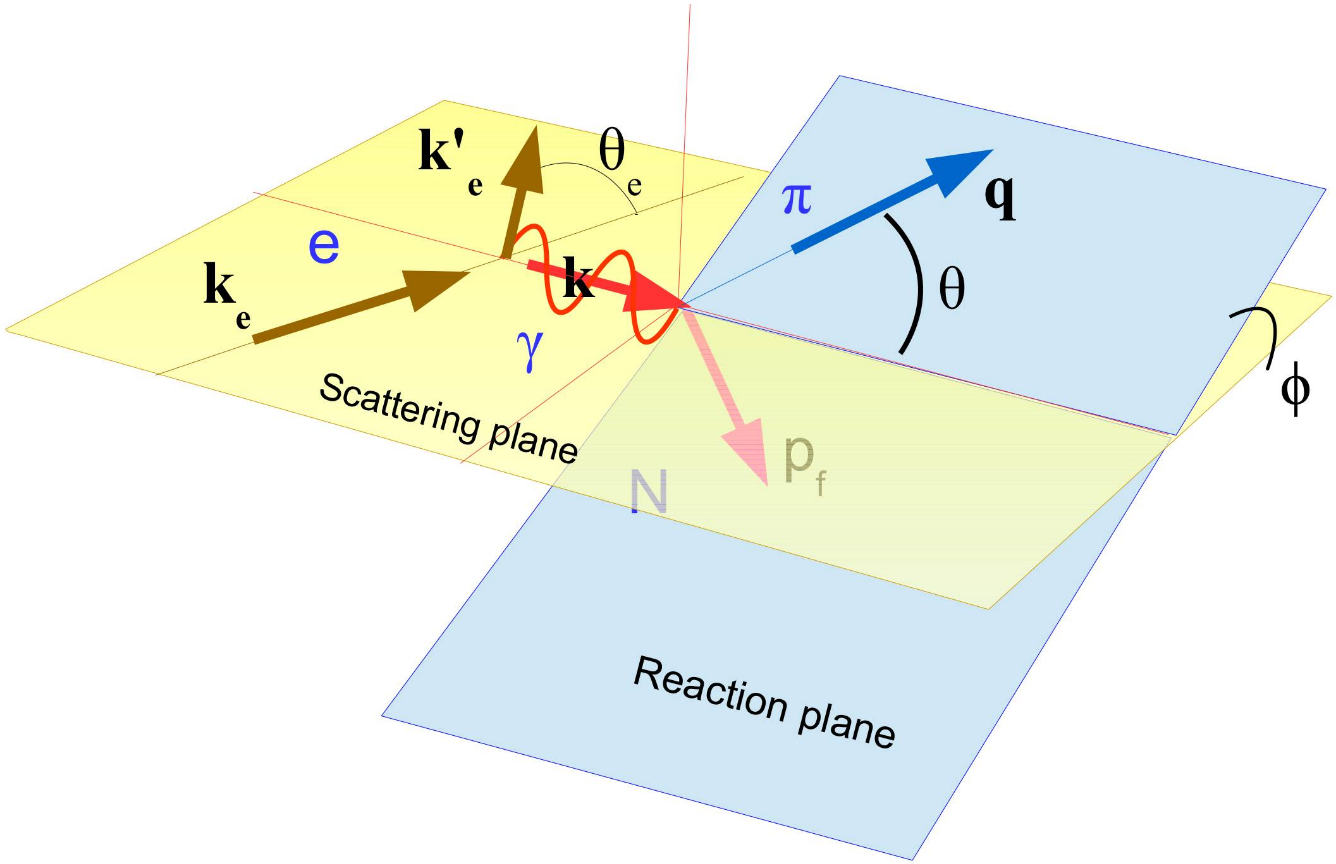
$\eta N,\ K\Lambda$:

Reaction	Observable	Q^2 [GeV]	W [GeV]	Ref.
$ep \to e'p'\eta$	$\sigma_U,\ \sigma_{LT},\ \sigma_{TT}$	$1.6 - 4.6$	$2.0 - 3.0$	[132]
	$\sigma_U,\ \sigma_{LT},\ \sigma_{TT}$	$0.13 - 3.3$	$1.5 - 2.3$	[137]
	$d\sigma/d\Omega$	$0.25 - 1.5$	$1.5 - 1.86$	[138]
$ep \to e'K^+\Lambda$	P_N^0	$0.8 - 3.2$	$1.6 - 2.7$	[139]
	$\sigma_U,\ \sigma_{LT},\ \sigma_{TT},\ \sigma_{LT'}$	$1.4 - 3.9$	$1.6 - 2.6$	[140]
	$P'_x,\ P'_z$	$0.7 - 5.4$	$1.6 - 2.6$	[141]
	$\sigma_T,\ \sigma_L,\ \sigma_{LT},\ \sigma_{TT}$	$0.5 - 2.8$	$1.6 - 2.4$	[142]
	$P'_x,\ P'_z$	$0.3 - 1.5$	$1.6 - 2.15$	[143]

ηp and $K^+\Lambda$ electroproduction data measured at CLAS for different photon virtualities Q^2 and total energy W. Based on material provided by courtesy of D. Carman (JLab) and I. Strakovsky (GW).

- **ANL-Osaka** PRC **80**, 025207 (2009), Few-Body Syst. 59, 24 (2018),...
- **Aznauryan, Burkert** et al., PRC **80**, 055203 (2009), Int.J.Mod.Phys. E22, 1330015 (2013),..
- **EtaMAID2018**, EPJA 54 (2018), 210
- **MAID2007**, EPJA 34 (2007) 69
- **SAID**, PiN Newsletter 16, 150 (2002)
- **Gent group** Phys. Rev. C 89, 065202 (2014),...

Kinematics



Unpolarized differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_T}{d\Omega} + \epsilon\frac{d\sigma_L}{d\Omega} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{d\Omega}\cos\phi + \epsilon\frac{d\sigma_{TT}}{d\Omega}\cos 2\phi + h\sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT'}}{d\Omega}\sin\phi$$

$$\epsilon = \frac{1}{1 + 2\frac{k_L^2}{Q^2}\tan\theta_e}$$

Decomposed in in electric, magnetic, and longitudinal multipoles

Formalism

- Photoproduction solution as constraint
- Constraints from (Pseudo)-threshold:

$$\left(E^I_{l+}, L^I_{l+}\right) \rightarrow \; k^l q^l \;\; (l \geq 0)$$
$$\left(M^I_{l+}, M^I_{l-}\right) \rightarrow \; k^l q^l \;\; (l \geq 1)$$
$$\left(L^I_{l}\right) \rightarrow \; kq \;\; (l = 1)$$
$$\left(E^I_{l-}, L^I_{l-}\right) \rightarrow k^{l-2} q^l (l \geq 2)$$

$$k = |\mathbf{k}| = \frac{\sqrt{\left((W-M_N)^2+Q^2\right)\left((W+M_N)^2+Q^2\right)}}{2W}$$
$$q = |\mathbf{q}| = \frac{\sqrt{\left((W-M_N)^2-M_m^2\right)\left((W+M_N)^2-M_m^2\right)}}{2W}$$

- Siegert's theorem

$$\frac{E_{l_+}}{L_{l_+}} \rightarrow 1, \qquad \frac{E_{l_-}}{L_{l_-}} \rightarrow \frac{-l}{l-1}$$

at pseudo-threshold

Amaldi, Fubini, Furlan,
Springer Tracts Mod. Phys. 83, 1 (1979)
Tiator, Few-body Systems 57, 1087 (2016)

- Watson's theorem, multi-channel unitarity

$$M_{\mu\gamma^*}(q,W,Q^2) = V_{\mu\gamma^*}(q,W,Q^2) + \sum_\kappa \int dp p^2 T_{\mu\kappa}(q,p,W) G_\kappa(p,W) V_{\nu\gamma^*}(p,W,Q^2)$$

$$V_{\mu\gamma^*}(p,W,Q^2) = \alpha^{NP}_{\mu\gamma^*}(p,W,Q^2) + \sum_i \frac{\gamma^a_{\mu;i}(p)\gamma^c_{\gamma^*;i}(W,Q^2)}{W-m^b_i}$$

Very preliminary results (before fit)

$W = 1232\,\mathrm{MeV}$

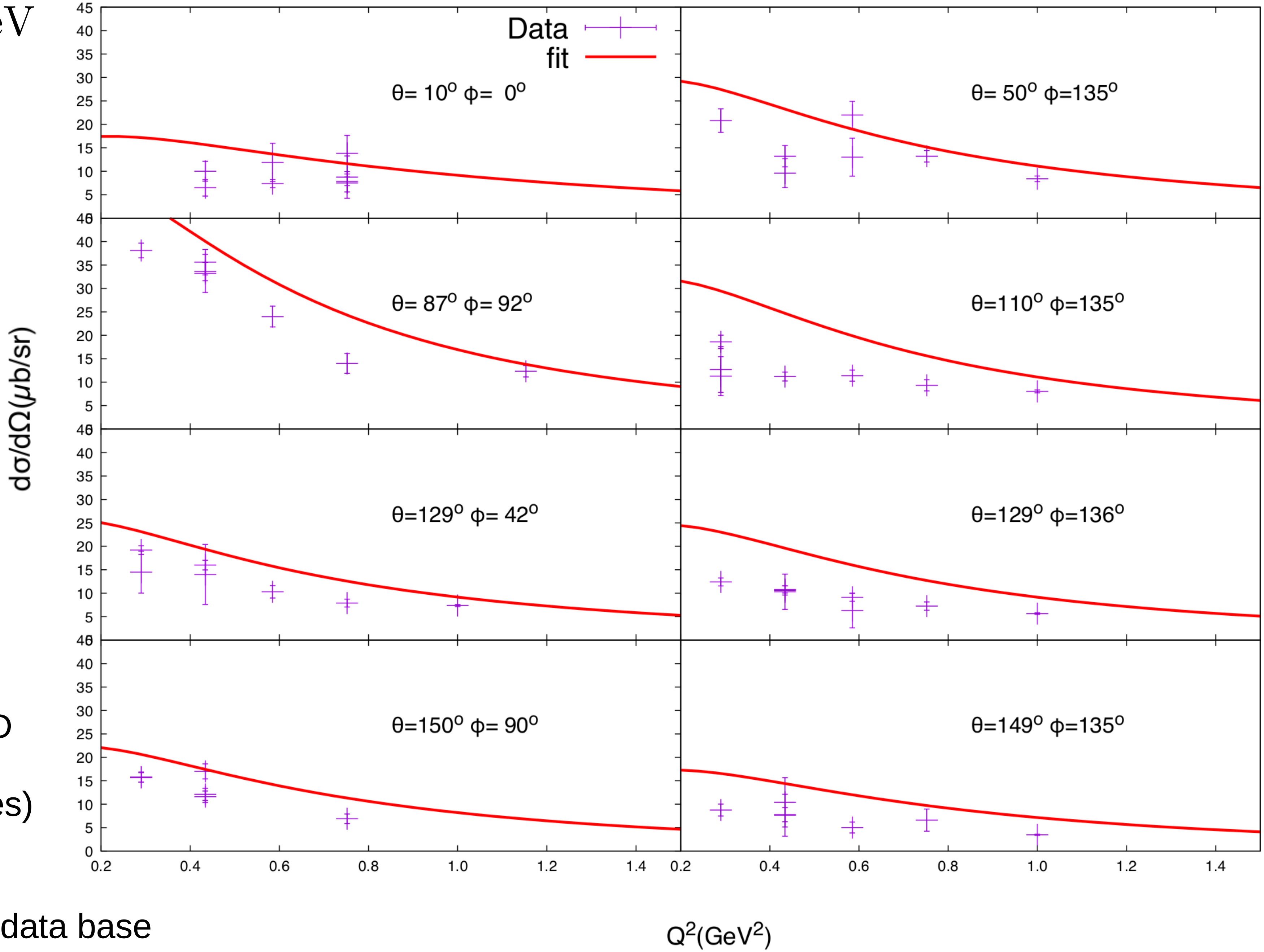
$\Delta W = 2\,\mathrm{MeV}$

$\Delta\theta \approx 1^\circ$

$\Delta\phi \approx 1^\circ$

$\epsilon = 0.95$

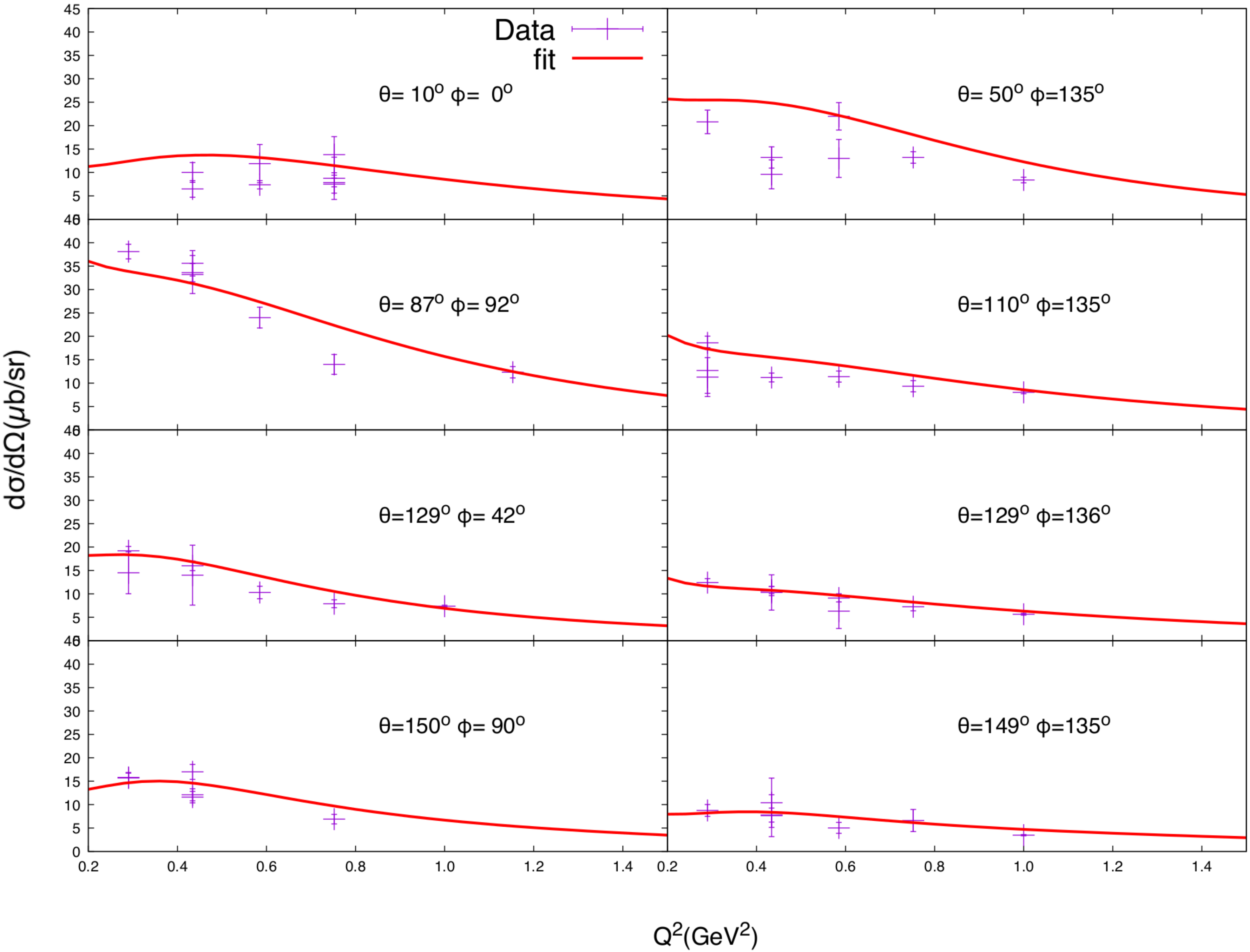
About
1,500 data



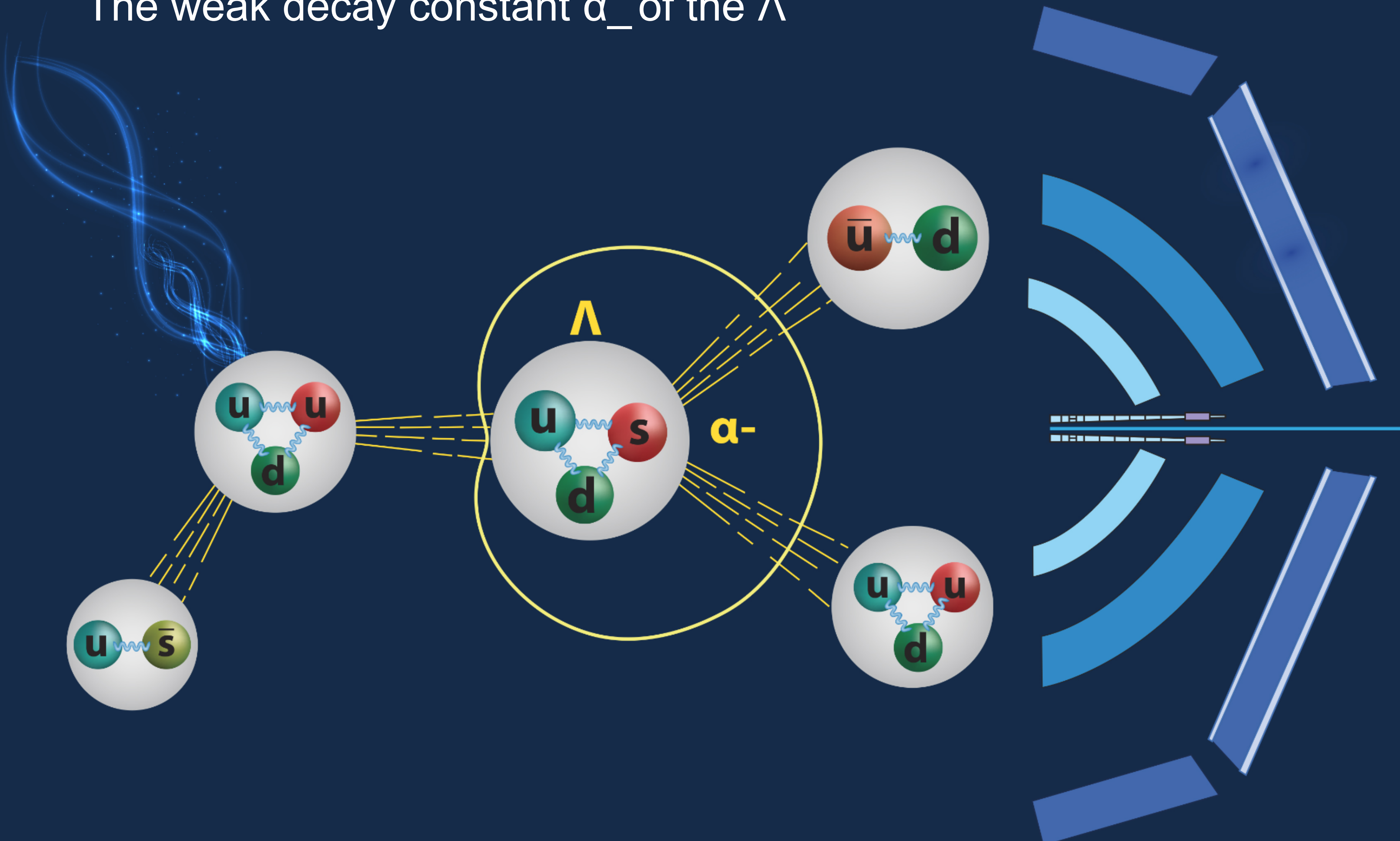
Solution after
fitting to MAID
multipoles
(up to p-waves)

Data: SAID data base

Selected Fit Results (after fit)



The weak decay constant α_ of the Λ



Ireland, M.D., Glazier, Haidenbauer, Mai, Murray-Smith, D. Rönchen, PRL 123 (2019) 182301

Affects

- Baryon spectroscopy
- Polarization experiments at STAR, ATLAS,…
- Decay properties of other hyperons (chain decays)

CERNCOURIER

HIGGS AND ELECTROWEAK | NEWS

Λ-hyperon anomaly confirmed

1 November 2019

The CLAS detector at Jefferson Laboratory in the US. Credit: Jefferson Laboratory

BESIII (2018) & this work

BESIII (2018)

BES III

Table 1 | Summary of the results

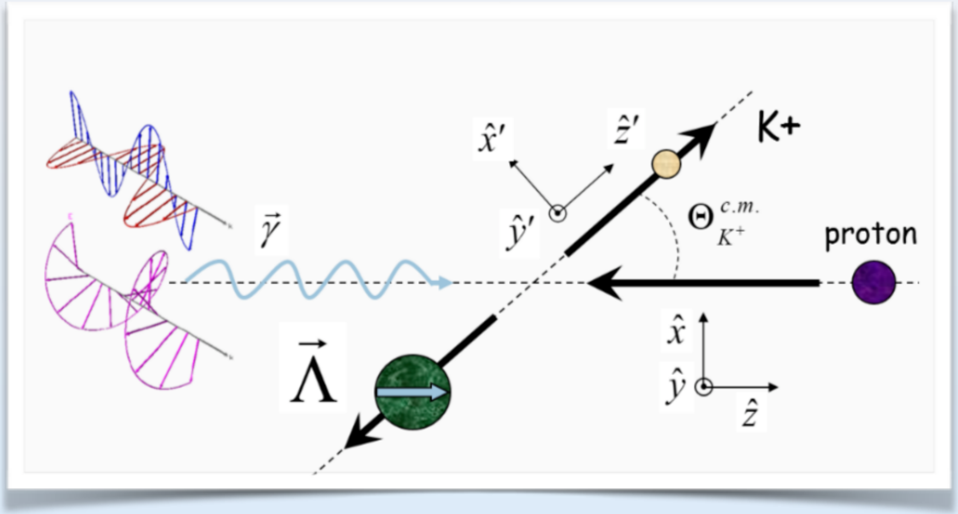
Parameters	This work (BES III)	Previous results (PDG)
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 (ref. [14])
$\Delta\Phi$	$42.4 \pm 0.6 \pm 0.5°$	-
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 (ref. [6])
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 (ref. [6])
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	-
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 (ref. [6])
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	-

$> 5\sigma$ **difference between new result and PDG**[12].

BES III coll., Nature (2019)

Kaon photoproduction (this work)

Experimental setup



Intensity

$$(LP):\ 1+\alpha_-\cos\theta_y\mathbf{P} - p_L^\gamma\cos 2\phi\boldsymbol{\Sigma} - \alpha_- p_L^\gamma\cos 2\phi\cos\theta_y\mathbf{T} - \alpha_- p_L^\gamma\sin 2\phi\cos\theta_x\mathbf{O_x} - \alpha_- p_L^\gamma\sin 2\phi\cos\theta_z\mathbf{O_z}$$

$$(CP):\ 1+\alpha_-\cos\theta_y\mathbf{P} + p_C^\gamma\alpha_-\cos\theta_x\mathbf{C_x} + p_C^\gamma\alpha_-\cos\theta_z\mathbf{C_z}$$

- *7 polarization observables:* $\mathbf{P},\ \boldsymbol{\Sigma},\ \mathbf{T},\ \mathbf{O_x},\ \mathbf{O_z},\ \mathbf{C_x},\ \mathbf{C_z}$

[CLAS] McCracken et al.(2010)
[CLAS] Bradford et al.(2007)
[CLAS] Paterson et al. (2016)

- *Kinematic variables:* $\theta_i,\ W_i$
- *1 fundamental:* α_-, *and 2 calibration parameters:* $p_L^\gamma,\ p_C^\gamma$

BUT: observables are not independent ⟶ **FIERZ IDENTITIES**

Chiang, Tabakin (1997)
Sandorfi et al. (2011)

Kaon photoproduction and Fierz identities

- **Helicity space maps on Clifford algebra ➤ Fierz identities:** Chiang, Tabakin (1997)

$$\Sigma P - C_x O_z + C_z O_x - T = 0 \quad \& \quad O_x^{\,2} + O_z^{\,2} + C_x^{\,2} + C_z^{\,2} + \Sigma^2 - T^2 + P^2 = 1$$

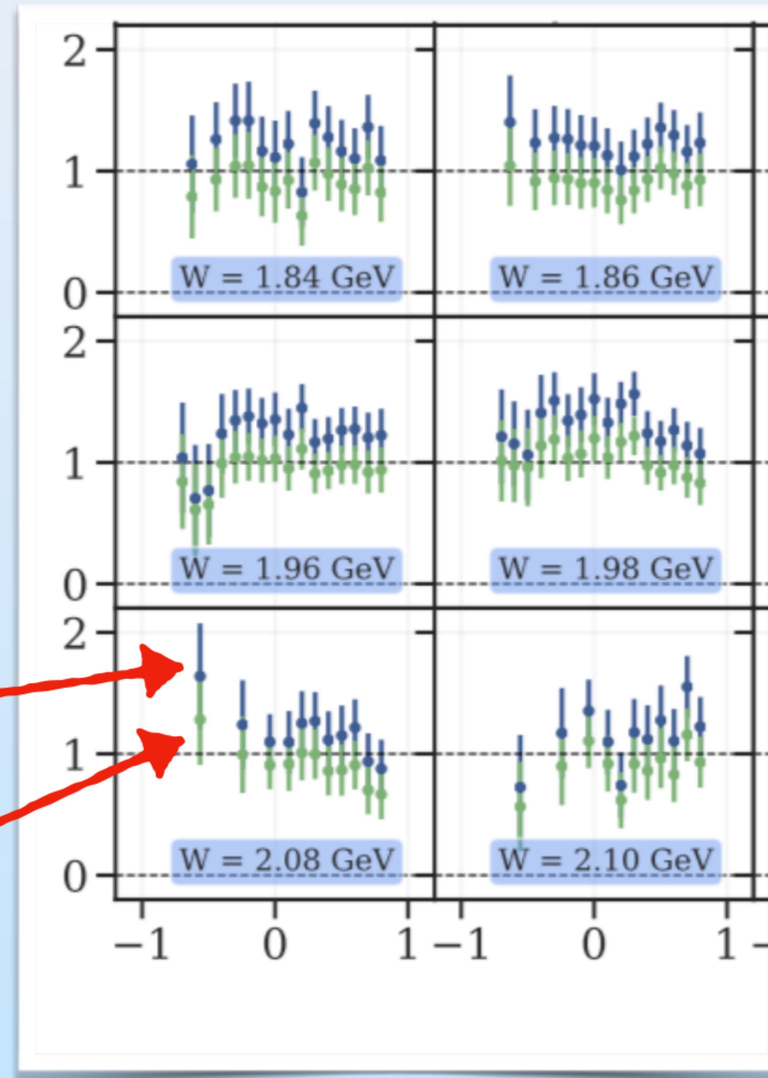
- **A-priori:**

  ⇒ *Observables are not independent*

  ⇒ *determine* α_- *such that FI are fulfilled*

  ⇒ *statistically non-trivial question*

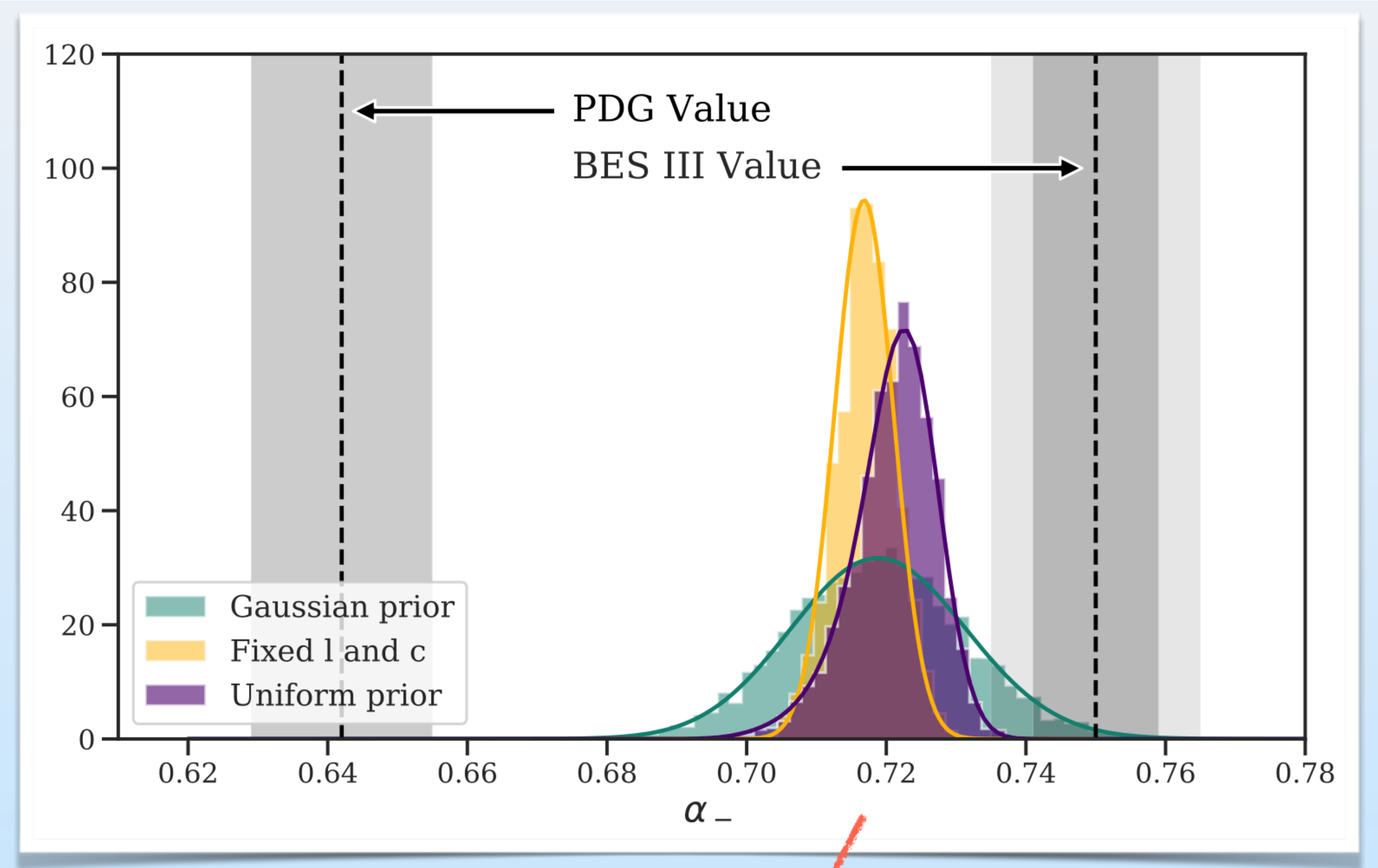
- Non-linear random variables
- Fit three data normalization constants (polarizations and α_) → Avoid biases!
- Observable sampling to solve full problem → Partial linearization possible



α_[PDG]

α_[PDG] / a

Overall result



$\alpha_{-} = 0.721 \pm 0.006 \pm 0.005$

More observables for a preciser α_-

- Sandorfi, Hoblit, Kamano, J.Phys. G38 (2011) 053001:

$$G^2 + H^2 + E^2 + F^2 + \Sigma^2 + T^2 - P^2 = 1.$$

$$O_{x'}^2 + O_{z'}^2 + C_{x'}^2 + C_{z'}^2 + \Sigma^2 - T^2 + P^2 = 1.$$

$$T_{x'}^2 + T_{z'}^2 + L_{x'}^2 + L_{z'}^2 - \Sigma^2 + T^2 + P^2 = 1.$$

$$G^2 + H^2 - E^2 - F^2 - O_{x'}^2 - O_{z'}^2 + C_{x'}^2 + C_{z'}^2 = 0.$$

$$G^2 - H^2 + E^2 - F^2 + T_{x'}^2 + T_{z'}^2 - L_{x'}^2 - L_{z'}^2 = 0.$$

$$O_{x'}^2 - O_{z'}^2 + C_{x'}^2 - C_{z'}^2 - T_{x'}^2 + T_{z'}^2 - L_{x'}^2 + L_{z'}^2 = 0.$$

+ many more

$$\Sigma = +TP + T_{x'}L_{z'} - T_{z'}L_{x'}.$$

$$T = +\Sigma P - C_{x'}O_{z'} + C_{z'}O_{x'}.$$

$$P = +\Sigma T + GF + EH.$$

$$G = +PF + O_{x'}L_{x'} + O_{z'}L_{z'}.$$

$$H = +PE + O_{x'}T_{x'} + O_{z'}T_{z'}.$$

$$E = +PH - C_{x'}L_{x'} - C_{z'}L_{z'}.$$

$$F = +PG + C_{x'}T_{x'} + C_{z'}T_{z'}.$$

$$O_{x'} = +TC_{z'} + GL_{x'} + HT_{x'}.$$

$$O_{z'} = -TC_{x'} + GL_{z'} + HT_{z'}.$$

$$C_{x'} = -TO_{z'} - EL_{x'} + FT_{x'}.$$

$$C_{z'} = +TO_{x'} - EL_{z'} + FT_{z'}.$$

$$T_{x'} = +\Sigma L_{z'} + HO_{x'} + FC_{x'}.$$

$$T_{z'} = -\Sigma L_{x'} + HO_{z'} + FC_{z'}.$$

$$L_{x'} = -\Sigma T_{z'} + GO_{x'} - EC_{x'}.$$

$$L_{z'} = +\Sigma T_{x'} + GO_{z'} - EC_{z'}.$$

Summary

- Phenomenology of excited baryons through coupled-channels, two- and three-body effects
- Global analyses of pion and photon-induced reactions

  → Jülich-Bonn analysis finds/confirms new states in analysis of photoproduction data

  → Extension to analysis of electroproduction data in progress

  → Statistical aspects: How to find a minimal resonance spectrum
- Data-driven new value for α_- determined. Changes polarization measurements at CLAS (baryon spectroscopy) but has impact in wide areas of hadron physics

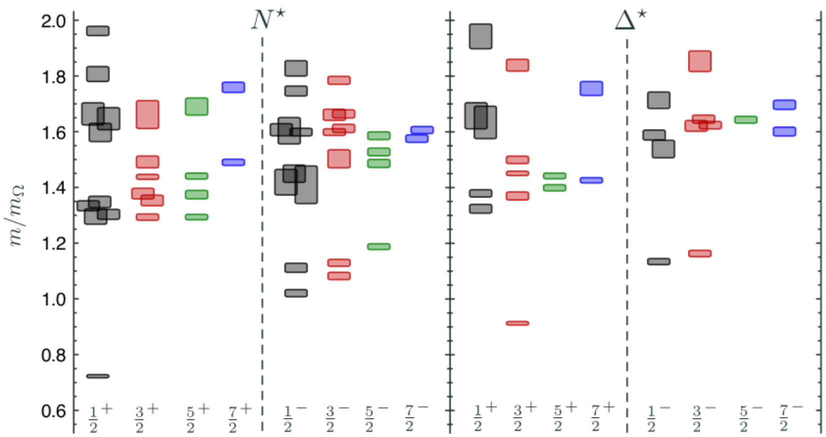
Spare slides

The Missing Resonance Problem

- above 1.8 GeV much more states are predicted than observed,

  “Missing resonance problem”

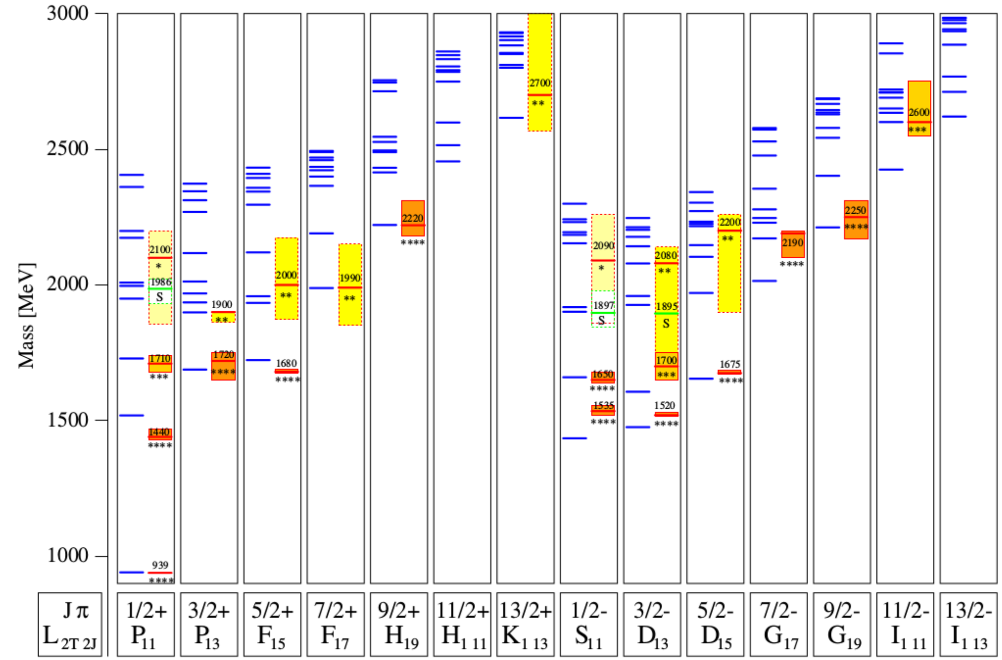
Lattice calculation (single hadron approximation):



[Edwards *et al.*, Phys.Rev. D84 (2011)]

- only 15 established N^* states (PDG 2015)
- $\sim$ 48% of the states have **** or *** status (PDG 1982: 58% with **** or ***)

N^* spectrum in a relativistic quark model:

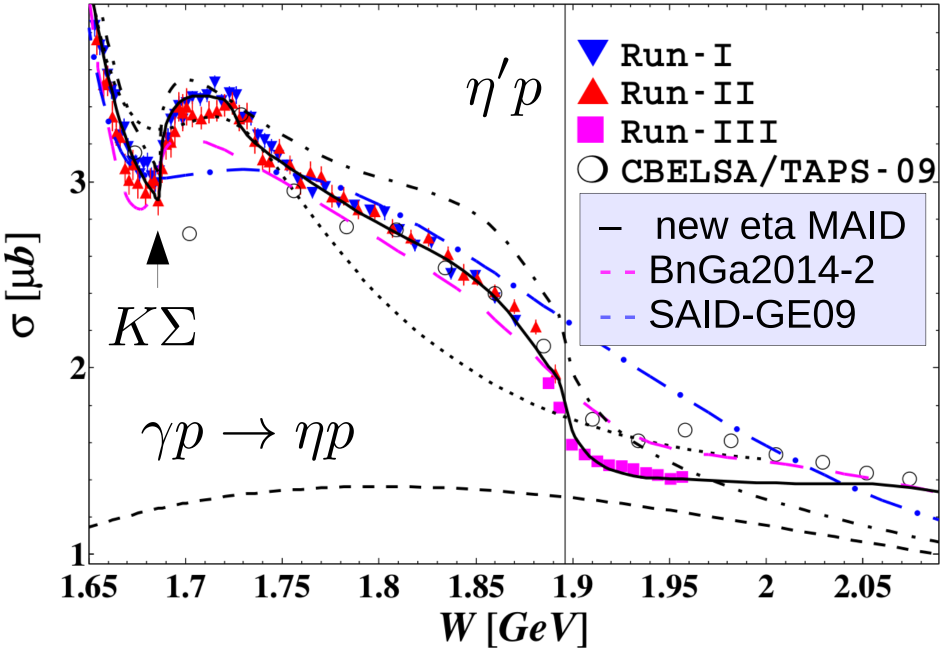


Löring *et al.* EPJ A 10, 395 (2001), experimental spectrum: PDG 2000

Overviews: Crede, Roberts, Rep. Prog. Phys. 76 (2013)
Aznauryan *et al.*, Int. J. Mod. Phys. E 22 (2013)

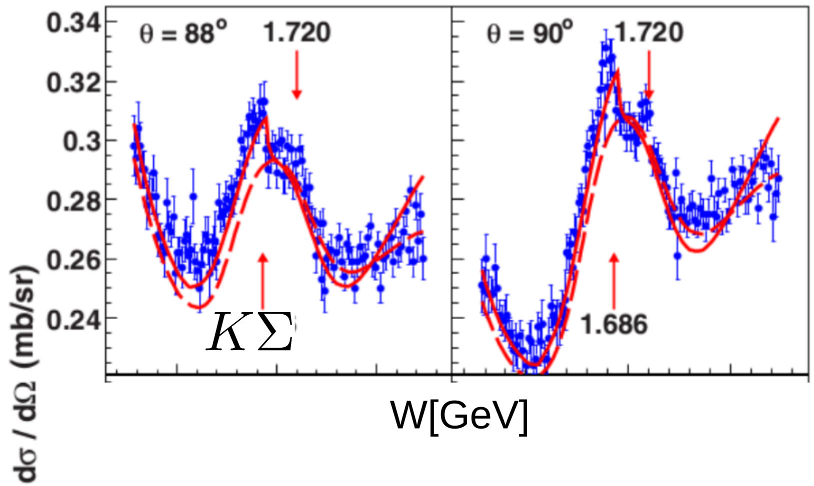
Resonances or not?

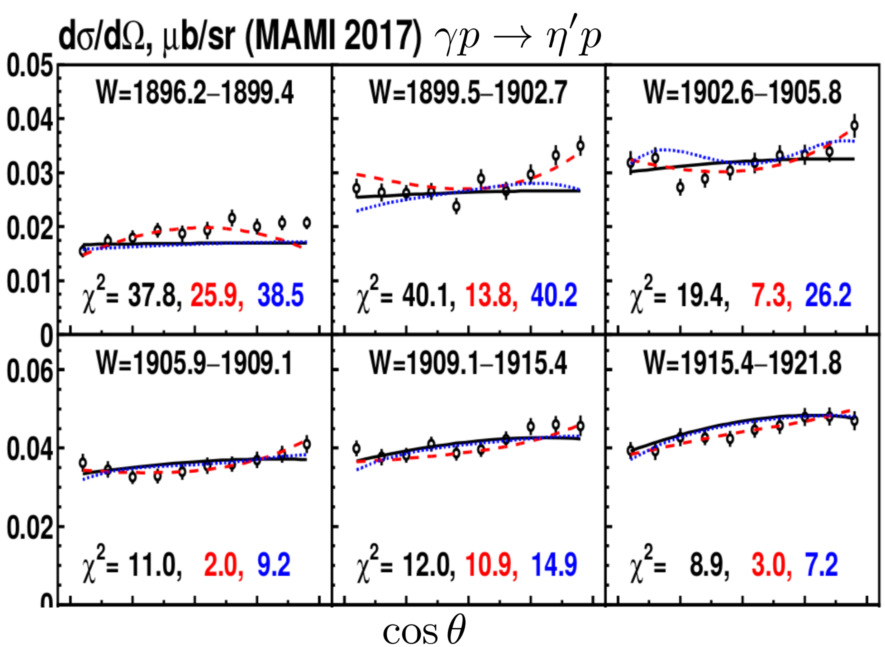
A2 MAMI, PRL 118 (2017) $S_{11}(1895)$



$\pi N \rightarrow \pi N$

EPECUR/SAID PRC 93 (2016)





BnGa
PLB785 (2018):

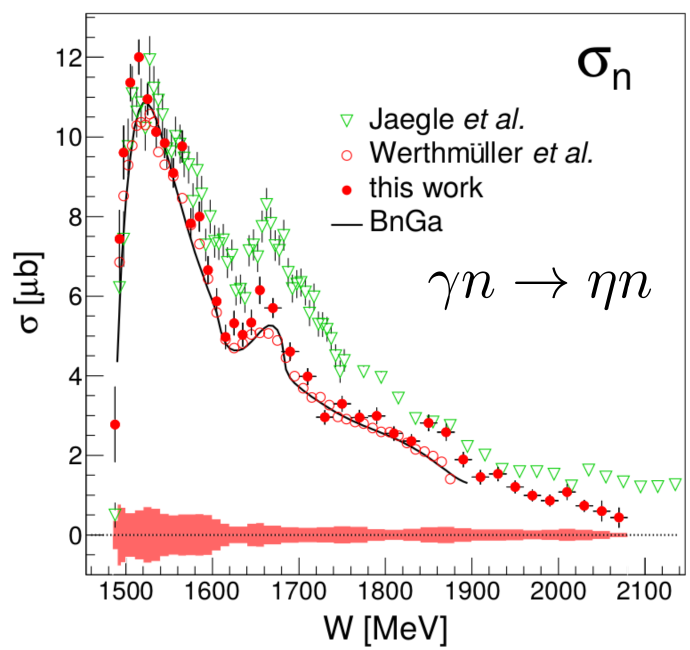
No narrow resonance

3/2⁻ narrow Resonance

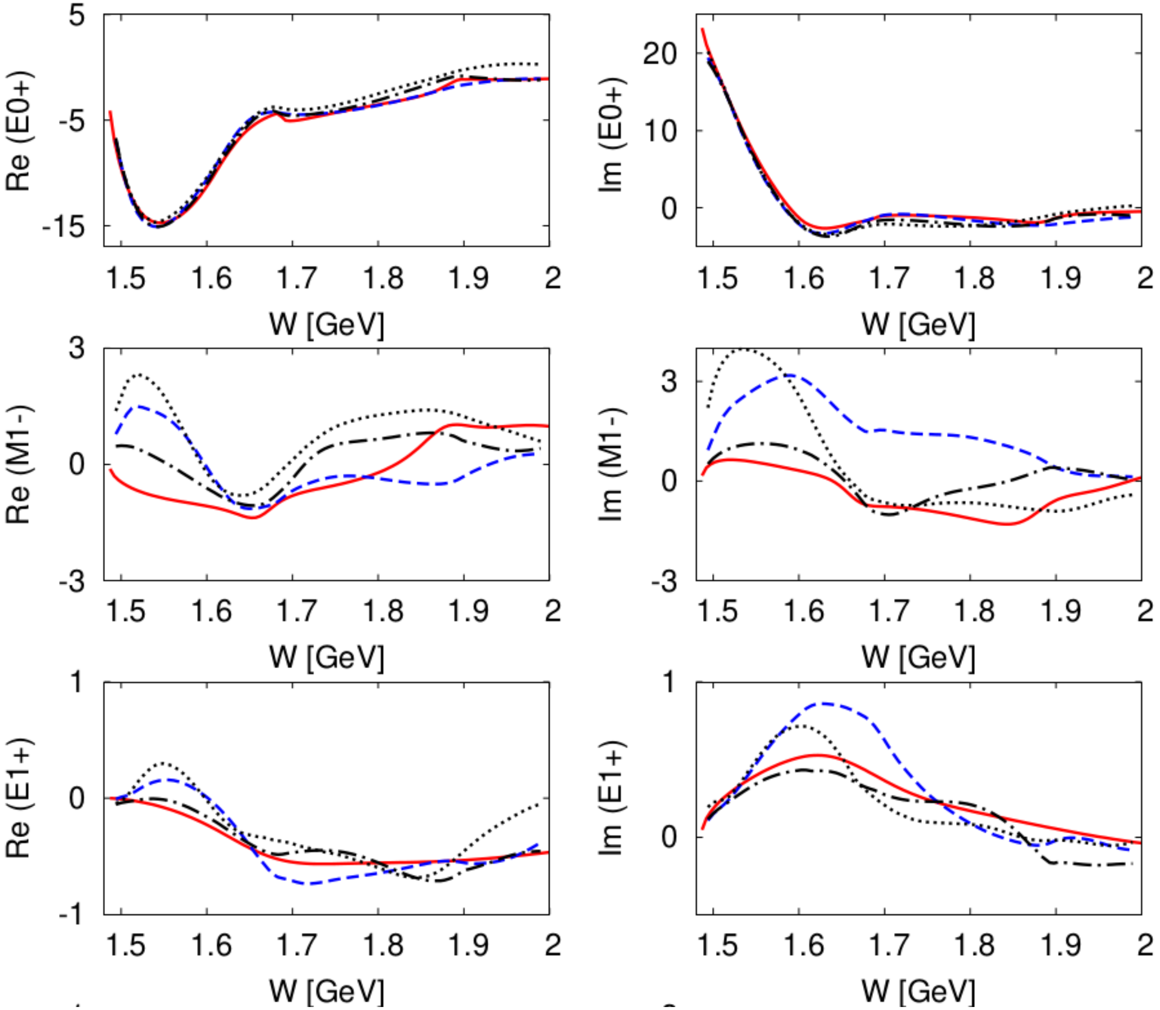
5/2⁻ narrow Resonance

Data: A2.Mami PRL 118 (2017)

[CBELSA/TAPS EPJA 53 (2017)]



Current state in η photoproduction: Multipoles from different groups



From: **EtaMAID2018**
[Tiator et al., EPJA54 (2018)]
Analyzes:

$$\gamma p \to \eta p$$

$$\gamma p \to \eta' p$$

$$\gamma n \to \eta n$$

$$\gamma n \to \eta' n$$

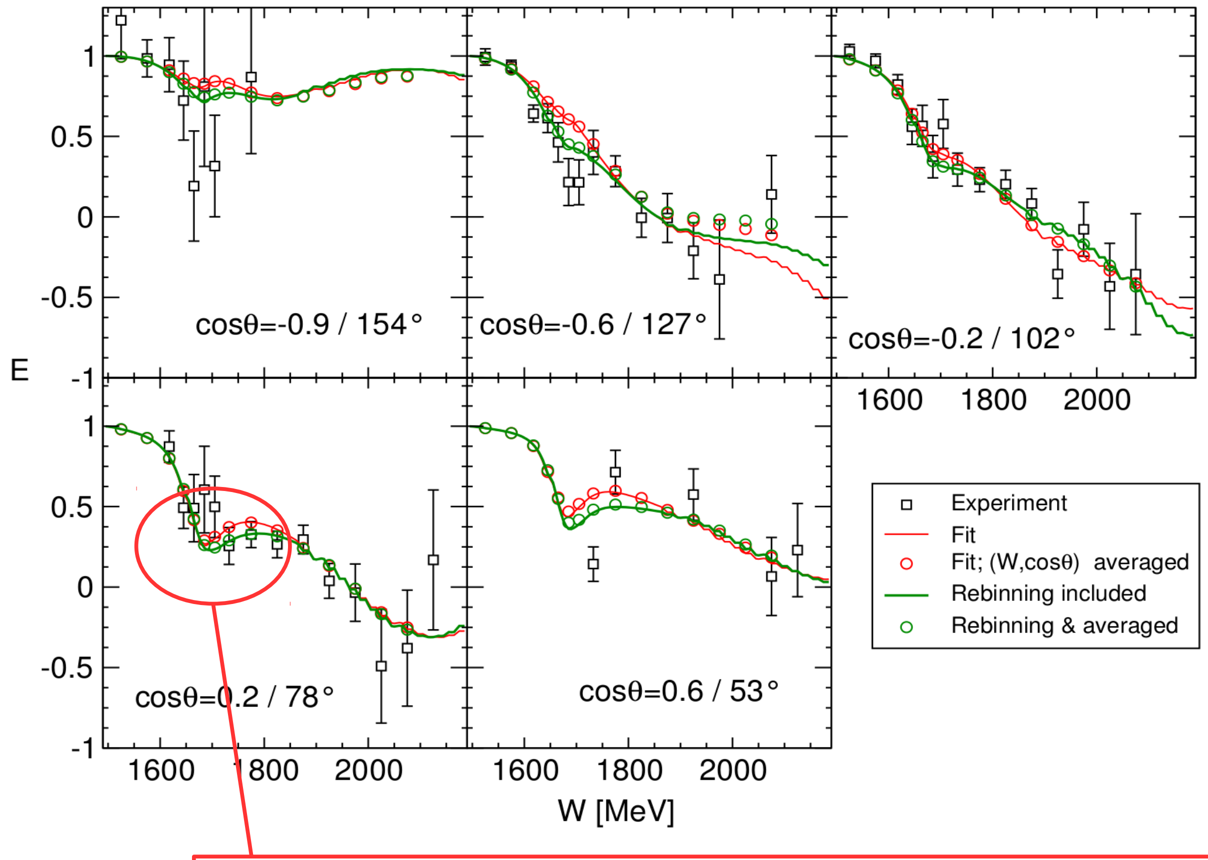
EtaMAID2018
BnGa [PLB 772 (2017)]
JuBo (dotted) [EPJA 54 (2018)]
KSU [1804.06031]

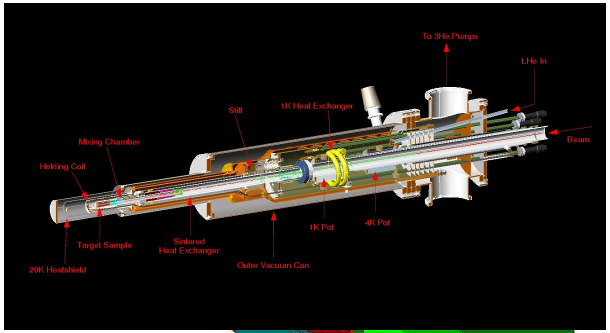
Review: Krusche, Wilkins,
[Prog.Part.Nucl.Phys. 80 (2014)]

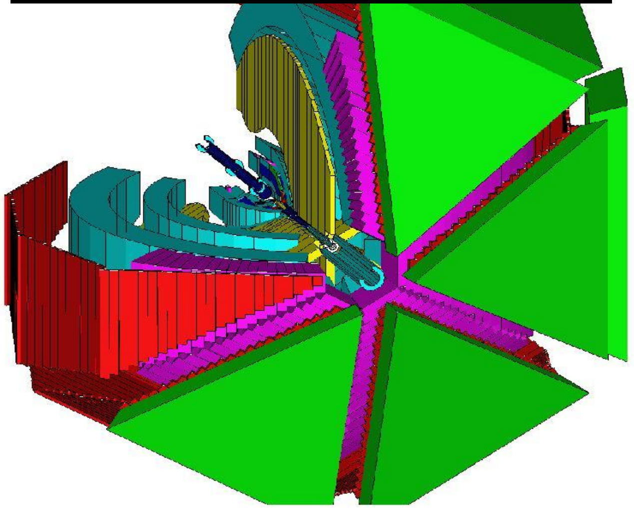
Resonances and other structures

CLAS/JuBo (M. D., D. Rönchen), Phys.Lett. B755 (2016)

- First-ever measurement of observable *E* in η photo-production, enabled through the CLAS <u>FROST</u> target







Is this a new narrow baryonic resonance?
→ Conventional explanation in terms of interference effects.
Systematic elimination of resonance through model selection
(LASSO and other methods, Phys.Rev. D99 (2019) 016001)

Phys.Lett. B771 (2017)
Phys.Lett. B755 (2016)

γp→X

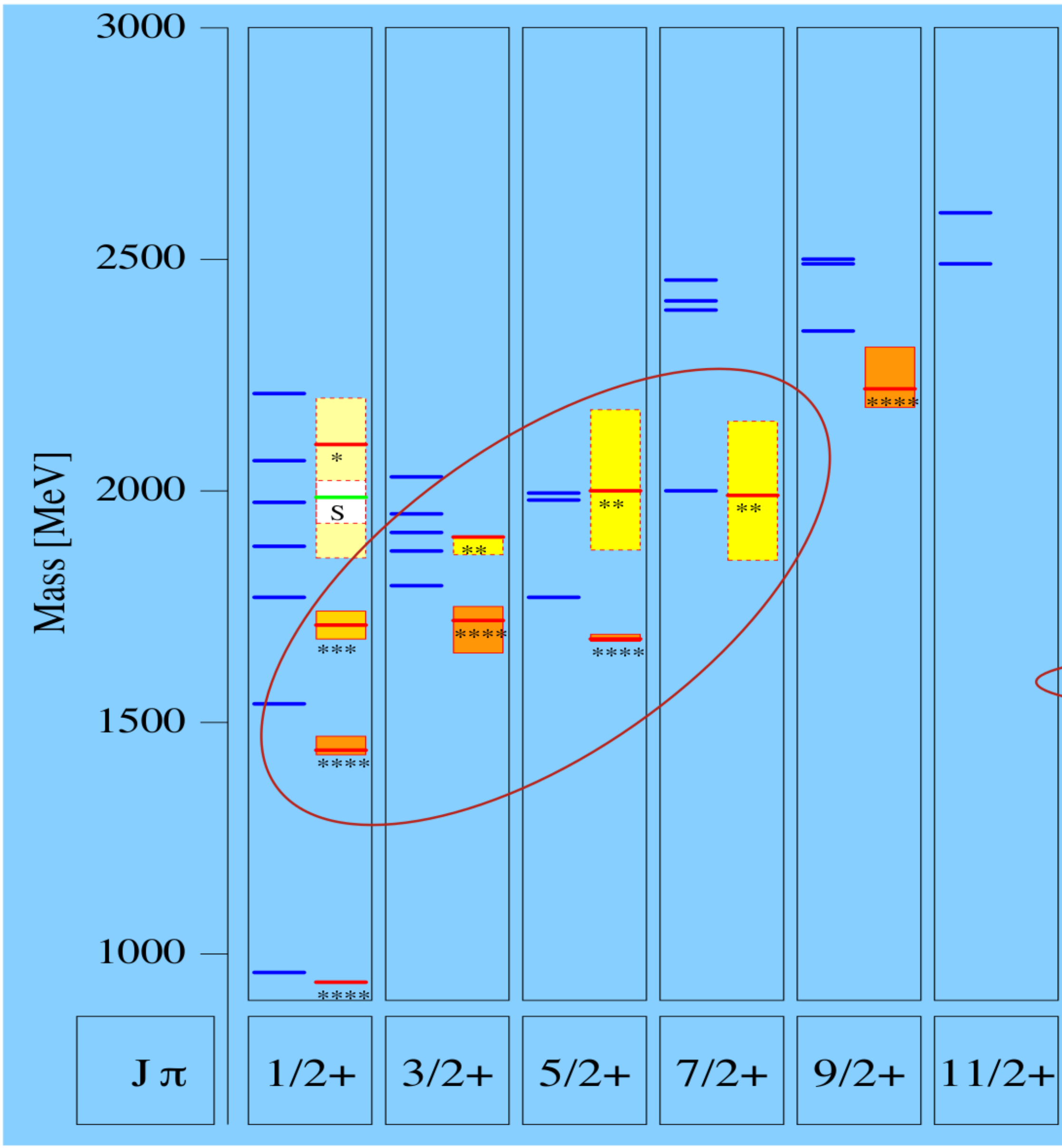
Observable	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^0$	✔	✔	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓		✔	✓	✓	✓								
$p\eta$	✔	✓	✓		✔	✓	✓	✓								
$p\eta'$	✔	✓	✓		✓	✓	✓	✓								
$K^+\Lambda$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$K^+\Sigma^0$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$p\omega/\phi$	✔	✓	✓		✓	✓	✓	✓	✔ SDME							
$K^{+*}\Lambda$	✔			✔					SDME							
$K^{0*}\Sigma^+$	✔	✓									✓	✓	SDME			

γn→X

Observable	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^-$	✔	✔			✔	✓	✓									
$p\rho^-$	✓	✓			✓	✓	✓									
$K^-\Sigma^+$	✔	✓			✓	✓	✓									
$K^0\Lambda$	✔	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

[Slide: V. Burkert]

Spectrum of N* resonances



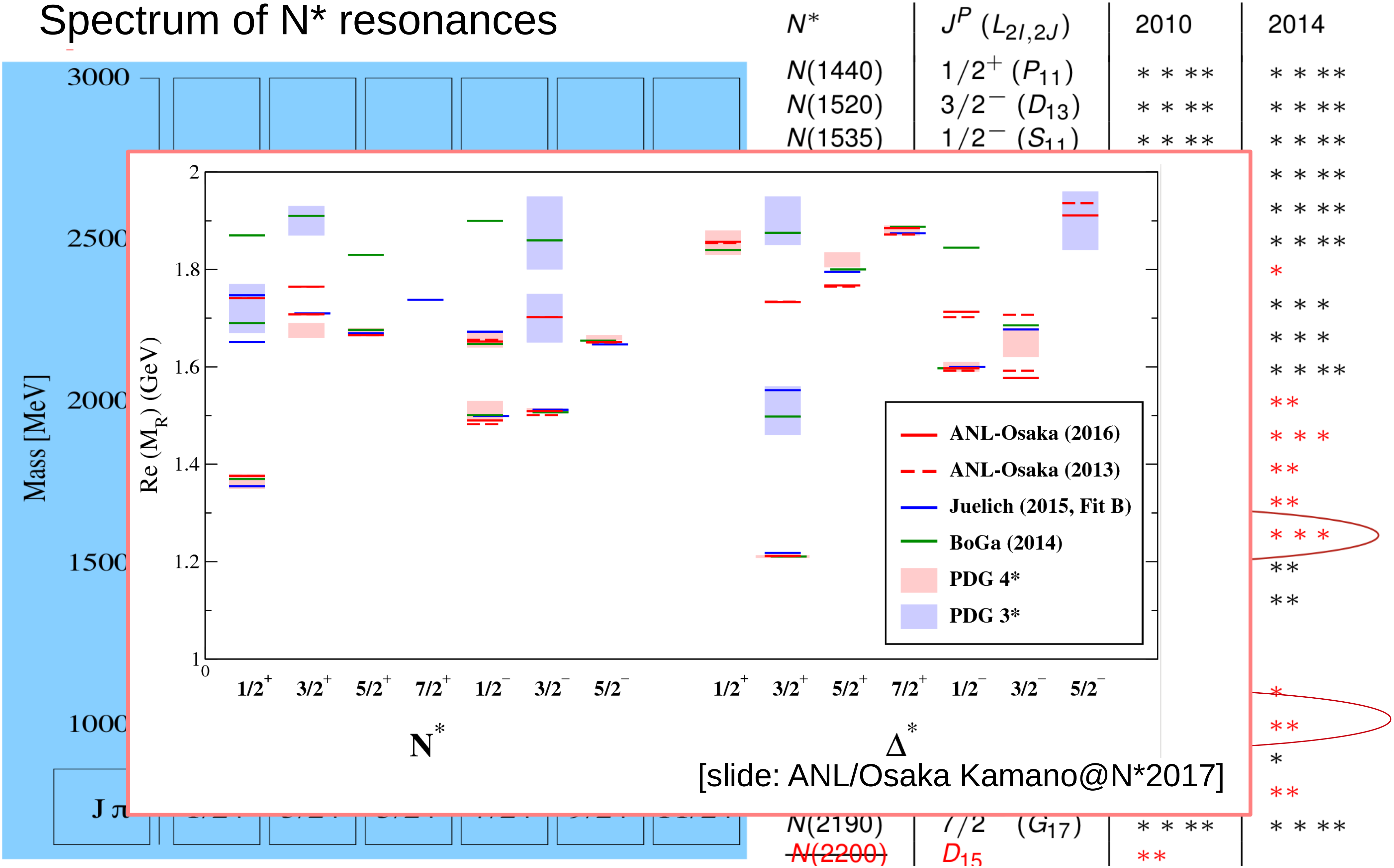
N^*	J^P $(L_{2I,2J})$	2010	2014
$N(1440)$	$1/2^+$ (P_{11})	∗ ∗ ∗∗	∗ ∗ ∗∗
$N(1520)$	$3/2^-$ (D_{13})	∗ ∗ ∗∗	∗ ∗ ∗∗
$N(1535)$	$1/2^-$ (S_{11})	∗ ∗ ∗∗	∗ ∗ ∗∗
$N(1650)$	$1/2^-$ (S_{11})	∗ ∗ ∗∗	∗ ∗ ∗∗
$N(1675)$	$5/2^-$ (D_{15})	∗ ∗ ∗∗	∗ ∗ ∗∗
$N(1680)$	$5/2^+$ (F_{15})	∗ ∗ ∗∗	∗ ∗ ∗∗
$N(1685)$			∗
$N(1700)$	$3/2^-$ (D_{13})	∗ ∗ ∗	∗ ∗ ∗
$N(1710)$	$1/2^+$ (P_{11})	∗ ∗ ∗	∗ ∗ ∗
$N(1720)$	$3/2^+$ (P_{13})	∗ ∗ ∗∗	∗ ∗ ∗∗
$N(1860)$	$5/2^+$		∗∗
$N(1875)$	$3/2^-$		∗ ∗ ∗
$N(1880)$	$1/2^+$		∗∗
$N(1895)$	$1/2^-$		∗∗
$N(1900)$	$3/2^+$ (P_{13})	∗∗	∗ ∗ ∗
$N(1990)$	$7/2^+$ (F_{17})	∗∗	∗∗
$N(2000)$	$5/2^+$ (F_{15})	∗∗	∗∗
~~$N(2080)$~~	D_{13}	∗∗	
~~$N(2090)$~~	S_{11}	∗	
$N(2040)$	$3/2^+$		∗
$N(2060)$	$5/2^-$		∗∗
$N(2100)$	$1/2^+$ (P_{11})	∗	∗
$N(2120)$	$3/2^-$		∗∗
$N(2190)$	$7/2^-$ (G_{17})	∗ ∗ ∗∗	∗ ∗ ∗∗
~~$N(2200)$~~	D_{15}	∗∗	

- Most new resonances by Bonn-Gatchina group;
- Many from kaon photoproduction

[Slide: V. Crede/Nstar 2017, slight modifications]

[See also: Crede, Roberts, Rep. Prog. Phys. 76 (2013)]

Spectrum of N* resonances



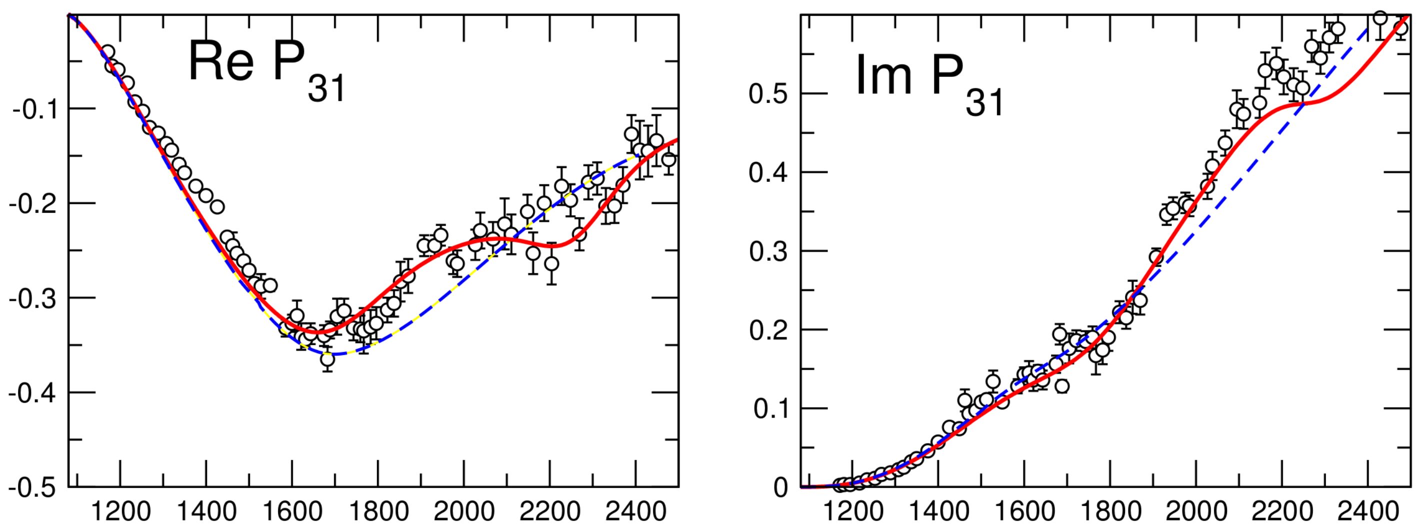
- Most new resonances by Bonn-Gatchina group;
- Many from kaon photoproduction

[Slide: V. Crede/Nstar 2017, slight modifications]

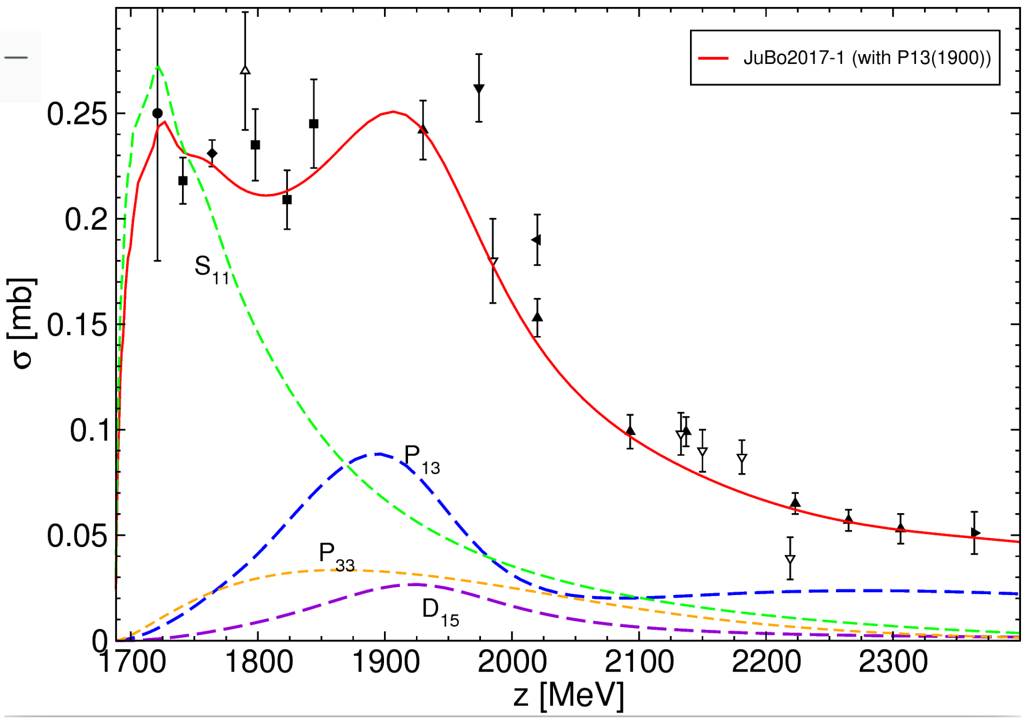
[See also: Crede, Roberts, Rep. Prog. Phys. 76 (2013)]

Visible influence of new states

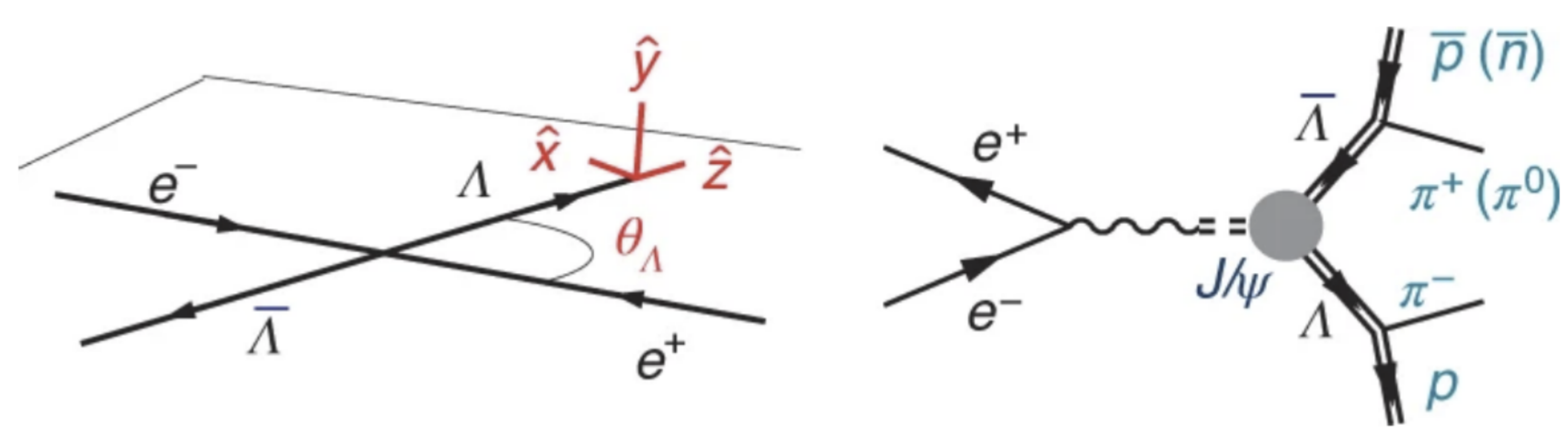
$\Delta(2190)3/2^{+}$ in πN PW



N(1900)$3/2^{+}$, N(2060)$5/2^{-}$ in σ_{tot} in $\pi^{-}p \rightarrow K^{+}\Sigma^{-}$



BES III: Direct measurement



$\Lambda\bar{\Lambda}$ production process.

$$\begin{aligned}
&\mathcal{W}(\xi;\alpha_\psi,\Delta\Phi,\alpha_-,\alpha_+)\\
&=1+\alpha_\psi\cos^2\theta_\Lambda+\ \alpha_-\alpha_+\left[\sin^2\theta_\Lambda\left(n_{1,x}n_{2,x}-\alpha_\psi n_{1,y}n_{2,y}\right)\right.\\
&\left.+\left(\cos^2\theta_\Lambda+\alpha_\psi\right)n_{1,z}n_{2,z}\right]\\
&+\alpha_-\alpha_+\sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda\left(n_{1,x}n_{2,z}+n_{1,z}n_{2,x}\right)\\
&+\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\ \sin\theta_\Lambda\cos\theta_\Lambda\left(\alpha_-n_{1,y}+\alpha_+n_{2,y}\right)
\end{aligned}$$

$\Lambda\bar{\Lambda}$ intensity distribution

BES III coll., Nature (2019)

- Λ **decays weakly to** $p\pi^+$

- **The decay parameter:** α_-

  - *essential for many modern experiments* — e.g. LEAR@CERN, STAR@BNL, ATLAS@CERN

  - *affects decay parameters of other hyperons* — e.g. Trippe et al. (1967), Bono et al. (CLAS) (2018)

Ω^- DECAY PARAMETERS

$\alpha(\Omega^-)\,\alpha_-(\Lambda)$ FOR $\Omega^- \to \Lambda K^-$

Some early results have been omitted.

VALUE	EVTS
0.0115 ± 0.0015	OUR AVERAGE

Ξ^0 DECAY PARAMETERS

See the ``Note on Baryon Decay Parameters'' ir

$\alpha(\Xi^0)\,\alpha_-(\Lambda)$

This is a product of the $\Xi^0 \to \Lambda\pi^0$ and $\Lambda \to p\pi^-$ as

VALUE	EVTS
-0.261 ± 0.006	OUR AVERAGE

PDG live (2019)

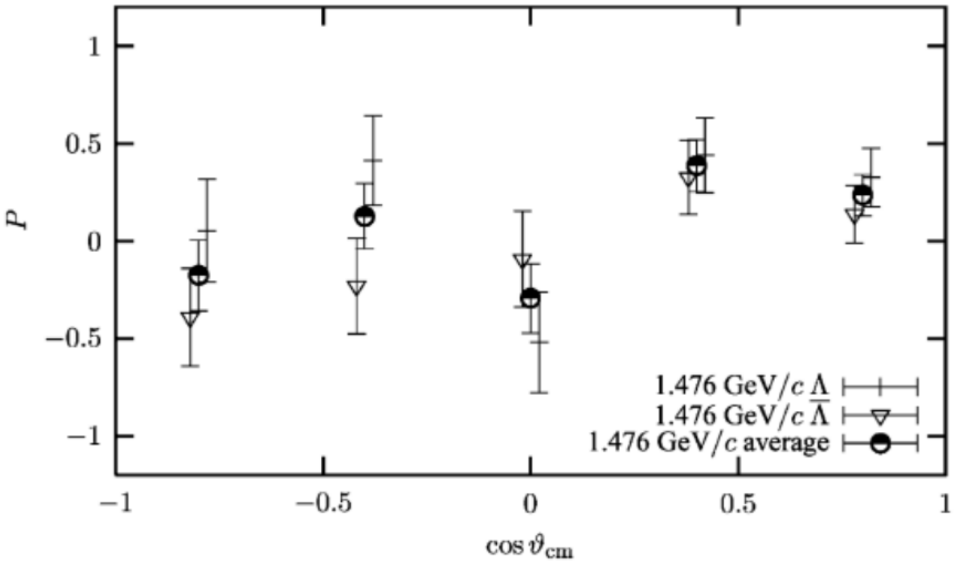
  - *impacts LO parameters of SU(3) baryon ChPT* — Holstein (2000)

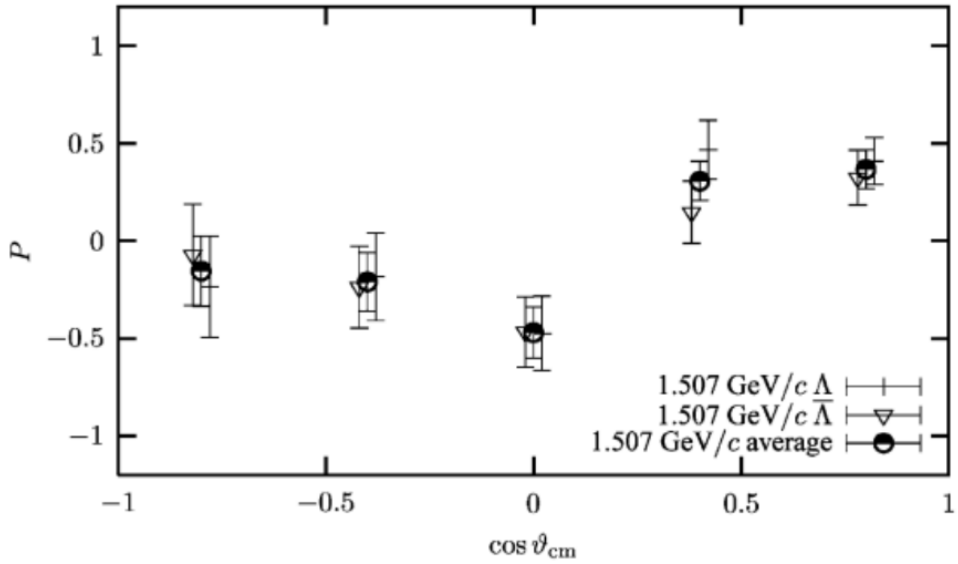
  - *essential for ($\gamma p \to K^+\Lambda$) — new measurement by (CLAS)*

THIS TALK: ESTIMATE α_-

Where α₋ matters (1):
Baryon spectroscopy

Where α_- matters (2):
$p\bar{p} \rightarrow \Lambda\bar{\Lambda}$

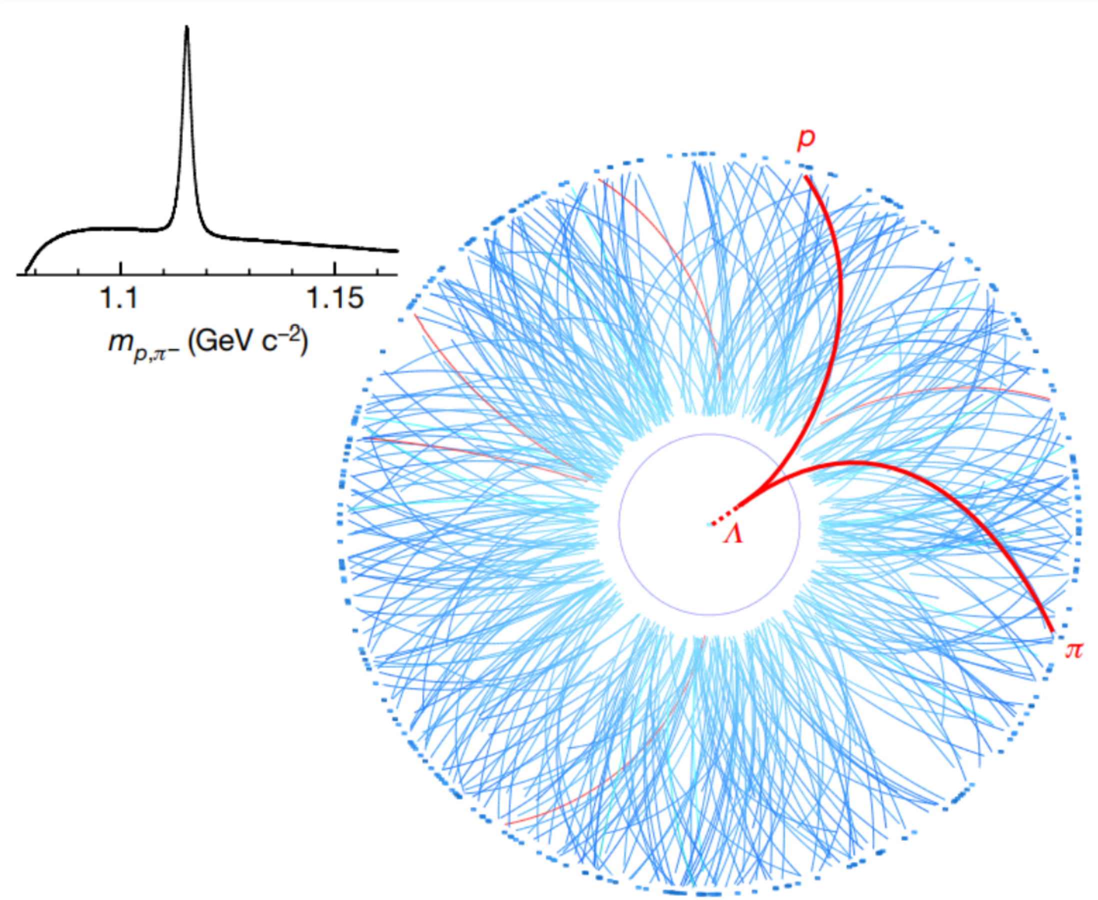




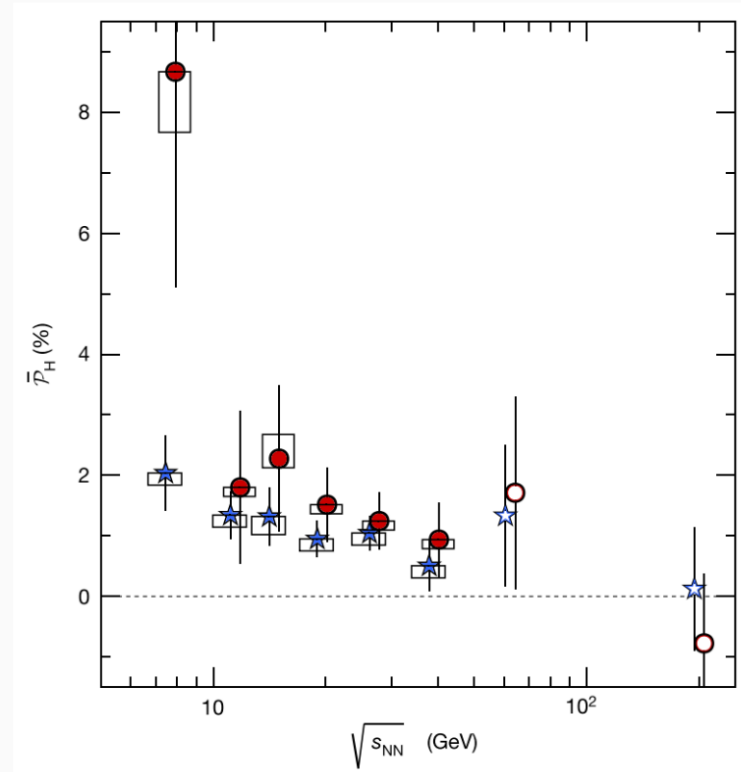
Klempt et al., Phys. Rept. (2002)

Where α_- matters (3):
Global Λ polarization in nuclear collisions

STAR Au-Au collision

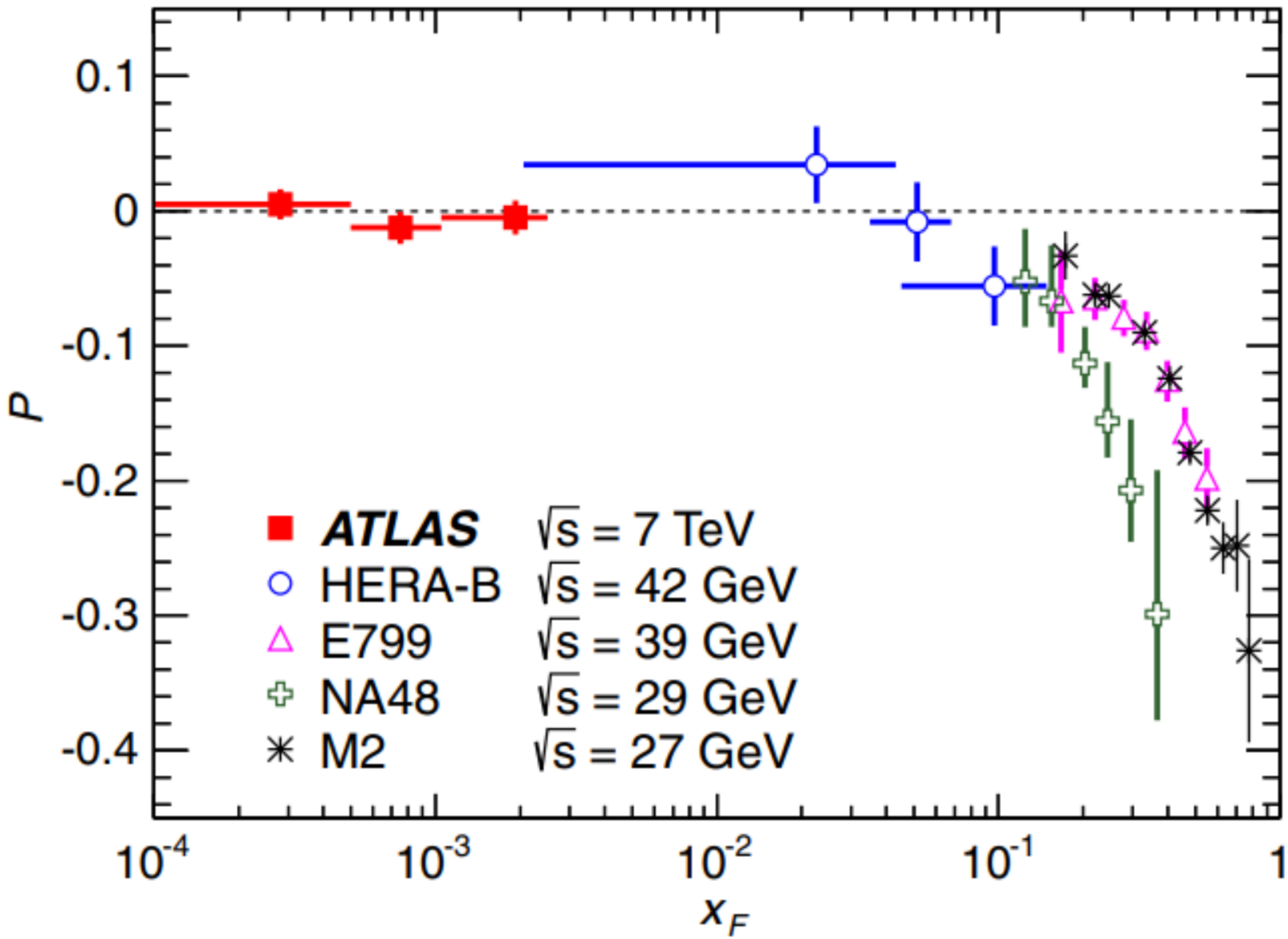


Average Λ ($\bar{\Lambda}$) polarization in collisions...



STAR coll., Nature (2017)

Where α_{-} matters (4):
Λ ($\bar{\Lambda}$) Transverse polarization with ATLAS



ATLAS coll., PRD (2015)

Definition of Fierz value and its distribution

- **Define random variables:**

$\mathcal{N}[\mu, \sigma^2]$ **from CLAS measurements**

$$\mathcal{F}_i^{(1)} = a^2 l^2 \left(\mathcal{O}_{x,i}^2 + \mathcal{O}_{z,i}^2 - \mathcal{T}_i^2 \right) + a^2 c^2 \left(\mathcal{C}_{x,i}^2 + \mathcal{C}_{z,i}^2 \right) + l^2 \Sigma_i^2 + a^2 \mathcal{P}_i^2$$

…similarly for second F.I.

- ***FV, a, l, c* become random variables, but:**

A. *Scaling:*
- *Data and errors are scaled with a, l, c*
- *Normalization of* $PDF[\, a^2 \mathcal{P}_i^2 \,]$

d'Agostini (1994)

B. *Most "observables" and scale parameters enter quadratically*

& Is there a closed form of $PDF[\, \mathcal{F}_i \,]$ *?*

Roe (2015)

Statistical challenges (1)

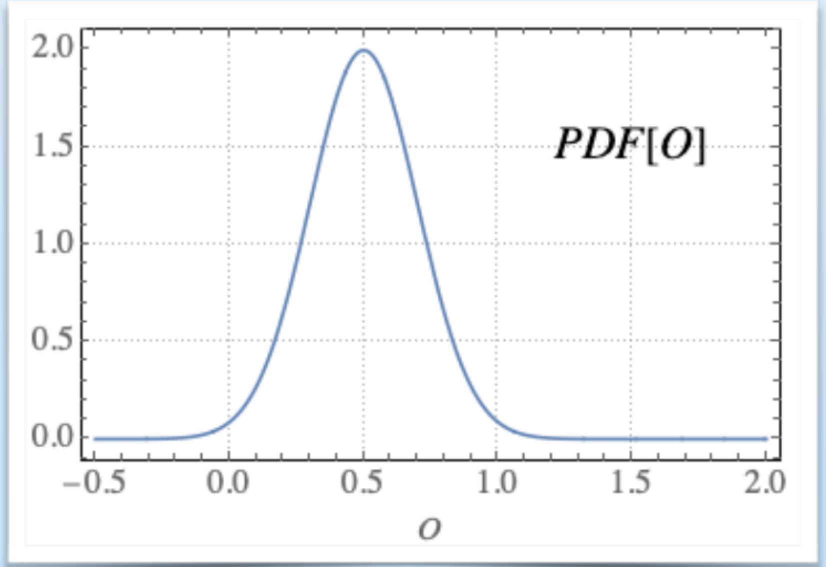
A. Scaling

Imagine linear case: $\mathscr{F} := a\,\mathscr{O} = 1$ $\qquad \mathscr{O} = \mathscr{N}[\mu, \sigma^2]$

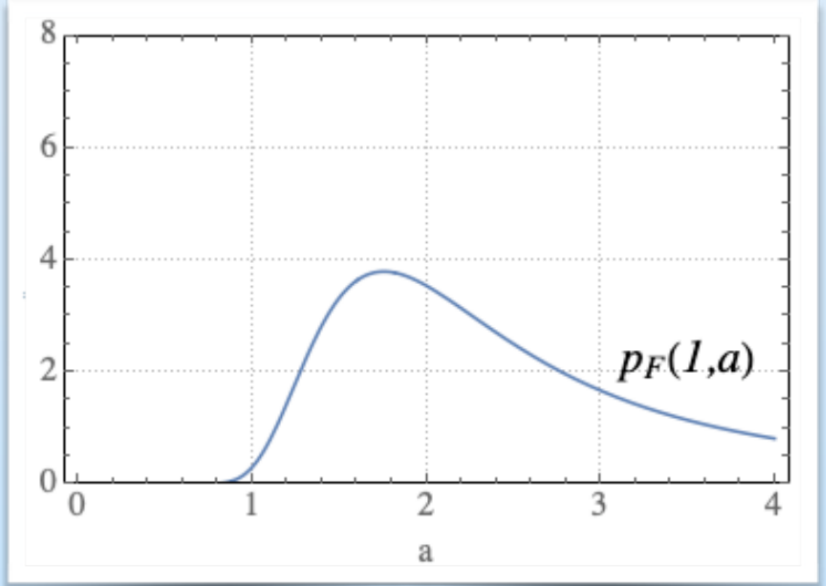
$$p_{\mathscr{F}}(f, a) = \int dO\, p(O)\delta(aO - f)$$

$$p_{\mathscr{F}}(1,a) = \frac{1}{a\sqrt{2\pi\mu\sigma}} e^{-\frac{(1-a\mu)^2}{2\,(a\sigma)^2}}$$ *conditional probability*

PDF of O suggests a=2



PDF of $\mathscr{F}$ peaks at a<2



$\Longrightarrow$ *remove a-dependence from the normalization*

Statistical challenges (1)

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conditional probability

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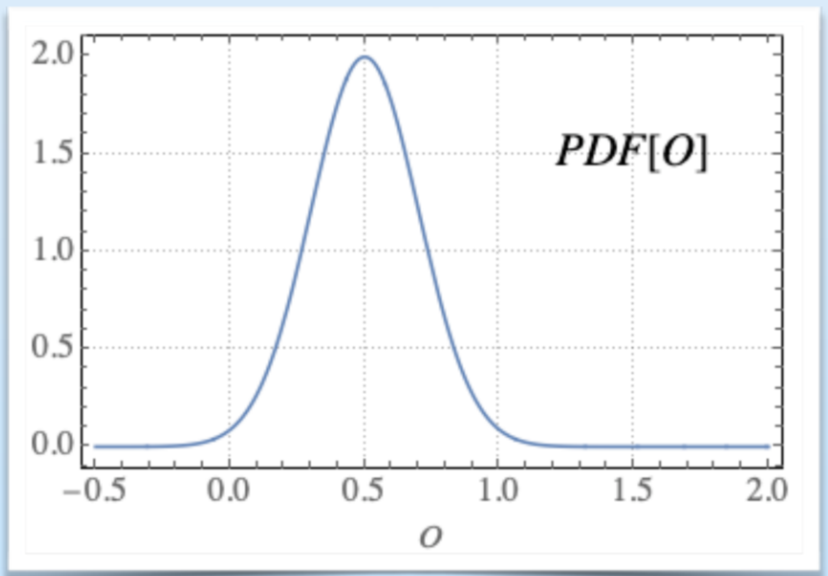

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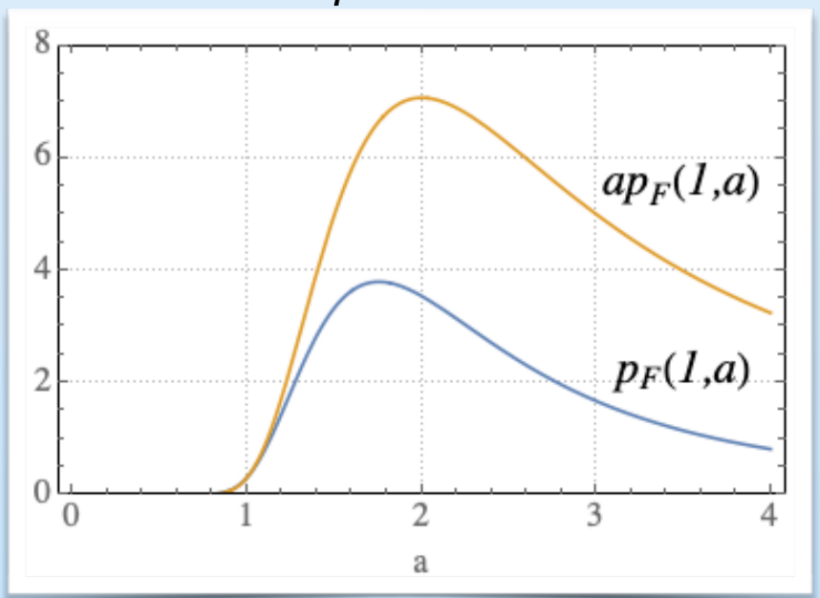


$\Longrightarrow$ *remove a-dependence from the normalization*

Statistical challenges (2)

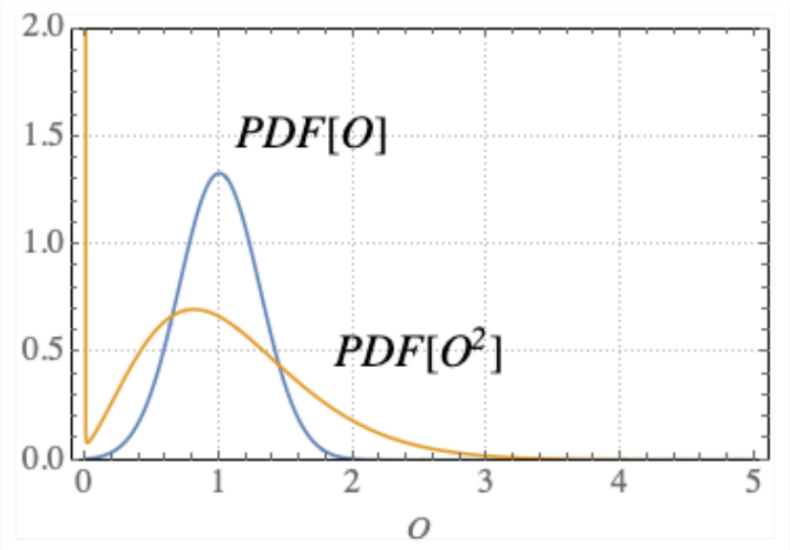
B. Non-linearity

$$\mathcal{O} \sim \mathcal{N}[\mu, \sigma^2] \implies \mathcal{Y} = \mathcal{O}^2 \sim NC_{\chi^2}$$

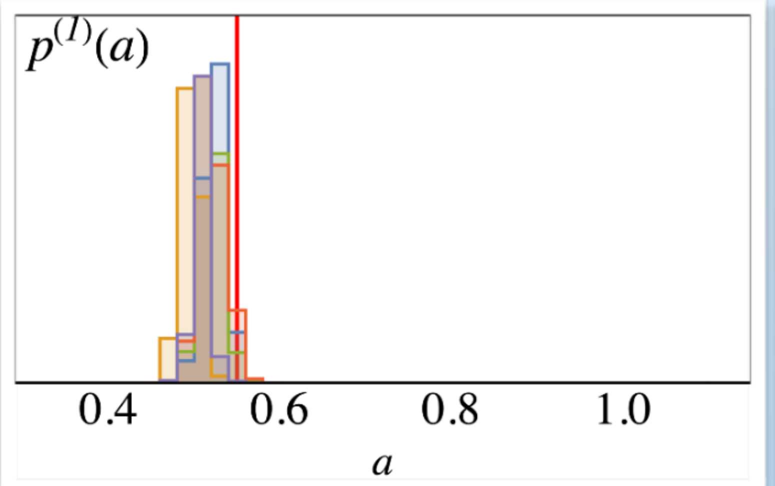
non-central chi squared distribution

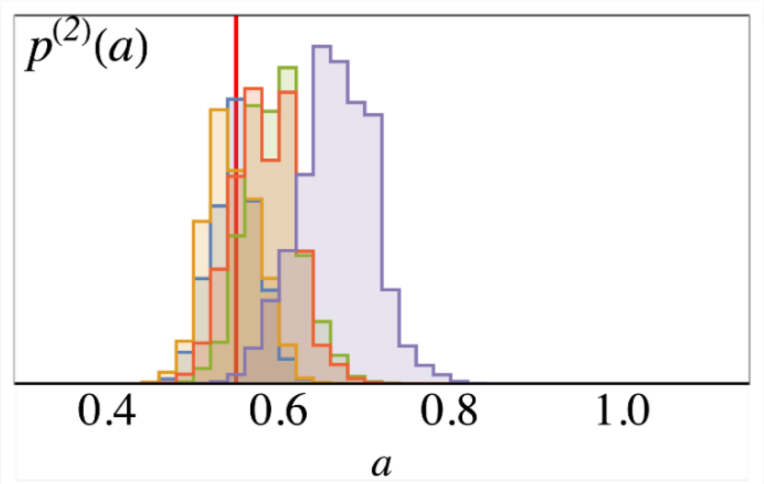
$$\mu_{\mathcal{Y}} = \mu_{\mathcal{O}}^2 + \sigma_{\mathcal{O}}^2, \quad \sigma_{\mathcal{Y}}^2 = 2\sigma_{\mathcal{O}}^2(2\mu_{\mathcal{O}}^2 + \sigma_{\mathcal{O}}^2)$$

$\implies$ *Expectation value of Fierz identity ≠ 1*



Ultimately— blind test on synthetic data





re-sampling test of both Fierz identities:

- *300 kin. points*
- *200 000 samples*
- ***a_{test} = 0.55***