

An abstract background featuring a dark blue field with numerous overlapping circles and lines in yellow, green, red, and white. The circles vary in size and opacity, creating a layered effect. The lines are thin and crisscross the entire area, some forming concentric circles.

Exotic Matter in the Spotlight

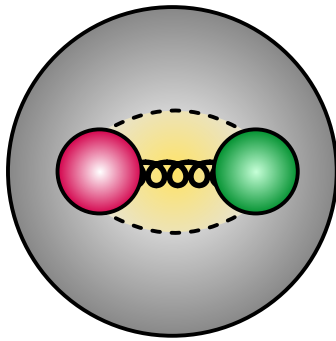
Meike Küßner

School of Computing, Data Sciences and Physics – College of William & Mary

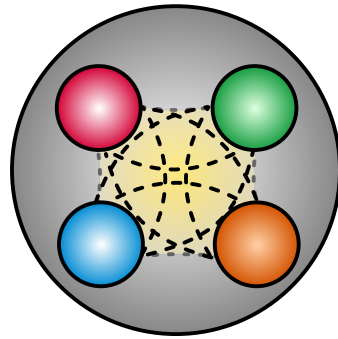
18th of June 2026

WILLIAM & MARY

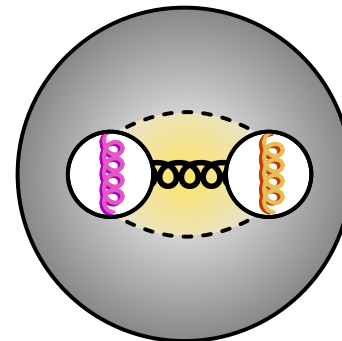
What is Exotic Matter?



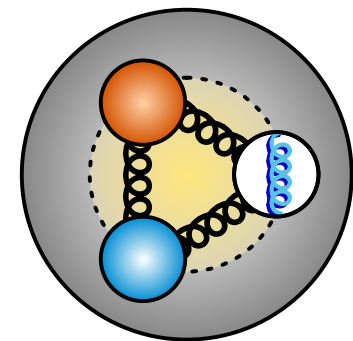
Meson



Tetraquark



Glueball



Hybrid

At least there are some characteristics that help to identify them:

- For a fermion-antifermion system not all quantum numbers can be formed

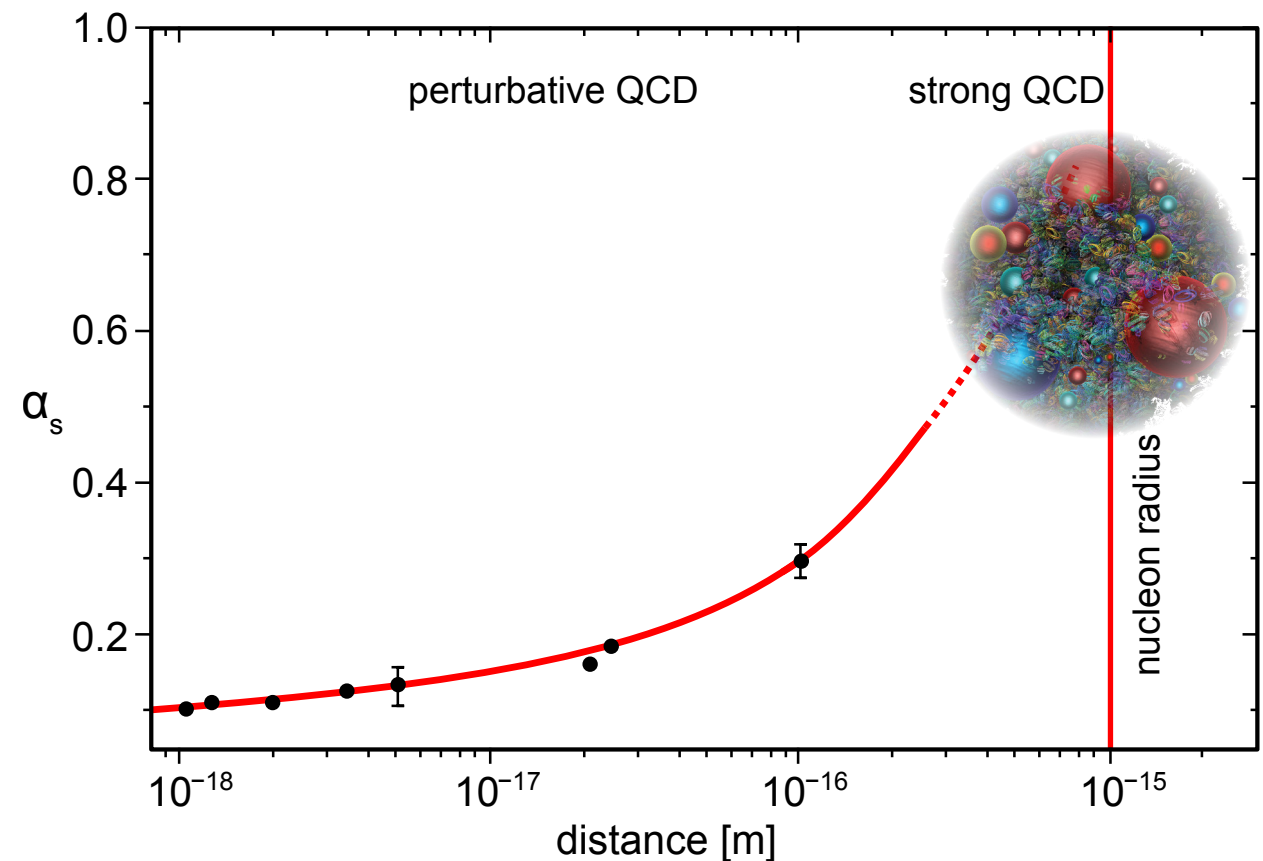
$$P = (-1)^{L+1}, C = (-1)^{L+S}$$

- Exotic quantum numbers: $J^{PC} = 0^{+-}, 0^{-+}, 1^{-+}, 2^{+-}, \dots$
 - States with exotic quantum numbers have indeed been found!
 - Other states show odd behavior and cannot be clearly classified (exotics?)
- ➡ Measure their resonance properties and occurrence in different production- and decay reactions

Open Questions of QCD

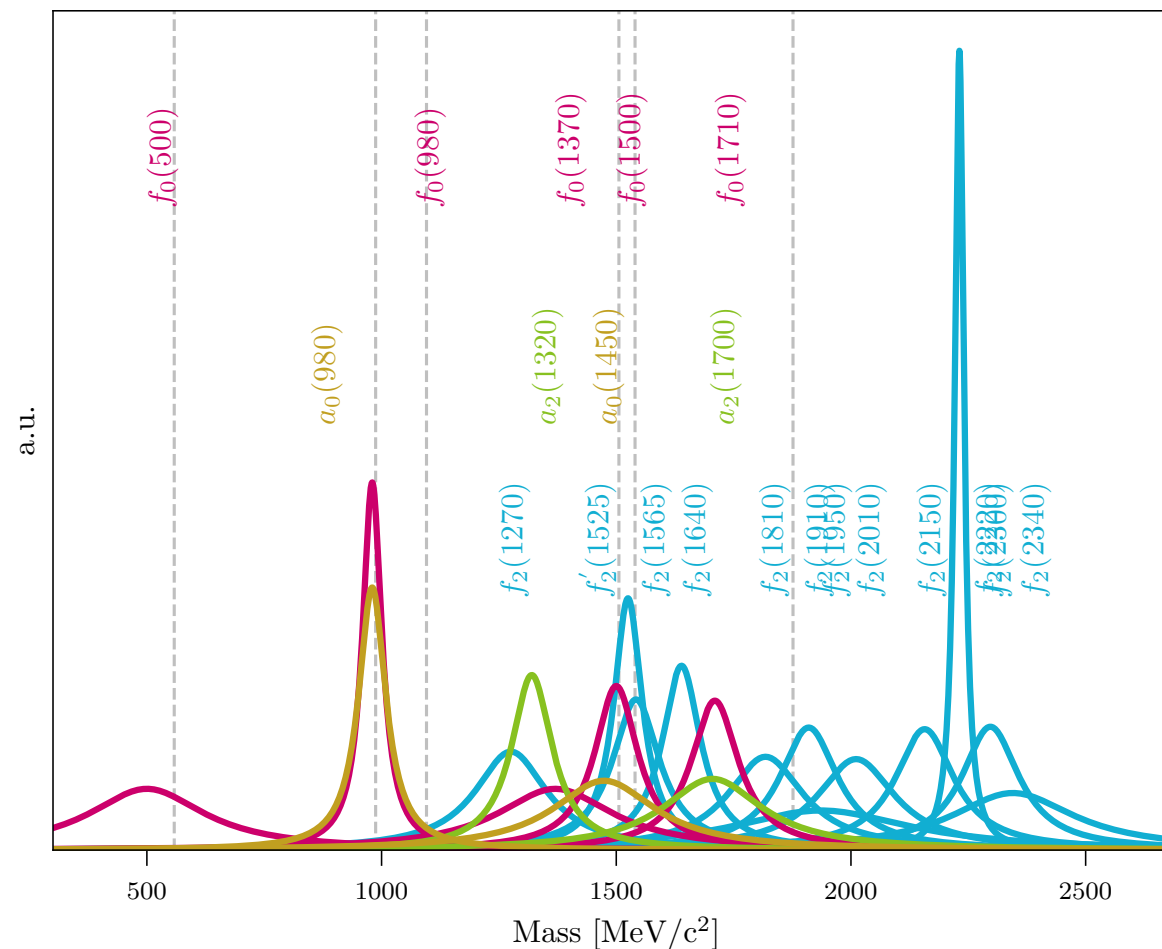
At a closer look, hadrons show a very complex inner structure!

- $\alpha_s \sim 1$, therefore processes are not suppressed anymore
- QCD becomes non-perturbative
- Theoretically very challenging since perturbative techniques fail
- Effective field theories are often model dependent and lattice calculations computational expensive



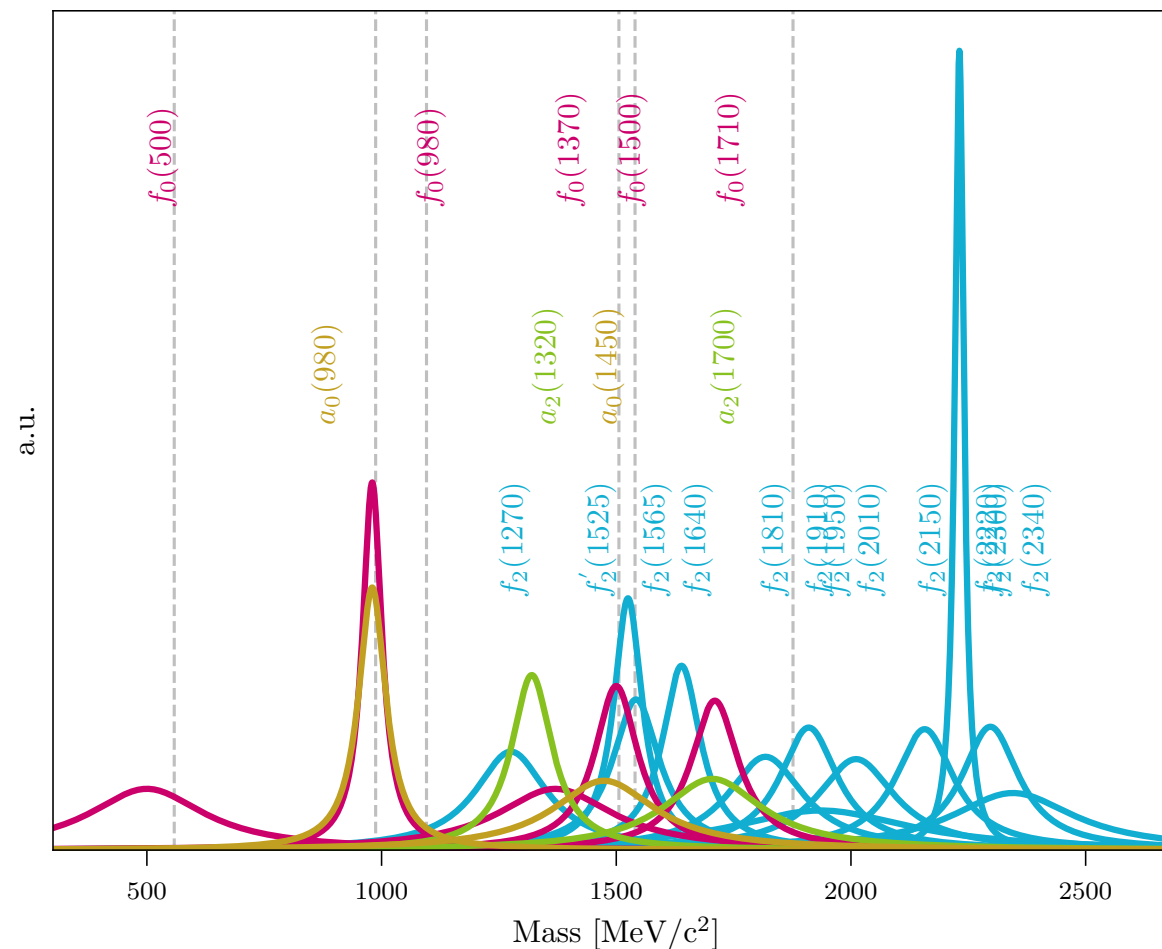
Hadron Spectroscopy

- Spectra are extremely populated due to several broad, interfering resonances
- Analyzing a single channel is not enough to disentangle the interference unambiguously
- More sophisticated tools and descriptions needed!
- Resonances not always look like peaks ↔ Peaks not necessarily caused by a resonance



Hadron Spectroscopy

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We should start thinking beyond experimental collaborations!

„Multi-Messenger“ Hadron Spectroscopy

- Compare different production mechanisms and decay channels to reveal a particle's nature and its inner structure
- Hadrons contain besides quarks and antiquarks also gluons!

Gluon rich processes

- Radiative charmonium decays
- $\bar{p}p$ annihilation
- pp collisions/central production
- ...

QED mediated processes

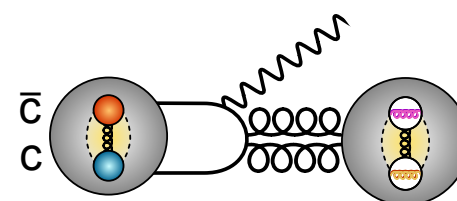
- Two-photon production

Weak decay processes

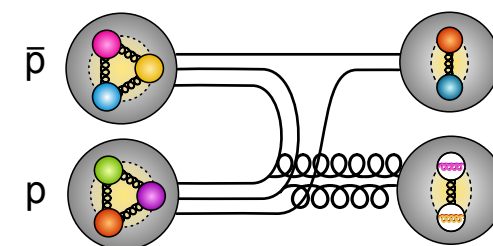
- B/D-meson decays



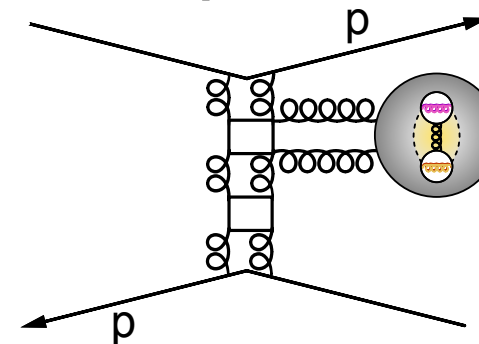
radiative J/ ψ decays



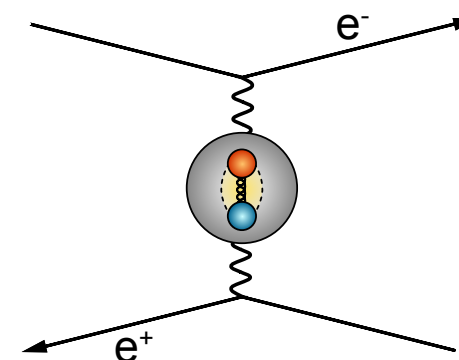
$\bar{p}p$ annihilation



central production

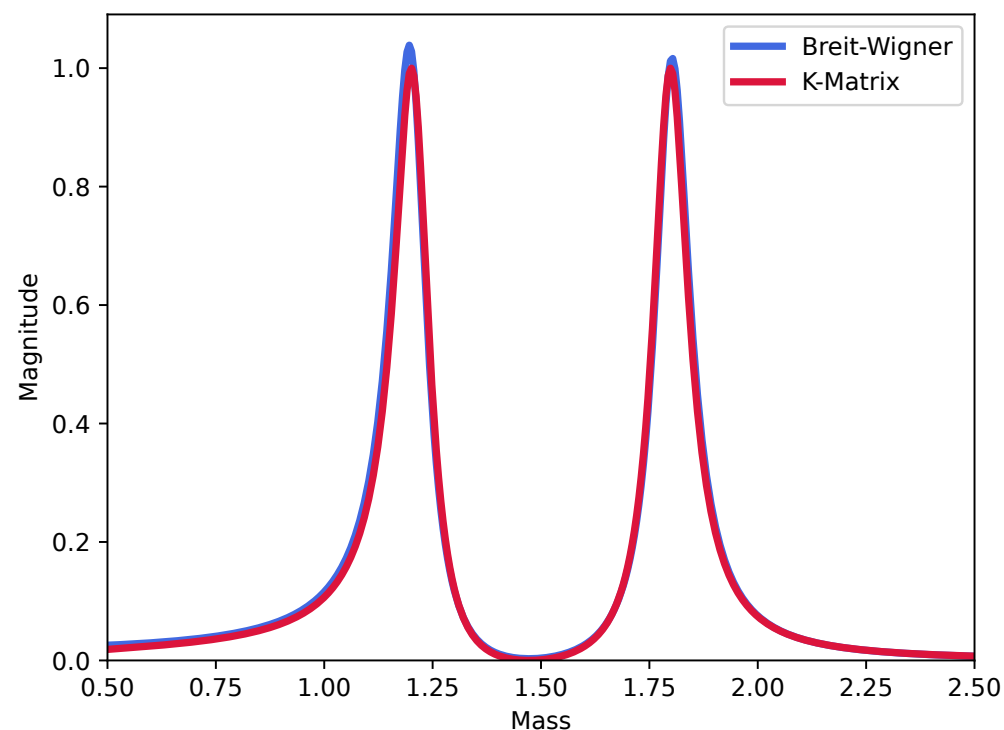


two-photon production

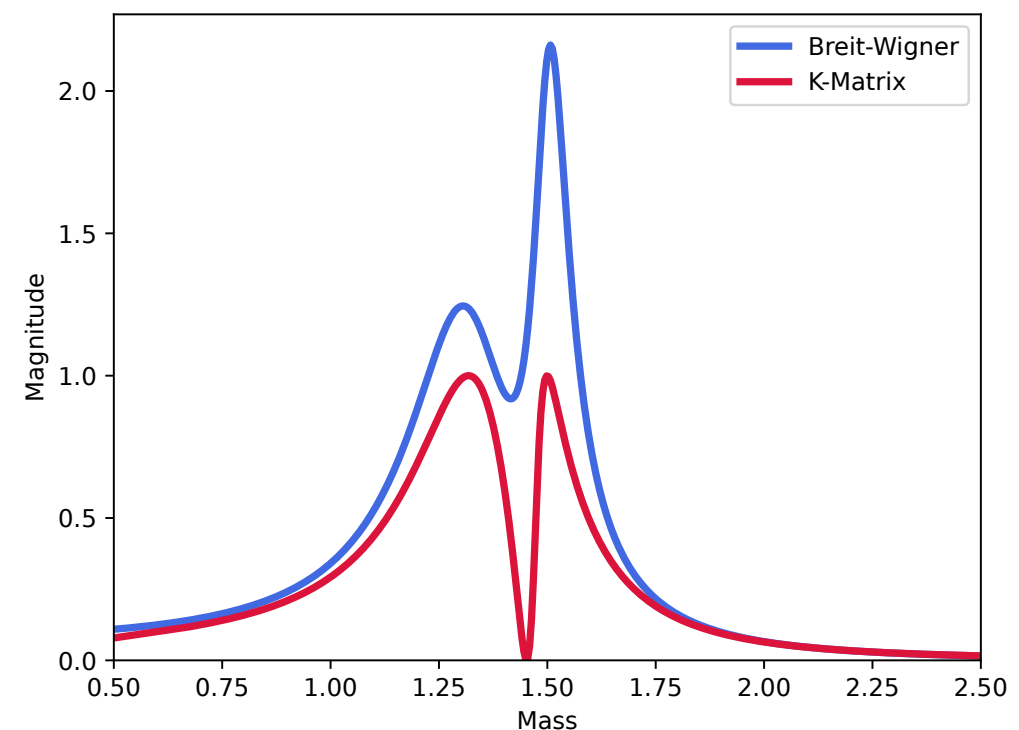


Resonance Description

- Breit-Wigner functions are widely used
 - But violate the unitarity
 - Extracted resonance parameters are not unique and depend on the production and decay process



$$M_1 = 1200 \text{ MeV}/c^2, \Gamma_1 = 100 \text{ MeV}$$
$$M_2 = 1800 \text{ MeV}/c^2, \Gamma_2 = 100 \text{ MeV}$$

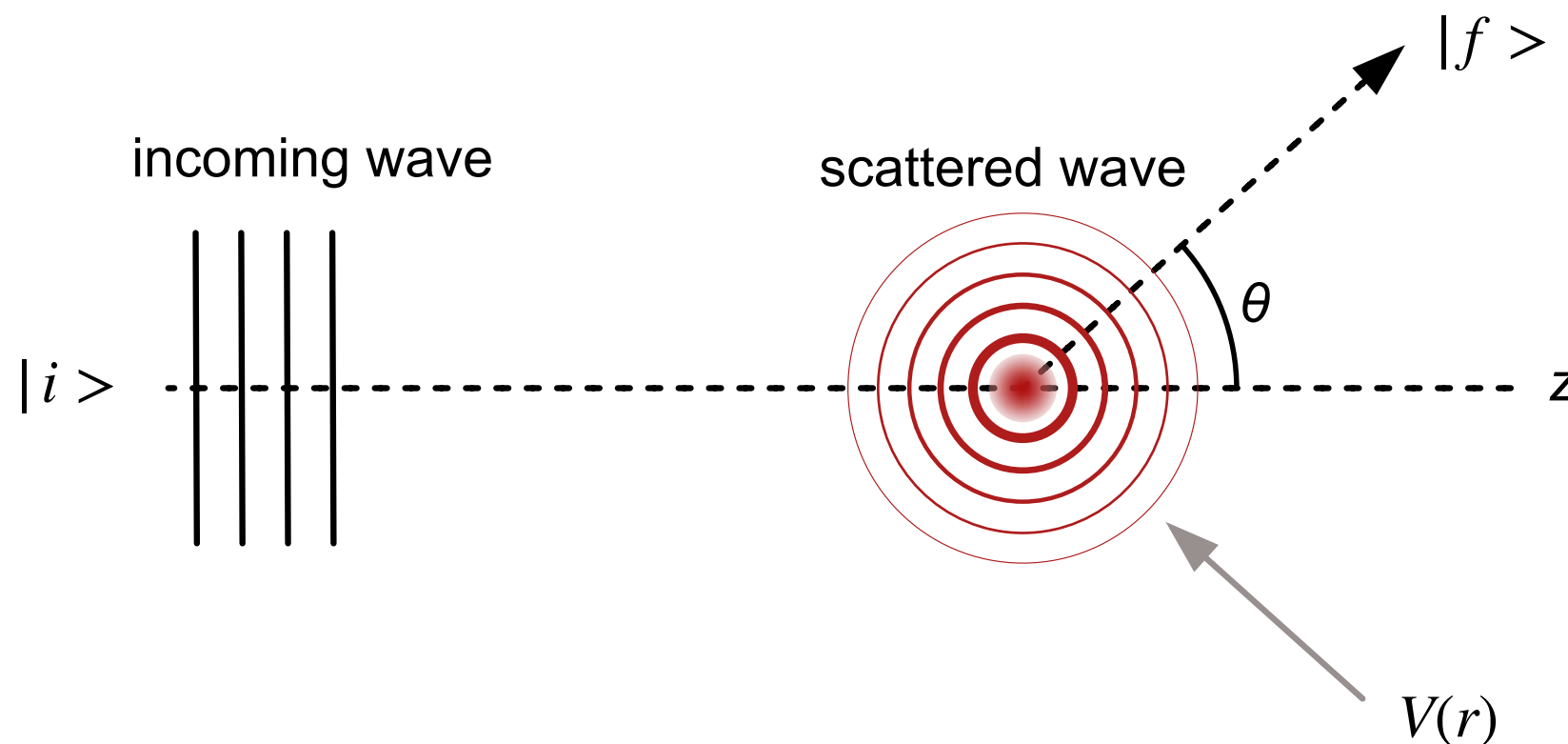


$$M_1 = 1300 \text{ MeV}/c^2, \Gamma_1 = 300 \text{ MeV}$$
$$M_2 = 1500 \text{ MeV}/c^2, \Gamma_2 = 100 \text{ MeV}$$

➡ More sophisticated descriptions needed e.g. K-Matrix, N/D-method, Two-Potential

K-Matrix Approach

- In scattering theory the S-matrix describes fully two body scattering



- The scattered wave $|f\rangle$ can be expanded in partial waves of angular momentum
- In general, the amplitude that an initial state $|i\rangle$ will be found in the final state $|f\rangle$ is given via the S-matrix $S_{fi} = \langle f | S | i \rangle$

K-Matrix Approach

- In scattering theory the S-matrix describes fully two body scattering
- With this we want to learn something about the potential and possible interactions with the incoming wave resulting in resonances
 - This way we can extract information on the amplitude level
 - But we can only access $\left| \langle f | S | i \rangle \right|^2$ experimentally...
 - This means we can only access relative phases
- The scattered wave $|f\rangle$ can be expanded in partial waves of angular momentum
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K-Matrix Approach

- In scattering theory the S-matrix describes fully two body scattering

$$S = I + 2i\sqrt{\rho}T\sqrt{\rho}$$

ρ : phase space factor

- T-matrix can be elegantly expressed by the K-matrix

$$T = (I + iKC)^{-1} K$$

C : Chew-Mandelstam function
guarantees analyticity

$$\rho(s) = -\text{Im}(C(s))$$

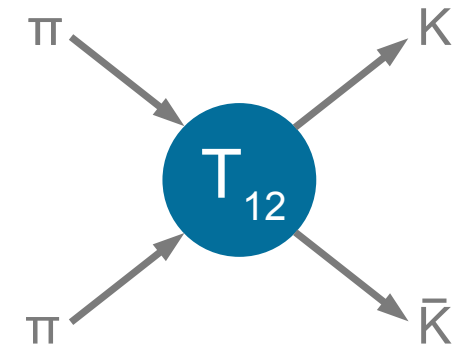
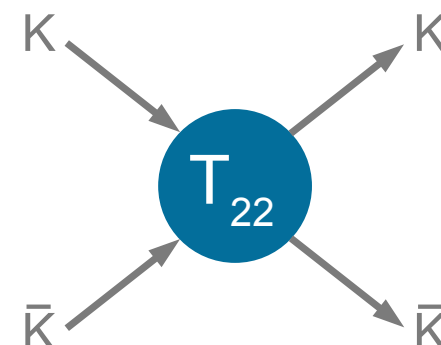
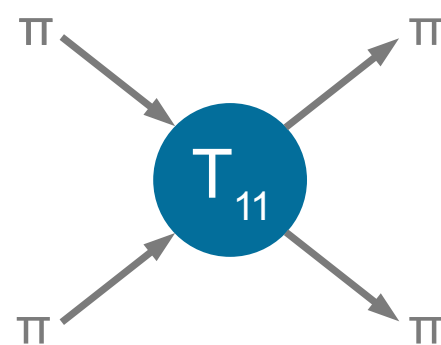
- K-matrix contains singularities $\Rightarrow$ poles and possibly background terms

$$K_{ij} = \sum_{\alpha} \frac{g_{\alpha i} g_{\alpha j}}{m_{\alpha}^2 - s} + \sum_k c_{kij} s^k$$

$g_{\alpha i}$: decay coupling
 m_{α} : pole bare mass

- The elements of the matrices also express interactions between different channels
Example: 1. channel: $\pi\pi$, 2. channel: $K\bar{K}$

$$T = \begin{pmatrix} T_{11} & T_{12} \\ T_{12} & T_{22} \end{pmatrix}$$



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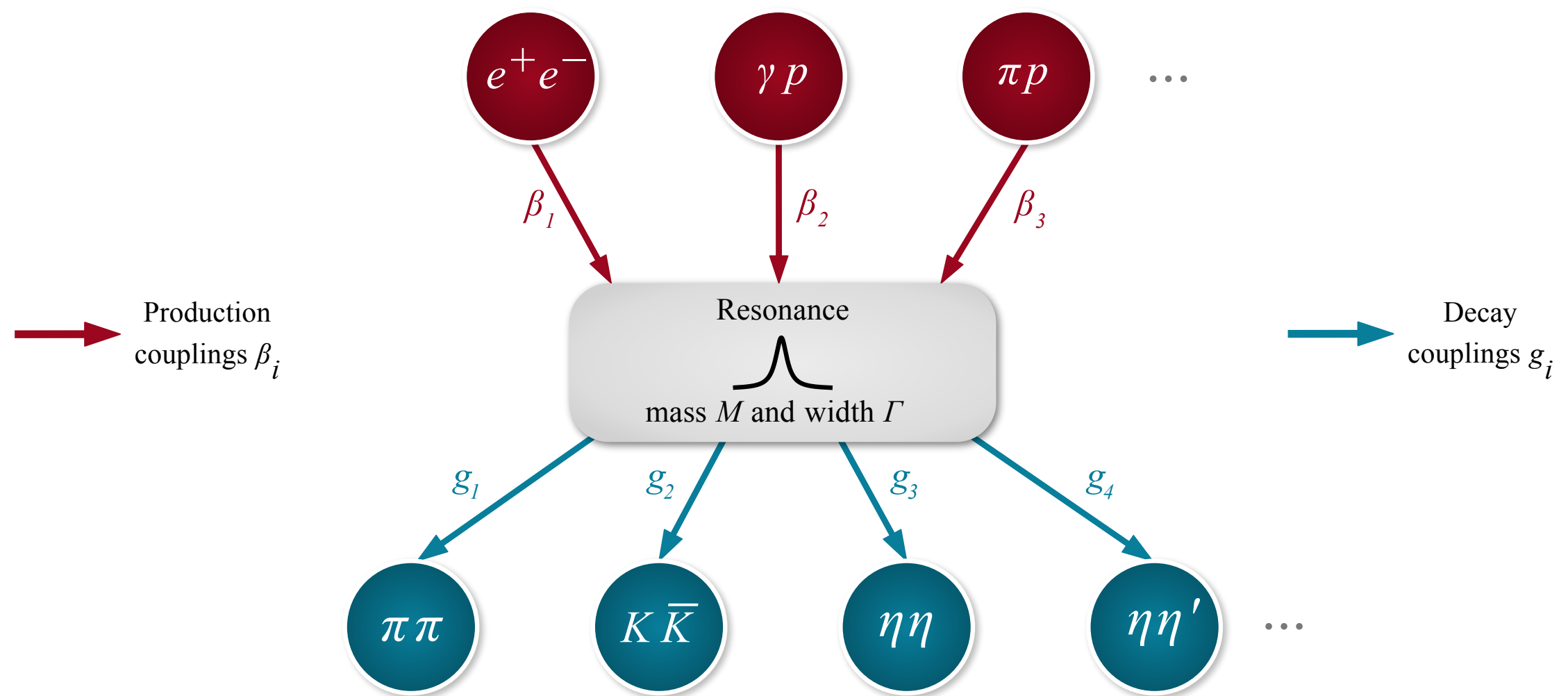
- In case of more complex production processes $\Rightarrow$ extension to so-called P-vector approach

$$F = (I + iKC)^{-1}P, \quad P_i = \sum_{\alpha} \frac{\beta_{\alpha} g_{\alpha_i}}{m_{\alpha}^2 - s} + \sum_k c_{ki} s^k$$

β_{α} : production coupling, in general complex

Coupled Channel Approach

Compare different production mechanism and decay channels to learn about the inner structure of particles



Many parameters can be shared and thus better determined

Better conservation of unitarity and description of threshold effects

Bringing all the pieces of the puzzle together

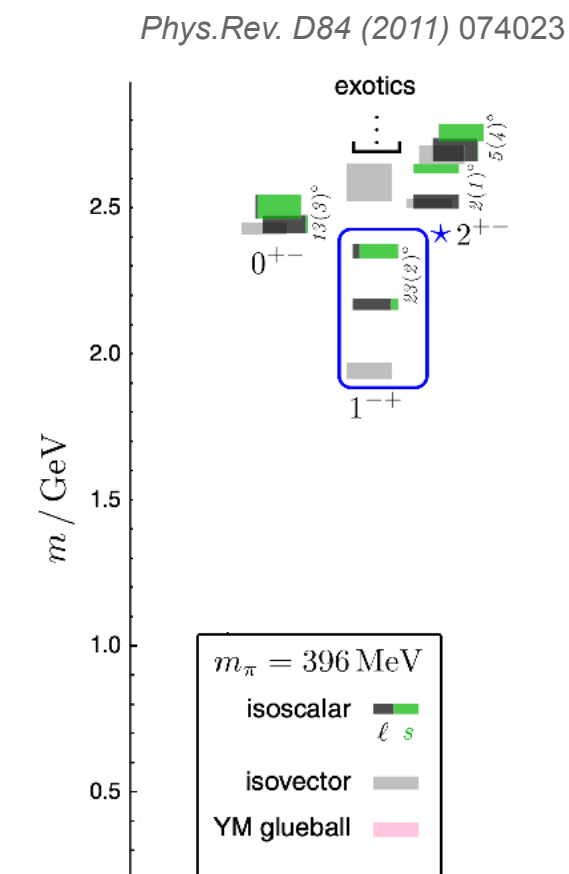
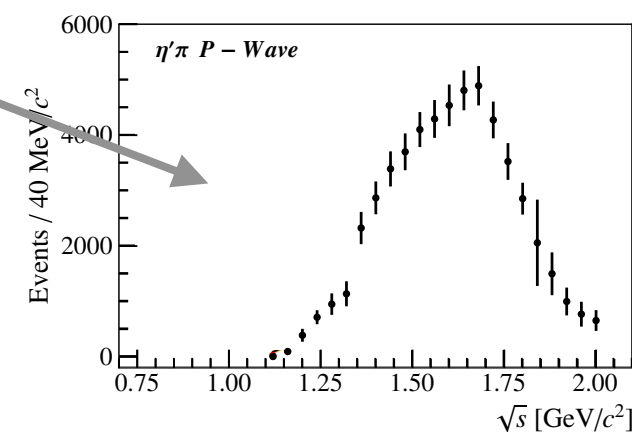
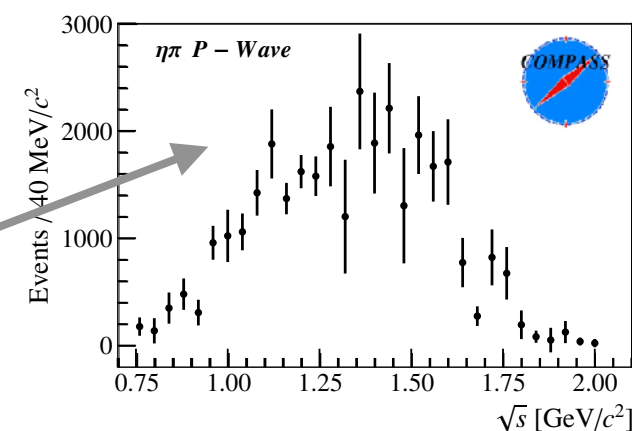


One Prominent Example: The Lightest Hybrid Candidate

Two π_1 hybrid candidates below 2 GeV are listed in PDG

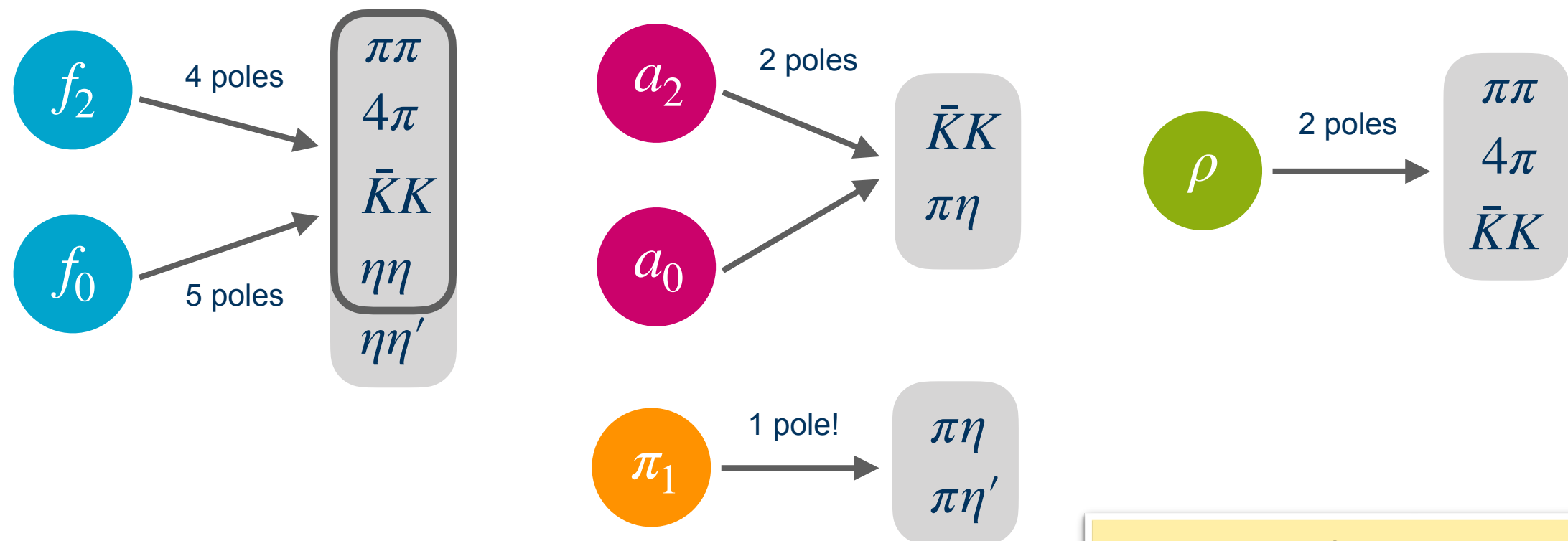
- one at around 1.4 GeV only seen in $\pi\eta$
 - the other at around 1.6 GeV seen in $\pi\eta'$ but not in $\pi\eta$
- ➡ Parameters obtained by Breit-Wigner fits!
- ➡ Theory: Only one π_1 state predicted slightly below 2 GeV

200 MeV apart!



Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$

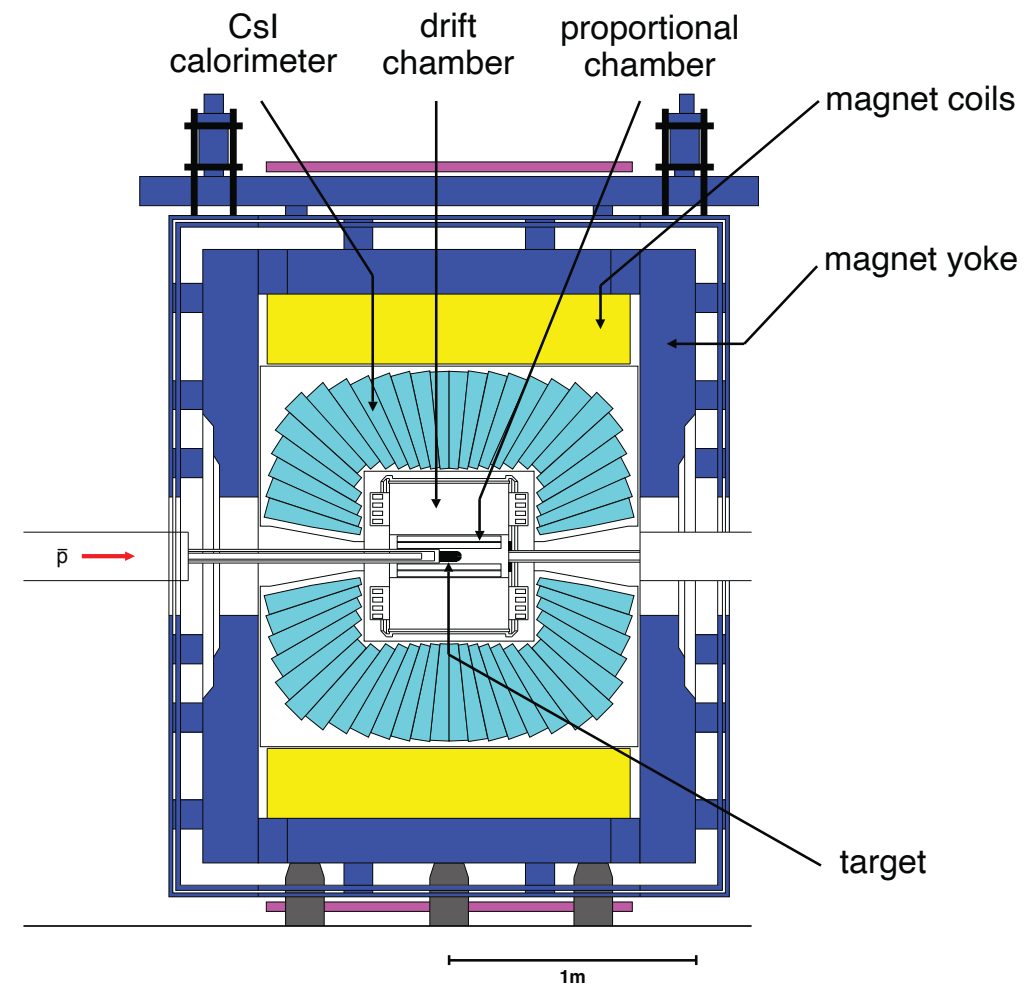
- Combining data from different experiments:
- $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$ data in flight from Crystal Barrel at LEAR
- COMPASS data of P- and D-waves in the $\pi\eta$ and $\pi\eta'$ systems
- 11 different $\pi\pi$ scattering data samples
- Simultaneously described using the K-Matrix formalism in the P-vector approach
- The whole process from the initial to the final state is described in all phase space dimensions



Eur. Phys. J. C (2021) 81, 1056

Crystal Barrel at LEAR

- Crystal Barrel was in operation from 1989 - 1996
 - Fixed target experiment at LEAR
 - $\bar{p}p$ annihilation at rest and in flight → fundamental studies in the light meson sector!
 - Highest beam momentum 1.94 GeV/c (overlap with $\bar{P}$ ANDA 1.5-15 GeV/c)

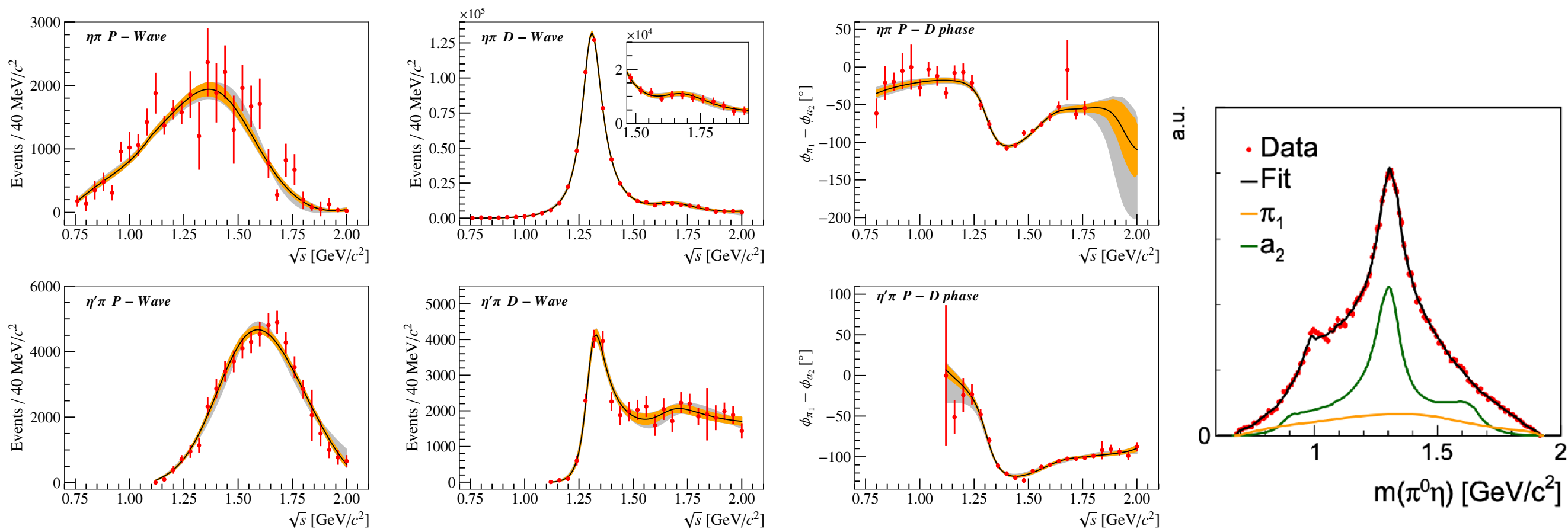


$\bar{P}$ ANDA will have a 100 times higher luminosity!
→ 1 year data taking becomes 3.5 days!

Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$, COMPASS and scattering data

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- Exotic π_1 wave significantly contributing in the $\pi^0 \eta$ system!
- Description with one pole possible!
- ➔ Confirmation of the JPAC analysis based on N/D-method *Phys. Rev. Lett.* 122 (2019) 4, 042002

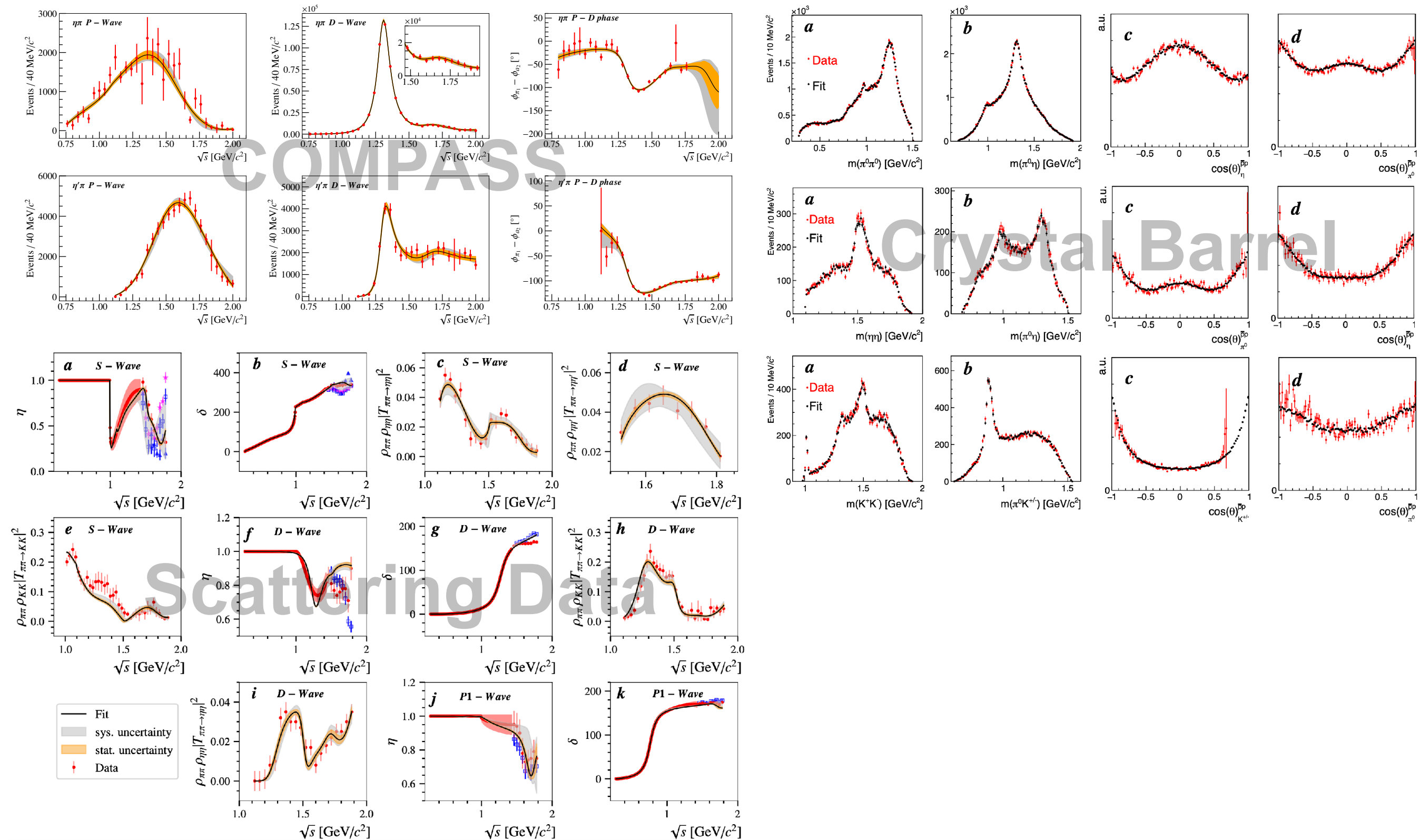


Obtained pole position:

$$M = 1623 \pm 47^{+24}_{-75} \text{ MeV}/c^2$$

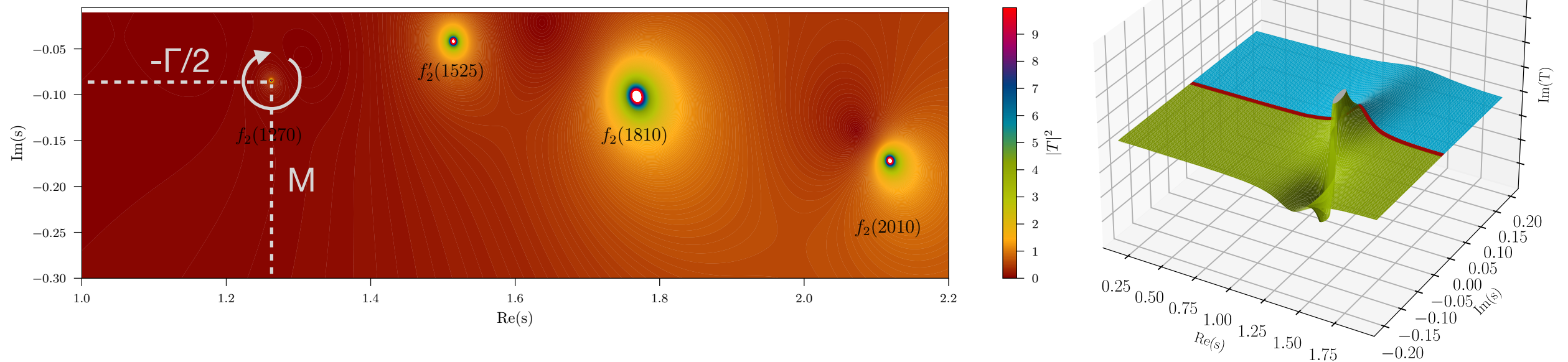
$$\Gamma = 455 \pm 88^{+144}_{-175} \text{ MeV}$$

Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$, COMPASS and scattering data



Extraction of Resonance Properties

Example: f_2 -wave



- K-matrix and thus the pole itself contain all resonance properties
- Masses and widths defined by the pole position in the complex energy plane of the T-matrix sheet closest to the physical sheet

$$\text{Res}_{k \rightarrow k}^\alpha = \frac{1}{2\pi i} \oint_{C_{z\alpha}} \sqrt{\rho_k} \cdot T_{k \rightarrow k}(z) \cdot \sqrt{\rho_k} \, dz$$

Coupled Channel Analysis of $\bar{p}p$ and COMPASS Data

name	relevant data	Breit-Wigner mass [MeV/ c^2]	Breit-Wigner width Γ [MeV]
$K^*(892)^\pm$	$\bar{p}p$	$893.8 \pm 1.0 \pm 0.8$	$56.3 \pm 2.0 \pm 1.0$
$\phi(1020)$	$\bar{p}p$	$1018.4 \pm 0.5 \pm 0.2$	4.2 (fixed)

name	relevant data	pole mass [MeV/ c^2]	pole width Γ [MeV]
$f_0(980)^{----++}$	scat	$977.8 \pm 0.6 \pm 1.4$	$98.8 \pm 6.6 \pm 11.2$
$f_0(980)^{--++}$	scat	$992.6 \pm 0.3 \pm 0.5$	$61.2 \pm 1.2 \pm 1.7$
$f_0(1370)$	scat	$1281 \pm 11 \pm 26$	$410 \pm 12 \pm 50$
$f_0(1500)$	$\bar{p}p + \text{scat}$	$1511.0 \pm 8.5^{+3.5}_{-14.0}$	$81.1 \pm 4.5^{+26.9}_{-0.5}$
$f_0(1710)$	$\bar{p}p + \text{scat}$	$1794.3 \pm 6.1^{+47.0}_{-61.2}$	$281 \pm 32^{+12}_{-80}$
$f_2(1810)$	scat	$1769 \pm 26^{+3}_{-26}$	$201 \pm 57^{+13}_{-87}$
$f_2(X)$	scat	$2119.9 \pm 6.4^{+25.7}_{-1.1}$	$343 \pm 11^{+32}_{-11}$

name	relevant data	pole mass [MeV/ c^2]	pole width Γ [MeV]	$\Gamma_{\pi\eta'}/\Gamma_{\pi\eta}$ [%]
π_1	$\bar{p}p + \pi p$	$1623 \pm 47^{+24}_{-75}$	$455 \pm 88^{+144}_{-175}$	$554 \pm 110^{+180}_{-27}$

name	relevant data	pole mass [MeV/ c^2]	pole width Γ [MeV]	$\Gamma_{KK}/\Gamma_{\pi\eta}$ [%]
$a_0(980)^{--}$	$\bar{p}p$	$1002.7 \pm 8.8 \pm 4.2$	$132 \pm 11 \pm 8$	$14.8 \pm 7.1 \pm 3.6$
$a_0(980)^{+-}$	$\bar{p}p$	$1003.3 \pm 8.0 \pm 3.7$	$101.1 \pm 7.2 \pm 3.0$	$13.5 \pm 6.2 \pm 3.1$
$a_0(1450)$	$\bar{p}p$	$1303.0 \pm 3.8 \pm 1.9$	$109.0 \pm 5.0 \pm 2.9$	$396 \pm 72 \pm 72$

name	relevant data	pole mass [MeV/ c^2]	pole width Γ [MeV]	$\Gamma_{KK}/\Gamma_{\pi\eta}$ [%]
$a_2(1320)$	$\bar{p}p + \pi p$	$1318.7 \pm 1.9^{+1.3}_{-1.3}$	$107.5 \pm 4.6^{+3.3}_{-1.8}$	$31 \pm 22^{+9}_{-11}$
$a_2(1700)$	$\bar{p}p + \pi p$	$1686 \pm 22^{+19}_{-7}$	$412 \pm 75^{+64}_{-57}$	$2.9 \pm 4.0^{+1.1}_{-1.2}$

name	relevant data	pole mass [MeV/ c^2]	pole width Γ [MeV]	$\Gamma_{\pi\pi}/\Gamma$ [%]
$f_2(1270)$	$\bar{p}p + \text{scat}$	$1262.4 \pm 0.2^{+0.2}_{-0.3}$	$168.0 \pm 0.7^{+1.7}_{-0.1}$	$87.7 \pm 0.3^{+4.8}_{-4.4}$
$f_2'(1525)$	$\bar{p}p + \text{scat}$	$1514.7 \pm 5.2^{+0.3}_{-7.4}$	$82.3 \pm 5.2^{+11.6}_{-4.5}$	$2.1 \pm 0.3^{+0.8}_{-0.0}$
$\rho(1700)$	$\bar{p}p + \text{scat}$	$1700 \pm 27^{+13}_{-16}$	$181 \pm 25^{+0.0}_{-16}$	$13.6 \pm 1.2^{+0.9}_{-0.5}$

Several resonance properties measured simultaneously in one fit!
(Although running 2 weeks on 200 CPUs)

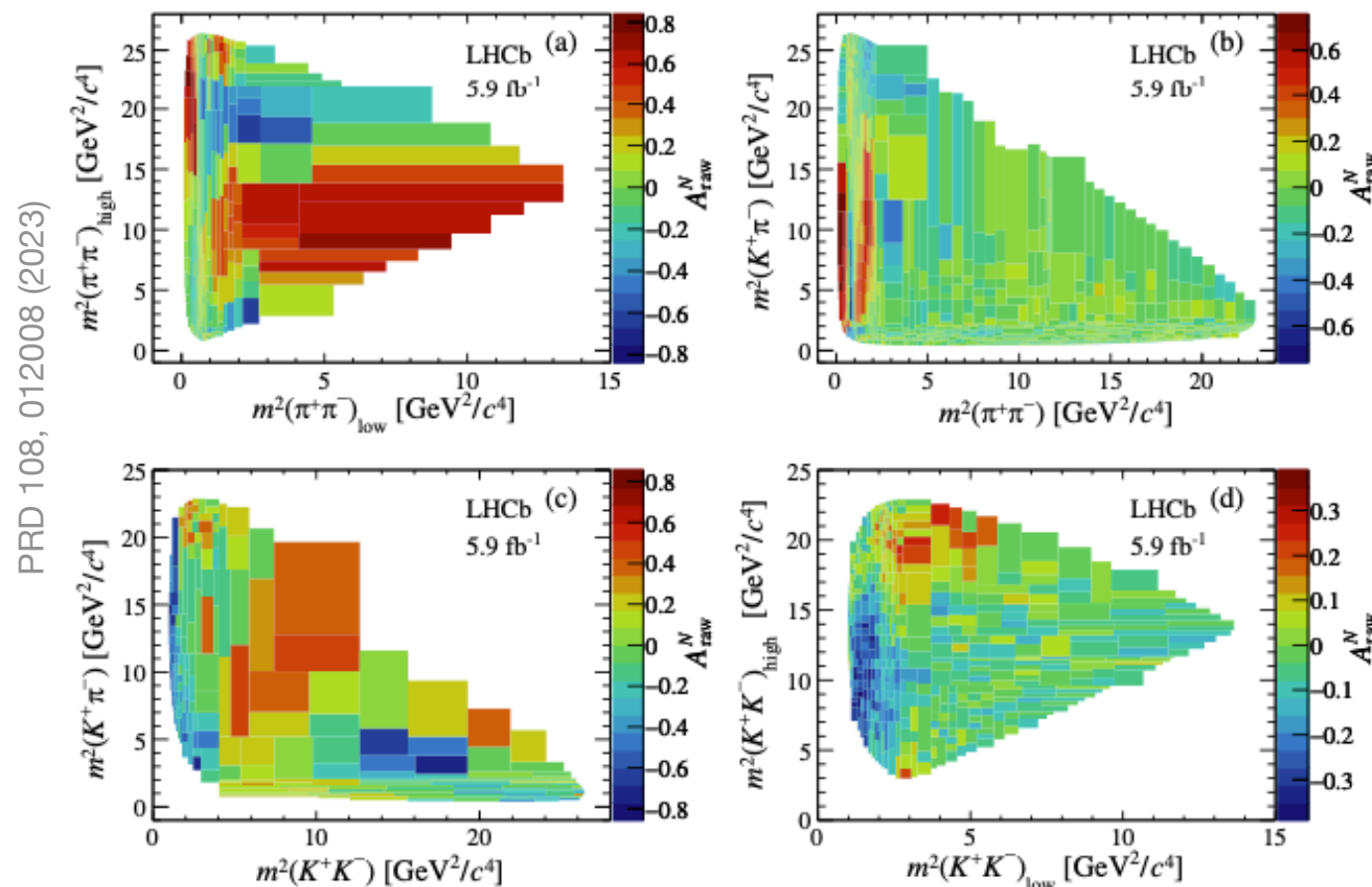
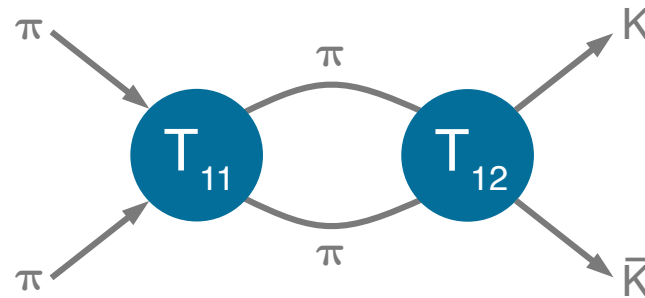
Such parameterizations are universal and can be used in other analyses!

But: Description used only data up to 2 GeV!

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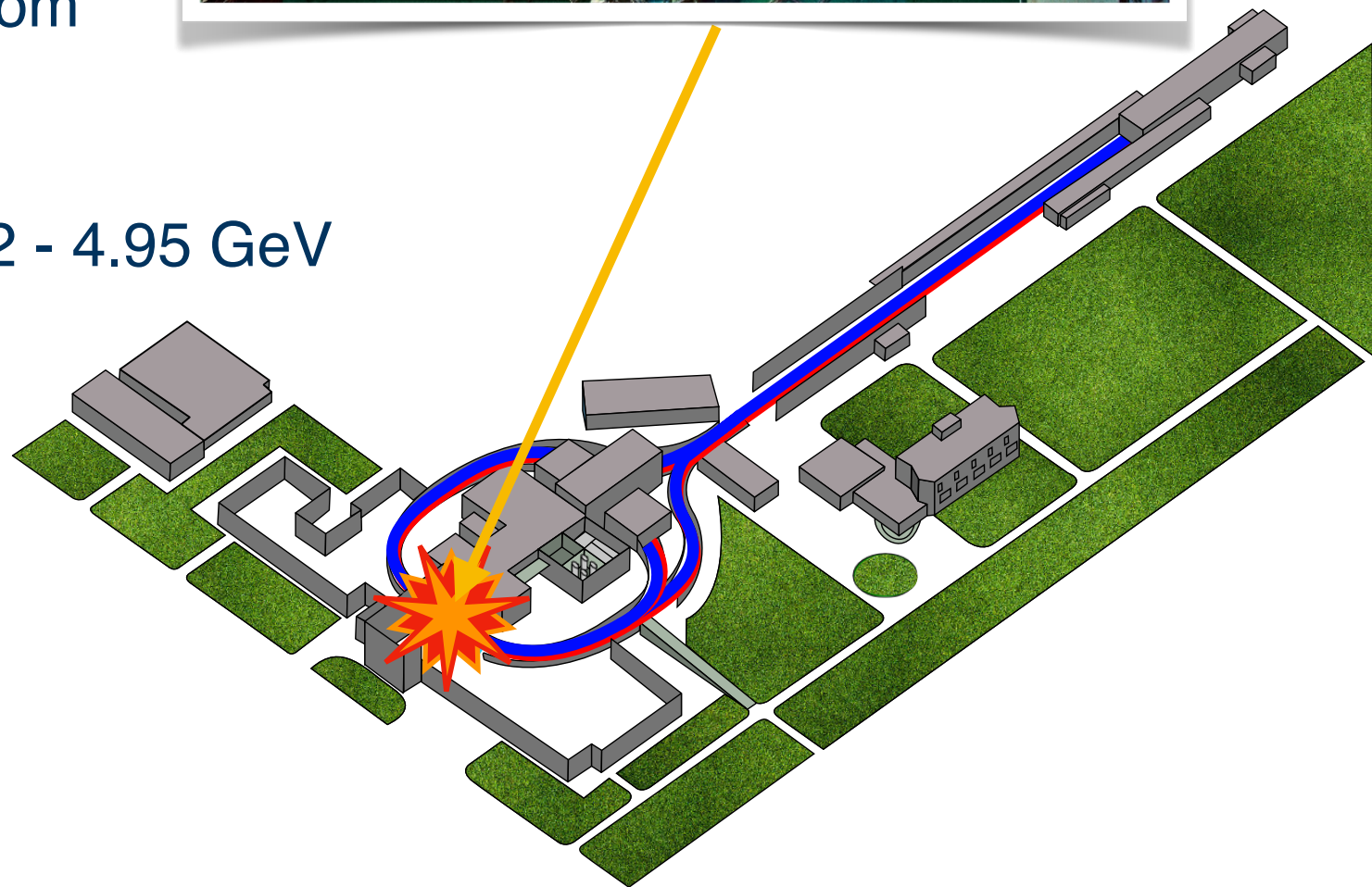
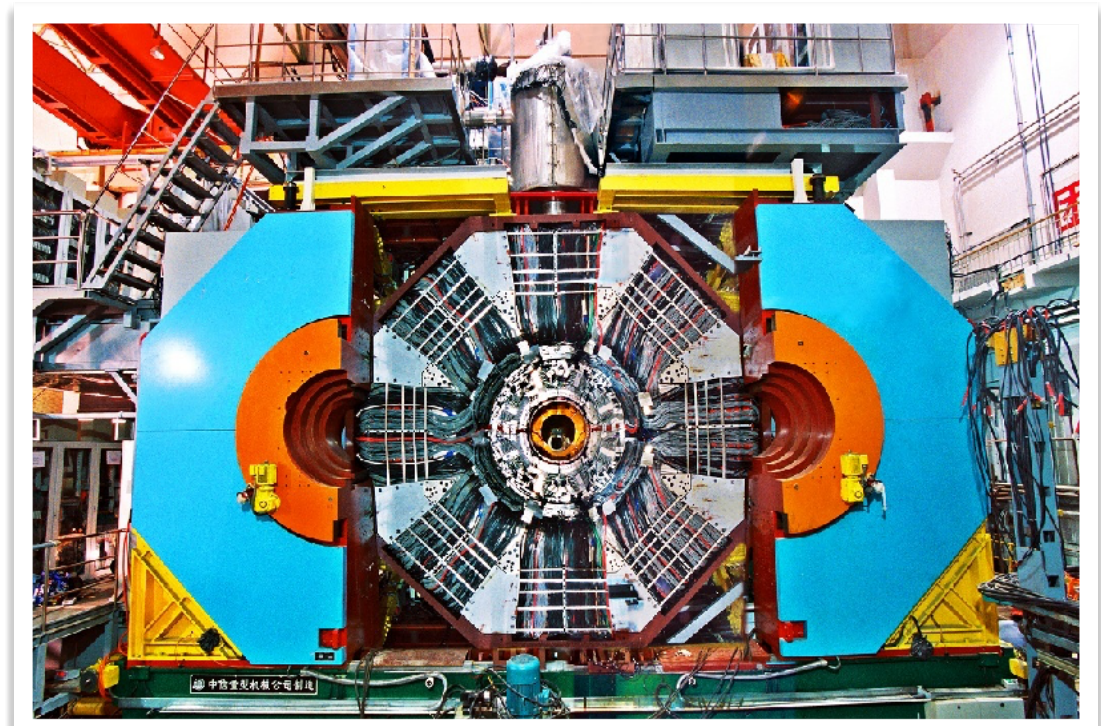
Input for CP Violation Studies?

- CP violation in $B \rightarrow 3h$ is very much depending on intermediate resonances
- Strong and weak phase CPV contributions need to be separated
- ➔ Mechanisms from strong interaction as final state interaction assumed to play a big role!

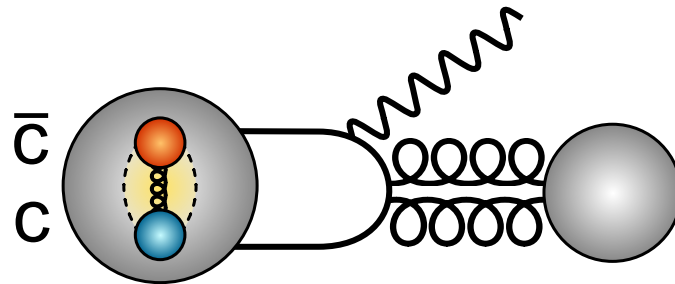
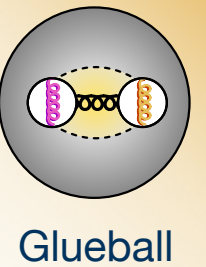


The BESIII Experiment

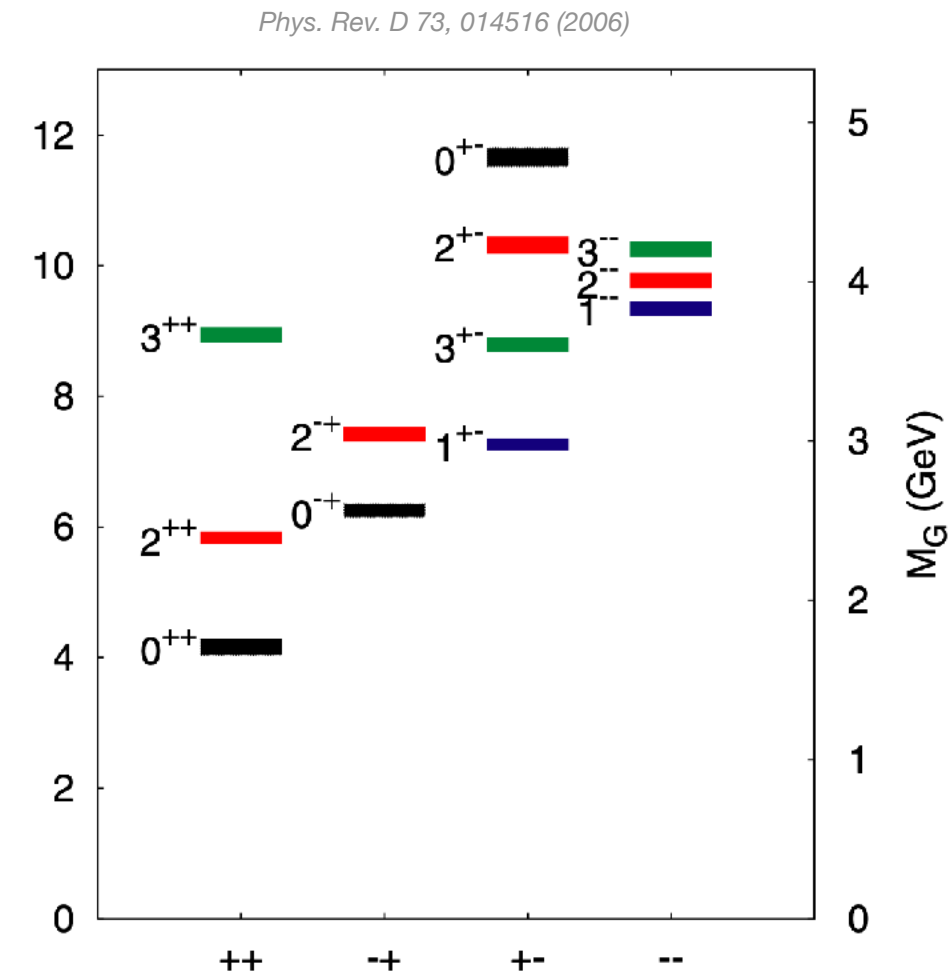
- Symmetric e^+e^- collider in Beijing
- In operation since 2009
- > 500 physicists from 70 institutes from 14 countries
- Beam energy: 1 - 2.3 GeV $\Rightarrow \sqrt{s} = 2 - 4.95$ GeV
- Several data samples with world leading statistics available



BESIII: Charmonium Decays



- Gluon-rich process → production of glueballs expected
- Lightest glueball 0^{++} is predicted below $2 \text{ GeV}/c^2$
- Observed states $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ likely to be mixtures of pure glueball and quark component
- BESIII has accumulated very high statistics at J/ψ , ψ' , ...
 - 50 times more than 10 years ago!

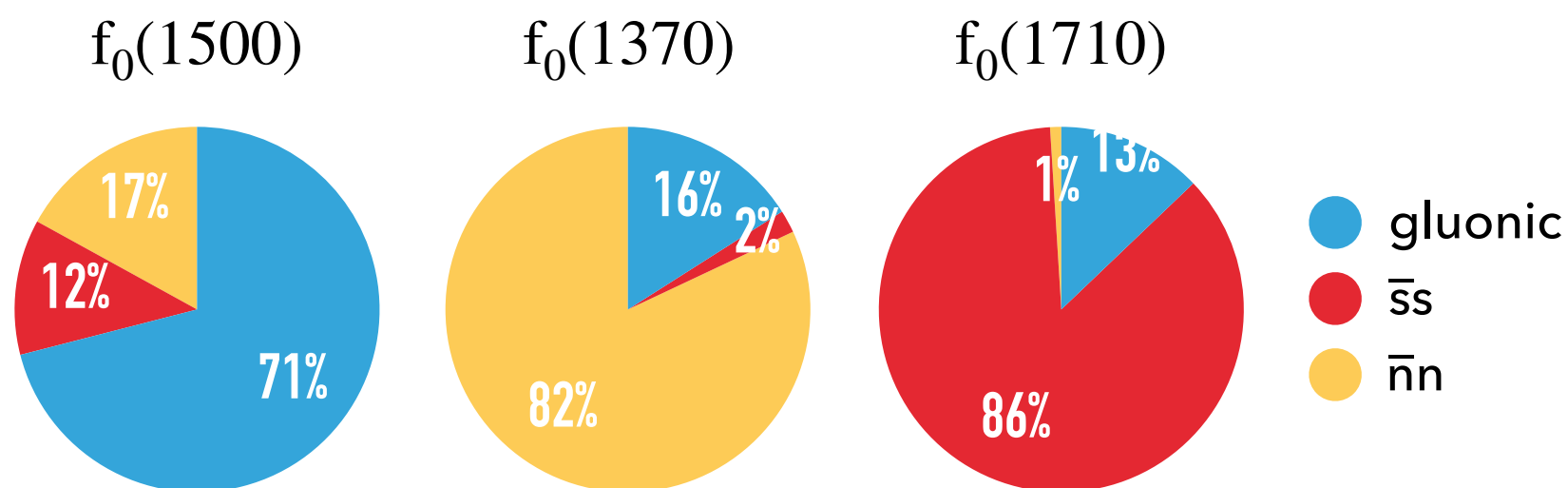


Candidates for the $J^{PC} = 0^{++}$ Glueball

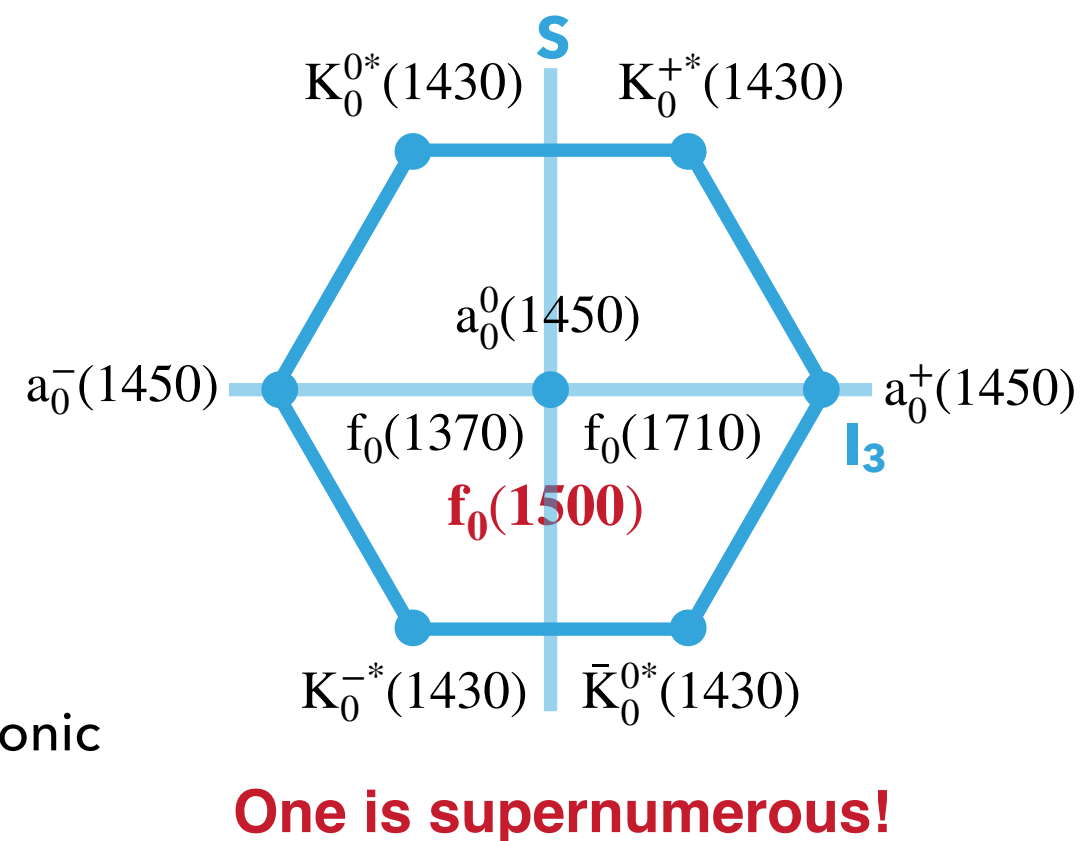
- Lattice calculations predict for the ground-state $M = 1400 - 1700 \text{ MeV}/c^2$:
- Scalar mesons below 1 GeV (e.g. $f_0(500)$, $f_0(980)$) are widely assumed as tetra quarks
- Same quantum numbers as ordinary $q\bar{q}$ mesons
- Glueball can mix with states close by in mass

s. PRD 91 (2015) 114015

$$\begin{pmatrix} |f_0(1370)\rangle \\ |f_0(1500)\rangle \\ |f_0(1700)\rangle \end{pmatrix} = U \begin{pmatrix} |gg\rangle \\ |\bar{s}s\rangle \\ |\bar{u}u + \bar{d}d\rangle / \sqrt{2} \end{pmatrix}$$

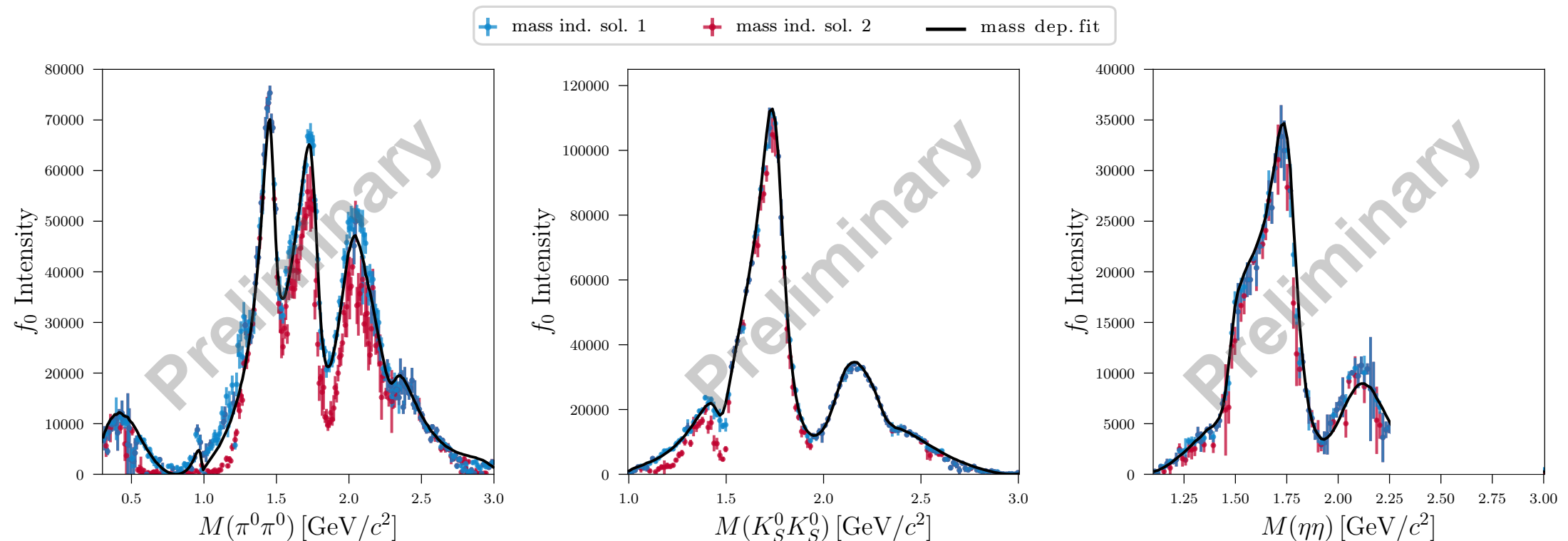


based on C. Amsler, Lecture Notes in Physics



Recently: Extend to full light hadron spectrum

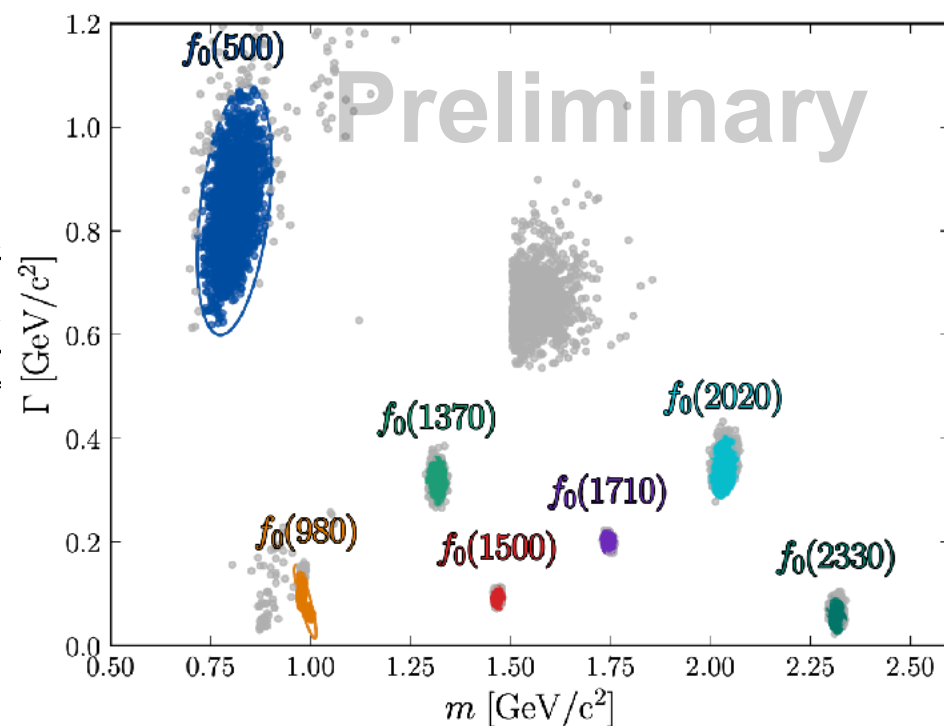
- Much higher statistics available (*50 times more now available!*) at **BESIII**
- Mass-independent amplitude analysis in preparation for $J/\psi \rightarrow \gamma\pi^0\pi^0$, $\gamma K_S^0 K_S^0$ and $\gamma\eta\eta$
 - ⊕ model-independent
 - ⊖ ambiguous solutions
- Mass-dependent coupled channel fits - based on 4-vectors for all channels ongoing
 - ➔ Ambiguities from model-independent f_0 to be solved
 - ➔ Proper determination of production strength of 0^{++} and 2^{++} states possible!



Recently: Extend to full light hadron spectrum

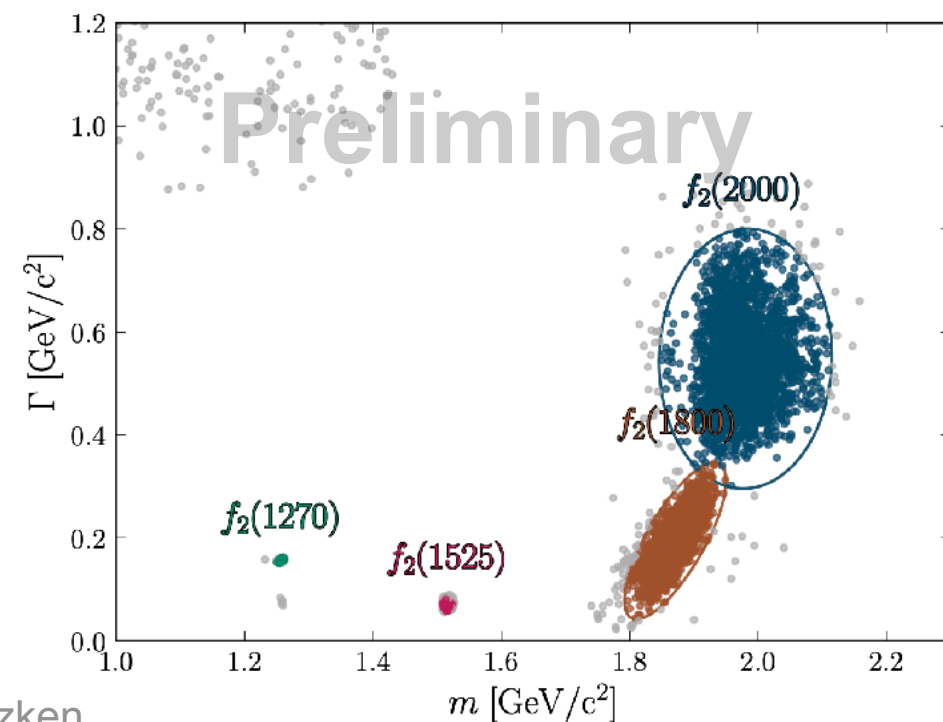
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f_0 resonances



PhD F. Hoelzken

f_2 resonances



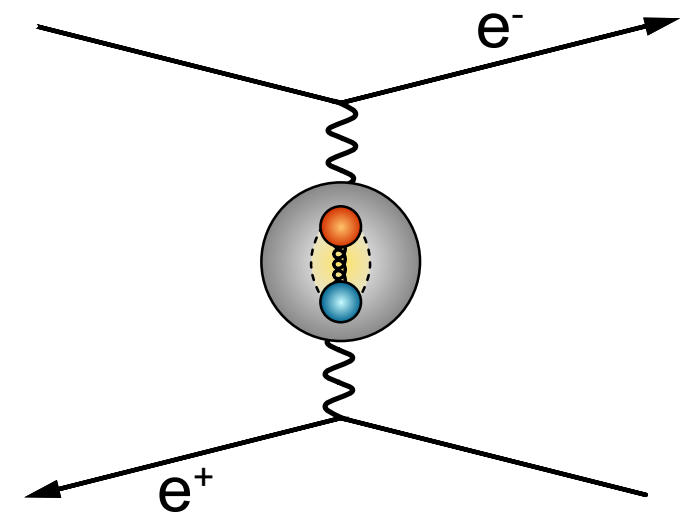
Two-Photon Reactions

Idea: Learning More About the Inner Structure

- Clean e.m. process, only sensitive to charge
- Complementary information on glueball candidates!
- States with even C-parity $0^{\pm+}$, $(1^{\pm+})$, $2^{\pm+}$, ... can be directly produced

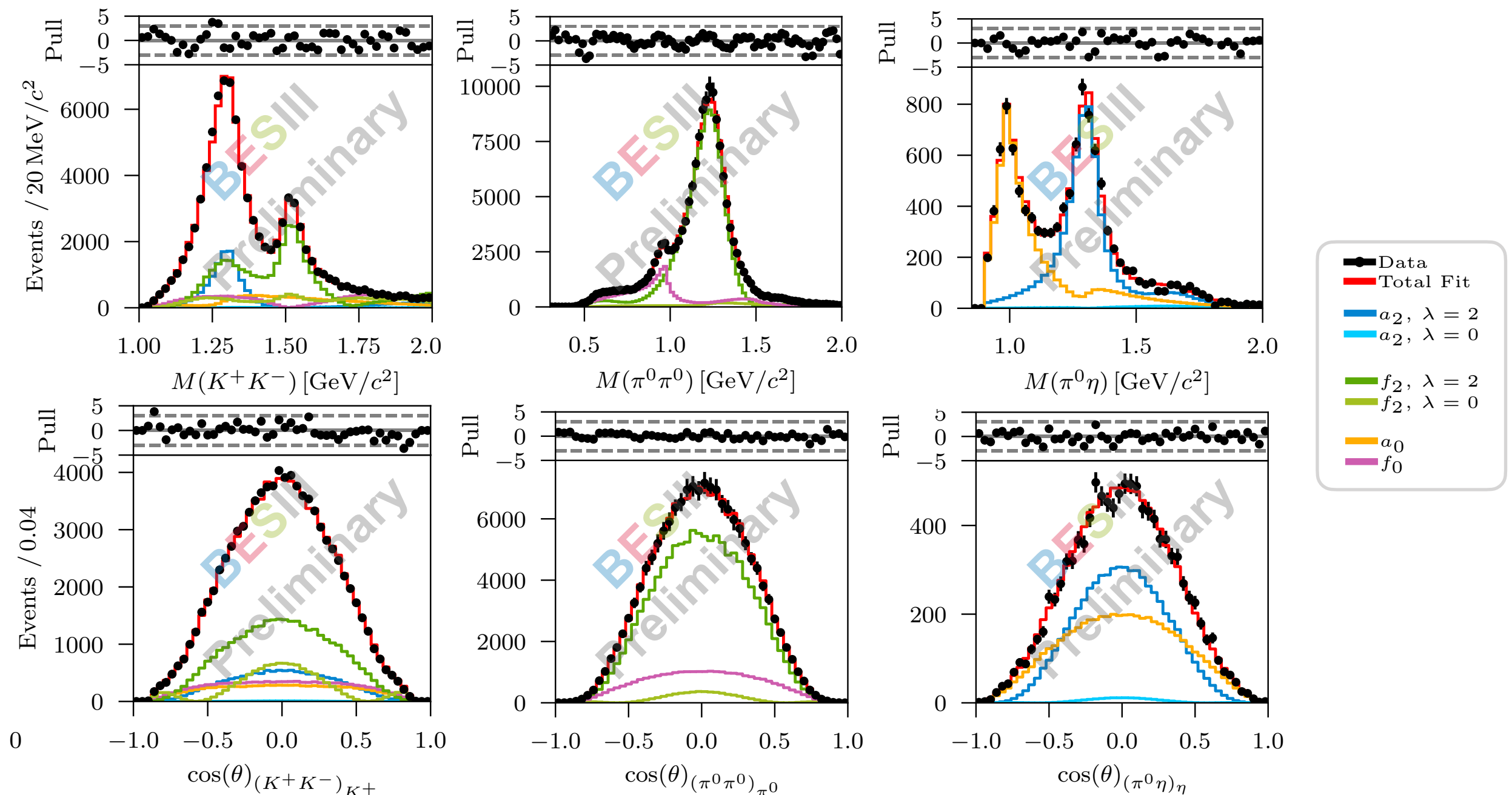
Untagged reactions:

- Scattering angles of electron and positron are small and are not detectable
- Quasi real photons carrying small virtuality → spin 1 strongly suppressed



Coupled Channel Analysis of Two-Photon Data

- Using obtained parameterization and fix all pole and decay parameters
- All structures can be well described
- Dominant contribution of $(J, \lambda) = (2,2), (0,0)$
- Best fit result using all 14 resonances and P-vector background terms: 1. order for f_2, a_2, a_0 -waves

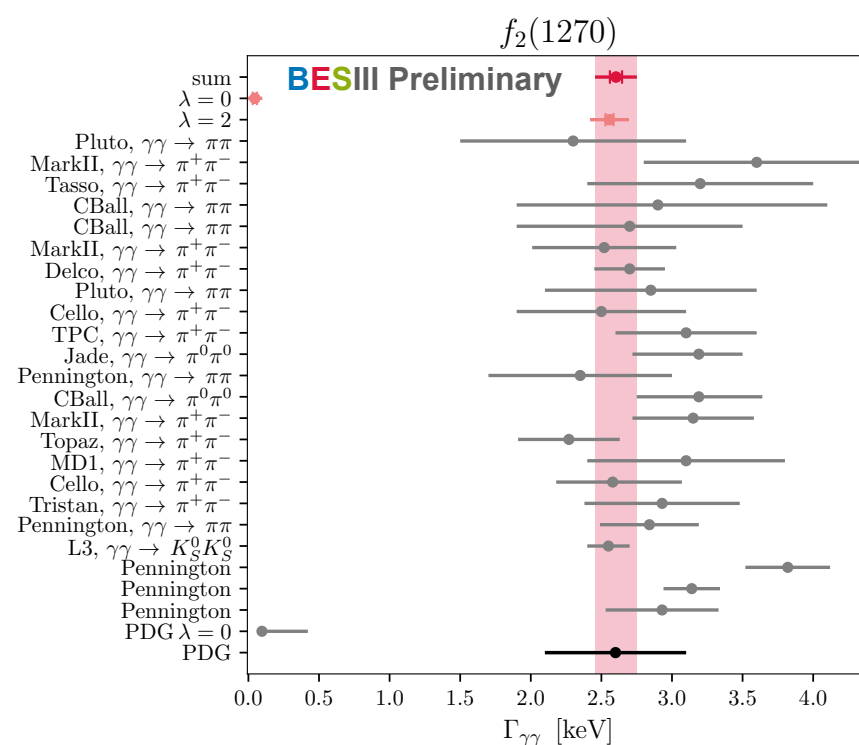


Determination of the Coupling Strength

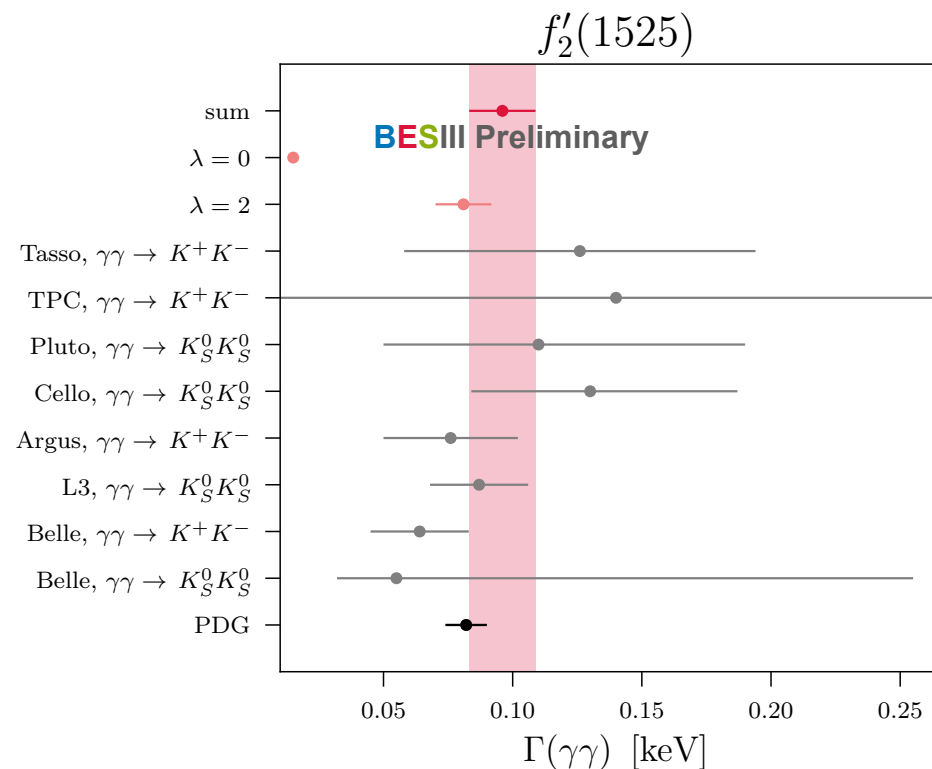
- Determination of the two-photon width using the F-vector pole residue itself
- More accurate method than based on Breit-Wigner peak intensities
 - Also heavily interfering resonances can be separated...
 - Helicity contributions can be determined

$$\Gamma(X \rightarrow \gamma\gamma) = \frac{\alpha^2}{4(2J+1)M_R} \cdot \frac{\text{Res}_X(\gamma\gamma \rightarrow FS)}{\Gamma_{dec}}$$

Phys. Rev. D **90**, 036004



Error bars include systematic uncertainties



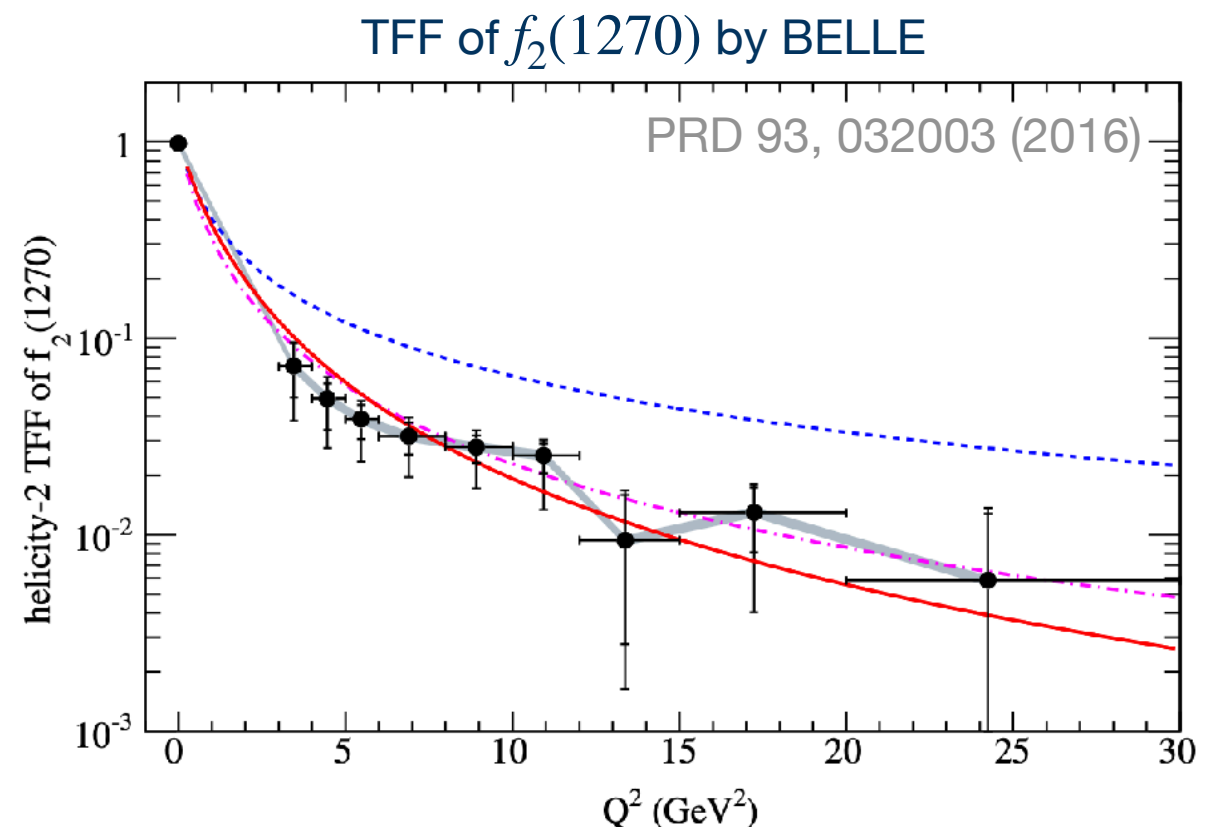
- Most accurate measurement for $f_2(1270)$ and $a_2(1320)$
- Scalar mesons $f_0(1370)$, $f_0(1500)$ und $f_0(1710)$ measured for the first time

Other Benefits of Two-Photon Data

Tagged two-photon reactions:

- Measuring transition form factors of light mesons might be useful for a clean determination of gluonic admixtures!
- Momentum transfer of involved photons can be measured
- Formation of $J = 1$ states possible due to non negligible γ virtuality

- TFF measurements at BESIII especially powerful at $Q^2 = 0.3 - 1.5 \text{ GeV}^2$
- Higher beam momenta needed to access higher Q^2 regime and states above 2 GeV , ($\chi_{c1}(3872) \dots$)
- Belle II (?)



Future Prospects

In order to perform such analyses in the future, we need to:

1

- Built detectors to perform large-scale experiments

- Develop software tools capable of such intensive analyses

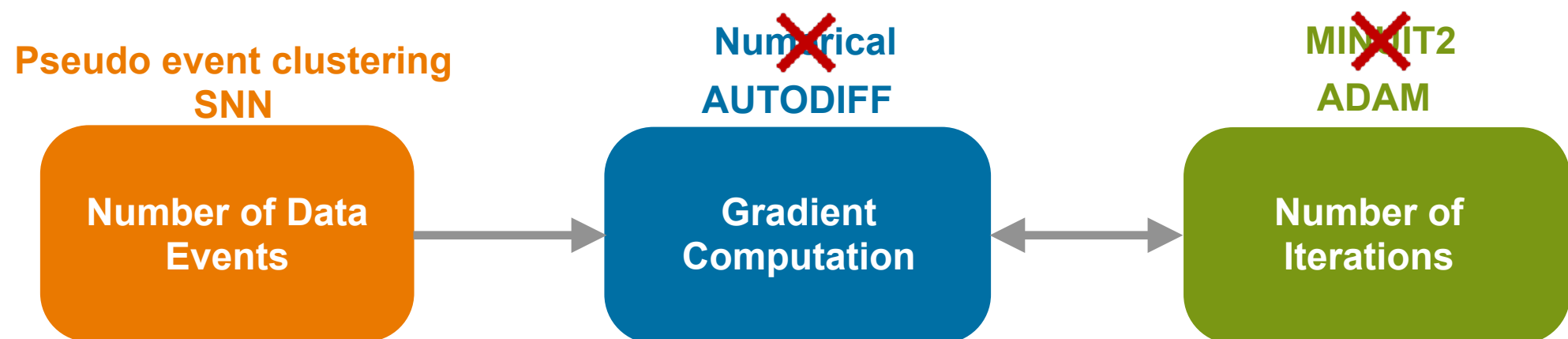
2

To perform expensive analyses with increasing statistics we need to get faster and more efficient!

Development of faster algorithms required:

- Including AI techniques where helpful

Fit time depends mainly on:

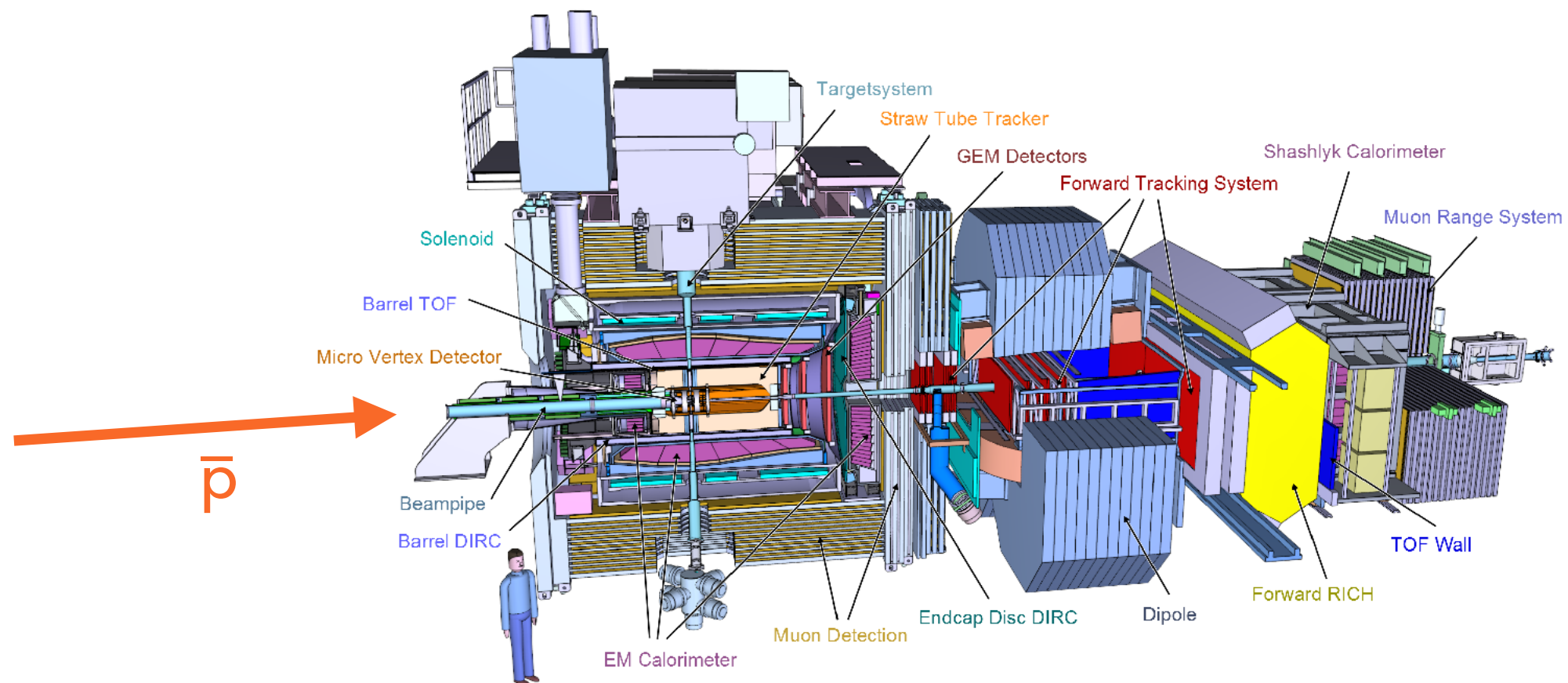


Preliminary results show speed-increase of up to 20!

Interesting for other experiments!

Unique possibilities of $\bar{p}p$ Annihilations

- Cross section for exotics similar to conventional states
- High-spin states possible without limitations on quantum numbers
- ➔ Allows to study whole spectrum of exotica
- In $\bar{p}p$ experiments states with all q.n. can be produced, not limited to $J^{PC} = 1^{--}$ like in e^+e^- experiments
- Only limited by the beam resolution and not by detector



PANDA Physics Program

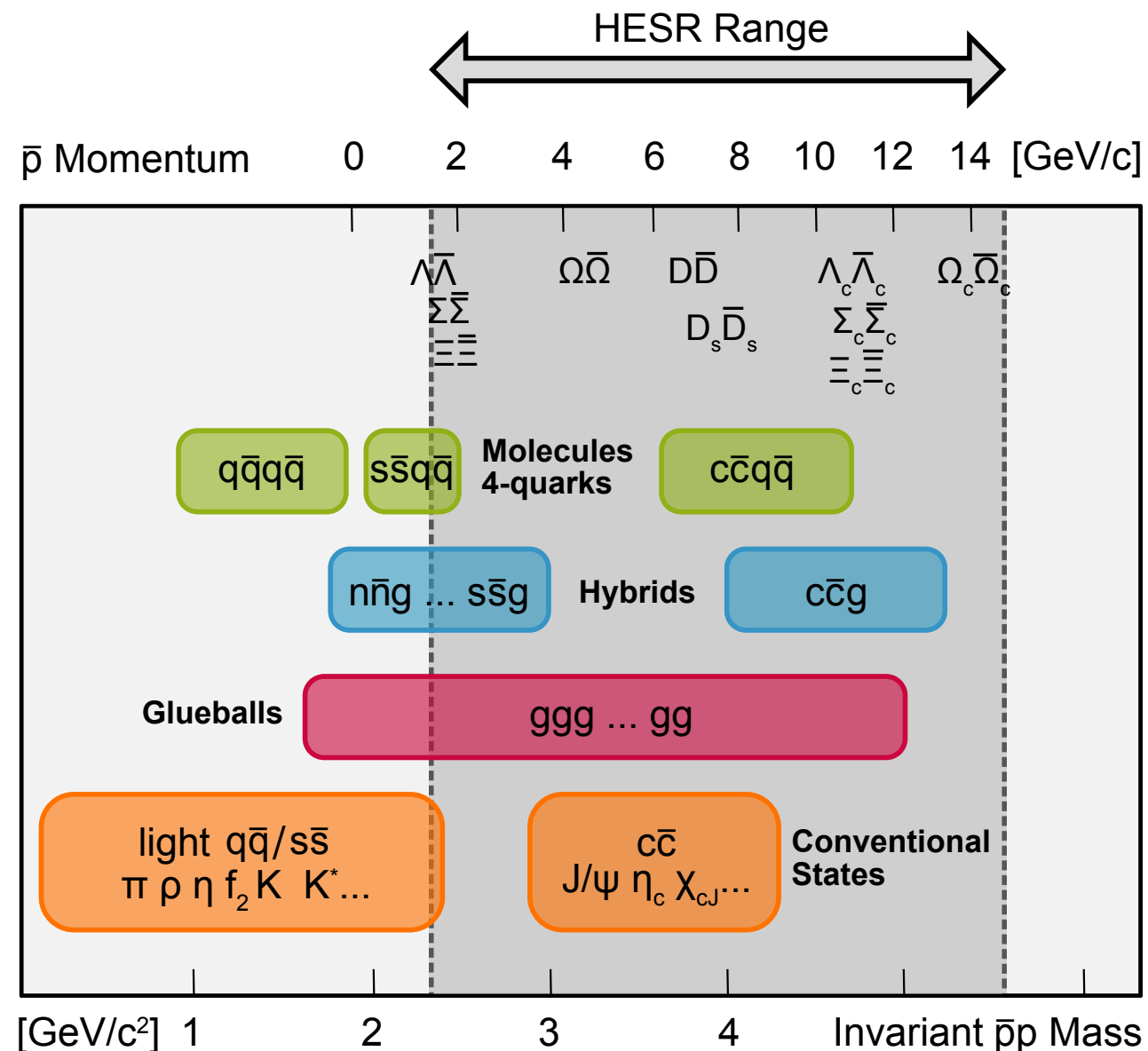
Hadron Spectroscopy

- Light mesons
- Exotic matter (Glueballs, Hybrids etc.)
- Charmonia (including XYZ states)
- Open Charm Physics
- Baryons and Hyperons

Nucleon Structure

- Generalised Parton Distributions (GPD)
- Transition Distribution Amplitudes (TDA)
- Time-like proton form factor
- Transverse Parton Distribution

Physics of Hypernuclei



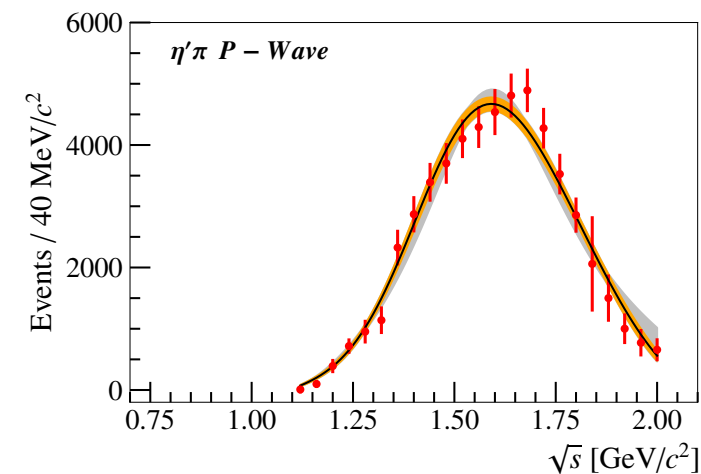
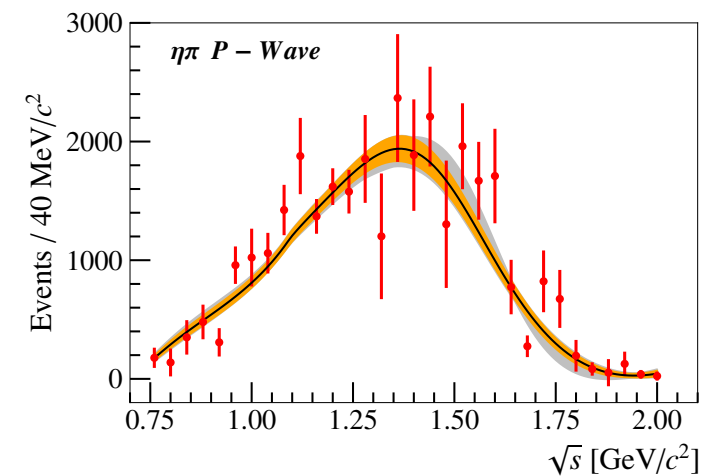
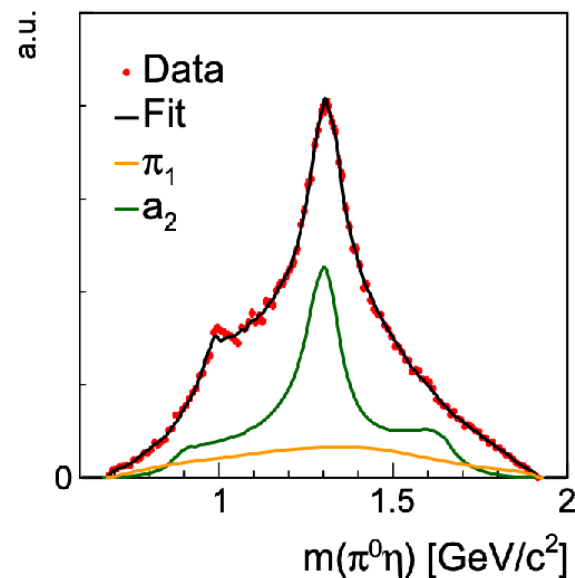
Very broad program

PANDA can contribute to various fields!

Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$

- Exotic π_1 wave contributing at the same level like „ordinary“ mesons!

process	cross section [μb]
$\bar{p}p \rightarrow K^*(892)^\pm K^\mp$	$396 \pm 29 \pm 19 \pm 42$
$\bar{p}p \rightarrow \phi(1020)\pi^0$	$20.2 \pm 3.6 \pm 1.4 \pm 2.1$
$\bar{p}p \rightarrow \pi_1 \pi^0, \pi_1 \rightarrow \pi^0 \eta$	$25.8 \pm 3.5 \pm 4.1 \pm 1.5$



$\bar{\text{P}}\text{ANDA}$ will have a 100 times higher luminosity!

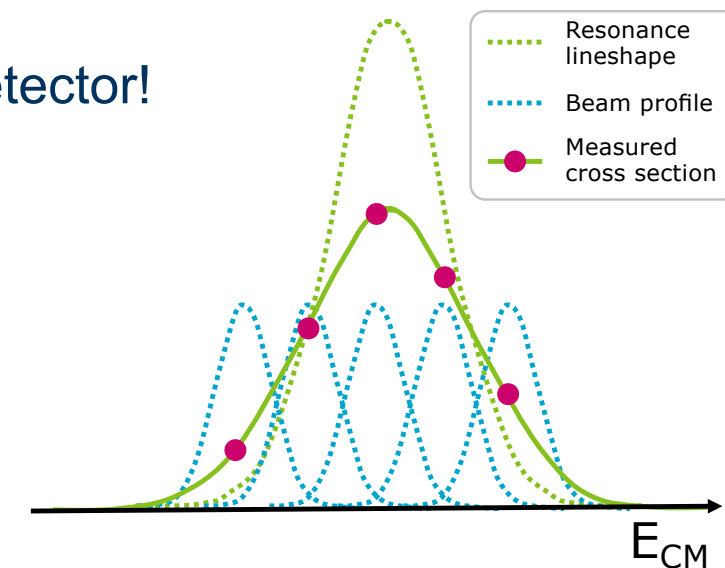
→ 1 year data taking becomes 3.5 days!

Formation Studies at $\bar{\text{P}}\text{ANDA}$

Powerful example: Measurement of the total width of the $\chi_{c1}(3872)$

- Compact (BW) or molecule (Flatté)?
 - Best measurement so far:
 - Width assuming Breit-Wigner (for sure not a good model at threshold...):
 $\Gamma = (1.39 \pm 0.24 \pm 0.10) \text{ MeV}$ (LHCb 2020)
 - Width assuming Flatté model:
 $\text{FWHM} = 0.22^{+0.06+0.25}_{-0.08-0.17} \text{ MeV}$ (LHCb 2020*)
- Molecule or virtual $\leftarrow$ Flatté parameter E_f
- Not possible to distinguish scenarios, pole mass still not distinguishable from $D\bar{D}^*$ threshold
- LHCb and other experiments measuring in production have reached their sensitivity to probe the natural width of $\chi_{c1}(3872)$

- For PANDA resolution only limited by the beam resolution and not by the detector!
 - $\Delta p/p \sim (10^{-4} - 10^{-5}) \Rightarrow$ sensitive to structures up to 30 keV width!



PANDA: Eur. Phys. J A55, 42 (2019)
PANDA: Eur. Phys. J A 57:184 (2021)
F. Nerling, PoS CHARM2020, 004 (2021).

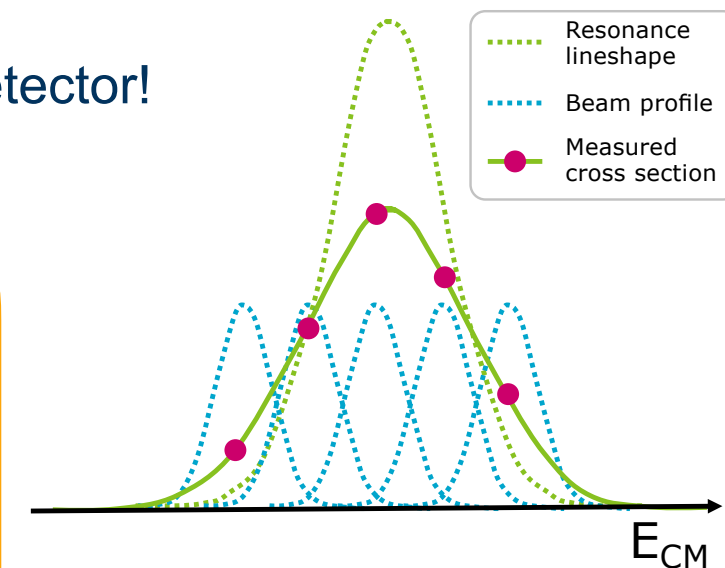
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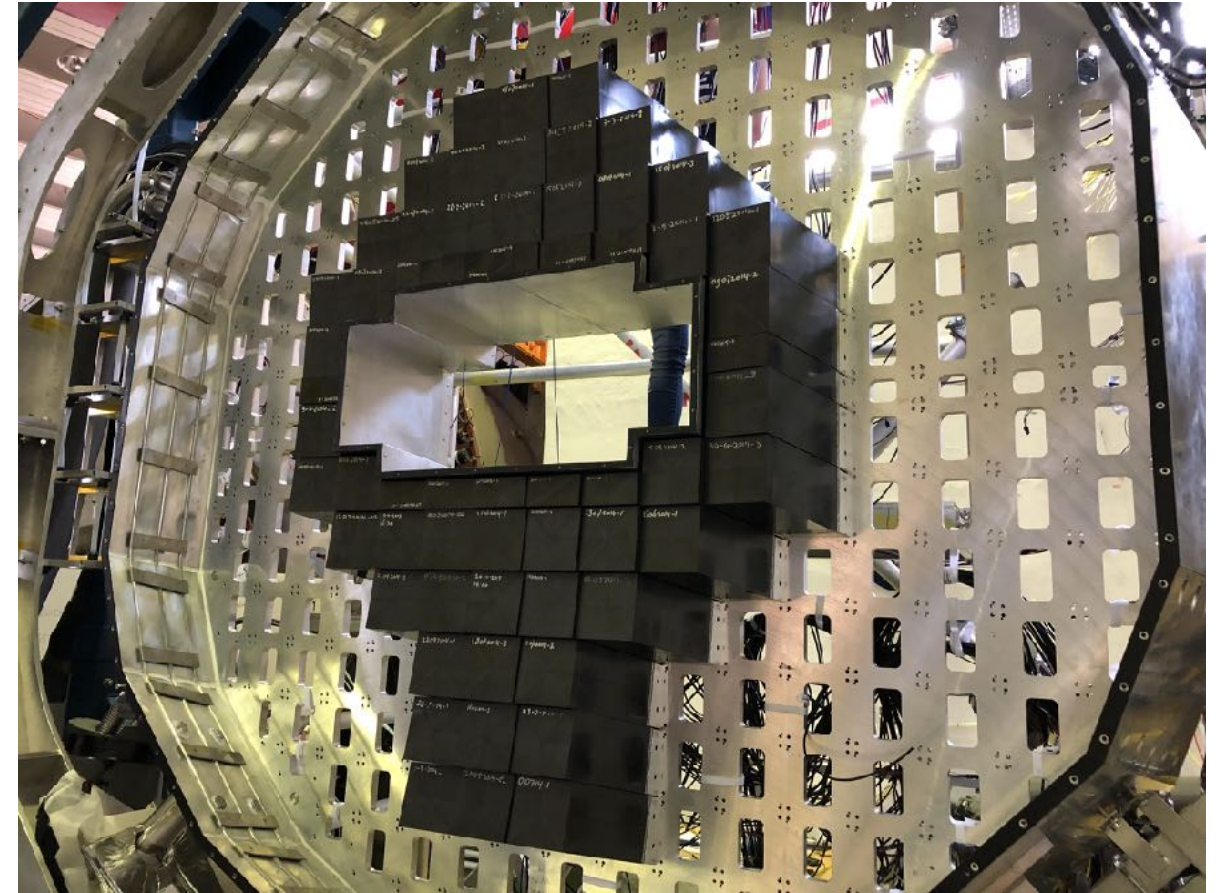
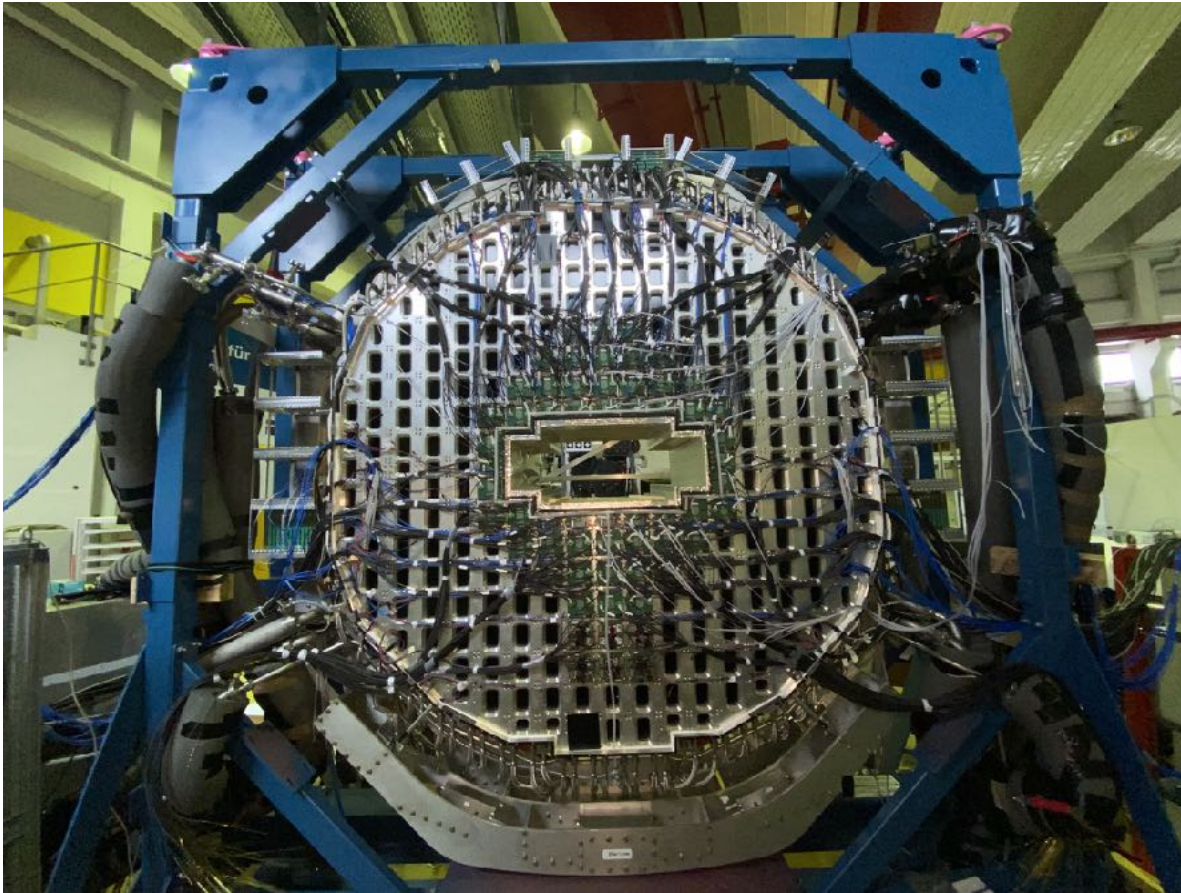
- For PANDA resolution only limited by the beam resolution and not by the detector!
 - $\Delta p/p \sim (10^{-4} - 10^{-5}) \Rightarrow$ sensitive to structures up to 30 keV width!

- $\Rightarrow$ Separation possible already in Phase One (~2 days per E-point)!
- $\Rightarrow$ Will establish its nature! And therefore most likely also for related states as T_{cc}
- $\Rightarrow$ Same applies to other states with $\bar{q}q$ quantum numbers!



PANDA: Eur. Phys. J A55, 42 (2019)
PANDA: Eur. Phys. J A 57:184 (2021)
F. Nerling, PoS CHARM2020, 004 (2021).

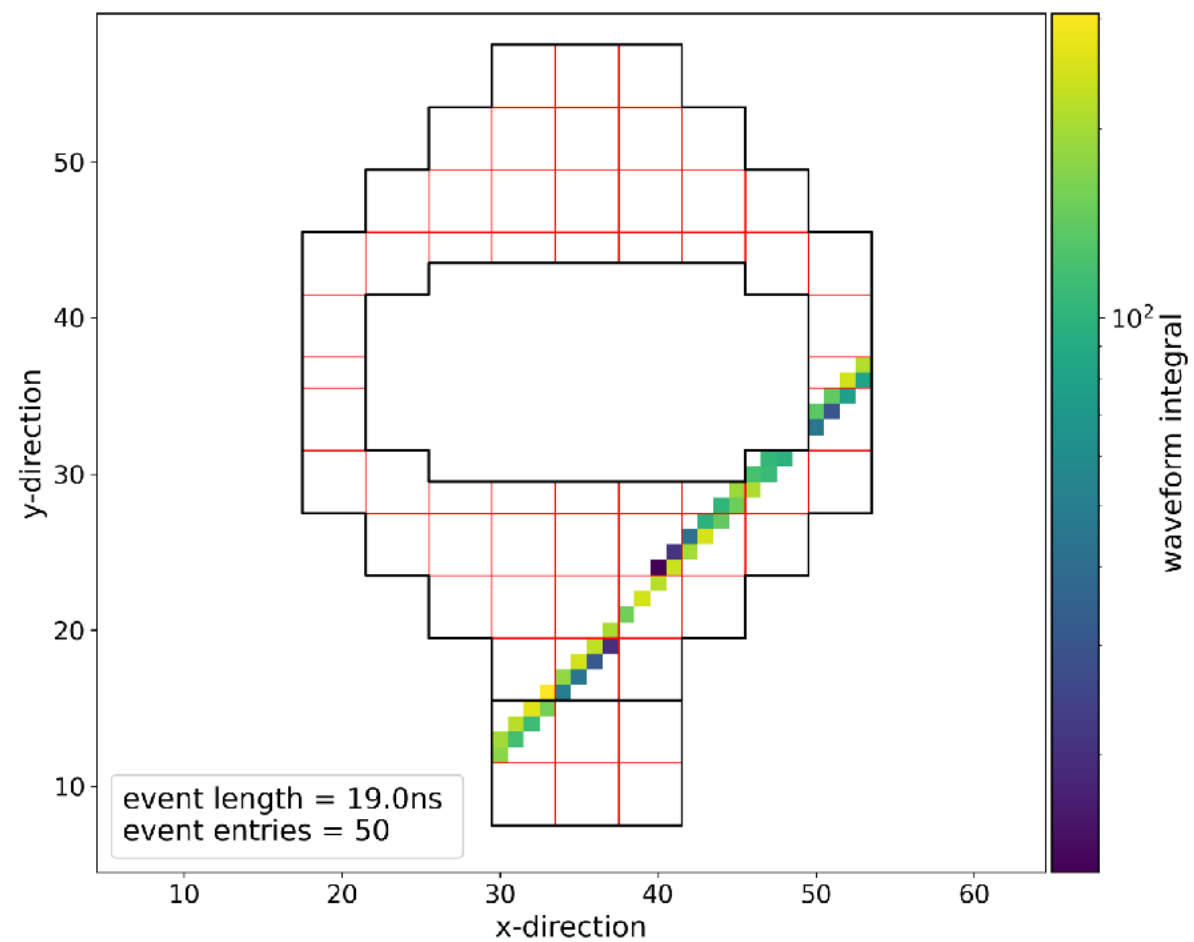
Forward Endcap EMC



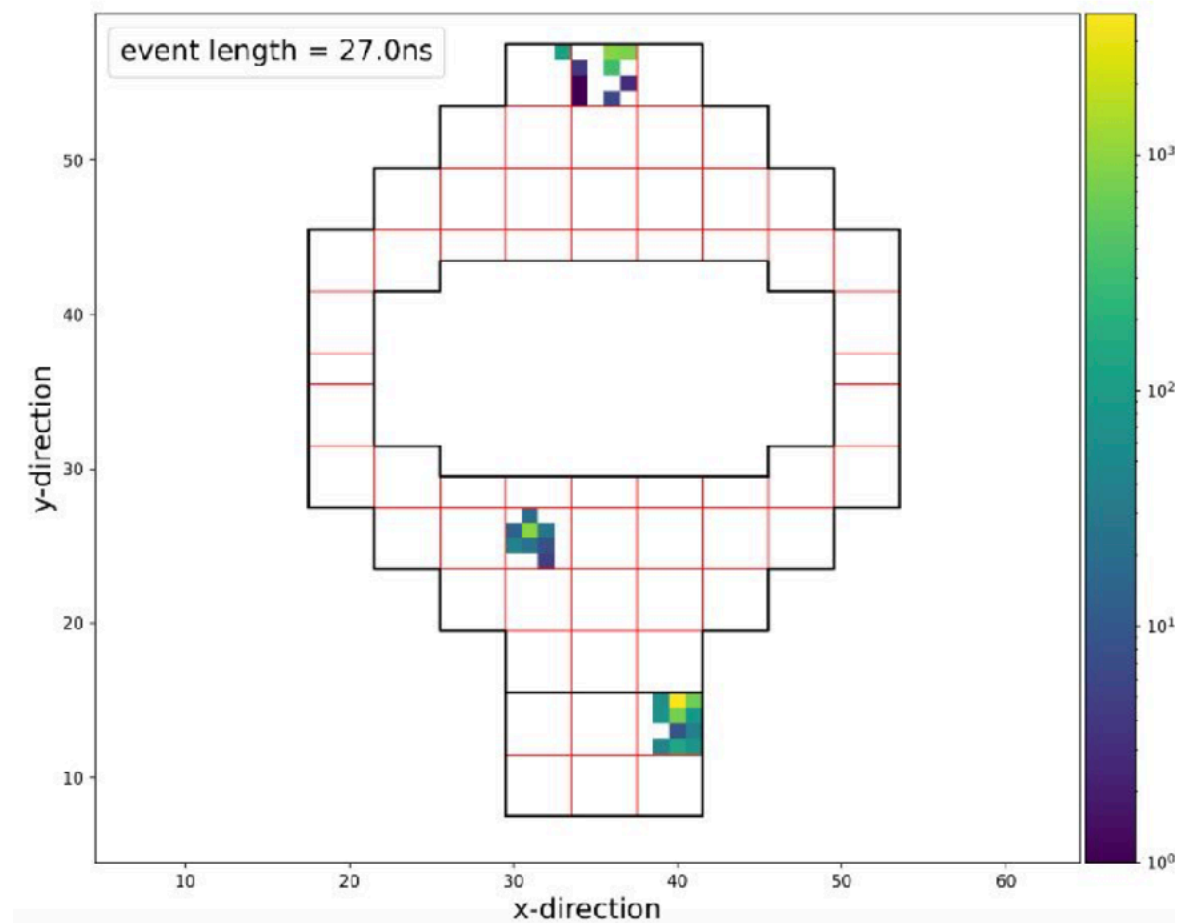
- Consisting of 3856 PbWO_4 crystals
- Operated at -25°C with a accuracy of $\pm 0.1^\circ\text{C}$ for best energy resolution
 - ➡ Challenging constraints on cooling system
- My inputs here:
 - Design and construction of the cooling system
 - Setup of the DCS system
 - Module construction/assembly during the last 8 years

Forward Endcap EMC

Cosmic event example

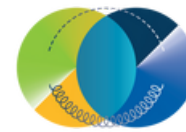


Proton event example



Outlook

- Successful transport to ELSA in Bonn! ✓
- Completion (mounting all submodules) and
- First long term physics operation at CB@ELSA before PANDA!

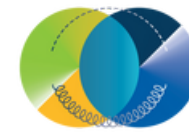


color meets flavor



Outlook

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color meets flavor

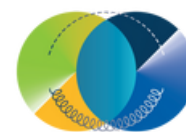


Investigation of the strong interaction
in the light flavor sector



Outlook

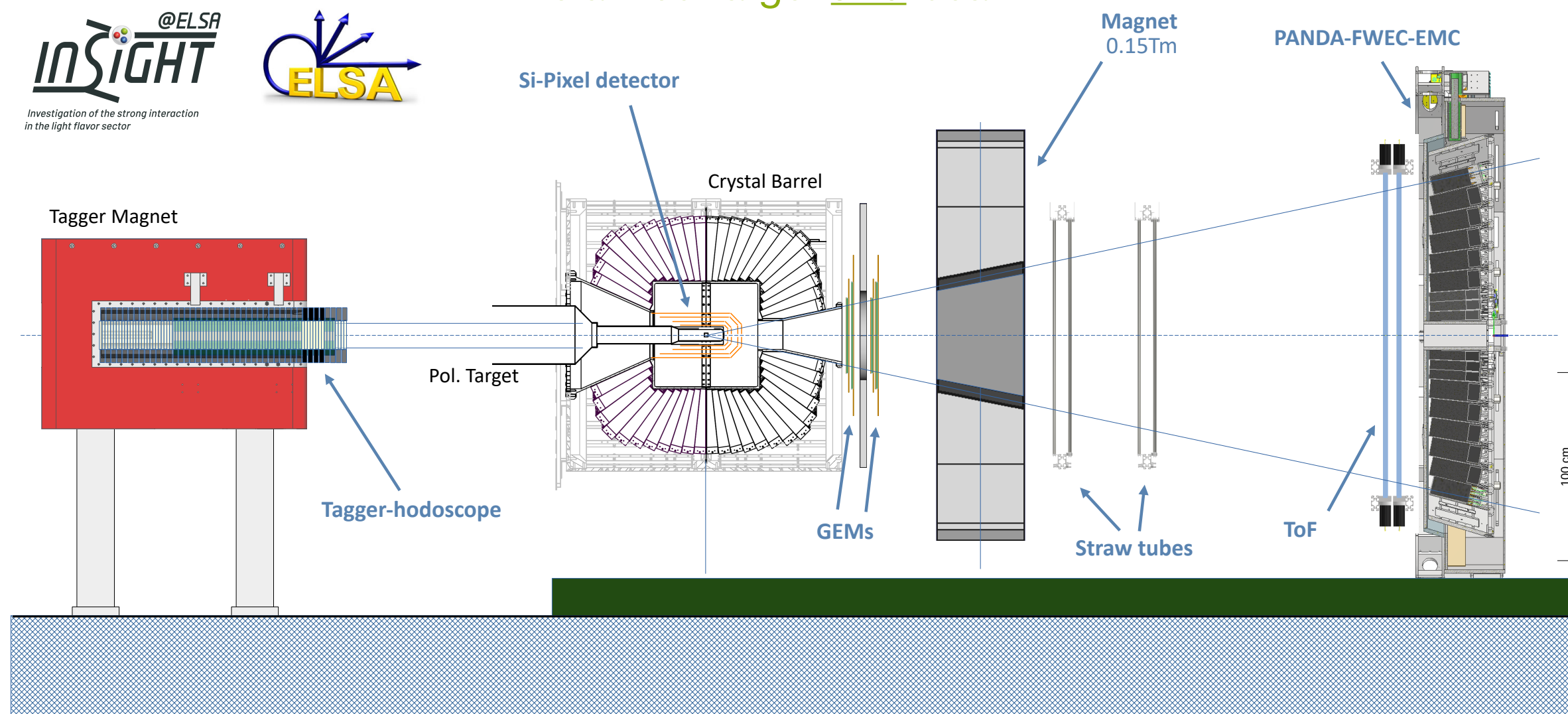
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color meets flavor

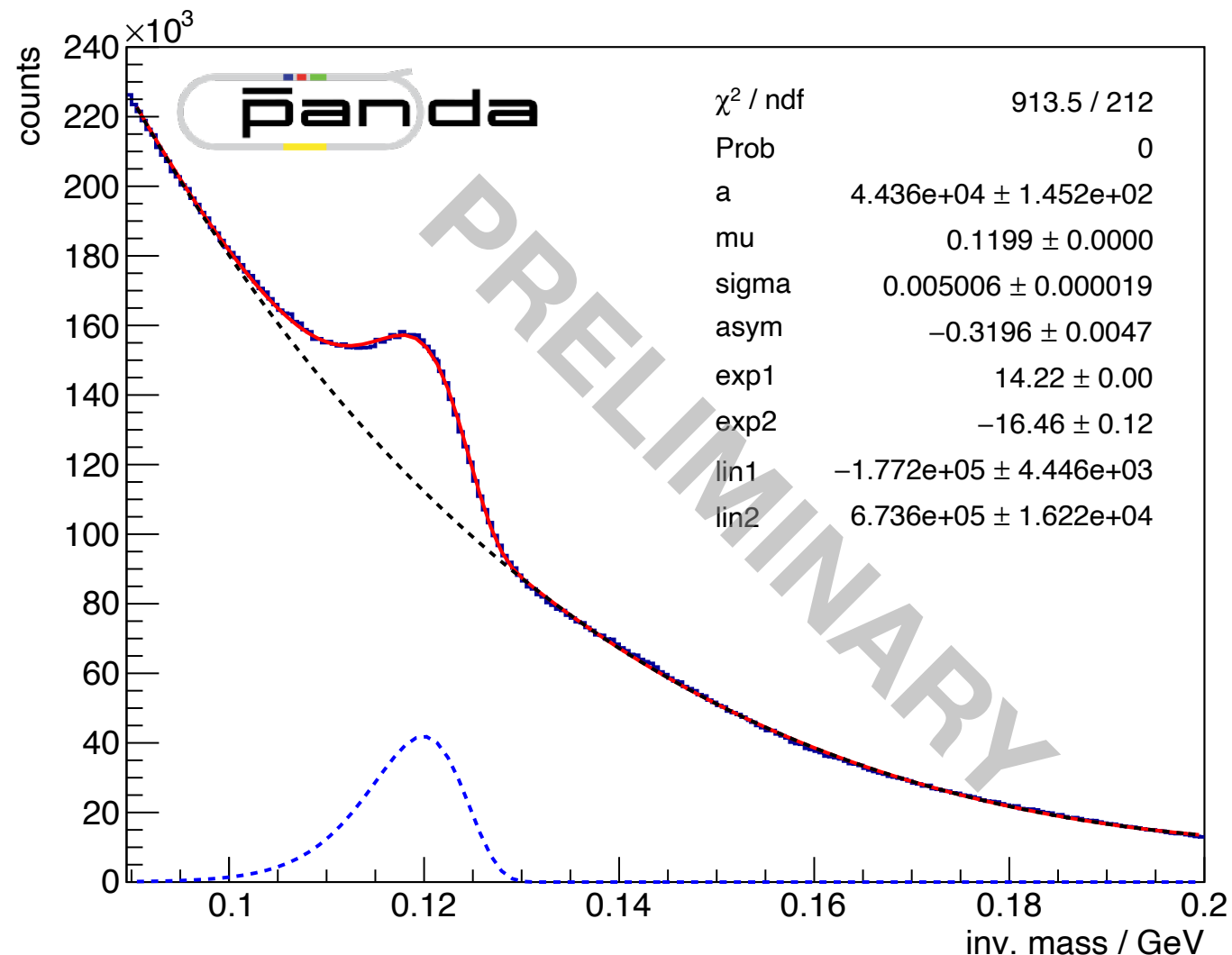


Polarized target and beam!



First Results on π^0 Calibration

- Eventually it payed off and worked just as we hoped in our dreams



- Width σ of resolution of π^0 5 MeV!
- “World leading” resolution yet without energy calibration!

Summary

- Although light mesons are studied for decades, there are still many open questions
- The non-perturbative regime of QCD challenges theory and experiment!
- This affects also other sectors as CP violation!
- Sophisticated line shape models should be used whenever possible
- Different experiments and theory need to collaborate to solve this
- Coupled channel analyses seem to be a good tool to disentangle crowded spectra
- Work closer together in the community - common effort is needed to answer fundamental questions!
- This strengthens the research field, especially in times when basic research is experiencing more headwinds

pp annihilation



two-photon production



...



radiative J/ψ decays

πp - , pp scattering
photo production





Thank You!