Measurement of the photoproduction cross section for $\gamma p \rightarrow \phi \pi^+\pi^- p$ and search for the Y(2175) at GlueX

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GSI Darmstadt, HFHF & GU Frankfurt
on behalf of the GlueX Collaboration

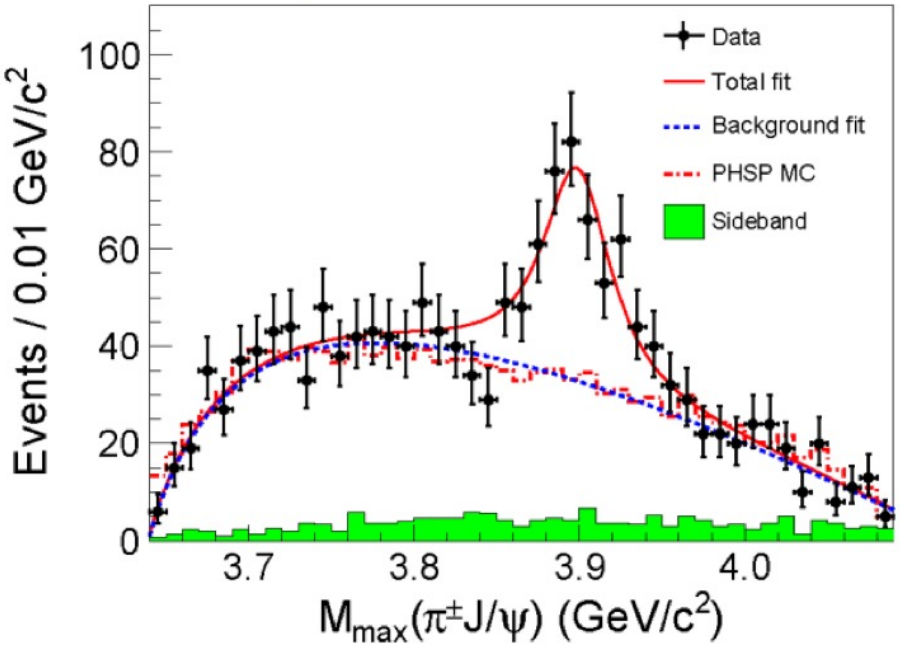
HADRON2023,
June 5th - June 9th 2023, Genova

Outline

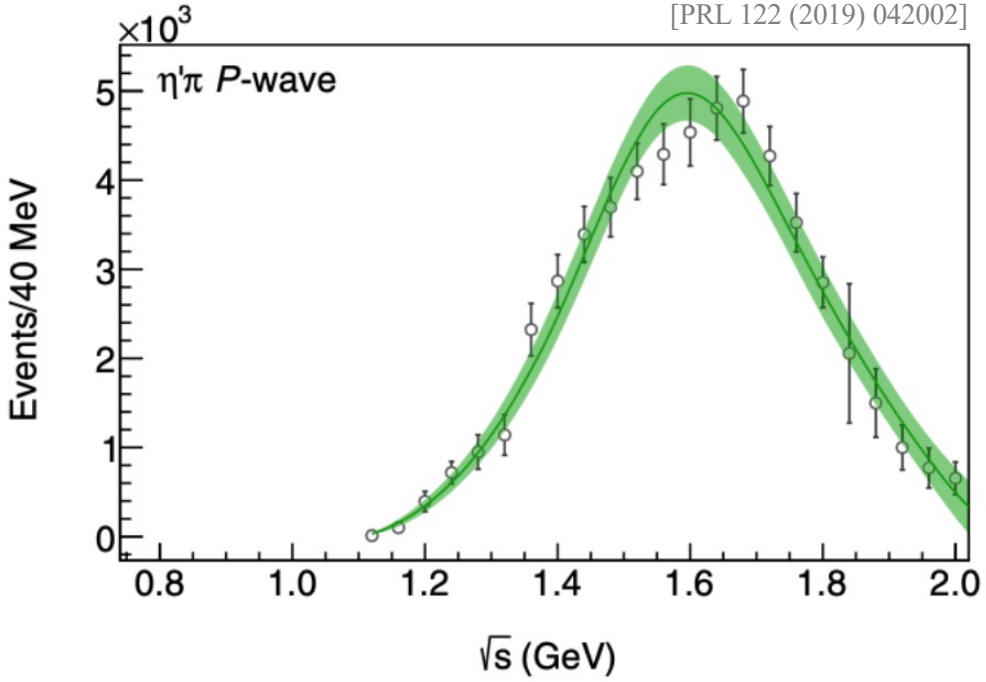
- **Introduction & motivation**
- **The GlueX experiment at JLab**
- **Analysis of $\gamma p \rightarrow \phi \pi^+\pi^- p$**
  - Measurement of differential cross section
  - Search for Y(2175)
- **Summary**

Recent hot topics

[PRL 110 (2013) 252001]

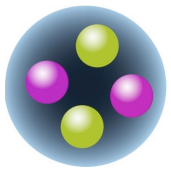


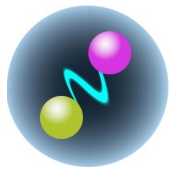
[PRL 122 (2019) 042002]



$Z_c(3900)^{+/-} \rightarrow J/\psi\pi^{+/-}$

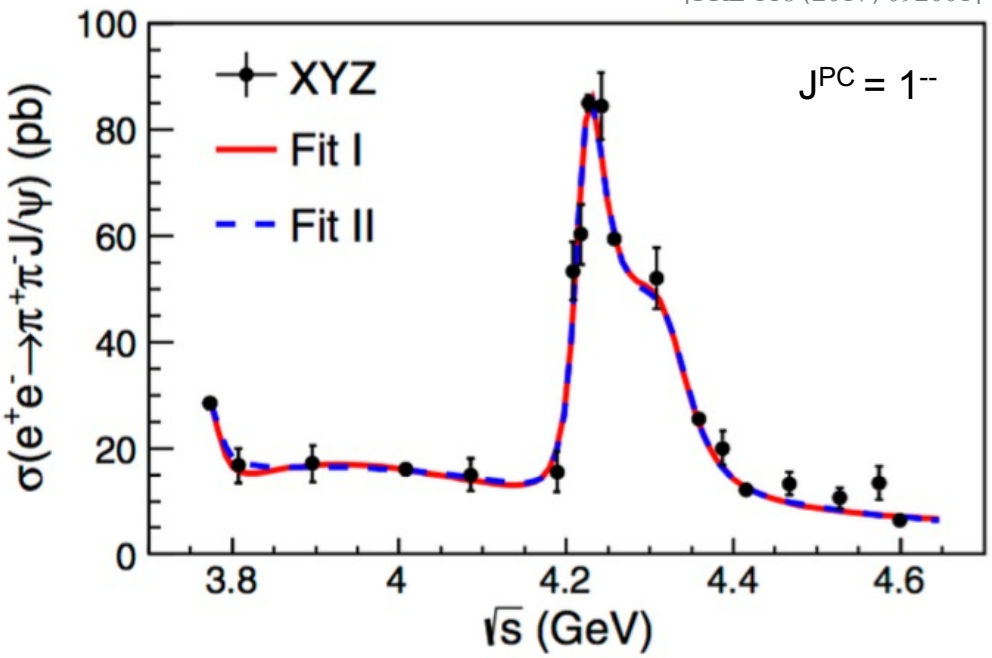
$\pi_1(1600) \rightarrow \eta'\pi$



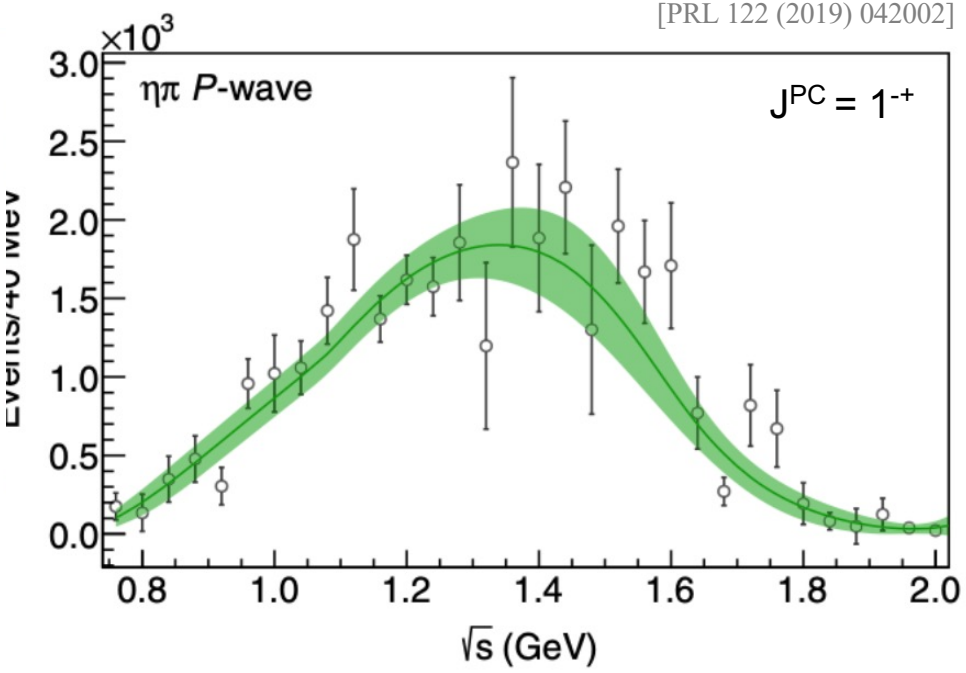


Recent hot topics

[PRL 118 (2017) 092001]

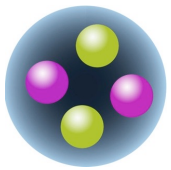


[PRL 122 (2019) 042002]



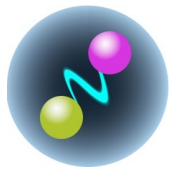
$Z_c(3900)^{+/-} \to J/\psi\pi^{+/-}$

$Y(4230) \to J/\psi\pi^+\pi^-$



$\pi_1(1600) \to \eta'\pi$

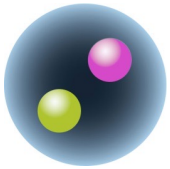
$\pi_1(1400) = \pi_1(1600) \to \eta\pi$



Mesons and exotic states

Simple Quark model

- Mesons: Color neutral $q\bar{q}$ systems



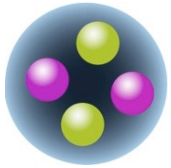
Conventional $(q\bar{q})$

QCD

- Meson states beyond $q\bar{q}$

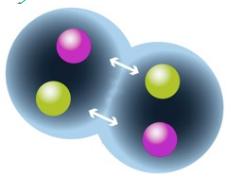
Alternative 4-quark configurations:

Hybrid $(q\bar{q})\,g$

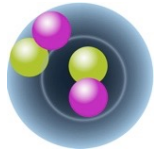


Tetraquark $(q\bar{q}q\bar{q})$

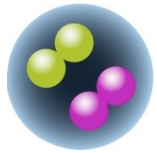
Glue-ball (gg) or (ggg)



Molecule $(q\bar{q})(q\bar{q})$



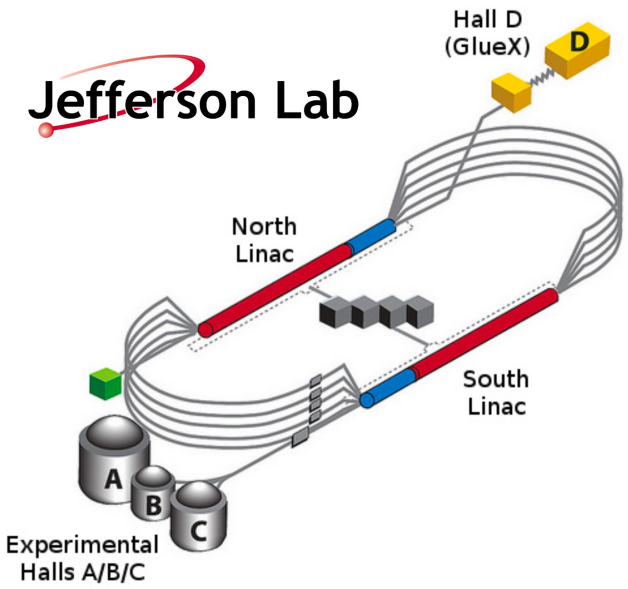
Hadro-quarkonium $(Q\bar{Q})(q\bar{q})$

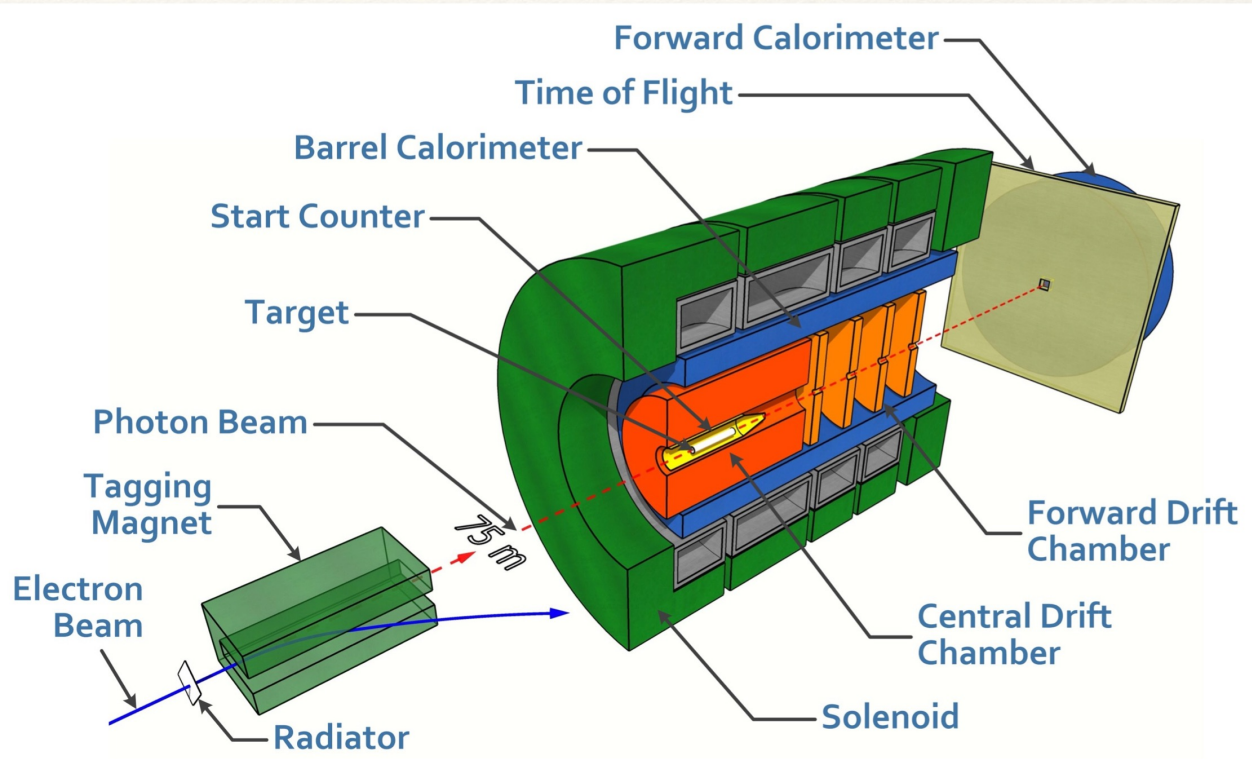


Di-quarkonium $(qq)(\bar{q}\bar{q})$

CEBAF at JLab

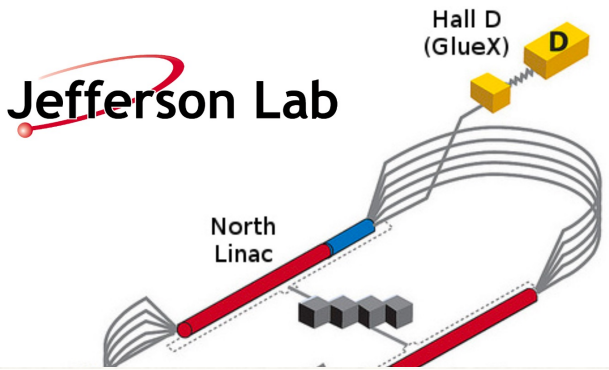
GlueX in Hall D at CEBAF, JLab

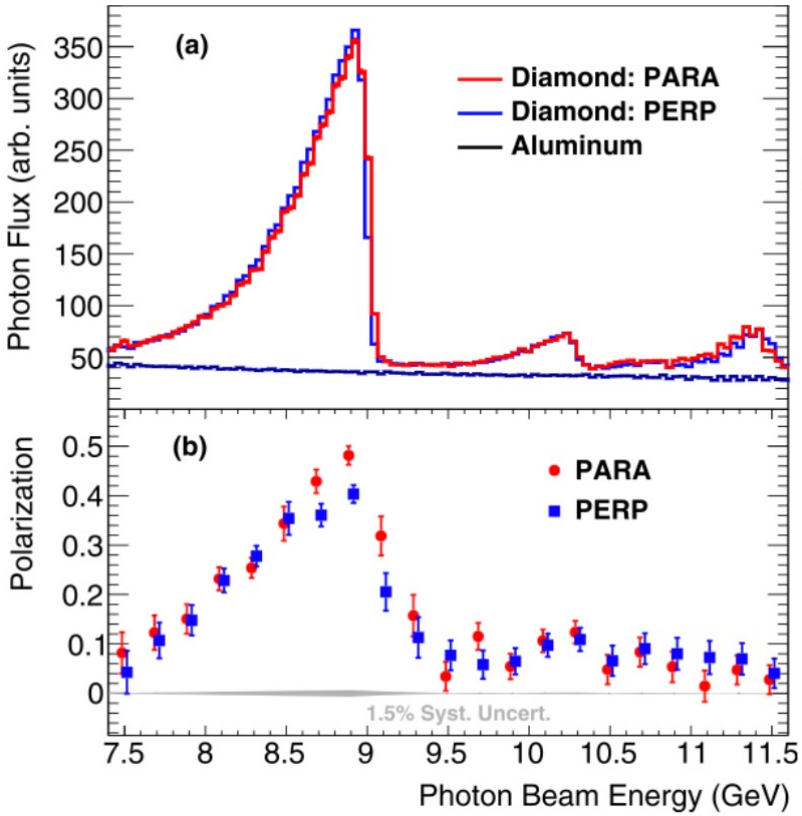


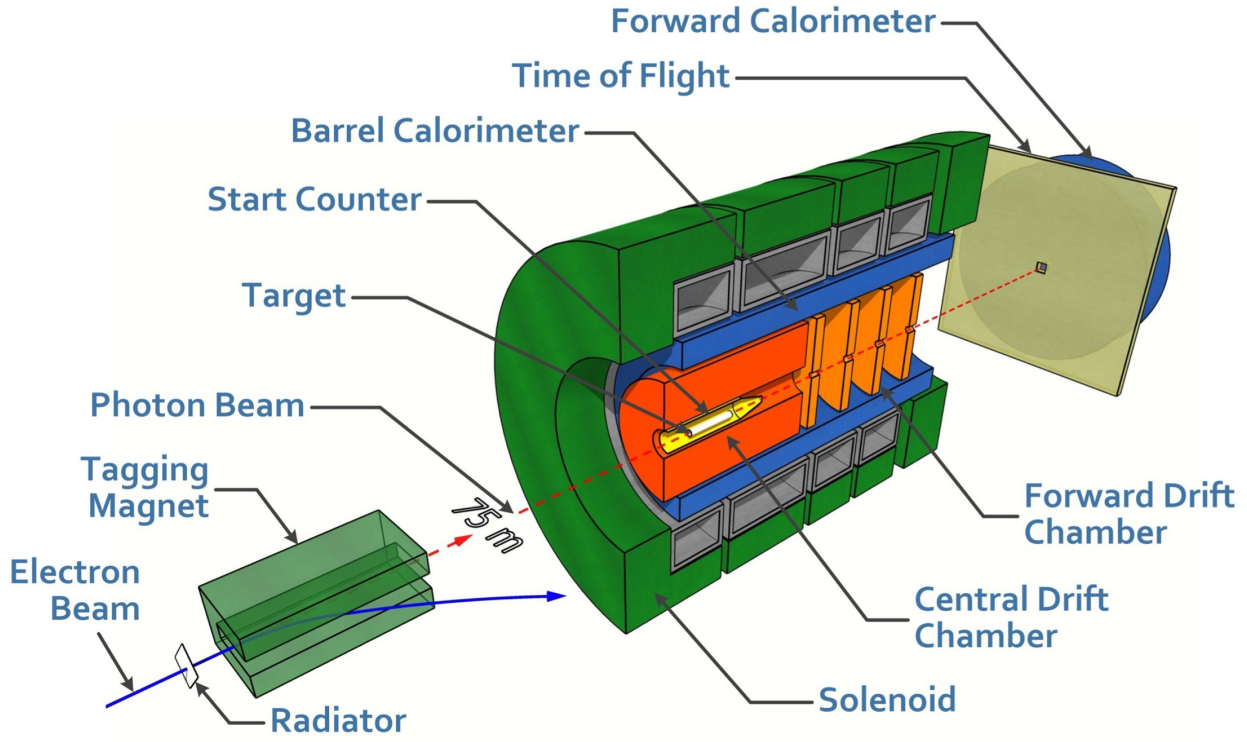


- 12 GeV electron beam from CEBAF accelerator
- Coherent Bremsstrahlung on diamond radiator
- Linear polarization in peak at ~9 GeV: Pγ ~ 40%
- Energy tagged by scattered electrons
- Beam intensity: $1 - 5 \cdot 10^7$ γ/s in peak

GlueX in Hall D at CEBAF, JLab



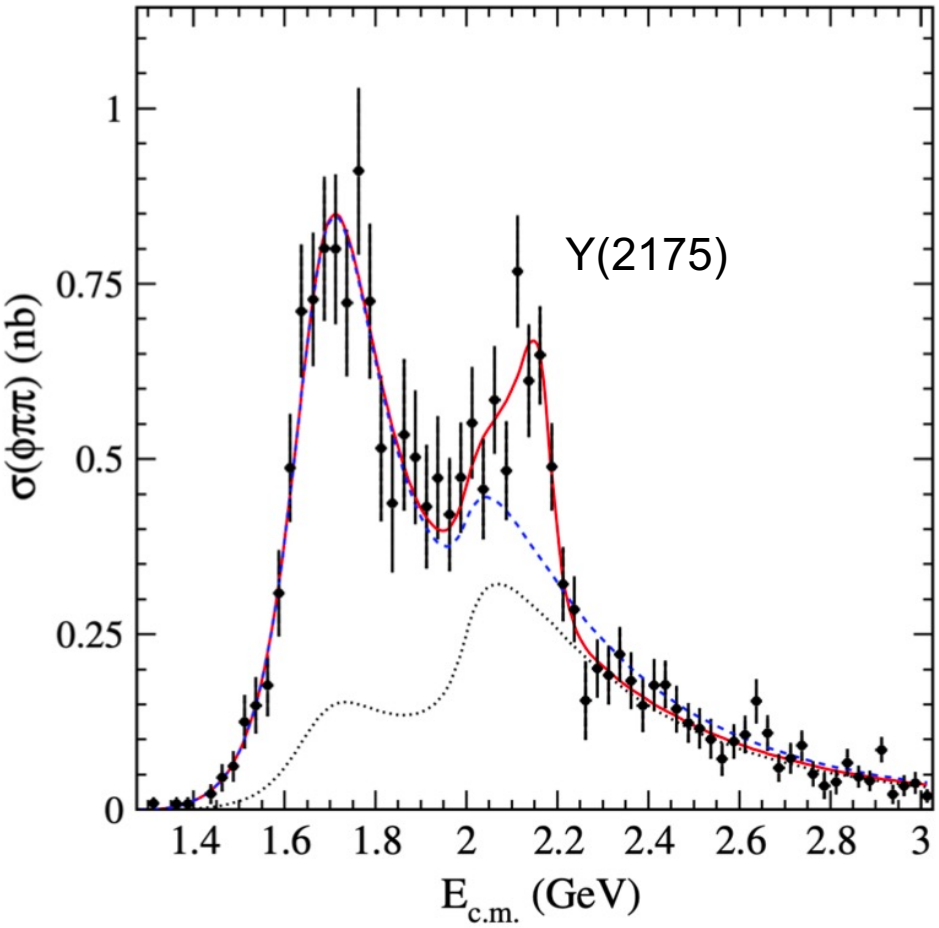




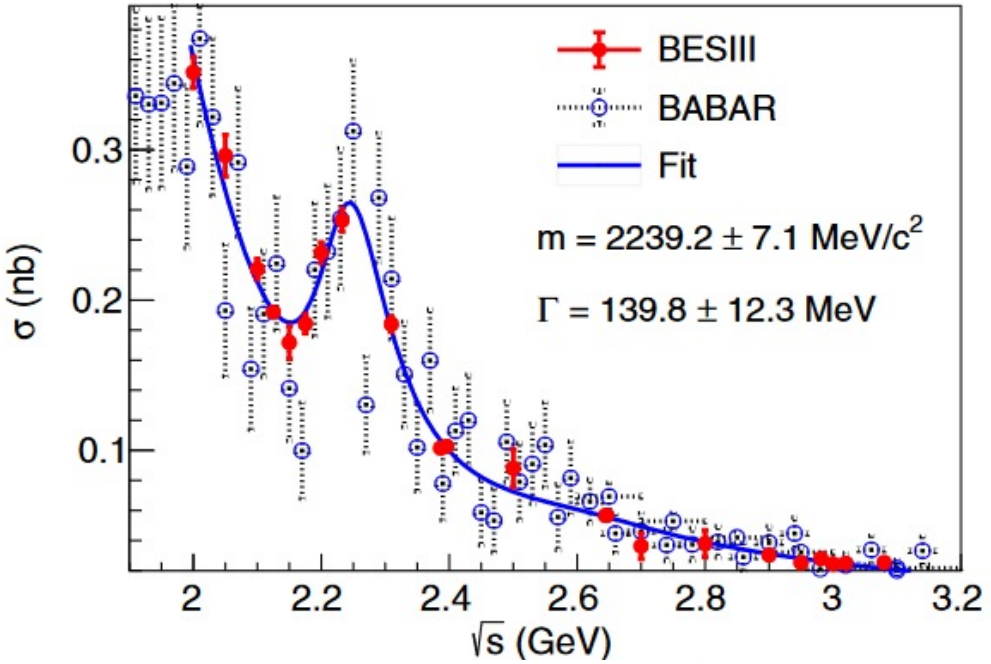
- 12 GeV electron beam from CEBAF accelerator
- Coherent Bremsstrahlung on diamond radiator
- Linear polarization in peak at ~9 GeV: $P_\gamma \sim 40\%$
- Energy tagged by scattered electrons
- Beam intensity: $1 - 5 \cdot 10^7$ γ/s in peak

The Y(2175) – strange partner of Y(4230)

[Phys. Rev. D. 74 (2006) 091103]



[Phys. Rev. D 99, (2019) 032001]



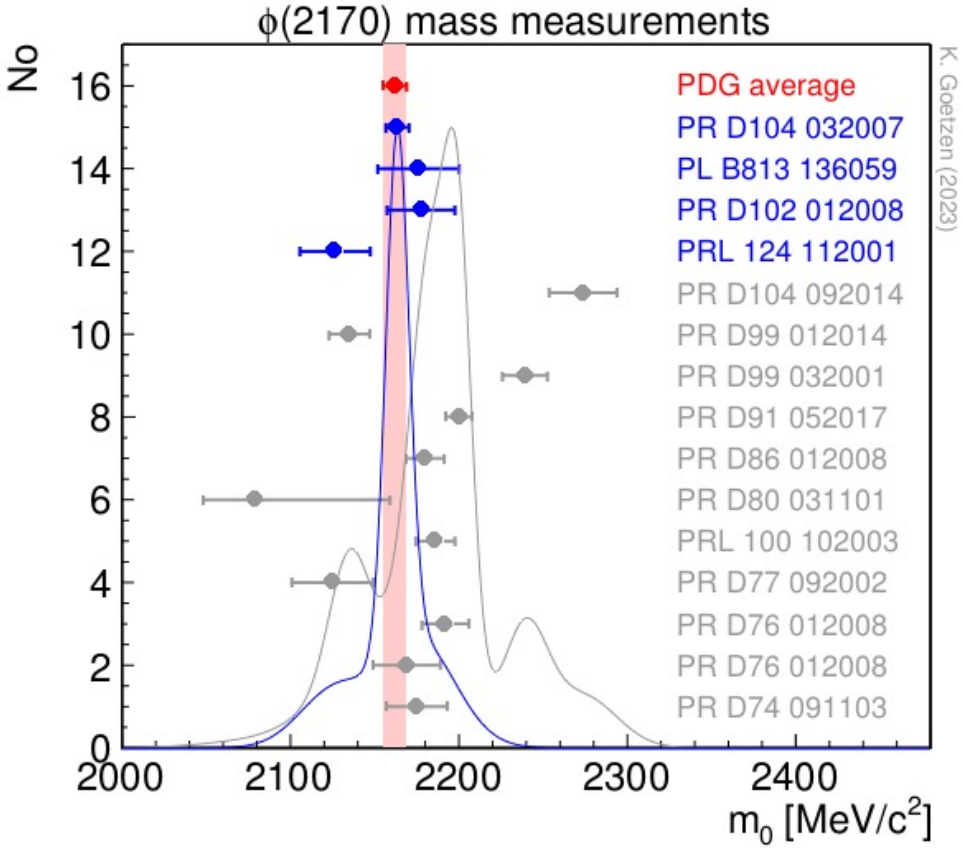
$e^+e^- \to K^+K^-$ cross section at $\sqrt{s} = 2.00 - 3.08$ GeV

$$M = 2239.2 \pm 7.1 \pm 11.3 \text{ MeV}/c^2$$
$$\Gamma = 139.8 \pm 12.3 \pm 20.6 \text{ MeV}$$

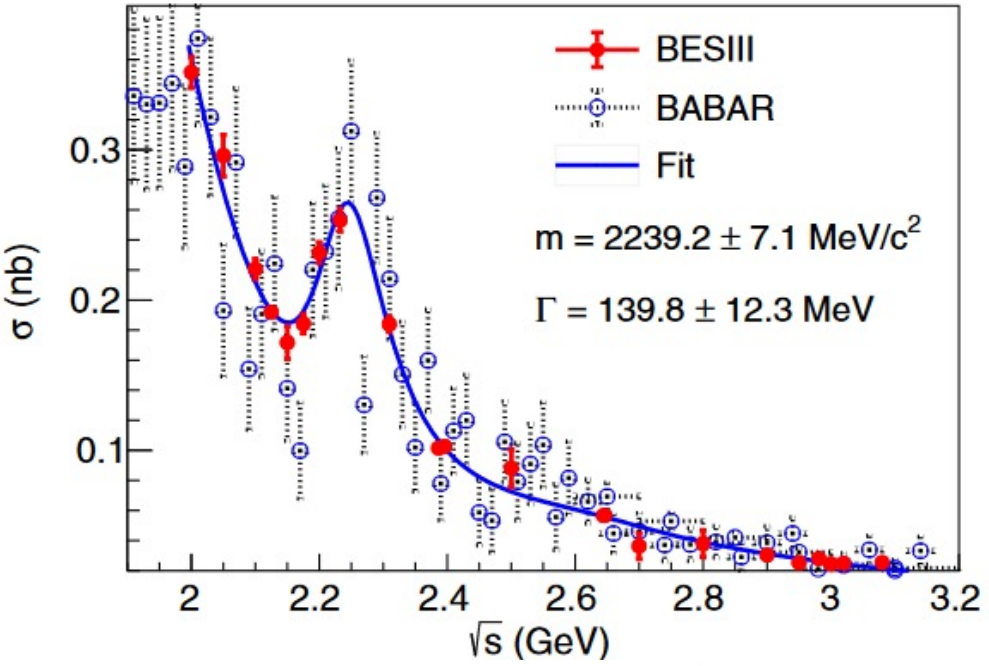
First observed in ISR, BaBar

PDG: Larger spread in individual resonance parameter measurements, e.g. above

The Y(2175) – strange partner of Y(4230)



[Phys. Rev. D 99, (2019) 032001]



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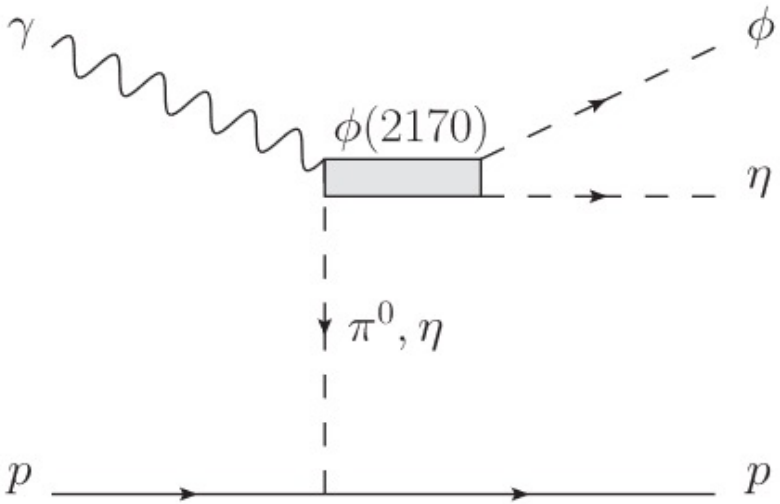
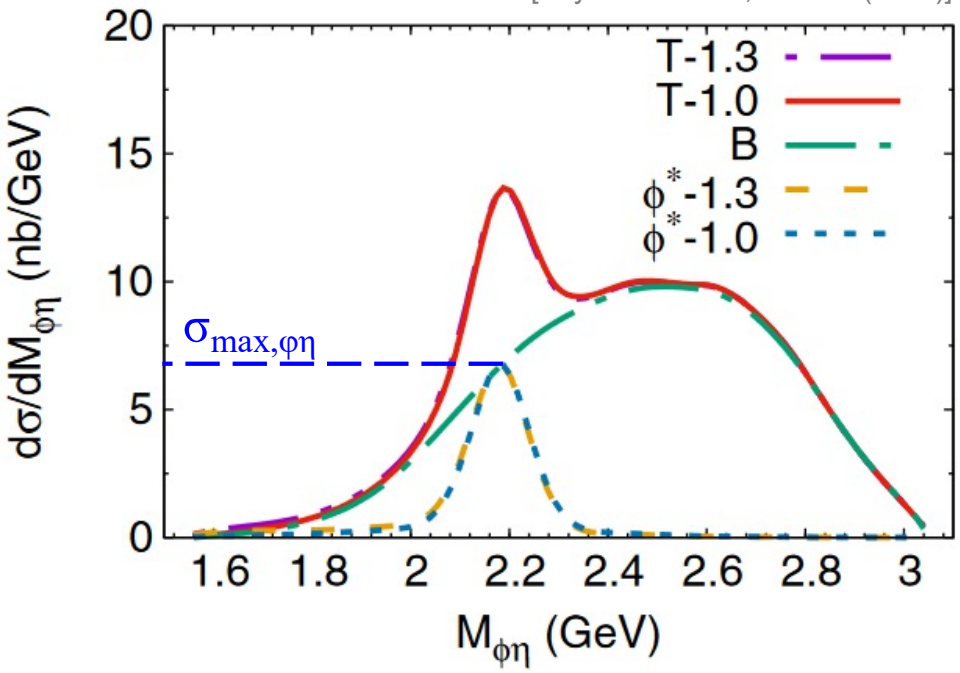
Prediction for photoproduction

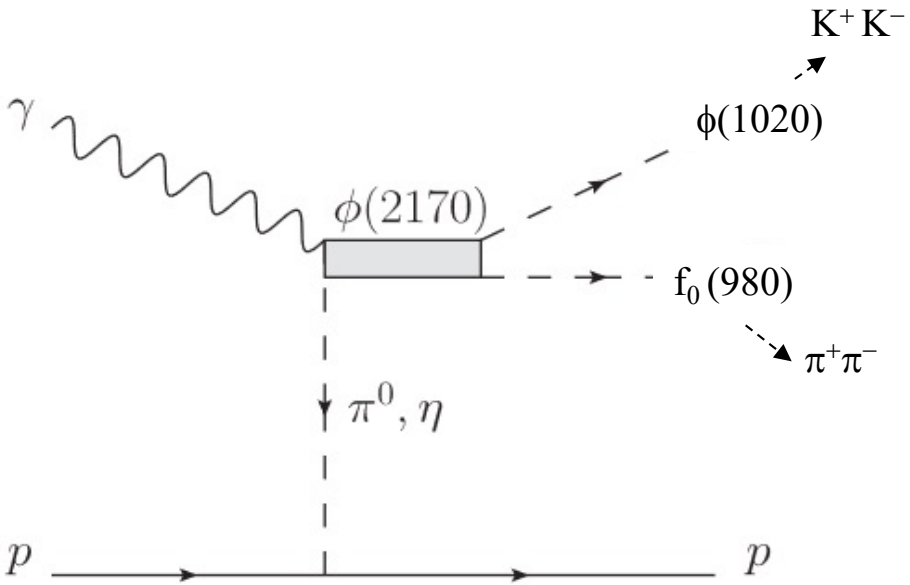


[Phys. Rev. D 99, 114014 (2019)]

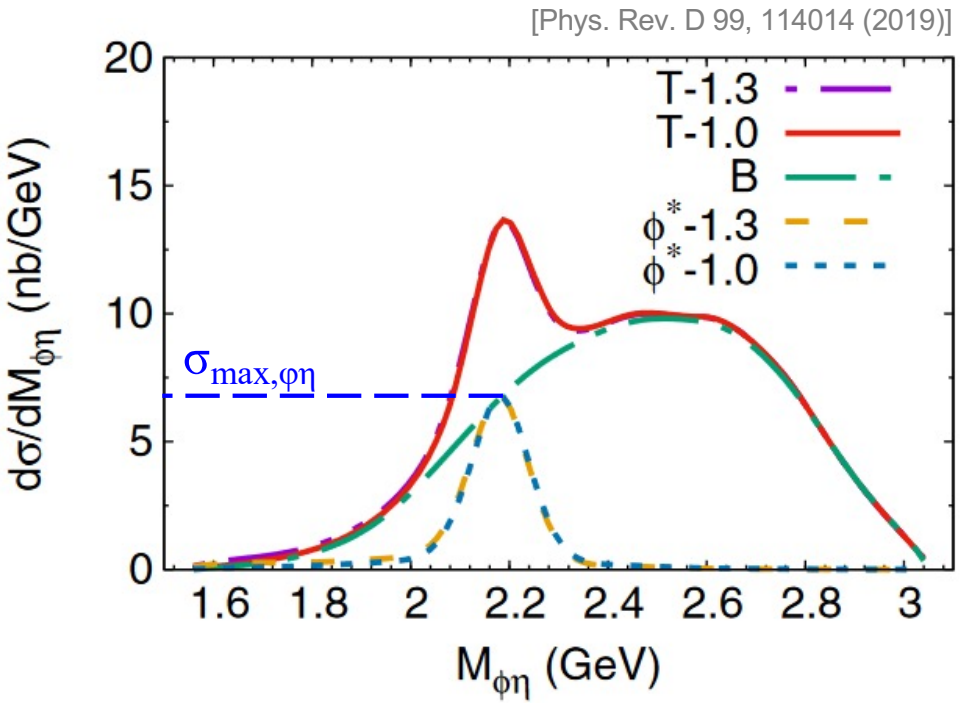


- Investigation of reaction $\gamma p \rightarrow \varphi\eta p$ @ $E_\gamma = 8$ GeV
- Assumption: $\Gamma(Y(2175) \rightarrow \varphi\eta) \approx 6.6$ MeV (quark model)
- Peak integral: $\sigma_{\varphi\eta} \approx 885$ pb (with $\sigma_{max} \approx 7$nb, $\Gamma = 83$ MeV/c^2)

Study $\phi\pi\pi$ photoproduction



[Phys. Rev. D 99, 114014 (2019)]



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- Peak integral: $\sigma_{\varphi\eta} \approx 885$ pb (with $\sigma_{max} \approx 7$nb, $\Gamma = 83$ MeV/c^2)
- $\Gamma(Y(2175) \rightarrow \varphi f_0(980)) / \Gamma(Y(2175) \rightarrow \varphi\eta)) \approx 1.37$
  - For $Y(2175) \rightarrow \varphi f_0(980)$: $\sigma_{\varphi f0} \approx 1212$ pb

Timeline	$\int \mathcal{L}$ (pb^{-1})
2017	22
2018	103
~~2020~~	~~132~~
2023	
2024	

Event selection

I)
- Apply loose PID selection (dE/dx, ToF)
- Form $\gamma\, K^+K^-\pi^+\pi^-\, p$ candidates
- Perform 4C of $K^+K^-\pi^+\pi^-\, p$ to γp_{target} system together with
- Vertex fit of $K^+K^-\pi^+\pi^-\, p$ system

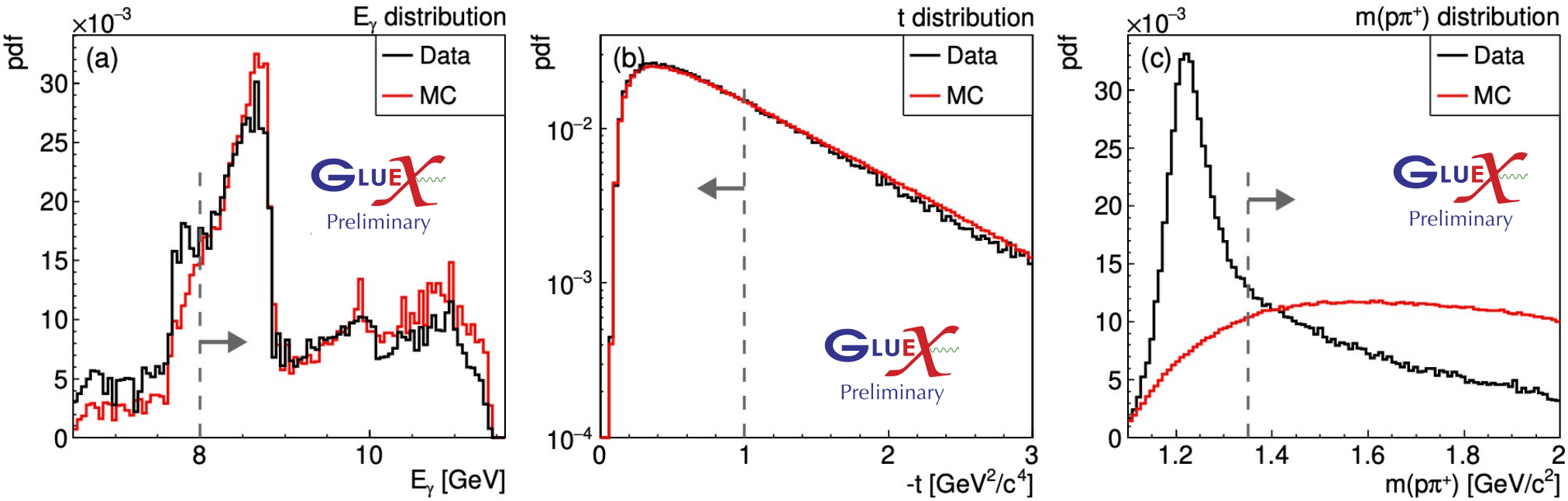
} event candidates

II)
- Apply beam energy cut $E_\gamma > 8$ GeV
- Apply momentum transfer cut $-t < 1\ \mathrm{GeV}^2/c^4$ (fiducial)
- Apply veto cut for $\Delta^{++}(1232)$: $m > 1.35\ \mathrm{GeV}/c^2$
- Require $|MM^2| < 50\ \mathrm{MeV}^2/c^4$ for missing mass squared
- Require $\chi^2_{4C+vtx} < 70$

} event selection cuts

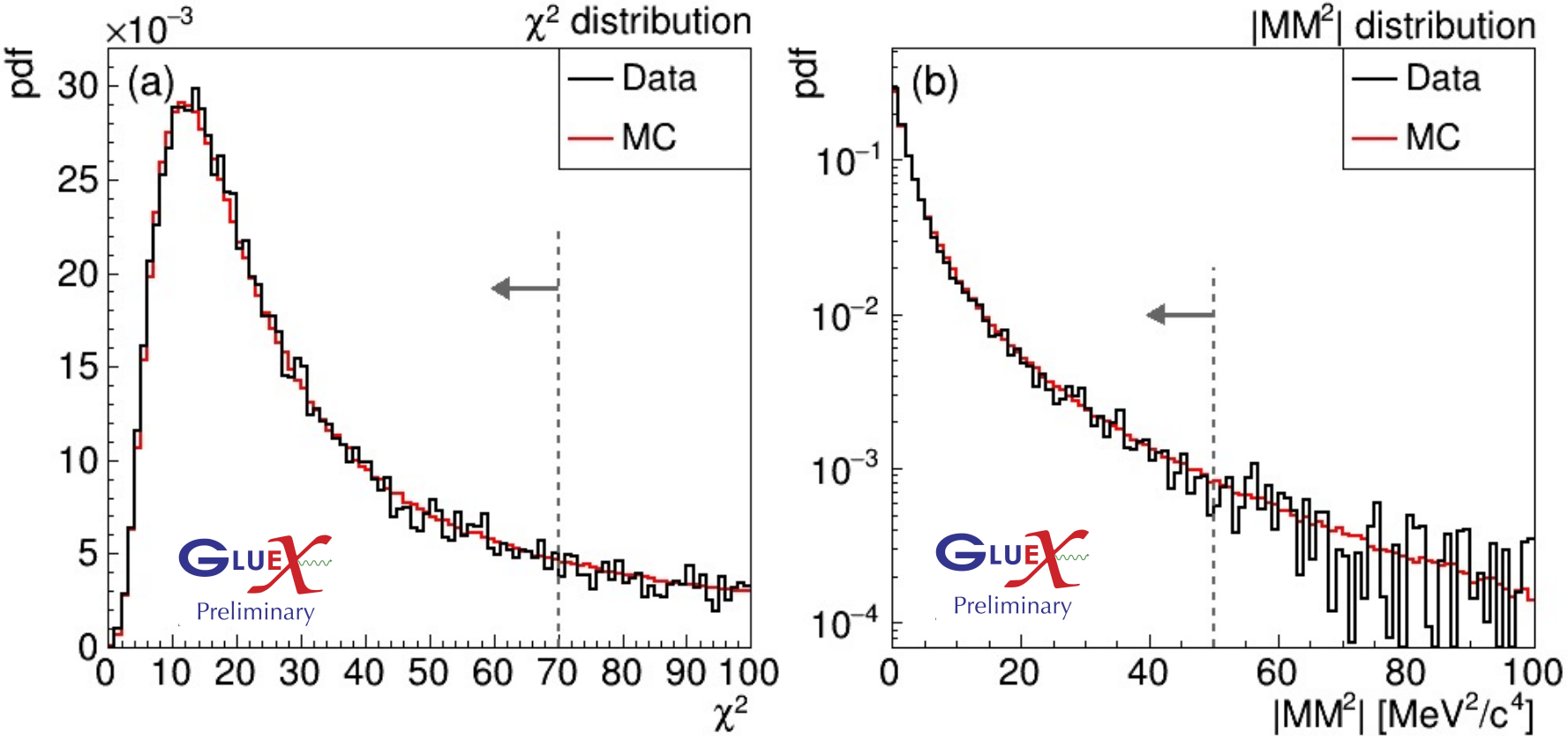
III)
- Determine $\phi(1020)$ yield using a Voigtian fctn.

Event selection (II): MC vs. Data



- Photon energy:
  $E_\gamma > 8$ GeV
- Momentum transfer:
  $-t < 1$ GeV^2/c^4
- Veto $\Delta(1232)^{++}$:
  $m(\pi^+ p) > 1.35$ GeV/c^2

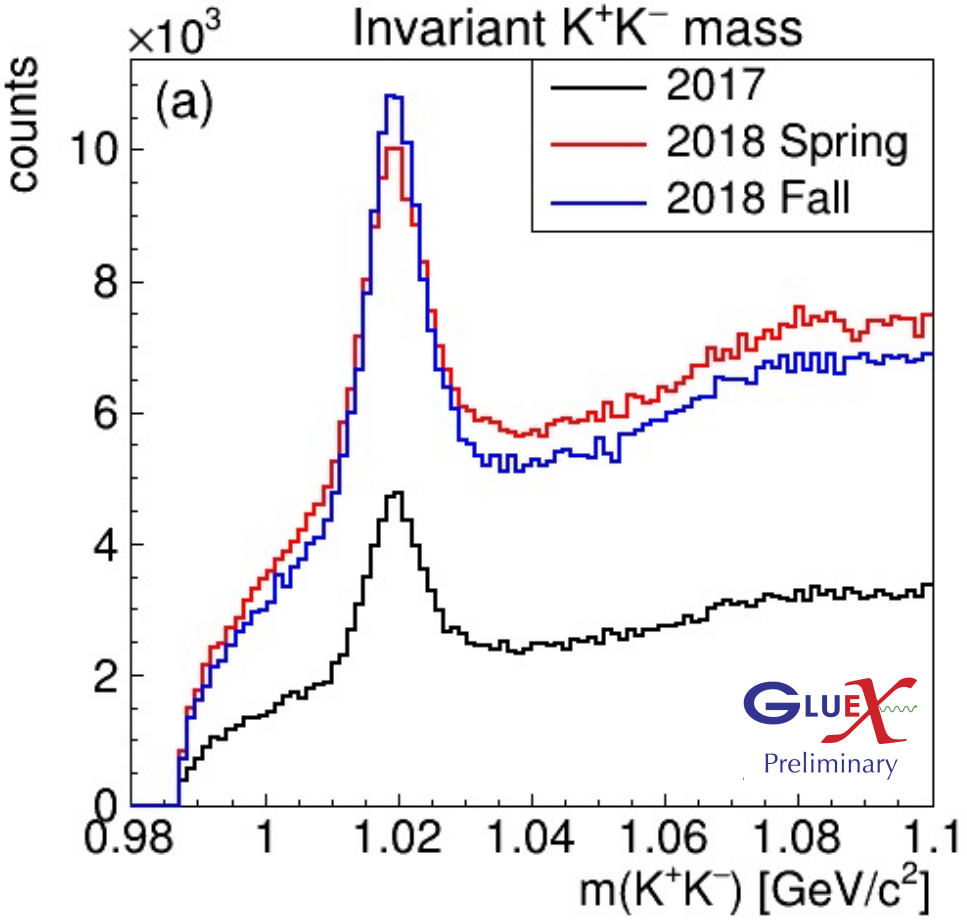
Event selection (II): Kinematics

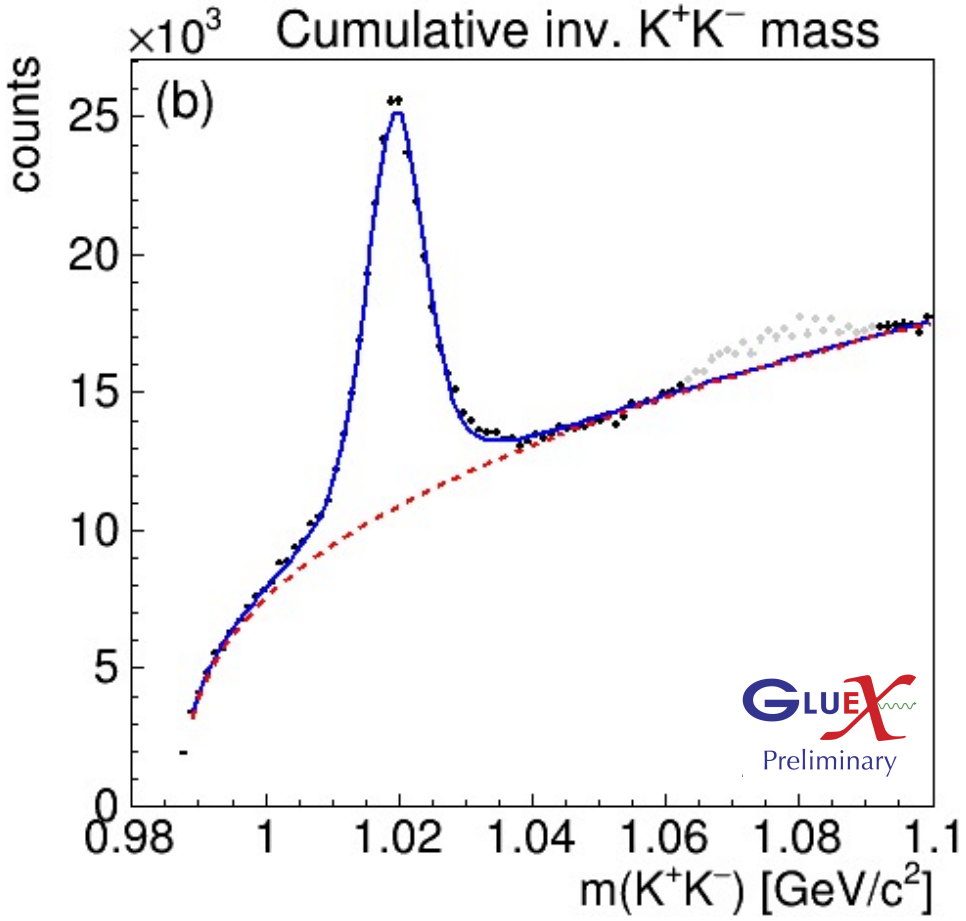


- 4C and vertex fit quality:
  $\chi^2 < 70$ (ndf = 11)

- Missing mass:
  $|MM^2| < 50$ MeV²/c⁴

φ(1020) signal in different data sets



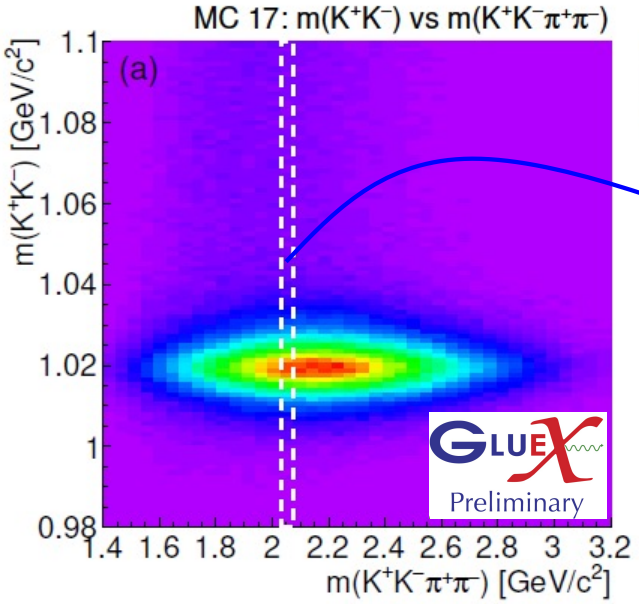


- Fit signal with function (V = Voigtian):

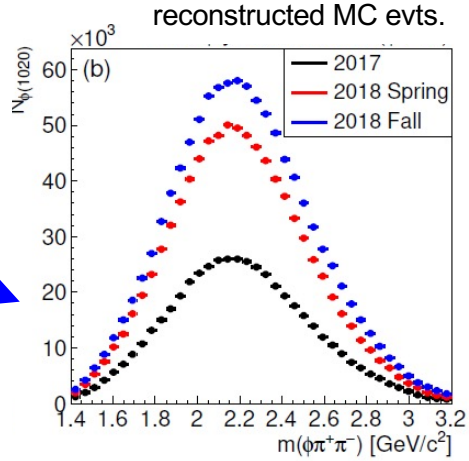
$$f(m) = V(m; m_0, \Gamma_0, \sigma_{\text{res}}) + |m - m_t|^p \cdot e^{-\lambda m} \qquad \text{for } m > m_t,$$

- Fix φ-shape parameters to extract distributions slice-wise

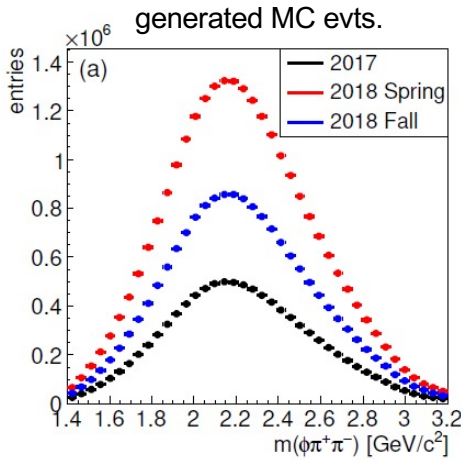
Slice-wise efficiency determination



reconstructed MC evts.

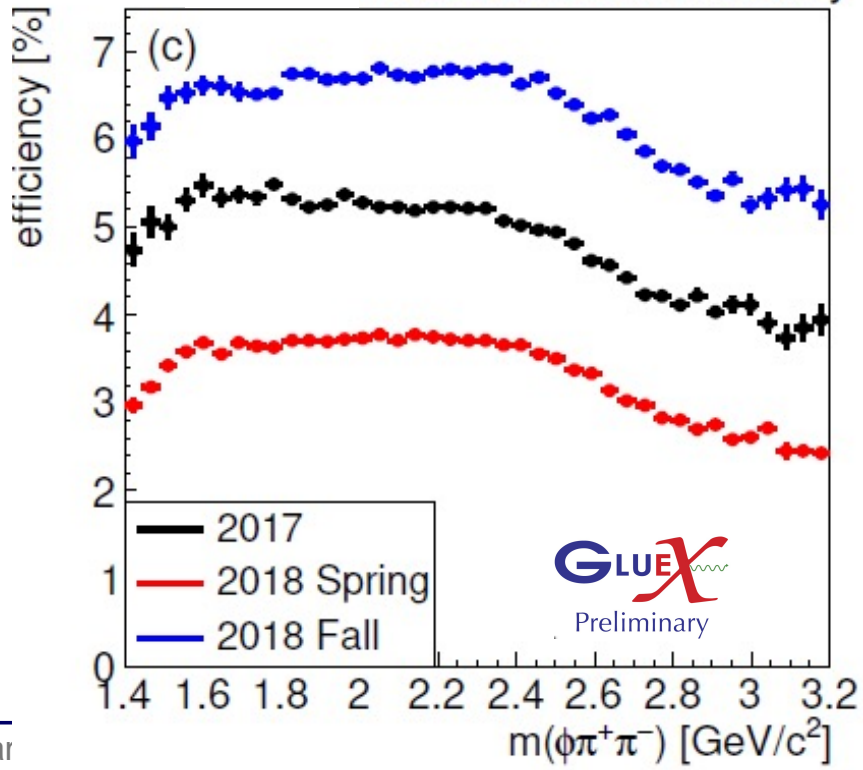


generated MC evts.

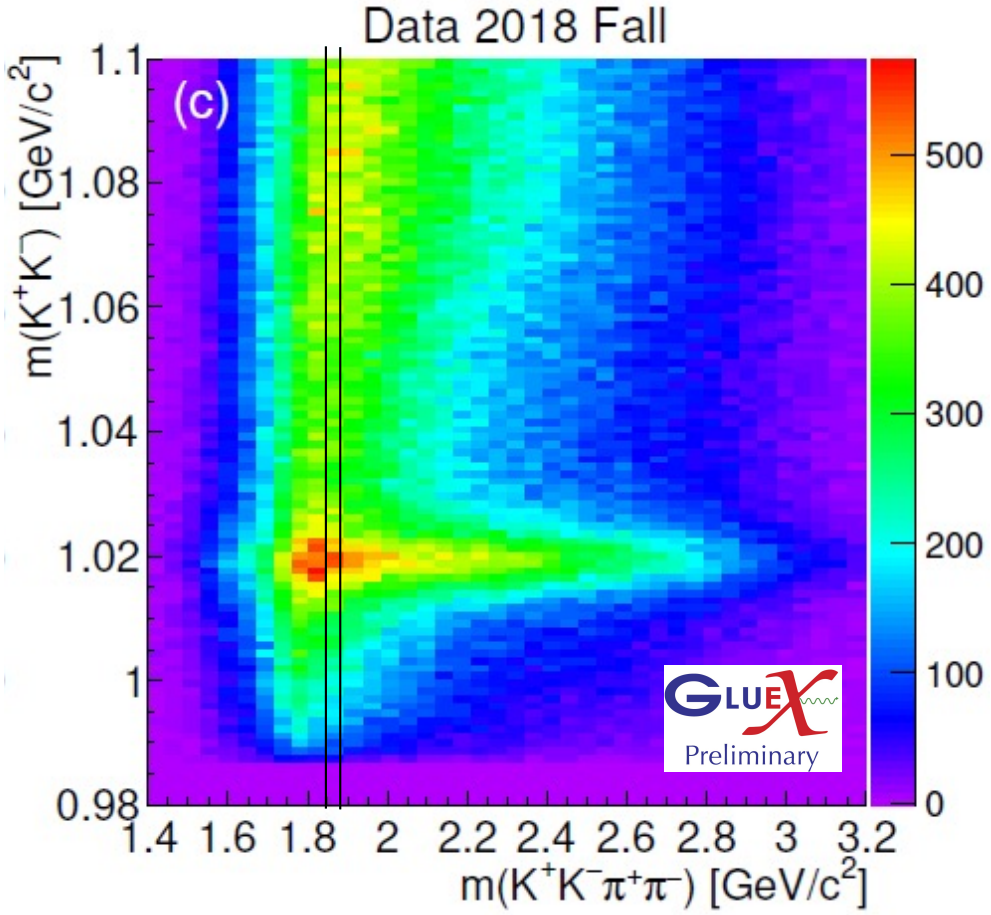


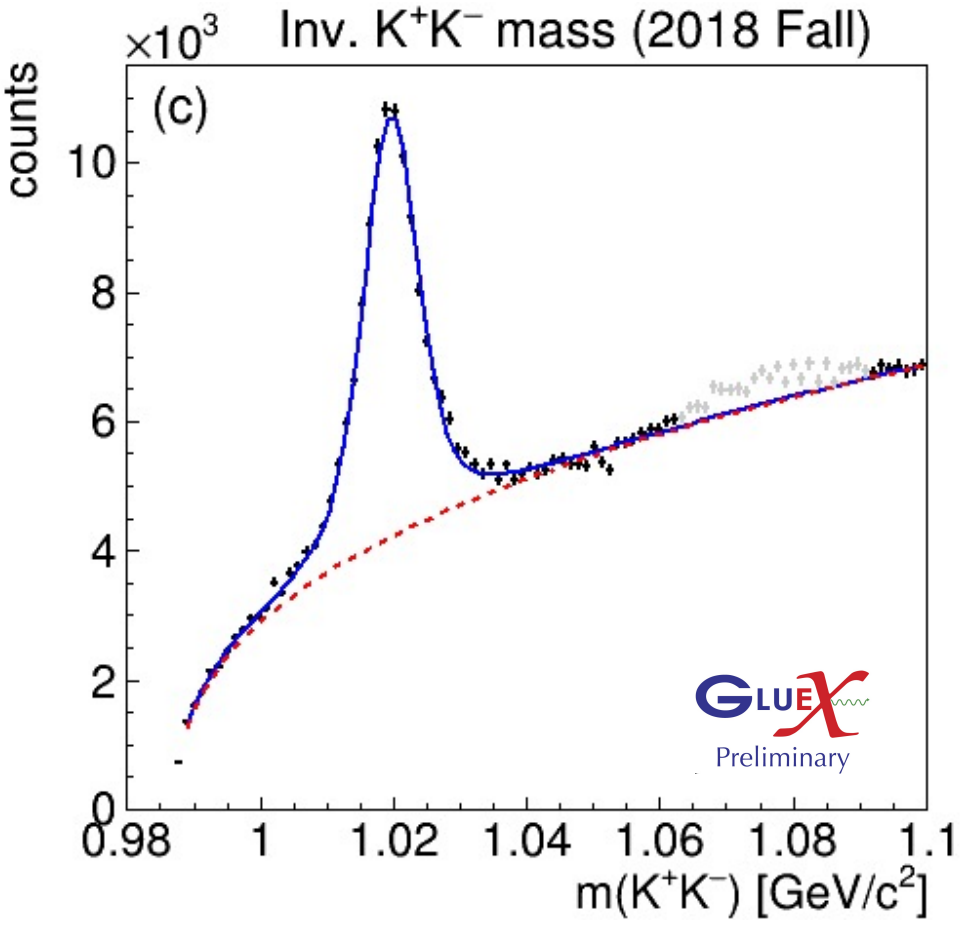
=>

reconstruction efficiency



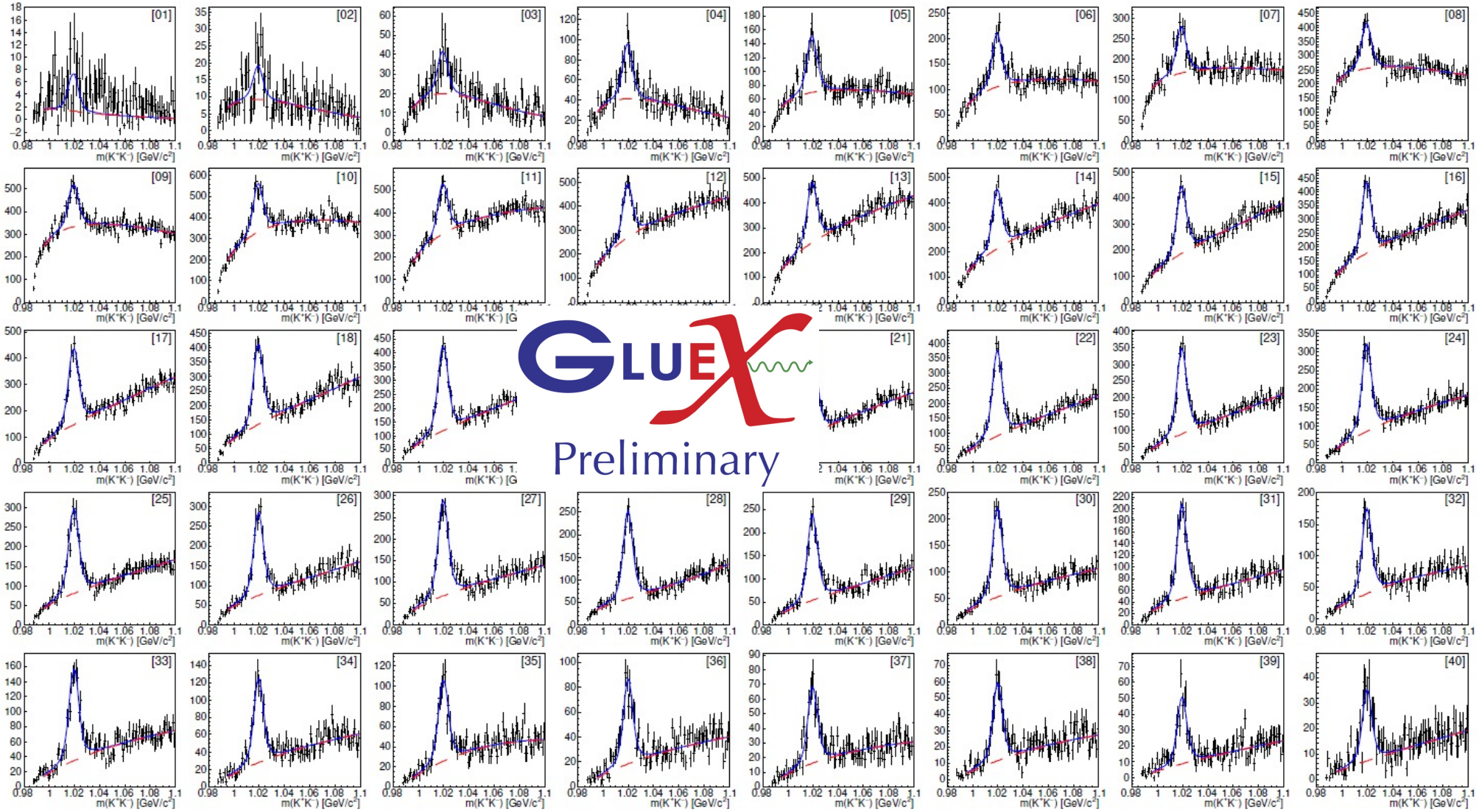
Slice-wise fits & φ signal shape parameters





- Fit yields in 45 MeV slices in 4-body mass with fixed signal shape
- Signal shape parameters m and σ_{res} determined from data (coarse scan)

„Slice-wise φ fits“, data

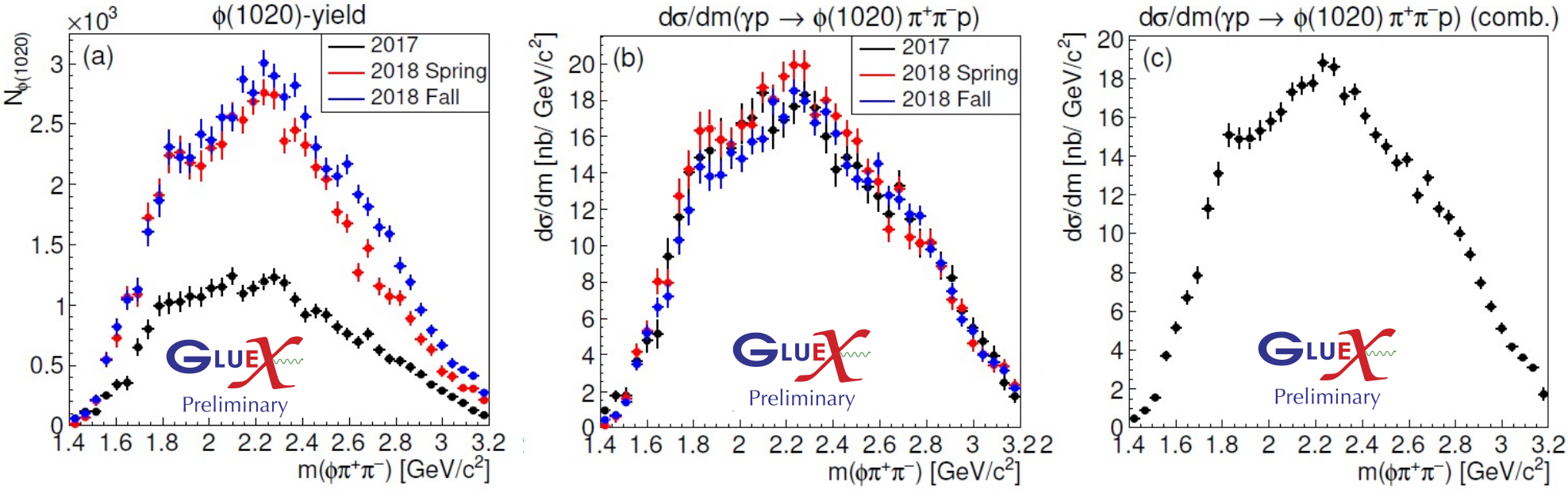


- Single slice fits data (here for 2018 Fall)

Differential cross section

- Determine mass-dependent cross section:

$$\frac{d\sigma}{dm}(m_i) = \frac{N_\phi(m_i)}{\varepsilon(m_i) \cdot F \cdot d_{\text{target}} \cdot \mathcal{B}(\phi(1020) \to K^+K^-)}$$



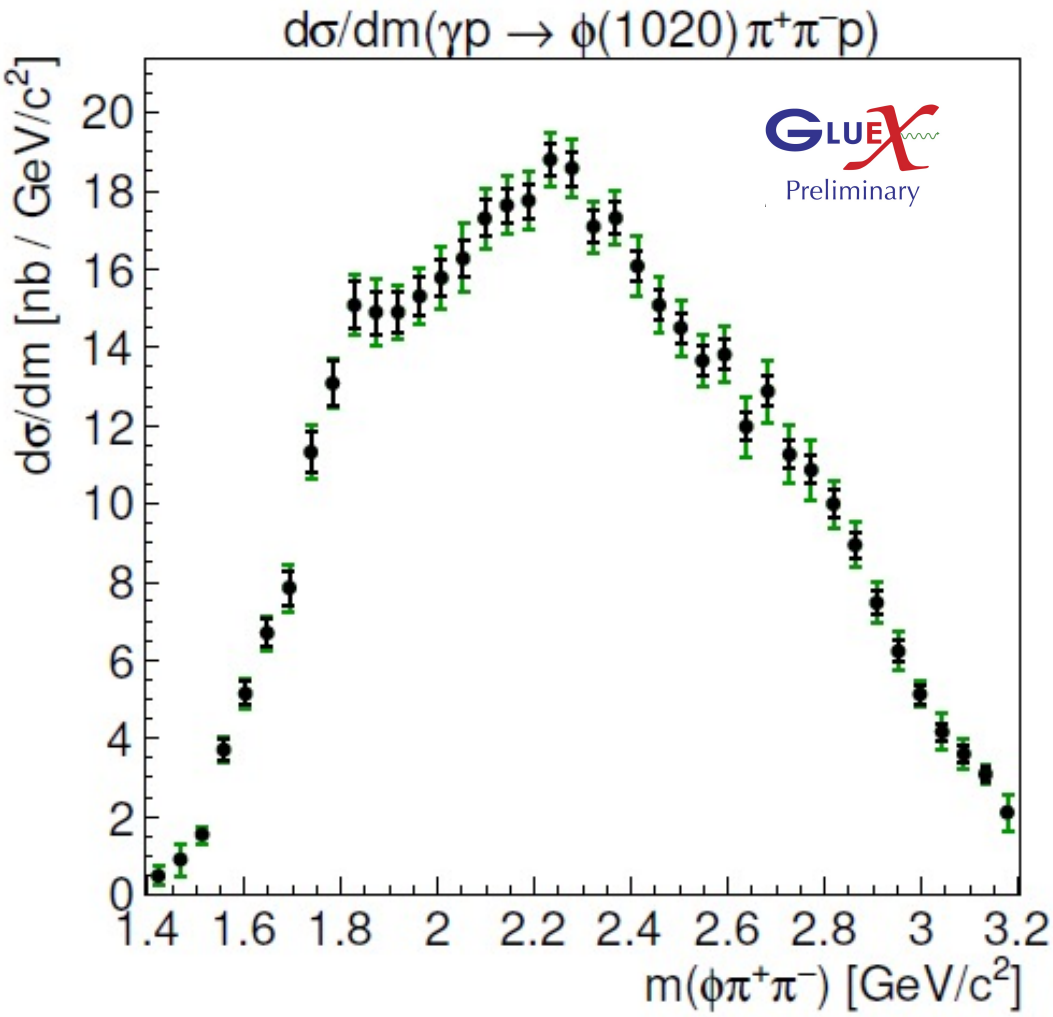
- Combine results by bin-wise via „weighted average“ method:

$$\hat{x} \pm \delta\hat{x} = \frac{\sum_i w_i x_i}{\sum_i w_i} \pm \left(\sum_i w_i^2\right)^{-1/2} \quad \text{with } w_i = 1/\delta x_i^2$$

Mass-dependent cross section result

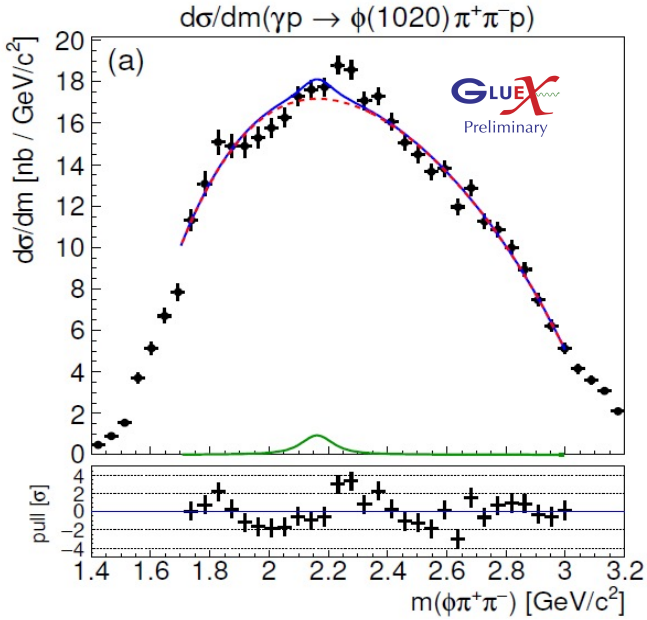
=> Take differences in cross section of default vs. varied fit as systematics

Source	$\delta_{\text{sys,avg}}$ [%]
$\phi(1020)$ branching fraction	1.0
χ^2 requirement	0.9
MM^2 requirement	0.4
Accidentals	0.5
K^+K^- binning	0.7
$\Delta(1232)^{++}$ veto	2.8
$\phi(1020)$ fit model data	0.8
$\phi(1020)$ fit model MC	0.7
$\phi(1020)$ fit range	1.6
$\phi(1020)$ veto range MC	0.5
$\phi(1020)$ integral range MC	0.1
$\phi(1020)$ param. interpolation	0.5
Total systematic uncertainty	4.7



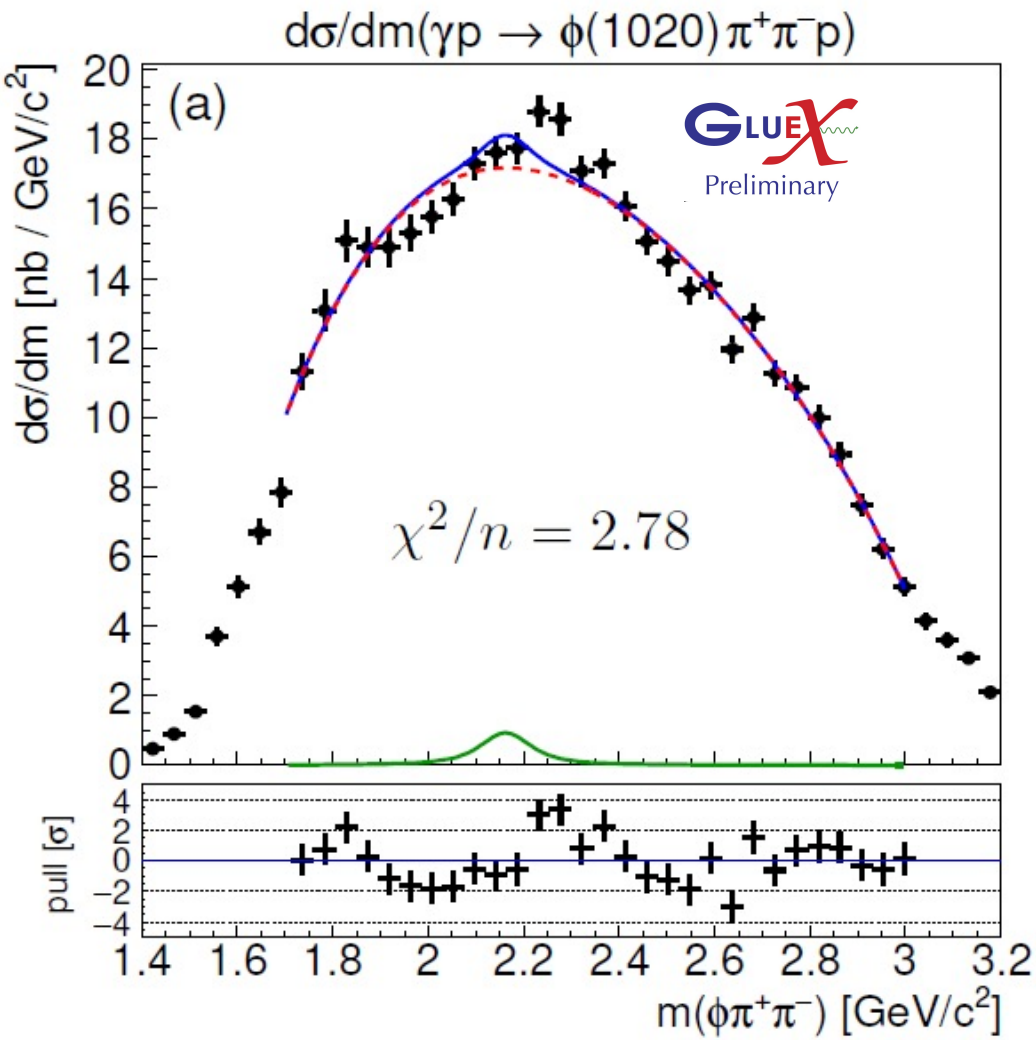
Search for resonances in m(φπ⁺π⁻)

- Fit signal + background in combined spectrum
  - 1 Res.: $f(m) = V(m; m_1, \Gamma_1, \sigma_{\rm res}) + T_4(m)$
  - 2 Res.: $f(m) = V_1(m; m_1, \Gamma_1, \sigma_{\rm res}) + V_2(m; m_2, \Gamma_2, \sigma_{\rm res}) + T_4(m)$
  - V = Voigtian, T_4 = 4th order Chebyshev polynomial
- Use weighted mass resolution from MC (σ_{res}= 24.6 MeV/c^2)
- Repeat for each systematic variation
- Systematic uncertainty: Difference to nominal result
- Additional systematics are:
  - m($\phi\pi\pi$) fit range
  - m($\phi\pi\pi$) fit model (degree of bkgd polynomial)
  - $\phi(2170)$ mass m_0 (by +/- 1σ)
  - $\phi(2170)$ width Γ_0 (by +/- 1σ)



- And we take the (larger) difference as systematic uncertainty

Fixed Y(2175) parameters – fit a_1)



R1: Fixed PDG parameters Y(2175)

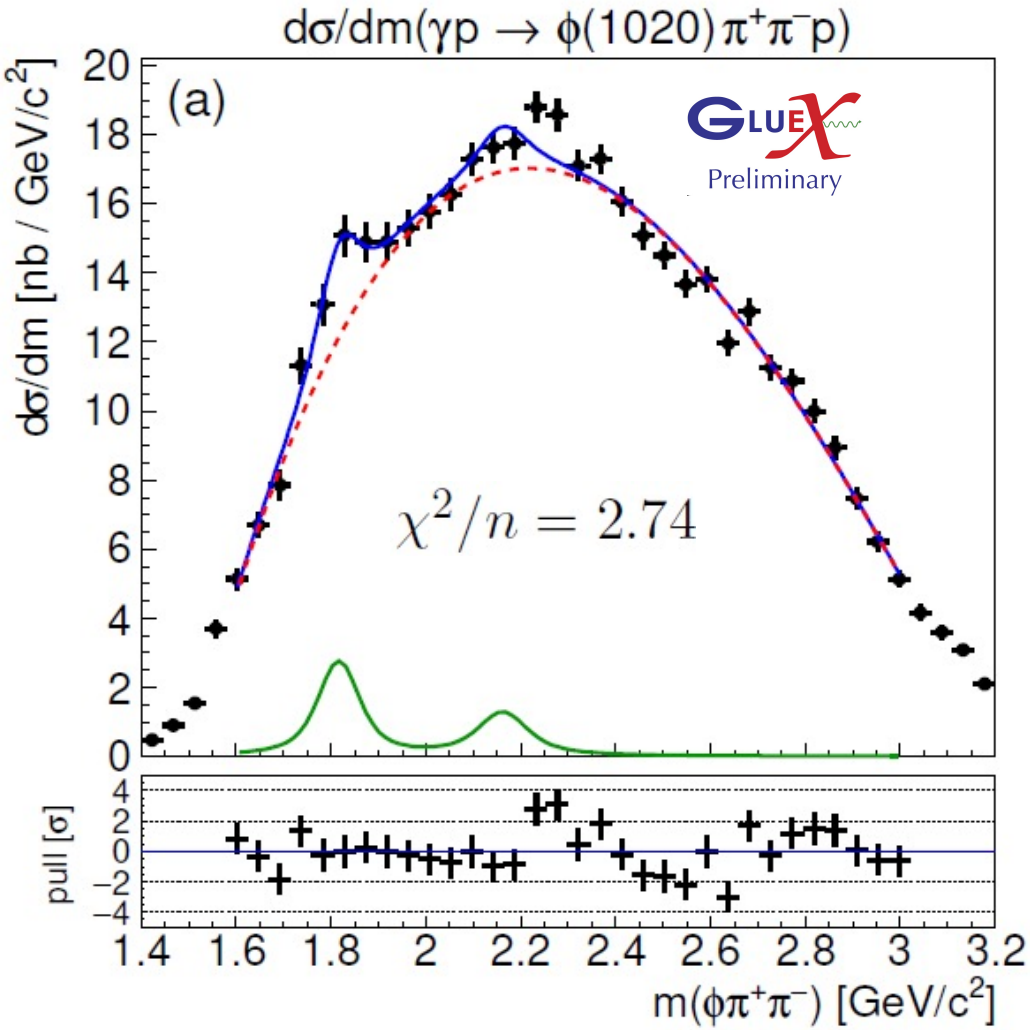
$$m_{\phi(2170)} = 2162 \pm 7 \text{ MeV}/c^2$$

$$\Gamma_{\phi(2170)} = 100^{+31}_{-21} \text{ MeV}/c^2$$

$$\sigma_{\phi(2170)} = 174 \pm 69\,(\text{stat.}) \pm 218\,(\text{sys.}) \text{ pb}$$

$$\sigma_{\phi(2170)} < 499 \text{ pb } (\text{CL90}) \quad [Z = 1.6\sigma\ (2.1\sigma)]$$

Fixed Y(2175) parameters – fit a_2)



R1: Fixed PDG parameters Y(2175)

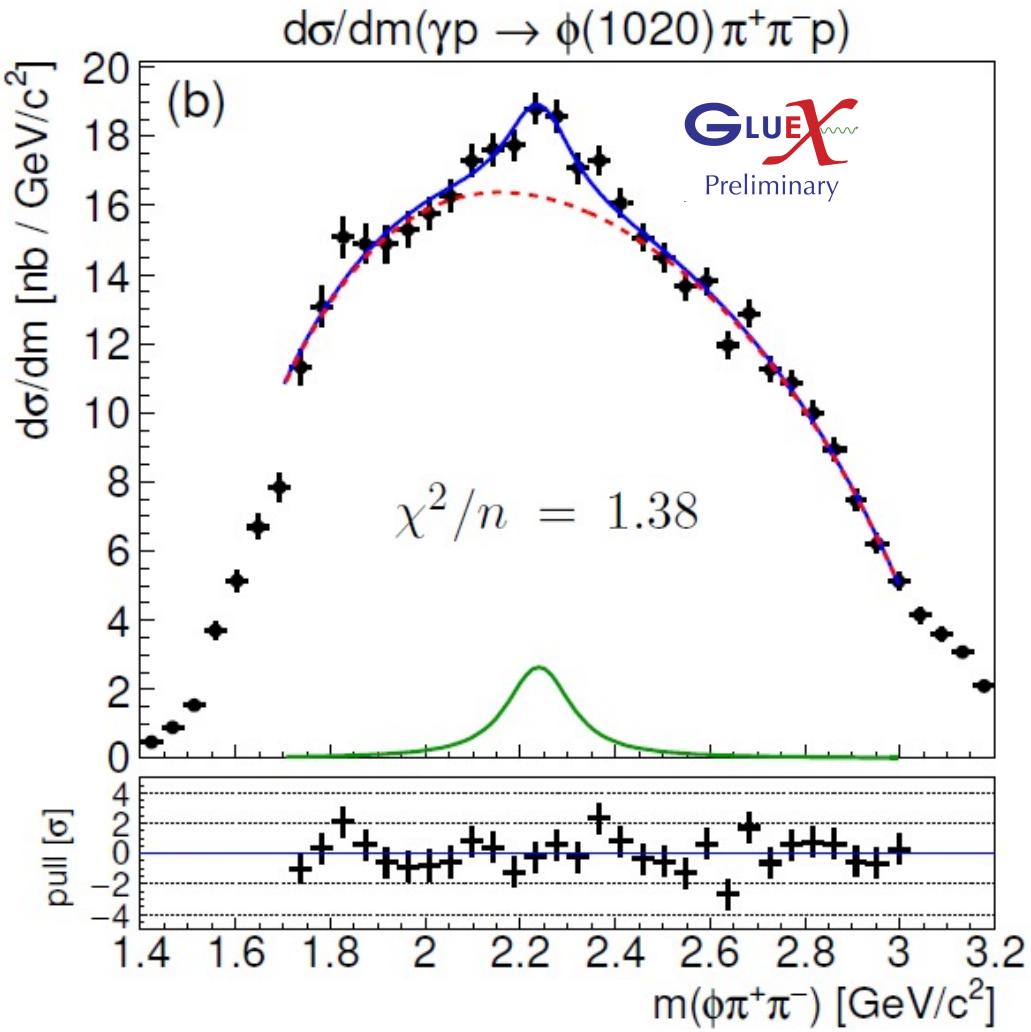
$$m_{\phi(2170)} = 2162 \pm 7 \text{ MeV}/c^2$$
$$\Gamma_{\phi(2170)} = 100^{+31}_{-21} \text{ MeV}/c^2$$

R2: Possible structure at m ~ 1.8 GeV

$$\sigma_{X(1800)} < 615 \text{ pb (CL90)}$$

$$\sigma_{\phi(2170)} = 232 \pm 68\,(\text{stat.}) \pm 91\,(\text{sys.}) \text{ pb}$$
$$\sigma_{\phi(2170)} < 379 \text{ pb (CL90)} \quad [Z = 1.5\sigma\ (1.8\sigma)]$$

Fixed Y(2239) parameters – fit b_1)



R1: Fixed parameters Y(2239)

$$m_{Y(2239)} = 2239.2 \pm 13.4 \text{ MeV}/c^2$$
$$\Gamma_{Y(2239)} = 139.8 \pm 24.0 \text{ MeV}/c^2$$

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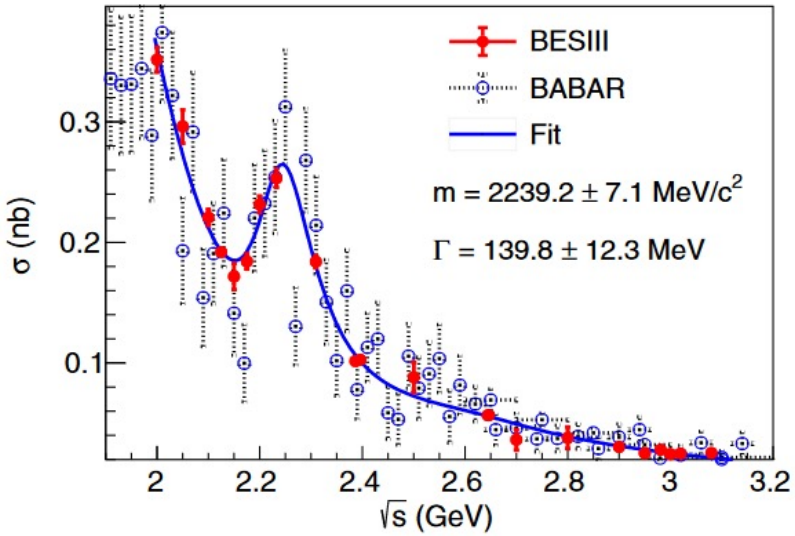
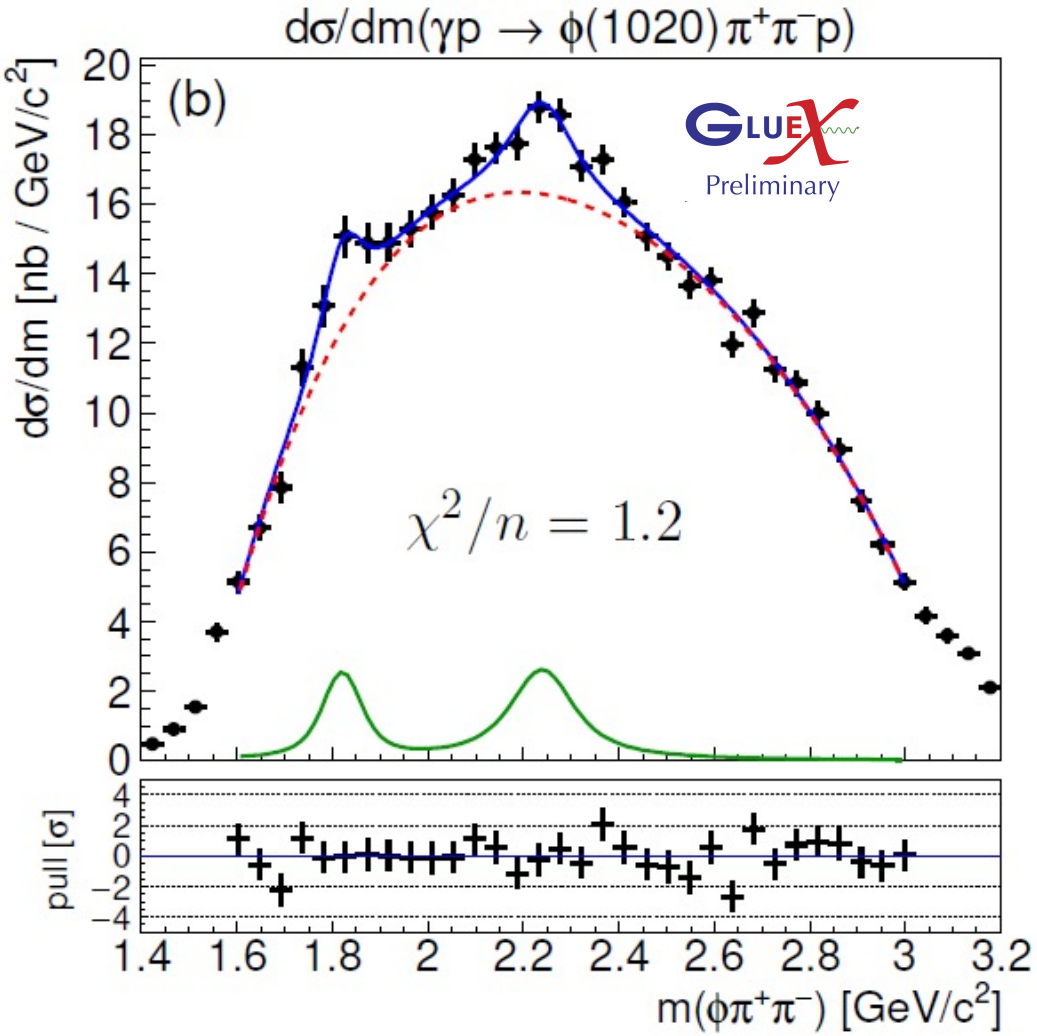


$$\sigma_{Y(2239)} = 641 \pm 82\,(\text{stat.}) \pm 181\,(\text{sys.})\ \text{pb}$$
$$\sigma_{Y(2239)} < 896\ \text{pb}\ (\text{CL90})\quad [Z = 5.7\sigma\ (6.0\sigma)]$$

Fixed Y(2175)‘ parameters – fit b_2)



R1: Fixed parameters Y(2239)

$$m_{Y(2239)} = 2239.2 \pm 13.4 \text{ MeV}/c^2$$
$$\Gamma_{Y(2239)} = 139.8 \pm 24.0 \text{ MeV}/c^2$$

R2: Possible structure at m ~ 1.8 GeV):

$$\sigma_{X(1800)} < 701 \text{ pb (CL90)}$$

$$\sigma_{Y(2239)} = 629 \pm 83\,(\text{stat.}) \pm 130\,(\text{sys.}) \text{ pb}$$
$$\sigma_{Y(2239)} < 826 \text{ pb (CL90)} \quad [Z = 4.7\sigma\ (5.1\sigma)]$$

Summary

- Analysis of reaction $\gamma p \rightarrow K^+K^-\pi^+\pi^- p$
- Measurement of differential $\varphi\pi^+\pi^-$ production cross section $\sigma(\gamma p \rightarrow \varphi\pi^+\pi^- p)$
- Search for Y(2175) + other resonances gives

Case	Cross Section [pb]	UL [pb]	Z_{stat}	Z_{tot}
Fit a_1: Y(2175) fixed	174 ± 69 ± 218	499	2.1	1.6
Fit a_2: Y(2175) fixed	232 ± 68 ± 91	379	1.8	1.5
Fit b_1: Y(2239) fixed	641 ± 82 ± 181	896	6.0	5.7
Fit b_2: Y(2239) fixed	629 ± 83 ± 130	826	5.1	4.7

- Fit with Y(2175) PDG parameters → no evidence ($Z < 3\sigma$)
- Alternative fits with Y(2239) parameters (fixed) → evidence/observation ($Z > 3$)
- Signal strength of Y(2239) in ball-park of predicted $\sigma \approx 1200$ pb
- Find 2nd structure at around $m \approx 1.8$ GeV/c^2
  - UL(CL90): $\sigma < 615$ pb (fit a_2) and $\sigma < 701$ pb (fit b_2)