Partial Wave Analysis of $\psi(3686) \longrightarrow \Lambda\bar{\Lambda}\phi$

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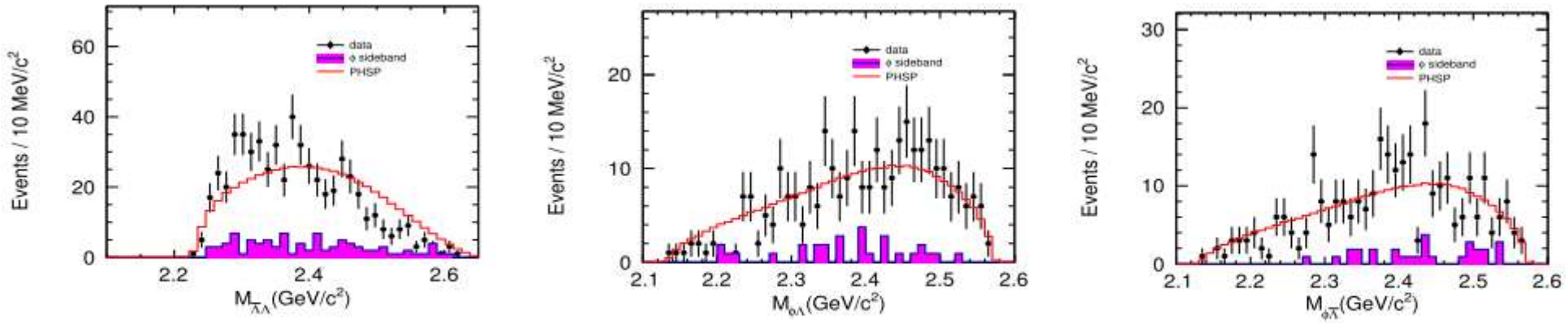
Outline

- **Motivation**
- **Data Samples**
- **Event selection criteria**
- **Background analysis**
- **Partial Wave Analysis**
- **Summary and Next to do**

Motivation

- **Search for possible intermediate resonances in the invariant mass of $\Lambda\bar{\Lambda}$, $\Lambda\phi$ or $\bar{\Lambda}\phi$.**

BAM-00421: Observation of psi(3686)->phi Lambda Lambda-bar decay, by Aonan Zhu et al.



- Charmonium mesons are a bridge between the light and heavy quarks, which will provide knowledge of its structure and may shed light on perturbative and non-perturbative strong interactions in this energy region.
- Study the baryon excited states consist of $\Lambda\phi$ or $\bar{\Lambda}\phi$

Data Samples

Data set	Number of events	BOSS version
09+12 ψ(3686) data	4.48×10^8	~ 2.7Billion
2021 ψ(3686) data	~22.5×10^8	
09+12 ψ(3686) inclusive MC	5.06×10^8	BOSS 7.0.9
2021 ψ(3686) inclusive MC	~23×10^8	
Signal MC (PHSP)	1.2 million for (09+12) 5 million for (2021)	

Event Selection criteria

Charged tracks

- $|\cos\theta| < 0.93$
- Kaons: $|V_z|$<10cm, $|V_r|$<1cm
- $\boldsymbol{N_{good} > 5}$, $\boldsymbol{N_{Kaon} > 1}$

Particle identification

- For Kaons (dE/dx + TOF)

  Prob(K)>Prob(π), Prob(K) >Prob(p)

  $\mathbf{N_{K+} = N_{K-} = 1}$
- For proton (dE/dx + TOF + EMC)

  Prob(p)>Prob(π), Prob(p) >Prob(K)
- Others are pions by default

  $\mathbf{N_p \geq 1, N_{\bar{p}} \geq 1, N_{\pi^+} \geq 1, N_{\pi^-} \geq 1}$

$\Lambda\&\bar{\Lambda}$ reconstruction

- $1.05 < \boldsymbol{M}_{p\pi^-} < 1.15\ \mathrm{GeV}/c^2$
- $1.05 < \boldsymbol{M}_{\bar{p}\pi^+} < 1.15\ \mathrm{GeV}/c^2$
- $\Lambda\&\bar{\Lambda}$ come from secondary vertex
- $min(\left|M_{p\pi^-} - m_\Lambda\right|^2 + \left|M_{\bar{p}\pi^+} - m_{\bar{\Lambda}}\right|^2)$
- $\Lambda\&\bar{\Lambda}: \frac{L}{\sigma} > 0$

4C-kinematic fit

- 4C-kinematic fit with $\Lambda, \bar{\Lambda}, K^+, K^-$
- $\chi^2_{4C} < 200$

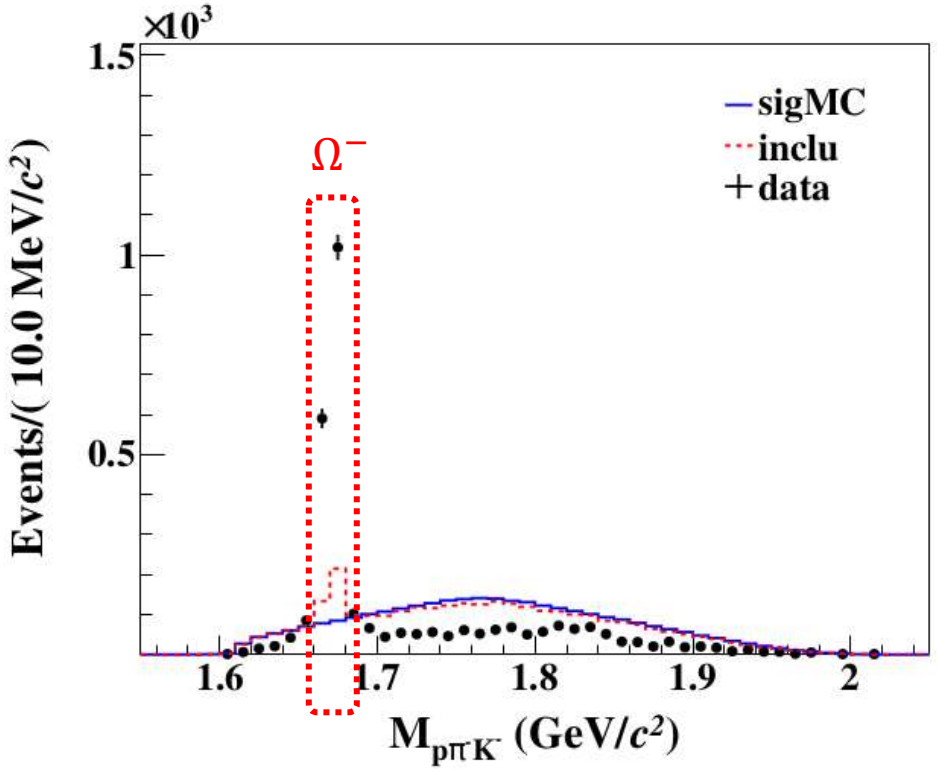
Background analysis

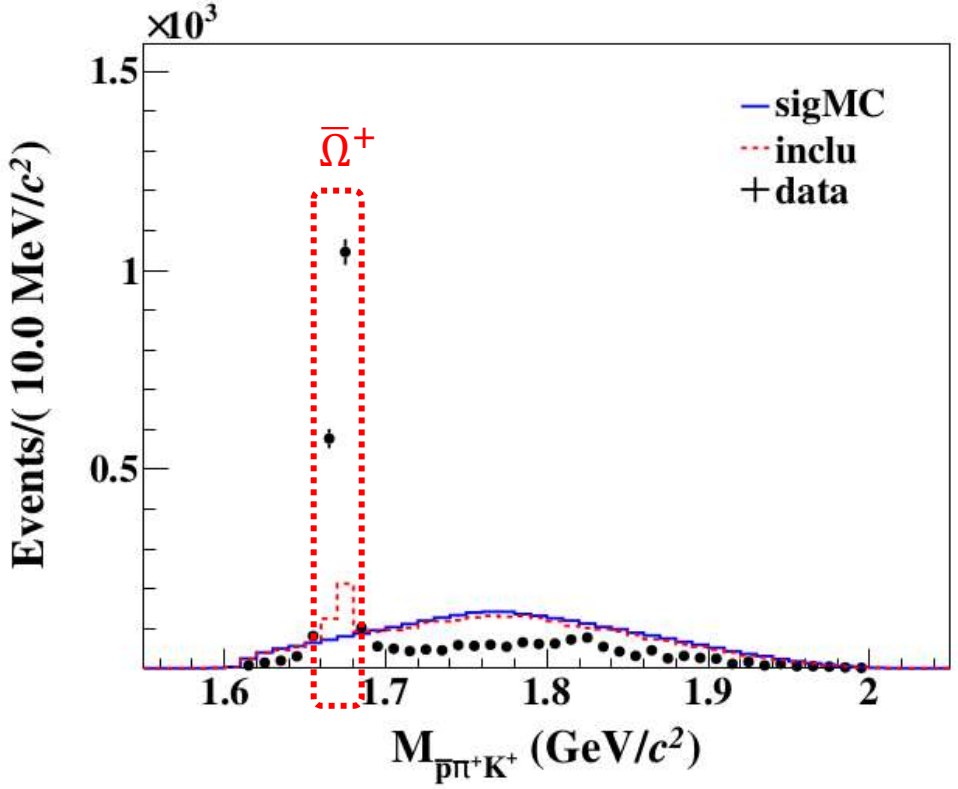
➢ **Topology** The main background is $\psi(3686) \longrightarrow \bar{\Omega}^{+}\Omega^{-}$

Table 1: Event trees and their respective initial-final states.

index	event tree (event initial-final states)	iEvtTr	iEvtIFSts	nEvts	nCmltEvts
1	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p})$	0	0	41933	41933
2	Main background $e^+e^- \to \psi', \psi' \to \bar{\Omega}^+\Omega^-, \bar{\Omega}^+ \to K^+\bar{\Lambda}, \Omega^- \to K^-\Lambda, \bar{\Lambda} \to \pi^+\bar{p}, \Lambda \to \pi^- p$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p})$	1	0	3253	45186
3	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p\gamma_{FSR}, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma_{FSR})$	2	1	37	45223
4	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}\gamma_{FSR}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma_{FSR})$	5	1	29	45252
5	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}\gamma$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma)$	6	2	17	45269
6	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to e^-\bar{\nu}_e p, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to e^-\bar{\nu}_e\pi^+ K^+K^- p\bar{p})$	12	5	15	45284
7	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-\gamma_{FSR}, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma_{FSR})$	8	1	14	45298
8	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p\gamma, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma)$	11	2	13	45311
9	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p, \bar{\Lambda} \to e^+\nu_e\bar{p}$ $(e^+e^- \to e^+\nu_e\pi^- K^+K^- p\bar{p})$	25	6	10	45321

➢ Reject $\psi(3686) \longrightarrow \bar{\Omega}^{+}\Omega^{-}$ events





- We reject the events in the range of $\boldsymbol{M_{p\pi K}} \in (1.668,1.674)$ GeV/c^2

- **Topology after vetoing $\psi(3686) \longrightarrow \bar{\Omega}^{+}\Omega^{-}$events.**

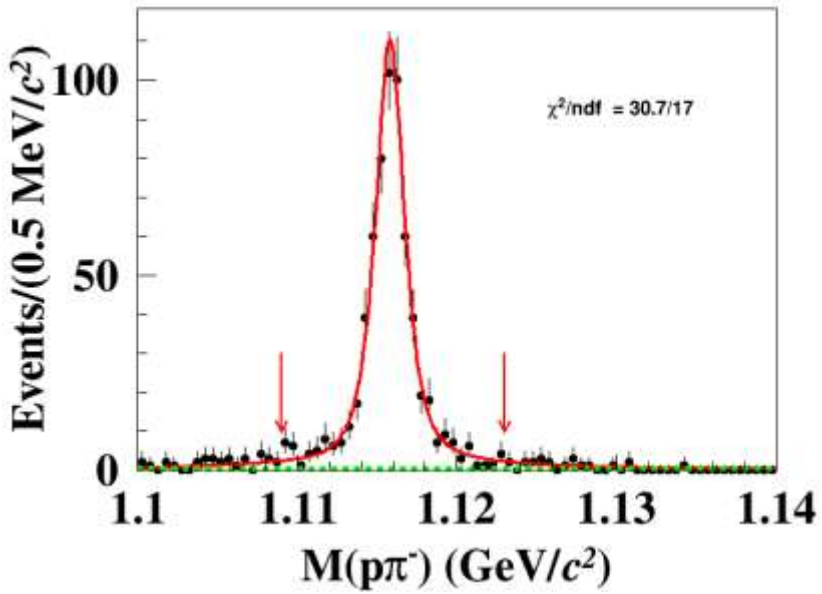
Backgrounds are less than 0.5%.

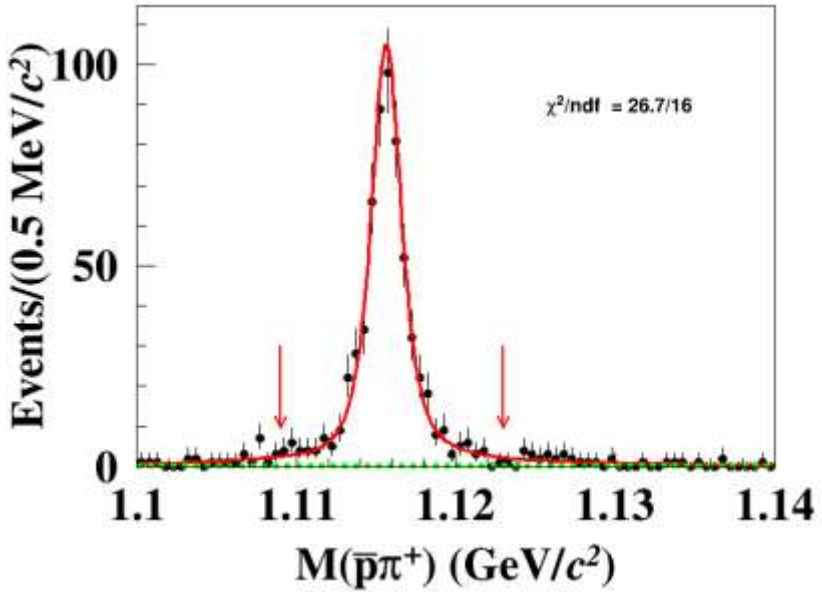
Table 1: Event trees and their respective initial-final states.

index	event tree (event initial-final states)	iEvtTr	iEvtIFSts	nEvts	nCmltEvts
1	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p})$	0	0	34344	34344
2	$e^+e^- \to \psi', \psi' \to \bar{\Omega}^+\Omega^-, \bar{\Omega}^+ \to K^+\bar{\Lambda}, \Omega^- \to K^-\Lambda, \bar{\Lambda} \to \pi^+\bar{p}, \Lambda \to \pi^- p$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p})$	2	0	59	34403
3	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p\gamma_{FSR}, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma_{FSR})$	1	1	26	34429
4	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}\gamma_{FSR}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma_{FSR})$	3	1	24	34453
5	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}\gamma$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma)$	4	2	14	34467
6	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to e^-\bar{\nu}_e p, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to e^-\bar{\nu}_e\pi^+ K^+K^- p\bar{p})$	7	4	12	34479
7	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-\gamma_{FSR}, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma_{FSR})$	6	1	11	34490
8	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p, \bar{\Lambda} \to e^+\nu_e\bar{p}$ $(e^+e^- \to e^+\nu_e\pi^- K^+K^- p\bar{p})$	11	5	8	34498
9	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p\gamma, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma)$	10	2	7	34505
10	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^- p, \bar{\Lambda} \to \mu^+\nu_\mu\bar{p}$ $(e^+e^- \to \mu^+\nu_\mu\pi^- K^+K^- p\bar{p})$	5	3	4	34509
11	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to f_0(980)\gamma, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}, f_0(980) \to K^+K^-$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma)$	8	2	2	34511
12	$e^+e^- \to \psi', \psi' \to \phi\Lambda\Sigma^0, \phi \to K^+K^-, \bar{\Lambda} \to \pi^+\bar{p}, \Sigma^0 \to \Lambda\gamma, \Lambda \to \pi^- p$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma)$	12	2	2	34513
13	$e^+e^- \to \psi', \psi' \to \Lambda\bar{\Lambda}a_0^0, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}, a_0^0 \to K^+K^-$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p})$	9	0	1	34514
14	$e^+e^- \to \psi', \psi' \to ??\gamma, ?? \to K^+K^-\Lambda\bar{\Lambda}, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma)$	13	2	1	34515
15	$e^+e^- \to \psi', \psi' \to \phi\Lambda\Sigma^0, \phi \to K^+K^-, \Lambda \to \pi^- p, \Sigma^0 \to \Lambda\gamma, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to \pi^+\pi^- K^+K^- p\bar{p}\gamma)$	14	2	1	34516
16	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to \pi^0 n, \bar{\Lambda} \to \pi^+\bar{p}\gamma$ $(e^+e^- \to \pi^+K^+K^- n\bar{p}\gamma\gamma)$	15	6	1	34517
17	$e^+e^- \to \psi', \psi' \to \phi\Lambda\bar{\Lambda}, \phi \to K^+K^-, \Lambda \to e^-\bar{\nu}_e p\gamma_{FSR}, \bar{\Lambda} \to \pi^+\bar{p}$ $(e^+e^- \to e^-\bar{\nu}_e\pi^+ K^+K^- p\bar{p}\gamma_{FSR})$	16	7	1	34518

Signal regions

➢ Signal regions of Λ, $\bar{\Lambda}$ peaks





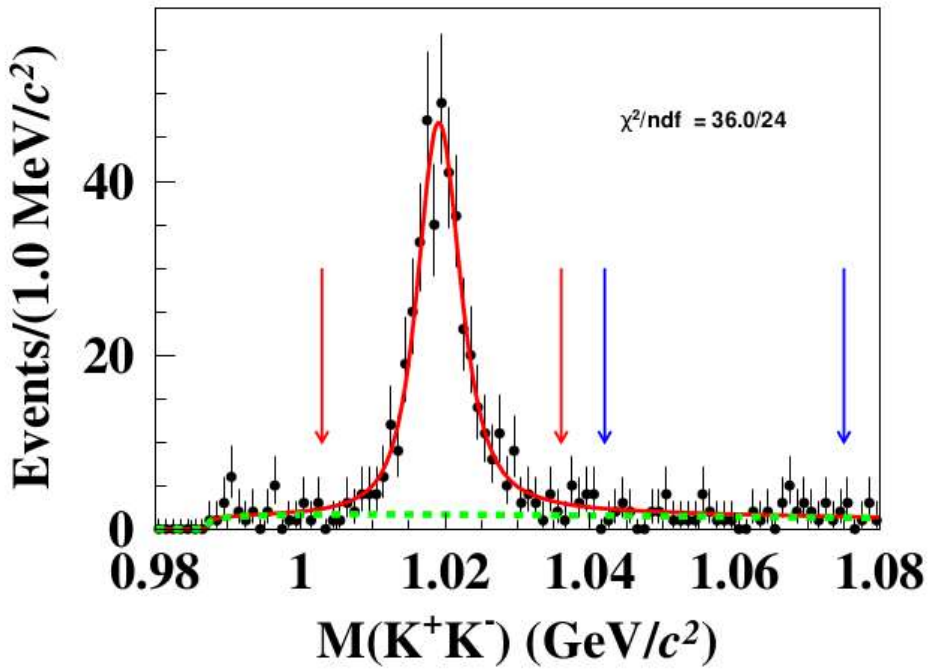
In the fit to $M(p\pi)$

- Signal shape: signal MC sample
- Bkg shape: Chebychev function

Λ / $\bar{\Lambda}$ mass region: (1.109,1.123) GeV/c^2

Signal regions

➢ Signal region of ϕ peak



In the fit to $M(K^+K^-)$

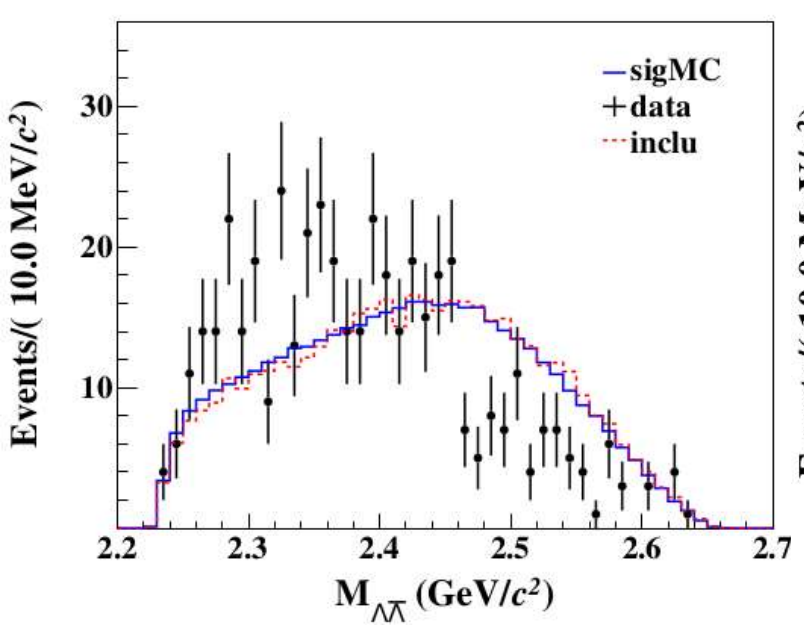
- Signal shape: signal MC sample
- Bkg shape: reverse Argus

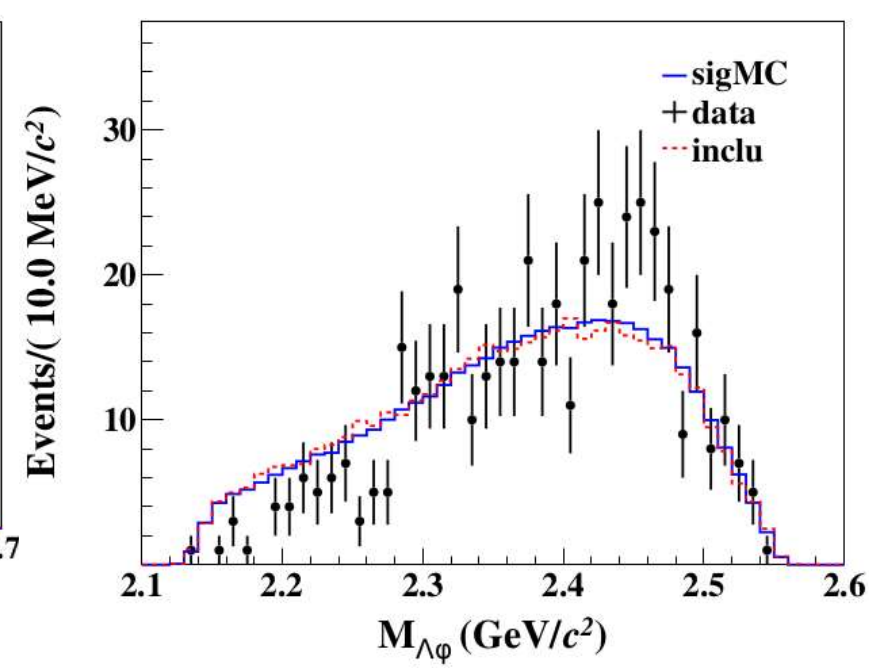
- ϕ mass region: (1.003,1.036) GeV/c^2
- ϕ sideband region: (1.042,1.075) GeV/c^2

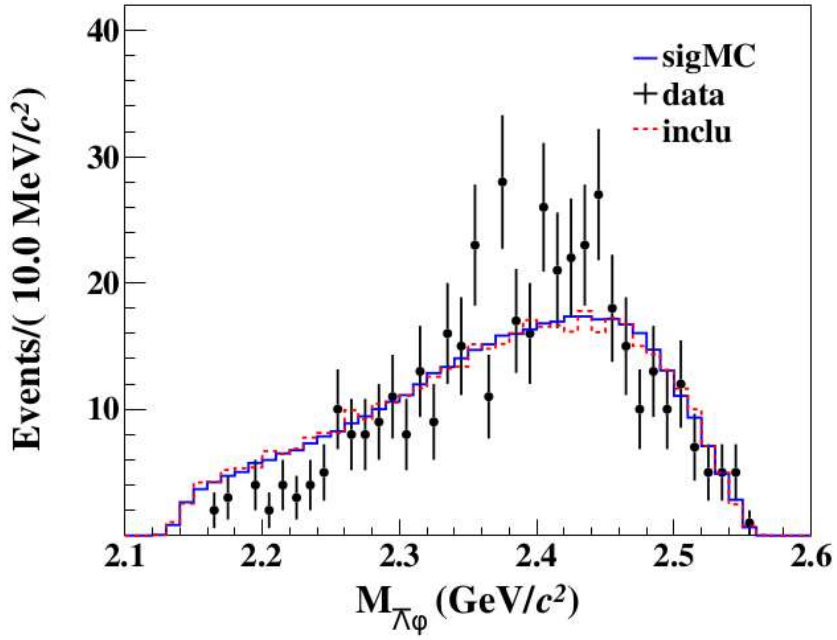
Comparisons of some distributions

- **Comparisons of the invariant mass of $\Lambda\bar{\Lambda}$, $\Lambda\phi$ or $\bar{\Lambda}\phi$**

A total of 449 events survived





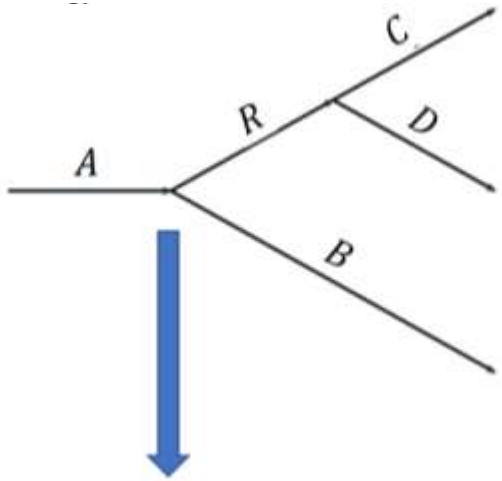


- The distributions from data are not consistent with those in signal MC (PHSP) and inclusive MC.
- There may be some intermediate structures, which can be extracted by the Partial wave analysis (PWA).

Partial Wave Analysis

➢ Introduction[1]

[1] Jiangyi: https://github.com/jiangyi15/tf-pwa



$$A^{R}_{\lambda_A,\lambda'_B,\lambda'_C,\lambda'_D}$$

$$=$$

$$\sum_{\lambda} F_{\lambda_R\lambda_B} D^{j_A\star}_{\lambda_A,\lambda_R-\lambda_B}(\varphi_1,\theta_1,0) R(M) F_{\lambda_C,\lambda_D} D^{j_R\star}_{\lambda_R,\lambda_C-\lambda_D}(\varphi_2,\theta_2,0)$$

$$D^{j_B\star}_{\lambda_B,\lambda_{B'}}(\alpha_B,\beta_B,\gamma_B) D^{j_C\star}_{\lambda_C,\lambda_{C'}}(\alpha_C,\beta_C,\gamma_C) D^{j_D\star}_{\lambda_D,\lambda_{D'}}(\alpha_D,\beta_D,\gamma_D)$$

$$\frac{d\sigma}{d\Phi} \propto \sum_{\lambda_A} \sum_{\lambda_B,\lambda_C,\lambda_D} \left| \sum_{R} A^{R}_{\lambda_A,\lambda_B,\lambda_C,\lambda_D} \right|^2$$

Automatically calculated from decay structure

Decay

Particle

$$F_{\lambda_1,\lambda_2} D^{j_0\star}_{\lambda_0,\lambda_1-\lambda_2}(\varphi,\theta,0)$$

Wigner-D matrix

$$R(M) = \frac{1}{m_0^2 - M^2 - i m_0 \Gamma}, \cdots$$

1

$$D^{j_1\star}_{\lambda_1,\lambda_{1'}}(\alpha,\beta,\gamma)$$

alignment

probability: $|\mathcal{A}|^2$

Decay Group: $\mathcal{A} = \tilde{A}_1 + \tilde{A}_2 + \cdots$

Decay Chain: $\tilde{A} = A_1 R A_2 \cdots$

Decay: Wigner D-matrix, $A = F D^{*J}(\phi,\theta,0)$

Particle: Breit-Wigner: $R(m)$, user defined

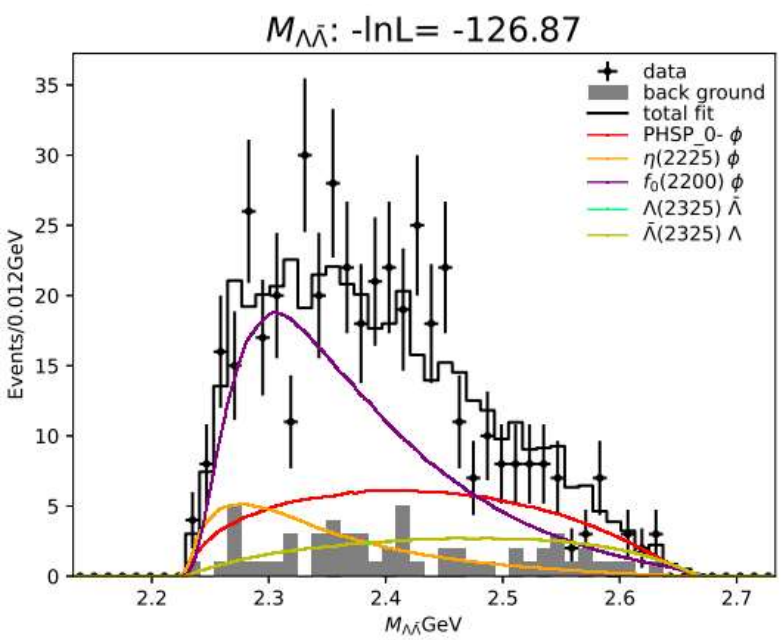
Possibly known resonances

➢ Possibly known resonances in $\psi(3686) \longrightarrow \Lambda\bar{\Lambda}\phi$

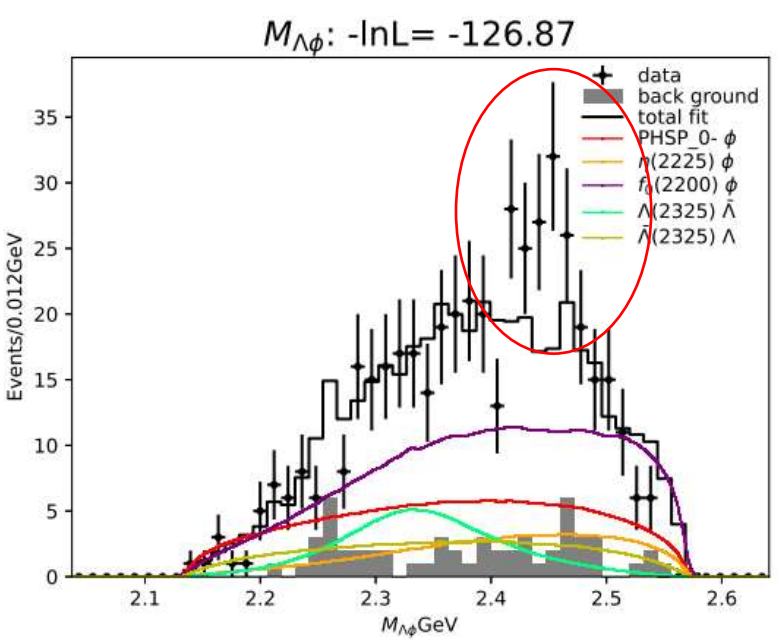
Final particles	Possibly known resonances	Quark components	$I^G(J^{PC})$	m_0 (GeV/c^2)	Γ_0 (GeV/c)
$\Lambda\bar{\Lambda}$ $(uds, \bar{u}\bar{d}\bar{s})$	$f_0(2200)$	$c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$	$0^+(0^{++})$	2.187	0.207
	$\eta(2225)$	$c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$	$0^+(0^{-+})$	2.221	0.185
	$f_0(2330)$	$c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$	$0^+(0^{++})$	2.312	0.065
	$f_0(2470)$	$c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$	$0^+(0^{++})$	2.470	0.075
$\Lambda\phi$ $(uds, s\bar{s})$	$\Lambda(2325)$	uds	$0(\frac{3^-}{2})$	2.342	0.177
	$\Sigma(2230)$	uds	$1(\frac{3^+}{2})$	2.240	0.345
$\bar{\Lambda}\phi$ $(\bar{u}\bar{d}\bar{s}, s\bar{s})$	$\bar{\Lambda}(2325)$	$\bar{u}\bar{d}\bar{s}$	$0(\frac{3^+}{2})$	2.342	0.177
	$\bar{\Sigma}(2230)$	$\bar{u}\bar{d}\bar{s}$	$1(\frac{3^-}{2})$	2.240	0.345

PWA results with known states

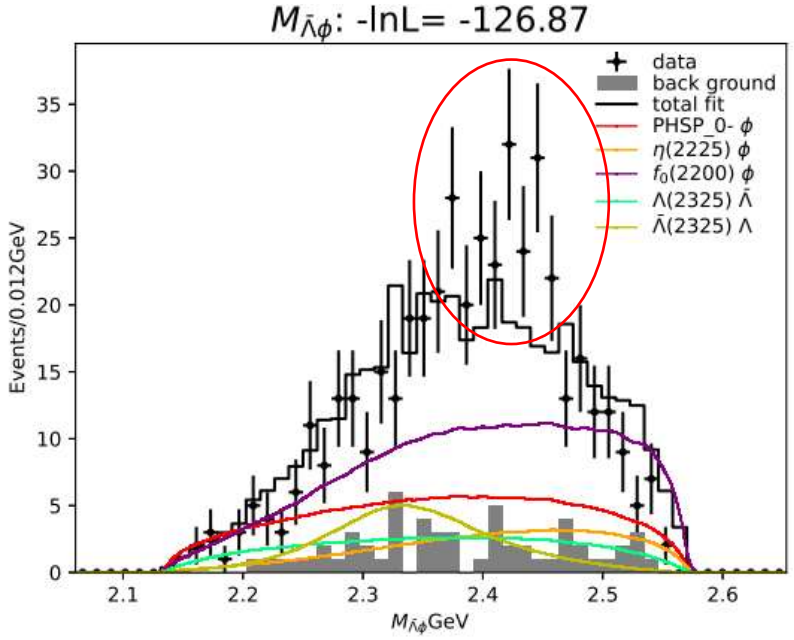
➢ The projections of the PWA results with possibly known resonances



$M_{\Lambda\bar{\Lambda}}$



$M_{\Lambda\phi}$



$M_{\bar{\Lambda}\phi}$

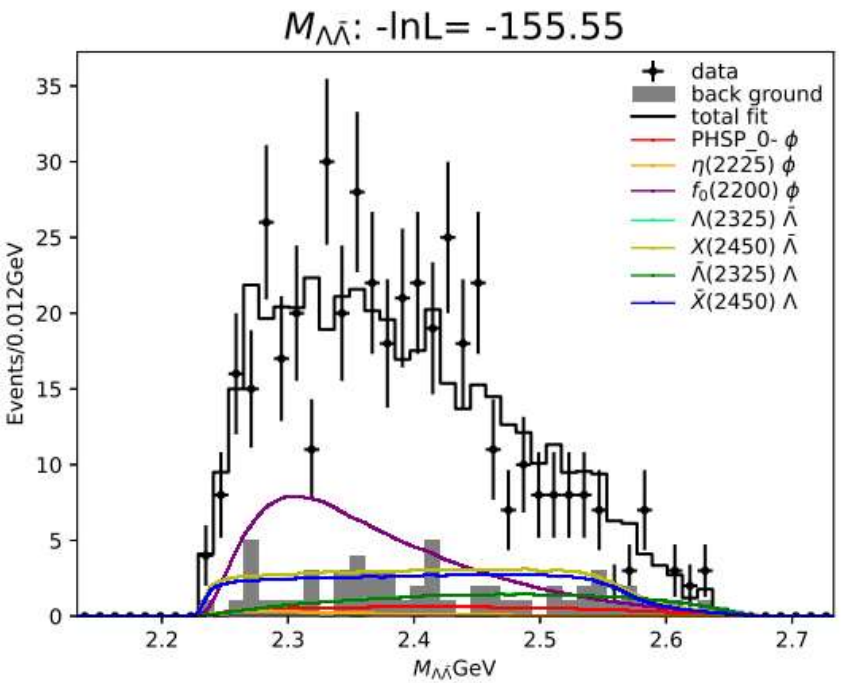
- It has been subtracted for the background events, which are described with the normalized events in ϕ sideband regions
- There are two missing pieces in $M_{\Lambda\phi}$ and $M_{\bar{\Lambda}\phi}$, and we try to add other particles.

Add an unknown resonance

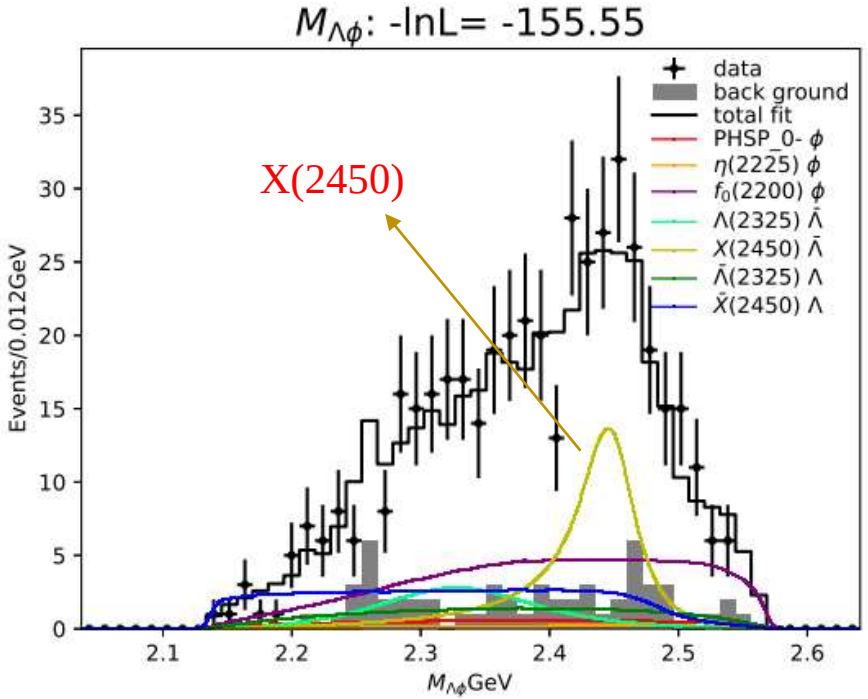
Final particles	Possibly known resonances	Quark components	$I^G(J^{PC})$	m_0 (GeV/c^2)	Γ_0 (GeV/c)
$\Lambda\bar{\Lambda}$ $(uds,\bar{u}\bar{d}\bar{s})$	$f_0(2200)$	$c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$	$0^+(0^{++})$	2.187	0.207
	$\eta(2225)$	$c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$	$0^+(0^{-+})$	2.221	0.185
$\Lambda\phi$ $(uds,s\bar{s})$	$\Lambda(2325)$	$\bar{u}\bar{d}\bar{s}$	$0(\frac{3^-}{2})$	2.342	0.177
	X(2450)	Not found in PDG	$(\frac{1^+}{2})$	2.45	0.05
$\bar{\Lambda}\phi$ $(\bar{u}\bar{d}\bar{s},s\bar{s})$	$\bar{\Lambda}(2325)$	$\bar{u}\bar{d}\bar{s}$	$0(\frac{3^+}{2})$	2.342	0.177
	$\bar{X}(2450)$	Not found in PDG	$(\frac{1^-}{2})$	2.45	0.05

PWA results with the unknown state

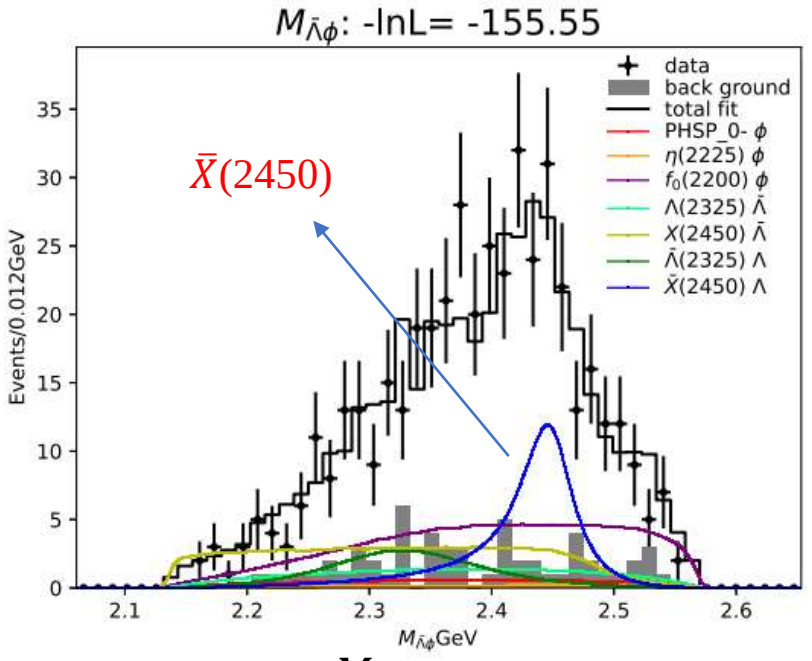
➢ **The projections of the PWA results with an additional unknown state.**



$M_{\Lambda\bar{\Lambda}}$



$M_{\Lambda\phi}$



$M_{\bar{\Lambda}\phi}$

- We can see that the projections of the PWA results are consistent with those in data, after considering the other unkown states.

Summary

- Using about 2.7 billion $\psi(3686)$ events collected by BESIII in 2009,2012 and 2021, a partial wave analysis is performed for $\psi(3686) \to \Lambda\bar{\Lambda}\phi$ decay.
  - Some known intermediate resonances are considered:
    - $\Lambda\bar{\Lambda}$ resonances: $\eta(2225), f_0(2200)$.
    - $\bar{\Lambda}\phi$ resonances: $\bar{\Lambda}(2325)$.
  - In order to fit data well, we tried to add an unknow state "X $/\bar{X}(2450)$" in $\mathrm{M}(\Lambda/\bar{\Lambda}\phi)$ distribution, and the projections are consistent with those in data.

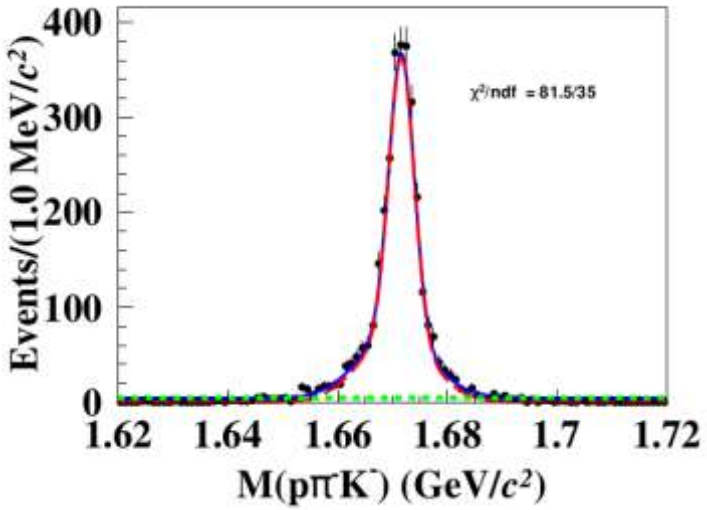
Next to do

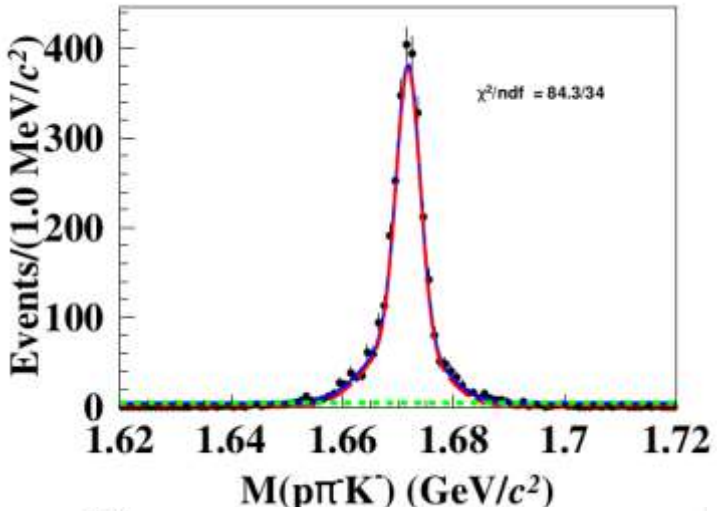
- Next to do:
  - Check the significances of the intermediate resonances.
  - More checks on the unknown "X $/\bar{X}(2450)$" state.
  - Search for other intermediate resonances states.

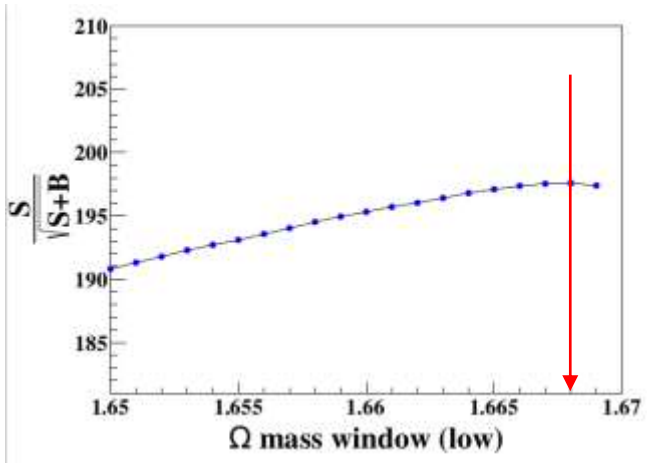
Thank you!

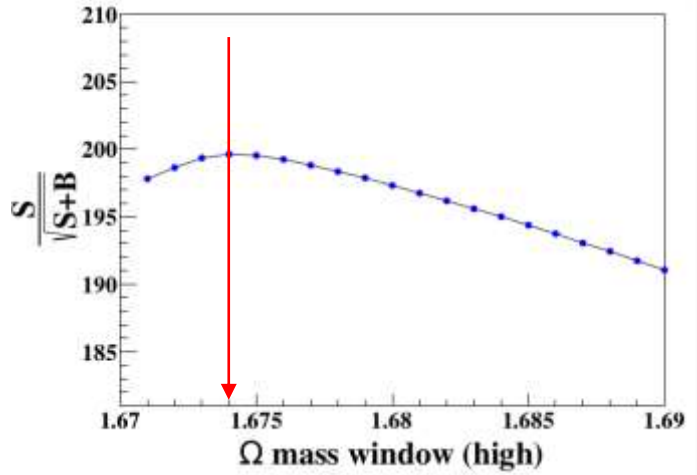
Back up

➢ Cut of Ω



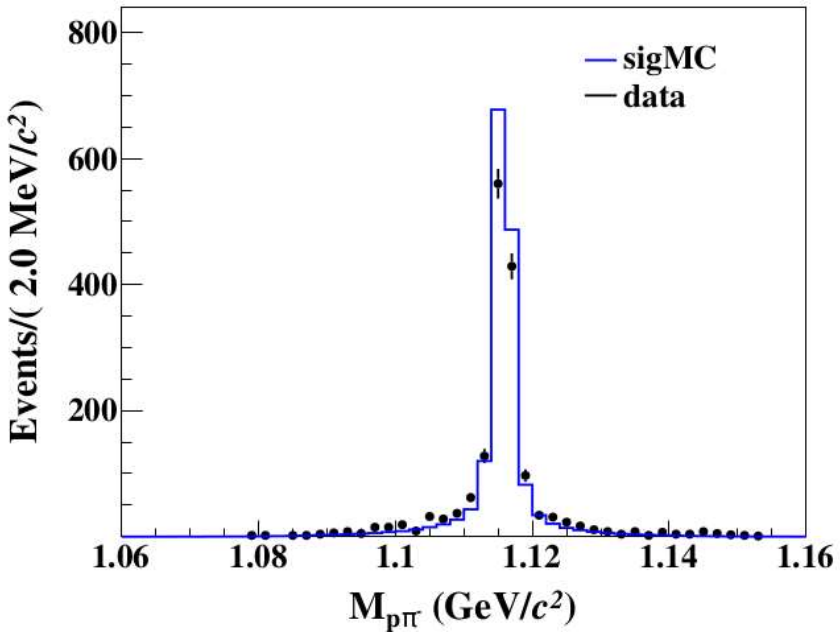


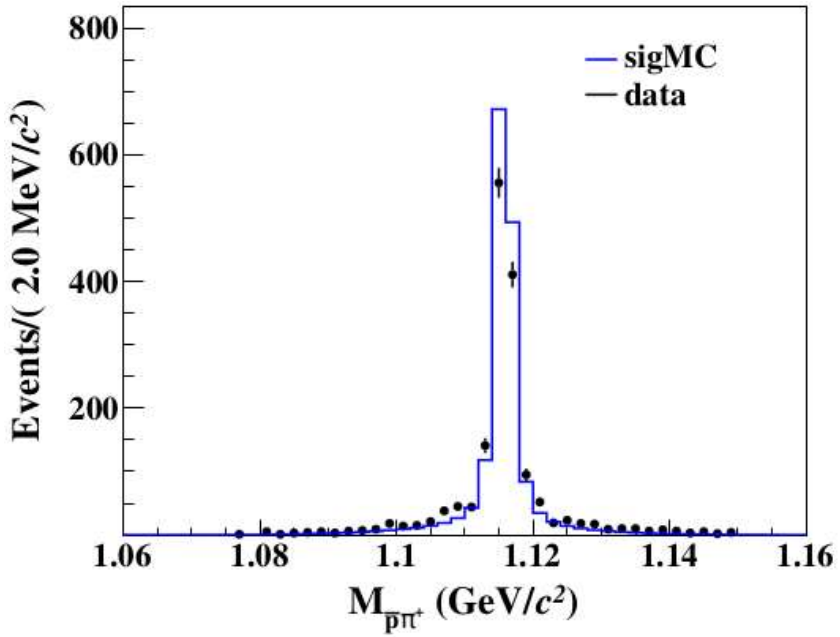


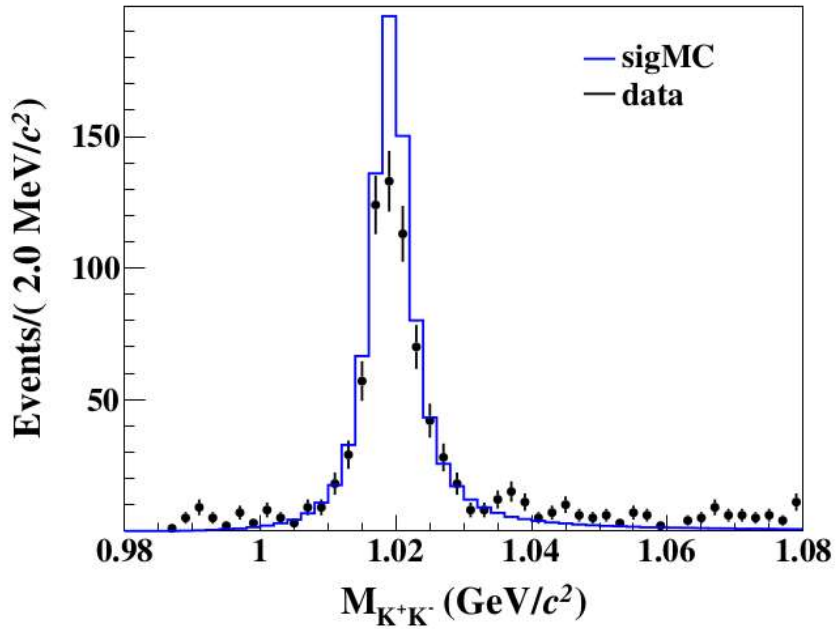


Choose cut : (1.668,1.674)

➢The invariant mass of Λ, $\bar{\Lambda}$ *and* ϕ







☐ Good photon:

- $0 \leq \mathrm{TDC} \leq 14$
- Barrel : $E > 0.025\ \mathrm{GeV}$

  $|\cos\theta| < 0.8$
- End cap : $E > 0.050\ \mathrm{GeV}$

  $0.86 < |\cos\theta| < 0.92$

➢ Possibly known resonances in $\psi(3686) \longrightarrow \Lambda\bar{\Lambda}\phi$

Final particles	Possibly known resonances	Quark components	$I^G(J^{PC})$	m_0 (GeV/c^2)	Γ_0 (GeV/c)
$\Lambda\,\bar{\Lambda}$ $(uds, \bar{u}\bar{d}\bar{s})$	$f_0(2200)$	$c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$	$0^+(0^{++})$	2.187	0.207
	$\eta(2225)$	$c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$	$0^+(0^{-+})$	2.221	0.185
	$f_0(2330)$	$c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$	$0^+(0^{++})$	2.312	0.065
	$f_0(2470)$	$c_1(u\bar{u}+d\bar{d})+c_2(s\bar{s})$	$0^+(0^{++})$	2.470	0.075
$\Lambda\phi$ $(uds, s\bar{s})$	$\Lambda(2325)$	uds	$0(\frac{3^-}{2})$	2.342	0.177
	$\Sigma(2230)$	uds	$1(\frac{3^+}{2})$	2.240	0.345
$\bar{\Lambda}\phi$ $(\bar{u}\bar{d}\bar{s}, s\bar{s})$	$\bar{\Lambda}(2325)$	$\bar{u}\bar{d}\bar{s}$	$0(\frac{3^+}{2})$	2.342	0.177
	$\bar{\Sigma}(2230)$	$\bar{u}\bar{d}\bar{s}$	$1(\frac{3^-}{2})$	2.240	0.345

Σ BARYONS

($S = -1$, $I = 1$)

$\Sigma^+ = uus$, $\Sigma^0 = uds$, $\Sigma^- = dds$

PDGID:B053 JSON (beta) INSPIRE

$\Sigma(2455)$ Bumps $I(J^P) = 1(?^?)$

There is also some slight evidence for Y^* states in this mass region from the reaction $\gamma p \to K^+ X$ — see GREENBERG 1968 .

$\Sigma(2455)$ MASS ≈ 2455 MeV

$\Sigma(2455)$ WIDTH

$\Sigma(2455)$ WIDTH

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
140	ABRAMS	1970	CNTR	$K^- p$, $K^- d$ total
100 ±20	BUGG	1968	CNTR	