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Looking inside the Strong Interaction with Charm Data

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XAPOF 第二届强子物理新发展研讨会暨强子物理在线论坛100期特别活动

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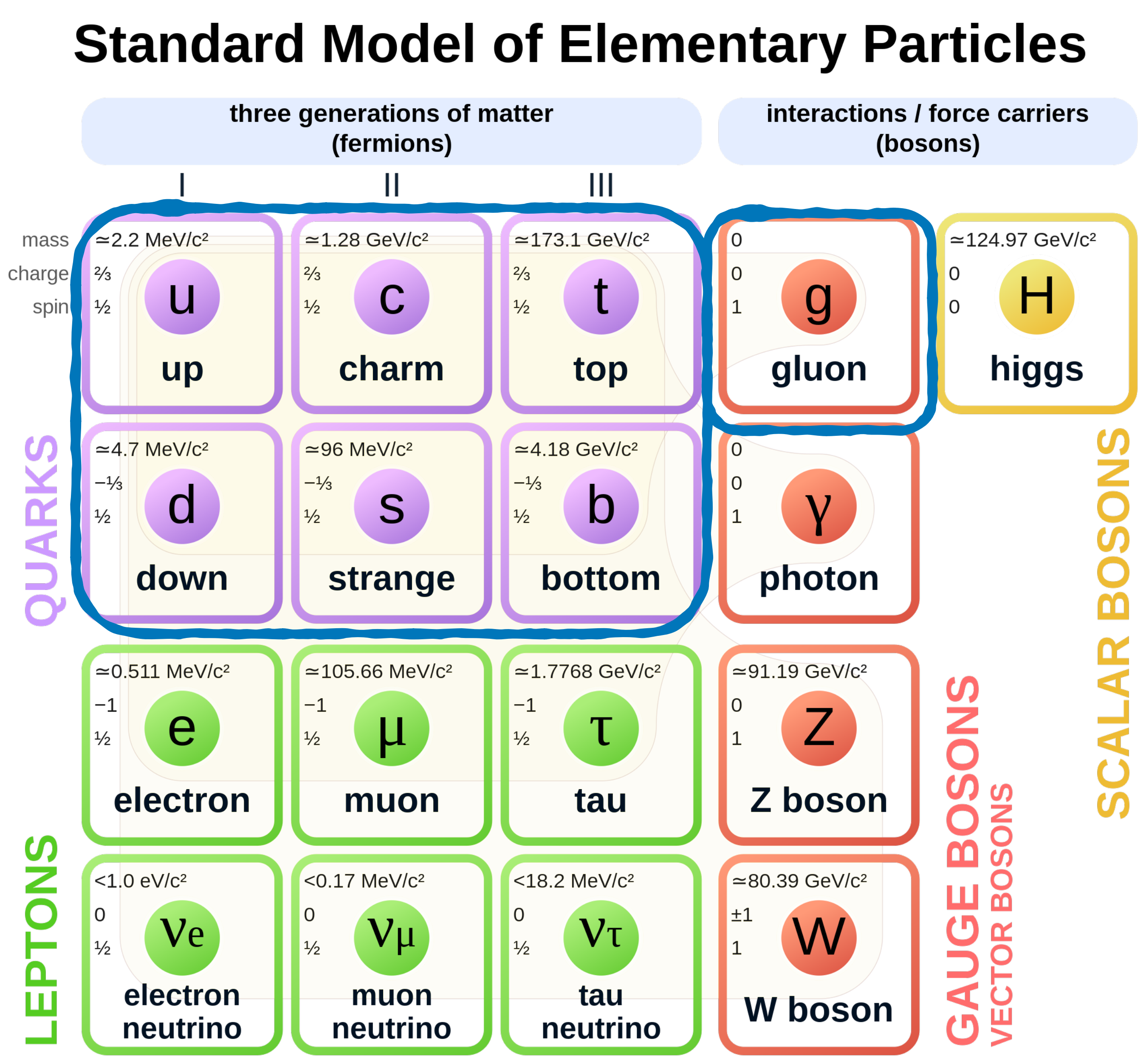
Standard Model in HEP

- Past successes in particle physics have revolutionized our understanding of the universe…

From P5 report

- The standard model (SM) is one of the “past” successes, but it’s not totally understood. ⟶ Still many puzzles.

  - The elementary particles and their interactions are demonstrated in SM.



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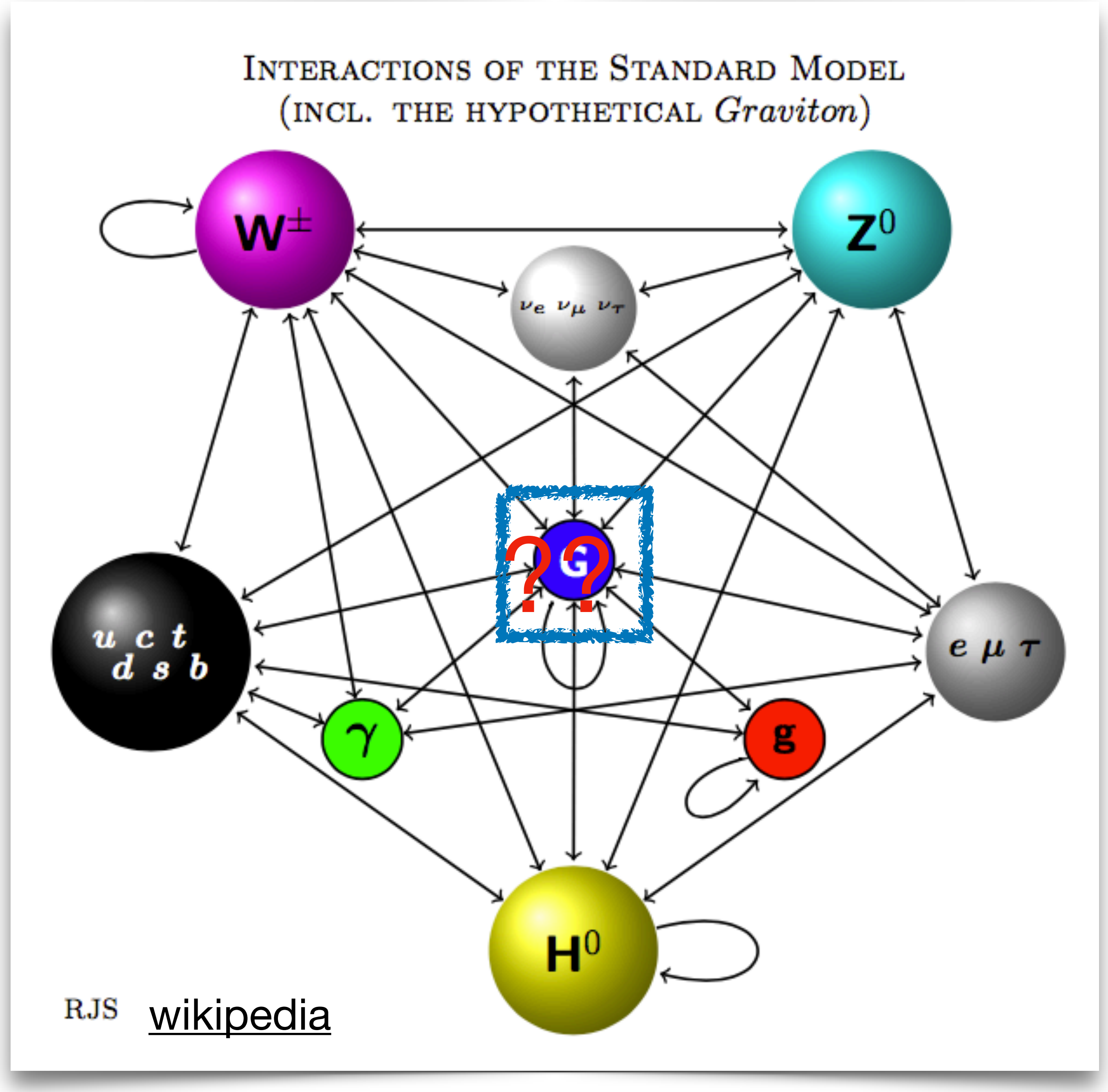
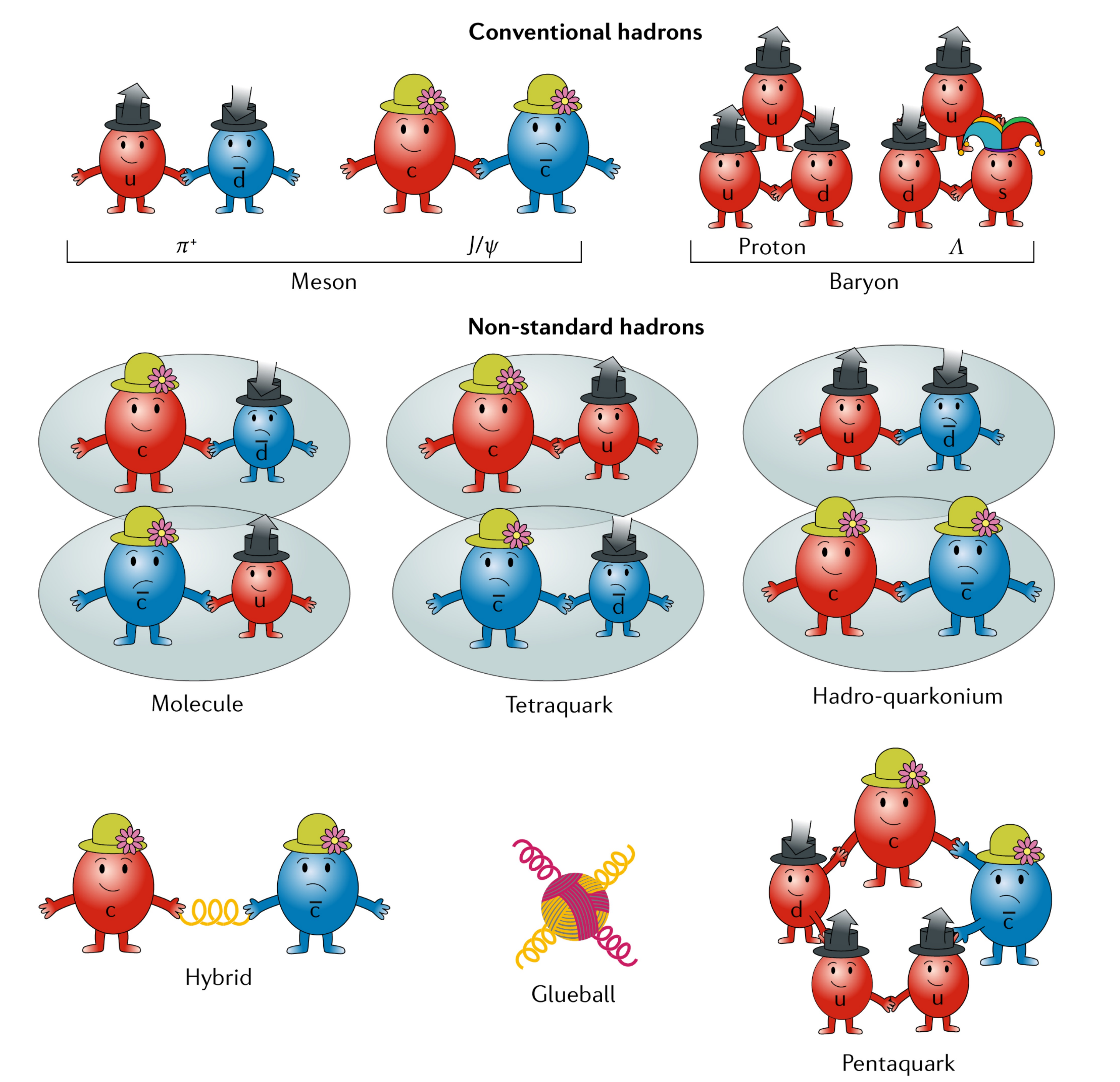


wikipedia

Strong Interaction

- In SM, the quarks and gluons form hadrons through strong interaction.
  - The mesons($q\bar{q}$) and baryons(qqq or $\bar{q}\bar{q}\bar{q}$) are observed in experiments over past decades.



Nature Rev.Phys. 1 (2019) 8, 480-494

- Furthermore, people realized that there may exist **exotic states** allowed by the QCD,
  - **Hybrid state, glueballs,**
  - **Multi-quark state,**
  - **Molecular state**

- In BESIII, hunting for these exotic states is one of major targets, that could help to reveal the nature of QCD.
  - The huge and clean **charm and charmonium data** will help a lot on these studies, such as J/ψ, $\psi(3686)$ and $\psi(3770)$…

Strong Interaction

- In SM, the Quantum Chromodynamics (QCD) describes the strong interaction among quarks and gluons.

$$\mathscr{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu\partial_\mu\delta_{ab} - g_s\gamma^\mu t^C_{ab}A^C_\mu - m_q\delta_{ab})\psi_{q,b} - \frac{1}{4}F^A_{\mu\nu}F^{A\mu\nu}$$

- The $\alpha_S = \frac{g_s^2}{4\pi}$ is the strong coupling constant,

  - Quantize the strength of strong interaction, and dictate many features of the strong interaction.

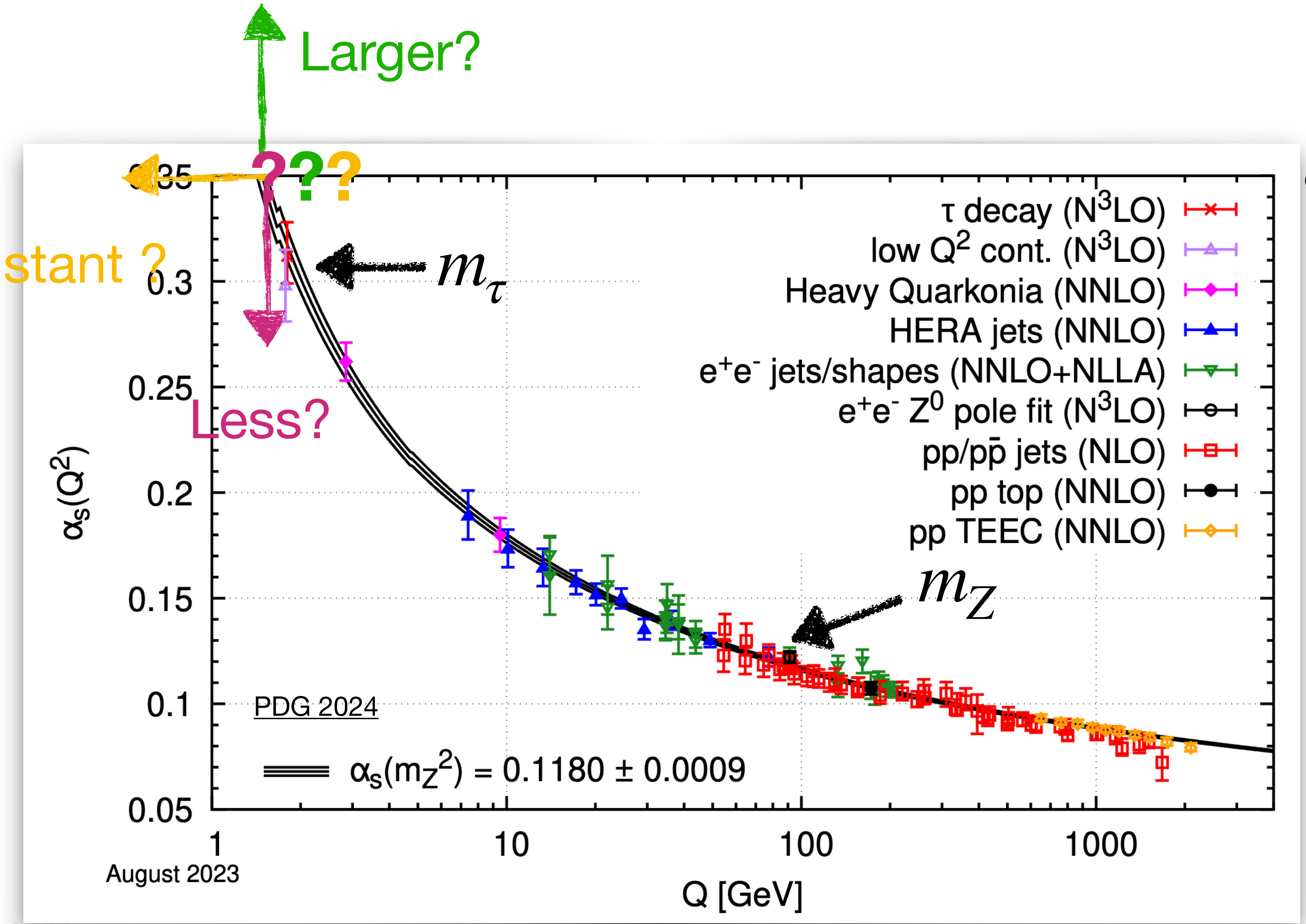
  - The α_S is measured using many methods, such as hadronic τ decay, PDF fits and EW precision fit…

  - In theory, the α_S follows the RGE, $\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$

Strong Interaction

- In the region from m_τ to ~$2\ TeV$, the α_S **increases** with the **energy scale decreasing** according to the measurements.
  - The "asymptotic freedom" and color confinement.

To David J.Gross, H. David Politzer, and Frank Wilczek in 2004.

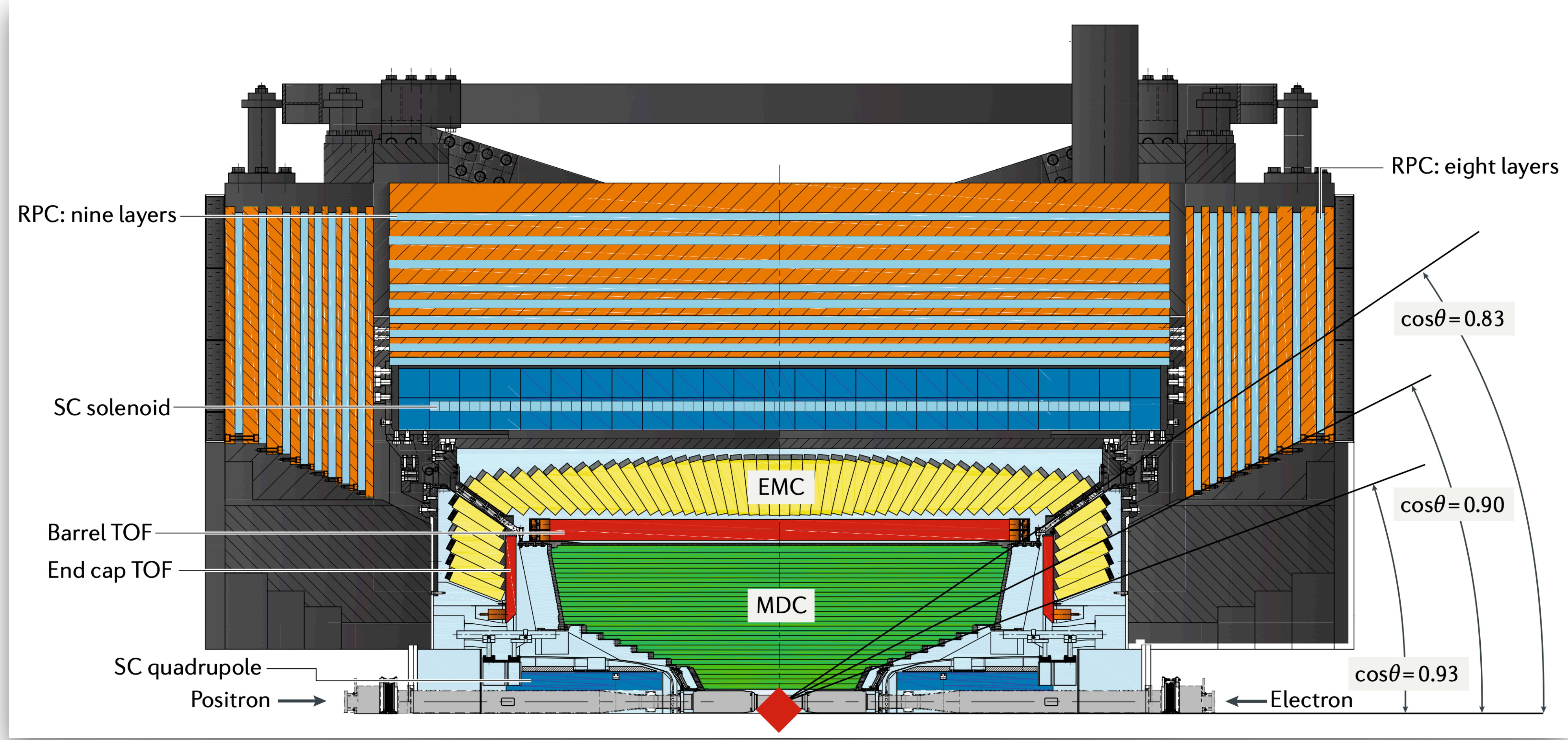


- If Q goes below m_τ, what will happen on α_S? Where does the logarithmic dependence of α_S disappear? what can we use as a tool to measure the α_S below m_τ?

✦The c **quark** may be a good choice, lighter than τ but not too light.

BESIII detector

- The huge charm data + **excellent detector performance**, provides **good potential to look into QCD.**



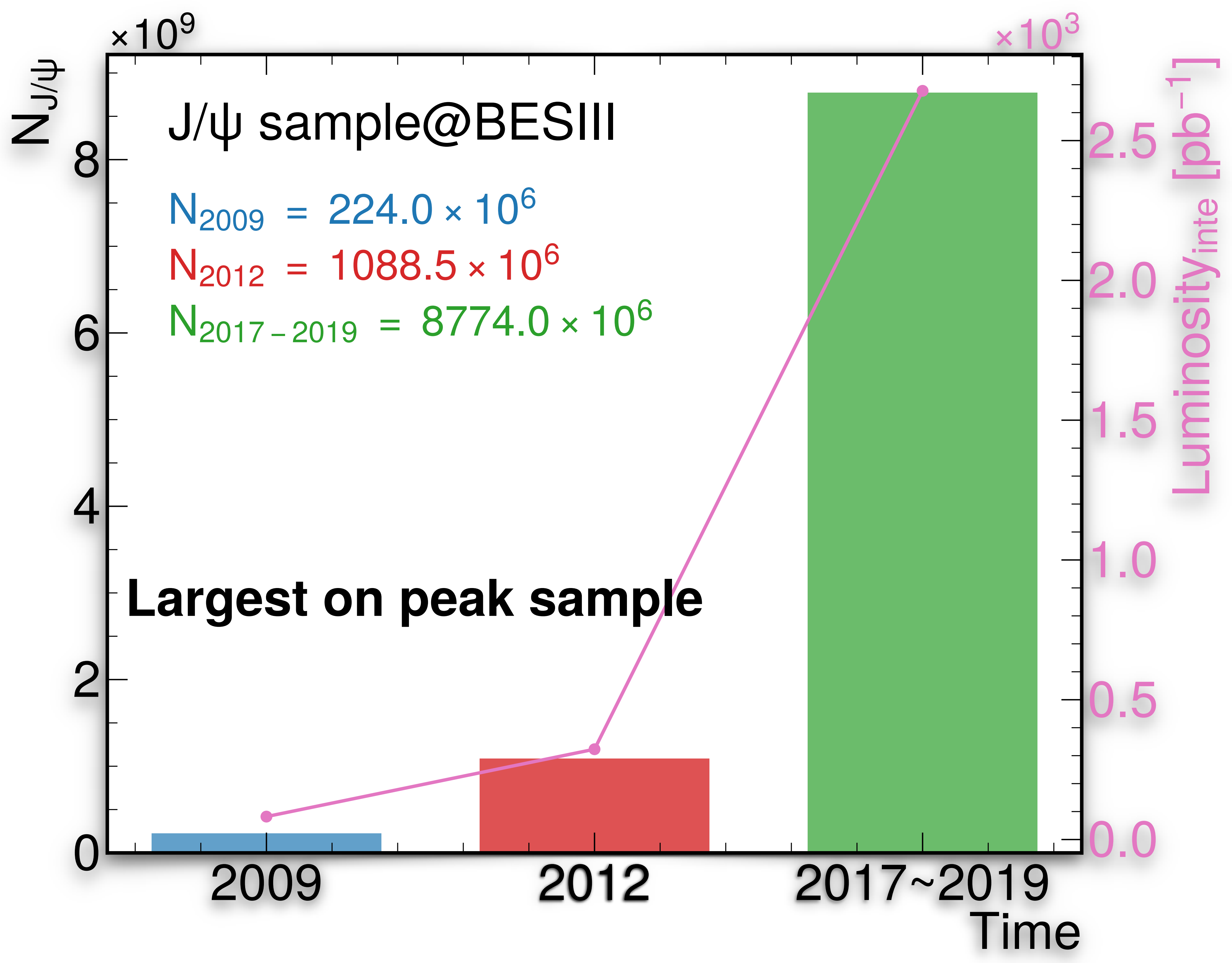
Nature Rev.Phys. 1 (2019) 8, 480-494

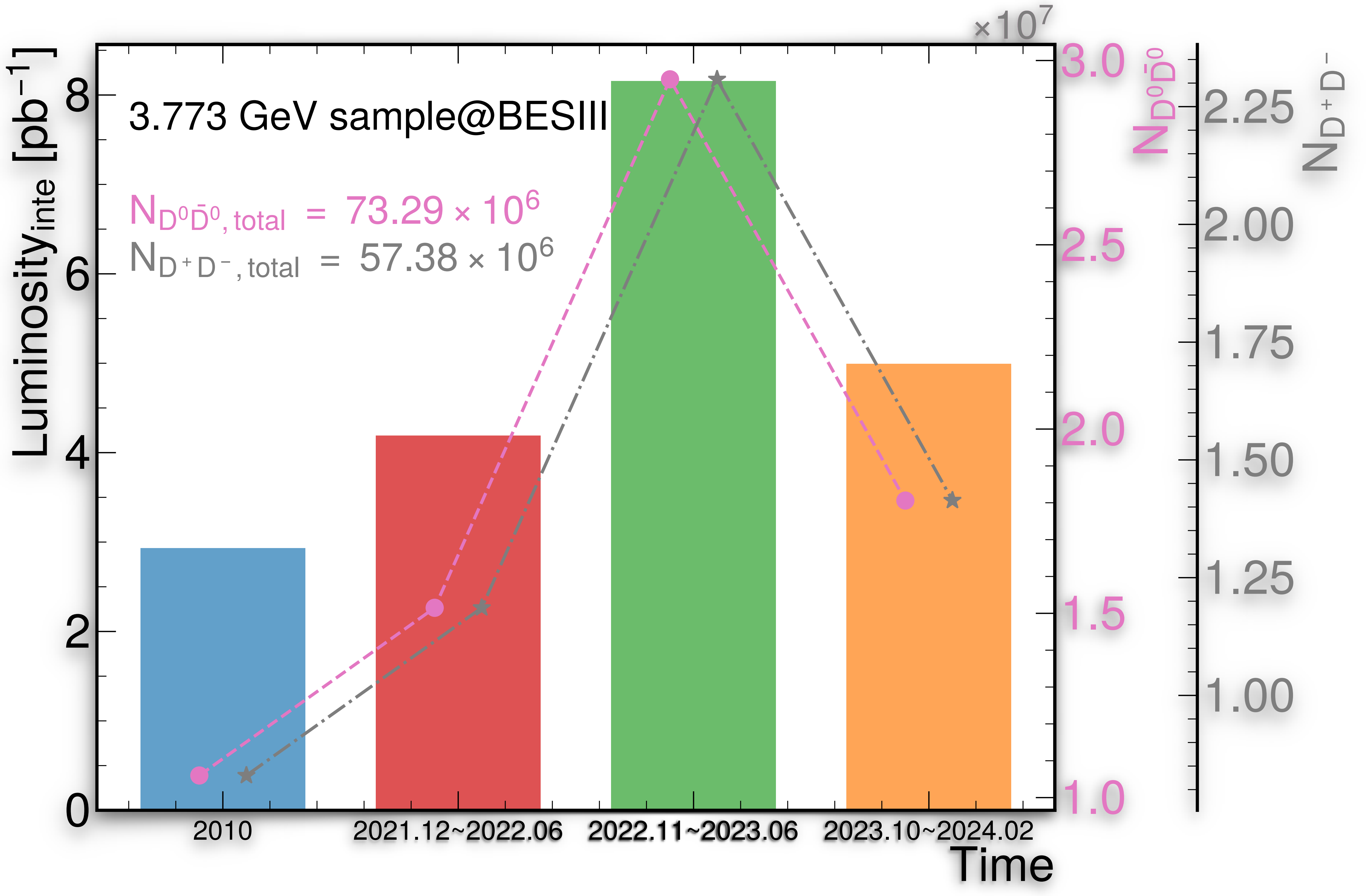
- 93% coverage of full solid angle
- $\sigma_{P,\ charged\ trk}@1GeV/c$: 0.5%
- $\sigma_{dE/dX}$ for electron : 6%
- $\sigma_{E_\gamma\ in\ EMC}@1\ GeV/c$: 2.5(5)% for barrel (end-cap) region.
- $\sigma_{t\ in\ TOF}$: 68(110)ps for barrel (end-cap) region, the updated end-cap gives 60 ps.

- The BESIII is still well-performed detector after 10+ years running.

J/ψ and $\psi(3770)$ at BESIII

- The BESIII has collected the $(10.09 \pm 0.04) \times 10^9$ J/ψ sample and ~20.3 fb^{-1} e^+e^- collision data sample at 3.773 GeV. Chin.Phys.C 46 (2022) 7, 074001 Arxiv.2406.05827

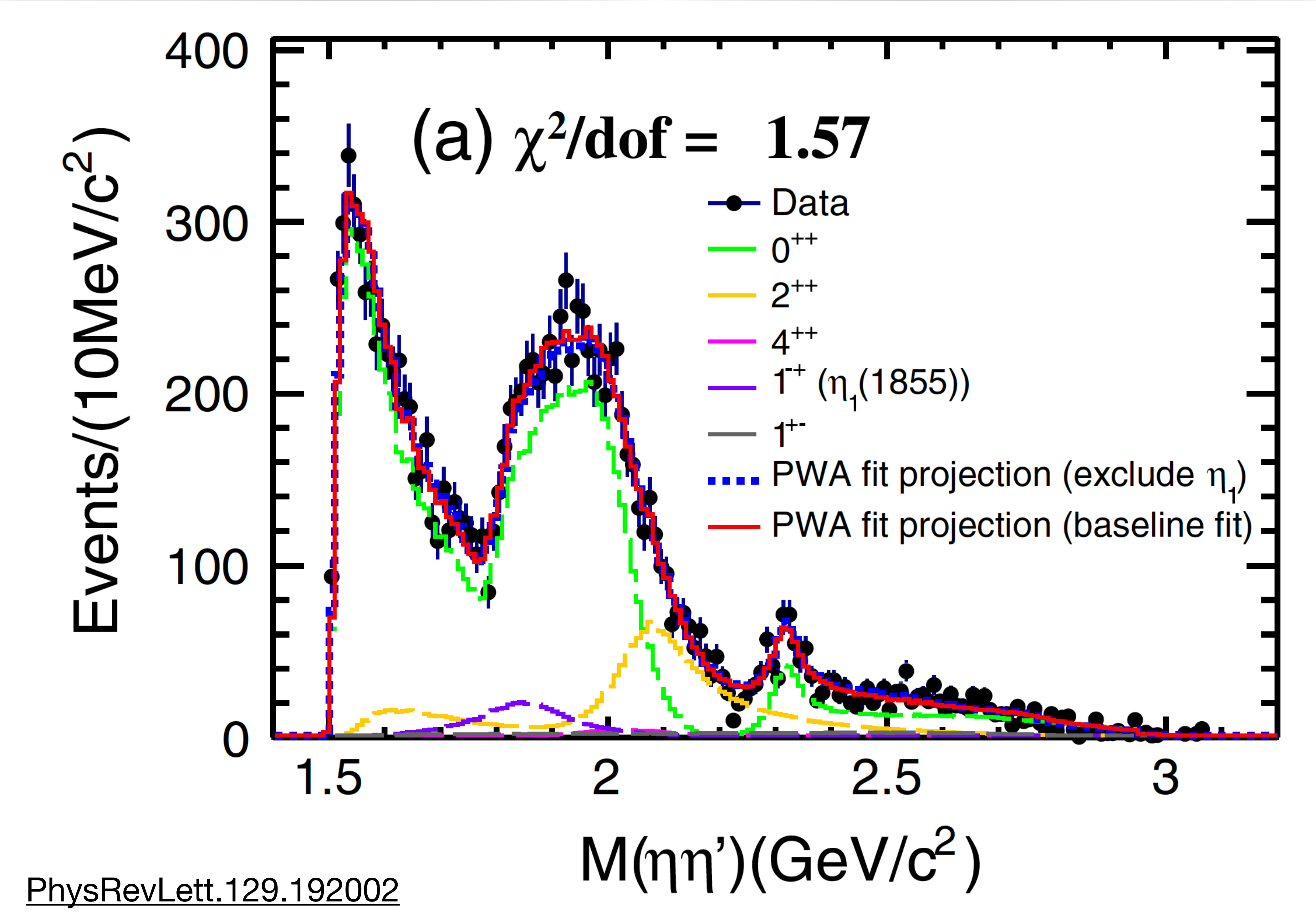


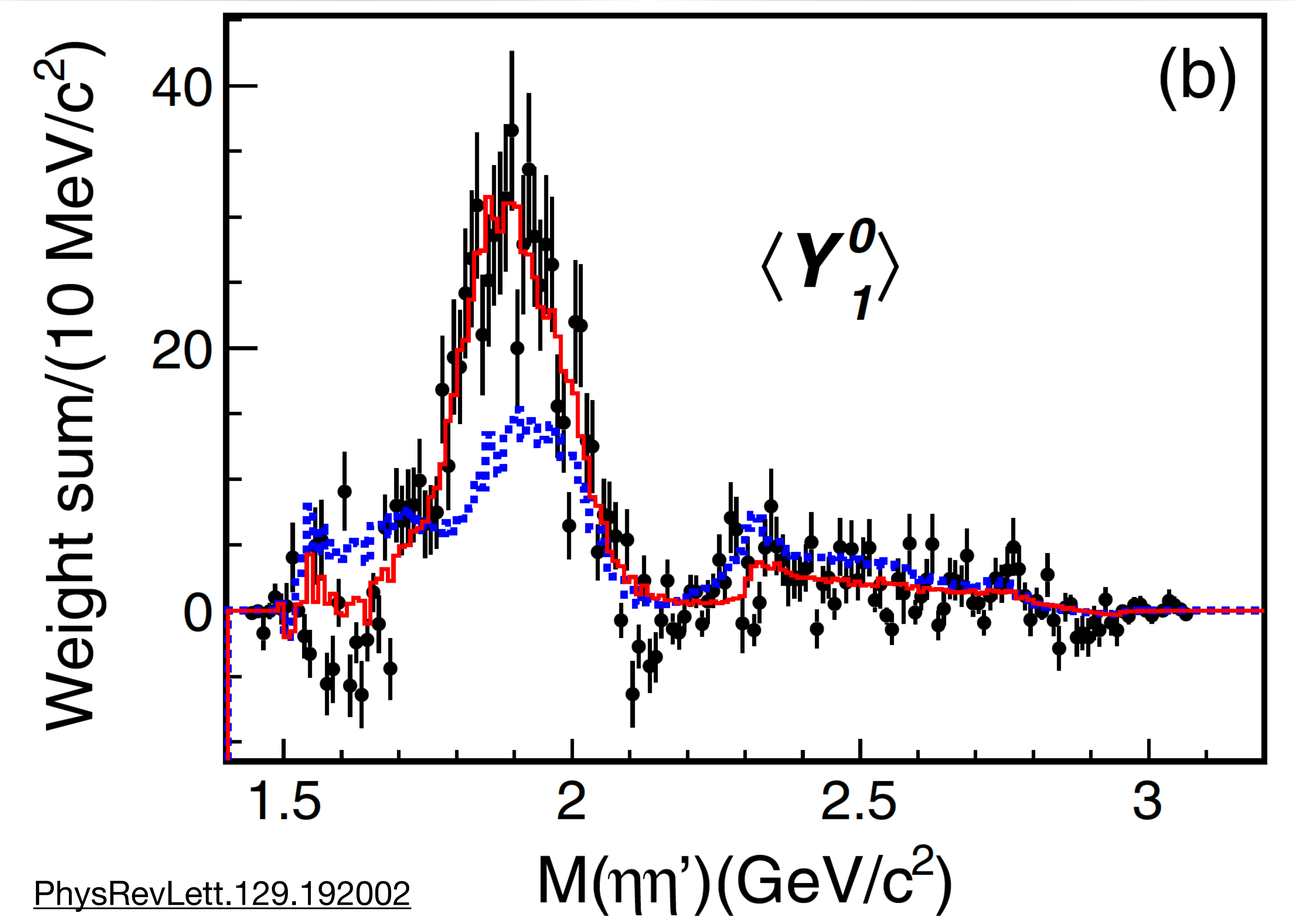


- J/ψ on peak sample : the world largest
- 3.773 GeV sample : 10~20 × CLEO-c → **Huge and clean charm data@BESIII**
- Less background in e^+e^- collision

1^{-+} exotics at BESIII

- The J^{PC} of the bump around 1.9 GeV is measured to be 1^{-+}, that is **an iso-scalar 1^{-+} exotic state**, named $\eta_1(1855)$, not a conventional $q\bar{q}$ state.



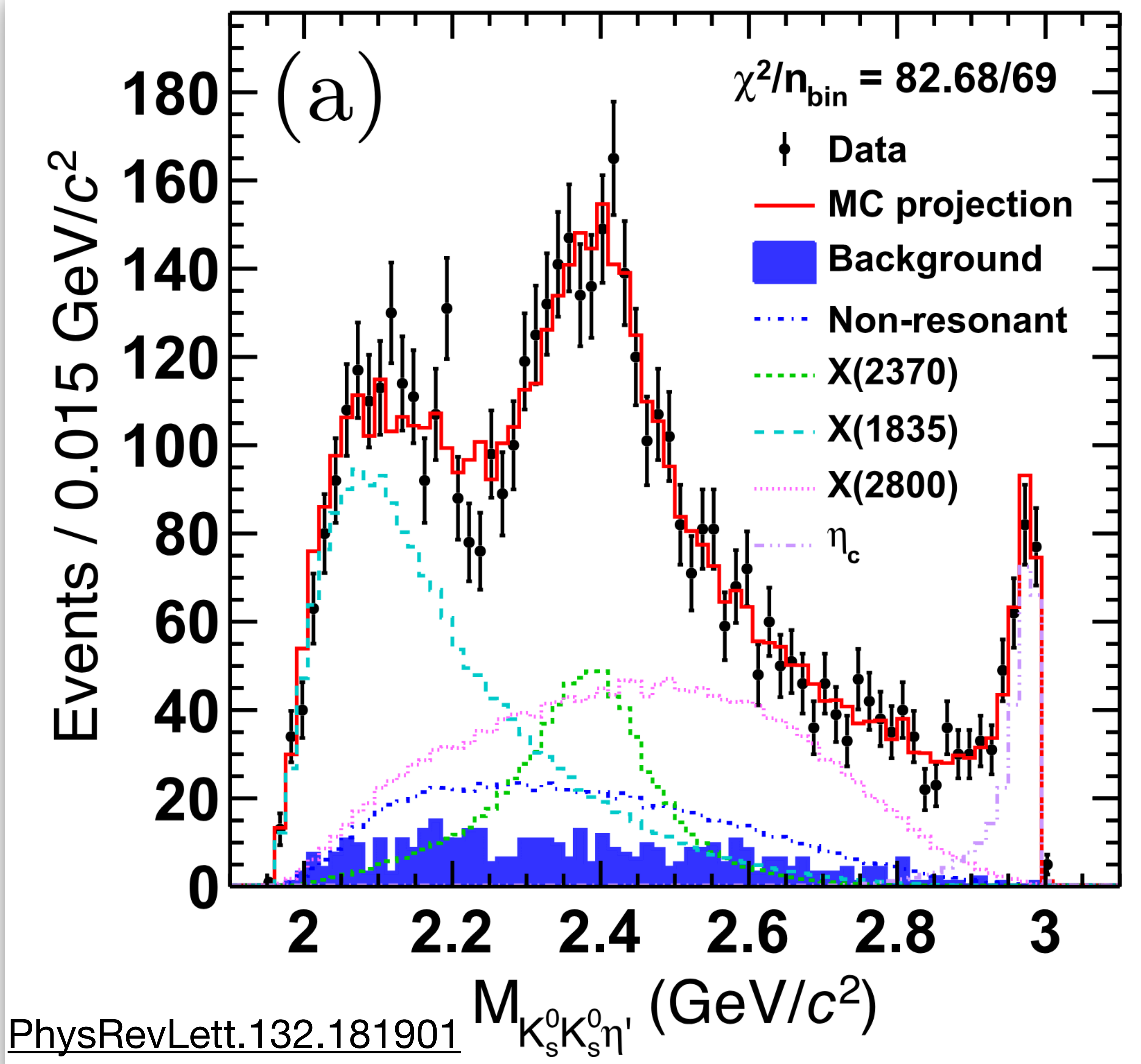


- **The huge J/ψ data contributes a lot to this study.**

Please see Prof. Beijiang Liu's report for the details.

Glueballs at BESIII

- The search for glueball is one of the main target of BES, BESII, and BESIII experiments, which is carried out by ~30 yeas.
- Recently, the J^{PC} of the X(2370) is determined to be 0^{-+}, that is constant with the pseudo-scalar glueball from LQCD calculation. PhysRevLett.132.181901



PhysRevLett.132.181901

TABLE V. The mass of pseudoscalar glueball, m_G, and the form-factor $\hat{V}(0)$ of $J/\psi \to \gamma G_{ps}$. The continuum limits of m_G and $\hat{V}(0)$ are achieved by linear extrapolations in a_s^2.

β	m_G (GeV)	$\hat{V}(0)$
2.4	2.724(18)	0.0307(59)
2.8	2.550(13)	0.0294(32)
3.0	2.464(11)	0.0247(33)
Continuum limit	2.395(14)	0.0246(43)
	2.560(35)(120) [2]	

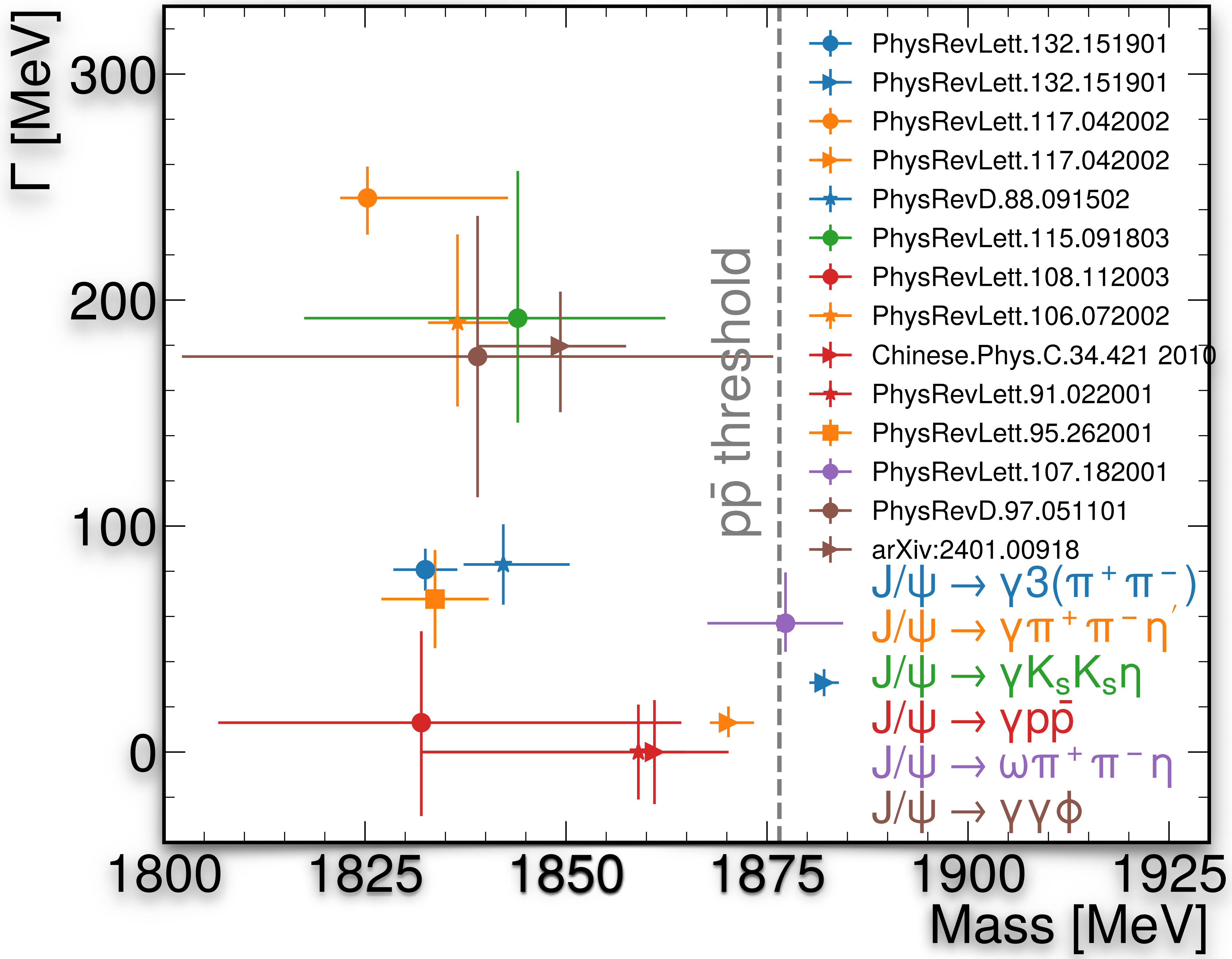
PhysRevD.100.054511 LQCD calculation

- **The huge J/ψ data also contributes a lot to this study.**

Please see Prof. Yanping Huang's report for details.

States near $p\bar{p}$ threshold at BESIII

- Several structures near $p\bar{p}$ are observed in the decay of J/ψ.



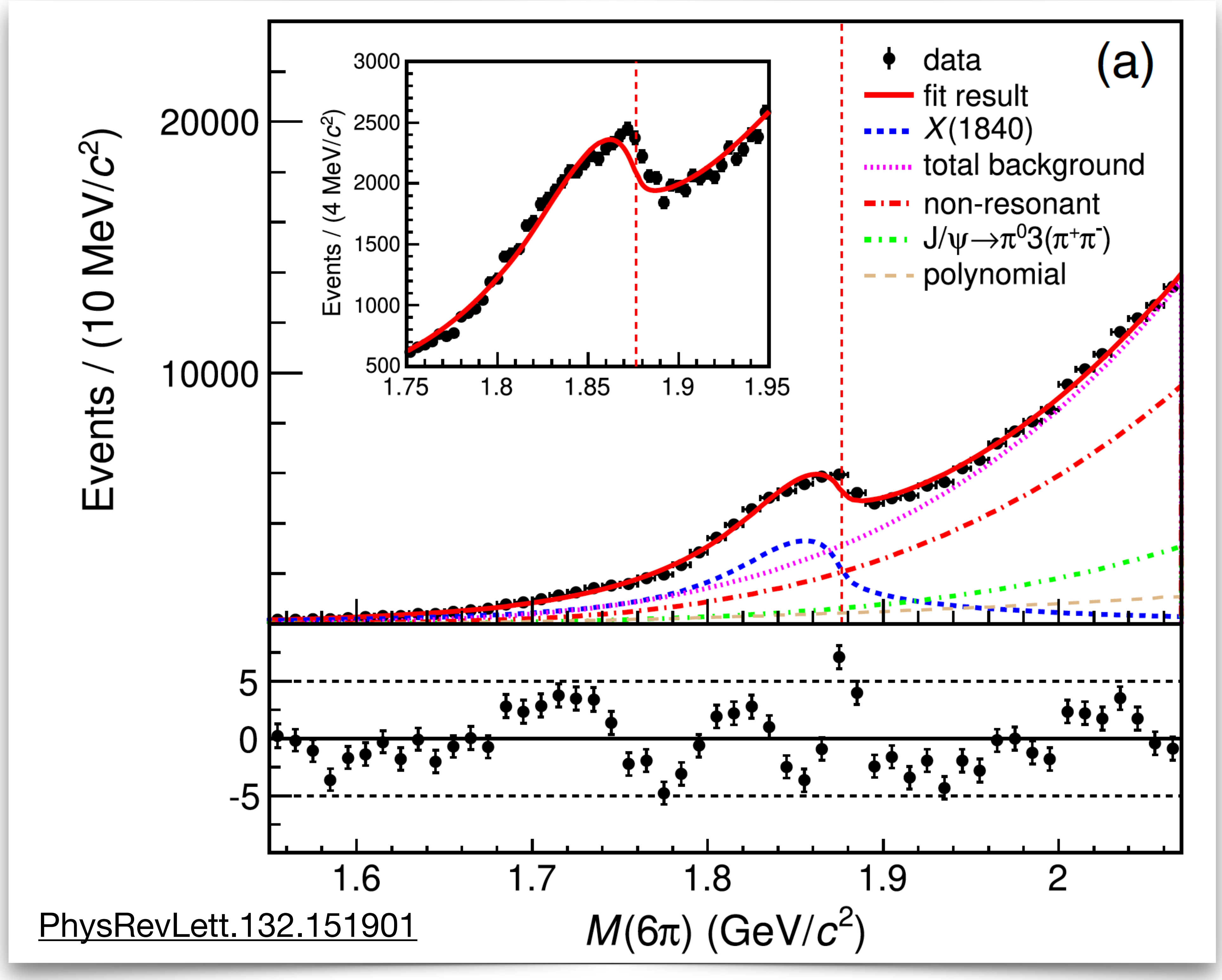
- **What are these states?** $p\bar{p}$ bound states, glueballs, radial excitation of η' meson?
  - A sizable $s\bar{s}$ component indicates more complicated nature.
- Are these states related to each other?
  - May need coupled channel amplitude analysis.

- With J/ψ sample increasing, we could clarify the nature of these states step by step.
  - Take $J/\psi \to \gamma 3(\pi^+\pi^-)$ as an example. PhysRevLett.132.151901

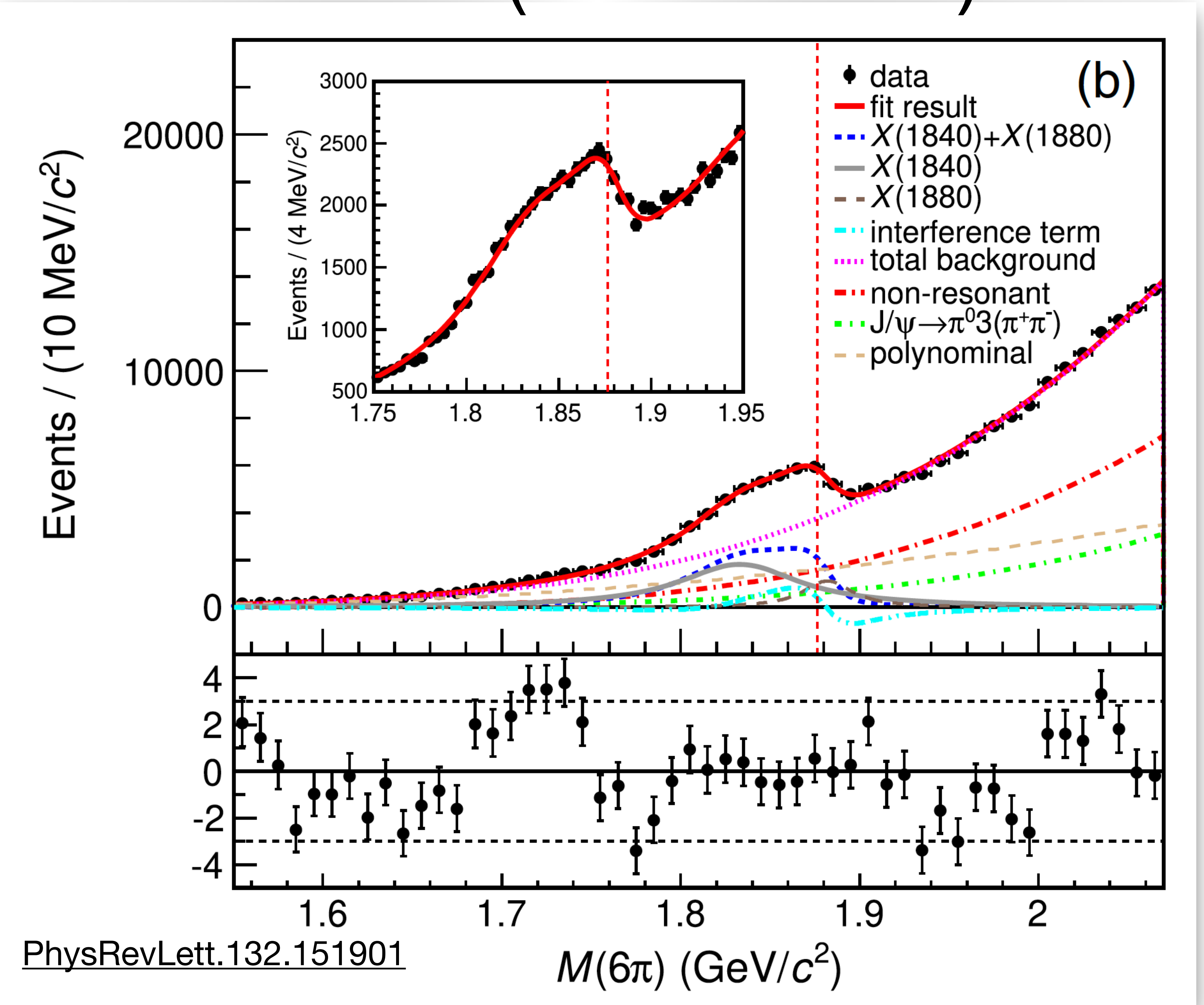
States near $p\bar{p}$ threshold at BESIII

- In $J/\psi \to \gamma 3(\pi^+\pi^-)$, **an anomalous line shape** around 1.84 GeV is observed. The mass spectrum fitting indicates there are **two overlapping resonant structures**.

1 state(Flatte formula)



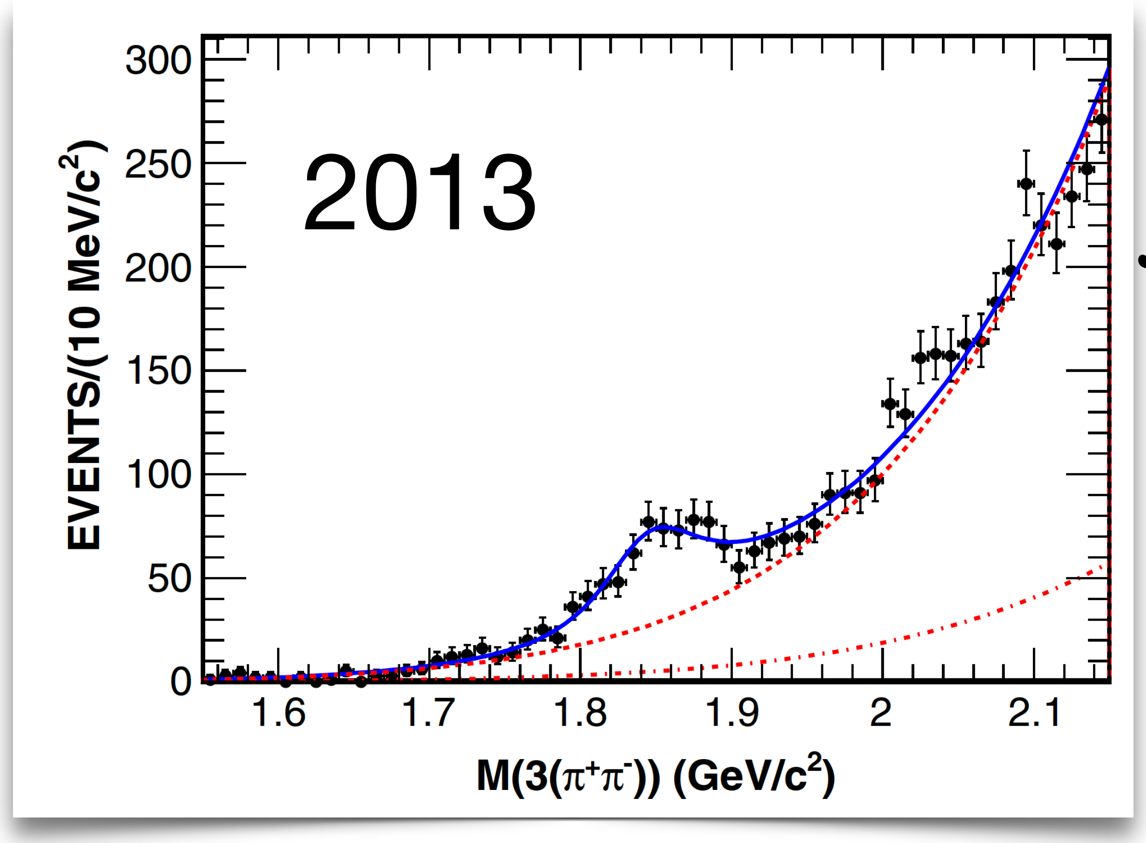
2 states(interference)



- The significance of second state is larger than 10σ.
- In $J/\psi \to \gamma\pi^+\pi^-\eta'$, an **anomalous line shape** around 1.8 GeV is also observed.

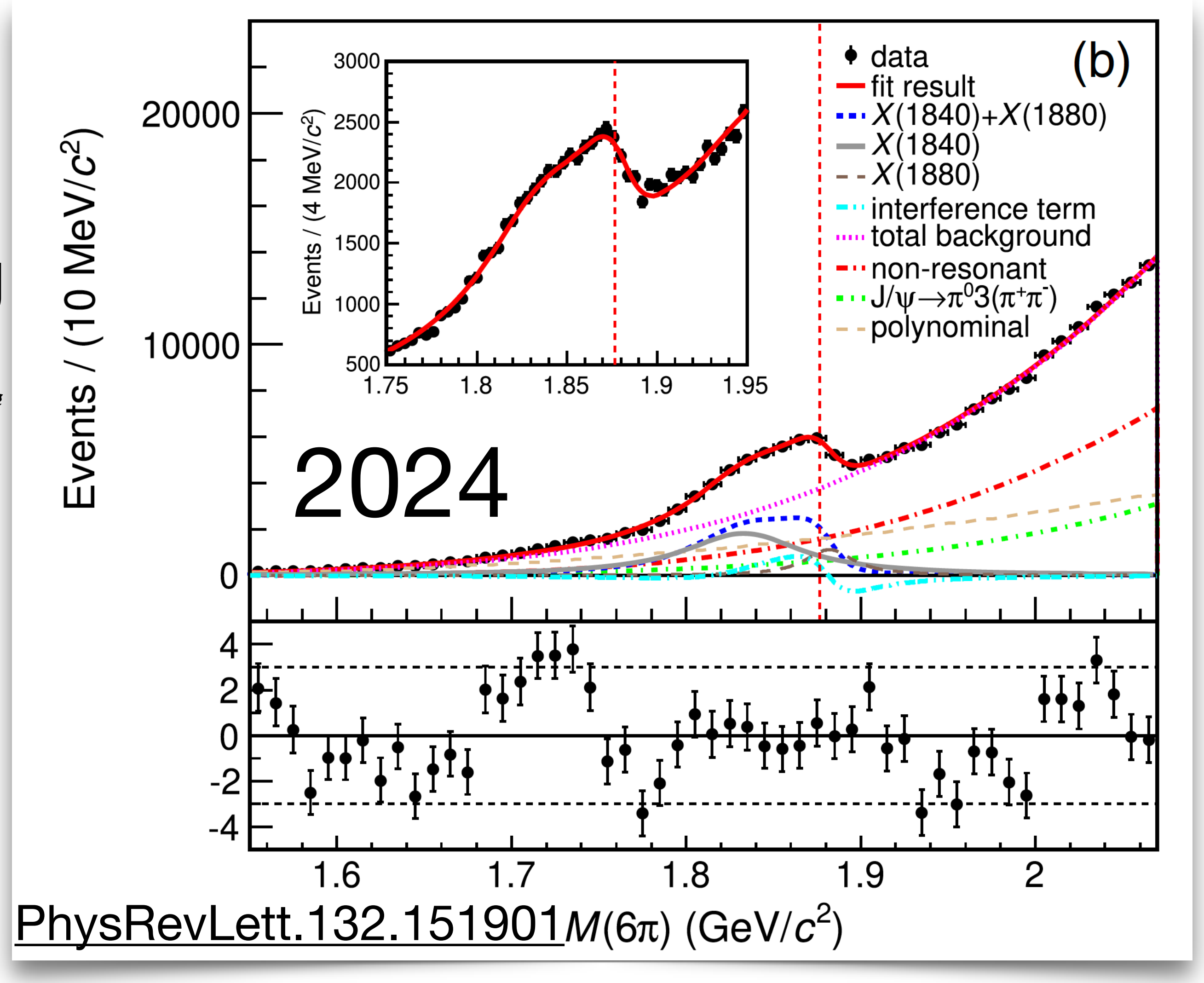
States near $p\bar{p}$ threshold at BESIII

- In $J/\psi \to \gamma 3(\pi^+\pi^-)$ and $J/\psi \to \gamma \pi^+\pi^-\eta'$, 2 **anomalous line shapes** near $p\bar{p}$ threshold are investigated using the J/ψ sample.



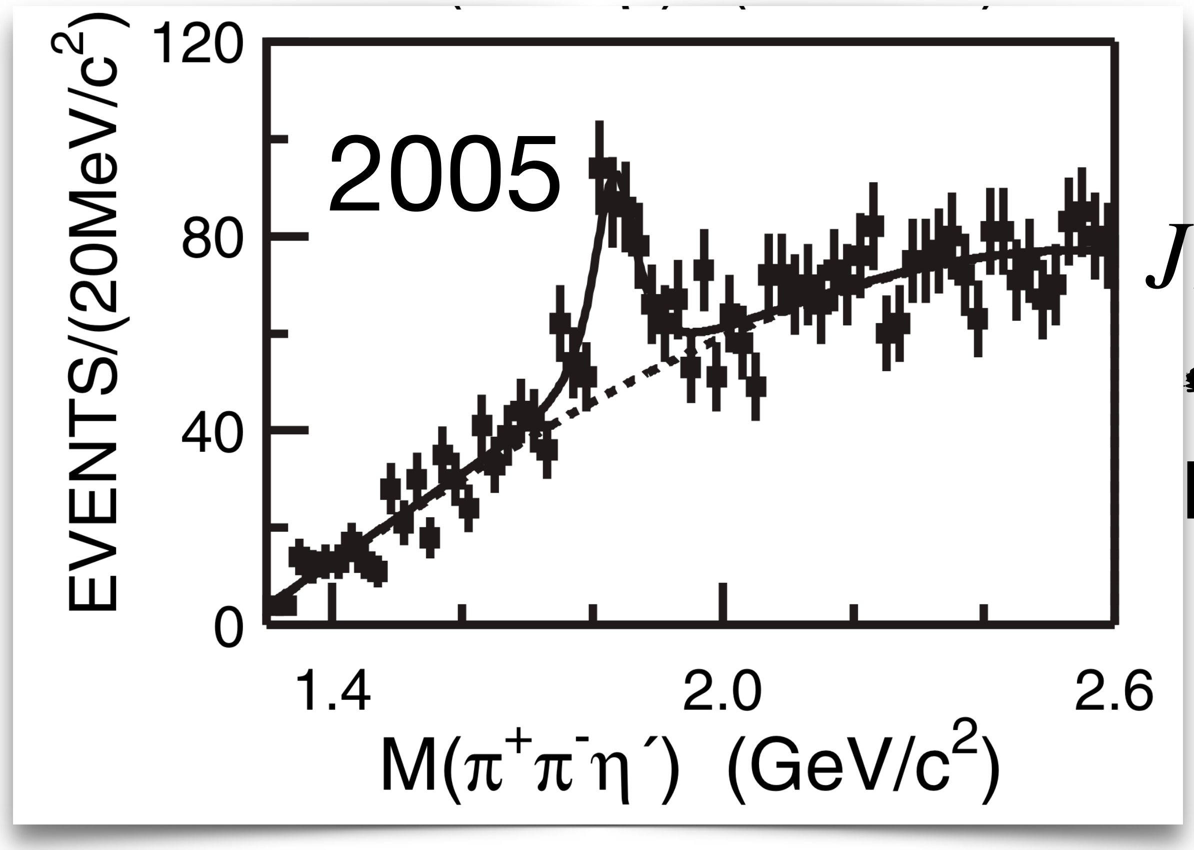
PhysRevD.88.091502

J/ψ **increasing**



PhysRevLett.132.151901

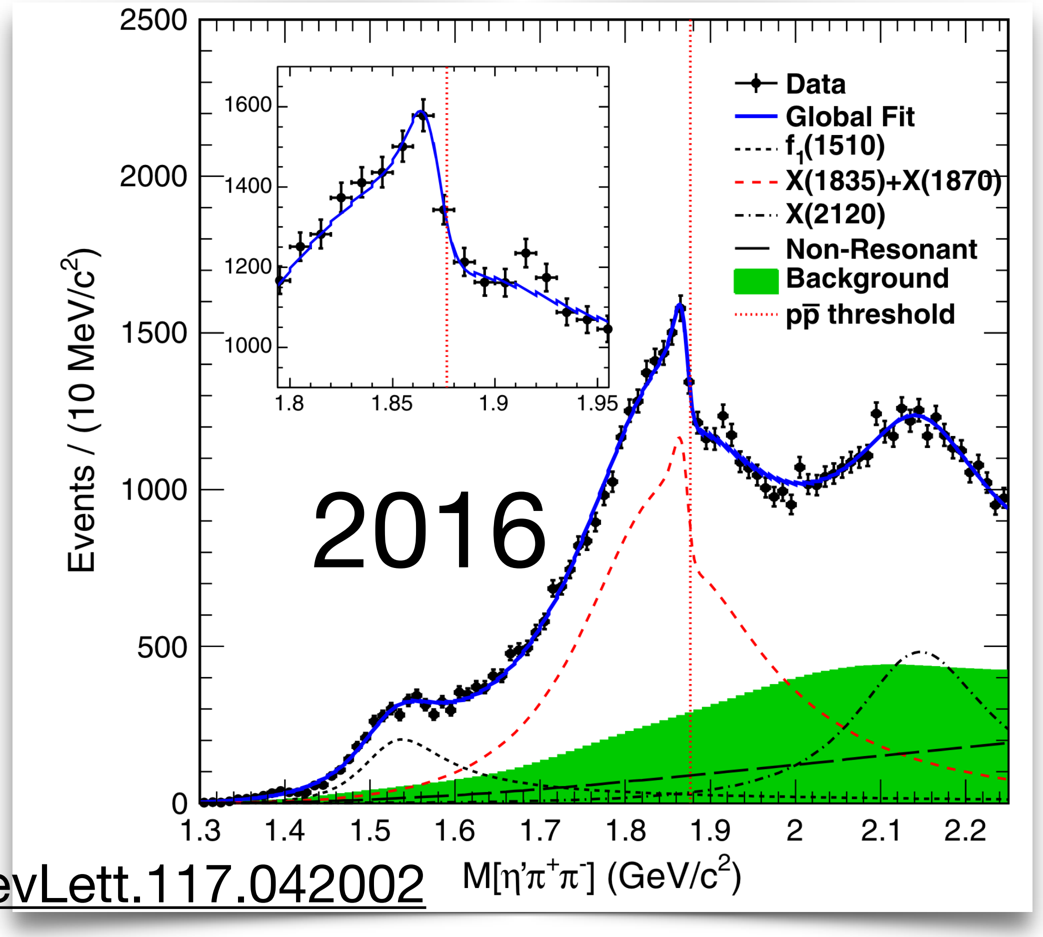
2 resonant states to describe the line shape.



PhysRevLett.95.262001

J/ψ **increasing**

Not all of data



PhysRevLett.117.042002

Can not distinguish if there are 2 states or not. Need use all of the J/ψ sample.

The **huge J/ψ sample could help a lot.**

States near $p\bar{p}$ threshold at BESIII

- Several states near $p\bar{p}$ threshold are observed, whose masses and widths are different with each other.

- To identify the relation among these states, coupled partial wave analysis are necessary.

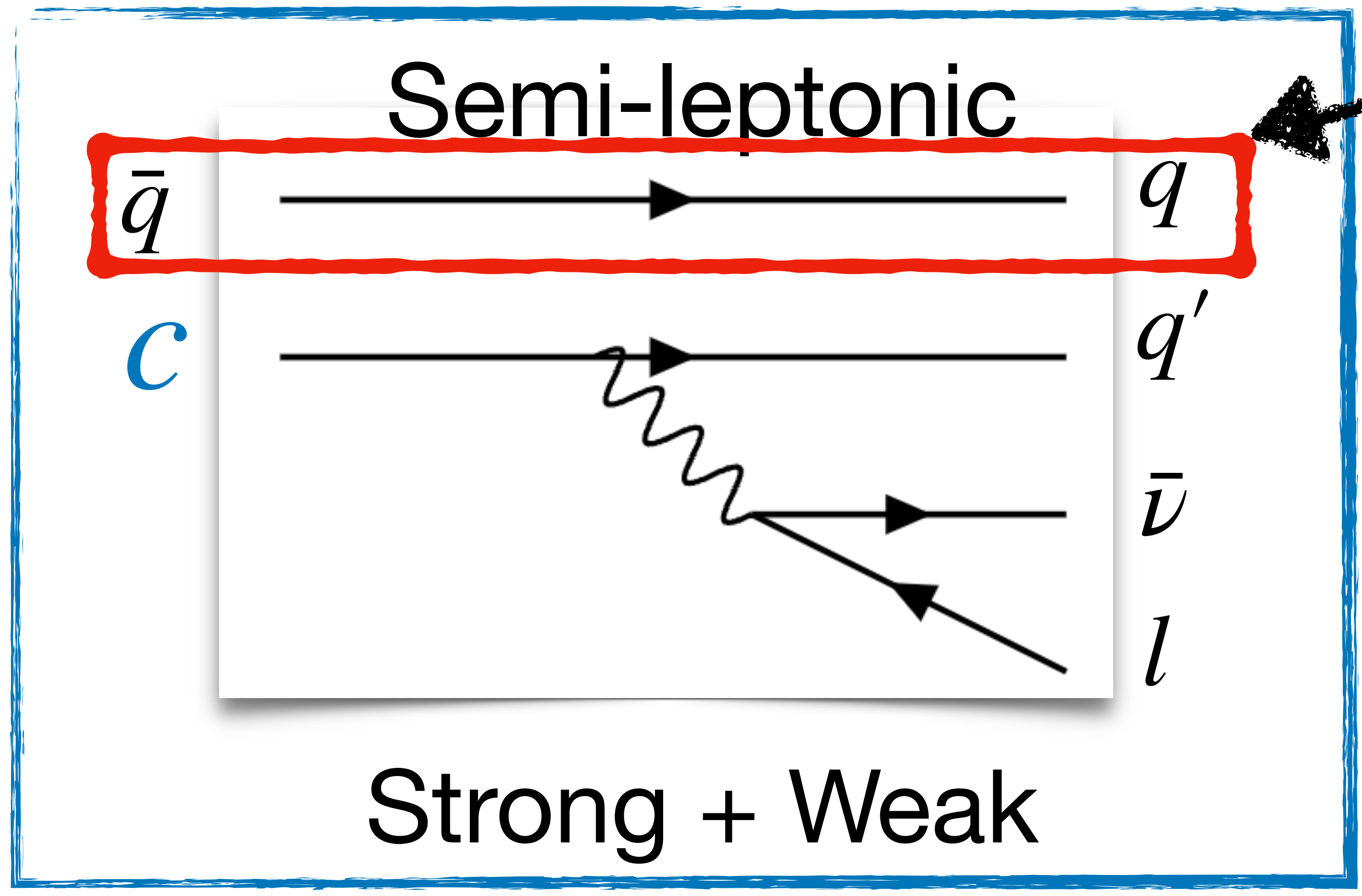
  - It is difficult, but worth to do.

- From the experience of $J/\psi \to \gamma 3(\pi^+\pi^-)$ and $J/\psi \to \gamma\pi^+\pi^-\eta'$, **the huge** J/ψ **sample is very meaningful to discover the underlying things in data.**

  - The underlying things could help to understand the nature of QCD.

α_S from charm data

- The c quark may be used to extract α_S, but it is confined in hadrons.
  - We cannot get a free c quark to measure α_S, so how about charmed mesons(has c)?
- We look at the inclusive semi-leptonic decays of charmed mesons,
  - The inclusive semi-leptonic decay widths (Γ_{SL}) are quite close.
  - The measurements indicate the impact of **spectator quark** in SL may be negligible.

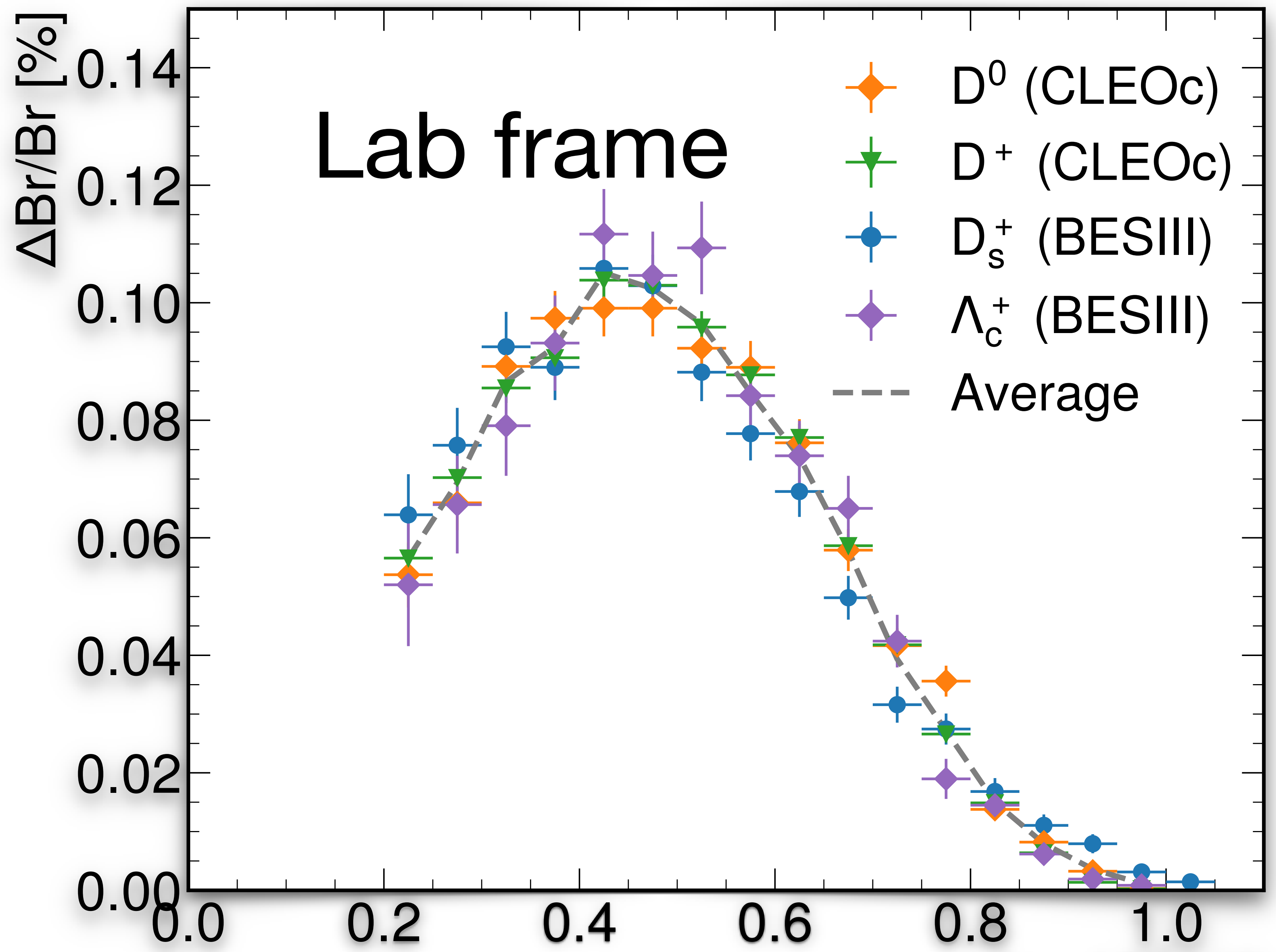


D_i	$\mathcal{B}_{SL}$ [%]	τ [10^{-13}s]	Γ_{SL} [10^{-15}GeV]
D^0	$6.46 \pm 0.09 \pm 0.11$	4.10 ± 0.01	104 ± 2
D^+	$16.13 \pm 0.10 \pm 0.29$	10.33 ± 0.05	103 ± 2
D_s^+	$6.30 \pm 0.13 \pm 0.09 \pm 0.04$	5.04 ± 0.04	82 ± 2

Arxiv. 2406.16119

α_S from charm data

- Except Γ_{SL}, we also check the distributions of $|p_{e^+}|$ in the SL of charmed mesons.



PhysRevD.81.052007 PhysRevD.107.052005

PhysRevD.81.052007

Kolmogorov-Smirnov tests among $|p_{e^+}|$ and average of $|p_{e^+}|$

Arxiv. 2406.16119

Test Samples	Test Statistic	P Value
$\|p_{e^+,D^0}\|$ and $\overline{\|p_{e^+}\|}$	0.125	0.999
$\|p_{e^+,D^+}\|$ and $\overline{\|p_{e^+}\|}$	0.063	1.000
$\|p_{e^+,D_s^+}\|$ and $\overline{\|p_{e^+}\|}$	0.132	0.992
$\|p_{e^+,\Lambda_c^+}\|$ and $\overline{\|p_{e^+}\|}$	0.125	0.999

Same distributions of $|p_{e^+}|$ among different charmed mesons, even baryons.

Heavy quarks "≈" heavy mesons for c quark in SL !!!

- The measurements demonstrate that we could use Γ_{SL} to extract α_S.
  - The measurements of $|p_e|$ is in lab frame, which cannot be used to extract α_S directly.

α_S from charm data

- The P. Gambino and J. F. Kamenik calculated the Γ_{SL} using Heavy Quark Expansion (HQE), which is expand as a series of $\alpha_S(m_c^2)$ and r (the ratio of m_s^2/m_c^2).

$$\Gamma_{SL} = \frac{G_F^2 m_c^5}{192\pi^3} \times |V_{cs}|^2 \times \left[f_0(r) + \frac{\alpha_S}{\pi} f_1(r) + \frac{\alpha_S^2}{\pi^2} f_2(r) + \frac{\mu_\pi^2}{m_c^2} f_\pi(r) + \frac{\mu_G^2}{m_c^2} f_G(r) + \frac{\rho_{LS}^3}{m_c^3} f_{LS}(r) + \frac{\rho_D^3}{m_c^3} f_D(r) + \frac{32\pi^2}{m_c^3} B_{WA} \right]$$

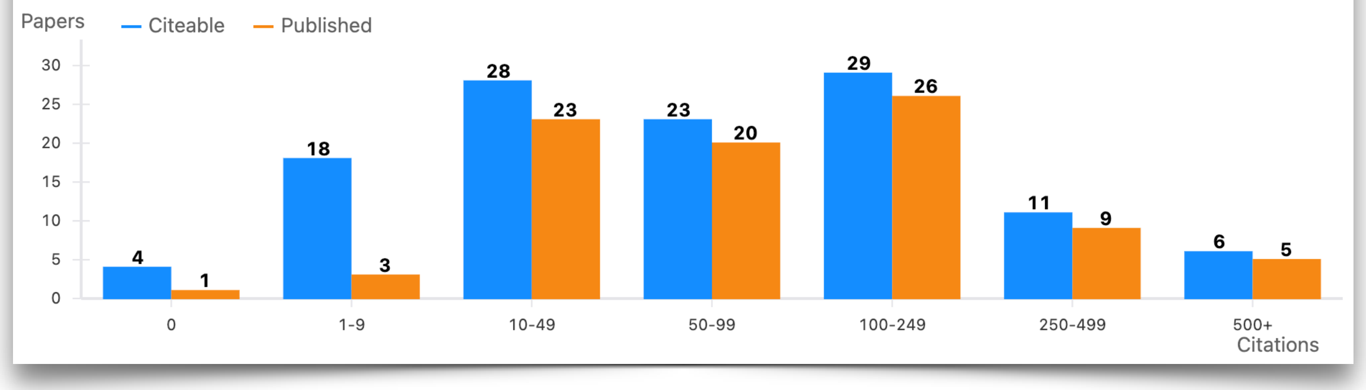
- Strong dependence of m_c
- Can extract the $|V_{cs}|$

- $\alpha_S = \alpha_S(m_c^2)$, **be can extracted from Γ_{SL}**

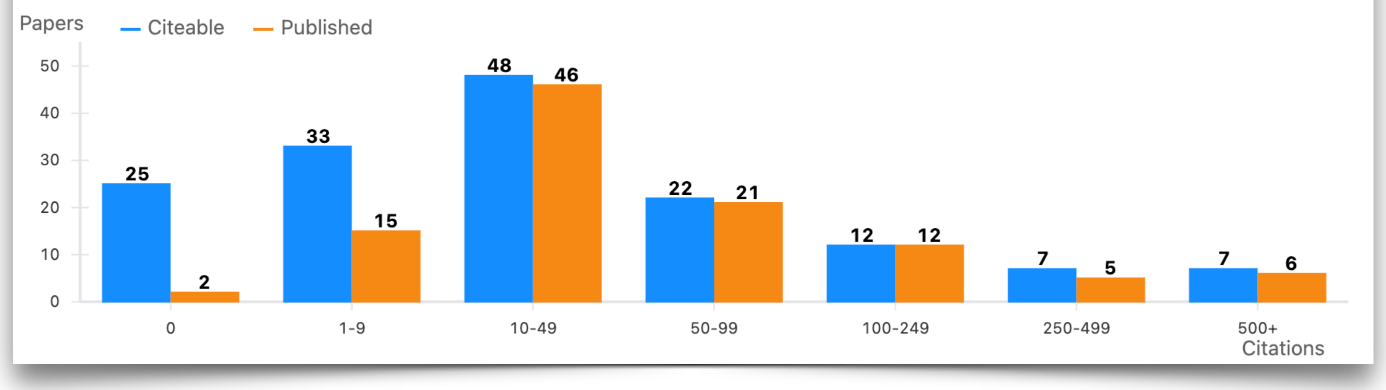
- $\mu^2_{\pi,\,G}$:the kinetic and chromo-magnetic dimension-five
- $\rho^3_{LS,\,D}$: Darwin and spin-orbital (LS) dimension-six operators.
- B_{WA}: weak annihilation (WA).

- The authors work on the inclusive semi-leptonic decay of beauty and charm mesons for almost 25 years.

	Citeable	Published
Papers	119	87
Citations	15,304	13,230
h-index	61	56
Citations/paper (avg)	128.6	152.1



	Citeable	Published
Papers	154	107
Citations	12,881	11,432
h-index	49	48
Citations/paper (avg)	83.6	106.8



Nucl.Phys.B 840 (2010) 424-437

α_S from charm data

- The parameters involved in the Γ_{SL} of charmed mesons are listed in table.
  - The values are from the measurements without involving the Γ_{SL} of D mesons.
  - To avoid the bad convergence behavior, we use the **kinetic scheme** to perform this study.

Parameter	Value
G_F	1.1663788×10^{-5}
$\|V_{cs}\|$	0.975 ± 0.006
$m_c(0.5\ \text{GeV})$	$(1.370 \pm 0.034)\ \text{GeV}$
$m_s(0.5\ \text{GeV})$	$(93.4 \pm 8.6)\ \text{MeV}$
$\mu_G^2(0.5\ \text{GeV})$	$(0.288 \pm 0.049)\ \text{GeV}^2$
$\mu_\pi^2(0.5\ \text{GeV})$	$(0.26 \pm 0.06)\ \text{GeV}^2$
$\rho_D^3(0.5\ \text{GeV})$	$(0.05 \pm 0.04)\ \text{GeV}^3$
$\rho_{LS}^3(0.5\ \text{GeV})$	$(-0.113 \pm 0.090)\ \text{GeV}^3$
$B_{WA,D^{+,0}}$	$-0.001\ \text{GeV}^3$
B_{WA,D_s^+}	$-0.002\ \text{GeV}^3$

- These parameters are used in the extraction of α_S.
- The uncertainties of these parameters are dominate uncertainty source of the extraction of α_S.
  - It is important to reduce the uncertainties of these parameters.

JHEP02(2024)206 PhysRevD.73.073008 PDG Arxiv. 2406.16119

α_S from charm data

- We calculate the Γ_{SL} of D_i meson using the mean lifetime (τ_{D_i}) and branching ratio of inclusive semi-leptonic decay (Br_{SL}).

$$\Gamma_{SL,\, D_i} = \frac{6.582 \times 10^{-25} \cdot Br_{SL}(D_i \to Xe\nu_e)}{\tau_{D_i}}\ \mathrm{GeV}$$

- The measured values of Γ_{SL} of charmed mesons are used to extract α_S.

D_i	$\mathcal{B}_{SL}$ [%]	τ [10^{-13}s]	Γ_{SL} [10^{-15}GeV]
D^0	$6.46 \pm 0.09 \pm 0.11$	4.10 ± 0.01	104 ± 2
D^+	$16.13 \pm 0.10 \pm 0.29$	10.33 ± 0.05	103 ± 2
D_s^+	$6.30 \pm 0.13 \pm 0.09 \pm 0.04$	5.04 ± 0.04	82 ± 2

PhysRevD.81.052007 PhysRevD.81.052007 PhysRevD.107.052005 PDG Arxiv. 2406.16119

α_S from charm data

- A χ^2 minimization method is employed to determine $\alpha_S(m_c^2)$ from the Γ_{SL},

$$\chi^2(\alpha_S, \theta_j) = \sum_i \frac{[\Gamma_{SL,D_i} - \hat{\Gamma}_{SL}(\alpha_S, \theta_j)]^2}{\sigma^2_{\Gamma_{SL,D_i}}} + \sum_j \frac{(\theta_j - \theta'_j)^2}{\sigma^2_{\theta'_j}}$$

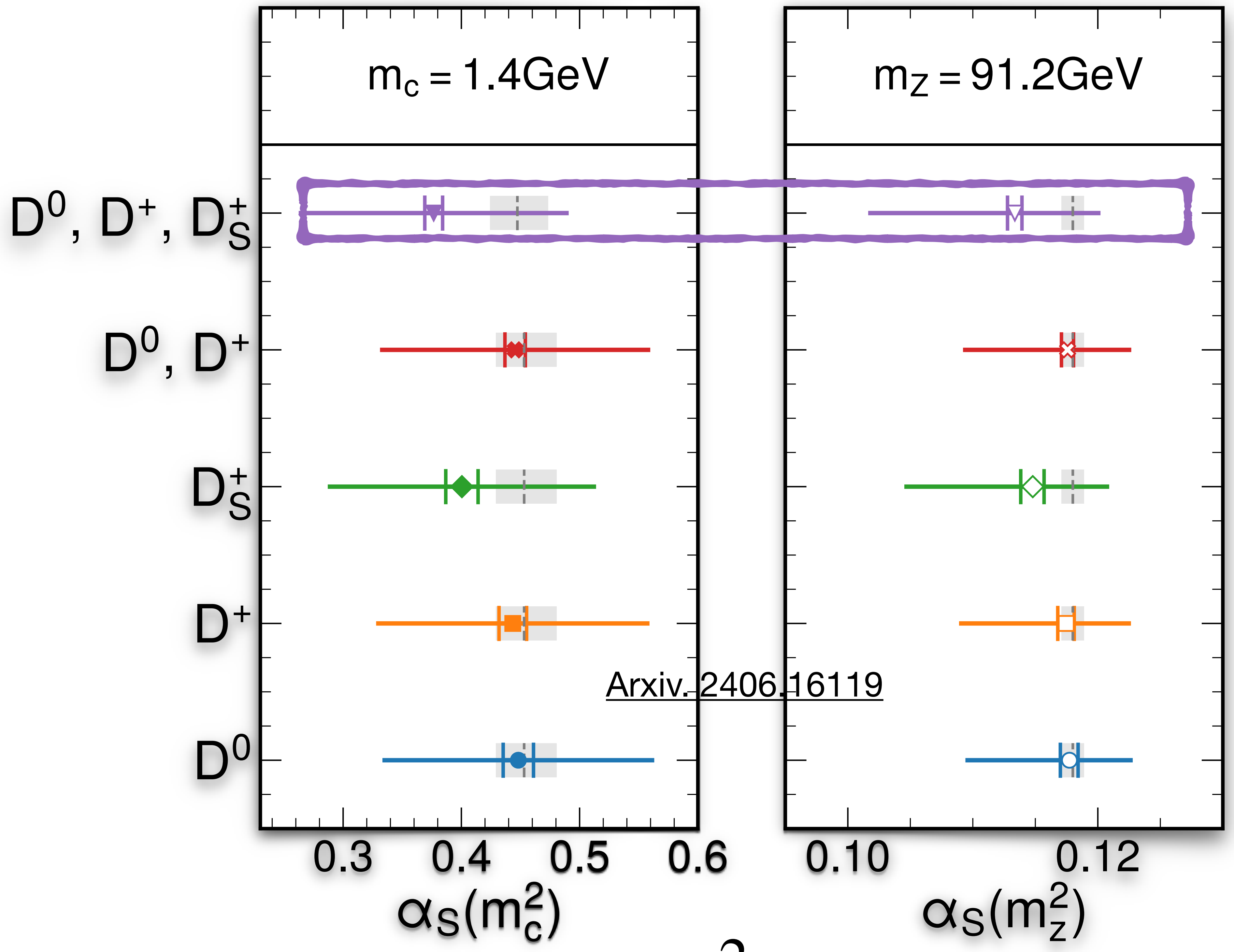
  - $\Gamma_{SL,\ D_i}$: measured Γ_{SL} for D_i meson.
  - $\sigma_{\Gamma_{SL,\ D_i}}$: uncertainty of Γ_{SL} for D_i meson.
  - $\hat{\Gamma}_{SL,\ D_i}$: predicational Γ_{SL} for D_i meson.
  - θ'_j and $\sigma_{\theta'_j}$: the value and uncertainty of constrained parameters in the fit.

- In this study, the predication of Γ_{SL} in reference is used to perform the fit.
  - The uncertainty caused by theoretical calculation is estimated by varying $\hat{\Gamma}_{SL}$ with 10% uncertainty. Details in backup.

Nucl.Phys.B 840 (2010) 424-437

α_S from charm data

- The $\alpha_S(m_c^2)$ is extracted for different combination among D^0, D^+, and D_s^+.
  - **Float the** m_c **and** $|V_{cs}|$**,** $\chi^2/ndof = 7.7/6$
  - **Fix the** m_c **and** $|V_{cs}|$**,** $\chi^2/ndof = 8.2/6$

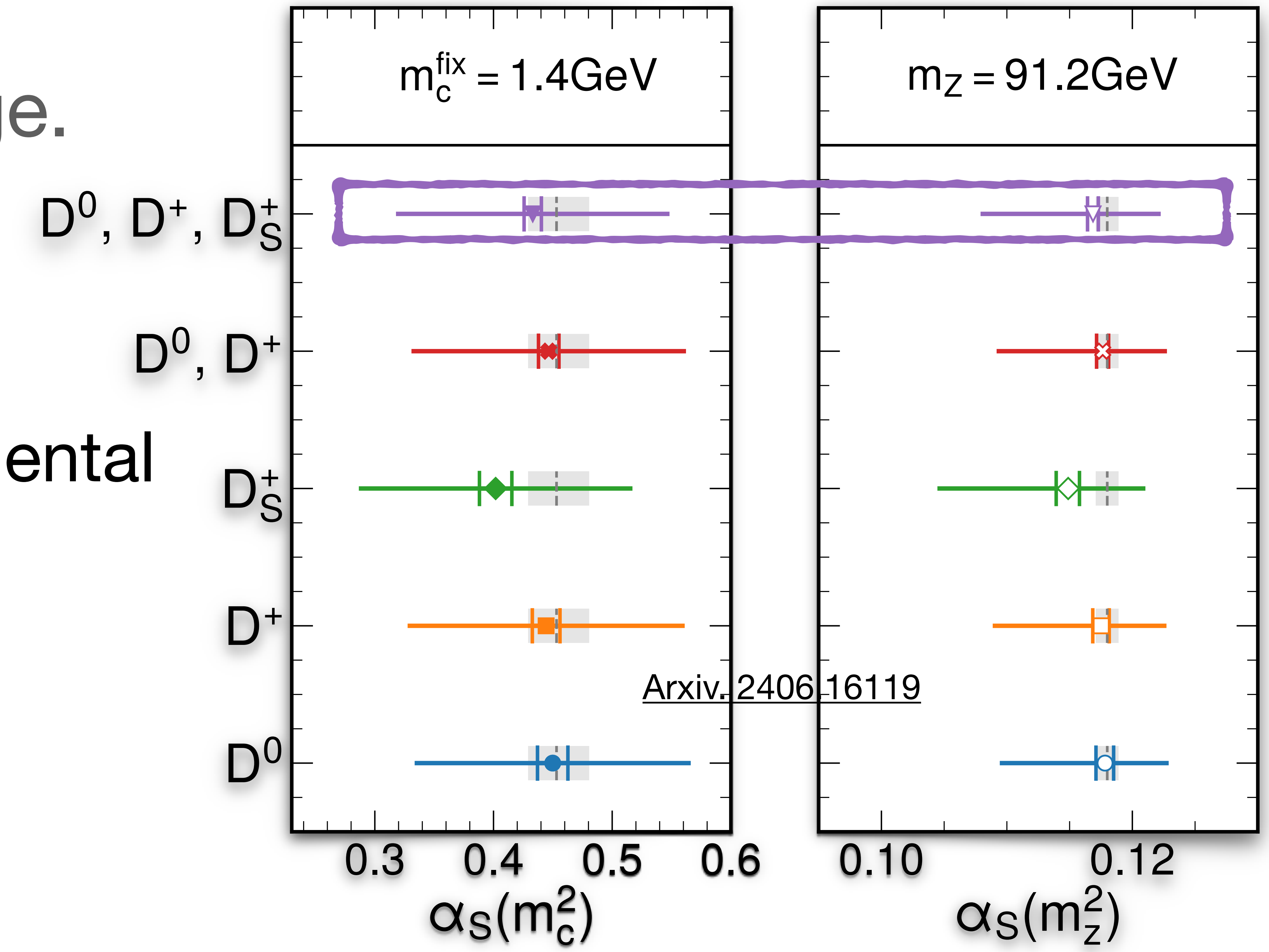


Shade : world average.

Marker : fitted α_S

Inner error bar : experimental uncertainty,

Outer error bar : total uncertainty,



- The values of $\alpha_S(m_c^2)$ are also **consistent within 1σ among different D mesons**, and **with the world average** of $\alpha_S(m_Z^2) = 0.1180 \pm 0.0009$.
- The consistence among different D mesons demonstrate the robustness of this method.
- The reasonable $\chi^2/ndof$ indicates that the method is reliable.

α_S from charm data

- If Q goes below m_τ, what will happen on α_S? Where does the logarithmic dependence of α_S disappear?

  ✦**The charmed mesons could be one of choices to extract the α_S below m_τ.**

  ✦**Low to $m_c = 1.4\ GeV$, the α_S looks still following the theoretical prediction.**

- what can we use as a tool to measure the α_S below m_τ?

  ✦We could use charmed mesons as a tool, and still need more investigation.

  ✦Even the charmed baryons may also be used to measure α_S, at least Λ_c^+.

- **The huge charmed data at BESIII could contributes a lot to this study.**

Summary

- We summarize a part of the recent progresses about QCD using the charm data, including J/ψ and D mesons.

- The charm data is an ideal ground to investigate and understand the puzzles in QCD.
  - ✦ Exotic hadrons, including hybrids and glueballs.
  - ✦ α_S and QCD at the low energy region.

- The huge charm data provides unprecedented opportunities, meanwhile considerable challenges.
  - ✦ Charmonium for the hunting of exotic states,
  - ✦ Charmed data for the α_S determination,
  - ✦ QCD at low energy scale region,
  - ✦ ….

Thanks for your listening!

Look forward the collaboration with you!

Backup

Γ_{SL} of charmed meson in theory

- Since the Γ_{SL} **has strong dependence on** m_c, the reasonable definition of m_c can simplify this study.

  - To avoid the bad convergence behavior, we use the **kinetic scheme** to perform this study.

- The relation of m_c between the $\overline{MS}$ and kinetic had been studied to N^{3}LO. The $m_c^{kin}(0.5\ GeV)$ is calculated from different scale in $\overline{MS}$.

$$m_c^{kin}(0.5\ \text{GeV}) = 1336\ \text{MeV from}\ \overline{m}_c(\mu_s = 3\ \text{GeV})$$
$$m_c^{kin}(0.5\ \text{GeV}) = 1372\ \text{MeV from}\ \overline{m}_c(\mu_s = 2\ \text{GeV})$$
$$m_c^{kin}(0.5\ \text{GeV}) = 1404\ \text{MeV from}\ \overline{m}_c(\mu_s = \overline{m}_c)$$

$$\overline{m_c^{kin}(0.5\ GeV)} = 1370 \pm 34\ MeV$$

The μ^{kin} is set to 0.5 GeV.

- The **average among 3 options** is taken into account for m_c in this study.

Nucl.Phys.B 426 (1994) 301-343 Phys.Rept. 494 (2010) 197-414 PhysRevLett.125.052003

The prediction of Γ_{SL}

- The P. Gambino and J. F. Kamenik calculated the Γ_{SL} using the framework of HQE[4].

$$f_0(r) = 1 - 8r + 8r^3 - r^4 - 12r^2 \cdot \log(r)$$

$$f_1(r) = 2.86\sqrt{r} - 3.84r \cdot \log(r)$$

$$f_2(r) = \beta_0[8.16\sqrt{r} - 1.21r \cdot \log(r) - 3.38]$$

$$f_G(r) = \frac{1}{2}f_0(r) - 2(1-r)^4$$

$$f_\pi(r) = -f_0(r)/2$$

$$f_{LS}(r) = -f_G(r)$$

$$f_D(r) = \frac{77}{6} + \mathcal{O}(r) + 8\log(\frac{\mu_{WA}^2}{m_c^2})$$

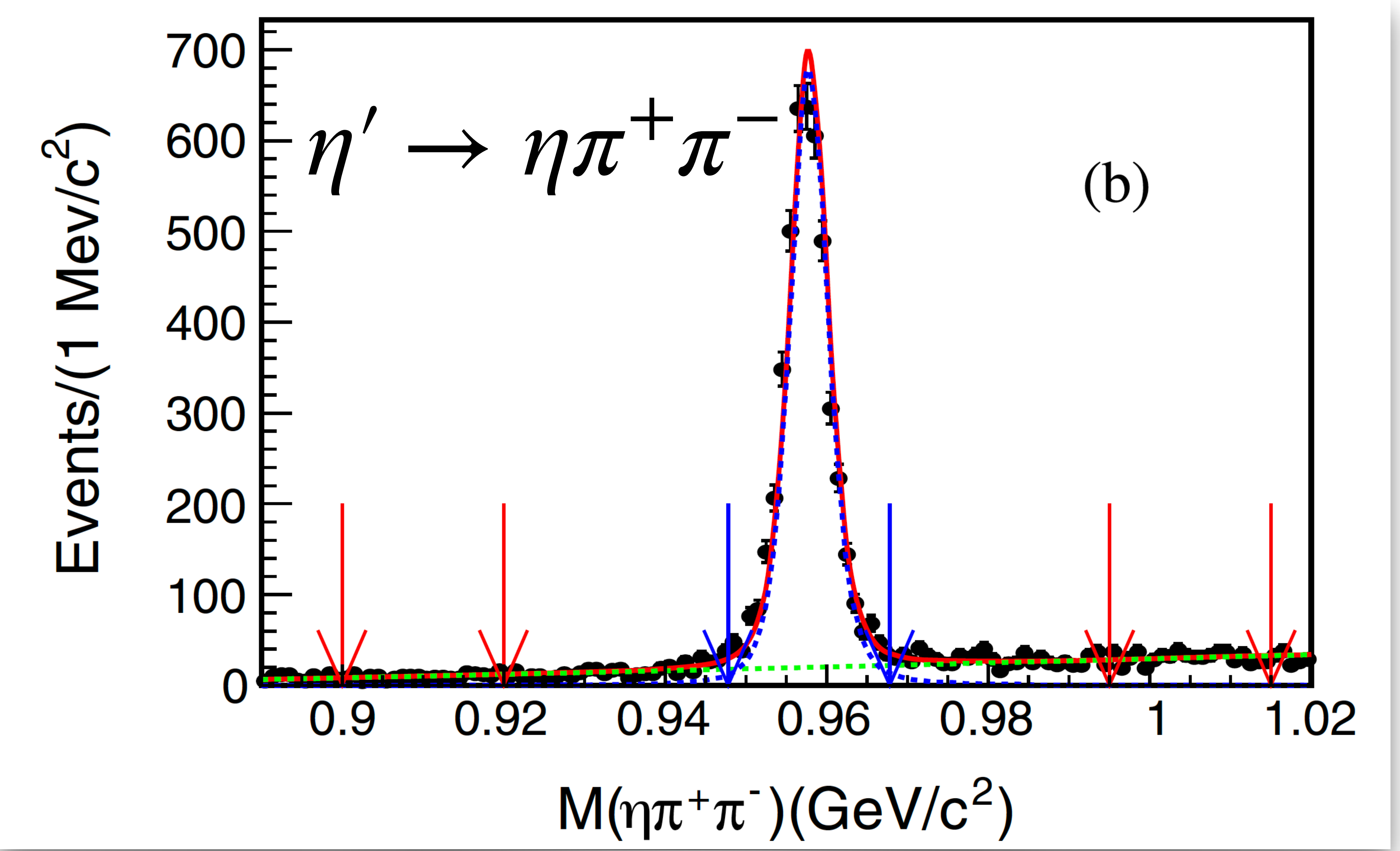
[4] Nucl.Phys.B 840 (2010) 424-437

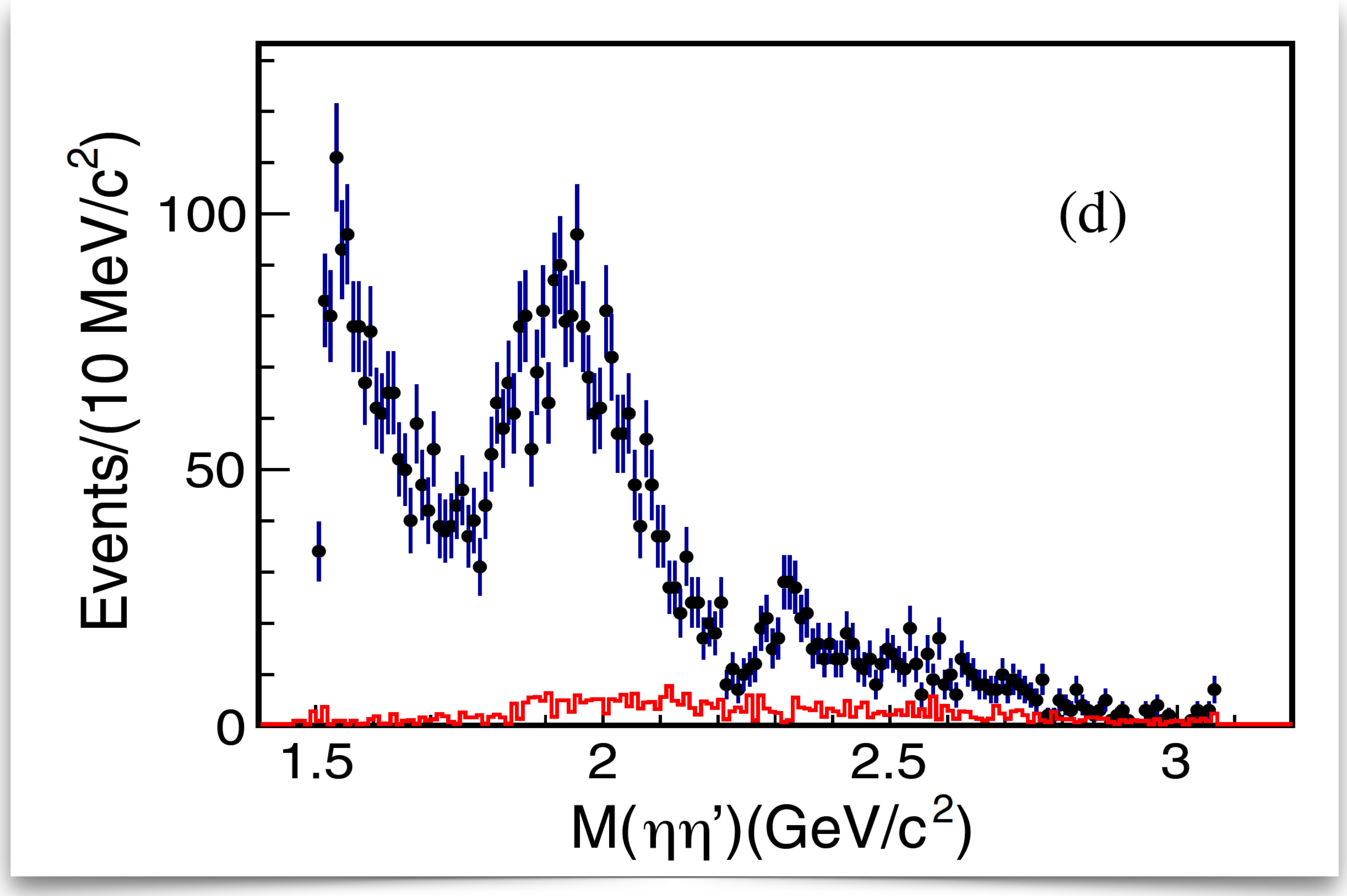
α_S from charm data

- In the prediction of Γ_{SL}, two parts are missed :
  - The high order α_S correction,
  - The absence of Cabibbo suppressed processes of $c \to dl\bar{\nu}$ in the calculation.
- The high order α_S correction in $b \to cl\bar{\nu}$ is less than 1%. We take **5 times larger than** $b \to cl\bar{\nu}$ as the high order correction in $c \to sl\bar{\nu}$, PhysRevD.104.016003
  - 5% is taken.
- The absence of $c \to dl\bar{\nu}$ causes the 5% uncertainty on Γ_{SL}, that is proportional to $|V_{cd}|^2/(|V_{cd}|^2 + |V_{cs}|^2) = 5\,\%$.
- In total, we take **10%** as the uncertainty of theoretical Γ_{SL}.

1^{-+} exotics at BESIII

- The process of $J/\psi \to \gamma\eta\eta'$ is investigated using the J/ψ sample via 2 decay modes of η'at BESIII.





α_S from charm data

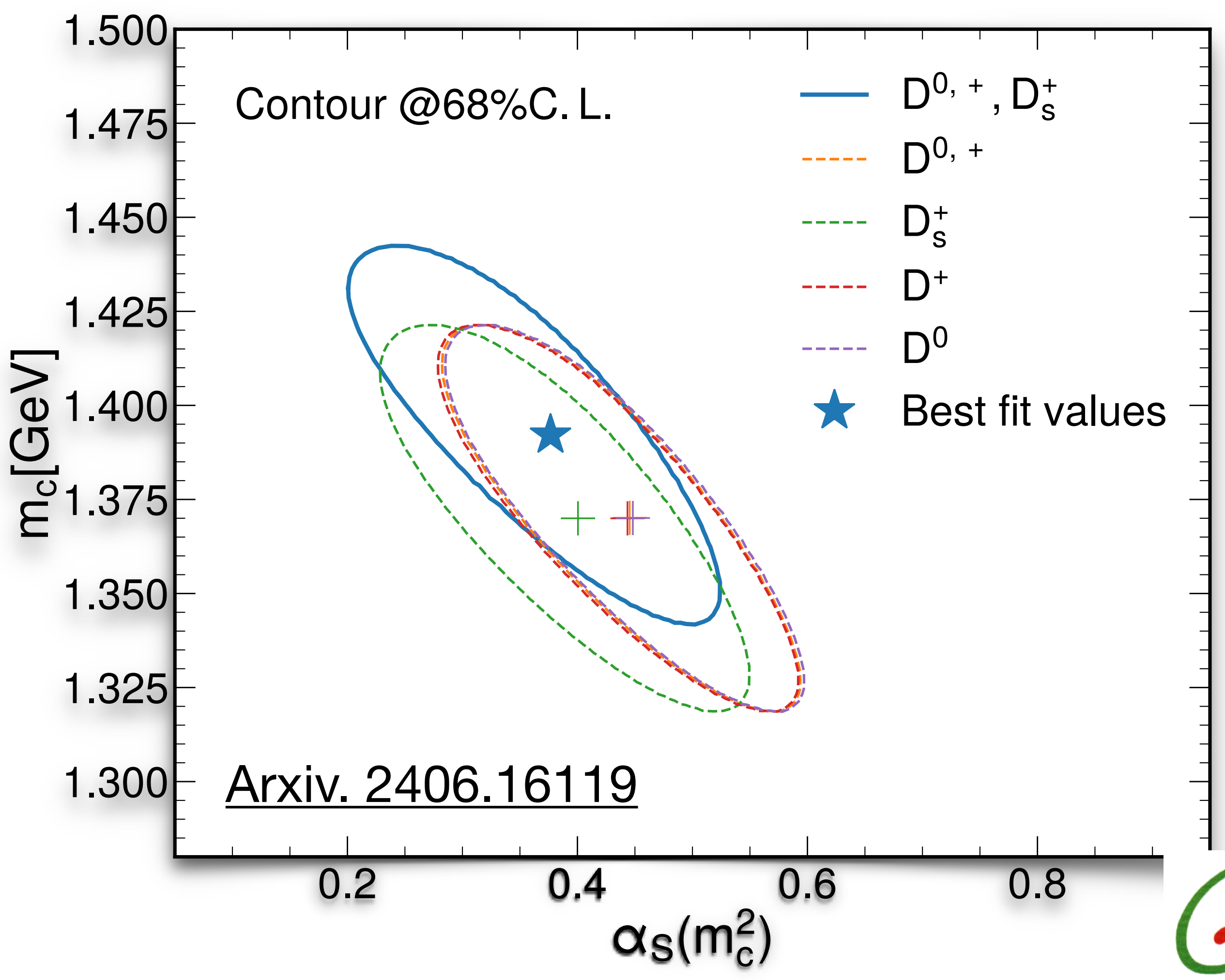
- The $\alpha_S(m_c^2)$ is extracted for different combination among D^0, D^+, and D_s^+.
  - **Float the m_c and $|V_{cs}|$**, the first and second uncertainty of α_S are experimental and theoretical uncertainty.

$\chi^2/ndof = 7.7/6$

Arxiv. 2406.16119

Combination	m_c^{float} [GeV]	$\alpha_S(m_c^2)$ $[10^{-3}]$	$\alpha_S(m_Z^2)$ $[10^{-4}]$
D^0	1.370 ± 0.034	$448 \pm 13 \pm 114$	1177^{+7+50}_{-7-83}
D^+	1.370 ± 0.034	$444 \pm 12 \pm 115$	1175^{+6+51}_{-7-85}
D_s^+	1.370 ± 0.034	$400 \pm 14 \pm 113$	$1148^{+9+60}_{-10-102}$
$D^{0,+}$	1.370 ± 0.034	$445 \pm 9 \pm 114$	1176^{+5+51}_{-5-84}
$D^{0,+}$, D_s^+	1.392 ± 0.033	$377 \pm 8 \pm 114$	1134^{+6+68}_{-6-117}

- The values of $\alpha_S(m_c^2)$ are **consistent within 1σ among different D mesons**, and **with the world average** of $\alpha_S(m_Z^2) = 0.1180 \pm 0.0009$.
- The combination of $D^{0,+}$ and D_s^+ changes the fit results of $\alpha_S(m_c^2)$ a lot. May be caused by the **strong dependence on m_c**.
- The reasonable $\chi^2/ndof$ indicates that the method is reliable.



α_S from charm data

- The $\alpha_S(m_c^2)$ is extracted for different combination among D^0, D^+, and D_s^+.
  - **Fix the m_c and $|V_{cs}|$**, the uncertainty is estimated by varying them by 1σ.
  - $m_c^{fix} = (1.370 \pm 0.034)\ GeV$, $|V_{cs}| = \sqrt{1 - |V_{cb}|^2 - |V_{cd}|^2} = 0.974 \pm 0.001$ is calculated using the unitarity of CKM matrix.

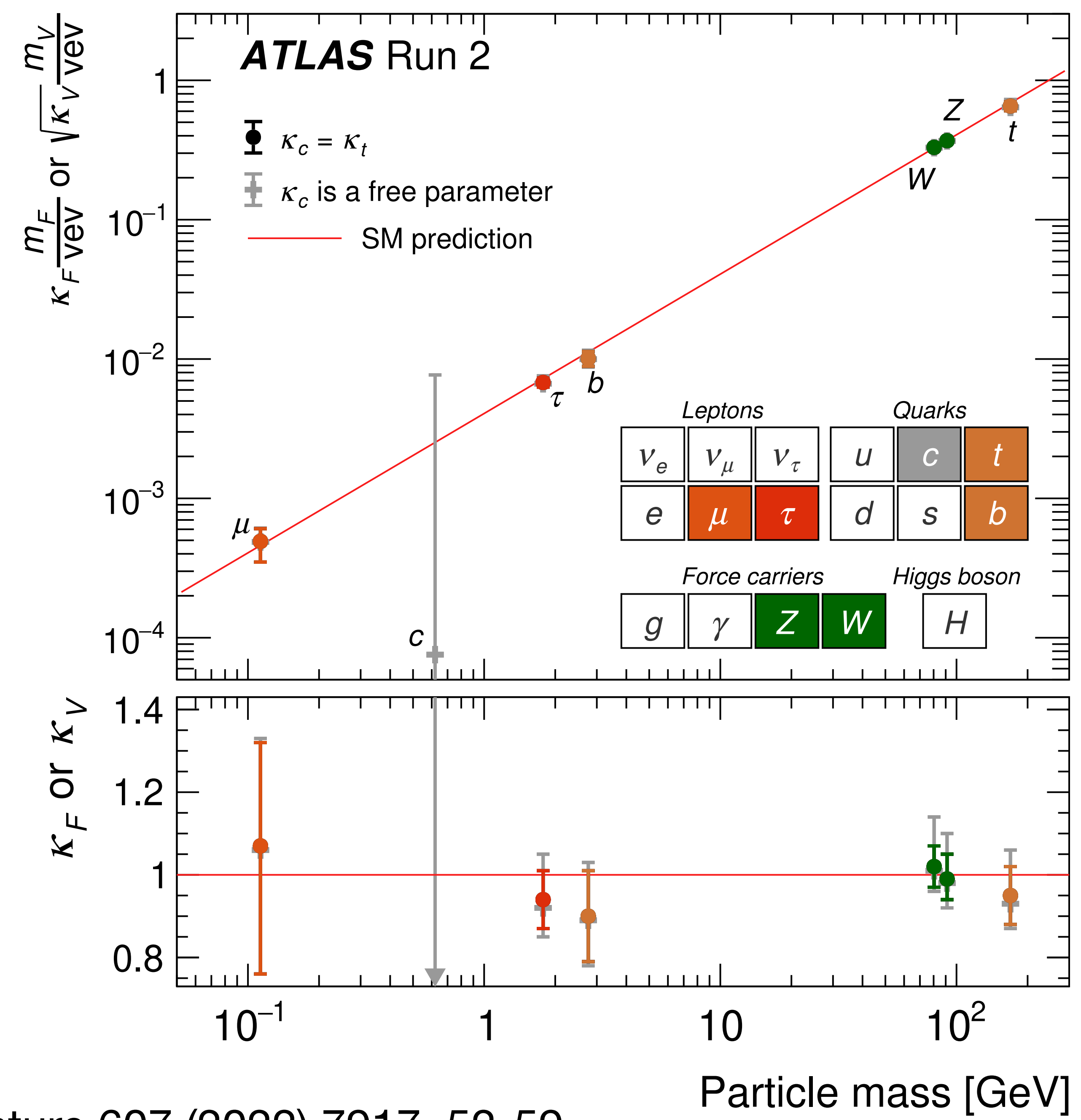
$\chi^2/ndof = 8.2/6$ Arxiv. 2406.16119

Combination	$m_c^{\rm fix}$ [GeV]	$\alpha_S(m_c^2)$ $[10^{-3}]$	$\alpha_S(m_Z^2)$ $[10^{-4}]$
D^0		$450 \pm 13 \pm 116$	1178^{+7+55}_{-7-75}
D^+		$444 \pm 12 \pm 116$	1175^{+6+56}_{-7-77}
D_s^+	1.370 ± 0.034	$402 \pm 14 \pm 114$	1149^{+9+70}_{-10-98}
$D^{0,+}$		$447 \pm 9 \pm 115$	1177^{+5+56}_{-5-76}
$D^{0,+}$, D_s^+		$433 \pm 7 \pm 115$	1168^{+4+61}_{-4-80}

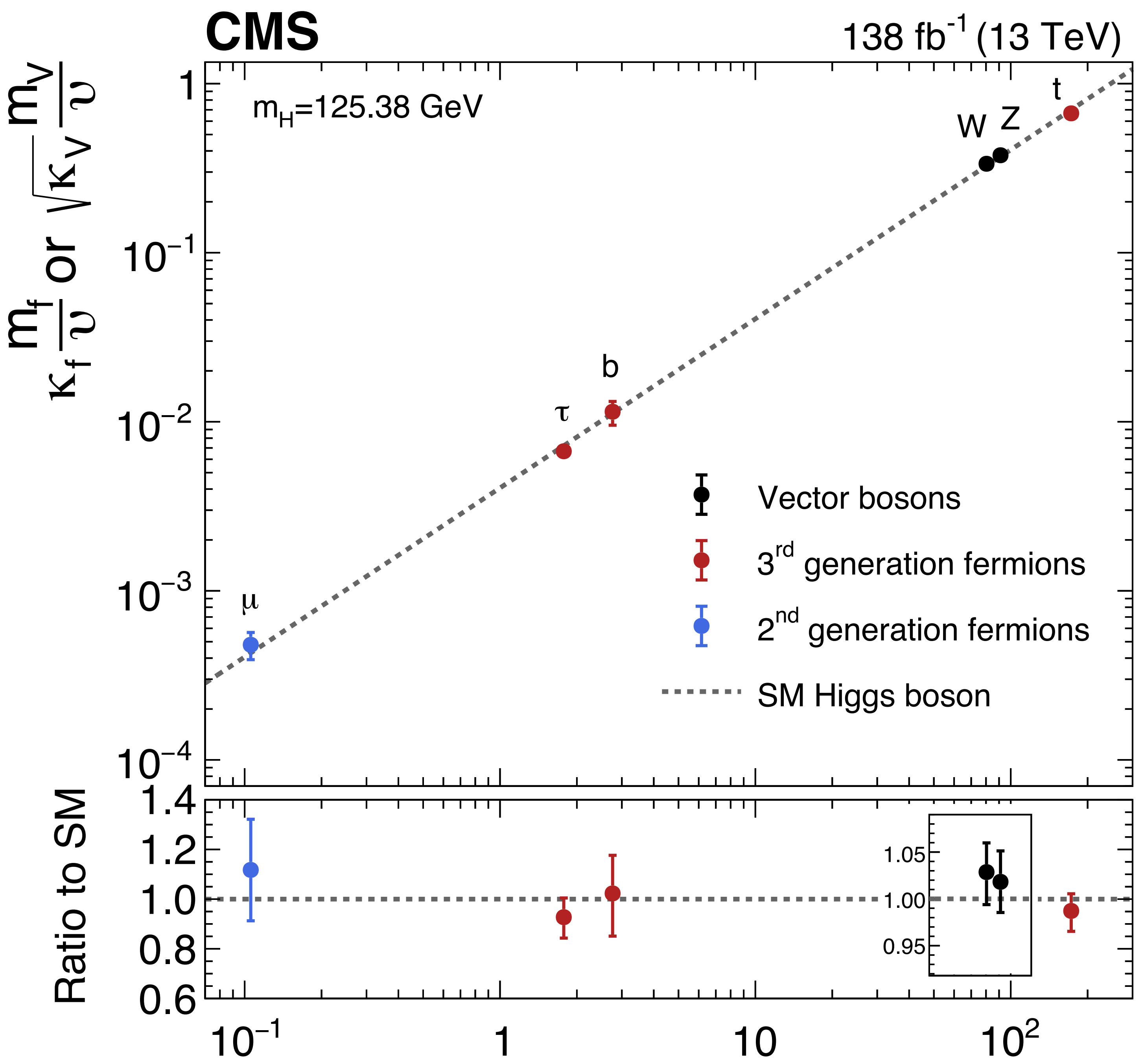
- The values of $\alpha_S(m_c^2)$ are also **consistent within 1σ among different D mesons**, and **with the world average** of $\alpha_S(m_Z^2) = 0.1180 \pm 0.0009$.

Strong Interaction

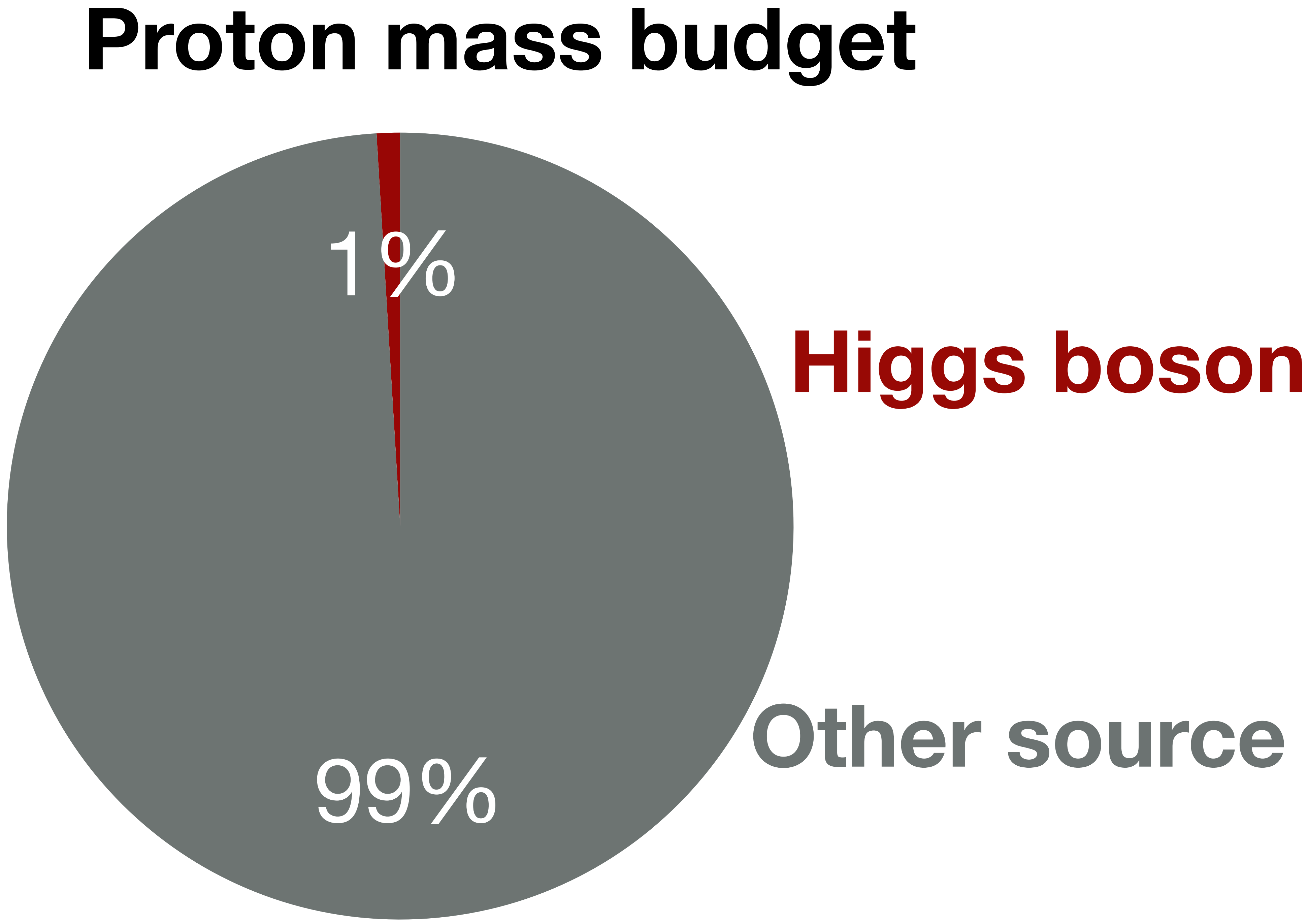
- The masses of elementary particles originate from the Higgs boson.



Nature 607 (2022) 7917, 52-59



Nature 607 (2022) 7917, 60-68



- Let's take proton as a naive example, $m_p \gg 2m_u + m_d$
  - The strong interaction may be one of the other source.
  - Need more careful investigation of strong interaction, especially in low energy scale region.

Charm and charmonium data can help!