中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

中国高等科学技术中心
China Center of Advanced Science and Technology

Possible measurements of α_S at BESIII

JinFei Wu[1,2], XinChou Lou[1], Gang Li[1], JingBo Ye[1]
IHEP,CAS[1] and CCAST[2]
Nov. 1, 2024

第一届基础物理研讨会暨基础物理平台年会，河南省科学院高能物理研究中心

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- **Introduction**
  - Strong interaction
  - Existing measurements of α_S
- Possible measurements of α_S at BESIII
  - Data samples at BESIII
  - α_S from inclusive semi-leptonic decay of charmed mesons
  - α_S from other methods
- Summary

May not cover all possibilities, please forgive my shortage!

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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 strong coupling constant, $\alpha_S = g_s^2/4\pi$,

- Quantizes the **strength**, and dictates **features** of the **strong interaction**.

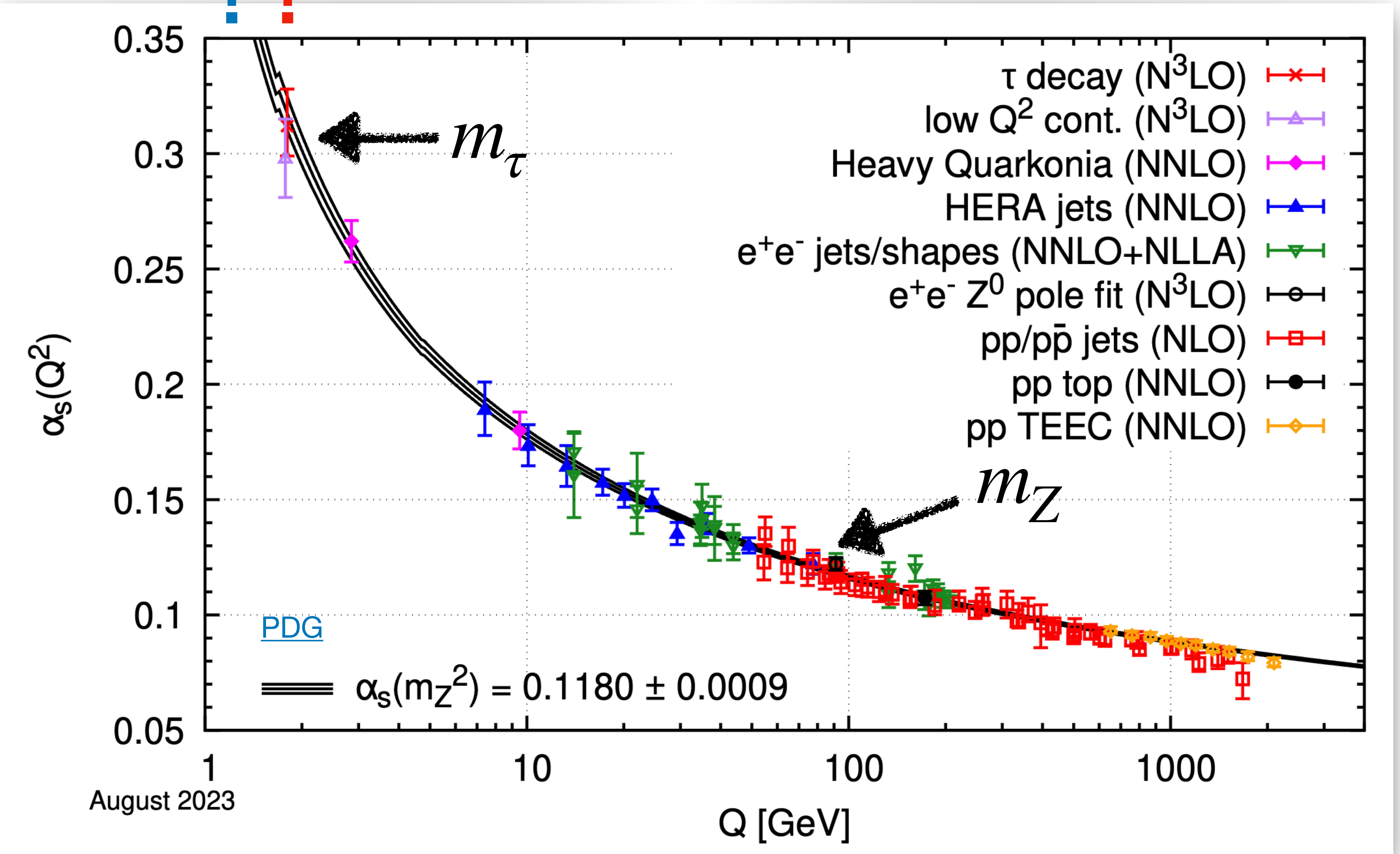
- The α_S has been measured using many methods, such as hadronic τ decay, PDF fits and EW precision fit etc. .

- The strong interaction is the **least known interaction** in SM, and **important for precise measurements** and **new physics search**.

Existing measurements of α_S

- In the region from m_τ to ~$2\ TeV$, the values of α_S have been determined at many energy scales, especially in higher energy region (> 10 GeV).
  - Demonstrate “asymptotic freedom” and color confinement.

??

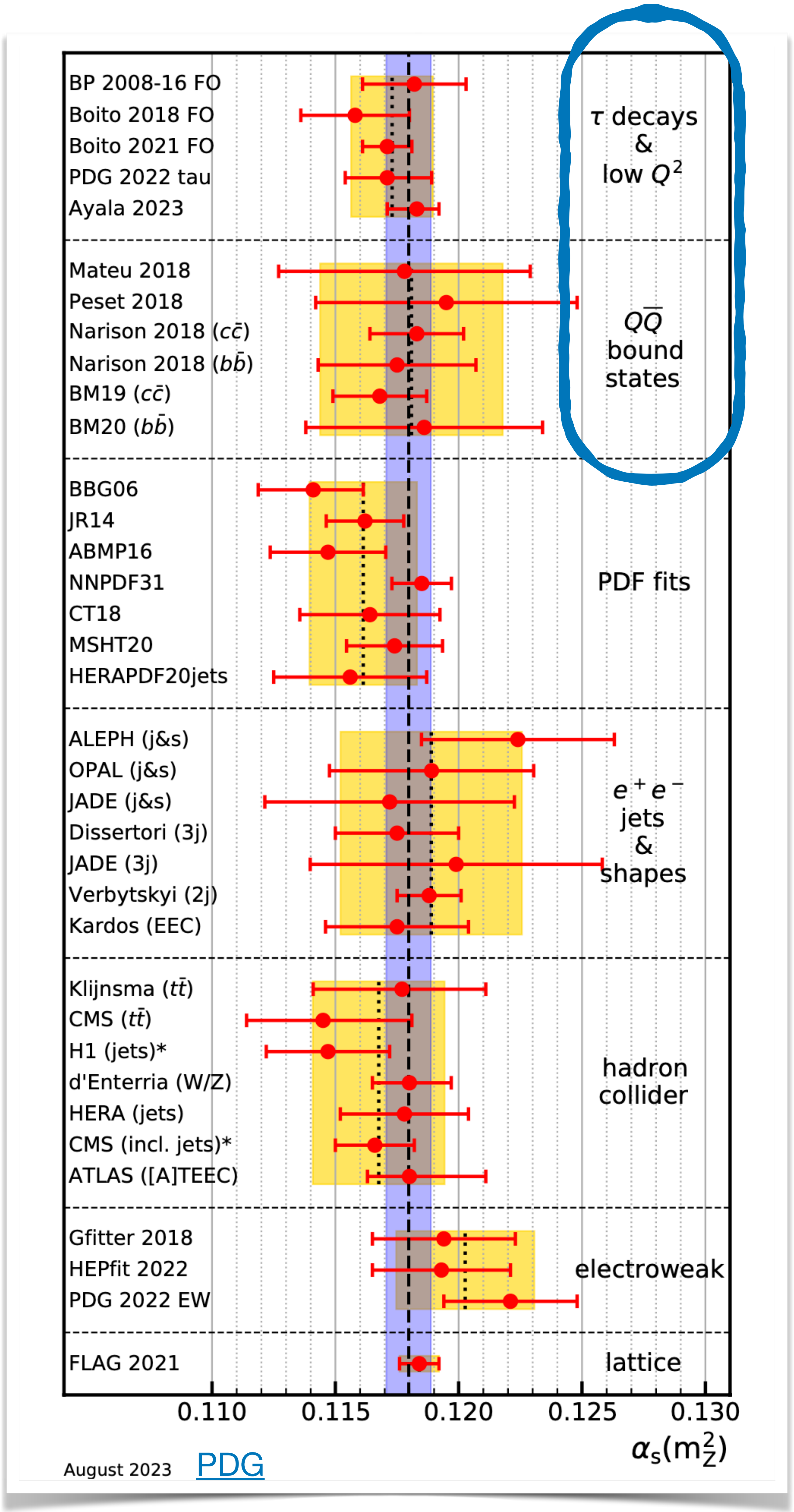


- Is there anything behind **color confinement** and “**asymptotic freedom**” ?

- What will happen on α_S **below** m_τ? what can we use as **a tool to measure the α_S below m_τ**?

Existing measurements of α_S

- The existing measurements of α_S include :
  - Hadronic τ decays and low Q^2 data, BESIII
  - Heavy quarkonia decays, BESIII
  - PDF fits,
  - Hadronic final states of e^+e^- annihilations, BESIII(need investigation)
  - Observables from hadron induced collisions,
  - Electro-weak precision fit,
  - Lattice QCD.



- What could we do to determine α_S at BESIII?
  - **Hadronic τ decays and low Q^2 data,**
  - **Heavy quarkonia decays,**
  - **Maybe new ideas.**

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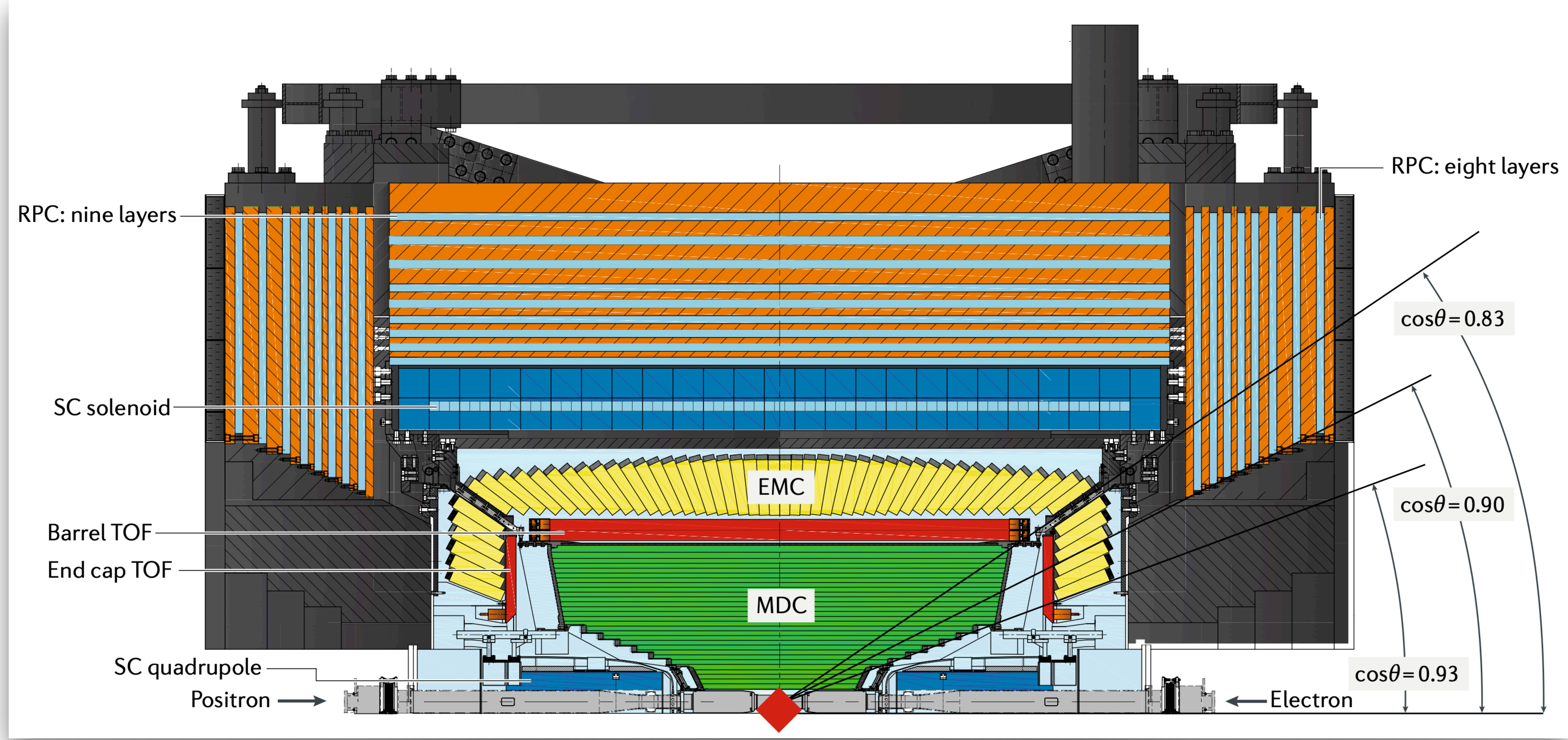
BESIII detector

- The **excellent detector performance** provides good potential to look into QCD.



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

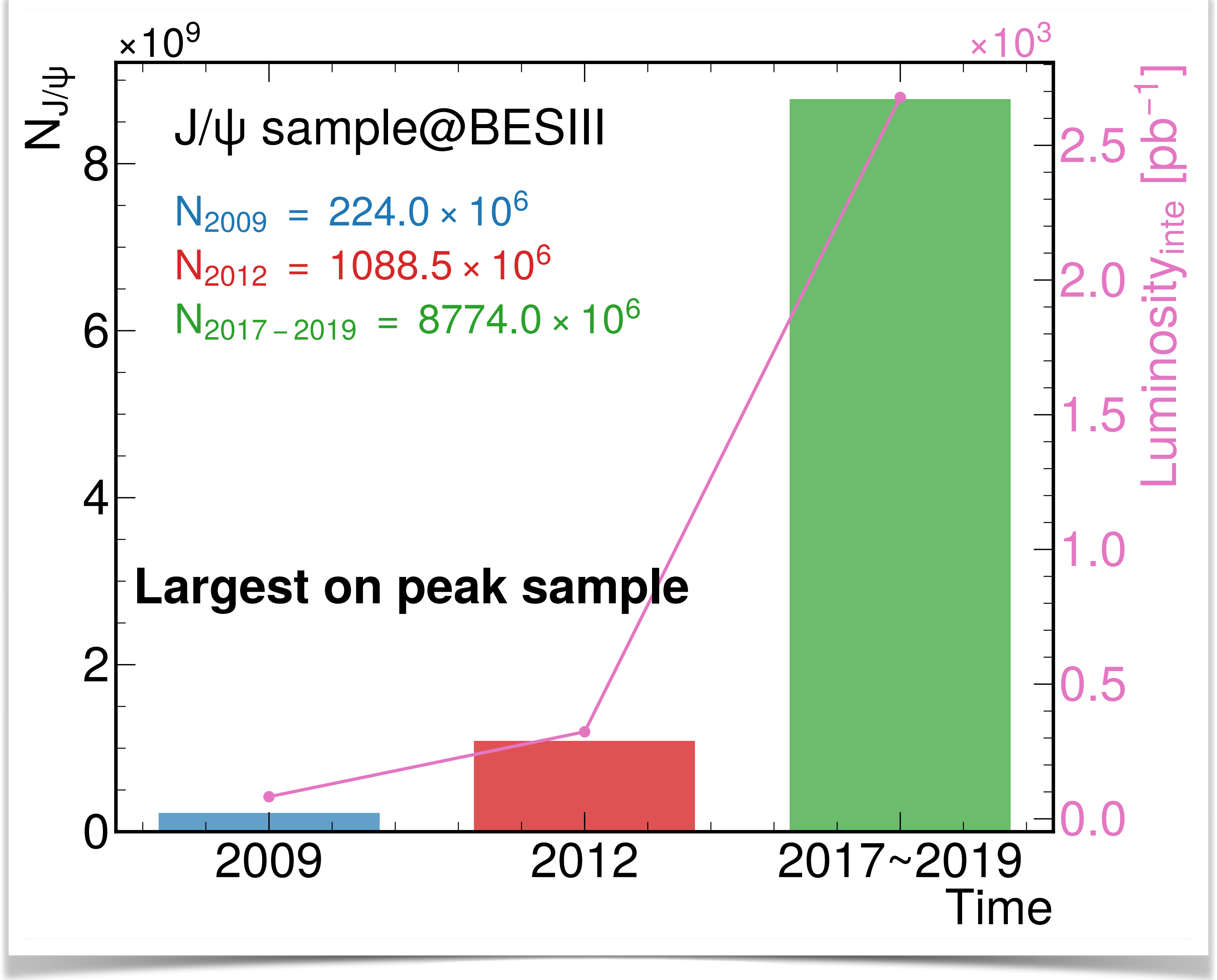
- 93% coverage of full solid angle
- $\sigma_{P,\ charged\ trk}@1GeV/c$: 0.5%
- $\sigma_{dE/dX}$ for electron : 6%
- $\sigma_{E_\gamma\ in\ EMC}@1\ GeV/c$: 2.5(5)% for barrel (end-cap) region.
- $\sigma_{t\ in\ TOF}$: 68(110)ps for barrel (end-cap) region, the updated end-cap gives 60 ps.

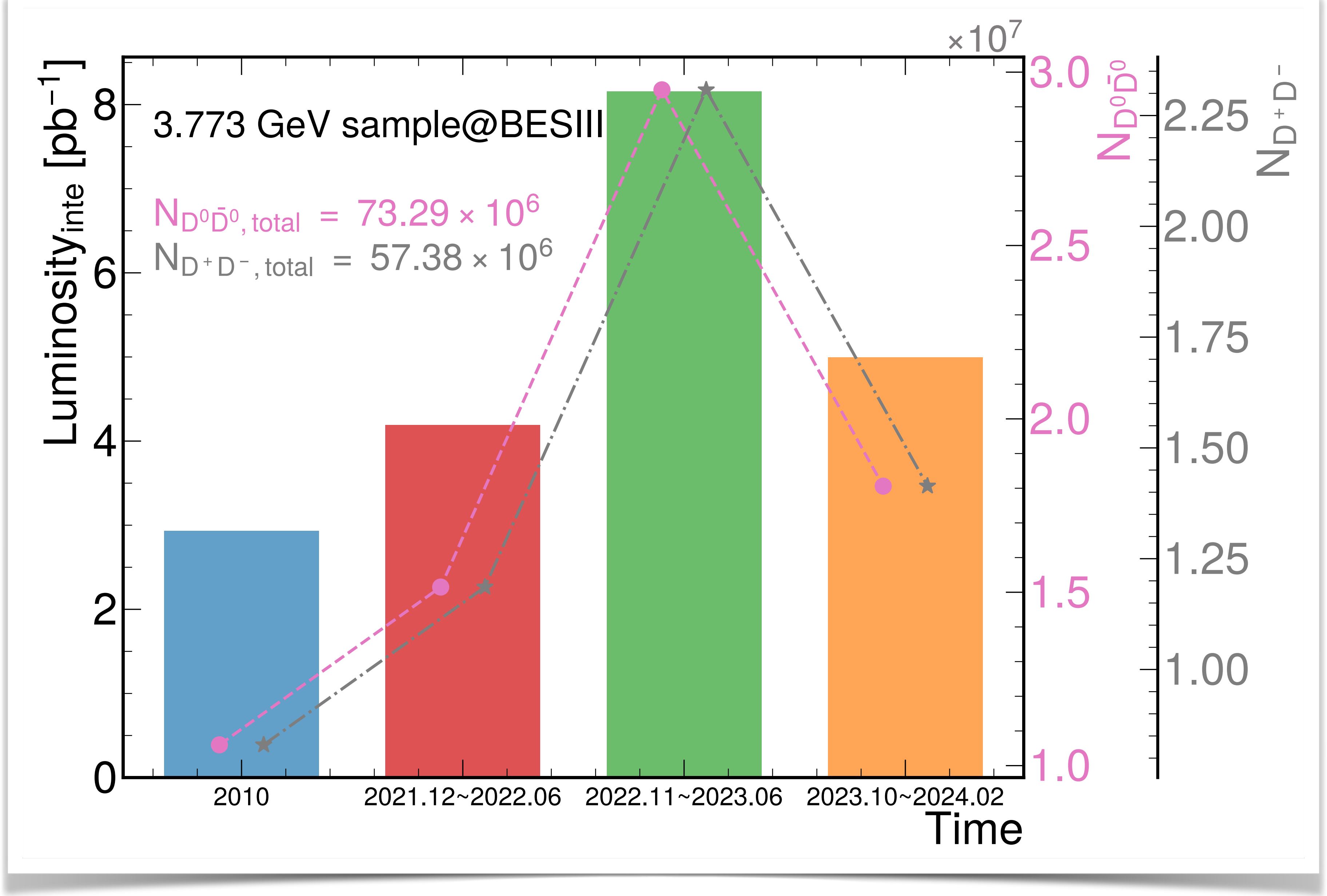
- The BESIII is a well-performed detector after 10+ years running.

Data samples at BESIII

- The BESIII has collected the $(10.09 \pm 0.04) \times 10^9\ J/\psi$ sample and ~20.3 $fb^{-1}\ e^+e^-$ collision data sample at 3.773 GeV.

- Except these data, there are also lots of e^+e^- collision data at many energy points.





BESIII started data taking for physics since 2009, and the following data samples were collected:

- 2009 : 0.225x10^9 J/psi at Ecm=3.097 GeV, 0.106x10^9 psi(3686) at Ecm=3.686 GeV
- 2010 + 2011 : 2.9 fb^{-1} psi(3770) at 3.773 GeV
- 2011 : 0.5 fb^{-1} psi(4040) at 4.009 GeV, 0.024 fb^{-1} tau mass scan at around 3.554 GeV, 2011
- 2012 : 1.3x10^9 J/psi at Ecm=3.097 GeV, 2009 (0.225x10^9) , 0.5x10^9 psi[illegible] at Ec[illegible]3.686 GeV, 2009 (0.106x10^9)
- 2013 : 1.9 fb^{-1} Y(4260) at 4.23 and 4.26 GeV, 0.5 fb^{-1} Y(4360) at 4.[illegible]6 GeV, 0.5 fb^{-1} Y(4260) and Y(4360) scan
- 2014 : 0.8 fb^{-1} R scan, 104 energy points between 3.85 and 4.59 GeV, 0.5 fb^{-1} at 4.60 GeV, 0.1 fb^{-1} at 4.47 and 4.53 GeV for line shape, 0.05 fb^{-1} around the threshold of Lambda_[illegible] pair, [illegible].0 fb^{-1} at 4.42 GeV
- 2015 : 0.5 fb^{-1} data for R scan from 2.0 to 3.08 GeV, 0.1[illegible] fb^{-1} data @ 2.125 GeV
- 2016 : 3.1 fb^{-1} data at 4.18 GeV
- 2017 : 3.8 fb^{-1} 8 energy points from 4190-42[illegible] MeV, [illegible].46 fb^{-1} around chi_c1 mass , 0.22 fb^{-1} around 3872 MeV
- 2018 : 4.6 x 10^9 J/psi data set (1.[illegible]/fb), 0.1[illegible] /fb tau scan data, 0.5 /fb, 9 points for psi(3686) scan data
- 2019 : 4.2 x 10^9 J/psi data s[illegible].218 /fb), 3.8/fb scan data for XYZ, 8points (4.13, 4.16, 4.29-4.44 GeV)
- 2020 : 3.8/fb scan data for XYZ and Lambda_c, 6 points (4.61-4.70 GeV)
- 2021 : 1.9/fb scan data at 6 points (4.74-4.946 GeV), 2.26 x 10^9 psi(3686) events (3.21/fb)
- 2022 : 0.4/fb data at 3.65 GeV, 0.4/fb data at 3.682 GeV, 5.0/fb data at 3.773 GeV
- 2023 : 8.16/fb data at 3.773 GeV

BESIII

Huge data

Huge and clean data sample@BESIII → Good opportunities@α_s and QCD

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α_s from inclusive semi-leptonic decay of charmed mesons

- Let's see B sector first,
  - The **lifetimes** and **branch ratios** are **close among different B mesons** (even B baryons), which means the **impact of spectator quark is negligible**.

Int.J.Mod.Phys.A 30 (2015) 10, 1543005

B-mesons

	$B_d = (\bar{b}d)$	$B^+ = (\bar{b}u)$	$B_s = (\bar{b}s)$	$B_c^+ = (\bar{b}c)$
Mass (GeV)	5.27955(26)	5.27925(26)	5.3667(4)	6.2745(18)
Lifetime (ps)	1.519(7)	1.641(8)	1.516(11)	0.452(33)
$\tau(X)/\tau(B_d)$	1	1.079 ± 0.007	0.998 ± 0.009	0.30 ± 0.02

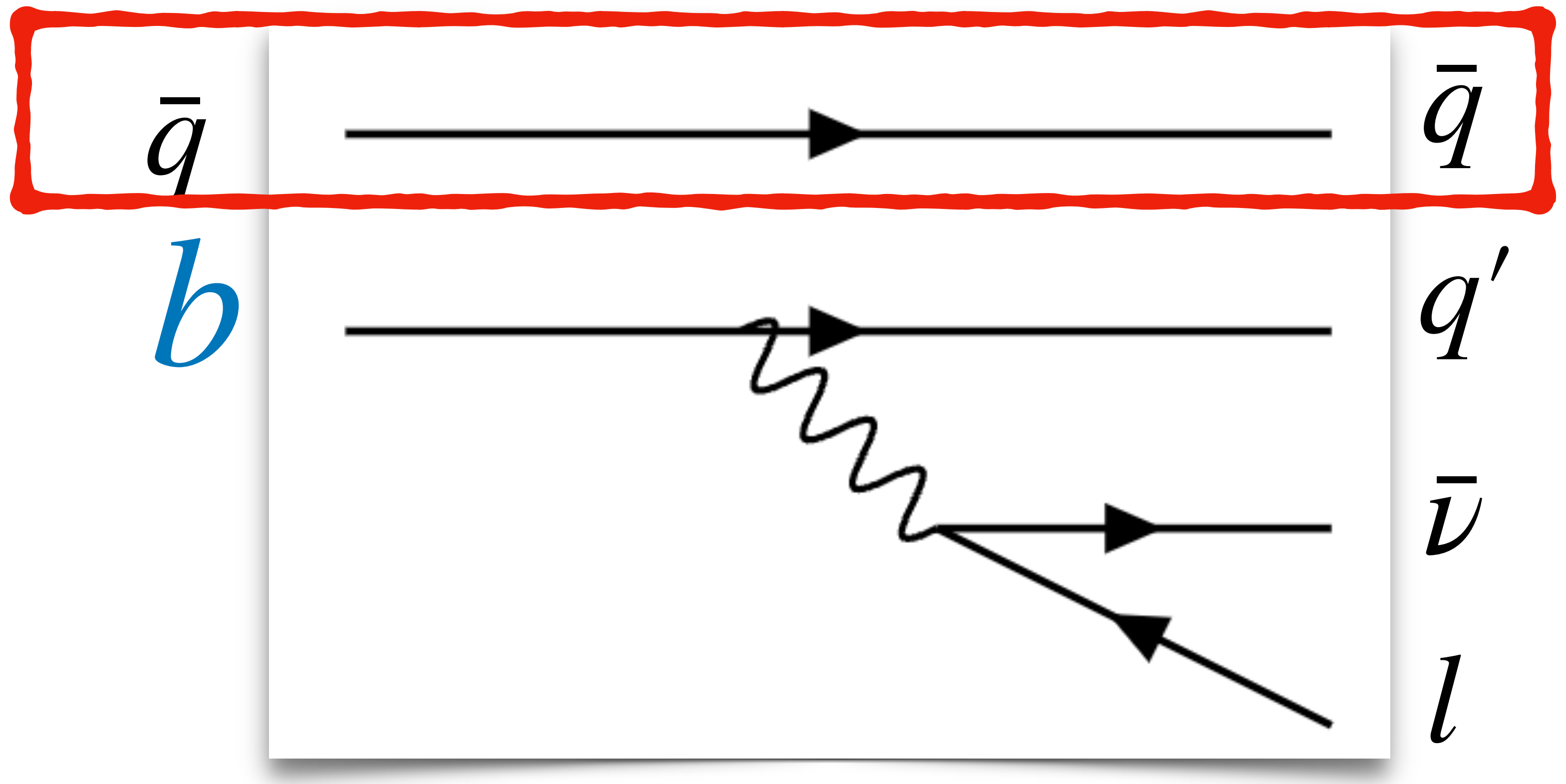
b-baryons

	$\Lambda_b = (udb)$	$\Xi_b^0 = (usb)$	$\Xi_b^- = (dsb)$	$\Omega_b^- = (ssb)$
Mass (GeV)	5.6194(6)	5.7918(5)	5.79772(55)	6.071(40)
Lifetime (ps)	1.451(13)	1.477(32)	1.599(46)	$1.54(^{+26}_{-22})$
$\tau(X)/\tau(B_d)$	0.955 ± 0.009	0.972 ± 0.021	1.053 ± 0.030	$1.01(^{+17}_{-14})$

Int.J.Mod.Phys.A 30 (2015) 10, 1543005

B mesons	Br_{SL} [%]
B_d	10.33 ± 0.28
B^+	10.99 ± 0.28
B_s	10.61 ± 0.89
B_{HQE}	11.6 ± 0.8

Not up-to-date



- The Heavy Quark Expansion (HQE) of b mesons is well established and used in the extraction of $|V_{cb}|$ [1,2,3,4,5].

- How about charm sector?

α_S from inclusive semi-leptonic decay of charmed mesons

- We look at the inclusive decays of charmed mesons,
  - Despite the τ changes a lot among different charmed mesons, the **inclusive semi-leptonic (SL) decay widths (Γ_{SL}) are quite close**, at least D^0 and D^+.
  - The measurements indicate the **impact of spectator quark in SL may be limited**.

$$\Gamma_{SL,\,D_i} = \frac{6.582\times10^{-25}\cdot Br_{SL}(D_i \to Xe\nu_e)}{\tau_{D_i}}\ \mathrm{GeV}$$

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

D_i	$\mathcal{B}_{SL}$ [%]	τ $[10^{-13}\mathrm{s}]$	Γ_{SL} $[10^{-15}\mathrm{GeV}]$
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

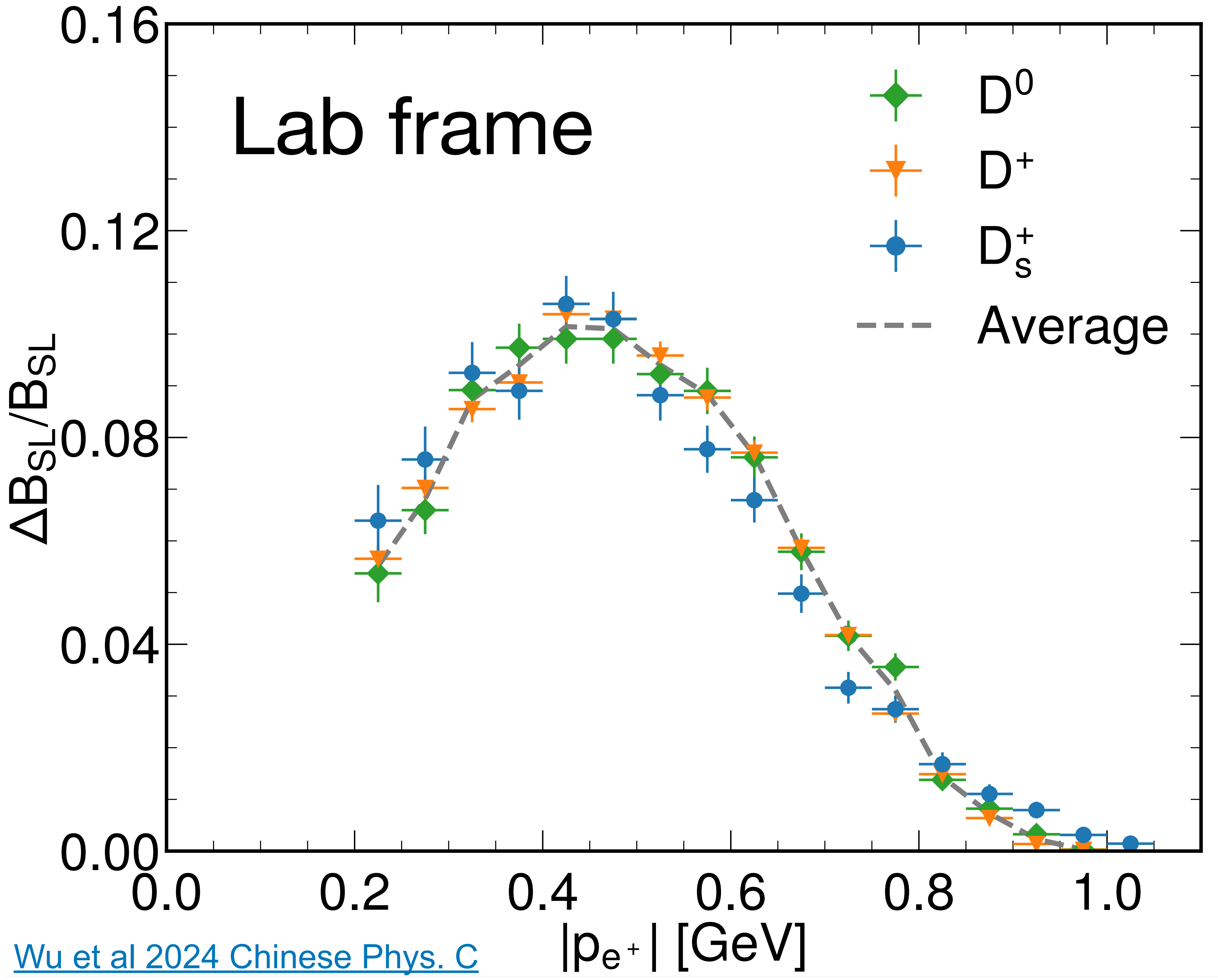
Wu et al 2024 Chinese Phys. C https://doi.org/10.1088/1674-1137/ad8baf

- The HQE can also describe the SL of charmed mesons (at least for D^0 and D^+), which may be used to determine α_S and $|V_{cs}|$....

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

α_S from inclusive semi-leptonic decay of charmed mesons

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



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

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

Same distributions of $|p_{e^+}|$ among different charmed mesons

- The measurements demonstrate that the impact of spectator quark in SL is limited.
  - The measurements of $|p_e|$ is in lab frame, which cannot be used to extract α_S directly.

α_S from inclusive semi-leptonic decay of charmed mesons

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

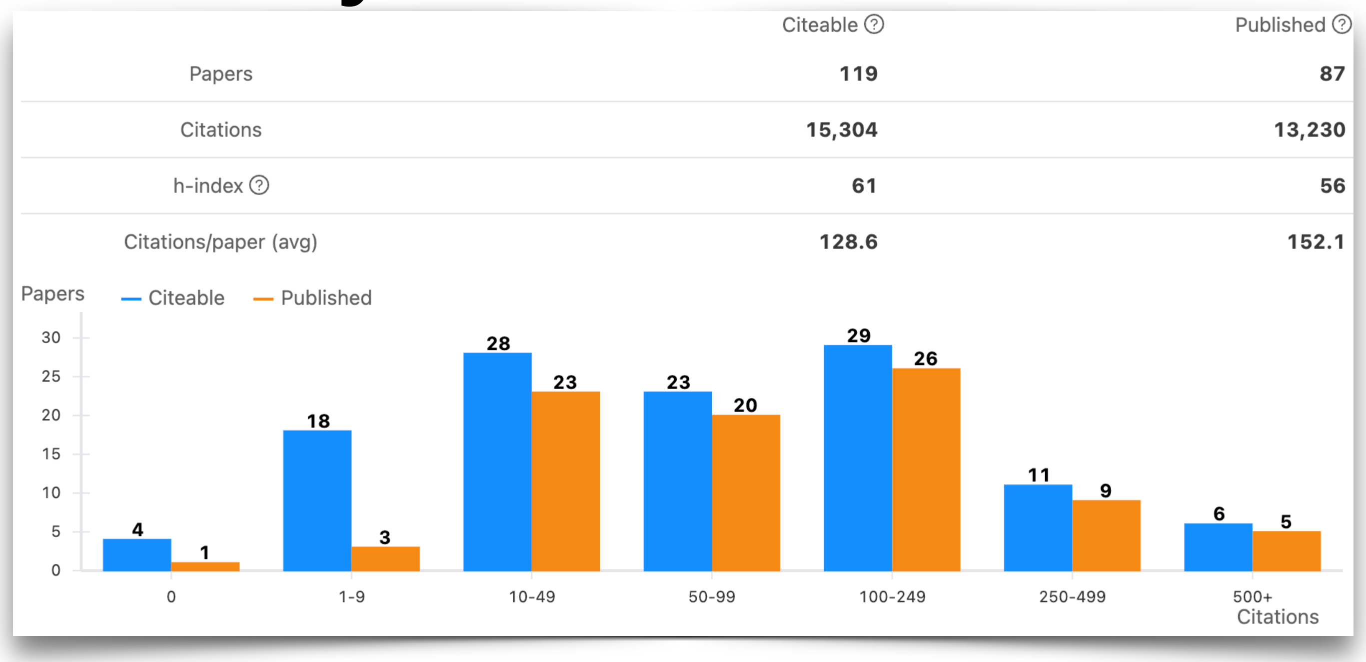
$$\Gamma_{SL} = \frac{G_F^2 \boxed{m_c^5}}{192\pi^3} \times \boxed{|V_{cs}|^2} \times [f_0(r) + \frac{\alpha_S}{\pi} f_1(r) + \frac{\alpha_S^2}{\pi^2} f_2(r) + \frac{\mu_\pi^2}{m_c^2} f_\pi(r) + \frac{\mu_G^2}{m_c^2} f_G(r) + \frac{\rho_{LS}^3}{m_c^3} f_{LS}(r) + \frac{\rho_D^3}{m_c^3} f_D(r) + \frac{32\pi^2}{m_c^3}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

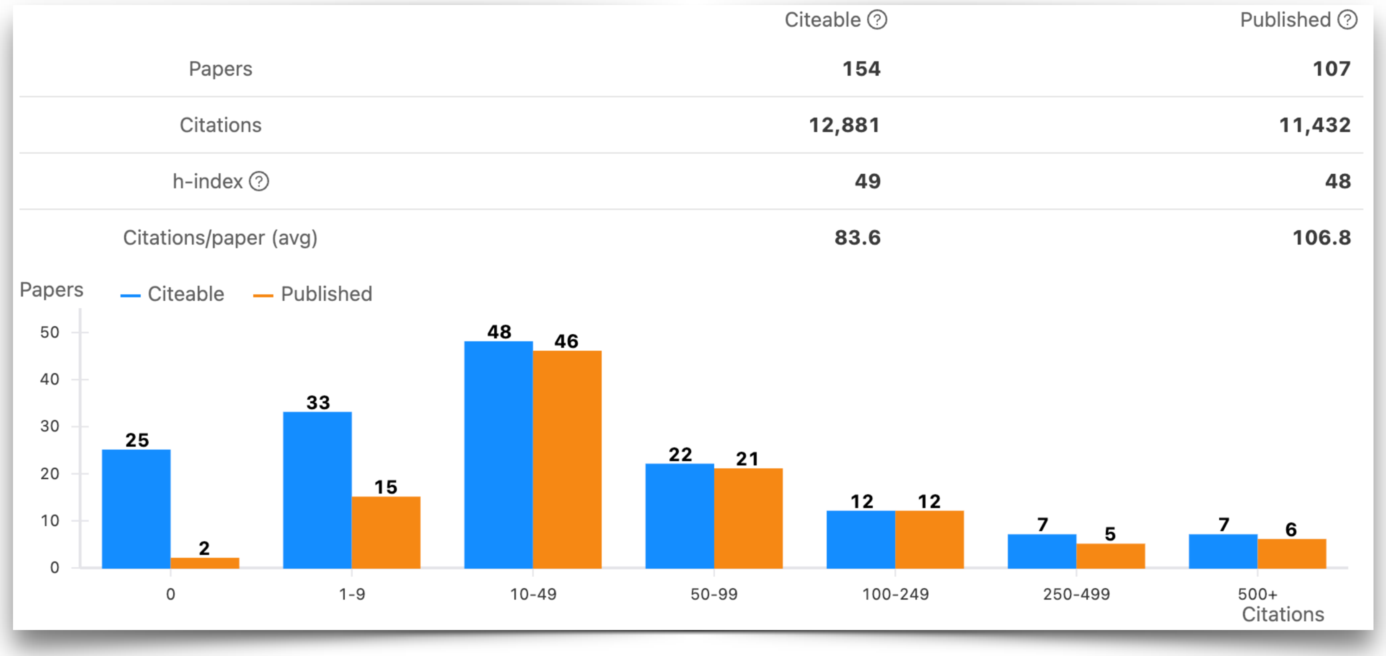
- Strong dependence of m_c
- Can extract the $|V_{cs}|$

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

- $\mu_{\pi,\,G}^2$:the kinetic and chromo-magnetic dimension-five
- $\rho_{LS,\,D}^3$: 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.





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α_S from inclusive semi-leptonic decay of charmed mesons

- 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.

- The uncertainty caused by theoretical prediction is estimated by varying $\hat{\Gamma}_{SL}$ with 10% uncertainty.
  - **High order perturbative corrections,** need **more precise calculation**.
  - **Cabibbo suppressed processes,** could be suppressed from **more measurements**.

α_S from inclusive semi-leptonic decay of charmed mesons

- The parameters involved in the Γ_{SL} of charmed mesons are,
  - The values are from the measurements without involving the Γ_{SL} of D mesons.
  - The **kinetic scheme** is used to avoid the bad convergence behavior.

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

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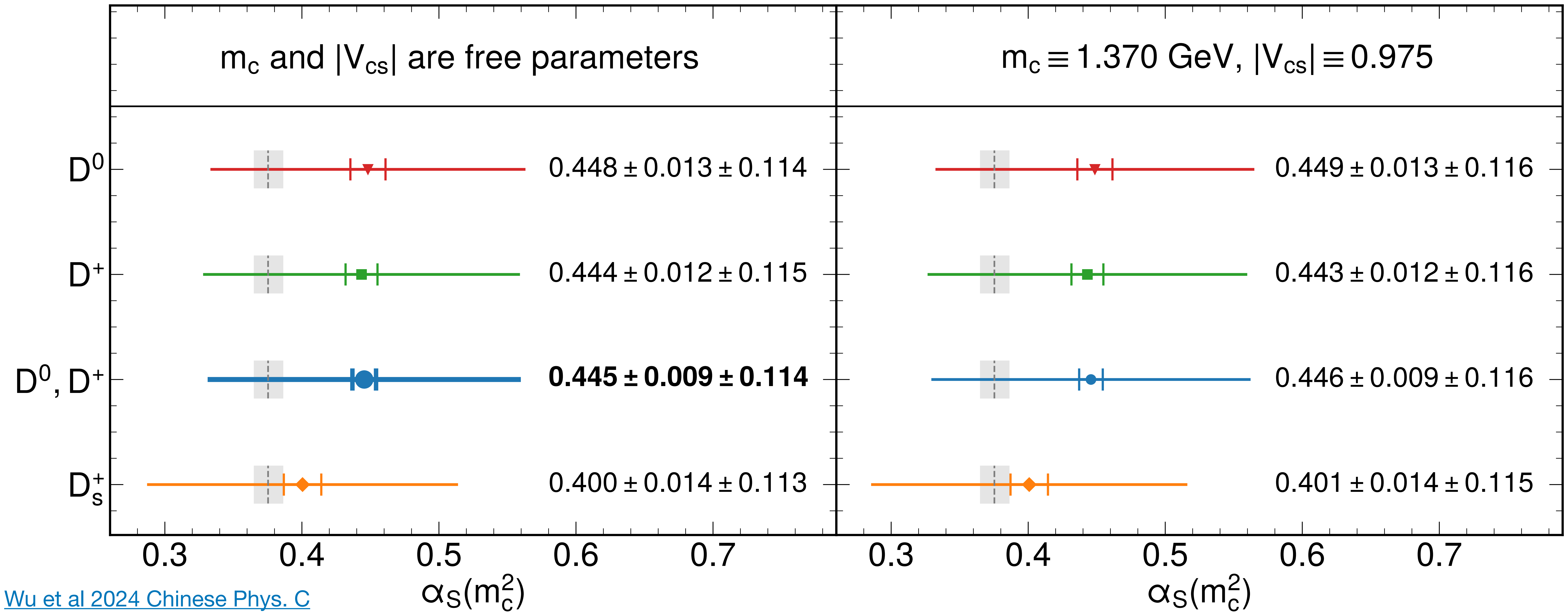
- The uncertainties of these parameters are dominate uncertainty sources in the extraction of α_S.
  - **More measurements at BESIII** will help to **reduce the uncertainties** of these parameters.

α_S from inclusive semi-leptonic decay of charmed mesons

- The values of $\alpha_S(m_c^2)$ are extracted for D^0, D^+, and D_s^+.



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Shade : world average.

Marker : fitted α_S

Inner error bar : experimental uncertainty,

Outer error bar : total uncertainty,

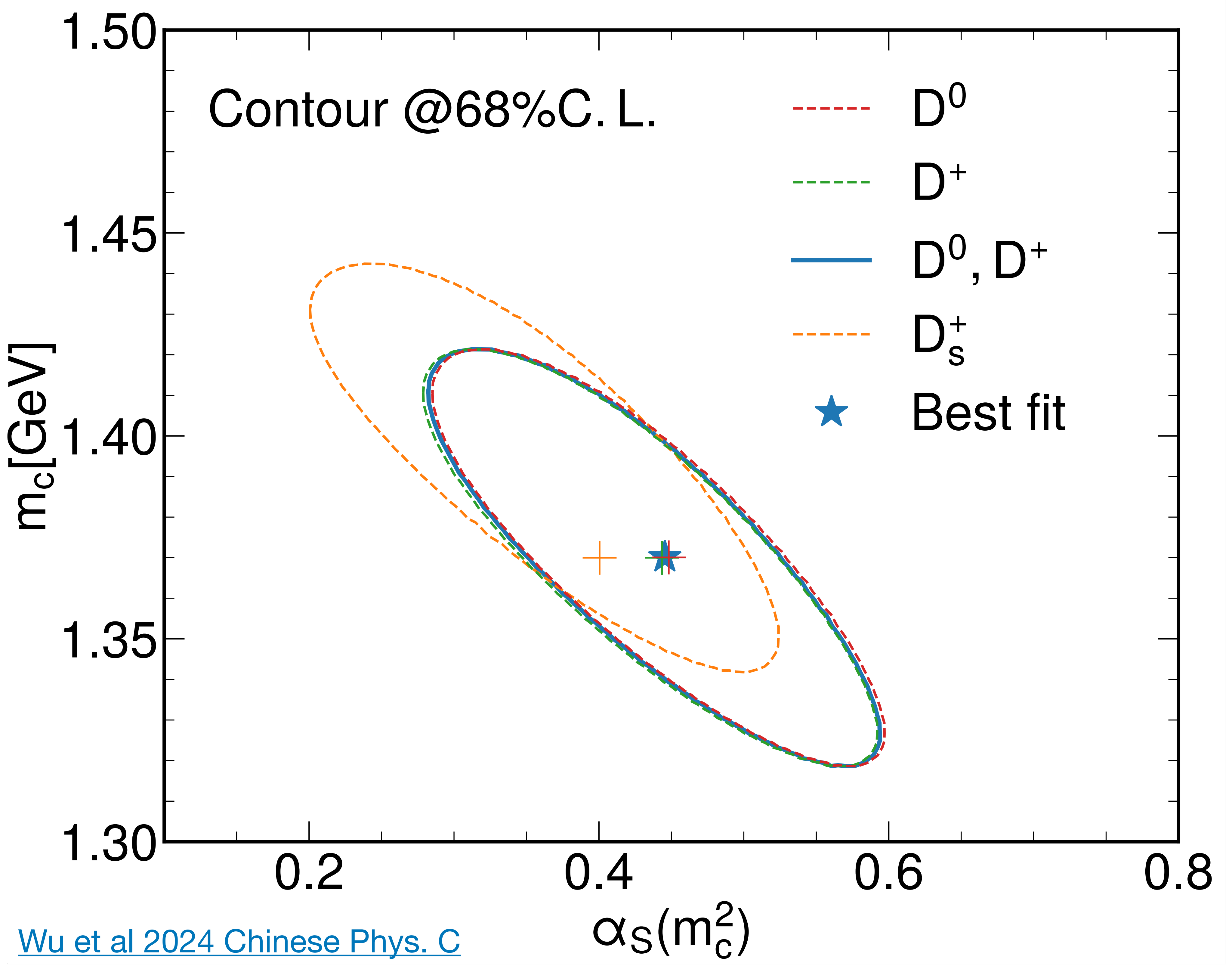
- The values of $\alpha_S(m_c^2)$ are **consistent** within 1σ **among different D mesons**, and with **the world average** (run $\alpha_S(m_Z^2)$ to m_c).

- The consistence among different D mesons demonstrate the robustness of this method.

α_S from inclusive semi-leptonic decay of charmed mesons

- The results of different charmed mesons,

Sample	D^0	D^+	$\boldsymbol{D^+, D^0}$	D_s^+
m_c[GeV]	1.3701 ± 0.0339	1.3699 ± 0.0340	$\mathbf{1.3701 \pm 0.0338}$	1.3699 ± 0.0340
$\alpha_S(m_c^2)[10^{-3}]$	$448 \pm 13 \pm 114$	$444 \pm 12 \pm 115$	$\mathbf{445 \pm 9 \pm 114}$	$400 \pm 14 \pm 113$



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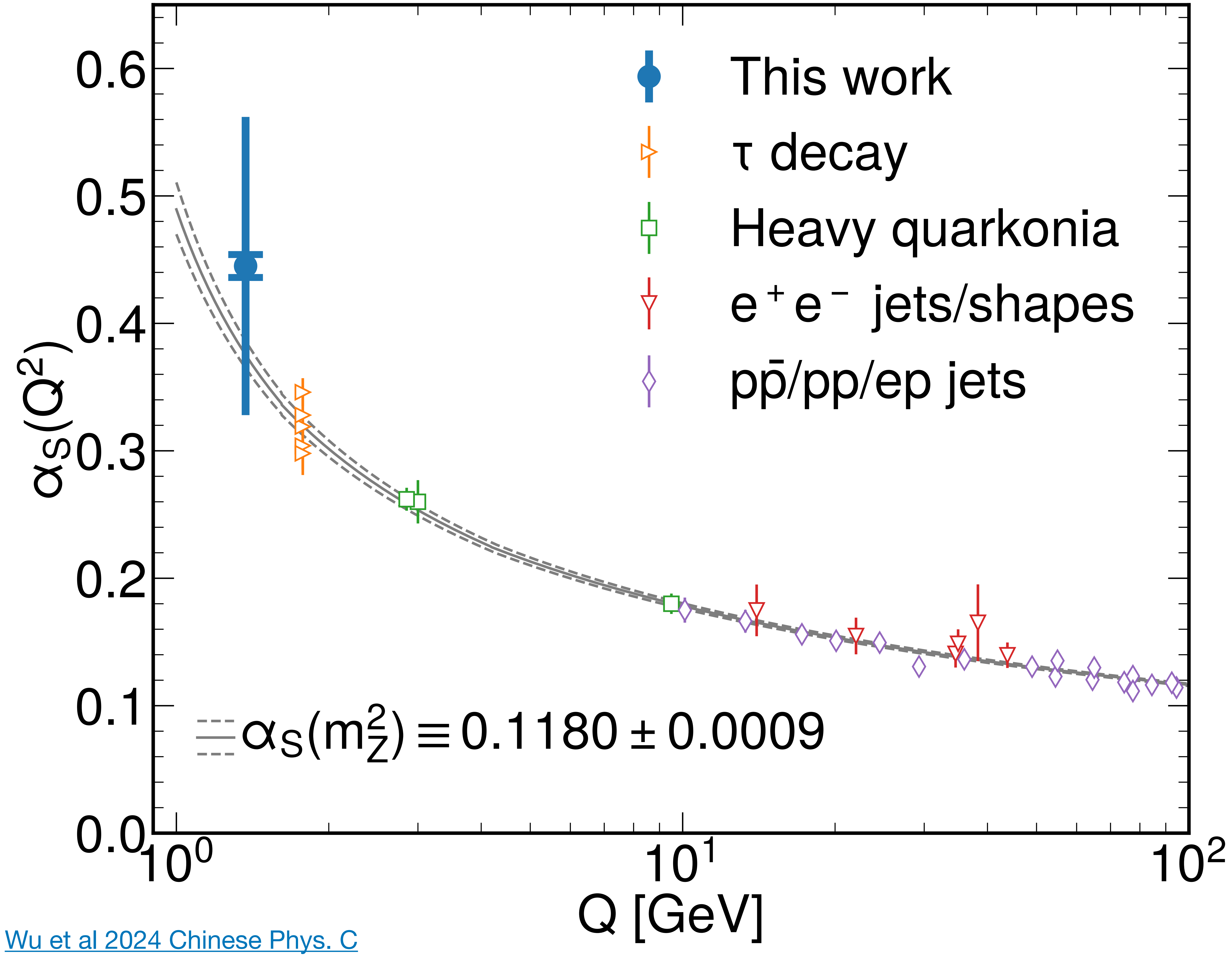
- The profile contours of $\alpha_S(m_c^2)$ VS m_c,
  - The consistence among different charmed mesons,
  - The strong dependence on m_c limit the precision of results, may need new observables to reduce this dependence.

α_S from inclusive semi-leptonic decay of charmed mesons

- The values of α_S at different energy scales are compared to the RGE running values.



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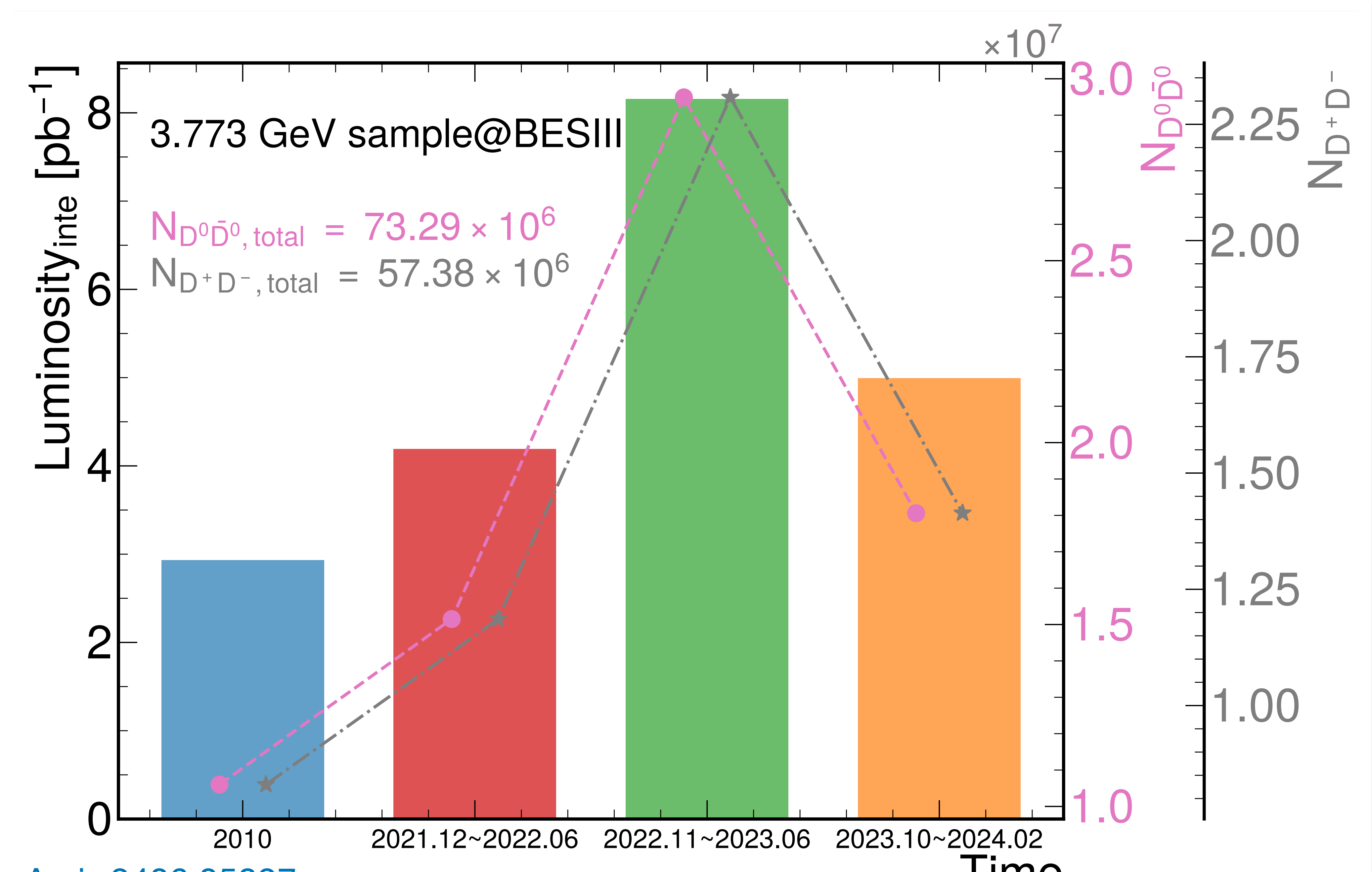
- The value of $\alpha_S(m_c^2)$ is firstly measured using the charm data, which is in good agreement with the value obtained by running $\alpha_S(m_Z^2)$ to m_c.
- The result indicates the **"asymptotic freedom" still works at 1.37 GeV**.
- This work offers a new approach to determine the value of α_S below m_τ.

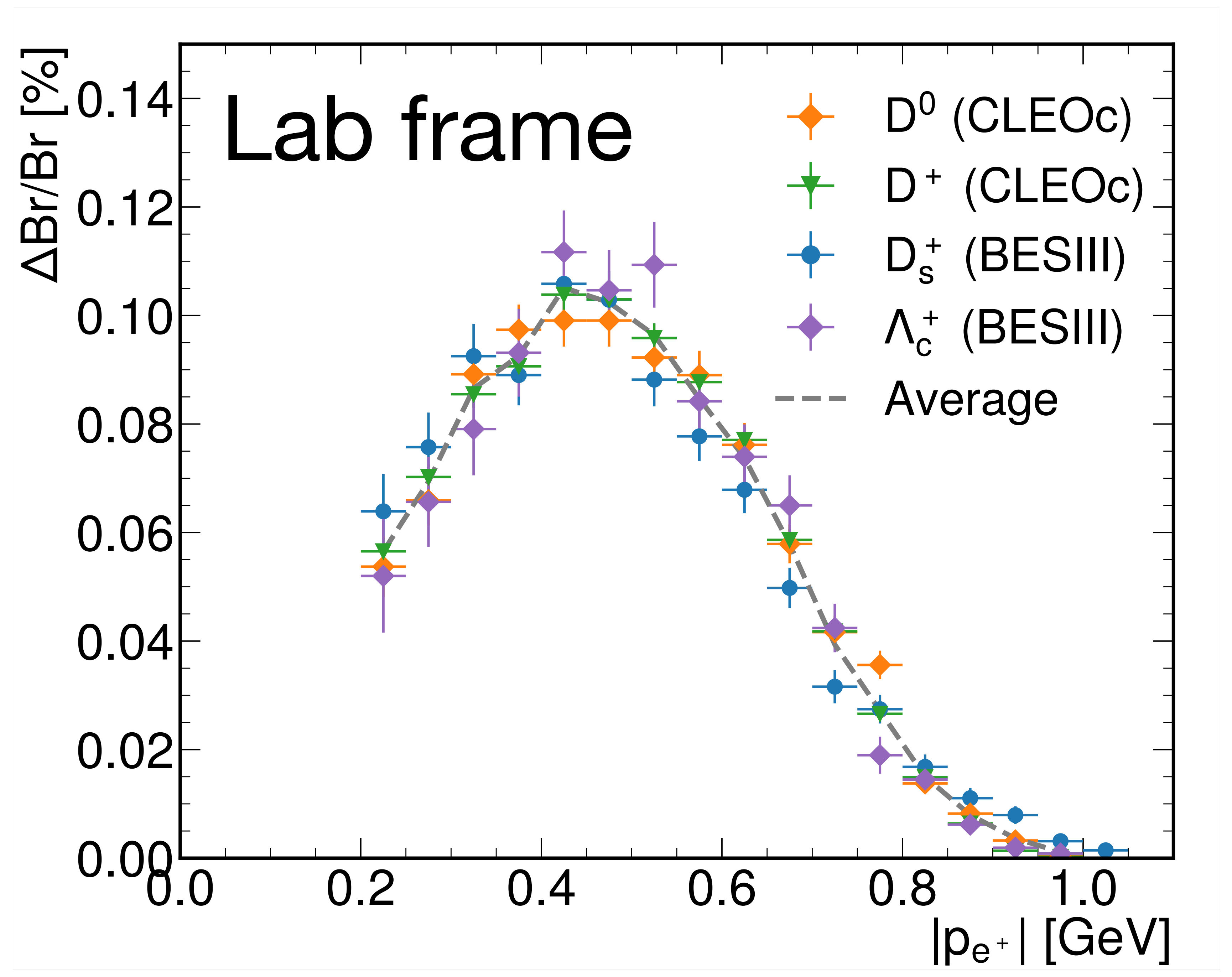
α_S from inclusive semi-leptonic decay of charmed mesons

- We could perform **more measurements** about SL of charmed mesons **at BESIII**.
  - Momentum of lepton in SL at the rest frame of charmed mesons.
  - Even the measurements of SL of charmed baryons.
  - …

Work in progress



Arxiv.2406.05827



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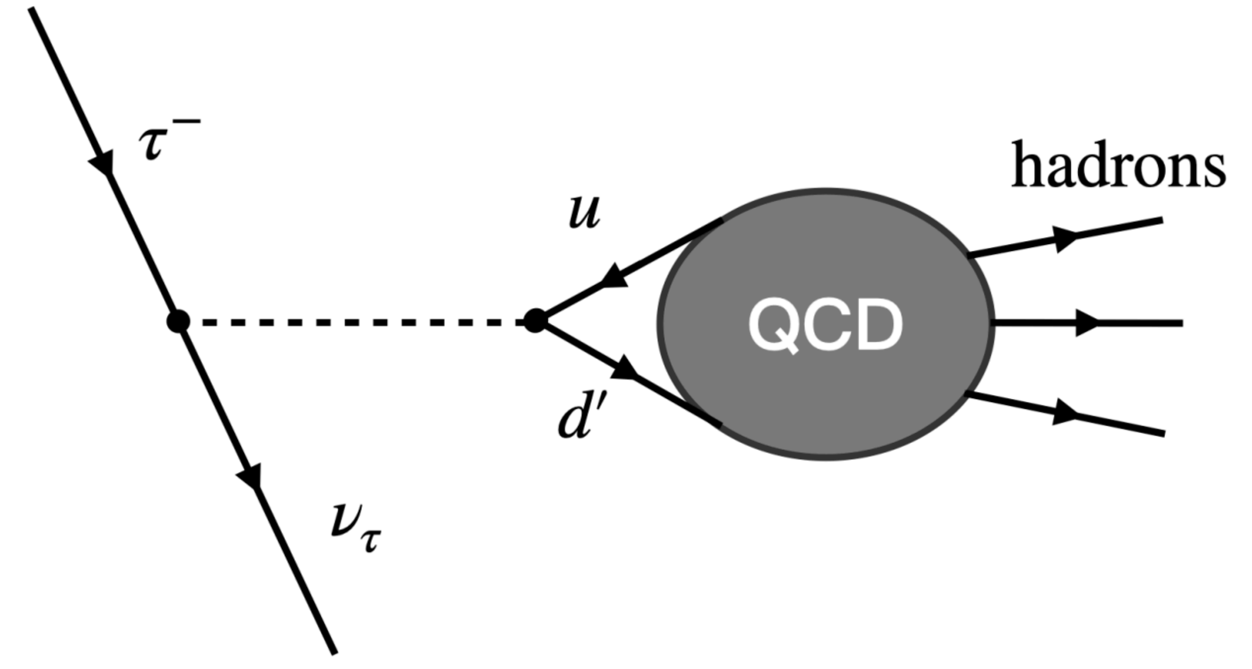
α_S from other methods

- At BESIII, we could also measure the α_S using τ.

How to extract $\alpha_s(m_\tau^2)$ from hadronic τ decay?

- Observables: $R_\tau \equiv \dfrac{\Gamma(\tau \to \nu_\tau \text{ hadrons })}{\Gamma(\tau \to l\nu_\tau\nu_l)} = R_{\tau,V} + R_{\tau,A} + R_{\tau,S}$
  - $R_{\tau,V+A} \equiv \dfrac{\Gamma(\tau \to \nu_\tau \text{ pions })}{\Gamma(\tau \to l\nu_\tau\nu_l)}$
  - $R^{kl}_{\tau,V/A}(s_0) = \displaystyle\int_0^{s_0} ds \left(1 - \frac{s}{s_0}\right)^k \left(\frac{s}{m_\tau^2}\right)^l \frac{dR_{\tau,V/A}}{ds}$
  - $D^{kl}_\tau = \dfrac{R^{kl}_\tau}{R^{00}_\tau}$



- Theoretical prediction:
  - $R^{kl}_{\tau,V/A}(s_0) = N_c S_{EW} \left|V_{ud}\right|^2 \left(r^{kl} \left(1 + \delta^{(0),kl}(s_0; \alpha_s(s_0))\right) + \displaystyle\sum_{D=2,4\ldots} \delta^{kl}_{ud,V/A}(s_0, D) \right)$

$$\delta_P = \underbrace{\sum_{n=1} K_n A^{(n)}(\alpha_s)}_{\text{CIPT}} = \underbrace{\sum_{n=1} r_n a_\tau^n}_{\text{FOPT}} \qquad a_\tau \equiv \frac{\alpha_s(m_\tau^2)}{\pi}$$

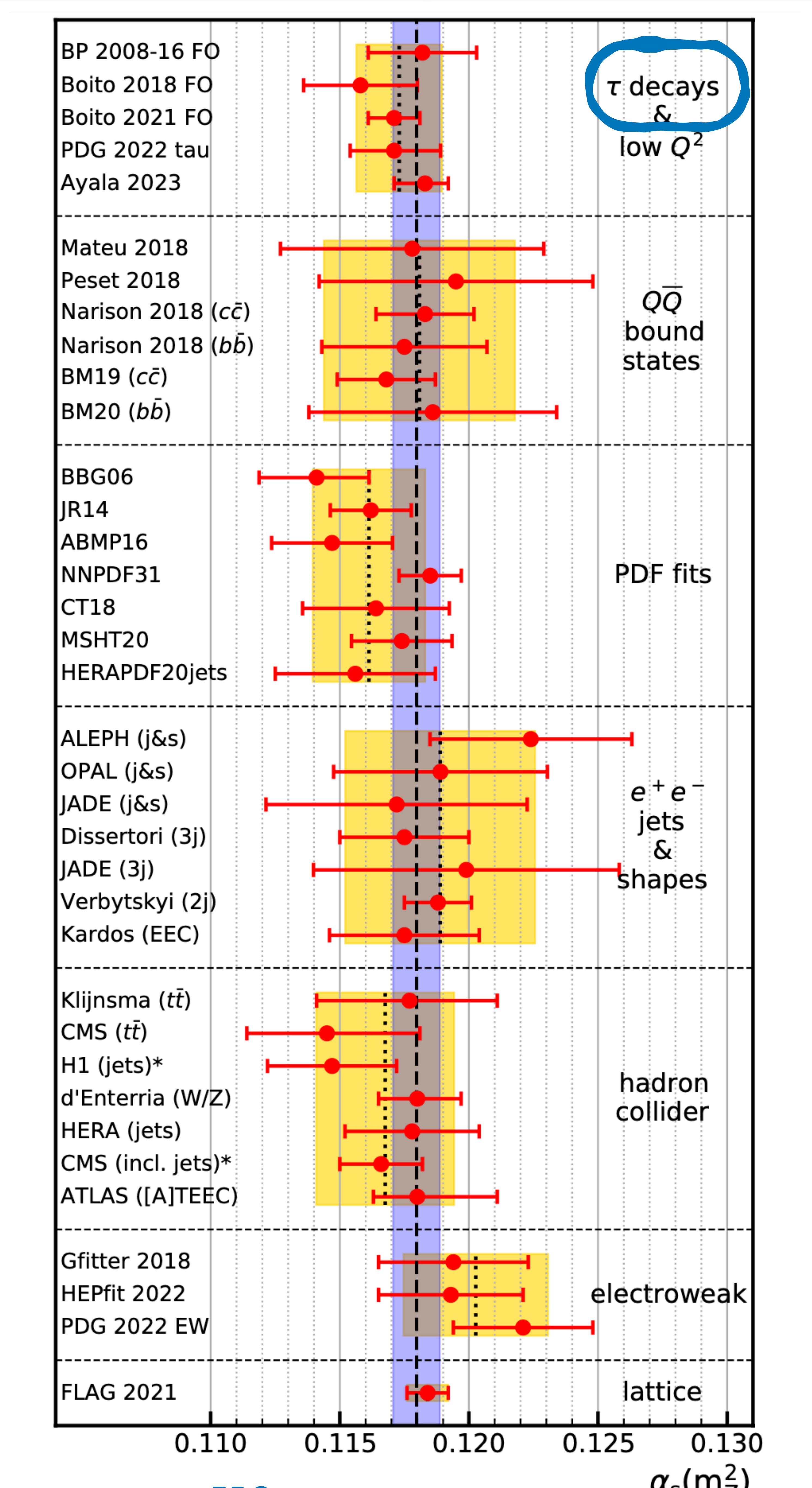
$$\delta_{NP} \sim F\left(\left\langle \frac{\alpha_s}{\pi} GG \right\rangle, \mathcal{O}(6), \mathcal{O}(8)\right)$$

- $\alpha_S(M_\tau^2)$ can be fit from R_τ, D^{10}, D^{12}, D^{13}

V/A denote vector/axial–vector components of non–strange hadronic τ decays.

Slides from Yuzhi Che

- The studies have been performed using BESIII data by Yuzhi Che et al. BESIII workshop

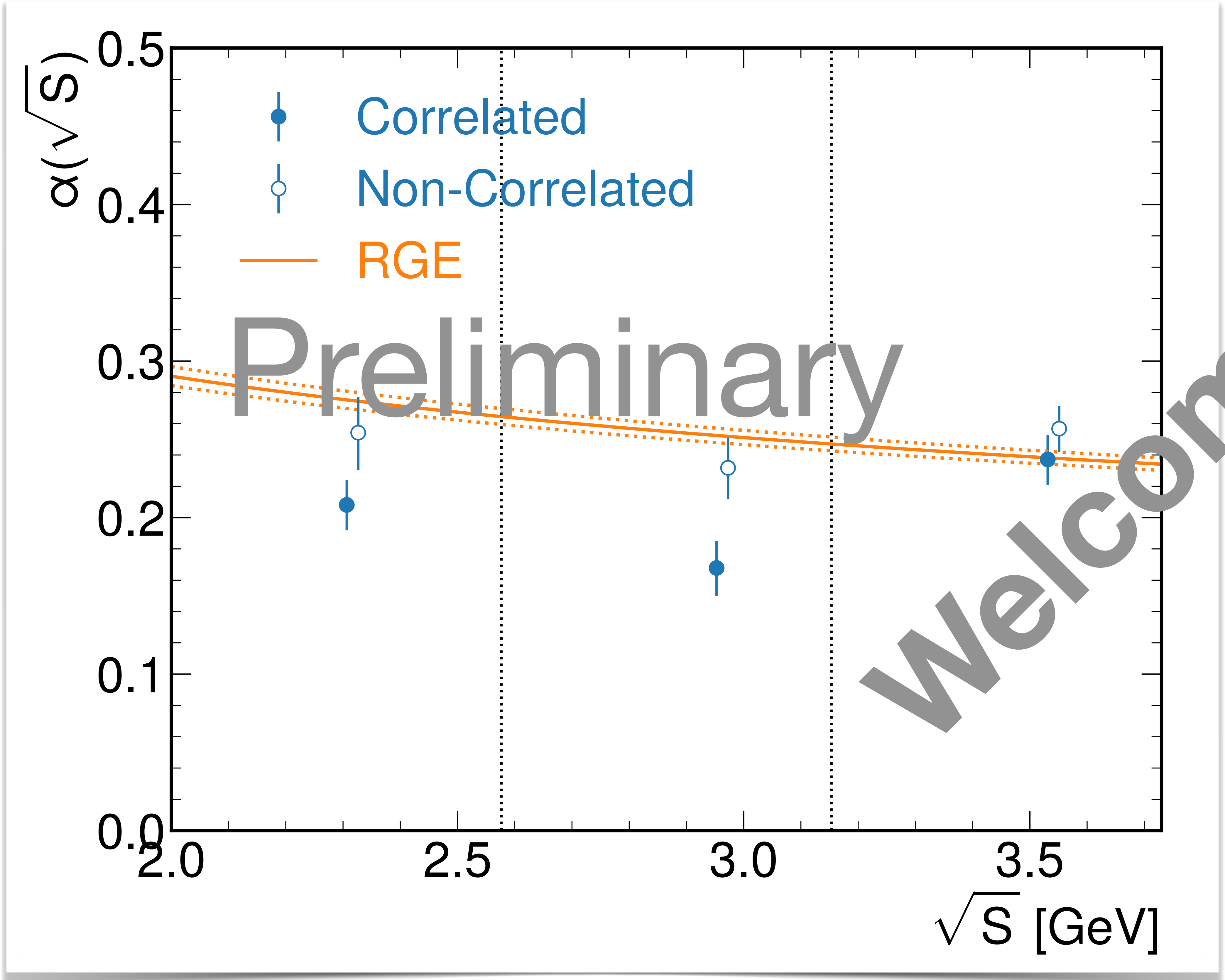


PDG

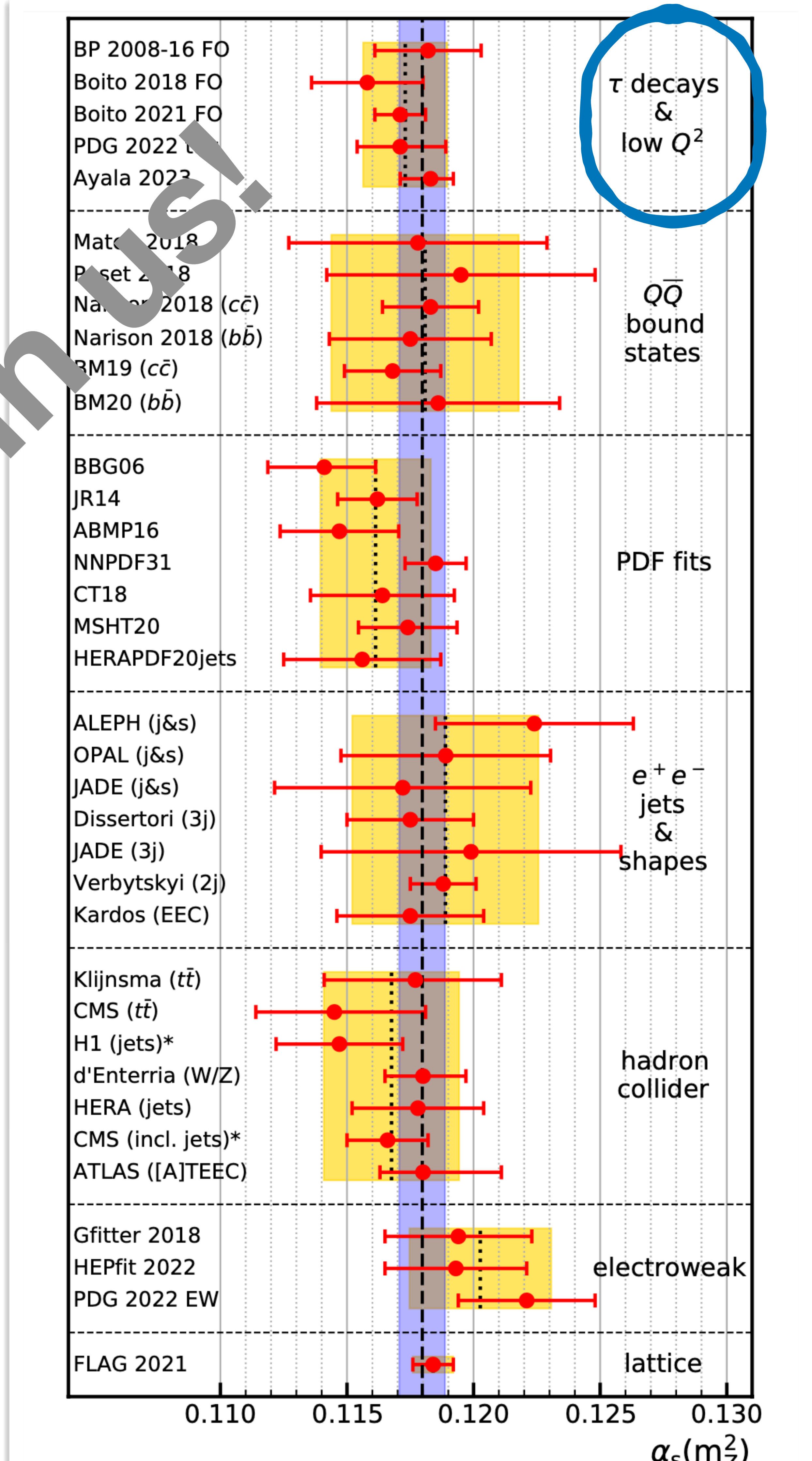
α_S from other methods

- The e^+e^- collision data samples could also be used to extract the values of α_S.
  - $R_{c\bar{c}}$ values using sum rules method, **work in progress**.

$$R_{q\bar{q}}(s) = \frac{3s}{4\pi\alpha^2}\sigma_{e^+e^-\to q\bar{q}+X}(s) \simeq \frac{\sigma_{e^+e^-\to q\bar{q}+X}(s)}{\sigma_{e^+e^-\to \mu^+\mu^-}(s)}$$



Welcome to join us!

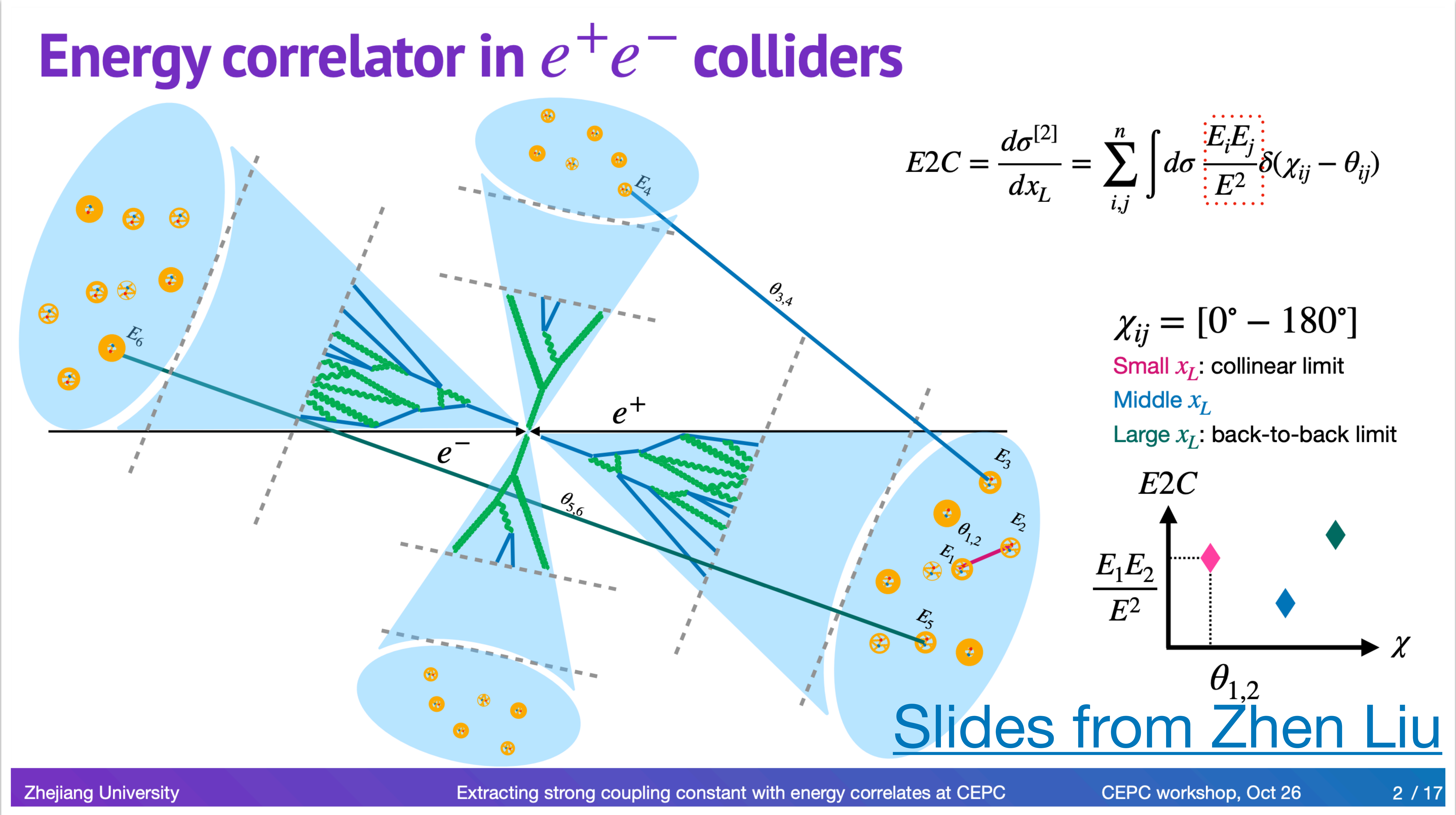


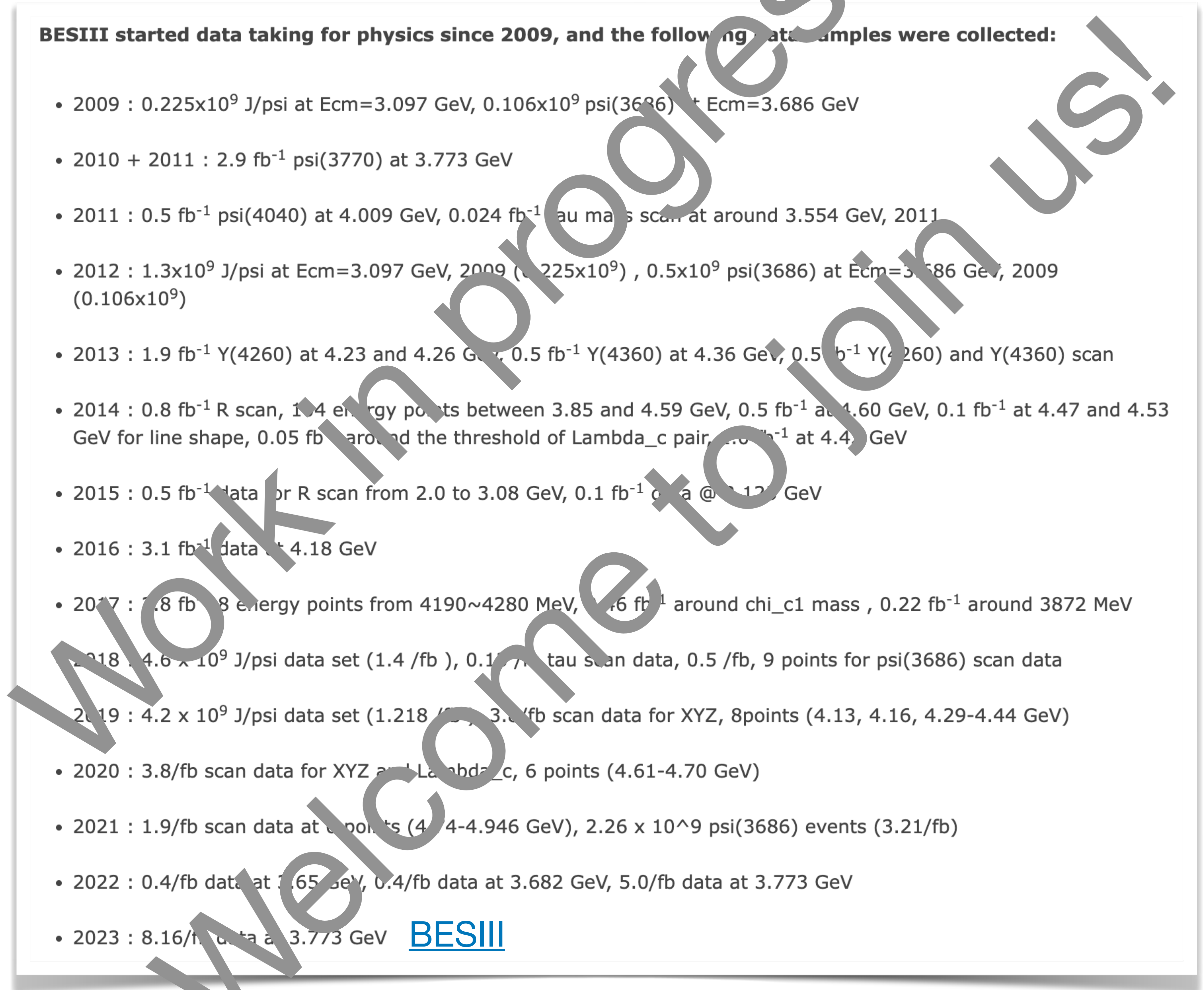
PDG

α_S from other methods

- The e^+e^- collision data samples provide new opportunities to extract the values of α_S.
  - Such as energy correlator. It might be useful at BESIII, still need further investigation.

PhysRevD.102.054012 PhysRevLett.133.071903 Arxiv.2406.10946





BESIII started data taking for physics since 2009, and the follow[illegible] [illegible]amples were collected:

- 2009 : 0.225×10^9 J/psi at Ecm=3.097 GeV, 0.106×10^9 psi(36[illegible]6) [illegible] Ecm=3.686 GeV
- 2010 + 2011 : 2.9 fb^{-1} psi(3770) at 3.773 GeV
- 2011 : 0.5 fb^{-1} psi(4040) at 4.009 GeV, 0.024 fb^{-1} [illegible]au ma[illegible]s sca[illegible] at around 3.554 GeV, 2011
- 2012 : 1.3×10^9 J/psi at Ecm=3.097 GeV, 2009 ([illegible]225x10^9) , 0.5×10^9 psi(3686) at Ecm=3[illegible]686 Ge[illegible], 2009 (0.106×10^9)
- 2013 : 1.9 fb^{-1} Y(4260) at 4.23 and 4.26 G[illegible], 0.5 fb^{-1} Y(4360) at 4.36 Ge[illegible], 0.5 [illegible]b^{-1} Y([illegible]260) and Y(4360) scan
- 2014 : 0.8 fb^{-1} R scan, 1[illegible]4 en[illegible]rgy po[illegible]ts between 3.85 and 4.59 GeV, 0.5 fb^{-1} a[illegible]4.60 GeV, 0.1 fb^{-1} at 4.47 and 4.53 GeV for line shape, 0.05 fb[illegible] aro[illegible]nd the threshold of Lambda_c pair, [illegible] fb^{-1} at 4.4[illegible] GeV
- 2015 : 0.5 fb^{-1} [illegible]ata [illegible]or R scan from 2.0 to 3.08 GeV, 0.1 fb^{-1} [illegible]a @ [illegible] GeV
- 2016 : 3.1 fb^{-1} data [illegible] 4.18 GeV
- 20[illegible]7 : [illegible].8 fb[illegible] 8 energy points from 4190~4280 MeV, [illegible]6 fb[illegible] around chi_c1 mass , 0.22 fb^{-1} around 3872 MeV
- [illegible]18 [illegible] 4.6 x 10^9 J/psi data set (1.4 /fb), 0.1[illegible] tau s[illegible]an data, 0.5 /fb, 9 points for psi(3686) scan data
- 2[illegible]19 : 4.2 x 10^9 J/psi data set (1.218 [illegible] 3.[illegible]/fb scan data for XYZ, 8points (4.13, 4.16, 4.29-4.44 GeV)
- 2020 : 3.8/fb scan data for XYZ a[illegible] La[illegible]bda_c, 6 points (4.61-4.70 GeV)
- 2021 : 1.9/fb scan data at [illegible] poi[illegible]ts (4[illegible]4-4.946 GeV), 2.26 x 10^9 psi(3686) events (3.21/fb)
- 2022 : 0.4/fb data at [illegible]65 GeV, 0.4/fb data at 3.682 GeV, 5.0/fb data at 3.773 GeV
- 2023 : 8.16/f[illegible] [illegible] 3.773 GeV BESIII

Work in progress

Welcome to join us!

Contents

- Introduction
  - Strong interaction
  - Existing measurements of α_S
- Possible measurements of α_S at BESIII
  - Data samples at BESIII
  - α_S from inclusive semi-leptonic decay of charmed mesons
  - α_S from other methods
- **Summary**

Summary

- The possible measurements of α_S at BESIII have been summarized,
  - The inclusive semi-leptonic decays of charmed mesons,
  - The hadronic τ decays,
  - The $R_{c\bar{c}}$ values using sum rules method,
  - The energy correlator at e^+e^- collision
  - ……
- The huge e^+e^- collision data at BESIII provides unprecedented opportunities, meanwhile considerable challenges.
  - It's worth to exploit the data to further understand strong interaction.
  - The deep understanding of strong interaction will benefit searching for new physics and future collider experiments.

Thanks for your listening

Please feel free to contact us

Backup

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