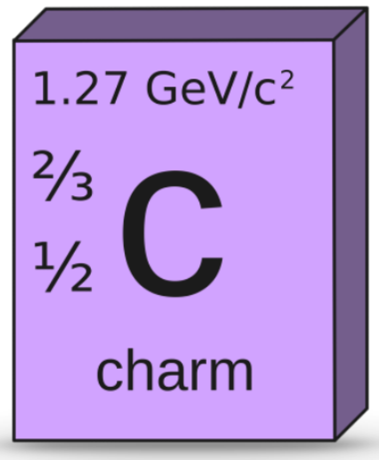

Electronic semi-inclusive charm decays

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Semi-inclusive charm decays

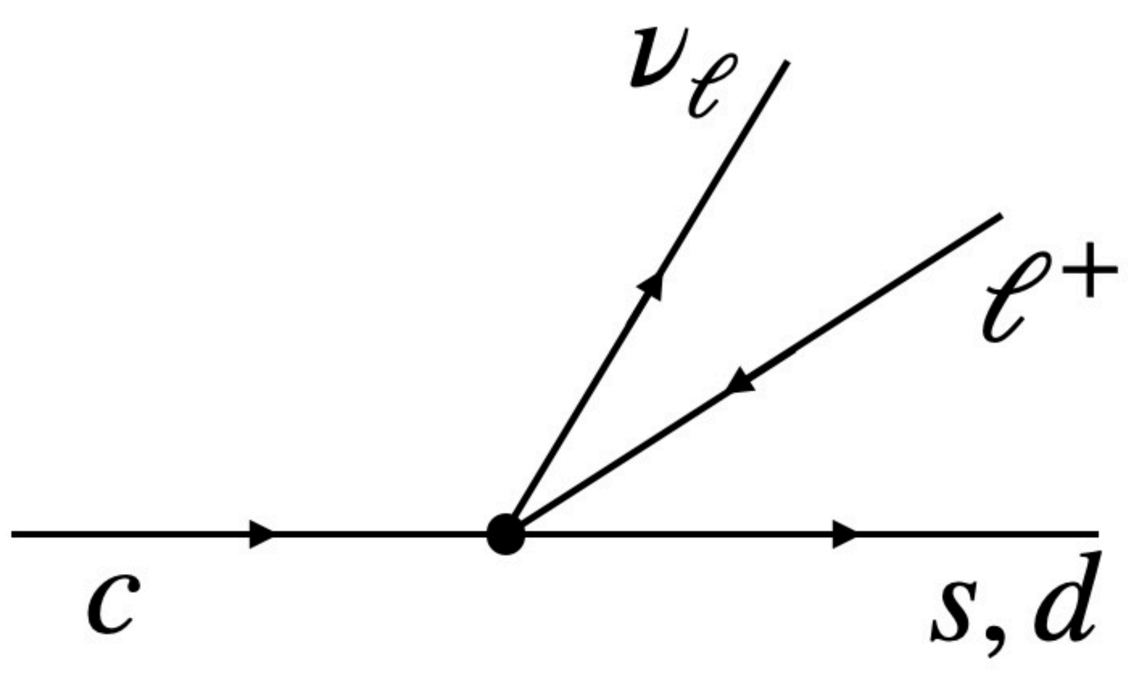
- **Experimental detection of partial final state particles**

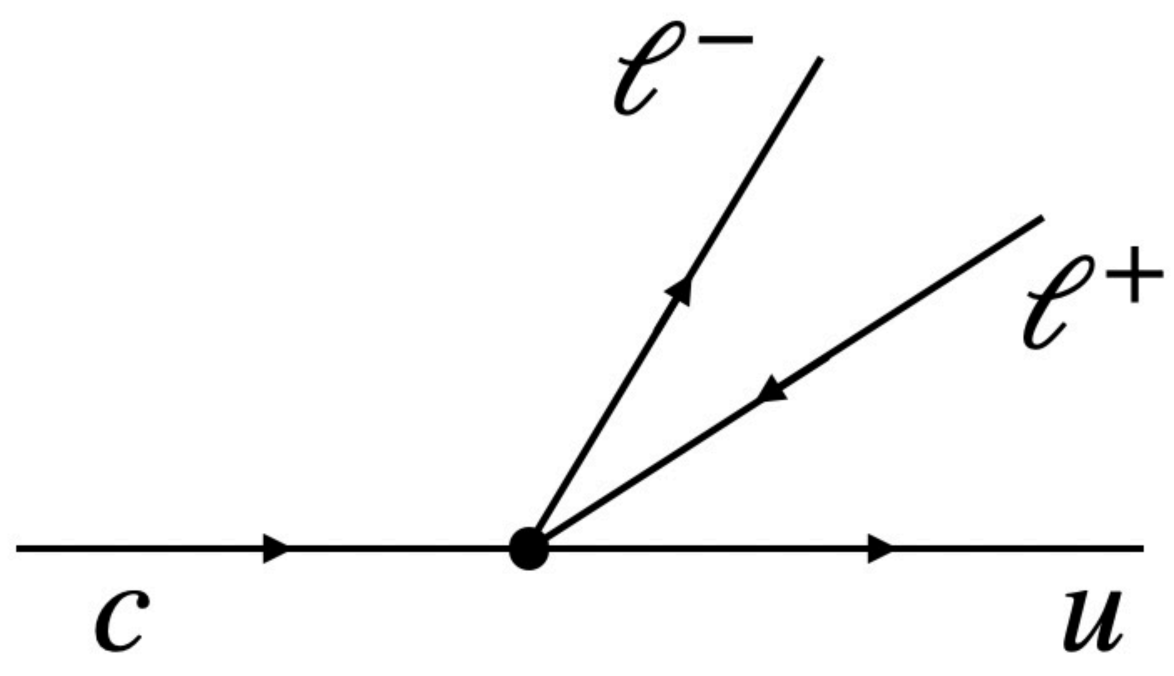
  ➡ $D \to e^+X$ ($D \to e^+\nu_e X$, only e^+ is detected)

- **Sum of a group of exclusive channels**

  ➡ $D^0 \to e^+X_s = D \to e^+\nu_e K^-, e^+\nu_e K^-\pi^0, e^+\nu_e \bar{K}^0\pi^-, \ldots$

  ➡ $D^0 \to e^+X_d = D \to e^+\nu_e \pi^-, e^+\nu_e \pi^-\pi^0, e^+\nu_e \pi^-\pi^+\pi^-, \ldots$





Why inclusive charm decays?

- **As weak decays of heavy hadrons**

  ➡ Probe new physics

  ➡ Understand QCD

- **Compared to exclusive decays**

  ➡ **Better theoretical control**

- **Compared to beauty decays**

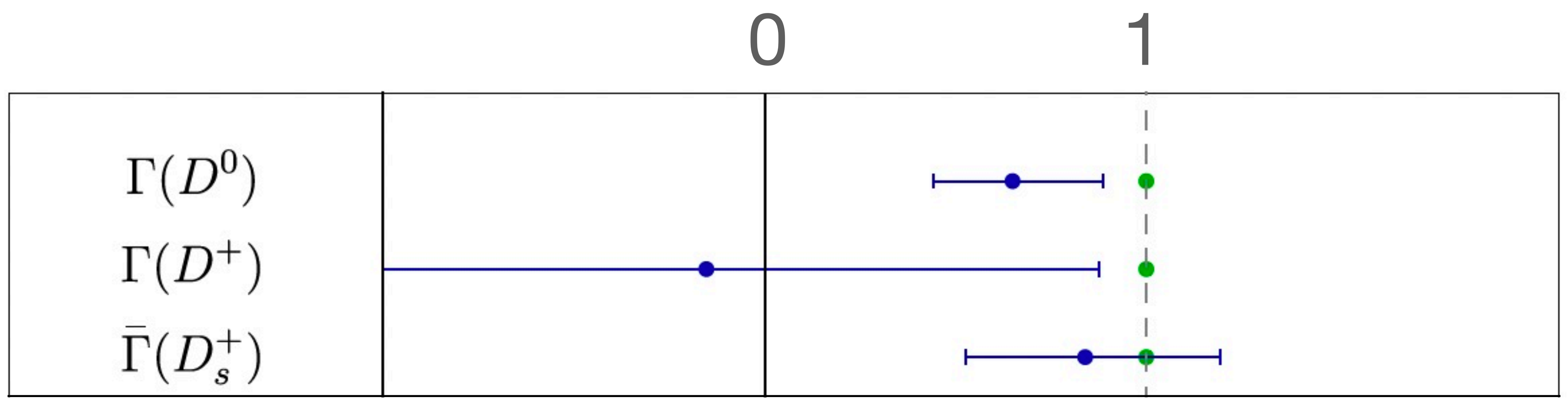
  ➡ **Special to new dynamics attached with up-type quarks**

  ➡ **More sensitive to power corrections**

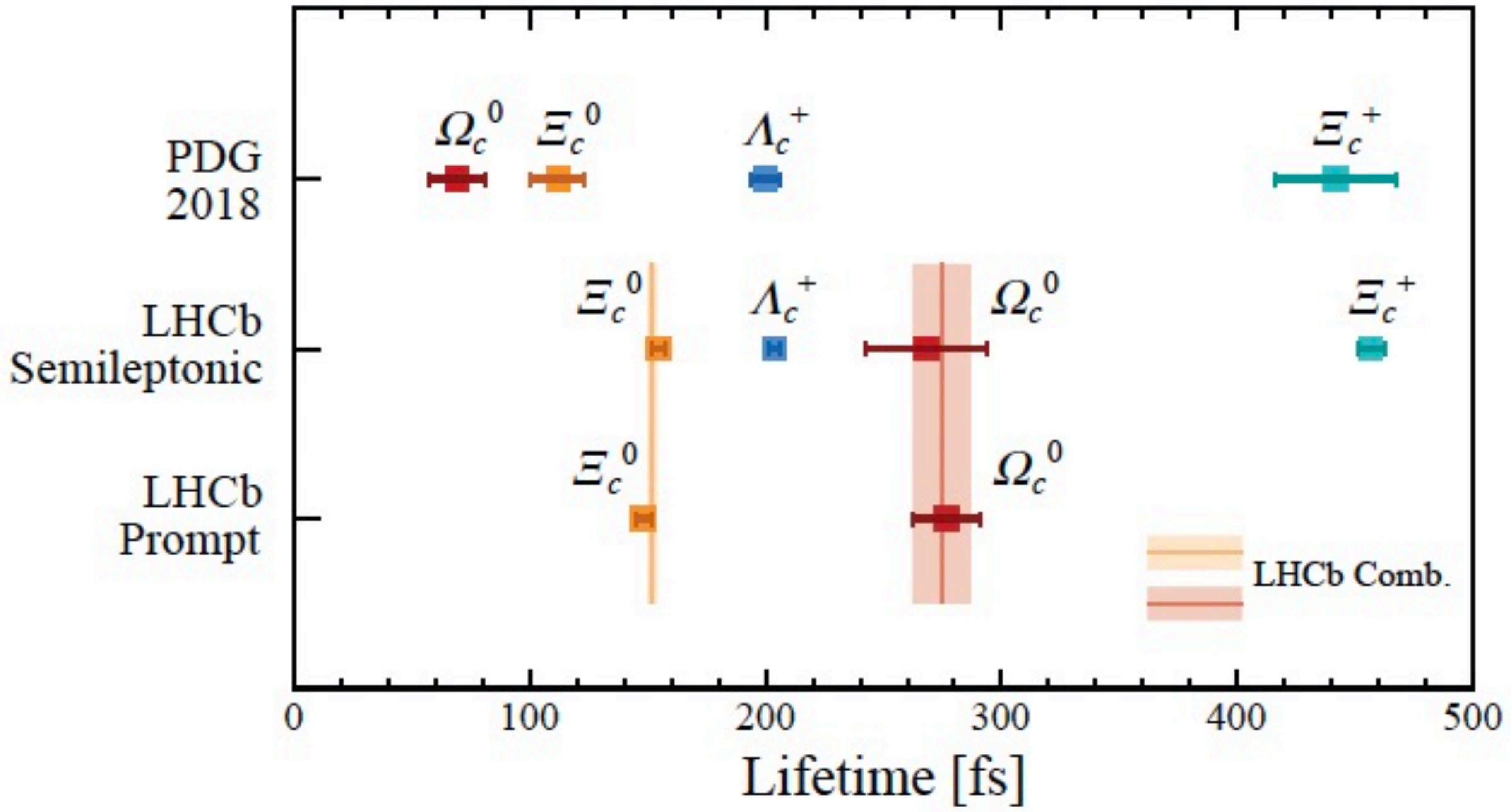
★ Determination by charm, application in beauty.

Why inclusive charm decays?

Flavor puzzles.



[Lenz et al, ’22]



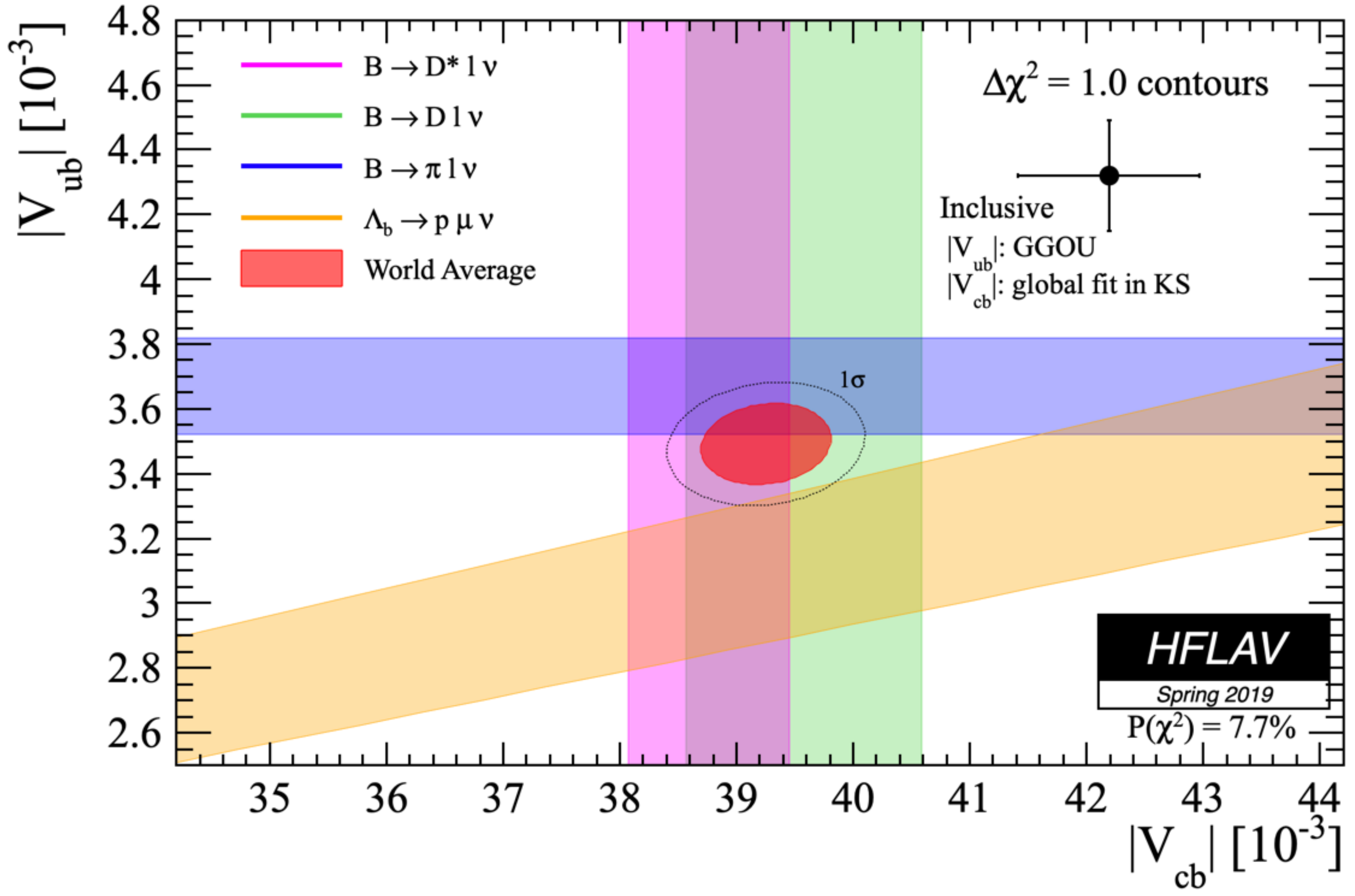
Charmed hadron lifetimes: theory vs experiment

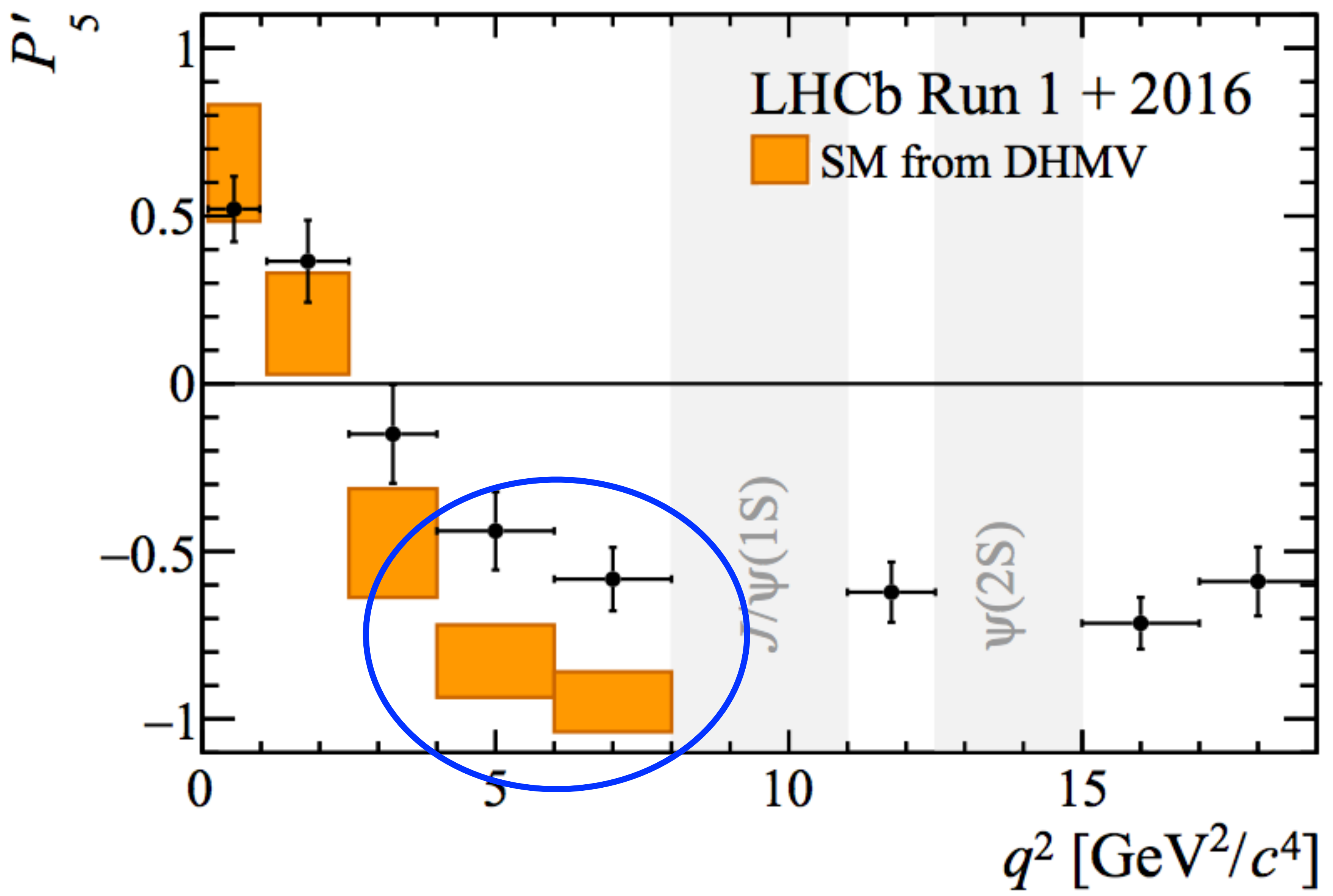
$$\mathcal{O}(1/m_c^3) \Rightarrow \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\boldsymbol{\Omega_c^0}),$$
$$\mathcal{O}(1/m_c^4) \Rightarrow \tau(\boldsymbol{\Omega_c^0}) > \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0),$$
$$\mathcal{O}(1/m_c^4) \text{ with } \alpha \Rightarrow \tau(\Xi_c^+) > \tau(\boldsymbol{\Omega_c^0}) > \tau(\Lambda_c^+) > \tau(\Xi_c^0).$$

[Cheng, ’21]

Why inclusive charm decays?

Flavor puzzles.





V_{cb}, V_{ub} **puzzles:**

inclusive vs exclusive

$b \to s$ **anomalies:**

P'_5 **in** $B \to K^* \ell \ell$

Why inclusive charm decays?

Solutions/hints to flavor puzzles.

- **Charmed hadron lifetimes: theory vs experiment**
  - ➡ Dependence on identical hadronic parameters in HQET, $\langle H_c | O_i | H_c \rangle$
  - ➡ Extraction in the inclusive decay spectrum and application to lifetime

Again a more precise experimental determination of μ_π^2 from fits to semileptonic D^+, D^0 and D_s^+ meson decays – as it was done for the B^+ and B^0 decays – would be very desirable.

[Lenz et al, '22]

- **V_{cb}, V_{ub} puzzles: inclusive vs exclusive**
  - ➡ V_{cd}, V_{cs} test: inclusive vs exclusive
  - ➡ Inclusive still missing
- **$b \to s$ anomalies: P_5' in $B \to K^* \ell\ell$**
  - ➡ Test the $c \to u$ transition, by angular distribution in $D \to X_u \ell\ell$

Theoretical framework

- Optical theorem

$$\sum \langle D|H|X\rangle\langle X|H|D\rangle \propto \mathrm{Im}\int \mathrm{d^4x}\langle \mathrm{D}|\mathrm{T}\{\mathrm{H(x)H(0)}\}|\mathrm{D}\rangle$$

- Operator product expansion (OPE)

➡ Short distance $x \sim 1/m_c$

➡ Fluctuation in D meson $\sim \Lambda_{\mathrm{QCD}}$

$$T\{H(x)H(0)\} = \sum_n C_n(x)O_n(0) \to 1 + \frac{\Lambda_{\mathrm{QCD}}}{m_c} + \frac{\Lambda^2_{\mathrm{QCD}}}{m_c^2} + \dots$$

Systematic OPE in HQET.

Theoretical framework

- **Heavy quark effective theory**

$$h_v(x) \equiv e^{-im_c v\cdot x}\frac{1+\gamma\cdot v}{2}c(x) \qquad v = (1,0,0,0)$$

Subtract the big intrinsic momentum,
Leave only ~Λ_{QCD} degrees of freedom.

$$L \ni \bar{h}_v iv\cdot D h_v$$

$$-\bar{h}_v\frac{D_\perp^2}{2m_c}h_v - a(\mu)g\bar{h}_v\frac{\sigma\cdot G}{4m_c}h_v + \dots$$

Similar to $\dfrac{m}{\sqrt{1-v^2}} = m + \dfrac{1}{2}mv^2 + \dots$

Theoretical framework

- **OPE**

$$T\{H(x)H(0)\} = \sum_n C_n(x)O_n(0)$$

➡ Dim-3: $\bar{h}_v h_v$ $(\bar{c}\gamma^\mu c) \to$ partonic decay rate.

➡ Dim-5: $\bar{h}_v D_\perp^2 h_v,\ g\bar{h}_v\sigma\cdot G h_v$.

➡ Dim-6: $\bar{h}_v D_\mu (v\cdot D) D^\mu h_v,\ (\bar{h}_v\Gamma_1 q)(\bar{q}\Gamma_2 h_v), \ldots$

- Contribute to inclusive decay rate and also lifetime

➡ Matrix elements of the same operators

➡ Only different short-distance coefficients

$$\lambda_1 \equiv \frac{1}{4m_D}\langle D|\bar{h}_v(iD)^2 h_v|D\rangle = -\mu_\pi^2$$

$$\lambda_2 \equiv \frac{1}{16(s_c\cdot s_q)}\frac{1}{2m_D}\langle D|\bar{h}_v g\sigma\cdot G h_v|D\rangle = \frac{\mu_G^2}{3}$$

Theoretical framework

- Analytical results

$$\frac{1}{\Gamma_0}\frac{\mathrm{d}\Gamma}{\mathrm{d}y} = \Big\{2(3-2y)y^2\theta(1-y)$$
$$-\frac{2\lambda_1}{m_b^2}\left[-\frac{5}{3}y^3\theta(1-y)+\frac{1}{6}\delta(1-y)\theta(1^+-y)+\frac{1}{6}\delta'(1-y)\theta(1^+-y)\right]$$
$$-\frac{2\lambda_2}{m_b^2}\left[-y^2(6+5y)\theta(1-y)+\frac{11}{2}\delta(1-y)\theta(1^+-y)\right]\Big\}$$

$$y \equiv 2E_e/m_c$$

- Up to finite power, the obtained differential decay rate is **NOT** the experimental spectrum

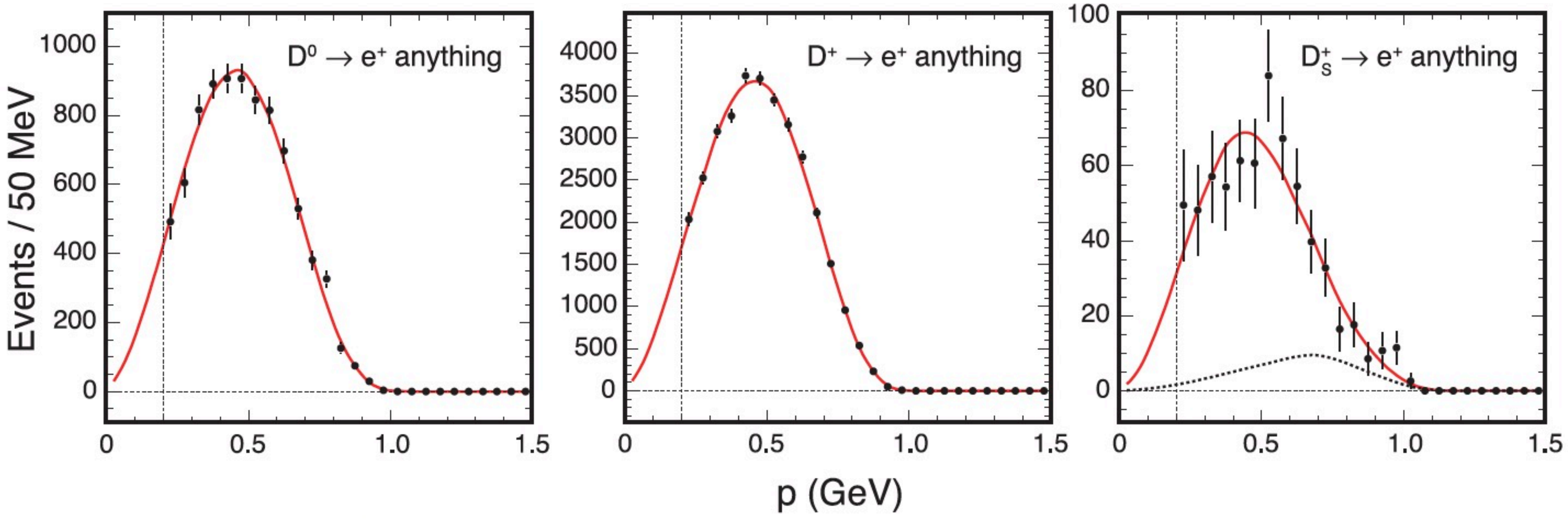
➡ Observables require integration over final states

➡ $\Gamma = \int \frac{d\Gamma}{dy} dy,\ \langle E_\ell \rangle = \frac{1}{\Gamma}\int \frac{d\Gamma}{dy} E_\ell\, dy,\ \langle E_\ell^2 \rangle = \frac{1}{\Gamma}\int \frac{d\Gamma}{dy} E_\ell^2\, dy, \ldots$

Experimental status

CLEO measurements

$D^0 \to e^+ X$ $D^+ \to e^+ X$ $D_s^+ \to e^+ X$

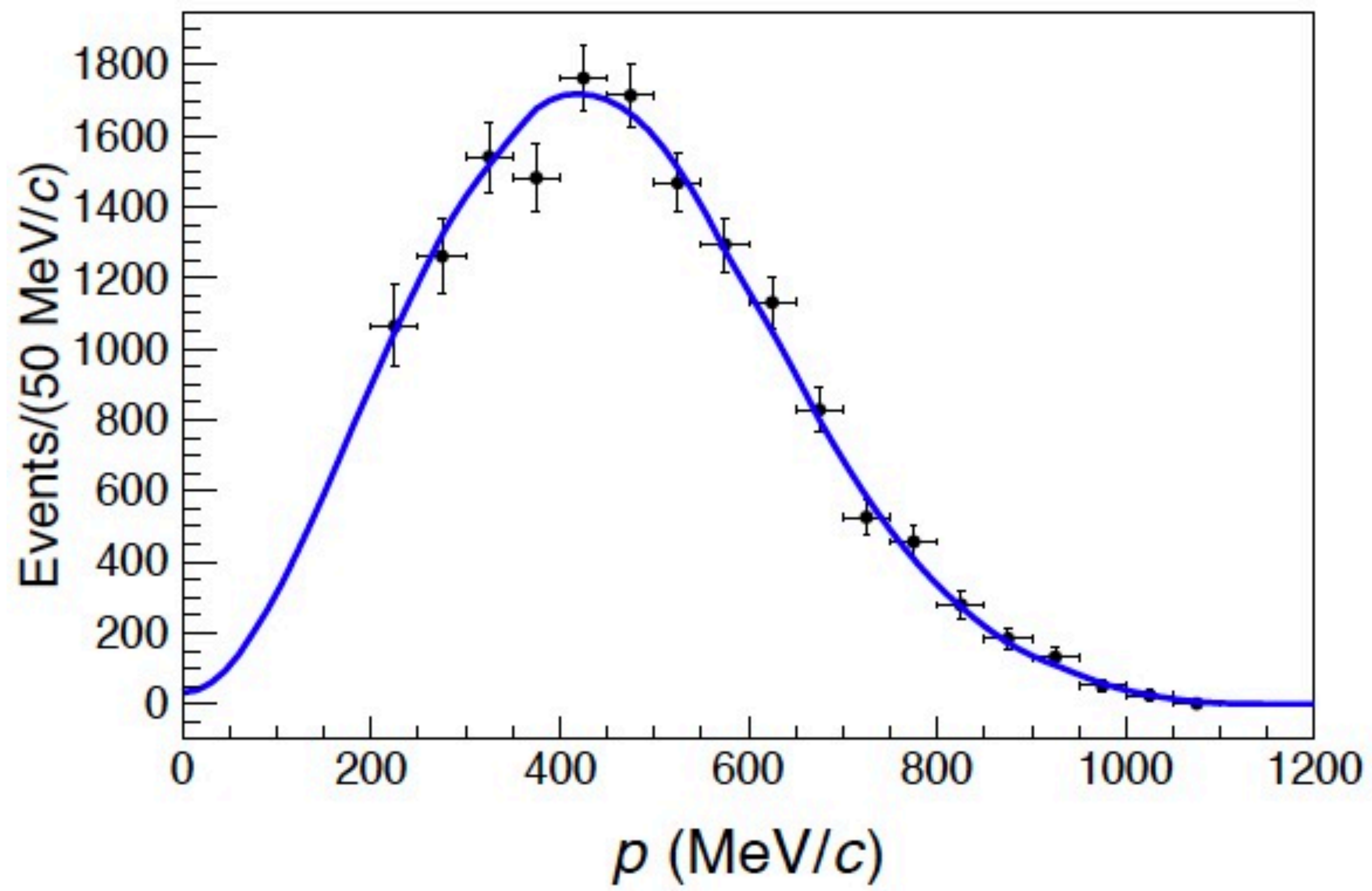


$$\mathcal{B}(D^0 \to X e^+ \nu_e) = (6.46 \pm 0.09 \pm 0.11)\%,$$
$$\mathcal{B}(D^+ \to X e^+ \nu_e) = (16.13 \pm 0.10 \pm 0.29)\%,$$
$$\mathcal{B}(D_s^+ \to X e^+ \nu_e) = (6.52 \pm 0.39 \pm 0.15)\%,$$

[CLEO, '09]

BESIII measurements

$D_s^+ \to e^+ X$



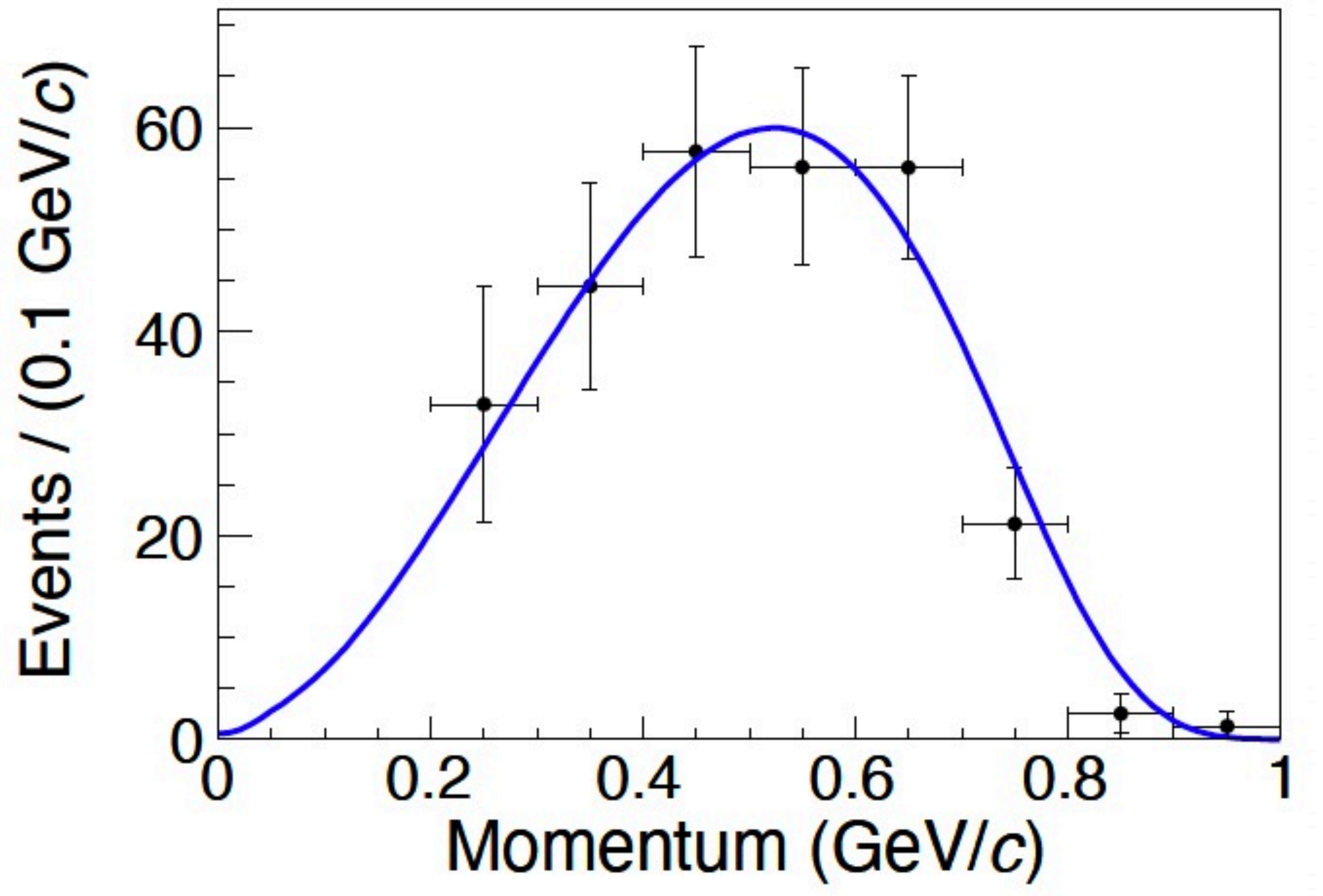
$$B(D_s^+ \to X e^+ \nu_e) = (6.30 \pm 0.13 \pm 0.10)\,\%$$

[BESIII, '21]

Experimental status

BESIII measurements

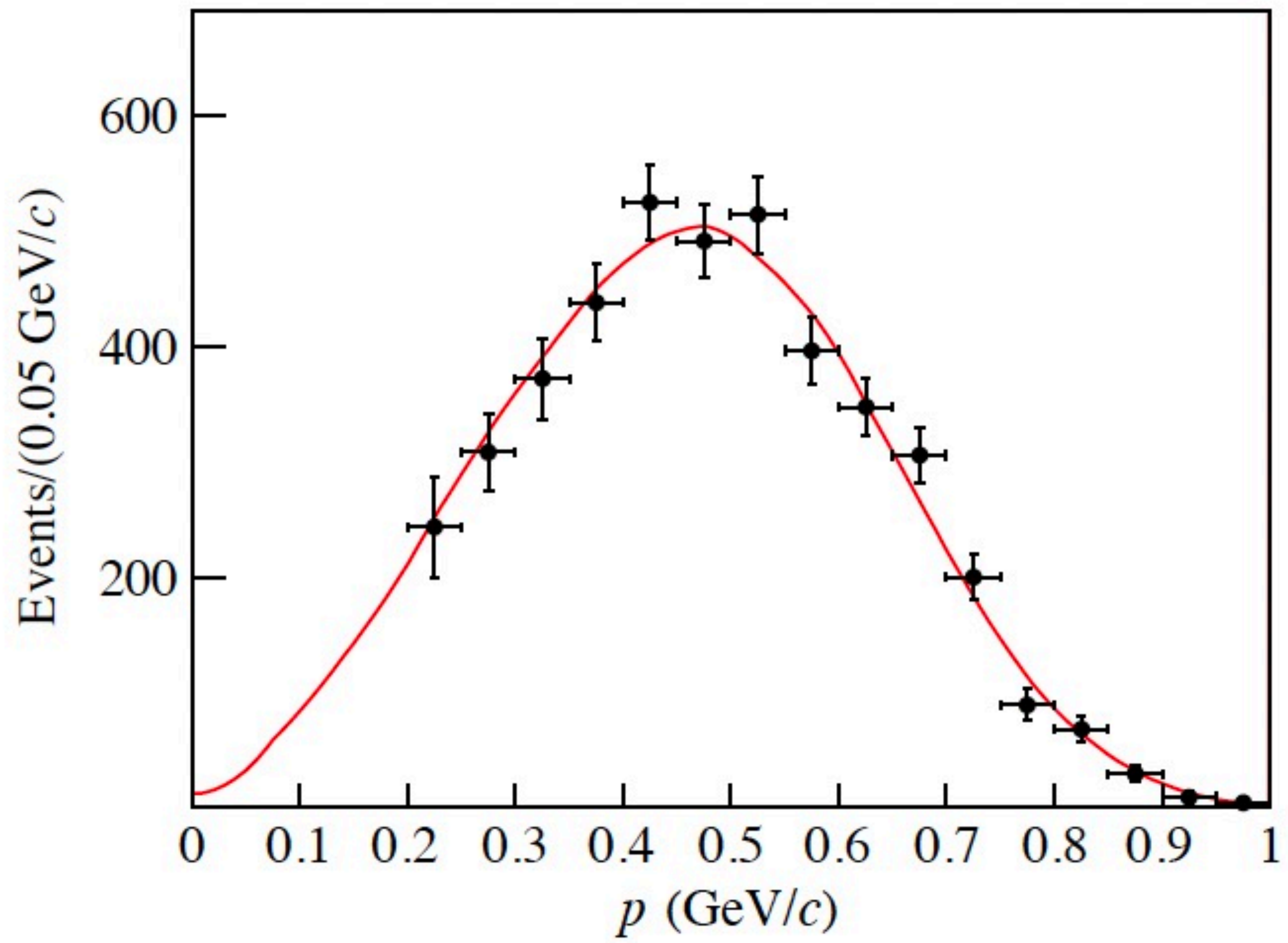
$\Lambda_c \to e^+ X$



$$B(\Lambda_c^+ \to X e^+ \nu_e) = (3.95 \pm 0.34 \pm 0.09)\,\%$$

[BESIII (567 pb^{-1}), '18]

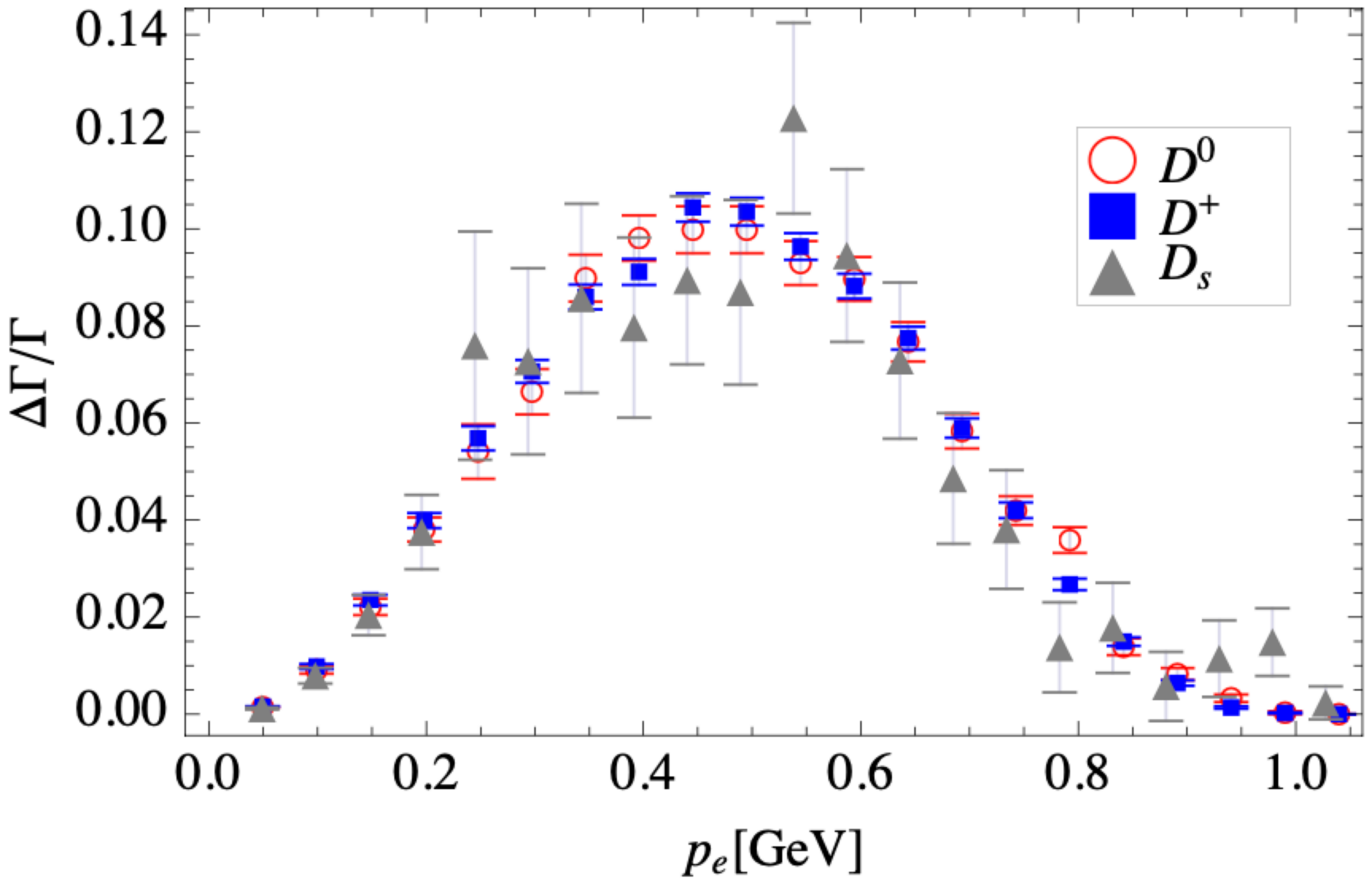
$\Lambda_c \to e^+ X$



$$\mathcal{B}(\Lambda_c^+ \to X e^+ \nu_e) = (4.06 \pm 0.10_{\text{stat.}} \pm 0.09_{\text{syst}})\%$$

[BESIII (4.5 fb^{-1}), '23]

Experimental status

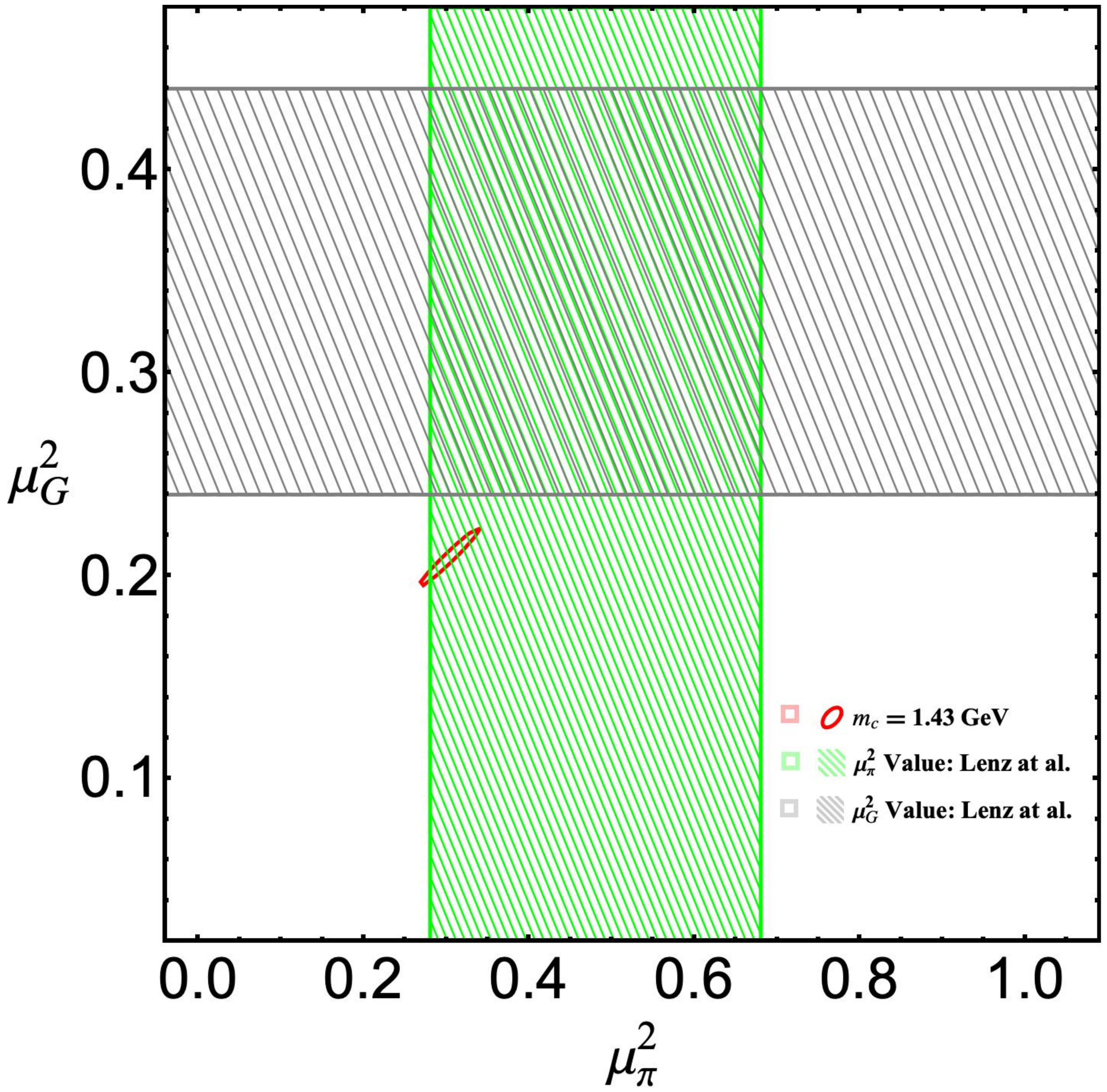


$$\langle E_e \rangle_{lab}^{D^0} = 0.465(3)\text{GeV}\,,$$
$$\langle E_e \rangle_{lab}^{D^+} = 0.459(1)\text{GeV}\,,$$
$$\langle E_e \rangle_{lab}^{D_s} = 0.466(12)\text{GeV}\,,$$

$$\langle E_e^2 \rangle_{lab}^{D^0} = 0.248(2)\text{GeV}^2\,,$$
$$\langle E_e^2 \rangle_{lab}^{D^+} = 0.242(1)\text{GeV}^2\,,$$
$$\langle E_e^2 \rangle_{lab}^{D_s} = 0.254(13)\text{GeV}^2\,.$$

[Gambino,Kamenik, ’10]

Global fit (preliminary)



$$\mu_\pi^2(D) = (0.48 \pm 0.20)\mathrm{GeV}^2$$

$$\mu_G^2(D) = (0.34 \pm 0.10)\mathrm{GeV}^2$$

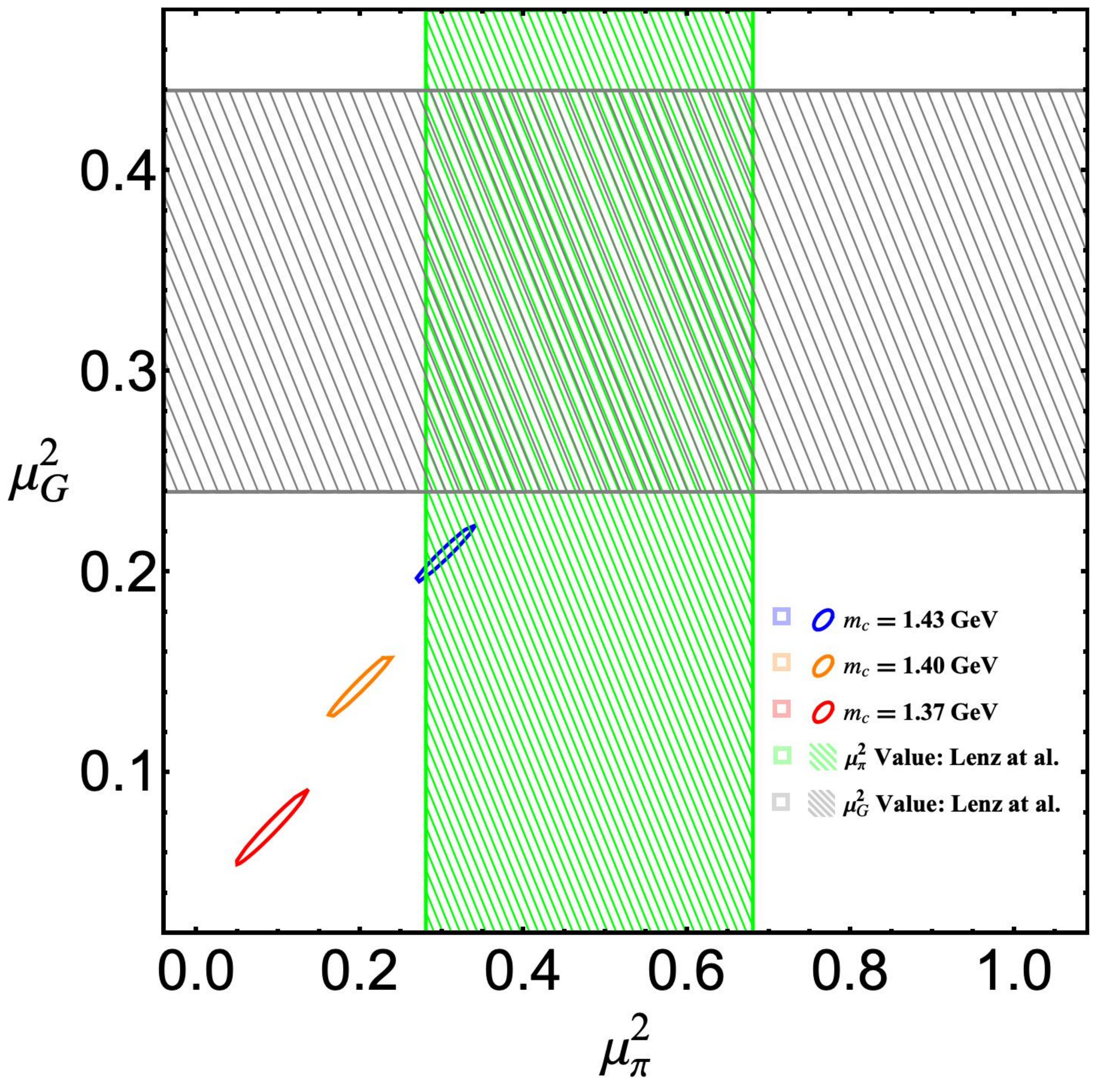
[Lenz et al, ’22]

$$\mu_\pi^2(D) = (0.304 \pm 0.037)\mathrm{GeV}^2$$

$$\mu_G^2(D) = (0.209 \pm 0.015)\mathrm{GeV}^2$$

[Our results]

Global fit (preliminary)



Pole mass scheme: mc=1.48 GeV

MS bar mass scheme:

$$m_c^{Pole} = \bar{m}_c\left(\bar{m}_c\right)\left[1 + \frac{4}{3}\frac{\alpha_s(\bar{m}_c)}{\pi}\right]$$

$$\bar{m}_c\left(\bar{m}_c\right) = 1.27\text{GeV}$$

Kinetic mass scheme：

$$m_c^{Pole} = m_c^{Kin}\left[1 + \frac{4\alpha_s}{3\pi}\left(\frac{4}{3}\frac{\mu^{\text{cut}}}{m_c^{Kin}} + \frac{1}{2}\left(\frac{\mu^{\text{cut}}}{m_c^{Kin}}\right)^2\right)\right]$$

$$m_c^{kin}(0.5\text{GeV}) = 1.363\text{GeV}$$

1S mass scheme：

$$m_c^{Pole} = m_c^{1S}\left(1 + \frac{(C_F\alpha_s)^2}{8}\right)$$

$$m_c^{1S} \approx 1.44\text{GeV}$$

Further Plans

- Include NLO corrections
- Include dimension-6 operator contributions
- Take into account the observable correlations
- Extract the hadronic parameters (and the charm mass)

Wishlist

- Precision measurements of leptonic energy spectrum in the rest frame of charmed hadrons

- q^2 spectrum, good for higher-dimensional operators

- Separate X_d, X_s, to give first measurements of V_{cd}, V_{cs}

- Rare decays: $D \to X_u \ell \ell$, STCF?

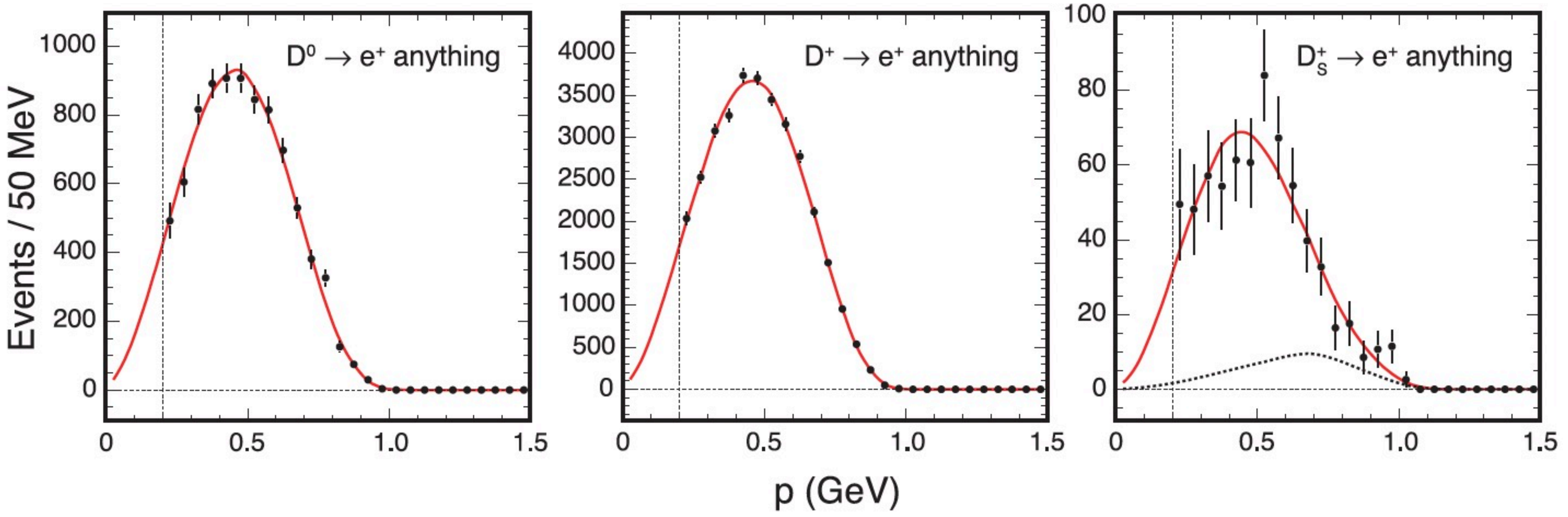
Thank you!

Backup

Experimental status

CLEO measurements

$D^0 \to e^+ X$ $D^+ \to e^+ X$ $D_s^+ \to e^+ X$

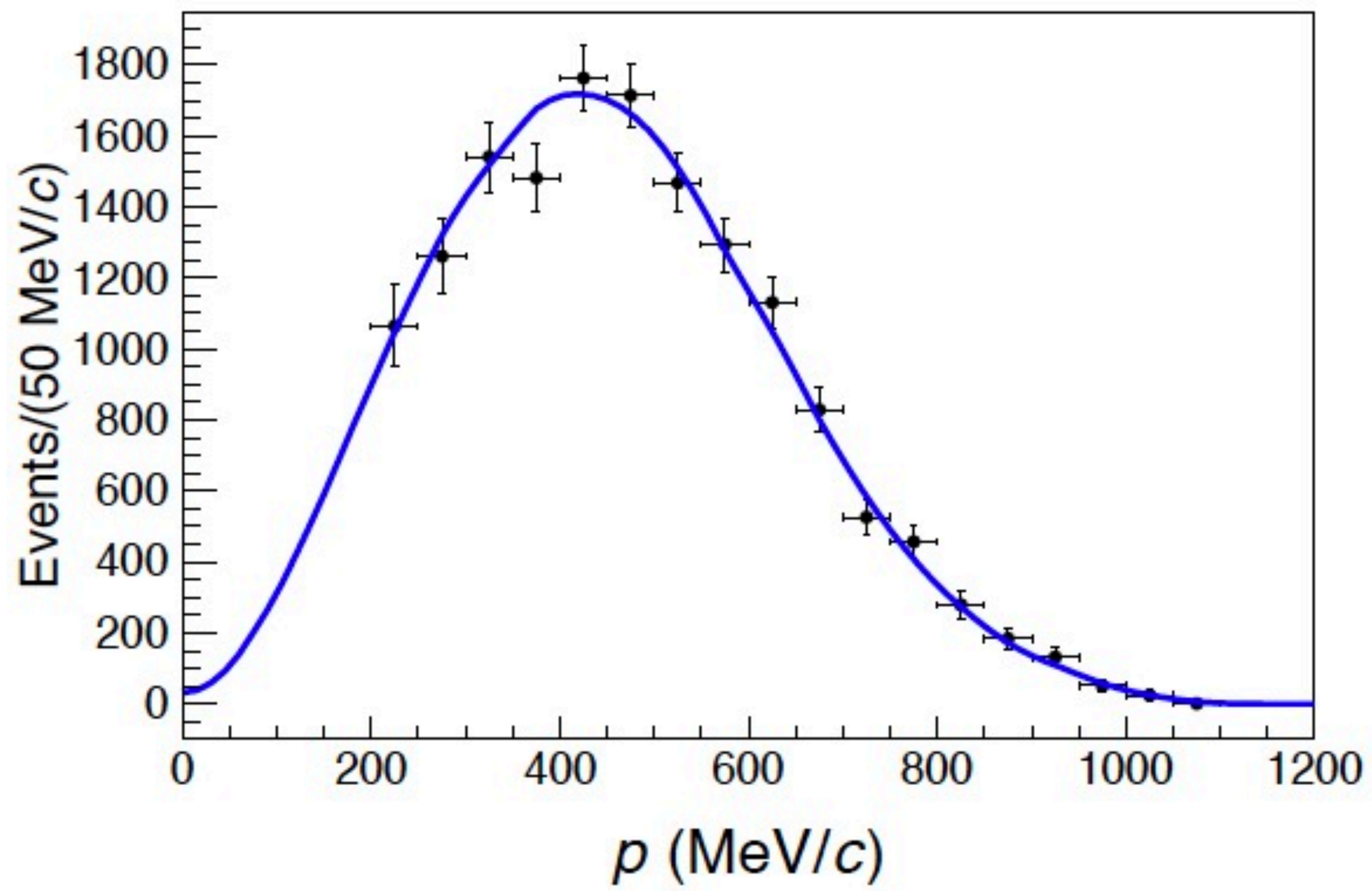


… 3.0×10^6 $D^0\bar{D}^0$ and 2.4×10^6 D^+D^- pairs, and is used to …ays. The latter data set contains 0.6×10^6 $D_s^{*\pm}D_s^{\mp}$ pairs,

[CLEO ($818\text{pb}^{-1}(D^{0,\pm})$, $602\text{pb}^{-1}(D_s^{\pm})$), '09]

BESIII measurements

$D_s^+ \to e^+ X$



$E_{\rm cm}$ (MeV)	$\int \mathcal{L}\, dt$ (pb^{-1})	$N_{D_s}(\times 10^6)$
4178	$3189.0 \pm 0.9 \pm 31.9$	6.4
4189	$526.7 \pm 0.1 \pm 2.2$	1.0
4199	$526.0 \pm 0.1 \pm 2.1$	1.0
4209	$517.1 \pm 0.1 \pm 1.8$	0.9
4219	$514.6 \pm 0.1 \pm 1.8$	0.8
4225 − 4230 [32]	$1047.3 \pm 0.1 \pm 10.2$ [33]	1.3

[BESIII, '21]