Charm CP Violation

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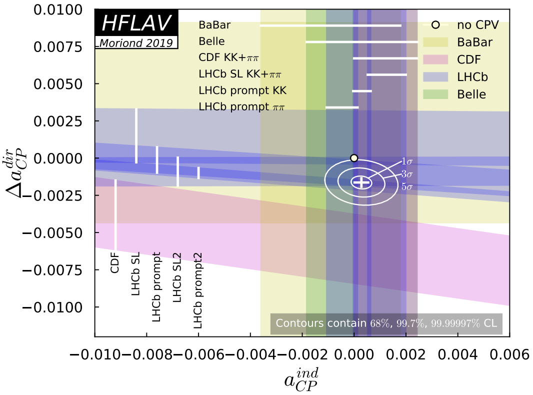
2019: Discovery of Charm Direct CP Violation by LHCb Among Physics World Top Ten Breakthrough 2019

$$\Delta A_{CP} \approx \Delta a_{CP}^{\text{dir}} \equiv a_{CP}^{\text{dir}}(D^0 \to K^+K^-) - a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-)$$



CP Violation as Probe for New Physics

- Naturalness strongly suggests that new physics should be accompanied by beyond Standard Model CP-odd phases.

- CP is not a symmetry of nature.
  Known since 1964. Found in B system in 2001.

- $\Rightarrow$ No reason that new physics should respect CP.

The $\Delta U = 0$ rule

[Y. Grossman and StS, 1903.10952]

Direct CP Violaton is an Interference Effect

$$a_{CP}^{\mathrm{dir}}(f) \equiv \frac{|\mathcal{A}(D^0 \to f)|^2 - |\mathcal{A}(\overline{D}^0 \to f)|^2}{|\mathcal{A}(D^0 \to f)|^2 + |\mathcal{A}(\overline{D}^0 \to f)|^2} \approx 2(r_{\mathrm{CKM}} \sin \varphi_{\mathrm{CKM}})(r_{\mathrm{QCD}} \sin \delta_{\mathrm{QCD}}) .$$

f = CP-eigenstate.

The decay amplitude:

$$\mathcal{A} = 1 + r_{\mathrm{CKM}}\, r_{\mathrm{QCD}}\, e^{i(\varphi_{\mathrm{CKM}} + \delta_{\mathrm{QCD}})}$$

- r_{CKM} : real ratio of CKM matrix elements.
- φ_{CKM} : weak phase.
- r_{QCD} : real ratio of hadronic matrix elements.
- δ_{QCD} : strong phase.

Where does the interference come from?

$$D^0 \to \pi^+\pi^-$$
$$D^0 \to K^+K^-$$

$KK \leftrightarrow \pi\pi$ rescattering into same final state.

[Grossman StS 1903.10952]

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^- \xrightarrow{\text{QCD}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^- \xrightarrow{\text{QCD}} K^+K^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^-$$

Interference of trees with $V_{cs}^* V_{us}$ and $V_{cd}^* V_{ud}$.

Why was CP Violation so hard to find? Because it enters only via small non-unitarity!

- The external quarks involve only first two generations.
- 2x2 submatrix of CKM approximately unitary.

$$\begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda \\ -\lambda & 1 \end{pmatrix},$$

$$V_{cd}^* V_{ud} \approx -V_{cs}^* V_{us} \approx -\lambda\,.$$

- CP violation in charm from small nonunitarity of 2x2 submatrix:

$$\text{Misalignment:} \quad V_{cd}^* V_{ud} + V_{cs}^* V_{us} = \Delta\,.$$

- Charm can be described in an effective two-generational theory.
- In the SM, non-unitarity enters via 3rd generation:

$$\Delta = -V_{cb}^* V_{ub}\,, \qquad |\lambda| \gg |V_{cb}^* V_{ub}|\,.$$

Weak and strong factors

[Grossman StS 1903.10952]

$$\frac{\mathcal{A}(D \to \pi\pi \to KK)}{\mathcal{A}(D \to KK)} = \left(r_{\text{CKM}} e^{i\varphi_{\text{CKM}}}\right)\left(r_{\text{QCD}} e^{i\delta_{\text{QCD}}}\right)$$

- r_{QCD}: ratio of rescattering amplitudes.
- $\delta_{\text{QCD}} = \mathcal{O}(1)$: strong phase.
- $r_{\text{CKM}} = 1$: ratio of CKM factors, $\left|V_{cd}^* V_{ud}/(V_{cs}^* V_{us})\right|$
- $\varphi_{\text{CKM}} \approx 6 \cdot 10^{-4}$: deviation from 2×2 unitarity.

Prediction

$$\Delta a_{CP}^{dir} \sim 10^{-3} \times r_{\text{QCD}}$$

- U-spin decomposition: $r_{\text{QCD}} = r_{\text{QCD}}^{\Delta U=0} \equiv \mathcal{A}^{\Delta U=0}/\mathcal{A}^{\Delta U=1}$.

$SU(3)_F$ Symmetry and Flavor Structure of Operators

- Approximate symmetry from $m_{u,d,s} \ll \Lambda_{\mathrm{QCD}}$.
- QCD approx. invariant under unitary rotations of $(u,\ d,\ s)$.
- Correlations and sum rules between various charm decays.
- SU(2) $\subset$ $SU(3)_F$ connecting u, d (Isospin) and d, s (U-spin).

States and operators = Representations under $SU(3)_F$

- $\left(D^0 = -|c\bar{u}\rangle\,,\quad D^+ = \left|c\bar{d}\right\rangle,\quad D_s = |c\bar{s}\rangle\right) = \bar{\mathbf{3}}$
- Pions and kaons: $[(\mathbf{8}) \otimes (\mathbf{8})]_S = (\mathbf{1}) \oplus (\mathbf{8}) \oplus (\mathbf{27})$
- $\mathcal{H} \sim \lambda\left(\mathbf{15} + \bar{\mathbf{6}}\right) + \lambda^5\,(\mathbf{15} + \mathbf{3})$

Strategies

- Analytical: Derive sum rules from group theory.
- Numerical: Extensive fits (HPC) to derive patterns.

Theory Challenge: Disentangle BSM Patterns from $SU(3)_F$-breaking $\mathcal{H}_{\text{break}} \sim m_s \bar{s} s \propto \mathbf{1} \oplus \mathbf{8}$

$$(\mathbf{15}) \otimes (\mathbf{8}) = (\mathbf{42}) \oplus (\mathbf{24}) \oplus (\mathbf{15_1}) \oplus (\mathbf{15_2}) \oplus (\mathbf{15'}) \oplus (\bar{\mathbf{6}}) \oplus (\mathbf{3})$$

$$(\bar{\mathbf{6}}) \otimes (\mathbf{8}) = (\mathbf{24}) \oplus (\mathbf{15}) \oplus (\bar{\mathbf{6}}) \oplus (\mathbf{3})$$

$$(\mathbf{3}) \otimes (\mathbf{8}) = (\mathbf{15}) \oplus (\bar{\mathbf{6}}) \oplus (\mathbf{3})$$

Decay d	$B_1^{3_1}$	$B_1^{3_2}$	$B_8^{3_1}$	$B_8^{3_2}$	$B_8^{\bar{6}_1}$	$B_8^{\bar{6}_2}$	$B_8^{15_1}$	...
$D^0 \to K^+K^-$	$\frac{1}{4\sqrt{10}}$	$\frac{1}{8}$	$\frac{1}{10\sqrt{2}}$	$\frac{1}{4\sqrt{5}}$	$\frac{1}{10}$	$-\frac{1}{10\sqrt{2}}$	$-\frac{7}{10\sqrt{122}}$	...
$D^0 \to \pi^+\pi^-$	$\frac{1}{4\sqrt{10}}$	$\frac{1}{8}$	$\frac{1}{10\sqrt{2}}$	$\frac{1}{4\sqrt{5}}$	$-\frac{1}{10}$	$\frac{1}{10\sqrt{2}}$	$-\frac{11}{10\sqrt{122}}$	...
$D^0 \to \bar{K}^0K^0$	$-\frac{1}{4\sqrt{10}}$	$-\frac{1}{8}$	$\frac{1}{5\sqrt{2}}$	$\frac{1}{2\sqrt{5}}$	0	0	$-\frac{9}{5\sqrt{122}}$	...
$D^0 \to \pi^0\pi^0$	$-\frac{1}{8\sqrt{5}}$	$-\frac{1}{8\sqrt{2}}$	$-\frac{1}{20}$	$-\frac{1}{4\sqrt{10}}$	$\frac{1}{10\sqrt{2}}$	$-\frac{1}{20}$	$\frac{11}{20\sqrt{61}}$	...
$D^+ \to \pi^0\pi^+$	0	0	0	0	0	0	0	...
$D^+ \to \bar{K}^0K^+$	0	0	$\frac{3}{10\sqrt{2}}$	$\frac{3}{4\sqrt{5}}$	$\frac{1}{10}$	$-\frac{1}{10\sqrt{2}}$	$\frac{7}{10\sqrt{122}}$	...
$D_s \to K^0\pi^+$	0	0	$\frac{3}{10\sqrt{2}}$	$\frac{3}{4\sqrt{5}}$	$-\frac{1}{10}$	$\frac{1}{10\sqrt{2}}$	$\frac{11}{10\sqrt{122}}$	...
$D_s \to K^+\pi^0$	0	0	$-\frac{3}{20}$	$-\frac{3}{4\sqrt{10}}$	$\frac{1}{10\sqrt{2}}$	$-\frac{1}{20}$	$-\frac{11}{20\sqrt{61}}$	...
...	...	...	...	...	...	...	...	...

[Table: Hiller Jung StS 1211.3734]

U-spin Flavor Structure of Hamiltonian for SCS Decays

- Approximate symmetry from $m_{u,d,s} \ll \Lambda_{\text{QCD}}$.
- QCD approx. invariant under unitary rotations of $(u,\ d,\ s)$.
- Correlations and sum rules between various charm decays.
- SU(2) $\subset$ SU(3)$_F$ connecting u, d (Isospin) and d, s (U-spin).

$$Q^{\bar{s}s} = (\bar{s}u)(\bar{c}s) \qquad Q^{\bar{d}d} = (\bar{d}u)(\bar{c}d)$$

$$Q^{\Delta U=1} = \frac{Q^{\bar{s}s} - Q^{\bar{d}d}}{2} \qquad Q^{\Delta U=0} = \frac{Q^{\bar{s}s} + Q^{\bar{d}d}}{2}$$

$$\mathcal{H}_{\text{eff}} \sim \underbrace{\frac{V_{cs}^* V_{us} - V_{cd}^* V_{ud}}{2}}_{\approx\, \lambda} Q^{\Delta U=1} + \underbrace{\frac{V_{cs}^* V_{us} + V_{cd}^* V_{ud}}{2}}_{=\, \frac{\Delta}{2}} Q^{\Delta U=0}$$

$\Delta I = 1/2$ and $\Delta U = 0$ rules

"$\Delta I = 1/2$ rules" for isospin in $P^+ \to \pi^+\pi^0$, $P^0 \to \pi^+\pi^-$, $P^0 \to \pi^0\pi^0$

- Relevant ratio of strong isospin matrix elements:

$r_{QCD}^{\Delta I=1/2} \equiv A^{\Delta I=1/2}/A^{\Delta I=3/2}$	Kaon	Charm	Beauty
Data	22	2.5	1.5
Enhancement	$\mathcal{O}(10)$	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_s)$

[D: Franco Mishima Silvestrini 2012, B: Grinstein Pirtskhalava Stone Uttayarat 2014]

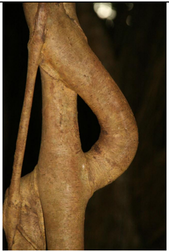
- Rescattering most important in K decays, less important but still significant in D decays, and small in B decays.

"$\Delta U = 0$ rule" [Grossman StS 1903.10952]

- We claim $\Delta U = 0$ follows a similar pattern: $r_{\mathrm{QCD}}^{\Delta U=0} \sim 1$.
- Both due to low energy QCD, rescattering.

Comparison of Mechanisms of CP Violation

[Grossman StS 1903.10952]

Beauty	Charm
Tree + Penguin	Tree + Rescattering
	

In charm: Loop/Tree $= \mathcal{O}(1)$ (non-perturbative)

Comparison of approaches: What is r_{QCD}?

Data

Assuming the SM, and $\delta_{\rm QCD} = \mathcal{O}(1)$, the data implies $r_{\rm QCD}^{\Delta U=0} \sim 1$.

Ref.	Theory Method/Assumptions	$r_{QCD}^{\Delta U=0}$	SM/NP
[Grossman StS 1903.10952]	Analogy to $\Delta I = 1/2$ rules Low energy QCD, rescattering is $\mathcal{O}(1)$	$\mathcal{O}(1)$	SM
[Brod Kagan Zupan 1111.5000]	Phenomenological analysis	$\mathcal{O}(1)$	SM
[Soni 1905.00907, StS Soni 2106.xxxx]	Resonance model	$\mathcal{O}(1)$	SM
[Petrov Khodjamirian 1706.07780] [Chala Lenz Rusov Scholtz 1903.10490]	Light Cone Sum Rules	$\mathcal{O}(\alpha_s/\pi)$	NP

Test case: Apply methods to $\Delta I = 1/2$ rule in charm.

What do we learn?

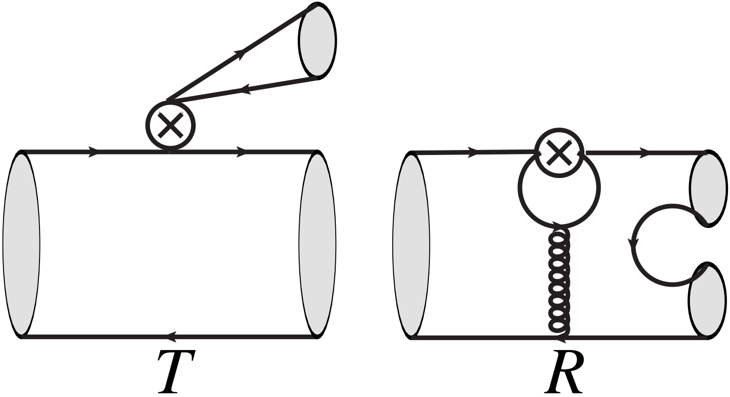
- Assumption of large rescattering at low energy agrees with the data.
- It is hard to argue that the LHCb result requires BSM.
- Yet, BSM can still be present.
- $\Delta I = 1/2$ in D decays also requires $\mathcal{O}(1)$ rescattering.

Probing the $\Delta U = 0$ Rule in Three-Body Charm Decays

[A. Dery, Y. Grossman, StS, A. Soffer: 2101.02560]

Parameters and Observables of $D^0 \to \rho^\pm \pi^\mp$

$$\mathcal{A}(D^0 \to \pi^+\rho^-) = -\lambda\, T^{P_1V_2} - V_{cb}^* V_{ub}\, R^{P_1V_2}$$
$$\mathcal{A}(D^0 \to \pi^-\rho^+) = -\lambda\, T^{P_2V_1} - V_{cb}^* V_{ub}\, R^{P_2V_1}$$



In overlap region of two resonances

Amplitude

$$\mathcal{A}(D^0 \to \pi^+\pi^-\pi^0) = \mathcal{A}\left(D^0 \to \pi^-(\rho^+ \to \pi^0\pi^+)\right) + \mathcal{A}\left(D^0 \to (\rho^- \to \pi^-\pi^0)\pi^+\right)$$

$$= \text{Breit Wigner} \times T^{P_2V_1} \times \left(-1 - \widetilde{\lambda}_b \widetilde{R}^{P_2V_1}\right) +$$

$$\text{Breit Wigner} \times T^{P_1V_2} \times \left(-1 - \widetilde{\lambda}_b \widetilde{R}^{P_1V_2}\right),$$

- $T^{P_iV_j}$ from $\Gamma(D^0 \to \pi^+\pi^-\pi^0)$ Dalitz plot (CP-limit excellent approx).
- $R_0^{P_iV_j}$ and their relative phase from CP difference:

$$\frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{-4|\Sigma|^2 \mathrm{Im}(\widetilde{\lambda}_b)} = \text{Breit Wigners (BWs)} \times |\widetilde{R}^{P_1V_2}| \sin(\delta_{\widetilde{R}^{P_1V_2}}) -$$

$$\text{BWs} \times |\widetilde{R}^{P_1V_2}| \sin\left(\text{BW phases} - \delta_{\widetilde{R}^{P_1V_2}}\right) +$$

$$\text{BWs} \times |\widetilde{R}_0^{P_2V_1}| \sin\left(\text{BW phases} + \delta_{\widetilde{R}_0^{P_2V_1}}\right) +$$

$$\text{BWs} \times |\widetilde{R}_0^{P_2V_1}| \sin(\delta_{\widetilde{R}_0^{P_2V_1}})$$

Conceptual difference between 2- and 3-body decays

- Time-integrated CP asym. of 2-body decays give only combinations

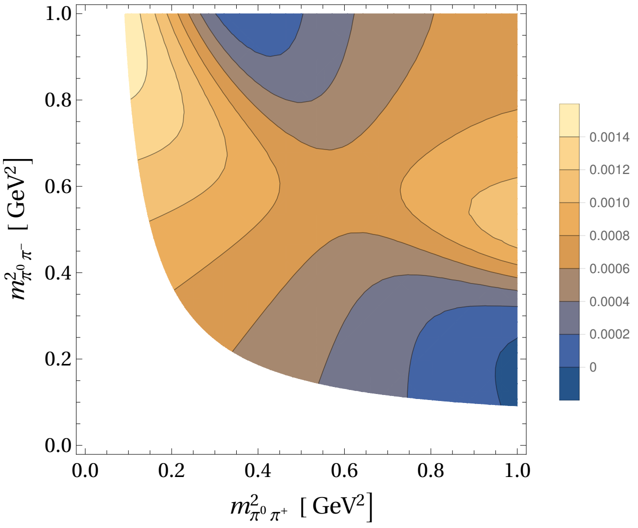
$$|\widetilde{R}^{P_1V_2}|\sin(\delta_{P_1V_2}) \qquad \text{and} \qquad |\widetilde{R}^{P_2V_1}|\sin(\delta_{P_2V_1}),$$

  but **not** magnitudes and phases separately.

- Three body decay changes 2 things:
  - We have additional kinematic dependences.
  - Only in a three-body decay we have interference between $D^0 \to \pi^+(\rho^- \to \pi^-\pi^0)$ and $D^0 \to \pi^-(\rho^+ \to \pi^+\pi^0)$.

  ↳Extraction of all parameters from time-integrated CP meas.

Numerical Example in overlap region of $\rho^{\pm}$ resonances



$$\widetilde{R}^{P_1 V_2} = \exp(i\pi/2), \quad \widetilde{R}^{P_2 V_1} = \frac{1}{4} \exp(i\pi/3)$$

The $\Delta U = 0$ Rule and Three-Body Decays

- $D^0 \to V^\pm P^\mp$ from Dalitz analysis of time-integrated three-body decays probe similar ratios as $D^0 \to P^\pm P^\mp$.

- Advantage: No time-dependent CPV measurements or employing correlated D^0–$\overline{D}^0$ states necessary to solve complete system, including the strong phases.

Enhancement of charm CPV due to nearby resonances

[StS and A. Soni, 2106.soon]

Scalar Resonances

- Nearby scalar resonances to $m_{D^0} = 1864.83 \pm 0.05$ MeV.
- $f_0(1710)$ and $f_0(1790)$ could cause CPV enhancements within SM.

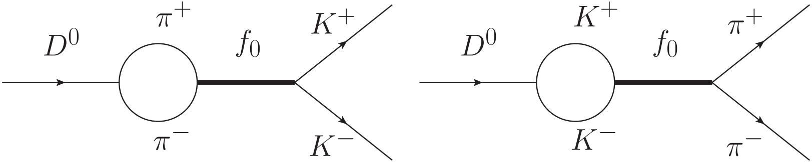
Resonance R	$I^G(J^{PC})$	mass m [MeV]	Γ [MeV]	Ref.
$f_0(1710)$	$0^+(0^{++})$	1704 ± 12	123 ± 18	[PDG2020]
$f_0(1790)$	$0^+(0^{++})$	1790^{+40}_{-30}	270^{+60}_{-30}	[LHCb 1402.6248]
				[BESII hep-ex/0411001]

- Note: $f_0(1790)$ not yet fully established (not listed in PDG). Seen by BESII and LHCb.
- Experimental information on scalar resonances rather sparse: Limiting factor for our predictions.
  ↳ Further data on these resonances is strongly advocated.

Modelling Rescattering with Scalar Resonances

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^-$$

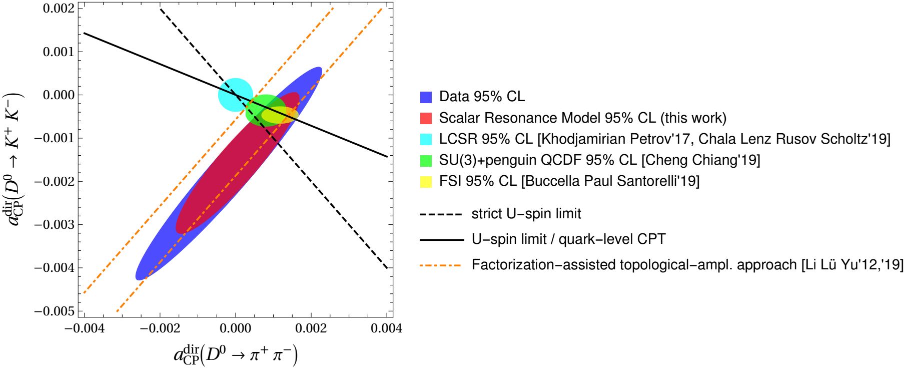
$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^- \xrightarrow{\text{QCD}} \pi^+\pi^-$$



- Breit-Wigner ansatz for $f_0(1710)$ and $f_0(1790)$.
- Additional model assumptions due to lack of data.

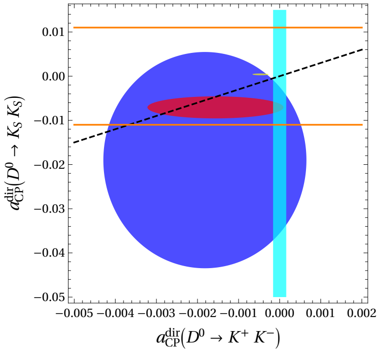
Comparison of data and theory scenarios

[preliminary results]



Comparison of data and theory scenarios, contd.

[preliminary results]



- Data 95% CL
- Scalar Resonance Model 95% CL (this work)
- $D^0 \to K^+ K^-$ LCSR 68 % CL [Khodjamirian Petrov ' 17, Chala Lenz Rusov Scholtz ' 19]
- FSI 95% CL [Buccella Paul Santorelli'19]
- SU(3) estimate [Hiller Jung Schacht '12]
- $D^0 \to K_S K_S$ 95 % CL [Nierste Schacht ' 15]

What will charm reveal next?

- Will the global charm fit give a consistent picture?
- Sum rules for baryon decays, including fully general $SU(3)_F$ breaking.
- How to define ΔA_{CP} for 4-body decays in an advantageous way?
- Optimal observable for detecting CPV in multibody decays?
  Smart binning?
- How to describe $SU(3)_F$-breaking effects from Dalitz phase space?
- How good is charm described by Light-Cone Sum Rules (LCSR) ?
- How good is charm described by QCD factorization (BBNS)?
- What can we learn about η–η'-mixing from charm decays?
- Isospin-breaking and electroweak corrections to
  nulltest isospin relations like $A_{CP}(D^+ \to \pi^0\pi^+) = 0$.
- What more can correlated D^0–$\overline{D}^0$ states tell us, e.g. at a future
  τ-charm factory?

Conclusion

- Charm CP violation discovered in 2019.
  - ➥ New research field. So much to learn.
- Charm has potential for discovery of BSM physics.
- Will also teach us about QCD.