



中国科学院大学
UNIVERSITY OF CHINESE ACADEMY OF SCIENCES

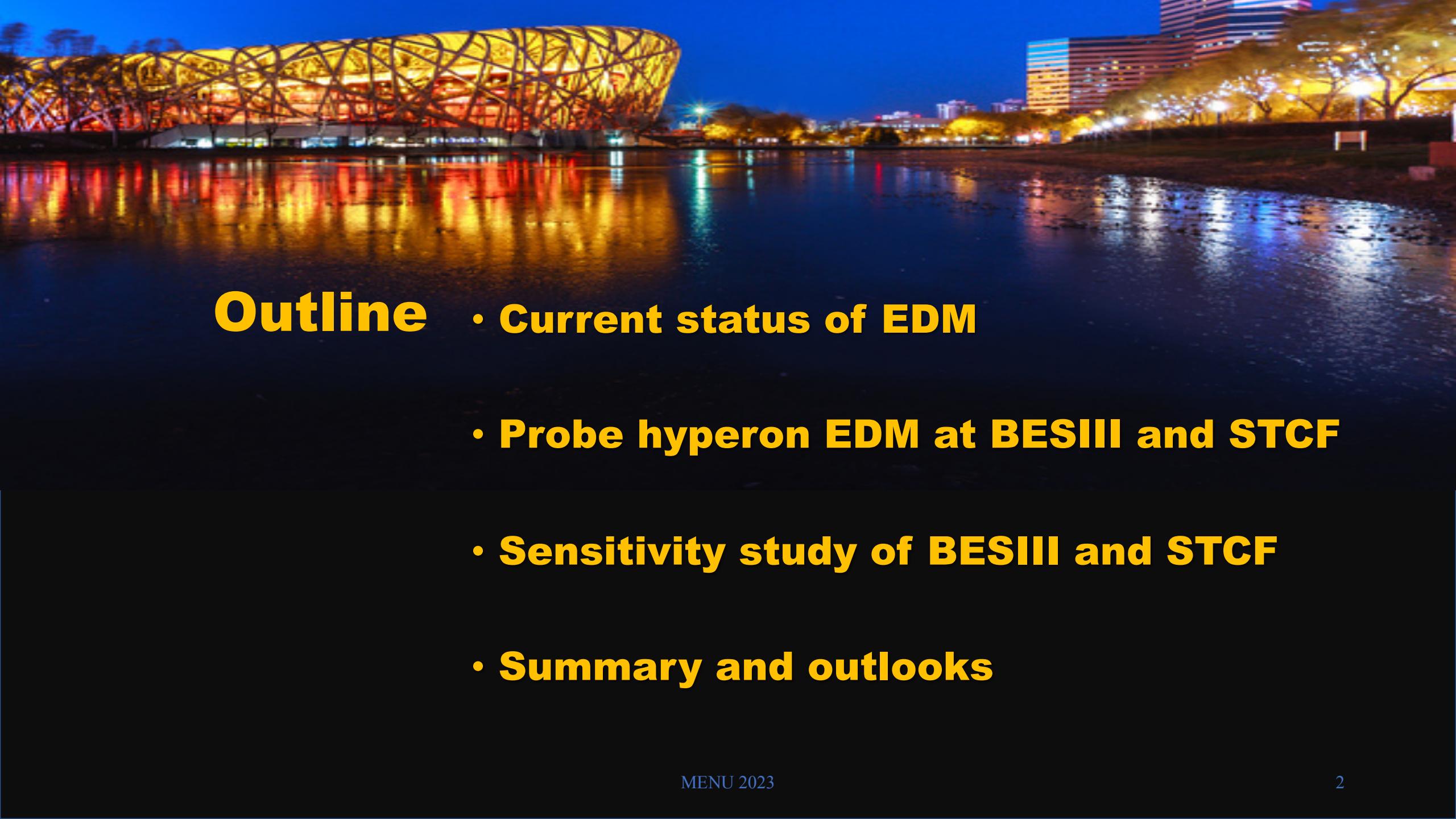
Probe hyperon electric dipole moments at e^+e^- colliders

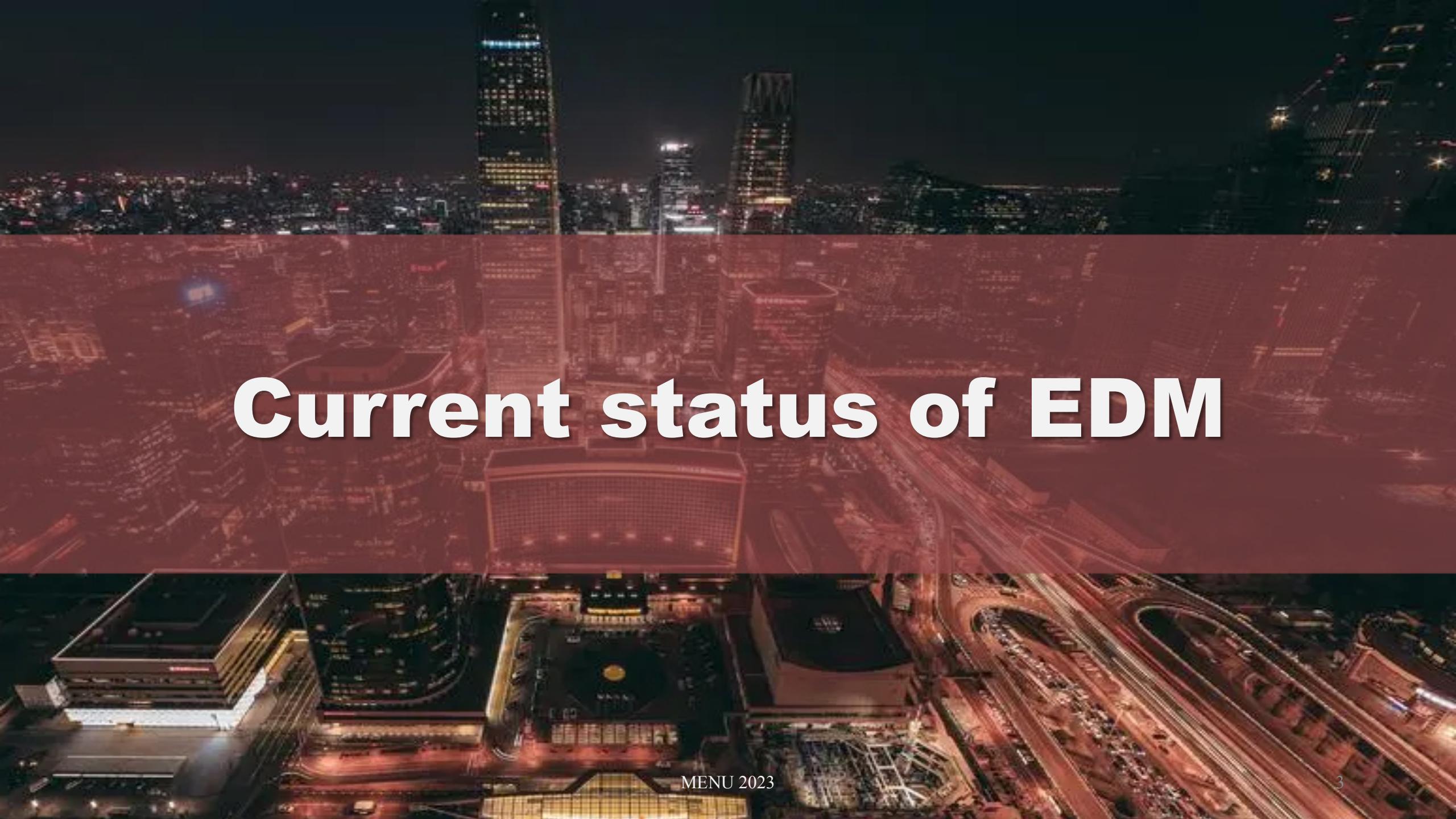
based on arxiv: 2307.04364

MENU 2023

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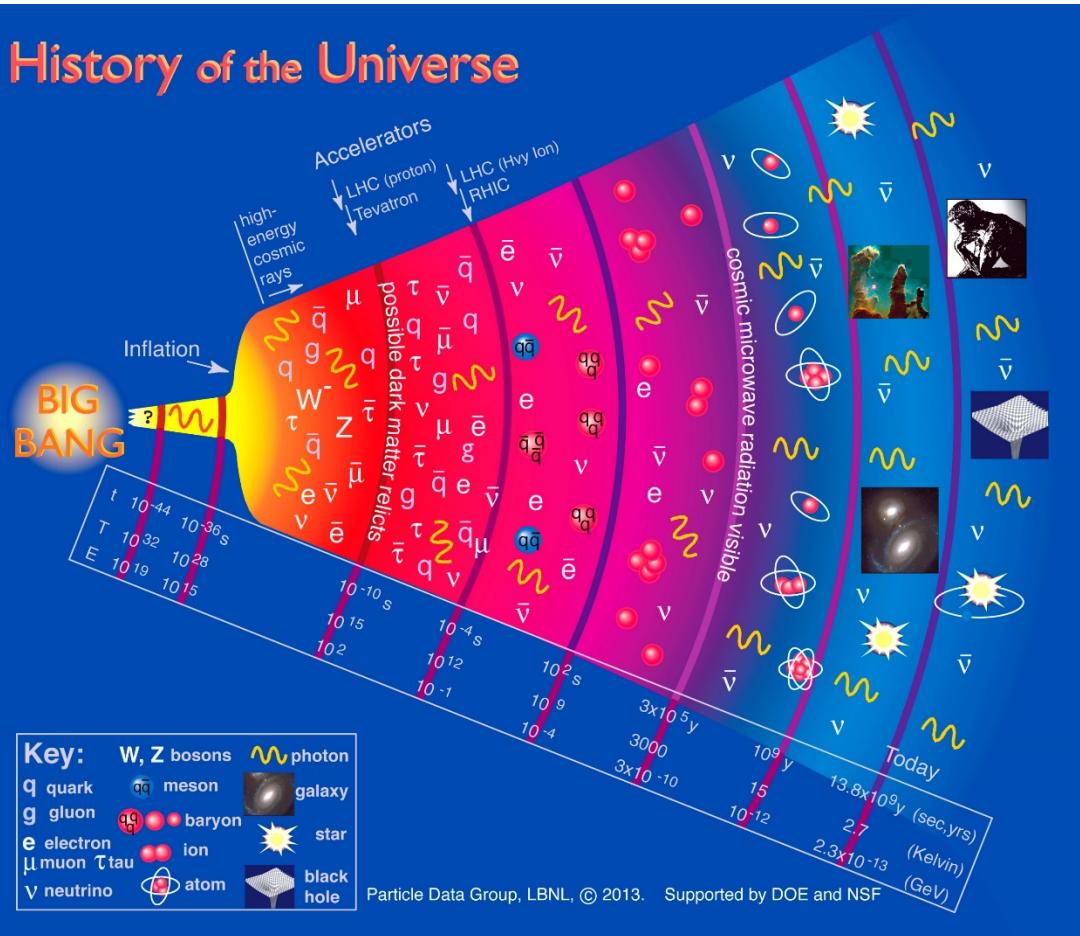
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- The background image shows the Beijing National Stadium, also known as the Bird's Nest, illuminated at night. Its intricate lattice structure is reflected in the dark water in front of it. In the distance, other buildings and lights are visible under a dark sky.
- ## Outline
- Current status of EDM
 - Probe hyperon EDM at BESIII and STCF
 - Sensitivity study of BESIII and STCF
 - Summary and outlooks

The background image is a wide-angle aerial photograph of a city at night. The sky is dark, and numerous skyscrapers are brightly lit from within, their windows glowing like stars. In the foreground, a massive highway interchange with multiple levels and ramps is visible, its lights forming a complex network. The overall scene conveys a sense of urban density and technological advancement.

Current status of EDM

Matter-antimatter asymmetry in the universe

History of the Universe



- Big matter and anti-matter asymmetry founded in the universe!

WMAP+COBE(2012):

$$(n_B - n_{\bar{B}})/n_\gamma|_{CMB} = (6.08 \pm 0.09) \times 10^{-10}$$

- Sakharov three conditions require:

C and CP symmetry violation

Pisma Zh. Eksp. Teor. Fiz., 1967, 5: 32-35.



- CP violation has been founded at K, B, D meson system, but not enough to explain matter dominant universe.

Standard Model (SM) prediction:

$$\hat{d}_{CP} = \frac{d_{CP}}{D^{12}} \sim 10^{-18} \ll 10^{-10}$$

W. Bernreuther
Lect. Notes Phys. 591
(2002) 237-293

Exploring new physics is extremely important

A brief history of Parity and CP violation



James Watson
Cronin



Nobel Prize 1980

Val Logsdon
Fitch



MENU 2023

- [1] Phys. Rev. 104 (1956) 254-258
- [2] Phys. Rev. Lett., 1964, 13: 138-140
- [3] Phys. Rev. Lett., 2001, 87: 091801
- [4] Phys. Rev. Lett., 2001, 87: 091802
- [5] Phys. Rev. Lett., 2019, 122(21): 211803

CPV in Standard Model

CKM mechanism:

$$V_{\text{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

CPV from phase δ



Dirac Medal
2010



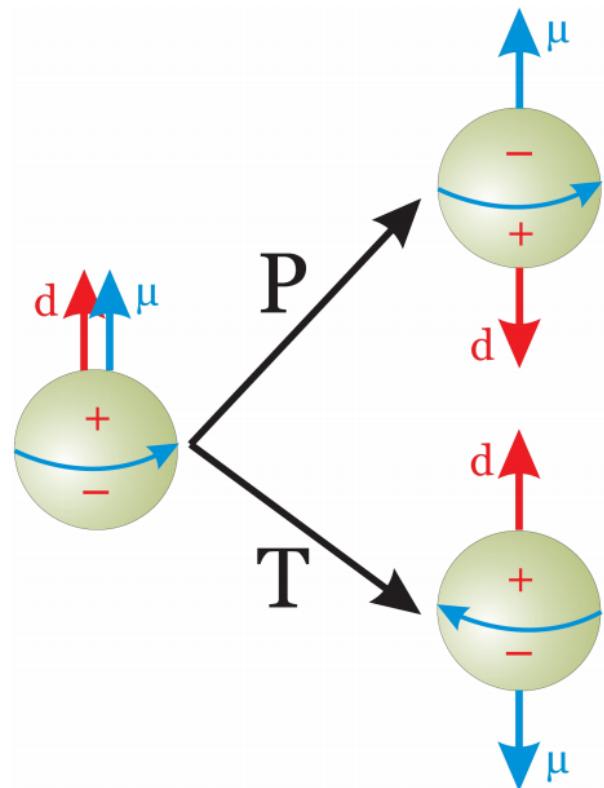
Nobel Price
2008

Strong CP

- $\bar{\theta}$ term : $\mathcal{L}_{\bar{\theta}} = -\frac{\alpha_s}{16\pi^2} \bar{\theta} \text{Tr}(G^{\mu\nu} \tilde{G}_{\mu\nu})$
- Mainly through measuring the Electric Dipole Moment (EDM) of atomic nuclei, atoms, and molecular systems,
- The current most stringent constraints come from the EDM experiments of neutrons and ^{199}Hg : $\bar{\theta} < 10^{-10}$

Electric Dipole Moment

μ : magnetic dipole moment
 d : electric dipole moment



$$\mathcal{H} = -\mu \cdot \mathbf{B} - \delta \cdot \mathbf{E} \xrightarrow{P} \mathcal{H} = -\mu \cdot \mathbf{B} + \delta \cdot \mathbf{E}$$

$$\mathcal{H} = -\mu \cdot \mathbf{B} - \delta \cdot \mathbf{E} \xrightarrow{T} \mathcal{H} = -\mu \cdot \mathbf{B} + \delta \cdot \mathbf{E}$$

Non-zero EDM will violate P and T symmetry:
 T violation $\leftrightarrow CP$ violation, if CPT holds.

The contribution of the Standard Model to EDM is very small:

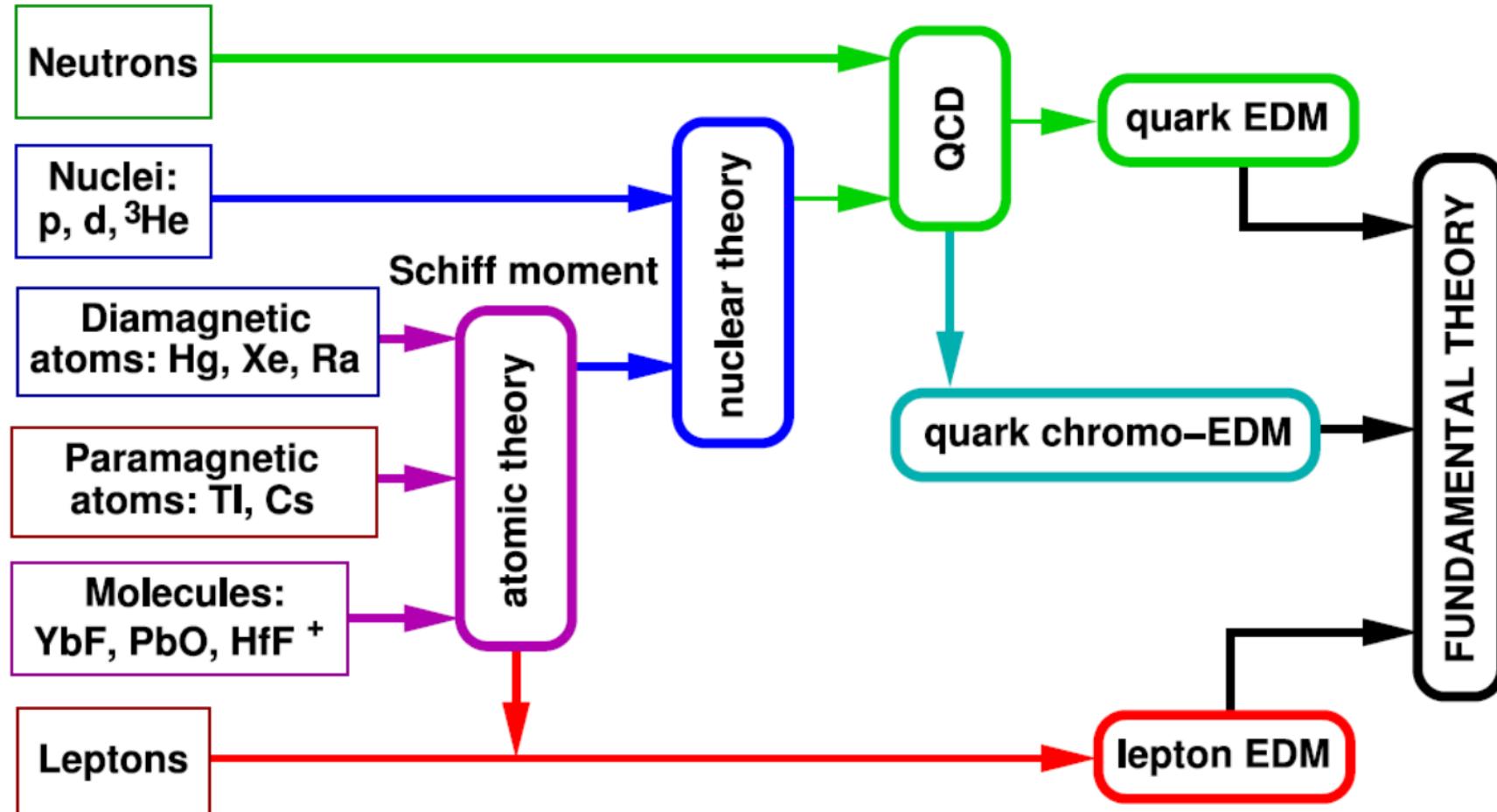
- CKM: highly suppressed by loop level (≥ 3) interaction
- QCD $\bar{\theta}$ term: main SM contributors to the EDM, $\bar{\theta} < 10^{-10}$
 - limited by neutron EDM:

$$d_n < 1.6 \times 10^{-26} \text{ ecm}$$

$$\mathcal{L}_{CPV} = \mathcal{L}_{CKM} + \mathcal{L}_{\bar{\theta}} + \mathcal{L}_{BSM}^{\text{eff}}$$

Very sensitive to BSM physics, large windows of opportunity for observing New Physics!

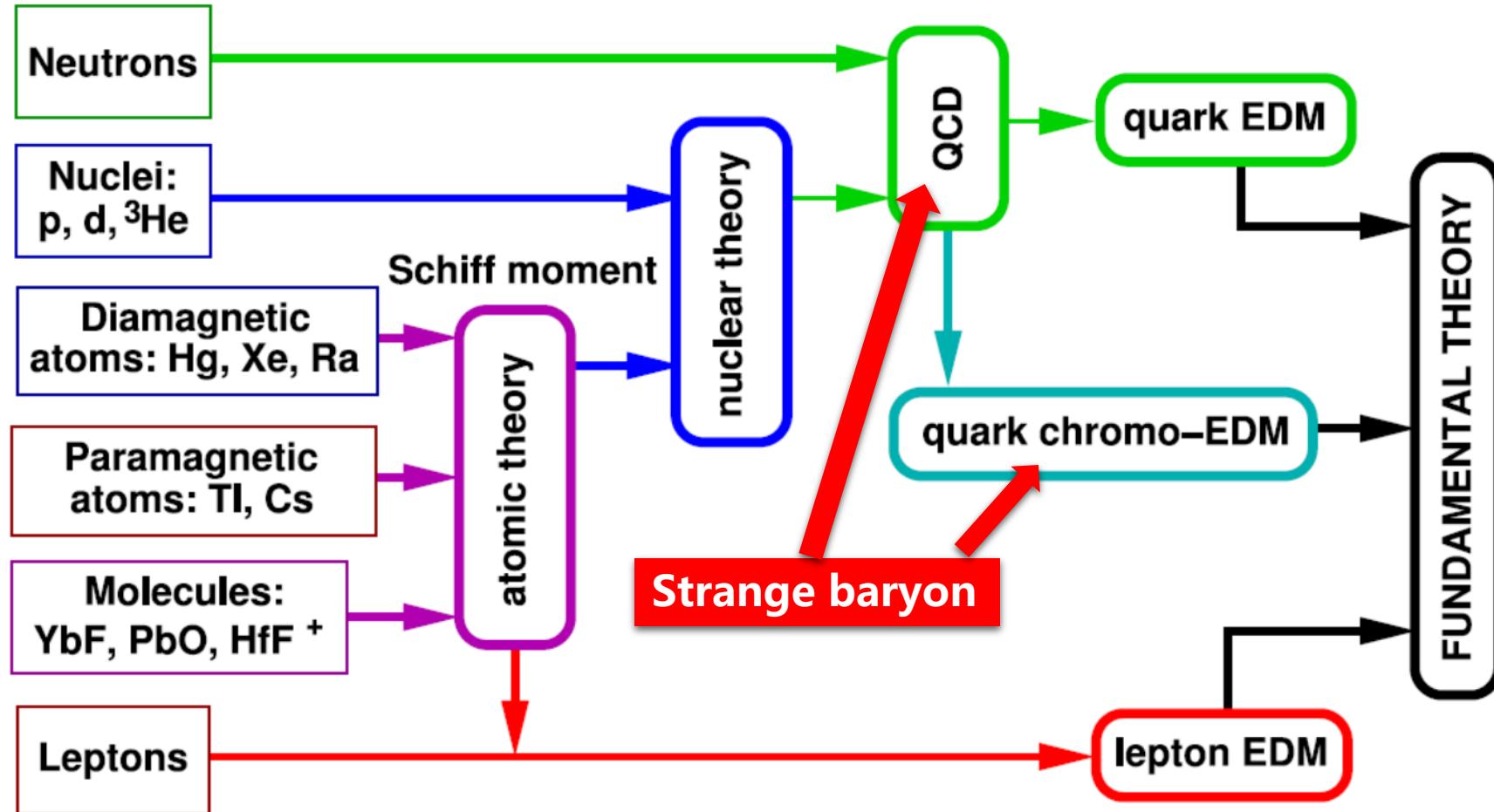
Map of EDM



C. R. Physique 13 168 (2012)

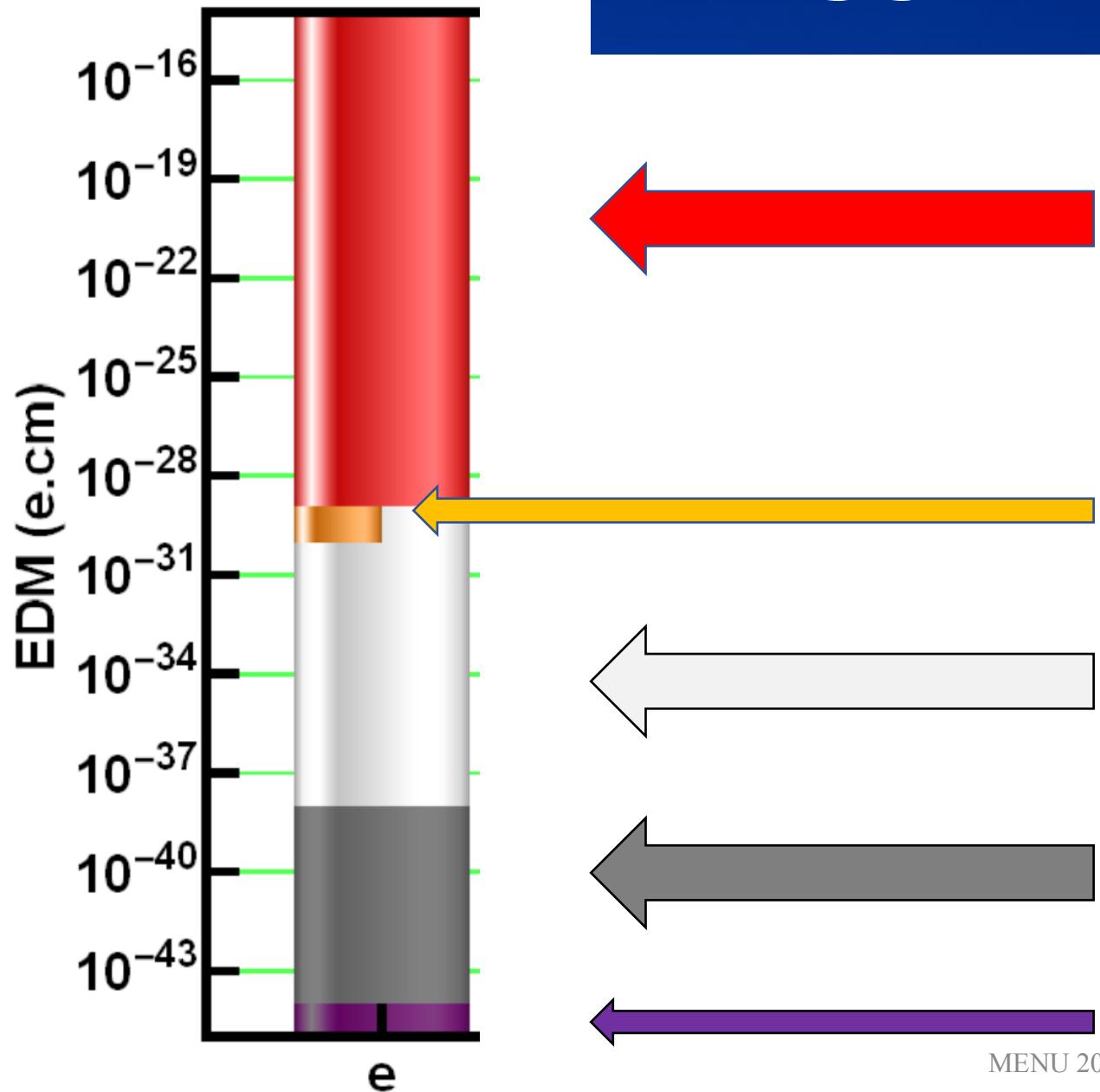
Map of EDM

The identification of the nature of the fundamental CP-violating mechanisms requires the study of EDMs in various systems



C. R. Physique 13 168 (2012)

ILLUSTRATION of EDM STATUS



Best measurements
Limits from experimental results

Expected experimental results
in the next few years

Safe BSM discovery territory

SM estimates from QCD $\bar{\theta}$ term

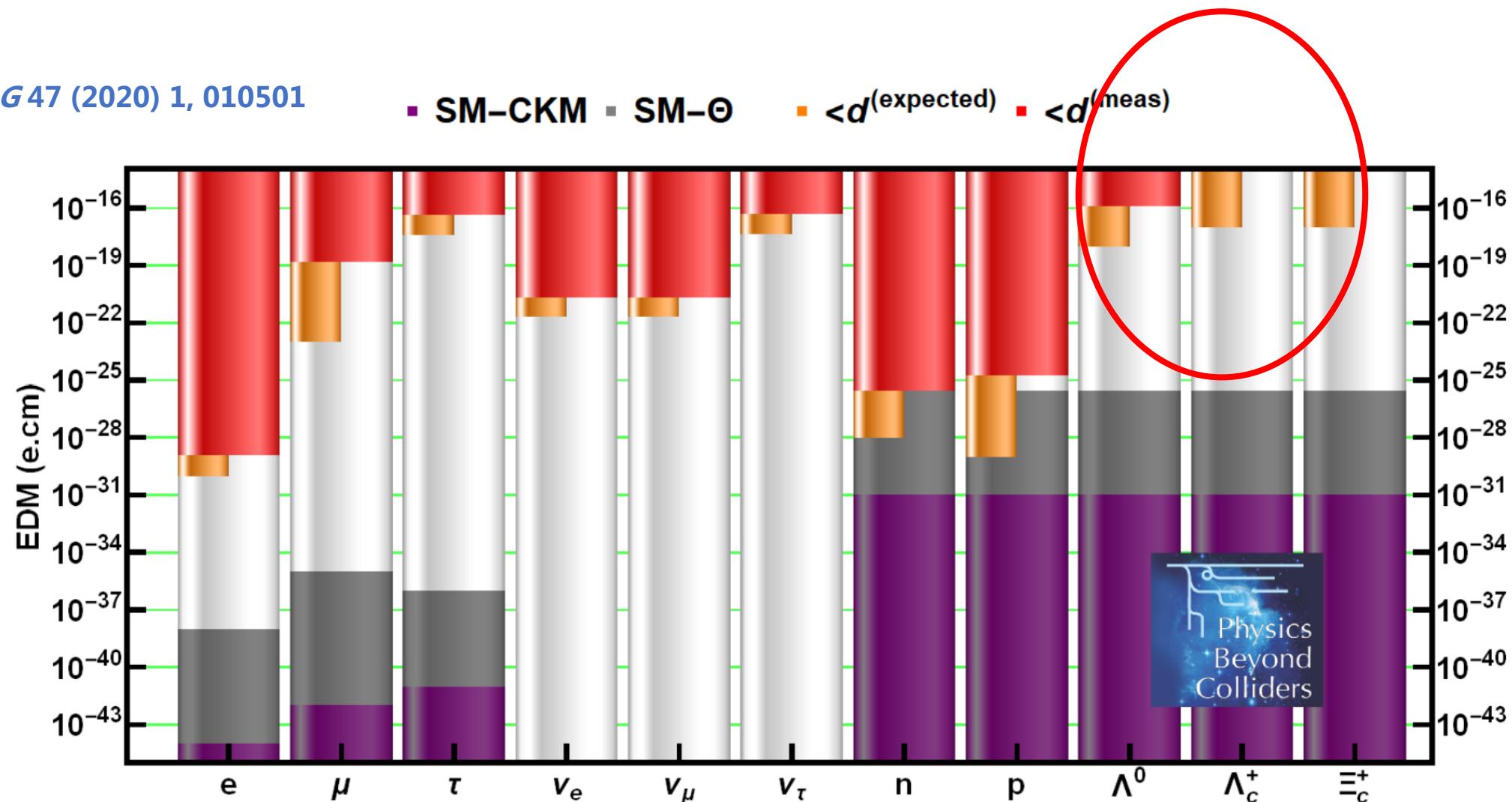
SM estimates from CKM

EDM Status

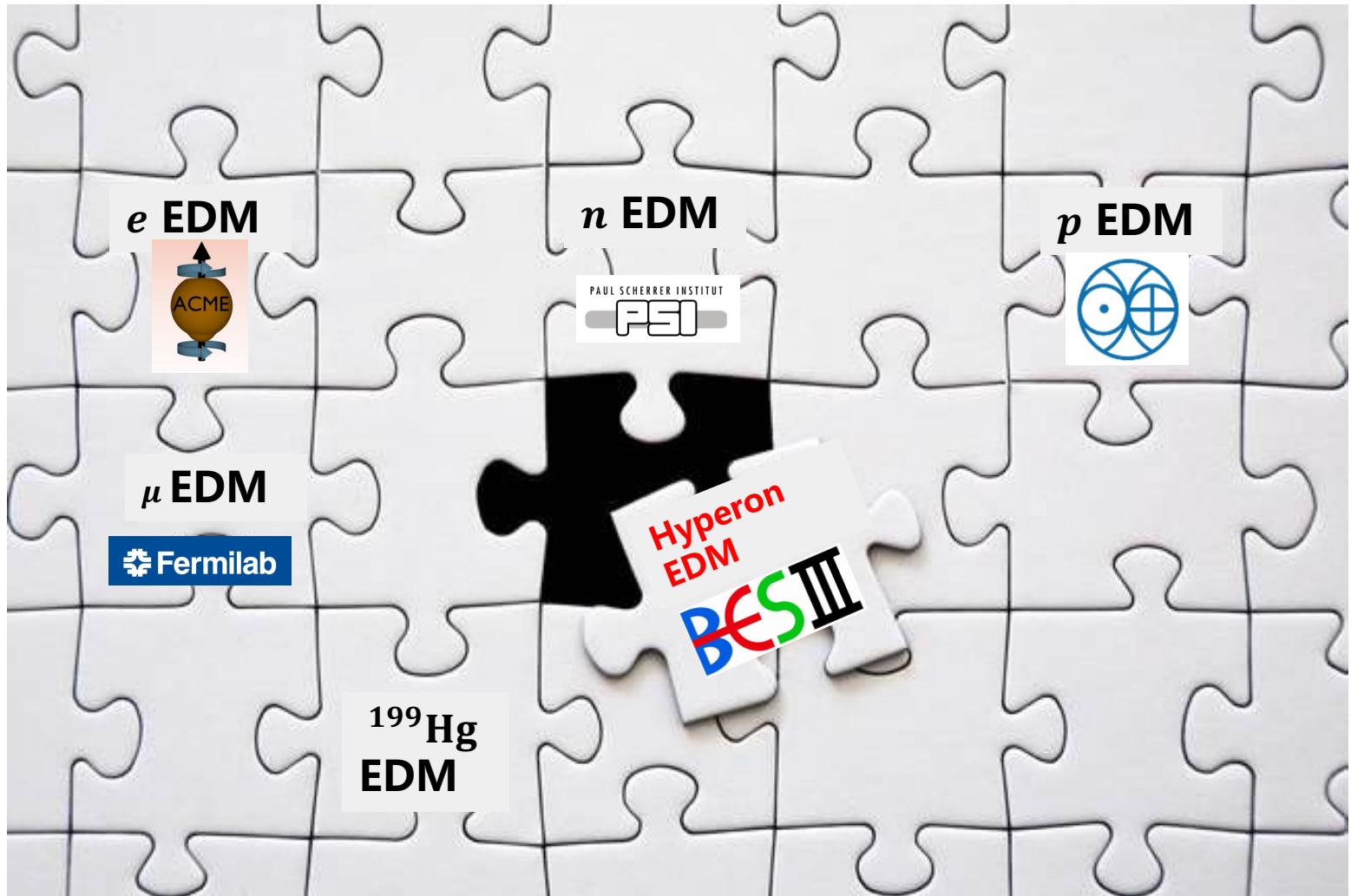
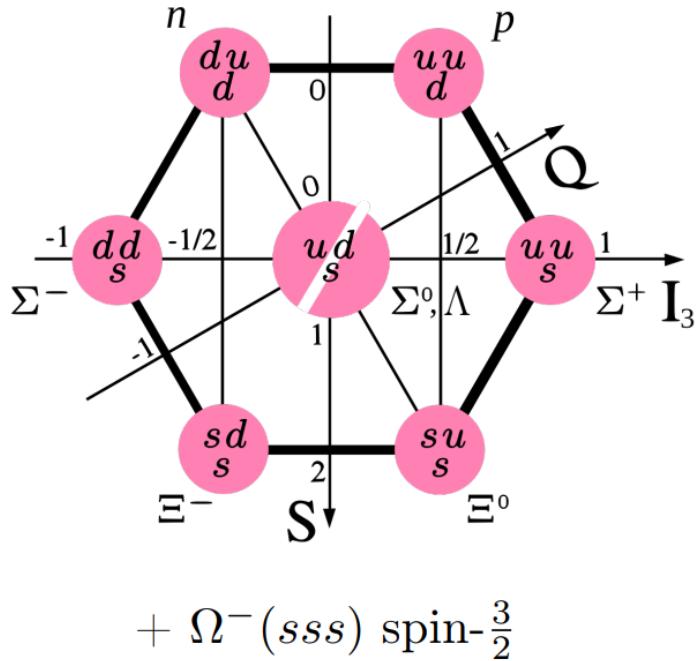
Only Λ hyperon has been measured
with a large uncertainty!

J.Phys.G 47 (2020) 1, 010501

■ SM-CKM ■ SM- Θ ■ $\langle d \rangle^{(\text{expected})}$ ■ $\langle d \rangle^{(\text{meas})}$



What can BESIII do for EDM?



Prob hyperon EDM at BESIII and STCF



BESIII and STCF : a hyperon factory

10 billion J/ψ events collected at BESIII:

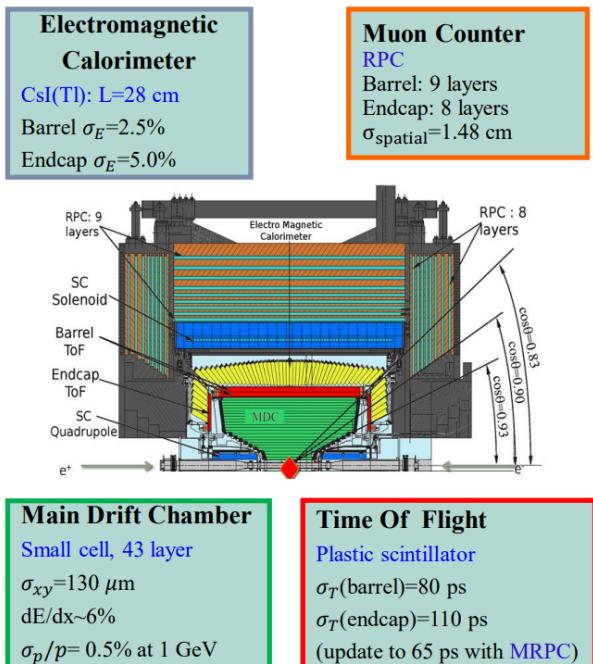
- Large Br. in J/ψ decay
- Quantum entangled pair productions
- High efficiency, background free

Decay	$\mathcal{B} (10^{-5})$	Events at BESIII
$J/\psi \rightarrow \Lambda\bar{\Lambda}$	189 ± 9	18.9×10^6
$J/\psi \rightarrow \Sigma^+\bar{\Sigma}^-$	150 ± 24	15.0×10^6
$J/\psi \rightarrow \Xi\bar{\Xi}$	97 ± 8	9.7×10^6
$\psi(2S) \rightarrow \Sigma\bar{\Sigma}$	23.2 ± 1.2	116×10^3
$\psi(2S) \rightarrow \Omega\bar{\Omega}$	5.66 ± 0.30	28×10^3

Front. Phys. 12(5), 121301

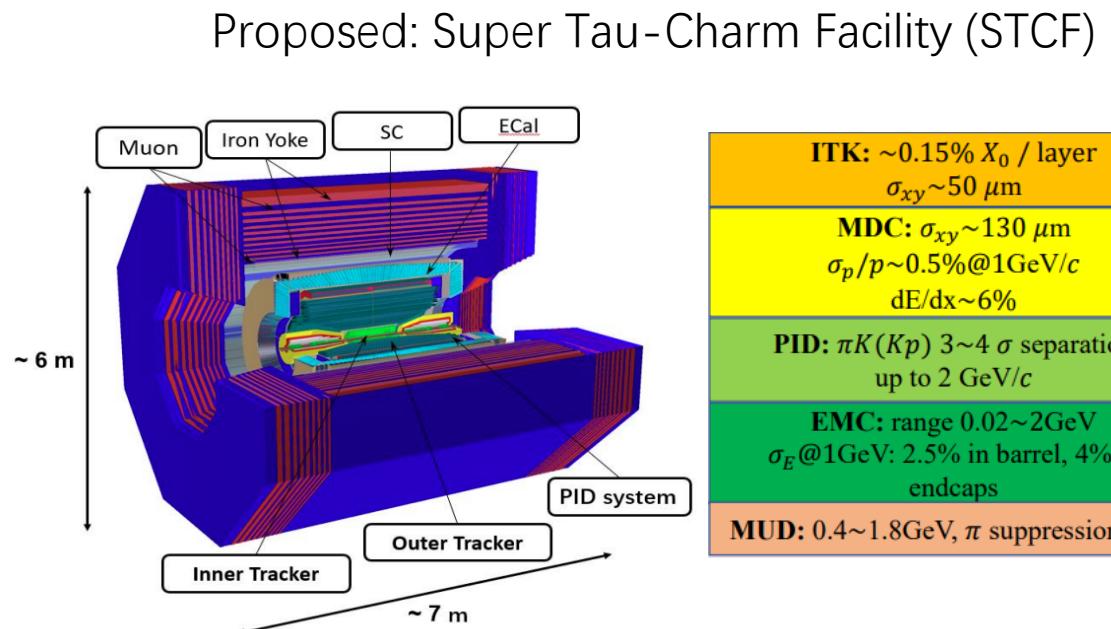
(2017)

Phys. Rev. D 100, 114005 (2019)



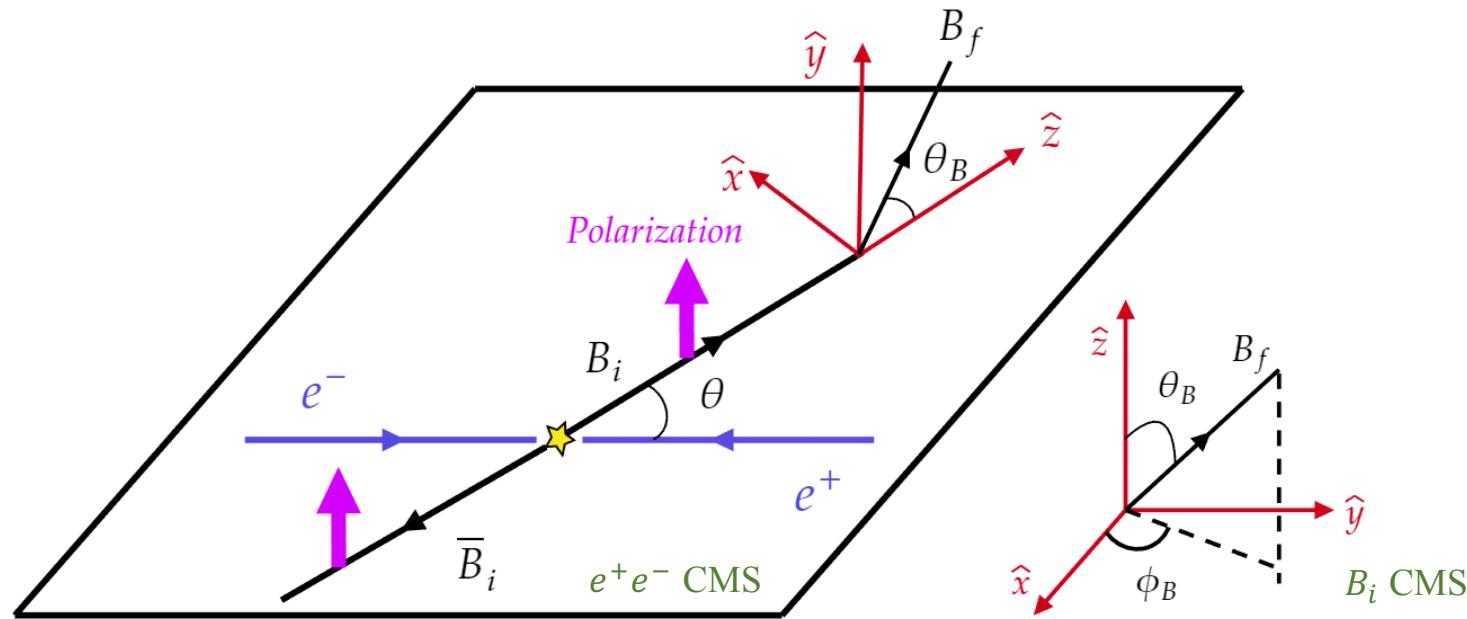
With 10 billion J/ψ collected at BESIII and $\sim 10^7$ entangled hyperon pairs can be studied.

At future, the STCF will collect 1 trillion J/ψ per year, and will provide $\sim 10^9$ hyperon pairs.



BESIII Detector

Polarized hyperon pairs produced in e^+e^- collisions



Two form factors are used to describe the production of hyperon pair: G_1, G_2 , which also known as $G_M = \frac{G_1}{e_g}$, $G_E = \frac{G_2}{e_g}$

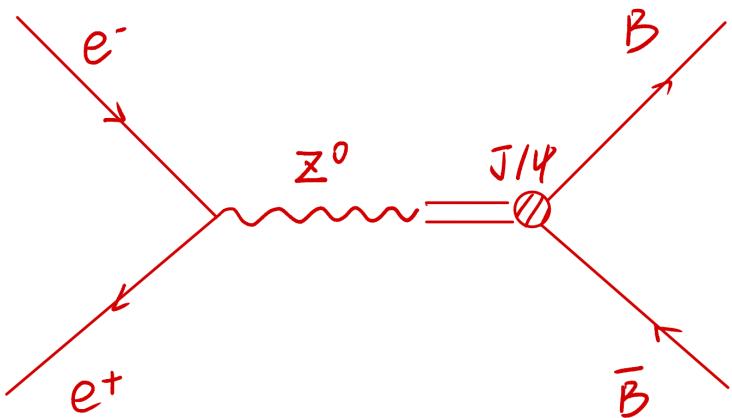
$$\alpha_\psi = \frac{s^2|G_1|^2 - 4m^2|G_2|^2}{s^2|G_1|^2 + 4m^2|G_2|^2}, \quad \frac{G_1}{G_2} = \left| \frac{G_1}{G_2} \right| e^{-i\Delta\Phi}$$

Polarization:

$$P_y(\cos\theta) = \frac{\sqrt{1-\alpha_\psi^2} \cos\theta \sin\theta}{1+\alpha_\psi \cos^2\theta} \sin(\Delta\Phi)$$

- Angular distribution of $\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta$, $\alpha_\psi \in [-1.0, 1.0]$
- If $\Delta\Phi \neq 0$, the hyperon will have transverse polarization even e^+e^- beams are unpolarized.

Polarization of J/ψ



No beam polarization :

$$P_L = \frac{\rho_{++} - \rho_{--}}{\rho_{++} + \rho_{--}}$$

Considering Z^0 contribution:
 J/ψ has longitude polarization:
denoted by P_L

$\rho_{mm'}$: J/ψ spin density matrix

$$P_L = \mathcal{A}_{LR}^0 = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{-\sin^2 \theta_W^{\text{eff}} + 3/8}{2 \sin^2 \theta_W^{\text{eff}} \cos^2 \theta_W^{\text{eff}}} \frac{M_{J/\psi}^2}{m_Z^2}$$

With beam polarization :

$$\xi = \frac{\sigma_R(1 + P_e)/2 - \sigma_L(1 - P_e)/2}{\sigma_R(1 + P_e)/2 + \sigma_L(1 - P_e)/2} = \frac{\mathcal{A}_{LR}^0 + P_e}{1 + P_e \mathcal{A}_{LR}^0} \approx P_e$$

Can be used for precise measurement beam polarization

Spin density matrix of hyperon-antihyperon

Polarization effects encoded in hyperon pair spin density matrix

$$R(\lambda_1, \lambda_2; \lambda'_1, \lambda'_2) \propto \sum_{m,m'} \rho_{m,m'} d_{m,\lambda_1-\lambda_2}^{j=1}(\theta) d_{m',\lambda'_1-\lambda'_2}^{j=1}(\theta) \\ \times \mathcal{M}_{\lambda_1, \lambda_2} \mathcal{M}_{\lambda'_1, \lambda'_2}^* \delta_{m,m'},$$

| Lorentz invariance introduces P and CP violation form factors in helicity amplitude

$$\mathcal{M}_{\lambda_1, \lambda_2} = \epsilon_\mu (\lambda_1 - \lambda_2) \bar{u}(\lambda_1, p_1) (F_V \gamma^\mu + \frac{i}{2M_\Lambda} \sigma^{\mu\nu} q_\nu H_\sigma \\ + \gamma^\mu \gamma^5 F_A + \sigma^{\mu\nu} \gamma^5 q_\nu H_T) v(\lambda_2, p_2).$$

X.G.He, J.P. Ma, Bruce McKellar,
Phys.Rev.D47(1993)1744

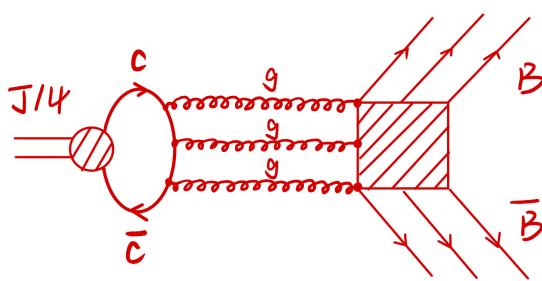
X.G.He, J.P. Ma,
Phys.Lett.B 839(2023)137834

Dynamics in $J/\psi \rightarrow B\bar{B}$

Detailed dynamics in J/ψ decay to Λ pair, have been studied:

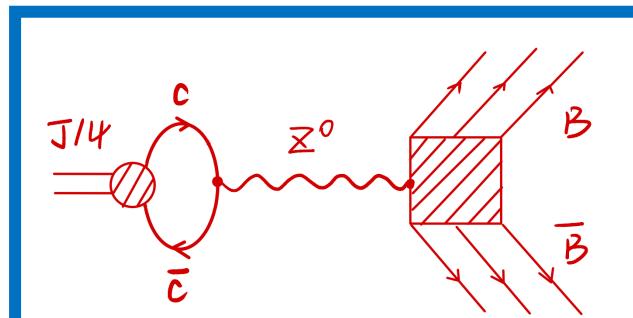
X.G.He, J.P. Ma, Phys.Lett.B 839(2023)137834

$$\mathcal{A} = \epsilon_\mu(\lambda)\bar{u}(\lambda_1) \left(\mathbf{F}_V \gamma^\mu + \frac{i}{2M_\Lambda} \sigma^{\mu\nu} q_\nu \mathbf{H}_\sigma + \gamma^\mu \gamma^5 \mathbf{F}_A + \sigma^{\mu\nu} \gamma^5 q_\nu \mathbf{H}_T \right) v(\lambda_2)$$

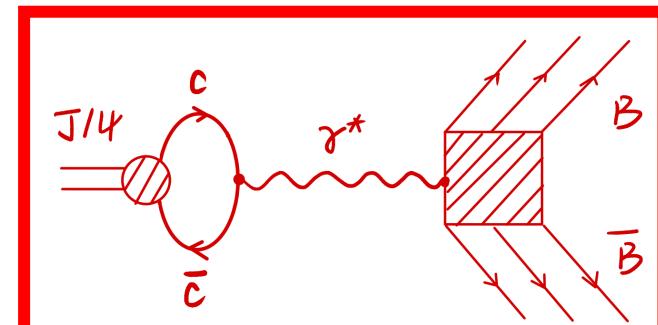


Dominant contribution
[arXiv:hep-ph/0412158](https://arxiv.org/abs/hep-ph/0412158)

Psionic form factor
 \mathbf{F}_V and \mathbf{H}_σ
 can also be represented
 as \mathbf{G}_1 and \mathbf{G}_2



P violation term
 Complex form factor, $F_A \neq 0$ indicate P violation



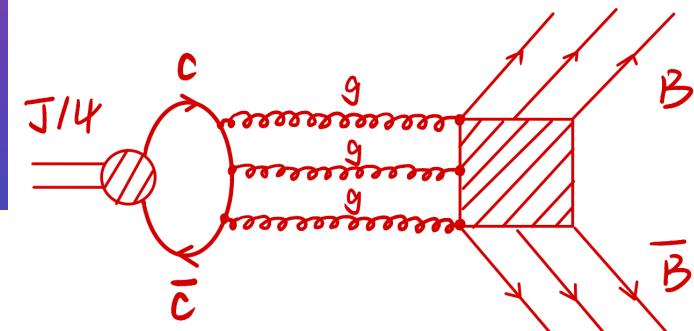
\mathbf{H}_T is included in this term

$$H_T(q^2) = \frac{2e}{3m_{J/\psi}^2} g_V d_B(q^2)$$

Assuming $d_B(q^2) \equiv d_B(0)$

$d_B(q^2)$: electric dipole form factor
 $d_B(0)$: electric dipole moment
[Physics Letters B 551 \(2003\) 16–26](https://doi.org/10.1016/j.physlettb.2003.09.045)

Psionic form factors G_1, G_2



Psionic form factors

$$F_V = G_1 - \frac{4M^2}{Q^2}(G_1 - G_2)$$

$$H_\sigma = \frac{4M^2}{Q^2}(G_1 - G_2)$$

Hyperon polarization parameters

$$\alpha_{J/\psi} = \frac{s \left| G_1 \right|^2 - 4m^2 \left| G_2 \right|^2}{s \left| G_1 \right|^2 + 4m^2 \left| G_2 \right|^2}$$

$$\frac{G_1}{G_2} = \left| \frac{G_1}{G_2} \right| e^{-i\Delta\Phi}$$

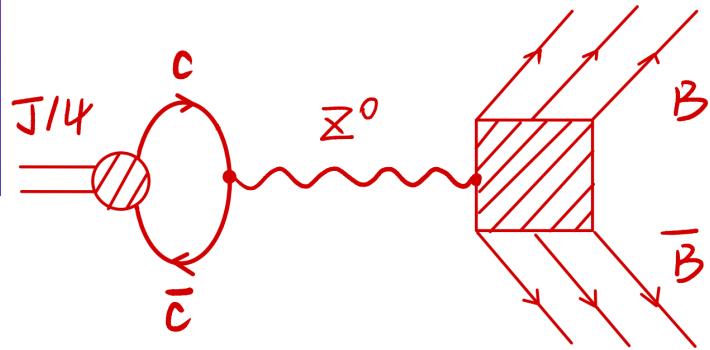
X.G.He, J.P. Ma, Bruce McKellar,
Phys.Rev.D47(1993)1744

X.G.He, J.P. Ma,
Phys.Lett.B 839(2023)137834

Göran Fäldt, Andrzej Kupsc
Physics Letters B 772 (2017) 16–20

| G_1 can be extracted from the measurement of $\Gamma(J/\psi \rightarrow B\bar{B})$

P violation form factor F_A



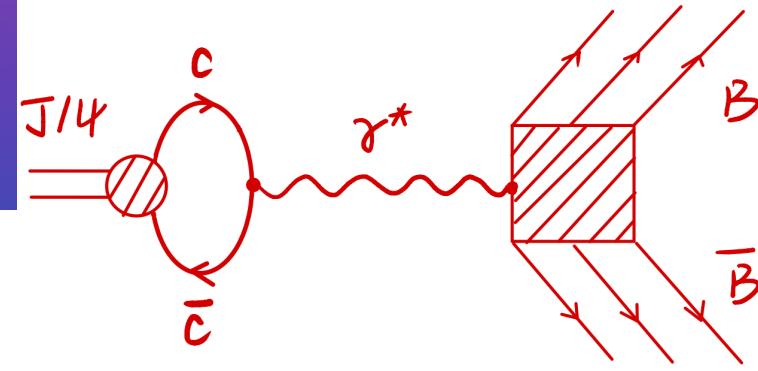
Primarily from Z-boson exchange between $c\bar{c}$ and light quark pairs

Related to weak mixing angle in SM

$$F_A \approx -\frac{1}{6} D g_V \frac{g^2}{4 \cos^2 \theta_W^{\text{eff}}} \frac{1 - 8 \sin^2 \theta_W^{\text{eff}}/3}{m_Z^2} \approx -1.07 \times 10^{-6}$$

X.G.He, J.P. Ma,
Phys.Lett.B 839(2023)137834

CP violation form factor H_T



Several CPV sources contributed to H_T

Take hyperon EDM as the major source for H_T

$$H_T = \frac{2e}{3M_{J/\psi}^2} g_V d_B \quad (q = M_{J/\psi})$$

Neglect q dependence, d_B for hyperon EDM

X.G.He, J.P. Ma, Bruce McKellar,
Phys.Rev.D47(1993)1744

X.G.He, J.P. Ma,
Phys.Lett.B 839(2023)137834

Full angular helicity amplitude of $e^+e^- \rightarrow J/\psi \rightarrow B\bar{B}$

Angular formular based on helicity amplitude are developed:

Jinlin Fu, Hai-Bo Li, Jianpeng Wang, Fusheng Yu,
and Jianyu Zhang, arxiv: 2307.04364

$$R(\lambda_1, \lambda_2; \lambda'_1, \lambda'_2) \propto \sum_{m,m'} \rho_{m,m'} d_{m,\lambda_1-\lambda_2}^{j=1}(\theta) d_{m',\lambda'_1-\lambda'_2}^{j=1}(\theta) \mathcal{M}_{\lambda_1, \lambda_2} \mathcal{M}_{\lambda'_1, \lambda'_2}^* \delta_{m,m'}$$

Total angular distribution of J/ψ to spin-1/2 baryon pair:

➤ $J/\psi \rightarrow B\bar{B}, B = \Lambda^0, \Sigma^-, \Sigma^+$

$$\frac{d\sigma}{d\Omega_k d\Omega_p d\Omega_{\bar{p}}} = N \sum_{[\lambda]} \textcolor{red}{R(\lambda_1, \lambda_2; \lambda'_1, \lambda'_2)} D_{\lambda_1, \lambda_p}^{j=1/2}(\theta_1, \phi_1) D_{\lambda'_1, \lambda_p}^{*j=1/2}(\theta_1, \phi_1) |h_{\lambda_p}|^2 D_{\lambda_2, \lambda_{\bar{p}}}^{j=1/2}(\theta_2, \phi_2) D_{\lambda'_2, \lambda_{\bar{p}}}^{*j=1/2}(\theta_2, \phi_2) |h_{\lambda_{\bar{p}}}|^2$$

➤ $J/\psi \rightarrow B\bar{B}, B = \Xi^0, \Xi^-$

$$\begin{aligned} \frac{d\sigma}{d\Omega_k d\Omega_\Lambda d\Omega_{\bar{\Lambda}} d\Omega_p d\Omega_{\bar{p}}} &= N \sum_{[\lambda]} \textcolor{red}{R(\lambda_1, \lambda_2; \lambda'_1, \lambda'_2)} D_{\lambda_1, \lambda_\Lambda}^{*j=1/2}(\theta_1, \phi_1) D_{\lambda'_1, \lambda'_\Lambda}^{j=1/2}(\theta_1, \phi_1) \mathcal{H}_{\lambda_\Lambda} \mathcal{H}_{\lambda'_\Lambda}^* D_{\lambda_2, \lambda_{\bar{\Lambda}}}^{*j=1/2}(\theta_2, \phi_2) \\ &\quad D_{\lambda'_2, \lambda'_{\bar{\Lambda}}}^{j=1/2}(\theta_2, \phi_2) \mathcal{H}_{\lambda_{\bar{\Lambda}}} \mathcal{H}_{\lambda'_{\bar{\Lambda}}}^* D_{\lambda_\Lambda, \lambda_p}^{*j=1/2}(\theta_3, \phi_3) D_{\lambda'_\Lambda, \lambda_p}^{j=1/2}(\theta_3, \phi_3) |h_{\lambda_p}|^2 D_{\lambda_{\bar{\Lambda}}, \lambda_{\bar{p}}}^{*j=1/2}(\theta_4, \phi_4) D_{\lambda'_{\bar{\Lambda}}, \lambda_{\bar{p}}}^{j=1/2}(\theta_4, \phi_4) |h_{\lambda_{\bar{p}}}|^2 \end{aligned}$$



Sensitivity study of BESII and STCF

Sensitivity study of BESIII and STCF

Sensitivity assessed from 500 psudoexperiments generated and fitted by using a probability density function based on the full angular distribution

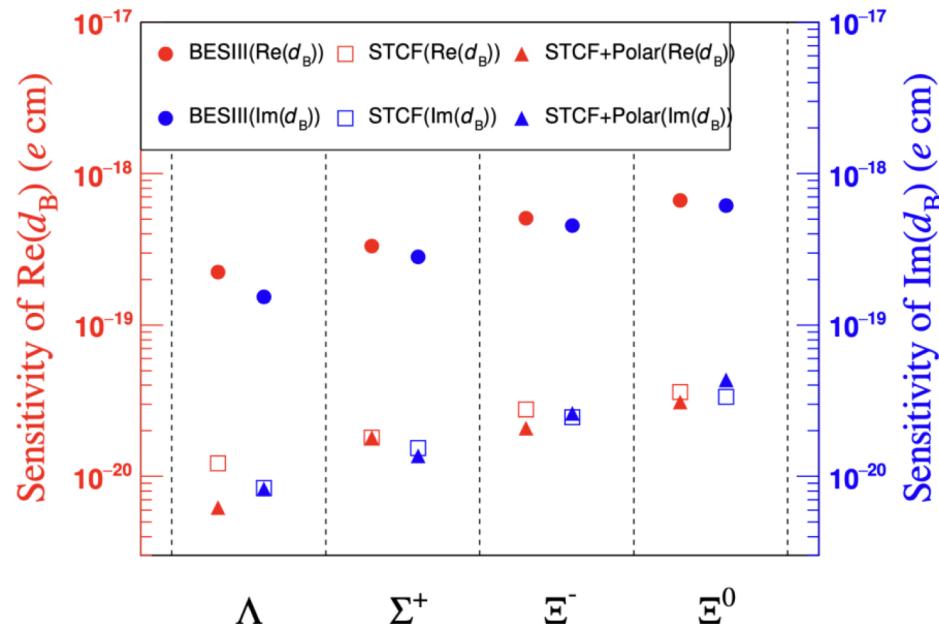
Expected yields, Form Factors and decay parameters are fixed to known values for generation: G_1 , $\alpha_{J/\psi}$, $\Delta\Phi$, F_A , H_T , α_B , $\alpha_{\bar{B}}$, ϕ_B and $\phi_{\bar{B}}$

| $P_L \sim 10^{-4}$ (80%) for unpolarized (longitudinally polarized) electron beam

Decay Channel	$J/\psi \rightarrow \Lambda\Lambda$	$J/\psi \rightarrow \Sigma^+\Sigma^-$	$J/\psi \rightarrow \Xi^-\Xi^+$	$J/\psi \rightarrow \Xi^0\Xi^0$
$B_{tag}/(\times 10^{-4})$ [29]	7.77	2.78	3.98	4.65
$\epsilon_{tag}/\%$ [22, 28, 30, 31]	40	25	15	7
$N_{tag}^{evt}/(\times 10^5)$ (BESIII)	31.3	7.0	6.0	3.3
$N_{tag}^{evt}/(\times 10^8)$ (STCF) [17]	10.6	2.4	2.0	1.1

Sensitivity of hyperon EDM measurements

reminder: $H_T = \frac{2e}{3M_{J/\psi}^2} g_V d_B$



(a) Sensitivity of $\text{Re}(d_B)$ and $\text{Im}(d_B)$

SM: $\sim 10^{-26} \text{ e cm}$

BESIII: milestone for hyperon EDM measurement
 $\Lambda 10^{-19} \text{ e cm}$ (FermiLab)
 10^{-16} e cm)
first achievement for Σ^+ , Ξ^- and Ξ^0 at level of 10^{-19} e cm
a litmus test for new physics

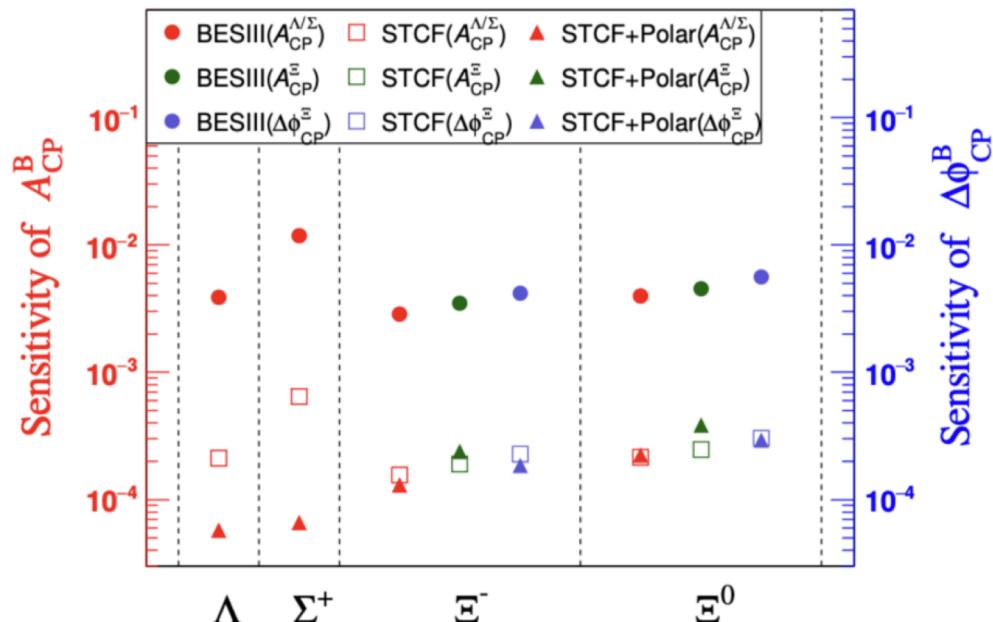
STCF: improved by 2 order of magnitude

Sensitivity of CP violation in hyperon decay

reminder:

$$A_{CP}^B = (\alpha_B + \bar{\alpha}_B) / (\alpha_B - \bar{\alpha}_B)$$

$$\Delta\phi_{CP}^B = (\phi_B + \bar{\phi}_B) / 2$$



(b) Sensitivity of A_{CP}^B and $\Delta\phi_{CP}^B$

N.G.Deshpande et al, PLB326(1994)307

J.Tandean et al, PRD67(2003)056001

J.F.Donoghue et al, PRD34(1986)833

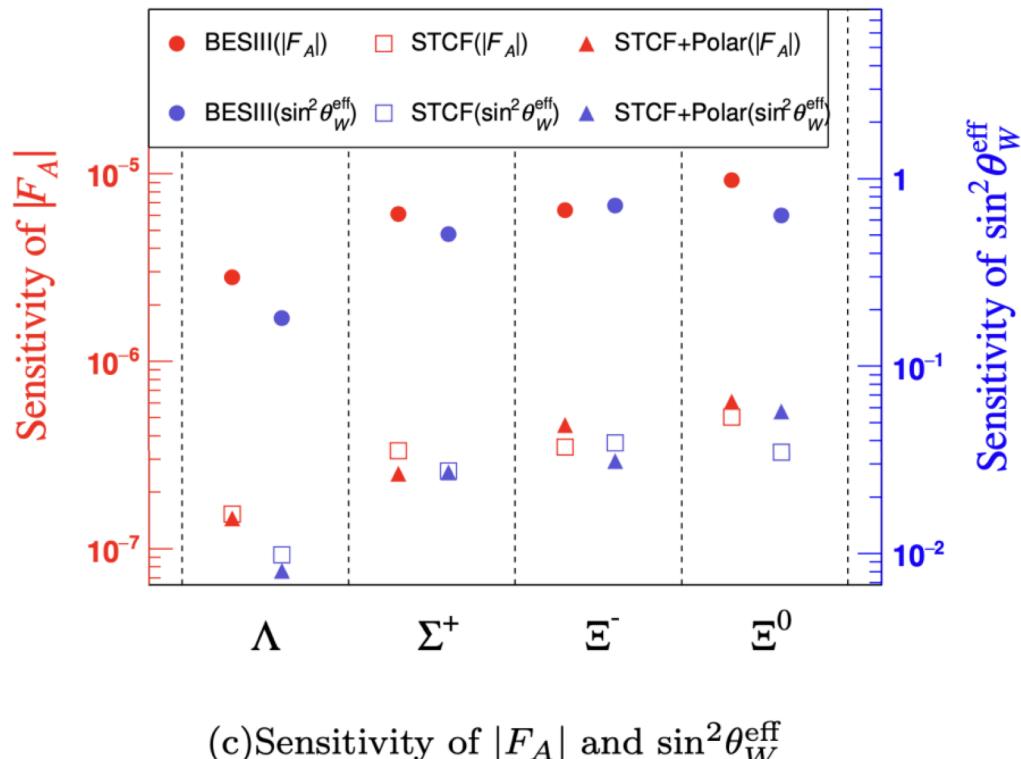
SM: $10^{-4} \sim 10^{-5}$

STCF:

SM prediction can be reached
and further improved with a
longitudinally polarized
electron beam

Sensitivity of F_A and $\sin^2 \theta_W^{\text{eff}}$ measurements

reminder: $F_A \approx -\frac{1}{6} D g_V \frac{g^2}{4 \cos^2 \theta_W^{\text{eff}}} \frac{1 - 8 \sin^2 \theta_W^{\text{eff}}/3}{m_Z^2}$

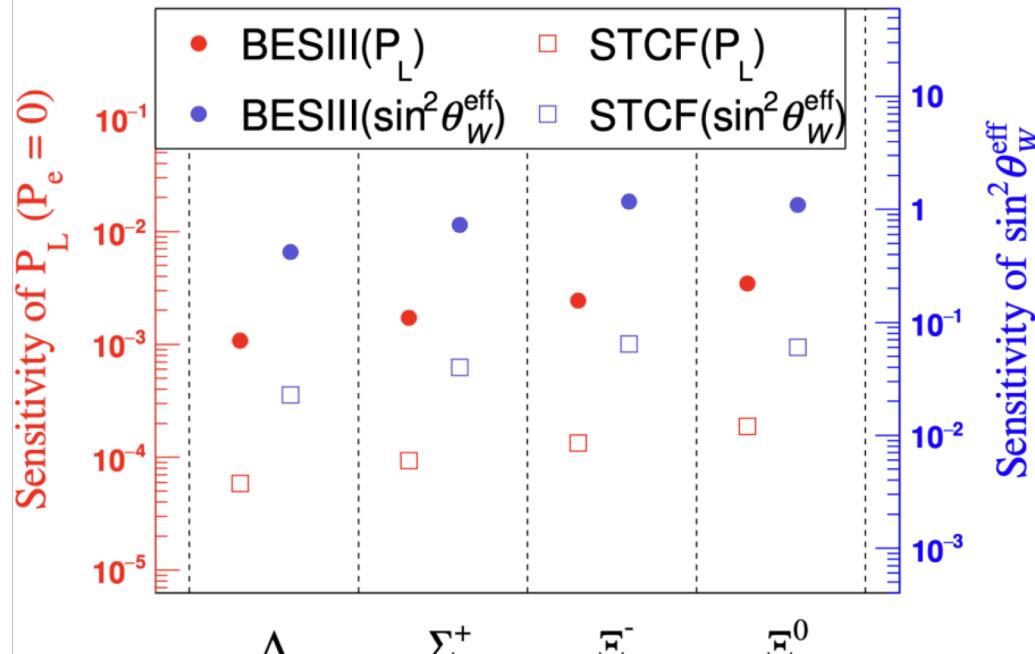


SM: $F_A \sim 10^{-6}$
 $\sin^2 \theta_W^{\text{eff}} \sim 0.235$

STCF:
Weak mixing angle at $Q = M_{J/\psi}$
can be determined at the level
of 8×10^{-3}

Sensitivity of P_L and $\sin^2 \theta_W^{\text{eff}}$ measurements

reminder: $P_L = \mathcal{A}_{LR}^0 = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{-\sin^2 \theta_W^{\text{eff}} + 3/8}{2 \sin^2 \theta_W^{\text{eff}} \cos^2 \theta_W^{\text{eff}}} \frac{M_{J/\psi}^2}{m_Z^2}$

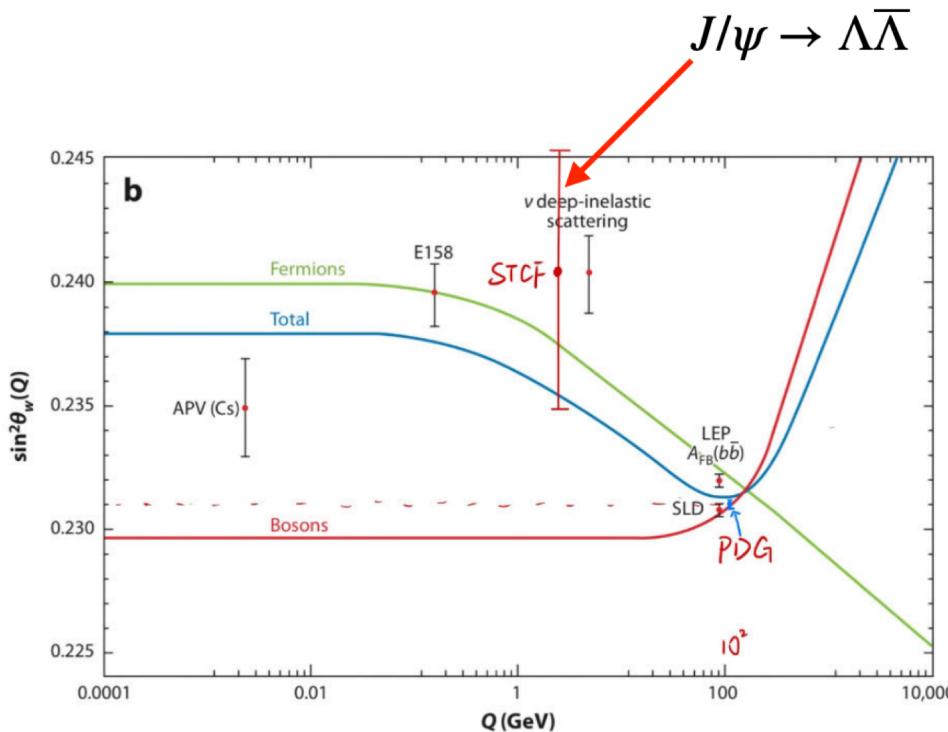


(d)Sensitivity of P_L

SM: $P_L \sim 10^{-4}$
 $\sin^2 \theta_W^{\text{eff}} \sim 0.235$

STCF:
Weak mixing angle at $Q = M_{J/\psi}$
can be determined at the level
of 2×10^{-2}

Sensitivity of $\sin^2 \theta_W^{\text{eff}}$ by simultaneous fit



Weak mixing angle shared by F_A and P_L

Sensitivity improved at the level 5×10^{-3}

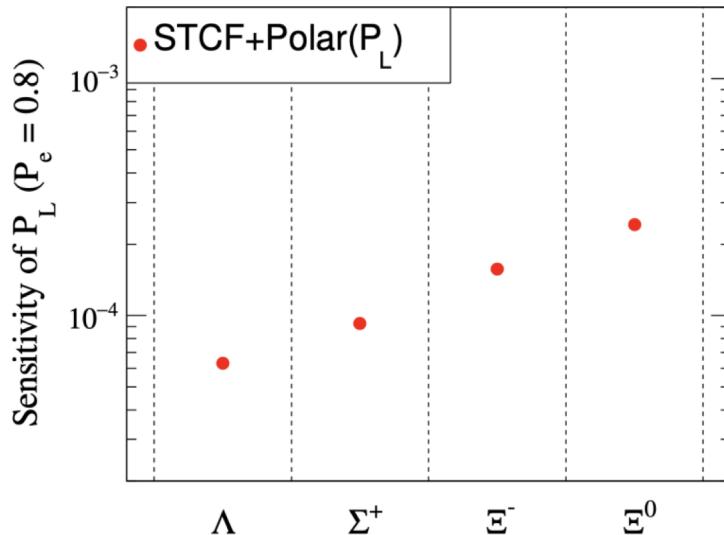
Figure 1

(a) $\sin^2 \theta_W(\mu_{\overline{\text{MS}}})$ (29) with an updated atomic parity violation (APV) result. (b) $\sin^2 \theta_W(Q^2)$, a one-loop calculation dominated by $\gamma - Z^0$ mixing (52). The red and green curves represent the boson and fermion contributions, respectively.

Sensitivity of beam polarization measurements

Precisely measured beam polarization (10^{-5}) as input value for $\sin^2 \theta_W^{\text{eff}}$ measurement

A. Bondar et al, JHEP 03 (2020) 076



$$\mathcal{A}_{\text{LR}} \equiv \frac{\sigma_{\mathcal{P}_e} - \sigma_{-\mathcal{P}_e}}{\sigma_{\mathcal{P}_e} + \sigma_{-\mathcal{P}_e}} = \mathcal{A}_{\text{LR}}^0 \boxed{\mathcal{P}_e}$$

$$\sigma_{\mathcal{P}_e} = \frac{N_{\mathcal{P}_e}}{\mathcal{L}_{\mathcal{P}_e} \varepsilon_{\text{eff}}}$$
$$\sigma_{-\mathcal{P}_e} = \frac{N_{-\mathcal{P}_e}}{\mathcal{L}_{-\mathcal{P}_e} \varepsilon_{\text{eff}}}$$

analysis Bhabha scattering events

$$\mathcal{A}_{\text{LR}}^0 = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{-\sin^2 \theta_W^{\text{eff}} + 3/8}{2 \sin^2 \theta_W^{\text{eff}} \cos^2 \theta_W^{\text{eff}}} \frac{M_{J/\psi}^2}{m_Z^2}$$

Summary and Outlooks

- To measure EDM, we developed a set of helicity amplitude formulas describing the J/ψ decay to $\Lambda, \Sigma, \Xi, \Omega$ pairs
- Pseudo experiments are performed and the sensitivity of the hyperon EDM
 - The prospect sensitivity of Λ EDM at BESIII is 1000 times higher than the world's best measurement under the same statistical condition.
 - BESIII has the opportunity of first measurements of the EDM of Σ^+, Ξ^-, Ξ^0 hyperons , and the sensitivity are at the order of 10^{-19} (BESIII) and 10^{-20} (STCF).



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