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Opportunities to Search for New Physics in Charm Sector at Low-Energy Accelerators

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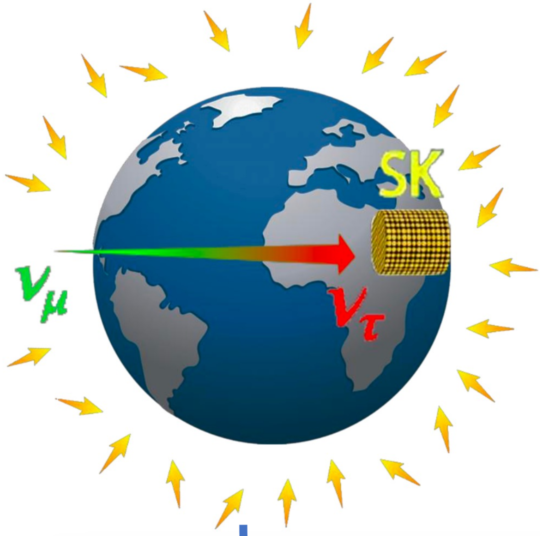
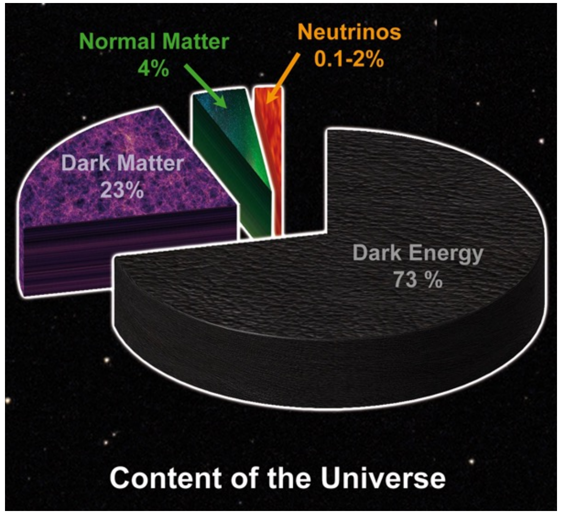
第六届重味物理与量子色动力学研讨会
2024/4/22, 青岛

Why we need New Physics?

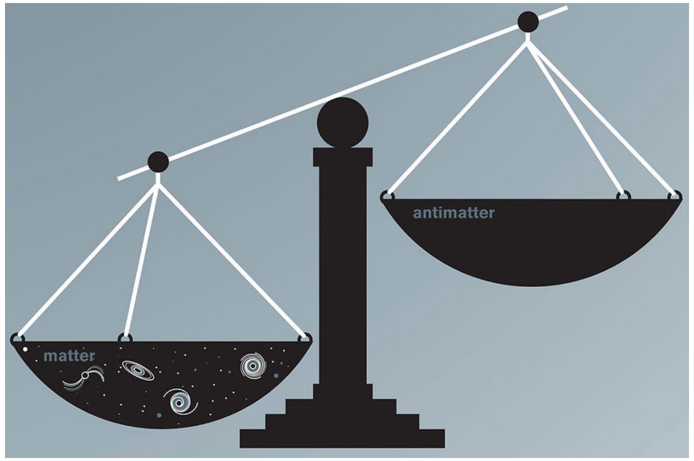
Neutrino oscillation



Dark matter

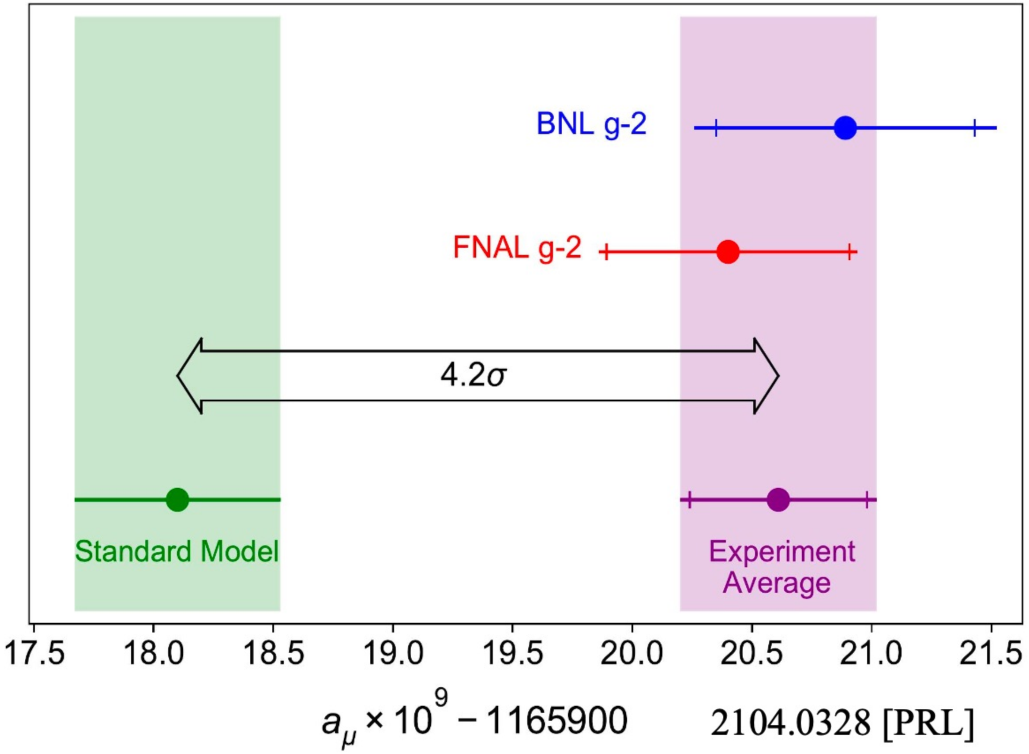


BAU



Call for New Physics beyond the SM

Hint of New Physics



2104.0328 [PRL]

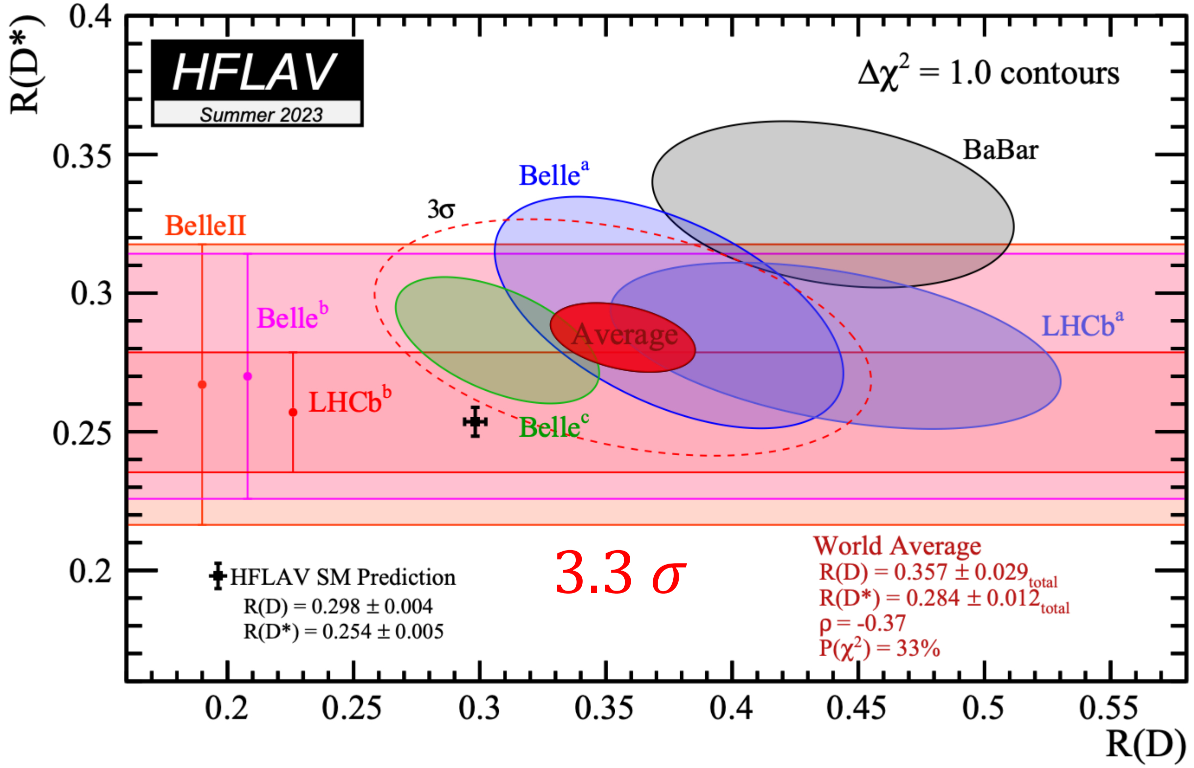
$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.51 \pm 0.59) \times 10^{-9}$$

4.2 σ

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = -(8.7 \pm 3.6) \times 10^{-13}$$

2.4 σ

B physics



3.3 σ

LHCb[a]: 2302.02886 [PRL]
LHCb[b]: 2305.01463 [PRD]
Belle II: Lepton Photon's talk 2023

Search for NP in charm sector?

FCNC in charm sector

In SM, the flavor-changing neutral-current (FCNC) transitions

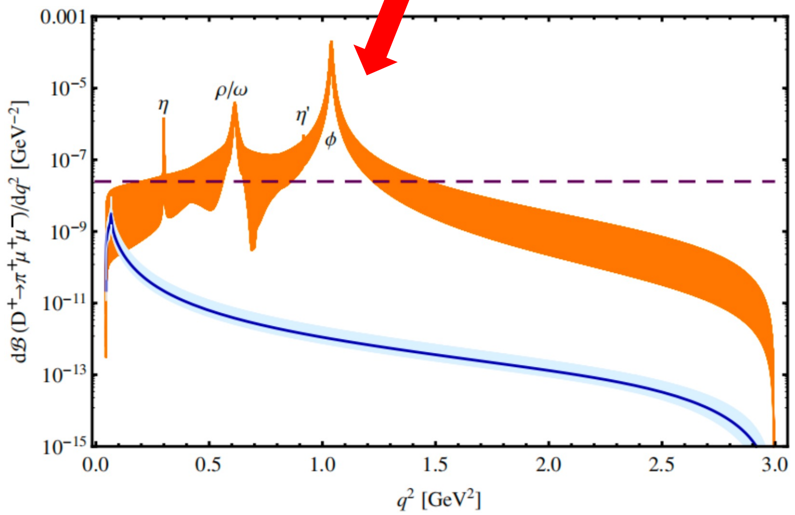
- **absent at the tree level**
- **Strongly GIM-suppressed in charm sector**

FCNC in charm sector:

- High-energy collider, e.g., $pp(q\bar{q}) \to \ell^+\ell^-$
  [J. Fuentes-Martin, 2003.12421]
- Rare weak decays
  - semileptonic decays, e.g., $D^+ \to \pi^+\mu^+\mu^-$
    [S. Boer 1510.00311]
  - leptonic decays, e.g., $D^0 \to \mu^+\mu^-$
    [S. Fajfer 1510.00965]
- **Low-energy ep scattering processes (NEW)**
  - unpolarized scattering processes ($e^-p \to e^-(\mu^-)\Lambda_c$)
  - polarized scattering processes ($e^-p \to e^-\Lambda_c$)

Li-Fen Lai, Xin-Qiang Li, **XY**, Ya-Dong Yang
2111.01463 [PRD], 2203.17104 [PRD]

Resonances problem



***e* beam, *p* target:**
polarized *e* beam, *p* target:

APEX: 1108.2750, Qweak: 1409.7100
COMPASS, hep-ex/0703049

Theoretical Framework

$$e^- p \to e^- \Lambda_c$$

$$e^- p \to \mu^- \Lambda_c$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{eff}}^{\text{SM}} + \mathcal{L}_{\text{eff}}^{\text{NP}}$$

$$\begin{aligned}
\mathcal{L}_{\text{eff}}^{\text{NP}} &= \sum g_{\alpha\beta} j_\alpha J_\beta \\
&= g_V^{LL}(\bar{\ell}_L \gamma_\mu \ell_L)(\bar{q}_L \gamma^\mu q_L) + g_V^{LR}(\bar{\ell}_L \gamma_\mu \ell_L)(\bar{q}_R \gamma^\mu q_R) \\
&+ g_V^{RL}(\bar{\ell}_R \gamma_\mu \ell_R)(\bar{q}_L \gamma^\mu q_L) + g_V^{RR}(\bar{\ell}_R \gamma_\mu \ell_R)(\bar{q}_R \gamma^\mu q_R) \\
&+ g_T^L(\bar{\ell}_R \sigma^{\mu\nu} \ell_L)(\bar{q}_R \sigma_{\mu\nu} q_L) + g_T^R(\bar{\ell}_L \sigma^{\mu\nu} \ell_R)(\bar{q}_L \sigma_{\mu\nu} q_R) \\
&+ g_S^L(\bar{\ell}_R \ell_L)(\bar{q}_R q_L) + g_S^R(\bar{\ell}_L \ell_R)(\bar{q}_L q_R)
\end{aligned}$$

Cross section and Kinematics

- **Fixed-target experiment** $e^-(k) + p(P) \to e^-(k') + \Lambda_c(P')$ **(LFC)**

Cross section

$$\sigma = \frac{1}{64\pi m_p^2 E^2} \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \, \overline{|\mathcal{M}|}^2$$

Amplitude

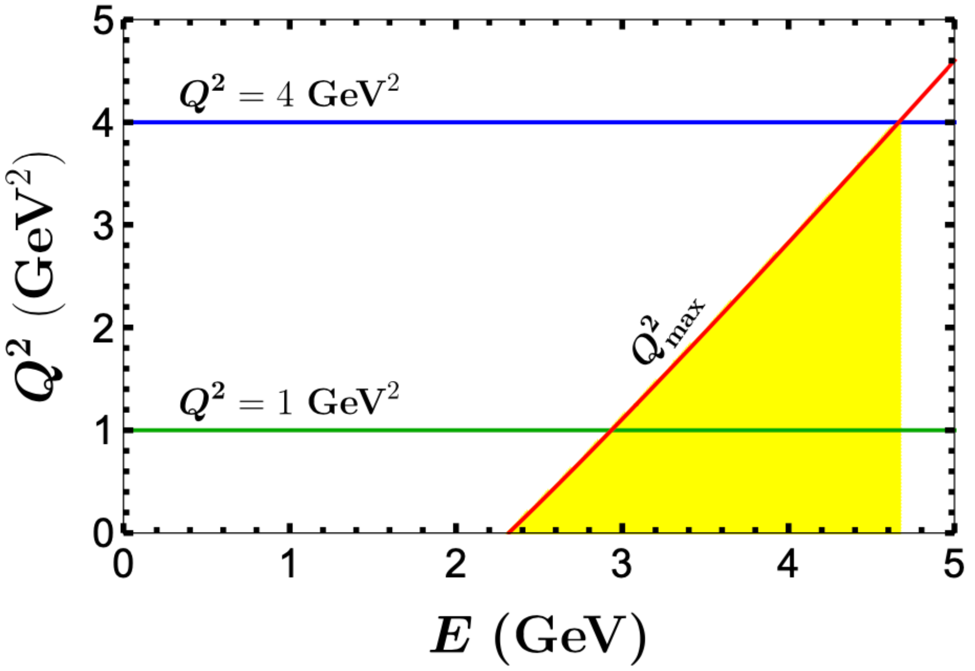
$$\mathcal{M} = \sum g_{\alpha\beta} \langle k' | j_\alpha | k \rangle \langle P', s' | J_\beta | P, s \rangle$$

- $\langle P', s' | J_\beta | P, s \rangle = \langle P, s | J^\dagger_\beta | P', s' \rangle^*$
- **parametrized by** $\Lambda_c \to p$ **from factors**
  ⇨ analytic!

Kinematics

❖ $q^2_{\text{max}} = 0, \; q^2_{\text{min}} = \frac{2E(M^2_{\Lambda_c} - m_p^2 - 2m_p E)}{m_p + 2E}$

⇨ $E \geq (M^2_{\Lambda_c} - m_p^2)/2m_p$ beam condition!



- $Q^2 = -q^2$
- focus on the lower Q^2 region, even though a high Q^2_{max} is available due to a high E

The desired experimental setup

- e^- beam: $E = 3$ GeV, $I = 150\ \mu$A [APEX, 1108.2750; R. Essig, 1001.2557]
- p target: liquid hydrogen, $L = 40$ cm, $\rho = 71.3 \times 10^{-3}$ g/cm^3 [Qweak, 1409.7100]

Model independent results (in units of $G_F^2 \alpha_e^2/\pi^2$)

LFC

Processes	$\lvert g_V^{LL,RR}\rvert^2$	$\lvert g_V^{LR,RL}\rvert^2$	$\lvert g_S^{L,R}\rvert^2$	$\lvert g_T^{L,R}\rvert^2$
$D^0 \to e^- e^+$ [1]	\	\	0.062	\
$D^+ \to \pi^+ e^- e^+$ [2]	14	14	6.3	13
$pp(q\bar{q}) \to e^- e^+$ [3]	3.6	3.6	22	0.57
$e^- p \to e^- \Lambda_c$	0.035	0.083	0.17	0.0056

[1] LHCb, 1512.00322; [2] BaBar, 1107.4465; [3] A. Angelescu, 2002.05684

We find

- **More competitive** constraints and a **further complementary** relation with $D^0 \to e^- e^+$
- Constraints on $g_V^{LL,RR}$ and $g_V^{LR,RL}$ are ***different*** compared with other processes

Same Exp Setup!

Model independent results (in units of $G_F^2 \alpha_e^2 / \pi^2$)

LFV

Processes	$\lvert g_V^{LL,RR} \rvert^2$	$\lvert g_V^{LR,RL} \rvert^2$	$\lvert g_S^{L,R} \rvert^2$	$\lvert g_T^{L,R} \rvert^2$
$D^0 \to e^- \mu^+$ [1]	\	\	0.010	\
$D^+ \to \pi^+ e^- \mu^+$ [2]	40	40	19	34
$pp(q\bar{q}) \to e^- \mu^+$ [3]	1.2	1.2	5.8	0.19
$e^- p \to \mu^- \Lambda_c$	0.039	0.091	0.18	0.0063

[1] LHCb, 1512.00322; [2] BaBar, 1107.4465; [3]A. Angelescu, 2002.05684

We find

- **More competitive** constraints and a **further complementary** relation with $D^0 \to e^- \mu^+$
- Constraints on $g_V^{LL,RR}$ and $g_V^{LR,RL}$ are ***different*** compared with other processes

Leptoquark model

What are the leptoquarks (LQs)?

- Convert a quark into a lepton and vice versa, e.g., $S_1 u_R e_R$
  $\Longrightarrow$ rich phenomenology
- 10 common LQs (without ν_R): 5 scalars and 5 vectors
- Predicted by many NP models, e.g., GUT

[I. Doršner, 1603.04993]

LQs can address:

LQ	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$(g-2)_\mu$
U_1	✔	✔	✔
V_2	✔	✔	✔
S_1	✘	✔	✔
S_3	✔	✘	✘
R_2	✘	✔	✔

[K. Ban 2104.06656; A. Angelescu 2103.12504; K. Cheung 2204.05942;...]

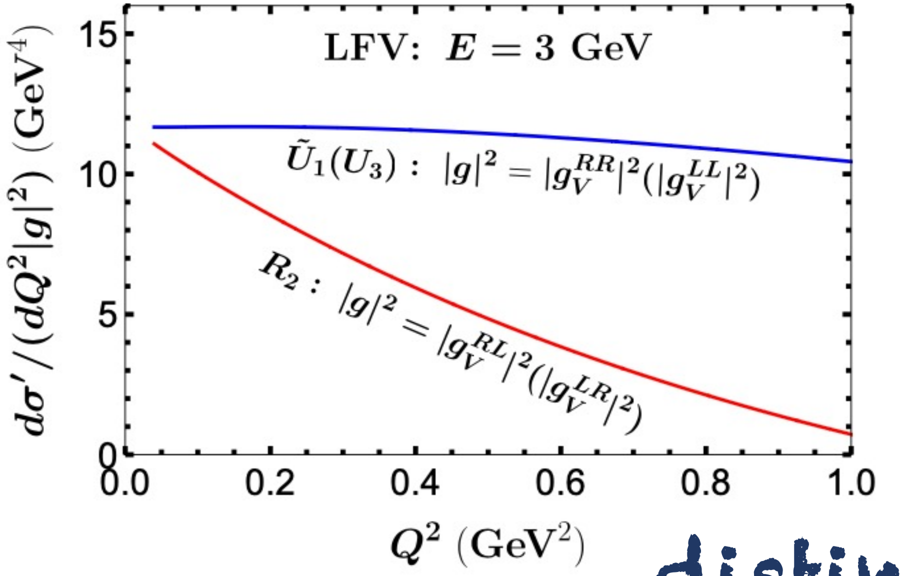
- Event rate forecast for LFV

LQs	g_V^{LL}	g_V^{RR}	$g_V^{LR,RL}$	$g_S^{L,R}$
R_2	\	\	13	0.039
U_3	31	\	\	\
$\tilde{U}_1$	\	31	\	\

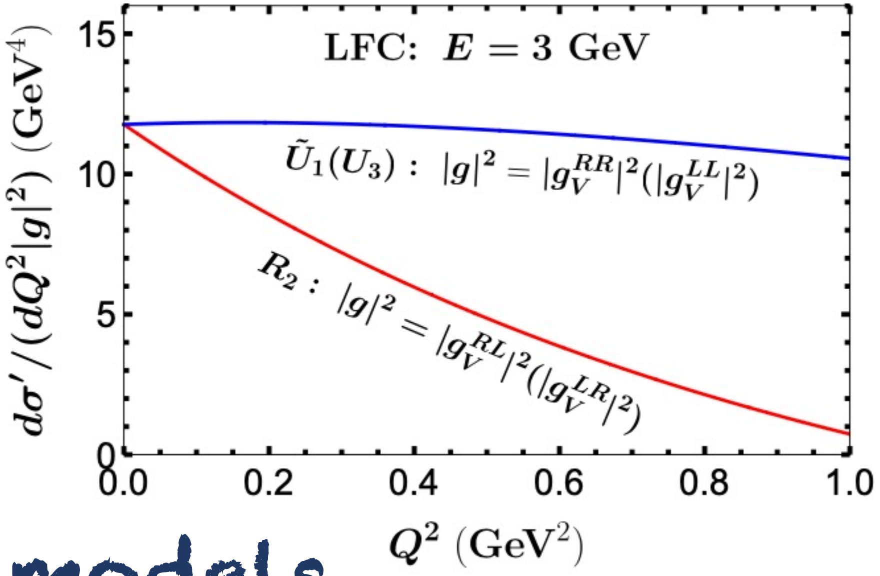
- Event rate forecast for LFC

LQs	g_V^{LL}	g_V^{RR}	$g_V^{LR,RL}$	$g_S^{L,R}$
R_2	\	\	43	0.25
U_3	103	\	\	\
$\tilde{U}_1$	\	103	\	\

☆ Differential cross section in the LFV case



☆ Differential cross section in the LFC case



distinguish models

Spin asymmetries

Li-Fen Lai, Xin-Qiang Li, **XY**, Ya-Dong Yang
2203.17104 [PRD]

- **Single-spin asymmetries**

$\vec{e}_L p \to e^- \Lambda_c$

$$A_L^e = \frac{\sigma_e^- - \sigma_e^+}{\sigma_e^- + \sigma_e^+}$$

$e^- \vec{p} \to e^- \Lambda_c$

$$A_L^p = \frac{\sigma_p^- - \sigma_p^+}{\sigma_p^- + \sigma_p^+}, \quad A_T^p = \frac{\tilde{\sigma}_p^- - \tilde{\sigma}_p^+}{\tilde{\sigma}_p^- + \tilde{\sigma}_p^+}$$

- **Double-spin asymmetries**

$\vec{e}_L \vec{p}_L \to e^- \Lambda_c$

$$A_{L1}^{ep} = \frac{\sigma^{--} - \sigma^{++}}{\sigma^{--} + \sigma^{++}}, \quad A_{L2}^{ep} = \frac{\sigma^{-+} - \sigma^{+-}}{\sigma^{-+} + \sigma^{+-}}$$

$$A_{L3}^{ep} = \frac{\sigma^{--} - \sigma^{-+}}{\sigma^{--} + \sigma^{-+}}, \quad A_{L4}^{ep} = \frac{\sigma^{--} - \sigma^{+-}}{\sigma^{--} + \sigma^{+-}}$$

$$A_{L5}^{ep} = \frac{\sigma^{++} - \sigma^{-+}}{\sigma^{++} + \sigma^{-+}}, \quad A_{L6}^{ep} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$\vec{e}_L \vec{p}_T \to e^- \Lambda_c$

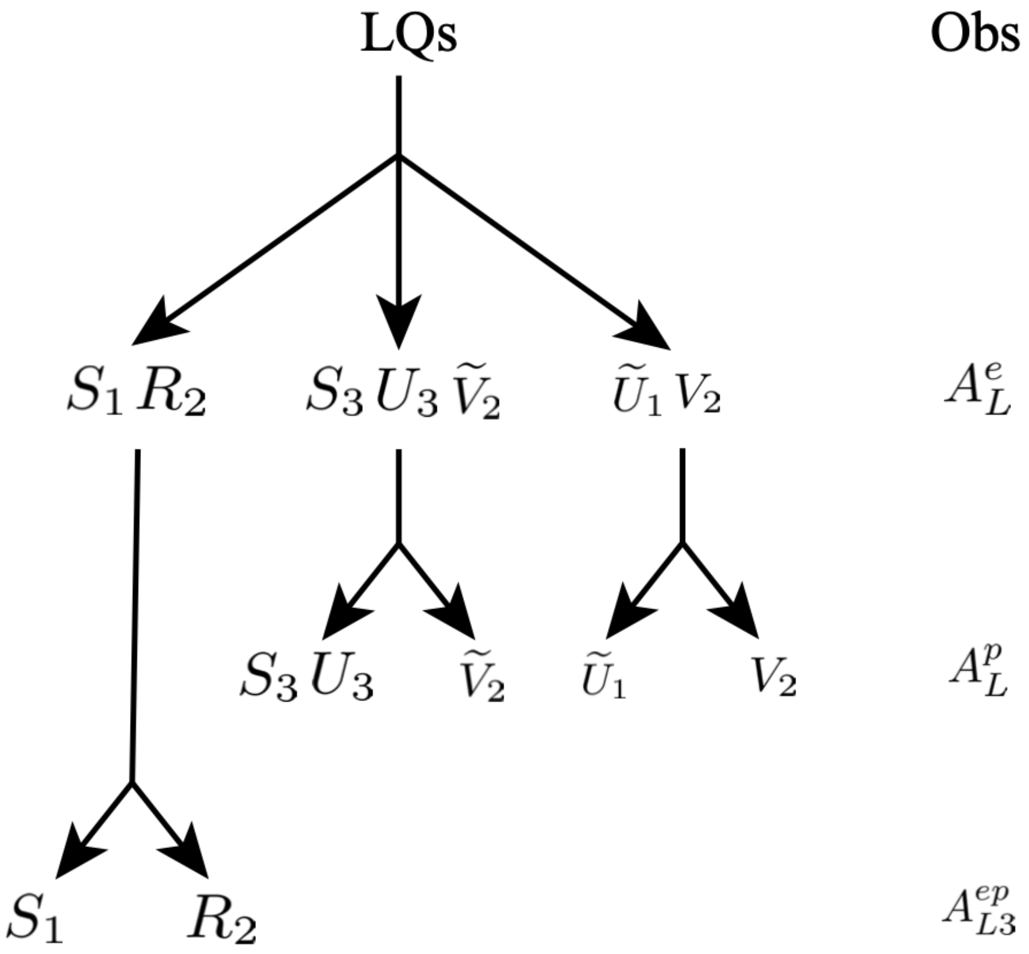
$$A_{T1}^{ep} = \frac{\tilde{\sigma}^{--} - \tilde{\sigma}^{++}}{\tilde{\sigma}^{--} + \tilde{\sigma}^{++}}, \quad A_{T2}^{ep} = \frac{\tilde{\sigma}^{-+} - \tilde{\sigma}^{+-}}{\tilde{\sigma}^{-+} + \tilde{\sigma}^{+-}}$$

$$A_{T3}^{ep} = \frac{\tilde{\sigma}^{--} - \tilde{\sigma}^{-+}}{\tilde{\sigma}^{--} + \tilde{\sigma}^{-+}}, \quad A_{T4}^{ep} = \frac{\tilde{\sigma}^{--} - \tilde{\sigma}^{+-}}{\tilde{\sigma}^{--} + \tilde{\sigma}^{+-}}$$

$$A_{T5}^{ep} = \frac{\tilde{\sigma}^{++} - \tilde{\sigma}^{-+}}{\tilde{\sigma}^{++} + \tilde{\sigma}^{-+}}, \quad A_{T6}^{ep} = \frac{\tilde{\sigma}^{++} - \tilde{\sigma}^{+-}}{\tilde{\sigma}^{++} + \tilde{\sigma}^{+-}}$$

LQ model identification

- **Set $E = 3$ GeV**



	A_L^e	A_L^p	A_{L3}^{ep}
S_1	c_1	c_3	-1
R_2	c_2	c_4	1
S_3	1	-1	-1
U_3	1	-1	-1
$\widetilde{V}_2$	1	1	1
$\widetilde{U}_1$	-1	1	0
V_2	-1	-1	0

τ polarization in charm sector

XY, Liang-Hui Zhang, Qin Chang, Ya-Dong Yang, 2402.16344 [PRD]

Consider: $e^- p \to \Lambda_c \tau^-$

$$m_{D^+} - m_{\pi^0} \simeq 1.735 \text{ GeV}$$

only leptonic (tauonic) decays are possible

only sensitive to axial and pseudoscalar OPs

Coeff.	Operator	Coeff.	Operator
g_V^{LL}	$(\bar{\tau}\gamma_\mu P_L e)(\bar{c}\gamma^\mu P_L u)$	g_V^{RR}	$(\bar{\tau}\gamma_\mu P_R e)(\bar{c}\gamma^\mu P_R u)$
g_V^{LR}	$(\bar{\tau}\gamma_\mu P_L e)(\bar{c}\gamma^\mu P_R u)$	g_V^{RL}	$(\bar{\tau}\gamma_\mu P_R e)(\bar{c}\gamma^\mu P_L u)$
g_S^{LL}	$(\bar{\tau}P_L e)(\bar{c}P_L u)$	g_S^{RR}	$(\bar{\tau}P_R e)(\bar{c}P_R u)$
g_S^{LR}	$(\bar{\tau}P_L e)(\bar{c}P_R u)$	g_S^{RL}	$(\bar{\tau}P_R e)(\bar{c}P_L u)$
g_T^{LL}	$(\bar{\tau}\sigma_{\mu\nu} P_L e)(\bar{c}\sigma^{\mu\nu} P_L u)$	g_T^{RR}	$(\bar{\tau}\sigma_{\mu\nu} P_R e)(\bar{c}\sigma^{\mu\nu} P_R u)$

$D^0 \to \tau e$

not measured yet!

Other observables are needed!

$$e^- p \to \Lambda_c \tau^- (\to \pi^- \nu_\tau, \rho^- \nu_\tau, \ell^- \bar{\nu}_\ell \nu_\tau)$$

Cross section:

$$d\sigma_d = \frac{1}{4F} \frac{1}{(k'^2 - m_\tau^2)^2 + m_\tau^2 \Gamma_\tau^2} \rho^P_{\lambda\lambda'} \rho^D_{\lambda'\lambda} d\Phi(k, p; p', p_d, p_\nu)$$

narrow width →

$$= \underbrace{\left[\frac{1}{4F} \rho^P_{\lambda\lambda'} d\Phi(k, p; p', k') \right]}_{\text{Lab}} \underbrace{\left[\frac{1}{2m_\tau \Gamma_\tau} \rho^D_{\lambda'\lambda} d\Phi(k'; p_d, p_\nu) \right]}_{\text{CM of } \tau}$$

Polarization of τ:

$$\rho^P_{\lambda\lambda'} = C\left(\delta_{\lambda\lambda'} + \sum_a \sigma^a_{\lambda\lambda'} P_a \right)$$

P_a: polarization component

Extraction of the τ polarization components

$$\frac{d^3\sigma_d}{dq^2 d\Omega_d} = \frac{\mathcal{B}_d}{4\pi}\frac{d\sigma_s}{dq^2}[g^d + g_D^d(P_T(q^2)\sin\theta_d\cos\phi_d + P_P(q^2)\sin\theta_d\sin\phi_d + P_L(q^2)\cos\theta_d)]$$

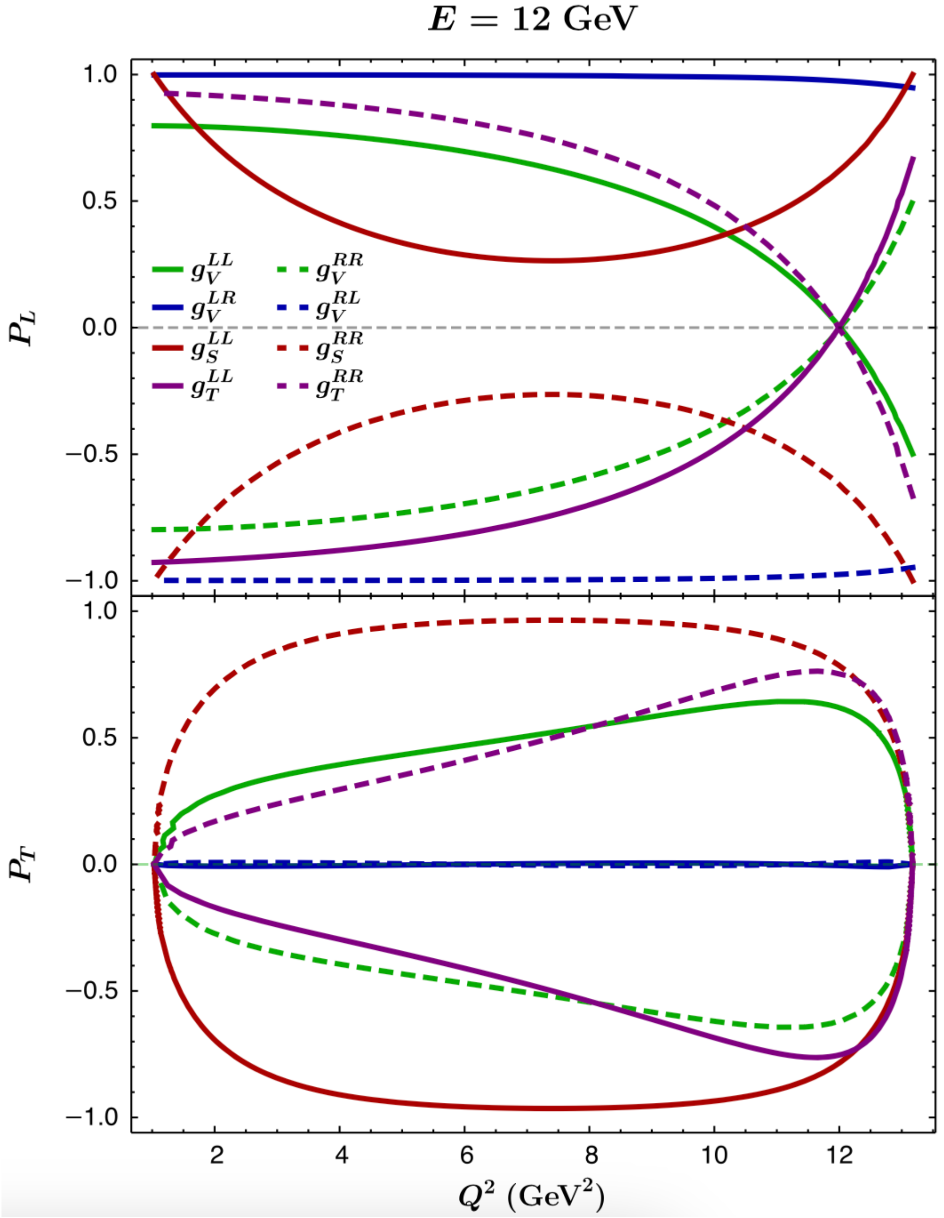
Integrate over ϕ_d:

$d = \pi, \rho, \ell$

$$P_L = \frac{2g^d}{g_D^d}\frac{\int_0^1 d\cos\theta_d \frac{d^2\sigma}{dq^2 d\cos\theta_d} - \int_{-1}^0 d\cos\theta_d \frac{d^2\sigma}{dq^2 d\cos\theta_d}}{\int_0^1 d\cos\theta_d \frac{d^2\sigma}{dq^2 d\cos\theta_d} + \int_{-1}^0 d\cos\theta_d \frac{d^2\sigma}{dq^2 d\cos\theta_d}}$$

FB asym

One can obtain P_P and P_T in a similar way, and τ polarization components can be extracted from analyzing the kinematics of the τ visible decay products.



Note that $P_P = 0$ in each case.

15 NP vector models (I-XV)

$\mathcal{O}_V^{LL}$, $\mathcal{O}_V^{LR}$, $\mathcal{O}_V^{RL}$, $\mathcal{O}_V^{RR}$;
$\mathcal{O}_V^{LL}+\mathcal{O}_V^{LR}$, $\mathcal{O}_V^{LL}+\mathcal{O}_V^{RL}$, $\mathcal{O}_V^{LL}+\mathcal{O}_V^{RR}$, $\mathcal{O}_V^{LR}+\mathcal{O}_V^{RL}$, $\mathcal{O}_V^{LR}+\mathcal{O}_V^{RR}$, $\mathcal{O}_V^{RL}+\mathcal{O}_V^{RR}$;
$\mathcal{O}_V^{LL}+\mathcal{O}_V^{LR}+\mathcal{O}_V^{RL}$, $\mathcal{O}_V^{LL}+\mathcal{O}_V^{LR}+\mathcal{O}_V^{RR}$, $\mathcal{O}_V^{LL}+\mathcal{O}_V^{RL}+\mathcal{O}_V^{RR}$, $\mathcal{O}_V^{LR}+\mathcal{O}_V^{RL}+\mathcal{O}_V^{RR}$;
$\mathcal{O}_V^{LL}+\mathcal{O}_V^{LR}+\mathcal{O}_V^{RL}+\mathcal{O}_V^{RR}$.

E =12 GeV, Q^2=6 GeV^2

	I	II	III	IV	V
$P_T(e_L)$	0.5	0	0	0	c
$P_T(e_R)$	0	0	0	−0.5	0

	VI	VII	VIII	IX	X
$P_T(e_L)$	0.5	0.5	0	0	0
$P_T(e_R)$	0	−0.5	0	−0.5	$-c$

	XI	XII	XIII	XIV	XV
$P_T(e_L)$	c	c	0.5	0	c
$P_T(e_R)$	0	−0.5	$-c$	$-c$	$-c$

$$\nu_\tau + n \to \tau^- + \Lambda_c$$

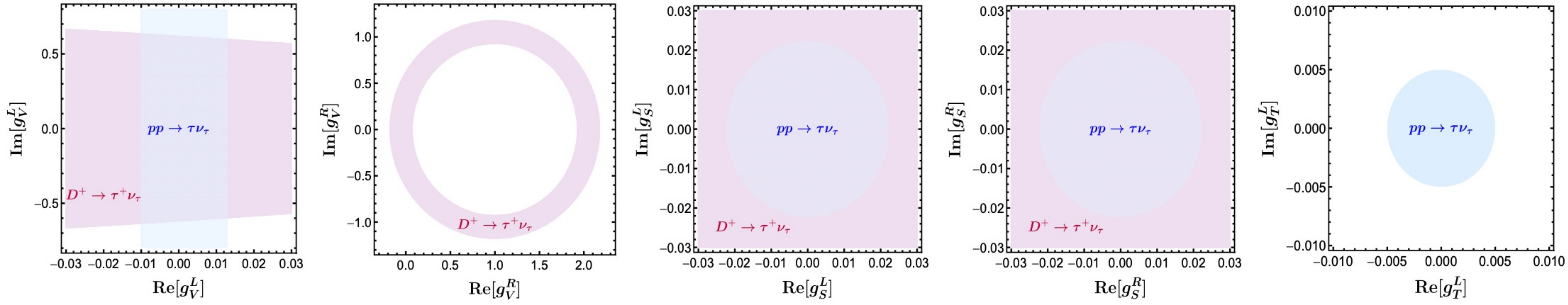
Polarization vector

Ya-Ru Kong, Li-Fen Lai, Xin-Qiang Li, **XY**,
Ya-Dong Yang, Dong-hui Zheng. 2307.07239 [PRD]

$$\mathcal{P}_l^\mu = \frac{\mathrm{Tr}[\rho_l(k')\gamma^\mu\gamma_5]}{\mathrm{Tr}[\rho_l(k')]}$$

$$\mathcal{P}_{l,h}^\mu = P_L^{l,h}(N_L^{l,h})^\mu + P_P^{l,h}(N_P^{l,h})^\mu + P_T^{l,h}(N_T^{l,h})^\mu$$

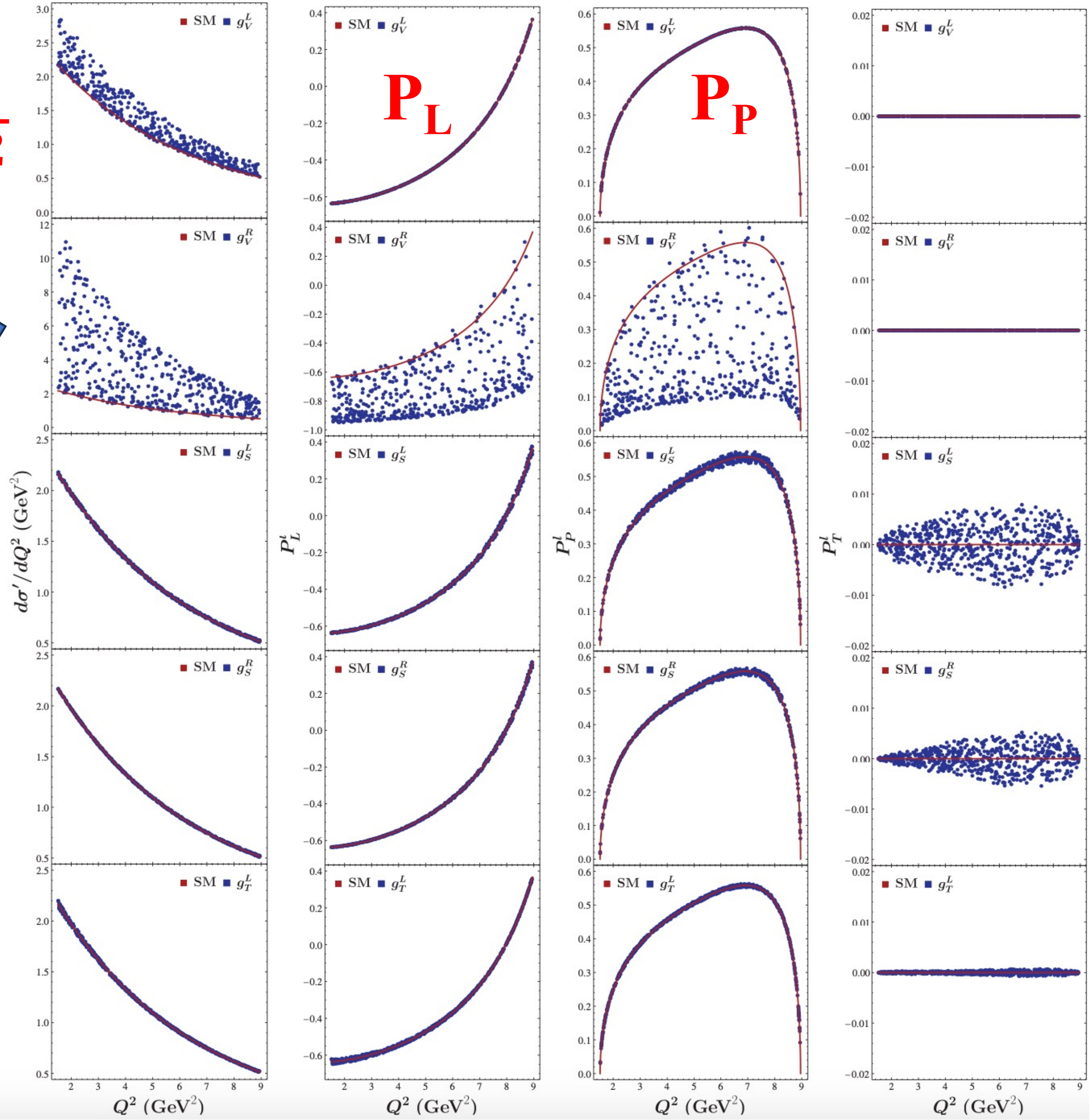
Constraints on the WC of $\mathcal{L}_{\rm eff}$ (can choose a different OP basis)



g_V^L g_V^R g_S^L g_S^R g_T^L

$\frac{d\sigma}{dQ^2}$

g_V^R



Involves all g_α

Challenge from Form Factors ($\Lambda_c \to N$)

RCQM: $$f(q^2) = \frac{f(0)}{1 - a\hat{s} + b\hat{s}^2}$$ **Double-pole**

T. Gutsche, etc, 1410.6043 [PRD]

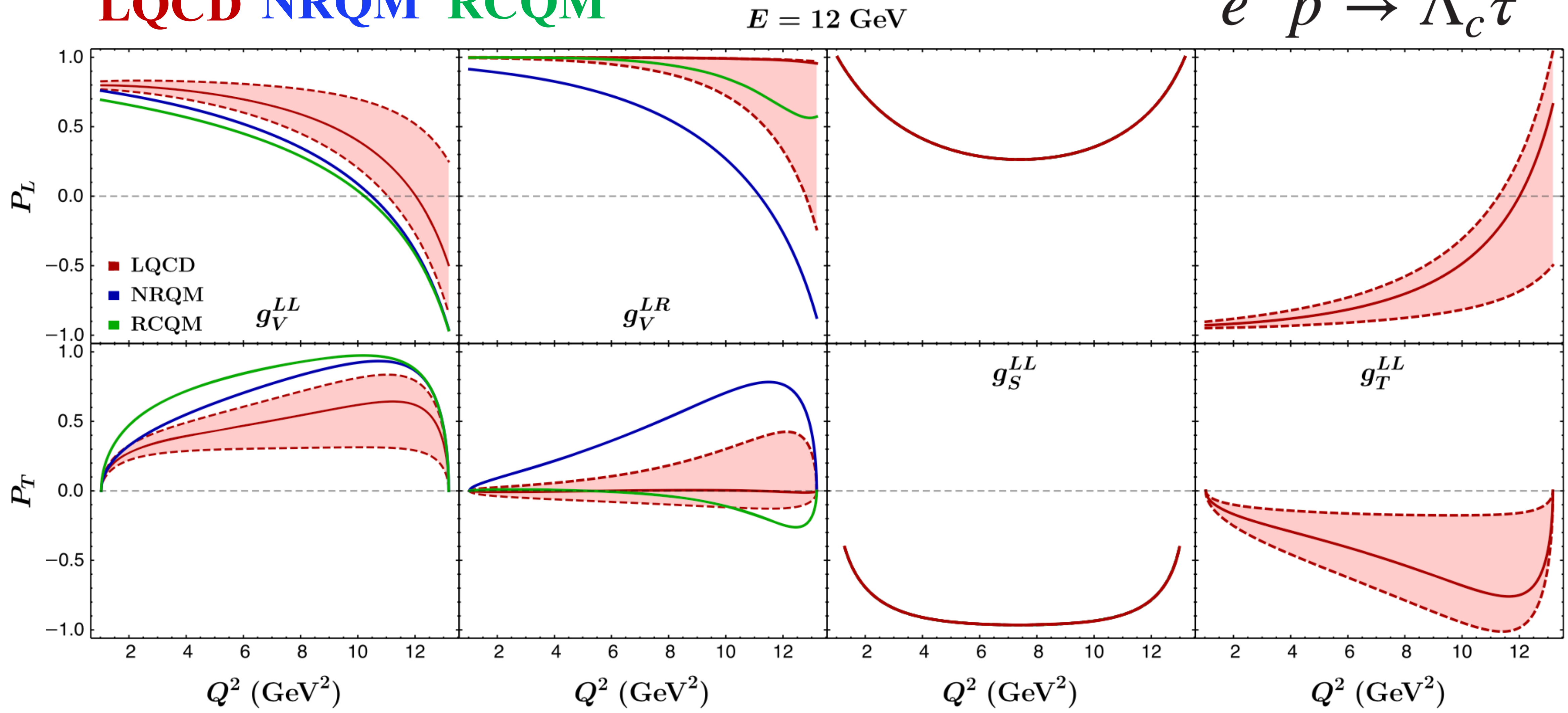
NRQM: $$f(q^2) = \frac{A}{(1 - q^2/M_R^2)^2}$$ **dipole**

M. Avila-Akoki, etc,
Phys.Rev.D 40 (1989) 2944

LQCD: $$f(q^2) = \frac{1}{1 - q^2/(m_{\rm pole}^f)^2} \sum_{n=0}^{n_{\rm max}} a_n^f [z(q^2)]^n$$ **z expansion**

S. Meinel, 1712.05783 [PRD]

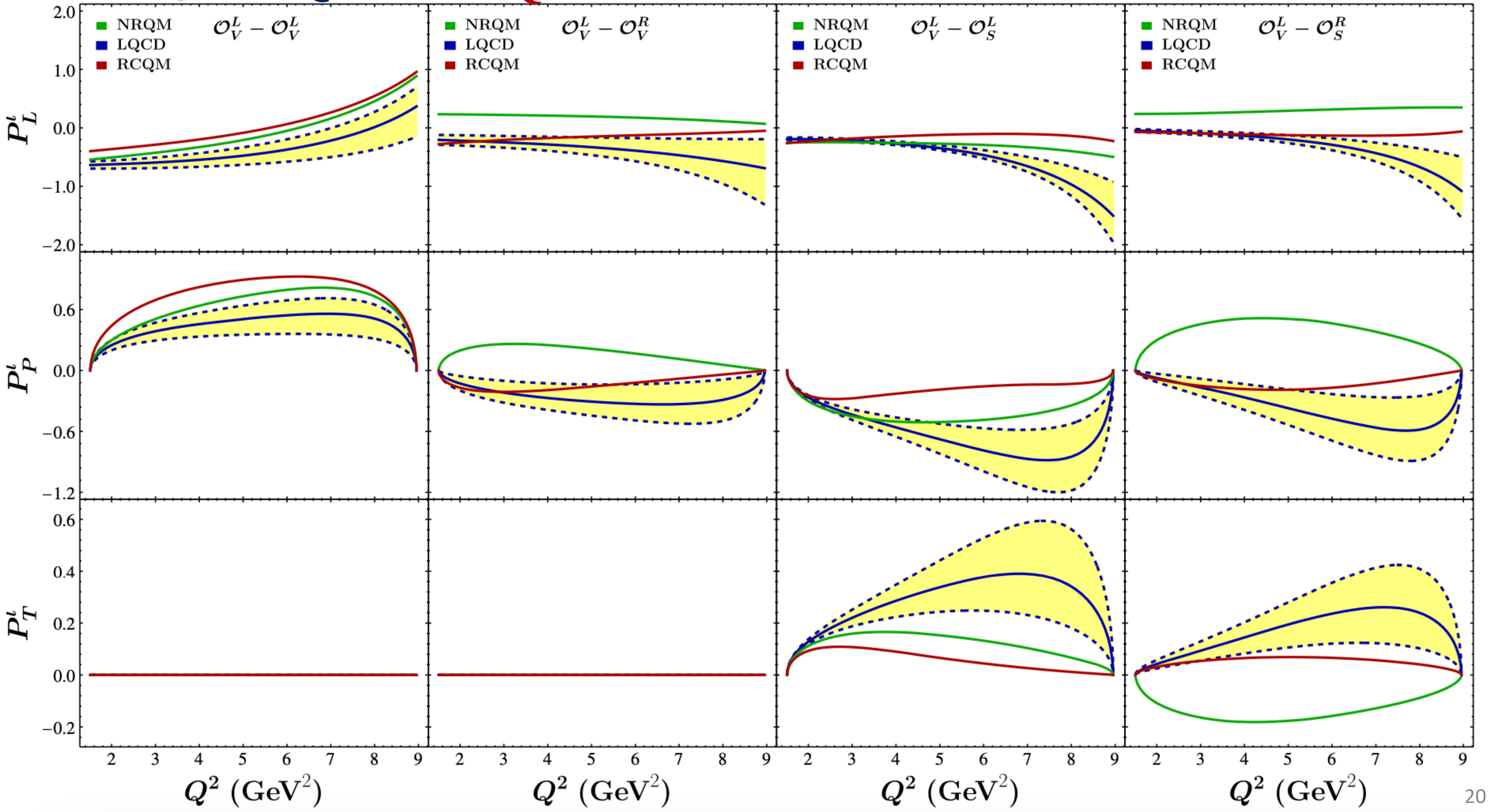
$e^- p \to \Lambda_c \tau^-$



Large uncertainties induced by form factors.

NRQM LQCD RCQM

$$\nu_\tau + n \to \tau^- + \Lambda_c$$



Summary

- **With desired experimental setups, competitive constraints can be provided by the low-E scattering, compared with other FCNC processes in the charm sector.**
- **The LQ models can be effectively distinguished by measuring 3 spin asymmetries, involving only longitudinally polarized scattering processes.**
- **τ polarization components can be extracted from analyzing the kinematics of the τ visible decay products, and can be used to distinguish 15 NP vector models.**
- **Large uncertainties of the polarization observables arise from using the different schemes and dwarf that from the error propagation of the form factors.**

Thank you for your patience

Backup slides

Theoretical Framework

$e^- p \to e^- \Lambda_c$

$e^- p \to \mu^- \Lambda_c$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{eff}}^{\text{SM}} + \mathcal{L}_{\text{eff}}^{\text{NP}}$$

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{\text{NP}} &= \sum g_{\alpha\beta} j_\alpha J_\beta \\ &= g_V^{LL}(\bar{\ell}_L \gamma_\mu \ell_L)(\bar{q}_L \gamma^\mu q_L) + g_V^{LR}(\bar{\ell}_L \gamma_\mu \ell_L)(\bar{q}_R \gamma^\mu q_R) \\ &+ g_V^{RL}(\bar{\ell}_R \gamma_\mu \ell_R)(\bar{q}_L \gamma^\mu q_L) + g_V^{RR}(\bar{\ell}_R \gamma_\mu \ell_R)(\bar{q}_R \gamma^\mu q_R) \\ &+ g_T^{L}(\bar{\ell}_R \sigma^{\mu\nu} \ell_L)(\bar{q}_R \sigma_{\mu\nu} q_L) + g_T^{R}(\bar{\ell}_L \sigma^{\mu\nu} \ell_R)(\bar{q}_L \sigma_{\mu\nu} q_R) \\ &+ g_S^{L}(\bar{\ell}_R \ell_L)(\bar{q}_R q_L) + g_S^{R}(\bar{\ell}_L \ell_R)(\bar{q}_L q_R)\end{aligned}$$

$\nu_\tau + n \to \tau^- + \Lambda_c$

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cd} \left[(1 + g_V^L)\mathcal{O}_V^L + g_V^R \mathcal{O}_V^R + g_S^L \mathcal{O}_S^L + g_S^R \mathcal{O}_S^R + g_T^L \mathcal{O}_T^L \right] + \text{H.c.},$$

SM

$$\begin{aligned}\mathcal{O}_V^{L,R} &= (\bar{c}\gamma^\mu P_{L,R} d)(\bar{\tau}\gamma_\mu P_L \nu_\tau), \\ \mathcal{O}_S^{L,R} &= (\bar{c} P_{L,R} d)(\bar{\tau} P_L \nu_\tau), \\ \mathcal{O}_T^{L} &= (\bar{c}\sigma^{\mu\nu} P_L d)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau),\end{aligned}$$

The desired experimental setup

- LP e^- beam: $E = 3.48$ GeV, $I = 100\ \mu$A, $P_e = 0.9$ [HAPPEX, 1107.0913]
- p target: liquid hydrogen, $L = 70$ cm, $\rho = 71.3 \times 10^{-3}$ g/cm^3 [Qweak, 1409.7100]
- LP&TP p target: solid NH3, $L = 6$ cm, $\rho = 0.917$ g/cm^3, $P_p = 0.8$ [J. Arrington, 2112.00060]

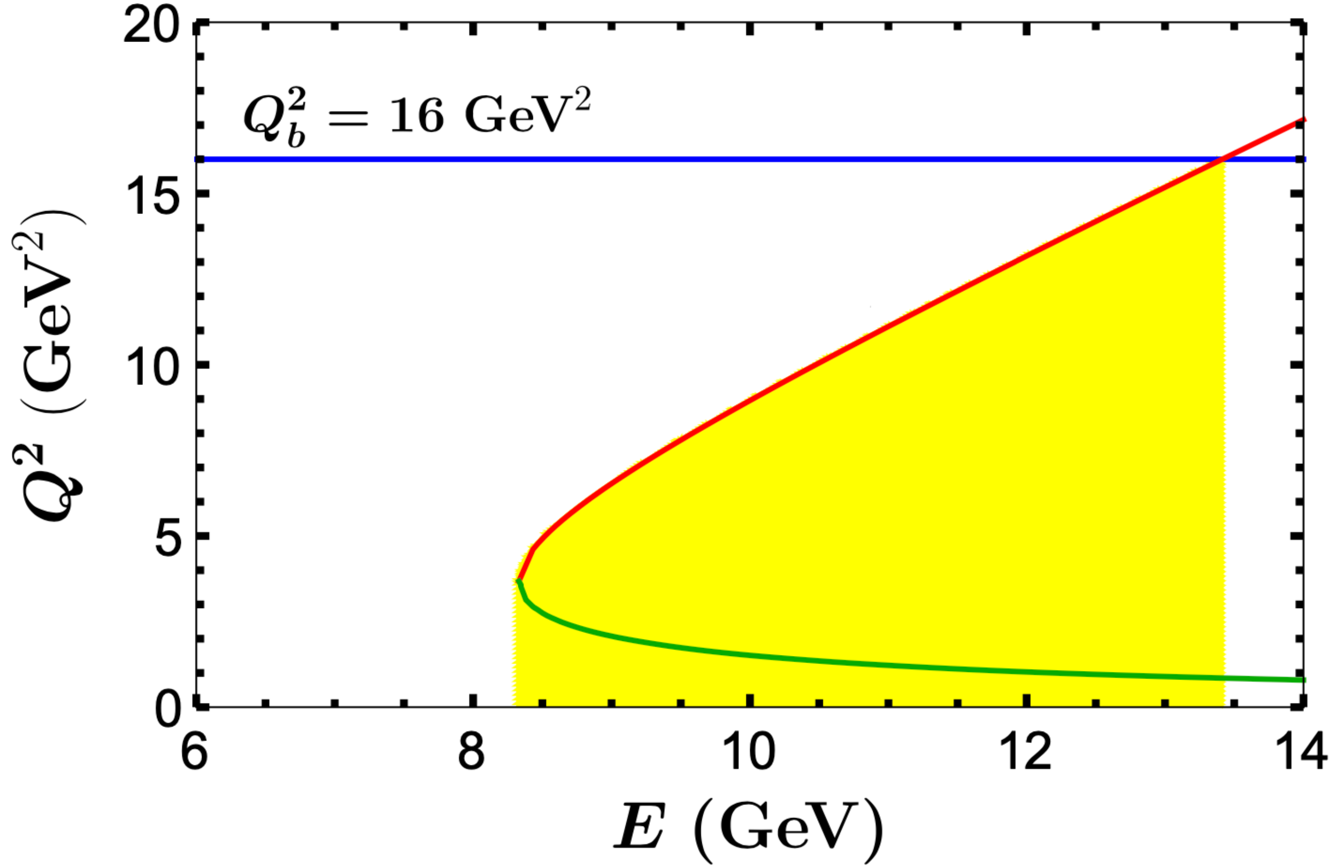
Polarized electron

	$\lvert g_V^{LL}\rvert^2$	$\lvert g_V^{RR}\rvert^2$	$\lvert g_V^{LR}\rvert^2$	$\lvert g_V^{RL}\rvert^2$	$\lvert g_S^{L}\rvert^2$	$\lvert g_S^{R}\rvert^2$	$\lvert g_T^{L}\rvert^2$	$\lvert g_T^{R}\rvert^2$
e_L^-	0.007	\	0.016	\	0.035	\	0.001	\
e_L^+	\	0.007	\	0.016	\	0.035	\	0.001

VS

Processes	$\lvert g_V^{LL,RR}\rvert^2$	$\lvert g_V^{LR,RL}\rvert^2$	$\lvert g_S^{L,R}\rvert^2$	$\lvert g_T^{L,R}\rvert^2$
$D^0 \to e^+e^-$	\	\	0.062	\
$D^+ \to \pi^+e^+e^-$	14	14	6.3	13
$pp(q\bar{q}) \to e^+e^-$	3.6	3.6	22	0.57

$$e^- p \to \Lambda_c \tau^-$$



$$\frac{\alpha - E\sqrt{\lambda}}{m_p + 2E} \le q^2 \le \frac{\alpha + E\sqrt{\lambda}}{m_p + 2E}$$

$$\alpha \equiv E(m_{\Lambda_c}^2 - m_p^2 + m_\tau^2 - 2m_p E) + m_p m_\tau^2,$$
$$\lambda \equiv m_{\Lambda_c}^4 + (m_p^2 + 2m_p E - m_\tau^2)^2$$
$$- 2m_{\Lambda_c}^2 (m_p^2 + 2m_p E + m_\tau^2).$$

$$e^- p \to \Lambda_c \tau^- (\to \pi^- \nu_\tau, \rho^- \nu_\tau, \ell^- \bar{\nu}_\ell \nu_\tau)$$

Processes	$\lvert g_V^{LL,RR} \rvert$	$\lvert g_V^{LR,RL} \rvert$	$\lvert g_S^{LL,RR} \rvert$	$\lvert g_T^{LL,RR} \rvert$
$pp \to \tau^\pm e^\mp$ [19]	5.27	5.27	11.1	2.11
$e^- p \to \Lambda_c \tau^- (\to d\nu_\tau)$	1.40	1.74	2.67	0.52

12 GeV CEBAF at Jlab, proposed SoLID:

XY, Liang-Hui Zhang, Qin Chang, Ya-Dong Yang, 2402.16344 [PRD]

E=12 GeV, $\mathcal{L} = 1.2 \times 10^{37}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Use form factors to parametrize the hadronic contributions as in charm decays (one example)

$$\langle p(P,s)|\bar{u}\gamma^\mu c|\Lambda_c(P',s')\rangle = \bar{u}_p(P,s)\Big[f_0(q^2)(m_{\Lambda_c}-m_p)\frac{q^\mu}{q^2}$$
$$+f_+(q^2)\frac{m_{\Lambda_c}+m_p}{s_+}\Big(P'^\mu + P^\mu - (m^2_{\Lambda_c}-m^2_p)\frac{q^\mu}{q^2}\Big)$$
$$+f_\perp(q^2)\Big(\gamma^\mu - \frac{2m_N}{s_+}P'^\mu - \frac{2m_{\Lambda_c}}{s_+}P^\mu\Big)\Big]u_{\Lambda_c}(P',s')$$

$$f(q^2) = \frac{1}{1-q^2/(m^f_{pole})^2}\sum_{n=0}^{n_{max}} a_n^f[z(q^2)]^n$$

$$z(q^2) = \frac{\sqrt{t_+-q^2}-\sqrt{t_+-t_0}}{\sqrt{t_+-q^2}+\sqrt{t_+-t_0}}$$

LQCD

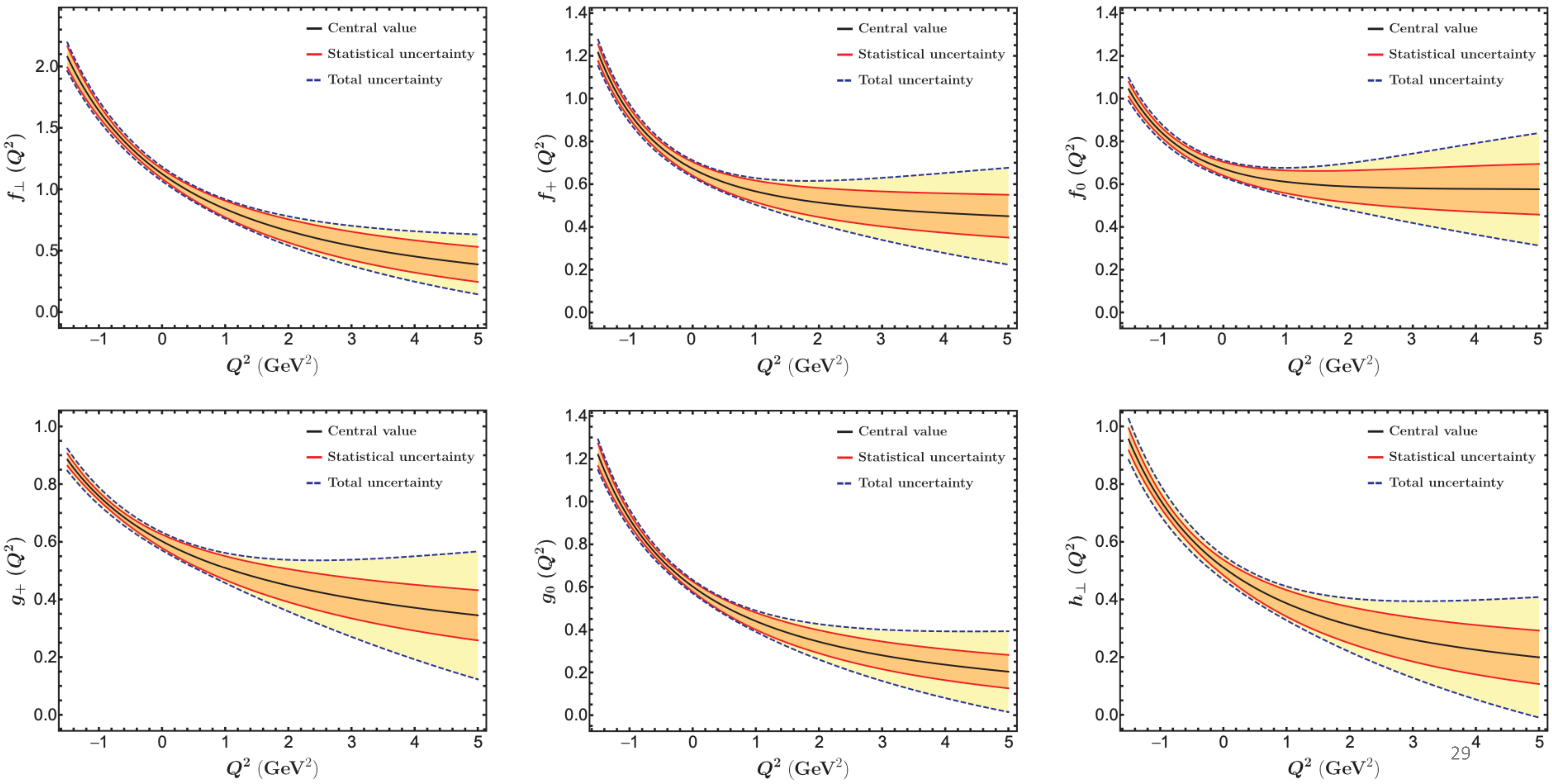
$$f(q^2) = \frac{f(0)}{1-a\hat{s}+b\hat{s}^2}$$

RCQM

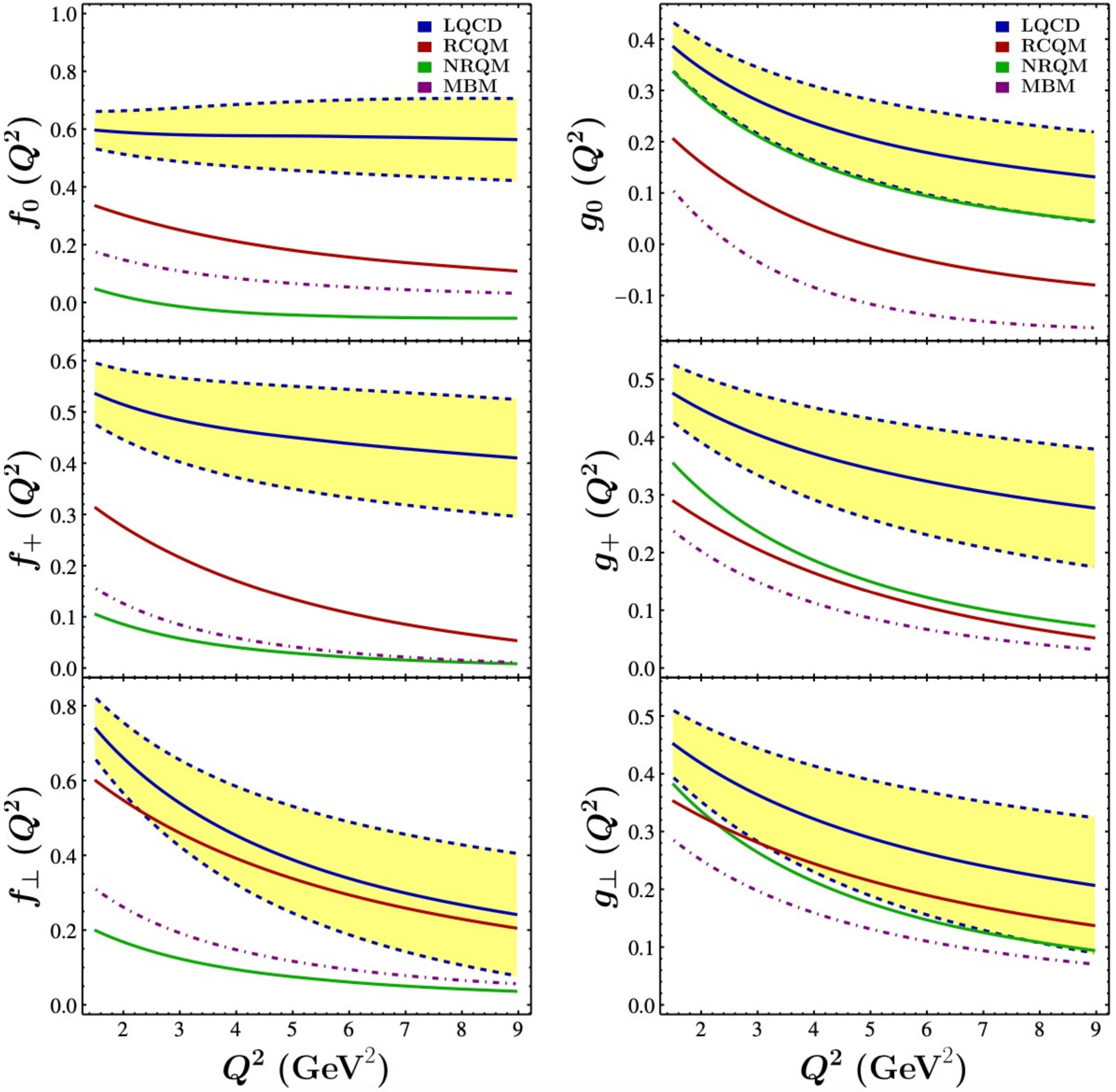
$$f(q^2) = \frac{A}{(1-q^2/M_R^2)^2}$$

NRQM

LQCD



Central value
Statistical uncertainty
Total uncertainty
$f_\perp(Q^2)$
$f_+(Q^2)$
$f_0(Q^2)$
$g_+(Q^2)$
$g_0(Q^2)$
$h_\perp(Q^2)$
Q^2 (GeV^2)



LQCD
RCQM
NRQM
MBM
$f_0\,(Q^2)$
$f_+\,(Q^2)$
$f_\perp\,(Q^2)$
$g_0\,(Q^2)$
$g_+\,(Q^2)$
$g_\perp\,(Q^2)$
Q^2 (GeV^2)
Q^2 (GeV^2)

Scalar cases

$$P_a = -(\mathcal{P} \cdot s_a) = \frac{\Sigma_P^a}{C} = \frac{2\Sigma_P^a}{|\mathcal{M}|^2},$$

$$2v^4 \Sigma_P^a = (|g_S^{LL}|^2 + |g_S^{LR}|^2 - |g_S^{RR}|^2 - |g_S^{RL}|^2) \mathcal{A}^{\tau}_{S_{LL}-S_{LL}}$$

$$v^4 |\mathcal{M}|^2 = (|g_S^{LL}|^2 + |g_S^{RR}|^2 + |g_S^{LR}|^2 + |g_S^{RL}|^2) \mathcal{A}_{S_{LL}-S_{LL}}$$

$$\mathcal{A}^{\tau}_{S_{LL}-S_{LL}} = \mathcal{A}_{S_{LL}-S_{LL}} \frac{2m_\tau (k \cdot s_a)}{m_\tau^2 - q^2}$$

P_a: independent of form factors!