

Searching for the New Physics with Jet Charge

Bin Yan

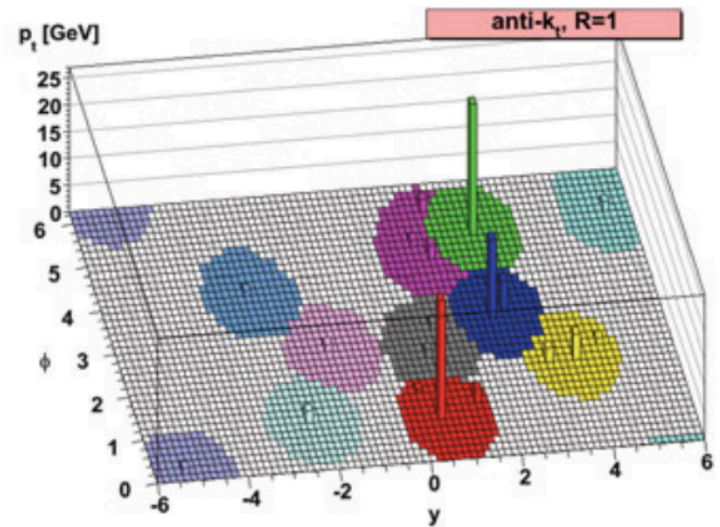
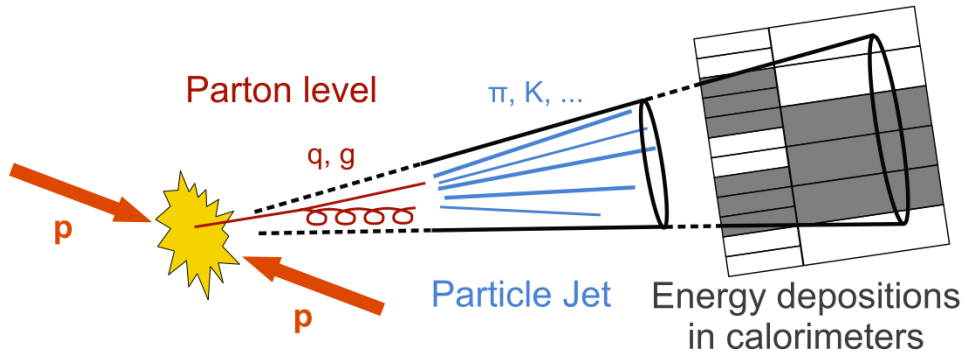
Institute of High Energy Physics

IAS Program on High Energy Physics

Feb 12, 2023

In cooperation with Hai Tao Li, Xiaorui Wong and C.-P. Yuan,
PLB833(2022)137300, 2301.07914, 2302.02084

Jet charge definition



Transverse-momentum-weighting scheme:

$$Q_J = \frac{1}{(p_T^j)^\kappa} \sum_{i \in jet} Q_i (p_T^i)^\kappa, \quad \kappa > 0$$

κ : To regulate the sensitivity of the soft gluon radiation

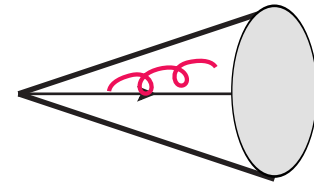
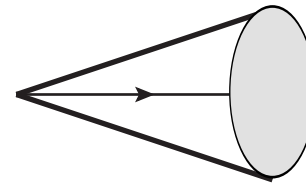
R.D. Field and R.P. Feynman, NPB136,1(1978)

Jet charge definition

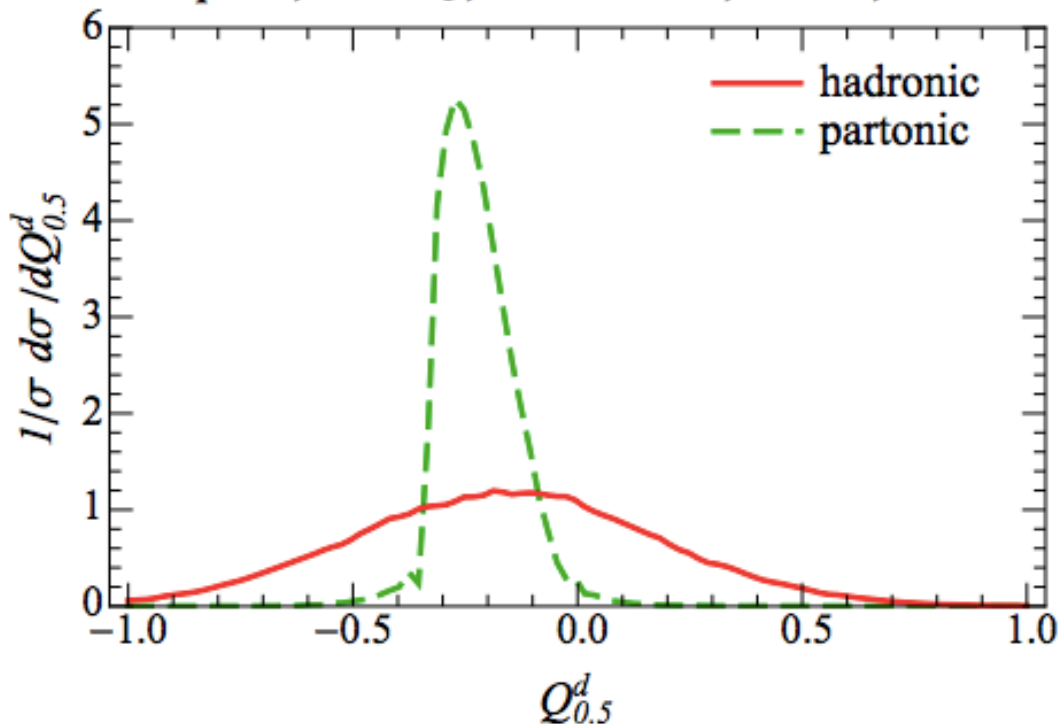
Jet charge is not an Infrared-safe quantity

The collinear radiation

$$Q_J = \frac{1}{(p_T^j)^\kappa} \sum_{i \in \text{jet}} Q_i (p_T^i)^\kappa, \quad \kappa > 0$$



d quark, anti- k_T , $E=100$ GeV, $R=0.5$, $\kappa=0.5$



W.J.Waalewijn, PRD86(2012)094030

$$Q_q \neq (1-z)^k Q_q$$

The jet charge can be defined only at the **hadron level**

It depends on the knowledge of the Fragmentation functions

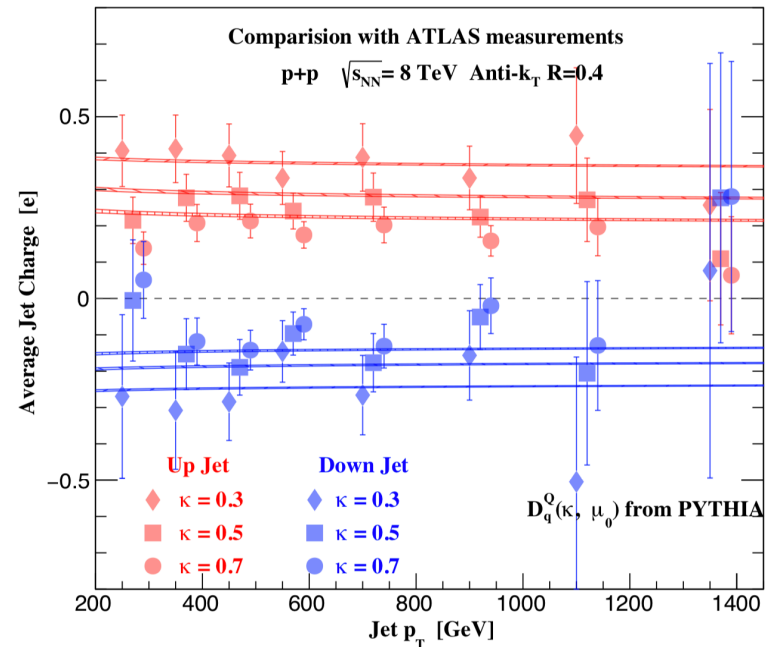
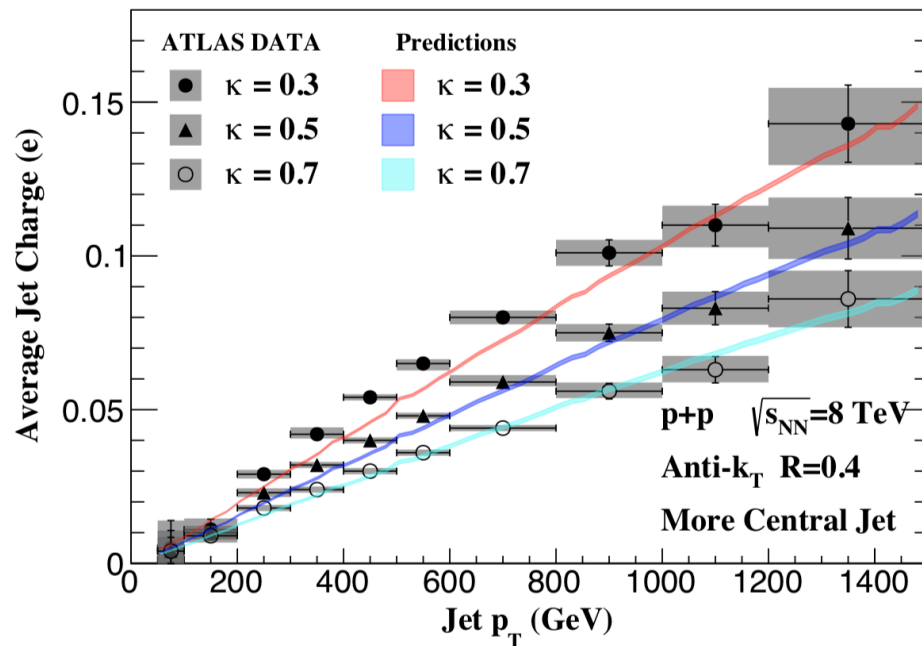
The average of Jet charge

$$\langle Q_k^q \rangle = \frac{1}{\sigma_{q-jet}} \int d\sigma_{q-jet} Q_\kappa(\sigma_{q-jet})$$

D. Krohn, M. D. Schwartz, T. Lin, W.J. Waalewijn, PRL 110(2013)21,212001

W.J.Waalewijn, PRD86(2012)094030

H. T. Li and I. Vitev, PRD 101(2020)076020



Perfect agreement between theory and data

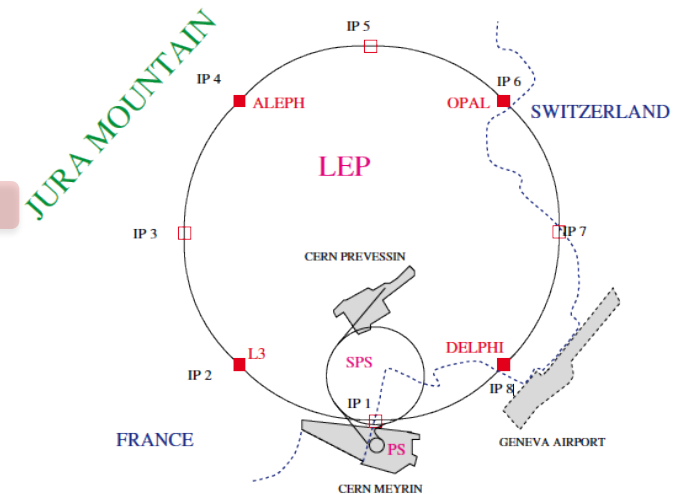
Probing the Zbb coupling with jet charge

Electroweak Precision measurement

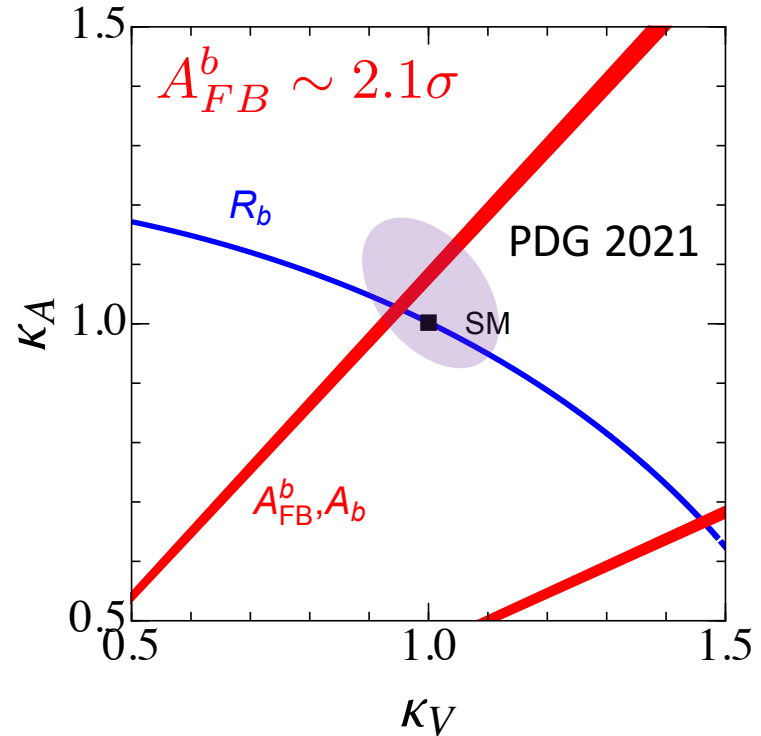
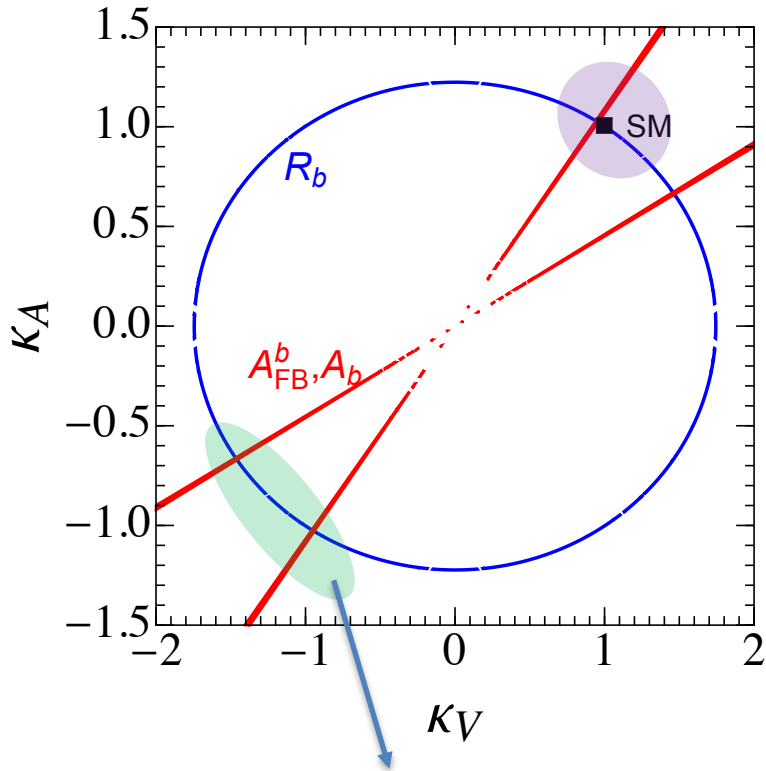
	Measurement with Total Error	Systematic Error	Standard Model High- Q^2 Fit	Pull
$\Delta\alpha_{\text{had}}^{(5)}(m_Z^2)$ [59]	0.02758 ± 0.00035	0.00034	0.02767 ± 0.00035	0.3
m_Z [GeV]	91.1875 ± 0.0021	^(a) 0.0017	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	^(a) 0.0012	2.4965 ± 0.0015	0.6
σ_{had}^0 [nb]	41.540 ± 0.037	^(a) 0.028	41.481 ± 0.014	1.6
R_ℓ^0	20.767 ± 0.025	^(a) 0.007	20.739 ± 0.018	1.1
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	^(a) 0.0003	0.01642 ± 0.00024	0.8
+ correlation matrix Table 2.13				
$\mathcal{A}_\ell(P_\tau)$	0.1465 ± 0.0033	0.0015	0.1480 ± 0.0011	0.5
$\mathcal{A}_\ell(\text{SLD})$	0.1513 ± 0.0021	0.0011	0.1480 ± 0.0011	1.6
R_b^0	0.21629 ± 0.00066	0.00050	0.21562 ± 0.00013	1.0
R_c^0	0.1721 ± 0.0030	0.0019	0.1723 ± 0.0001	0.1
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	0.0007	0.1037 ± 0.0008	2.8
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	0.0017	0.0742 ± 0.0006	1.0
\mathcal{A}_b	0.923 ± 0.020	0.013	0.9346 ± 0.0001	0.6
\mathcal{A}_c	0.670 ± 0.027	0.015	0.6683 ± 0.0005	0.1
+ correlation matrix Table 5.11				
$\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{FB}}^{\text{had}})$	0.2324 ± 0.0012	0.0010	0.23140 ± 0.00014	0.8
m_t [GeV] (Run-I [212])	178.0 ± 4.3	3.3	178.5 ± 3.9	0.1
m_W [GeV]	80.425 ± 0.034		80.389 ± 0.019	1.1
Γ_W [GeV]	2.133 ± 0.069		2.093 ± 0.002	0.6
+ correlation given in Section 8.3.2				

Phys.Rept. 427 (2006) 257-454

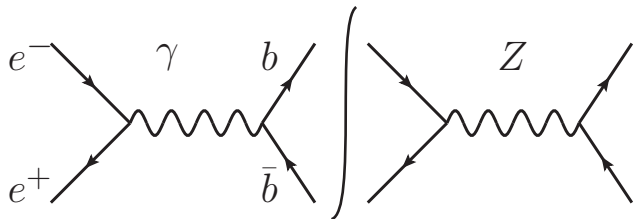
LEP: 1989-2000



Status of Zbb couplings



Excluded by off-Z pole data

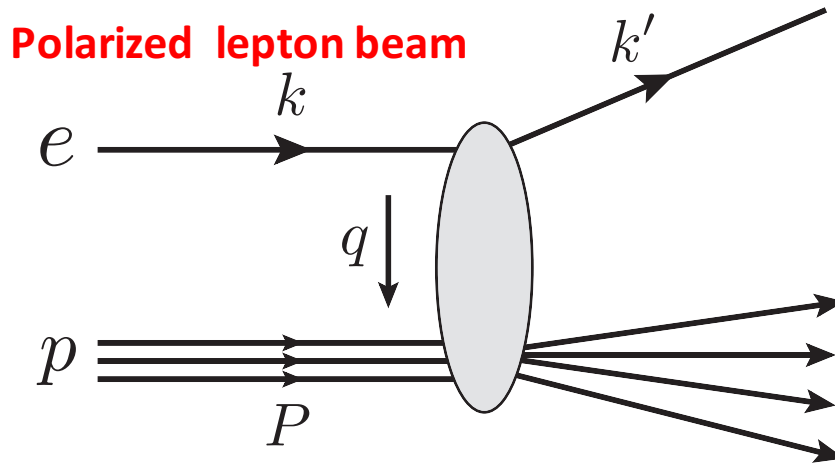


$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5)bZ_\mu$$

- Large deviation of the Zbb coupling
- The **degeneracy** of the Zbb coupling

Zbb couplings@EIC

Bin Yan, Zhite Yu and C.-P. Yuan, PLB822(2021)136697



Single-Spin Asymmetry (SSA):

$$A_e^b = \frac{\sigma_{b,+}^{\text{tot}} - \sigma_{b,-}^{\text{tot}}}{\sigma_{b,+}^{\text{tot}} + \sigma_{b,-}^{\text{tot}}}$$

+/-: right/left-handed lepton

1. Photon-only diagrams will **cancel** in SSA
2. Leading contribution: **γ -Z interference**
3. Only sensitive to the **vector component** of the Zbb coupling

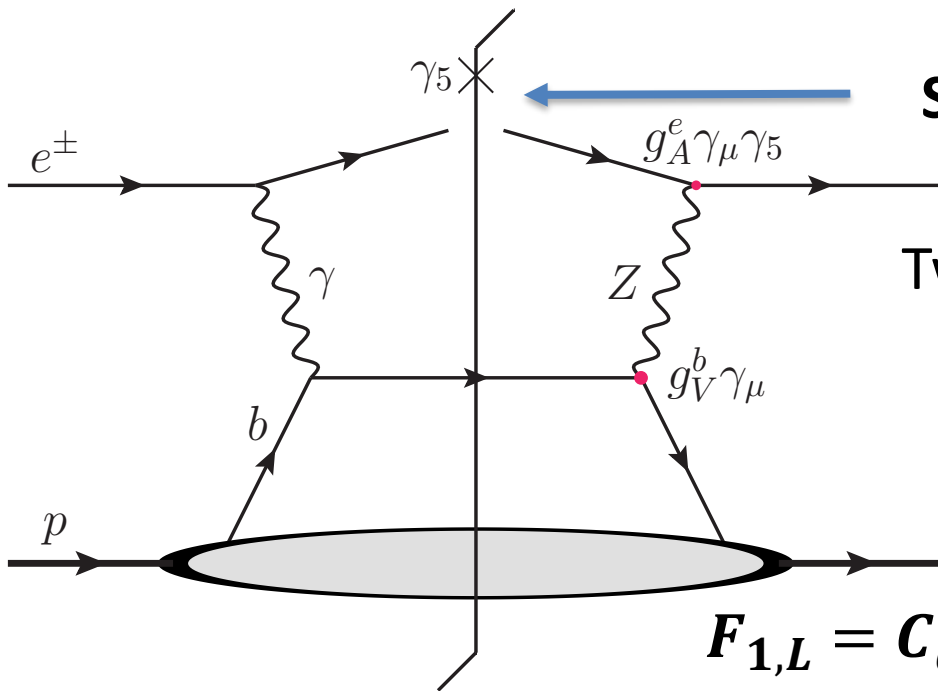
DIS cross section

Polarized cross section

$$F_{1,L,3} \equiv F_{1,L,3}(\lambda_e)$$

$$\frac{d\sigma_{\lambda_e}^{\pm}}{\sigma_0 dx dy} = F_1 \left((1-y)^2 + 1 \right) + F_L \frac{1-y}{x} \mp \underline{F_3} \lambda_e \left(y - \frac{y^2}{2} \right)$$

$\lambda_e = \pm 1$: lepton helicity



SSA: $\sigma_{b,+} - \sigma_{b,-}$

Two possible combination:

$$g_A^e g_V^b$$



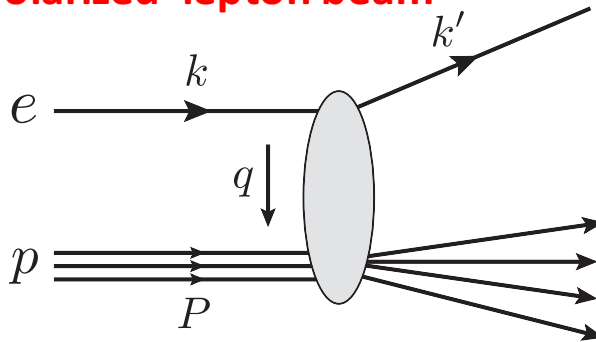
$$g_V^e g_A^b$$

$$F_{1,L} = C_q \otimes (q + \bar{q}) \quad F_3 = C_q \otimes (q - \bar{q})$$

$$\mathcal{L}_{\text{eff}} = \frac{g_W}{2c_W} \bar{f} \gamma_\mu (g_V^f - g_A^f \gamma_5) f Z_\mu$$

Zbb couplings @EIC

Polarized lepton beam



Single-Spin Asymmetry:

$$A_e^b = \frac{\sigma_{b,+}^{\text{tot}} - \sigma_{b,-}^{\text{tot}}}{\sigma_{b,+}^{\text{tot}} + \sigma_{b,-}^{\text{tot}}}$$

vector component of the Zbb coupling

Is it possible to probe the axial-vector component at the EIC?

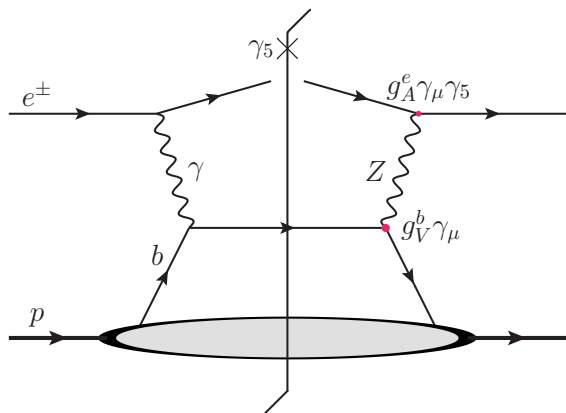
Average jet charge weighted Single-Spin Asymmetry (WSSA):

$$A_e^{bQ} = \frac{\sigma_{b,+}^Q - \sigma_{b,-}^Q}{\sigma_{b,+}^Q + \sigma_{b,-}^Q}$$

$$\sigma_{b,\pm}^Q = \int dp_T^j \frac{d\sigma_{b,\pm}^{\text{tot}}}{dp_T^j} \langle Q_J \rangle_b(p_T^j)$$

$$\langle Q_J \rangle_b(p_T^j) = \sum_{q=u,d,c,s,b} \left[f_J^q(p_T^j, \epsilon_q^b) - f_J^{\bar{q}}(p_T^j, \epsilon_q^b) \right] \langle Q_J^q \rangle_b(p_T^j)$$

Jet Charge Weighted SSA



SSA: $\sigma_{b,+} - \sigma_{b,-}$



$$g_A^e g_V^b$$

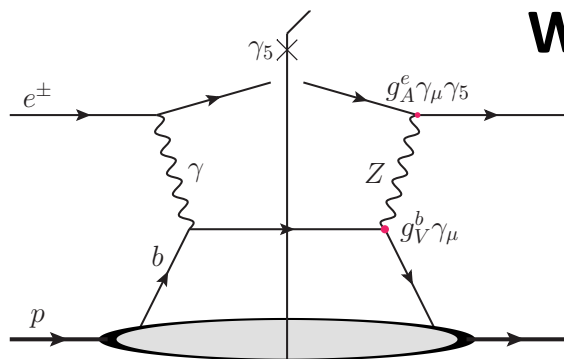
$$F_{1,L} = C_q \otimes (q + \bar{q})$$

$$g_V^e g_A^b$$

$$F_3 = C_q \otimes (q - \bar{q})$$

Key point:

$$\langle Q_J^q \rangle = -\langle Q_J^{\bar{q}} \rangle$$



WSSA: $\sigma_{b,+}^Q - \sigma_{b,-}^Q$

$$g_A^e g_V^b$$

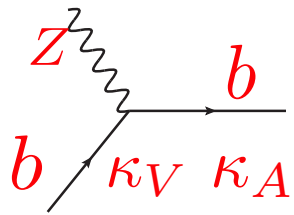
$$F_{1,L} = C_q \otimes (q - \bar{q}) \langle Q_J^q \rangle$$

$$g_V^e g_A^b$$

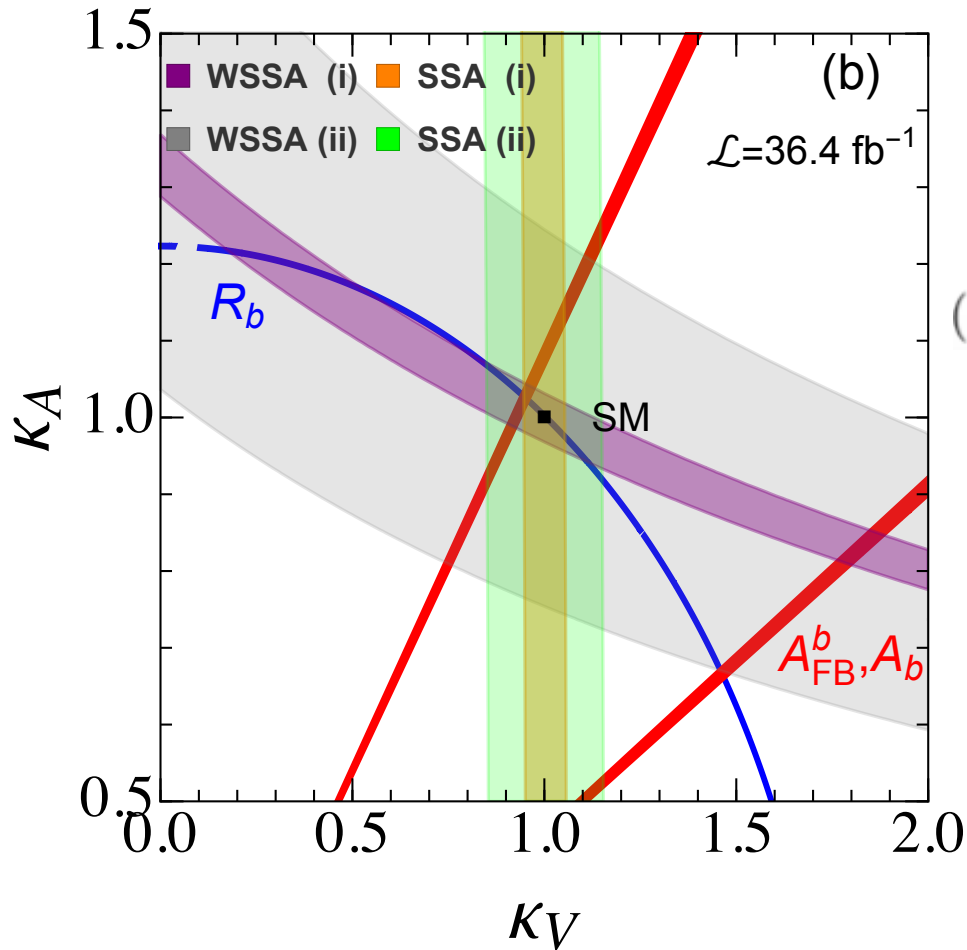
$$F_3 = C_q \otimes (q + \bar{q}) \langle Q_J^q \rangle$$



$$\mathcal{L}_{\text{eff}} = \frac{g_W}{2c_W} \bar{f} \gamma_\mu (g_V^f - g_A^f \gamma_5) f Z_\mu$$



Zbb couplings @EIC



$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5)bZ_\mu$$

- (i) $\epsilon_q^b = 0.001, \quad \epsilon_c^b = 0.03, \quad \epsilon_b = 0.7;$
(ii) $\epsilon_q^b = 0.01, \quad \epsilon_c^b = 0.2, \quad \epsilon_b = 0.5.$

WSSA

(i) : $\mathcal{L} > 0.6 \text{ fb}^{-1};$

(ii) : $\mathcal{L} > 36.4 \text{ fb}^{-1}.$

SSA

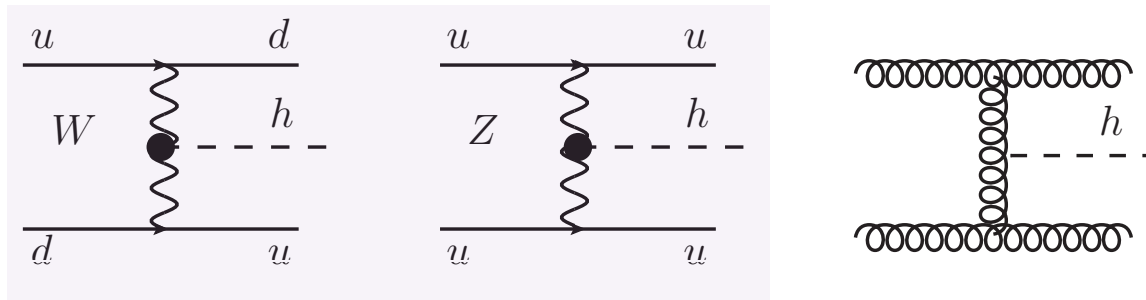
(i) : $\mathcal{L} > 0.5 \text{ fb}^{-1};$

(ii) : $\mathcal{L} > 4.0 \text{ fb}^{-1}.$

Probing the Higgs properties with jet charge

Higgs production mechanisms

Discriminating VBF and gluon fusion Higgs production



1. The rapidity gap and the invariant mass of the two jets

V.D. Barger, K.m.Cheung, T. Han, J. Ohnemus and D. Zeppenfeld, 1991

N. Kauer, T. Plehn, D. L. Rainwater and D. Zeppenfeld, 2001

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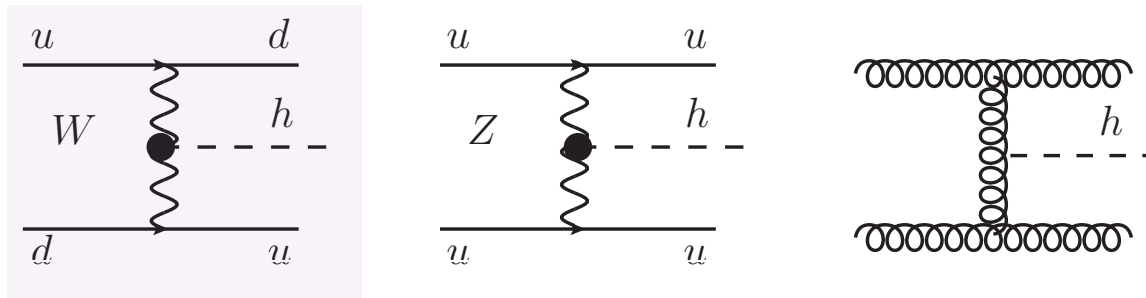
2. Soft gluon radiation effects

V. Rentala, N. Vignaroli, H.N. Li, Zhao LI and C.-P. Yuan, 2013

P. Sun, C.-P. Yuan and F. Yuan, 2016, 2018

Higgs production mechanisms

Discriminating W-boson fusion, Z-boson fusion and gluon fusion Higgs production



Separating the W boson's contribution from the VBF Higgs production is an important task for determining the Higgs gauge coupling

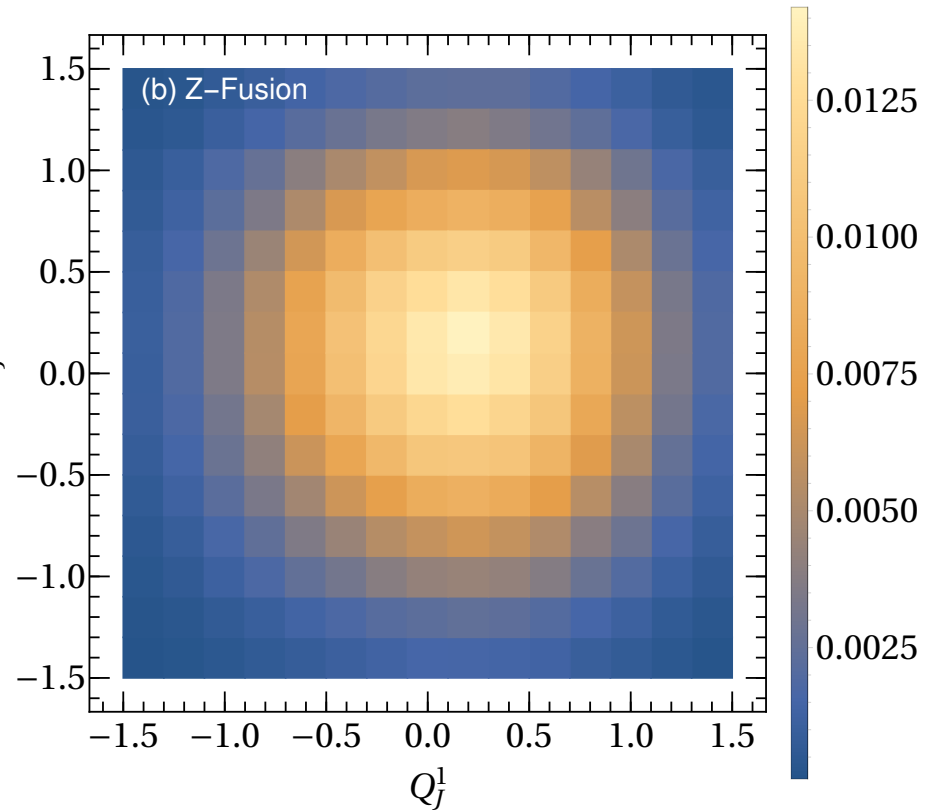
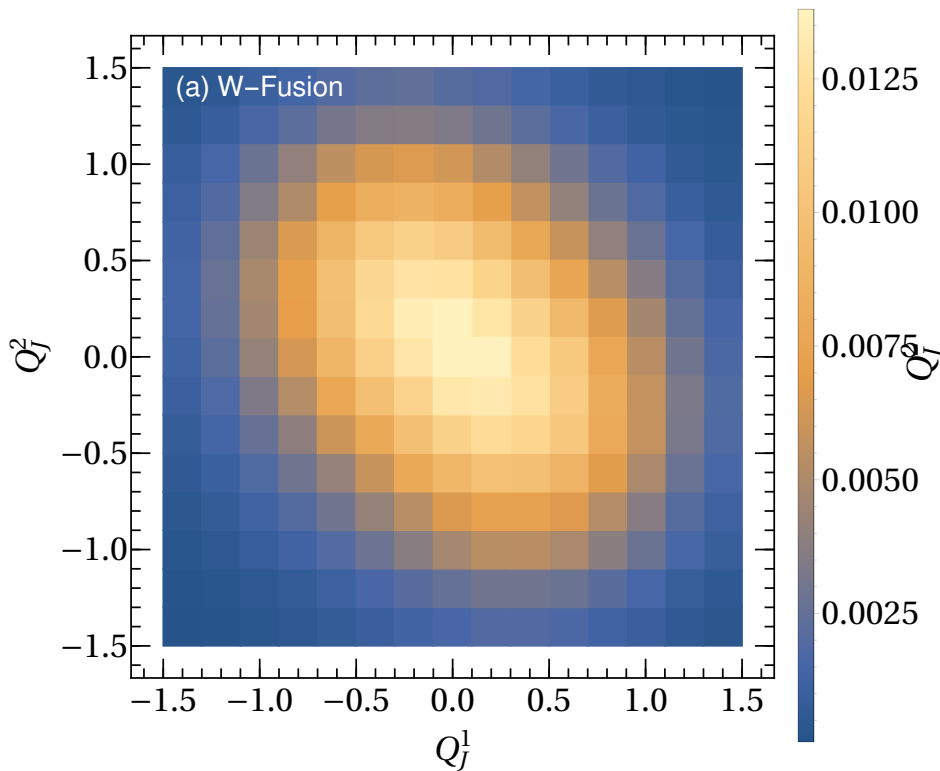
The key observable: **Jet Charge**

W: **opposite sign** for the two jet charges

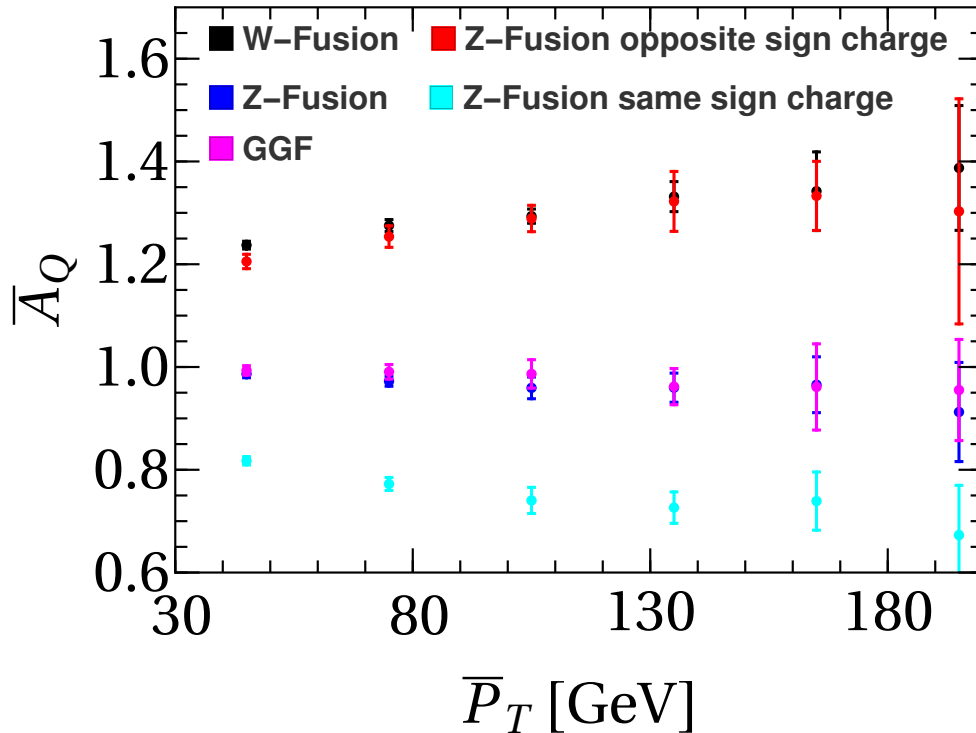
Z: **same or opposite sign** for the two jet charges

G: the sign of the jet charge is arbitrary

Higgs production mechanisms



Higgs production mechanisms



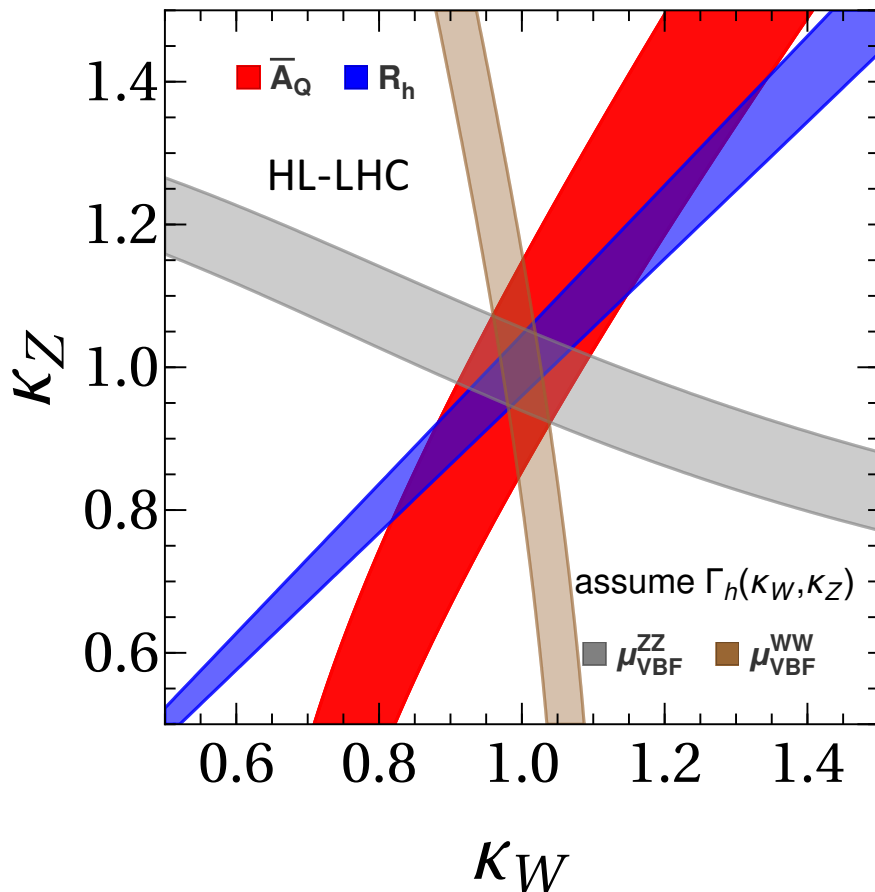
$\langle Q \rangle$ means the Average value

$$\bar{A}_Q = \frac{\langle |Q_J^1 - Q_J^2| \rangle}{\langle |Q_J^1 + Q_J^2| \rangle}$$

$$\bar{P}_T = \frac{p_T^1 + p_T^2}{2}$$

Higgs production mechanisms

$$h \rightarrow 4\ell/2\ell 2\nu_e$$



$$\bar{A}_Q^{\text{tot}} = \frac{f_W \langle Q^- \rangle_W + f_Z \langle Q^- \rangle_Z + f_G \langle Q^+ \rangle_G}{f_W \langle Q^+ \rangle_W + f_Z \langle Q^- \rangle_Z + f_G \langle Q^+ \rangle_G}$$

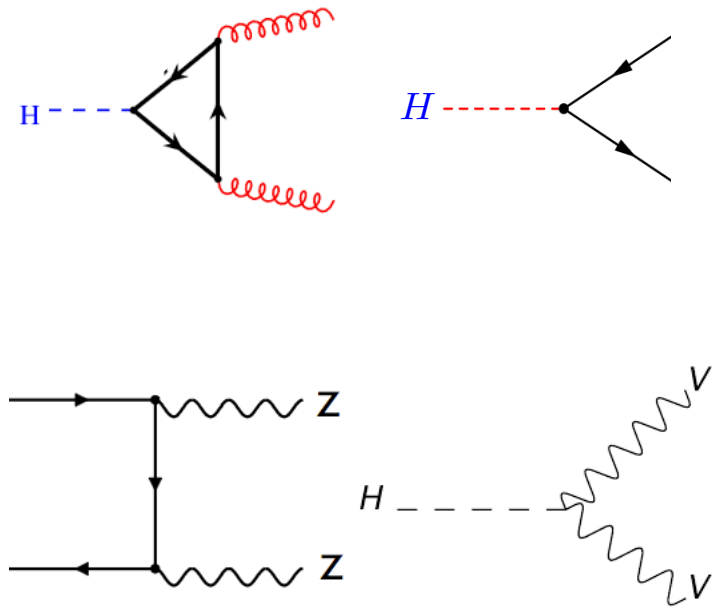
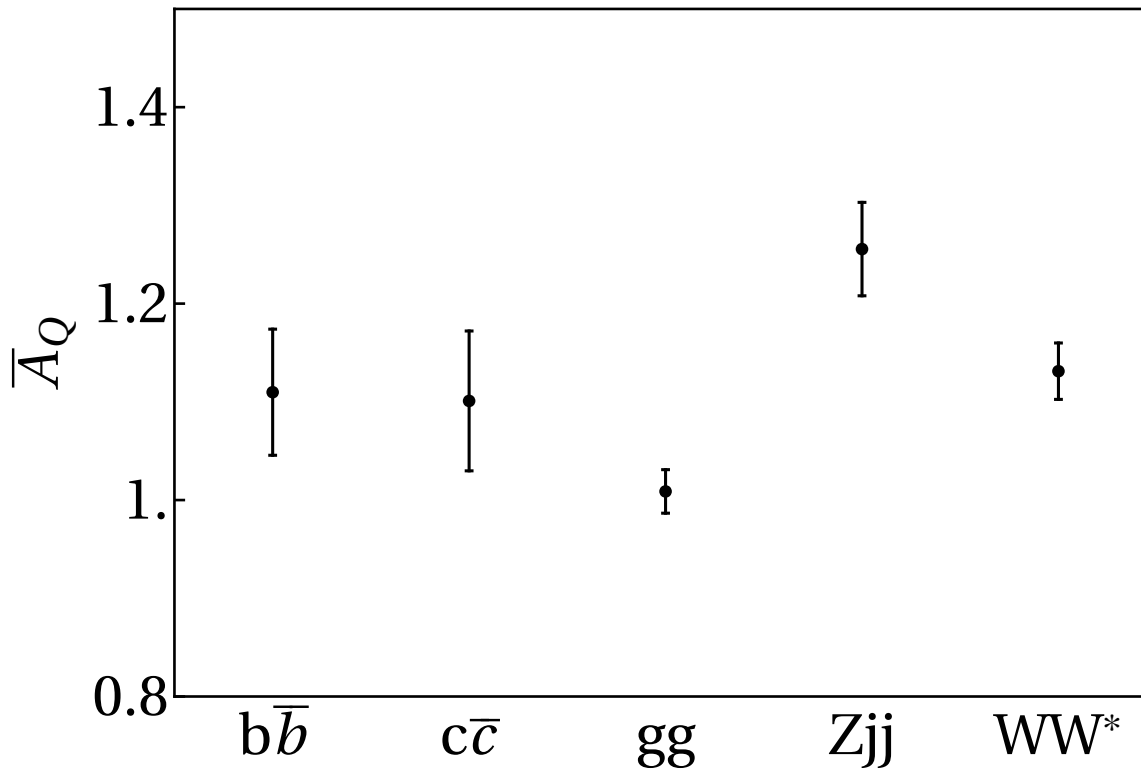
$$R_h = \frac{\mu(gg \rightarrow h \rightarrow WW^*)}{\mu(gg \rightarrow h \rightarrow ZZ^*)} = \frac{\kappa_W^2}{\kappa_Z^2}$$

$$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{\text{SM}}}$$

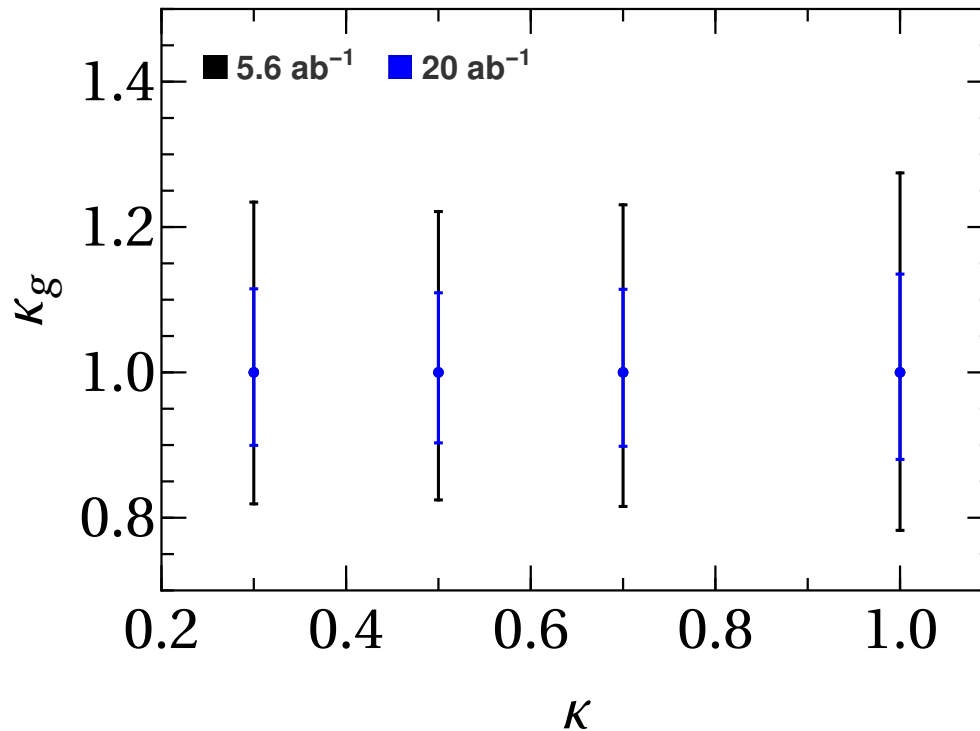
The limits from R_h and jet charge asymmetry **are not depending** on the assumption of the **Higgs width**

Higgs gluon effective couplings@ CEPC

The jet charges **are uncorrelated for the signal**, while it exhibits a **strong correlation for the backgrounds**



Higgs gluon effective couplings@CEPC



The jet charge information should be considered for the BDT or Machine Learning analysis

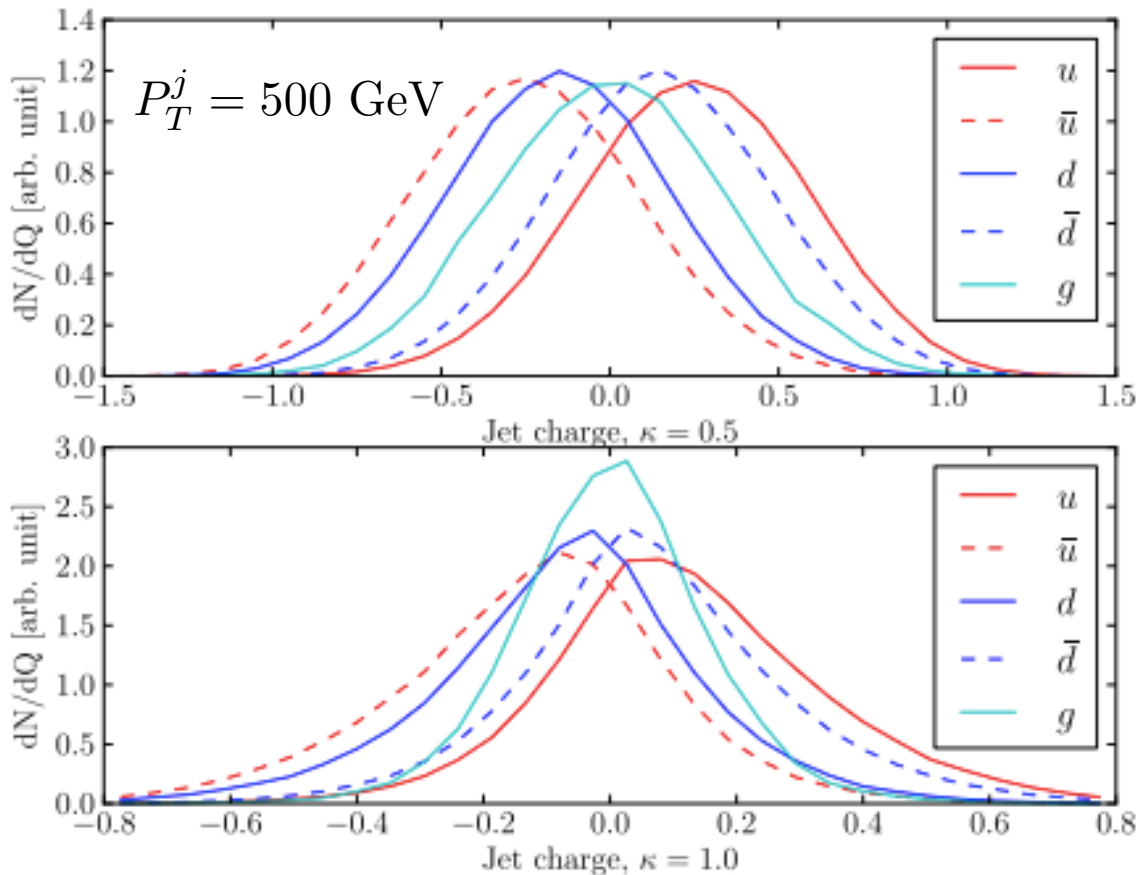
Summary

- A. The jet charge is a useful observable for both the QCD and new physics searches;
- B. We proposed to use jet charge weighted single-spin asymmetry to probe the Zbb anomalous couplings;
- C. We demonstrated that the jet charge can be used to discriminate Higgs production mechanisms and probe the Higgs gluon effective couplings.

Thank you!

Jet charge definition

$$Q_J = \frac{1}{(p_T^j)^\kappa} \sum_{i \in \text{jet}} Q_i (p_T^i)^\kappa, \quad \kappa > 0$$



D. Krohn, M. D. Schwartz, T. Lin, W.J. Waalewijn, PRL 110(2013)21,212001

Parton shower and hadronization **can not wash out** the primordial quark charge information