

# Application of the jet charge in electroweak and Higgs physics

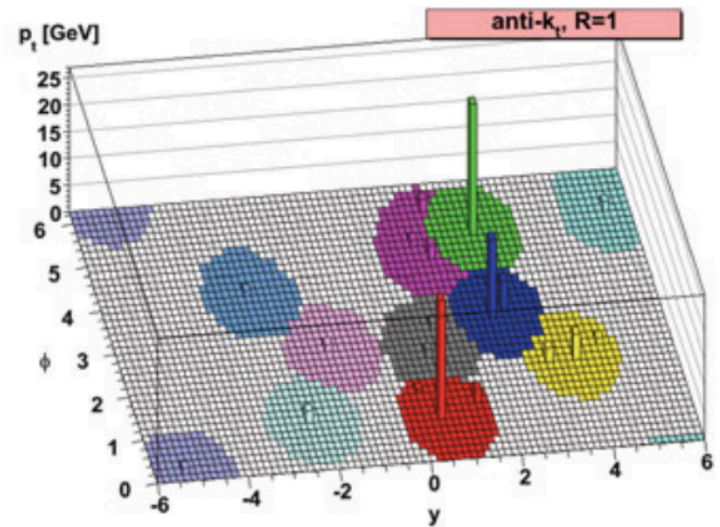
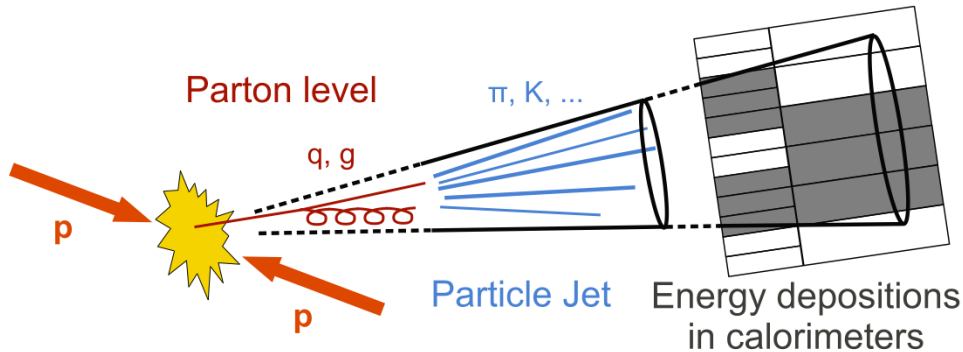
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Institute of High Energy Physics

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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:

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

$$d_{ij} = \min \left( \frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2} \right) \frac{\Delta R_{ij}^2}{R^2}$$

K: To regulate the sensitivity of the soft gluon radiation

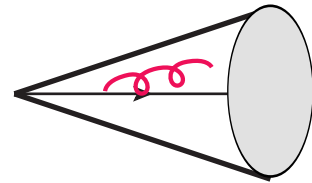
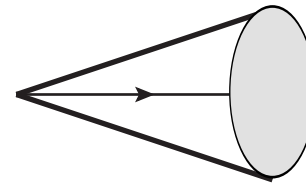
R.D. Field and R.P. Feynman, NPB136,1(1978)

# Jet charge definition

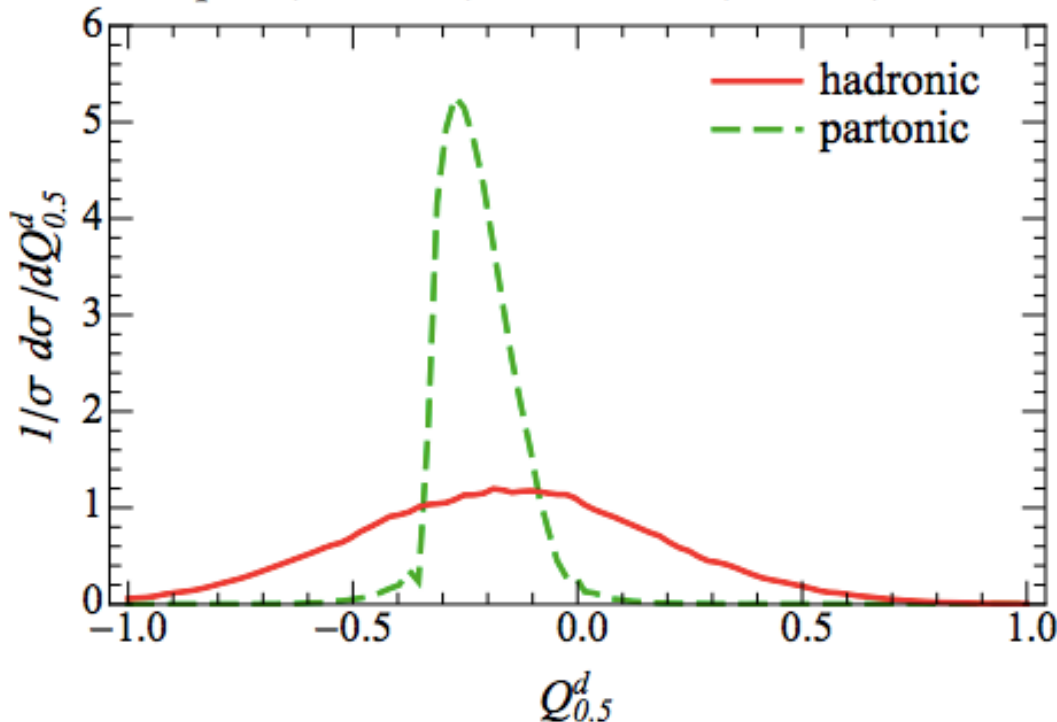
Jet charge is not an Infrared-safe quantity

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

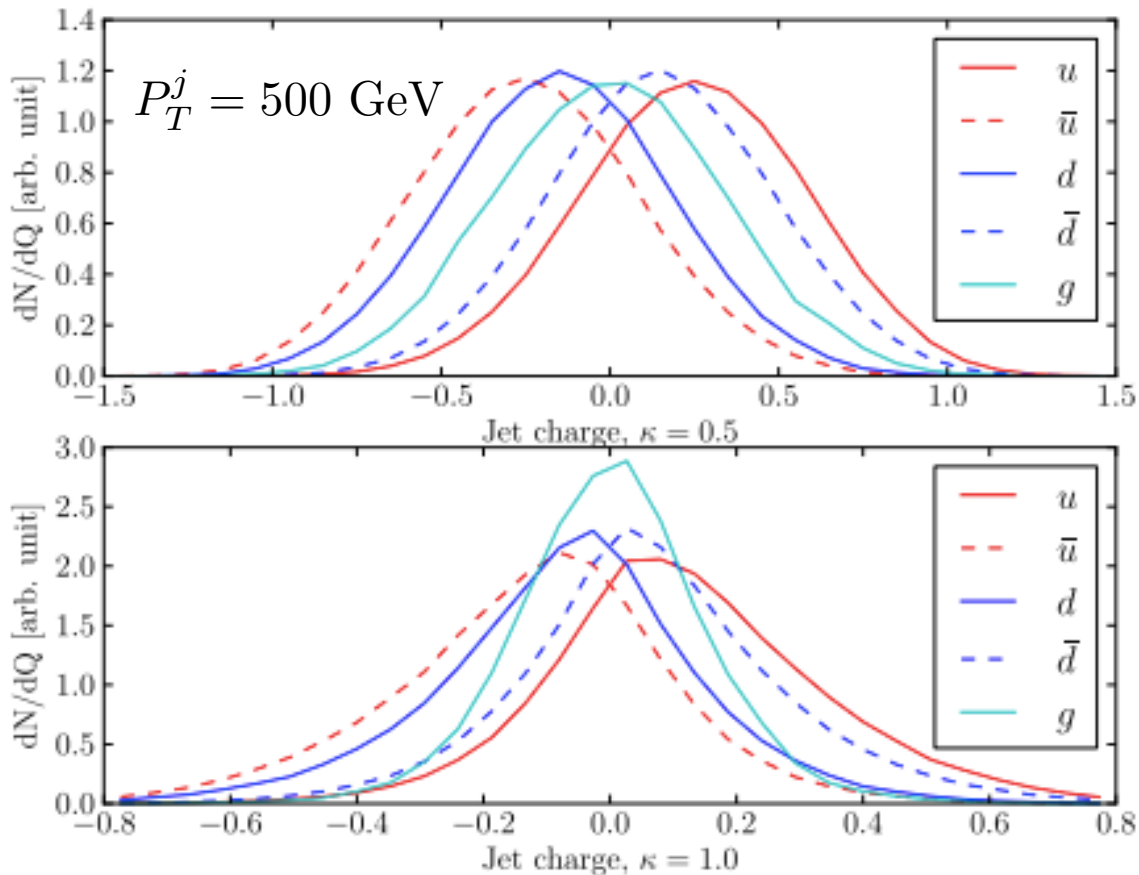
$$Q_q \neq (1-z)^k Q_q$$

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

It depends on the knowledge of the Fragmentation functions

# 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

# jet charge @ LEP

ALEPH Collaboration, PLB 259,377 (1991)

$$T = \max_{\vec{n}} \left( \frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right)$$

Jet charge asymmetry & forward-backward asymmetry

$$\sigma_{FB}^f = \frac{\sigma_F^f - \sigma_B^f}{\sigma_F^f + \sigma_B^f}$$

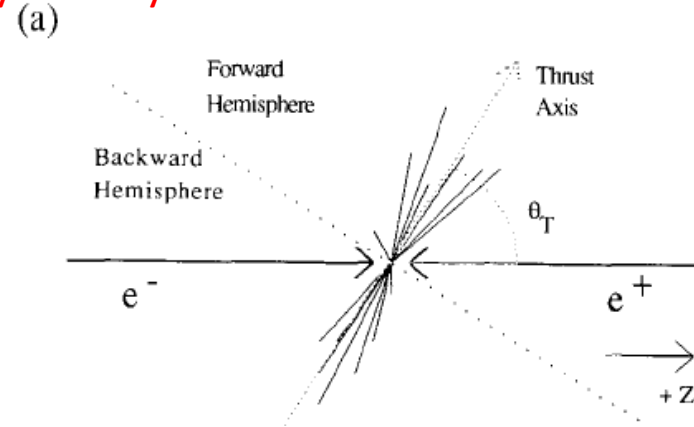
Average charges

$$\langle Q_F^f \rangle = q^f A_{FB}^f, \quad \langle Q_B^f \rangle = -q^f A_{FB}^f$$

$$\langle Q_{FB}^f \rangle = 2q^f A_{FB}^f$$

The electroweak properties of the Z boson

$$\sin^2 \theta_W(M_Z^2) = 0.23 \pm 0.0034(\text{stat}) \pm 0.001(\text{sys}) \pm 0.0038(\text{the})$$



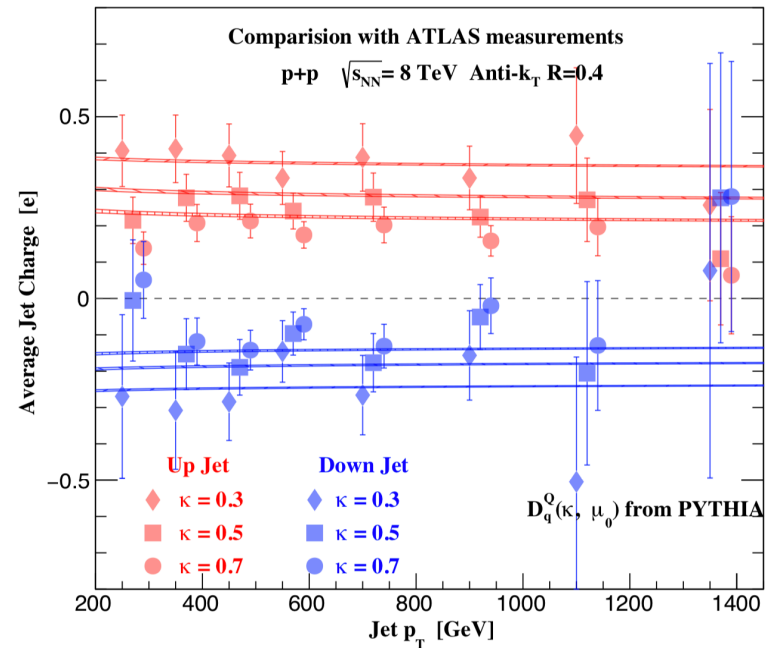
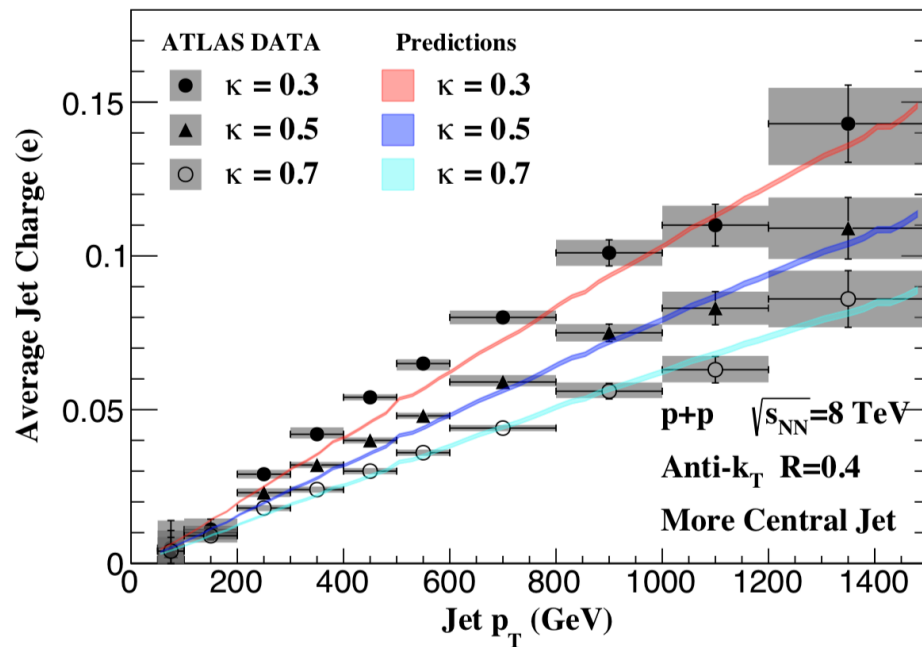
# Jet charge @ LHC

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

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

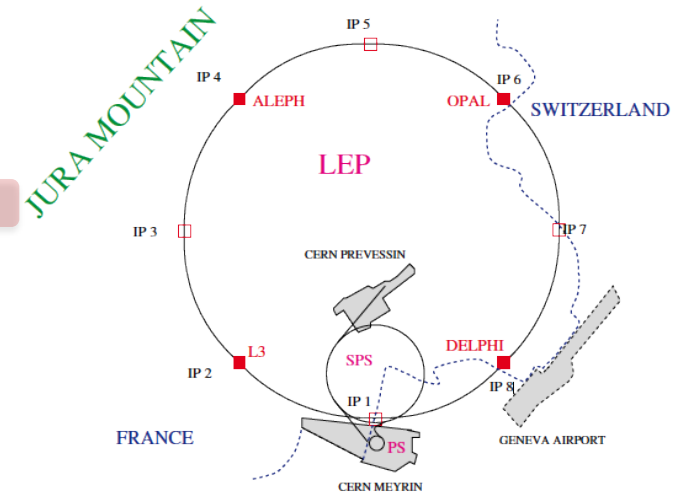
# Probing the $Zbb$ coupling with jet charge

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

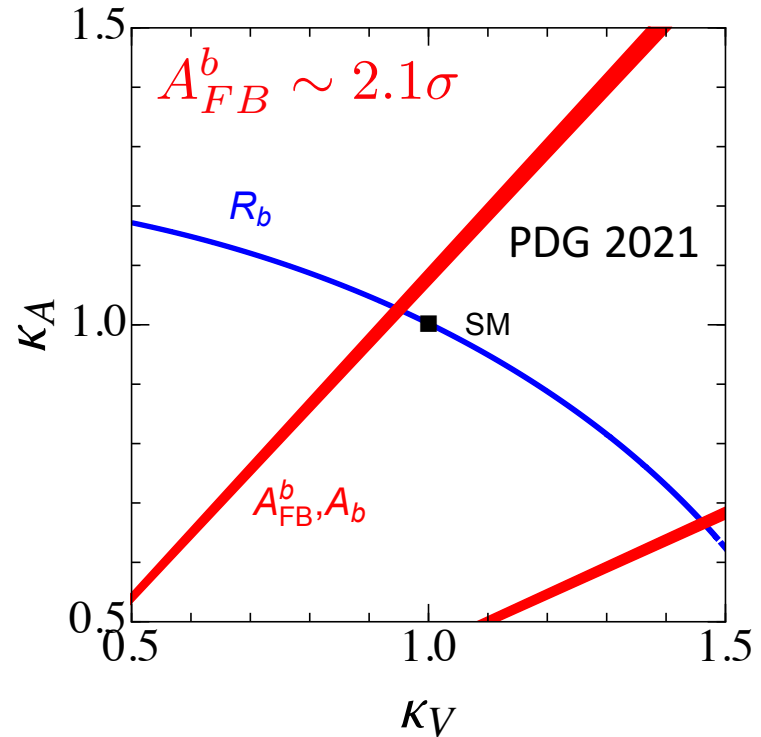
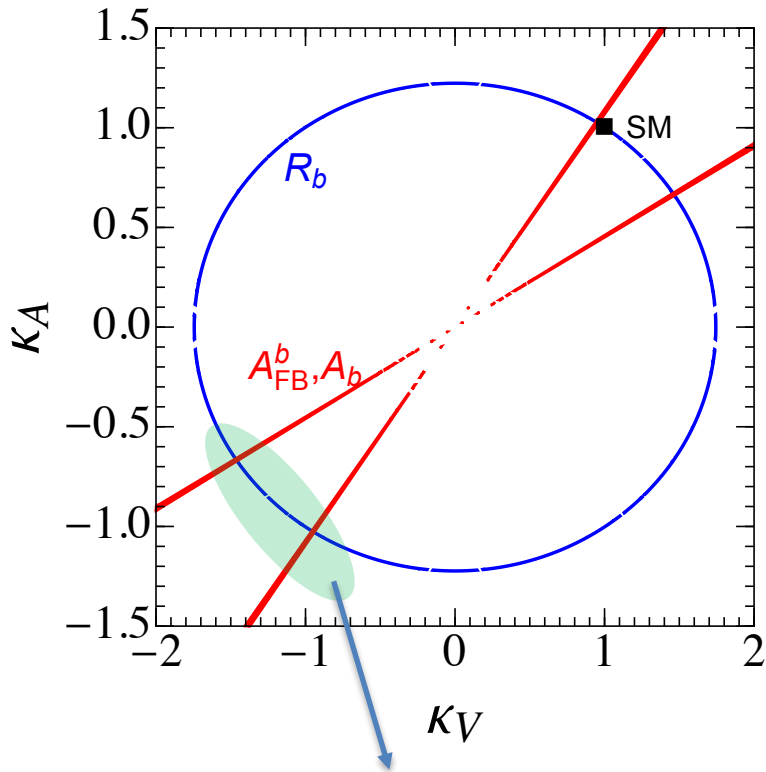
*Phys.Rept.* 427 (2006) 257-454

LEP: 1989-2000

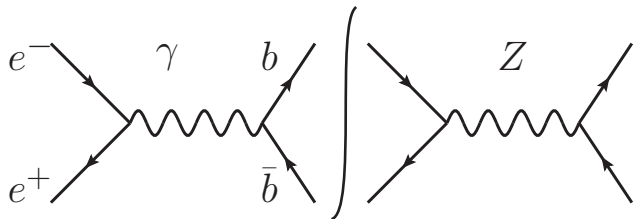




# Status of Zbb couplings



Excluded by off-Z pole data

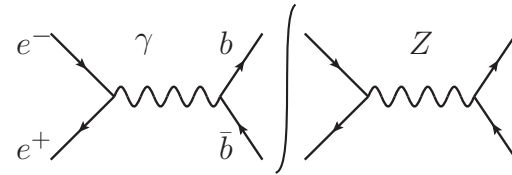


$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5)bZ_\mu$$

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

# Zbb couplings@ colliders

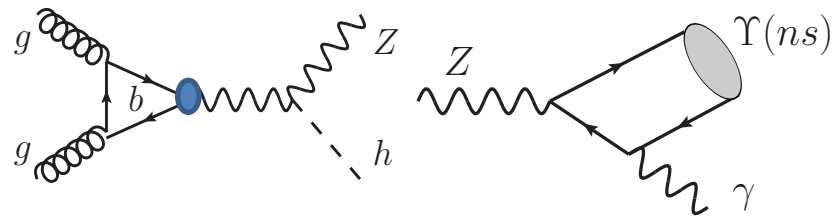
## A. Lepton colliders:



S. Gori, Jiayin Gu, Lian-Tao Wang, JHEP 04(2016) 062

**Bin Yan**, C.-P. Yuan and Shu-Run Yuan, work in progress

## B. LHC Zh production and Z boson rare decay:



**Bin Yan**, C.-P. Yuan, PRL127(2021)5,051801

Hongxin Dong, Peng Sun, **Bin Yan** and C.-P. Yuan, PLB829(2022)137076

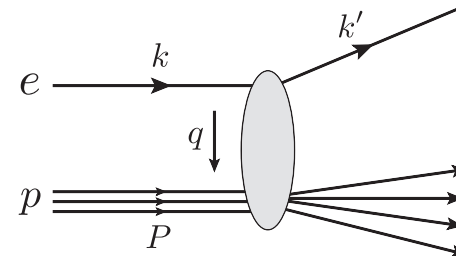
## C. LHC Z+2b-jet production

F. Bishara and Zhuoni Qian, 2306.15109

## D. HERA and EIC with polarized lepton beam:

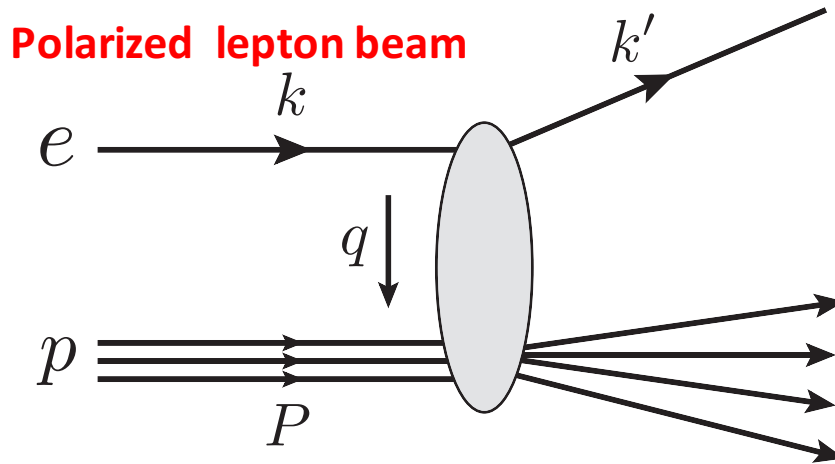
**Bin Yan**, Zhite Yu and C.-P. Yuan, PLB822(2021)136697

Hai Tao Li, **Bin Yan** and C.-P. Yuan, PLB833(2022)137300



# 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:  **$\gamma$ -Z interference**
3. Only sensitive to the **vector component** of the Zbb coupling

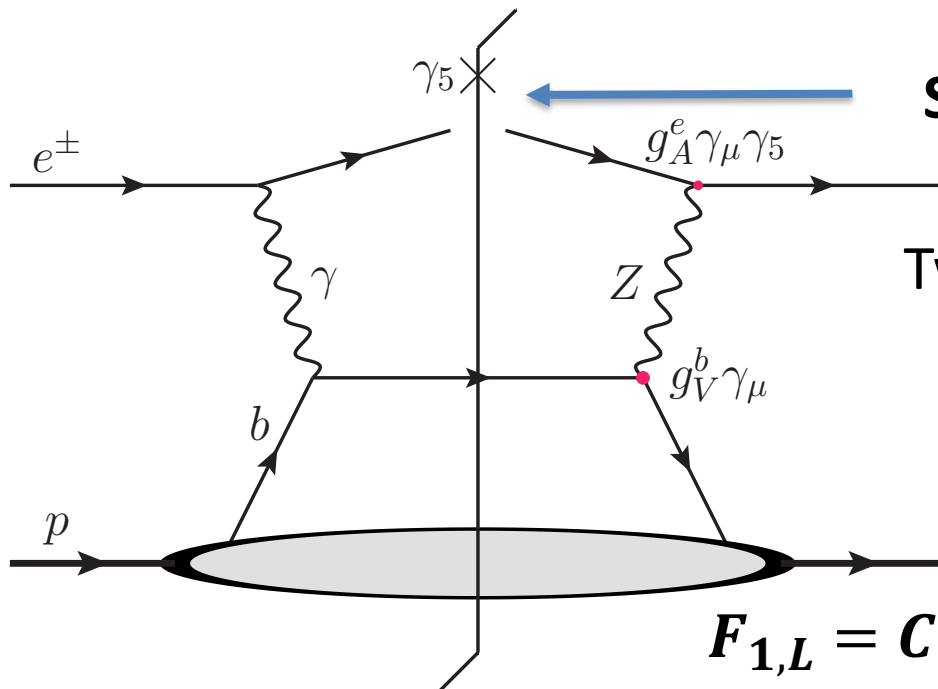
# DIS cross section

Polarized cross section

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

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

$\lambda_e = \pm 1$ : lepton helicity



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

Two possible combination:

$$g_A^e g_V^b$$



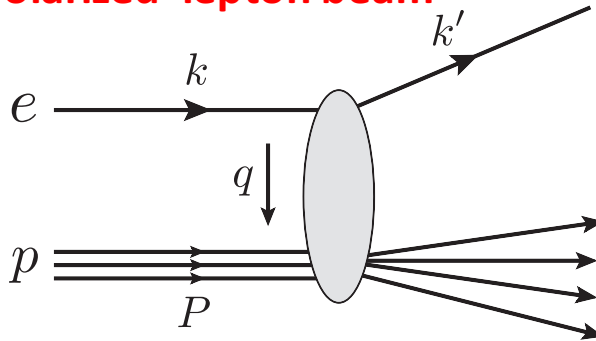
$$g_V^e g_A^b$$

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

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

# 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?

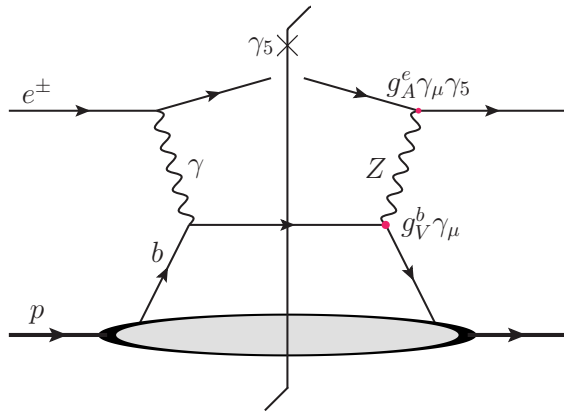
Average jet charge weighted Single-Spin Asymmetry (WSSA):

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

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

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

# Jet Charge Weighted SSA



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



$$g_A^e g_V^b$$

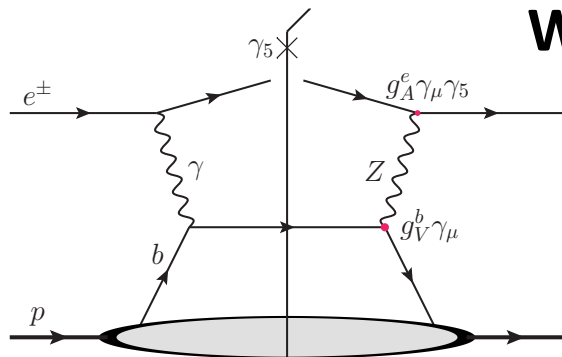
$$F_{1,L} = C_q \otimes (q + \bar{q})$$

$$g_V^e g_A^b$$

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

**Key point:**

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



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

$$g_A^e g_V^b$$

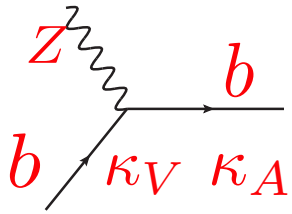
$$F_{1,L} = C_q \otimes (q - \bar{q}) \langle Q_J^q \rangle$$

$$g_V^e g_A^b$$

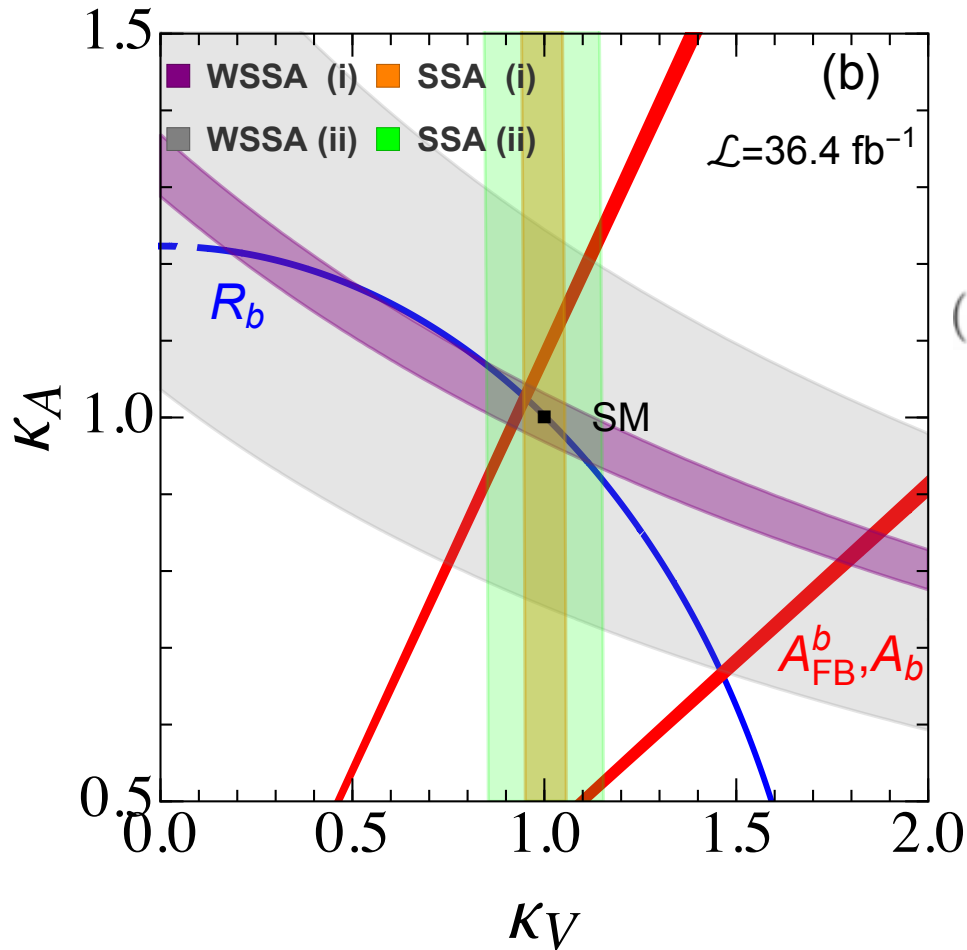
$$F_3 = C_q \otimes (q + \bar{q}) \langle Q_J^q \rangle$$



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



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

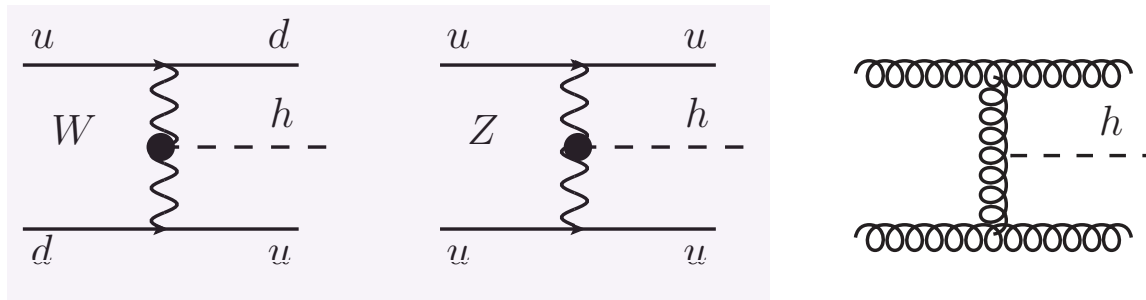
(ii) :  $\mathcal{L} > 4.0 \text{ fb}^{-1}.$

# 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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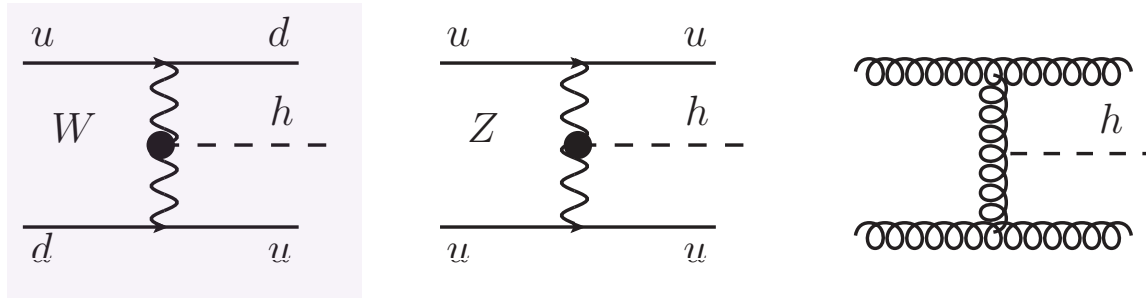
## 2. Soft gluon radiation effects

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

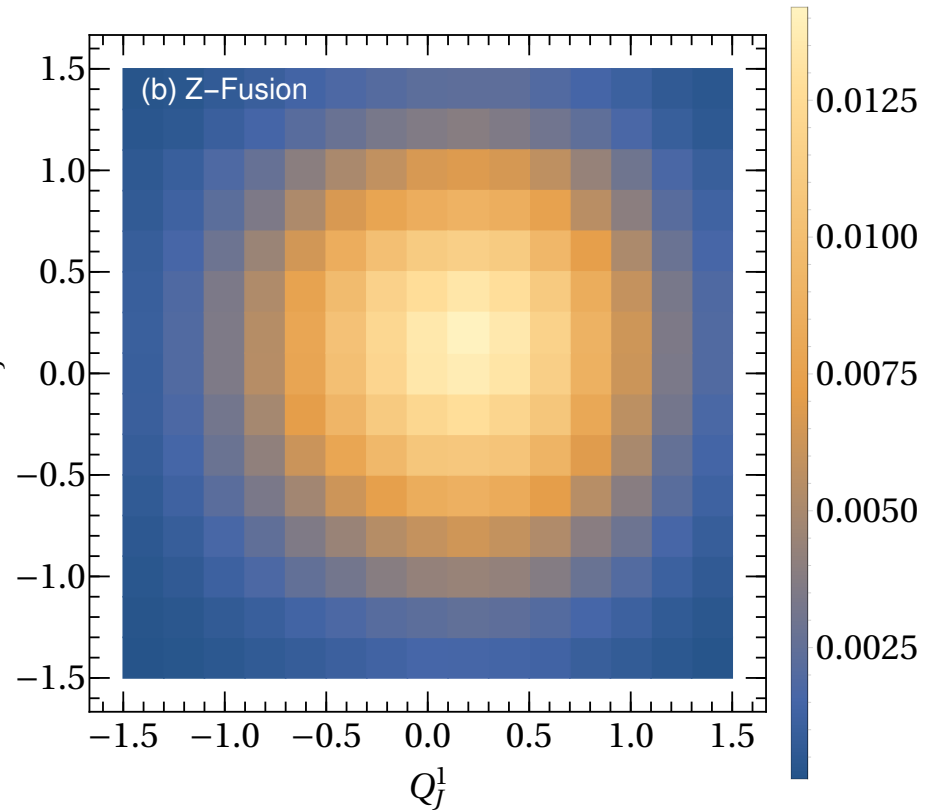
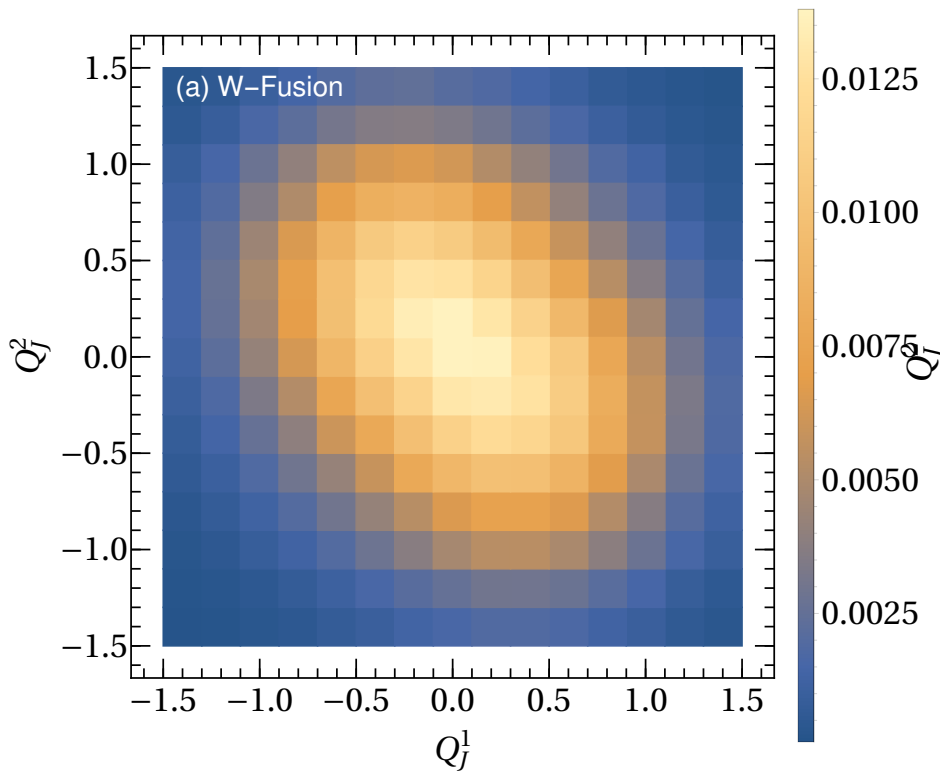
The key observable: **Jet Charge**

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

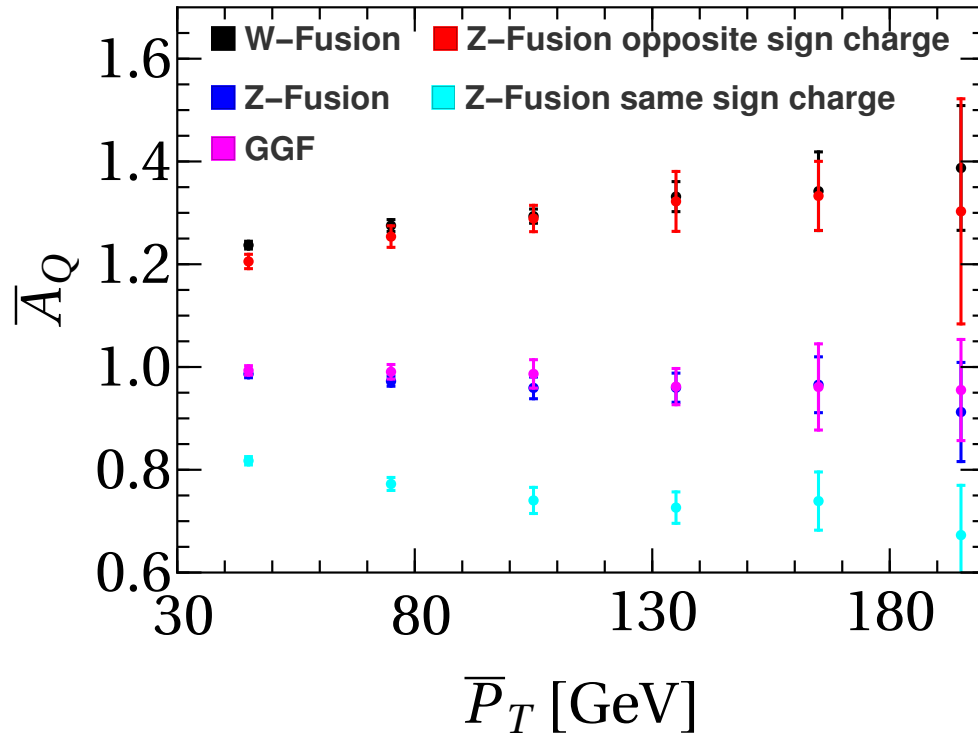
Z: **same or opposite sign** for the two jet charges

G: the sign of the jet charge is arbitrary

# Higgs production mechanisms



# Jet charge asymmetry



$$\mathcal{L} = 300 \text{ fb}^{-1}$$

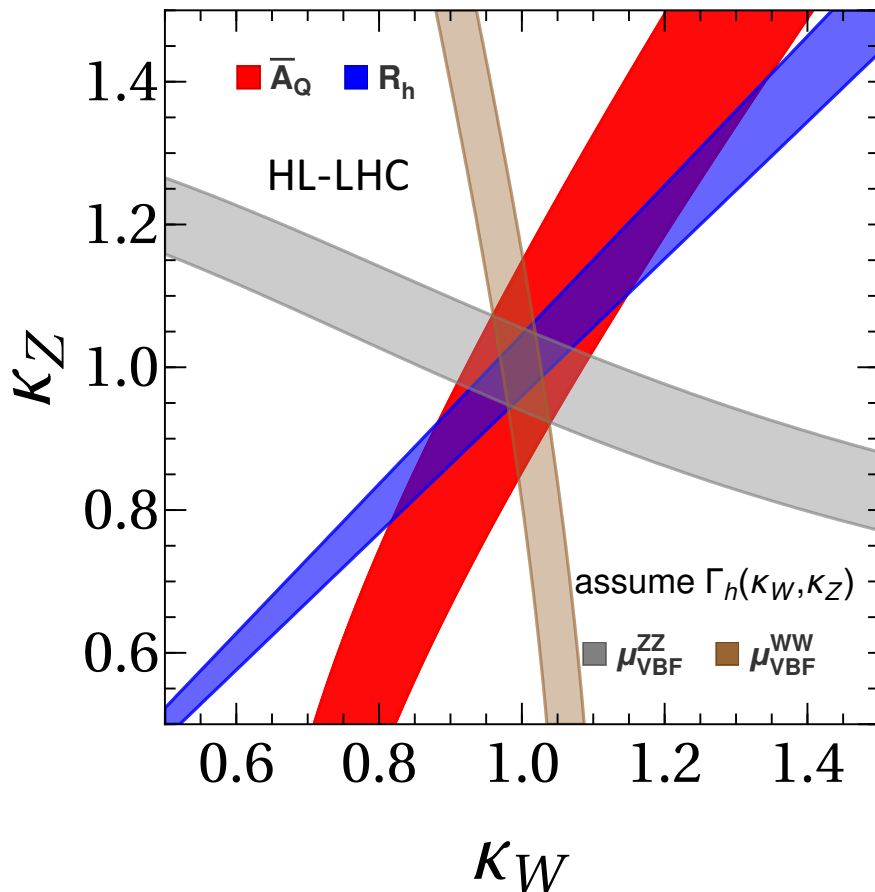
$\langle Q \rangle$  means the Average value

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

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

# 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**

# 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 couplings.

Thank you!

# Jet charge asymmetry

