Application of the jet charge in electroweak and Higgs physics

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第二届无中微子双贝塔衰变及相关物理研讨会
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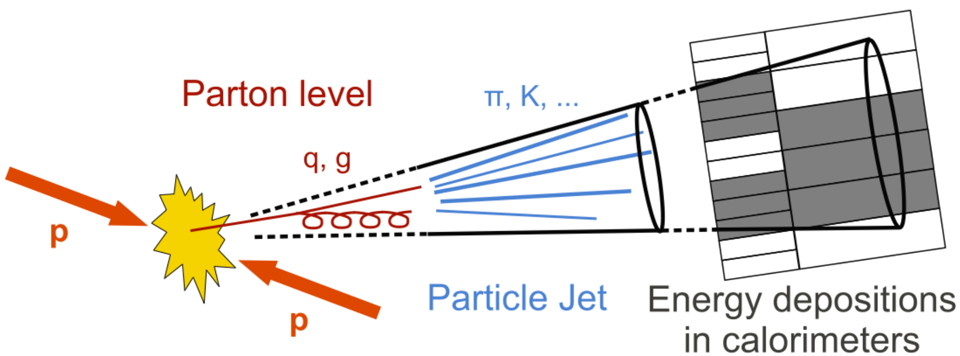
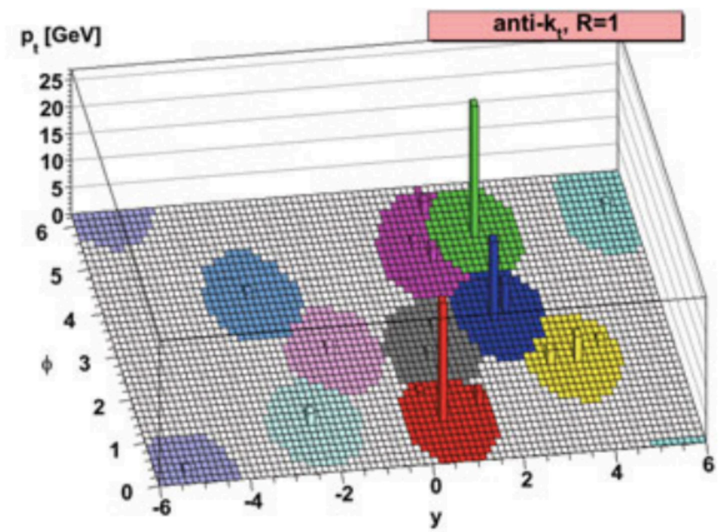
In cooperation with Hai Tao Li, Xiaorui Wong and C.-P. Yuan,
PLB833(2022)137300，2301.07914，2302.02084

Jet charge definition





Transverse-momentum-weighting scheme:

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

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

K: To regulate the sensitivity of the soft gluon radiation

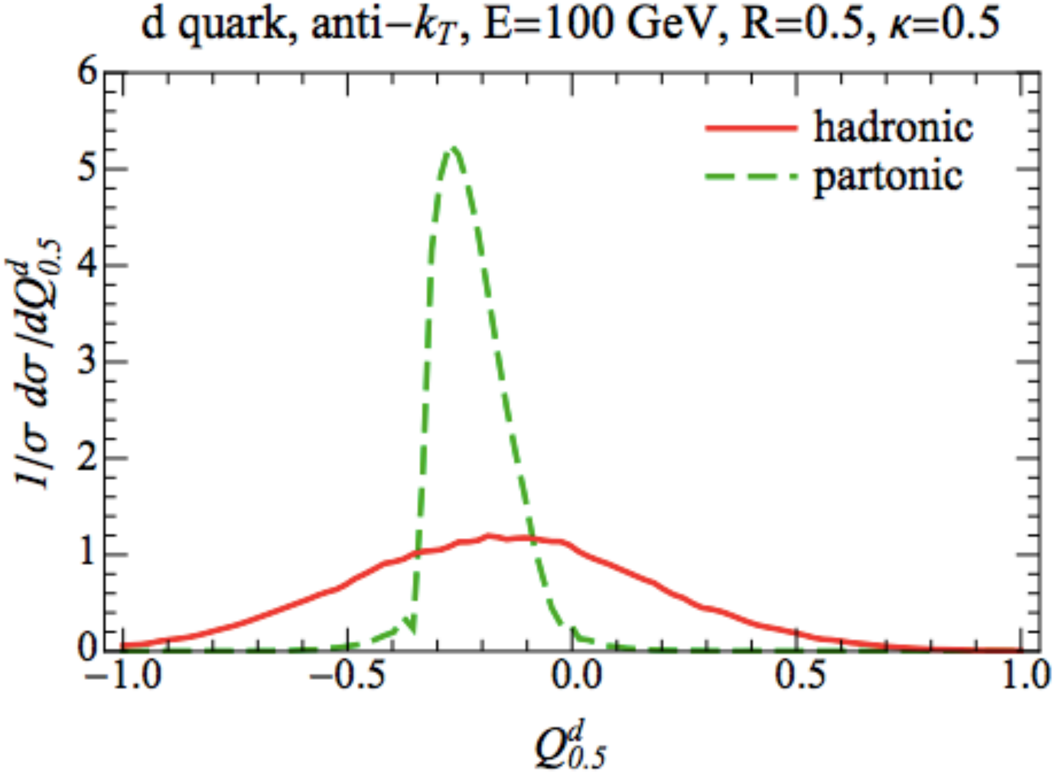
R.D. Field and R.P. Feynman, NPB136,1(1978)

Jet charge definition

Jet charge is not an Infrared-safe quantity

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

The collinear radiation



W.J.Waalewijn, PRD86(2012)094030

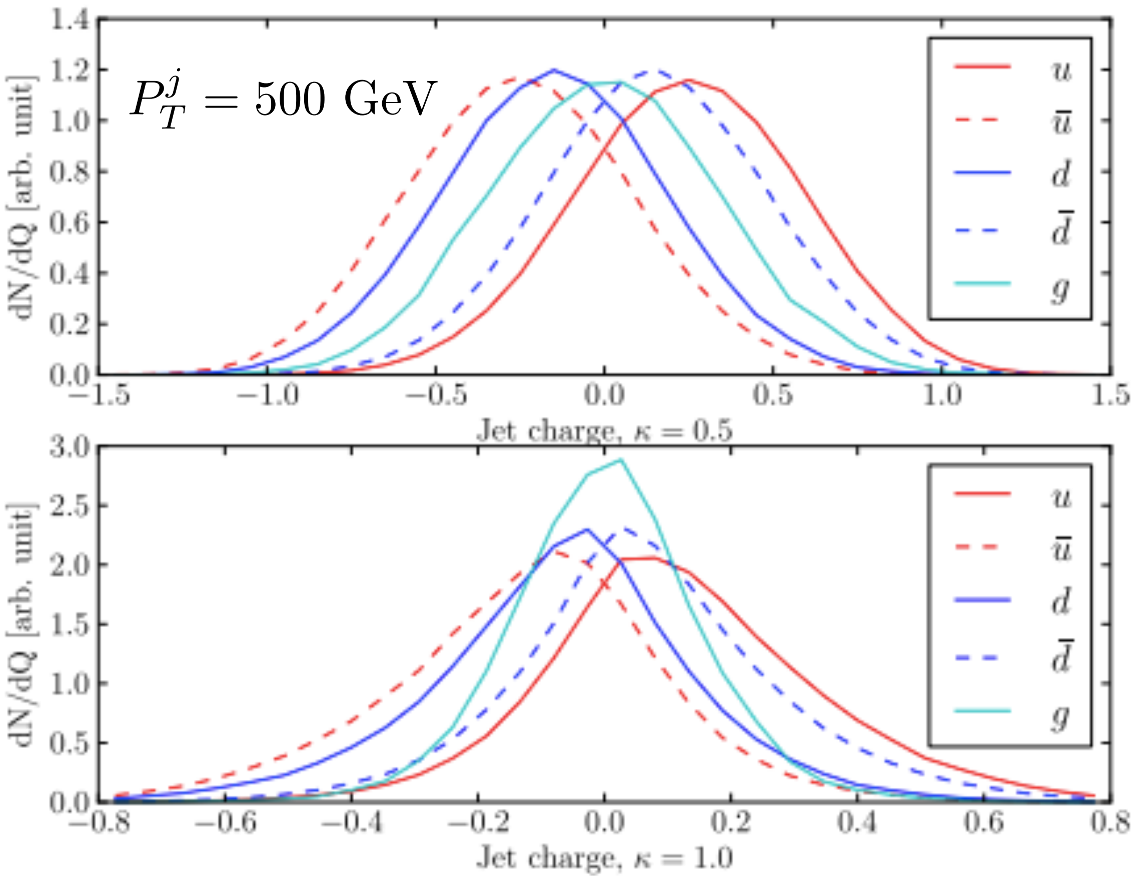
$$Q_q \neq (1-z)^k Q_q$$

The jet charge can be defined only at the hadron level

It depends on the knowledge of the Fragmentation functions

Jet charge definition

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



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

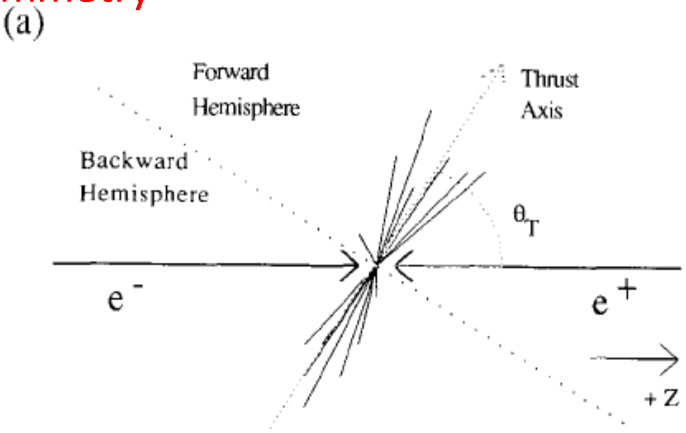
jet charge @ LEP

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

$$\sigma^f_{FB} = \frac{\sigma^f_F - \sigma^f_B}{\sigma^f_F + \sigma^f_B}$$



Average charges

$$\langle Q^f_F \rangle = q^f A^f_{FB}, \quad \langle Q^f_B \rangle = -q^f A^f_{FB}$$

$$\langle Q^f_{FB} \rangle = 2 q^f A^f_{FB}$$

The electroweak properties of the Z boson

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

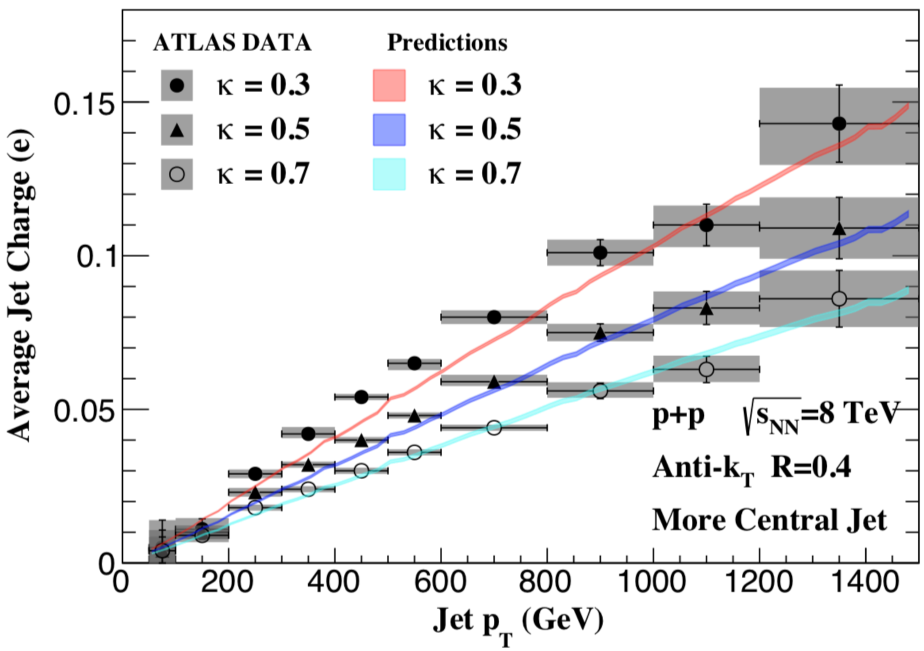
Jet charge @ LHC

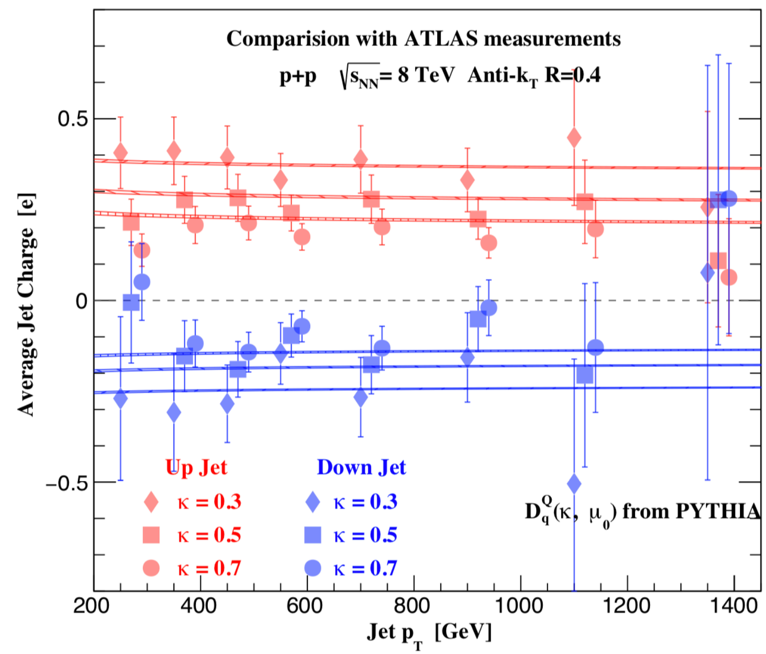
$$\langle Q_k^q \rangle = \frac{1}{\sigma_{q-jet}} \int d\sigma_{q-jet} Q_\kappa(\sigma_{q-jet})$$

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

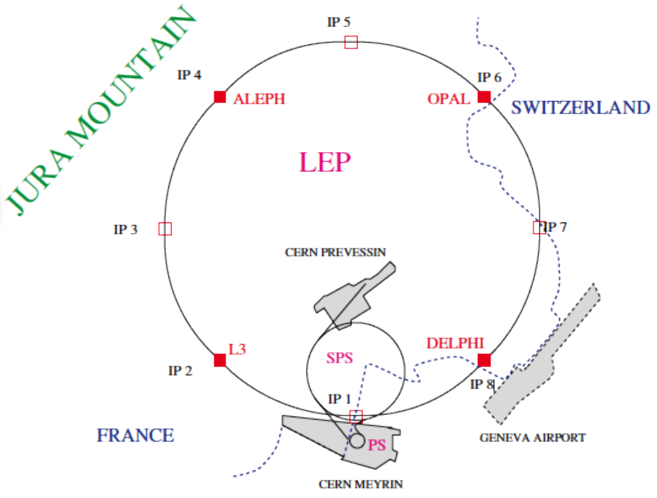
Probing the Zbb coupling with jet charge

Electroweak Precision measurement

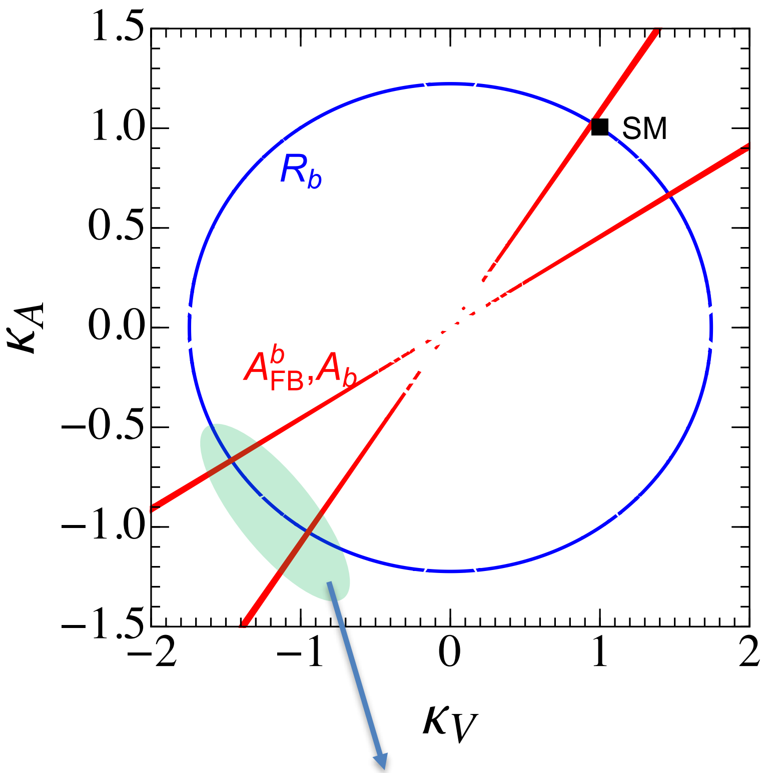
	Measurement with Total Error	Systematic Error	Standard Model High-Q^2 Fit	Pull
$\Delta\alpha^{(5)}_{\rm had}(m_Z^2)$ [59]	0.02758 ± 0.00035	0.00034	0.02767 ± 0.00035	0.3
m_Z [GeV]	91.1875 ± 0.0021	$^{(a)}0.0017$	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	$^{(a)}0.0012$	2.4965 ± 0.0015	0.6
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	$^{(a)}0.028$	41.481 ± 0.014	1.6
R^0_ℓ	20.767 ± 0.025	$^{(a)}0.007$	20.739 ± 0.018	1.1
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	$^{(a)}0.0003$	0.01642 ± 0.00024	0.8
+ correlation matrix Table 2.13				
$\mathcal{A}_\ell$ ($\mathcal{P}_\tau$)	0.1465 ± 0.0033	0.0015	0.1480 ± 0.0011	0.5
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.0011	0.1480 ± 0.0011	1.6
$R^0_{\rm b}$	0.21629 ± 0.00066	0.00050	0.21562 ± 0.00013	1.0
$R^0_{\rm c}$	0.1721 ± 0.0030	0.0019	0.1723 ± 0.0001	0.1
$A^{0,\rm b}_{\rm FB}$	0.0992 ± 0.0016	0.0007	0.1037 ± 0.0008	2.8
$A^{0,\rm c}_{\rm FB}$	0.0707 ± 0.0035	0.0017	0.0742 ± 0.0006	1.0
$\mathcal{A}_{\rm b}$	0.923 ± 0.020	0.013	0.9346 ± 0.0001	0.6
$\mathcal{A}_{\rm c}$	0.670 ± 0.027	0.015	0.6683 ± 0.0005	0.1
+ correlation matrix Table 5.11				
$\sin^2\theta^{\rm lept}_{\rm eff}$ ($Q^{\rm had}_{\rm FB}$)	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				

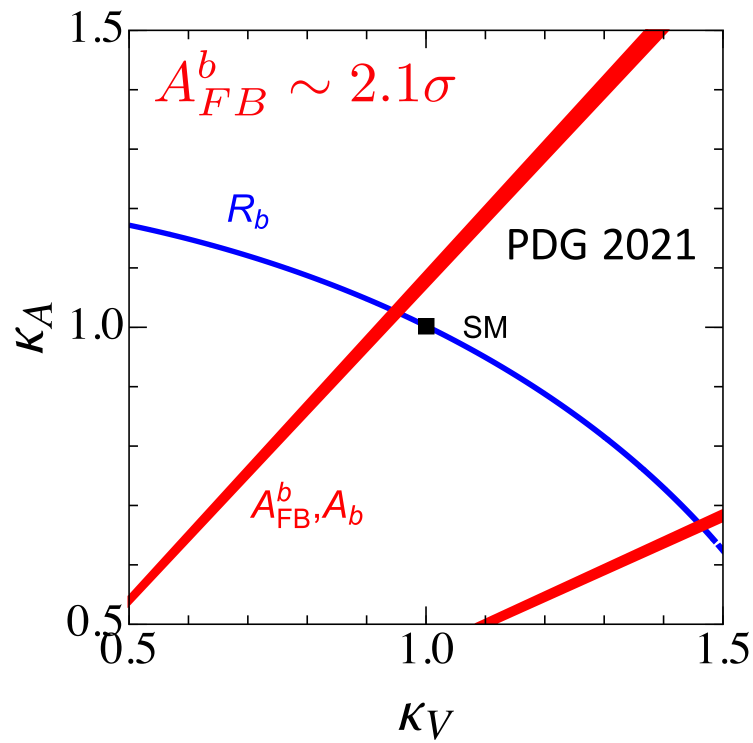
Phys.Rept. 427 (2006) 257-454

LEP： 1989-2000



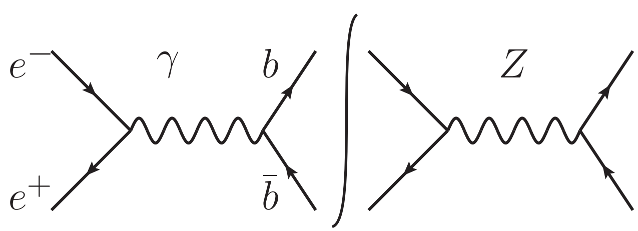
Status of Zbb couplings





Excluded by off-Z pole data

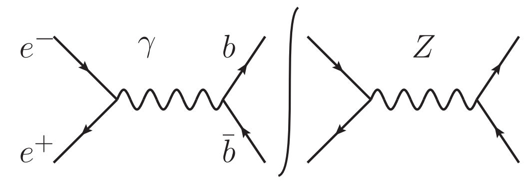
$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5) b Z_\mu$$



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

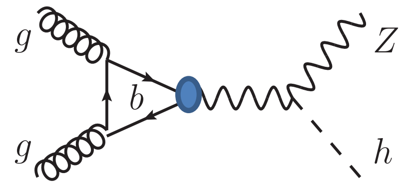
Zbb couplings@ colliders

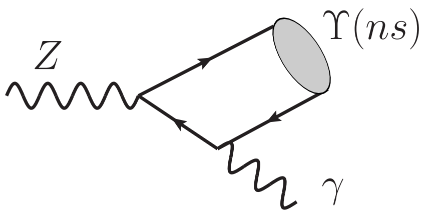
A. Lepton colliders:



S. Gori, Jiayin Gu, Lian-Tao Wang, JHEP 04(2016) 062
Bin Yan and Shu-Run Yuan, work in progress

B. LHC Zh production and Z boson rare decay:

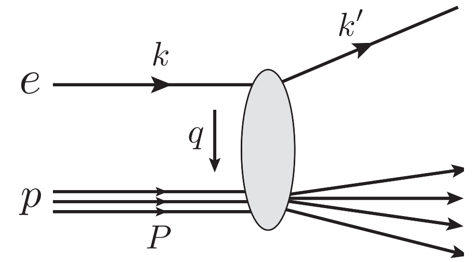




Bin Yan, C.-P. Yuan, PRL127(2021)5,051801

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

C. HERA and EIC with polarized lepton beam:

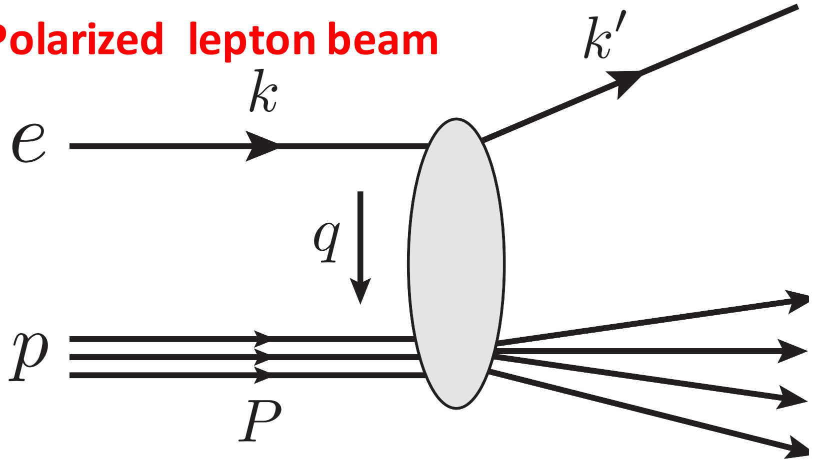


Bin Yan, Zhite Yu and C.-P. Yuan, PLB822(2021)136697
Hai Tao Li, Bin Yan and C.-P. Yuan, PLB833(2022)137300
Zhuoni Qian and Bin Yan, work in progress

Zbb couplings@EIC

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

Polarized lepton beam



Single-Spin Asymmetry (SSA):

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

$+/-$: 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

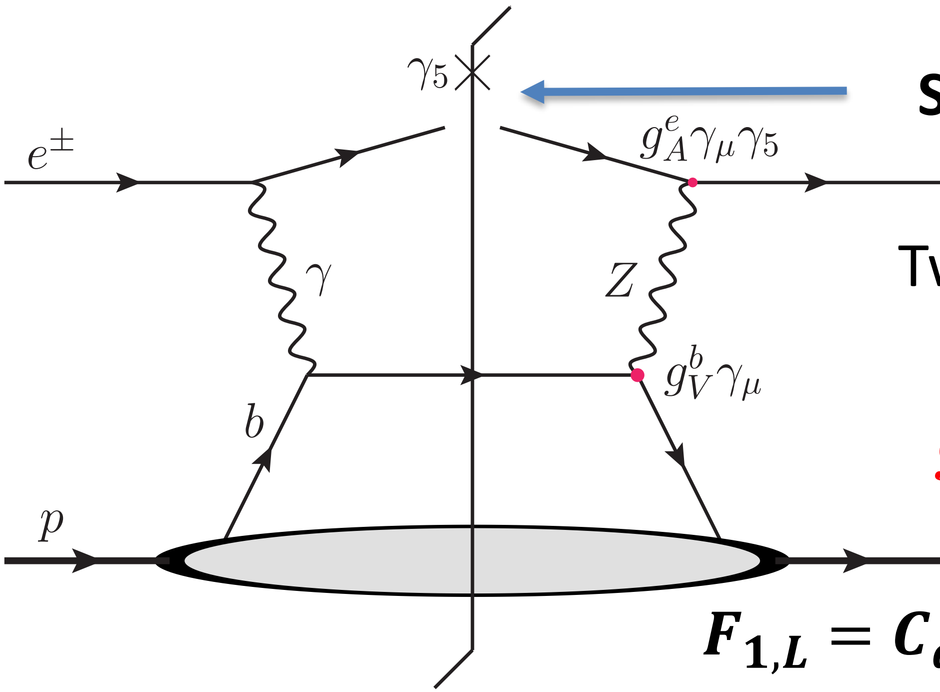
DIS cross section

Polarized cross section

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

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

$\lambda_e = \pm 1$: lepton helicity



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

Two possible combination:

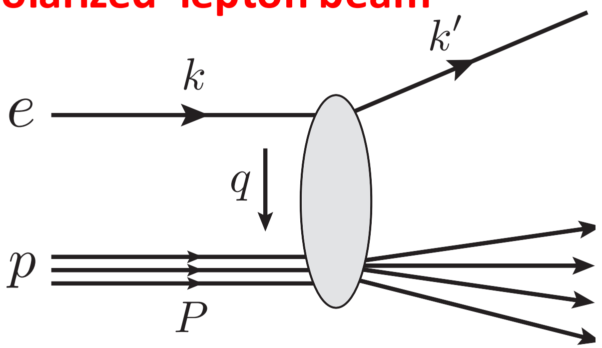
$g_A^e g_V^b$  $g_V^e g_A^b$

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

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

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?

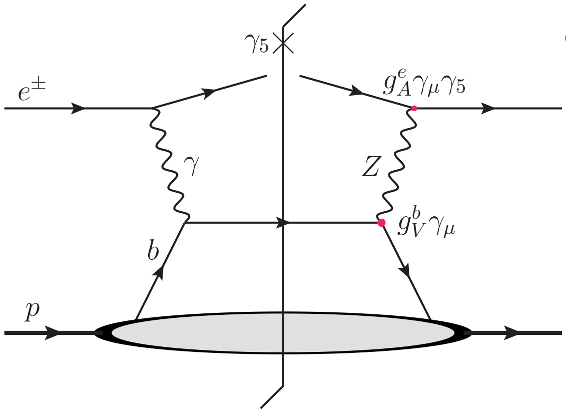
Average jet charge weighted Single-Spin Asymmetry (WSSA):

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

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

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

Jet Charge Weighted SSA



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

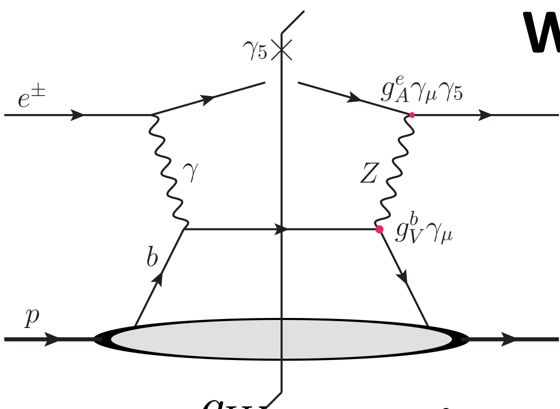
✓ $g_A^e g_V^b$

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

$g_V^e g_A^b$

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

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



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

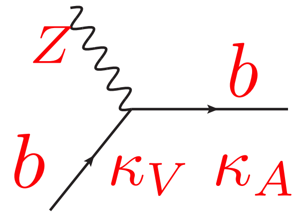
$g_A^e g_V^b$

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

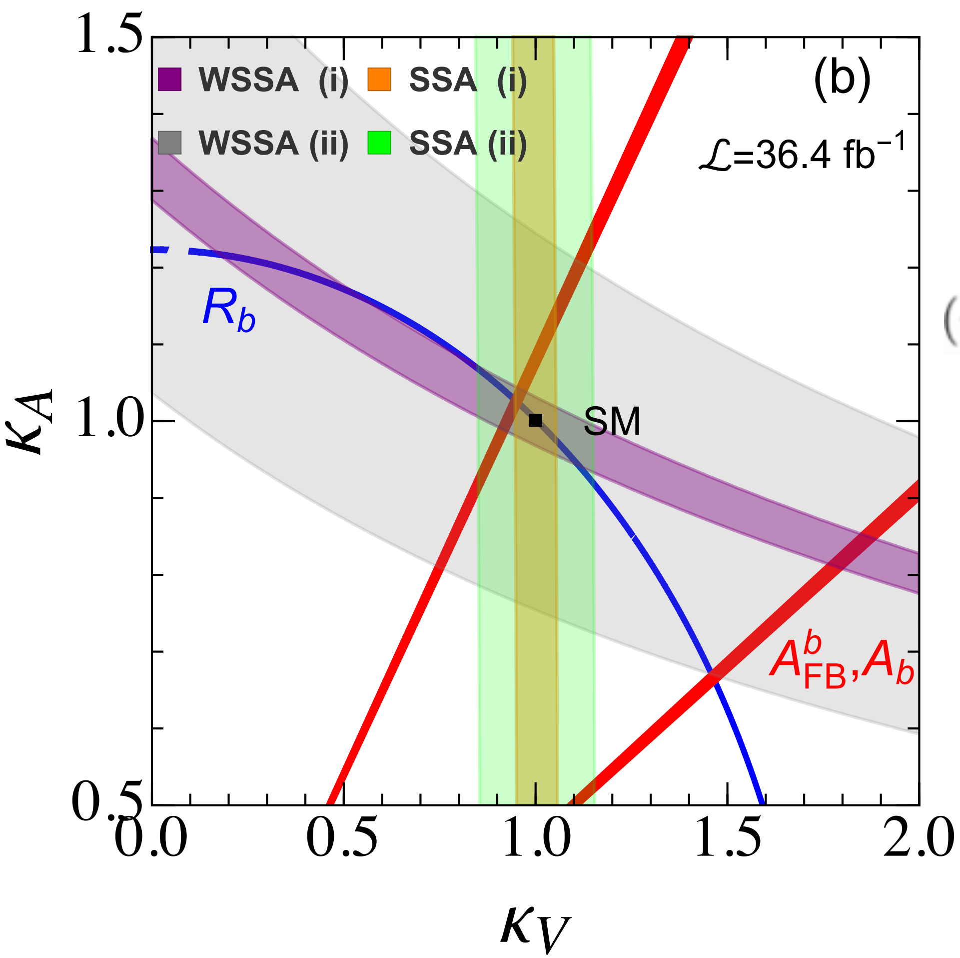
$g_V^e g_A^b$ ✓

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

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



Zbb couplings @EIC



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

$(i)\ \epsilon_q^b = 0.001, \quad \epsilon_c^b = 0.03, \quad \epsilon_b = 0.7;$

$(ii)\ \epsilon_q^b = 0.01, \quad \epsilon_c^b = 0.2, \quad \epsilon_b = 0.5.$

WSSA

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

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

SSA

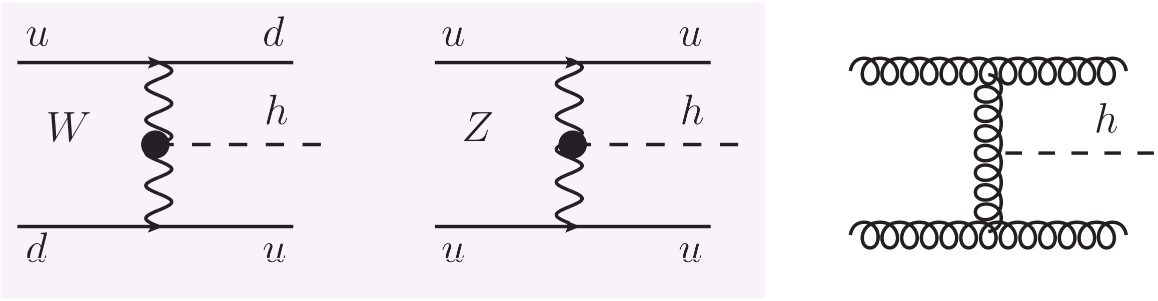
$(i) : \mathcal{L} > 0.5\ \text{fb}^{-1};$

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

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

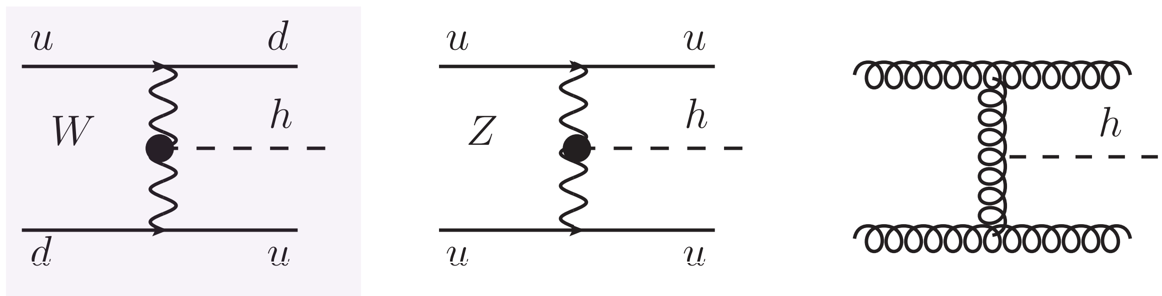
V.D. Bargeer, K.m.Cheung. T. Han, J. Ohnemus and D. Zeppenfeld, 1991
N. Kauer, T. Plehn, D. L. Rainwater and D. Zeppenfeld, 2001
……

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

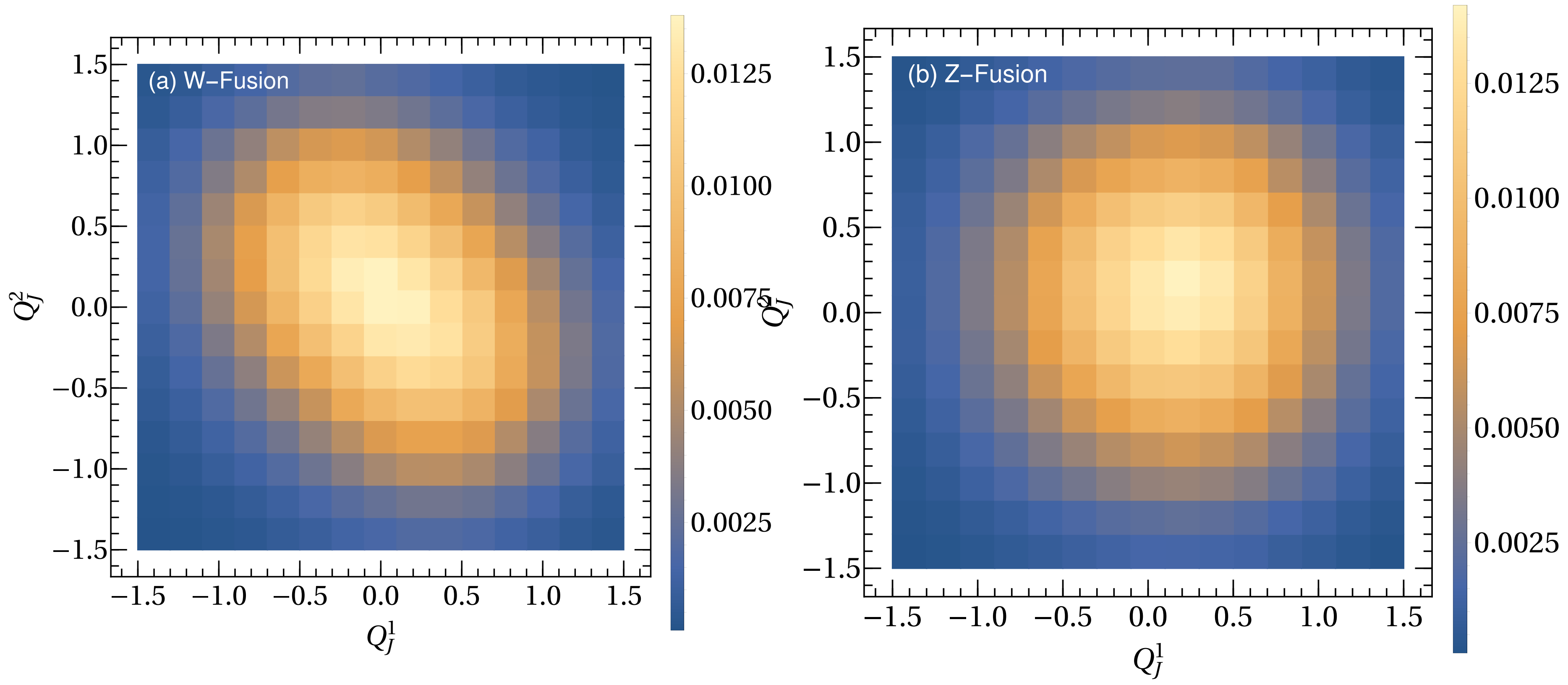
The key observable: Jet Charge

W: opposite sign for the two jet charges

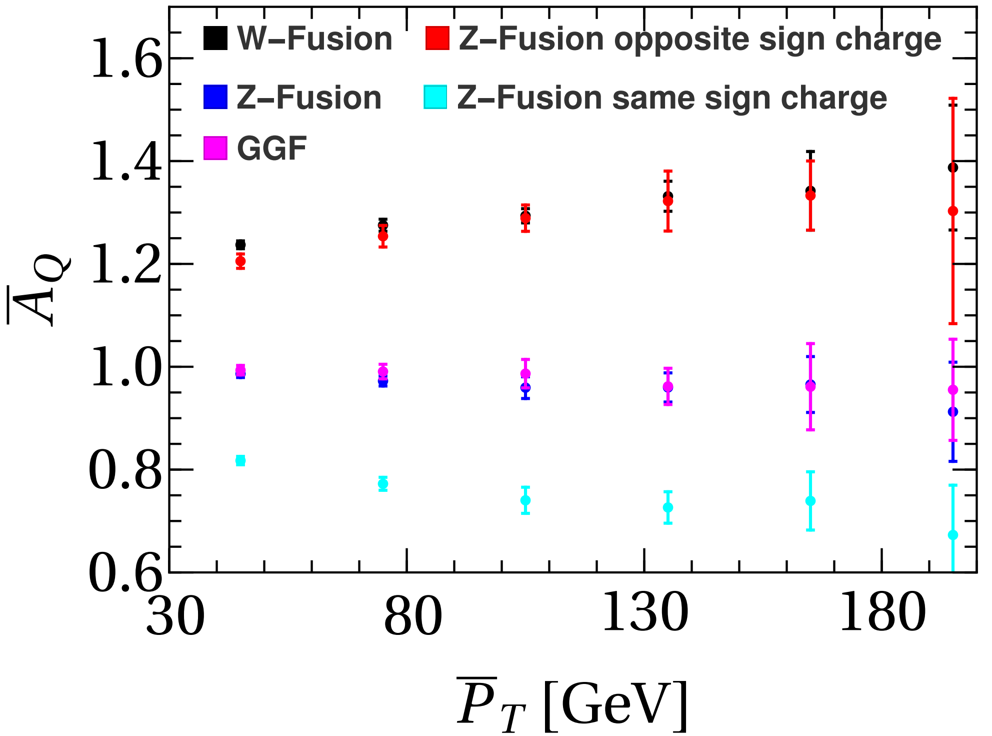
Z: same or opposite sign for the two jet charges

G: the sign of the jet charge is arbitrary

Higgs production mechanisms



Jet charge asymmetry



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

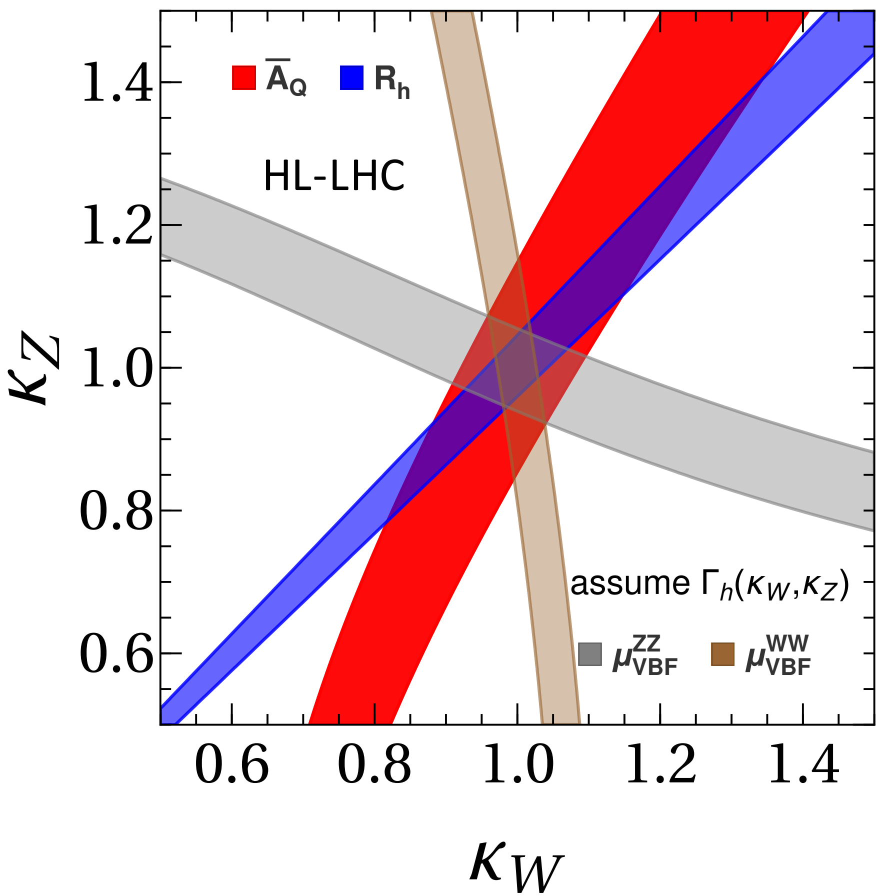
<Q> means the Average value

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

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

Higgs production mechanisms

$$h \to 4\ell/2\ell 2v_\ell$$



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

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

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

The limits from Rh 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