Discriminating between Higgs Production Mechanisms via Jet Charge at the LHC

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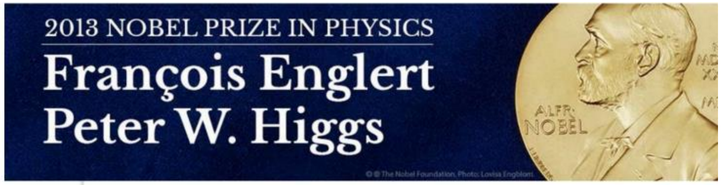
In cooperation with Hai Tao Li and C.-P. Yuan
PRL 131 (2023) 4,041802

The Era of the Higgs Physics



Understanding of origin of mass of subatomic particles

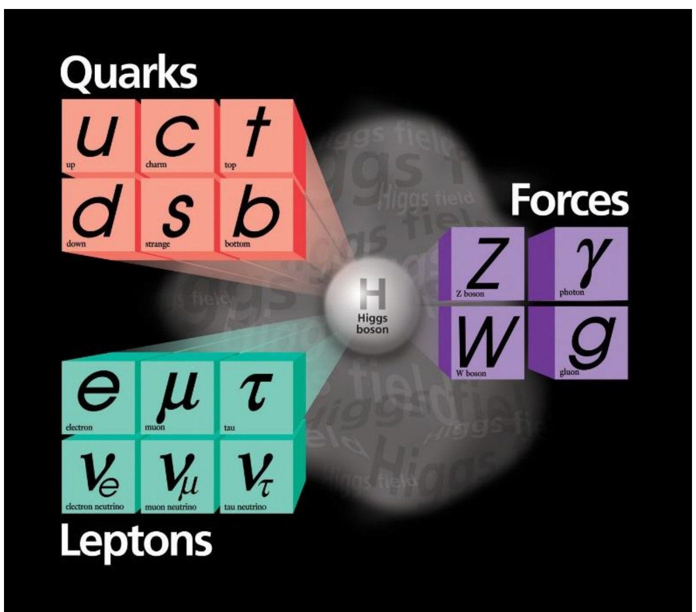
8 October 2013

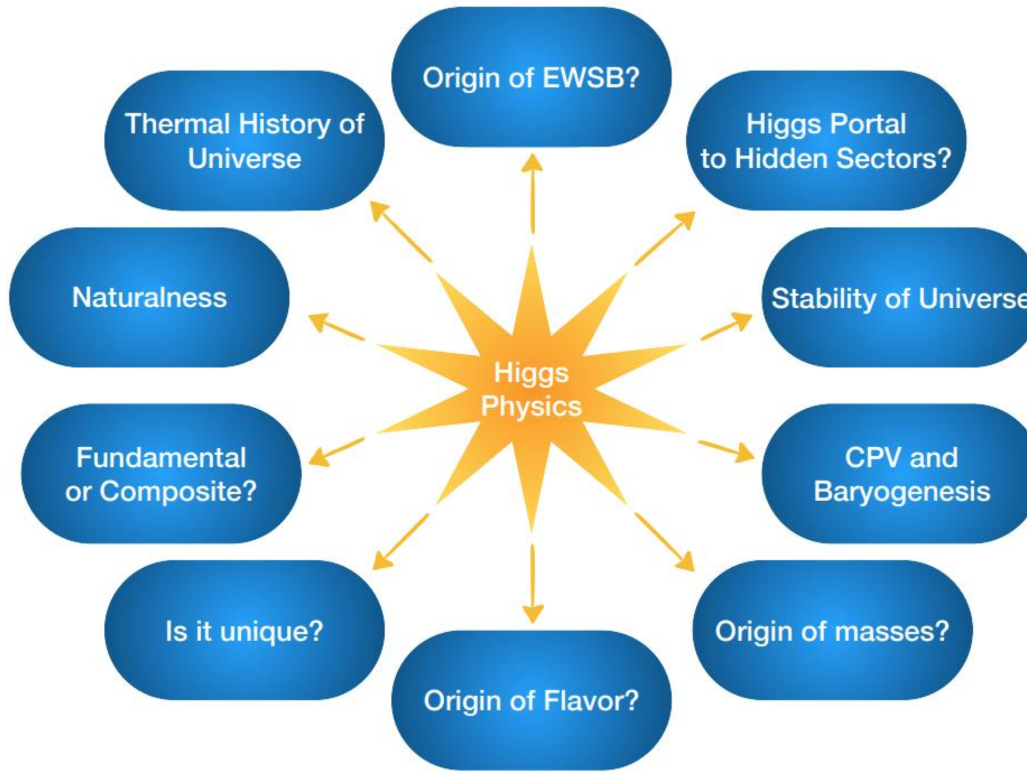
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert and Peter Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

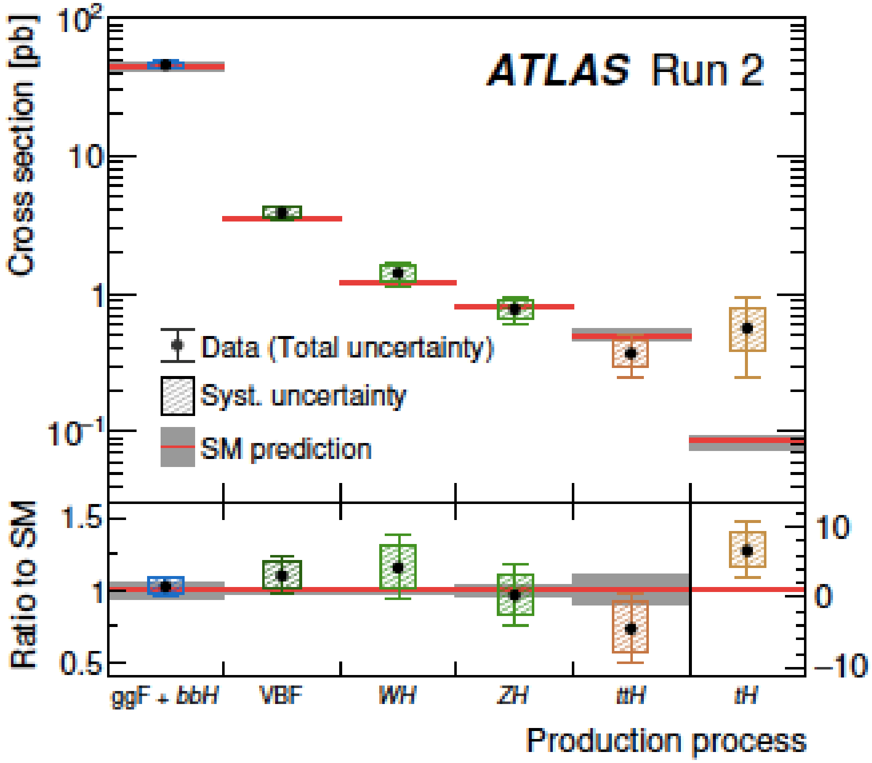
Snowmass 2021, 2209.07510

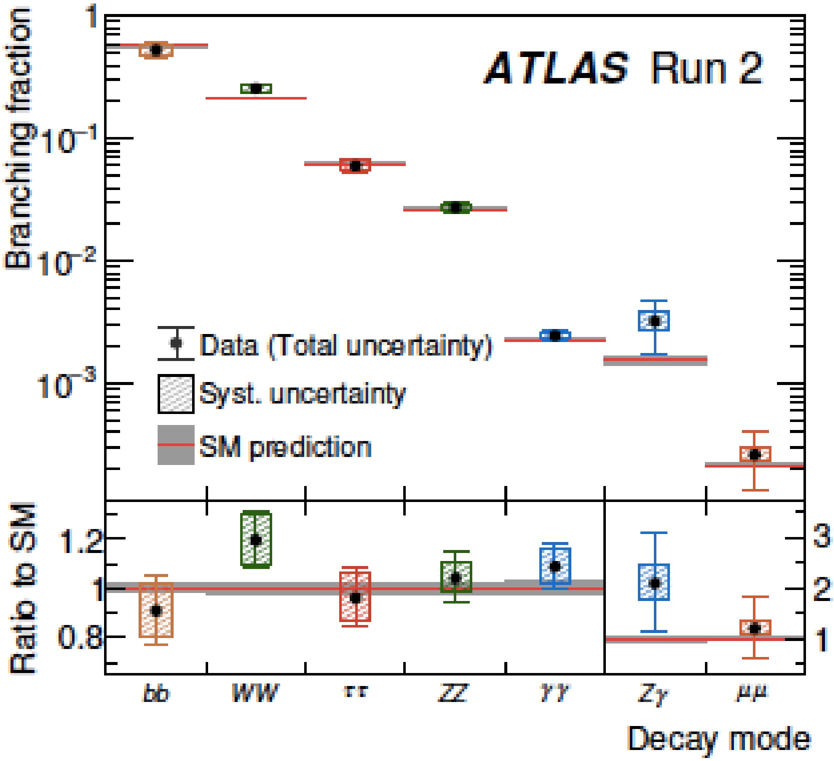




The measurements @ LHC

Nature 607 (2022)7917,52-59

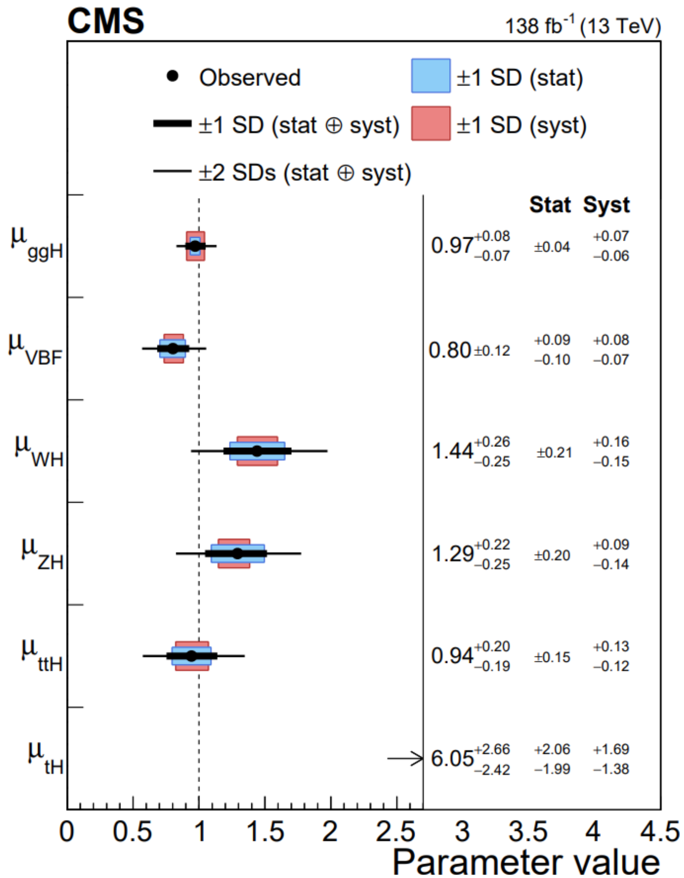


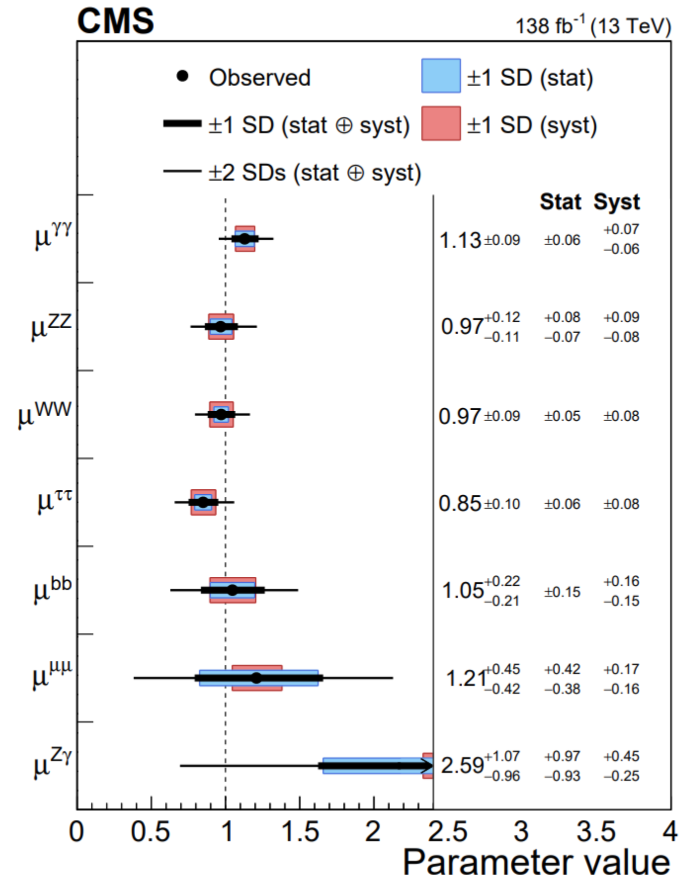


The data agrees with the SM prediction very well

The measurements @ LHC

Nature 607 (2022)7917,60-68

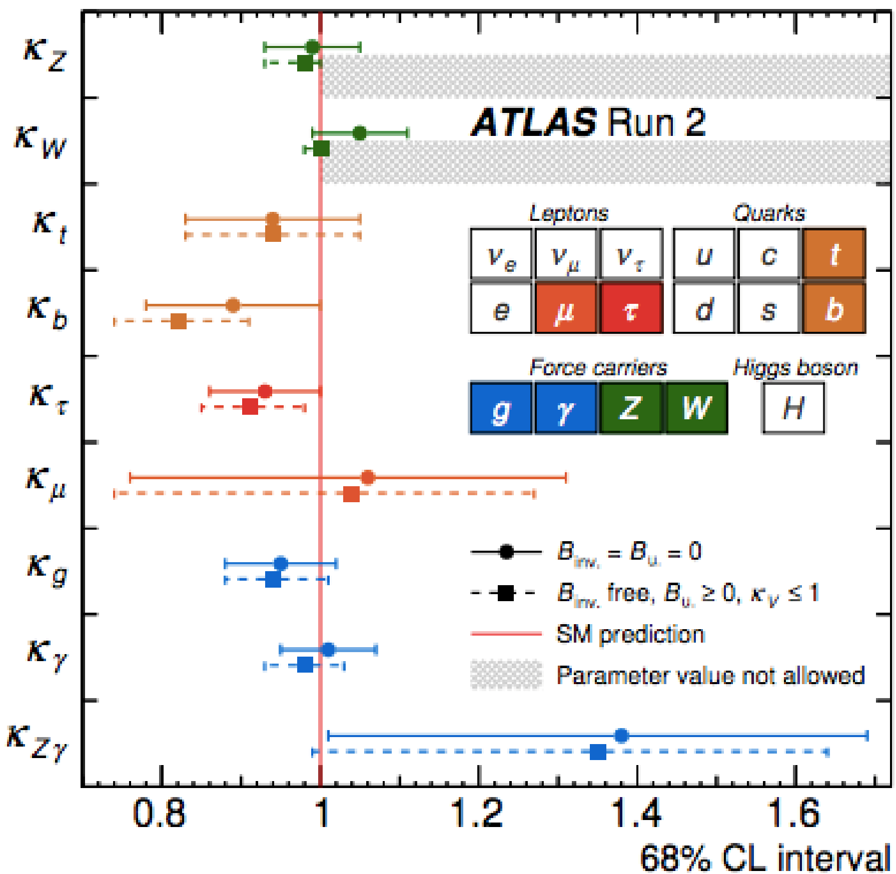




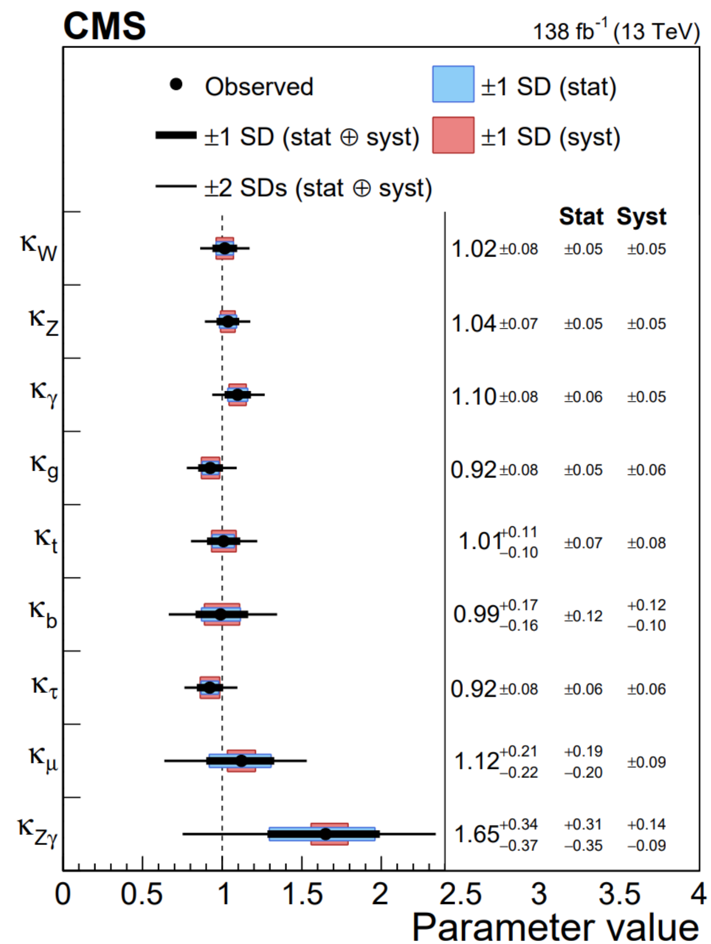
The data agrees with the SM prediction very well

Higgs couplings @LHC

Nature 607 (2022)7917,52-59

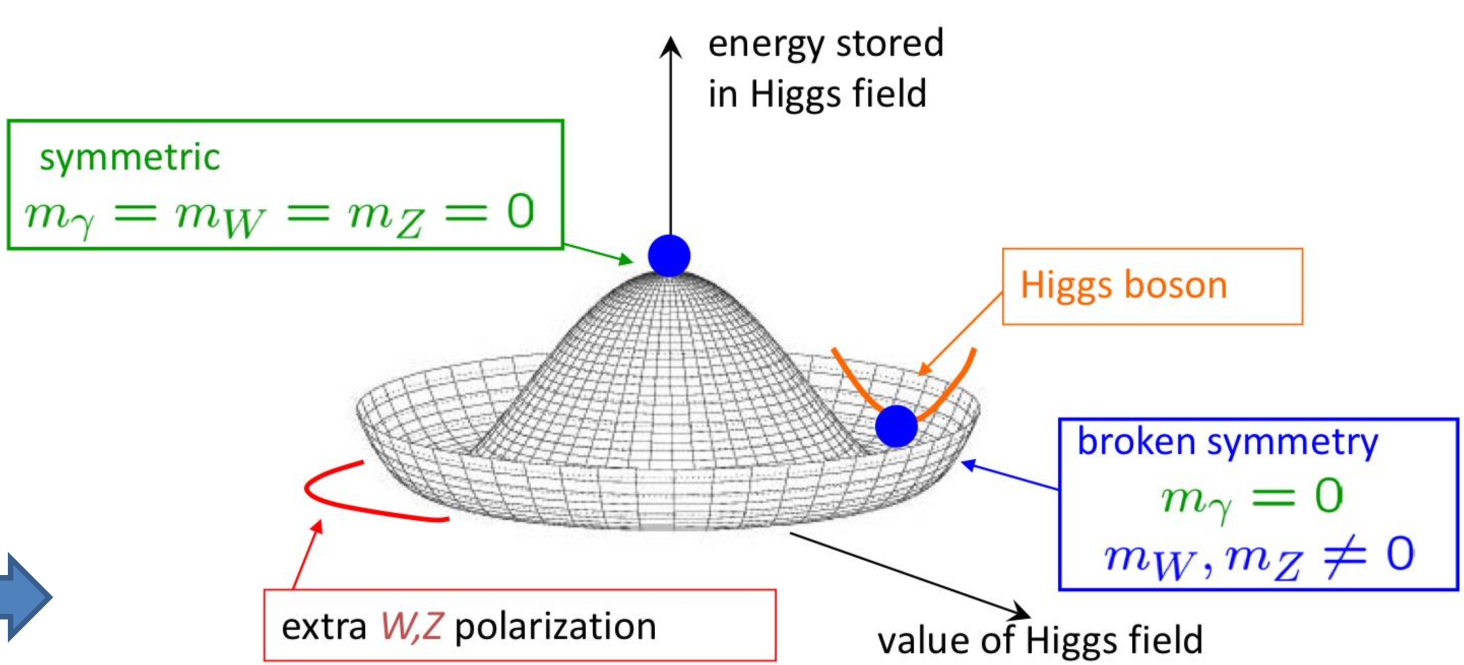


Nature 607 (2022)7917,60-68



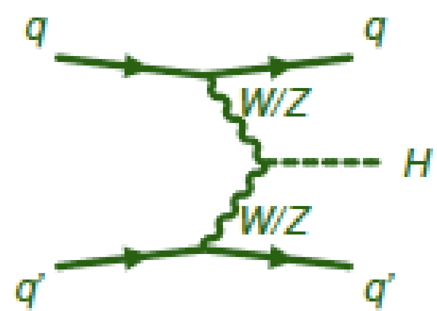
The data agrees with the SM prediction very well $o(10\%)$

Testing the EWSB @ LHC



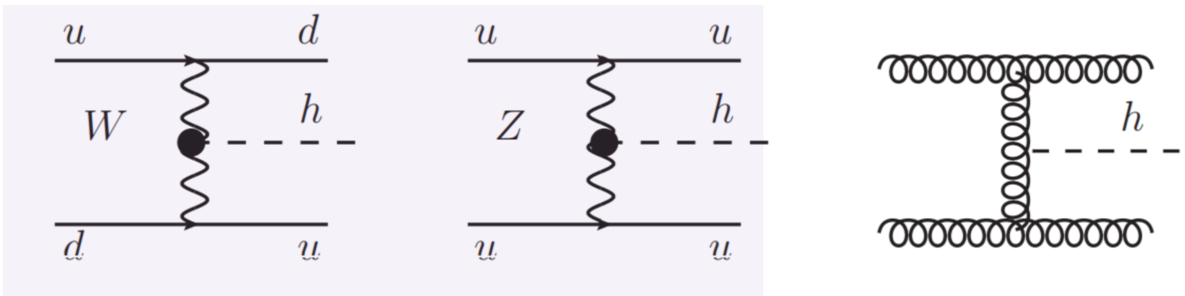
Precisely determine the Higgs gauge couplings are also important for testing the EWSB

$$\mathscr{L}_{hVV} = \kappa_W g^{\rm SM}_{hWW} h W^+_\mu W^{-\mu} + \frac{\kappa_Z}{2} g^{\rm SM}_{hZZ} h Z_\mu Z^\mu$$

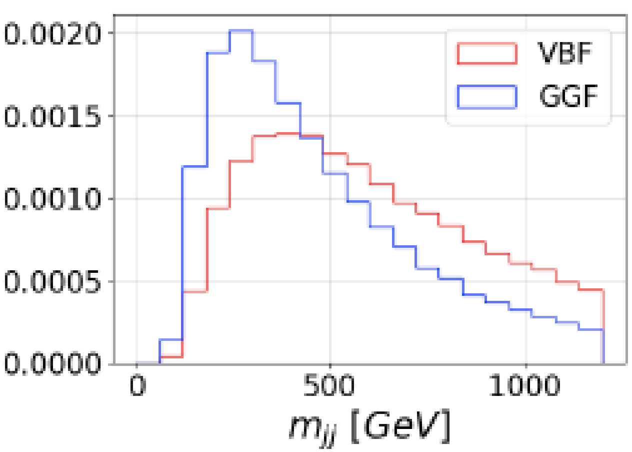


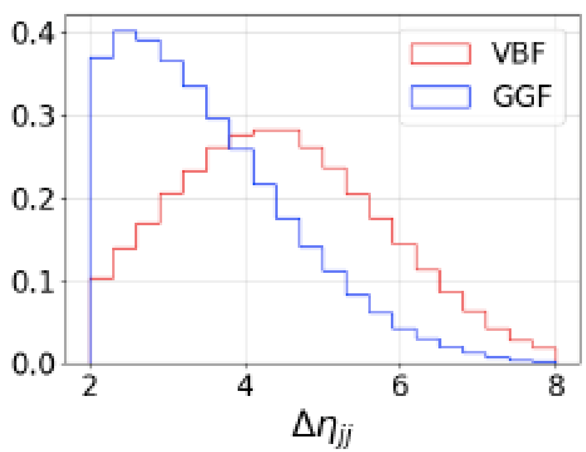
Higgs production mechanisms

VBF Higgs production is the main process to verify the Higgs gauge couplings



The rapidity gap and the invariant mass of the two jets

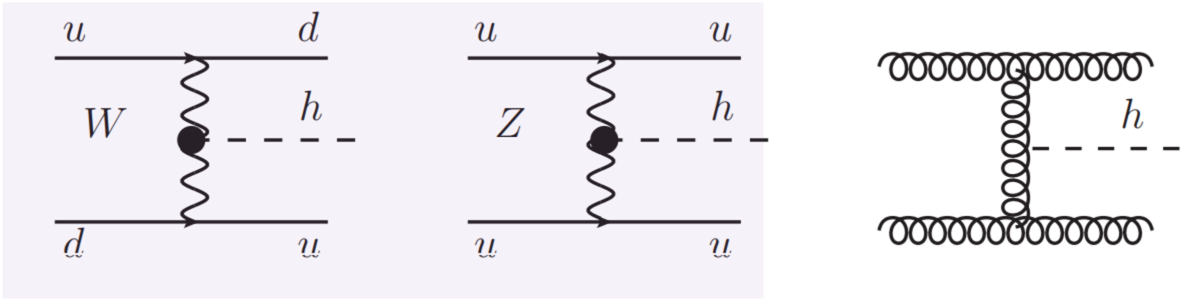




V.D. Bargeer, K.m.Cheung. T. Han, J. Ohnemus and D. Zeppenfeld, 1991
N. Kauer, T. Plehn, D. L. Rainwater and D. Zeppenfeld, 2001,
Cheng-Wei Chiang, D. Shih, Shang-Fu Wei, 2022
……

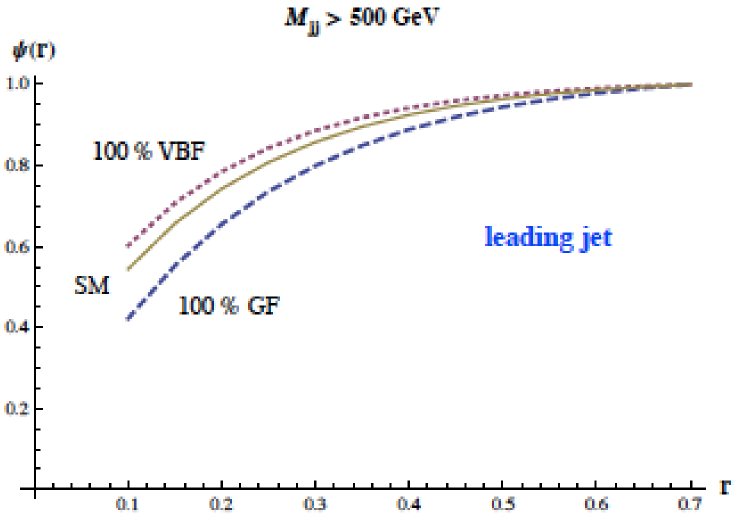
Higgs production mechanisms

Discriminating VBF and gluon fusion Higgs production

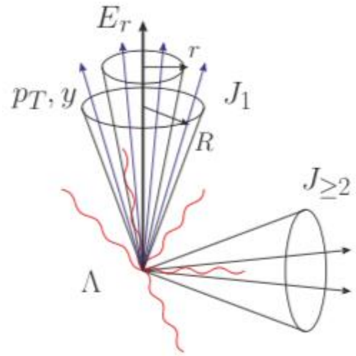


Soft gluon radiation effects: Jet energy profile

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

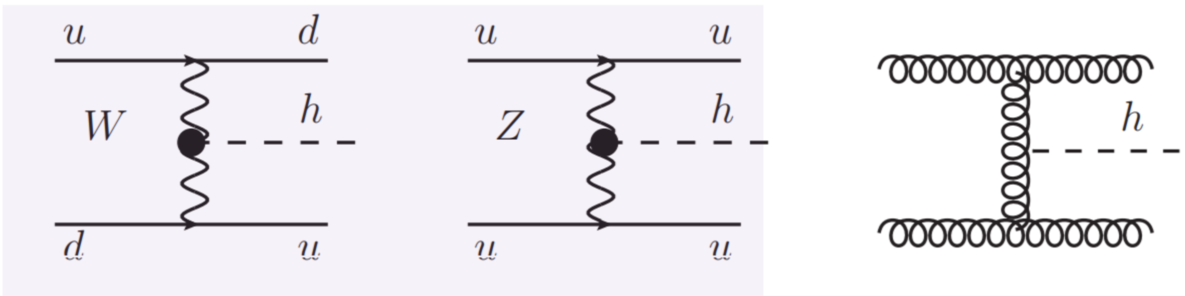


$$\Psi_J(r) = \frac{\sum_{i,d_{i,\hat{n}}<r} E_T^i}{\sum_{i,d_{i,\hat{n}}<R} E_T^i}$$

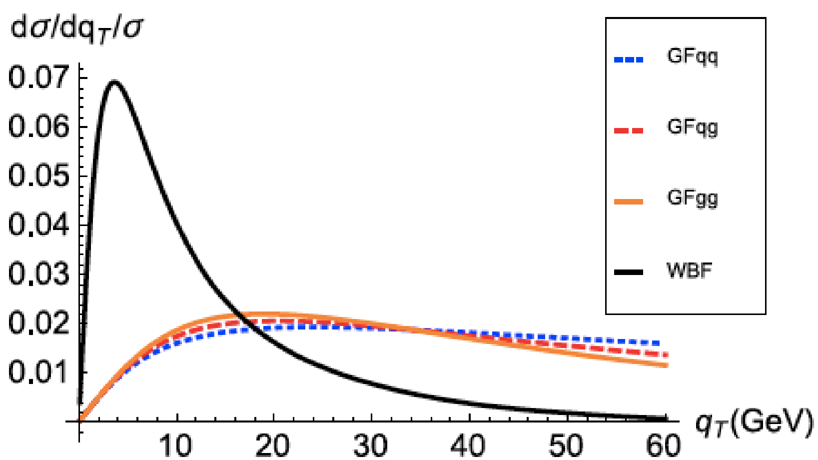


Higgs production mechanisms

Discriminating VBF and gluon fusion Higgs production



Soft gluon radiation effects: TMD effects



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

This observable has been applied in the VBF Higgs analysis

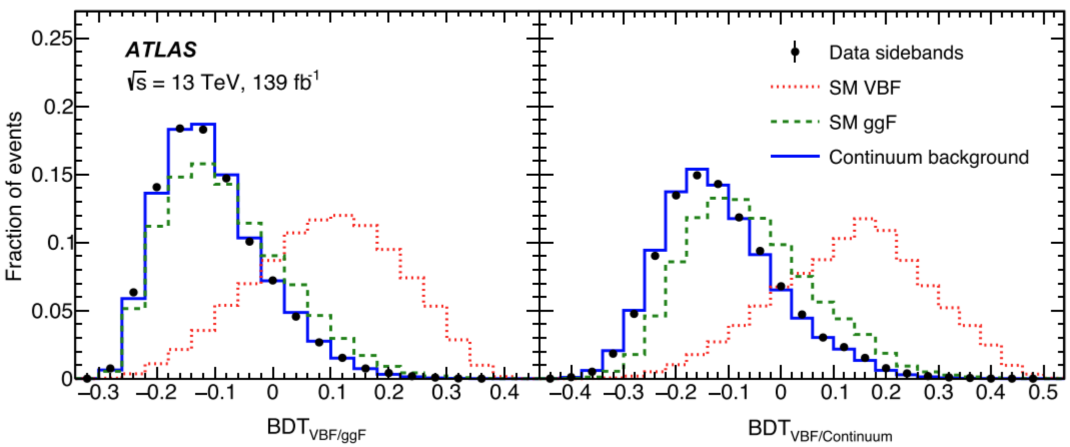
Higgs production mechanisms

Variable	Definition	VBF-ggF separation	VBF-yy separation
m_{jj}	Invariant mass of dijet	0.218	0.241
$\Delta\eta_{jj}$	Pseudo-rapidity separation of dijet	0.152	0.219
p_T^{Hjj}	Transverse momentum of Higgs+jj system	0.127	0.230
$\Delta\Phi_{\gamma\gamma,jj}$	Azimuthal angle between diphoton and dijet systems	0.120	0.186
$\Delta R^{min}_{\gamma,j}$	Minimum ΔR between one of the two leading photons and the corresponding leading jets	0.108	0.204
η^{Zepp}	$\|\eta_{\gamma\gamma} - (\eta_{j1} + \eta_{j2})/2\|$	0.060	0.078
$p_{Tt}^{\gamma\gamma}$	Diphoton p_T projected perpendicular to the diphoton thrust axis	0.011	0.040

Table 7: Variables used for VBF categorization and their separation power.

Soft gluon radiation effects: TMD effects

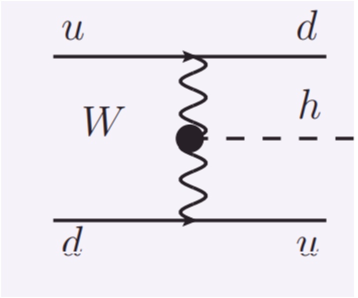
ATLAS, Phys.Rev.Lett. 131 (2023) 6, 061802

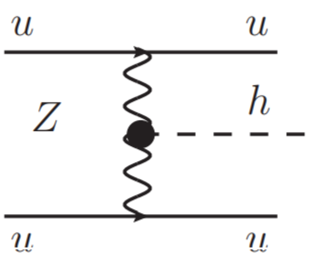


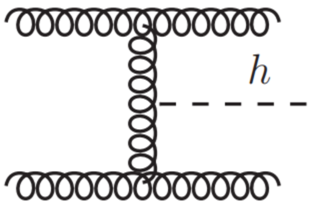
The VBF Higgs production can be well seperated from the GGF process

Higgs production mechanisms

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



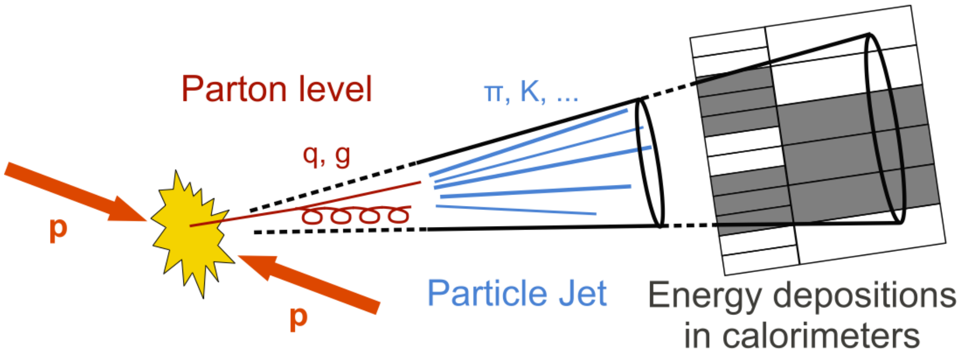


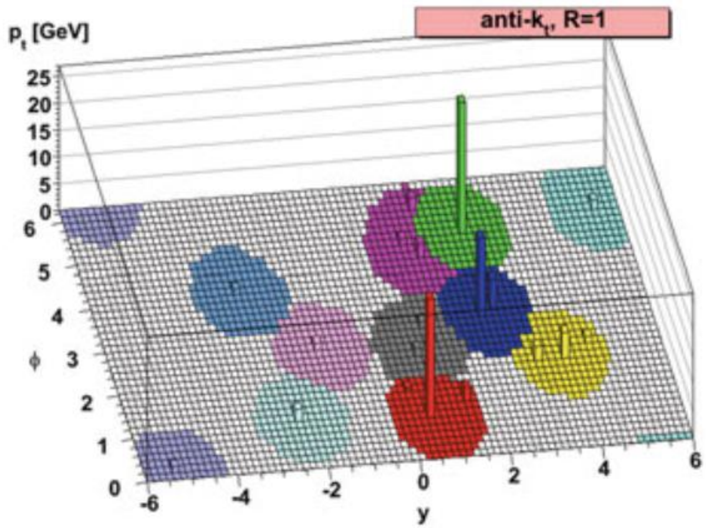


Separating the W boson's contribution from the VBF Higgs production is an important task for determining the Higgs gauge coupling

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

Jet charge definition





Transverse-momentum-weighting schem

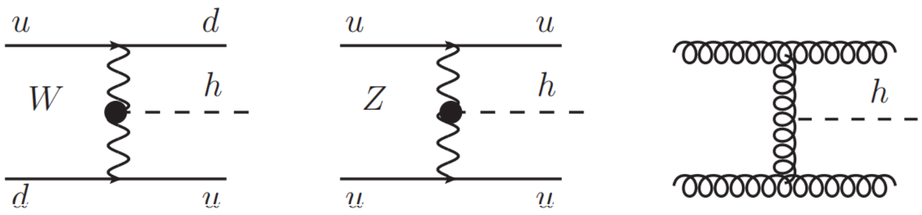
$$d_{ij} = \min\left(\frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

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

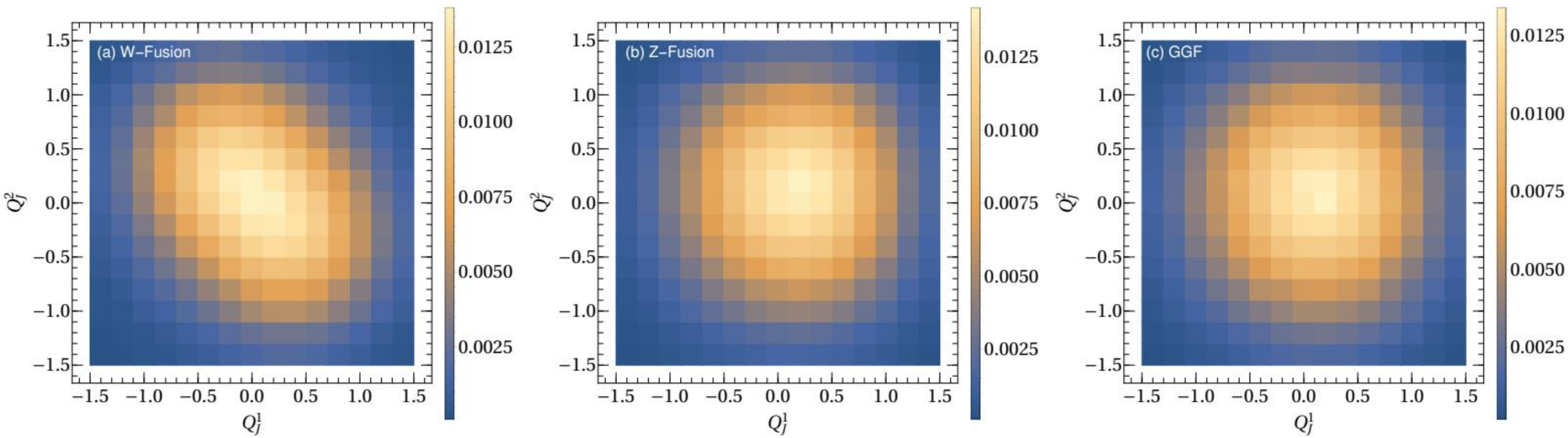
K: To regulate the sensitivity of the soft gluon radiation

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

Higgs production mechanisms



$$p_T^j > 30\ \text{GeV}, \qquad 1 < |\eta_j| < 4.5,$$
$$m_{jj} > 120\ \text{GeV}, \qquad |\Delta\eta_{jj}| > 3.5, \qquad |\eta_h| < 2.5$$

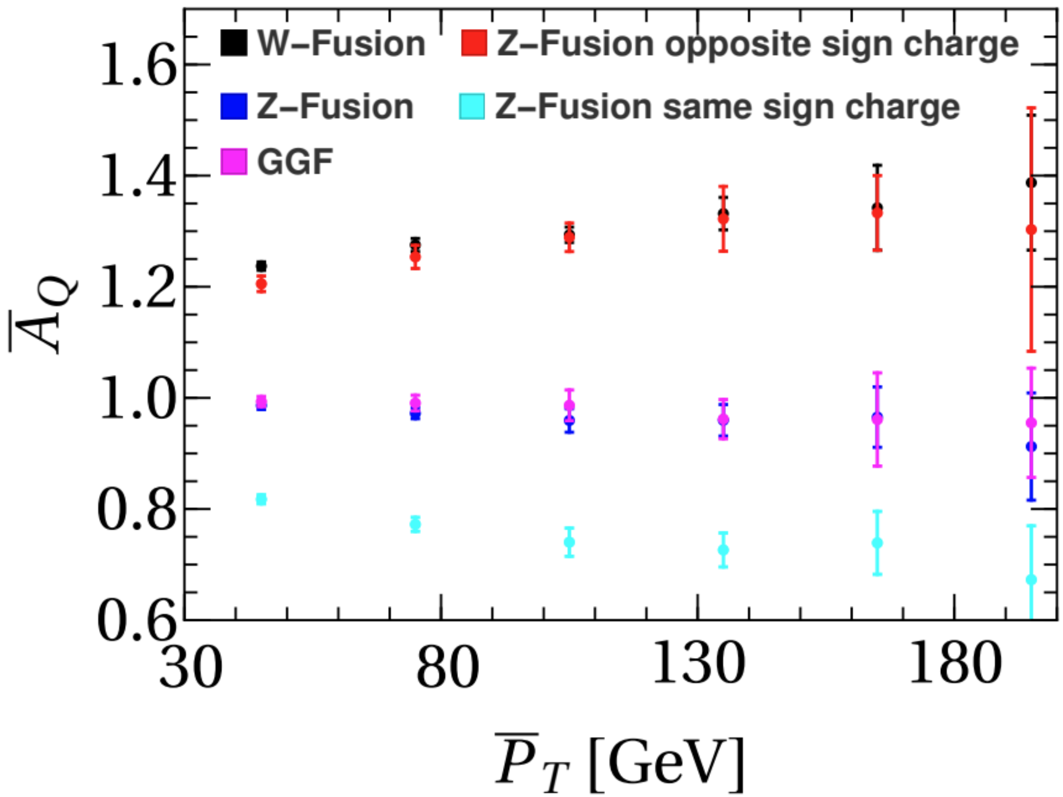


opposite sign for the two jet charges

same or opposite sign

the sign of the jet charge is arbitrary

Jet charge asymmetry



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

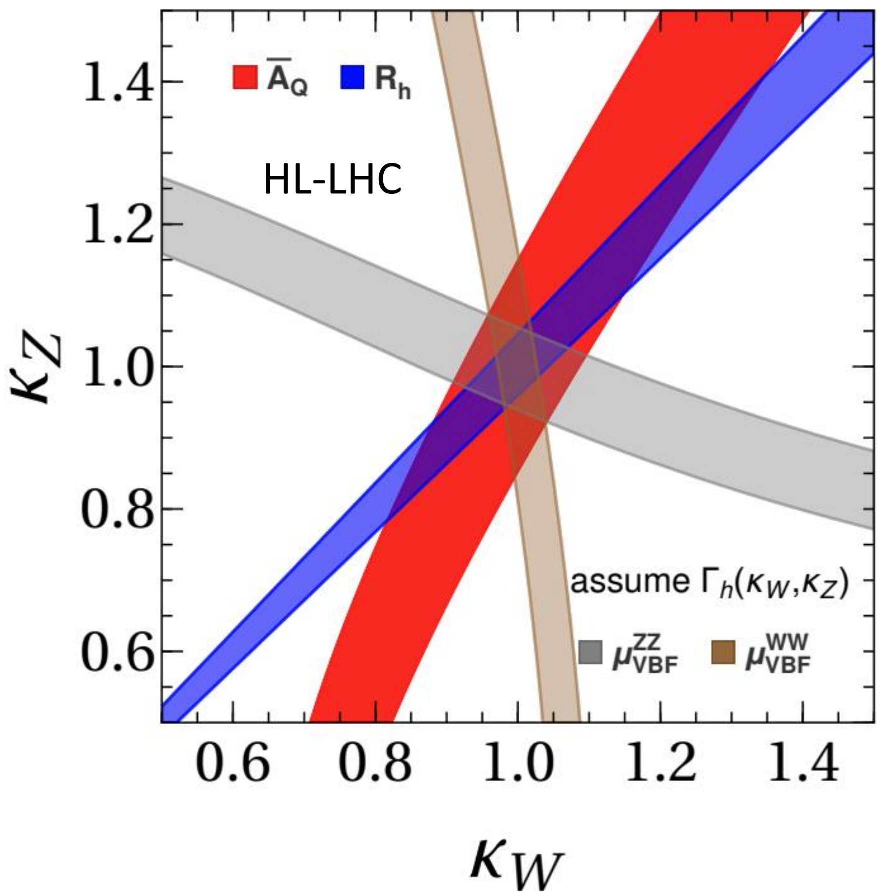
<Q> means the Average value

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

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

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. VBF Higgs production plays the key role to test the electroweak symmetry break mechanism

B. We demonstrated that the jet charge can be used to separate the W-fusion from the Z-fusion and the GGF processes

C. This novel observable can be used to probe the hVV gauge couplings and the results are not depending on the assumption of the Higgs decay width

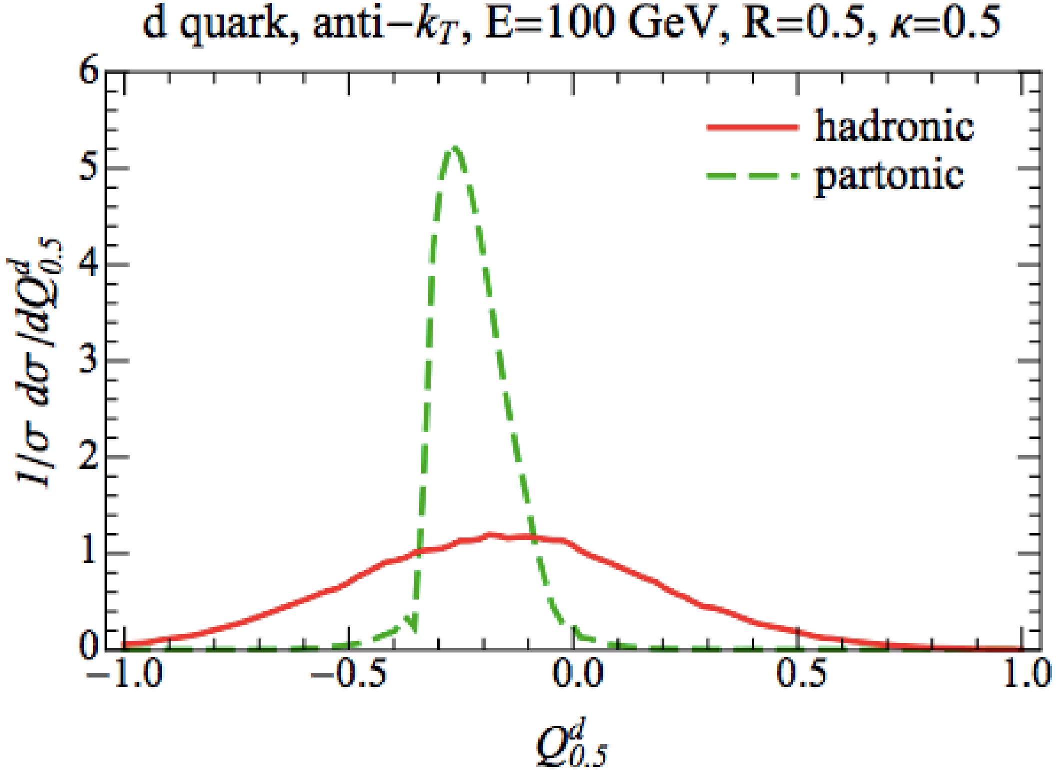
Thank you!

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

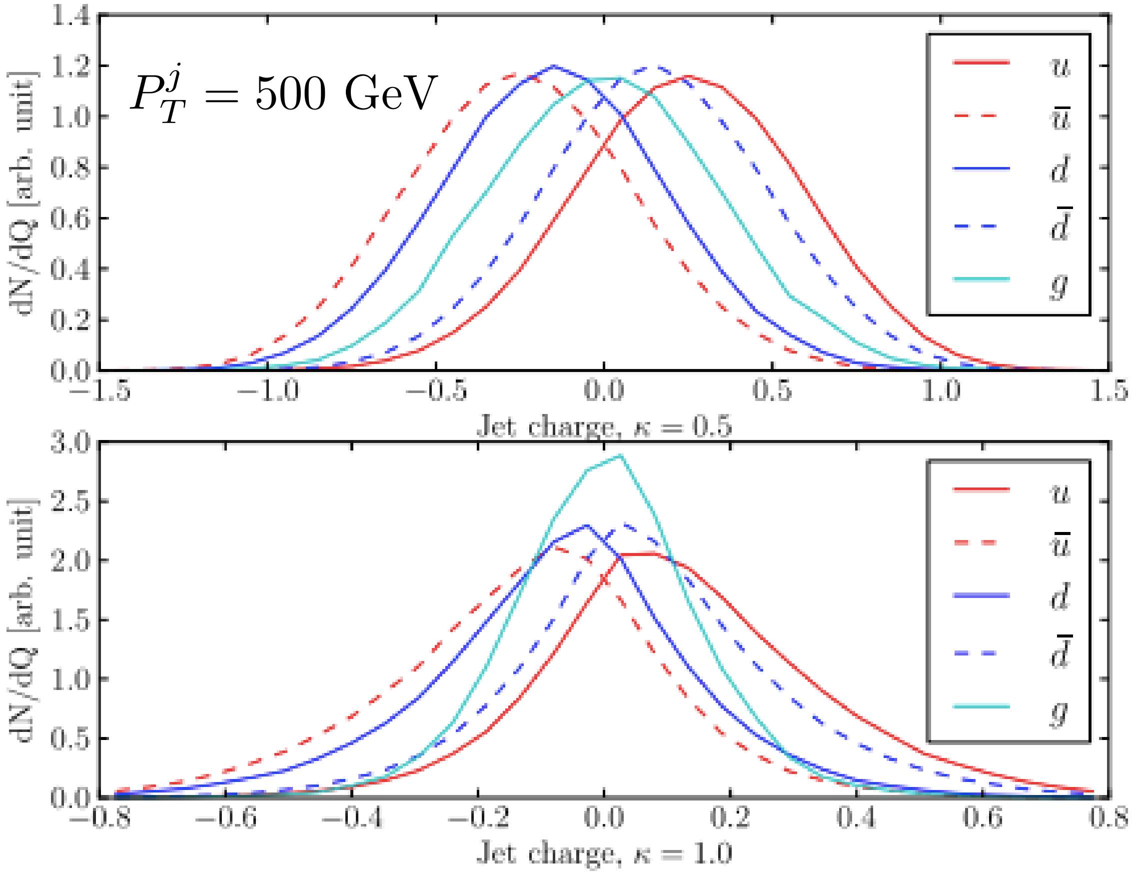
$$Q_q \neq (1-z)^k Q_q$$

The jet charge can be defined only at the hadron level

It depends on the knowledge of the Fragmentation functions

Jet charge definition

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

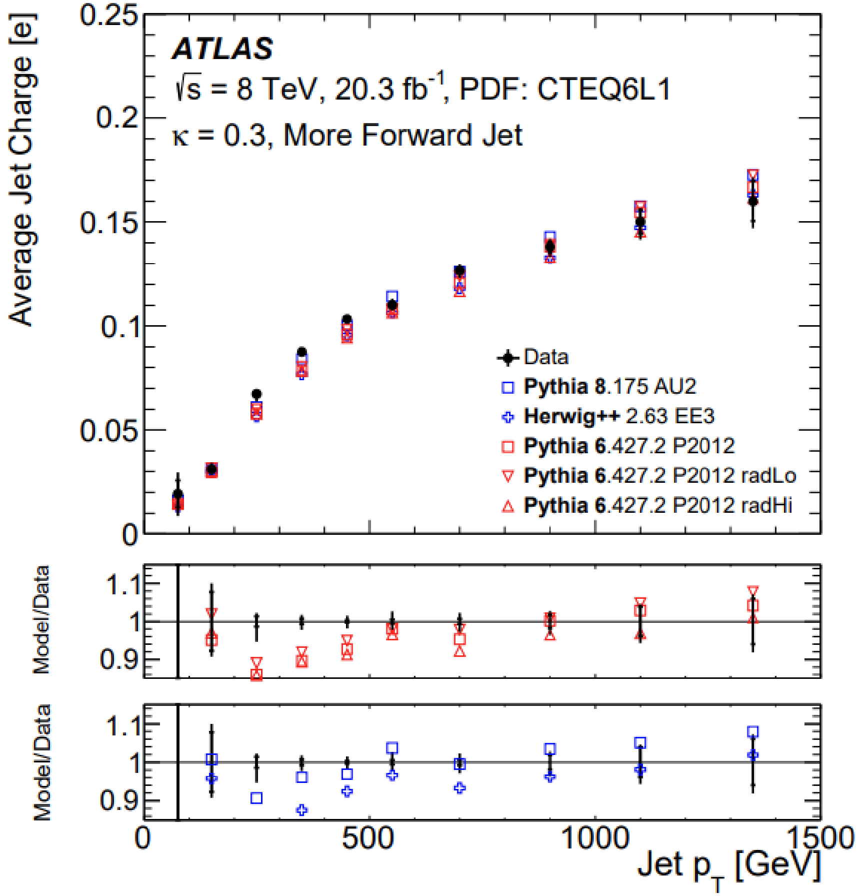


D. Krohn, M. D. Schwartz, T. Lin, W.J. Waalewijn, PRL 110(2013)21,212001

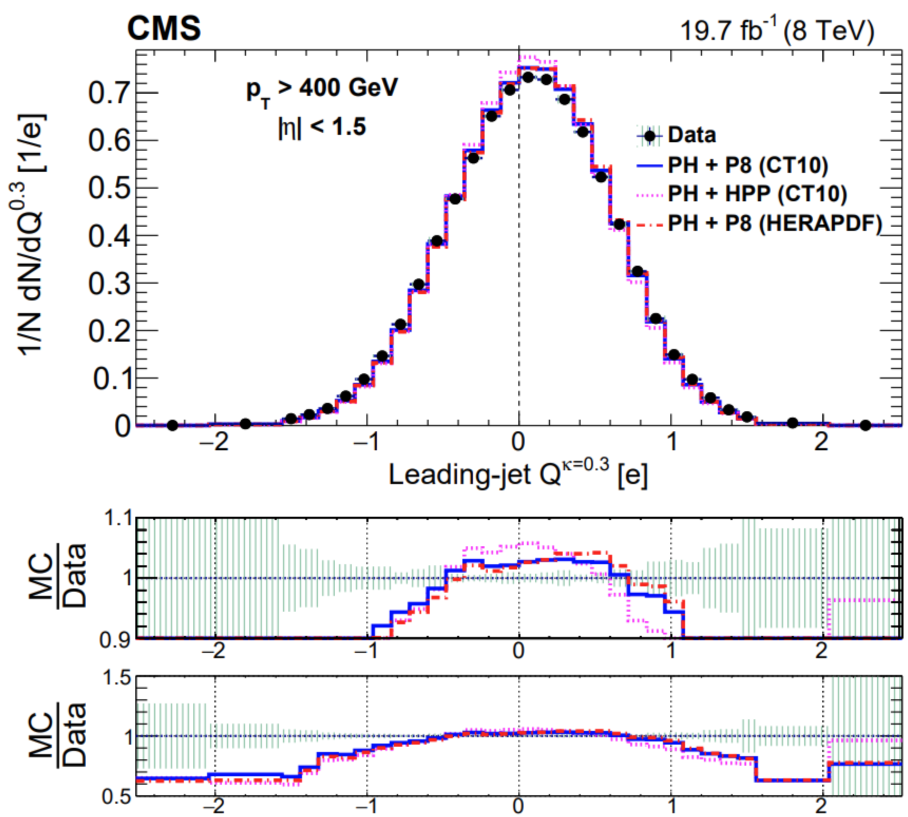
Parton shower and hadronization can not wash out the primordial quark charge information

Jet charge @ LHC

ATLAS Collaboration, Phys.Rev.D 93 (2016) 5, 052003



CMS Collaboration, *JHEP* 10 (2017) 131



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

$$\left\langle Q_{\kappa,q} \right\rangle = \frac{\tilde{\mathcal{J}}_{qq}(E,R,\kappa,\mu)}{J_q(E,R,\mu)} \exp\left[\int_{1GeV}^{\mu} \frac{d\mu}{\mu}\frac{\alpha_s(\mu)}{\pi} P_{qq}(\kappa)\right] \times \tilde{D}_q^Q(\kappa, \mu_0 = 1GeV)$$

- Perturbative
- Scale and R dependence

- Non-Perturbative
- Only depends on k and q

$$\tilde{\mathcal{J}}_{ij}(E,R,\kappa,\mu) = \int_0^1 dz z^\kappa \mathcal{J}_{ij}(E,R,\kappa,\mu)$$

(κ + 1)-th Mellin moment of the Wilson coefficient for matching the quark fragmenting jet function onto a quark fragmentation function

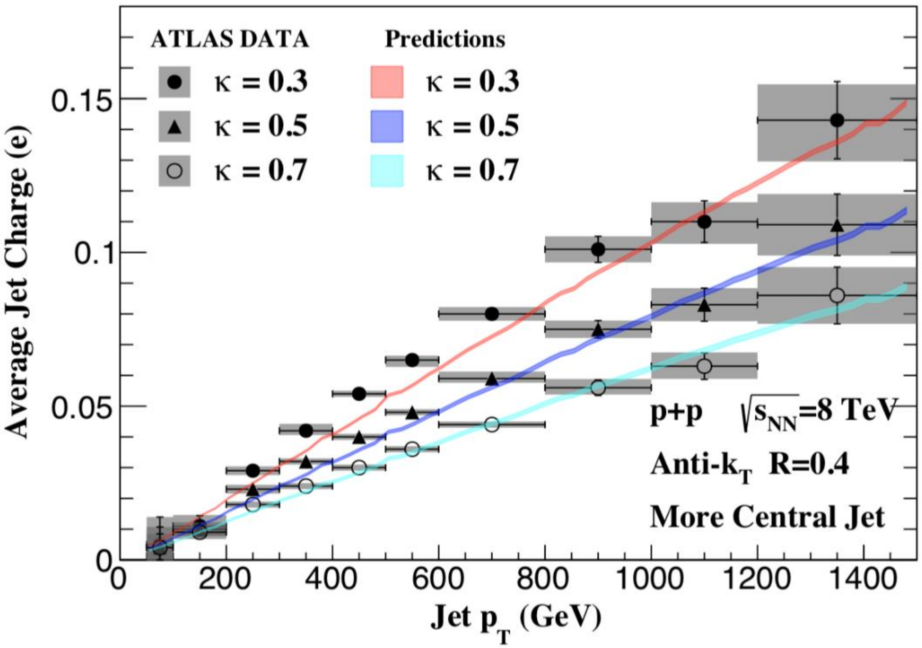
Jet charge @ LHC

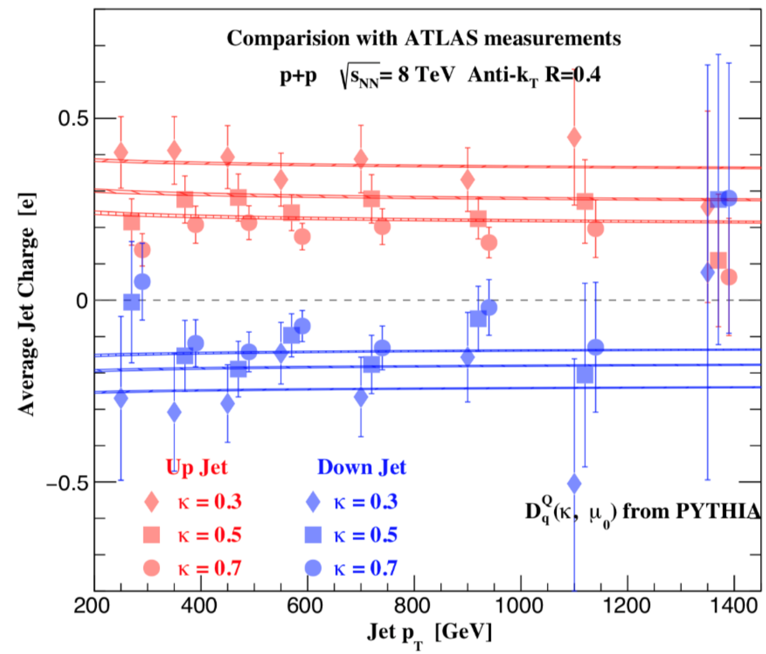
$$\langle Q_k^q \rangle = \frac{1}{\sigma_{q-jet}} \int d\sigma_{q-jet} Q_\kappa(\sigma_{q-jet})$$

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