对撞机物理唯象学基础与前沿

岩斌
中国科学院高能物理研究所

微扰量子场论及其前沿讲习班@山东大学

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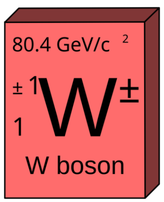
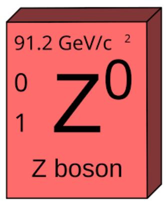
粒子物理基础知识

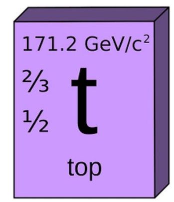
➢ 高能对撞机实验极大地推动了粒子物理的发展





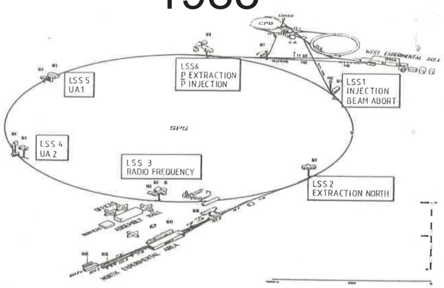
1983

标准模型电弱精确检验

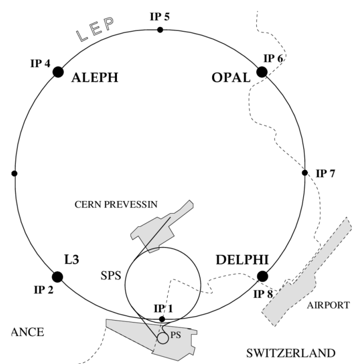


1995

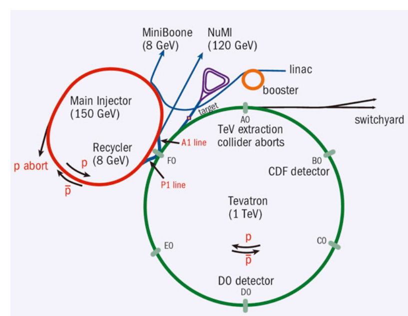
2012



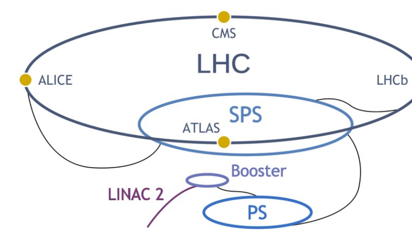
Super Proton Synchrotron



LEP



Tevatron



LHC

电弱统一理论

希格斯机制

粒子物理基础知识

➢ 对撞机相关参数

- 对撞能量

$$s \equiv (p_1 + p_2)^2 = \begin{cases} (E_1 + E_2)^2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0 \\ m_1^2 + m_2^2 + 2(E_1E_2 - \vec{p}_1 \cdot \vec{p}_2). \end{cases}$$

- 高能对撞实验，束流处于极端相对论情况，质量效应可忽略

$$E_{CM} \equiv \sqrt{s} \approx \begin{cases} 2E_1 \approx 2E_2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ \sqrt{2E_1 m_2} & \text{in the fixed target frame } \vec{p}_2 = 0. \end{cases}$$

- 对撞机实验可以极大地利用束流能量，而固定靶实验对能量的利用率较低，其优势在于靶物质密度极高，积分亮度较大

粒子物理基础知识

- 同步辐射导致的能量损失

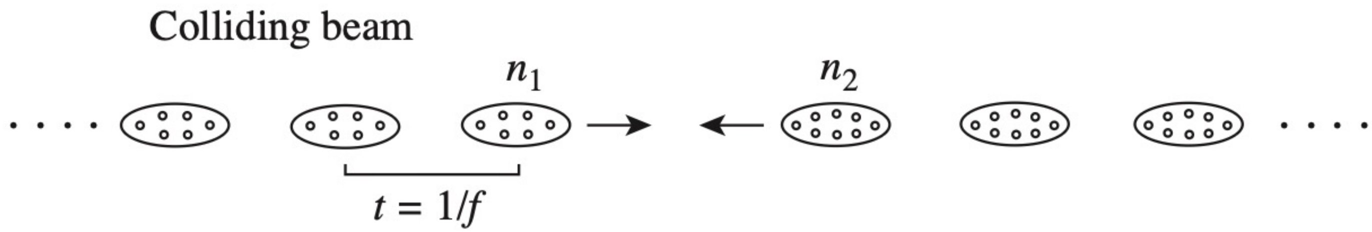
$$\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$$

- 环形对撞机的半径 *R*, 束流能量E, 粒子质量m。大的半径以及重的粒子更有利于实现高能对撞机

- 环形正负电子对撞机（如：CEPC）能量 1 TeV 以下
- 环形谬子对撞机：～10 TeV
- 直线加速器可以实现高能量对撞机，但亮度较小

粒子物理基础知识

- 积分亮度



- 总的事例数：$n_{1,2}$ 表示束流中的粒子数密度，A 表示束流的横向分布面积，面积越小，则单位面积内的粒子数密度越高

$$N = \frac{\sigma n_1 n_2 f}{A} \qquad L = \frac{n_1 n_2 f}{A}$$

- 瞬时亮度 L：单位时间内通过碰撞点单位面积的粒子数，仅仅依赖对撞机的硬件设计

- 积分亮度：$\mathcal{L} = \int_0^T dt L$

散射截面

- 考虑2 →n的散射过程，忽略初态粒子质量，采用PDG的约定

$$d\sigma_{a+b\to n} = \frac{(2\pi)^4}{4p_a \cdot p_b} \overline{|M_{a+b\to n}|^2} d\Phi_n$$

- n体相空间定义为：

$$d\Phi_n = \delta^4\left(p_a + p_b - \sum_{i=1}^{n} p_i\right) \prod_{j=1}^{n} \frac{d^3 p_j}{(2\pi)^3 2E_j}$$

- 散射截面的大小由相互作用（散射振幅）和相空间共同决定。相互作用越强，相空间越大，散射几率越大

相空间分析

- 1体相空间，考虑过程 $a+b\to c$ $s=(p_a+p_b)^2$

$$
\begin{aligned}
d\Phi_1 &= \frac{d^3\mathbf{p}_1}{(2\pi)^3 2E}\delta^4(p_a+p_b-p_1) \\
&= (2\pi)^{-3} d^4p_1 \delta^+(p_1^2-m_1^2)\delta^4(p_a+p_b-p_1) \\
&= (2\pi)^{-3}\delta(s-m_1^2) \\
&= \frac{1}{s(2\pi)^3}\delta(1-m_1^2/s)
\end{aligned}
$$

- 无质量粒子的2体相空间

$$
\begin{aligned}
\Phi_2 &= \int \delta(\sqrt{s}-E_1-E_2)\delta^3(p_1+p2)\frac{|p_1|^2 d|p_1| d\Omega_1 d^3p_2}{(2\pi)^6 4E_1E_2} \\
&= \int \delta(\sqrt{s}-2p)\frac{dp d\Omega}{4(2\pi)^6} = \frac{1}{128\pi^5}
\end{aligned}
$$

相空间分析

- 无质量粒子的相空间满足下面的递推关系

$$\frac{\Phi_{n+1}}{\Phi_n} = \frac{s}{16\pi^2 n(n-1)}$$

- 相空间的比值带有量纲，因此定义无量纲化的相空间

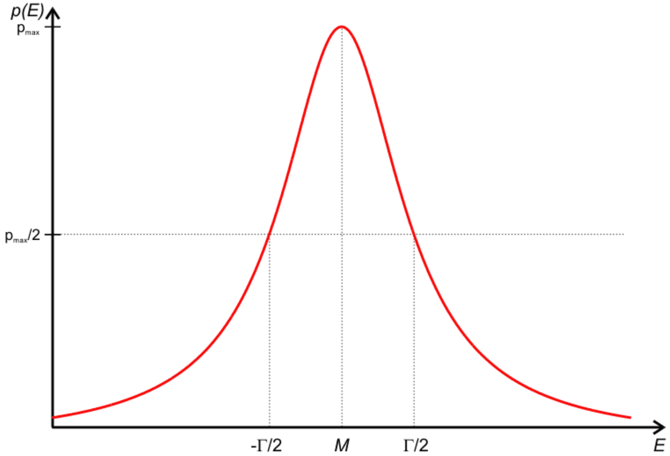
$$\Phi'_n = \frac{\Phi_n}{s^{n-2}} \qquad \frac{\Phi'_{n+1}}{\Phi'_n} = \frac{1}{16\pi^2 n(n-1)}$$

- 末态粒子每增加1个，无量纲化的相空间将减少2个数量级

$$\frac{\Phi'_2}{\Phi'_1} = \frac{1}{16\pi^2} \qquad \frac{\Phi'_3}{\Phi'_2} = \frac{1}{32\pi^2}$$

衰变宽度

- 不稳定粒子单位时间内发生衰变的几率
- 粒子的寿命与宽度的关系 $\Gamma = 1/\tau$
- 实验测量方法：
  共振峰扫描，拟合Breit-Wigner分布

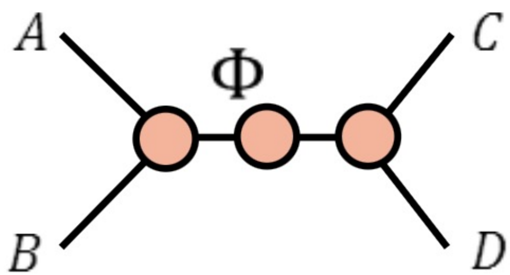


- 宽度较小无法直接测量时，可观测量为衰变分支比

$$\Gamma_{\text{tot}} = \sum_n \Gamma_{a\to n} \qquad d\Gamma_{a\to n} = \frac{1}{2m_a}\delta^4\left(m_a - \sum_i^n p_i\right)\overline{|M(a\to n)|^2}d\Phi_n$$

$$\text{Br}(a\to i) = \frac{\Gamma_{a\to i}}{\Gamma_{\text{tot}}}$$

窄宽度近似

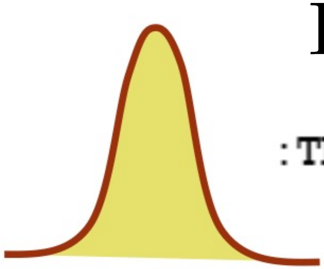


$$d\hat{\sigma} = \frac{1}{2s}\left|\mathcal{M}_{prod}\right|^2 \left|\frac{1}{p^2 - M^2 + iM\Gamma}\right|^2 \left|\mathcal{M}_{dec}\right|^2 d\phi_{CD}$$

Production • BW^2 • Decay

Using the Narrow Width Approximation (NWA)

$$\Gamma \ll M$$



: The area is $\frac{\pi}{M\Gamma}$

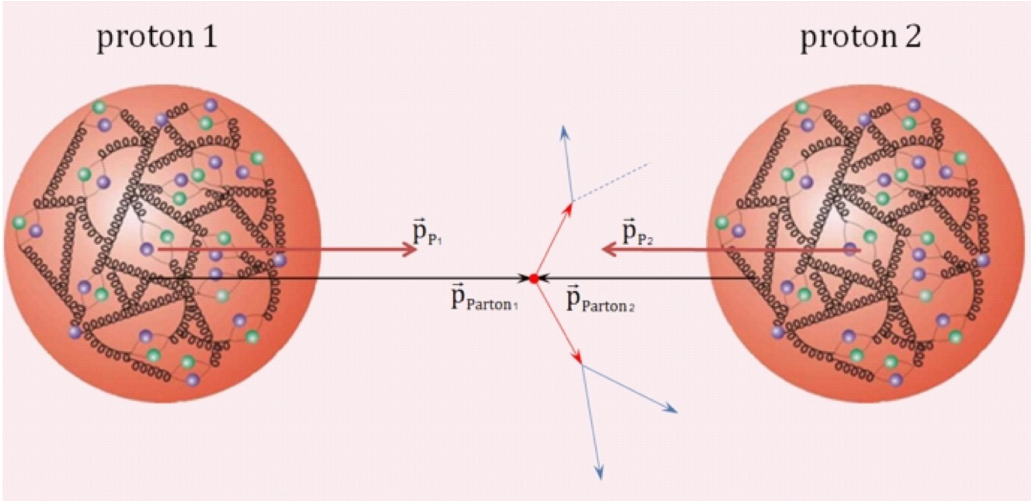
$$\left|\frac{1}{p^2 - M^2 + iM\Gamma}\right|^2 \cong \frac{\pi}{M\Gamma}\delta(p^2 - M^2)$$

$$d\hat{\sigma} = \frac{1}{2s}\left|\mathcal{M}_{prod}\right|^2 2\pi\delta(p^2 - M^2) \cdot \frac{1}{\Gamma}\frac{1}{2M}\left|\mathcal{M}_{dec}\right|^2 d\phi_{CD}$$

$$\sigma(AB \to \Phi \to CD) = \sigma_{prod} \cdot \mathrm{Br}$$

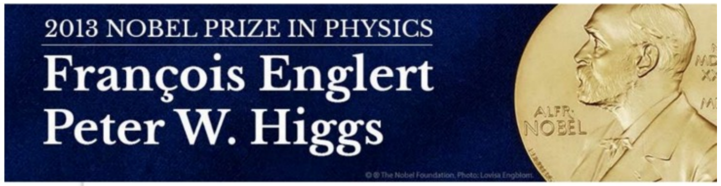
强子对撞机物理

- 电子对撞机的实验背景干净，但因为电子电磁辐射强，导致环形电子对撞机碰撞能量严重受限
- 谬子对撞机和强子（如质子）对撞机由于质量较大则可以积累较高的碰撞能量，有利于探测高能标的新物理效应。谬子对撞机实验条件不成熟，强子对撞机则强子背景复杂，不利于信号提取
- 强子对撞机的物理过程理论计算依赖于因子化定理



希格斯物理简介

The Era of the Higgs Physics

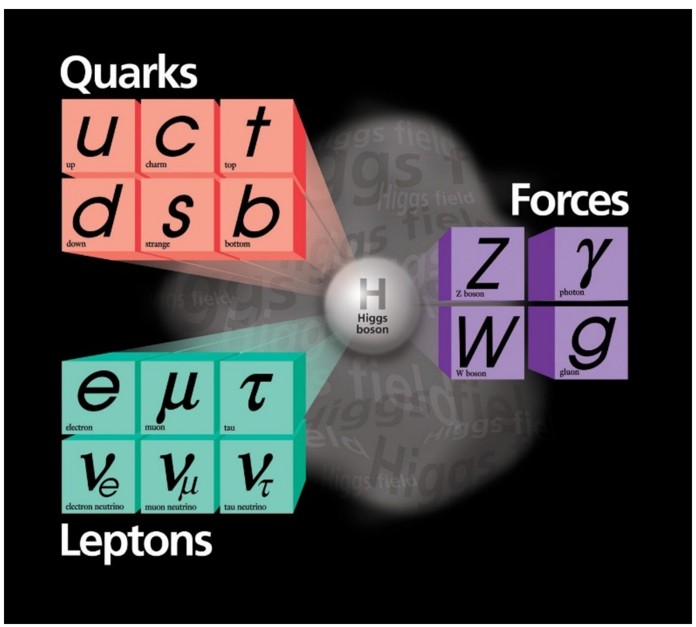


8 October 2013

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

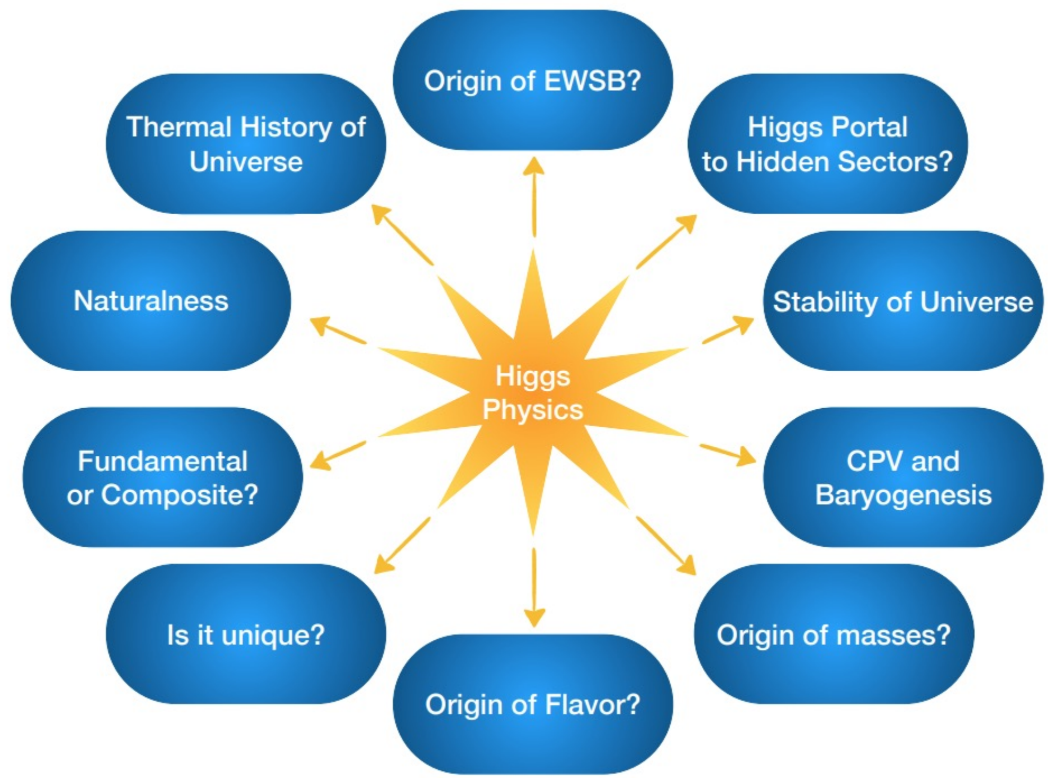
François Englert and Peter Higgs

"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"



Understanding of origin of mass of subatomic particles

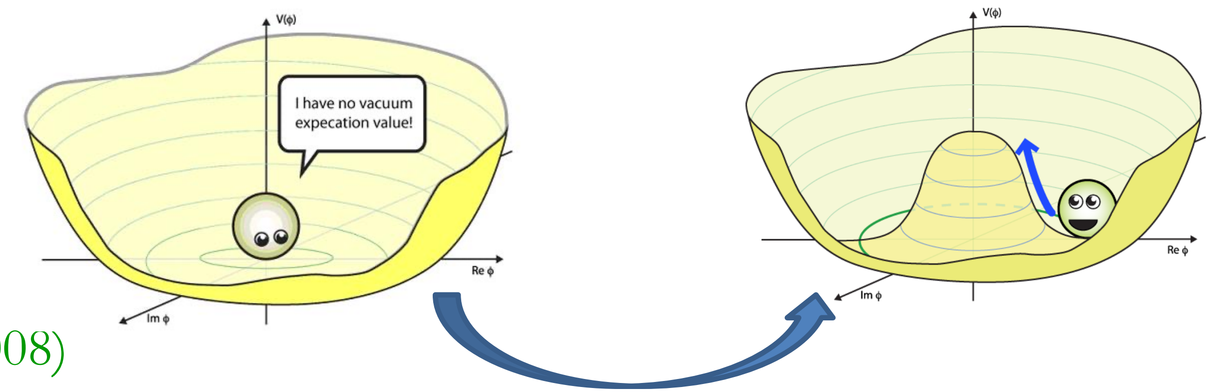
Snowmass 2021, 2209.07510



Brout-Englert-Higgs Mechanism

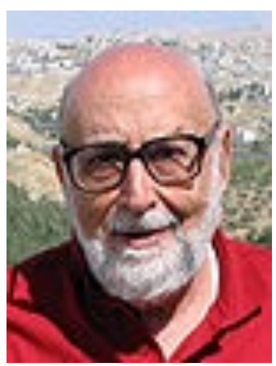
- **Spontaneous broken symmetry**: the Lagrangian is invariant under the symmetry, but the ground state of the theory is not

Nambu (Nobel Prize 2008)



- Brout-Englert-Higgs Mechanism (1964)

Brout



Englert

Peter Higgs

> **Goldstone's theorem:** Spontaneous breaking of continuous global symmetries implies the existence of massless particles

Englert, Higgs
2013 Nobel Prize

Example: Linear sigma model

复标量场：U(1) global symmetry $\phi(x) \to e^{i\alpha}\phi(x)$

$$\mathcal{L} = (\partial_\mu \phi^\star)(\partial_\mu \phi) + m^2 \phi\phi^\star - \frac{\lambda}{4}\phi^2\phi^{\star 2}$$

势能项： $V(\phi) = -m^2|\phi|^2 + \frac{\lambda}{4}|\phi|^4$ $\langle v \rangle = \sqrt{\frac{2m^2}{\lambda}}$

将标量场进行重新参数化：

$$\phi(x) = \left(\sqrt{\frac{2m^2}{\lambda}} + \frac{1}{\sqrt{2}}\sigma(x)\right) e^{i\frac{\pi(x)}{F_\pi}}$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \sigma)^2 + \left(\sqrt{\frac{2m^2}{\lambda}} + \frac{1}{\sqrt{2}}\sigma(x)\right)^2 \frac{1}{F_\pi^2}(\partial_\mu \pi)^2 - \left(-\frac{m^4}{\lambda} + m^2\sigma^2 + \frac{1}{2}\sqrt{\lambda} m \sigma^3 + \frac{1}{16}\lambda\sigma^4\right)$$

只有动能项，
而无质量项
Goldstone

Brout-Englert-Higgs Mechanism

An Abelian Example: 电磁场+复标量场

$$D_\mu = \partial_\mu + ieA_\mu$$

$$V(\phi) = -\mu^2 \phi^* \phi + \frac{\lambda}{2}(\phi^* \phi)^2$$

$$\mathcal{L} = -\tfrac{1}{4}(F_{\mu\nu})^2 + |D_\mu \phi|^2 - V(\phi)$$

U(1) 规范变换：

$$\phi(x) \to e^{i\alpha(x)}\phi(x), \qquad A_\mu(x) \to A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x)$$

对称性自发破缺：

$$\phi(x) = \phi_0 + \frac{1}{\sqrt{2}}(\phi_1(x) + i\phi_2(x)) \qquad \langle \phi \rangle = \phi_0 = \left(\frac{\mu^2}{\lambda}\right)^{1/2}$$

$$|D_\mu \phi|^2 = \tfrac{1}{2}(\partial_\mu \phi_1)^2 + \tfrac{1}{2}(\partial_\mu \phi_2)^2 + \sqrt{2} e \phi_0 \cdot A_\mu \partial^\mu \phi_2 + e^2 \phi_0^2 A_\mu A^\mu + \cdots$$

Goldstone boson to disappear from the spectrum and the gauge boson to become massive

Brout-Englert-Higgs Mechanism

标准模型电弱规范对称性 $\mathcal{L} = \left|D_\mu \phi\right|^2 + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2$

$$D_\mu \phi = \left(\partial_\mu - igA_\mu^a \tau^a - i\tfrac{1}{2}g' B_\mu\right)\phi$$

电弱规范玻色子质量项：

$$\Delta\mathcal{L} = \frac{1}{2}\frac{v^2}{4}\left[g^2(A_\mu^1)^2 + g^2(A_\mu^2)^2 + (-gA_\mu^3 + g'B_\mu)^2\right]. \qquad (20.62)$$

There are three massive vector bosons, which we will notate as follows:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(A_\mu^1 \mp iA_\mu^2) \qquad \text{with mass} \qquad m_W = g\frac{v}{2};$$

$$Z_\mu^0 = \frac{1}{\sqrt{g^2 + g'^2}}(gA_\mu^3 - g'B_\mu) \qquad \text{with mass} \qquad m_Z = \sqrt{g^2 + g'^2}\,\frac{v}{2}. \qquad (20.63)$$

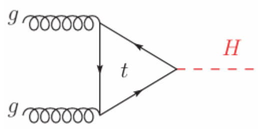
The fourth vector field, orthogonal to Z_μ^0, remains massless:

$$A_\mu = \frac{1}{\sqrt{g^2 + g'^2}}(g'A_\mu^3 + gB_\mu) \qquad \text{with mass} \qquad m_A = 0. \qquad (20.64)$$

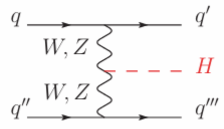
$$SU(2)_L \times U(1)_Y \to U(1)_{\text{EM}}$$

Higgs production at the LHC

➢ Gluon Fusion



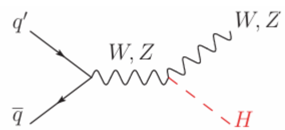
Loop suppressed, but large top quark Yukawa coupling, large gluon PDF enhancement



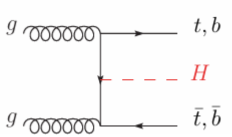
➢ VBF production

Forward & backward jet=> helps to identify Higgs event
Direct probe of HVV couplings

➢ VH associated production

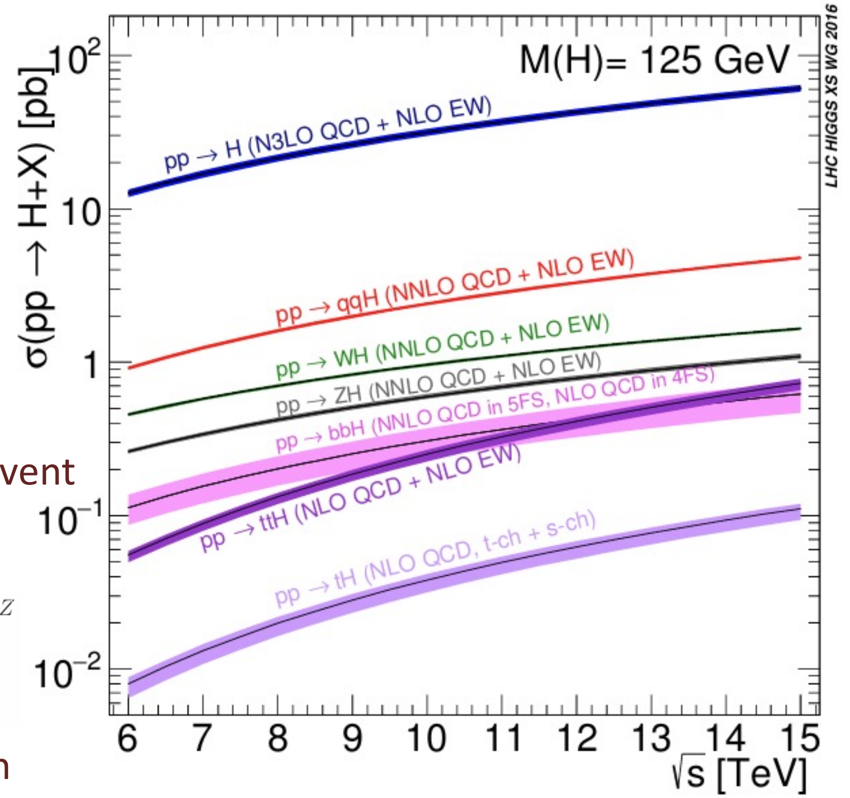


Leptons from V decay help with event identification
Direct probe of HVV couplings



➢ ttH production

Challenging final state; direct probe of ttH coupling



Higgs decays

- Bottom quark (58%)

  B quark form short-lived B hadrons, can be identified by displaced tracks; large QCD background

- Vector bosons (Z: 3%, W: 21%)

  One of the V has to be off-shell; small event rates when including decays to leptons, but clean detector signature

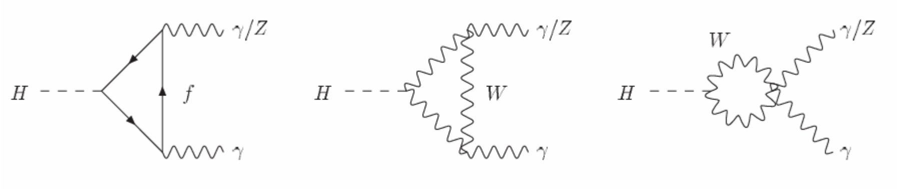
- Gluons (8.2%)

  Huge QCD backgrounds at LHC

- Photons ($Z\gamma$,$\gamma\gamma$ 0.2%)

  Small BR, but clear detector signature; destructive interferences

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	2.1%
$H \to ZZ$	2.62×10^{-2}	$\pm 1.5\%$
$H \to W^+W^-$	2.14×10^{-1}	$\pm 1.5\%$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$\pm 1.6\%$
$H \to b\bar{b}$	5.82×10^{-1}	$^{+1.2\%}_{-1.3\%}$
$H \to c\bar{c}$	2.89×10^{-2}	$^{+5.5\%}_{-2.0\%}$
$H \to Z\gamma$	1.53×10^{-3}	$\pm 5.8\%$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$\pm 1.7\%$

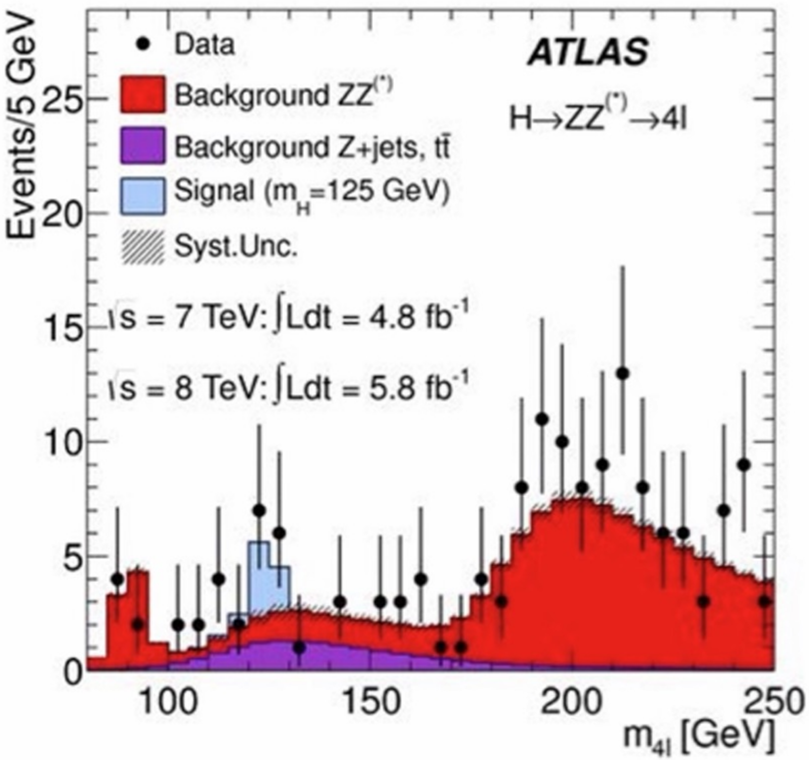


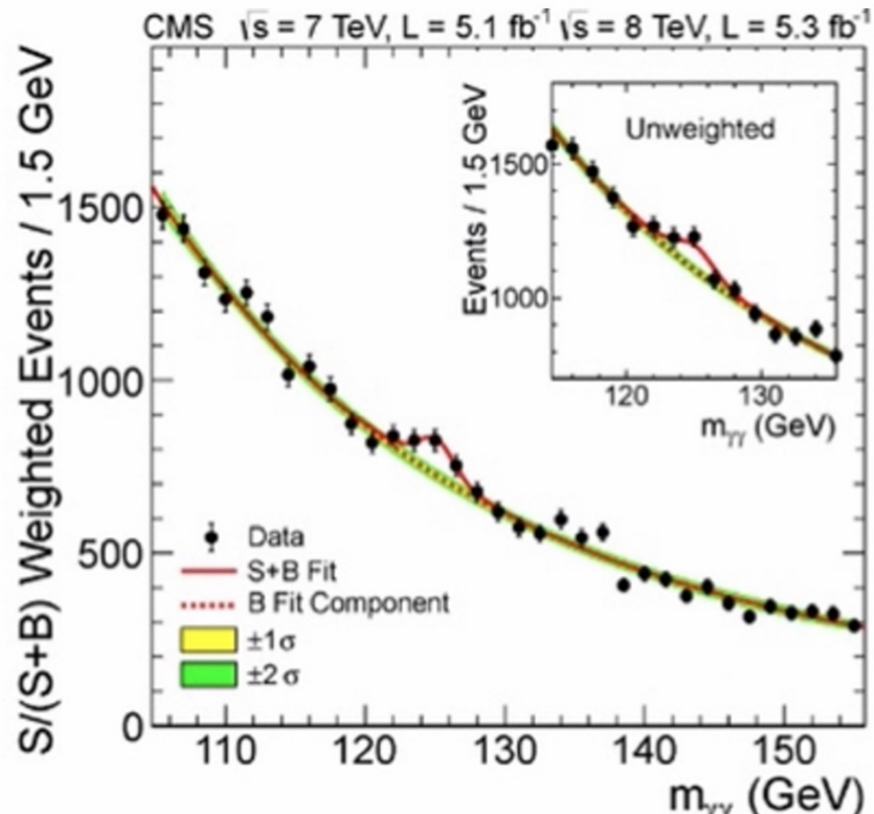
Higgs Discovery

From Matthias Kerner

July 4, 2012: ATLAS and CMS announce the observation of a new particle, compatible with the SM Higgs with $m_H = 125$ GeV

→ resonance in the m_{4l} $(H \to ZZ^* \to 4l)$ and $m_{\gamma\gamma}$ $(H \to \gamma\gamma)$ spectrum





Higgs Discovery

From Matthias Kerner

Karlsruhe Institute of Technology

July 4, 2012: ATLAS and CMS announce the observation of a new particle, compatible with the SM Higgs with $m_H = 125$ GeV

→ many happy faces ...

SM Higgs boson?

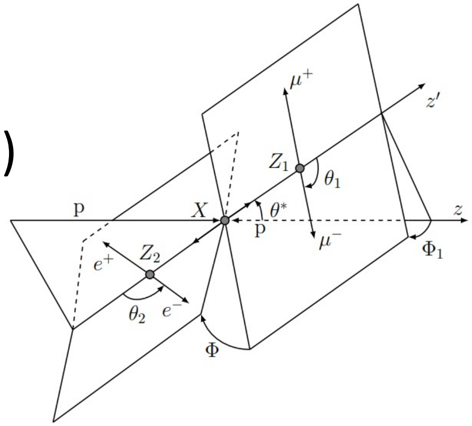
- Spin, Parity?
- Couplings to other SM particles?
- Higgs potential?

... and a year later:

Nobel Prize awarded to François Englert & Peter Higgs
(*1932) (1929-2024)

Higgs spin and CP properties

- Spin ½ and 1 (due to $H \to \gamma\gamma$: Landau-Yang theorem) excluded
- Only real contender: spin 0 & 2



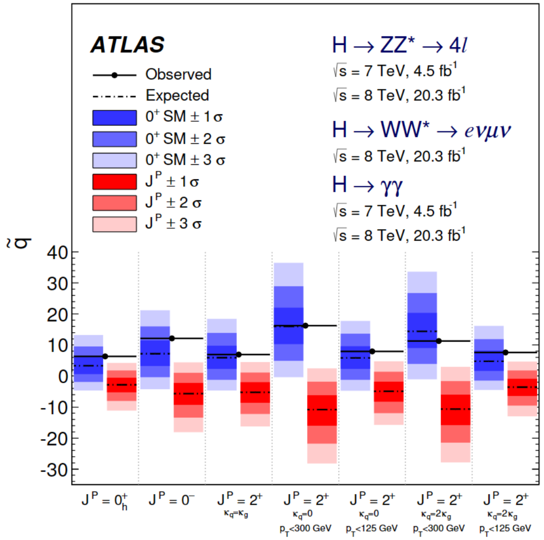
- Spin 0: $f^{*(i)}_{\mu\nu} = \varepsilon^{\mu}_{i} q^{\nu} - \varepsilon^{\nu}_{i} q^{\mu}$ $\quad \tilde{f}^{*(i)}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\rho\sigma} f^{*(i)\rho\sigma}$

$$m^2_{V_1}\varepsilon^*_{V_1}\varepsilon^*_{V_2} + a_2^{VV} f^{*(1)}_{\mu\nu} f^{*(2)\mu\nu} + a_3^{VV} f^{*(1)}_{\mu\nu}\tilde{f}^{*(2)\mu\nu}$$

CP-odd interaction

$$\frac{d\sigma}{d\phi} \propto \cos^2\phi \qquad \text{CP-even} \qquad \vec{\varepsilon}_{Z_1}\cdot\vec{\varepsilon}_{Z_2}$$

$$\frac{d\sigma}{d\phi} \propto \sin^2\phi \qquad \text{CP-odd} \qquad \vec{\varepsilon}_{Z_1}\times\vec{\varepsilon}_{Z_2}$$



- Spin 2 : θ^* distributions is different for spin 2 and spin 0, $d^J_{m1,m2}(\theta^*)$

e.g. Bolognesi, Gao, Gritsan, Melnikov, Schulze, 2012

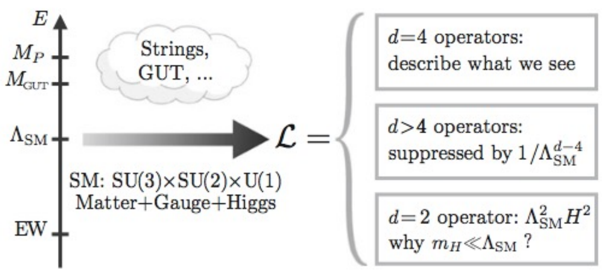
实验数据与标准模型一致，$J^P = 0^+$

Higgs coupling measurements

The Framework for the Higgs physics

1. The κ framework for the couplings:
BSM physics is expected to affect the production modes and decay channels by a SM like interactions

2. The Standard Model Effective Field Theory



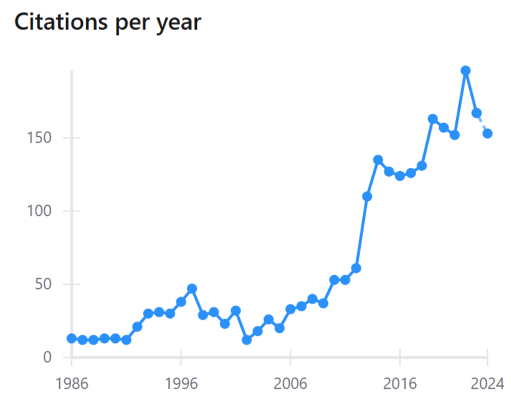
Linear realized EFT

Higgs is a fundamental particle
Weak interacting

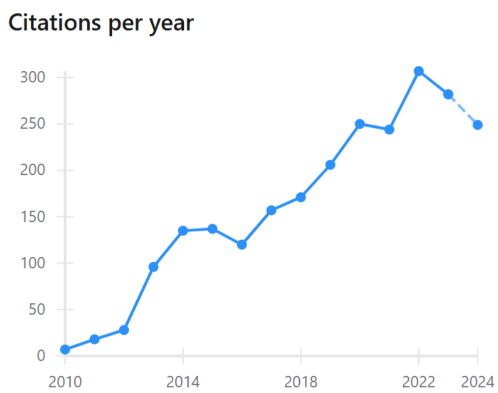
W. Buchuller, D. wyler 1986
B. Grzadkowski et al, 2010
L. Lehman, A. Marin, 2015
B. Henning et al, 2015
H-L. Li et al, 2020
Murphy, 2020

$$\mathcal{L} = \frac{C_6}{\Lambda^2}\mathcal{O}_6 + \frac{C_8}{\Lambda^4}\mathcal{O}_8 + \ldots$$

W. Buchuller, D. wyler 1986



B. Grzadkowski et al, 2010

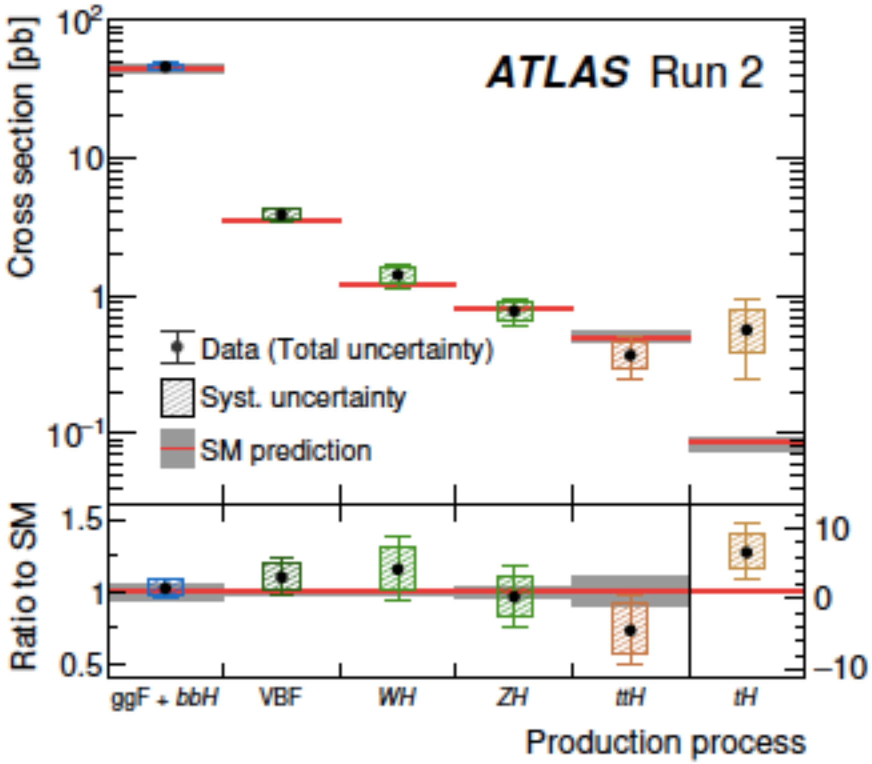


3. Higgs Effective Field Theory

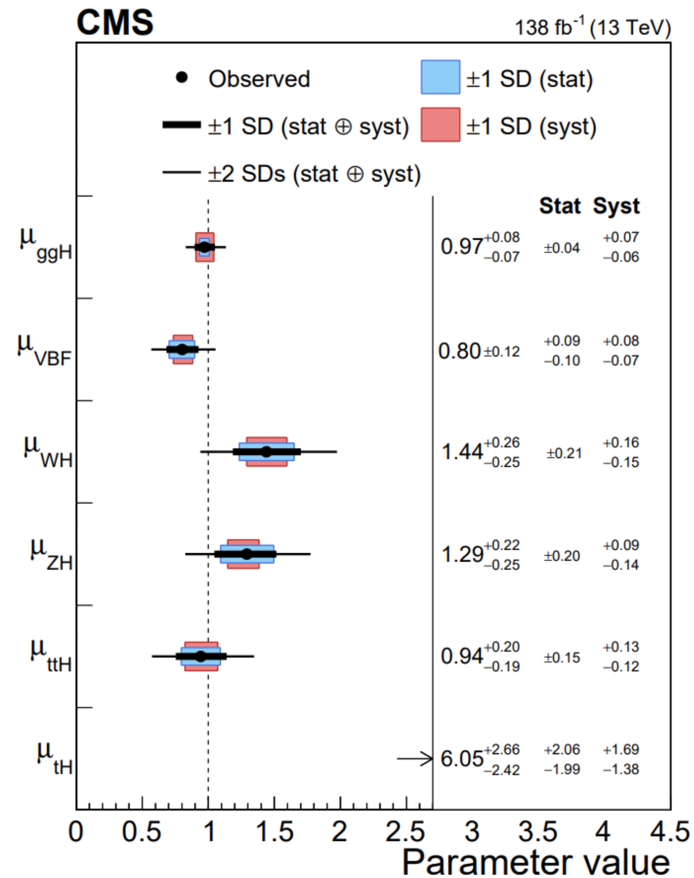
Callan, Coleman, Wess, Zumino, 1969
The electroweak chiral Lagrangian+light Higgs, A.C. Longhitano, 1980,....

The measurements @ LHC

Nature 607 (2022)7917,52-59



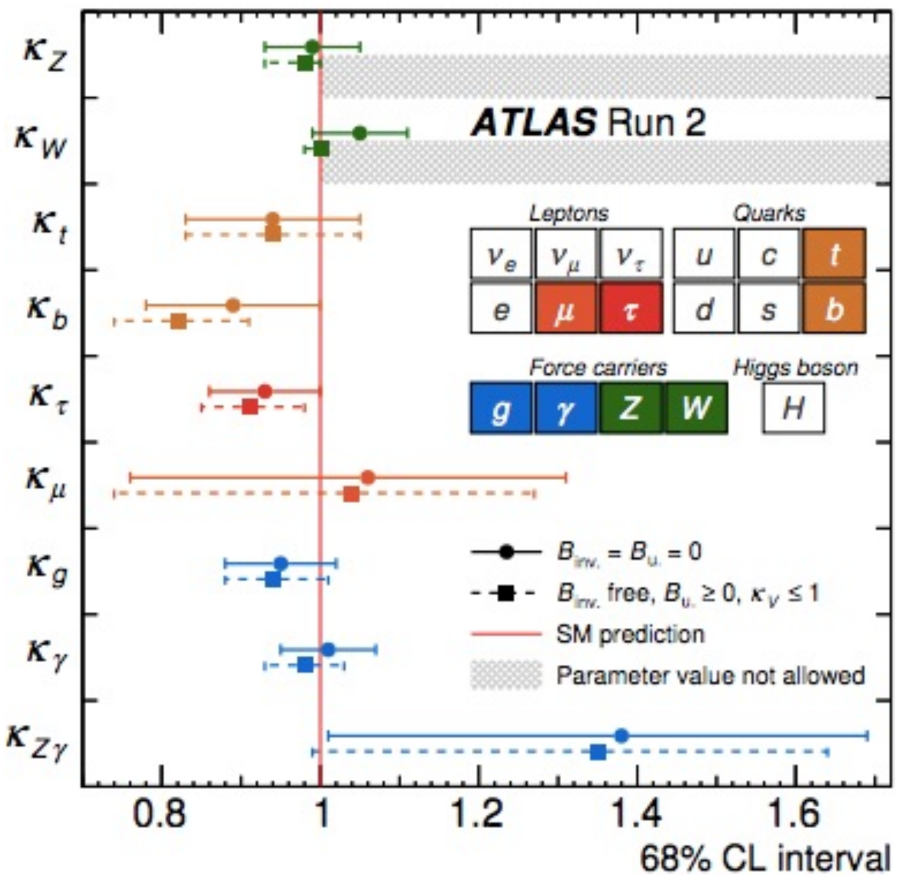
Nature 607 (2022)7917,60-68



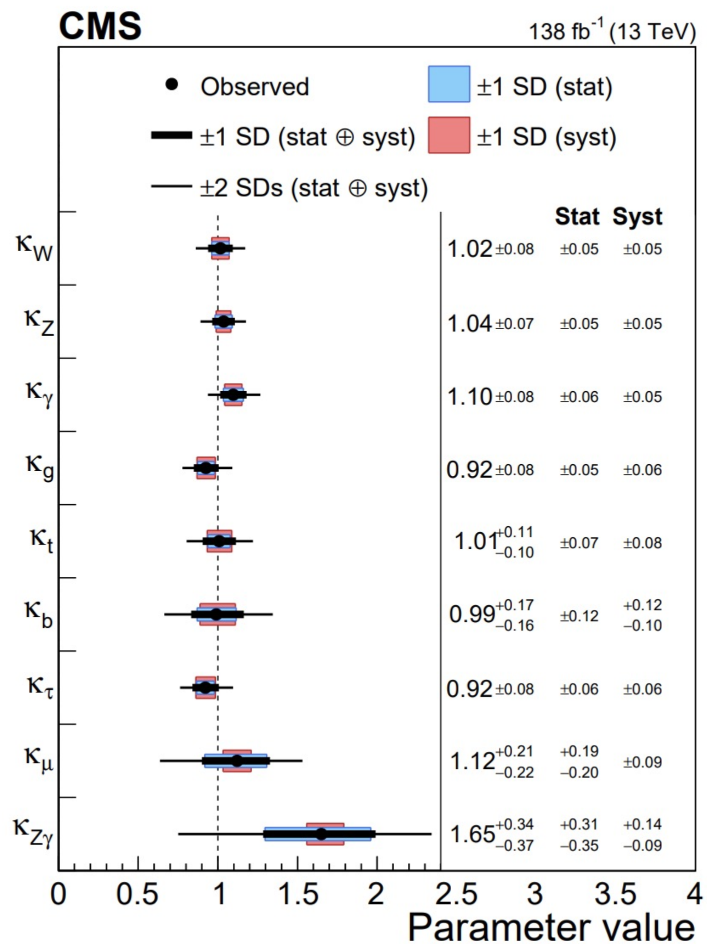
截面与信号强度（实验测量结果与标准模型理论预言的比值）测量结果

Higgs couplings @LHC

Nature 607 (2022)7917,52-59

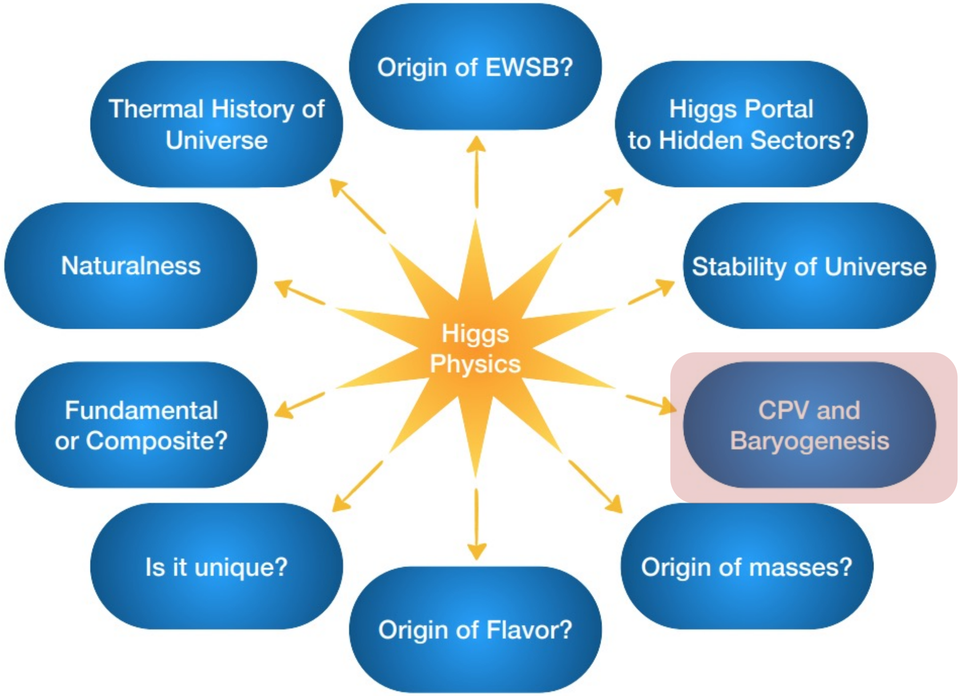


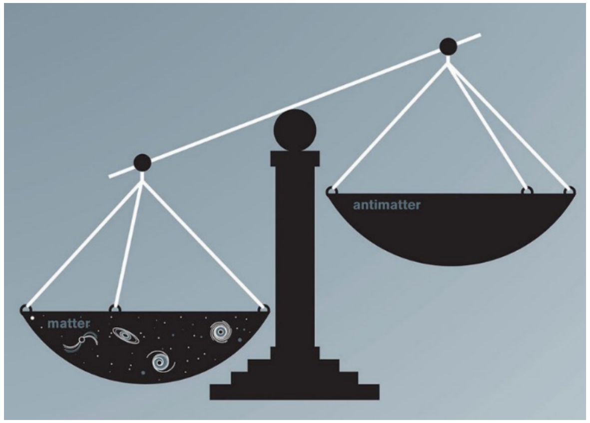
Nature 607 (2022)7917,60-68



$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

Higgs CP violation





Sakharov Criteria (1967)

- B violation
- C & CP violations
- Departure from the equilibrium

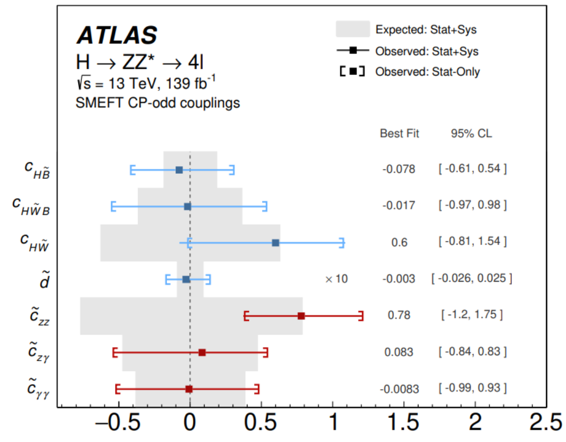
- A purely CP-odd Higgs has been excluded
- A CP-mixture Higgs boson is still possible

Higgs CP violation

- ➢ CP-odd interactions with gauge bosons (loop induced operators)

ATLAS,2304.09612

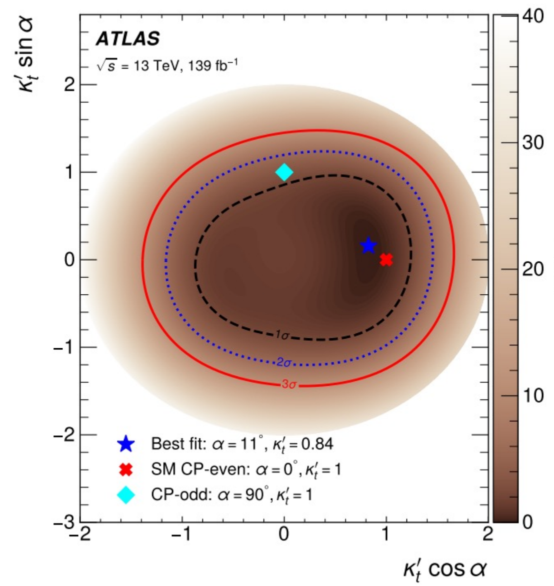
Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$



- ➢ CP-odd interactions with fermions

ATLAS：2303.05974
CMS：2208.02686

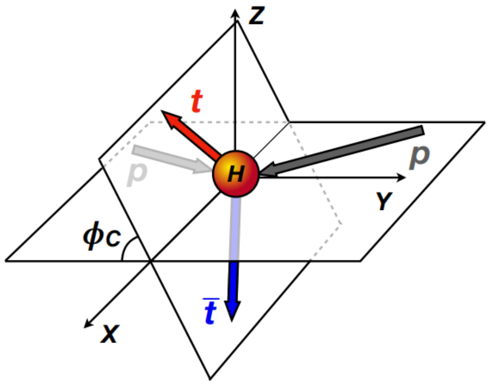
Gunion, He, PRL. 76, 4468 (1996)
Boudjema, Godbole, Guadagnolo, Mohan, PRD 92, 015019 (2015)
Mileo, Kiers, Szynkman, Crane, Gegner, JHEP 07, 056 (2016)
Gritsan, Rntsch, Schulze, Xiao, PRD 94, 055023 (2016)
S. Amor Dos Santos et al, PRD 96, 013004 (2017)
Kobakhidze, Liu, Wu, Yue, PRD 95 (2017) 1, 015016
Gouveia et al, 1801.04954
Gonalves, Kong, Kim, JHEP 06, 079 (2018)
Ren, Wu, Yang, 1901.05627
ATLAS, PRL 125 (2020) 6,061802
CMS, PRL 125 (2020) 6,061801
Q.-H. Cao, K.-P. Xie, H. Zhang , R. Zhang,CPC45 (2021)2,023117
Zhite Yu and C.-P. Yuan, 2211.00845
…

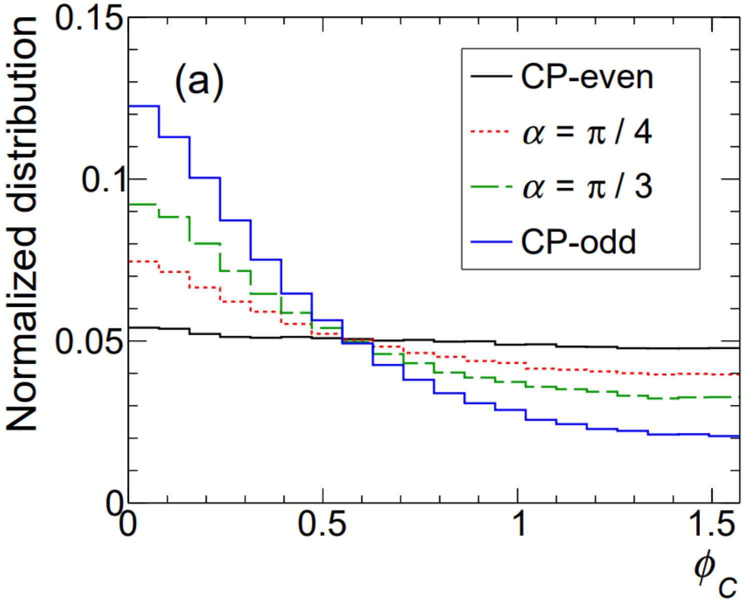


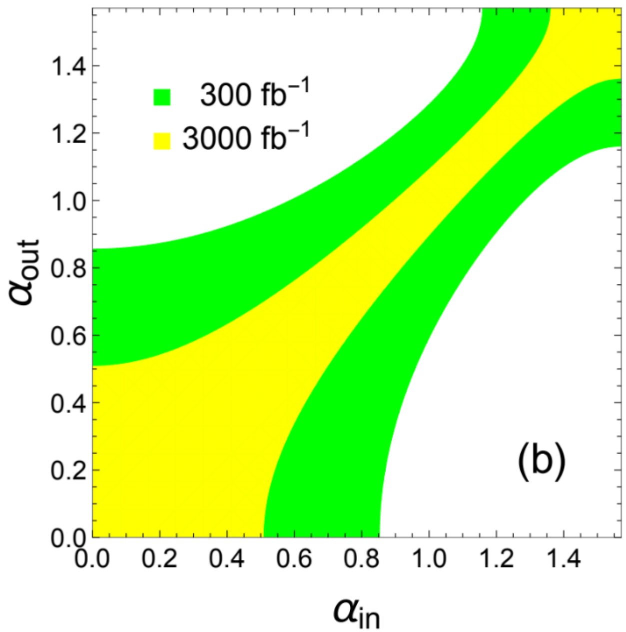
Higgs CP violation

$$\mathscr{L} = y_f h \bar{f}(\cos\alpha_f + i\gamma_5 \sin\alpha_f) f$$

$$\phi_C = \arccos\left|(\mathbf{n}_{p_1} \times \mathbf{n}_{p_2}) \cdot (\mathbf{n}_t \times \mathbf{n}_{\bar{t}})\right|$$





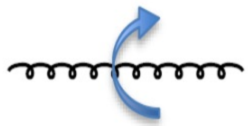


Q.-H. Cao, K.-P. Xie, H. Zhang , R. Zhang,CPC45 (2021)2,023117

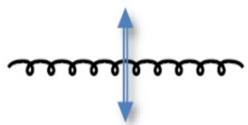
$$gg \to t\bar{t}h$$

New polarization observables

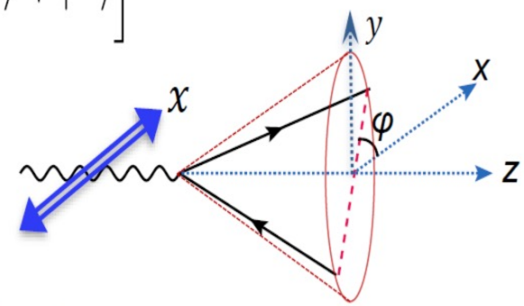
- **Linear polarization vs. helicity/circular polarization**

helicity pol.  $|\pm 1\rangle$

$$M \propto e^{i(\lambda_1-\lambda_2)\phi} d^J_{\lambda_1,\lambda_2}$$

linear pol.  $|x\rangle = -\frac{1}{\sqrt{2}}\Big[|+\rangle - |-\rangle\Big], \quad |y\rangle = \frac{i}{\sqrt{2}}\Big[|+\rangle + |-\rangle\Big]$

$$|e^{+i\phi} \pm e^{-i\phi}|^2 \to 2(1 \pm \cos 2\phi)$$



Interference of helicity λ_1 and λ_2 causes azimuthal distributions

$$\cos(\lambda_1 - \lambda_2)\phi, \quad \sin(\lambda_1 - \lambda_2)\phi$$

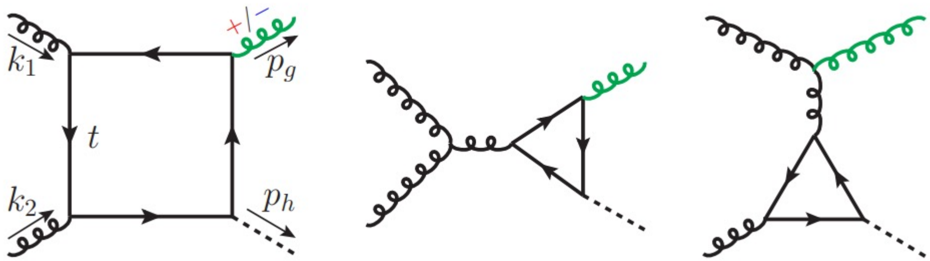
CP even   **CP odd**

Useful probes of new physics

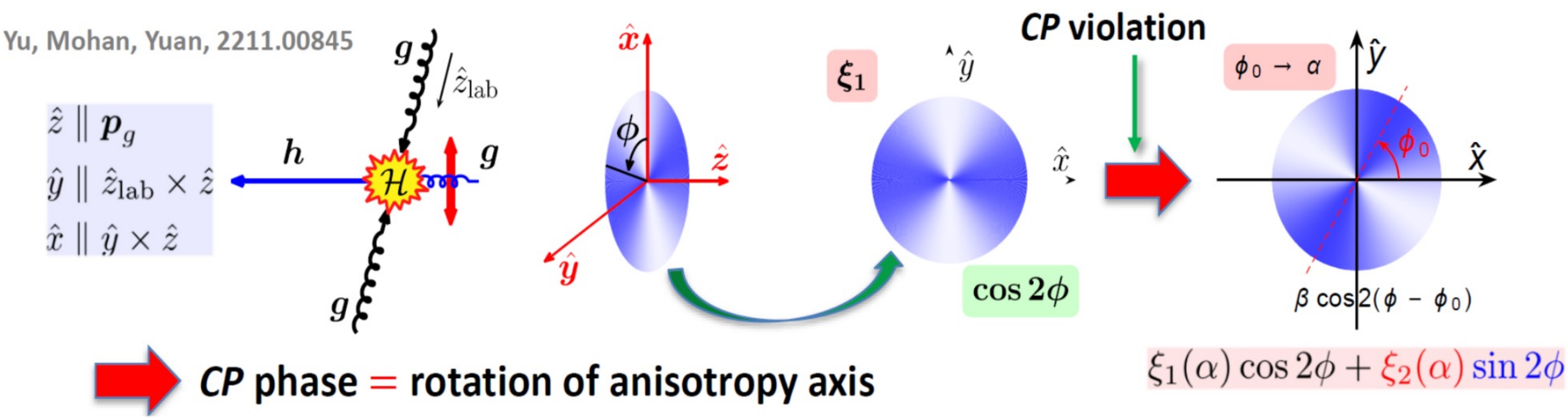
C.-P. Yuan's talk @ MBI 2023

New polarization observables

Linear polarization of gluon

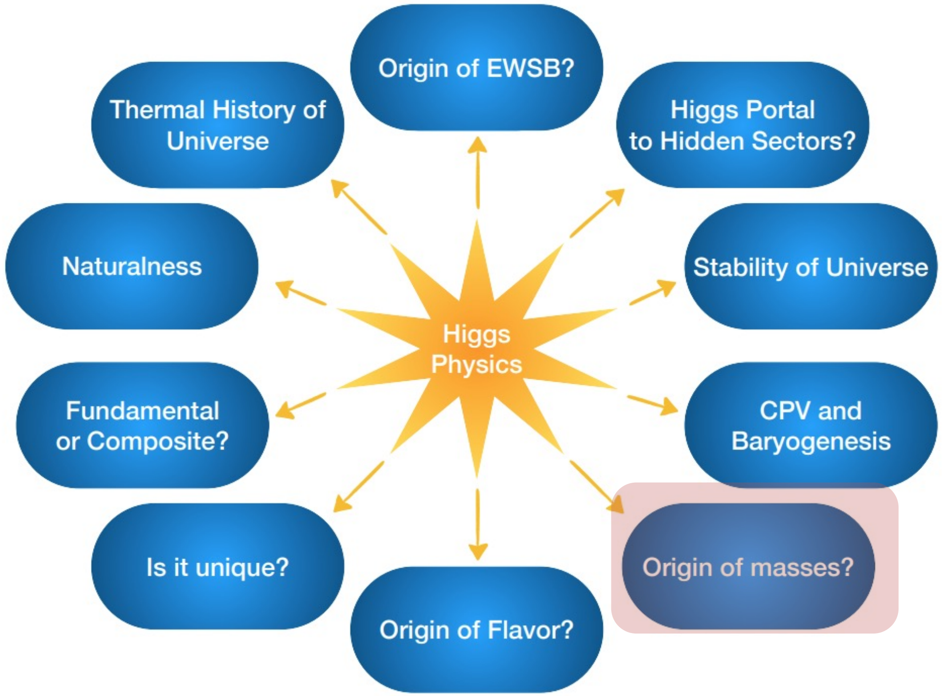


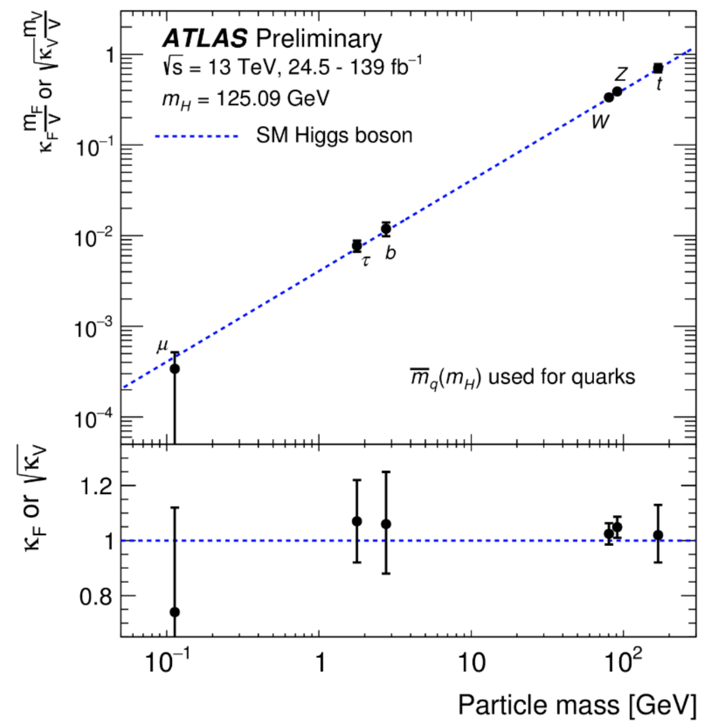
$$\rho_{\lambda\lambda'} = \frac{1}{2}(1+\boldsymbol{\xi}\cdot\boldsymbol{\sigma})_{\lambda\lambda'} = \frac{1}{2}\begin{pmatrix} 1+\xi_3 & \xi_1 - i\,\xi_2 \\ \xi_1 + i\,\xi_2 & 1-\xi_3 \end{pmatrix}$$



C.-P. Yuan's talk @ MBI 2023

Higgs Yukawa couplings



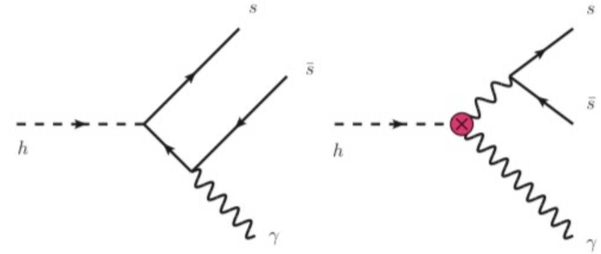


All fundamental particles get their mass from Higgs boson vev

How about light quarks?
Does Higgs mechanism still work?

Light quark Yukawa couplings@LHC

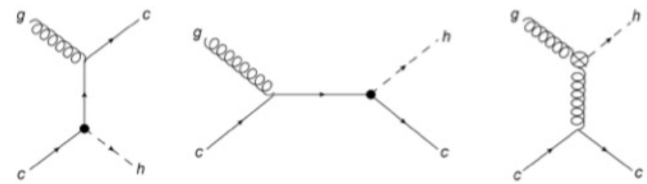
A. Rare decay: $h \to J/\Psi\gamma\ (\phi\gamma, \rho\gamma, \omega\gamma)$



G. T. Bodwin, F. Petriello, S. Stoynev, M. Velasco, PRD88 (2013) 5, 053003
A. L. Kagan, G. Perez, F. Petriello, Y. Soreq, S. Stoynev, PRL114 (2015) 10,101802

e.g. 14 TeV HL-LHC $y_s/y_b < 0.39$ $y_c/y_c^{\rm SM} < 220$

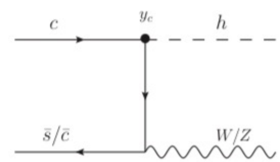
B. Higgs+charm production



I. Brivio, F. Goertz, G. Isidori, PRL115 (2015)21,211801

e.g. 14 TeV HL-LHC $y_c/y_c^{\rm SM} < 2.5$

C. Higgs data global analysis:



G. Perez, Y. Soreq, E. Stamou, K. Tobioka, PRD92(2015)3, 033016, PRD93(2016)1,013001
Y. Zhou, PRD93(2016) 1,013019

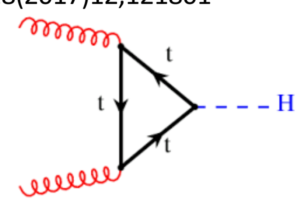
e.g. 14 TeV HL-LHC $y_c/y_c^{\rm SM} < 6.2$

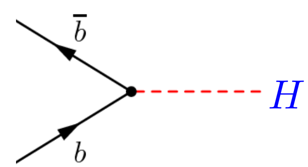
D. Higgs p_T analysis:

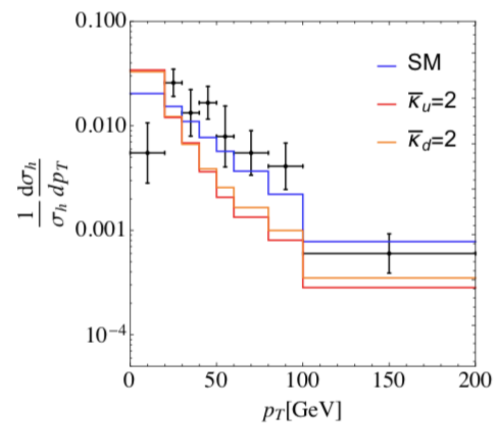
Y. Soreq, H.X. Zhu, J. Zupan, JHEP 12(2016)045
F. Bishara, U. Haisch, P. F. Monni, E. Re, PRL 118(2017)12,121801
G. Bonner, H. E. Logan, 1608.04376

$y_{u,d}/y_b < 0.4 \sim 0.5$

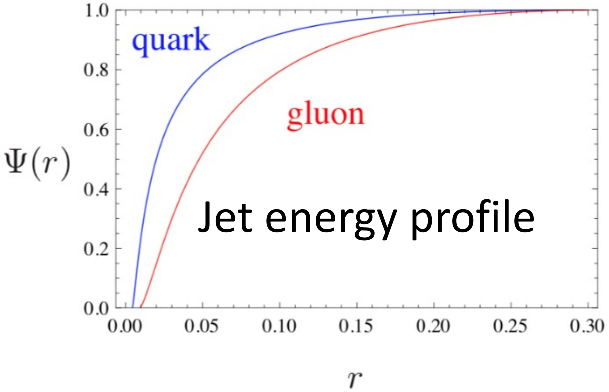
Soft gluon radiation

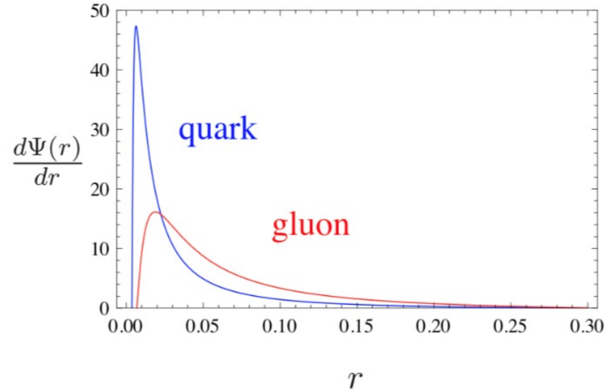




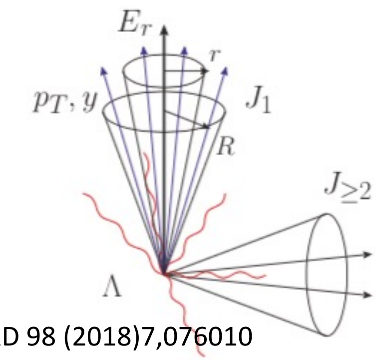


Light quark Yukawa couplings@ e^+e^-



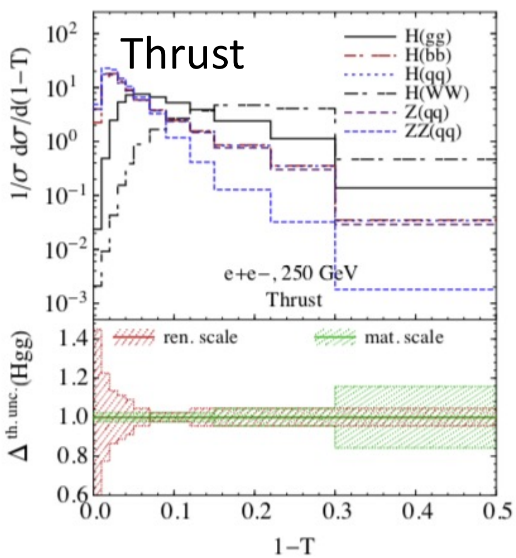


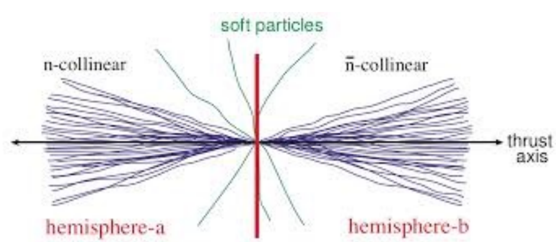
$$\Psi_J(r) = \frac{\sum_{i,d_{i,\hat{n}}<r} E_T^i}{\sum_{i,d_{i,\hat{n}}<R} E_T^i}$$



H. N. Li, Z. Li and C.-P. Yuan, PRL 107 (2011)152001; Y. T. Chien, I. Vitev, JHEP 12(2014)061

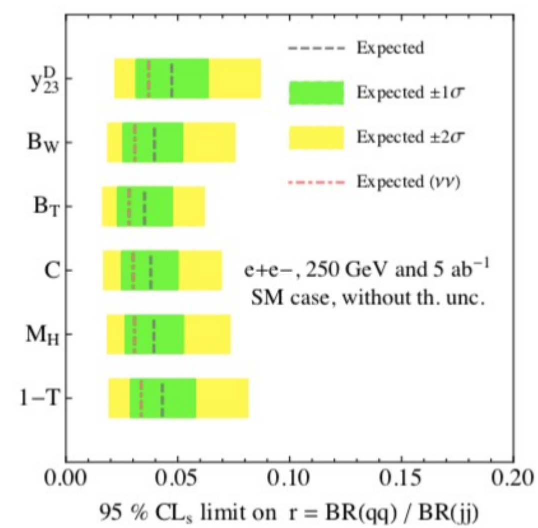
J. Isaacson, H.N. Li, Z. Li and C.-P. Yuan, PLB 771 (2017)619-623; G. X. Li, Z. Li, Y.D. Liu, Y. Wang, X. R. Zhao, PRD 98 (2018)7,076010





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

$y_{u,d,s}/y_b < 0.091$



J. Gao, JHEP 01 (2018) 038

Event shapes

One class of event shapes: $$e(X) = \frac{1}{Q}\sum_{i\in X} |p_\perp^i| f_e(\eta_i)$$

Examples:

Thrust $$f_{1-T}(\eta) = e^{-|\eta|}$$ Brandt, Peyrou, Sosnowski, Wroblewski,64; Farhi, 77

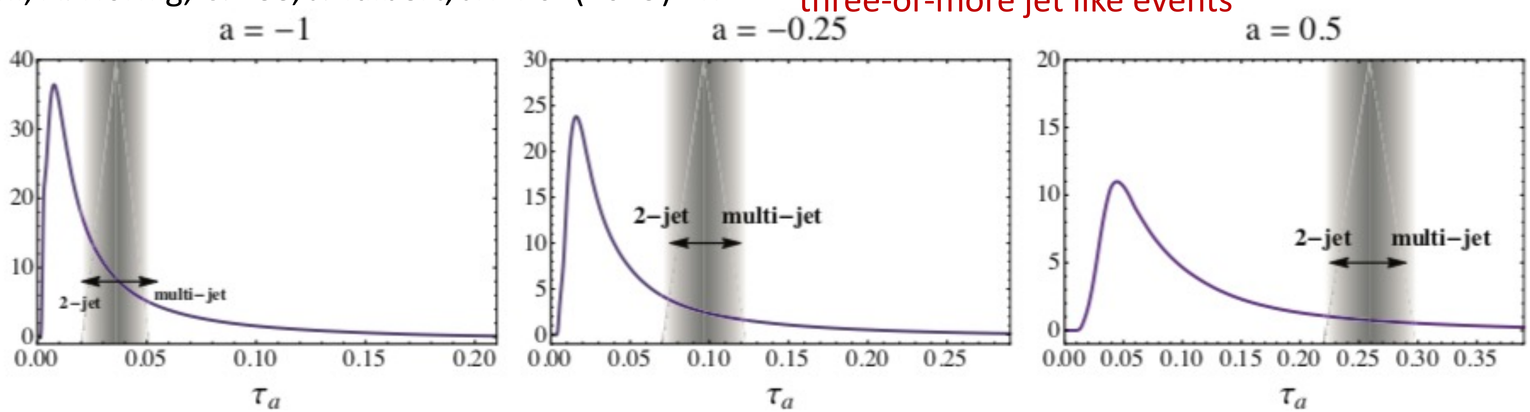
Jet broadening $$f_B(\eta) = 1$$ Catani, Turnock, Webber, 92

C-Parameter $$f_C(\eta) = \frac{3}{\cosh(\eta)}$$ Ellis, Ross, Terrano, 81

Angularities $$f_{\tau_a}(\eta) = e^{-|\eta|(1-a)}$$ Berger, Kucs, Sterman, 03 (relatively new)

The proportions of two jet-like and three-or-more jet like events

G. Bell, A. Hornig, C. Lee, J. Talbert, JHEP01(2019)147

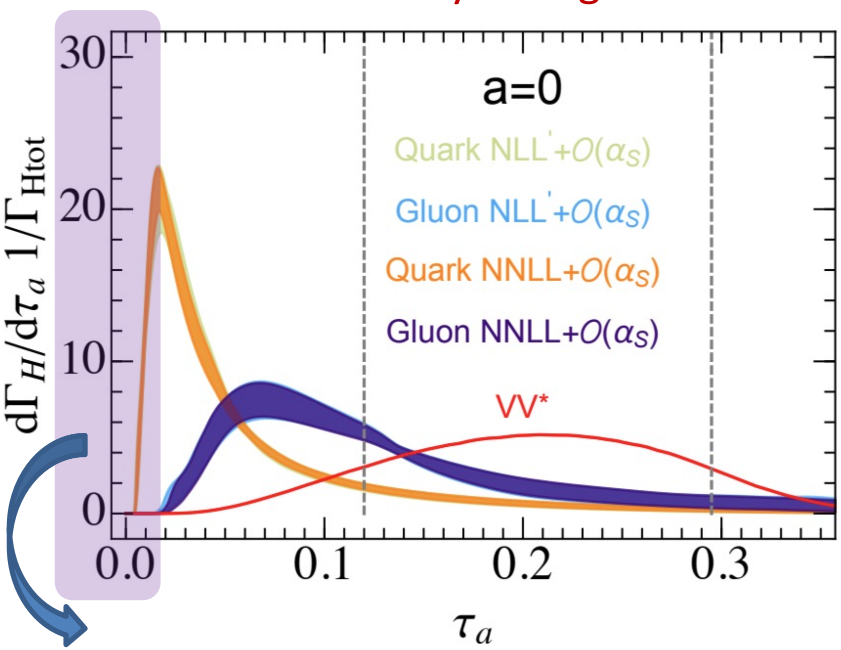


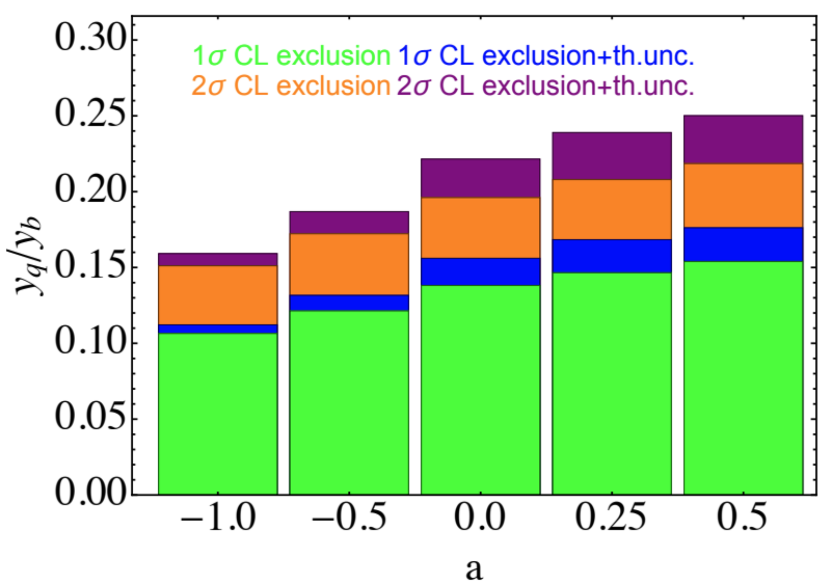
Higgs Yukawa couplings

J. Gao, Y. Gong, W.-L. Ju and L. L. Yang, JHEP 03 (2019) 030
J. Zhu, J. Gao, D. Kang, T. Maji, 2311.07282
Bin Yan, C. Lee, JHEP 03 (2024) 123

Angularity distributions are very different for quark and gluon final state

Analysis Region

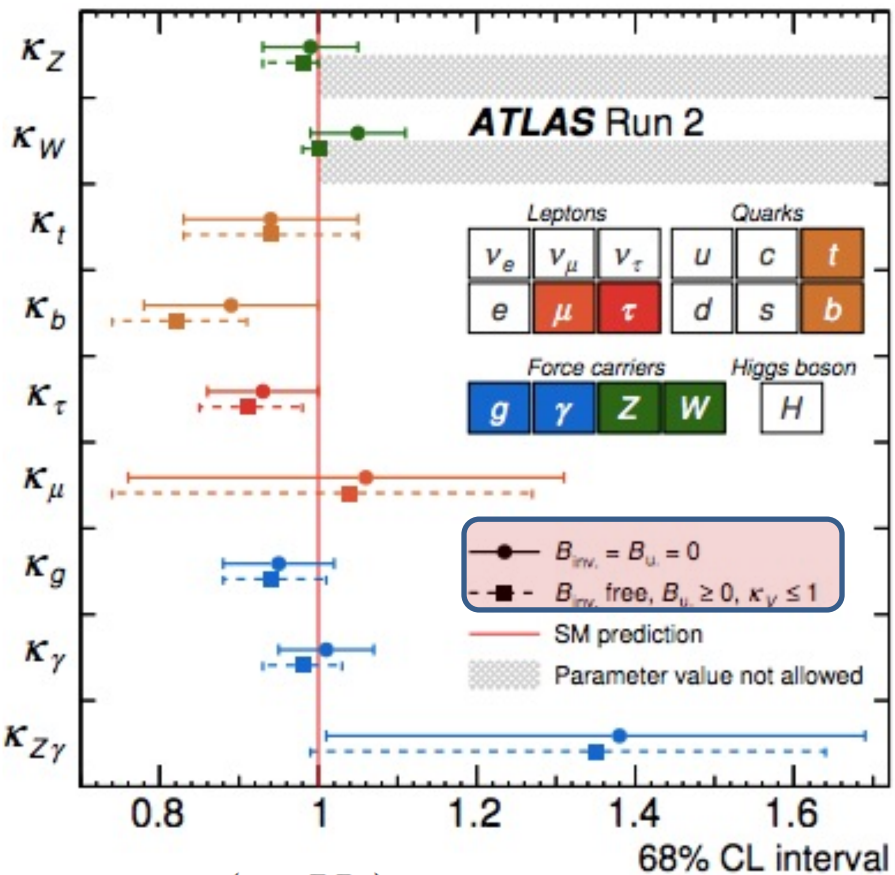




Sensitive to non-perturbative assumptions

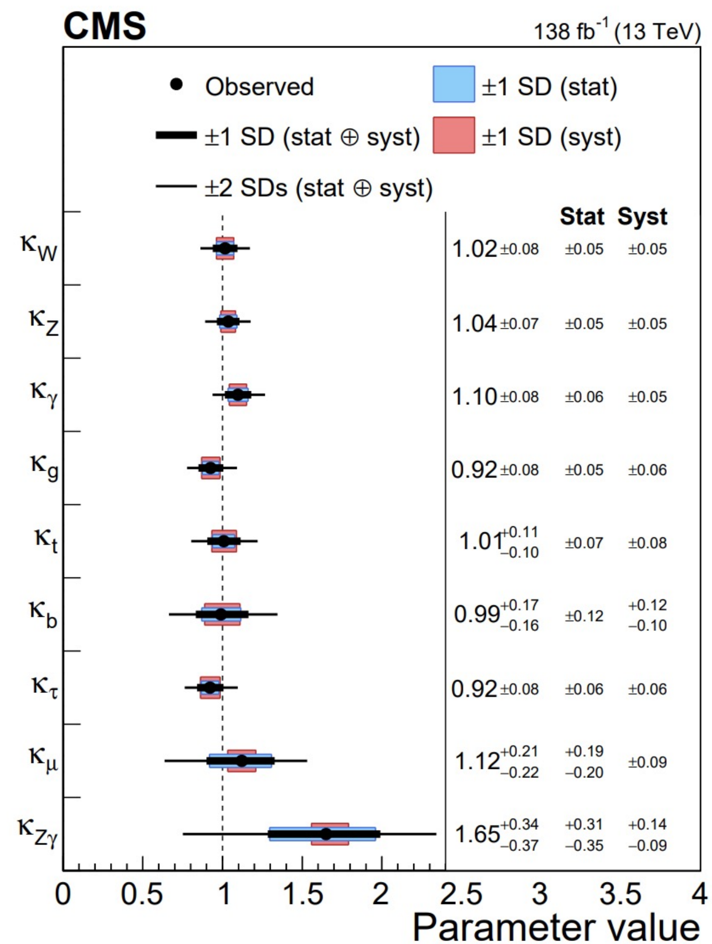
Higgs couplings @LHC

Nature 607 (2022)7917,52-59



$$\mu = \frac{(\sigma_p \times BR_d)_{\text{obs}}}{(\sigma_p \times BR_d)_{\text{SM}}}$$

Nature 607 (2022)7917,60-68

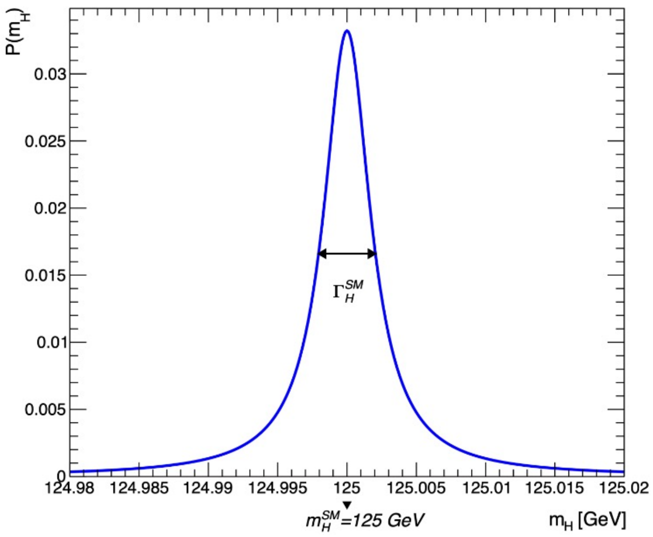


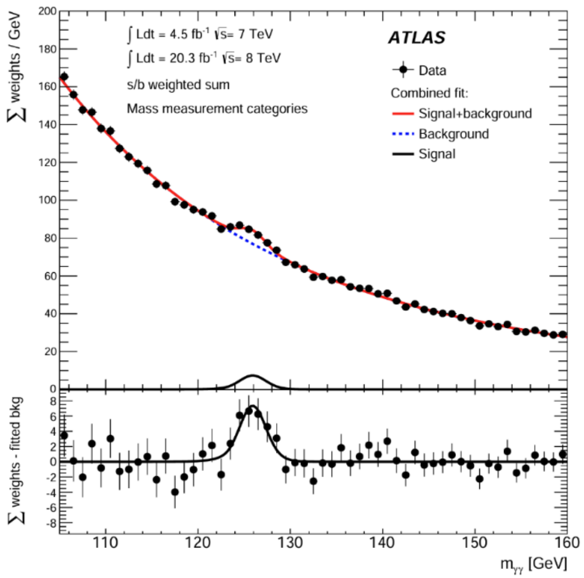
全局拟合结果依赖对希格斯宽度的假设 ⟹ 直接测量希格斯宽度至关重要

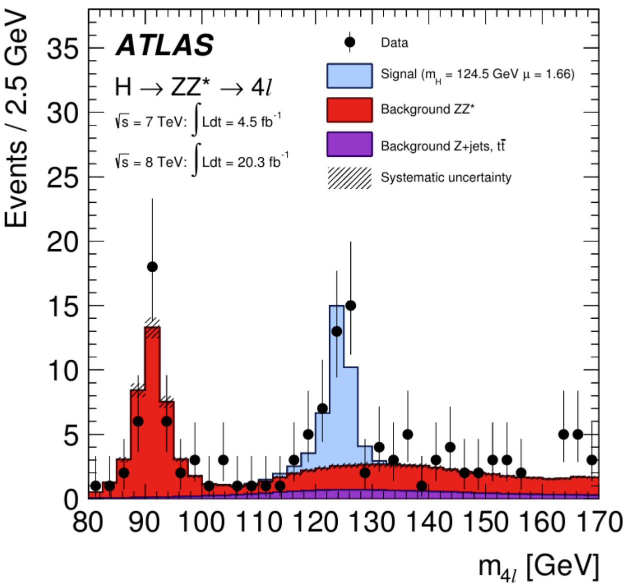
Higgs width measurements

Direct constraints: reconstructed mass line-shape

The intrinsic mass resolution: 1-2 GeV, Higgs width (SM): 4.1 MeV



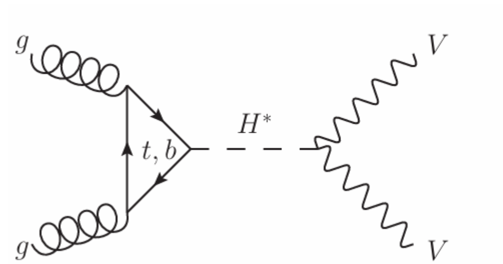


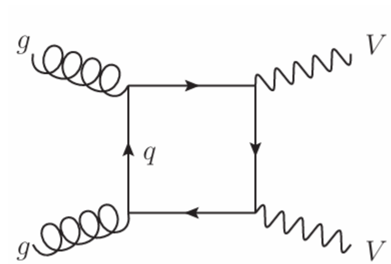


- the modelling of resolution uncertainties
- the modelling of the interference between the signal and the background which can be sizeable for large widths
- CMS: 330 MeV

Higgs width measurements

Indirect constraints from off-shell couplings





$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

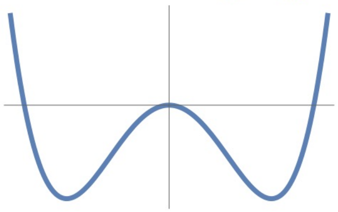
$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

Assuming the couplings are same for the on-shell and off-shell regions

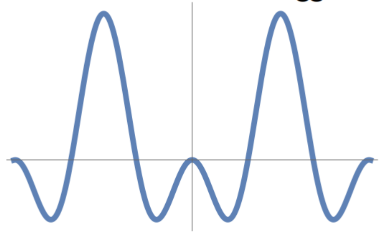
$$\text{(ATLAS)}\ \ \Gamma_H = 4.5^{+3.3}_{-2.5}\ \ [4.1^{+3.8}_{-3.8}\ \text{(exp)}]\ \text{MeV},$$
$$\text{(CMS)}\ \ \Gamma_H = 3.2^{+2.4}_{-1.7}\ \ [4.1^{+4.0}_{-3.5}\ \text{(exp)}]\ \text{MeV}.$$

$$\Gamma_H = 4.1^{+0.7}_{-0.8}\ \text{MeV}$$ (HL-LHC)

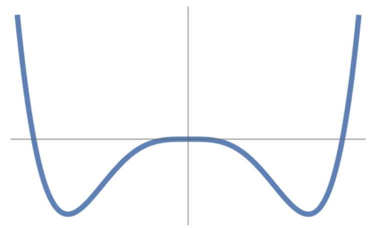
Higgs potential



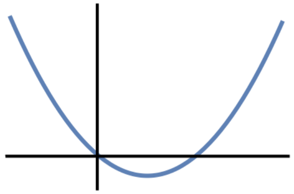
$V(\phi) = -m^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$



$V(\phi) = a\sin^2(\phi/f) + b\sin^4(\phi/f)$

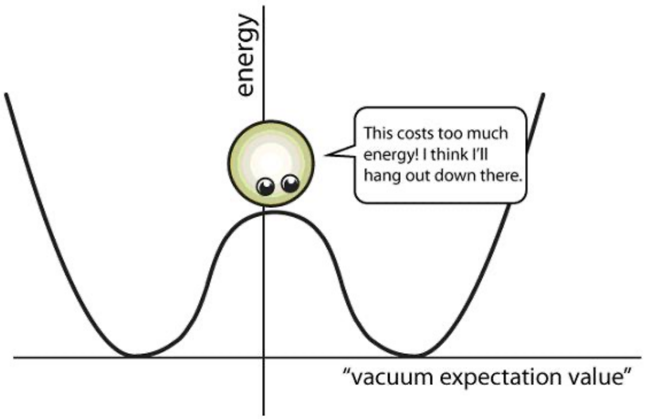


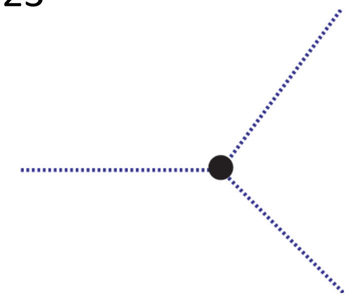
$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2\log\frac{\phi^\dagger\phi}{\mu^2}$



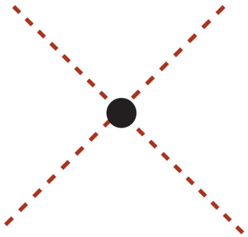
$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$

Agrawal, Saha, Xu, Yu, Yuan, PRD 101 (2020) 075023





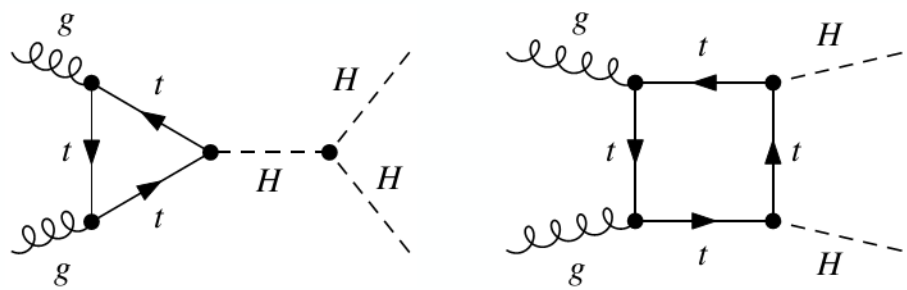
$$\lambda_{HHH} = \frac{3m_H^2}{v}$$



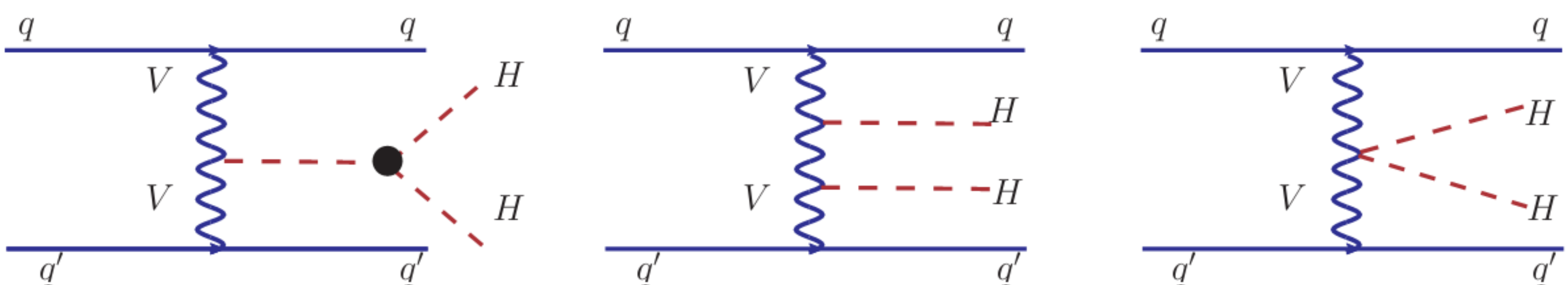
$$\lambda_{HHHH} = \frac{3m_H^2}{v^2}$$

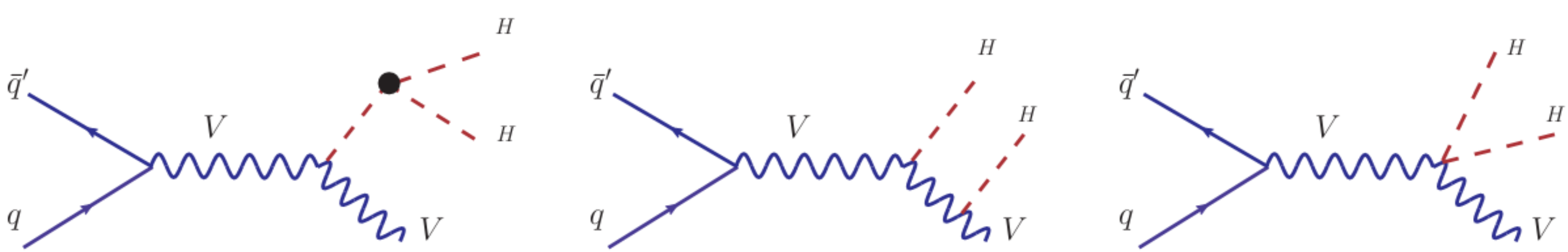
Higgs pair production

E. W. N.Glover et al (1988)
U. Baur et al (2002)
A.Papaefstathuou et al (2013)
J. Baglio et al (2013)
Q. Li et al (2015) .....



M. J. Dolan et al (2014,2015)

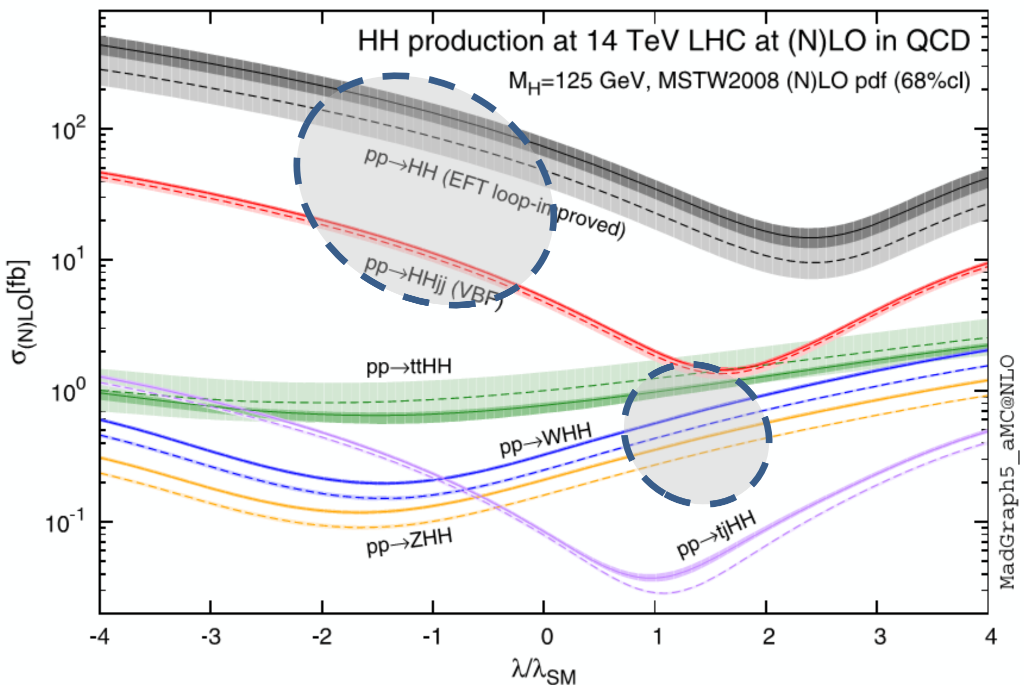




M. Moretti et al (2005), Q. H. Cao et al (2017)

Higgs pair production

$\sqrt{s}[TeV]$	$\sigma^{NLO}_{gg\to HH}$[fb]	σ^{NLO}_{HHjj}[fb]	σ^{NLO}_{WHH}[fb]	σ^{NLO}_{ZHH}[fb]
8	8.16	0.49	0.21	0.14
14	33.89	2.01	0.57	0.42
100	1417.83	79.55	8.00	8.27



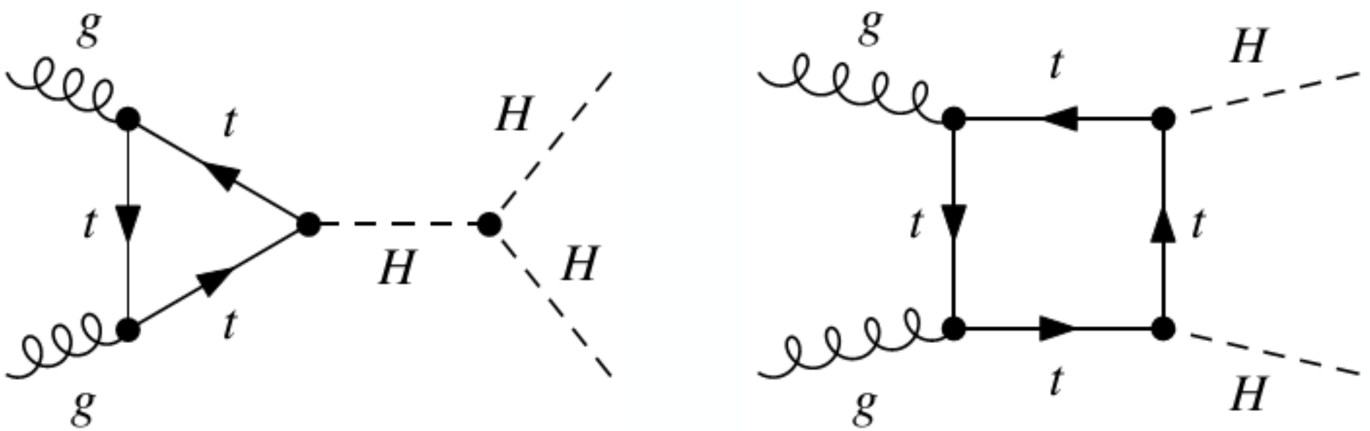
J. Baglio, A. Djouadi et al.
JHEP 1304(2013)51

- GGF and VBF 敏感于负区间
- VHH敏感于正区间

Higgs pair production

Low-energy theorem: Dawson and Haber (1989)

$$\eta = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$



$$-\frac{\alpha_s}{24\pi} G^{a,\mu\nu} G^a_{\mu\nu} \sum_n \frac{y_t^n h^n}{n!} \frac{\partial^n}{\partial m_t^n} \log\left(\frac{\Lambda_{UV}^2}{m_t^2}\right)$$

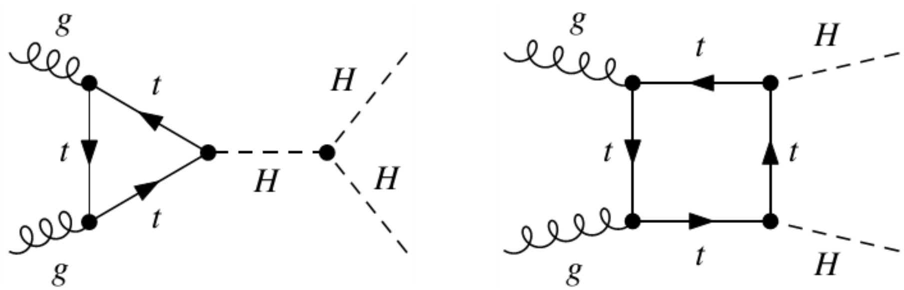
n=1

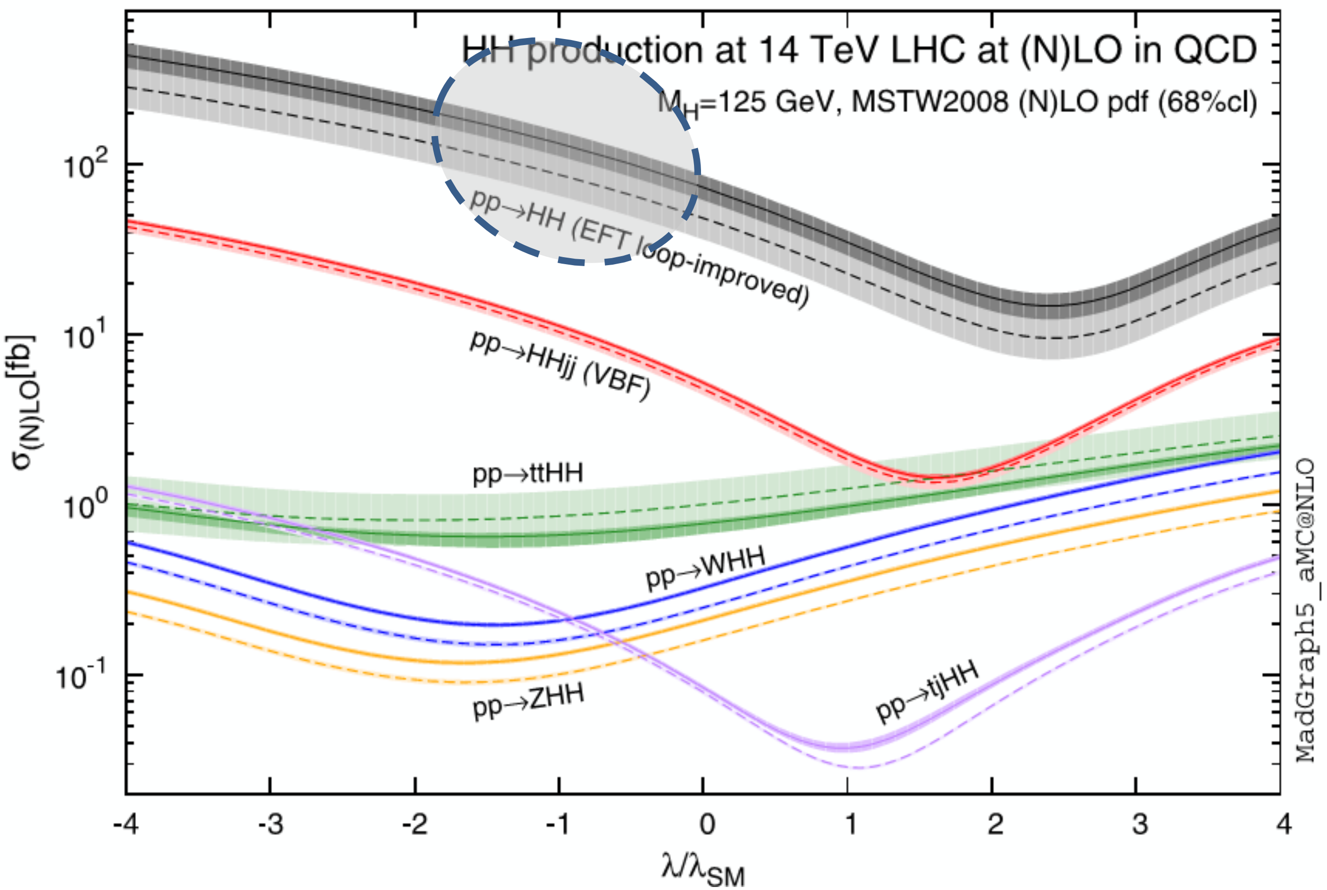
$$\eta \frac{\alpha_s}{12\pi v} G^{a,\mu\nu} G^a_{\mu\nu} h$$

n=2

$$-\frac{\alpha_s}{24\pi v^2} G^{a,\mu\nu} G^a_{\mu\nu} h^2$$

Higgs pair production

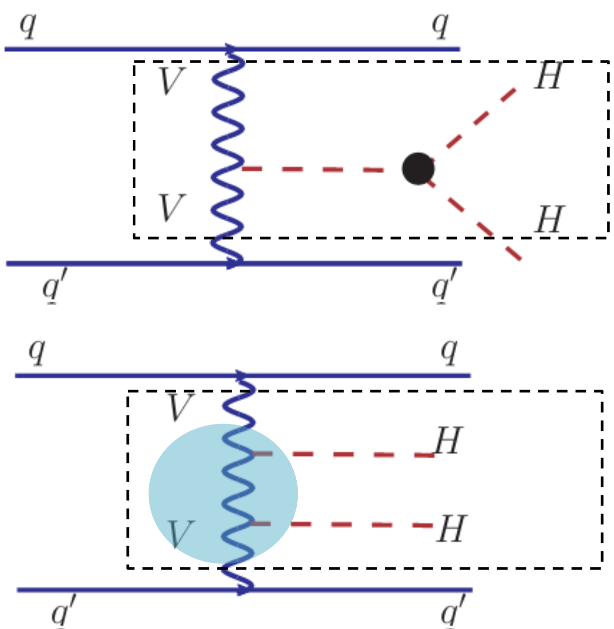




在标准模型中两个图贡献相互抵消，从而敏感依赖负的希格斯自相互作用

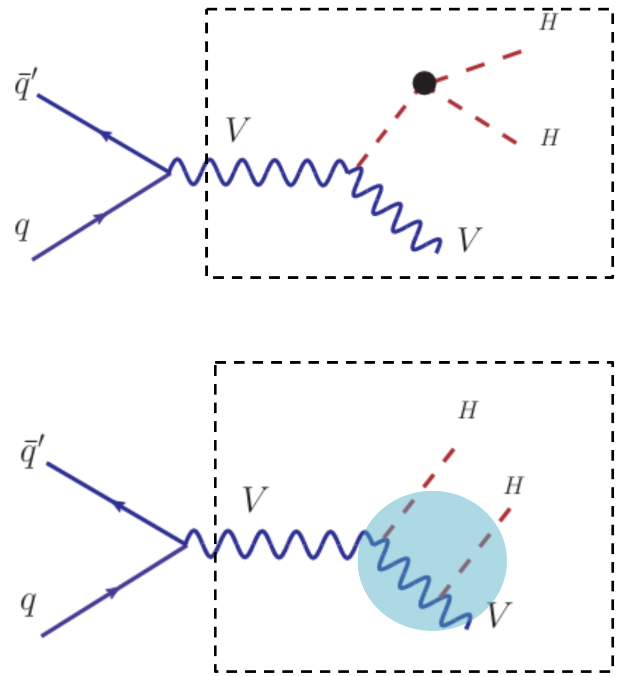
Higgs pair production

VBF Higgs pair

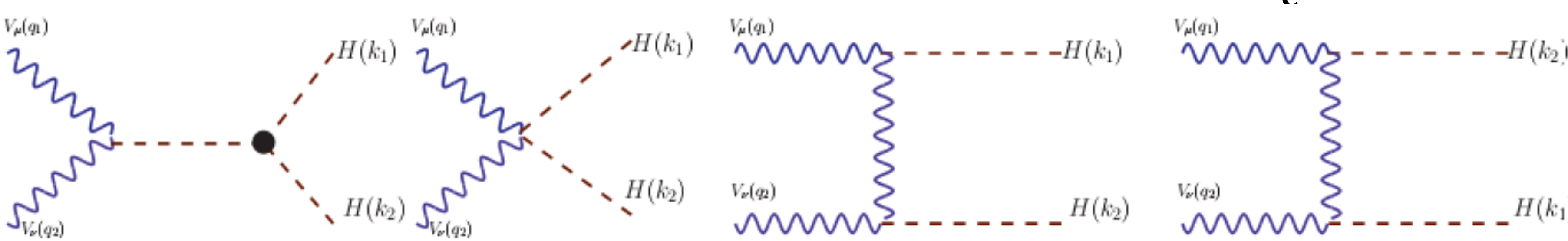


$Q^2 < 0$

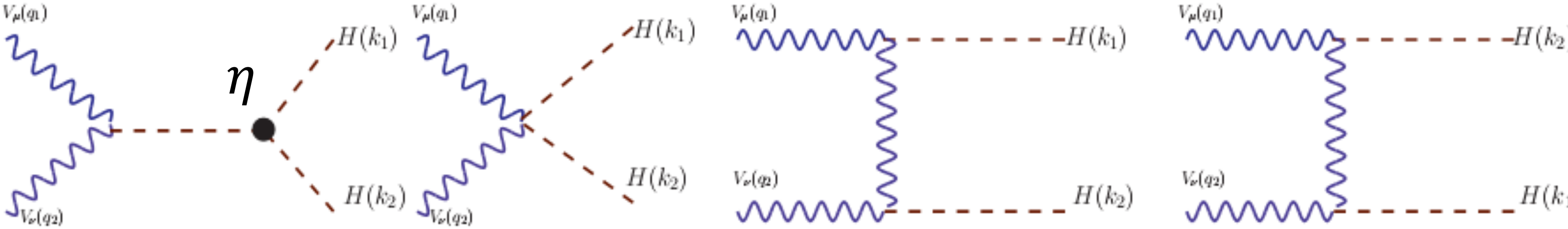
VHH Higgs pair



$Q^2 > 0$



Higgs pair production



$$M^{\mu\nu} = \left[\frac{m_W^2}{v^2}\frac{6m_H^2\eta}{s-m_H^2} + \frac{2m_W^2}{v^2} + \frac{4m_W^4}{v^2}\left(\frac{1}{t-m_W^2} + \frac{1}{u-m_W^2}\right)\right] g^{\mu\nu} + A^{\mu\nu}(q_1, k_1, k_2)$$

$$\eta = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

Near the Threshold:

$s = 4m_H^2, t = u = 0$ For VBF $\qquad M^{\mu\nu} = \frac{2m_W^2}{v^2}(\eta - 3)g^{\mu\nu} + \ldots$

$s = 4m_H^2, t = u = (m_H + m_V)^2$ For VHH $\qquad M^{\mu\nu} = \frac{2m_W^2}{v^2}(\eta + 1)g^{\mu\nu} + \ldots$

Higgs pair production

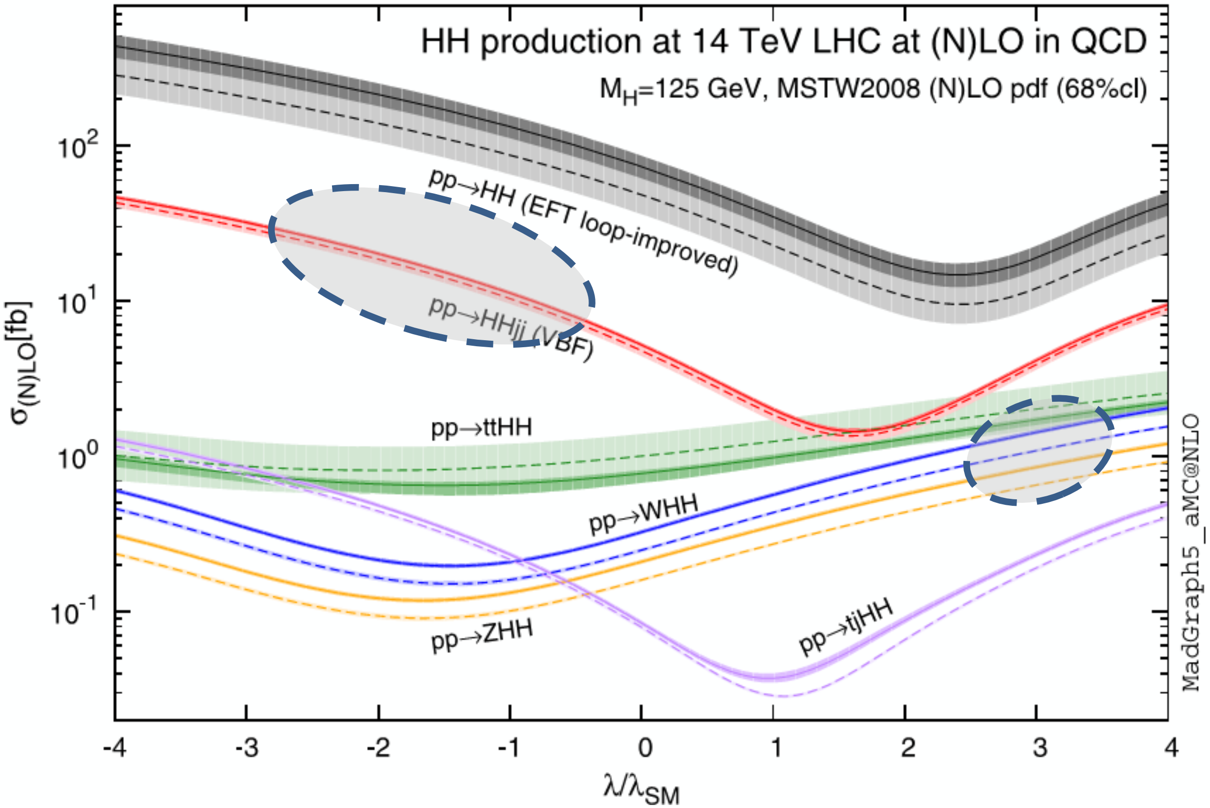
Near the Threshold:

VBF Higgs pair:

$$M^{\mu\nu} = \frac{2m_W^2}{v^2}(\eta - 3)g^{\mu\nu} + \ldots$$

VHH Higgs pair:

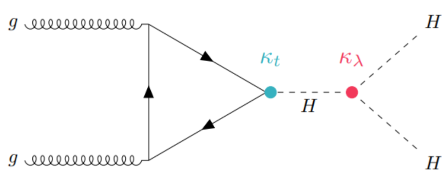
$$M^{\mu\nu} = \frac{2m_W^2}{v^2}(\eta + 1)g^{\mu\nu} + \ldots$$

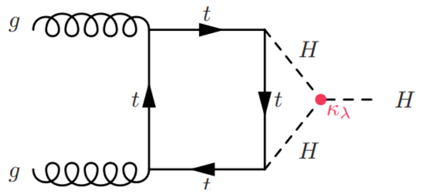


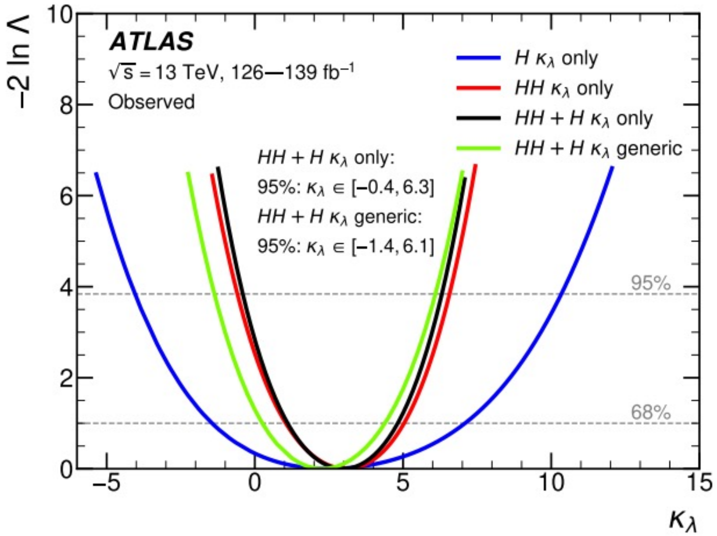
VBF 过程敏感负参数区间， VHH 过程敏感正的参数区间

Higgs potential

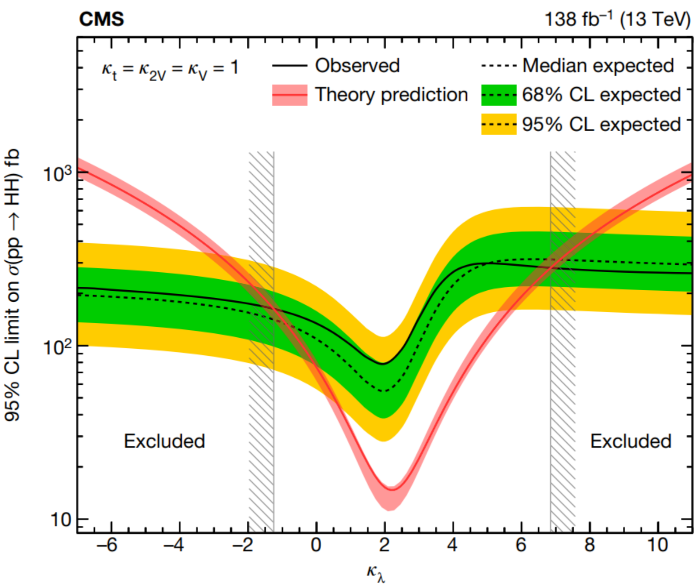
To determine the Higgs potential shape is challenge!







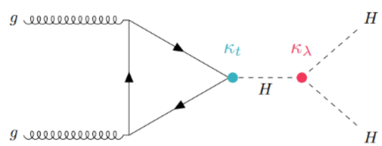
ATLAS, PRD108 (2023)5, 052003



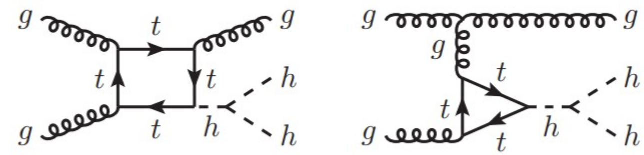
Nature 607 (2022) 60

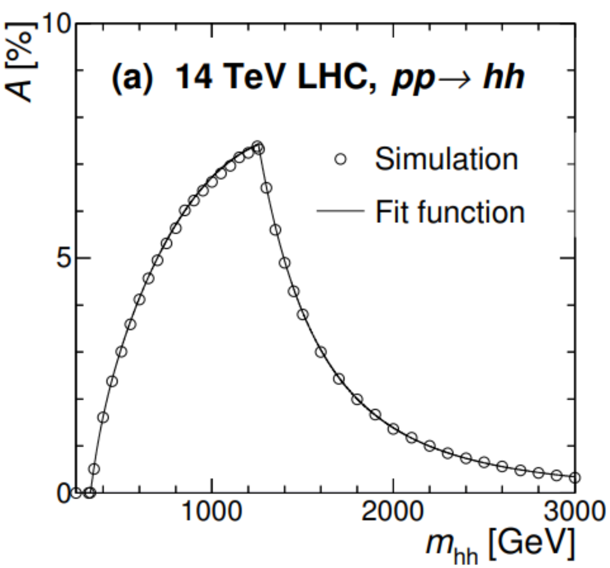
Higgs potential@ LHC

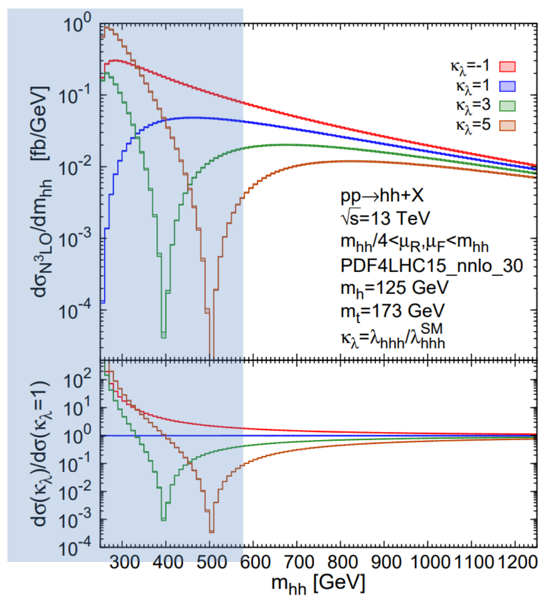
Current experimental searches mainly focus on the high di-Higgs invariant mass region

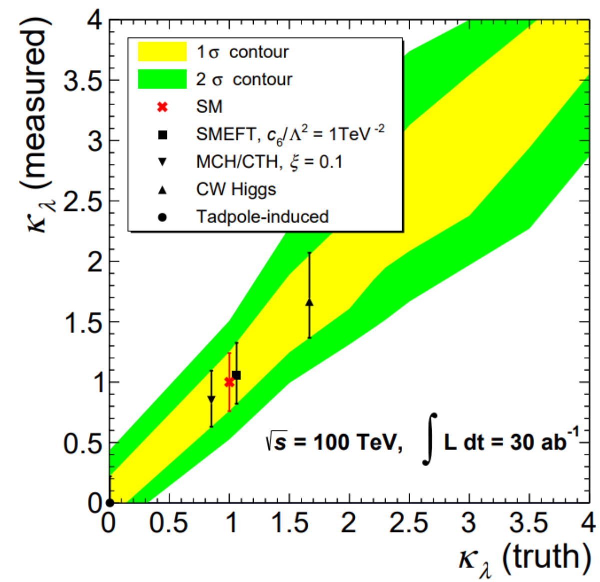


The low di-Higgs invariant mass region is more sensitive to the Higgs shape







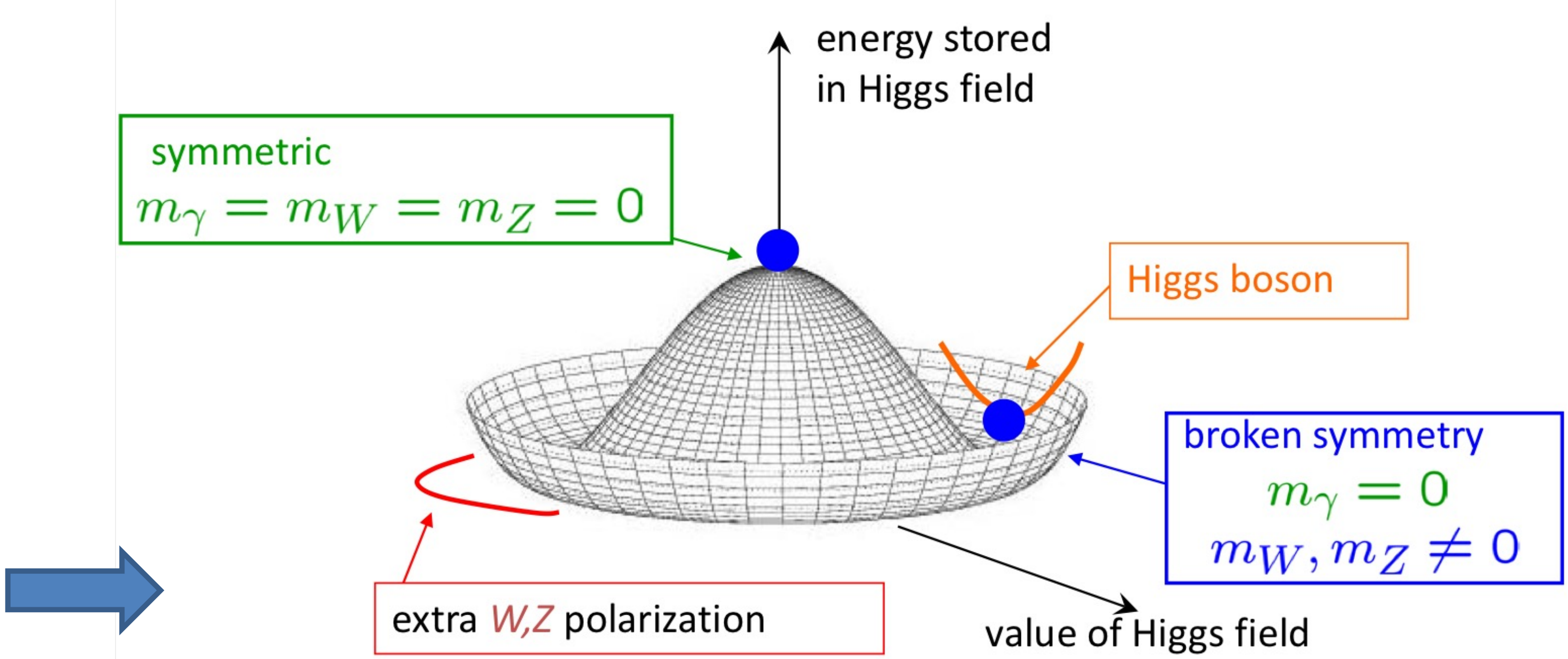


Q.-H. Cao, Bin Yan, D.-M. Zhang, H. Zhang, PLB 752 (2016) 285-290

L. B. Chen, H. T. Li, H. S. Shao, J. Wang, PLB 803 (2020) 135292, JHEP 03 (2020) 072

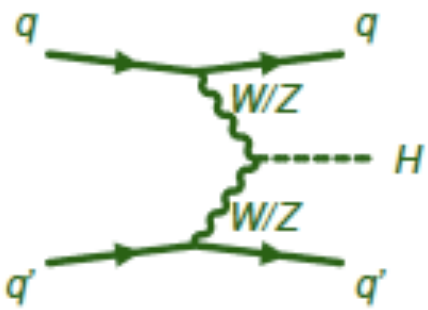
K. Chai, J.-H. Yu, H. Zhang, PRD 107(2023) 5,055031

Testing the EWSB @ LHC



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

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

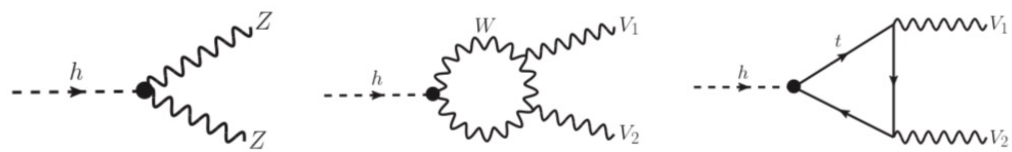


Higgs couplings and EWSB

- The magnitude of the Higgs gauge couplings
- The relative sign between hWW and hZZ couplings

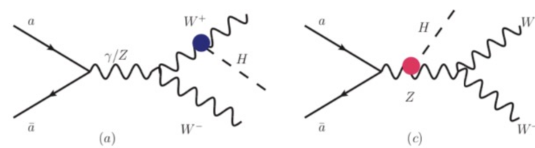
Y. Chen et al, PRL 2016

- Interference between tree and loop level in Higgs decay

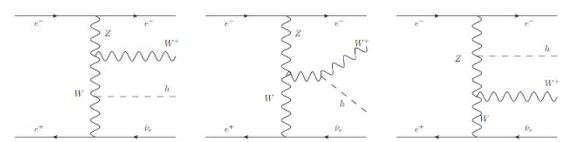


- Lepton Colliders

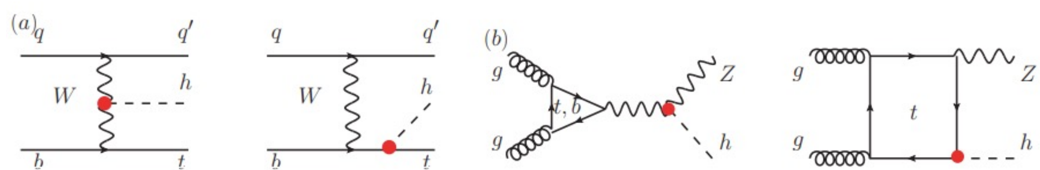
C.W Chiang, X. G. He and G. Li, JHEP08(2018) 126



D. Stolarski, Y. Wu, PRD 102 (2020)3, 033006



- th and Zh production

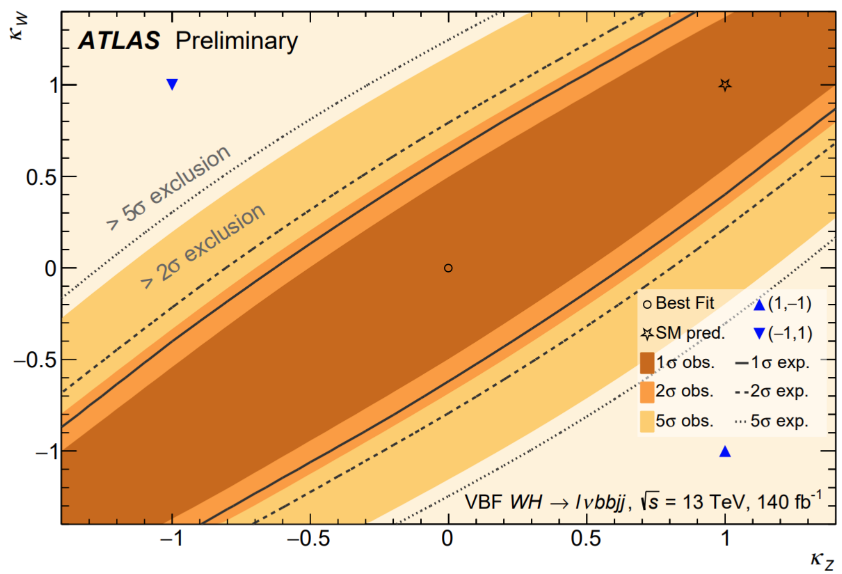


The data favors the same sign

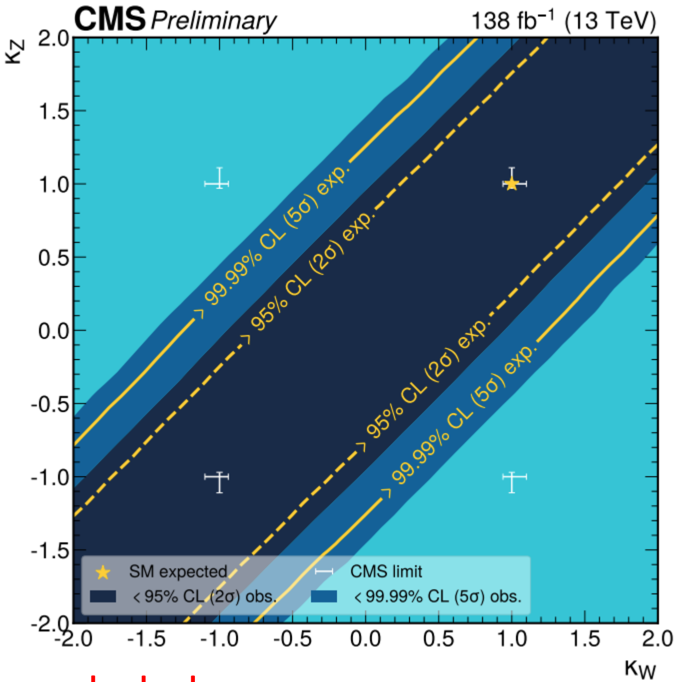
K. P. Xie and Bin Yan, PLB 820 (2021) 136515

Higgs couplings and EWSB

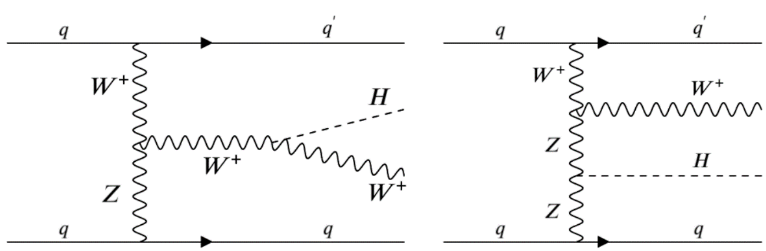
ATLAS-CONF-2023-057



CMS-PAS-HIG-23-007



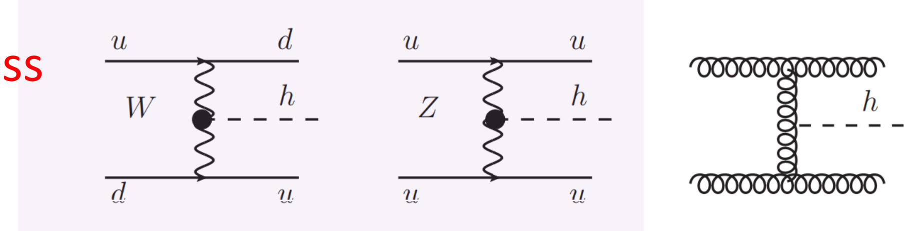
The opposite-sign coupling hypothesis has been excluded



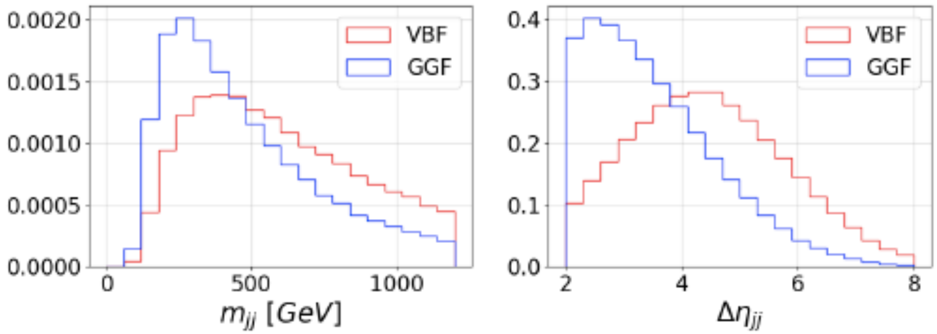
The magnitude of the Higgs gauge couplings would be the key task for testing EWSB

Higgs production mechanisms

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

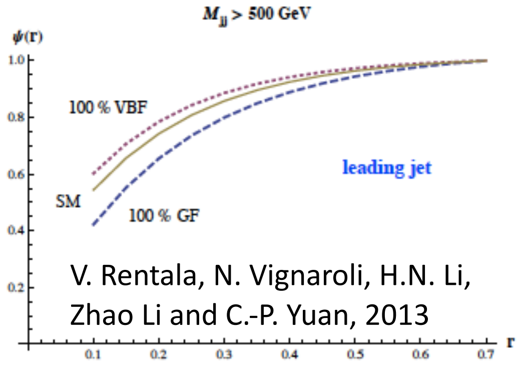


- The rapidity gap and the invariant mass of the two jets



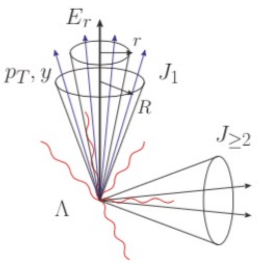
V.D. Bargeer, K.m.Cheung. T. Han, J. Ohnemus and D. Zeppenfeld, 1991
N. Kauer, T. Plehn, D. L. Rainwater and D. Zeppenfeld, 2001
……

- Soft gluon radiation effects: Jet energy profile, TMD effects

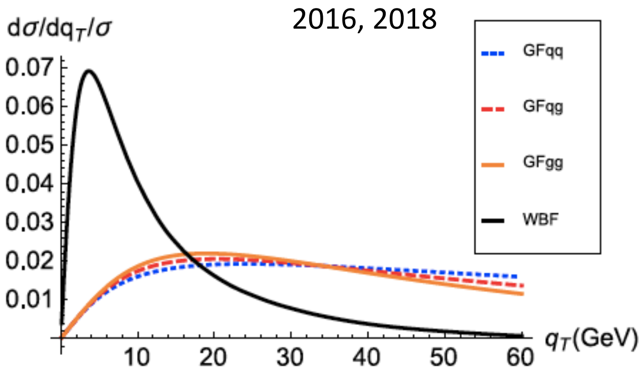


V. Rentala, N. Vignaroli, H.N. Li, Zhao Li and C.-P. Yuan, 2013

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



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



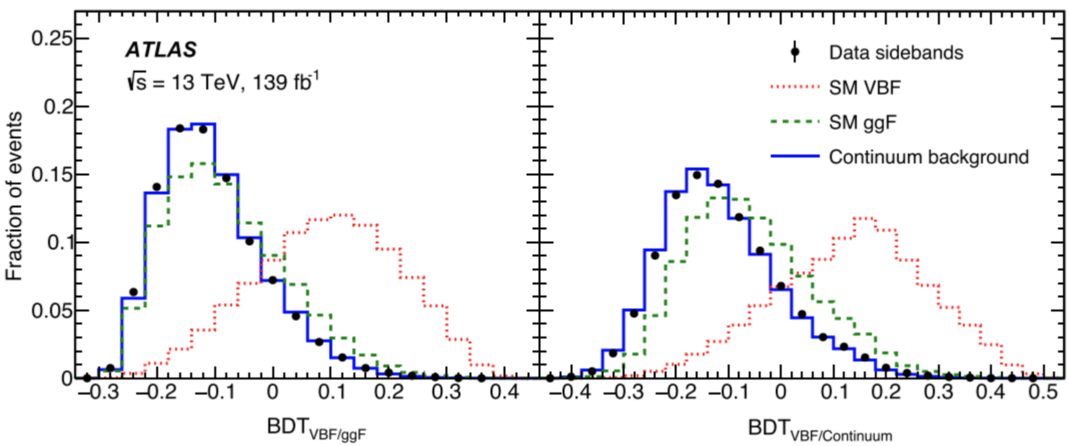
Higgs production mechanisms

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}	$\lvert\eta_{\gamma\gamma} - (\eta_{j1} + \eta_{j2})/2\rvert$	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

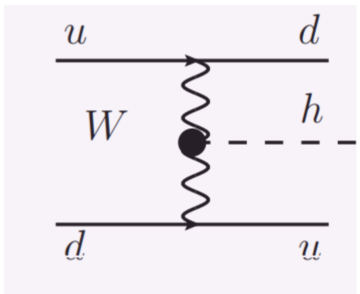
ATLAS, Phys.Rev.Lett. 131 (2023) 6, 061802

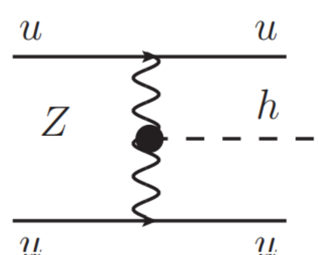


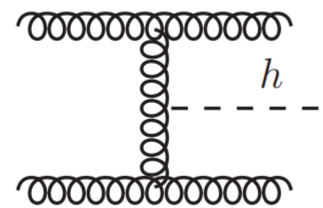
The VBF Higgs production can be well separated from the GGF process

Higgs production mechanisms

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







H. T. Li, Bin Yan, C.-P. Yuan, PRL 131 (2023) 4, 041802

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

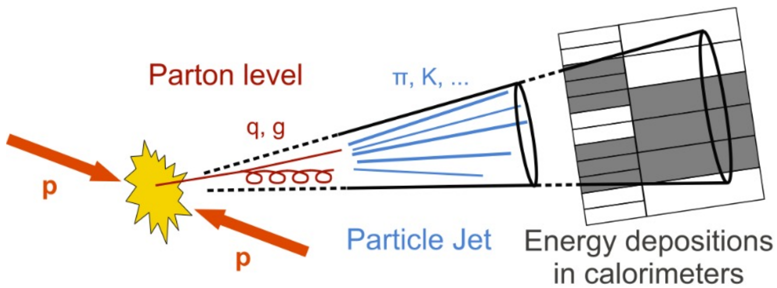
The key observable: Jet Charge

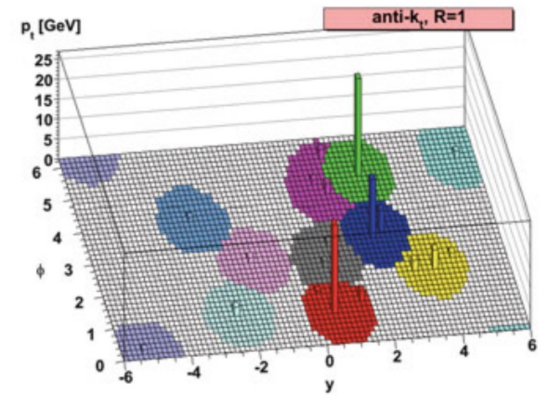
W: opposite sign for the two jet charges

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 scheme:

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

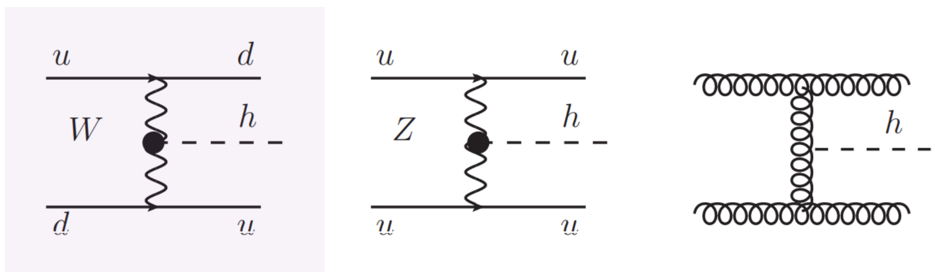
R.D. Field and R.P. Feynman, NPB136,1(1978)

κ: To regulate the sensitivity of the soft gluon radiation

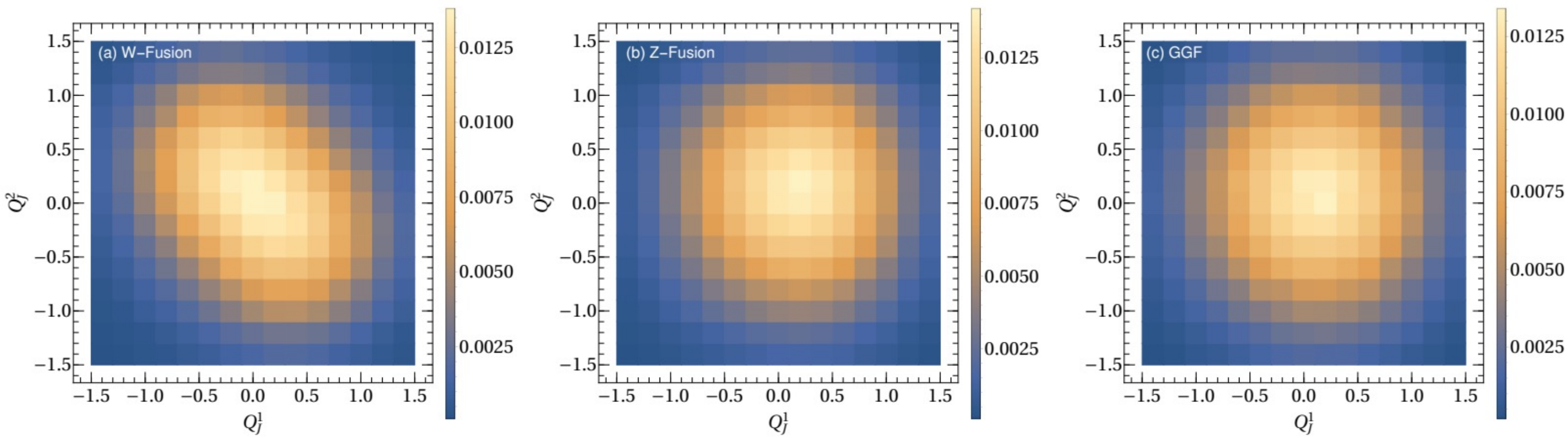
- SCET calculation — D. Krohn et al, PRL, 2013, W.J.Waalewijn, PRD, 2012
- Quark/gluon jet discrimination — K.Fraser and M.D. Schwartz, JHEP, 2018, Zhong-Bo Kang, Xiaohui Liu, et al, PRD, 2021
- Nuclear medium effects — H. T. Li and I. Vitev, PRD, 2020, PRL, 2021
- Quark flavor structure — Zhong-Bo Kang, Xiaohui Liu, et al, PRD, 2021, + Ding Yu Shao,PRL, 2020
- Non-perturbative model — Zhong-Bo Kang et al, PRL, 2023
- Electroweak and Higgs physics — H. T. Li, Bin Yan and C.-P. Yuan, PLB 2022, PRL 2023; Xiao-Rui Wang, Bin Yan, PRD 2023; H. Cui, M. Zhao, Y. Wang, H. Liang, Manqi Ruan, 2023

Higgs coupings @ VBF

The key observable: Jet Charge



H. T. Li, Bin Yan, C.-P. Yuan, PRL 131 (2023) 4, 041802



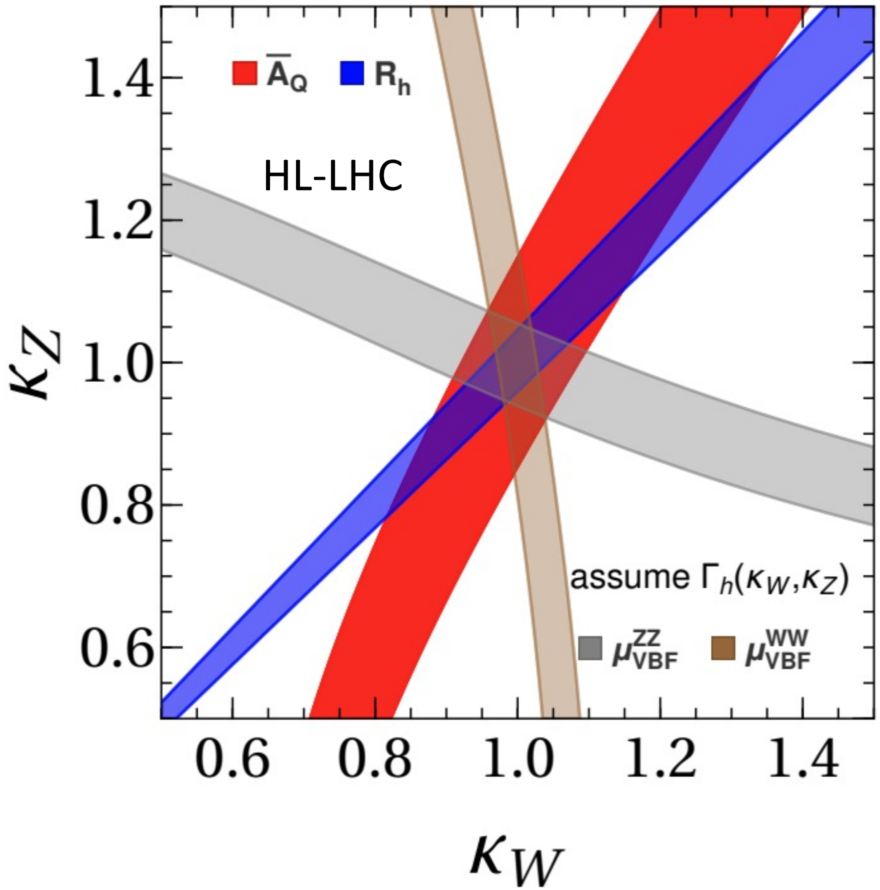
opposite sign for the two jet charges

same or opposite sign

the sign of the jet charge is arbitrary

Higgs couplings @ VBF

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



$$Q^{(\pm)} = |Q_J^1 \pm Q_J^2|$$

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

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

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

H. T. Li, Bin Yan, C.-P. Yuan, PRL 131 (2023) 4, 041802

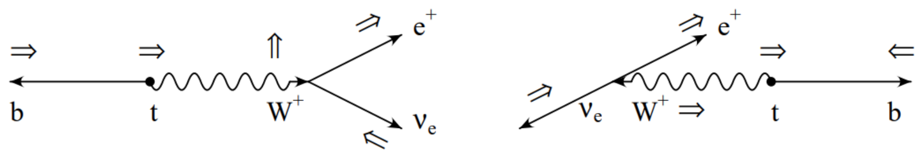
The limits from Rh and jet charge asymmetry are not depending on the assumption of the Higgs width

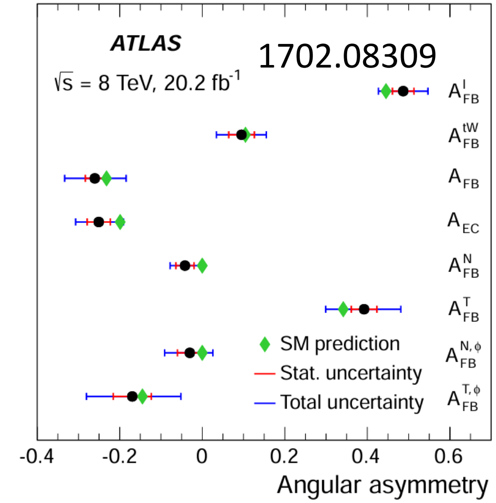
对撞机物理前沿进展

横向极化效应

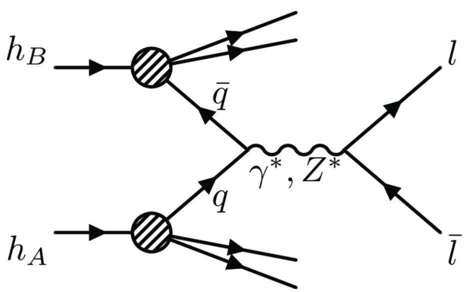
Spin effects and New Physics

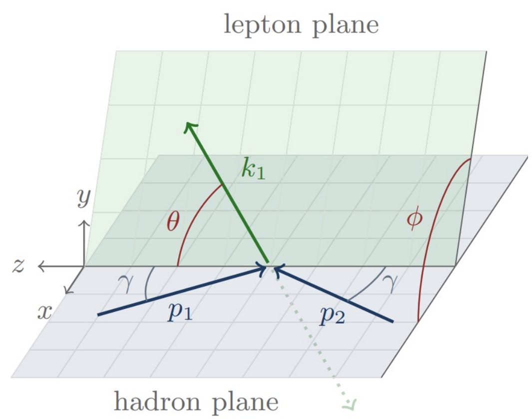
- Top quark polarization:

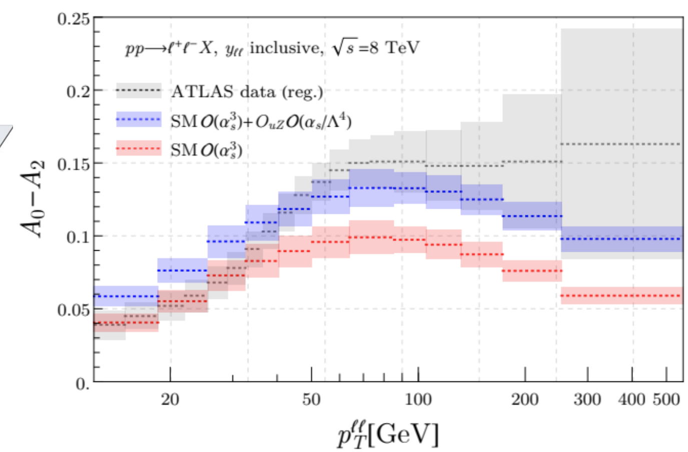




- Gauge boson polarization





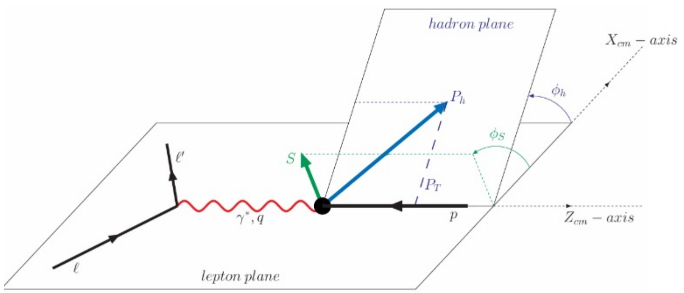


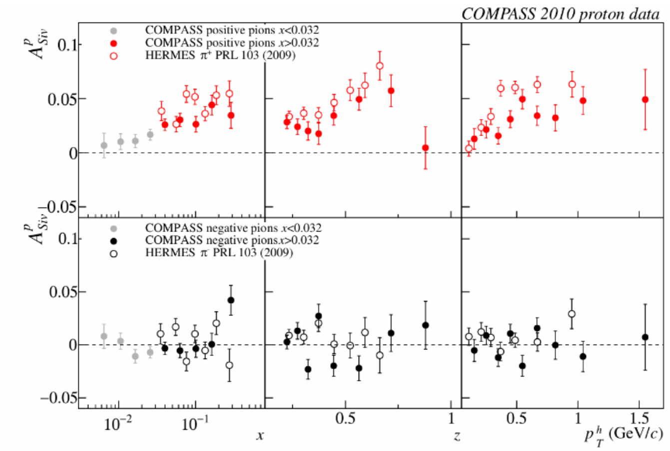
$$A_0(1 - 3\cos^2\theta) + A_2 \sin^2\theta \cos(2\phi)$$

Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

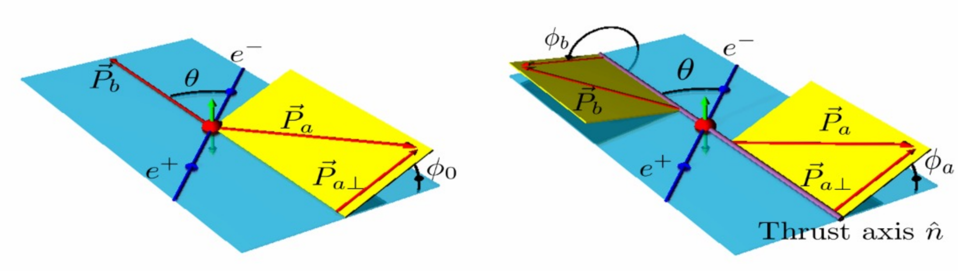
Spin effects in QCD

- Nucleon structure: PDFs

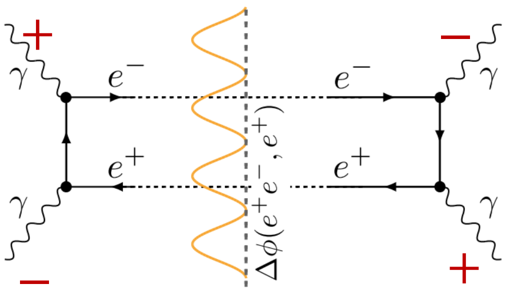


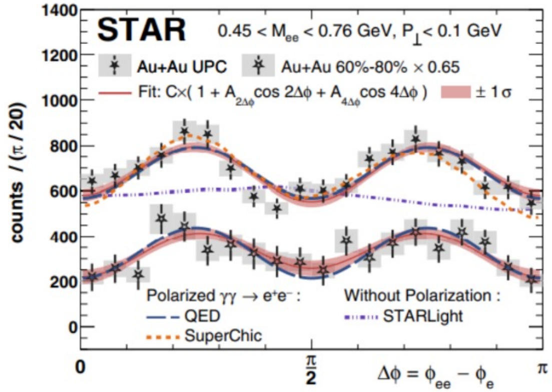


- Nucleon structure: FFs



- UPCs





QCD Spin effects and New physics

- **What type of new physics would exhibit sensitivity to the effects of QCD spin?**

Dipole moments

$$-\mu_e \frac{\vec{S}}{|\vec{S}|} \cdot \vec{B} \quad \Leftrightarrow \quad e\left(\bar{e}\gamma_\mu e\right) A^\mu + a_e \frac{e}{4m_e}\left(\bar{e}\sigma_{\mu\nu} e\right) F^{\mu\nu}$$

$$-d_e \frac{\vec{S}}{|\vec{S}|} \cdot \vec{E} \quad \Leftrightarrow \quad + d_e \frac{i}{2}\left(\bar{e}\sigma_{\mu\nu}\gamma_5 e\right) F^{\mu\nu}$$

$$\mu_e = g_e \frac{e}{2m_e} \quad \text{and} \quad \left(g_e - 2\right) = 2a_e$$

New physics and Dipole Operator

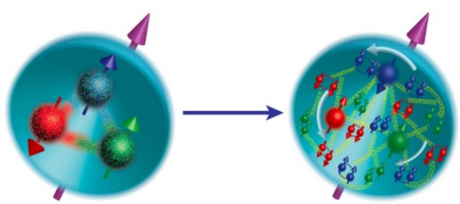
➢ Magnetic dipole moments: probing the internal structures of particles

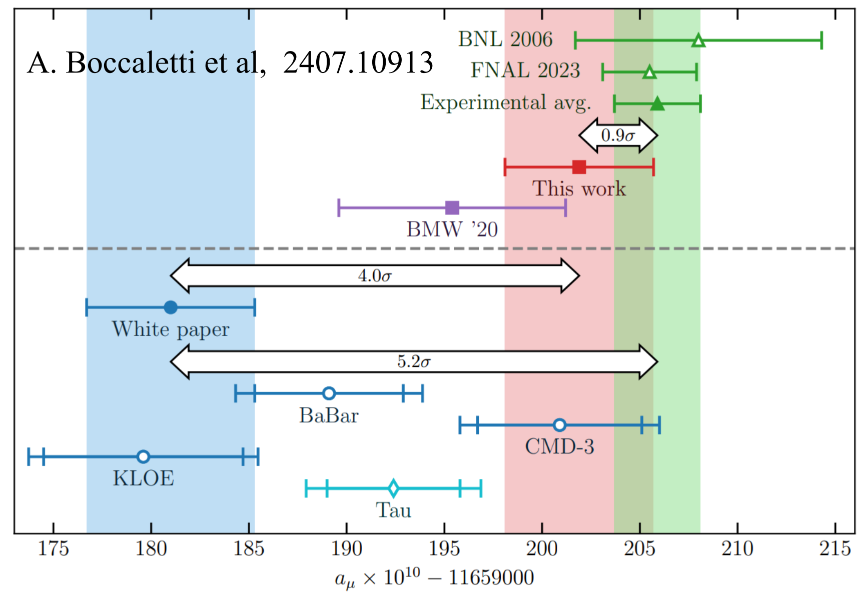
- Elementary particle:

Electron: g/2=1.001159…
Muon: g/2=1.0011659..

- Composite particle:

Proton: g/2=2.7928444..
Neutron: g/2=-1.91394308..

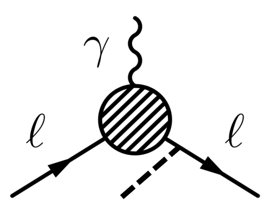




- Quarks: any internal structures?

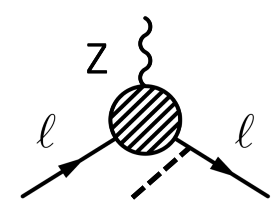
- From MDM and EDM to weak dipole moments?

$$\bar{\ell}\,\sigma^{\mu\nu} e \tau^I \varphi W^I_{\mu\nu}\,,\ \bar{\ell}\,\sigma^{\mu\nu} e \varphi B_{\mu\nu}$$



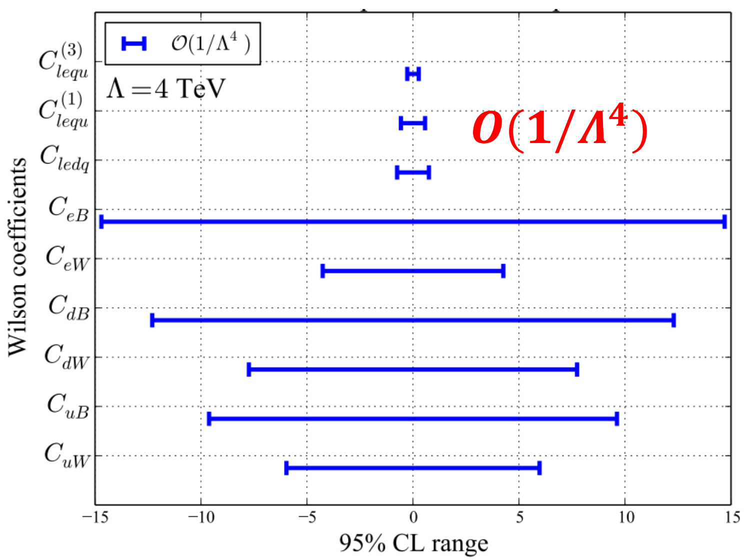
May have same physics source

$B_{\mu\nu}, W_{\mu\nu}$

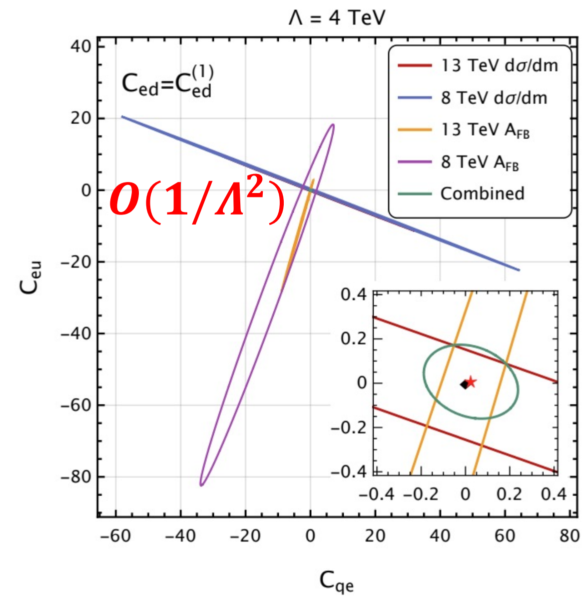


Example: Electroweak Dipole Operator

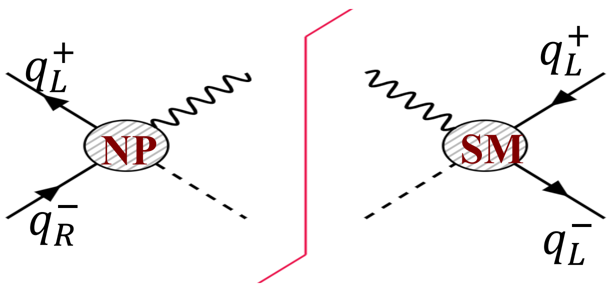
Single-Parameter-Analysis: EW dipole couplings are poorly constrained by Drell-Yan data



R. Boughezal et al, PRD 104 (2021) 095022



R. Boughezal et al, 2303.08257



=0 for the cross section

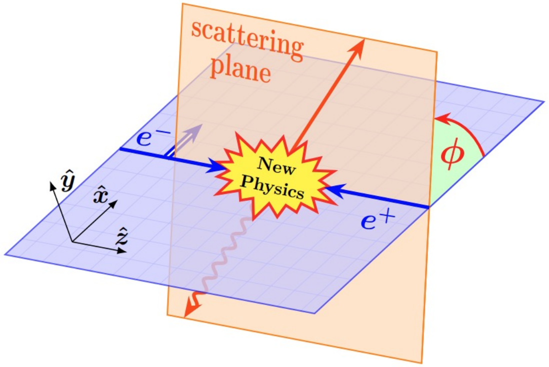
Leading contribution: $\left|\frac{c_{dipole}}{\Lambda^2}\right|^2$

➢ It is difficult to probe the electroweak dipole interactions at colliders

Electroweak dipole moments of leptons

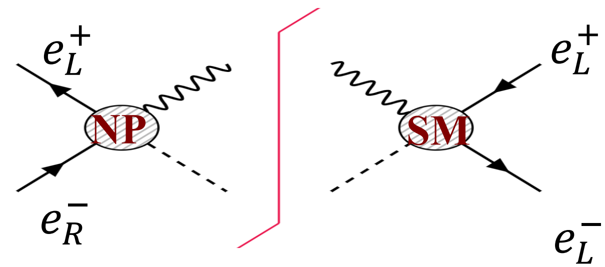
➢ Transversely polarized effect of beams @ lepton collider

The interference between the different helicity states



$$\boldsymbol{s} = (b_1, b_2, \lambda) = (b_{\mathrm{T}}\cos\phi_0, b_{\mathrm{T}}\sin\phi_0, \lambda)$$

$$\rho = \frac{1}{2}(1 + \boldsymbol{\sigma}\cdot\boldsymbol{s}) = \frac{1}{2}\begin{pmatrix} 1+\lambda & b_{\mathrm{T}}e^{-i\phi_0} \\ b_{\mathrm{T}}e^{i\phi_0} & 1-\lambda \end{pmatrix}$$



Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801

$$\bar{e}_L\sigma_{\mu\nu}e_R A^{\mu\nu}, \bar{e}_L\sigma_{\mu\nu}e_R Z^{\mu\nu}$$

$$M \propto e^{i(\alpha 1 - \alpha 2)\phi} d(\theta)$$

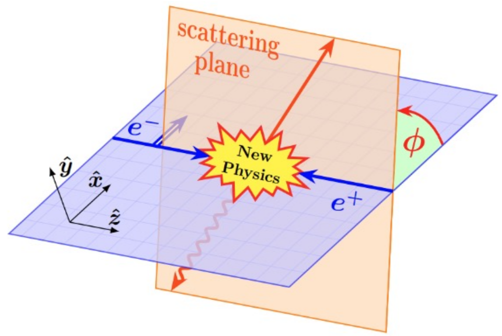
	U	L	T
U	$\lvert\mathcal{M}\rvert^2_{UU} \to 1$	$\lvert\mathcal{M}\rvert^2_{UL} \to 1$	$\lvert\mathcal{M}\rvert^2_{UT} \to \cos\phi, \sin\phi$
L	$\lvert\mathcal{M}\rvert^2_{LU} \to 1$	$\lvert\mathcal{M}\rvert^2_{LL} \to 1$	$\lvert\mathcal{M}\rvert^2_{LT} \to \cos\phi, \sin\phi$
T	$\lvert\mathcal{M}\rvert^2_{TU} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TL} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$

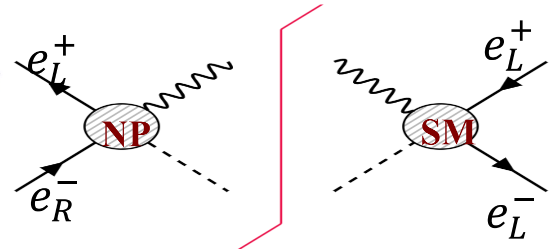
Breaking the rotational invariance & A nontrivial azimuthal behavior

Electroweak dipole moments of leptons

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,

PRL 131 (2023) 241801





$M \infty e^{i(\alpha 1-\alpha 2)\phi} d(\theta)$

$e^{i\phi * 0}$ $e^{i\phi}$

	U	L	T
U	$\lvert\mathcal{M}\rvert^2_{UU} \to 1$	$\lvert\mathcal{M}\rvert^2_{UL} \to 1$	$\lvert\mathcal{M}\rvert^2_{UT} \to \cos\phi, \sin\phi$
L	$\lvert\mathcal{M}\rvert^2_{LU} \to 1$	$\lvert\mathcal{M}\rvert^2_{LL} \to 1$	$\lvert\mathcal{M}\rvert^2_{LT} \to \cos\phi, \sin\phi$
T	$\lvert\mathcal{M}\rvert^2_{TU} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TL} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$

$$\frac{2\pi\, d\sigma^i}{\sigma^i\, d\phi} = 1 + \underline{A_R^i(b_T, \bar{b}_T)} \cos\phi + \underline{A_I^i(b_T, \bar{b}_T)} \sin\phi + \underline{b_T\, \bar{b}_T\, B^i} \cos 2\phi + \mathcal{O}(1/\Lambda^4)$$

Re[C_{dipole}] Im[C_{dipole}] SM & other NP

CP-conserving CP-violation

- Linearly dependent on the dipole couplings C_{dipole} and spin b_T
- Without depending on other NP operators

Single Transverse Spin Asymmetries

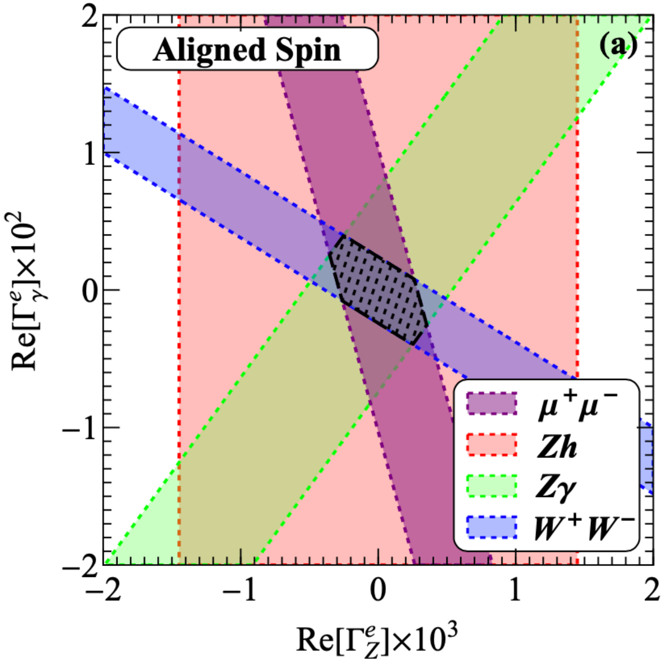
$$A^i_{LR} = \frac{\sigma^i(\cos\phi > 0) - \sigma^i(\cos\phi < 0)}{\sigma^i(\cos\phi > 0) + \sigma^i(\cos\phi < 0)} = \frac{2}{\pi} A^i_R$$

$$A^i_{UD} = \frac{\sigma^i(\sin\phi > 0) - \sigma^i(\sin\phi < 0)}{\sigma^i(\sin\phi > 0) + \sigma^i(\sin\phi < 0)} = \frac{2}{\pi} A^i_I,$$

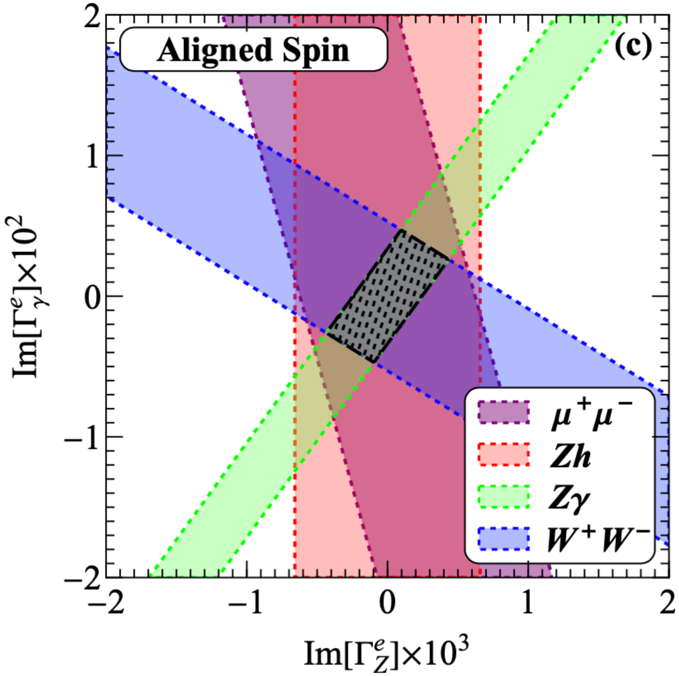
$\sqrt{s} = 250$ GeV, $\mathcal{L} = 5\ \mathrm{ab}^{-1}$ $\quad (b_T, \bar{b}_T) = (0.8, 0.3)$

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,

PRL 131 (2023) 241801



CP-conserved dipole operator

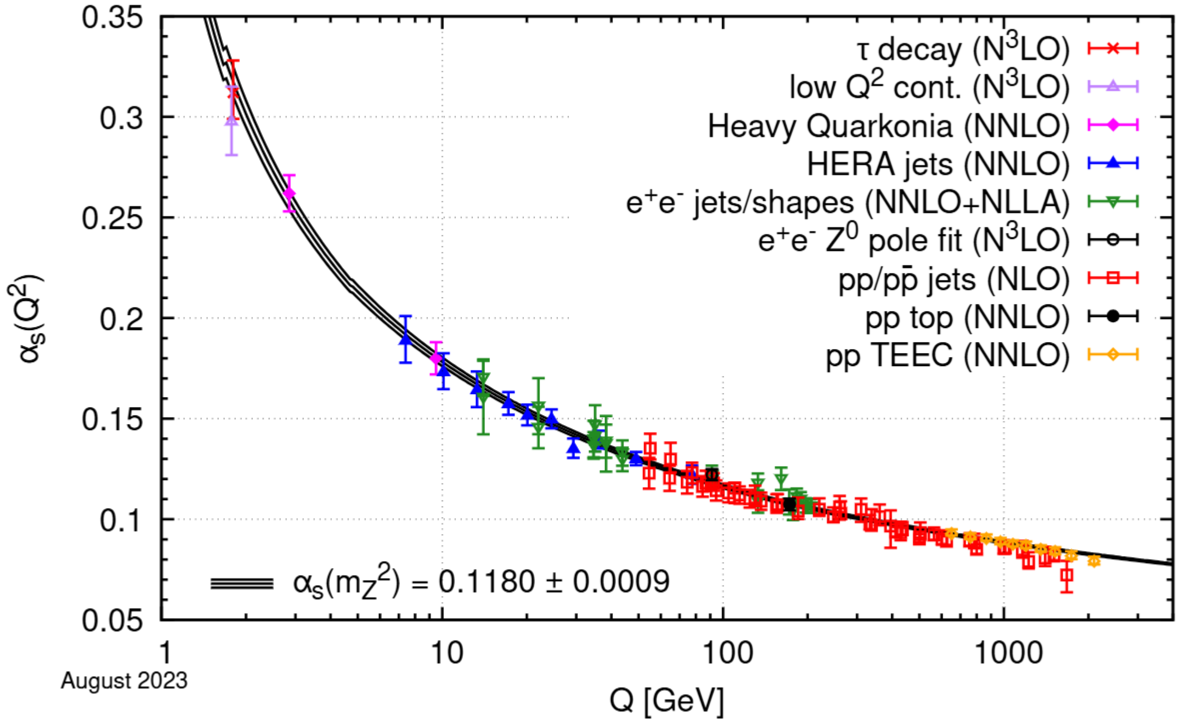


CP-violated dipole operator

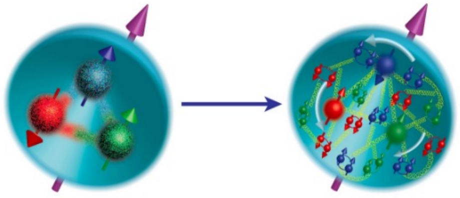
- Our bounds are much stronger than other approaches by 1~2 orders of magnitude
- Weak dipole coupling, SSA: 0.01%, LHC: 1%

Electroweak dipole moments of quarks

➢ The quark can not be a free particle due to the QCD confinement



Asymptotic freedom of QCD theory



➢ How to probe the spin information of quarks?

The non-perturbative functions, i.e., the parton distirbuion functions and the fragmentation functions

Transverse spin effects of quark @ EIC

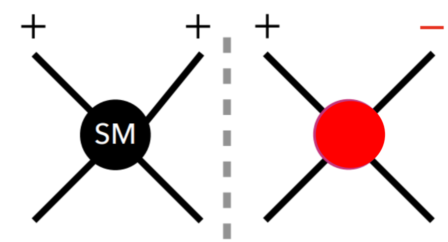
➢ Quark dipole operators

R. Boughezal, D. Florian, F. Petriello, W. Vogelsang, PRD 107 (2023) 7, 075028
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan, PRD 109 (2024) 095025

Leading Quark TMDPDFs — Nucleon Spin, Quark Spin

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = Boer-Mulders
L		g_1 = Helicity	$h_{1L}^\perp$ = Worm-gear
T	$f_{1T}^\perp$ = Sivers	$g_{1T}^\perp$ = Worm-gear	h_1 = Transversity $h_{1T}^\perp$ = Pretzelosity

$$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}u)\tau^I\varphi W^I_{\mu\nu},$$
$$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}u)\varphi B_{\mu\nu},$$
$$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}d)\tau^I\varphi W^I_{\mu\nu},$$
$$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}d)\varphi B_{\mu\nu}.$$



$$\sim \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

➢ The transversity is difficult to be constrained: chiral-odd

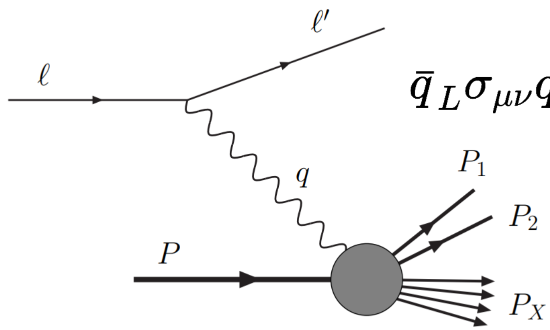
$$A_{UT} = \frac{\sigma(e^U p^\uparrow) - \sigma(e^U p^\downarrow)}{\sigma(e^U p^\uparrow) + \sigma(e^U p^\downarrow)}$$

- ☐ Collins Azimuthal Asymmetries in SIDIS, Collins function
- ☐ Low energy Drell-Yan process
- ☐ Dihadron production in SIDIS, Interference dihadron fragmentation

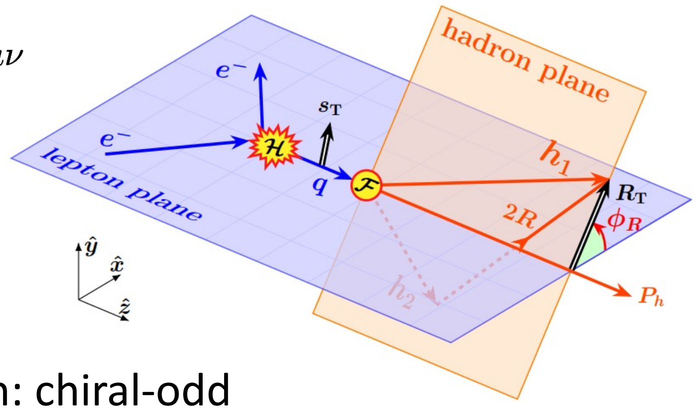
Kang, Prokudin, Sun, Yuan, PRD 93 (2016) 014009; Zeng, Dong, Liu, Sun, Zhao, PRD 109 (2024) 056002;
JAM Collaboration, PRD 106 (2022) 034014

Transverse spin effects of quark @ EIC

- The transverse spin of quarks can be generated by the quark dipole moments



$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$



- The interference dihadron fragmentation function: chiral-odd

$$\frac{d\sigma}{dx\,dy\,dz\,dM_h\,d\phi_R} = \frac{N}{2\pi}\sum_q f_q(x,Q)\big[D_{h_1h_2/q}(z,M_h;Q)$$

$$-\,(\boldsymbol{s}_{T,q}(x,Q)\times\hat{\boldsymbol{R}}_T)^z H_{h_1h_2/q}(z,M_h;Q)\big]C_q(x,Q)$$

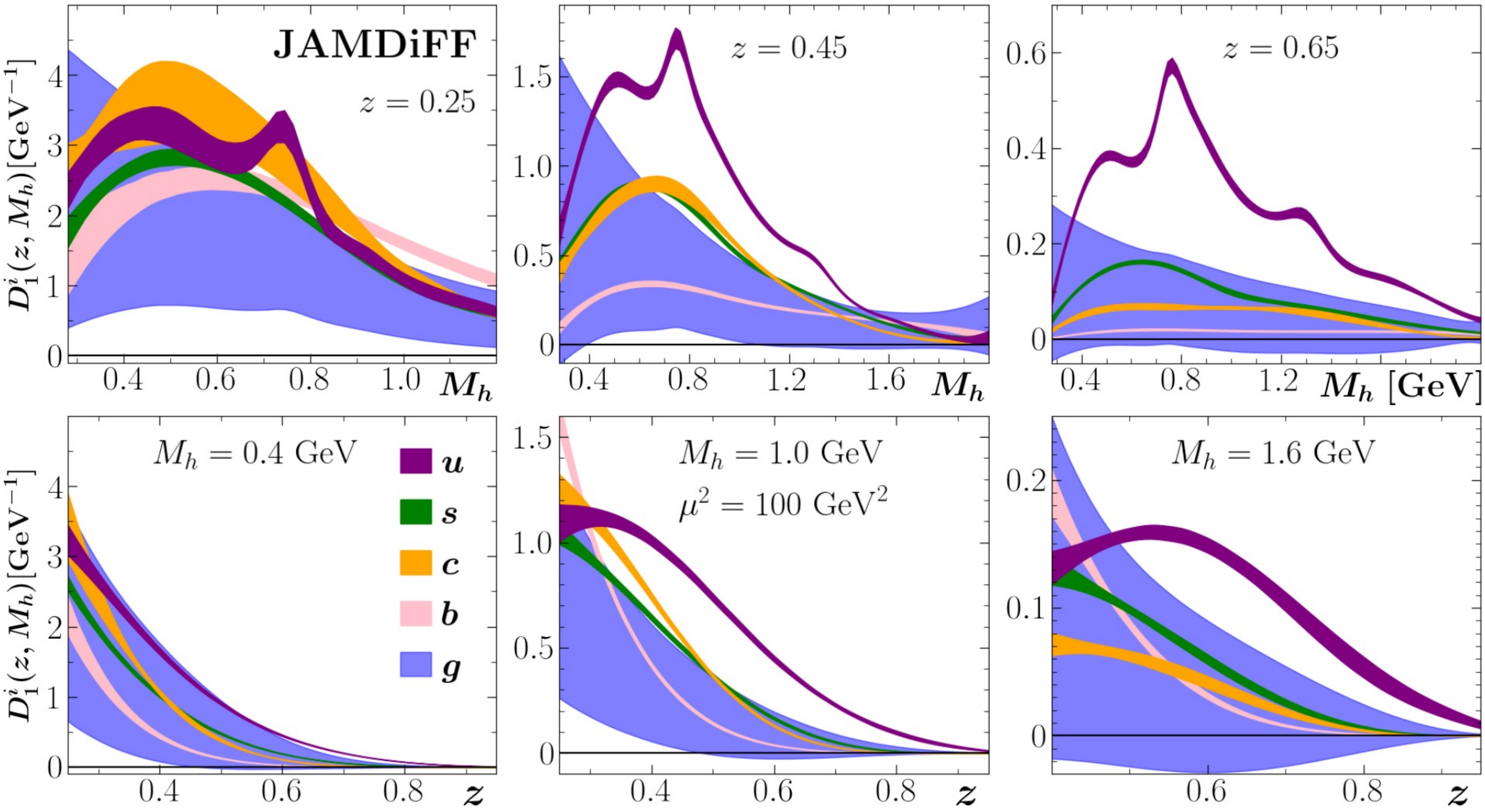
$$s_q^x = \frac{2}{C_q}\left(w_\gamma^q\,\mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\,\mathrm{Re}\,\Gamma_Z^q\right)$$

$$(\boldsymbol{s}_{T,q}\times\hat{\boldsymbol{R}}_T)^z = s_q^x\sin\phi_R - s_q^y\cos\phi_R$$

$$s_q^y = \frac{2}{C_q}\left(w_\gamma^q\,\mathrm{Im}\,\Gamma_\gamma^q + w_Z^q\,\mathrm{Im}\,\Gamma_Z^q\right)$$

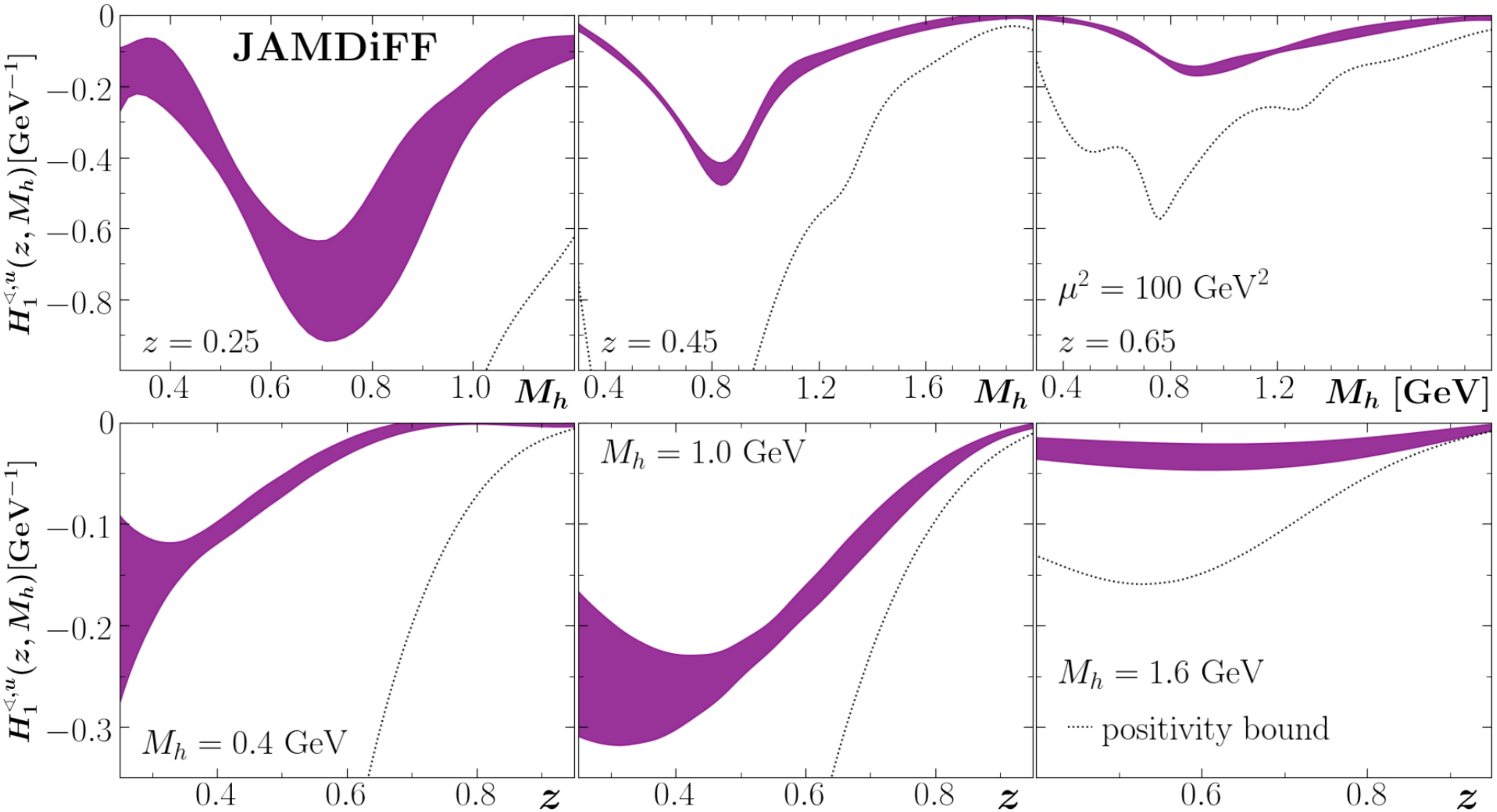
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255

$\pi^+\pi^-$ Dihadron fragmentation functions



JAM Collaboration, PRL 132 (2024) 091901 , PRD 109 (2024) 034024

$\pi^+\pi^-$ Dihadron fragmentation functions



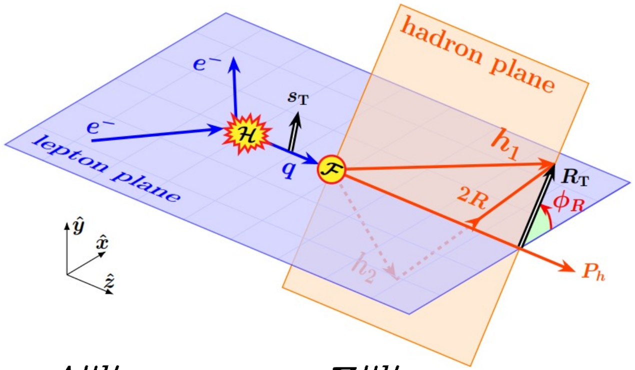
JAM Collaboration, PRL 132 (2024) 091901 , PRD 109 (2024) 034024

Transverse spin effects of quark @ EIC

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255

The non-trivial azimuthal distribution requires parity-violation effects:

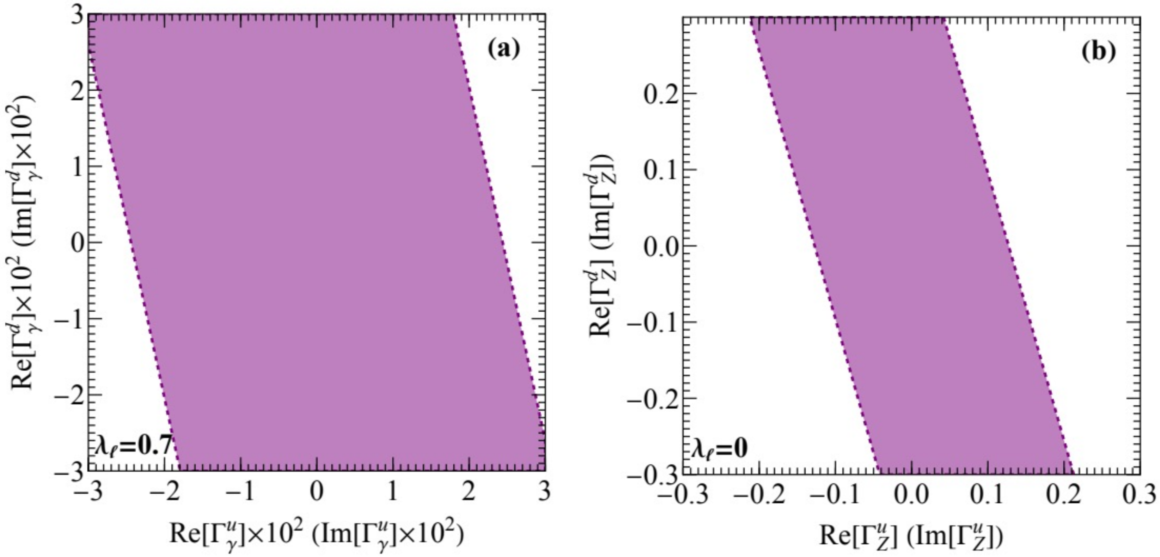
- the longitudinal polarization of the electron
- the parity-violating Z interactions



$$(\boldsymbol{s}_{T,q} \times \hat{\boldsymbol{R}}_T)^z = s_q^x \sin\phi_R - s_q^y \cos\phi_R$$

$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu},\ \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$

$$A_{LR} = \frac{\sigma(\cos\phi_R > 0) - \sigma(\cos\phi_R < 0)}{\sigma(\cos\phi_R > 0) + \sigma(\cos\phi_R < 0)} = \frac{2}{\pi} A_I \qquad A_{UD} = \frac{\sigma(\sin\phi_R > 0) - \sigma(\sin\phi_R < 0)}{\sigma(\sin\phi_R > 0) + \sigma(\sin\phi_R < 0)} = \frac{2}{\pi} A_R$$



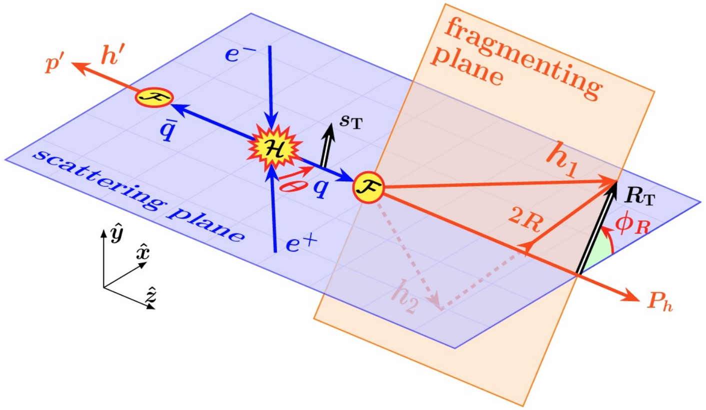
$\sqrt{s} = 105$ GeV, $\mathcal{L} = 1\ \text{ab}^{-1}$

- Photon dipole: O(0.01)
- Z-boson dipole: O(0.1)

The flat direction in dipole couplings?

Transverse spin effects of quark @ CEPC

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 24011.13845



$$\frac{d\sigma}{dy\,dz\,d\bar{z}\,dM_h\,d\phi_R} = \frac{1}{32\pi^2 s} \sum_{q,\,q\to\bar{q}} C_q(y)\, D_{\bar{q}}^{h'}(\bar{z})$$
$$\times \left[D_q^{h_1h_2}(z, M_h) - (\boldsymbol{s}_{T,q}(y) \times \hat{\boldsymbol{R}}_T)^z H_q^{h_1h_2}(z, M_h)\right]$$

$$s_q^x = \frac{2}{C_q}\left(w_\gamma^q\ \mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\ \mathrm{Re}\,\Gamma_Z^q\right)$$
$$s_q^y = \frac{2}{C_q}\left(w_\gamma^q\ \mathrm{Im}\,\Gamma_\gamma^q + w_Z^q\ \mathrm{Im}\,\Gamma_Z^q\right)$$

$$\bar{q}_L\sigma_{\mu\nu}q_R A^{\mu\nu}, \bar{q}_L\sigma_{\mu\nu}q_R Z^{\mu\nu}$$

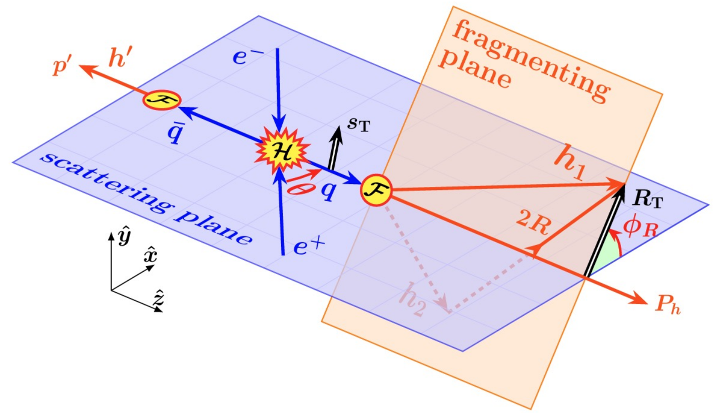
Isospin and charge conjugation symmetries:

$$D_u^{\pi^+\pi^-} = D_d^{\pi^+\pi^-}, \quad H_u^{\pi^+\pi^-} = -H_d^{\pi^+\pi^-}, \quad H_{s,\bar{s},c,\bar{c},b,\bar{b}}^{\pi^+\pi^-} = 0$$

$$D_q^{\pi^+\pi^-} = D_{\bar{q}}^{\pi^+\pi^-}, \quad H_q^{\pi^+\pi^-} = -H_{\bar{q}}^{\pi^+\pi^-}$$

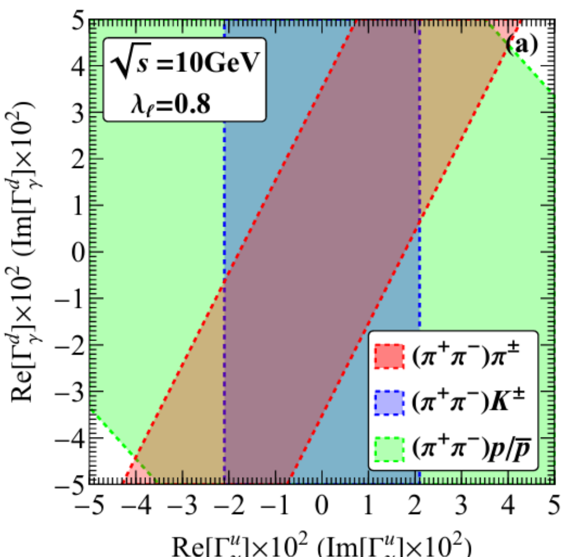
Transverse spin effects of quark @ CEPC

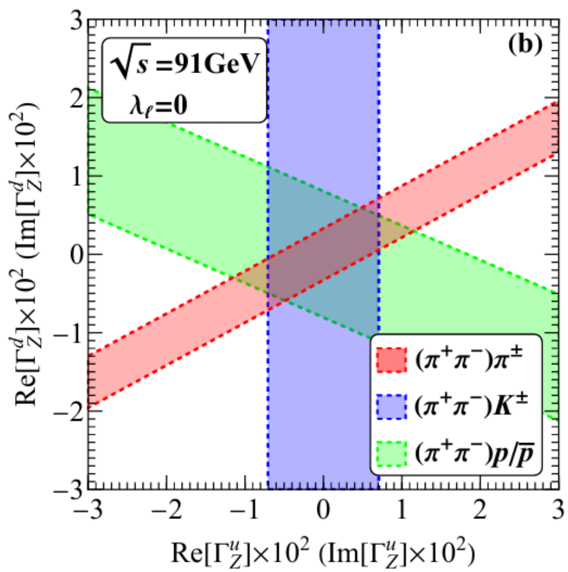
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 24011.13845



$$\frac{d\sigma}{dz\, d\bar{z}\, dM_h\, d\phi_R} = \frac{B^0 - B^x \sin\phi_R + B^y \cos\phi_R}{32\pi^2 s}$$

$$B^0 = \sum_q \langle C_q \rangle D_q^{\pi^+\pi^-} \left(D_q^{h'} + D_{\bar{q}}^{h'}\right) \qquad B^i = H_u^{\pi^+\pi^-} \left[\langle S_u^i \rangle \left(D_{\bar{u}}^{h'} - D_u^{h'}\right) - \langle S_d^i \rangle \left(D_{\bar{d}}^{h'} - D_d^{h'}\right)\right]$$



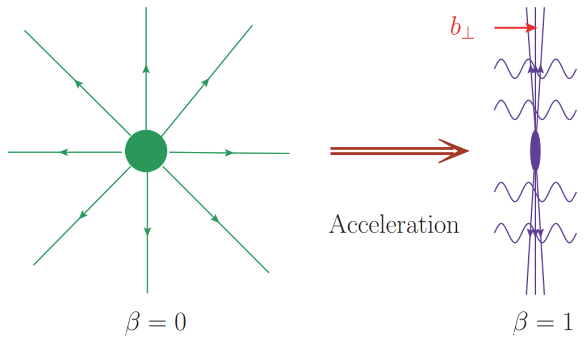


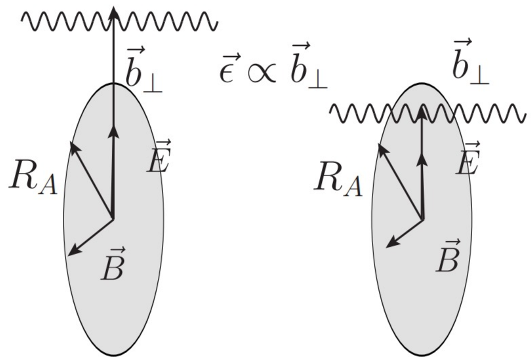
$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$

$$\mathcal{L} = 1\ \text{ab}^{-1}$$

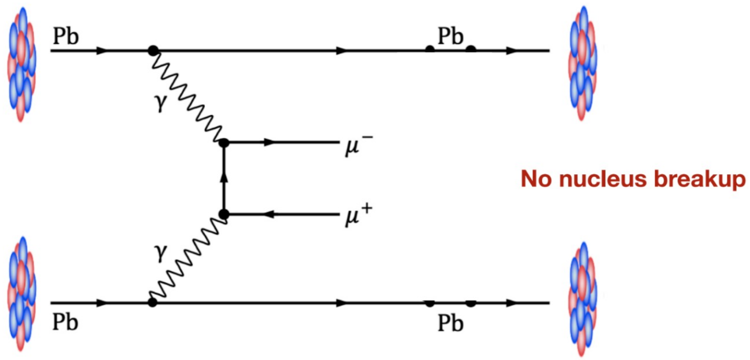
- The flat direction can be closed by combing more processes
- Photon dipole: O(0.01)
- Z-boson dipole: O(0.001)

Linear polarization @ UPCs





C. Li, J. Zhou, Y. J. Zhou, Phys. Lett. B. 795, 576 (2019)

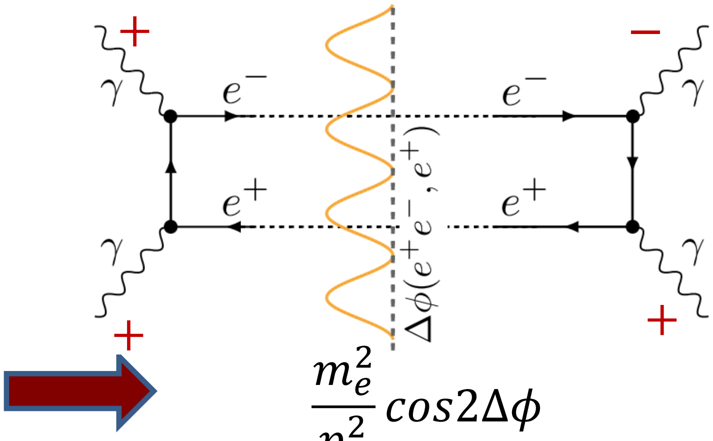


- Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field
- Weizsacker-Williams equivalent photon approximation
- Photons are linearly polarized
- Large quasi-real photon flux $\propto Z^2$
- The impact parameter $b_\perp > 2R_A$

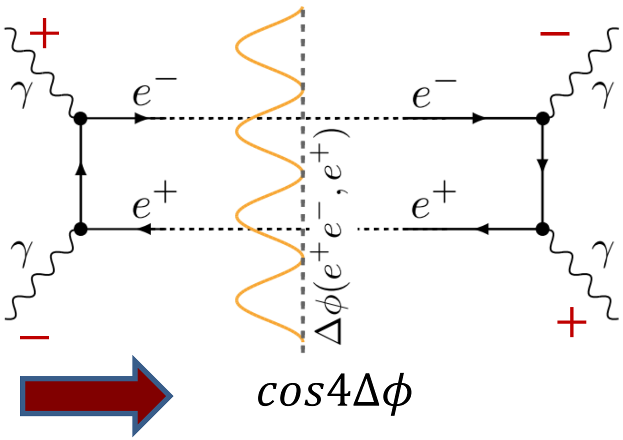
The linear polarization for gluons based on the NEEC:
Yuxun Guo, Xiaohui Liu, Feng Yuan, HuaXing Zhu, 2406.05880
Xiao Lin Li, Xiaohui Liu, Feng Yuan, HuaXing Zhu, PRD 108 (2023) L091502

Linear polarization @ UPCs

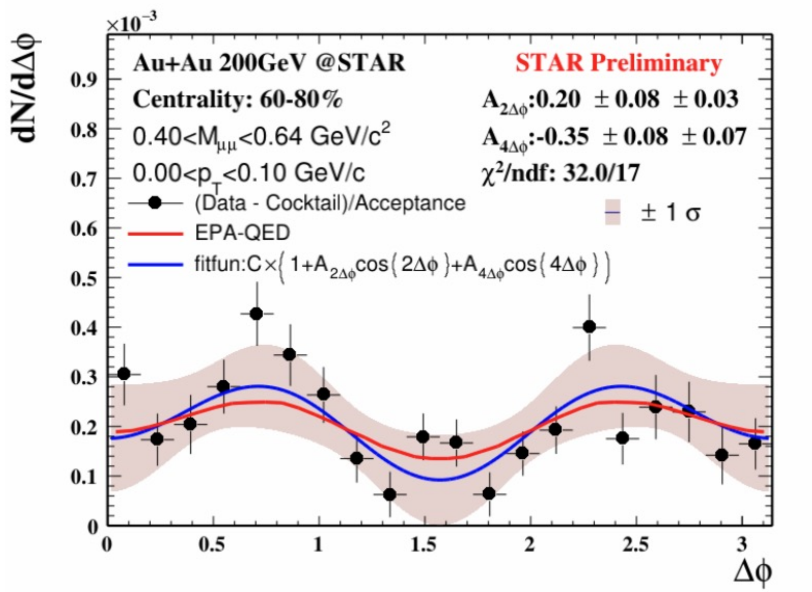
D. Y. Shao, C. Zhang, J. Zhou, Y. Zhou, PRD107 (2023) 3, 036020



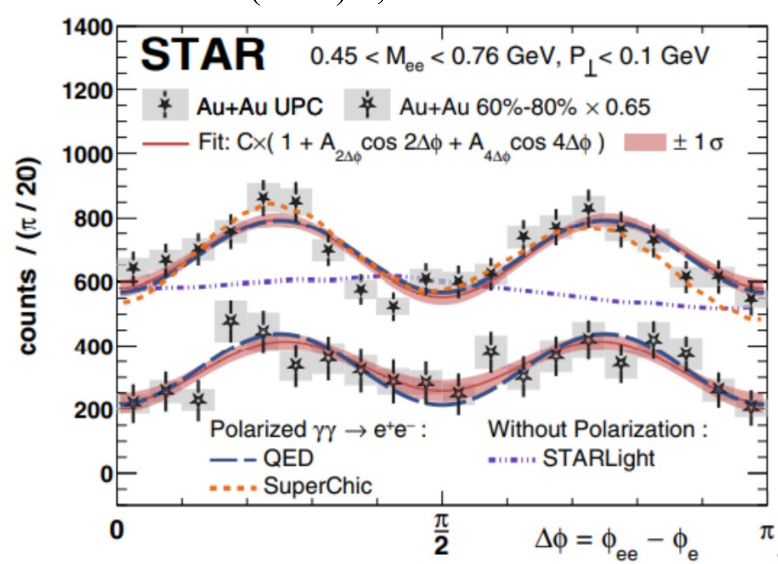
$$\frac{m_e^2}{p_T^2} cos2\Delta\phi$$



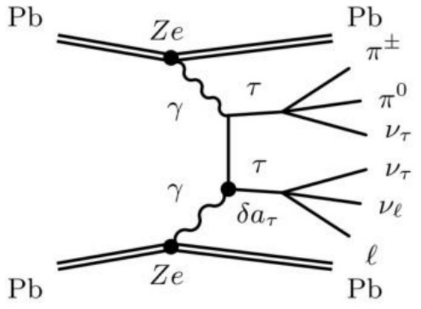
$$cos4\Delta\phi$$



PRL 127 (2021) 5, 052302

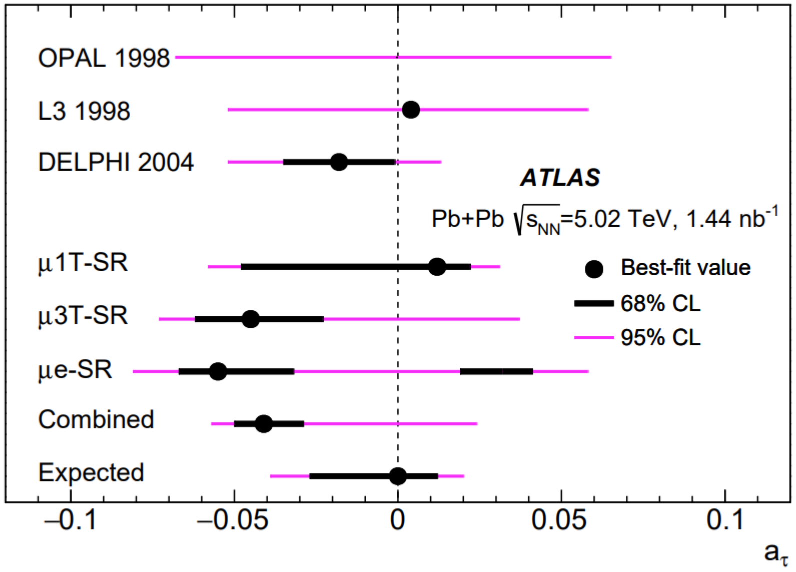


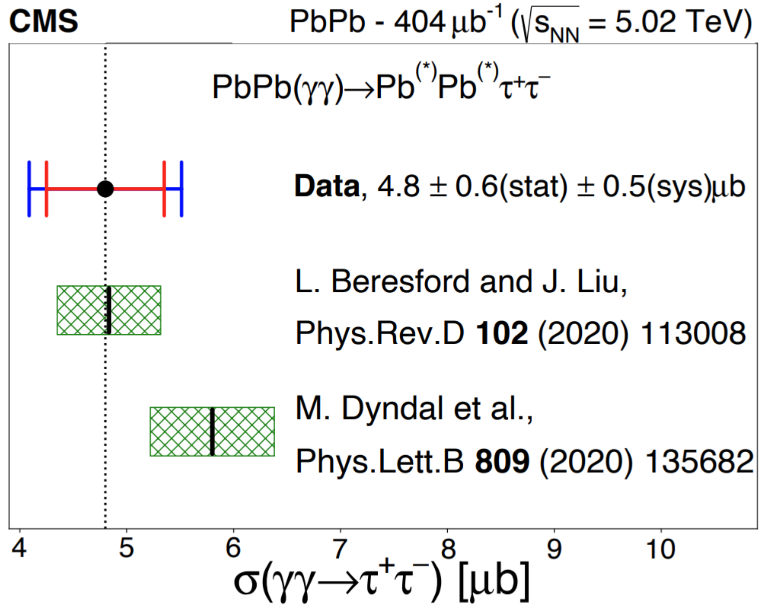
Tau pair production @ UPCs



$$\Gamma^{\mu}_{\text{eff.}}(q^2) = -ie\left[iF_2(q^2) + F_3(q^2)\gamma^5\right]\frac{\sigma^{\mu\nu}q_\nu}{2m_\tau}$$

$$F_2(0) = a_\tau, \quad F_3(0) = 2\frac{m_\tau d_\tau}{e}$$





Phys. Rev. Lett. 131 (2023) 15, 151802

Phys. Rev. Lett. 131 (2023) 151803

Linear polarization @ UPCs

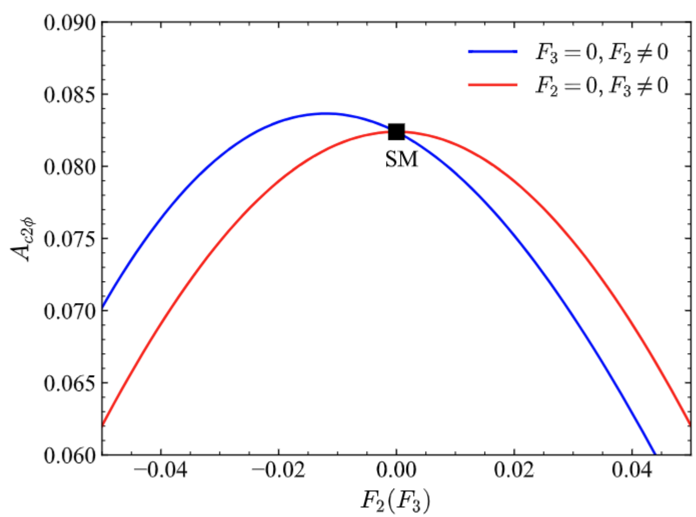
Dingyu Shao, Bin Yan, Shu-Ruan Yuan, Cheng Zhang,
Sci. China Phys. Mech. Astron. 67 (2024) 281062

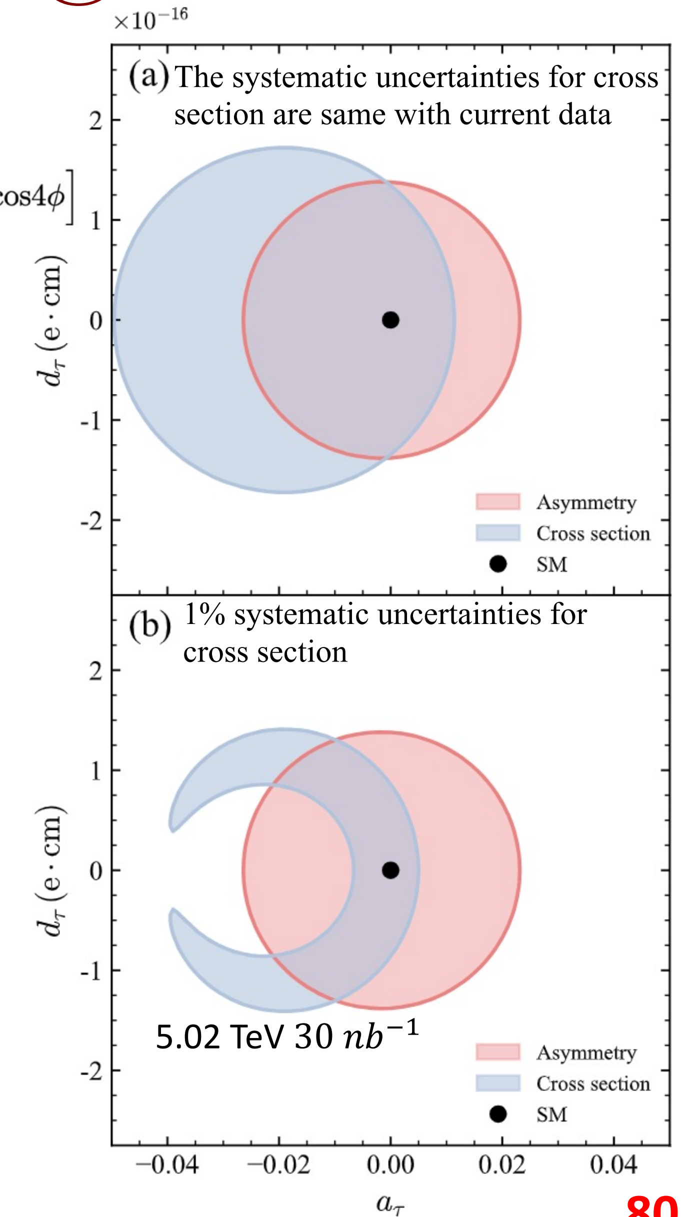
$$d\sigma \sim \left[A_0 + B_0^{(1)} F_2 + B_0^{(2)} F_2^2 + C_0^{(2)} F_3^2 + \left(A_2 + B_2^{(2)} F_2^2 + C_2^{(2)} F_3^2\right)\cos 2\phi + A_4 \cos 4\phi\right]$$

$$F_2(0) = a_\tau, \quad F_3(0) = 2\frac{m_\tau d_\tau}{e}$$

Suppressed by lepton mass

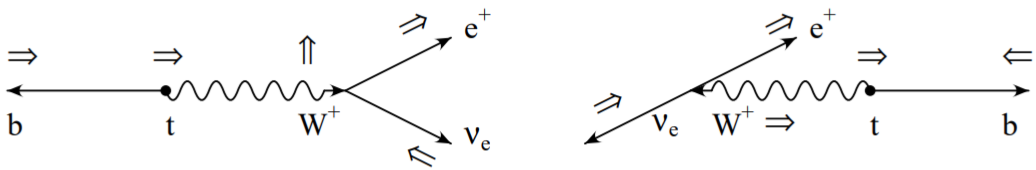
$$A_{c2\phi} = \frac{\sigma(\cos 2\phi > 0) - \sigma(\cos 2\phi < 0)}{\sigma(\cos 2\phi > 0) + \sigma(\cos 2\phi < 0)}$$

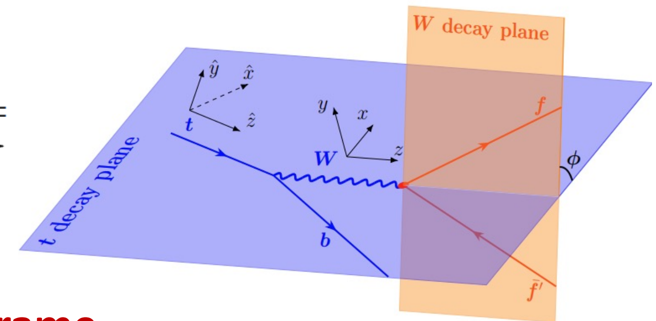




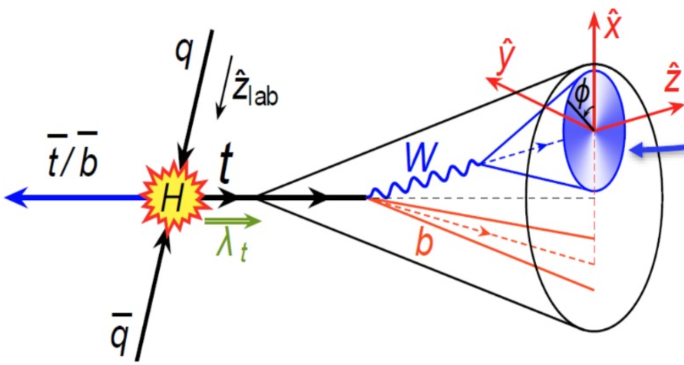
Linear polarization of W boson

Zhite Yu, C.-P. Yuan, PRL 129 (2022) 11,11





W boson is not linearly polarized in top quark rest frame



$$\frac{dE}{d\phi} = \frac{E_{tot}}{2\pi}[1 + \xi \cos 2\phi]$$ **Infrared safe**

Boosted limit: $\xi = \xi(\lambda_t) = 0.145(\lambda_t - 1)$

[Assuming SM tbW coupling]

Azimuthal correlation

Boosted top polarization

- Measuring longitudinal polarization of boosted top
- New top tagger against QCD jets

A new tool to probe the NP effects,
e.g. the CP violation in top quark decay

总结

- 粒子物理研究物质最深层次的结构和最基本的相互作用
- 当前粒子物理最成功的理论是粒子物理标准模型
- 粒子物理目前仍然面临众多挑战

  暗物质的性质，中微子的质量起源

  宇宙中观测到的正反物质不对称性

  电弱对称性的自发破缺机制
- 对撞机实验是寻找超出标准模型新物理的重要探针
- 希格斯物理是当前和未来对撞机实验关注的重要研究方向
- 极化效应将是寻找超出标准模型新物理的重要手段
- Madgraph ≠ 对撞机物理