

Electroweak Symmetry Restoration @ High Energies

Tao Han

Pitt PACC, University of Pittsburgh

60th Rencontres de Moriond EW
La Thuile, March 18, 2026





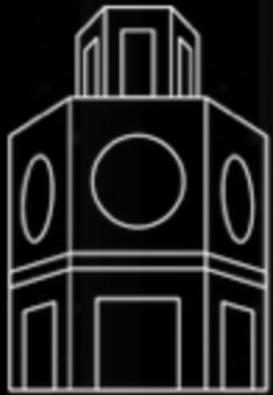
What is Particle Theory?

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Theoretical Physics



What Is “Electroweak Theory”?



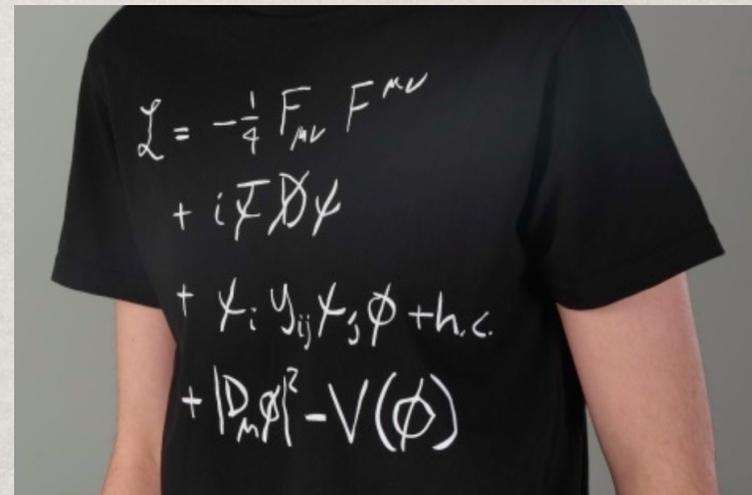
What is Particle Theory?

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What Is “Electroweak Theory”?

**The answer is:
or not ?**



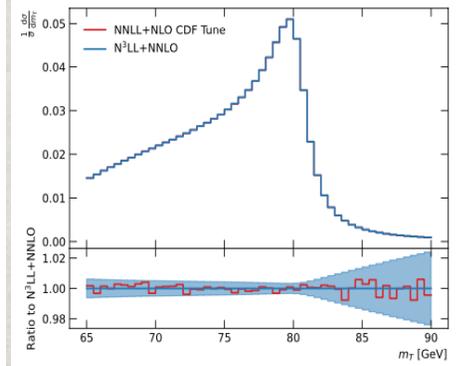
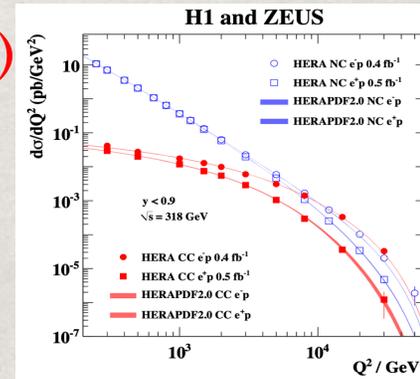
In light of the EW Rencontres of Moriond

• Electroweak Gauge Theory

- In our daily life, we live in a **deeply broken phase**, no sign of EW gauge symmetry! The “weak” force:

$$\mathcal{M}(n \rightarrow p^+ e^- \bar{\nu}) \sim G_F \bar{p} \mathcal{O}^\mu n \bar{e} \mathcal{O}_{\mu\nu} \nu, \quad G_F \approx 1/(300 \text{ GeV})^2$$

- At the EW scale $\sim \mathcal{O}(100 \text{ GeV})$
 - Non-Abelian gauge structure
 - Gauge coupling universality
 - Spontaneous symm breaking



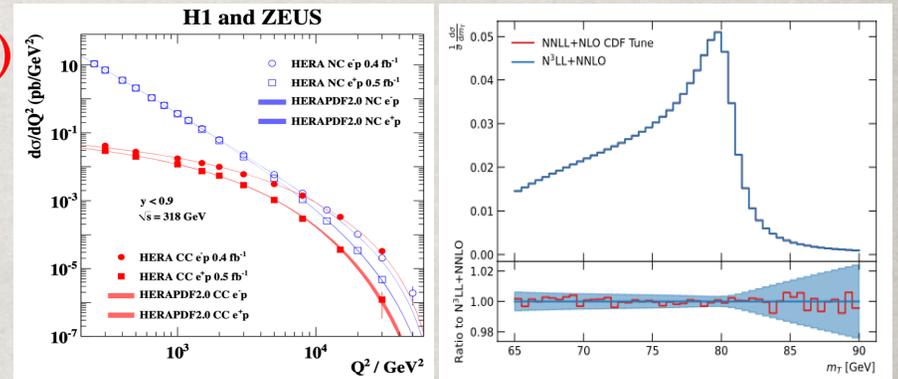
CDF: $\Delta M_w / M_w \sim 10^{-4}$

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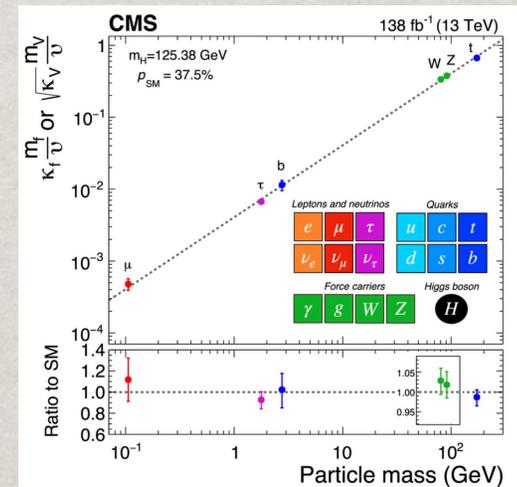
Yet, we are still in a **broken phase**:
massive bosons:

$$\begin{aligned} & M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \\ & \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \right. \\ & \left. \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\ & W_\nu^- \partial_\nu W_\mu^+)] - ig s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \end{aligned}$$

massive fermions & flavor mixing:

$$\begin{aligned} & \frac{g}{2} \frac{m_e^\lambda}{M} [H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\ & m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \end{aligned}$$

CDF: $\Delta M_w / M_w \sim 10^{-4}$



$\Delta m_h / m_h \sim 10^{-3}$

• Spontaneous Symmetry Breaking

- In a **broken or superconducting phase**:
London penetration depth
-- the Meissner effect:

$$\lambda \sim 1/M_W \approx 10^{-9} \text{ nm, in } 10^{-24} \text{ s}$$

The SM scalar sector:

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV}$$

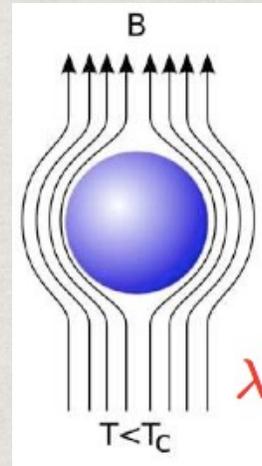
$$m_H = \sqrt{2\lambda}v = 125 \text{ GeV}$$

In CM, **BCS** as the underlying theory to calculate $\alpha(T)$ & $\beta(T)$!

What is the underlying theory to calculate μ^2 & λ ?

In any given theory: $\Delta m_h^2 \propto \Lambda^2$!

→ “naturalness” or Little Hierarchy problem.



← Superconducting phase

$$E^2 = p^2 c^2 + m^2 c^4$$

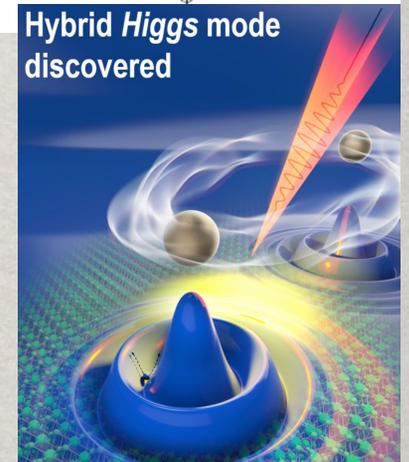
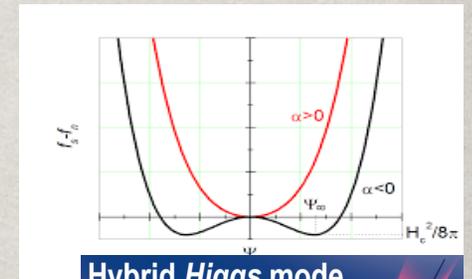
gap leads to $\sim \exp(-r/\lambda)$

$\lambda \sim m^{-1}$ penetration depth

Landau-Ginzburg Theory:

$$F = \alpha(T)|\psi|^2 + \frac{\beta(T)}{2}|\psi|^4$$

$$|\psi|^2 = -\frac{\alpha(T)}{\beta(T)}$$



Laser @ 10^{12} Hz (2021)

• Longitudinal gauge bosons

- 1st observation of W_L in top decay (CDF/D0, 2000)

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta^*} = \frac{3}{4} (1 - \cos^2 \theta^*) F_0 + \frac{3}{8} (1 - \cos \theta^*)^2 F_L + \frac{3}{8} (1 + \cos \theta^*)^2 F_R$$

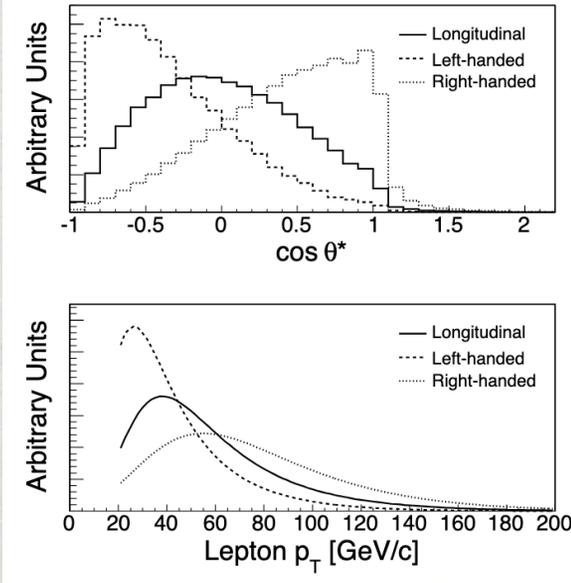
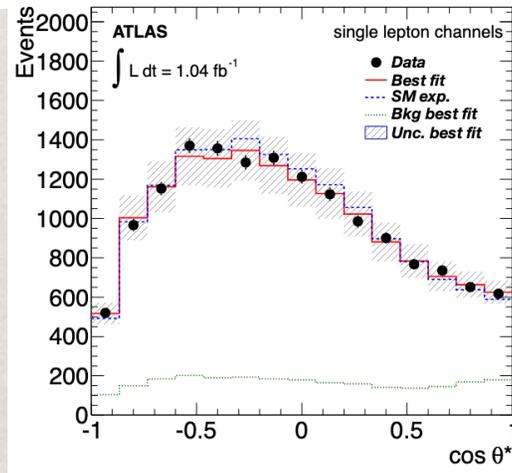
$$\Gamma_{W_L} / \Gamma_{W_T} \approx m_t^2 / 2M_W^2 \approx 2.$$

W_L dominant!

CDF: hep-ex/0511023;

ATLAS: 1205.2484;

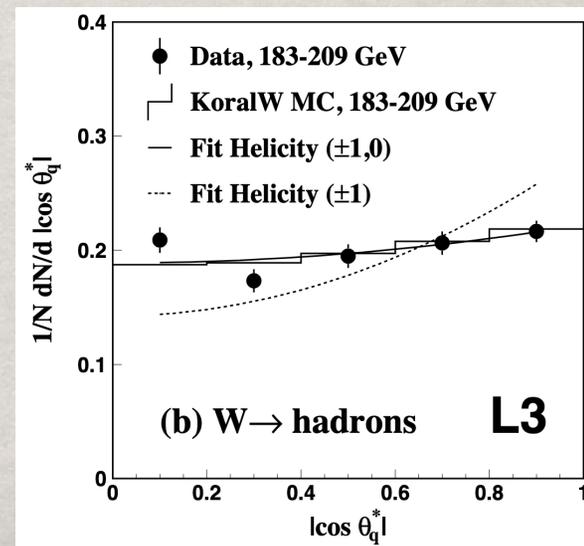
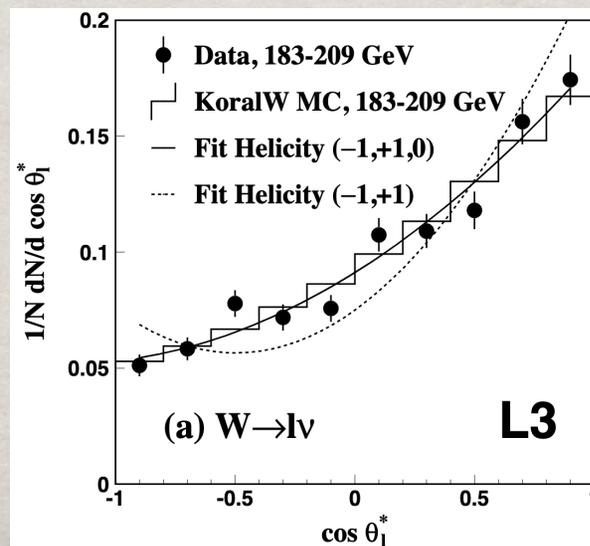
CMS: 1308.3879



- 2nd observation: $e^+e^- \rightarrow W^+W^-$ at LEP (L3, 2003)

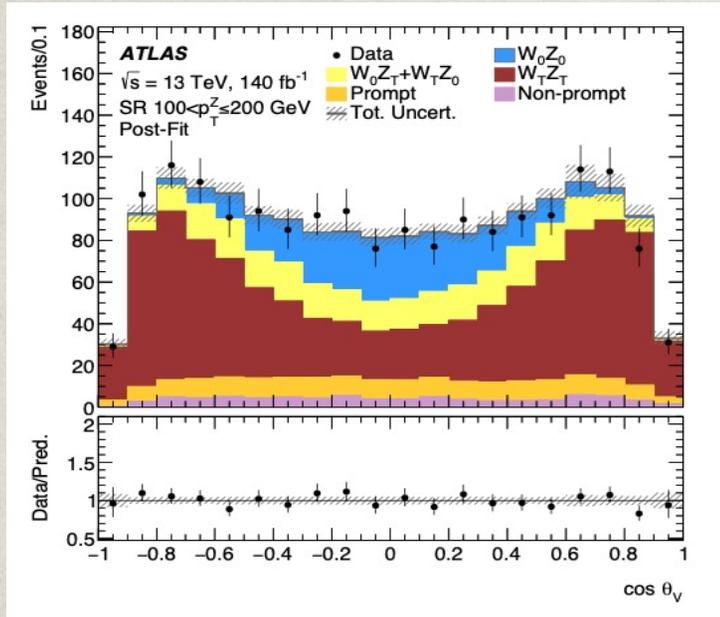
W_L fits at 3σ

PLB557, 147(2003)



• Longitudinal gauge bosons

- 3rd observation: $q\bar{q} \rightarrow W_L^\pm Z_L @ 7.1\sigma$ at ATLAS:



$W_L Z_L$ observation
 & utilization of the
 “Radiation Amplitude Zero”

ATLAS:

arXiv:2211.09435: PLB 2023

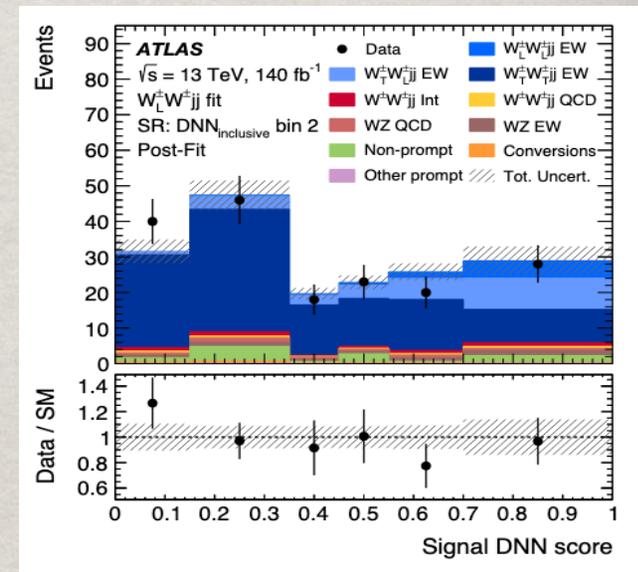
arXiv:2402.16365: PRL 2024

- 4th observation (?): $W^\pm W^\pm \rightarrow W_L^\pm W_L^\pm$
 at the LHC: at least $1 W_L @ 3.3\sigma$

CMS: arXiv:2009.09429, ATLAS: arXiv:2503.11317

(see talks in this conference)

Great step to scrutinizing EWSB !



Goldstone-boson Equivalence Theorem (GET):

Lee, Quigg, Thacker (1977); Chanowitz, Gailard (1984);
Y.-P. Yao, C.-P. Yuan (1988); J. Bagger, C. Schmidt (1990) ...

At high energies $E \gg M_W$, the longitudinally polarized gauge bosons behave like the corresponding Goldstone bosons. (They remember their origin!)

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V_L wavefunction:

$$\epsilon_L^\mu(p) = \frac{E}{M}(\beta, \hat{p}) = \frac{p^\mu}{M} - \frac{1}{1+\beta} \frac{M}{E} n^\mu$$

trivial “scalarization”
(for any vector state)

symmetry
breaking residual

- Goldstone-bosons Equivalence Theorem:

At high energies: $\mathcal{M}(W_L^i W_L^j \rightarrow W_L^i W_L^j) \approx \mathcal{M}(\omega^i \omega^j \rightarrow \omega^i \omega^j)$

$W_L^i \rightarrow$ Correspond to the broken generators

- incomplete representation: $U = \exp\{i\omega^i \tau^i / v\}$
- nothing to say about the “Higgs boson”

\rightarrow The Higgs mechanism DOES NOT require a Higgs boson!

• The Higgs Boson

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.⁸ It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.⁹

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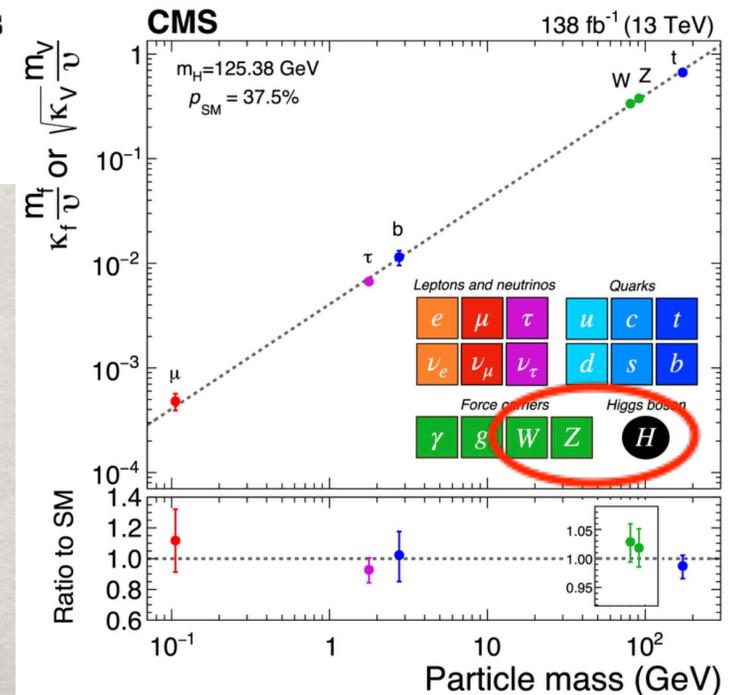
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Weak interactions at very high energies: The role of the Higgs-boson mass

Benjamin W. Lee,* C. Quigg,[†] and H. B. Thacker
Fermi National Accelerator Laboratory,[‡] Batavia, Illinois 60510
(Received 20 April 1977)

At energies very large compared with the Higgs-boson mass the trilinear term in the interaction Lagrangian (3.9) becomes ineffectual (contact terms dominate pole graphs at the tree level), so the theory displays an asymptotic O(4) symmetry. The fields $w_1, w_2, z,$ and h form a four-vector in

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} w_1 \\ w_2 \\ z \\ h \end{pmatrix} \quad \text{or} \quad U = \exp\{i\omega^i \tau^i / v\}$$

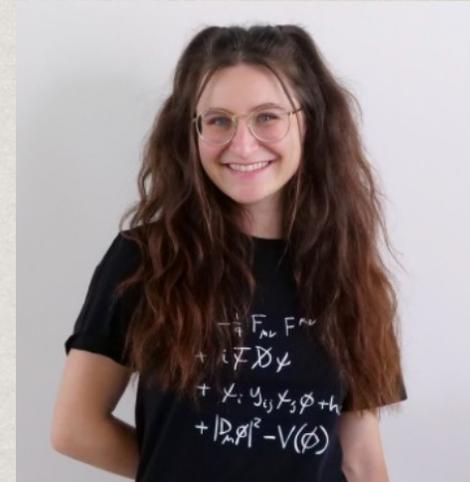


• EW Symmetry Restoration (EWSR)

$$\frac{v}{E} : \frac{v (250 \text{ GeV})}{10 \text{ TeV}} \approx \frac{\Lambda_{QCD} (300 \text{ MeV})}{10 \text{ GeV}} \quad v/E, m_t/E, M_W/E \rightarrow 0!$$

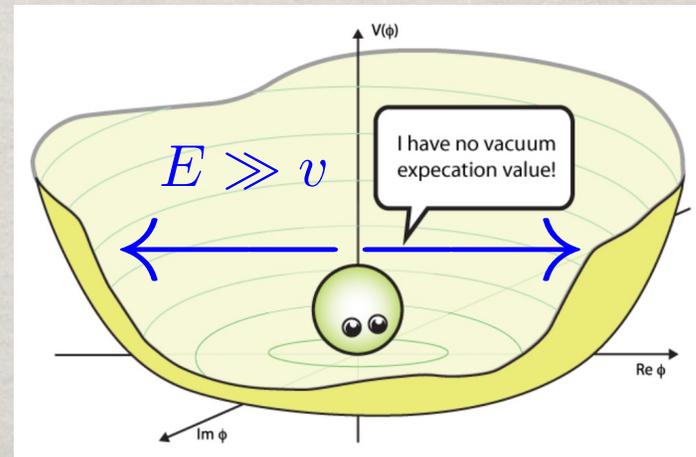
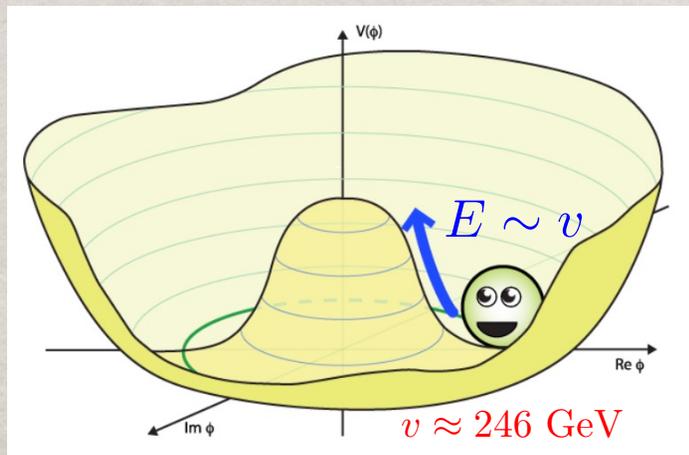
(i) the physics of the transverse gauge bosons (W_T^\pm, Z_T, γ) and fermions is described by a massless theory in the unbroken phase;

(ii) the longitudinal gauge bosons (W_L^\pm, Z_L) are scalarized as Goldstone bosons (ω^\pm, ω^0), and join the Higgs boson to restore the unbroken $O(4)$ symmetry (ω^\pm, ω^0, H) in the Higgs sector.



parametrically measured by: $\delta = \frac{M_W}{2E_W}$

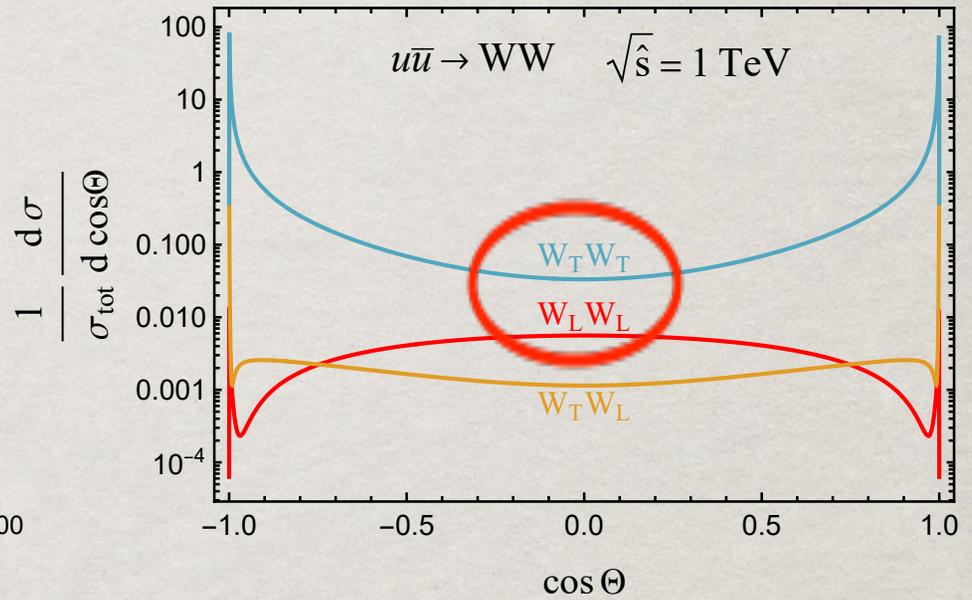
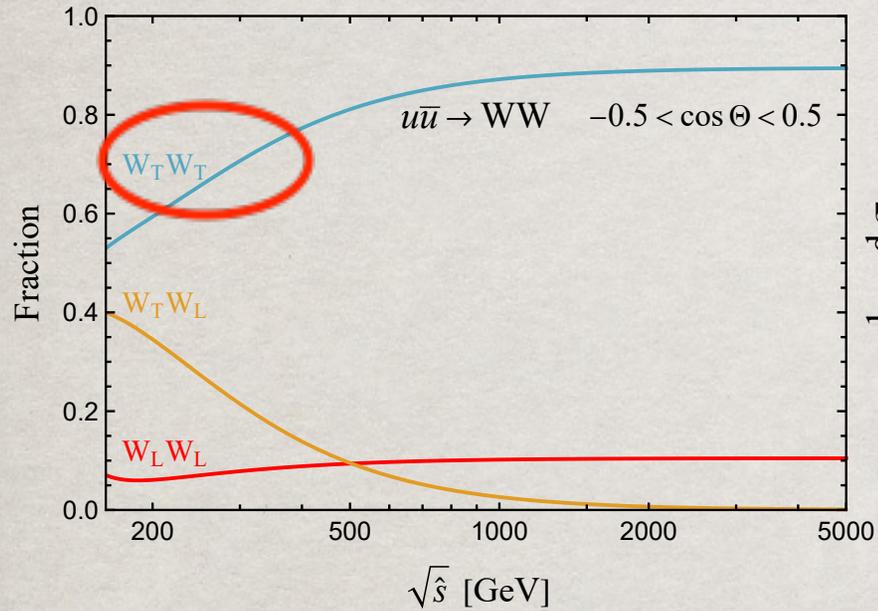
R. Capdevilla, TH, arXiv:2412.12336, PRL



Physics with Gauge Boson Pairs

$$pp \rightarrow W^+ W^-$$

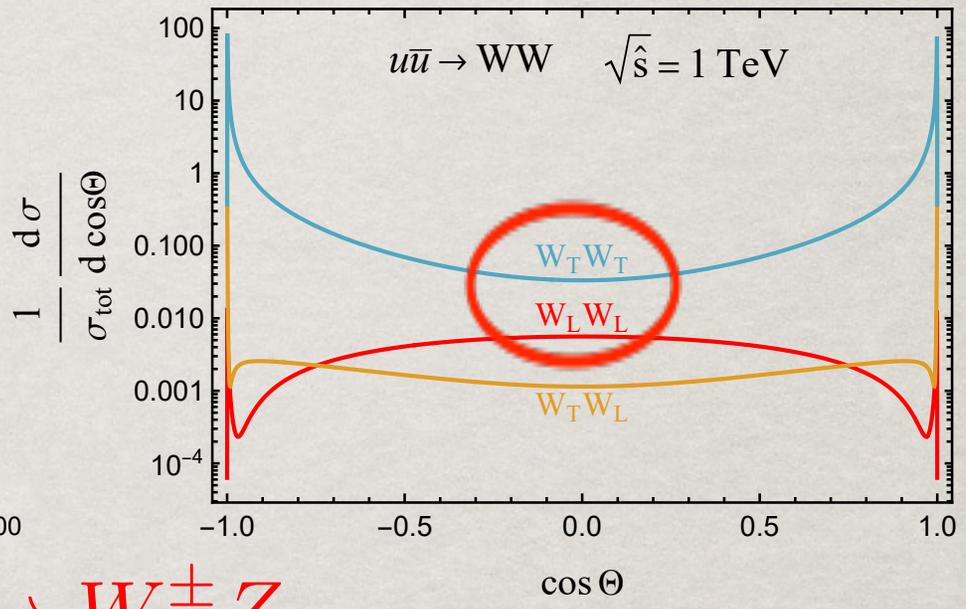
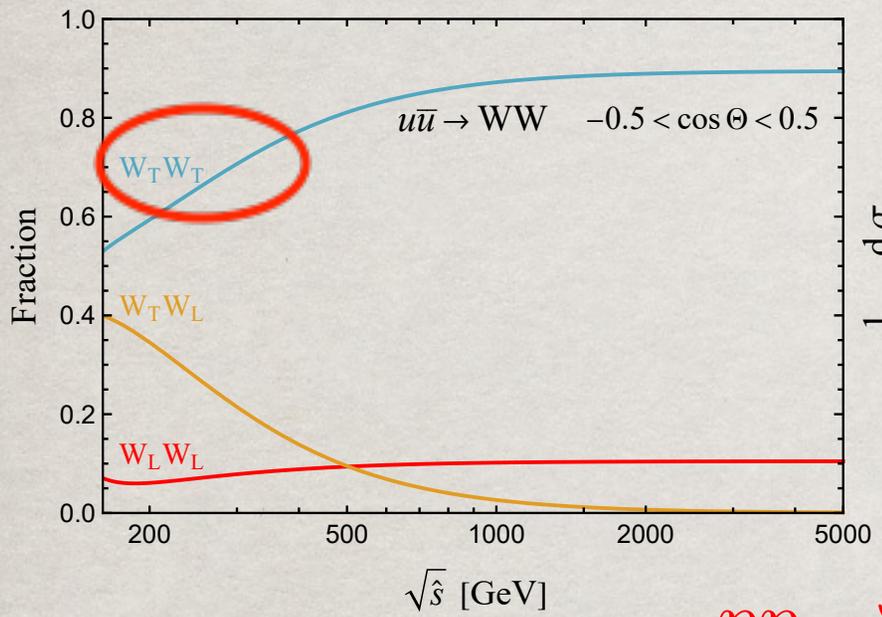
K. Cheng, TH, T. A. Wu, to appear



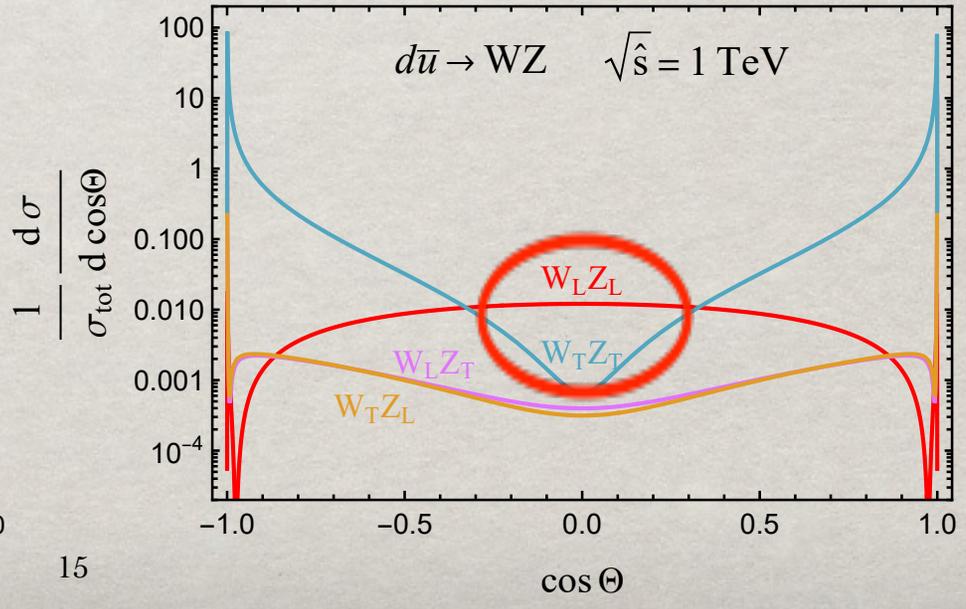
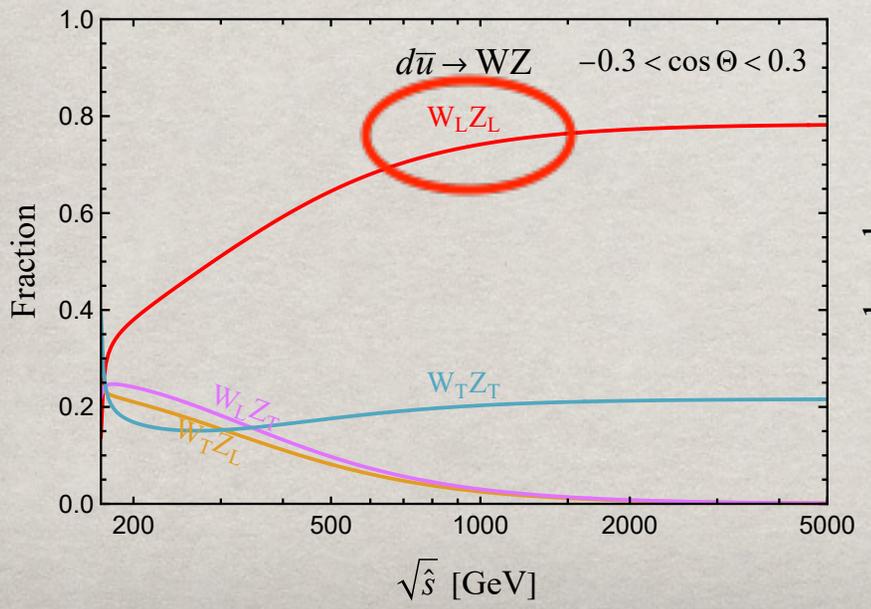
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$pp \rightarrow W^\pm Z$



• Radiation Amplitude Zeros (RAZs)

VOLUME 43, NUMBER 11

PHYSICAL REVIEW LETTERS

10 SEPTEMBER 1979

Magnetic Moment of Weak Bosons Produced in pp and $p\bar{p}$ Collisions

K. O. Mikaelian and M. A. Samuel

Physics Department, Oklahoma State University, Stillwater, Oklahoma 74074

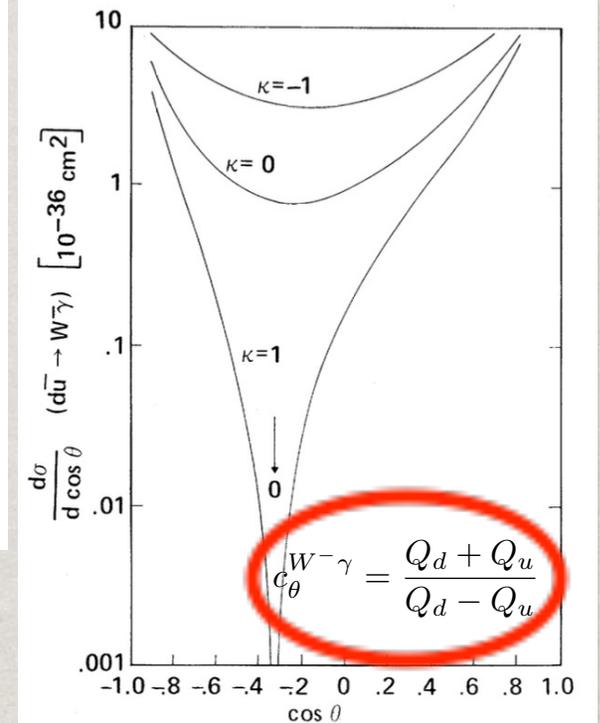
and

D. Sahdev

Physics Department, Case Western Reserve University, Cleveland, Ohio 44106

(Received 5 June 1979)

We suggest that the reactions $p\bar{p} \rightarrow W^\pm \gamma X$ and $p\bar{p} \rightarrow W^\pm \gamma X$ are good candidates for measuring the magnetic moment parameter κ in $\mu_W = (e/2M_W)(1+\kappa)$. The angular distribution of the W bosons in $p\bar{p} \rightarrow W^\pm \gamma X$ is particularly sensitive to this parameter. For the gauge-theory value of $\kappa = 1$, we have found a peculiar zero in $d\sigma(d\bar{u} \rightarrow W^- \gamma)/d \cos \theta$ at $\cos \theta = -\frac{1}{3}$, the location of this zero depending on the quark charge through $\cos \theta = -(1+2Q_d)$. A similar zero occurs in $d\sigma(u\bar{d} \rightarrow W^+ \gamma)/d \cos \theta$. We can offer no explanation for this behavior.



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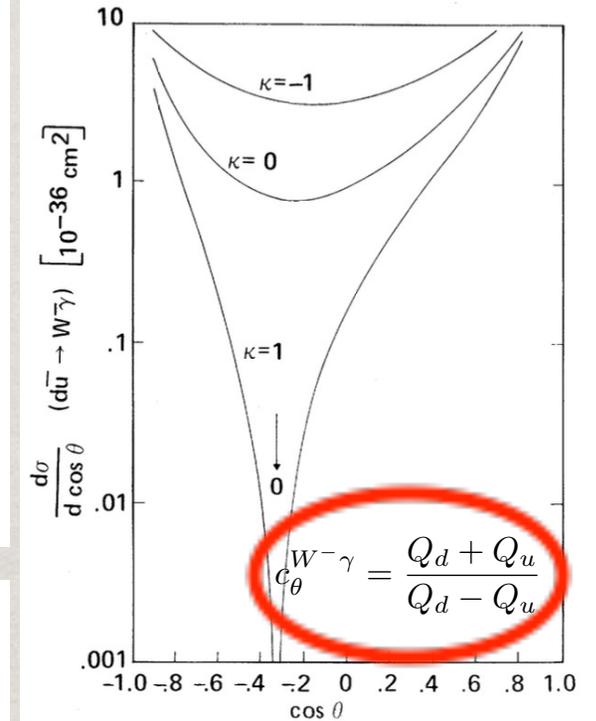
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VOLUME 72, NUMBER 25

PHYSICAL REVIEW LETTERS

20 JUNE 1994

Amplitude Zeros in $W^\pm Z$ Production

U. Baur

Department of Physics, Florida State University, Tallahassee, Florida 32306

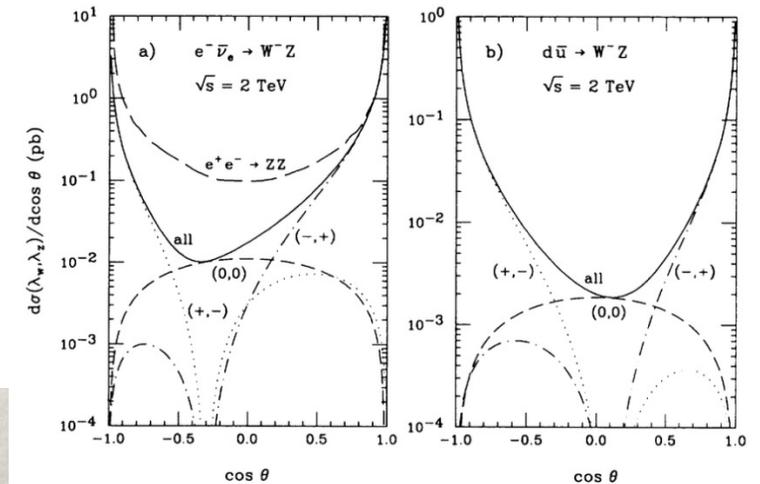
T. Han and J. Ohnemus

Department of Physics, University of California, Davis, California 95616

(Received 9 March 1994)

We demonstrate that the standard model amplitude for $f_1 \bar{f}_2 \rightarrow W^\pm Z$ at the Born level exhibits an approximate zero located at $\cos\theta = (g_-^{f_1} + g_-^{f_2}) / (g_-^{f_1} - g_-^{f_2})$ at high energies, where the $g_-^{f_i}$ ($i = 1, 2$) are the left-handed couplings of the Z boson to fermions and θ is the center of mass scattering angle of the W boson. The approximate zero is the combined result of an exact zero in the dominant helicity amplitudes $\mathcal{M}(\pm, \mp)$ and strong gauge cancellations in the remaining amplitudes. For non-standard WWZ couplings these cancellations no longer occur and the approximate amplitude zero is eliminated.

$$C_\theta^{W^- Z_T} = \frac{g_-^d + g_-^u}{g_-^d - g_-^u}$$



Gauge / scalar separation: R. Capdevilla, TH, arXiv:2412.12336 (PRL)

$$\begin{aligned}
 f_1 \bar{f}_2 &\rightarrow W^\pm \gamma, \\
 f_1 \bar{f}_2 &\rightarrow W^\pm Z, \\
 f_1 \bar{f}_2 &\rightarrow W^\pm H.
 \end{aligned}$$

$$\begin{aligned}
 \mathcal{M}_{\pm\mp}^{W\gamma} &\approx -\frac{geV_{12}}{\sqrt{2}} \frac{(\lambda_w - c_\theta)}{s_\theta} \left[Q_{(1-2)c_\theta} - Q_{(1+2)} \right], \\
 \mathcal{M}_{\pm\mp}^{WZ} &\approx \frac{gg_z V_{12}}{\sqrt{2}} \frac{(\lambda_w - c_\theta)}{s_\theta} \left[g_-^{(1-2)} c_\theta - g_-^{(1+2)} \right], \\
 \mathcal{M}_{00}^{WZ} &\approx -\frac{g_z^2 V_{12}}{2\sqrt{2}} s_\theta g_-^{(1-2)} = \frac{g^2 V_{12}}{2\sqrt{2}} s_\theta, \\
 \mathcal{M}_0^{WH} &\approx \frac{g^2 V_{12}}{2\sqrt{2}} s_\theta,
 \end{aligned}$$

- Gauge sector: Radiation Amplitude Zeros (RAZs)

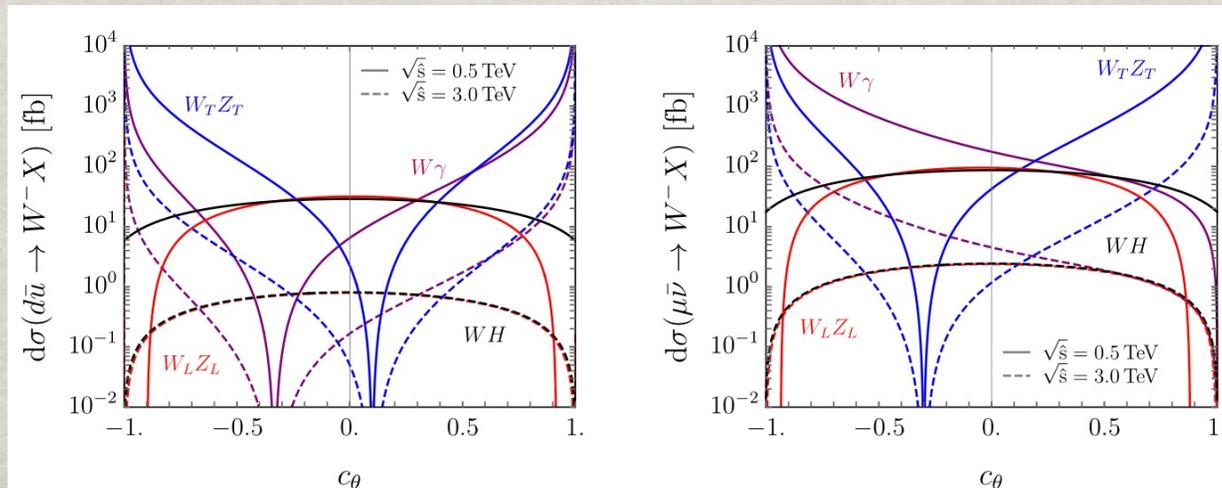
EM: $c_\theta^{W^- \gamma} = \frac{Q_d + Q_u}{Q_d - Q_u}$; EW (transverse): $c_\theta^{W^- Z_T} = \frac{g_-^d + g_-^u}{g_-^d - g_-^u}$

Mikaelian, Samuel (1979)

$$c_{\theta_0} = \begin{cases} -1/3 (\approx 0.1) & \text{for } d\bar{u} \rightarrow W_T^- \gamma (W_T^- Z_T), \\ 1 (\approx -0.3) & \text{for } \ell^- \bar{\nu} \rightarrow W_T^- \gamma (W_T^- Z_T), \end{cases}$$

U. Baur, TH, JO, (1994)

- Higgs scalar sector: $\mathcal{M}^{W_L Z_L} (\delta \ll 1) \approx \mathcal{M}^{W_L h} (\delta \ll 1)$



Test EWSR @ LHC / muon Collider

R. Capdevilla, TH, arXiv:2412.12336; Huang, Lewis, Lane, Liu, arXiv:2009.09429

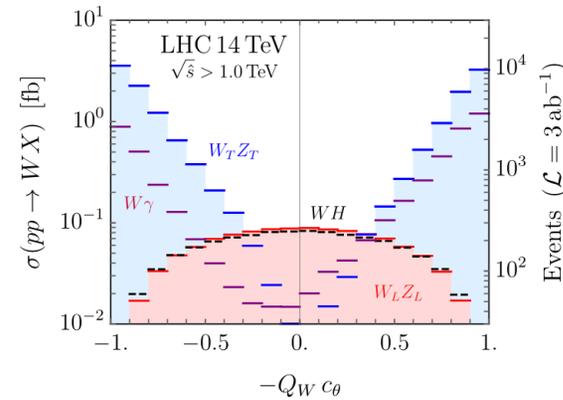
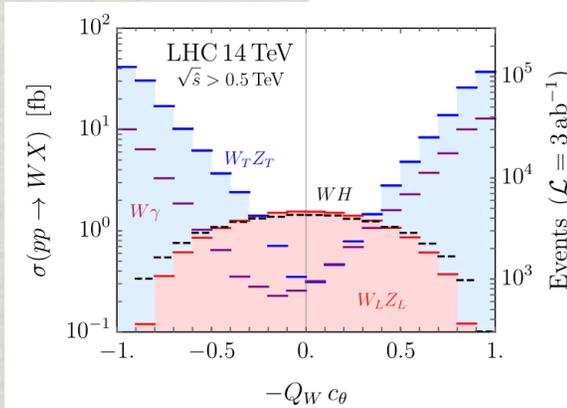
Massless gauge sector & Higgs sector:

$$r_{Z\gamma} = \frac{\sigma(WZ)}{\sigma(W\gamma)}, \quad r_{ZH} = \frac{\sigma(WZ)}{\sigma(WH)}$$

For $\delta = M_W/2E \ll 1$:

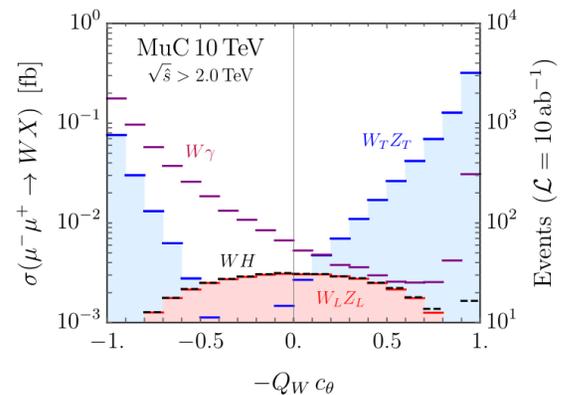
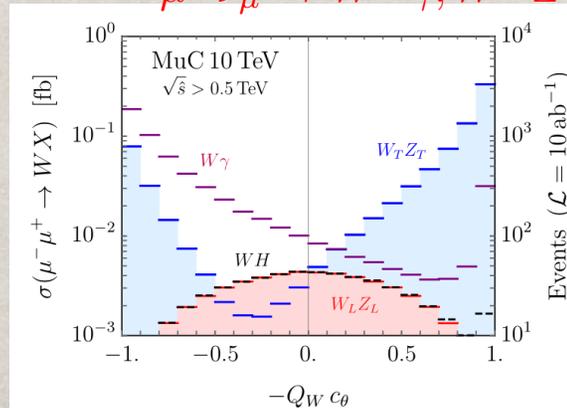
$$\frac{\sigma(W_T Z_T)}{\sigma(W_T \gamma)} \approx \frac{g_z^2 (g_-^{f1})^2 + (g_-^{f2})^2}{e^2 (Q_1^2 + Q_2^2)} \quad \sigma(W_L^\pm Z_L) \sim \sigma(W_L^\pm H),$$

$$\text{or } \sigma(\omega^\pm \omega^0) \sim \sigma(\omega^\pm H)$$



$$\mu^\pm \nu_\mu \rightarrow W^\pm \gamma, W^\pm Z$$

$$\delta \approx M_W/2 \text{ TeV} < 5\%$$



What do we learn in testing EWSR?

“endlessly confirm the correctness of SM” - Carlo Rubia

SMEFT BSM

vs.

HEFT BSM

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + H + i\phi^0 \end{pmatrix},$$

$$\mathcal{L}_{\text{SMEFT},\mu\phi} = - \sum_{n=1}^{\infty} \frac{c_{\varphi}^{(2n+4)}}{\Lambda^{2n}} (\varphi^\dagger \varphi)^{n+2}$$

$$U = e^{2i\phi^a T_a / v} \quad \text{with} \quad \phi^a T_a = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix},$$

$$\mathcal{L}_{Uh} = \frac{v^2}{4} \text{tr}[D_\mu U^\dagger D^\mu U] F_U(H) + \frac{1}{2} \partial_\mu H \partial^\mu H - V(H)$$

weakly coupled (SUSY, 2HDM)

strongly coupled (composite)

new scale $\sim \Lambda$

nearby scale $\sim 4\pi v$

At the LHC: Higgs coupling SM-like $\sim 10\%$

What do we learn in testing EWSR?

“endlessly confirm the correctness of SM” - Carlo Rubia

SMEFT BSM

vs.

HEFT BSM

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + H + i\phi^0 \end{pmatrix},$$

$$\mathcal{L}_{\text{SMEFT}, \mu\phi} = - \sum_{n=1}^{\infty} \frac{c_{\varphi}^{(2n+4)}}{\Lambda^{2n}} (\varphi^\dagger \varphi)^{n+2}$$

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weakly coupled (SUSY, 2HDM)

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At the LHC: Higgs coupling SM-like $\sim 10\%$

(light) Fermion Yukawa's wide open:

$$- \sum_{n=1}^{\infty} \frac{c_{\ell\varphi}^{(2n+4)}}{\Lambda^{2n}} (\varphi^\dagger \varphi)^n (\bar{\ell}_L \varphi \mu_R + \text{h.c.})$$

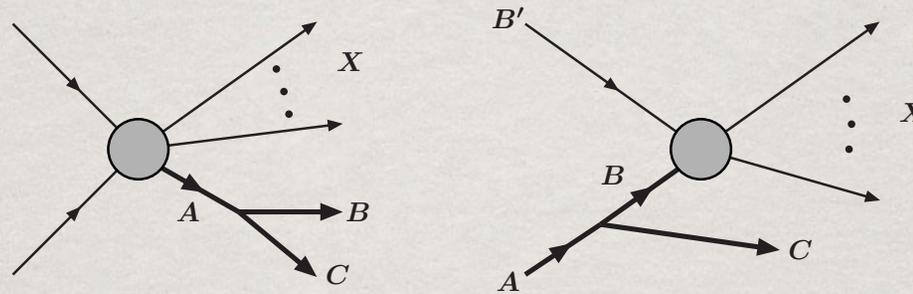
$$- \frac{v}{\sqrt{2}} [\bar{\ell}_L Y_\ell(H) U P_- \ell_R + \text{h.c.}]$$

$$Y_\ell(H) = \frac{\sqrt{2} m_\mu}{v} + \sum_{k \geq 1} y_{\ell,k} \left(\frac{H}{v} \right)^k$$

E. Celada, TH et al., arXiv:2312.13082

Other Aspects of EWSR

Splitting: the dominant phenomena

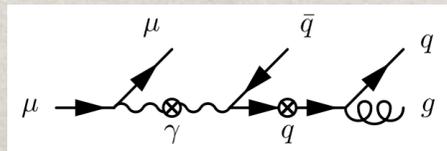


$$d\sigma_{X,BC} \simeq d\sigma_{X,A} \times d\mathcal{P}_{A \rightarrow B+C}$$

For the factorization to be valid:

- Power corrections suppressed: $M_W^2/Q^2 \ll 1$
- Log corrections (RGE) large: $\alpha_2 \ln^2(Q^2/M_W^2) \sim \mathcal{O}(1)$

EW “partons” dynamically generated



$$\frac{df_i}{d \ln Q^2} = \sum_I \frac{\alpha_I}{2\pi} \sum_j P_{i,j}^I \otimes f_j$$

EW shower/jets: $W^* \rightarrow q\bar{q}g \dots, \ell^\pm \nu \gamma \dots$
 $t^* \rightarrow b\bar{b}W^*, tZ^*, th^* \dots$
 $\nu^* \rightarrow \ell^\pm W^* \dots \rightarrow \text{EW jets}$

Conclusions

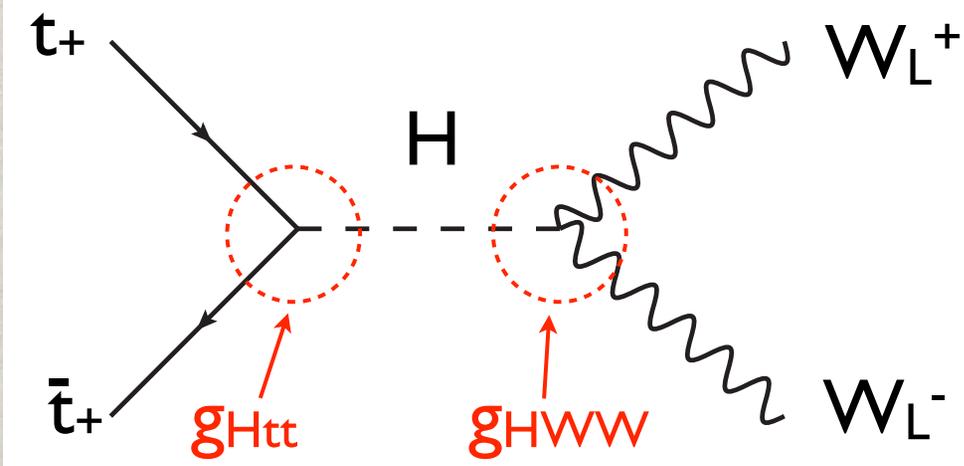
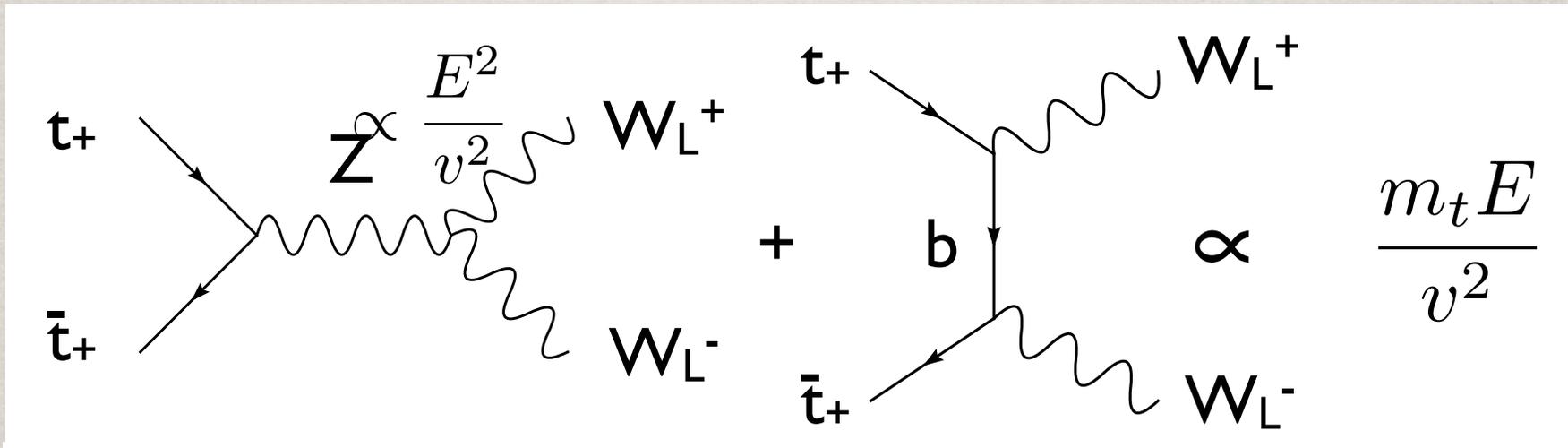
- EW physics @ high energies remains exciting and challenging!
 - We are approaching the EW symmetric phase measured by $M_W/2E$.
- Longitudinal gauge bosons (W_L^i) + Higgs (h) form an $O(4)$ multiplet:
sensitive to underlying EWSB as well as BSM:
weakly coupled vs strongly coupled theories.
- EW PDF's & EW jets to emerge @ high energies!

Electroweak physics rich!

Thank you!

High-energy behavior: V_L & the role of H

$$\epsilon(k)_L^\mu = \frac{E}{m_W} (\beta_W, \hat{k}) \approx \frac{k^\mu}{m_W} \quad \text{“bad” high-energy behavior!}$$



Higgs boson save the day:

$$\propto \frac{m_t m_H}{v^2}$$

“UV complete”? How far?

D. Dicus & V. Mathur (1973);
Lee, Quigg, Thacker (1977).

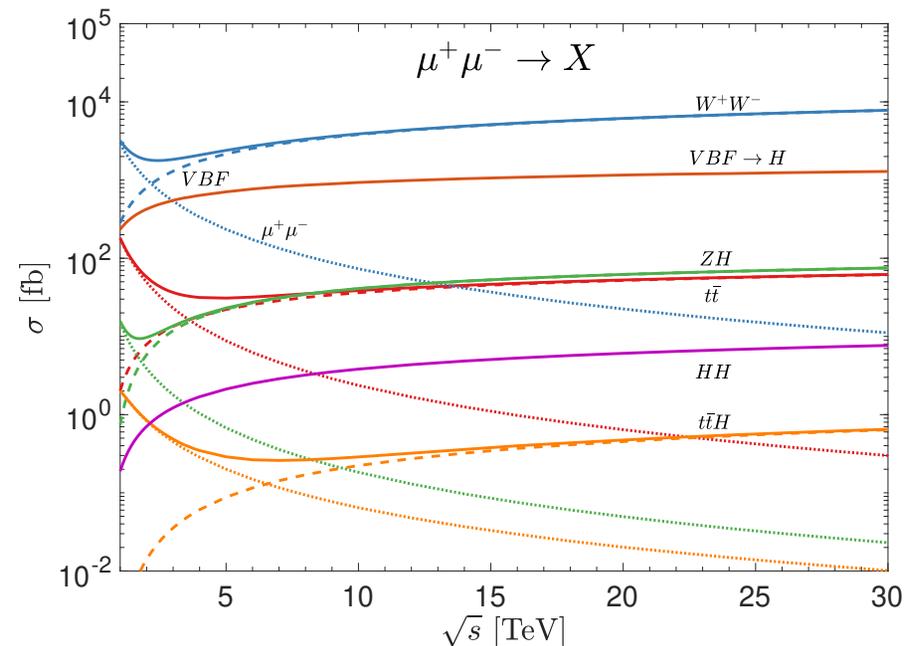
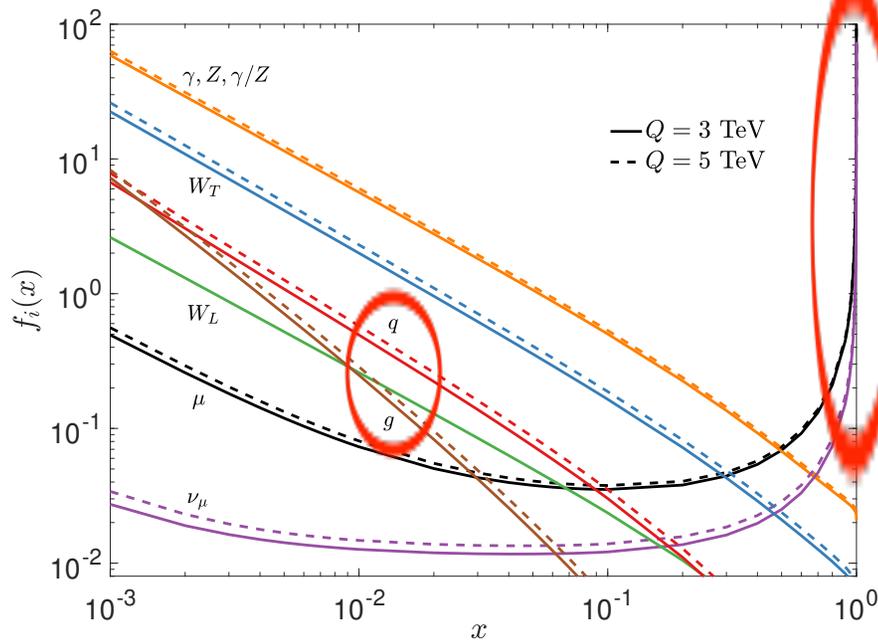
A Multi-TeV $\mu^+\mu^-$ Collider

EW PDF's via DGLAP

$$\frac{df_i}{d \ln Q^2} = \sum_I \frac{\alpha_I}{2\pi} \sum_j P_{i,j}^I \otimes f_j$$

$\mu^+\mu^-$ annihilations $\sigma \sim \beta^{2\ell+1}/S$

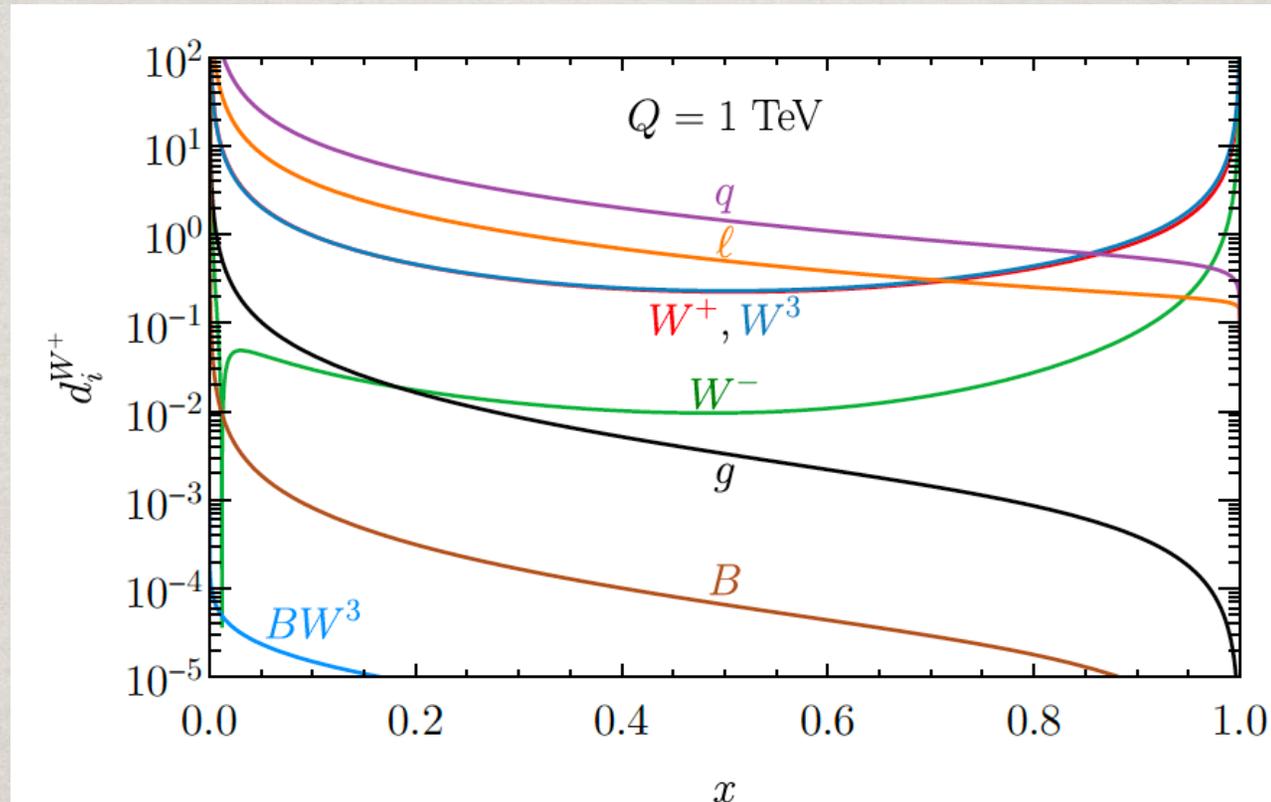
VBF $\sigma \sim \frac{1}{M_{VV}^2} \ln \frac{Q^2}{M_W^2}$



J.M. Chen, TH & B. Tweedie, arXiv:1611.00788;
TH, Ma, Xie, arXiv:2203.11129

“Leptonic showering”

finding a W^+ in the mother particle i (i.e., $i \rightarrow W$)



- With **W/Z** showers, all **leptons/neutrino** components exist!
- EW “jets”: *e.g.*, a HE $\nu \rightarrow$ an **observable jet!**

J.M. Chen, TH & B. Tweedie, arXiv:1611.00788;
TH, Ma, Xie, arXiv:2203.11129